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## Analysis Note

# Measurement of charged particle production in diffractive proton-proton collisions at $\sqrt{s} = 200$ GeV with tagging of the forward scattered proton

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In this note we present the analysis of the Single Diffractive Dissociation process with the STAR Roman Pot (RP) detectors at RHIC. The measurement is focused on the charged particle multiplicity, its dependence on the transverse momentum and pseudorapidity in three regions of  $\xi$ :  $0.02 < \xi < 0.05$ ,  $0.05 < \xi < 0.1$  and  $0.1 < \xi < 0.2$ . The identified particle to antiparticle (pion, kaon, proton and their antiparticle) multiplicity ratios as a function of transverse momentum in above three  $\xi$  regions are also measured. The data come from proton-proton collisions collected in 2015. The forward proton was tagged in the STAR Roman Pot system while the charged particle tracks were reconstructed in the STAR Time Projection Chamber (TPC). We describe all stages of the analysis involving comparison of the data with MC simulations and systematic uncertainty studies. More technical parts of the analysis are described in a supplementary analysis note [1].

<sup>3</sup> **List of contributions**

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|                    |   |
|--------------------|---|
| Leszek Adamczyk    | Analysis coordination/supervision, production of picoDST, production of embedded MC samples |
| Lukasz Fulek*      | Main analyzer, write-up author  |
| Mariusz Przybycień | Analysis supervision  |
| Rafal Sikora       | Analysis support  |

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<sup>7</sup> \* - contact editor

<sup>9</sup> **Change log**

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<sup>44</sup> **Acronyms**

|               |            |                          |
|---------------|------------|--------------------------|
| <sup>45</sup> | <b>CD</b>  | Central Diffraction      |
| <sup>46</sup> | <b>DD</b>  | Double Diffraction       |
| <sup>47</sup> | <b>MBR</b> | Minimum Bias Rockefeller |
| <sup>48</sup> | <b>MC</b>  | Monte Carlo              |
| <sup>49</sup> | <b>ND</b>  | Non-Diffractive          |
| <sup>50</sup> | <b>QCD</b> | Quantum Chromodynamics   |
| <sup>51</sup> | <b>RP</b>  | Roman Pot                |
| <sup>52</sup> | <b>SaS</b> | Schuler and Sjöstrand    |
| <sup>53</sup> | <b>SD</b>  | Single Diffraction       |
| <sup>54</sup> | <b>TPC</b> | Time Projection Chamber  |

# 1. Introduction

Inclusive measurements of charged-particle distributions in proton–proton ( $pp$ ) collisions probe the strong interaction in the low-momentum transfer, non-perturbative regime of Quantum Chromodynamics (QCD). In this kinematic region interactions are usually described by phenomenological models implemented in Monte Carlo (MC) event generators. Measurements can be used to constrain the free parameters of these models. An accurate description of low-energy strong interaction processes is essential for understanding and precise simulation of different types of  $pp$  processes and the effects of multiple  $pp$  collisions in the same bunch crossing at high instantaneous luminosity at hadron colliders. Measurements with tagging of the forward-scattered proton are of special interest. They give direct access to specific but still significant part of  $pp$  processes called diffraction. In addition precise modelling of forward particle production is essential for better understanding of the longitudinal development of air showers observed in experiments studying cosmic radiation.

We present a measurement of charged particle production in events with single forward proton tagging (dominated by Single Diffraction (SD):  $p + p \rightarrow p + X$ ). The following observables are studied:

$$\frac{1}{N_{\text{ev}}} \frac{dN_{\text{ev}}}{dn_{\text{ch}}}, \quad \frac{1}{N_{\text{ev}}} \frac{1}{2\pi p_{\text{T}}} \frac{d^2 N}{d\bar{\eta} dp_{\text{T}}}, \quad \frac{1}{N_{\text{ev}}} \frac{dN}{d\bar{\eta}} \quad (1.1)$$

where  $n_{\text{ch}}$  is the number of primary charged particles within kinematic range given by  $p_{\text{T}} > 200$  MeV and  $|\eta| < 0.7$ ,  $N_{\text{ev}}$  is the total number of events with  $2 \leq n_{\text{ch}} \leq 8$ ,  $N$  is the total number of charged particles within the above kinematic acceptance and  $\bar{\eta}$  is the pseudorapidity of the charged particle with longitudinal momentum taken with respect to direction of the forward scattered proton. To suppress non-SD events the trigger system required no signal in BBC-small in the direction of forward scattered proton and signal in BBC-small in opposite direction. The measurements are performed in a fiducial phase space of the forward scattered protons of  $0.04 < -t < 0.16$  GeV $^2/c^2$  and  $0.02 < \xi < 0.2$ , where  $\xi$  is the fractional energy loss of the scattered proton and  $t$  is the squared four momentum transfer. In case of SD process  $\xi = M_X^2/s$ , where  $M_X$  is the mass of the state  $X$  into which one of the incoming proton dissociates and  $s$  is the center of mass energy squared of the  $pp$  system. The Mandelstam variable  $t$  is defined by  $t = (p_1 - p_3)^2$ , where  $p_1$  is the four-momentum of the incoming proton,  $p_3$  is the four-momentum of the outgoing proton. The above mentioned observables are presented in three  $\xi$  regions:  $0.02 < \xi < 0.05$ ,  $0.05 < \xi < 0.1$  and  $0.1 < \xi < 0.2$ . In addition their average values are presented as a function of  $\xi$ .

We have also studied an identified particle to antiparticle (pion, kaon, proton and their anti-particle) multiplicity ratios as a function of  $p_{\text{T}}$  also in the above mentioned three regions of  $\xi$ . The system  $X$  into which proton diffractively dissociates has net charge and baryon number +1. It is believed that initial charge and barion number should appear in the very forward direction leading to the equal amount of particles and antiparticles in the central region created by fragmentation and hadronization processes. However other scenarios are also possible where extra baryon is uniformly distributed over rapidity [2] or even appear close to the gap edge [3]. It is natural to expect that possible charge and baryon number transfer to central region will be better visible at small  $\xi$  where amount of particle-antiparticle creation is smaller due to the generally smaller particle multiplicity or due to the fact that gap edge is inside our fiducial region of  $|\eta| < 0.7$ .

## 96 2. Monte Carlo Samples

97 MC samples used to correct data for detector effects were obtained by the embedding MC technique  
 98 [4], in which simulated particles are mixed with the real Zerobias events at the raw data  
 99 level. Zerobias data events used in the embedding were sampled over the entire data-taking period  
 100 in order to properly describe the data set used in the analysis. Two samples of embedding MC  
 101 were produced:

- 102 1. Single particle MC, in which particles are generated from flat distributions in  $\eta$  and  $p_T$ , in  
 103 order to have similar statistics in all bins.
- 104 2. The Schuler and Sjöstrand (SaS) model implemented in PYTHIA 8 with 4C tune.

105 Generated particles were passed through the full simulation of the STAR TPC and RP system  
 106 detectors using GEANT3 and GEANT4, respectively, and then embedded into real data sample.  
 107 These embedding events were next processed through the full event reconstruction chain.

108 It is preferred to get the detector corrections from a MC, which is dedicated to simulate  
 109 the studied physics process. However, for this purpose, the statistics in the MC should be several  
 110 times greater than in the analysed data sample. Since this is not possible with low efficiency of  
 111 TPC and TOF, the basic method of corrections used in the analysis for  $p_T$  and  $\bar{\eta}$  distributions  
 112 is a method of factorization of global efficiency into the product of single-particle efficiencies. In  
 113 this way, statistically precise multidimensional corrections on TPC and TOF were obtained from  
 114 the single particle MC. The energy loss correction was also determined from the same MC sample.  
 115 The charged-particle multiplicity distributions were unfolded from the measured multiplicities of  
 116 TPC tracks based on the response matrix, which takes into account all detector effects. In this  
 117 procedure single particle MC samples were not used.

118 All other detector corrections were obtained from PYTHIA 8 4C (SaS). In order to keep  
 119 statistical precision coming from the corrections high, samples filtered on true-level values of  $\xi$   
 120 and  $t$  (not necessarily with reconstructed proton track in RP) are used.

121 Several additional MC samples were generated, in which simulated particles were propagated  
 122 through full simulation and reconstruction chain but were not embedded into Zerobias events.  
 123 Systematic uncertainty related to hadronization of the diffractive system was determined by using  
 124 alternative hadronization models as implemented in HERWIG and EPOS. Results are compared  
 125 to model predictions from PYTHIA 8 4C (SaS), HERWIG, EPOS and alternative PYTHIA 8  
 126 model Minimum Bias Rockefeller (MBR) with A2 tune. EPOS predicts very large contribution  
 127 of forward protons, which originate from Non-Diffractive (ND) events and are well separated in  
 128 rapidity from other final state particles. This is the result of low mass excitation of the proton  
 129 remnant ( $< 1$  GeV) leading to hadronization of the beam remnant back to the proton. Therefore  
 130 EPOS predictions were separated in two classes: diffractive (EPOS SD) modelled by Pomeron  
 131 exchange and ND modelled by low mass excitation of the proton remnant (EPOS SD'). Such  
 132 remnant treatment is very unique in EPOS compared to other string models, especially, to that  
 133 used in PYTHIA 8, where ND forward protons are rare and arise from string fragmentation and  
 134 hadronization. In all PYTHIA 8 models, diffractive cross-sections are scaled by the factors, which  
 135 were introduced in order to describe the full phase space [5, 6]. In the SaS model, the scaling  
 136 factors for SD and DD,  $F_{SD}$  and  $F_{DD}$ , are defined as a function of diffractive masses:

$$F_{SD} = \left(1 - \frac{M^2}{s}\right) \left(1 + \frac{c_{res} M_{res}^2}{M_{res}^2 + M^2}\right) \quad (2.1)$$

$$F_{DD} = \left(1 - \frac{M_a^2 + M_b^2}{s}\right) \left(\frac{sm_p^2}{sm_p^2 + M_a^2 M_b^2}\right) \times \left(1 + \frac{c_{res} M_{res}^2}{M_{res}^2 + M_a^2}\right) \left(1 + \frac{c_{res} M_{res}^2}{M_{res}^2 + M_b^2}\right) \quad (2.2)$$

137 where  $M$  and  $M_a, M_b$  are the invariant masses of the systems  $X$  and  $X_a, X_b$  for SD and DD,  
138 respectively,  $c_{\text{res}} = 2$  and  $M_{\text{res}} = 2 \text{ GeV}/c^2$  were obtained from a fit to  $pp/\bar{p}p$  data [5]. On  
139 the other hand, in the MBR model the scaling factor is given as a function of the rapidity gap [6]:  
140

$$S = \frac{1}{2} \left[ 1 + \text{erf} \left( \frac{\Delta y - \Delta y_S}{\sigma_S} \right) \right] \quad (2.3)$$

141 where  $\Delta y$  is the rapidity gap,  $\Delta y_S = 2$  and  $\sigma_S = 0.5$ . As a result, diffractive cross sections are  
142 artificially suppressed at relatively large values of  $\xi (> 0.05)$ . This artificial suppression significantly  
143 changes predicted distribution of  $\xi$  and fractions of different processes in our fiducial phase space.  
144 Therefore data is also compared with expectations obtained without suppression of the diffractive  
145 cross sections (MBR-tuned).

146 Figure 2.1 (left) shows the distribution of  $\xi$  generated with EPOS (SD and SD+SD') and  
147 PYTHIA 8 SD (SaS, MBR and MBR-tuned). PYTHIA 8 (MBR) predicts a strong dependence of  
148 the cross section on  $\xi$ , which is much weaker in PYTHIA 8 (SaS and MBR-tuned) and the weakest  
149 in EPOS. This difference between PYTHIA 8 SaS and MBR models is expected since they are  
150 based on different Pomeron trajectories ( $\epsilon_{\text{SaS}} = 0, \epsilon_{\text{MBR}} = 0.104$ ). Only 30% of events in EPOS  
151 are SD, while the rest are SD'. Since all MC samples were generated with forward proton filter  
152 (a cut on the proton position in front of the RPs), the shapes of  $|t|$  distributions for these samples  
153 are biased. In order to compare them with each other, only their ratio to PYTHIA 8 (MBR)  
154 predictions is presented as a function of  $|t|$ . EPOS SD is only relevant for very small  $|t|$  (below  
155  $0.04 \text{ GeV}^2/c^2$ ) and is suppressed in the STAR acceptance region,  $0.04 < |t| < 0.16$ , where EPOS  
156 SD' contribution dominates. The  $t$ -slope is very different for EPOS SD and EPOS SD', while it  
157 is similar for EPOS SD+SD' and PYTHIA 8 (SaS and MBR-tuned), EPOS SD and PYTHIA 8  
158 (MBR). This is related to the smaller average value of  $\xi$  for EPOS SD and PYTHIA 8 (MBR)  
compared to EPOS SD+SD' and PYTHIA 8 (SaS and MBR-tuned).

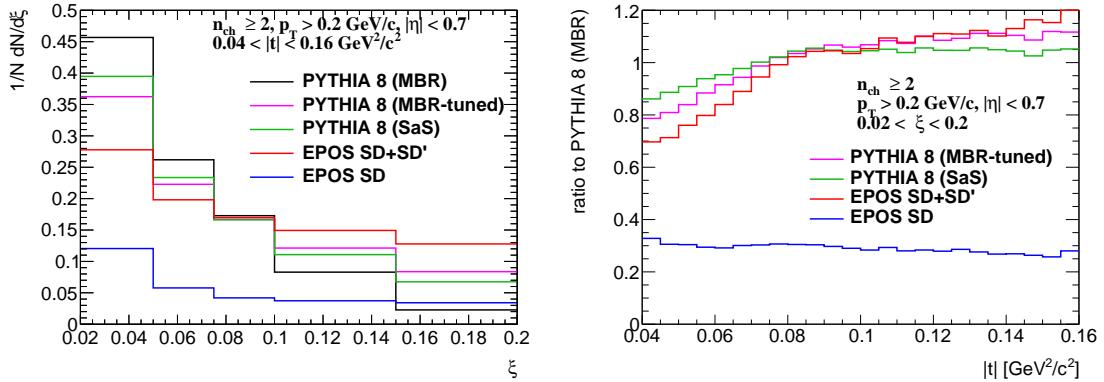


Figure 2.1: (left)  $\xi$  distribution for various MC generators and (right) ratios of different MCs to PYTHIA 8 (MBR) predictions as a function of  $|t|$  at  $\sqrt{s} = 200 \text{ GeV}$ .

159

# 3. Data Sample and Event Selection

The data sample used in this analysis was collected in proton-proton collisions at centre-of-mass energy of  $\sqrt{s} = 200$  GeV during RHIC Run 15.

All of the studies in this analysis use data from only the SDT trigger condition, which was the main trigger designed for SD studies in Run 15. The logic of the trigger was formed by the following conditions combined with the logical AND:

1. RP\_EOR || RP\_WOR - signal in at least one RP on any side of the STAR central detector,
2. veto on any signal in small BBC tiles or ZDC on the triggered RP side of the STAR central detector,
3. at least two TOF hits.

The above requirements were imposed in accordance with the diffractive event topology. Veto on any signal in small BBC tiles and ZDC allowed to accept only events with rapidity gap and reject diffractive events with simultaneous pile-up event. The requirement of at least two TOF hits was applied to ensure activity in the mid-rapidity.

Integrated luminosity delivered by the RHIC to the STAR experiment in  $pp$  collisions during Run 15 amounts to  $185.1 \text{ pb}^{-1}$  [9], whereas about 34.4M SDT events were gathered by the STAR detector, shown in Fig. 3.1, which corresponds to  $16 \text{ nb}^{-1}$  of integrated luminosity.

## Event Selection

Events were selected from those passing the SDT trigger condition. In order to remove events of poor quality and to suppress background the following conditions were required:

1. trigger signals in exactly two stations of one arm of RP system (this requirement divides the sample into four sub-samples, which were later analysed independently, e.g. for background studies),
2. any trigger signal in small BBC tiles on the opposite side of the STAR central detector to the triggered RP station,

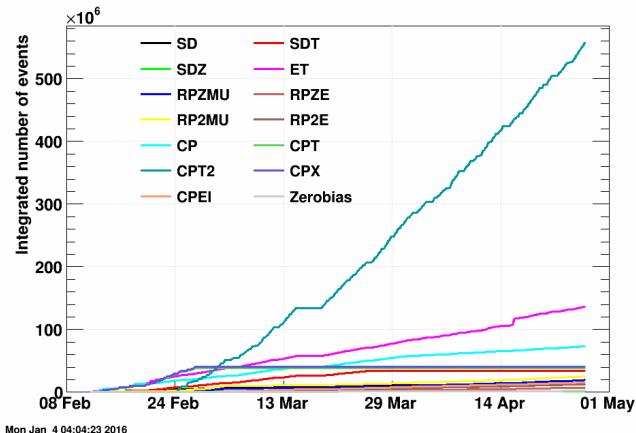


Figure 3.1: Cumulative number of events collected for each trigger in the RP data stream during Run 15 [7, 8].

- 186     3. exactly one proton track in the above RP stations with  $0.02 < \xi < 0.2$  and  $0.04 < -t <$   
 187      $0.16 \text{ GeV}^2/\text{c}^2$ .
- 188     4. exactly one vertex reconstructed from TPC tracks matched with hits in TOF (later in the text  
 189       such vertex is referred as a TOF vertex),
- 190     5. TOF vertex within  $|V_z| < 80 \text{ cm}$  - events with vertices away from the nominal IP have low  
 191       acceptance for the central and forward tracks,
- 192     6. at least two but no more than eight primary TPC tracks,  $2 \leq n_{\text{sel}} \leq 8$ , matched with hits  
 193       in TOF and satisfying the selection criteria described in Sec. 3.1,
- 194     7. if there are exactly two primary tracks satisfying the above criteria and exactly two global  
 195       tracks used in vertex reconstruction (Sec. 5.1), the longitudinal distance between these global  
 196       tracks should be smaller than 2 cm,  $|\Delta z_0| < 2 \text{ cm}$ .

197     Figure 3.2 shows the multiplicity of TOF vertices  $n_{\text{vrt}}$  (left) and the  $z$ -position of reconstructed  
 198       vertices in single TOF vertex events (right). Data are compared to embedded PYTHIA 8 SD  
 199       sample. These distributions are not significantly process-dependent, therefore, contributions from  
 200       other processes are not included in these plots. Most events with  $n_{\text{vrt}} > 1$  originate from in-time  
 201       pile-up and are excluded from the analysis.

### 202     3.1 Track Selection

203     The following quality cuts had to be passed by the selected primary tracks:

- 204     1. the tracks must be matched with hits reconstructed in TOF,
- 205     2. the number of the TPC hits used in the helix fit  $N_{\text{hits}}^{\text{fit}}$  must be greater than 24,
- 206     3. the ratio of  $N_{\text{hits}}^{\text{fit}}$  to the number of all possible TPC hits,  $N_{\text{hits}}^{\text{fit}}/N_{\text{hits}}^{\text{possible}}$ , must be greater  
 207       than 0.52,
- 208     4. the number of the TPC hits used to determine the  $dE/dx$  information  $N_{\text{hits}}^{\text{dE/dx}}$  must be  
 209       greater than 14,
- 210     5. the transverse impact parameter with respect to the beamline  $d_0$  must be less than 1.5 cm,

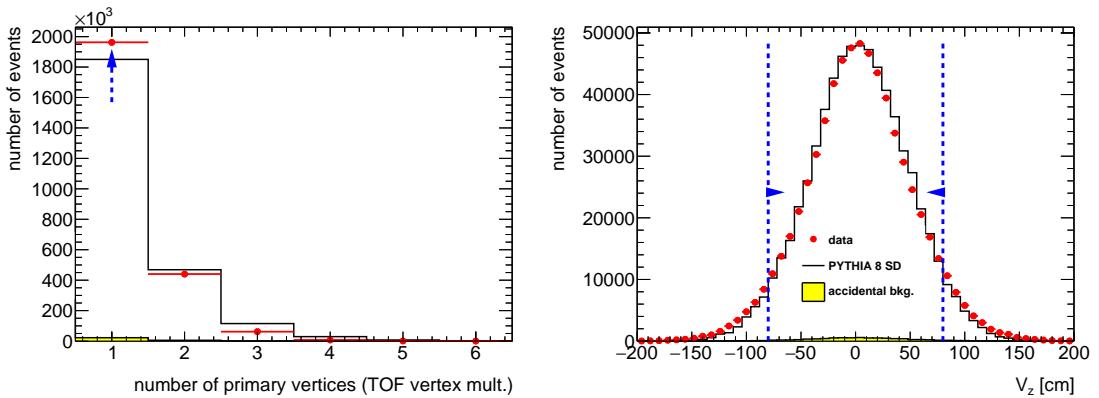


Figure 3.2: (left) Vertex multiplicity and (right) the  $z$ -position of reconstructed vertices in single  
 TOF vertex events before applying the cut on the quantity shown. Blue lines indicate regions  
 accepted in the analysis.

- 211     6. the radial component of the distance of the closest approach between the global helix and  
 212     the vertex  $DCA_{xy}$  must be less than 1.5 cm,  
 213     7. the absolute magnitude of longitudinal component of the distance of the closest approach  
 214     between the global helix and the vertex  $|DCA_z|$  must be less than 1 cm,  
 215     8. the track's transverse momentum  $p_T$  must be greater than 0.2 GeV/c,  
 216     9. the track's absolute value of pseudorapidity  $|\eta|$  must be smaller than 0.7.

217     The  $N_{\text{hits}}^{\text{fit}}$  and  $N_{\text{hits}}^{\text{fit}}/N_{\text{hits}}^{\text{possible}}$  cuts are used to reject low quality TPC tracks and avoid track  
 218     splitting effects. The  $d_0$  and global  $DCA_{xy}$ ,  $|DCA_z|$  cuts are used to select tracks that originate  
 219     from the primary interaction vertex. The cut on  $N_{\text{hits}}^{\text{dE/dx}}$  is used to ensure that selected tracks  
 220     have sufficient energy loss information for particle identification purposes. In this analysis tracks

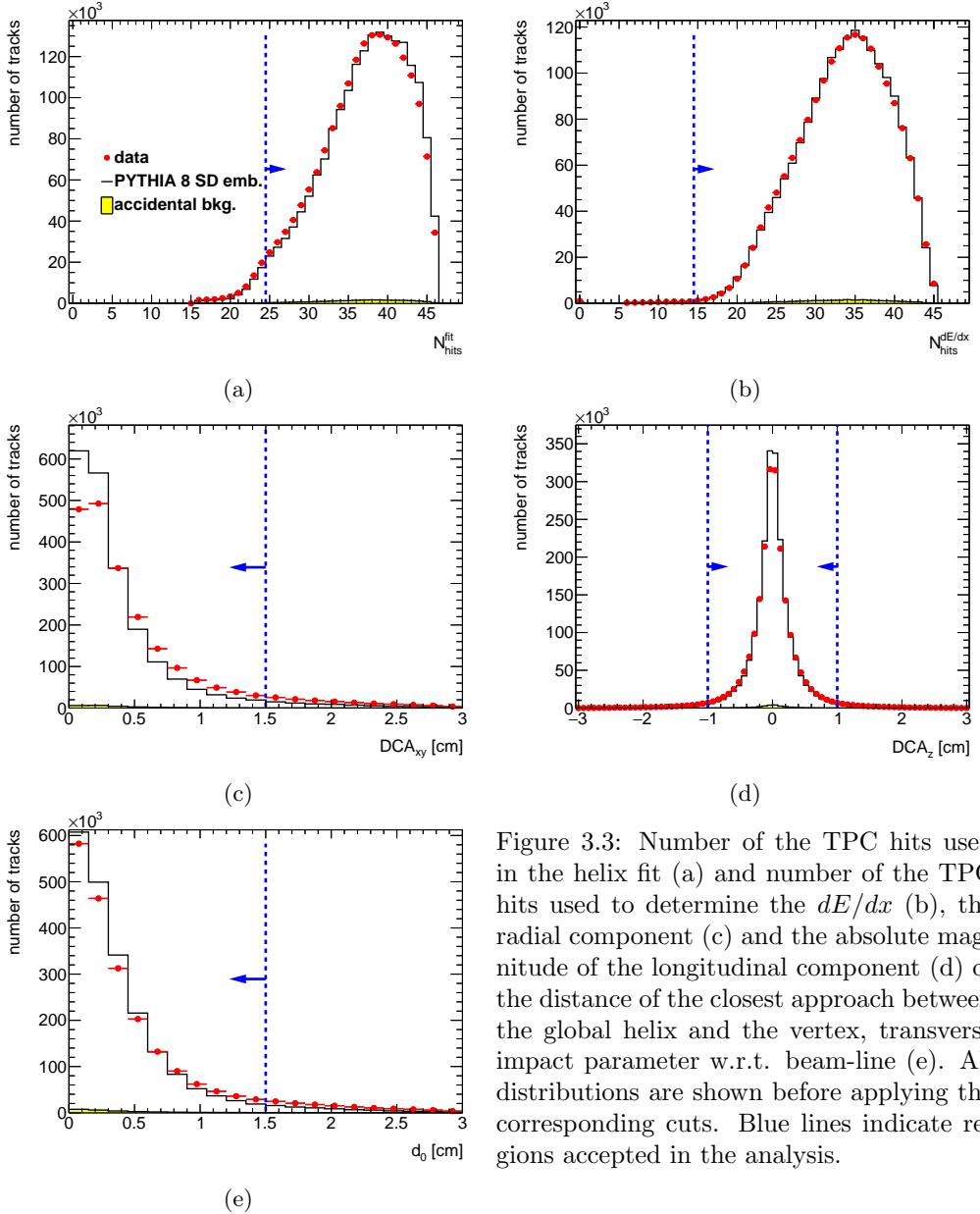


Figure 3.3: Number of the TPC hits used in the helix fit (a) and number of the TPC hits used to determine the  $dE/dx$  (b), the radial component (c) and the absolute magnitude of the longitudinal component (d) of the distance of the closest approach between the global helix and the vertex, transverse impact parameter w.r.t. beam-line (e). All distributions are shown before applying the corresponding cuts. Blue lines indicate regions accepted in the analysis.

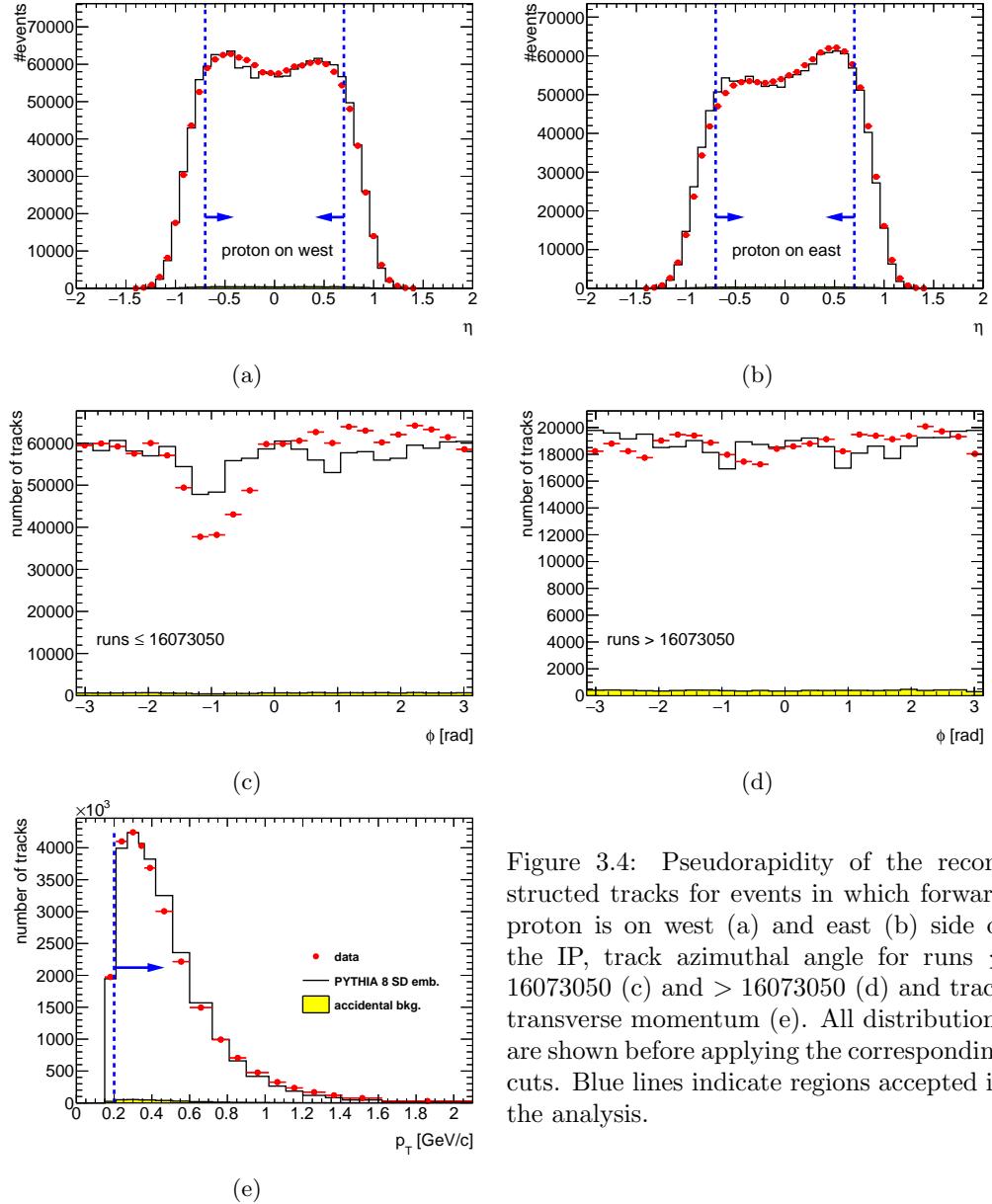


Figure 3.4: Pseudorapidity of the reconstructed tracks for events in which forward proton is on west (a) and east (b) side of the IP, track azimuthal angle for runs  $\leq 16073050$  (c) and  $> 16073050$  (d) and track transverse momentum (e). All distributions are shown before applying the corresponding cuts. Blue lines indicate regions accepted in the analysis.

without identification are required to have  $p_T > 0.2$  GeV/c and  $|\eta| < 0.7$  due to high track reconstruction and TOF matching efficiencies in this region. For the identified particle-antiparticle ratio analysis, where charged pions, charged kaons and (anti)protons are measured, the  $p_T$  cut was increased for kaons and (anti)protons to 0.3 and 0.4 GeV/c, respectively. The distributions of the  $DCA_{xy}$ ,  $|DCA_z|$ ,  $d_0$ ,  $N_{\text{hits}}^{\text{fit}}$  and  $N_{\text{hits}}^{\text{dE/dx}}$  quantities together with applied cuts are shown in Fig. 3.3, while the  $p_T$ ,  $\eta$  and the azimuthal angle,  $\phi$ , of the reconstructed tracks are shown in Fig. 3.4. Data are compared to embedded PYTHIA 8 SD sample.

The azimuthal angle of the reconstructed tracks for runs  $\leq 16073050$  is not described by PYTHIA 8. The inner sector #19 in the TPC was dead for this running period and some effects related to it were presumably not taken into account in the TPC detector simulation. Therefore, additional data-driven corrections to track efficiencies are used [1]. The larger accidental background is observed for runs  $> 16073050$ , probably due to the higher bunch intensities in this running period [10].

### 3.2 Fiducial Region of the Measurement

A fiducial phase space of measurement is defined by the following criteria. Primary charged particles are defined as charged particles with a mean lifetime  $\tau > 300$  ps, either directly produced in  $pp$  interaction or from subsequent decays of directly produced particles with  $\tau < 30$  ps. Primary charged particles had to be contained within the kinematic range of  $p_T > 0.2$  GeV/c and  $|\eta| < 0.7$ . The results are corrected to the region of the total number of primary charged particles (without identification),  $2 \leq n_{ch} \leq 8$ . In identified charged antiparticle to particle ratio measurement, the lower transverse momentum limit was set for the analysed particles as follows: 0.2 GeV/c (pions), 0.3 GeV/c (kaons), 0.4 GeV/c (protons and antiprotons).

The measurements were performed in a fiducial phase space of the forward-scattered protons of  $0.04 < -t < 0.16$  GeV $^2/c^2$  and  $0.02 < \xi < 0.2$ . Figure 3.5 shows that the fraction of events containing at least two primary charged particles,  $\epsilon_{n_{ch} \geq 2}(\log_{10} \xi)$ , is reduced by half for  $\xi < 0.02$  compared to the region of larger  $\xi$ . In addition, the accidental background contribution at  $\xi < 0.02$  is significant and approximately equal to 10% (Sec. 4). For these reasons the lower  $\xi$  cut was introduced. The upper  $\xi$  cut was required since the region of larger  $\xi$  is dominated by Double Diffraction (DD) and ND (Sec. 4.2). The joint RP acceptance and track reconstruction efficiency was defined as the probability that true-level proton was reconstructed as a track passing the selection criteria. This efficiency was calculated as a function of  $-t$  for three ranges of  $\xi$  separately and is shown in Fig. 3.6. Events were accepted only if the reconstructed values of  $-t$  for protons fall within  $> 5\%$  acceptance regions, which were required to be the same for each  $\xi$  region and similar to those defined in the elastic analysis [11]. Therefore, cuts on  $0.04 < -t < 0.16$  GeV $^2/c^2$  were introduced. All measured observables are presented in three  $\xi$  regions:  $0.02 < \xi < 0.05$ ,  $0.05 < \xi < 0.1$  and  $0.1 < \xi < 0.2$ .

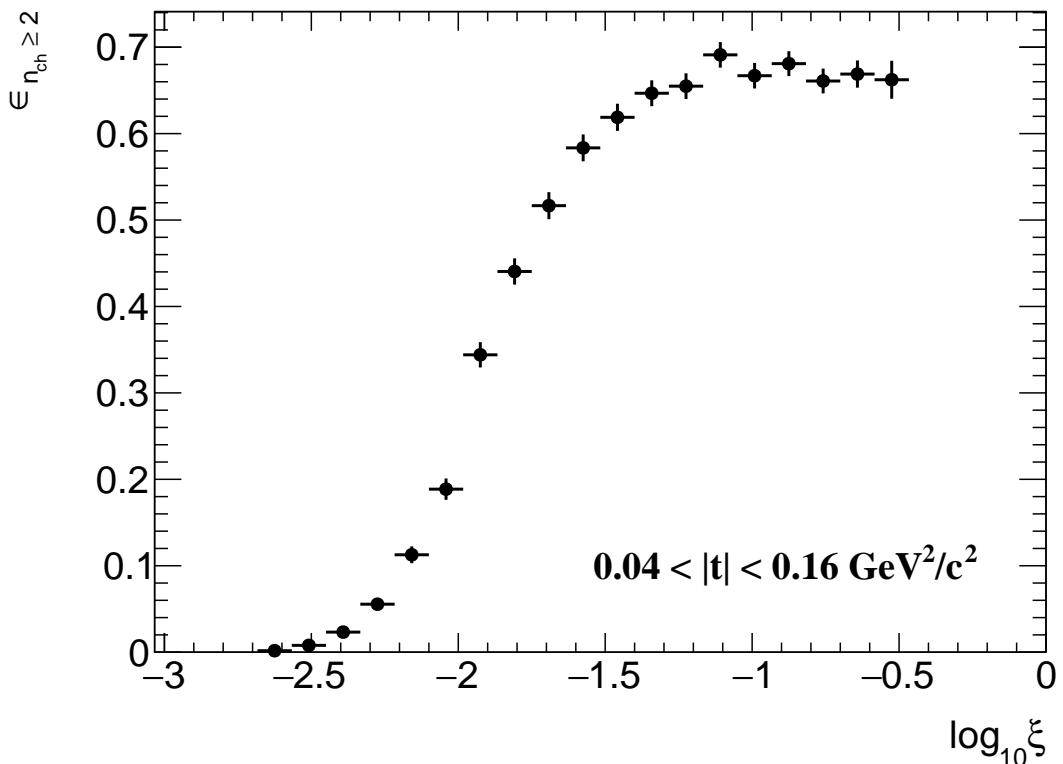


Figure 3.5:  $\epsilon_{n_{ch} \geq 2}$  as a function of  $\log_{10} \xi$  calculated from PYTHIA 8 (MBR).

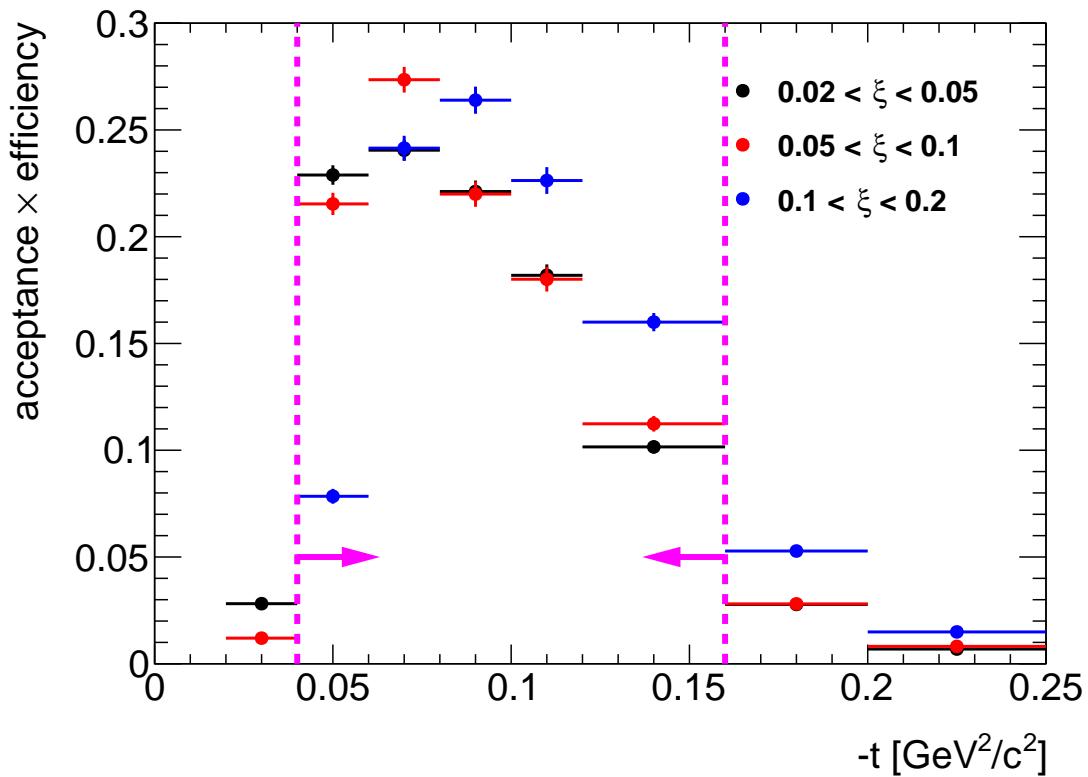


Figure 3.6: RP acceptance and track reconstruction efficiency as a function  $-t$  in three ranges of  $\xi$ , calculated using PYTHIA 8 4C (SaS). Magenta lines indicate region accepted in the analysis.

# 4. Background Contribution

258 The background contributions to the charged-particle distributions can be divided into event-level  
259 and track-level backgrounds, and are described in detail below:

- 260 • Accidental background refers to events which do not originate from a single collision of two  
261 protons.
- 262 • Track backgrounds from non-primary tracks consist of secondary tracks and fake tracks; the  
263 first come mostly from decays, the short-lived particles with mean life  $30 < \tau < 300$  ps,  
264 or secondary interactions with the detector dead material, while the second comes from the  
265 track reconstruction algorithms and out-of-time pile-up with no corresponding true particles.

## 266 Accidental Background

267 The accidental backgrounds (same bunch pile-up background) are quantified using data-driven  
268 method and defined as a process where in single bunch crossing there is coincidence of two inter-  
269 actions, where any single-side proton signal is collected in coincidence with an independent signal  
270 in the TPC+TOF+BBC detector. This type of background may come from the overlap of a signal  
271 in RP (proton from beam-halo, low mass SD process without activity in TOF, elastic or low mass  
272 Central Diffraction (CD) processes with undetected proton on the other side) with a signal in  
273 TPC+TOF+BBC (mainly ND events without forward-scattered proton).

274 The accidental background contribution was calculated from Zerobias data (colliding bunches),  
275 where two signatures of such background were investigated: the reconstructed proton in RP and  
276 the reconstructed vertex from TPC tracks matched with TOF. The analysis was done for each RP  
277 arm separately and thus the Zerobias data was firstly required to pass the following criteria:

- 278 1. no trigger in any RP or trigger in exactly one arm (two RPs) with exactly one reconstructed  
279 proton track in that arm,
- 280 2. veto on any signal in small BBC tiles or ZDC on the same side of the IP as the RP arm  
281 under consideration,
- 282 3. no or exactly one reconstructed vertex with at least two TOF-matched tracks passing the  
283 quality criteria. The latter includes also signal in BBC small tiles on the opposite side of  
284 the IP to the RP arm under study.

285 The sample of selected Zerobias data with total number of events  $N$  was divided into four classes:  
286

$$N = N_{PS} + N_{RS} + N_{PT} + N_{RT} \quad (4.1)$$

287 where:  $N_{PS}$  is the number of events with reconstructed proton in exactly one RP and reconstruc-  
288 ted TOF vertex,  $N_{RS}$  is the number of events with no trigger in any RP and reconstructed TOF  
289 vertex,  $N_{PT}$  is the number of events with reconstructed proton in exactly one RP and no recon-  
290 structed TOF vertex,  $N_{RT}$  is the number of events with no trigger in any RP and no recon-  
291 structed TOF vertex. Since the signature of the signal is a reconstructed proton in exactly one RP and  
292 a reconstructed TOF vertex, the number of such events can be expressed as:

$$N_{PS} = N(p_3 + p_1 p_2) \quad (4.2)$$

293 where:  $p_1$  is the probability that there is a reconstructed proton in RP and there is no reconstruc-  
294 ted TOF vertex,  $p_2$  is the probability that there is no reconstructed proton in RP and there is  
295 a reconstructed TOF vertex,  $p_3$  is the probability that there is a reconstructed proton in RP and  
296 there is a reconstructed TOF vertex (not accidental).

297        The other classes of events given in Eq. (4.1) can be expressed in terms of the above probabilities  
 298        as:

$$\begin{aligned} N_{RS} &= N(1 - p_1)p_2(1 - p_3) \\ N_{PT} &= N(1 - p_2)p_1(1 - p_3) \\ N_{RT} &= N(1 - p_1)(1 - p_2)(1 - p_3) \end{aligned} \quad (4.3)$$

299        Finally, the accidental background contribution  $A_{\text{bkg}}^{\text{accidental}}$  is given by:

$$A_{\text{bkg}}^{\text{accidental}} = \frac{p_1 p_2}{p_3 + p_1 p_2} = \frac{N_{RS} N_{PT} N}{N_R N_T N_{PS}} \quad (4.4)$$

300        where:  $N_R = N_{RS} + N_{RT}$  and  $N_T = N_{PT} + N_{RT}$ .

301        The shapes of the accidental background related to TPC distributions come from the above  
 302        Zerobias data events which pass all the analysis selection except having no trigger in any RP.  
 303        The templates corresponding to RP distributions are from protons in the above data sets but  
 304        with no reconstructed TOF vertex. The normalization is given by Eq. (4.4). Figure 4.1 shows  
 305        distributions of the reconstructed  $\xi$  with the accidental background contribution for events with  
 306        proton reconstructed in EU, ED, WU and WD arms. Accidental background in the range of  
 307         $0.02 < \xi < 0.2$  is below 1% and increases to 10% at  $\xi < 0.02$ . Unphysical negative values of  
 308        reconstructed  $\xi$  are due to the detector resolution.

309        The selection of Zerobias events, which is not unique, may provide some bias to the normalization  
 310        of the accidental background. As a systematic check, two criteria for Zerobias selection were  
 311        changed to:

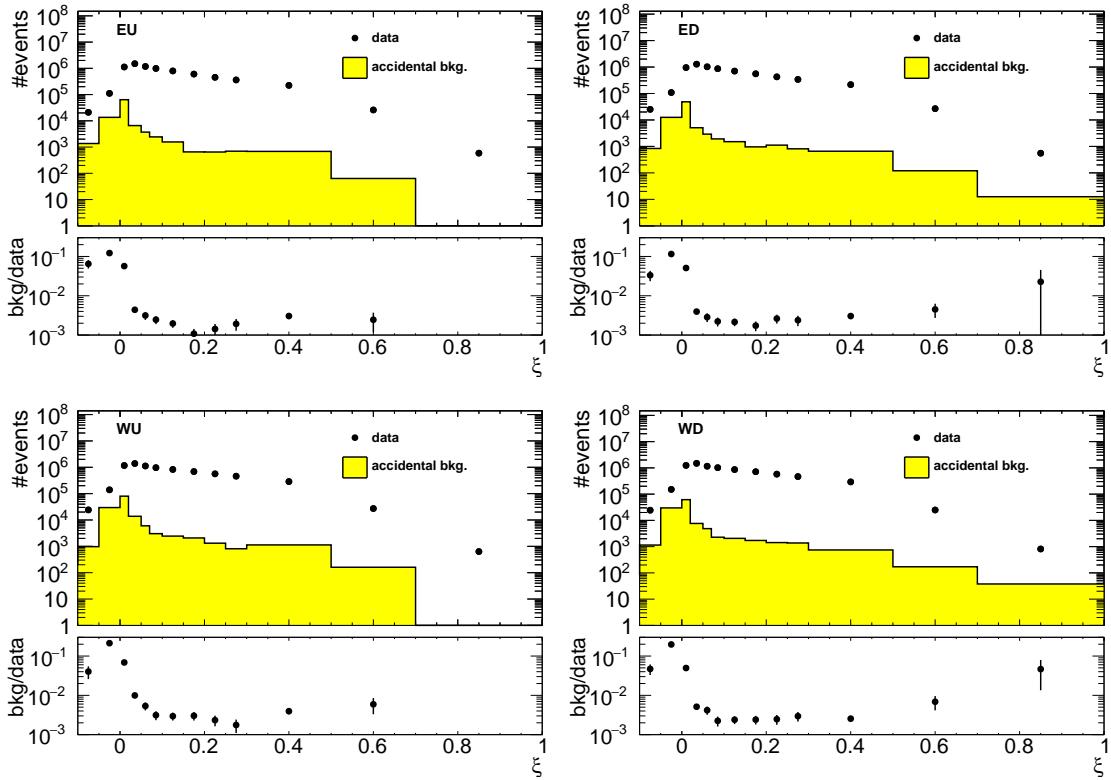


Figure 4.1: Uncorrected distributions of the reconstructed  $\xi$  for events with proton reconstructed in (top left) EU, (top right) ED, (bottom left) WU and (bottom right) WD arms. Data is shown as black markers, whereas the accidental background contribution is shown as yellow histogram. The ratio of accidental background and data is shown in the bottom panels.

- 312     1. no trigger in any RP or trigger in exactly one arm (two RPs) with *no more* than one  
 313       reconstructed proton track in that arm, i.e. events with trigger signals in exactly one arm  
 314       and without reconstructed proton track in that arm were also used,  
  
 315     2. no or exactly one reconstructed TOF vertex (*without any additional requirements*), i.e.  
 316       events with a reconstructed TOF vertex that does not have at least two primary tracks  
 317       satisfying the selection criteria (Sec. 3.1), or with a reconstructed TOF vertex that is out of  
 318       the range of  $|V_z| < 80$  cm, were also accepted. The requirement of signal in BBC small tiles  
 319       remains unchanged.

320     As a result of this change, the accidental background normalization increases of about 50% with  
 321       respect to the nominal value. A symmetric systematic uncertainty of 50% of the normalization of  
 322       accidental background is applied to the measurement.

## 323     4.1 Background from Non-Primary Tracks

324     Reconstructed tracks matched to a non-primary particle, so-called background tracks, originate  
 325       mainly from the following sources:

- 326       • decays of short-lived primary particles with strange quark content (mostly  $K^0, \Lambda^0$ ),  
 327       • photons from  $\pi^0$  and  $\eta$  decays which are converting to  $e^+e^-$ ,  
 328       • hadronic interactions of particles with the beam-pipe or detector dead material.

329     Figure 4.2 (left) shows the background from non-primary tracks,  $f_{\text{bkg}}(p_T, \eta)$ , as a function  
 330       of tracks'  $p_T$  and  $\eta$ , predicted by PYTHIA 8 SD model. There were no differences observed in  
 331       the background contribution in different  $\xi$  ranges, hence, all three  $\xi$  ranges were merged for this  
 332       study. The highest background fraction, which varies between 5 – 10%, was found to be at low  
 333        $p_T$ .

334     Figure 4.2 (right) shows the background track contribution to reconstructed tracks as a function  
 335       of  $p_T$  and  $\eta$  calculated from EPOS SD+SD'. The differences between PYTHIA 8 and EPOS,  
 336       which are up to 50% for  $p_T > 0.5$  GeV/c (as shown in Fig. 4.3), were symmetrized and taken as  
 337       a systematic uncertainty.

338     There is also a small (< 0.5%) contribution from fake tracks,  $f_{\text{fake}}(p_T, \eta)$ , i.e. tracks not associated  
 339       with true-level particles, coming from out-of-time pile-up or formed by a random combination  
 340       of TPC hits. The change by  $\pm 100\%$  in this contribution was taken as a systematic uncertainty.

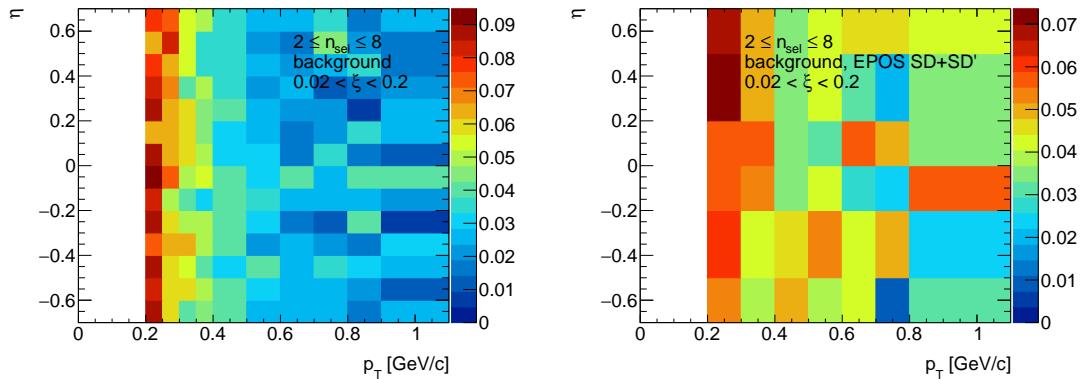


Figure 4.2: Distribution of fraction of selected tracks associated with non-primary particles in the range  $0.02 < \xi < 0.2$  as predicted by (left) PYTHIA 8 4C (SaS) embedding and (right) EPOS SD+SD'.

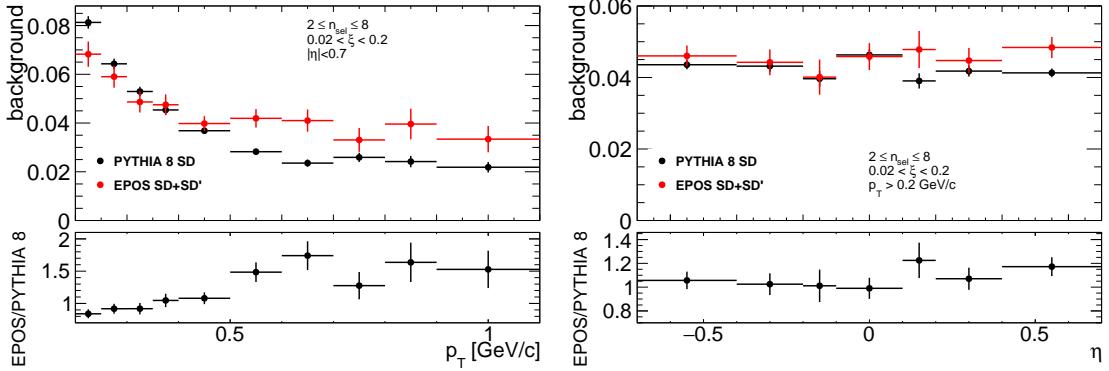


Figure 4.3: PYTHIA 8 SD and EPOS SD+SD' predictions of fraction of selected tracks associated with non-primary particles as a function of (left)  $p_T$  and (right)  $\eta$ . The ratio of EPOS and PYTHIA 8 predictions is shown in the bottom panels.

### 341 Proton Background

342 Secondary particles can be created due to the interaction of particles with detector dead-material.  
 343 The proton sample contains background from such protons knocked out from the detector materials [12].  
 344 Most of these protons have large DCA to the primary vertex and are not associated with it.  
 345 However, the protons with small DCA are included in the primary track sample. Antiprotons  
 346 do not have knockout background, hence the DCA tail is almost absent in their DCA distributions.

347 The fraction of knock-out background protons depends on a number of factors, including  
 348 the amount of detector material, analysis cuts and the  $\xi$  of diffractive proton. While it is natural  
 349 to calculate the fractions of primary and background protons in the MC sample, the MC models  
 350 do not necessarily predict the fraction of knock-out background protons without any bias. Hence,  
 351 data-driven methods should be used to calculate this type of background.

352 In order to correct for the knock-out background protons, sample enriched in proton back-  
 353 ground was used for background normalization, where  $\text{DCA}_{xy}$ ,  $\text{DCA}_z$  and  $d_0$  cuts were aban-  
 354 doned. Additionally, at least one, instead of exactly one, reconstructed vertex was allowed in this  
 355 sample. Figures 4.4 and 4.5 show the DCA distributions of protons and antiprotons, respectively,  
 356 for nominal (bottom) and background enriched (top) samples. The distributions for other  $p_T$   
 357 and  $\xi$  regions are shown in Appendix A. The protons and antiprotons are selected by a  $dE/dx$   
 358 cut of  $-1 < n\sigma_{p,\bar{p}} < 3$  where  $n\sigma_{p,\bar{p}}$  is given by Eq. (7.10). In some  $p_T$  regions, the  $dE/dx$  of  
 359 (anti)protons and pions starts to overlap, hence, the asymmetric  $n\sigma_{p,\bar{p}}$  cut was introduced in or-  
 360 der to select as clean (anti)proton sample as possible. The fraction of knock-out protons within  
 361 the selected sample is determined via MC template fits. The templates of reconstructed tracks  
 362 with  $dE/dx$  corresponding to the proton and antiproton are obtained from PYTHIA 8 embedding  
 363 MC separately for:

- 364     • primary (anti)protons,
- 365     • knock-out background protons (labeled as dead-material),
- 366     • fake tracks,
- 367     • secondary particles with  $dE/dx$  of (anti)proton (labeled as wrong PID - sec.),
- 368     • tracks associated with primary (anti)protons, but with the reconstructed vertex not matched  
       369        to true-level primary vertex (labeled as wrong vtx),
- 370     • reconstructed track is partially matched to true-level particle (labeled as wrong match, track  
       371        to true-level particle matching is described in [1]), i.e. track and true-level particle have  
       372        appropriate number of common hit points but the distance between true-level particle and

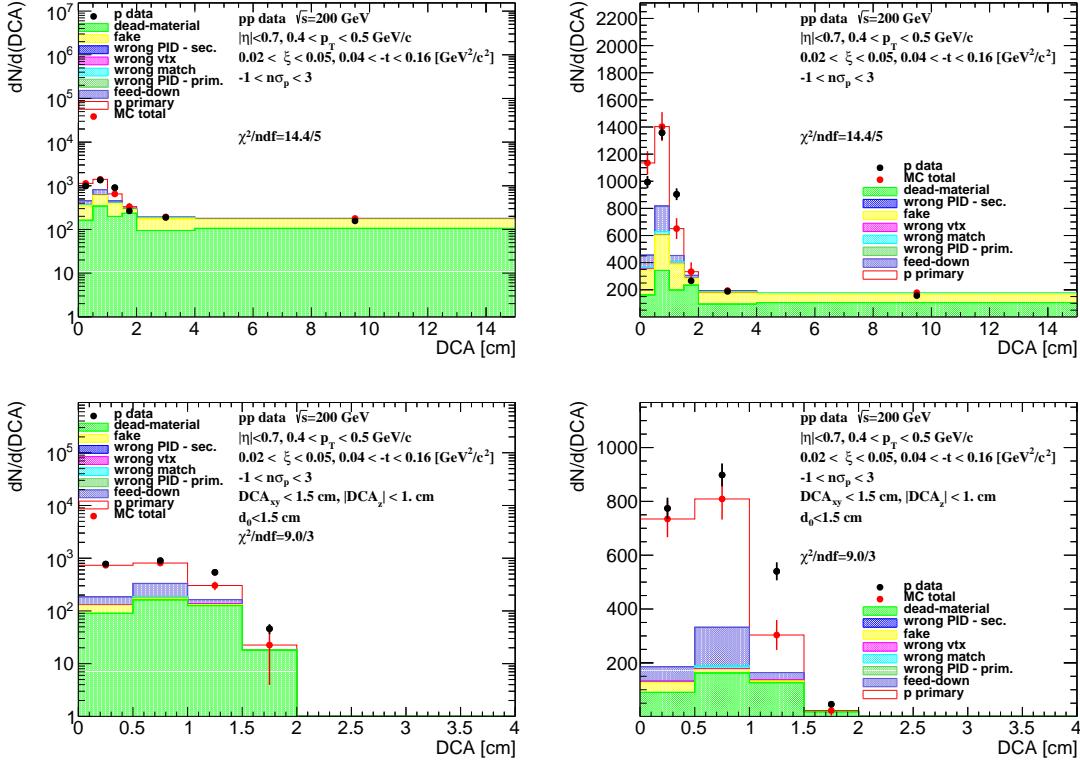


Figure 4.4: The DCA distributions of protons for  $0.4 < p_T < 0.5 \text{ GeV}/c$  shown for single range of  $0.02 < \xi < 0.05$  (shown in log and linear scale in left and right column, respectively). The MC contributions are shown after scaling the dead-material template to the tail of large DCA values,  $2 < \text{DCA} < 15 \text{ cm}$ . (top) Background enriched samples were used in the normalization procedure, whereas (bottom) the proton background was estimated from the nominal sample.

373 track is too large,  $\delta^2(\eta, \phi) > (0.15)^2$ , thus, track is not considered as primary particle  
 374 according to discussion in [1],

- 375 • primary particles with  $dE/dx$  of (anti)proton (labeled as wrong PID - prim.),  
 376 • (anti)proton as a product of short-lived decays, mainly  $\Lambda^0$  (labeled as feed-down).

377 First, the background enriched sample was analyzed (Fig. 4.4, top), where the template of  
 378 knock-out background protons was normalized to the number of events in the fake-subtracted tail  
 379 of the DCA distribution,  $2 < \text{DCA} < 15 \text{ cm}$ . Next the knock-out proton and fake background  
 380 was subtracted from the DCA distribution and the sum of other templates was normalized to  
 381 the number of events in the signal region,  $\text{DCA} < 1.5 \text{ cm}$ .

382 The fraction of the knock-out proton background in the signal region,  $\text{DCA} < 1.5$ , was es-  
 383 timated from the nominal sample (Fig. 4.4, bottom), where  $\text{DCA}_{xy}$ ,  $\text{DCA}_z$  and  $d_0$  track cuts  
 384 were applied and exactly one reconstructed vertex was required. The normalization of each MC  
 385 contribution was kept the same as that estimated for the background enriched sample. Figure 4.6  
 386 shows the knock-out proton background as a function of  $p_T$  in three ranges of  $\xi$ . The following  
 387 functional form was found to describe the background protons:

$$f_{\text{bkg}}^p(p_T) = p_0 \exp(p_1 p_T) \quad (4.5)$$

388 where  $p_0$  and  $p_1$  are free parameters obtained from a fit.

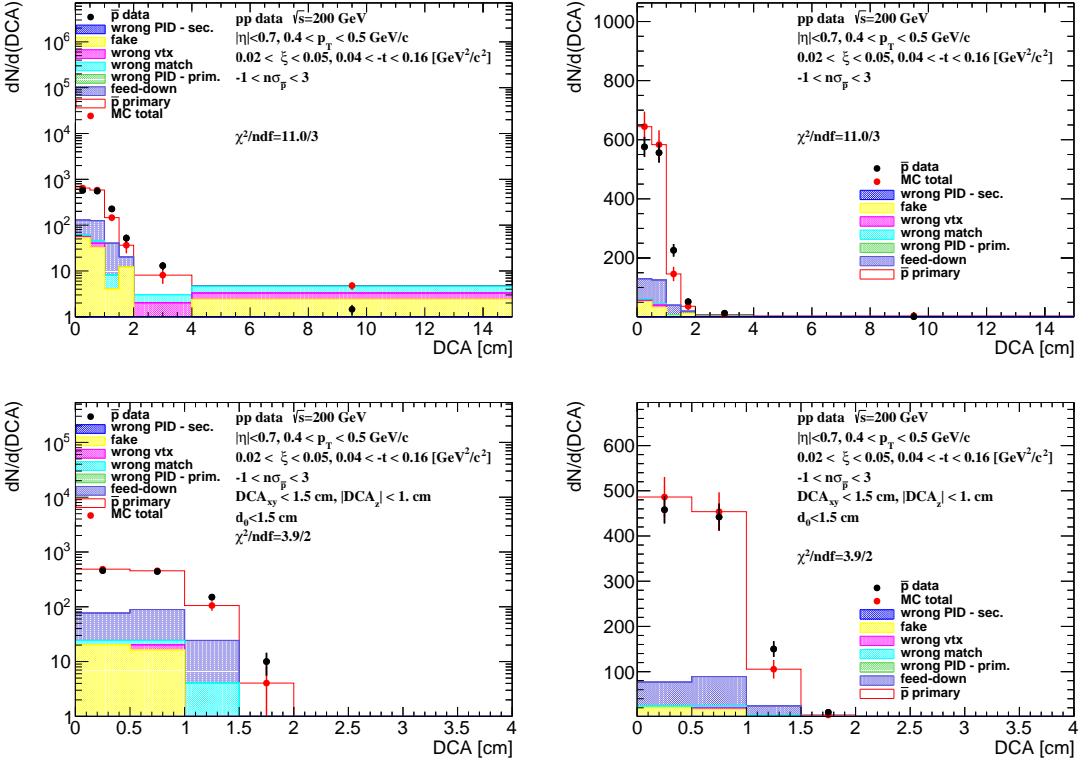


Figure 4.5: The DCA distributions of antiprotons for  $0.4 < p_T < 0.5$  GeV/c shown for one range of  $0.02 < \xi < 0.05$  (log and linear scale in left and right column, respectively). The MC contributions are shown as colour histograms. (top) Background enriched and (bottom) nominal samples were used.

389     The obtained fraction of knock-out background protons is approximately 20% at  $p_T = 0.45$   
390     GeV/c and less than 10% at  $p_T = 1.0$  GeV/c. In PYTHIA 8 SD predictions (also shown in Fig. 4.4),  
391     such fraction is much smaller and equals to approximately 7% at  $p_T = 0.45$  GeV/c and about 5%  
392     at  $p_T = 1.0$  GeV/c. This may suggest that there are differences in the amount of dead material in  
393     front of TPC between data and simulation, which is consistent with the studies presented in [1].

394     Figure 4.5 shows the corresponding DCA distributions with MC templates for antiprotons,  
395     where the background from knock-out particles is not present. Therefore, there was no need for  
396     any fit to be performed in this comparison. The MC templates fairly well describe the DCA  
397     distribution for both, protons, after tuning the fraction of knock-out background to data, and  
398     antiprotons.

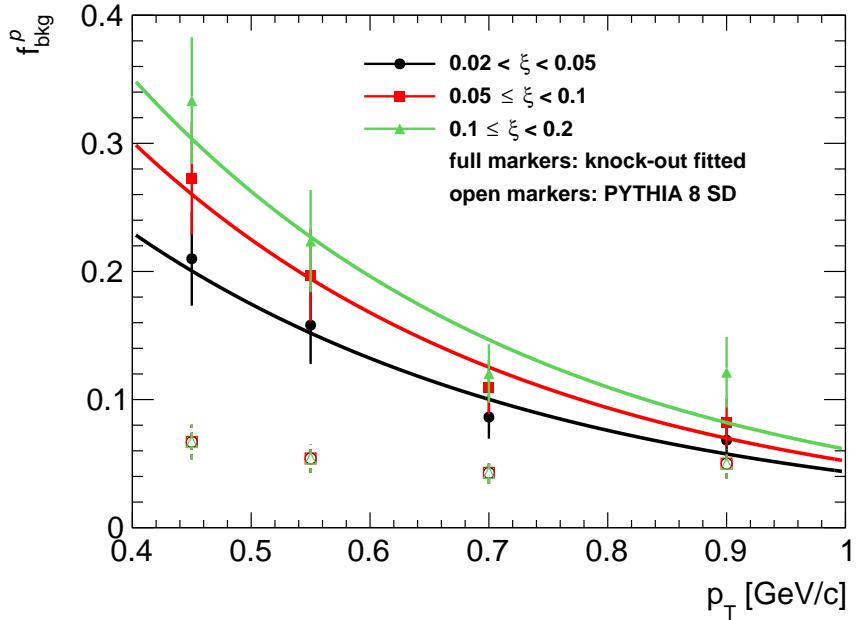


Figure 4.6: The fraction of knock-out proton background as a function of  $p_T$  in three ranges of  $\xi$  with fitted parametrizations. Full markers represent fitted knock-out background and open markers represent PYTHIA 8 SD predictions.

### 399 Systematic Uncertainty Related to Proton Background

400 The knock-out proton background estimation introduces systematic uncertainties. First, the nor-  
 401 malization interval of the knock-out proton background template in the background enriched  
 402 sample was changed to  $4 < \text{DCA} < 15$  cm. This introduced a relative systematic uncertainty of  
 403 up to 30% for  $p_T \approx 0.9$  GeV/c.

404 The knock-out proton background contribution was parameterized as it is shown in Eq. (4.5).  
 405 The systematic uncertainty related to the parameterization procedure was estimated by varying the  
 406 parameters,  $p_0$  and  $p_1$ , by their statistical uncertainties ( $\pm 1\sigma$ ). As a result, a relative systematic  
 407 uncertainties of about 10% were obtained.

408 Differences in the shape of the DCA distribution between data and MC can affect the knock-  
 409 out proton background estimation procedure. Figure 4.7 (top left) shows the data to MC ratio of  
 410 the number of events in the background dominated region,  $2 < \text{DCA} < 15$  cm. Since this region  
 411 is used to estimate background normalization, and the shape of the DCA distribution in the data  
 412 differs from that observed in the simulation, the predicted background in the  $\text{DCA} < 1.5$  cm region  
 413 can change. Thus, the following functional form was used to estimate the slope between data and  
 414 MC:

$$\frac{\text{data}}{\text{MC}}(\text{DCA}) = A(\text{DCA} - 8.5) + B \quad (4.6)$$

415 where  $A$  (slope) and  $B$  are fit free parameters. Differences in slope between data and MC were used  
 416 to estimate how many more background tracks would fit into the signal region and a systematic  
 417 uncertainty, which varies up to 5% for  $0.02 < \xi < 0.05$ , was introduced.

418 All above components of the systematic uncertainty related to the knock-out proton back-  
 419 ground, shown in Fig. 4.7, are added in quadrature. Those related to the fit range and the shape  
 420 of the proton background are symmetrized. Figure 4.8 shows the fraction of knock-out proton  
 421 background in three ranges of  $\xi$  and the total systematic uncertainty related to it.

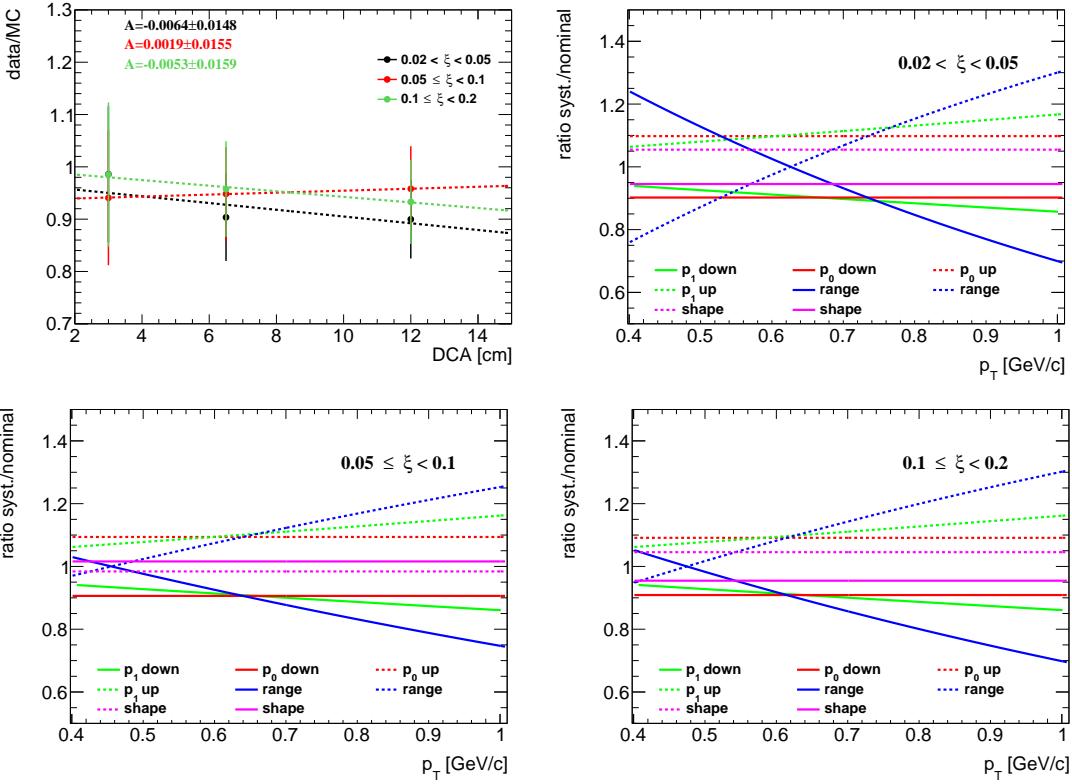


Figure 4.7: (top left) Data to MC ratio of the number of events in the background dominated region in three ranges of  $\xi$  with fitted functional form given by Eq. (4.6). (top right and bottom) Components of the systematic uncertainty related to the knock-out background protons contribution in three  $\xi$  ranges.

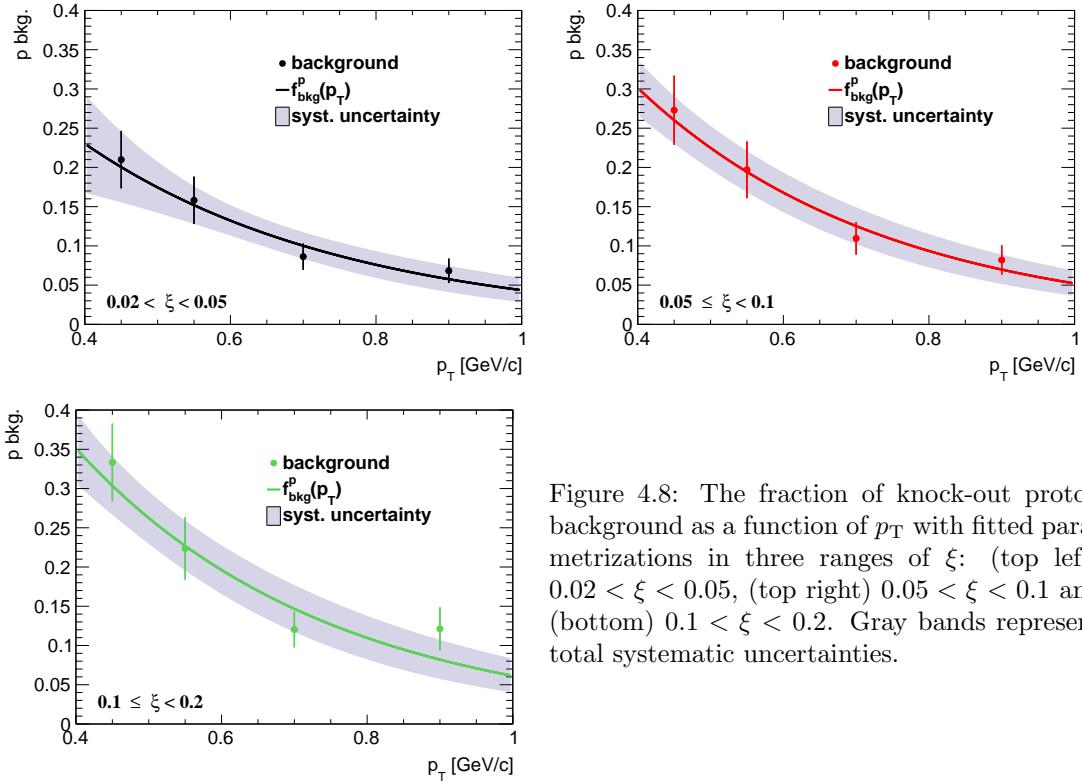


Figure 4.8: The fraction of knock-out proton background as a function of  $p_T$  with fitted parametrizations in three ranges of  $\xi$ : (top left)  $0.02 < \xi < 0.05$ , (top right)  $0.05 \leq \xi < 0.1$  and (bottom)  $0.1 \leq \xi < 0.2$ . Gray bands represent total systematic uncertainties.

422 **Pion Background**

423 The pion spectra are corrected for weak decays (mainly of  $K_S^0$  and  $\Lambda^0$ ), muon contribution and  
 424 background from the detector dead-material interactions. The pion decay muons can be identified  
 425 as pions due to the similar masses. These background contributions are obtained from PYTHIA 8  
 426 SD. Figure 4.9 shows the background contribution to the pion spectra as a function of  $p_T$  in  
 427 three ranges of  $\xi$ , separately for  $\pi^-$  and  $\pi^+$ . Since there were negligible differences observed  
 428 between these three ranges of  $\xi$ , the background contribution was averaged over  $\xi$ . The following  
 429 parametrization was found to describe it:

$$f_{\text{bkg}}^\pi(p_T) = a_0 \exp(a_1 p_T) + a_2 p_T^2 + a_3 p_T \quad (4.7)$$

430 where  $a_i$ ,  $i = 0, \dots, 3$  are free parameters of the fitted function.

431 The pion background contribution varies between 5% at low- $p_T$  ( $p_T = 0.25$  GeV/c) and about  
 432 1% at  $p_T = 1.0$  GeV/c for both negatively and positively charged pions. In addition, the back-  
 433 ground was calculated from EPOS SD+SD' for the full range of  $\xi$ . The differences between  
 434 PYTHIA 8 and EPOS are up to 1% for  $\pi^-$ .

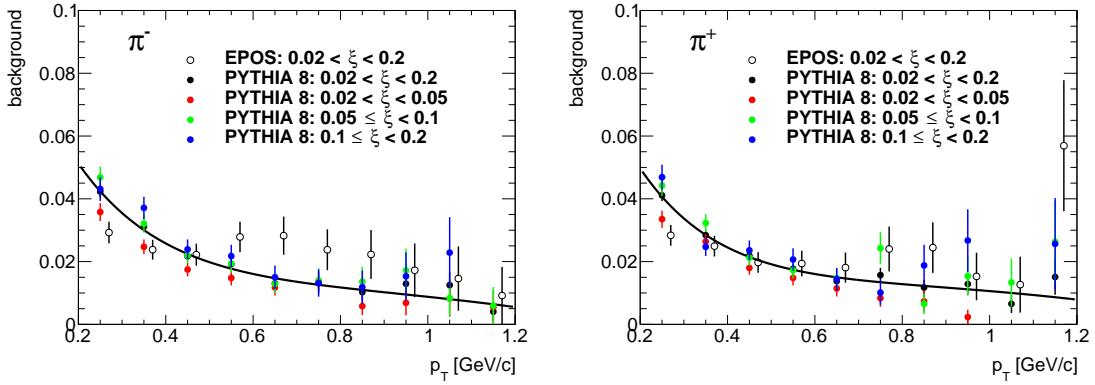


Figure 4.9: Pion background fraction as a function of  $p_T$  shown separately for (left) negatively and (right) positively charged pions in three ranges of  $\xi$ : (red)  $0.02 < \xi < 0.05$ , (green)  $0.05 < \xi < 0.1$ , (blue)  $0.1 < \xi < 0.2$ . (full black points) The pion background averaged over three ranges of  $\xi$  with fitted parametrization is also shown. Open black points represent EPOS predictions for the full  $\xi$  range.

435    **4.2 Control Plots**

436    Events, in which forward-scattered proton and reconstructed TOF vertex are the result of the same  
437     $pp$  interaction, may originate from ND, DD, SD, and CD processes. It is preferred to estimate  
438    the background contribution from data, using dedicated control regions. Since such regions were  
439    not found, the relative contributions from the above processes were estimated from MC models  
440    and are therefore model dependent. Tracks reconstructed in RPs may also be:

- 441    • forward-scattered protons produced in the SD, CD or DD diffractive systems or from ND  
442    events,
- 443    • secondary particles from showering initiated by interaction of forward-scattered protons with  
444    beam-line elements. This contribution is negligible.

445    Figure 4.10 shows the uncorrected  $\xi$  and  $t$  distributions in data compared to various MC models:  
446    PYTHIA 8 A2 (MBR), PYTHIA 8 A2 (MBR-tuned), PYTHIA 8 4C (SaS) and EPOS. The MC  
447    distributions are split into SD, ND, DD and CD components. For EPOS, SD' is separated from  
448    the ND events. Additionally, the accidental background is also shown. PYTHIA 8 A2 (MBR)  
449    predictions, shown in Fig. 4.10 (a-b), do not agree with the data, especially there is small number  
450    of events in the region of large values of  $\xi$ . This effect may be due to the scaling factors, which  
451    are introduced in PYTHIA 8 to artificially suppress diffractive cross sections in the high mass  
452    region, or due to too large Pomeron intercept ( $\epsilon = 0.104$ ). Therefore, additional two samples of  
453    PYTHIA 8 were generated: without this artificial suppression (MBR-tuned) and with  $\epsilon = 0$  (SaS).  
454    Their predictions, shown in Fig. 4.10 (c-f), agree much better with the data than PYTHIA 8 A2  
455    (MBR) and result also in a suppression of non-SD events. Amongst PYTHIA 8 models, PYTHIA 8  
456    A2 (MBR-tuned) shows the best agreement with the data. EPOS predictions, shown in Fig. 4.10  
457    (g-h), describes data better than PYTHIA 8 but shows a dominant contribution of SD' events.  
458    The CD contribution in EPOS is several times greater than in PYTHIA 8 (MBR), but it was never  
459    tuned to describe any data, as opposed to PYTHIA 8 (MBR) in which the CD cross sections are  
460    constrained by CDF measurements [13]. The CD component in the SaS model is based on simple  
461    scaling assumption, therefore, it is not usually used by the experimental communities. All MCs  
462    predict significant DD and ND background at large  $\xi$ , thereby the analysis was limited to  $\xi < 0.2$ .

463    Figures 4.11 to 4.13 show the uncorrected distributions of variables used in the later analysis:  
464     $n_{\text{sel}}$ ,  $p_T$  an  $\bar{\eta}$ . The contributions from non-SD (except EPOS SD') interactions differ a bit between  
465    each other, i.e. EPOS predicts significantly larger CD contribution, whereas DD and ND are  
466    suppressed in PYTHIA 8 A2 (MBR-tuned) and PYTHIA 8 4C (SaS). PYTHIA 8 A2 (MBR)  
467    is used as the default model of non-SD contribution subtracted from the data with systematic  
468    uncertainty  $\pm 50\%$ , which covers all differences between the models except EPOS SD'. In this  
469    analysis EPOS SD' is considered as an alternative to PYTHIA 8 SD model of events with forward-  
470    scattered proton in the final state, where one of the proton remnants hadronizes back to a single  
471    proton (non-diffractive process), while in PYTHIA 8 the initial proton stays intact (diffractive  
472    process). As a consequence, results are compared with the sum of SD and SD' processes for EPOS  
473    model.

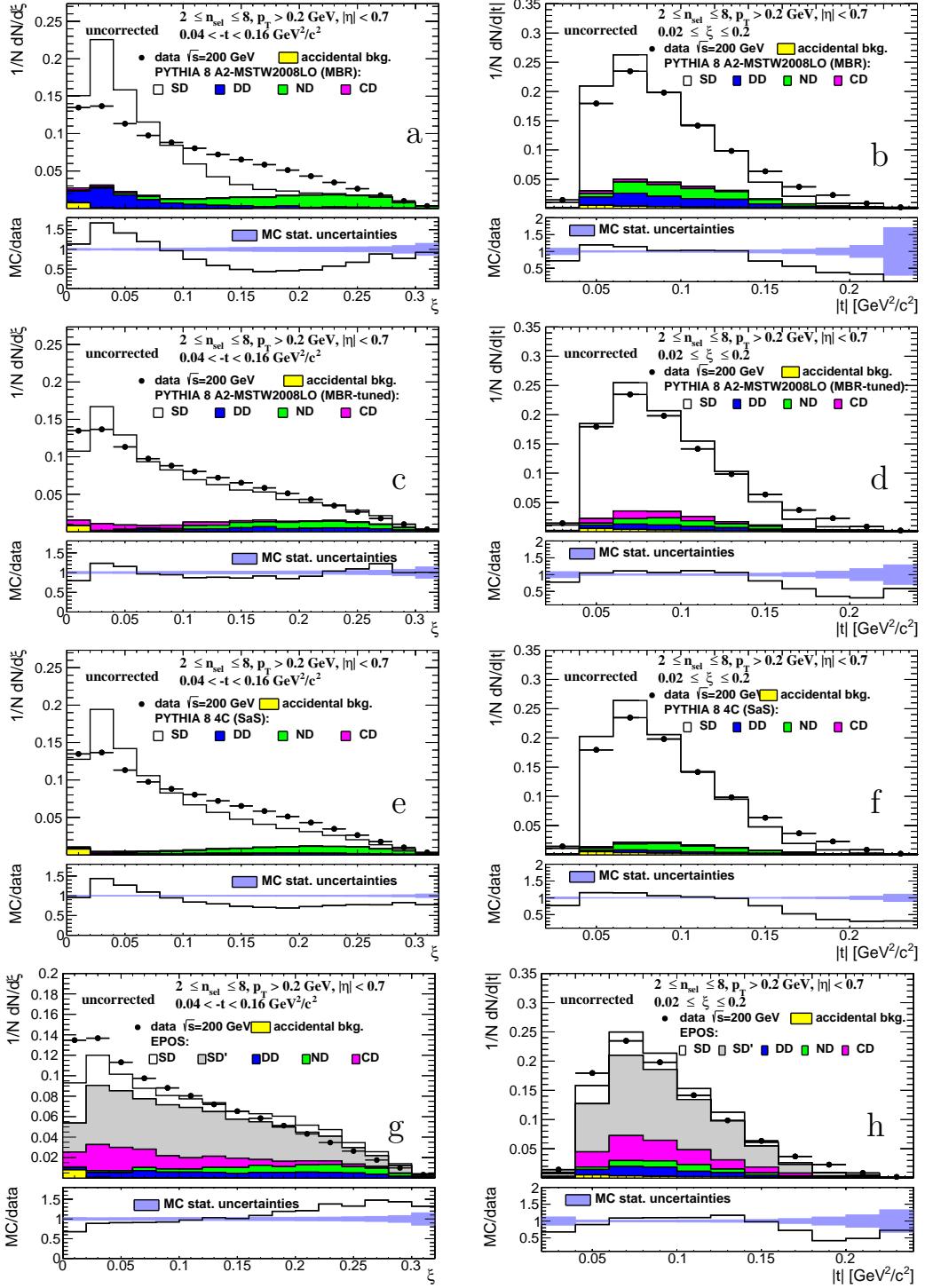


Figure 4.10: Uncorrected distributions of data compared to various MC models: (a-b) PYTHIA 8 A2 (MBR), (c-d) PYTHIA 8 A2 (MBR-tuned), (e-f) PYTHIA 8 4C (SaS) and (g-h) EPOS, as a function of (left column)  $\xi$  and (right column)  $|t|$ . The ratio of MC predictions and data is shown in the bottom panels.

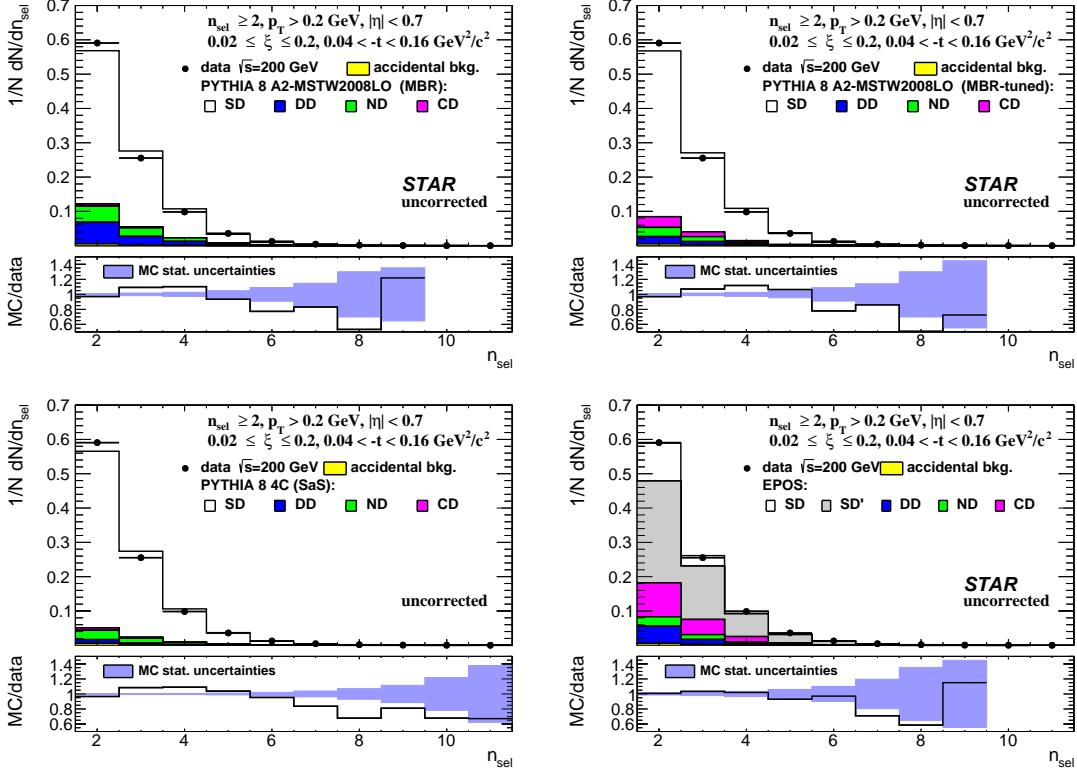


Figure 4.11: Uncorrected distributions of data compared to various MC models: (top left) PYTHIA 8 A2 (MBR), (top right) PYTHIA 8 A2 (MBR-tuned), (bottom left) PYTHIA 8 4C (SaS) and (bottom right) EPOS, as a function of  $n_{\text{sel}}$ . The ratio of MC predictions and data is shown in the bottom panels.

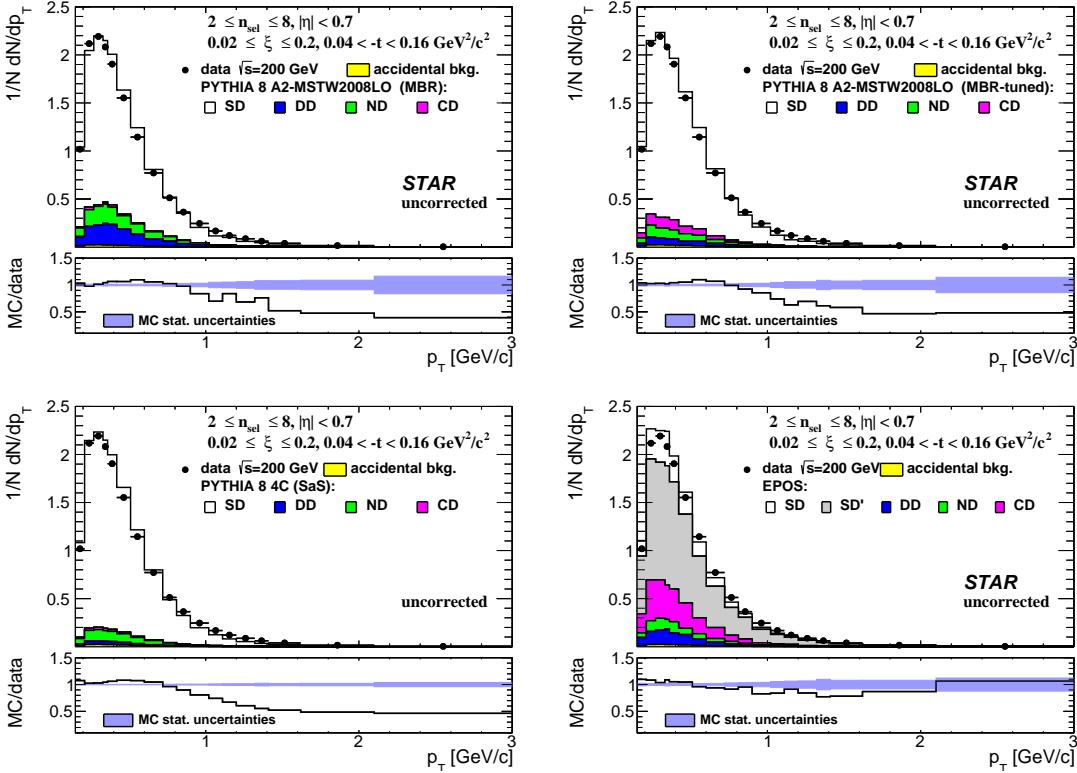


Figure 4.12: Uncorrected distributions of data compared to various MC models: (top left) PYTHIA 8 A2 (MBR), (top right) PYTHIA 8 A2 (MBR-tuned), (bottom left) PYTHIA 8 4C (SaS) and (bottom right) EPOS, as a function of  $p_T$ . The ratio of MC predictions and data is shown in the bottom panels.

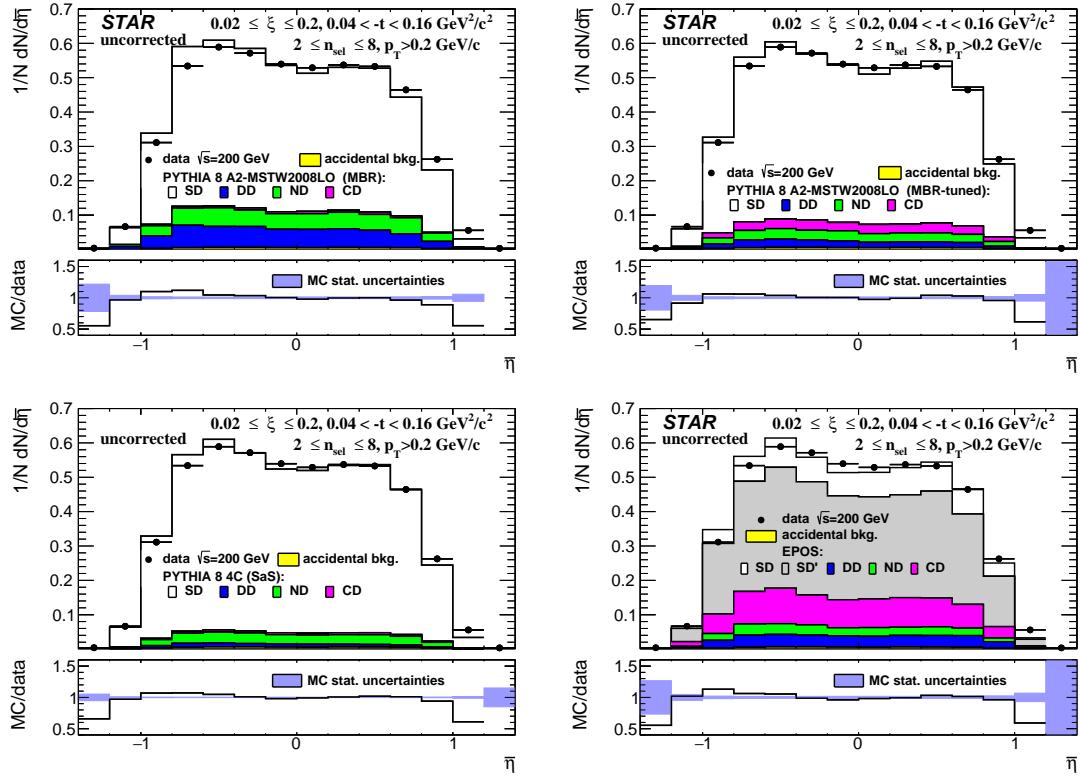


Figure 4.13: Uncorrected distributions of data compared to various MC models: (top left) PYTHIA 8 A2 (MBR), (top right) PYTHIA 8 A2 (MBR-tuned), (bottom left) PYTHIA 8 4C (SaS) and (bottom right) EPOS, as a function of  $\bar{\eta}$ . The ratio of MC predictions and data is shown in the bottom panels.

# 5. Selection Efficiencies

## 5.1 Vertex Reconstruction

When the charged-particle multiplicity is low, the vertex-finding algorithm sometimes fails to find the primary vertex. In addition, at high luminosity, vertex finder can fail due to the contribution of pile-up interactions, providing a wrong reconstructed vertex. In the study of vertex reconstruction efficiency we required at least two reconstructed global tracks  $n_{\text{sel}}^{\text{global}} \geq 2$  passing all the quality cuts listed in Sec 3.1, except vertex-related cuts on  $\text{DCA}_{xy}$  and  $\text{DCA}_z$ , and associated to true-level primary particles. Additionally, MC events were accepted if the  $z$ -coordinate of the true-level primary vertex was between  $-80$  and  $80$  cm and  $n_{\text{ch}} \geq 2$ . All corrections, described in this section, were calculated in three ranges of  $\xi$  separately using PYTHIA 8 SD embedding MC.

The global tracks (not necessarily associated to a true-level primary particles), which are used by the vertex-finder algorithm, had to pass the following quality cuts:

1. tracks must be matched with hits reconstructed in TOF,
2. the number of the TPC hits used in the helix fit  $N_{\text{hits}}^{\text{fit}}$  must be greater than 20,
3. the ratio of the number of TPC hits used in the helix fit to the number of possible TPC hits  $N_{\text{hits}}^{\text{fit}}/N_{\text{hits}}^{\text{poss}}$  must be greater than 0.52,
4. the transverse impact parameter with respect to the beamline  $d_0$  must be less than 2 cm,
5. the track's transverse momentum  $p_T$  must be greater than 0.2 GeV/c.

The above track selection criteria are different than those used in the nominal analysis. Primary vertex reconstruction efficiency and fake vertex rate were calculated as a function of the number of global tracks used in vertexing  $n_{\text{virt}}^{\text{global}}$  instead of  $n_{\text{sel}}^{\text{global}}$  ( $n_{\text{virt}}^{\text{global}} \geq n_{\text{sel}}^{\text{global}}$ ).

In the nominal analysis exactly one vertex with  $n_{\text{sel}} \geq 2$  is required. However, in the study of vertex reconstruction, events with additional vertices were studied. Therefore, we define the best vertex as the reconstructed vertex with the highest number of TOF-matched tracks. This vertex does not have to be associated to true-level primary vertex (fake or secondary vertex). The algorithm, which matches reconstructed vertices to true-level vertices, checks for reconstructed tracks originating from them. If at least one reconstructed track is assigned to a true-level particle, then the reconstructed vertex is assigned to the true-level vertex from which the true-level particle originates. Since the fake vertices (not matched to the true-level primary vertex) are allowed in the analysis, the overall vertex-finding efficiency,  $\epsilon_{\text{virt}}(n_{\text{virt}}^{\text{global}})$ , is expressed as:

$$\epsilon_{\text{virt}}(n_{\text{virt}}^{\text{global}}) = \epsilon_{\text{virt}}^{\text{best}}(n_{\text{virt}}^{\text{global}}) + \delta_{\text{virt}}^{\text{fake}}(n_{\text{virt}}^{\text{global}}) \quad (5.1)$$

where:

$\epsilon_{\text{virt}}^{\text{best}}(n_{\text{virt}}^{\text{global}})$  is the primary vertex reconstruction efficiency, determined as the ratio of the number of good reconstructed events (best primary vertex with  $n_{\text{sel}} \geq 2$  matched to the true-level primary vertex) to the number of input MC events,

$\delta_{\text{virt}}^{\text{fake}}(n_{\text{virt}}^{\text{global}})$  is the fake vertex rate, determined as the ratio of the number of good reconstructed events (best primary vertex with  $n_{\text{sel}} \geq 2$  not matched to the true-level primary vertex) to the number of input MC events. Due to the contribution of pile-up, it is possible that the best vertex originates from fake tracks instead of true-level particles.

512 The vertex-finding efficiency as a function of  $n_{\text{virt}}^{\text{global}}$ , shown in Fig. 5.1 (left), is larger than 75% for  
 513 all  $n_{\text{virt}}^{\text{global}}$ . However, for  $n_{\text{virt}}^{\text{global}} > 8$ , there are more fake than true-level primary vertices. When  
 514 there are exactly two global tracks used in the vertex reconstruction,  $n_{\text{virt}}^{\text{global}} = 2$ , the vertex-  
 515 finding efficiency depends on the longitudinal distance between these tracks  $|\Delta z_0|$ . Therefore,  
 516 the vertex-finding efficiency for such events  $\epsilon_{\text{virt}}(|\Delta z_0|)$  is given by:

$$\epsilon_{\text{virt}}(|\Delta z_0|) = \epsilon_{\text{virt}}^{\text{best}}(|\Delta z_0|) + \delta_{\text{virt}}^{\text{fake}}(|\Delta z_0|) \quad (5.2)$$

517 where:  $\epsilon_{\text{virt}}^{\text{best}}(|\Delta z_0|)$  is the primary vertex reconstruction efficiency,  $\delta_{\text{virt}}^{\text{fake}}(|\Delta z_0|)$  is the fake vertex  
 518 rate.

519 Figure 5.1 (right) shows the vertex-finding efficiency for events with  $n_{\text{virt}}^{\text{global}} = 2$ . This efficiency  
 520 is smaller than 20% for tracks with  $|\Delta z_0| > 2$  cm, hence the analysis was limited to events with  
 521  $|\Delta z_0| < 2$  cm, when  $n_{\text{virt}}^{\text{global}} = 2$ . The rate of fake vertices is negligibly low (open points overlap  
 522 with full points).

523 Events are rejected if more vertices are reconstructed in addition to the best one. Rejected  
 524 events can be classified as:

- 525 a) two or more additional vertices,
- 526 b) additional secondary vertex from interactions with the detector dead-material,
- 527 c) additional fake vertex,
- 528 d) additional primary vertex (vertex splitting or background vertex reconstructed as best ver-  
 529 tex),
- 530 e) additional secondary vertex from the decay.

531 The fraction of such events,  $f_{\text{virt}}^{\text{veto}}(n_{\text{virt}}^{\text{global}})$ , is given by:

$$f_{\text{virt}}^{\text{veto}}(n_{\text{virt}}^{\text{global}}) = \frac{\text{number of events with more than one reconstructed TOF vertex}}{\text{number of events with at least one reconstructed TOF vertex}} \quad (5.3)$$

$$= f_a + f_b + f_c + f_d + f_e$$

532 where  $f_a$  to  $f_e$  are the fractions of events with additional vertices, with labels corresponding to  
 533 the items in the listing above.

534 As before, the fraction was calculated as a function of  $|\Delta z_0|$  for events with  $n_{\text{virt}}^{\text{global}} = 2$ .  
 535 Figure 5.2 shows the fraction of multi-vertex events with respect to the  $n_{\text{virt}}^{\text{global}}$ . There is a large  
 536 fraction of events ( $> 90\%$ ) with additional background vertices for  $n_{\text{virt}}^{\text{global}} \geq 9$ , what would result  
 537 in large correction factor. Hence, the analysis was limited to events with  $n_{\text{sel}}^{\text{global}} \leq 8$  ( $n_{\text{sel}}^{\text{global}} \leq$

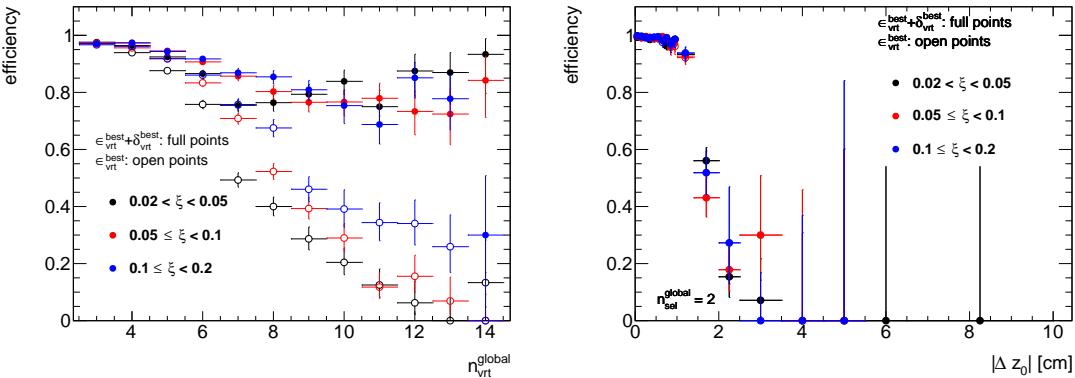


Figure 5.1: Vertex-finding efficiency in three ranges of  $\xi$  as a function of (left)  $n_{\text{virt}}^{\text{global}}$  and (right)  
 with respect to the  $|\Delta z_0|$  between reconstructed tracks in events with  $n_{\text{virt}}^{\text{global}} = 2$ .

538  $n_{\text{vrt}}^{\text{global}}$ ). The total fraction of multi-vertex events,  $f_a + f_b + f_c + f_d + f_e$ , as a function of  $n_{\text{vrt}}^{\text{global}}$   
539 and  $|\Delta z_0|$ , shown in Fig. 5.3, demonstrates that  $f_{\text{veto}}^{\text{veto}}(|\Delta z_0|)$  is very small (< 2%) for events with  
540  $n_{\text{vrt}}^{\text{global}} = 2$ .

541 Although, the analysis was limited to  $n_{\text{sel}}^{\text{global}} \leq 8$  ( $n_{\text{sel}}^{\text{global}} \leq n_{\text{vrt}}^{\text{global}}$ ), a fraction of events with  
542 additional background vertices was still relatively large. Since most of these additional vertices  
543 are fake (and as accidental not correlated with true-level primary distributions), it was checked  
544 whether the charged-particle multiplicity distributions are different for events with and without  
545 reconstructed fake vertices. These distributions, as shown in Fig 5.4, are in good agreement, thus,  
546 above studies of vertex reconstruction were repeated using MC events that do not contain recon-  
547 structed fake vertices. It means that events with additional fake vertex were rejected (similarly to  
548 the analysis of real data) and no correction is needed for such losses since it only affects overall  
549 normalization (not the shapes of distributions under study). The vertex-finding efficiency, which  
550 was calculated from such events, is shown in Fig. 5.5. It is greater than 95% for events with  
551  $2 \leq n_{\text{vrt}}^{\text{global}} \leq 8$ . In addition, the corresponding fraction of multi-vertex events, shown in Figs. 5.6

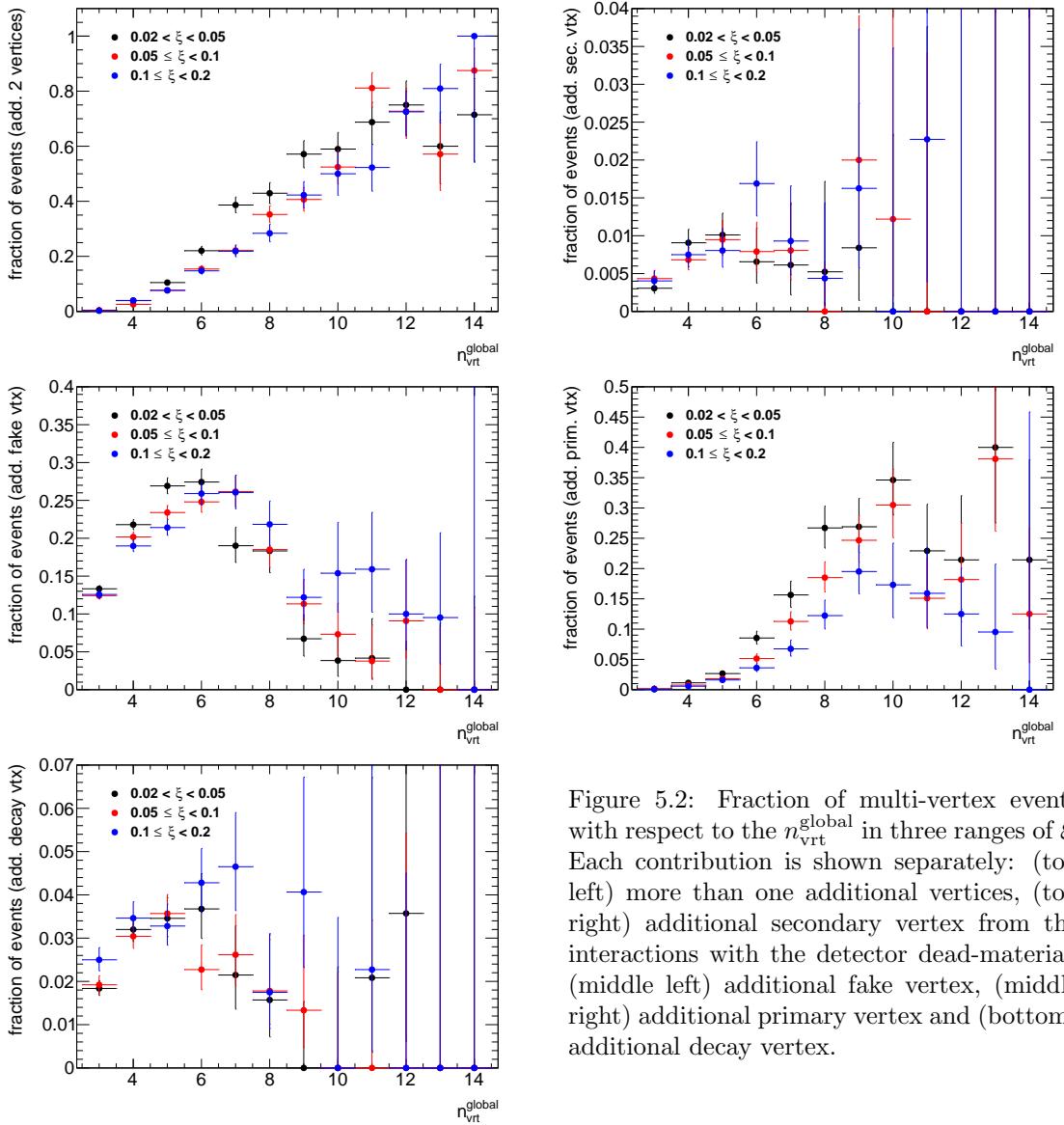


Figure 5.2: Fraction of multi-vertex events with respect to the  $n_{\text{vrt}}^{\text{global}}$  in three ranges of  $\xi$ . Each contribution is shown separately: (top left) more than one additional vertices, (top right) additional secondary vertex from the interactions with the detector dead-material, (middle left) additional fake vertex, (middle right) additional primary vertex and (bottom) additional decay vertex.

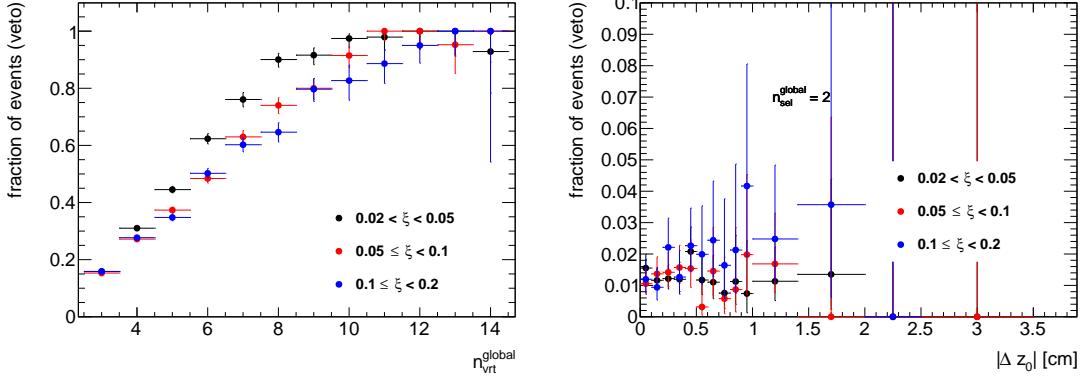


Figure 5.3: Total fraction of multi-vertex events as a function of (left)  $n_{\text{vrt}}^{\text{global}}$  for events with  $n_{\text{vrt}}^{\text{global}} > 2$  and (right)  $|\Delta z_0|$  for events with  $n_{\text{vrt}}^{\text{global}} = 2$  in three ranges of  $\xi$ .

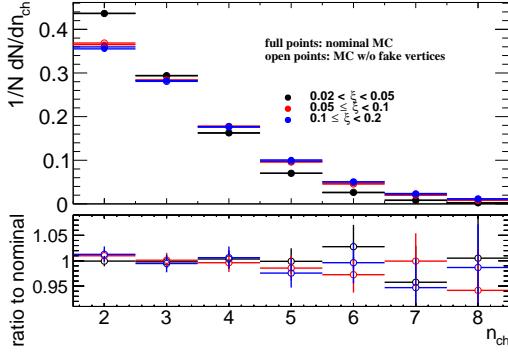


Figure 5.4: Normalized charged-particle multiplicity distributions in three ranges of  $\xi$  calculated from PYTHIA 8 SD embedding MC for (full points) all generated events and (open points) events without reconstructed fake vertices.

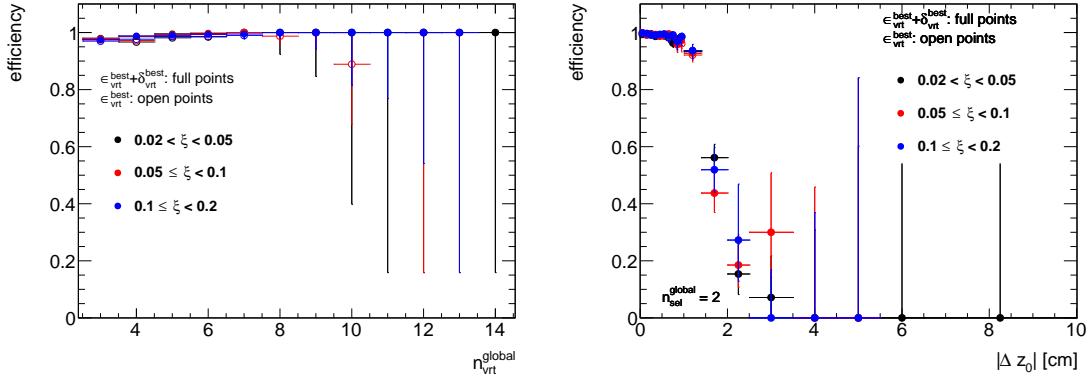


Figure 5.5: Vertex-finding efficiency in three ranges of  $\xi$  as a function of (left)  $n_{\text{vrt}}^{\text{global}}$  and (right) with respect to the  $|\Delta z_0|$  between reconstructed tracks in events with  $n_{\text{vrt}}^{\text{global}} = 2$ . Only events that do not contain additional fake vertices were used.

and 5.7, is smaller than 20%. Since fake vertices were rejected from this study, the  $f_c$  term from Eq. (5.3) is equal to 0. The correction factors calculated from MC events that do not contain reconstructed fake vertices were used in the analysis instead of the one obtained from the full MC sample.

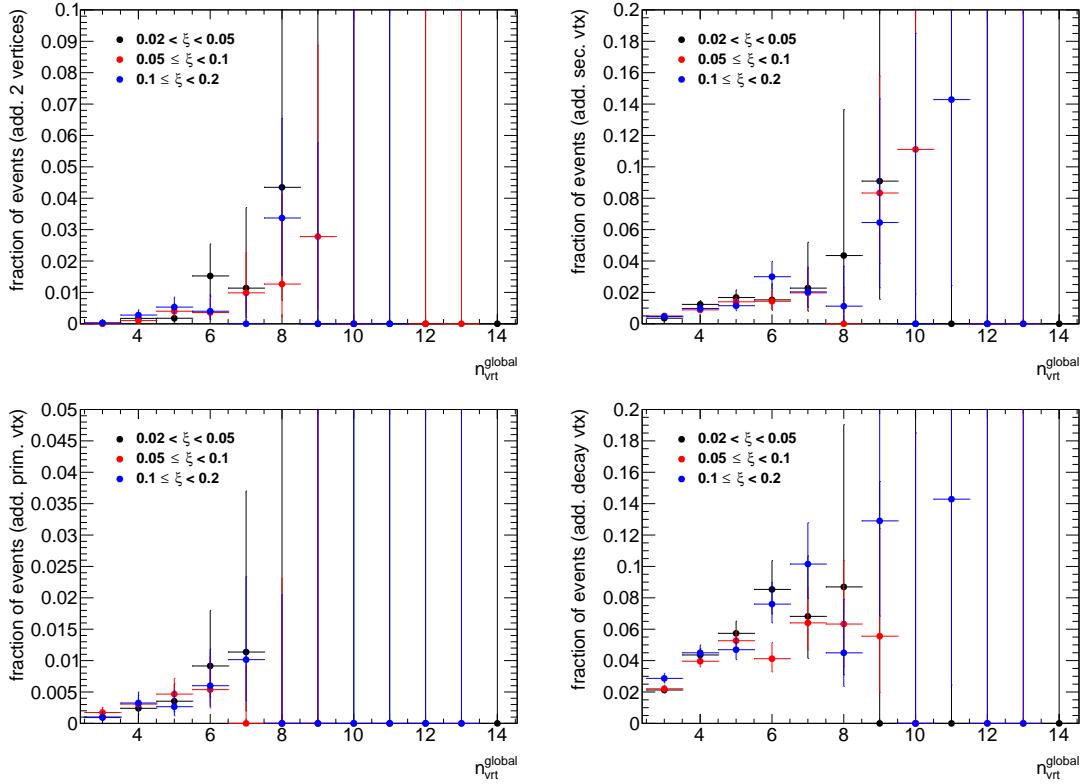


Figure 5.6: Fraction of multi-vertex events with respect to the  $n_{\text{vrt}}^{\text{global}}$  in three ranges of  $\xi$ . Each contribution is shown separately: (top left) more than one additional vertices, (top right) additional secondary vertex from the interactions with the detector dead-material, (bottom left) additional primary vertex and (bottom right) additional decay vertex. Only events that do not contain additional fake vertices were used.

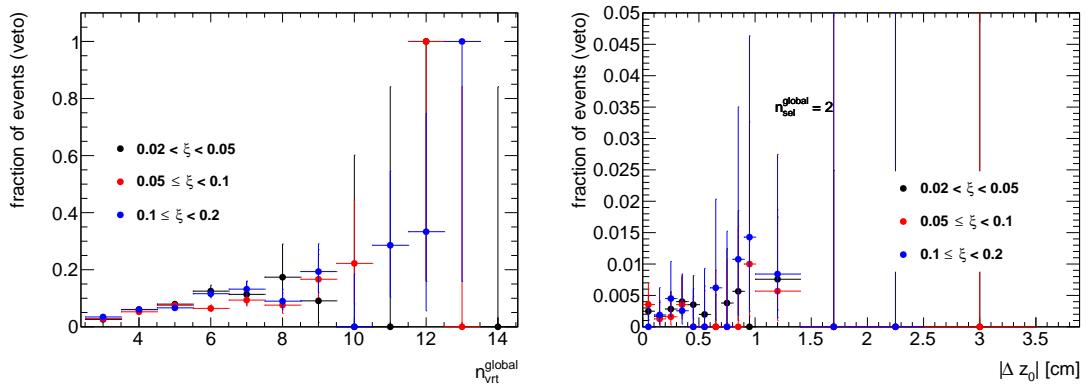


Figure 5.7: Total fraction of multi-vertex events as a function of (left)  $n_{\text{vrt}}^{\text{global}}$  for events with  $n_{\text{vrt}}^{\text{global}} > 2$  and (right)  $|\Delta z_0|$  for events with  $n_{\text{vrt}}^{\text{global}} = 2$  in three ranges of  $\xi$ . Only events that do not contain additional fake vertices were used.

## 5.2 Correction to BBC-Small

The SDT trigger conditions imposed a signal in RPs and a veto on any signal in the same-side small BBC tiles, whereas a signal in the opposite-side BBC-small was required by the offline event selection. These requirements were imposed in order to accept only events with rapidity gap and reduce DD, ND and accidental backgrounds. A joined BBC-small efficiency,  $\epsilon_{BBC}$ , was obtained as a function of each measured quantity using PYTHIA 8 4C (SaS) SD embedded into Zerobias data, EPOS SD+SD' and HERWIG SD MC. The efficiency was calculated for events within fiducial region as follows:

$$\epsilon_{BBC} = \frac{\text{number of MC events satisfying the BBC-small selection criteria}}{\text{number of MC events}} \quad (5.4)$$

Figures 5.8 to 5.10 show the fraction of generated true-level MC events, within the fiducial region of the measurement, in which the selection criteria on BBC-small signal and veto are fulfilled. The efficiency weakly depends on the measured variables ( $n_{ch}$ ,  $p_T$  and  $\bar{\eta}$ ). In addition, veto, signal and joined BBC-small efficiencies are presented separately as a function of  $\xi$  in Fig. 5.11. The  $\epsilon_{BBC}$  strongly depends on  $\xi$  and varies from about 90% for events with  $\xi$  within 0.02 – 0.05 to about 60% for events with  $0.1 < \xi < 0.2$ . However, measurements of corrected  $\xi$  distributions are out of the scope of this analysis.

Data is corrected for BBC-small efficiency using PYTHIA 8 4C (SaS). The uncertainty related to this correction is estimated by using HERWIG and EPOS SD+SD' samples, where the hadronization models are different from that used in PYTHIA 8. Figure 5.12 shows the PYTHIA 8 prediction on BBC efficiency divided by the HERWIG prediction in three ranges of  $\xi$ . The deviations between these two models are of the order of 4% at  $0.02 < \xi < 0.05$ , 2% at  $0.05 < \xi < 0.1$  and about 10% at  $0.1 < \xi < 0.2$ . The differences between PYTHIA 8 and EPOS SD+SD' predictions are shown in Fig. 5.13. Most of them are of the order of 3%, except  $n_{ch} \leq 3$  for which the difference varies up to 6%. The maximum difference between PYTHIA 8 and HERWIG/EPOS hadronization models is used as systematic uncertainty.

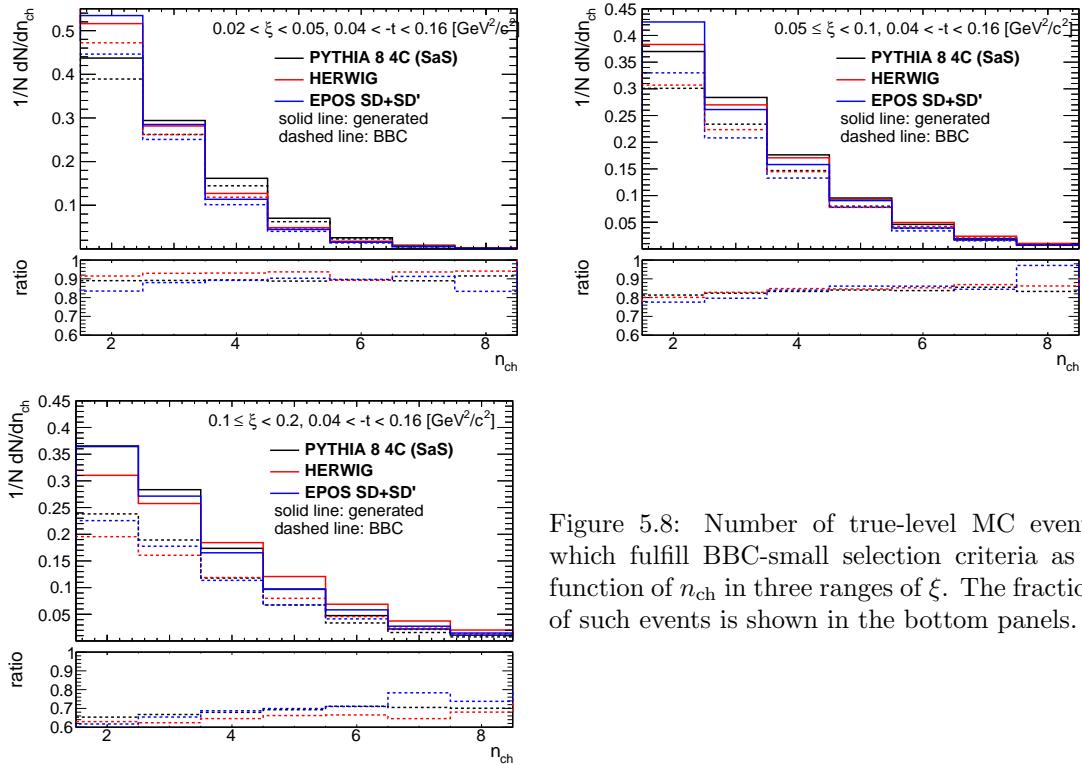


Figure 5.8: Number of true-level MC events which fulfill BBC-small selection criteria as a function of  $n_{ch}$  in three ranges of  $\xi$ . The fraction of such events is shown in the bottom panels.

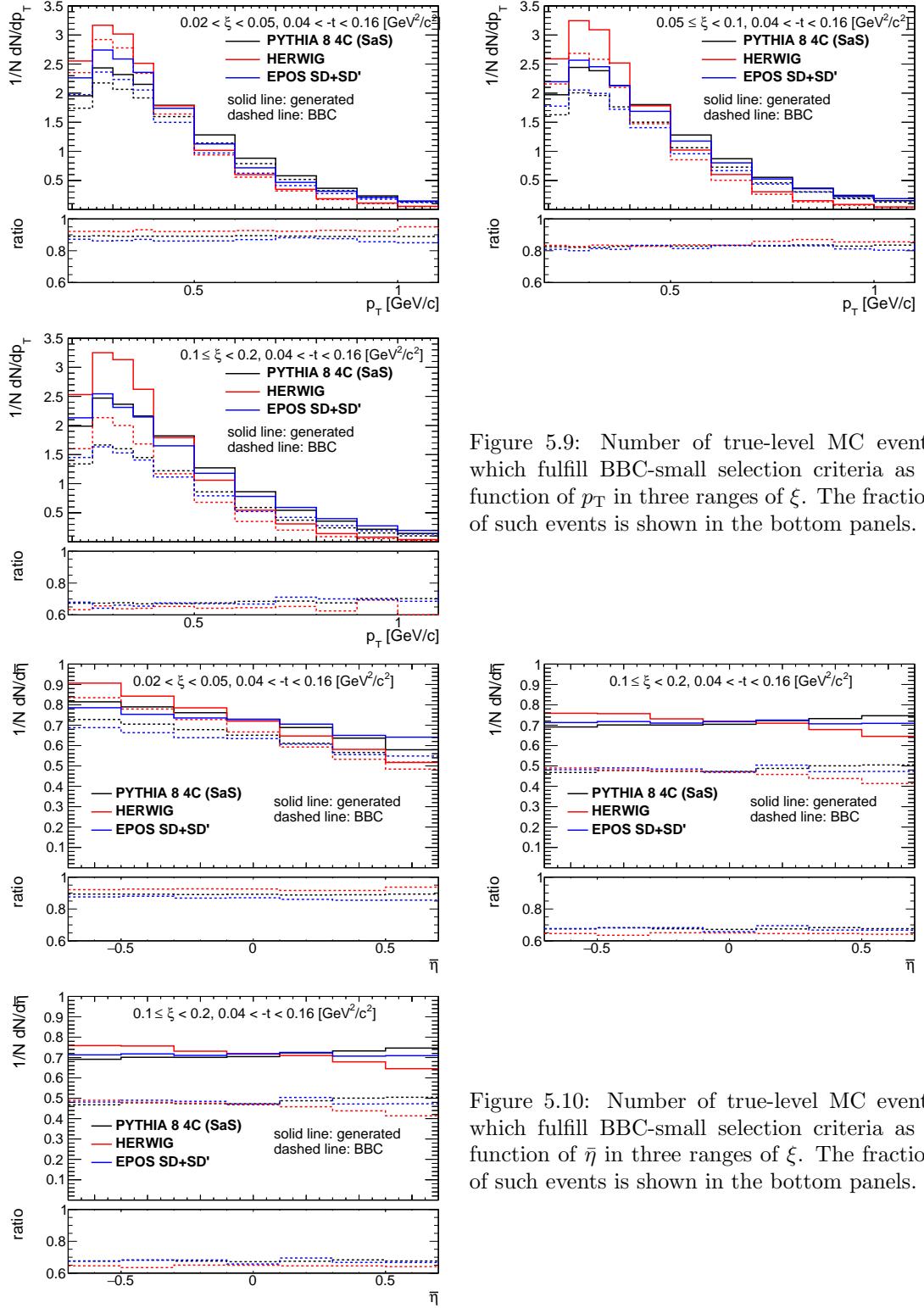


Figure 5.9: Number of true-level MC events which fulfill BBC-small selection criteria as a function of  $p_T$  in three ranges of  $\xi$ . The fraction of such events is shown in the bottom panels.

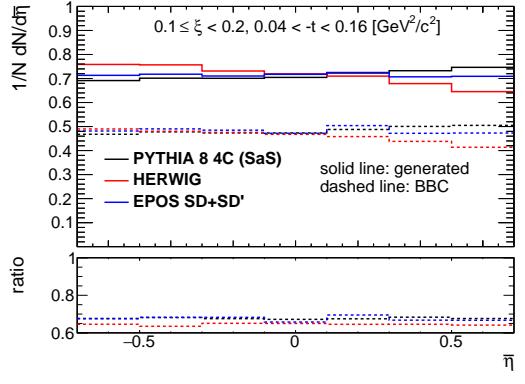


Figure 5.10: Number of true-level MC events which fulfill BBC-small selection criteria as a function of  $\bar{\eta}$  in three ranges of  $\xi$ . The fraction of such events is shown in the bottom panels.

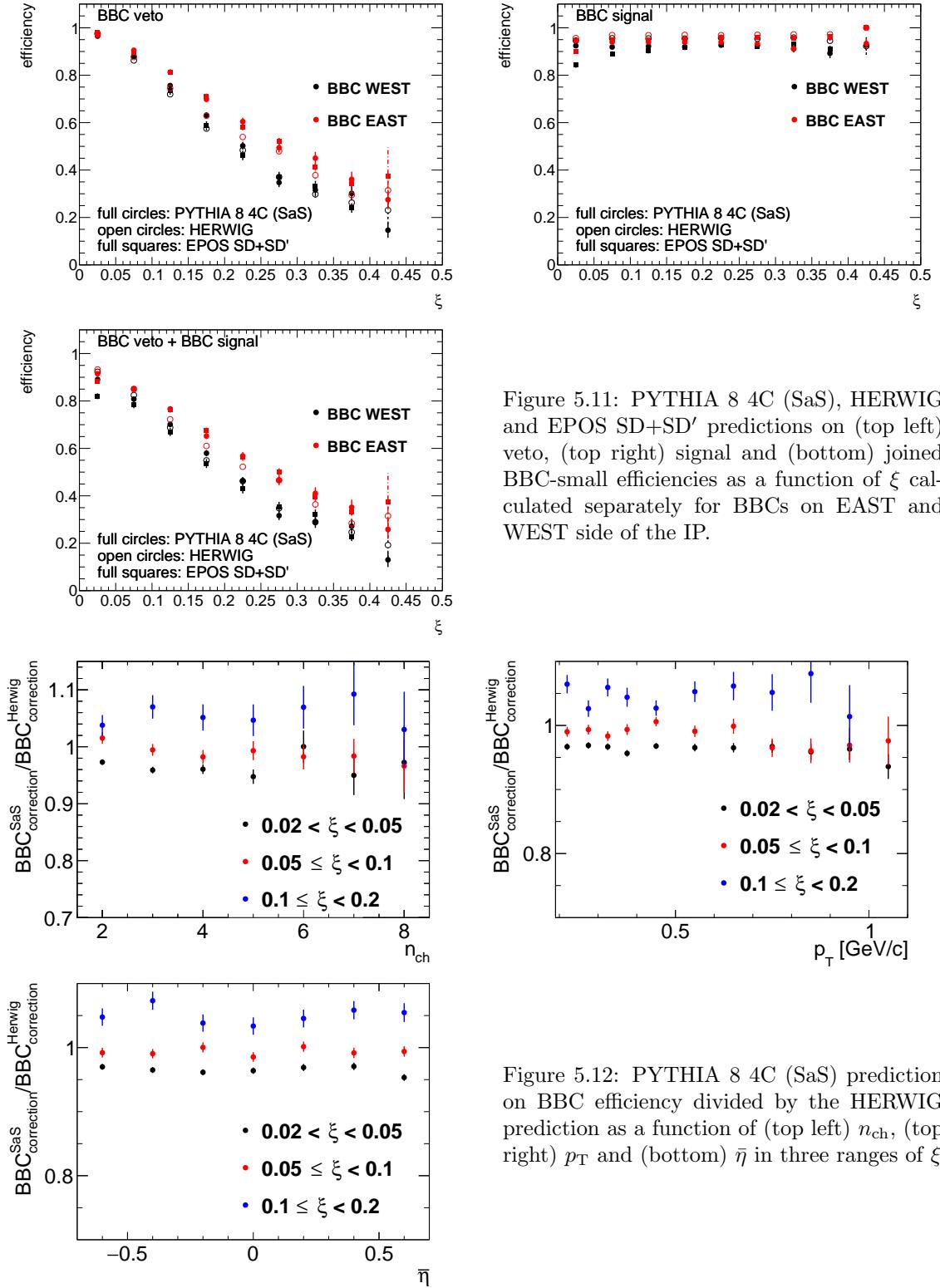


Figure 5.11: PYTHIA 8 4C (SaS), HERWIG and EPOS SD+SD' predictions on (top left) veto, (top right) signal and (bottom) joined BBC-small efficiencies as a function of  $\xi$  calculated separately for BBCs on EAST and WEST side of the IP.

Figure 5.12: PYTHIA 8 4C (SaS) prediction on BBC efficiency divided by the HERWIG prediction as a function of (top left)  $n_{ch}$ , (top right)  $p_T$  and (bottom)  $\bar{\eta}$  in three ranges of  $\xi$

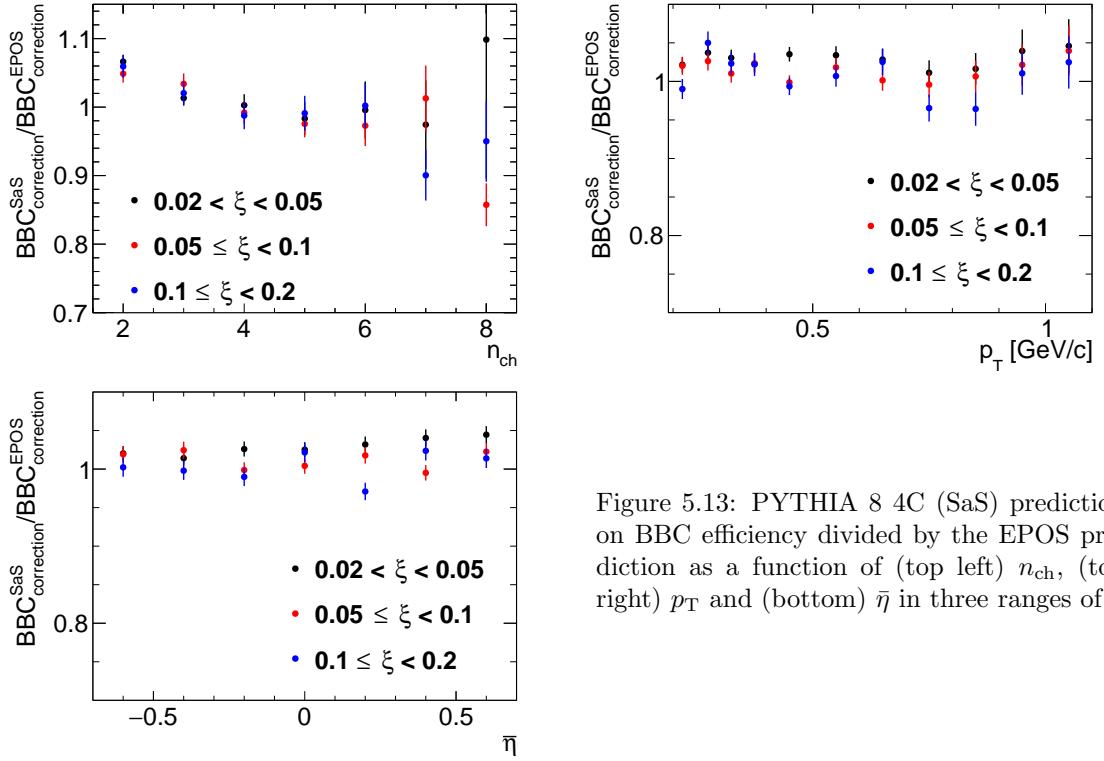


Figure 5.13: PYTHIA 8 4C (SaS) prediction on BBC efficiency divided by the EPOS prediction as a function of (top left)  $n_{\text{ch}}$ , (top right)  $p_{\text{T}}$  and (bottom)  $\bar{\eta}$  in three ranges of  $\xi$

# 6. Migrations into and out of the Fiducial Region

In this section the corrections due to the migrations of tracks and forward-scattered protons into and out of the fiducial region are described.

## 6.1 Migrations of Tracks into and out of the Fiducial Region

The procedure, described in this section, accounts for migrations of tracks into and out of the fiducial region, which originate from TPC resolution effects. The correction factor for such tracks,  $f_{\text{okr}}(p_T, \eta)$  is defined as follows:

$$f_{\text{okr}}(p_T, \eta) = \frac{1 - f_{\text{okr}}^-(p_T, \eta)}{1 - f_{\text{okr}}^+(p_T, \eta)} \quad (6.1)$$

where  $f_{\text{okr}}^-(p_T, \eta)$  is the fraction of reconstructed tracks for which the corresponding primary particle is outside of the kinematic range of the measurement and  $f_{\text{okr}}^+(p_T, \eta)$  is the fraction of primary particles for which the corresponding reconstructed track is outside of the kinematic range of the measurement.

The resulting residual migrations, shown in Fig. 6.1, were estimated using PYTHIA 8 SD embedding MC. The main effect was observed at  $|\eta| \sim 0.7$ , where about 2 – 6% reconstructed tracks were associated to primary particle outside the fiducial region. However, above contributions to the correction factor,  $f_{\text{okr}}(p_T, \eta)$ , cancel each other and the resulting factor is about 2% at  $|\eta| \sim 0.7$ .

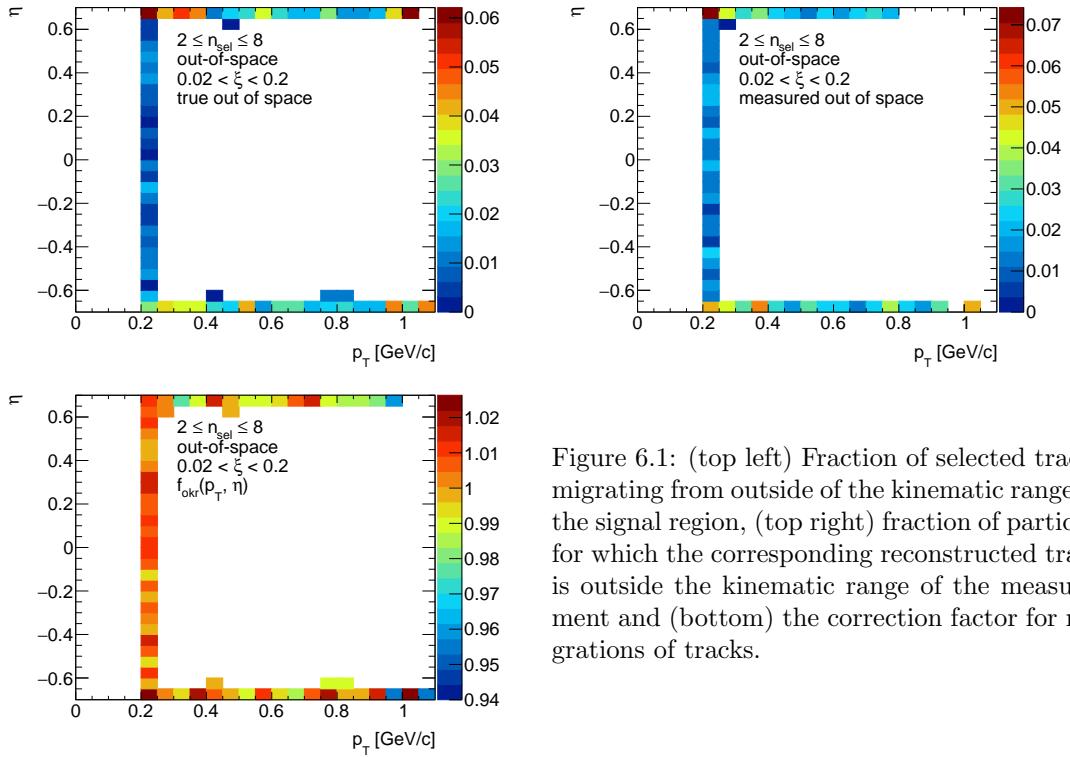


Figure 6.1: (top left) Fraction of selected tracks migrating from outside of the kinematic range to the signal region, (top right) fraction of particles for which the corresponding reconstructed track is outside the kinematic range of the measurement and (bottom) the correction factor for migrations of tracks.

## 597 6.2 Migrations in $\xi$

598 The analysis was performed in three ranges of  $\xi$ . Thus, there are migrations into and out of these  $\xi$   
 599 regions. They mainly originate from the resolution of  $\xi$  reconstructed from RP tracks. Figure 6.2  
 600 shows the resolution of  $\xi$  as a function of the true-level  $\xi$  (denoted as  $\xi_{\text{true}}$ ) with fitted zeroth order  
 601 polynomial. The resolution of  $\xi$  is fairly constant and equals to about 0.3%.

602 The corrections due to migrations into and out of  $\xi$  regions was defined as:

$$f_\xi = \frac{1 - f_\xi^-}{1 - f_\xi^+} \quad (6.2)$$

603 where  $f_\xi^-$  is the fraction of events for which the corresponding true-level,  $\xi_{\text{true}}$ , is outside of the  $\xi$   
 604 region and  $f_\xi^+$  is the fraction of events for which the corresponding reconstructed,  $\xi_{\text{reco}}$ , is outside  
 605 of the  $\xi$  region.

606 The  $f_\xi$  was calculated for each measured variable separately. Figures 6.3 to 6.5 show the  
 607 fraction of events  $f_\xi^-$  and  $f_\xi^+$  as a function of  $n_{\text{ch}}$ ,  $p_{\text{T}}$  and  $\bar{\eta}$ . The lower panel in each figure shows  
 608 the corresponding correction factor  $f_\xi$ . The largest differences between migrations into and out  
 609 of the  $\xi$  regions were observed at  $0.02 < \xi < 0.05$ , where they are of the order of 2 – 4%. In the  
 610 other  $\xi$  regions, the difference between  $f_\xi^-$  and  $f_\xi^+$  is smaller than 1%.

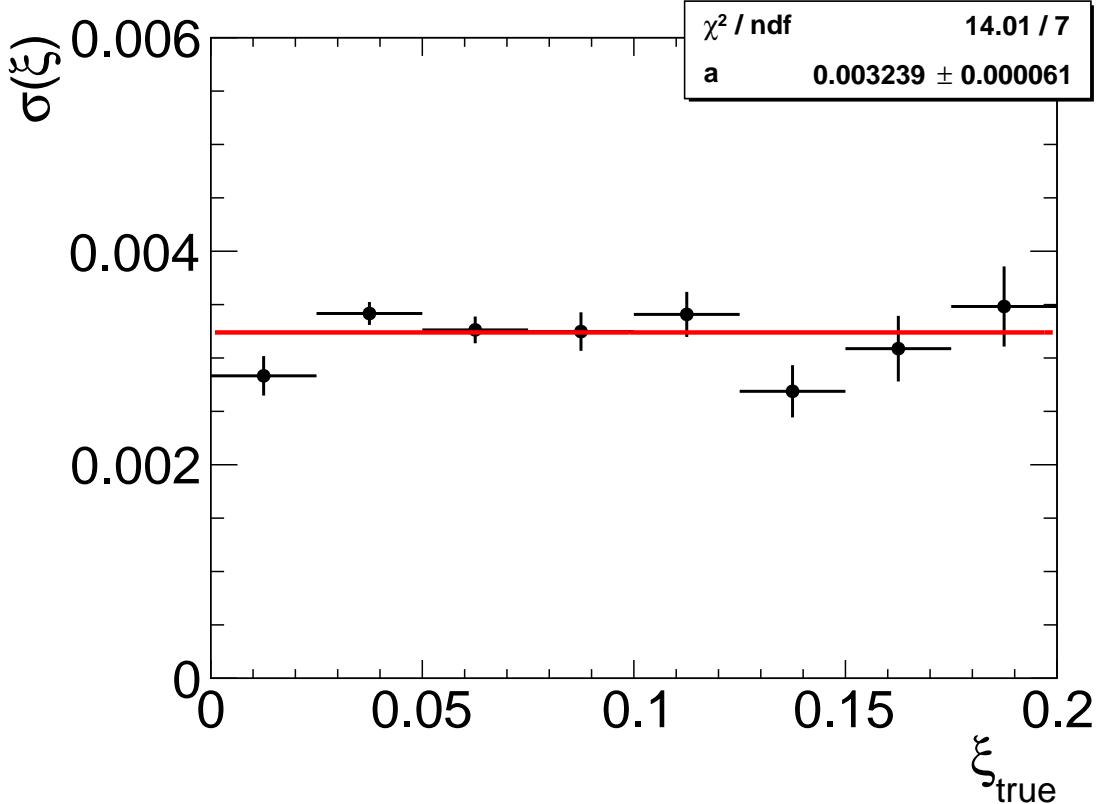


Figure 6.2: The resolution of  $\xi$  as a function of  $\xi_{\text{true}}$ . The zeroth order polynomial, shown as red line, was fitted.

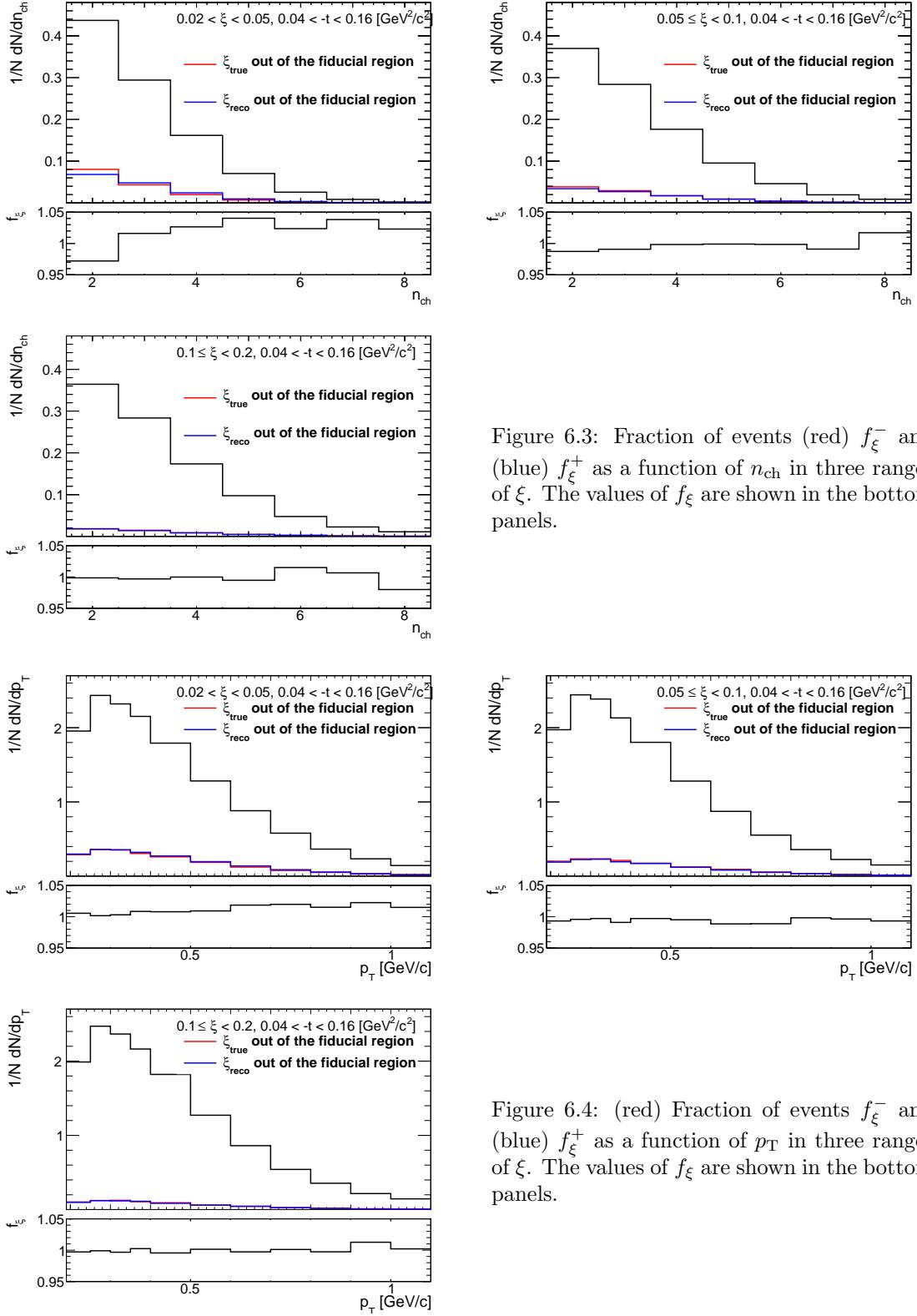


Figure 6.3: Fraction of events (red)  $f_\xi^-$  and (blue)  $f_\xi^+$  as a function of  $n_{ch}$  in three ranges of  $\xi$ . The values of  $f_\xi$  are shown in the bottom panels.

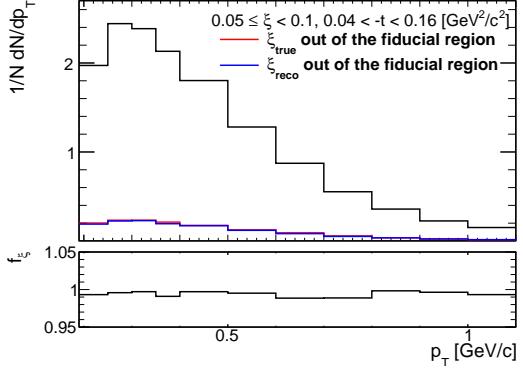


Figure 6.4: (red) Fraction of events  $f_\xi^-$  and (blue)  $f_\xi^+$  as a function of  $p_T$  in three ranges of  $\xi$ . The values of  $f_\xi$  are shown in the bottom panels.

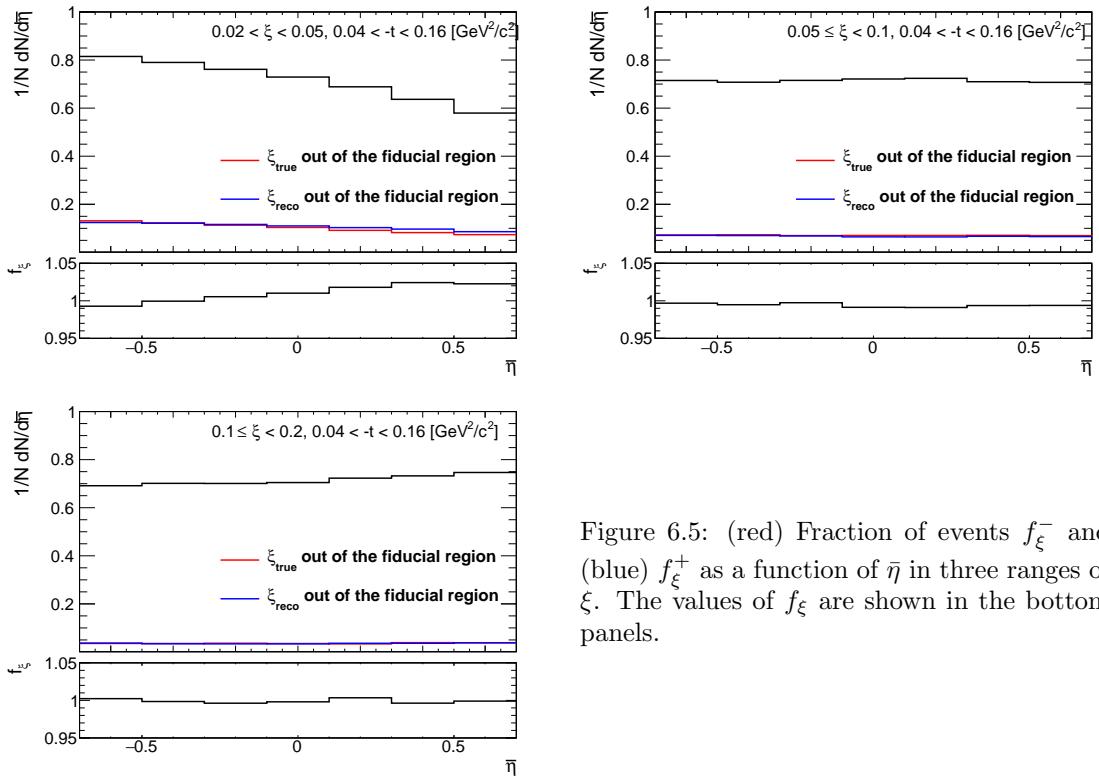


Figure 6.5: (red) Fraction of events  $f_\xi^-$  and (blue)  $f_\xi^+$  as a function of  $\bar{\eta}$  in three ranges of  $\xi$ . The values of  $f_\xi$  are shown in the bottom panels.

# 611 7. Event Corrections and 612 Unfolding Procedure

613 After subtraction of accidental, DD, CD and ND backgrounds (as described in Sec. 4 and 4.2),  
614 the data was corrected for detector inefficiencies to obtain the distributions of charged particles  
615 and particle to antiparticle (pion, kaon, proton and their antiparticle) multiplicity ratios. These  
616 corrections include:

- 617 • event-by-event weights due to vertex reconstruction efficiency:

$$w_{\text{ev}}^{\text{vrt}}(n_{\text{vrt}}^{\text{global}}, |\Delta z_0|) = \frac{1}{\epsilon_{\text{vrt}}(n_{\text{vrt}}^{\text{global}}, |\Delta z_0|)} \cdot \frac{1}{1 - f_{\text{veto}}(n_{\text{vrt}}^{\text{global}}, |\Delta z_0|)} \quad (7.1)$$

618 where the  $|\Delta z_0|$  dependence is only applicable for events with  $n_{\text{vrt}}^{\text{global}} = 2$  as described in  
619 Sec. 5.1.

- 620 • track-by-track weights due to track reconstruction efficiency, track backgrounds, migrations  
621 of tracks into and out of the fiducial region:

$$w_{\text{trk}}(p_T, \eta, V_z) = \frac{1 - f_{\text{bkg}}(p_T, \eta) - f_{\text{fake}}(p_T, \eta)}{\epsilon_{\text{TPC}}(p_T, \eta, V_z) \epsilon_{\text{TOF}}(p_T, \eta, V_z)} f_{\text{okr}}(p_T, \eta) \quad (7.2)$$

622 where:  $\epsilon_{\text{TPC}}(p_T, \eta, V_z)$  is TPC track reconstruction efficiency [1],  $\epsilon_{\text{TOF}}(p_T, \eta, V_z)$  is TOF  
623 matching efficiency [1],  $f_{\text{okr}}(p_T, \eta)$  is a factor accounting for migrations of tracks into and  
624 out of the fiducial region,  $f_{\text{bkg}}(p_T, \eta)$  is a fraction of background tracks, and  $f_{\text{fake}}(p_T, \eta)$   
625 is a fraction of fake tracks. These corrections were not applied for  $n_{\text{ch}}$  measurements since  
626 they were taken into account in the unfolding procedure.

- 627 • event-by-event (for  $n_{\text{ch}}$  distribution ) or track-by-track (for  $p_T, \bar{\eta}$  distributions) weights,  $f_\xi$ ,  
628 due to migrations of events between three  $\xi$  regions.

629 Additionally, the obtained distributions were corrected for BBC-small efficiency,  $\epsilon_{\text{BBC}}$ , using  
630 the following weight, which was calculated for each true-level quantity  $(n_{\text{ch}}, p_T, \bar{\eta})$  in three ranges  
631 of  $\xi$  separately:

$$w_{\text{BBC}} = \frac{1}{\epsilon_{\text{BBC}}} \quad (7.3)$$

632 In the following sections, the correction procedure for each of the measured distributions is  
633 presented separately.

## 634 7.1 Correction to $dN/dn_{\text{sel}}$

635 In order to express the multiplicity distribution in terms of the number of charged particles,  $n_{\text{ch}}$ ,  
636 instead of the number of selected tracks,  $n_{\text{sel}}$ , the following procedure based on the Bayesian un-  
637 folding [14, 15] was used. First, the  $n_{\text{sel}}$  distribution was corrected for vertex reconstruction effects  
638 by applying event-by-event weights,  $w_{\text{ev}}^{\text{vrt}}(n_{\text{vrt}}^{\text{global}}, |\Delta z_0|)$ . The number of events in which  $n_{\text{ch}}$  are  
639 produced,  $N_{\text{ev}}(n_{\text{ch}})$ , can be associated with the number of events in which  $n_{\text{sel}}$  are reconstructed,  
640  $N_{\text{ev}}(n_{\text{sel}})$ . Since there are several possible  $n_{\text{sel}}$  observed in  $n_{\text{ch}}$  event,  $N_{\text{ev}}(n_{\text{ch}})$  is given by:

$$\begin{aligned} N_{\text{ev}}(n_{\text{ch}}) &= \sum_{n_{\text{sel}}=0}^8 P(n_{\text{ch}}|n_{\text{sel}}) \cdot N_{\text{ev}}(n_{\text{sel}}) \\ &= \frac{1}{\epsilon_m(n_{\text{ch}})\epsilon_r(n_{\text{ch}})} \sum_{n_{\text{sel}}=2}^8 P(n_{\text{ch}}|n_{\text{sel}}) \cdot N_{\text{ev}}(n_{\text{sel}}) \end{aligned} \quad (7.4)$$

641 where:

642  $P(n_{\text{ch}}|n_{\text{sel}})$  is the conditional probability of having  $n_{\text{ch}}$  charged particles in an event in which  
 643  $n_{\text{sel}}$  tracks were found,

644  $\epsilon_m(n_{\text{ch}})$  is a factor, which recovers events that are lost due to TPC track reconstruction and TOF  
 645 matching inefficiencies, i.e. those with  $n_{\text{ch}} \geq 2$  but  $n_{\text{sel}} < 2$ ,

646  $\epsilon_r(n_{\text{ch}})$  is a factor, which recovers events which are lost due to fake tracks, i.e. those with  $n_{\text{ch}} \leq 8$   
 647 but  $n_{\text{sel}} > 8$ . It was checked that this effect is negligible (smaller than 1%) and can be  
 648 omitted.

649 Figure 7.1 shows  $\epsilon_m(n_{\text{ch}})$  in three ranges of  $\xi$ . It was derived from PYTHIA 8 embedding MC  
 650 and varies from about 25% for  $n_{\text{ch}} = 2$  to 95% for  $n_{\text{ch}} = 8$ . Since there are additional data-driven  
 651 corrections to TPC and TOF efficiencies, MC simulations were modified by randomly removing  
 652 or adding tracks. This was done in accordance with differences in the efficiencies between data  
 653 and MC. Figure 7.2 shows  $\epsilon_m(n_{\text{ch}})$  calculated in three ranges of  $\xi$  using no-pile-up PYTHIA 8 and  
 654 EPOS SD+SD'. The differences between these two models, which are up to 8% for  $n_{\text{ch}} = 2$  and  
 655  $0.1 < \xi < 0.2$ , were symmetrized and taken as a systematic uncertainty.

656 The probability  $P(n_{\text{ch}}|n_{\text{sel}})$  can be derived using Bayes' theorem, which can be stated mathematically  
 657 in terms of charged particle and charged track multiplicities as:

$$P(n_{\text{sel}}|n_{\text{ch}}) \cdot P(n_{\text{ch}}) = P(n_{\text{ch}}|n_{\text{sel}}) \cdot P(n_{\text{sel}}) \quad (7.5)$$

658 where:  $P(n_{\text{sel}})$  and  $P(n_{\text{ch}})$  are probabilities of observing  $n_{\text{sel}}$  and  $n_{\text{ch}}$  respectively,  $P(n_{\text{ch}}|n_{\text{sel}})$  and  
 659  $P(n_{\text{sel}}|n_{\text{ch}})$  are conditional probabilities.

660 In order to improve the estimate of  $P(n_{\text{ch}}|n_{\text{sel}})$ , the unfolding is done iteratively:

- 661 • In the first iteration, it is assumed that:

$$P(n_{\text{ch}}|n_{\text{sel}}) = P = P^{\text{MC}}(n_{\text{sel}}|n_{\text{ch}}) \frac{P^{\text{MC}}(n_{\text{ch}})}{P^{\text{MC}}(n_{\text{sel}})} \quad (7.6)$$

$$N_{\text{ev}}(n_{\text{ch}}) = \frac{1}{\epsilon_m(n_{\text{ch}})} \sum_{n_{\text{sel}}=2}^8 N_{\text{ev}}(n_{\text{sel}}) \cdot P \quad (7.7)$$

662 where  $P^{\text{MC}}(n_{\text{sel}}|n_{\text{ch}})$ ,  $P^{\text{MC}}(n_{\text{ch}})$  and  $P^{\text{MC}}(n_{\text{sel}})$  are obtained from MC.  $P^{\text{MC}}(n_{\text{sel}}|n_{\text{ch}})$  is  
 663 the same for each iteration.

- 664 • In the  $(i + 1)$ th iteration we have:

$$P^{i+1} = P^{\text{MC}}(n_{\text{sel}}|n_{\text{ch}}) \frac{N_{\text{ev}}^i(n_{\text{ch}})}{N_{\text{ev}}(n_{\text{sel}})} \quad (7.8)$$

$$N_{\text{ev}}^{i+1}(n_{\text{ch}}) = \frac{1}{\epsilon_m(n_{\text{ch}})} \sum_{n_{\text{sel}}=2}^8 N_{\text{ev}}(n_{\text{sel}}) \cdot P^{i+1} \quad (7.9)$$

665 where  $N_{\text{ev}}^i(n_{\text{ch}})$  is calculated in the previous iteration, and  $N_{\text{ev}}(n_{\text{sel}})$  is taken from data.

666 The unfolding matrices  $P(n_{\text{ch}}|n_{\text{sel}})$  for each  $\xi$  region, shown in Fig. 7.3, were obtained from  
 667 PYTHIA 8 embedding MC and used in all iterations of the above procedure. Similarly to  $\epsilon_m(n_{\text{ch}})$ ,  
 668 the matrices were modified by randomly removing or adding tracks in order to take into account  
 669 additional data-driven corrections to TPC and TOF efficiencies. In order to increase statistical  
 670 precision of the unfolding matrices, all simulated events were used, i.e. also those with additional  
 671 fake vertices (with  $n_{\text{sel}}$  defined as a number of primary tracks associated with the best vertex).  
 672 The systematic uncertainty related to limited statistics in PYTHIA 8 was estimated by performing  
 673 50 pseudo-experiments, in which the unfolding matrices were smeared according to their statistical  
 674 precision.

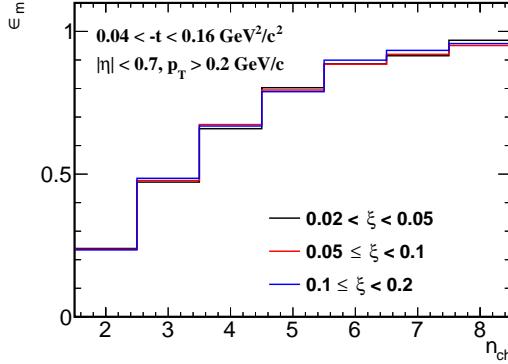


Figure 7.1:  $\epsilon_m(n_{\text{ch}})$  calculated separately in three ranges of  $\xi$  using PYTHIA 8 embedding MC.

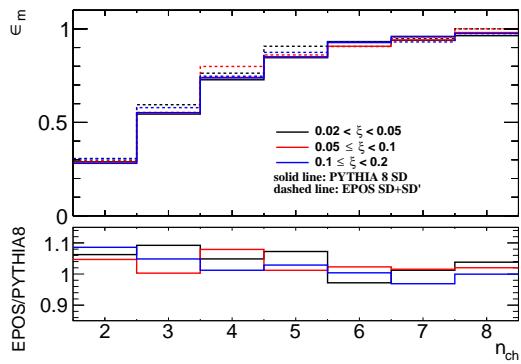


Figure 7.2: Comparison of  $\epsilon_m(n_{\text{ch}})$  calculated separately in three ranges of  $\xi$  using PYTHIA 8 SD and EPOS SD+SD' no-pile-up MCs. The ratios of EPOS to PYTHIA 8 predictions are shown in the bottom panel.

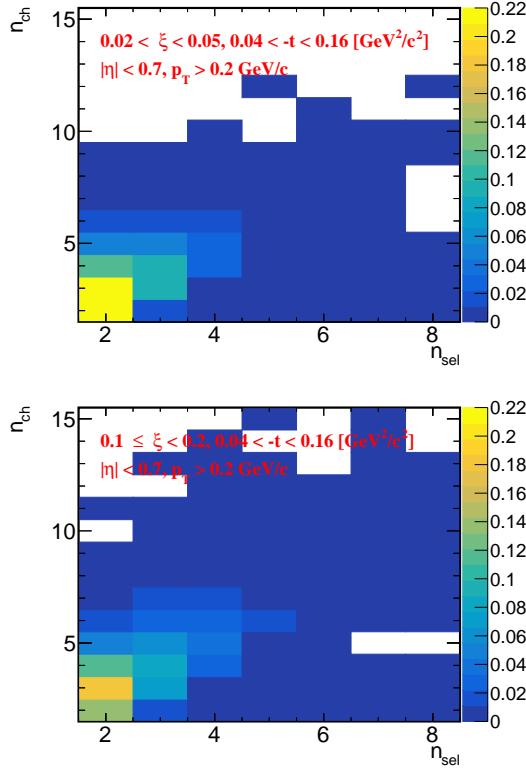


Figure 7.3: The unfolding matrices calculated from PYTHIA 8 embedding MC for three ranges of  $\xi$  separately.

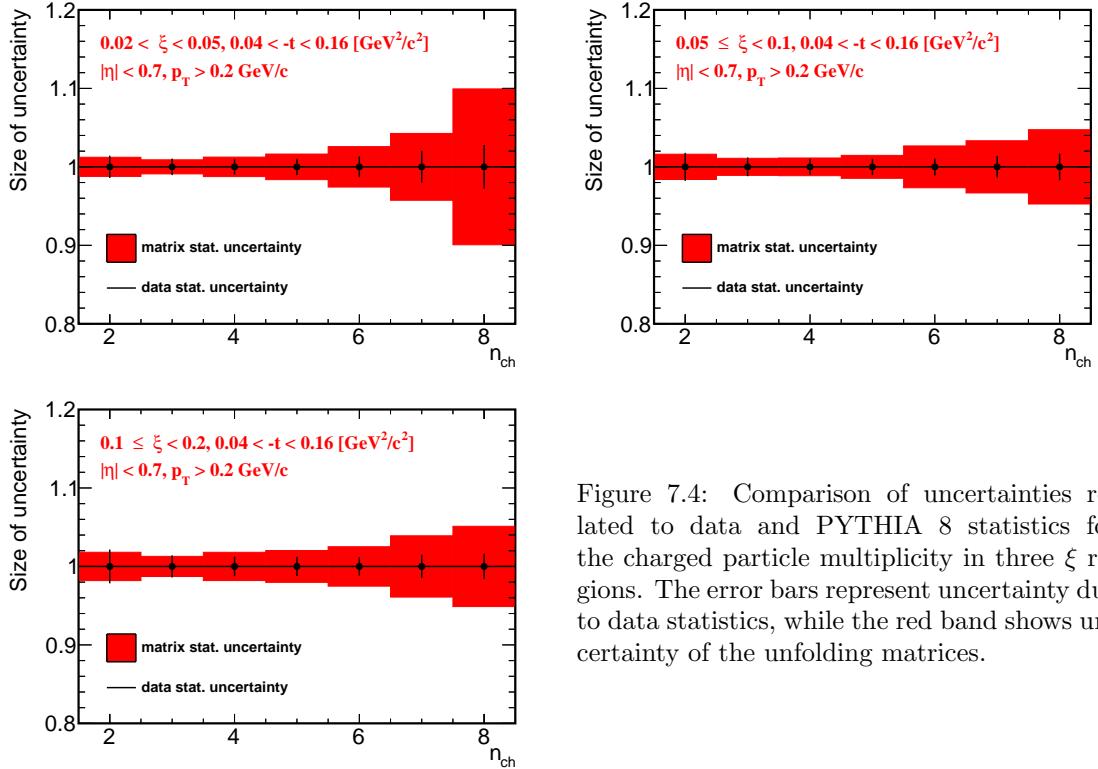


Figure 7.4: Comparison of uncertainties related to data and PYTHIA 8 statistics for the charged particle multiplicity in three  $\xi$  regions. The error bars represent uncertainty due to data statistics, while the red band shows uncertainty of the unfolding matrices.

uncertainties. It affects mainly large charged-particle multiplicities, where it is about 8 – 10% (as shown in Fig. 7.4), and is smaller or at the same level as other components contributing to the total systematic uncertainty.

The distribution  $dN/dn_{\text{ch}}$  obtained after the unfolding procedure was corrected for BBC-small efficiency, through  $w_{\text{BBC}}(n_{\text{ch}})$  weights, and migrations of events between  $\xi$  ranges, through  $f_{\xi}(n_{\text{ch}})$  weights. Since the unfolding matrices contain track reconstruction efficiencies, non-primary track backgrounds, migrations of tracks into and out of the fiducial region, the weight  $w_{\text{trk}}(p_{\text{T}}, \eta, V_z)$  was not used.

Finally, the  $dN/dn_{\text{ch}}$  distribution was normalized to the total number of events,  $N_{\text{ev}} = N$ , which was calculated as the integral of the unfolded distribution.

## 7.2 Correction to Transverse Momentum and Pseudorapidity Distributions

First the accidental and non-SD backgrounds were subtracted from the  $p_{\text{T}}$  and  $\bar{\eta}$  distributions. Next, each event was corrected for vertex reconstruction efficiency by applying  $w_{\text{ev}}^{\text{vrt}}(n_{\text{vrt}}^{\text{global}}, |\Delta z_0|)$  weights. Then, the tracks were corrected for the track reconstruction efficiency, non-primary track background contribution, track and  $\xi$  migrations, BBC-small efficiency (the product of  $w_{\text{trk}}(p_{\text{T}}, \eta, V_z)$ ,  $f_{\xi}$  and  $w_{\text{BBC}}$  weights was applied,  $f_{\xi}$  and  $w_{\text{BBC}}$  were calculated as a function of true-level  $p_{\text{T}}$  and  $\bar{\eta}$  separately).

In order to obtain charged-particle densities, the  $p_{\text{T}}$  and  $\bar{\eta}$  distributions were normalized to unity and scaled by the average charged particle multiplicity in an event  $\langle n_{\text{ch}} \rangle$ . The latter was calculated from the corrected charged particle multiplicity distribution  $dN/dn_{\text{ch}}$  (Sec. 7.1). The above procedure was done to correct the data also for events that are lost due to  $n_{\text{sel}} < 2$  but  $n_{\text{ch}} \geq 2$  since such correction was not included in any event-by-event and track-by-track weights. There was an assumption that  $p_{\text{T}}$  and  $\eta$  distributions are the same for lost and measured events, but it

701 was validated by the closure tests (Sec. 7.3). The mean  $p_T$  and  $\bar{\eta}$  in an event,  $\langle p_T \rangle$  and  $\langle \bar{\eta} \rangle$ , were  
702 obtained from the measured distributions.

### 703 7.3 Closure Tests

704 In order to validate the correction procedures, closure tests were performed, i.e. full correction  
705 procedure was applied to the MC detector-level distributions and the results were directly com-  
706 pared to the true-level distributions. Figure 7.5 shows closure tests of multiplicity, transverse  
707 momentum and pseudorapidity distributions for three ranges of  $\xi$ , separately. PYTHIA 8 SD  
708 embedding MC was used as an input. In order to compare corrected and true-level distributions,  
709 the statistical uncertainties of the true-level distributions were assumed to be 0. The difference  
710 between true-level and corrected distributions was taken as a systematic uncertainty.

### 711 7.4 EAST-WEST asymmetry

712 Another kind of consistency check can be performed by comparing the results obtained by tag-  
713ging forward-scattered protons in different detectors. Therefore, each distribution was measured  
714separately for events in which forward-scattered proton is on one and the other side of the IP  
715(east-west). Figure 7.6 shows the tests of multiplicity, transverse momentum and pseudorapidity  
716distributions for three ranges of  $\xi$ , separately. Both statistical uncertainty components, due to  
717input data and due to unfolding matrix, are added in quadrature for  $n_{ch}$  distributions. The largest  
718difference is observed for charged-particle multiplicity distributions, where it varies up to 20% for  
719 $n_{ch} = 8$  and  $0.02 < \xi < 0.1$ . For the rest multiplicities and  $\xi$  ranges, the differences are smaller  
720(< 10%). In case of  $p_T$  and  $\bar{\eta}$  distributions, a level of these disagreements is below 5%. As a result,  
721half of the differences between east and west distributions were used to be systematic uncertainty.

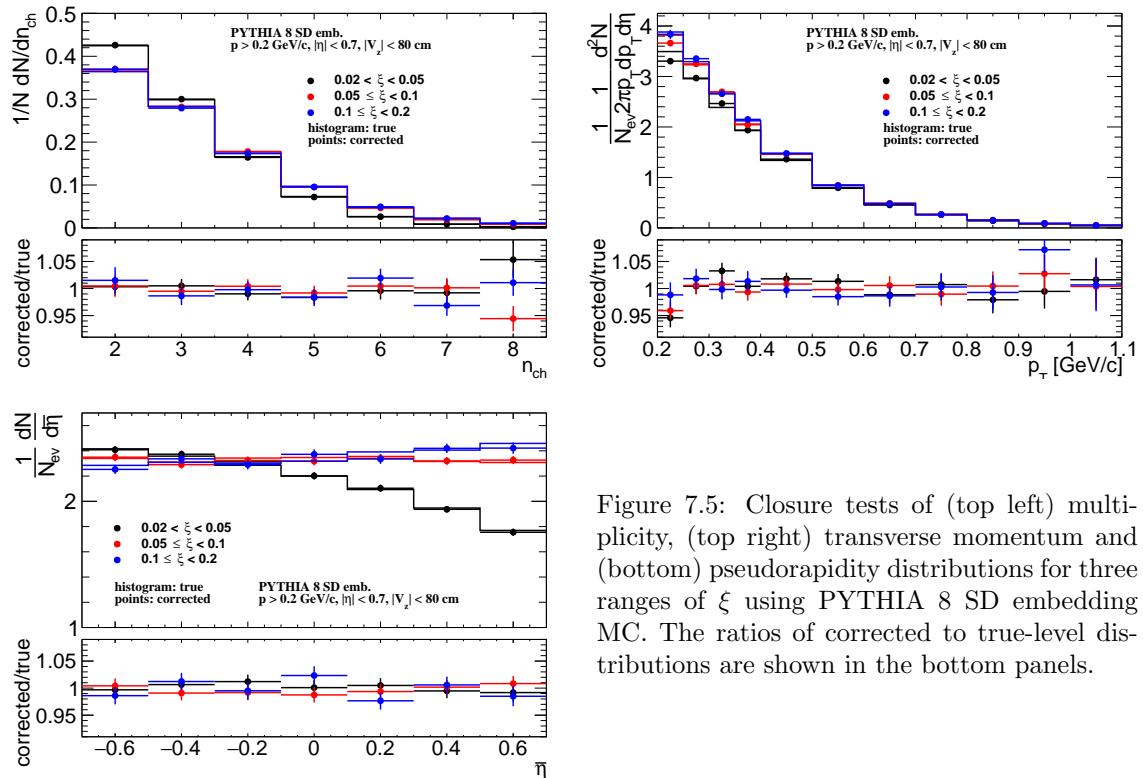


Figure 7.5: Closure tests of (top left) multiplicity, (top right) transverse momentum and (bottom) pseudorapidity distributions for three ranges of  $\xi$  using PYTHIA 8 SD embedding MC. The ratios of corrected to true-level distributions are shown in the bottom panels.

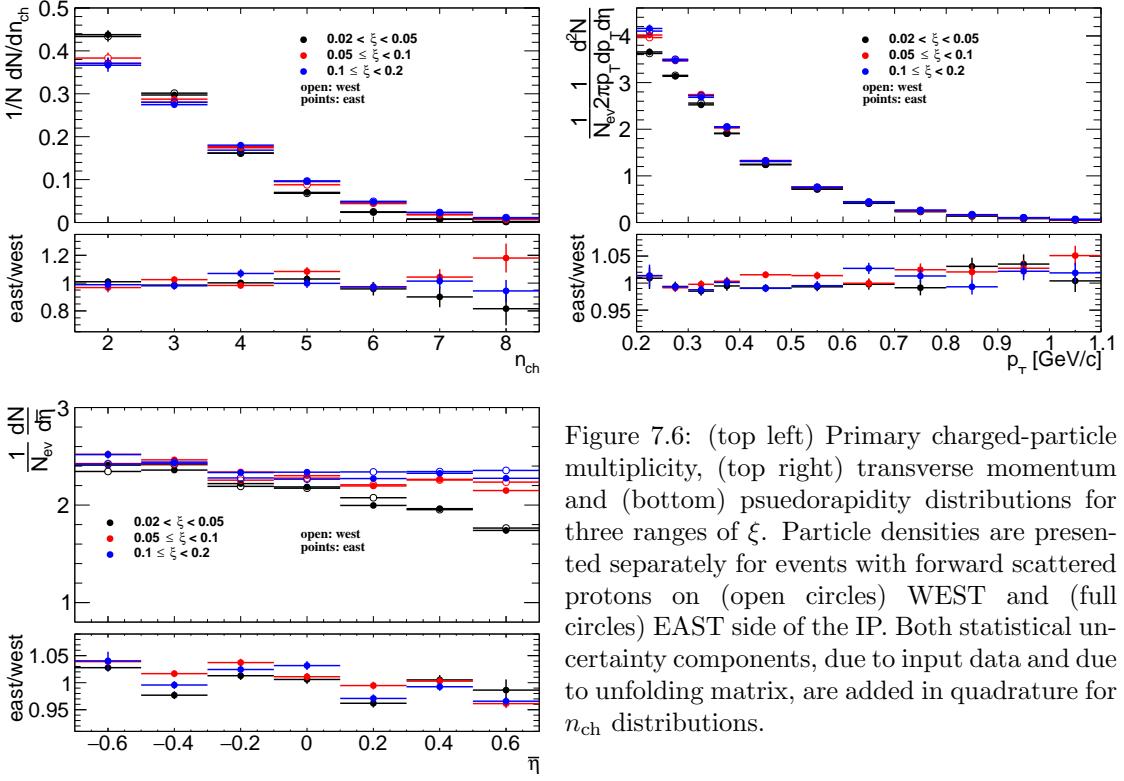


Figure 7.6: (top left) Primary charged-particle multiplicity, (top right) transverse momentum and (bottom) psuedorapidity distributions for three ranges of  $\xi$ . Particle densities are presented separately for events with forward scattered protons on (open circles) WEST and (full circles) EAST side of the IP. Both statistical uncertainty components, due to input data and due to unfolding matrix, are added in quadrature for  $n_{ch}$  distributions.

## 7.5 Particle Identification

Specific ionization energy loss, the  $dE/dx$ , is a function of the magnitude of a particle momentum. In this section the particle identification with help of  $dE/dx$  is described. Due to a low particle multiplicity and lack of signal in VPDs on the outgoing proton side (presence of the rapidity gap) in SD events, the time of collision is not defined precisely enough, therefore, the particle identification by the TOF is not possible and the analysis was limited to identification only by  $dE/dx$ .

The ionization energy loss of charged particles in material is given by the Bethe-Bloch formula and for the STAR TPC by the more precise Bichsel formula [16]. The particle type can be determined by comparison of particle's  $dE/dx$  with the Bethe-Bloch (Bichsel) expectations. Figure 7.7 shows the  $dE/dx$  versus rigidity  $q \times p$  for particles in  $|\eta| < 0.7$ . Particles are well separated at low  $|q \times p|$ , whereas at higher  $|q \times p|$  the  $dE/dx$  of different particle species starts to overlap:  $e^\pm$  and  $K^\pm$  merge at  $\sim 0.4$  GeV/c,  $K^\pm$  and  $\pi^\pm$  merge at  $\sim 0.65$  GeV/c, and  $p(\bar{p})$  and  $\pi^\pm$  merge at  $\sim 1$  GeV/c. Since the  $dE/dx$  distribution for a given particle type is not Gaussian, the following variable for each particle type was defined:

$$n\sigma_{dE/dx}^i = \ln \left( \frac{dE/dx}{(dE/dx)_i^{\text{BB}}} \right) / \sigma \quad (7.10)$$

where  $(dE/dx)_i^{\text{BB}}$  is the Bethe-Bloch (Bichsel) expectation of  $dE/dx$  for the given particle type  $i$  ( $i = \pi, K, p$ ),  $\sigma$  - the relative  $dE/dx$  resolution. The expected value of  $n\sigma_{dE/dx}^i$  for the particle under consideration is 0 and the width equals to 1. The sample  $n\sigma_{dE/dx}^i$  distribution for  $\pi^\pm$ ,  $K^\pm$  and  $p(\bar{p})$  in one  $\xi$  range,  $0.02 < \xi < 0.05$ , is shown in Fig. 7.8.

Figure 7.9 shows the  $n\sigma_{dE/dx}^{\pi^\pm}$ ,  $n\sigma_{dE/dx}^{K^\pm}$  and  $n\sigma_{dE/dx}^{p(\bar{p})}$  distributions for  $0.6 < p_T < 0.65$  GeV/c in the  $\xi$  range,  $0.02 < \xi < 0.05$ , each corrected for the energy loss (mass of  $i$ -particle was assumed) [1] and vertexing (other  $p_T$  bins are shown in Appendix B). To extract the particle yield for a given

particle type, a multi-Gaussian fit is applied to the  $n\sigma_{dE/dx}^i$  distribution in each  $p_T$  bin and  $\xi$  range. The parameters of the multi-Gaussian fit are the centroids  $\mu_{i^-/i^+}$ , widths  $\sigma_{i^-/i^+}$ , sums and ratios of yields  $C_{i^-/i^+}$ ,  $r_{i^-/i^+}$  for negative  $i^-$  and positive  $i^+$  particles ( $\pi^\pm$ ,  $e^\pm$ ,  $K^\pm$ ,  $p$  and  $\bar{p}$ ). The positive and negative particle  $n\sigma_{dE/dx}^i$ -distributions are fitted simultaneously, where the centroids and widths are kept the same for particle and antiparticle. In some  $p_T$  regions, the fit does not converge, because different particle species are not well separated there. Therefore, multiple steps of the fitting procedure are performed to reduce the number of free parameters in the final fit and ensure its stability. Almost all centroids and widths are constrained by a function with free parameters  $p_k$ , where  $k \in \mathbb{N}$ . The function is chosen to describe the data as best as possible. Since  $dE/dx$  is a function of the particle's momentum and its shape should be independent of the process under study, the values of  $p_k$  are obtained only for events with  $0.02 < \xi < 0.05$  and kept the same for other  $\xi$  ranges. The electron contributions are fitted only in the first analysed  $p_T$  range, separately for each particle species and  $\xi$  range. For higher  $p_T$  ranges, they are estimated from PYTHIA 8 embedding MC, and scaled according to the ratio of PYTHIA 8 predictions and contributions fitted in the first  $p_T$  bin. The procedure slightly differs for different particle types. In each step, the multi-Gaussian fit is performed first, then the widths and centroids are fitted in  $p_T$  ranges in which the fit applied to  $n\sigma_{dE/dx}^i$  converges. Later, the widths and centroids are extrapolated to other  $p_T$  ranges, in which particle species are not well separated:

1.  $\pi^\pm$ :

- Step 1 (Fig. 7.10):
  - Analyze data with  $0.2 < p_T < 0.65$  GeV/c
  - Fit  $\mu_{\pi^-/\pi^+}$  and  $\sigma_{\pi^-/\pi^+}$  as a function of  $p_T$  with a polynomial  $p_0 p_T^3 + p_1 p_T^2 + p_2 p_T + p_3$
  - Fit  $r_{e^-/e^+}$  as a function of  $p_T$  with a polynomial  $p_0 p_T^2 + p_1 p_T + p_2$
  - Fit  $C_{e^-/e^+}$ ,  $\mu_{K^-/K^+}$  as a functions of  $p_T$  with  $p_0 \exp(p_1 p_T) + p_2$
  - Fit  $\mu_{e^-/e^+}$  as a function of  $p_T$  with  $p_0 \exp[-(p_1 p_T)^{p_2}]$
  - Fit  $\sigma_{K^-/K^+}$  as a function of  $p_T$ , for  $0.3 < p_T < 0.5$  GeV/c, with constant  $p_0$
  - Fit  $\mu_{\bar{p}/p}$  and  $\sigma_{\bar{p}/p}$  as a function of  $p_T$  with  $p_0 \exp(p_1 p_T)$

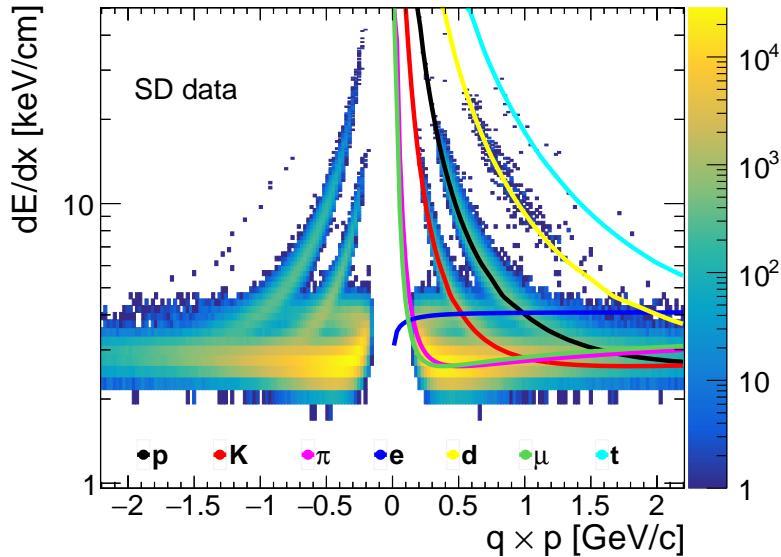


Figure 7.7: Specific ionization energy loss  $dE/dx$  as a function of rigidity  $q \times p$  for particles in  $|\eta| < 0.7$ . The Bichsel predictions for each particle species are also shown.

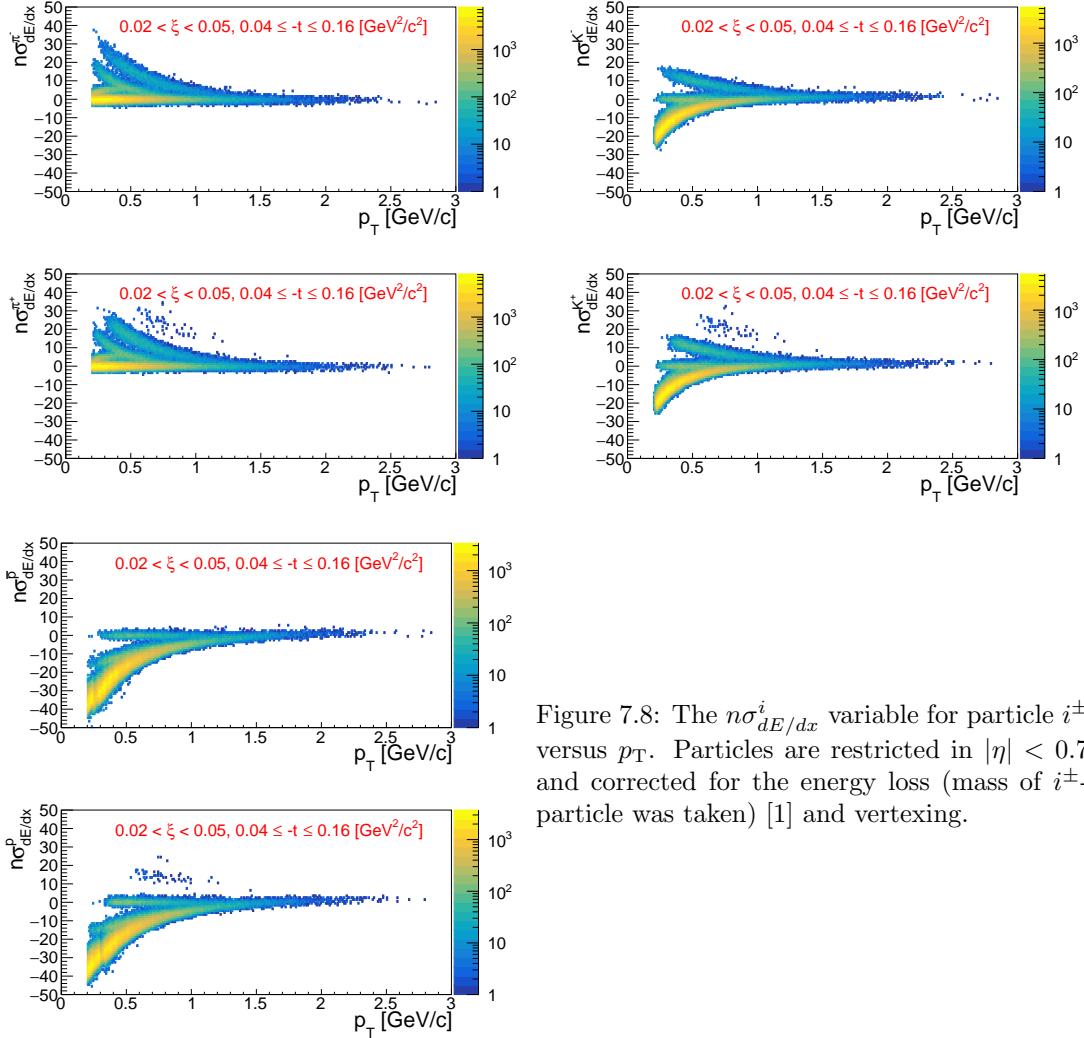


Figure 7.8: The  $n\sigma_{dE/dx}^i$  variable for particle  $i^\pm$  versus  $p_T$ . Particles are restricted in  $|\eta| < 0.7$  and corrected for the energy loss (mass of  $i^\pm$ -particle was taken) [1] and vertexing.

• Step 2:

- $\sigma_{e^-/e^+}$  fixed to 1.2 and 0.8 for  $0.2 < p_T < 0.4$  and  $0.4 < p_T < 0.7$ , respectively
- Fit  $\sigma_{K^-/K^+}$  as a function of  $p_T$ , for  $0.3 < p_T < 0.7$  GeV/c, with constant  $p_0$  and fix it to the value of  $p_0$
- The rest parameters from Step 1 are fixed to the values calculated from functions obtained in Step 1:  $\mu_{\pi^-/\pi^+}$ ,  $\sigma_{\pi^-/\pi^+}$ ,  $r_{e^-/e^+}$ ,  $C_{e^-/e^+}$ ,  $\mu_{e^-/e^+}$ ,  $\mu_{K^-/K^+}$ ,  $\mu_{\bar{p}/p}$ ,  $\sigma_{\bar{p}/p}$

2.  $K^\pm$ :

• Step 1 (Fig. 7.11):

- Analyze data with  $0.2 < p_T < 0.6$  GeV/c
- Fit  $\mu_{\pi^-/\pi^+}$  as a function of  $p_T$  with  $-\exp(p_0 + p_1 p_T)$
- Fit  $\sigma_{\pi^-/\pi^+}$ ,  $C_{e^-/e^+}$ ,  $\sigma_{e^-/e^+}$ ,  $\sigma_{K^-/K^+}$  as a function of  $p_T$  with  $\exp(p_0 + p_1 p_T)$
- Fit  $r_{e^-/e^+}$  as a function of  $p_T$  with constant  $p_0$
- Fit  $\mu_{e^-/e^+}$  as a function of  $p_T$  with a polynomial  $p_0 p_T^3 + p_1 p_T^2 + p_2 p_T + p_3$
- Fit  $\mu_{K^-/K^+}$  as a function of  $p_T$  with a polynomial  $p_0 + p_1 p_T^2$

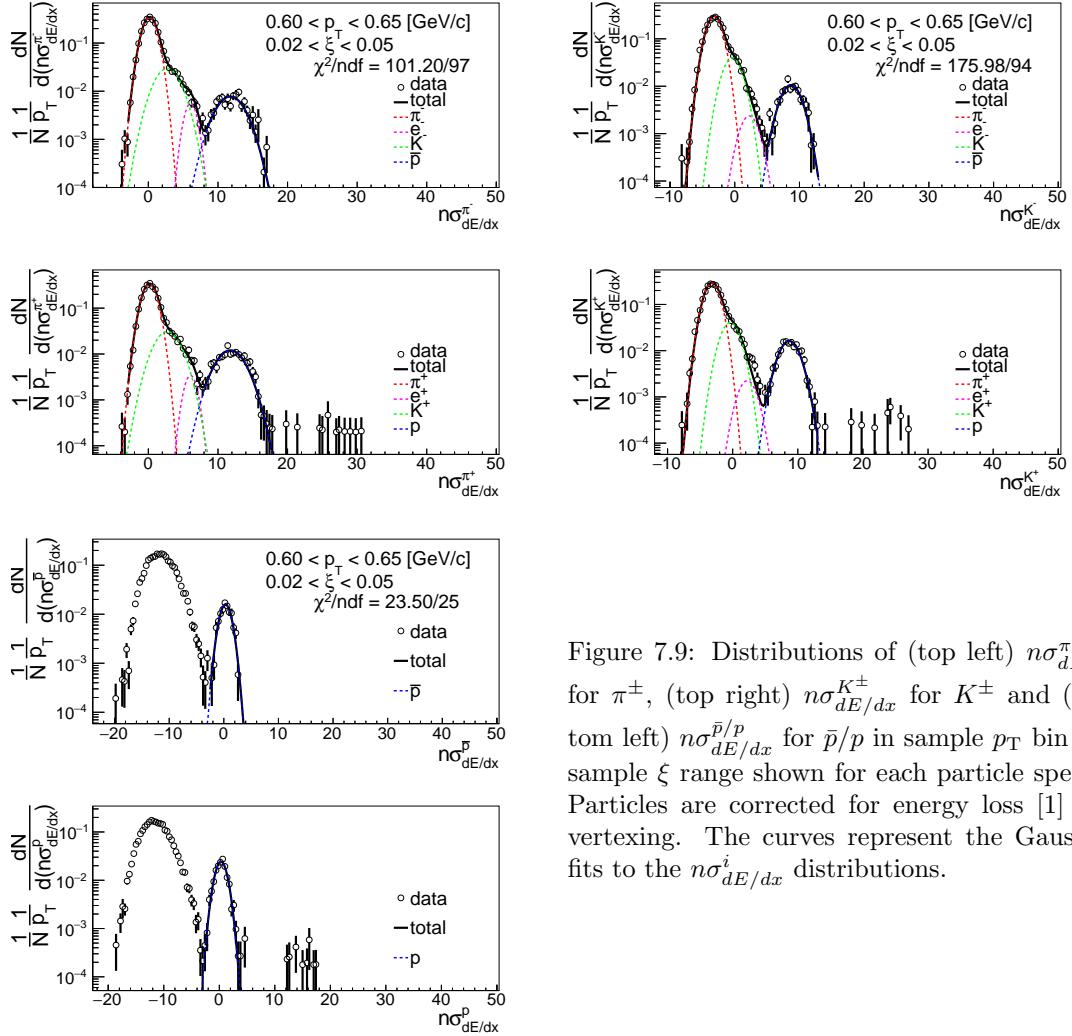


Figure 7.9: Distributions of (top left)  $n\sigma_{dE/dx}^{\pi^\pm}$ , (top right)  $n\sigma_{dE/dx}^{K^\pm}$  and (bottom left)  $n\sigma_{dE/dx}^{\bar{p}/p}$  for  $\bar{p}/p$  in sample  $p_T$  bin and sample  $\xi$  range shown for each particle species. Particles are corrected for energy loss [1] and vertexing. The curves represent the Gaussian fits to the  $n\sigma_{dE/dx}^i$  distributions.

- Step 2:
  - All parameters from Step 1 except  $\sigma_{e^-/e^+}$  are fixed to the values calculated from functions obtained in Step 1
  - Fit  $\sigma_{e^-/e^+}$  as a function of  $p_T$ , for  $0.45 < p_T < 0.65$  GeV/c, with constant  $p_0$
- Step 3:
  - $\sigma_{e^-/e^+}$  fixed to the values calculated from functions obtained in Steps 1 and 2 for  $0.3 < p_T < 0.45$  and  $0.45 < p_T < 0.65$ , respectively.
  - The rest parameters from Step 1 are fixed to the values calculated from functions obtained in Step 1:  $\mu_{\pi^-/\pi^+}$ ,  $\sigma_{\pi^-/\pi^+}$ ,  $r_{e^-/e^+}$ ,  $C_{e^-/e^+}$ ,  $\mu_{e^-/e^+}$ ,  $\mu_{K^-/K^+}$ ,  $\sigma_{K^-/K^+}$

795     3.  $\bar{p}, p$ :

- Step 1 (Fig. 7.12):
  - Analyze data with  $0.4 < p_T < 0.9$  GeV/c
  - Fit  $\mu_{\pi^-/\pi^+}$ ,  $\mu_{K^-/K^+}$  as a function of  $p_T$  with a polynomial  $p_0 p_T + p_1$
  - Fit  $\sigma_{\pi^-/\pi^+}$  as a function of  $p_T$  with a polynomial  $p_0 p_T^2 + p_1 p_T + p_2$

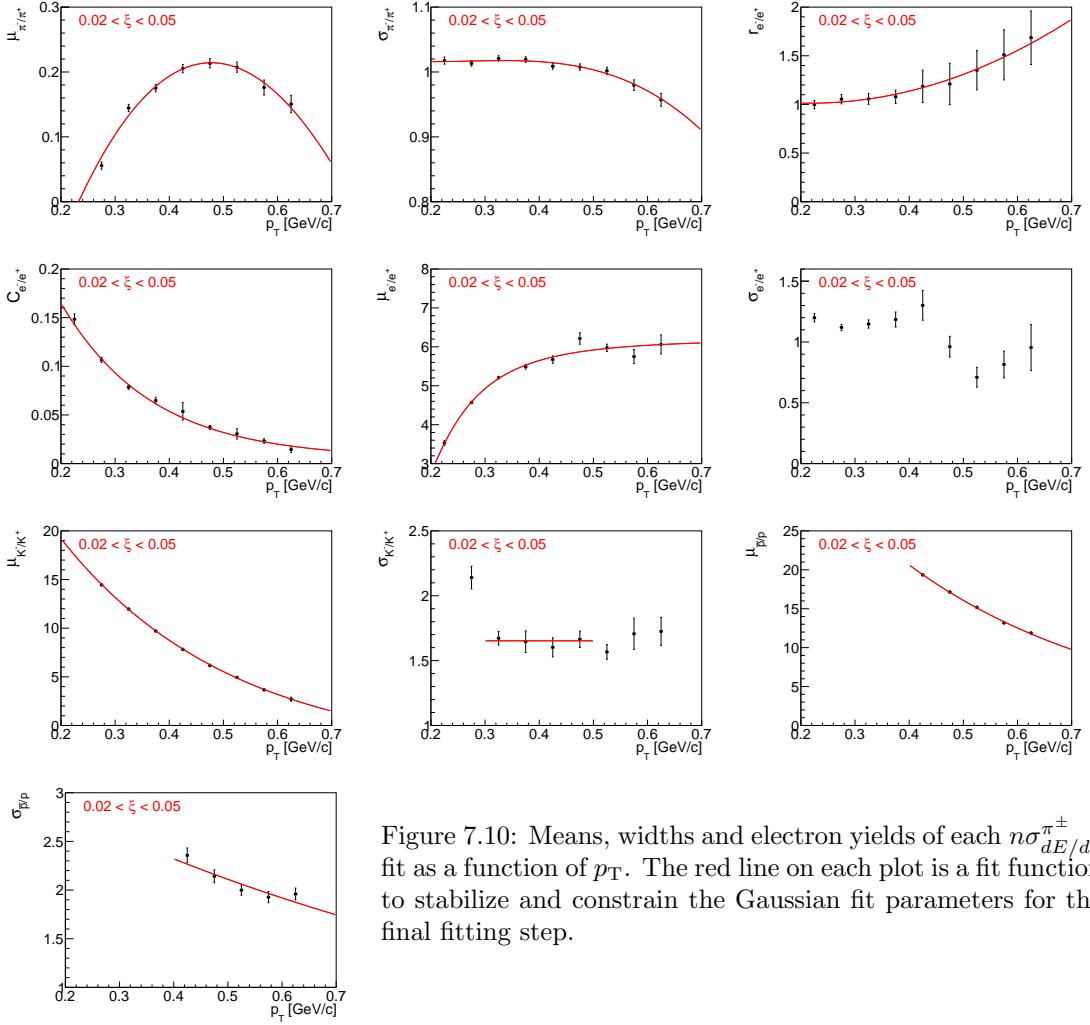


Figure 7.10: Means, widths and electron yields of each  $n\sigma_{dE/dx}^{\pi^\pm}$  fit as a function of  $p_T$ . The red line on each plot is a fit function to stabilize and constrain the Gaussian fit parameters for the final fitting step.

- 800           – Fit  $\sigma_{K^-/K^+}$  as a function of  $p_T$  with  $\exp(p_0 + p_1 p_T)$
- 801   • Step 2:
  - 802           –  $\mu_{K^-/K^+}$  fixed to the values calculated from a function obtained in Step 1
  - 803           – All the rest parameters from Step 1 are limited to the values calculated from functions obtained in Step 1
  - 804           – Fit  $\mu_{\pi^-/\pi^+}$ ,  $\sigma_{\pi^-/\pi^+}$ ,  $\sigma_{K^-/K^+}$  as a function of  $p_T$  with a polynomial  $p_0 p_T^2 + p_1 p_T + p_2$
  - 805           – Fit  $\mu_{\bar{p}/p}$  as a function of  $p_T$ , for  $0.7 < p_T < 1.0$  GeV/c, with constant  $p_0$
- 806   • Step 3:
  - 807           –  $\mu_{K^-/K^+}$  fixed to the values calculated from a function obtained in Step 1
  - 808           –  $\mu_{\bar{p}/p}$  fixed to the values calculated from a function obtained in Step 2 for  $0.7 < p_T < 1.0$
  - 809           – The rest parameters from Step 2 are fixed to the values calculated from functions obtained in Step 2:  $\mu_{\pi^-/\pi^+}$ ,  $\sigma_{\pi^-/\pi^+}$ ,  $\sigma_{K^-/K^+}$

813   The particle yield is extracted from the fit to the corresponding  $n\sigma_{dE/dx}^i$  distribution (corrected  
 814   only for the energy loss and vertexing). As shown in Fig. 7.8, the  $dE/dx$  of each particle type merge  
 815   at large  $p_T$ . Hence, the particle identification is limited. Pions can be identified in the momentum  
 816   range of 0.2 – 0.7 GeV/c, kaons in 0.3 – 0.65 GeV/c and (anti)protons in 0.4 – 1.0 GeV/c.

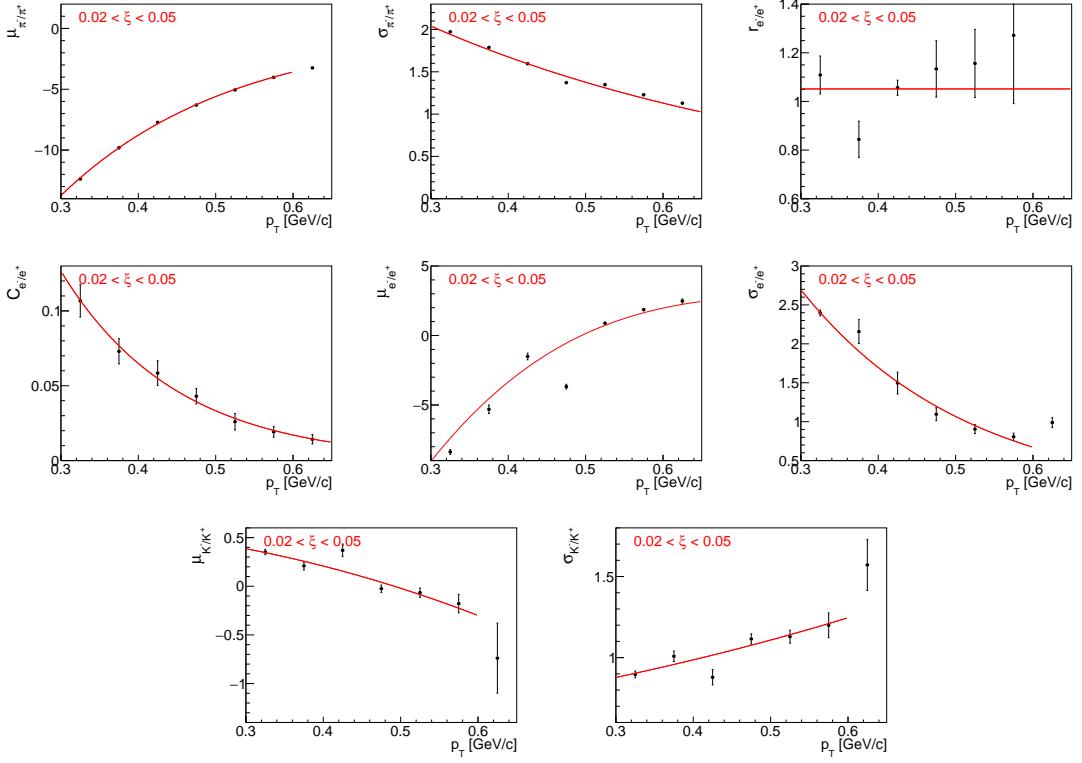


Figure 7.11: Means, widths and electron yields of each  $n\sigma_{dE/dx}^{K^\pm}$  fit as a function of  $p_T$ . The red line on each plot is a fit function to stabilize and constrain the Gaussian fit parameters for the final fitting step.

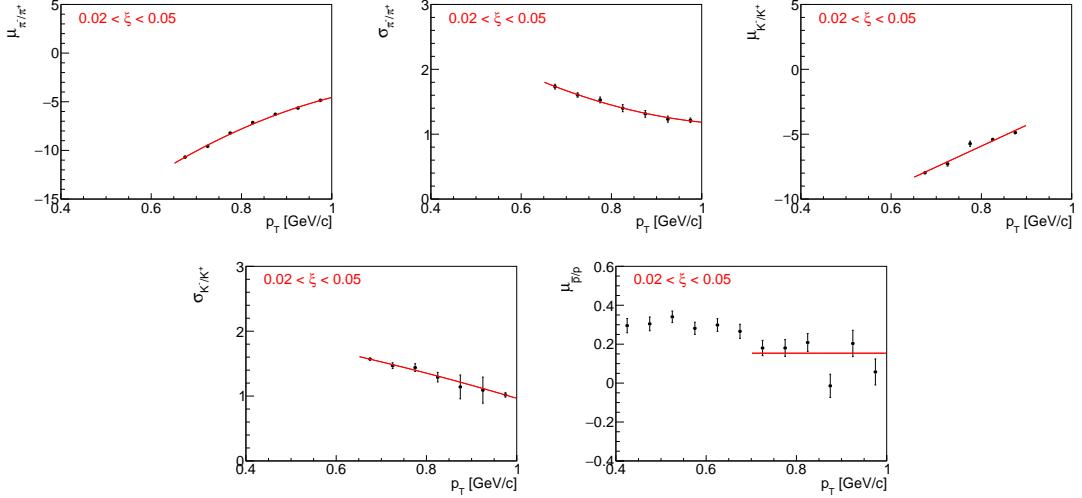


Figure 7.12: Means and widths of each  $n\sigma_{dE/dx}^{\bar{p}/p}$  fit as a function of  $p_T$ . The red line on each plot is a fit function to stabilize and constrain the Gaussian fit parameters for the final fitting step.

## 817 7.6 Antiparticle-to-Particle Ratios

818 The following steps were taken to correct the identified antiparticle to particle (pion, kaon, proton  
 819 and their antiparticle) multiplicity ratios as a function of  $p_T$  in three ranges of  $\xi$ :

- 820 • The raw identified particle yields were obtained through multi-Gaussian fits to the  $n\sigma_{dE/dx}^i$   
 821 distributions (Sec. 7.5), where the vertex reconstruction and energy loss corrections [1] were  
 822 applied. The latter depends on the particle type.
- 823 • The non-SD background (Sec. 4.2) is the same for particles and antiparticles, thus, it was  
 824 not subtracted. The accidental background contribution (Sec. 4) is very small, hence, any  
 825 particle-antiparticle differences have a negligible effect on the result. Therefore, it was as-  
 826 sumed that the accidental background does not depend on the particle type and for this  
 827 reason it was not subtracted.
- 828 • The particle yields were corrected for track reconstruction efficiencies [1], which depend on  
 829 the particle type and charge. These corrections are averaged over  $\eta$  and  $V_z$ . The ratio of  
 830 particle to antiparticle TPC-TOF efficiencies is shown in Fig. 7.13. It weakly depends on  $\xi$   
 831 range, therefore, only sample results for single range of  $0.02 < \xi < 0.05$  are presented.
- 832 • The background from non-primary tracks was subtracted (Sec. 4.1):
  - 833 –  $\pi^\pm$ : weak decays pions, muon contribution and background from detector dead-material  
   interactions,
  - 834 –  $p$ : background from detector dead-material interactions,
  - 835 –  $p, \bar{p}$ : reconstructed tracks which have the appropriate number of common hit points  
   with true-level particle, but the distance between them is too large (this background is  
   negligibly small for other particle types),
  - 836 – fake track contribution was assumed to be the same for each particle type, hence, it  
   was not subtracted.
- 841 • Since track and  $\xi$  migrations, and BBC-small efficiency, do not depend on the particle type  
 842 and charge, these corrections are not applied.
- 843 • Finally, each antiparticle  $p_T$  distribution was divided by the corresponding particle  $p_T$  dis-  
 844 tribution to obtain fully corrected identified antiparticle to particle multiplicity ratios.
- 845 • Additionally, the average antiparticle to particle ratios over fiducial region of  $p_T$  in each  $\xi$   
 846 region were calculated.

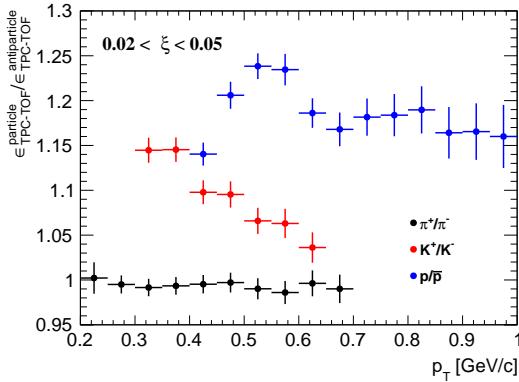


Figure 7.13: Ratio of particle to antiparticle TPC-TOF efficiencies for  $0.02 < \xi < 0.05$ .

## 8. Systematic Uncertainties

Apart from the statistical uncertainties there are also systematic uncertainties originating from inefficiencies and limitations of the measurement devices and techniques. The following sources of systematic uncertainties were considered:

- the effect of off-time pile-up on TPC track reconstruction efficiency [1],
- the uncertainty of TPC track reconstruction efficiency related to the description of dead-material in simulation [1],
- representation of data sample in embedding MC [1],
- variation in the track quality cuts [1],
- non-primary track background contribution (Sec. 4.1),
- fake track background contribution (Sec. 4.1),
- TOF system simulation accuracy [1],
- accidental background contribution (Sec. 4),
- the effect of alternative model of hadronization on BBC-small efficiency (Sec. 5.2),
- non-SD background contribution (Sec. 4.2),
- the effect of alternative model on  $\epsilon_m$  correction (Sec. 7.1),
- non-closure (Sec 7.3),
- non-closure of  $N_{\text{ev}}$ , applied only to  $p_T$  and  $\bar{\eta}$  distributions,
- difference in the distributions calculated separately for events in which forward proton is on one and the other side of the IP (east-west, Sec 7.4).

Some of the systematic uncertainties on  $1/N dN/dn_{\text{ch}}$  (related to TPC and TOF reconstruction efficiencies, fake track background contribution) are propagated by randomly removing and adding tracks in the  $n_{\text{sel}}$  distribution before unfolding procedure. For each track, a random number is generated. If this number is smaller than the absolute value of systematic uncertainty, then  $n_{\text{sel}}$  is increased or decreased, depending on the sign of systematic uncertainty.

Figures 8.1 to 8.3 show the components contributing to the total systematic uncertainty for charged particle distributions without the identification. The dominant systematic uncertainty for  $p_T$  and  $n_{\text{ch}}$  distributions is related to TOF system simulation accuracy. It affects mainly low- $p_T$  particles, where it is about 6 – 8%, and large charged particle multiplicities, where it varies up to 50% for  $n_{\text{ch}} = 8$  and  $0.02 < \xi < 0.05$ . In case of  $\bar{\eta}$  distribution, the systematic uncertainty on TOF mainly refers to charged particles produced at the edge of the fiducial region, for which it is about 4%. The largest (up to 30%) systematic uncertainty for  $\langle \bar{\eta} \rangle$ , is related to the observed difference in the distributions calculated separately with respect to the forward-scattered proton direction. The rest of the components have smaller contributions to the total systematic uncertainty. The systematic uncertainty on non-closure is on average at the level of 2% which proves the accuracy of the correction procedure.

Figures 8.4 to 8.7 show breakdown of all different systematics for the antiparticle-to-particle multiplicity ratio distributions. An additional systematic contribution for  $\bar{p}/p$  multiplicity ratio due to proton background estimation was introduced. Since most of the corrections are the same for particle and its antiparticle, nearly all systematic uncertainties cancel out in the antiparticle-to-particle ratios. The largest sources of systematics, which do not, are related to proton background estimation and dead-material effect on TPC track reconstruction efficiency. The former was found to be up to 6%, whereas the latter varies up to 2% for low- $p_T$   $\bar{p}/p$  multiplicity ratio.

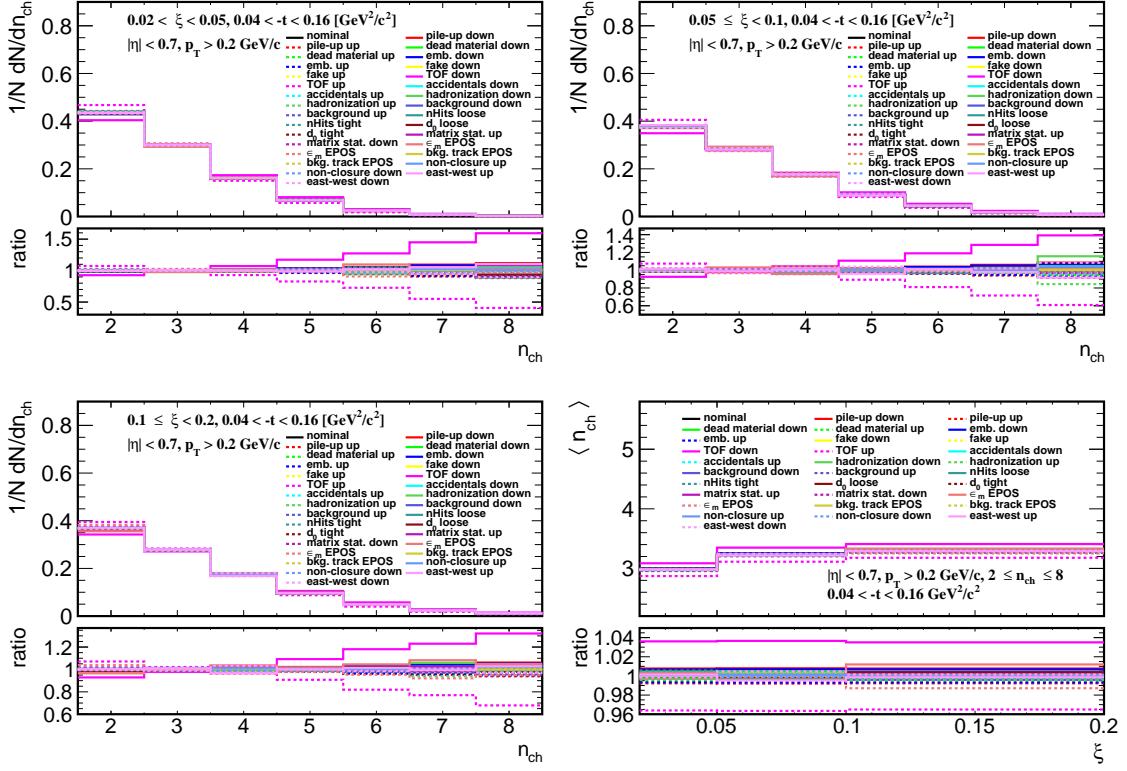


Figure 8.1: Components of the systematic uncertainties for the charged particle multiplicity in three  $\xi$  regions and for the average charged particle multiplicity.

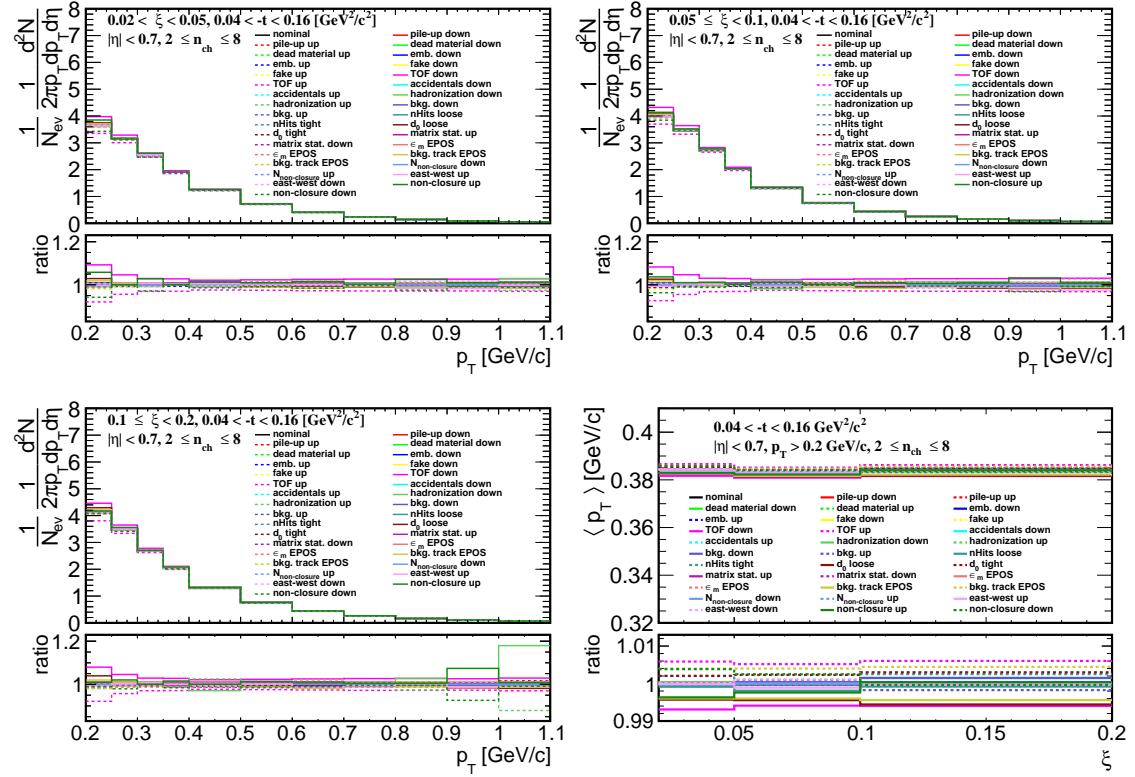


Figure 8.2: Components of the systematic uncertainties for  $p_T$  distributions in three  $\xi$  regions and for an average  $p_T$  distribution.

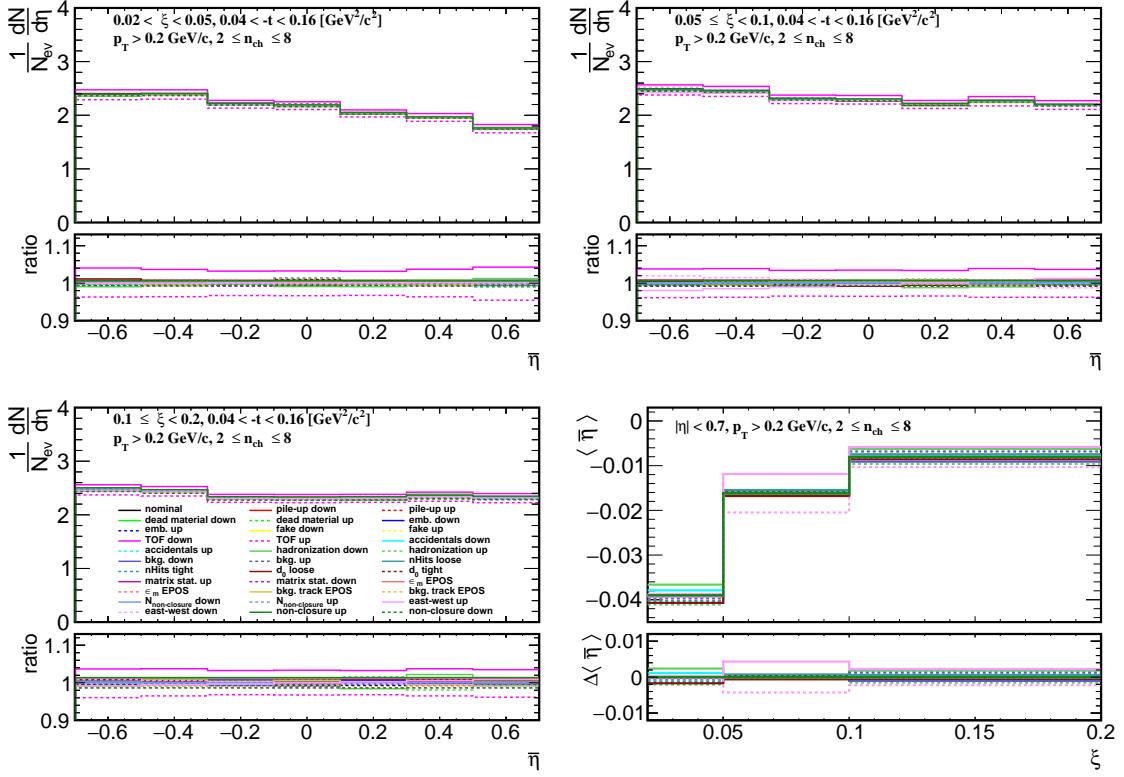


Figure 8.3: Components of the systematic uncertainties for  $\bar{\eta}$  distributions in three  $\xi$  regions and for an average  $\bar{\eta}$  distribution.

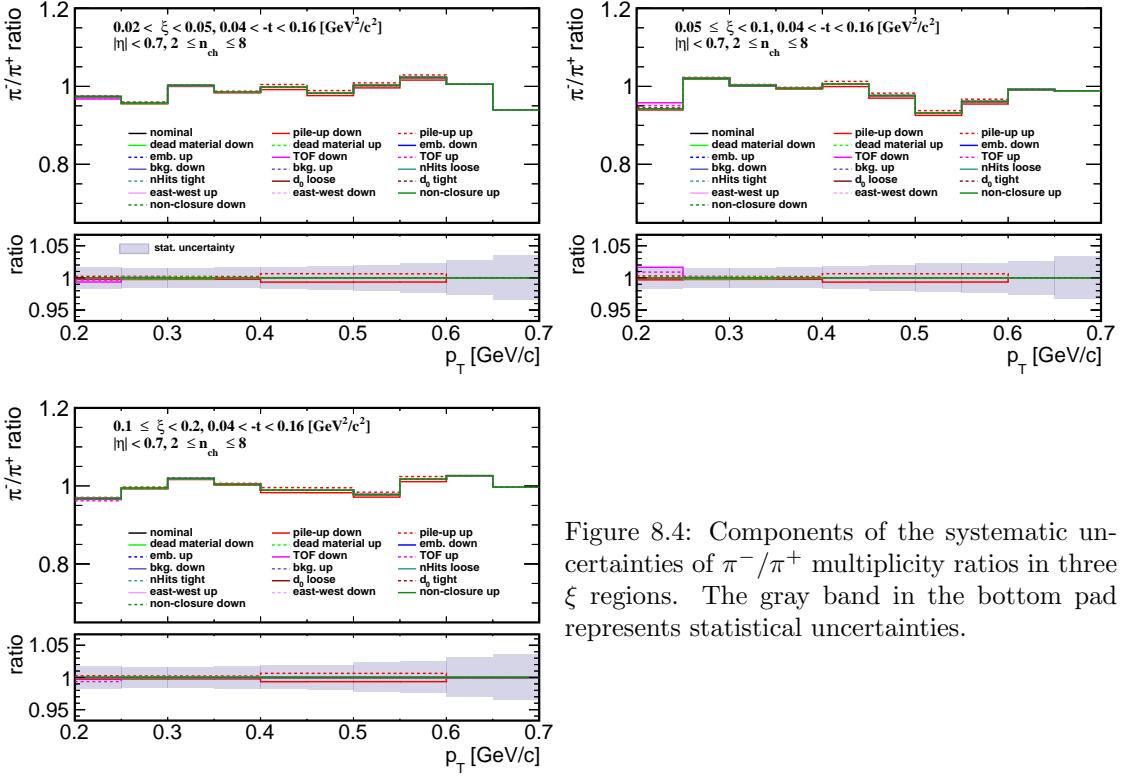


Figure 8.4: Components of the systematic uncertainties of  $\pi^-/\pi^+$  multiplicity ratios in three  $\xi$  regions. The gray band in the bottom pad represents statistical uncertainties.

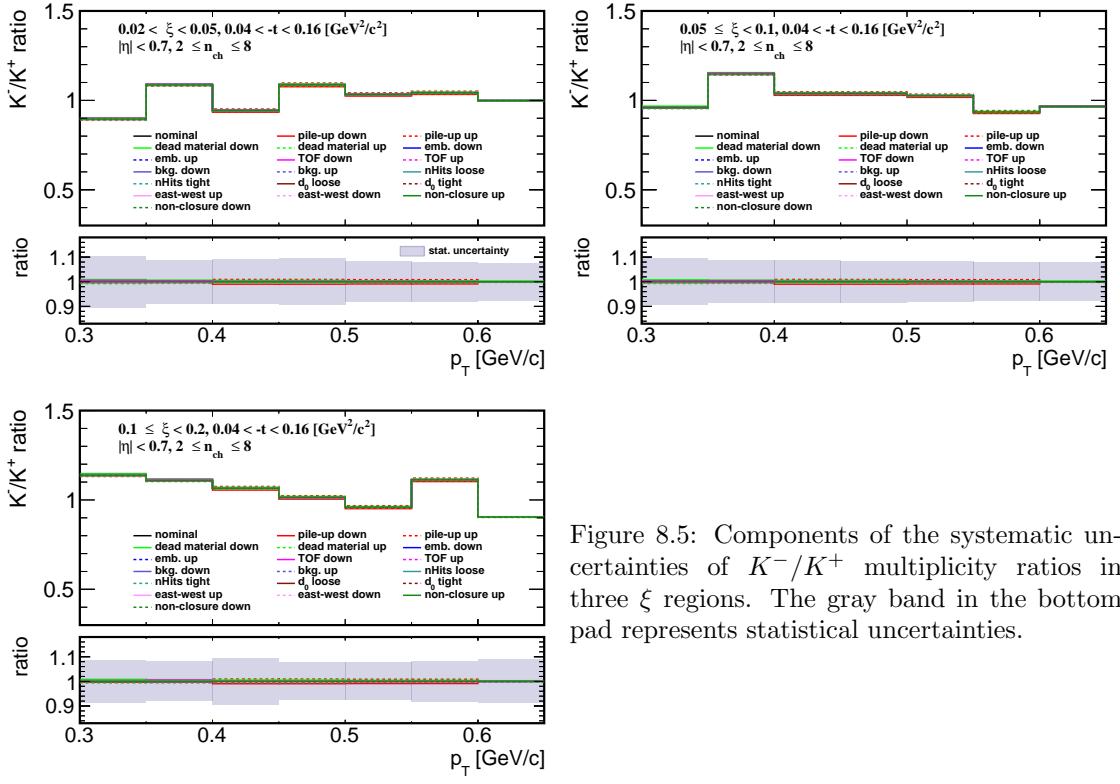


Figure 8.5: Components of the systematic uncertainties of  $K^-/K^+$  multiplicity ratios in three  $\xi$  regions. The gray band in the bottom pad represents statistical uncertainties.

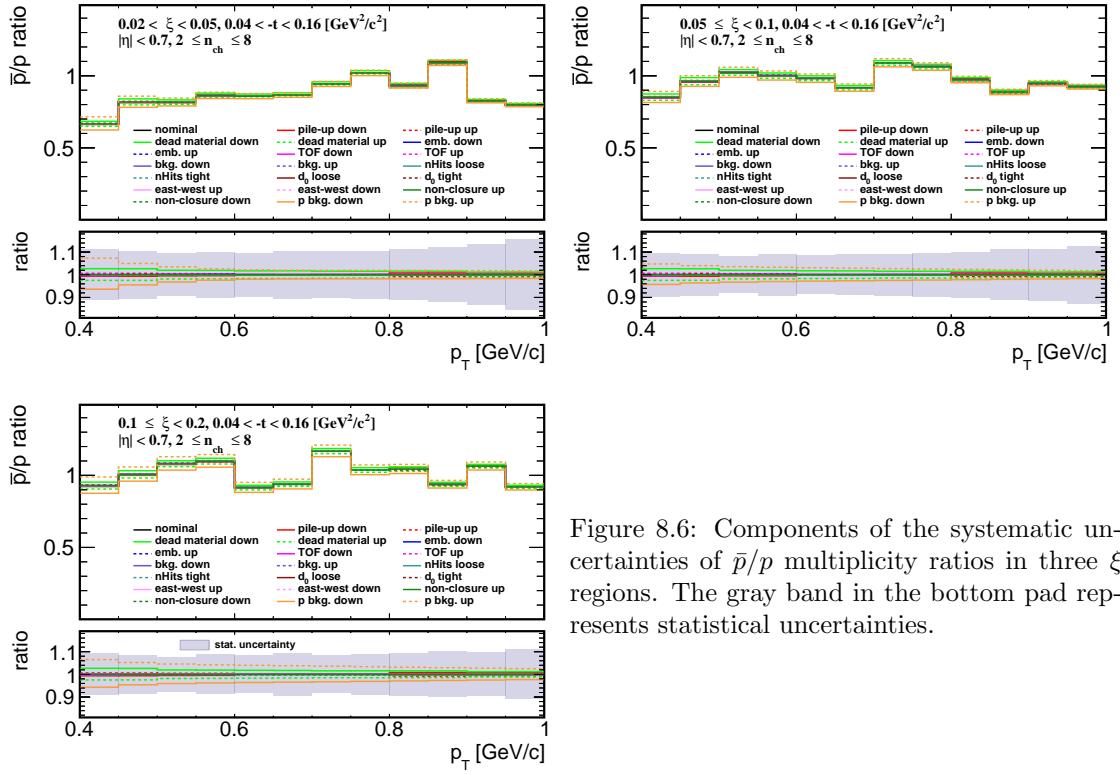


Figure 8.6: Components of the systematic uncertainties of  $\bar{p}/p$  multiplicity ratios in three  $\xi$  regions. The gray band in the bottom pad represents statistical uncertainties.

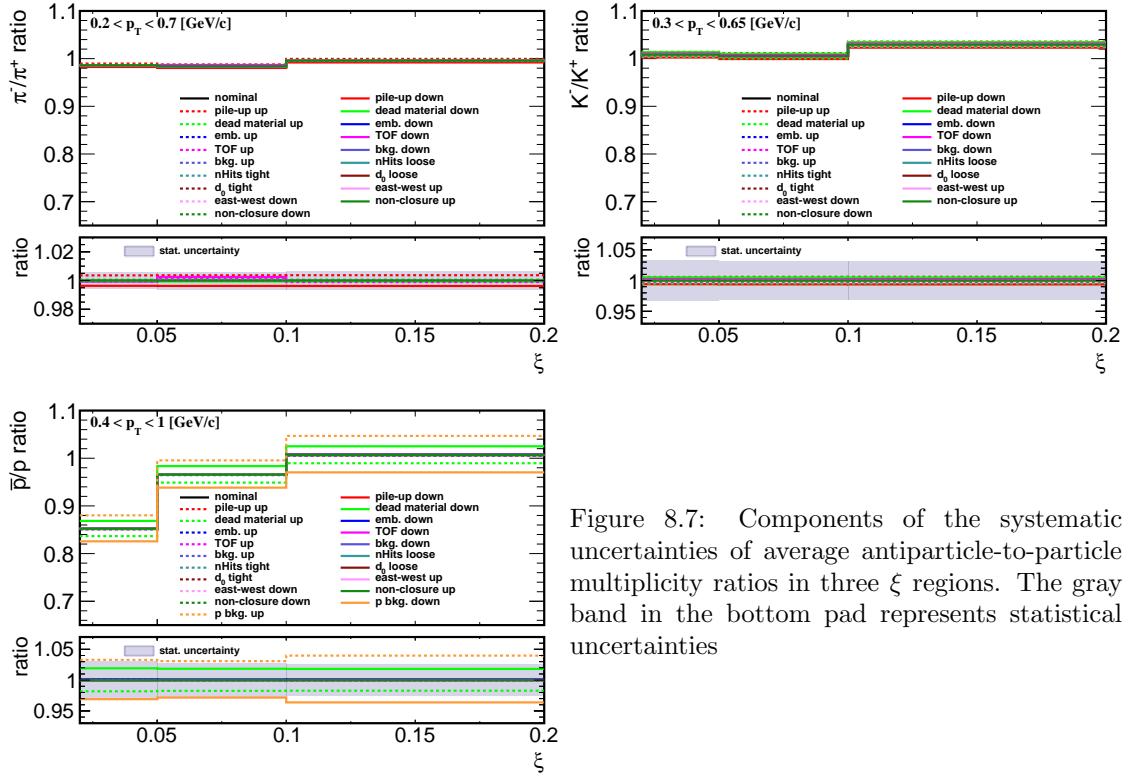


Figure 8.7: Components of the systematic uncertainties of average antiparticle-to-particle multiplicity ratios in three  $\xi$  regions. The gray band in the bottom pad represents statistical uncertainties

# 9. Results

In the following section, the final-state charged particle distributions are compared with various SD MC predictions, i.e.

- PYTHIA 8 4C (SaS),
- PYTHIA 8 A2 (MBR),
- PYTHIA 8 A2 (MBR-tuned),
- HERWIG 7,
- EPOS LHC with combined two classes of processes: diffractive (EPOS SD) and non-diffractive (EPOS SD'),
- EPOS LHC SD'.

In all figures, data are shown as solid points with error bars representing the statistical uncertainties. Gray boxes represent statistical and systematic uncertainties added in quadrature. Predictions from MC models are shown as colour histograms and markers. The lower panel in each figure shows the ratio of data to the models' predictions. All results are presented separately for three ranges of  $\xi$ :  $0.02 < \xi < 0.05$ ,  $0.05 < \xi < 0.1$ ,  $0.1 < \xi < 0.2$ .

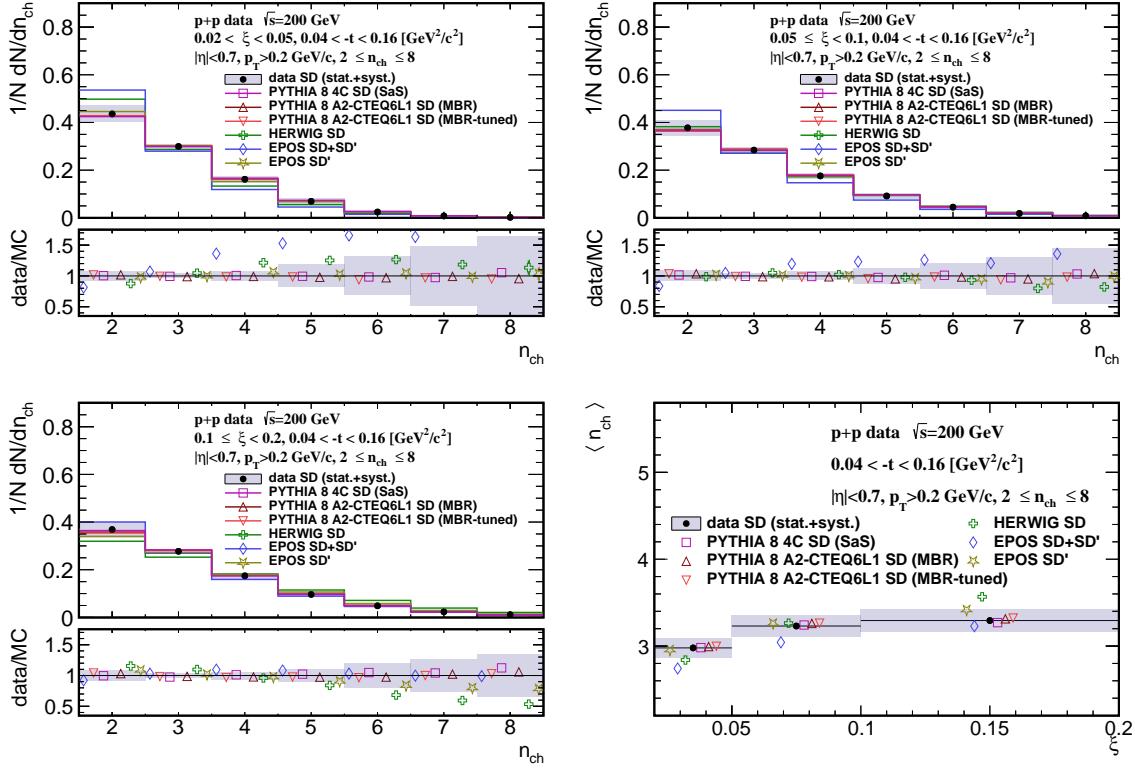


Figure 9.1: Primary charged-particle multiplicity shown separately for the three ranges of  $\xi$ : (top left)  $0.02 < \xi < 0.05$ , (top right)  $0.05 < \xi < 0.1$ , (bottom left)  $0.1 < \xi < 0.2$  and (bottom right) the mean multiplicity  $\langle n_{ch} \rangle$  as a function of  $\xi$ .

905     Figure 9.1 shows primary charged-particle multiplicity separately for the three ranges of  $\xi$  and  
906     the mean multiplicity  $\langle n_{\text{ch}} \rangle$  as a function of  $\xi$ . Data follow the expected increase of  $\langle n_{\text{ch}} \rangle$  with  
907      $\xi$  due to the larger diffractive masses probed by increasing  $\xi$  in SD process. The shapes of the  
908     measured distributions are reproduced reasonably well by all models except EPOS SD+SD' and  
909     HERWIG SD which predicts smaller  $\langle n_{\text{ch}} \rangle$  for  $0.02 < \xi < 0.1$  and  $0.02 < \xi < 0.05$ , respectively.  
910     HERWIG SD predicts too large  $\langle n_{\text{ch}} \rangle$  for  $0.1 < \xi < 0.2$ .

911     Figure 9.2 shows primary charged-particle multiplicities as a function of  $p_T$  separately for  
912     the three ranges of  $\xi$  and the mean transverse momentum  $\langle p_T \rangle$  as a function of  $\xi$ . Data show  
913     that  $\langle p_T \rangle$  depends very weakly on  $\xi$ . Models describe data fairly well except HERWIG SD which  
914     predicts much steeper dependence of particle density with  $p_T$  in all three  $\xi$  ranges.

915     Figure 9.3 shows primary charged-particle multiplicity as a function of  $\bar{\eta}$  separately for the three  
916     ranges of  $\xi$  and the mean pseudorapidity  $\langle \bar{\eta} \rangle$  as a function of  $\xi$ . Data show expected flattening of  
917     the  $\bar{\eta}$  distribution with increasing  $\xi$  which reflects SD event-asymmetry and fact that the gap-edge  
918     at large  $\xi$  is outside  $|\bar{\eta}| < 0.7$  region leading to more flat distribution of particle density as a  
919     function of  $\bar{\eta}$ . Models describe data fairly well except EPOS SD+SD', which predicts less steep  
920     dependence of particle density with  $\bar{\eta}$  for  $0.02 < \xi < 0.1$ , and HERWIG SD, which predicts steeper  
921     distribution for all three  $\xi$  ranges.

922     Figure 9.4 shows the ratio of production yields of  $\pi^-/\pi^+$  as a function of  $p_T$  separately for  
923     the three ranges of  $\xi$ . Data in all three  $\xi$  ranges are consistent with equal amounts of  $\pi^+$  and  
924      $\pi^-$  with no significant  $p_T$  dependence. Models agree with data (except HERWIG) predicting on  
925     average small deviation from unity by  $\sim 2\%$  what is smaller than data uncertainties. HERWIG  
926     in first two  $\xi$  ranges predicts too large asymmetry between  $\pi^+$  and  $\pi^-$ .

927     Figure 9.5 shows the ratio of production yields of  $K^-/K^+$  as a function of  $p_T$  separately for

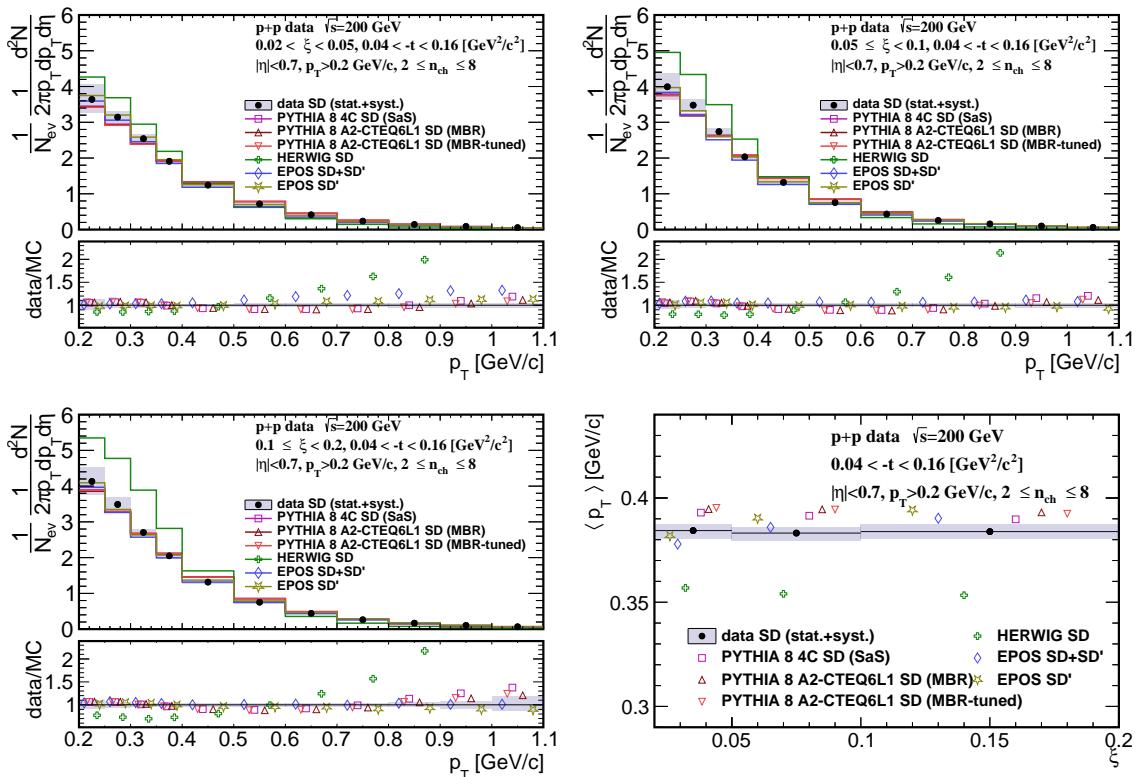


Figure 9.2: Primary charged-particle multiplicities as a function of  $p_T$  shown separately for the three ranges of  $\xi$ : (top left)  $0.02 < \xi < 0.05$ , (top right)  $0.05 < \xi < 0.1$ , (bottom left)  $0.1 < \xi < 0.2$  and (bottom right) the mean transverse momentum  $\langle p_T \rangle$  as a function of  $\xi$ .

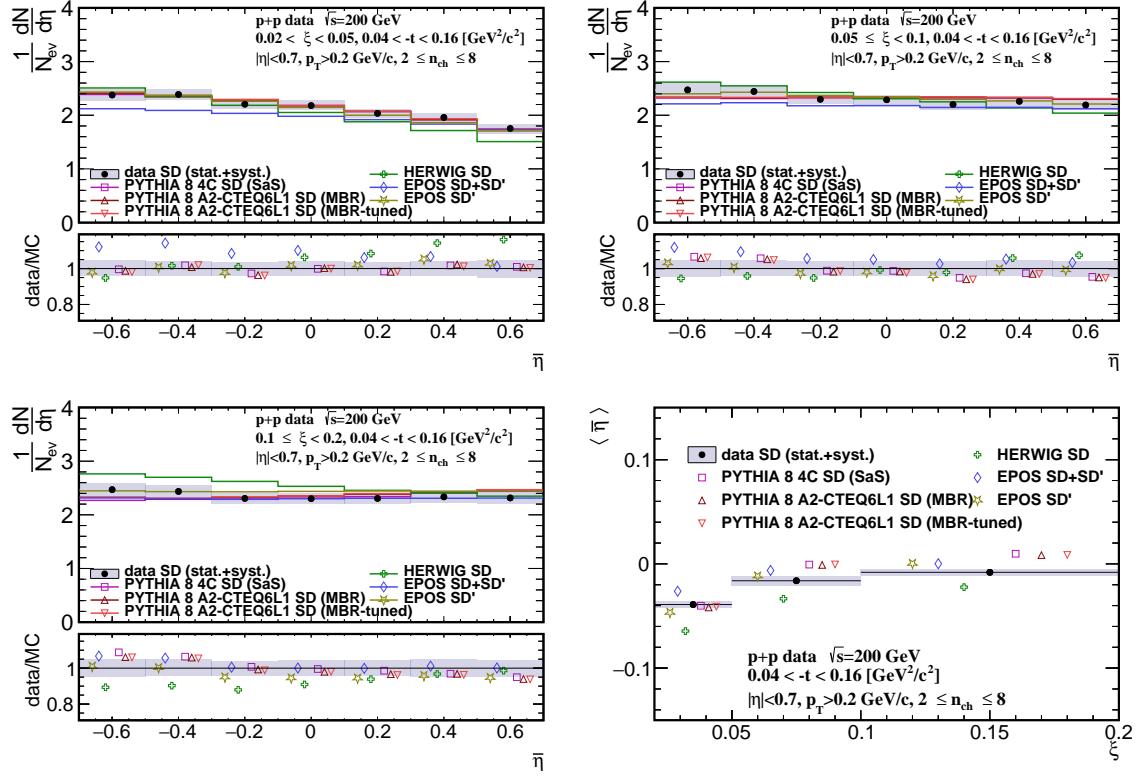


Figure 9.3: Primary charged-particle multiplicity as a function of  $\bar{\eta}$  shown separately for the three ranges of  $\xi$ : (top left)  $0.02 < \xi < 0.05$ , (top right)  $0.05 < \xi < 0.1$ , (bottom left)  $0.1 < \xi < 0.2$  and (bottom right) the mean pseudorapidity  $\langle \bar{\eta} \rangle$  as a function of  $\xi$ .

the three ranges of  $\xi$ . Data in all three  $\xi$  ranges are consistent with equal amounts of  $K^+$  and  $K^-$  with no  $p_T$  dependence. Models agree with data except HERWIG in the first  $\xi$  range predicting too large ratio of  $K^-$  to  $K^+$ .

Figure 9.6 shows the ratio of production yields of  $\bar{p}/p$  as a function of  $p_T$  separately for the three ranges of  $\xi$ . Data in the last two  $\xi$  ranges are consistent with equal amounts of  $p$  and  $\bar{p}$  with no  $p_T$  dependence. However, in the first  $\xi$  range at  $p_T < 0.7$  GeV/c data shows significant deviation from unity indicating a significant transfer of the baryon number from the forward to the central region. PYTHIA8, EPOS SD' and EPOS SD+SD' agree with data in the last two  $\xi$  ranges. In first  $\xi$  range PYTHIA8 and EPOS SD' predict small deviation from unity by  $\approx 7\%$  which is smaller than observed in data ( $\bar{p}/p = 0.85 \pm 0.04$ ), whereas EPOS SD+SD' predicts an asymmetry between  $\bar{p}$  and  $p$  of  $\sim 30\%$  which is larger than observed in data except  $p_T < 0.5$  GeV/c. HERWIG predicts much larger baryon number transfer compared to data in first two  $\xi$  ranges and shows consistency with data in last  $\xi$  range.

Figure 9.7 shows mean ratio of production yields of  $\pi^-/\pi^+$ ,  $K^-/K^+$  and  $\bar{p}/p$  as a function of  $\xi$ .

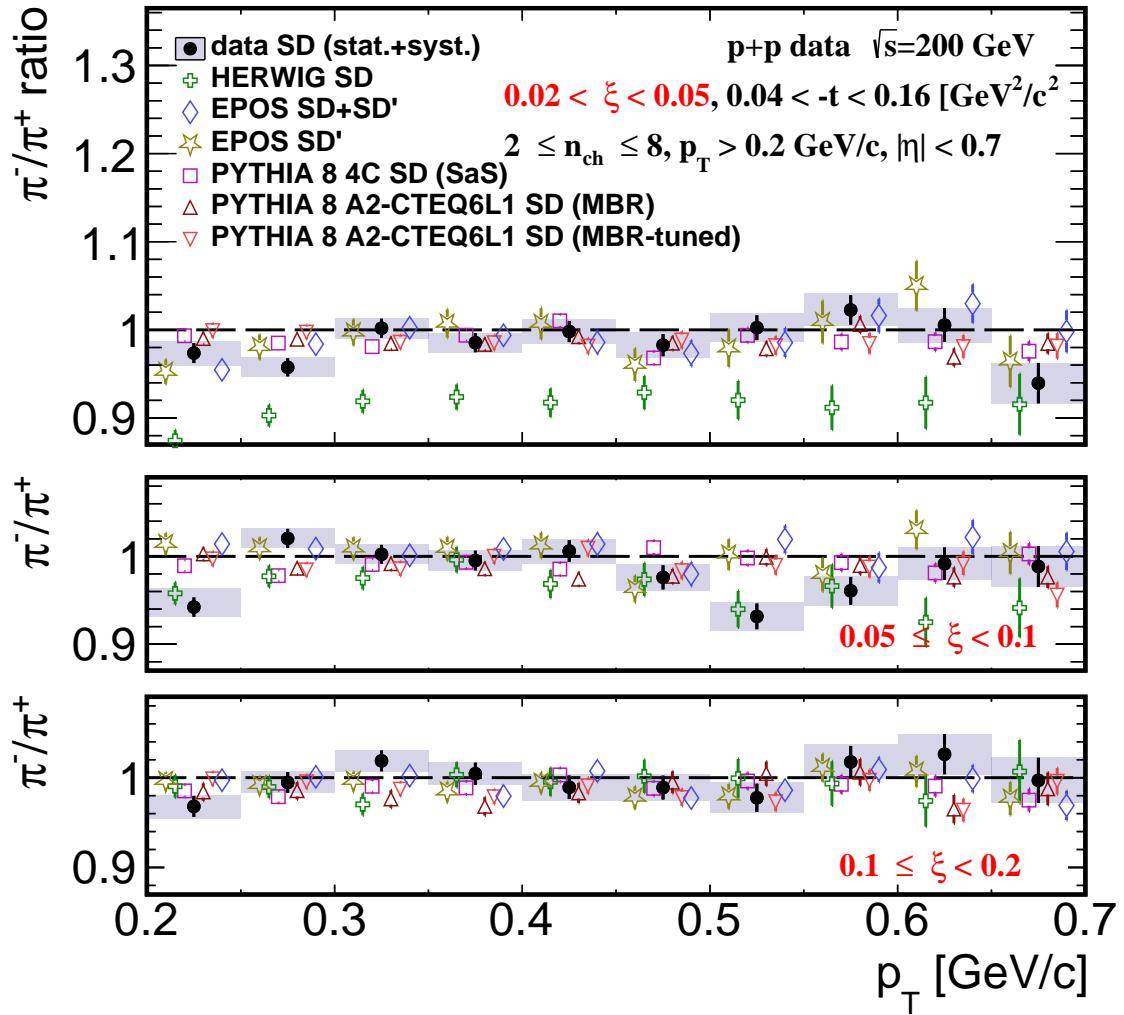


Figure 9.4: Ratio of production yields of  $\pi^-/\pi^+$  as a function of  $p_{\text{T}}$  shown separately for the three ranges of  $\xi$ : (top)  $0.02 < \xi < 0.05$ , (middle)  $0.05 < \xi < 0.1$ , (bottom)  $0.1 < \xi < 0.2$ .

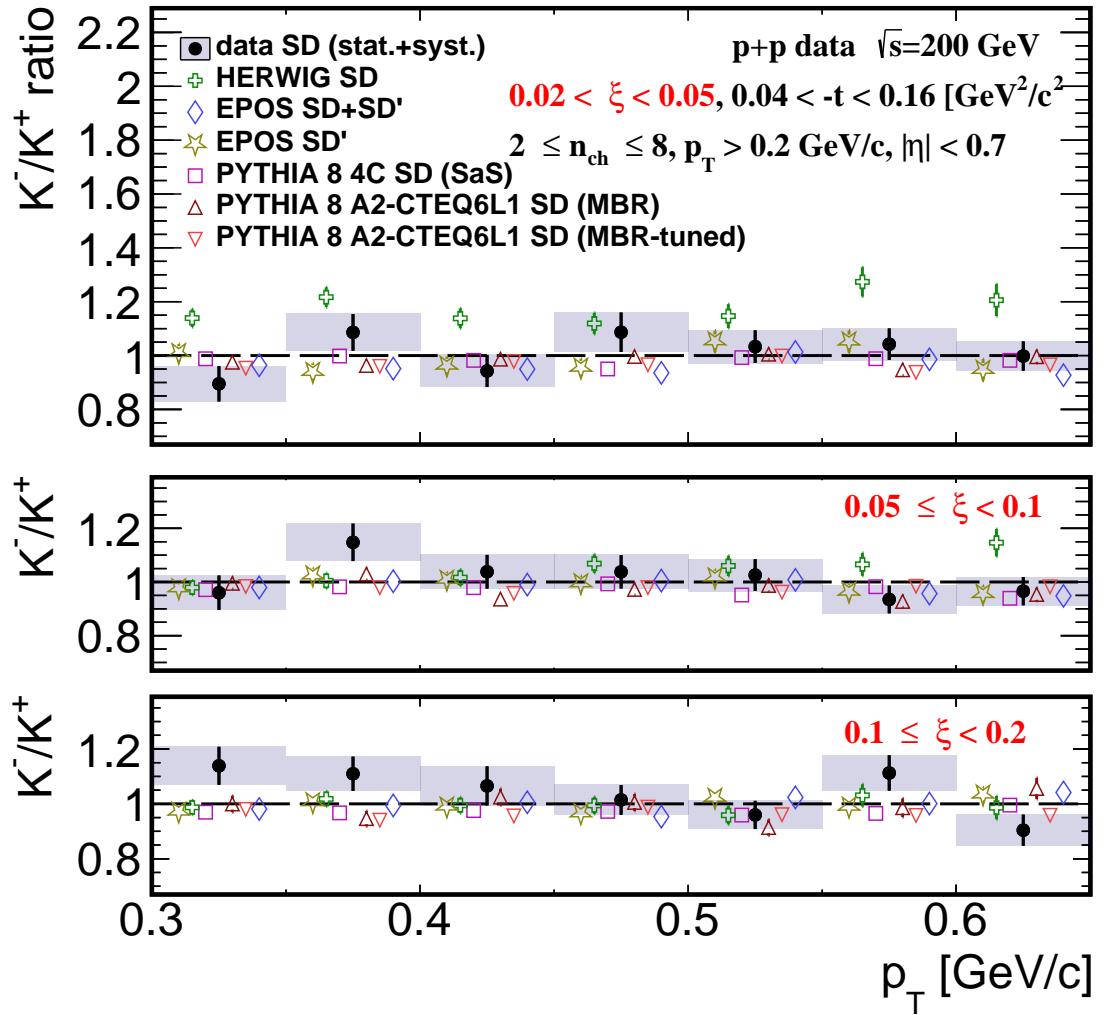


Figure 9.5: Ratio of production yields of  $K^-/K^+$  as a function of  $p_T$  shown separately for the three ranges of  $\xi$ : (top)  $0.02 < \xi < 0.05$ , (middle)  $0.05 < \xi < 0.1$ , (bottom)  $0.1 < \xi < 0.2$ .

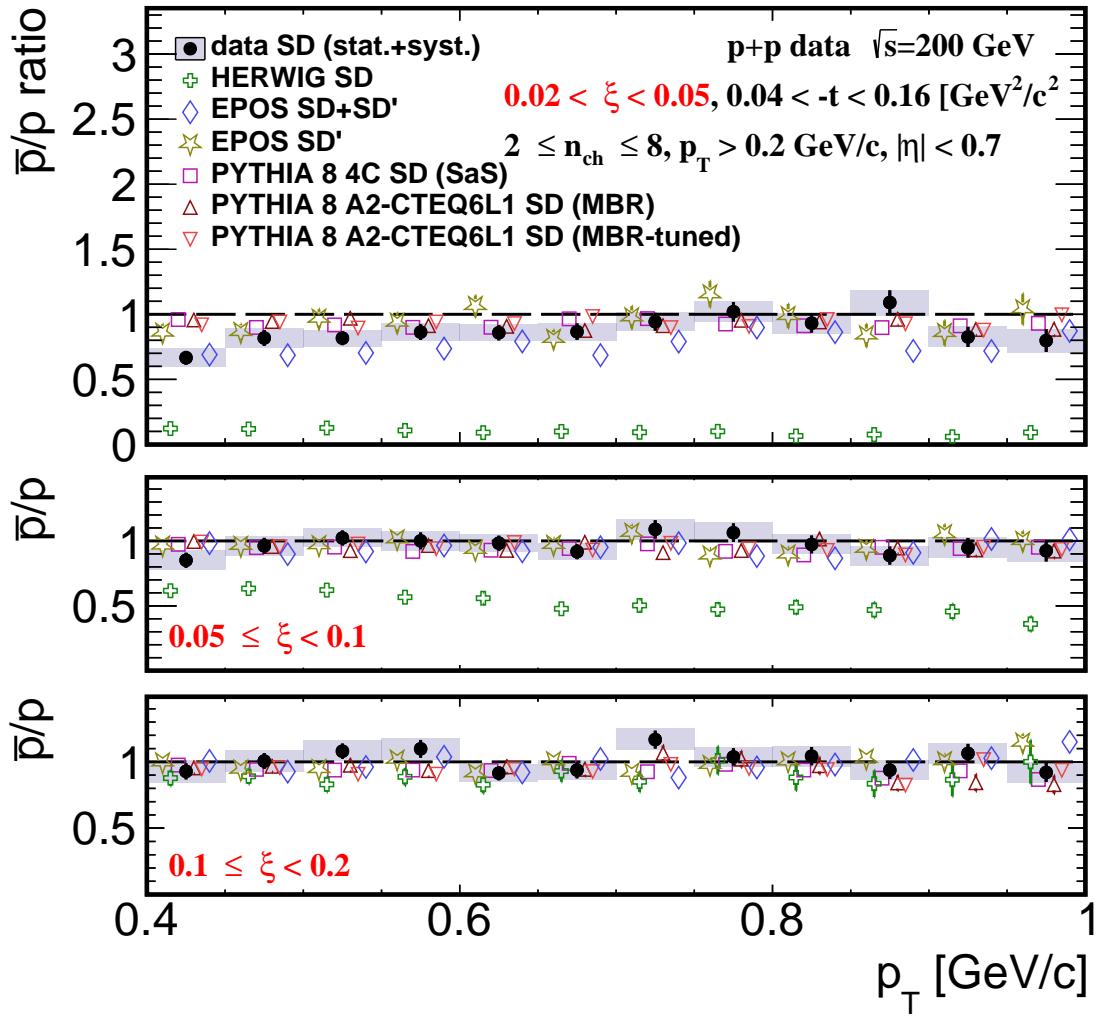


Figure 9.6: Ratio of production yields of  $\bar{p}/p$  as a function of  $p_{\text{T}}$  shown separately for the three ranges of  $\xi$ : (top)  $0.02 < \xi < 0.05$ , (middle)  $0.05 < \xi < 0.1$ , (bottom)  $0.1 < \xi < 0.2$ .

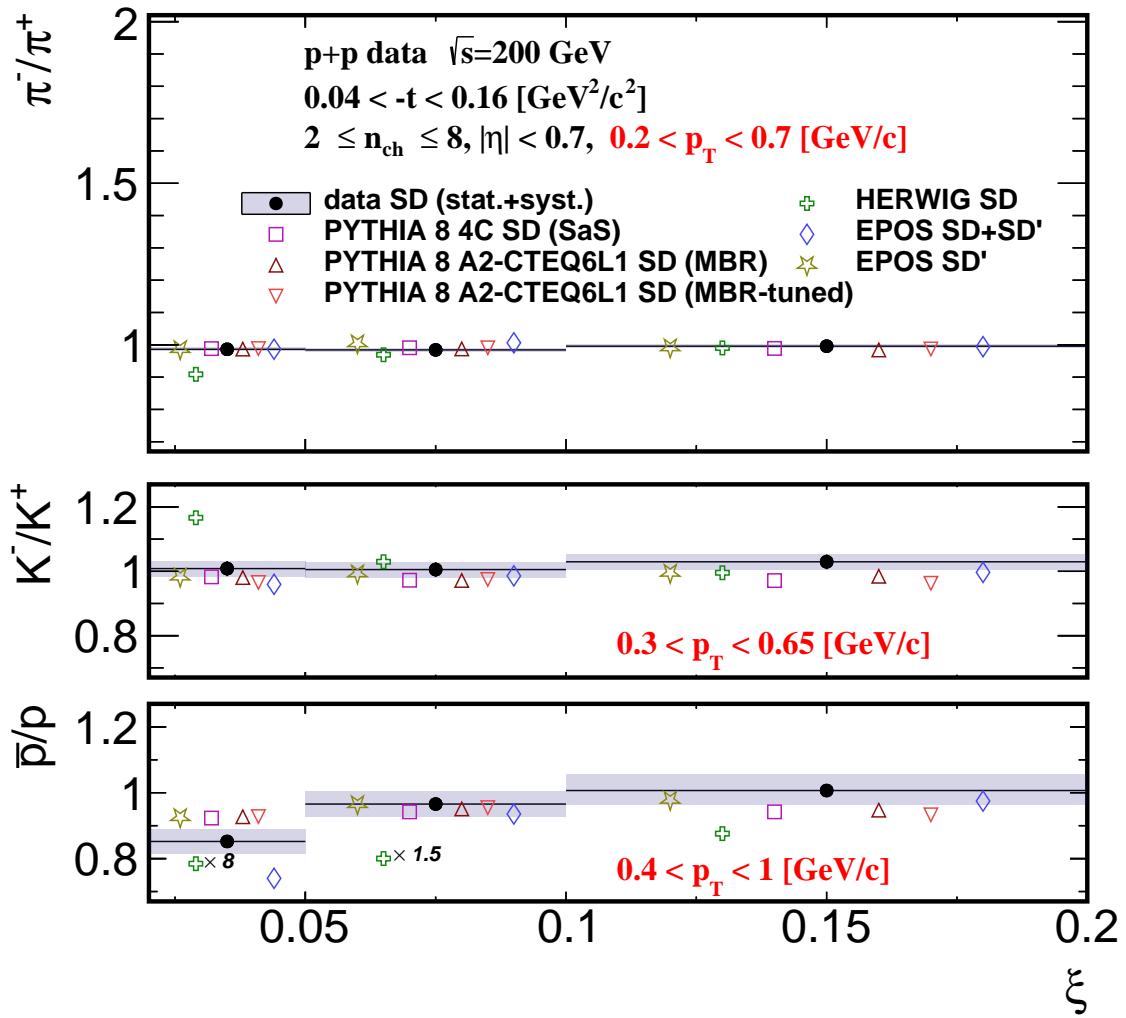


Figure 9.7: Ratio of production yields of  $\pi^-/\pi^+$ ,  $K^-/K^+$  and  $\bar{p}/p$  as a function of  $\xi$ .

# 943 10. Summary and Conclusions

944 Inclusive and identified (pion, kaon, proton and their antiparticles) charged particle production in  
945 Single Diffractive Dissociation process has been measured in proton-proton collisions at  $\sqrt{s} = 200$   
946 GeV with the STAR detector at RHIC using data corresponding to an integrated luminosity of  
947  $15 \text{ nb}^{-1}$ .

948 Significant differences are observed between the measured distributions of  $\xi$  and MC model  
949 predictions. Amongst the models considered, EPOS and PYTHIA 8 (MBR) without artificial  
950 suppression of diffractive cross sections at large  $\xi$  provide the best description of the data.

951 Charged-particle multiplicity and its dependence on the pseudorapidity and the transverse  
952 momentum are well described by PYTHIA8 and EPOS SD' models. EPOS SD+SD' and HERWIG  
953 do not describe the data.

954  $\pi^-/\pi^+$  and  $K^-/K^+$  production ratios are close to unity and consistent with most of model  
955 predictions except for HERWIG.

956  $\bar{p}/p$  production ratio shows a significant deviation from unity in the  $0.02 < \xi < 0.05$  range  
957 indicating a non-negligible transfer of the baryon number from the forward to the central region.  
958 Equal amount of protons and antiprotons are observed in the  $\xi > 0.05$  range. PYTHIA8, EPOS  
959 SD+SD' and EPOS SD' agree with data for  $\xi > 0.05$ . For  $0.02 < \xi < 0.05$  PYTHIA 8 and  
960 EPOS SD' predict small deviations from unity (0.93) which is however higher than observed  
961 in data ( $0.85 \pm 0.04$ ). EPOS SD+SD' predicts an asymmetry between  $\bar{p}$  and  $p$  of  $\sim 30\%$  at  
962  $0.02 < \xi < 0.05$ . HERWIG predicts much larger baryon number transfers compared to data for  
963  $\xi < 0.1$  and shows consistency with data for  $\xi > 0.1$ .

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# Appendices

<sub>1003</sub> **A. Proton and Antiproton DCA  
Distributions**

<sub>1004</sub>

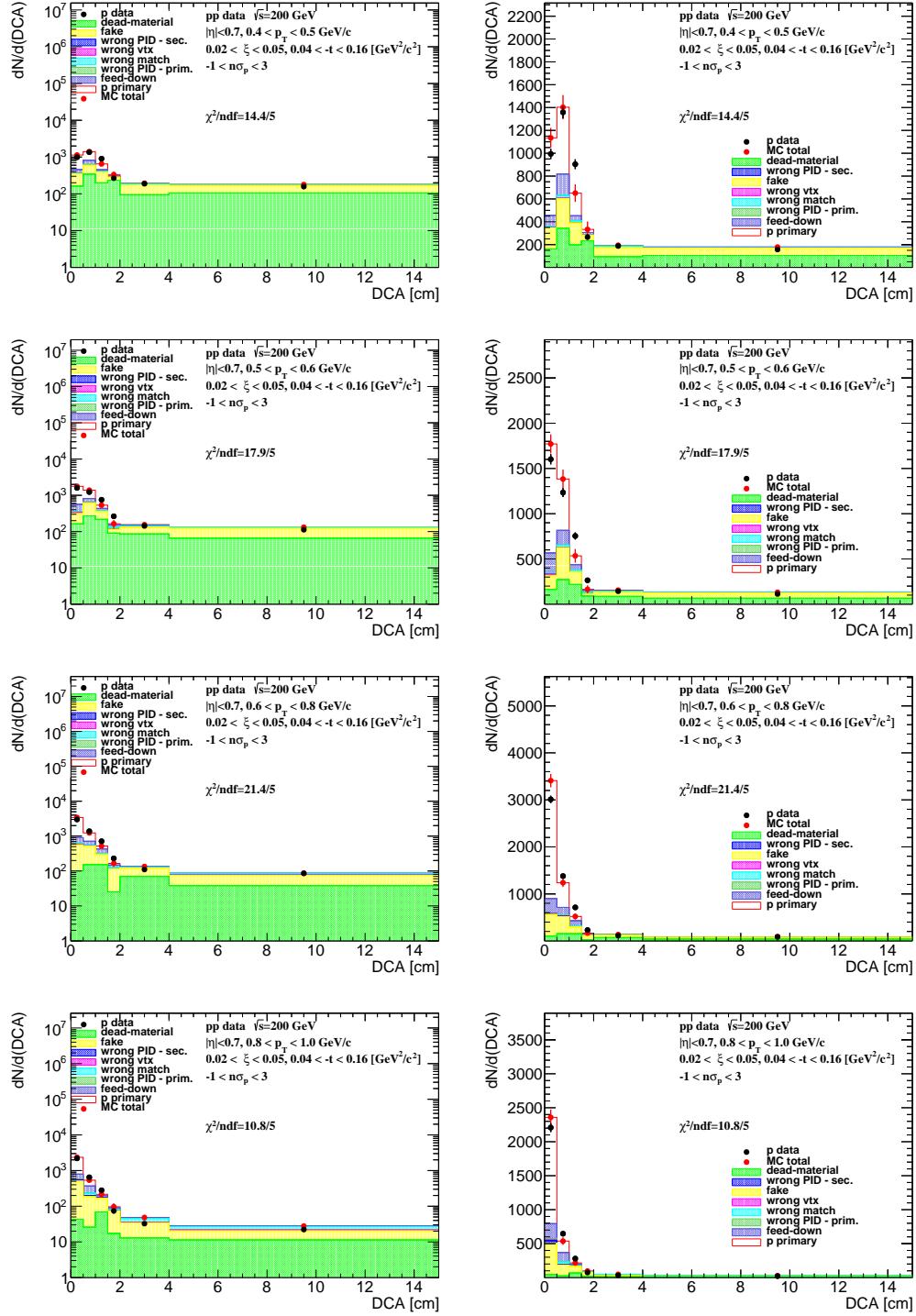


Figure A.1: Distributions of DCA for protons in SD interactions with  $0.02 < \xi < 0.05$  and loose selection.

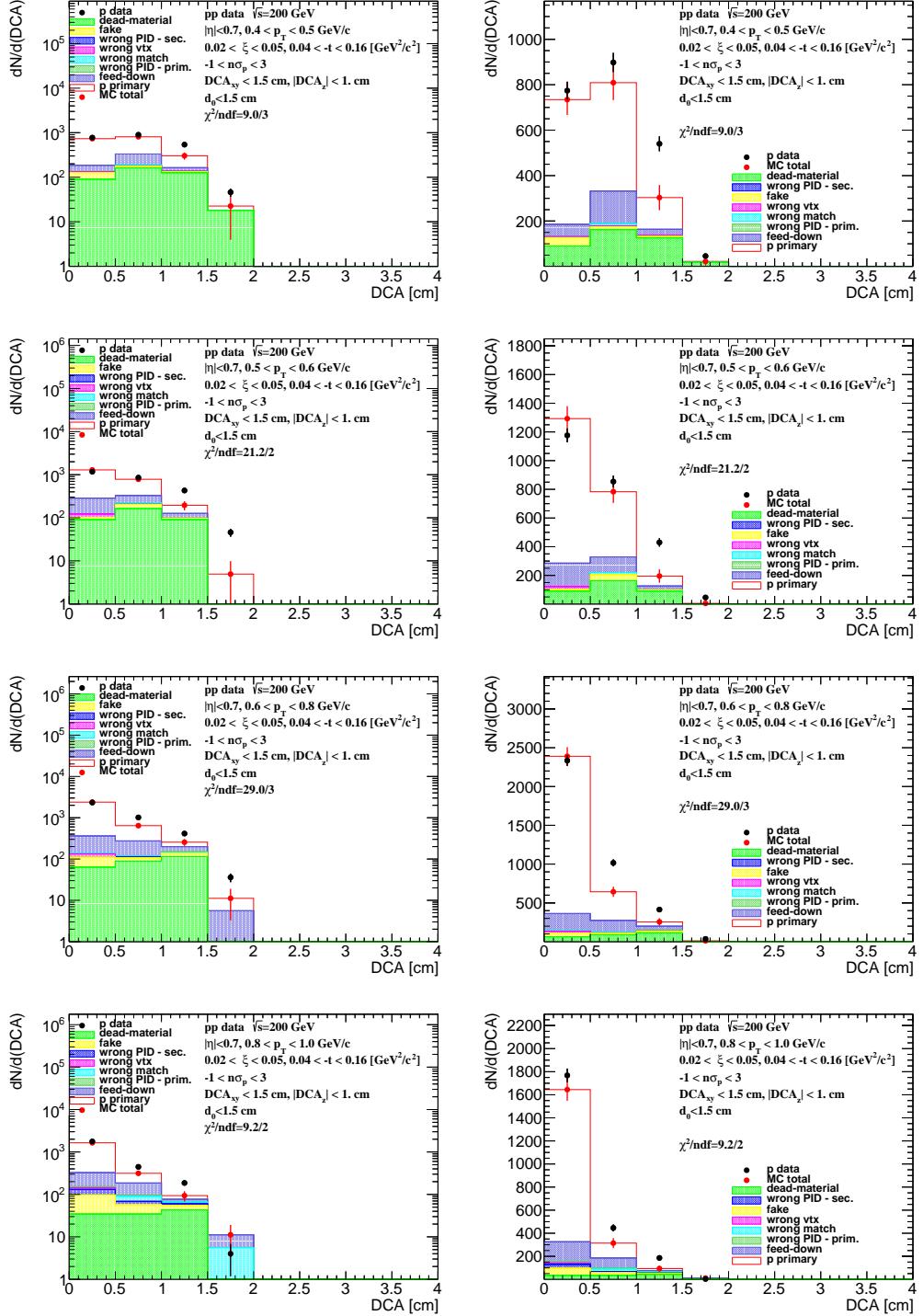


Figure A.2: Distributions of DCA for protons in SD interactions with  $0.02 < \xi < 0.05$  and normal selection.

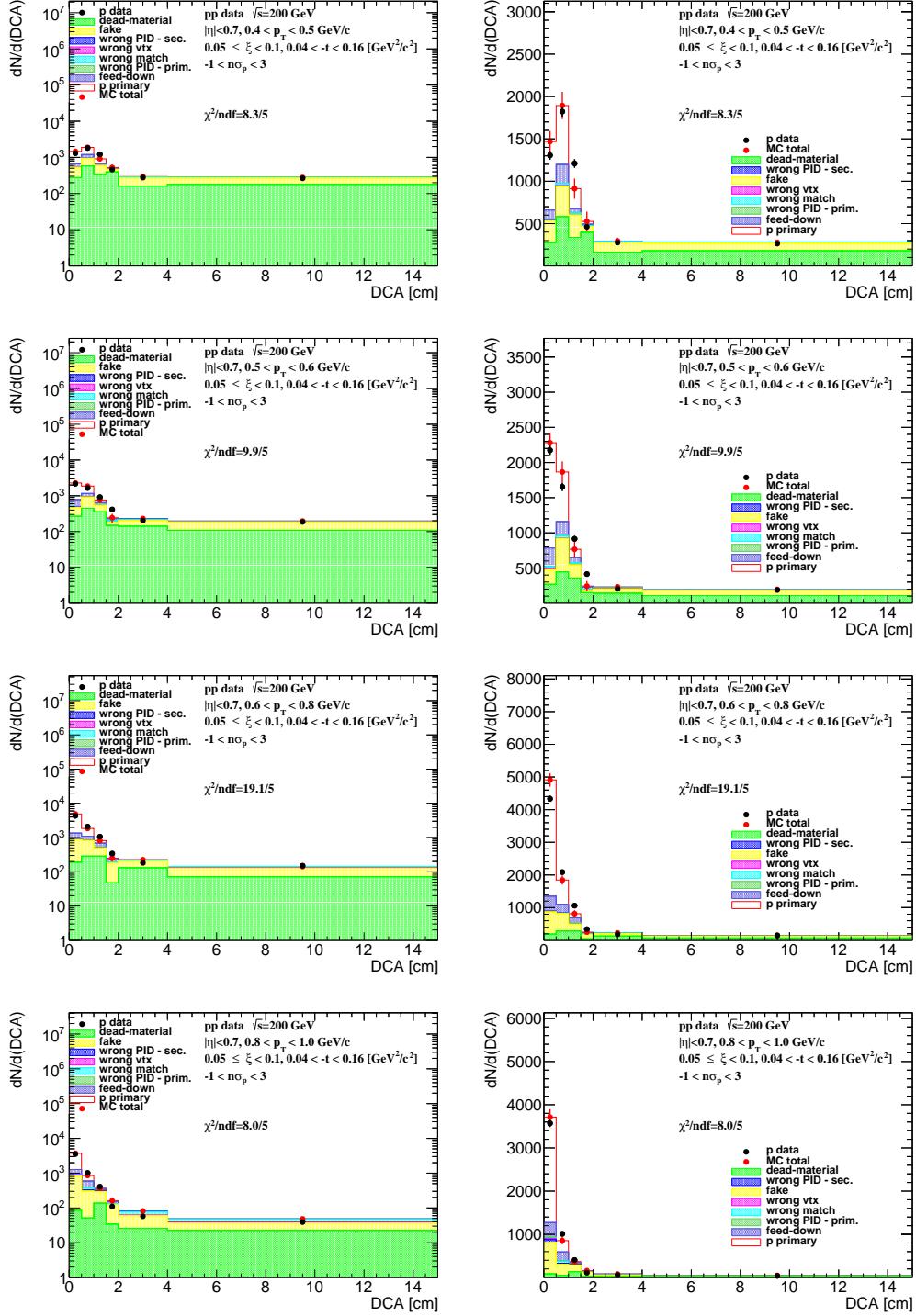


Figure A.3: Distributions of DCA for protons in SD interactions with  $0.05 < \xi < 0.1$  and loose selection.

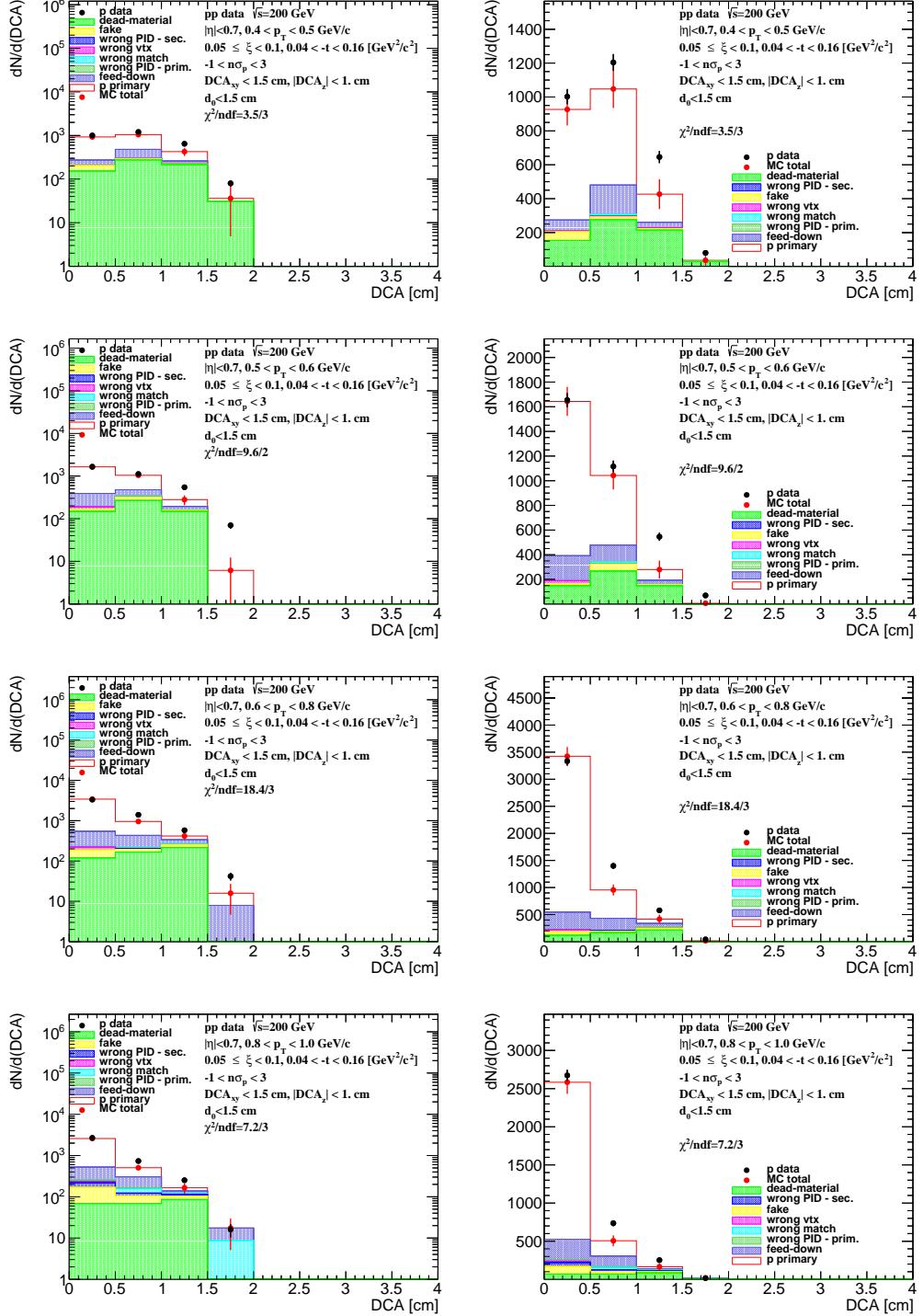


Figure A.4: Distributions of DCA for protons in SD interactions with  $0.05 < \xi < 0.1$  and normal selection.

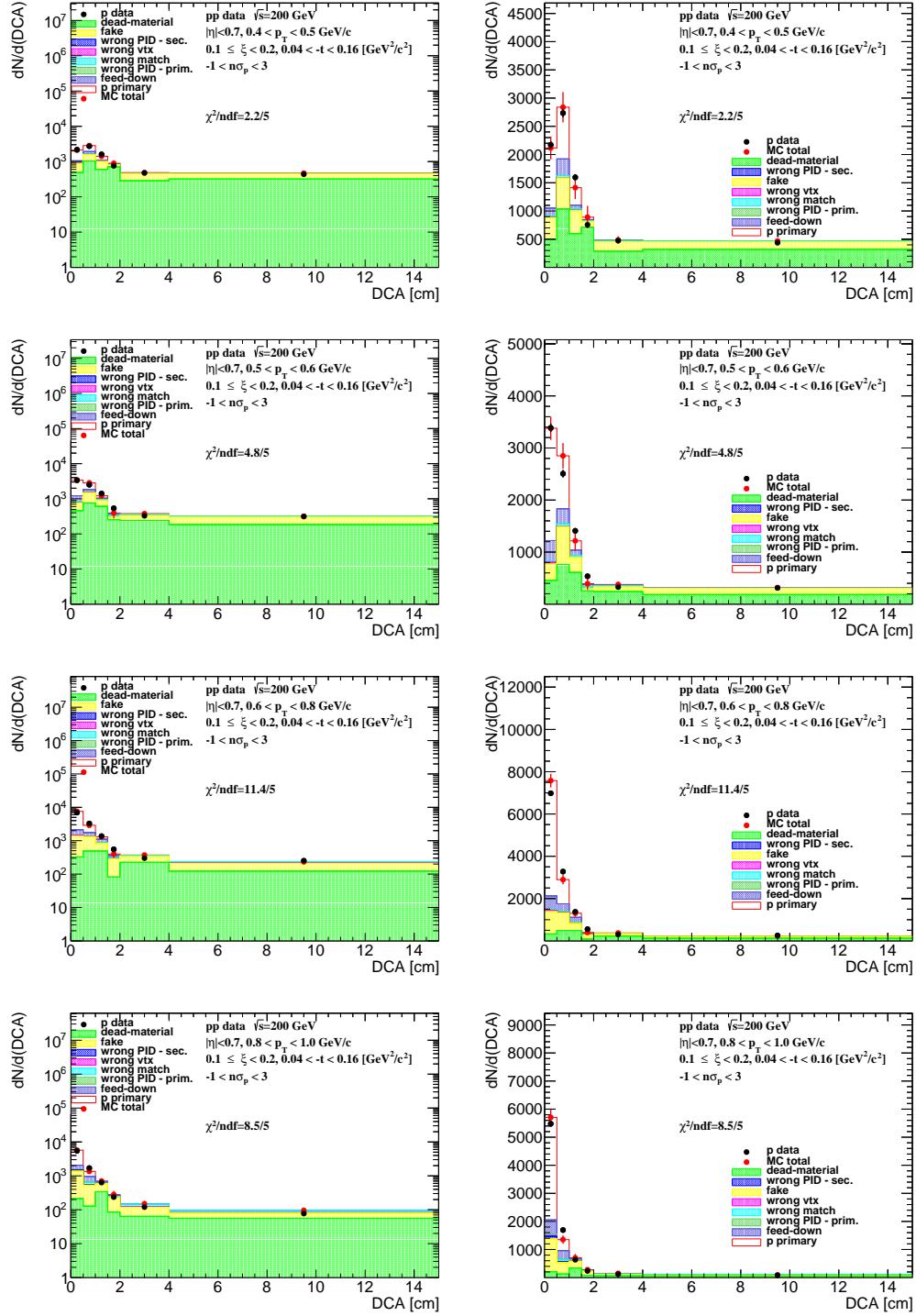


Figure A.5: Distributions of DCA for protons in SD interactions with  $0.1 < \xi < 0.2$  and loose selection.

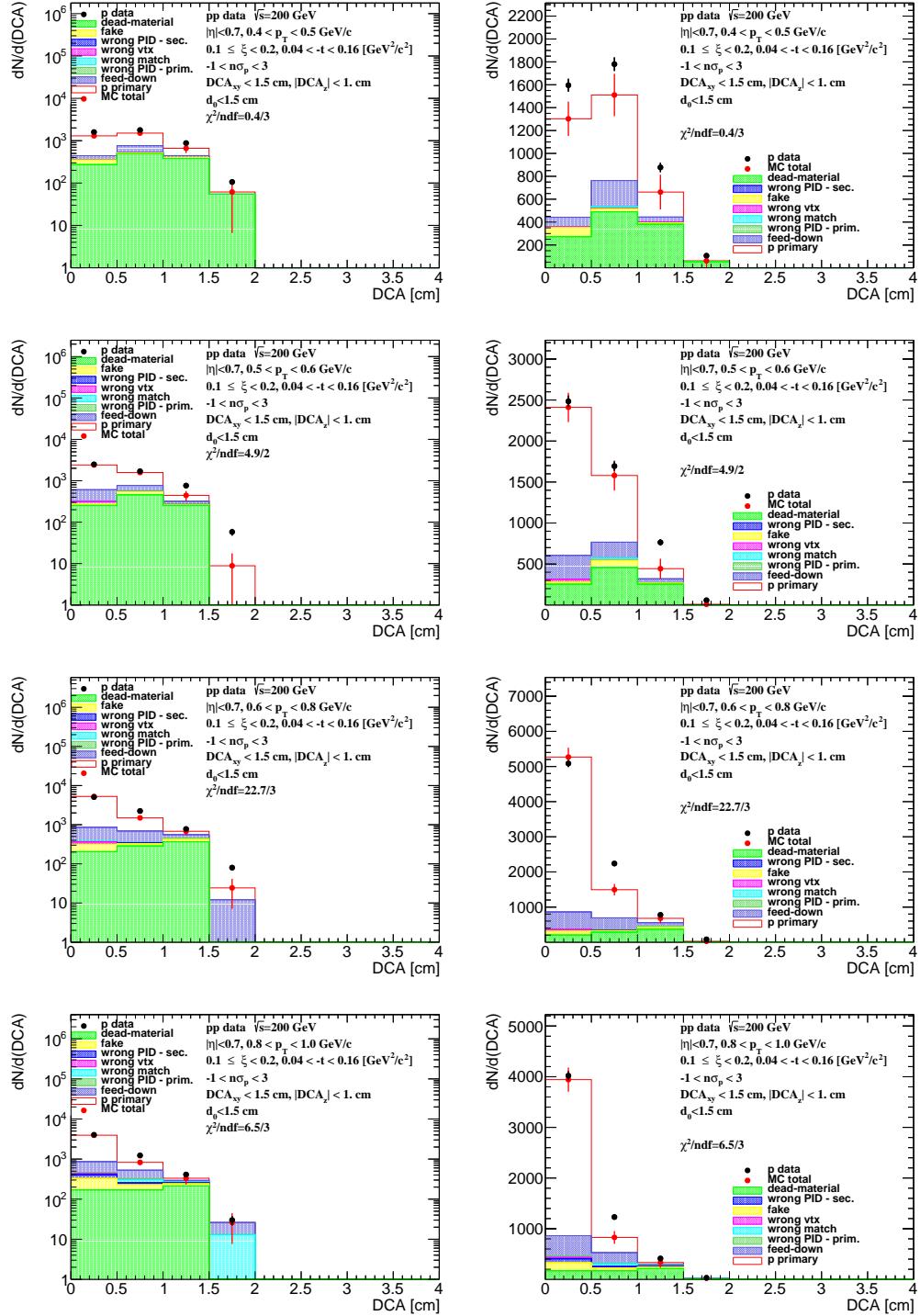


Figure A.6: Distributions of DCA for protons in SD interactions with  $0.1 < \xi < 0.2$  and normal selection.

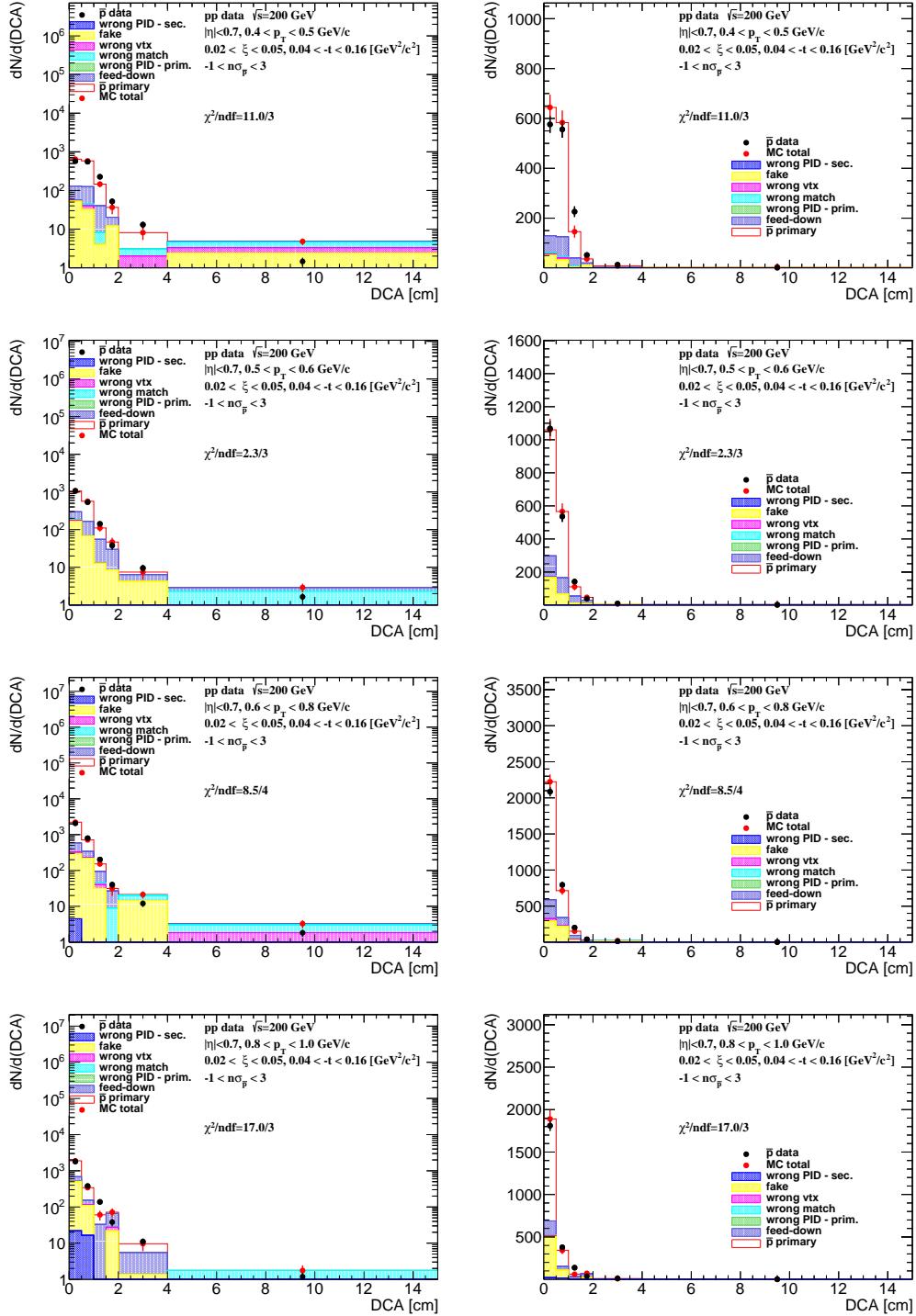


Figure A.7: Distributions of DCA for antiprotons in SD interactions with  $0.02 < \xi < 0.05$  and loose selection.

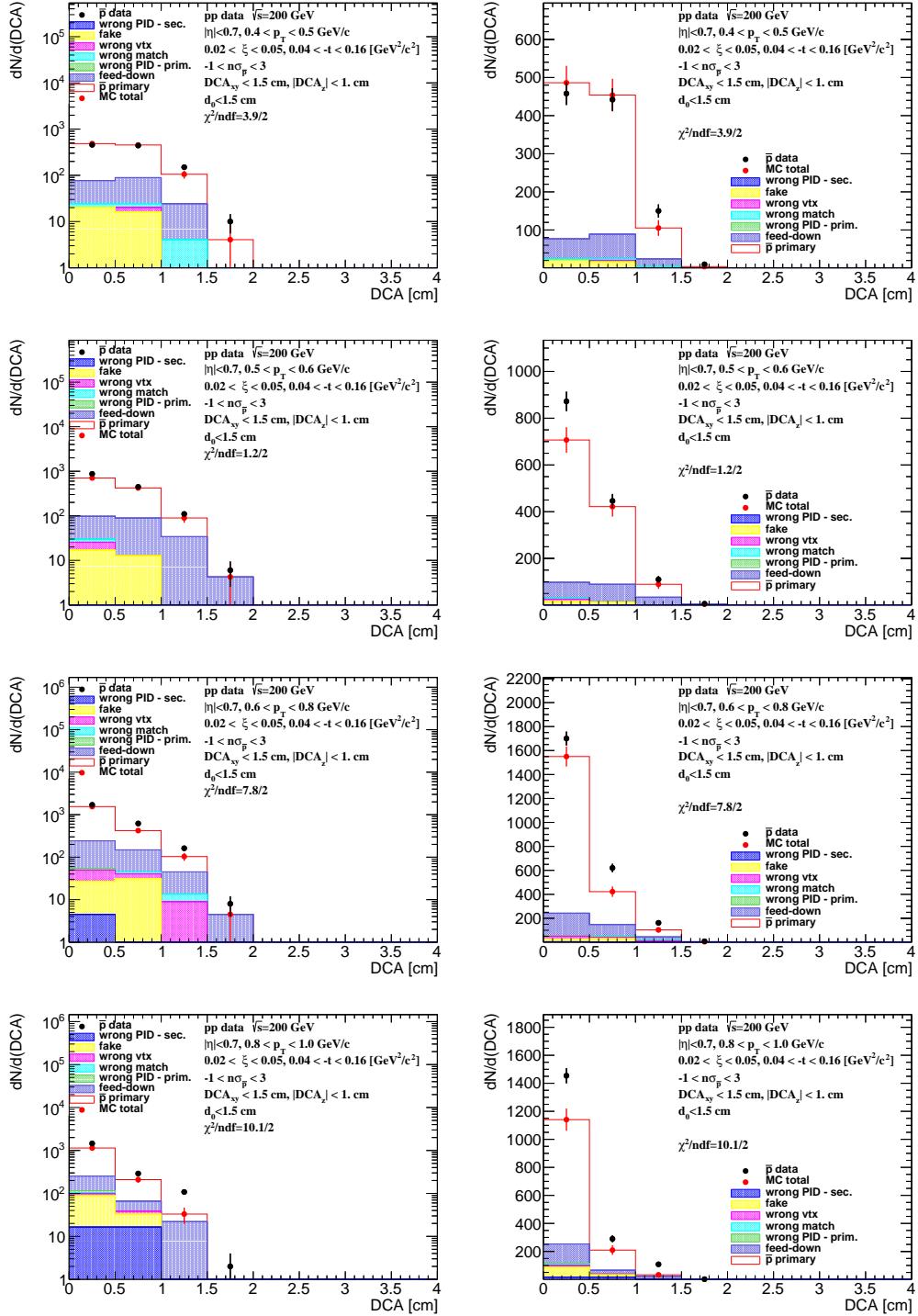


Figure A.8: Distributions of DCA for antiprotons in SD interactions with  $0.02 < \xi < 0.05$  and normal selection.

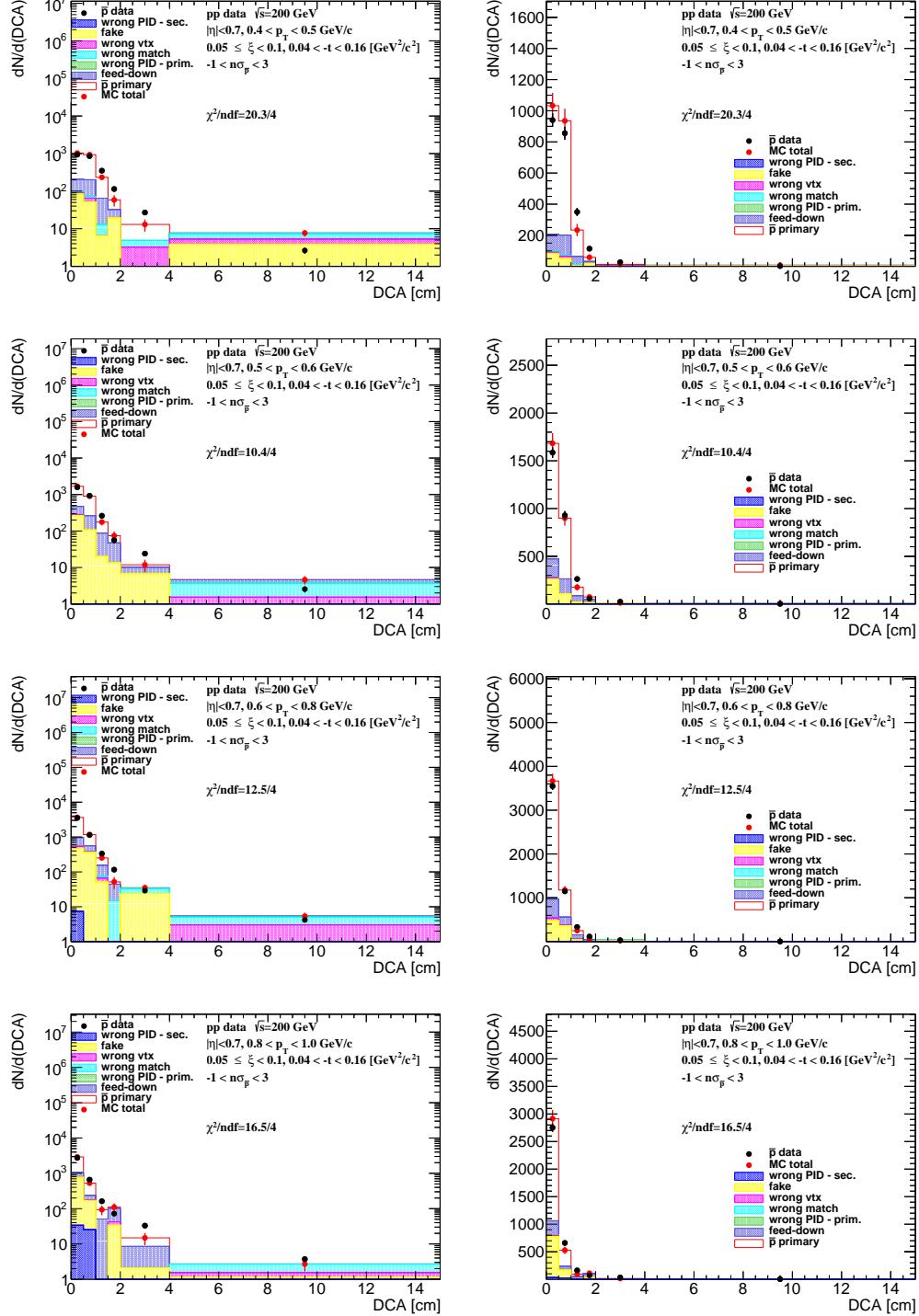


Figure A.9: Distributions of DCA for antiprotons in SD interactions with  $0.05 < \xi < 0.1$  and loose selection.

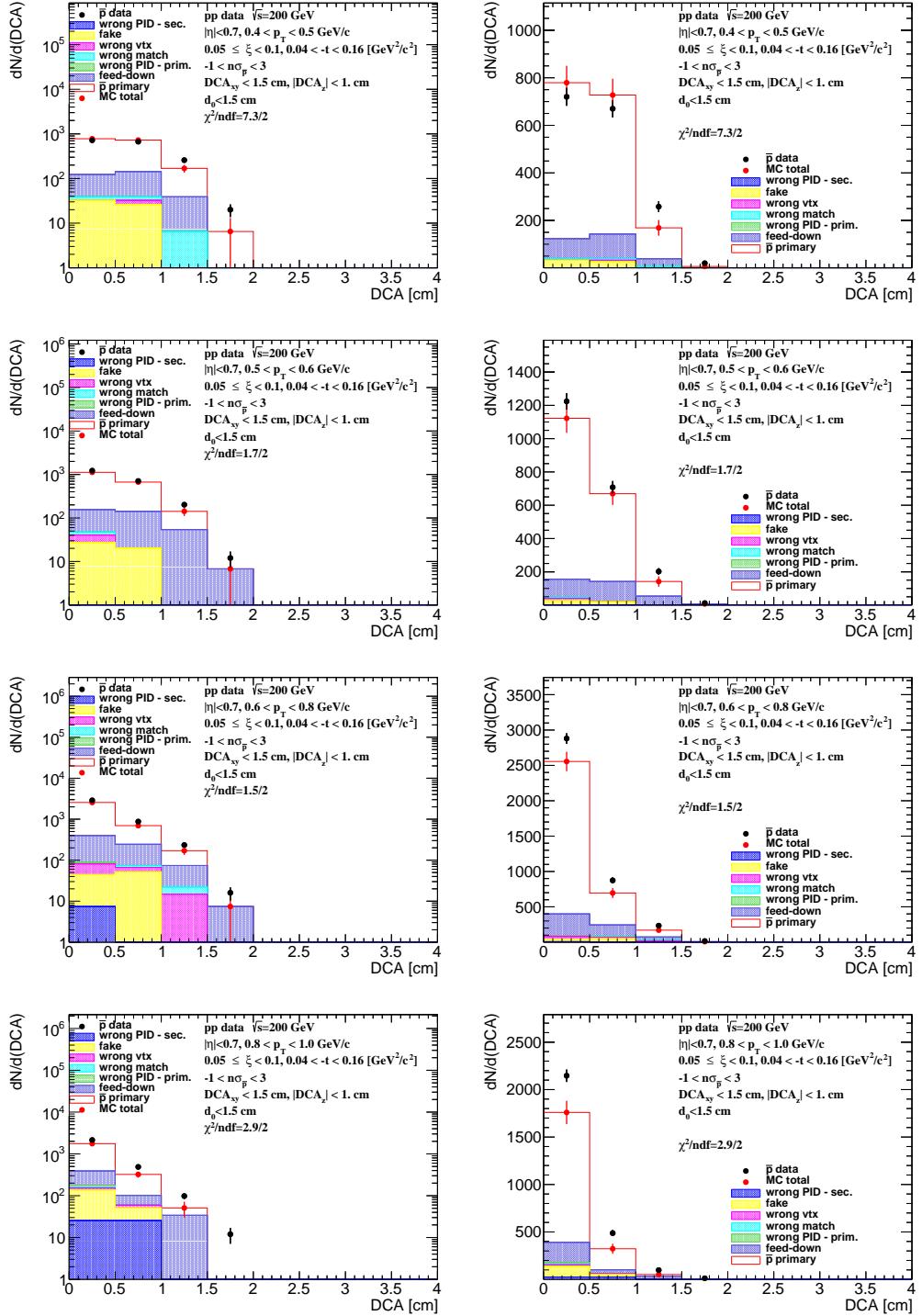


Figure A.10: Distributions of DCA for antiprotons in SD interactions with  $0.05 < \xi < 0.1$  and normal selection.

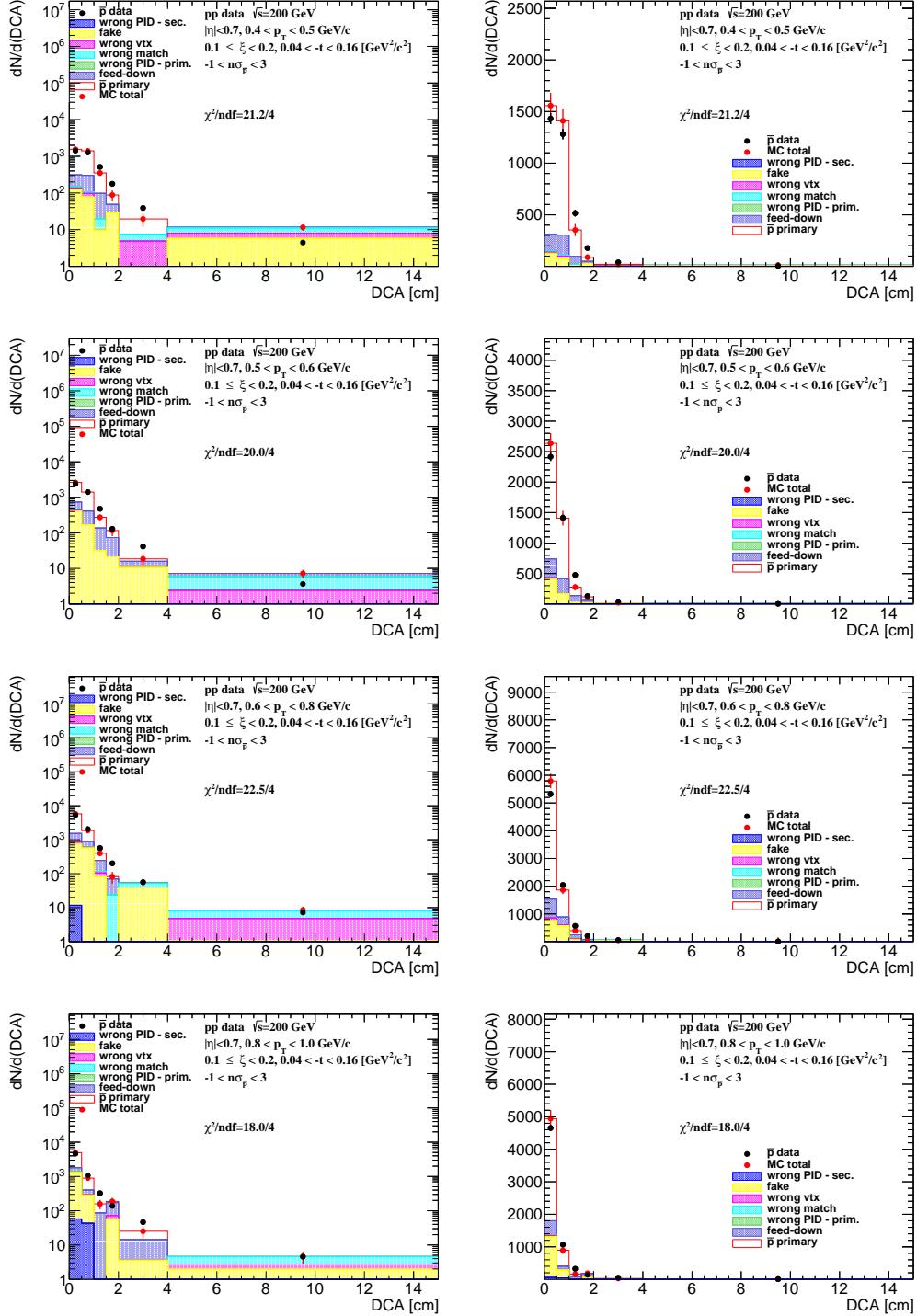


Figure A.11: Distributions of DCA for antiprotons in SD interactions with  $0.1 < \xi < 0.2$  and loose selection.

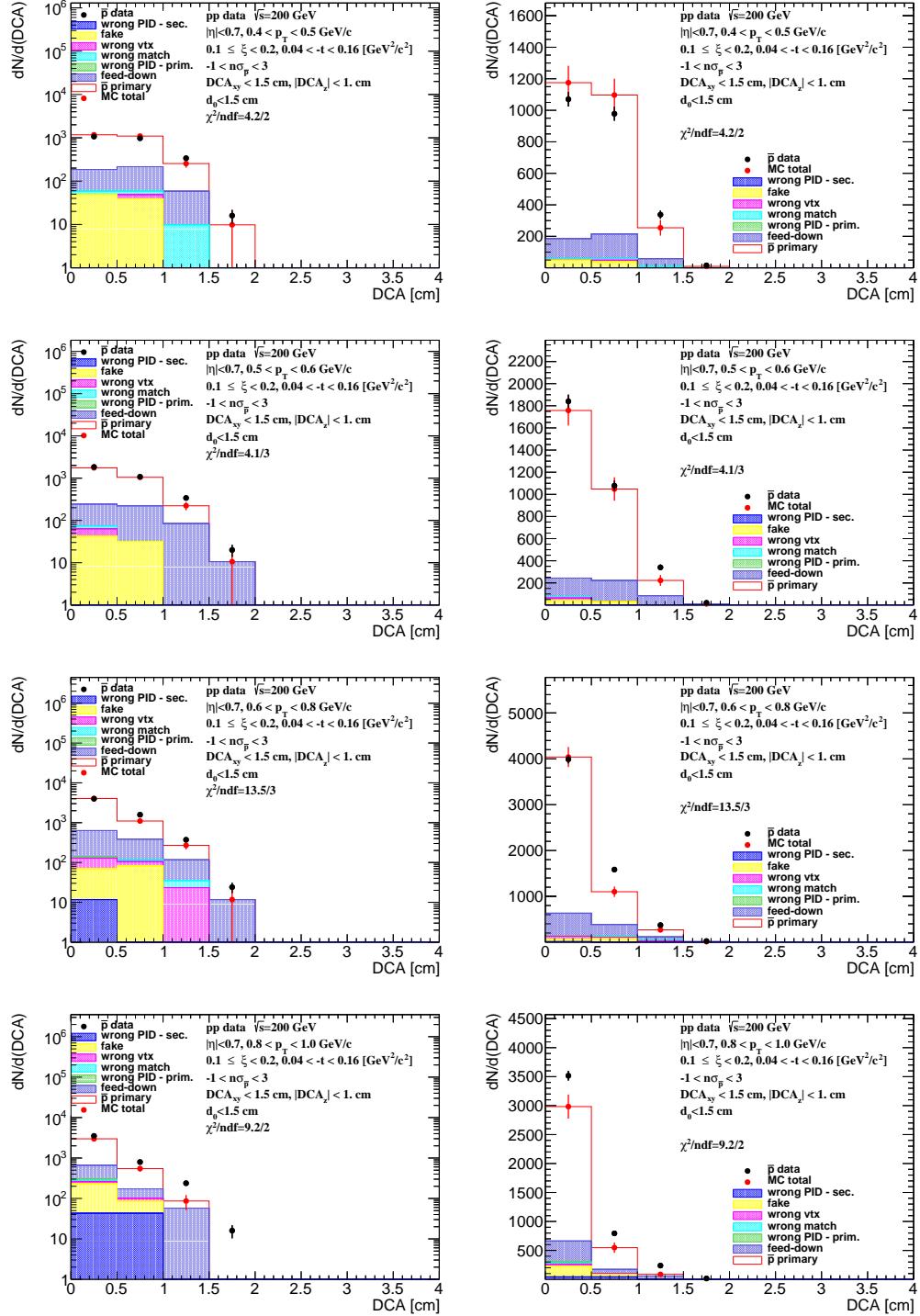


Figure A.12: Distributions of DCA for antiprotons in SD interactions with  $0.1 < \xi < 0.2$  and normal selection.

## B. Distributions of $n\sigma_{dE/dx}^i$ in SD

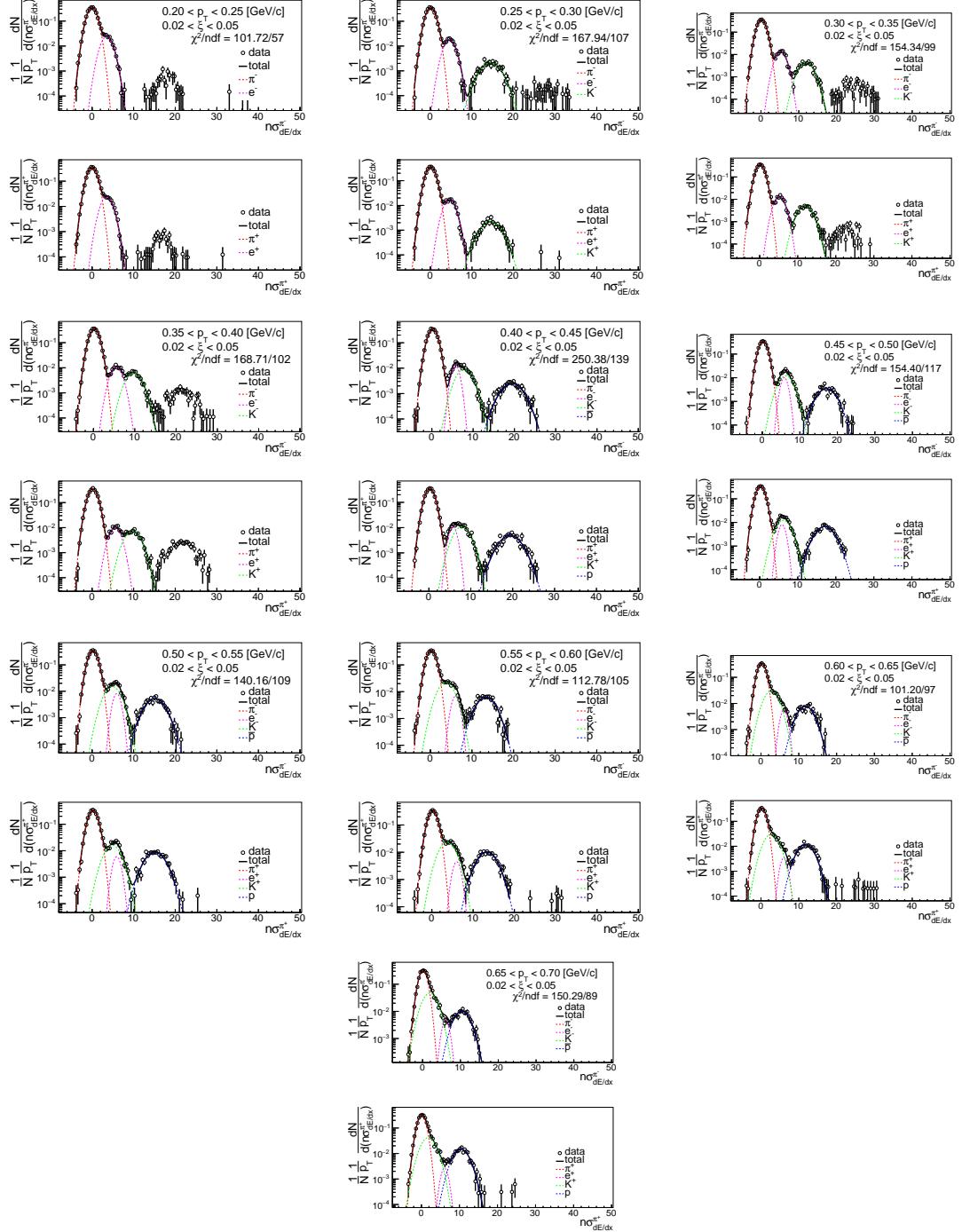


Figure B.1: Distributions of  $n\sigma_{dE/dx}^{\pi^\pm}$  for  $\pi^\pm$  in SD interactions with  $0.02 < \xi < 0.05$ .

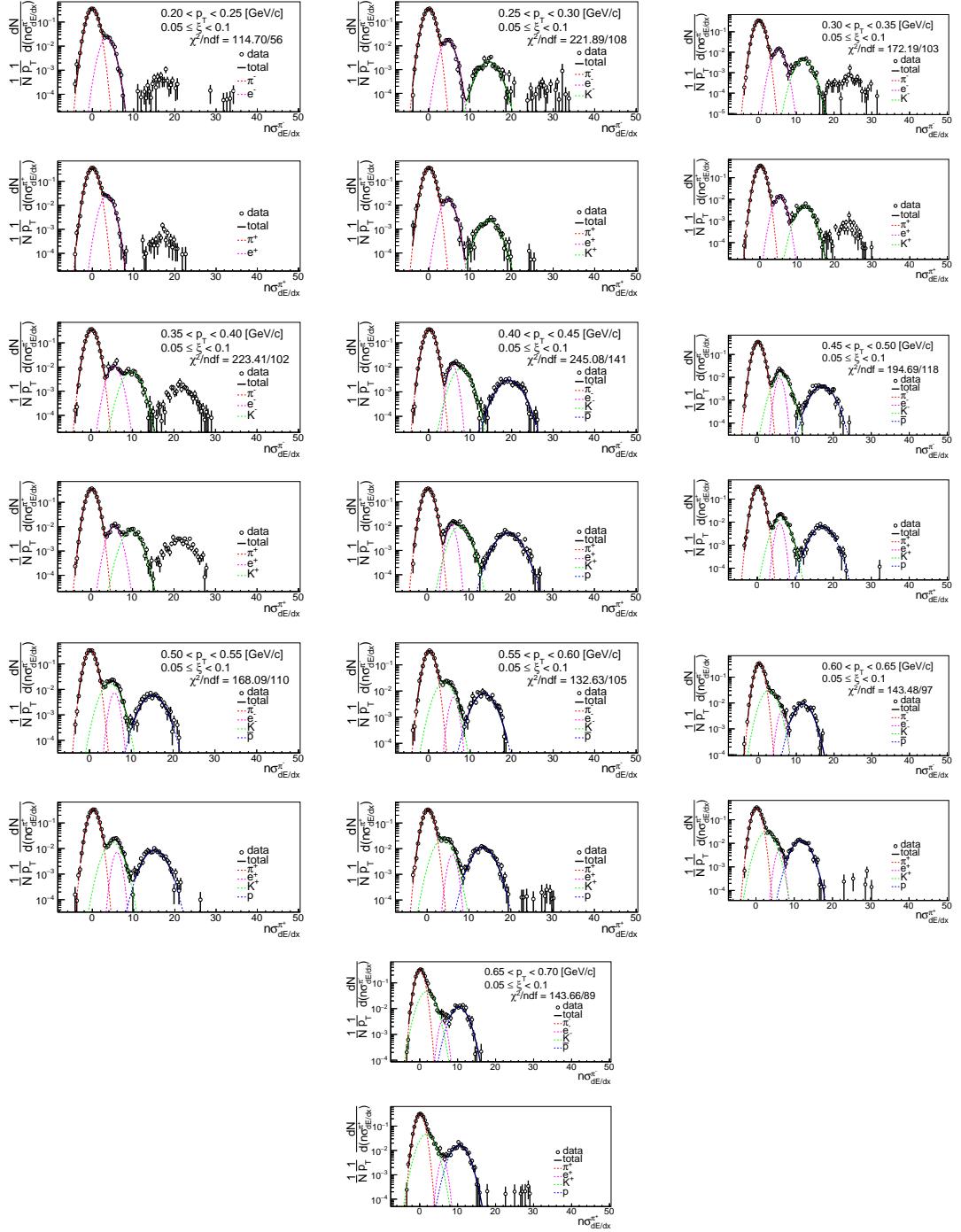


Figure B.2: Distributions of  $n\sigma_{dE/dx}^{\pi^\pm}$  for  $\pi^\pm$  in SD interactions with  $0.05 < \xi < 0.1$ .

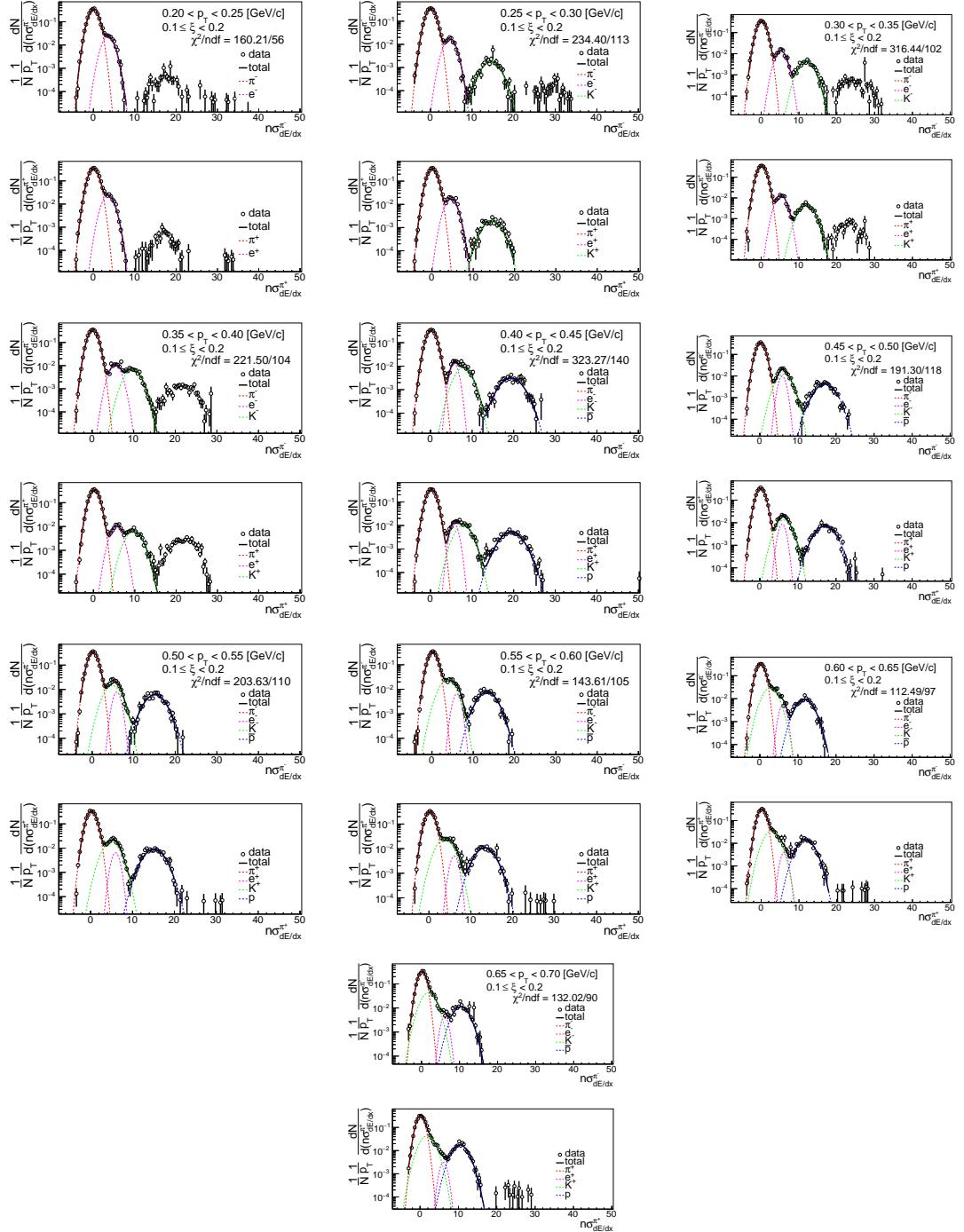


Figure B.3: Distributions of  $n\sigma_{dE/dx}^{\pi^\pm}$  for  $\pi^\pm$  in SD interactions with  $0.1 < \xi < 0.2$ .

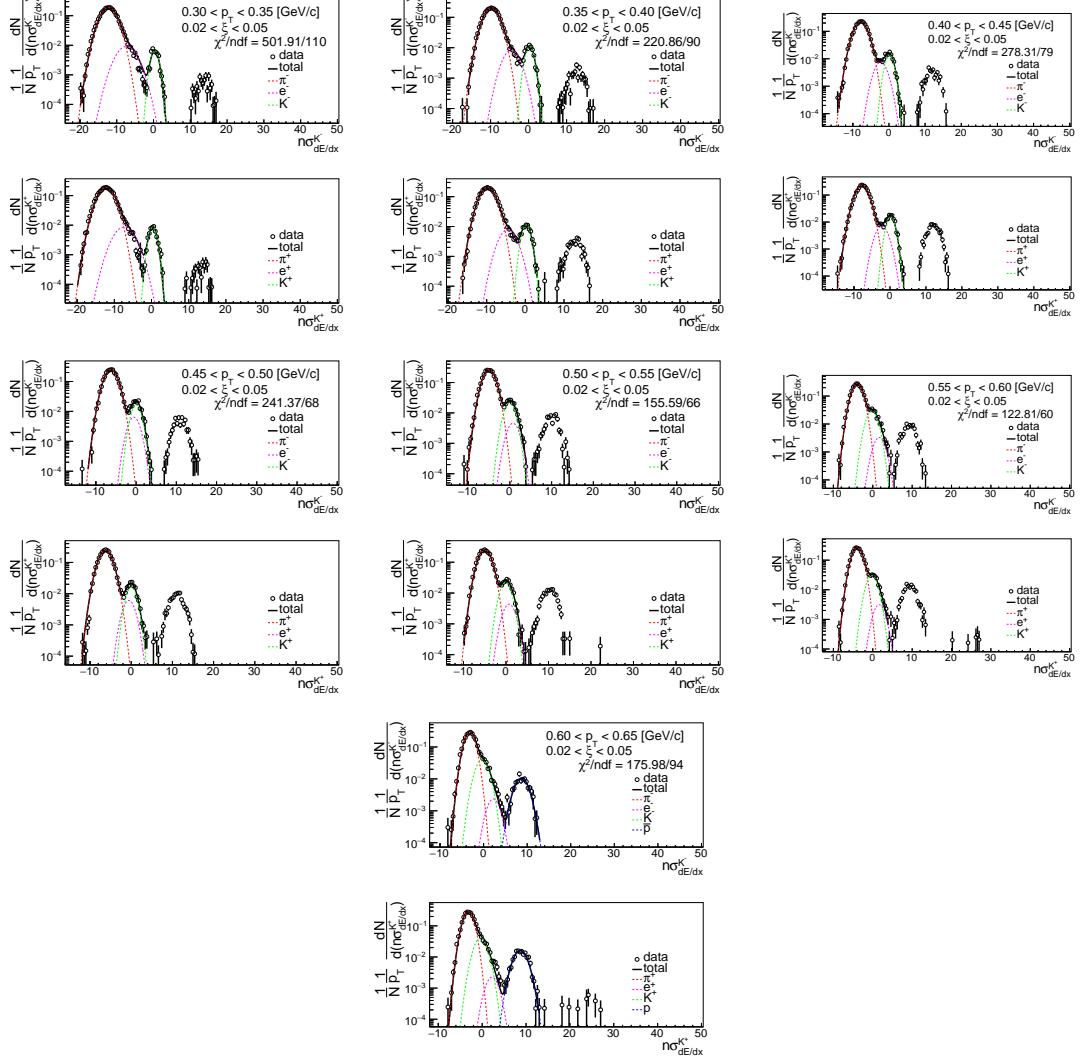


Figure B.4: Distributions of  $n\sigma_{dE/dx}^{K^\pm}$  for  $K^\pm$  in SD interactions with  $0.02 < \xi < 0.05$ .

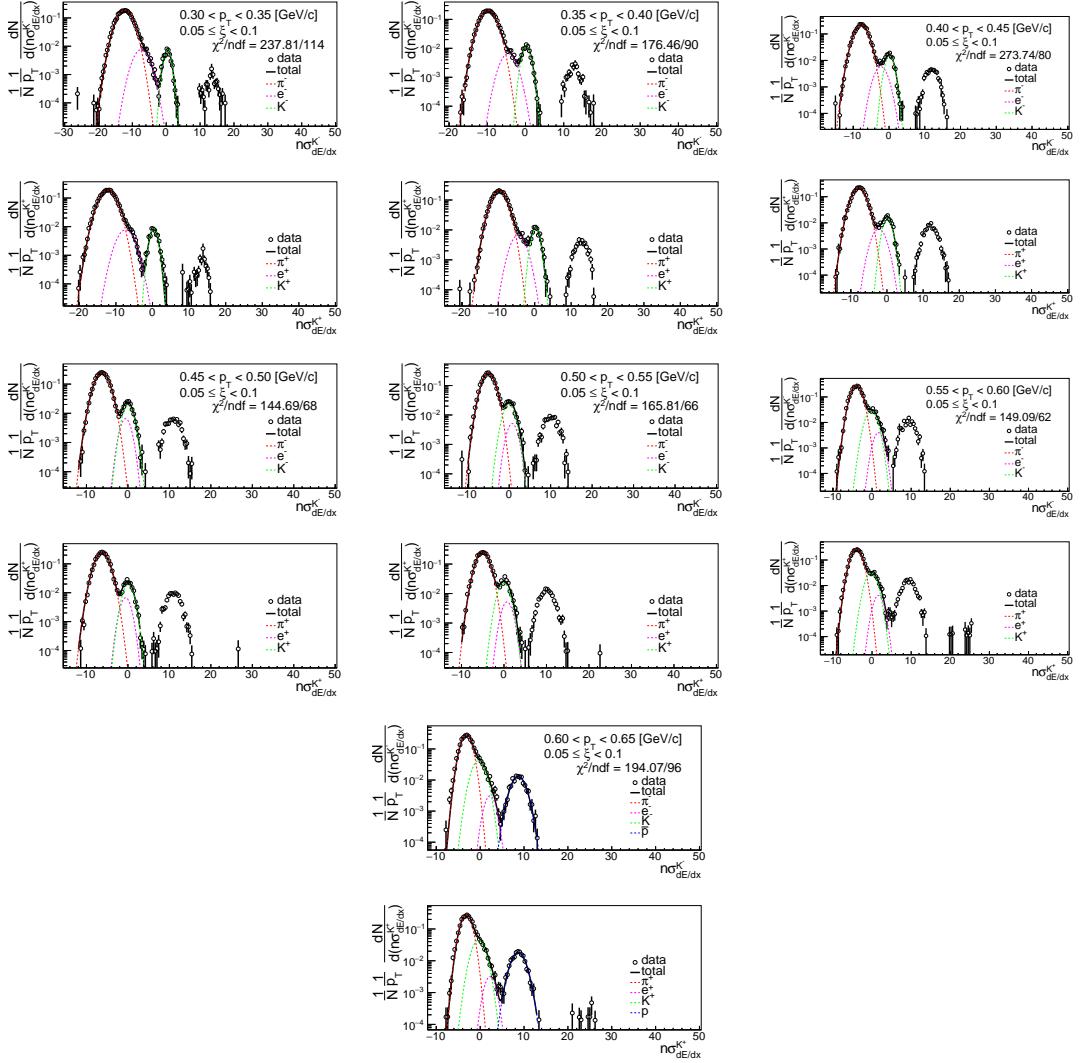


Figure B.5: Distributions of  $n\sigma_{dE/dx}^{K^\pm}$  for  $K^\pm$  in SD interactions with  $0.05 < \xi < 0.1$ .

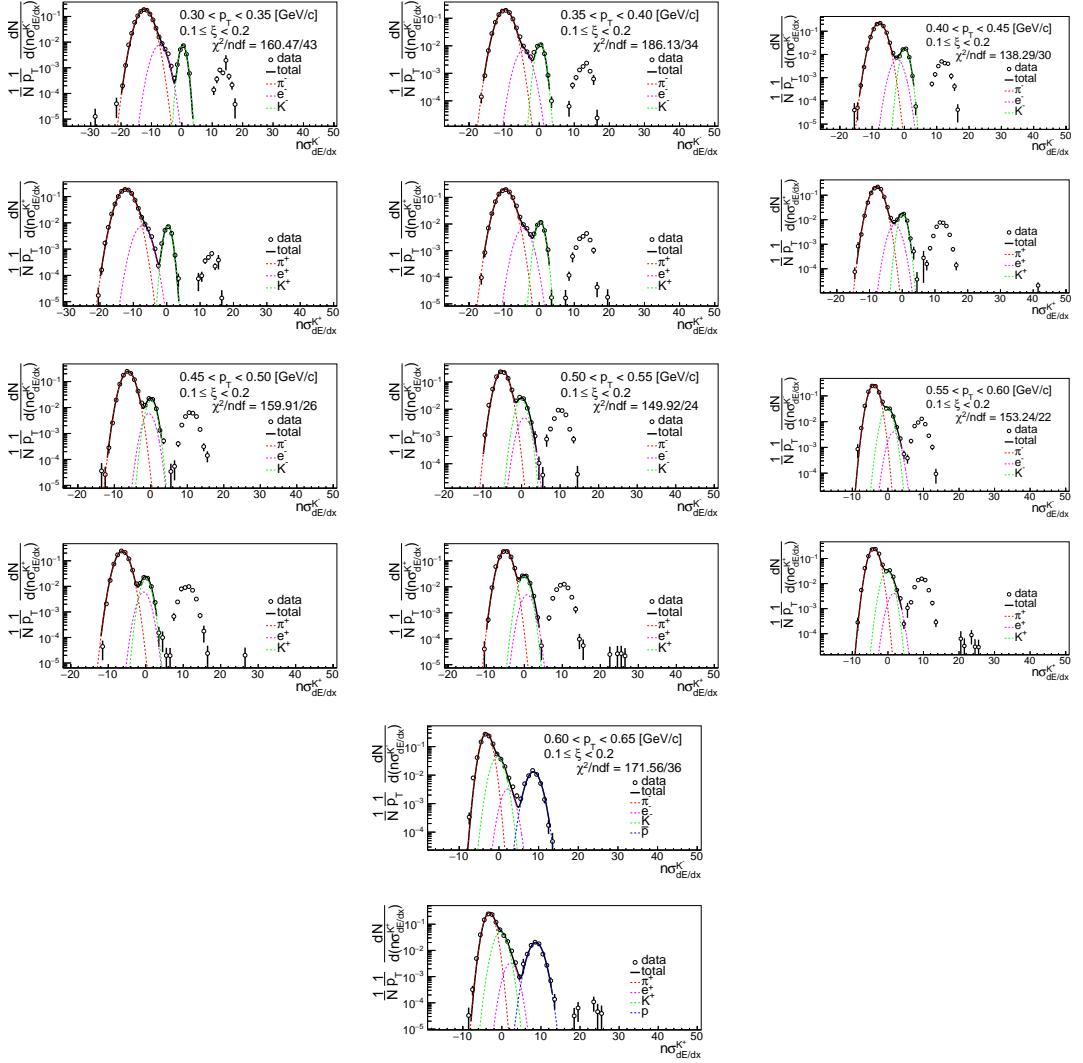


Figure B.6: Distributions of  $n\sigma_{dE/dx}^{K^\pm}$  for  $K^\pm$  in SD interactions with  $0.1 < \xi < 0.2$ .

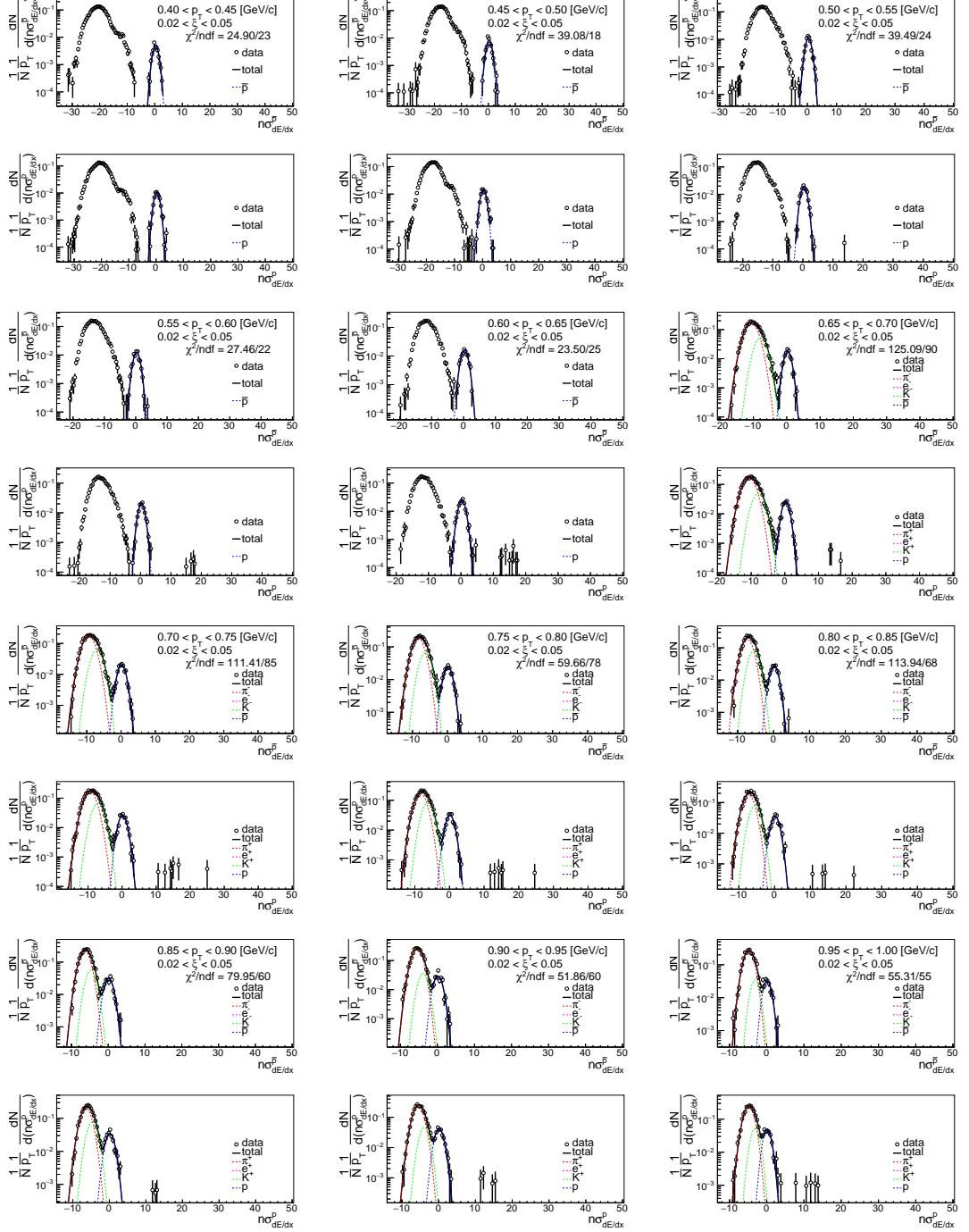


Figure B.7: Distributions of  $n\sigma_{dE/dx}^{\bar{p}, p}$  for  $\bar{p}, p$  in SD interactions with  $0.02 < \xi < 0.05$ .

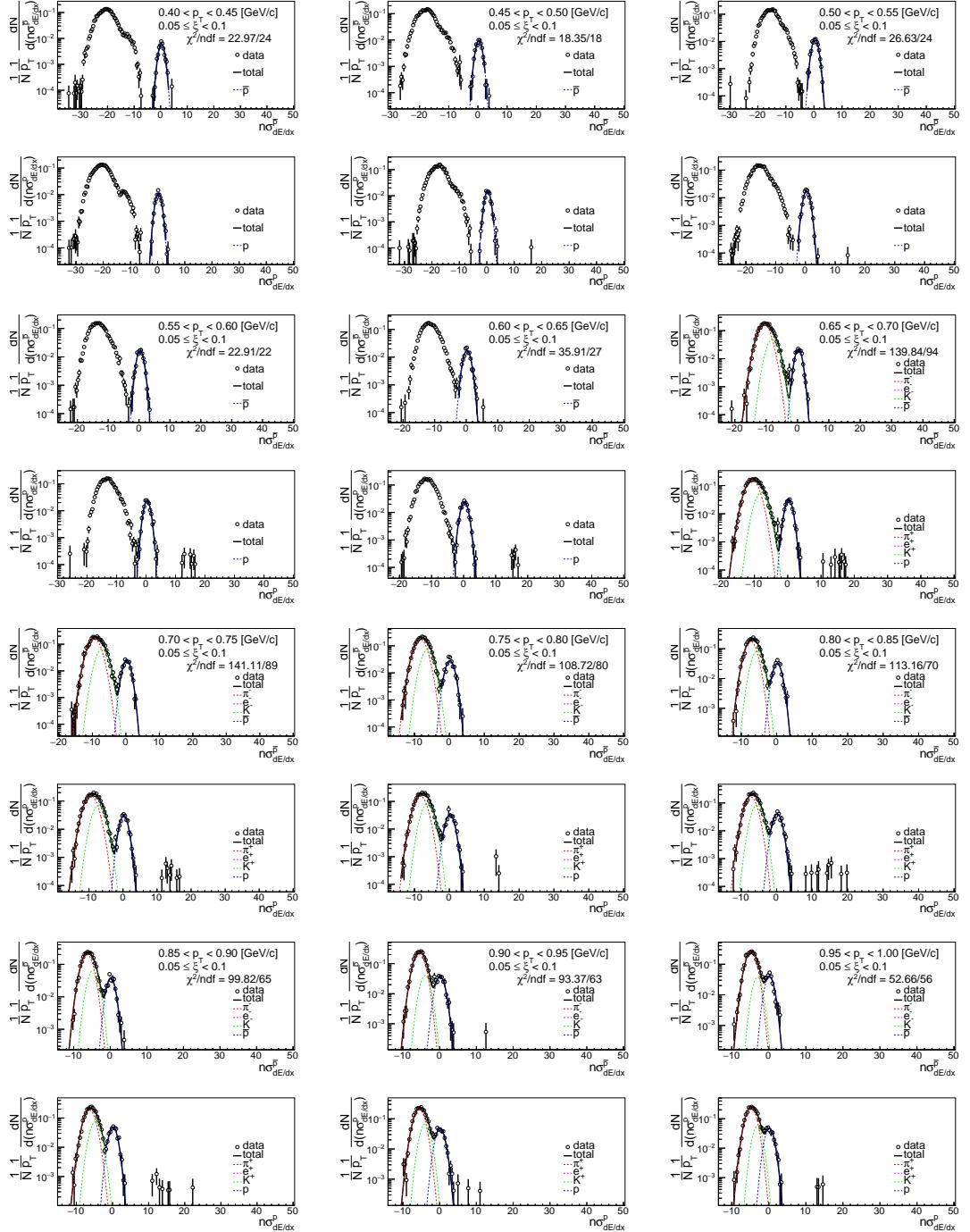


Figure B.8: Distributions of  $n\sigma_{dE/dx}^{\bar{p},p}$  for  $\bar{p}, p$  in SD interactions with  $0.05 < \xi < 0.1$ .

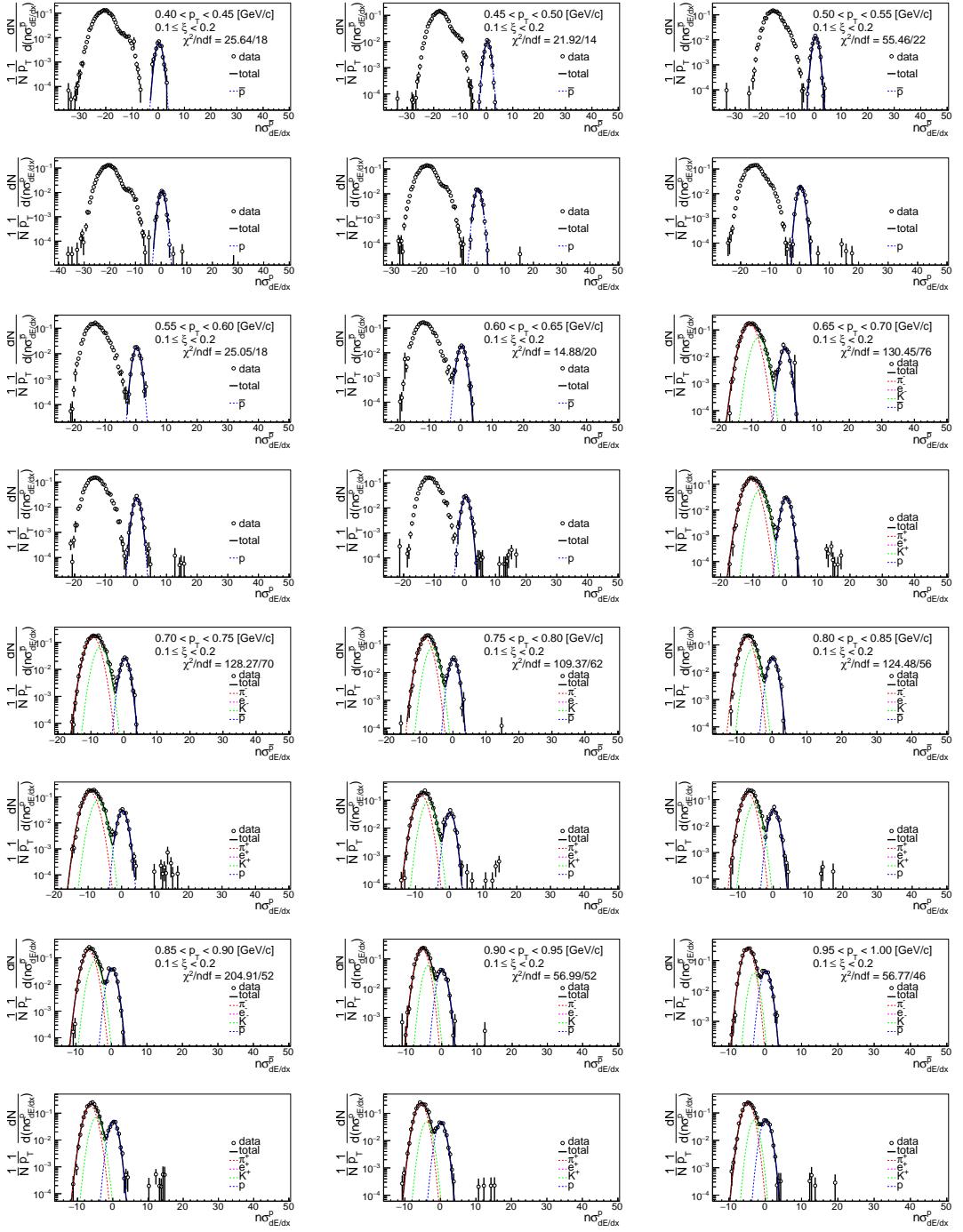


Figure B.9: Distributions of  $n\sigma_{dE/dx}^{\bar{p}, p}$  for  $\bar{p}, p$  in SD interactions with  $0.1 < \xi < 0.2$ .