Measurement of D^+- charged hadron azimuthal correlations in pp and p-Pb collisions with ALICE at the LHC

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Acting Supervisor: Prof. Tapnendu Kundu

ALICE

Outline

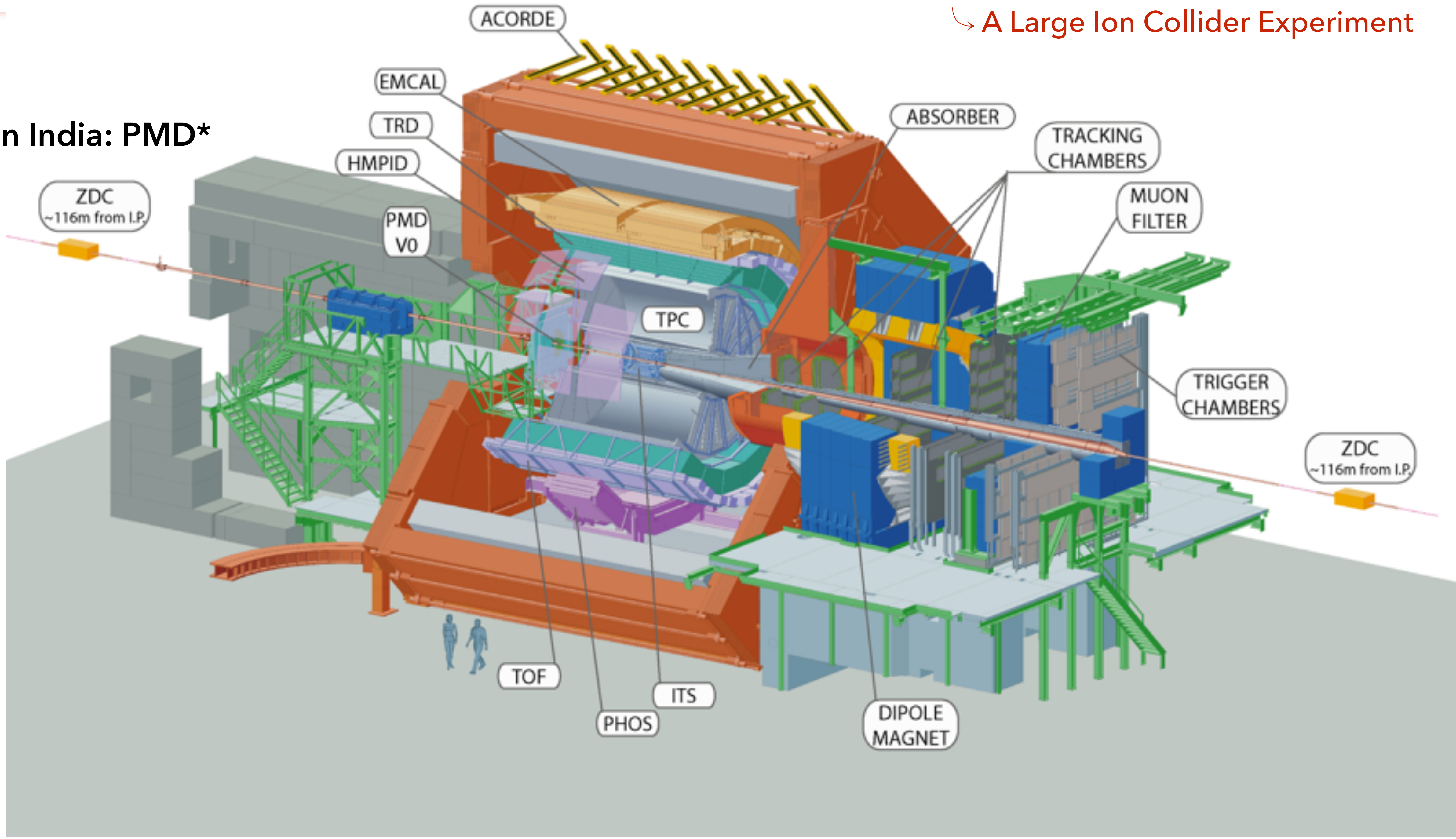
- Motivation
- ALICE detector
- Analysis strategy
  - D^+ selection and signal extraction*
  - Charged hadrons (associated track) selection*
  - Raw Correlation and background subtraction*
- Corrections
  - D^+ and charged particle efficiency correction*
  - Detector acceptance and inhomogeneity via Mixed Event
  - Sample Purity, Secondary particle contamination*
  - Feed down correction*
- Systematics*(+others), Simulations and Final Results
- Summary and outlook

Prelude

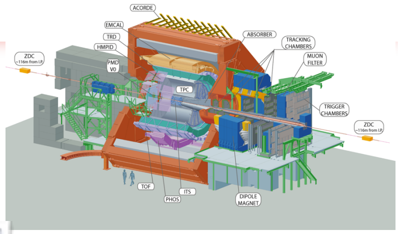
Physics w/ ALICE Detector at the LHC

↳ A Large Ion Collider Experiment

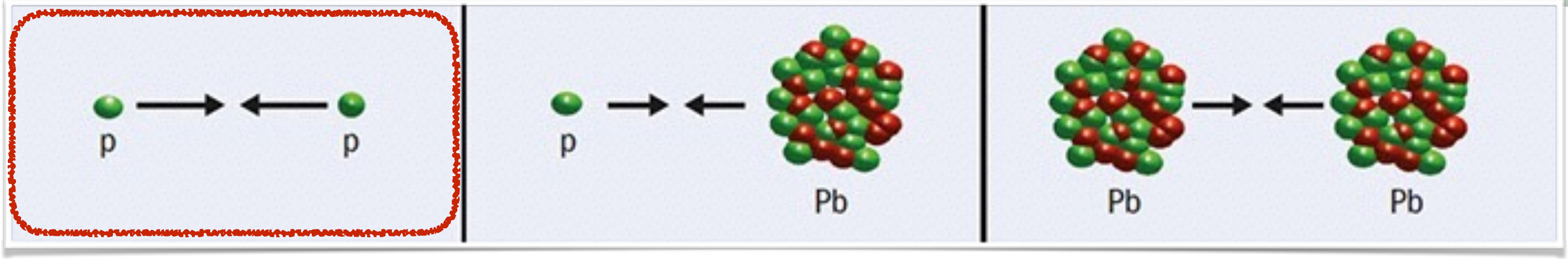
Made in India: PMD*



- ↳ The detector is optimised to study the physics of strongly interacting matter, and in particular the properties of the **Quark-Gluon Plasma (QGP).**
- ↳ Proposed in 1993 and accepted in 1997 by the LHC committee.
- ↳ Data analysis in different collisions allow us to study a variety of issues those are able to provides understanding of QCD.
- ↳ Provide excellent tracking down to low p_T and particle identification in central barrel part.



Three types of collision systems

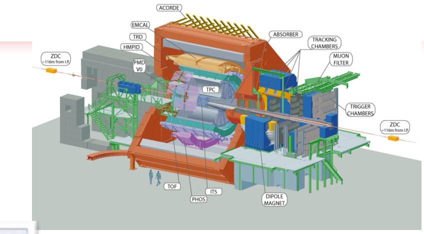


1. pp collisions (nucleon-nucleon collisions)

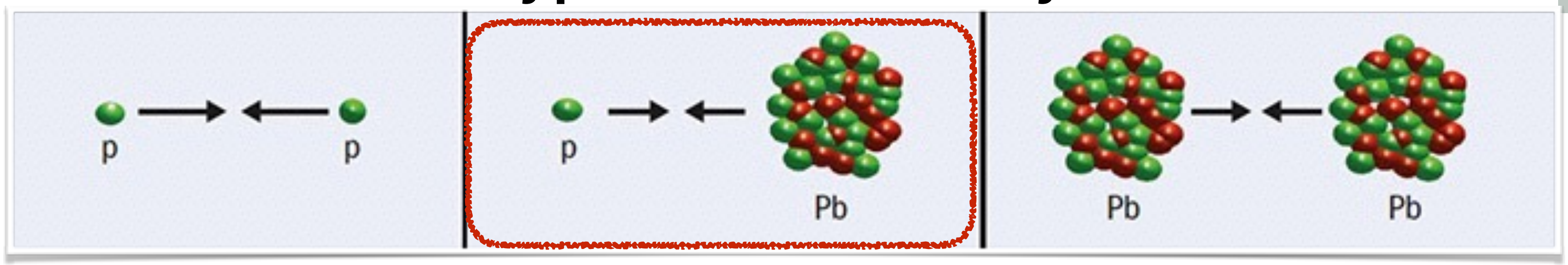
- Address plethora of issues relevant for the understanding of QCD processes
  - – **Physics from observables:** *Multiplicity, particle spectra, cross-sections, strangeness, heavy-flavours, photons and di-lepton, correlation measurements, fluctuations, quarkonia physics, and jets and so on..*
- Provide a reference or baseline for the analysis of p-Pb and Pb-Pb collisions
- High-multiplicity events allow to study several effects typically of heavy-ion phenomenology
  - – evidence of collectivity in small systems[1,2,3].

1. Khachatryan, V. et al. (CMS Collaboration). **JHEP 9, 091 (2010)**
2. Khachatryan, V. et al. (CMS Collaboration). **Phys. Lett. B 765, 193–220 (2017)**
3. ALICE Collaboration Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions. **Nature Physics 13, 535–539 (2017)**

Prelude



Three types of collision systems

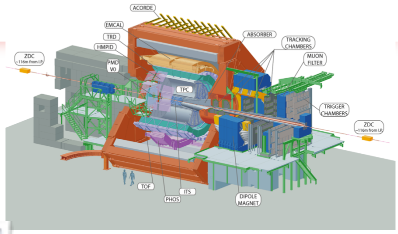


2. p-Pb collisions (nucleon-nuclei collisions)

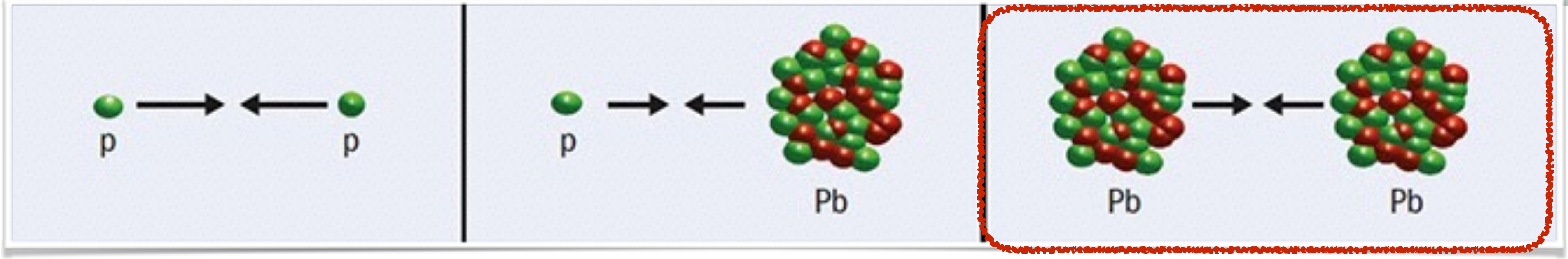
↳ Study of p-Pb collision system is important to disentangle the medium effects (in Pb-Pb collisions) from cold nuclear matter (CNM) effects in the initial and final states of the collision

↳ Reference for heavy-ion (Pb-Pb) collision measurements

↳ Study can be done by comparing physics observables measured in p-Pb collisions to that measured in Pb-Pb collisions



Three types of collision systems

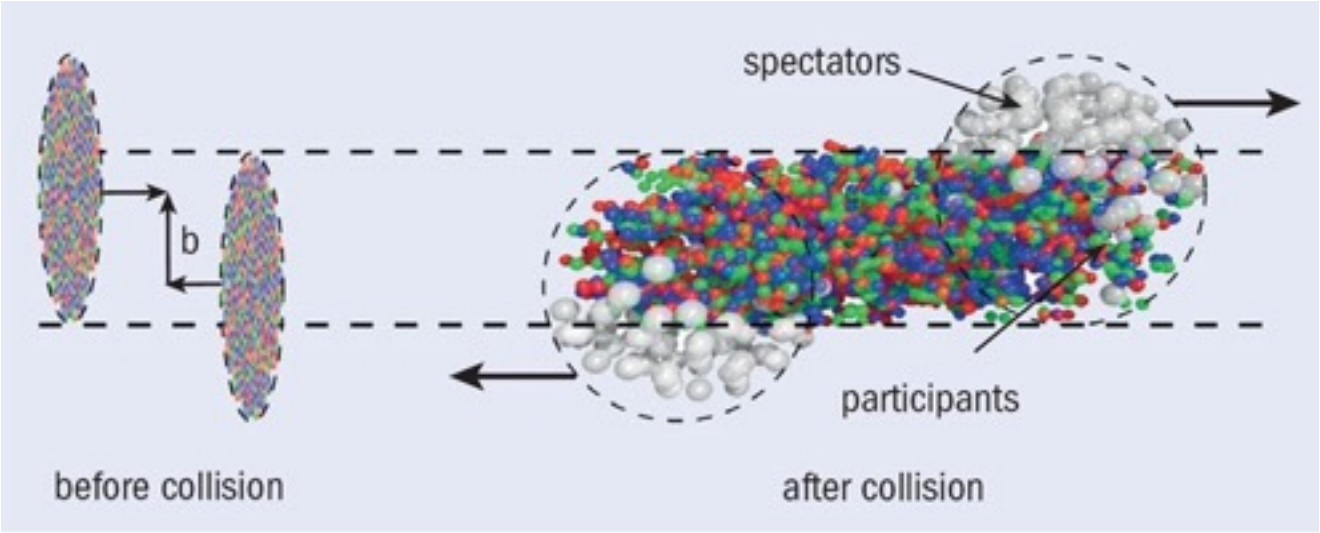


3. Pb-Pb collisions (nuclei-nuclei collisions)

↳ Using heavy-ion collision data one can address the properties of nuclear matter under extreme density and temperature., for example,

- ↳ Characterise the nature of the QCD phase diagram.
- ↳ **The Quark–Gluon Plasma (QGP):** at sufficiently high temperature and energy density, nuclear matter undergoes a transition to deconfined state of quarks and gluons.

Such an exotic state of strongly interacting QCD matter is produced in the laboratory in heavy nuclei high-energy collisions.



4. LHC.Shuryak, E. V. Quantum chromodynamics and the theory of superdense matter **Phys. Rep. 61, 71–158 (1980)**

3. Pb-Pb collisions (nuclei-nuclei collisions)

↳ **The first:** indications of the creation of a deconfined state of matter were found at the Super Proton Synchrotron (SPS) at CERN colliding Pb nuclei at 17.2 GeV.
↳ **The Second:** Relativistic Heavy-Ion Collider (RHIC) further studied by colliding Au and Cu ions at 200 GeV.
↳ .. **and then:** A remarkable step towards a deeper understanding was done at CERN in 2010 when the Large Hadron Collider (LHC) started to collide Pb nuclei at 2.76 TeV. (5.02 TeV latest).

Signature or experimental observables of QGP

↳ **Using global properties:** They can provide information on the energy density, the temperatures and collective motion.
- Particle multiplicity and energy density
- Particle spectra,
- Strangeness enhancement
- Elliptic flow and so on..

↳ **Hard probes:** Give insights into the mechanism of parton energy loss which is expected to be relevant in presence of a hot and dense deconfined medium
- Jet measurements,
- **Di-hadron correlations**
- Di-jet asymmetry,
- Nuclear modification factor and so on..

↳ **Quarkonia production**
↳ **Direct photons measurements**

Motivation

This thesis !

Measurement of D^{+}- charged hadron azimuthal correlations in pp and p-Pb collisions with ALICE

- Why Heavy-flavour measurements are special and interesting ?
- What we learn from correlations measurement (about HF-Jets, QGP or CNM effects) ?
- Recent results and discussion on **(HF) angular correlation**!

Why heavy-flavour measurement ?

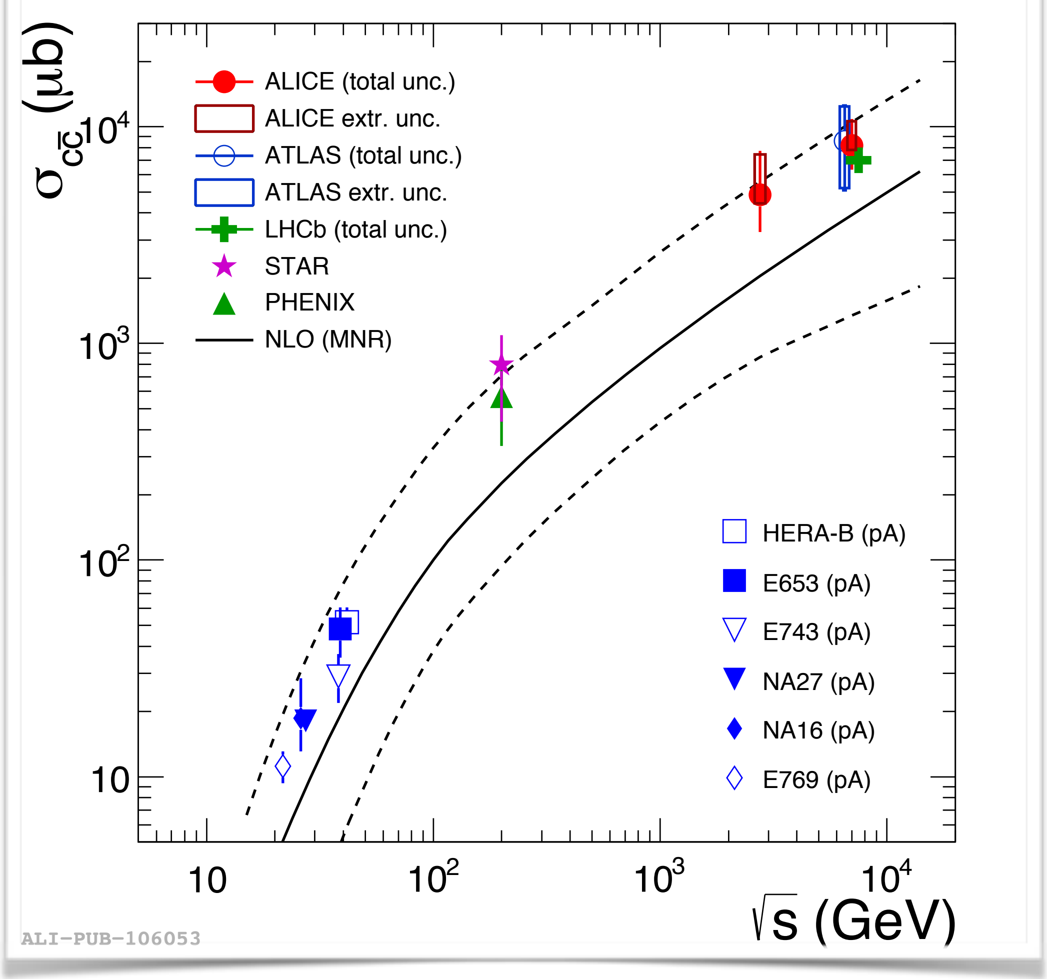
- Heavy quarks are produced in hard scatterings at the initial stage of the collision
  - ↳ They experience the complete evolution of the medium formed (**heavy-ion collisions)**
  - ↳ Tool to study the hot and dense **Quark-Gluon Plasma** (**heavy-ion collisions)**
  - ↳ Described well by pQCD calculations (**pp collisions)**

- Energy loss for heavy quarks predicted to be different from that experienced by gluons and light quarks

- At LHC energies, heavy-quark production allows one to probe the Parton Distribution Functions (PDFs) at very low values of Bjorken scale **(x ~ 10^{-4})**

- Study of p-Pb collision system is important to disentangle the medium effects from CNM effects in the initial and final states of the collision.

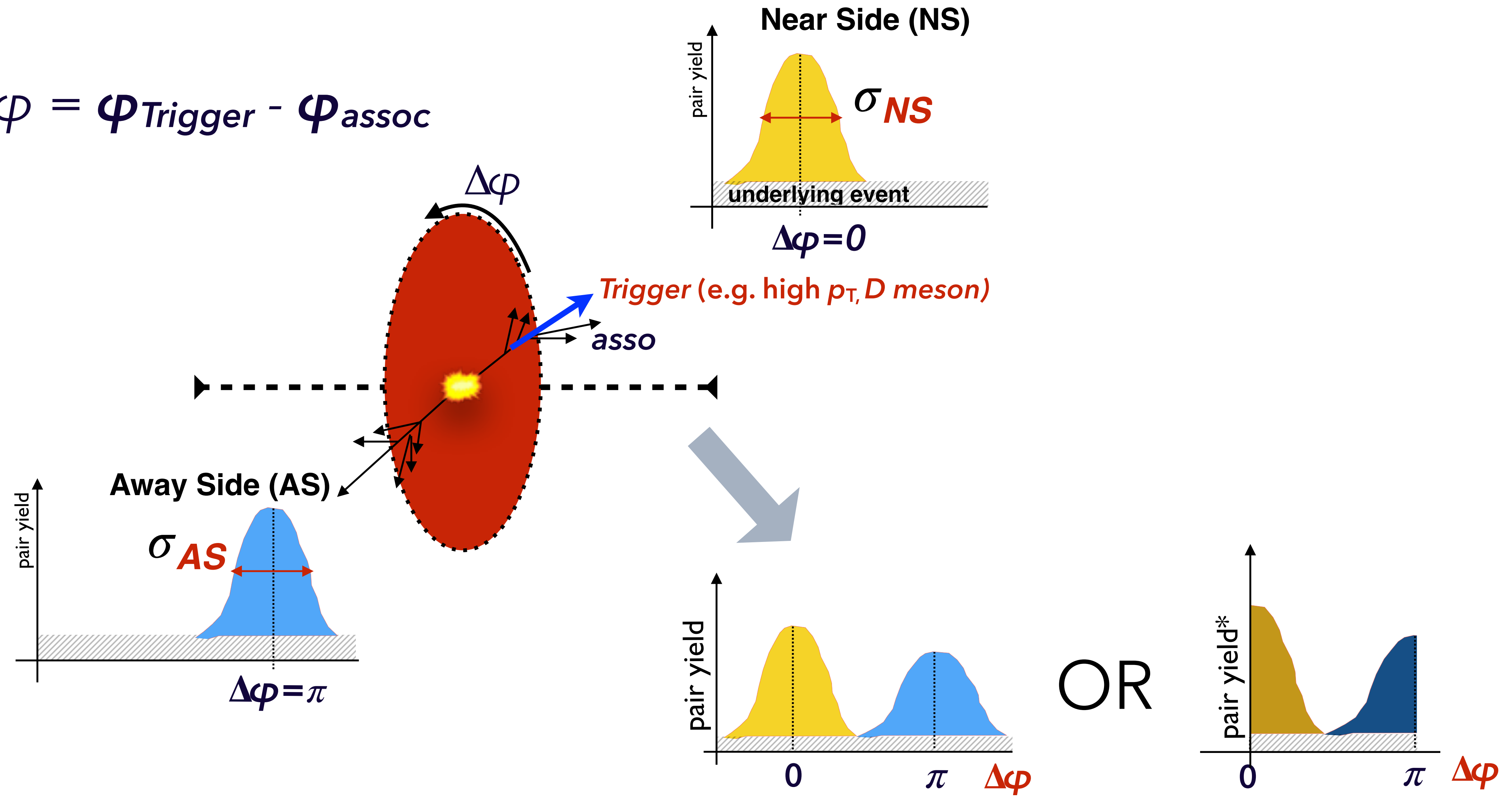
Phys. Rev. C 94, 054908 (2016)



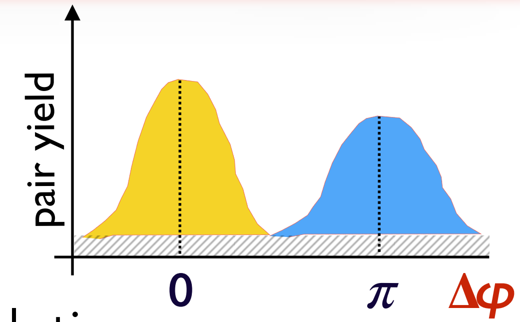
Two particle azimuthal correlations

Parton pairs are produced with back to back topology and manifest corresponding jets in back to back direction.

$$\Delta\varphi = \varphi_{Trigger} - \varphi_{assoc}$$



Note*: The topology breaks when any of the radiated gluon carrying high momenta starts producing an additional spray of hadrons or jet.



In proton-proton collision

It was proposed that the study of high-p_T particles, in particular, via angular correlations one can get information about jet production in hadron-hadron collisions[1, 2].

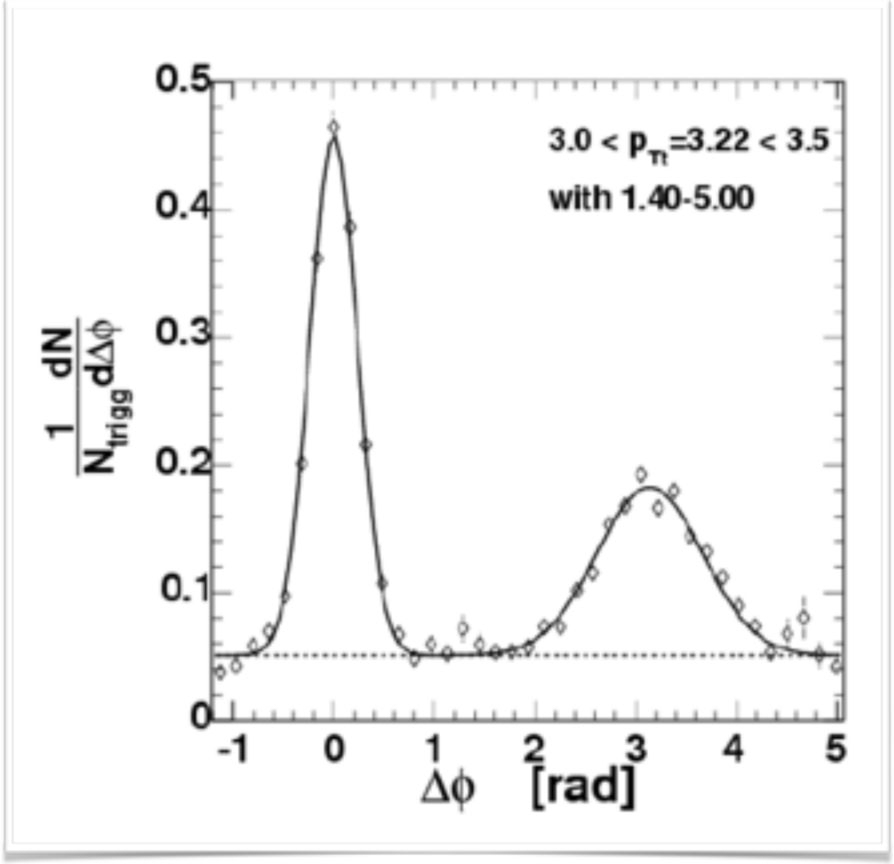
– *This later was eclipsed by the jet reconstruction algorithms.*

The First: The above proposed method first adopted by PHENIX experiment and measured angular correlations using high p_T pions (π^0) [3].

↳ Figure clearly shows angular correlations demonstrate expected jet-induced correlations.

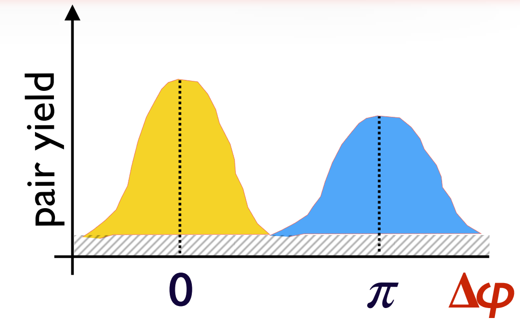
↳ PHENIX **(at RHIC)** extracted related jet kinematics and found it to be consistent with the previous jet measurements as well as with PYTHIA simulations.

↳ This measurement established that the two-particle correlation method is an indirect tool to study jet properties.



1. R.D. Field and R.P. Feynman
Phys. Rev. D 2616 (1977) 15:2590.
2. R.P. Feynman, R.D. Field and G.C. Fox
Nucl. Phys. B 65 (1977) 128:1
3. PHENIX Collaboration, S.S. Adler et al.
Phys. Rev. D 74 (2006) 072002.

Similar possibility for heavy flavours ?



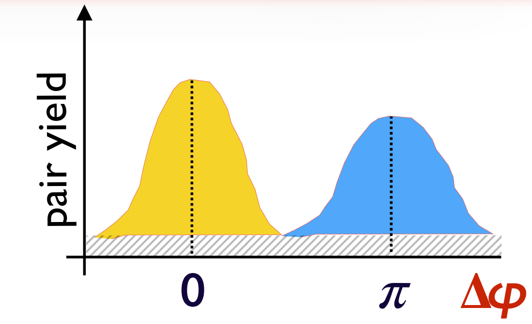
In Pb-Pb collision

↳ Partons of jets loose their energy via gluon bremsstrahlung and multiple scattering phenomena while passing through the medium.

↳ The loss in partons energies depends on their initial energy or in other words depends on the path length they travel in the medium, which can even remove the demonstration of jets, knows as ``**jet quenching**''.

$$I_{AA} = \frac{Y_{PbPb}}{Y_{pp}}$$

> 1 (x mechanism) ?
< 1 (medium effects)
= 1 (no medium effects)



In Pb-Pb collision

$$I_{AA} = \frac{Y_{PbPb}}{Y_{pp}}$$

Results from heavy-ion collision (RHIC)

The first evidence of jet quenching in heavy-ion collisions via two-particle correlation was measured by STAR collaboration in Au+Au and p+p collisions at 200 GeV [1, 2].

Highlights

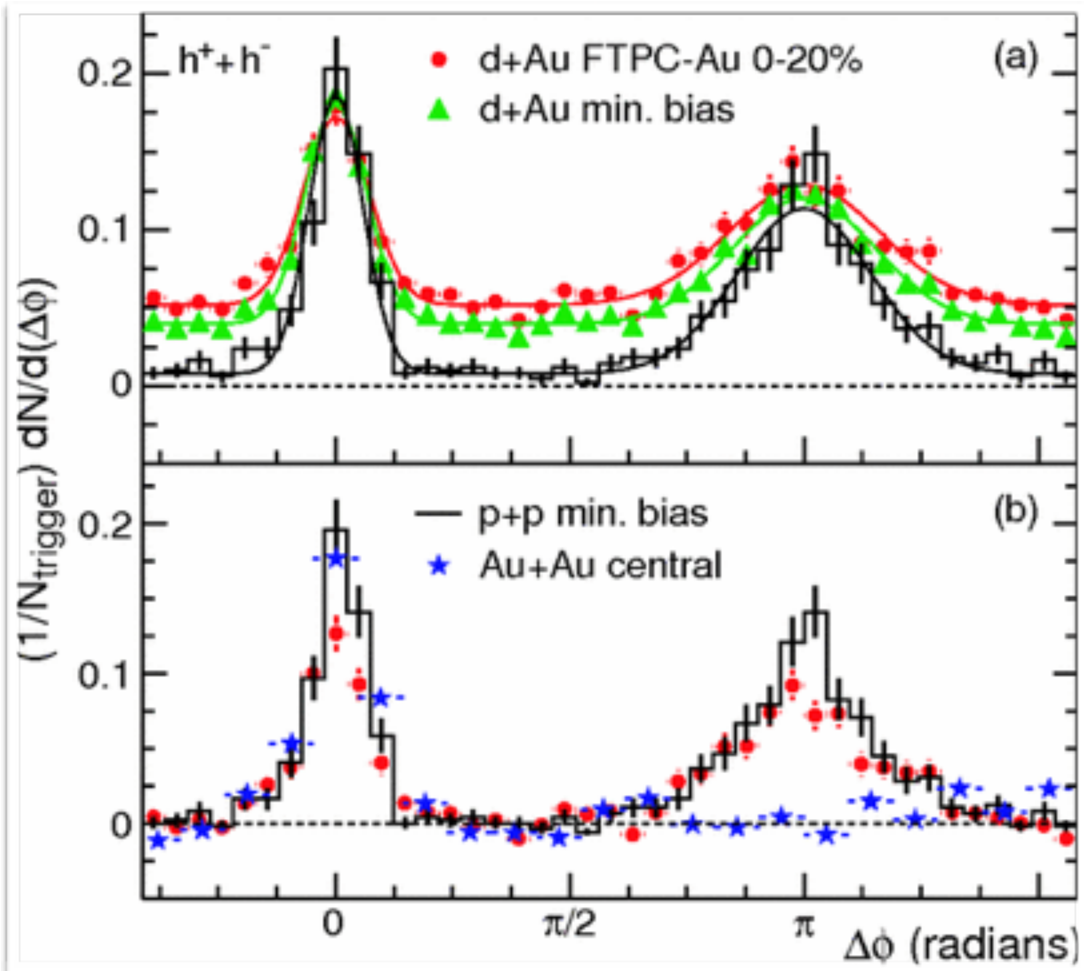
NS correlation peak have similar patterns

AS peak in Au–Au collisions dramatically disappeared

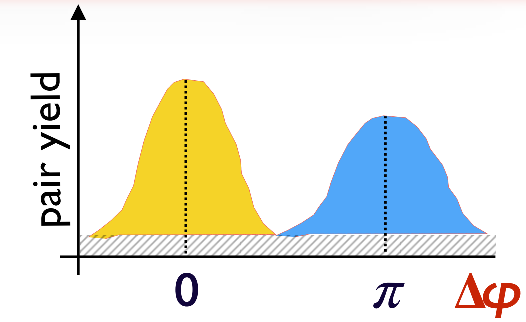
The role of initial state effects with d+Au collisions.

–enhancement in correlation baseline only

PHENIX collaboration later also measured di-hadron correlations and these two measurements at RHIC, were the first that confirmed the evidence of ***jet-quenching via two particle correlations.*** ***Phys. Rev. C 78 (2008) 014901.***



[1] STAR Collaboration, J. Adams *et al.*, Phys. Rev. Lett. **91** (2003) 072304.
[2] STAR Collaboration, C. Adler *et al.*, Phys. Rev. Lett. **90** (2003) 082302.



$$I_{AA} = \frac{Y_{PbPb}}{Y_{pp}}$$

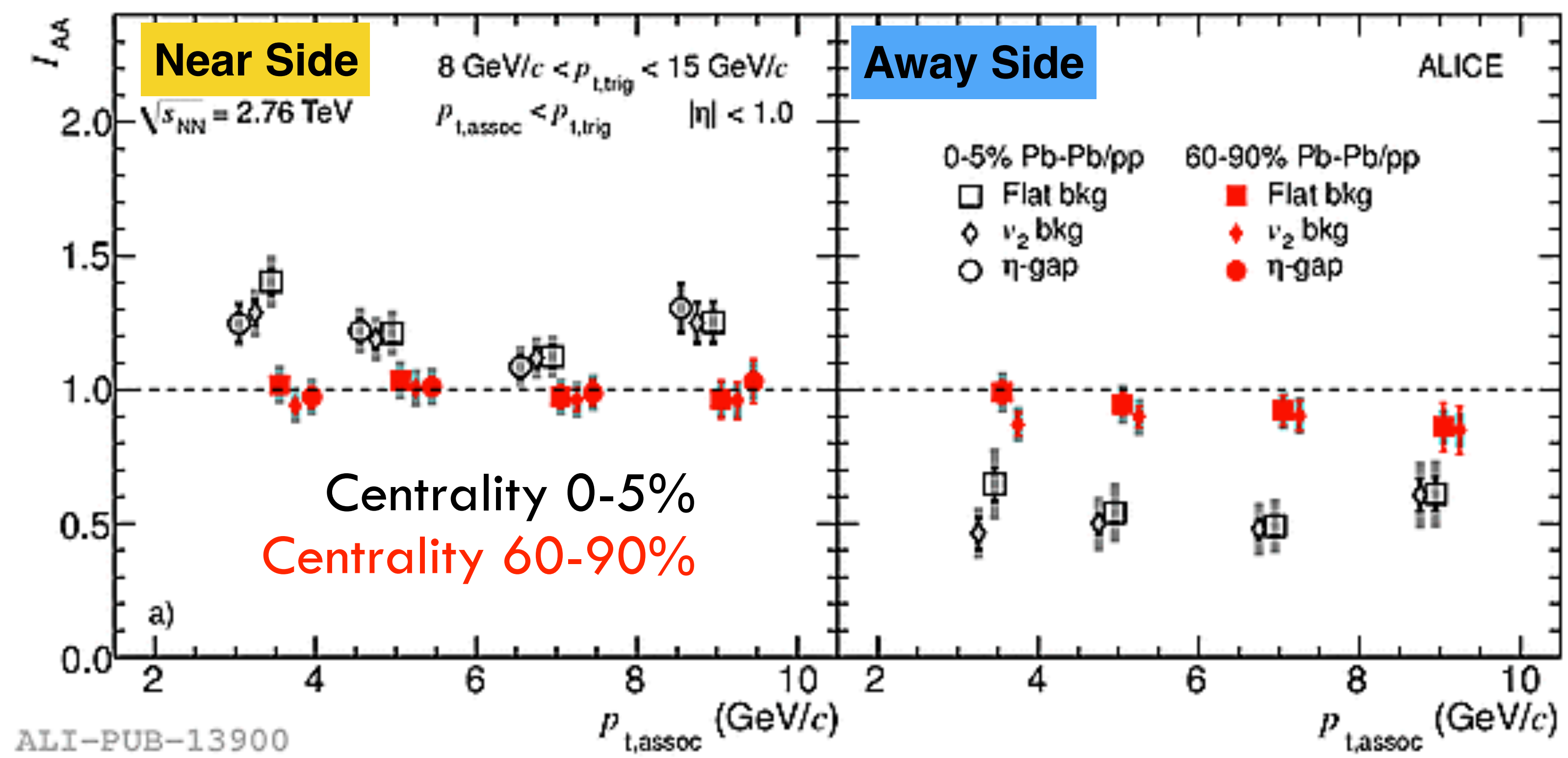
In Pb-Pb collision

Results from heavy-ion collision (LHC)

Higher beam energies in heavy ion collisions at LHC provide larger jet cross section, which allows one to study jet quenching phenomena in extended kinematic range and also with better precision.

Highlights

1) Pb-Pb collisions (0-5%)
   – NS correlation 20% enhancement
   – AS peak 50% suppression*
2) Pb-Pb collisions (60-90%)
   – NS and AS correlation are pp like

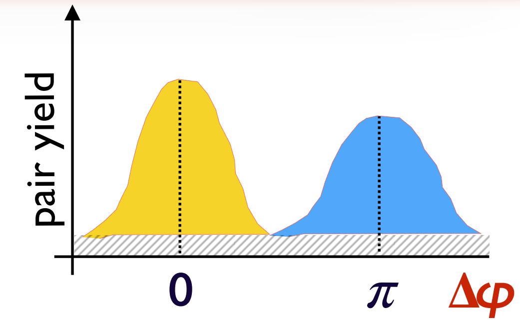


Phys. Rev. Lett. 108 (2012) 092301

I_{AA} of heavy flavours ?

[1] ALICE Collaboration, K. Aamodt *et al.*, Phys. Rev. Lett. **108** (2012) 092301

Motivation

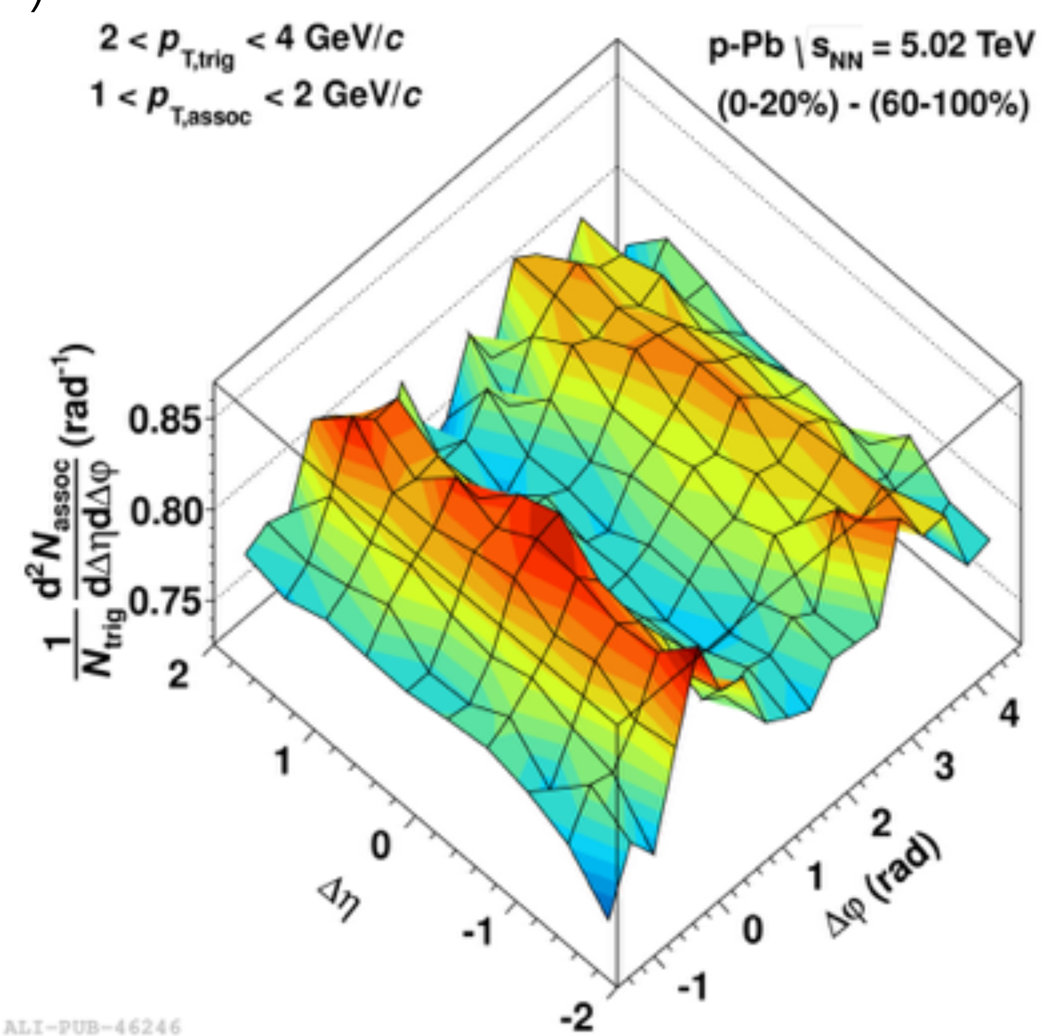


$$I_{AA} = \frac{Y_{PbPb}}{Y_{pp}}$$

In p-Pb collision

Long-range correlations in p-Pb collisions have been observed at the LHC by CMS and ALICE (CGC[1]? Hydrodynamics[2] ?)

- **ALICE: di-hadron correlations (light-flavour sector)**
  - structure may be due to collectivity or gluon saturation effects



Phys.Lett.B 719 (2013) 29-41

Similar effect present in the heavy-flavour sector ?

1) K. Dusling and R. Venugopalan, Phys. Rev. D 87 (2013) 094034
2) P. Bozek, Phys. Rev. C 85 (2012) 014911

Correlation measurement in Heavy-flavour sector

In pp collisions:

– HF-Correlation in pp provide insight into charm production and fragmentation processes.

– The study of charm-charm correlations or charm-associated particle correlations therefore, can provide information about the production mechanism of charm as well as the properties of events that contain heavy-flavour particles.

– The study of heavy-flavour correlations in pp collisions also provide necessary reference for heavy-ion measurements.

– Charm/beauty-decay electron separation[1, 2,3]

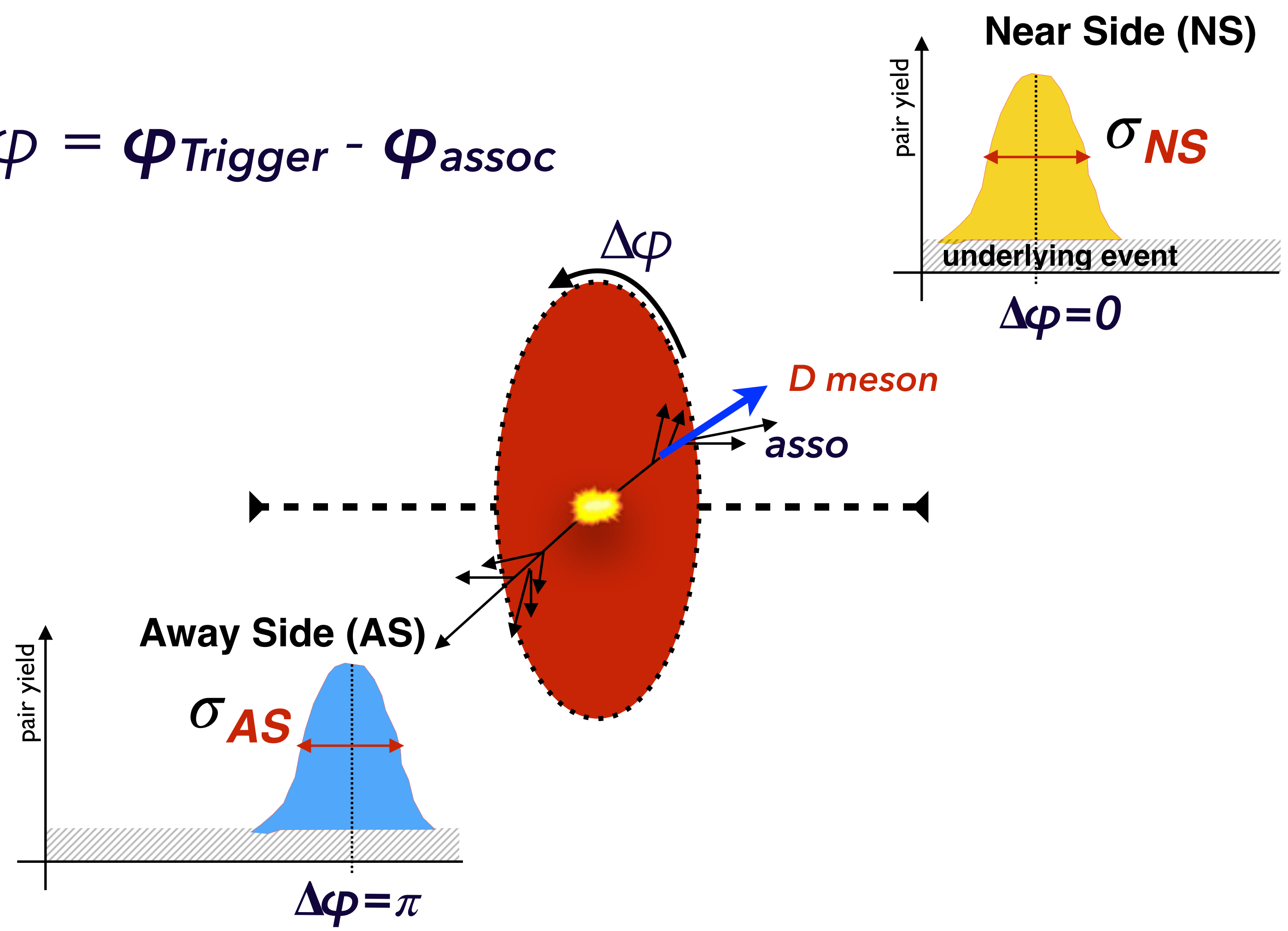
In p-Pb and Pb-Pb collisions: + CNM and medium effect in heavy-flavour sector

*LHCb collaboration measured correlation between heavy-flavour hadrons (D, λ_c) using cc and cc(bar) events in pp collisions at 7 TeV[4]. (**backup**)*

1. STAR Collaboration, M.M. Aggarwal *et al.*, Phys. Rev. Lett. **105** (2010) 202301
2. PHENIX Collaboration, A. Adare *et al.*, Phys. Rev. C **83** (2011) 044912
3. ALICE Collaboration, B. Abelev *et al.*, Phys. Lett. B **738** (2014) 97-108.
4. LHCb Collaboration, R. Aaij *et al.*, JHEP **03** (2014) 108

This Thesis : HF-Correlation

$\Delta\varphi = \varphi_{Trigger} - \varphi_{assoc}$



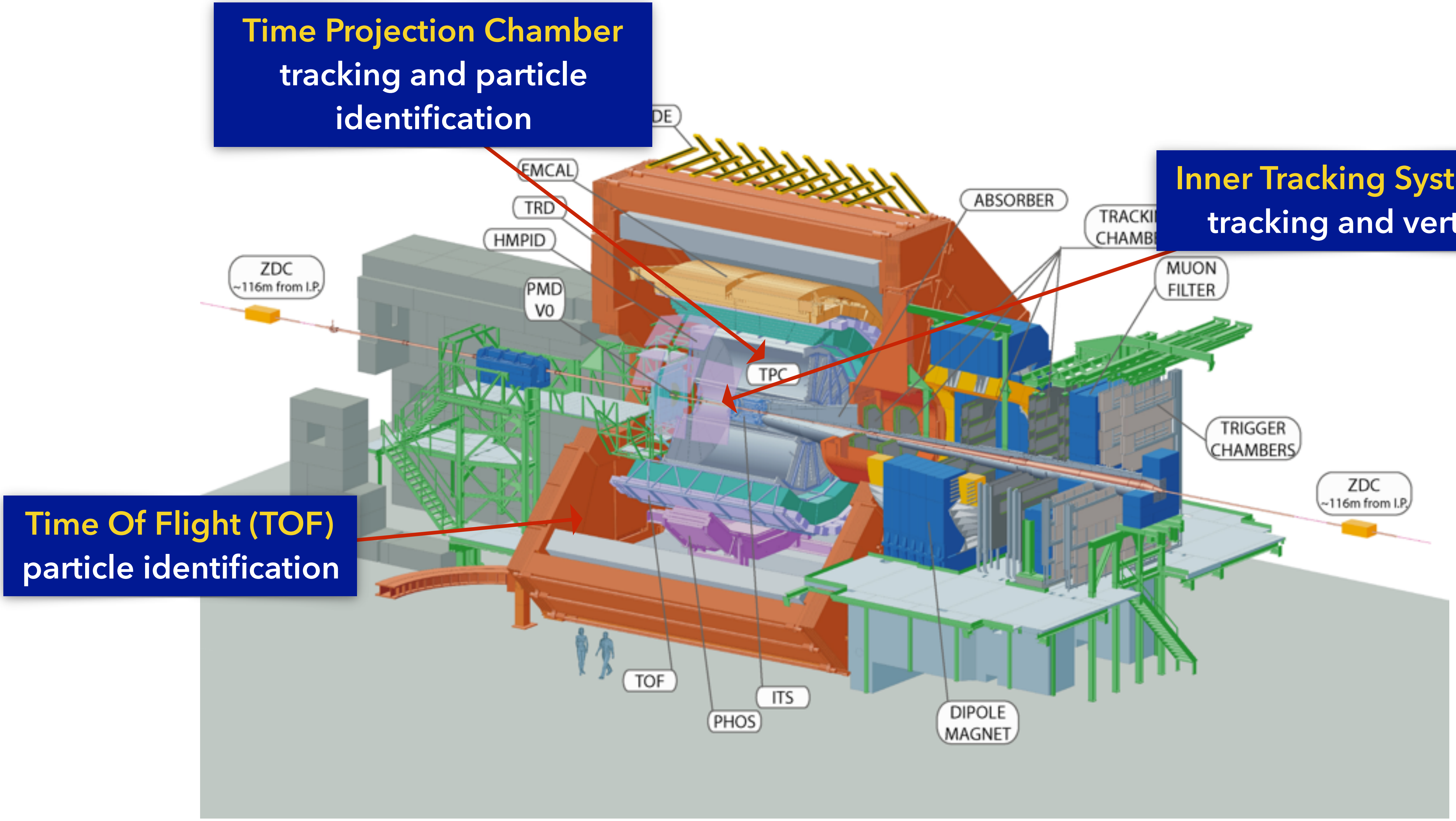
Thesis Analysis

Measurement of D^+ meson - charged hadron azimuthal correlations in pp and p-Pb collisions with ALICE at the LHC

Analysis Steps

- 1. Selection of **D^+ meson (done via invariant mass analysis)** [p_T = 3-16 GeV/c]
- 2. Selection of **charged hadron** [p_T > 0.3, 1.0 and 0.3-10 GeV/c]
- 3. 2D Correlations in **$\Delta\varphi = \varphi_{D^+} - \varphi_{assoc}$** and **$\Delta\eta = \eta_{D^+} - \eta_{assoc}$**
- 4. Removing **correlation background** (explained in detail later)
- 5. **Correction** for various sources (explained in detail later)
- 6. **Final correlation** in 1D projection: **$\Delta\varphi = \varphi_{D^+} - \varphi_{assoc}$** and fits for **quantities.**

ALICE Detector



DATA samples

p-p collisions, $\sqrt{s}$ = 7.0 TeV, 3.0 x10^8 minimum-bias trigger (2010 sample)

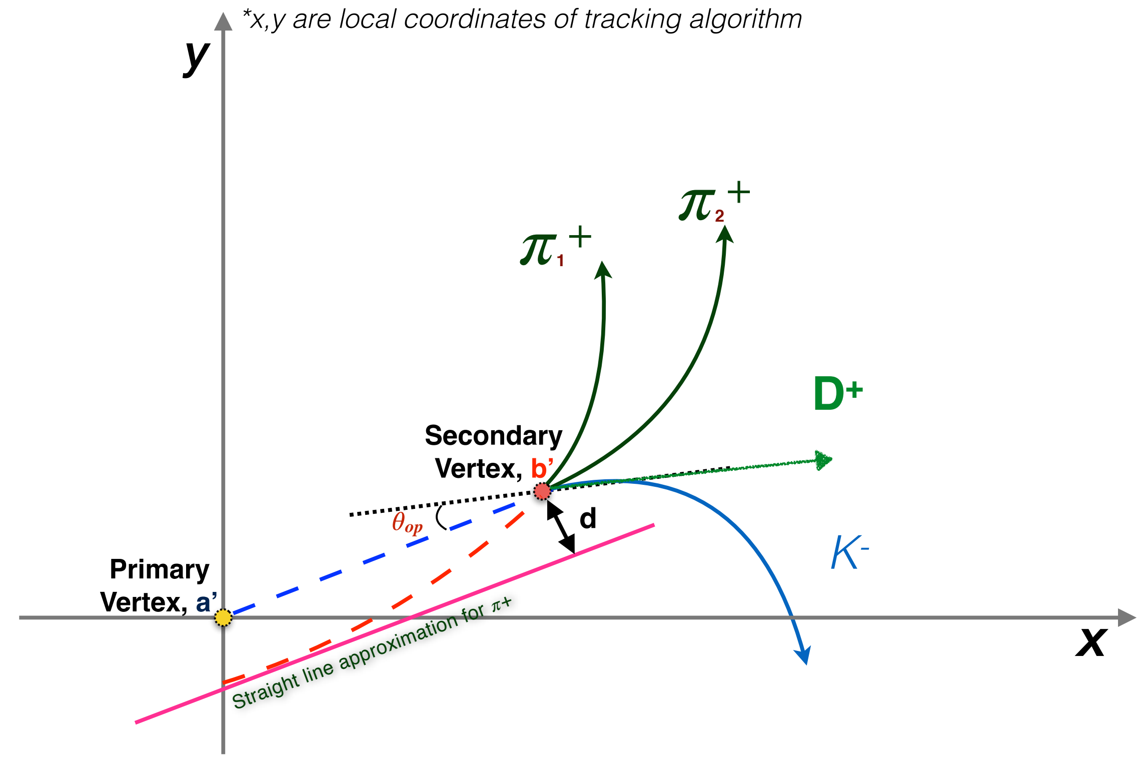
p-Pb collisions, $\sqrt{s_{NN}}$ = 5.02 TeV, 1.0 x10^8 minimum-bias trigger (2013 sample)

Analysis Methods

Step 1

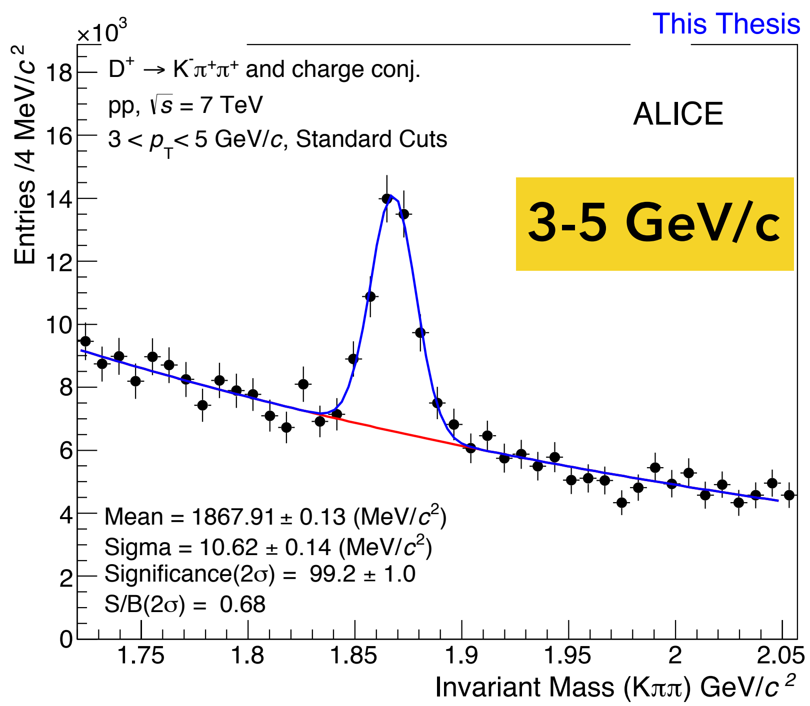
D^+ selection and signal extraction

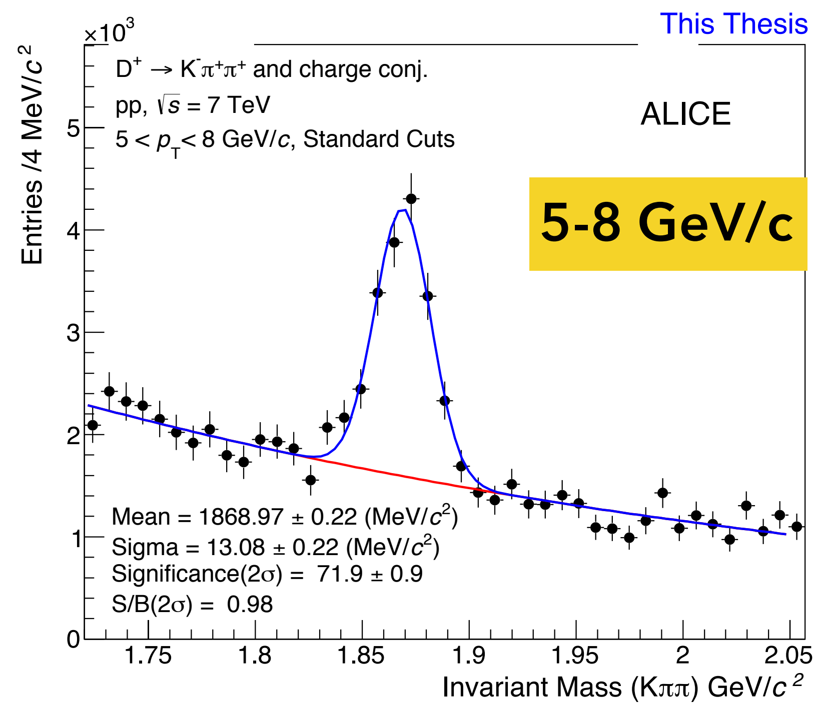
- Invariant mass analysis via hadronic decay channel
- Selection of displaced-vertex topologies
- PID on decay products

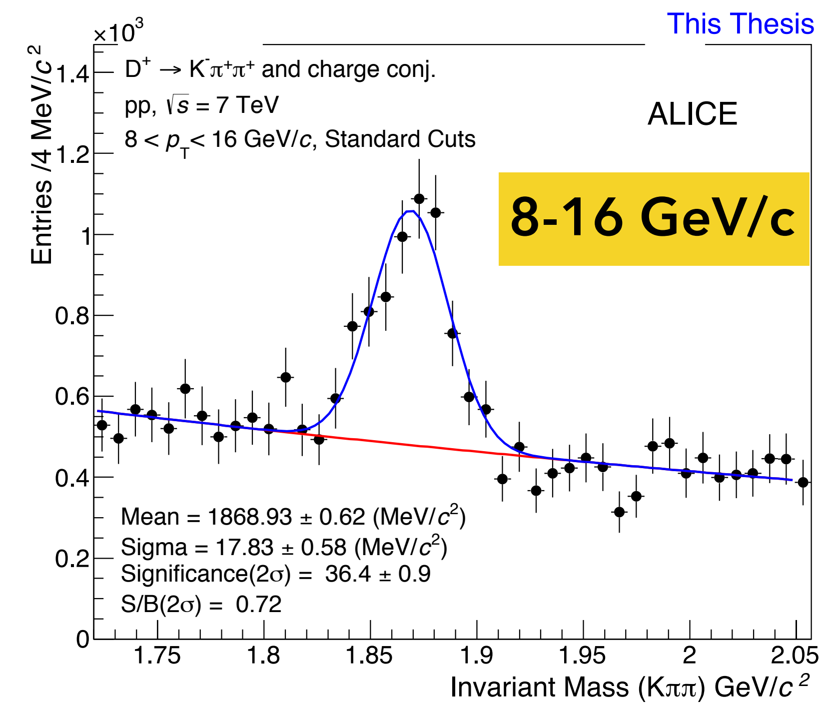


Decay channel	Branching ratio
$D^+ \rightarrow K^- \pi^+ \pi^+$	$9.13 \pm 0.19\%$

pp collision at 7 TeV

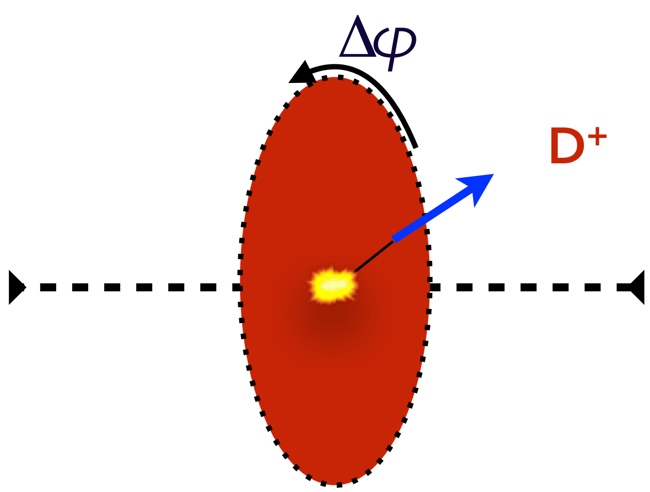


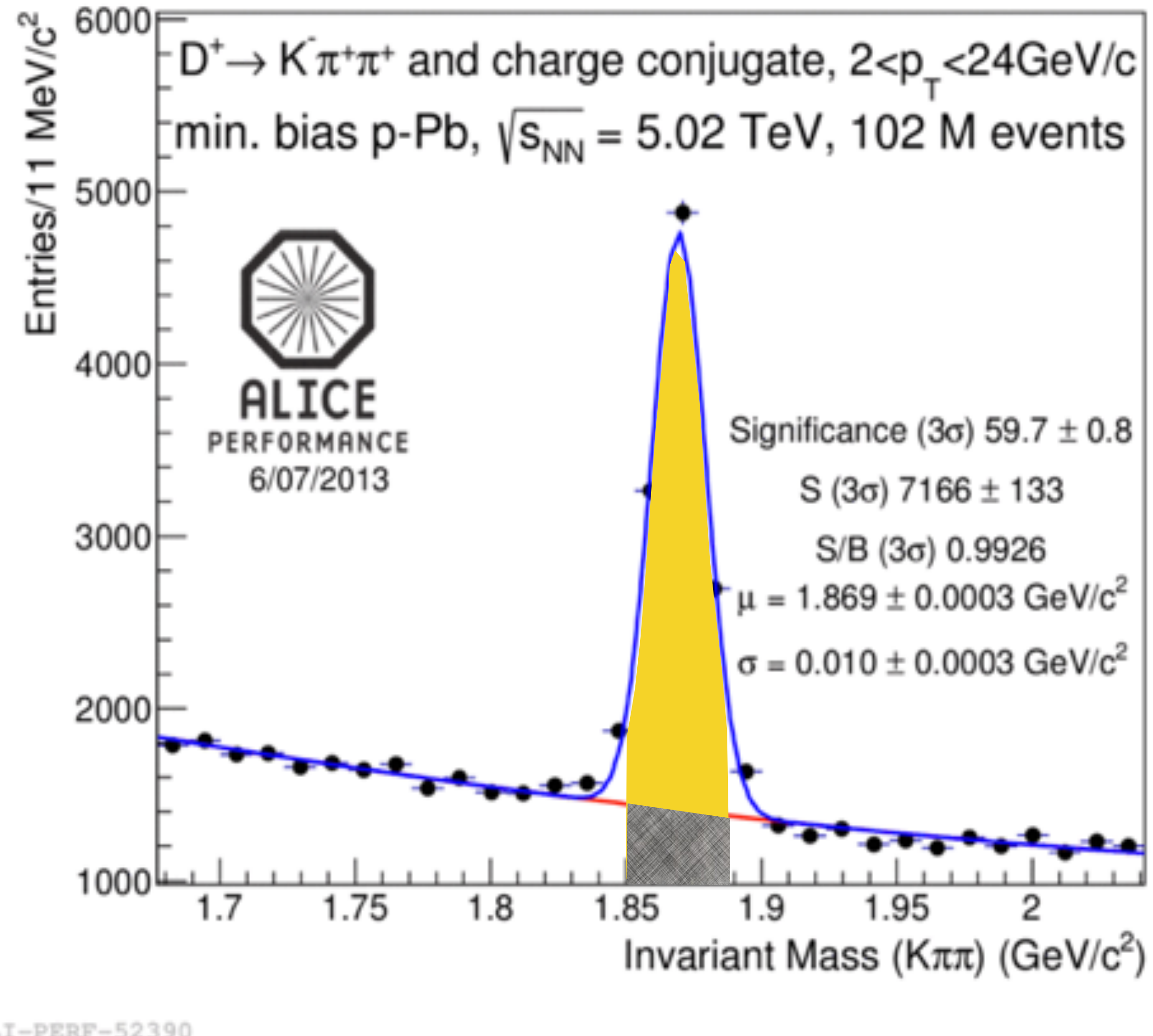




p-Pb collision at 5.02 TeV + w/ efficiency correction in backup

D⁺ selection and signal extraction

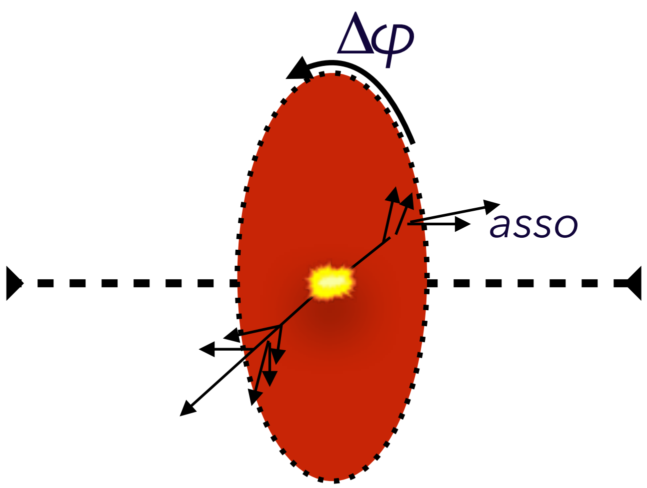




Way to build correlation using D^+ signal only (or background removal)

Calculate $\Delta\varphi$ **(±3σ)** in signal region and use sideband (left and right part) for background correlation and remove them from signal region (**"Side Band Subtraction"** method).

Associated Charged Track Selection

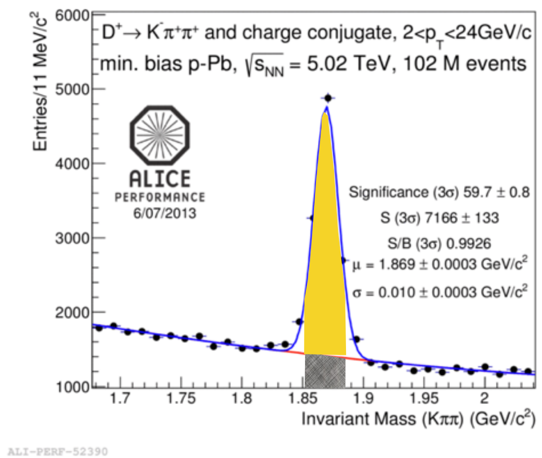


Track Cut Type	Set1 Value (Std)	Set2 Value	Set3 Value
SigmaToVertex	kFALSE	kFALSE	kFALSE
RequireITSRefit	kFALSE	kFALSE	kTRUE
RequireTPCRefit	kTRUE	kTRUE	kTRUE
MinNClustersITS (Min)	3	0	3
MinNClustersTPC (Min)	70	70	70
Chi2PerClusterTPC (Max)	4	4	4
DCAToVertexZ (Max)	1.0	1.0	1.0
DCAToVertexXY (Max)	0.25	0.25	0.25
SPDClusterRequire	No	No	Yes

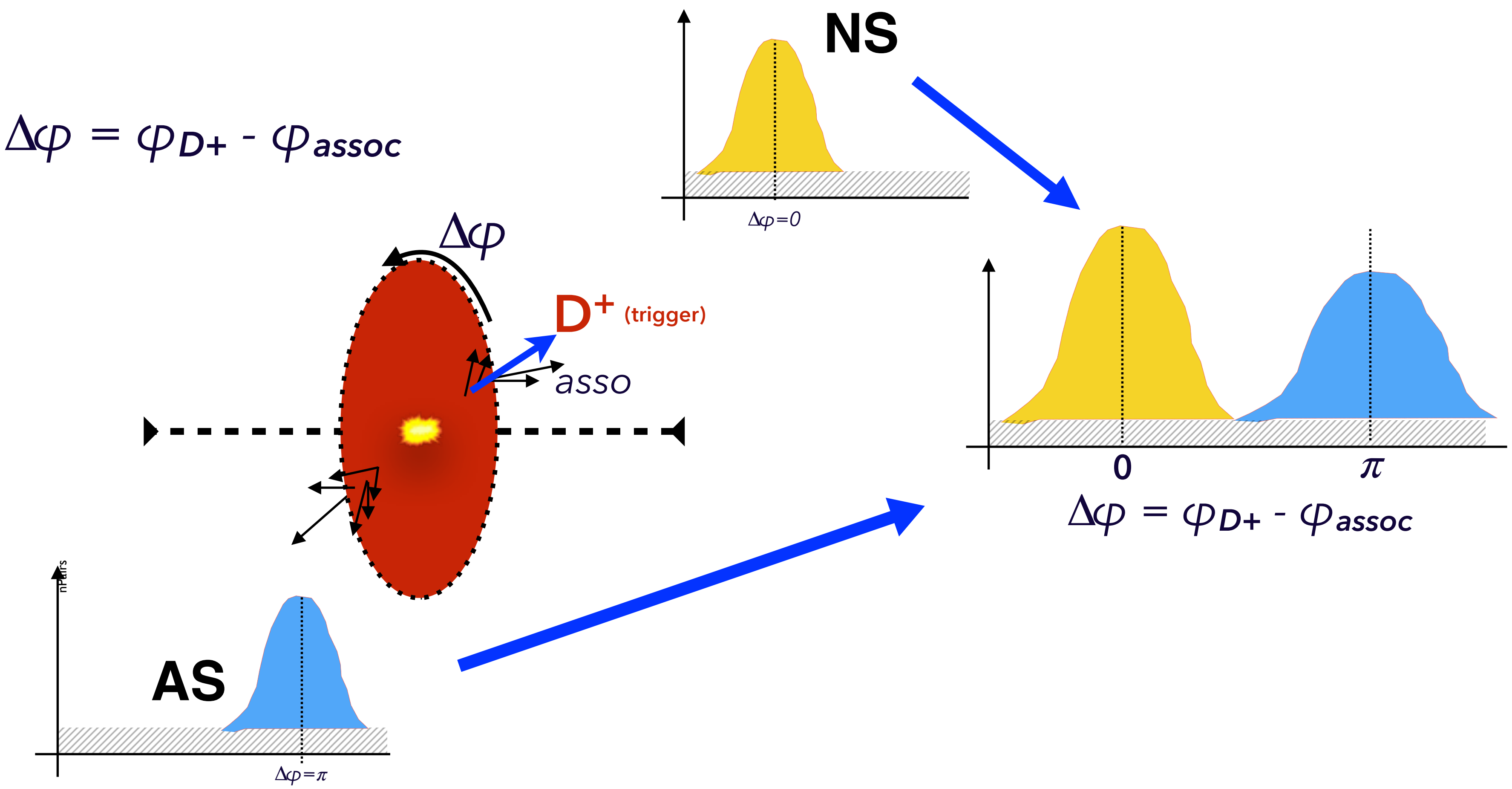
Analysis Methods

Step 3

Raw Azimuthal Correlations ($\Delta\varphi$-$\Delta\eta$) – D^+ and charged particles



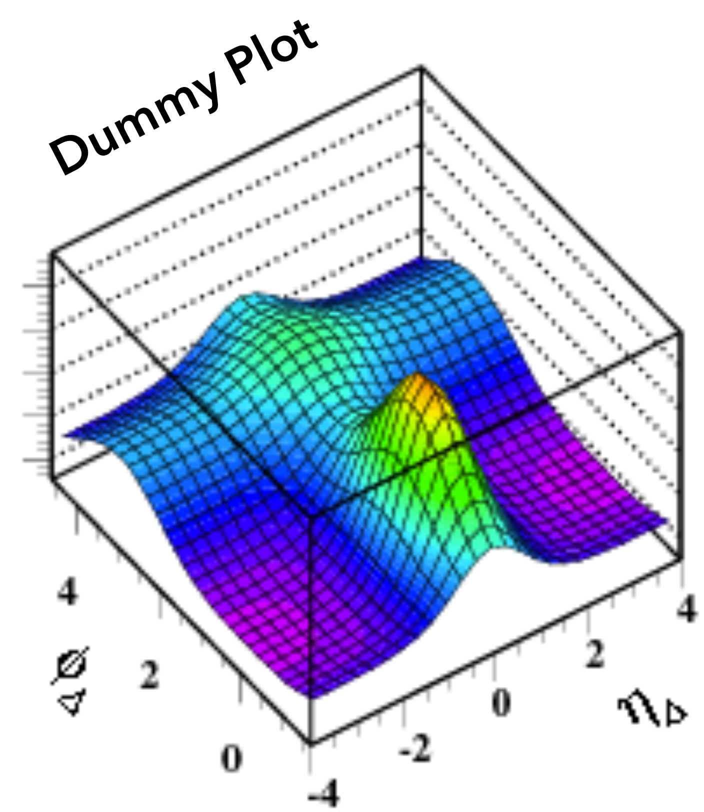
$\Delta\varphi = \varphi_{D+} - \varphi_{assoc}$



$\Delta\varphi = \varphi_{D+} - \varphi_{assoc}$

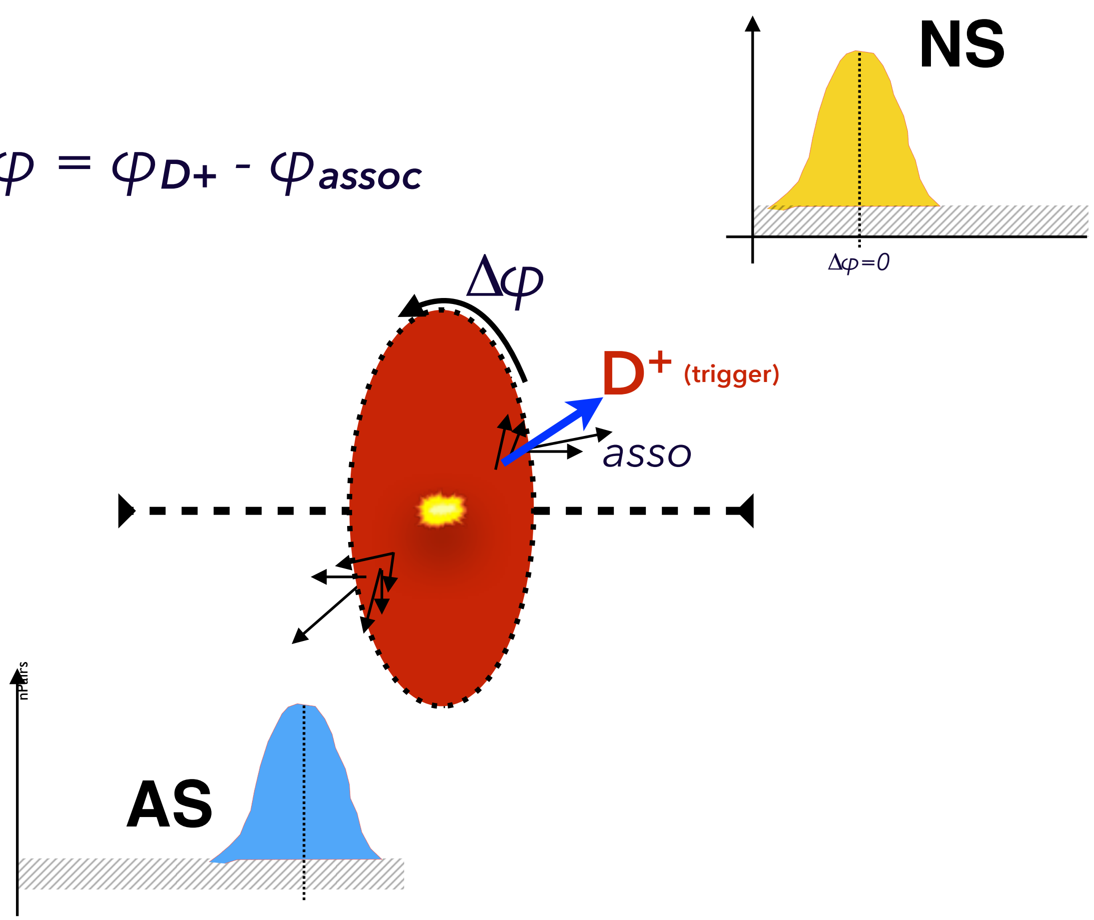
$\Delta\varphi = \varphi_{D+} - \varphi_{assoc}$

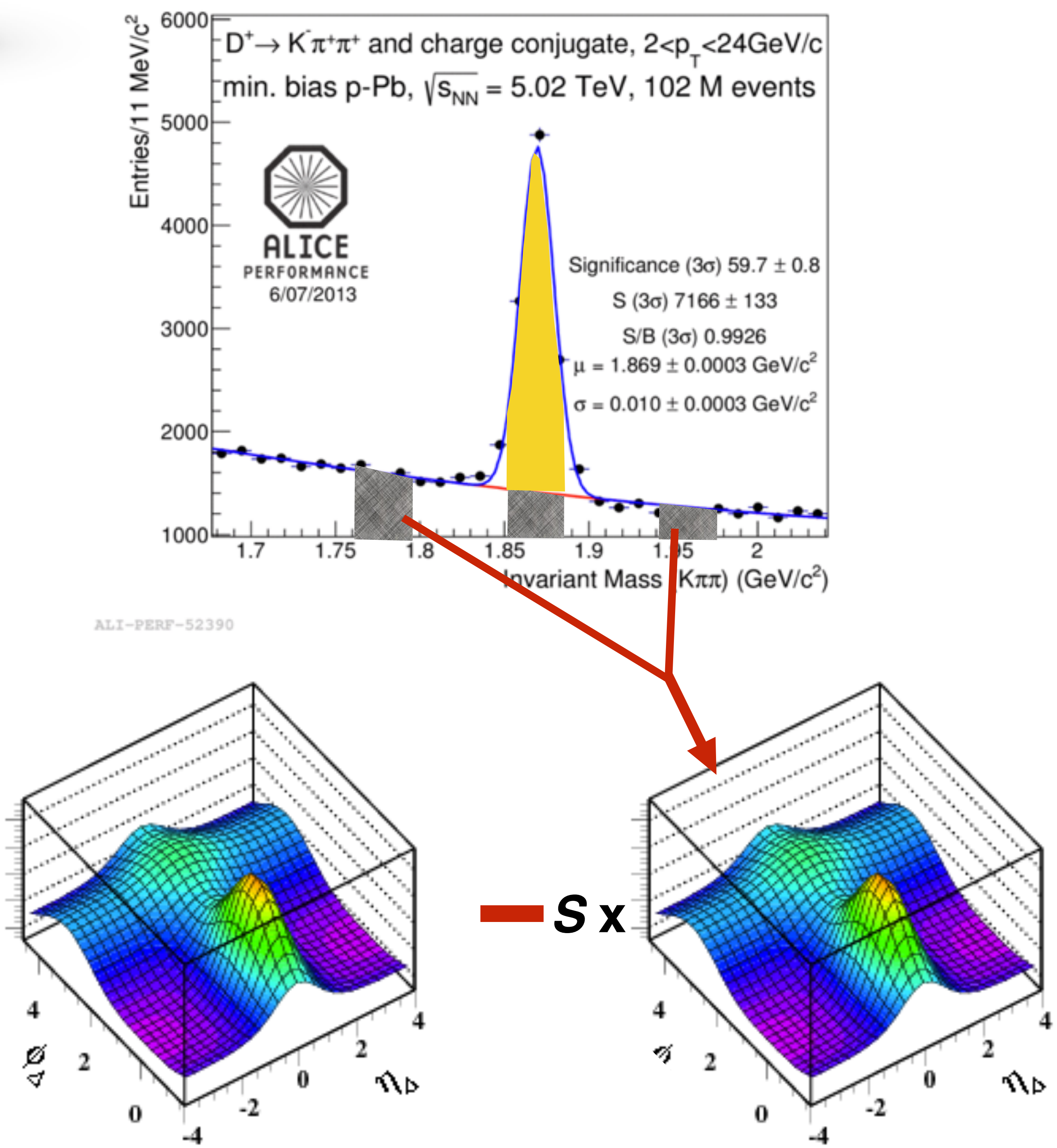
$\Delta\eta = \eta_{D+} - \eta_{assoc}$



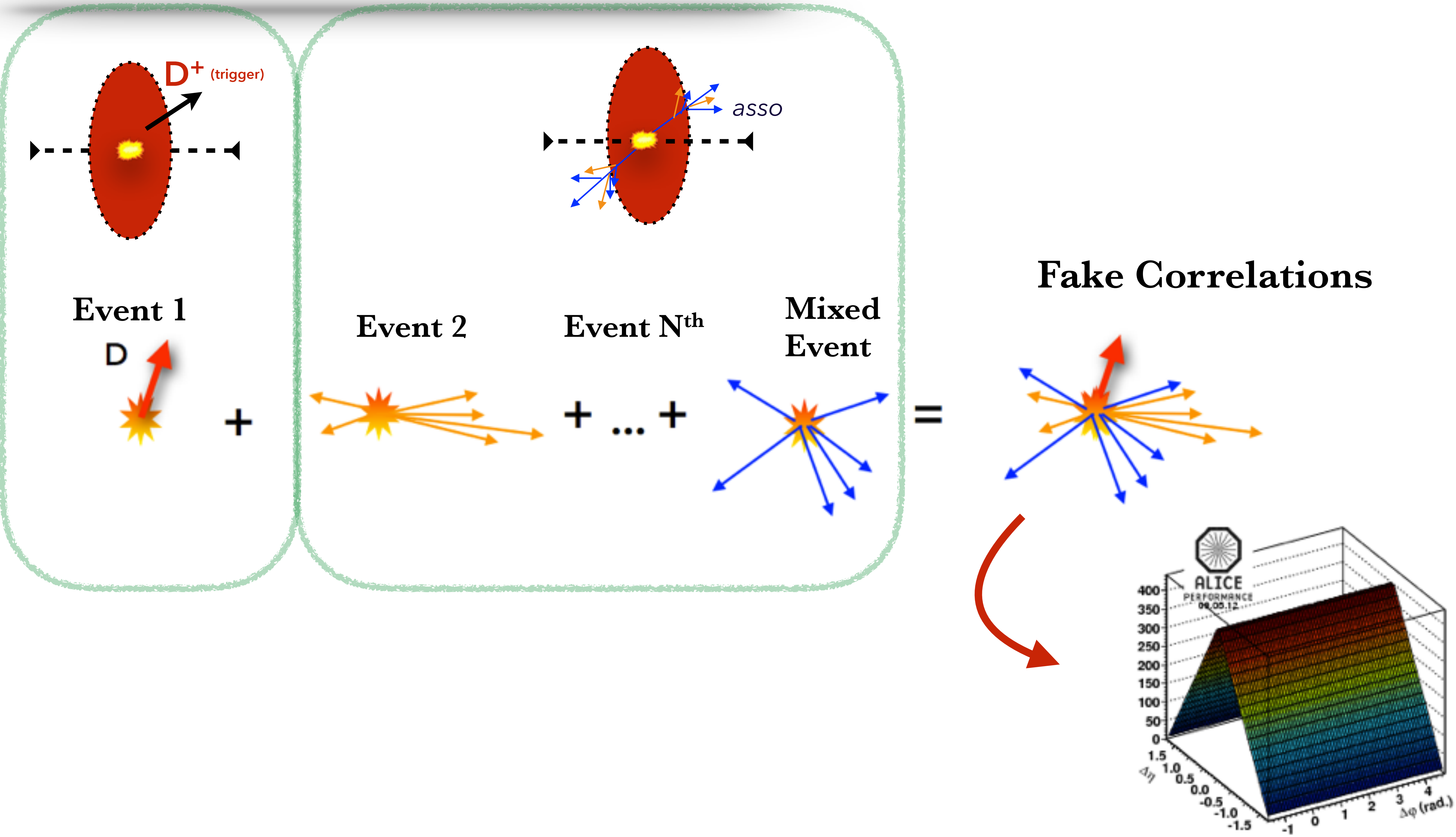
Background subtraction (Δφ-Δη) – D⁺ and charged particles

$\Delta\varphi = \varphi_{D+} - \varphi_{assoc}$



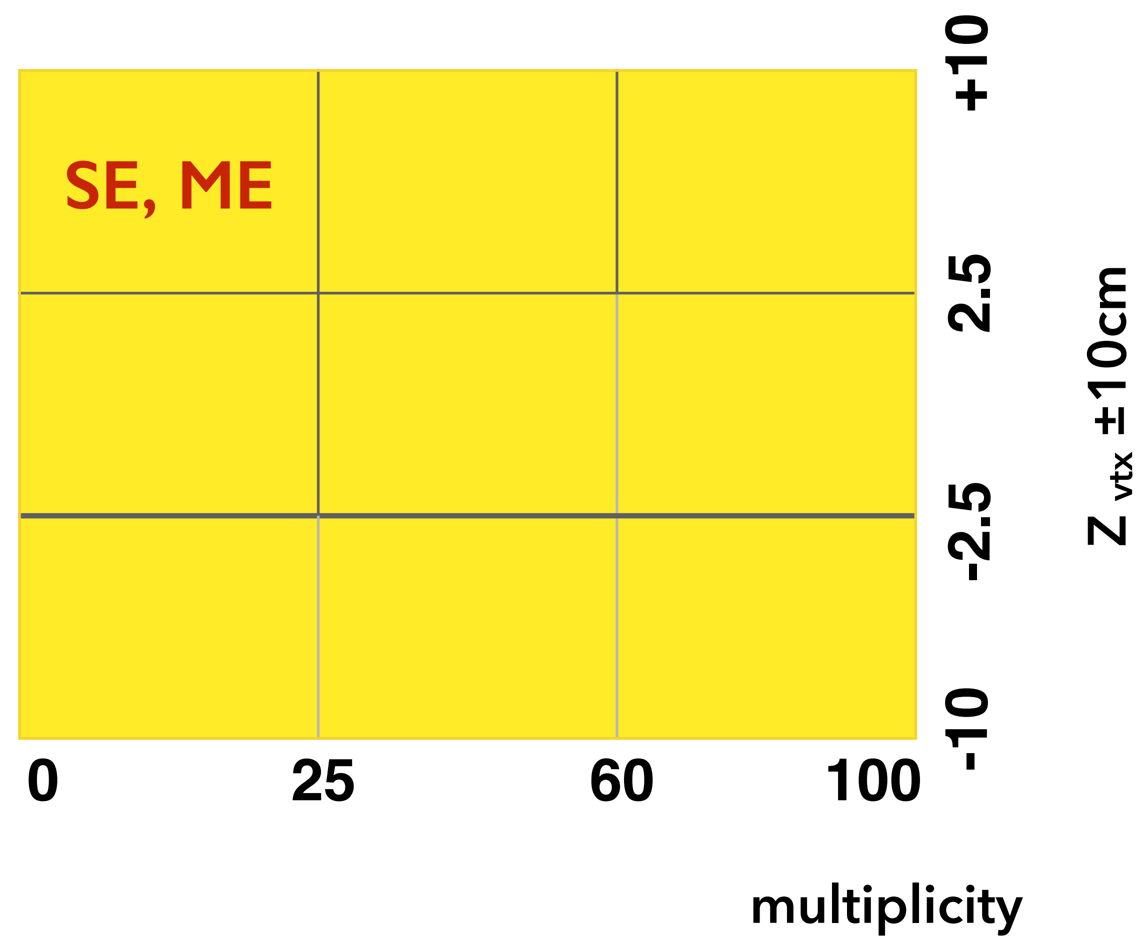


Detector acceptance and inhomogeneity – via Mixed Event



Detector acceptance and inhomogeneity – via Mixed Event

Event Pool =



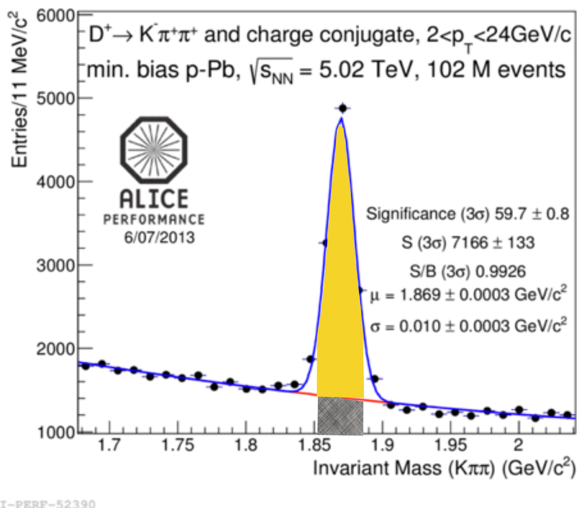
Method

$$fCorr^{2D} = \frac{1}{N_{trig}} \sum_{i=0}^{nPool} \frac{SE_i^{2D}}{\frac{1}{norm} ME_i^{2D}}$$

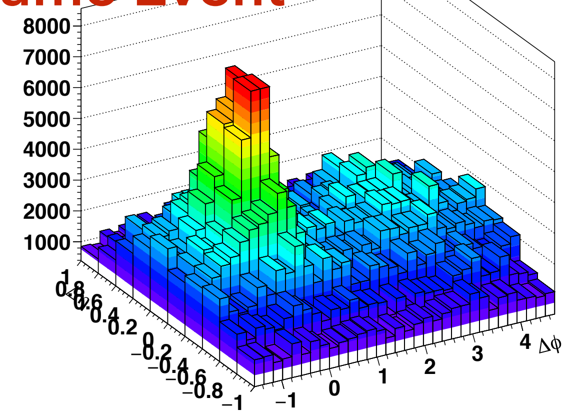
Analysis Methods

Step 5

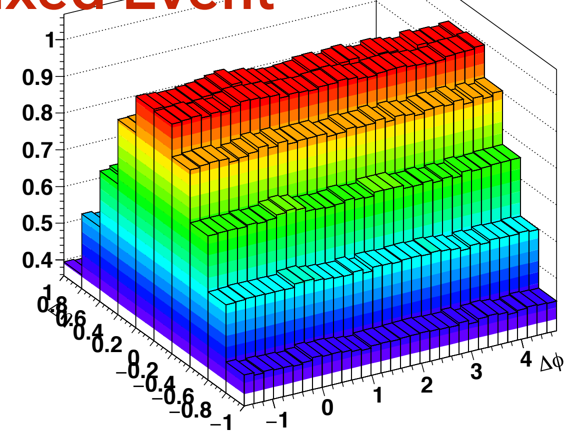
Signal+Background	Sidebands(background)	**Signal Only**



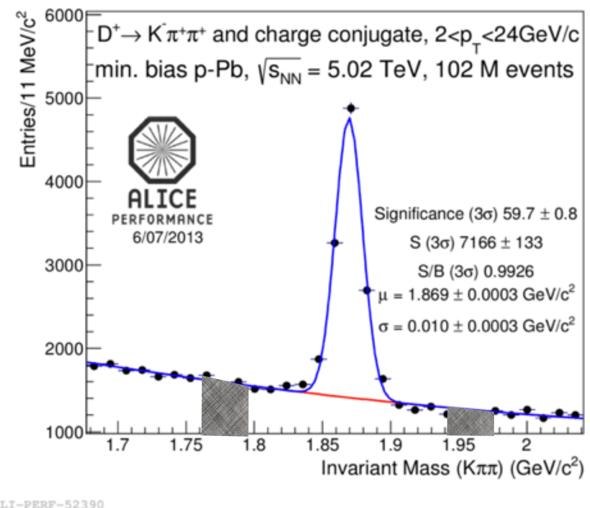
Same Event



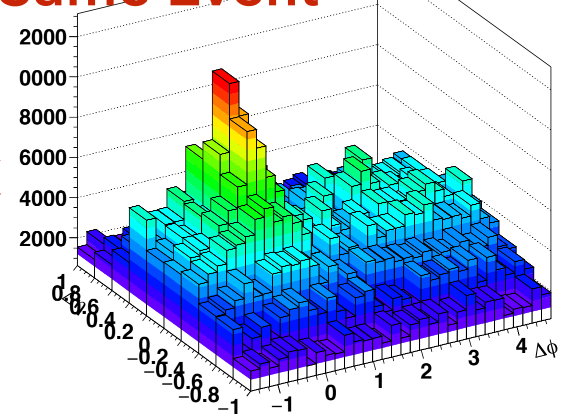
Mixed Event



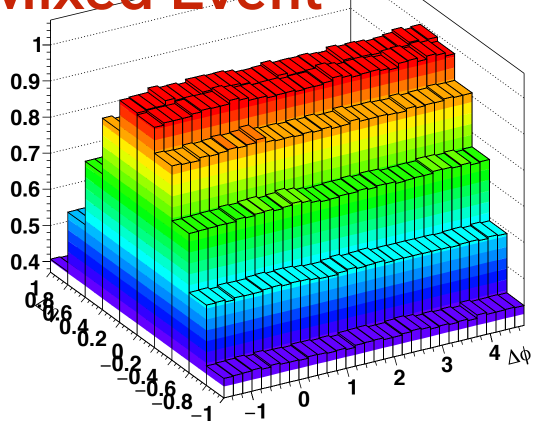
− *S* x

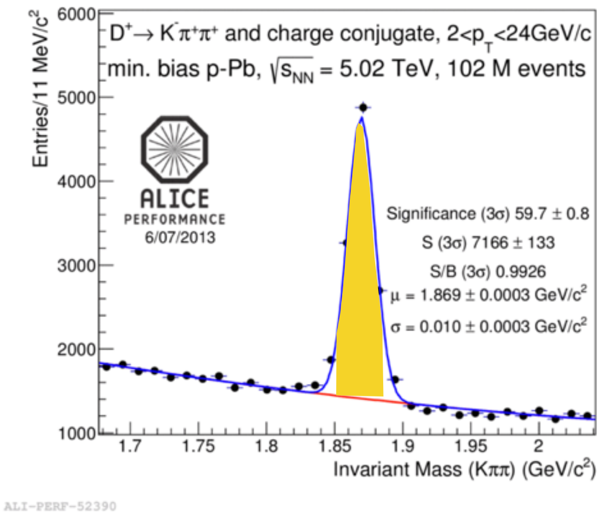


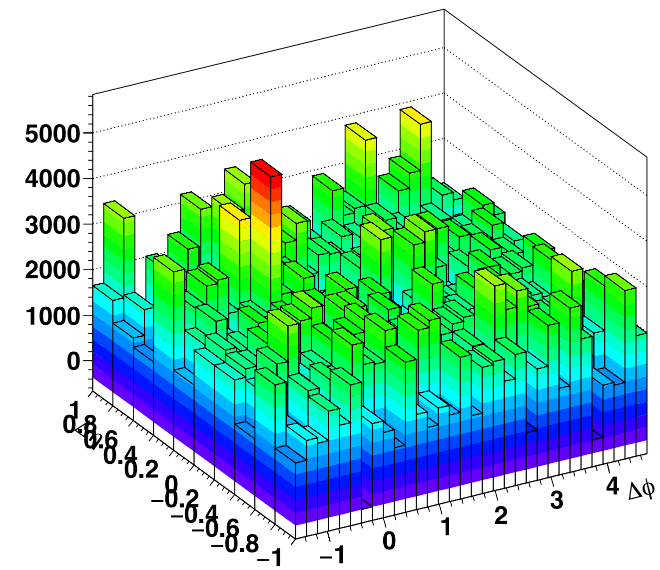
Same Event



Mixed Event



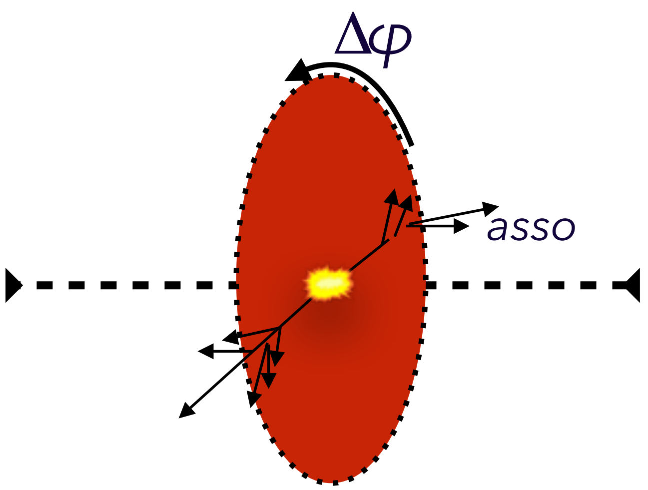


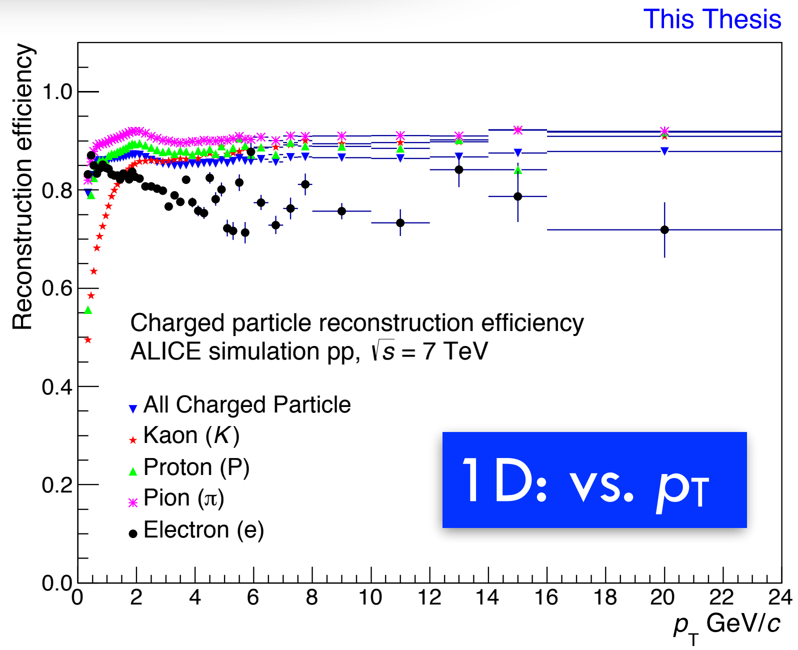


Correction #1.

Analysis Methods

Associated and trigger particle efficiency – efficiency correction



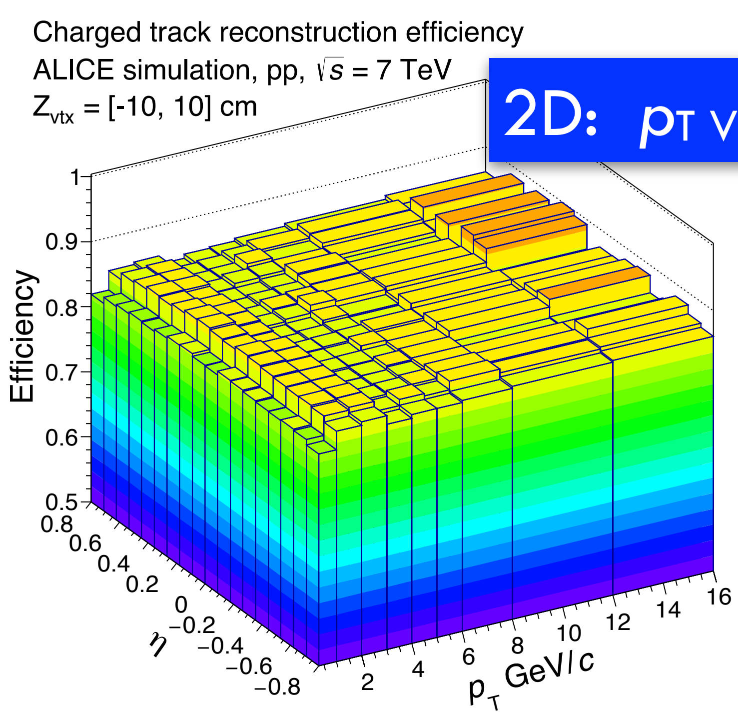


1D: vs. p_T

Used in analysis

3D: p_T Vs. Zvtx vs Eta

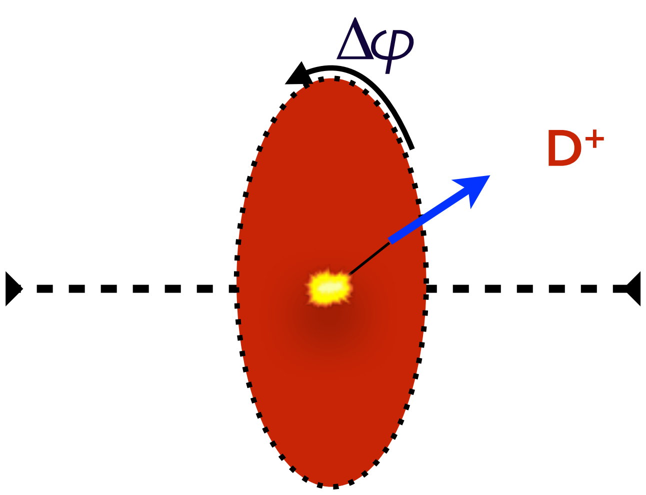
$$\epsilon_{N^{part}} = \frac{N^{part}_{reconstructed}}{N^{part}_{generated}}$$

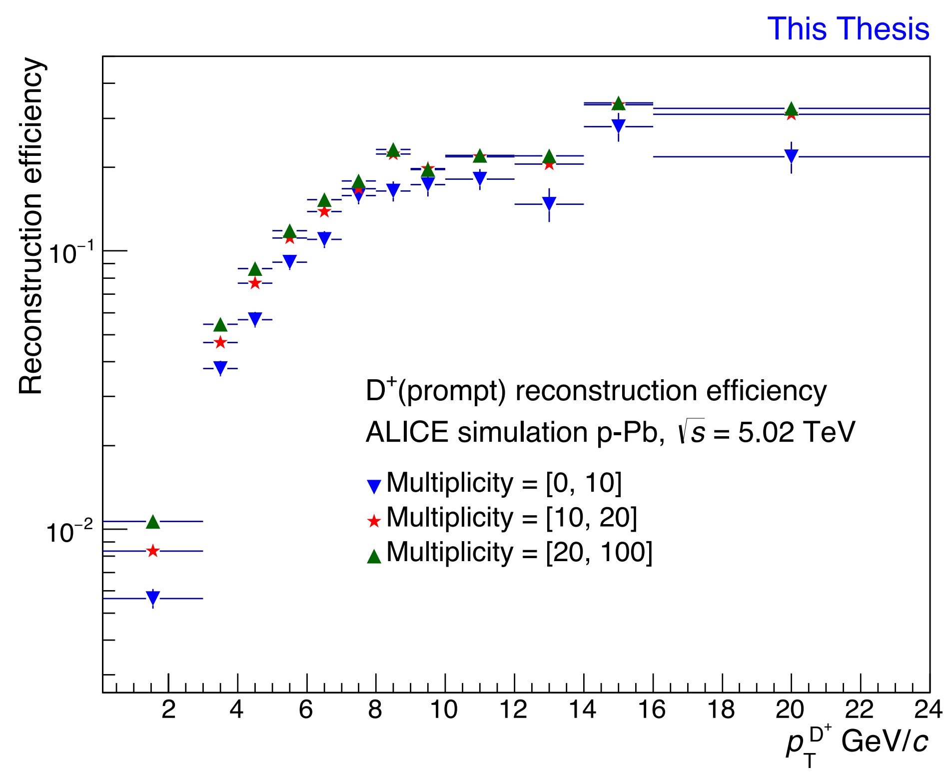


2D: p_T Vs. Eta

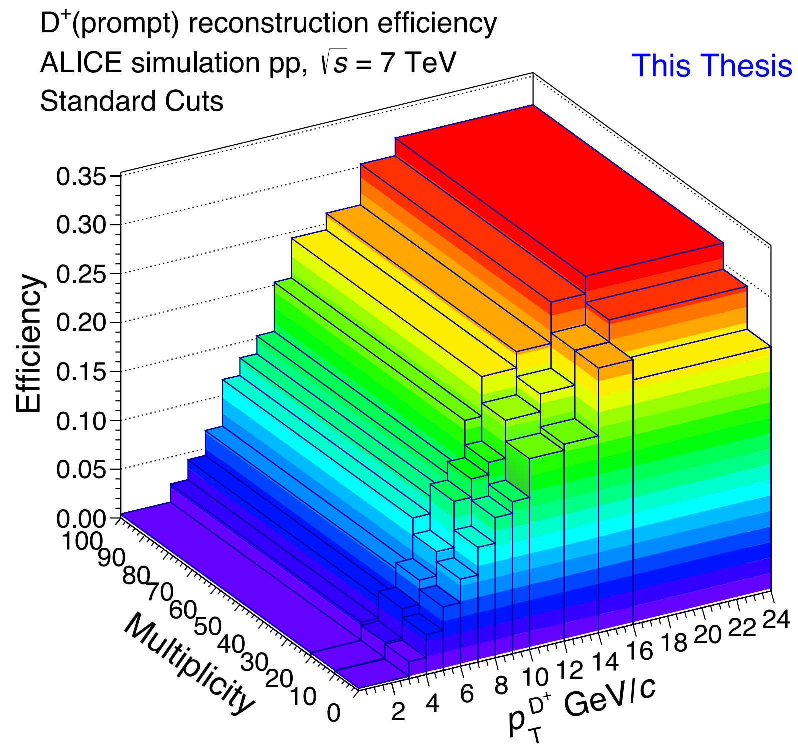
Correction #2.

Associated and trigger particle efficiency – efficiency correction





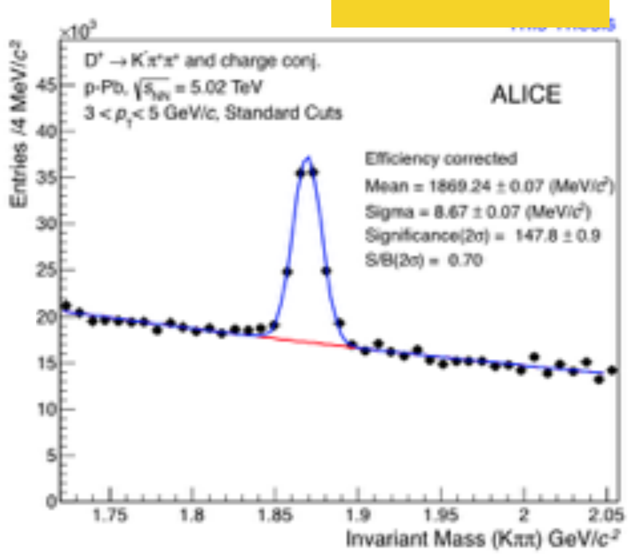
Used in analysis



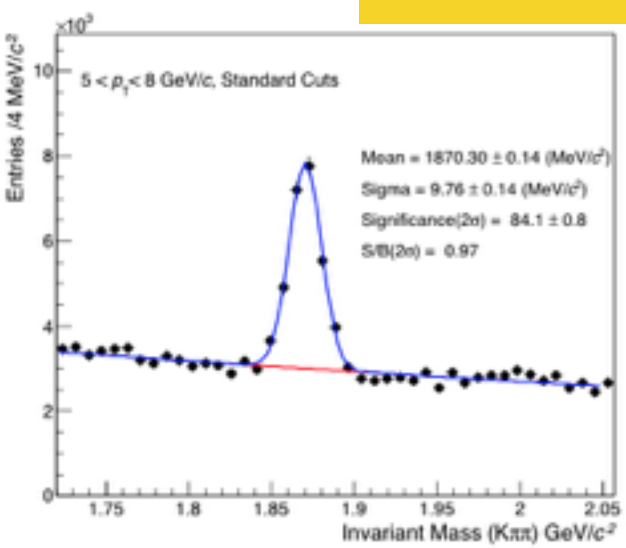
Correction #3.

- C#4. Feed-Down Correction
- C#5. Purity Correction

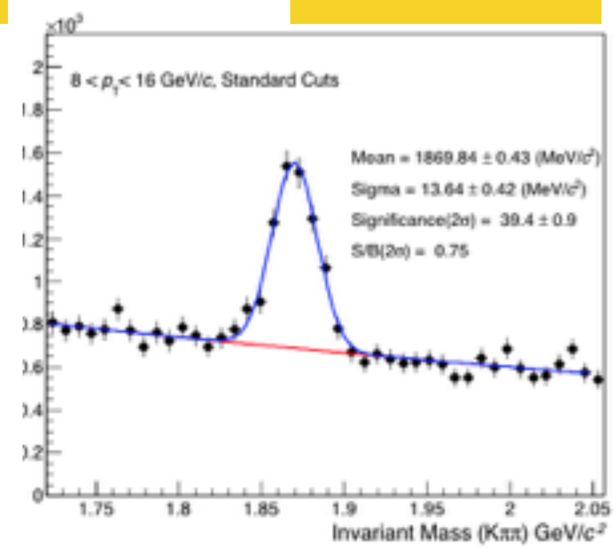
3-5 GeV/c



5-8 GeV/c



8-16 GeV/c



Analysis Method: Summary

all steps

Same/Mixed Correlations in Signal+Background region

$$fCorr^{2D}_{S+B} = \sum_{i=1}^{nPool} \frac{SE_i^{2D[S+B]}}{\frac{1}{norm} ME_i^{2D[S+B]}}$$

$$SE_i^{2D} = \frac{d^2 N^{SameEvent}}{d\varphi d\eta}$$

$$ME_i^{2D} = \frac{d^2 N^{MixedEvent}}{d\varphi d\eta}$$

Same/Mixed Correlations in sideband region

$$fCorr^{2D}_{sideband} = \sum_{i=1}^{nPool} \frac{SE_i^{2D[sideband]}}{\frac{1}{norm} ME_i^{2D[sideband]}}$$

Correlations in signal region

$$fCorr^{2D}_{S} = fCorr^{2D}_{S+B} - scalefactor \times fCorr^{2D}_{sideband}$$

Final corrected correlation

$$fCorr'^{2D}_{S} = \frac{1}{N_{trigger}} \times fCorr^{2D}_{S}\Big|_{\text{w/ correction}}$$

Systematics

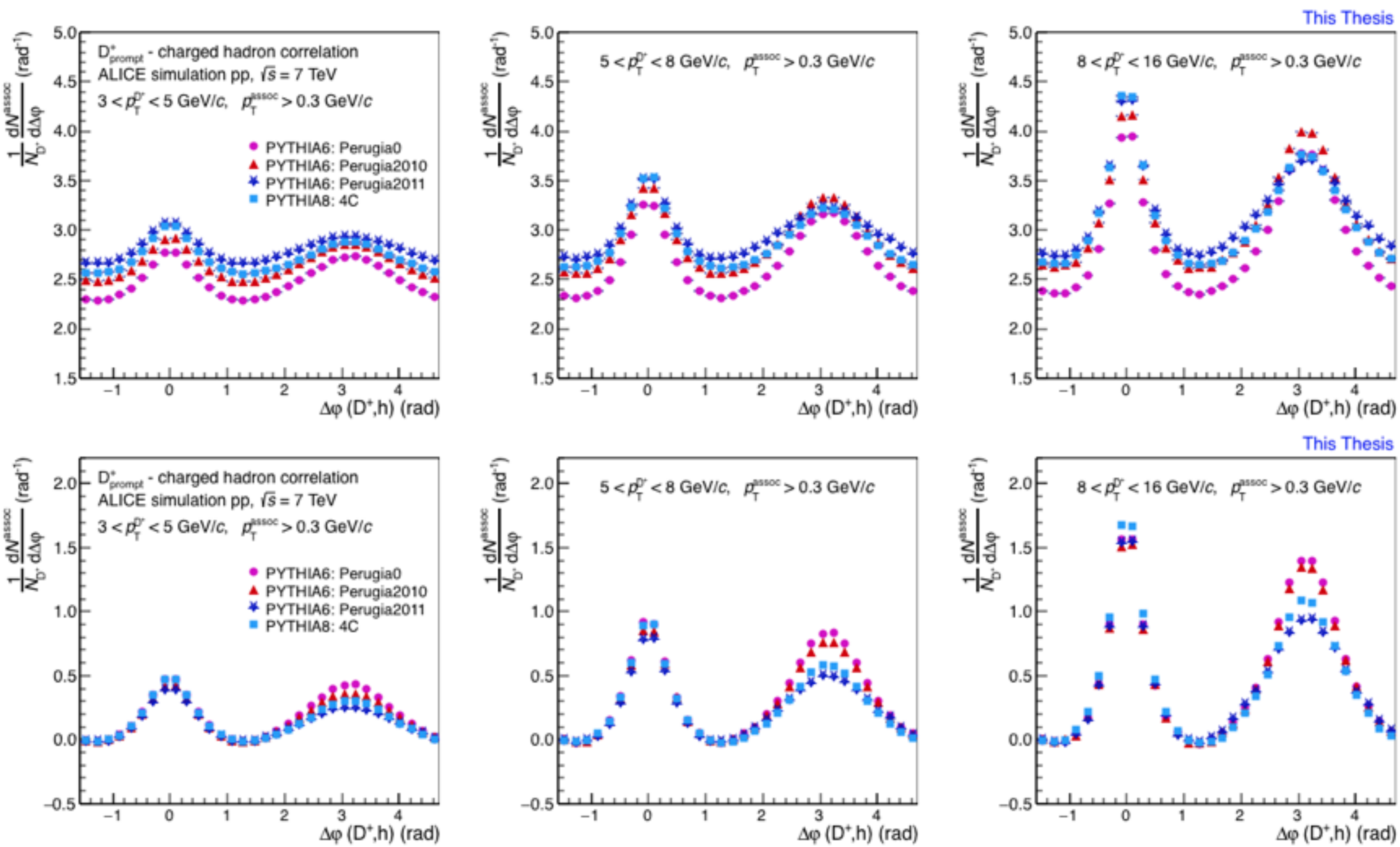
Systematics source	**More details**	**Final Uncertainties**
Trigger Efficiency	Variations of the D^{+} meson (trigger) selections cut (tightened and softer)	5%(10%)
Charged Particle Efficiency	Effect due to the charged track selection variations	[10, -5%] **(4%)**
Secondary Contamination	Variation in the secondary particle contamination via DCA cut and corresponding purity values.	5% **(3.5%)**
Background Subtraction	Variation of the sidebands range and method (fit, bin-counting)	5% (10%)
Trigger Yield Extraction	Variation of the signal (sigma) region, fit range, bin-width, background fit function and yield extraction via fit/bin-counting	10%
Beauty Feed Down Subtraction	Variation of the different simulation templates and f_{prompt} values	8%
MC Closure test	Correlation with MC sample for both prompt and feed-down D mesons	-2%NS (2%)

*Related example plots are in backup !

Monte Carlo Simulations

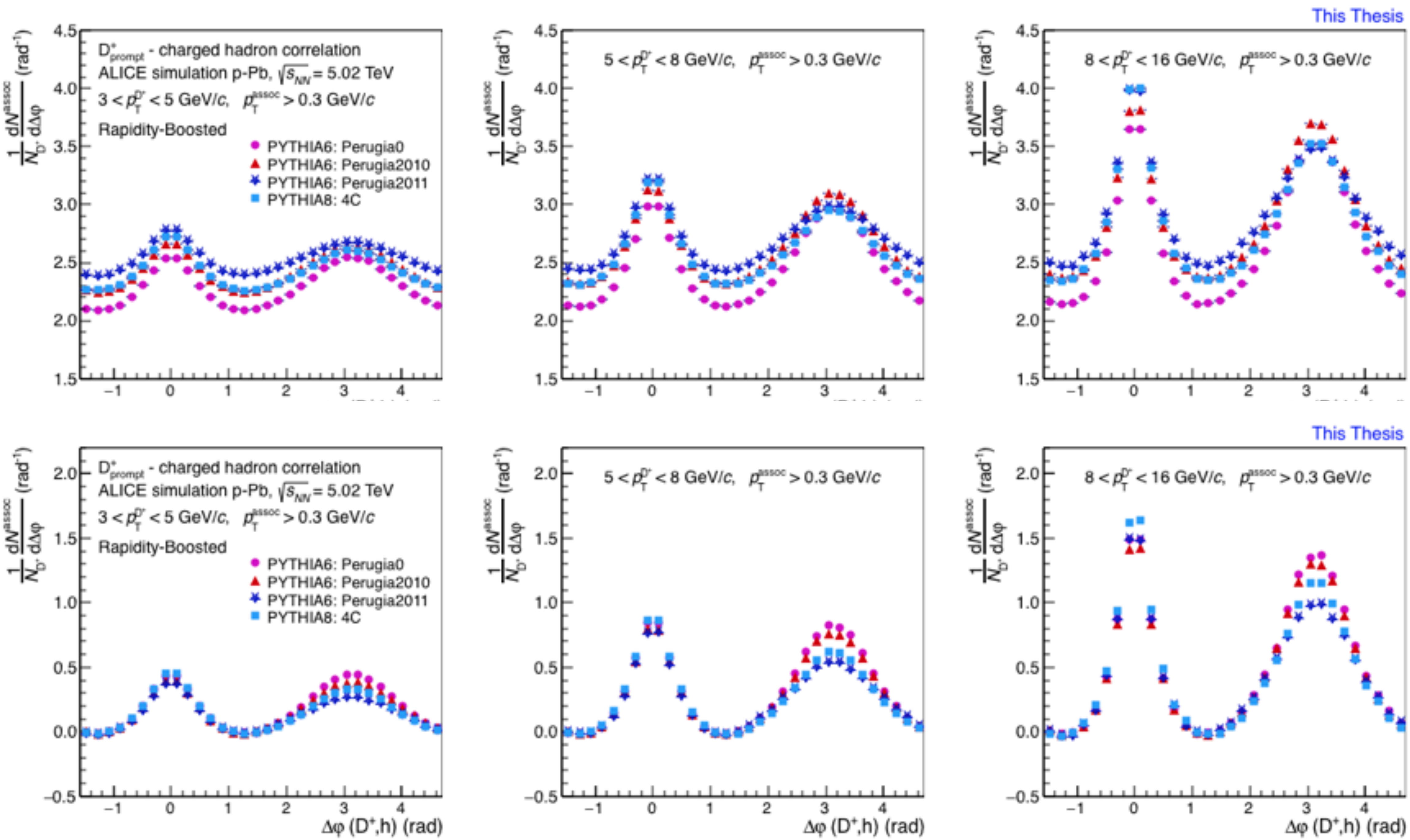
D$^+$ (Charm Origin) : vs. Different Pythia tunes

pp simulation, w/ & w/o baseline (uncorrelated tracks)



D^+ (Charm Origin) : vs. Different Pythia tunes

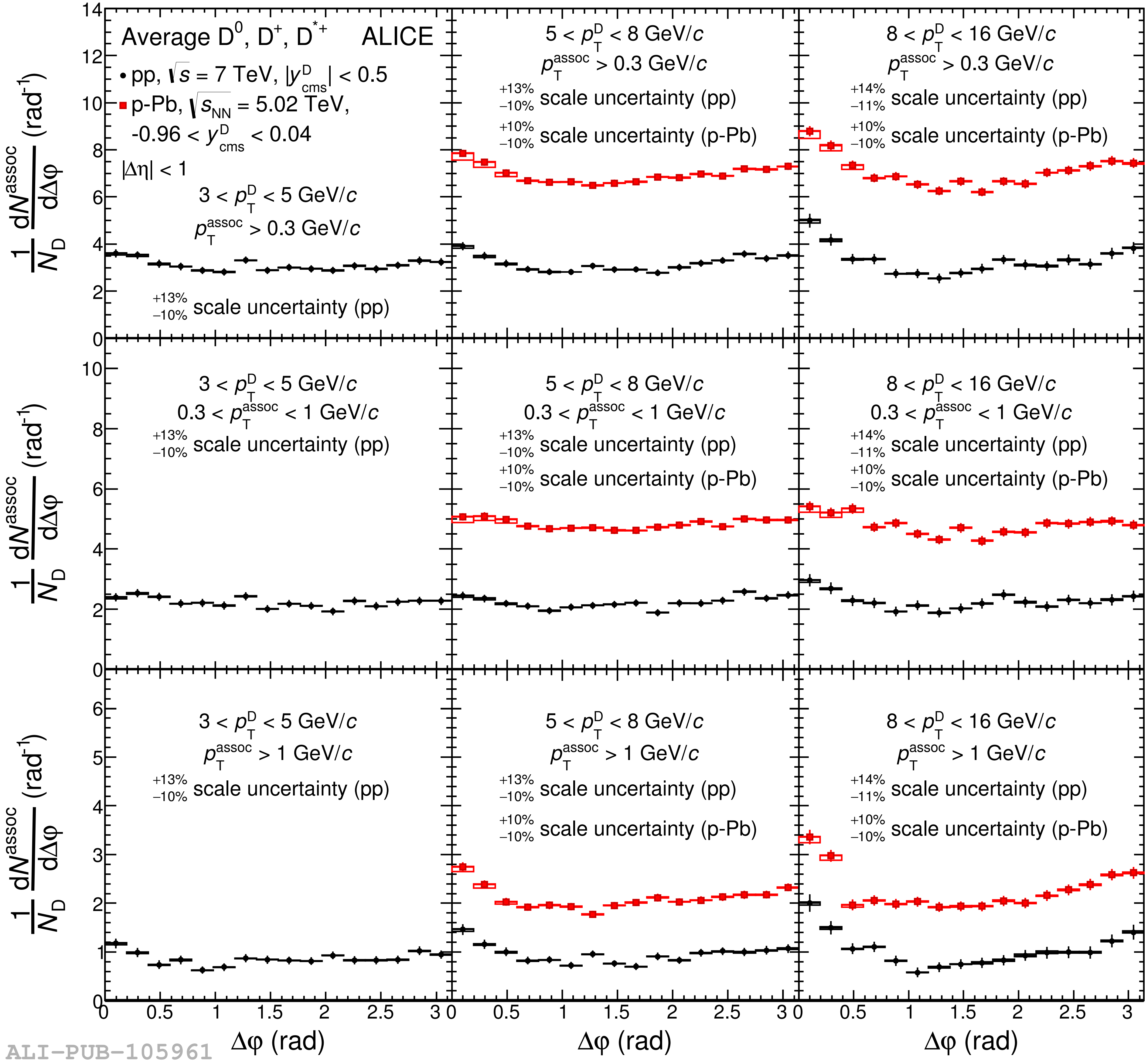
p-Pb simulation, w/ & w/o baseline (uncorrelated tracks)



Final Results

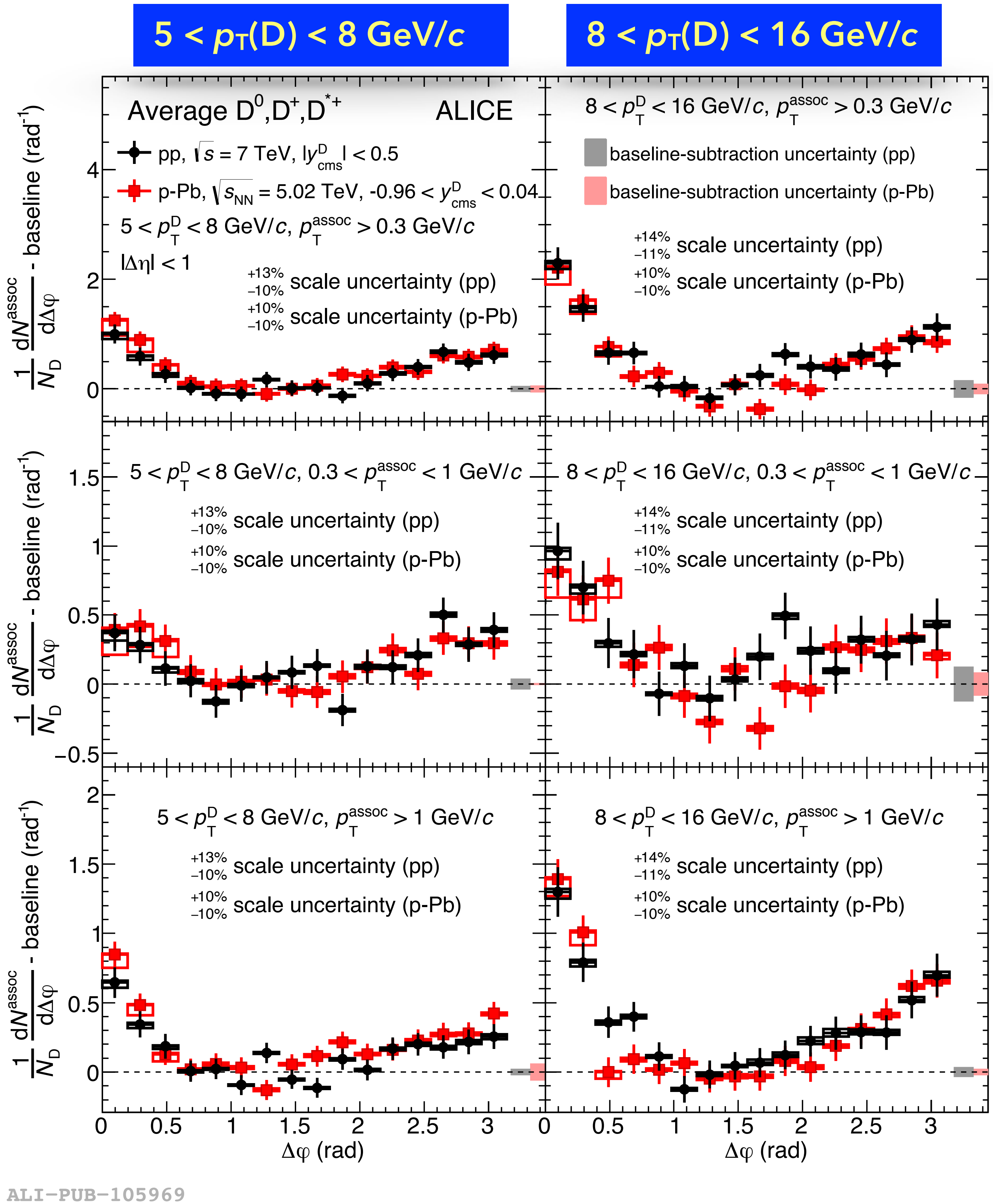
- Measured for D^0, D^{*+} and D^+ mesons
  - *Correlation from* D^0, D^{*+} and D^+ *have good compatibility within the uncertainties.*
  - *In order to reduce the overall uncertainties a weighted average is performed for all three D meson correlation results*
- In different p_T intervals of D: low(3-5), mid(5-8), high(8-16) GeV/c
- w/ different thresholds on associated particle p_T > 0.3, 1.0 and 0.3-1.0 GeV/c

Final Results ☝ Average of D^0, D^{*+}, D^+ mesons



Final Results ☝ Average of D^0, D^{*+}, D^+ mesons

arXiv:1605.06963 [nucl-ex]
Eur. Phys. J. C77 (2017), 245



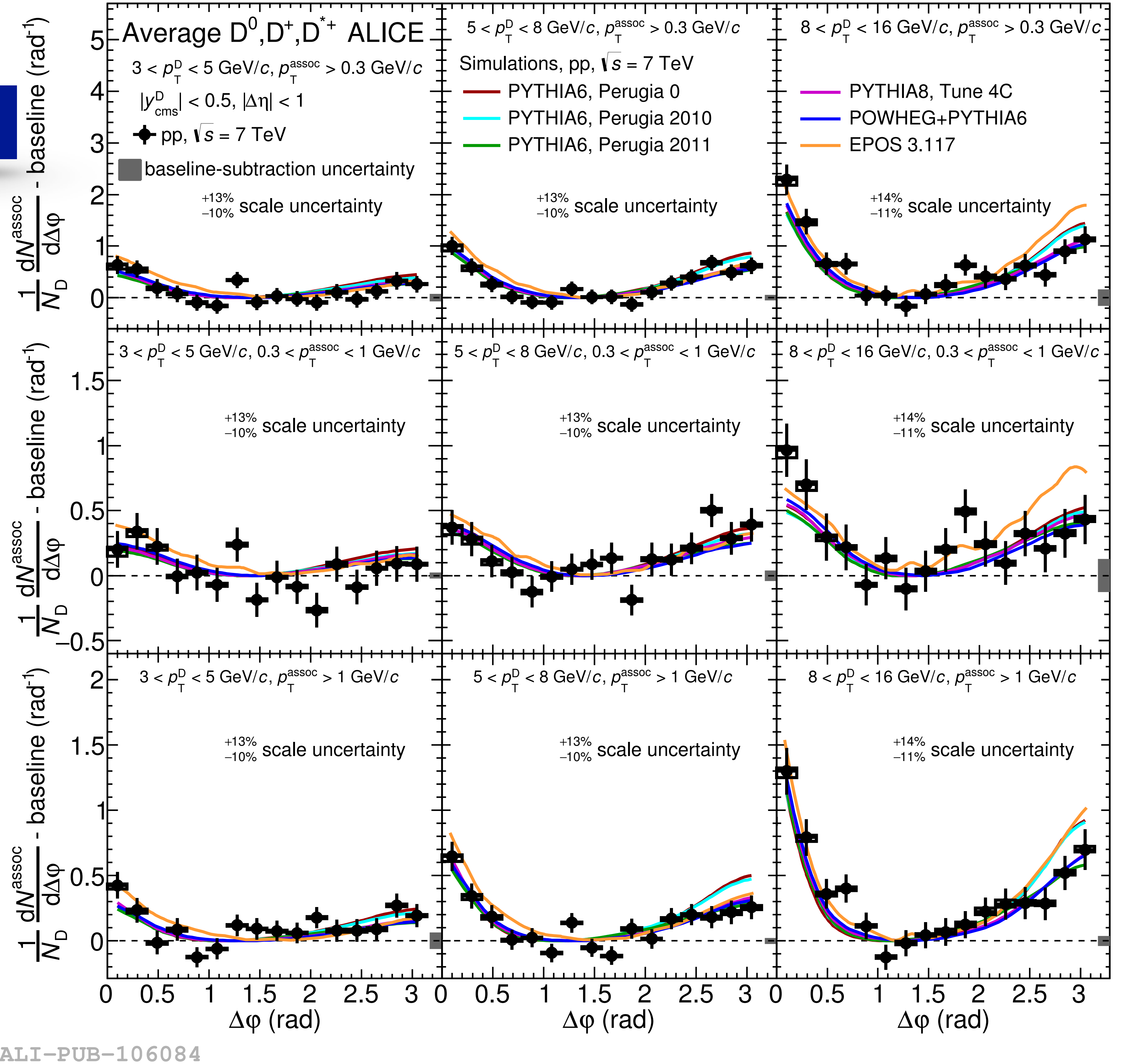
- Angular correlation between D mesons and charged particles in pp and p–Pb collisions after subtracting correlation baseline.
- D meson (trigger) p_T = 5-8 and 8-16 GeV/c
- Charged particles p_T = >0.3, 0.3-1.0 and >1.0 GeV/c

  - Results from pp at $\sqrt{s}$ = 7 TeV and p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV are **compatible within uncertainties**

Final Results ☟ Average of D^0, D^{*+}, D^+ mesons

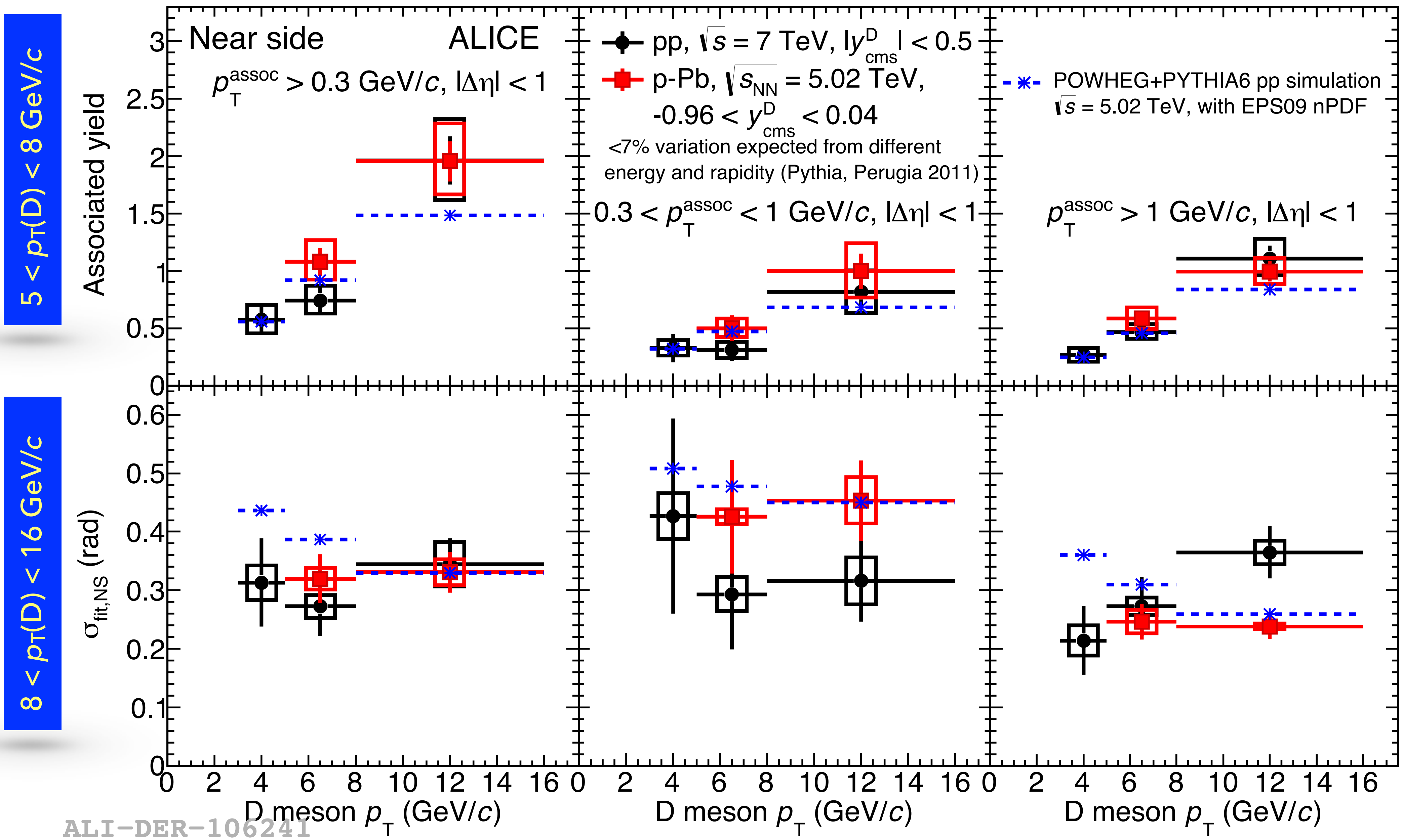
Comparison of Data vs. MC

- Data points are described within uncertainties by different PYTHIA tunes



Final Results ☞ Average of D^0, D^{*+}, D^+ mesons

arXiv:1605.06963 [nucl-ex]
Eur. Phys. J. C77 (2017), 245



Near-side (NS) associated yield and width as a function of p_T(D), for different p_T(assoc)

- NS associated yield exhibits an increasing trend with p_T(D)
- NS associated width does not exhibit any dependency with p_T(D)
- Results from pp and p–Pb collisions data are compatible within uncertainties
- Simulations show lower NS yield in trigger 8-16 GeV/*c* and associated (> 0.3 GeV/*c*) but compatible within 2σ
- With the current uncertainties, it is not possible to conclude about collective effects in p–Pb results

Summary

↳ This is first ever measurement of heavy-flavour azimuthal correlation between D meson and charged particles in pp and p-Pb collision.

↳ Results in pp and p-Pb collisions are compatible with predictions from different PYTHIA tunes.

↳ Results from p-Pb collisions are compatible with pp collisions after baseline subtraction.

↳ Both pp and p-Pb analyses results are also published in **Eur. Phys. J. C77 (2017), 245**.

↳ The results with current level of uncertainty don't show hint of CNM effect.

↳ A central ALICE framework for the calculation of single track efficiency has been developed along with this work.

↳ A fast generator independent simulation framework in ALICE is also developed and results are used in Feed-down subtraction as well as in Model comparison (e.g. Pythia, HerWig, POWHEG).

Outlook

- Will provide better precision on the current pp and p-Pb measurements.
- Possible to study the multiplicity dependence in both pp and p-Pb collisions.
- Study with high multiplicity pp collisions.
- Long-range correlations study in p-Pb collisions.
- The study as a function of multiplicity may allow to measure a possible non-zero v_2 for D mesons in p-Pb collisions.

List of presentation

Presentations and Seminar

2016 Presentation: XXII DAE-BRNS Symposium 2016, at University of Delhi, India.

2015 Poster: 7th International Conference on Physics and Astrophysics of Quark Gluon Plasma (ICPAQGP), Kolkata, India.

2015 Poster: 5th Annual Symposium of the Department of Physics at IIT Bombay, India.

2015 Presentation: Hard Probes 2015 at the McGill University, Montreal, Canada.

2014 Presentation: The 5th Asian Triangle Heavy Ion Conference (ATHIC-2014) at Osaka, Japan.

2014 Poster: LHC students poster session 2014 at CERN, Geneva.

2013 Poster: International Symposium on Nuclear Physics 2013, at BARC Mumbai, India.

Extra Slides

Heavy-flavour production affected
by nuclear effects ?

Nuclear Modification Factor

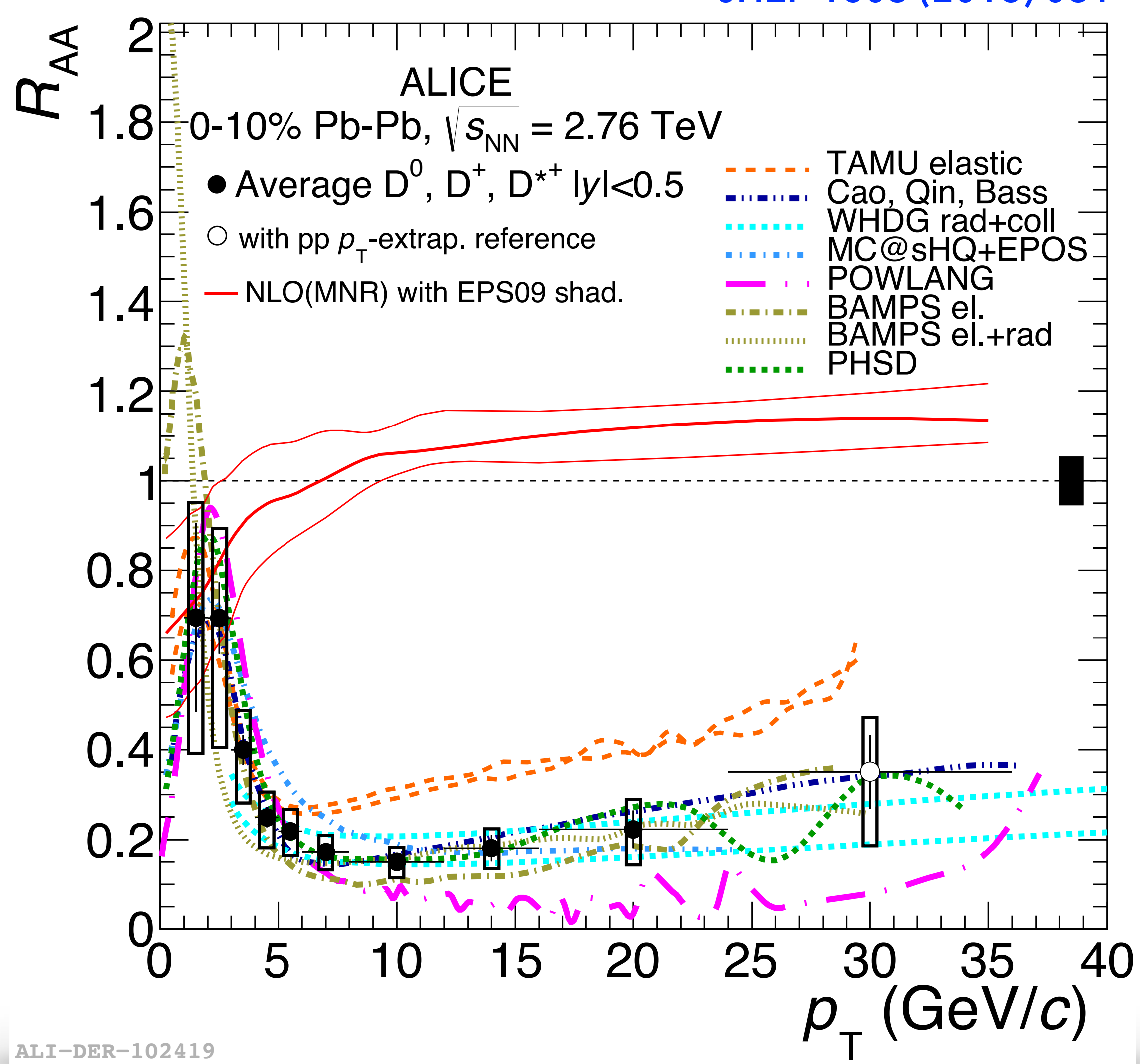
$$R_{pPb} = \frac{1}{A}\frac{(d\sigma/dp_T)_{pPb}}{(d\sigma/dp_T)_{pp}} \begin{cases} \neq 1 \text{ (nuclear effect)} \\ = 1 \text{ (no nuclear effect)} \end{cases}$$

Recap: D mesons in heavy-ion collisions

$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \cdot \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

Strong modification of the momentum distribution of D mesons in Pb-Pb compared to pp collisions for $p_T > 3$ GeV/c. → **heavy quark in-medium energy loss**

JHEP 1603 (2016) 081



Medium (QGP) effect only ?
Any role of Cold Nuclear Matter effects ?

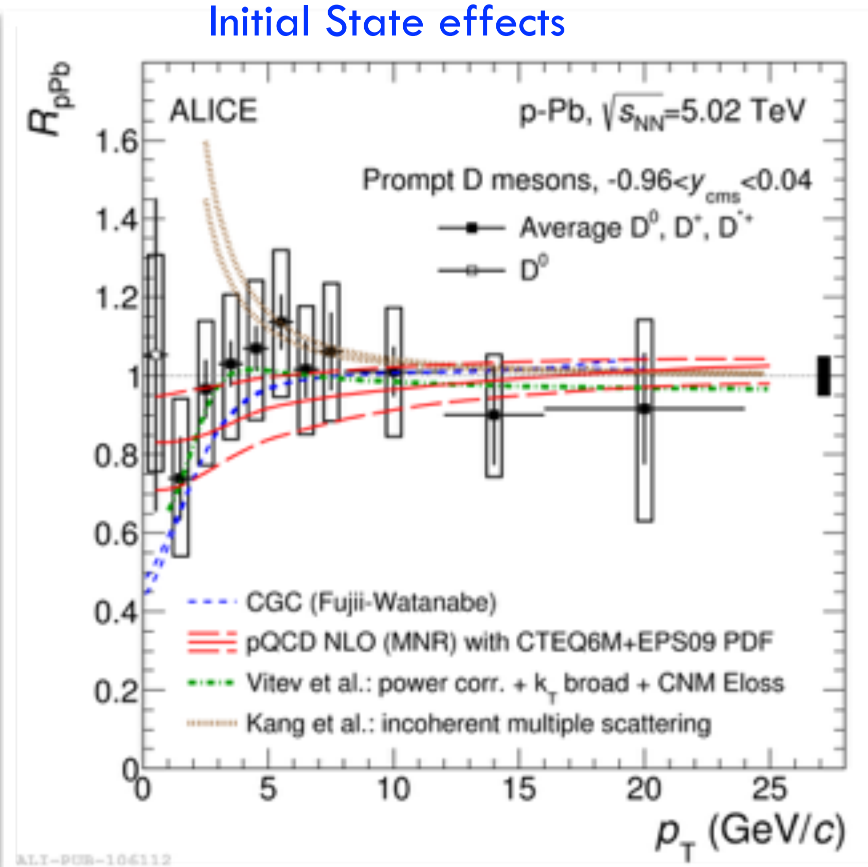
$$R_{pPb} = \frac{1}{A} \frac{(d\sigma/dp_T)_{pPb}}{(d\sigma/dp_T)_{pp}}$$

Average of D^0, D^{*+}, D^+ mesons

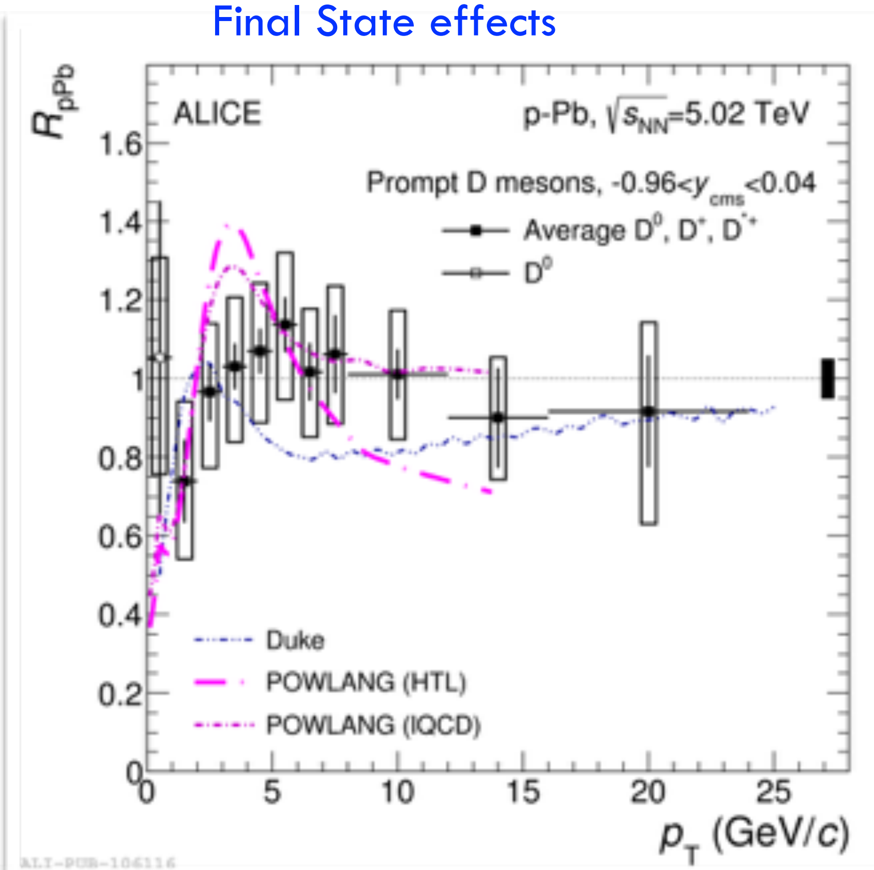
D mesons in p-Pb

New: R_{pPb} down to $p_T = 0$

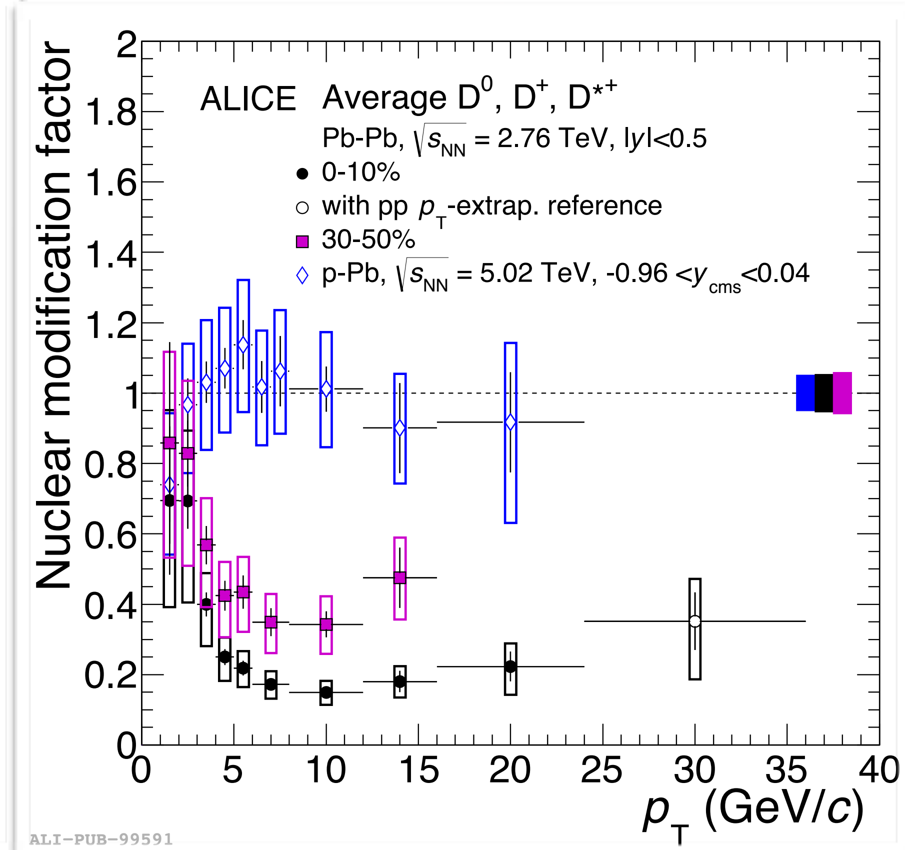
Comparison w/ models include Initial State effects



Comparison w/ models include Final State effects



Comparison w/ Pb-Pb collisions results



Phys. Rev. Lett. 113 (2014) 232301

New: Phys. Rev. C 94 (2016) 054908

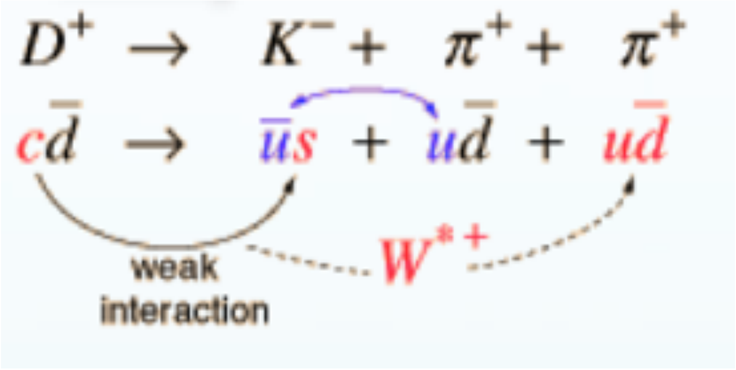
Within uncertainties

- Compatible with unity in the whole p_T range
- For $p_T > 2$ GeV/c compatible with models which include **"initial"** as well as with models which includes **"initial and final"** state effects **(left and middle plot)**
- **Strong suppression in Pb-Pb collisions is due to in-medium effects (right plot) !**

Heavy-flavour measurement !

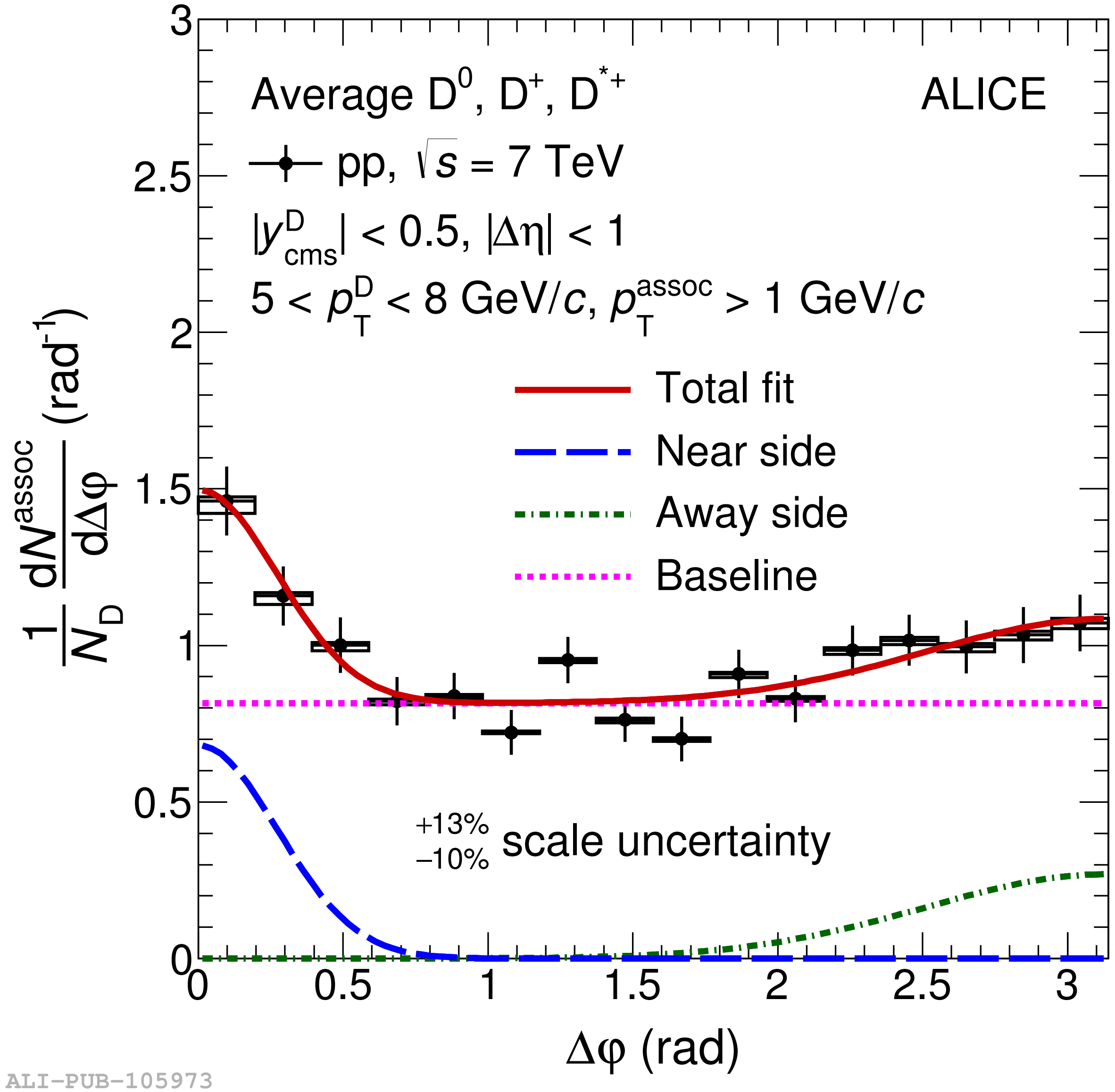
- The masses of heavy quarks (m_c = ~1.29 GeV and m_b = ~4.19 GeV) are much larger compared to light quarks (m_u = ~2.3 MeV, m_d = ~4.8 MeV and m_s = ~95 MeV) and QCD scale parameter Λ_{QCD} (~ 200 MeV/c). *– production time ~ 1/2m_Q = 0.5 to 1.5 fm/c*
- Their production is governed by perturbative QCD (m_Q >> Λ_{QCD}).
- The special feature of heavy-quarks is, even at zero momentum they introduce hard scale due to their large masses, therefore pQCD can be used to calculate their production cross sections over all momenta which is not the case for gluon and light quarks
- The pairs of heavy quarks and its anti-quarks are predominantly produced in hard scattering processes *– flavour creation, flavour excitation and gluon splitting*
- mass = 1.869 MeV, lifetime = $1.040 \pm 0.007 \times 10^{-12}$

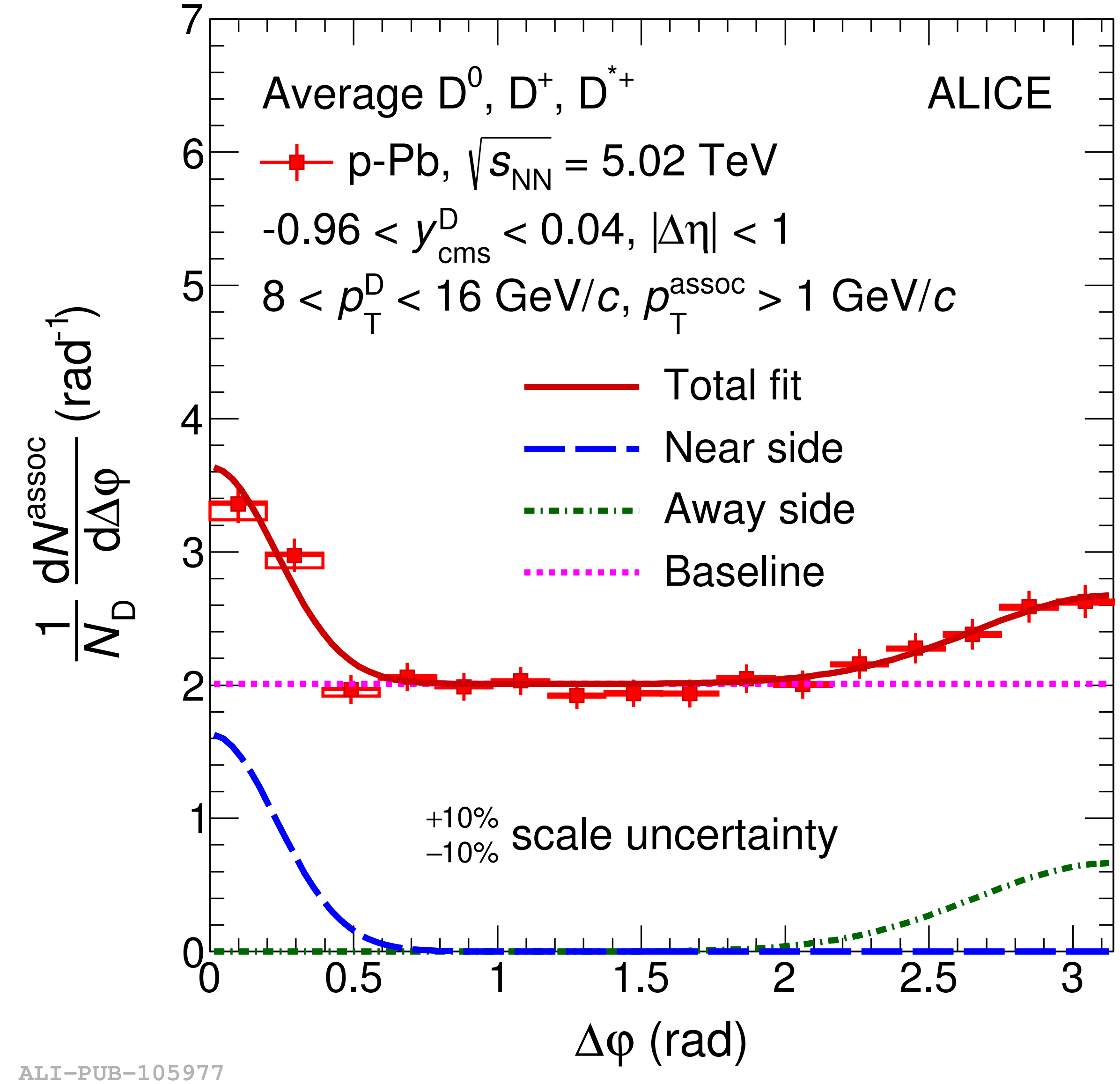
Decay channel	Branching ratio
$D^+ \rightarrow K^- \pi^+ \pi^+$	9.13 ± 0.19%
$D^0 \rightarrow K^- \pi^+$	3.88 ± 0.05%
$D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$	2.62 ± 0.10%



**Beauty = 4.18 GeV*
**charm = 1.275 GeV*
**d = 4.8 MeV*

Example of correlation fits





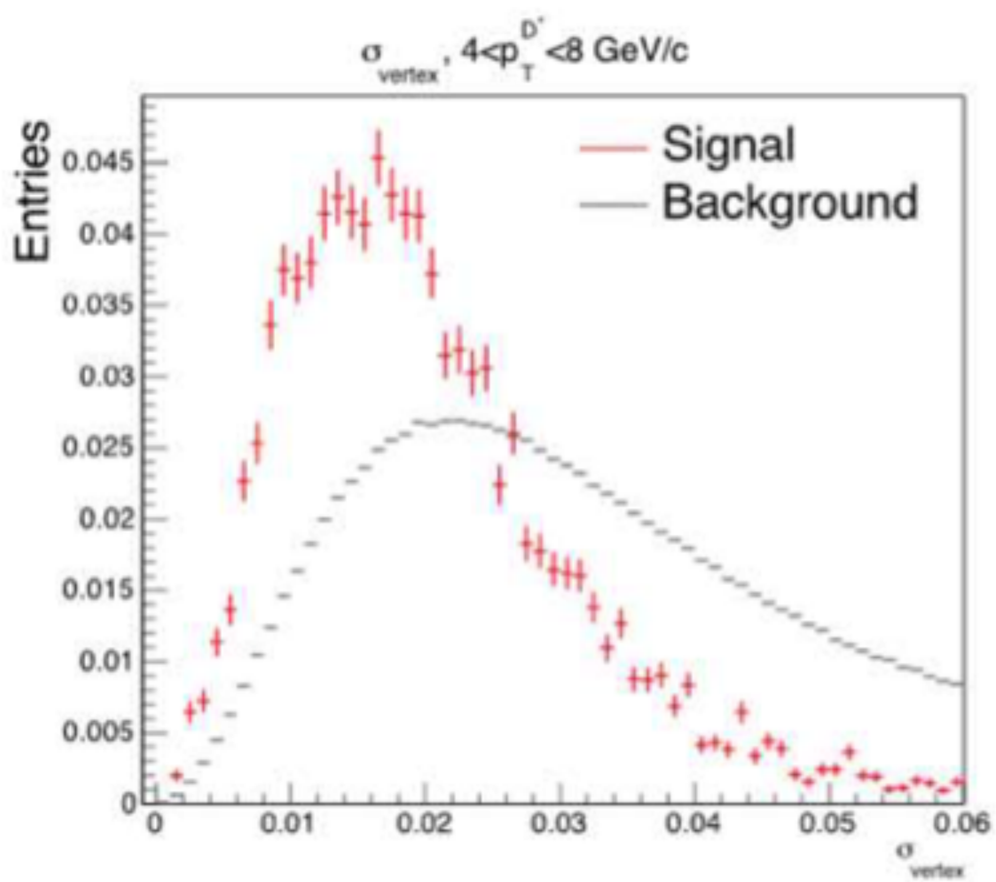
D+ topological cuts example

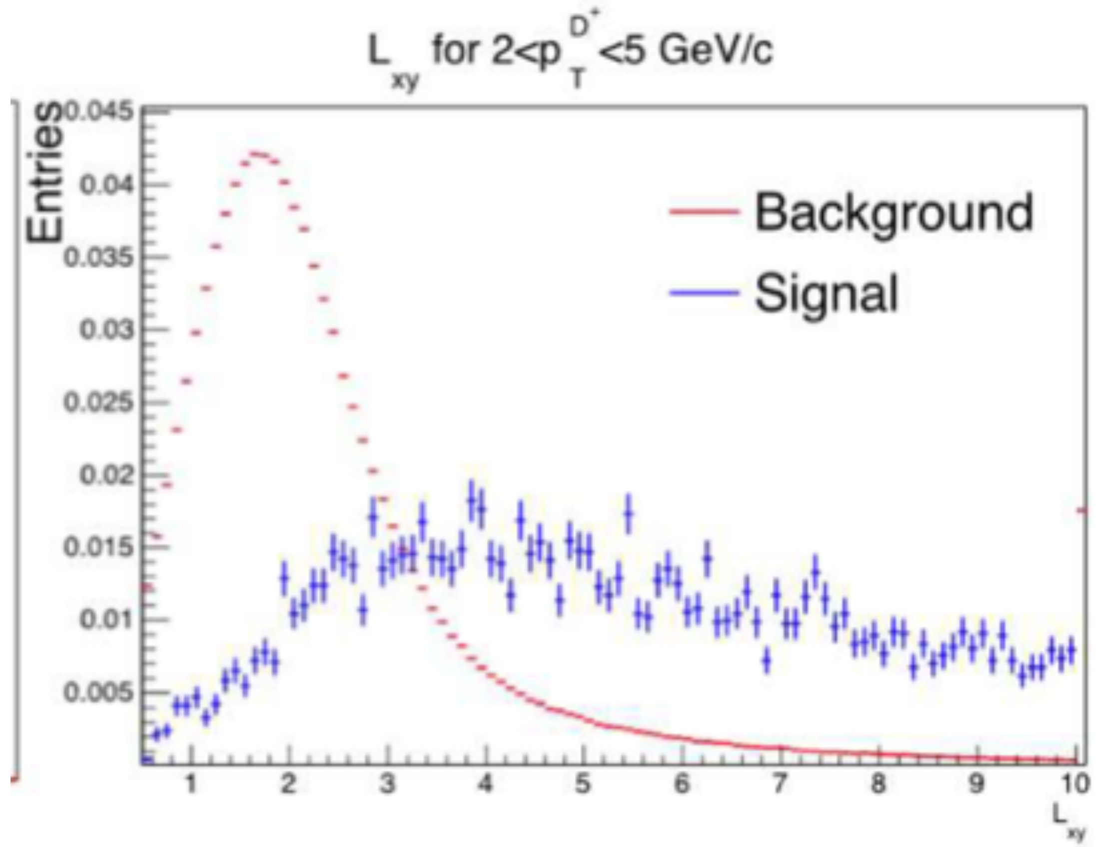
Cut	System	Values	Properties
Invariant mass $D^+(M_{inv})$ (GeV/c^2)	p-p	1.70-2.05	• Mass window around the PDF value of D^+ mass 1869.62 ± 0.2 GeV/c^2 • Bin width of about 0.012 GeV/c^2 • Allows to consider the side bands region for background estimation.
	p-Pb	1.70-2.05	
Daughter Transverse Momentum $p_T(K, \pi)$ (MeV/c)	pp	$K > 200$	• Kinematically reject the low p_T background tracks • Kaons with opposite charge w.r.t D^+ mother • Pions with same charge w.r.t D^+ mother
		$\pi > 400$	
	pPb	$K > 200$	
		$\pi >$ 350-400	
Pointing angle $\cos(\theta^*)$	pp	<0.990	• Cosine of pointing angle $\cos(\theta^*)$ is used • The value < 1 for D^+ mesons with $p_T > 0$ GeV/c
	p-Pb	<0.990	
Pointing angle XY $\cos(\theta_{xy}^*)$	pp	<0.990	• The pointing angle in the transverse plane
	p-Pb	< 0.995 to < 0.990	
Impact parameter $d_0(r\varphi)$ cm	pp	$K > 0.$	• The cut is applied w.r.t primary vertex • The lower limit rejects the primary particles • The upper limit remove highly displaced tracks
		$\pi > 0.$	
	p-Pb	$K > 0.$	
		$\pi > 0.$	

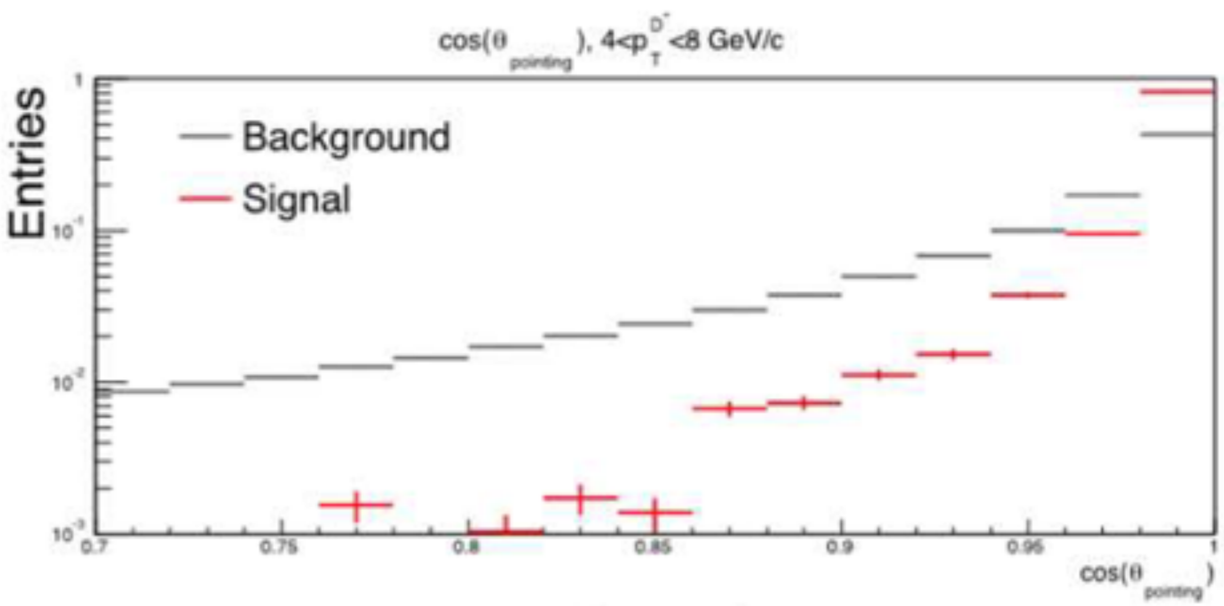
D+ topological cuts example

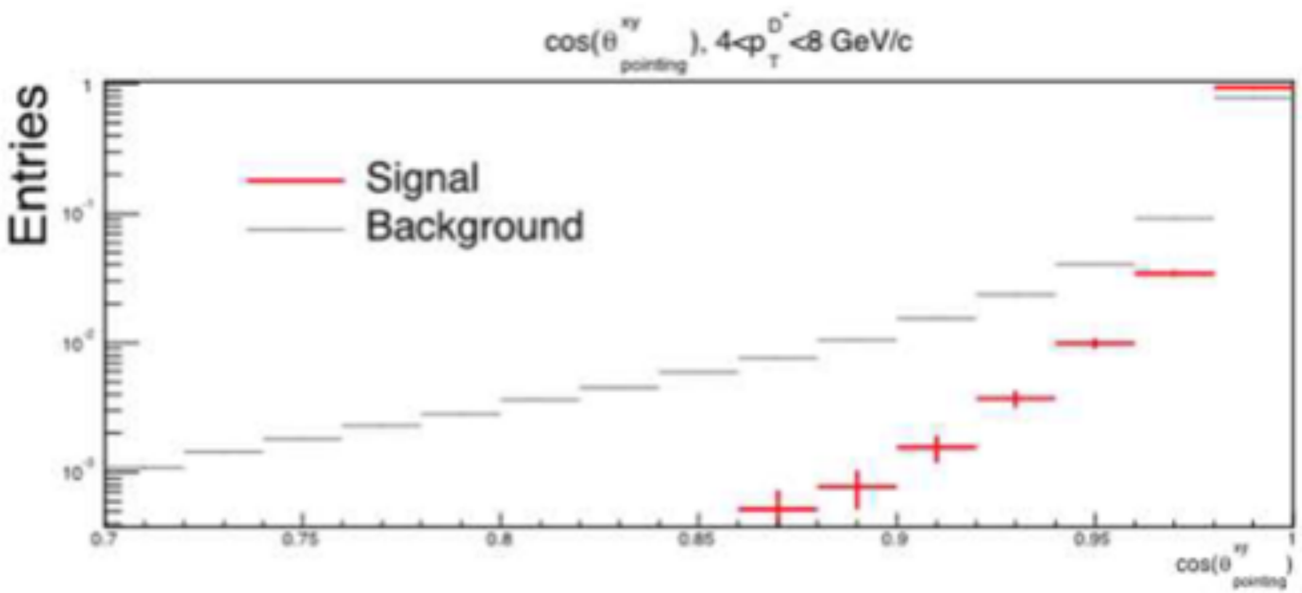
Distance to closure approach DCA (μm)	pp	>0.25	• The dca is determined by the resolution on the track positions. • The lower limit rejects the primary particles
	p-Pb	>0.25-1.00	
Decay Length L_{len} (μm)	pp	>2.0-10.0	• Normalized decay length in transverse/xy plane • Distance between the primary and the decay vertex • Normalized by the uncertainty on the measurement
	p-Pb	>2.0-10.0	
Distance of Primary and Secondary Vertex dist1-2 (μm)	pp	>300-400	• Removes background via secondary vertex to primary vertex distance
	p-Pb	>300-600	
Impact parameter square $d^2_0(r\varphi)$ cm^2	pp	>0.0	• Impact parameter cut on the basis of sign daughter tracks • For signal candidate this value should be -ive and large while for background it is around 0.
	p-Pb	>0.0	
Transverse Momentum p_T(max)	pp		• Additional max pT cut for Kaons and Pions to reject fake tracks or reduce the combinatorial background.
	p-Pb		

D+ topological cuts example

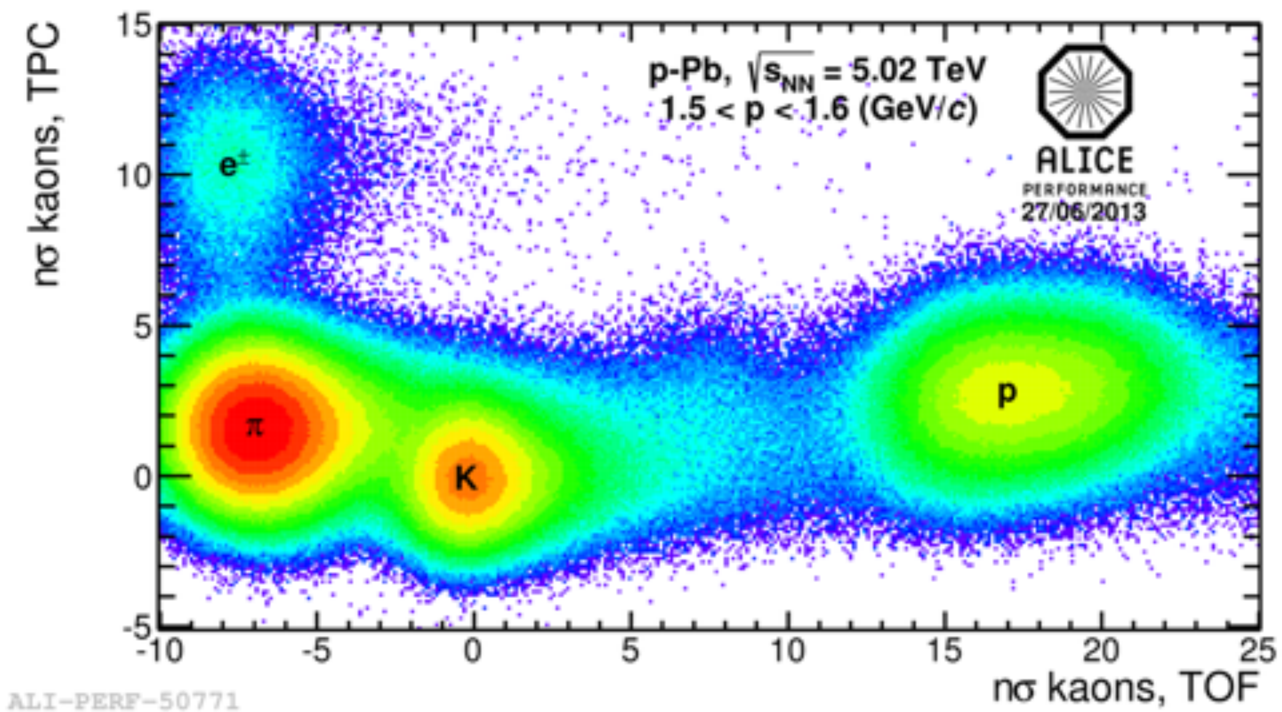


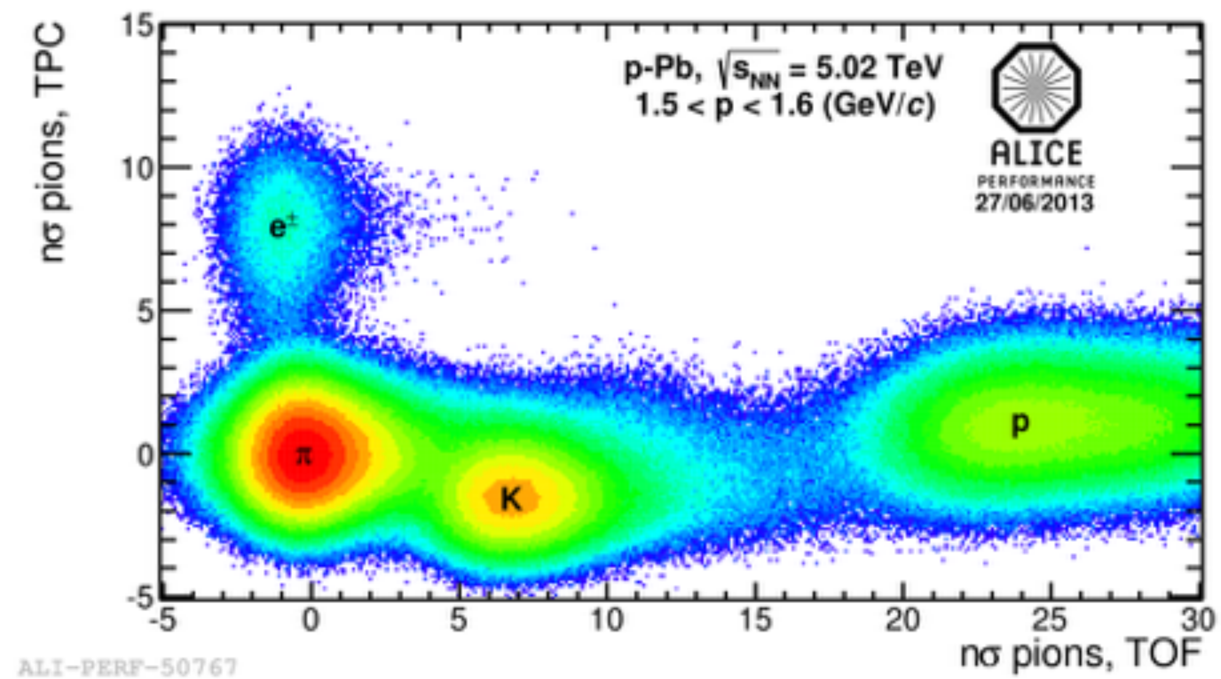






Particle Identification in ALICE

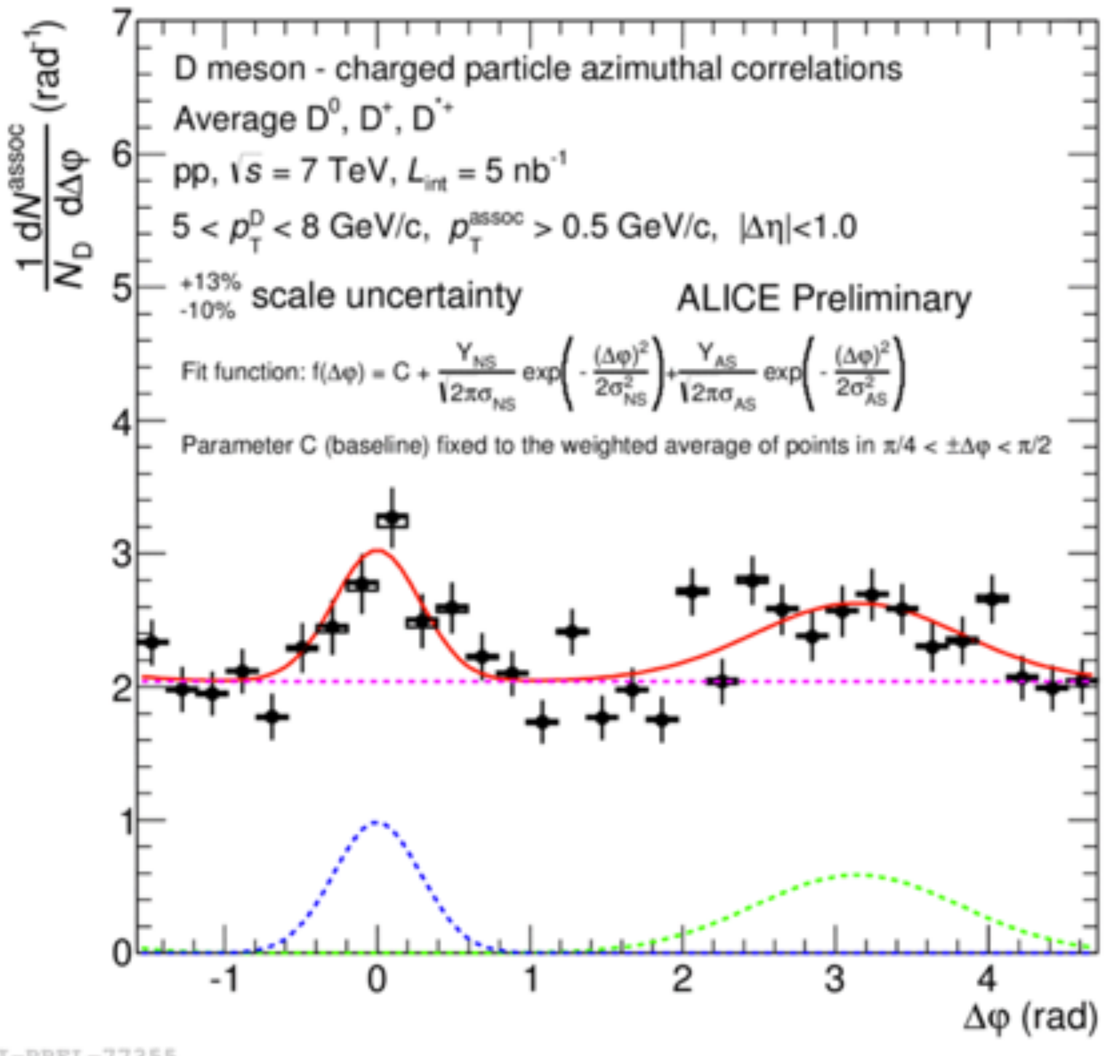




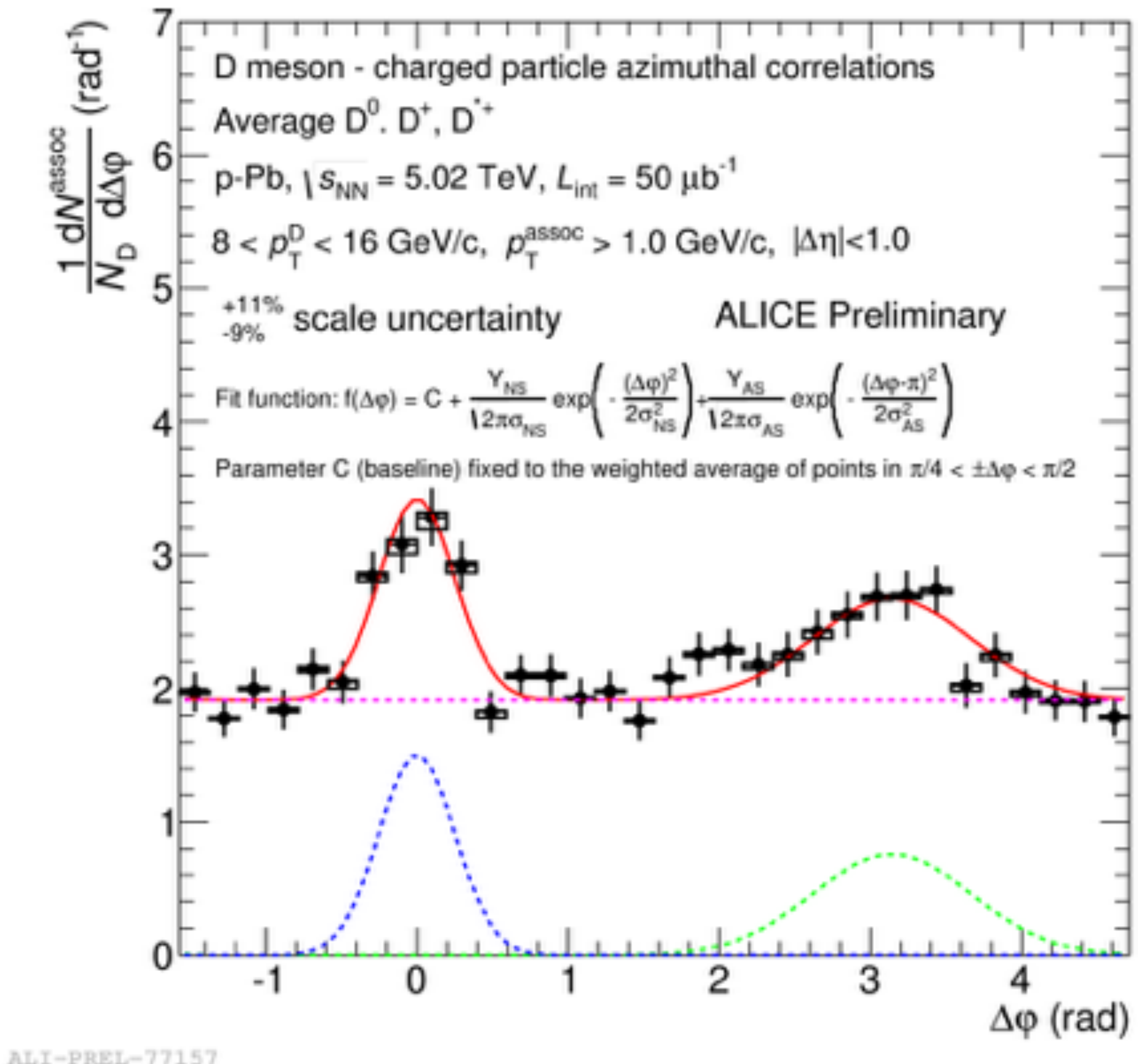
Final Results

Average of the D^0, D^{*+}, D^+ mesons

pp collisions: D-meson p_T 5-8 GeV/c and hadron p_T > 0.5 GeV/c



p-Pb collisions: D-meson p_T 8-16 GeV/c and hadron p_T > 1.0 GeV/c

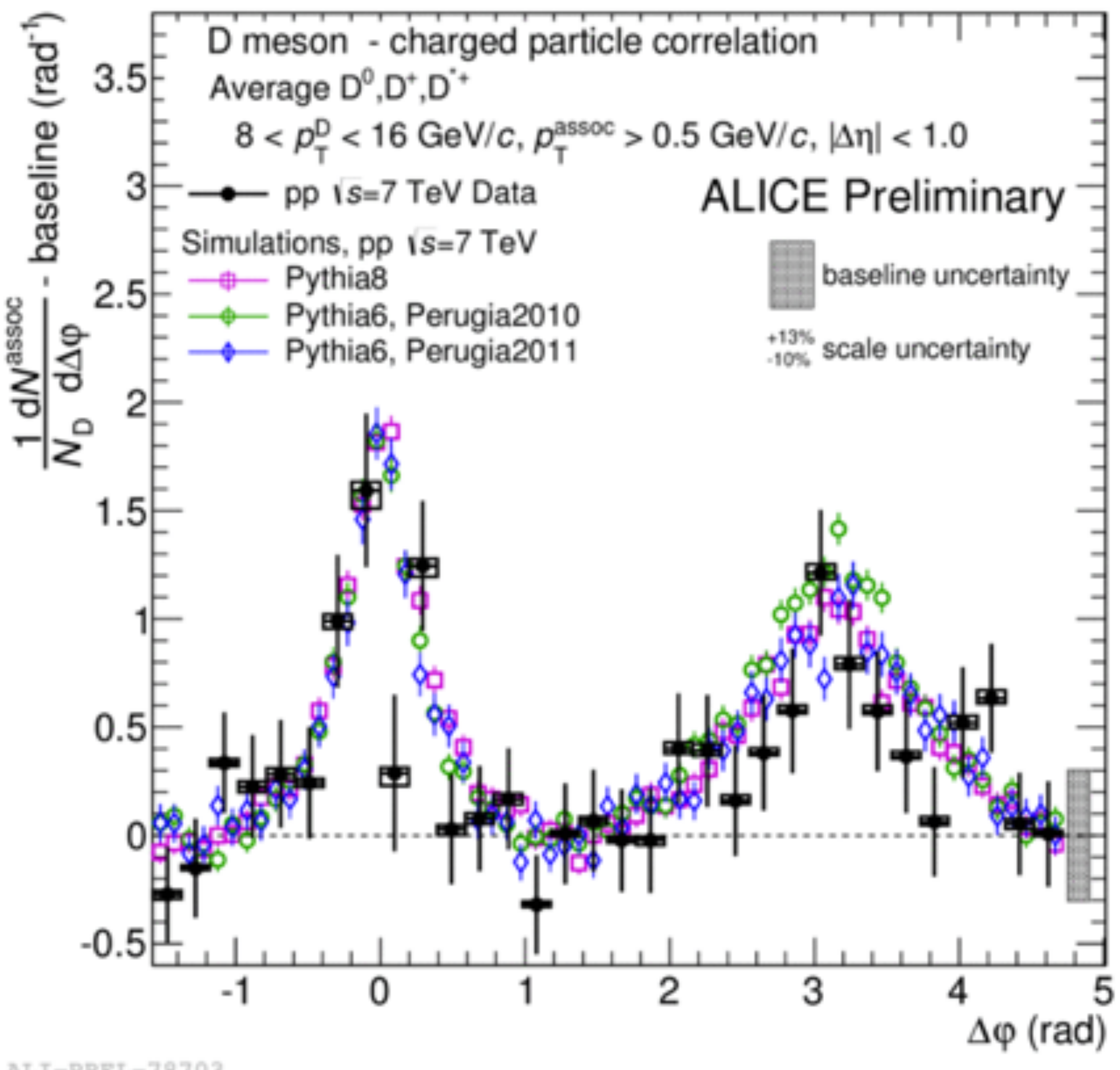


Final Results

Average of the D^0, D^{*+}, D^+ mesons

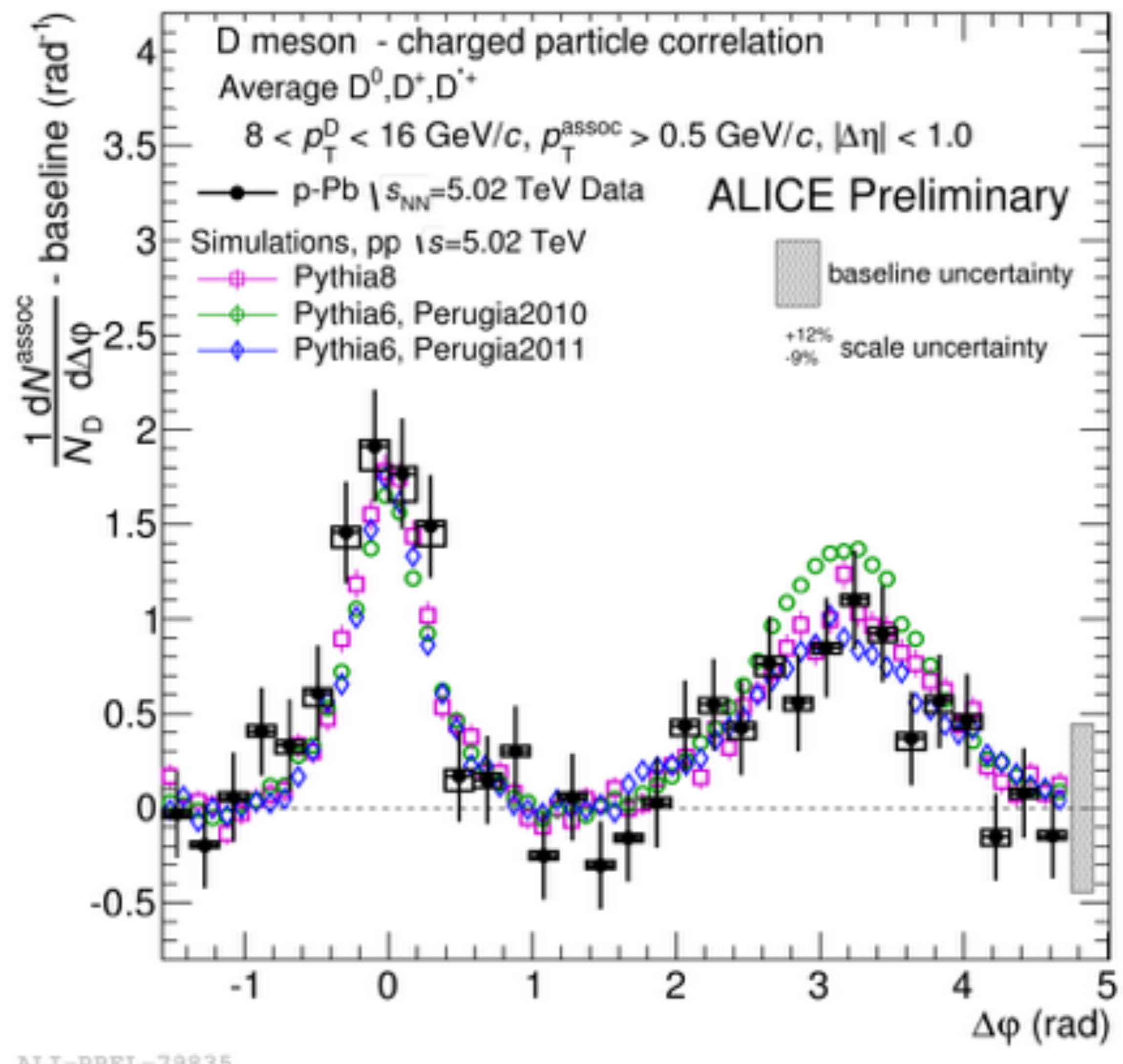
Data (pp) vs. PYTHIA

D-meson p_T 8-16 GeV/c and hadron p_T > 0.5 GeV/c



Data (p-Pb) vs. PYTHIA

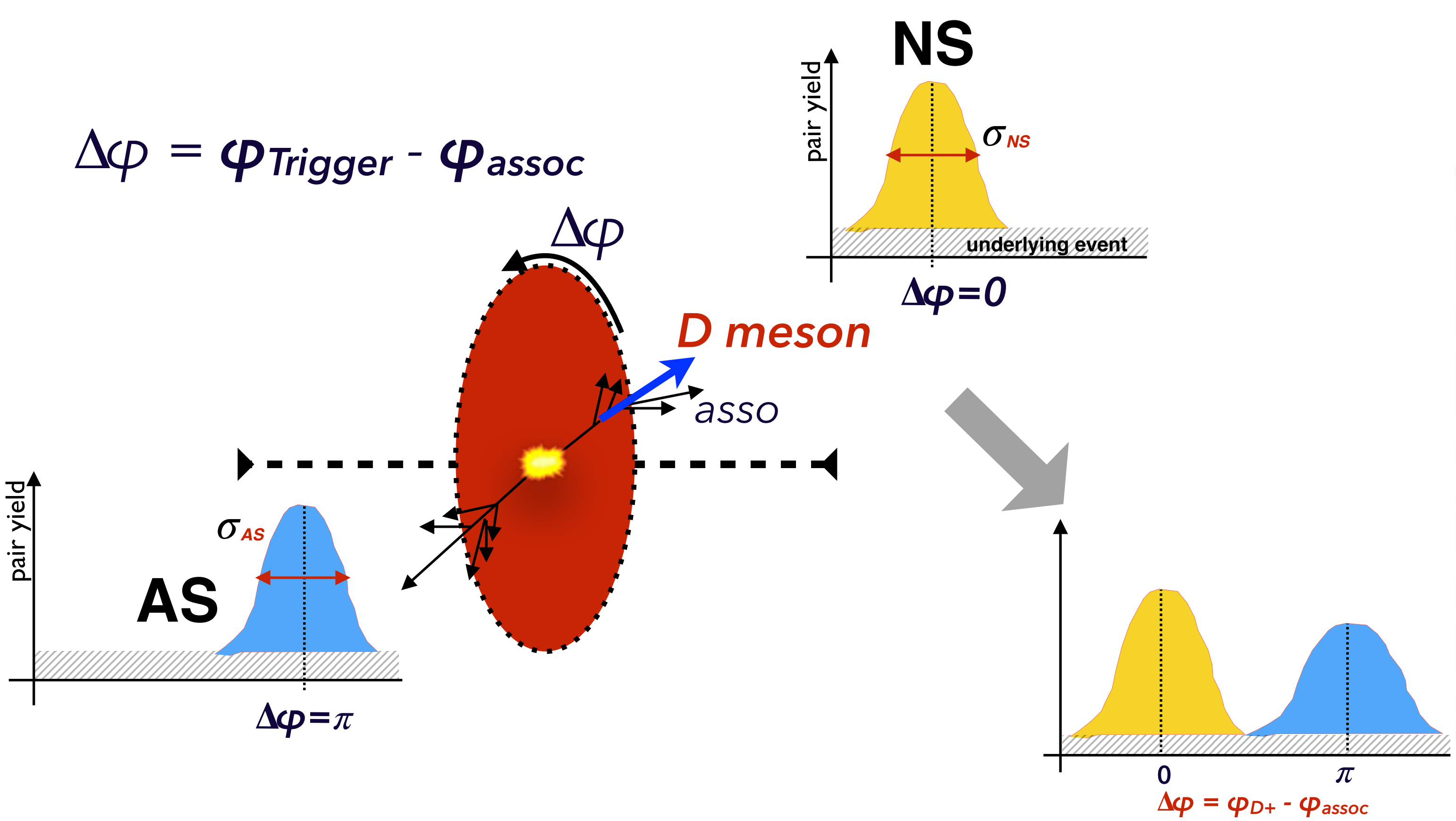
D-meson p_T 8-16 GeV/c and hadron p_T > 0.5 GeV/c



- Data point are described within uncertainties by different PYTHIA tunes

Angular correlations measurement

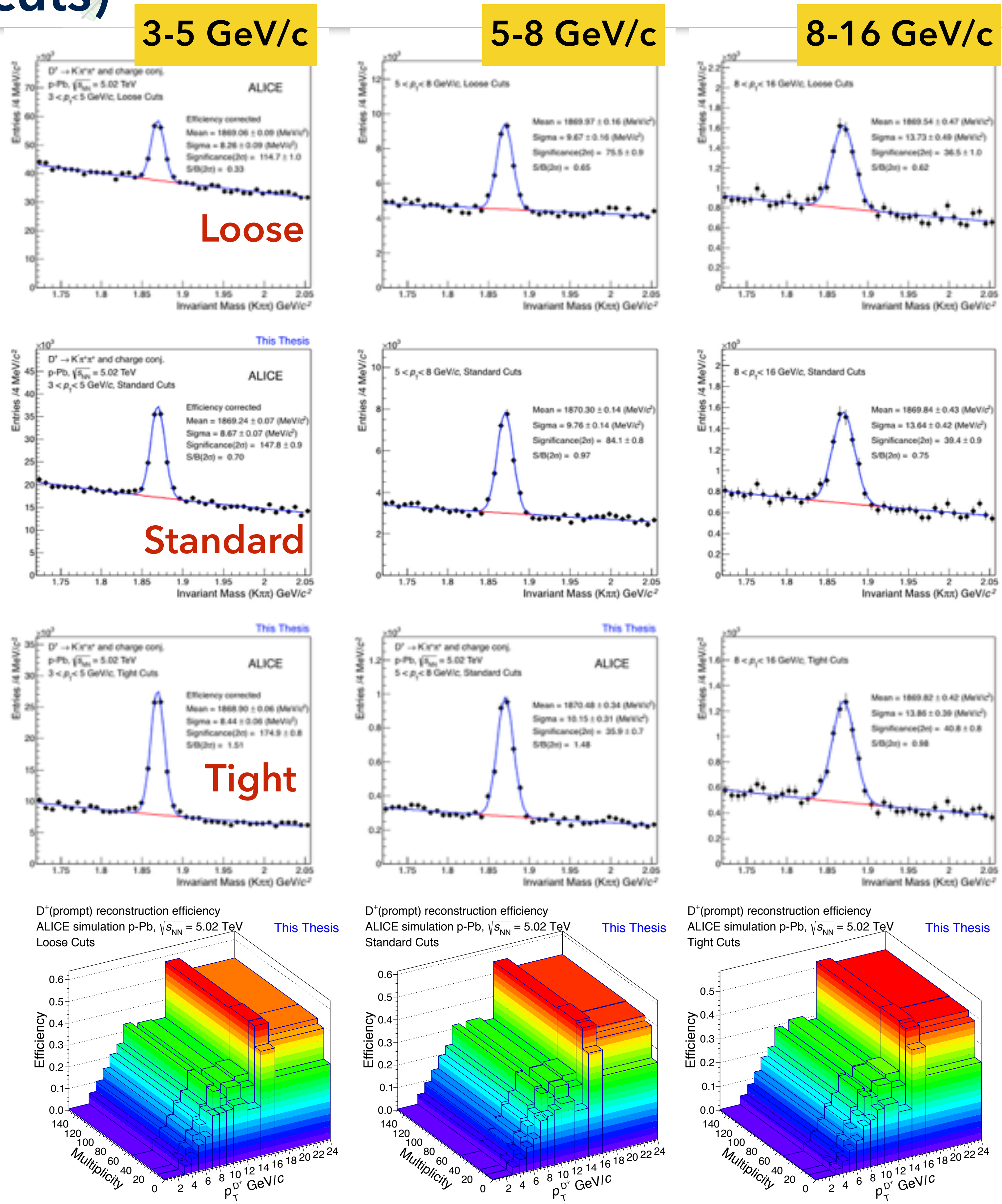
$\Delta\varphi = \varphi_{Trigger} - \varphi_{assoc}$



Per trigger yield (Y)

$$I_{AA} = \frac{Y_{PbPb}}{Y_{pp}} \begin{cases} > 1 \text{ (x machenism) ?} \\ < 1 \text{ (medium effects)} \\ = 1 \text{ (no medium effects)} \end{cases}$$

Systematics Study (D^{+} track cuts)



Invariant Mass from different D^{+} topological cuts

Systematics Study (D^+ track cuts)

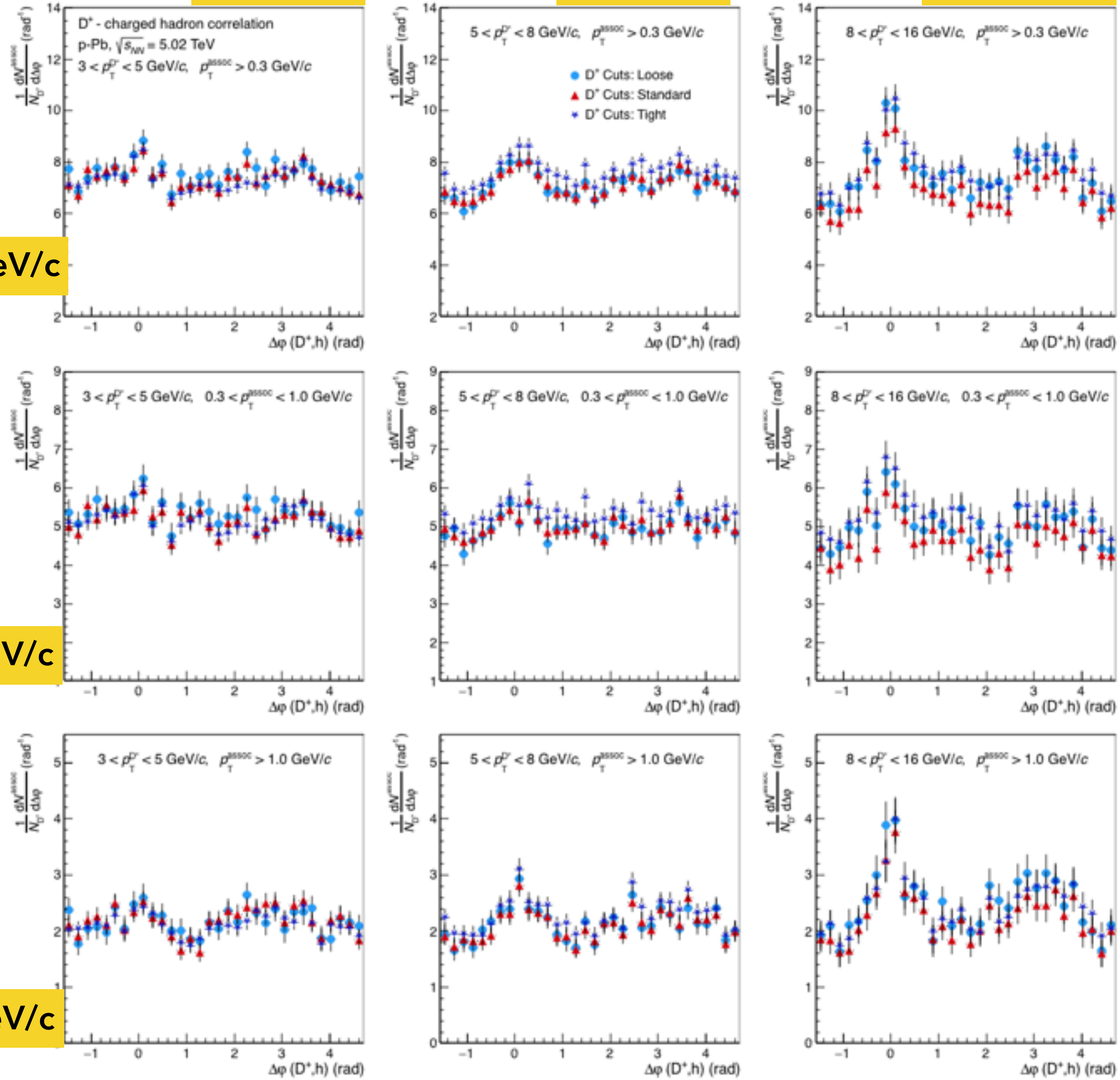
D^+: 3-5 GeV/c | D^+: 5-8 GeV/c | D^+: 8-16 GeV/c

Hadron p_T

> 0.3 GeV/c

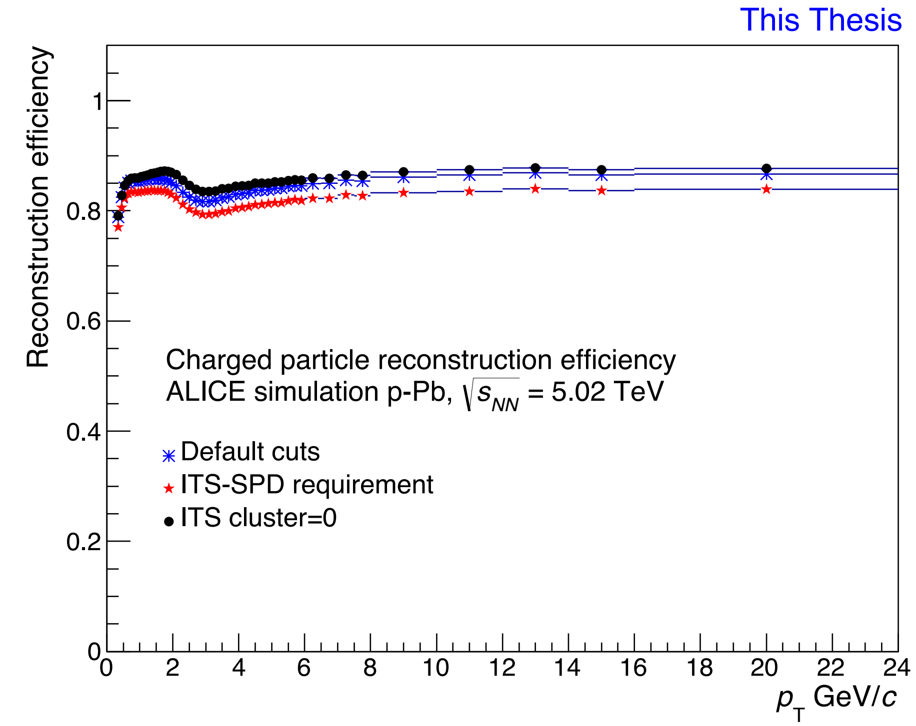
0.3-1.0 GeV/c

>1.0 GeV/c

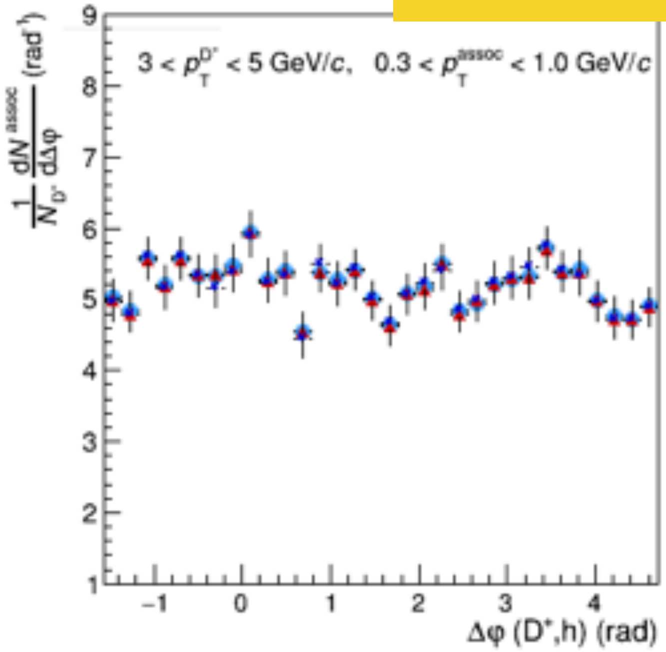


Systematics Study (associated track cuts)

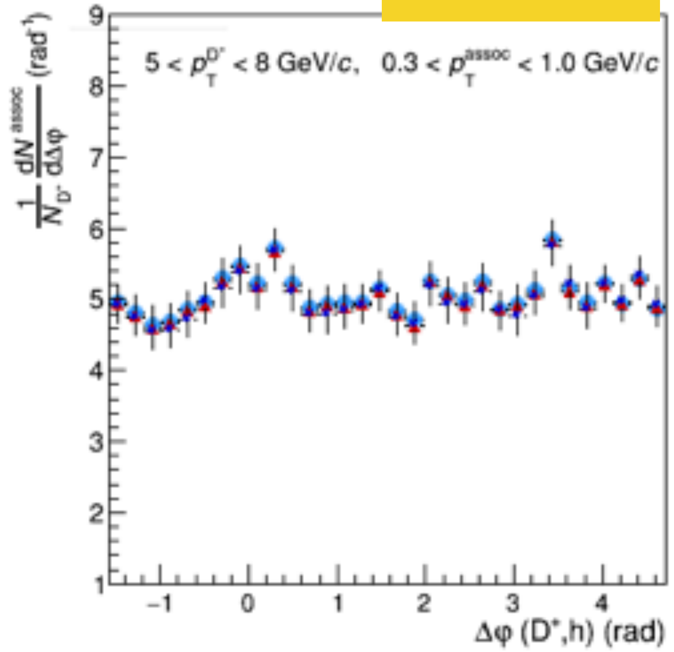
Track Cut Type	Set1 Value (Std)	Set2 Value	Set3 Value
SigmaToVertex	kFALSE	kFALSE	kFALSE
RequireITSRefit	kFALSE	kFALSE	kTRUE
RequireTPCRefit	kTRUE	kTRUE	kTRUE
MinNClustersITS (Min)	3	0	3
MinNClustersTPC (Min)	70	70	70
Chi2PerClusterTPC (Max)	4	4	4
DCAToVertexZ (Max)	1.0	1.0	1.0
DCAToVertexXY (Max)	0.25	0.25	0.25
SPDClusterRequire	No	No	Yes



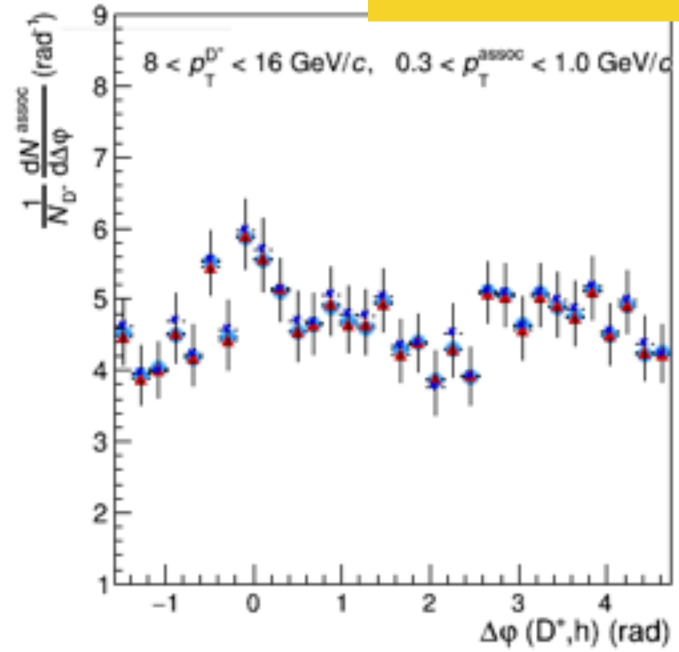
3-5 GeV/c



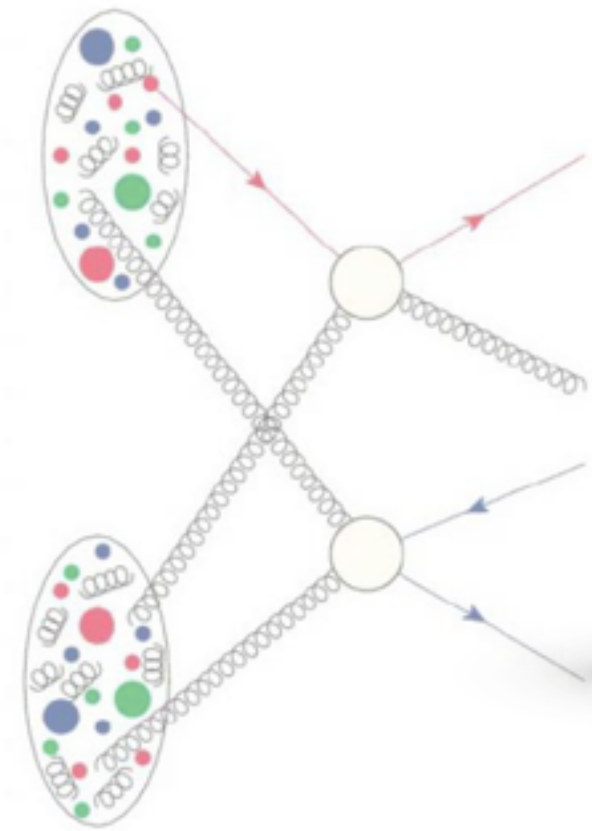
5-8 GeV/c



8-16 GeV/c



Experimental observables



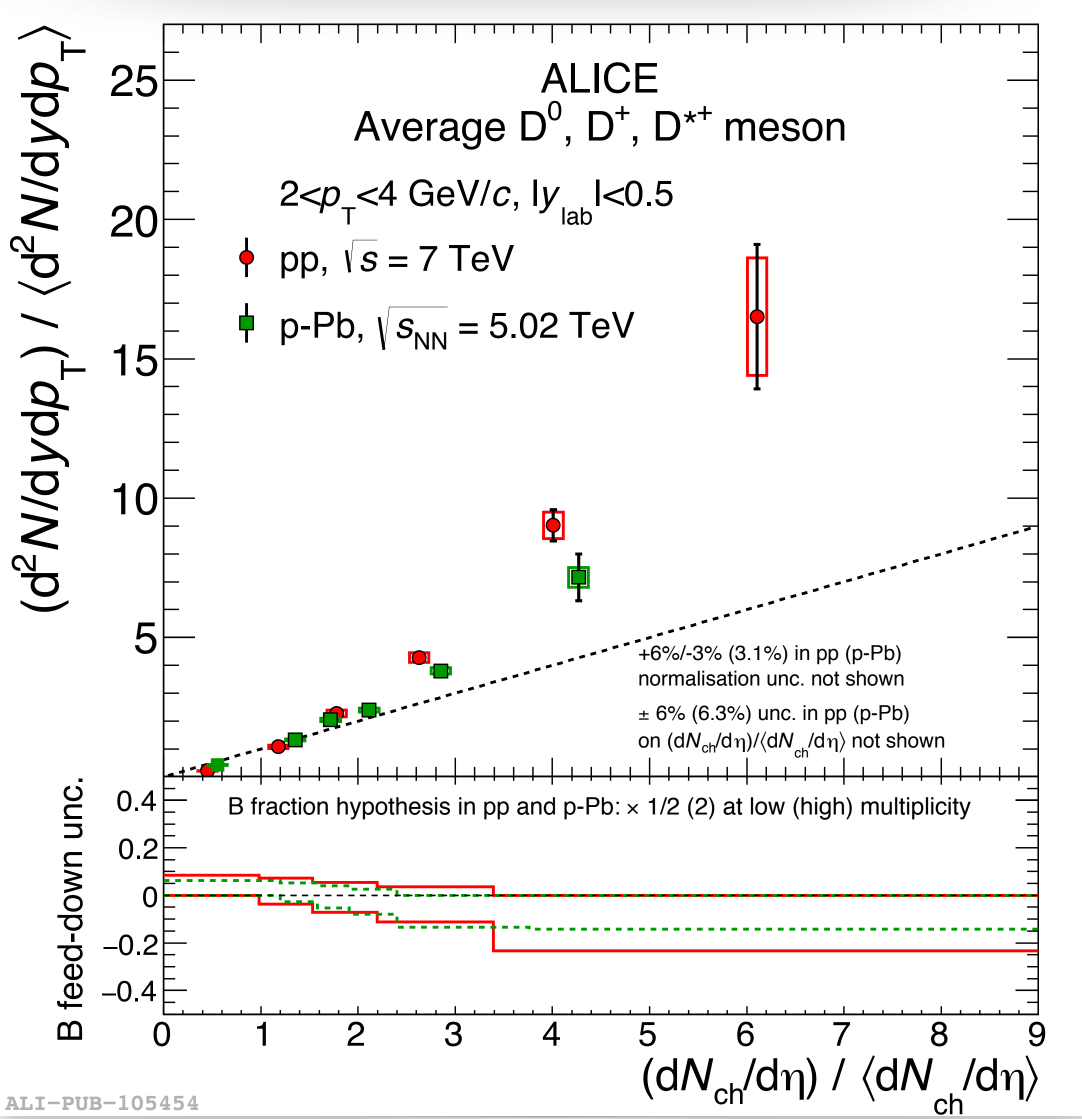
Heavy flavours vs. event multiplicity

- Interplay between hard and soft processes
- Investigate role of multi-partonic interactions (MPI)
- Investigate centrality dependent modification of p_T spectra

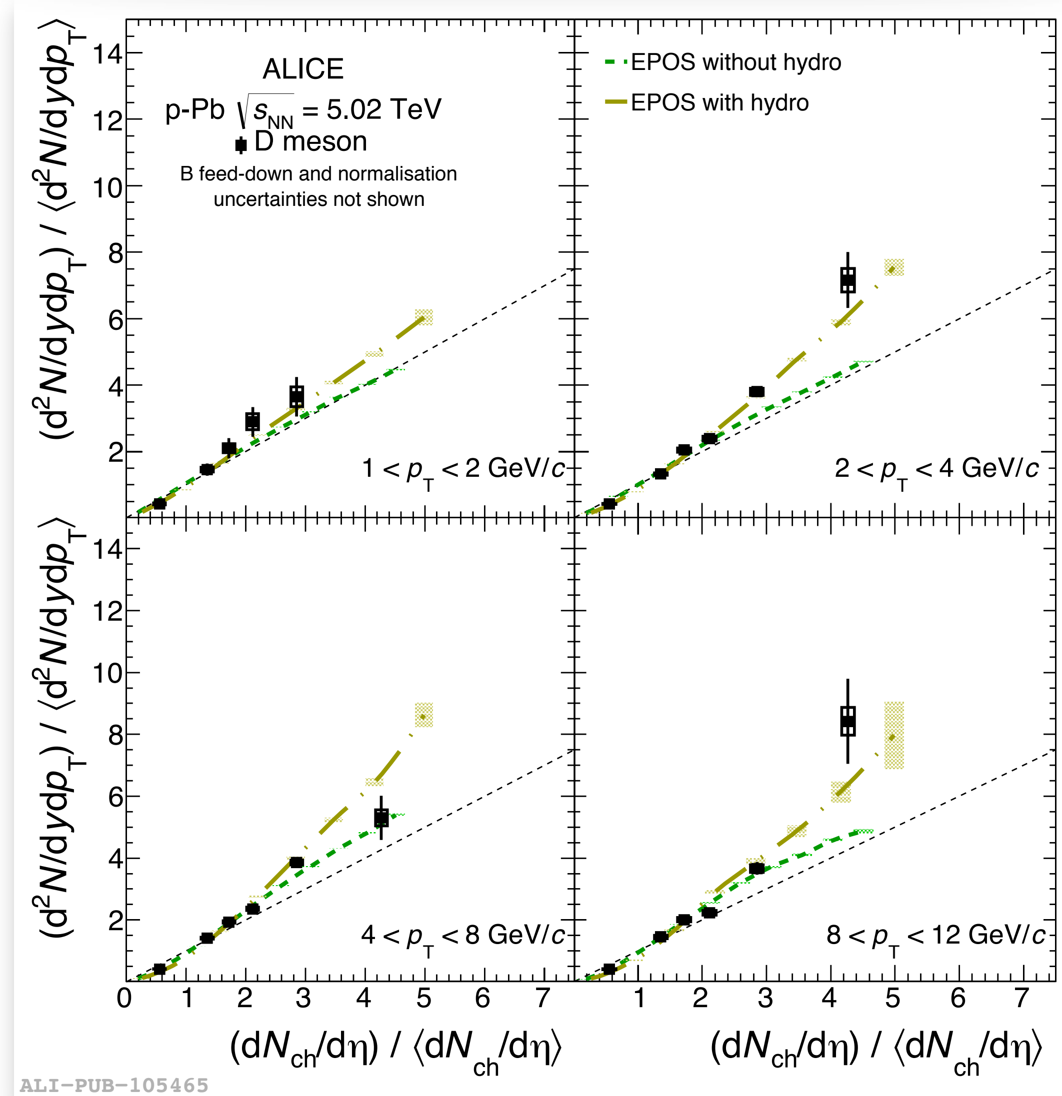
Heavy flavours vs. event multiplicity

Average of D^0, D^{*+}, D^+ mesons

Comparison pp vs. p-Pb



Comparison: p-Pb vs. models



↳ **(Left plot) Comparison with pp results**

Behaviour at high multiplicities is consistent

↳ **(Right plot) Comparison with simulations**

Data are consistent with EPOS-3 (including hydro) calculations

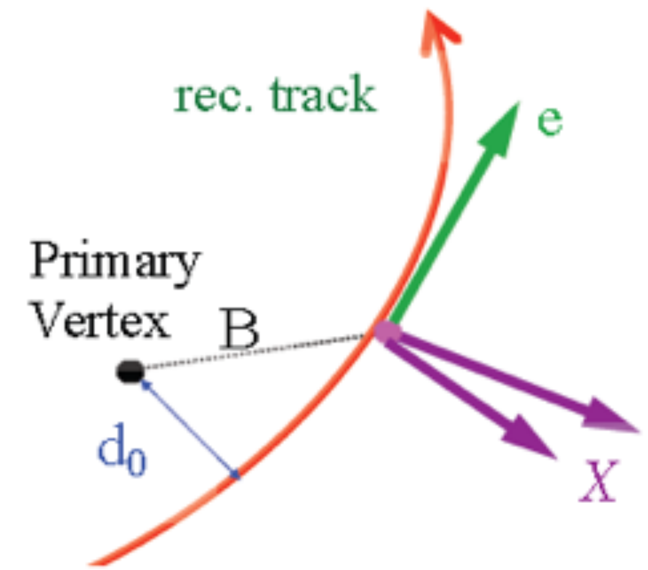
Talk by: Bala, Renu

JHEP 1608 (2016) 078

Heavy-flavour decays

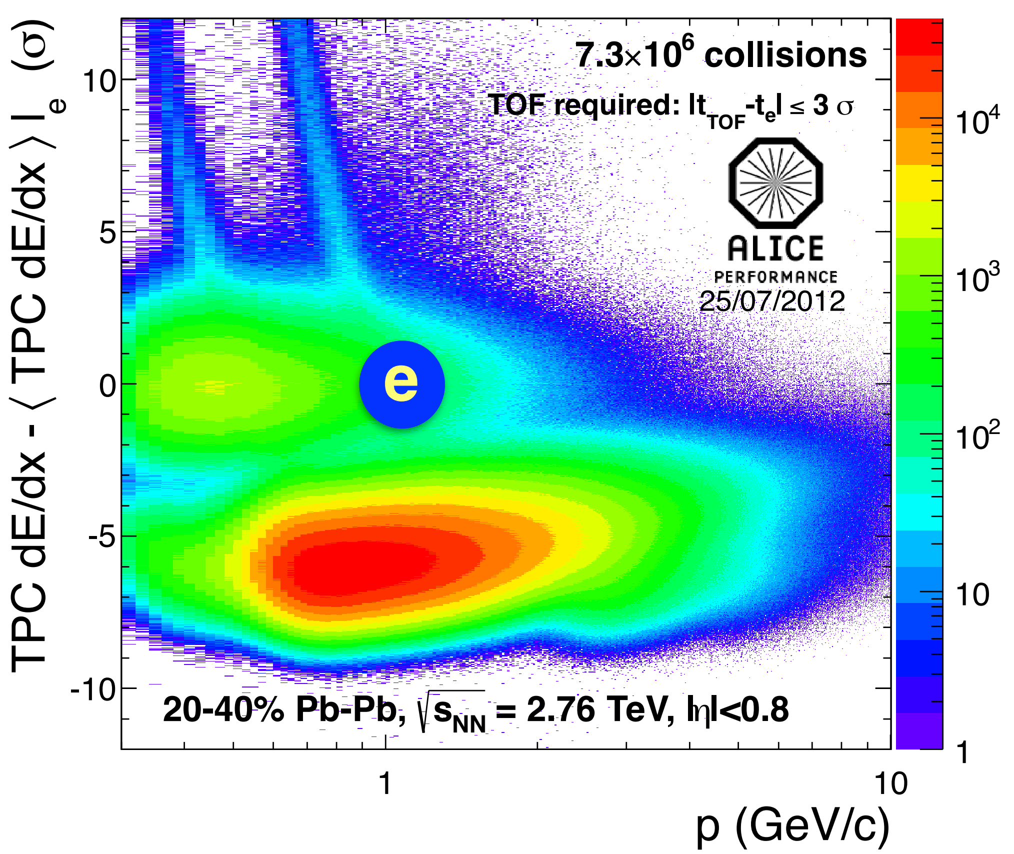
Heavy-flavour decays (e/μ) in ALICE

$D \rightarrow e + X$ or $B \rightarrow e + X$	~10%	at mid rapidity
$D \rightarrow \mu + X$ or $B \rightarrow \mu + X$	~10%	at forward rapidity



Particle identification

Example: HF-decay electrons



ALI-PERF-31572

Electron background (π^0 and η Dalitz decays, photon conversions) subtracted via:

- **Invariant mass method** (e^+e^- pairs)
- **Cocktail:** using Monte Carlo generator

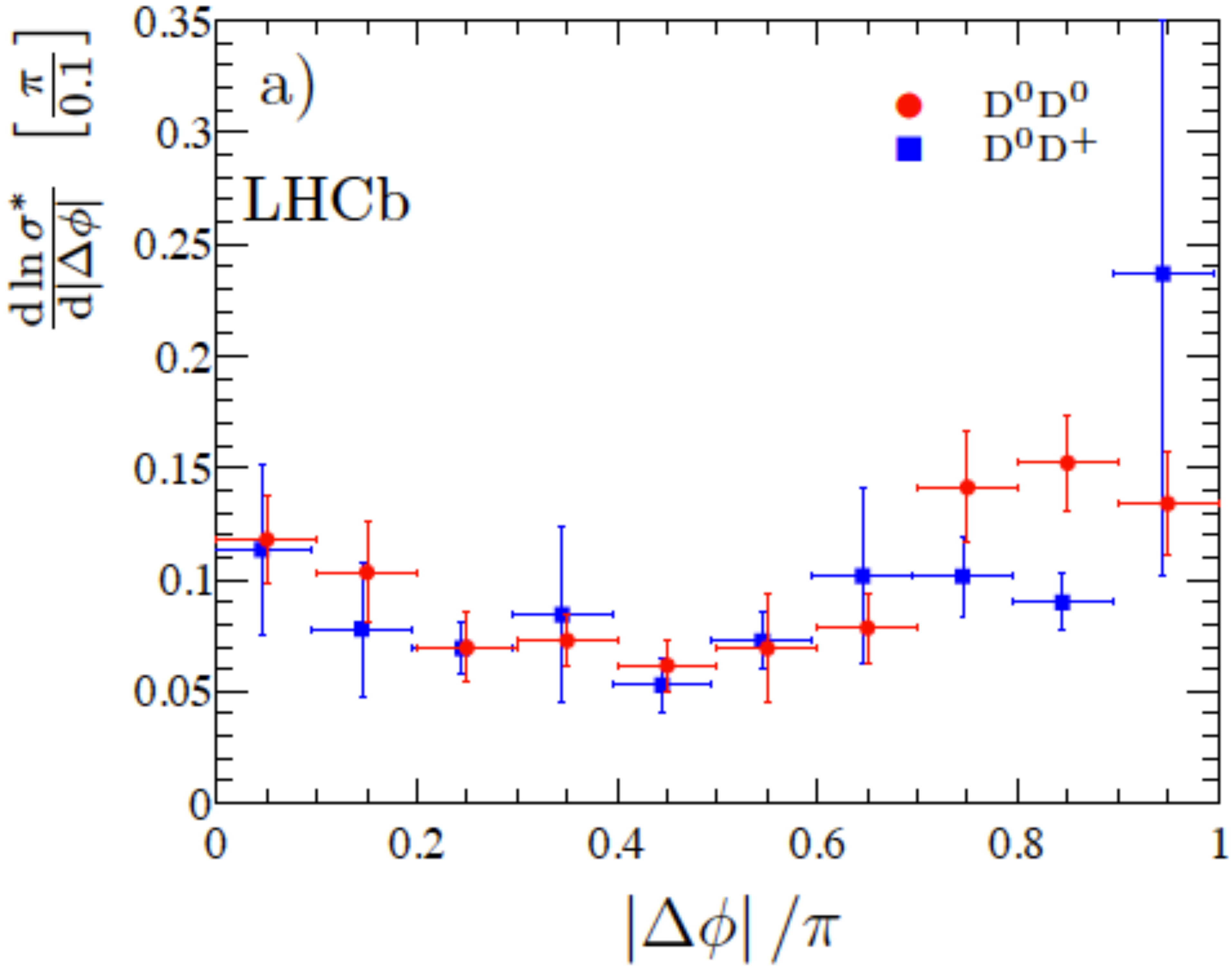
Muon background ($\pi, K \rightarrow \mu$) subtracted via:

- **with MC (pp)**
- **Cocktail with data tuned MC (p-Pb)**

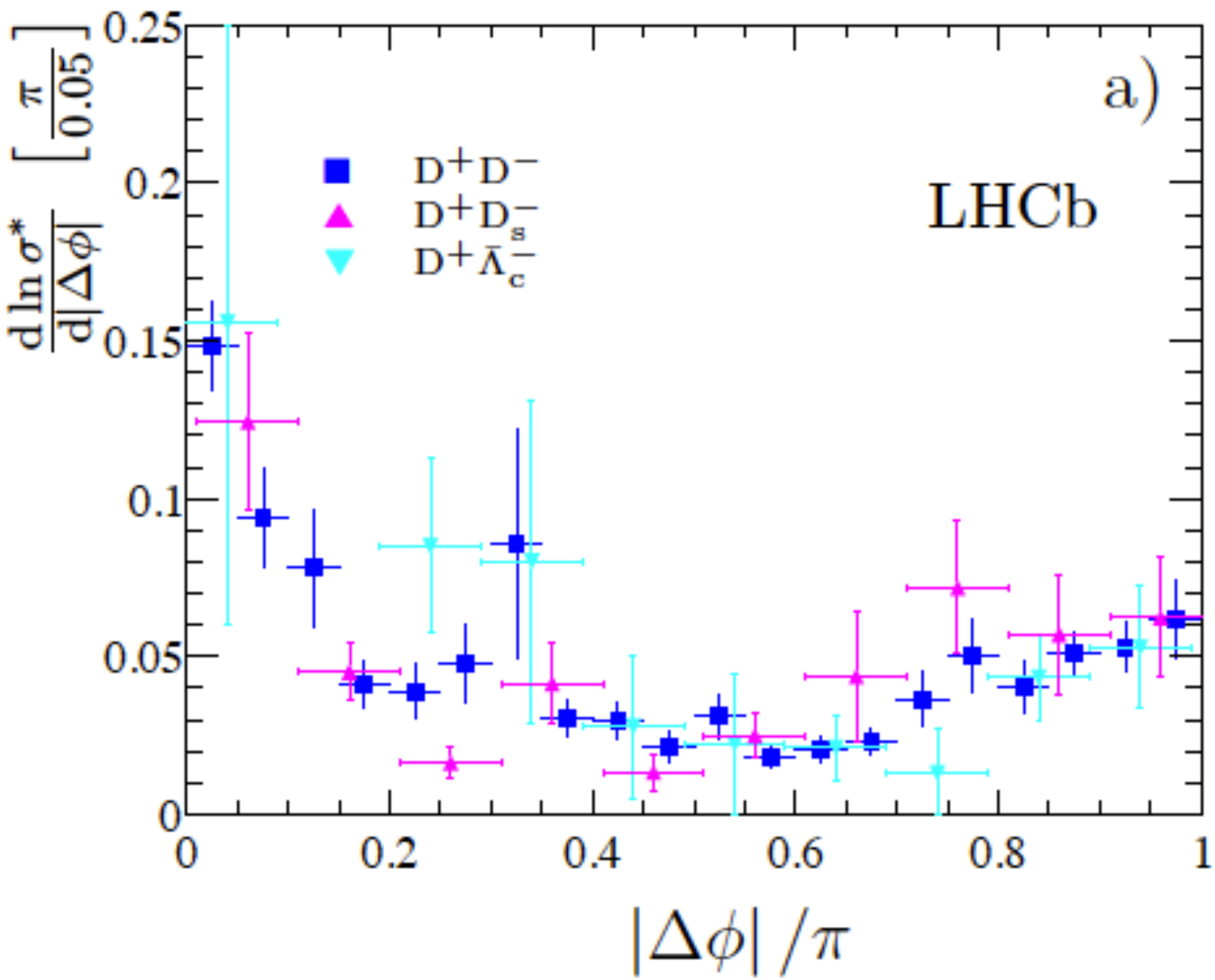
Measurement of beauty-decay electrons

- via track impact parameter cut
- via separation based on e-h correlations

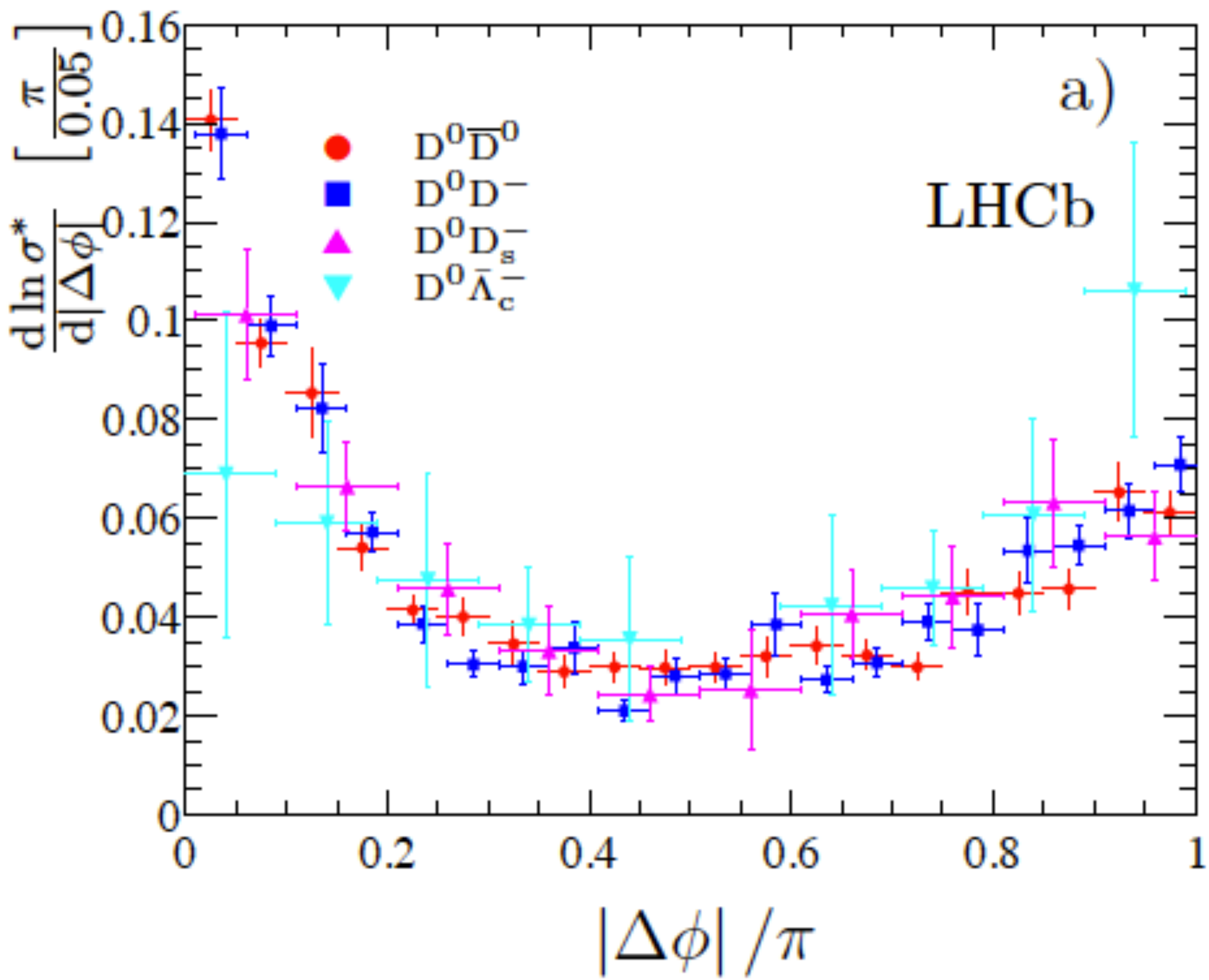
LHCb results for c-cbar event correlations



LHCb results for c-cbar event correlations



LHCb results for c-cbar event correlations



Final Results

Average of D meson correlations

$$\left\langle \frac{1}{N_{\mathrm{D}}} \frac{d\mathrm{N}^{assoc}}{d\Delta\varphi} \right\rangle_D = \frac{\sum_{i=D} w_i \frac{1}{\mathrm{ND}} \frac{dN_i^{assoc}}{d\Delta\varphi}}{\sum_{i=D} w_i}$$

$$w_i = \frac{1}{\sigma^2_{i,stat} + \sigma^2_{i,uncorr-syst}}$$

Beauty Feed Down Subtraction

$$\tilde{C}_{\mathrm{prompt-D}}(\Delta\varphi) = \frac{1}{f_{\mathrm{prompt}}}\left(\tilde{C}_{\mathrm{inclusive}}(\Delta\varphi) - (1 - f_{\mathrm{prompt}})\tilde{C}^{\mathrm{MC-tempt}}_{\mathrm{feed-down}}(\Delta\varphi)\right)$$

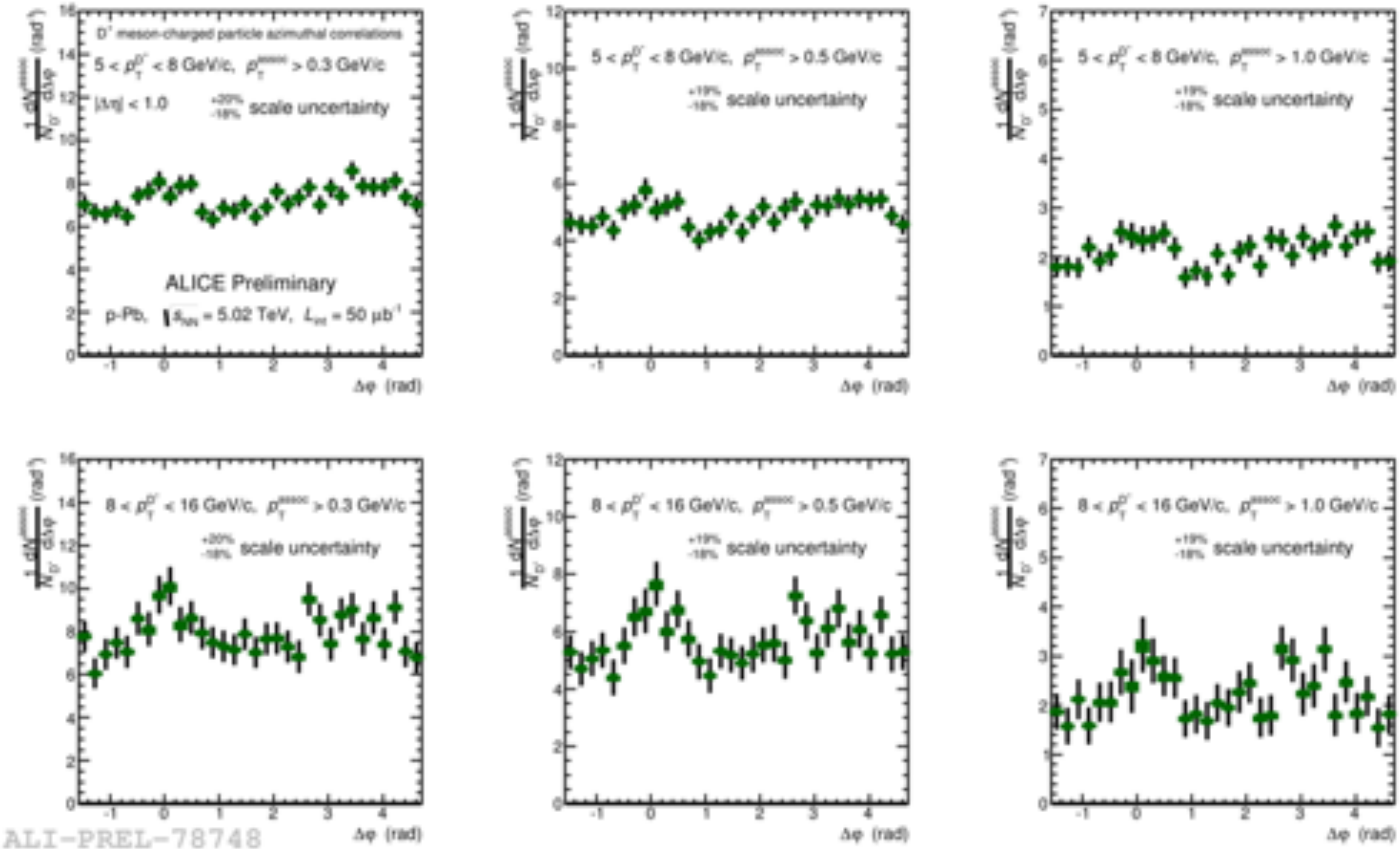
f_{prompt} is the fraction of prompt D meson

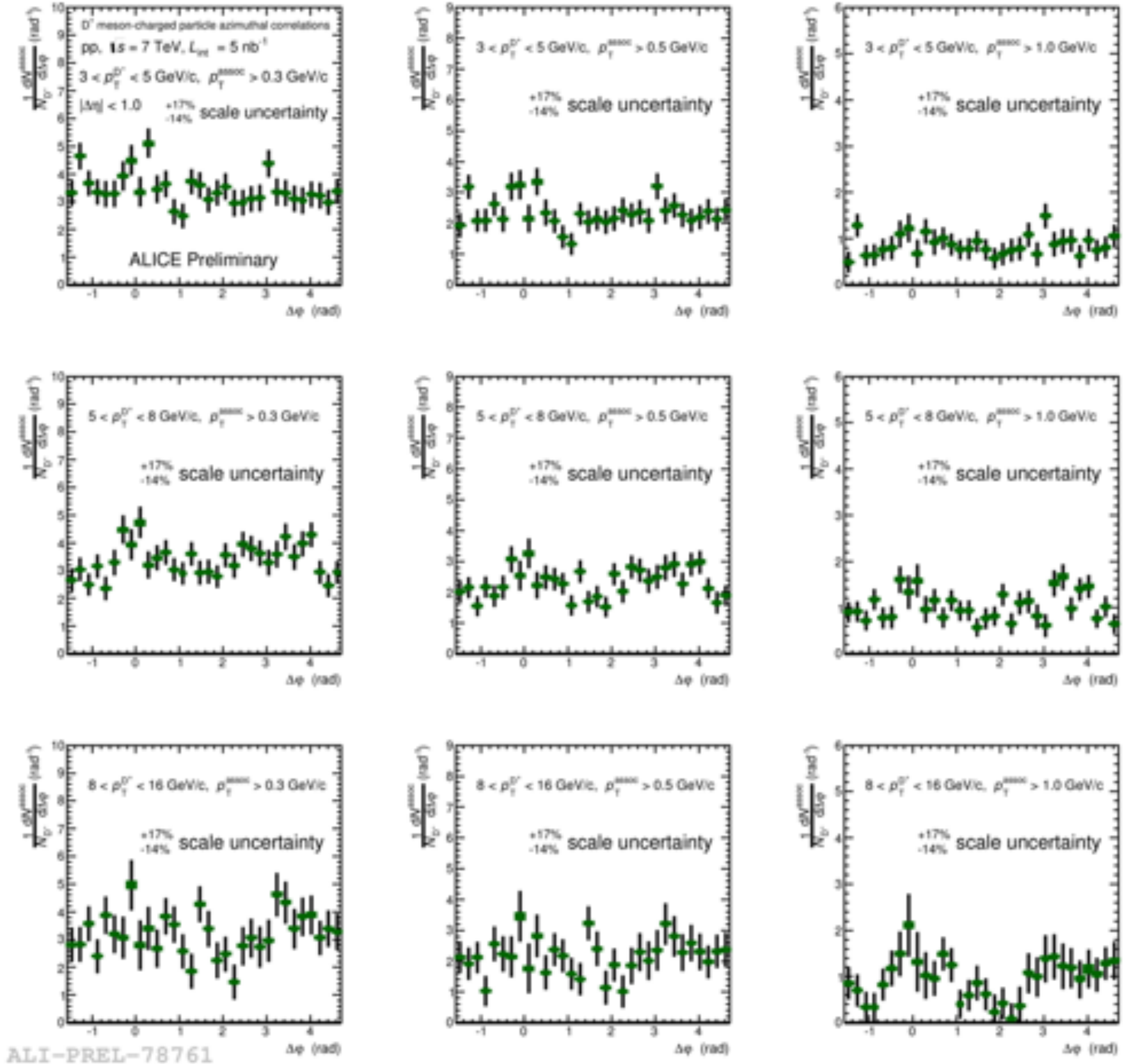
Asymptotic freedom and Quark confinement

$$\alpha(Q^2) \equiv \frac{g_s(Q^2)}{4\pi} = \frac{4\pi}{(11 - \frac{2}{3}n_f)ln\frac{Q^2}{\Lambda^2_{QCD}}} \tag{1.2}$$

g_s = QCD coupling constant,
n_f = number of quarks,
Q^2 = momentum transferred in strong interaction,
and Λ_{QCD} = QCD scale parameter and the expected value is $\simeq$ 250 MeV.

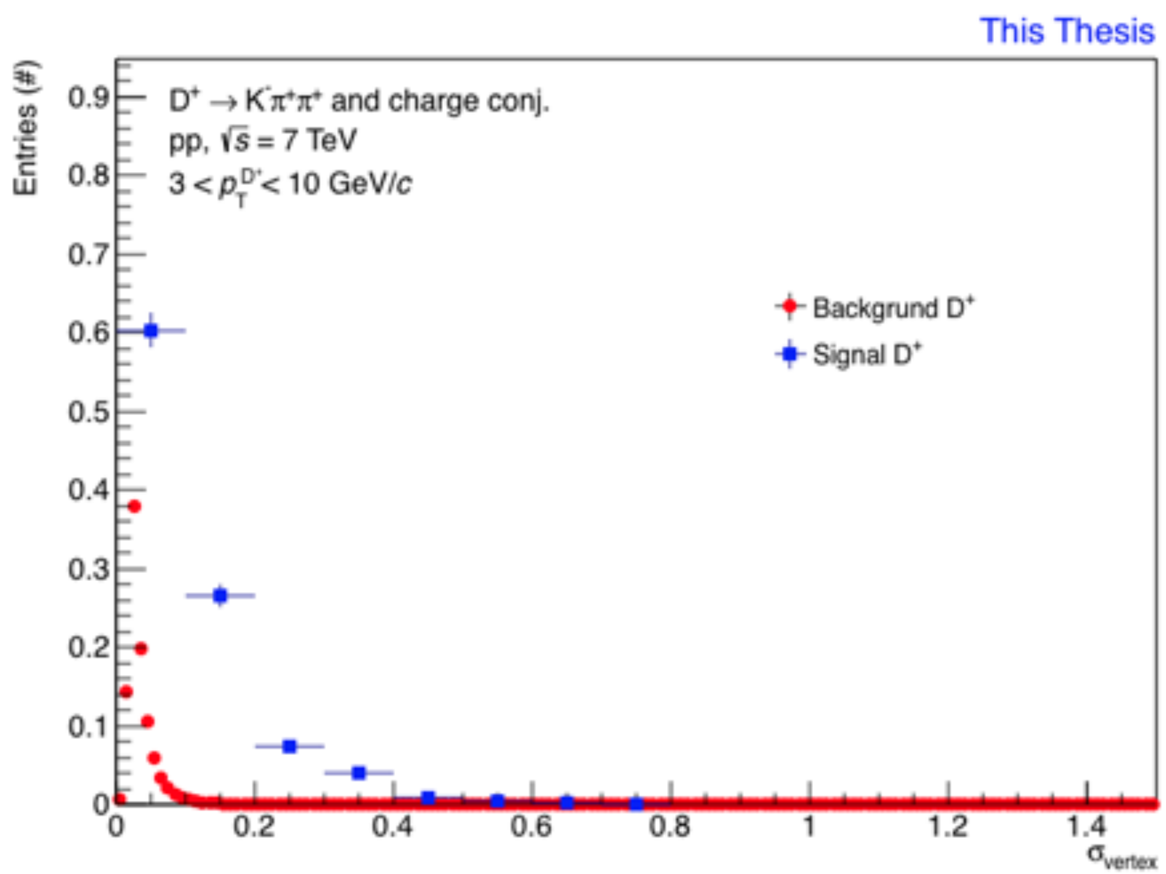
Final Results

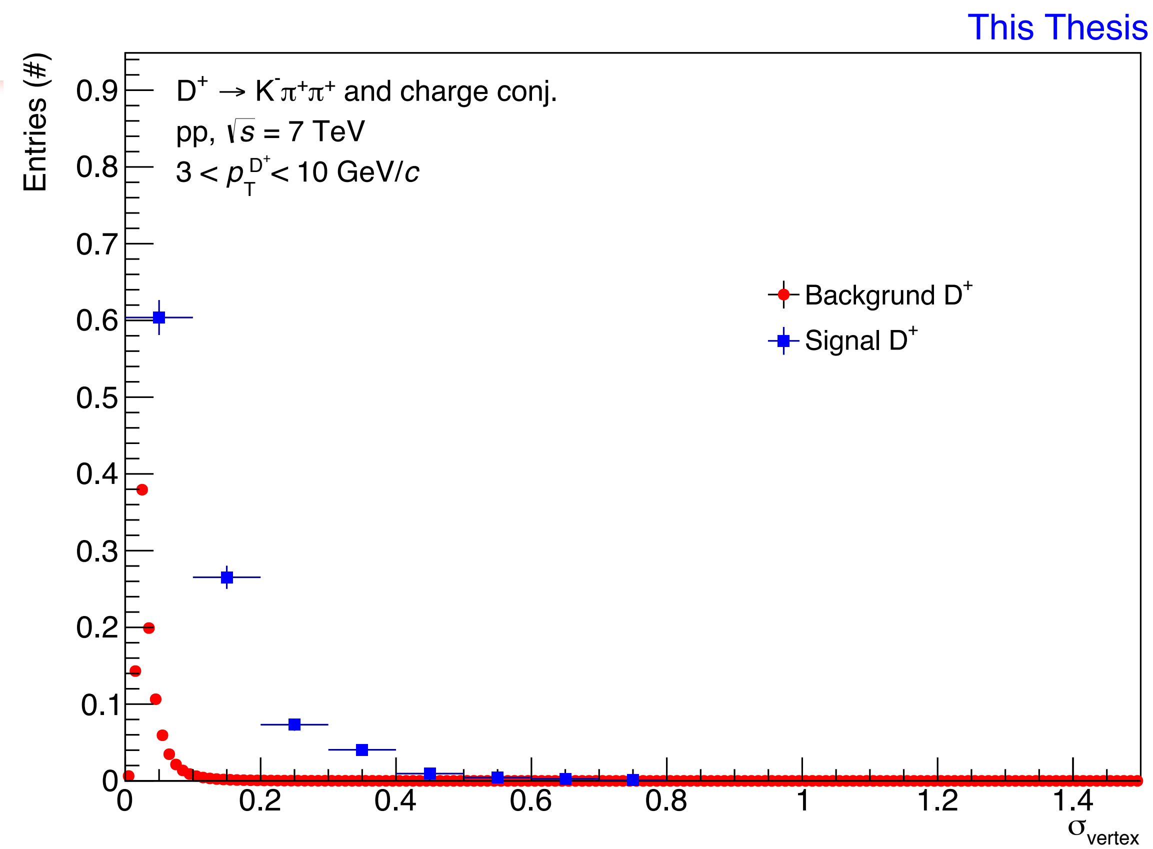


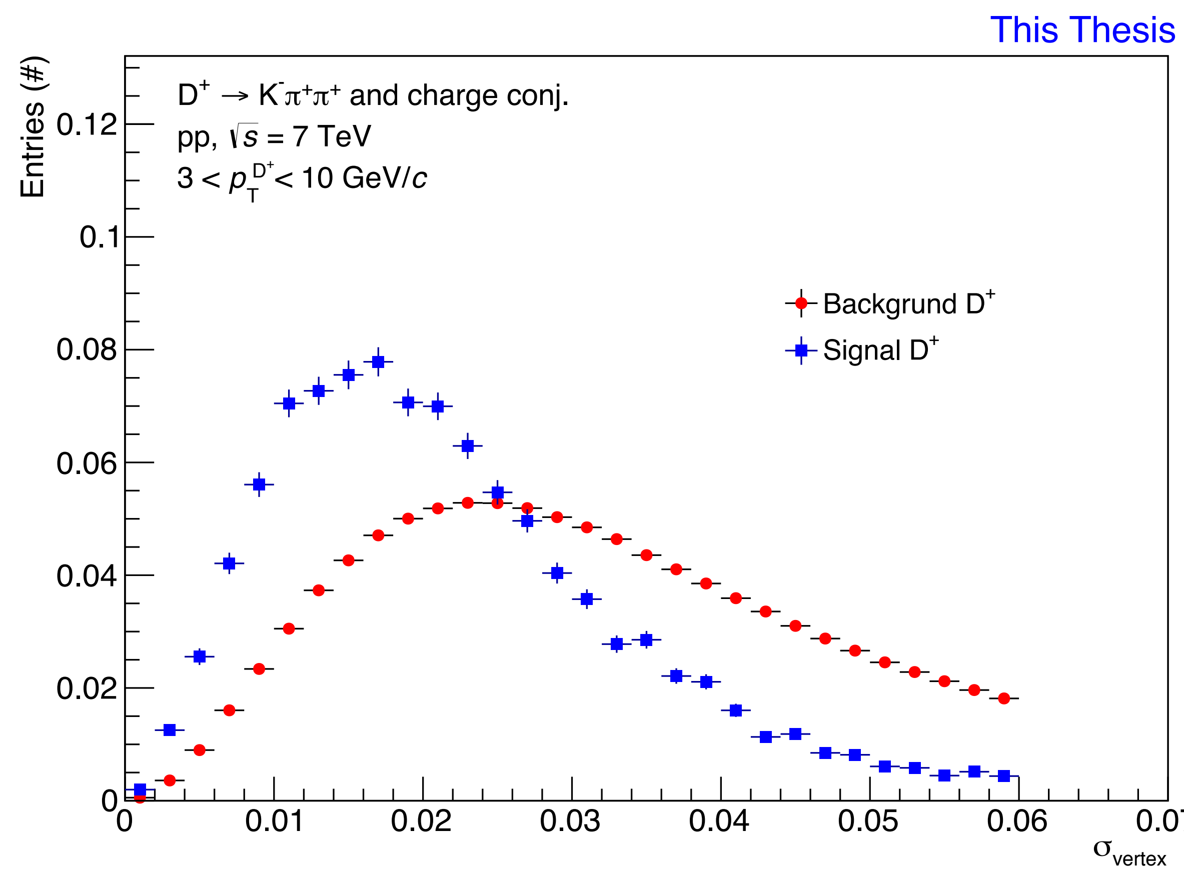


D* meson-charged particle azimuthal correlations
pp, √s = 7 TeV, L_int = 5 nb⁻¹
3 < p_T^D* < 5 GeV/c, p_T^assoc > 0.3 GeV/c
|Δη| < 1.0
+17% -14% scale uncertainty
ALICE Preliminary
3 < p_T^D* < 5 GeV/c, p_T^assoc > 0.5 GeV/c
3 < p_T^D* < 5 GeV/c, p_T^assoc > 1.0 GeV/c
5 < p_T^D* < 8 GeV/c, p_T^assoc > 0.3 GeV/c
5 < p_T^D* < 8 GeV/c, p_T^assoc > 0.5 GeV/c
5 < p_T^D* < 8 GeV/c, p_T^assoc > 1.0 GeV/c
8 < p_T^D* < 16 GeV/c, p_T^assoc > 0.3 GeV/c
8 < p_T^D* < 16 GeV/c, p_T^assoc > 0.5 GeV/c
8 < p_T^D* < 16 GeV/c, p_T^assoc > 1.0 GeV/c
Δφ (rad)
ALI-PREL-78761

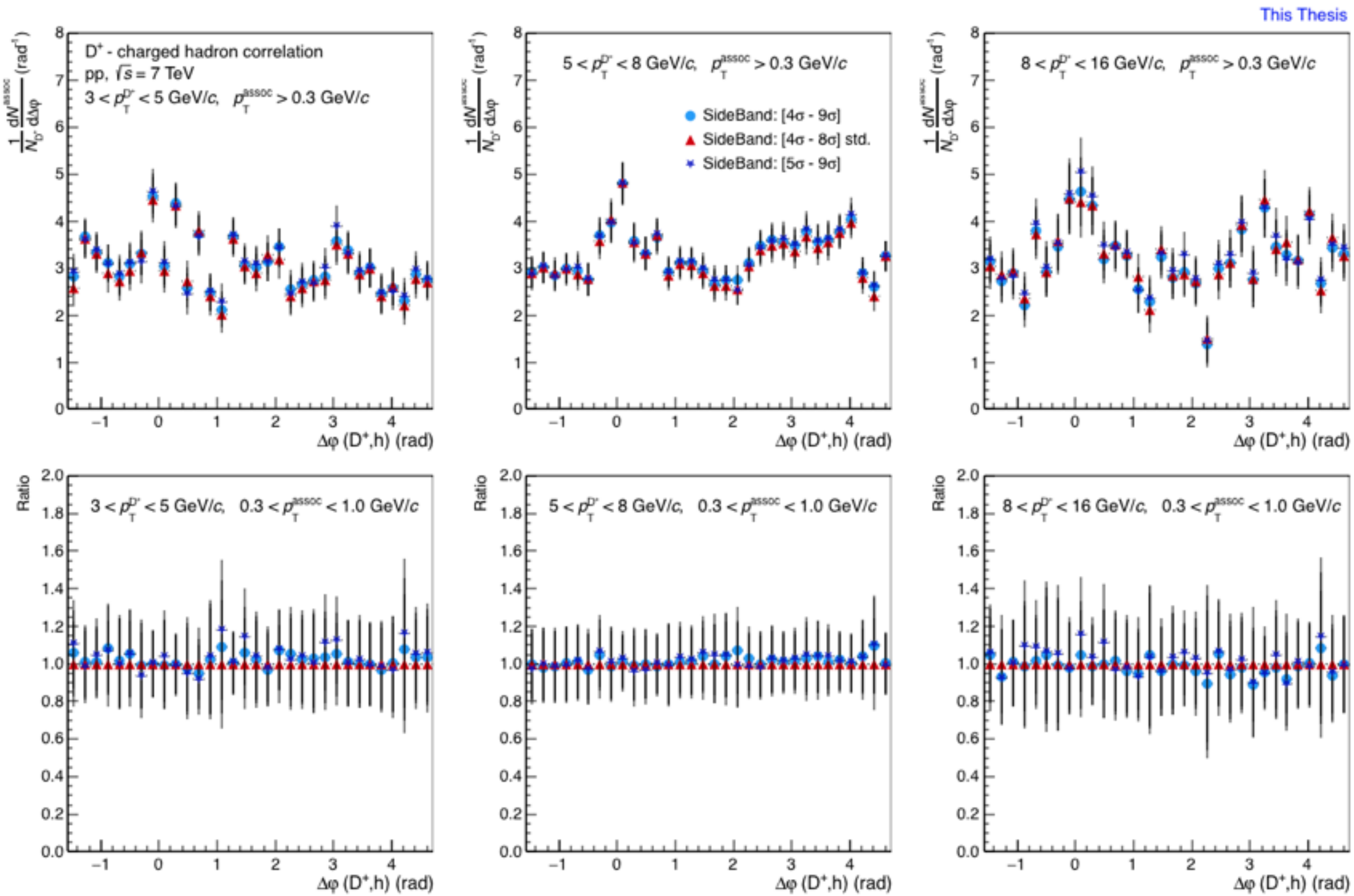
Cut Distribution of D meson

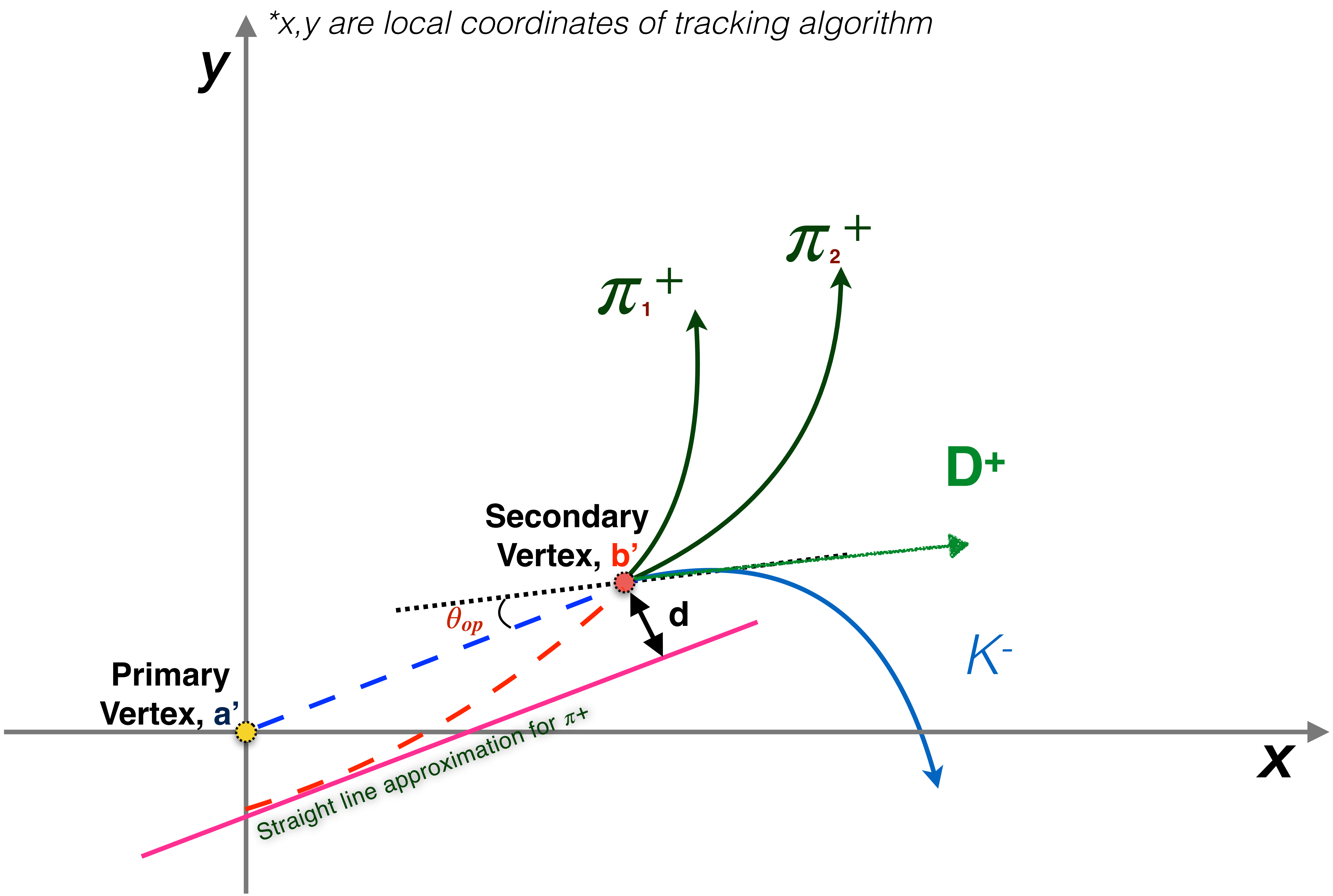






Example of systematic studies..




*x,y are local coordinates of tracking algorithm
y
x
π_1^+
π_2^+
D+
Secondary Vertex, b'
Primary Vertex, a'
θ_{op}
d
K^-
Straight line approximation for $\pi+$

CNM effect in p-Pb collisions !

- Nuclear shadowing
- Initial/final-state energy loss
- Initial-state k_T broadening
- Multiple nucleon-nucleon collisions

k_T broadening via cronin effect:

– initial-state multiple scatterings of the partons in cold nuclei resulting parton transverse momentum kick

Nuclear Shadowing:

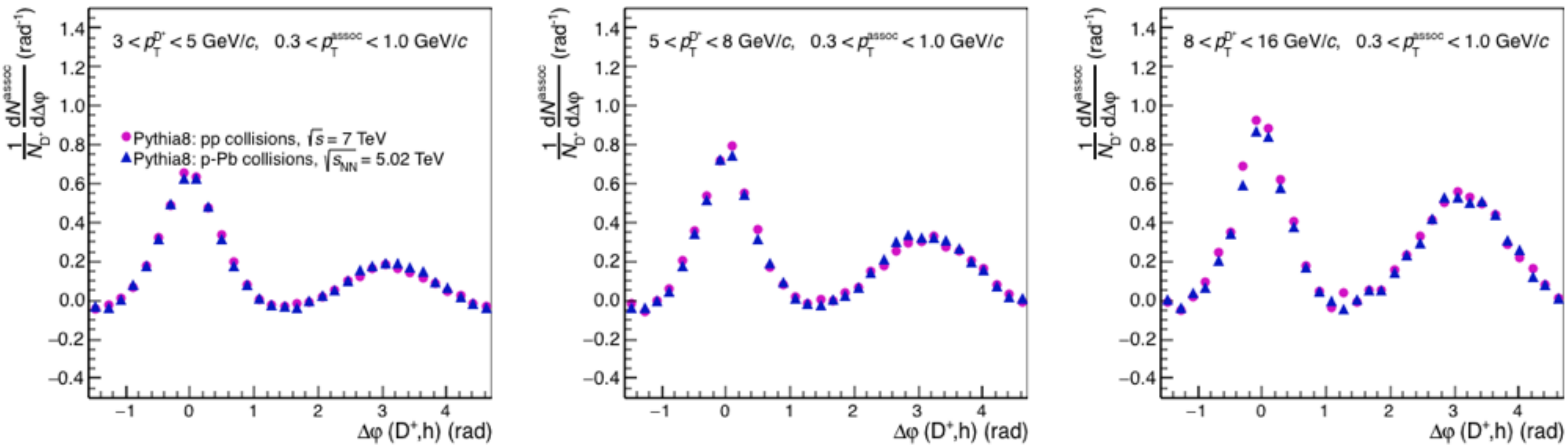
– The PDFs of colliding parton in the nucleus gets modified due to presence of other partons (screening).

– Gluon distribution functions are modified in nuclear medium

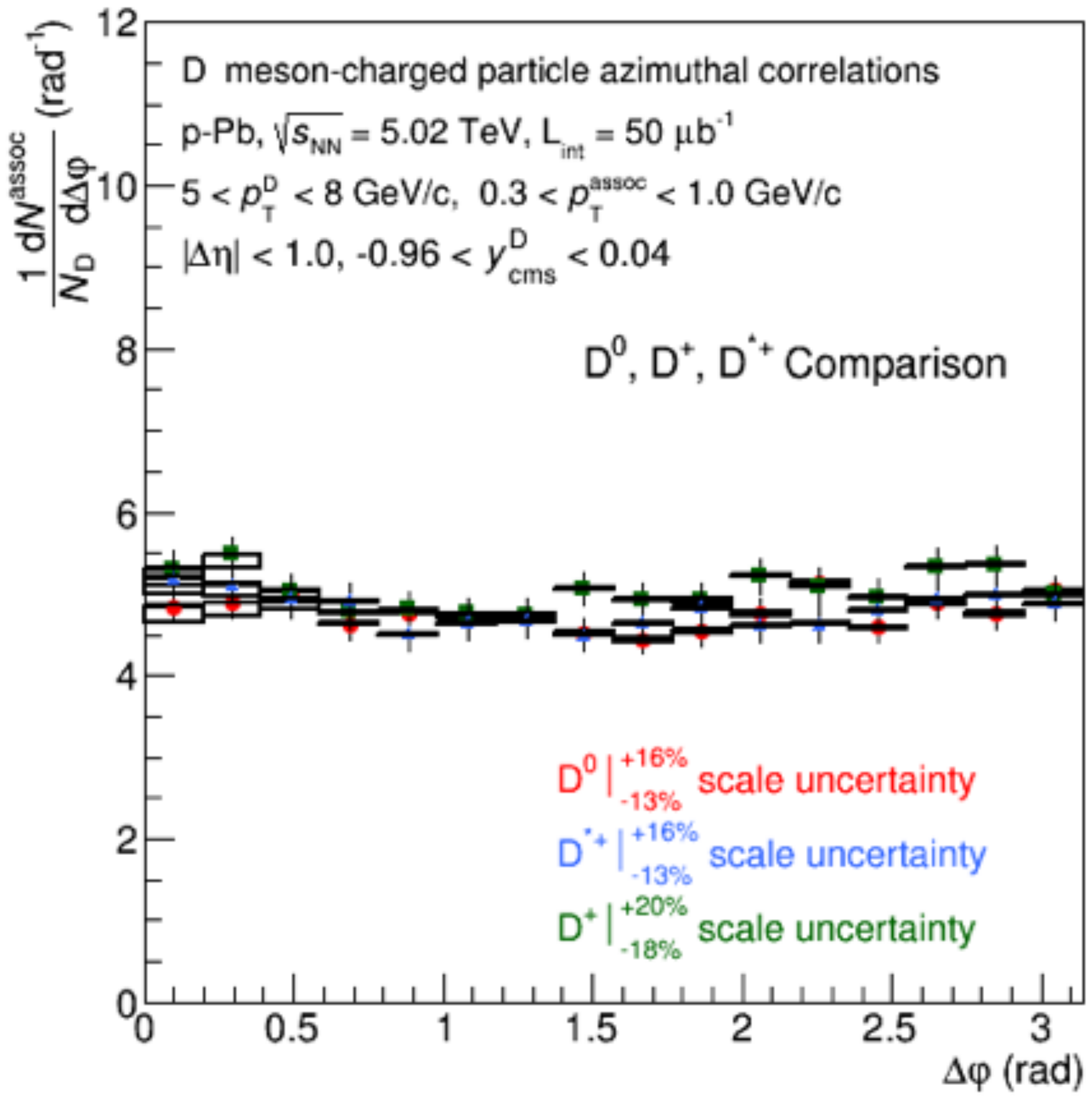
Initial state energy loss

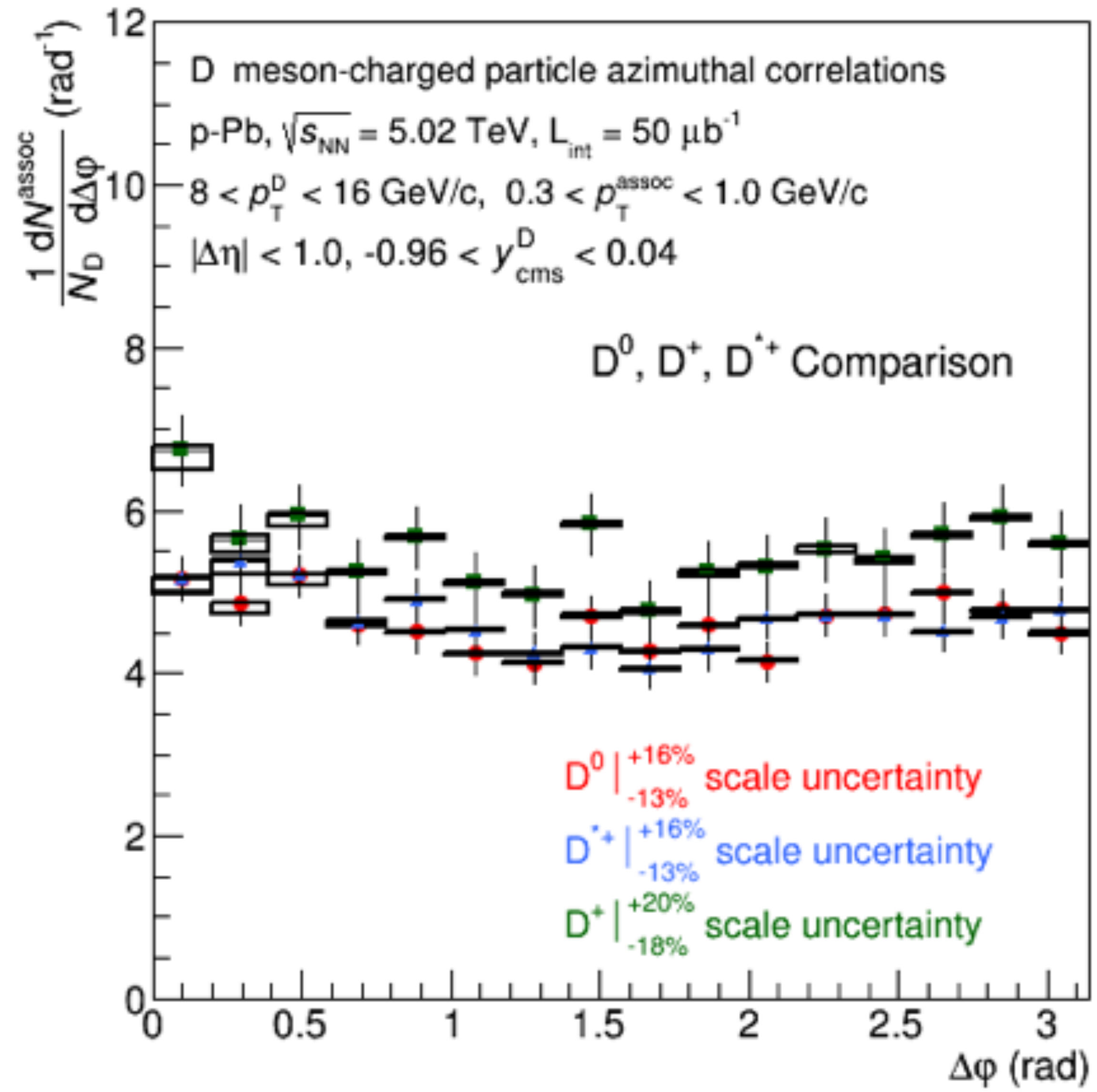
– Energy loss in cold nuclear matter: Before hard collisions, the partons from the protons can lose their energy inside the cold nucleus.

Example of simulation pp vs p-Pb collisions
~ 7% difference max < Current uncertainties

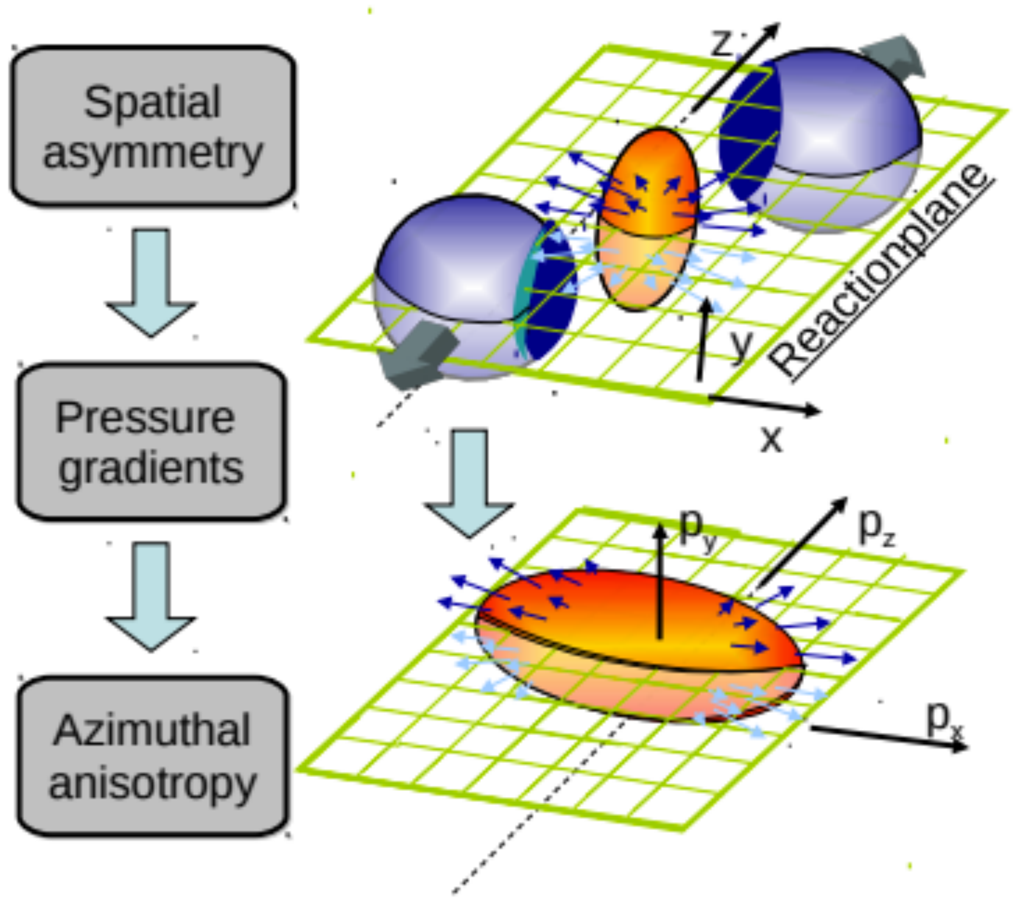


Comparison of Different D mesons





elliptic flow measurement !



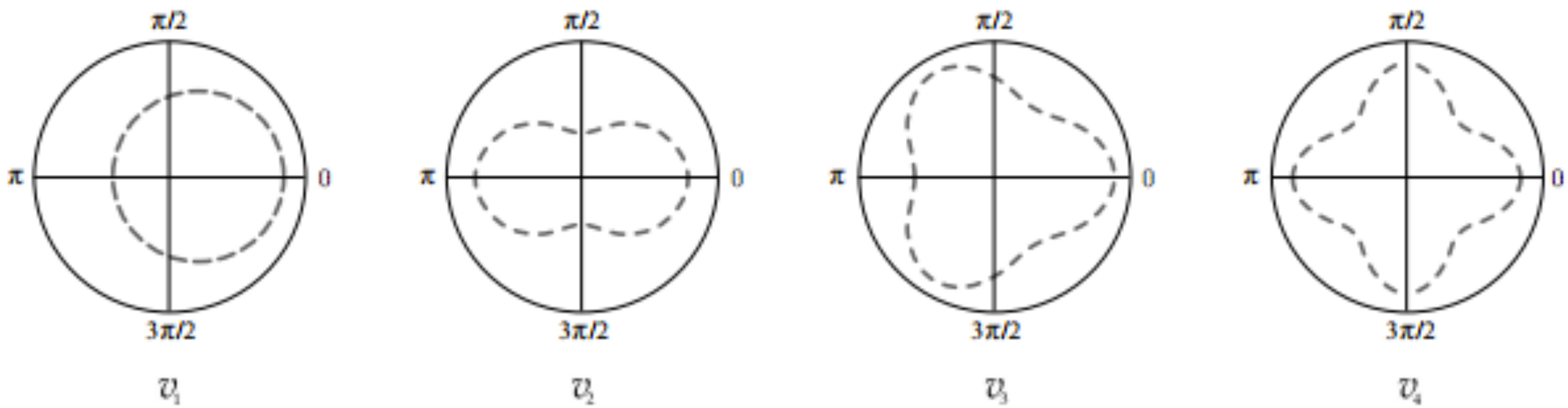


Figure 2.2: Illustration of the first four harmonics in the transverse plane, v_1, v_2, v_3 and v_4.

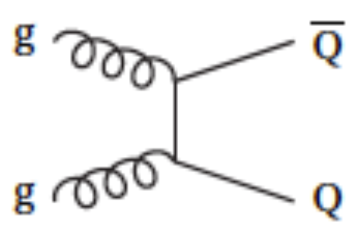
Surface bias

↳The probability of particle interaction with medium increases with path length, hence the high-p_T hadrons are more sensitive to particles travelling outward from near-surface region of the collision zone, also known as ``surface biased effect''.

– This increases the probability of interaction for opposite side jet (``di-jet asymmetry'')

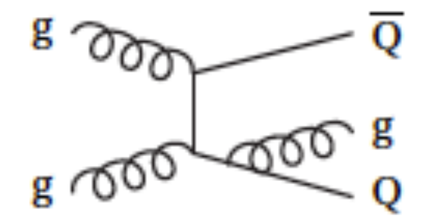
HF-Production

The pairs of heavy quarks and its anti-quarks are predominantly produced in hard scattering processes (e.g. flavour creation, flavour excitation and gluon splitting).

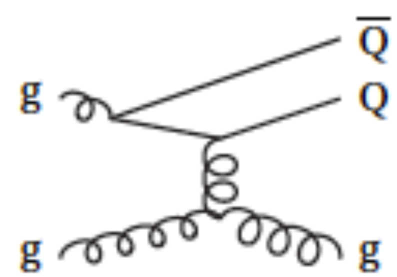


Leading order process (1)

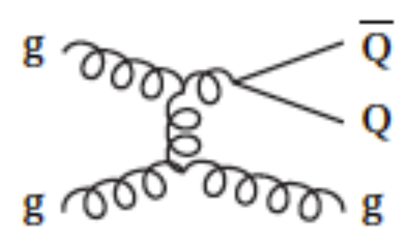
Leading order process (2)



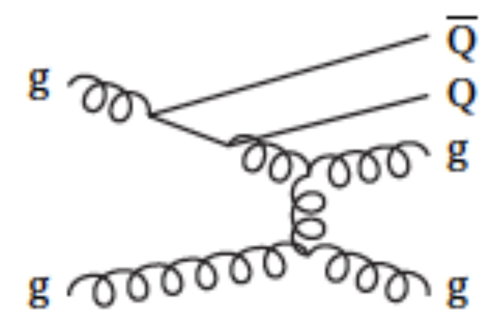
Pair creation
(with gluon emission)



Flavour excitation

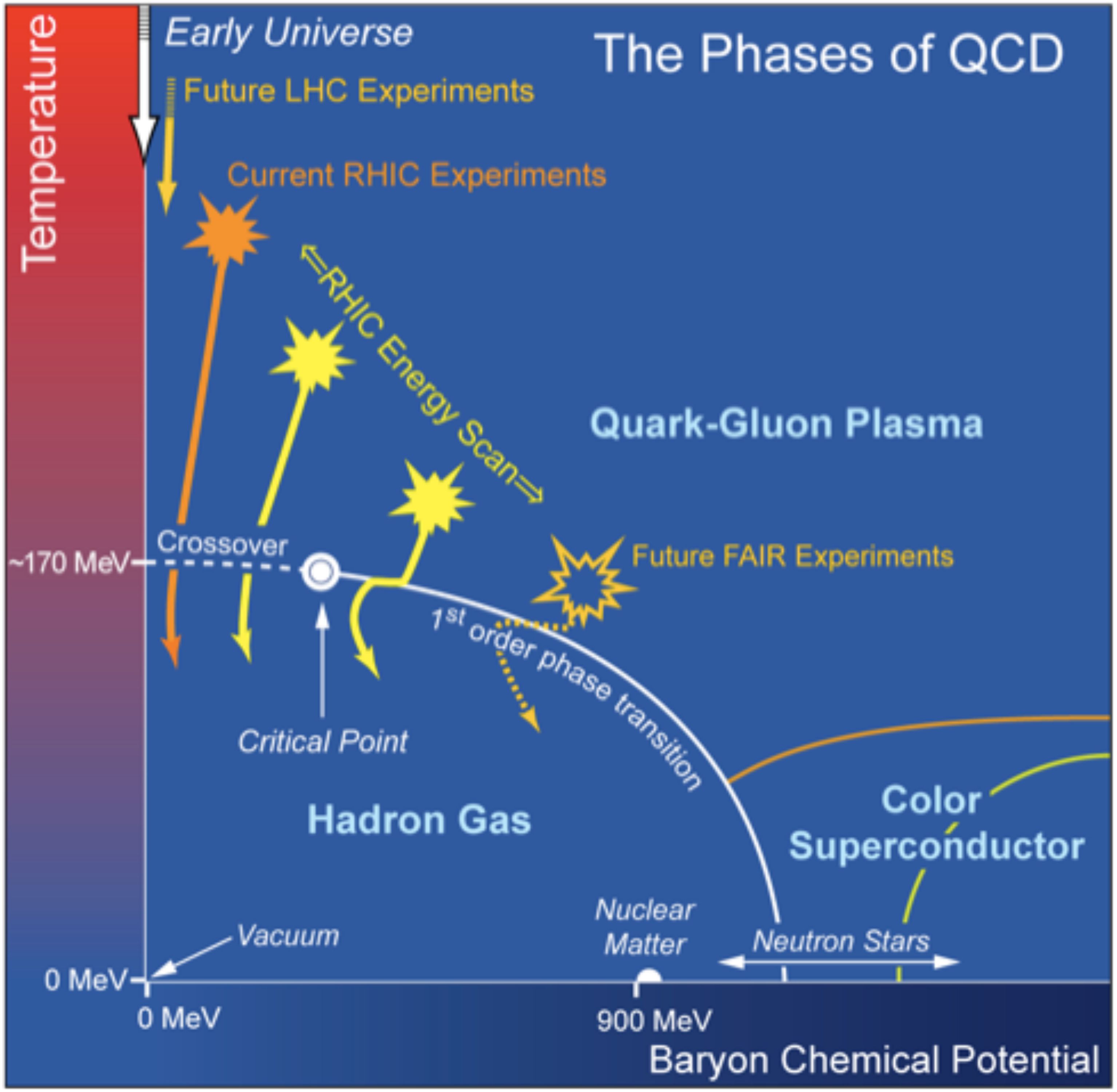


Gluon splitting



Gluon splitting
(w/ flavour-excitation character)

QCD Phase Diagram



QGP time evaluation