QCD measurements in the forward region at LHCb

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QCD and High Energy Interactions

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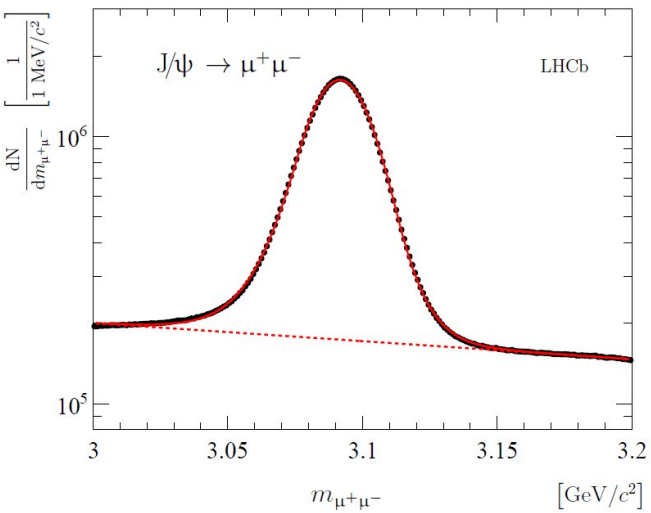
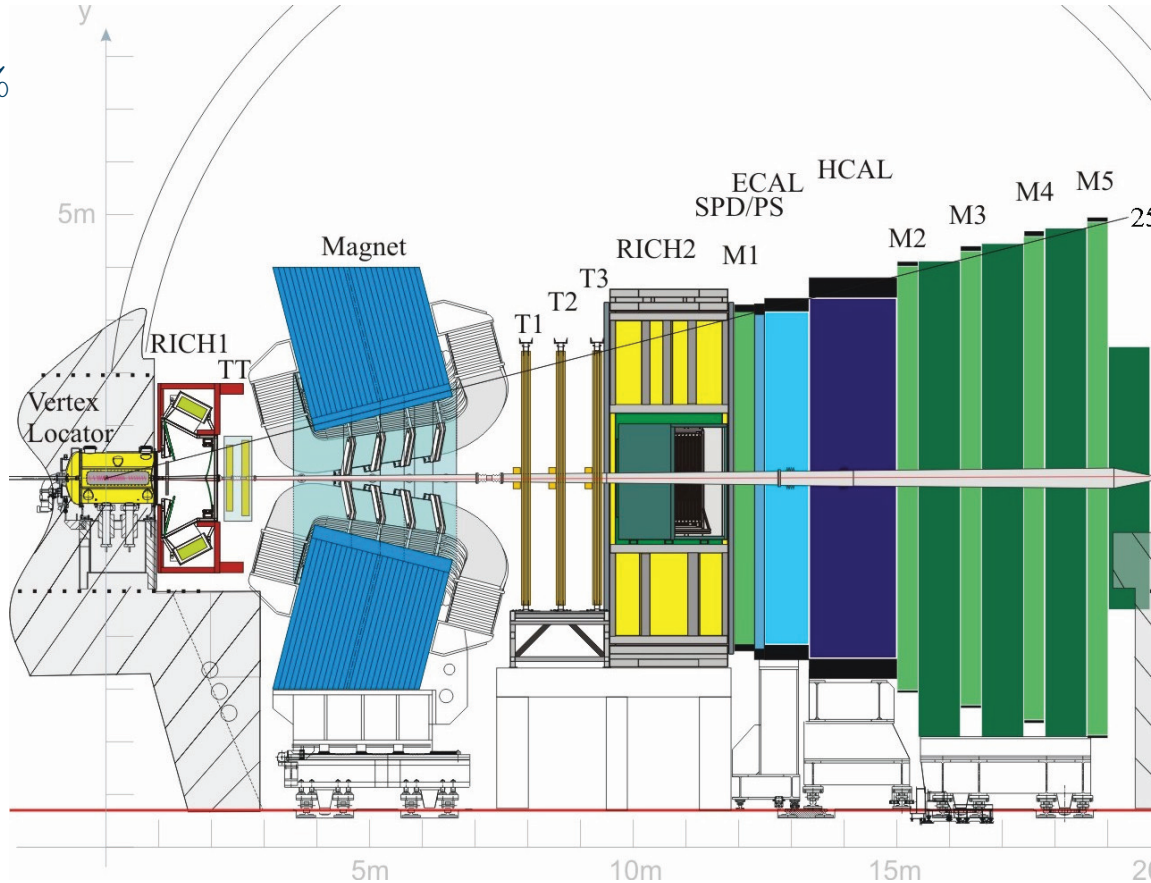
Outline

1. LHCb experiment
2. Selected QCD results
   - $\sigma(\chi_c \to J/\psi\gamma)/\sigma(J/\psi)$
   - $\psi(2S)$ production cross section
   - Double charm production
   - Charged track multiplicity
   - $\overline{p}/p$ ratio

- Designed for CP violation and rare decays of heavy mesons
- Single arm forward spectrometer, $b\bar{b}$ pair production correlated, 40 % in the acceptance.
- Unique kinematic region (among the LHC experiments): high rapidity ($2 < \eta < 5$) and able to access low p_T
- Huge amount of $b\bar{b}$ produced ($\sigma \sim 300\,\mu$b)
- Excellent momentum resolution and PID





New result - Never shown before.

$$\sigma(\chi_c \to J/\psi\gamma)/\sigma(J/\psi)$$

LHCb-PAPER-2011-030

$\sigma(\chi_c \to J/\psi\gamma)/\sigma(J/\psi)$

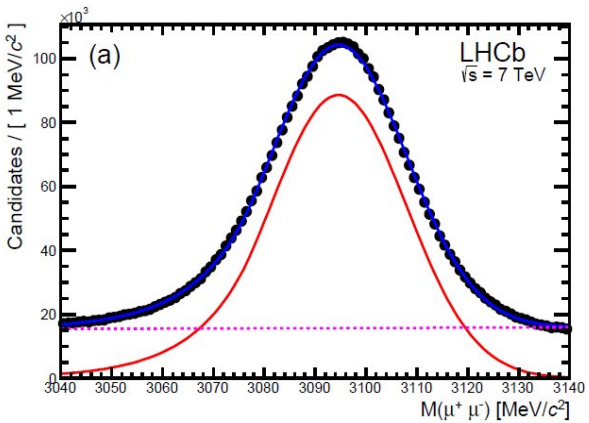
- χ_c provide important test of NRQCD and color-singlet / color-octet production mechanisms
- Prompt χ_c give substantial feed-down to J/ψ production:
  crucial for polarization studies

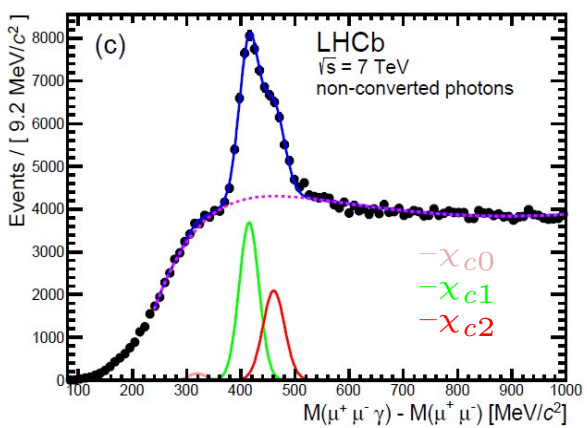
first measurement

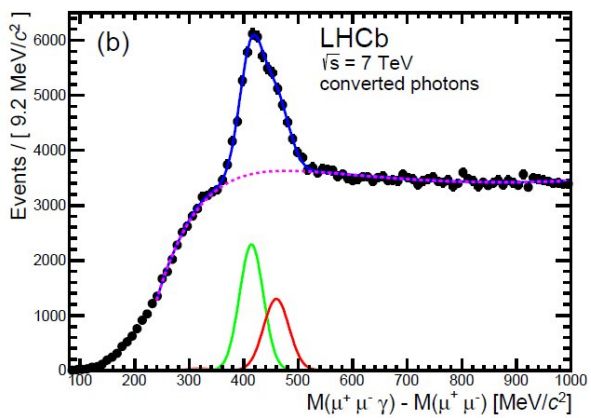
- Ratio of P-wave charmonia $\chi_{cJ}(1P)$ with J=0,1,2 production cross-section to the production of J/ψ in promptly produced charmonium $\sigma(\chi_c \to J/\psi\gamma)/\sigma(J/\psi)$ as a function of $p^T_{J/\psi}$.

• Complementary to the measurement of J/ψ production [EPJ C71 (2011) 1645] and to the cross-section ratio $\sigma(\chi_{c1})/\sigma(\chi_{c2})$ for prompt production [LHCb-PAPER-2011-019].
• Extend the $p^T_{J/\psi}$ coverage with respect from HERA-B and CDF measurements [PRD 79 (2009) 012001, PRL 98 (2007) 232001].

$\chi_c \to J/\psi\gamma$
$J/\psi \to \mu^-\mu^+$
$2 < y_{J/\psi} < 4.5$
$2 < p^T_{J/\psi} < 15\,\mathrm{GeV}/c$
$\int \mathcal{L} = 36\,\mathrm{pb}^{-1}$
γ reconstruction using calorimeter clusters only
prompt separation:
$d_Z(M(J/\psi)/p_Z) < 0.1\,\mathrm{ps}$

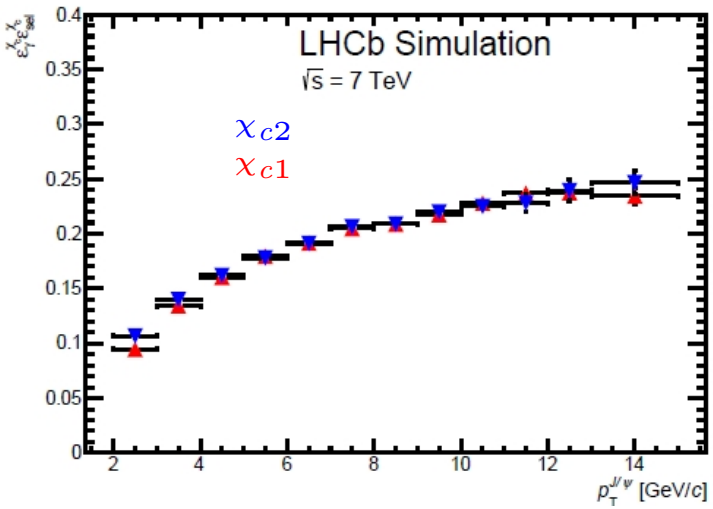


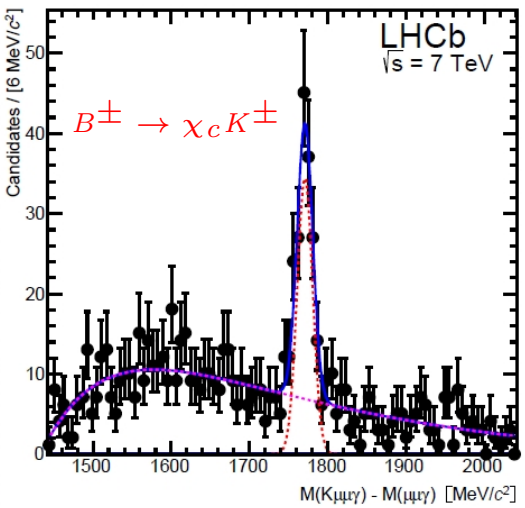


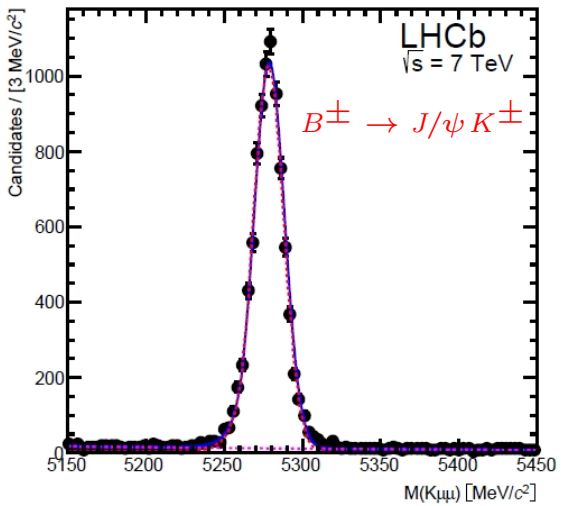


photon efficiency

- Measurement relies on knowing the photon efficiency $\epsilon_\gamma^{\chi_{cJ}}$.
- $\epsilon_\gamma^{\chi_{cJ}}$ using MC is validated on data $B^\pm \to J/\psi K^\pm$ and $B^\pm \to \chi_c K^\pm$

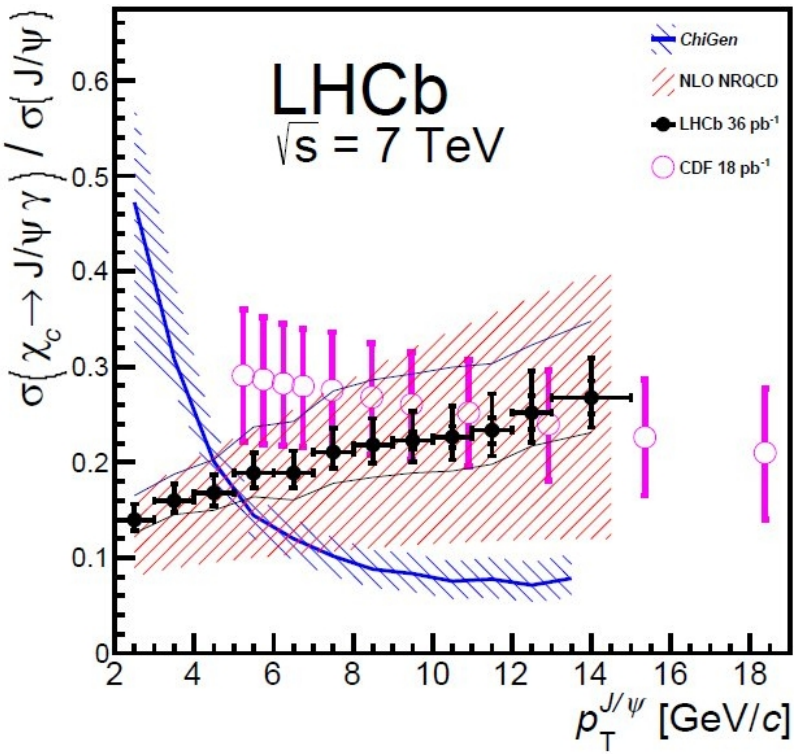






J/ψ and χ_c polarization's

- J/ψ and χ_c polarized states modify ϵ_x^{part} from MC (unpolarized)
- A polarisation weights in $p_{J/\psi}^T$ bins all combinations (J/ψ, χ_{c1}, χ_{c2}) with $\lambda_{J/\psi} = +1, -1, 0$: ie. fully transverse, fully longitudinal, unpolarised
- The polarisation error is given separately



ratio $\sigma(\chi_c \to J/\psi\gamma)/\sigma(J/\psi)$ in bins of $p^T_{J/\psi}$

- Lines surrounding the data: the maximum effect of the unknown J/ψ and χ_c polarizations.
- Results in agreement with NLO NRQCD (Ma, Wang and Chao [PR D83 (2001) 111503])
- *ChiGen* Monte Carlo generator (LO+CSM) does not well reproduce the total J/ψ cross-section (prompt + feeddown) at low p_T [hepforge.org/superchic/chigen.html]

$\psi(2S)$

LHCb-PAPER-2011-045

$\psi(2S)$ production cross section

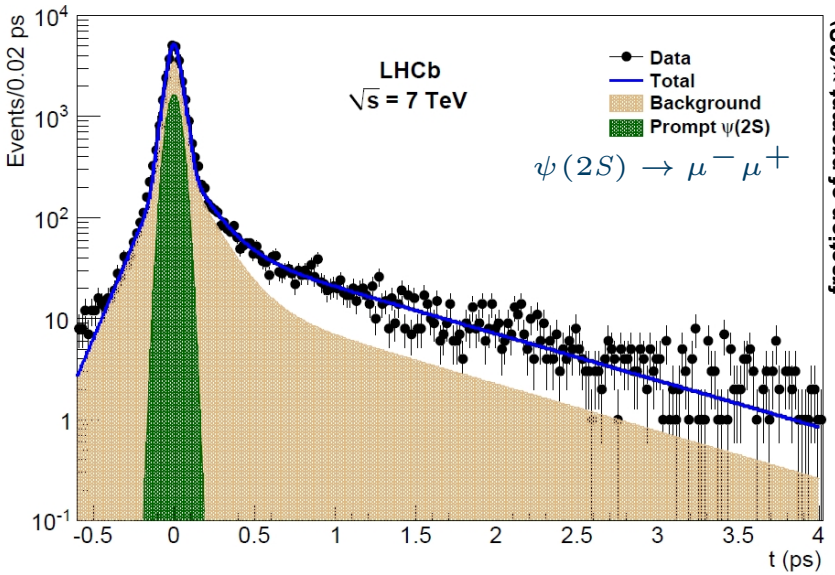
- Ideal laboratory for QCD studies: since prompt $\psi(2S)$ = direct $\psi(2S)$ the cross-section is easy to interpret (no feed-down mechanism).
- Several theoretical predictions (NRQCD CSM and COM) have been carried out over the last years.

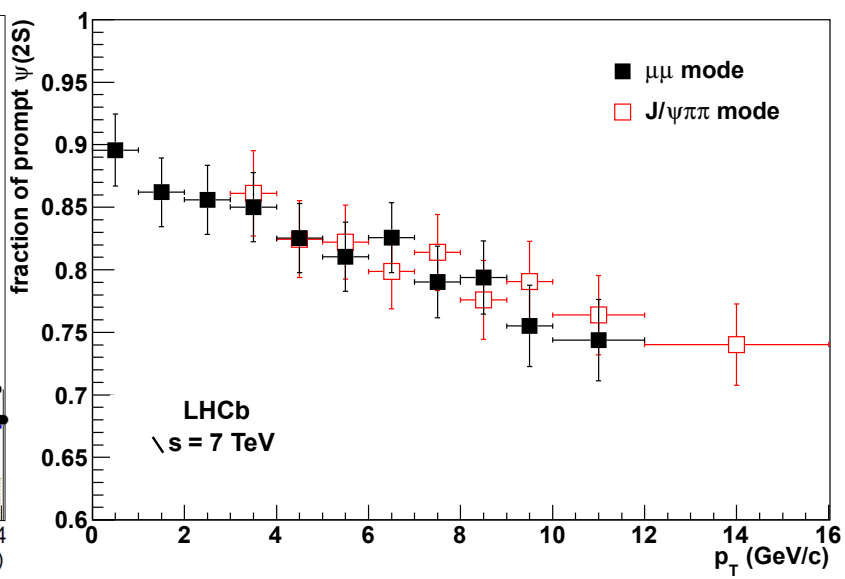
measurement

- $\psi(2S)$ cross-section through two decay channels: $\psi(2S) \to \mu^-\mu^+$ and $\psi(2S) \to J/\psi(\mu^-\mu^+)\pi^+\pi^-$

Separation between prompt and coming from B hadron with the decay time variables ($t = d_Z(M/p_Z)$)

$2 < y_{\psi(2S)} < 4.5$
$p^T_{\psi(2S)} < 16\,\mathrm{GeV}/c$
$\int \mathcal{L} = 36\,\mathrm{pb}^{-1}$

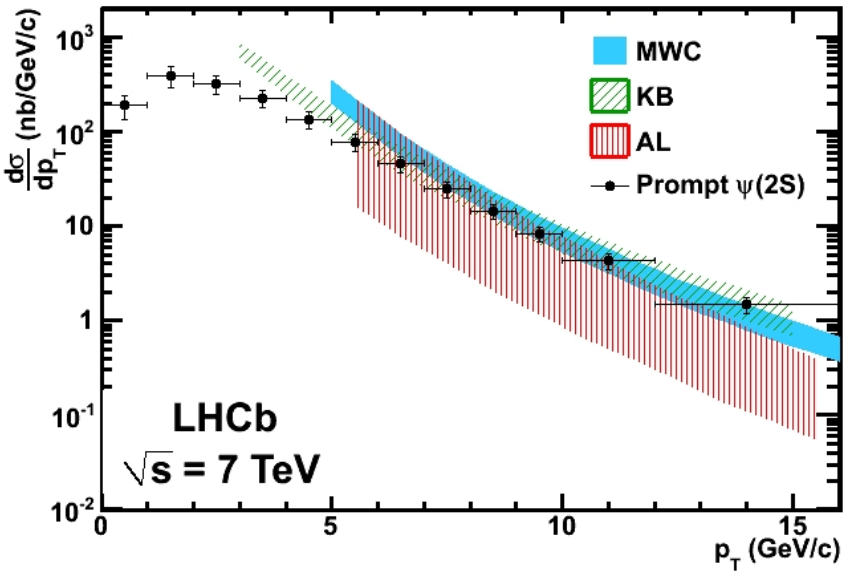


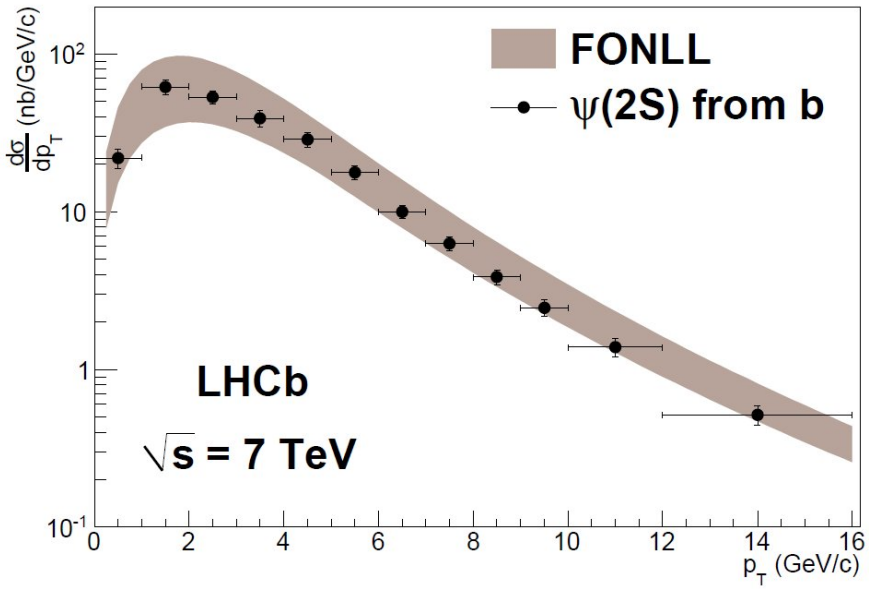


$\psi(2S)$ production cross sections

$\sigma_{\text{prompt}}(\psi(2S)) = 1.44 \pm 0.01(\text{stat}) \pm 0.12(\text{sys})^{+0.20}_{-0.40}(\text{pol})\,\mu\text{b}^{-1}$

$\sigma_b(\psi(2S)) = 0.25 \pm 0.01(\text{stat}) \pm 0.02(\text{sys})\,\mu\text{b}^{-1}$



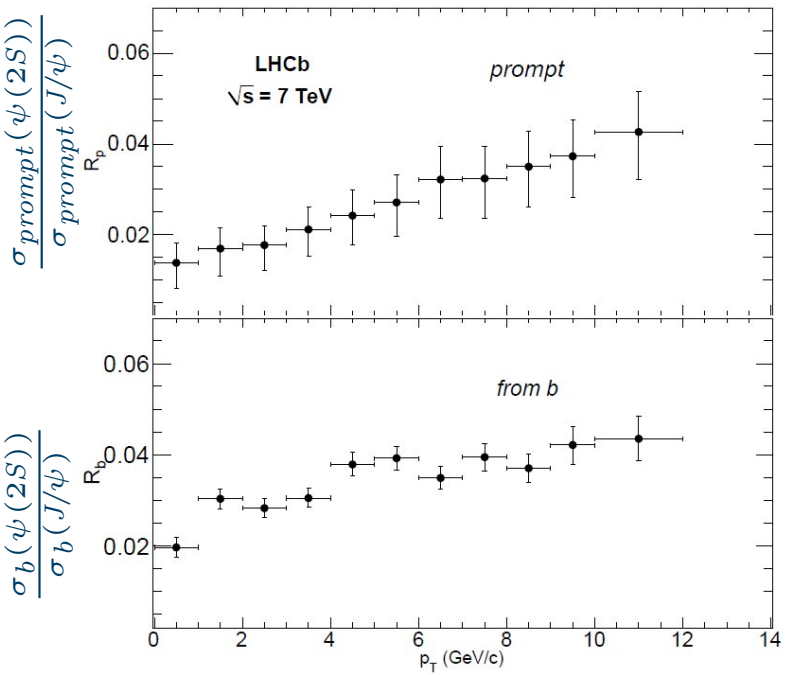


MWC: Ma, Wang and Chao [1012:1030]

KB: Kniehl and Butenschön [PRL 106 (2006) 022003]

AL: Artoisenet et al [PRL 101 (2008) 152001] and Lansber [EPJ C61 (2009) 693]

FONLL: [JHEP 0407 (2004) 033]



inclusive $b \to J/\psi$ and $b \to \psi(2S)$ can be used to extract $\mathcal{B}(b \to \psi(2S)X)$ know at 50 % level: $(4.8 \pm 2.4) \times 10^{-3}$ [PDG]

$$\mathcal{B}(b \to \psi(2S)X) = \zeta \frac{\sigma_b(\psi(2S))}{\sigma_b(J/\psi)} \mathcal{B}(b \to J/\psi X),$$

ζ: extrapolation factor to the full phase space of both decays.

$$\mathcal{B}(b \to \psi(2S)X) = (2.73 \pm 0.06(\text{stat}) \pm 0.16(\text{stat}) \pm 0.24(\text{BR})) \times 10^{-3}$$

agrement with CMS [CMS-BPH-10-014]: $\mathcal{B}(b \to \psi(2S)X) = (3.08 \pm 0.18(\text{stat} + \text{sys}) \pm 0.42(\text{BR})) \times 10^{-3}$

Double Charm Production

LHCb-PAPER-2012-003

Double charm production

Double J/ψ, J/ψ with open charm ($J/\psi C$) and double open charm (CC)

Double Charm production models:

- Pertubative QCD (pQCD) matrix elements, agrees well with $J/\psi\, J/\psi$
  $gg \to J/\psi\, J/\psi$ is measured by NA3 in 1982 [PLB 114 457,PLB 158, 85] and LHCb in 2011 [PLB 707 52]
  LHCb measurement is in excellent agreement with pQCD calculations for
  $\sigma_{\rm LHCb} = 5.1 \pm 1.0 \pm 1.1\,{\rm nb}$ vs $\sigma_{\rm pQCD} = 4.1 \pm 1.2\,{\rm nb}$
  Calculation in LHCb acceptance region: $\sigma(J/\psi\, C) \sim 18\,{\rm nb}$ and : $\sigma(CC) \sim 100\,{\rm nb}$

- Intrinsic Charm Model (IC): testing/constraining (badly known) charm PDFs

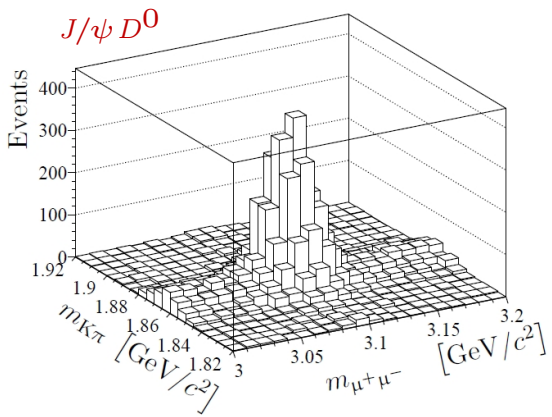
- Double Parton Scattering (DPS), neglecting partonic correlation in the proton:
  $\sigma^{AB}_{DPS} = \frac{m}{2}\frac{\sigma^{A}_{SPS}\sigma^{B}_{SPS}}{\sigma^{DPS}_{eff}}$, $m = 1\,(2)\,{\rm for\,A = B}\,(\neq)$,
  CDF measured in multi-jet events: $\sigma^{DPS}_{eff} = 14.5 \pm 1.7^{+1.7}_{-2.3}\,{\rm mb}$ [PDR 56 3811 (1997)]

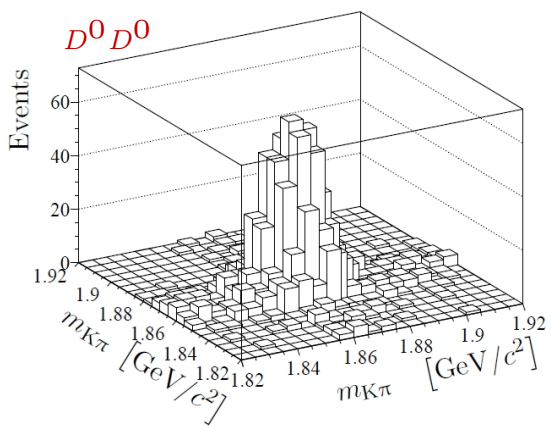
Mode	$\sigma_{\rm gg}$		$\sigma_{\rm DPS}$	$\sigma_{\rm IC}$
		[nb]		
$J/\psi\, D^0$	10 ± 6	7.4 ± 3.7	146 ± 39	220
$J/\psi\, D^+$	5 ± 3	2.6 ± 1.3	60 ± 17	100
$J/\psi\, D^+_s$	1.0 ± 0.8	1.5 ± 0.7	24 ± 7	30
$J/\psi\, \Lambda^+_c$	0.8 ± 0.5	0.9 ± 0.5	56 ± 22	—

Double Charm @ LHCb

- We want to measure $c\bar{c}\,c\bar{c}$: $J/\psi\,C$ and CC
  (bonus: $C\overline{C}$, dominated by the regular $gg \to c\bar{c}$)
- In total 25 possible modes:
  $c\bar{c}\,c\bar{c}$: $J/\psi\,J/\psi + 4J/\psi\,C + 10CC$
  $gg \to c\bar{c}$: $10C\overline{C}$
- Charm hadron selection:
  - Cuts on tracks χ^2 and particle PID
  - Vertex quality cuts: PV and decay consistency
  - Cut on c_τ for open charm hadrons
  - Require both hadrons consistent with the same PV

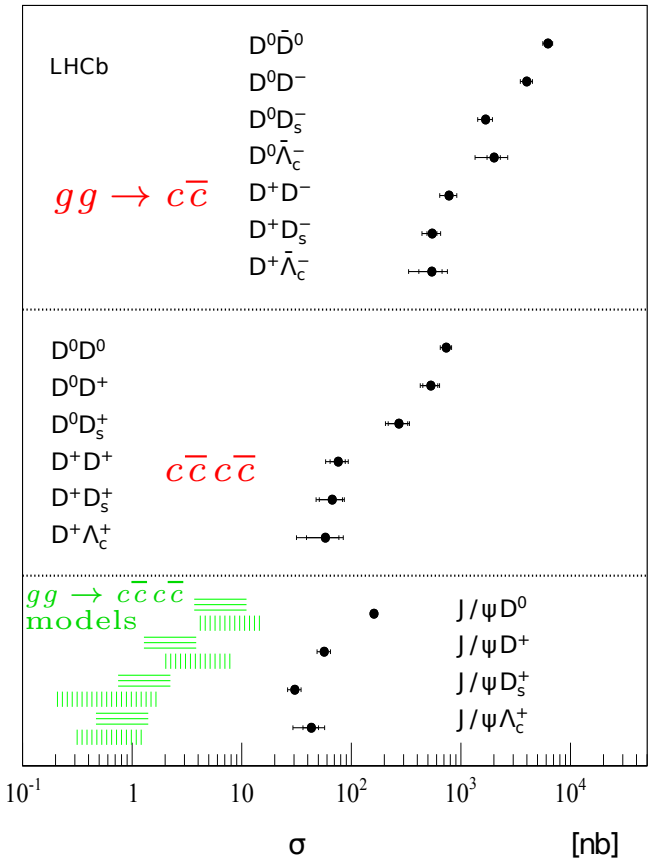
$C = D^0,\ D^+,\ D_s^+,\ \Lambda_c^+$
$2 < y_{J/\psi,C} < 4$
$3 < p_C^T < 12\,\mathrm{GeV}/c$
$p_{J/\psi}^T < 12\,\mathrm{GeV}/c$
$\int \mathcal{L} = 355\,\mathrm{pb}^{-1}$
$J/\psi \to \mu^+\mu^-$,
$D^0 \to K^-\pi^+$,
$D^+ \to K^-\pi^+\pi^+$,
$D_s^+ \to (K^+K^-)_\phi\pi^+$,
$\Lambda_c^+ \to pK^-\pi^+$.

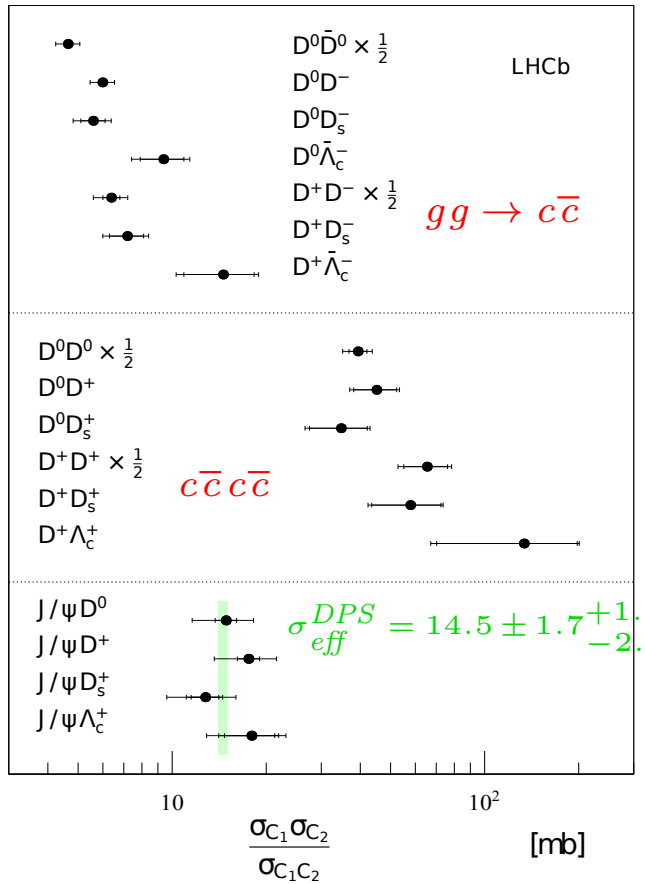




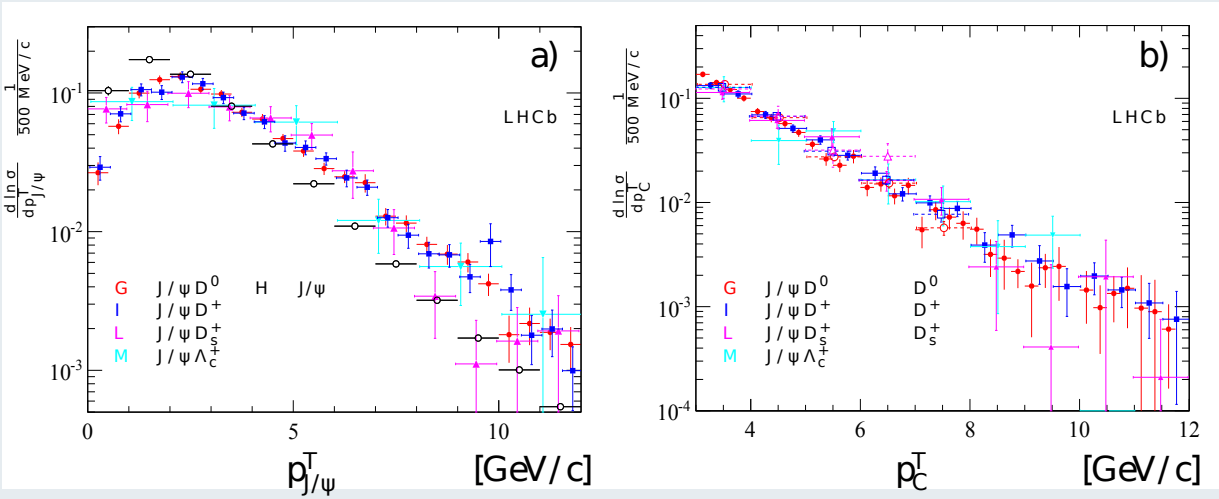
Mode,	$\mathcal{Y}$	$\mathcal{S}_\sigma$
$J/\psi\,D^0$	4875 ± 86	$> 30\sigma$
$D^0\,D^0$	1087 ± 37	27σ

Double charm production

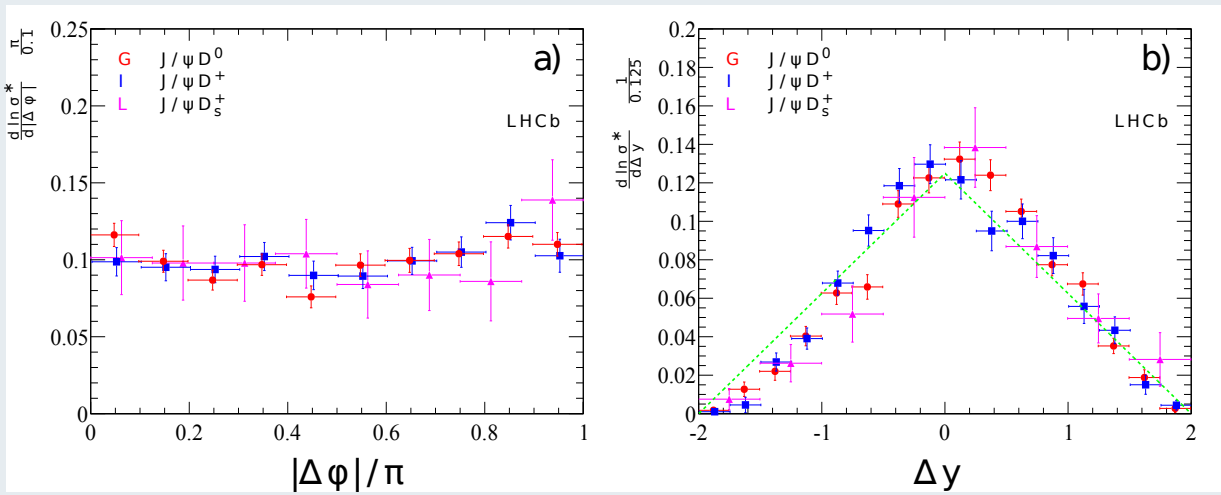




- $J/\psi\, C$ production has been measured ($> 7\sigma$) for the first time in a hadron machine. CC production has been observed for the first time for six modes with $> 5\sigma$ significance.
- the $J/\psi\, C$ measured coress-section significantly exceed the expectation from gluon-gluon fusion, but agree qualtitatively with the DPS.
- For $c\bar{c}\,c\bar{c}$ and $c\bar{c}$ theoretical uncertainties cancel in the ratio. In DPS the ratio is the effective cross-section. Effective Cross-section for $J/\psi\, C$ agrees with Tevatron value, for $c\bar{c}\,c\bar{c} \sim 3$ higher.



Extensive study of spectra in transverse momenta and global invariant mass.
Harder p_T for J/ψ from $J/\psi C$ compared to prompt one (a), no difference for C.



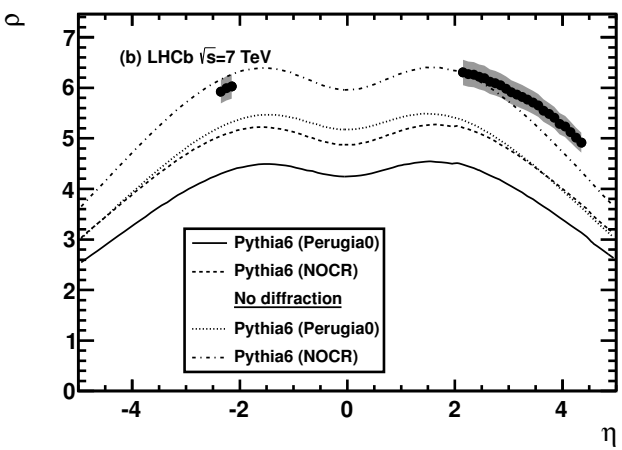
Azimuthal (a) and rapidity (b) correlations for three $J/\psi C$ decays.
No correlation in the angle (expected in gluon fusion), but mostly uncorrelated.

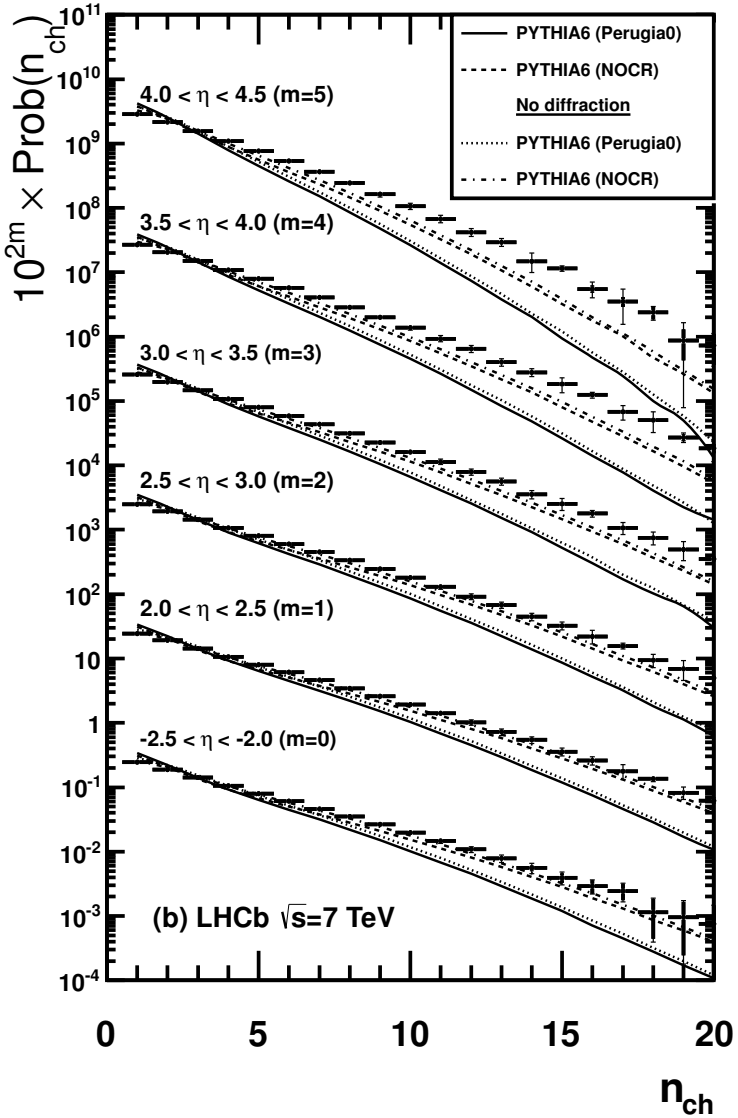
Charged Track Multiplicity

LHCb-PAPER-2011-011

Charged Track Multiplicity

- Important for good simulation of environment aside from hard scatter
- Particles counted by reconstructing tracks in the VELO outside magnetic field, no momentum measurement
- Correction for non-prompt contamination (5-10 %) and for efficiency drop at low p_T (residual field)
- All models fail to describe the mean charged particle multiplicity per unit of pseudorapidity, (mainly at high η).
- The Perugia (NOCR) tune [PR D82 (2010) 074018] gives the best description of the data in the backward direction but fails to reproduce the size of the asymmetry.

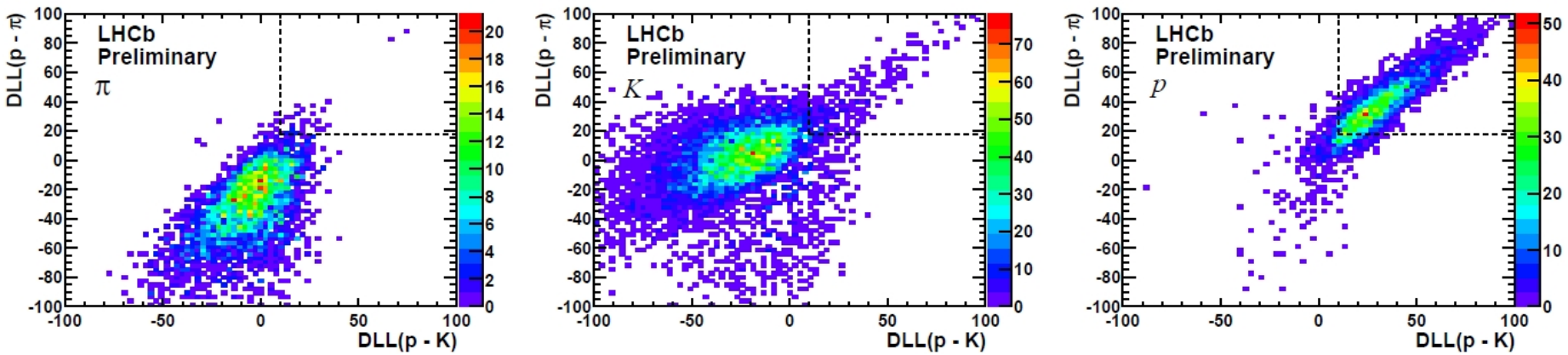




$\overline{p}/p$ ratio

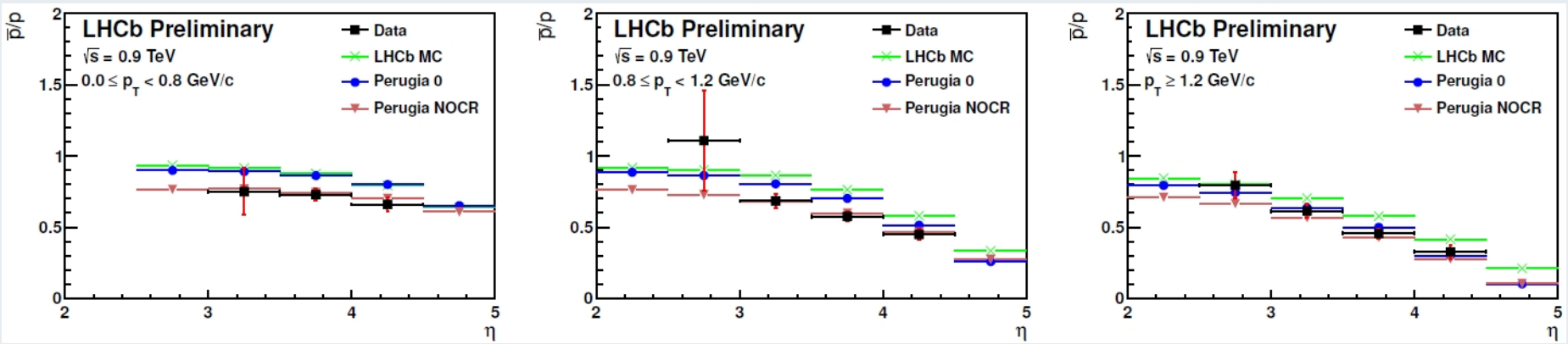
LHCb-CONF-2010-009 Updated

- $\overline{p}/p = \frac{\sigma_{pp\to\overline{p}X}}{\sigma_{pp\to pX}}$ probes the baryon number transport.
- Several models exist to describe this transport, but it is not clear which mechanisms are most important in driving the phenomenon.
- Prompt protons with $p > 5\,\text{GeV}/c$ are selected with PID requirements ($\sim 95\,\%$ purity on MC, with efficiency $\sim 85\,\%$).
- Efficiency and purity of the PID evaluated on data using tag and probe method on calibration samples: $\phi \to K^+K^-$, $K^0_S \to \pi^+\pi^-$ and $\Lambda \to \pi p$

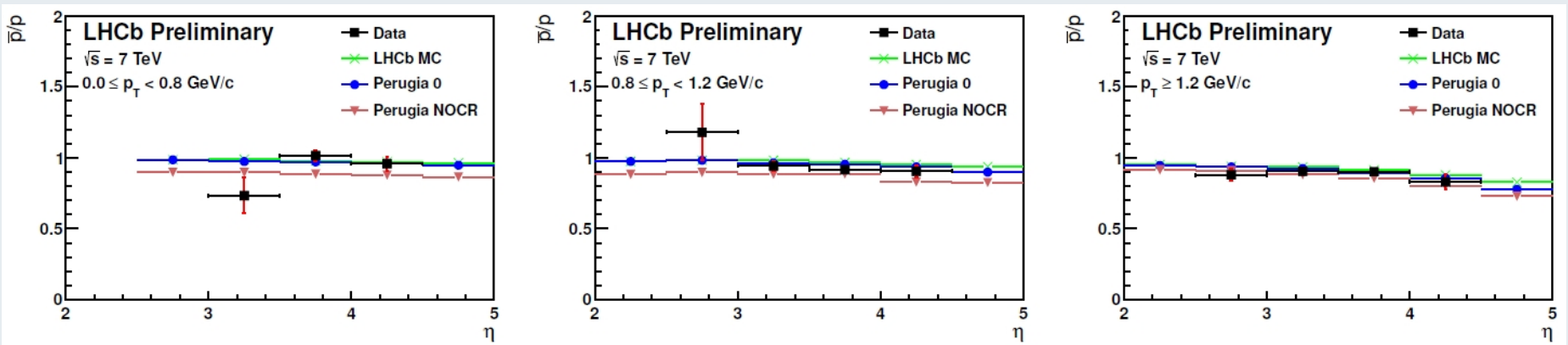


- Measurements are done in 3 bins of p_T $(0; 0.8; 1.2\,\text{GeV/c})$ and 5 bins of rapidity $2.0 < y < 4.5$
- Measurements performed at $\sqrt{s} = 900\,\text{GeV}$ $(0.3\,\text{nb}^{-1})$ and $\sqrt{s} = 7\,\text{TeV}$ $(1.8\,\text{nb}^{-1})$.

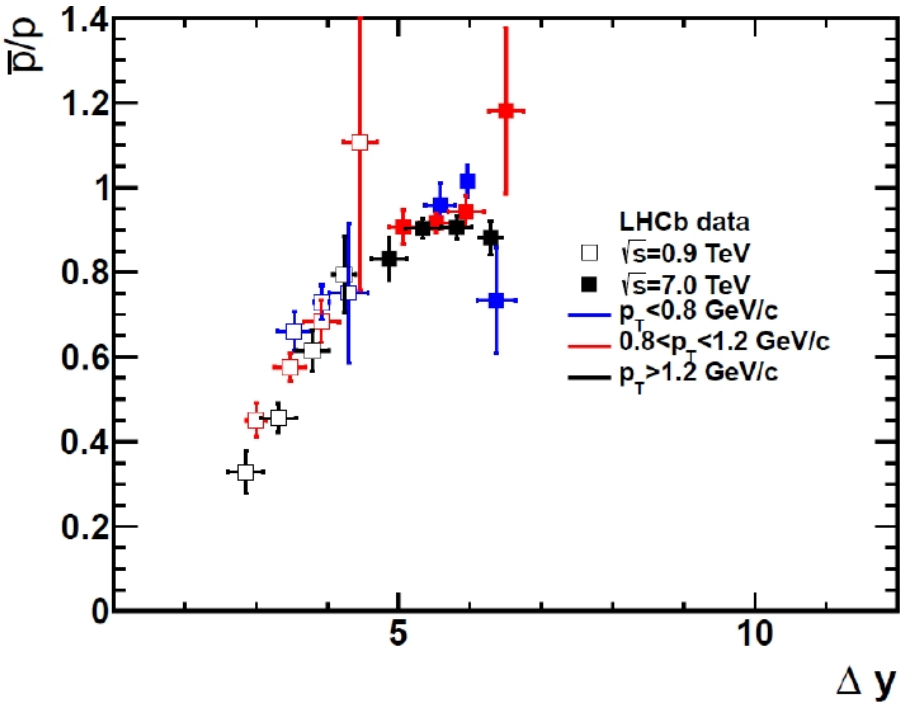
$\overline{p}/p$ at $\sqrt{s} = 900\,\text{GeV}$

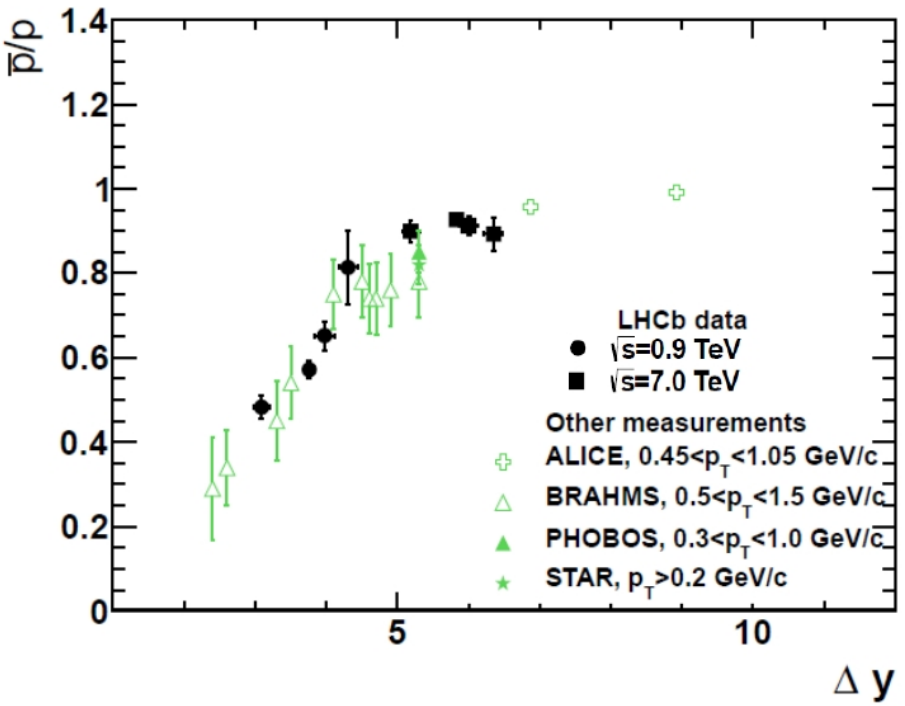


$\overline{p}/p$ at $\sqrt{s} = 7\,\text{TeV}$



analysis extented to K^-/K^+, π^-/π^+, $(\overline{p}+p)/(K^-+K^+)$, $(\overline{p}+p)/(\pi^-+\pi^+)$ and $(K^-+K^+)/(\pi^-+\pi^+)$





- No evidence of signifcant p_T dependency.
- Consistent with previous experiments but signifcantly more precise.

Conclusions

- LHCb probes high rapidity region at LHC.
- Important results for improving models, charged track multiplicity above any generator prediction.
- A lot of measurements in the quarkonia sector as input for theories:
  production cross-sections, ratios.
- This was only a non-exhaustive list of LHCb soft QCD measurements, more are available and/or in preparation.
- Looking forward to run at 8 TeV.