EPS-HEP 2019, Ghent, Belgium
10th -17th Jul.

Production of open heavy flavor hadrons in pPb collisions at LHCb

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CERN

11 July 2019

Outline

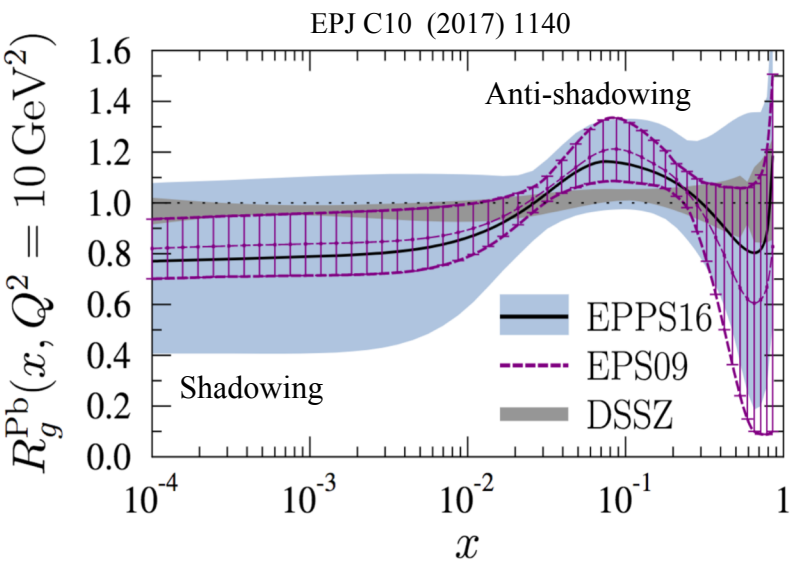
- Introduction
- The LHCb experiment
- Open heavy flavor measurements in pPb collisions
  - ➢ D^0 production at $\sqrt{s_{\mathrm{NN}}} = 5$ TeV [JHEP 10 (2017) 090]
  - ➢ Λ_c^+ production at $\sqrt{s_{\mathrm{NN}}} = 5$ TeV [LHCb-PAPER-2018-021]
  - ➢ Beauty production at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV [PRD 99 (2019) 052011]
- Summary

Introduction

- Unique probe in heavy-ion collisions
  - ➢ $m_Q \gg \Lambda_{QCD}$, allows perturbative calculations
  - ➢ $t_{\text{prod}} \ll t_{\text{QGP}}$, experience whole time evolution of collision

- Study also cold nuclear matter effects
  - ➢ Modification of parton distribution functions: nPDF or CGC
  - ➢ Energy-loss with (in)coherent small-angle gluon radiation
  - ➢ Interacting with co-moving particles

- Heavy flavor measurements
  - ➢ Particle correlations
  - ➢ Kinematics, track multiplicity and species dependence
  - ➢ Variations in collision systems



LHCb experiment

Precision measurements in b, c flavor sectors

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

$\tau(H_b)\sim 1.5$ ps, $\tau(H_c)\sim 0.1-1$ ps

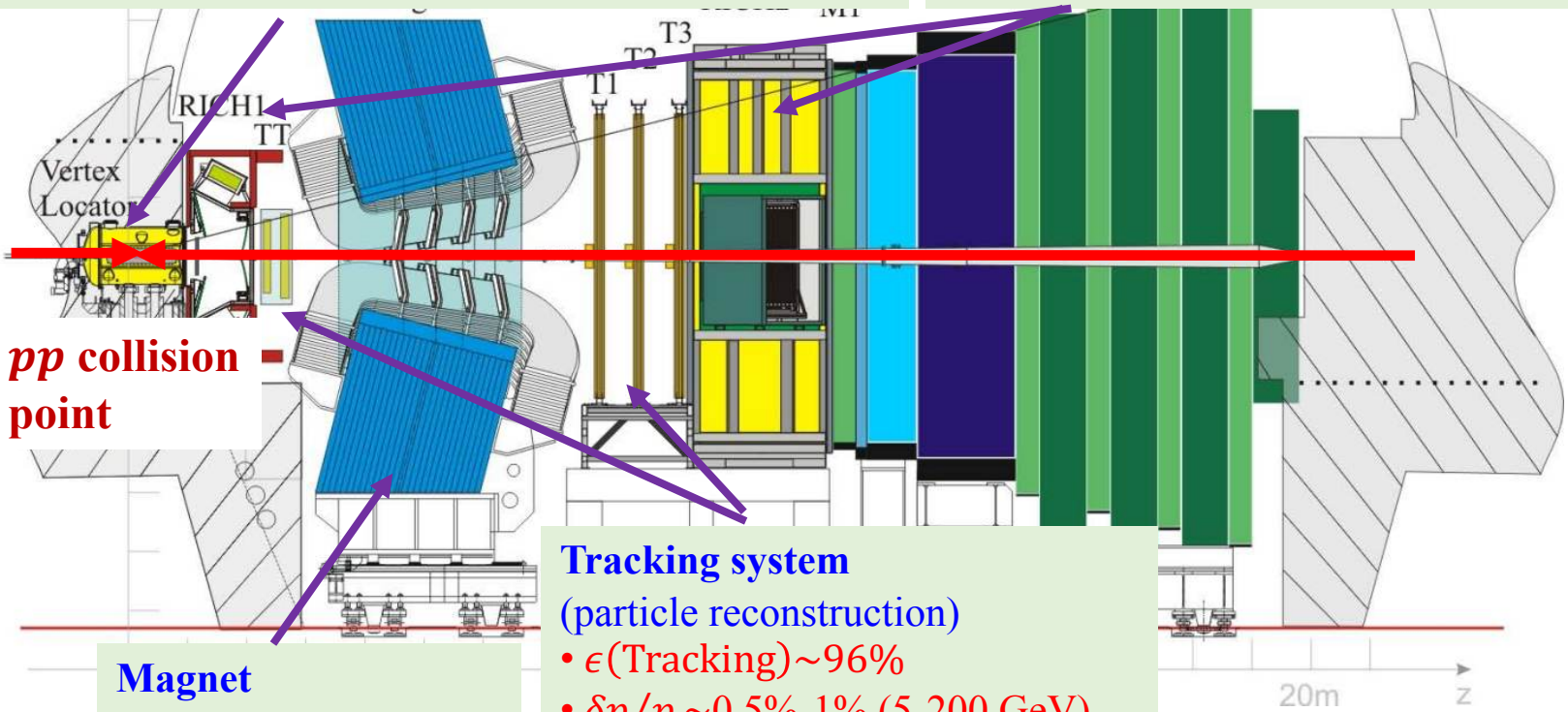
Vertex Locator (vertex reconstruction)

- Impact parameter resolution: $(15+29/p_T)\mu$m
- Time resolution: 45 fs, resolving HF decay vertex

Decays: $b \to c \to s\ (K^{\pm})$;
Baryon → proton

RICH detectors ($K/\pi/p$ separation)

- $\epsilon(K \to K)\sim 95\%$ for $r(\pi \to K)\sim 5\%$



***pp* collision point**

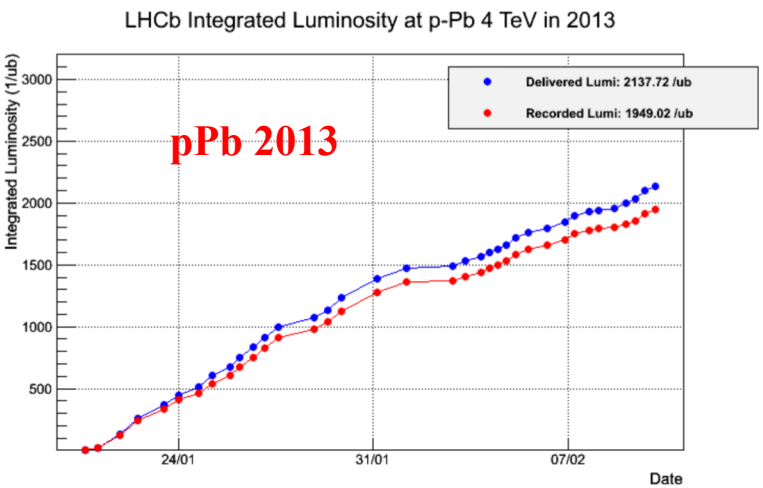
Magnet
Bending power: 4 Tm

Tracking system
(particle reconstruction)

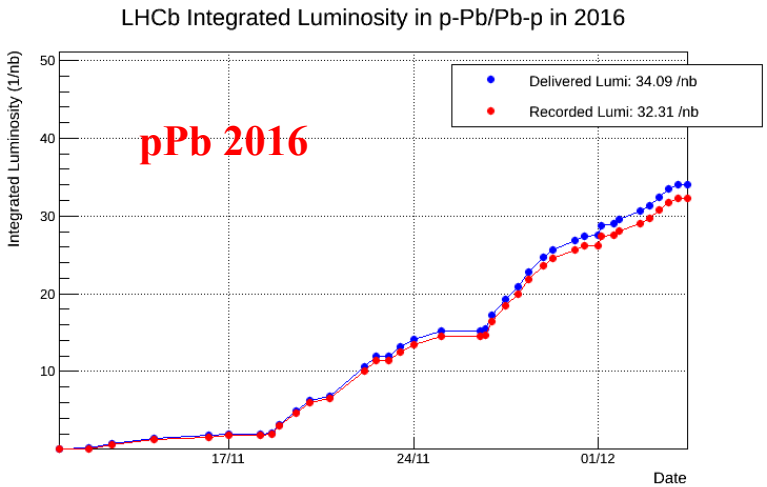
- ϵ(Tracking)$\sim 96\%$
- $\delta p/p \sim 0.5\%$-1% (5-200 GeV)
- $\sigma(m_{B\to hh}) \approx 22$ MeV

LHCb proton-lead data taking

- 2013 pPb runs: collected about 2 nb^{-1} data at $\sqrt{s_{\mathrm{NN}}} = 5$ TeV

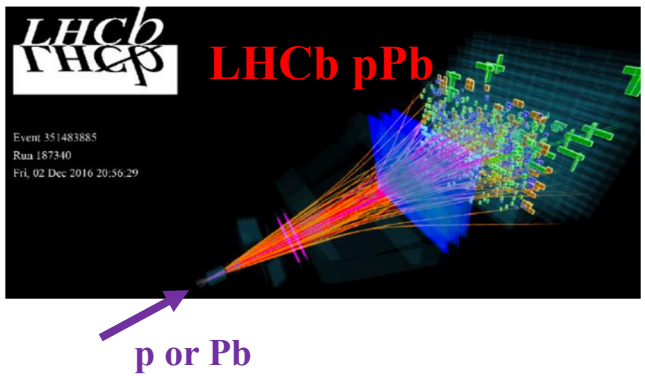


- 2016 pPb runs: collected about 30 nb^{-1} data at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV



Proton and lead beam inverted → two beam configurations

- LHCb collected collisions in either proton (positive rapidity) or lead beam (negative rapidity) direction



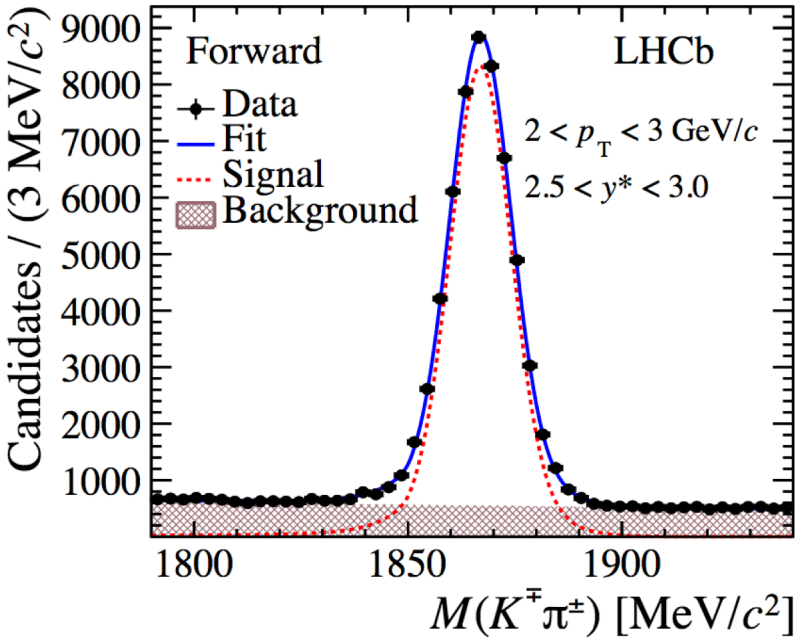
Measurements with pPb collisions

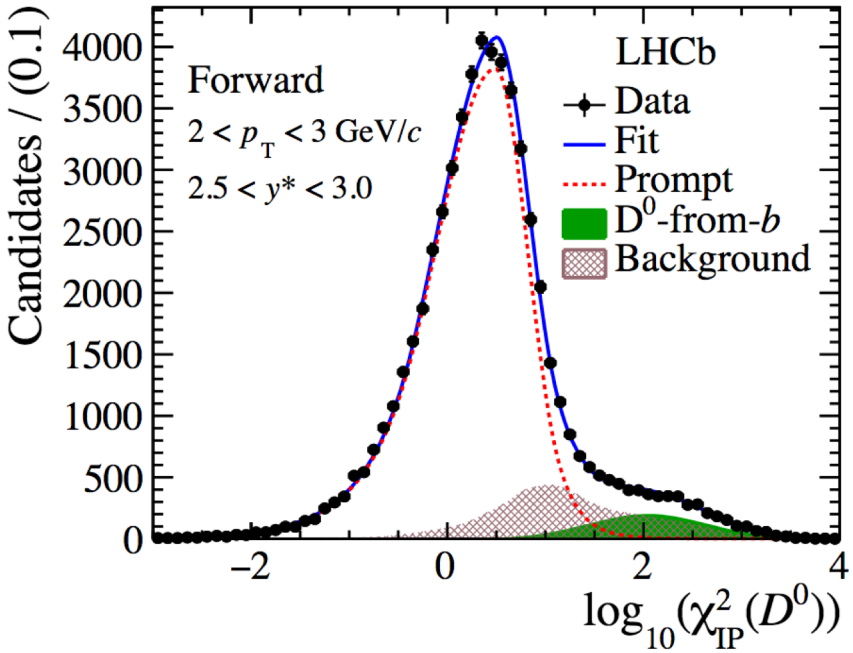
- D^0 production at $\sqrt{s_{\mathrm{NN}}} = 5$ TeV [JHEP 10 (2017) 090]
- Λ_c^+ production at $\sqrt{s_{\mathrm{NN}}} = 5$ TeV [JHEP 02 (2019) 102]
- Beauty production at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV [PRD 99 (2019) 052011]

Prompt D^0 in pPb data

JHEP 10 (2017) 090

- D^0 fully reconstructed through $D^0 \to K^{\mp}\pi^{\pm}$ decays
- Prompt and secondary D^0 yields separated using impact parameter w.r.t. PV
- Reconstruction and particle ID efficiency calibrated using data
- Measurement down to zero-p_T



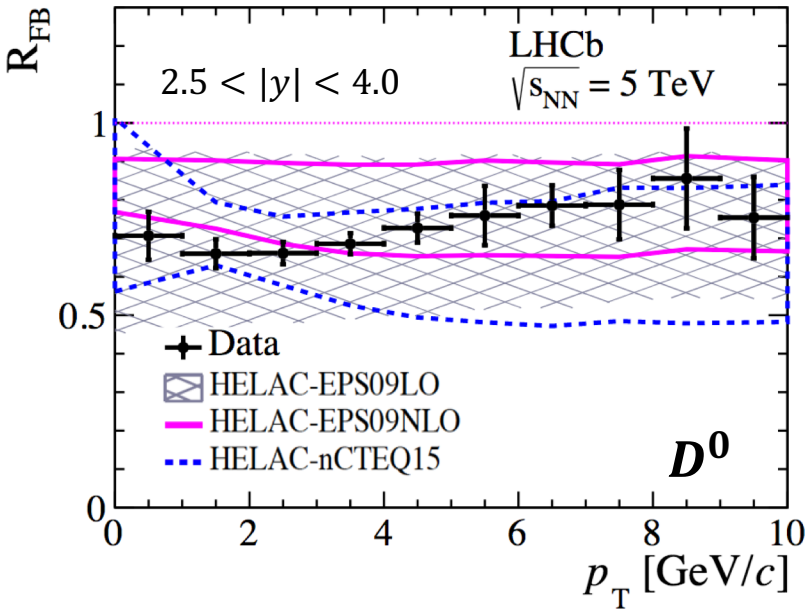


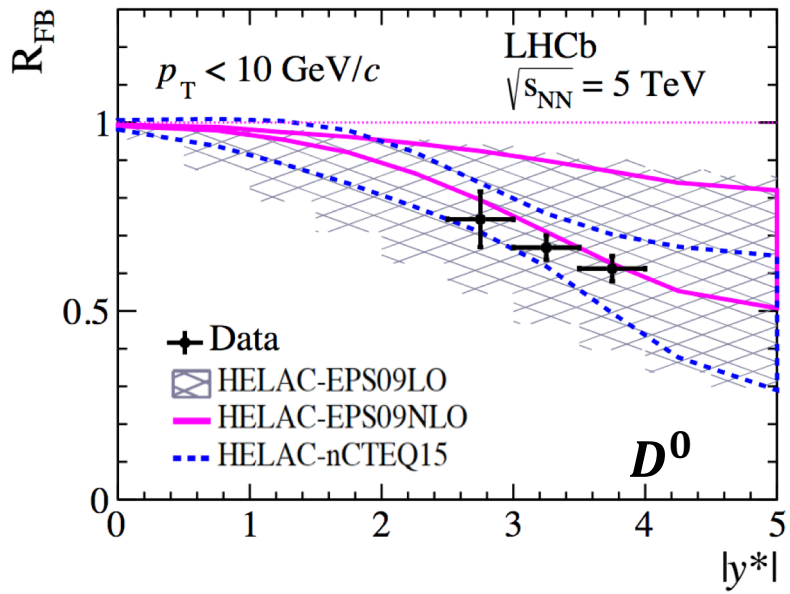
Forward-backward ratio

JHEP 10 (2017) 090

- Comparing production in proton and lead beam directions

$$R_{\mathrm{FB}}(p_{\mathrm{T}}, y^*) \equiv \frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_{\mathrm{T}}, +|y^*|)/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{\mathrm{Pb}p}(p_{\mathrm{T}}, -|y^*|)/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*}$$



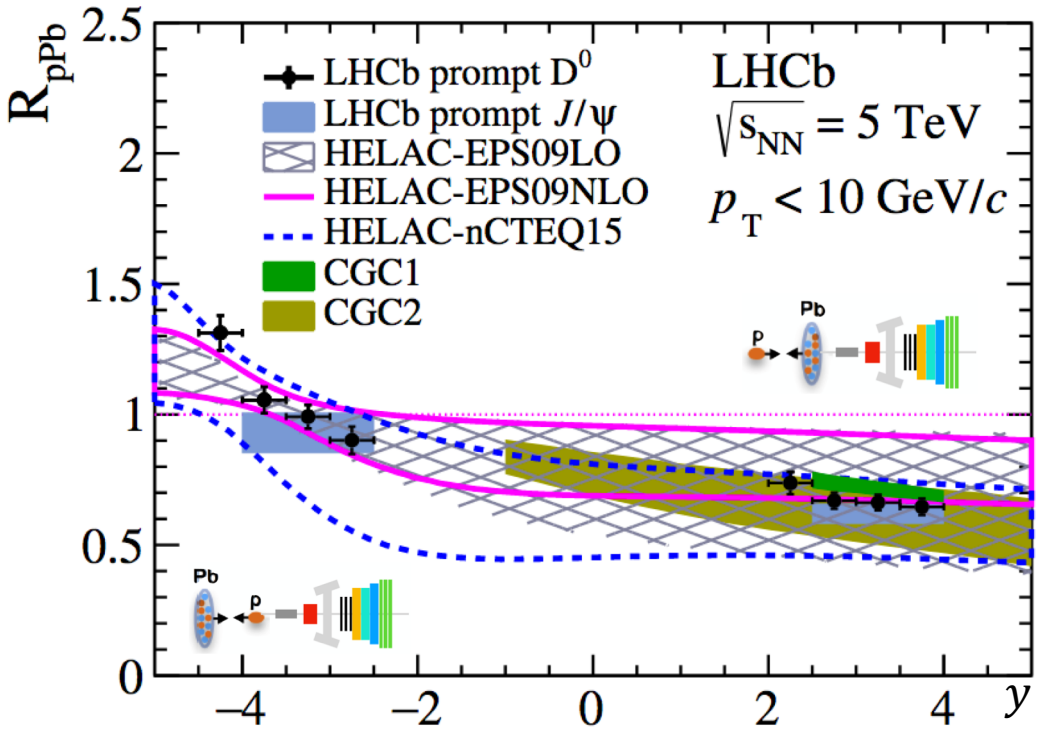


- R_{FB} indicates significant production asymmetry between p- and Pb-beam direction
  Asymmetry increases with rapidity and decreases at high p_{T}
- Data consistent with predictions with various nPDF sets

Comput.Phys.Commun. 198 (2016) 23
JHEP 04 (2009) 065, EPJ C77 (2017) 1

Nuclear modification factor

JHEP 10 (2017) 090



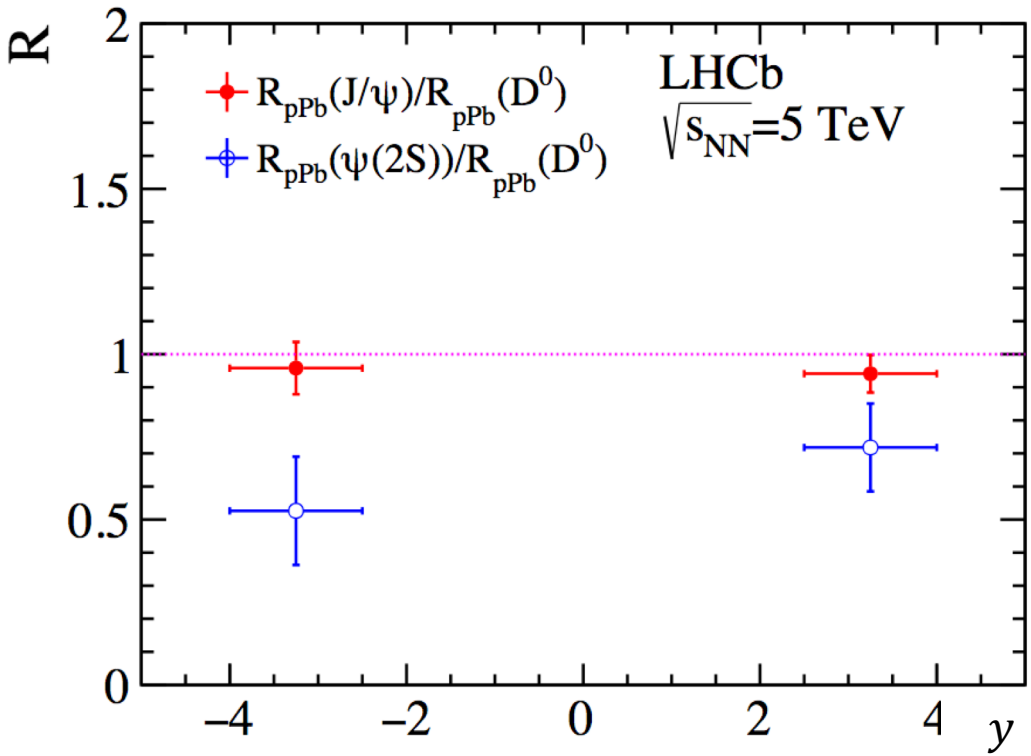
Strong suppression at positive rapidity (~30%), compatible with no suppression and hint of enhancement → different nuclear modification in proton and lead beam direction

nPDF: Comput.Phys.Commun. 198 (2016) 23
JHEP 04 (2009) 065, EPJ C77 (2017) 1

CGC: PR D91 (2015) 114005
arXiv:1706.06728

Nuclear modification factor

JHEP 10 (2017) 090



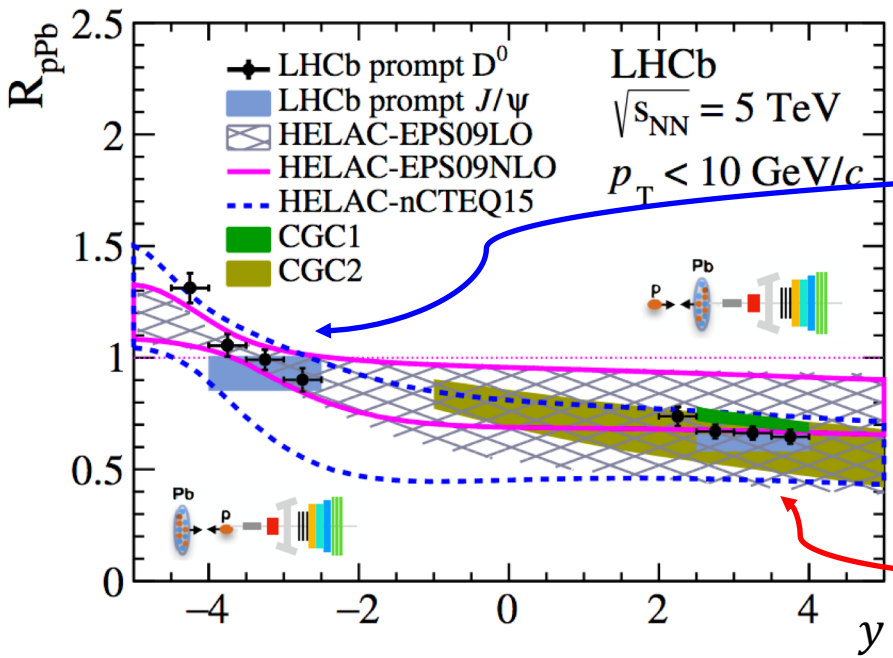
Similar nuclear modification for D^0 and J/ψ: $\frac{R_{p\mathrm{Pb}}(J/\psi)}{R_{p\mathrm{Pb}}(D^0)} \approx 1$; $\psi(2S)$ more suppressed

nPDF: Comput.Phys.Commun. 198 (2016) 23
JHEP 04 (2009) 065, EPJ C77 (2017) 1

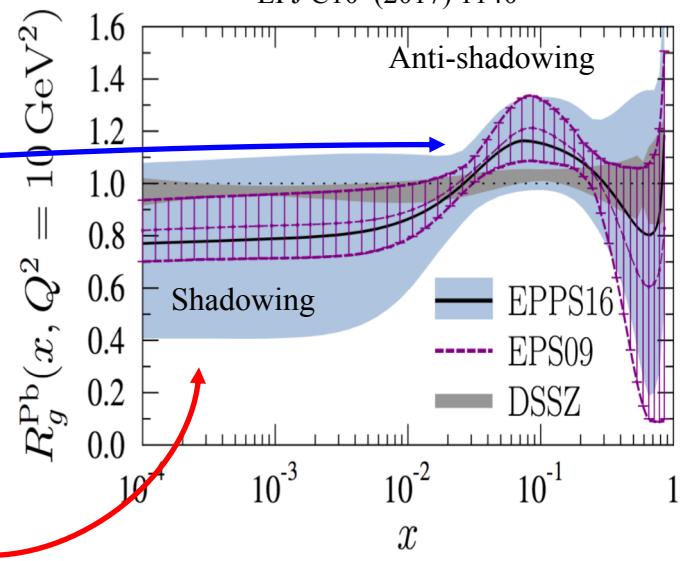
CGC: PR D91 (2015) 114005
arXiv:1706.06728

Nuclear modification factor

JHEP 10 (2017) 090



EPJ C10 (2017) 1140



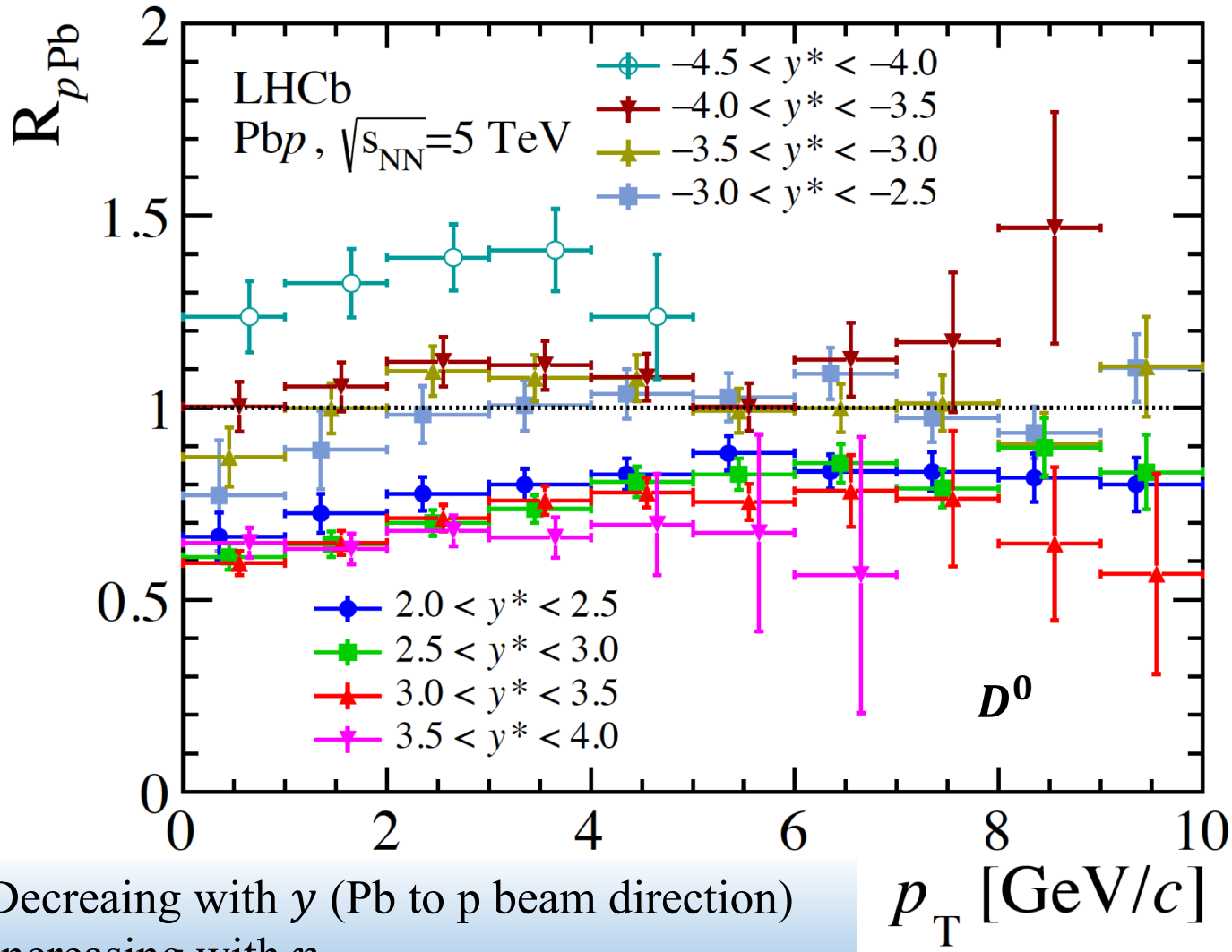
- Suppression-enhancement pattern predicted by nPDFs
- At positive rapidity region also consistent with CGC, with a proper saturation scale

nPDF: Comput.Phys.Commun. 198 (2016) 23
JHEP 04 (2009) 065, EPJ C77 (2017) 1

CGC: PR D91 (2015) 114005
arXiv:1706.06728

R_{pA}: double differential

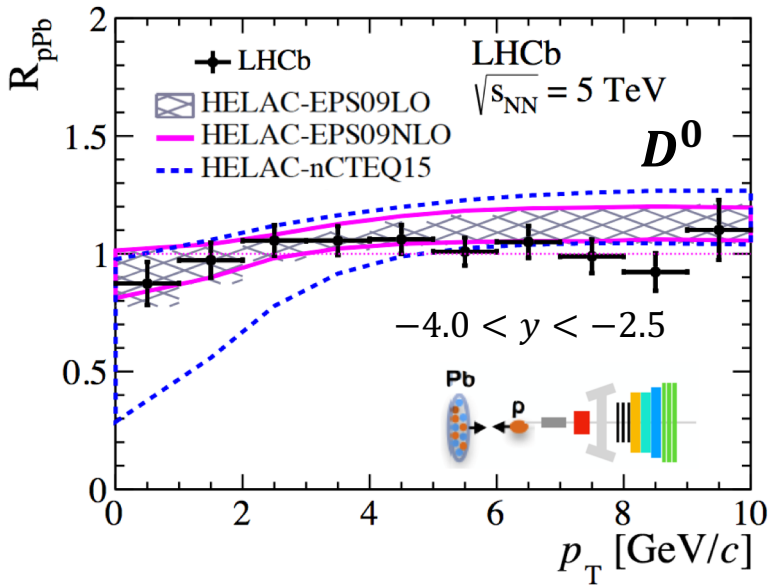
JHEP 10 (2017) 090

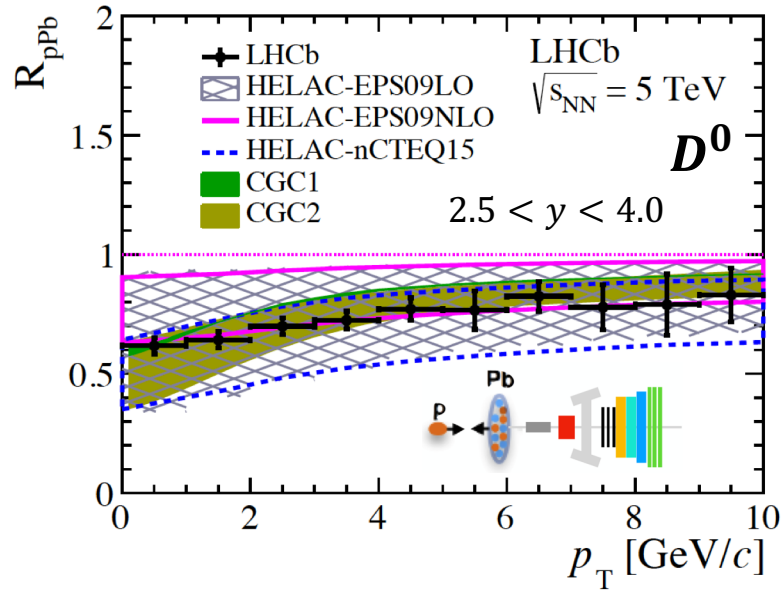


Decreaing with y (Pb to p beam direction)
Increasing with p_T

Nuclear modification factor

JHEP 10 (2017) 090

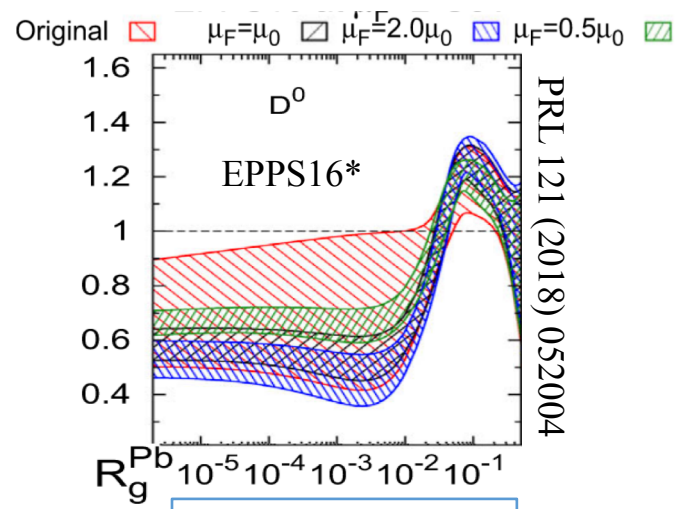




- Observation described by calculations using nPDFs or the CGC model (p-direction)
- Data help to reduce nPDF uncertainties
  - ➢ Complexities: scale uncertainties, other nuclear effects

nPDF: Comput.Phys.Commun. 198 (2016) 23
JHEP 04 (2009) 065, EPJ C77 (2017) 1

CGC: PR D91 (2015) 114005
arXiv:1706.06728



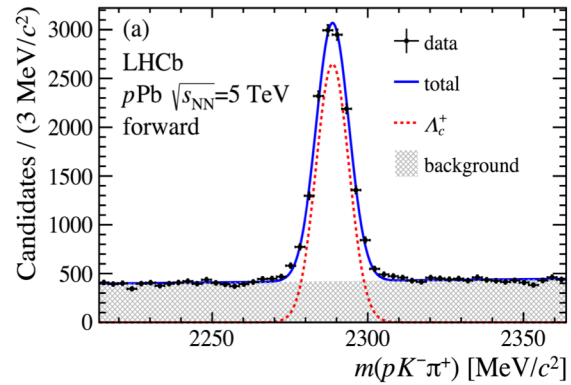
PRL 121 (2018) 052004

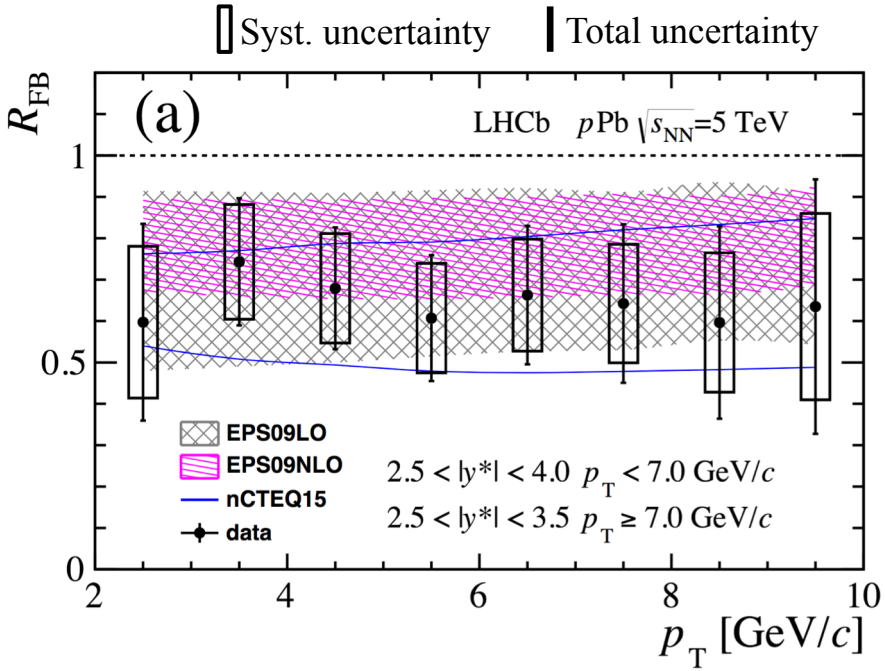
+ arXiv:1906.02512

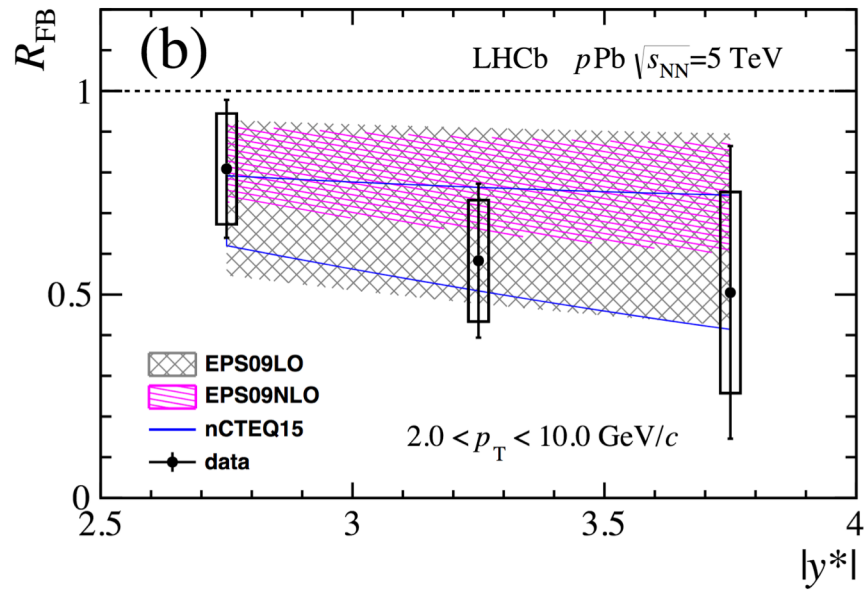
Prompt Λ_c^+ in pPb data

JHEP 02 (2019) 102

- Studied in $\Lambda_c^+ \to pK^-\pi^+$ decays, also high signal purity. ~11/4K signals at positive/negative rapidity
- Same strategy as prompt D^0 analysis







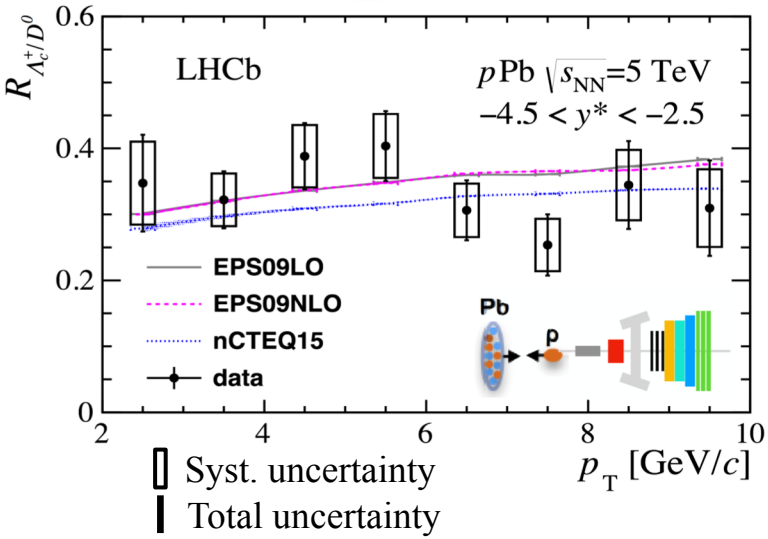
Forward-backward ratio consistent with calculations using nPDF, however large uncertainty bands on both data and calculations

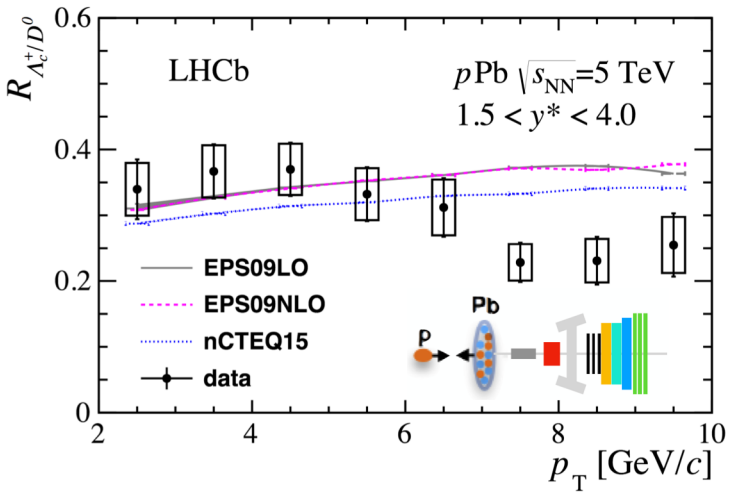
Comput.Phys.Commun. 198 (2016) 23
JHEP 04 (2009) 065, EPJ C77 (2017) 1

Baryon over meson ratio

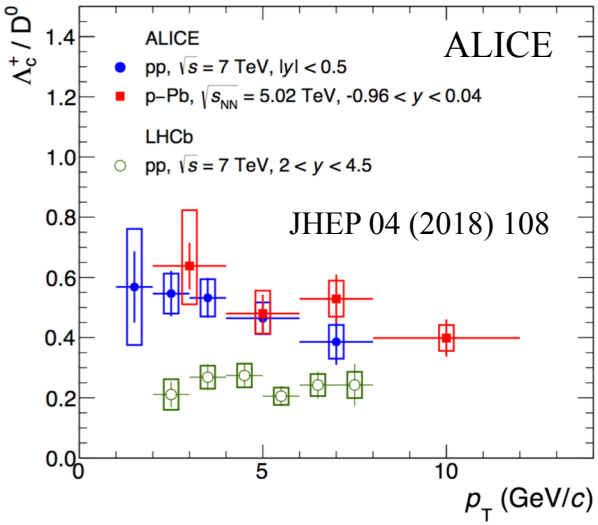
JHEP 02 (2019) 102

- Most nPDF uncertainties cancel out, sensitive to charm quark fragmentation





- ➢ Λ_c^+/D^0 similar in p and Pb beam directions
- ➢ Generally consistent with expectations from pp data $\Lambda_c^+/D^0 \sim 0.3$, hint of discrepancy at high p_T for proton beam direction
- ➢ Tensions between LHCb and ALICE?



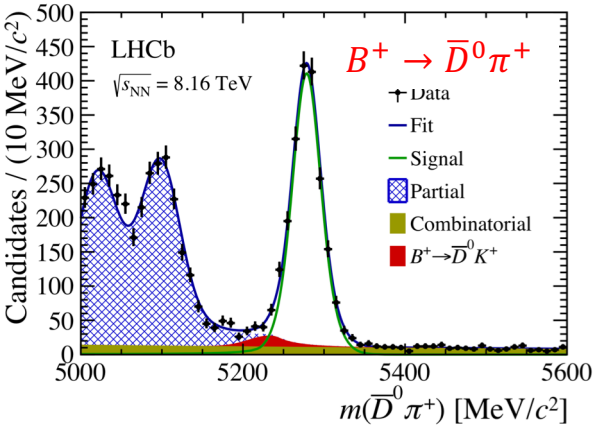
Analyses with new data essential!

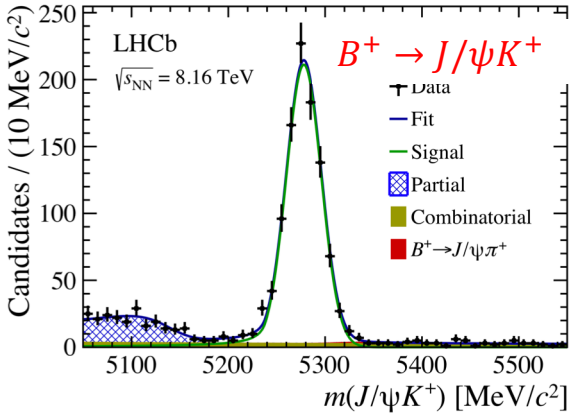
Comput. Phys.Commun. 198 (2016) 23
JHEP 04 (2009) 065, EPJ C77 (2017) 1

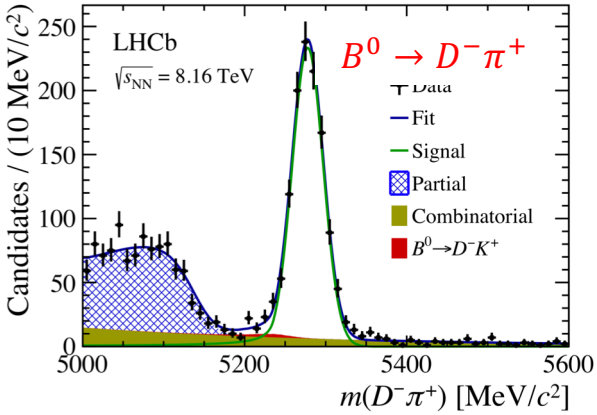
Beauty hadron production

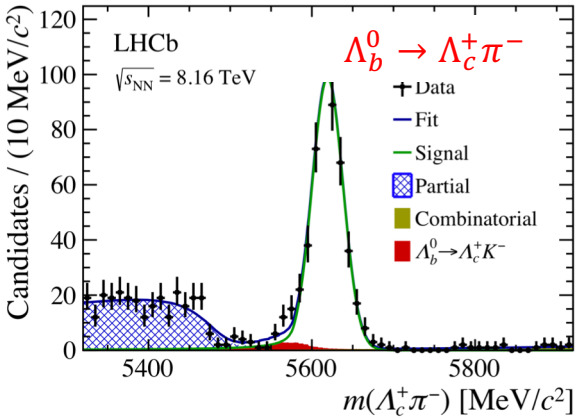
PRD 99 (2019) 052011

- Beauty fragmentation fractions in pPb data
- $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV, $\sim$30 nb^{-1} (positive + negative rapidity)
- Exclusive decay modes: $B^+ \to J/\psi K^+, \overline{D}^0\pi^+$, $B^0 \to D^-\pi^+$, $\Lambda_b^0 \to \Lambda_c^+\pi^-$









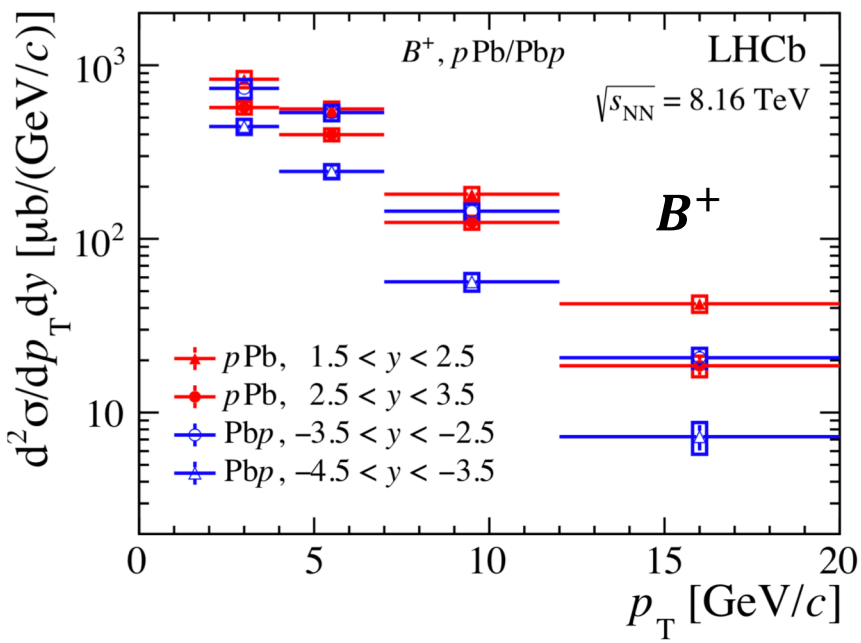
Signal yields

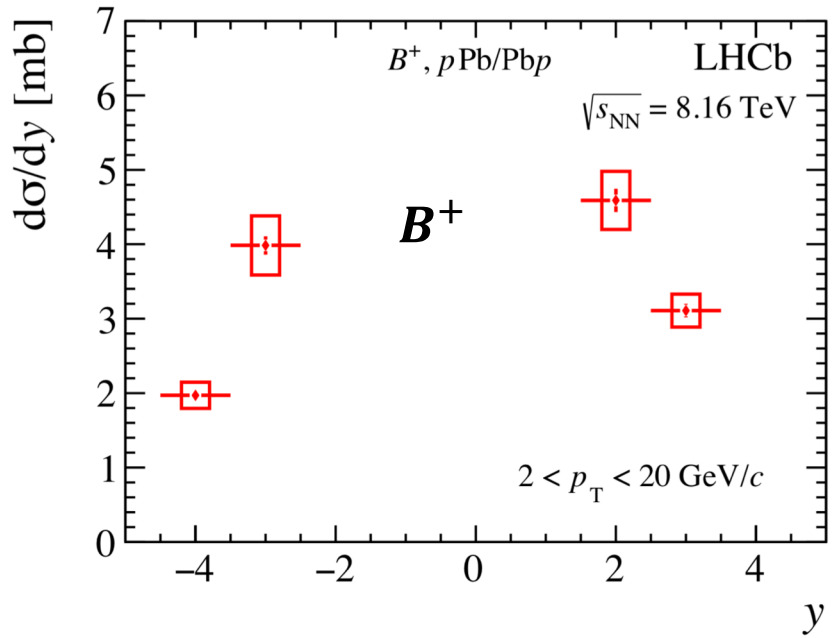
Decay	pPb	Pbp
$B^+ \to \overline{D}^0\pi^+$	1958 ± 54	1806 ± 55
$B^+ \to J/\psi\, K^+$	883 ± 32	907 ± 33
$B^0 \to D^-\pi^+$	1151 ± 38	889 ± 34
$\Lambda_b^0 \to \Lambda_c^+\pi^-$	484 ± 24	399 ± 23

Cross-sections

PRD 99 (2019) 052011

- B^+ cross-section studied in $J/\psi K^+$ and $\overline{D}^0\pi^+$ modes consistent, systematic effects under control. Precision improved in weighted average



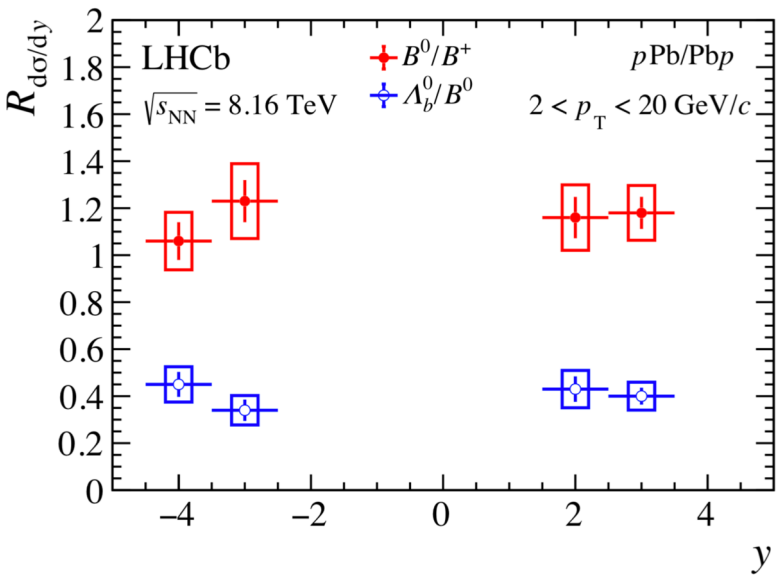


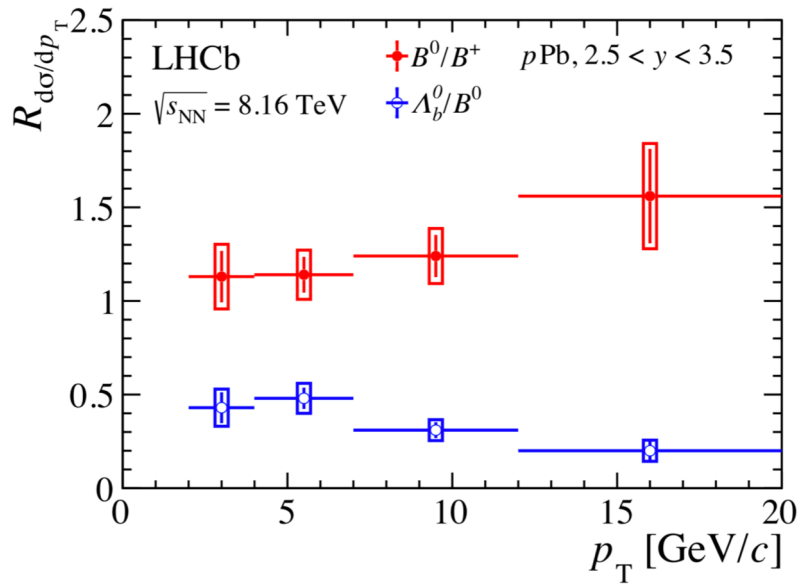
Statistics limited for $p_T < 2$ GeV, excluded for measurements

Cross-sections ratios

PRD 99 (2019) 052011

- Probing relative b-quark fragmentation into different beauty hadrons

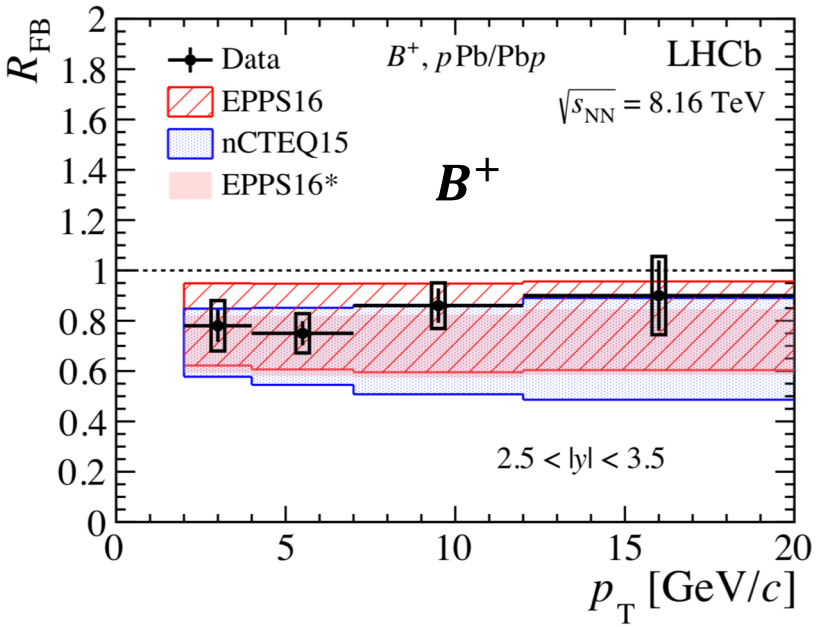


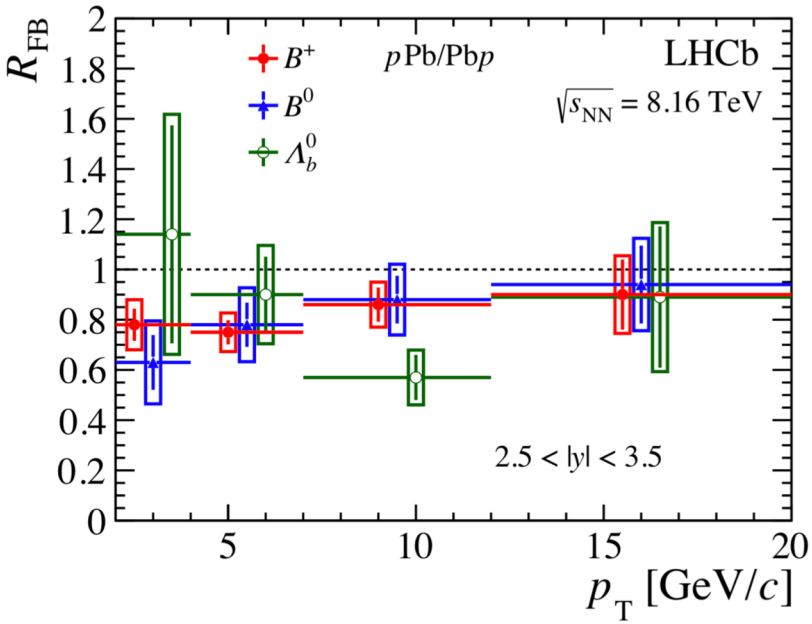


- B^0/B^+ ratio independent of y and p_T, about 1-σ away from unity (isospin symmetry), explained by systematic uncertainties.
- $\Lambda_b^0/B^0 \approx 40\%$, decreasing with p_T, no hint of strong rapidity dependence. similar to results in LHCb pp data [JHEP 08 (2014) 143]
- Λ_b^0/B^0 ratio reaches LEP data at high p_T, 0.20 ± 0.02 [arXiv:1612.07233]

Forward backward ratio

PRD 99 (2019) 052011





- Production at positive rapidity ≈ 25% lower compared with negative rapidity
- No evidence of p_T depdendence with current precision
- In good agreement with the calculation using different nPDF sets.
- R_{FB} for B^+, B^0 and Λ_b^0 are compatible

Comput. Phys.Commun. 198 (2016) 23
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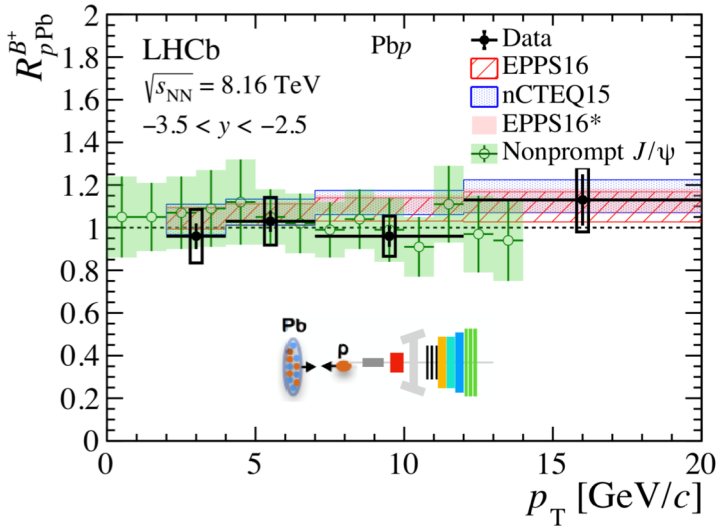
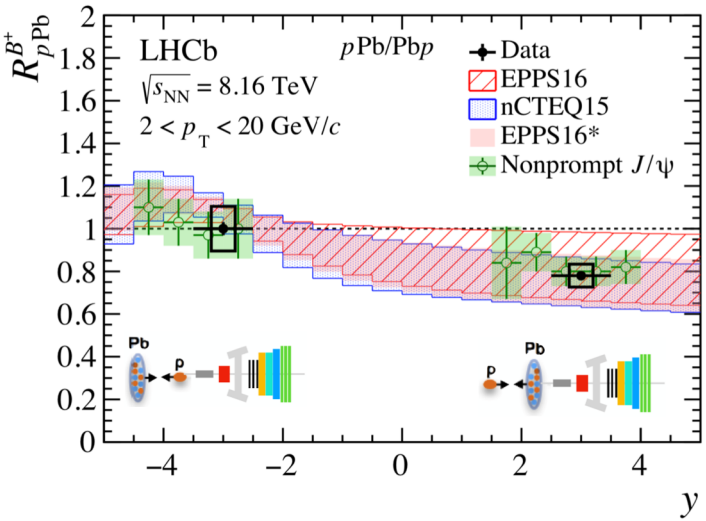
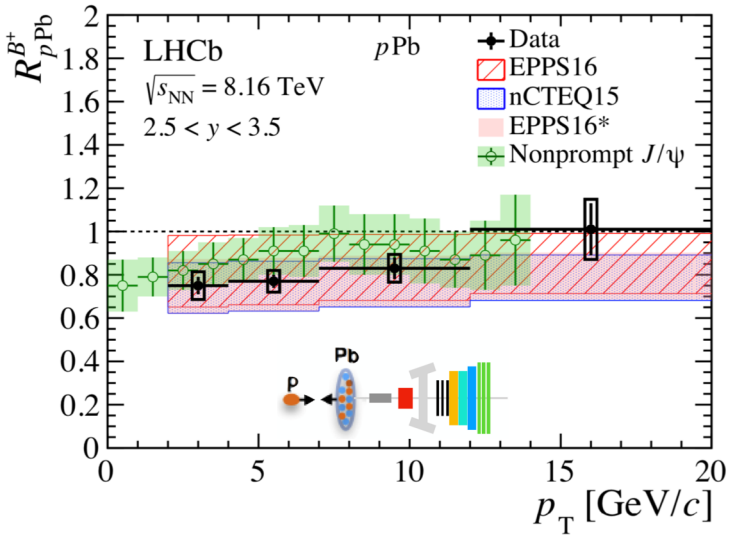
B^+ nuclear modification

PRD 99 (2019) 052011







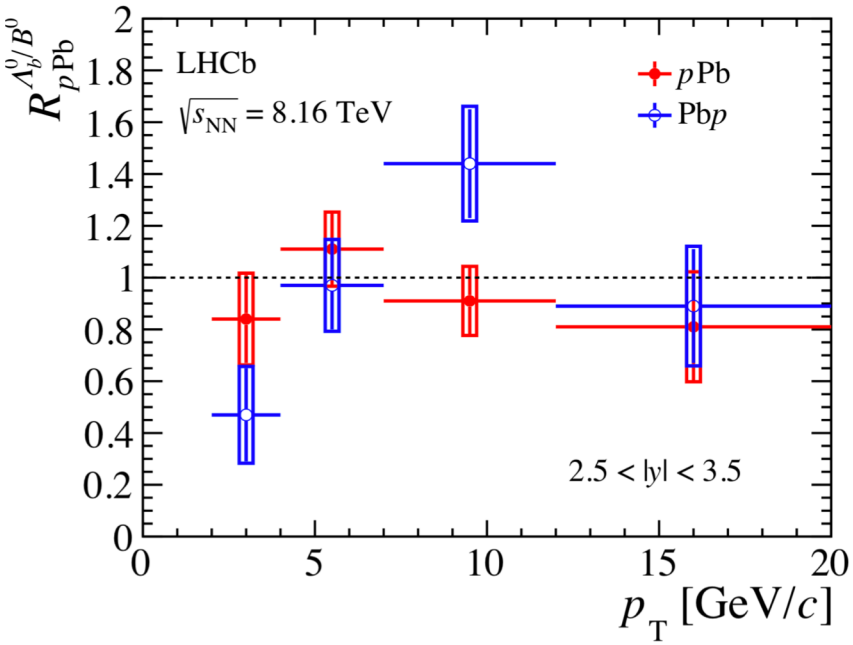
- Pattern consistent with R_{pA} of D^0 hadron
- Significant suppression ($\approx$ 25%) in positive rapidity, suppression decreased at large p_T
- Consistent with unity at negative rapidity
- Measurements in good agreement with J/ψ-from-b decay data [PLB74 (2017) 159] and calculations using nPDF sets
- Experimental uncertainties smaller than nPDF

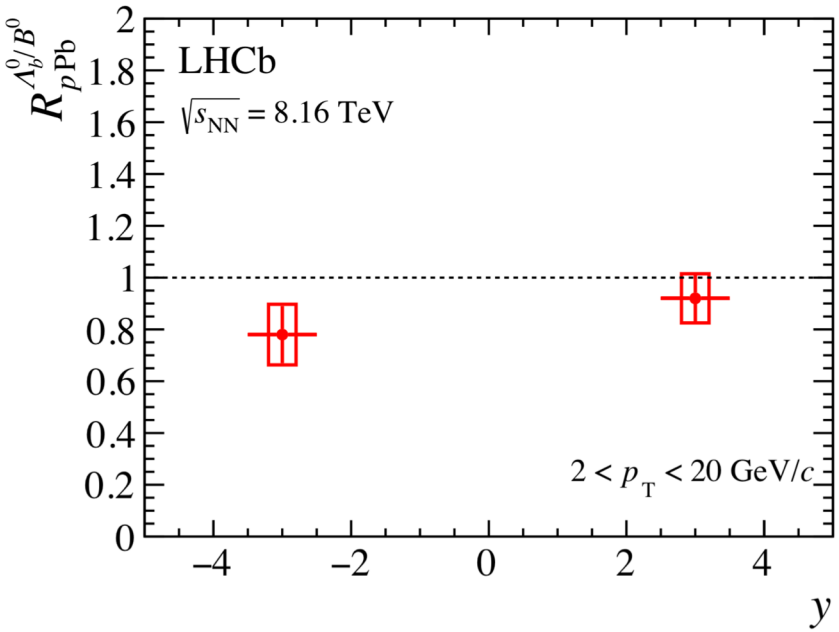
Comput. Phys.Commun. 198 (2016) 23
JHEP 04 (2009) 065, EPJ C77 (2017) 1

Λ_b^0 and B^0 relative modification

PRD 99 (2019) 052011

- Ratio of R_{pA} between Λ_b^0 and B^0 hadrons





Consistent with unity in all kinematic bins → b-quark fragmentation function similar in pPb and pp collisions

Statistical uncertainty dominated, demanding more statistics to understand better

Summary and outlook

- LHCb has made unique contributions to heavy ion studies
- Studied production of D^0, Λ_c^+, bottom mesons and Λ_b^0 baryon
  - Precise data for prompt D^0 down to zero p_{T}: strong suppression in proton beam direction. Moderate nuclear effect at lead beam direction, hint of enhancement for extreme rapidity
  - Prompt Λ_c^+/D^0 cross-section ratio consistent with expectation at low p_{T}, possible discrepancy at high p_{T} at positive rapidity
  - First measurement of beauty hadrons using exclusive hadronic states. Nuclear effect for B^+ consistent with J/ψ-from-b data and similar to D^0 mesons.
  - First direct measurement of Λ_b^0 baryon in heavy ion collisions, similar suppression compared to beauty mesons
- Millions of charm hadrons to be explored in new data ($\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV)
  - $D^{0/+}, D_s^+, \Lambda_c^+, \Xi_c^{+/0}$ ..., Di-charm, correlations, track multiplicity dependence
- Improvement of beauty yields studying more decay modes

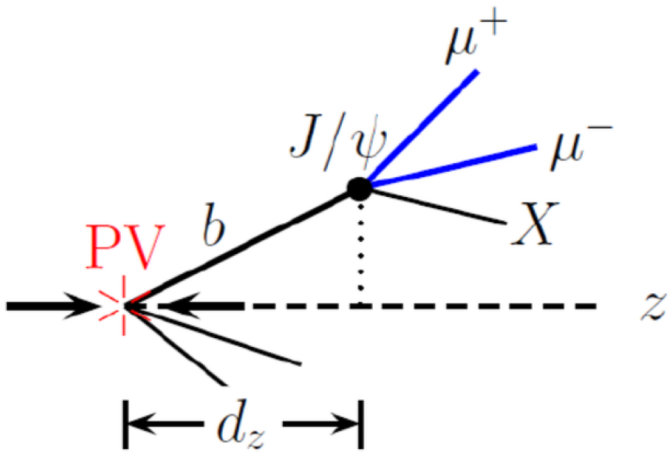
Thank you for your attention

Additional material

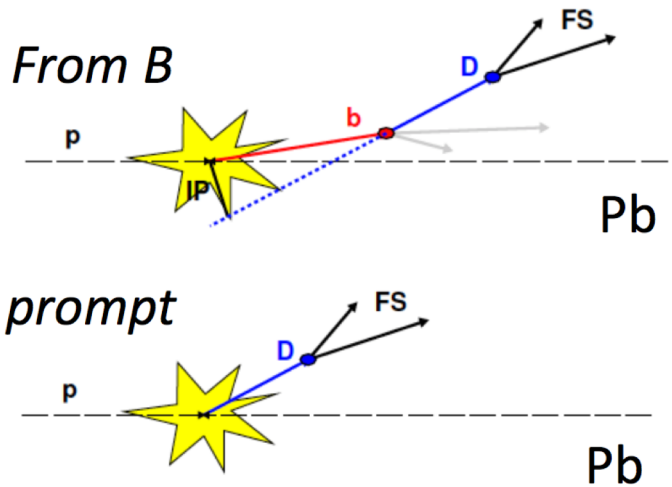
Separation from prompt and detached

Pseudo-decay time of ψ

$$t_Z = \frac{(Z_{J/\Psi} - Z_{PV}) \times M_{J/\Psi}}{}$$



IP of D^0



LHCb experiment

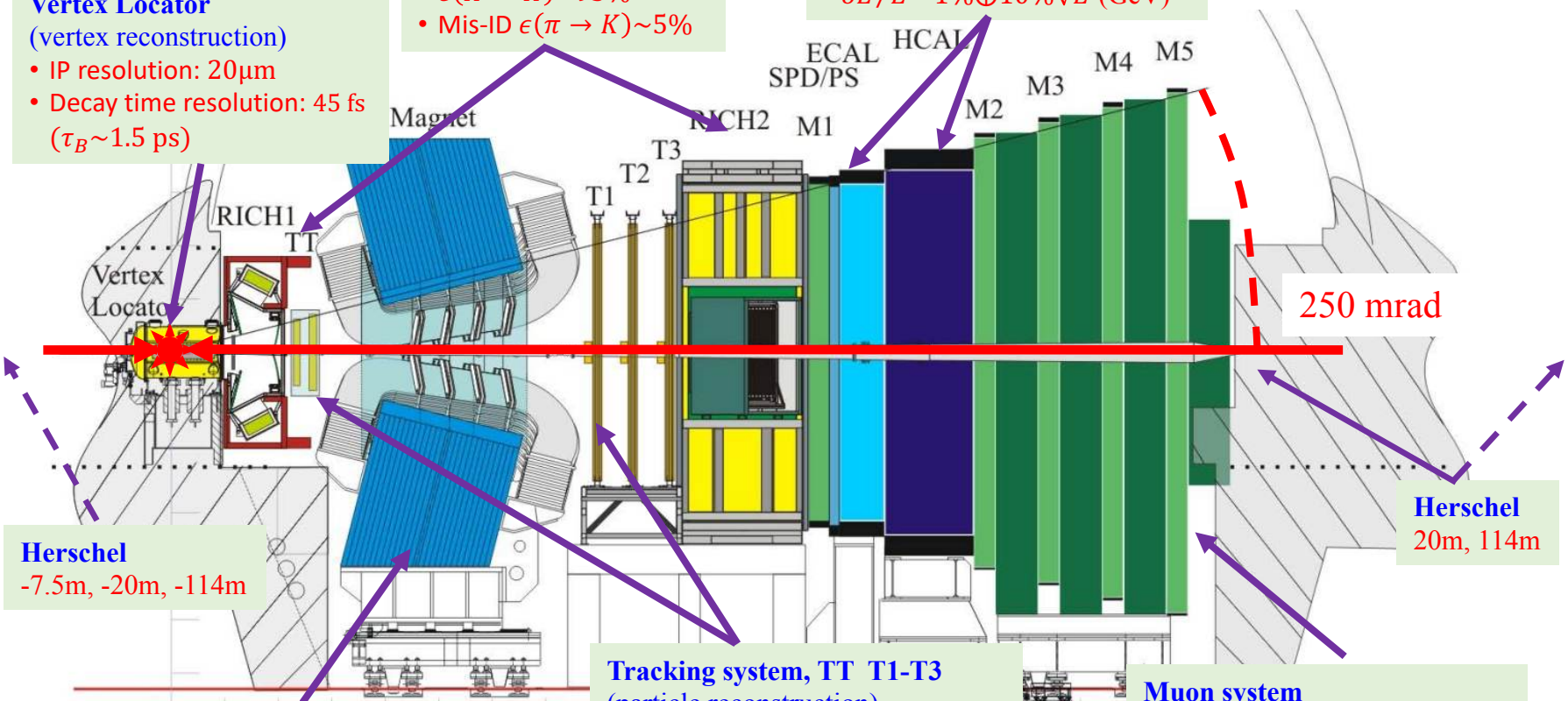
Aiming for precision measurements in b, c sectors

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

Vertex Locator
(vertex reconstruction)
- IP resolution: 20μm
- Decay time resolution: 45 fs (τ_B~1.5 ps)

RICH detectors
(K/π /p separation)
- $\epsilon(K \to K)$~95%
- Mis-ID $\epsilon(\pi \to K)$~5%

Calorimeters (ECAL, HCAL)
(e/γ identification)
- $\delta E/E$ ~1%⊕10%$\sqrt{E}$ (GeV)



Herschel
-7.5m, -20m, -114m

Herschel
20m, 114m

Bending magnet
bending power: 4 Tm

Tracking system, TT T1-T3
(particle reconstruction)
- ϵ(Tracking)~96%
- $\delta p/p$ ~0.5%-1% (5-200 GeV)
- $\sigma(m_{B\to hh}) \approx$ 22 MeV

Muon system
(μ identification)
- $\epsilon(\mu \to \mu)$~97%
- Mis-ID $\epsilon(\mu \to \mu)$~1 − 3%

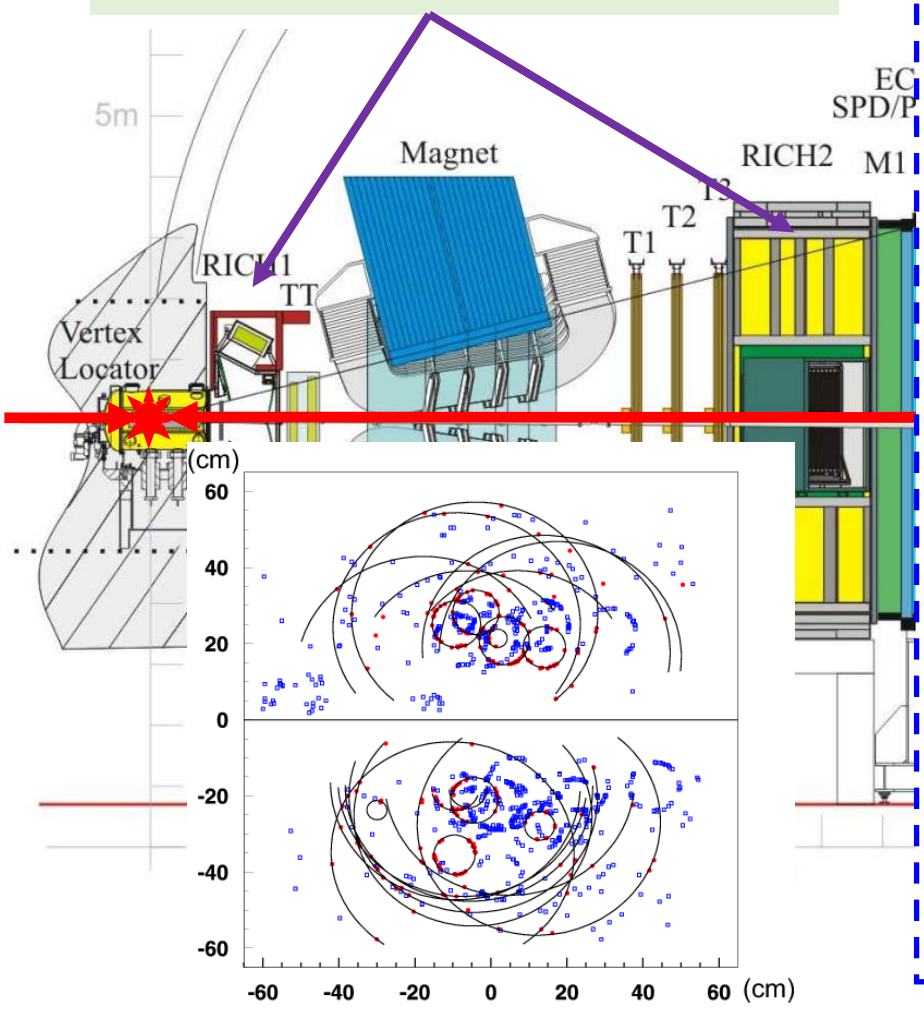
LHCb experiment

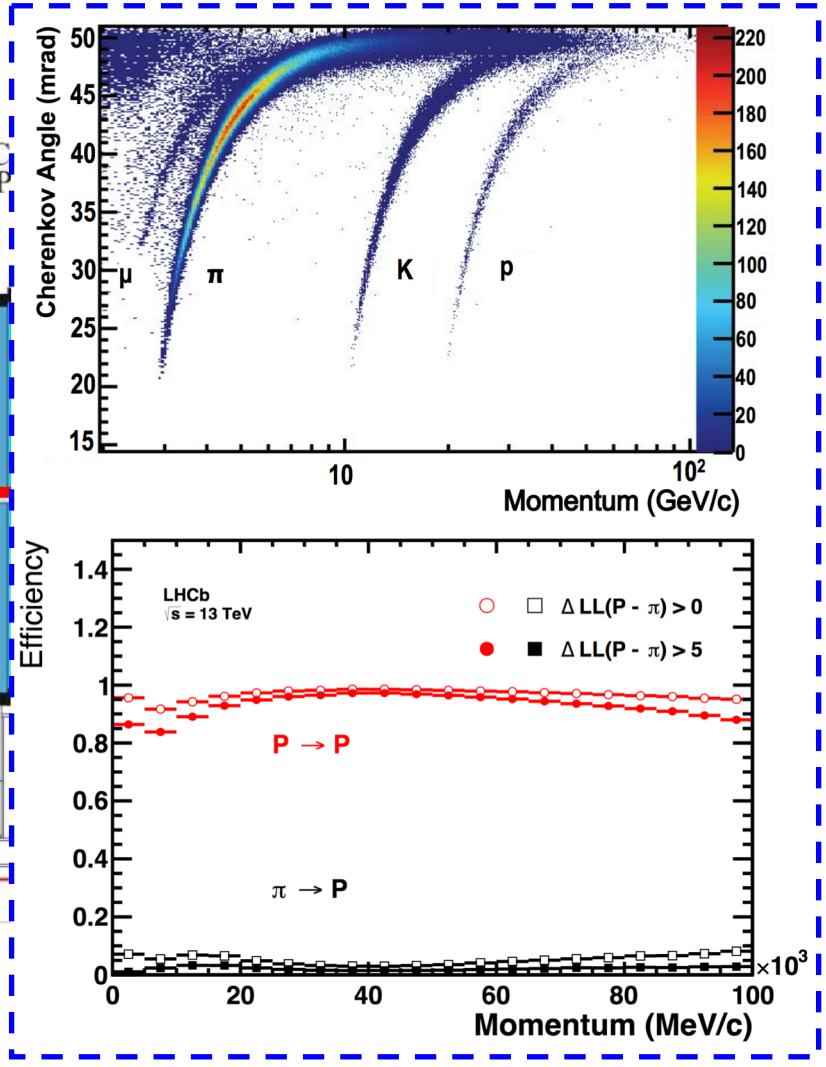
Decays: $b \to c \to s\ (K^{\pm})$; Baryon → proton

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

RICH detectors ($K/\pi\ /p$ separation)

- $\epsilon(K \to K)$~95% for $r(\pi \to K)$~5%

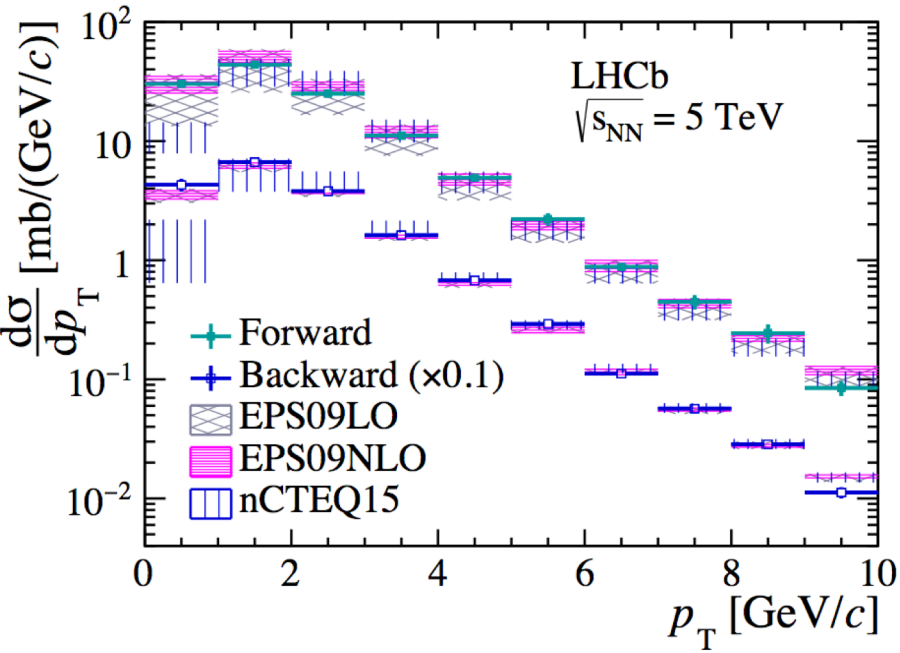


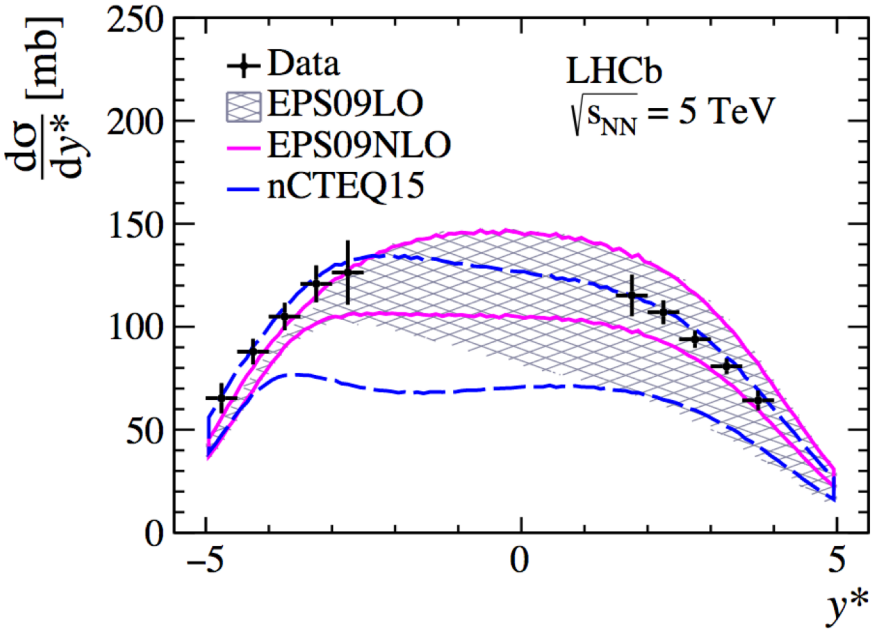


Prompt D^0 cross-section

JHEP 10 (2017) 090

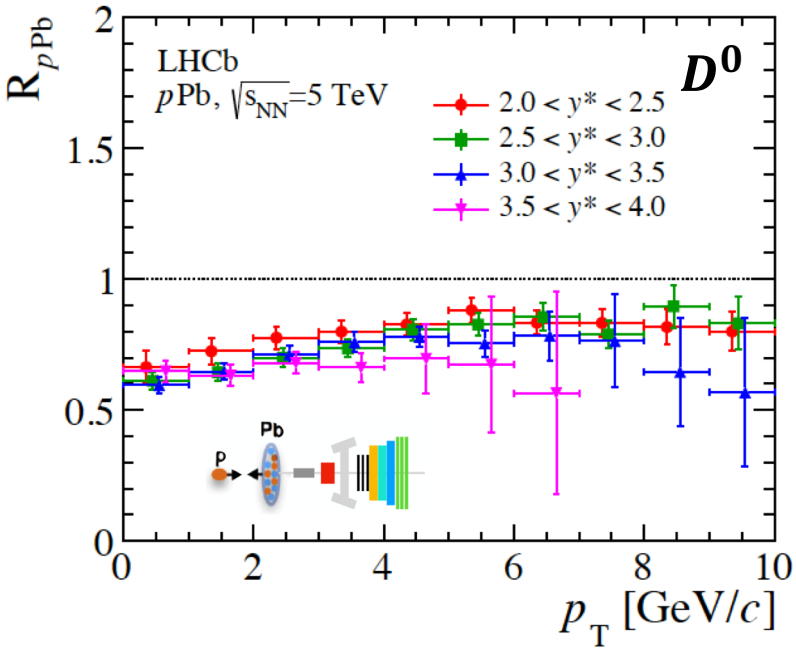
- Differential cross-sections

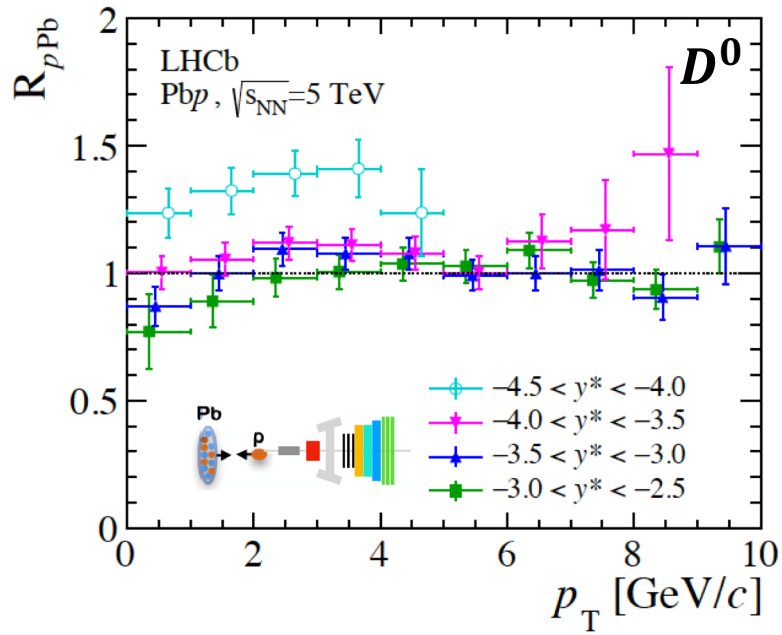




R_{pA}: double differential

JHEP 10 (2017) 090



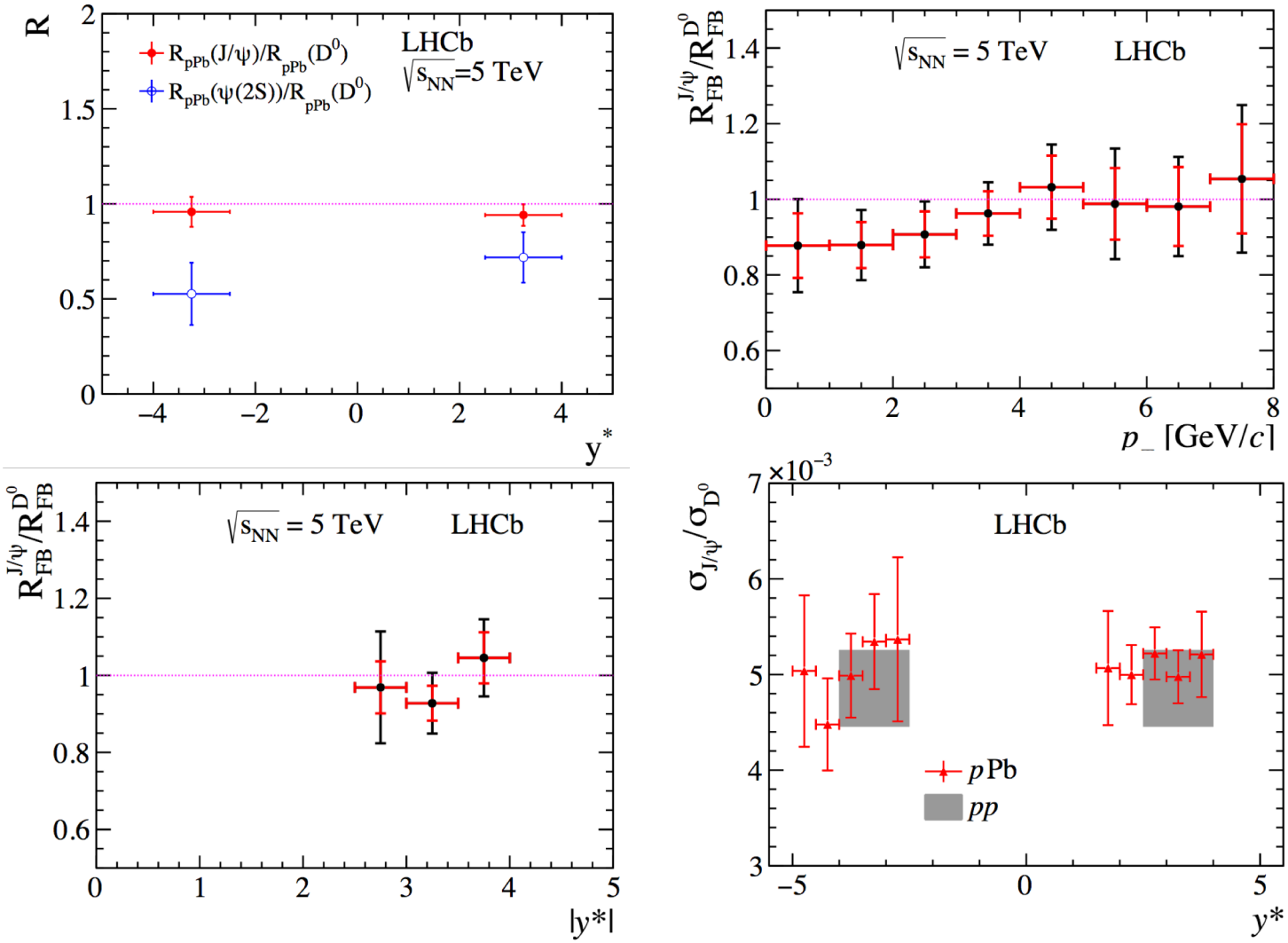


- Fixing p_T region, R_{pA} increases from proton to lead beam direction
- For the same y, R_{pA} increases with p_T, from strong suppression to moderate suppression for positive rapidity, small suppression at very low p_T and hint of enhancement at high p_T
- Large enhancement when getting closer to lead beam rapidity

Open charm vs charmonium

- (Double) ratios

JHEP 10 (2017) 090



Charm baryons over mesons

- Ratios

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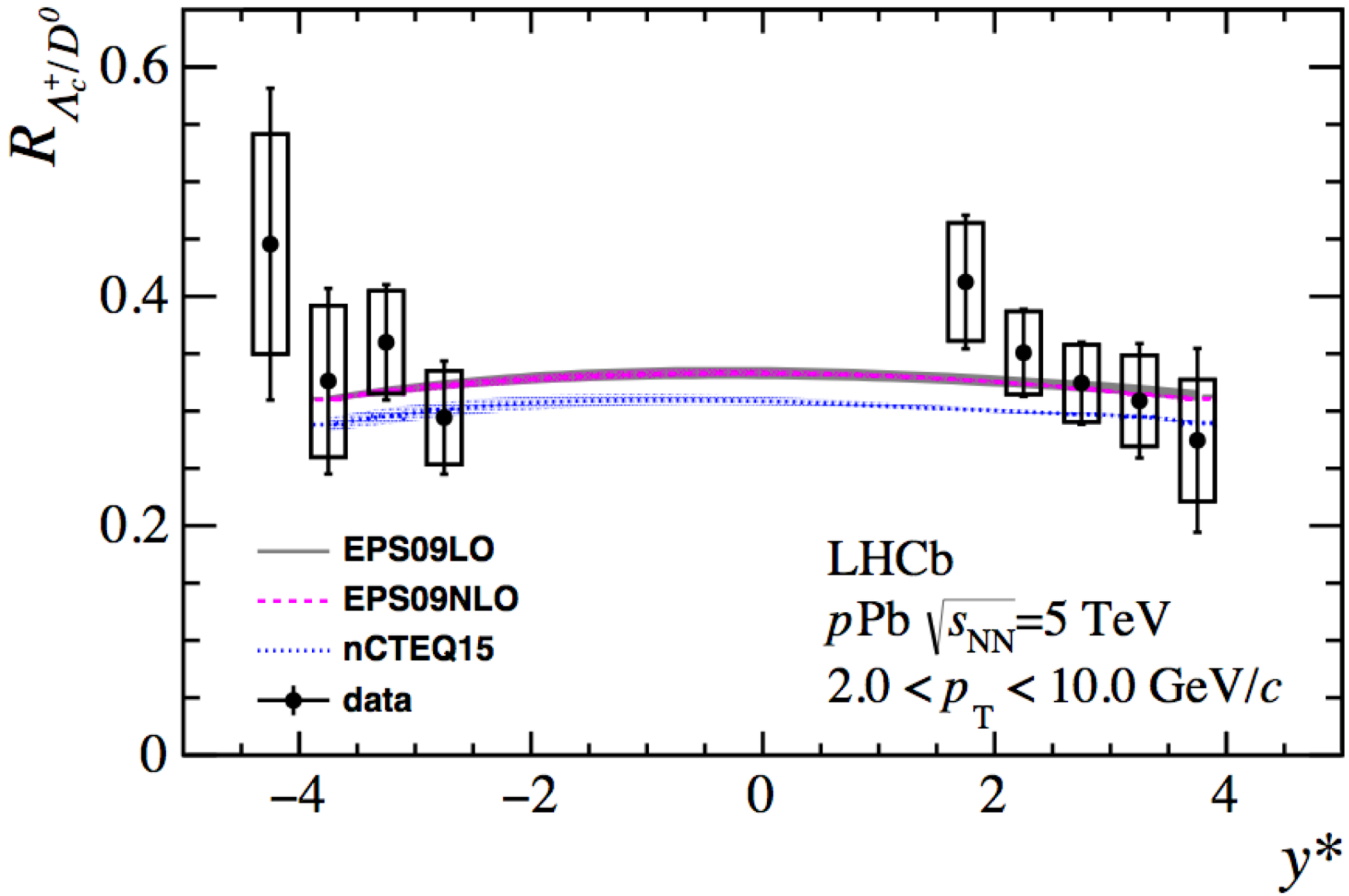
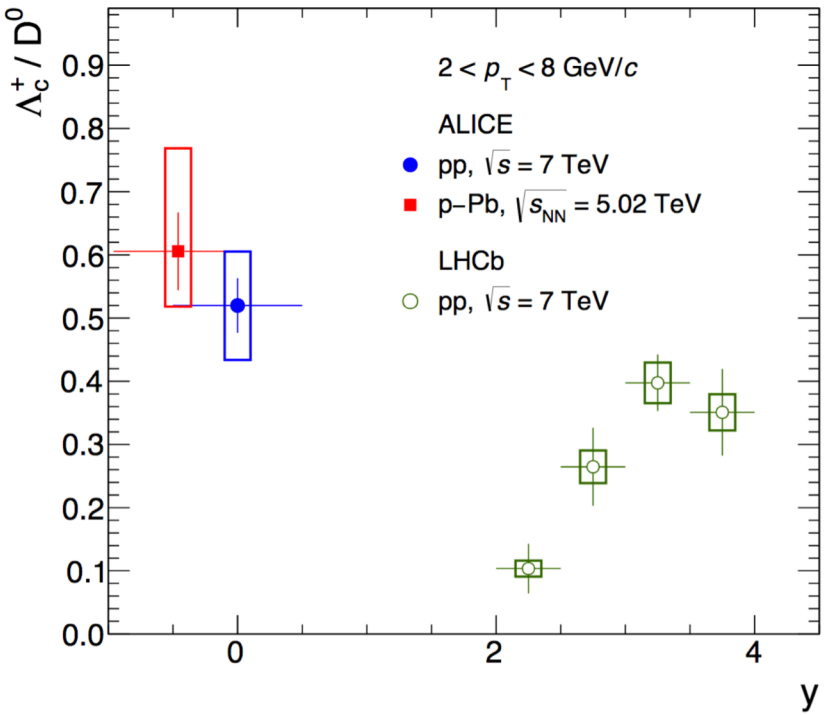
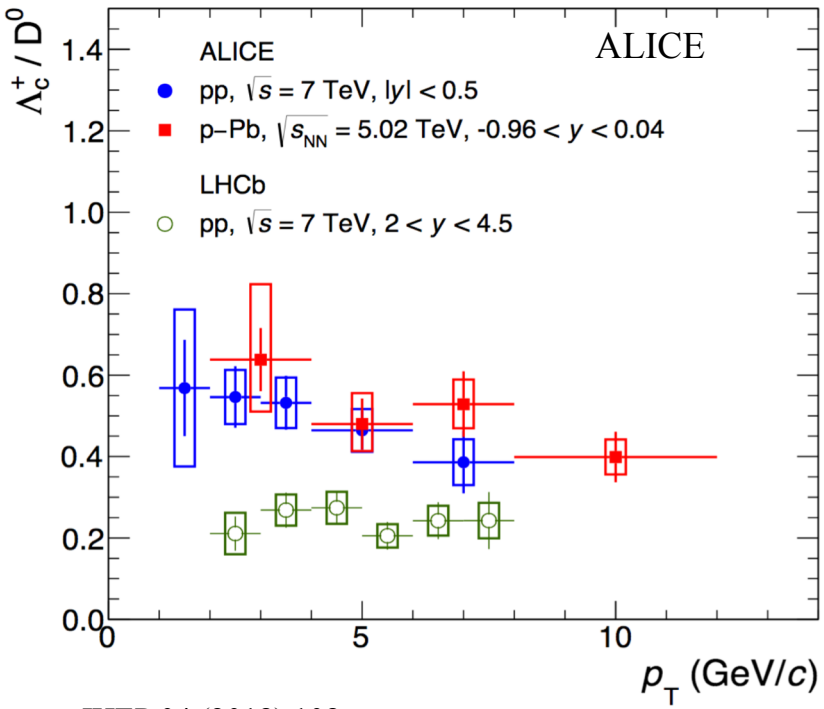


Baryon over meson ratio

LHCb-PAPER-2018-021

- Overall scale is different in LHCb and ALICE in *pp* collisions
- Unexpected rapidity dependence

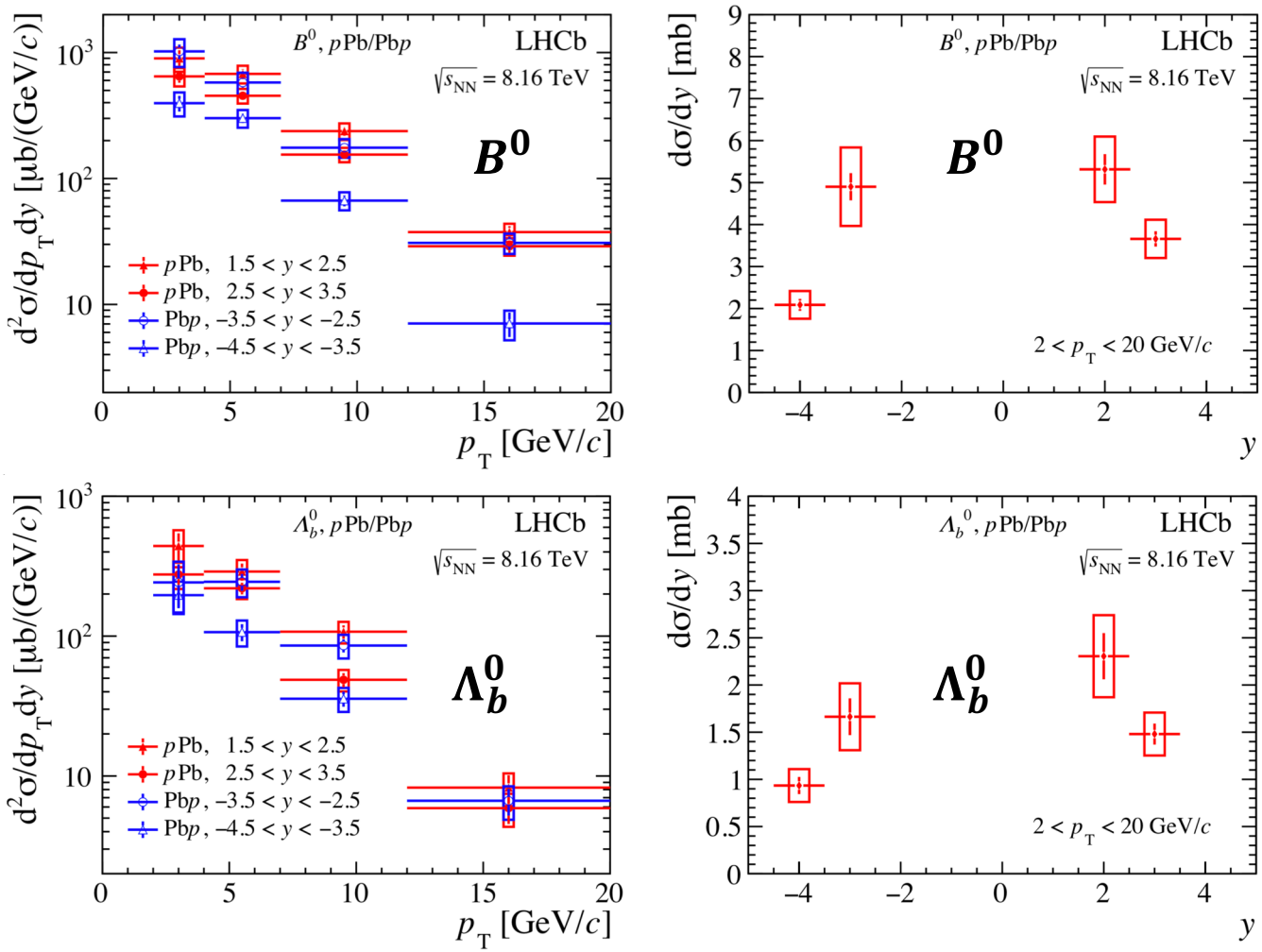




JHEP 04 (2018) 108
JHEP 10 (2017) 090

Cross-sections (cont.)

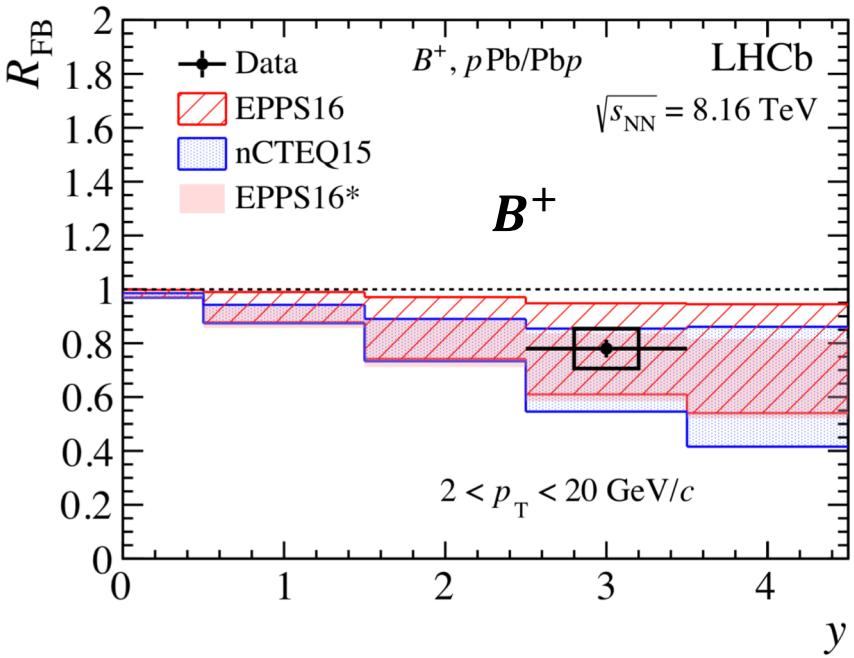
PRD 99 (2019) 052011

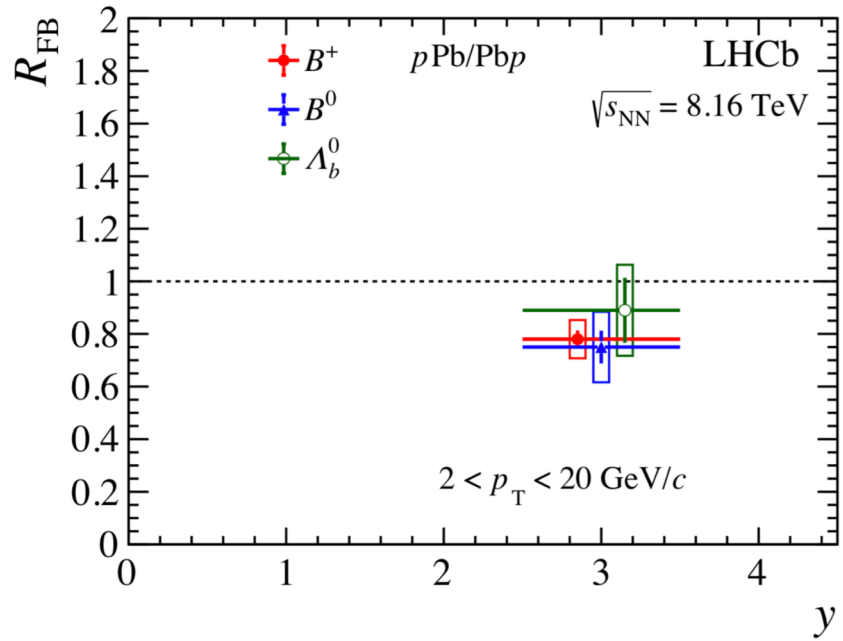


Similar p_T and y distributions for B^+, B^0 and Λ_b^0 hadrons

Forward backward ratio

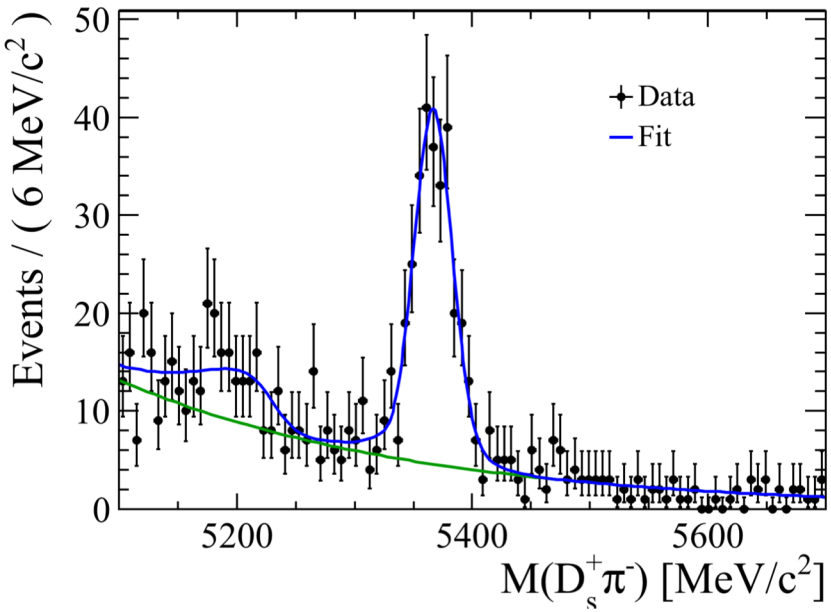
PRD 99 (2019) 052011



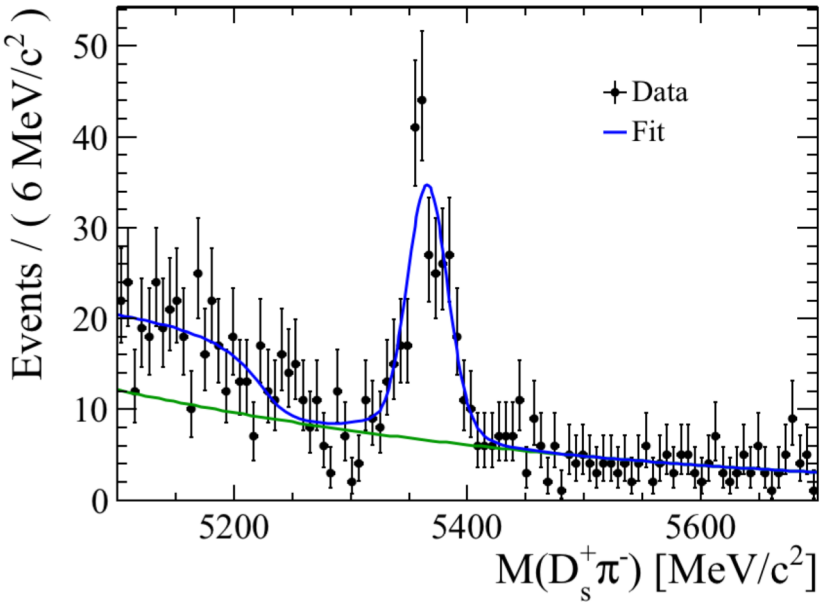


- Magnitude of R_{FB} for B^+, B^0 and Λ_b^0 are compatible

$B_s^0 \to \bar{D}_s^- \pi^+$ mass



Fwd: N_{sig}~270



Bwd: N_{sig}~220

Signal yield much smaller due to small production and branching fraction.
Due to smaller $f_{B_s^0}$ and $B(B_s^0 \to D_s^- \pi^+) \times B(D_s^- \to K^+ K^- \pi^+)$