Production of open heavy flavour hadrons in *p*Pb and fixed-target collisions at LHCb

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On behalf of the LHCb collaboration

Tsinghua University

Outline

- Open heavy flavor in pPb collisions
  - Prompt $D^0$and Λ_c^+ production in pPb collisions at 5.02 TeV D^0: JHEP 10 (2017) 090 Λ_c^+: JHEP 02 (2019) 102
  - B^+, $B^0$and Λ_b^0 production in pPb collisions at 8.16 TeV PRD99 052011 (2019)

- Fixed target results
  - Charm production in pNe and pAr at 87, 110GeV PRL 122 (2019) 132002
  - Antiproton production cross-section in pNe at 110GeV PRL 121 (2018) 222001

Heavy flavor in *p*Pb collisions

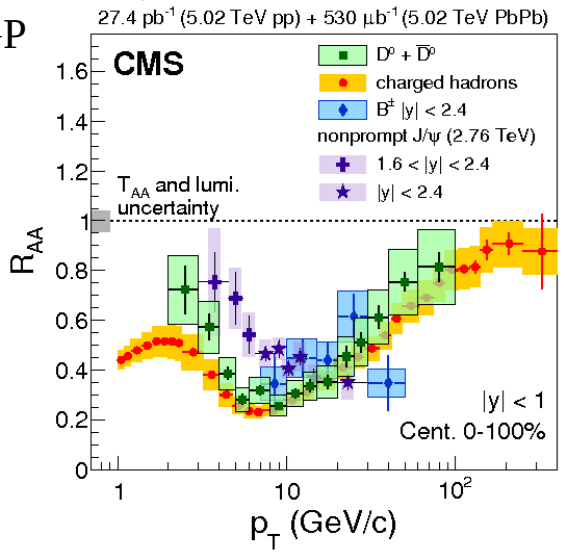
- Heavy flavor states are sensitive probes to study the properties of the QGP created in AA collision.
  - Produced in the early stage of the collisions
  - Strong interaction with the medium
  - Baryon/meson ratio in charm and bottom sectors

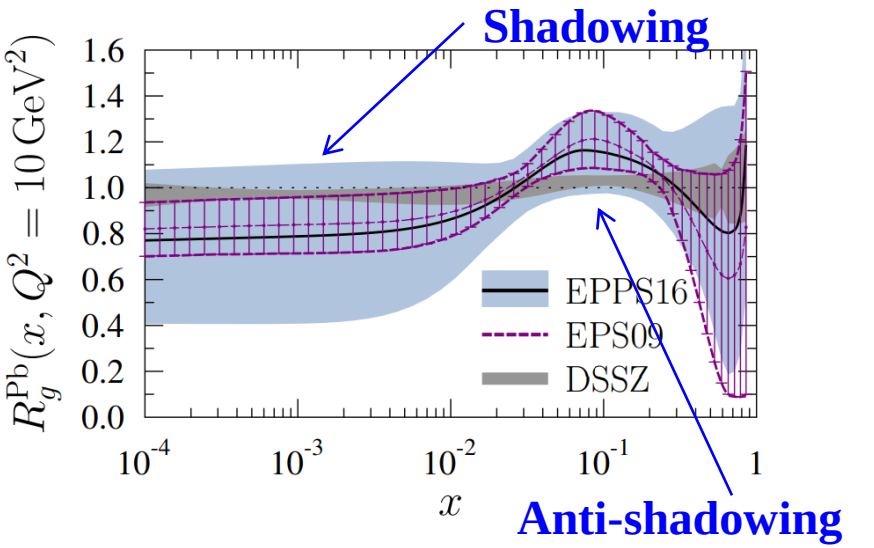
- Heavy flavor in *p*A collisions provide baseline measurements to disentangle cold nuclear matter effects from effects of hot and dense medium.

- LHCb well suited for such measurements:
  - Heavy flavor measurement down to p_T close to 0
  - Separation of prompt and *b* decay components

- Cold Nuclear Matter effects
  - Initial state:
    - Modification of nuclear PDF
    - Gluon saturation
  - Multiple scattering of partons in the nucleus

Phys. Lett. B 782 (2018) 474

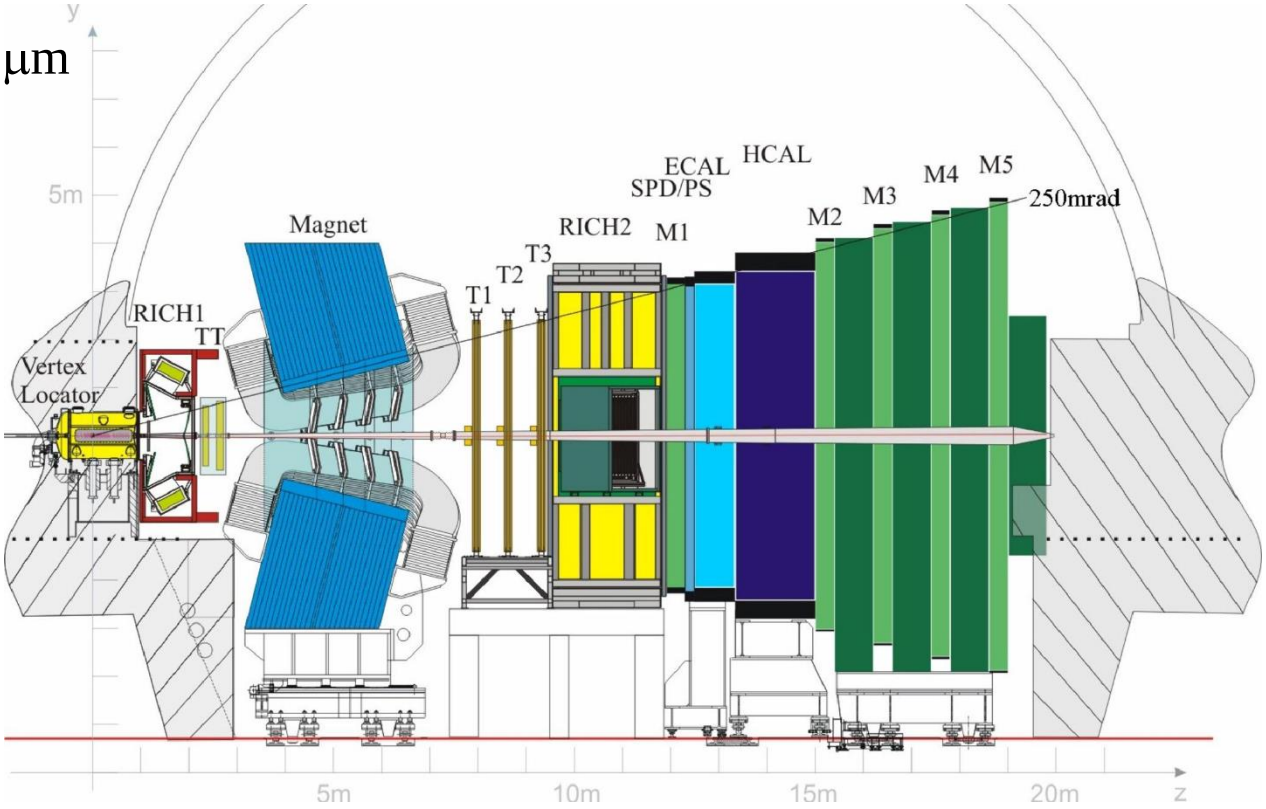




arXiv:1802.05927

LHCb detector

- A single arm forward spectrometer designed for the study of particles containing *c* or *b* quark.
- Acceptance: $2 < \eta < 5$
- Vertex detector
  - IP resolution ~ 20 μm
- Tracking system
  - $\frac{\Delta p}{p} = 0.5\% - 1\%$ (5-200 GeV/*c*)
- RICH
  - K/π/p separation (up to 100 GeV/*c*)
- Electromagnetic + hadronic Calorimeters
- Muon systems

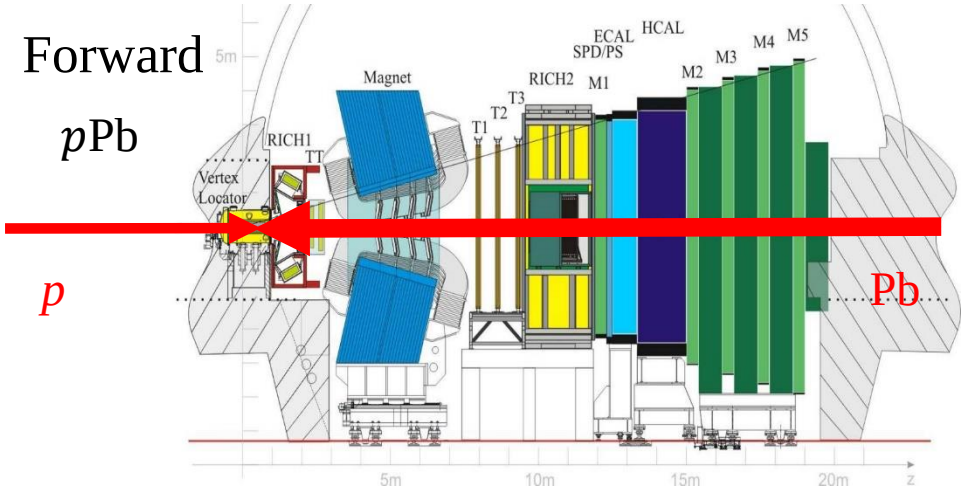


JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

LHCb pPb datasets

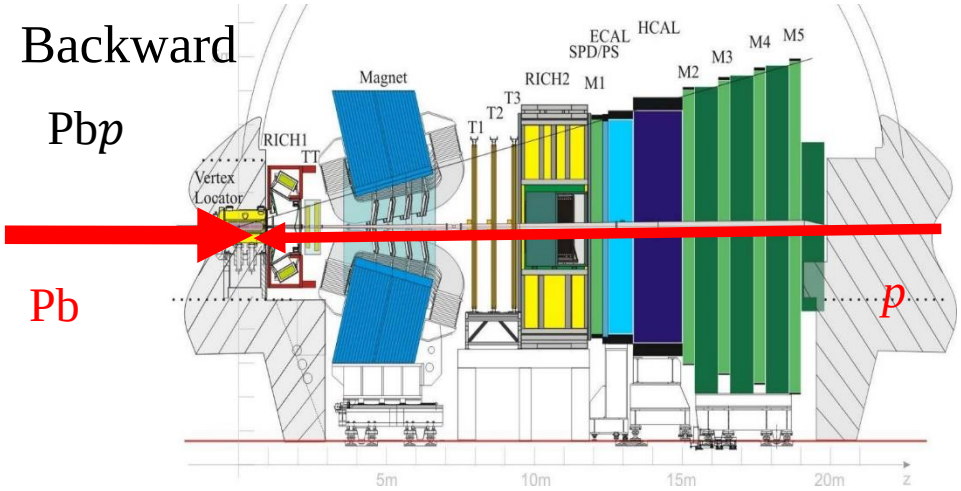
Forward

pPb



Backward

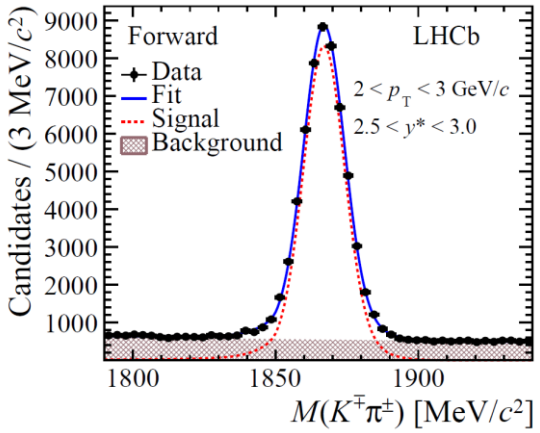
Pbp

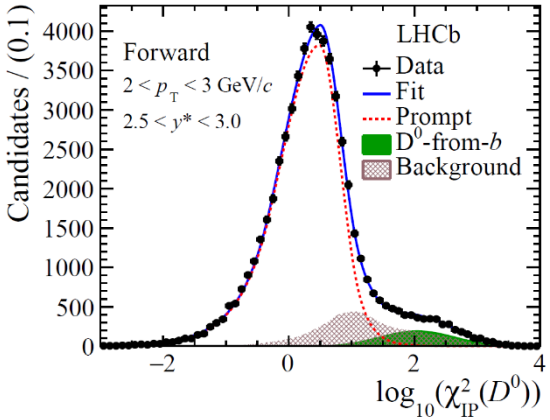


- Rapidity Coverage
  - y^*: rapidity in nucleon-nucleon cms
  - $y_{\mathrm{cms}} = \pm 0.465$
  - Forward: $1.5 < y^* < 4.0$
  - Backward: $-5.0 < y^* < -2.5$
  - Common region: $2.5 < |y^*| < 4.0$
- $\sqrt{s_{NN}} = 5.02$ TeV (2013)
  - pPb (1.06 nb^{-1}) + Pbp (0.52 nb^{-1})
- $\sqrt{s_{NN}} = 8.16$ TeV (2016)
  - pPb (13.6 nb^{-1}) + Pbp (21.8 nb^{-1})

Prompt D^0 and Λ_c^+ measurement in pPb at 5.02 TeV

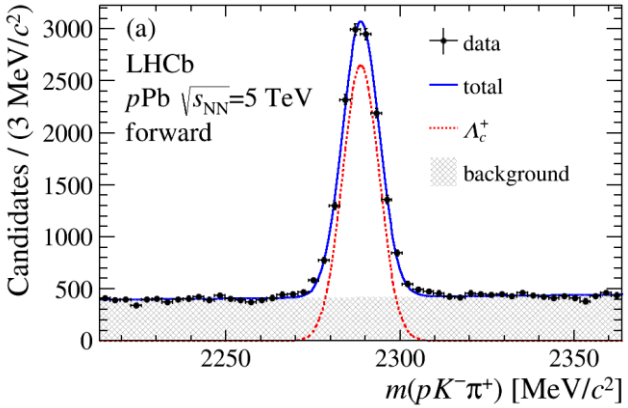
$D^0 \downarrow$

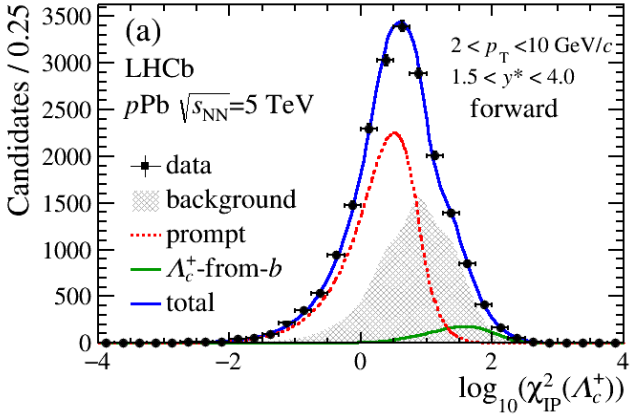




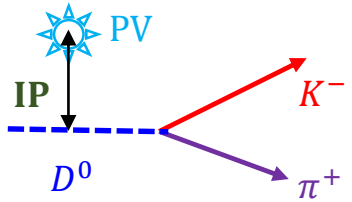
JHEP 10 (2017) 090

$\Lambda_c^+ \downarrow$





JHEP 02 (2019) 102



Reconstructed through decay channel:

$D^0 \to K^-\pi^+$

$\Lambda_c^+ \to pK^-\pi^+$

Inclusive D^0/Λ_c^+ signals from fitting invariant mass dist.:

- Signal:
  Crystal Ball+Gaussian (D^0)
  Gaussin (Λ_c^+)
- Background: linear

Prompt charm fraction extracted from fitting impact parameter dist.:

- Prompt: simulation
- from-b: simulation (D^0)
  sPlot+MC (Λ_c^+)
- Background: sideband in data

Prompt D^0 at 5.02 TeV nuclear modification factor in pPb

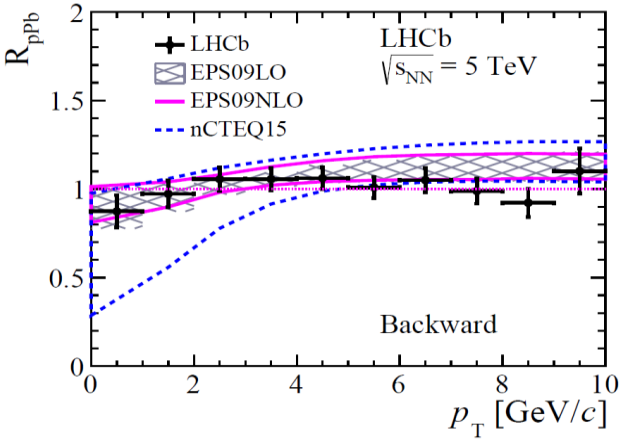
Models:
JHEP 10 (2003) 046
Eur. Phys. J. C77 (2017) 1
Comput. Phys. Commun. 184 (2013) 2562
Comput. Phys. Commun. 198 (2016) 238

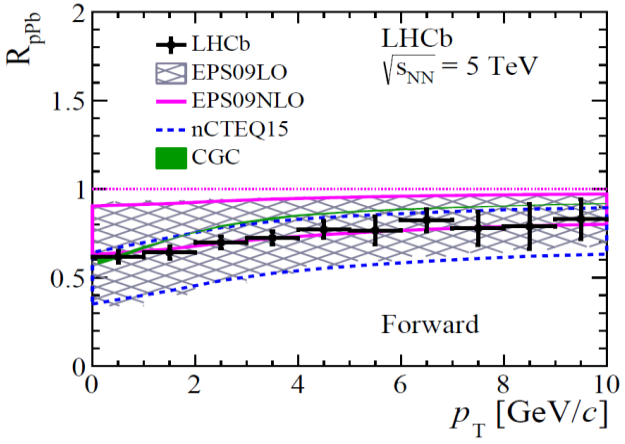
$$R_{p\mathrm{Pb}}(y^*, p_\mathrm{T}) = \frac{1}{A} \times \frac{\mathrm{d}\sigma_{p\mathrm{Pb}}(y^*, p_\mathrm{T}, \sqrt{s_\mathrm{NN}})/\mathrm{d}x}{\mathrm{d}\sigma_{pp}(y^*, p_\mathrm{T}, \sqrt{s_\mathrm{NN}})/\mathrm{d}x}, \quad A{=}208$$

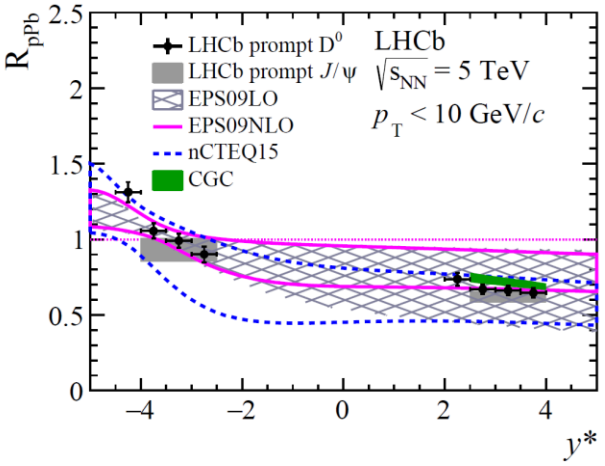
- pp reference directly measured by LHCb
- $R_{p\mathrm{Pb}}$ suppressed at forward rapidity
  - slight increase with increasing p_T
- $R_{p\mathrm{Pb}}$ closer to 1 at backward rapidity
  - hint of enhancement at large rapidity

- Measurements consistent with models with nPDF, CGC
- **Data has smaller uncertainties than theory**

JHEP 10 (2017) 090





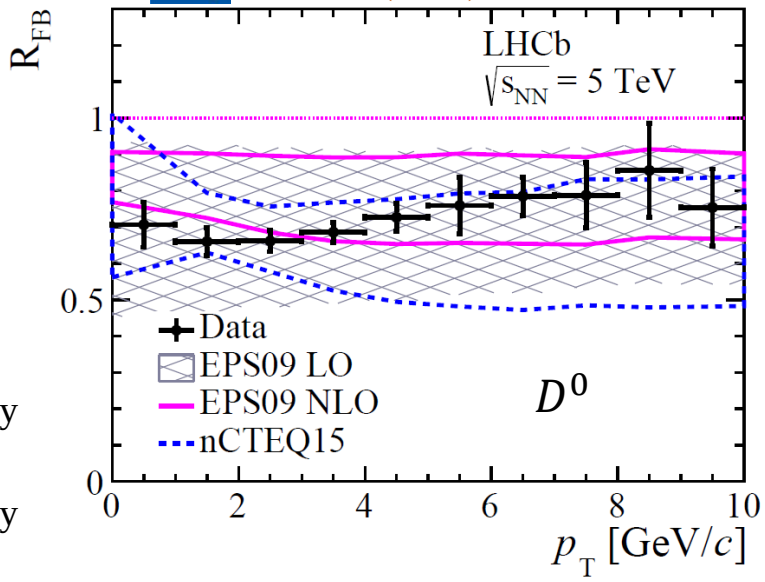


Prompt charm production at 5.02 TeV forward-backward production ratio

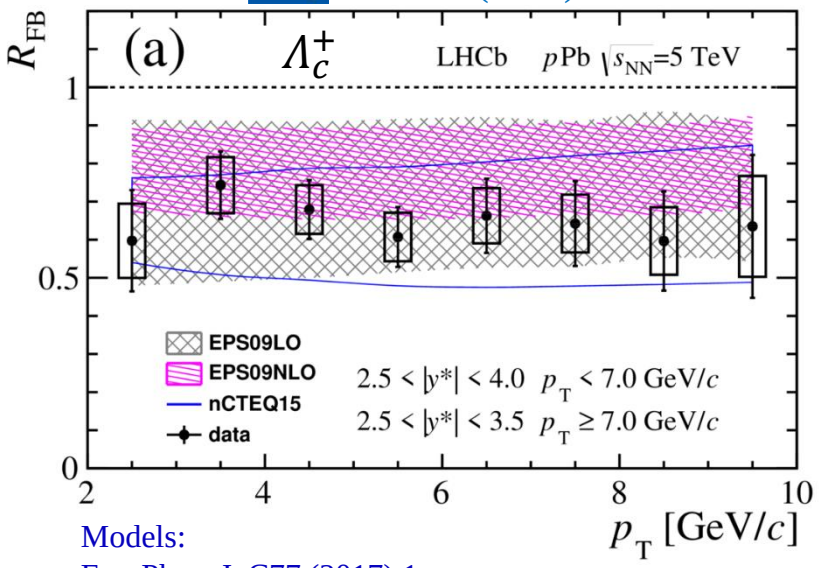
$$R_{\mathrm{FB}} = \frac{\sigma(+|y^*|, p_{\mathrm{T}})}{\sigma(-|y^*|, p_{\mathrm{T}})}$$

- R_{FB} does not need results from pp collisions.
- Compared to Helac-Onia calculations incorporating different nPDFs
  - Model parameterisation constrained by existing LHC pp cross-section measurements
- Consistent with nPDF predictions within uncertainty
- **D^0 meson show smaller uncertainties than nPDF calculations**

JHEP 10 (2017) 090



JHEP 02 (2019) 102



Total uncertainty

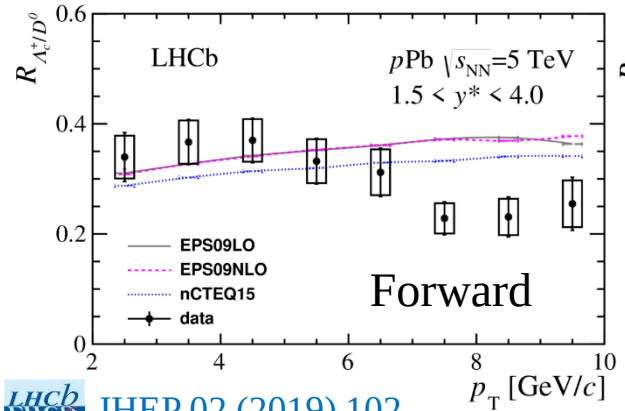
syst. uncertainty

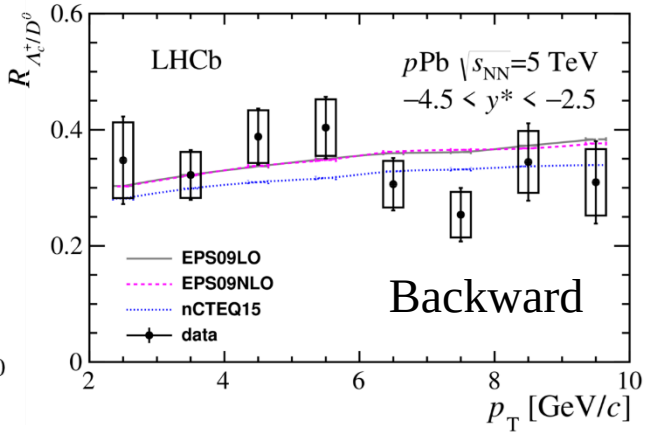
Models:
Eur. Phys. J. C77 (2017) 1
Comput. Phys. Commun. 184 (2013) 2562
Comput. Phys. Commun. 198 (2016) 238

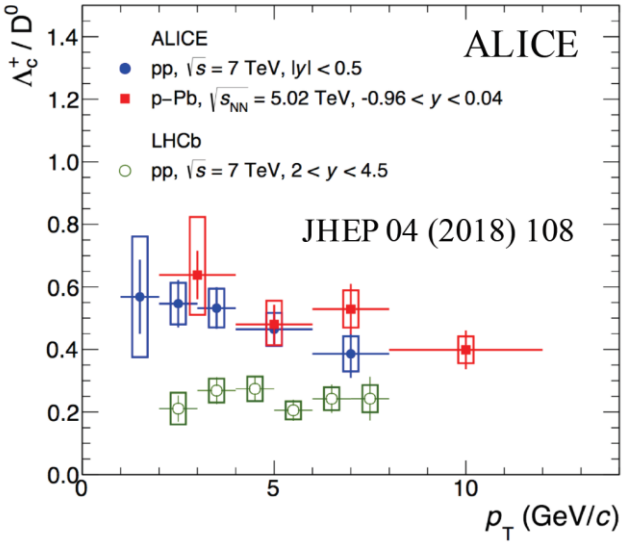
Charmed baryon/meson production ratio $R_{\Lambda_c^+/D^0}$ at 5.02 TeV

$$R_{\Lambda_c^+/D^0} = \frac{\sigma_{\Lambda_c^+}(y^*, p_T)}{\sigma_{D^0}(y^*, p_T)}$$

Models:
Eur. Phys. J. C77 (2017) 1
Comput. Phys. Commun. 184 (2013) 2562
Comput. Phys. Commun. 198 (2016) 238







JHEP 02 (2019) 102

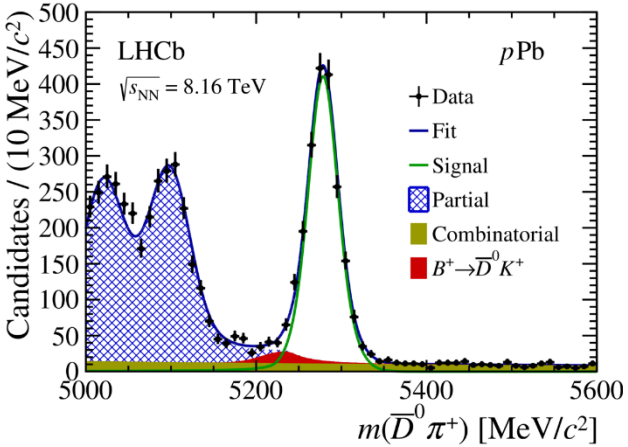
- Sensitive to charm hadronisation mechanisms
- Model based on measured *pp* cross-section
- nPDF effects mostly cancel
  - EPS09LO & EPS09NLO similar
  - nCTEQ15 slightly lower.
- Slight increase with increasing p_T

- Forward:
  - Consistent at lower p_T
  - Below theories at higher p_T
- Backward:
  - Consistent for all p_T
- Consistent with LHCb *pp* results ~0.3
- Lower than ALICE points in midrapidity for both *pp* and *p*Pb

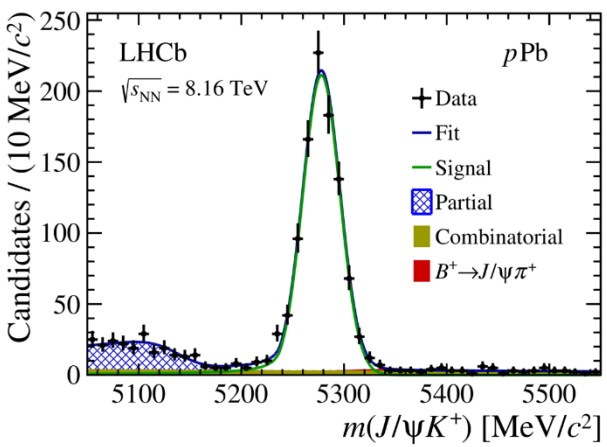
Beauty hadron production in pPb at 8.16 TeV

PRD99 052011 (2019)

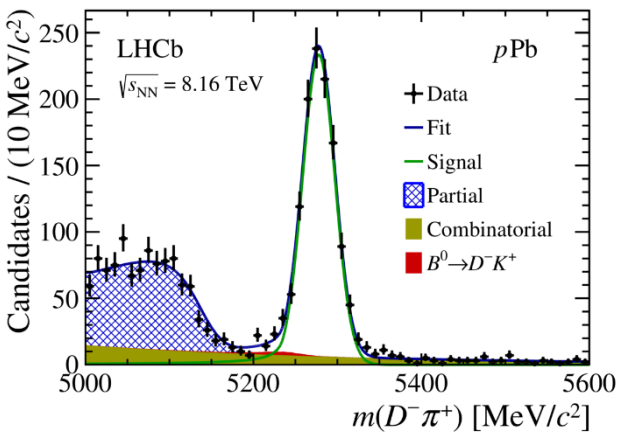
$B^+ \to \overline{D}^0\pi^+$



$B^+ \to J/\psi K^+$



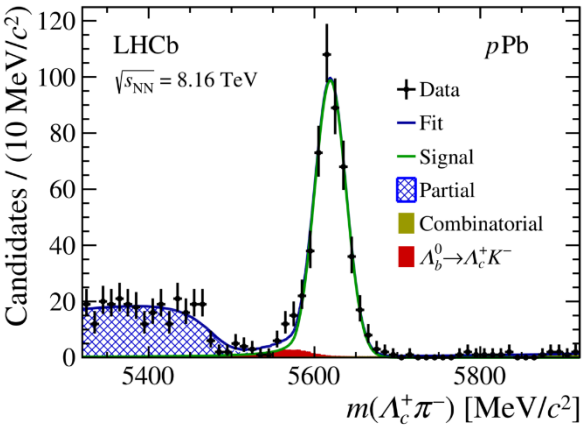
$B^0 \to D^-\pi^+$



Reconstructed through exclusive hadronic decay modes:

Decay	pPb	Pbp
$B^+ \to \bar{D}^0\pi^+$	1958 ± 54	1806 ± 55
$B^+ \to J/\psi K^+$	0883 ± 32	0907 ± 33
$B^0 \to D^-\pi^+$	1151 ± 38	0889 ± 34
$\Lambda_b^0 \to \Lambda_c^+\pi^-$	0484 ± 24	0399 ± 23

$\Lambda_b^0 \to \Lambda_c^+\pi^-$

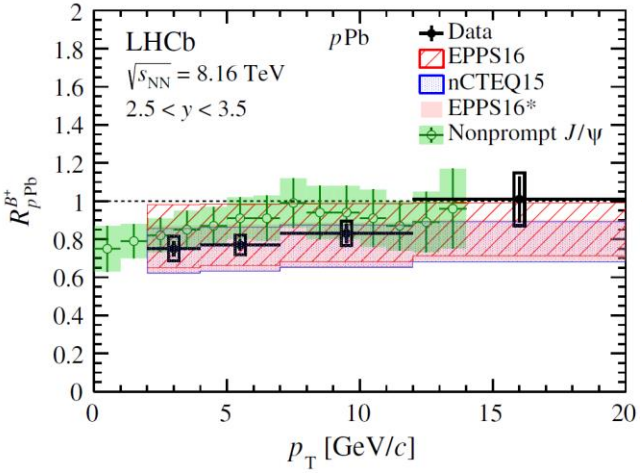


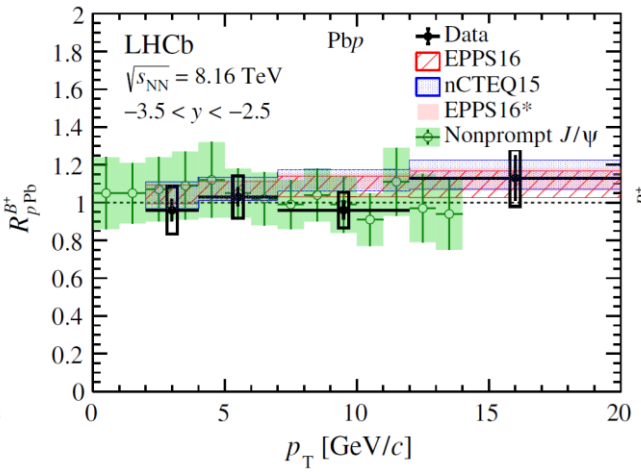
b-hadron production in pPb at 8.16 TeV
B^+ nuclear modification factor

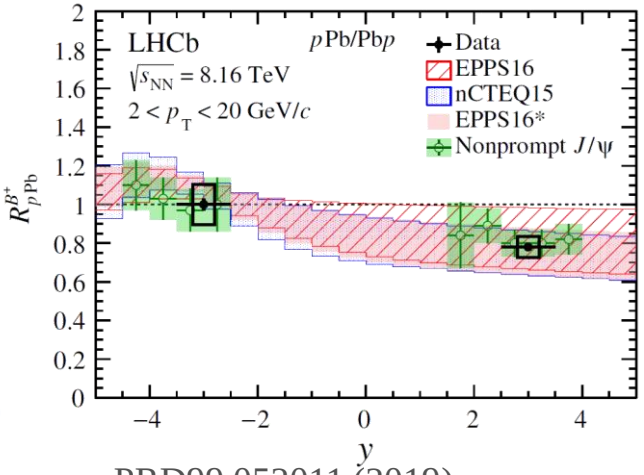
$$R_{p\mathrm{Pb}}(y^*, p_\mathrm{T}) = \frac{1}{A} \times \frac{\mathrm{d}\sigma_{p\mathrm{Pb}}(y^*, p_\mathrm{T}, \sqrt{s_\mathrm{NN}})/\mathrm{d}x}{\mathrm{d}\sigma_{pp}(y^*, p_\mathrm{T}, \sqrt{s_\mathrm{NN}})/\mathrm{d}x}, \; A{=}208$$

- pp reference interpolated between 7 & 13 TeV measurements from LHCb
- $R_{p\mathrm{Pb}}$ suppressed at forward rapidity
  - increase with increasing p_T
- $R_{p\mathrm{Pb}}$ consistent with 1 at backward rapidity

- Measurements consistent with calculations with nPDFs EPPS16 and nCTEQ15
- Consistent with J/ψ-from-b
- Trend similar to D^0 $R_{p\mathrm{Pb}}$





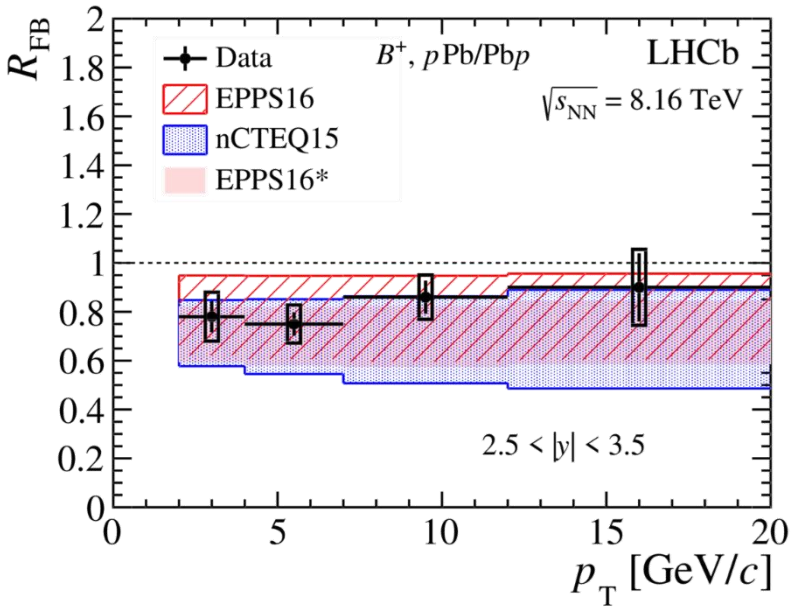


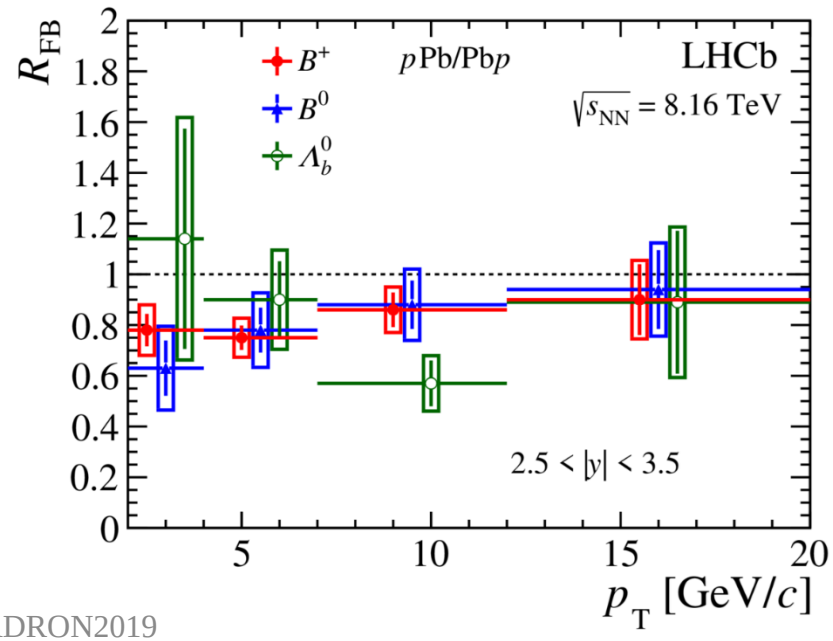
PRD99 052011 (2019)

b-hadron production in pPb at 8.16 TeV
B^+, B^0 and Λ_b^0 forward-backward production ratio

- B^+ production suppressed in the forward rapidity region compared to the backward.
- Limited statistics to observe clear trend wrt p_{T}
- Consistent with nPDF expectations
- Small uncertainty on B^+ R_{FB} compared to nPDF
- Consistent R_{FB} between B^+, B^0 and Λ_b^0

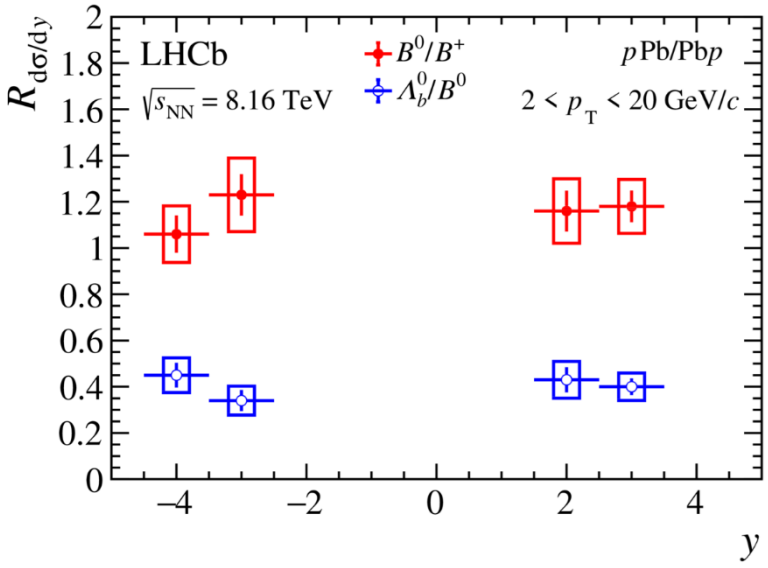
$$R_{\mathrm{FB}} = \frac{\sigma(+|y^*|, p_{\mathrm{T}})}{\sigma(-|y^*|, p_{\mathrm{T}})}$$

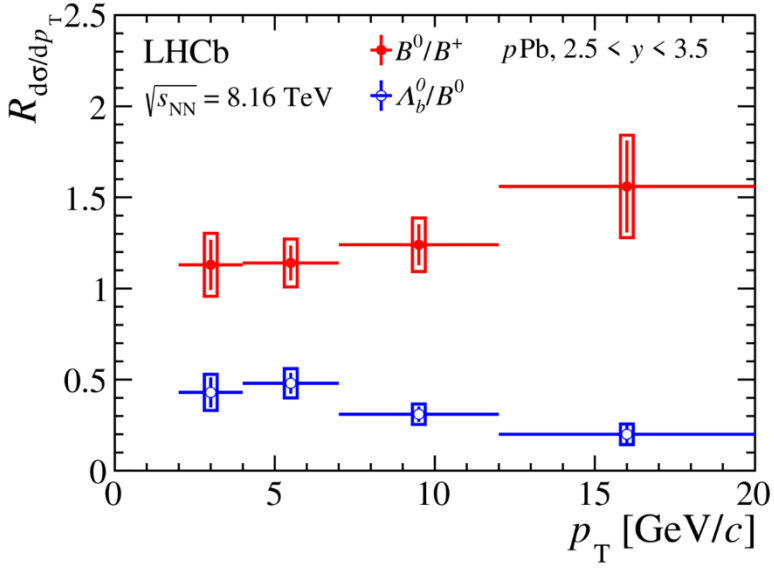




PRD99 052011 (2019)

b-hadron production in *p*Pb at 8.16 TeV
Production cross-section ratio





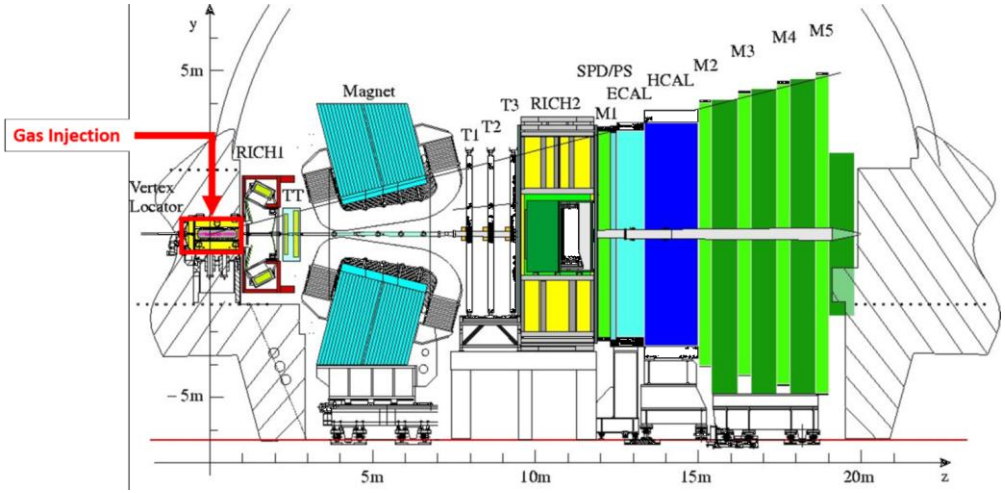
- R_{B^0/B^+}
  - No significant dependence on rapidity and p_T
- $R_{\Lambda_b^0/B^0}$
  - ~0.4, no strong rapidity dependence
  - Similar values observed in LHCb *pp* measurement JHEP 08 (2014) 143
  - Decreases with p_T when $p_T > 5$ GeV/c

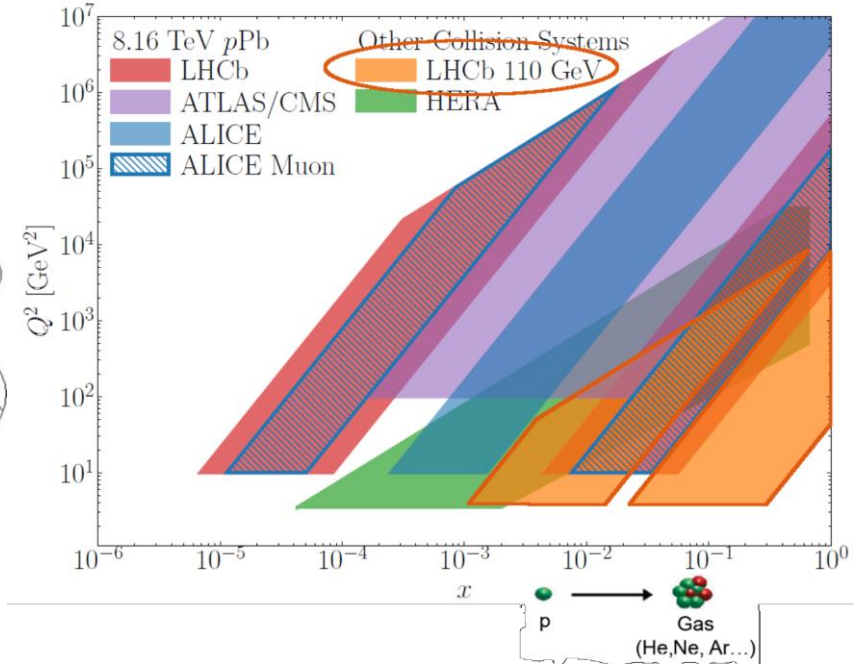
PRD99 052011 (2019)

Fixed target physics

JINST 9 (2014) P12005

- LHCb: only experiment at the LHC can operate in fixed-target mode
- The System for Measuring Overlap with Gas (SMOG) allows a small amount of noble gas injection inside the LHC beam close to the interaction point
- Allows *p*-gas and ion-gas collisions (He, Ne, Ar, ~ 2×10^7mbar)
- $\sqrt{s_{NN}}$ =69-110 GeV between 20 GeV (SPS) and 200 GeV (RHIC)
- $-2.8 < y^* < 0.2$
- Access nPDF anti-shadowing region and intrinsic charm content in the nucleon





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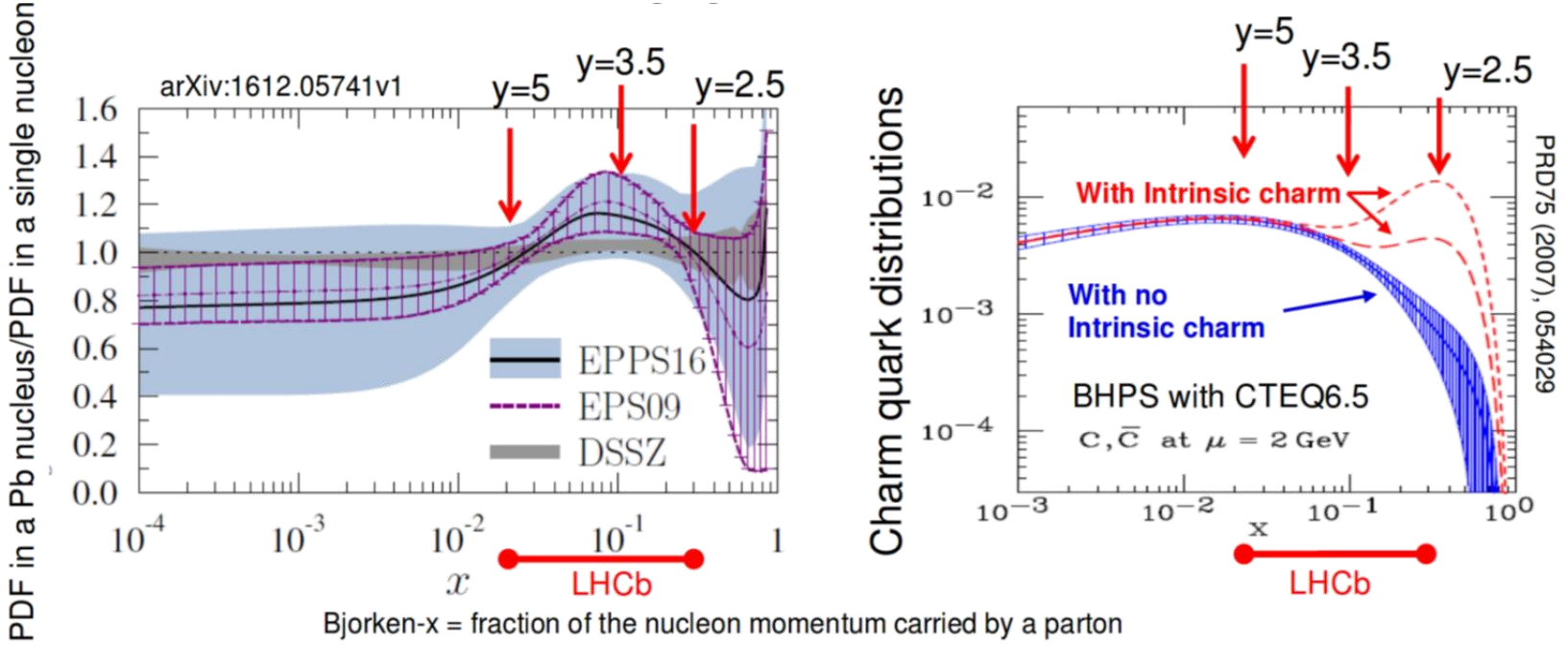
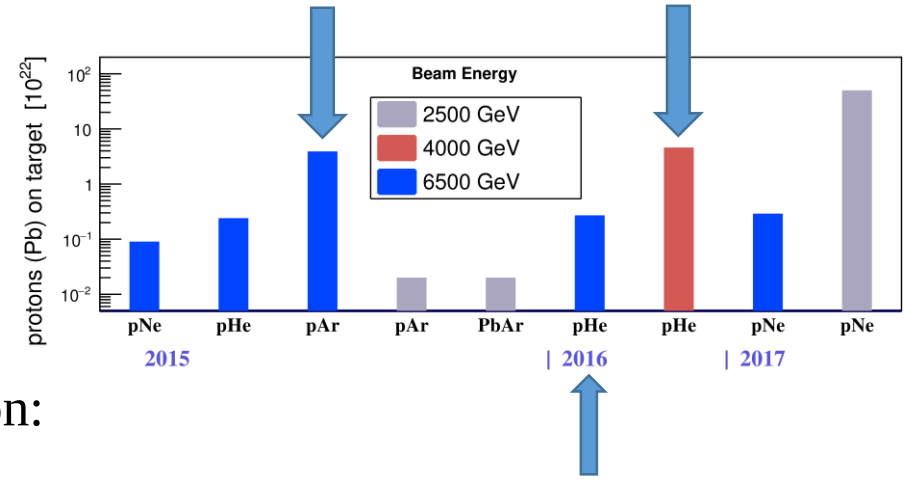


Data samples:

- Measurement of J/ψ and D^0 production:
  - pAr at $\sqrt{s_{NN}} = 110.4$GeV (2015)
    - ~ 4×10^{22} Protons On Target
  - pNe at $\sqrt{s_{NN}} = 86.6$GeV (2016)
    - ~ 5×10^{22} Protons On Target
    - $\mathcal{L}_{p\mathrm{Ne}} = 7.6 \pm 0.5\mathrm{nb}^{-1}$



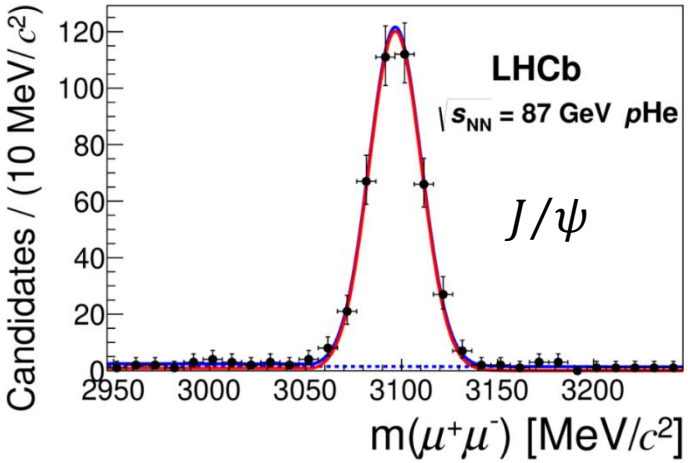
- Measurement of antiproton production:
  - pNe at $\sqrt{s_{NN}}$ =110GeV (2016)
    - $\mathcal{L}_{p\mathrm{Ne}} \sim 0.5\mathrm{nb}^{-1}$

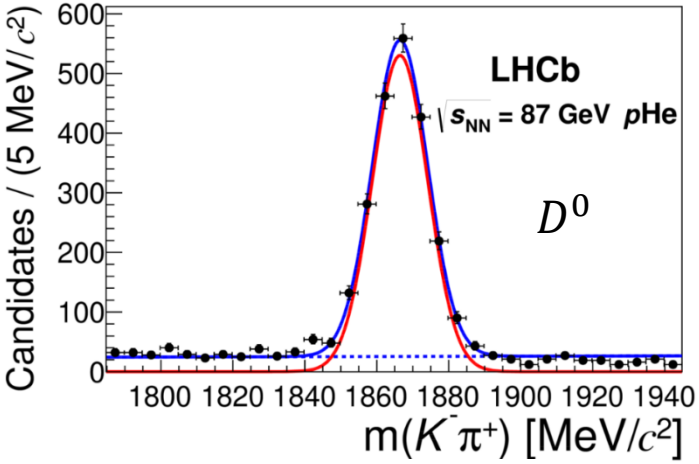
E_{beam}(p)	pp	p-SMOG	p-Pb/Pb-p	Pb-SMOG	Pb-Pb
450 GeV	0.90 TeV				
1.38 TeV	2.76 TeV				
2.5 TeV	5 TeV	69 GeV			
3.5 TeV	7 TeV				
4.0 TeV	8 TeV	87 GeV	5. TeV	54 GeV	
6.5 TeV	13 TeV	110 GeV	8.2 TeV	69 GeV	5.1 TeV
7.0 TeV	14 TeV	115 GeV	8.8 TeV	72 GeV	5.5 TeV

Charm production in fixed-target pN collision

Phys. Rev. Lett. 122 (2019) 132002

- J/ψ and D^0 inclusive cross-section in pNe collisions at 86.6 GeV
- First determination of $c\bar{c}$ cross-section at this energy scale
- Cross-section measurement agree with previous results and theoretical calculations



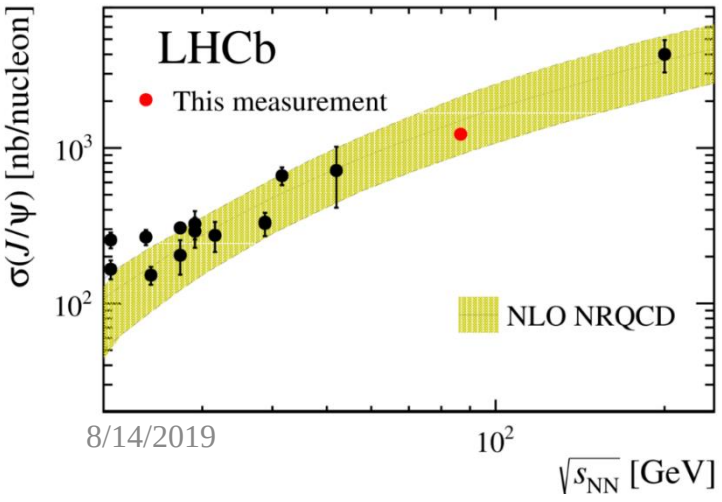


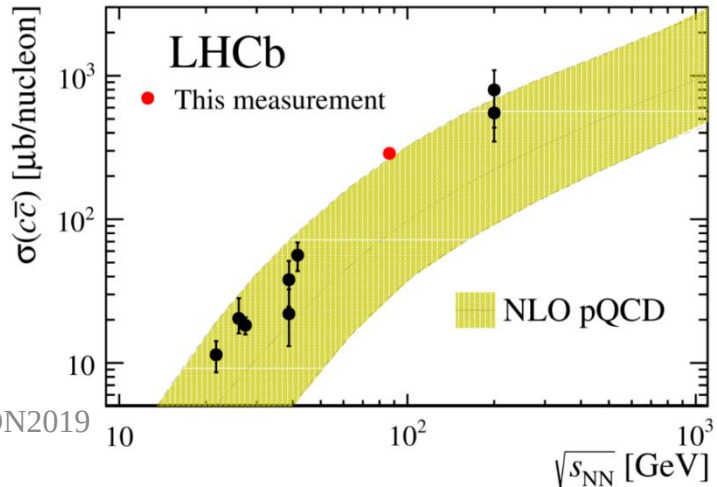
$\sigma_{J/\psi} = 1225.6 \pm 100.7$ nb/nucleon

$\sigma_{D^0} = 156.0 \pm 13.1$ μb/nucleon

$\sigma_{c\bar{c}} = 288 \pm 24.2 \pm 6.9 \mu$b/nucleon

With fraction $(c \to D^0) = 0.542 \pm 0.024$



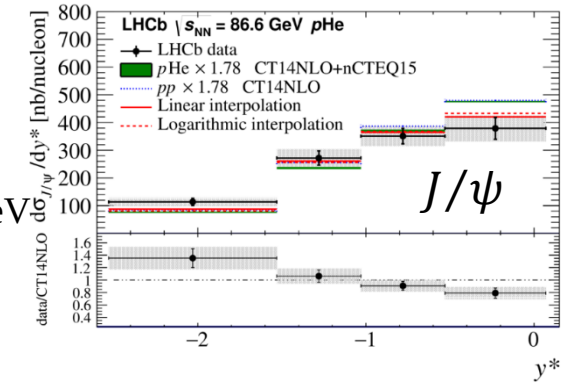


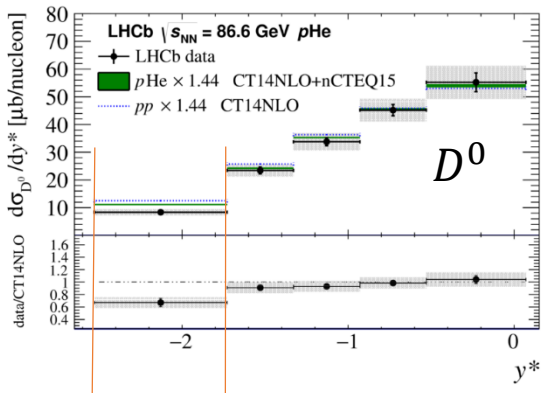
Charm production in fixed-target *p*N collision

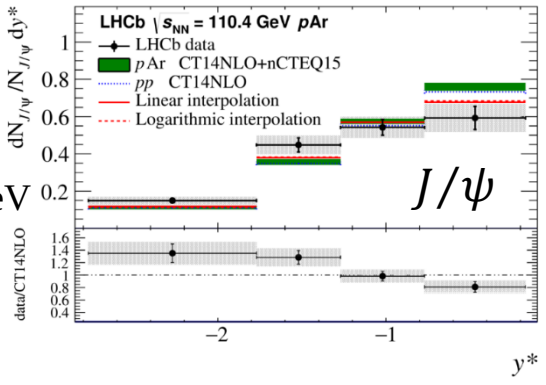
PRL 122 (2019) 132002

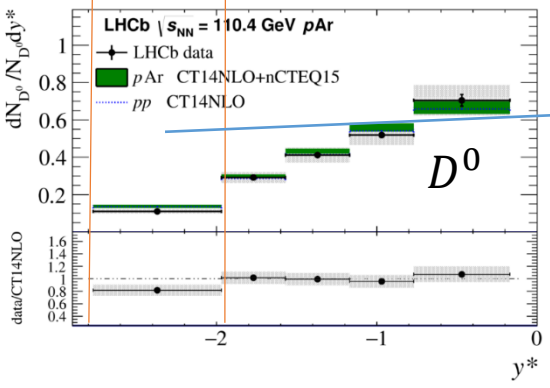
*p*Ne @ 86.6GeV

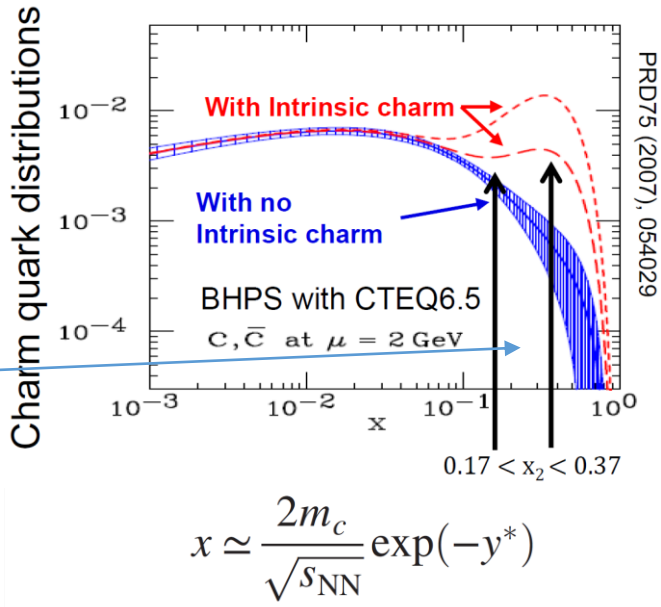
*p*Ar @ 110.4GeV











$$x \simeq \frac{2m_c}{\sqrt{s_{NN}}}\exp(-y^*)$$

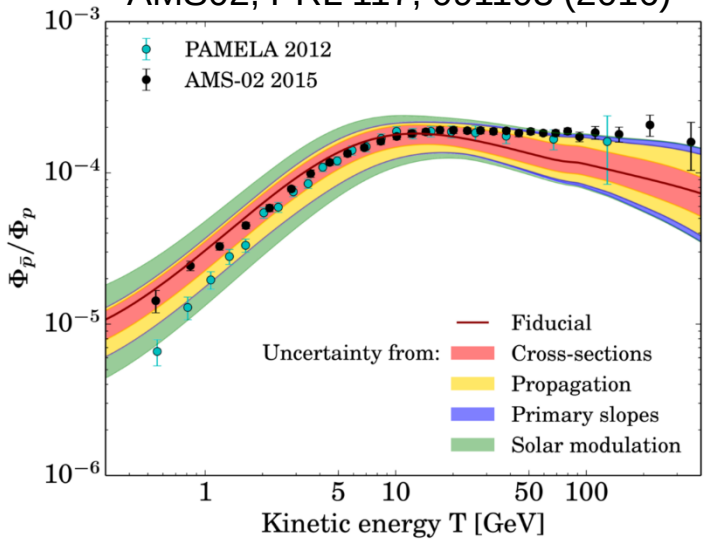
- Differential cross-section (*p*Ne @ 86.6GeV), differential yields (*p*Ar @ 110.4GeV)
- Reasonable agreement with Helac-Onia predictions in rapidity shape
- -2.53<y*<-1.73 → 0.17<*x*<0.37
- Little evidence of intrinsic charm observed

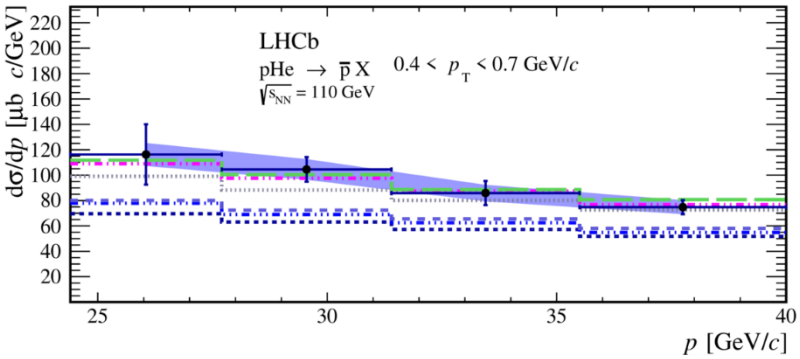
Models:
Eur. Phys. J. C77 (2017) 1
Comput. Phys. Commun. 184 (2013) 2562
Comput. Phys. Commun. 198 (2016) 238

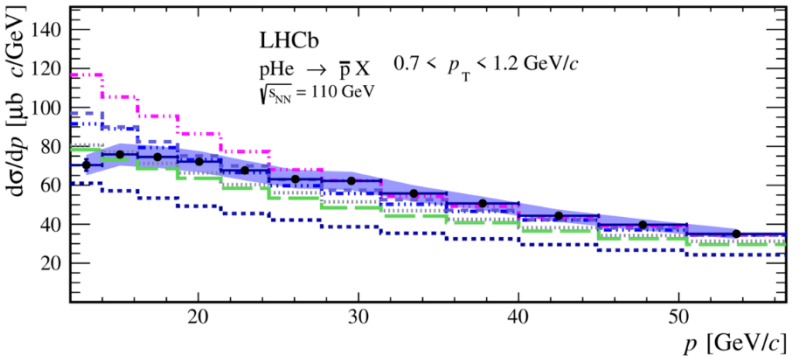
$\bar{p}$ production in pHe collisions

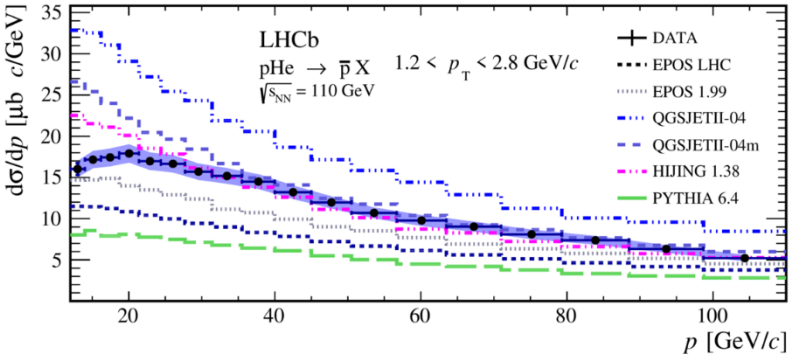
Phys. Rev. Lett. 121 (2018) 222001

AMS02, PRL 117, 091103 (2016)









- AMS-2: possible anti-proton excess at high energies
- $\bar{p}/p$ ratio predictions limited by uncertainties on $\bar{p}$ production cross-sections, particularly for p-He
- Prompt production at $\sqrt{s_{NN}} = 110$ GeV
- First measurement of $\bar{p}$ production in pNe
- Uncertainty (below 10%) smaller than the spread of models

Conclusions

- Production cross-sections of open charm and beauty hadrons in pPb collisions at 5.02 TeV and 8.16 TeV
  - Precise prompt D^0 meson measurement down to zero p_{T}. Suppression in the forward rapidity observed.
  - Prompt Λ_c^+/D^0 ratio consistent with theoretical calculations and pp results
  - First measurement of b-hadrons using exclusive hadronic modes. Smaller suppression in the forward rapidity than D^0 meson at low p_{T}.
  - First direct measurement of Λ_b^0 baryon in heavy ion collisions.

    Λ_b^0/B^0 ratio ~ 0.4
- Fixed-target mode (SMOG)
  - Charm production: no strong evidence for intrinsic charm contribution
  - Antiproton: valuable inputs to astrophysics

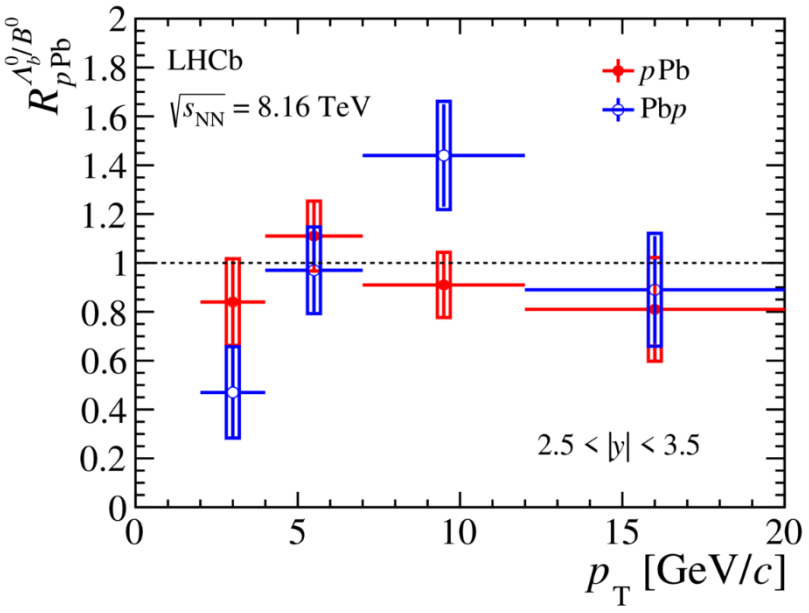
Conclusions

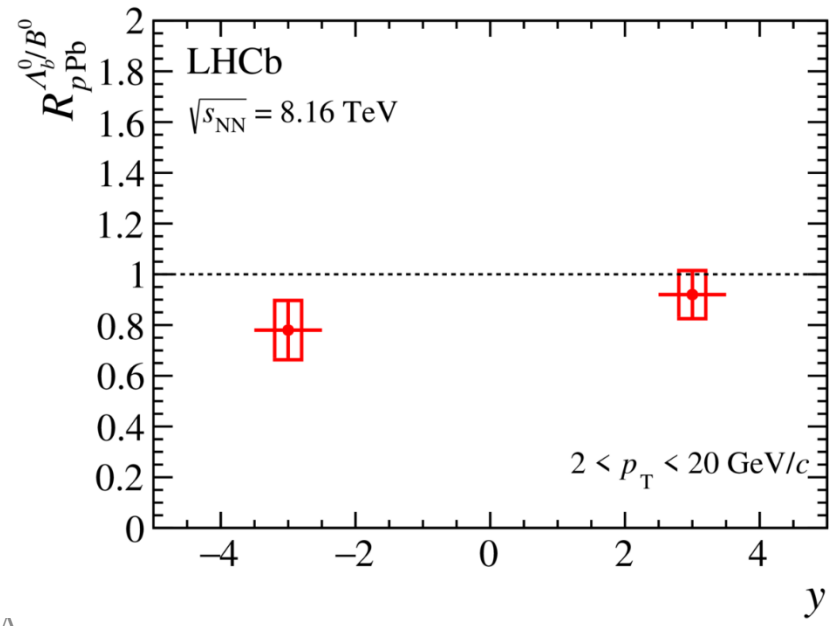
- For the future
  - Analyses of other open heavy flavor hadrons using the 2016 *p*Pb dataset
  - 2018 PbPb dataset (20 times larger than 2015)
  - *p*Ne and PbNe data sets at 69 GeV
  - Upgrade of SMOG system: SMOG2
    - More gases (H_2, deuteron…)
    - Density of the target gas increase → luminosity increase up to a factor of 100

Backup

b-hadron production in pPb at 8.16 TeV
B^0 and Λ_b^0 relative modification

- forward rapidity: consistent with 1
- backward rapidity: hint of more suppression for Λ_b^0.



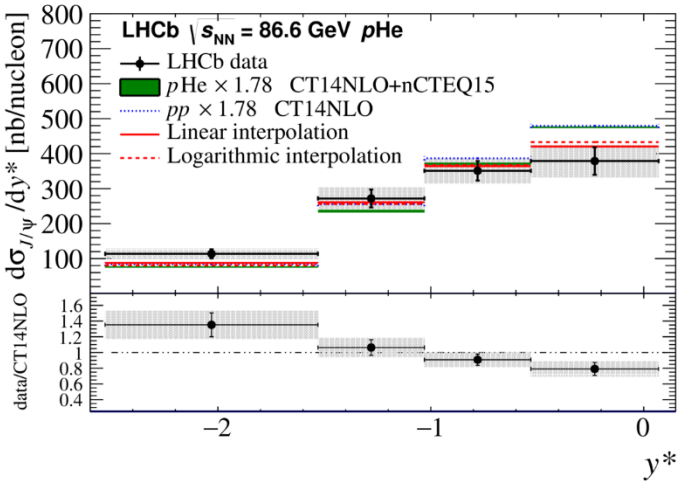


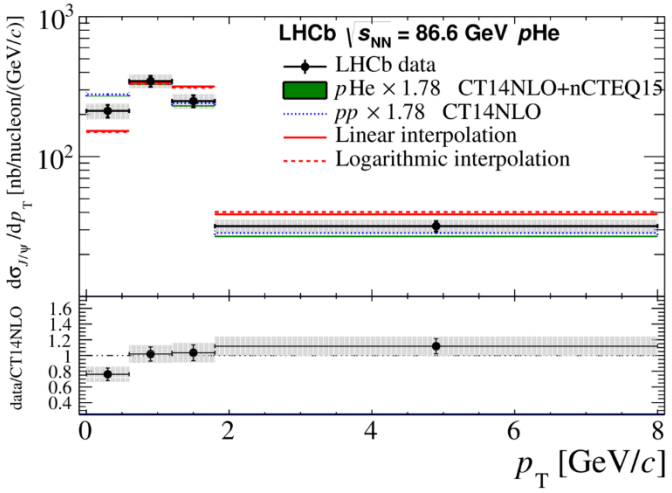
PRD99 052011 (2019)

J/ψ production in fixed-target pN collision

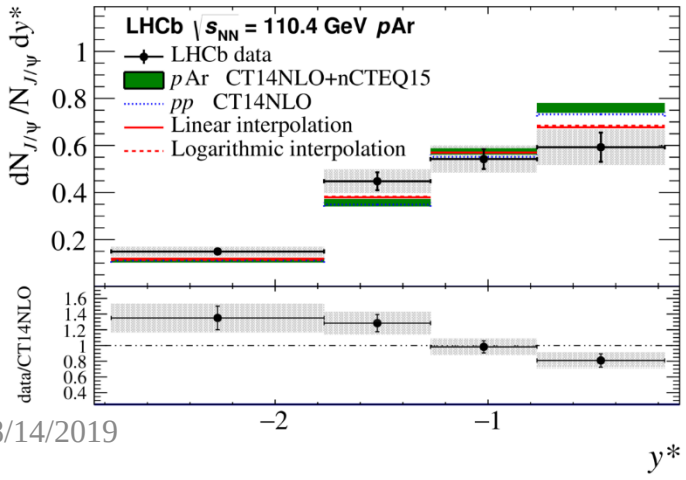
Phys. Rev. Lett. 122 (2019) 132002

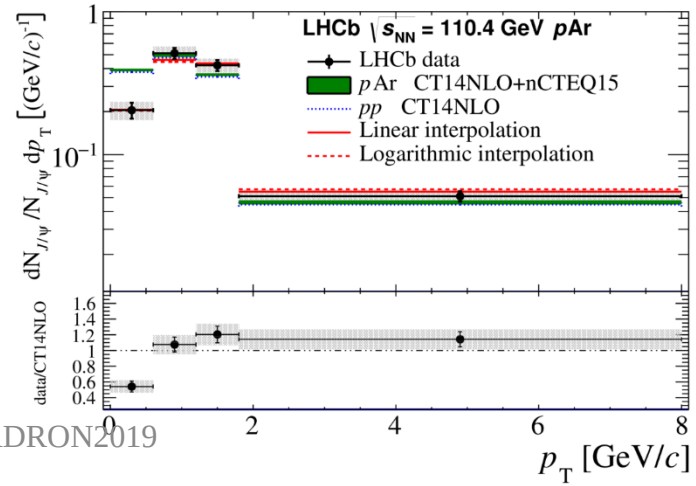
- Differential cross-section (pNe @ 86.6GeV)
- Differential yields (pAr @ 110.4GeV)
- Helac-Onia underestimate the J/ψ cross-section by a factor of 1.78
- Reasonable agreement in rapidity shape





pNe @ 86.6GeV



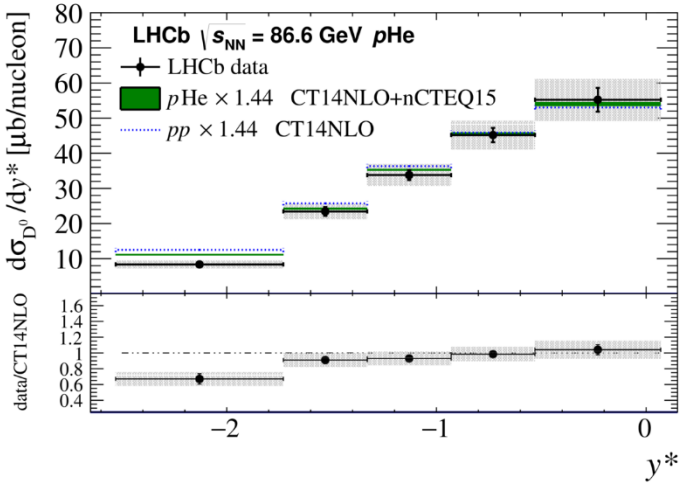


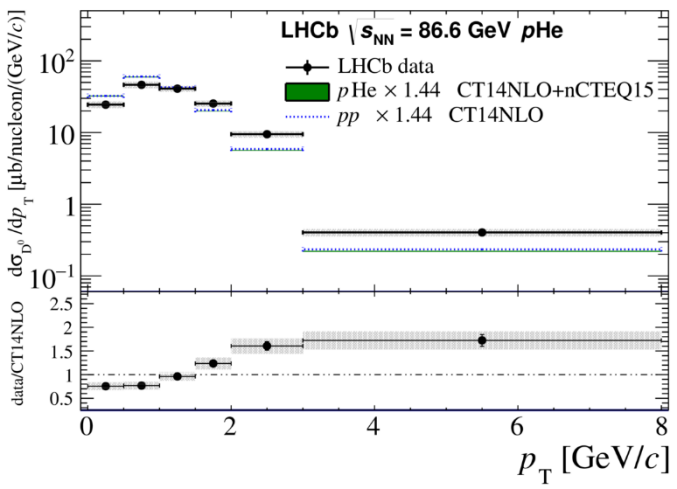
pAr @ 110.4GeV

D^0 production in fixed-target pN collision

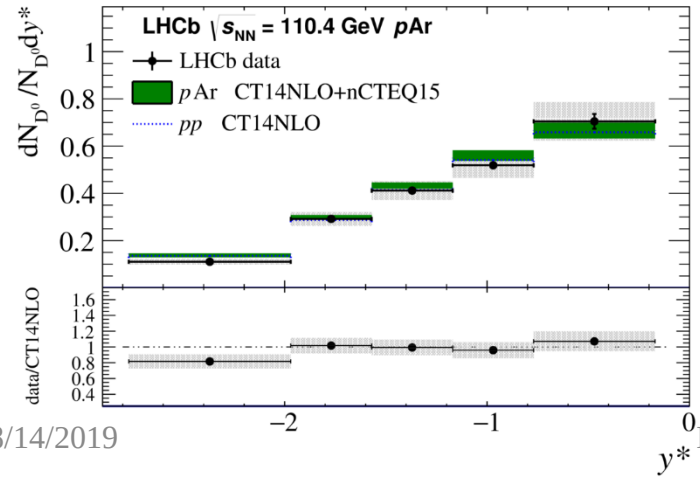
Phys. Rev. Lett. 122 (2019) 132002

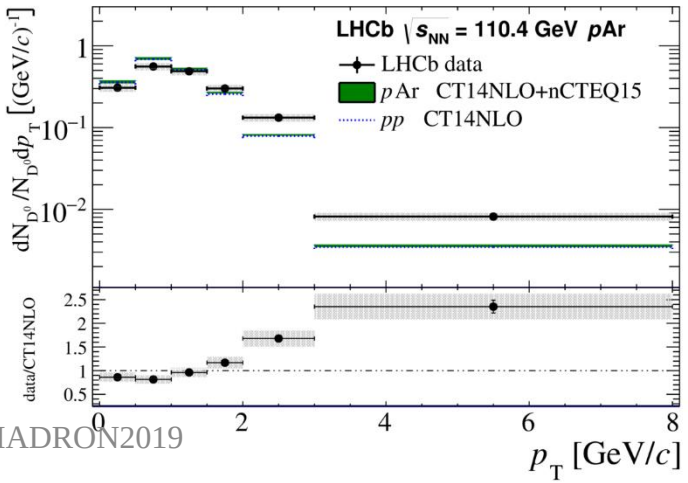
- Differential cross-section (pNe @ 86.6GeV)
- Differential yields (pAr @ 110.4GeV)
- Helac-Onia underestimate the D^0 x-section by a factor of 1.44
- Reasonable agreement in rapidity shape





pNe @ 86.6GeV





pAr @ 110.4GeV