Recent heavy-ion results from the LHCb experiment

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第十八届全国中高能核物理大会

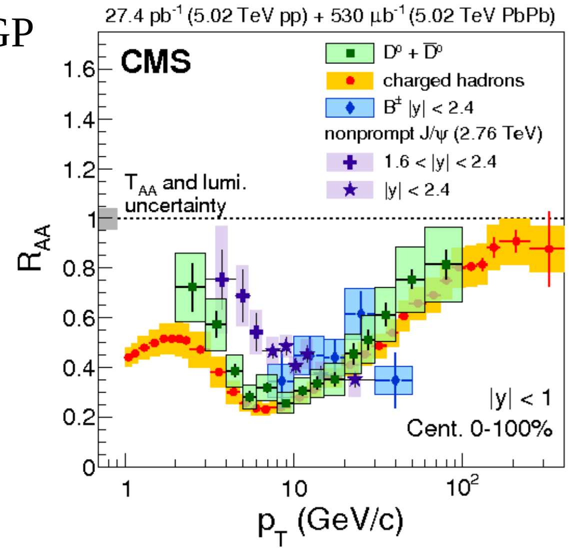
Recent heavy-ion results

- Results in Collider mode
  - Open heavy flavor in pPb collisions
    - Prompt $D^0$and Λ_c^+ production in pPb collisions at 5.02 TeV
    - B^+, $B^0$and Λ_b^0 production in pPb collisions at 8.16 TeV
  - Quarkonium in pPb collisions
    - J/ψ production in pPb collisions at 8.16 TeV
    - Upsilon $\Upsilon(nS)$ production in pPb collisions at 8.16 TeV
  - Quarkonium in Ultra-Peripheral PbPb (preliminary)

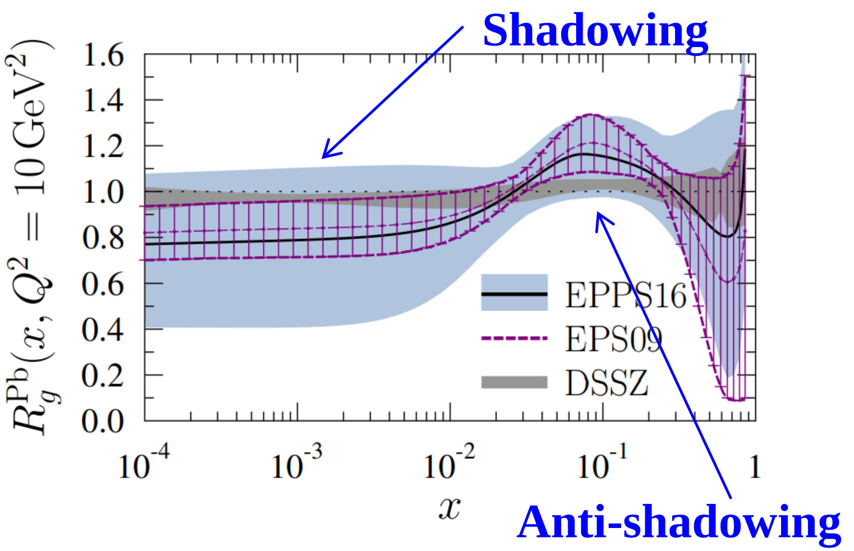
- Fixed target results
  - Charm production in pNe and pAr at 87, 110GeV
  - Antiproton production cross-section in pNe at 110GeV

Heavy flavor in *p*Pb collisions

Phys. Lett. B 782 (2018) 474



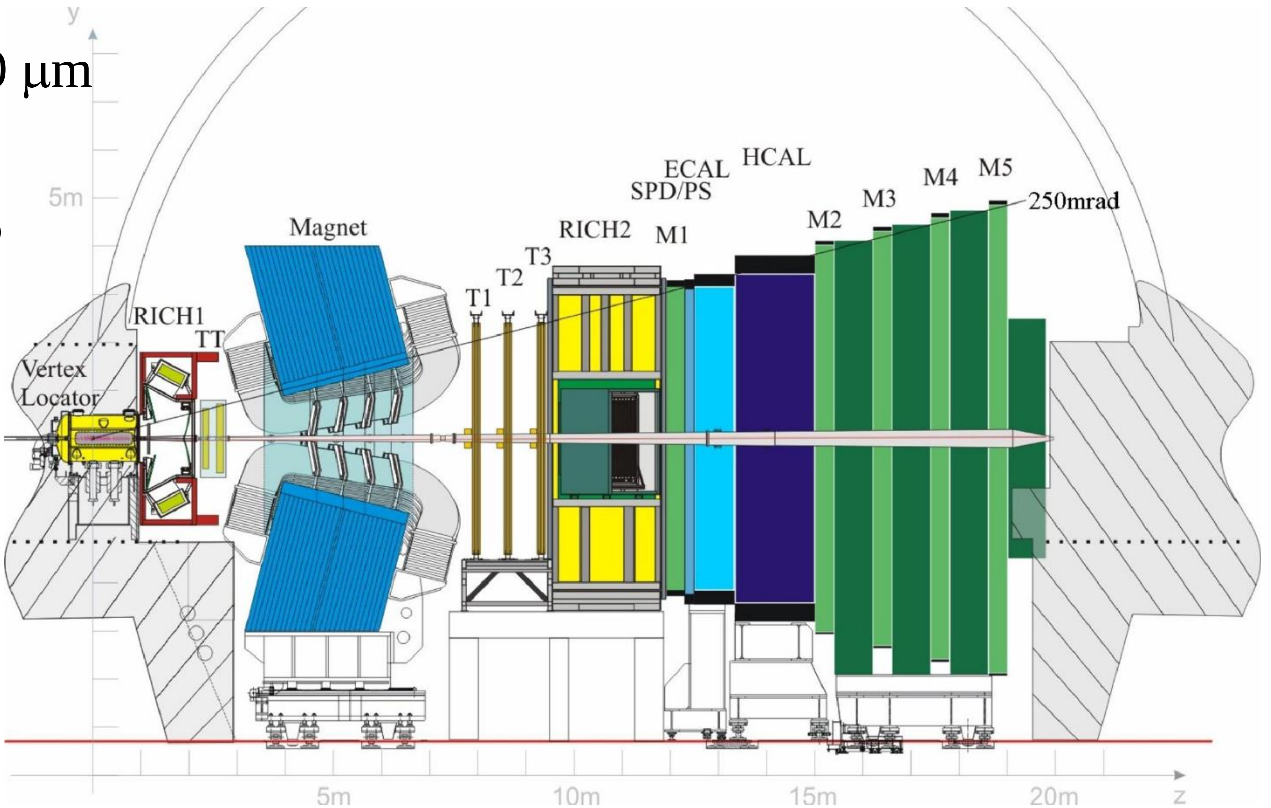
- Heavy flavor states are sensitive probes to study the properties of the QGP created in AA collision.
  - Produced in the early stage of the collisions
  - Strong interaction with the medium
  - Quarkonia states sequential melting
  - Baryon/meson ratio in charm and bottom sectors
- Heavy flavor in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



arXiv:1802.05927

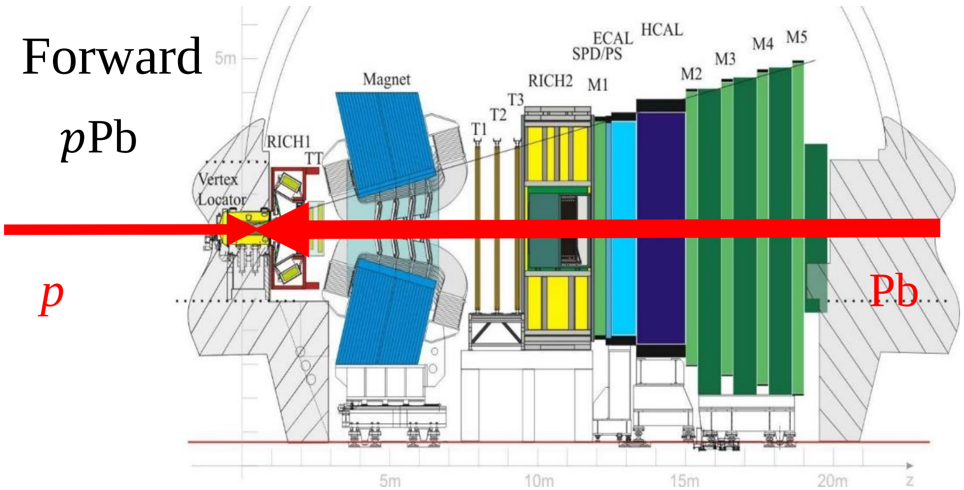
LHCb detector

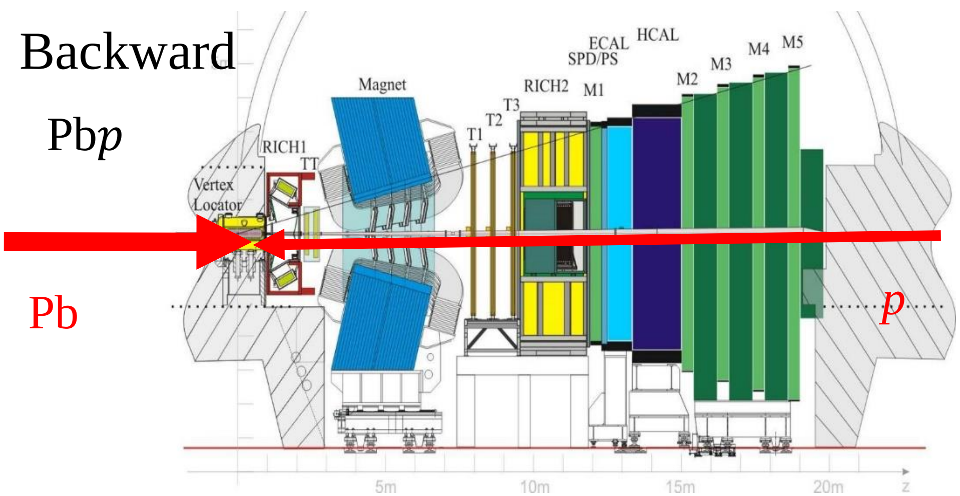
- A single arm forward spectrometer designed for the study of particles containing *c* or *b* quark.
- Acceptance: $2 < \eta < 5$
- Vertex detector
  - IP resolution ~ 20 μm
- Tracking system
  - $\frac{\Delta p}{p} = 0.5\% - 1\%$ (5-200 GeV/*c*)
- RICH
  - K/π/p separation
- Electromagnetic + hadronic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



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

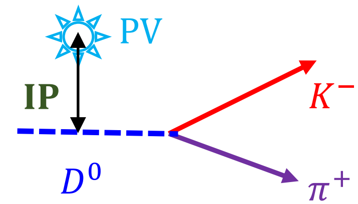
LHCb pPb datasets



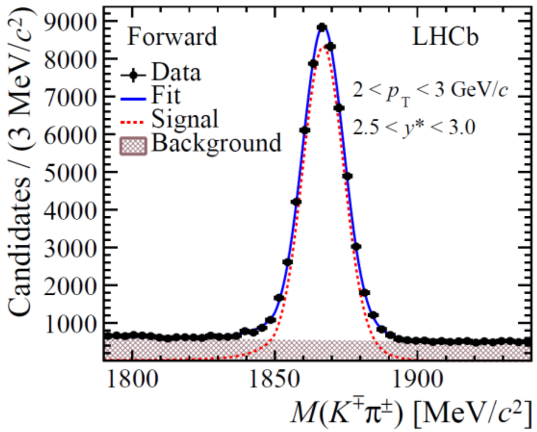


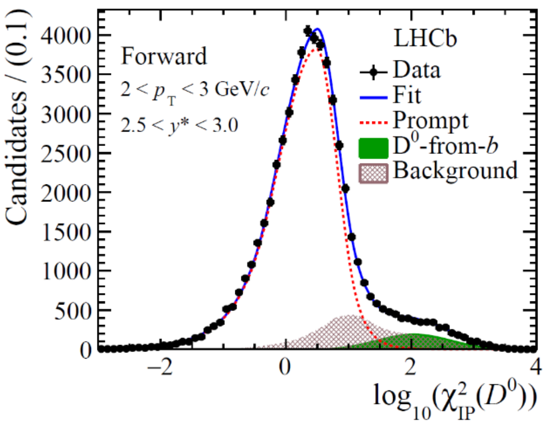
- Rapidity Coverage
  - y^*: rapidity in nucleon-nucleon cms
  - $y_{\text{cms}} = \pm 0.465$
  - Forward: $1.5 < y^* < 4.0$
  - Backward: $-5.0 < y^* < -2.5$
  - Common region: $2.5 < |y^*| < 4.0$
- $\sqrt{s_{NN}} = 5.02$ TeV (2013)
  - pPb (1.06 nb^{-1}) + Pbp (0.52 nb^{-1})
- $\sqrt{s_{NN}} = 8.16$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

Prompt D^0 and Λ_c^+ measurement in pPb at 5 TeV



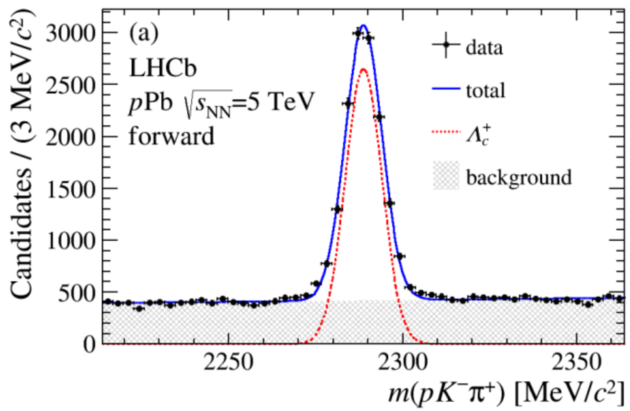
$D^0\downarrow$

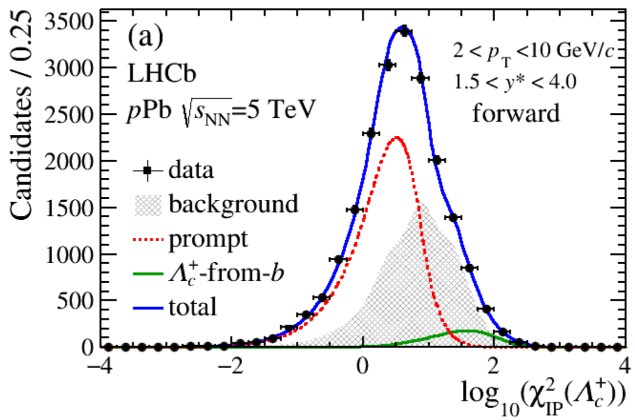




JHEP 10 (2017) 090

$\Lambda_c^+\downarrow$





JHEP 02 (2019) 102

Reconstructed through decay channel:

$$D^0 \rightarrow K^-\pi^+$$
$$\Lambda_c^+ \rightarrow pK^-\pi^+$$

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 TeV nuclear modification factor in pPb

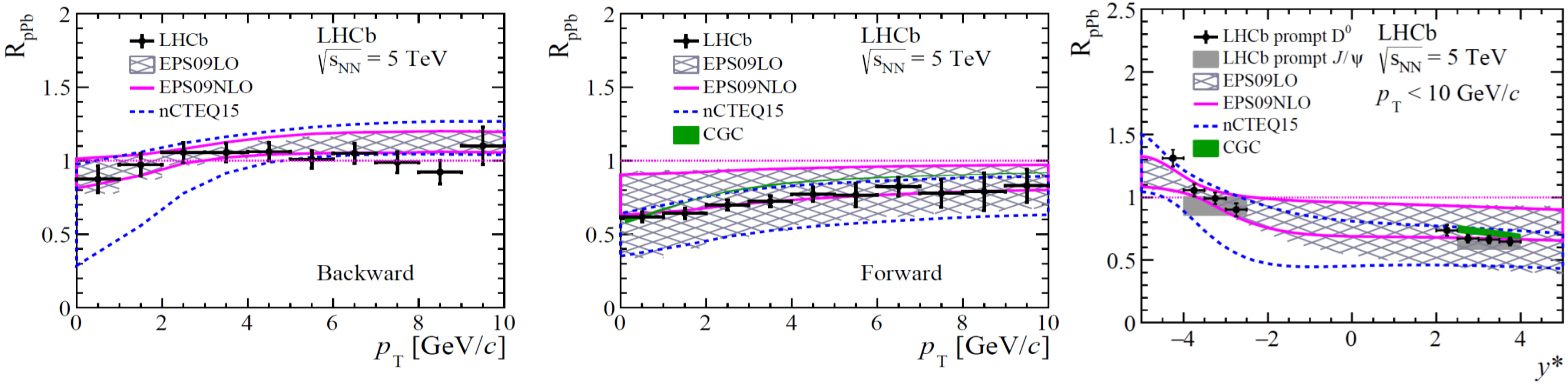
JHEP 10 (2003) 046
Eur. Phys. J. C77 (2017) 1
Comput. Phys. Commun. 184 (2013) 2562
Comput. Phys. Commun. 198 (2016) 238

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

- *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



Charmed baryon/meson production ratio $R_{\Lambda_c^+/D^0}$ at 5 TeV

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

Eur. Phys. J. C77 (2017) 1
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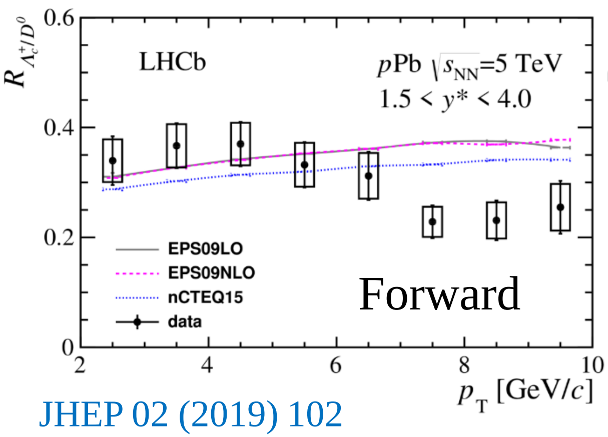
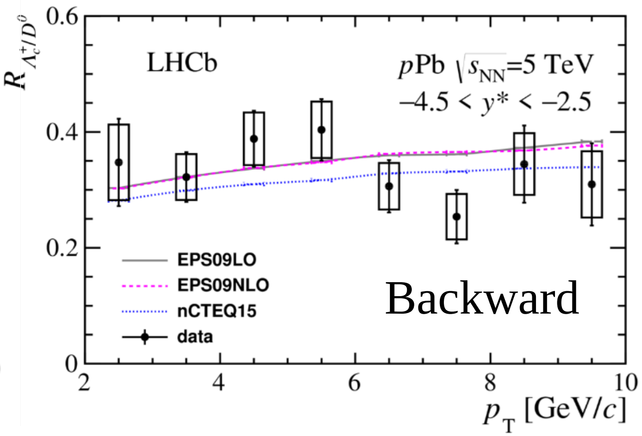
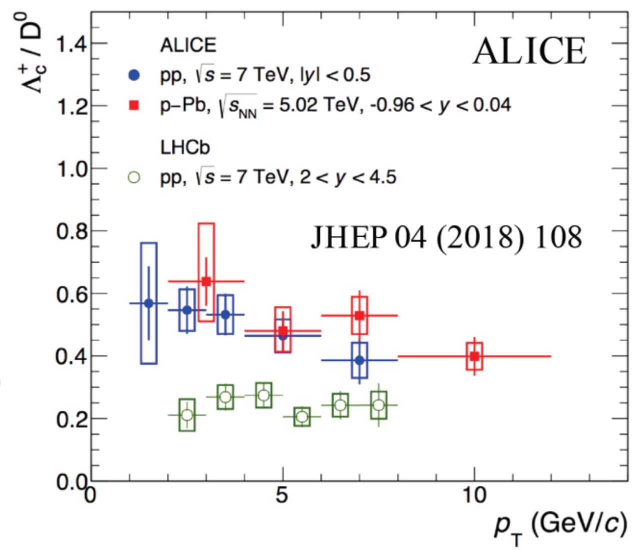






JHEP 02 (2019) 102

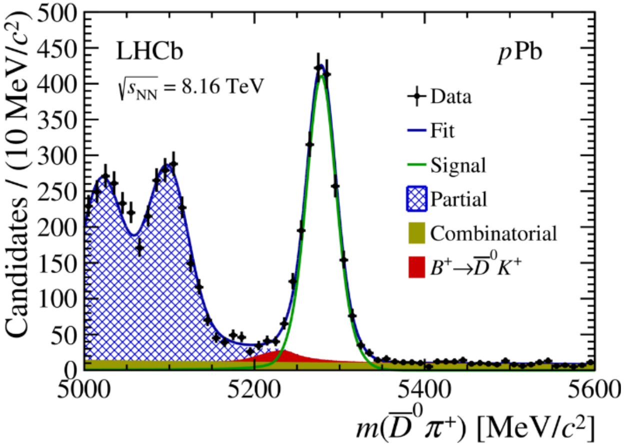
- Sensitive to charm hadronisation mechanisms
- Model based on measured *pp* cross-section
- nPDF effects mostly cancel
  - EPS09LO & EPS09NLO similar
  - nCTEQ15 slightly lower.
- Slight increase with increasing p_T

- 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

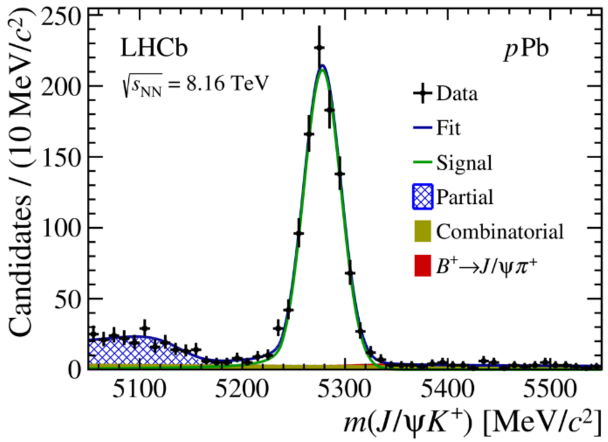
Beauty hadron production in pPb at 8.16 TeV

PRD99 052011 (2019)

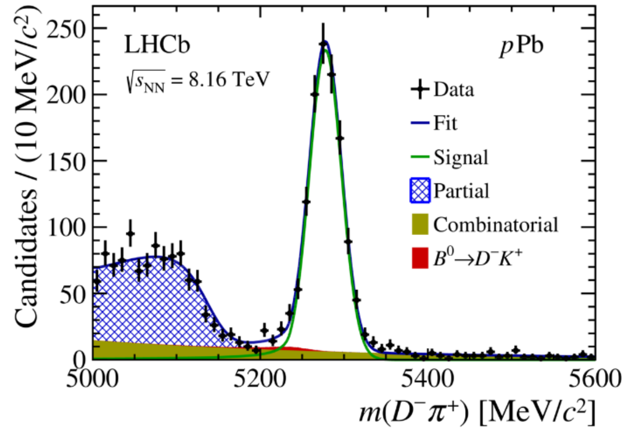
$B^+ \to \bar{D}^0\pi^+$



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



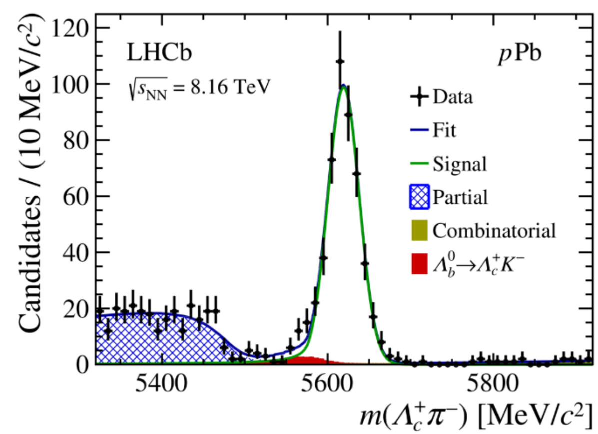
$B^0 \to D^-\pi^+$



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

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

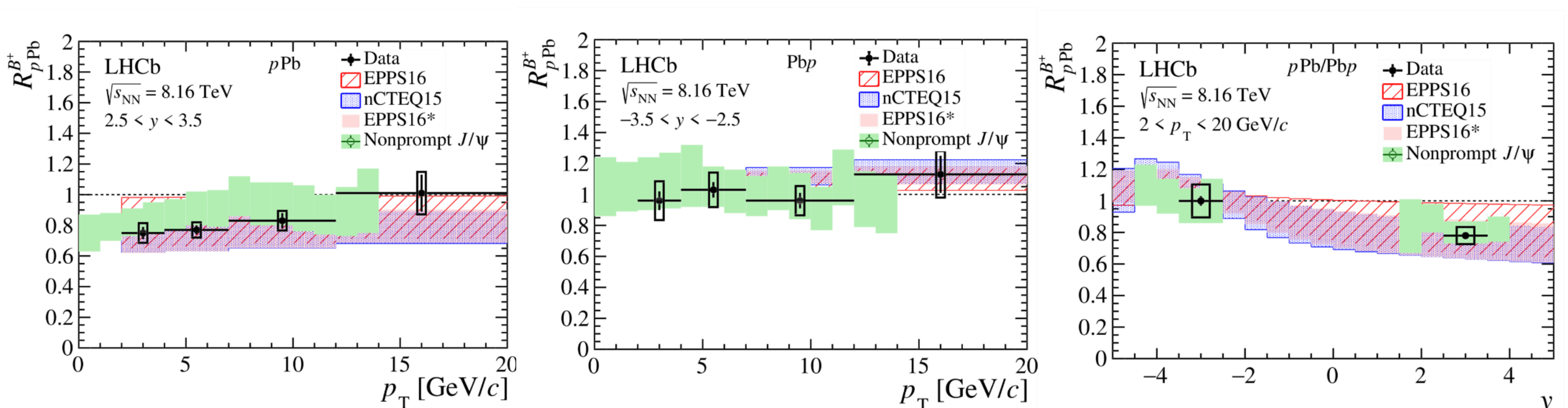


b-hadron production in pPb at 8.16 TeV
B^+ nuclear modification factor

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

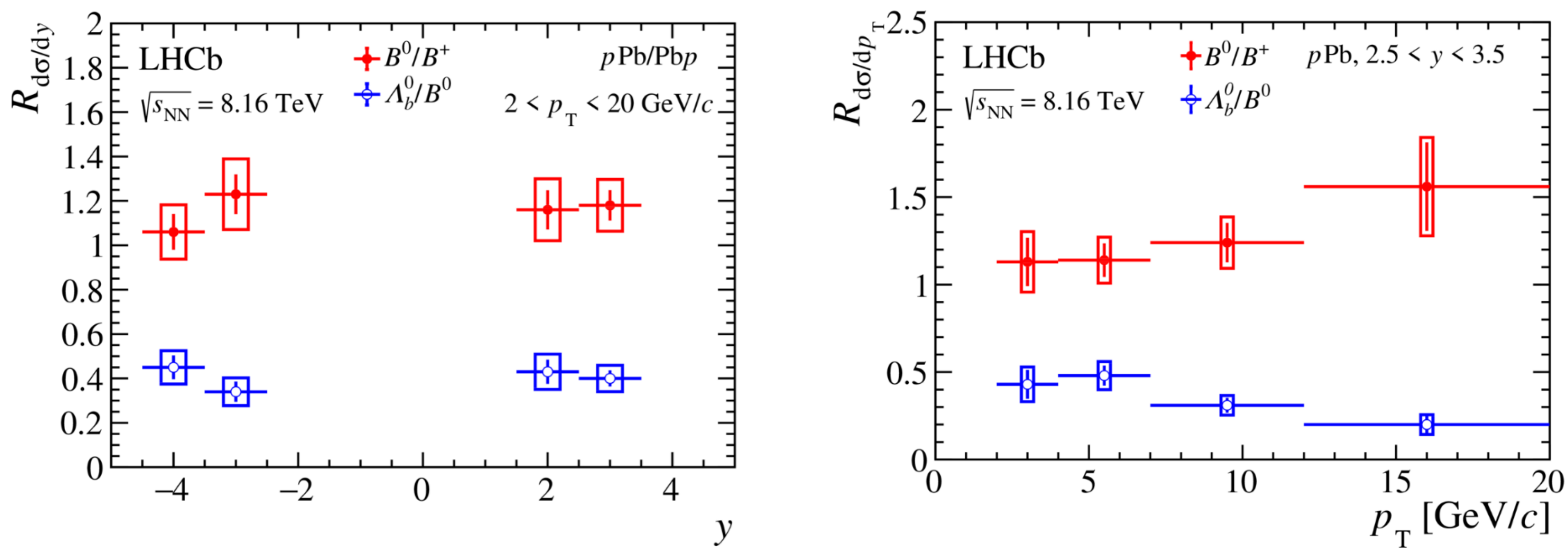
- *pp* reference interpolated between 7 & 13 TeV measurements from LHCb
- $R_{p\mathrm{Pb}}$ suppressed at forward rapidity
    - increase with increasing p_T
- $R_{p\mathrm{Pb}}$ consistent with 1 at backward rapidity

- 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
Production cross-section ratio



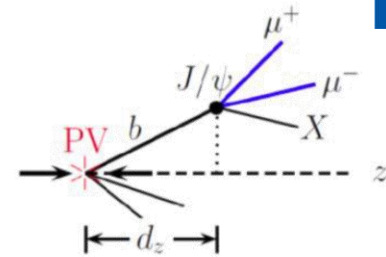
- R_{B^0/B^+}
  - No significant dependence on rapidity and p_T
- $R_{\Lambda_b^0/B^0}$
  - ~0.4, no strong rapidity dependence
  - Similar values observed in LHCb pp measurement JHEP 08 (2014) 143
  - Decreases with p_T when p_T > 5 GeV/c

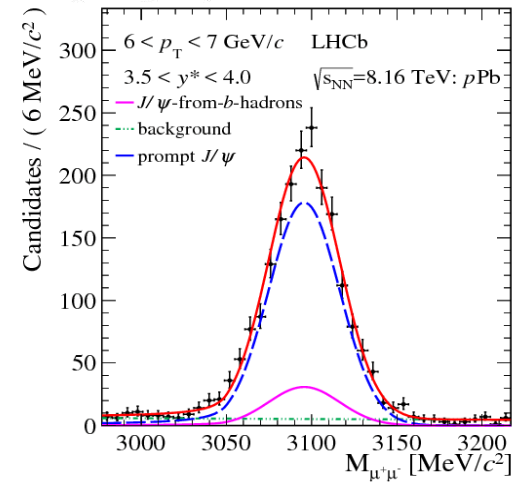
PRD99 052011 (2019)

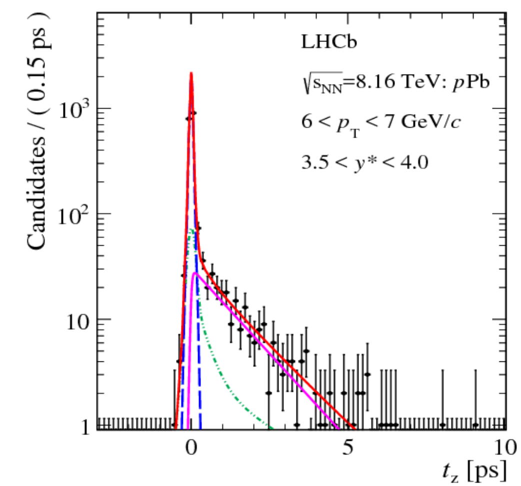
Prompt and nonprompt J/ψ in pPb at 8.16 TeV

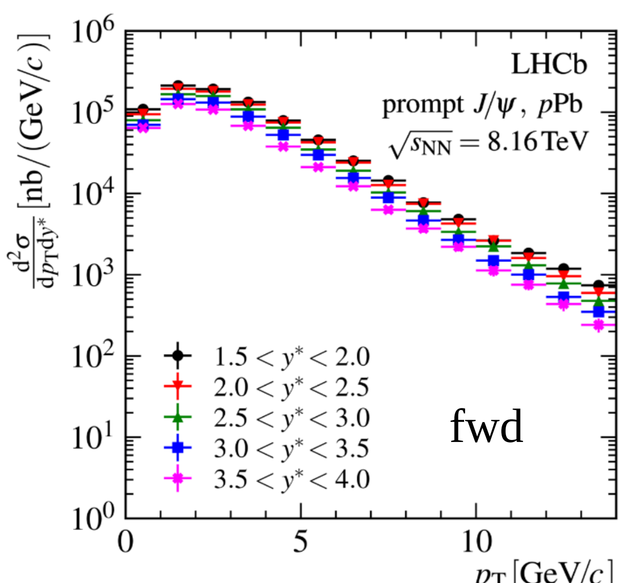
- Sources
  - Prompt: direct production, feed down from heavier states $\psi(2S)$, χ_c
  - Nonprompt: from-b-hadrons decays
- Reconstructed through $J/\psi \rightarrow \mu^+\mu^-$
- Prompt and nonprompt (from-b-hadrons) separated: the pseudo proper decay time

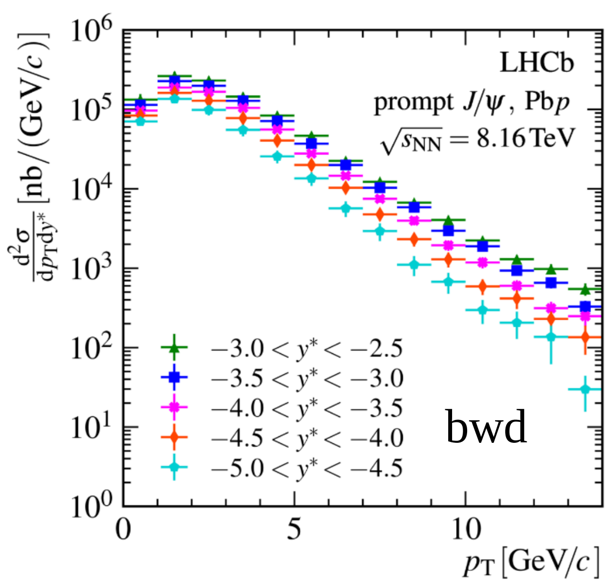
$$t_z \equiv \frac{(z_{J/\psi} - z_{PV}) \times M_{J/\psi}}{p_z}$$











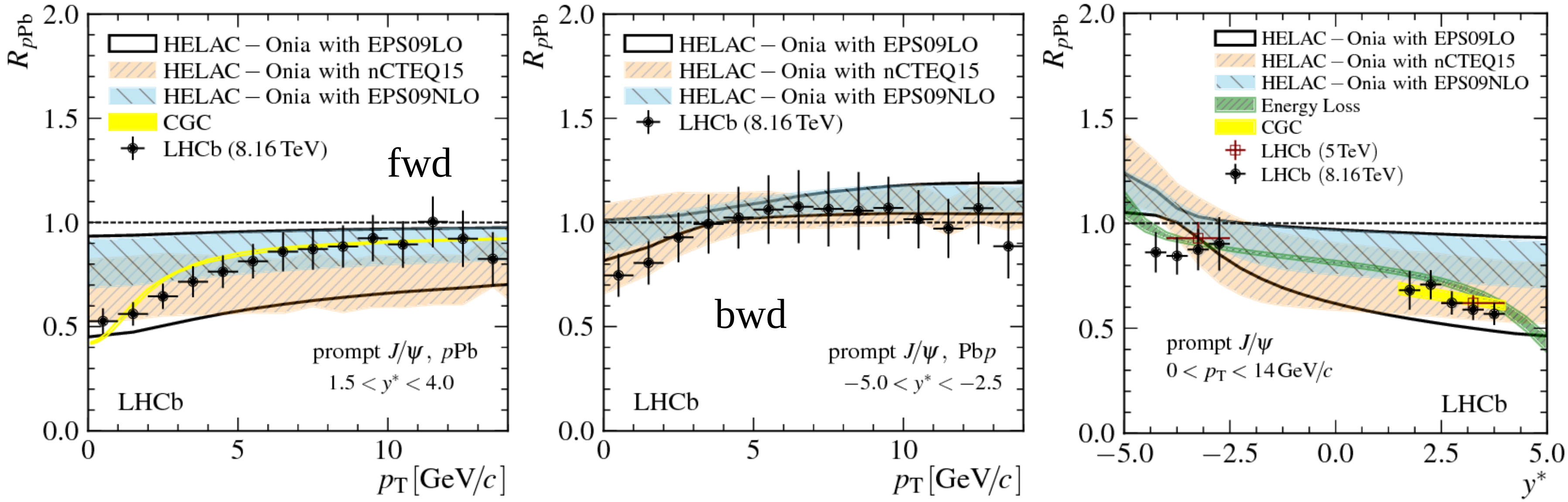
PLB 774 (2017) 159

Prompt J/ψ at 8.16 TeV nuclear modification factor in pPb

PLB 774 (2017) 159

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

- ***pp* reference**: interpolation of LHCb measurements at 7, 8 and 13 TeV
- **Forward rapidity**: suppression up to 50% at low p_{T}, decreasing with increasing p_{T}
- **Backward rapidity**: closer to unity
- Overall agreement with models with large uncertainties on the gluon PDFs at low x
- Compatible with 5 TeV results



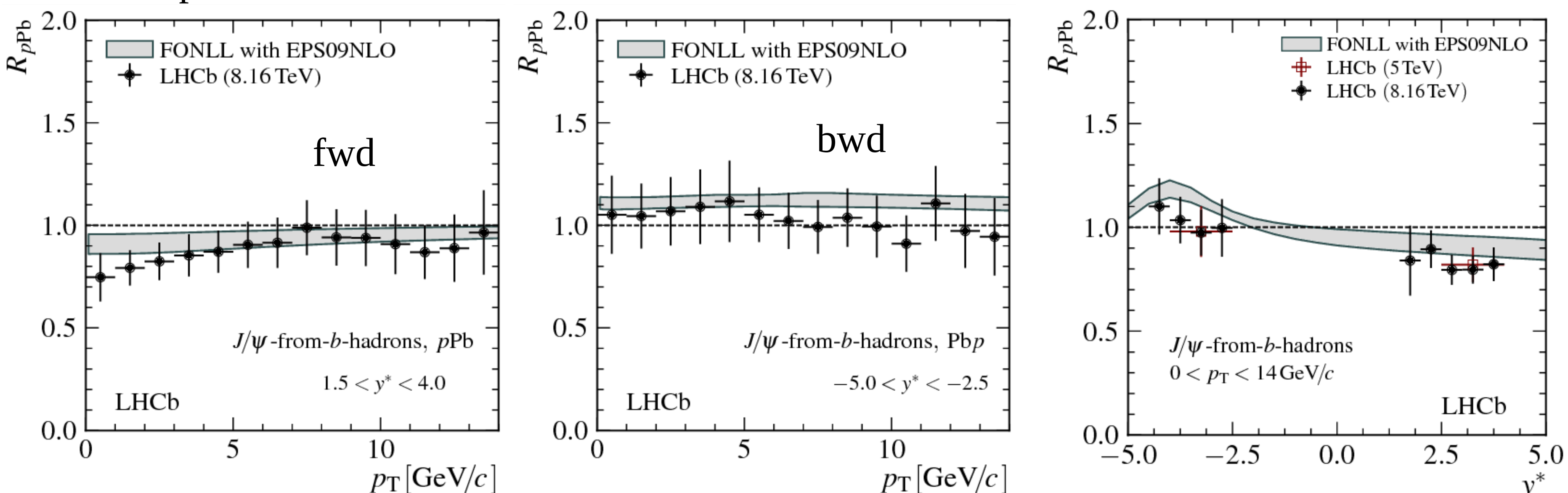
J/ψ-from-b-hadrons at 8.16 TeV nuclear modification factor in pPb

PLB 774 (2017) 159

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

- ***pp* reference**: interpolation of LHCb measurements at 7, 8 and 13 TeV
- **Forward rapidity**: smaller suppression up to 30% at low p_T, reach unity at higher p_T
- **Backward**: compatible with unity
- FONLL with EPS09NLO consistent with data
- Compatible with 5 TeV results

EPS09 JHEP 04 (2009) 065

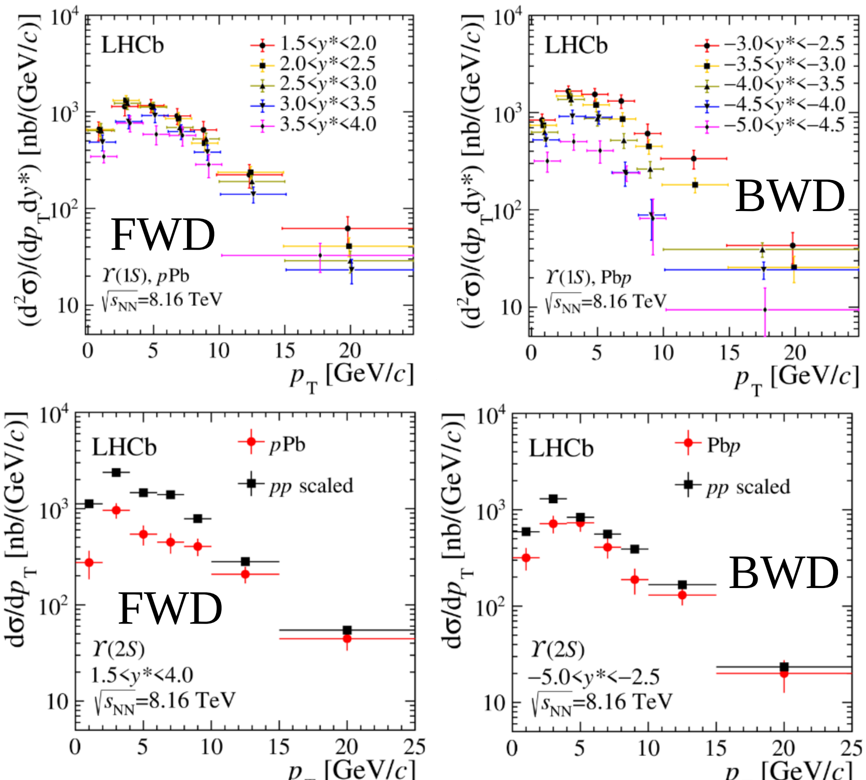


$\Upsilon(nS)$ in pPb collisions at 8.16 TeV

JHEP 11 (2018) 194

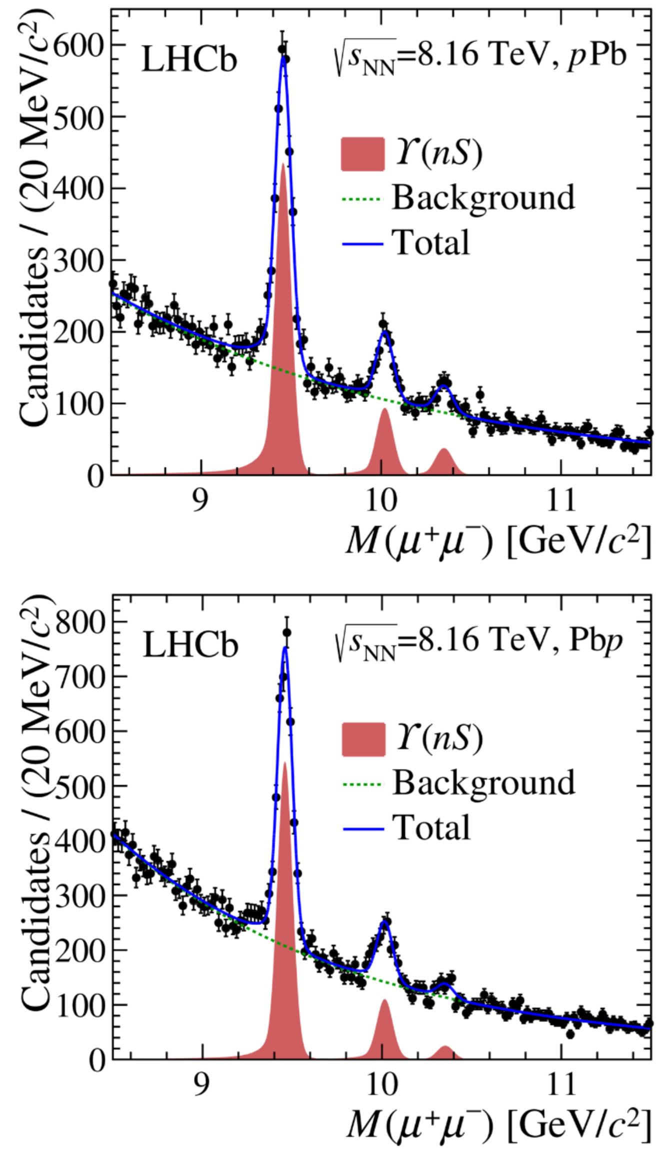
New differential analysis using 2016 pPb data
Nice $\Upsilon(3S)$ signals in forward and backward configurations

Samples	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\mathcal{L}$
pPb	2705 ± 87	584 ± 49	262 ± 44	$12.5\,\mathrm{nb}^{-1}$
Pbp	3072 ± 82	679 ± 54	159 ± 39	$19.3\,\mathrm{nb}^{-1}$



$\leftarrow\Upsilon(1S)$

$\leftarrow\Upsilon(2S)$

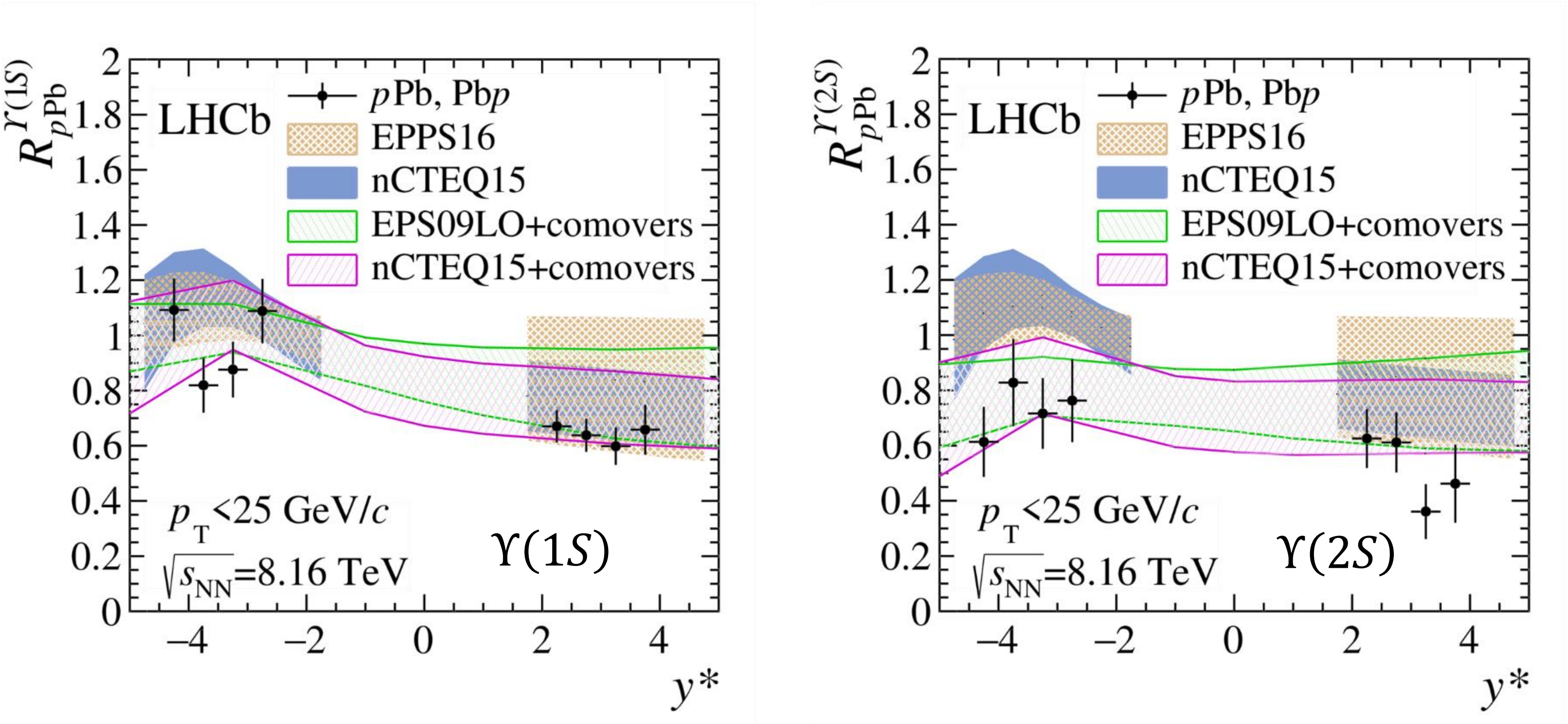


$\Upsilon(nS)$ nuclear modification factor

JHEP 11 (2018) 194

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

***pp* reference**: interpolation of LHCb measurements at 2.76, 7, 8 and 13 TeV
Forward rapidity: suppression for both states, compatible with nPDFs
Backward rapidity: $\Upsilon(2S)$ more suppressed than $\Upsilon(1S)$, consistent with nPDFs+comovers calculation



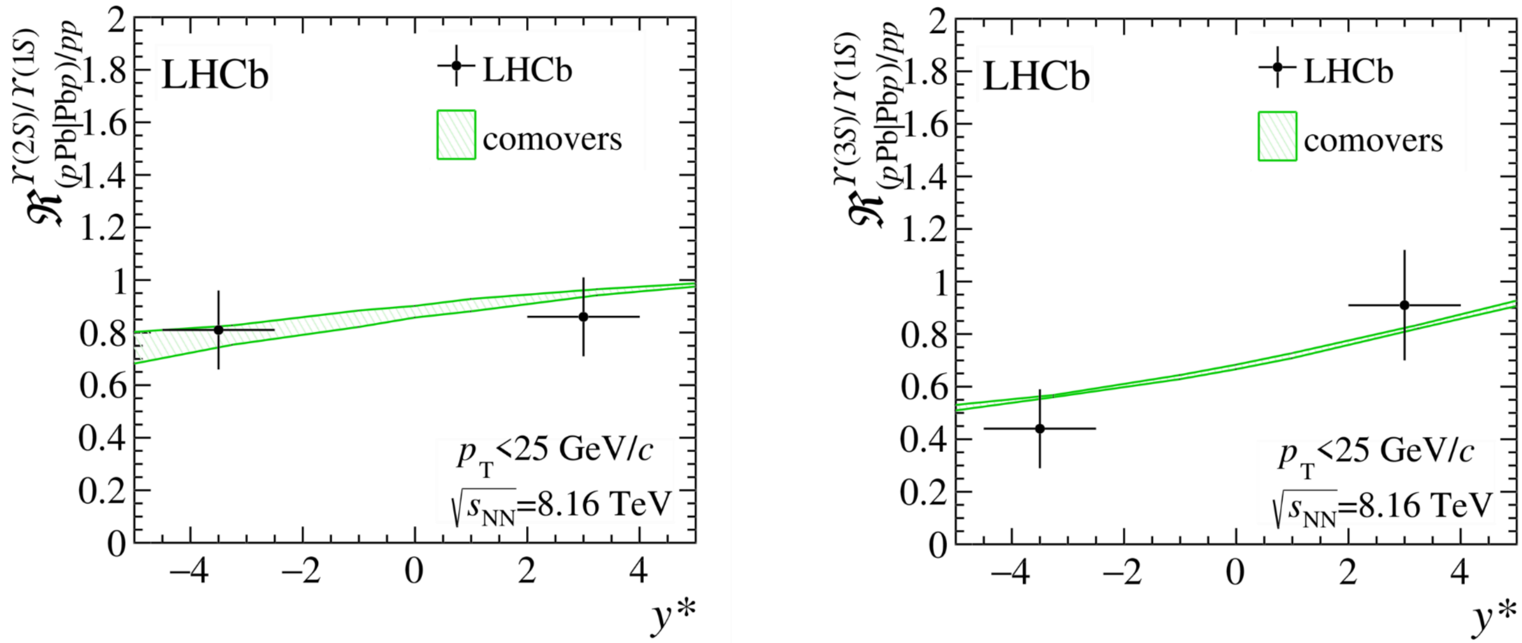
Double ratio

JHEP 11 (2018) 194

$$\mathfrak{R}^{\Upsilon(nS)/\Upsilon(1S)}_{(p\mathrm{Pb}|\mathrm{Pb}p)/pp} = \frac{R(\Upsilon(nS))_{p\mathrm{Pb}|\mathrm{Pb}p}}{R(\Upsilon(nS))_{pp}}$$

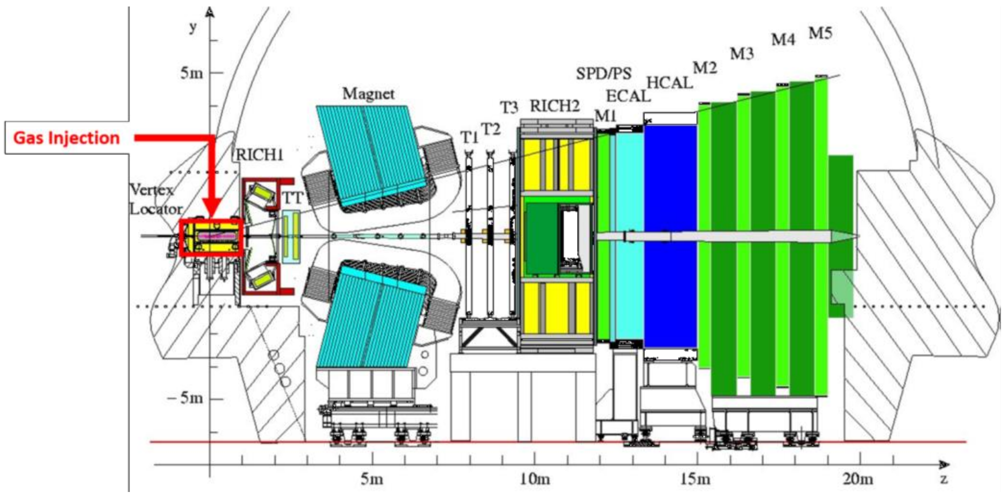
$$R(\Upsilon(nS)) = \frac{[\mathrm{d}^2\sigma/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*]\,(\Upsilon(nS))}{[\mathrm{d}^2\sigma/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*]\,(\Upsilon(1S))}.$$

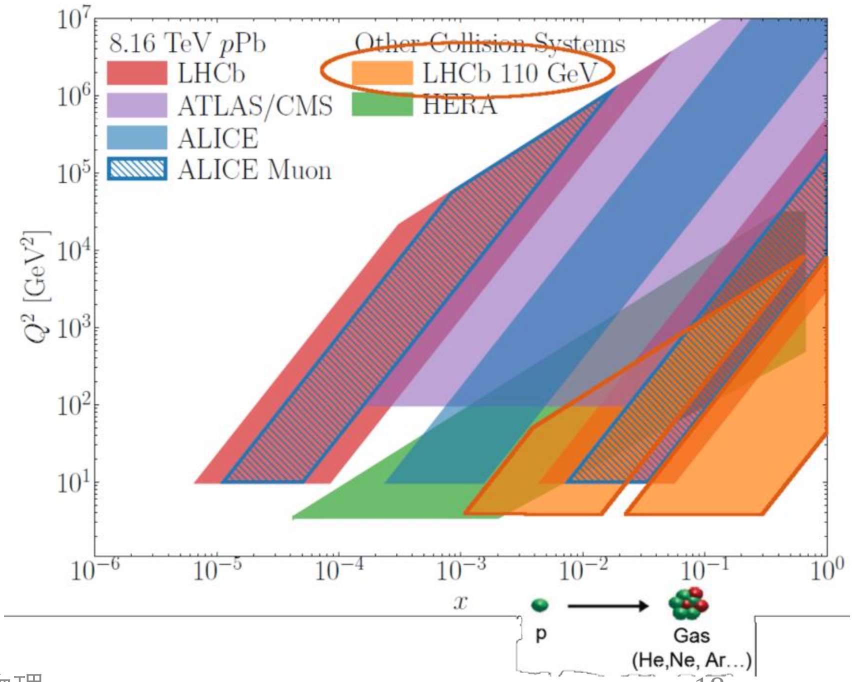
- Double ratio of $\Upsilon(nS)/\Upsilon(1S)$ in pPb and pp
- Sequential suppression also observed in pPb
- Suggests final state effects…
- Agrees with predictions of "comovers" model



Fixed target physics

- 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
- $\sqrt{s_{NN}}$ region between 20 GeV (SPS) and 200 GeV (RHIC)
- Access nPDF anti-shadowing region and intrinsic charm content in the nucleon





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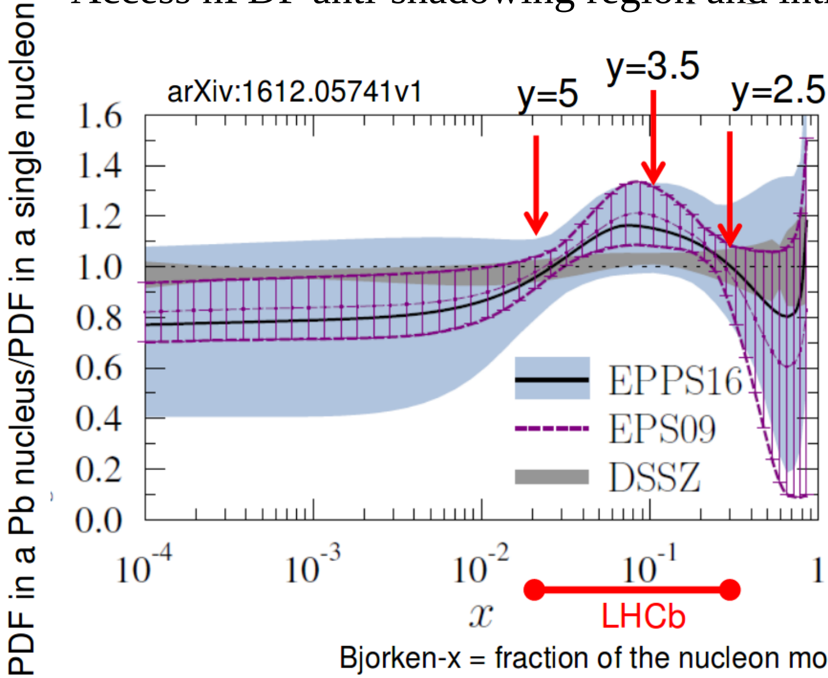
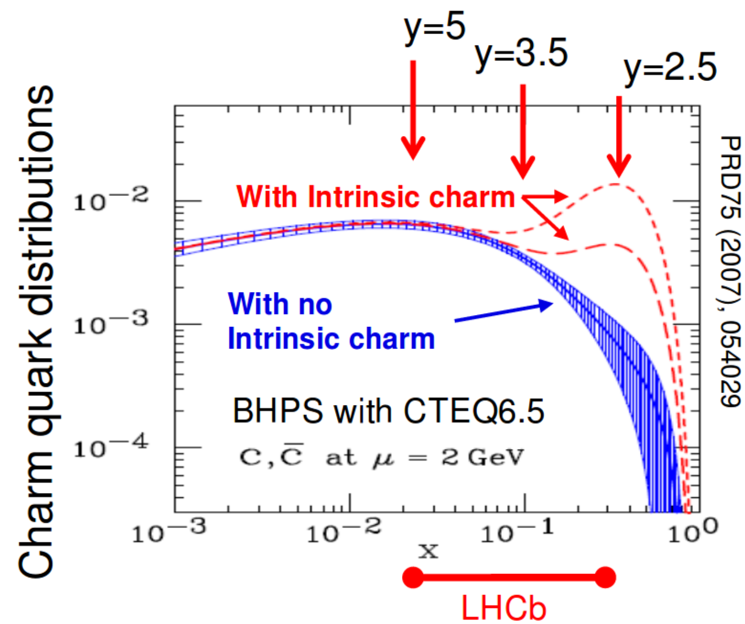
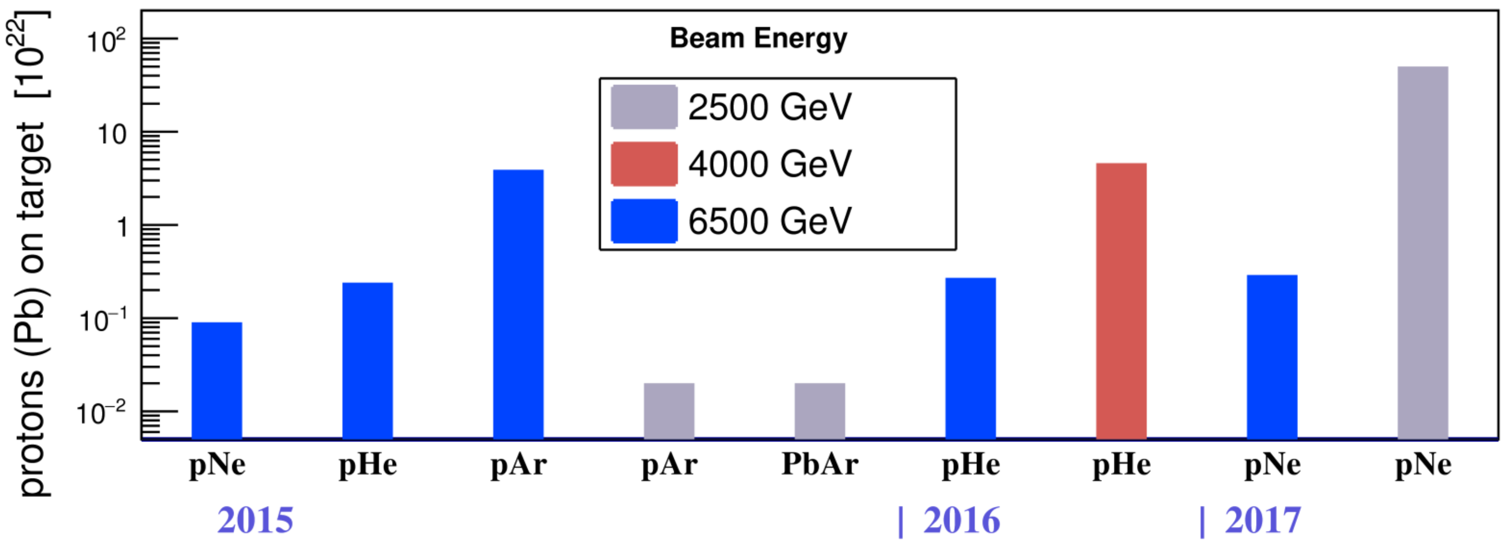




Bjorken-x = fraction of the nucleon momentum carried by a parton

Data samples:

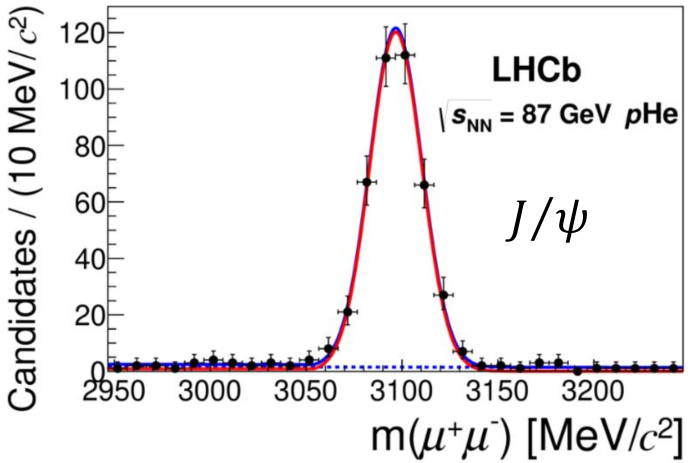
- pAr at $\sqrt{s_{NN}} = 110.4\text{GeV}$ (2015)
  - $\sim 4\times 10^{22}$ Protons On Target
- pNe at $\sqrt{s_{NN}} = 86.6\text{GeV}$ (2016)
  - $\mathcal{L}_{p\text{Ne}} = 7.6 \pm 0.5\text{nb}^{-1}$
- pNe at $\sqrt{s_{NN}}$ =110GeV (2016)
  - $\mathcal{L}_{p\text{Ne}} \sim 0.5\text{nb}^{-1}$

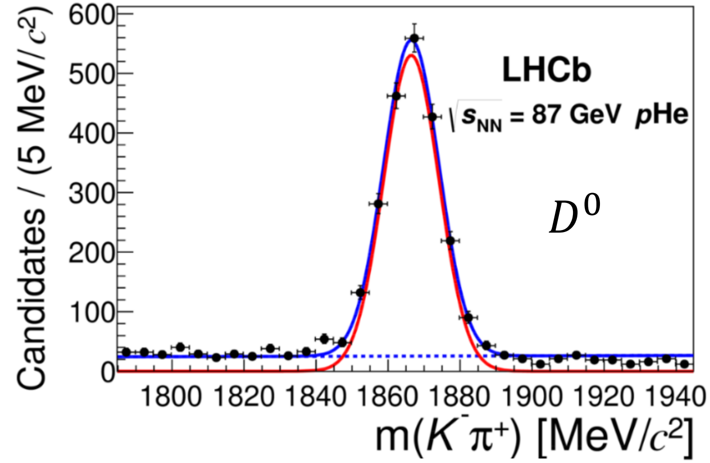


Charm production in fixed-target pN collision

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

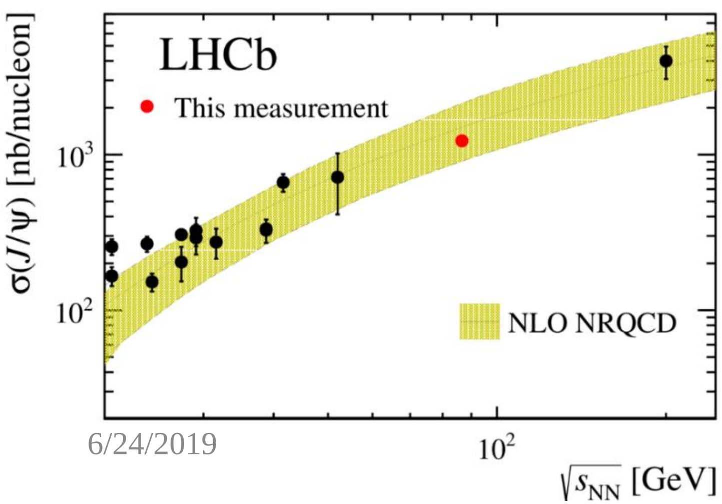


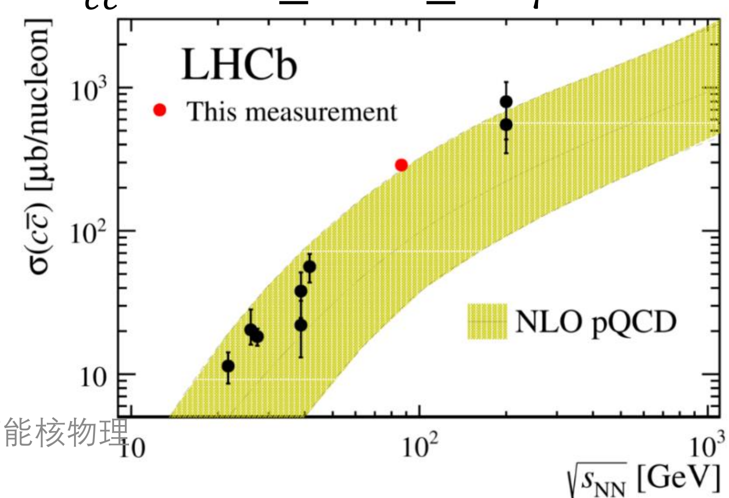


$\sigma_{J/\psi} = 1225.6 \pm 100.7$ nb/nucleon

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

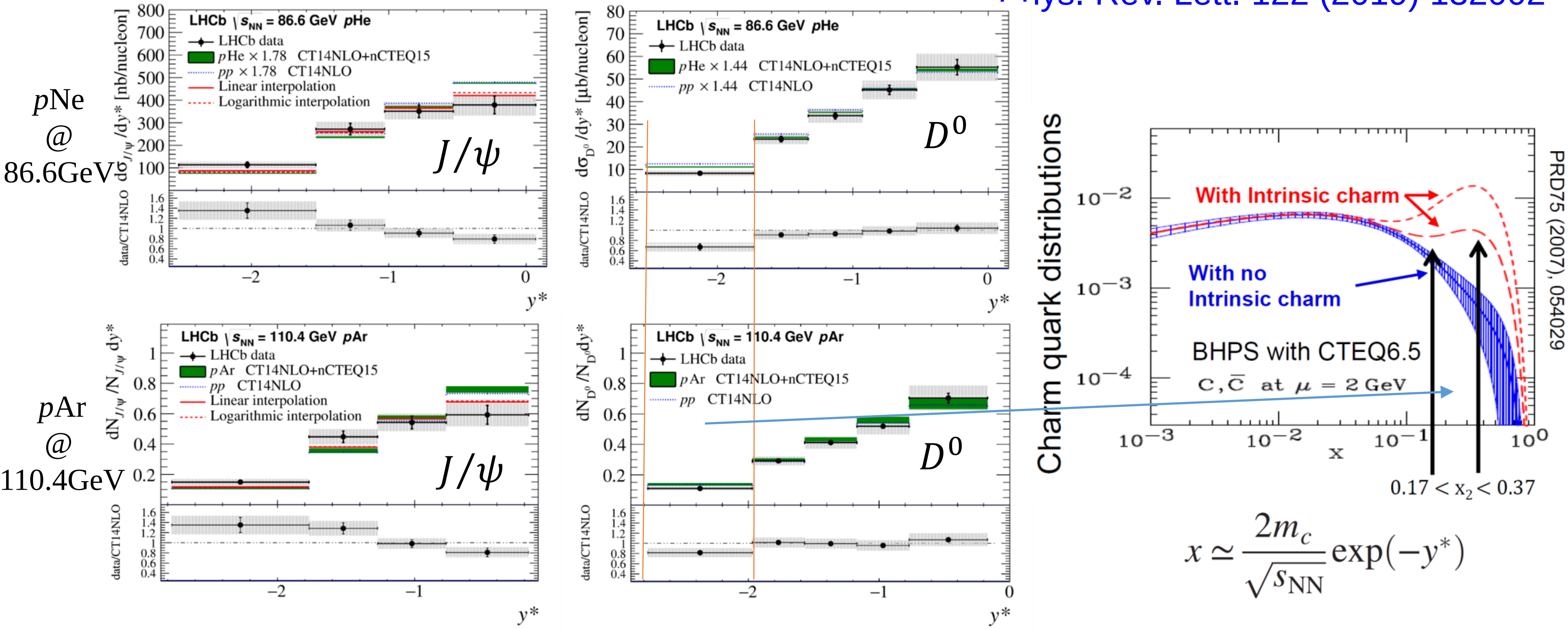
$\sigma_{c\bar{c}} = 288 \pm 24.2 \pm 6.9 \mu$b/nucleon





HF production in fixed-target pN collision

Phys. Rev. Lett. 122 (2019) 132002



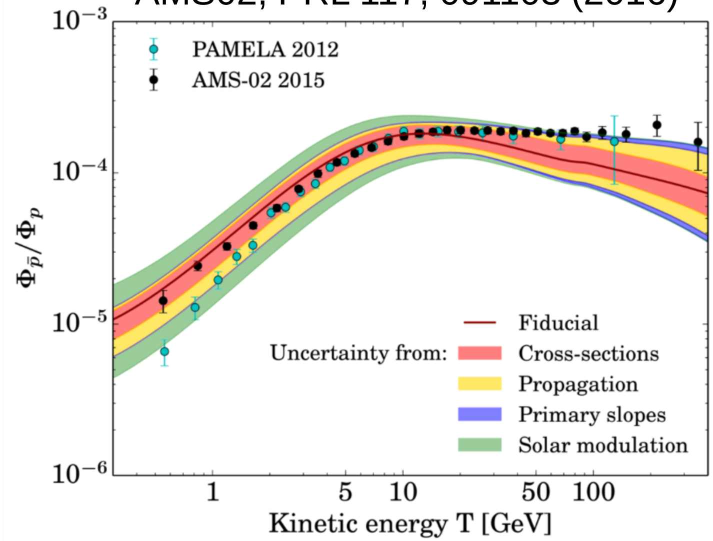
$$x \simeq \frac{2m_c}{\sqrt{s_{NN}}} \exp(-y^*)$$

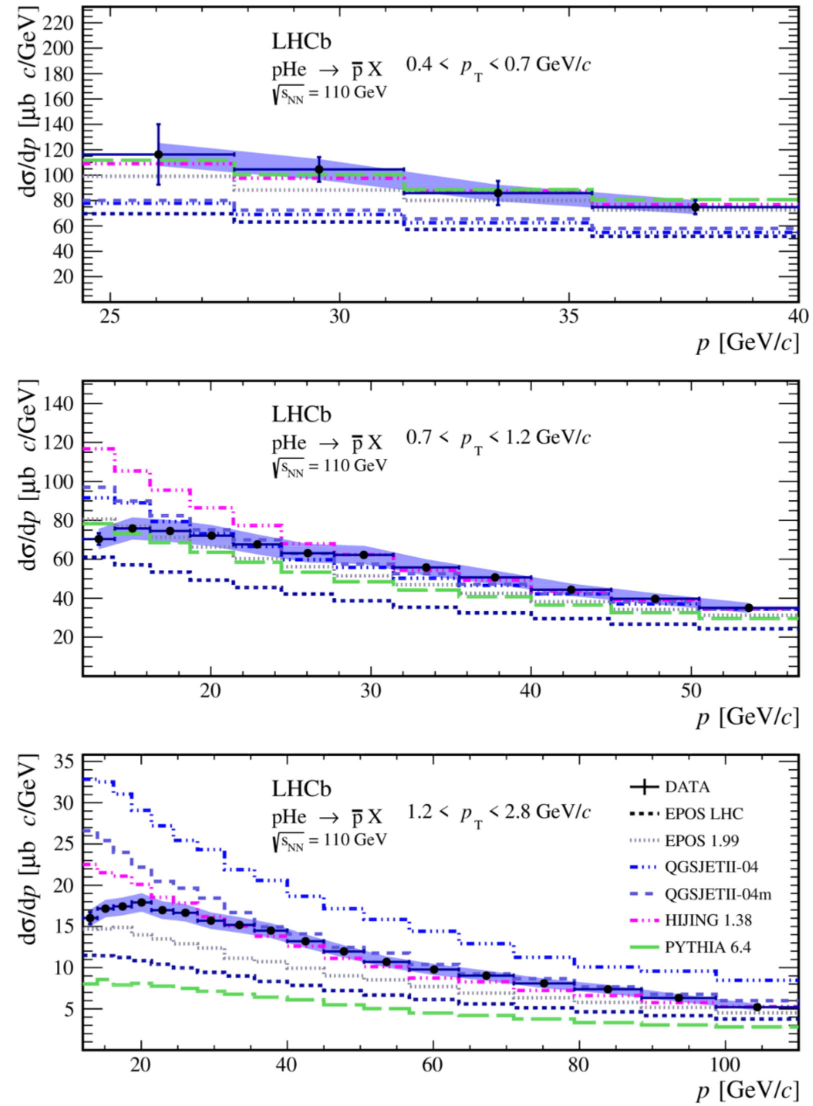
- Differential cross-section (pNe @ 86.6GeV), differential yields (pAr @ 110.4GeV)
- Reasonable agreement with Helac-Onia predictions in rapidity shape
- $-2.53<y^*<-1.73$ → $0.17<x<0.37$
- Little evidence of intrinsic charm observed

$\bar{p}$ 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 smaller than the spread of models

Conclusions

- Production cross-sections of open charm and beauty hadrons in pPb collisions at 5.02 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
- Production of quarkonia in pPb collisions at 8.16 TeV
  - J/ψ: suppression similar to open heavy flavor results
  - $\Upsilon(nS)$: sequential melting observed in pPb
- Fixed-target mode (SMOG)
  - Charm production: no strong evidence for instrinsic charm contribution
  - Antiproton: valuable inputs to anstrophysics

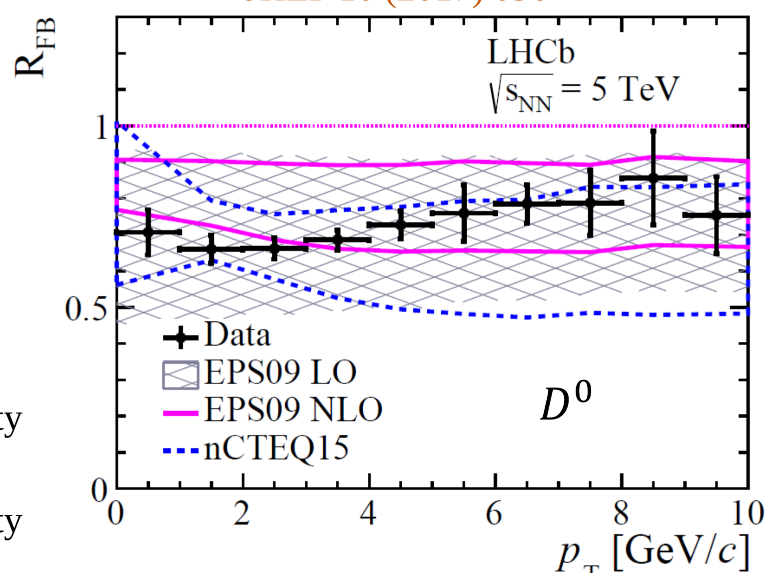
Backup

Prompt charm production at 5 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

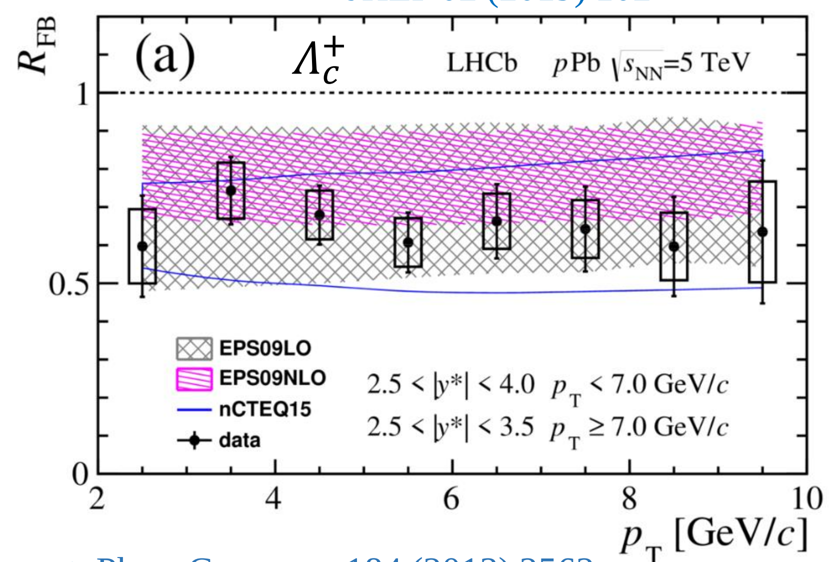


I Total uncertainty

☐ syst. uncertainty

Eur. Phys. J. C77 (2017) 1

JHEP 02 (2019) 102



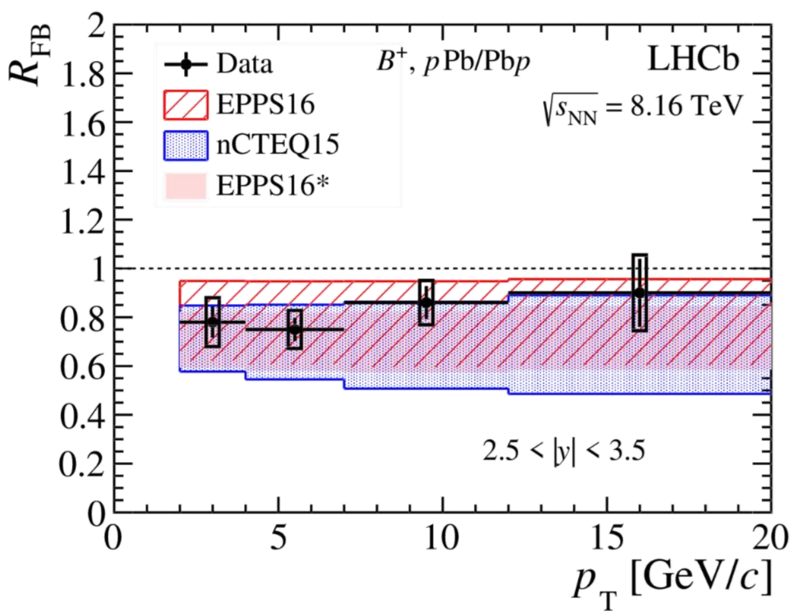
Comput. Phys. Commun. 184 (2013) 2562

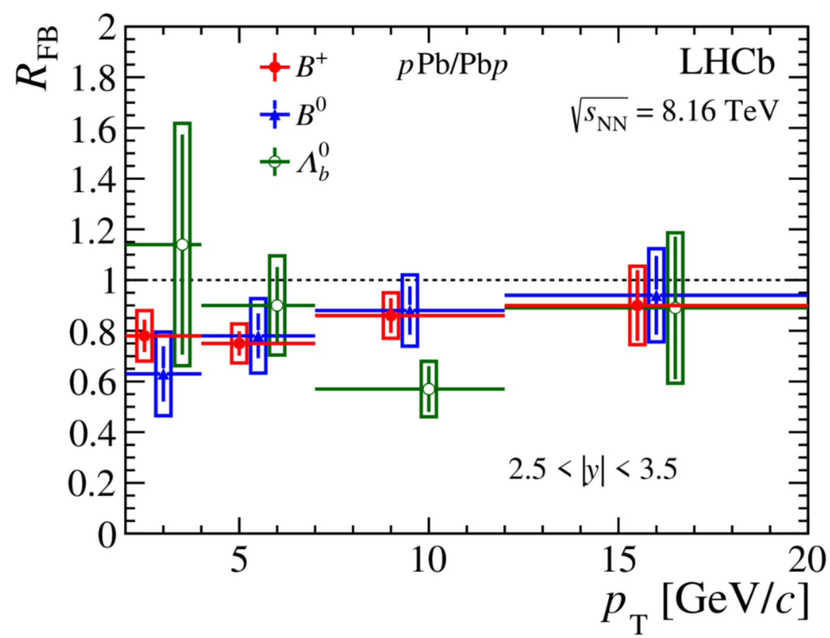
Comput. Phys. Commun. 198 (2016) 238

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}
- Consistent R_{FB} between B^+, B^0 and Λ_b^0

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

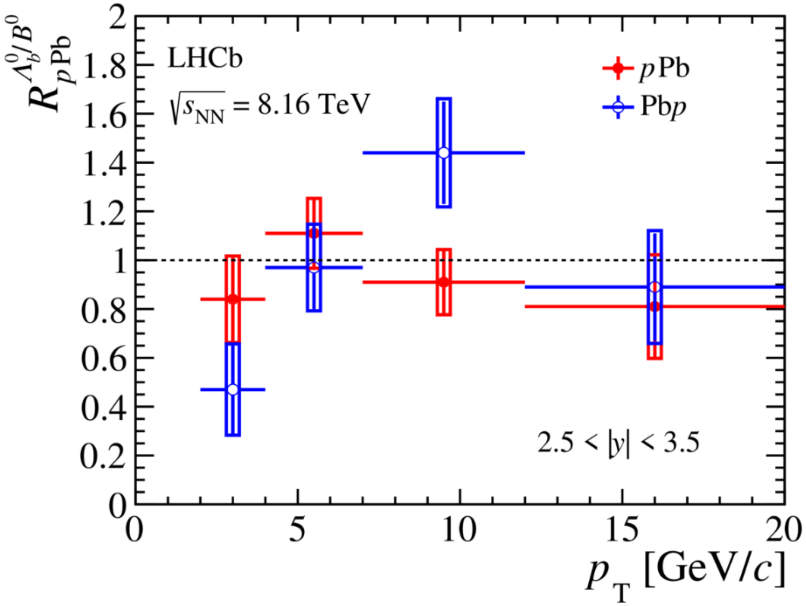


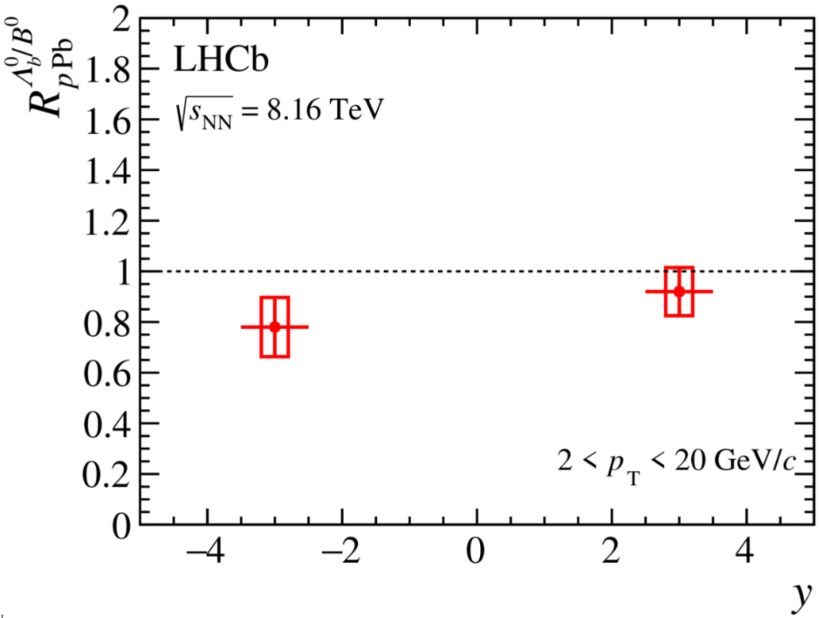


PRD99 052011 (2019)

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)

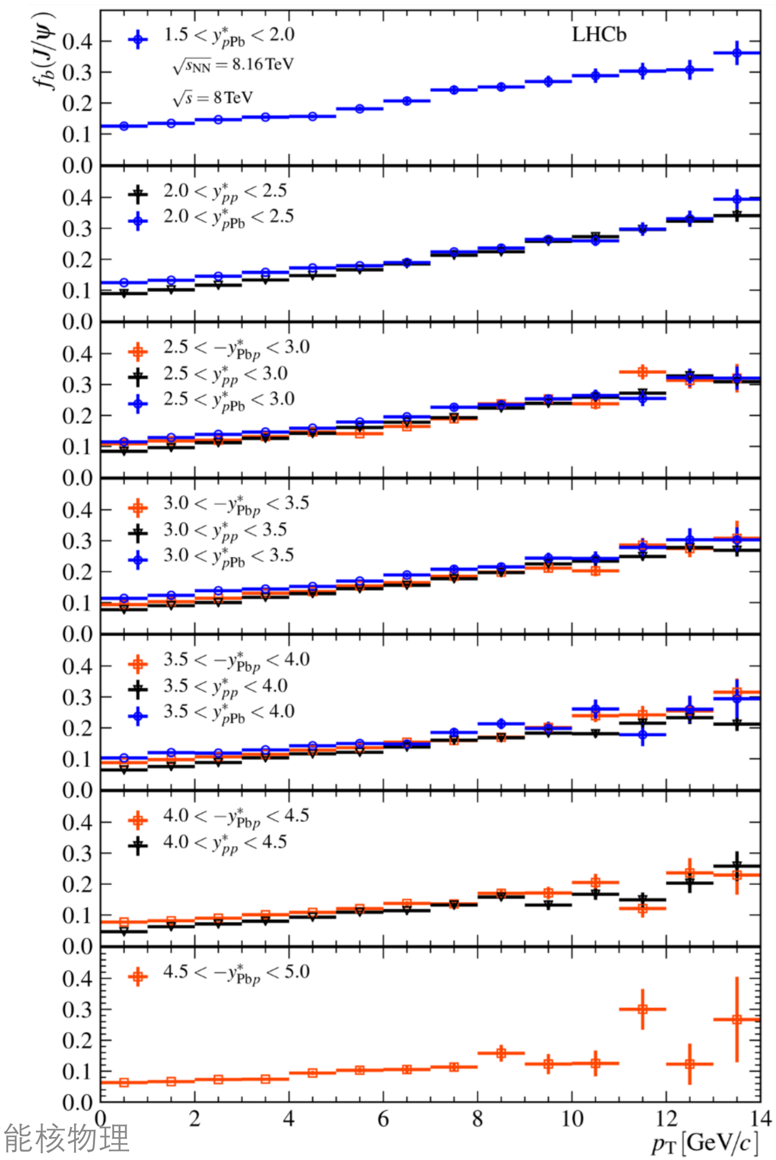
Prompt and nonprompt J/ψ in pPb at 8 TeV

PLB 774 (2017) 159

- Separation of prompt and nonprompt J/ψ with p_{T} down to 0
- Fraction from b hadrons:

$$f_b = \frac{\dfrac{d^2\sigma_{J/\psi\text{-from-}b}}{dp_{\mathrm{T}}\,dy^*}}{\dfrac{d^2\sigma_{\mathrm{Prompt}\,J/\psi}}{dp_{\mathrm{T}}\,dy^*} + \dfrac{d^2\sigma_{J/\psi\text{-from-}b}}{dp_{\mathrm{T}}\,dy^*}}$$

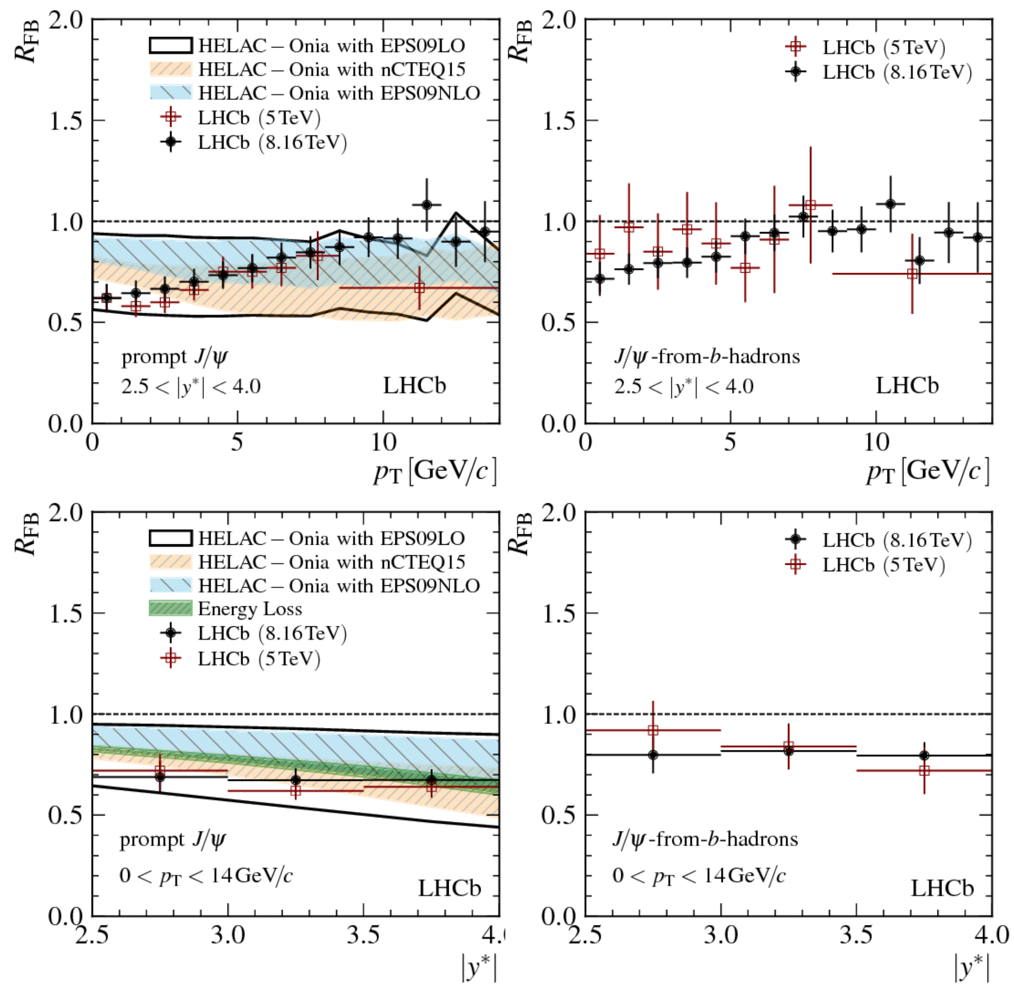
- pp, forward, backward compared:
  - similar trends
  - Increasing with p_{T}
  - Small differences at low p_{T}: cold nuclear matter effects different for the prompt and nonprompt



Prompt J/ψ at 8 TeV forward-backward production ratio

PLB 774 (2017) 159

- $R_{\mathrm{FB}} = \dfrac{\mathrm{d}\sigma(+|y^*|, p_{\mathrm{T}})/\mathrm{d}x}{\mathrm{d}\sigma(-|y^*|, p_{\mathrm{T}})/\mathrm{d}x}$
- R_{FB} does not need inputs from pp collisions.
- Prompt J/ψ:
  - Clear forward-backward asymmetry
  - Increasing trend with increasing p_{T}
- Nonprompt J/ψ:
  - Closer to unity
- Models for prompt J/ψ only
- Consistent with 5 TeV results



$\Upsilon(1S)$ nuclear modification factor

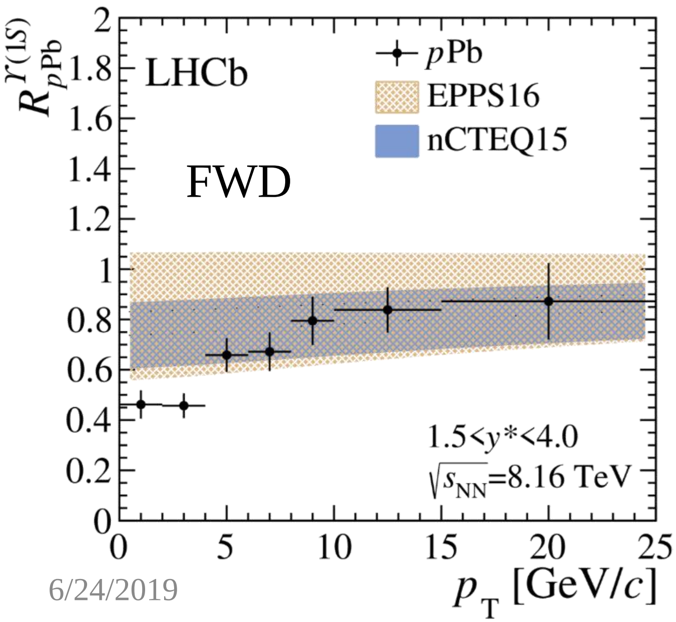
JHEP 11 (2018) 194

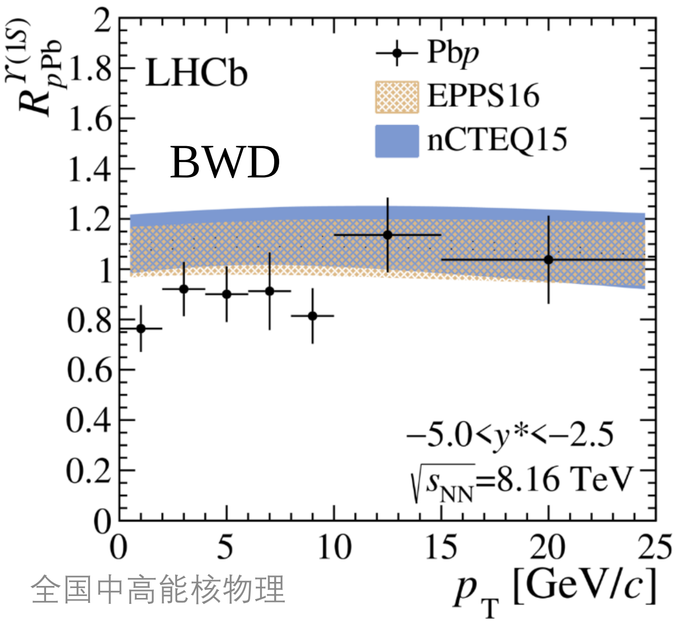
$$R_{p\mathrm{Pb}}(y^*, p_T) = \frac{1}{A} \times \frac{\mathrm{d}\sigma_{p\mathrm{Pb}}(y^*, p_\mathrm{T}, \sqrt{s_{NN}})/\mathrm{d}x}{\mathrm{d}\sigma_{pp}(y^*, p_\mathrm{T}, \sqrt{s_{NN}})/\mathrm{d}x}, \ A{=}208$$

***pp* reference**: interpolation of LHCb measurements at 2.76, 7, 8 and 13 TeV

Forward rapidity: suppression for for $\Upsilon(1S)$ and $\Upsilon(2S)$ states, compatible with nPDFs

Backward rapidity: $\Upsilon(2S)$ more suppressed than $\Upsilon(1S)$, consistent with nPDFs+comovers calculation





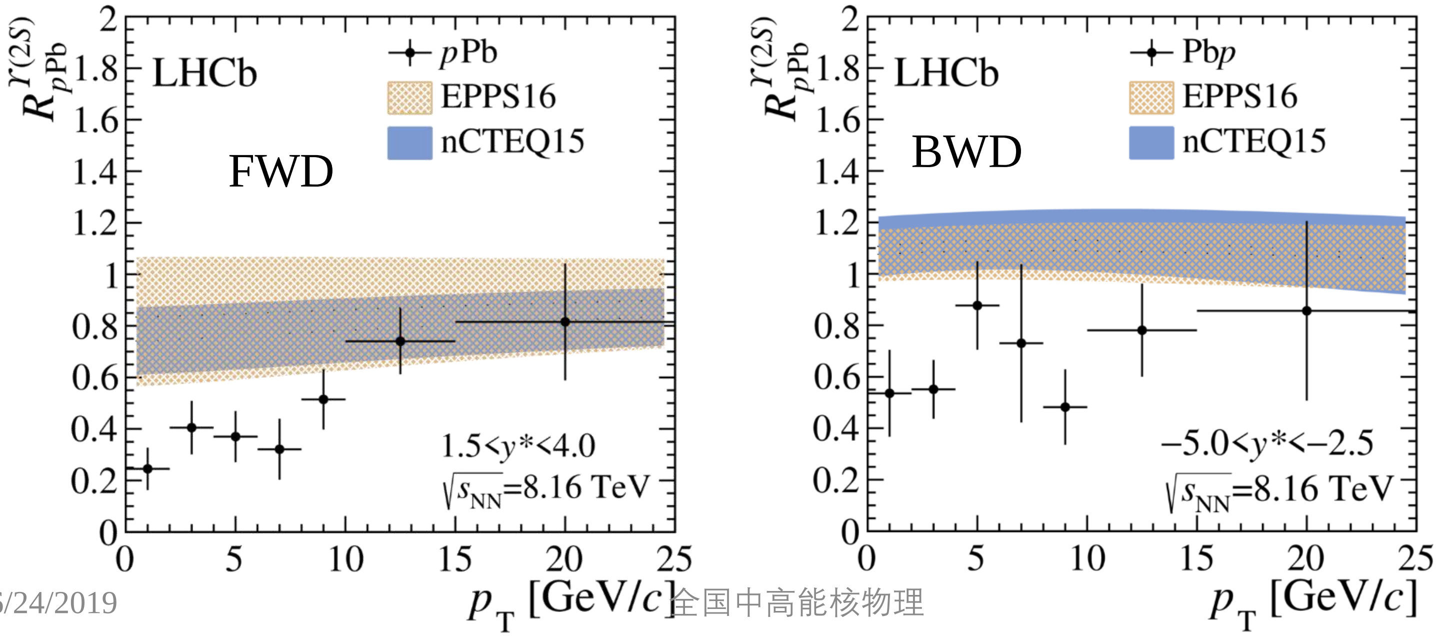
$\Upsilon(1S)$

$\Upsilon(2S)$ nuclear modification factor

JHEP 11 (2018) 194

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

***pp* reference**: interpolation of LHCb measurements at 2.76, 7, 8 and 13 TeV
Forward rapidity: suppression for $\Upsilon(1S)$ and $\Upsilon(2S)$ states, compatible with nPDFs
Backward rapidity: $\Upsilon(2S)$ more suppressed than $\Upsilon(1S)$, consistent with nPDFs+comovers calculation

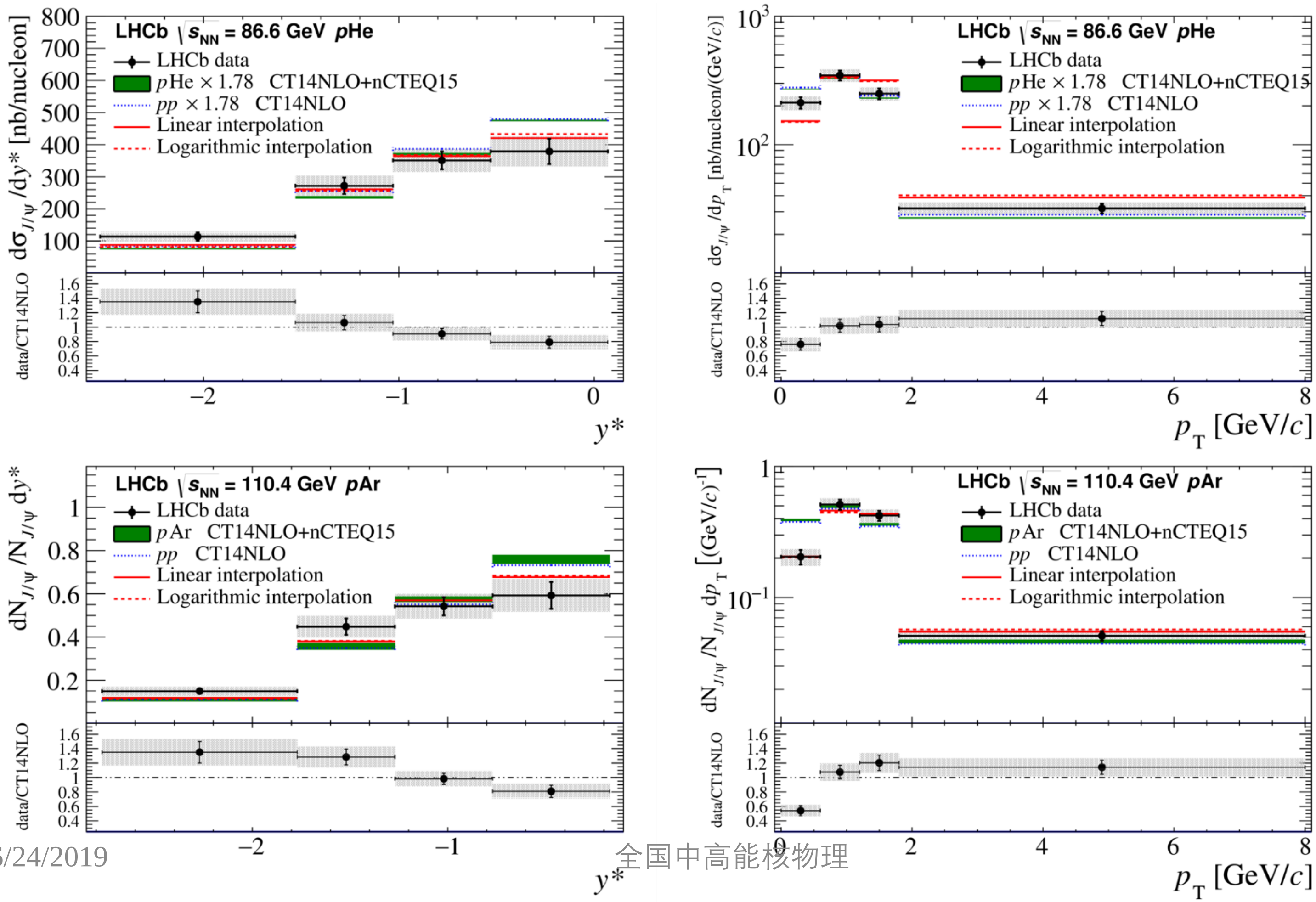


$\Upsilon(2S)$

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



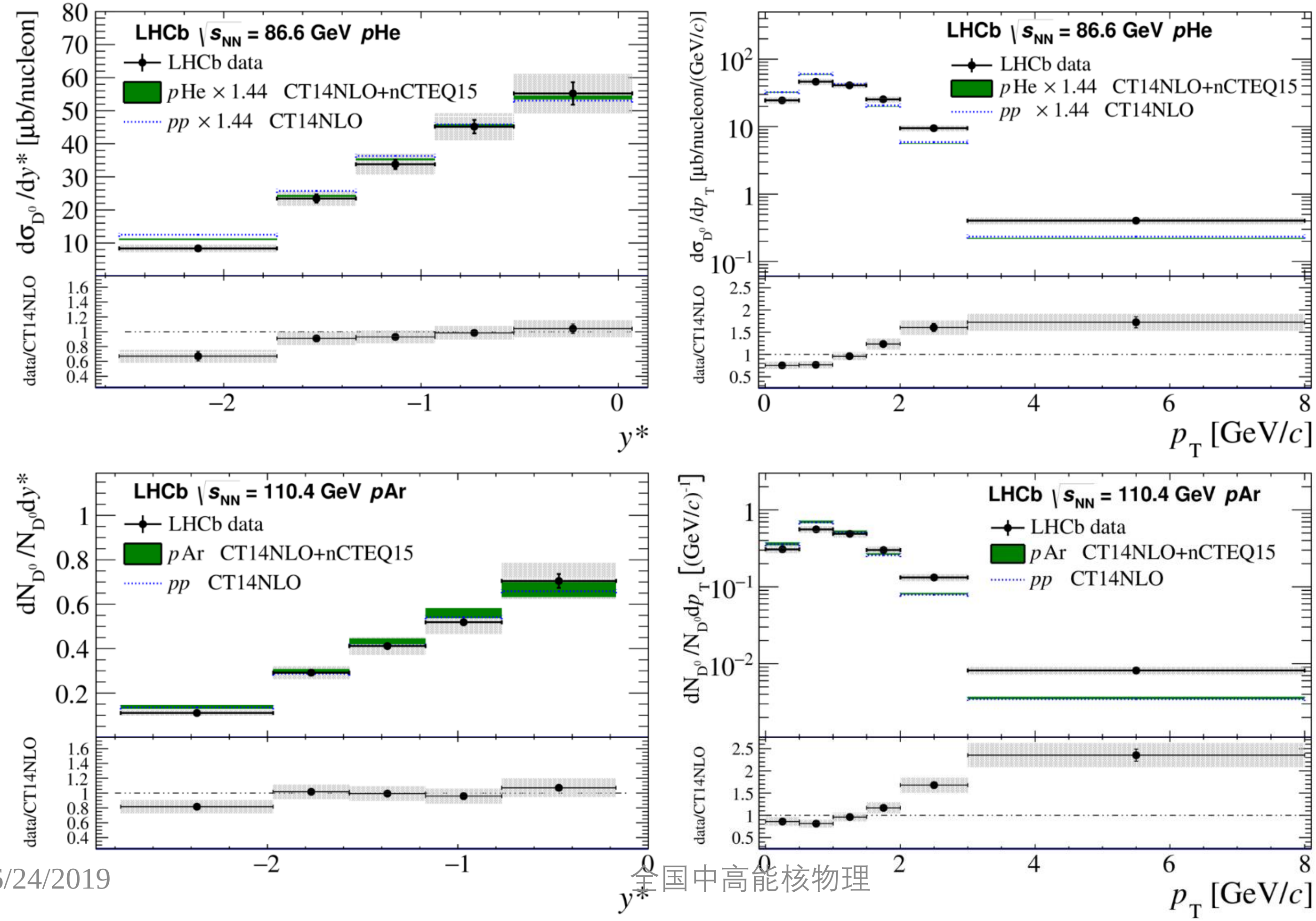
pNe @ 86.6GeV

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