Recent LHCb results from heavy ion collisions

Jiayin Sun

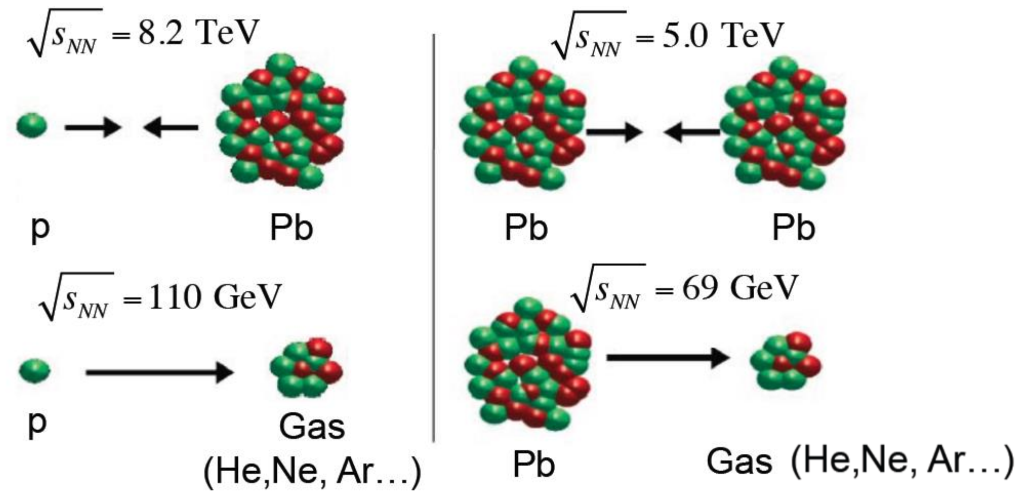
Tsinghua University

Implications of LHCb measurements and future prospects

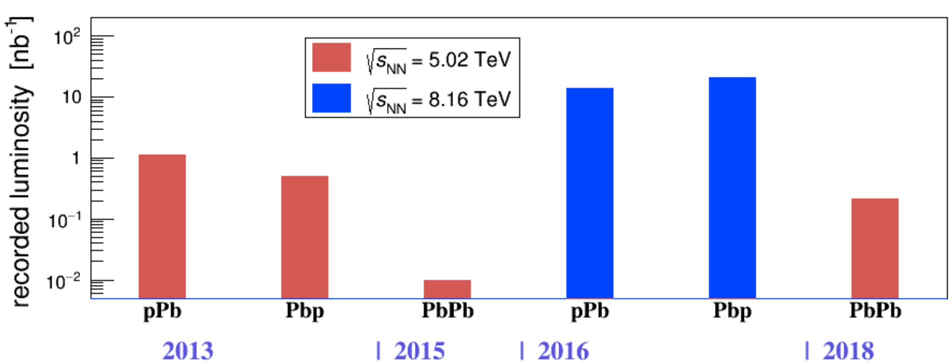
LHCb heavy ion collision modes

Collider mode

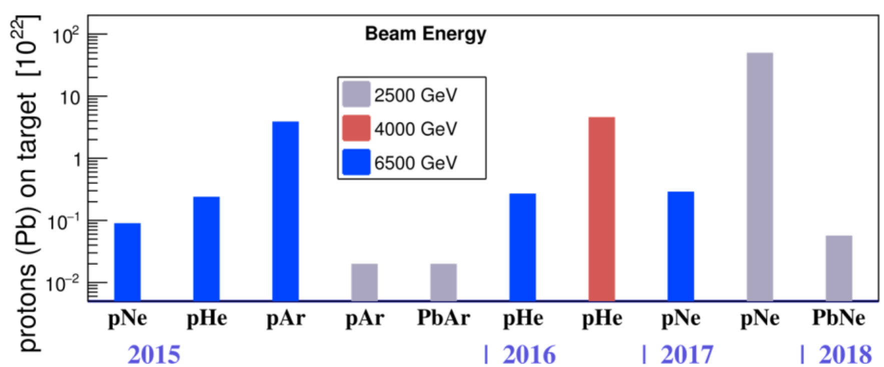
Fixed target mode



Collider mode



Fixed target mode



Recent heavy-ion results

- Results in Collider mode
  - Open heavy flavor in pPb collisions — D^0: JHEP 10 (2017) 090; Λ_c^+: JHEP 02 (2019) 102
    - 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 — PRD99 052011 (2019)
  - Quarkonium in pPb collisions
    - J/ψ production in pPb collisions at 8.16 TeV — PLB 774 (2017) 159
    - Upsilon $\Upsilon(nS)$ production in pPb collisions at 8.16 TeV — JHEP 11 (2018) 194
  - Quarkonium in Ultra-Peripheral PbPb (preliminary) — LHCb-CONF-2018-003

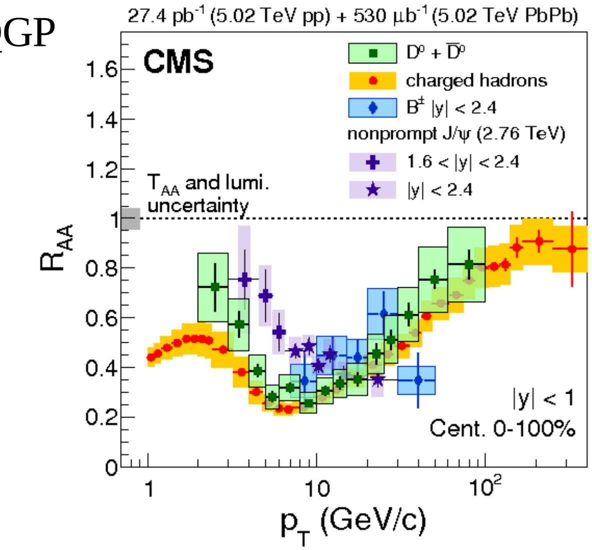
Albert Bursche's talk
Thursday 15:45

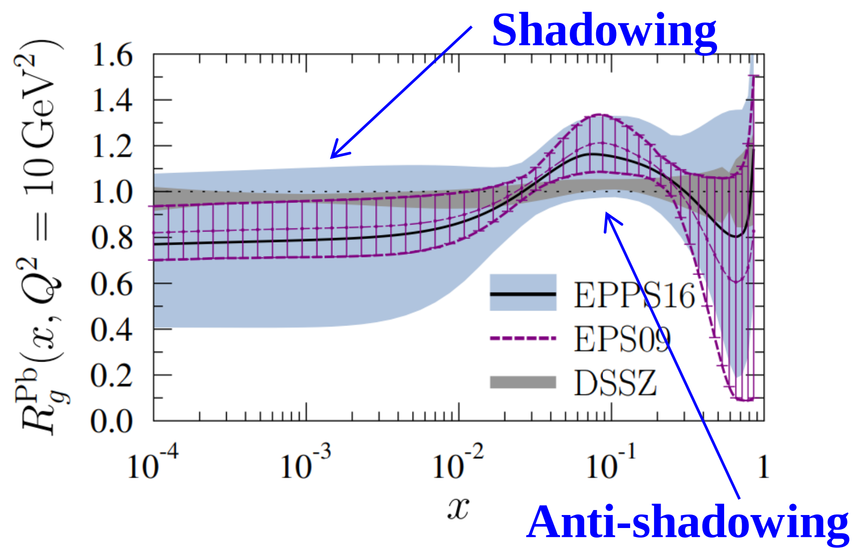
- Fixed target results
  - Charm production in pHe and pAr at 87, 110 GeV — PRL 122 (2019) 132002
  - Antiproton production cross-section in pHe at 110 GeV — PRL 121 (2018) 222001

Heavy flavor in pPb 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
  - Quarkonium states sequential melting
  - Baryon/meson ratio in charm and bottom sectors probes hadronisation
- Heavy flavor in pA 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

Phys. Lett. B 782 (2018) 474



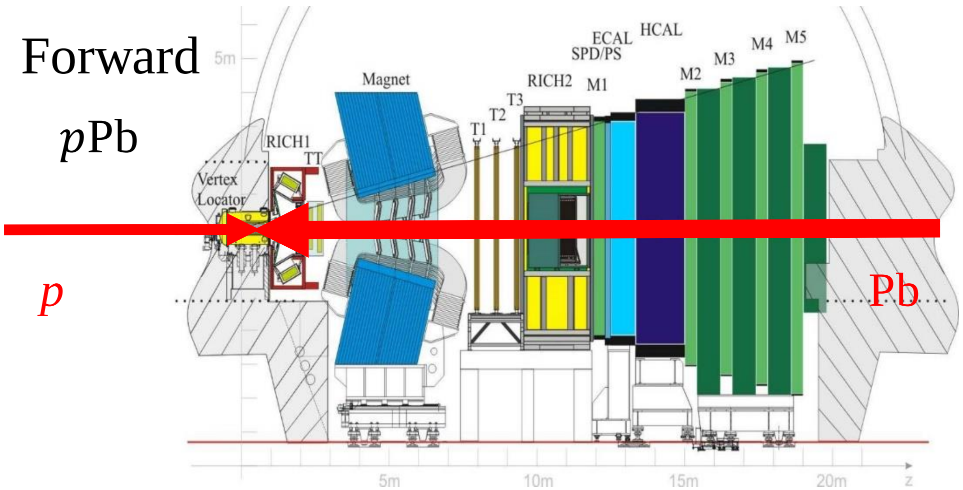


arXiv:1802.05927

LHCb pPb datasets

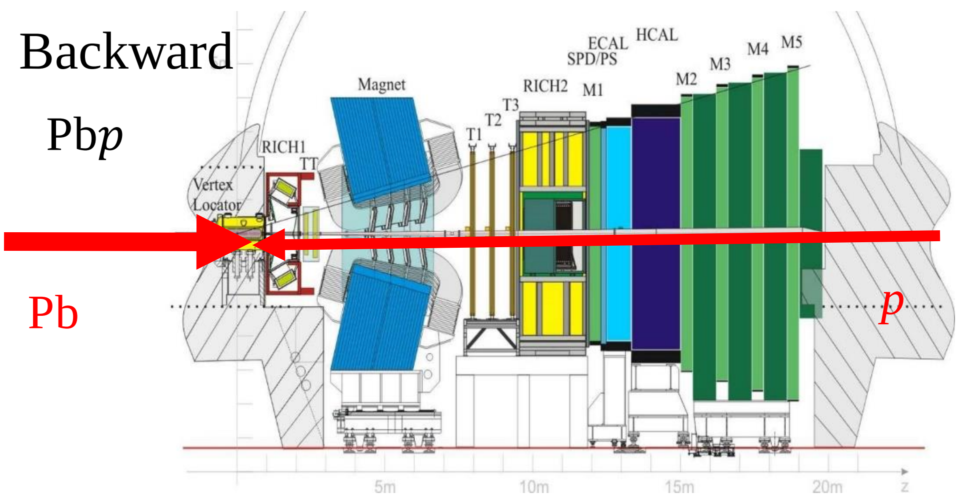
Forward

pPb



Backward

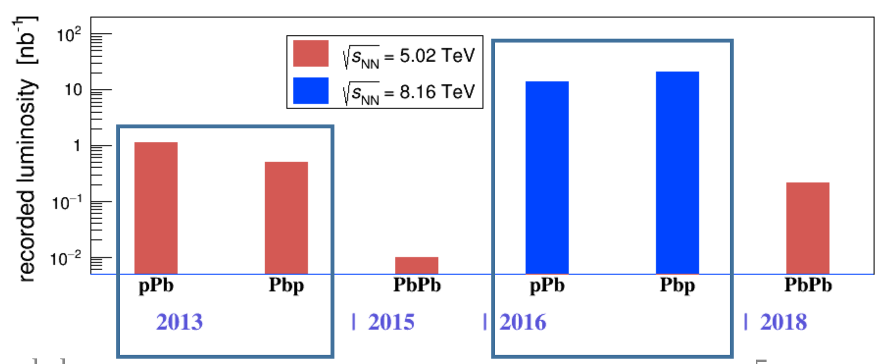
Pbp



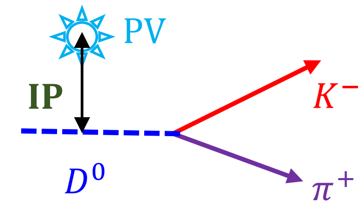
- Rapidity Coverage
  - y^*: rapidity in nucleon-nucleon cms
  - $y_{\text{cms}} = \pm 0.465$
  - Forward: $1.5 < y^* < 4.0$
  - Backward: $-5.0 < y^* < -2.5$
  - Common region: $2.5 < |y^*| < 4.0$

- $\sqrt{s_{NN}} = 5.02$ TeV (2013)
  - pPb (1.06 nb^{-1}) + Pbp (0.52 nb^{-1})

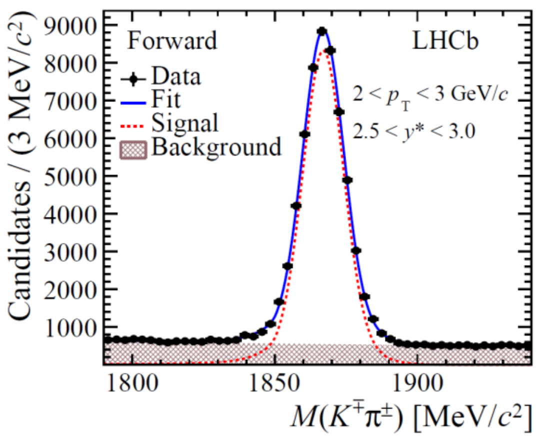
- $\sqrt{s_{NN}} = 8.16$ TeV (2016)
  - pPb (13.6 nb^{-1}) + Pbp (21.8 nb^{-1})

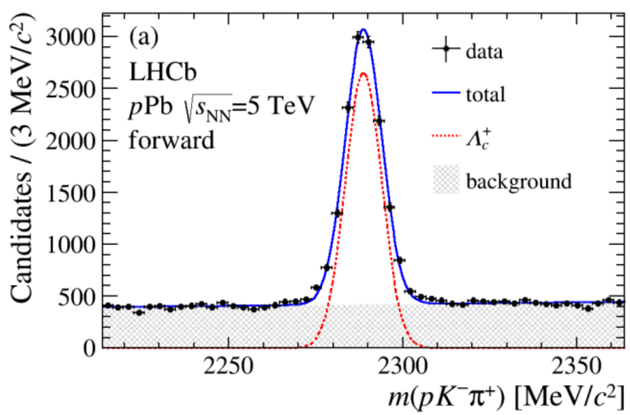


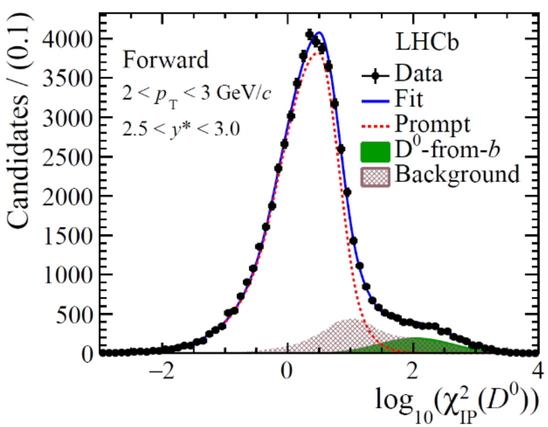
Prompt D^0 and Λ_c^+ measurement in pPb at 5 TeV

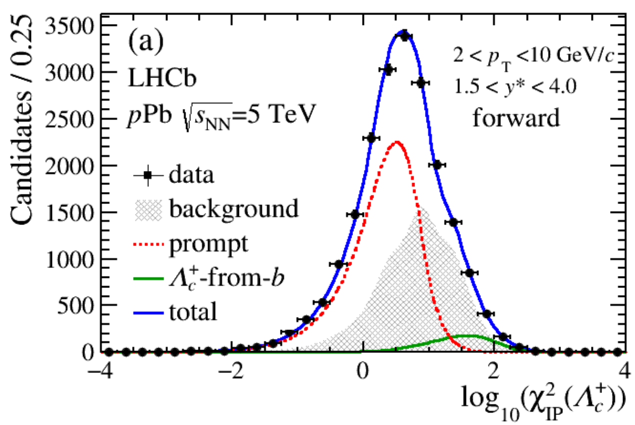


D^0 ↓ Λ_c^+ ↓









JHEP 10 (2017) 090

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

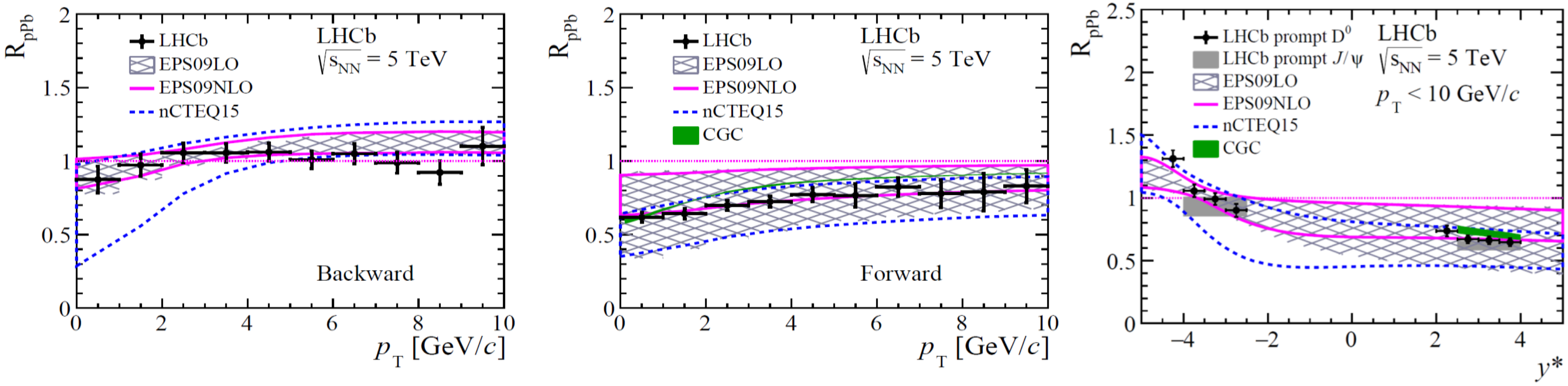
$$R_{p\mathrm{Pb}}(y^*, p_\mathrm{T}) = \frac{1}{A} \times \frac{\mathrm{d}\sigma_{p\mathrm{Pb}}(y^*, p_\mathrm{T}, \sqrt{s_\mathrm{NN}})/\mathrm{d}x}{\mathrm{d}\sigma_{pp}(y^*, p_\mathrm{T}, \sqrt{s_\mathrm{NN}})/\mathrm{d}x}, \quad A=208$$

- *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
- **Results constrain nPDFs in low *x***

PRL 121,052004(2018)
arXiv:1906.03943

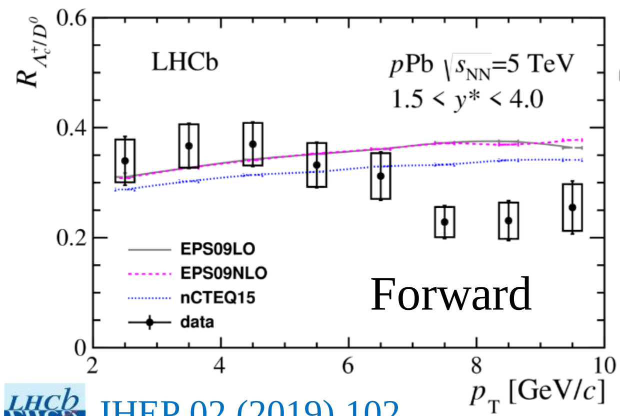
JHEP 10 (2017) 090

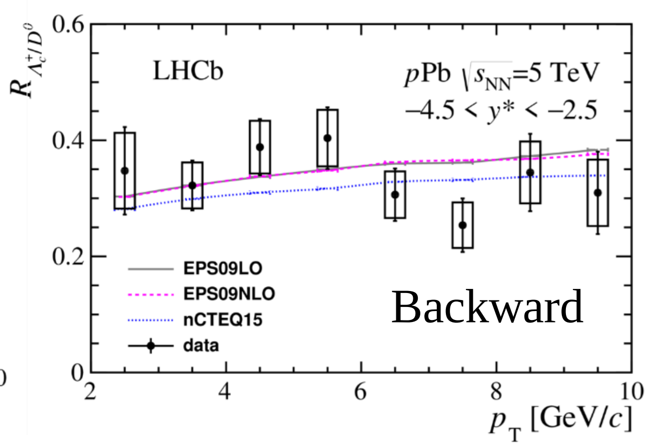


Charmed baryon/meson production ratio $R_{\Lambda_c^+/D^0}$ at 5.02 TeV

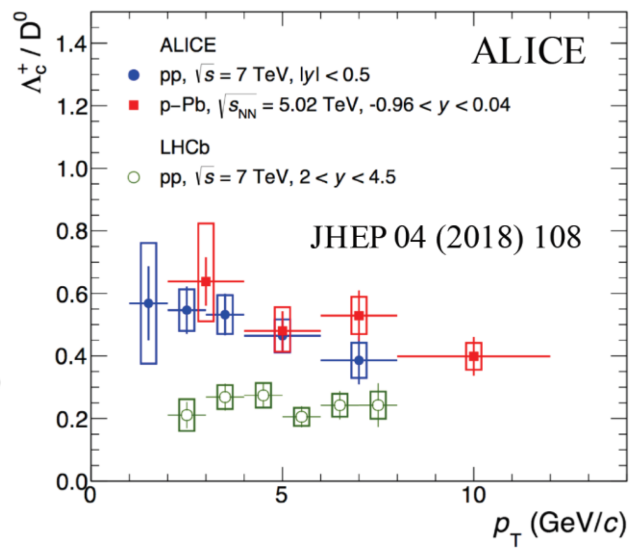
$$R_{\Lambda_c^+/D^0} = \frac{\sigma_{\Lambda_c^+}(y^*, p_T)}{\sigma_{D^0}(y^*, p_T)}$$

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





JHEP 02 (2019) 102



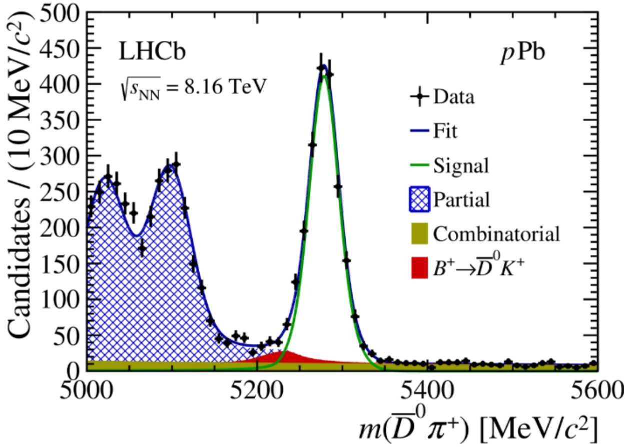
- Sensitive to charm hadronisation mechanisms
- Model based on measured *pp* cross-section
- nPDF uncertainty mostly cancel
  - EPS09LO & EPS09NLO similar
  - nCTEQ15 slightly lower.

- 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

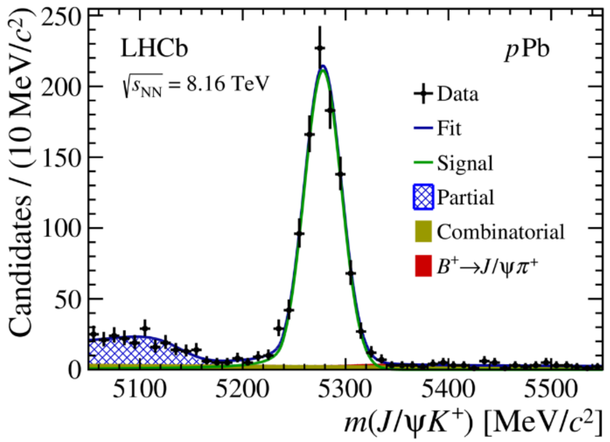
Beauty hadron production in pPb at 8.16 TeV

PRD99 052011 (2019)

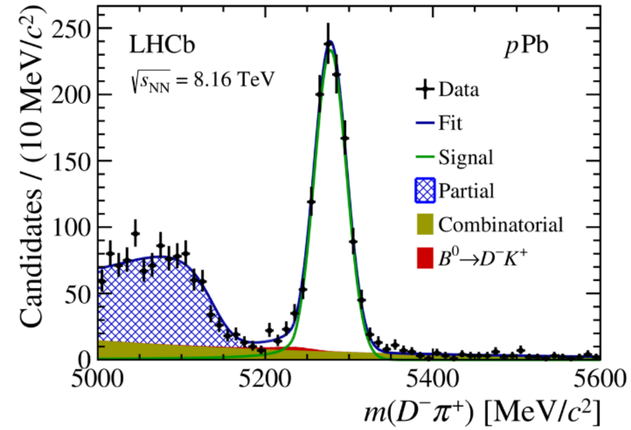
$B^+ \to \bar{D}^0\pi^+$



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



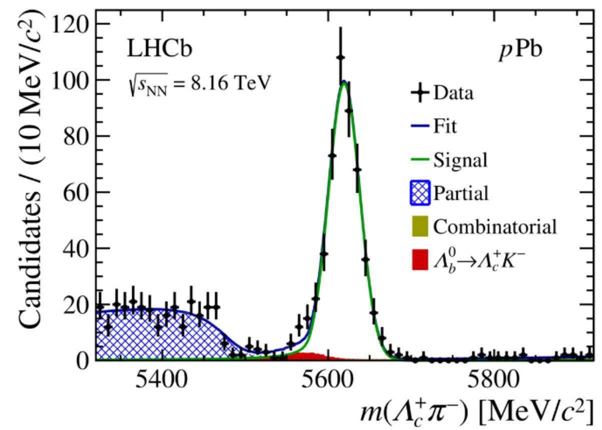
$B^0 \to D^-\pi^+$



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

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



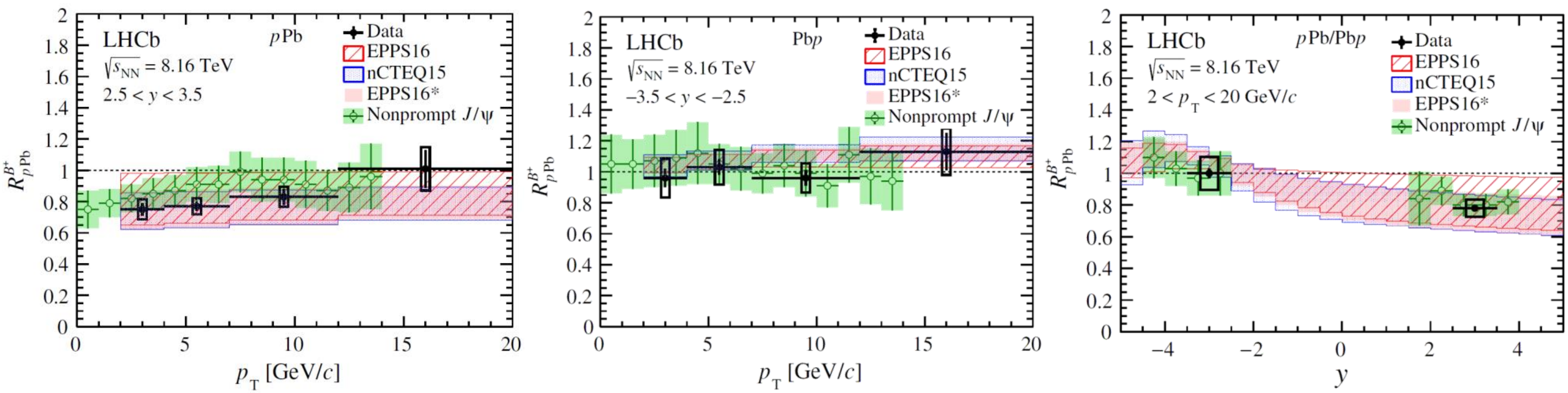
b-hadron production in pPb at 8.16 TeV
B^+ nuclear modification factor

PRD99 052011 (2019)

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

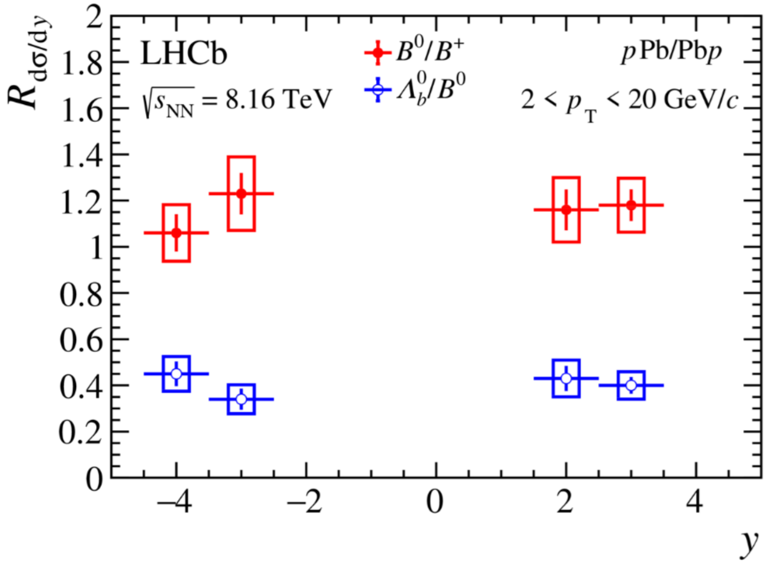
- *pp* reference interpolated between 7 & 13 TeV measurements from LHCb
- $R_{p\mathrm{Pb}}$ suppressed at forward rapidity
  - increase with increasing p_T
- $R_{p\mathrm{Pb}}$ consistent with 1 at backward rapidity

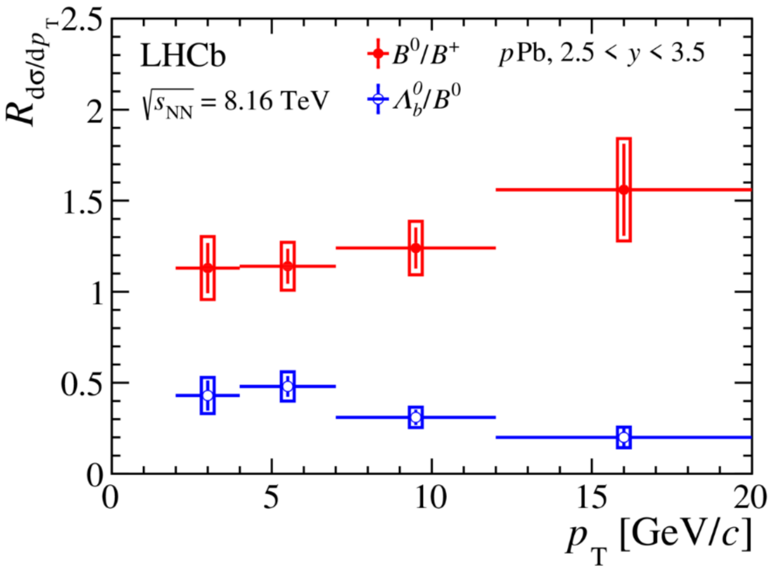
- Measurements consistent with calculations with nPDFs EPPS16 and nCTEQ15
- Consistent with J/ψ-from-b
- Trend similar to D^0 $R_{p\mathrm{Pb}}$



b-hadron production in pPb at 8.16 TeV
Production cross-section ratio

PRD99 052011 (2019)



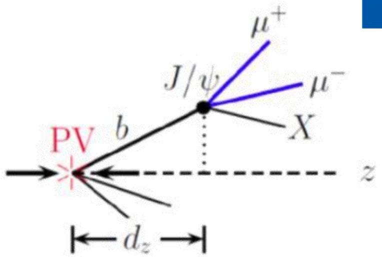


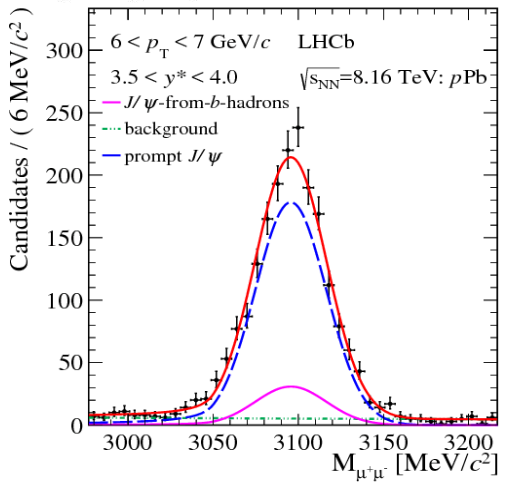
- R_{B^0/B^+}
  - No significant dependence on rapidity and p_T
- $R_{\Lambda_b^0/B^0}$
  - ~0.4, no strong rapidity dependence
  - Similar values observed in LHCb *pp* measurement JHEP 08 (2014) 143
  - Decreases with p_T when $p_T > 5$ GeV/c

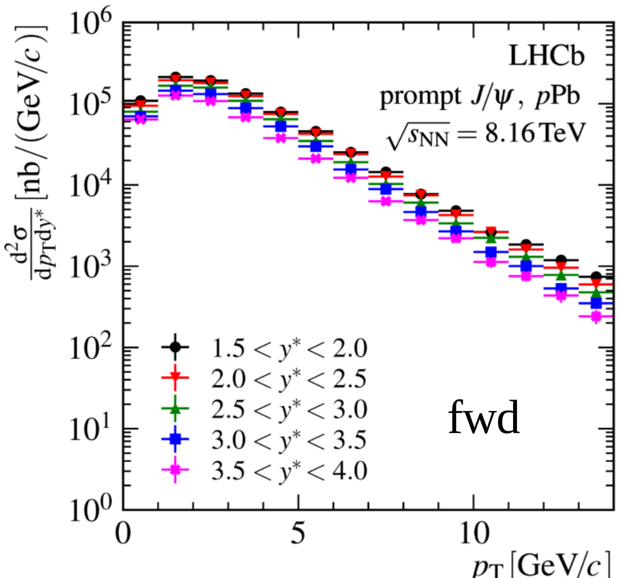
Prompt and nonprompt J/ψ in pPb at 8.16 TeV

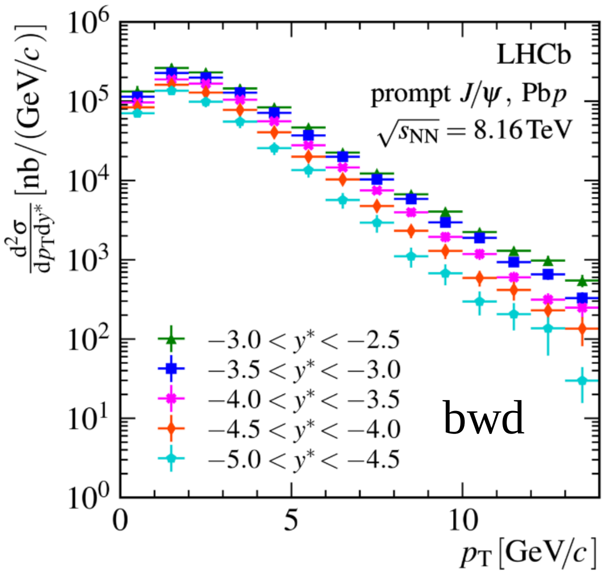
- Sources
  - Prompt: direct production, feed down from heavier states $\psi(2S)$, χ_c
  - Nonprompt: from-b-hadrons decays
- Reconstructed through $J/\psi \to \mu^+\mu^-$
- Prompt and nonprompt (from-b-hadrons) separated: the pseudo proper decay time

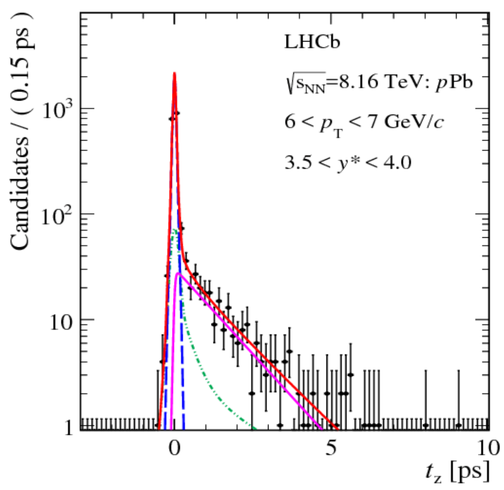
$$t_z \equiv \frac{(z_{J/\psi} - z_{PV}) \times M_{J/\psi}}{p_z}$$











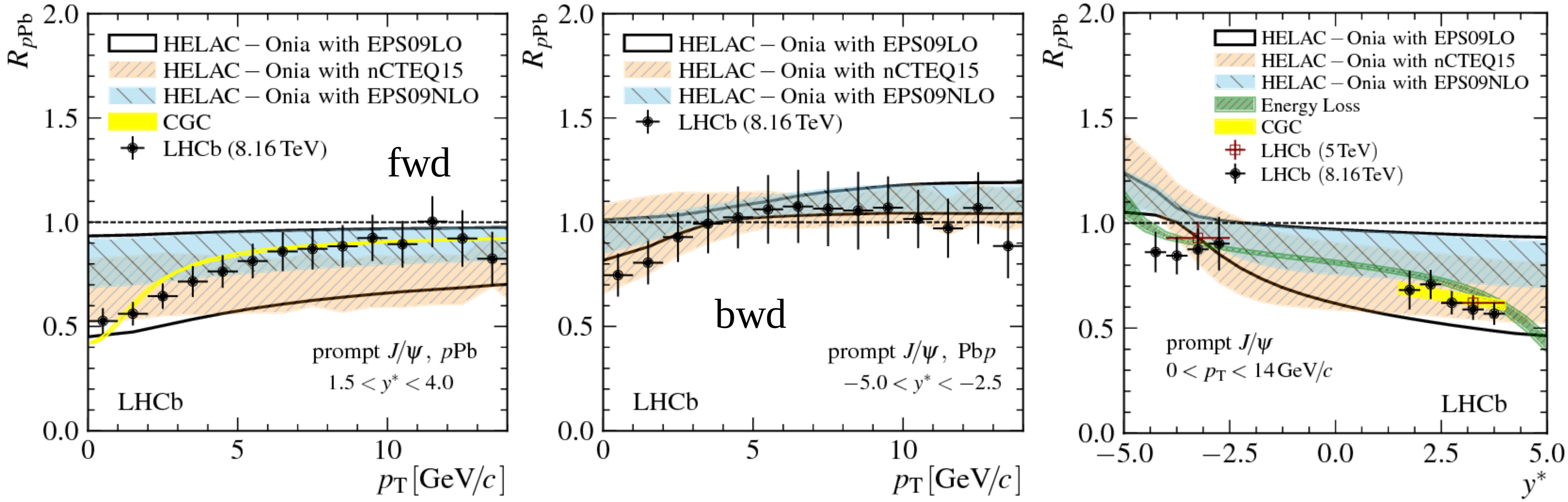
PLB 774 (2017) 159

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

PLB 774 (2017) 159

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

- ***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
- **Results constrain nPDFs in low x down to $x{\sim}7\times10^{-6}$** PRL 121,052004(2018)



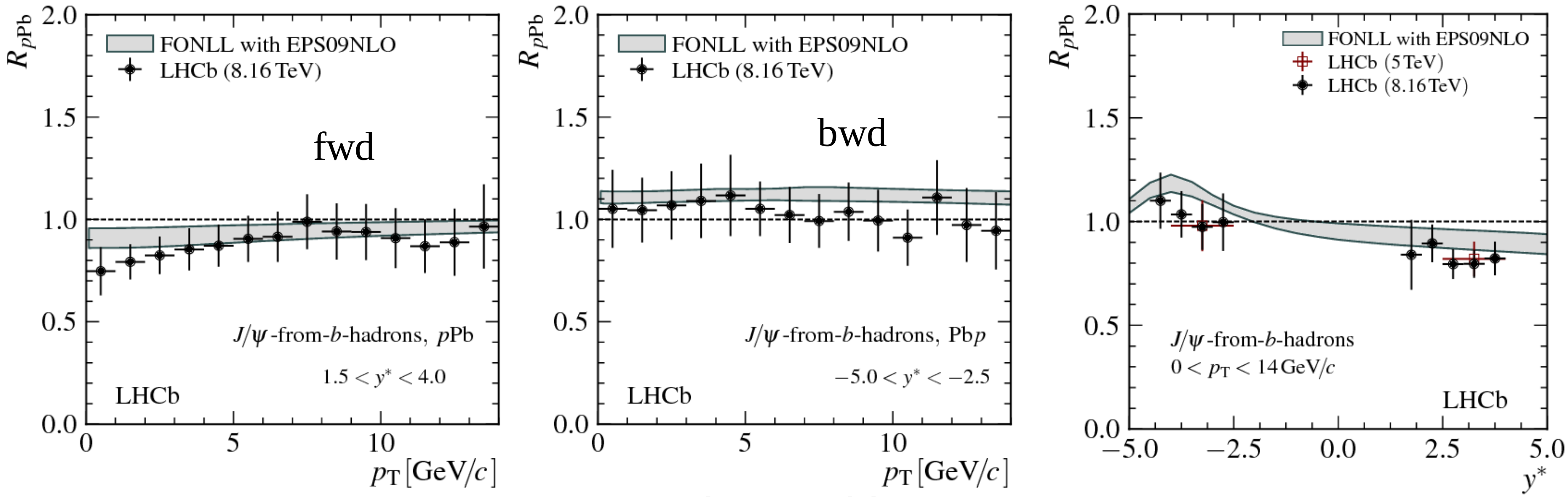
J/ψ-from-b-hadrons at 8.16 TeV nuclear modification factor in pPb

PLB 774 (2017) 159

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

- ***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 5.02 TeV results

EPS09 JHEP 04 (2009) 065

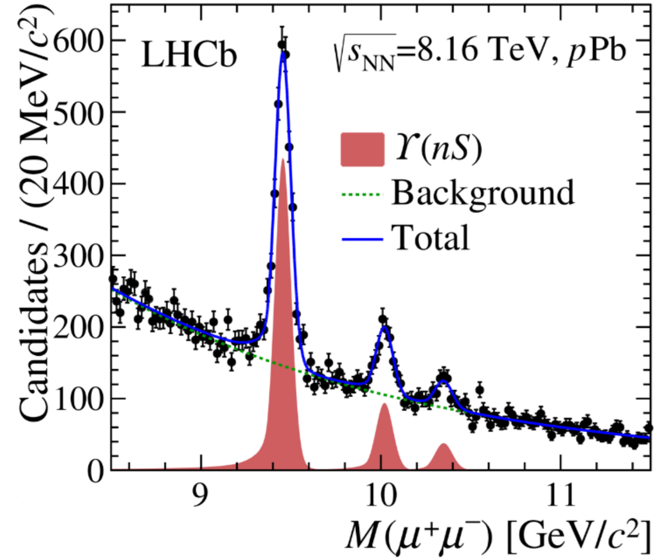


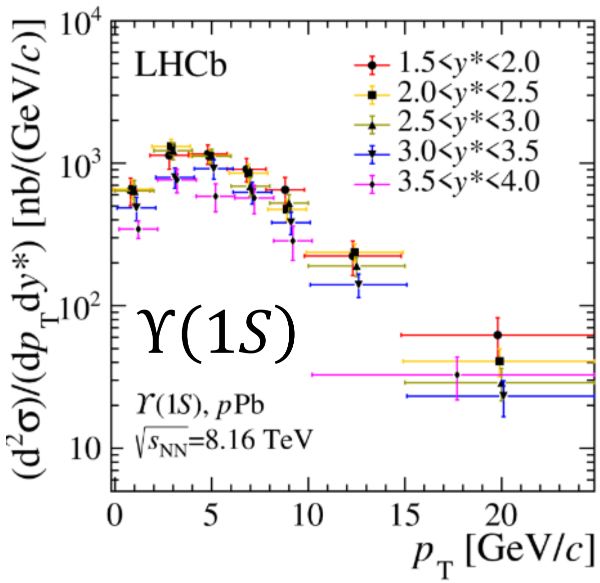
$\Upsilon(nS)$ in pPb collisions at 8.16 TeV

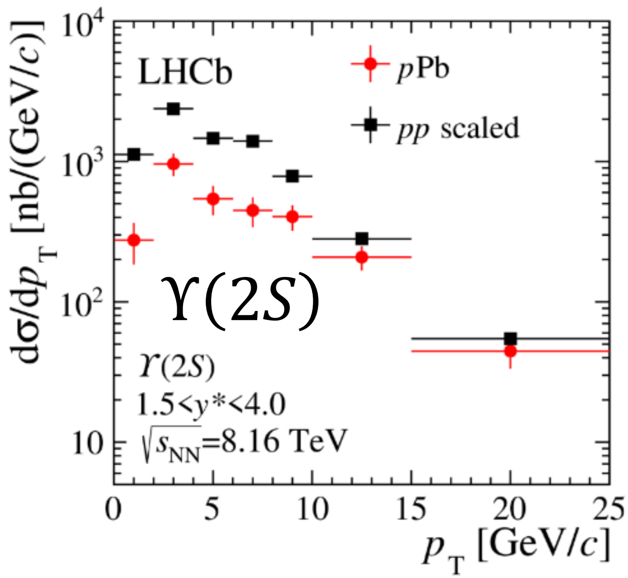
JHEP 11 (2018) 194

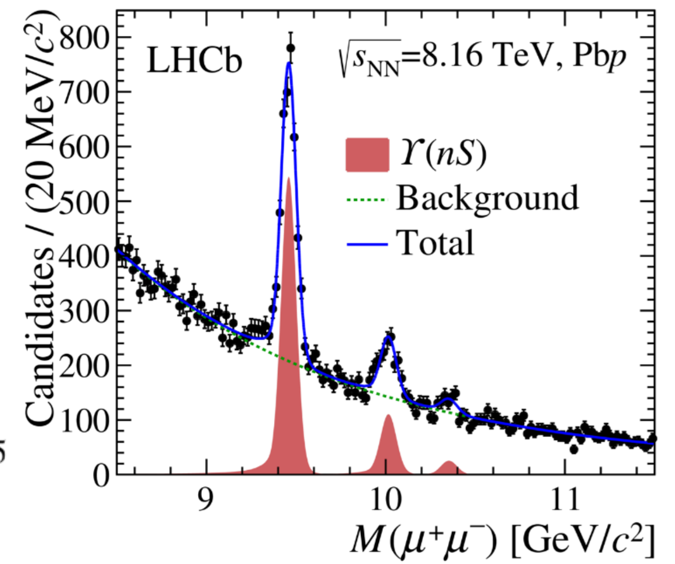
New differential analysis using 2016 pPb data
Nice $\Upsilon(3S)$ signals in forward and backward configurations

Samples	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
pPb	2705 ± 87	584 ± 49	262 ± 44
Pbp	3072 ± 82	679 ± 54	159 ± 39









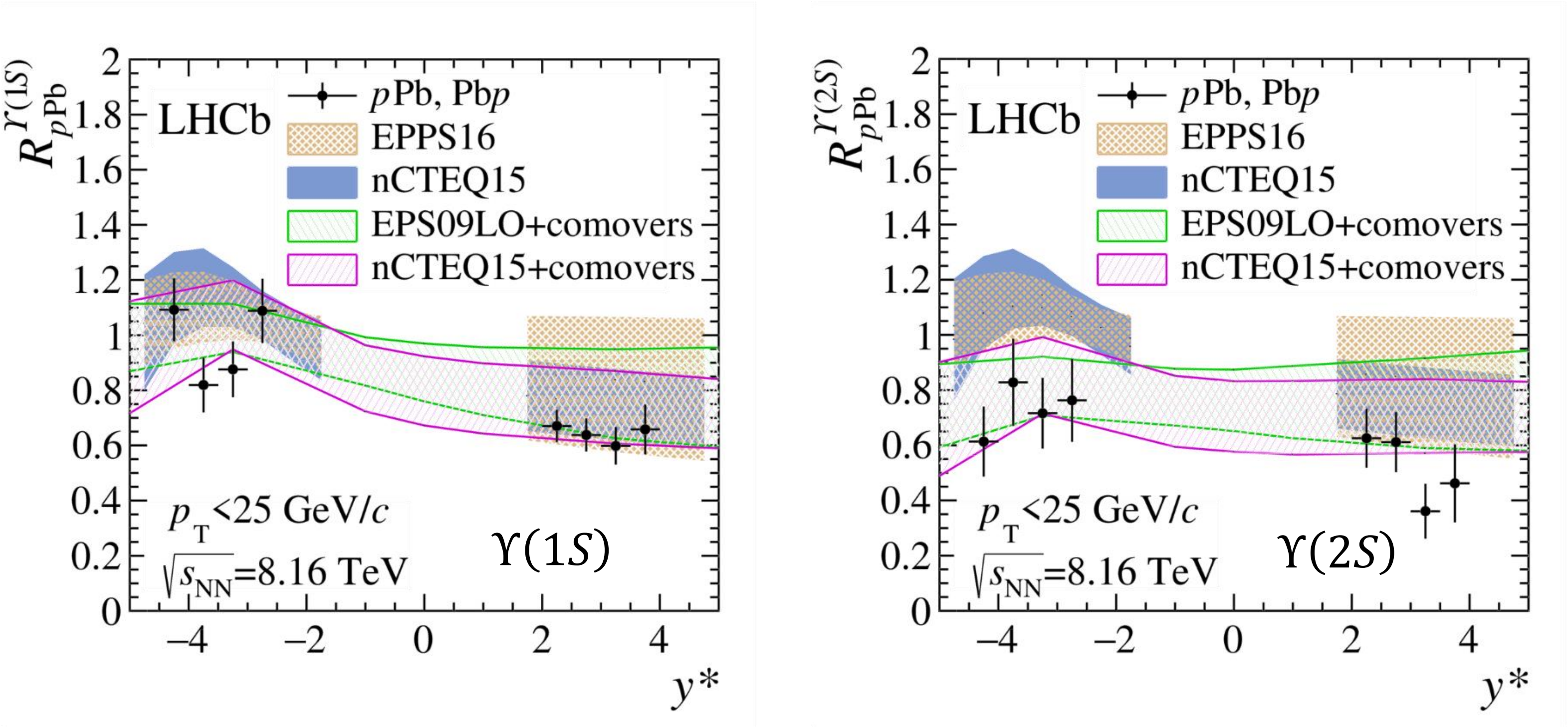
FWD

$\Upsilon(nS)$ 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



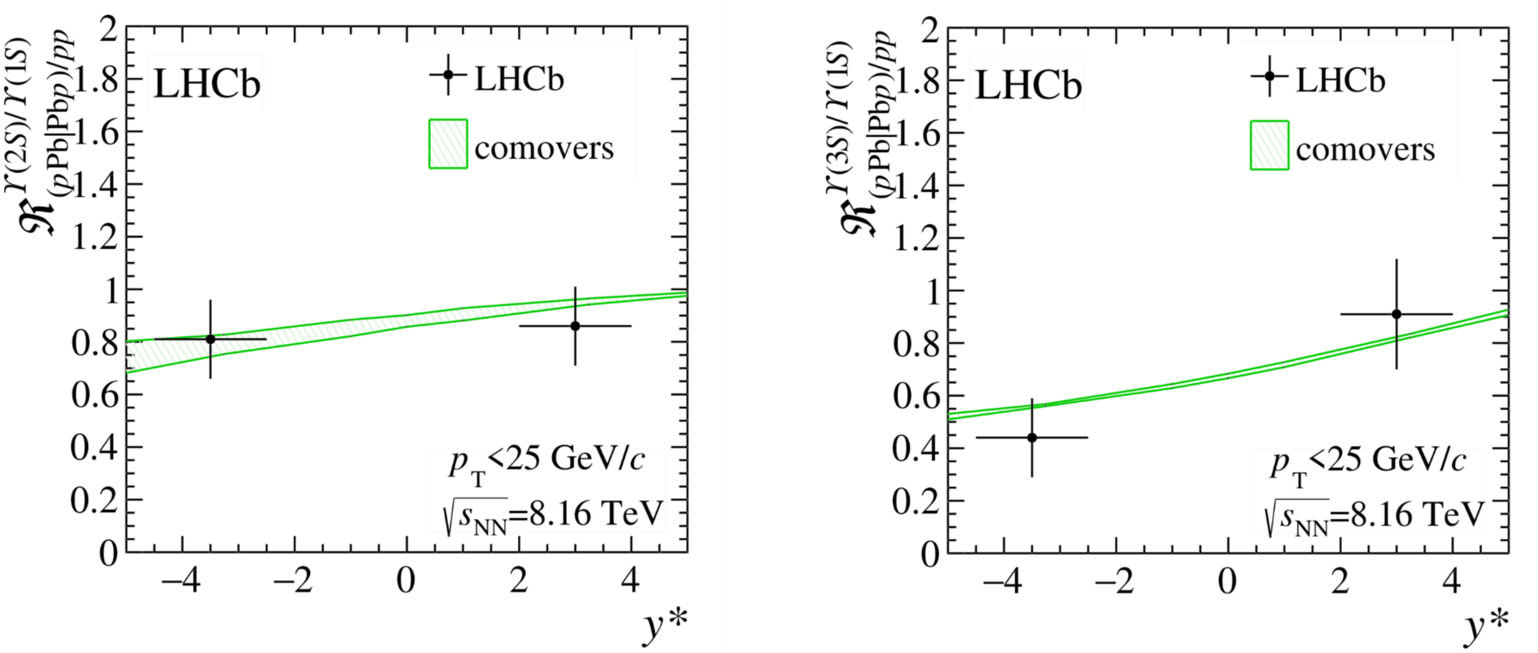
Double ratio

JHEP 11 (2018) 194

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

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

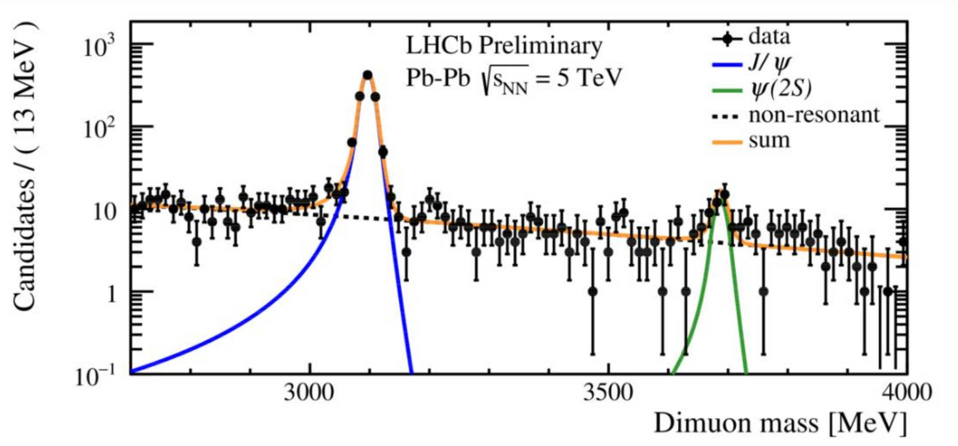
- Double ratio of $\Upsilon(nS)/\Upsilon(1S)$ in *p*Pb and *pp*
- $\Upsilon(3S)$ more suppressed than $\Upsilon(2S)$ in the backward rapidity
- Suggests final state effects…
- Agrees with predictions of "comovers" model

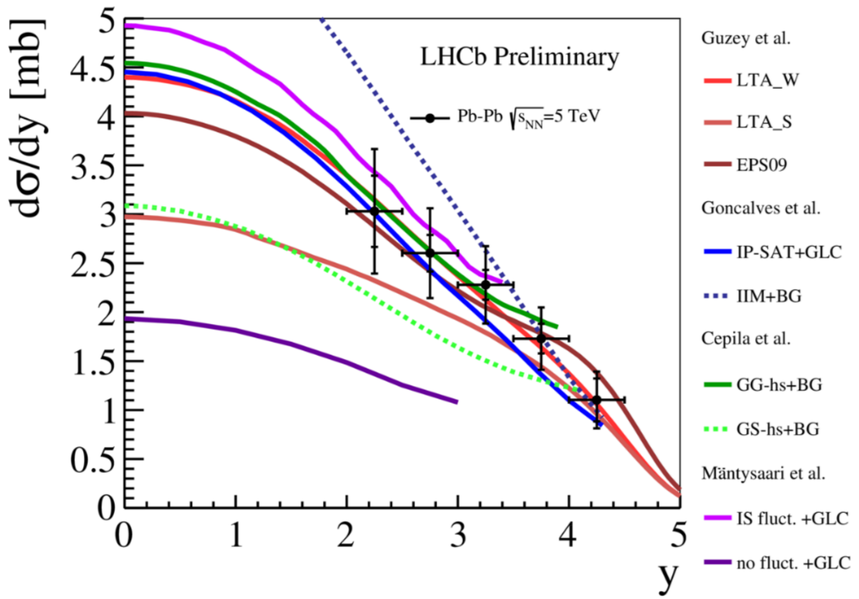


J/ψ in PbPb ultra peripheral collisions

- $J/\psi \rightarrow \mu^+\mu^-$ in ultra peripheral collisions (UPC) PbPb collisions at 5 TeV
- First preliminary result by LHCb on PbPb collisions
- Coherent J/ψ photo-production

Albert Bursche's talk
Thursday 15:45

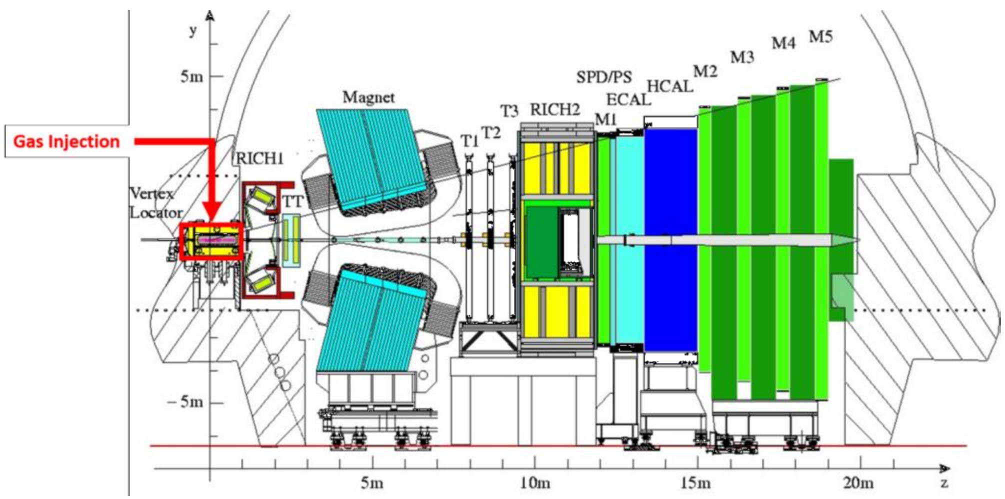


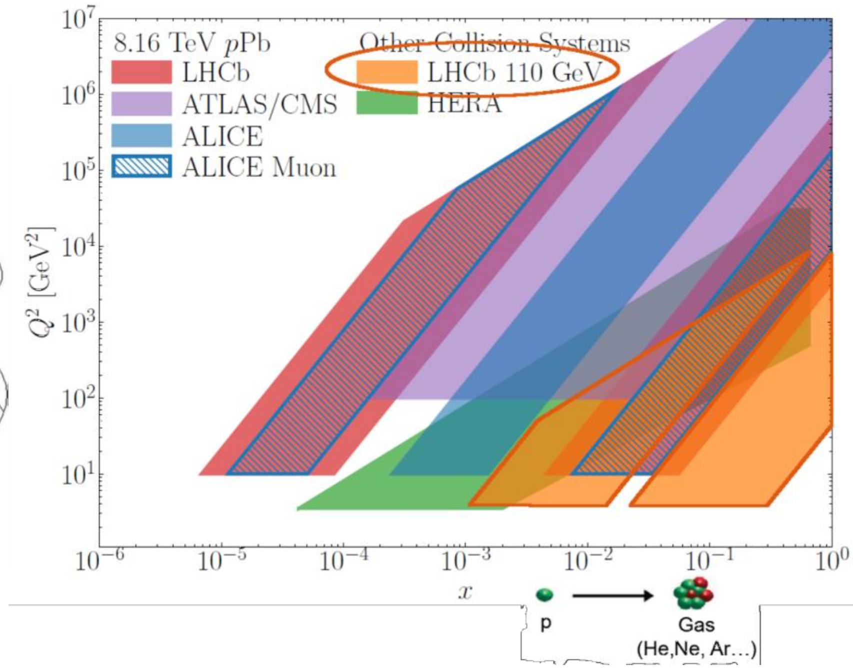


Fixed target physics

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 the injection of a small amount of noble gas into the LHC beam close to the interaction point
- Allows *p*-gas and ion-gas collisions (He, Ne, Ar,… $\sim 2 \times 10^7$mbar)
- $\sqrt{s_{NN}}$ = 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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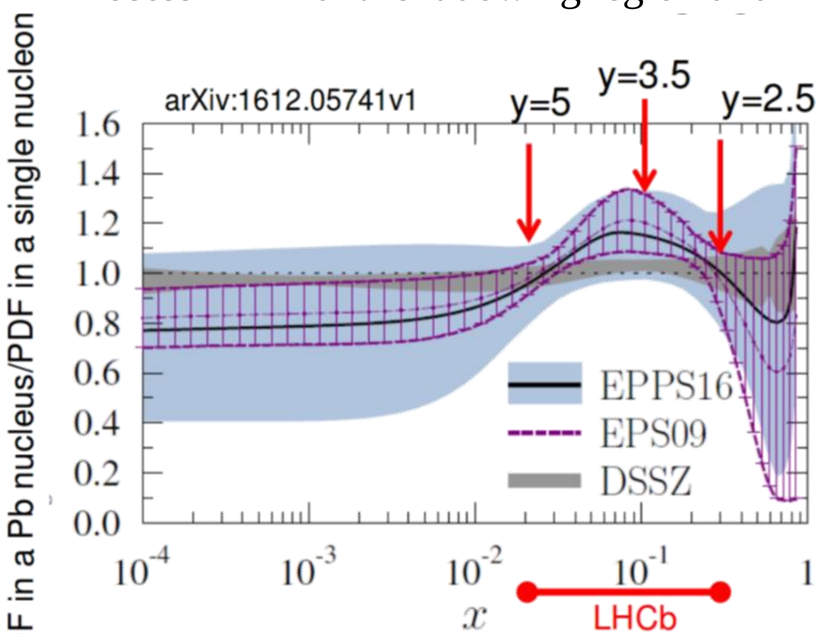
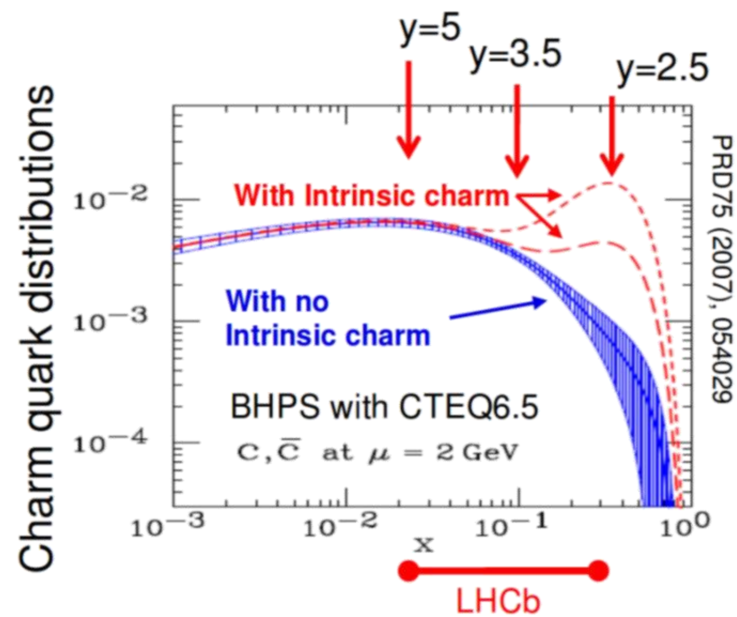
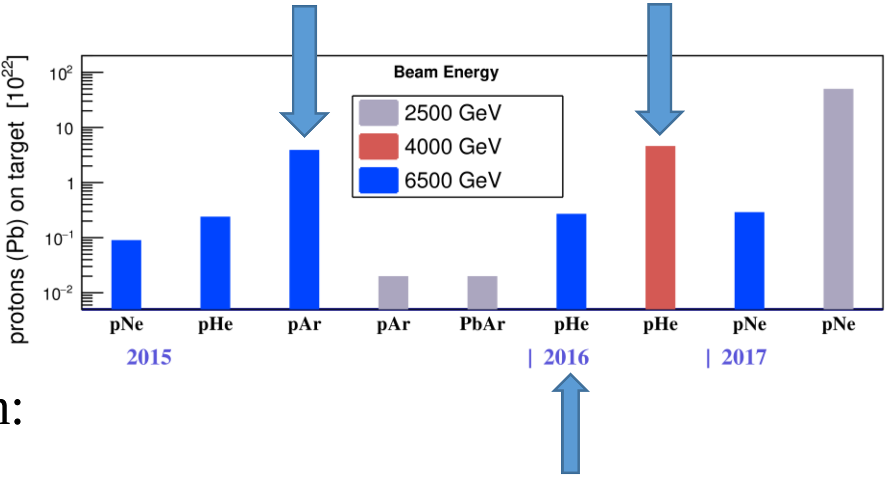




Bjorken-x = fraction of the nucleon momentum carried by a parton

Data samples:

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



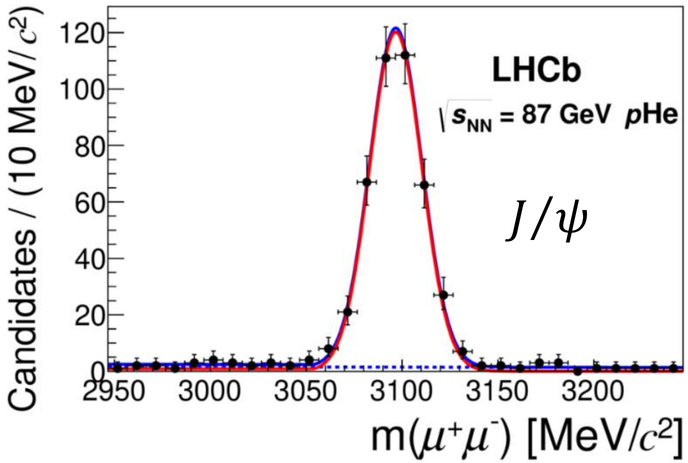
- Measurement of antiproton production:
  - pHe at $\sqrt{s_{NN}}$ =110 GeV (2016)
    - $\mathcal{L}_{p\mathrm{He}} \sim 0.5\mathrm{nb}^{-1}$

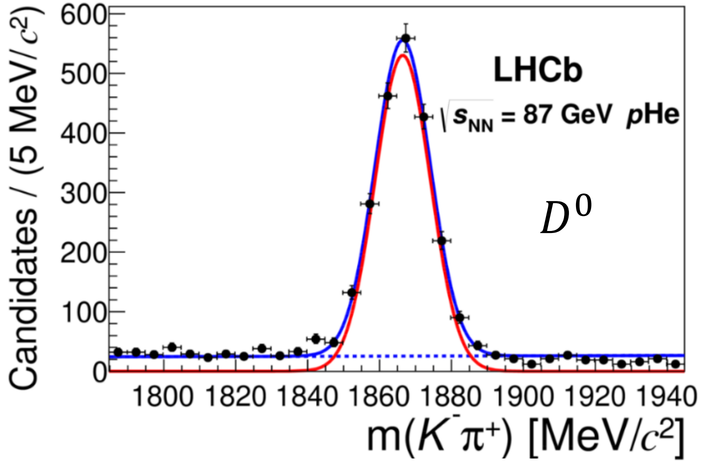
	E_{beam}(p)	pp	p-SMOG	p-Pb/Pb-p	Pb-SMOG	Pb-Pb
	450 GeV	0.90 TeV				
	1.38 TeV	2.76 TeV				
	2.5 TeV	5 TeV	69 GeV			
	3.5 TeV	7 TeV				
	4.0 TeV	8 TeV	87 GeV	5. TeV	54 GeV	
	6.5 TeV	13 TeV	110 GeV	8.2 TeV	69 GeV	5.1 TeV
Run3&4→	7.0 TeV	14 TeV	115 GeV	8.8 TeV	72 GeV	5.5 TeV

Charm production in fixed-target pA collision

PRL 122 (2019) 132002

- J/ψ and D^0 inclusive cross-section in pHe 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



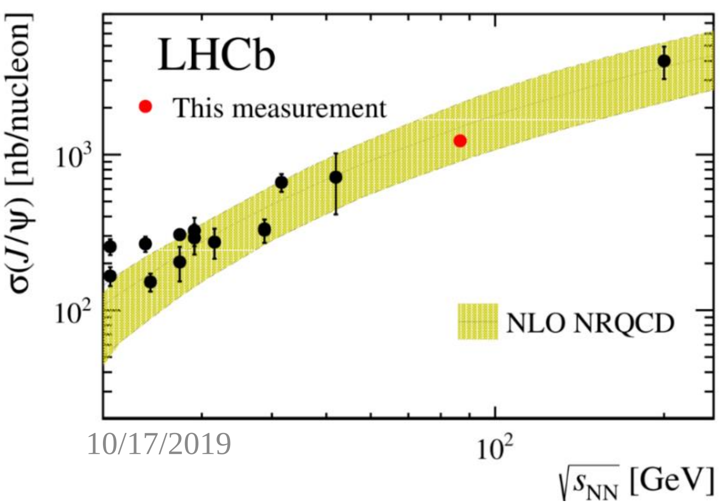


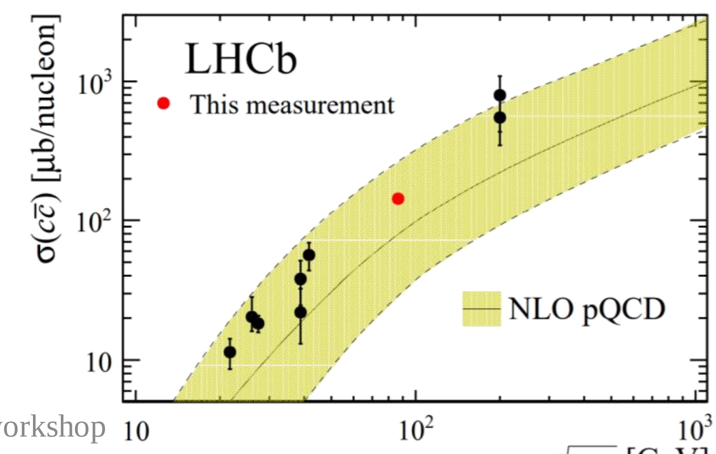
$\sigma_{D^0} = 156.0 \pm 13.1\ \mu\text{b/nucleon}$

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

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

$\sigma_{c\bar{c}} = 144 \pm 12.1 \pm 3.5\ \mu\text{b/nucleon}$





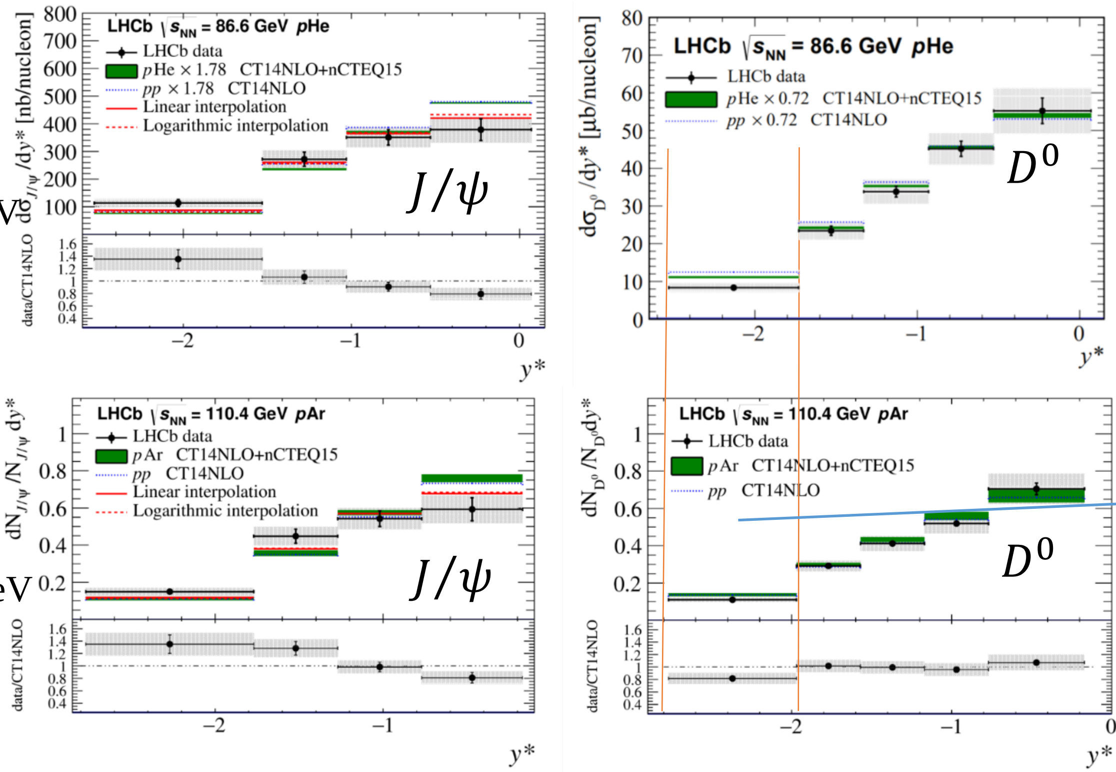
Erratum is being submitted

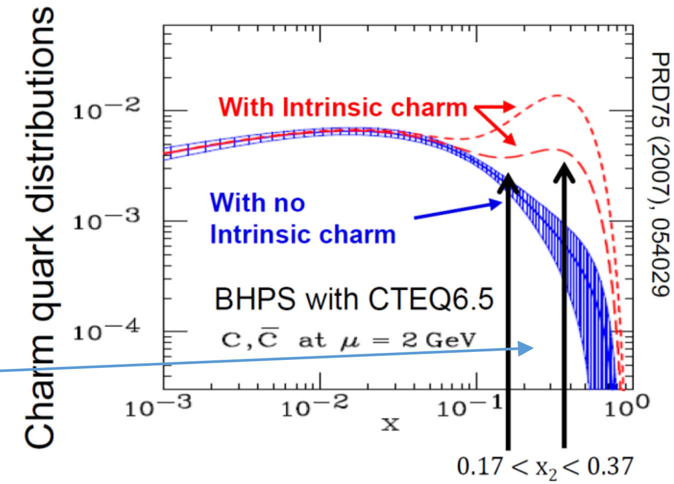
Charm production in fixed-target pA collision

PRL 122 (2019) 132002
Erratum is being submitted

pNe @ 86.6 GeV

pAr @ 110.4 GeV





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

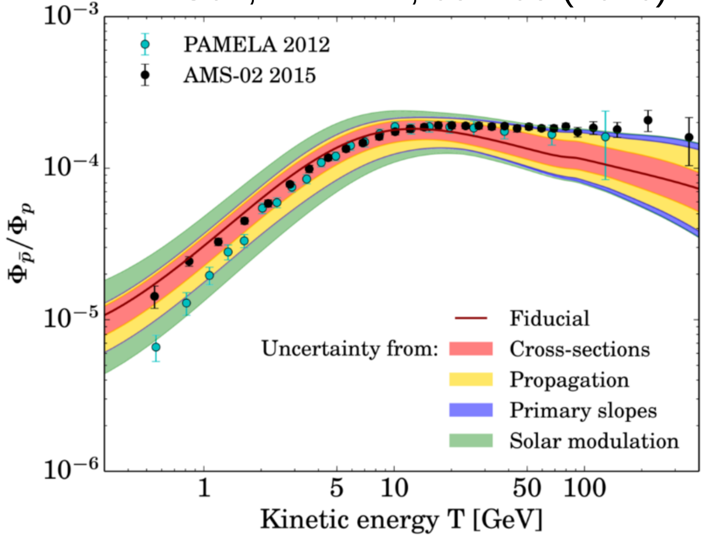
- Differential cross-section (pHe @ 86.6 GeV), differential yields (pAr @ 110.4 GeV)
- Reasonable agreement with Helac-Onia predictions in rapidity shape
- -2.53<y*<-1.73 → 0.17<x<0.37
- No evidence of strong intrinsic charm contribution observed

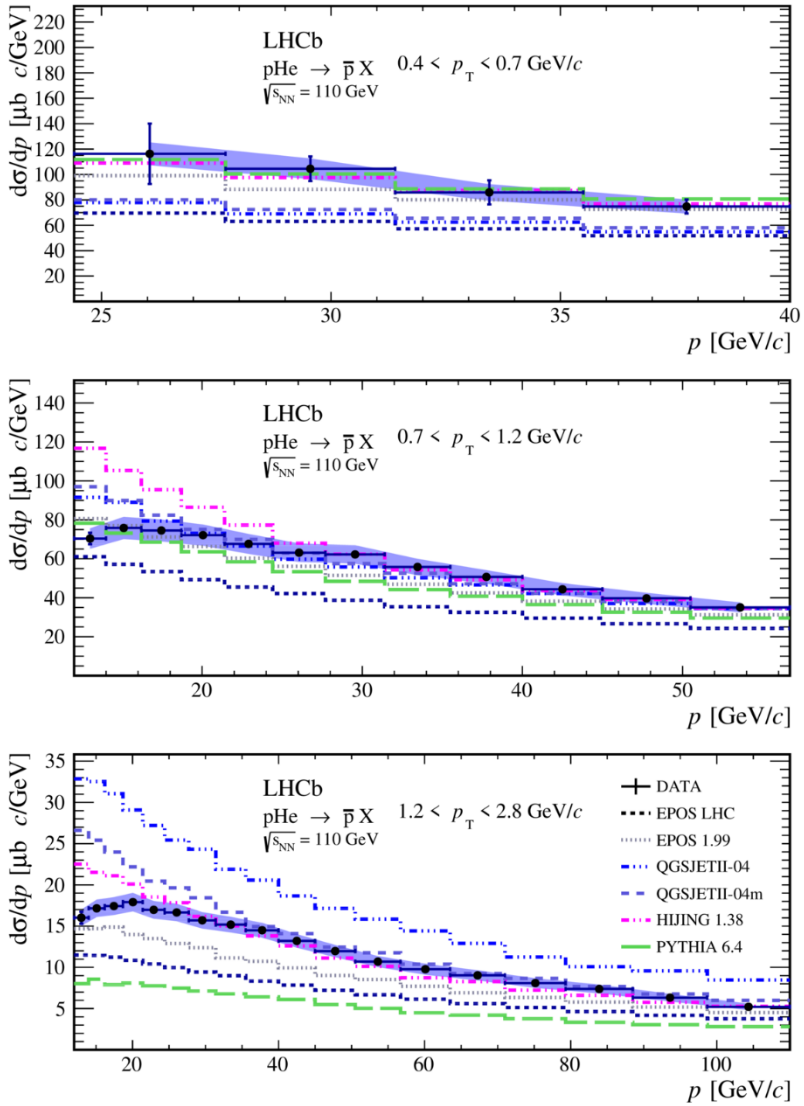
Models:
Eur. Phys. J. C77 (2017) 1
Comput. Phys. Commun. 184 (2013) 2562
Comput. Phys. Commun. 198 (2016) 238

$\bar{p}$ production in pHe collisions

PRL 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 pHe
- 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}. Relative suppression to *pp* collisions 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 relative 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: relative suppression similar to open heavy flavor results
  - $\Upsilon(nS)$: relative suppression of $\Upsilon(nS)$ states observed in pPb
- Fixed-target mode (SMOG)
  - Charm production: no evidence of strong intrinsic charm contribution
  - Antiproton: valuable inputs to astrophysics

Conclusions

- For the future:
  - Upcoming results:
    - D^0 and Z production cross sections in *p*Pb at 8.16 TeV
    - X(3872) and ψ (2S) in high multiplicity *pp* collision at 8 TeV
    - Charmonia in UPC PbPb (2018)
  - Various ongoing analyses:
    - Charmed hadrons, direct photons, χ_c, V^0, etc. in *p*Pb, PbPb and SMOG data
  - 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

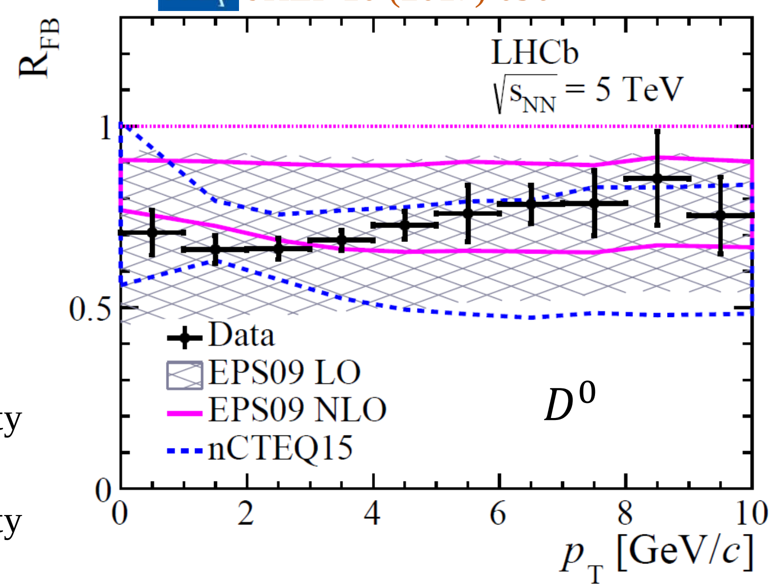
Backup

Prompt charm production at 5.02 TeV forward-backward production ratio

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

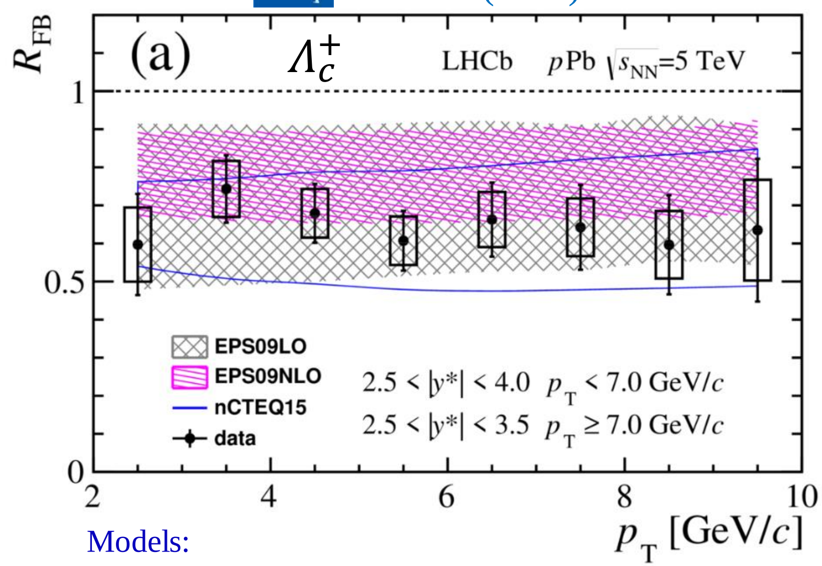
- R_{FB} does not need results from *pp* collisions.
- Compared to Helac-Onia calculations incorporating different nPDFs
  - Model parameterisation constrained by existing LHC *pp* cross-section measurements
- Consistent with nPDF predictions within uncertainty
- **D^0 meson show smaller uncertainties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

JHEP 10 (2017) 090



I Total uncertainty
□ syst. uncertainty

JHEP 02 (2019) 102

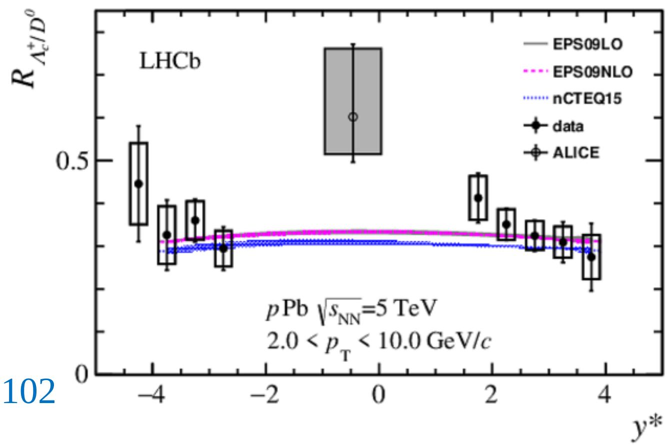


Models:
Eur. Phys. J. C77 (2017) 1
Comput. Phys. Commun. 184 (2013) 2562
Comput. Phys. Commun. 198 (2016) 238

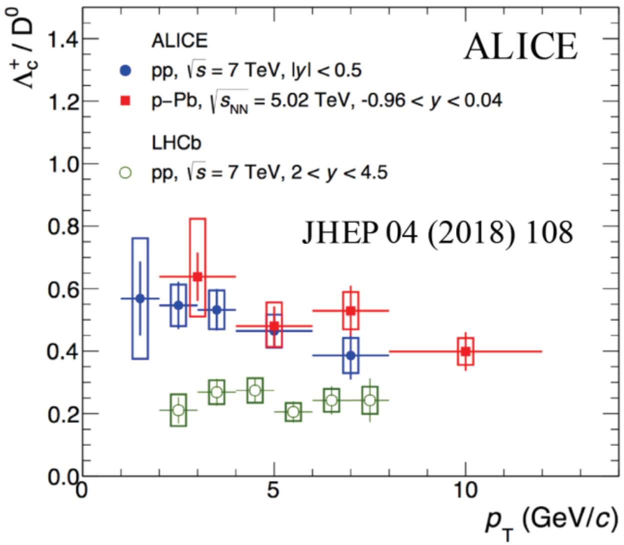
Charmed baryon/meson production ratio $R_{\Lambda_c^+/D^0}$ at 5.02 TeV

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

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



JHEP 02 (2019) 102



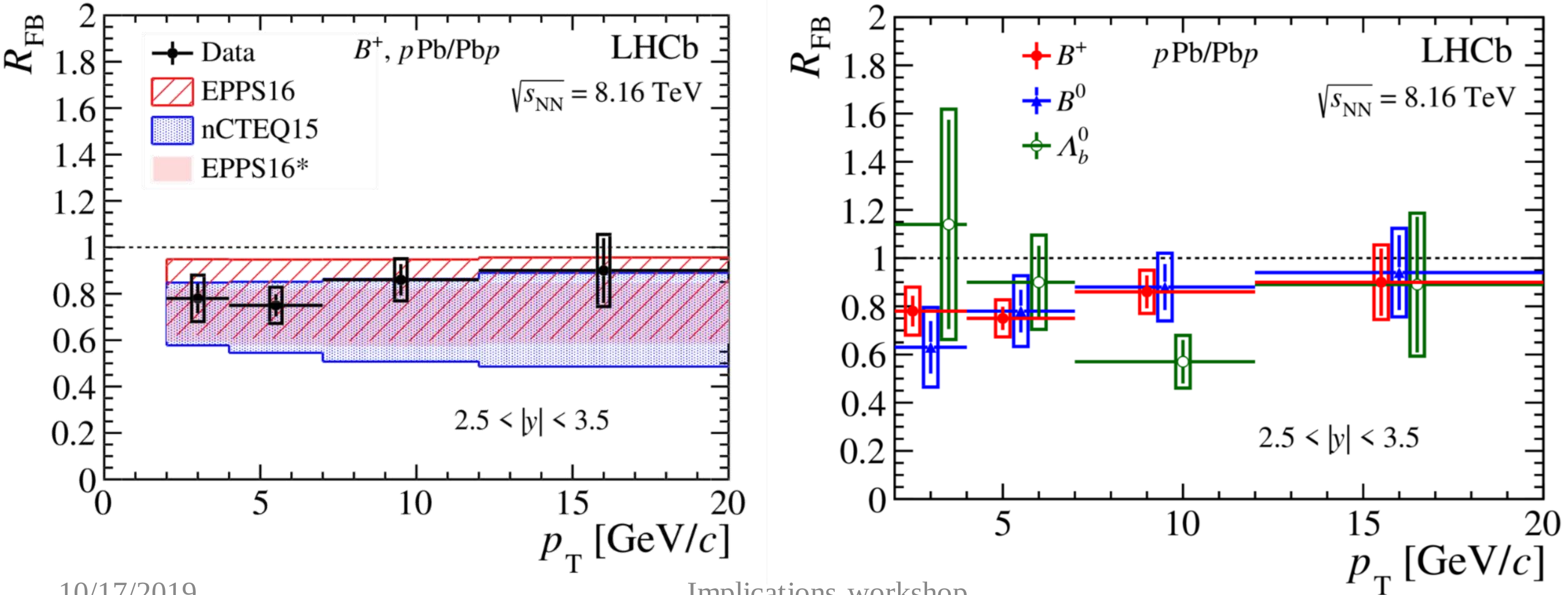
- Sensitive to charm hadronisation mechanisms
- Model based on measured *pp* cross-section
- nPDF effects mostly cancel
  - EPS09LO & EPS09NLO similar
  - nCTEQ15 slightly lower.
- Slight increase with increasing p_T

- 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

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

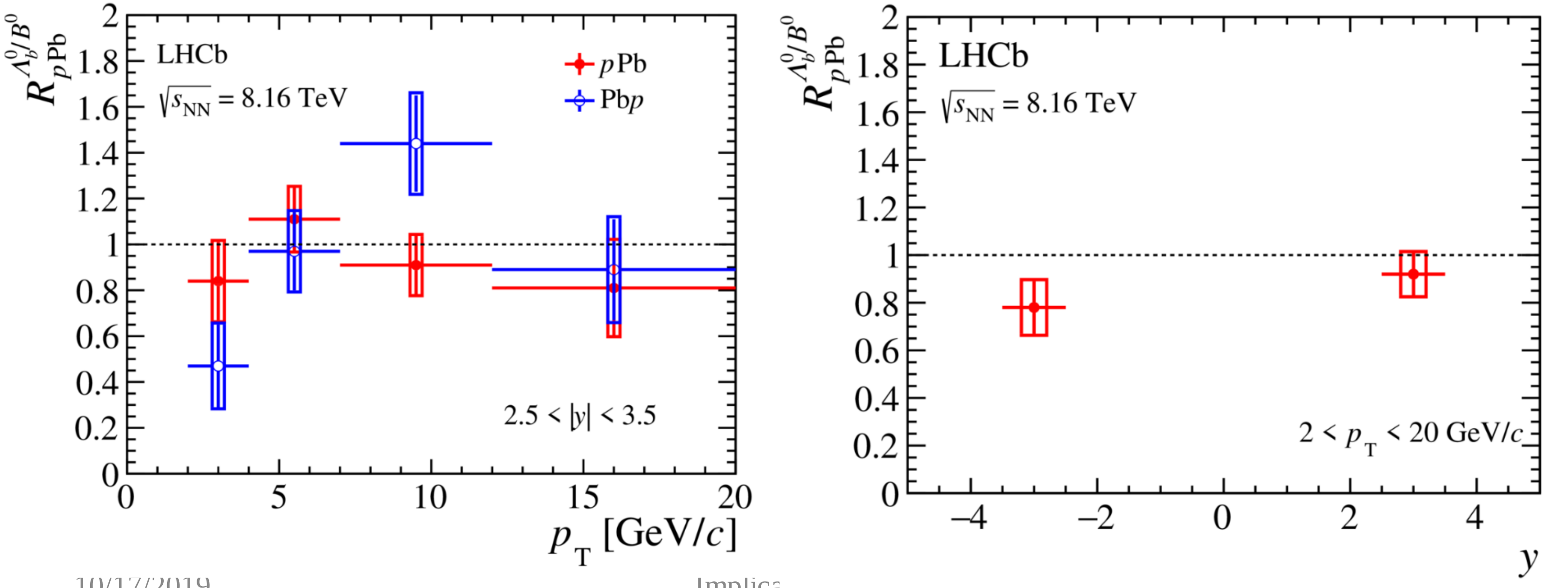
$$R_{\mathrm{FB}} = \frac{\sigma(+|y^*|, p_{\mathrm{T}})}{\sigma(-|y^*|, p_{\mathrm{T}})}$$



PRD99 052011 (2019)

b-hadron production in 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

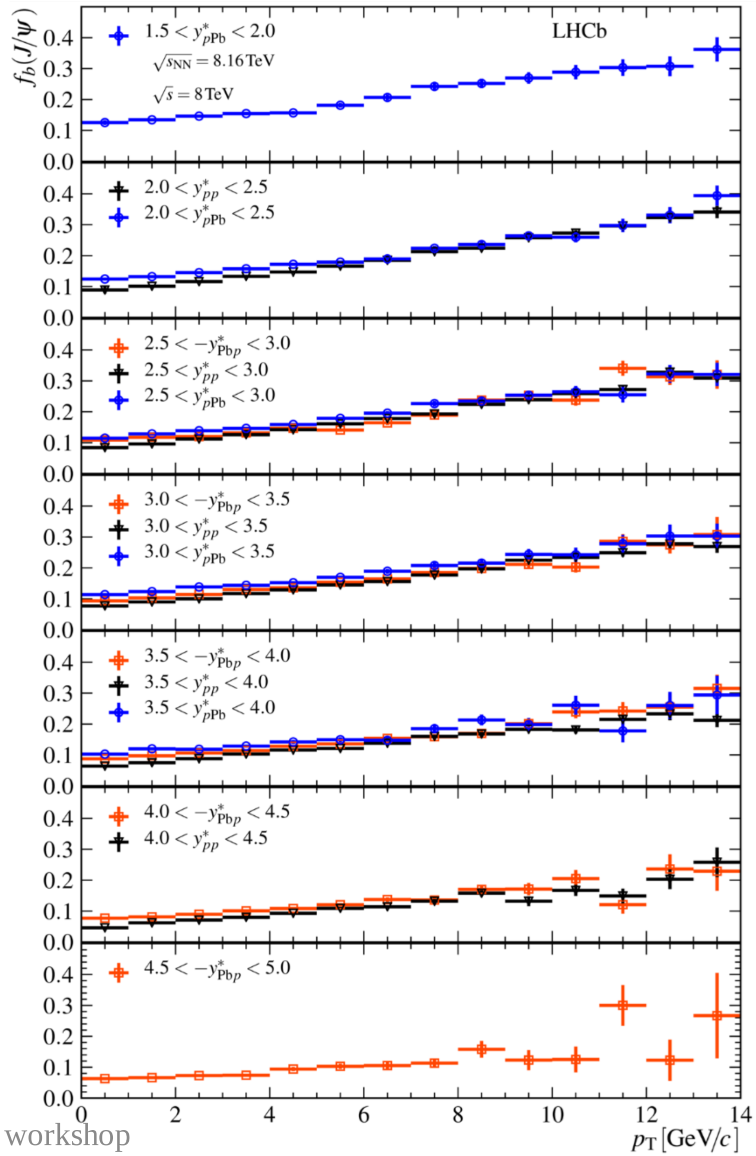
PLB 774 (2017) 159

- Separation of prompt and nonprompt J/ψ with p_{T} down to 0

- Fraction from b hadrons:

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

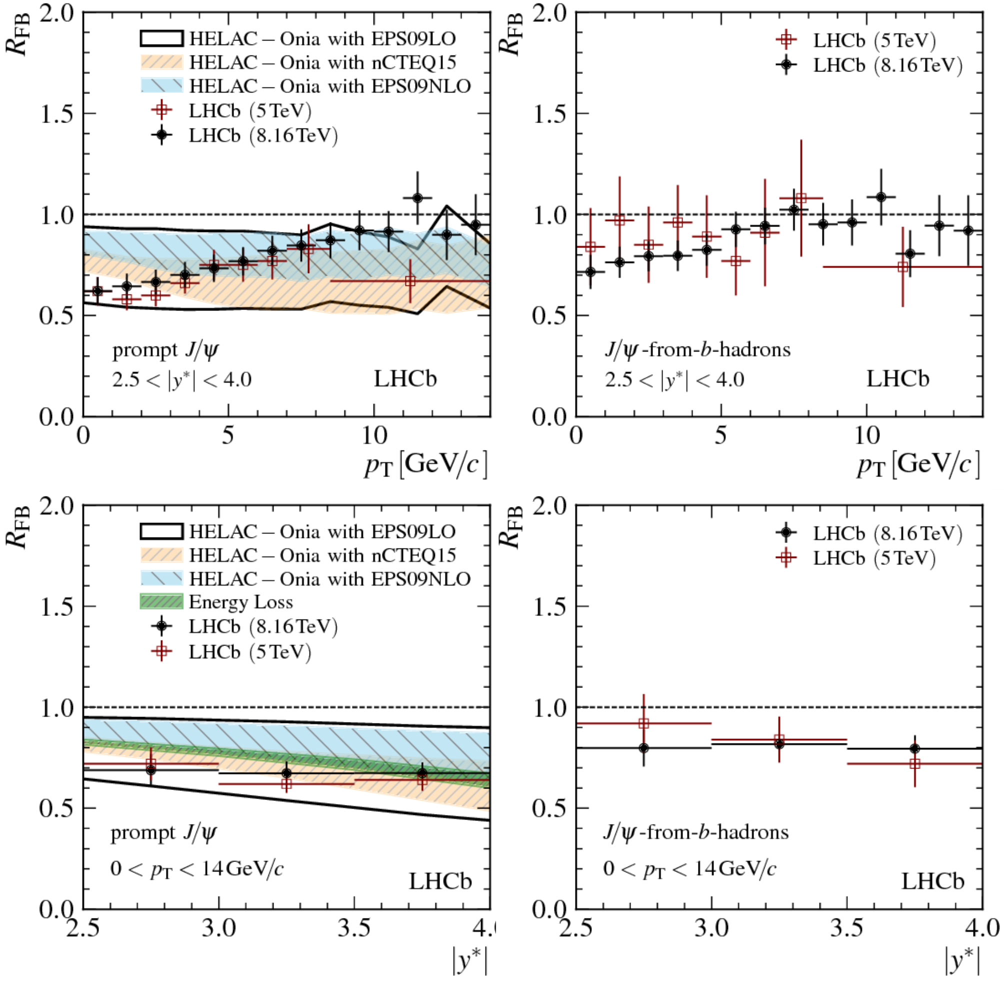
- *pp*, forward, backward compared:
  - similar trends
  - Increasing with p_{T}
  - Small differences at low p_{T}: cold nuclear matter effects different for the prompt and nonprompt



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

PLB 774 (2017) 159

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

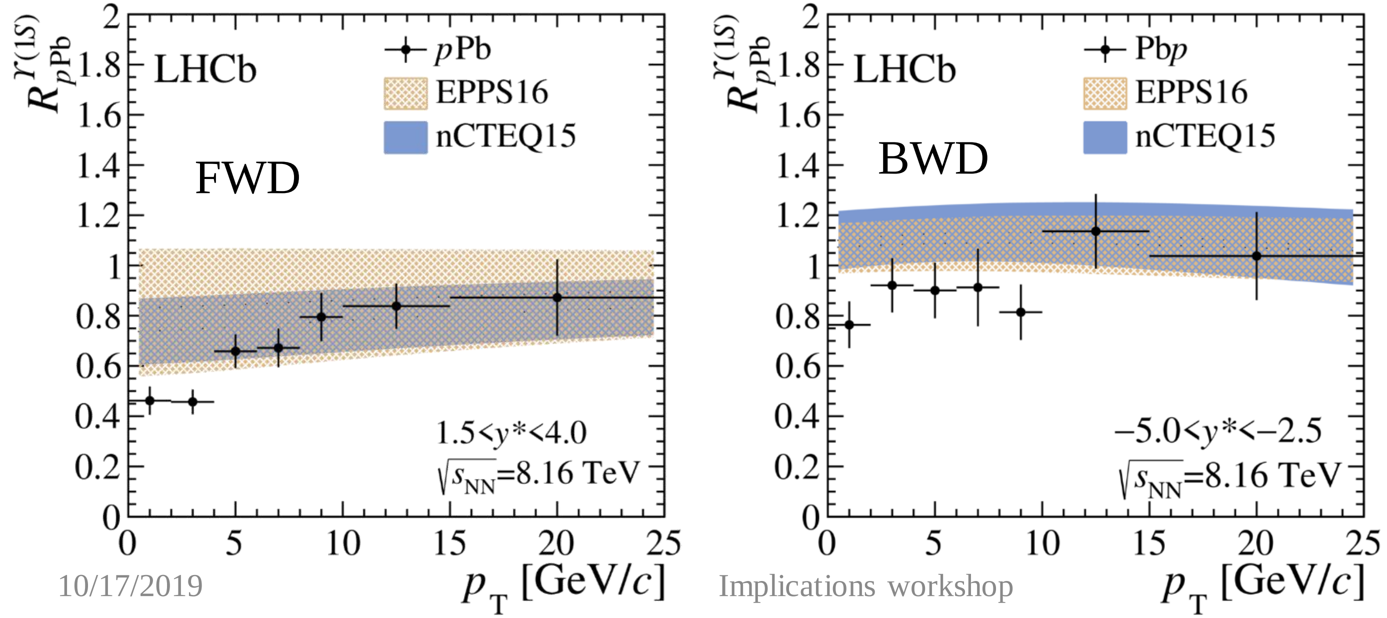


$\Upsilon(1S)$ nuclear modification factor

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



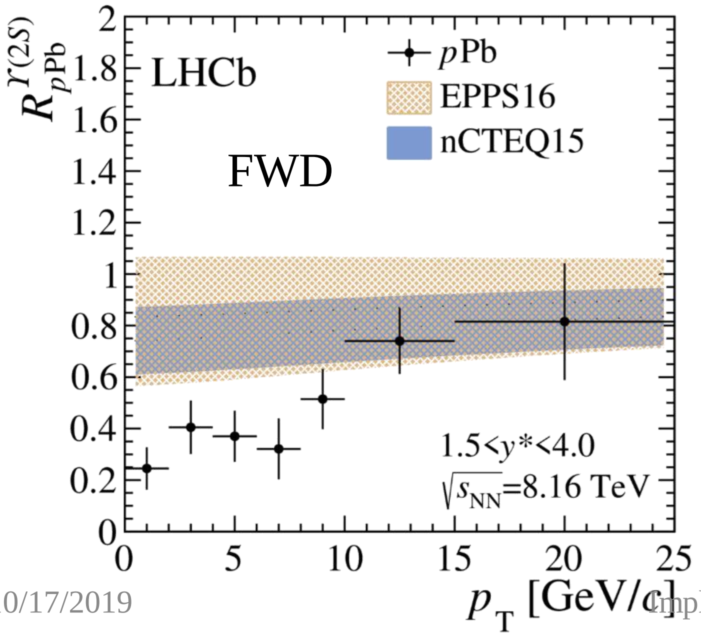
$\Upsilon(1S)$

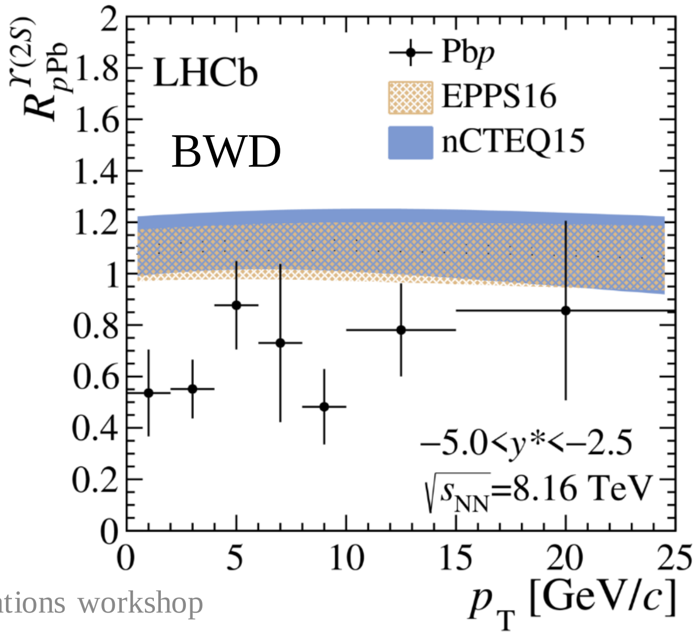
$\Upsilon(2S)$ nuclear modification factor

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



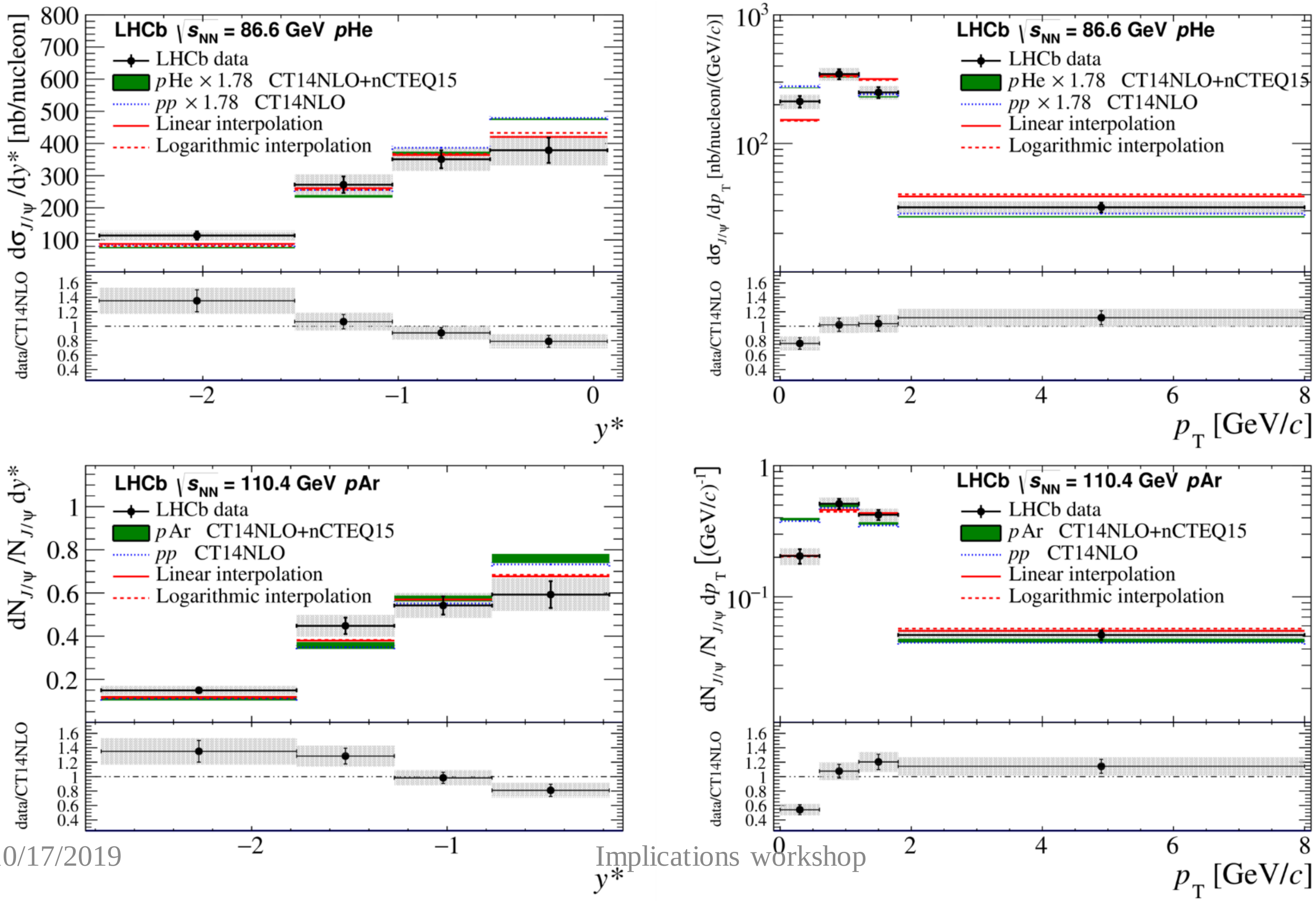


$\Upsilon(2S)$

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