Heavy quarkonium in *p*Pb collisions and fixed-target results at LHCb

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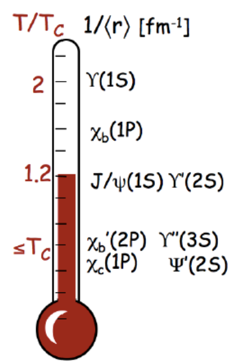
The 2nd FCPPL quarkonium production workshop

Outline

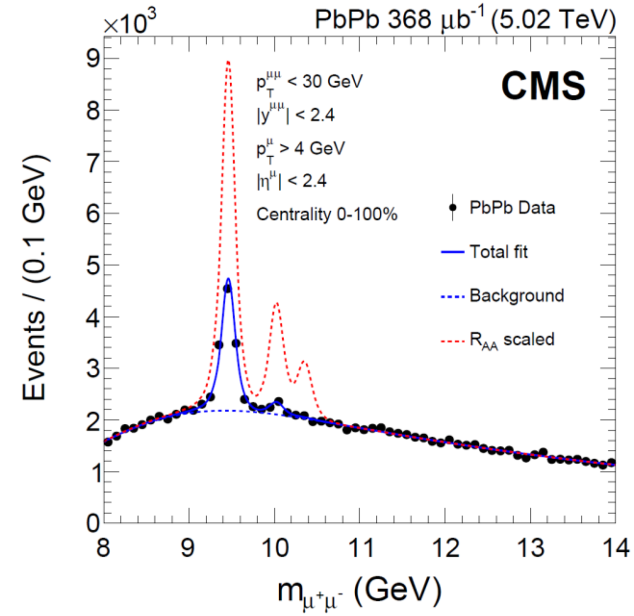
- Quarkonium in pPb
  - J/ψ
  - Upsilon $\Upsilon(nS)$
- Fixed target results
  - Charm production cross-section
  - Antiproton production cross-section

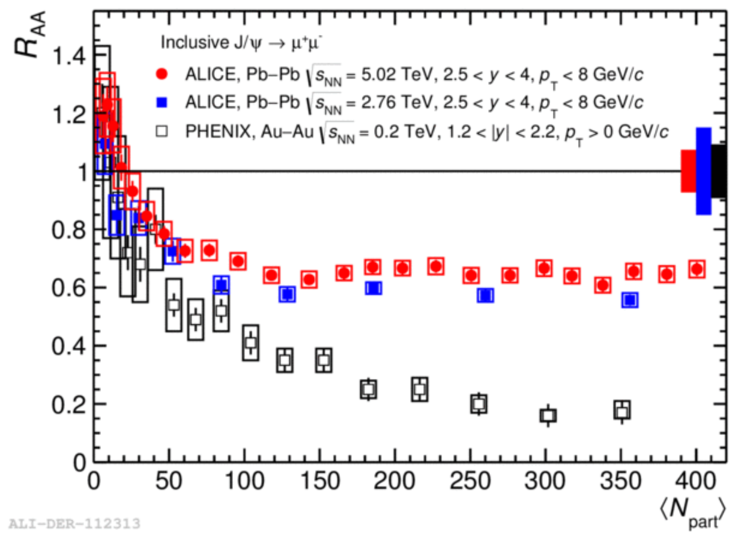
Quarkonia in PbPb Collisions

- Color screening: $Q\bar{Q}$ potential is screened by surrounding color charge, leading to dissociation
    - J/ψ suppression a signature of deconfinement
- Sequential melting: quarkonia states (e.g. Υ family) dissociate at different temperatures
    - QGP thermometer



- Hot medium effects:
    - Suppression by color screening
    - Regeneration via statistical recombination
    - Medium induced energy loss
- Cold nuclear matter (CNM) effects
    - Studied via proton-nucleus collisions
    - Crucial for the interpretation of AA results



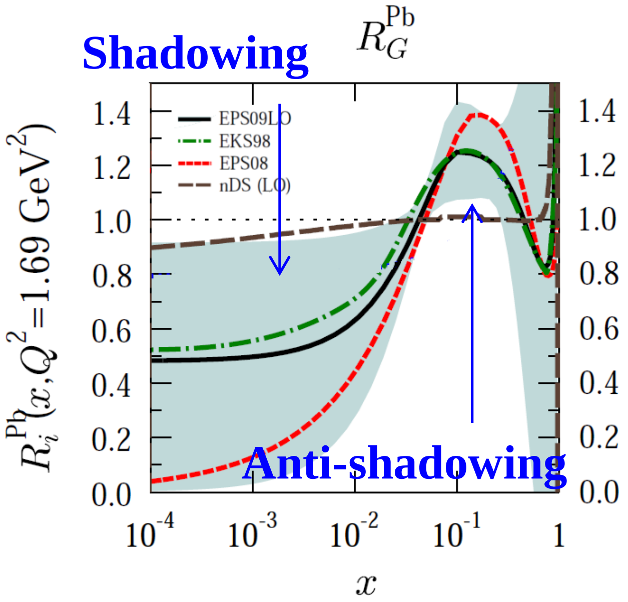


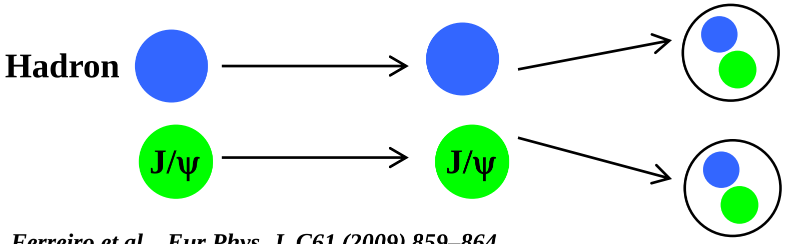
CMS PLB 790 (2019) 270
ALICE PLB766(2017) 212

Quarkonia in pPb Collisions

Ferreiro et al., PRC 81(2010) 064911
Eskola et al., Eur.Phys.J. C9 (1999) 61-68
Eskola. et al., JHEP 0807 (2008) 102
Eskola et al., JHEP 0904 (2009) 065
De Florian et al., PRD69 (2004) 074028

- Cold Nuclear Matter effects
  - Initial state:
    - Modification of nuclear PDF
    - Gluon saturation
  - Multiple scattering of partons in the nucleus
  - Final state:
    - nuclear absorption (negligible at LHC energy)
    - Co-movers effect
      - Break-up of quarkonium by co-moving hadrons outside of nuclear remnant
      - study via $\psi(2S)$, $\Upsilon(nS)$
      -



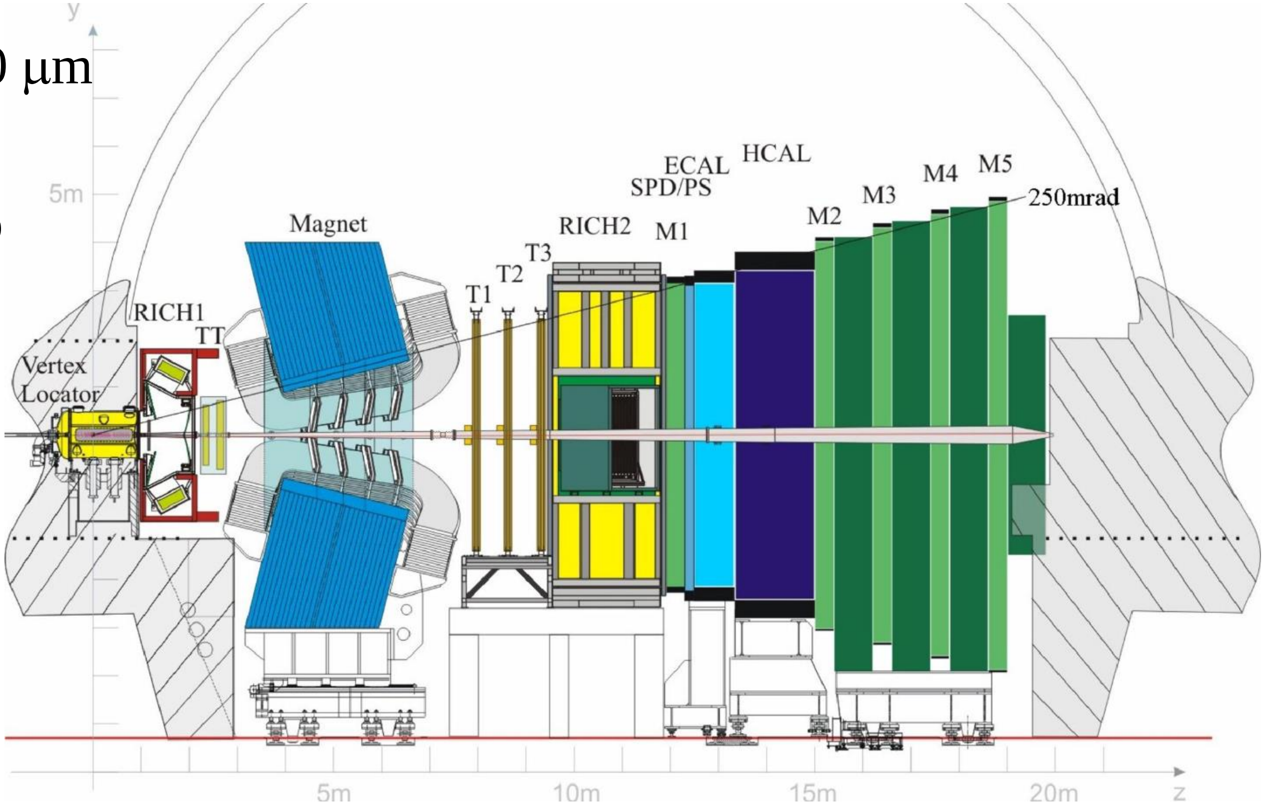


Ferreiro et al., Eur.Phys. J. C61 (2009) 859–864
Ferreiro et al., PLB680 (2009) 50–55
Ferreiro, et al., PRC81 (2010) 064911

Co-mover effect

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

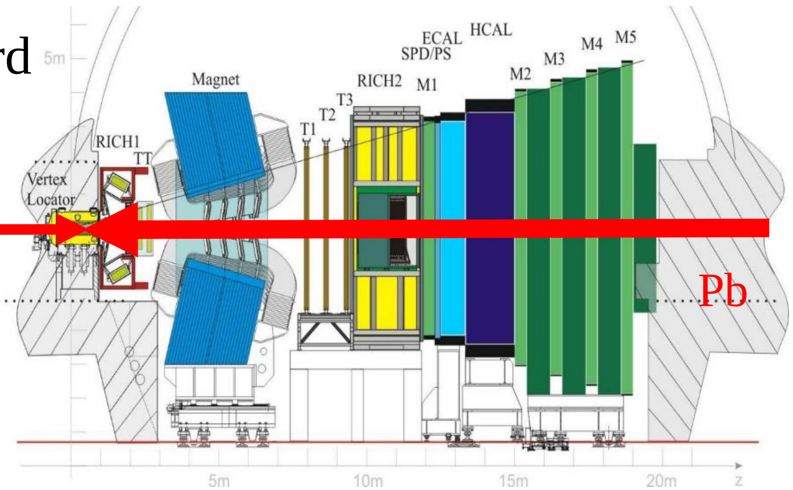


JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

pPb @ 8TeV dataset

Forward

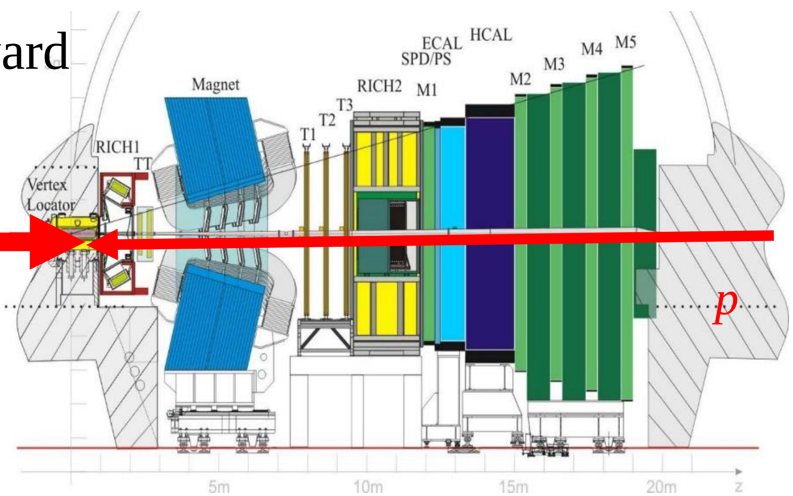
pPb



p Pb

Backward

Pbp



Pb p

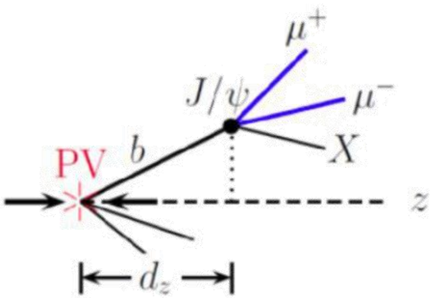
- Rapidity Coverage
  - y^*: rapidity in nucleon-nucleon cms
  - $y_{\text{cms}} = \pm 0.465$
  - Forward: $1.5 < y^* < 4.0$
  - Backward: $-5.0 < y^* < -2.5$
  - Common region: $2.5 < |y^*| < 4.0$

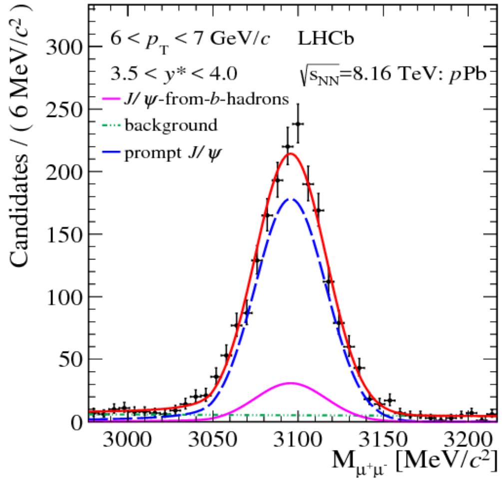
- $\sqrt{s_{NN}} = 8$ TeV (2016)
  - pPb (13.6 nb^{-1}) + Pbp (21.8 nb^{-1})

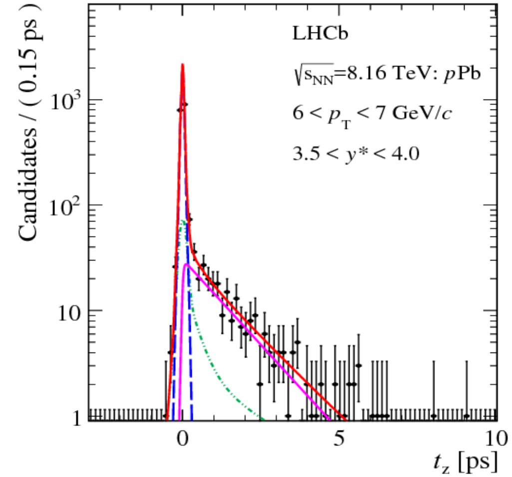
Prompt and nonprompt J/ψ in pPb at 8 TeV

PLB 774 (2017) 159

- Sources
  - Prompt: direct production, feed down from heavier states $\psi(2S)$, χ_c
  - Nonprompt: from-b-hadrons decays







- First Run2 result in heavy ion collisions
- Reconstructed through $J/\psi \rightarrow \mu^+\mu^-$
- Prompt and nonprompt (from-b-hadrons) separated: the pseudo proper decay time

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

- Signal extraction with 2D simultaneous fit to mass and the pseudo proper decay time

Prompt and nonprompt J/ψ in pPb at 8 TeV

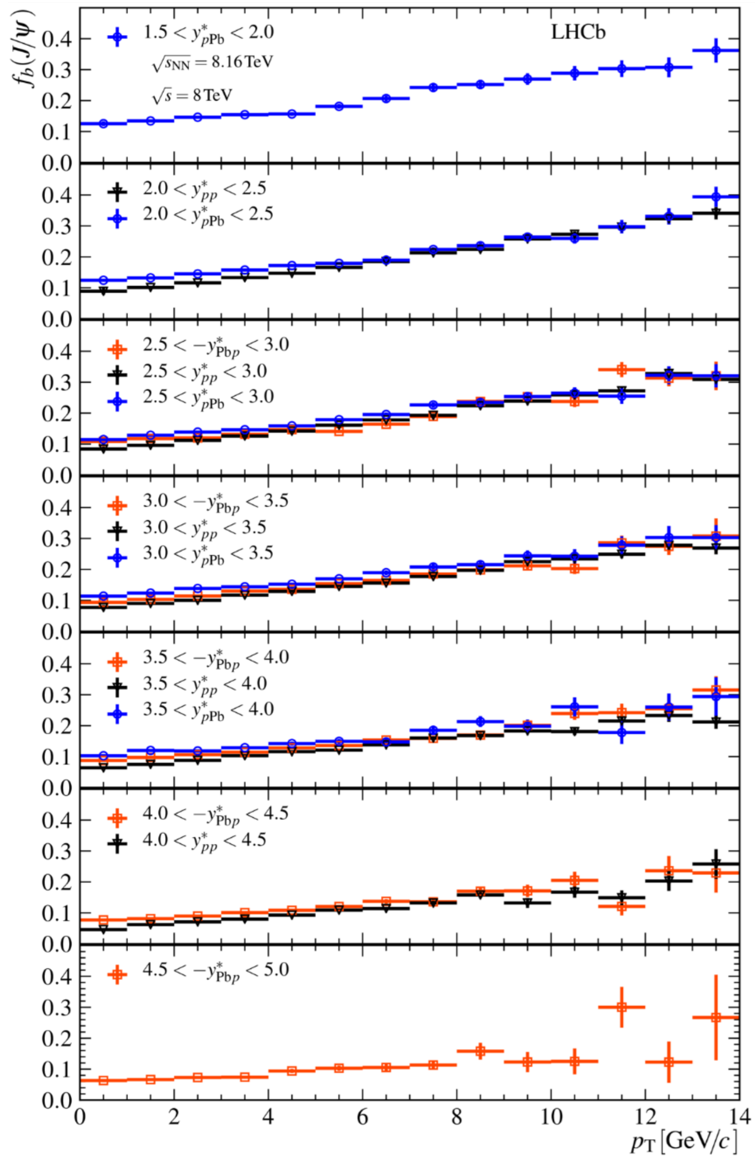
PLB 774 (2017) 159

- 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

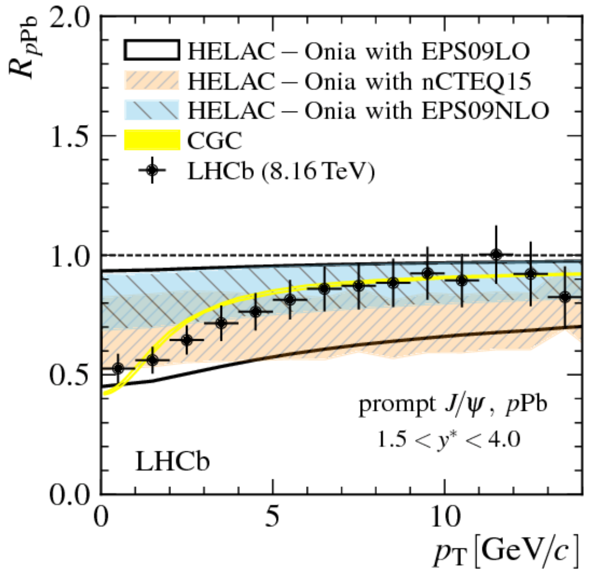


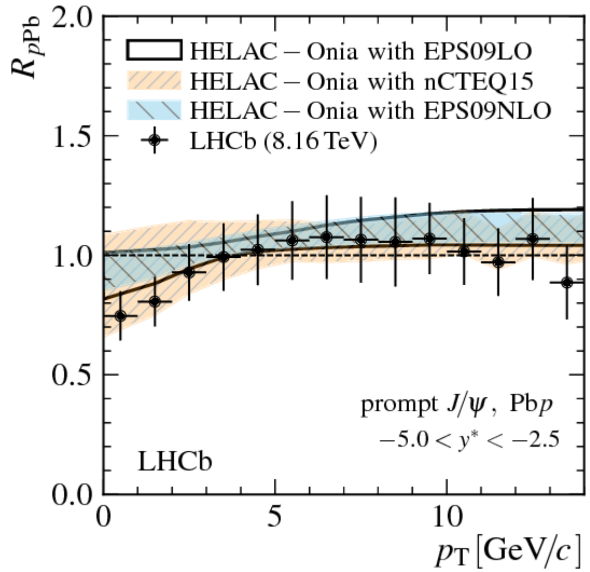
Prompt J/ψ at 8 TeV nuclear modification factor in pPb

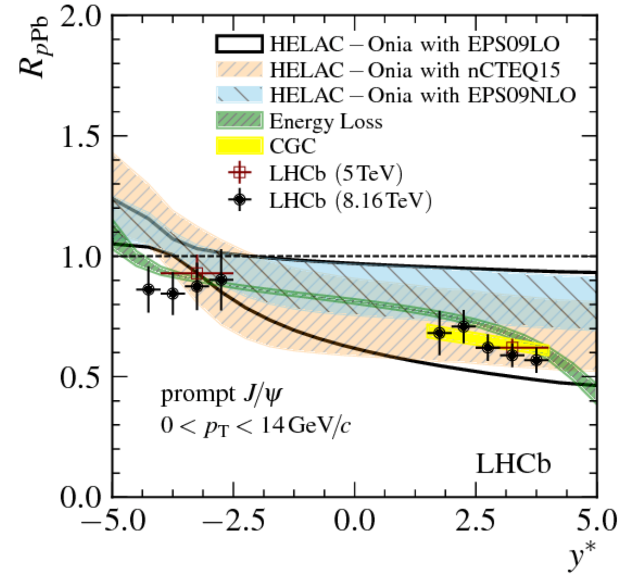
PLB 774 (2017) 159

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

- ***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
- Compatible with 5 TeV results







J/ψ-from-b-hadrons at 8 TeV nuclear modification factor in pPb

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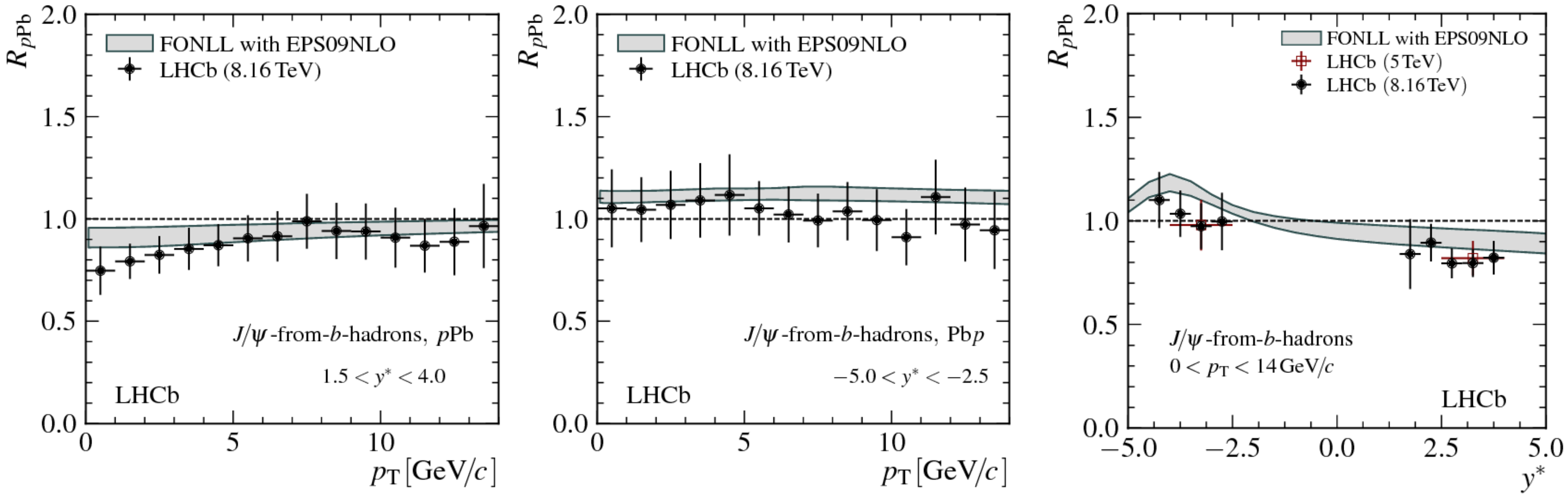
$$R_{p\mathrm{Pb}}(y^*, p_T) = \frac{1}{A} \times \frac{\mathrm{d}\sigma_{p\mathrm{Pb}}(y^*, p_\mathrm{T}, \sqrt{s_{NN}})/\mathrm{d}x}{\mathrm{d}\sigma_{pp}(y^*, p_\mathrm{T}, \sqrt{s_{NN}})/\mathrm{d}x},\ A{=}208$$

- ***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 TeV results

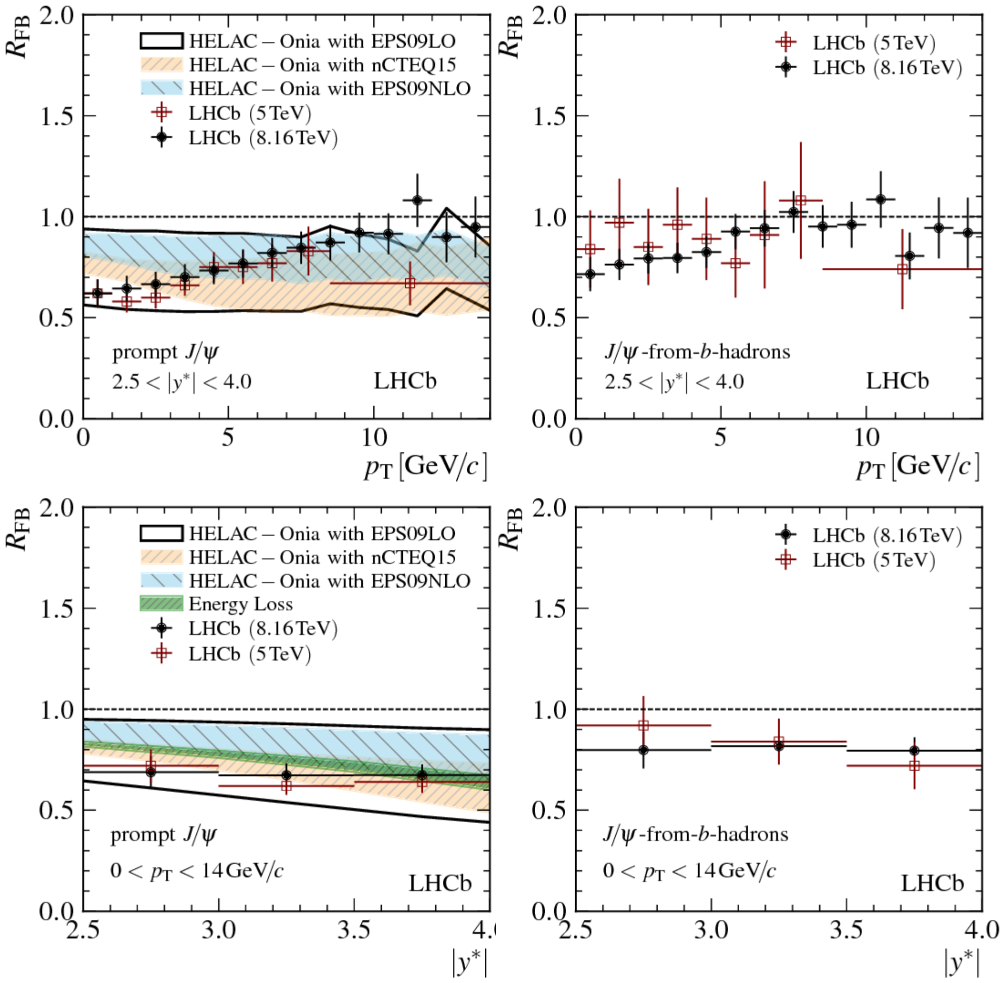
EPS09 JHEP 04 (2009) 065



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

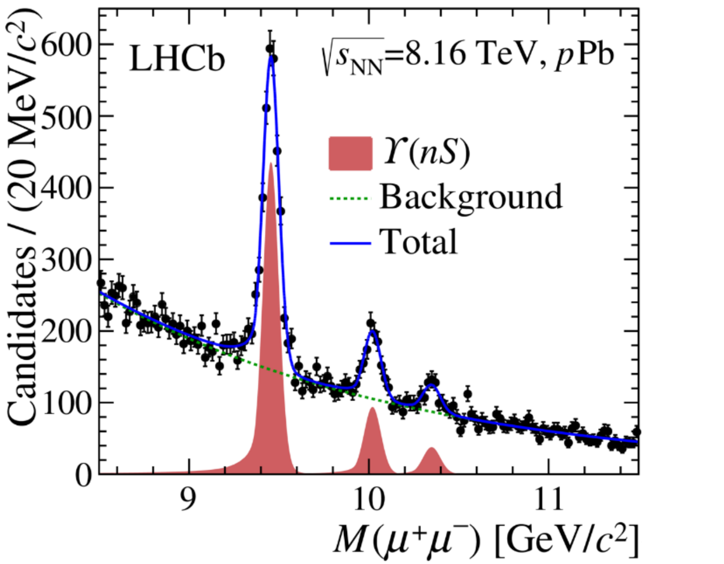


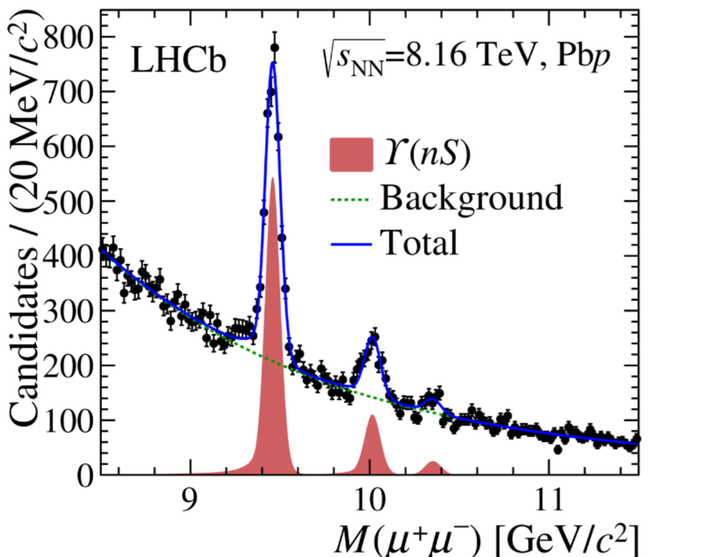
$\Upsilon(nS)$ in pPb collisions

JHEP 11 (2018) 194

- New differential analysis of 2016 pPb data
  - Double differential for $\Upsilon(1S)$
  - Single differential for $\Upsilon(2S)$
- Cross-section, $R_{p\mathrm{Pb}}$, double ratio of $\Upsilon(nS)/\Upsilon(1S)$ for all $\Upsilon(nS)$ states
- 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	$19.3\,\mathrm{nb}^{-1}$





$\Upsilon(nS)$ cross-section

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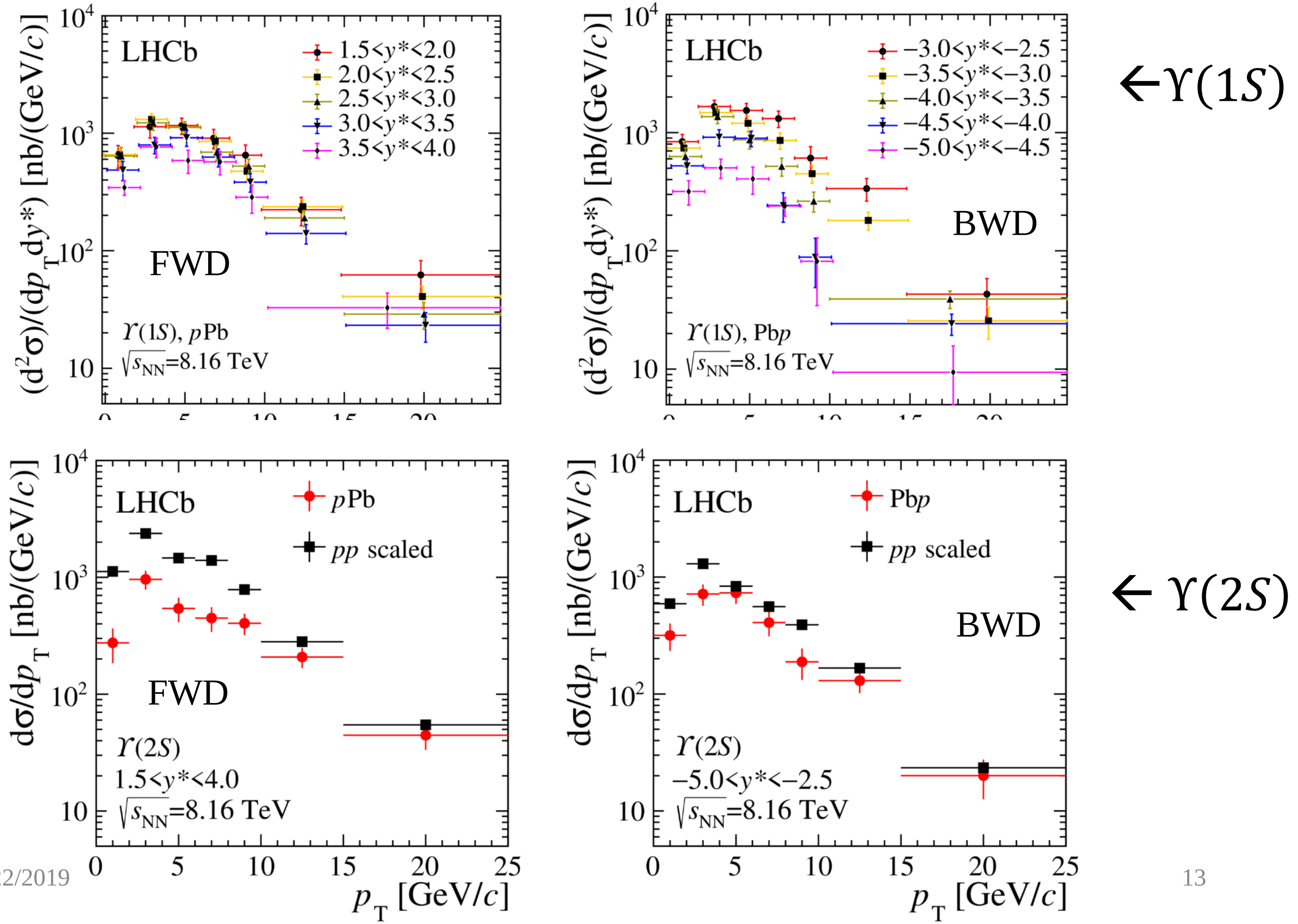

$\Upsilon(1S)$ nuclear modification factor

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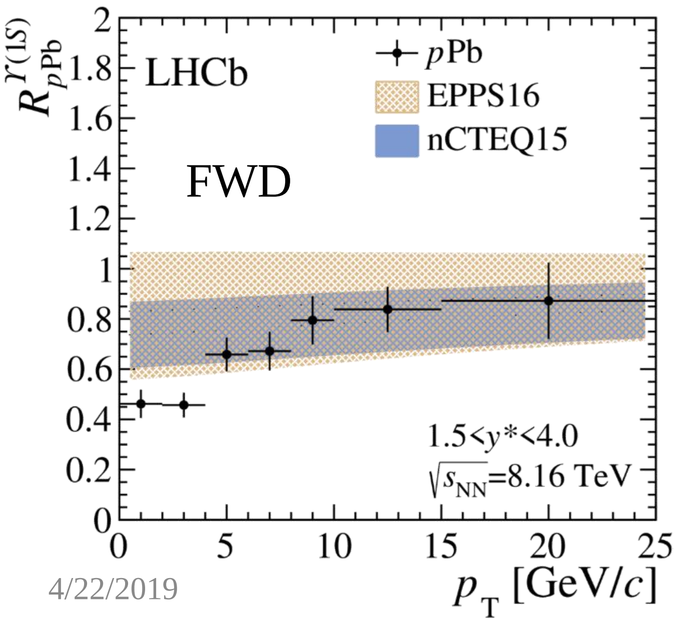
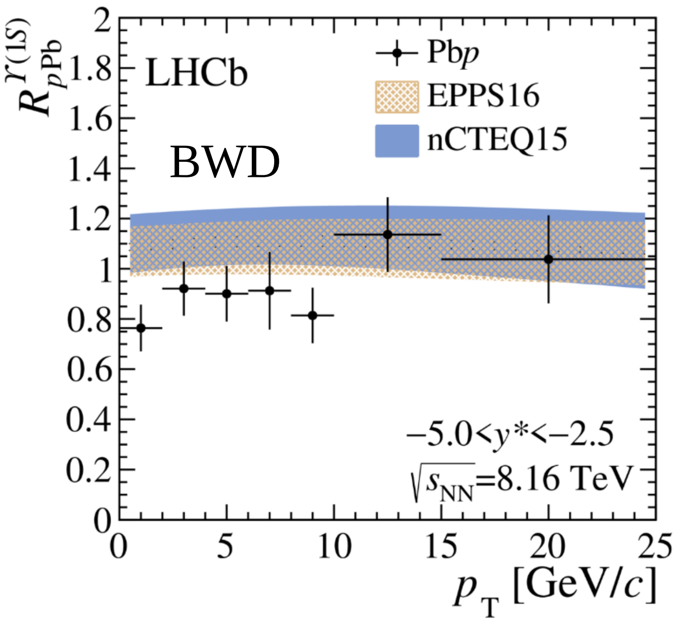
$$R_{p\mathrm{Pb}}(y^*, p_T) = \frac{1}{A} \times \frac{\mathrm{d}\sigma_{p\mathrm{Pb}}(y^*, p_\mathrm{T}, \sqrt{s_{NN}})/\mathrm{d}x}{\mathrm{d}\sigma_{pp}(y^*, p_\mathrm{T}, \sqrt{s_{NN}})/\mathrm{d}x}, \quad A{=}208$$

***pp* reference**: interpolation of LHCb measurements at 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

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

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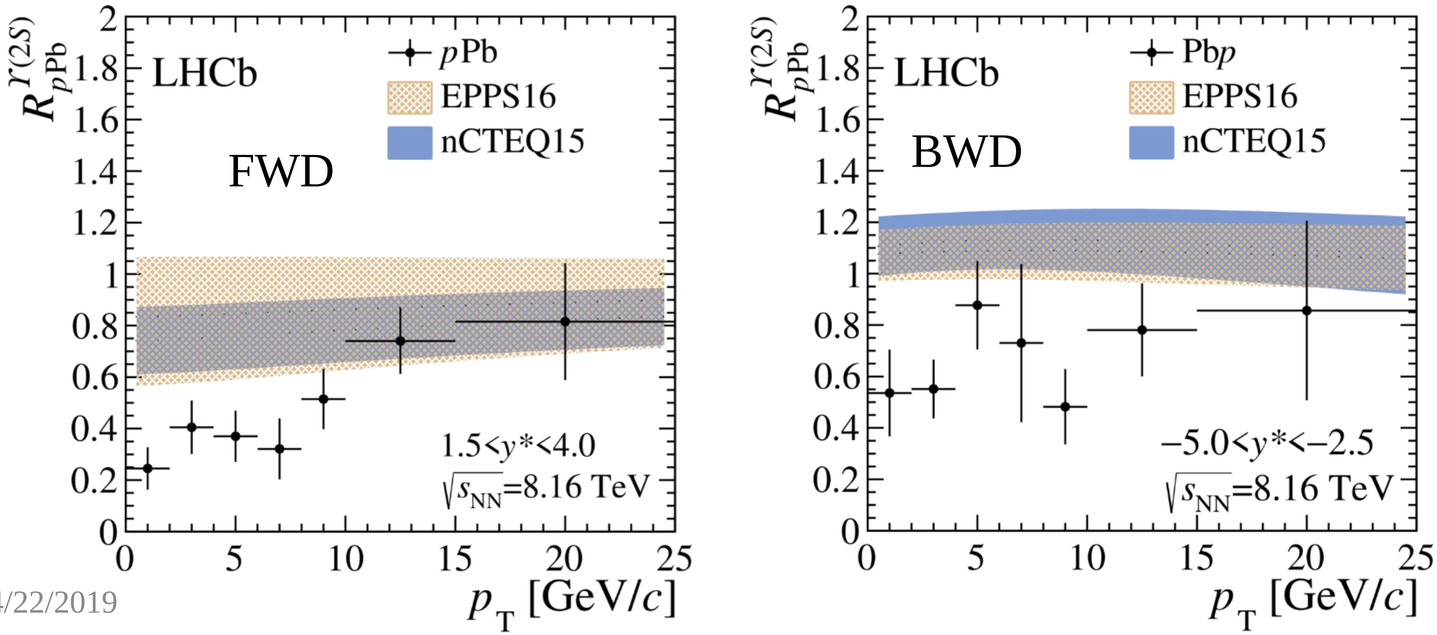

$\Upsilon(2S)$

$\Upsilon(nS)$ nuclear modification factor

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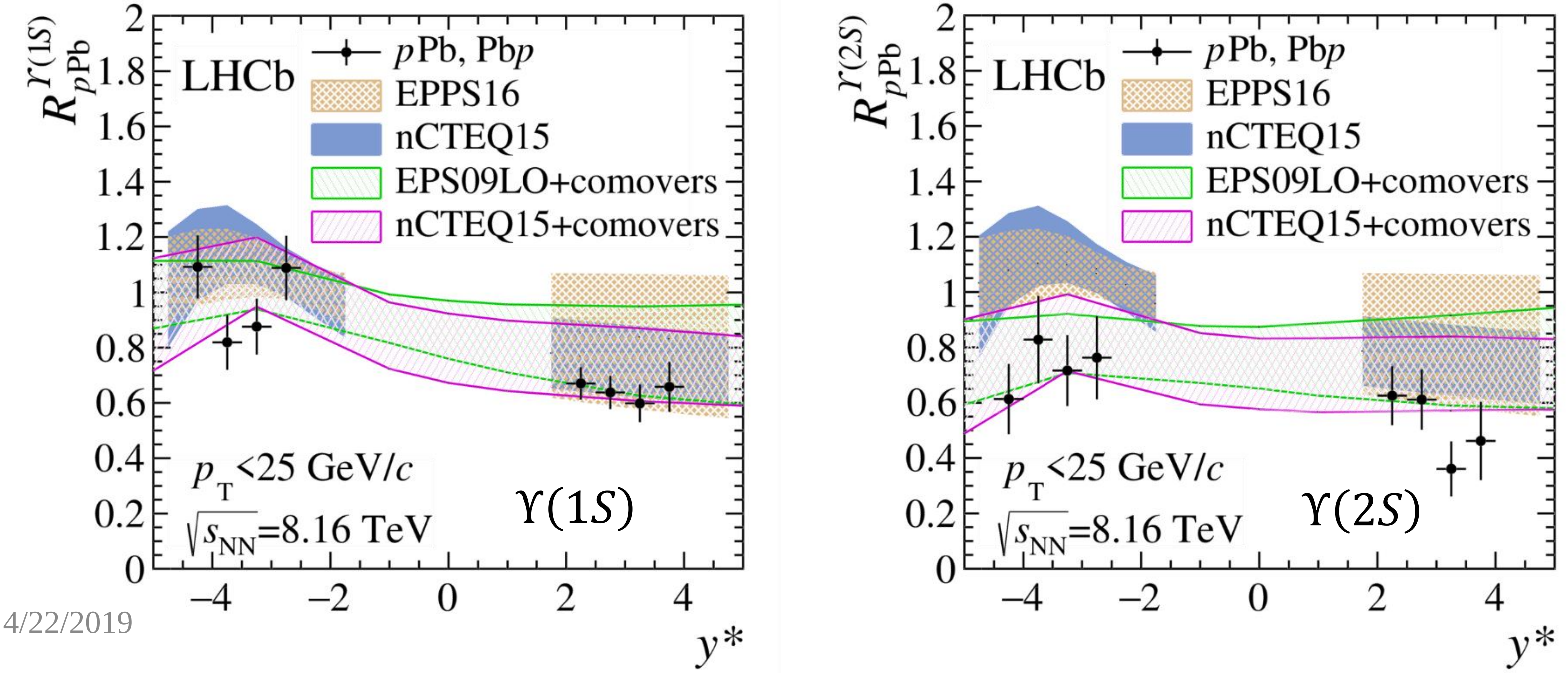
$$R_{p\mathrm{Pb}}(y^*, p_T) = \frac{1}{A} \times \frac{\mathrm{d}\sigma_{p\mathrm{Pb}}(y^*, p_\mathrm{T}, \sqrt{s_{NN}})/\mathrm{d}x}{\mathrm{d}\sigma_{pp}(y^*, p_\mathrm{T}, \sqrt{s_{NN}})/\mathrm{d}x}, \ A{=}208$$

***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



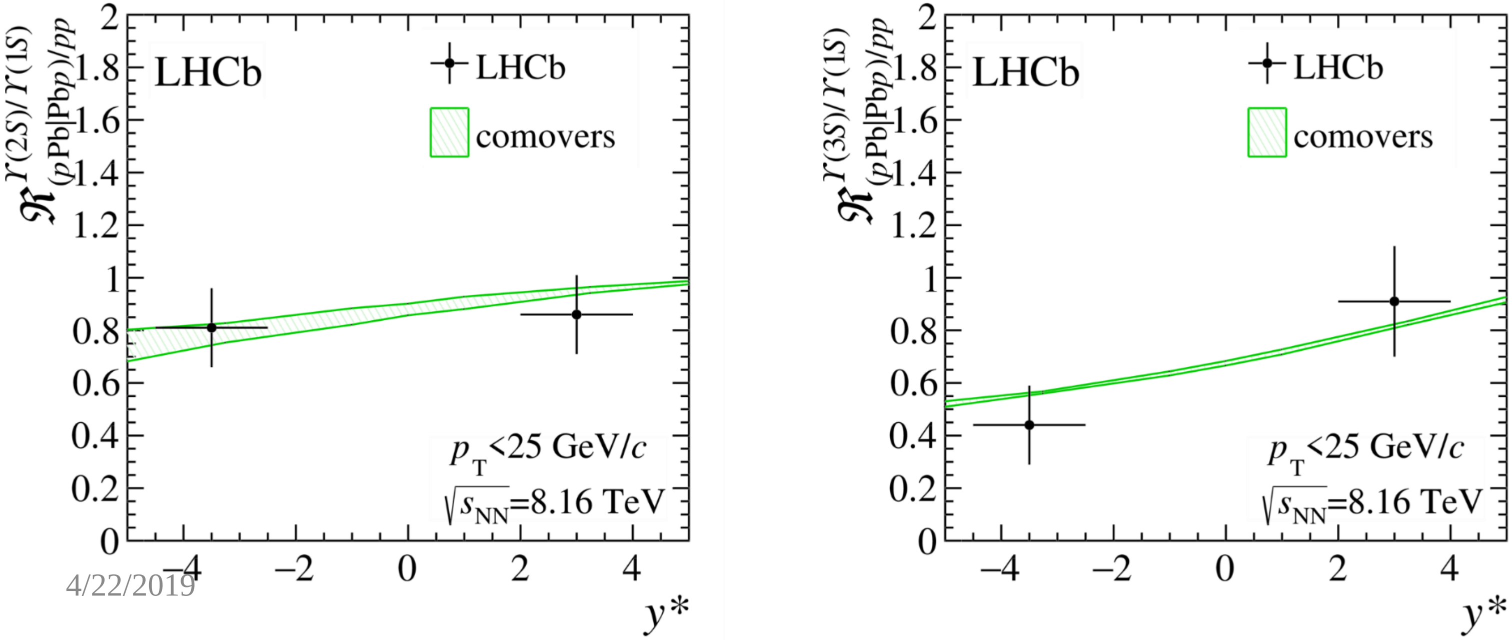
Double ratio

JHEP 11 (2018) 194

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

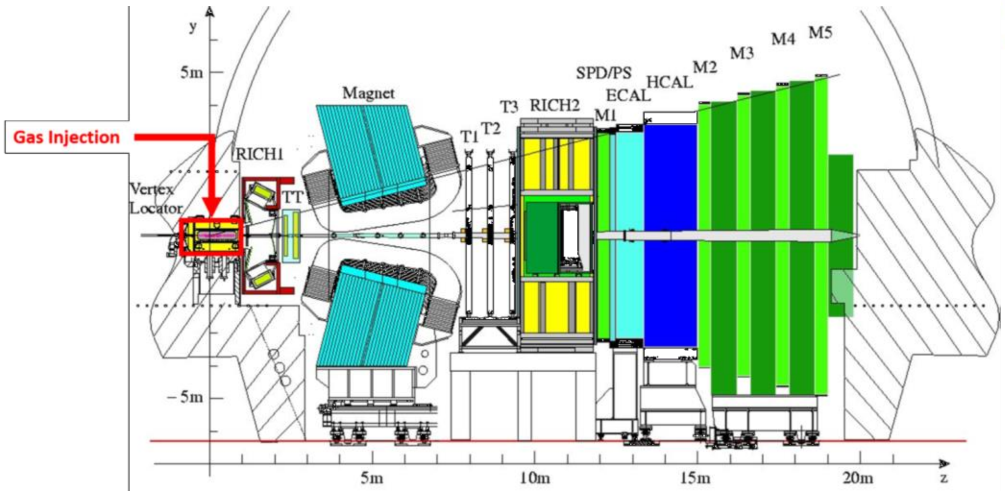
$$R(\Upsilon(nS)) = \frac{[\mathrm{d}^2\sigma/\mathrm{d}p_\mathrm{T}dy^*]\,(\Upsilon(nS))}{[\mathrm{d}^2\sigma/\mathrm{d}p_\mathrm{T}dy^*]\,(\Upsilon(1S))}.$$

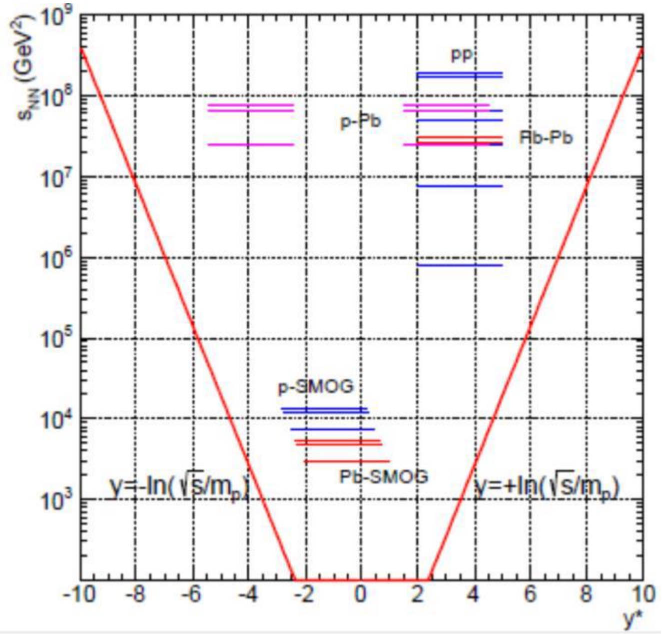
- Double ratio of $\Upsilon(nS)/\Upsilon(1S)$ in *p*Pb and *pp*
- Sequential suppression also observed in *p*Pb
- Suggests final state effects…
- Agrees with predictions of "comovers" model



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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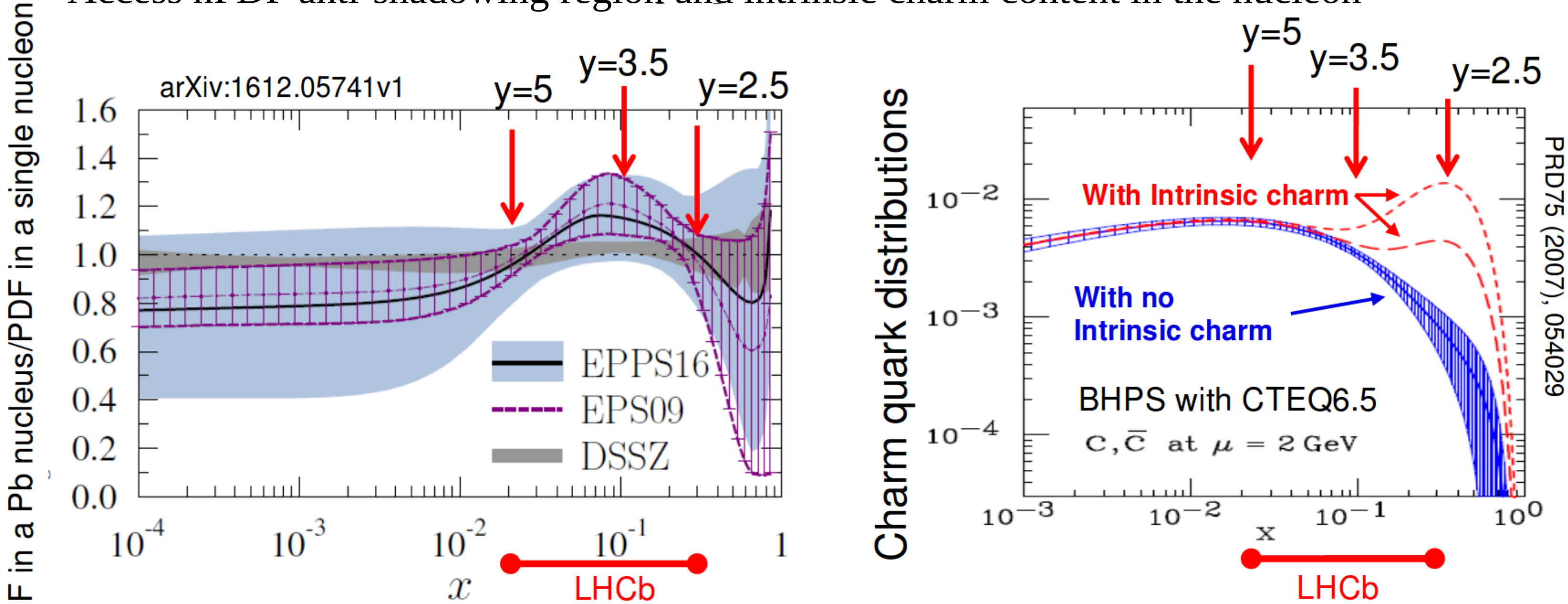
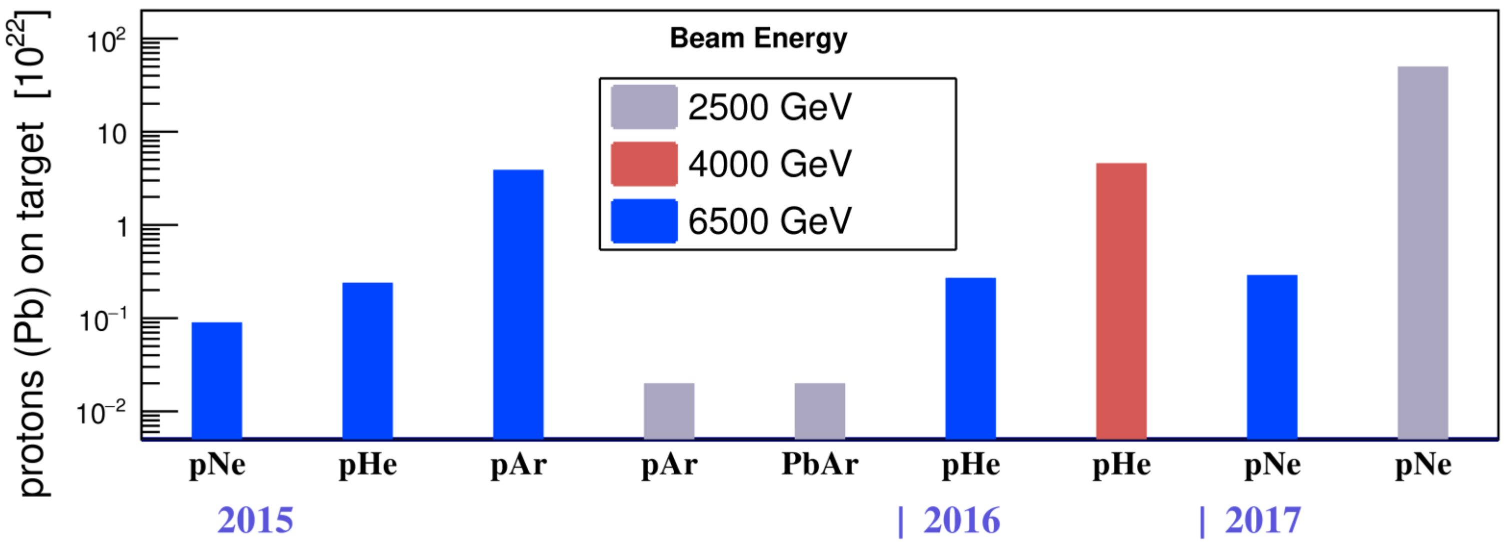


Bjorken-x = fraction of the nucleon momentum carried by a parton

Data samples:

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

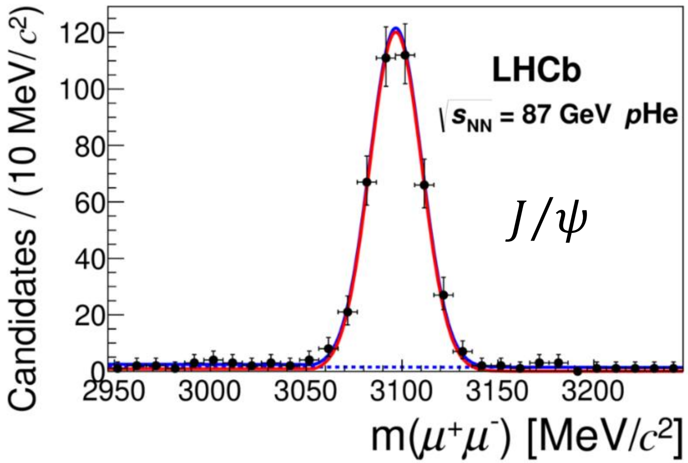
- pNe at $\sqrt{s_{NN}}$ =110GeV (2016)
  - $\mathcal{L}_{p\mathrm{Ne}} \sim 0.5\mathrm{nb}^{-1}$

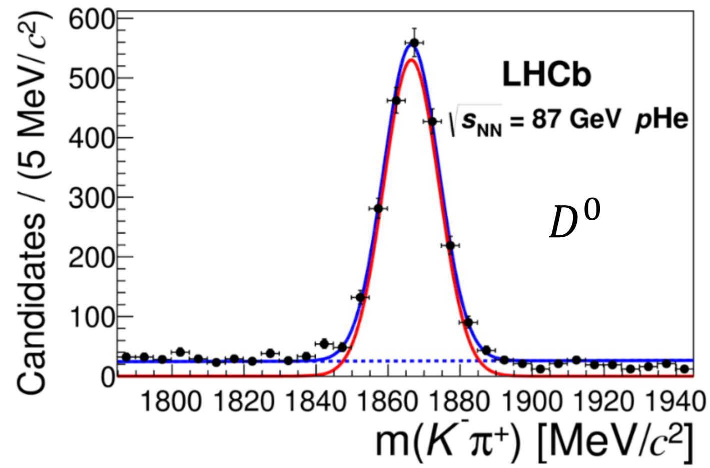


Charm production in fixed-target pN collision

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

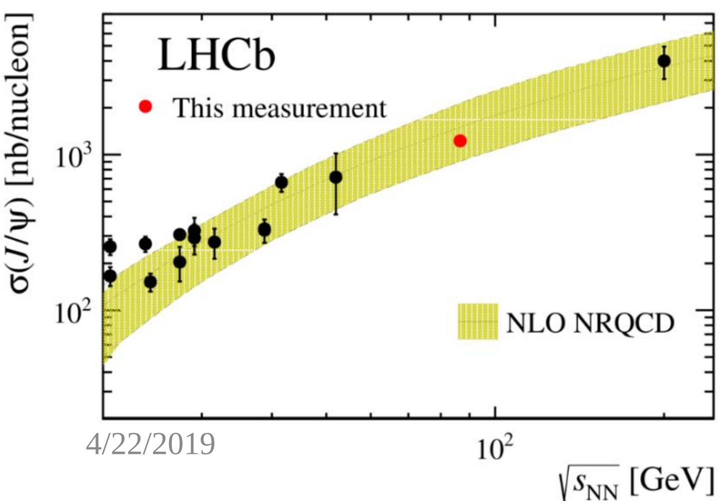


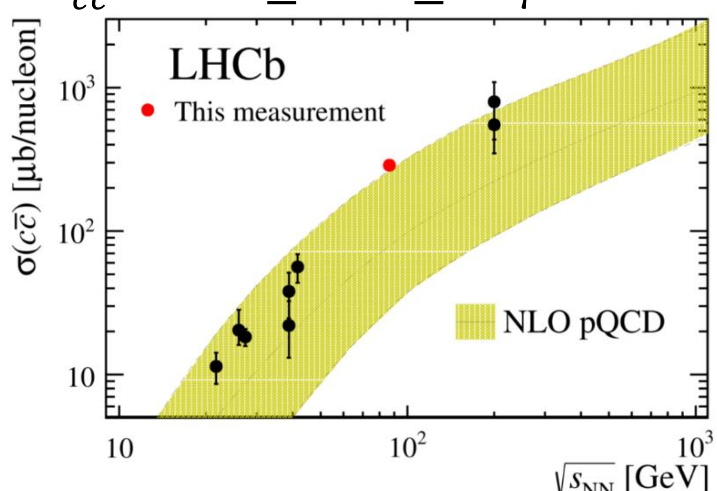


$\sigma_{J/\psi} = 1225.6 \pm 100.7$ nb/nucleon

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

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

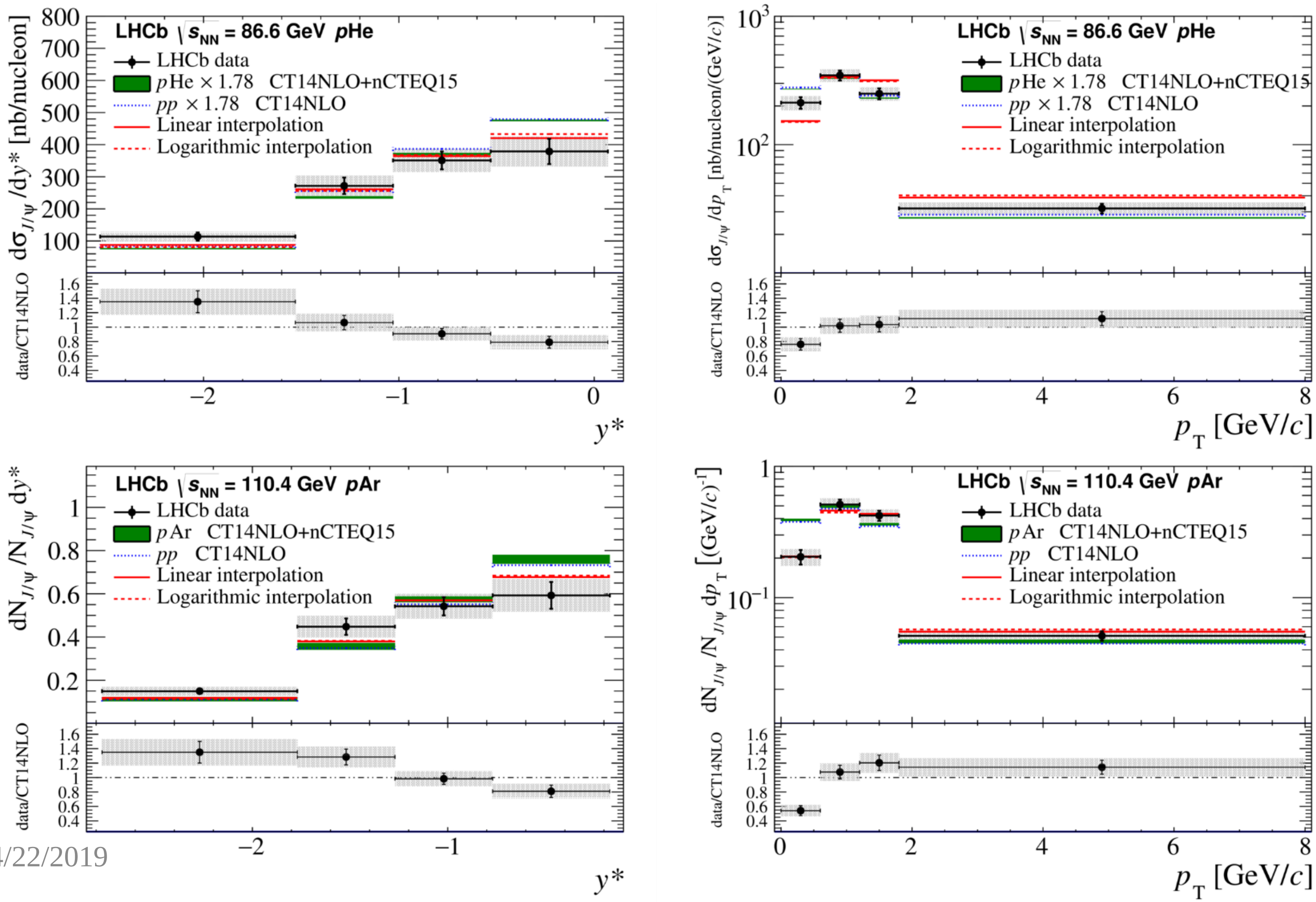




J/ψ production in fixed-target pN collision

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



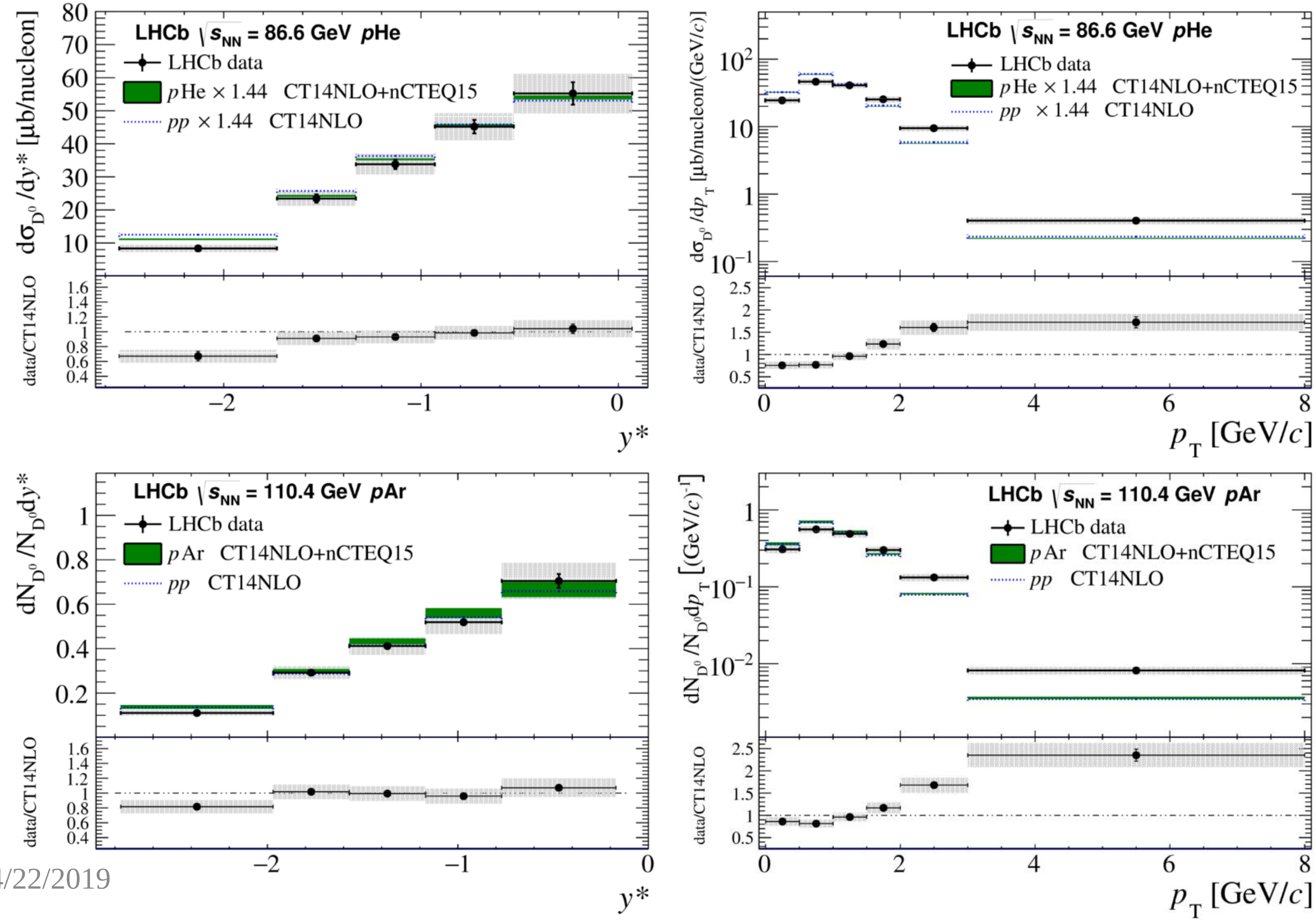
pNe
@ 86.6GeV

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



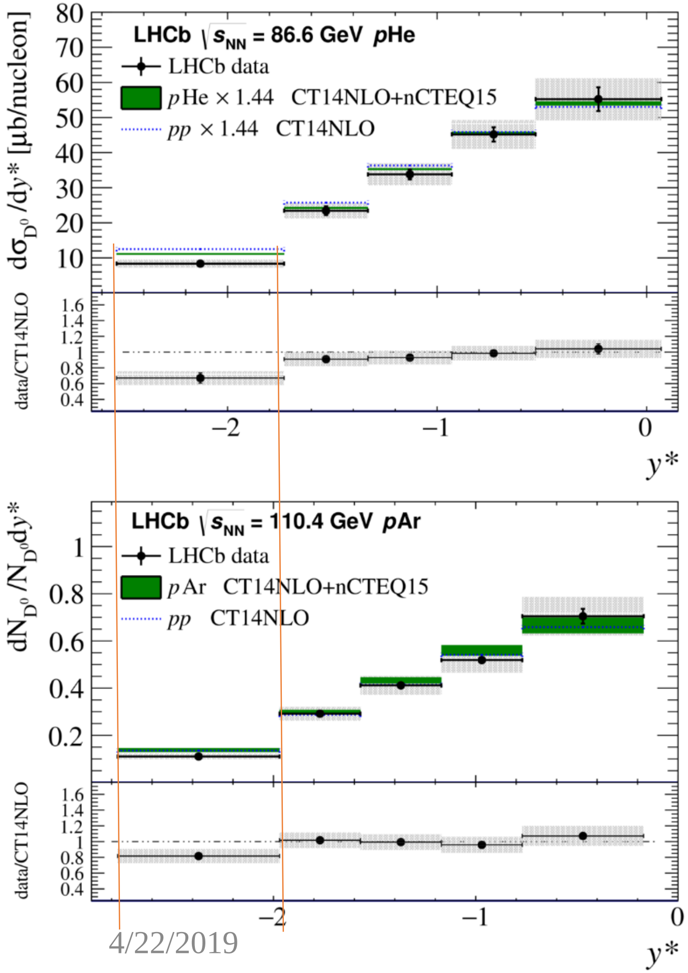
pNe
@ 86.6GeV

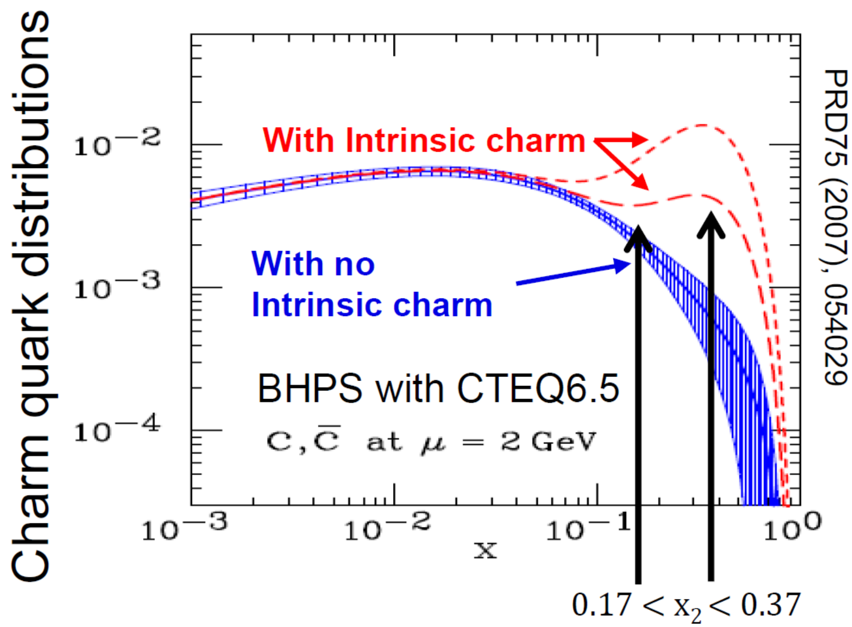
pAr
@ 110.4GeV

Charm production in fixed-target pN collision

Phys. Rev. Lett. 122 (2019) 132002

- $-2.53<y^*<-1.73 \rightarrow 0.17<x<0.37$
- Little evidence of intrinsic charm observed



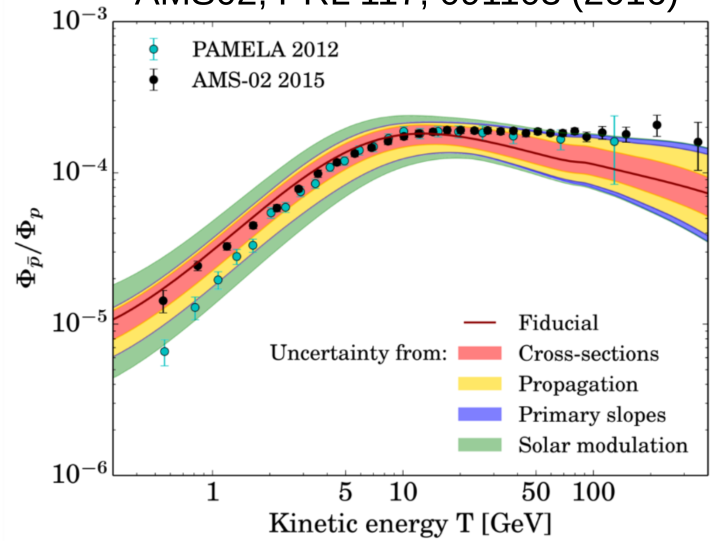


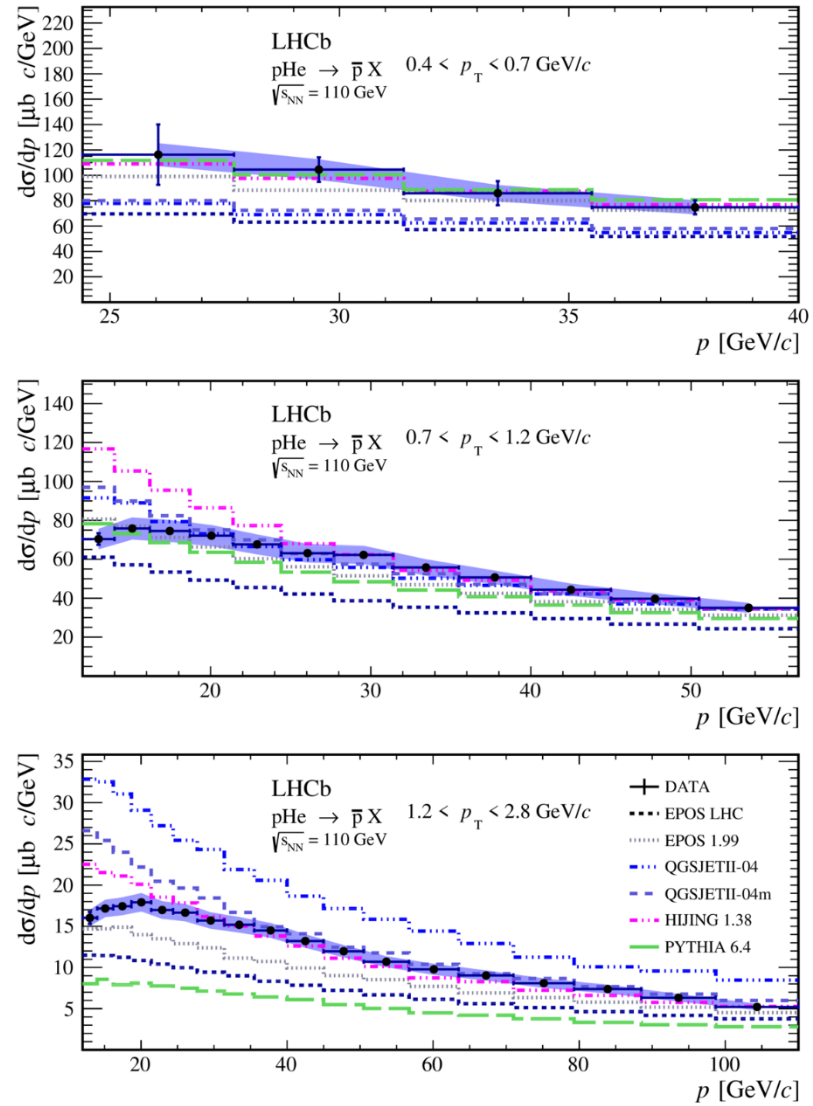
$$x \simeq \frac{2m_c}{\sqrt{s_{NN}}}\exp(-y^*)$$

$\bar{p}$ 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

Conclusion

- Recent results with heavy ions at LHCb
  - Heavy quarkonia in *p*Pb: J/ψ and $\Upsilon(nS)$
  - Fixed-target mode: charm and anriproton
- For the future
  - Analyses of other quarkonia using the *p*Pb dataset
  - 2018 PbPb dataset (20 times larger than 2015)
  - Upgrade for Run3/4
  - Upgrade of SMOG system for Run3
    - More gases (H_2, deuteron…)
    - Density of the target gas increase → luminosity increase up to a factor of 100