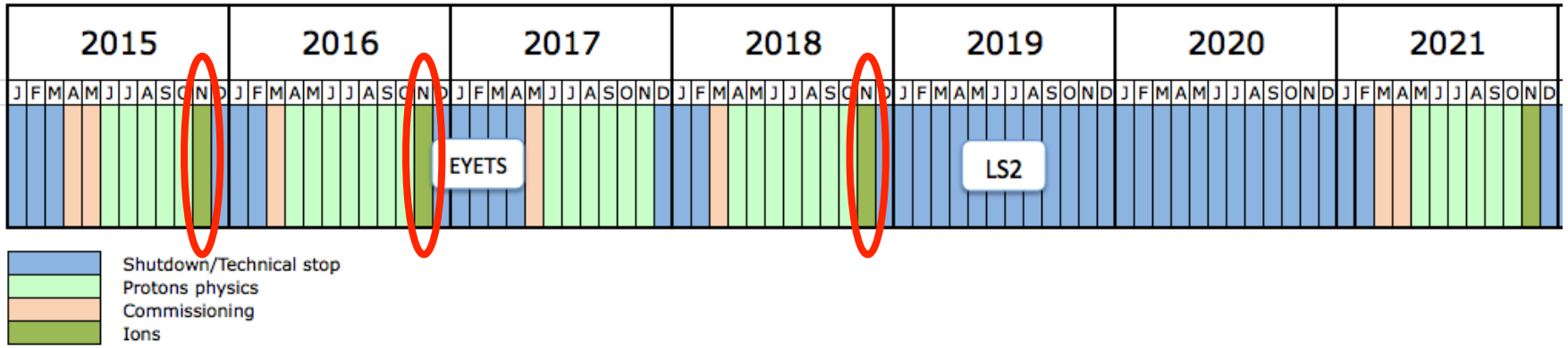
LHCb: Recent results on heavy ions

Shanzhen Chen, on behalf of the LHCb collabration
Universita e INFN, Cagliari

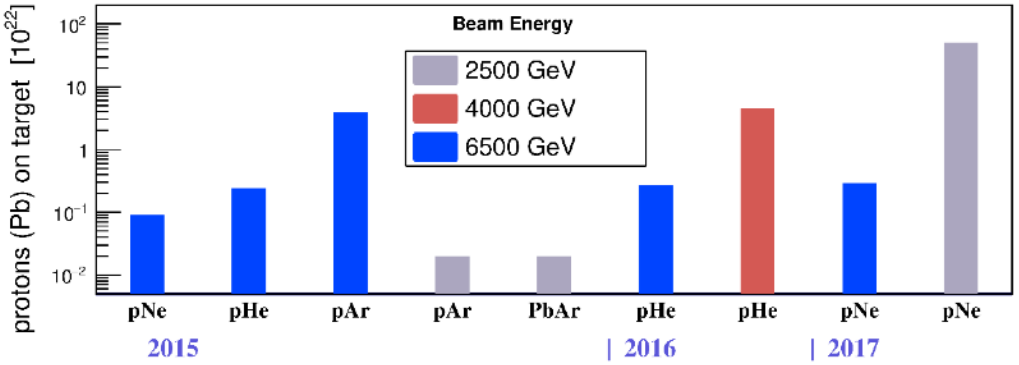
Implications of LHCb measurements and future prospects
19th October 2018

LHCb heavy ion modes

- *pp* collider: 2010-2018, $\sqrt{s_{NN}}$ = 2.76, 5, 7, 8, 13 TeV, L≈ 9 fb^{-1}
- *p*Pb collider: 2013 and 2016, $\sqrt{s_{NN}}$ = 5 & 8.16 TeV, L≈ 2 & 34 nb^{-1}
- PbPb collider: 2015, $\sqrt{s_{NN}}$ = 5 TeV, L≈ 10 μb^{-1}. Next run: end 2018



- Fixed target mode:
  parasitic to collider mode,
  inject noble gas into VELO,
  use non-colliding bunches



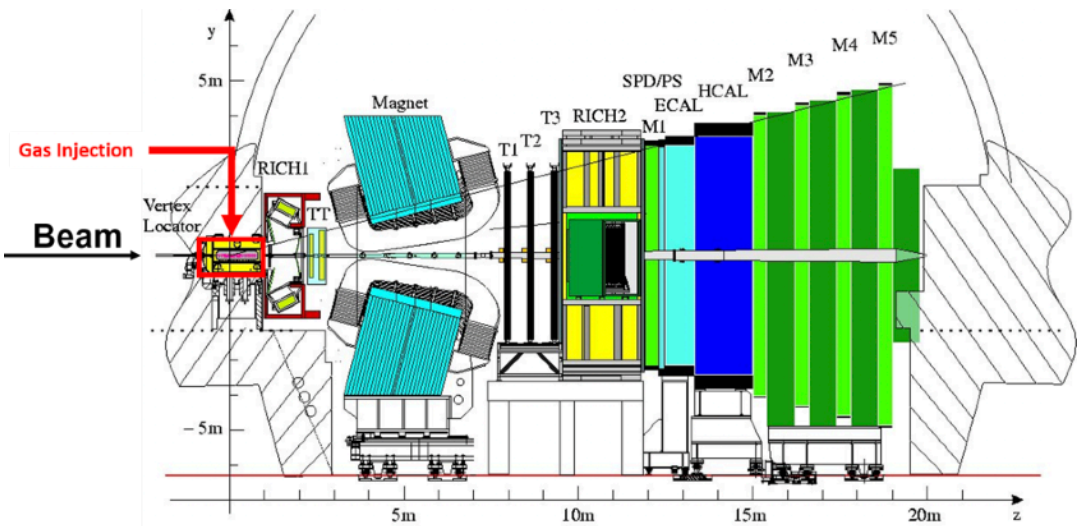
LHCb heavy ion recent results

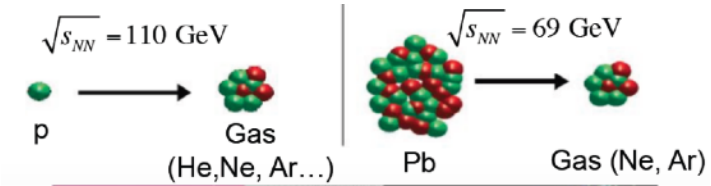
- Antiproton production in fixed-target configuration
  - LHCb-PAPER-2018-031, arXiv:1808.06127
- Charm production in fixed-target configuration
  - LHCb-PAPER-2018-023, arXiv:1810.07907
- Heavy flavour production in *p*Pb collisions
  - D^0@5.02TeV: LHCb-PAPER-2017-015, JHEP (2017) 090
  - Λ_c^+@5.02TeV: LHCb-PAPER-2018-021, arXiv:1809.01404
  - J/ψ@8.16TeV: LHCb-PAPER-2017-014, PLB774 (2017) 159
  - B^+, B^0, Λ_b^0@8.16TeV: LHCb-CONF-2018-004
  - $\Upsilon(nS)$@8.16TeV: LHCb-PAPER-2018-035, arXiv:1810.07655
- Exclusive photonuclear J/ψ production in ultra-peripheral PbPb collisions @5TeV
  - LHCb-CONF-2018-003, see Paolo's talk on Wednesday

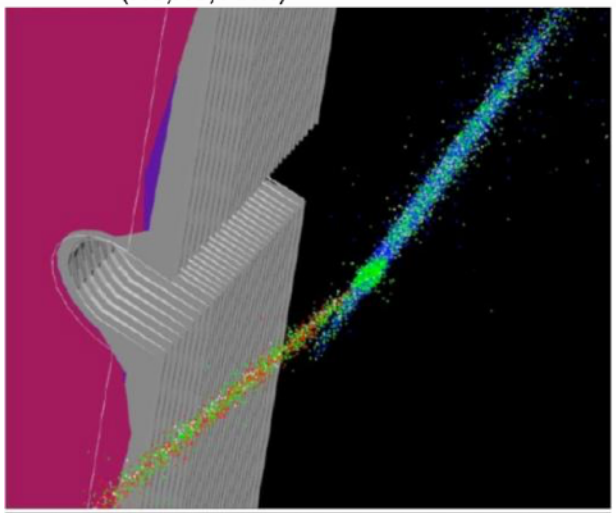
Fixed-target mode setups at LHCb

- **Noble gas injected in VELO = ^{4}He, ^{20}Ne, ^{40}Ar, …**
- **Access: $\sqrt{s_{NN}}$ in [69, 110] GeV, backward rapidity**
- **Fills the gap between SPS and RHIC energies**

$$\sqrt{s_{NN}}^{SPS} \sim 20GeV, \sqrt{s_{NN}}^{LHCb-FT} \in [69,110]GeV, \sqrt{s_{NN}}^{RHIC} = 200GeV, \sqrt{s_{NN}}^{LHC} = 5TeV$$







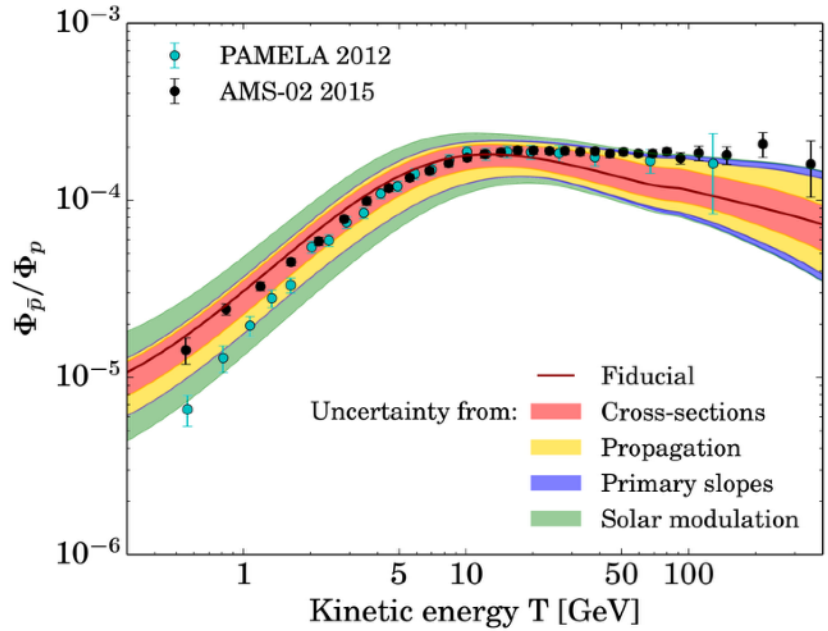
Distribution of vertices overlaid on detector display. z-axis is scaled by 1:100 compared to transverse dimensions to see the beam angle.

Beam 1 - Beam 2, Beam 1 - Gas, Beam 2 - Gas.

arXiv:1808.06127

$\bar{p}$ production in fixed-target pHe collisions

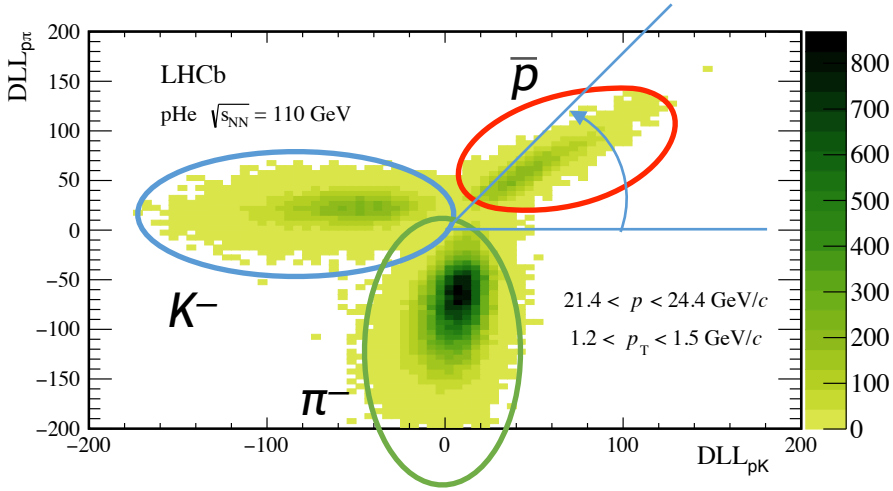
- Antiproton/proton ratio known with great precision in cosmic rays
  - AMS02 (PRL 117, 091103 (2016))
  - PAMELA (JETP Letters 96 (2013) 621)
- Hint for a possible excess
- Flux prediction uncertainties in 10-100 GeV kinetic energy range: dominated by production cross-sections uncertainties
  - Need to reduce uncertainty
  - pHe scattering cross-section results can serve as external input
- $\bar{p}$-production in pHe collisions never directly measured
- LHCb in fixed-target mode: pioneer with well suited kinematics

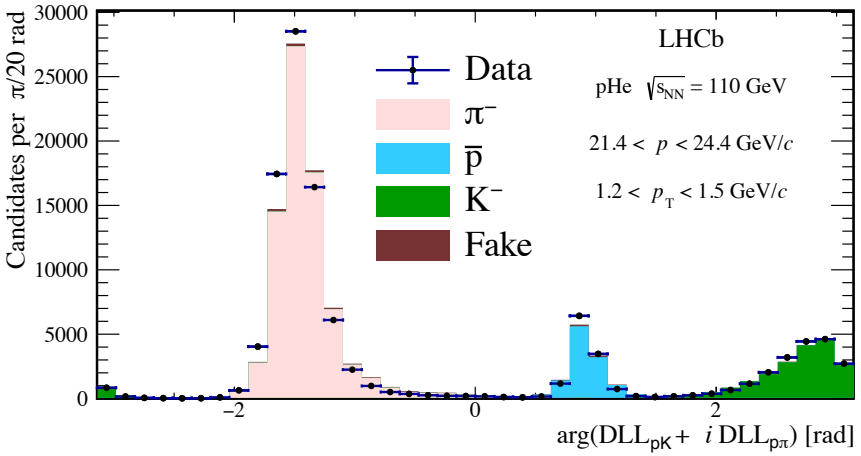


arXiv:1808.06127

$\bar{p}$ production in fixed-target pHe collisions

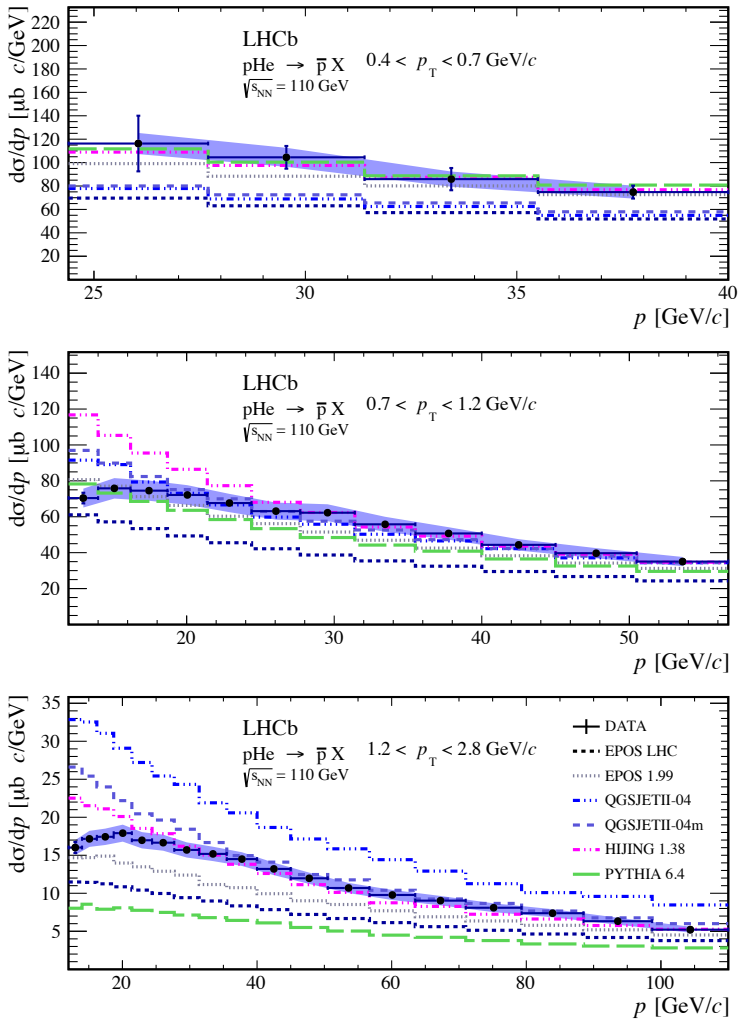
- Data collected in 2016 in pHe collisions at $\sqrt{s_{NN}}$ = 110 GeV
- Counting antiproton in (p, p_T) bins
- Access to range 12 GeV/c <p< 110 GeV/c, p_T> 0.4 GeV/c
- PID with 2 RICH detectors
- Account for background by residual gas
- Luminosity from pe^- elastic scattering





arXiv:1808.06127

$\bar{p}$ production in fixed-target pHe collisions



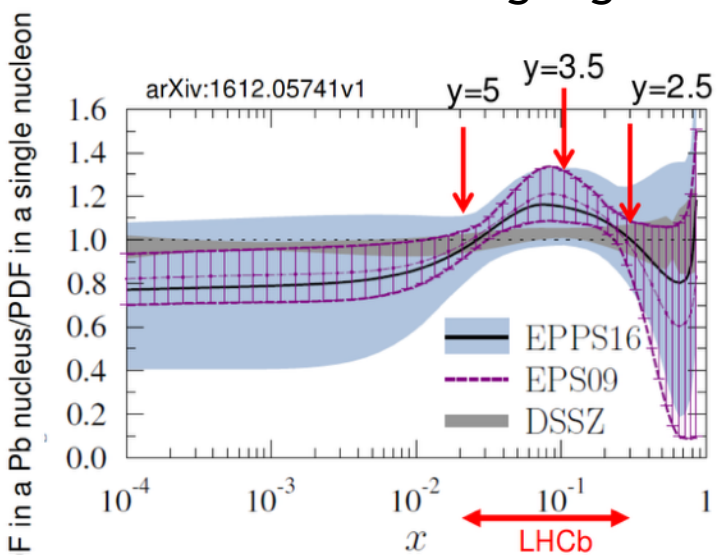
- Compared with [EPOS LHC](), [EPOS 1.99](), [QGSJET-II](), [QGSJETII-04m](), [Hijing](), [PYTHIA 6.4]().
  [ICRC '17: difference summary by T. Pierog]()
- Uncertainties smaller than model spread
- EPOS LHC tuned on LHC collider data underestimates $\bar{p}$-production
- Unique and precise:
  - decisive contribution to shrink background uncertainties in dark matter searches in space

arXiv:1810.07907

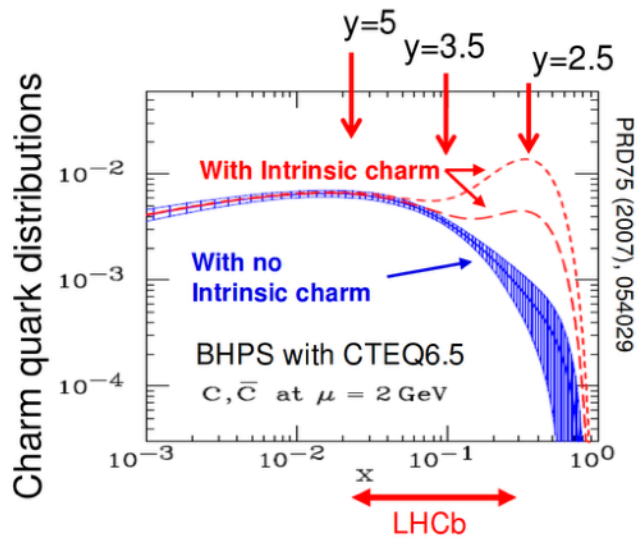
Charm production in fixed-target *p*-A collisions

- **Access to intrinsic charm via backward rapidity coverage**
- **Cover large Bjorken-x in the target**

nPDF anti-shadowing region



Valence-like intrinsic charm content in the nucleon

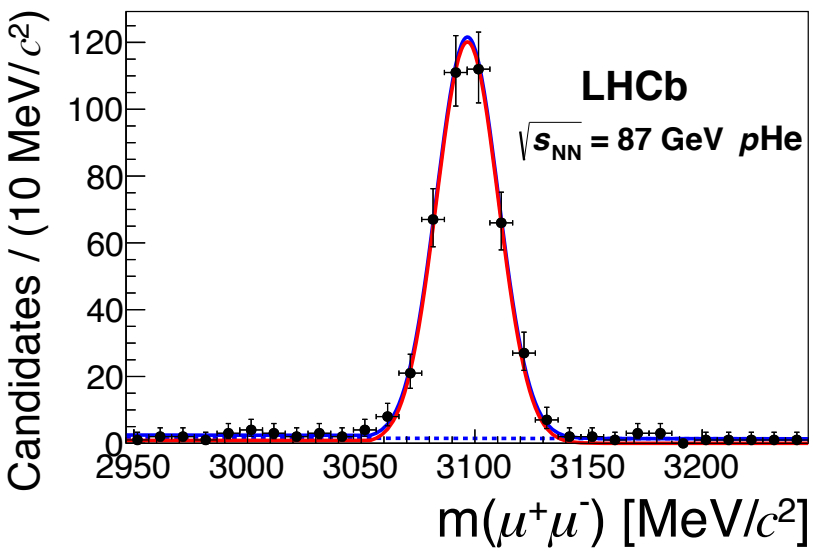


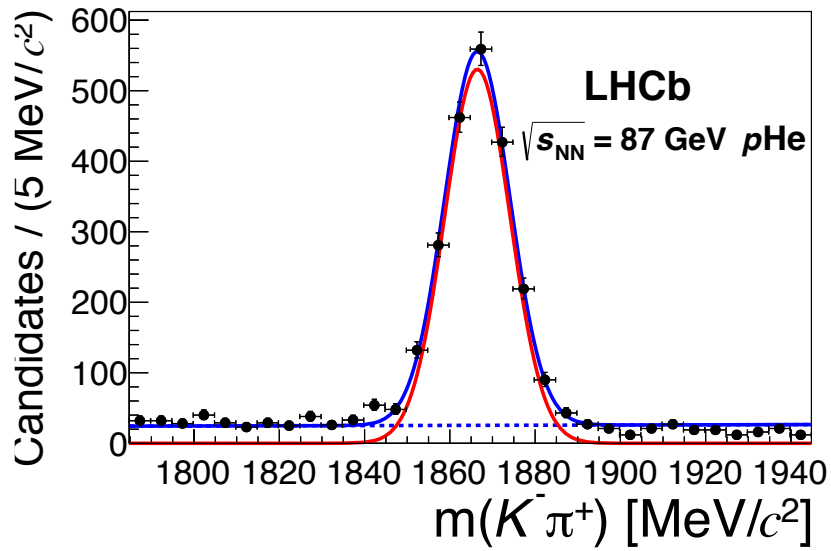
Bjorken-x = fraction of the nucleon momentum carried by a parton

arXiv:1810.07907

Charm production in fixed-target p-A collisions

- Data collected in 2016 in pHe collisions at $\sqrt{s_{NN}}$ = 86.6 GeV
- Cross sections measured with $J/\psi \to \mu^+\mu^-$ and $D^0 \to K^-\pi^+$ decays





arXiv:1810.07907

Charm production in fixed-target *p*-A collisions

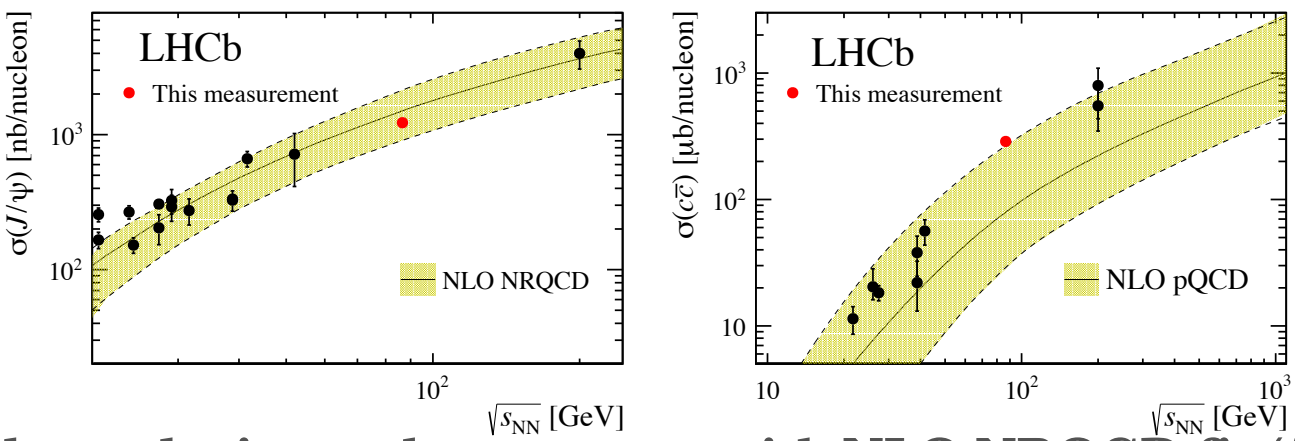
- ***J/ψ* and *D⁰* inclusive cross sections in *p*He @86.6 GeV**

$$\sigma_{J/\psi}^{86.6\ \mathrm{GeV}} = 1225.6 \pm 62.0(stat.) \pm 81.6(syst.)\ \mathrm{nb/nucleon}$$

$$\sigma_{D^0}^{86.6\ \mathrm{GeV}} = 156.0 \pm 4.6(stat.) \pm 12.3(syst.)\ \mu\mathrm{b/nucleon}$$

- **Scaling the *D⁰* cross-section with the global fragmentation ratio f($c \to D^0$) = 0.542±0.024, $c\bar{c}$ production cross section can be obtained:**

$$\sigma_{c\bar{c}}^{86.6\ \mathrm{GeV}} = 287.8 \pm 8.5(stat.) \pm 25.7(syst.)\ \mu\mathrm{b/nucleon}$$

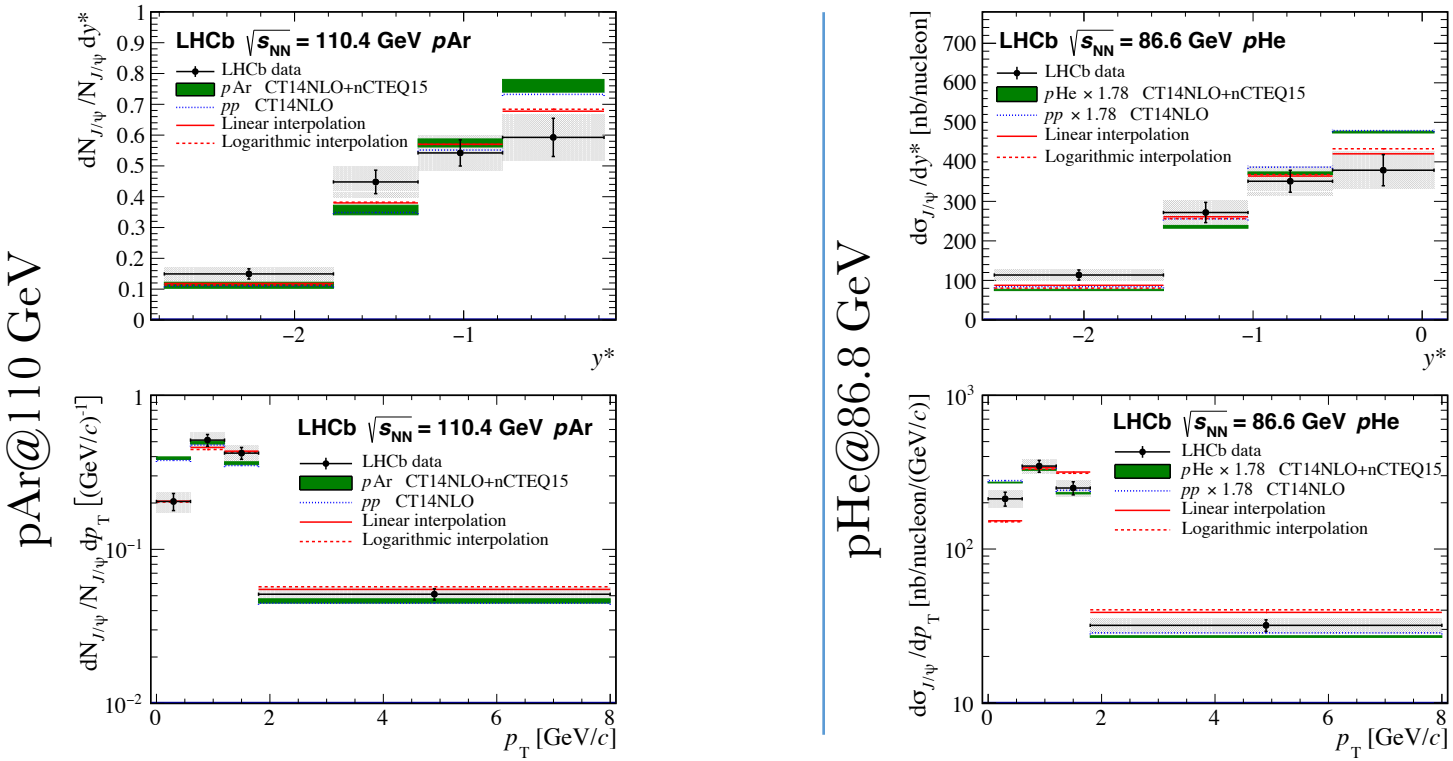


- **LHCb results in good agreement with NLO NRQCD fit (*J/ψ*, left) and NLO pQCD predictions ($c\bar{c}$, right) and other measurements**

arXiv:1810.07907

Charm production in fixed-target *p*-A collisions

- ***J/ψ*** **differential yields (*p*Ar@110GeV) and cross-section (*p*He@86.6GeV)**



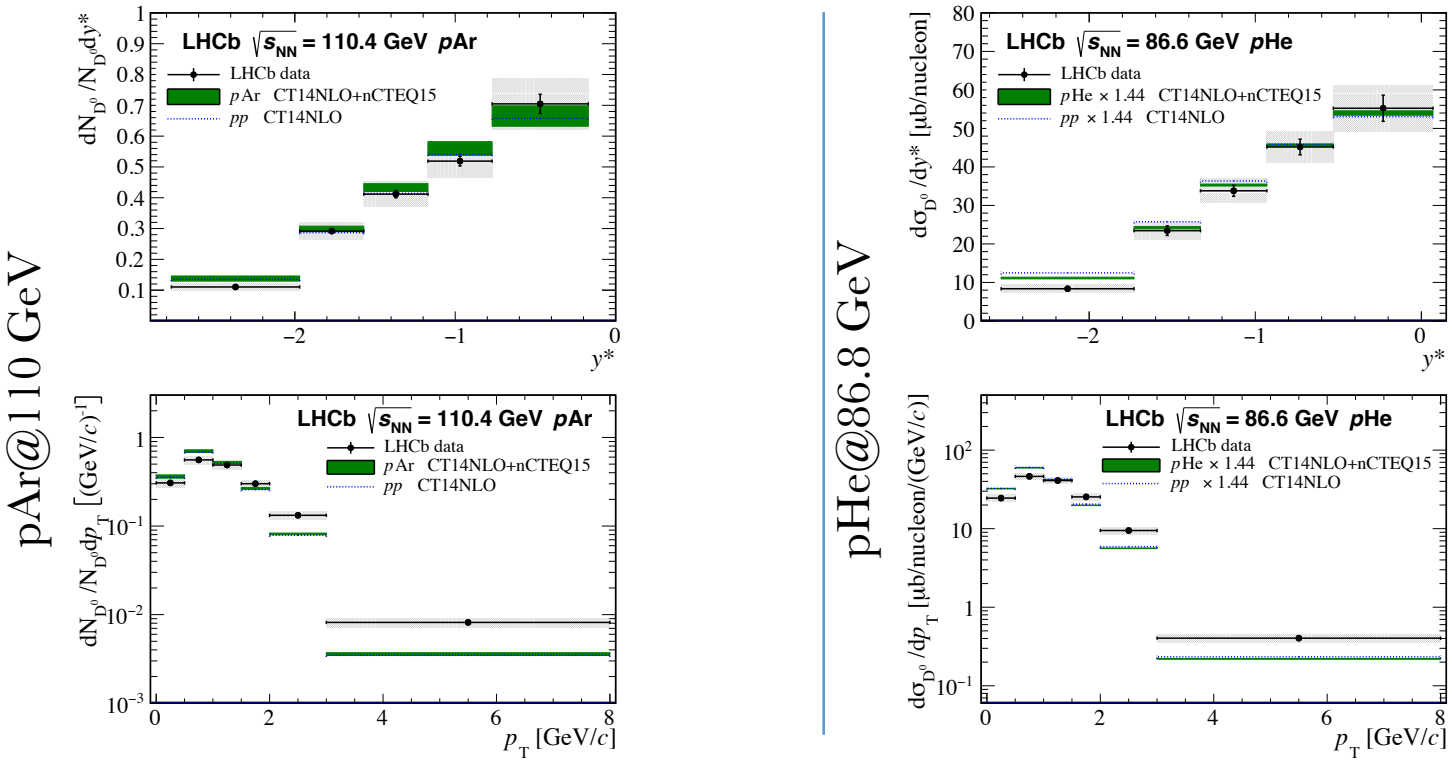
- **HELAC-ONIA [EPJC 77:1 (2017)] predictions for *pp* (blue line) and *p*A (Green box) overlaid with measurement. HELAC-ONIA underestimate the *J/ψ* cross section (*p*He) by a factor 1.78.**

- **Plain and dashed red lines: phenomenological parametrization [JHEP 1303(2013) 122]. Good shape agreement with phenomenological predictions.**

arXiv:1810.07907

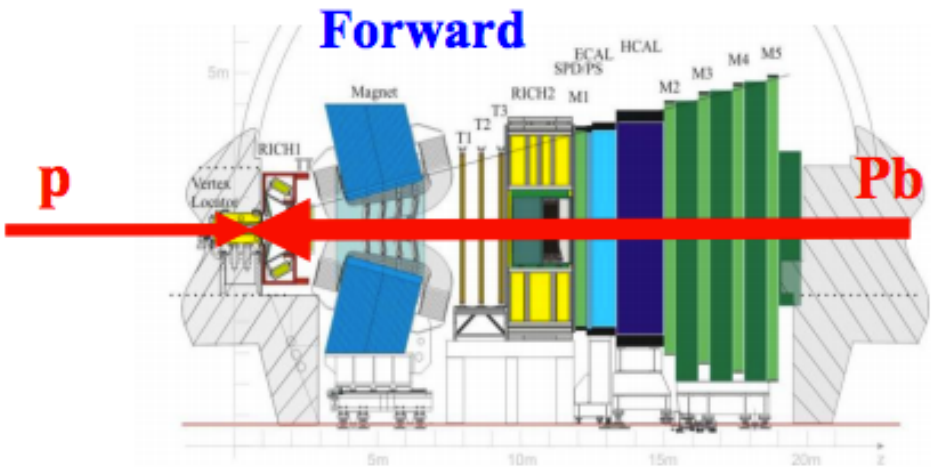
Charm production in fixed-target *p*-A collisions

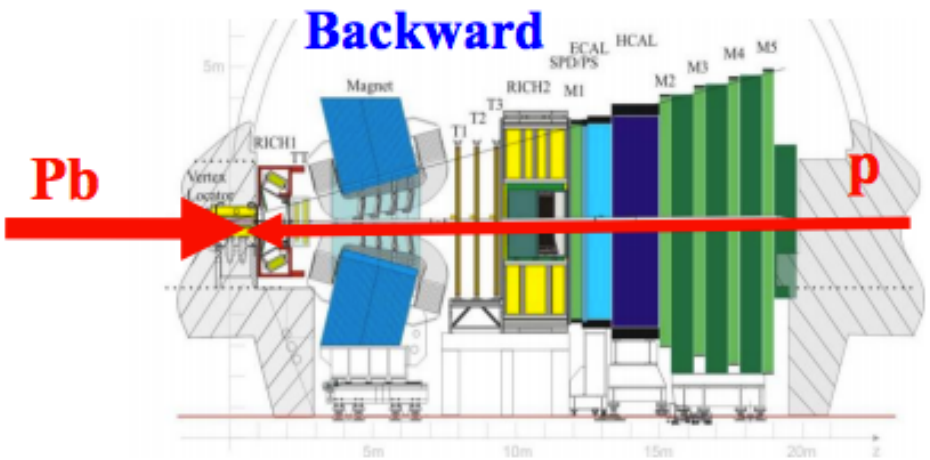
- ***D⁰*** **differential yields (*p*Ar@110GeV) and cross-section (*p*He@86.6GeV)**



- **HELAC-ONIA [EPJC 77:1 (2017)] predictions for *pp* (blue line) and *p*A (Green box) overlaid with measurement. HELAC-ONIA underestimate the *D⁰* cross section (*p*He) by a factor 1.44.**
- **Good agreement in rapidity shapes between data and predictions**
- **No evidence of substantial valence-like intrinsic charm contribution**

Proton-lead modes setups at LHCb





Ion = $^{208}_{82}$Pb

Forward region:

- $y^* = y_{lab} - 0.465$
- pPb: $1.5 < y < 4.0$

Backward region:

- $y^* = -(y_{lab} + 0.465)$
- Pbp : $-5.0 < y < -2.5$

2013 data taking: $\sqrt{s_{NN}} = 5.02$ TeV

- 1.1 nb^{-1} (Fwd), 0.5 nb^{-1} (Bwd)

2016 data taking: $\sqrt{s_{NN}} = 8.16$ TeV

- 13.6 nb^{-1} (Fwd), 20.8 nb^{-1} (Bwd)

Proton-lead collisions

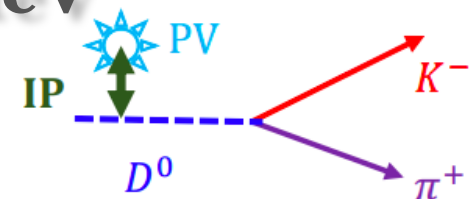
- **Allow us to study QGP in a barely explored regime**
- **Study of cold nuclear matter effects and their disentangling from QGP effects**
- **Nuclear effects quantified by nuclear modification factor:**

$$R_{p\mathrm{Pb}}(p_{\mathrm{T}}, y^*) \equiv \frac{1}{A}\frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_{\mathrm{T}}, y^*)/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{pp}(p_{\mathrm{T}}, y^*)/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*}, A = 208$$

- **where *pp* cross-sections at 5 TeV are from *pp* 5 TeV measurements, and *pp* cross-sections at 8.16 TeV are from interpolations with *pp* 2.76, 5, 7, 8, 13 TeV data**

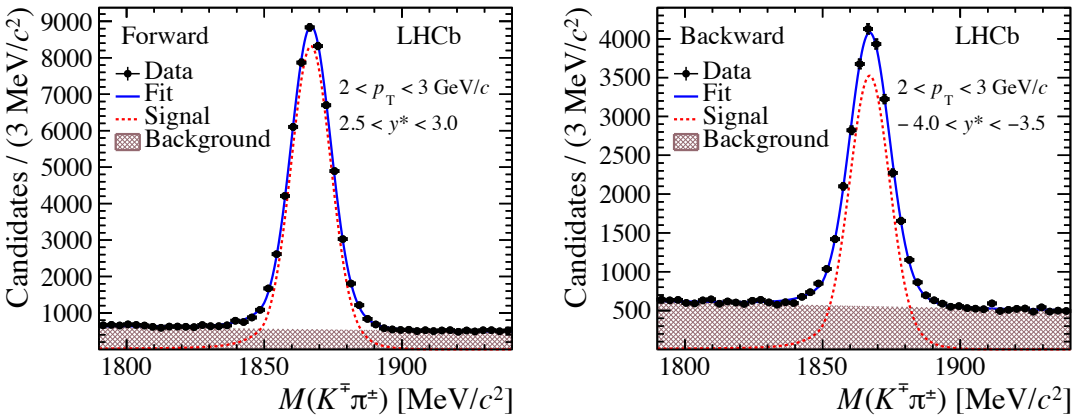
JHEP (2017) 090

Prompt D^0 production in pPb at 5.02 TeV

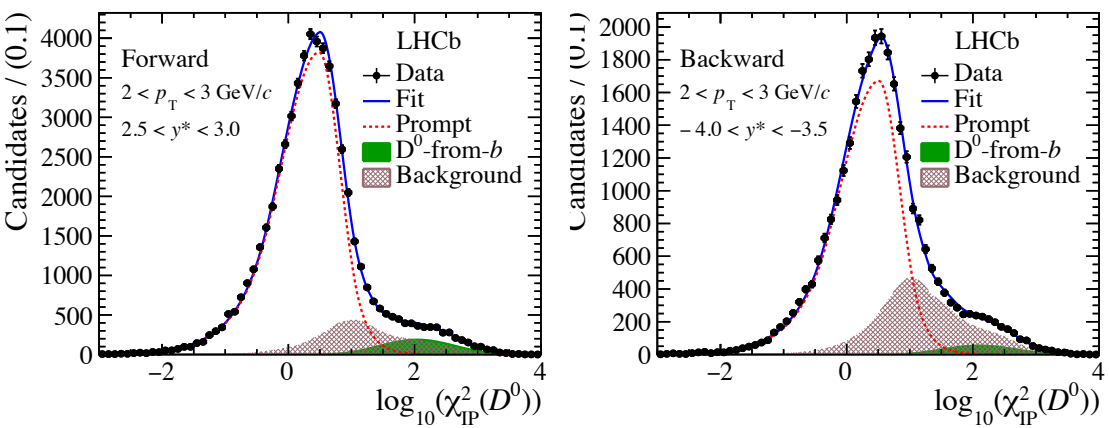


- **Reconstructed through $D^0 \to K^-\pi^+$ decays**
- **Simultaneous 2D fit to D^0 mass and impact parameter (IP)**

Forward backward



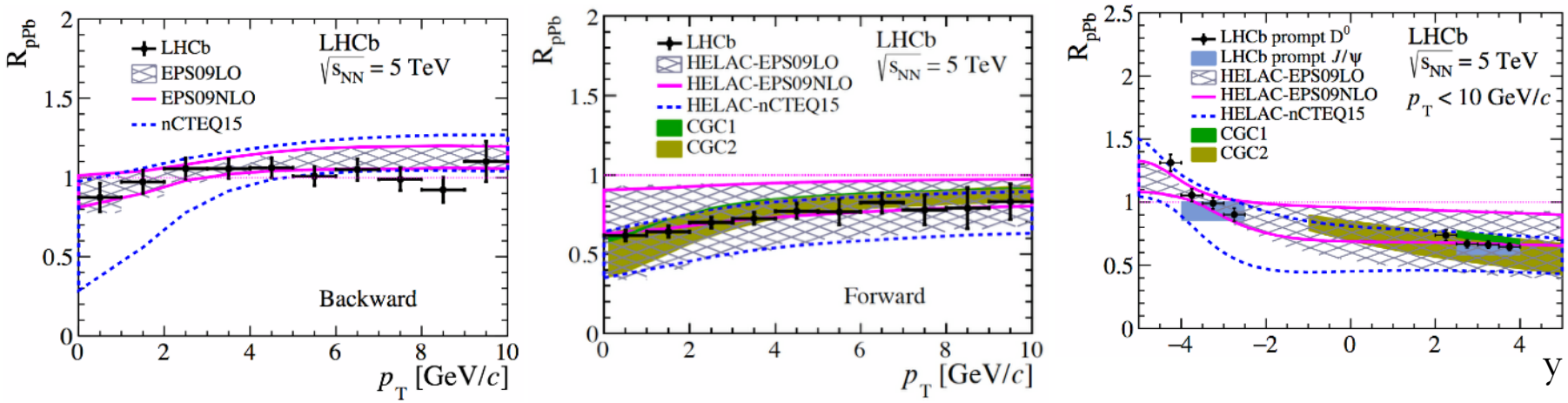
Mass distribution:
Signal: Crystal Ball
Background:Linear



IP distribution:
Prompt signal: from simulation
D0 from b: from simulation
Background: shape from sidebands

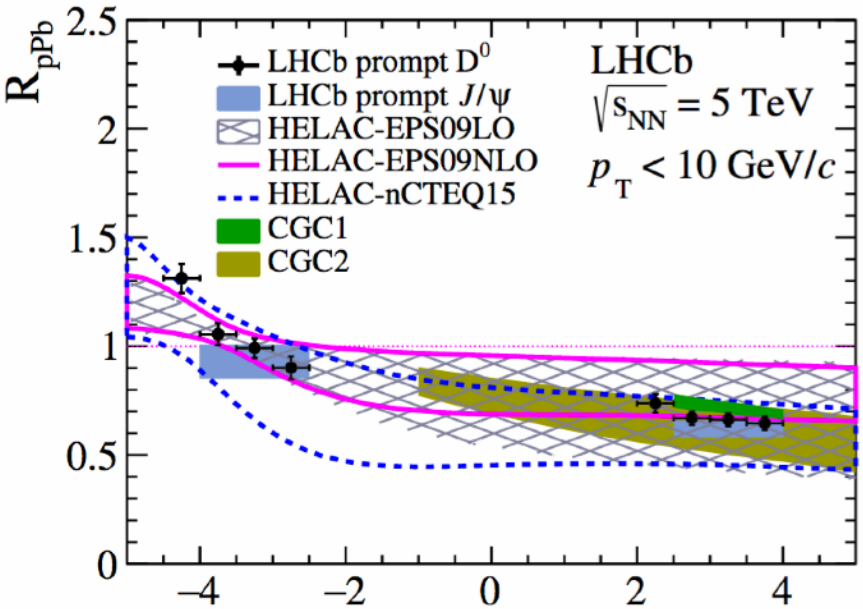
JHEP (2017) 090

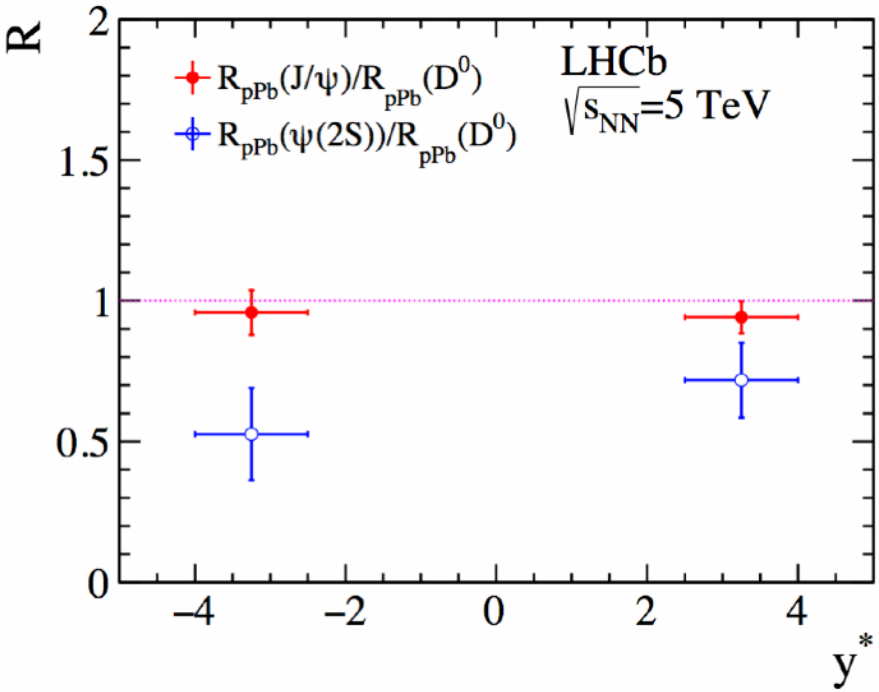
Prompt D^0 nuclear modification factor



- **Strong suppression at forward rapidity (~30%),**
- **Backward rapidity: compatible with no suppression and hint of enhancement —> different nuclear effect in forward and backward regions**
- **Suppression-enhancement pattern predicted by nPDFs [Eur. Phys. J. C77 (2017) 1, Comput. Phys. Commun. 184 (2013) 2562, Comput. Phys. Commun. 198 (2016) 238]**
- **At forward rapidity region also consistent with Colour Glass Condensate (CGC) models [Phys. Rev. D91 (2015) 114005, arXiv:1706.06728], with a proper saturation scale**

Prompt D^0 nuclear modification factor



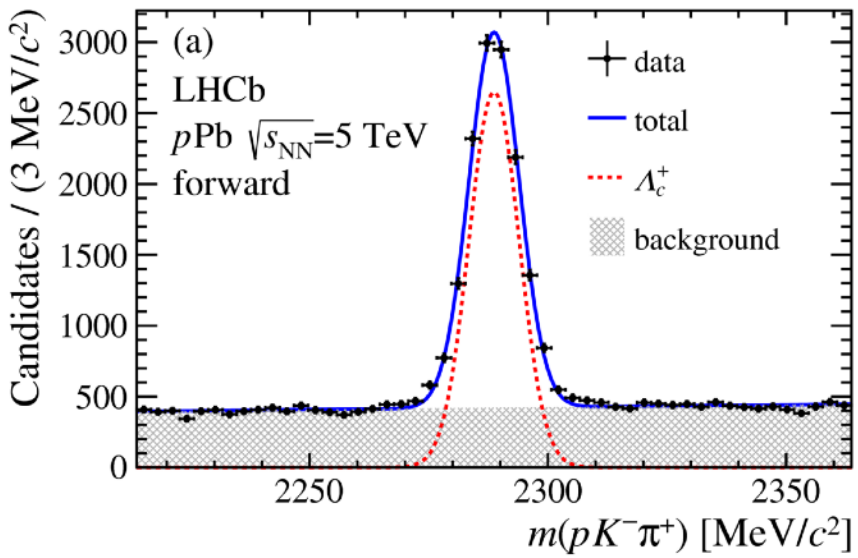


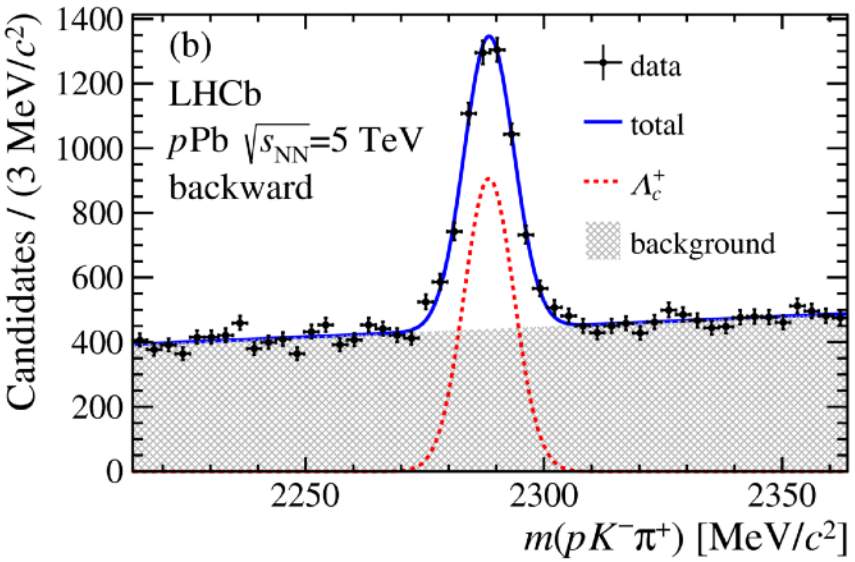
- **Compare with J/ψ and $\psi(2S)$ results at 5 TeV**
- **Similar nuclear modification factor for J/ψ to D^0,** $\frac{R_{pPb}(J/\psi)}{R_{pPb}(D^0)} \sim 1$
- **More suppressed for $\psi(2S)$ to D^0**

arXiv:1809.01404

Prompt Λ_c^+ production in pPb at 5.02 TeV

- **Reconstructed through $\Lambda_c^+ \to pK^-\pi^+$ decays**

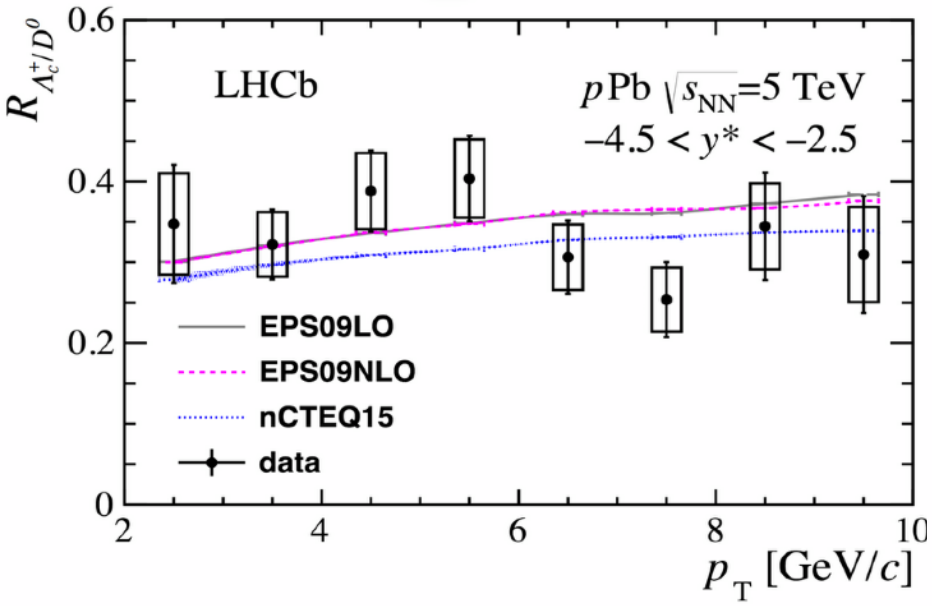


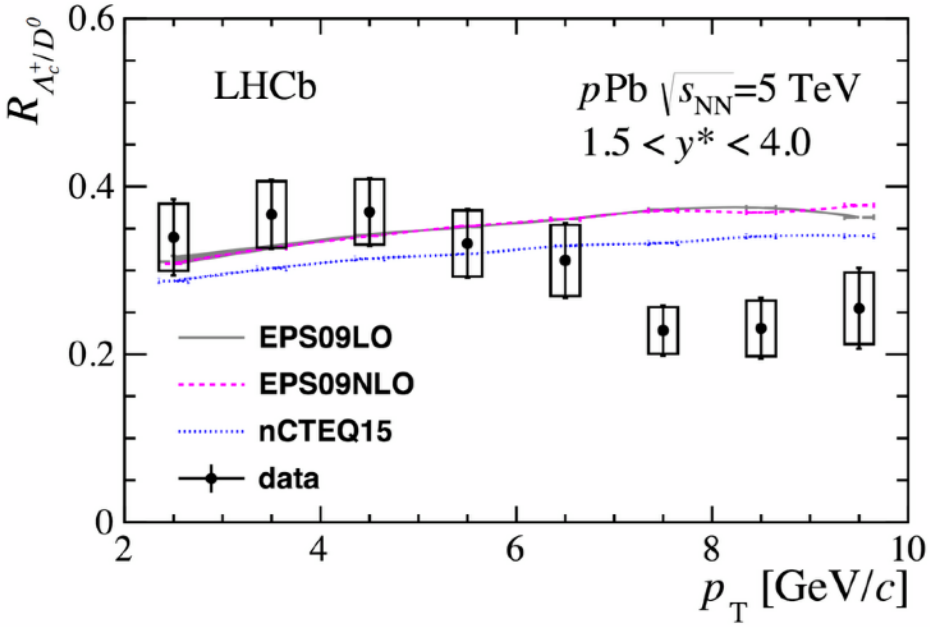


- **Similar analysis strategy as D^0**

arXiv:1809.01404

Prompt Λ_c^+ production in pPb at 5.02 TeV



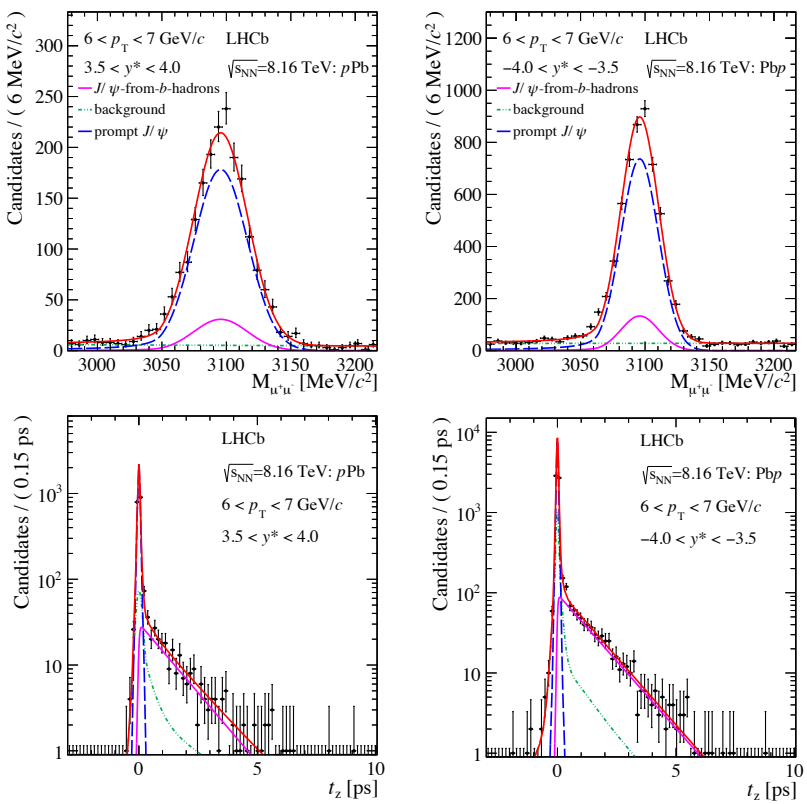


- Λ_c^+/D^0 similar in forward and backward directions
- Generally consistent with expectations from pp data $\Lambda_c^+/D^0 \sim 0.3$,
- Compared with nPDFs [JHEP 04 (2009) 065, EPJ C77 (2017) 1, Comput. Phys. Commun. 198 (2016) 238], hint of discrepancy at high p_T in forward direction

J/ψ production in pPb at 8.16 TeV

- 2016 pPb collision data, 8.16 TeV
- Prompt J/ψ and J/ψ-from-b are extracted by simultaneous fit of mass and pseudo-proper time: $t_Z=(Z_{J/\psi}-Z_{PV})\times M_{J/\psi}/p_Z$

Forward **Backward**



Mass distribution:
Signal: Crystal Ball
Background: exponential

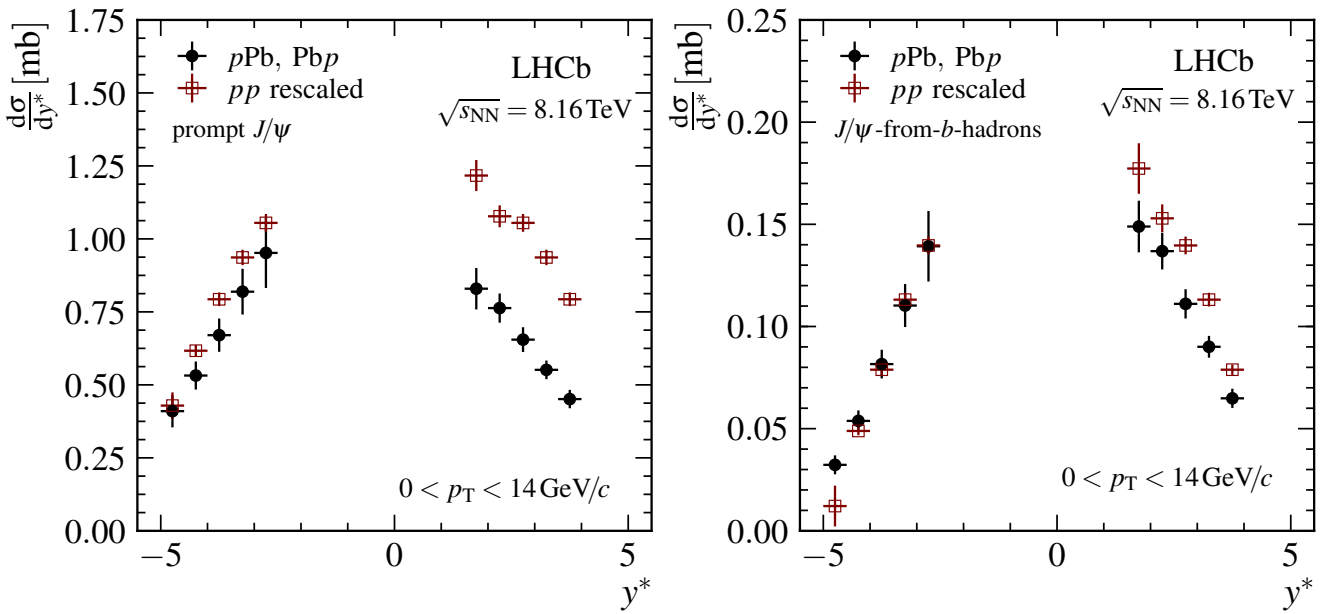
t_Z distribution:
Signal: $\delta(t_Z)$ for prompt J/ψ;
Exponential for J/ψ-from-b.
Background: empirical function from sideband

Total yields:

	prompt	from-b
Forward:	3.8×10^5;	6.7×10^4
Backward:	5.6×10^5;	7.1×10^4

J/ψ differential cross-section

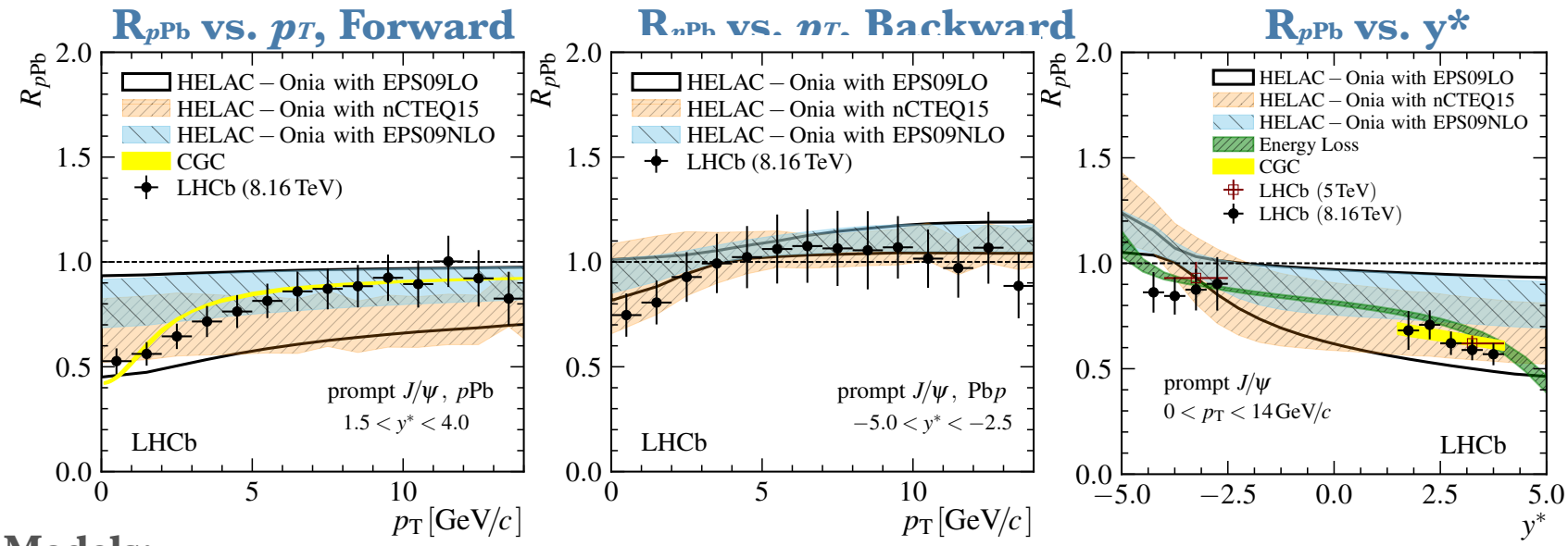
Prompt **From b**



- **The cross-sections as a function of y*, integrated over the p_T**
- **Sizeable forward-backward asymmetry**

Prompt J/ψ nuclear modification factor

- In Fwd: suppression at low p_T up to 50%, converging to unity at high p_T
- In Bwd: R_{pPb} closer to unity. Intriguing low values in Bwd at low p_T
- Overall agreement with theoretical models. Compatible with pPb 5 TeV results.

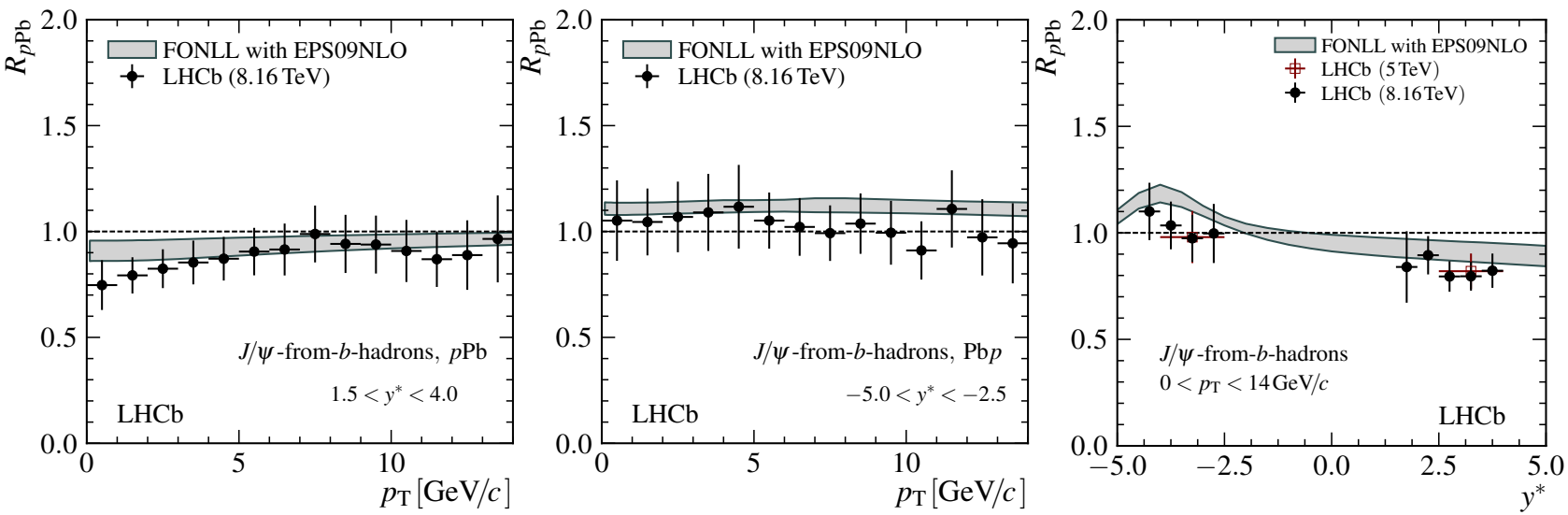


Models:
HELAC: Eur. Phys. J. C77 (2017)1; Comput.Phys.Comm.184(2013) 2562, Comput. Phys. Comm.198 (2016) 238. EPS09: JHEP 04 (2009) 065, arXiv:0902.4154.
nCTEQ15: Phys. Rev. D93 (2016) 085037.
EnergyLoss: JHEP 03 (2013) 122, arXiv:1212.0434.
CGC: Phys. Rev. D91 (2015) 114005

J/ψ-from-b nuclear modification factor

- In Fwd: suppression at low p_T up to 30%, converging to unity at high p_T
- In Bwd: R_{pPb} slightly above unity
- Overall agreement with theoretical models. Compatible with pPb 5 TeV results.

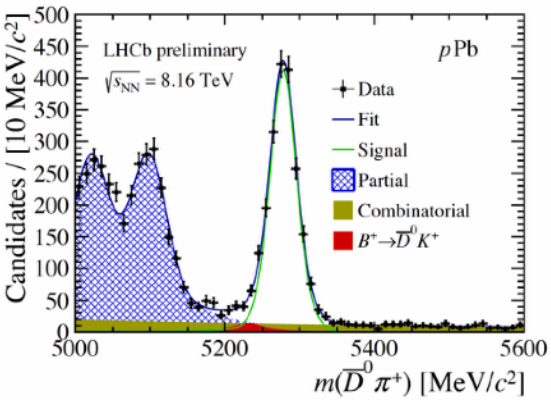
R_{pPb} vs. p_T, Forward **R_{pPb} vs. p_T, Backward** **R_{pPb} vs. y***

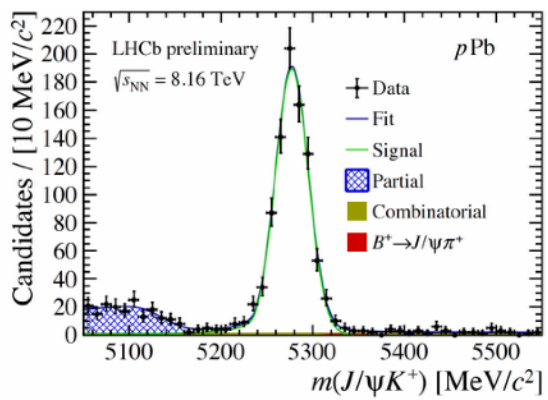


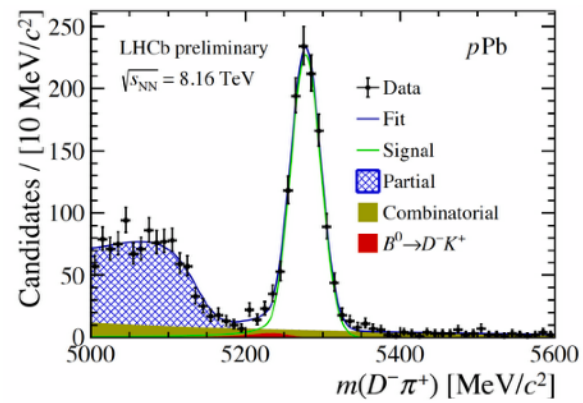
Model:
FONLL: JHEP 05(1998) 007, JHEP03 (2001) 006

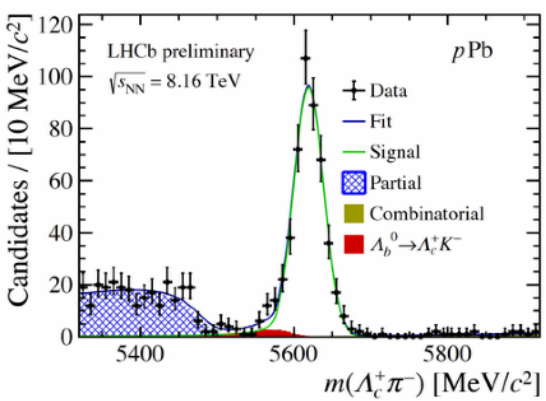
b-hadron production in *p*Pb at 8.16 TeV

- **Exclusive decay modes: $B^+ \to J/\psi K^+$, $B^+ \to D^0\pi^+$, $B^0 \to D^-\pi^+$, $\Lambda_b^0 \to \Lambda_c^+\pi^-$**





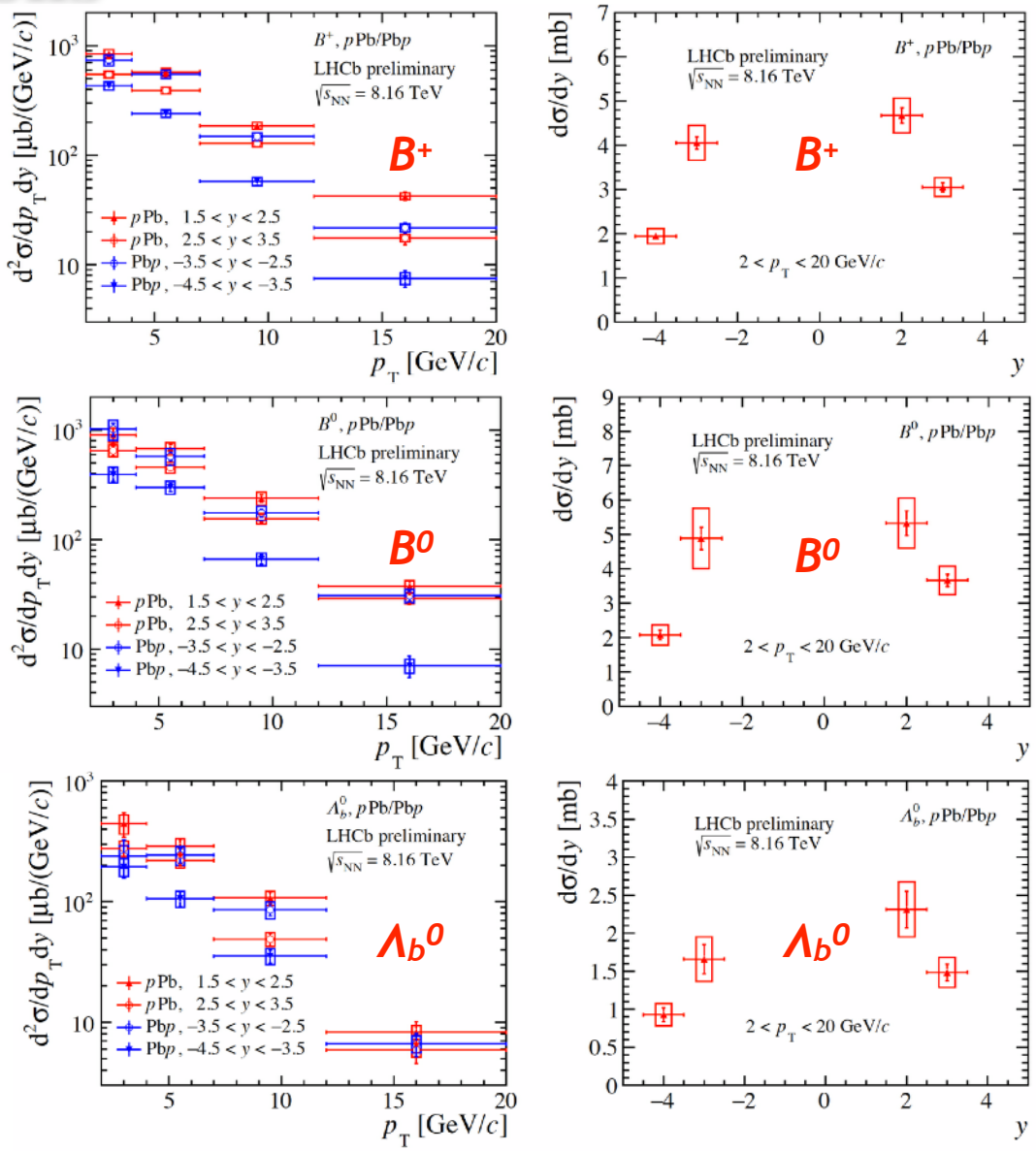




Decay	pPb	Pbp
$B^+ \to \overline{D}^0\pi^+$	1943 ± 58	1824 ± 64
$B^+ \to J/\psi\, K^+$	883 ± 32	905 ± 33
$B^0 \to D^-\pi^+$	1155 ± 39	886 ± 34
$\Lambda_b^0 \to \Lambda_c^+\pi^-$	484 ± 24	397 ± 23

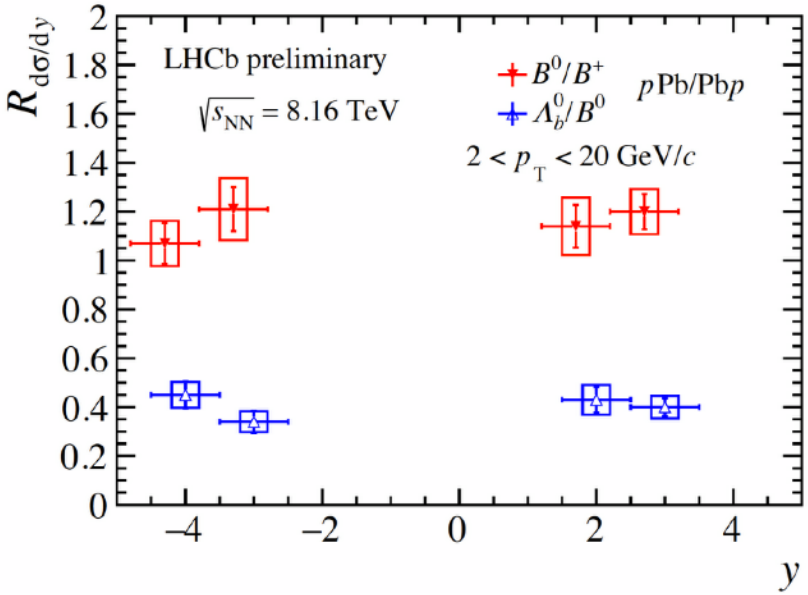
b-hadron cross-sections

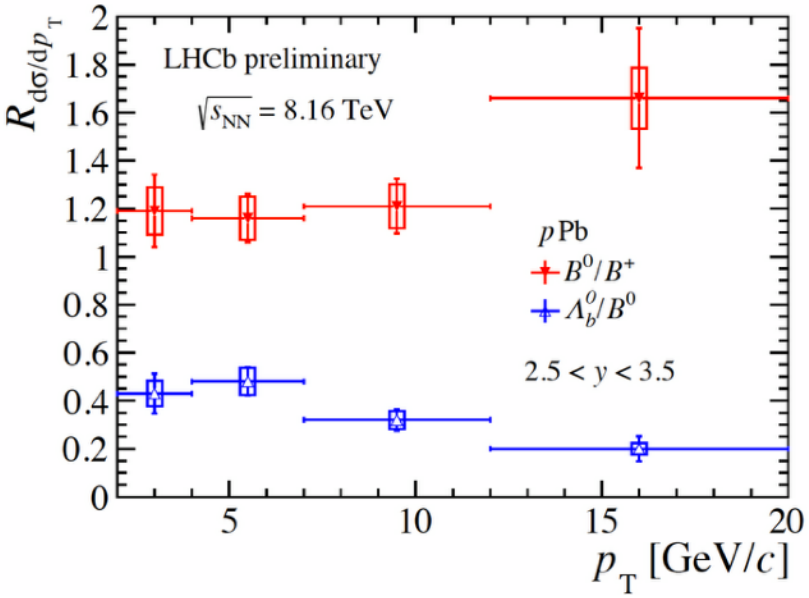
- B^+ cross-section studied in $J/\psi K^+$ and $D^0\pi^+$ modes. Both modes consistent. Weighted average shown here
- Similar p_T and y distributions for B^+, B^0 and Λ_b^0 hadrons



b-hadron cross-section ratios

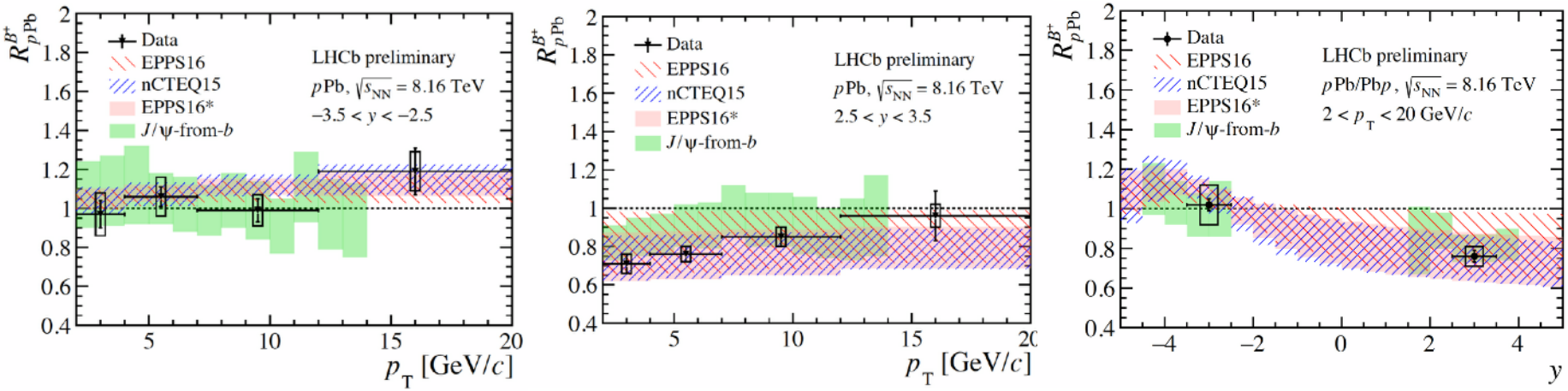
- **Probing relative *b*-quark fragmentation into different *b*-hadrons**





- ***B^0/B^+* ratio independent of *y* and *p_T*, slightly above unity (isospin symmetry)**
- ***Λ_b^0/B^0* ≈40%, decreasing with *p_T*, no hint of strong rapidity dependence. similar to results in LHCb *pp* data [JHEP 08 (2014) 143]**
- ***Λ_b^0/B^0* ratio reaches LEP data at high *p_T*, 0.20 ± 0.02 [arXiv:1612.07233]**

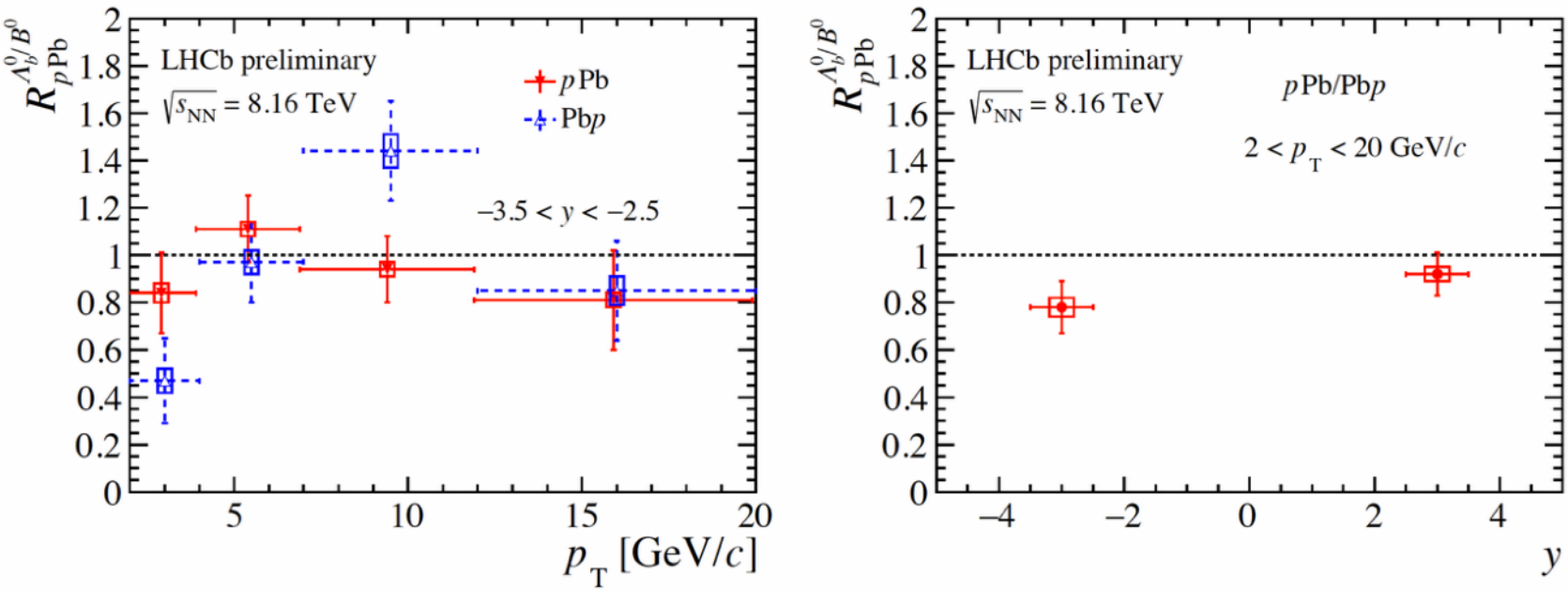
B^+ nuclear modification factors



- **Pattern consistent with R_{pA} of D^0 hadron**
- **Significant suppression (≈ 25%) in forward rapidity, suppression decreased at large p_T**
- **Consistent with unity at backward rapidity**
- **Measurements in good agreement with J/ψ-from-b decay data and calculations using nPDF sets [JHEP 04 (2009) 065, EPJ C77 (2017) 1, Comput. Phys. Commun. 198 (2016) 238]**

Λ_b^0 and B^0 relative modification

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

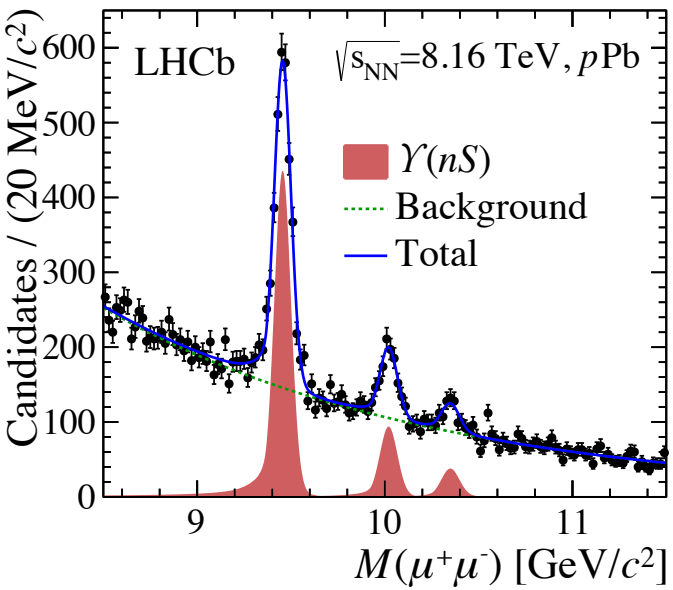


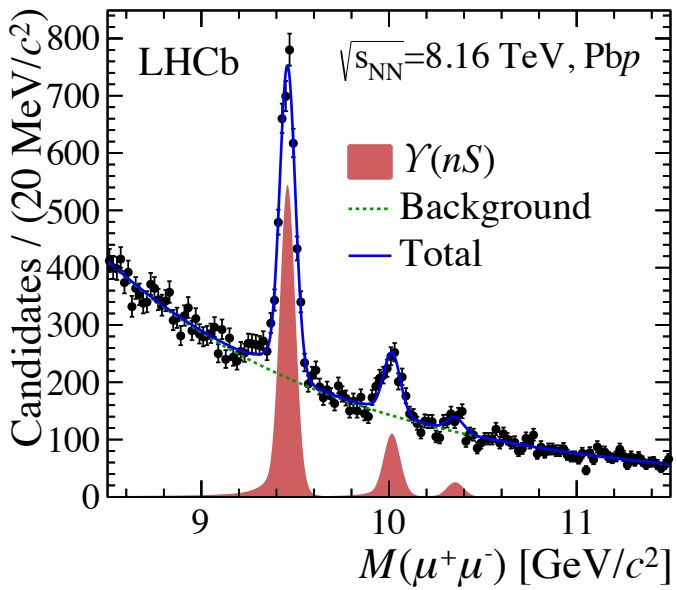
- **Forward rapidity: consistent with unity in all kinematic bins —> *b*-quark fragmentation function at forward rapidity similar to *pp***
- **Backward rapidity: hint of stronger suppression for Λ_b^0 compared with B^0. Demanding more statistics for a firm conclusion.**

arXiv:1810.07655

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

- Quarkonium: QCD hydrogen atom → probe deconfinement in PbPb
- $\Upsilon(nS)$ suppression observed in PbPb by CMS and ALICE
- Observed additional suppression of $\Upsilon(2S,3S)$ at low-p_T also in pPb/Pbp by LHC collaborations in Run 1, but statistics limited

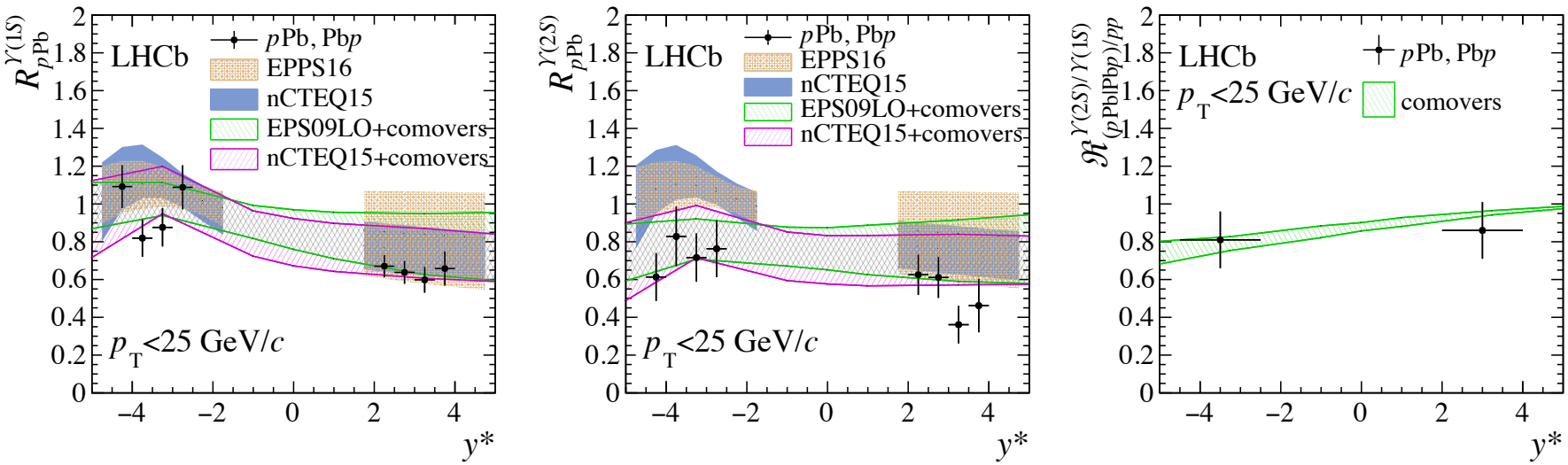




- LHCb Run-2: Factor 20 more luminosity in 2016 than in Run 1
- Mass spectra are fitted with double crystal ball functions
- Clear $\Upsilon(3S)$ signal in both forward and backward rapidity

arXiv:1810.07655

$\Upsilon(1S)$ and $\Upsilon(2S)$ nuclear modification factor



$$\mathfrak{R}^{\Upsilon(nS)/\Upsilon(1S)}_{(pPb|Pbp)/pp} = \frac{R(\Upsilon(nS))_{pPb|Pbp}}{R(\Upsilon(nS))_{pp}}$$

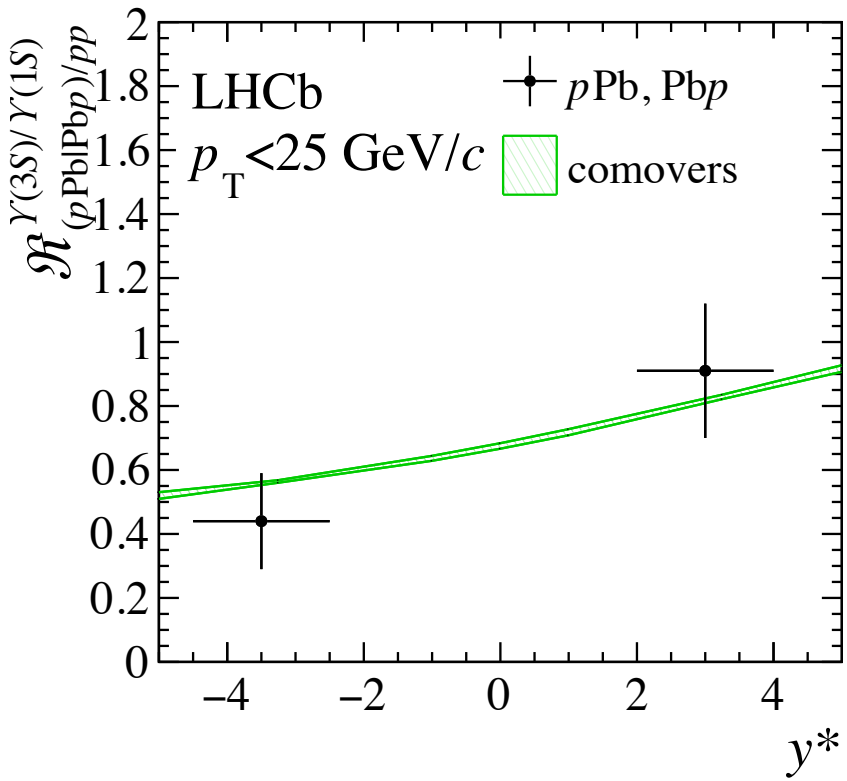
- $\Upsilon(1S)$: forward: suppressed by ~30%
- $\Upsilon(1S)$: backward: compatible with unity within nPDF uncertainties
- $\Upsilon(2S)$: additional suppression confirmed
- Double ratio: shadowing cancels
- Consistent with comovers model

MODELS:
EPPS16: Eur. Phys. J. C (2017) 77: 163
EPS09: JHEP 04 (2009) 065, arXiv:0902.4154.
nCTEQ15: Phys. Rev. D93 (2016) 085037.
Comovers: arXiv:1804.04474; Phys. Lett. B749 (2015) 98, arXiv:1411.0549

arXiv:1810.07655

$\Upsilon(3S)$ double ratios

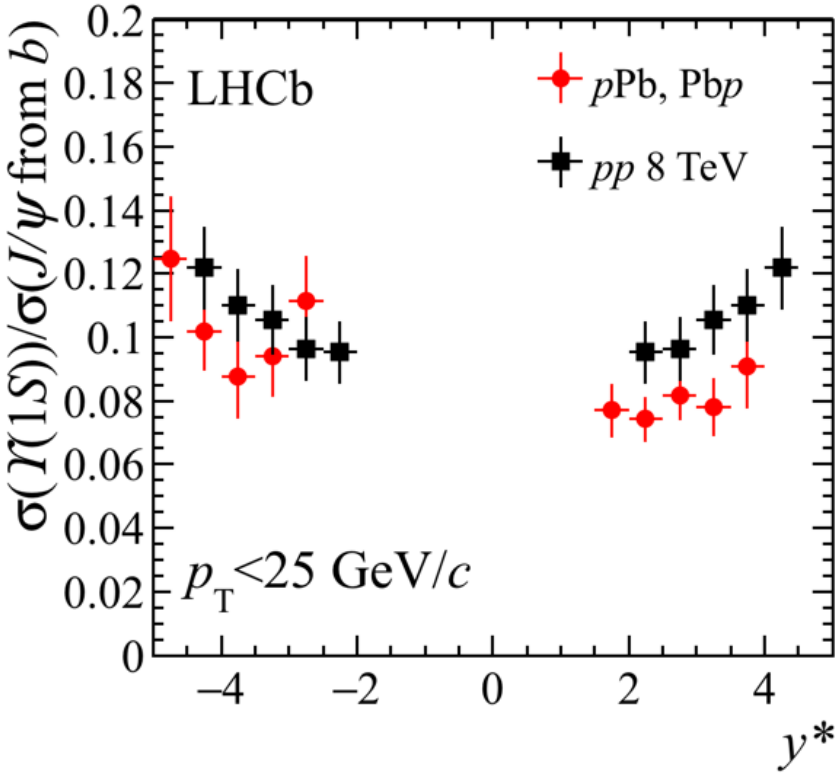
$$\mathfrak{R}^{\Upsilon(nS)/\Upsilon(1S)}_{(p\mathrm{Pb}|\mathrm{Pb}p)/pp} = \frac{R(\Upsilon(nS))_{p\mathrm{Pb}|\mathrm{Pb}p}}{R(\Upsilon(nS))_{pp}}$$



- **An even larger suppression for $\Upsilon(3S)$ observed**
- **Consistent with comovers model**

arXiv:1810.07655

$\Upsilon(1S)$ to J/ψ-from-b ratio



- p_T -integrated $\Upsilon(1S)$ to J/ψ-from-b similar in pp & in pPb/Pbp:
- Small suppression indicate different suppression mechanism for quarkonia with different binding energies

Conclusions

- **LHCb has strong capabilities to study heavy flavor in heavy ion collisions**
- **$\bar{p}$ production in fixed-target pHe collisions**
  - **Valuable input to astrophysics community**
- **Charm production in fixed-target proton-nucleus collisions**
  - **No evidence of strong intrinsic charm contribution**
- **Heavy flavour production in pPb collisions**
  - **Tested heavy-flavour bound state hadronisation & fragmentation down to low-p_T**
  - **Tested different suppression mechanism for quarkonia with different binding energies**
  - **Nuclear suppressions in pPb forward: up to 50% at low-p_T for charm and 20-30% for beauty**
- **Many studies are ongoing with current heavy-ion programmes and in view of future upgrades**

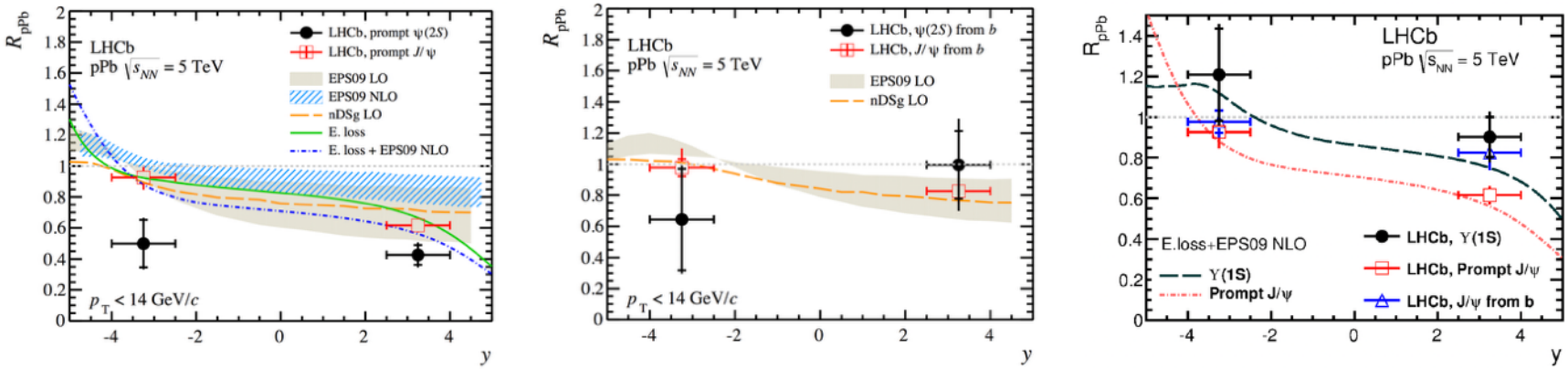
Backups

LHCb 5 TeV quarkonium results - J/ψ, $\psi(2S)$ and $\Upsilon(1S)$

[JHEP 1402 (2014) 072]
[JHEP 1407 (2014) 094]
[JHEP 1603 (2016) 133]

- Candidates fully reconstructed from well identified muons
- Prompt J/ψ, $\psi(2S)$ and those from b decays separated using pseudo-proper decay time

Prompt J/ψ, $\psi(2S)$ | **J/ψ, $\psi(2S)$ from b** | **$\Upsilon(1S)$**



Forward rapidity

- Significant suppression for J/ψ , even larger for $\psi(2S)$
- Modest suppression for non-prompt J/ψ , similar to $\Upsilon(1S)$

Backward rapidity

- No suppression for J/ψ and $\Upsilon(1S)$
- Unexpected large suppression for $\psi(2S)$, not described by E.loss and shadowing