The 18th International Conference on
Strangeness in Quark Matter (SQM 2019)
10-15 June 2019, Bari (Italy)

Recent heavy ion results from LHCb

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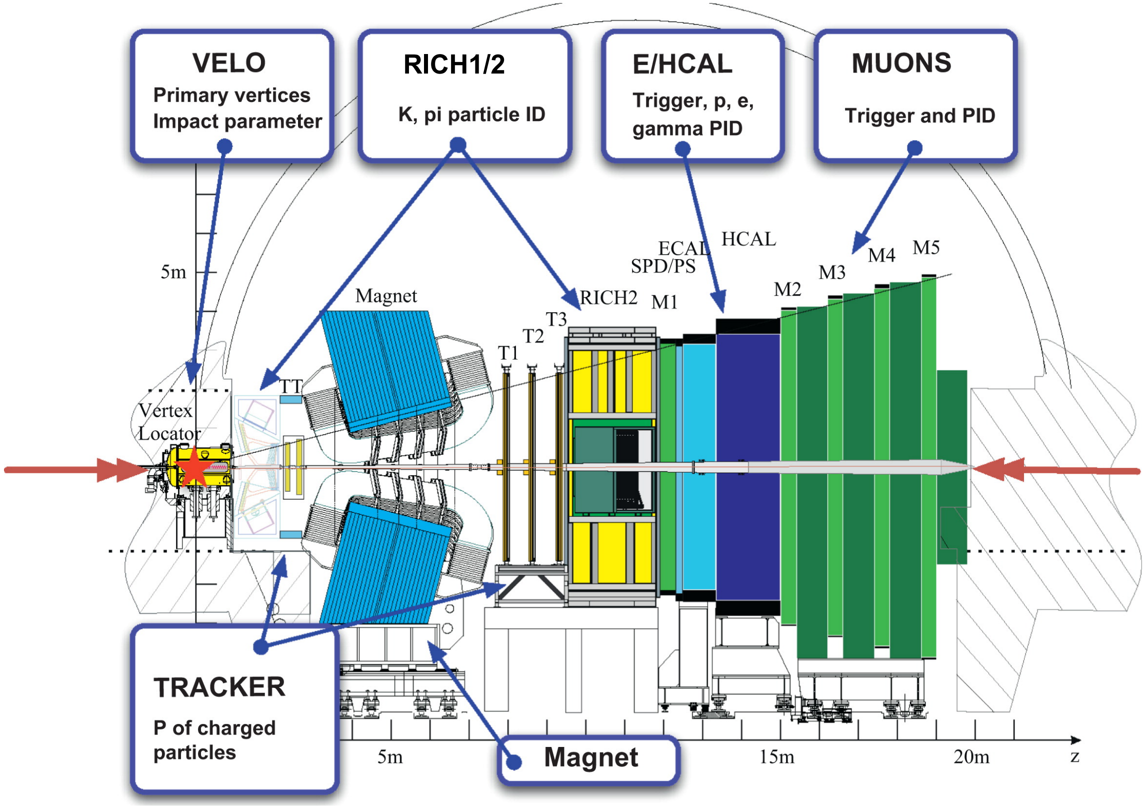
10th June 2019

LHCb detector

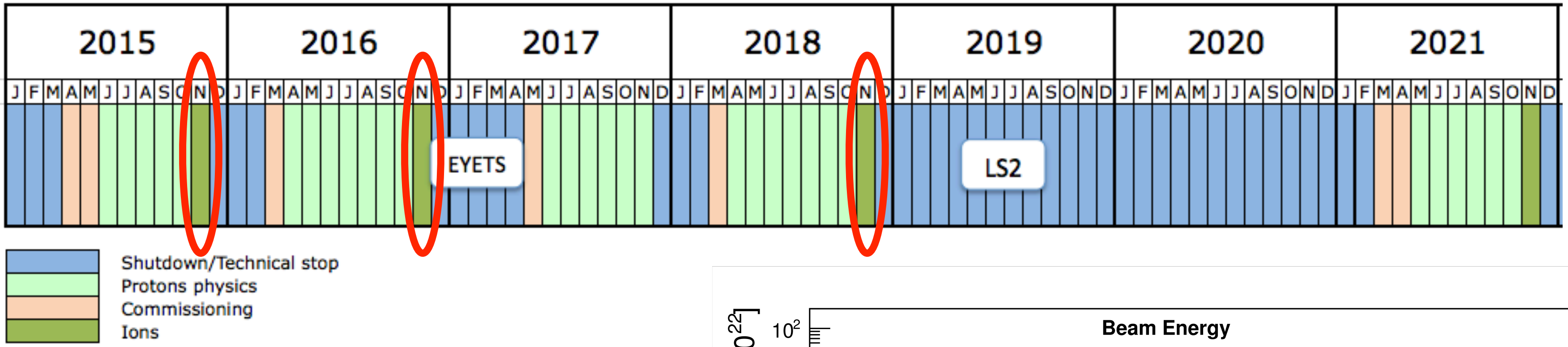
- LHCb - single armed forward spectrometer, located at LHC
- Acceptance $2 < \eta < 5$
- Proton-proton interaction at up to $\sqrt{s} = 13$ TeV
- Physics goals:
  - Designed for: *CP* violation in *b* and *c* sectors
  - Today: also general purpose physics in forward region



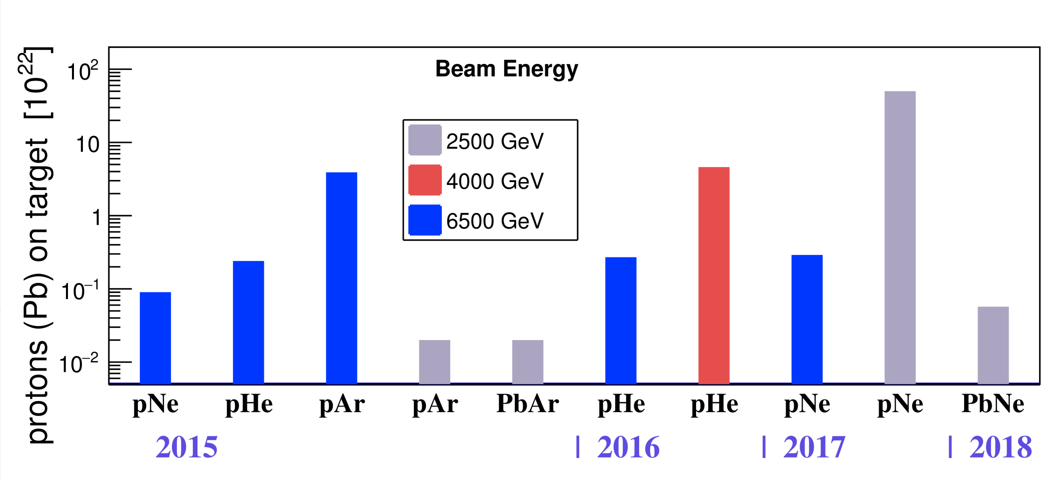
[IJMPA 30, 1530022 (2015)] [2008 JINST 3 S08005]

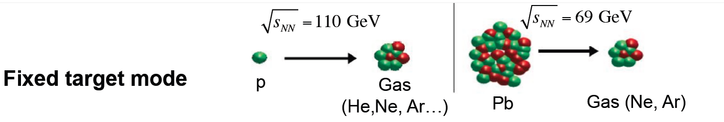
LHCb recorded data

- *pp* collider: 2010-2018, $\sqrt{s_{NN}}$ = 2.76, 5, 7, 8, 13 TeV, L≈ 9 fb^{-1}
- *p*Pb collider: 2013 and 2016, $\sqrt{s_{NN}}$ = 5.02 & 8.16 TeV, L≈ 2 & 34 nb^{-1}
- PbPb collider: 2015 and 2018, $\sqrt{s_{NN}}$ = 5 TeV, L≈ 10 μb^{-1} & 210 μb^{-1}

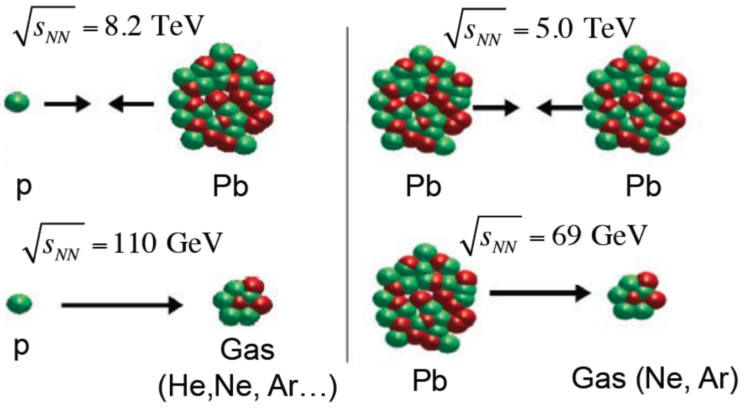


- Fixed-target mode: parasitic to collider mode, inject noble gas into VELO, use non-colliding bunches

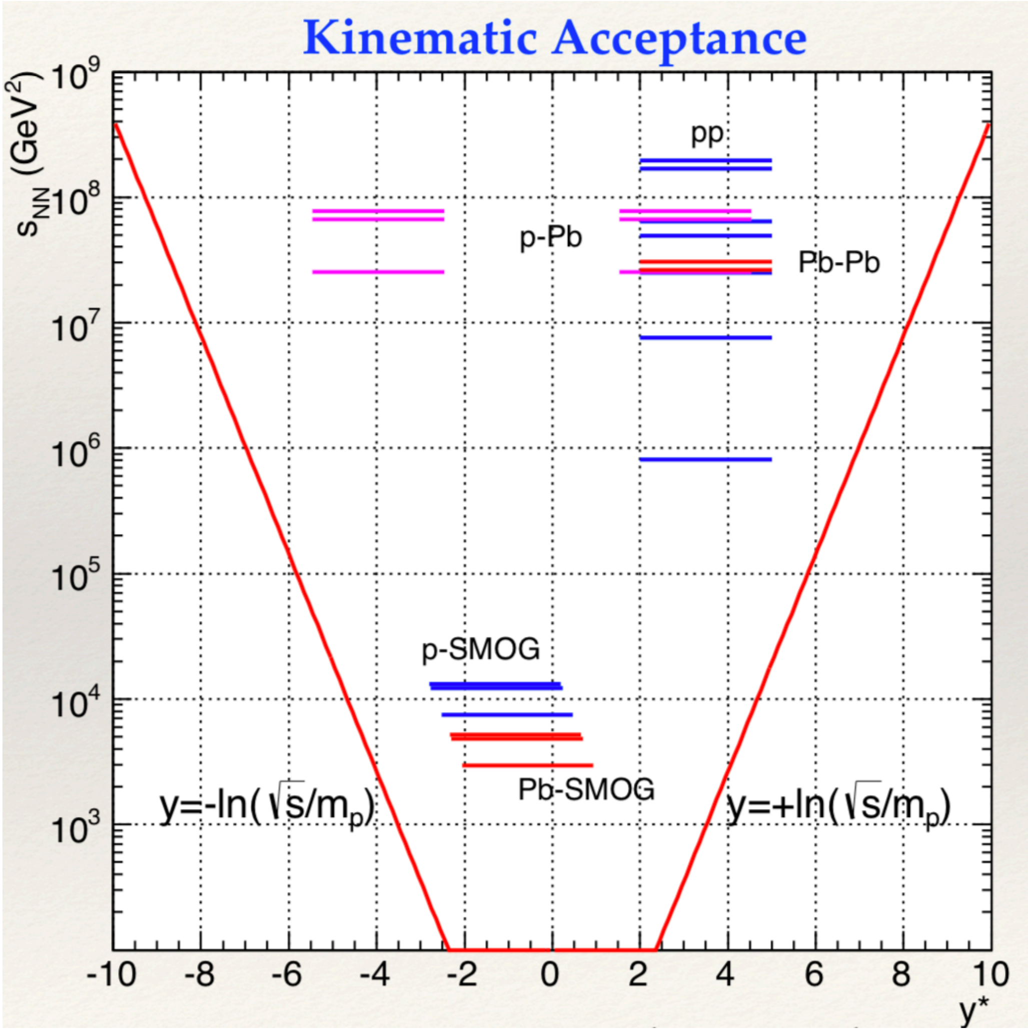




LHCb heavy-ion modes and kinematic coverage



- **Collider modes:**
  - ***pp***
  - ***p*Pb, PbPb**
- **Fixed-target modes:**
  - ***p*Ne, *p*He, *p*Ar**
  - **PbAr, PbNe**



LHCb heavy-ion recent results

- **Antiproton production in fixed-target configuration**
  - **LHCb-PAPER-2018-031, PRL 121 (2018) 222001**
- **Charm production in fixed-target configuration**
  - **LHCb-PAPER-2018-023, PRL 122 (2019) 132002**
- **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, JHEP 02 (2019) 102**
  - **B^+, B^0, Λ_b^0@8.16TeV: LHCb-PAPER-2018-048, PRD99 052011 (2019)**
  - **J/ψ@8.16TeV: LHCb-PAPER-2017-014, PLB774 (2017) 159**
  - **$\Upsilon(nS)$@8.16TeV: LHCb-PAPER-2018-035, JHEP 11 (2018) 194**
- **Exclusive photonuclear J/ψ production in ultra-peripheral PbPb collisions @5TeV**
  - **LHCb-CONF-2018-003**

LHCb heavy-ion recent results

- **Antiproton production in fixed-target configuration**
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Luciano's talk
on Thursday

- **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, JHEP 02 (2019) 102**
  - **B^+, B^0, Λ_b^0@8.16TeV: LHCb-PAPER-2018-048, PRD99 052011 (2019)**

Di's talk
on Tuesday

  - **J/ψ@8.16TeV: LHCb-PAPER-2017-014, PLB774 (2017) 159**
  - **$\Upsilon(nS)$@8.16TeV: LHCb-PAPER-2018-035, JHEP 11 (2018) 194**

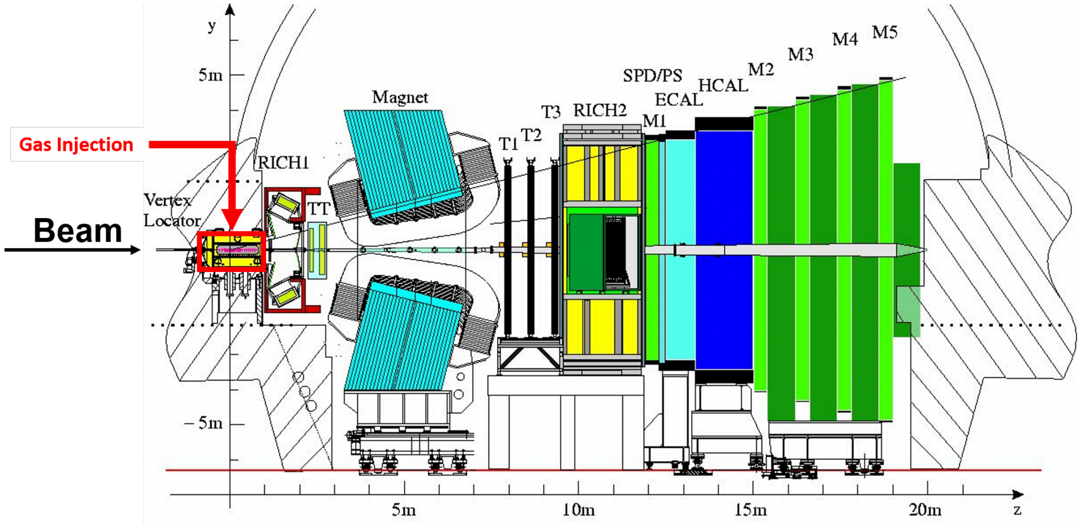
Hengne's talk
on Thursday

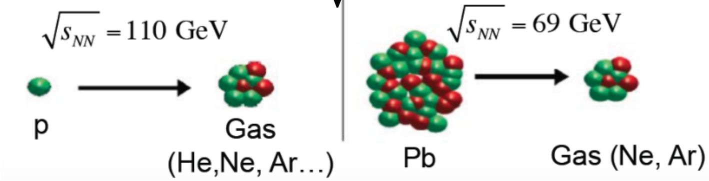
- **Exclusive photonuclear J/ψ production in ultra-peripheral PbPb collisions @5TeV**
  - **LHCb-CONF-2018-003**

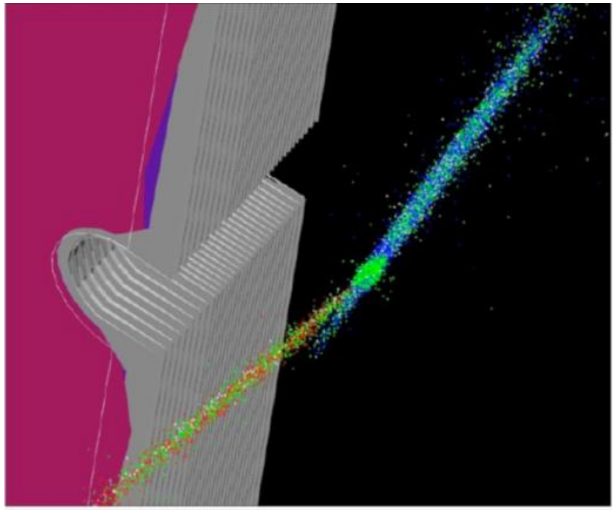
Fixed-target mode setups at LHCb

- **SMOG = System for Measuring Overlap with Gas**
- **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**

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







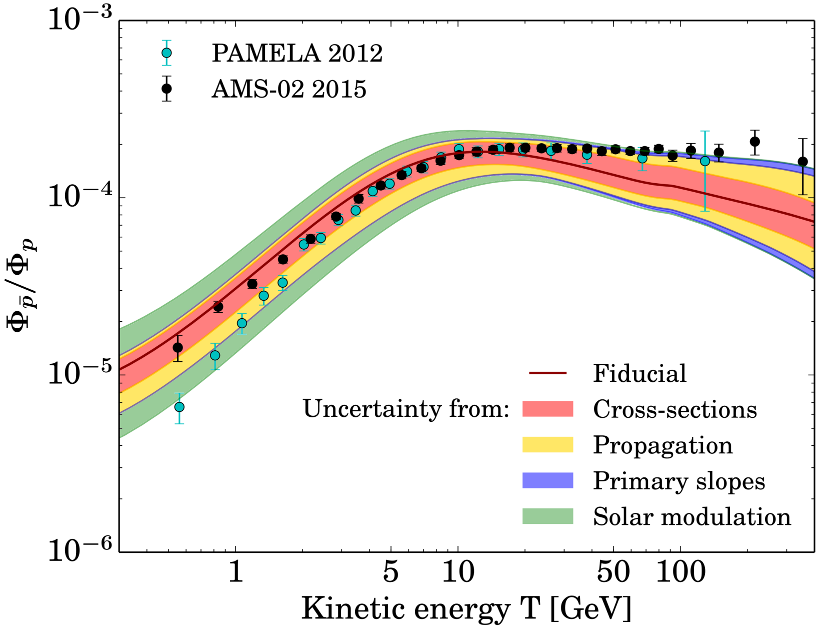
Distribution of vertices overlaid on detector display. z-axis is scaled by 1:100 compared to transverse dimensions to see the beam angle.

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

PRL 121 (2018) 222001

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

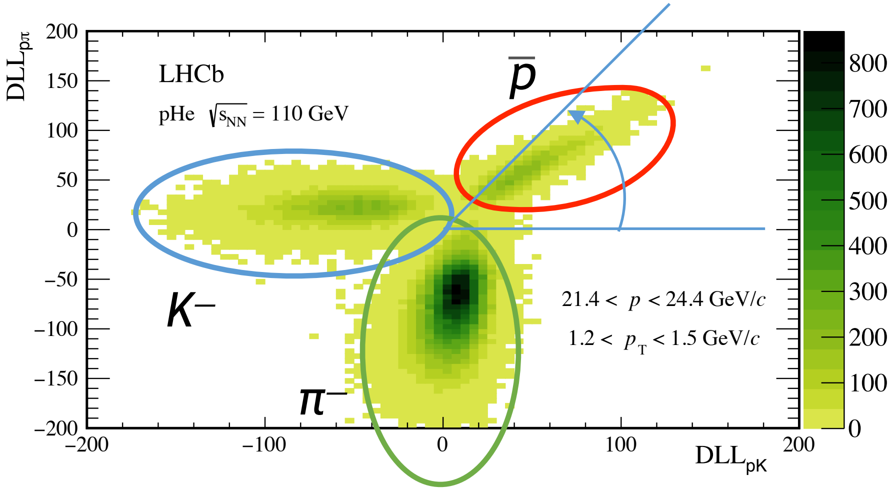
- Antiproton/proton ratio known with great precision in cosmic rays
  - AMS02 (PRL 117, 091103 (2016))
  - PAMELA (JETP Letters 96 (2013) 621)
- Hint for a possible excess
- Flux prediction uncertainties in 10-100 GeV kinetic energy range: dominated by production cross-sections uncertainties
  - Need 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

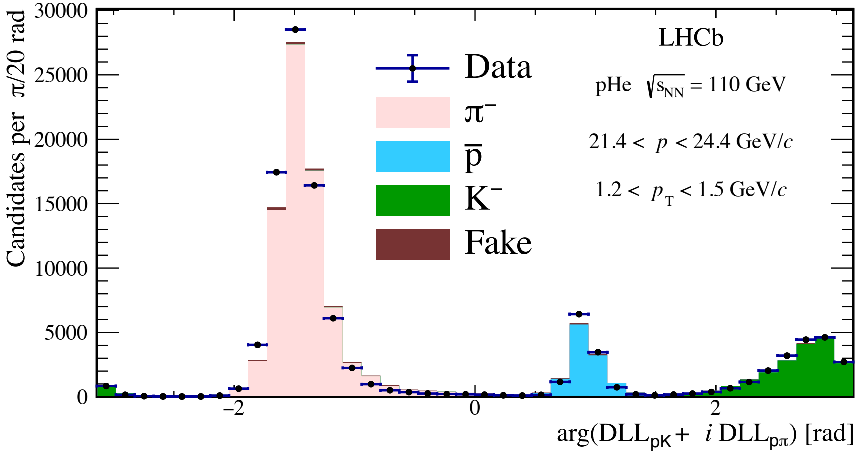


PRL 121 (2018) 222001

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

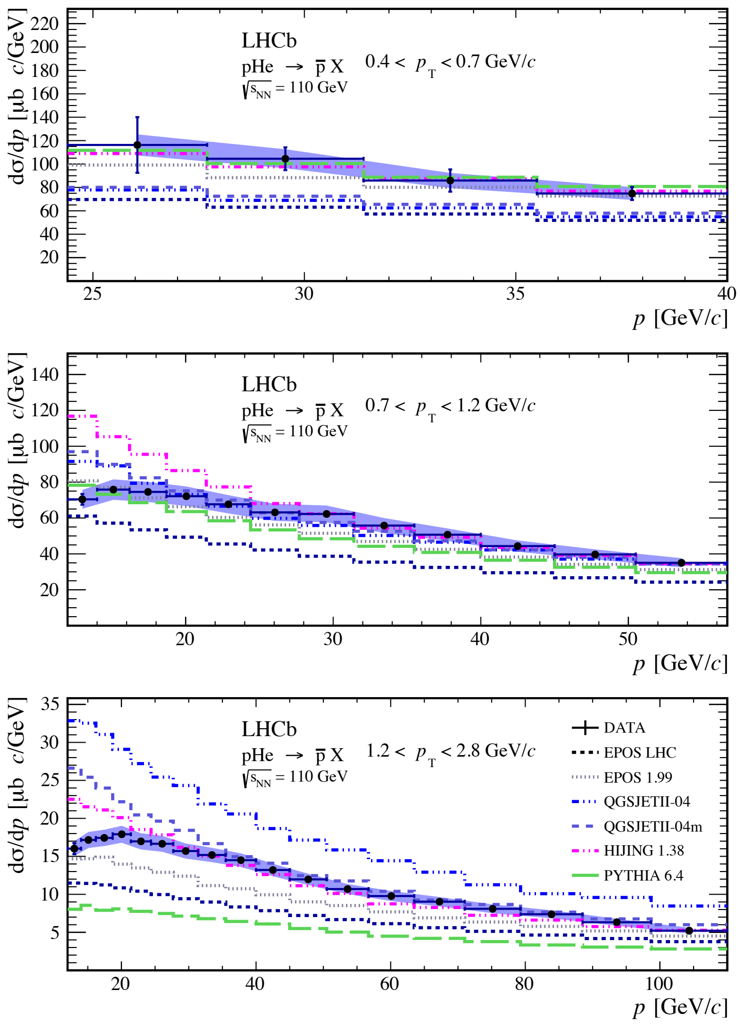
- Data collected in 2016 in pHe collisions at $\sqrt{s_{NN}} = 110$ GeV
- Counting antiproton in (p, p_T) bins
- Access to range 12 GeV/c < p < 110 GeV/c, p_T > 0.4 GeV/c
- PID with 2 RICH detectors
- Account for background by residual gas
- Luminosity from pe^- elastic scattering





PRL 121 (2018) 222001

$\bar{p}$ 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**

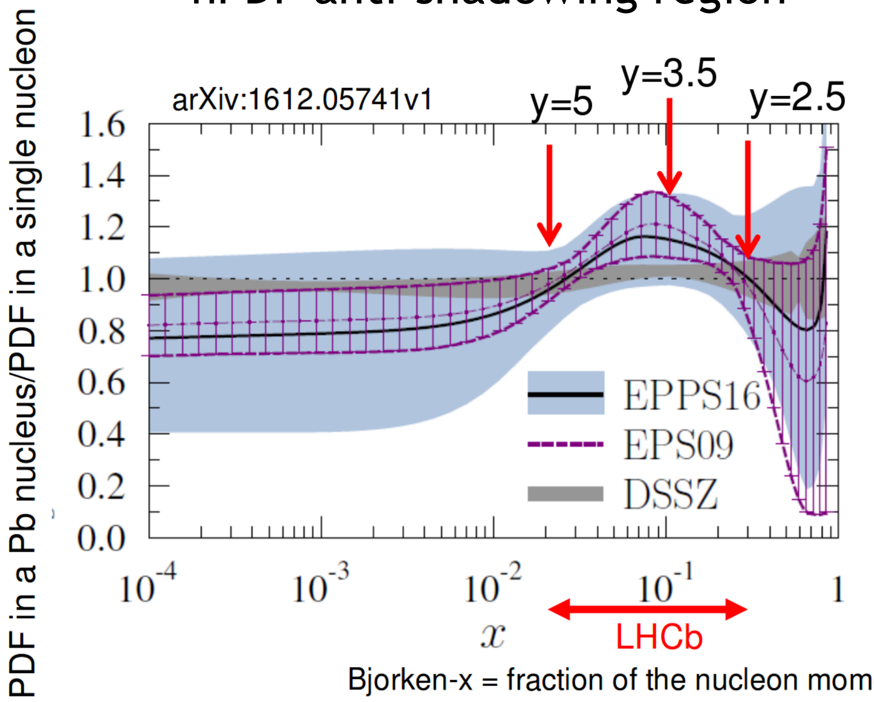
Also see Luciano's talk

PRL 122 (2019) 132002

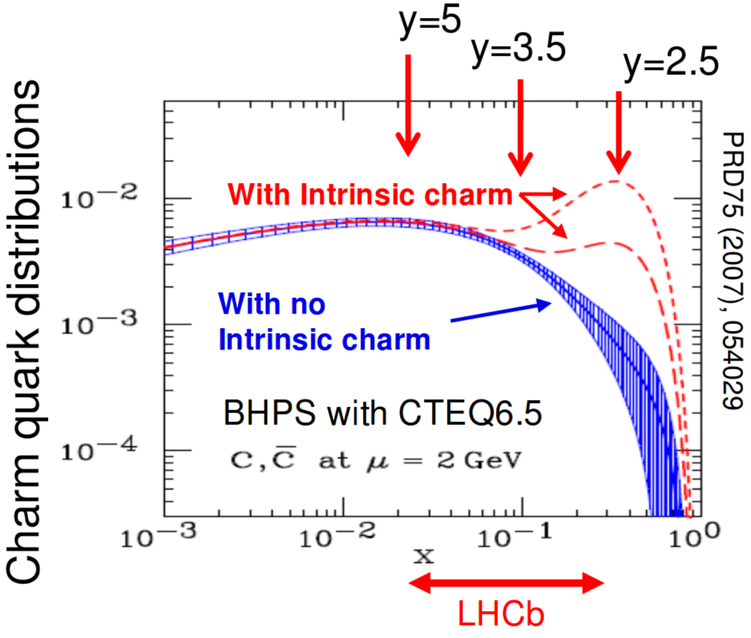
Charm production in fixed-target *p*-A collisions

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

nPDF anti-shadowing region



Valence-like intrinsic charm content in the nucleon

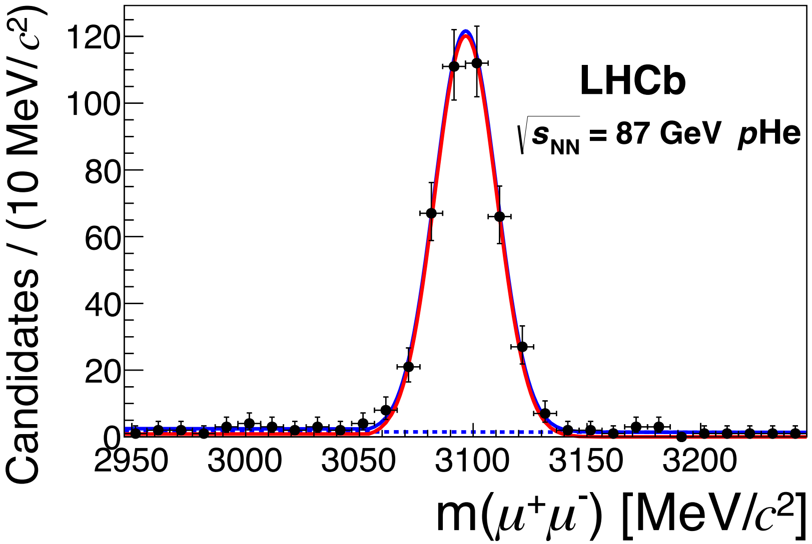


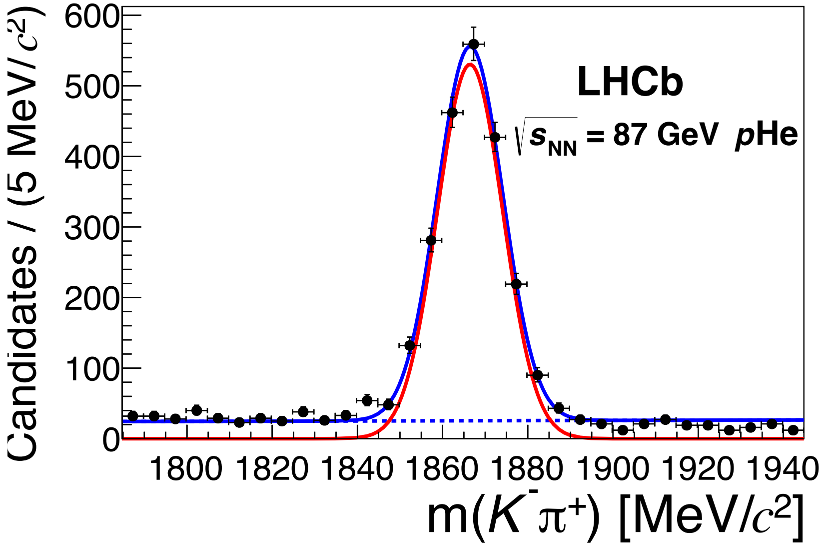
Bjorken-x = fraction of the nucleon momentum carried by a parton

PRL 122 (2019) 132002

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

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





PRL 122 (2019) 132002

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

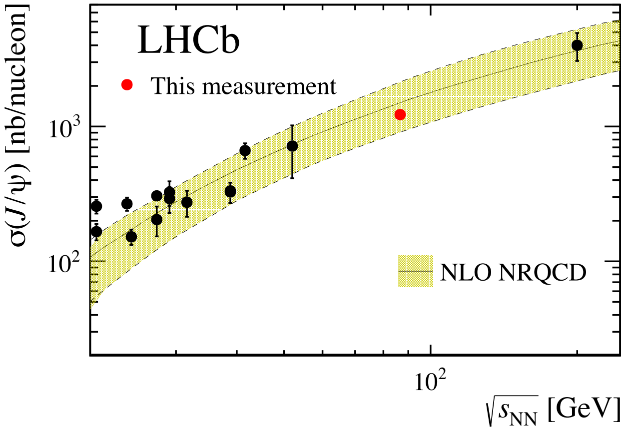
- **J/ψ and D^0 inclusive cross sections in *p*He @86.6 GeV**

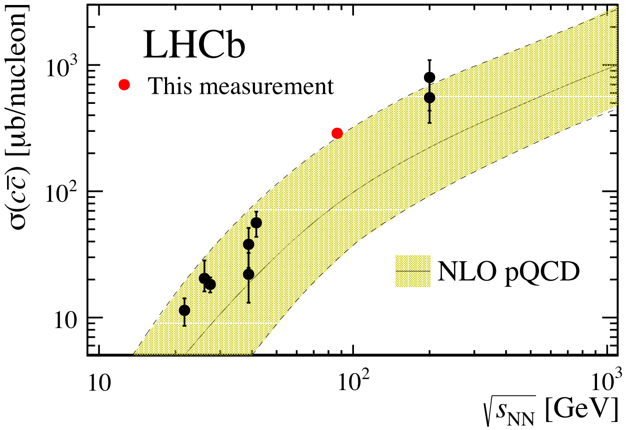
$$\sigma_{J/\psi}^{86.6\ \mathrm{GeV}} = 1225.6 \pm 62.0(stat.) \pm 81.6(syst.)\ \mathrm{nb/nucleon}$$

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

- **Scaling the D^0 cross-section with the global fragmentation ratio f($c \rightarrow D^0$) = 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**

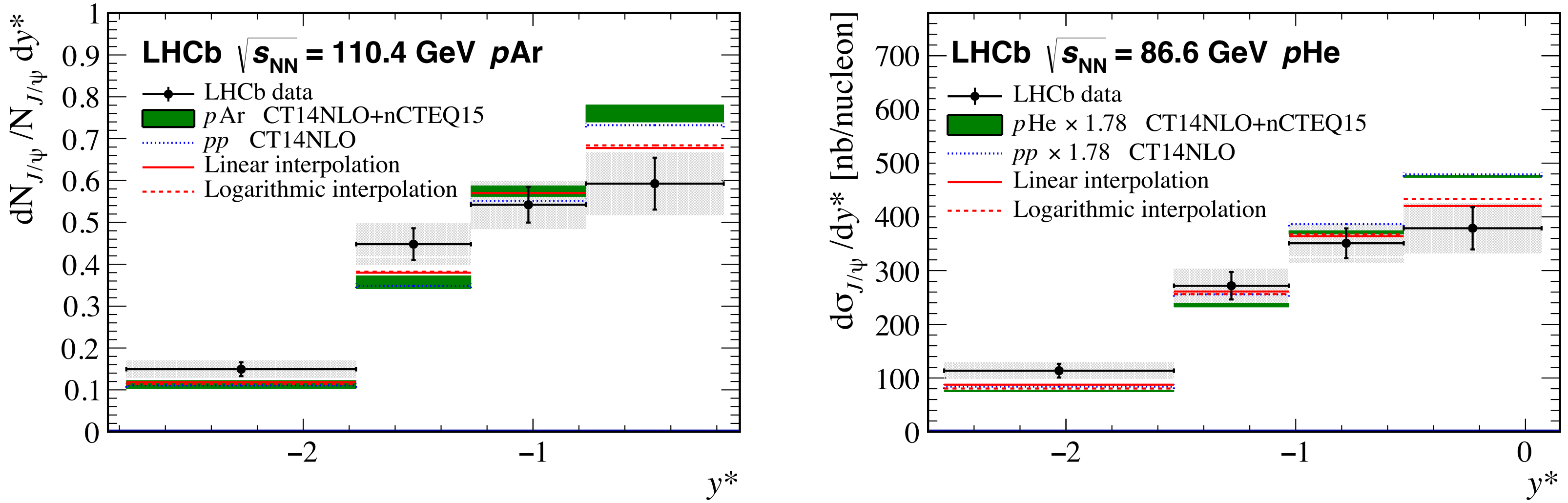
PRL 122 (2019) 132002

Charm production in fixed-target p-A collisions

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

pAr@110 GeV

pHe@86.8 GeV

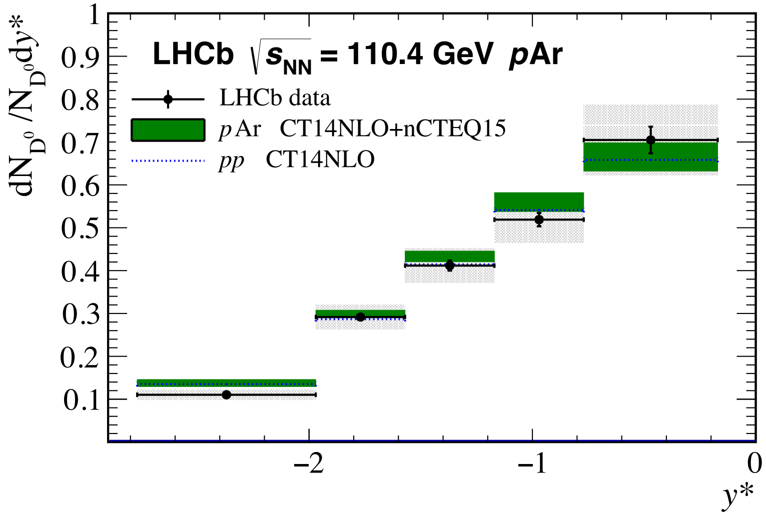


- **HELAC-ONIA [EPJC 77:1 (2017)] predictions for *pp* (blue line) and *p*A (Green box) overlaid with measurement. HELAC-ONIA underestimate the J/ψ cross section (*p*He) by a factor 1.78.**
- **Plain and dashed red lines: phenomenological parametrization [JHEP 1303(2013) 122]. Good shape agreement with phenomenological predictions.**

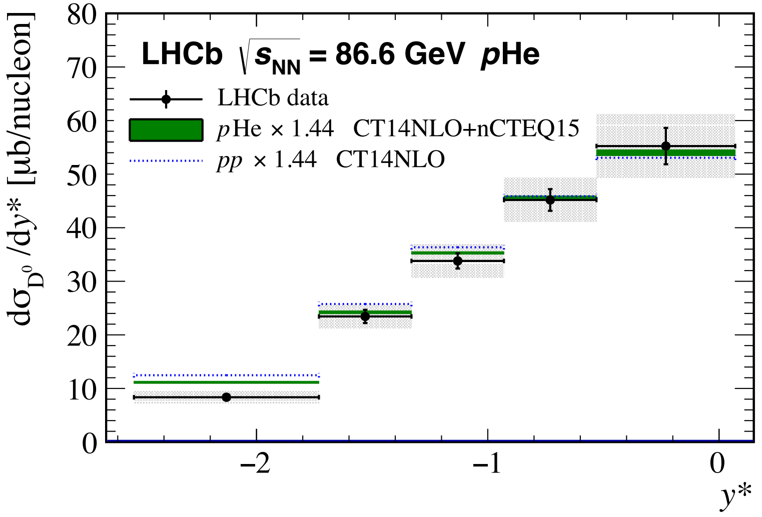
PRL 122 (2019) 132002

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

- ***D^0* differential yields (*p*Ar@110GeV) and cross-section (*p*He@86.6GeV)**



pAr@110 GeV

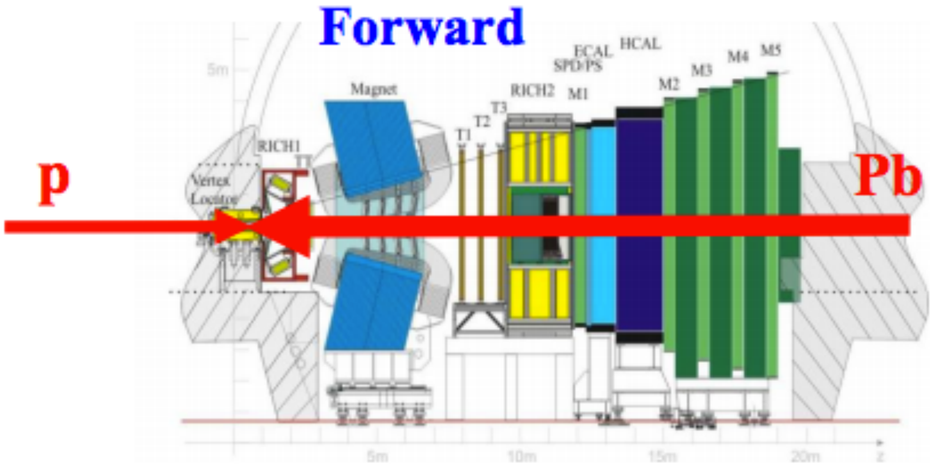


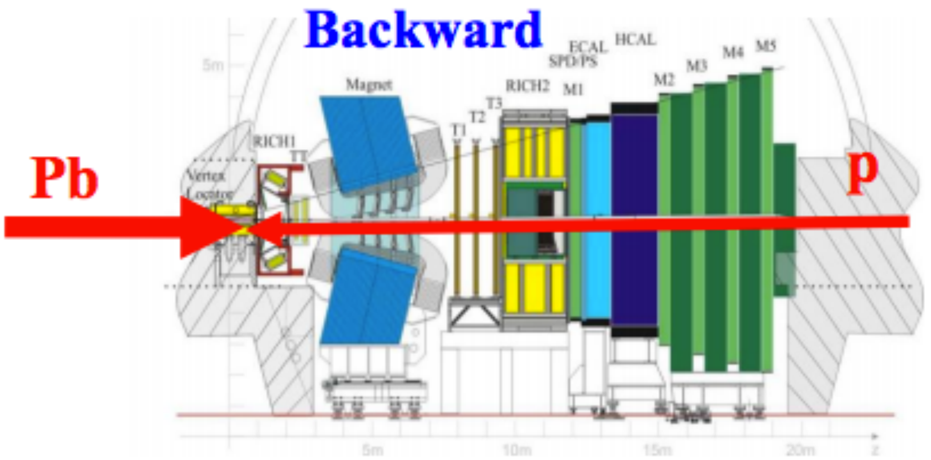
pHe@86.8 GeV

- **HELAC-ONIA [EPJC 77:1 (2017)] predictions for *pp* (blue line) and *p*A (Green box) overlaid with measurement. HELAC-ONIA underestimate the *D^0* 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**

Also see Luciano’s talk

Proton-lead modes setups at LHCb


Forward


Backward

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

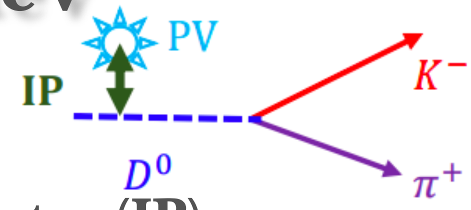
- **Study of cold nuclear matter effects and their disentangling from QGP effects**
- **Nuclear effects quantified by nuclear modification factor:**

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

where reference σ_{pp} at 5.02 TeV are from *pp* 5 TeV measurements, and reference σ_{pp} at 8.16 TeV are from interpolations with *pp* 2.76, 5, 7, 8, 13 TeV data

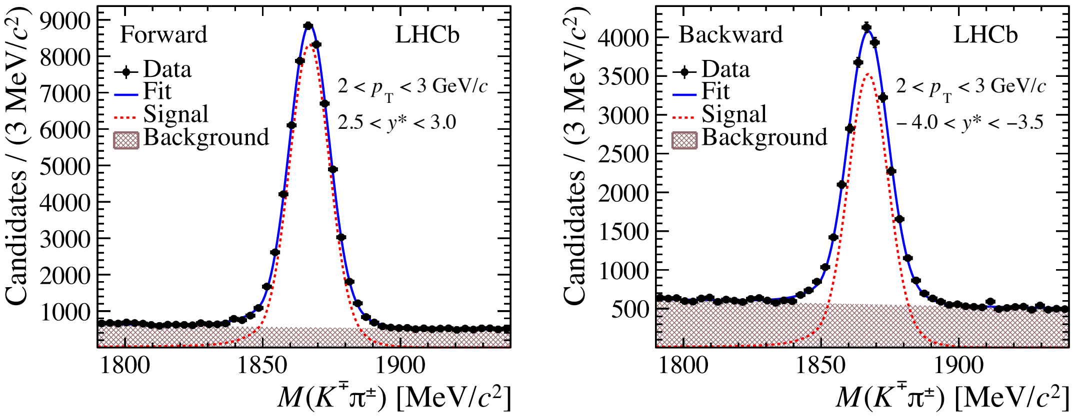
JHEP (2017) 090

Prompt D^0 production in pPb at 5.02 TeV

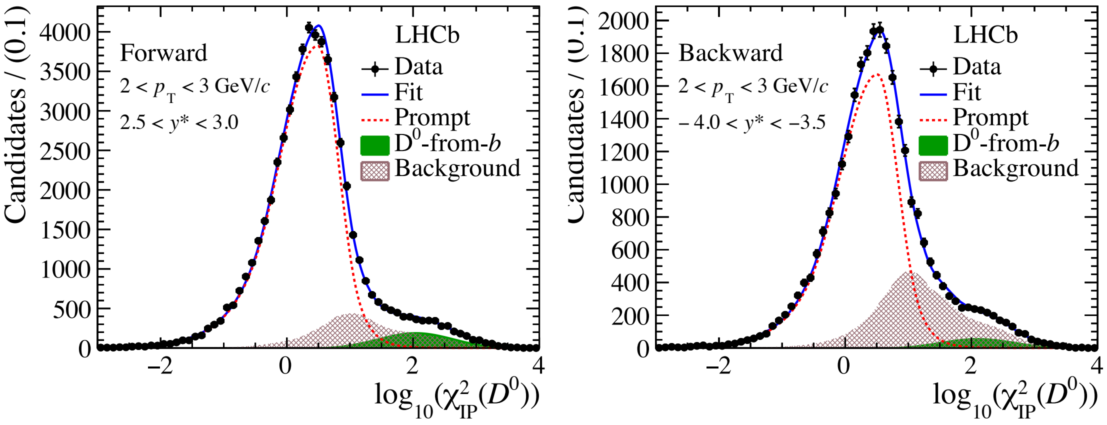


- **Reconstructed through $D^0 \to K^-\pi^+$ decays**
- **Simultaneous 2D fit to D^0 mass and impact parameter (IP)**

Forward backward



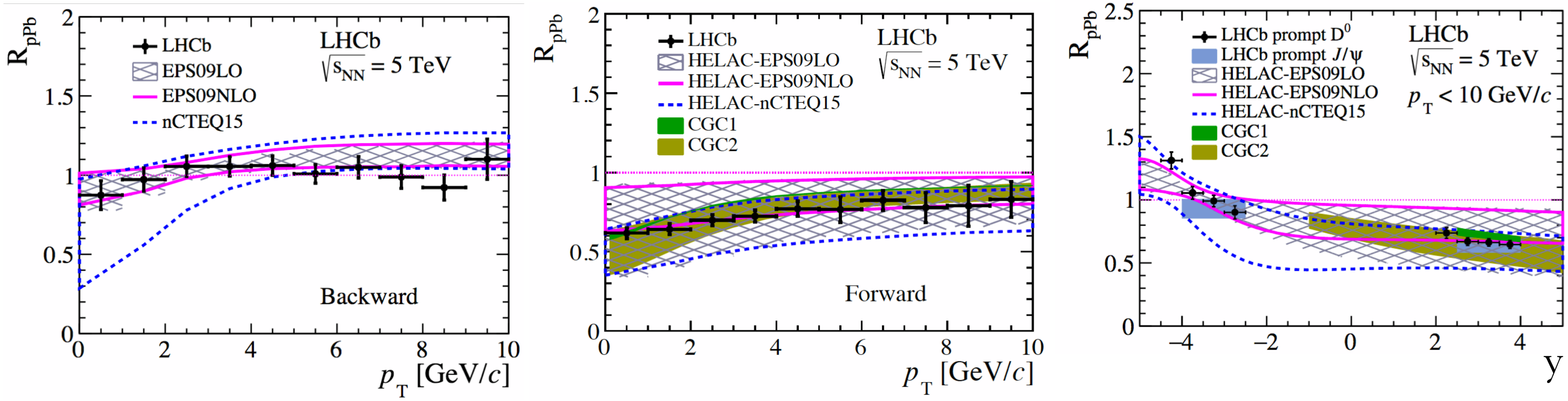
Mass distribution:
Signal: Crystal Ball
Background:Linear



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

JHEP (2017) 090

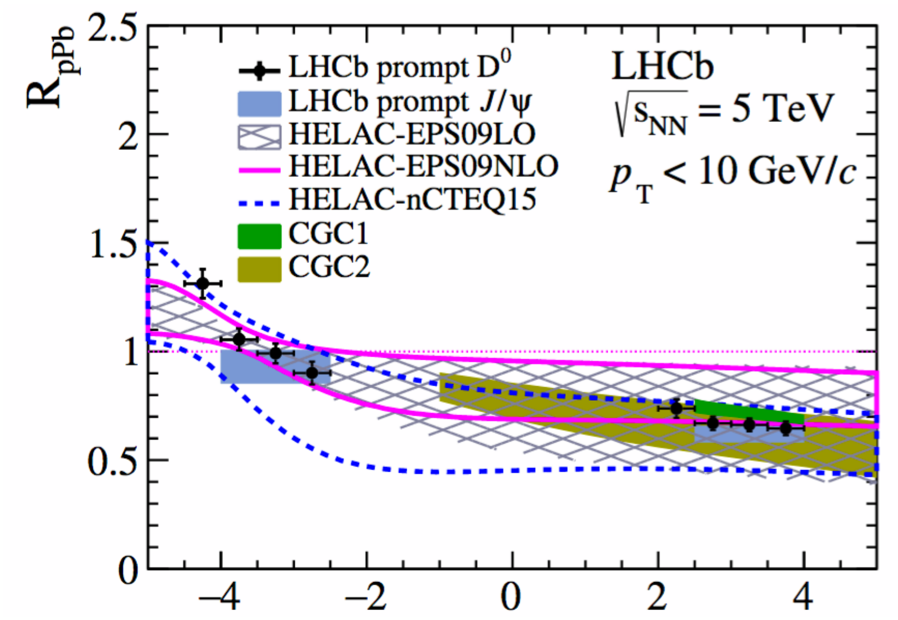
Prompt D^0 nuclear modification factor

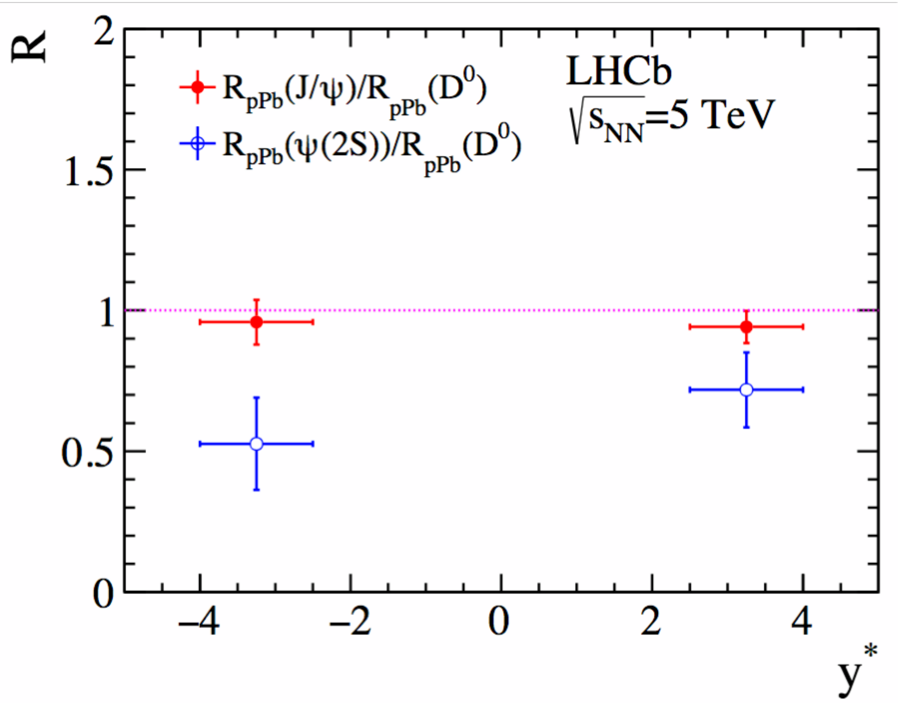


- **Strong suppression at forward rapidity (~30%),**
- **Backward rapidity: compatible with no suppression and hint of enhancement —> different nuclear effect in forward and backward regions**
- **Suppression-enhancement pattern predicted by nPDFs [Eur. Phys. J. C77 (2017) 1, Comput. Phys. Commun. 184 (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**

JHEP (2017) 090

Prompt D^0 nuclear modification factor





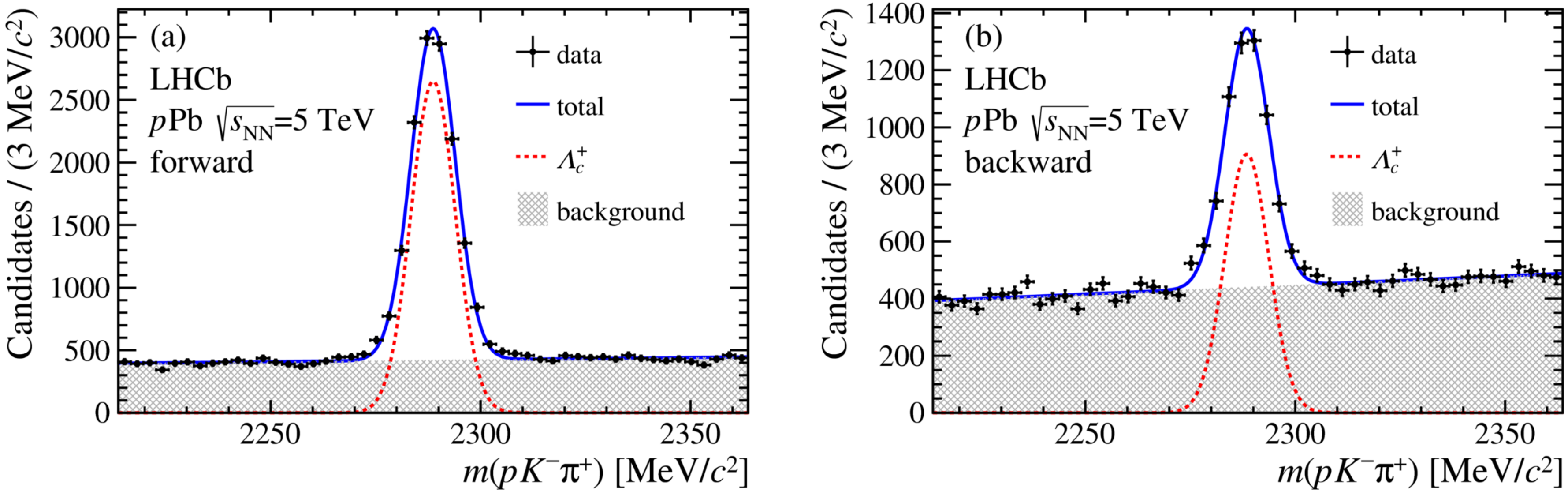
- **Compare with** J/ψ **and** $\psi(2S)$ **results at 5 TeV**
- **Similar nuclear modification factor for** J/ψ **to** D^0**,** $\frac{R_{pPb}(J/\psi)}{R_{pPb}(D^0)} \sim 1$
- **More suppressed for** $\psi(2S)$ **to** D^0

Also see Di's talk

JHEP 02 (2019) 102

Prompt Λ_c^+ production in *p*Pb at 5.02 TeV

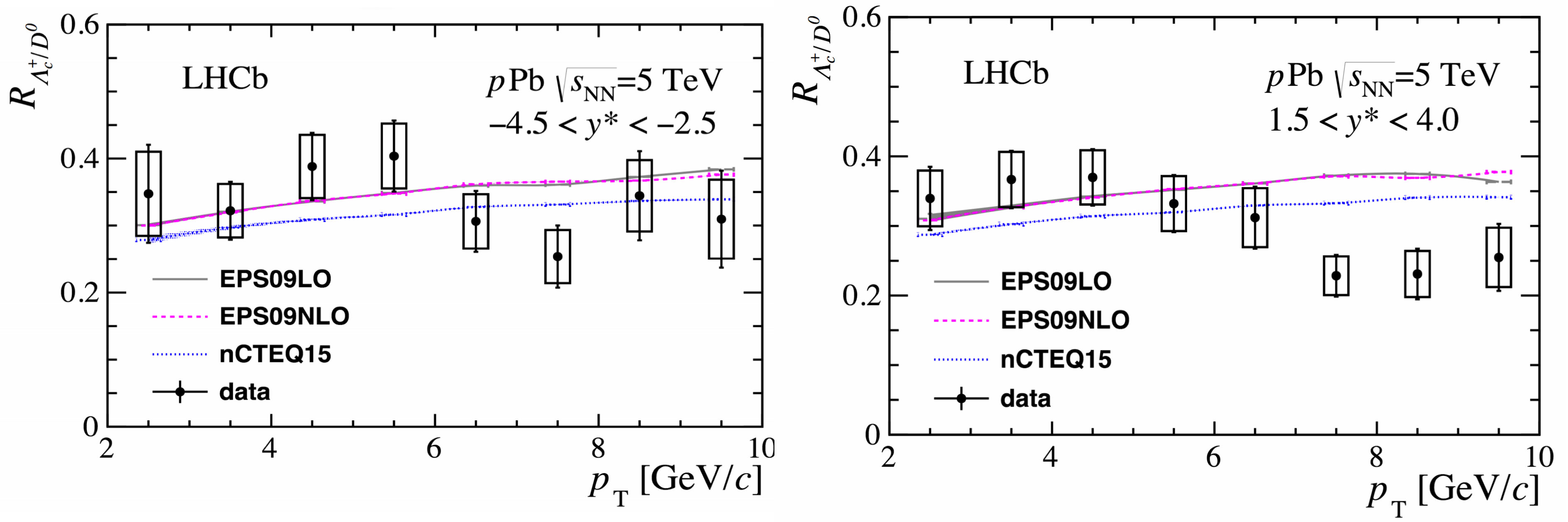
- **Reconstructed through $\Lambda_c^+ \to pK^-\pi^+$ decays**



- **Similar analysis strategy as *D⁰***

JHEP 02 (2019) 102

Prompt Λ_c^+ production in pPb at 5.02 TeV



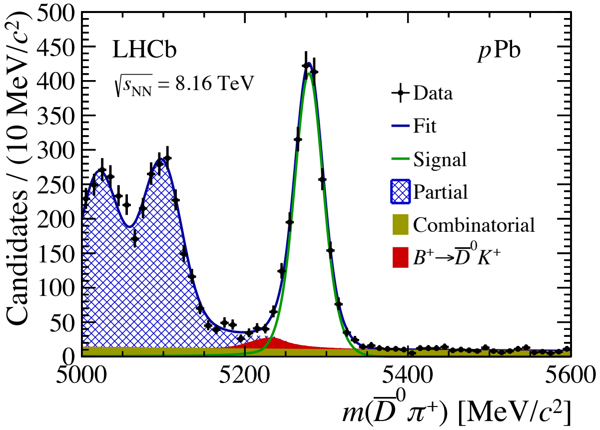
- Λ_c^+/D^0 similar in forward and backward directions
- Generally consistent with expectations from pp data $\Lambda_c^+/D^0 \sim 0.3$,
- Compared with nPDFs [JHEP 04 (2009) 065, EPJ C77 (2017) 1, Comput. Phys. Commun. 198 (2016) 238], hint of discrepancy at high p_T in forward direction

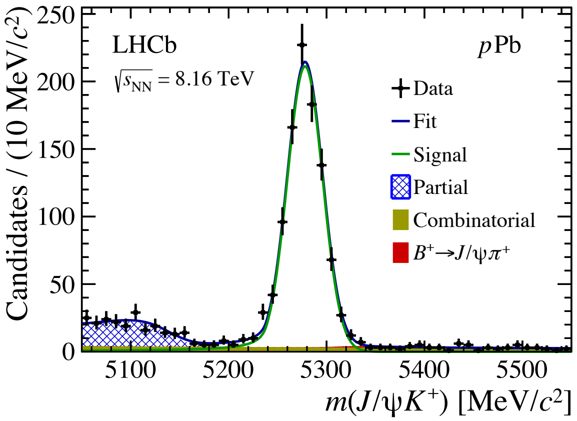
Also see Di's talk

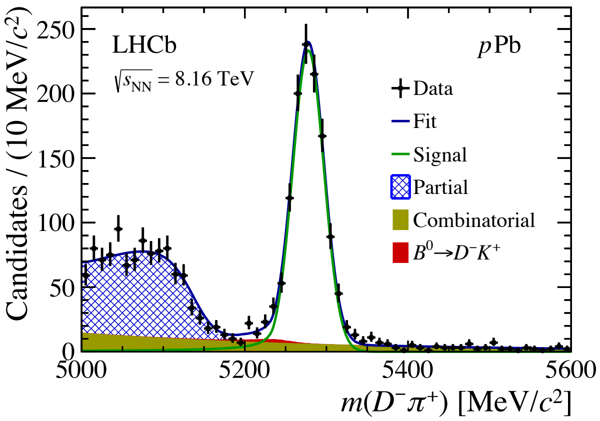
PRD99 052011 (2019)

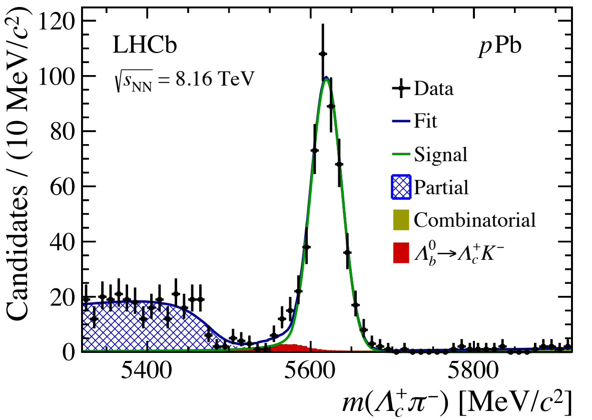
b-hadron production in pPb at 8.16 TeV

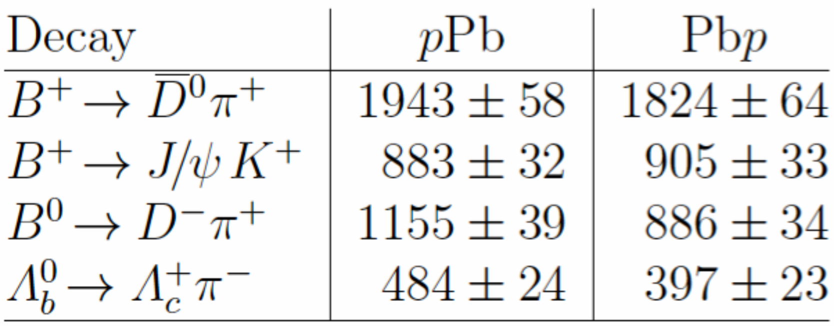
- **Exclusive decay modes: $B^+ \to J/\psi K^+$, $B^+ \to D^0\pi^+$, $B^0 \to D^-\pi^+$, $\Lambda_b^0 \to \Lambda_c^+\pi^-$**









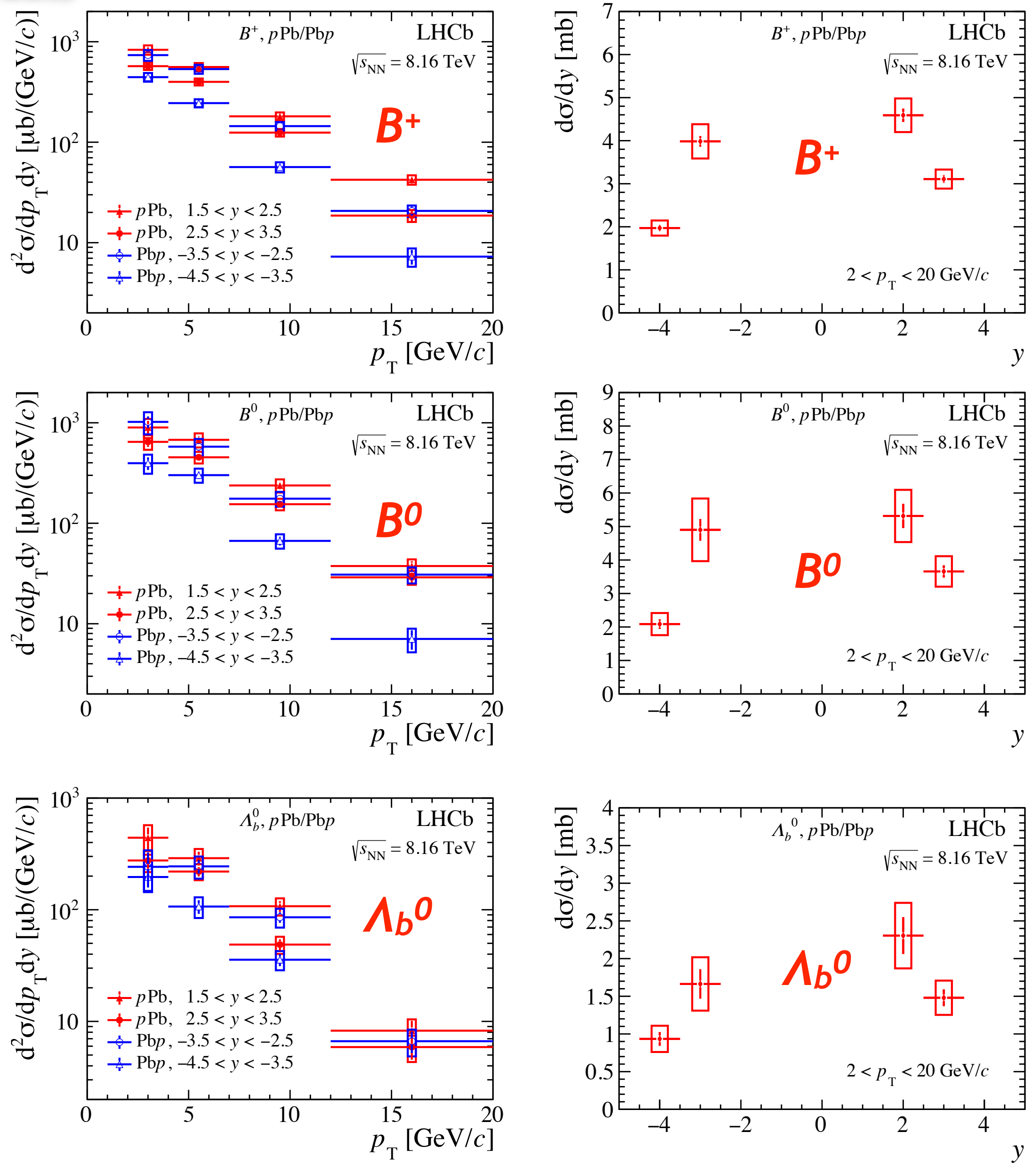


Decay	pPb	Pbp
$B^+ \to \overline{D}^0\pi^+$	1943 ± 58	1824 ± 64
$B^+ \to J/\psi\, K^+$	883 ± 32	905 ± 33
$B^0 \to D^-\pi^+$	1155 ± 39	886 ± 34
$\Lambda_b^0 \to \Lambda_c^+\pi^-$	484 ± 24	397 ± 23

PRD99 052011 (2019)

b-hadron cross-sections

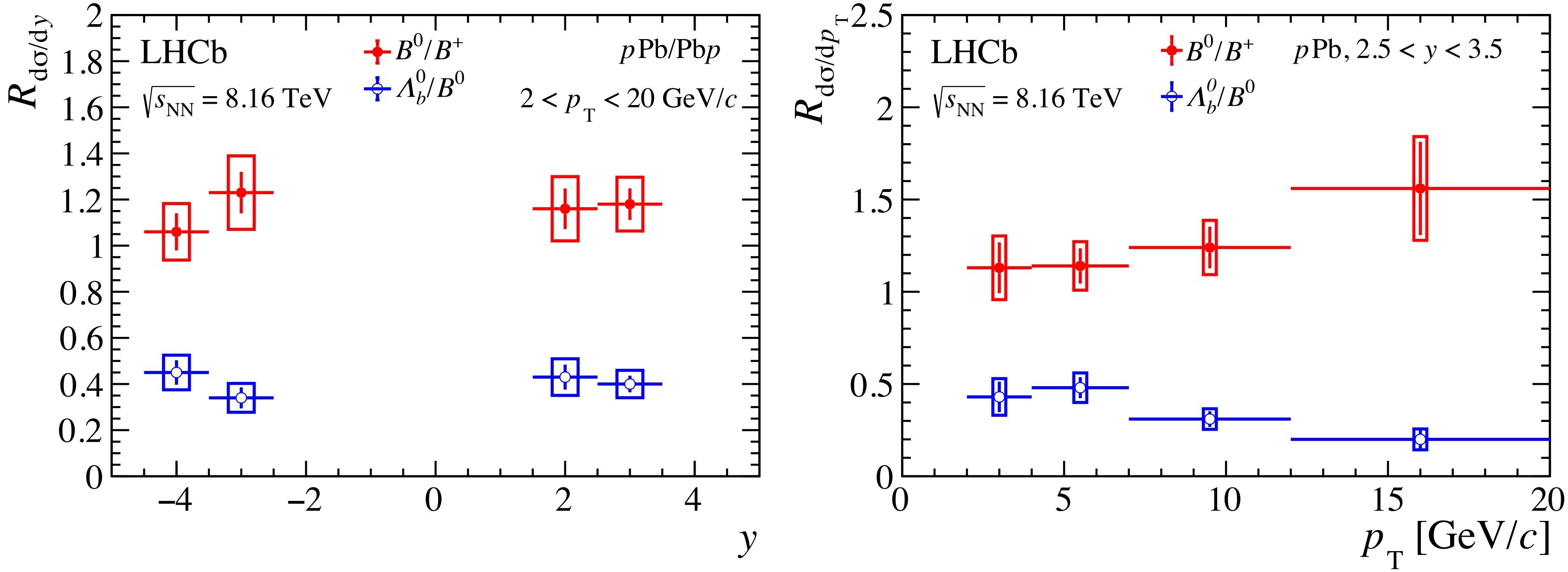
- B^+ cross-section studied in $J/\psi K^+$ and $D^0\pi^+$ modes. Both modes consistent. Weighted average shown here
- Similar p_T and y distributions for B^+,B^0 and Λ_b^0 hadrons



PRD99 052011 (2019)

b-hadron cross-section ratios

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

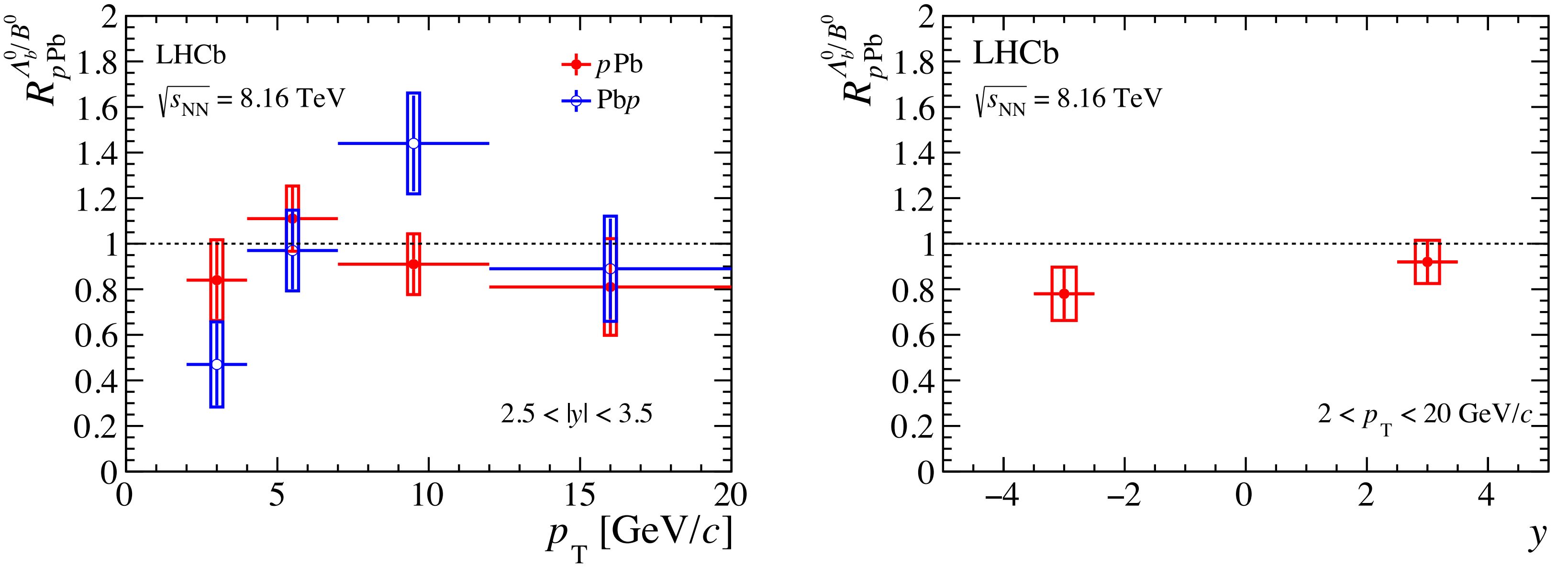


- ***B^0/B^+* ratio independent of *y* and *p_T*, slightly above unity (isospin symmetry)**
- ***Λ_b^0/B^0* ≈40%, decreasing with *p_T*, no hint of strong rapidity dependence. similar to results in LHCb *pp* data [JHEP 08 (2014) 143]**
- ***Λ_b^0/B^0* ratio reaches LEP data at high *p_T*, 0.20 ± 0.02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

PRD99 052011 (2019)

Λ_b^0 and B^0 relative modification

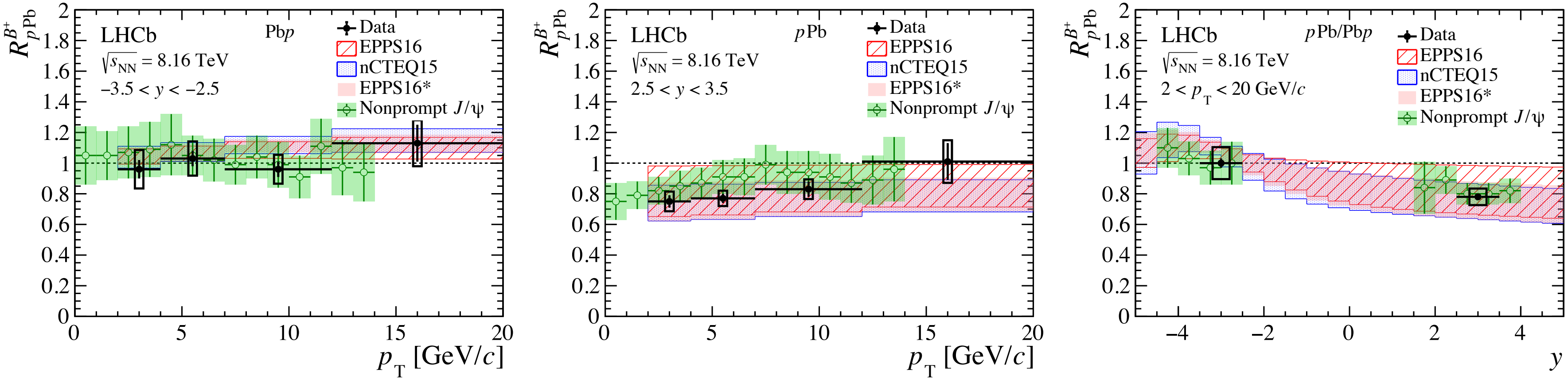
- **Ratio of R_{pA} between Λ_b^0 and B^0 hadrons**



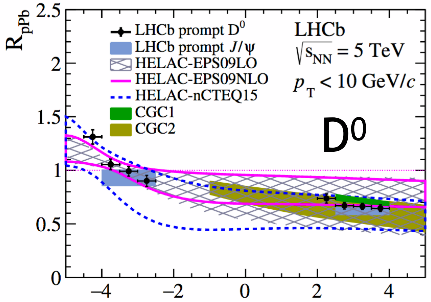
- **Forward rapidity: consistent with unity in all kinematic bins —> *b*-quark fragmentation function at forward rapidity similar to *pp***
- **Backward rapidity: hint of stronger suppression for Λ_b^0 compared with B^0. Demanding more statistics for a firm conclusion.**

PRD99 052011 (2019)

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]**

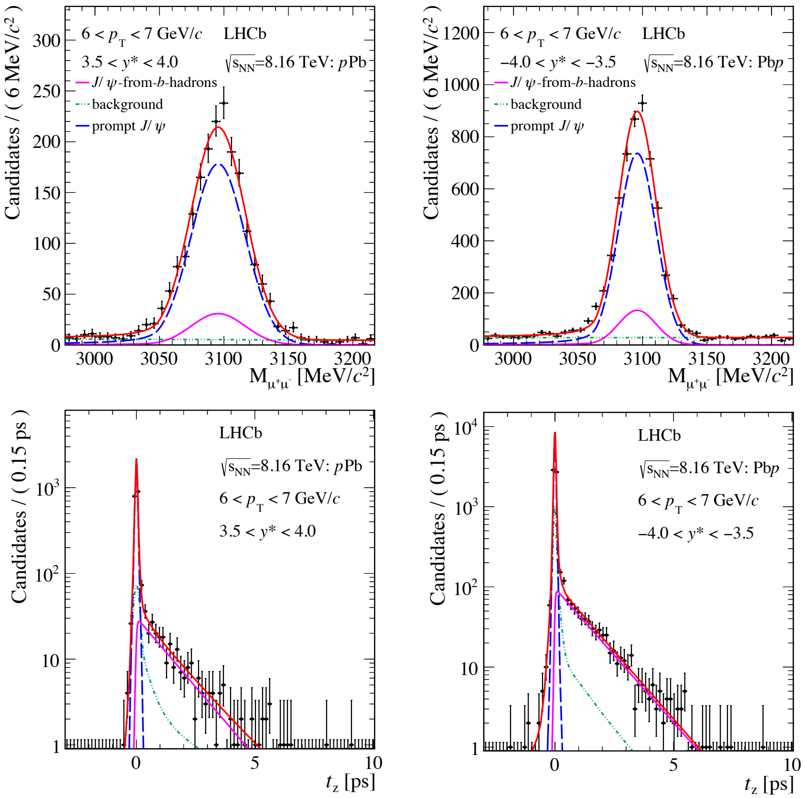
Also see Di's talk

PLB774 (2017) 159

J/ψ production in pPb at 8.16 TeV

- **Quarkonium: QCD hydrogen atom → probe deconfinement in PbPb**
- **J/ψ , $\Upsilon(nS)$ suppression observed in PbPb by CMS and ALICE**
- **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:

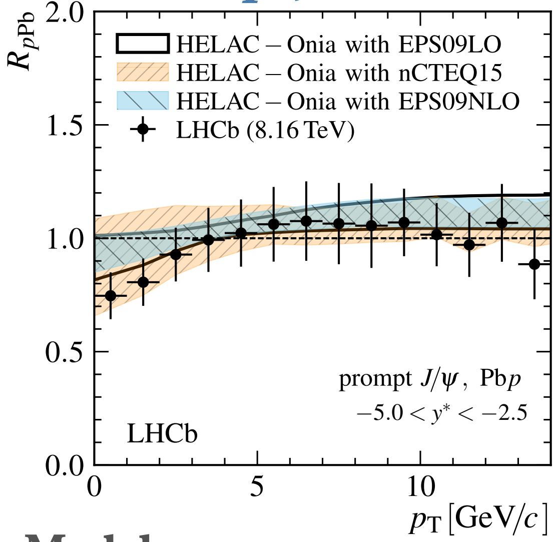
	prompt	from-b
Forward:	3.8×10^5;	6.7×10^4
Backward:	5.6×10^5;	7.1×10^4

PLB774 (2017) 159

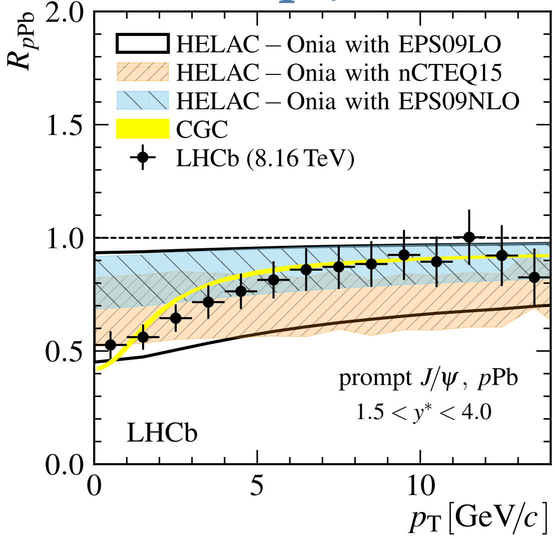
Prompt J/ψ nuclear modification factor

- **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 *p*Pb 5 TeV results.**

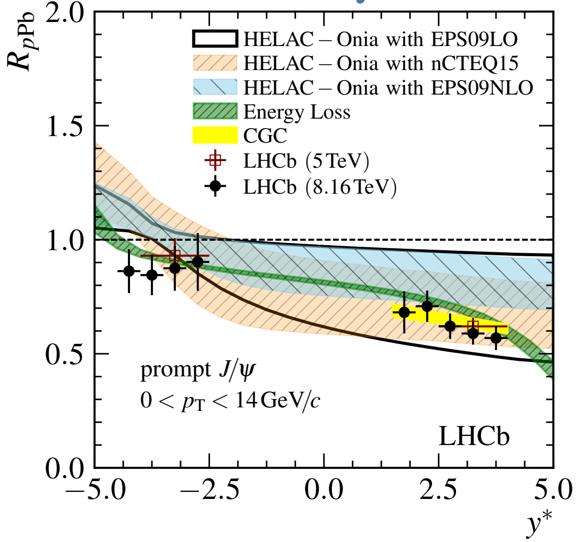
R_{pPb} vs. p_T, Backward



R_{pPb} vs. p_T, Forward



R_{pPb} vs. y*



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

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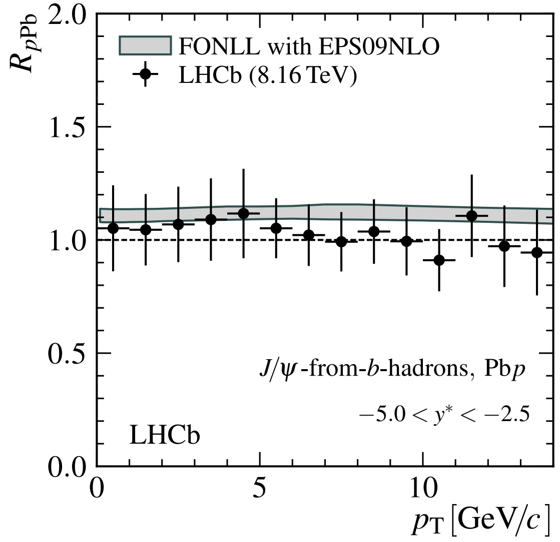
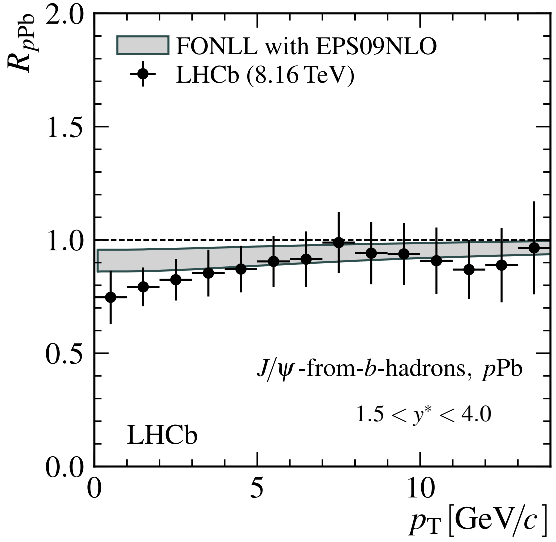
J/ψ-from-b nuclear modification factor

- **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.**

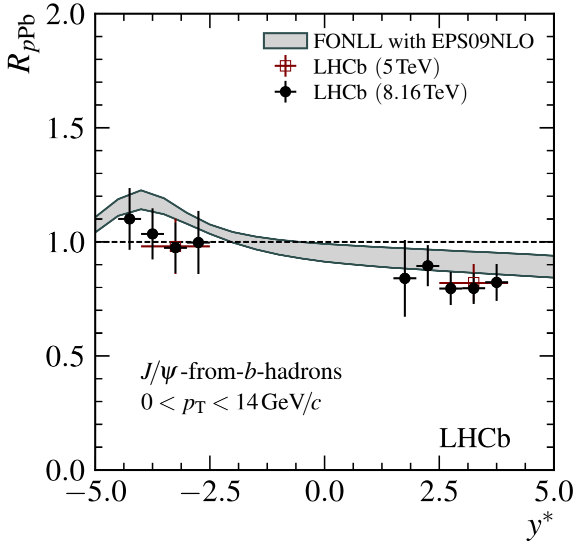
R_{pPb} vs. p_T, Backward



R_{pPb} vs. p_T, Forward



R_{pPb} vs. y*

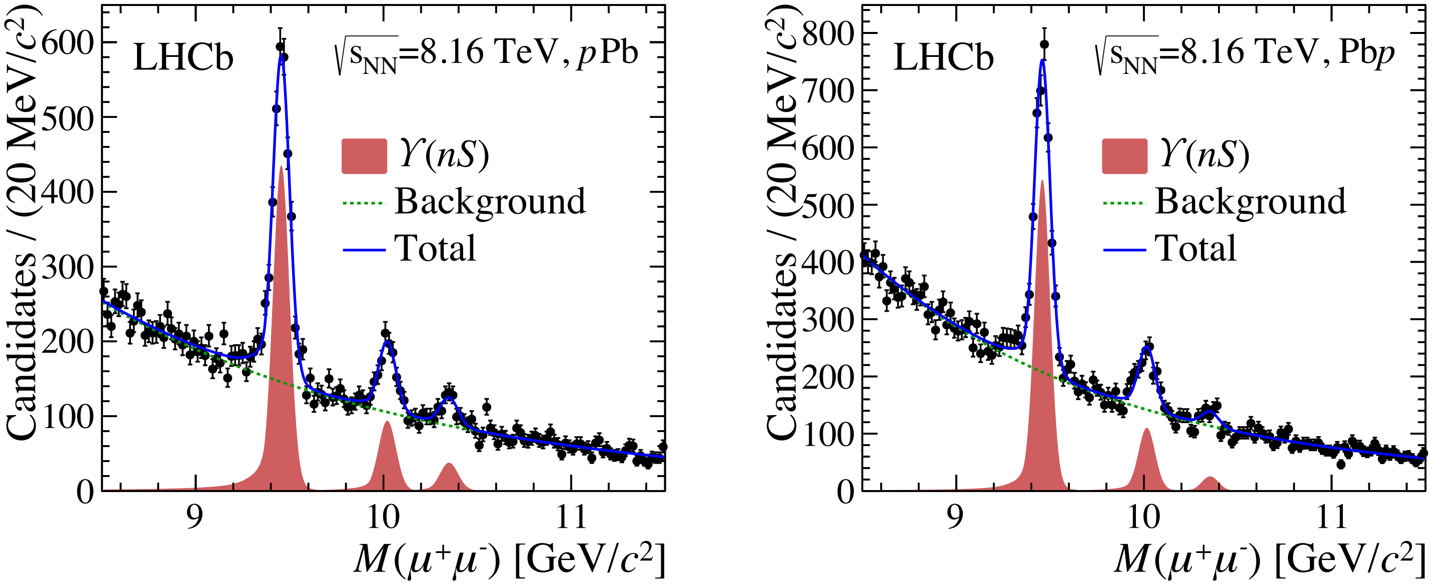


Model:
FONLL: JHEP 05(1998) 007, JHEP03 (2001) 006

Also see Hengne's talk

ϒ(nS) production in *p*Pb at 8.16 TeV

- **Observed additional suppression of *ϒ(2S,3S)* at low-p_T in *p*Pb/Pb*p* by LHCb collaborations in Run-I, but statistics limited**



- **LHCb Run-II: Factor 20 more luminosity in 2016 than in Run-I**
- **Mass spectra are fitted with double crystal ball functions**
- **Clear *ϒ(3S)* signal in both forward and backward rapidity**

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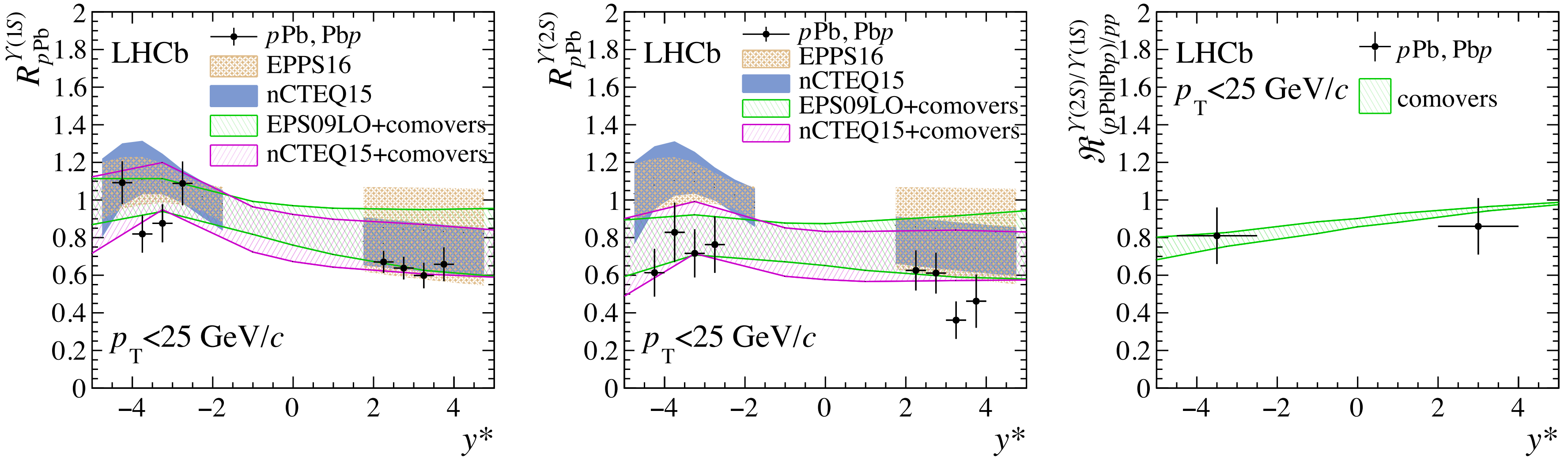
Υ(1S) and *Υ(2S)* nuclear modification factor



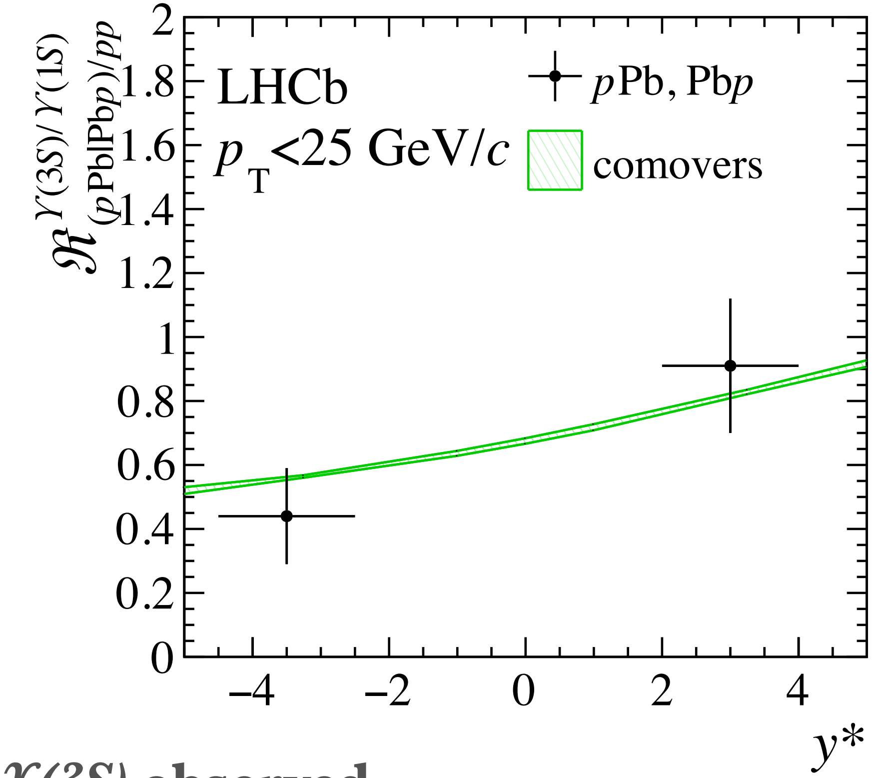
$$\Re^{\Upsilon(nS)/\Upsilon(1S)}_{(p\text{Pb}|\text{Pb}p)/pp} = \frac{R(\Upsilon(nS))_{p\text{Pb}|\text{Pb}p}}{R(\Upsilon(nS))_{pp}}$$

- ***Υ(1S)*: forward: suppressed by ~30%**
- ***Υ(1S)*: backward: compatible with unity within nPDF uncertainties**
- ***Υ(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

Υ(3S) double ratios

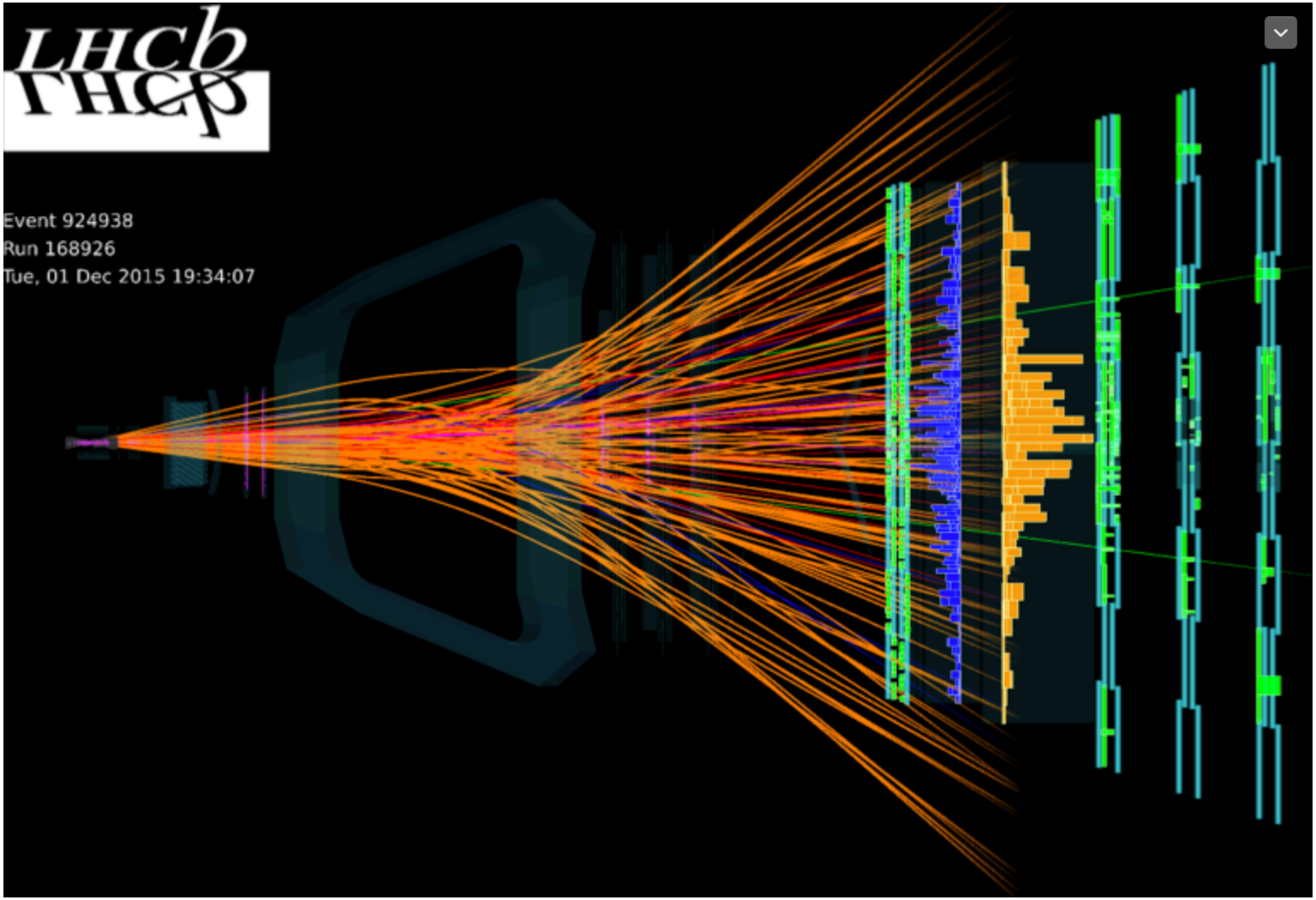
$$\mathfrak{R}^{\Upsilon(nS)/\Upsilon(1S)}_{(p\mathrm{Pb}|\mathrm{Pb}p)/pp} = \frac{R(\Upsilon(nS))_{p\mathrm{Pb}|\mathrm{Pb}p}}{R(\Upsilon(nS))_{pp}}$$



- **An even larger suppression for Υ(3S) observed**
- **Consistent with comovers model**
- **Similar behaviour for ψ(2S)**

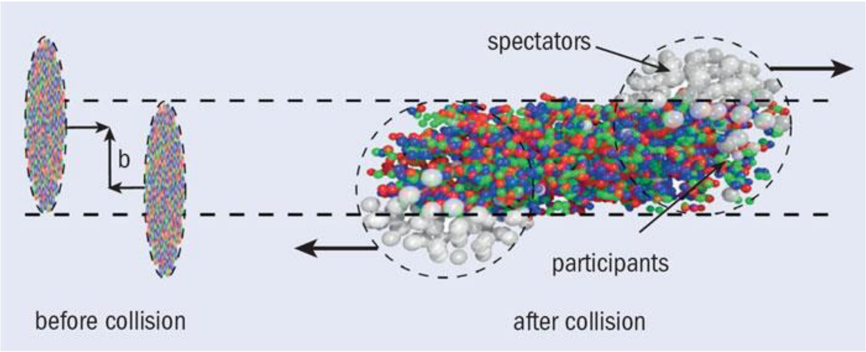
Also see Hengne's talk

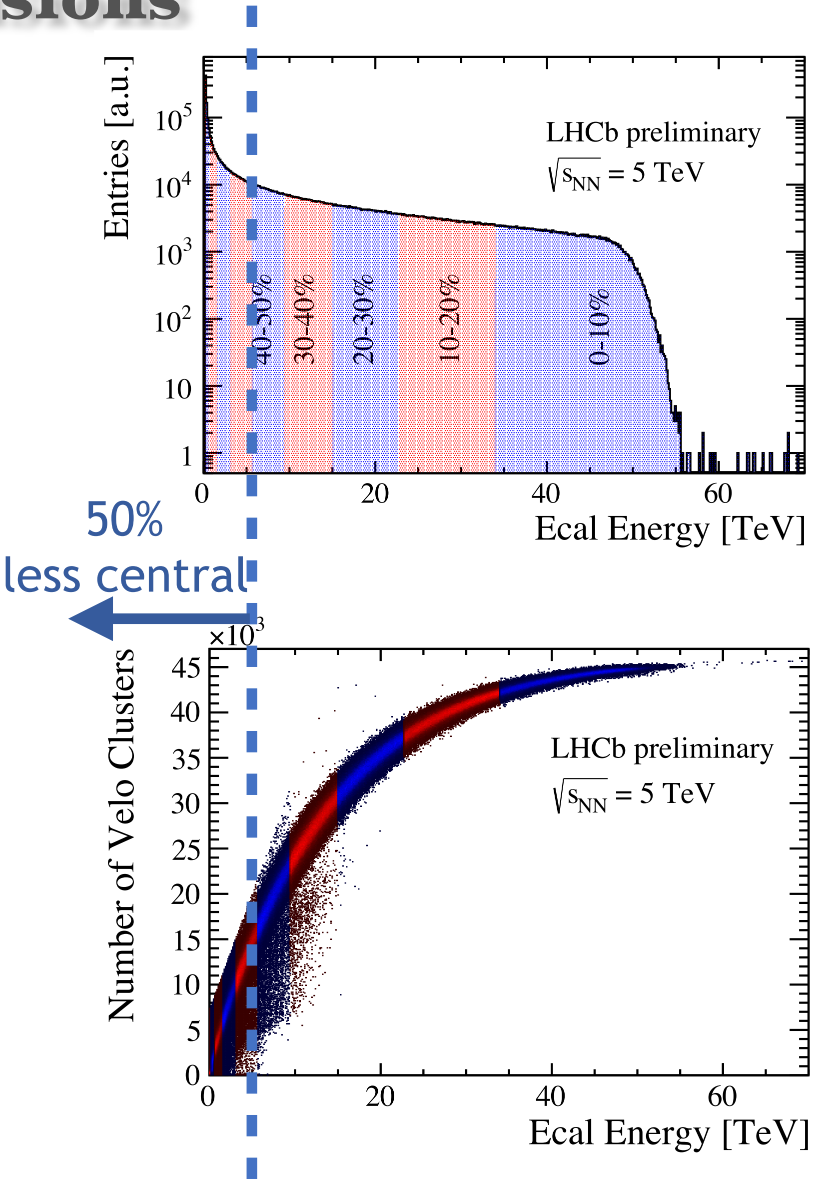
Lead-lead mode



Centrality of the PbPb collisions

- Detector limitation: Saturation in the VELO and the tracking system for the most central PbPb collisions
- Current LHCb tracking algorithm, efficient for centrality above 50%
- Centrality measured using the total energy deposited in the calorimeters:
  - A good centrality estimator.
  - No saturation of calorimeter signals even for most central collisions



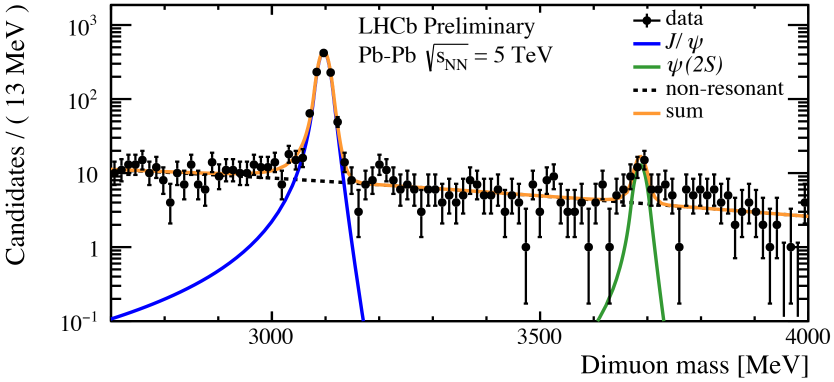


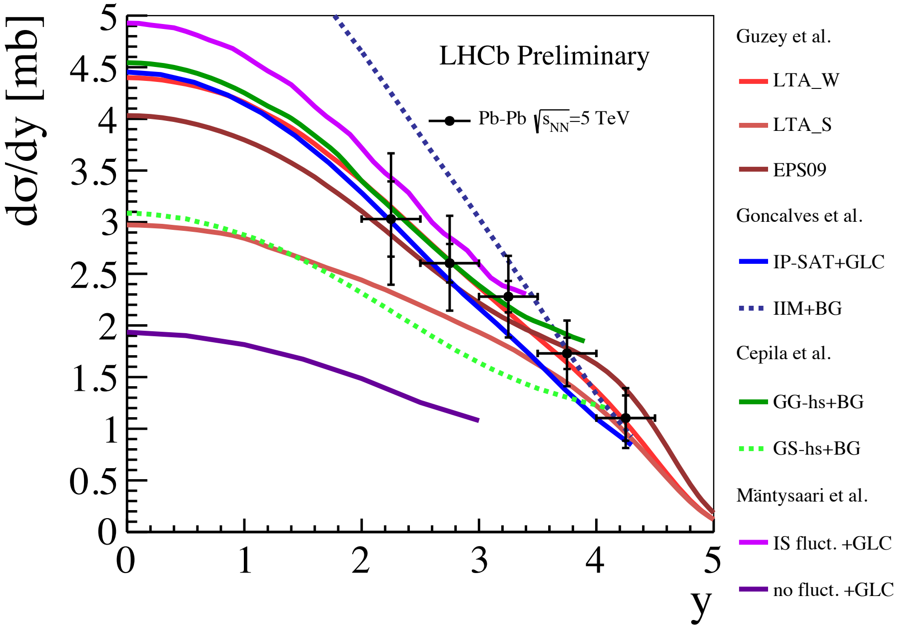
50%
less central

J/ψ production in ultra-peripheral PbPb collisions

LHCb-CONF-2018-003

- **Ultra-peripheral collisions: Two nuclei bypass each other with impact parameter larger than the sum of their radii.**
- **Photon-induced J/ψ production cross-section is enhanced by the strong electromagnetic field of the nucleus**
- **Coherent (photon couples to all nucleons) J/ψ production gives constraints to nPDF**
- **Cross section for coherent J/ψ production at 5 TeV:**
  - **σ= 5.3 ± 0.2 (stat) ± 0.5 (syst) ± 0.7 (lum mb,**
- **Phenomenological models:**
  - **PRC 97 024901 (2018), PRD 96 094027 (2017), PRC 93 055206 (2016), PLB 772 (2017) 832**





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 at LHCb with current heavy-ion programmes and in view of future upgrades
    - New SMOG2 system will be installed for Run-III

Conclusions

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More details in Luciano's talk

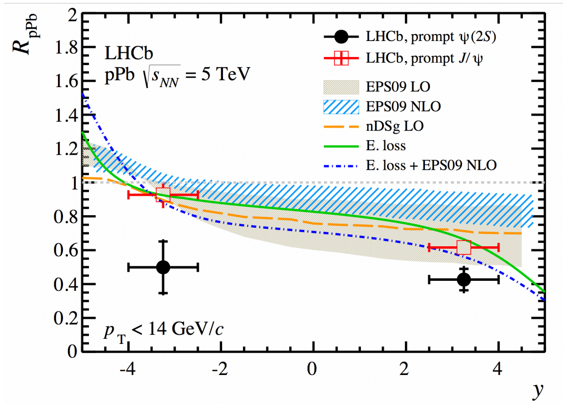
Backups

LHCb 5 TeV quarkonium results - *J/ψ, ψ(2S)* and *ϒ(1S)*

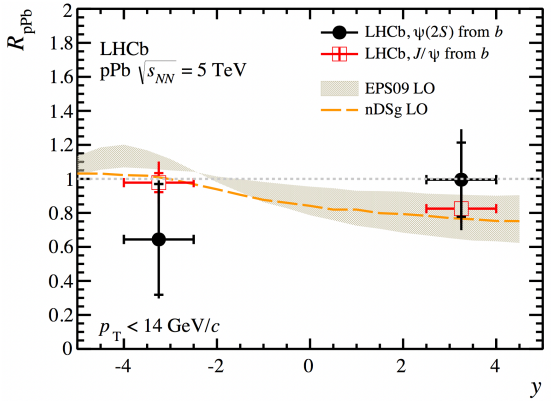
[JHEP 1402 (2014) 072]
[JHEP 1407 (2014) 094]
[JHEP 1603 (2016) 133]

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

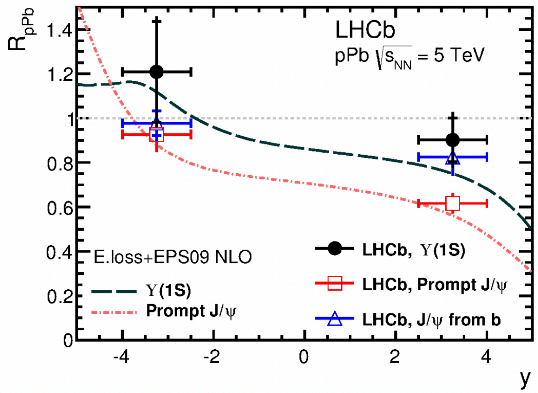
Prompt *J/ψ, ψ(2S)*



J/ψ, ψ(2S)* from *b



ϒ(1S)



Forward rapidity

- **Significant suppression for *J/ψ* , even larger for *ψ(2S)***
- **Modest suppression for non-prompt *J/ψ* , similar to *ϒ(1S)***

Backward rapidity

- **No suppression for *J/ψ* and *ϒ(1S)***
- **Unexpected large suppression for *ψ(2S)*, not described by E.loss and shadowing**

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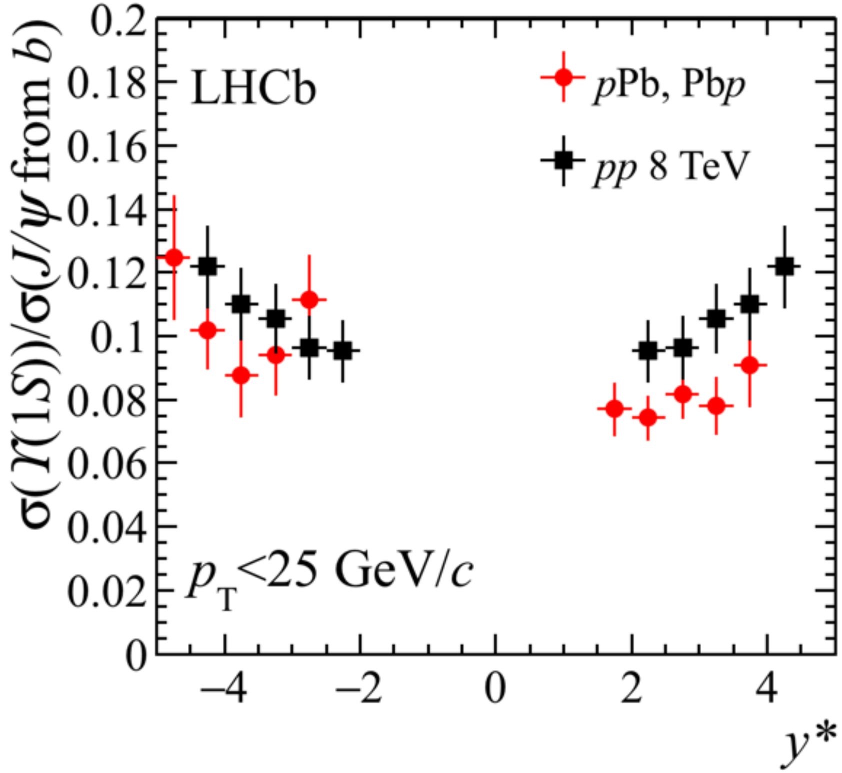
Υ(1S) to *J/ψ*-from-*b* ratio



- **p_T -integrated *Υ(1S)* to *J/ψ*-from-*b* similar in *pp* & in *p*Pb/Pb*p*:**
- **Small suppression indicate different suppression mechanism for quarkonia with different binding energies**