Results from proton-lead and fixed target collisions at LHCb

Óscar Boente García
on behalf of the LHCb Collaboration

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Instituto Galego de Física de Altas Enerxías - Universidade de Santiago de Compostela
Contact: oscar.boente@usc.es

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The LHCb detector

- One-arm spectrometer at LHC fully instrumented in $2 < \eta < 5$
- Designed for heavy flavour physics but acts as a general-purpose detector in the forward region

VELO

Vertex reconstruction

✓ Decay time resolution ~45 fs

✓ IP reconstruction: $\left(15 + \frac{29}{p_T\,[\mathrm{GeV}]}\right)\,\mu\mathrm{m}$

Calorimeters

✓ ECAL resolution: $1\% \oplus \frac{10\,\%}{\sqrt{E\,[\mathrm{GeV}]}}$

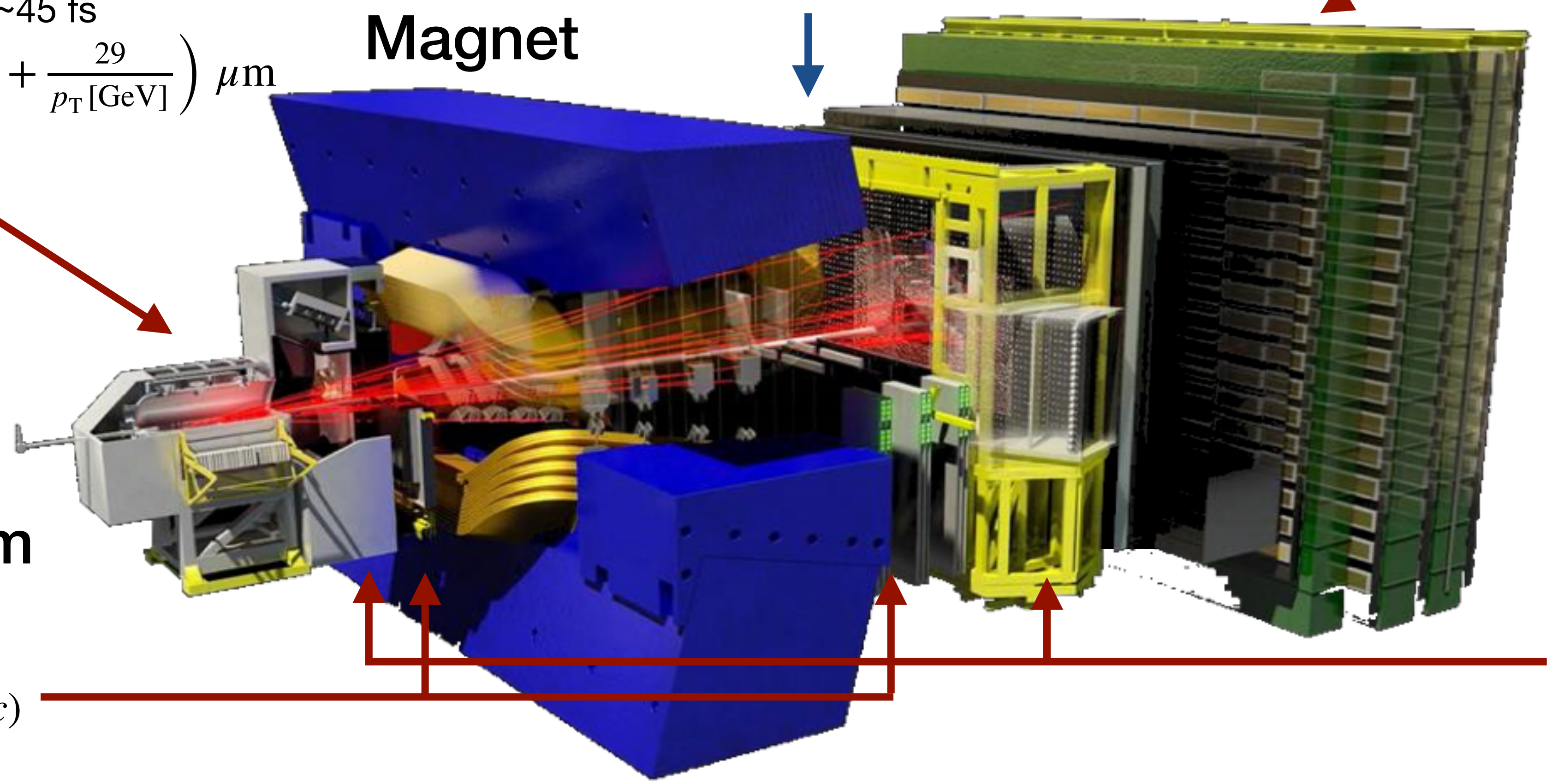
Magnet

Muon System

Muon identification

✓ $\varepsilon(\mu \to \mu) \sim 97\,\%$

✓ Miss-ID: $\varepsilon(\pi \to \mu) \sim 1-3\,\%$



Tracking System

✓ Momentum resolution: $\Delta p/p = 0.5-1\,\%$ $(5\,\mathrm{GeV}/c - 100\,\mathrm{GeV}/c)$

RICH detectors

$p/K/\pi$ separation

✓ $\varepsilon(K \to K) \sim 95\,\%$

✓ Miss-ID: $\varepsilon(\pi \to K) \sim 5\,\%$

Unique capabilities in HEAVY-ION PHYSICS

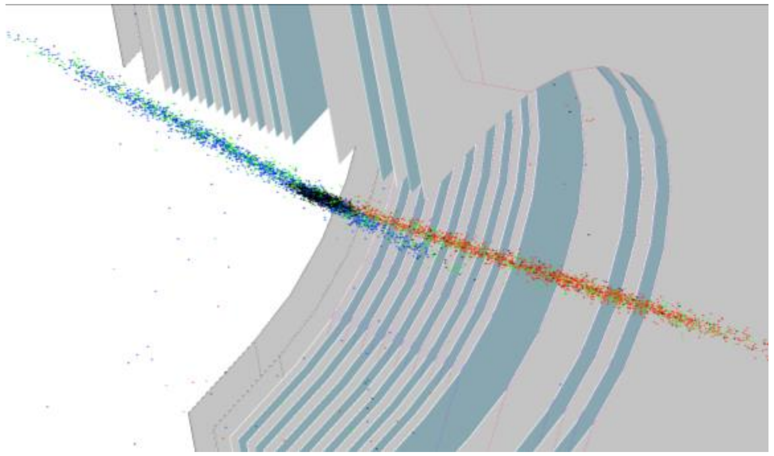
- Precision down to very low p_T
- Excellent dimuon mass resolution
- Excellent hadron ID
- Precise vertexing, reconstruction and tracking

LHCb: JINST 3 (2008) S08005

LHCb performance IJMPA 30 (2015) 1530022

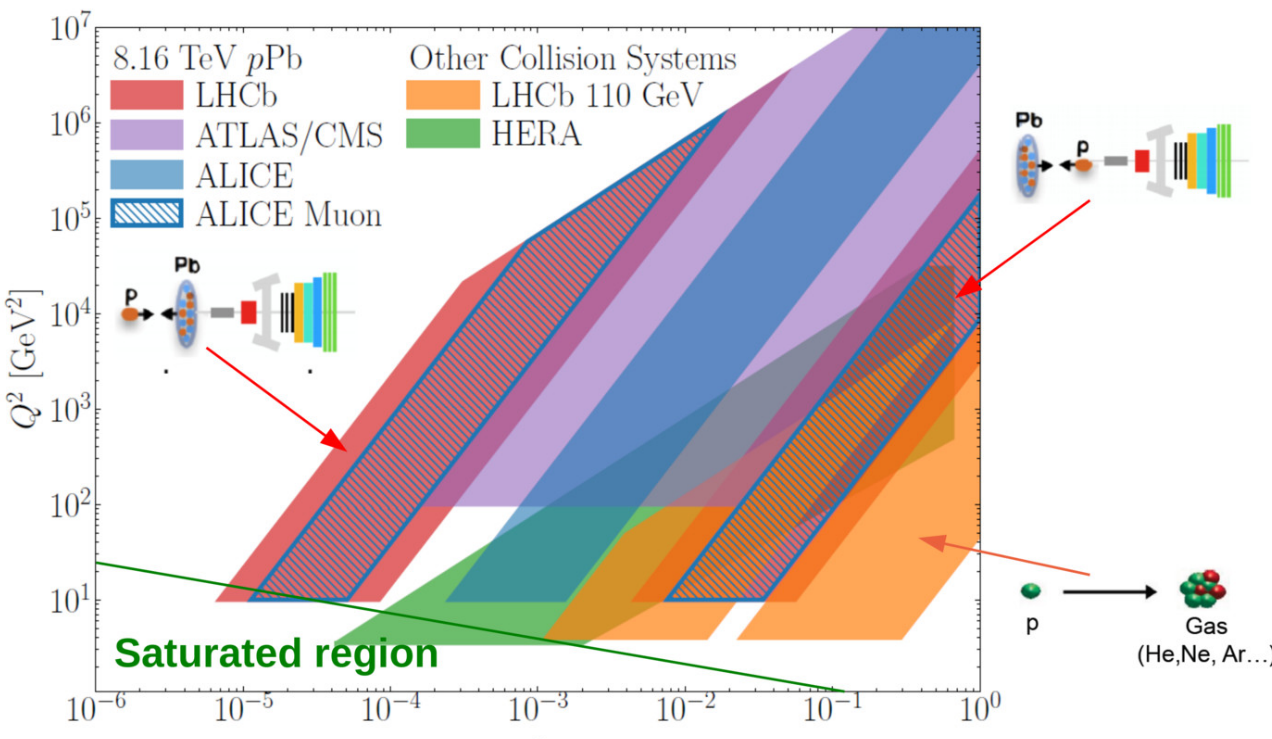
Fixed-target mode

Unique Fixed-Target configuration at the LHC



- Exploits fixed-target like geometry of LHCb
- SMOG system: initially for luminosity, now physics
- Gas injection at VErtex LOcator (VELO)
- p-gas and ion-gas collisions with many targets: He, Ne, Ar and more in the future

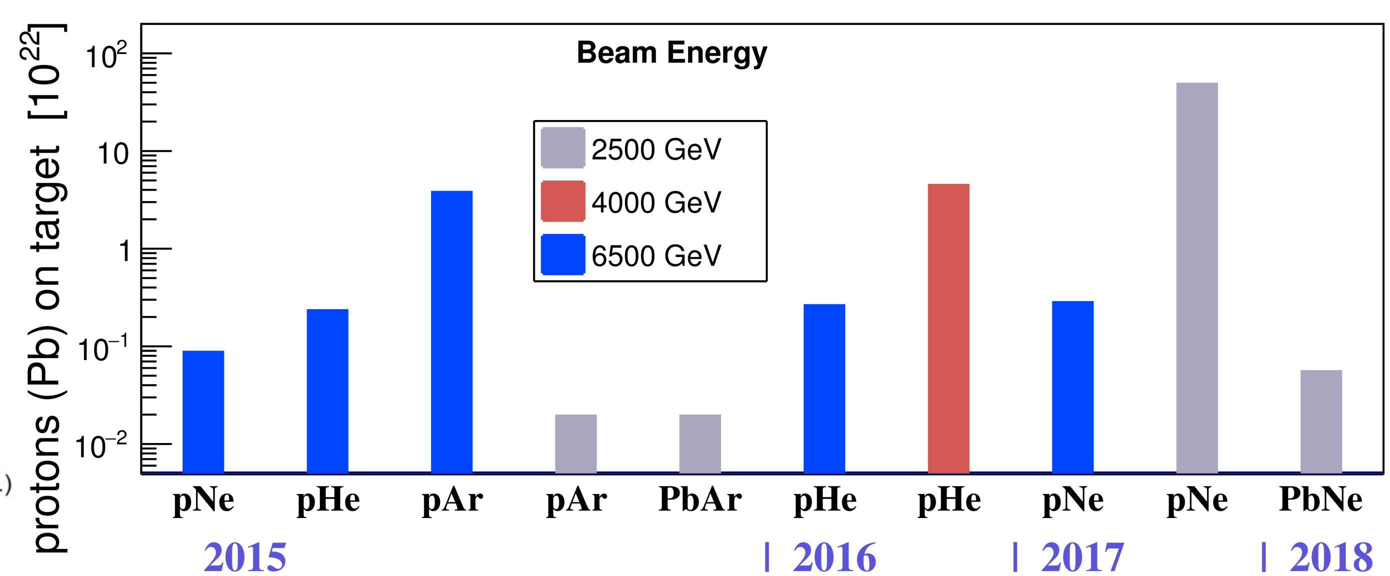
- Access to high Bjorken-x region in the target nucleon
- Can probe: antishadowing/EMC region, intrinsic heavy quark content in nucleons



- Energies in centre-of-mass system:

$$\sqrt{s_{NN}} = 68.8\,\text{GeV}, 86.6\,\text{GeV}, 110.4\,\text{GeV}$$

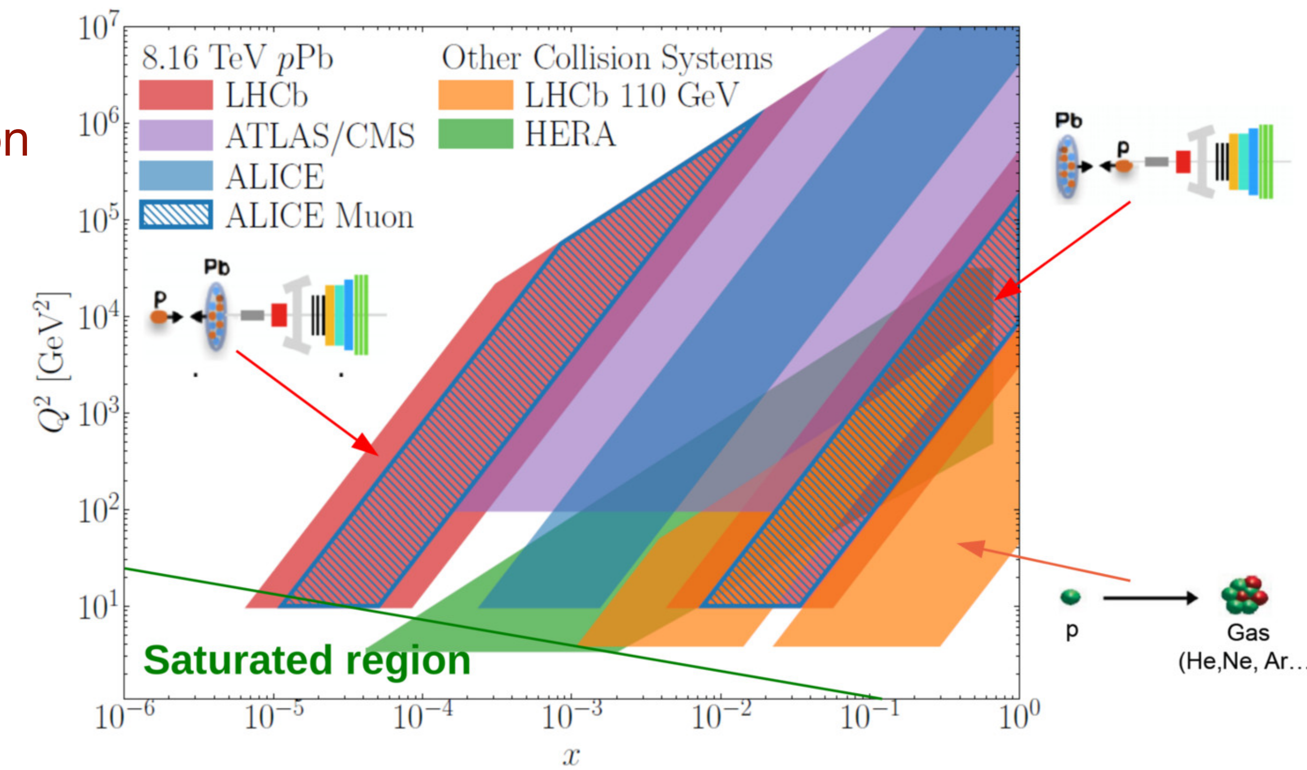
  - Covers gap between SPS (20 GeV) and RHIC (200 GeV)



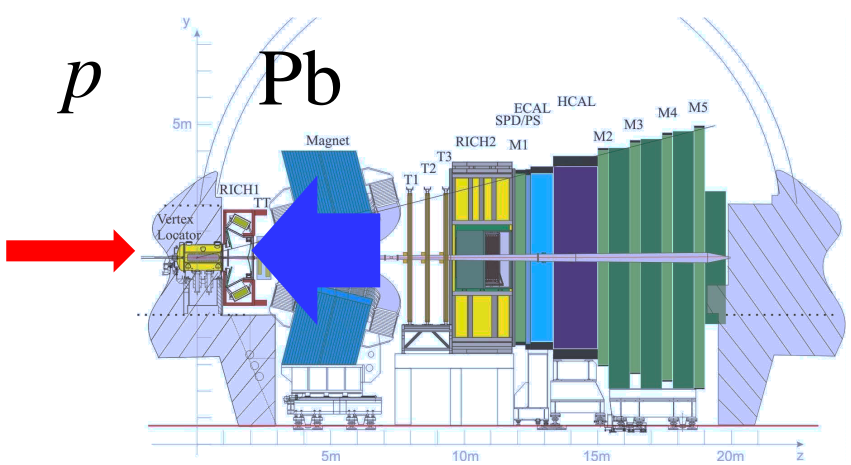
Collider mode at LHCb

- Unique perspectives due to forward acceptance
- Access to low (*p*Pb) and medium (Pb*p*) Bjorken-x region
- Data from different runs & configurations:

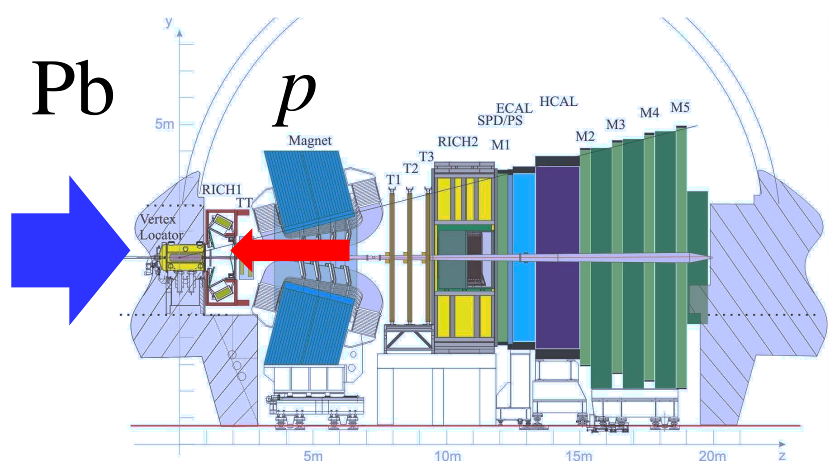
	year	$\sqrt{s_{NN}}$	$\mathscr{L}$
*p*Pb/Pb*p*	2013	5.02 TeV	$1.6\,\text{nb}^{-1}$
PbPb	2015	5.02 TeV	$10\,\mu\text{b}^{-1}$
*p*Pb/Pb*p*	2016	8.16 TeV	$34\,\text{nb}^{-1}$
XeXe	2017	5.44 TeV	$0.4\,\mu\text{b}^{-1}$
PbPb	2018	5.02 TeV	$210\,\mu\text{b}^{-1}$



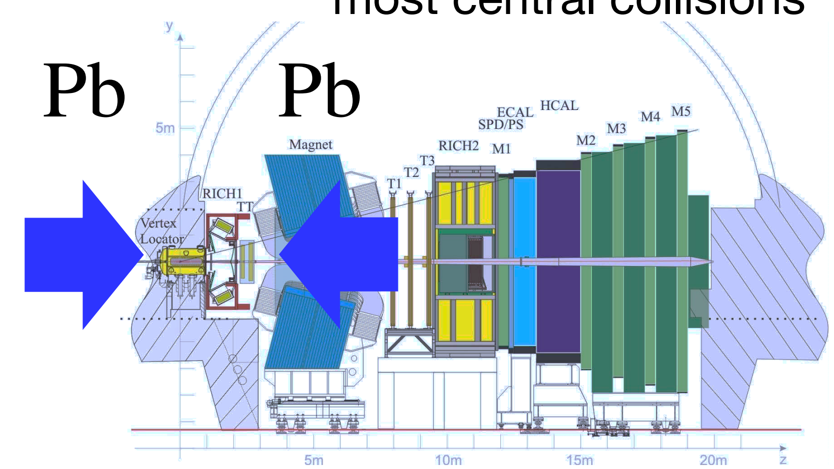
Forward configuration



Backward configuration



PbPb ✓ Detector saturation in most central collisions



Collider mode results:

- Heavy flavour production in *p*Pb:
  - B-hadron production in *p*Pb Phys. Rev. D99 052011 (2019)
  - $\Upsilon(ns)$ production in *p*Pb JHEP 11 (2018) 194
  - Λ_c^+ production in *p*Pb JHEP 02 (2019) 102

- Exclusive photo nuclear J/ψ production in UPC in PbPb

  LHCb-CONF-2018-003

B hadron production in pPb

[Phys. Rev. D99 052011 (2019)](#)

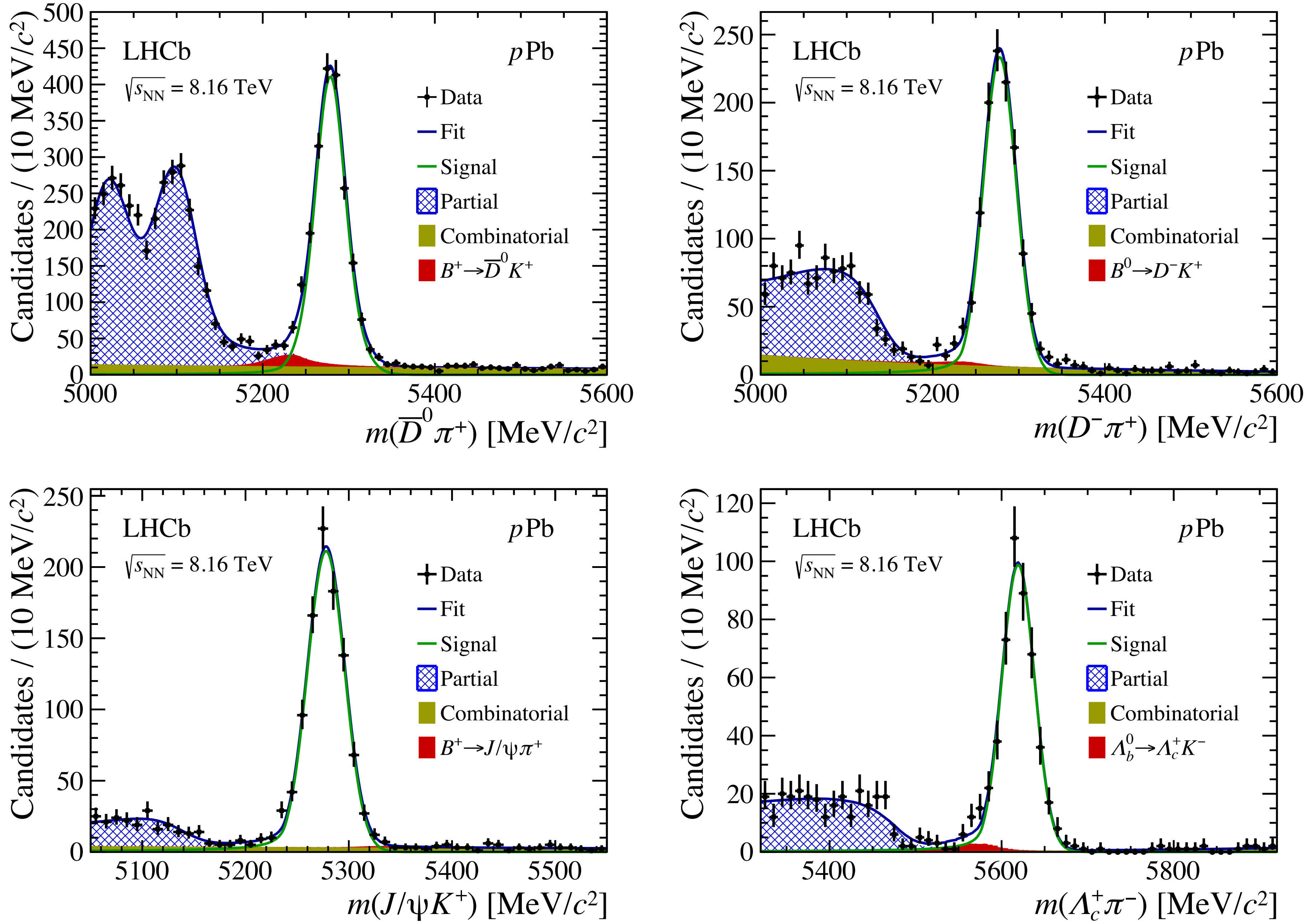
- Data sample: pPb 2016, $\sqrt{s_{NN}} = 8.16\,\mathrm{TeV}$ (30x data Run I)
- Uses exclusive decay modes for B^+, B^0 and Λ_b^0 production

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

- Kinematic range:

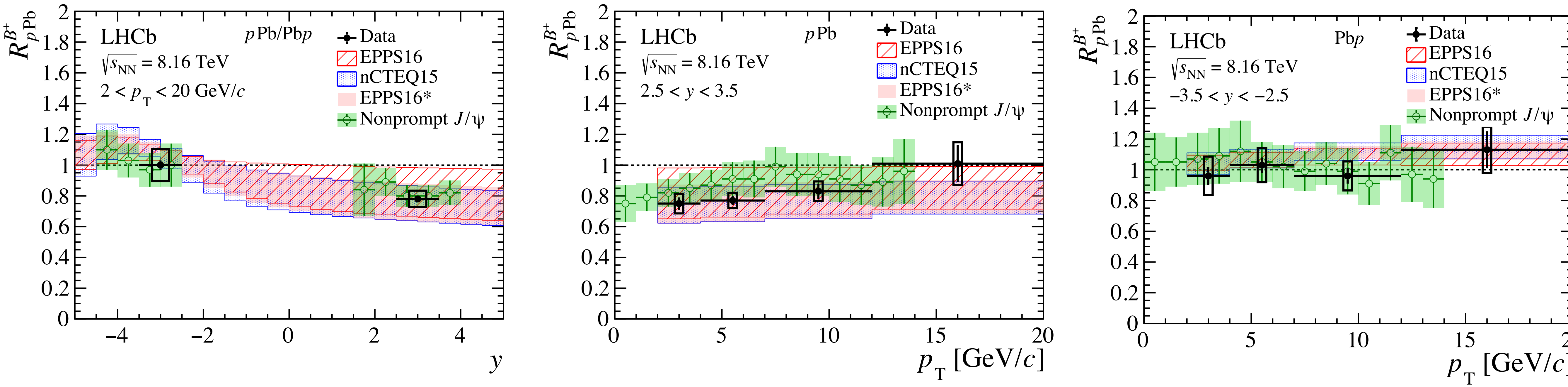
$$2 < p_T < 20\,\mathrm{GeV/c}$$
$$1.5 < y^* < 3.5$$
$$-4.5 < y^* < -2.5$$

- Double-differential cross-sections, R_{pPb}, R_{FB} and baryon-to-meson ratio



B hadron production in *p*Pb

[Phys. Rev. D99 052011 (2019)](#)



- Suppression at forward rapidity decreasing with p_T, no suppression in backward
- Good agreement with nonprompt J/ψ data and nPDFs → JHEP 04 (2009) 065, EPJ C77 (2017) 1, CPC. 198 (2016) 238
- Consistent with R_{pA} of D^0 hadron
- Ratio Λ_b^0/B^0 consistent with measurement in *pp* collisions in forward, tensions in backward

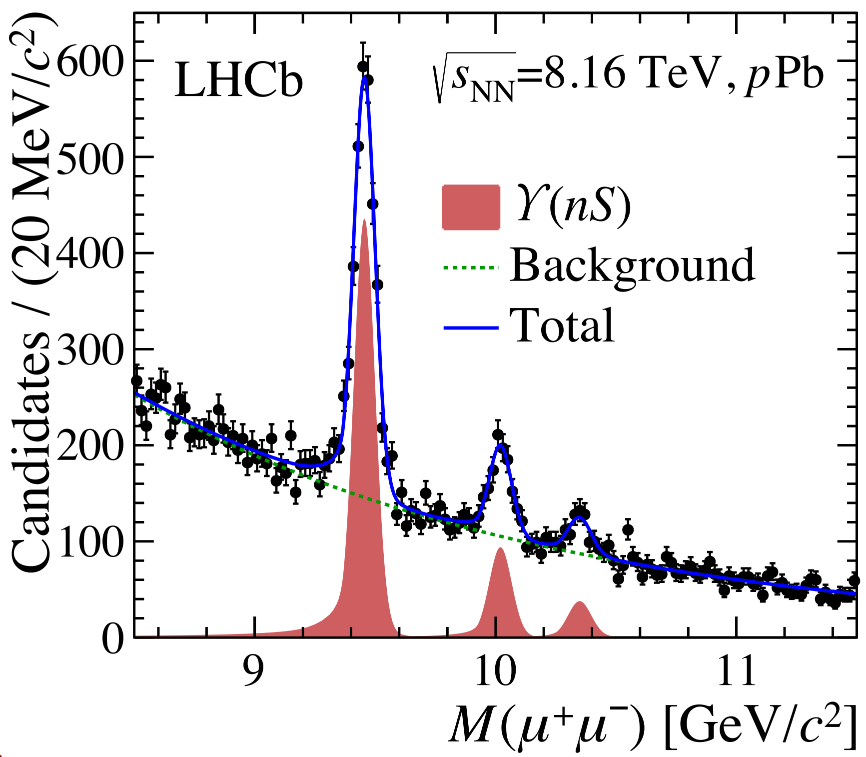
$\Upsilon(nS)$ production in *p*Pb

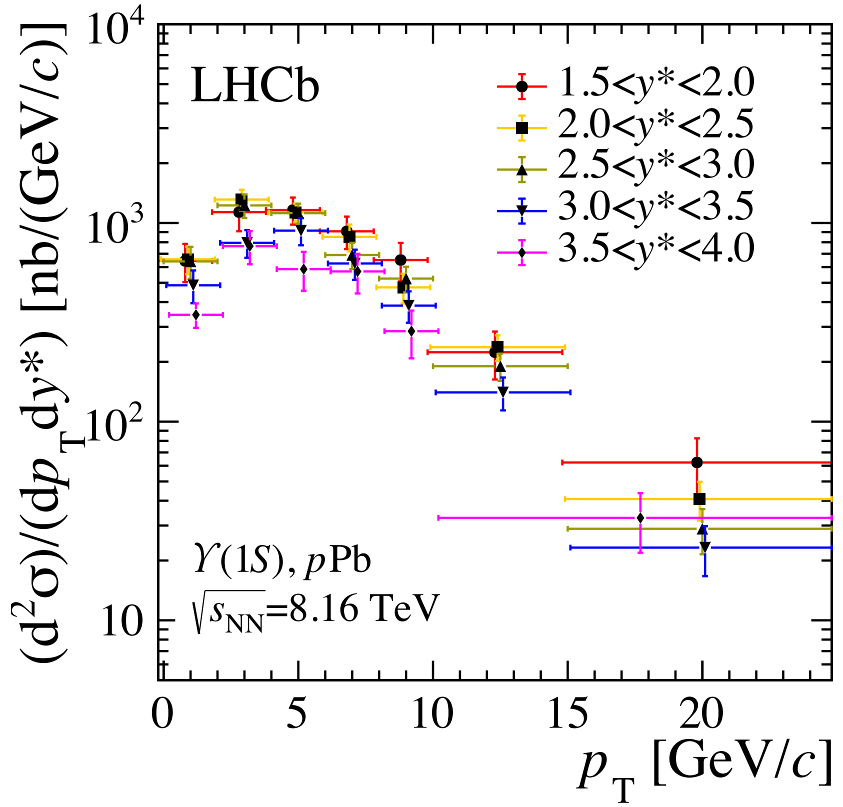
JHEP 11 (2018) 194

- Quarkonium suppression probes deconfinement in PbPb
- $\Upsilon(nS)$ sequential suppression observed in PbPb by CMS and ALICE

→ **Important to explore CNM effects in *p*Pb to understand results**

- Differential analysis with 2016 sample
- Measured differential cross-sections, $R_{p\mathrm{Pb}}$ and R_{FB} for all $\Upsilon(nS)$ states
- $\Upsilon(3S)$ signal in forward and backward rapidities





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	$19.3\,\mathrm{nb}^{-1}$

$\Upsilon(nS)$ production in *p*Pb

JHEP 11 (2018) 194

$R^{\Upsilon(1S)}_{p\mathrm{Pb}}$ and $R^{\Upsilon(2S)}_{p\mathrm{Pb}}$

- Forward: suppression for both states, compatible with nPdFs
- Backward: enhanced suppression for $\Upsilon(2S)$, predicted by nPdFs+comovers

EPS16: Eur. Phys. J. C (2017) 77: 163

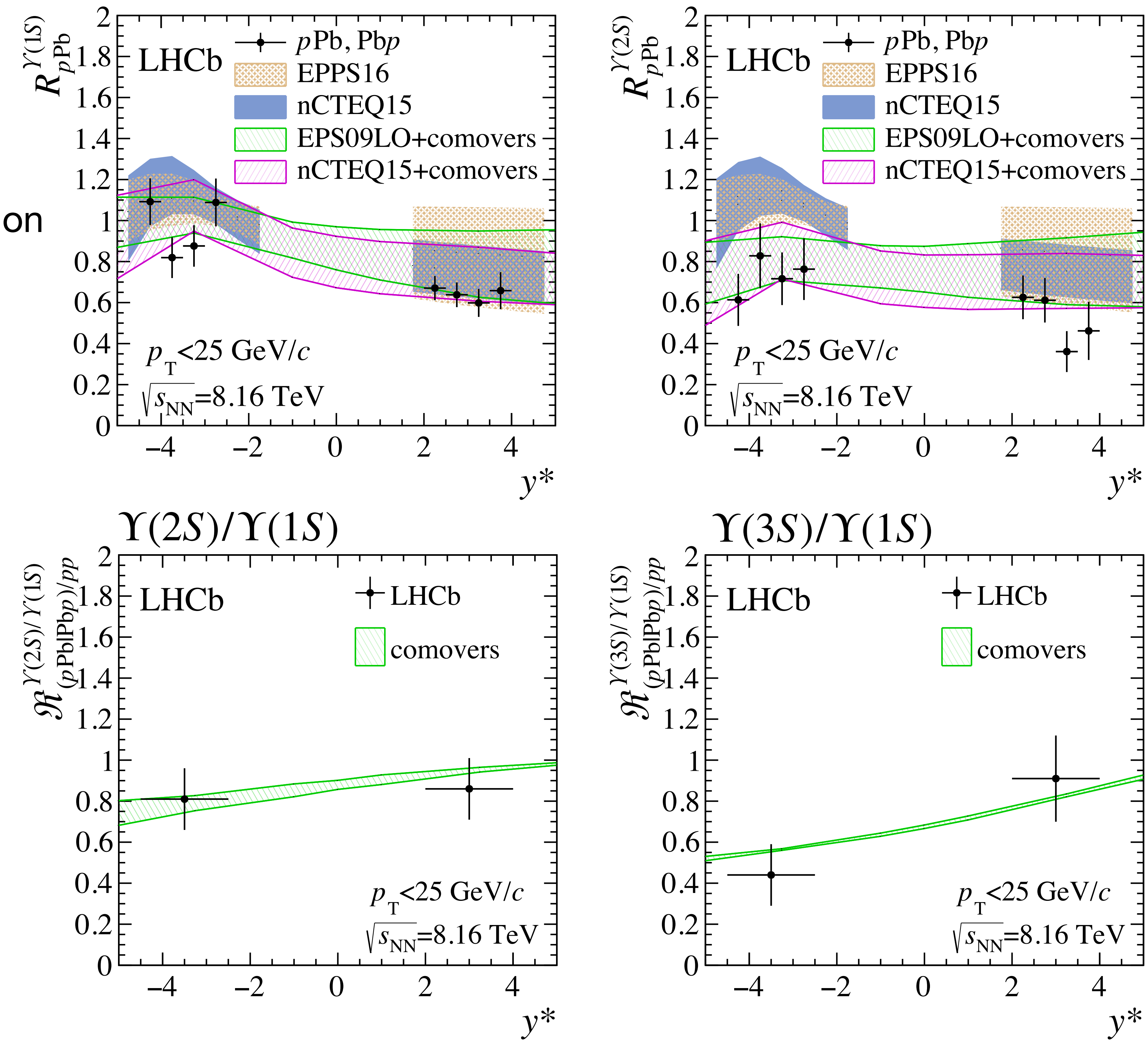
EPS09: JHEP 04 (2009) 065, arXiv:0902.4154

nCTEQ15: Phys. Rev. D93 (2016) 085037

Comovers: arXiv:1804.04474; Phys. Lett. B749 (2015) 98, arXiv:1411.0549

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

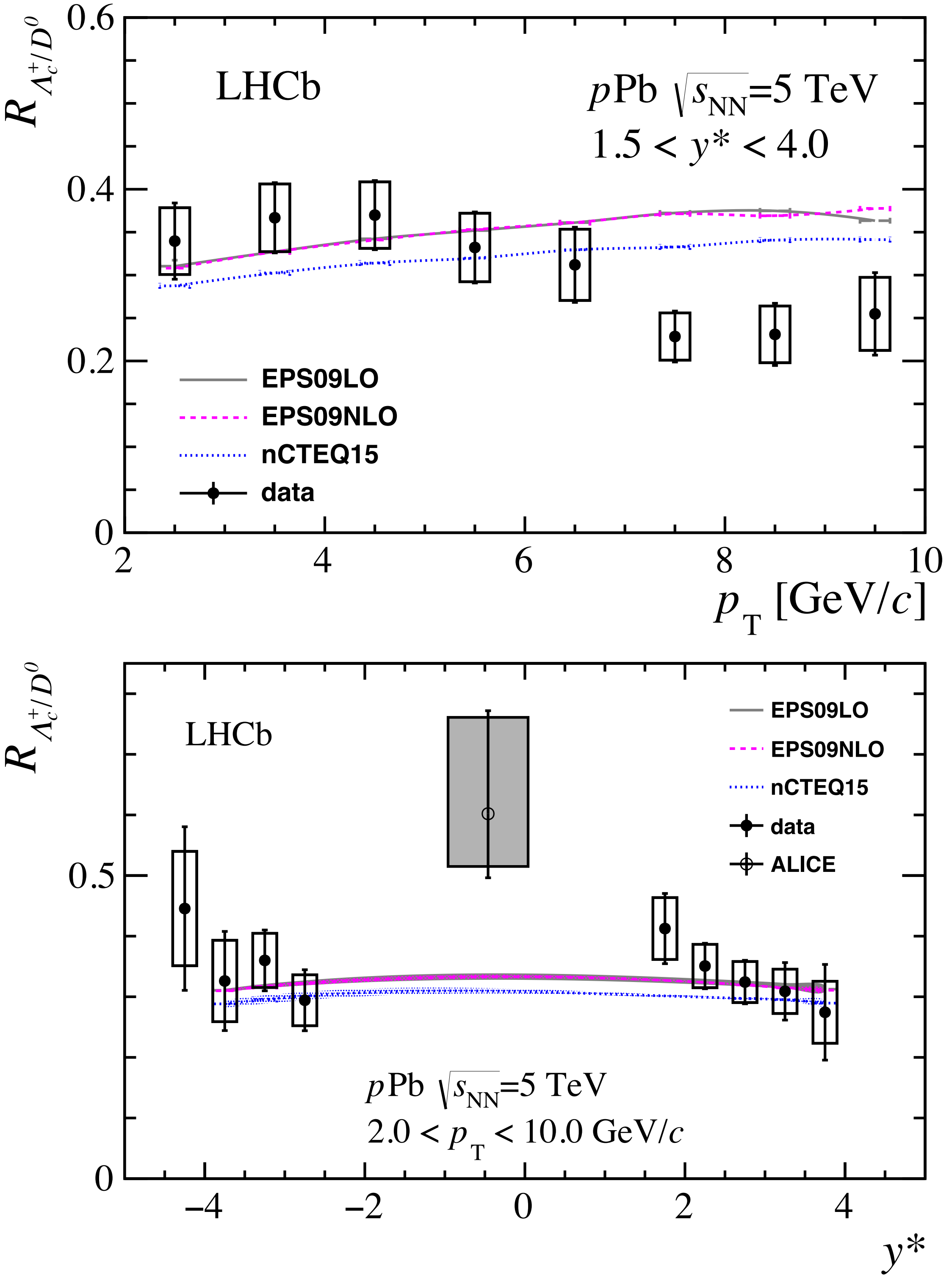
- Double ratio of $\Upsilon(2S)$ and $\Upsilon(3S)$ over $\Upsilon(1S)$ in *pp* and *p*Pb|Pb*p*
- Consistent with *comovers* model



Prompt Λ_c^+ production in pPb

JHEP 02 (2019) 102

- 2013 pPb $\sqrt{s_{NN}} = 5\,\mathrm{TeV}$ data sample
- Reconstruct with $\Lambda_c^+ \to pK^-\pi^+$
- Measured $R_{FB} = \sigma(y^* > 0)/\sigma(y^* < 0)$
  ➡ similar suppression as D^0
- Measured $R_{\Lambda_c^+/D^0} = \sigma_{\Lambda_c^+}/\sigma_{D^0}$ for charm hadronisation mechanism
  - Consistent with expectations from *pp* data (~0.3)
  - Comparison with nPDFs, hint of discrepancy at high p_T in the forward region



EPS09LO: Comput. Phys. Commun. 184 (2013) 2562

EPS09NLO: Comput. Phys. Commun. 198 (2016) 238

nCTEQ15: Phys. Rev. D93 (2016) 085037

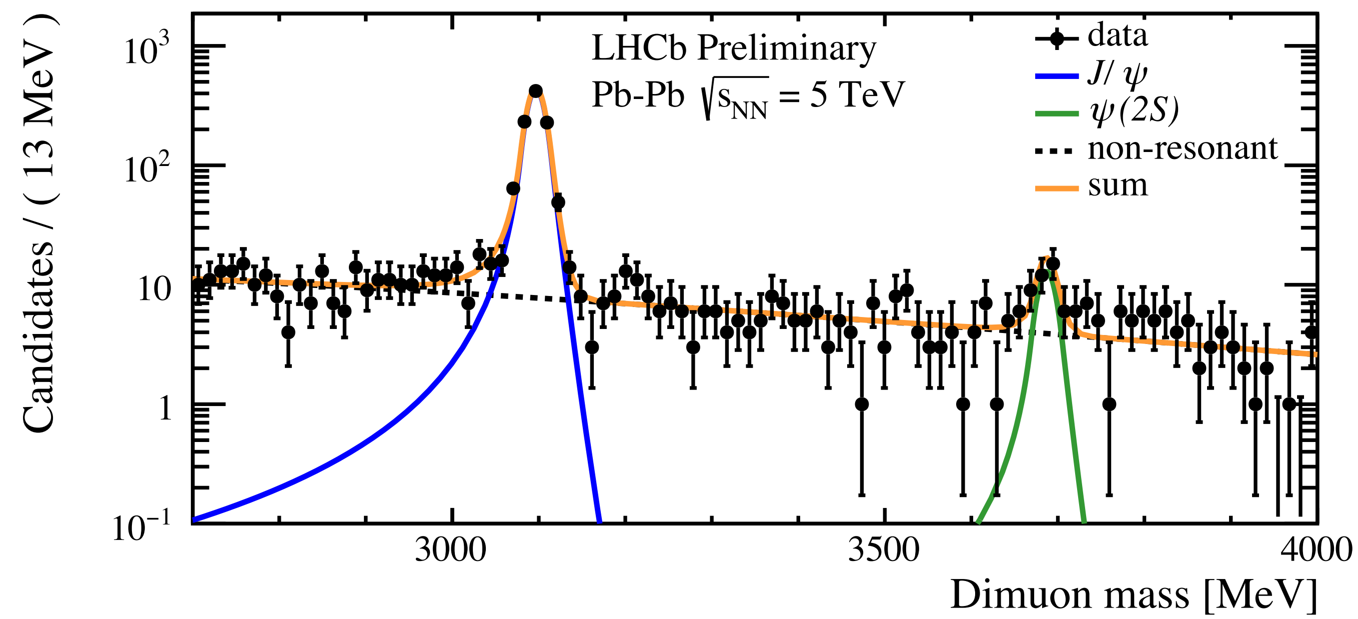
Coherent J/ψ photo-production in PbPb in UPC

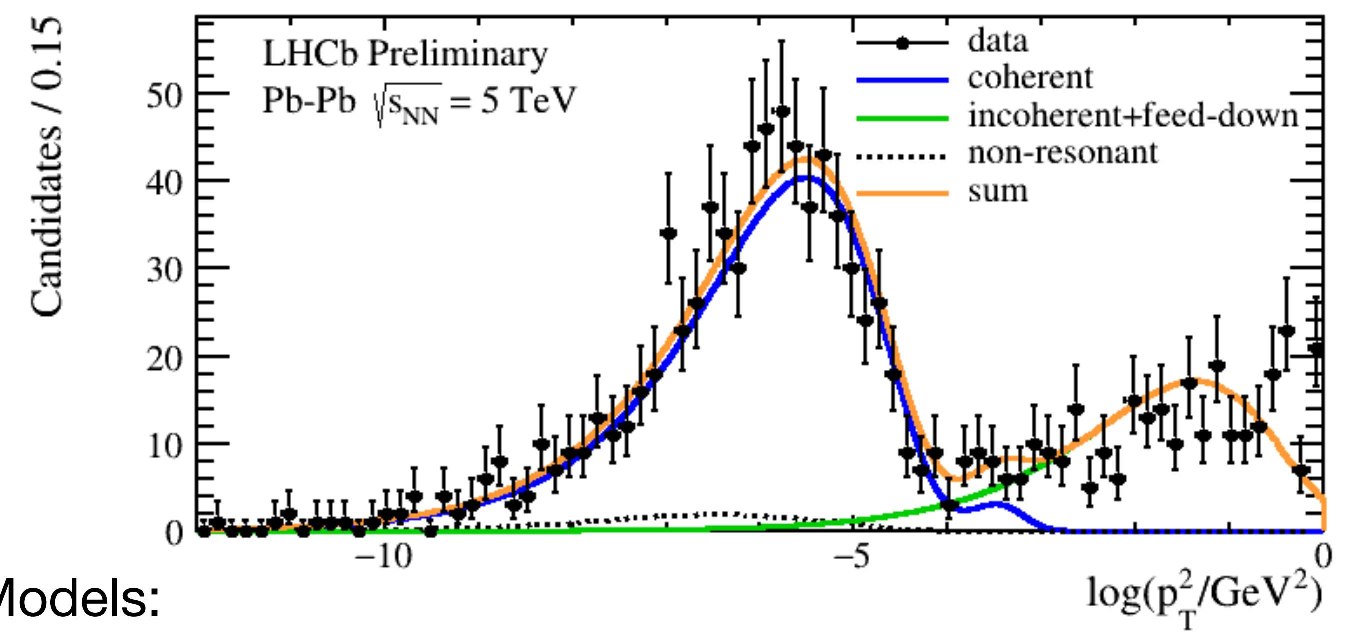
LHCb-CONF-2018-003

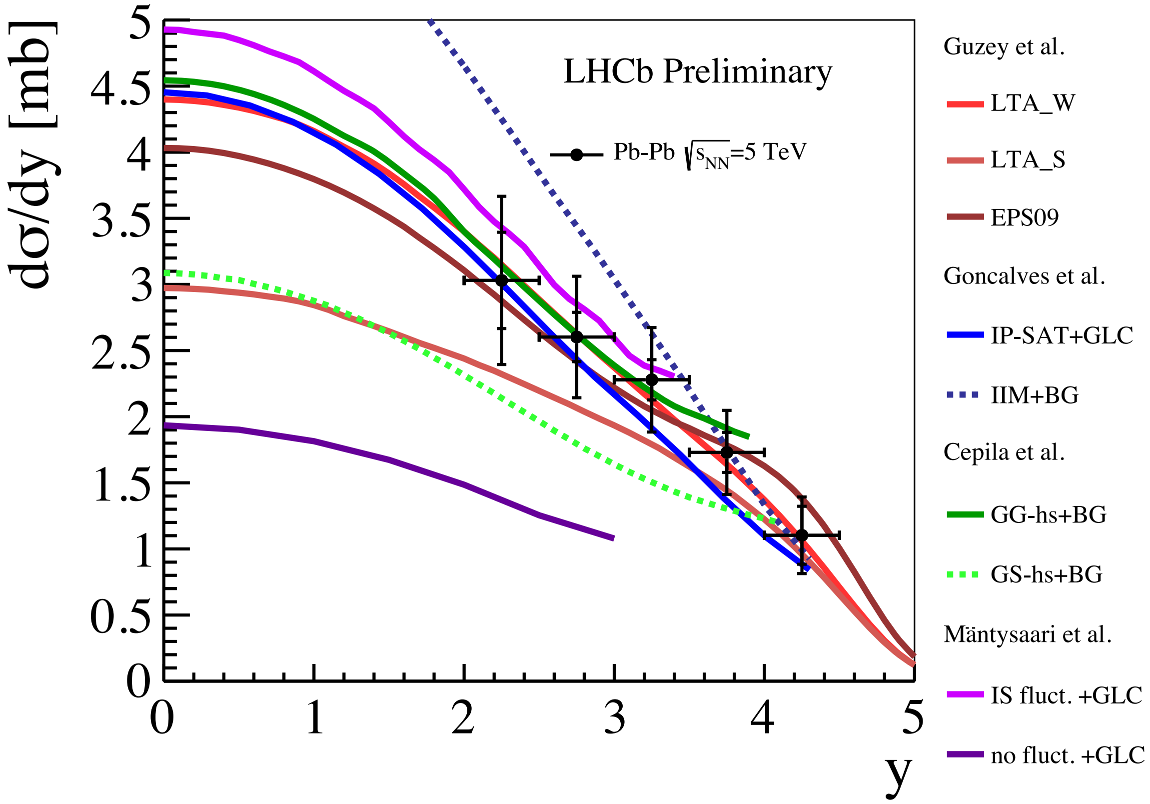
- Interaction between the electromagnetic field of the ions
- First result with PbPb sample with small luminosity $\mathscr{L} = 0.4\,\mu\text{b}^{-1}$

$$\sigma = 5.3 \pm 0.2(stat) \pm 0.5(syst) \pm 0.7(lumi)\,\text{mb}$$

- Very good prospects with 2018 data sample







- Models:

Cepilla et al. PRC 97 024901 (2018)
Goncalves et al. PRD 96 094027 (2017)
Guzey et al. PRC 93 055206 (2016)
Mäntysaari et al.B 772 (2017) 832

Fixed-target results

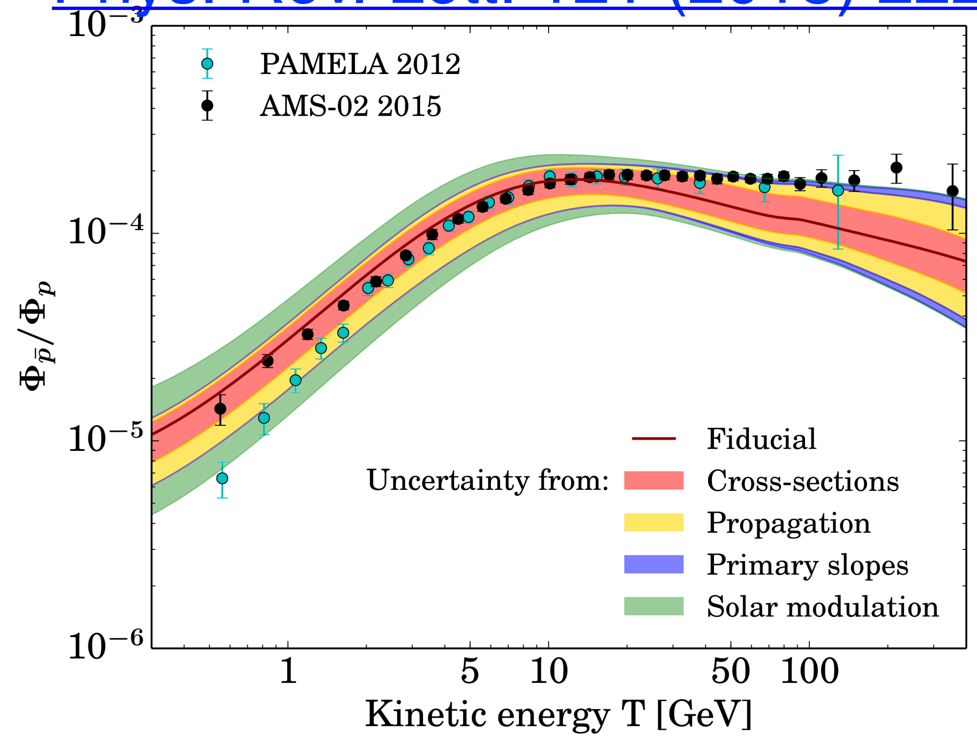
- Antiproton production in *p*He
  - Phys. Rev. Lett. 121 (2018) 222001
- Charm production in fixed target
  - Phys. Rev. Lett. 122 (2019) 132002

Antiproton production in pHe

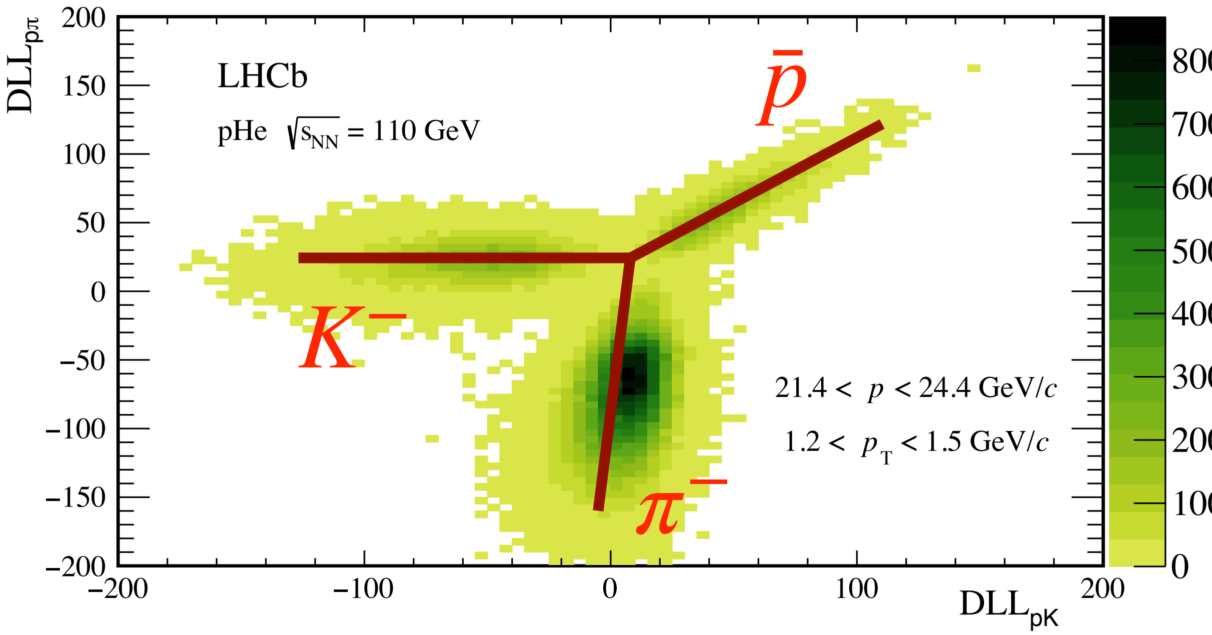
Phys. Rev. Lett. 121 (2018) 222001

- Motivation comes from dark matter searches in cosmic rays
- Hint of a possible excess in 10-100 GeV kinetic energy range

$\bar{p}$ production in pHe never directly measured at these energies



- Data from pHe 2016 at $\sqrt{s_{NN}} = 110\,\text{GeV}$
- Kinematic range: $\begin{cases} 12 < p < 110\,\text{GeV/c} \\ p_T > 0.4\,\text{GeV/c} \end{cases}$

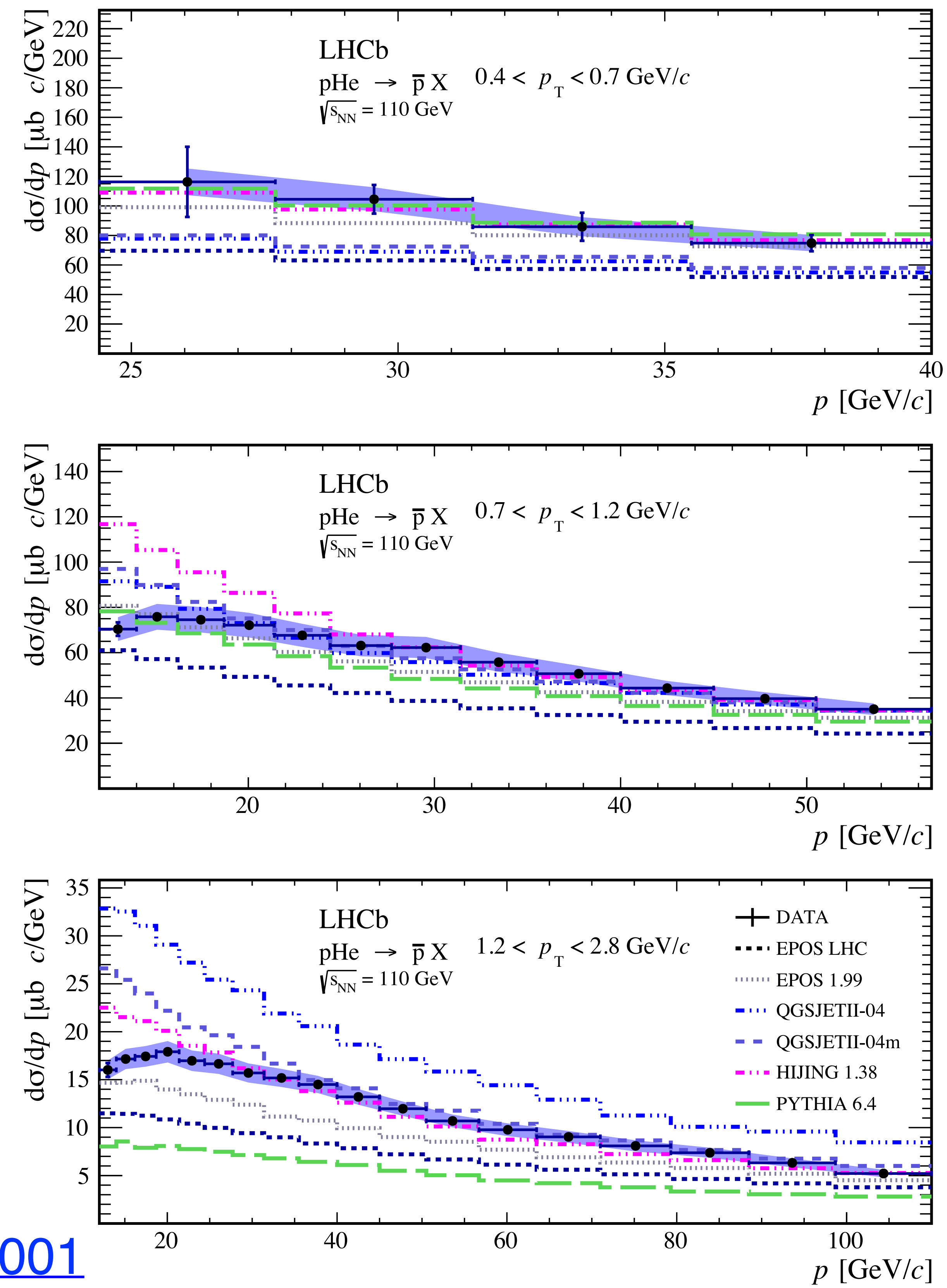


- RICH detectors separate $\bar{p}$ from K^- and π^-
- Luminosity from pe^- elastic scattering

Antiproton production in *p*He

- Comparison of the result with MC generators:
  - EPOS LHC
  - QGSJETII-04m
  - EPOS 1.99
  - HIJING 1.34
  - QGSJET-II-04
  - PYTHIA 6.4

- Error bar smaller than predictions spread
- EPOS LHC underestimates $\bar{p}$ production



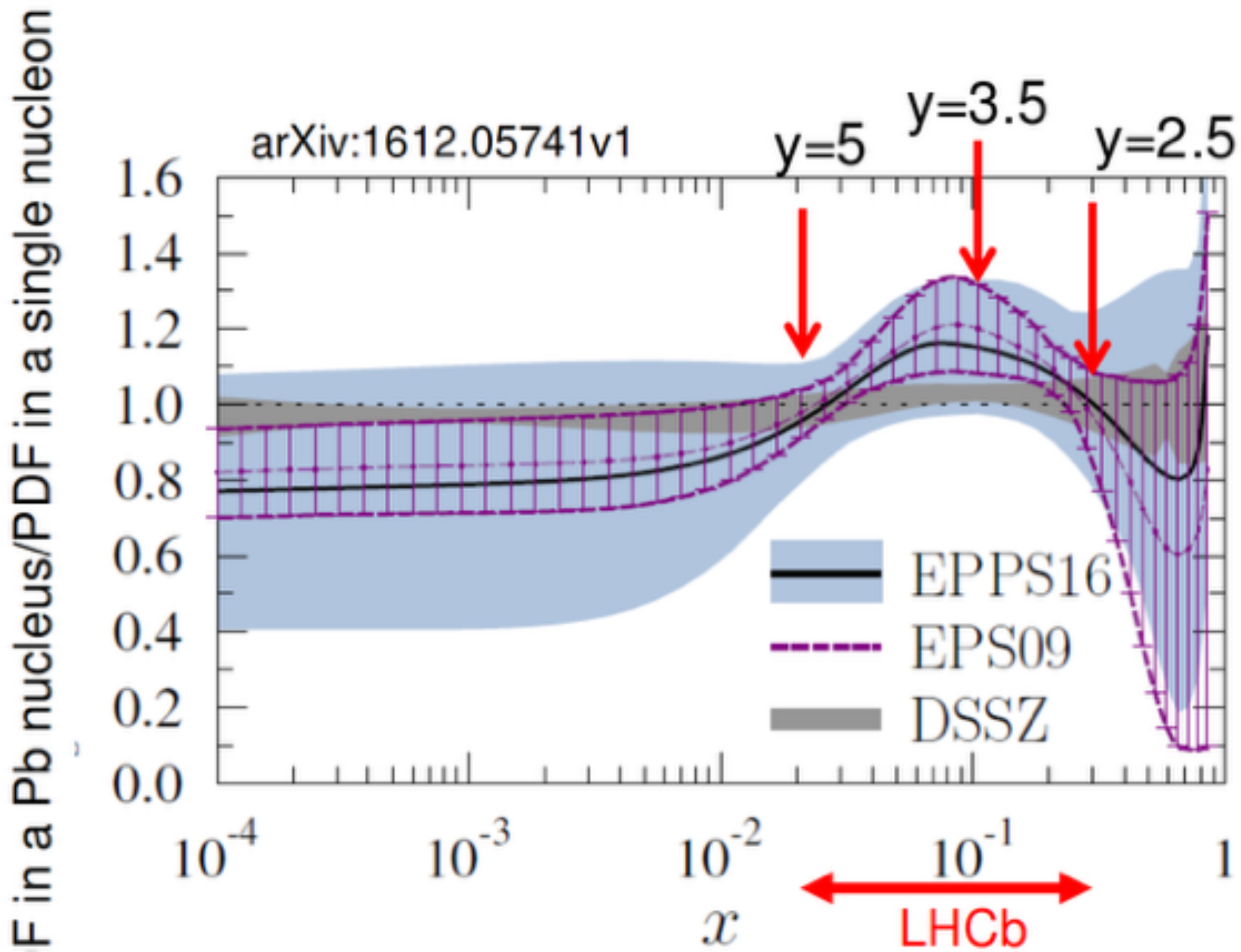
> Decisive contribution to reduce background uncertainties in dark matter searches

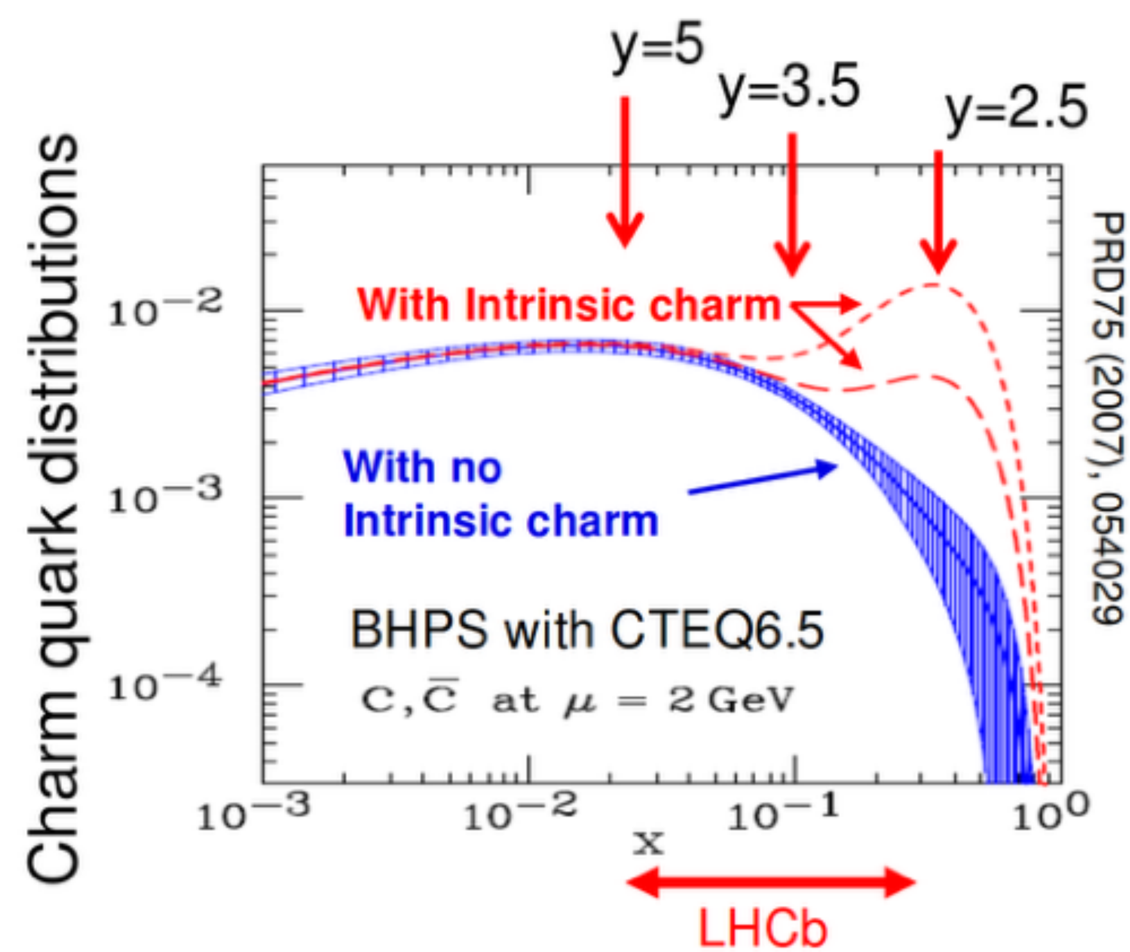
Phys. Rev. Lett. 121 (2018) 222001

Charm production in fixed target

[Phys. Rev. Lett. 122 (2019) 132002]

- Coverage of unique region at LHC due to unique kinematics → **Large Bjorken-x in the target**
  - Access nPDF in anti-shadowing region
  - Probe intrinsic charm in the nucleon





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

Charm production in fixed target

Phys. Rev. Lett. 122 (2019) 132002

- Data from 2016:
  - pHe at $\sqrt{s_{NN}} = 86.6\,\mathrm{GeV}$
  - pAr at $\sqrt{s_{NN}} = 110.4\,\mathrm{GeV}$
- Cross-sections with $J/\psi \to \mu^+\mu^-$ and $D^0 \to K^-\pi^+$

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

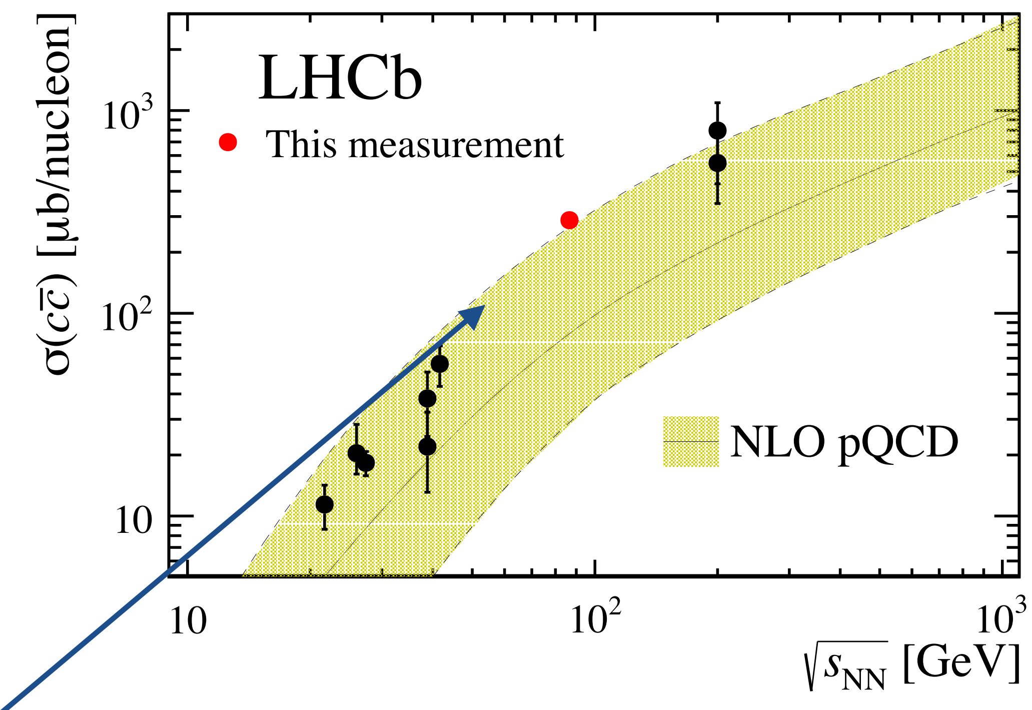
$$\sigma_{D^0}^{86.6\,\mathrm{GeV}} = 156.0 \pm 4.6(stat.) \pm 12.3(syst)\,\mu\mathrm{b/nucleon}$$

- Scaling D^0 cross-section with global fragmentation ratio $f(c \to D^0) = 0.542 \pm 0.024$

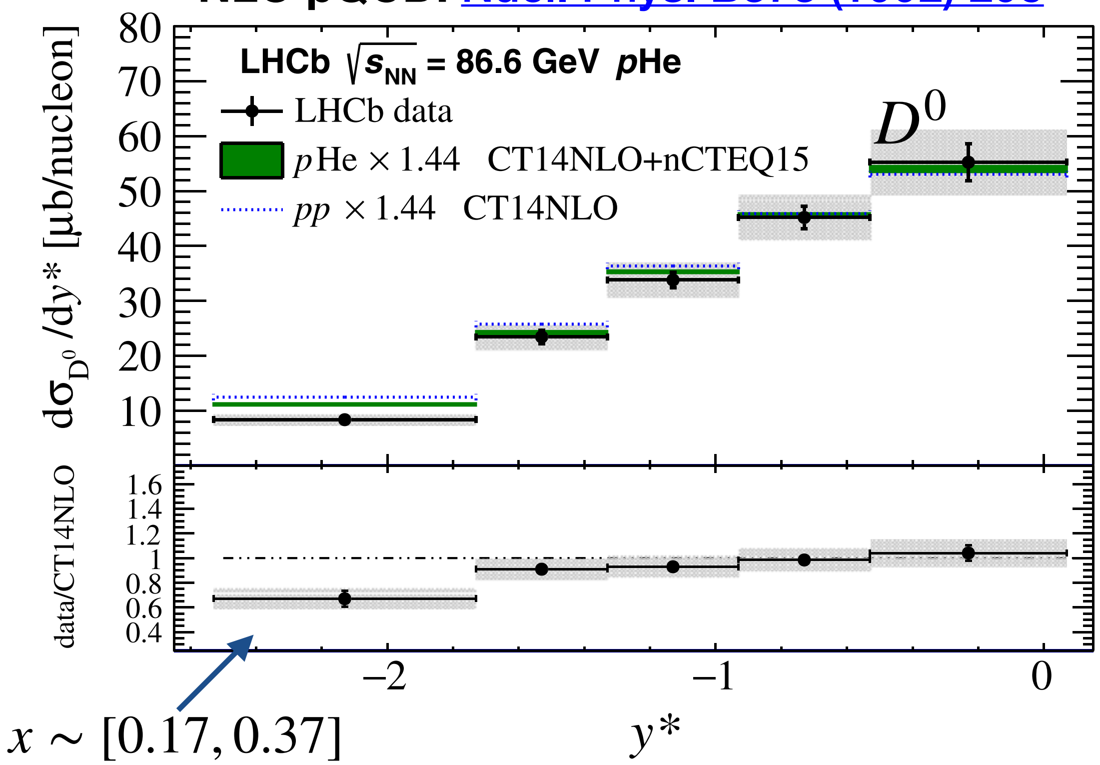
$$\sigma_{c\bar{c}}^{86.6\,\mathrm{GeV}} = 287.8 \pm 8.5(stat.) \pm 25.7(syst)\,\mu\mathrm{b/nucleon}$$

- Cross-section measurements in agreement with theoretical predictions
- Shape of differential cross-sections compared with HELAC-ONIA model predictions (rescaled) without intrinsic charm

➡ *No evidence for large valence-like intrinsic charm contribution*



NLO pQCD: Nucl. Phys. B373 (1992) 295



(pp) CT14NLO: Phys. Rev. D93 (2016) 033006

(pHe) CT14NLO+nCTEQ15: *Phys. Rev. D93 (2016) 085037*

Summary and outlook

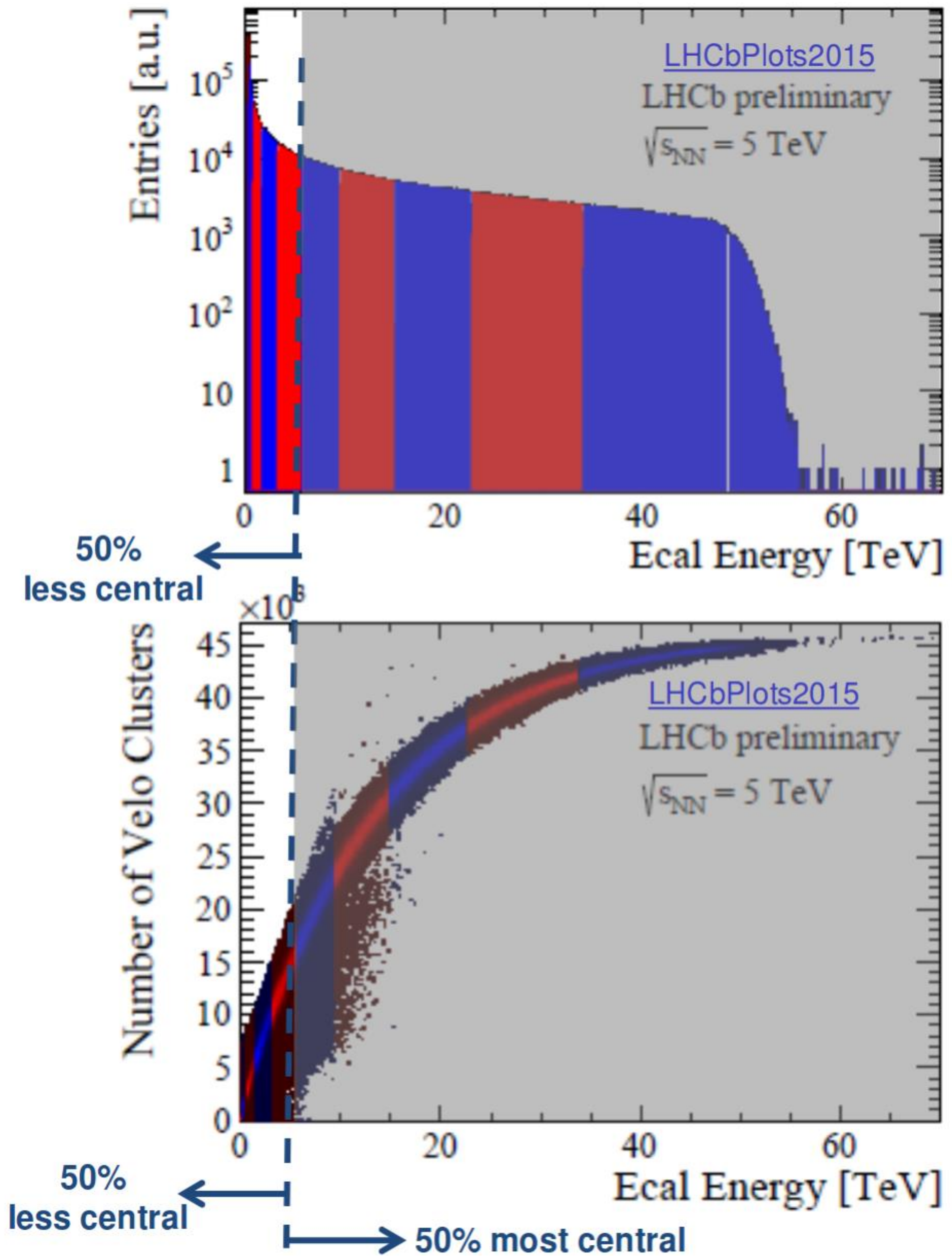
- Latest measurements with heavy ions at LHCb have been reported:
  - Fixed-target mode:
    - $\bar{p}$ production in *p*He
    - Charm production
  - *p*Pb and PbPb:
    - Coherent J/ψ production in UPC PbPb collisions
    - Heavy flavour production in *p*Pb (Λ_c^+, B hadron, $\Upsilon(nS)$)
- Not everything covered, full list here
- Prospects for the future…
  - 2018 PbPb data sample to be analysed! (x20 data w.r.t 2015)
  - Studies in view of Run3/4 with new detector (Prospects in LHCb-CONF-2018-005)
  - Upgrade of SMOG system for Run3
    - More gases, including H_2 for reference
    - Up to a factor 100 more in integrated luminosity

Much more to come in *p*Pb & PbPb & fixed target at LHCb!

Backup slides

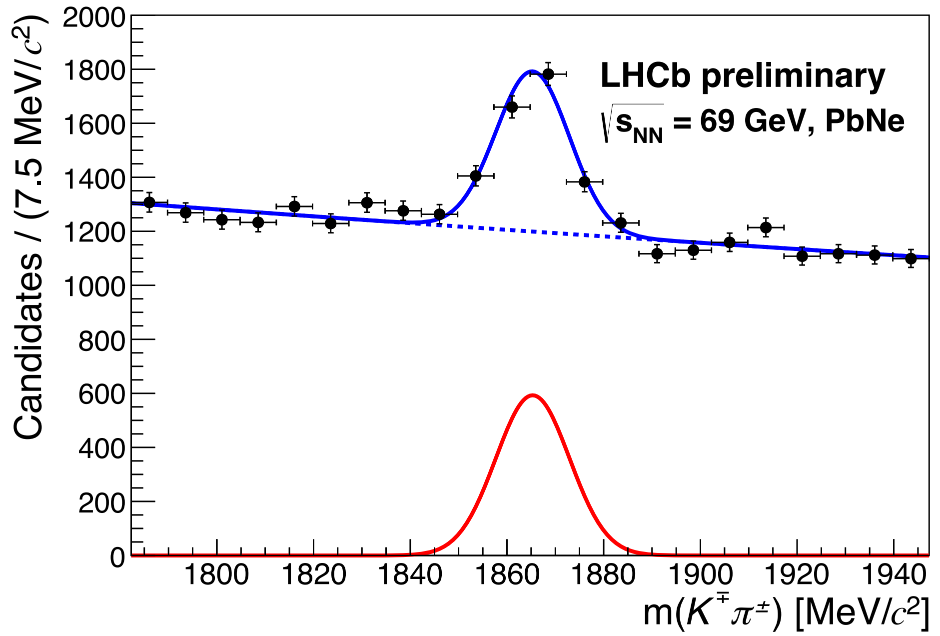
Centrality in PbPb

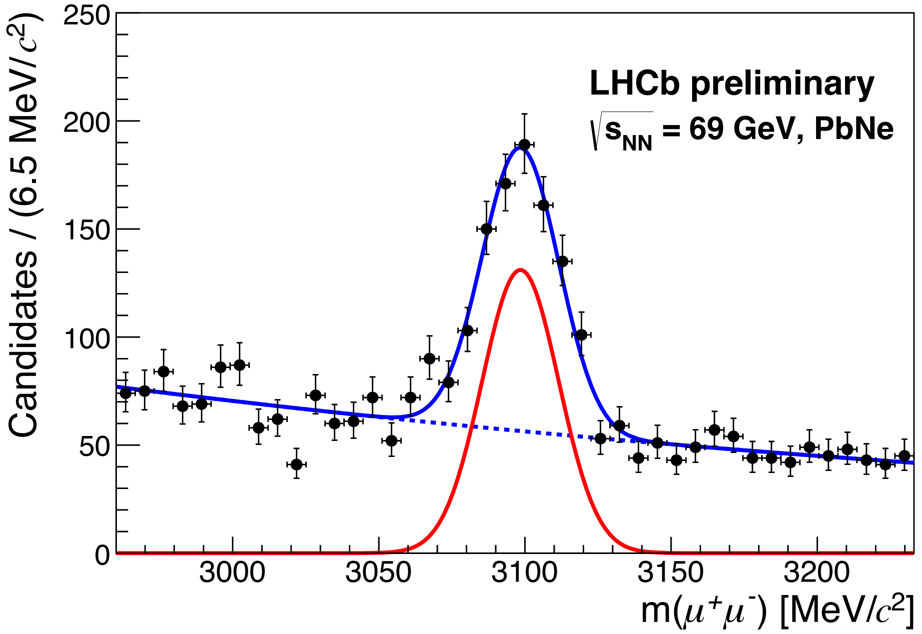
- Current centrality reach in PbPb limited to ~50% due to VELO and tracking system saturation
- Limit for current measurements in PbPb
- Studies with 2018 data set
- After Upgrade-I:
  - Improved performance in VELO and tracking system
  - Upgrade of SMOG system
    - More gases, including H_2 for reference
    - x 10 - 100 integrated luminosity
    - Precise determination of the pressure



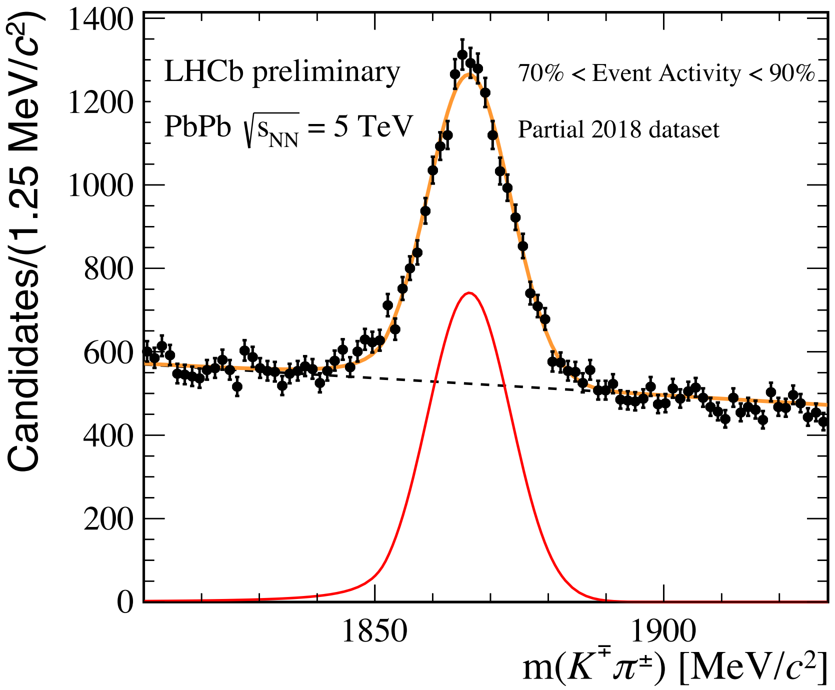
Preliminar yields from 2018 PbPb run

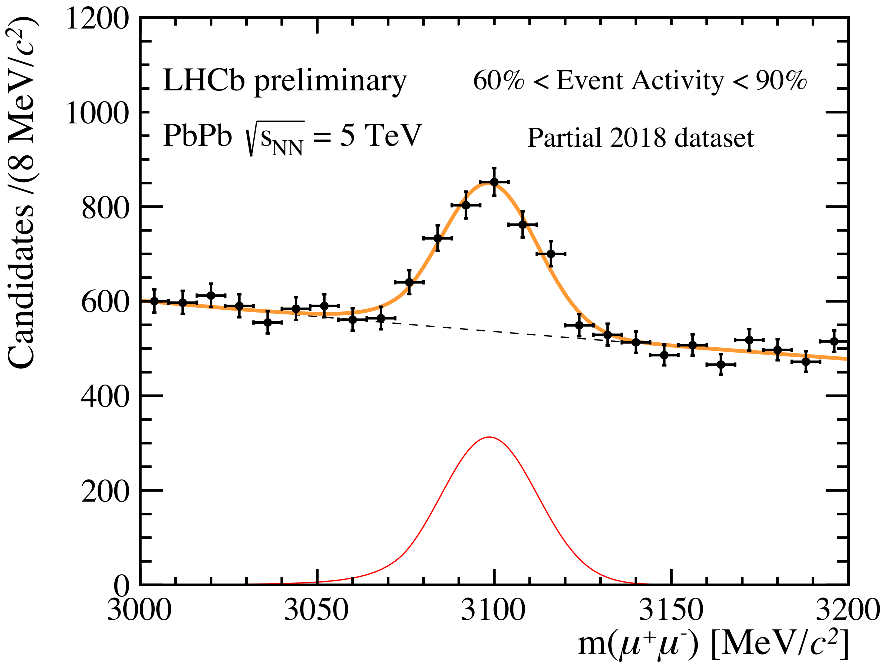
PbNe (SMOG)





PbPb

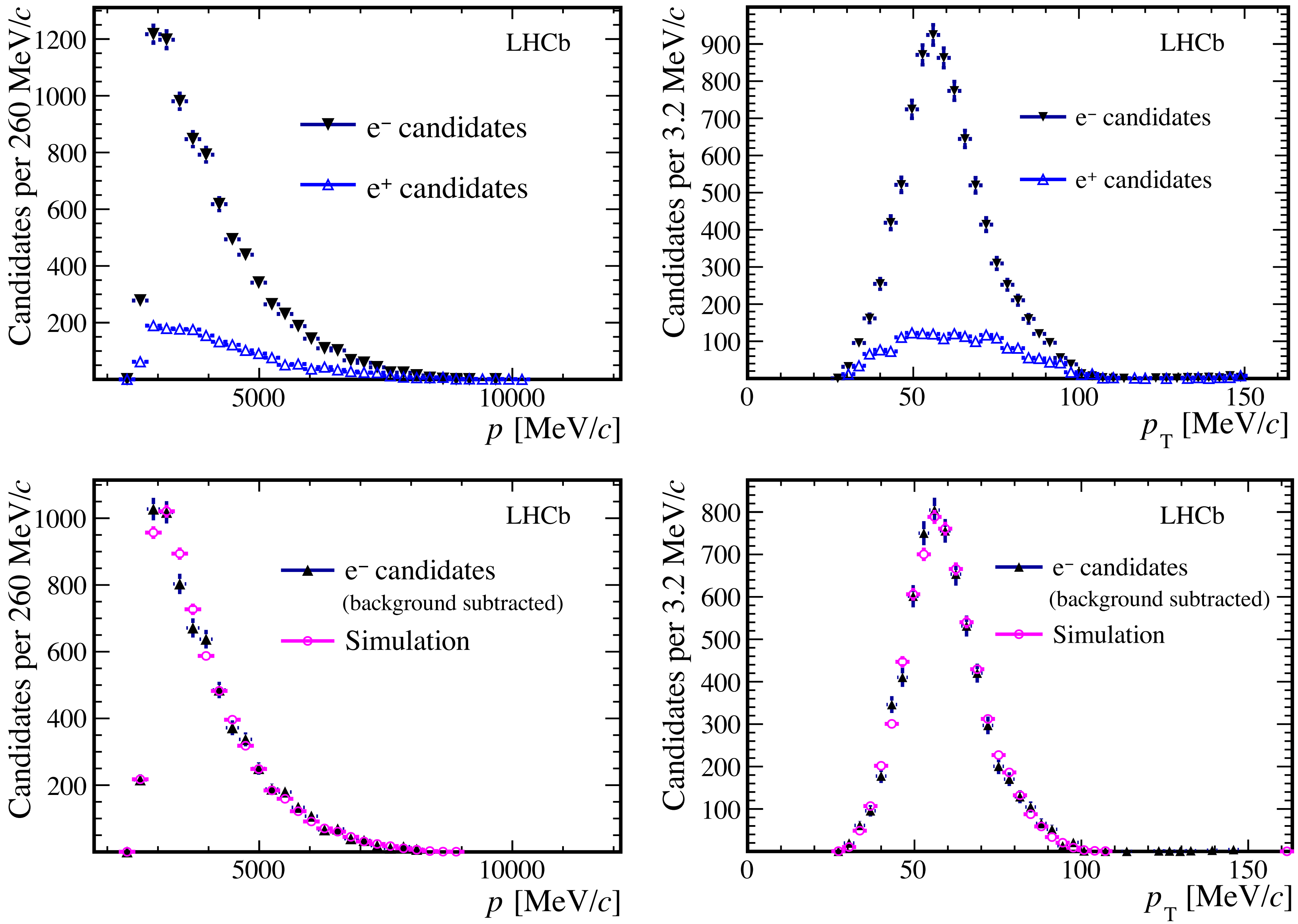




Antiproton production in pHe

[Phys. Rev. Lett. 121 (2018) 222001](https://doi.org/10.1103/PhysRevLett.121.222001)

- Luminosity determination in fixed-target configuration not trivial
- Not possible to measure directly gas pressure inside VELO
- Solution: pe^{-}elastic scattering



Nuclear modification factor in *p*Pb

- **Nuclear modification factor**: scaled ratio between particle production cross-sections in *p*Pb collisions and *pp* collisions

$$R^{X}_{p\mathrm{Pb}}(\eta^*, p_T) = \frac{1}{A}\frac{d^2\sigma^{X}_{p\mathrm{Pb}}/dp_T d\eta^*}{d^2\sigma^{X}_{pp}/dp_T d\eta^*} \qquad A = 208$$

Deviations from unity → **Cold Nuclear Matter Effects (CNM)**

- Many different sources: initial state effects (nPdF), coherent parton energy loss, interaction with comovers, p_T broadening…
- CNM effects must be disentangled from QGP ➡ Importance of *p*Pb collisions