# Results on heavy ion physics at LHCb

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**on behalf of the LHCb Collaboration**

**Workshop on Discovery Physics at the LHC, Kruger 2018**
**December 3, 2018**

# The LHCb experiment

**LHCb** is the experiment devoted to heavy flavours at the LHC.

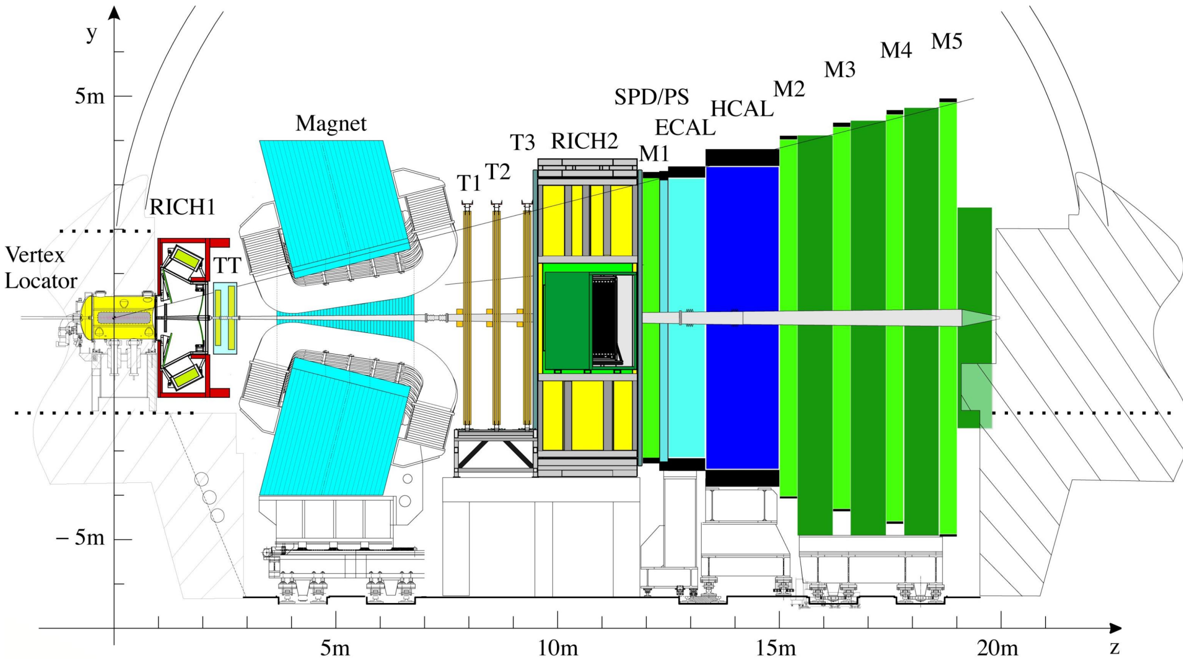
Detector requirements:

**Forward geometry** to optimize acceptance for $b\bar{b}$ pairs: $2 < \eta < 5$

**Tracking** : optimal resolution for proper time ($\sim$ 45 fs) and momentum ($<$ 1% for $p < 200$ GeV/$c$)

**Particle ID** : excellent capabilities to select exclusive decays

**Trigger** : high flexibility and bandwidth (1 MHz at hardware level, up to 15 kHz to disk)



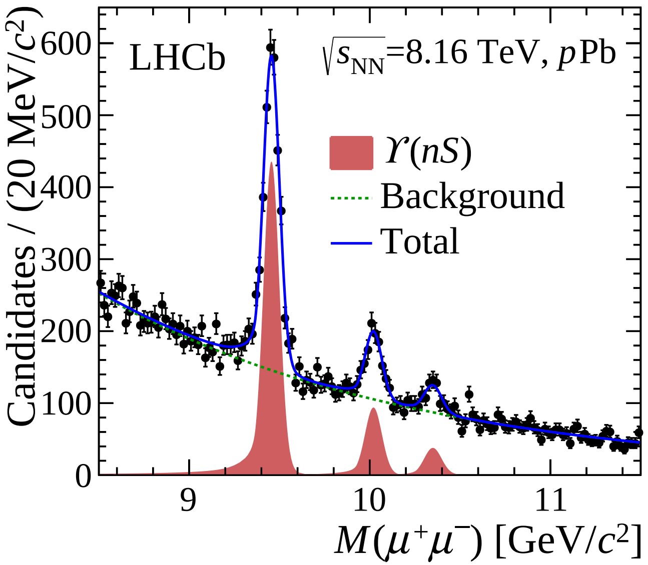

JINST 3, (2008) S08005
Int.J.Mod.Phys.A30 (2015) 1530022

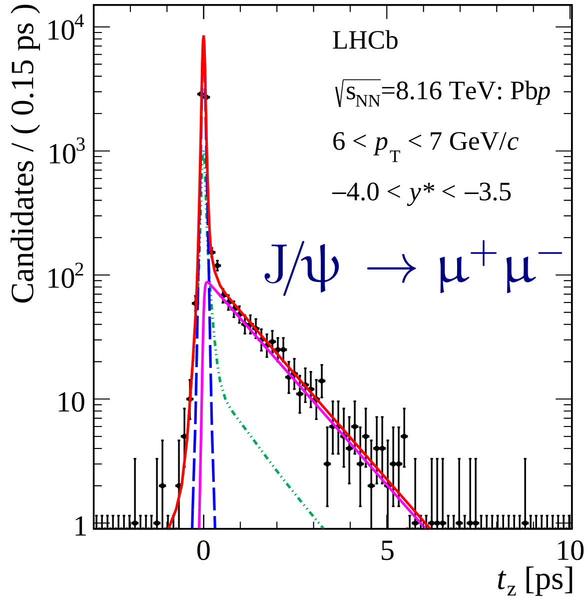
Some unique features are also attractive for heavy ion physics:

- excellent detector performance, notably for heavy flavour
- forward acceptance
- possibility to run in fixed-target mode

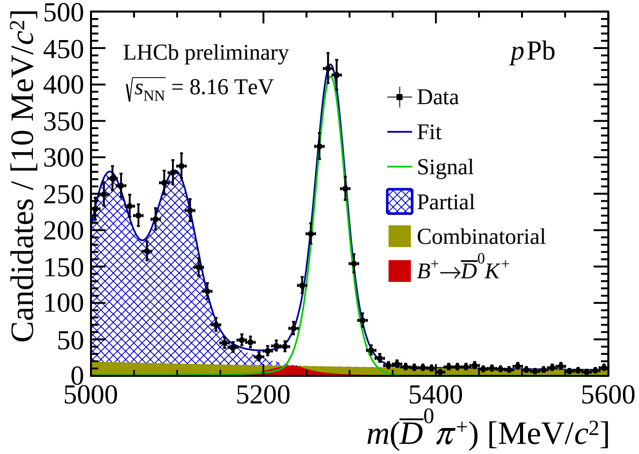
# Key feature: detector performance and trigger

- Extreme vertexing performance and excellent PID: ideal to reconstruct heavy flavour states, disentangling charm and beauty components




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



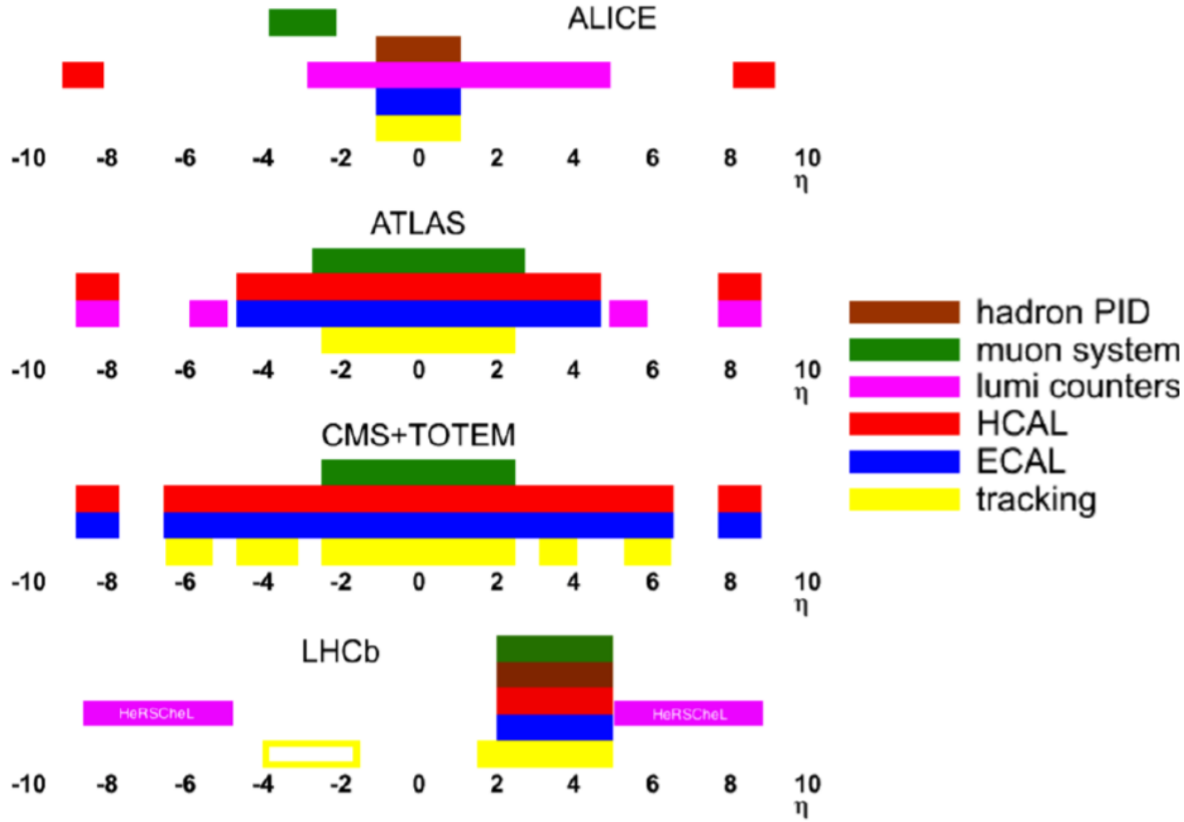

- No rate limitations from trigger and DAQ for heavy ion runs:
  - large samples of MB events
  - heavy flavour triggers with low $p_T$ thresholds ($\sim$ 1 GeV)
- ⚠ tracking saturates for most central PbPb collisions

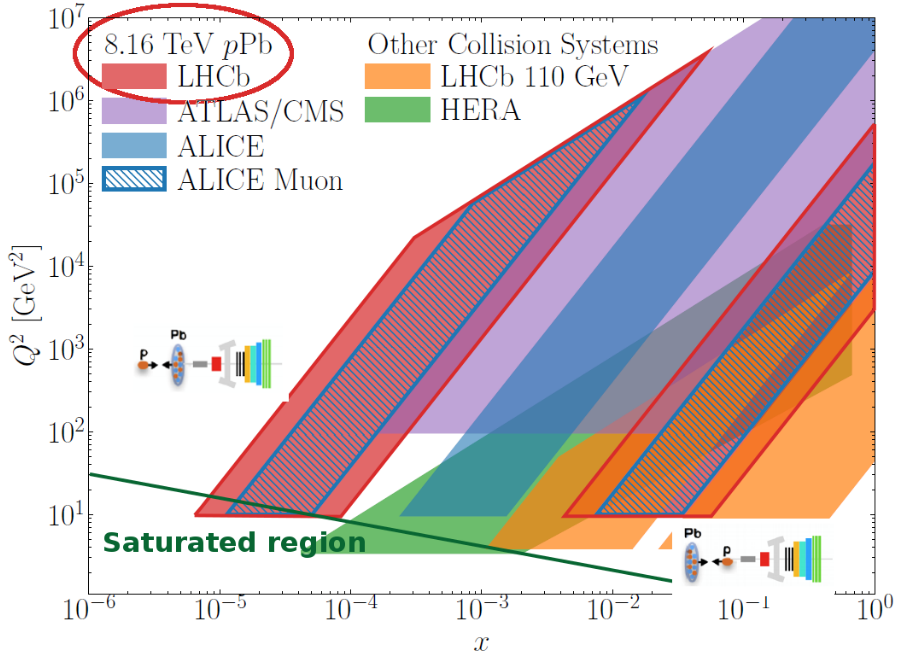
  ➨ LHCb more suited for small collision systems (pA collisions)

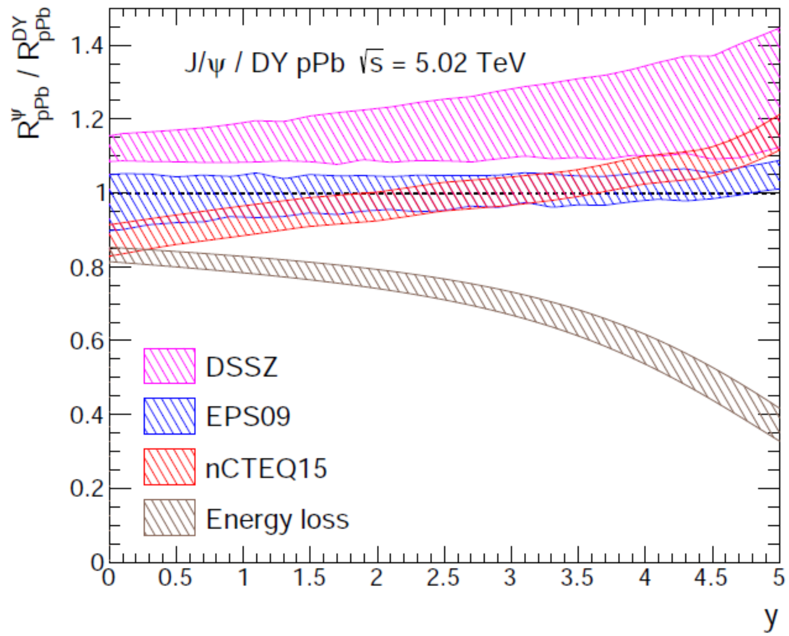
  crucial environment to understand cold nuclear matter effects and collectivity in small systems

# Key feature: forward acceptance

- Unique forward coverage at LHC



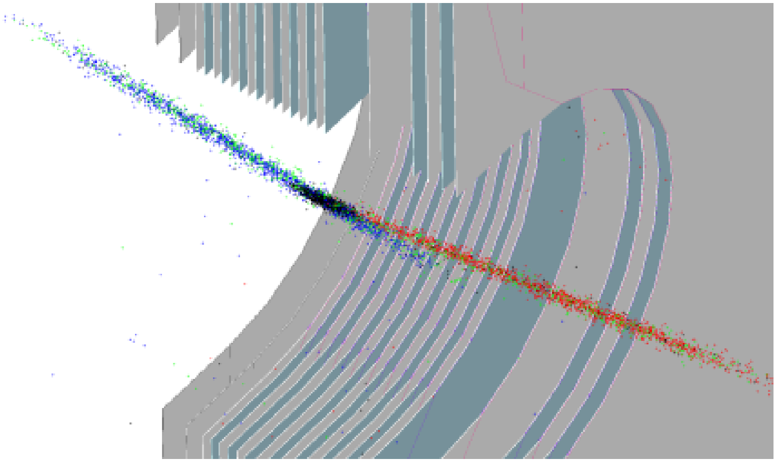

Arleo and Peigné, Phys. Rev. D95 (2017) 011502

- Sensitivity to small $x$ (down to $\sim 10^{-5}$)
  ➨ gluon saturation
- and to anti-shadowing region

- Rapidity dependence can disentangle nuclear effects (energy loss, comovers, . . . )
- Nicely complementing other LHC experiments

# Key feature: the SMOG system

“Fixed-target like” geometry very well suited for…fixed-target physics!



The System for Measuring Overlap with Gas (SMOG) allows to inject small amount of noble gas in the LHC beam pipe around ($\sim \pm 20$ m) the LHCb collision region.

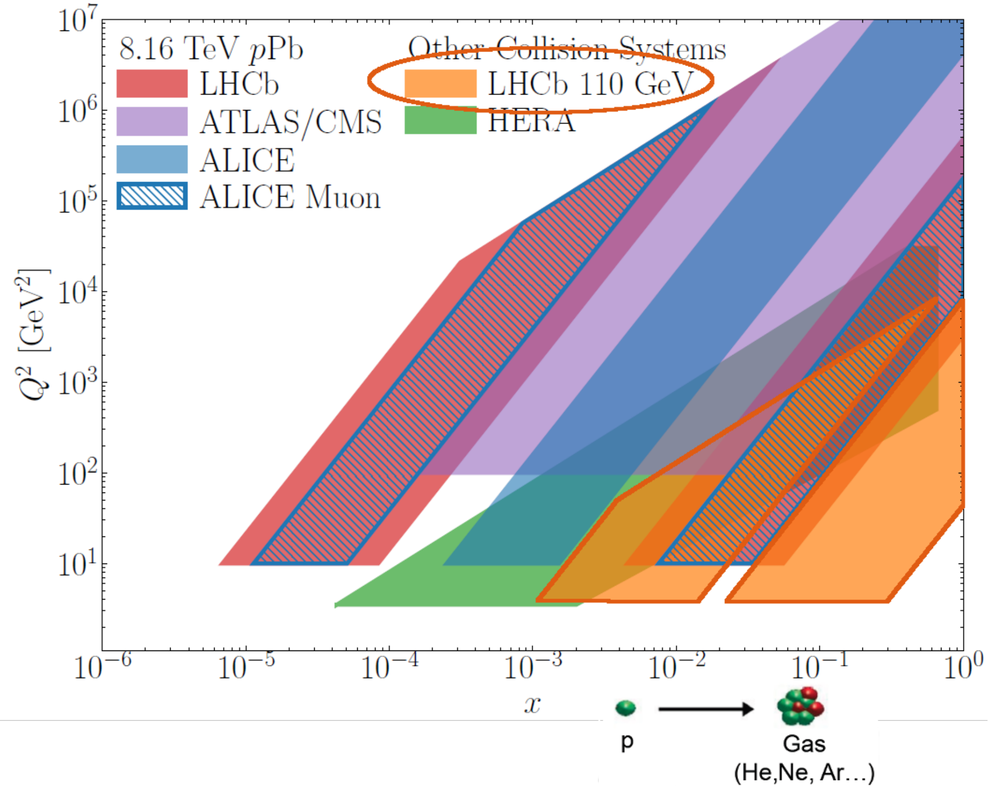
**Turns LHCb into a fixed-target experiment!**

Possible targets: **He, Ne, Ar**, and more in the future

Typical pressure $\sim 2 \times 10^{-7}$ mbar

➡ luminosity up to $10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

- Collisions at $\sqrt{s_{\mathrm{NN}}} = \sqrt{2E_{beam}M_p}$
  41-110 GeV for $E_{beam} = 0.9 - 6.5$ TeV
  ➡ relative unexplored energy scale between SPS and LHC experiments
- at $\sqrt{s_{\mathrm{NN}}} = 110$ GeV, c.m. rapidity is $-2.8 < y^* < 0.2$ backward detector with access to large $x$ value in target nucleon, for different nuclear targets
  ➡ study nPDF in antishadowing/EMC region, possible intrinsic heavy quark content in nucleons

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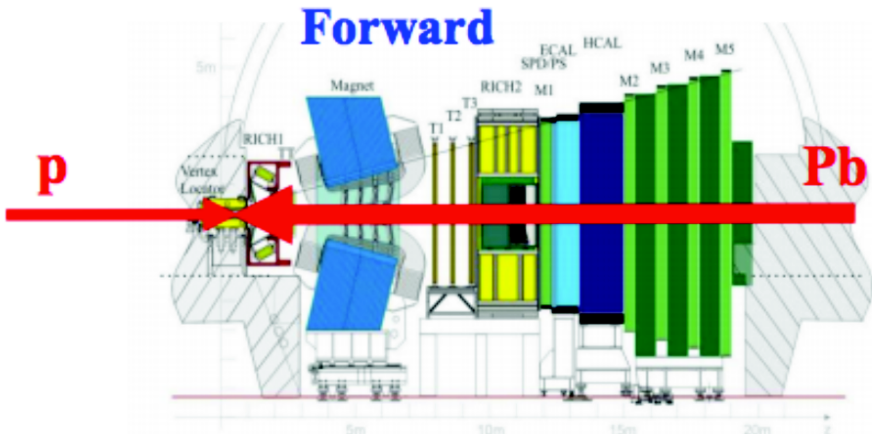
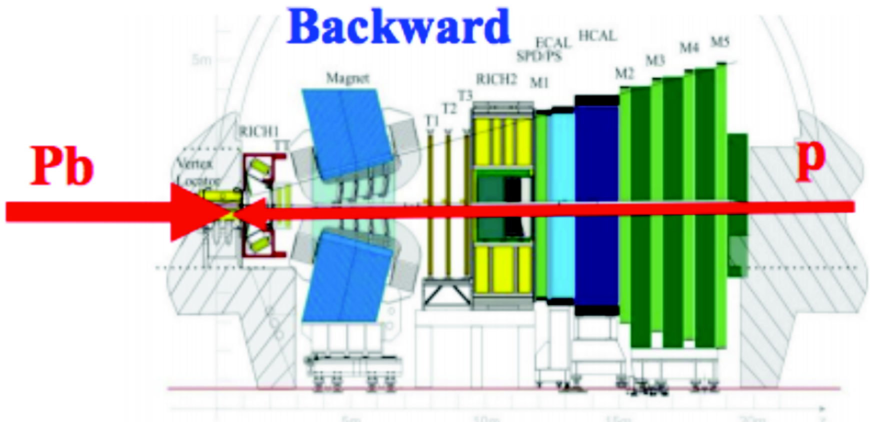
# pPb collisions

# pPb Data sets




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

**Forward region:**

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

**Backward region:**

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

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

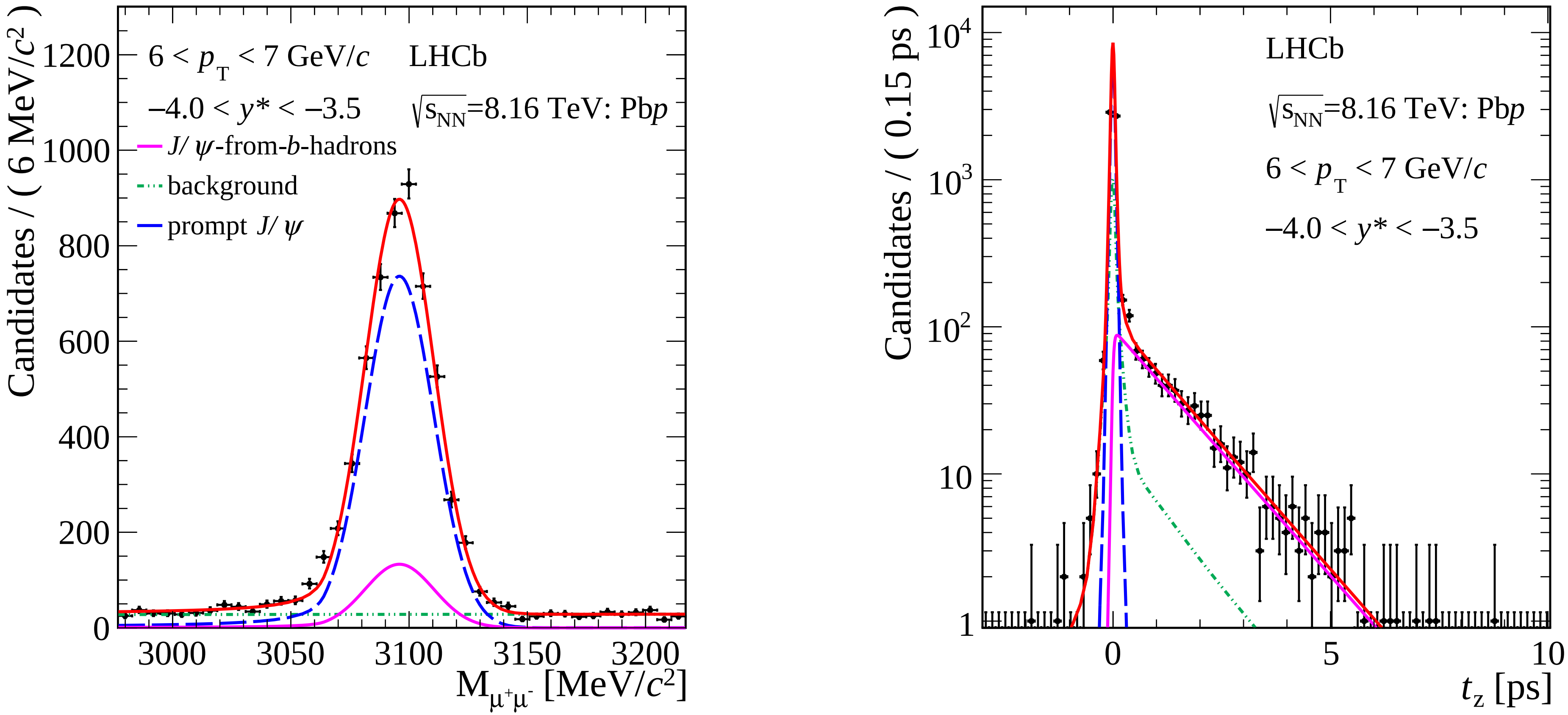
- **1.1 nb$^{-1}$ (Fwd), 0.5 nb$^{-1}$ (Bwd)**

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

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

# J/ψ in pPb@8 TeV

PLB 774 (2017) 159




- Very clean sample, down to 0 $p_T$
- Measurement double differential in $p_T$ and rapidity
- Powerful probe of gluon PDF at low $x$
- **separation of prompt and from-b components**, through pseudo-proper time

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

# J/ψ in pPb: nuclear modification

PLB 774 (2017) 159

- Strong suppression in forward direction
- Clearly larger for prompt J/ψ

$$R_{pPb} = \frac{1}{A}\frac{\sigma_{pPb}}{\sigma_{pp}}$$

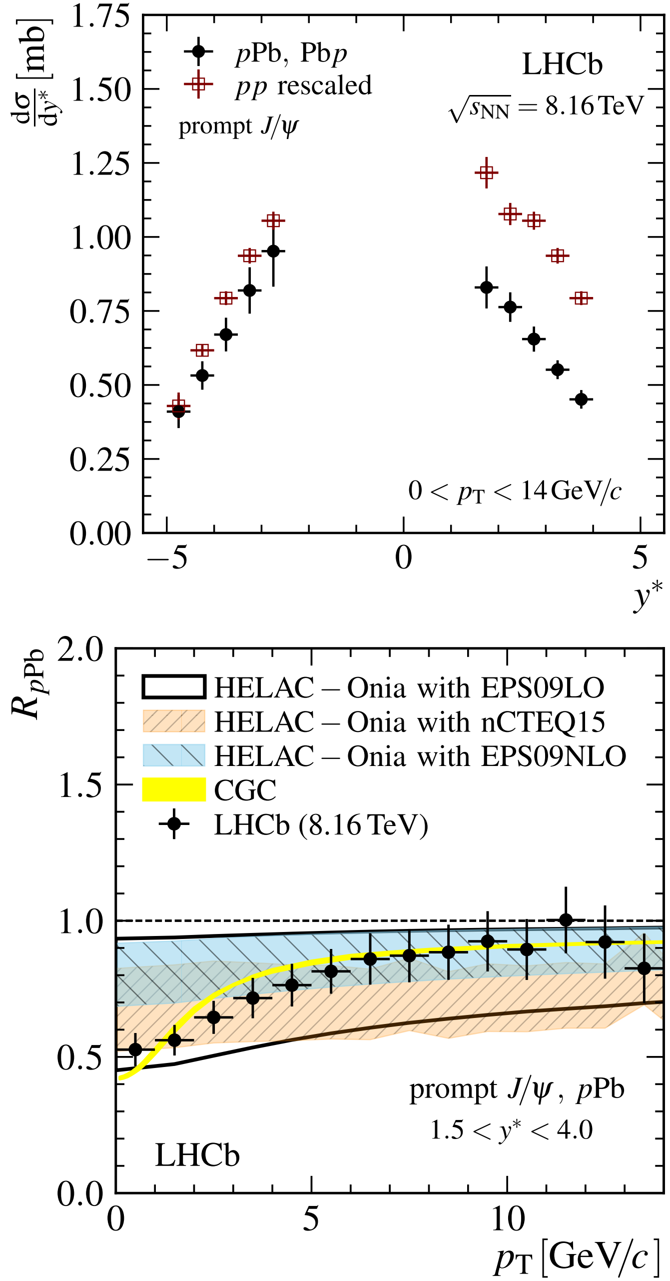
- Compatible with initial-state (nPDF) effects

**prompt: HELAC-onia (collinear fact.)**
**Shao, Comp.Phys.Comm. 198 (2016) 238**
**from-b: pQCD at FONLL**
**Cacciari et al, JHEP 05 (1998) 007**

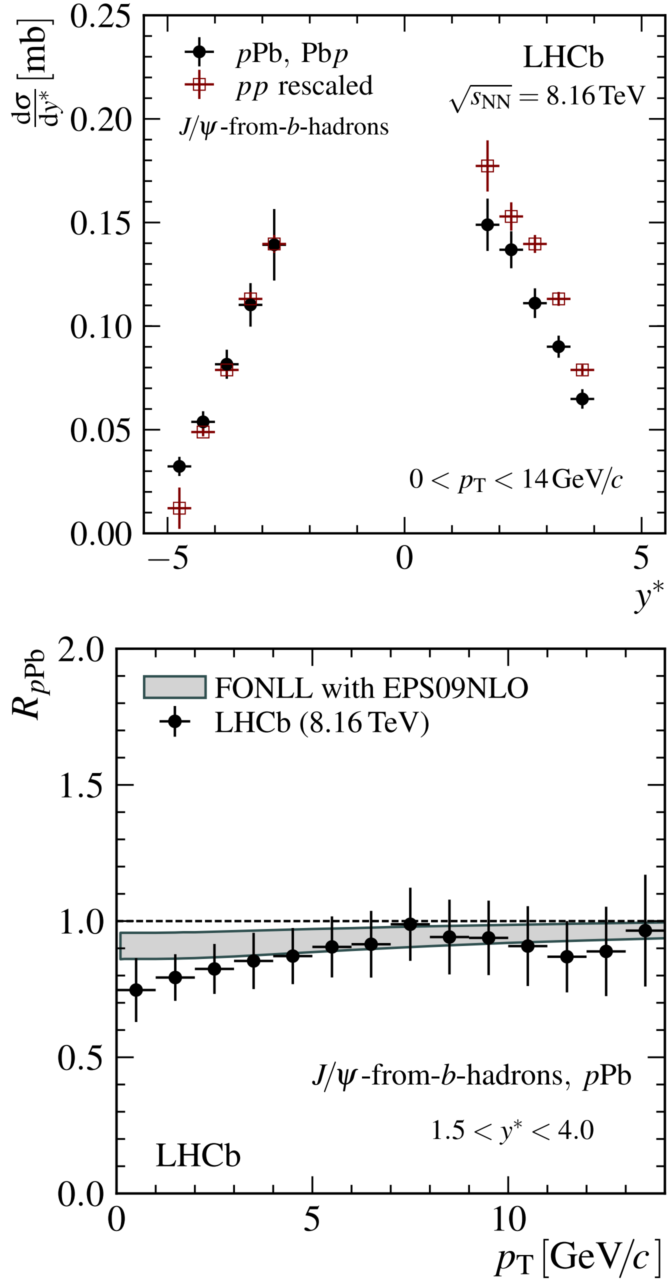
- Good agreement with (latest) CGC-model prediction

**Ducloué et al, PRD94 (2016) 074031**

## Prompt




## From b



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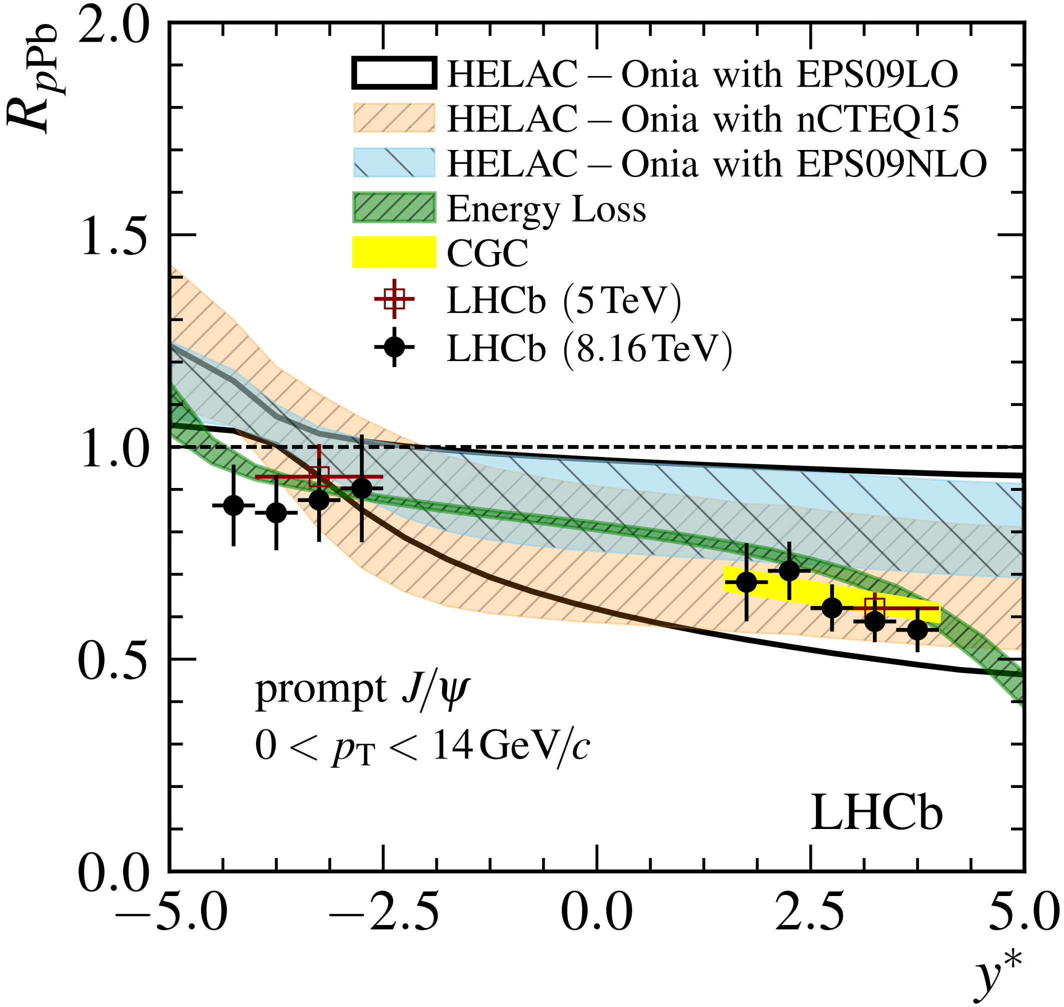
PLB 774 (2017) 159

## Prompt

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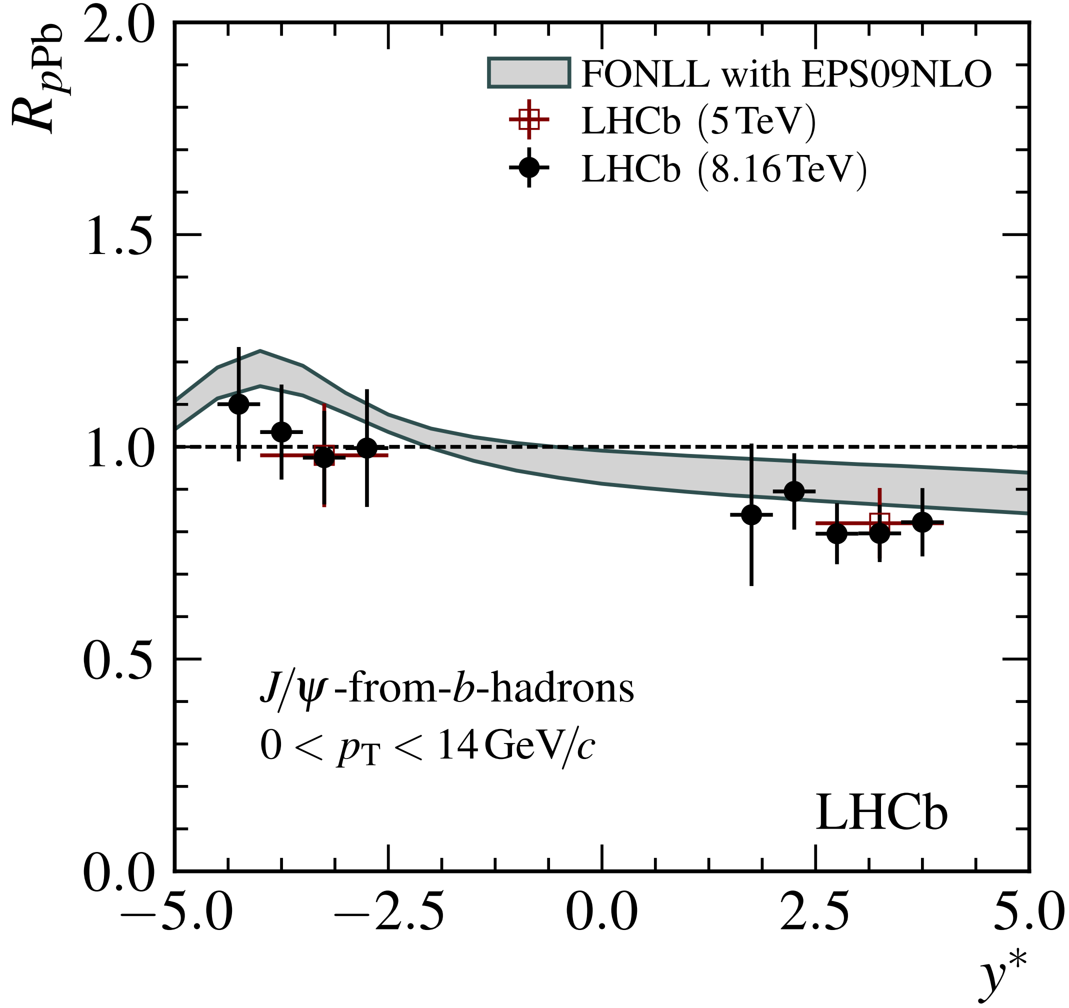


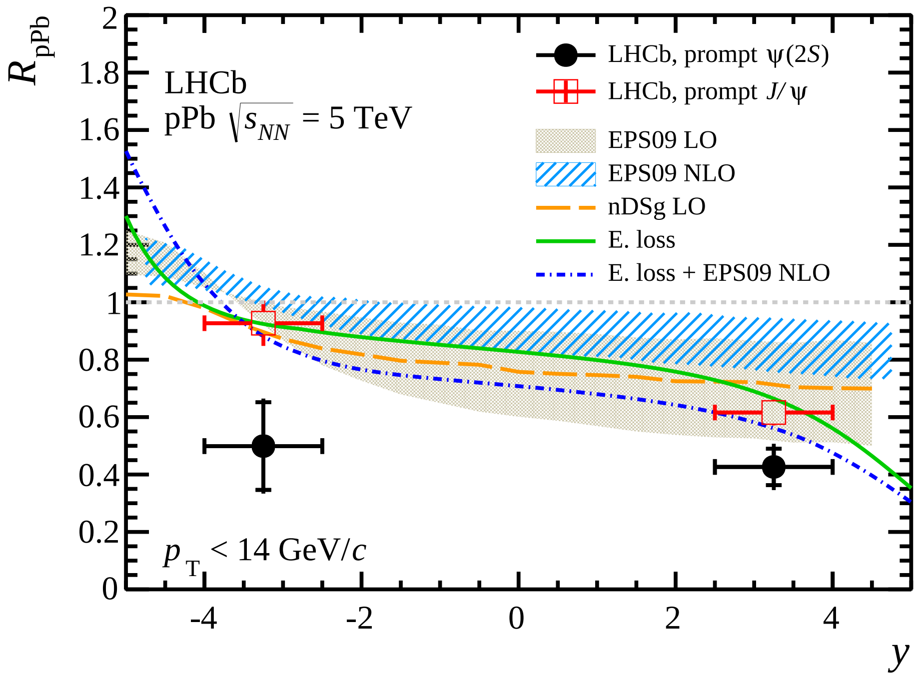

- Rapidity dependence can also be explained by coherent energy loss

**Arleo and Peigné, JHEP 03 (2013) 122**

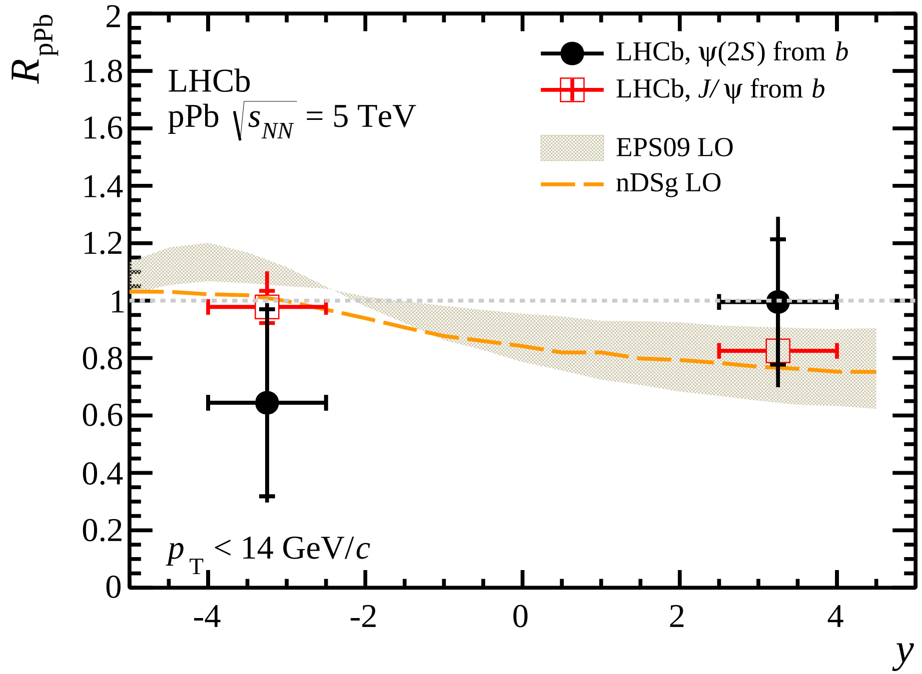
# J/ψ and ψ(2S) in pPb

JHEP 1603 (2016) 133

**Prompt**




**From b**

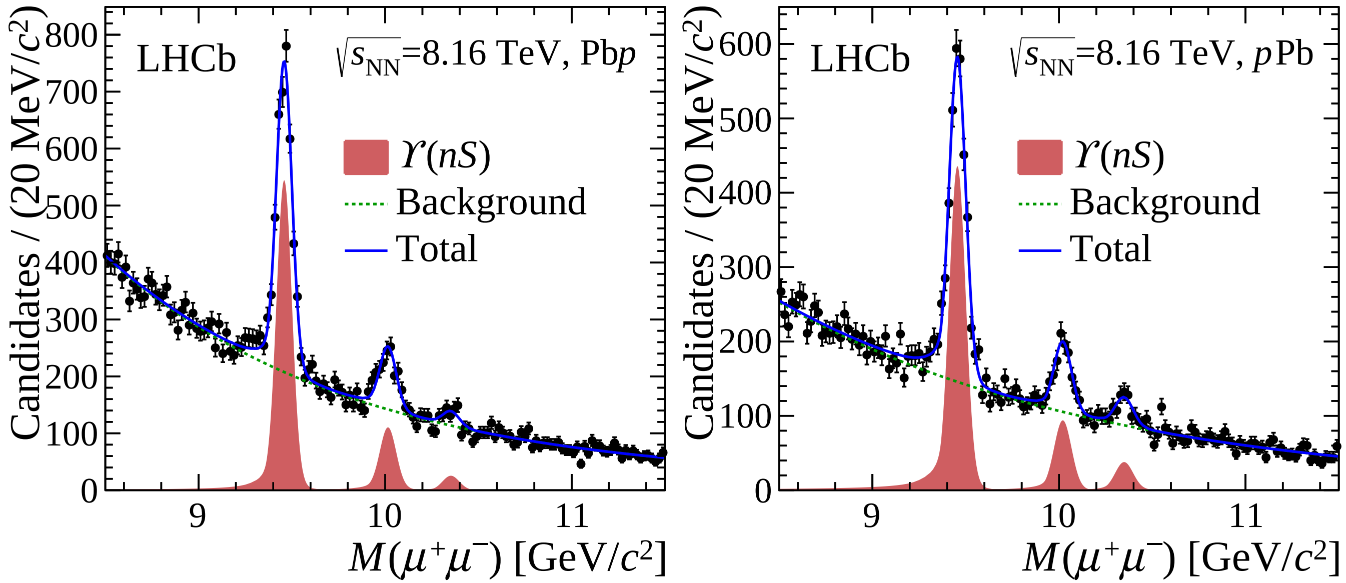



- Results from the smaller sample at 5 TeV show a stronger suppression for ψ(2S), not expected from initial state effects or energy loss
- Confirms similar findings from PHENIX, ALICE
- Stay tuned for the update from 8 TeV data

# Bottomonia in pPb@8 TeV

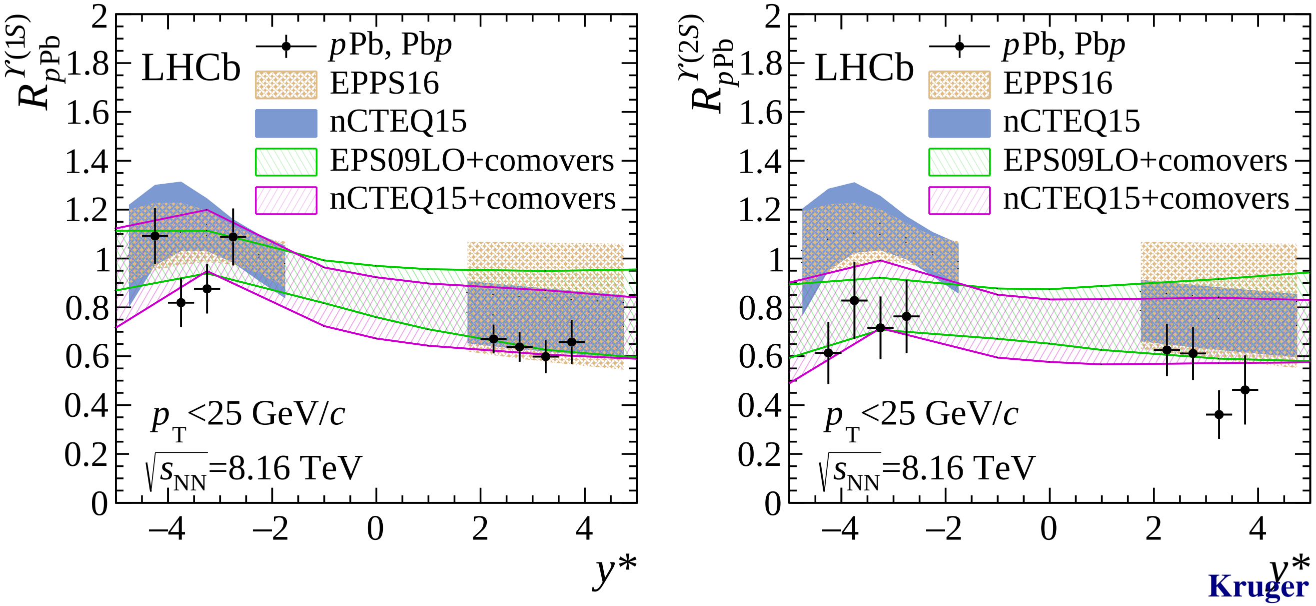
arXiv:1810.07655, accepted by JHEP

**Backward** **Forward**




- Clean separation of three nS states

**R for $\Upsilon(1S)$** **R for $\Upsilon(2S)$**



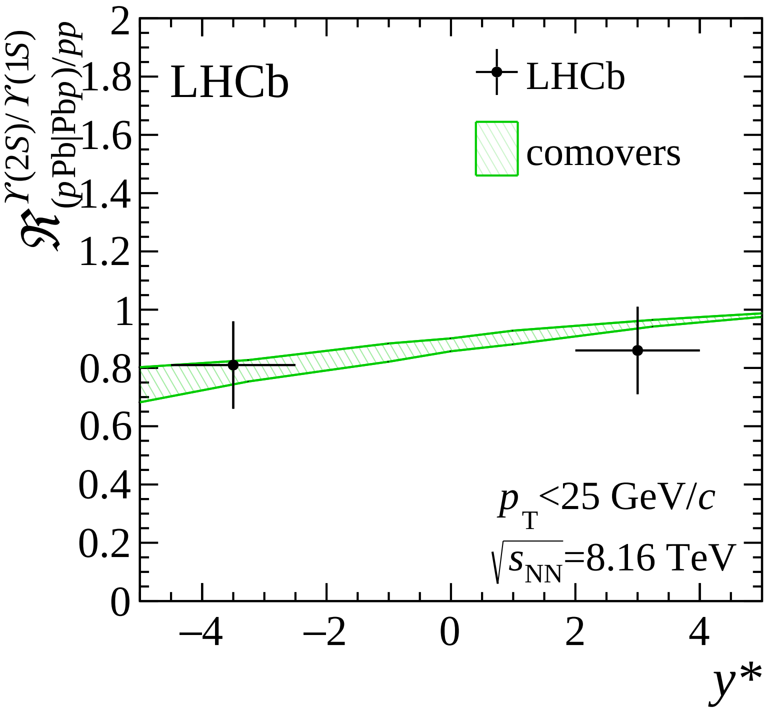

- "Comover" model predicts large final-state effects, larger for excited states and in backward direction

**Ferreiro and Lansberg, JHEP 10 (2018) 094**

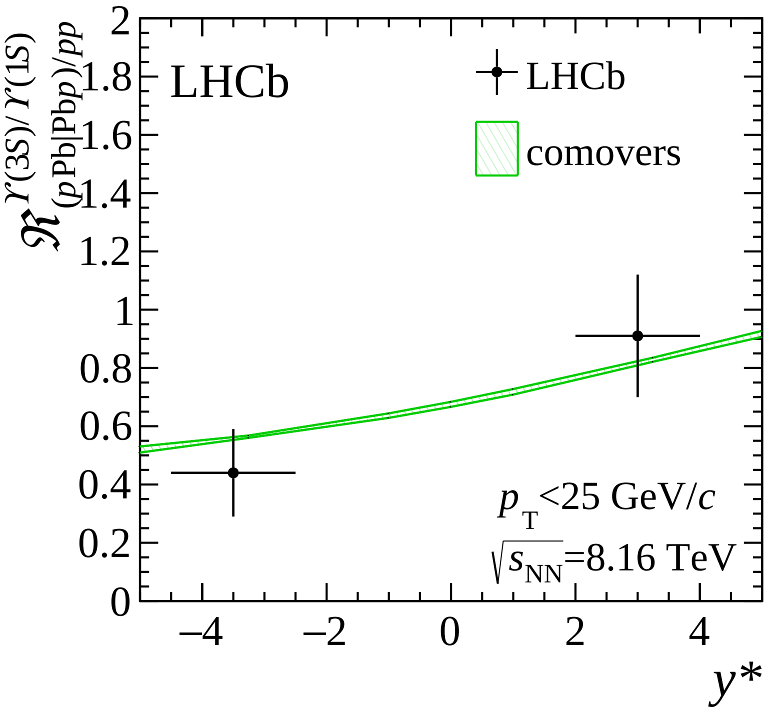
- Patterns observed in data support this picture…

**Kruger 2018**

**R**($\Upsilon(2S)$)/**R**($\Upsilon(1S)$)



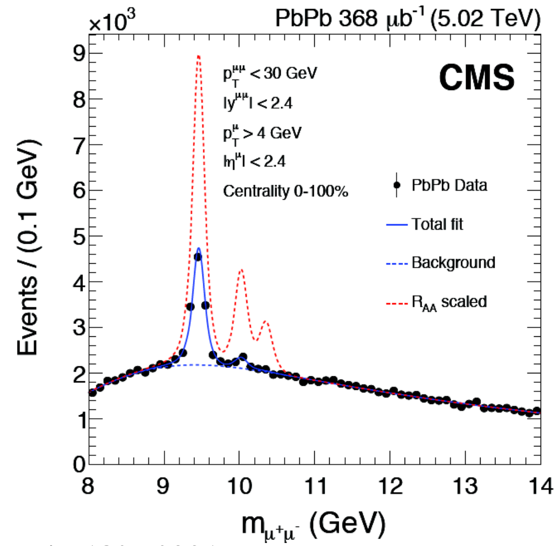

**R**($\Upsilon(3S)$)/**R**($\Upsilon(1S)$)




…notably for $\Upsilon(3S)$ ! Smoking gun for comovers?

$$\mathfrak{R}^{\Upsilon(2S)/\Upsilon(1S)}_{p\mathrm{Pb}/pp} = 0.86 \pm 0.15,$$
$$\mathfrak{R}^{\Upsilon(3S)/\Upsilon(1S)}_{p\mathrm{Pb}/pp} = 0.81 \pm 0.15,$$
$$\mathfrak{R}^{\Upsilon(2S)/\Upsilon(1S)}_{\mathrm{Pb}p/pp} = 0.91 \pm 0.21,$$
$$\mathfrak{R}^{\Upsilon(3S)/\Upsilon(1S)}_{\mathrm{Pb}p/pp} = 0.44 \pm 0.15.$$

Understanding this effect is crucial to a correct interpretation of QGP-induced sequential quarkonia suppression observed in PbPb



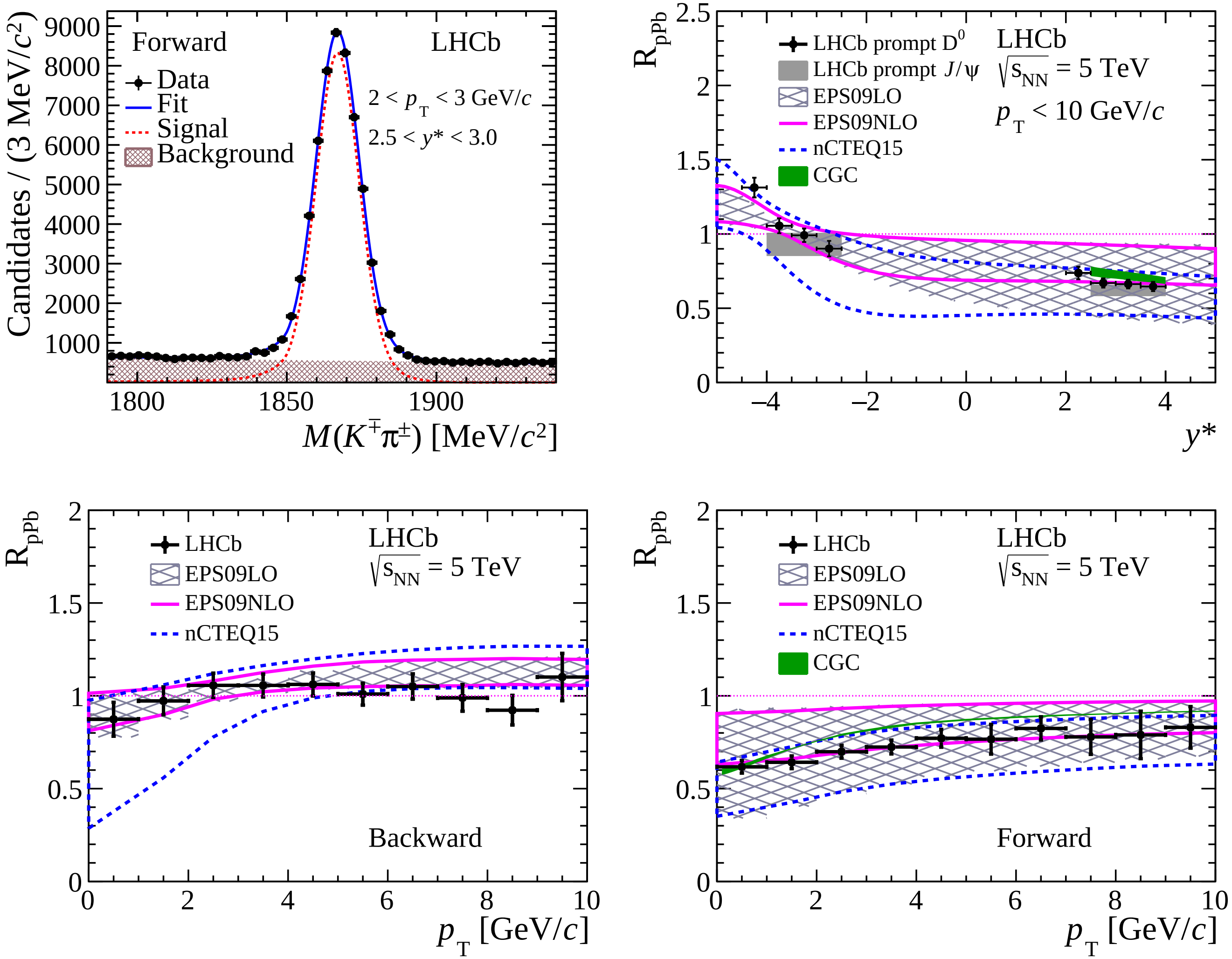

arXiv:1805.09215

# Open charm in pPb

JHEP 1710 (2017) 090

- Unique data down to 0 $p_{\mathrm{T}}$
- Precision measurement already with 5 TeV sample
- Strong suppression at forward rapidity and low $p_{\mathrm{T}}$ seen also here, expected from shadowing
- Data can constrain nPDFs in unexplored area at low $x$, assuming no other effects.

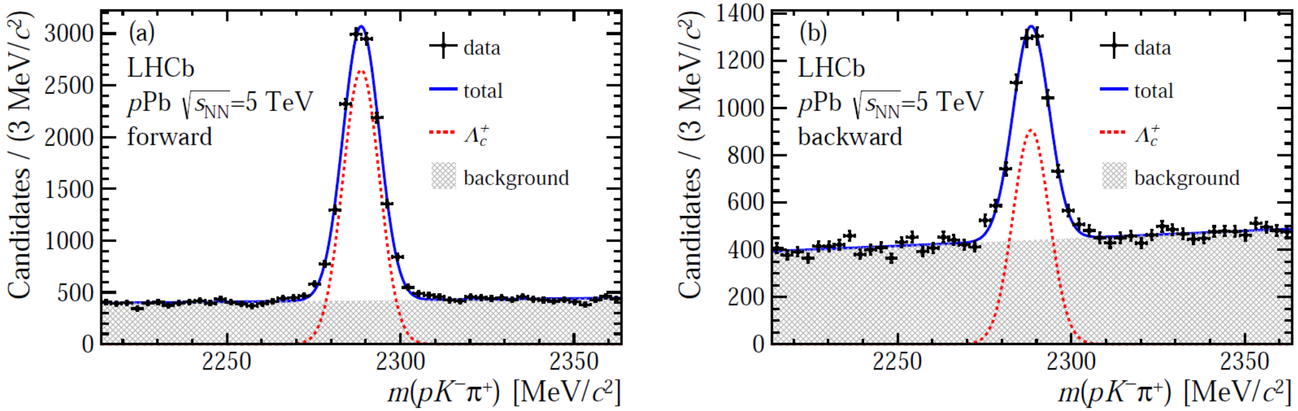
  (Coherent energy loss predicts similar patterns qualitatively)



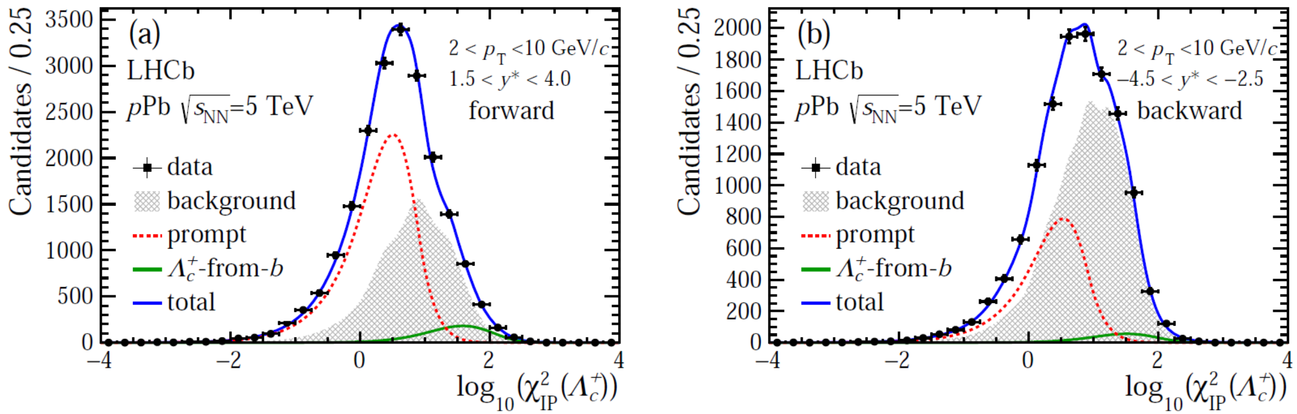
# Charmed baryons in pPb

arXiv:1809.01404

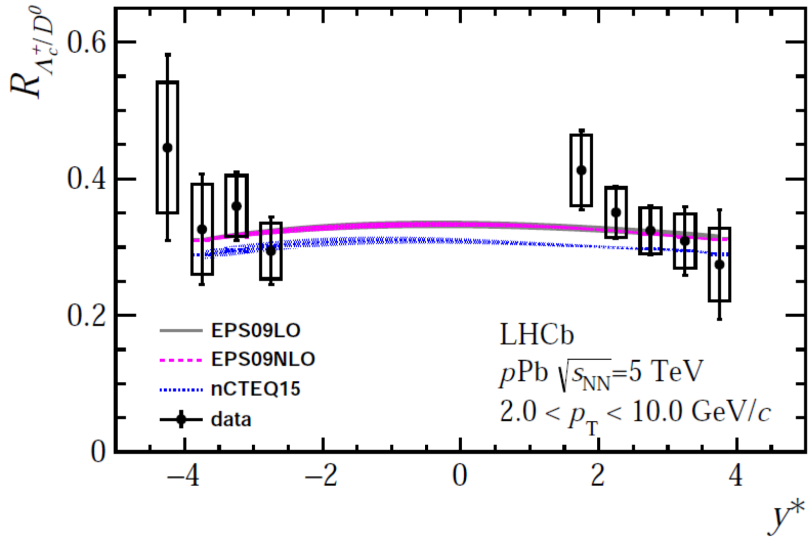
- $\Lambda_c^+/D^0$ ratio is an important input to hadronisation phenomenology
- Baryon enhancement expected from production via coalescence, also affected by thermal properties of the nuclear medium
- Large charmed baryon enhancement observed in central AuAu collisions at RHIC
- ALICE sees no enhancement in pPb collisions: no hint from effect of cold nuclear matter



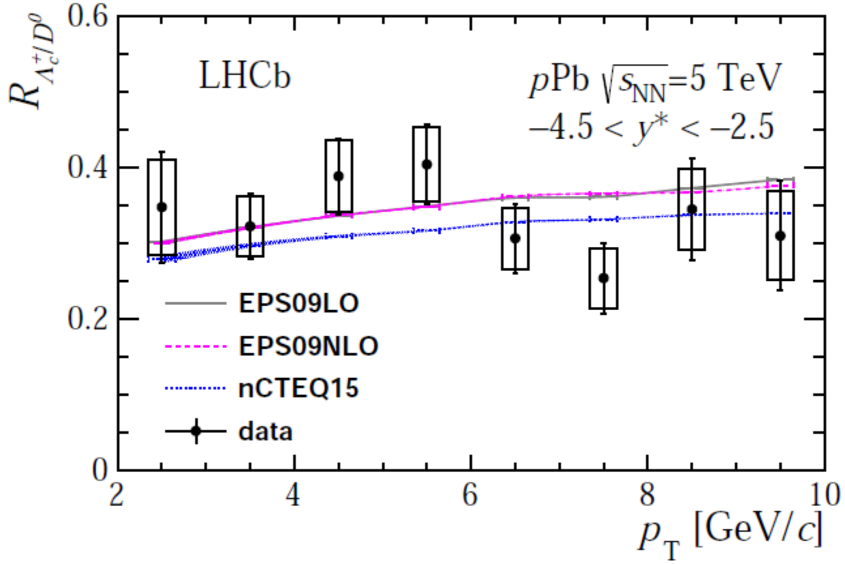

- Ratio measured by LHCb in 5 TeV $p$Pb data
- Contribution from $b$ decays subtracted using impact parameter distribution



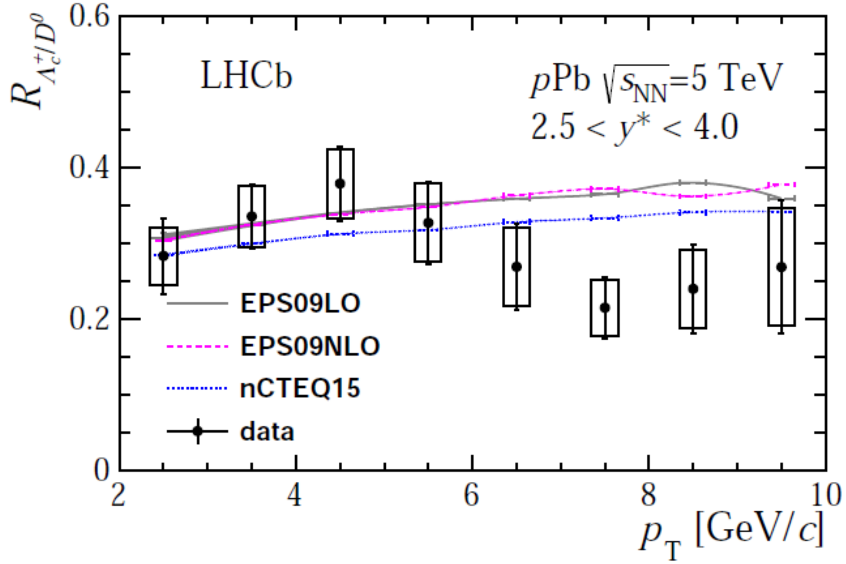
arXiv:1809.01404




**Backward**




**Forward**



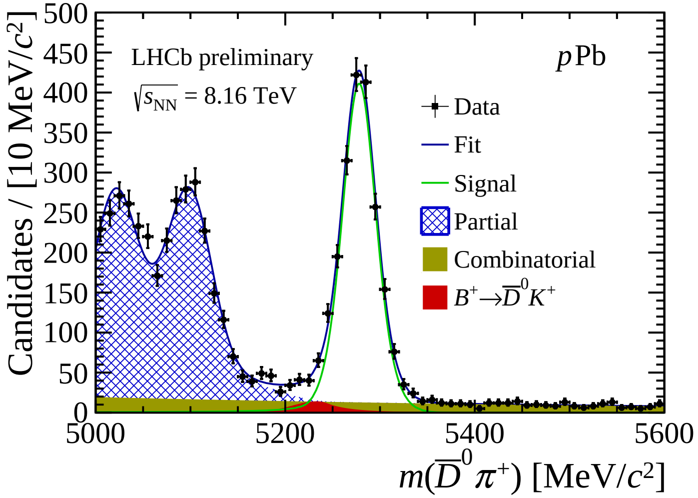

- No strong kinematic dependence observed, substantial agreement with predictions in collinear factorisation based on *pp* data
- Need update with 8 TeV data to determine dependence on event activity

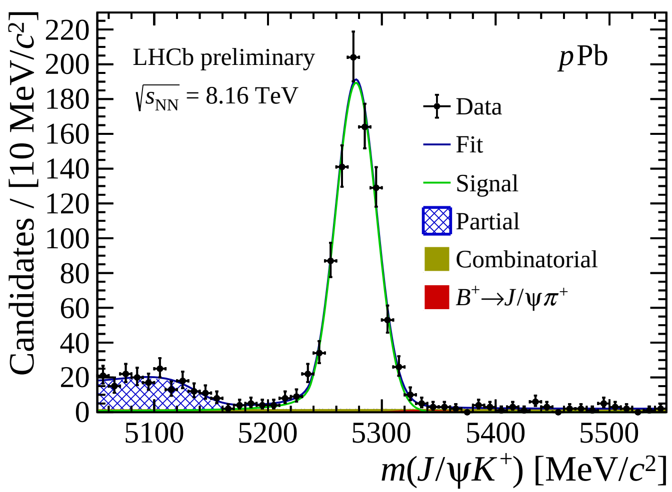
# Open beauty in pPb

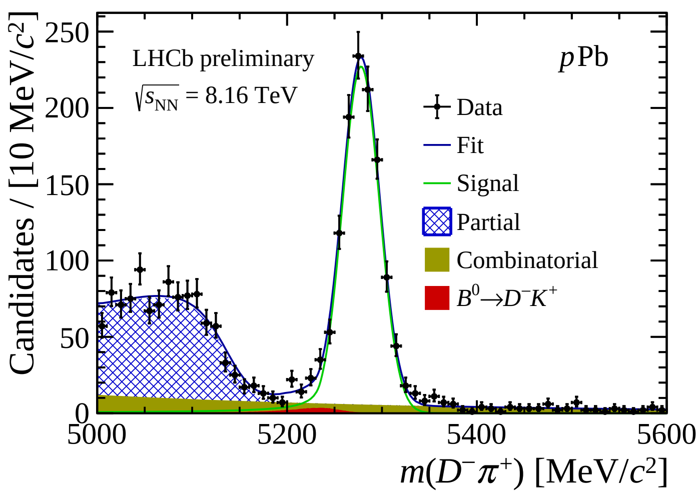
LHCb-CONF-2018-004

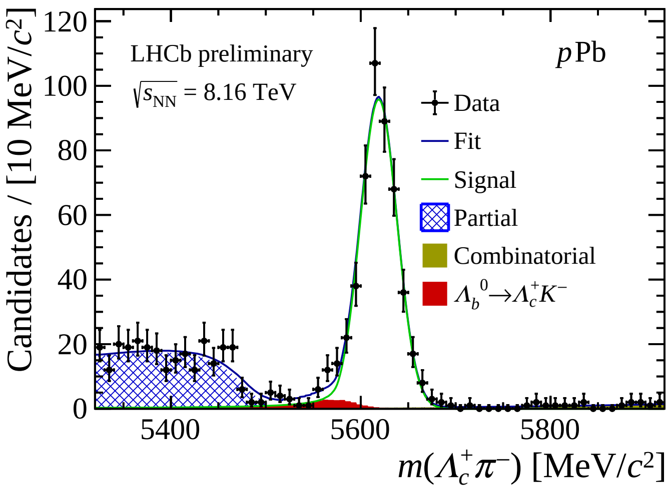
## Clean signals in exclusive decay modes:

$B^+ \to \bar{D}^0\pi^+$, $B^+ \to J/\psi\, K^+$, $B^0 \to D^-\pi^+$, $\Lambda_b^0 \to \Lambda_c^+\pi^-$



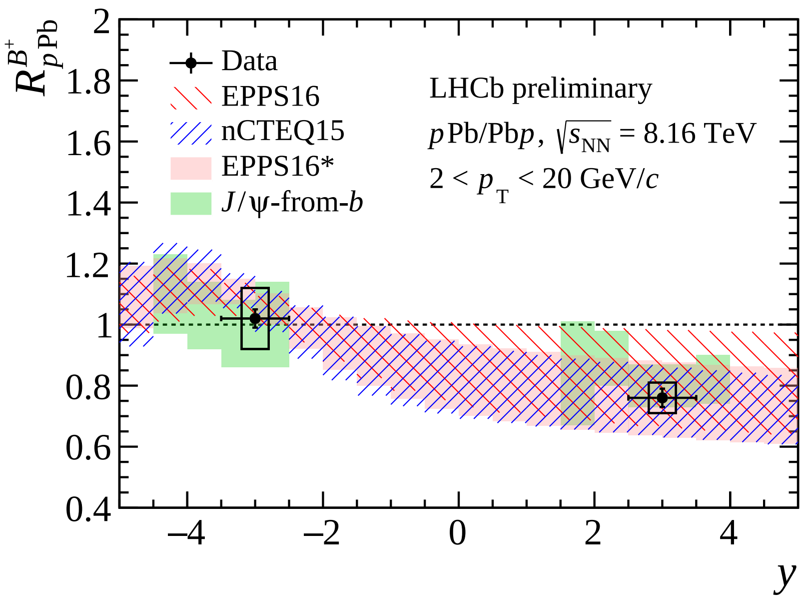



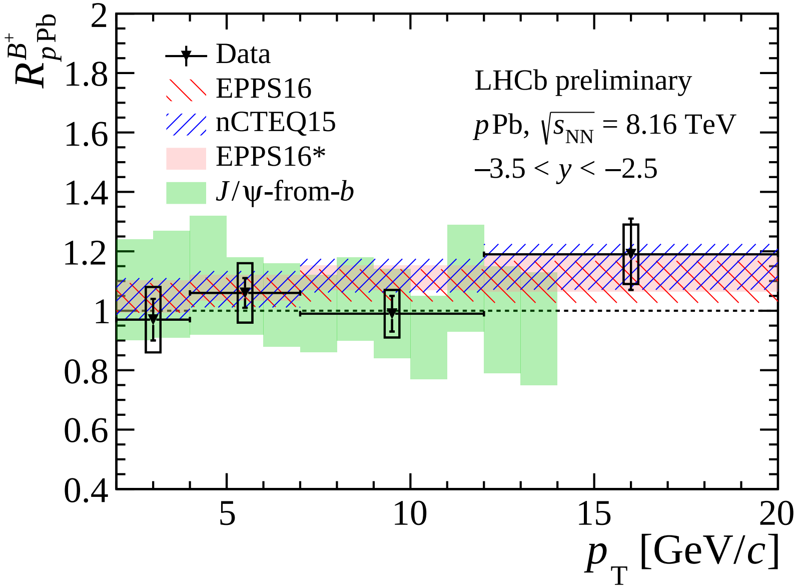




| Decay | $p$Pb | Pb$p$ |
|---|---|---|
| $B^+ \to \overline{D}^0\pi^+$ | $1943 \pm 58$ | $1824 \pm 64$ |
| $B^+ \to J/\psi\, K^+$ | $883 \pm 32$ | $905 \pm 33$ |
| $B^0 \to D^-\pi^+$ | $1155 \pm 39$ | $886 \pm 34$ |
| $\Lambda_b^0 \to \Lambda_c^+\pi^-$ | $484 \pm 24$ | $397 \pm 23$ |

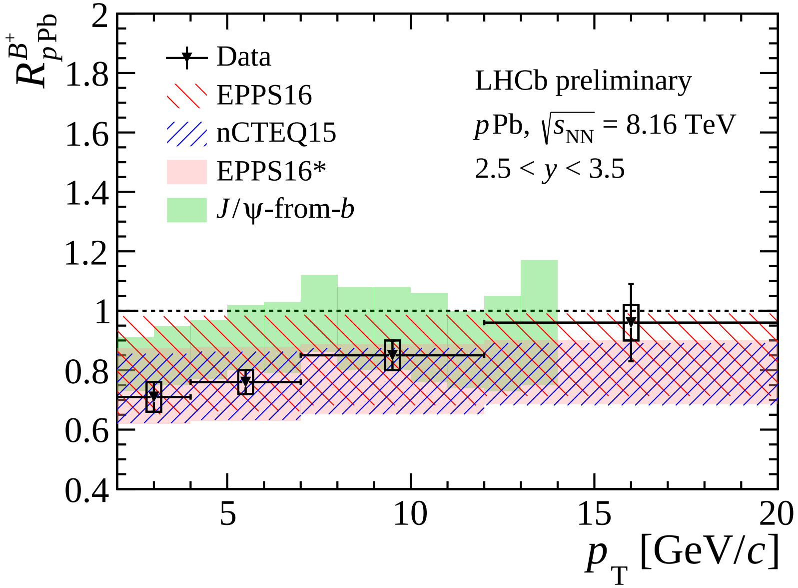
First measurement in nuclear collisions, down to low $p_T$ (< hadron mass)!




**Backward**



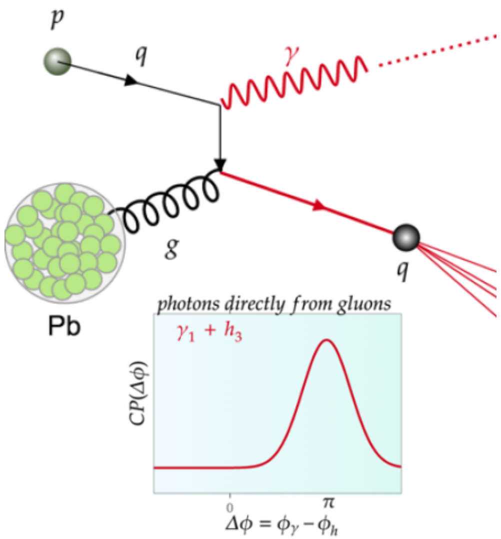

**Forward**



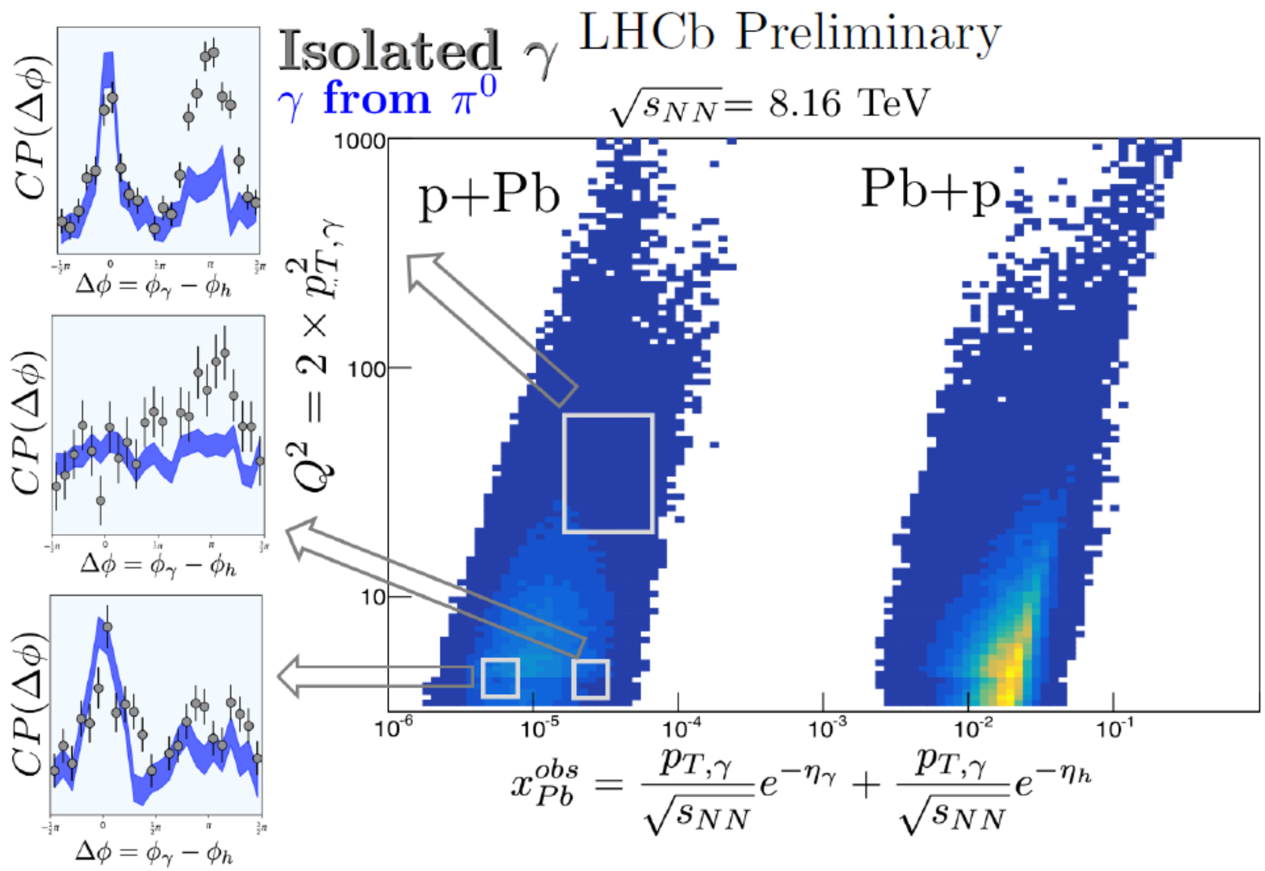

- Confirming suppression pattern observed in J/ψ from b, consistent with nPDF effect
- $\Lambda_b^0/B^0$ ratio also measured and found consistent with pp

# Photons in pPb

- Direct photons give access to saturation region, unique kinematic reach in LHCb
- Reconstruct photons through conversions inside the tracking system (better resolution than using e.m. calorimeter)
- Two approaches:
  - Extract direct photons from inclusive spectra, after subtracting the $\pi^0/\eta$ contribution, normalized at low $p_{\mathrm{T}}$
  - Exploit correlations with hadrons in inverse Compton processs



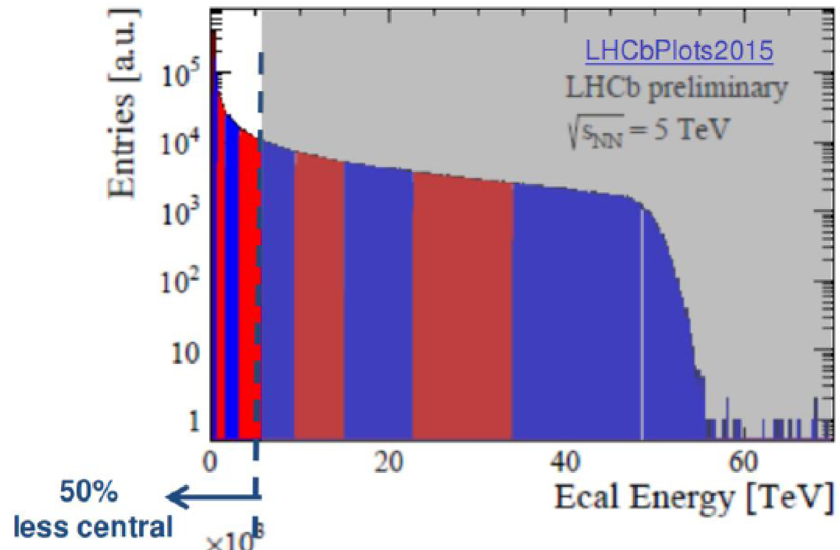

- Di-jet background measured in data from identified $\pi^0$
- First evidence for direct photons from gluons in the potential saturated region

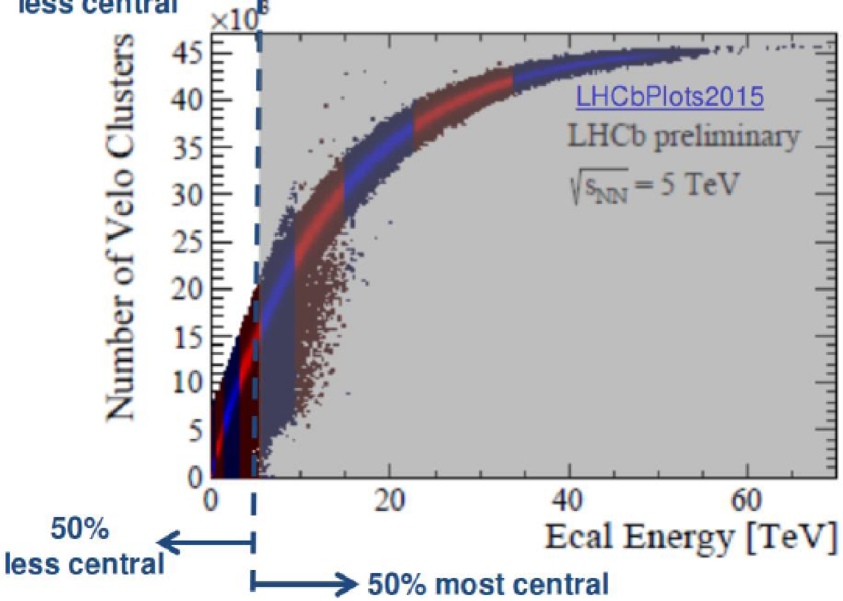


# PbPb collisions

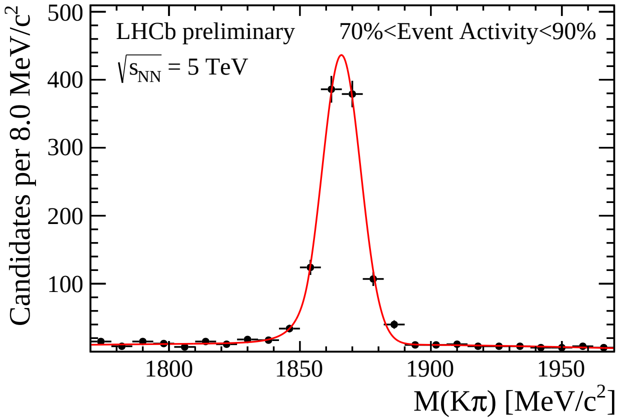
# PbPb data and centrality reach

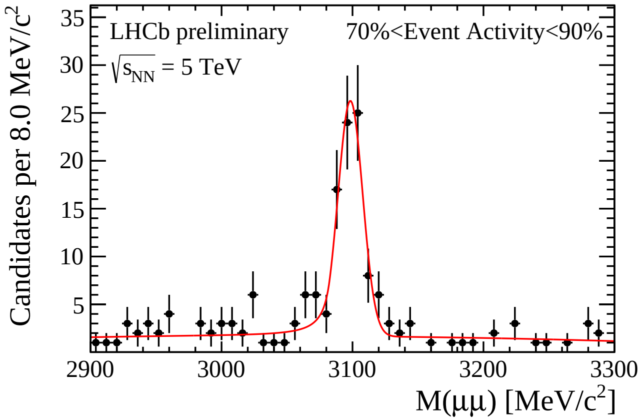
- LHCb entered PbPb data taking in 2015.
  About 10 $\mu$b recorded by LHCb
- Tracking performance studied: saturation occurs at about 50% centrality
- 2018 PbPb run just finished, collected 210$\mu$b




- Still interesting physics from peripheral collisions:
  - J/ψ photoproduction (low-$p_T$ "excess")
  - J/ψ/$D^0$ ratio and Υ states vs centrality
  - flow for $D^0$

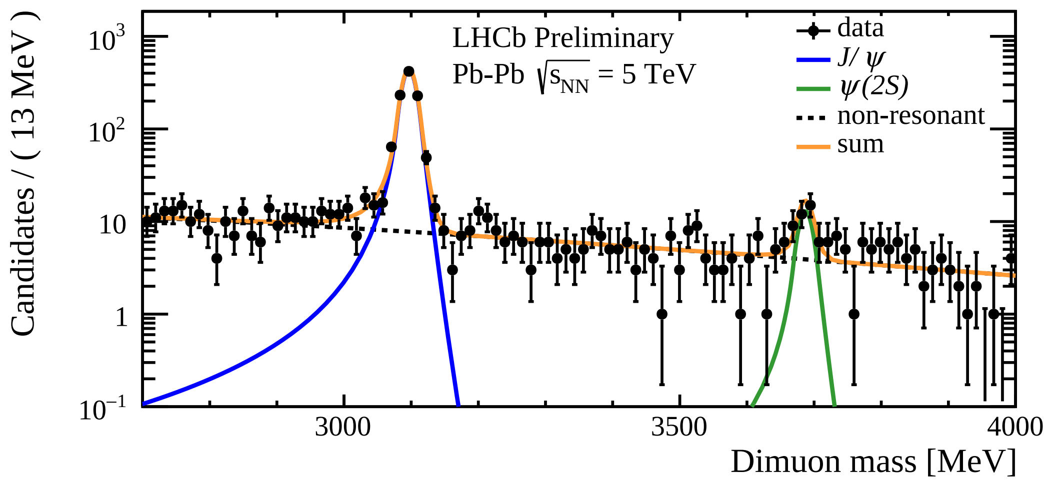


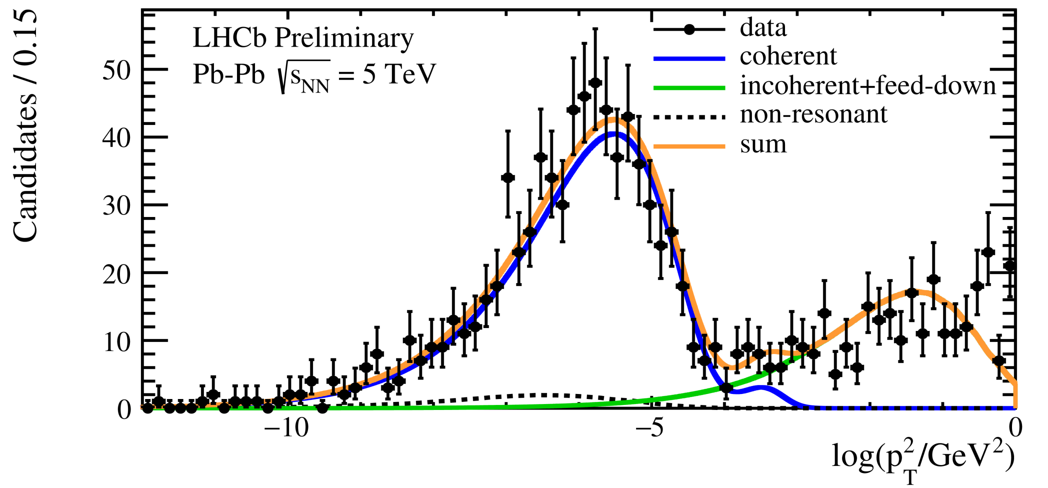



# Ultra Peripheral Collisions

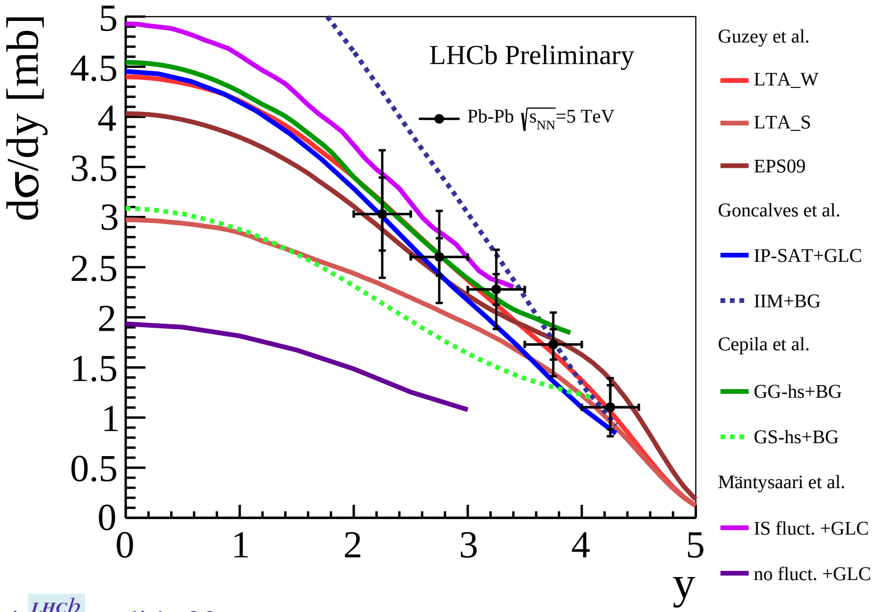
LHCb-CONF-2018-003

- hadron photo-production enhanced by photon flux ($\propto Z^2$) in PbPb
- sensitive to gluon distribution at $x$ down to $10^{-5}$, saturation region
- coherent and incoherent J/ψ photo-production can be distinguished from $p_T$ shape
- limited statistics, but precision of the measurement demonstrated
- very good prospects with 2018 data




(templates from STARLIGHT)




Result for coherent x-section, compared with phenomenological models



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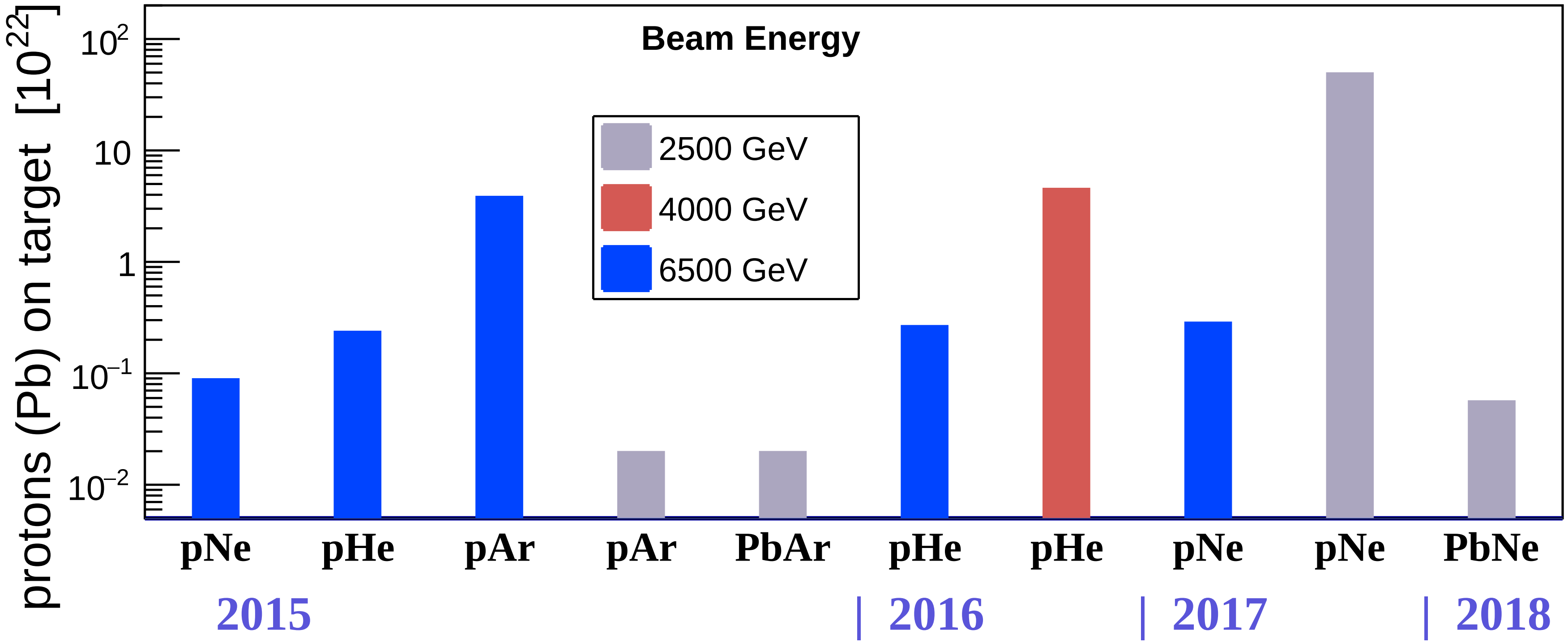
# Collisions on fixed targets

# Fixed-target Samples



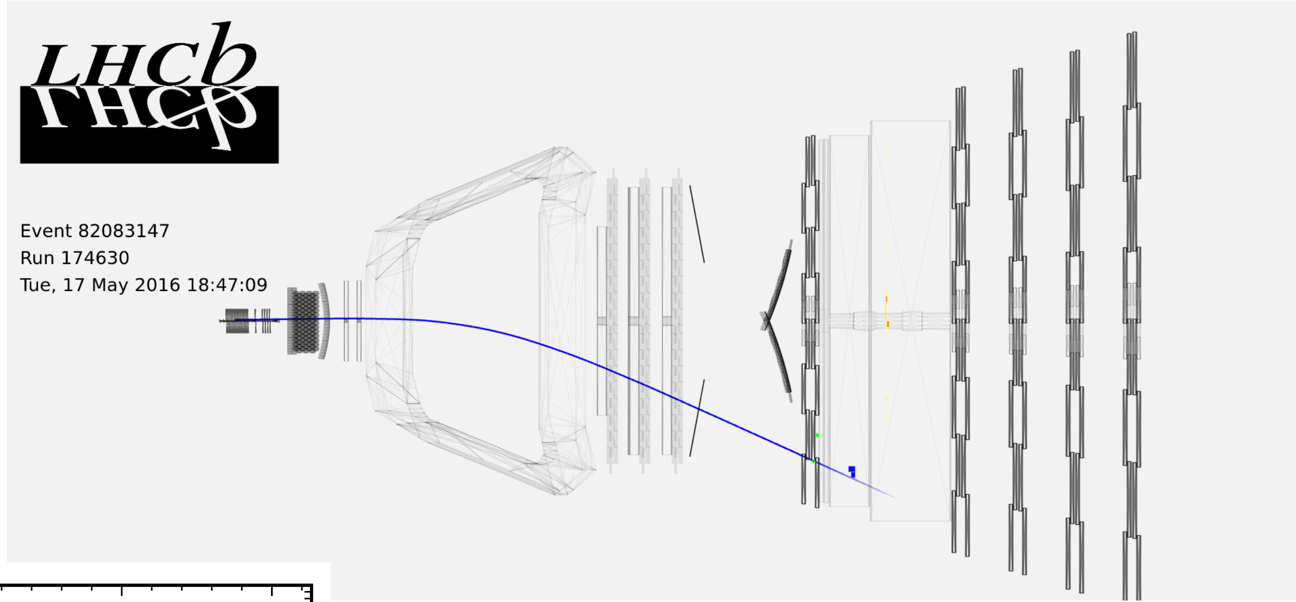

(at nominal SMOG pressure, $10^{22}$ POT correspond to 5/nb for 1 m of gas )

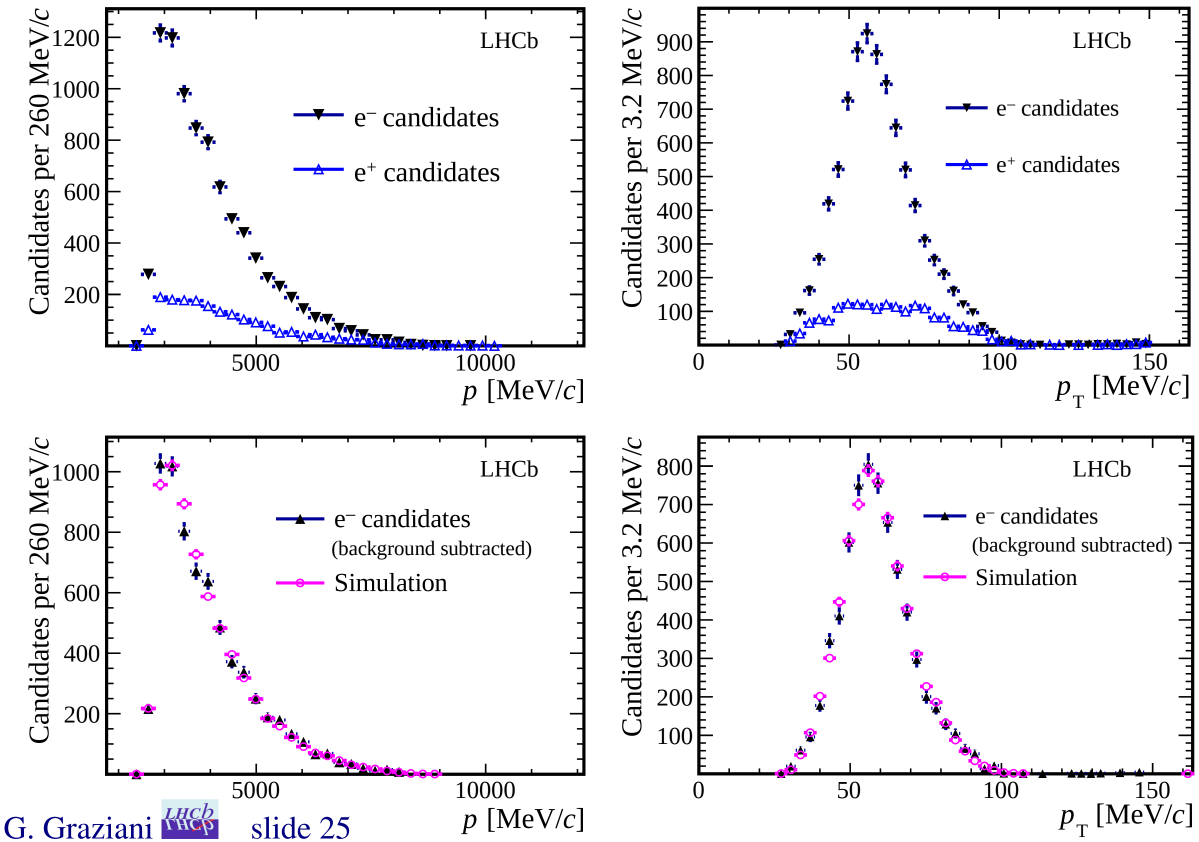
- First papers from the first samples collected in 2015 and 2016 :
  - antiproton production in pHe **PRL 121 (2018), 222001**
  - charm production in pAr and pHe **arXiv:1809.01404**
- Large sample ($\sim$ 100nb$^{-1}$) of pNe collisions acquired at the end of 2017, sample of PbNe collisions at same energy just collected

# Fixed-target Luminosity

PRL 121 (2018), 222001

- SMOG gas pressure not precisely known. Absolute cross sections normalized to p-$e^-$ elastic scattering




- Background measured from data, using events with single positive track
- Systematic uncertainty of 6%, due to low electron reconstruction efficiency ($\sim$ 16%)



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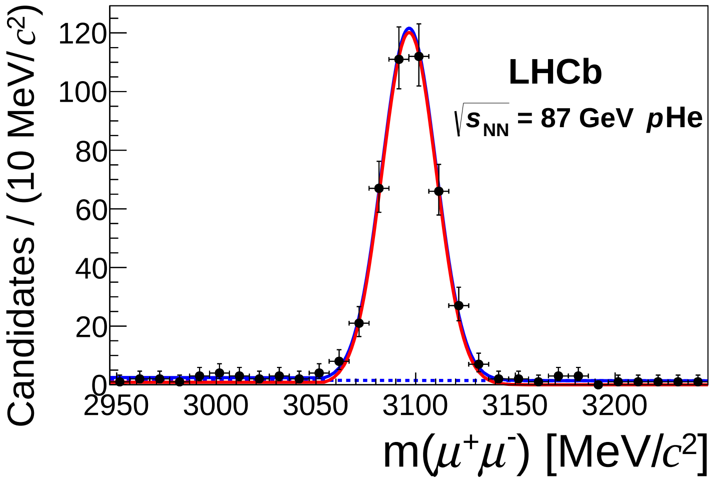
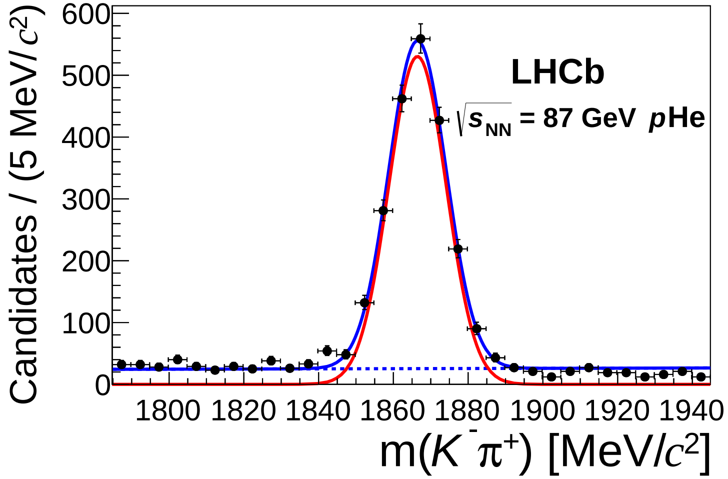
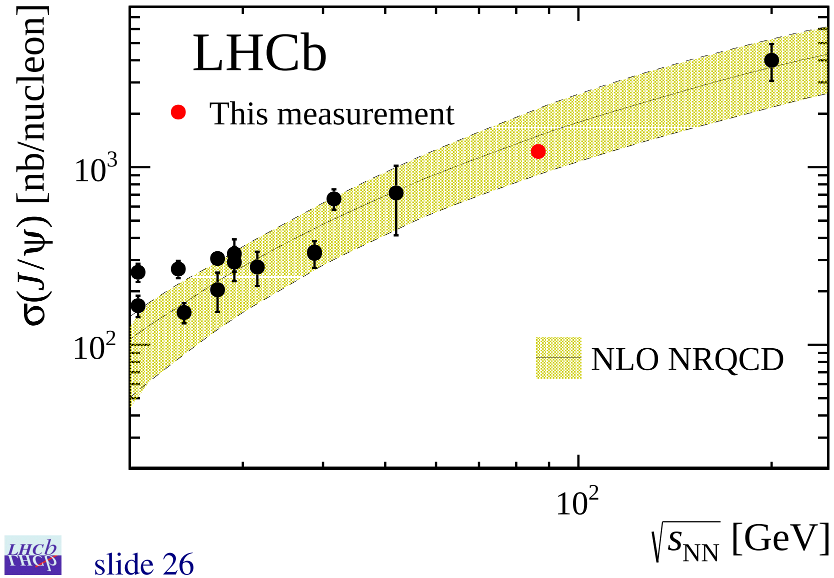
# Charm production in fixed targets

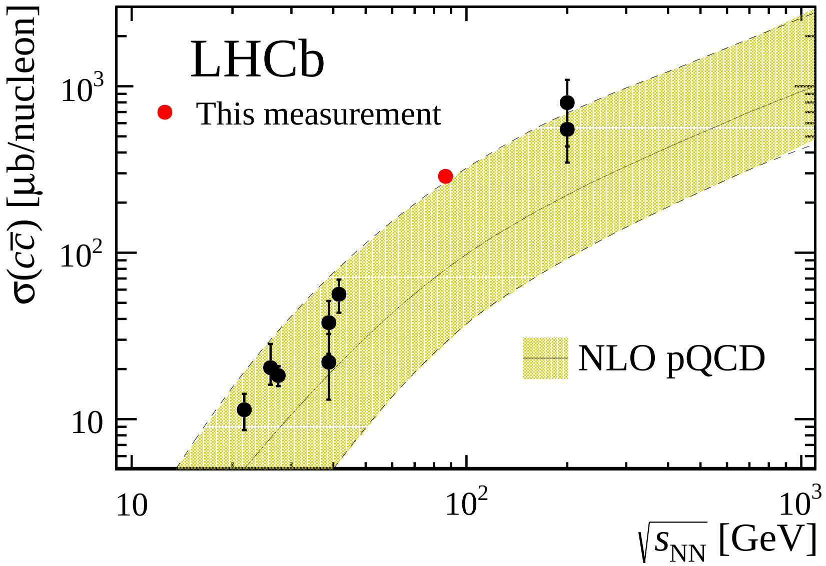
arXiv:1809.01404, subm. to PRL




- First charm samples from pHe@69 GeV ($7.6 \pm 0.5\ \mathrm{nb}^{-1}$) and pAr@110 GeV (few $\mathrm{nb}^{-1}$)
- First determination of $c\bar{c}$ cross-section at this energy scale

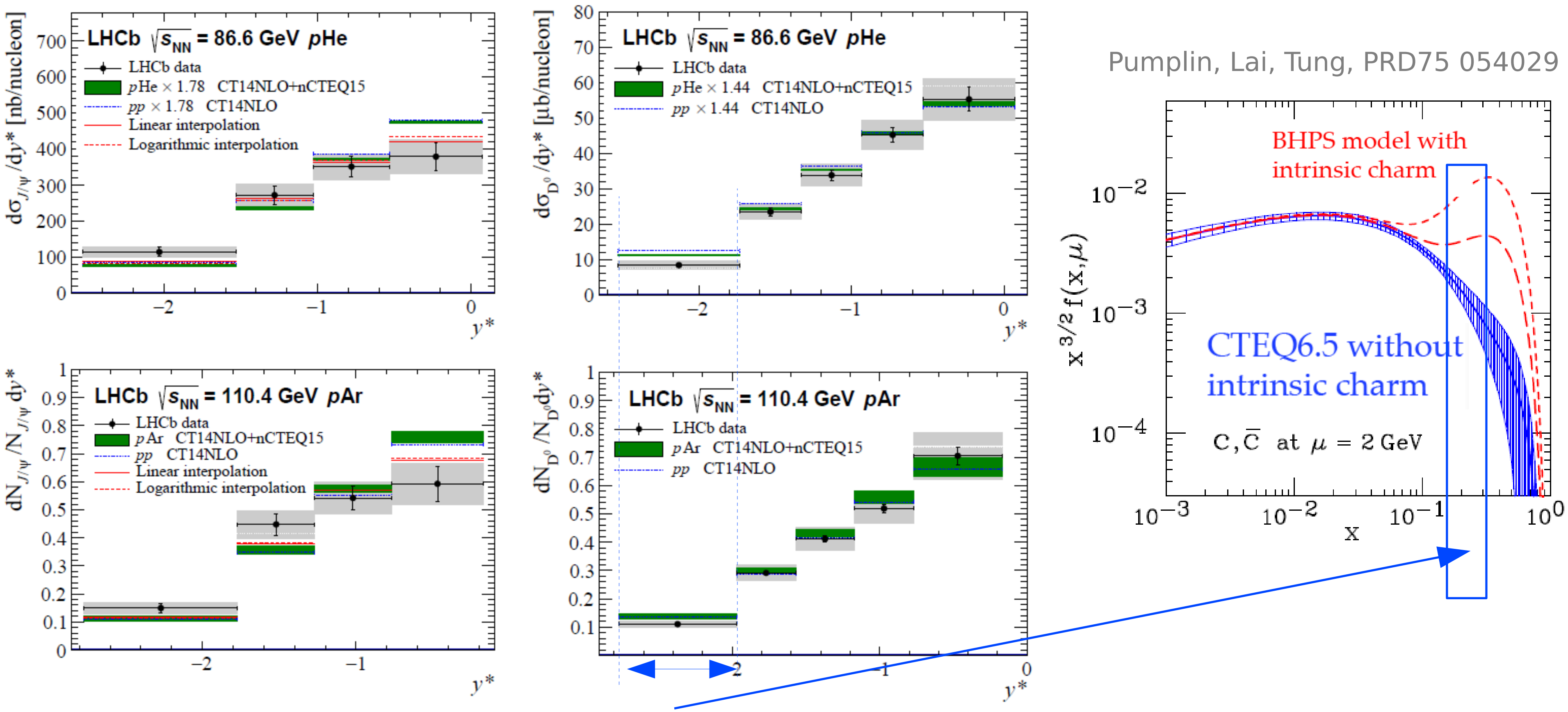


$J/\psi$ $D^0$

pHe

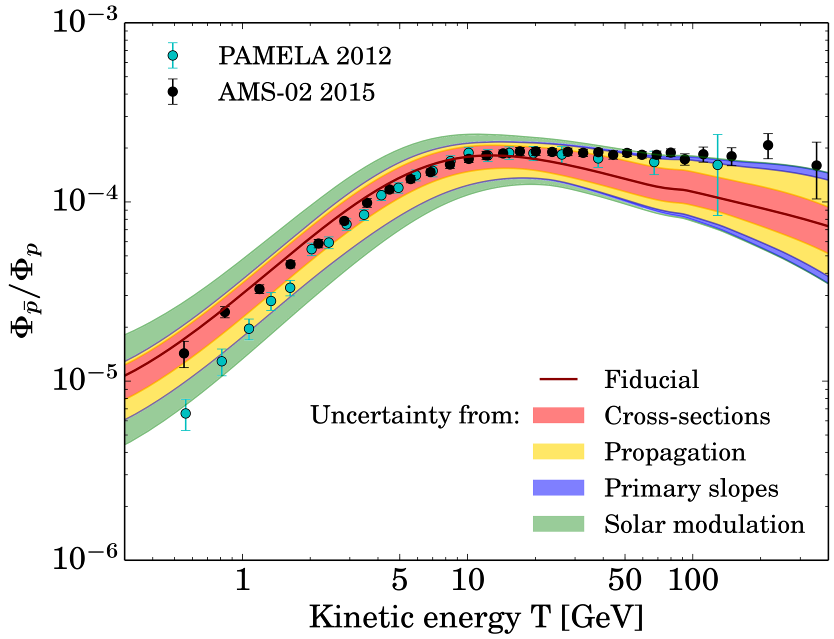
pAr



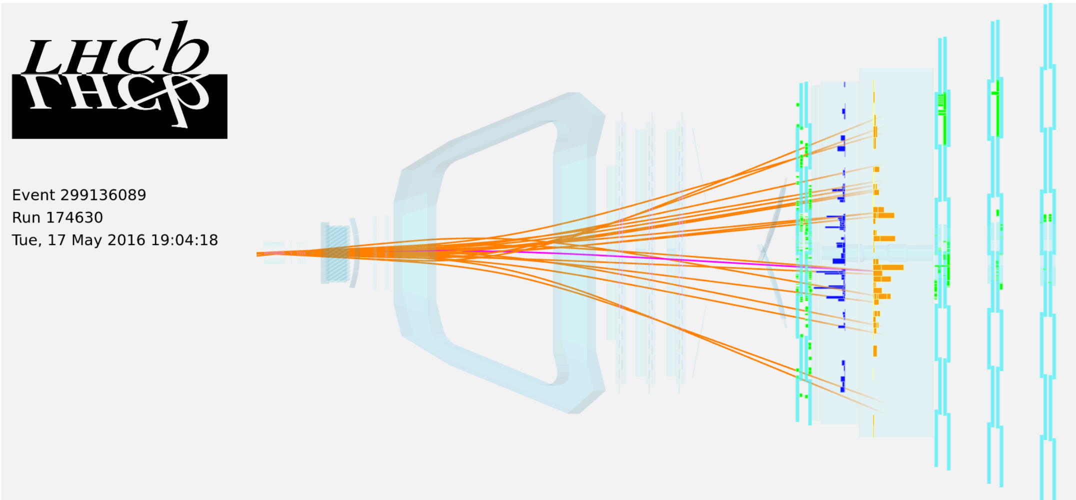

- No evidence for sizeable intrinsic charm contribution

# Cosmic Antiprotons

- Precision AMS-02 measurements of $\overline{\mathrm{p}}/\mathrm{p}$ ratio in cosmic rays at high energies, indirect search for Dark Matter **PRL 117, 091103 (2016)**
- Hint for a possible excess, and milder energy dependence than expected
- Prediction for $\overline{\mathrm{p}}/\mathrm{p}$ ratio from spallation of primary cosmic rays on intestellar medium (H and He) is **presently limited by uncertainties on $\overline{\mathrm{p}}$ production cross-sections**



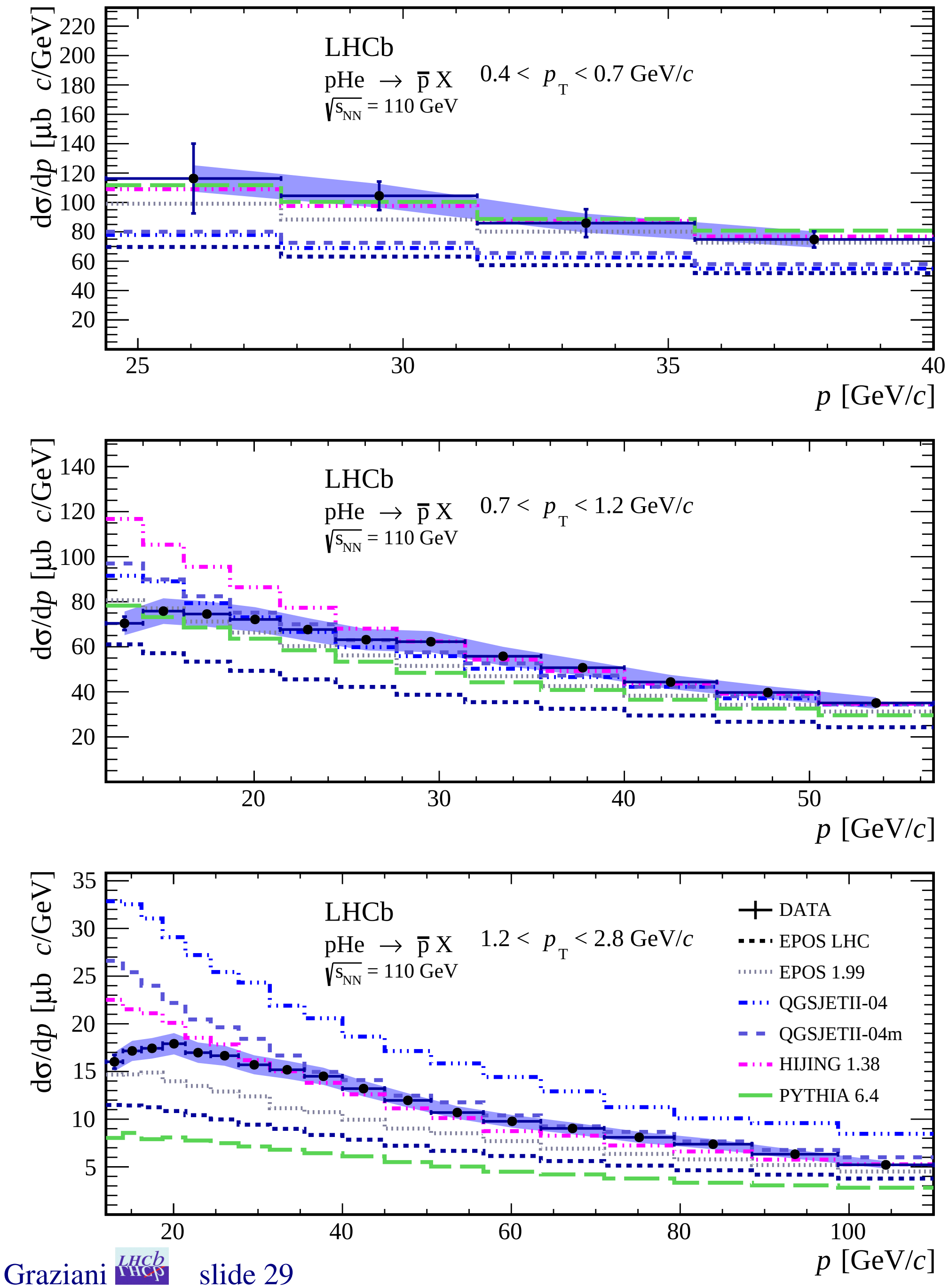

**Giesen et al., JCAP 1509, 023 (2015)**




- Large uncertainties ($\sim$ factor 2) on cross-sections from models of hadronic interactions
- Empirical parameterizations mostly based on SPS pp data, but **no previous measurement of $\overline{\mathrm{p}}$ production in p-He**
- **Scaling violations** at $\sqrt{s_{\mathrm{NN}}} \sim 100$ GeV, poorly constrained
- The LHC energy scale and LHCb +SMOG very well suited to this measurement

# pHe Antiprotons results

PRL 121 (2018), 222001




Result for **prompt** production compared to

**EPOS LHC** **PRC92 (2015) 034906**

underestimating $\bar{p}$ prod. by $\sim 1.5$

**EPOS 1.99** **Nucl.Phys.Proc.Suppl. 196 (2009) 102**

**QGSJETII-04** **PRD83 (2011) 014018**

**QGSJETII-04m** **Astr. J. 803 (2015) 54**

**HIJING 1.38** **Comp. Phys. Comm. 83 307**

**PYTHIA 6.4** (2pp + 2pn) **JHEP 05 (2005) 026**

Visible inelastic cross section compatible with EPOS LHC:

$$\sigma_{\mathrm{vis}}^{\mathrm{LHCb}} / \sigma_{\mathrm{vis}}^{\mathrm{EPOS-LHC}} = 1.08 \pm 0.07 \pm 0.03$$

➨ excess of $\bar{p}$ yield over EPOS LHC from $\bar{p}$ multiplicity

Prospects:

- Extend to $\bar{p}$ from anti-hyperon decays (20-30% of production)
- Repeat on 4 TeV beam data ➨ measure scaling violations

# Prospects

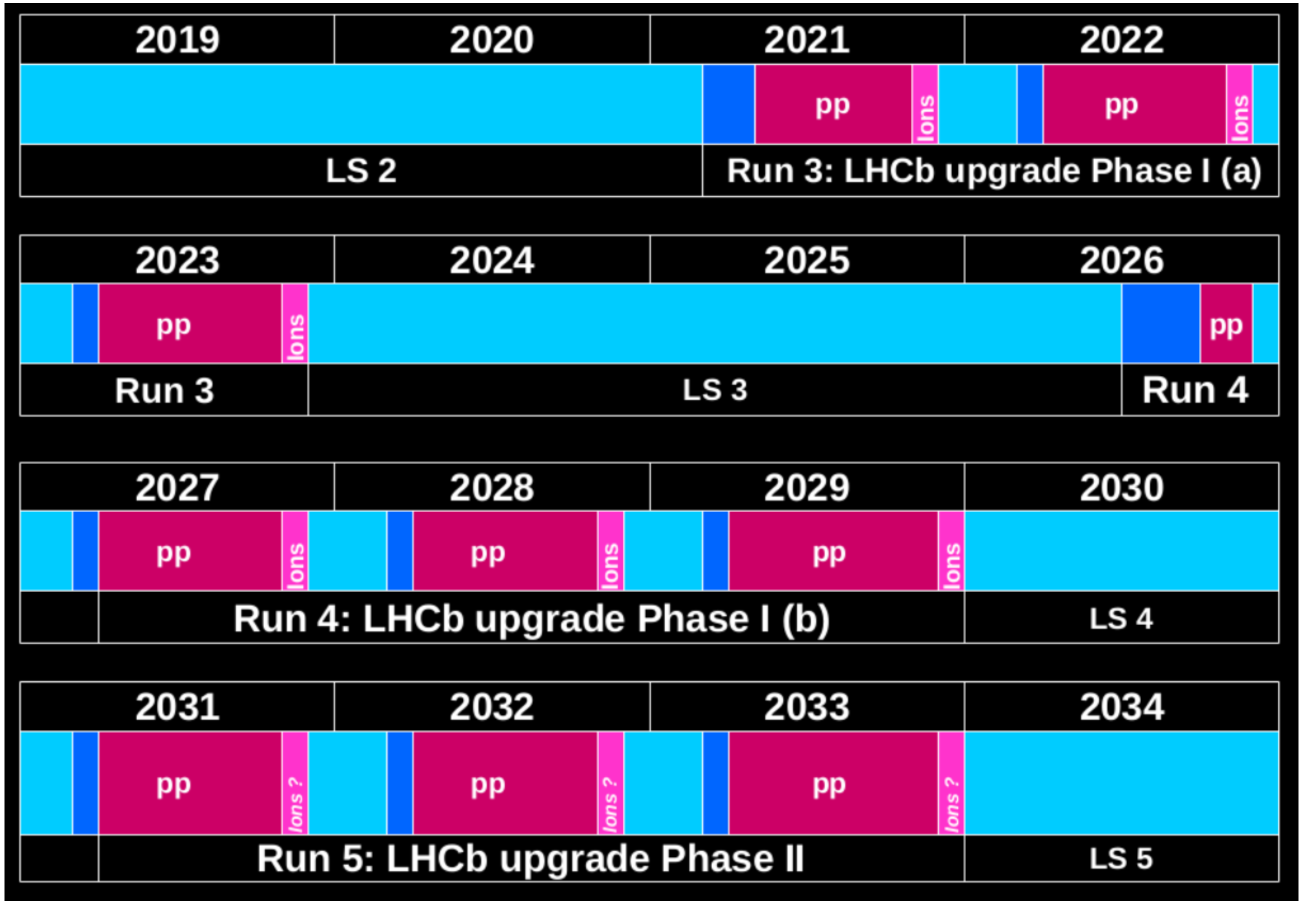
Much more to harvest, notably in pPb:

- More quarkonia states: $\chi_c$, $\eta_c$
- $D^0\overline{D}^0$ correlations
- Drell Yan, vector bosons
- dihadron correlations (ridge), BEC
- Flow studies with identified particles

…

And substantial development of the program in future LHC runs, profiting also from the upgraded detector **LHCb-TDR-12 (2012), talk by O.Steinkamp on Thursday**

# Heavy ions in future LHC Runs

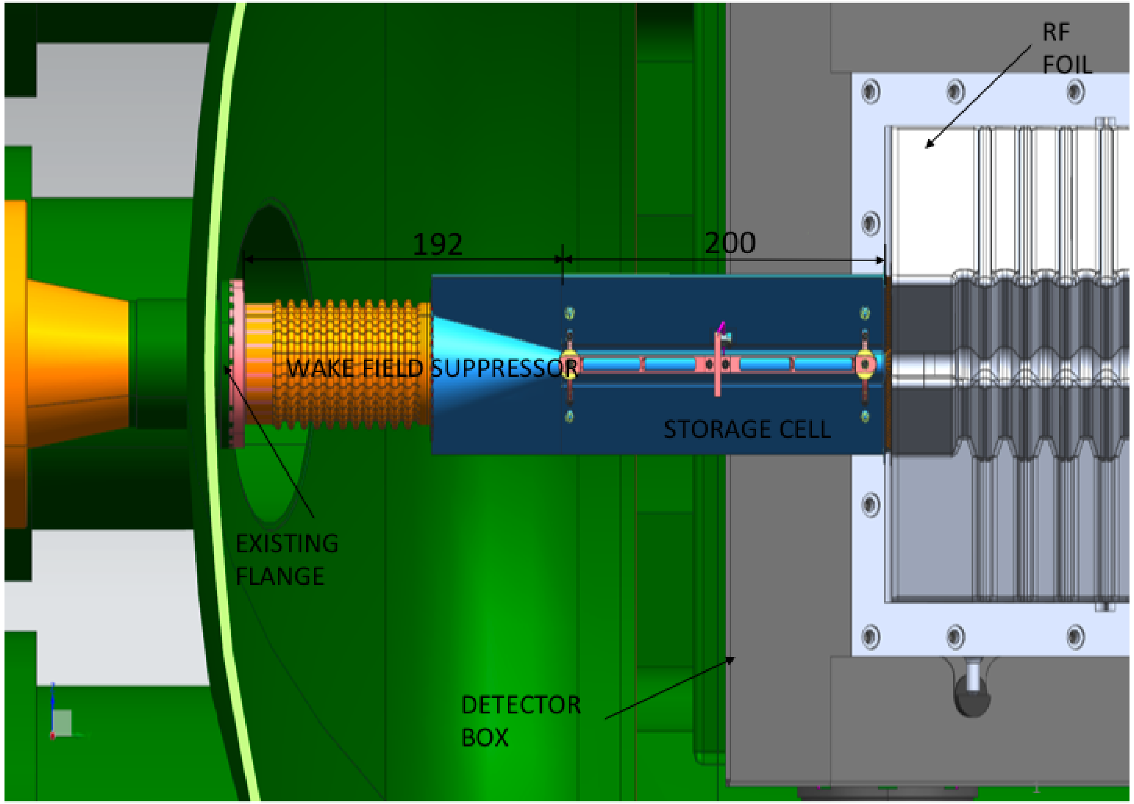



- pp luminosity will increase by factor 5 in Run 3
- plans for larger integrated luminosities, at least factor 10, also for pPb and PbPb in LHCb
- Phase II Upgrade in design phase LHCB-TDR-019 (2018): aim at 50 × Run 2 luminosity in pp ➡ dream detector for heavy-ion physics

# Fixed target upgrade(s)

LHCb is considering an upgraded gas target, consisting in a storage cell located in the proximity of the interaction point. Could be operational already in Run 3

- allows larger gas density where needed ➨ increase luminosity by up to 2 orders of magnitudes with same gas flow
- more gas species possible: hydrogen and deuterium, heavier gas (Kr, Xe)
- precise control of gas density




More proposals for the future (see *Physics Beyond Colliders* forum):

- polarized gas target
- solid target coupled with bent crystal, to study electric and magnetic moments of charmed baryons
- solid microstrip target



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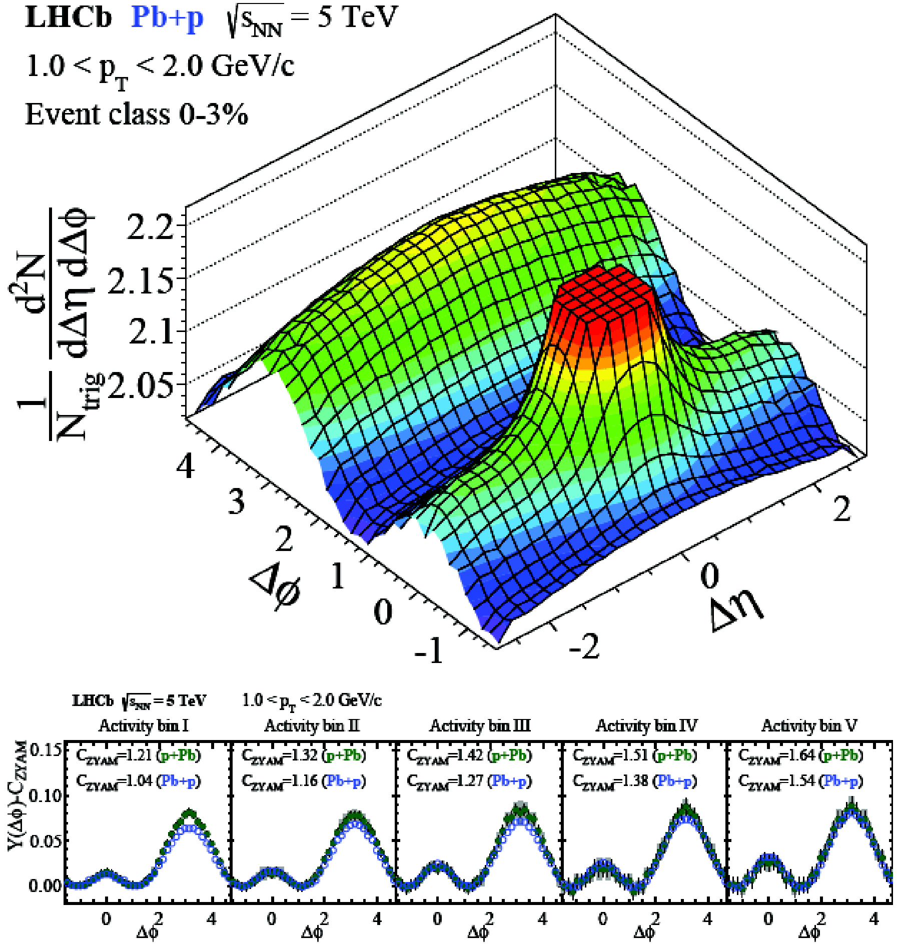
# Conclusions

- LHCb developed a lively and fast growing heavy ion program, with very specific capabilities
- First lessons learned, with some unique inputs:
  - heavy flavour states (open charm and beauty, quarkonia) in pPb at large rapidity are in general well described by nPDFs and CGC (when applicable)
  - but suppression of excited quarkonia states points to the effect of comoving particles, notably from $\Upsilon(3S)$ in pPb
  - no evidence of charmed baryon enhancement from coalescence in pPb
  - no evidence of intrinsic charm at large-x (for now) from charm production in fixed target
  - improved knowledge of antiproton production in cosmic-like pHe collisions ➡ better reference for dark matter searches
- much more data from Run 2 to be analyzed
- and substantial development of the program in the next future

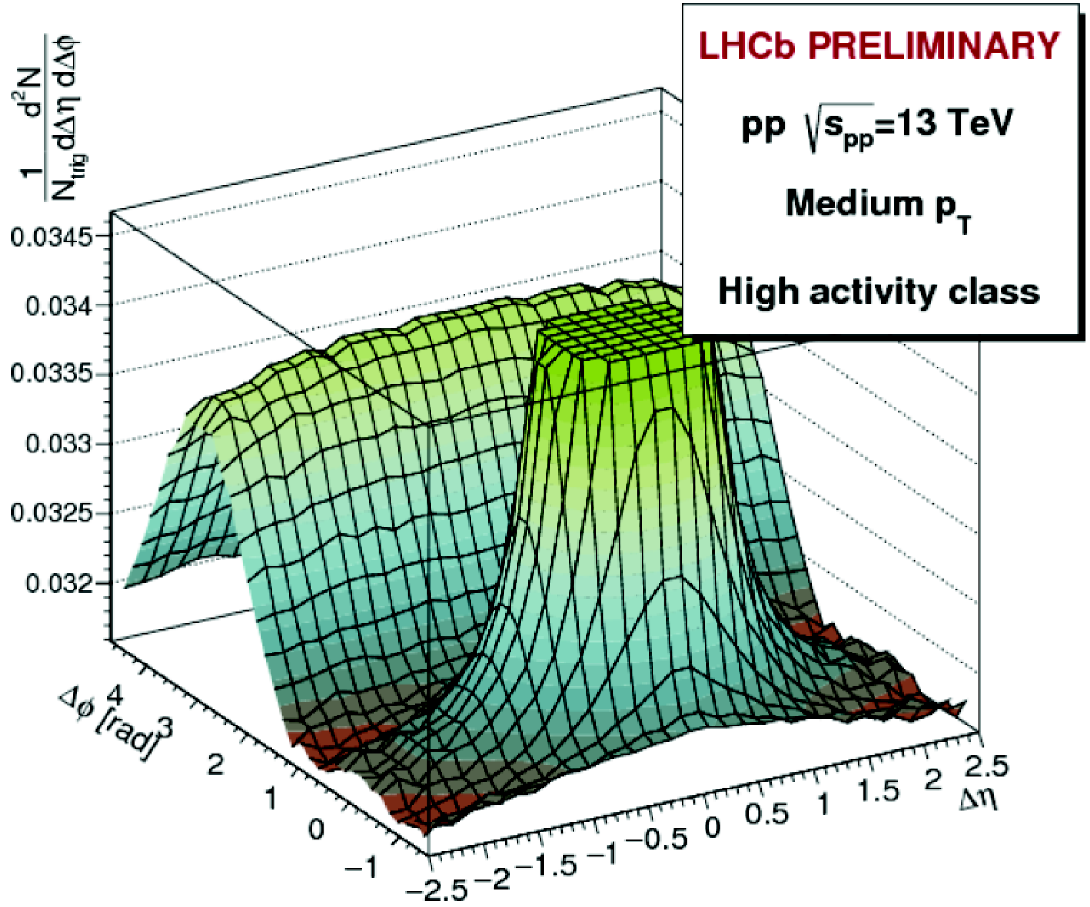
# Backup material

# Collective phenomena

## Dihadron correlations in unique forward acceptance

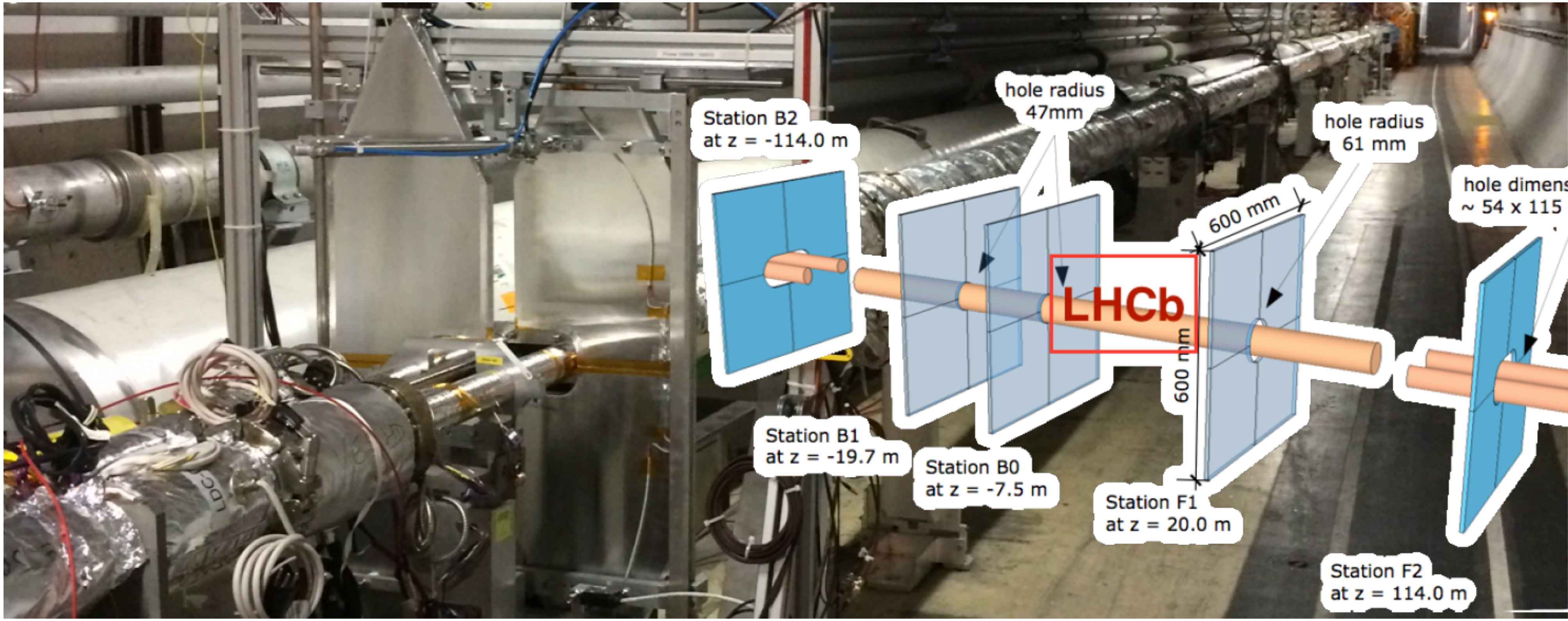



Phys.Lett. B762 (2016) 473-483

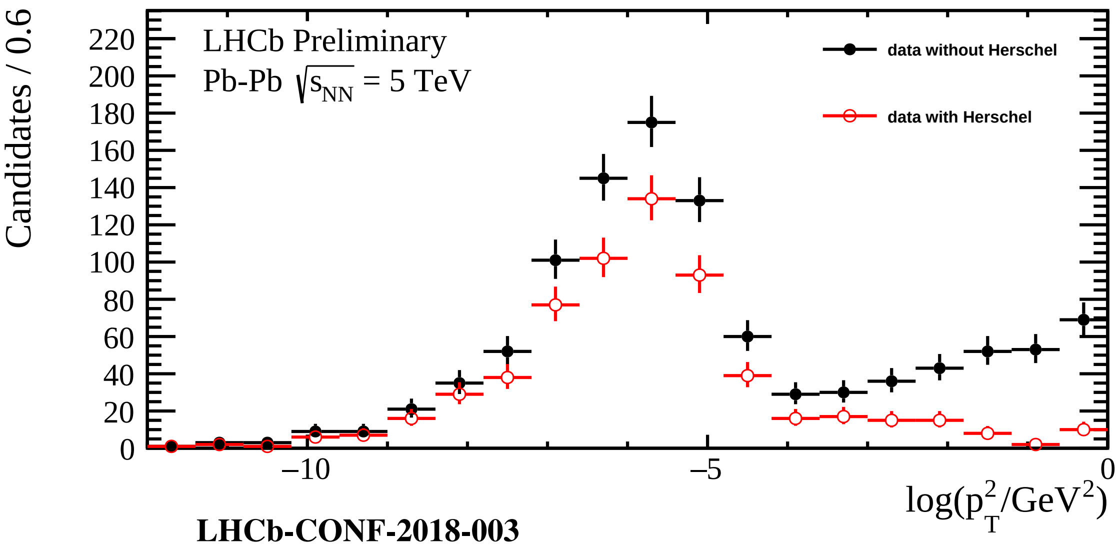



arXiv:1709.09906.

# Expanding rapidity gap for UPC: Herschel




- Scintillator planes covering rapidity 5 to 7.5, can be used as a veto to extend the rapidity gap
- Allows to further improve separation of coherent and uncoherent J/ψ photoproduction




LHCb-CONF-2018-003



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