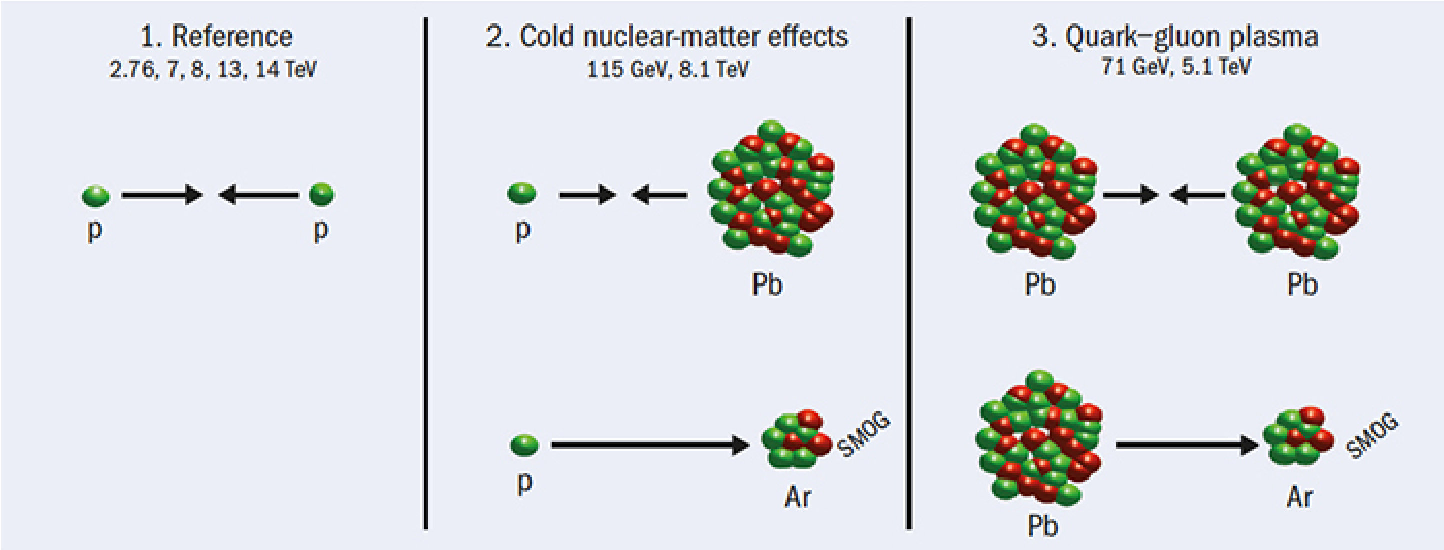
# Recent LHCb results for heavy ions





**Giacomo Graziani (INFN Firenze)**
**on behalf of the LHCb Collaboration**


**QCD@Work**
**International Workshop on QCD, theory and experiment**
**June 28, 2022**

# The LHCb experiment

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

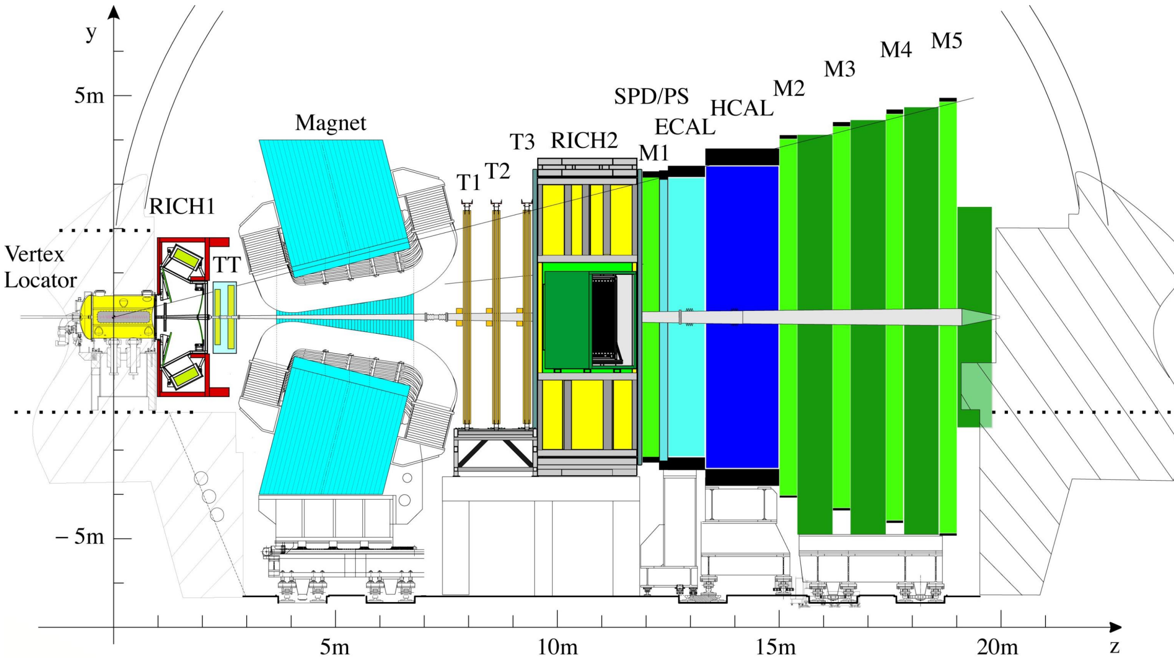
Detector requirements:

**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)



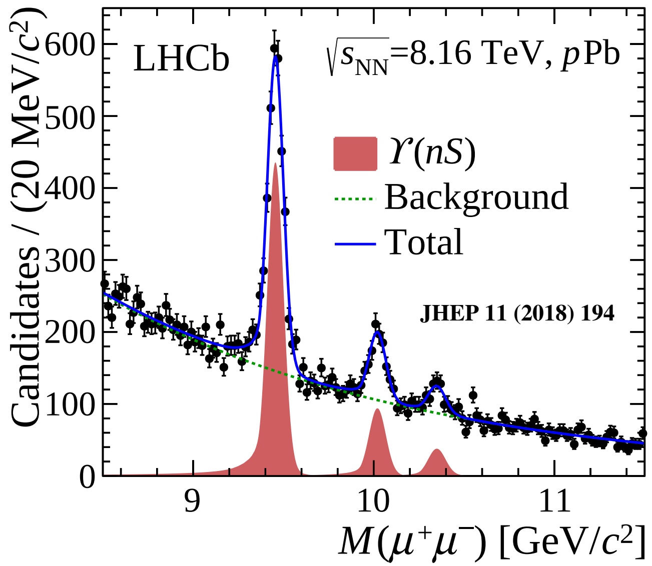

JINST 3, (2008) S08005
Int.J.Mod.Phys.A30 (2015) 1530022

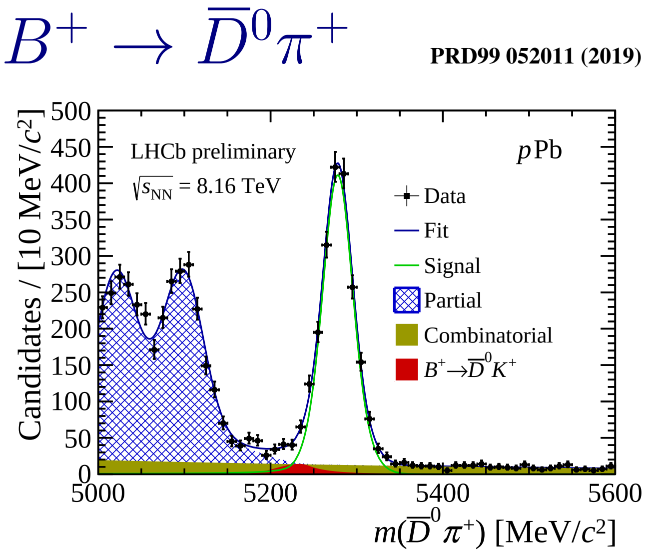
Some unique features are also attractive for heavy ion physics:

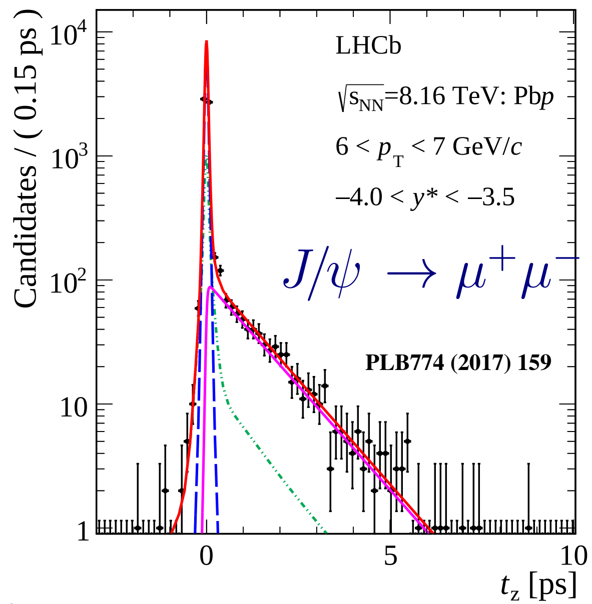
- excellent detector performance, notably for heavy flavour
- forward acceptance
- possibility to run in fixed-target mode

# Key feature: detector performance and trigger

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



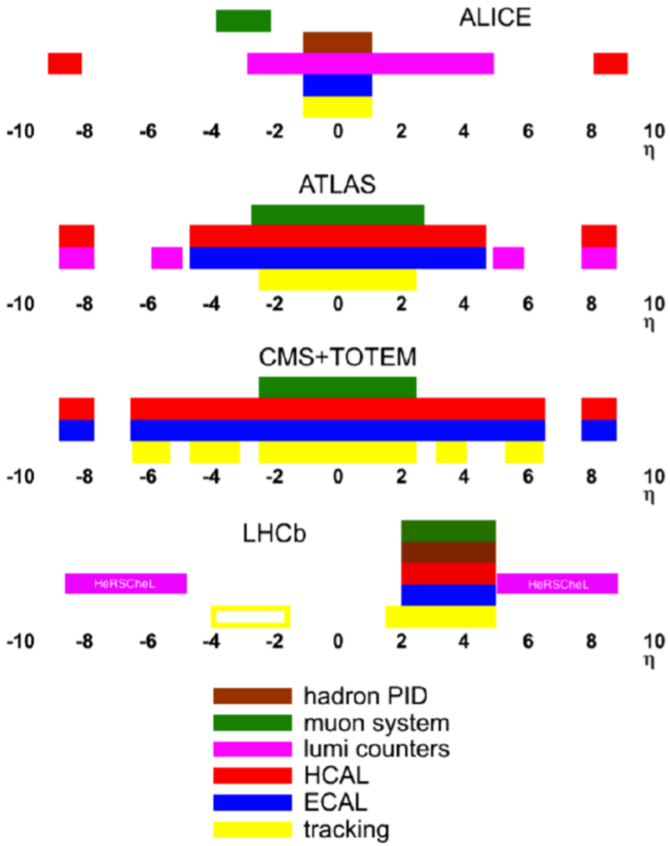

- No rate limitations from trigger and DAQ for heavy ion runs:
  - large samples of MB events
  - heavy flavour triggers with low $p_T$ thresholds ($\sim$ 1 GeV)
- ⚠ tracking saturates for most central PbPb collisions

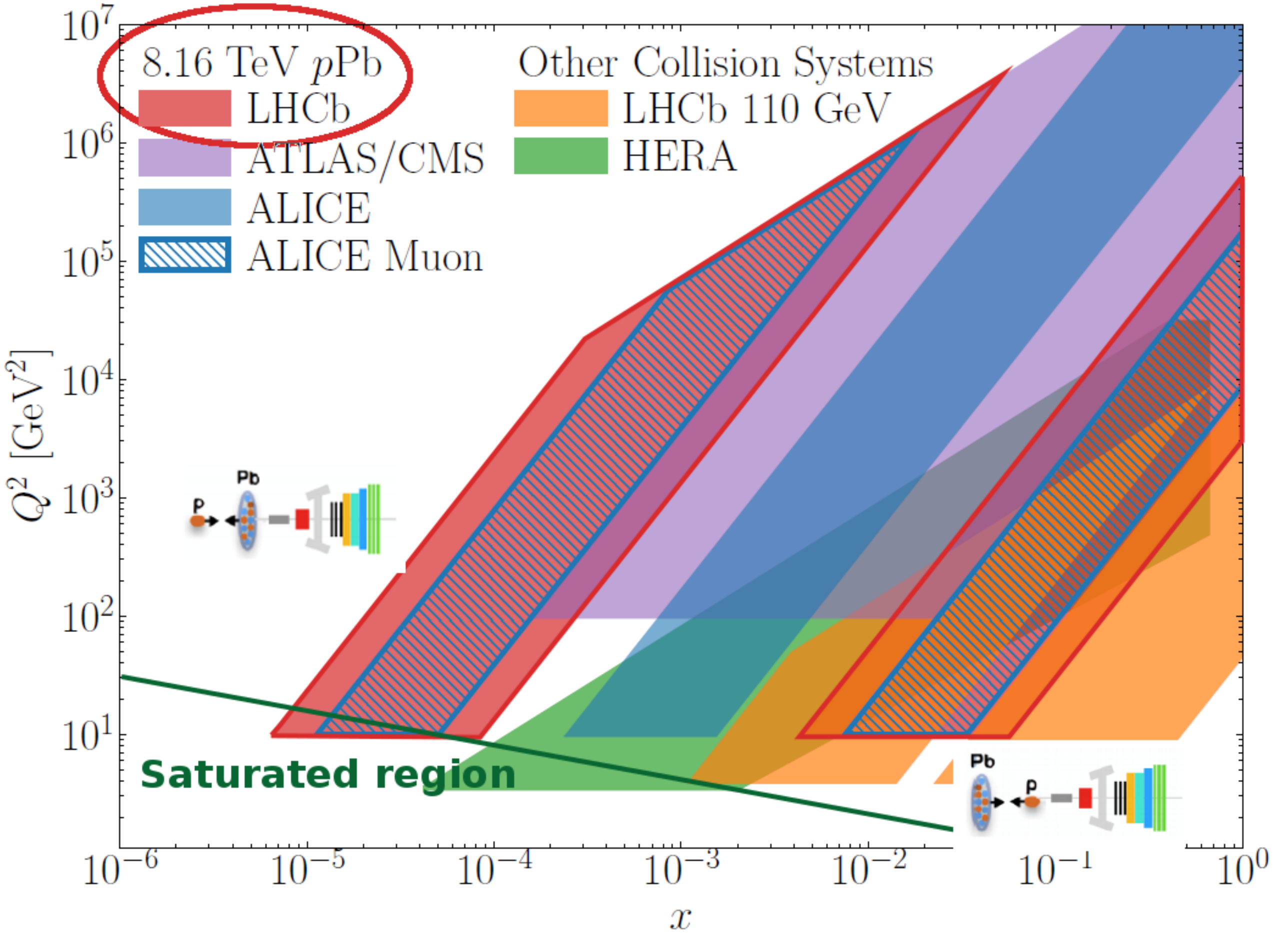
  ➡ LHCb more suited for small collision systems (pA collisions)

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

# Key feature: forward acceptance

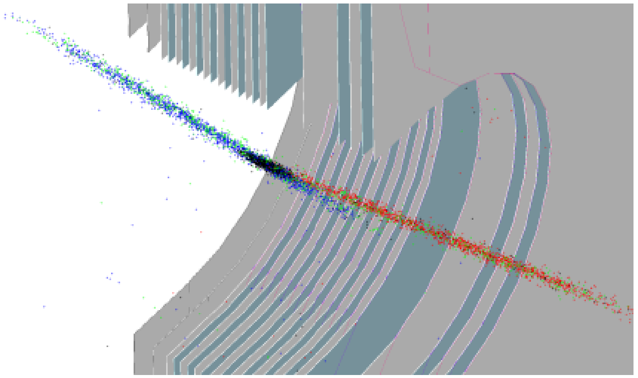
- Unique forward coverage at LHC




- Sensitivity to small $x$ (down to $\sim 10^{-6}$)
  ➡ gluon saturation
  and to anti-shadowing region
- Nicely complementing other LHC experiments (rapidity dependence helps disentangling nuclear effects)

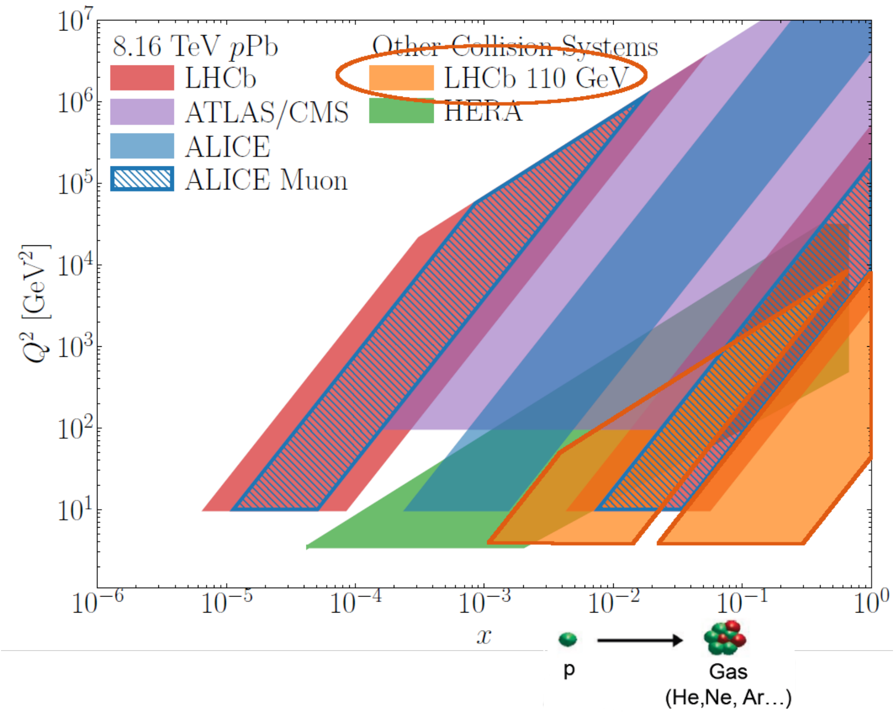
# Key feature: Fixed-target collisions



During Run 2, tiny amount of noble gas injected in the LHC beam pipe thanks to the SMOG system.
Run2 targets: **He, Ne, Ar** with typical pressure $\sim 2 \times 10^{-7}$ mbar
➡ luminosity up to $10^{30} \text{cm}^{-2}\text{s}^{-1}$

For Run 3, the system has been upgraded (SMOG2) to increase luminosity and assortment of gas targets

- Recorded collisions at $\sqrt{s_{\rm NN}} = \sqrt{2E_{beam}M_p}$ 68-110 GeV for $E_{beam} = 2.5 - 6.5$ TeV
  ➡ relative unexplored energy scale between SPS and LHC experiments
- At $\sqrt{s_{\rm NN}} = 110$ 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, sensitive to intrinsic charm in nucleons




- He target provides testbench for cosmic ray - interstellar medium collisions

# Overview of recent results

## $p$-Pb collisions

- Z production @8 TeV — **arXiv:2205.10213**
- $D^0$ production @8 TeV — **arXiv:2205.03936**
- Charged particle production @5 TeV — **PRL 128(2022) 142004**
- $\pi^0$ production @8 TeV — **arXiv:2204.10608, accepted by PRL**
- $\chi_{c1}(3872)$ production @8 TeV — **LHCb-CONF-2022-001**

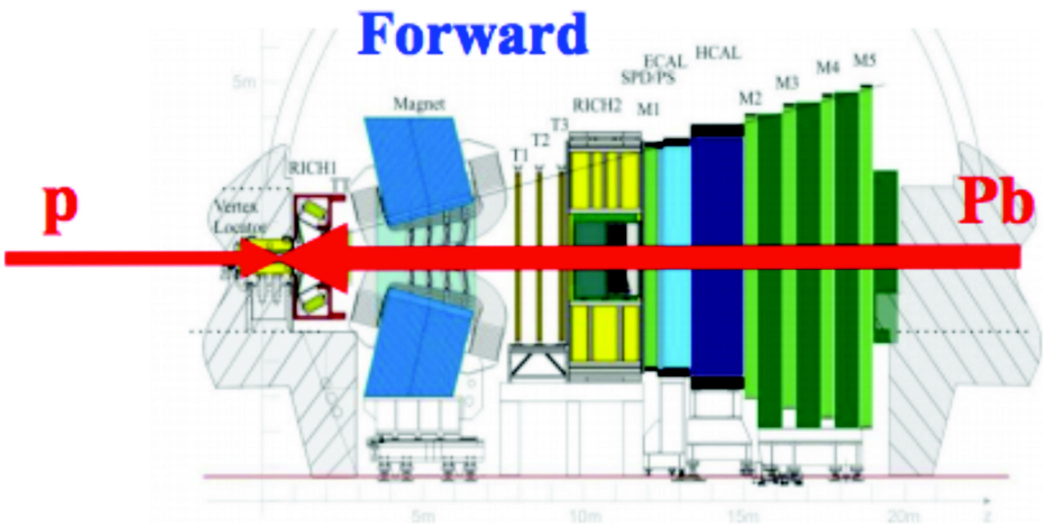
## Pb-Pb collisions @5 TeV

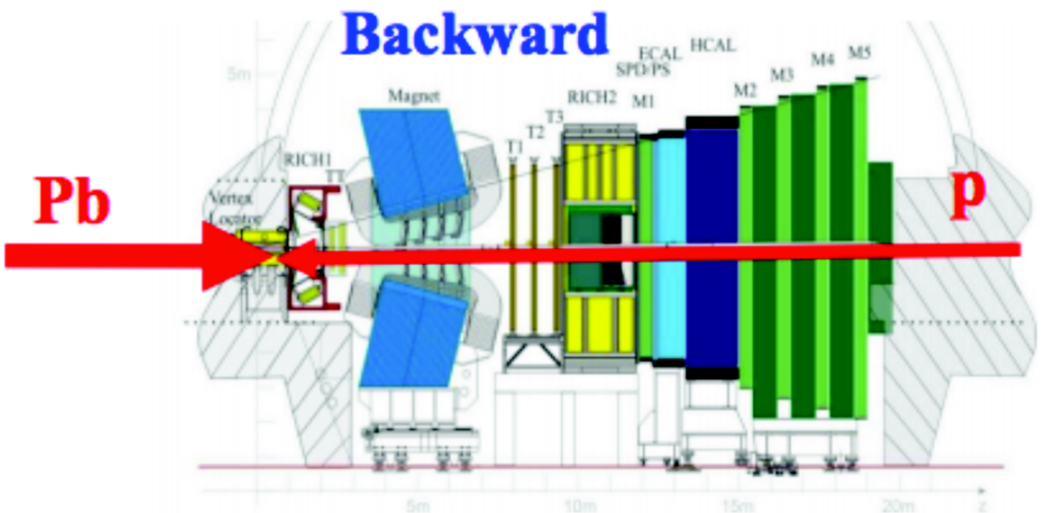
- $\Lambda_c^+/D^0$ ratio in peripheral collisions — **LHCb-PAPER-2021-046, in preparation**
- Quarkonia photoproduction in Ultra Peripheral Collisions — **arXiv:2206.08221**

## Fixed target collisions

- Charm production in Pb-Ne @68 GeV — **LHCb-PAPER-2022-011 in preparation**
- Detached antiprotons in $p$-He @110 GeV — **arXiv:2205.09009**

# pPb collisions




**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)

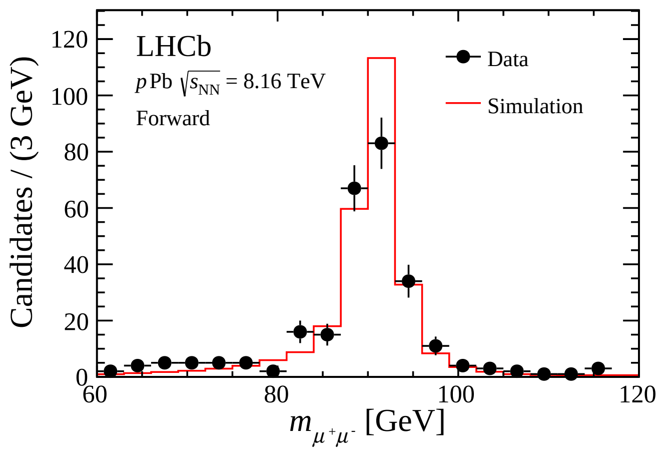
**2016 data taking: $\sqrt{s_{NN}} = 8.16$ TeV**

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

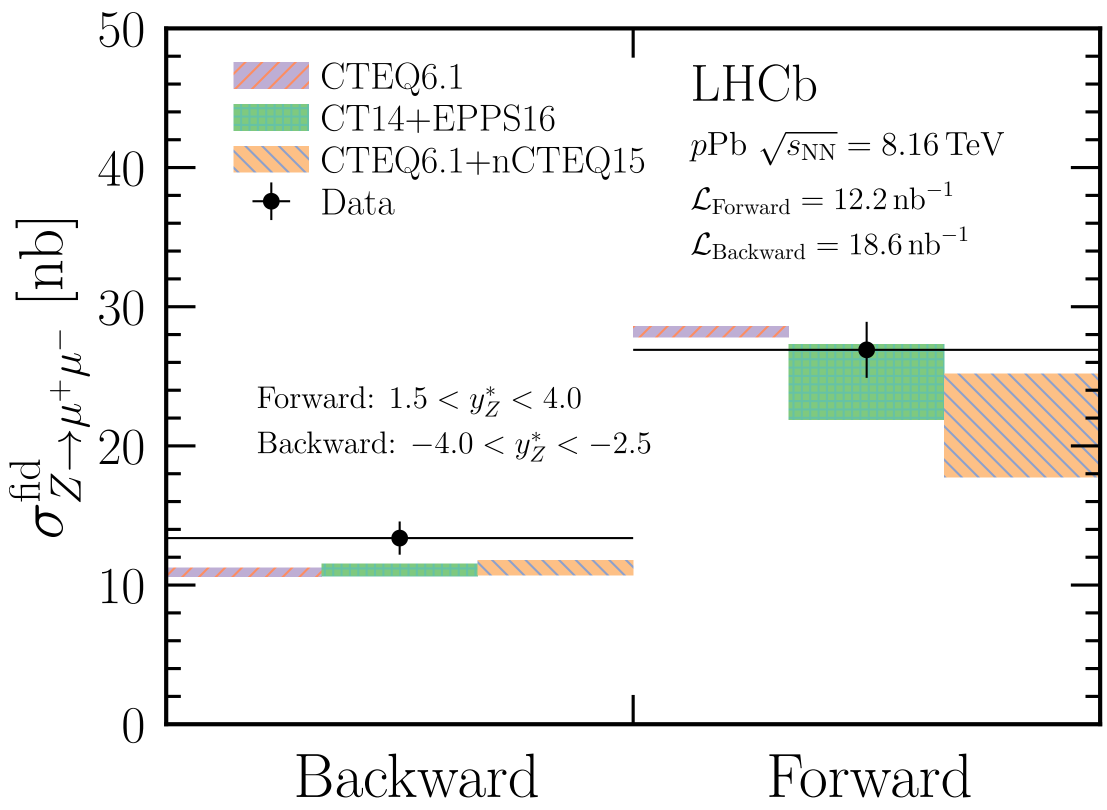
# Z production in $p$-Pb @8 TeV

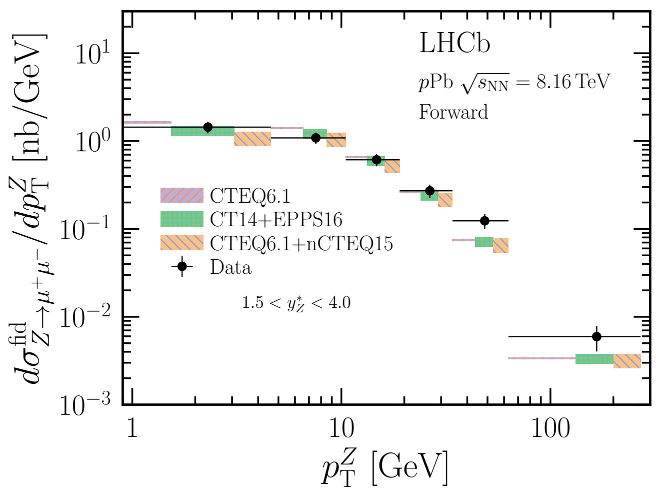
arXiv:2205.10213

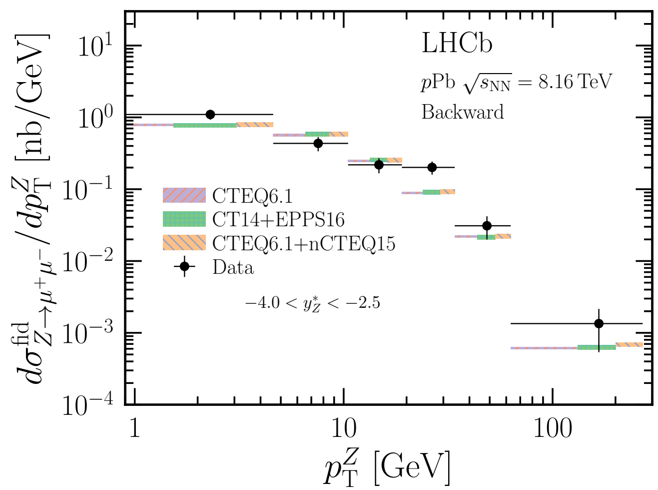
- Clean probe of initial state
- Results based on about 250 (forward) and 150 (backward) candidates from the 8 TeV data sample




- General good agreement with EPPS16 and nCTEQ15 nPDFs



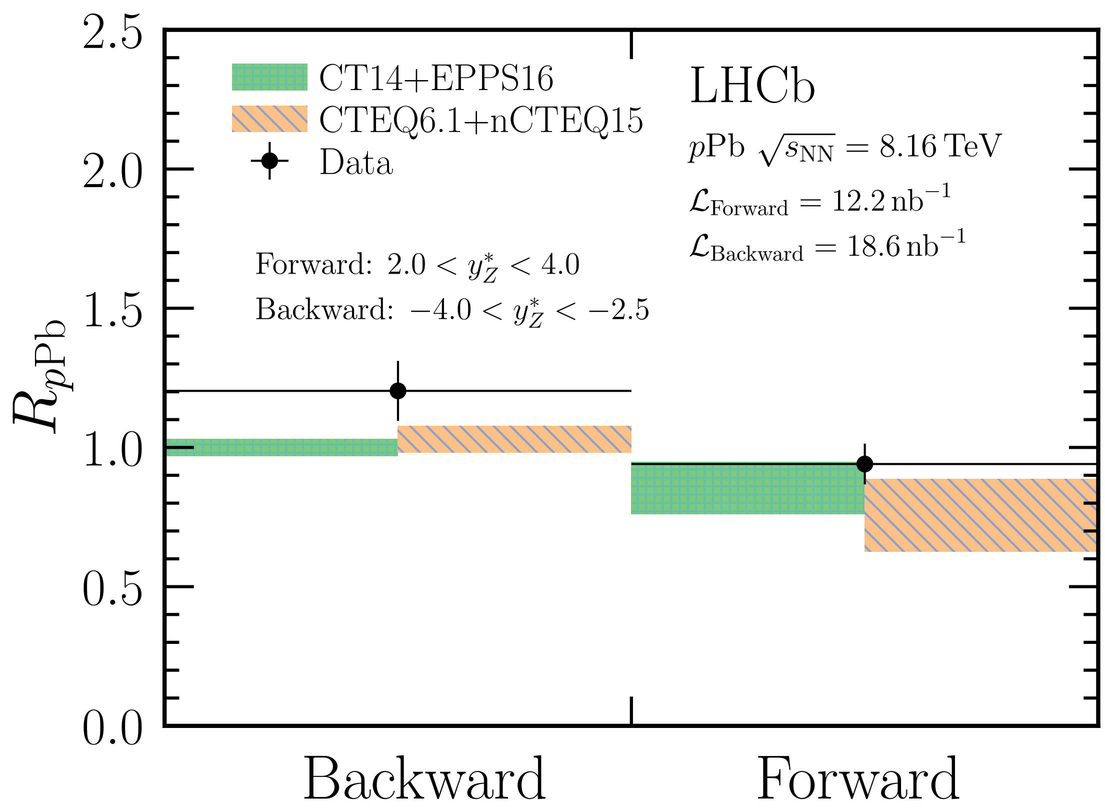
# Z production: nuclear modification factor

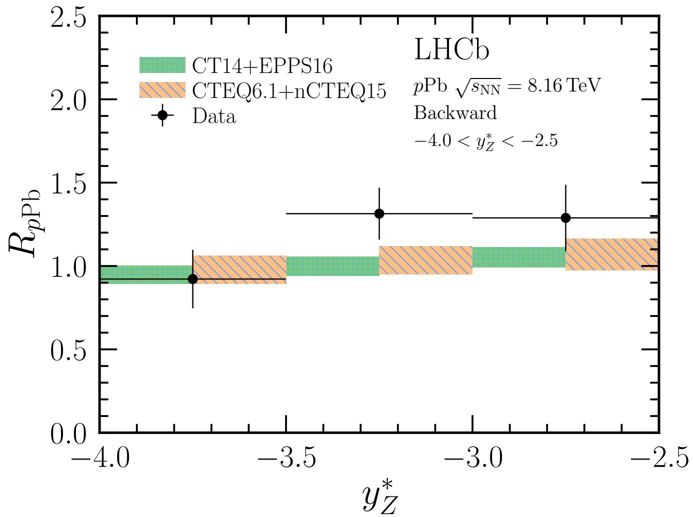
arXiv:2205.10213

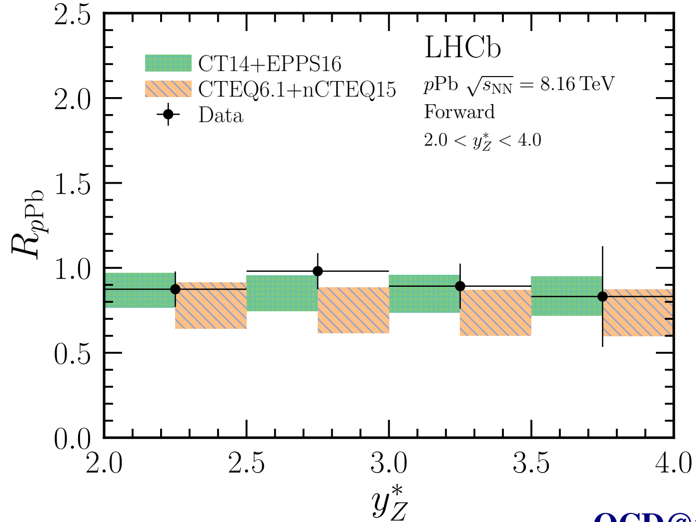
$$R_{p\text{Pb}} \equiv \frac{1}{A}\frac{\sigma_{p\text{Pb}}}{\sigma_{pp}}$$

$$(A = 208)$$

- Hint for the expected rapidity dependence from nPDFs
- Constraints on the nPDFs at high rapidity ($x \sim 10^{-4}$ to $10^{-3}$)



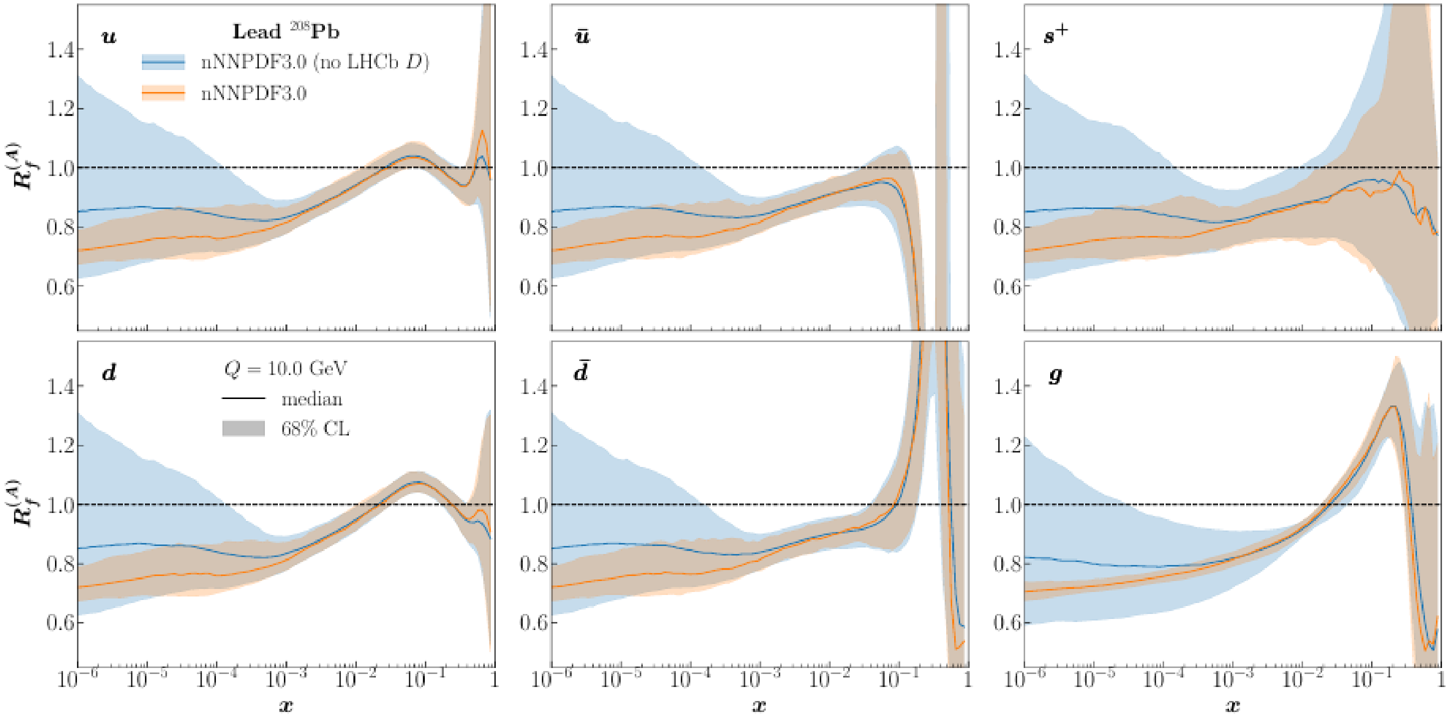



# $D^0$ production: impact on nPDFs

- Open charm production ($D^0 \to K^-\pi^+$ +cc) provides large statistics and can also be used to probe initial state.
- LHCb data are significantly more precise than nuclear PDF uncertainties: can constrain nPDF down to $x \sim 10^{-6}$ if assuming negligible effect of final state interactions.

Example: nNNPDF set with or without $D^0$ LHCb 5 TeV results



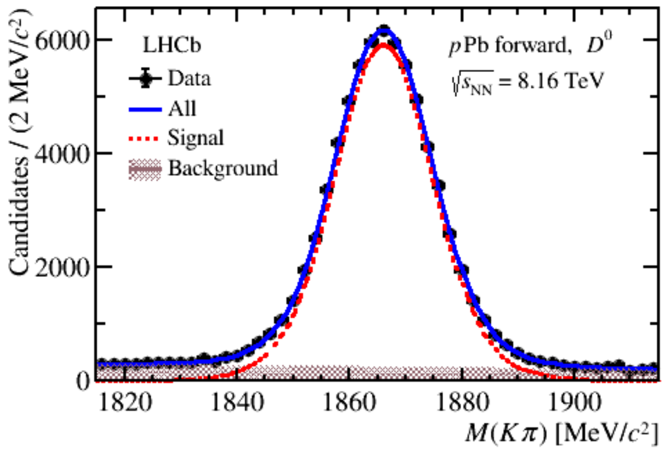

**nNNPDF team, arXiv:2201.12363**

- Results have now been updated with the 8 TeV sample (20 times more statistics!)

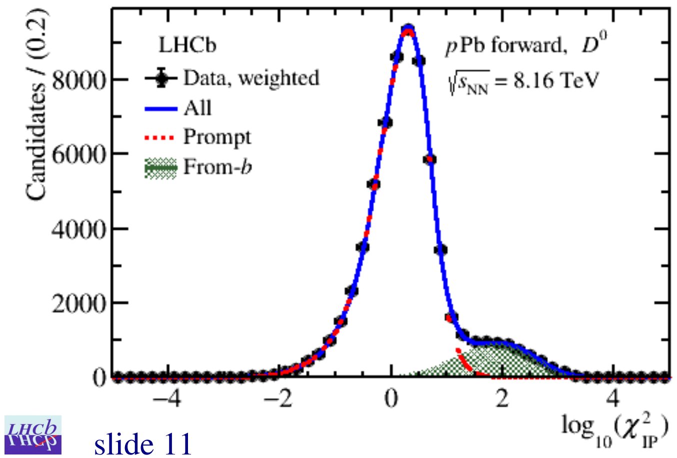
# $D^0$ production $p$-Pb @8 TeV

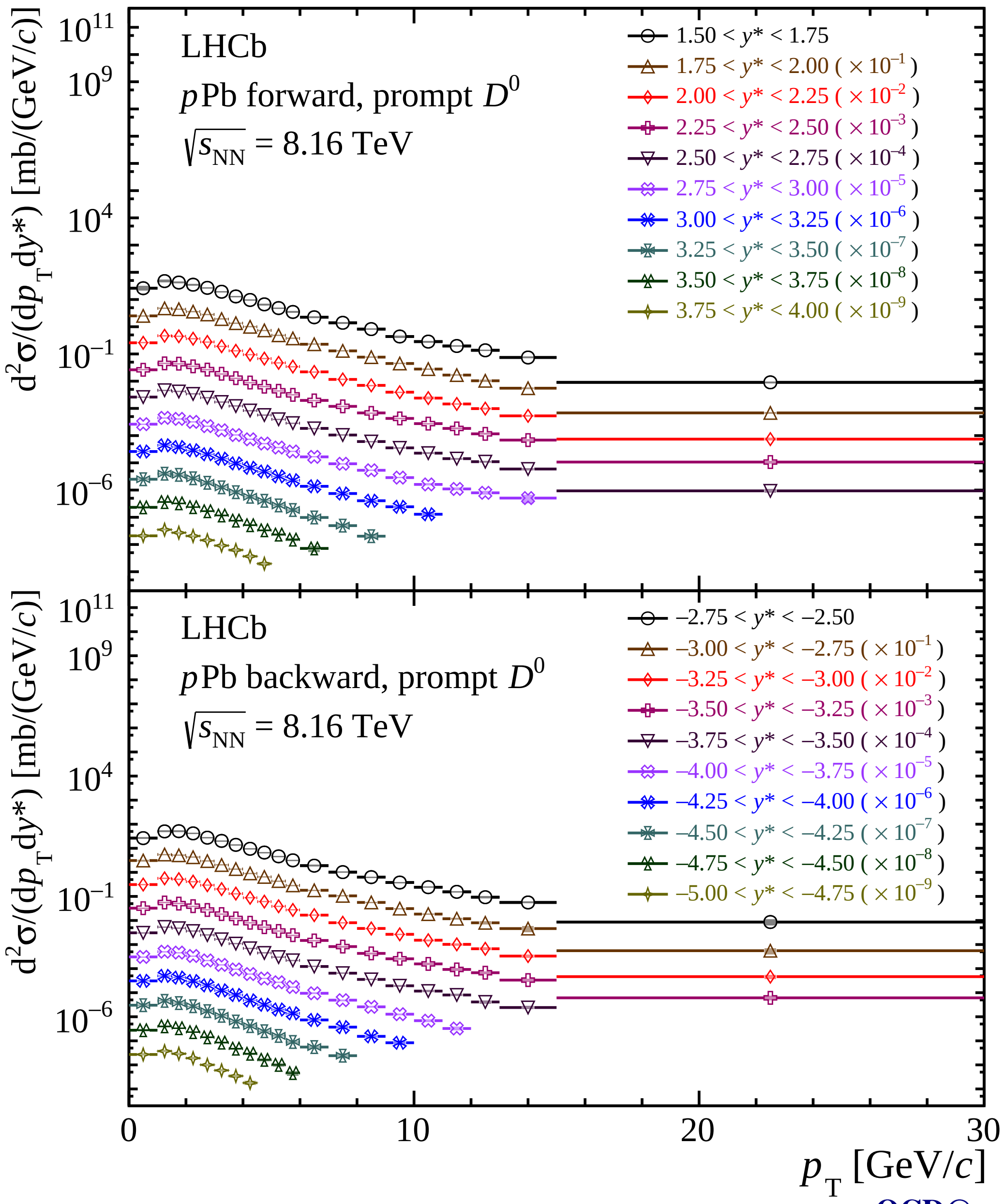
**arXiv:2205.03936**

- Millions of $D^0 \to K^-\pi^+$ (+cc) decays reconstructed




- Measurement down to 0 $p_T$
- Prompt and $b$-decay components cleanly separated

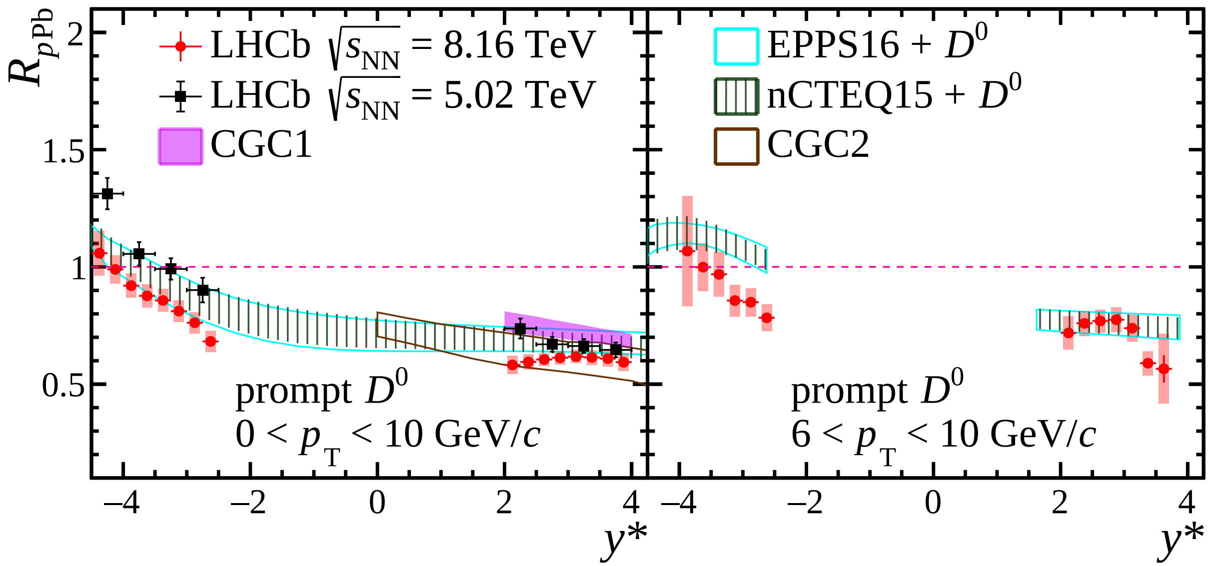


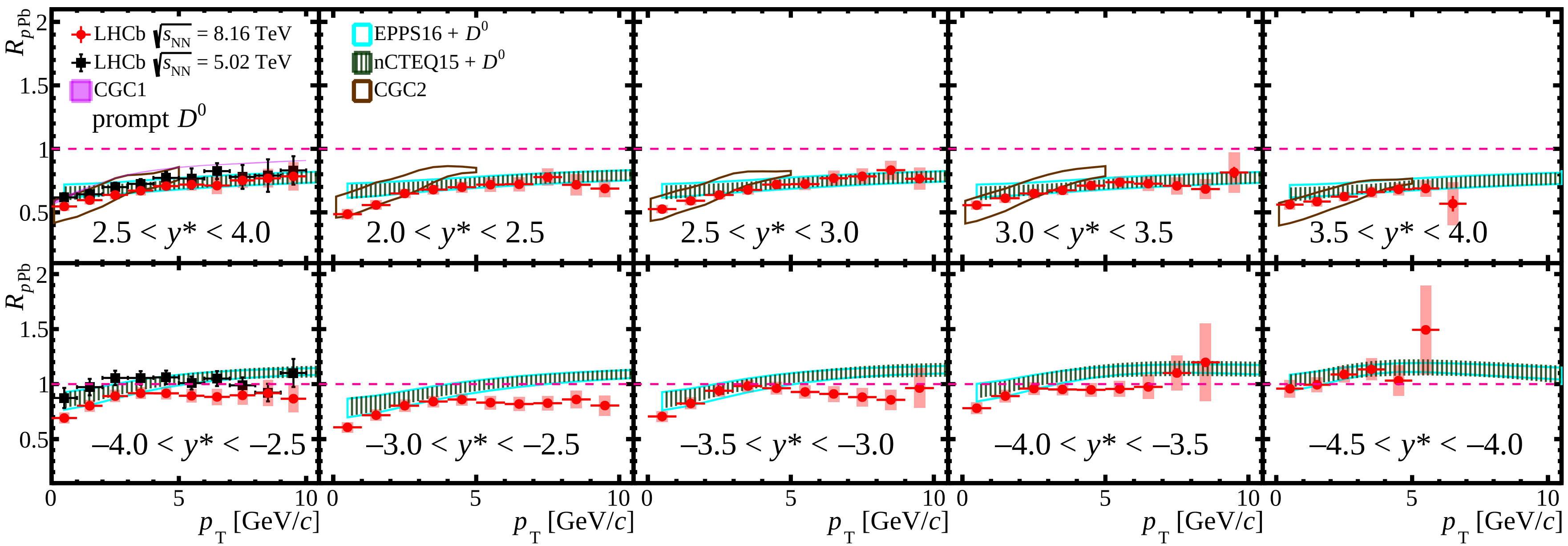



# $D^0$ production: nuclear modification factor

**arXiv:2205.03936**

- Precision measurement of suppression at forward rapidity and low $p_T$, consistent with 5 TeV results and more accurate than nPDF uncertainty
- Enhancement at backward rapidity: room for final state effects

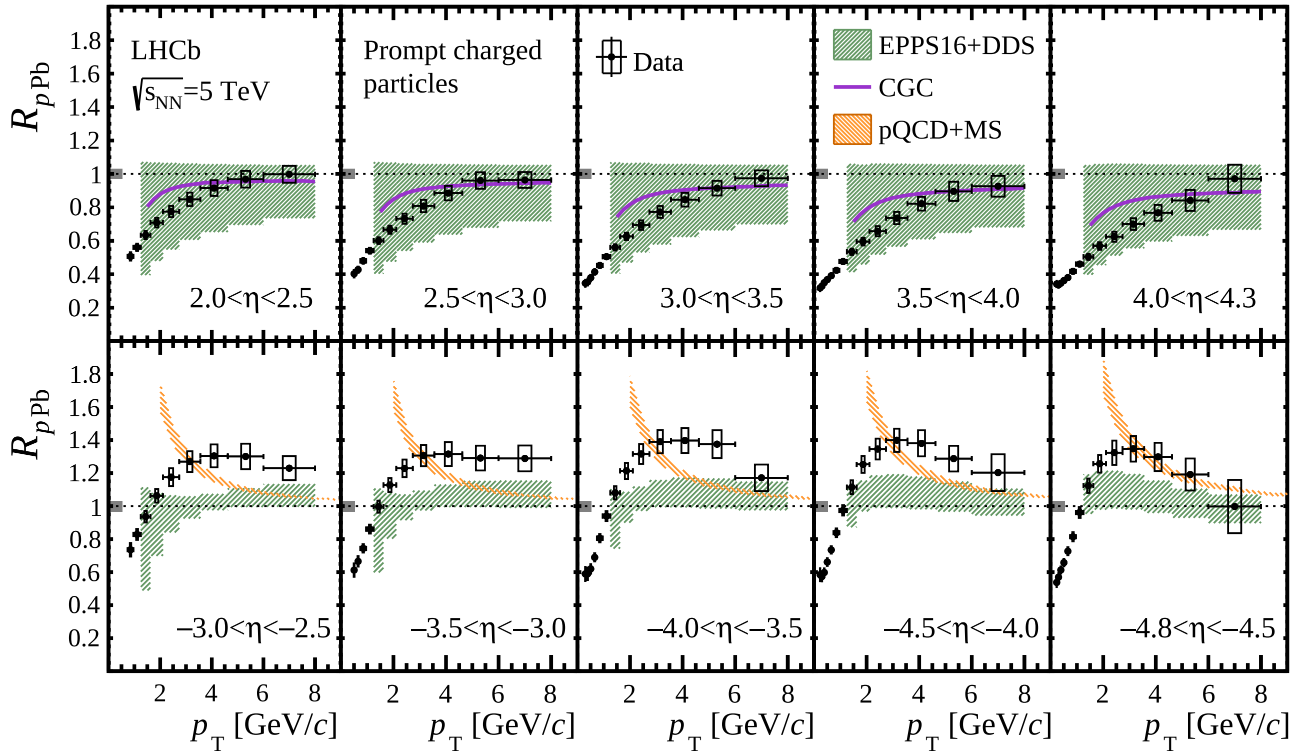


# Charged particle production $p$-Pb @5 TeV

**PRL 128(2022) 142004**

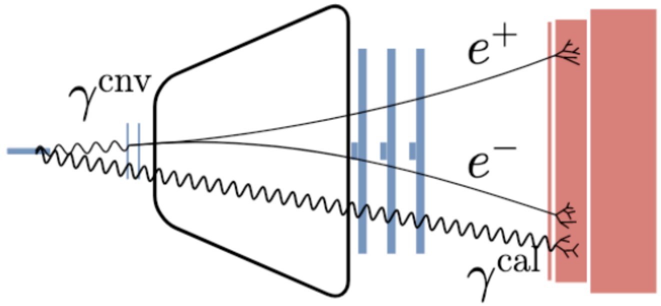
- LHCb probes unprecedented Bjorken-x range with forward coverage:
  Forward: $10^{-6} < x < 10^{-4}$
  Backward: $10^{-3} < x < 10^{-1}$
- Accurate measurements (down to 2.8% syst. error on x-section, 4.2% on $R_{p\mathrm{Pb}}$)
- Strong suppression at forward rapidity and enhancement at backward rapidity for $p_{\mathrm{T}} > 1.5\,\mathrm{GeV}/c$
- No model can successfully describe the data across the full rapidity range

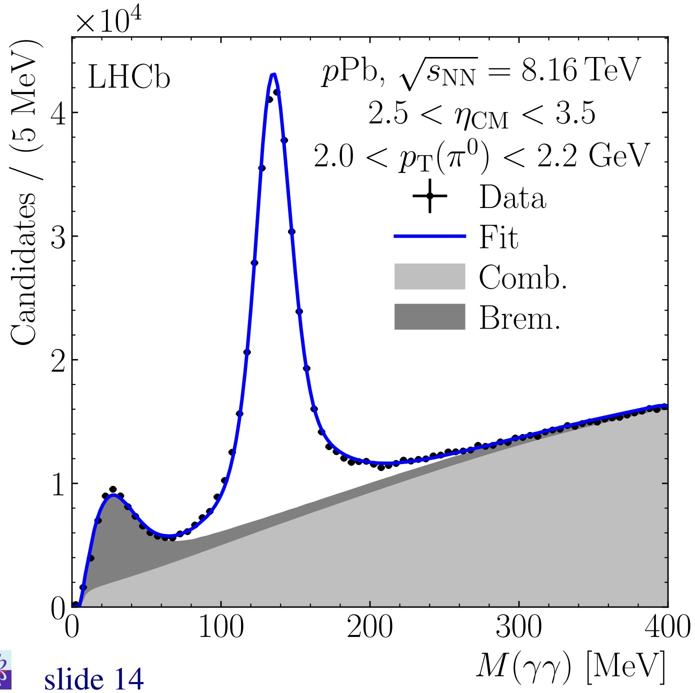


# $\pi^0$ production $p$-Pb @8 TeV

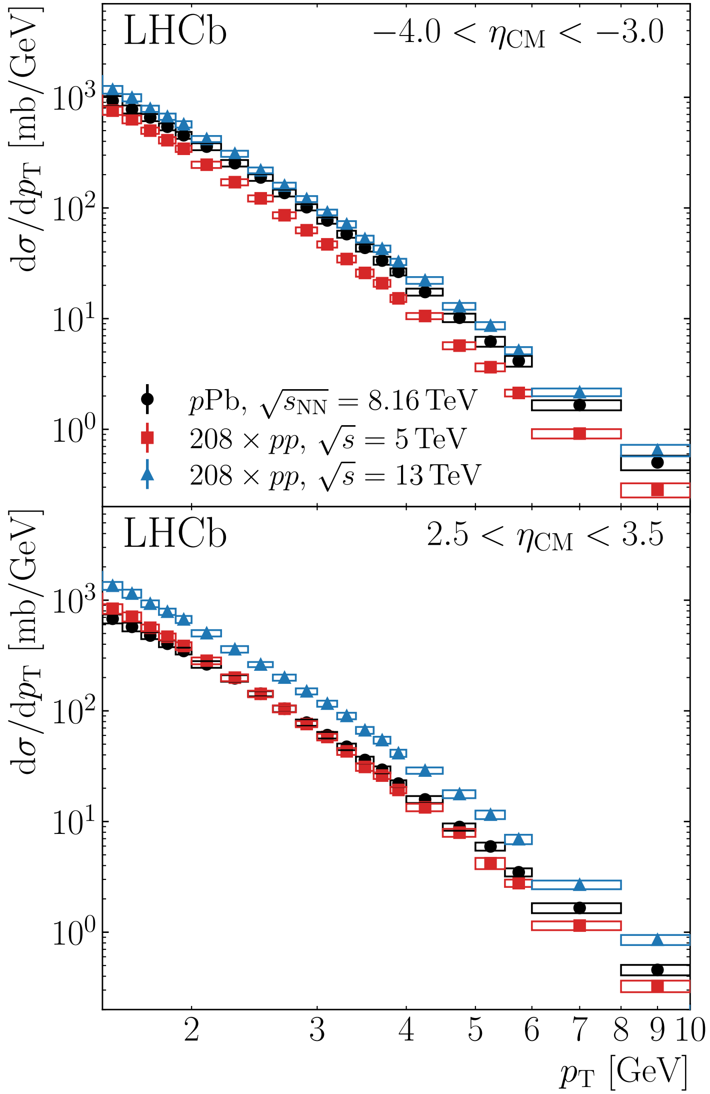
**arXiv:2204.10608, accepted by PRL**

- First $\pi^0$ result in forward rapidity at LHC
- Important also as a step toward direct photon production
- $\pi^0$ candidates obtained from $\pi^0 \to \gamma^{cnv}\gamma^{cal}$ (avoid overlapping $\gamma$s in ECAL)



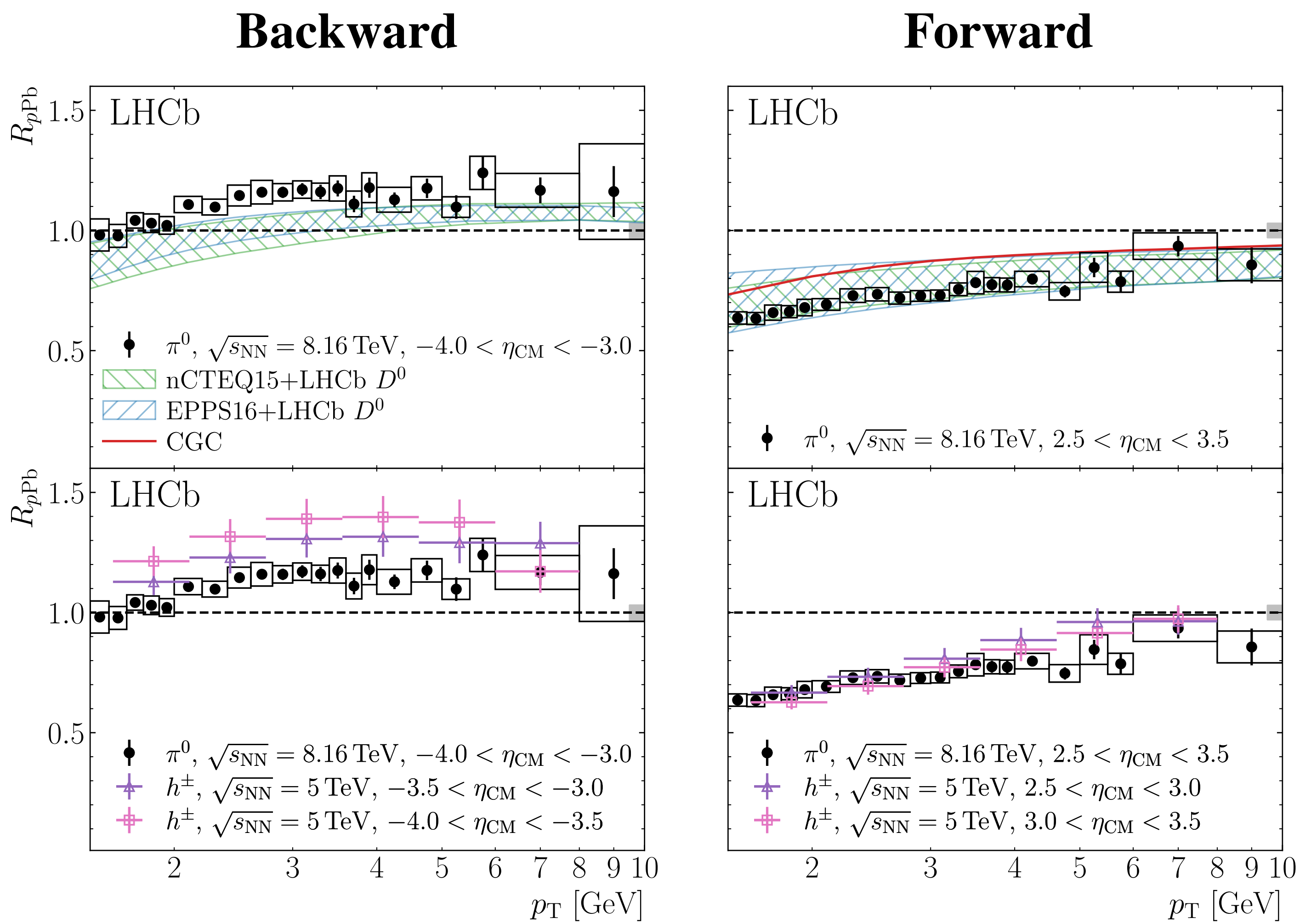

$p$-$p$ reference obtained interpolating measurements at 5 and 13 TeV



# $\pi^0$ nuclear modification factor

**arXiv:2204.10608, accepted by PRL**

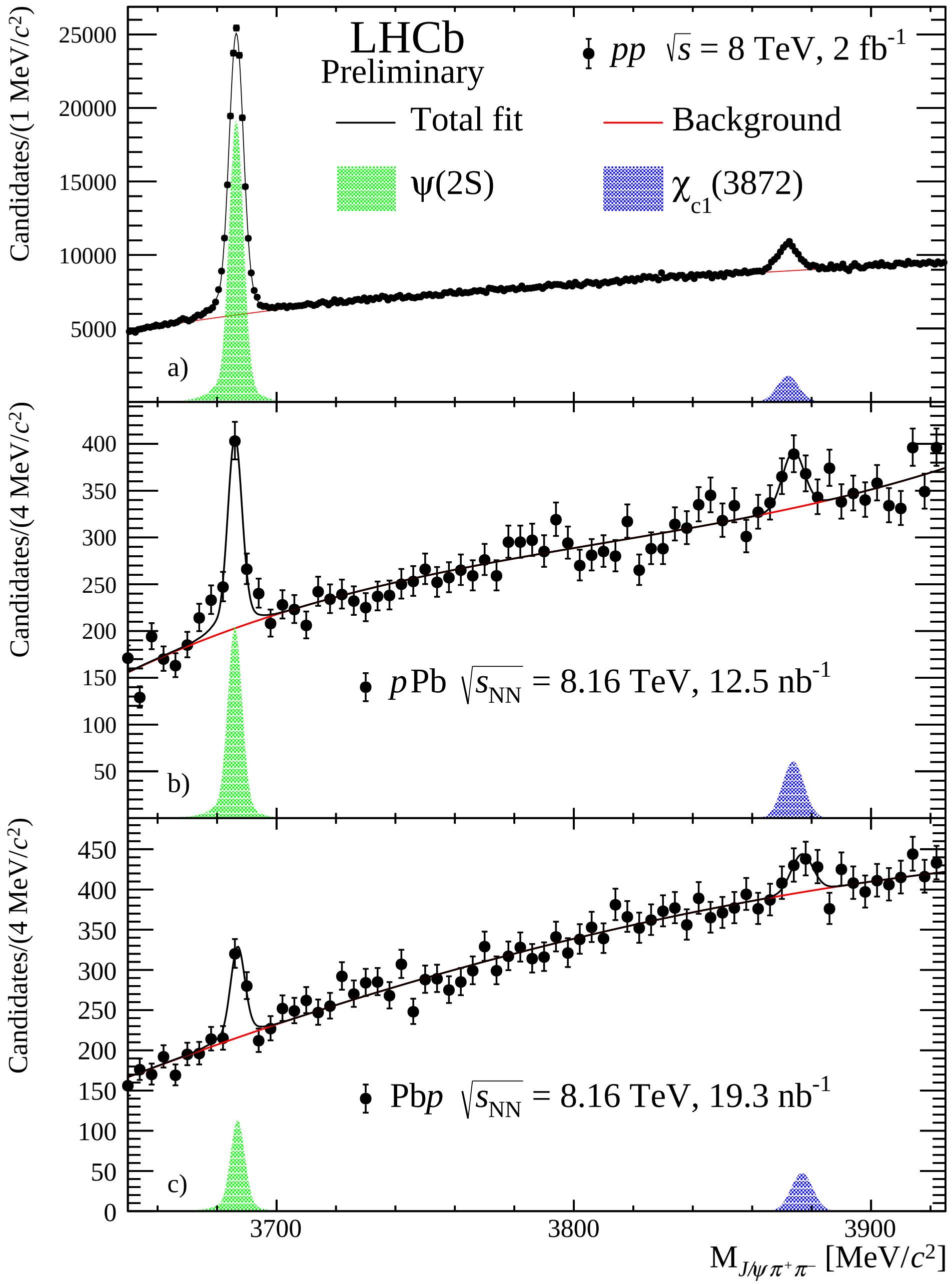
- Forward suppression looks universal. Can constrain nPDF down to $x \sim 10^{-6}$
- First observation of Cronin-like $\pi^0$ enhancement in $p$-Pb, smaller than the one observed for charged particles. This suggests mass ordering, consistent with radial flow or baryon enhancement from final state recombination



# $\chi_{c1}(3872)/\psi(2S)$ in $p$-Pb @8 TeV

**LHCb-CONF-2022-001**

- Previous LHCb results showed evidence for breakup of charmonia and bottomonia in cold (?) nuclear medium in $p$-Pb collisions. Study is now being extended to exotic hadron $\chi_{c1}(3872)$, whose nature is still debated
- $\chi_{c1}(3872)$ and $\psi(2S)$ reconstructed from the same final state $J/\psi\,(\rightarrow \mu^+\mu^-)\pi^+\pi^-$
- Comparison between $p$-$p$, $p$-Pb, Pb-$p$ systems
- Prompt production disentangled from $b$ decays
- Constraints on models of hadronization and final state interactions

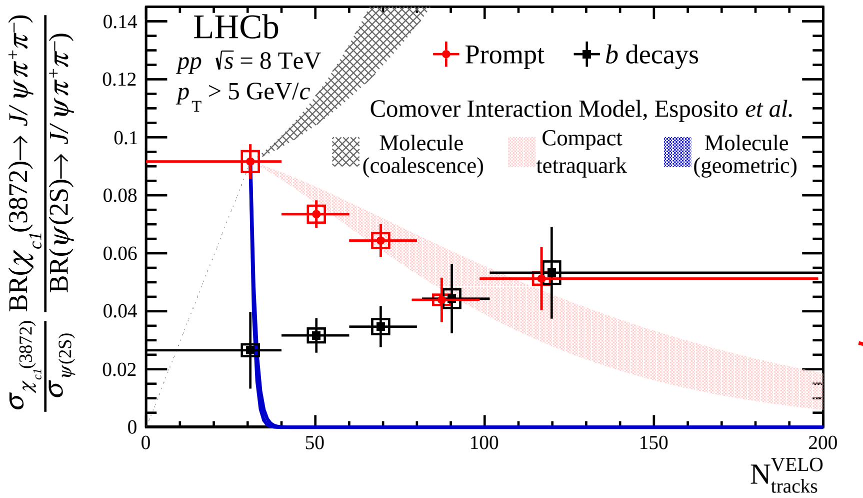


# $\chi_{c1}(3872)/\psi(2S)$ results

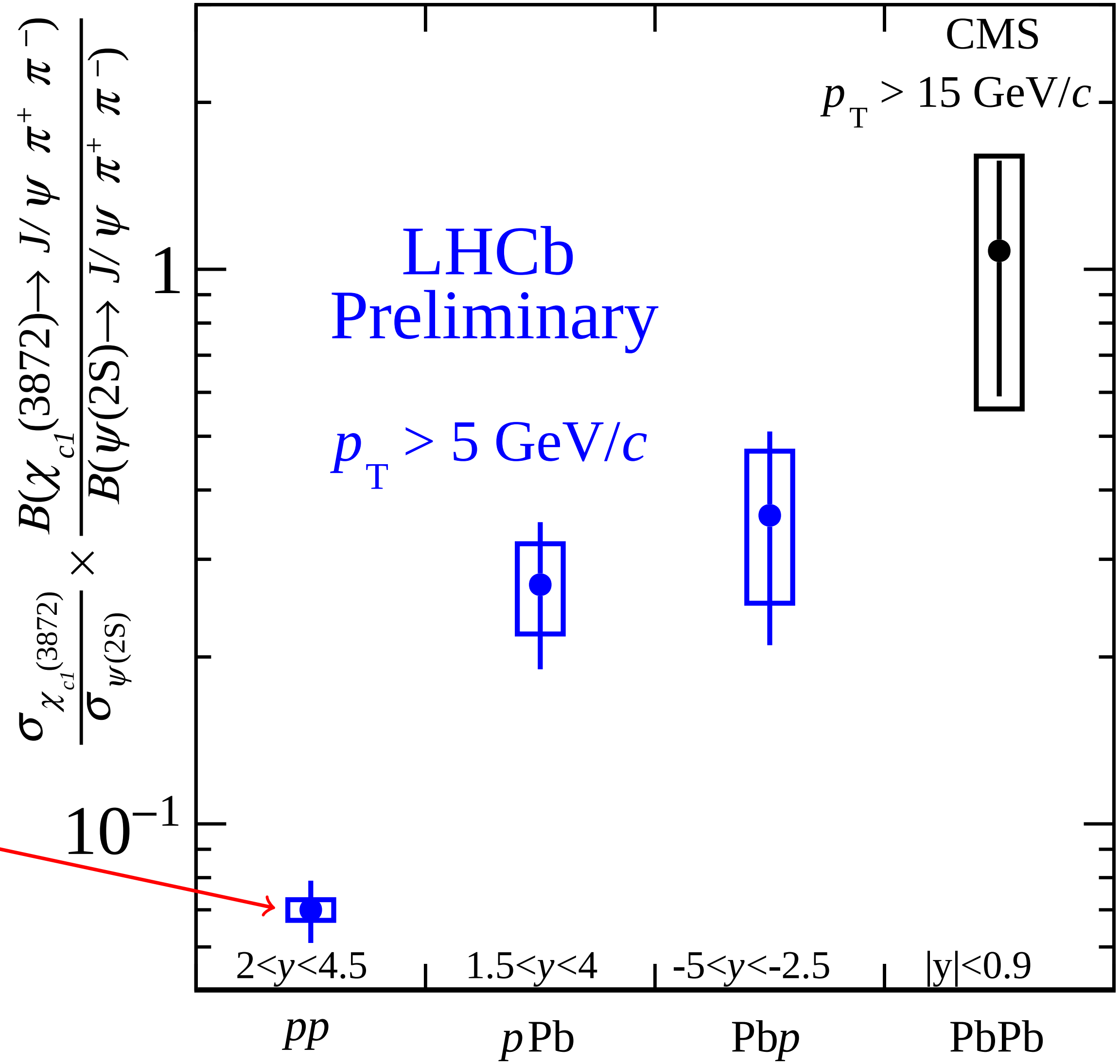
**LHCb-CONF-2022-001**

Enhanced production of $\chi_{c1}(3872)$ through coalescence?

Note that ratio decreases with multiplicity in $p$-$p$, where breakup in final state seems to dominate

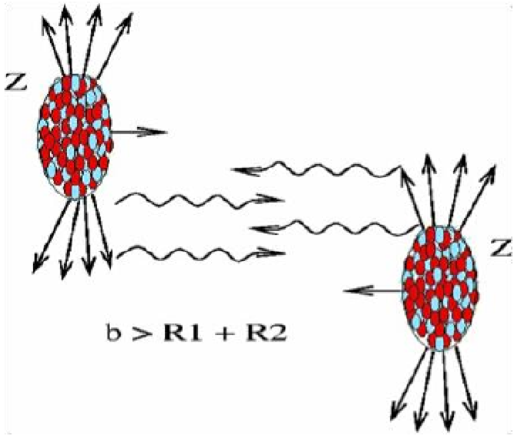



**PRL 126 (2021) 092001**

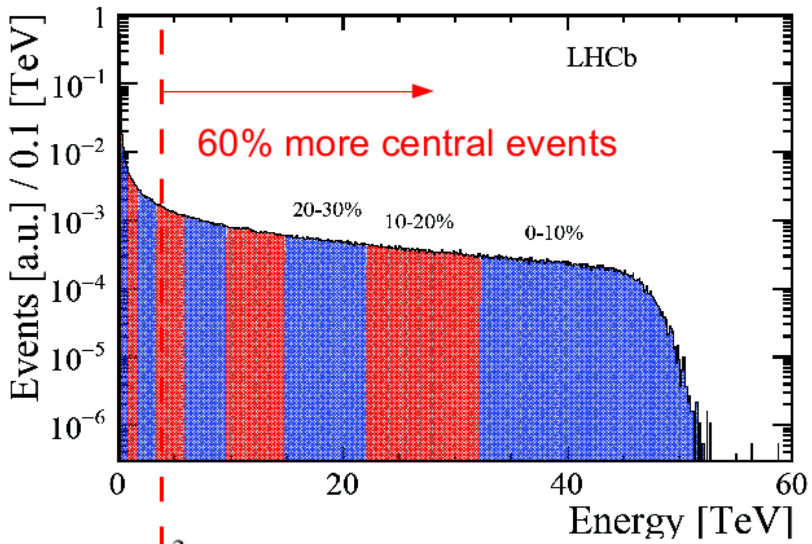


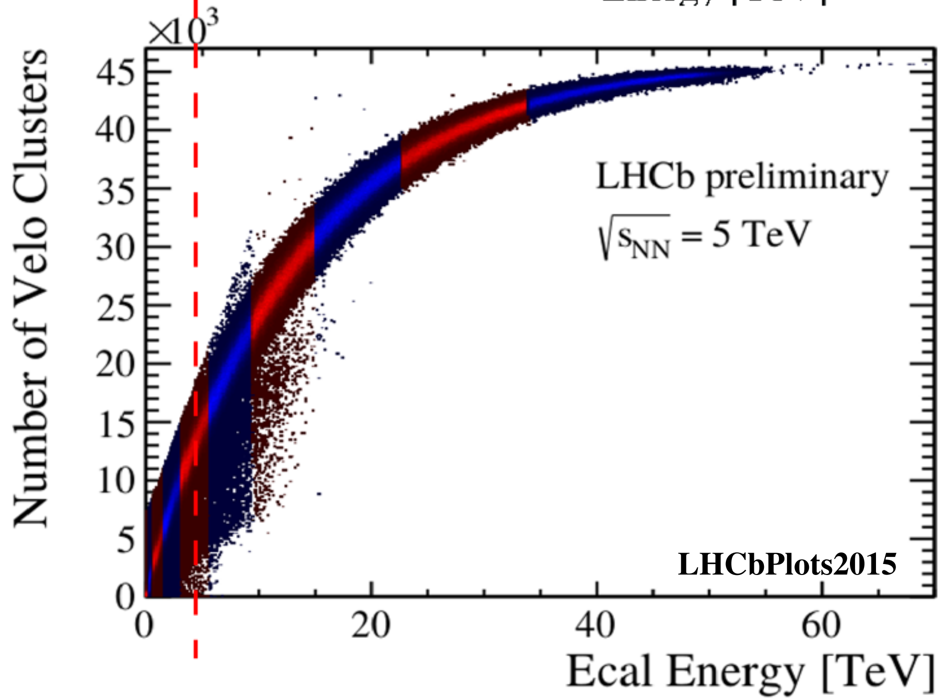
# Pb-Pb collisions

- LHCb collected PbPb data at 5 TeV in 2015 ( about 10 $\mu$b) and in 2018 (230$\mu$b)
- Tracking exhibits saturation at about 50% centrality
- Still interesting physics from Peripheral and Ultra-Peripheral Collisions (UPC)




JINST 17 (2022) P05009

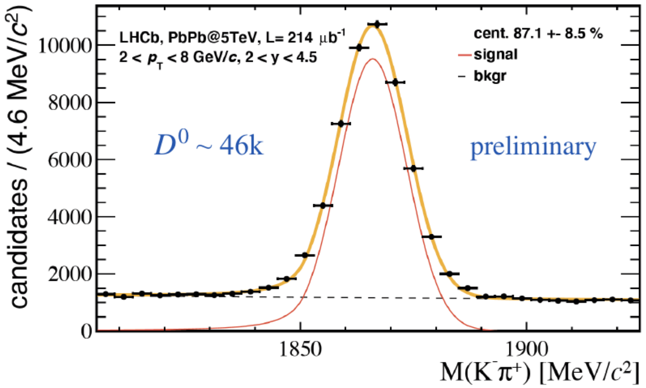


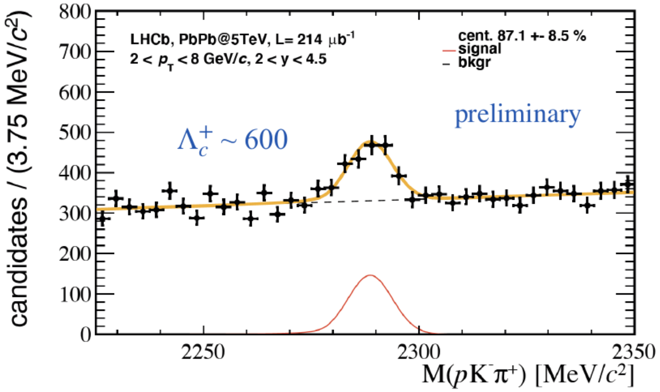



# $\Lambda_c^+/D^0$ ratio in peripheral Pb-Pb@5 TeV

**LHCb-PAPER-2021-046, in preparation**

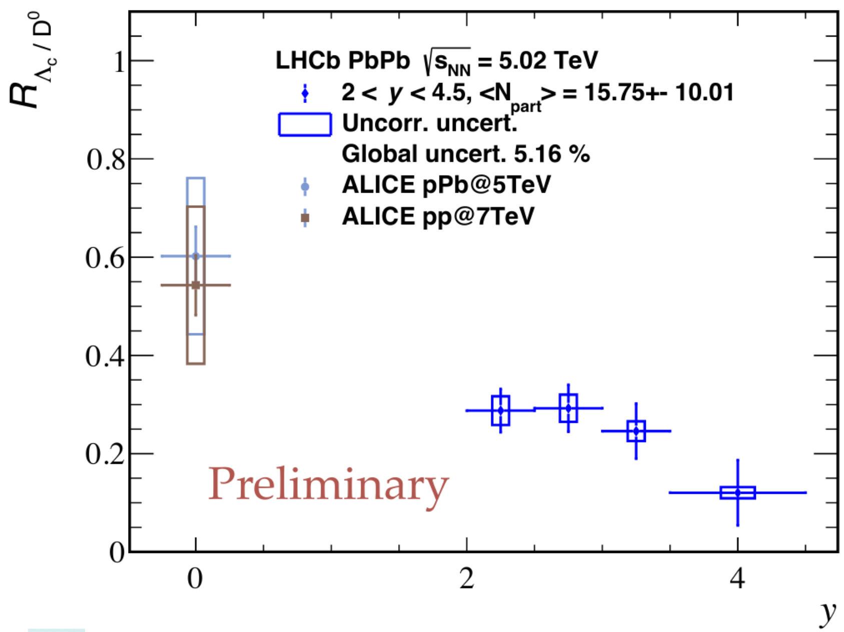
- Prompt charm baryon/meson ratio studied in collisions with centrality between 60 and 90%
- $b$-hadron decay component subtracted using impact parameter

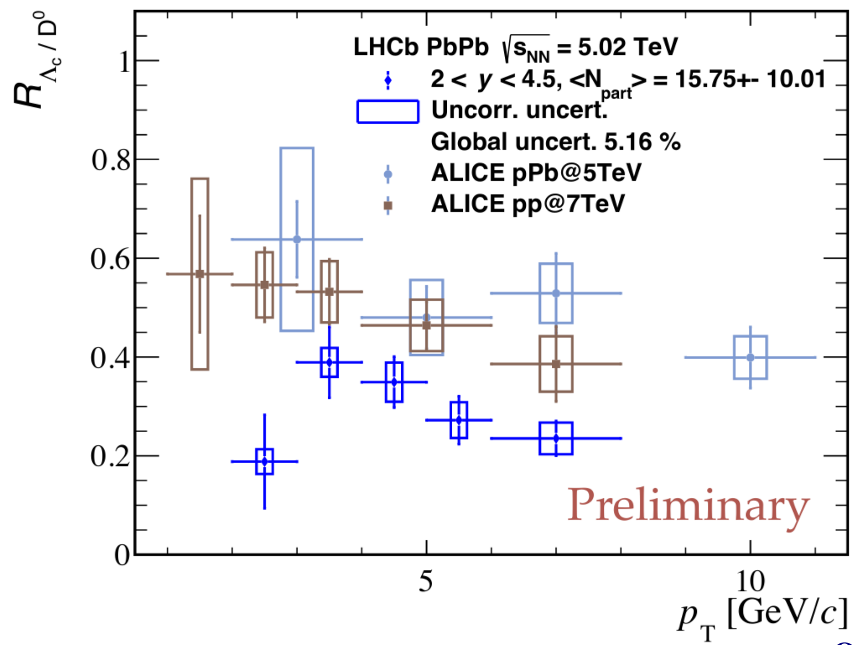



- Result is consistent with same measurement in $p$-Pb
- inconsistent with ALICE results at central rapidity, even in $p$-$p$ and $p$-Pb

…rapidity-dependent baryon enhancement? $p_T$ dependence similar to ALICE result

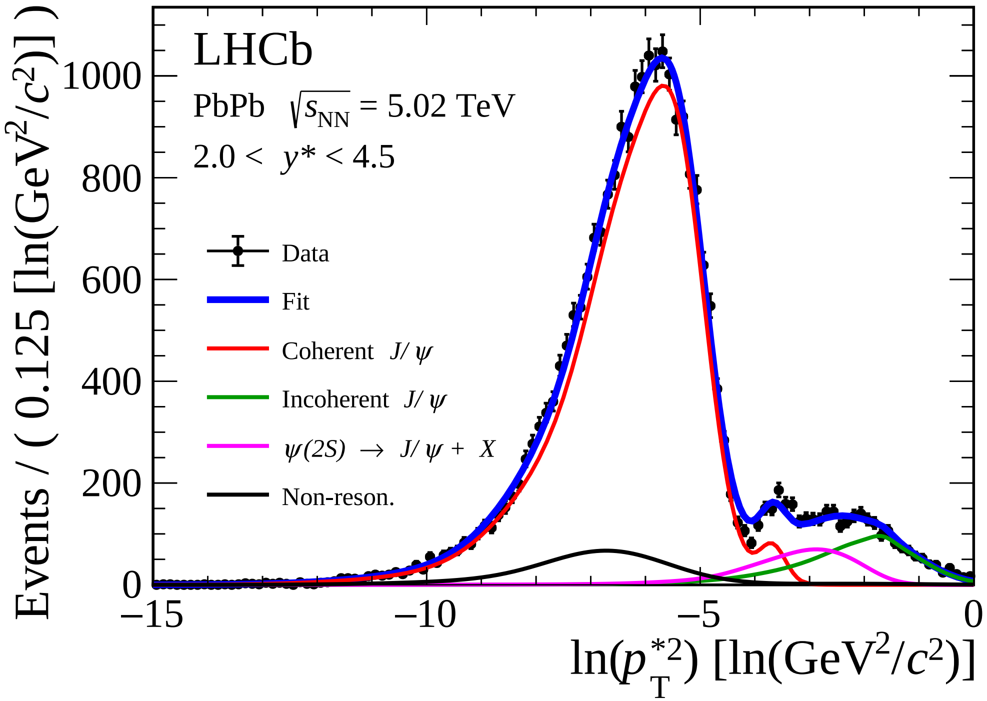


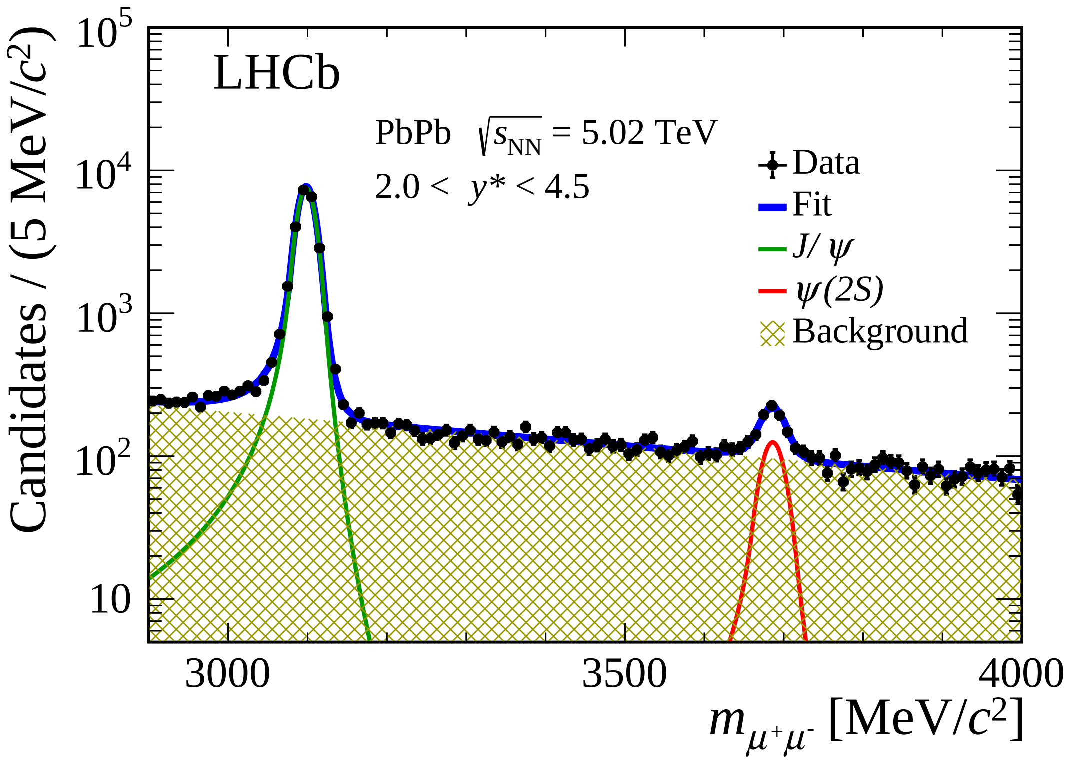



# Quarkonia photoproduction in UPC Pb-Pb @5 TeV

**arXiv:2206.08221**

- Photoproduction of both $J/\psi$ and $\psi(2S)$ vs rapidity and $p_T$
- Coherent and uncoherent production cleanly resolved thanks to $p_T$ resolution

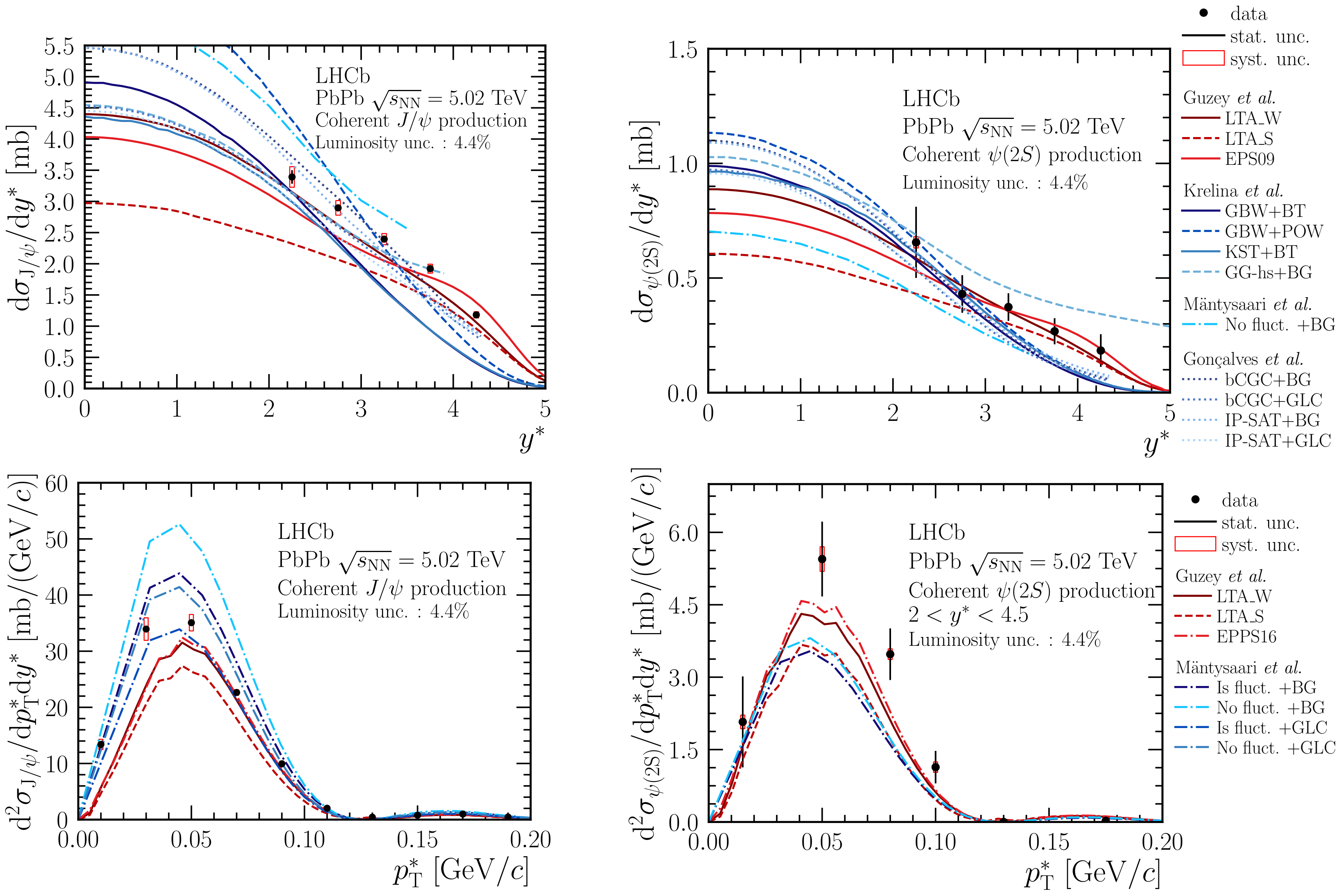


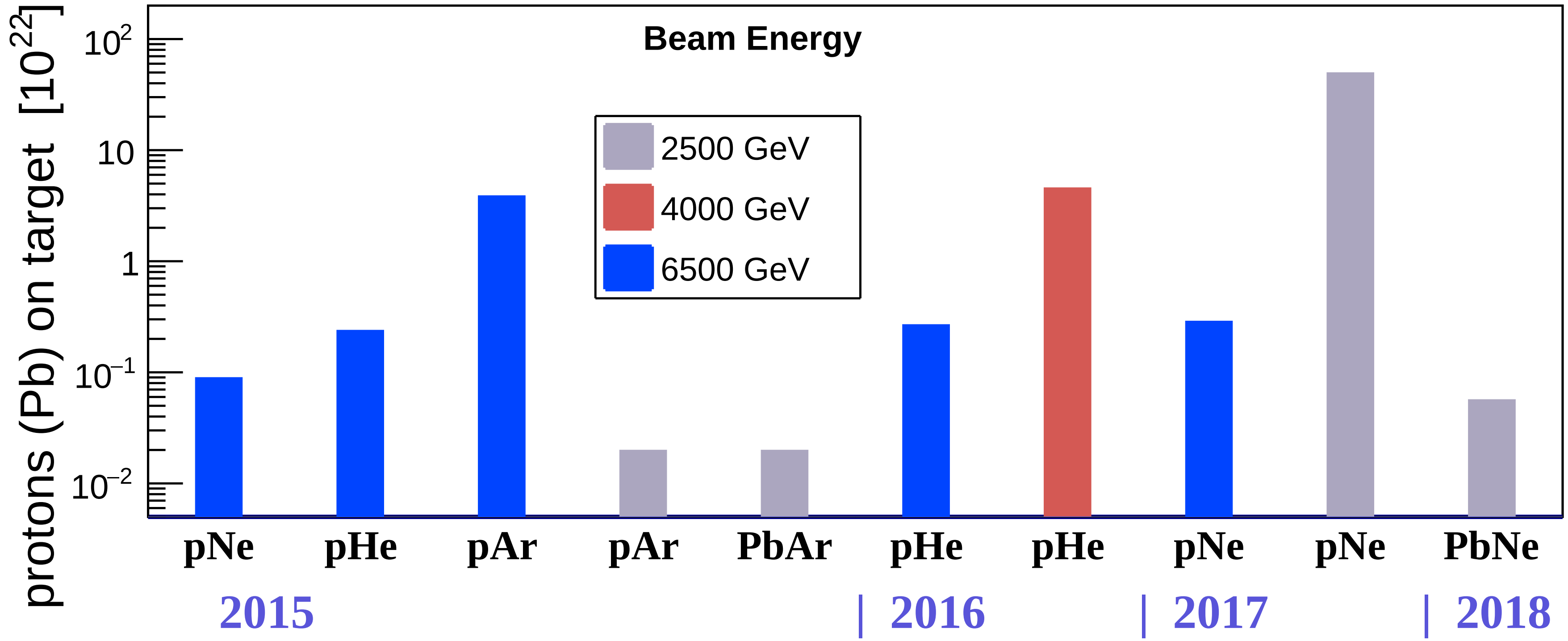
# UPC in Pb-Pb: cross-section results

arXiv:2206.08221

- Sensitive to gluon PDF down to $x \sim 10^{-5}$
- Reasonable agreement with models based on nPDF/CGC



# Fixed-target collisions



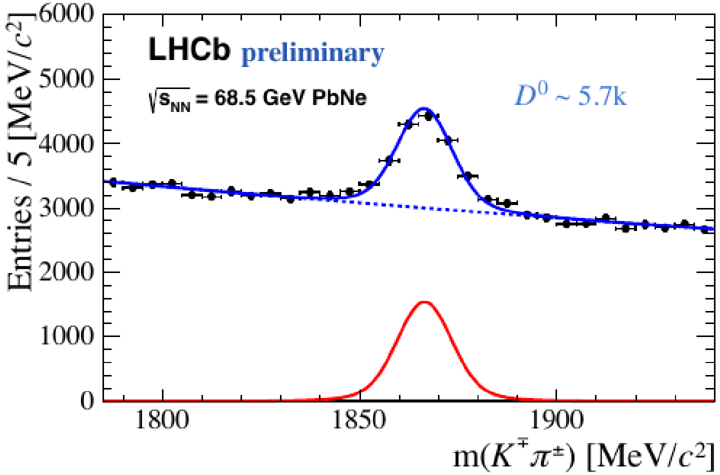

(at nominal SMOG pressure, $10^{22}$ POT correspond to 5/nb for 1 m of gas )

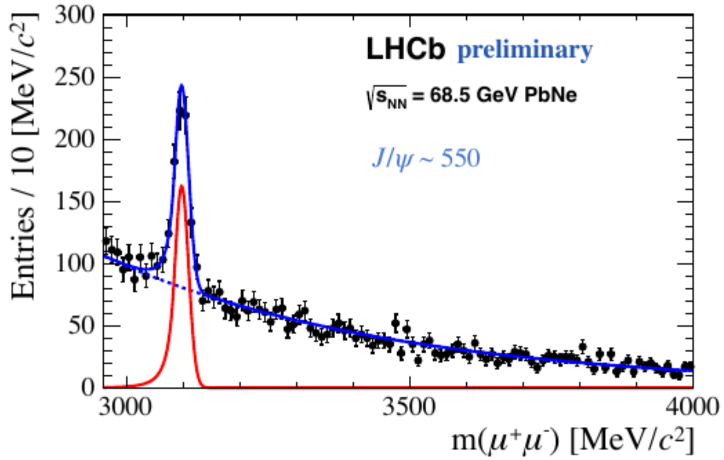
- First papers from first physics runs in 2015 and 2016
- Larger samples of pNe collisions ($\sim 100\text{nb}^{-1}$) and PbNe collisions at same energy collected in 2017 and 2018

# Charm production in Pb-Ne @68 GeV

**LHCb-PAPER-2022-011, in preparation**

- $D^0$ and $J/\psi$ production observed
- $D^0$ reference for studying quarkonium modification inside nuclear medium

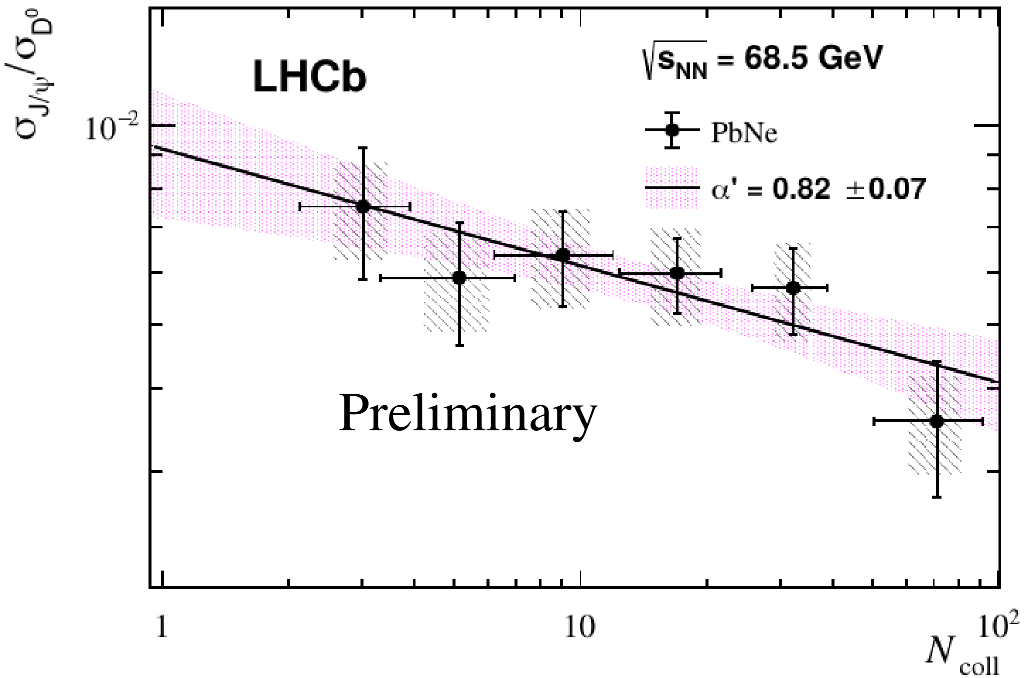



- clear decrease of $J/\psi/D^0$ ratio with increasing centrality, fitted with power law

$$\sigma_{J/\psi}/\sigma_{D^0} \propto < N_{coll} >^{\alpha'-1}$$

- Result $\alpha' = 0.82 \pm 0.07$ agrees with measurements by NA50 **PLB410 (1997) 337**
- No anomalous $J/\psi$ suppression expected from QGP formation is observed

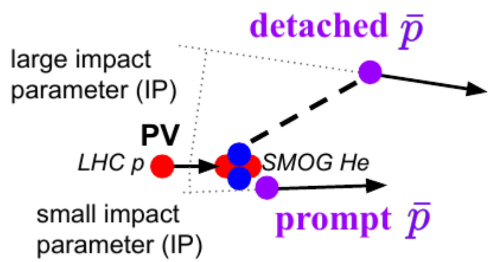


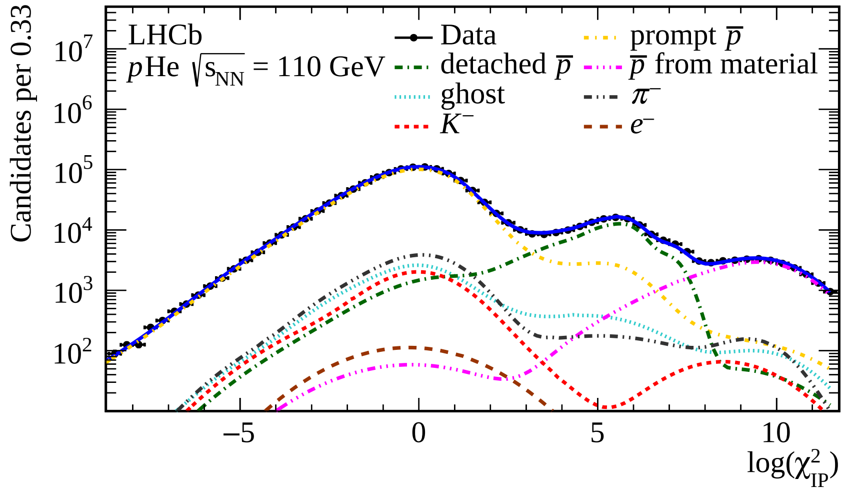
# Antiprotons from antihyperons in $p$-He @110 GeV

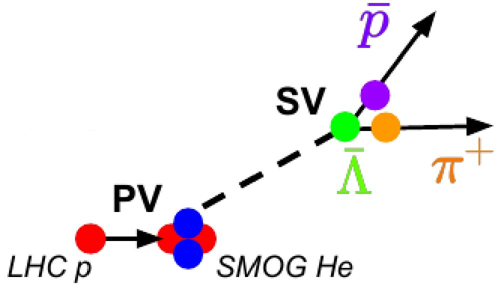
arXiv:2205.09009

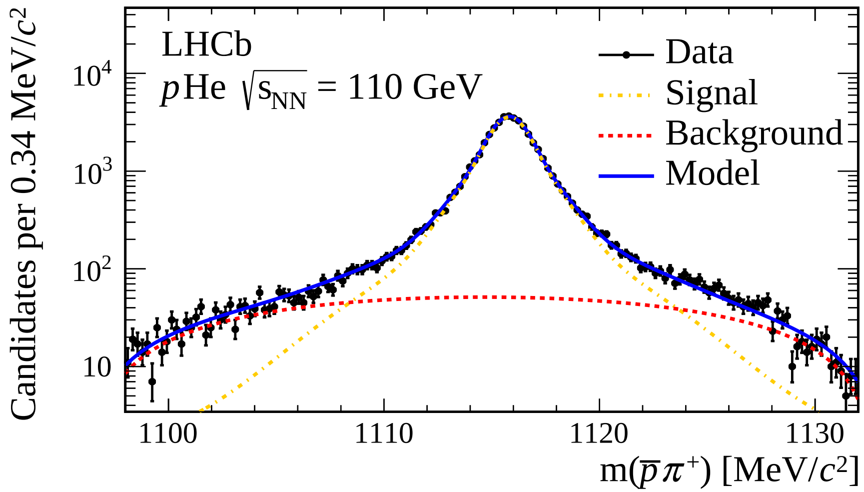
- $p$-He@110 GeV mimic cosmic ray- interstellar medium collisions at the energy scale relevant for the AMS-02 measurements of antimatter in space
- Prompt $\overline{p}$ measurement already constrained models of secondary cosmic $\overline{p}$ PRL 121 (2018), 222001

- Measurements now extended to antiprotons produced by antihyperons decays
- Two complementary approaches followed:
  - Inclusive measurements of detached antiprotons using impact parameter and $\overline{p}$ identification
  - Exclusive measurement of the dominant contribution: $\overline{\Lambda} \to \overline{p}\pi^+$



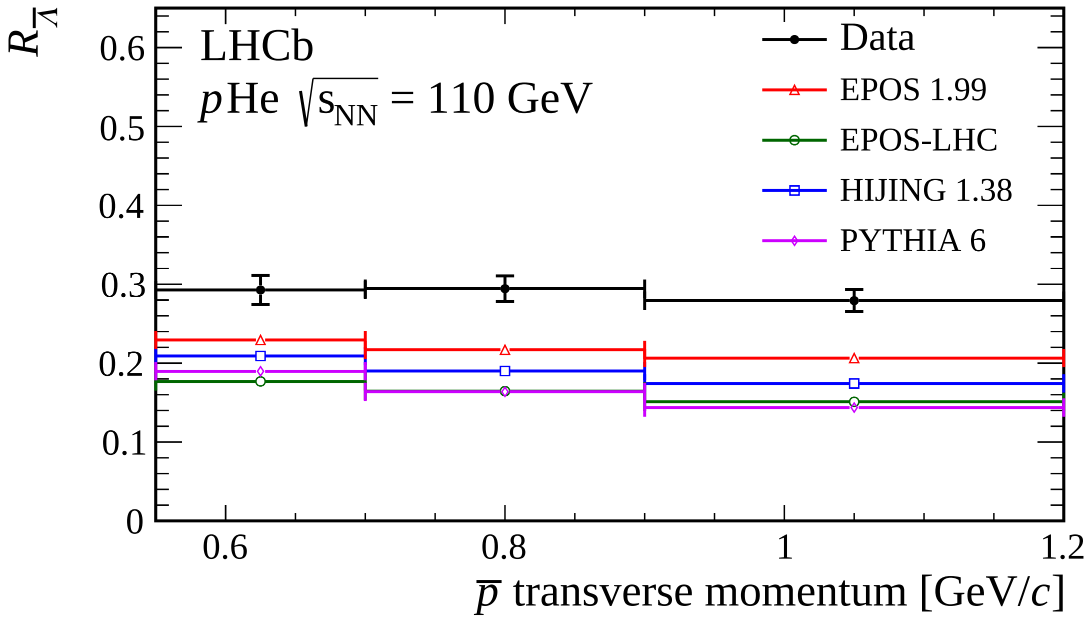



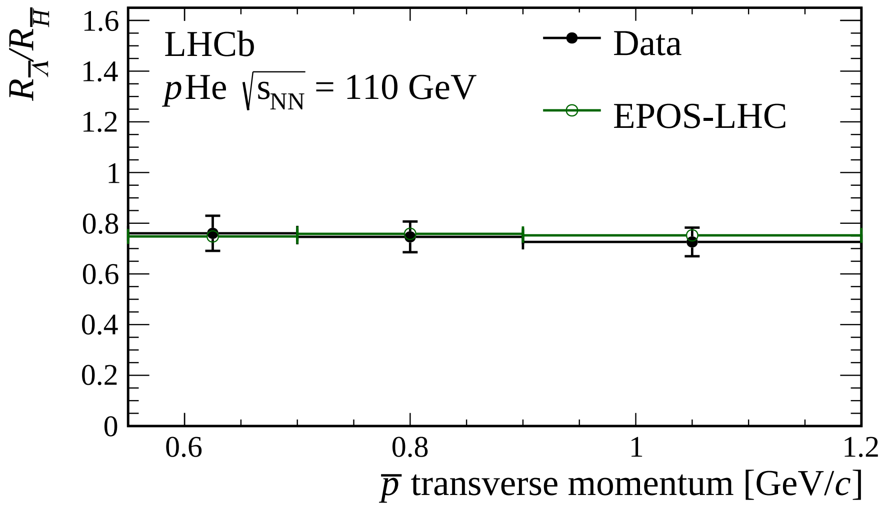



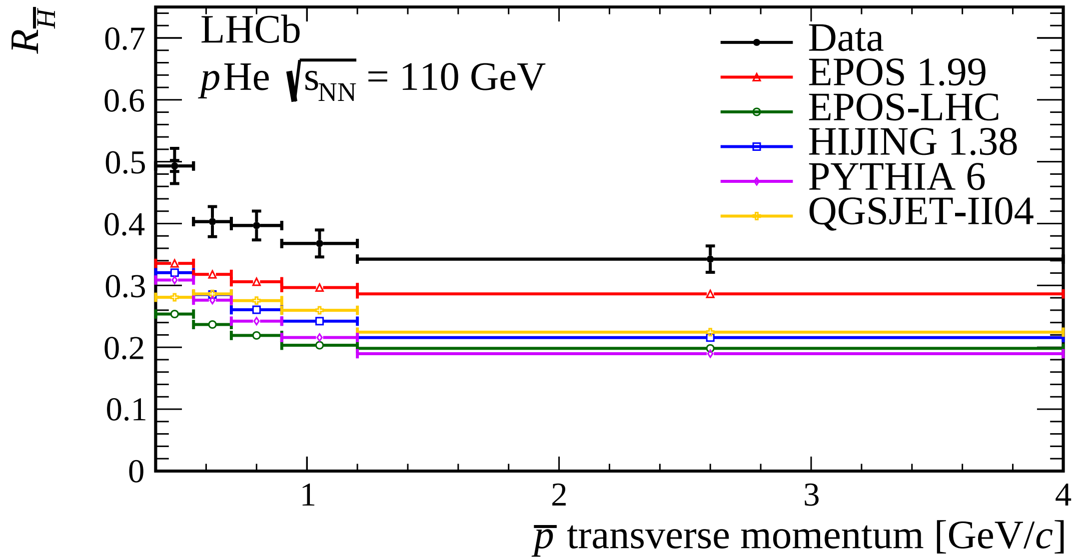
# Detached Antiprotons in $p$-He: results

arXiv:2205.09009

- Both approaches indicate larger anti-hyperon production than predicted by most commonly used hadronic models
- Nice agreement of the excl.$\overline{\Lambda}$/incl.antihyperon ratio with theoretical expectations



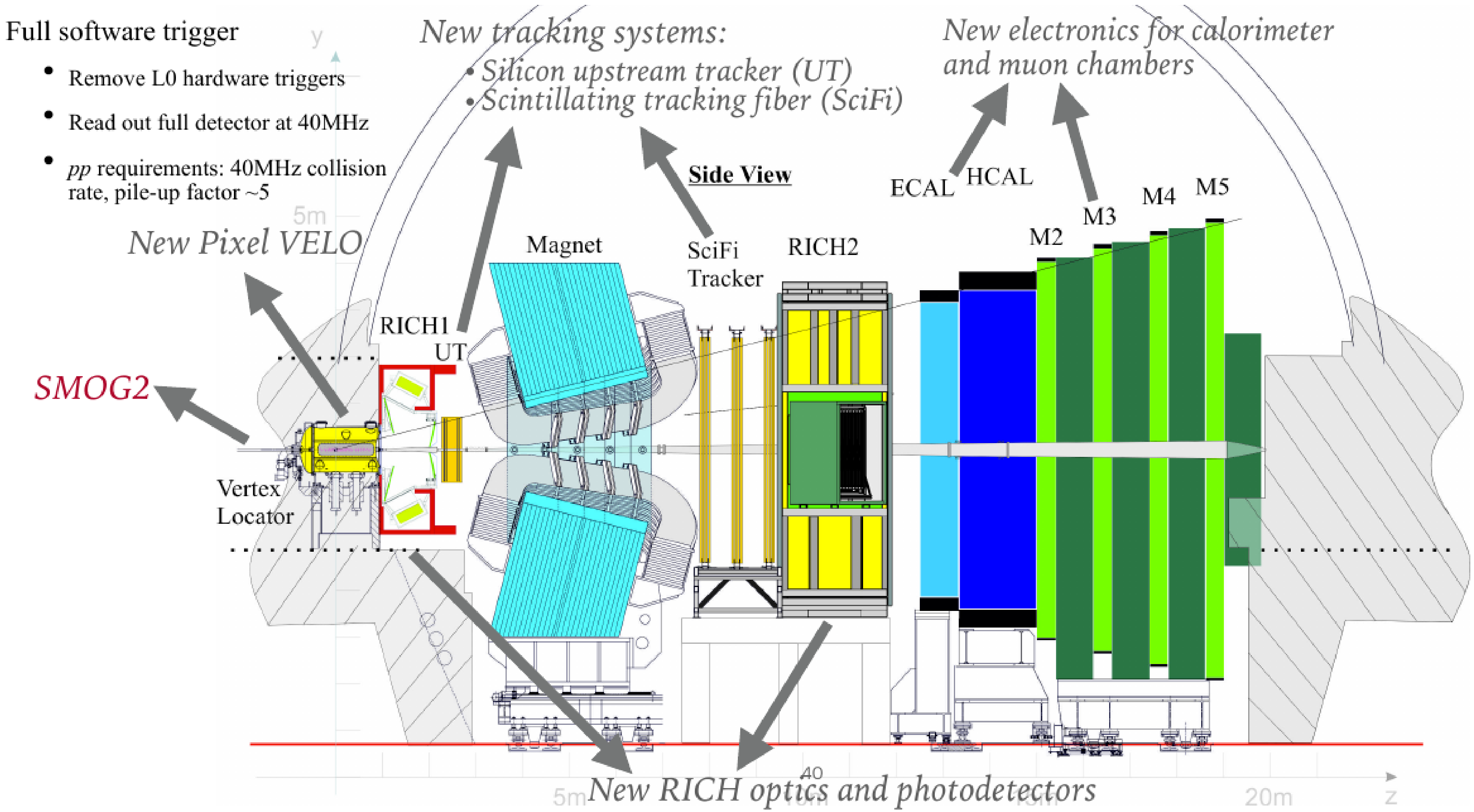



# Ready for Run3: the LHCb Upgrade

LHCB-TDR-012

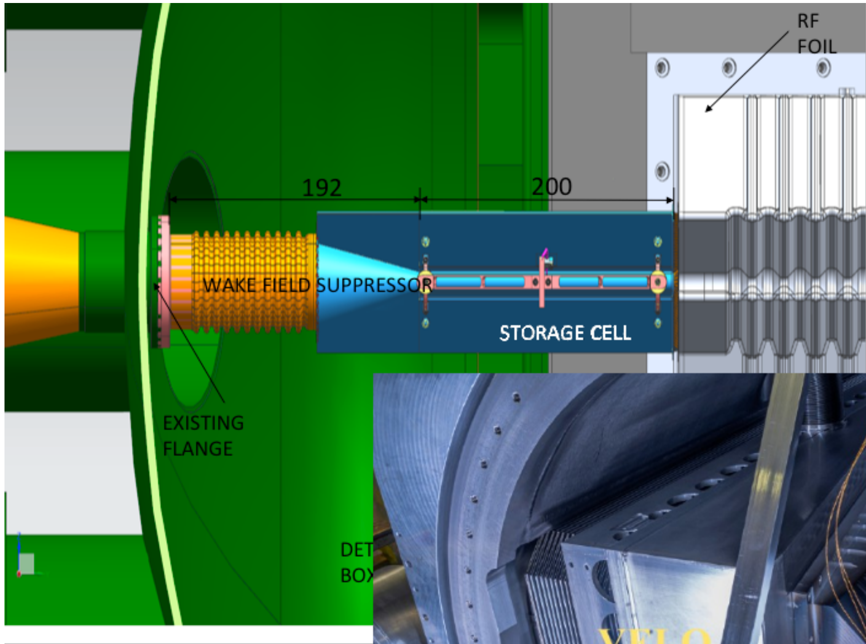
- LHCb has been almost totally refurbished for the LHC Run 3, starting right now
- New vertexing/tracking detectors with higher granularity
  - ➡ will increase centrality reach for HI collisions

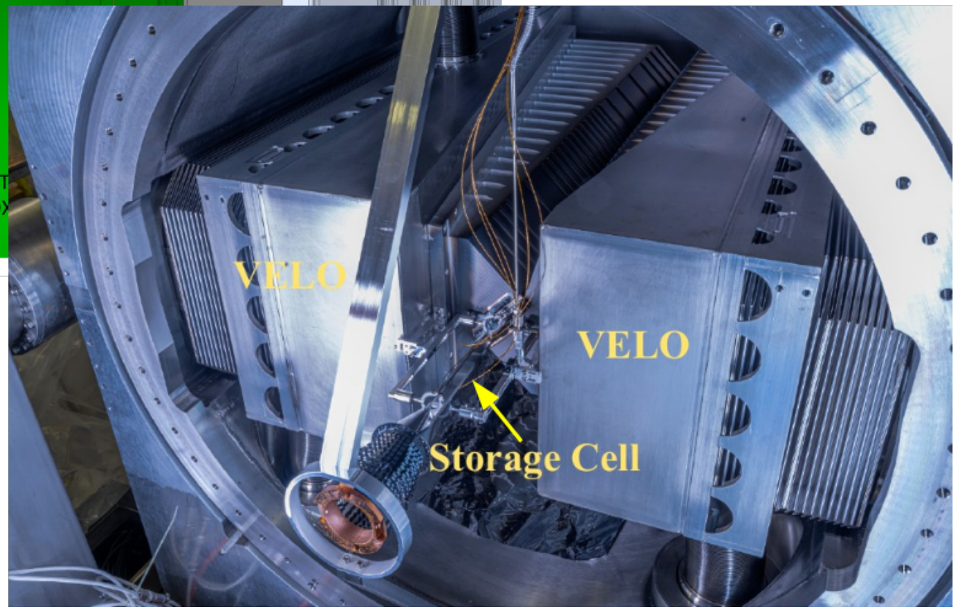


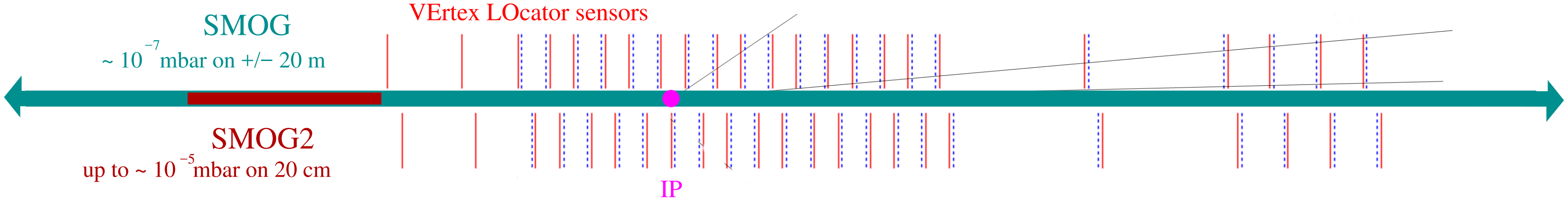
# The Fixed Target Upgrade

LHCB-TDR-020

- new fixed target device (SMOG2): gas contained in 20 cm long storage cell:
  - increase luminosity by $\sim$ 2 orders of magnitude for the same gas flux.
  - possibly inject other gas species ($^2$H, $^2$D, O, Kr…)



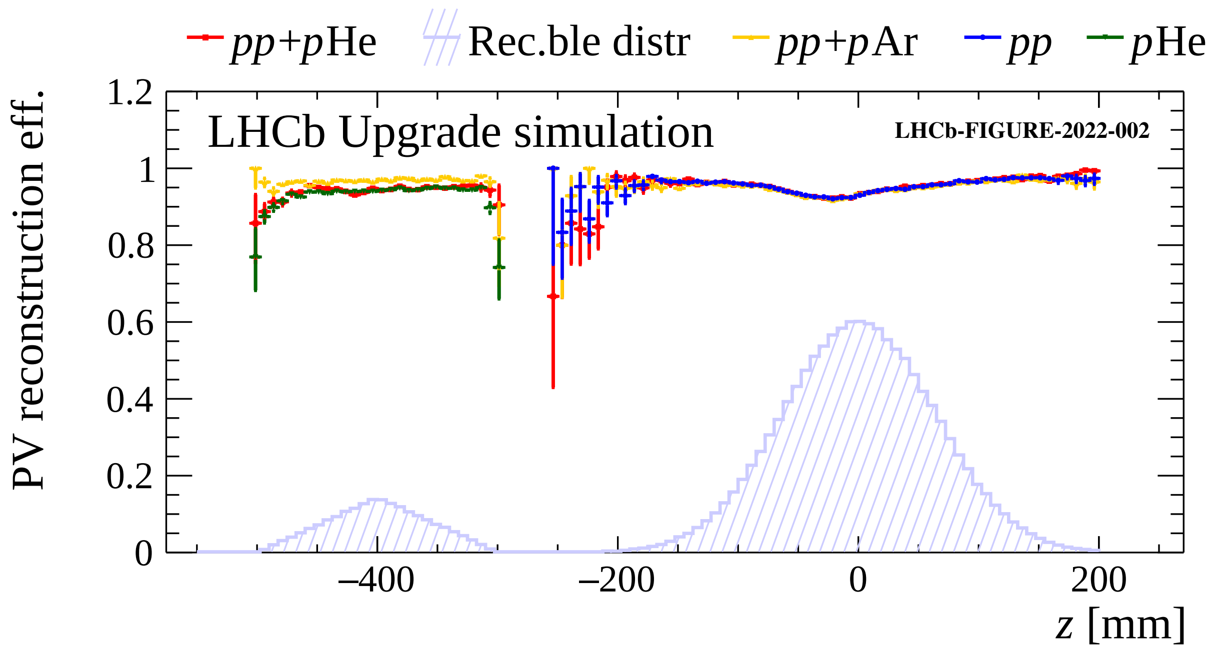



# Prospects for Fixed Target at LHC energy

**LHCB-PUB-2018-015**

- Fixed target events to be routinely acquired simultaneously with $p$-$p$ data taking

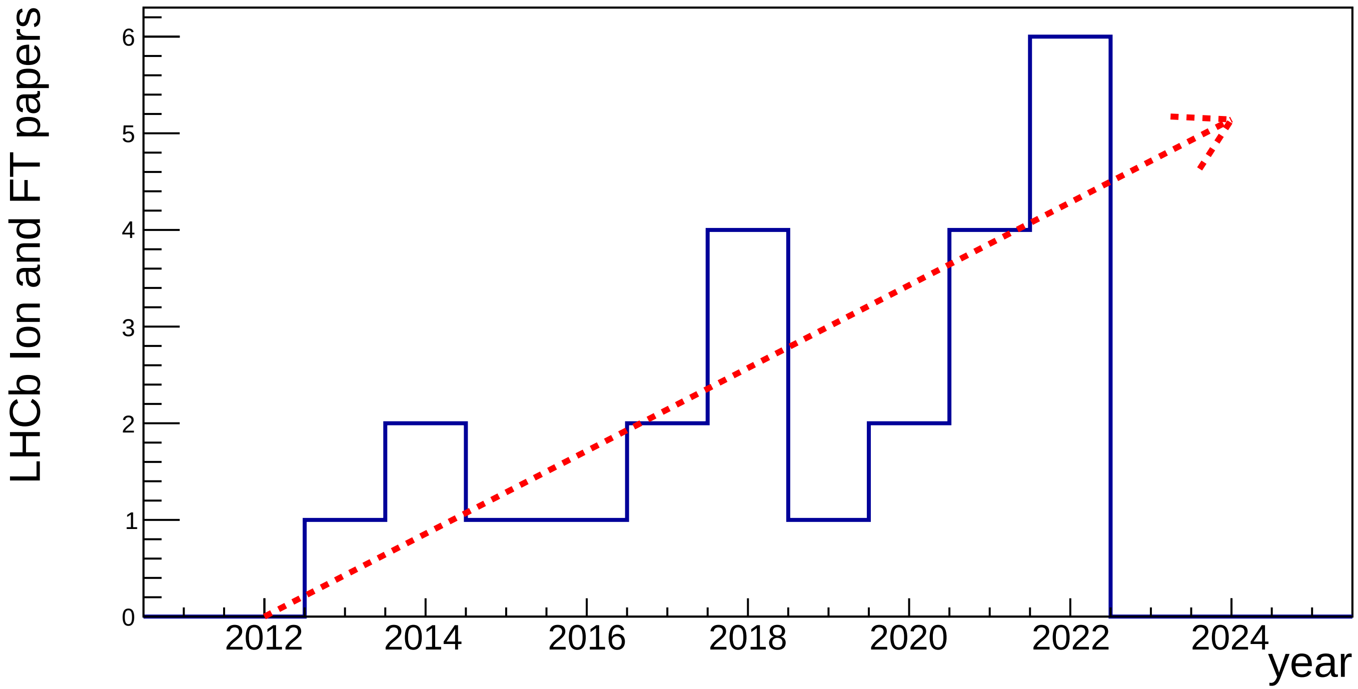



- Expect increase of the integrated luminosities by three orders of magnitudes, reaching O(100/pb): first full scale fixed-target experiment using LHC beams
- Novel possibilities for nuclear physics, study of 3D structure functions. cosmic ray physics. . .

| | SMOG largest sample p–Ne@68 GeV | SMOG2 example p–Ar@115 GeV |
|---|---|---|
| Integrated luminosity | $\sim 100$ nb$^{-1}$ | 100 pb$^{-1}$ |
| syst. error on J/$\psi$ x-sec. | 6–7% | 2–3 % |
| J/$\psi$ yield | 15k | 35M |
| $D^0$ yield | 100k | 350M |
| $\Lambda_c$ yield | 1k | 3.5M |
| $\psi$(2S) yield | 150 | 400k |
| $\Upsilon$(1S) yield | 4 | 15k |
| Low-mass ($5 < M_{\mu\mu} < 9$ GeV/$c^2$) Drell-Yan yield | 5 | 20k |

# Conclusions

- LHCb became an important contributor to heavy ion physics (and cosmic ray physics, too)
- Latest results include the study of new probes ($\pi^0$, exotic hadrons) and the first results from nucleus-nucleus collisions in fixed target using LHC beams
- Dramatic prospects for the LHC Run 3

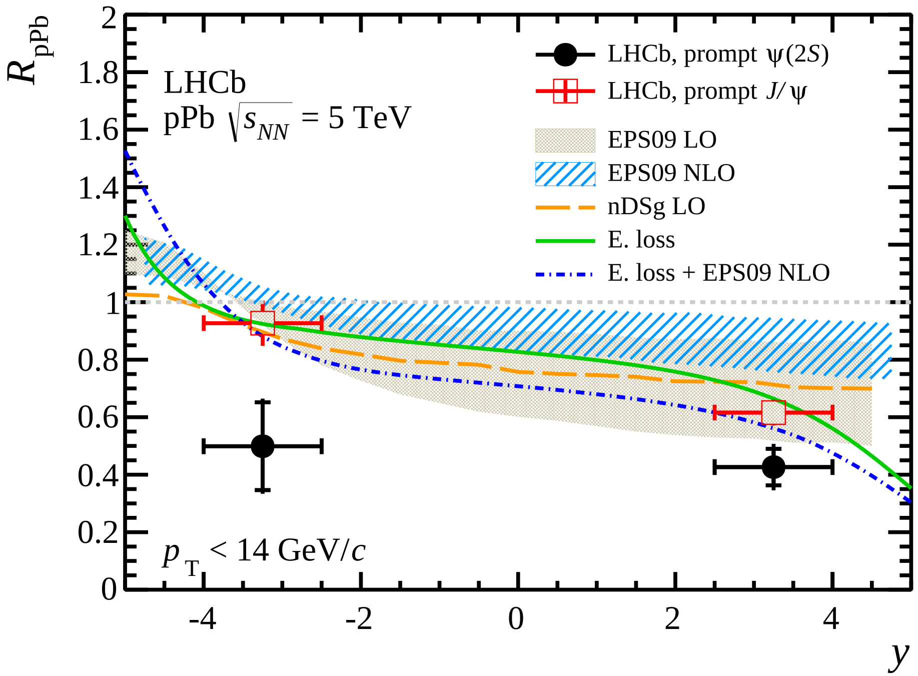


# Additional Material

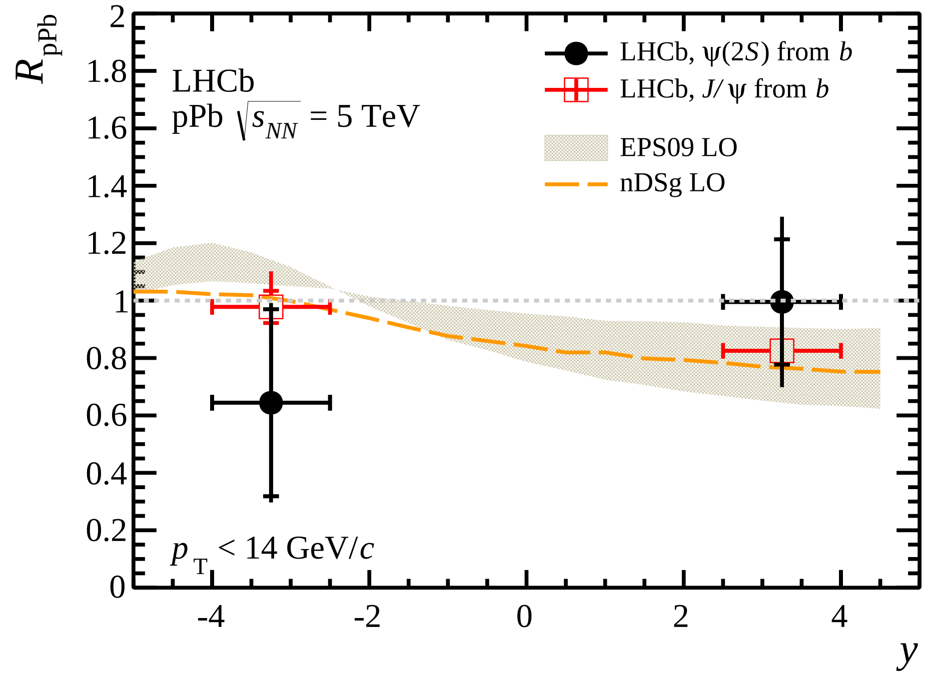
# $J/\psi$ and $\psi(2S)$ in pPb

JHEP 1603 (2016) 133

## Prompt




## From $b$

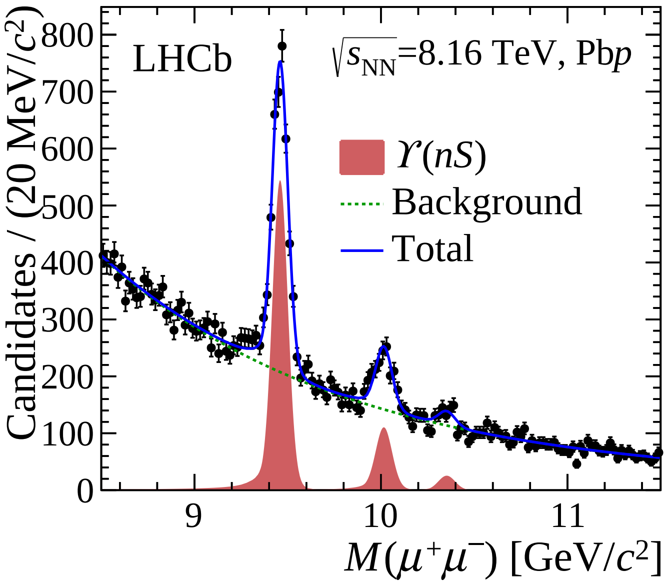


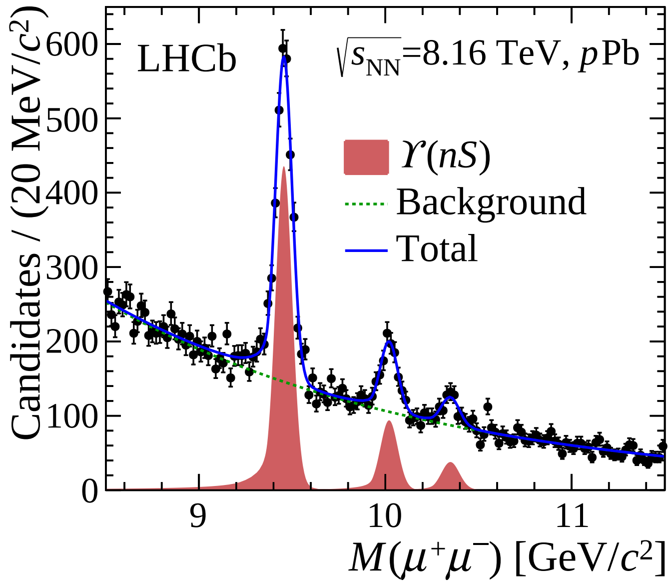

- Results from the smaller sample at 5 TeV show a stronger suppression for $\psi(2S)$, not expected from initial state effects or energy loss
- Confirms similar findings from PHENIX, ALICE
- Stay tuned for the update from 8 TeV data

# Bottomonia in pPb@8 TeV

arXiv:1810.07655, accepted by JHEP

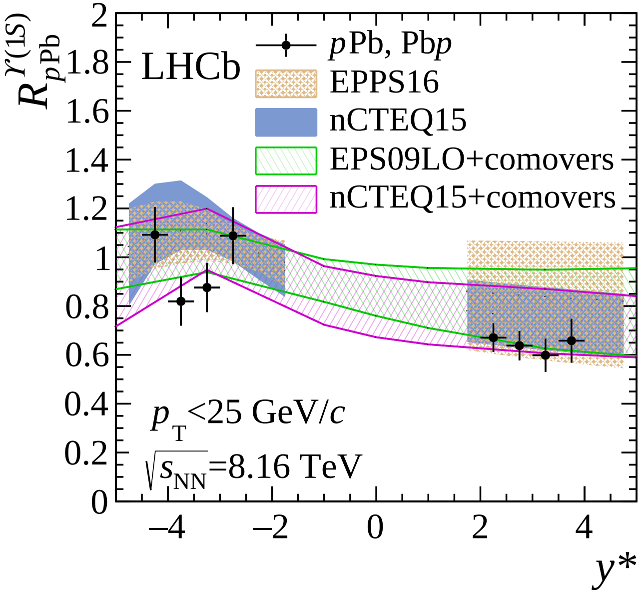
**Backward** **Forward**

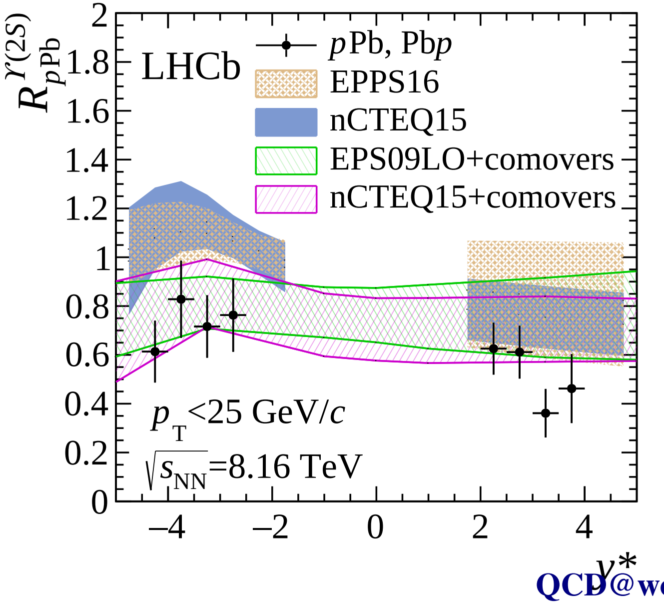



- Clean separation of three nS states

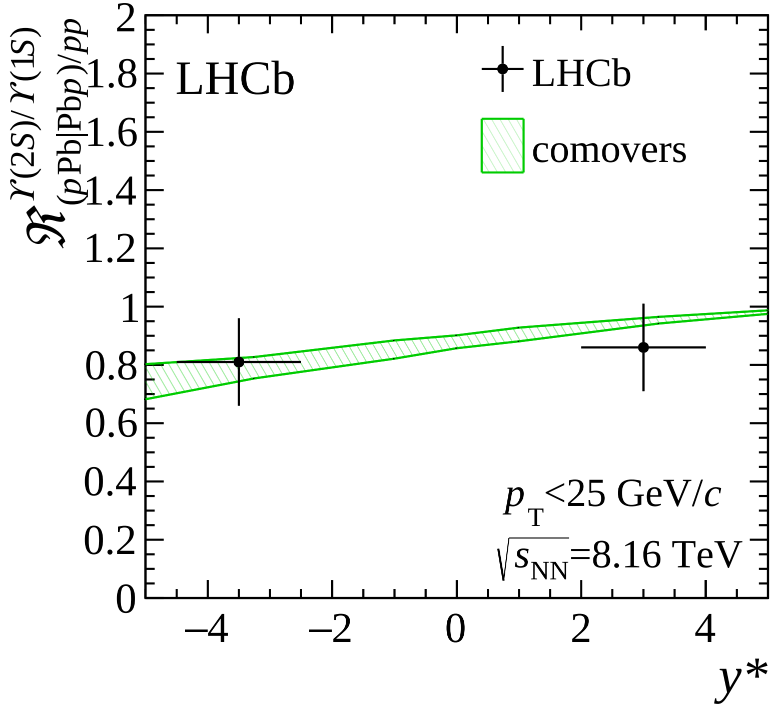
**R for $\Upsilon(1S)$** **R for $\Upsilon(2S)$**



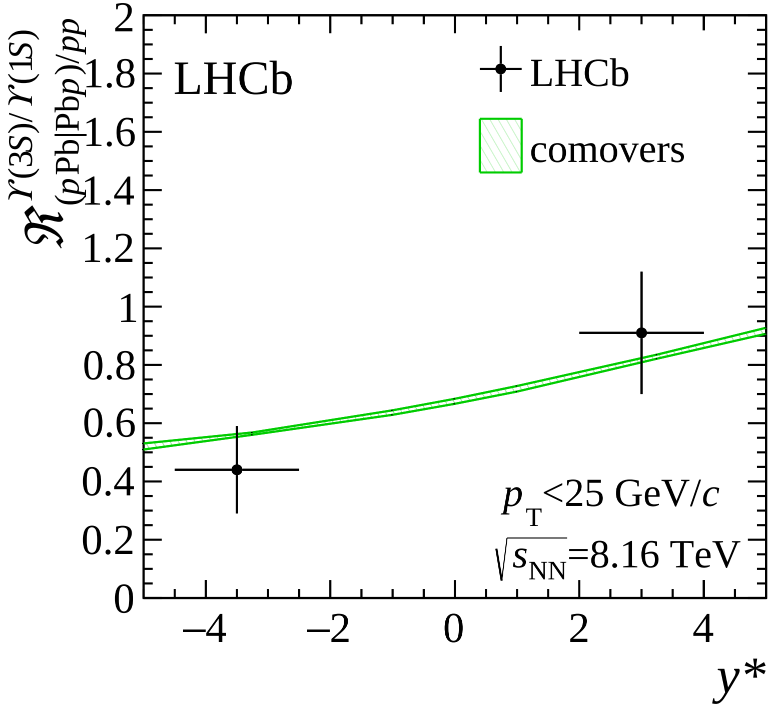




- "Comover" model predicts large final-state effects, larger for excited states and in backward direction
  Ferreiro and Lansberg, JHEP 10 (2018) 094
- Patterns observed in data support this picture…

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



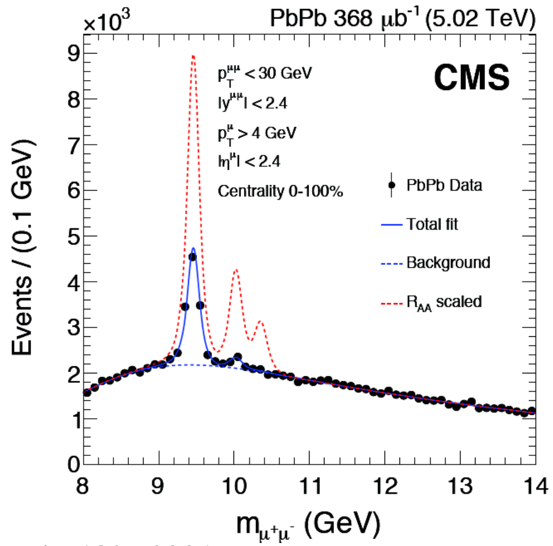

**R($\Upsilon(3S)$)/R($\Upsilon(1S)$)**




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

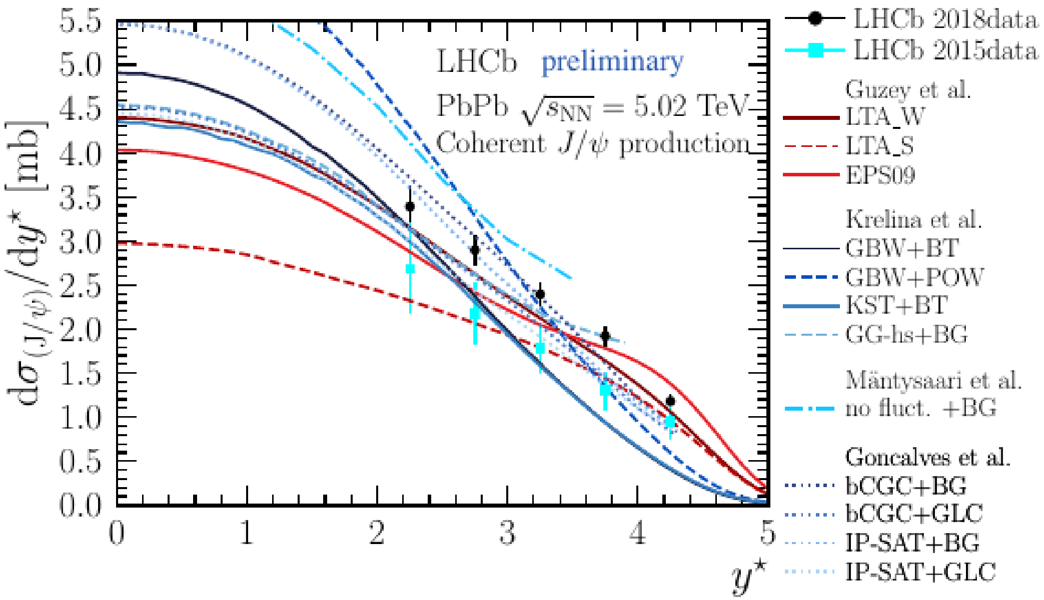
$$\Re^{\Upsilon(2S)/\Upsilon(1S)}_{p\mathrm{Pb}/pp} = 0.86 \pm 0.15,$$
$$\Re^{\Upsilon(3S)/\Upsilon(1S)}_{p\mathrm{Pb}/pp} = 0.81 \pm 0.15,$$
$$\Re^{\Upsilon(2S)/\Upsilon(1S)}_{\mathrm{Pb}p/pp} = 0.91 \pm 0.21,$$
$$\Re^{\Upsilon(3S)/\Upsilon(1S)}_{\mathrm{Pb}p/pp} = 0.44 \pm 0.15.$$

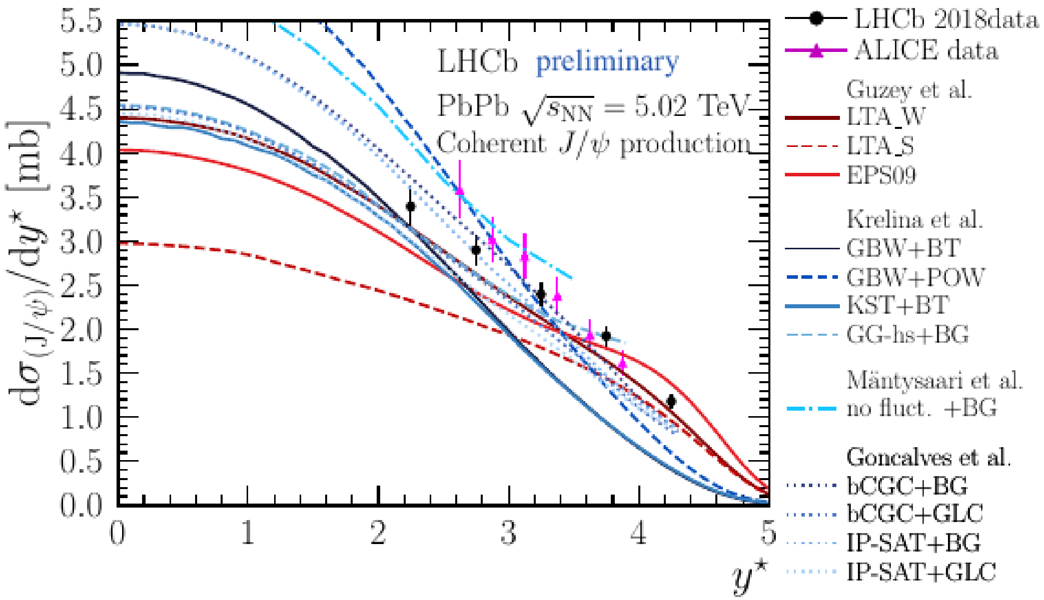
Understanding this effect is crucial to a correct interpretation of QGP-induced sequential quarkonia suppression observed in PbPb




arXiv:1805.09215

# $J/\psi$ in UPC PbPb: comparison with previous results

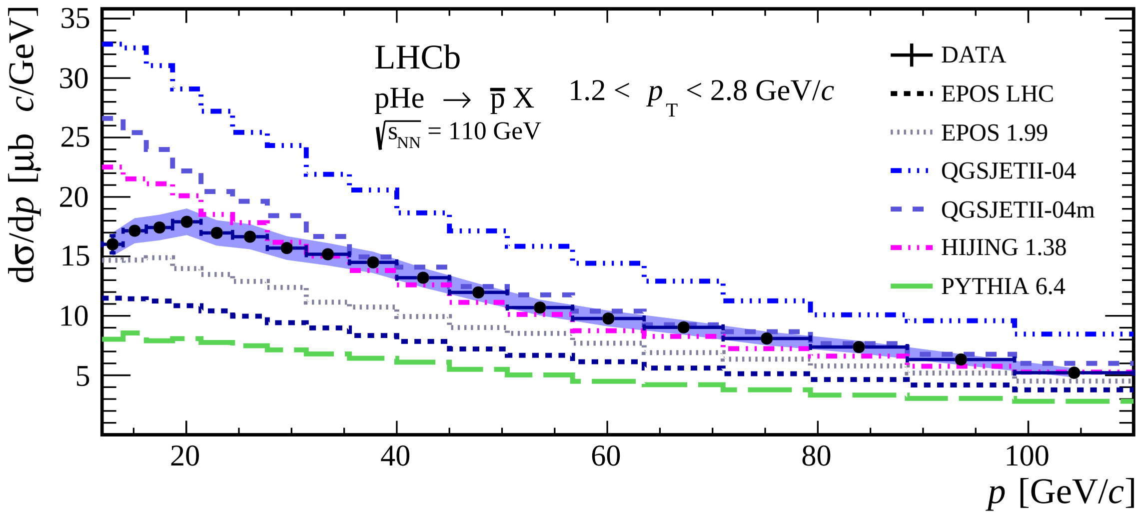



- New results is above the older 2015 measurement by $2.0\sigma$
- Compatible with ALICE data

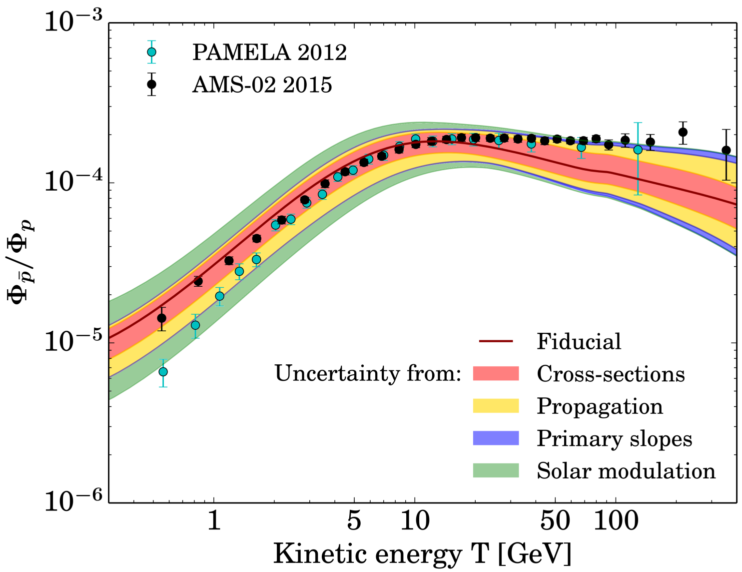
# $p$-He antiproton result

LHCb-PAPER-2018-031PRL 121 (2018), 222001

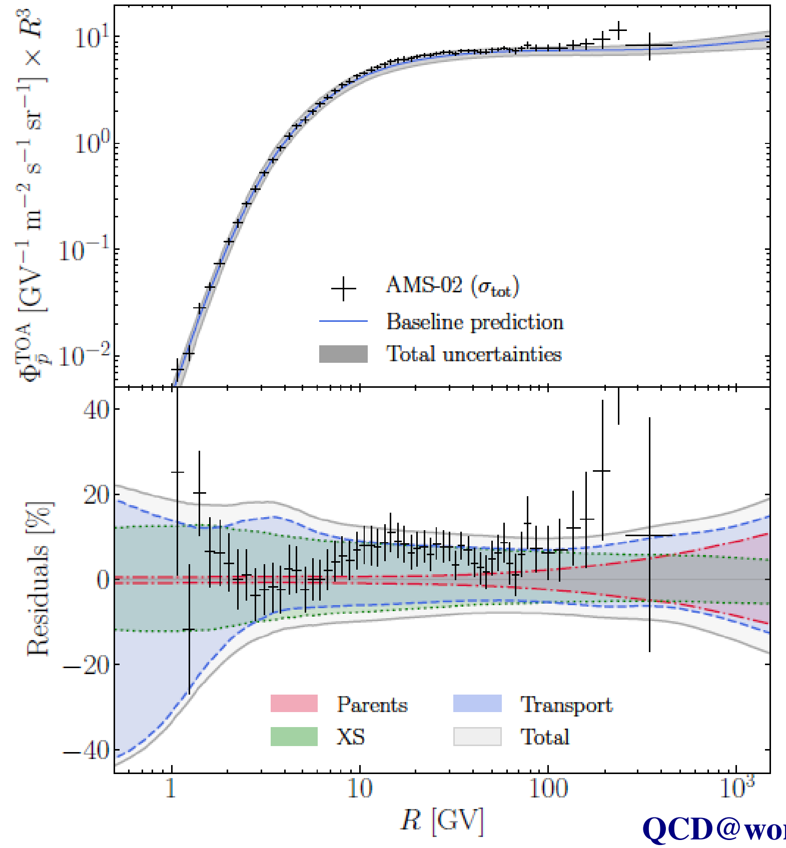



- Result for prompt $\bar{p}$ production
- Accuracy better than 10 %, lower than spread among models

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




**2019** Boudad et al., arXiv:1906.07119




- Significant shrinking of uncertainty for the predicted secondary antiproton flux from the use of LHCb and NA61 ($p$-$p$) new data (plus other improvements)

# The case for LHC Fixed Target

*Concluding slide from C. Vallée (convener of the PBC forum) at EPS 2019 (ECFA session)*

CERN Physics Beyond Colliders

**THE MAIN PBC MESSAGES TO THE EPPSU**

**FOR CERN PROJECTS**

**LHC Fixed-Target opens a worldwide unique domain to both SF and QGP measurements**

***Requires support for full exploitation of its potential on the LHC lifetime***

*from ESPP Update 2020*

European Strategy Update

**Physics Briefing Book**

CERN-ESU-004
30 September 2019

*Input for the European Strategy for Particle Physics Update 2020*

The multi-TeV LHC proton- and ion-beams allow for the most energetic fixed-target (LHC-FT) experiments ever performed opening the way for unique studies of the nucleon and nuclear structure at high $x$, of the spin content of the nucleon and of the nuclear-matter phases from a new rapidity viewpoint at seldom explored energies [117, 118].

On the high-$x$ frontier, the high-$x$ gluon, antiquark and heavy-quark content (e.g. charm) of the nucleon and nucleus is poorly known (especially the gluon PDF for $x \gtrsim 0.5$). In the case of nuclei, the gluon EMC effect should be measured to understand that of the quarks. Such LHC-FT studies have strong connections to high-energy neutrino and cosmic-ray physics.

The physics reach of the LHC complex can greatly be extended at a very limited cost with the addition of an ambitious and long term LHC-FT research program. The efforts of the existing LHC experiments to implement such a programme, including specific R&D actions on the collider, deserve support.