

# QCD AT HIGH TEMPERATURES AND FINITE DENSITIES: HEAVY-ION COLLISIONS



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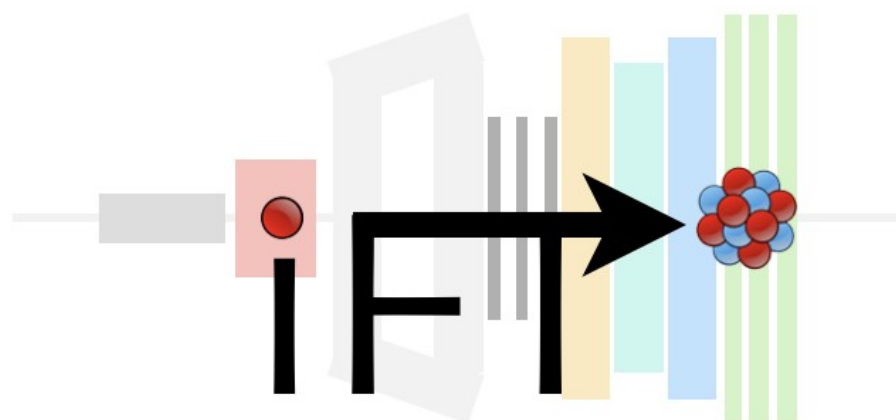
*on behalf of the LHCb Collaboration*

*Excited QCD 2022*

*24-28 October*

*Giardini Naxos, Italy*

*October, 25<sup>th</sup> 2022*

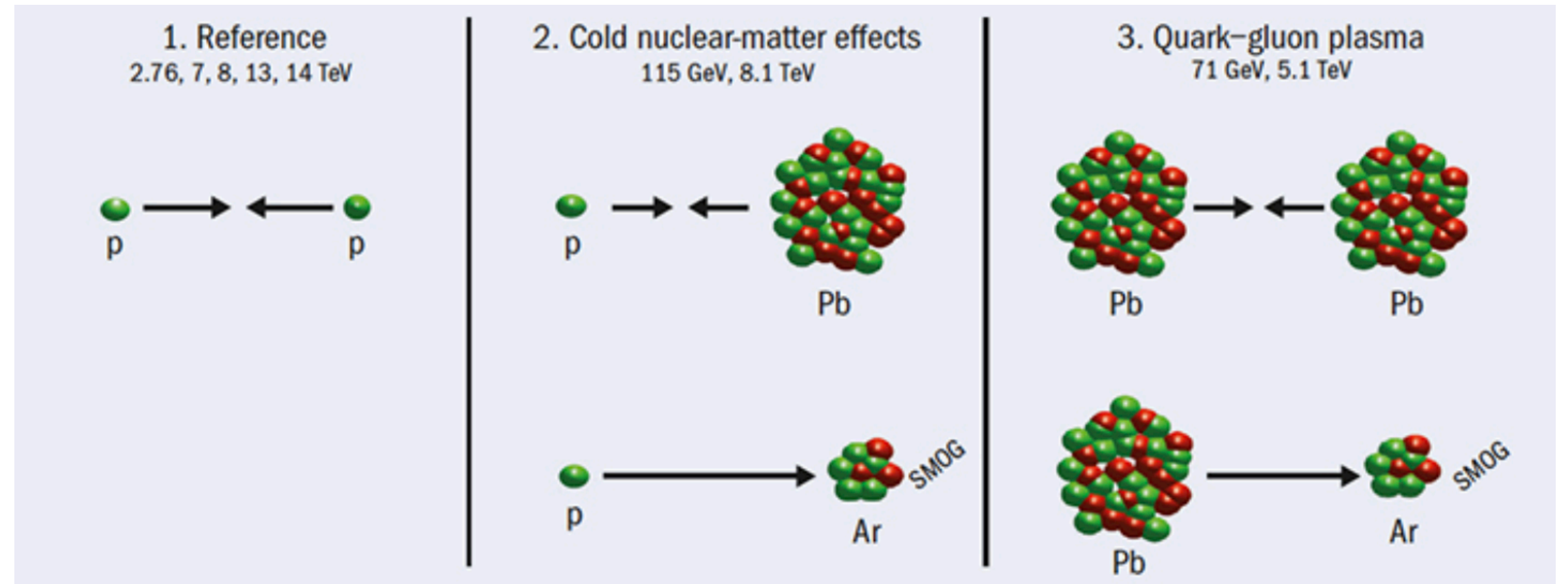
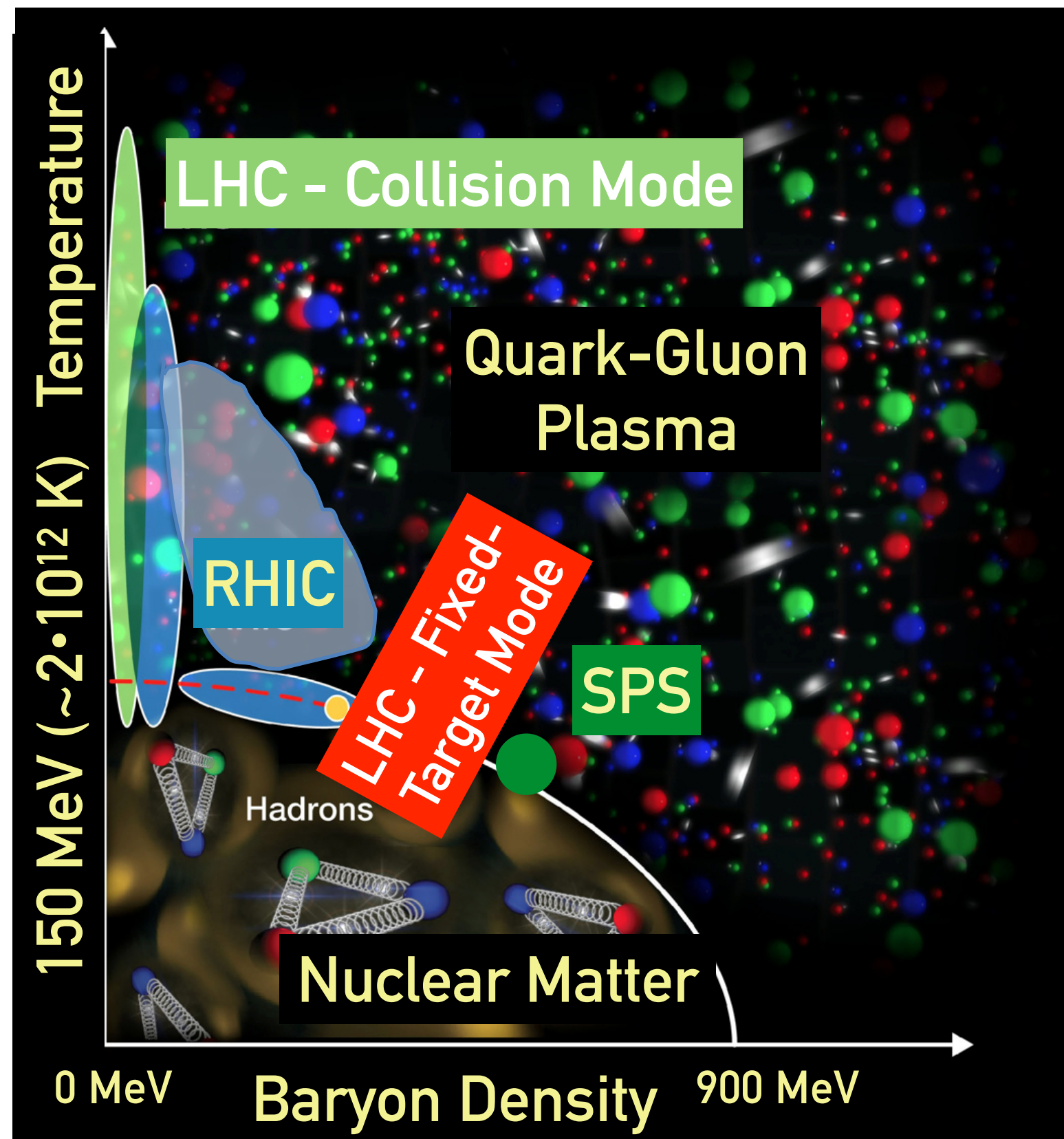


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# INTRODUCTION: HEAVY ION PHYSICS

- At high temperature and density, a plasma of quarks and gluons free from color confinement (Quantum ChromoDynamics, QCD) as in early universe is predicted to form: the **Quark-Gluon Plasma** (QGP)
- QGP can be created with high-relativistic **heavy-ion** (HI) collisions at accelerators

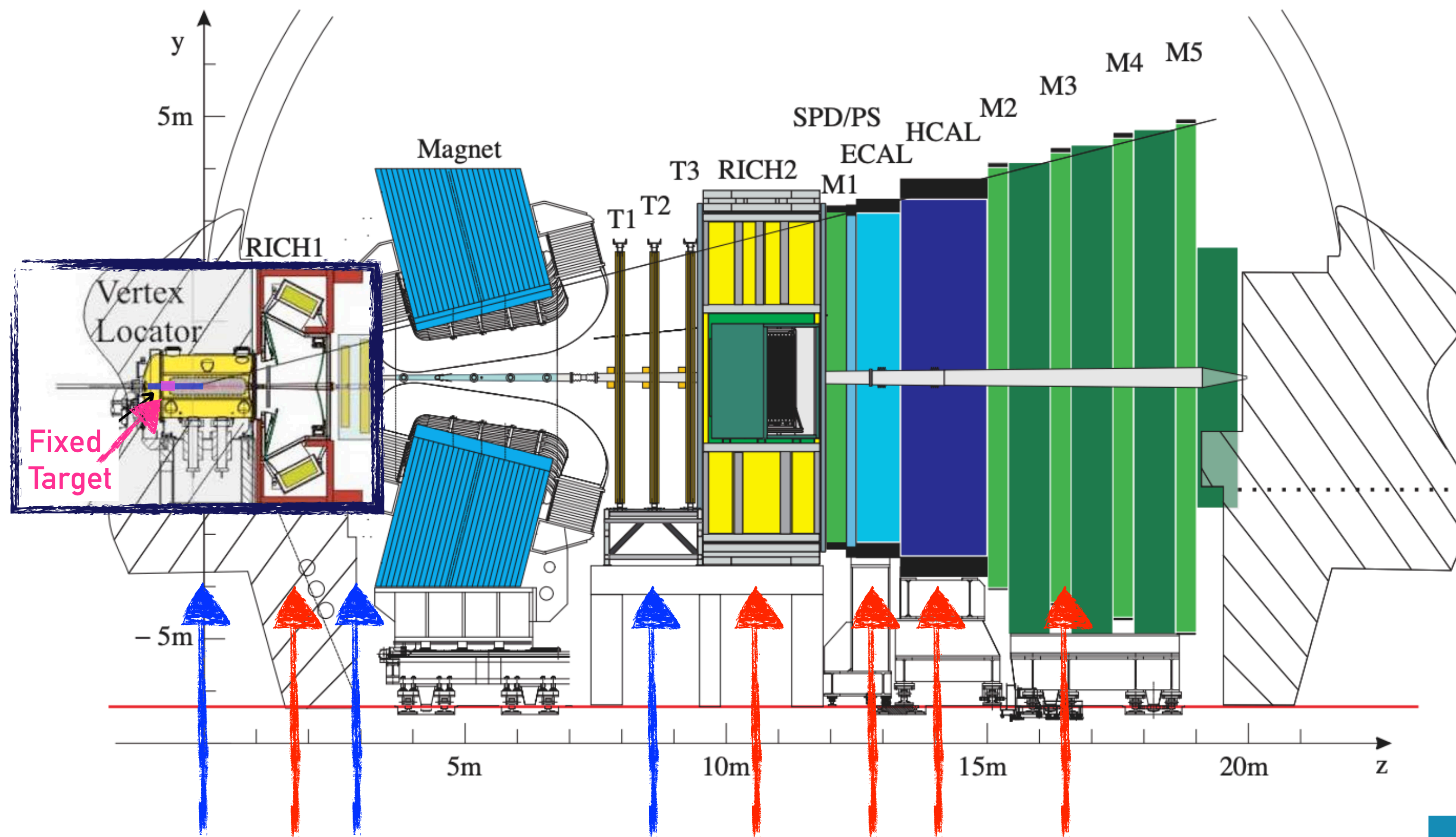


- In order to clearly establish the presence of QGP is important to study also collisions where QGP is not formed
- Many experiments study HI collisions and LHCb is one of those at different  $\sqrt{s}$

# INTRODUCTION: THE LHCb EXPERIMENT

JINST 3 (2008) S08005

- Single arm forward spectrometer originally devoted to **heavy flavour** physics, now a general purpose experiment with unique coverage  $2 < \eta < 5$  (QCD, SM, heavy ion and fixed-target)



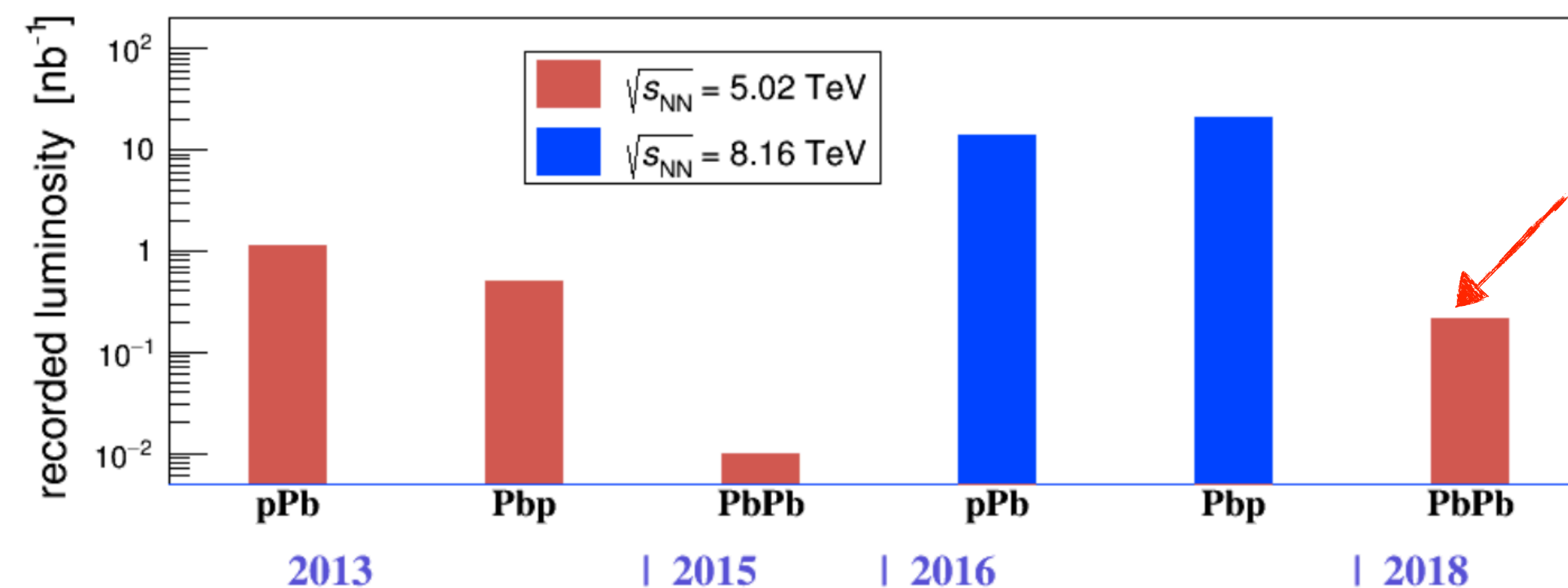
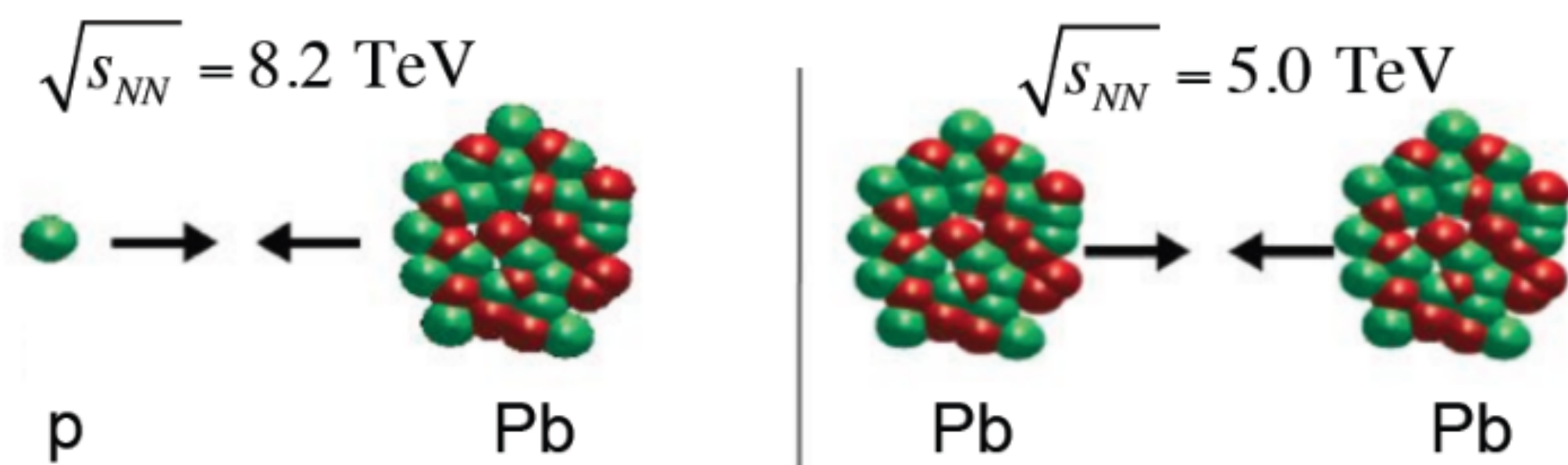
- pp/pPb/PbPb and fixed target mode
- Excellent vertexing, tracking, Particle Identification (PID)
  - **Tracking system**: optimal resolution for IP (10-80  $\mu\text{m}$ ) and momentum ( $< 1.0\%$  for  $p < 200 \text{ GeV}/c$ )
  - **PID**: excellent  $e, \mu, \pi, K, p, \gamma$  identification
- Trigger: high flexibility and bandwidth (1 MHz hardware; 15 kHz to disk)

→ Large variety of possible measurements!

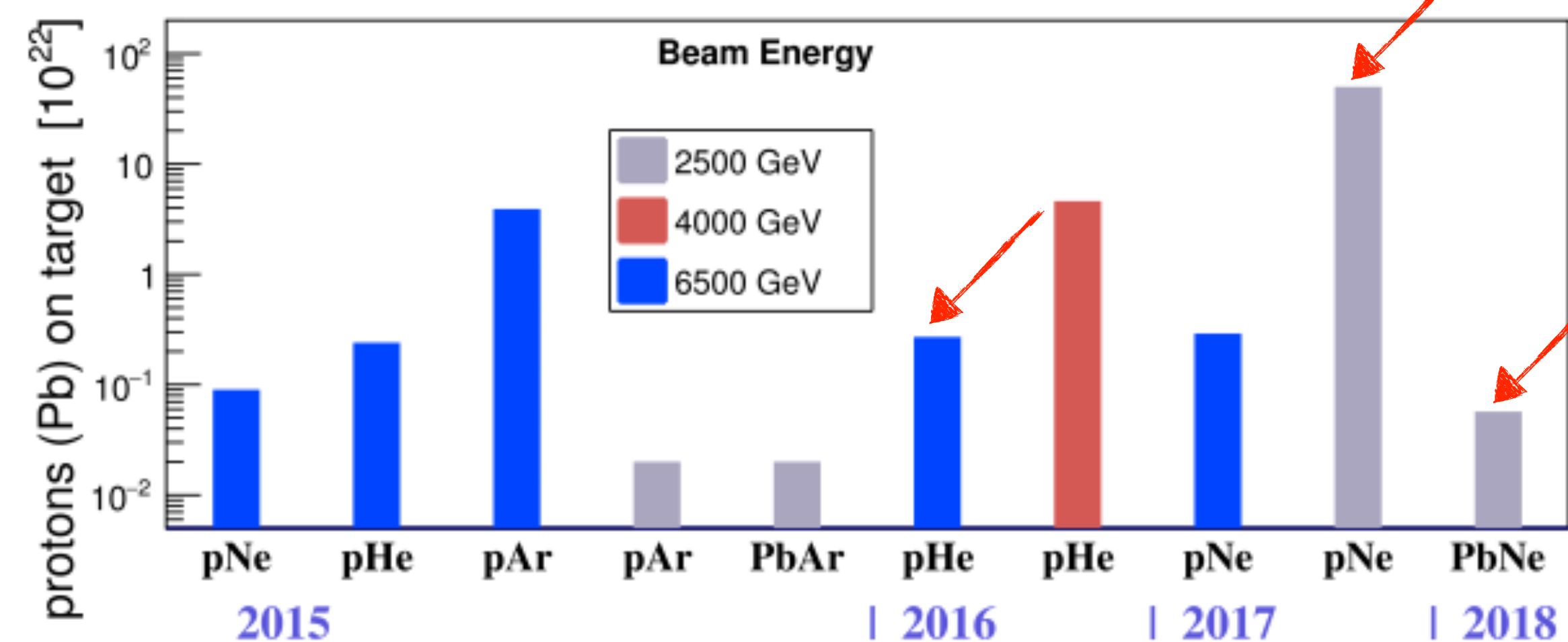
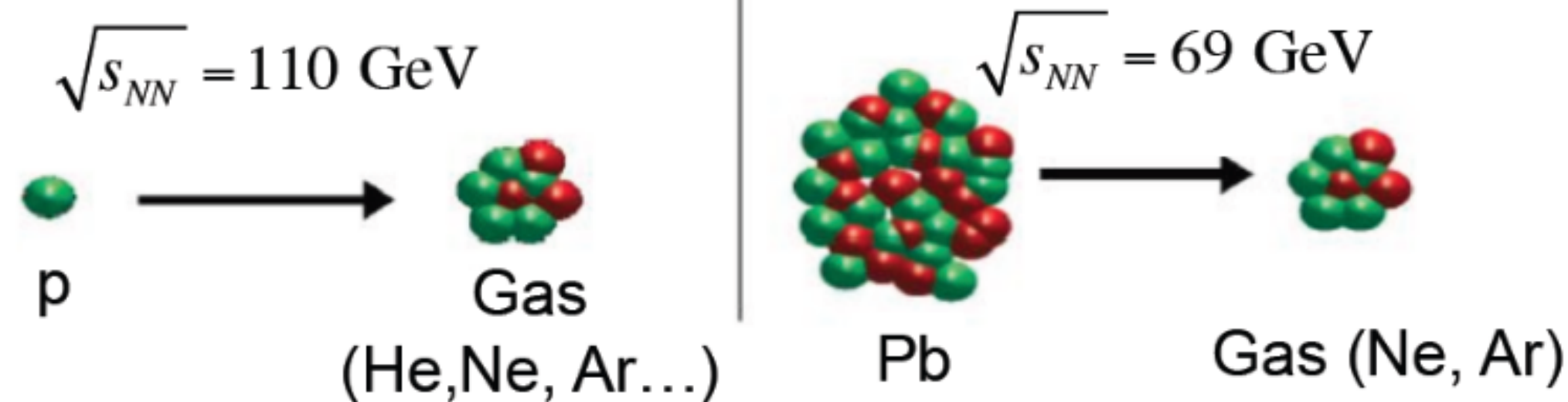
# INTRODUCTION: RUN 2 SAMPLES

- Large variety of samples
- LHCb can run in collider and fixed-target mode simultaneously

## Collider Mode Samples



## Fixed-Target Mode Samples



# OVERVIEW OF RECENT RESULTS FROM HEAVY IONS

## ➤ *p-p, p-Pb collisions:*

→ **b hadrons in *p-p* @ 13 TeV**

[arXiv:2204.13042](https://arxiv.org/abs/2204.13042)

→ **Z production in *p-Pb* @ 8 TeV**

[arXiv:2205.10213](https://arxiv.org/abs/2205.10213), accepted by JHEP

→  **$D^0$  production in *p-Pb* @ 8 TeV**

[arXiv:2205.03936](https://arxiv.org/abs/2205.03936)

→ **Charged particle production in *p-Pb* @ 5 TeV**

[PRL 128\(2022\) 142004](https://arxiv.org/abs/2205.03936)

→  **$\pi^0$  production in *p-Pb* @ 8 TeV**

[arXiv:2204.10608](https://arxiv.org/abs/2204.10608), accepted by PRL

→  **$\chi_{c1}$  (3872) production in *p-p* and *p-Pb* @ 8 TeV**

[LHCb-CONF-2022-001](https://arxiv.org/abs/2204.10608)

## ➤ **Pb-Pb collisions @ 5 TeV:**

→  **$\Lambda_c^+/D^0$  ratio in peripheral collisions**

[arXiv:2210.06939](https://arxiv.org/abs/2210.06939)

→ **Quarkonia photoproduction in Ultra-Peripheral Collisions**

[arXiv:2206.08221](https://arxiv.org/abs/2206.08221)

## ➤ **Fixed-target collisions:**

→ **Detached antiprotons in *p-He* @ 110 GeV**

[arXiv:2205.09009](https://arxiv.org/abs/2205.09009)

→ **Charm production in *p-Ne* and *Pb-Ne* @ 68.5 GeV**

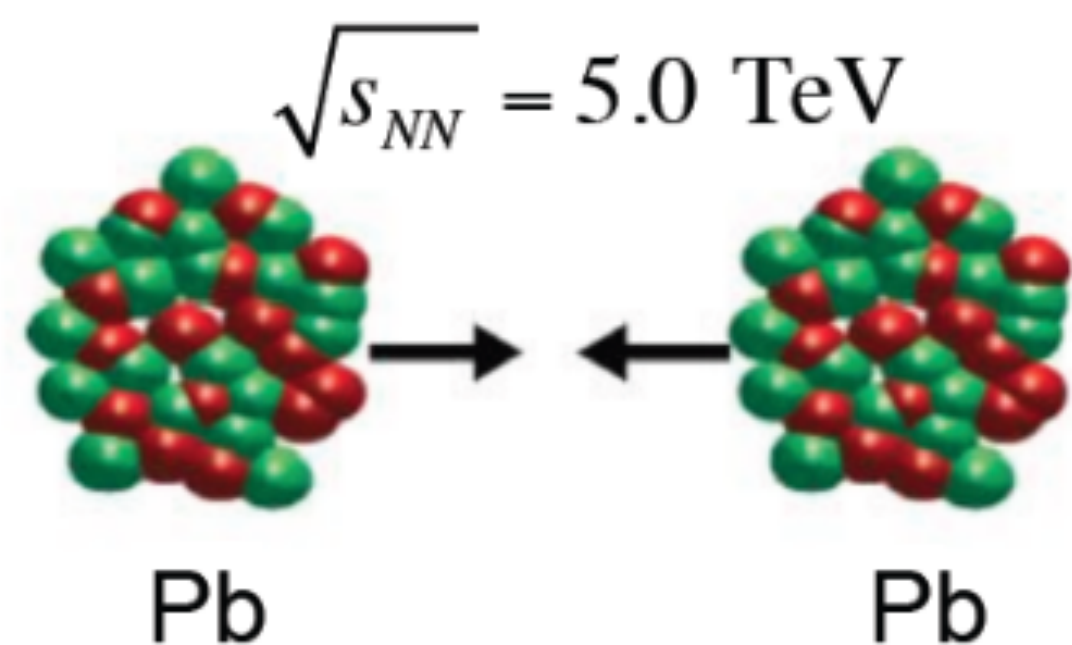
LHCb-PAPER-2022-014, in preparation

LHCb-PAPER-2022-011, in preparation

# Pb–Pb COLLISIONS RESULTS

# Pb-Pb COLLISIONS

- Pb-Pb samples @ 5.02 TeV:  
→ 2018 with  $L \sim 210 \mu\text{b}^{-1}$



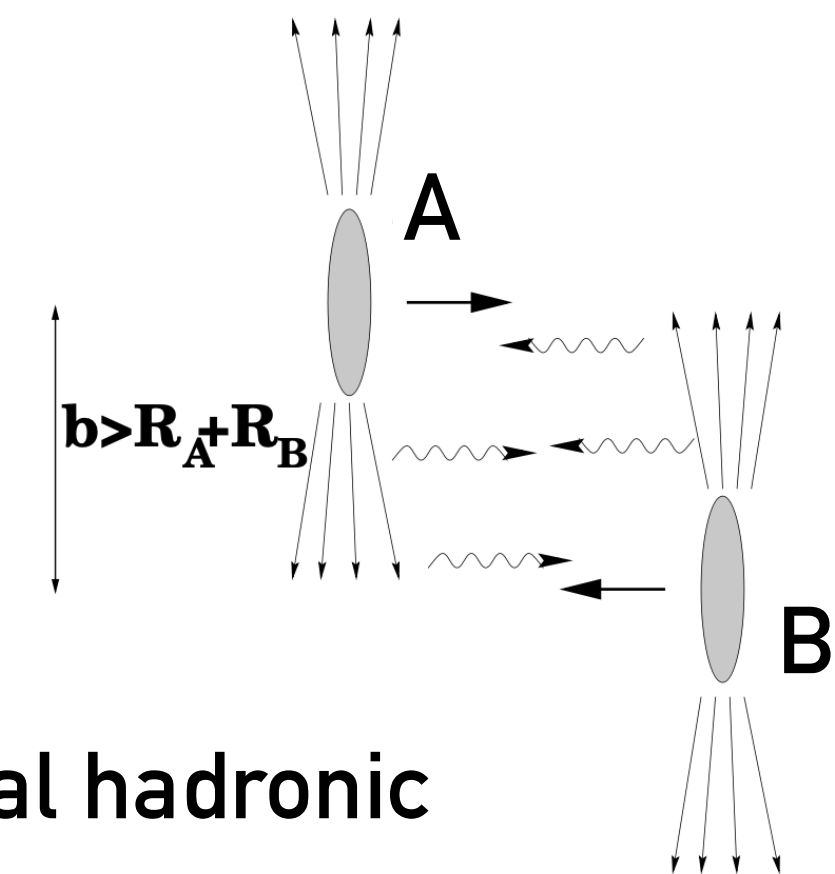
Pb-Pb data were acquired in the 60-100% centrality range, limited because of the hardware saturation due to the high track density in the forward region

- Physics from **peripheral** and **Ultra-Peripheral Collisions (UPC)**

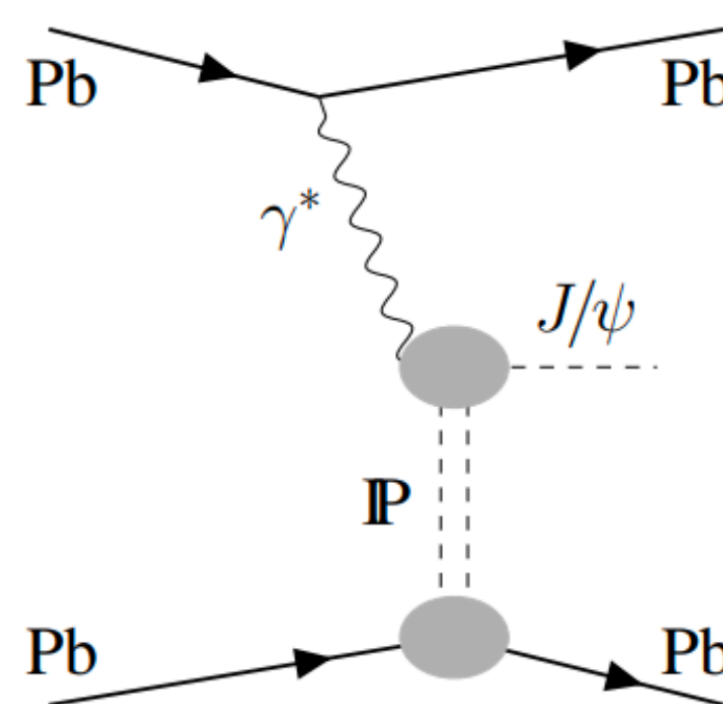
→ Impact parameter:

- $b < 2R_{Pb}$  for peripheral collisions
- $b > R_A + R_B$  for UPC

- UPC: interaction between two nuclei with no actual hadronic collisions → photon exchange

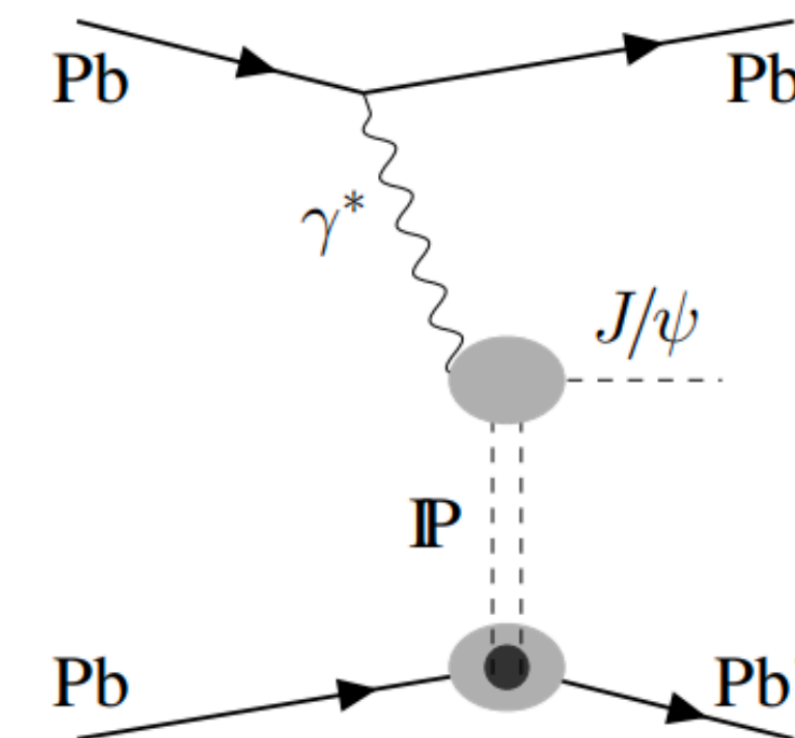


- **Coherent** quarkonia production:



photon interacts with the whole nucleus coherently → **constraint on gluon PDF**

- **Incoherent** production:

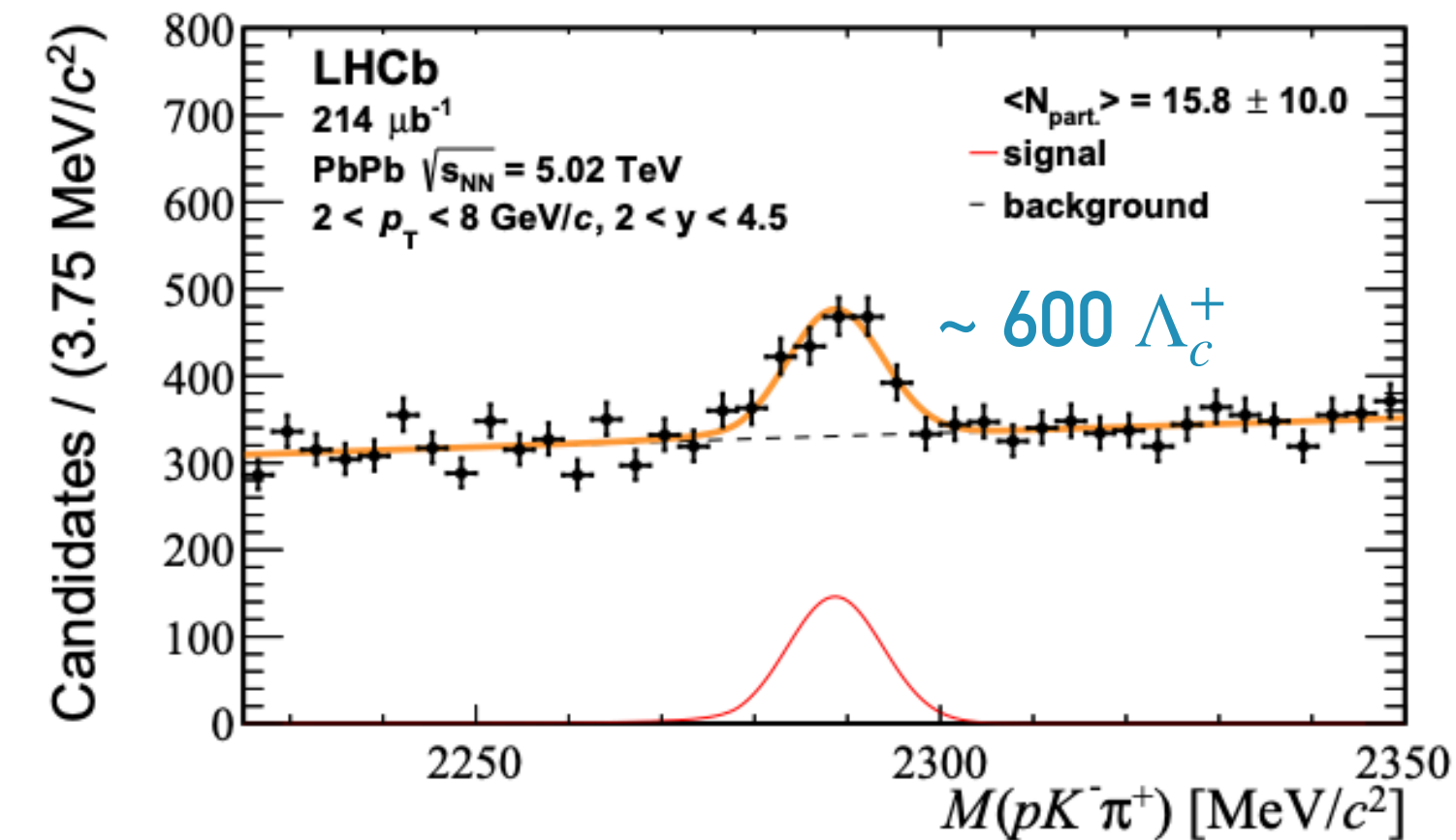
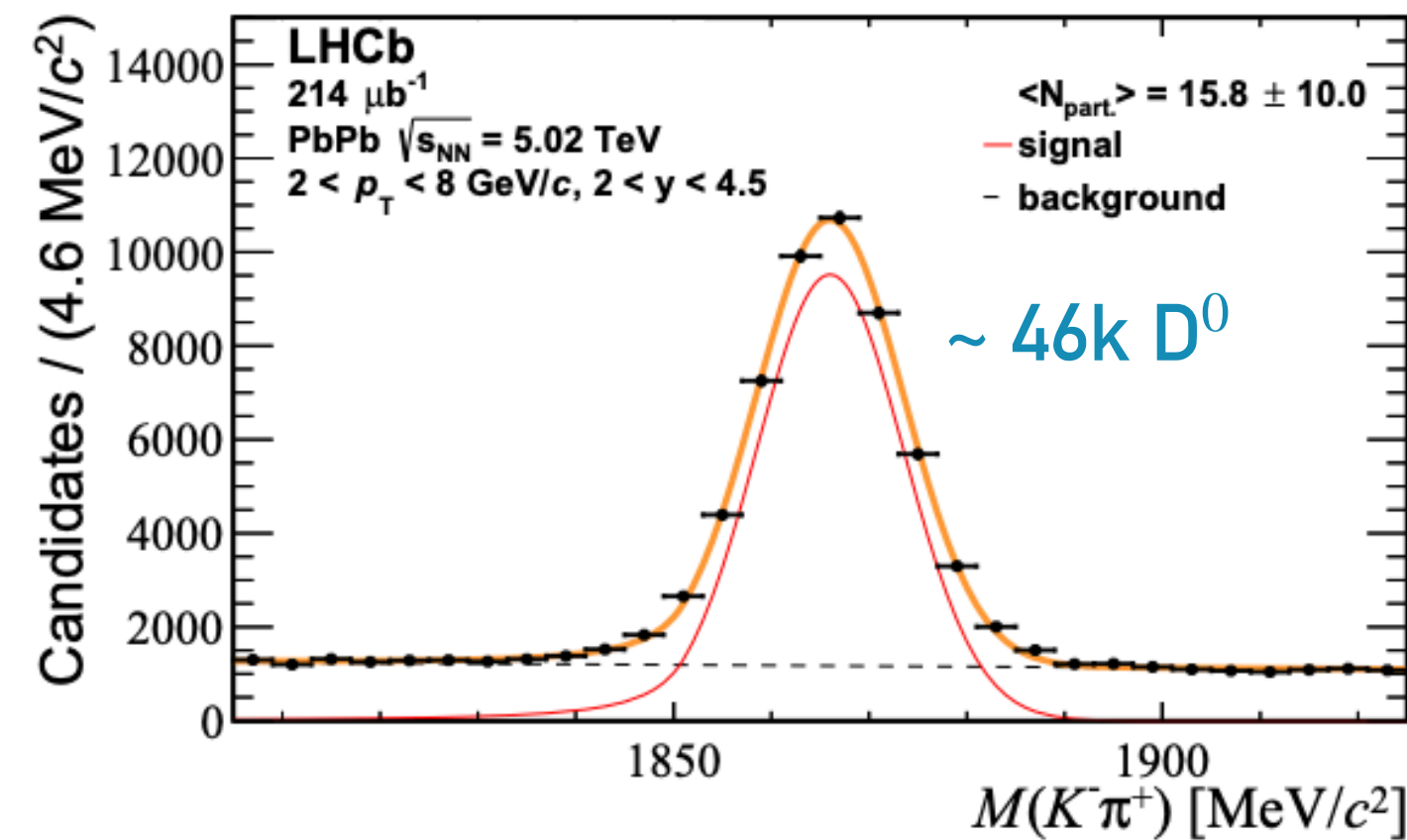


photon interacts with particular nucleons in the nucleus → **constraint on vector meson wave function in dipole scattering models**

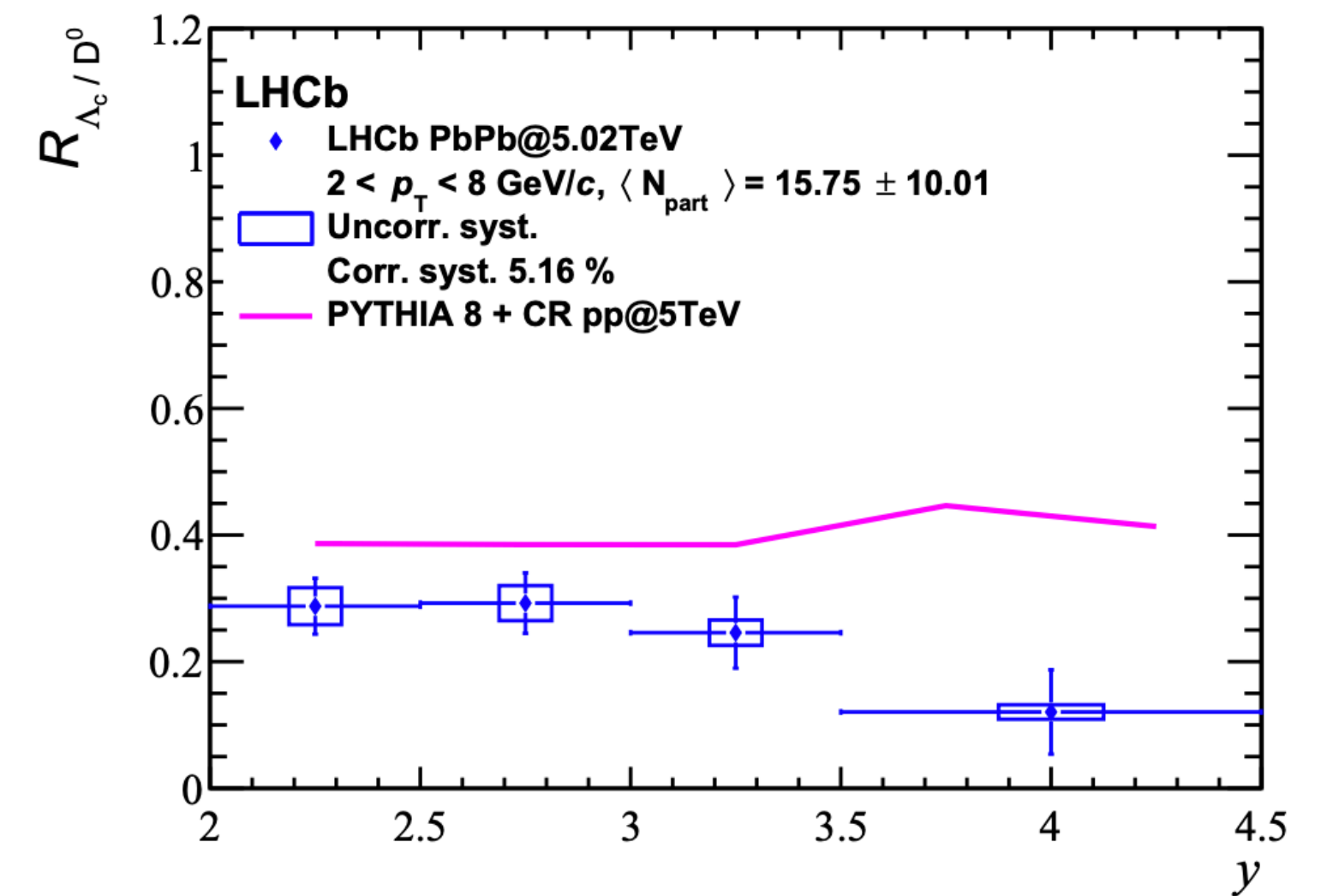
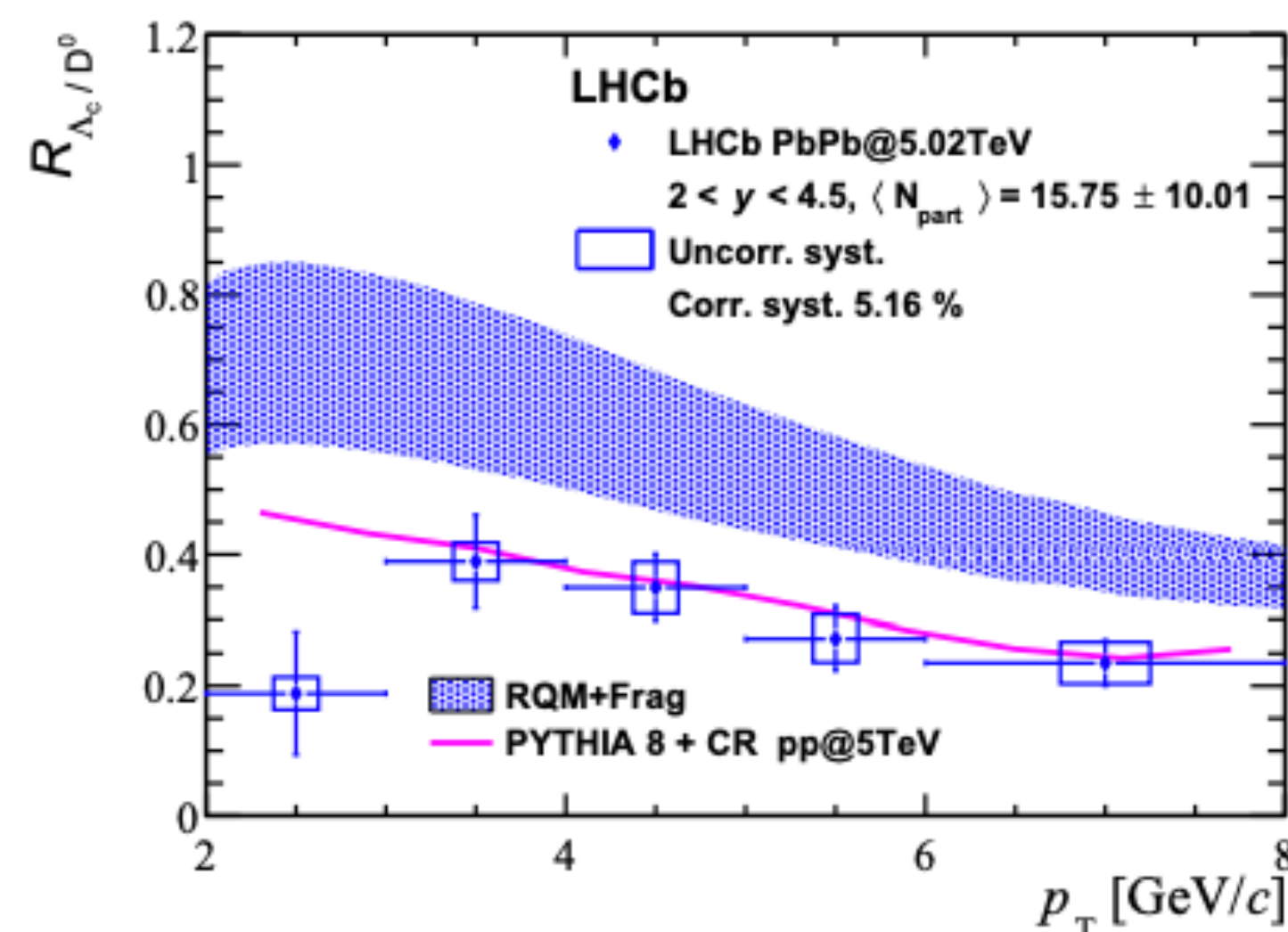
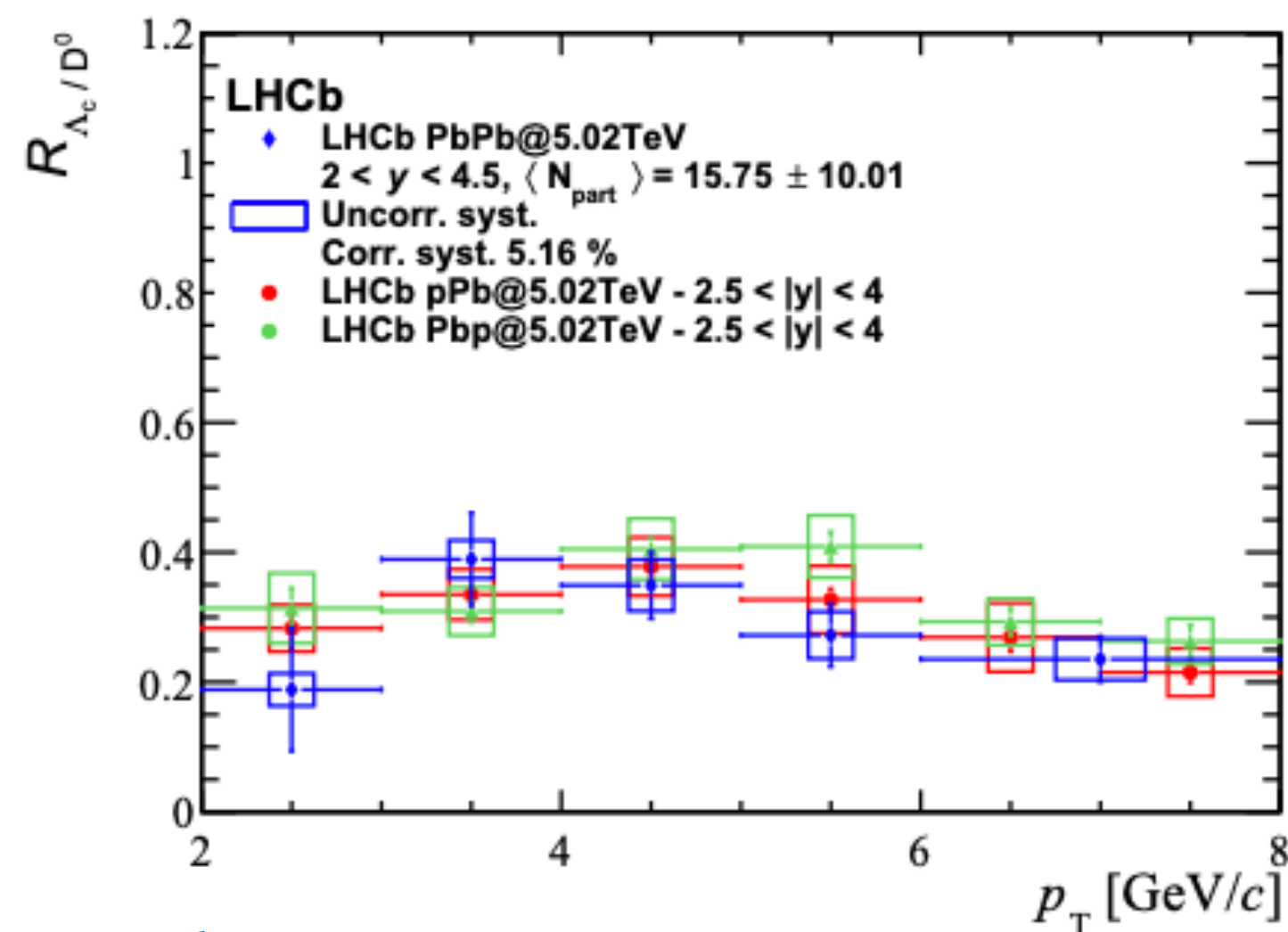
# Pb-Pb COLLISIONS: $\Lambda_c^+/D^0$ RATIO

arXiv:2210.06939

- **Motivation:** to probe the hadronisation of the  $c$ -quark by measuring  $\Lambda_c^+/D^0$  ratio in 65-90% centrality Pb-Pb collisions



- Results are consistent with previous LHCb measurements in  $p$ -Pb collisions @ 5.02 TeV
- Compatibility with PYTHIA 8 in  $p$ - $p$  collisions @ 5.02 TeV including colour recombination except at low  $p_T$ ; Tension with Statistical Hadronisation Model
- Ratio vs rapidity: **suggests a rapidity dependence?**

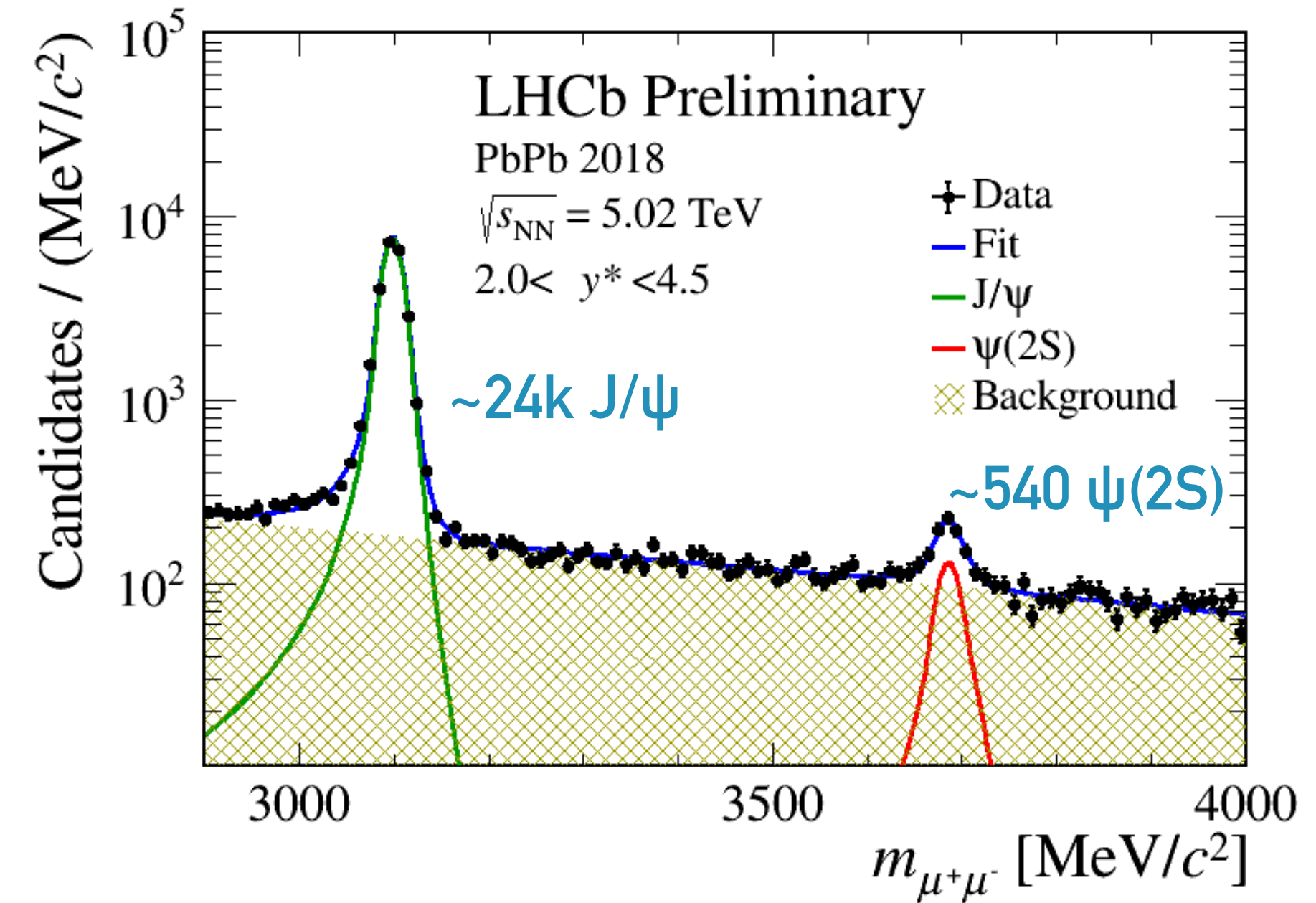




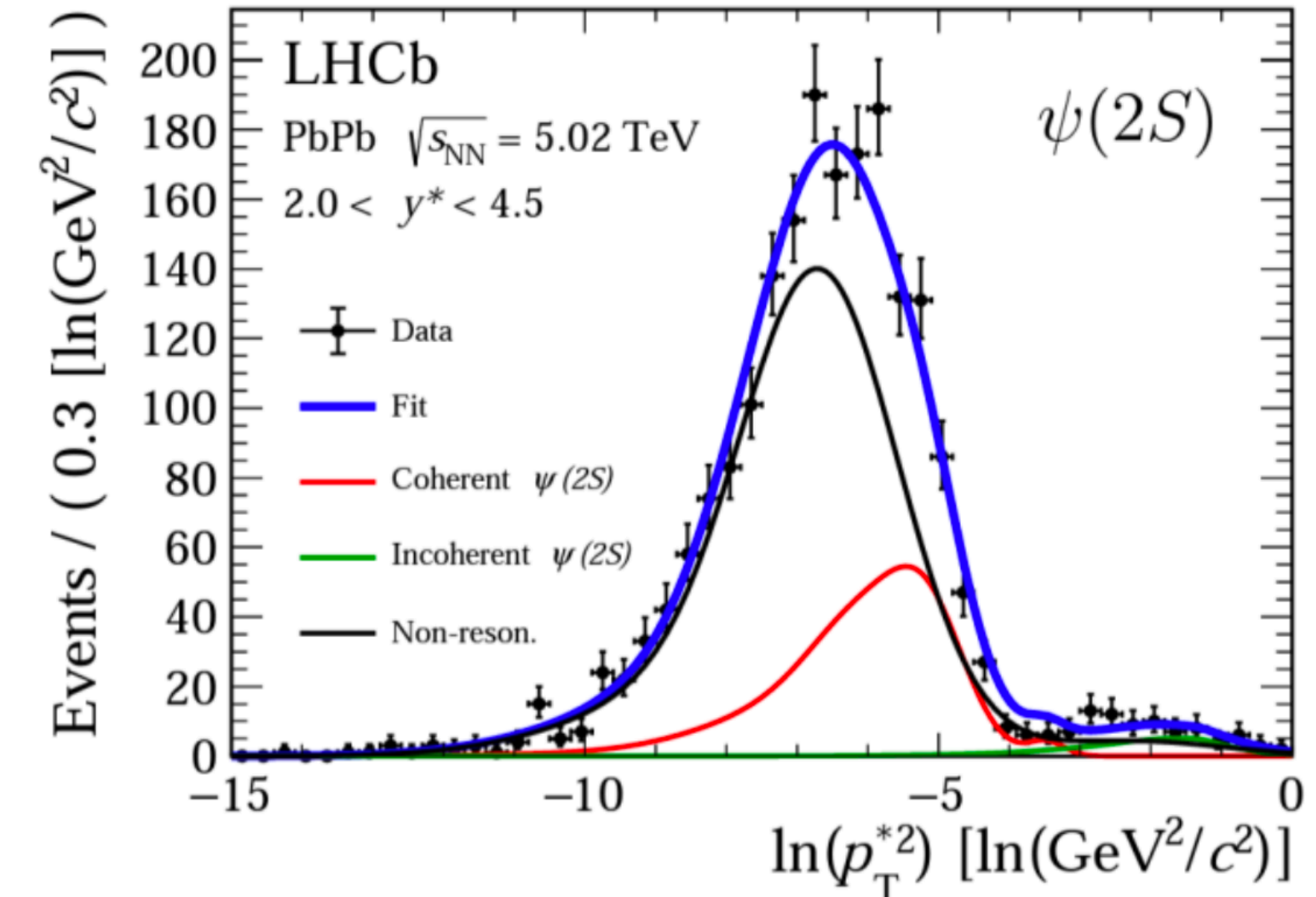
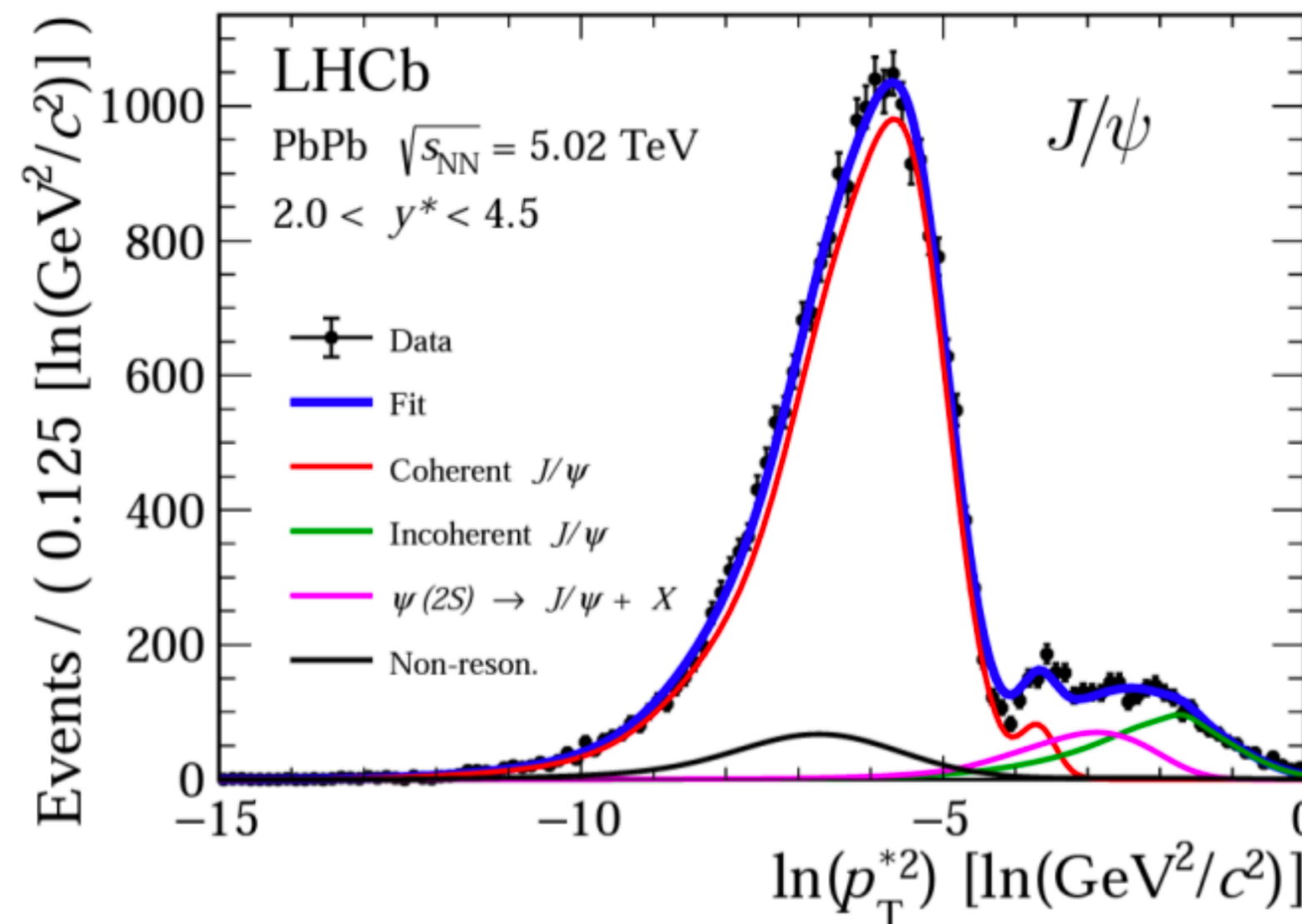
# Pb-Pb COLLISIONS: QUARKONIA PHOTOPRODUCTION

arXiv:2206.08221

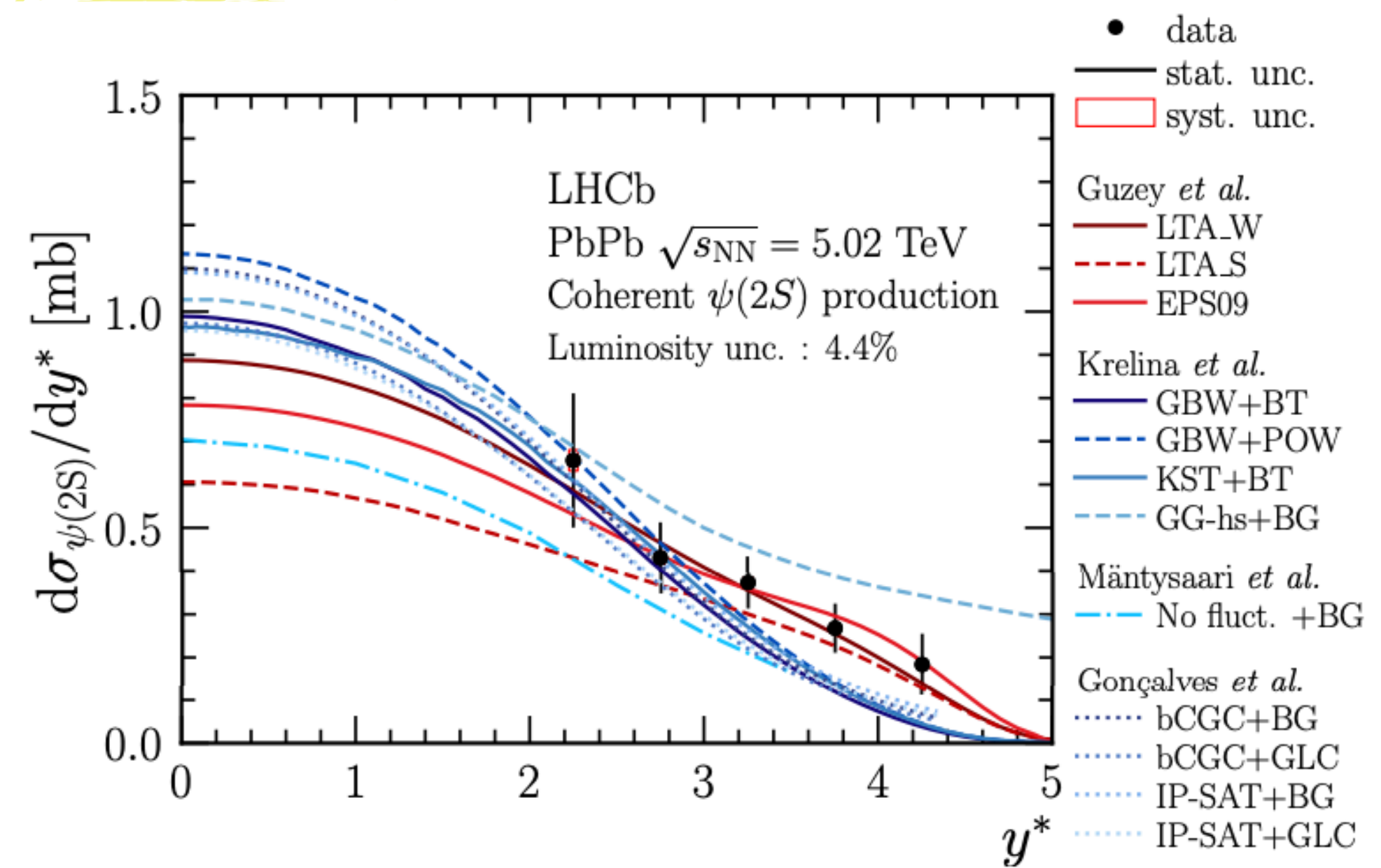
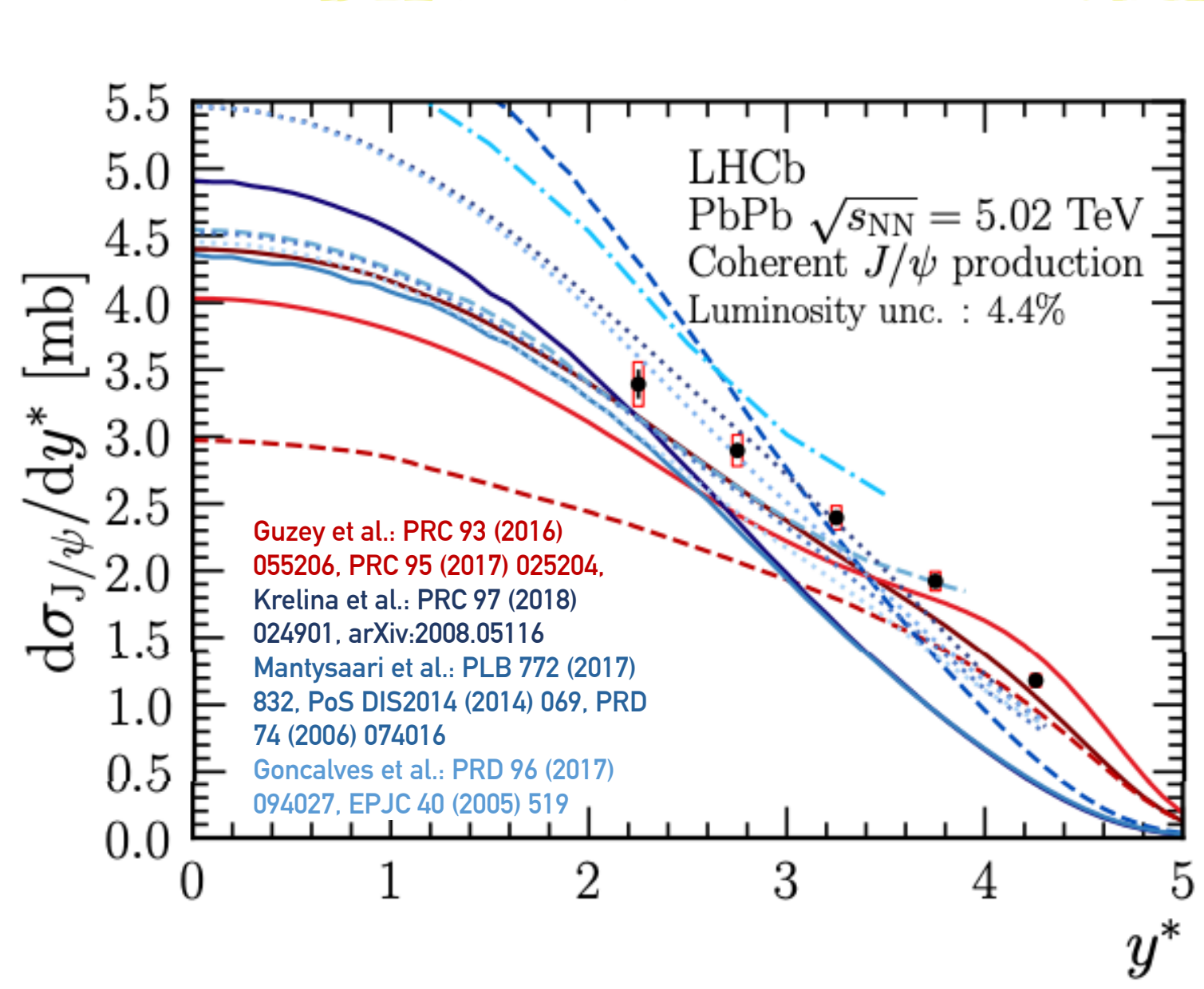
- Charmonium yields are extracted from dimuon mass fit
- Photoproduction of both  $J/\psi$  and  $\psi(2S)$  vs  $p_T$   
→ their production constraints the gluon PDF
- Both signal contain coherent and incoherent produced candidates  
→ the coherent part is extracted from a  $\ln(p_T^{*2})$  fit



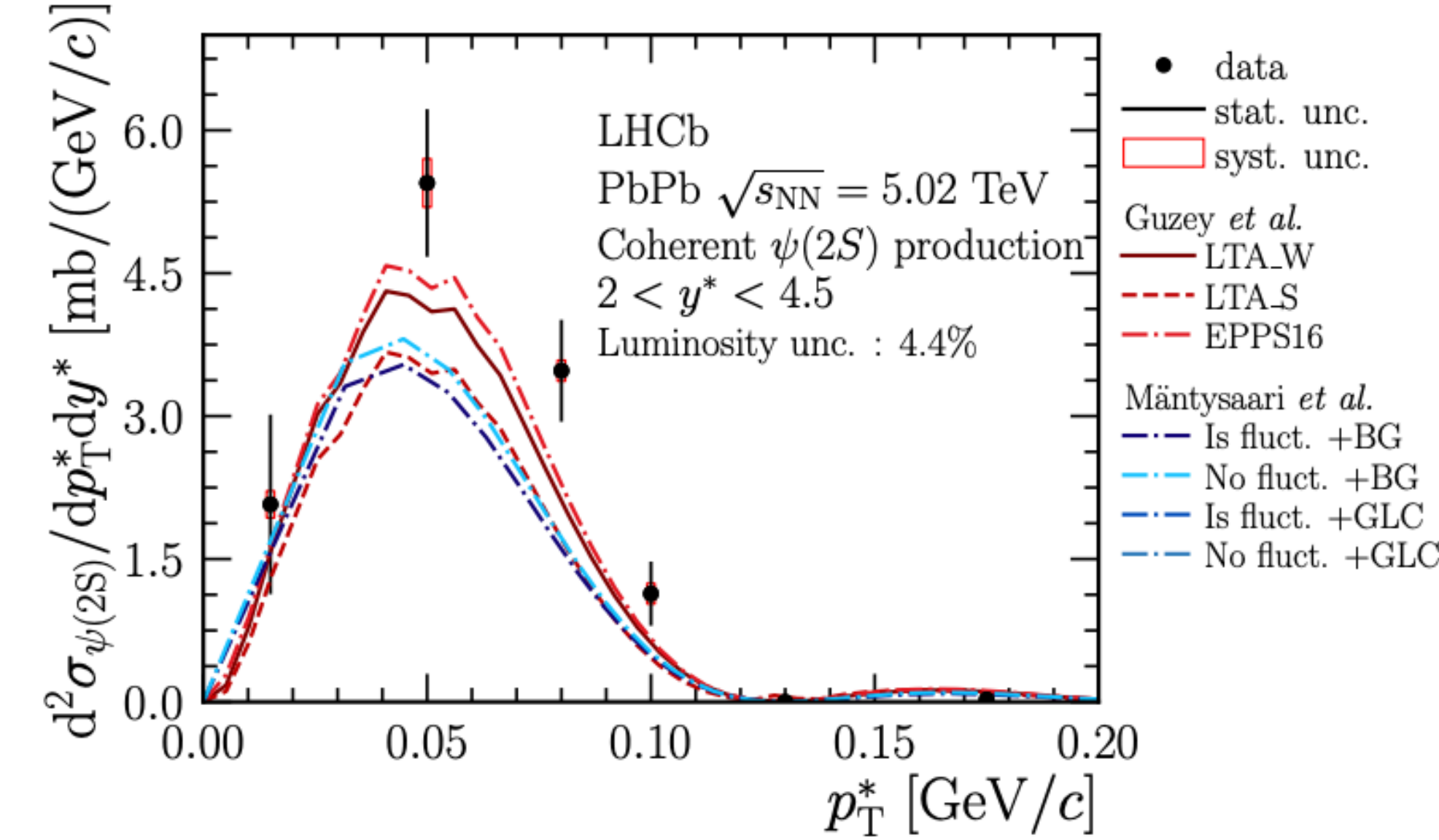
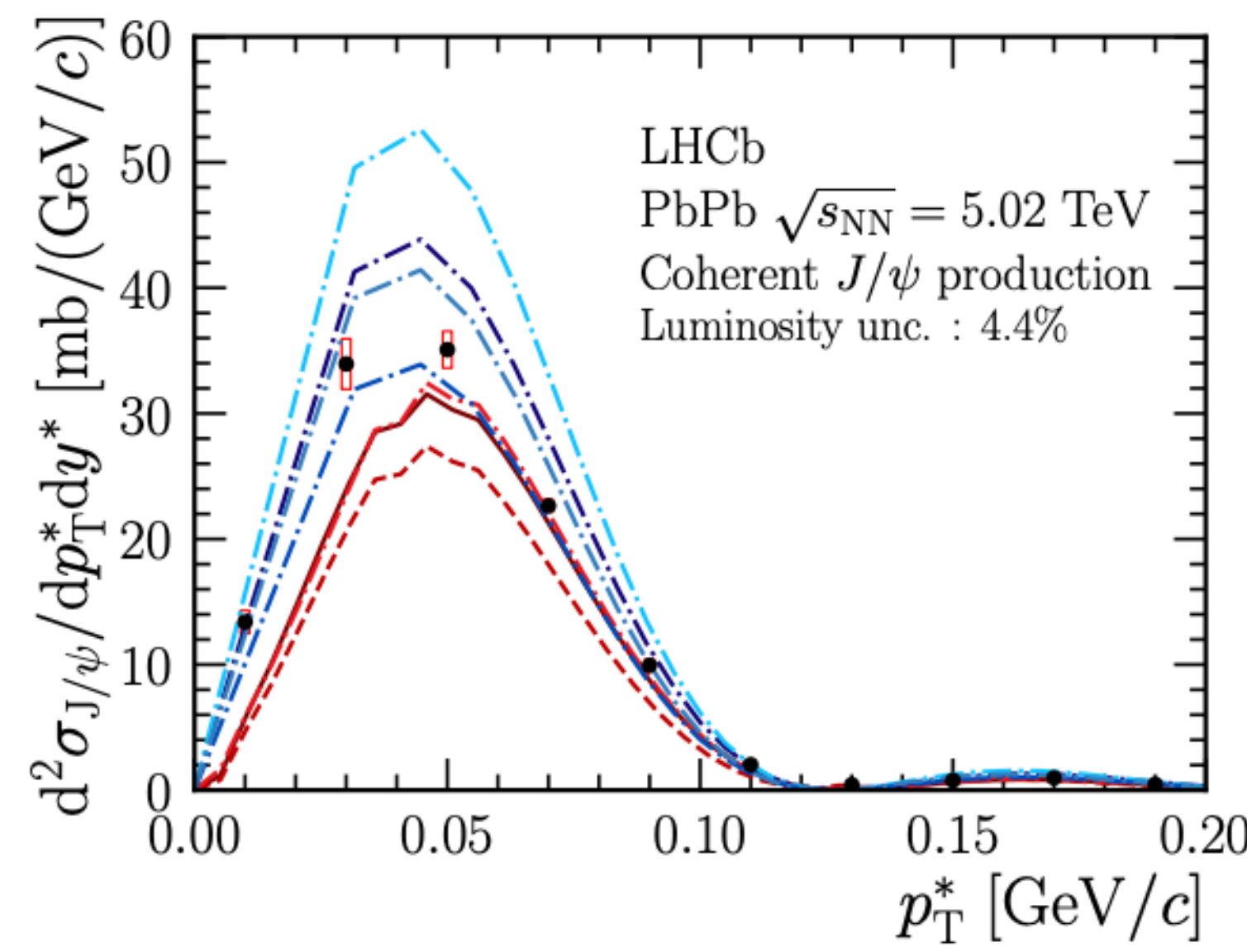
Really precise measurement of coherent  $J/\psi$  and  $\psi(2S)$  production in UPC Pb-Pb collisions 2018 thanks to  $p_T$  resolution



# Pb-Pb COLLISIONS: QUARKONIA PHOTOPRODUCTION



- Differential cross-section vs rapidity (compared to CGC and models using different nPDFs)
  - The most precise measurement for coherent  $J/\psi$  production in Pb-Pb UPC in the forward rapidity today
  - First coherent  $\psi(2S)$  measurement in forward rapidity region at the LHC



- Differential cross-section vs charmonium  $p_T$  (compared to CGC and models using different nPDFs)
  - The first and most precise measurement of the coherent  $J/\psi$  and  $\psi(2S)$  production cross section vs  $p_T$  in Pb-Pb UPC today

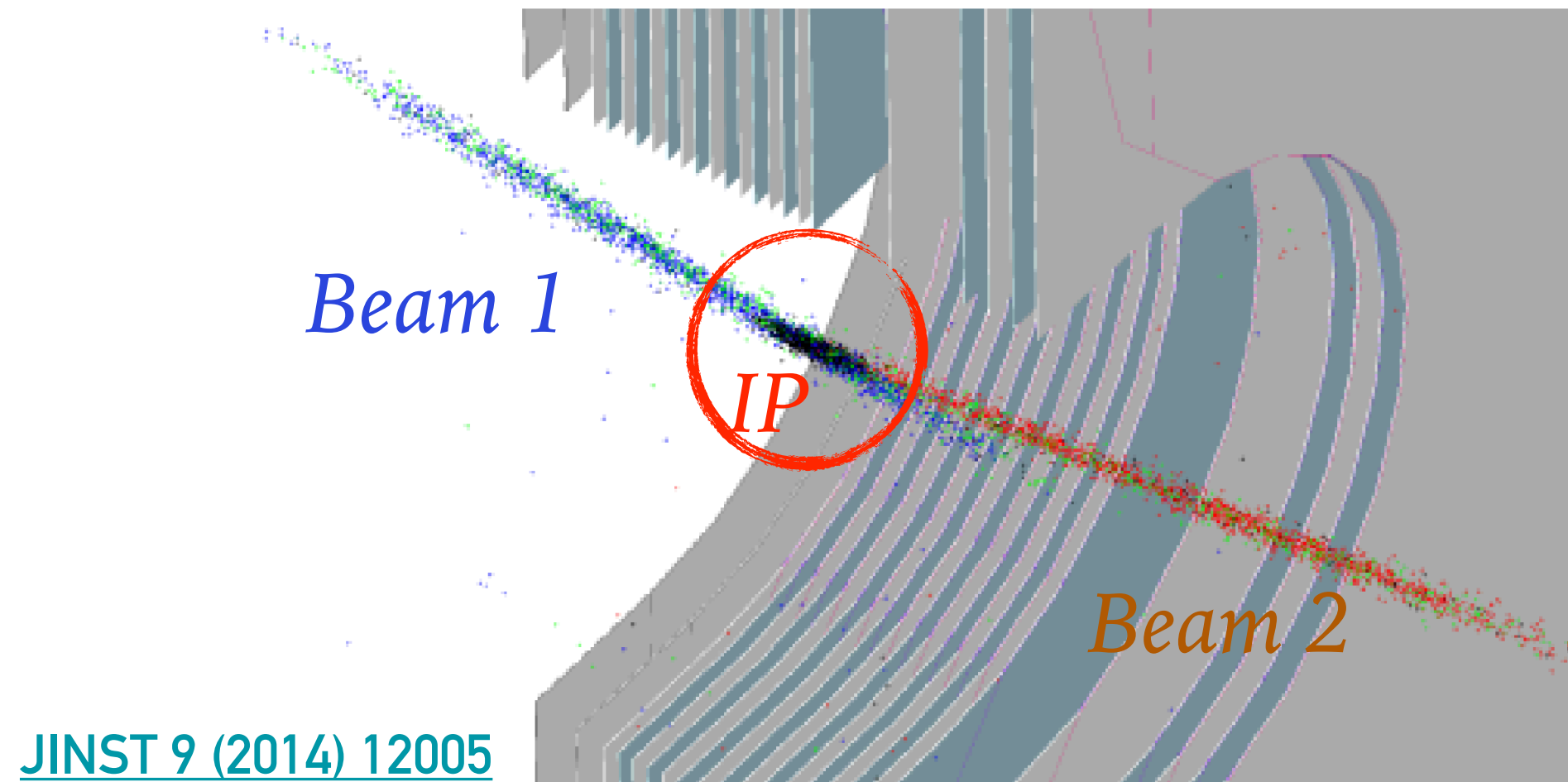
# FIXED-TARGET COLLISIONS RESULTS

# FIXED-TARGET COLLISIONS: SMOG

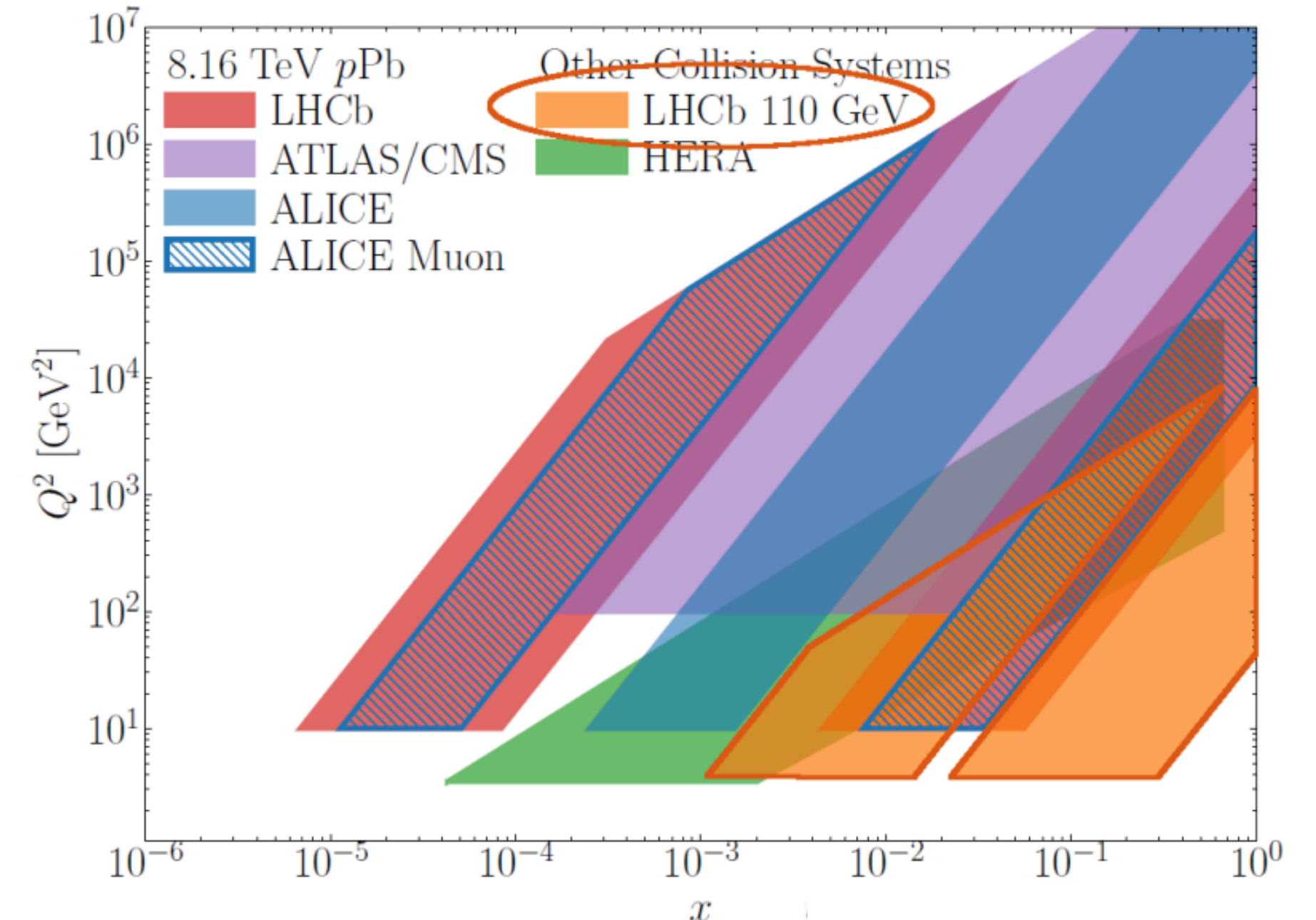
- SMOG: **S**ystem for **M**easuring **O**verlap with **G**as

UNIQUE energy scale  $\sqrt{s_{NN}} = 68.5\text{-}110\text{ GeV}$   
between SPS ( $\sim 10\text{-}30\text{ GeV}$ ) & RHIC ( $\sim 200\text{ GeV}$ )

- Access to the high- $x$  and intermediate  $Q^2$  kinematic region, mostly unexplored by previous experiments  
→ Unique experimental inputs to models!



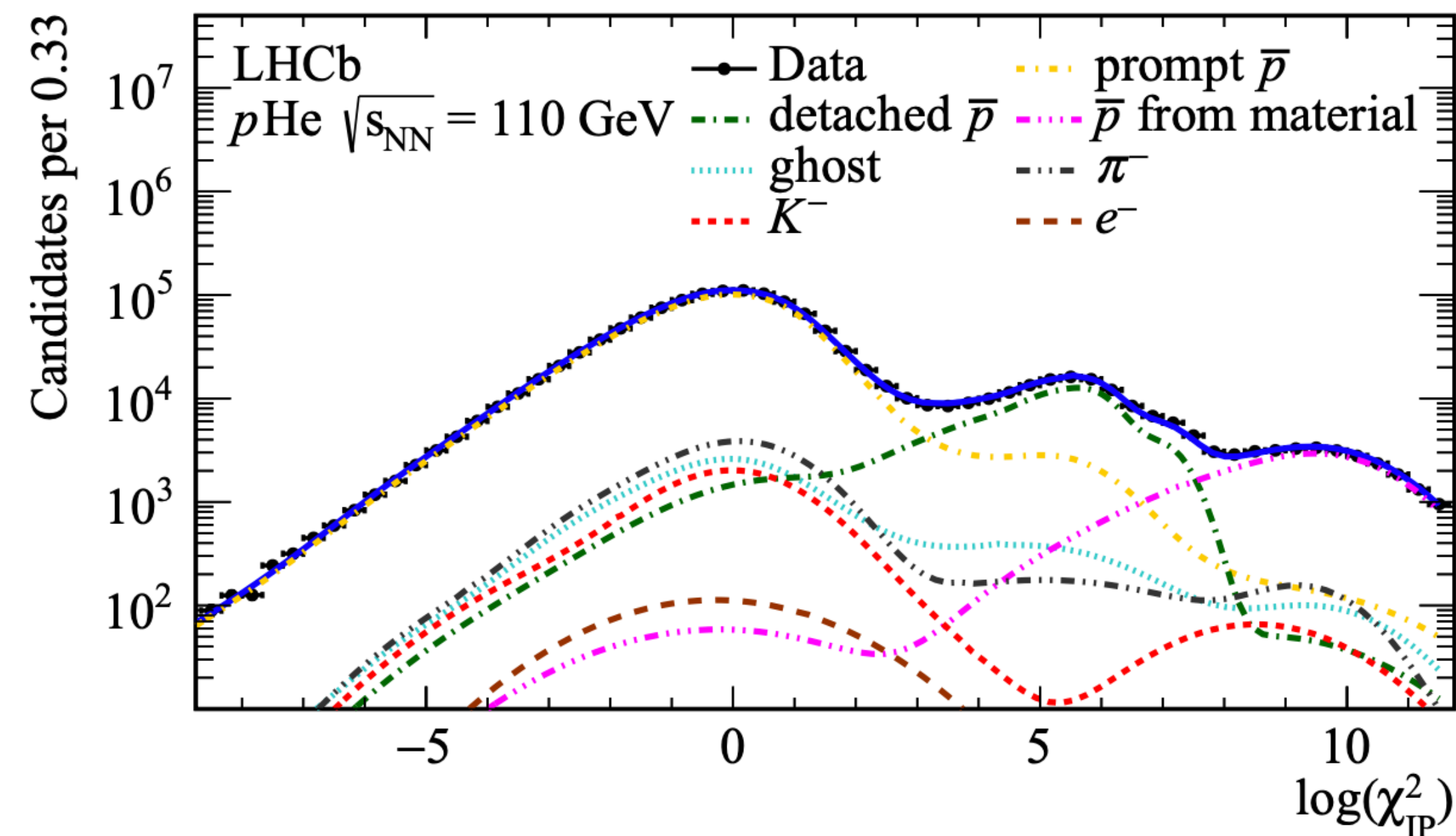
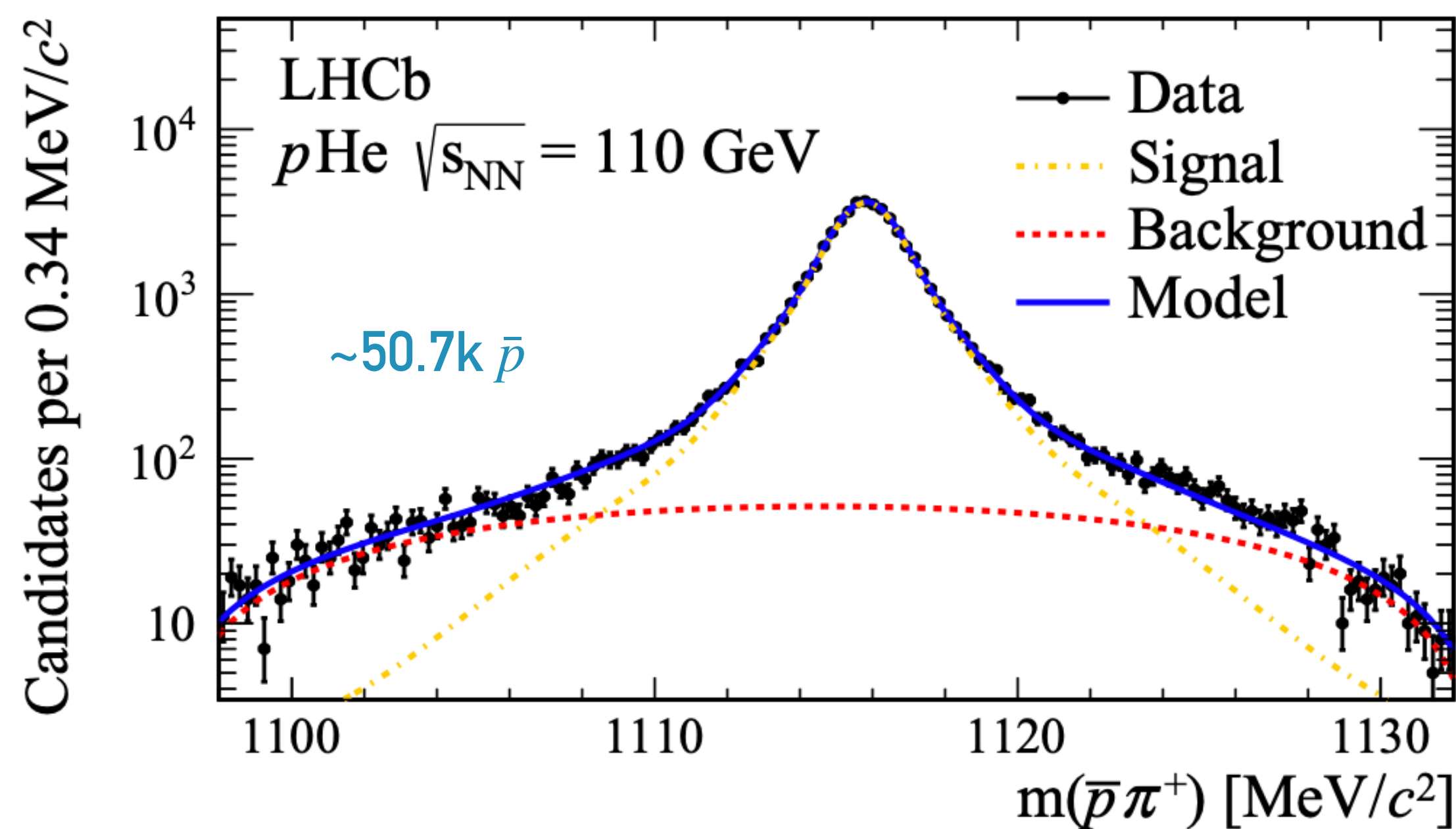
- Noble gas (He, Ne, Ar) at  $\sim 2 \times 10^{-7}$  mbar is injected into the LHC vacuum around the LHCb interaction region
- Forward detector and gas target  
→ **highest-energy fixed-target ever!**



# ANTIPROTON FROM ANTIHYPERON IN $p$ -He AT 110 GeV

arXiv:2205.09009

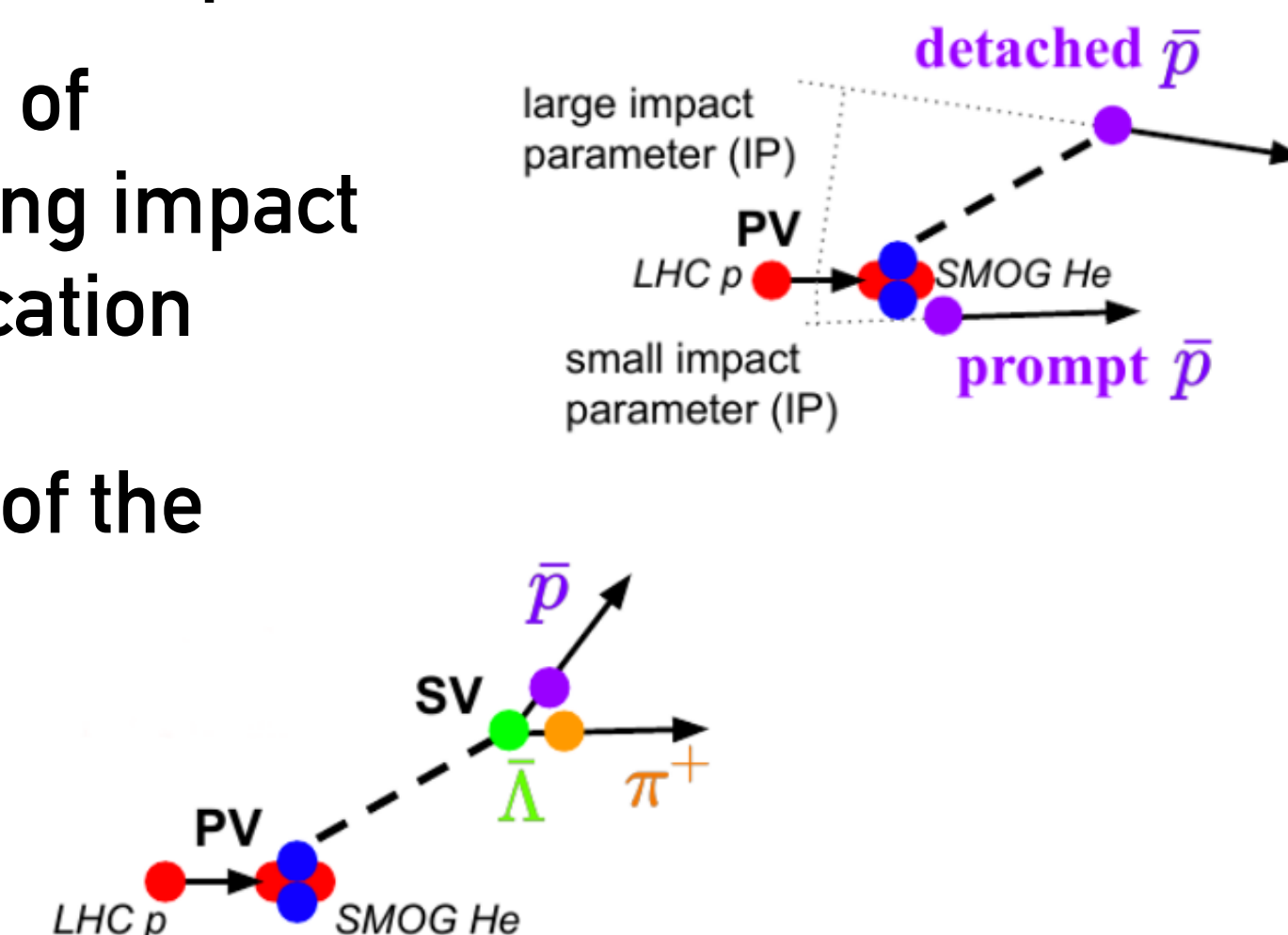
- ▶  $p$ -He @ 110 GeV ( $L \sim 0.5 \text{ nb}^{-1}$ ) mimic cosmic ray-interstellar medium collisions at energy scale relevant for the AMS-02 measurements of antimatter in space (and dark matter?)
- ▶ Prompt  $\bar{p}$  measurement already constrained models of secondary cosmic  $\bar{p}$  [PRL 121 \(2018\) 222001](#)
- ▶ Measurements now extended to antiprotons produced by antihyperons decays



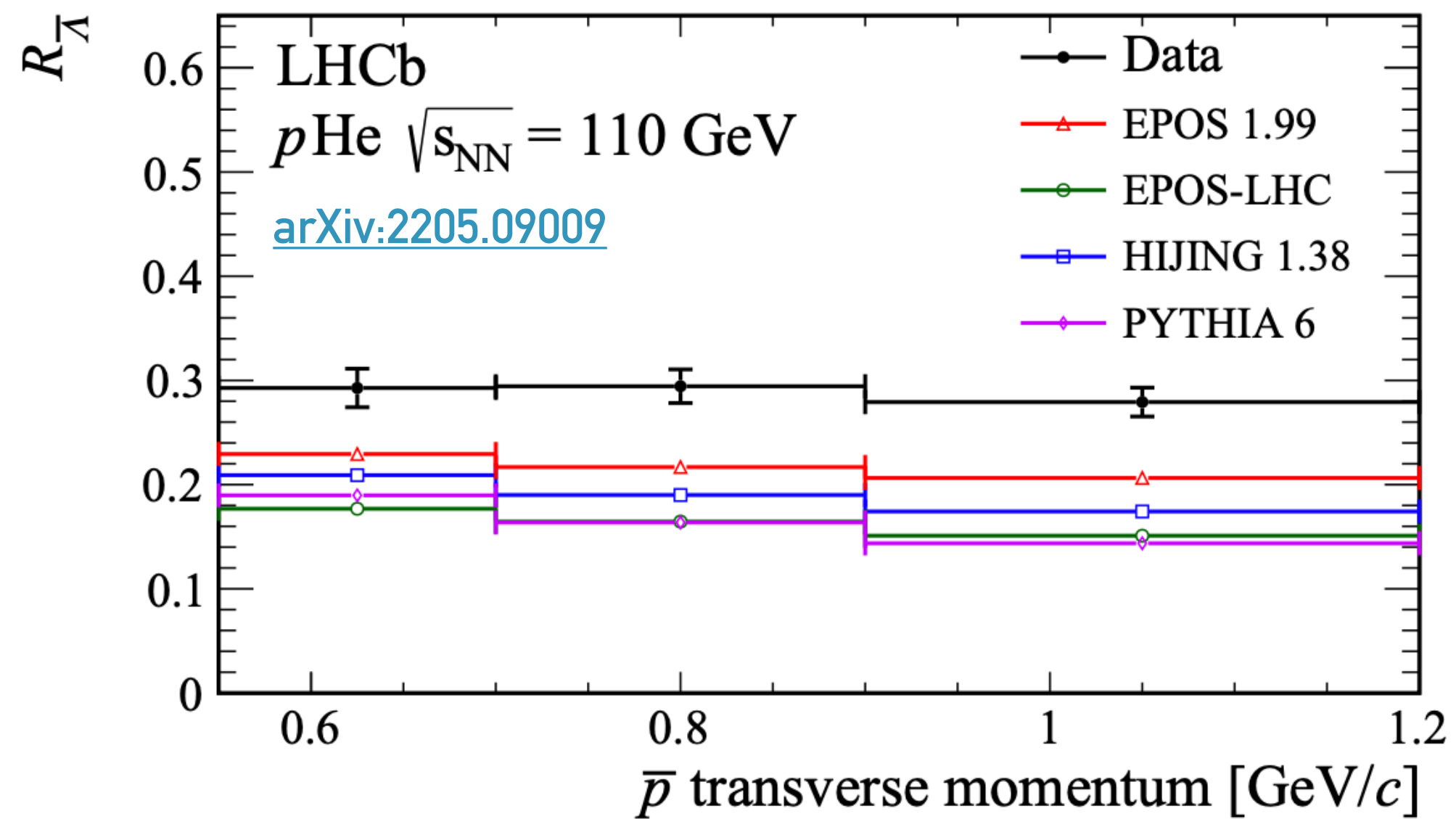
- ▶ Two complementary approaches performed

→ Inclusive measurements of detached antiprotons using impact parameter and  $\bar{p}$  identification

→ Exclusive measurement of the dominant contribution



# ANTIPROTON FROM ANTIHYPERON IN $p$ -He AT 110 GeV



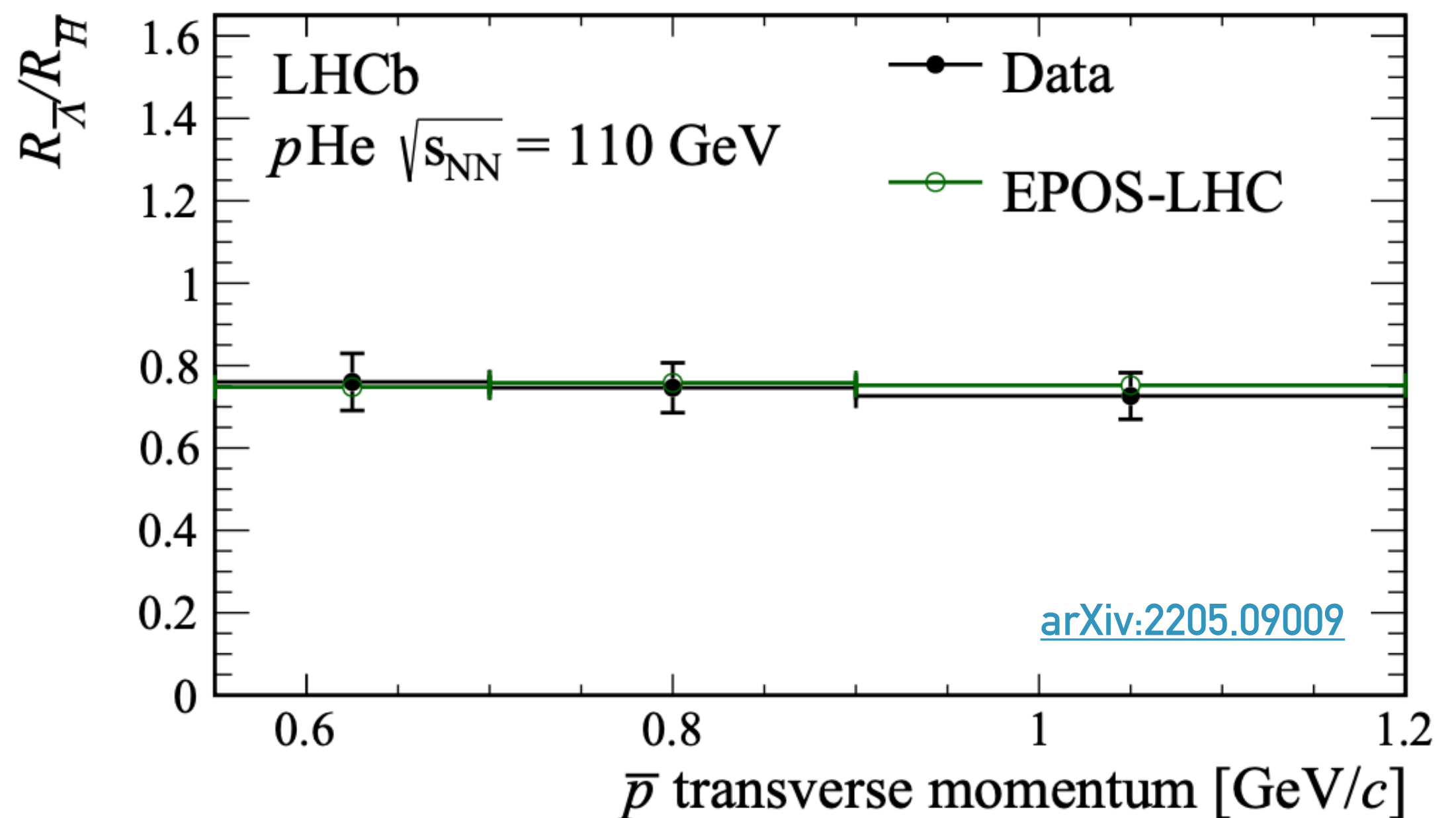
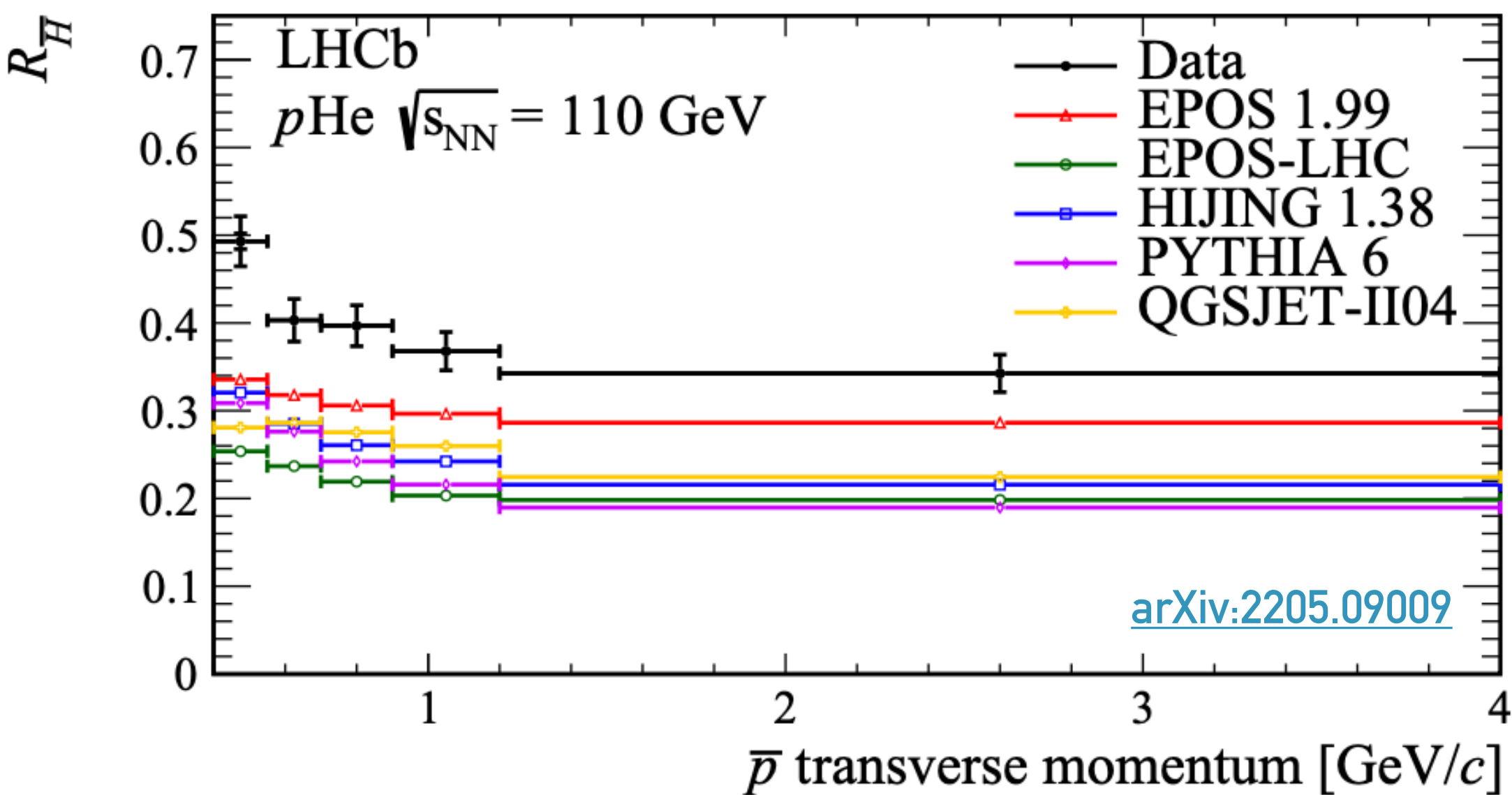
- Most commonly used hadronic models underestimate the antihyperon contributions to the total yield
- Agreement of the exclusive  $\bar{\Lambda}$  over inclusive antihyperon ratio  $R_{\bar{\Lambda}}/R_{\bar{H}}$  with theoretical expectations [Becattini et al, EPJC 66, 377–386 \(2010\)](https://arxiv.org/abs/1007.4632)

$$R_{\bar{\Lambda}} \equiv \frac{\sigma(p\text{He} \rightarrow \bar{\Lambda}X \rightarrow \bar{p}\pi^+X)}{\sigma(p\text{He} \rightarrow \bar{p}_{\text{prompt}}X)}$$

$$R_{\bar{H}} \equiv \frac{\sigma(p\text{He} \rightarrow \bar{H}X \rightarrow \bar{p}X)}{\sigma(p\text{He} \rightarrow \bar{p}_{\text{prompt}}X)}$$

$\bar{H} = \bar{\Lambda}, \bar{\Sigma}, \bar{\Xi}, \bar{\Omega}$

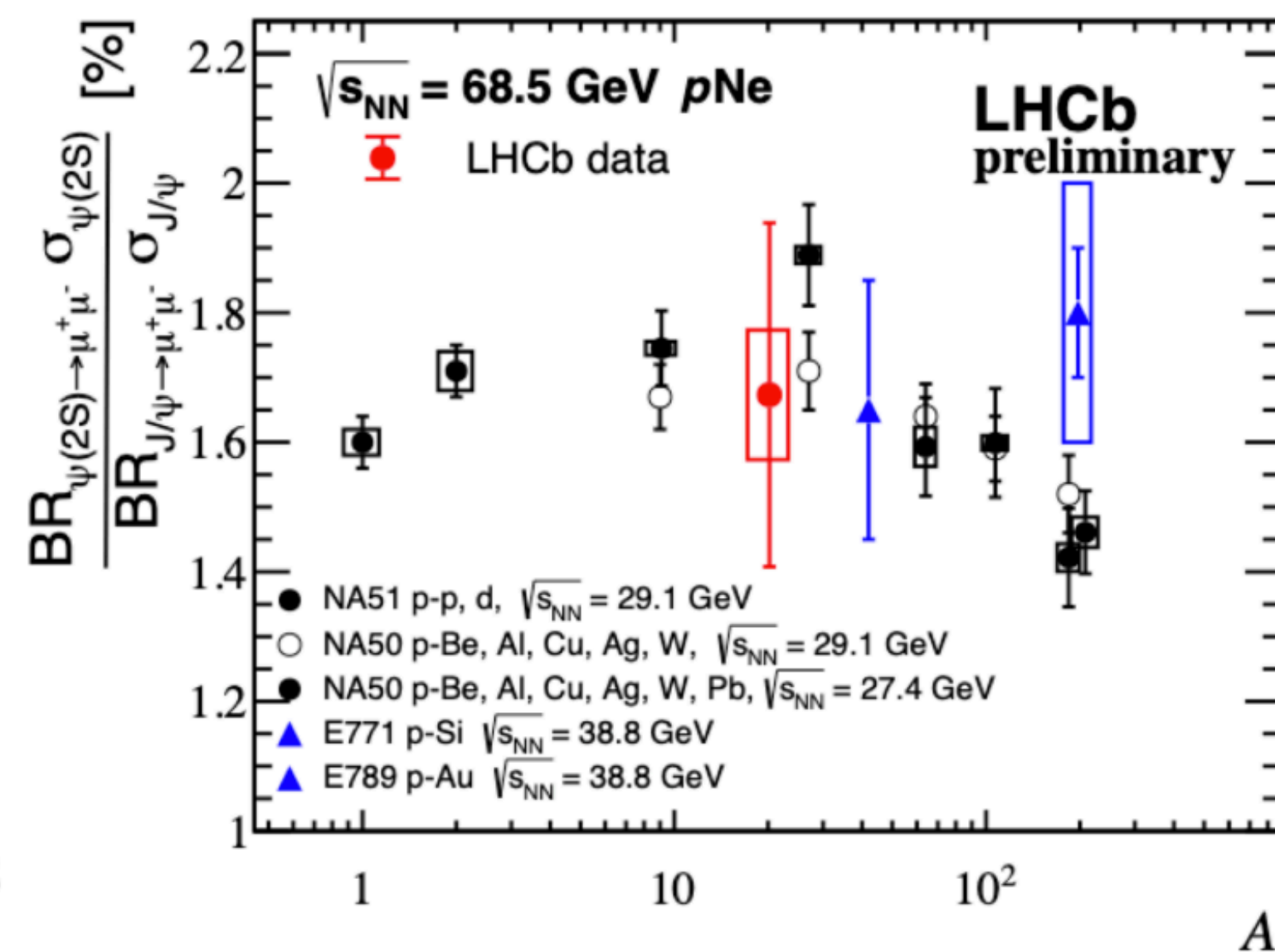
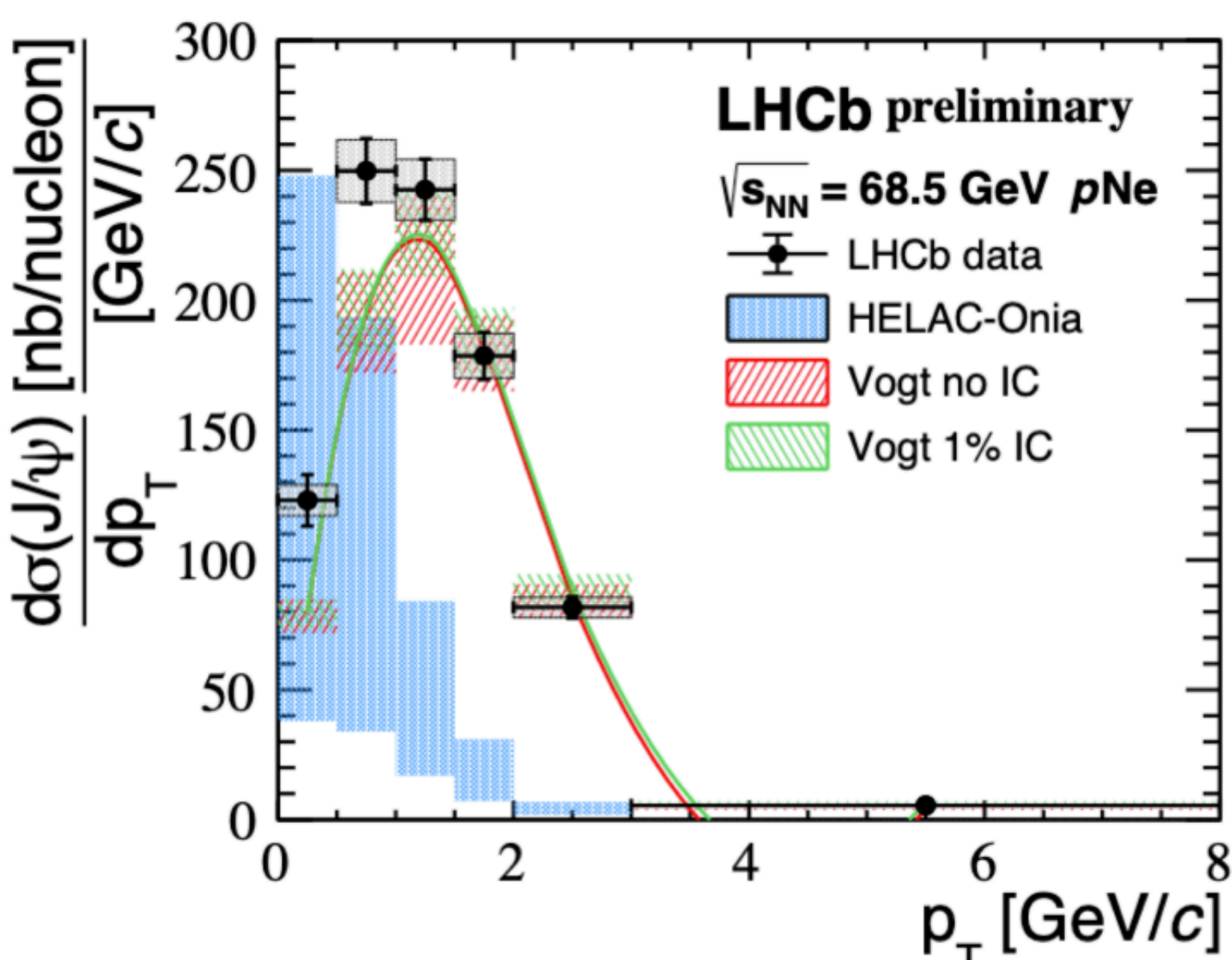
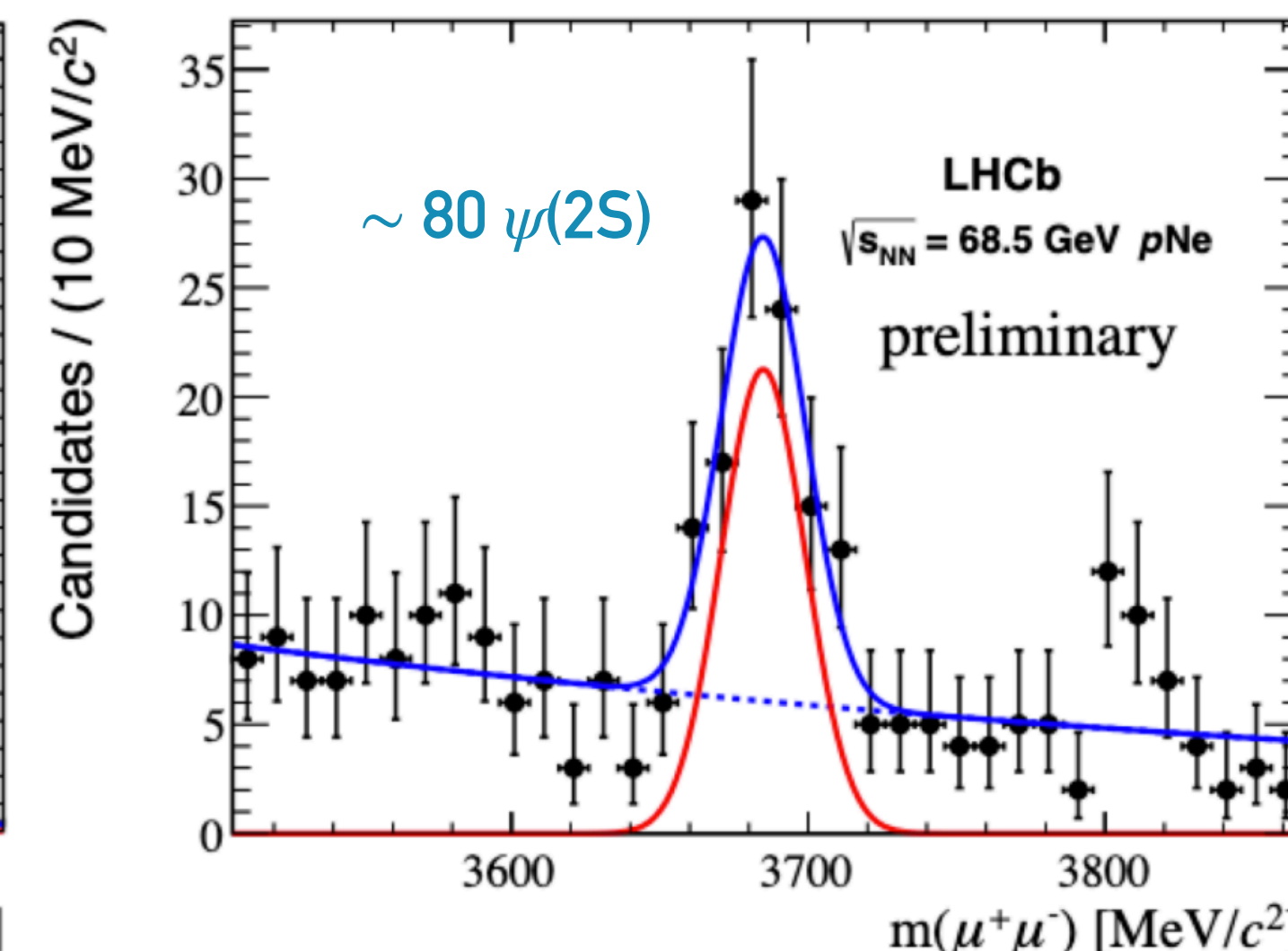
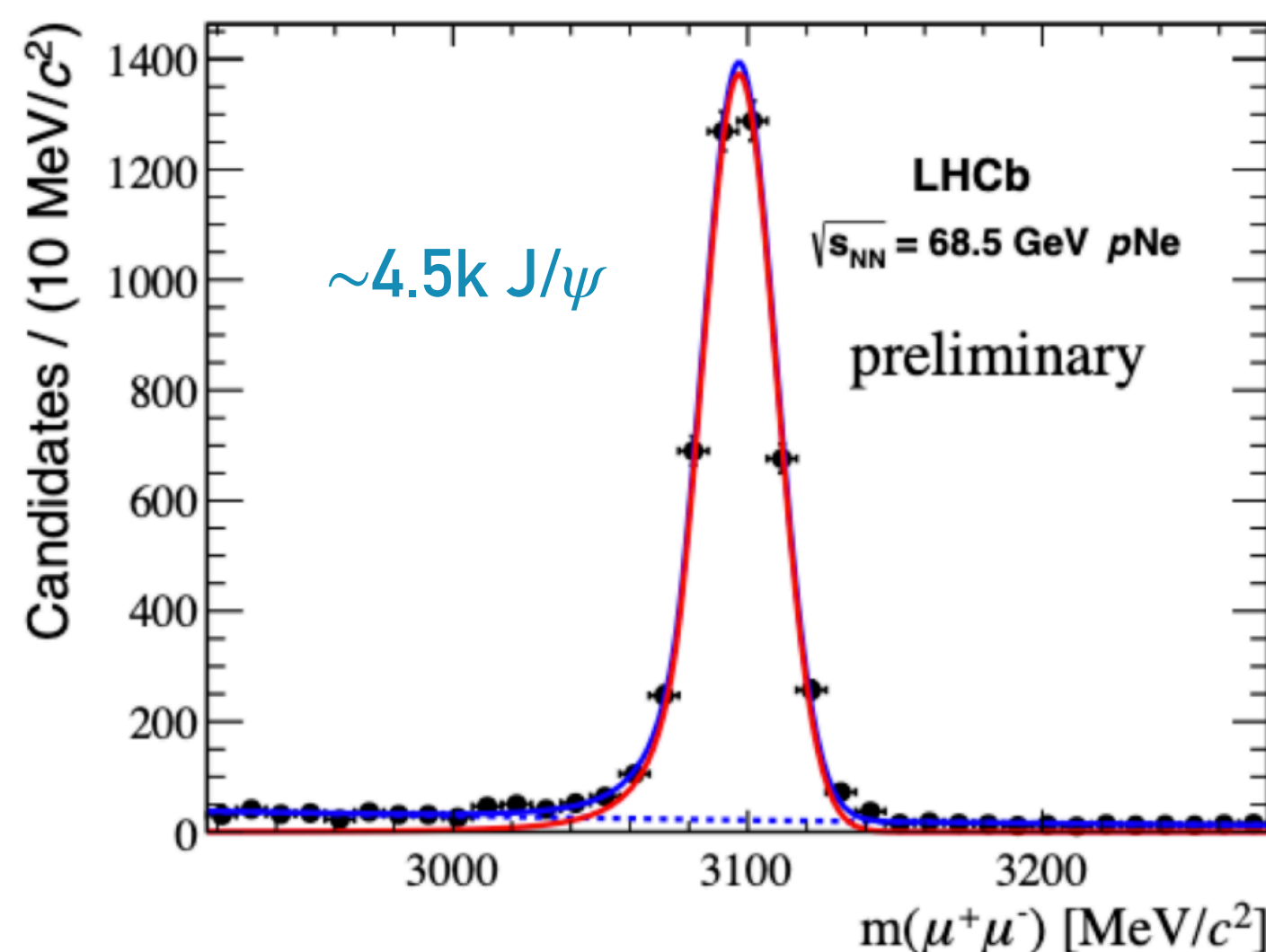
[arXiv:2205.09009](https://arxiv.org/abs/2205.09009)  
[PRL 121 \(2018\) 222001](https://arxiv.org/abs/1805.02201)



# CHARM PRODUCTION IN $p$ -Ne AT 68.5 GeV

LHCb-PAPER-2022-014, in preparation

- Charmonia production is an excellent probe for Cold Nuclear Matter effects (PDF nuclear modification, nuclear absorption, multiple scatterings...)
- Dataset: 2.5 TeV protons on rest Neon nuclei with SMOG  $\rightarrow L = 21.7 \pm 1.4 \text{ nb}^{-1}$   
 $\rightarrow$  Center of mass rapidity coverage :  $-2.3 < y^* < 0$



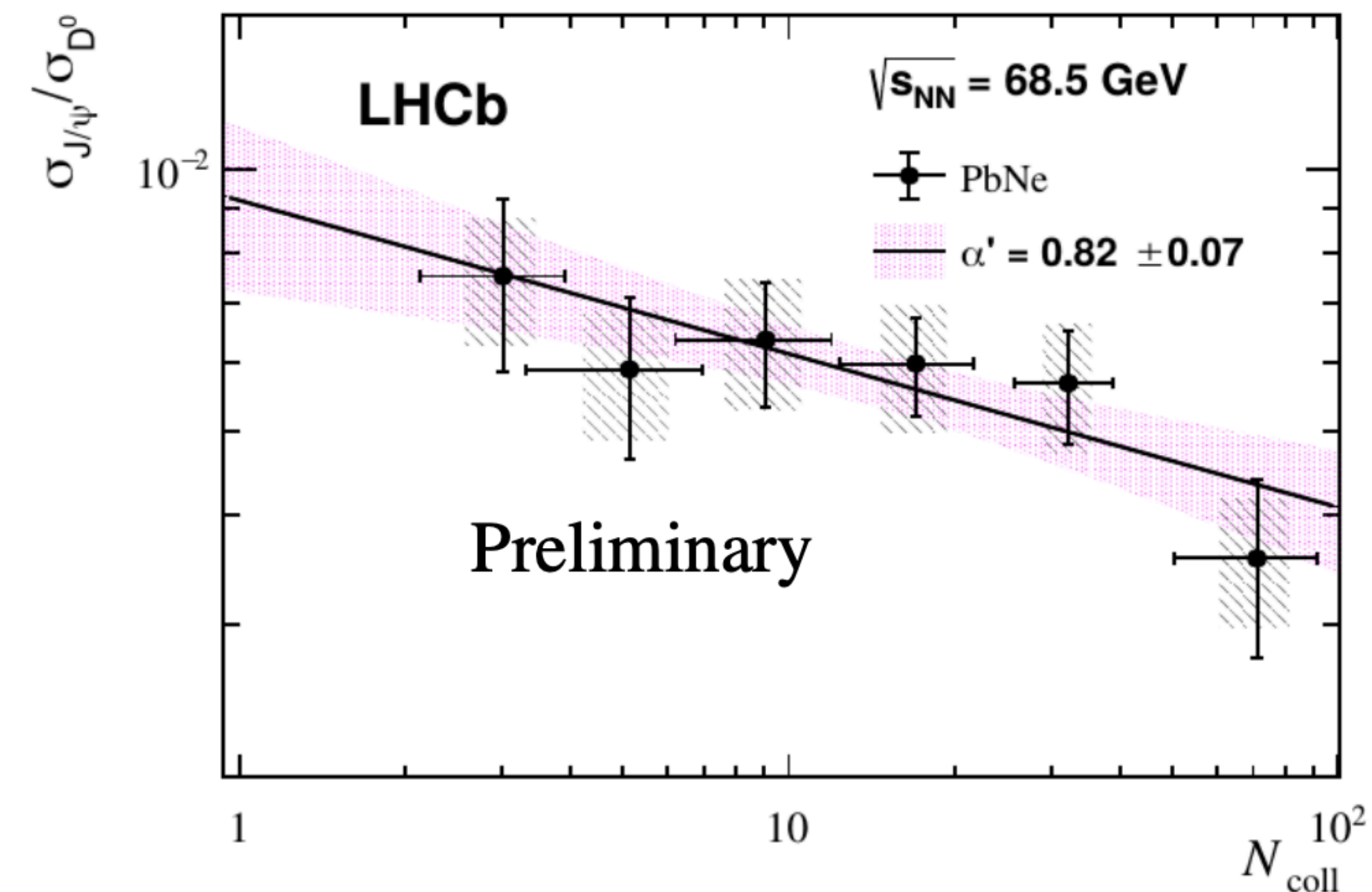
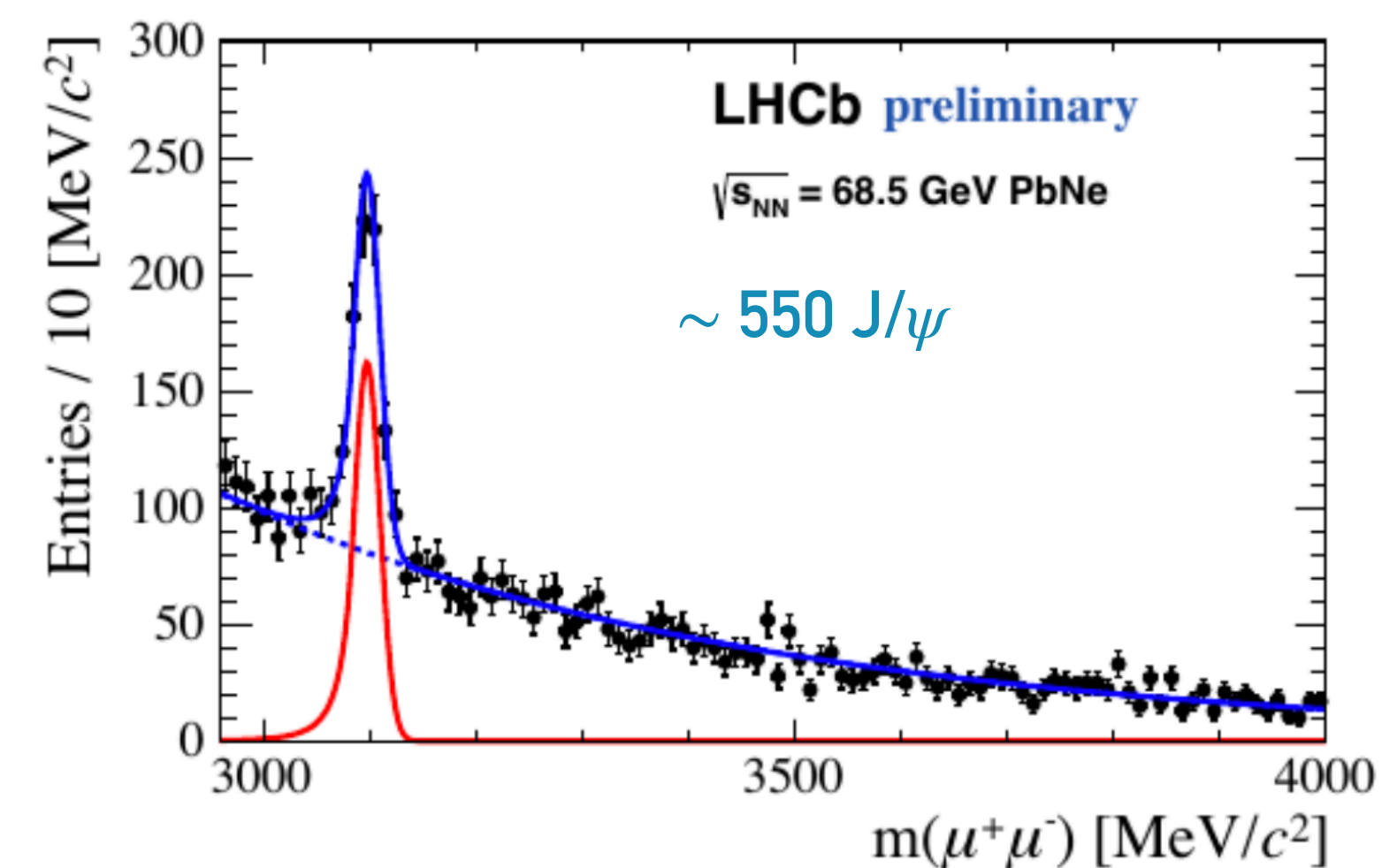
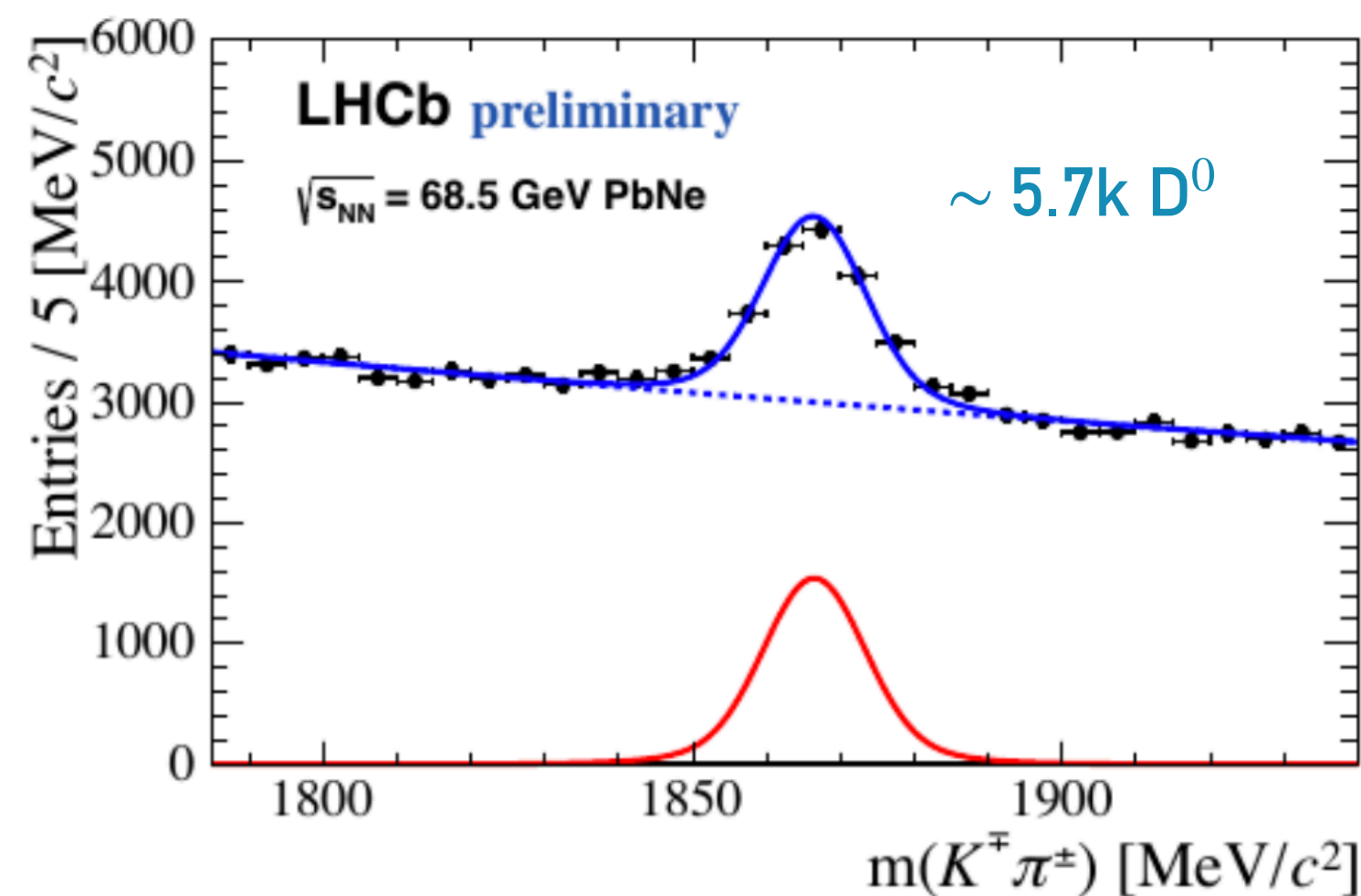
- $J/\psi$  differential cross-section
  - $\rightarrow$  Good agreement with prediction without and with 1% Intrinsic Charm contribution,
  - $\rightarrow$  Tension between data and HELAC-ONIA
- **First** measurement of  $\psi(2S)$  to  $J/\psi$  production ratio with SMOG
- Consistent with other  $p$ -A measurements at small atomic mass number  $A$ , but statistically limited

$\rightarrow$  **motivation to upgrade the fixed-target programme!**

# CHARM PRODUCTION IN Pb-Ne AT 68.5 GeV

LHCb-PAPER-2022-011, in preparation

- $D^0$  and  $J/\psi$  production observed
- $D^0$  as reference to study quarkonium modification inside nuclear medium



- Decrease of  $J/\psi$  over  $D^0$  ratio with increasing centrality, fitted with power law:

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

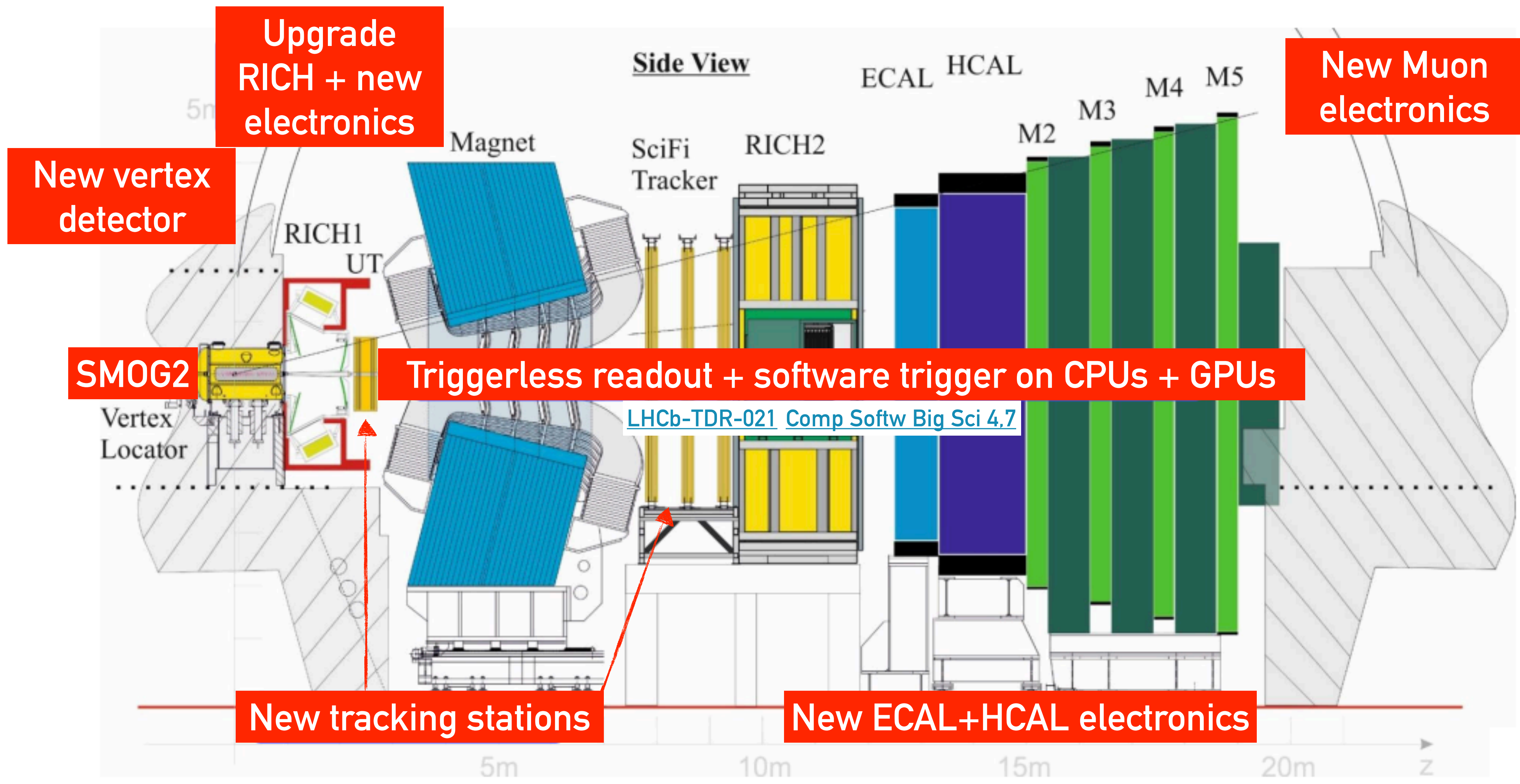
- Result:  $\alpha' = 0.82 \pm 0.07$  in agreement with NA50-SPS  $p$ -A measurements [PLB410 \(1997\) 337](#)
- **No anomalous  $J/\psi$  suppression expected from QGP formation is observed**
- First results from SMOG AB collisions



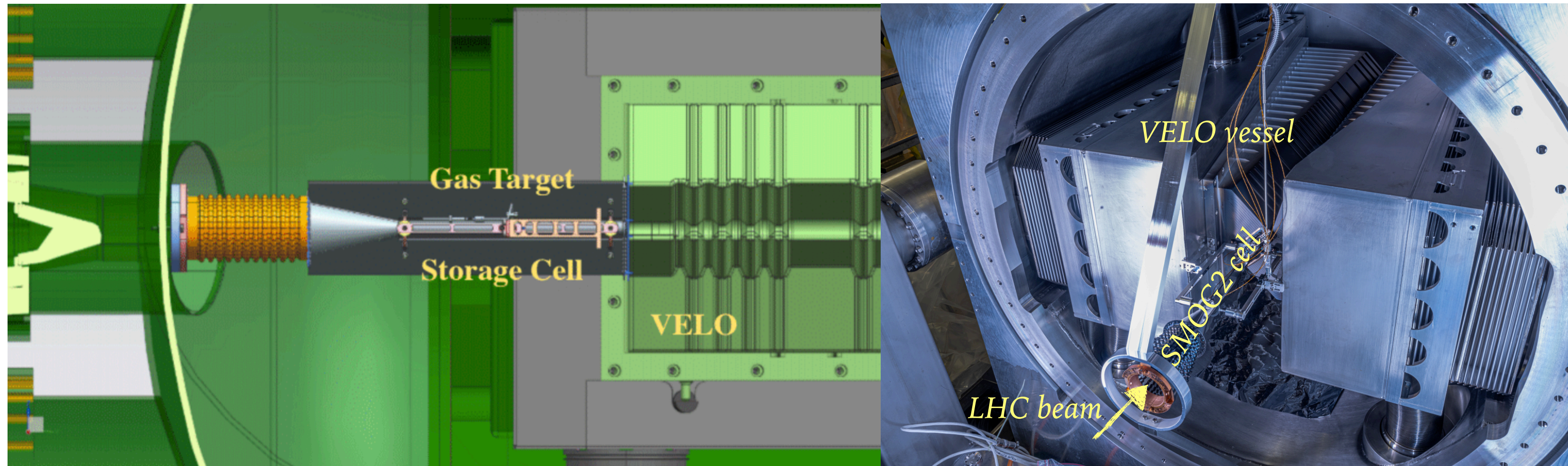


# RUN 3 PERFORMANCES: THE LHCb UPGRADE

# LHCb EXPERIMENT IN RUN 3



## ► SMOG2: System for Measuring Overlap with Gas Upgrade

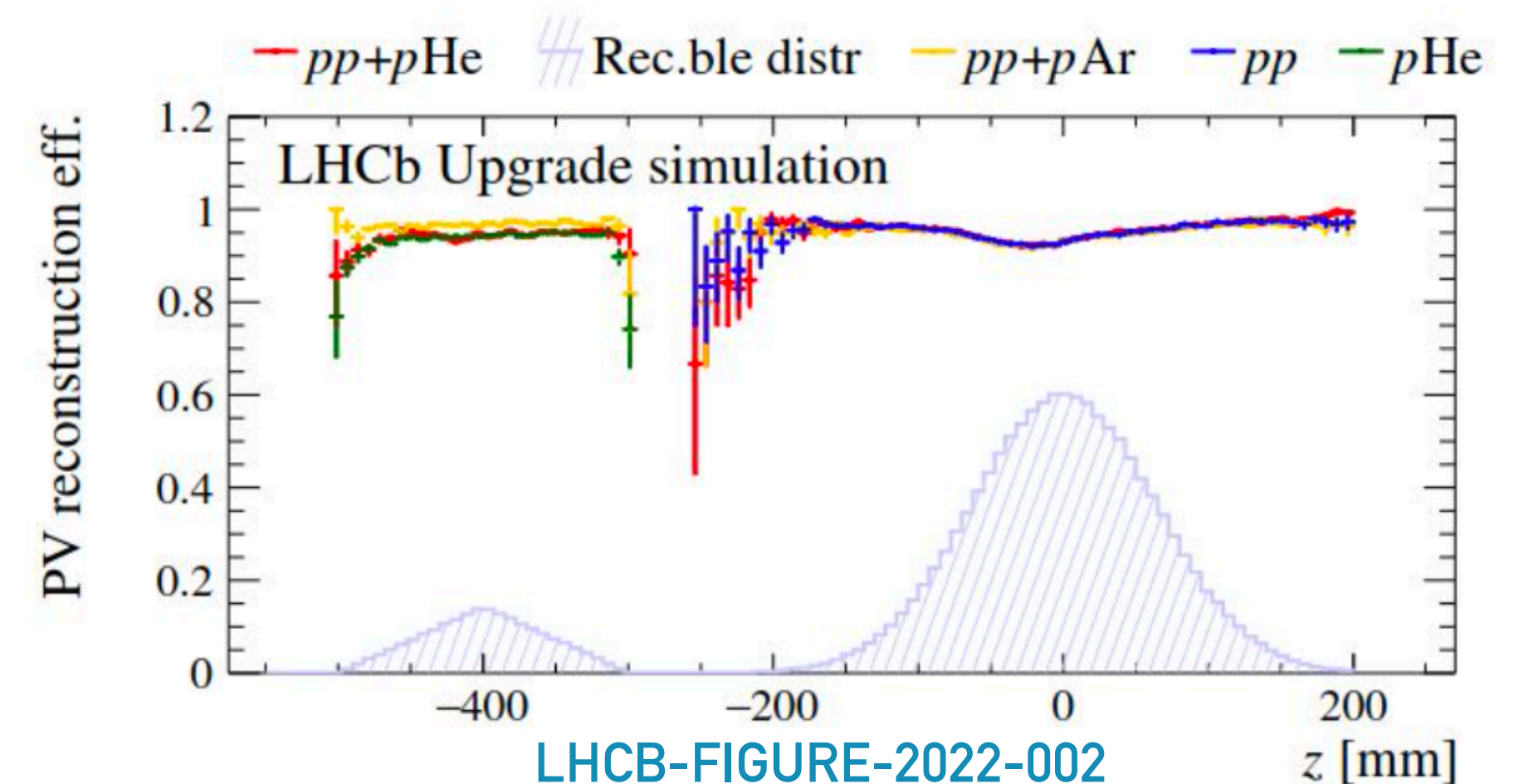


## ► Physics opportunities:

- Charmonia spectra in different collision systems,  $b$ -quark and low mass Drell Yan states
- Cosmic Ray Physics
- High- $x$  parton PDFs, nucleon structure

**!! With increased statistics !!**

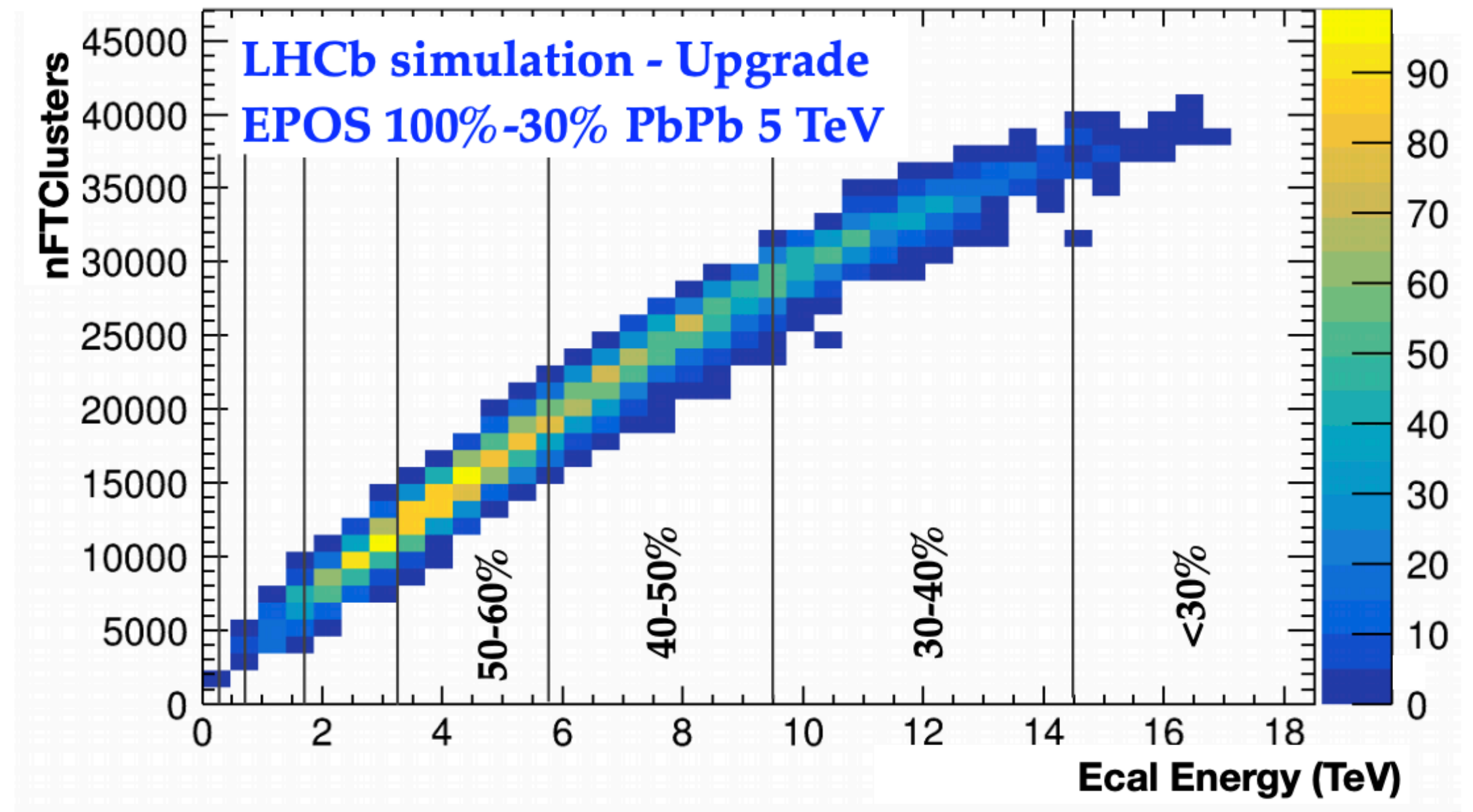
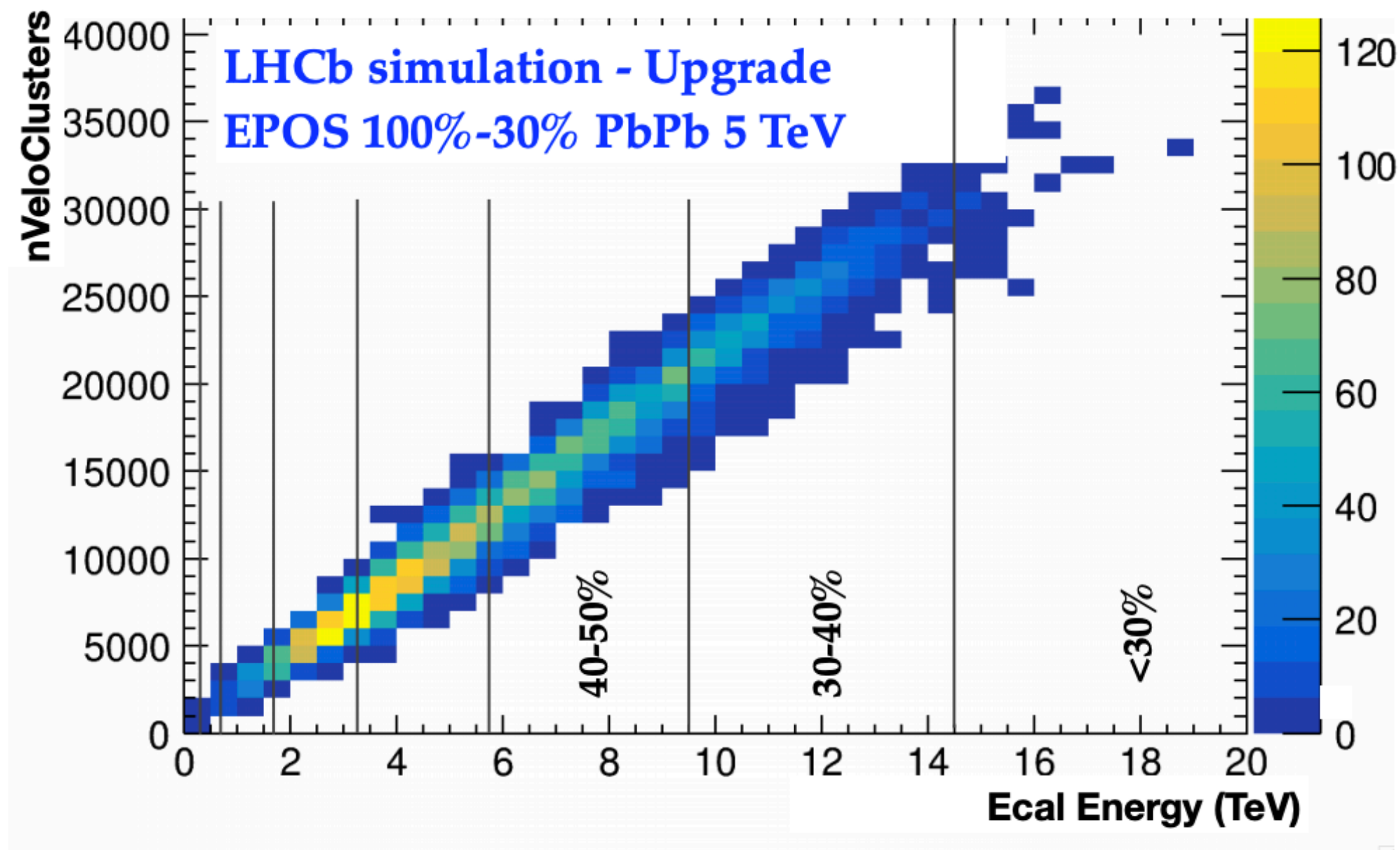
- SMOG has been replaced by SMOG2 since 2022!
- Gas confinement in a cell upstream of the LHCb IP ( $z \in [-500, -300]$  mm)
- Up to x100 gas pressure wrt SMOG for the same gas flow
- Large variety of gases can be injected (Kr, Xe, H<sub>2</sub>, D<sub>2</sub>, O<sub>2</sub>, N<sub>2</sub> ...)
- **Simultaneous beam-beam beam-gas data-taking**



# LHCb EXPERIMENT IN RUN 3: Pb-Pb PERFORMANCES

## ► Pb-Pb collisions

LHCb-FIGURE-2019-021



- No significant saturation up to 30% central collisions (simulation for higher centralities are being produced)
- Semi-central Pb-Pb collisions soon available: QGP studies for LHCb in Run 3
- Increased statistics: improvement of UPC studies

# CONCLUSIONS

- LHCb became an important contributor to heavy ion physics and cosmic ray physics, too
- **First** measurement of  $R_{\Lambda_c^+/D^0}$  production cross-section ratio in peripheral Pb-Pb collisions
- A **new** measurement of exclusive coherent  $J/\psi$  and  $\psi(2S)$  production and their cross-section ratio in UPC Pb-Pb collisions
- **First** results from nucleus-nucleus collisions in fixed target using LHC beams
  - Detached-to-prompt antiproton production in  $p$ -He
  - Charm production in  $p$ -Ne and Pb-Ne
- More results to come and better performances expected after the upgrade!

**STAY TUNED!**

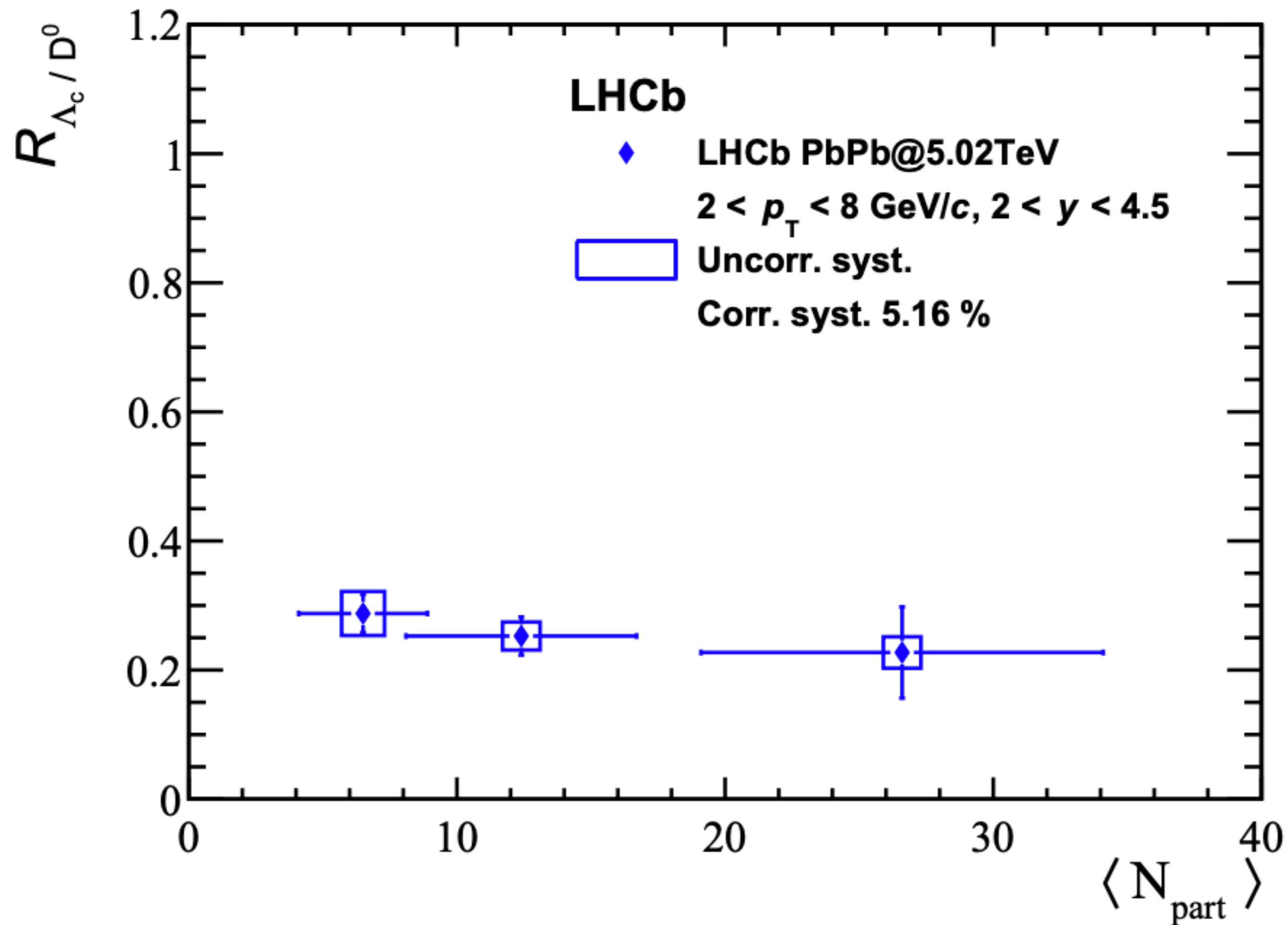
**THANK YOU!**



# BACK UP

# Pb-Pb COLLISIONS: $\Lambda_c^+/D^0$ RATIO

arXiv:2210.06939



►  $R_{\Lambda_c^+/D^0}$  shows no dependence on  $\langle N_{part} \rangle$  within uncertainties, with a mean value  $\langle R_{\Lambda_c^+/D^0} \rangle \sim 0.27$