

Recent LHCb results on heavy-ion and fixed-target data



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XII International Conference
on New Frontiers in Physics

10-23 July 2023, OAC, Kolymbari, Crete, Greece

Outline:

- The LHCb detector at LHC
- Recent results in heavy-ion collisions
- Conclusions and outlook

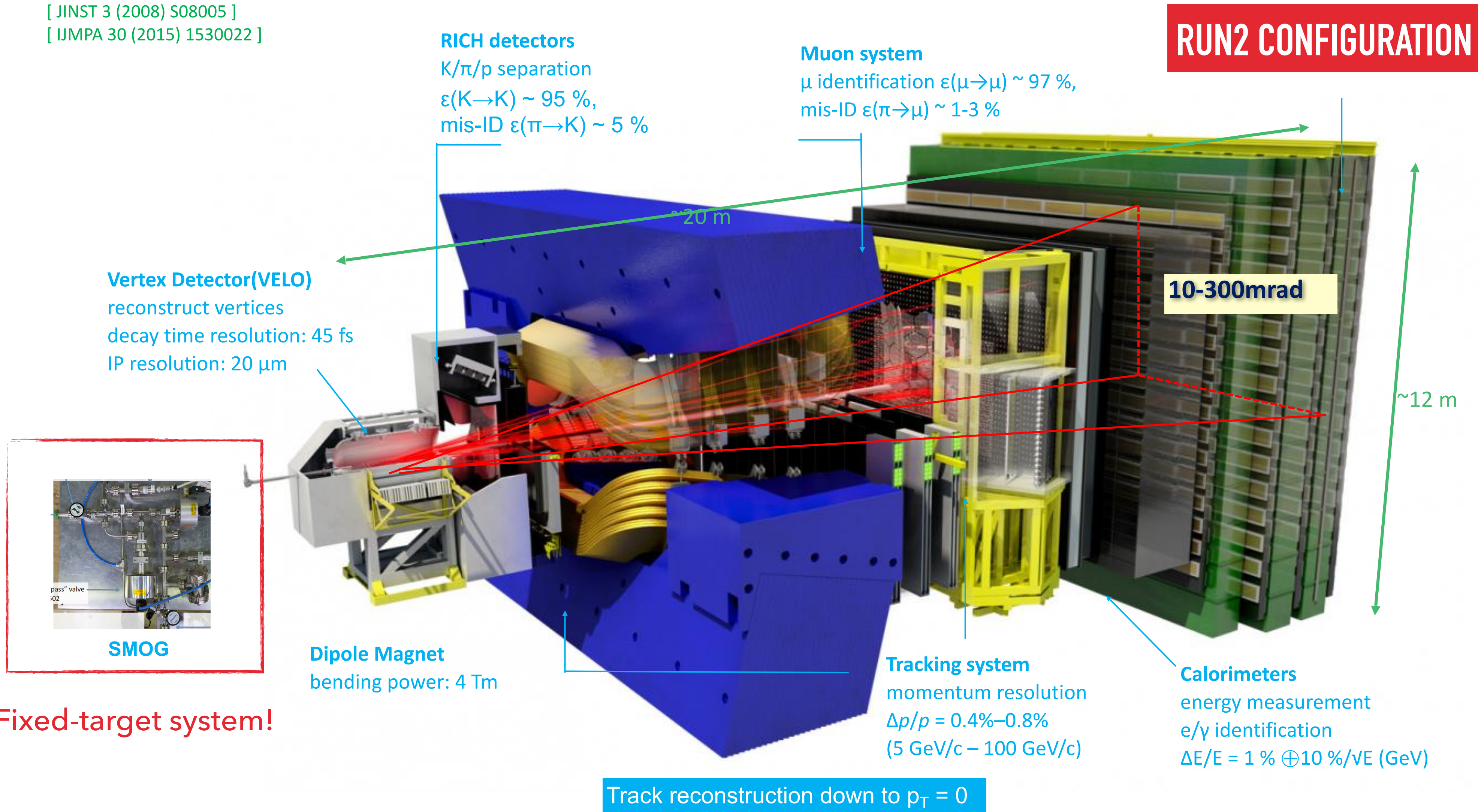
THE LHCb DETECTOR

- ▶ Single arm forward spectrometer with **unique coverage** $2 < \eta < 5$

[JINST 3 (2008) S08005]
[JIMPA 30 (2015) 1530022]

- ▶ Designed for heavy-flavour physics, now a **general purpose experiment**

- ▶ **Forward and backward coverage** for asymmetric beams



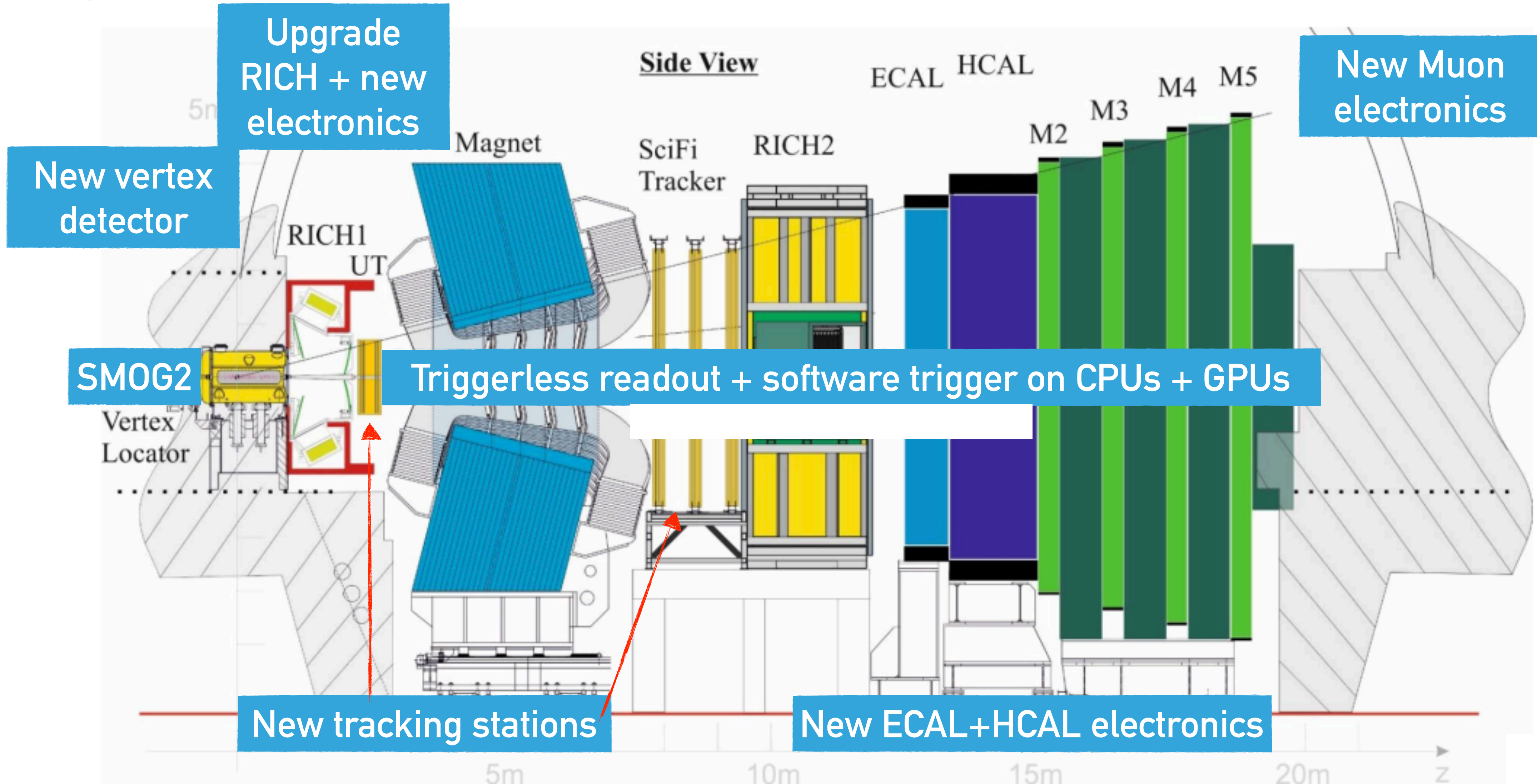
LHCb DETECTOR IN RUN3

UPGRADE I

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RUN3 CONFIGURATION

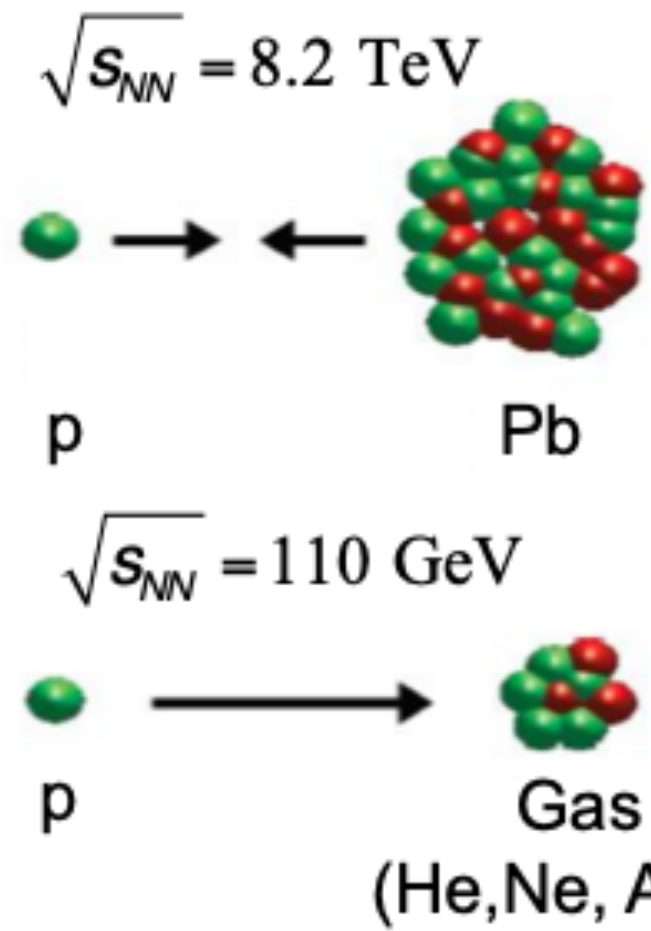
[LHCb-TDR-12]



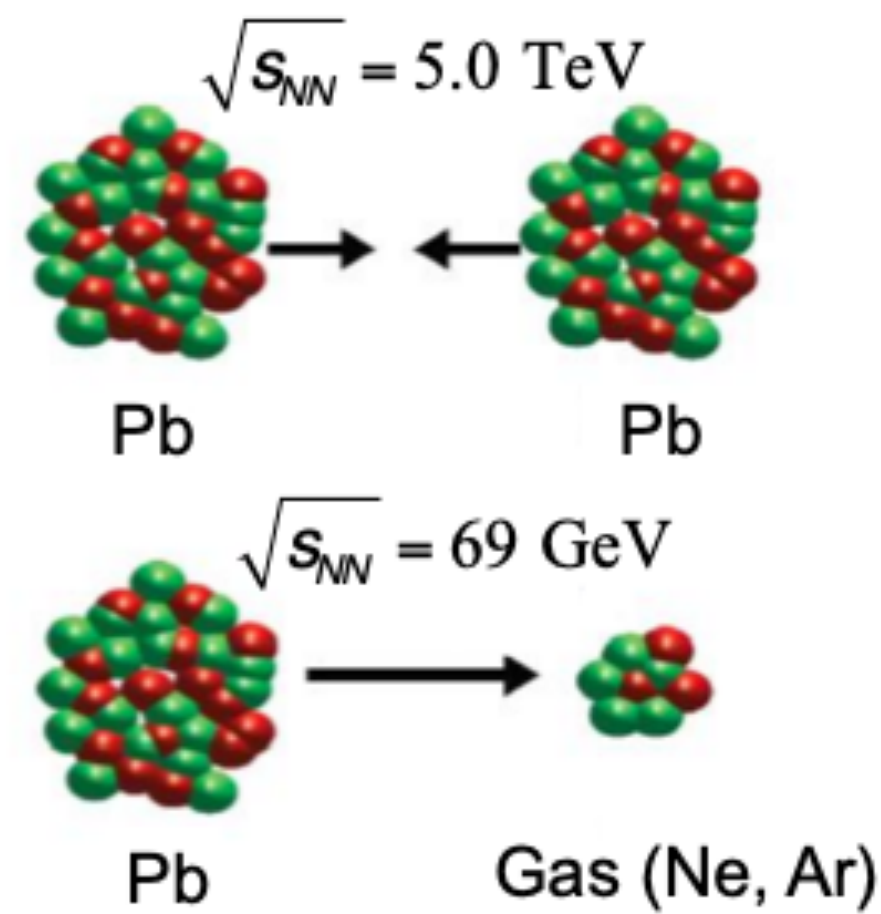
LHCb EXPERIMENTAL SET-UP

► Large variety of colliding system other than pp :

Cold Nuclear Matter



Quark Gluon Plasma



► $p\text{Pb}/\text{Pbp}$

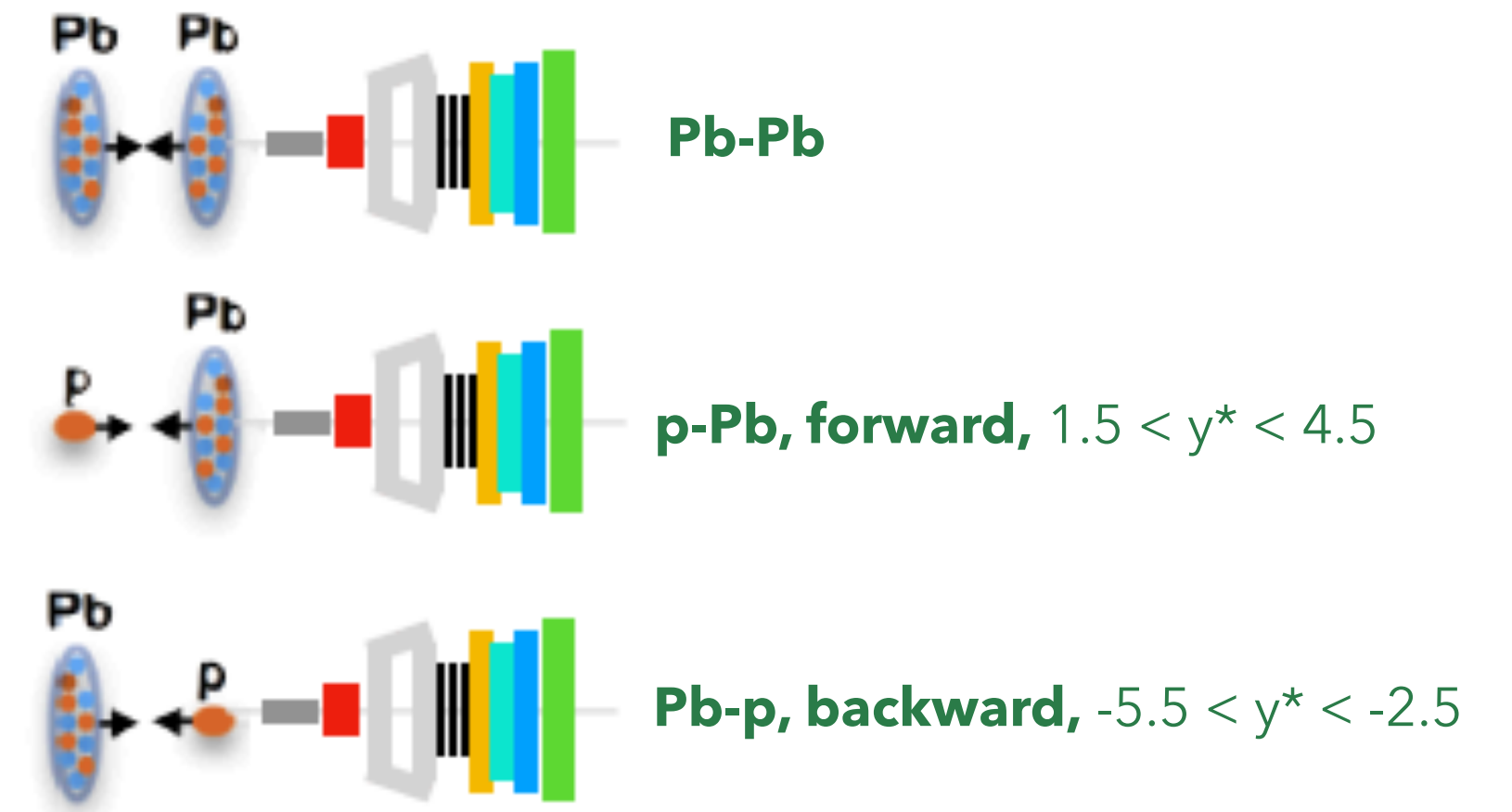
► PbPb

► pA

► PbA

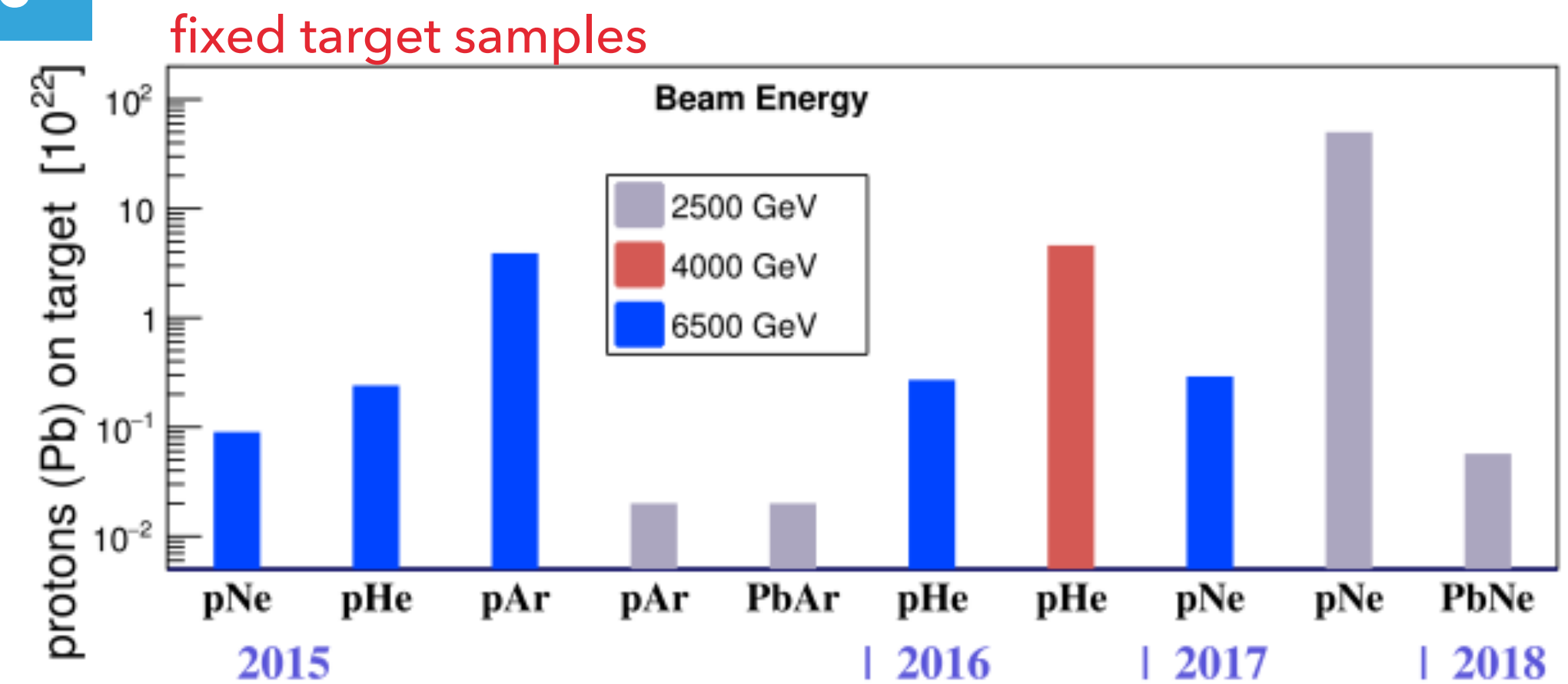
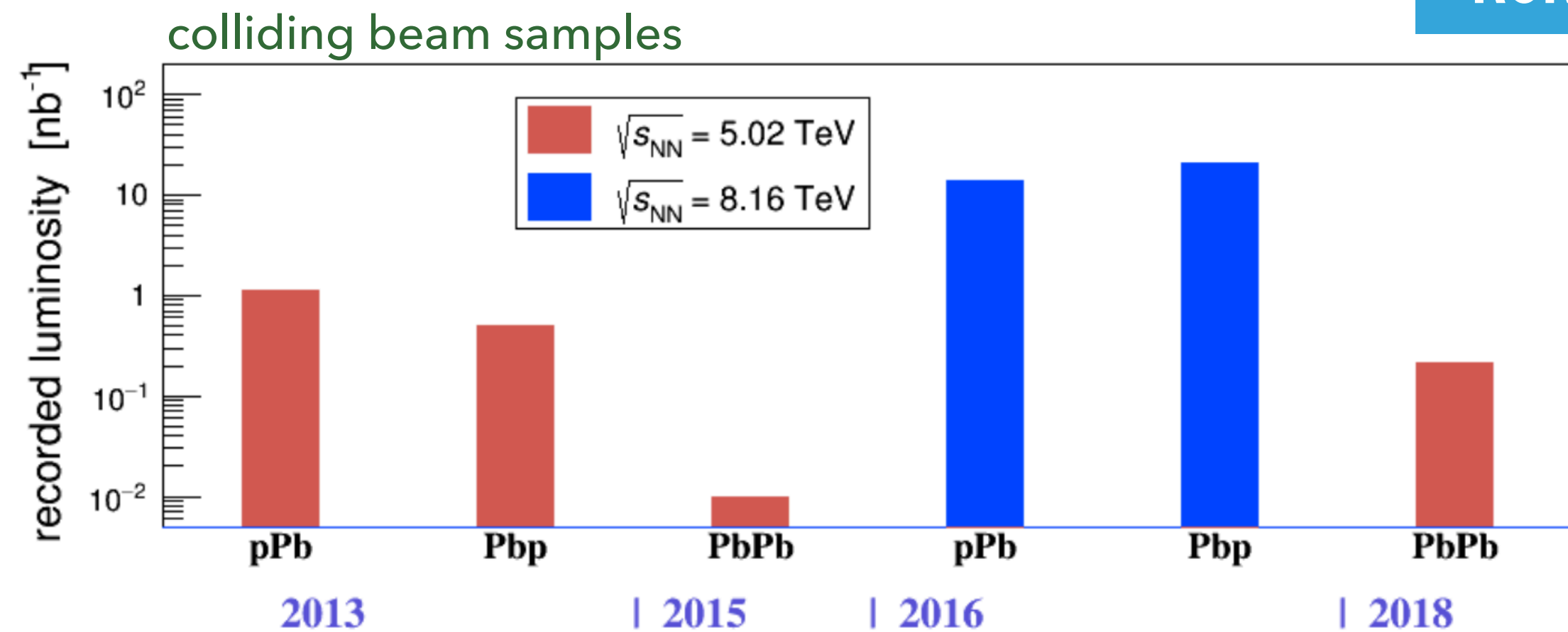
} colliding beam mode

} fixed-target mode (SMOG)



Injection of noble gases (He, Ne, Ar) into the interaction region → **unique kinematical region accessible!**

RUN2 SAMPLES



$p\text{Pb}/\text{Pb}p$ collisions

- ▶ Ξ_c^+ production in $p\text{Pb}$ collisions at $\sqrt{s} = 8.16$ TeV *Arxiv:2305.06711, submitted to PRL*
- ▶ Prompt D^+ , D_s^+ production in $p\text{Pb}$ collisions at $\sqrt{s} = 5$ TeV *LHCb-PAPER-2023-006, in preparation*
- ▶ Prompt D^0 nuclear modification factor in $p\text{Pb}$ collisions at $\sqrt{s} = 8.16$ TeV *Arxiv:2205.03936, accepted by PRL*
- ▶ π^0 production in $p\text{Pb}$ collisions at $\sqrt{s} = 8.16$ TeV *Arxiv:2205.10608, accepted by PRL*

PbPb collisions

- ▶ Coherent charmonium production in UPC PbPb collisions at $\sqrt{s} = 5$ TeV *ArXiv:2206.08221, submitted to JHEP*
- ▶ Λ_c^+ to D^0 production cross-section ratio in peripheral PbPb collisions *JHEP06(2023)132*

p -gas fixed-target collisions

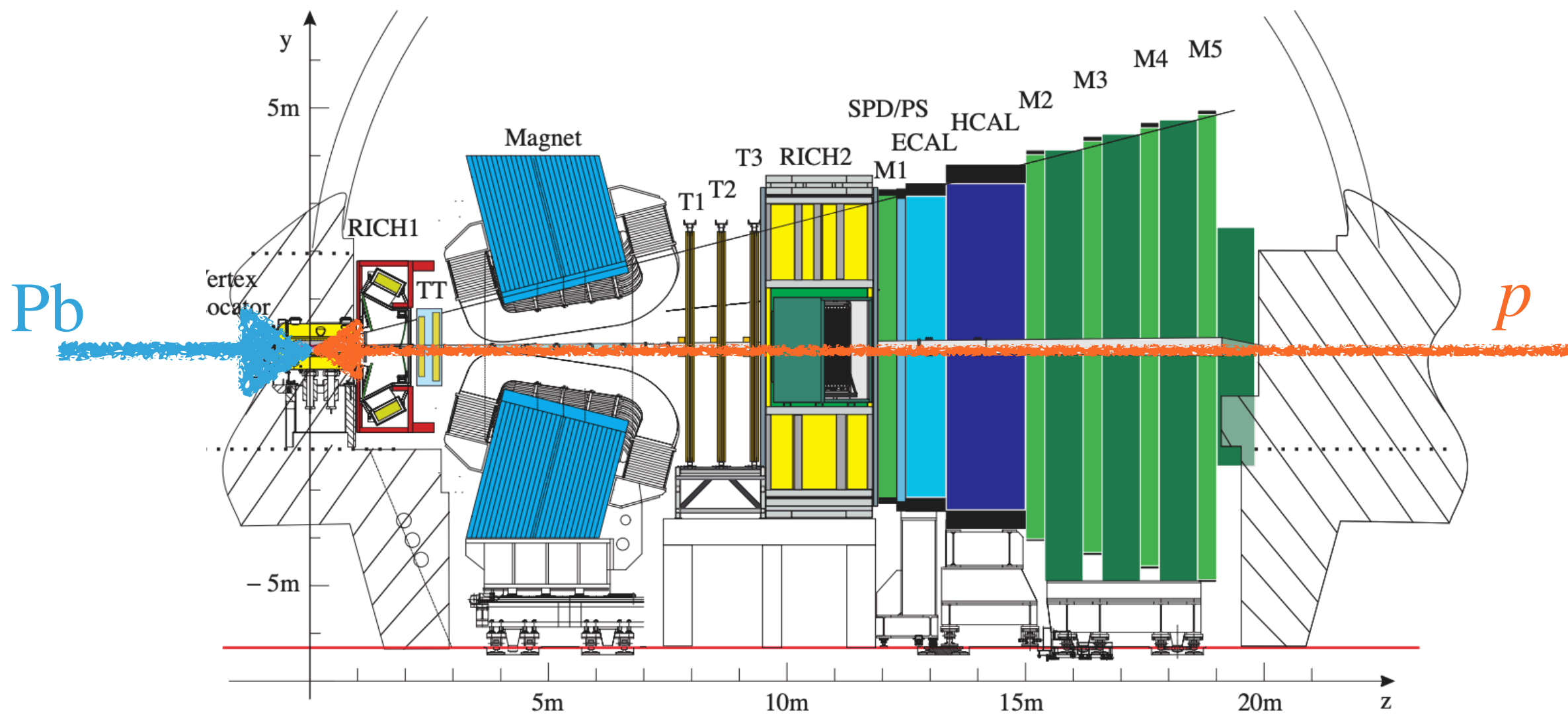
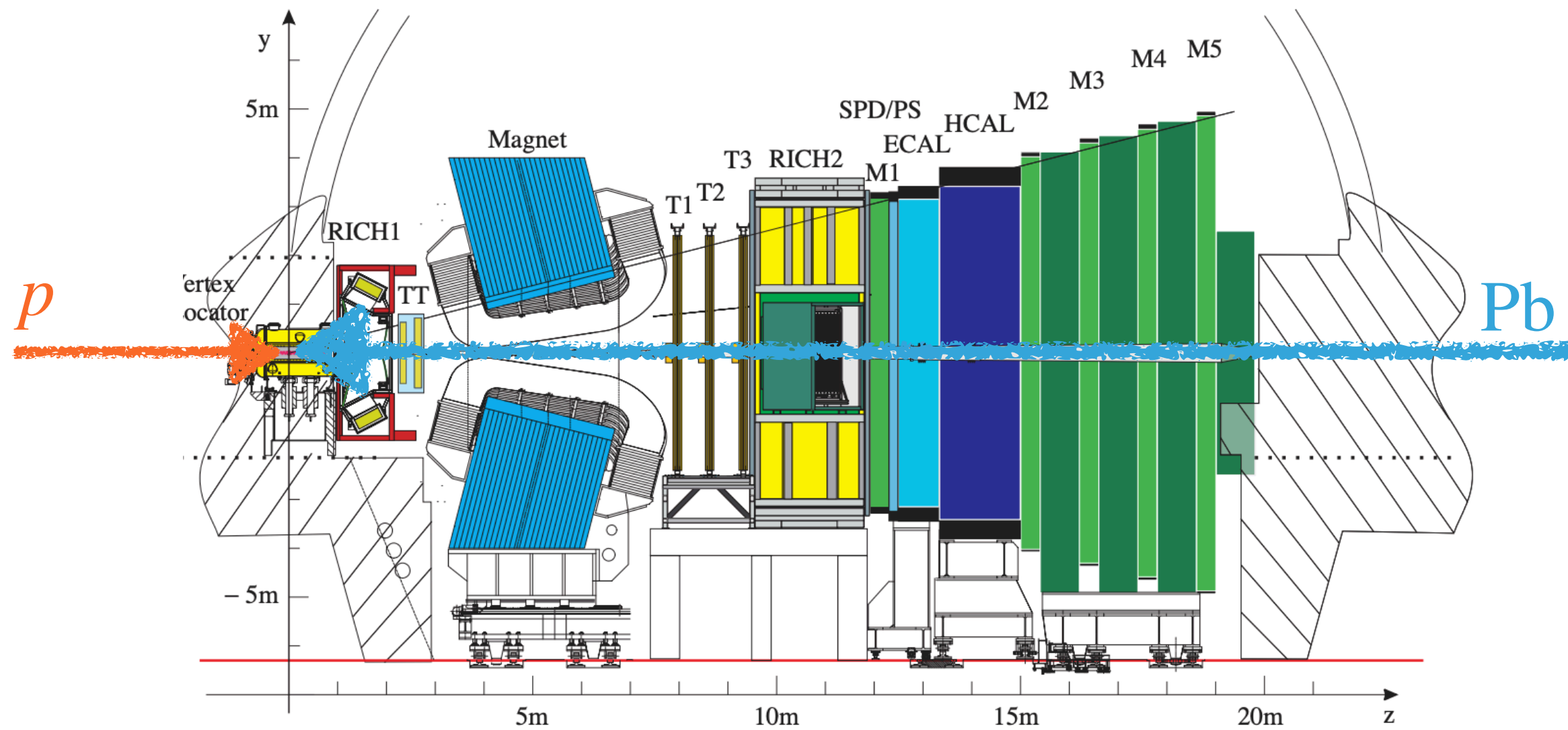
- ▶ Charmonium production in $p\text{Ne}$ collisions at $\sqrt{s} = 68.5$ GeV *Arxiv:2211.11633, arxiv: 2211.11645, submitted to EPJC*

Pb-gas fixed-target collisions

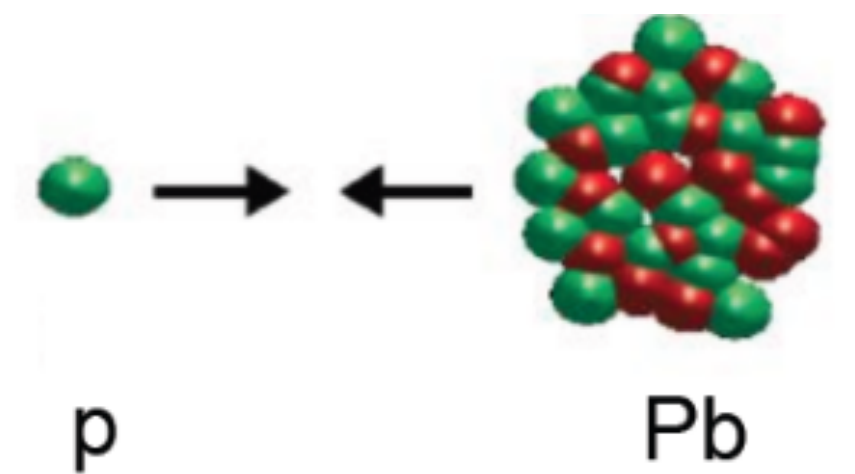
- ▶ J/ψ and D^0 production in $\sqrt{s} = 68.5$ GeV PbNe collisions *Arxiv: 2211.11652, submitted to EPJC*

PROTON-LEAD

p Pb AND Pb p COLLISIONS



- **Forward region:** $1.5 < y^* < 4.0$
- p Pb (2013) @ $\sqrt{s_{NN}} = 5.02$ TeV
→ $L \sim 1.1 \text{ nb}^{-1}$
- p Pb (2016) @ $\sqrt{s_{NN}} = 8.16$ TeV
→ $L \sim 12.5 \text{ nb}^{-1}$



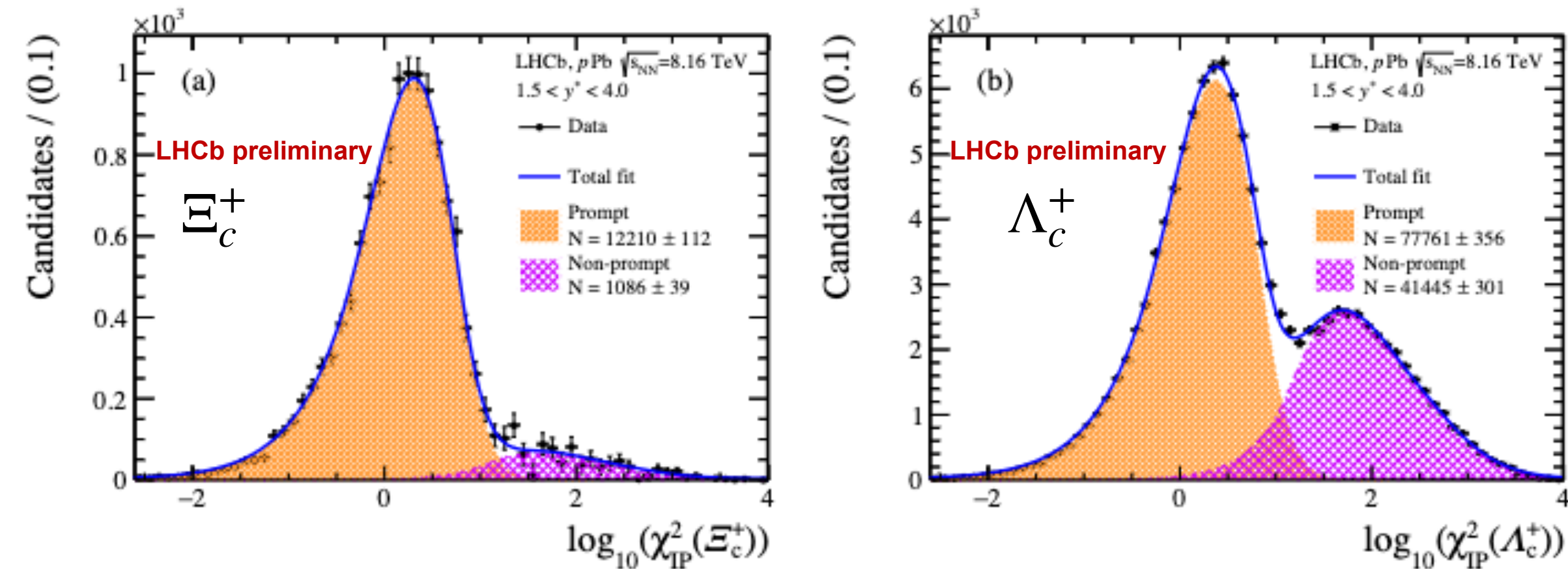
- **Backward region:** $-5.0 < y^* < -2.5$
- Pb p (2013) @ $\sqrt{s_{NN}} = 5.02$ TeV
→ $L \sim 0.4 \text{ nb}^{-1}$
- Pb p (2016) @ $\sqrt{s_{NN}} = 8.16$ TeV
→ $L \sim 17.4 \text{ nb}^{-1}$

Ξ_c^+ PRODUCTION IN $p\text{Pb}$ COLLISIONS AT $\sqrt{s} = 8.16$ TeV

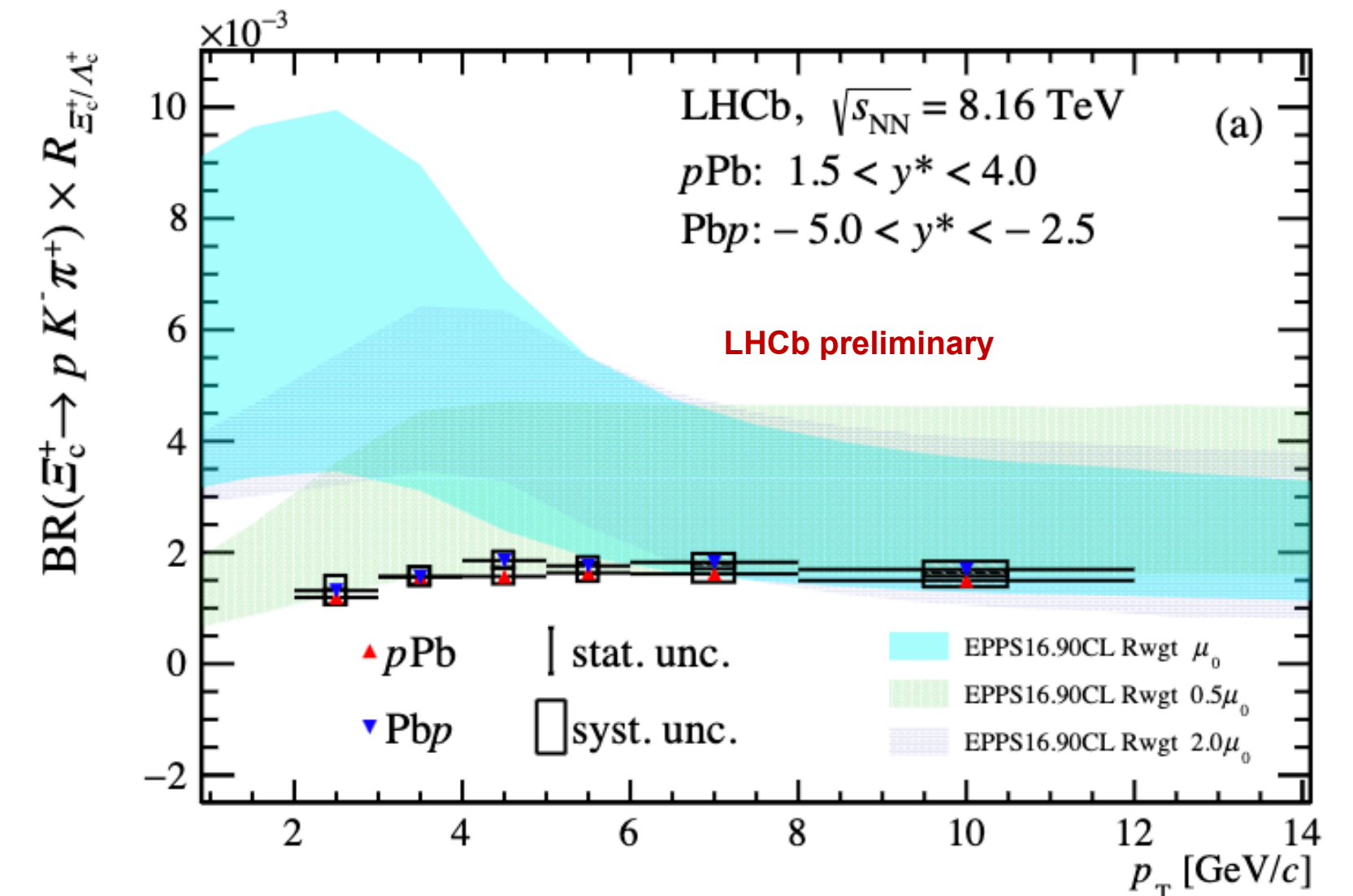
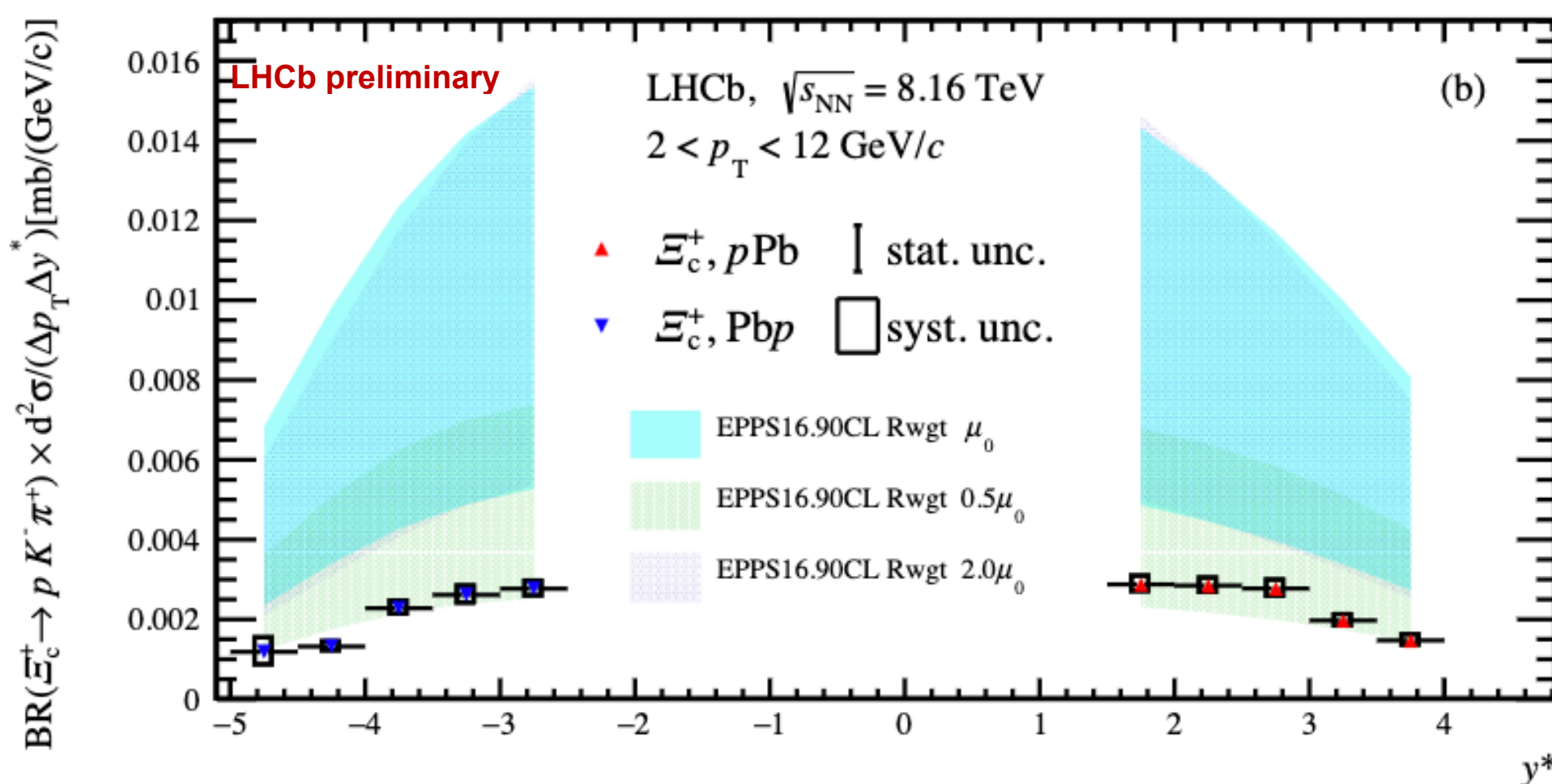
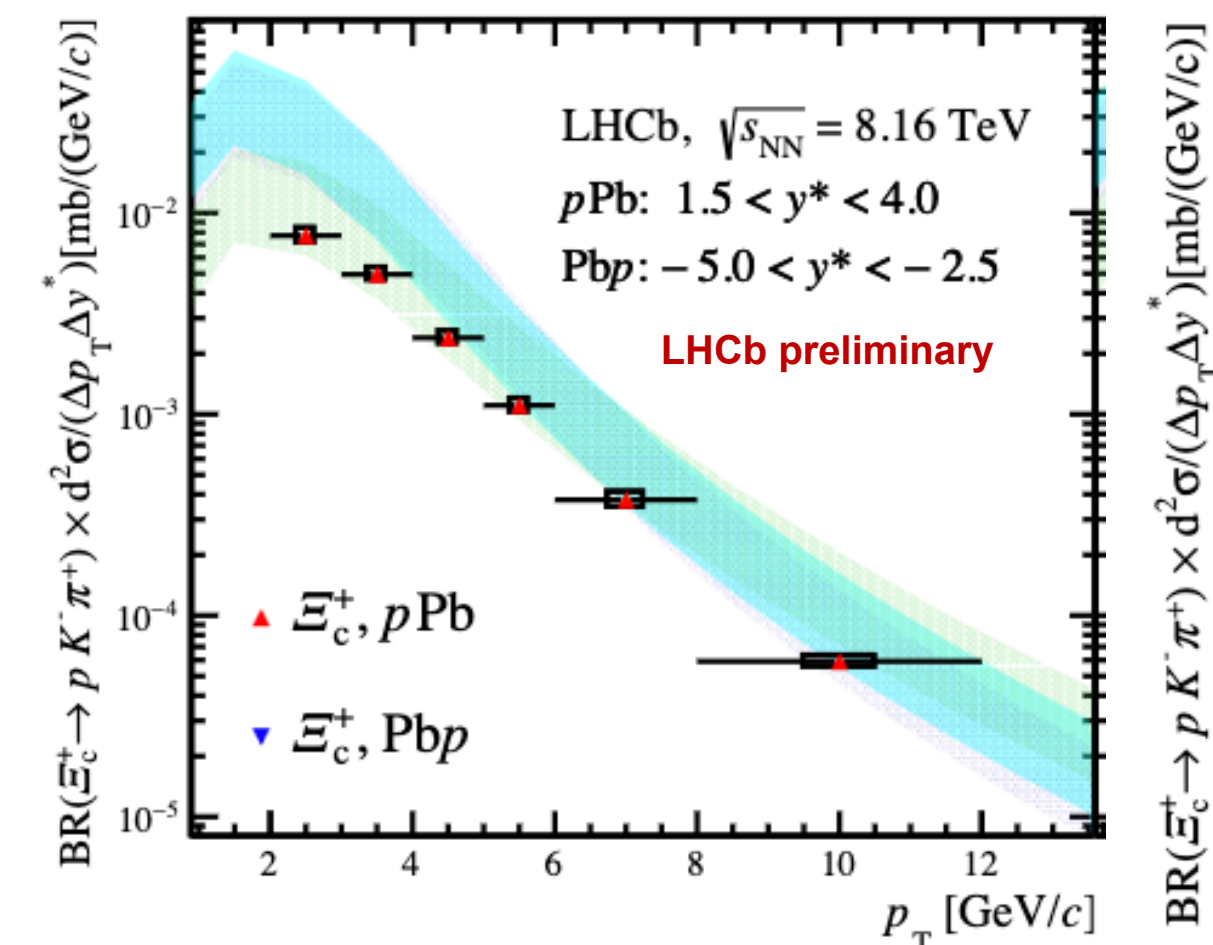
Arxiv:2305.06711,
submitted to PRL

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- ▶ First measurement of this baryon in heavy-ion collisions: $\Xi_c^+ \rightarrow p K^- \pi^+$
- ▶ Prompt Ξ_c^+ cross-section measured as a function of p_T and y^*
- ▶ Double Ξ_c^+ differential cross-section
 - ▶ Data compared with HELAC-Onia simulations with 3 factorisation scales
 - ▶ Better agreement with factorisation scale $0.5\mu_0$



- ▶ Measurement of the production ratio Ξ_c^+ / Λ_c^+
- ▶ No clear sign of strangeness enhancement



Theory: Phys. Rev. Lett. 121 (2018) 052004

PROMPT D^+ , D_s^+ PRODUCTION IN pPb COLLISIONS AT $\sqrt{s} = 5$ TeV 9

LHCb-PAPER-2023-006,
in preparation

▶ **First measurement of prompt D^+ and D_s^+ at low p_T and forward rapidities in heavy ion collisions**

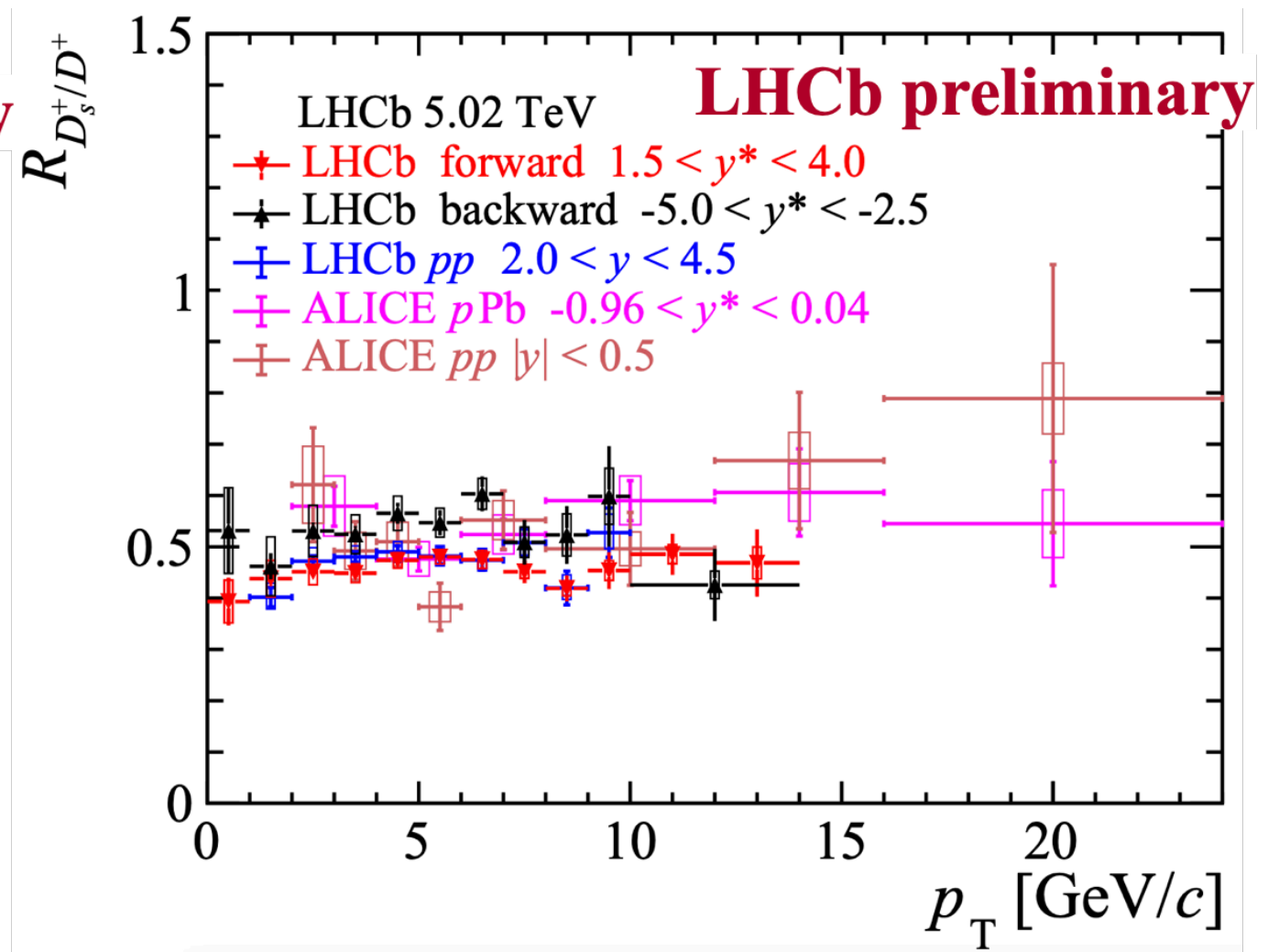
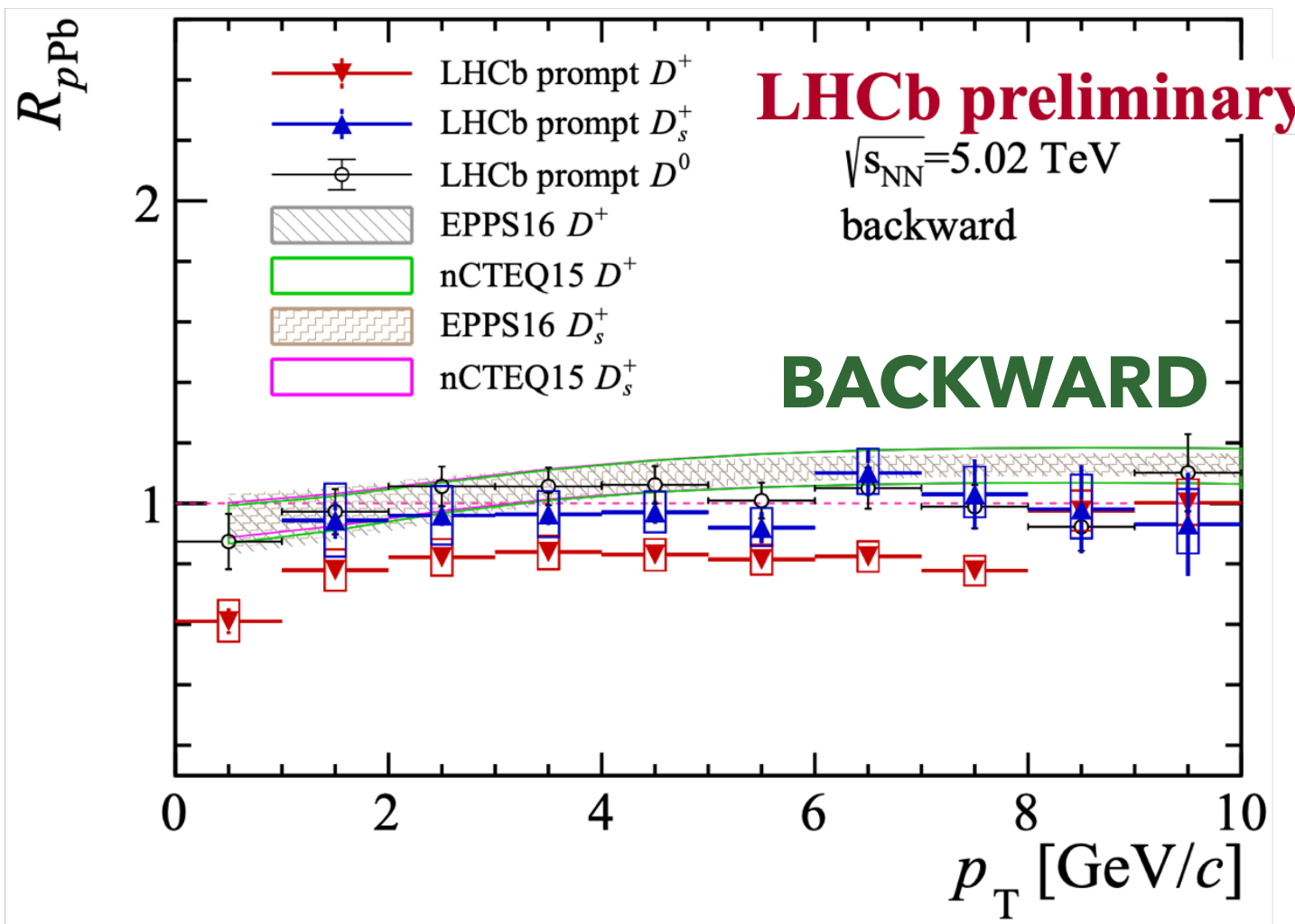
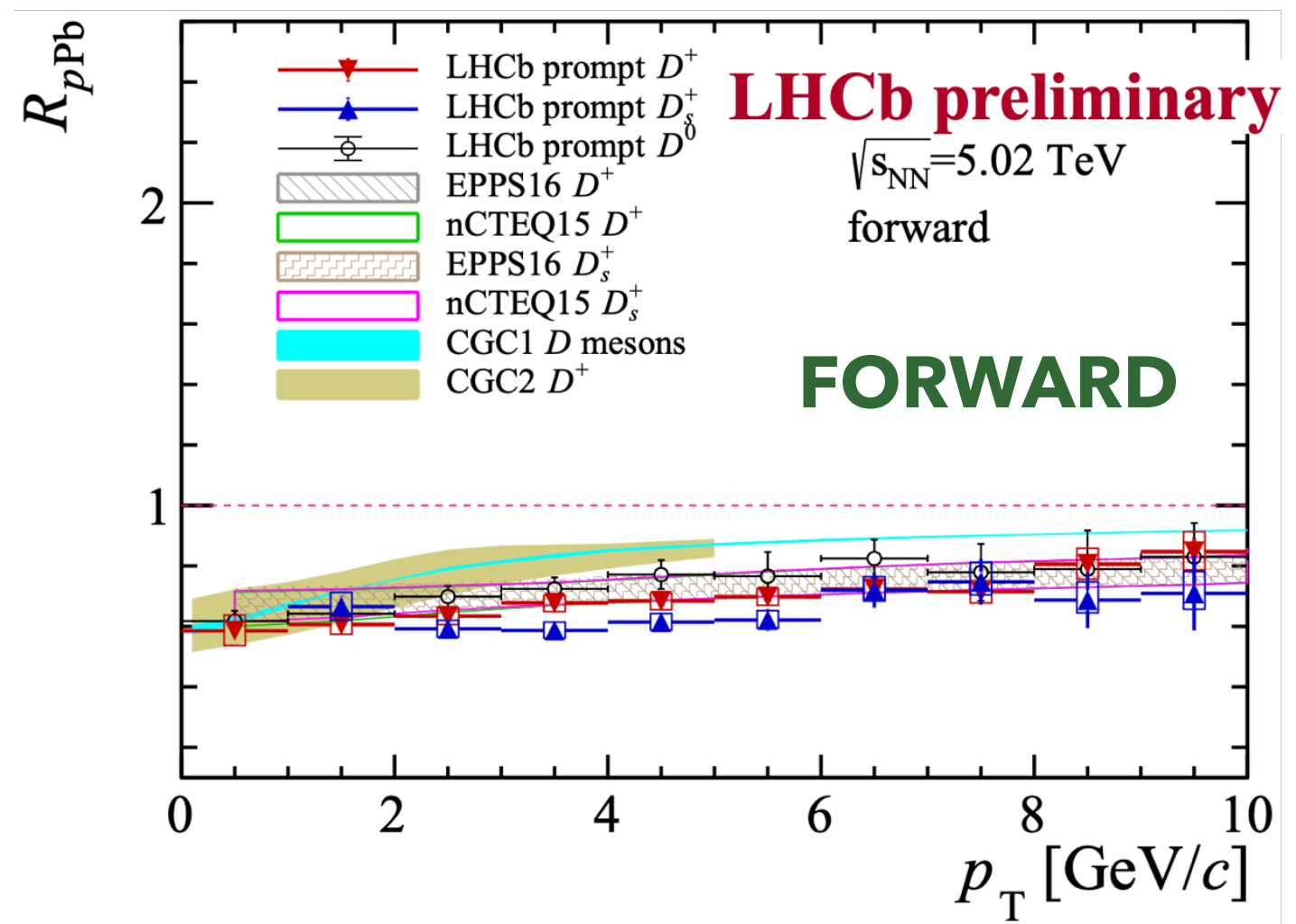
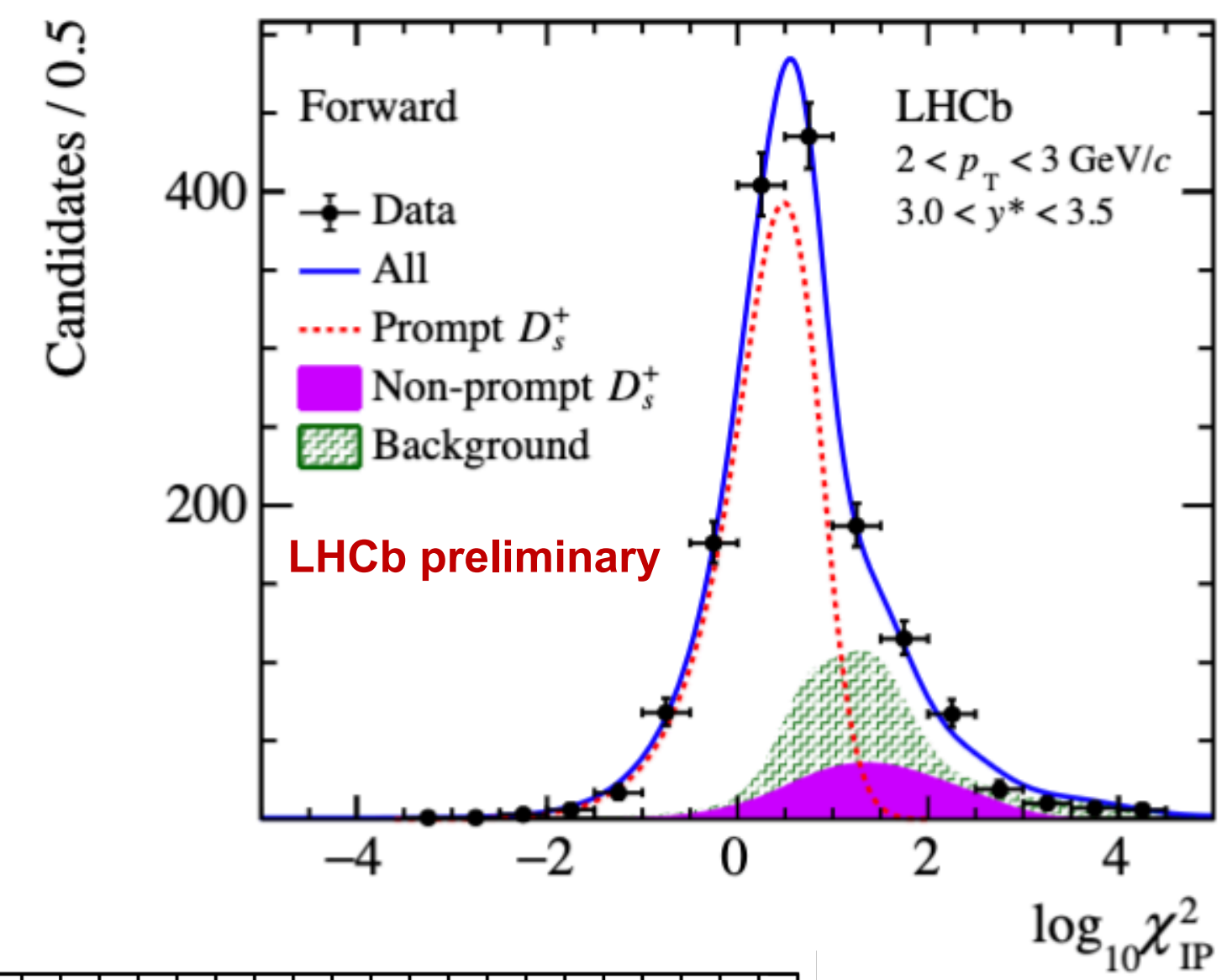
▶ **Forward:**

- ▶ Significant suppression consistent with nPDFs
- ▶ Consistent between D^0 , D^+ and D_s^+

▶ **Backward:**

- ▶ D_s^+ and D^0 in agreement with nPDFs
- ▶ D_s^+/D^+ ratio consistent with LHCb pp result and ALICE pp/pPb measurements at mid rapidity

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



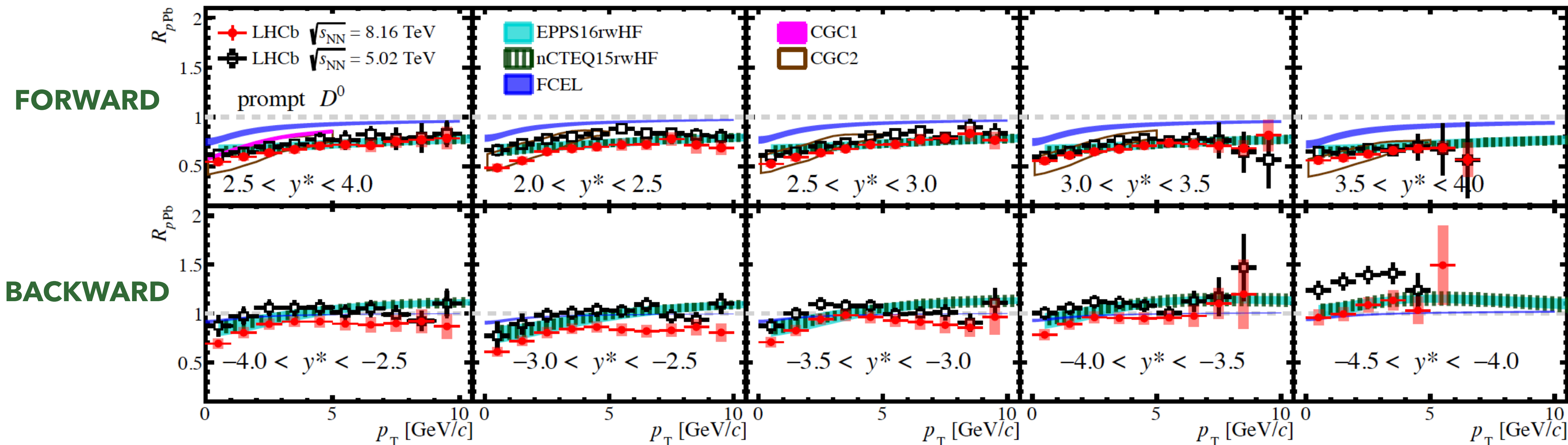
CGC1 : Phys. Rev. D91 (2015) 114005, arXiv:1503.02789, Nucl. Part. Phys. Proc. 289-290 (2017) 309, arXiv:1612.04585
CGC2: arXiv:1706.06728.
EPPS16: Eur. Phys. J. C 77 (2017)
CTEQ15: Phys. Rev. D 93 (2016) 085037

D^0 PRODUCTION IN pPb COLLISIONS AT $\sqrt{s} = 8.16$ TeV

Arxiv:2205.03936,
accepted by PRL

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- ▶ Measurements of D^0 nuclear modification factor important to disentangle **charmonia** and **open charm effects**



▶ Forward:

- ▶ Suppression observed consistent with 5 TeV result
- ▶ In agreement with nPDF and CGC predictions

▶ Backward:

- ▶ **Data lower than nPDF at high p_T**
- ▶ Additional effects?

π^0 PRODUCTION IN pPb COLLISIONS AT $\sqrt{s} = 8.16$ TeV

Arxiv:2204.10608,
accepted by PRL

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- ▶ **First π^0 measurements** in forward rapidity at LHC

$$\pi^0 \rightarrow \gamma\gamma$$

- ▶ **Forward:**

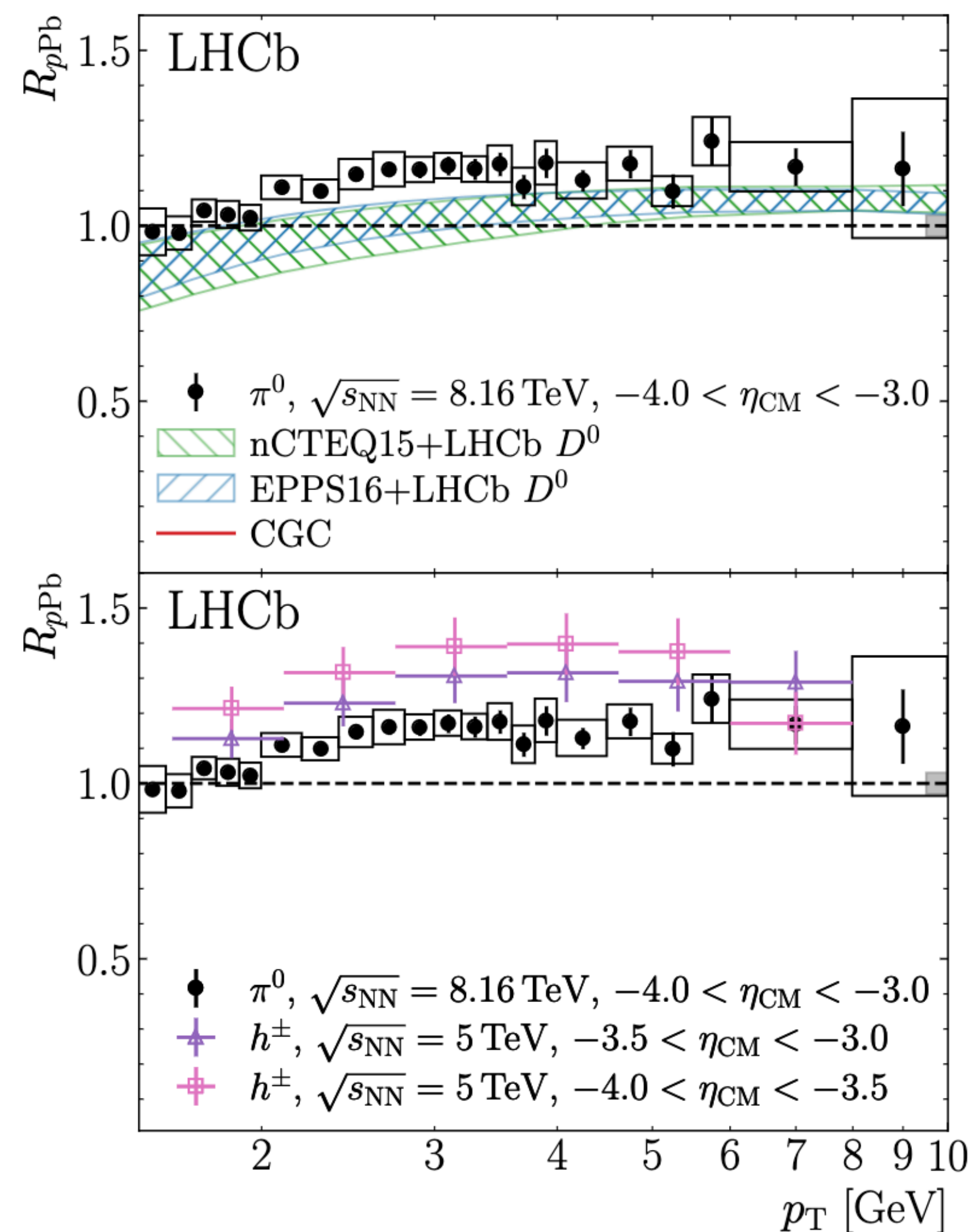
- ▶ More precise than nPDF calculation
- ▶ Consistent with charged hadrons

- ▶ **Backward:**

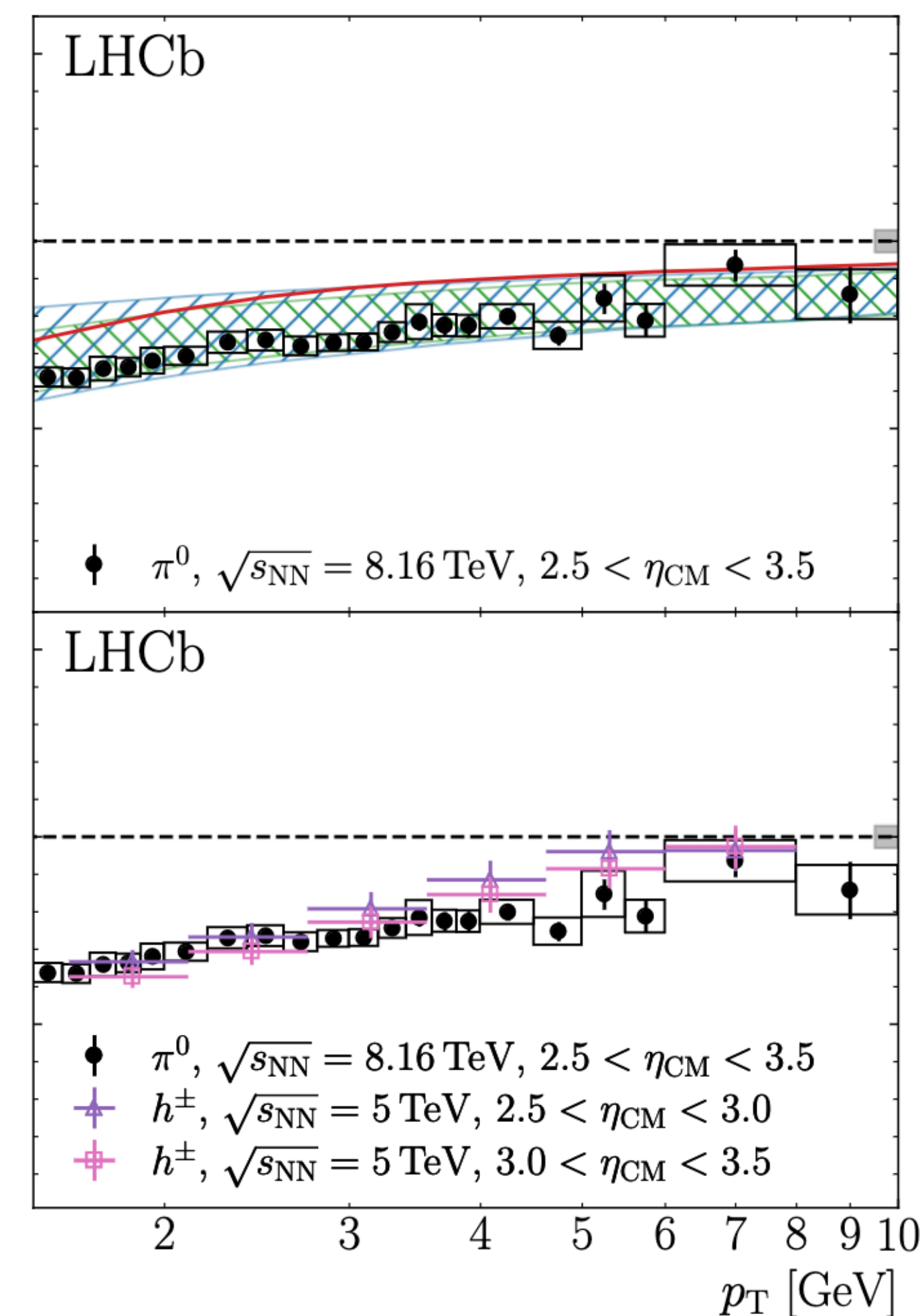
- ▶ **Enhancement above nPDFs**
- ▶ Lower than charged hadrons, mass ordering effects?

- ▶ Open the route to direct photon production measurements

BACKWARD



FORWARD



LEAD-LEAD

CHARMONIUM PRODUCTION IN UPC PbPb AT $\sqrt{s} = 5$ TeV

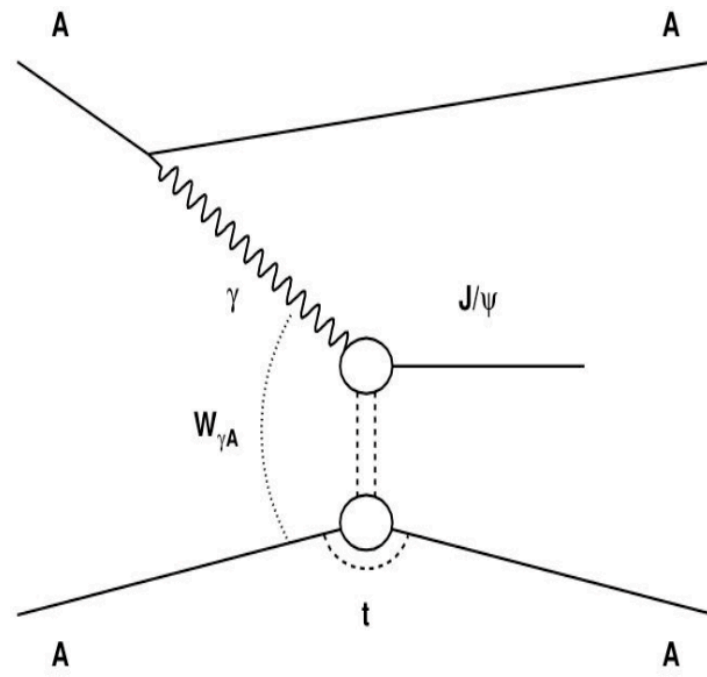
ArXiv:2206.08221,
submitted to JHEP

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coherent photo-production

▶ Ultra-peripheral lead-lead collisions:

- ▶ Impact parameter $b > R_A + R_B$
- ▶ **Coherent charmonia** produced by interaction between photon and pomeron
- ▶ Probe for the **gluon density distribution functions**

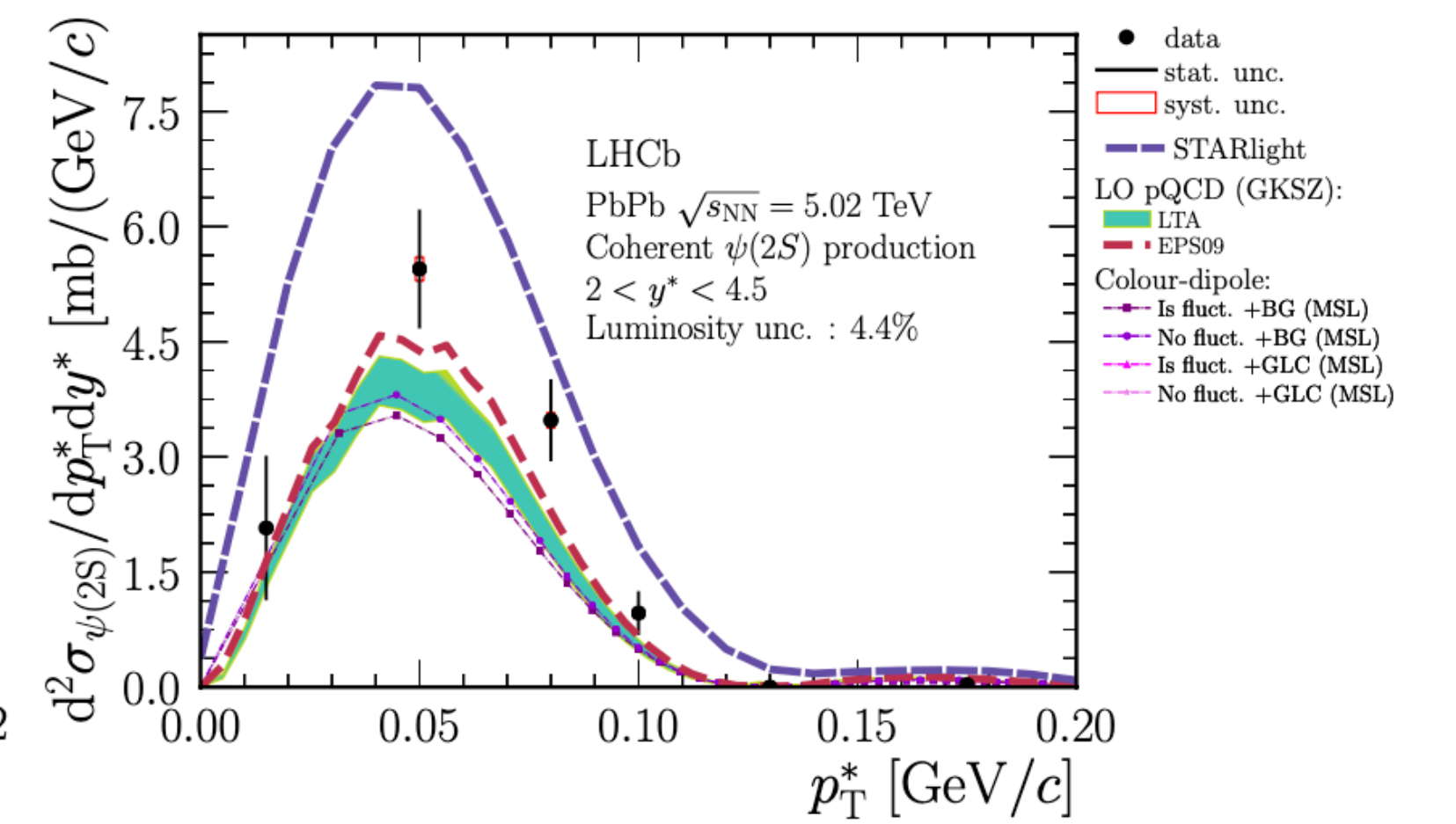
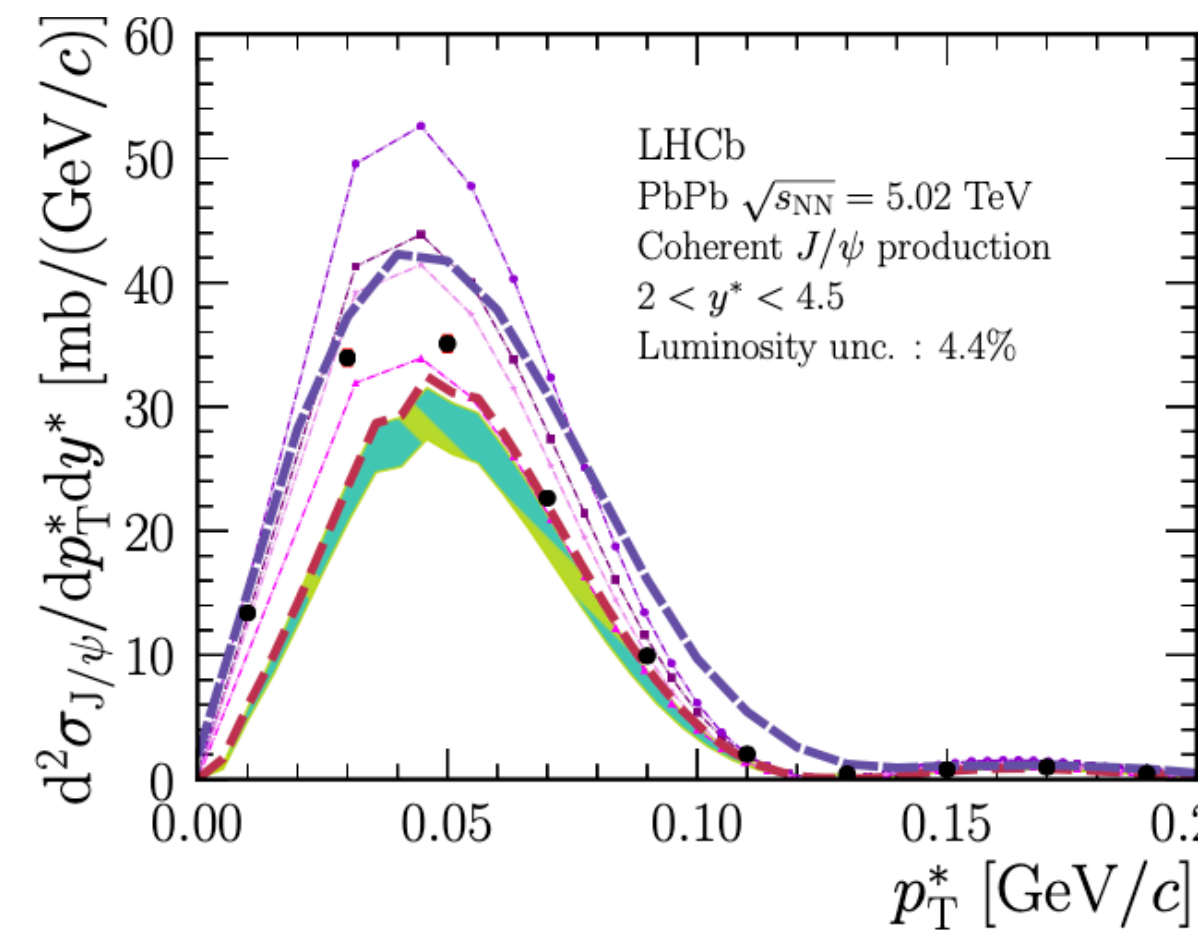
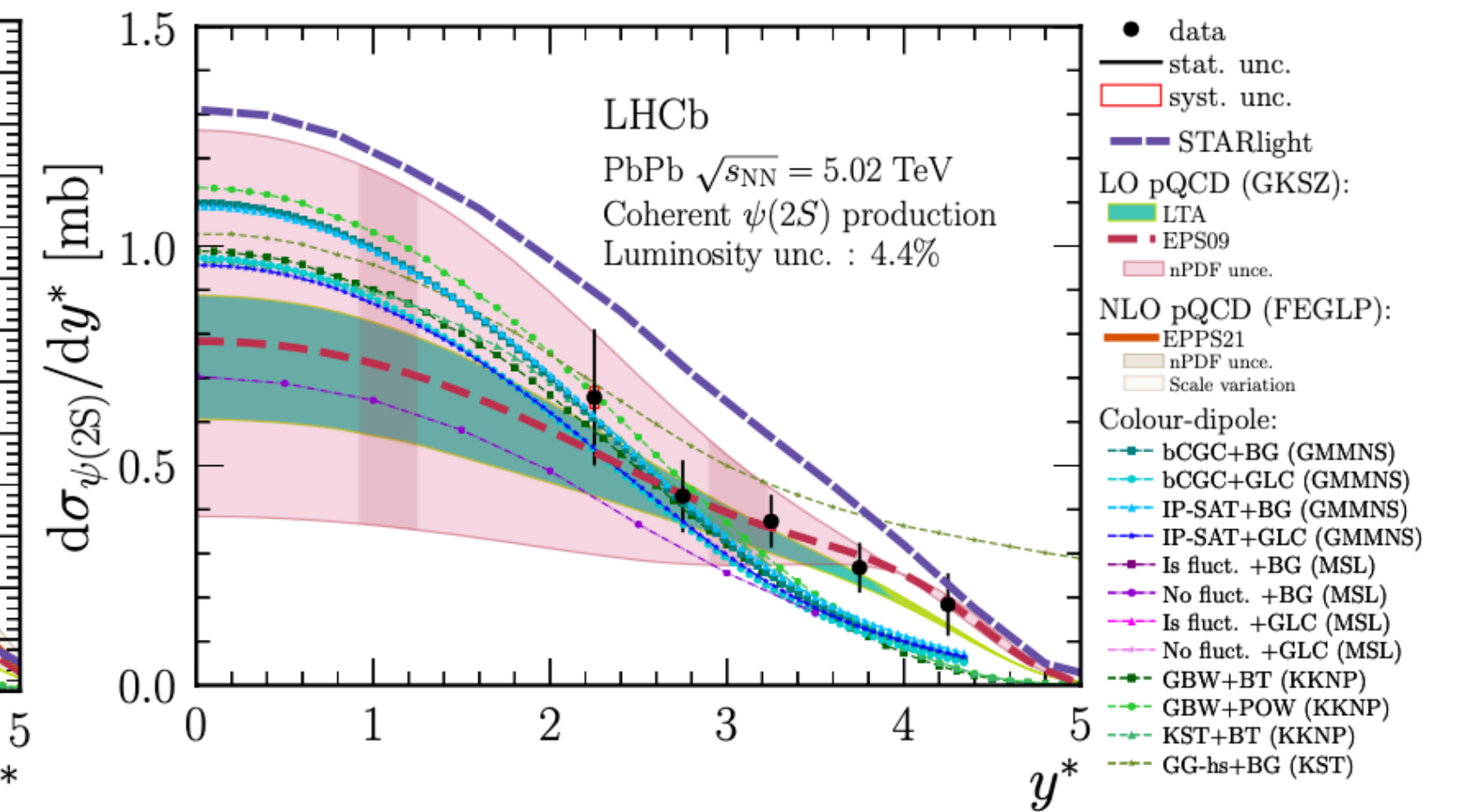
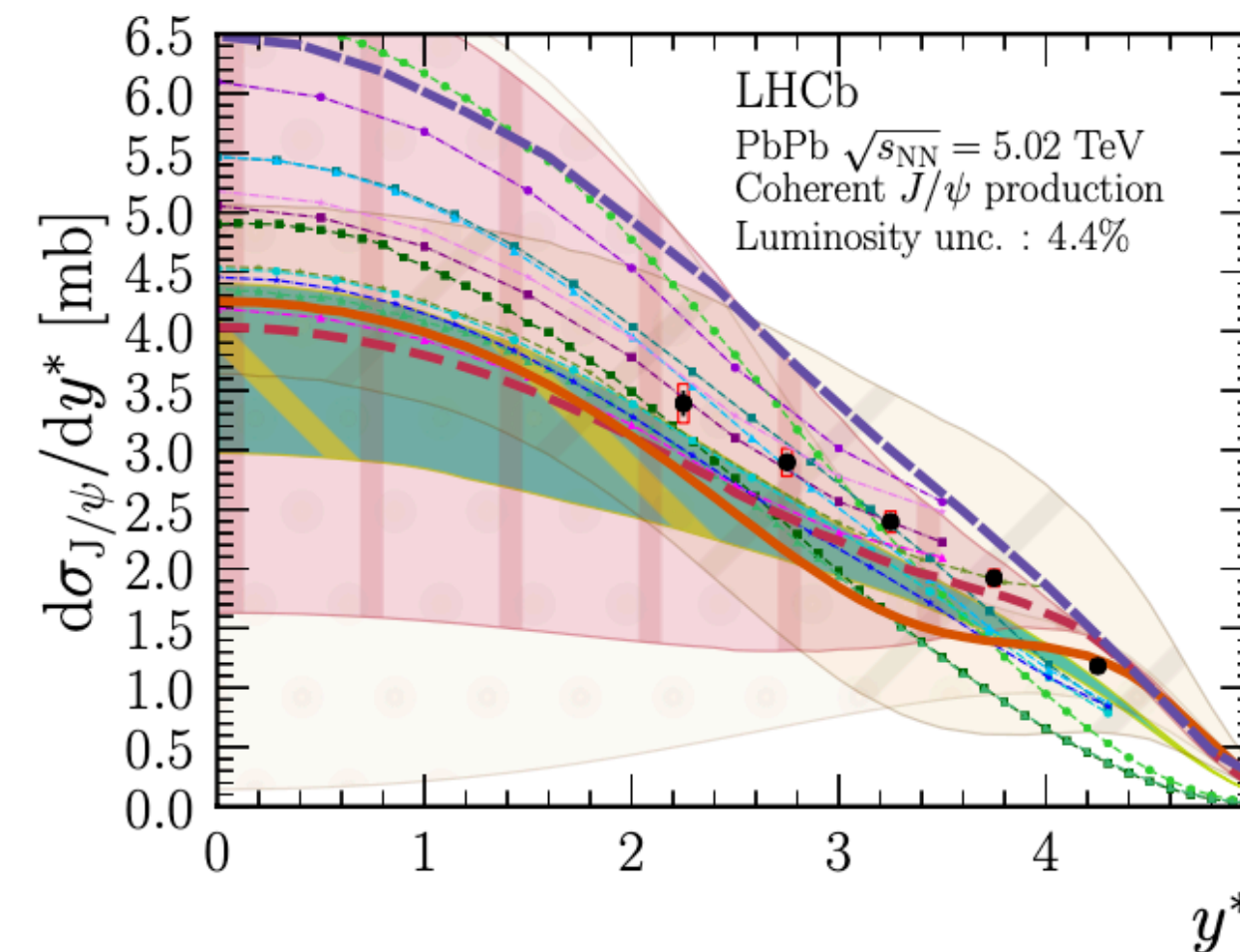


▶ **The most precise measurement of the coherent J/ψ**

▶ **First coherent $\psi(2S)$ forward measurement at LHC**

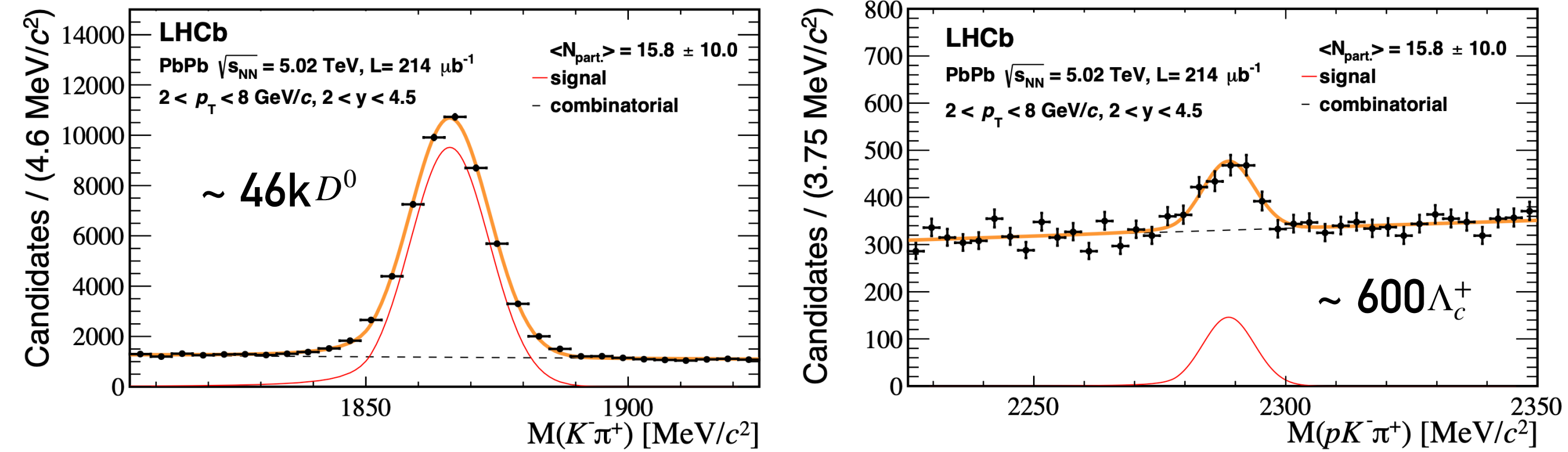
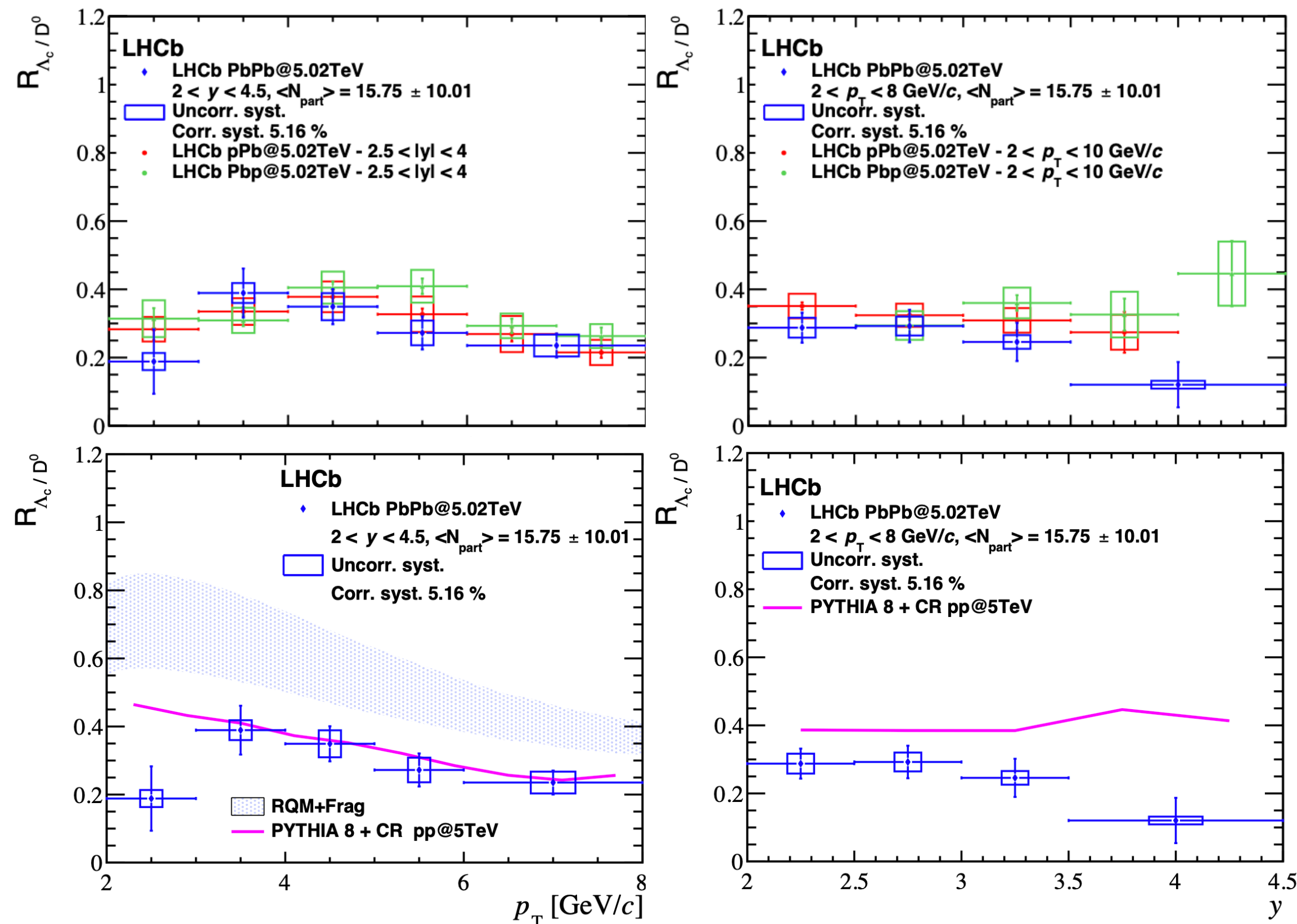
▶ **Reasonable description of data by models based on nPDF/CGC**

▶ J/ψ uncertainty much smaller than the spread of theoretical curves



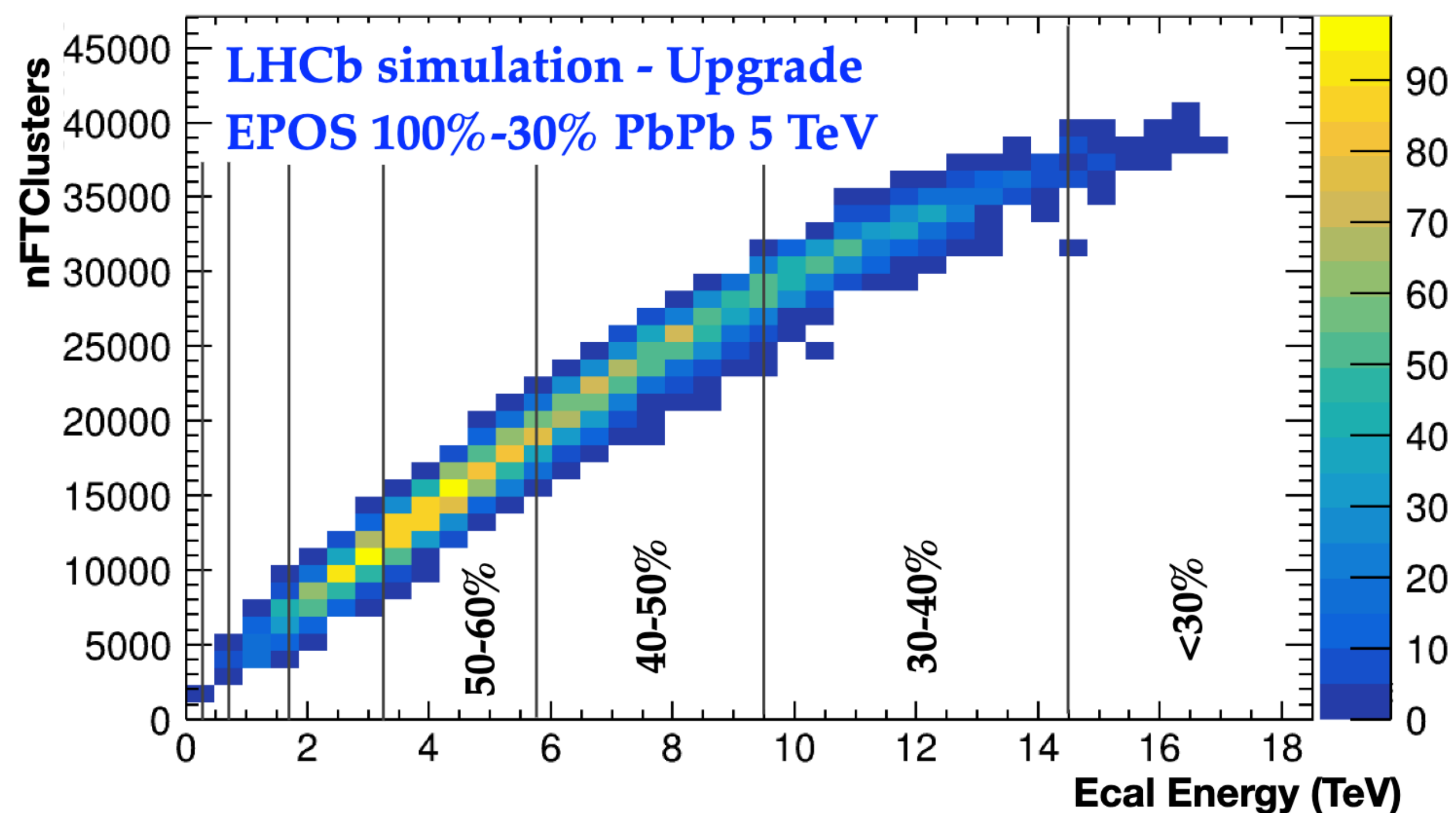
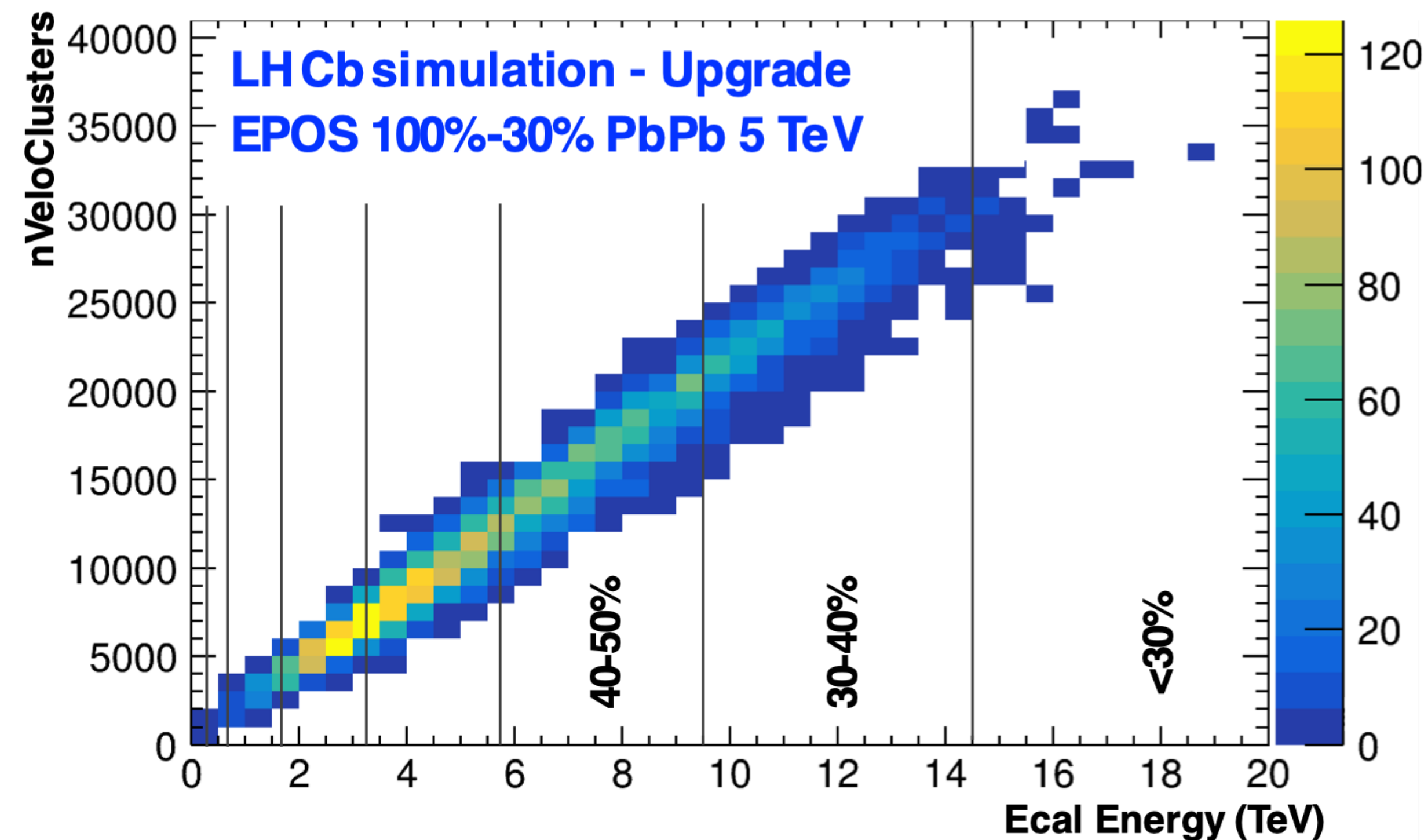
Λ_c^+ AND D^0 IN PERIPHERAL PbPb AT $\sqrt{s} = 5$ TeV

- ▶ **First measurement of the ratio Λ_c^+/D^0 in PbPb at forward rapidities**
- ▶ Important to probe the **c-quark hadronization**



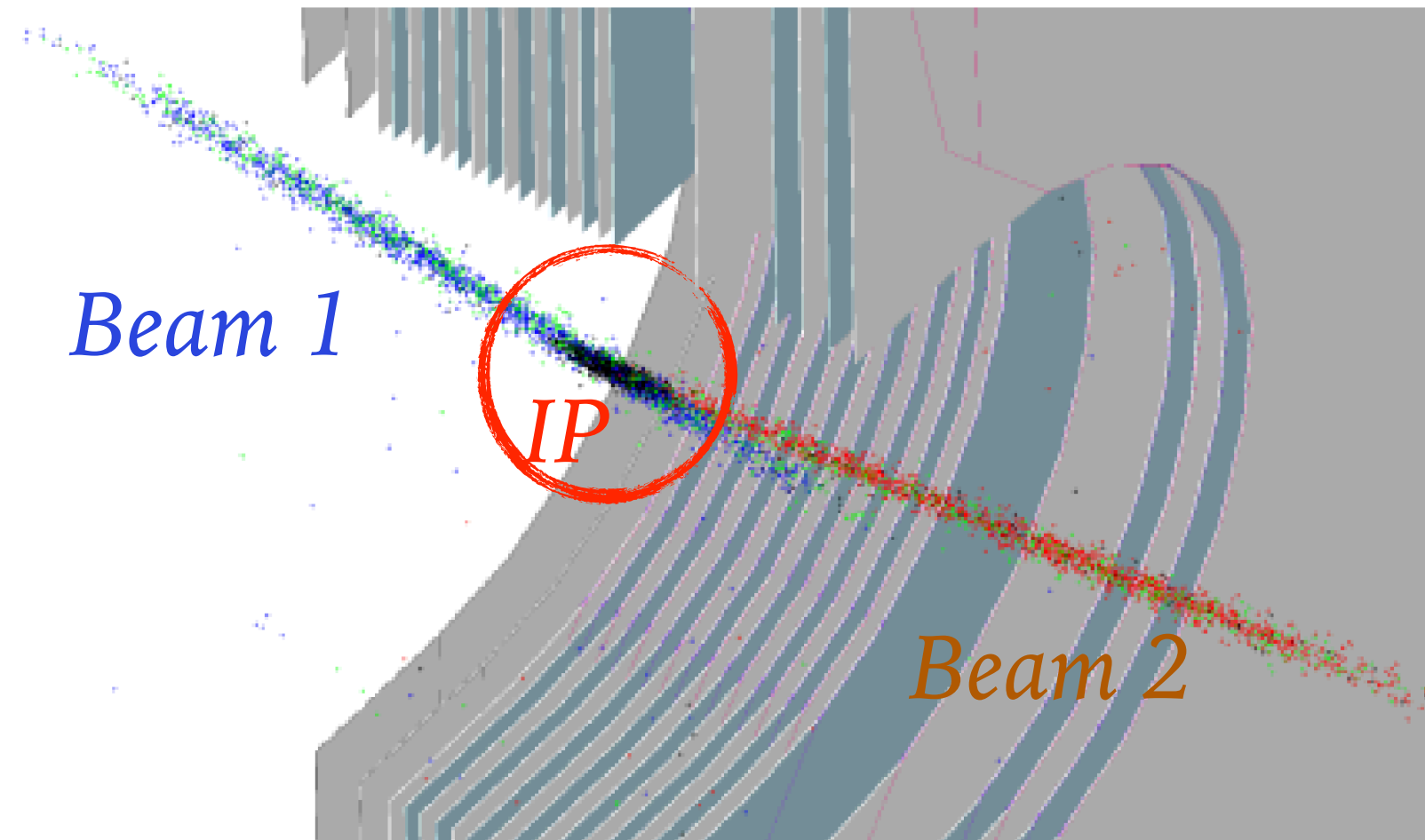
- ▶ **Results consistent with previous LHCb measurements in pPb collisions at the same energy**
- ▶ **Agreement with PYTHIA8 vs. p_T simulations including colour reconnection**
- ▶ Tension with the Statistical Hadronization Model
- ▶ Need more data to understand charm hadronization

RUN3 CONFIGURATION



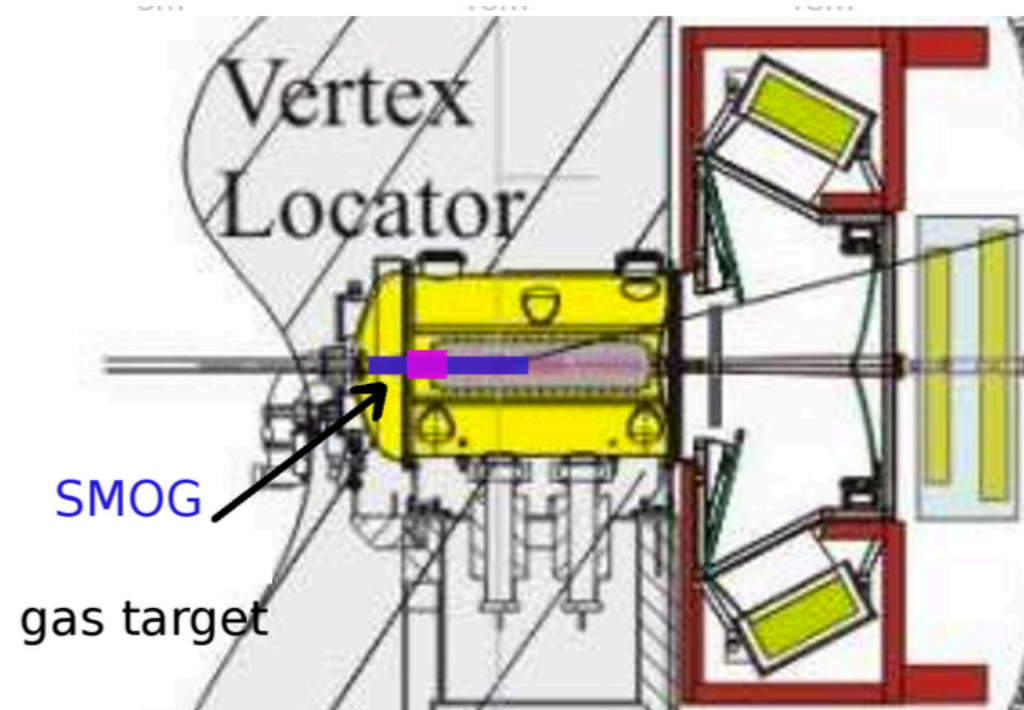
No saturation up to 30% centrality!

FIXED-TARGET



▶ **SMOG**: System for Measuring Overlap with Gas

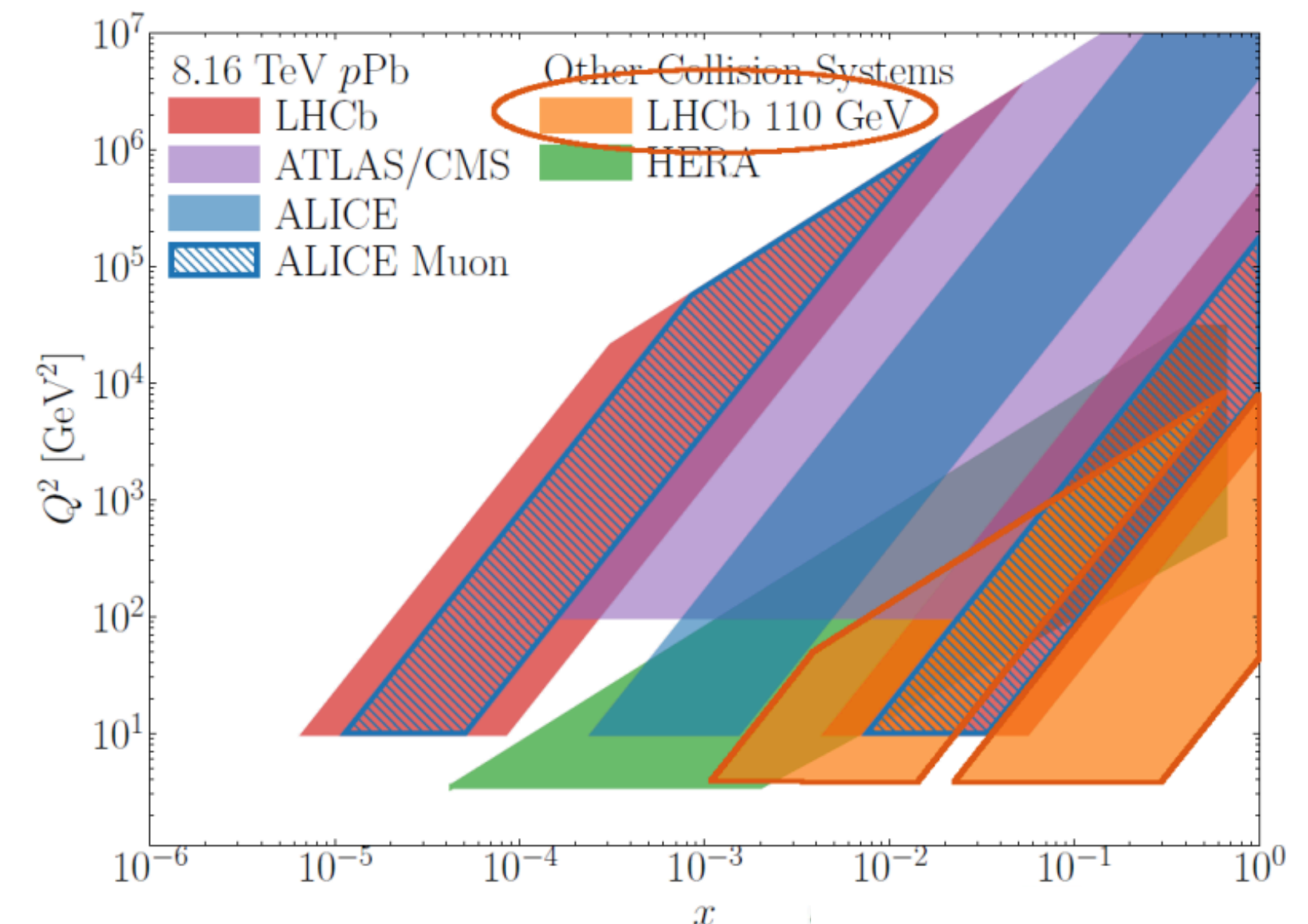
- ▶ **Noble gases (He, Ar, Ne) injected** into the LHC beam pipe around the Interaction Point (IP), $P \sim 10^{-7}$ mbar
- ▶ **Highest-energy** fixed-target experiment ever built → bridge between the SPS and LHC energies



▶ **Unique kinematical region** accessible

▶ $\sqrt{s_{NN}} \sim \sqrt{2E_N M_N} = 41 - 115 \text{ GeV}$

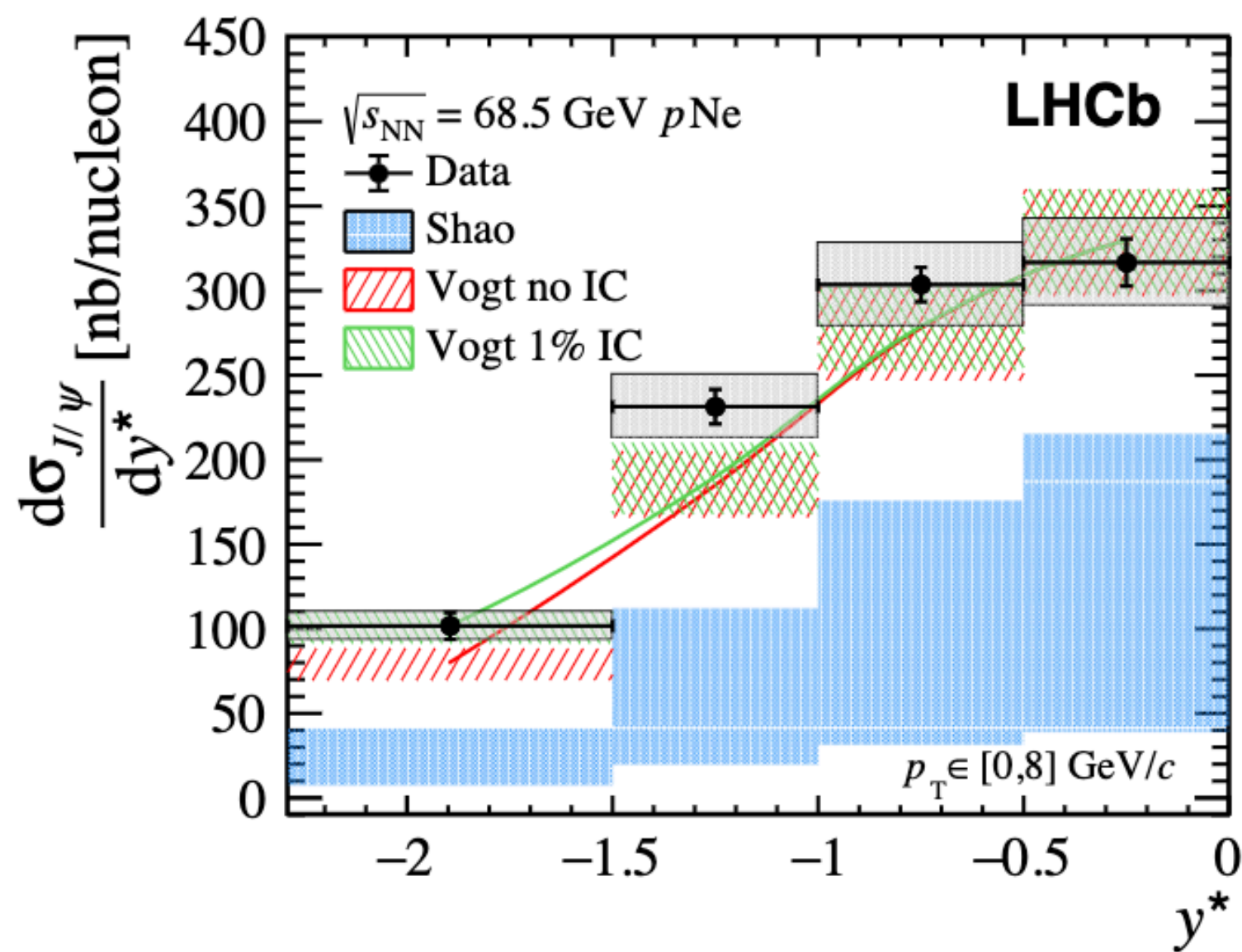
▶ Investigates the **high- x** of the nucleon target at **intermediate Q^2**



CHARMONIUM IN $p\text{Ne}$ COLLISIONS AT $\sqrt{s} = 68.5$ GeV

► **Charmonium production** good probe for QCD $\rightarrow c\bar{c}$ bound state suppression is one of the smoking guns of **QGP formation**

► **pA collisions** are crucial to study **CNM (Cold Nuclear Matter)** effects which **can mimic QGP presence in AA**



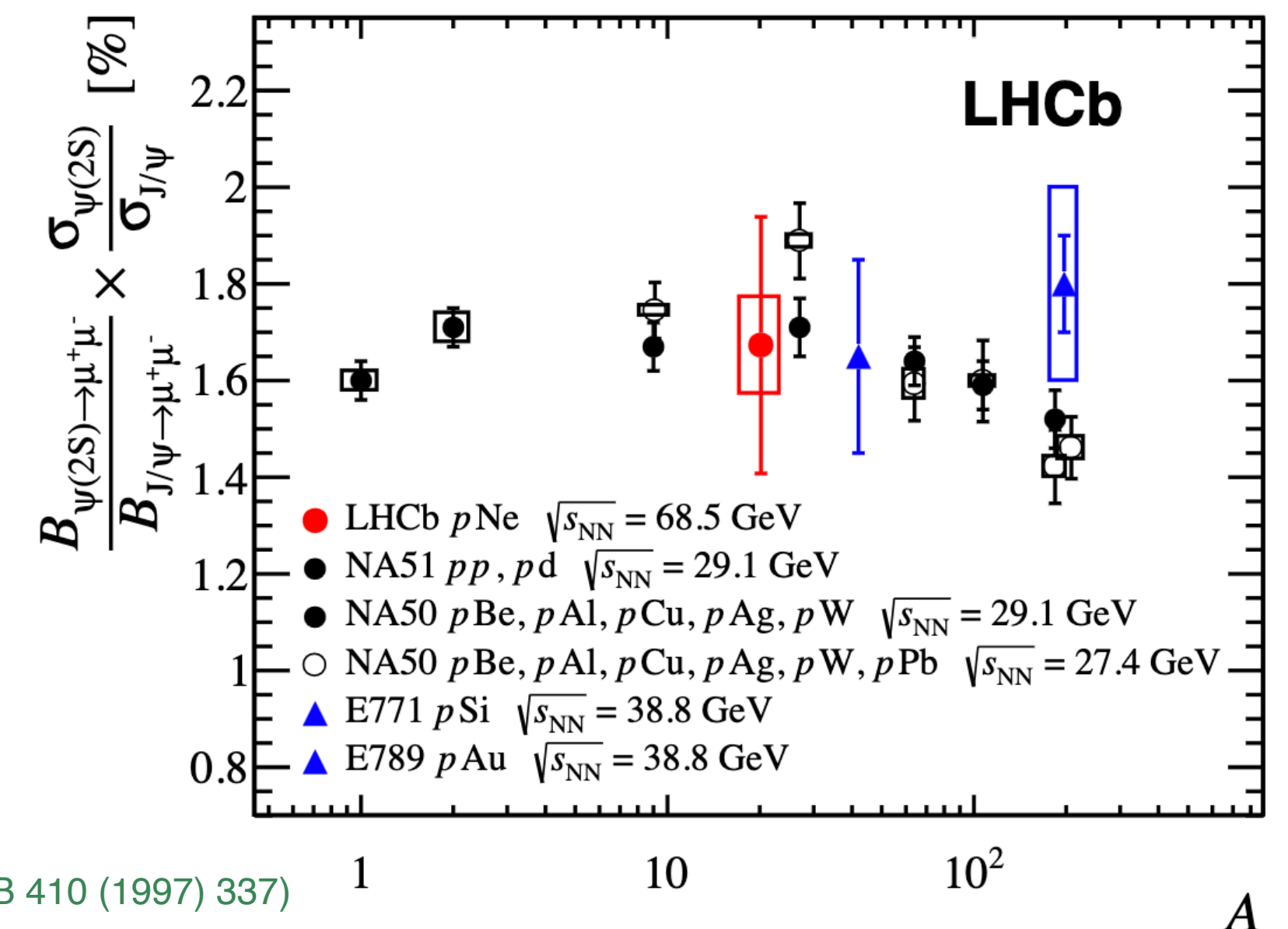
► J/ψ differential cross section

- Data in **agreement with Vogt's predictions** but **not sensitive to Intrinsic Charm (IC)**.
- **HELAC-Onia** simulations **underestimate** the cross section

THEORY:
Eur.Phys.J.C77(2017),
Phys. Rev.C103(2021)035204

► $\psi(2S)$ to J/ψ production ratio as a function of the target nuclei

- **Good agreement with other fixed-target experiments** at lower energies and different atomic mass number A



J/ψ AND D^0 PRODUCTION IN PbNe COLLISIONS AT $\sqrt{s} = 68.5$ GeV ¹⁹

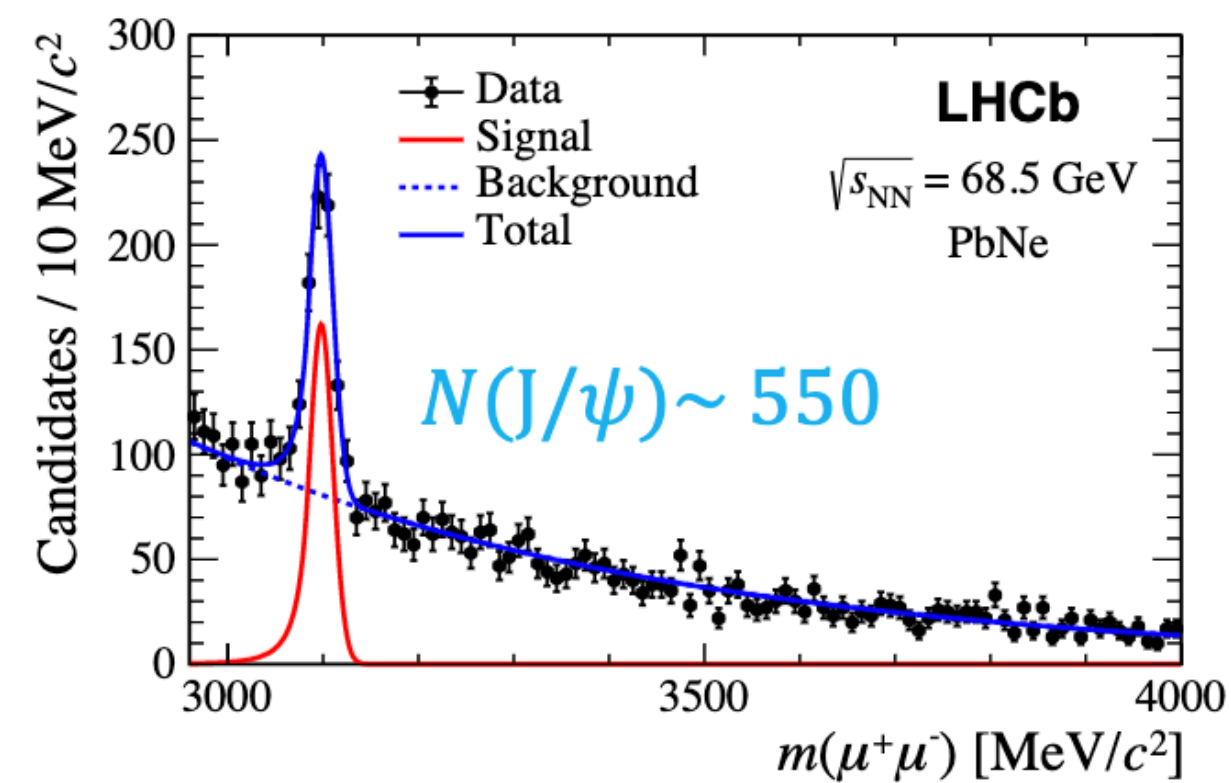
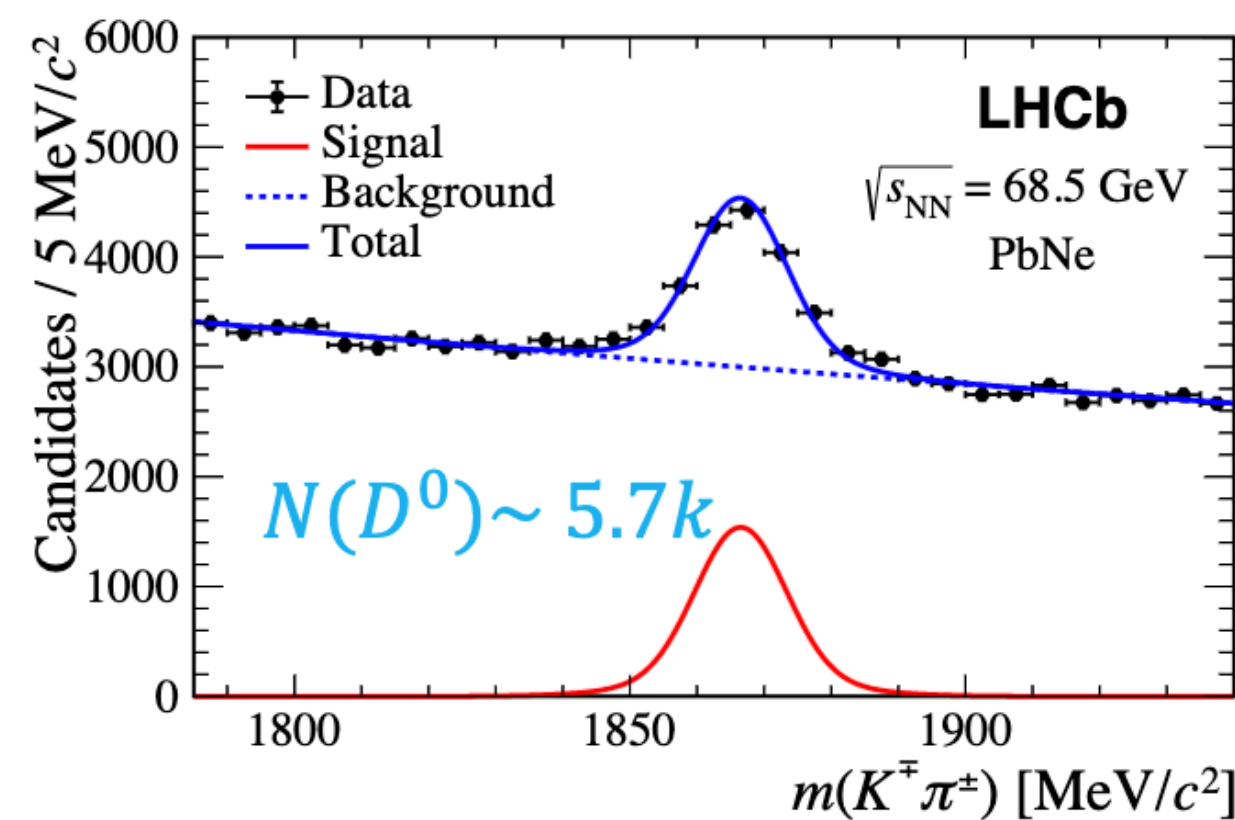
Arxiv: 2211.11652,
submitted to EPJC

▶ J/ψ and D^0 behave differently in the medium

▶ D^0 production

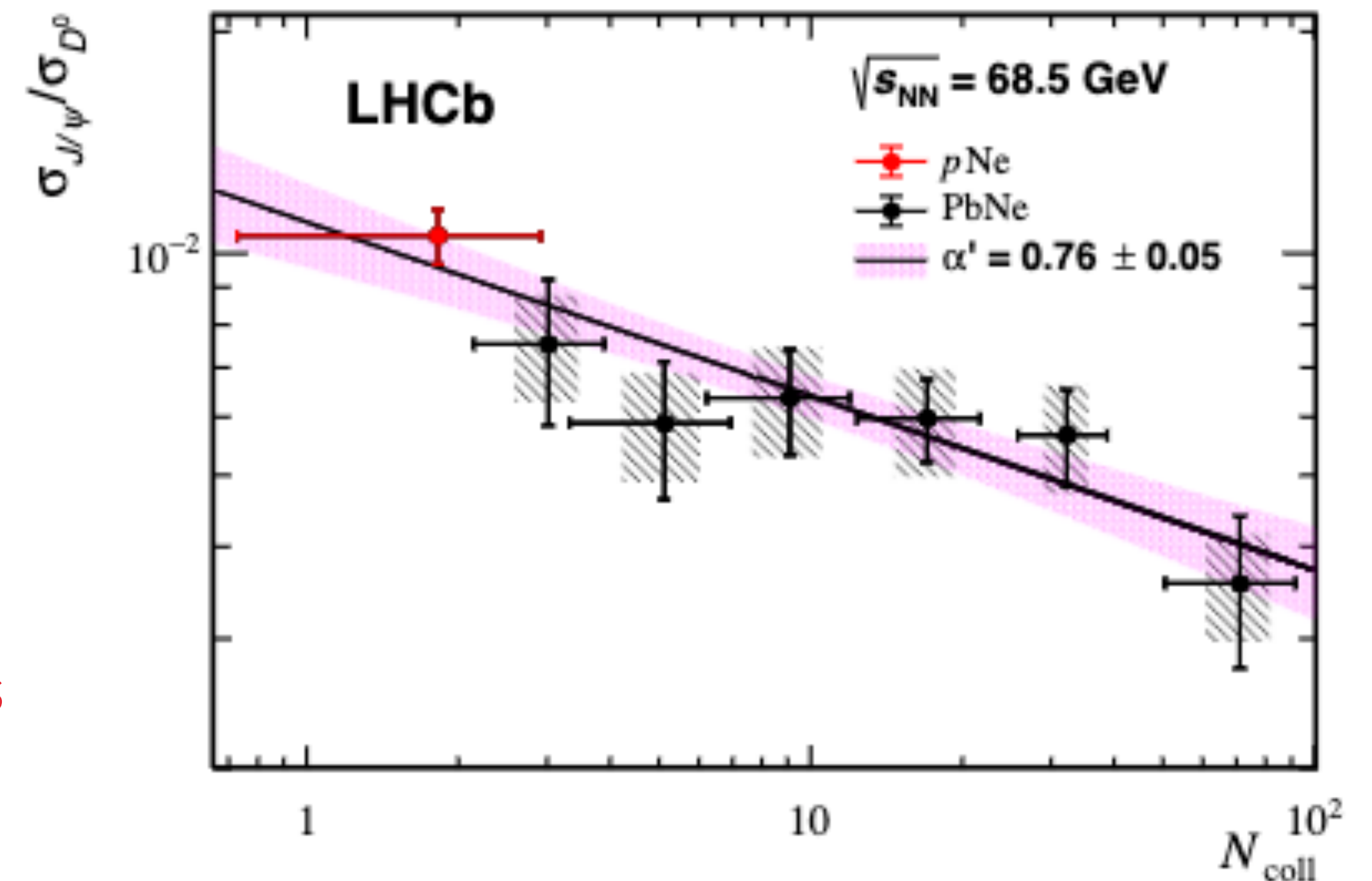
- good reference for the total charm cross-section

▶ J/ψ and D^0 invariant mass distributions



▶ Comparison of the $J/\psi/D^0$ ratio between PbNe and p Ne

- J/ψ is affected by additional nuclear effects with respect to D^0 , but the **suppression trend is similar from p Ne to PbNe** in largest N_{coll} bin

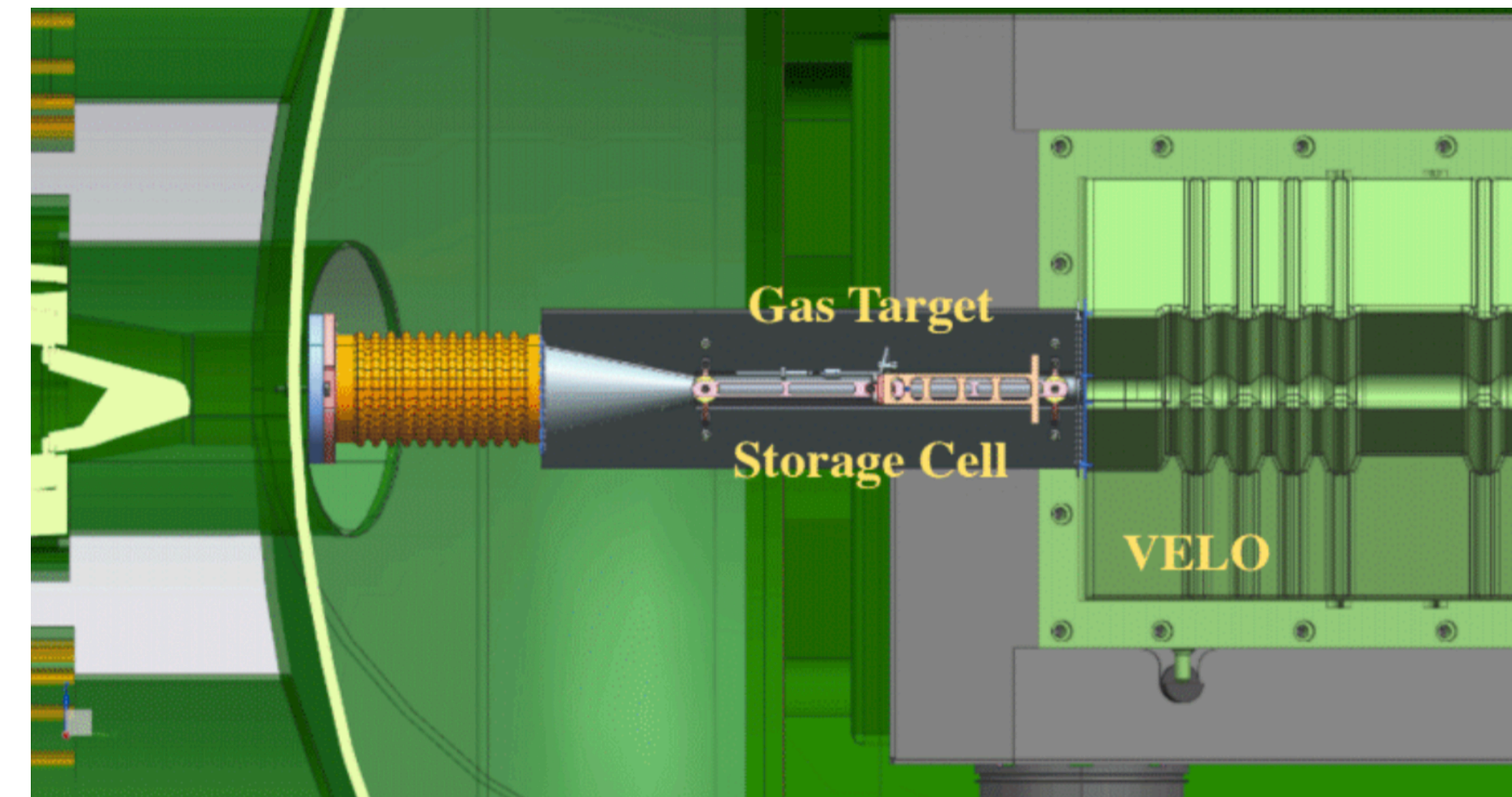
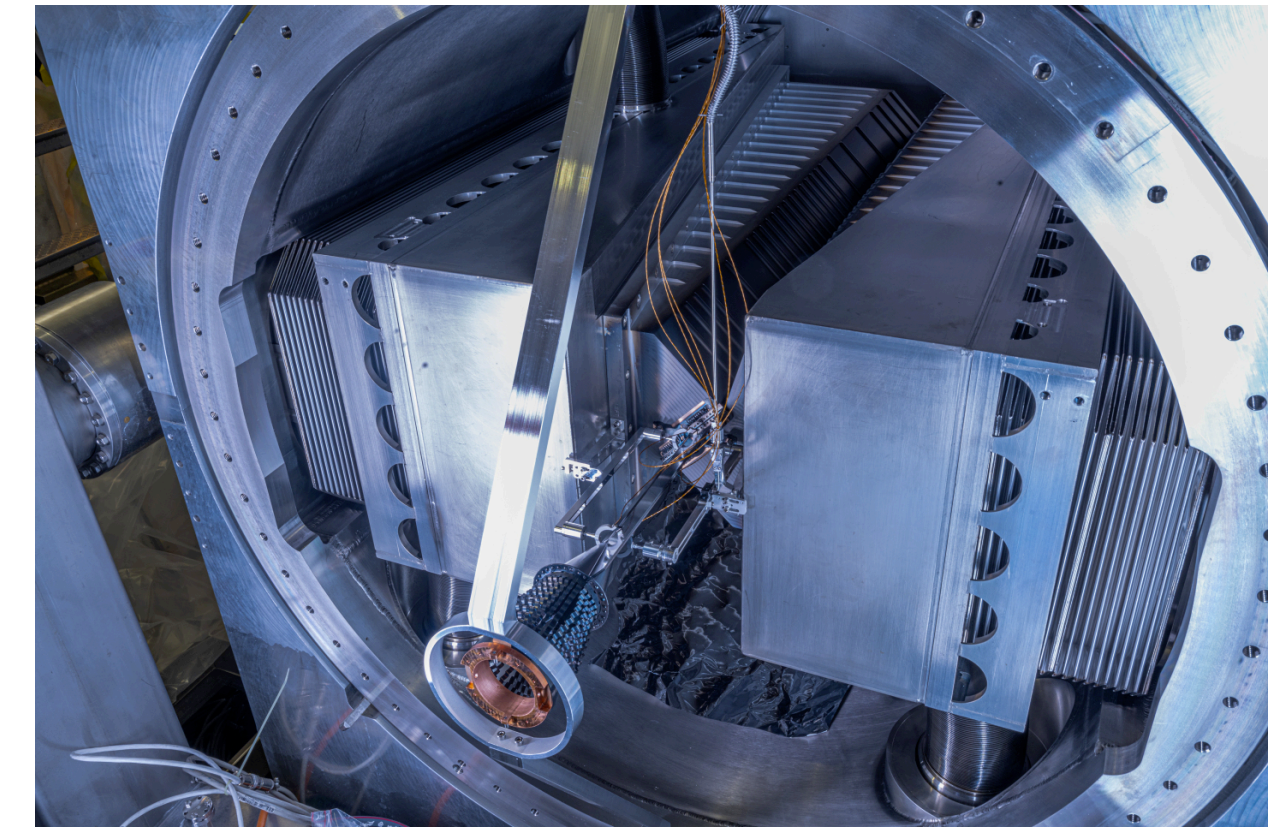


- **First measurement** in fixed-target nucleus-nucleus collisions

FIXED TARGET COLLISIONS AT LHCb: SMOG2

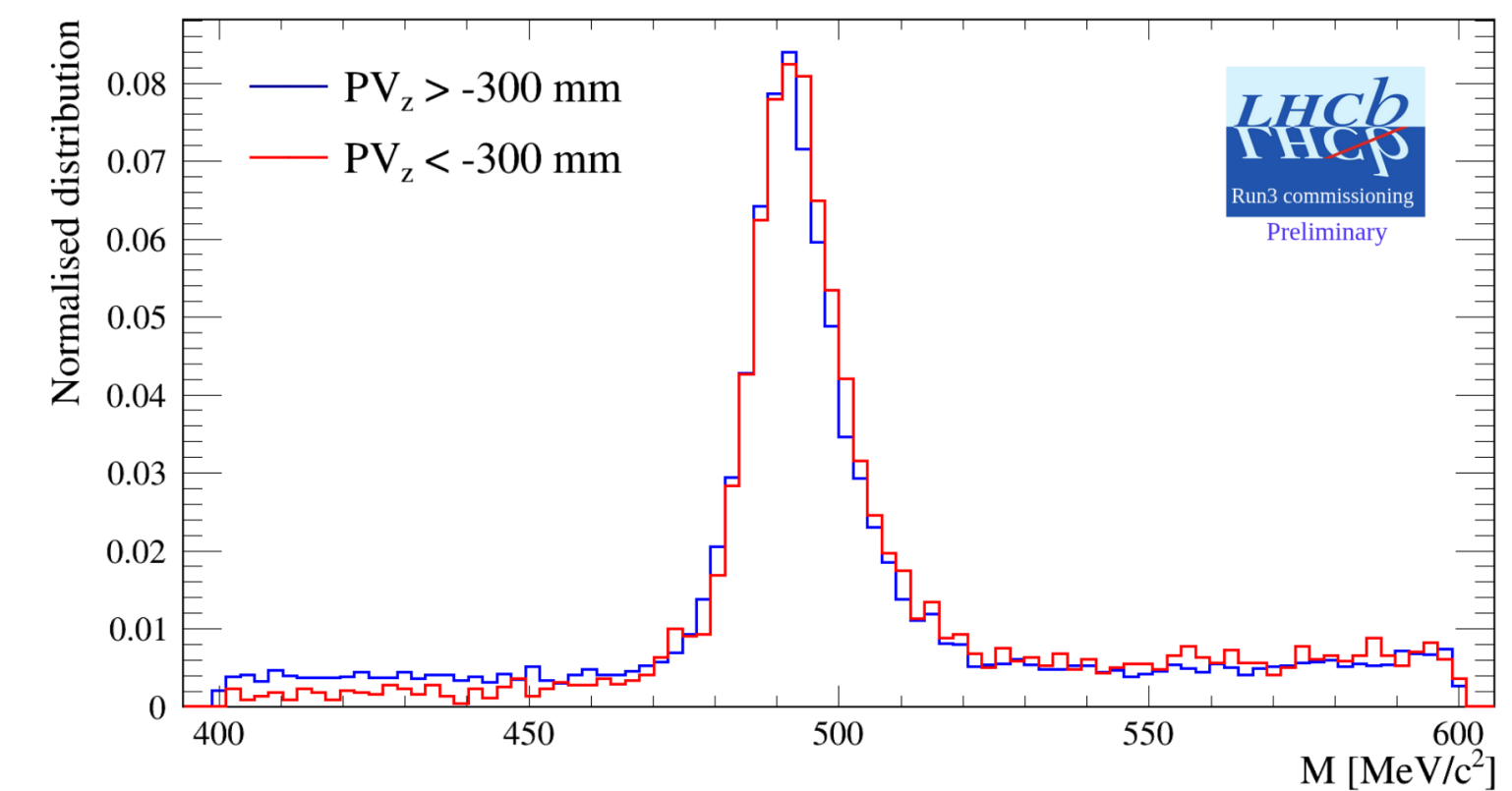
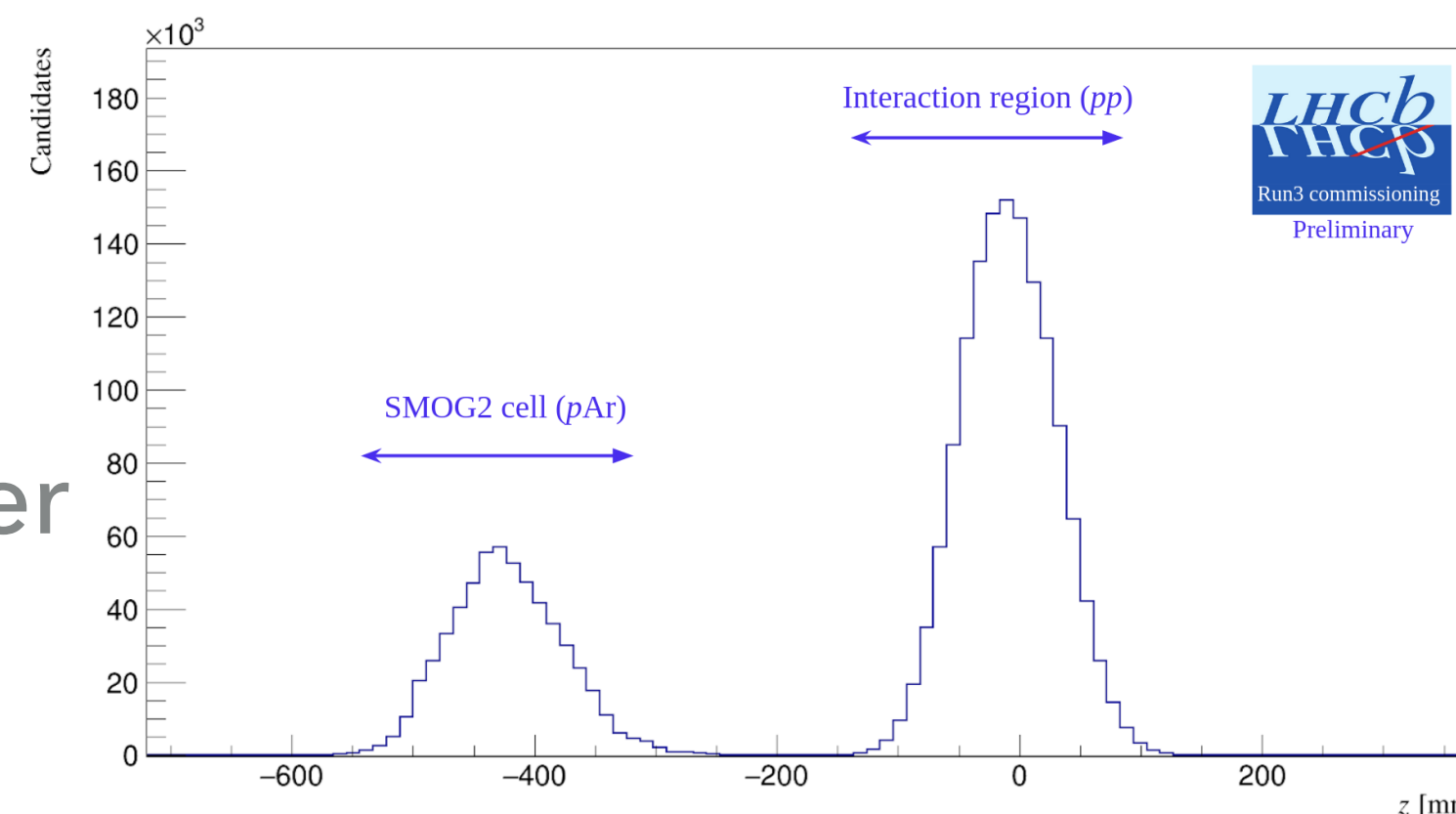
- ▶ **SMOG2:** gas confined in a 20 cm long **storage cell**
- ▶ **Higher areal density** than SMOG (luminosity increased up to $\sim \times 100$)
- ▶ **Wider choice of gases to be injected:** $H_2, D_2, He, Ne, N_2, O_2, Ar, Kr, Xe$
- ▶ **Data taken simultaneously in pp and pA modes**

RUN3 CONFIGURATION



▶ **Data collected in November 2022:**

- **Independent interaction point** between pp and pA
- **Same resolution** of the spectrometer for the two collision modes

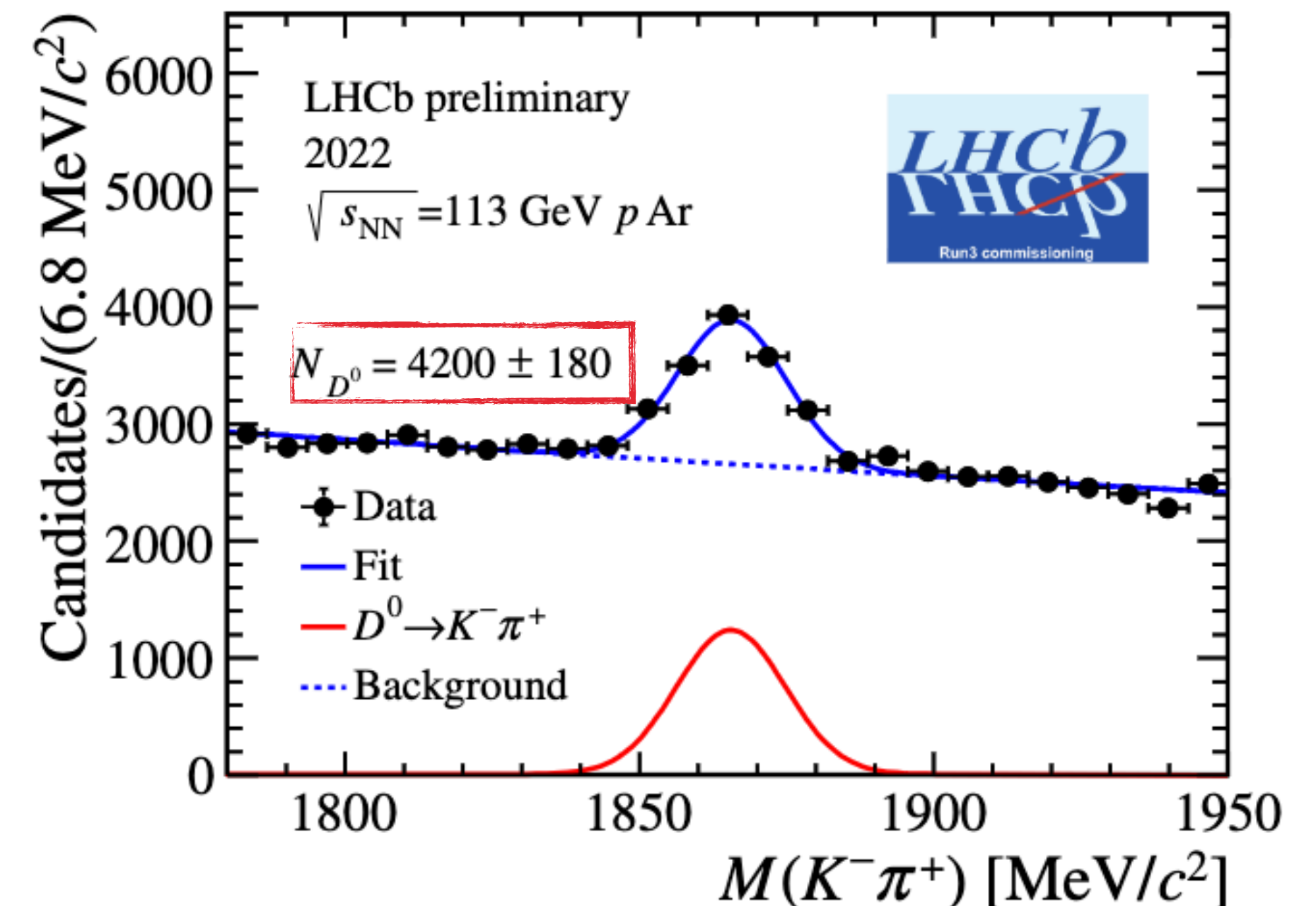
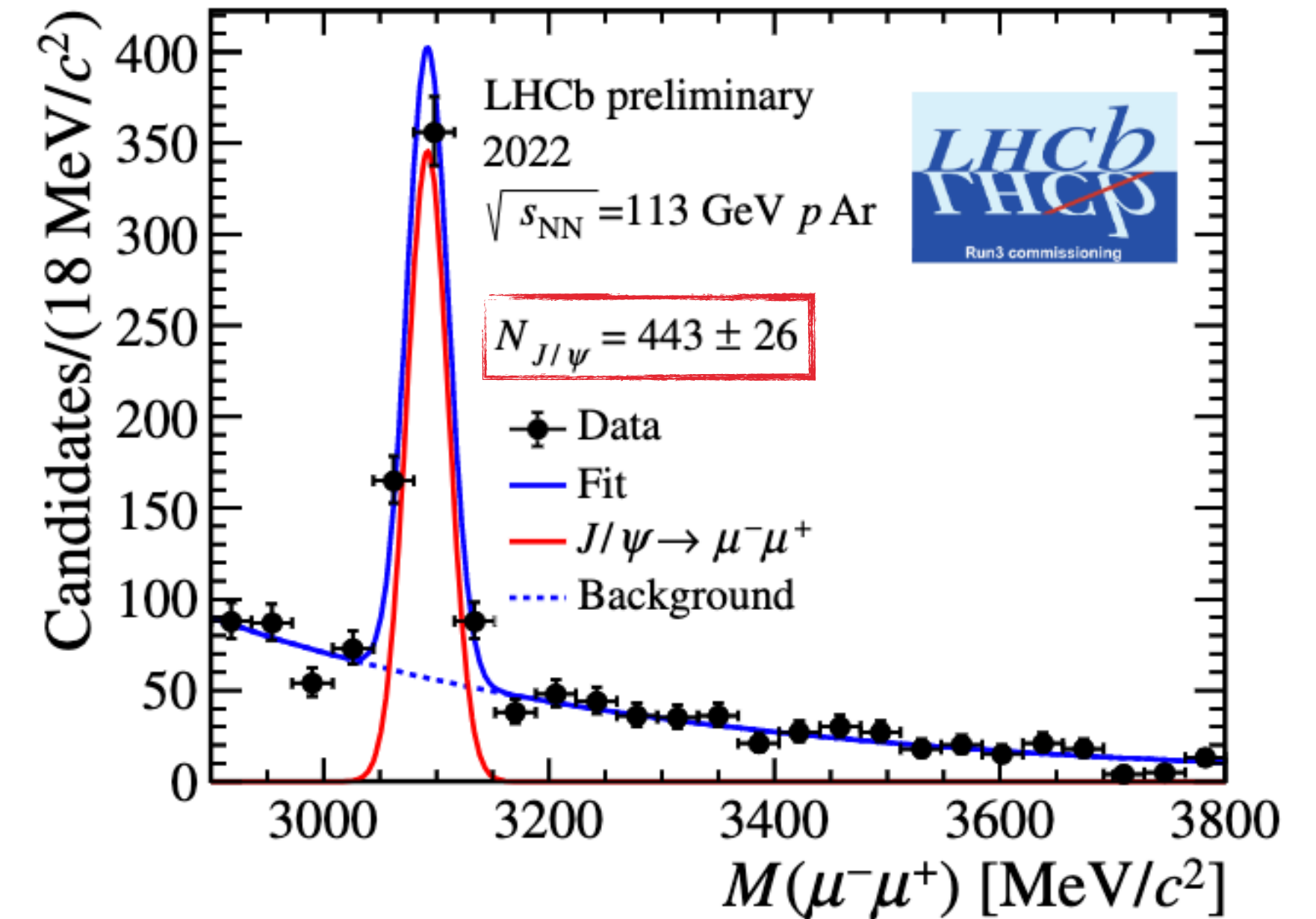


FIXED TARGET COLLISIONS AT LHCb: SMOG2

RUN3 CONFIGURATION

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- ▶ **SMOG2**: gas confined in a 20 cm long **storage cell**
- ▶ **Higher areal density** than SMOG (luminosity increased up to $\sim \times 100$)
- ▶ **Wider choice of gases to be injected**: $H_2, D_2, He, Ne, N_2, O_2, Ar, Kr, Xe$
- ▶ **Data taken simultaneously in pp and pA modes**
- ▶ **Data collected in November 2022:**
 - **Ar injection, 18 minutes of data taking:**
 - **443 J/ψ** and **4200 D^0** (similar to SMOG with 170h of data taking)



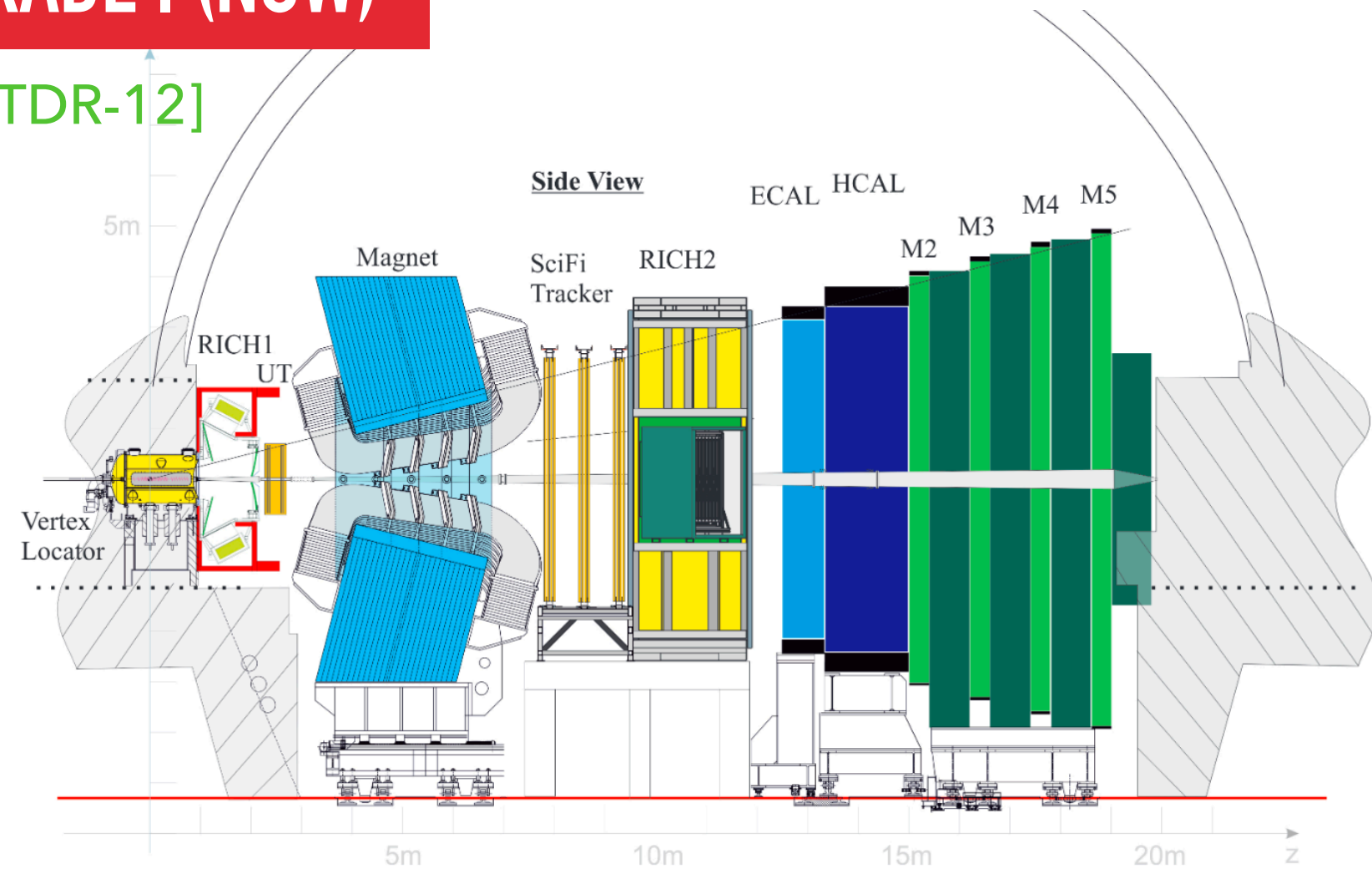
UPGRADE II

LHCb DETECTOR UPGRADE II

CERN-LHCC-2021-012 ; LHCb-TDR-023

UPGRADE I (NOW)

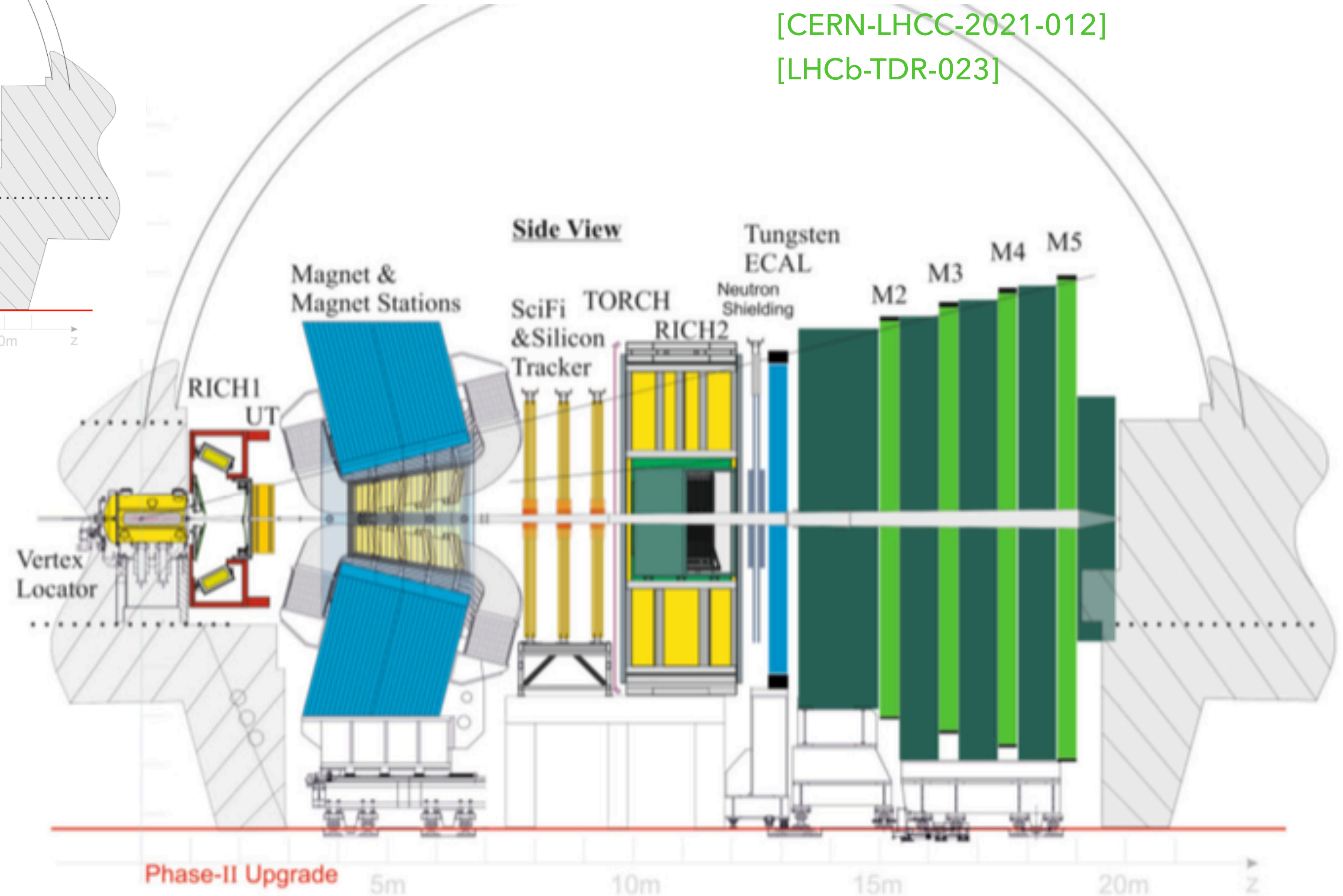
[LHCb-TDR-12]



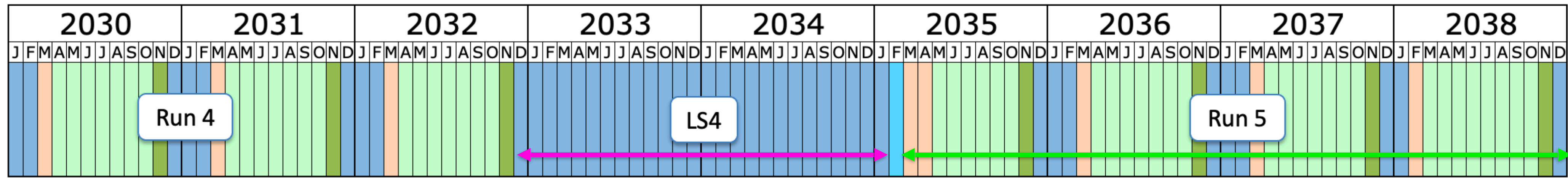
UPGRADE II (2035)

[CERN-LHCC-2021-012]

[LHCb-TDR-023]



PHASE II IN A NUTSHELL



Installation

Data taking

Last updated: January 2022

VELO

Upstream Tracker

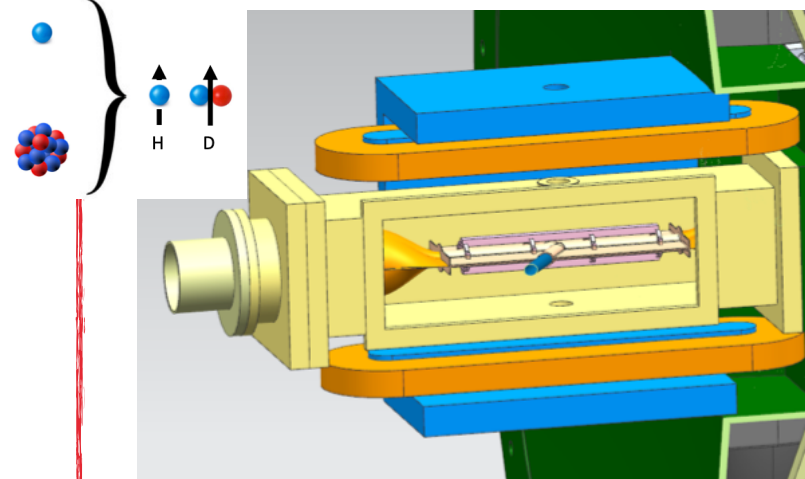
Magnet Station

Mighty Tracker

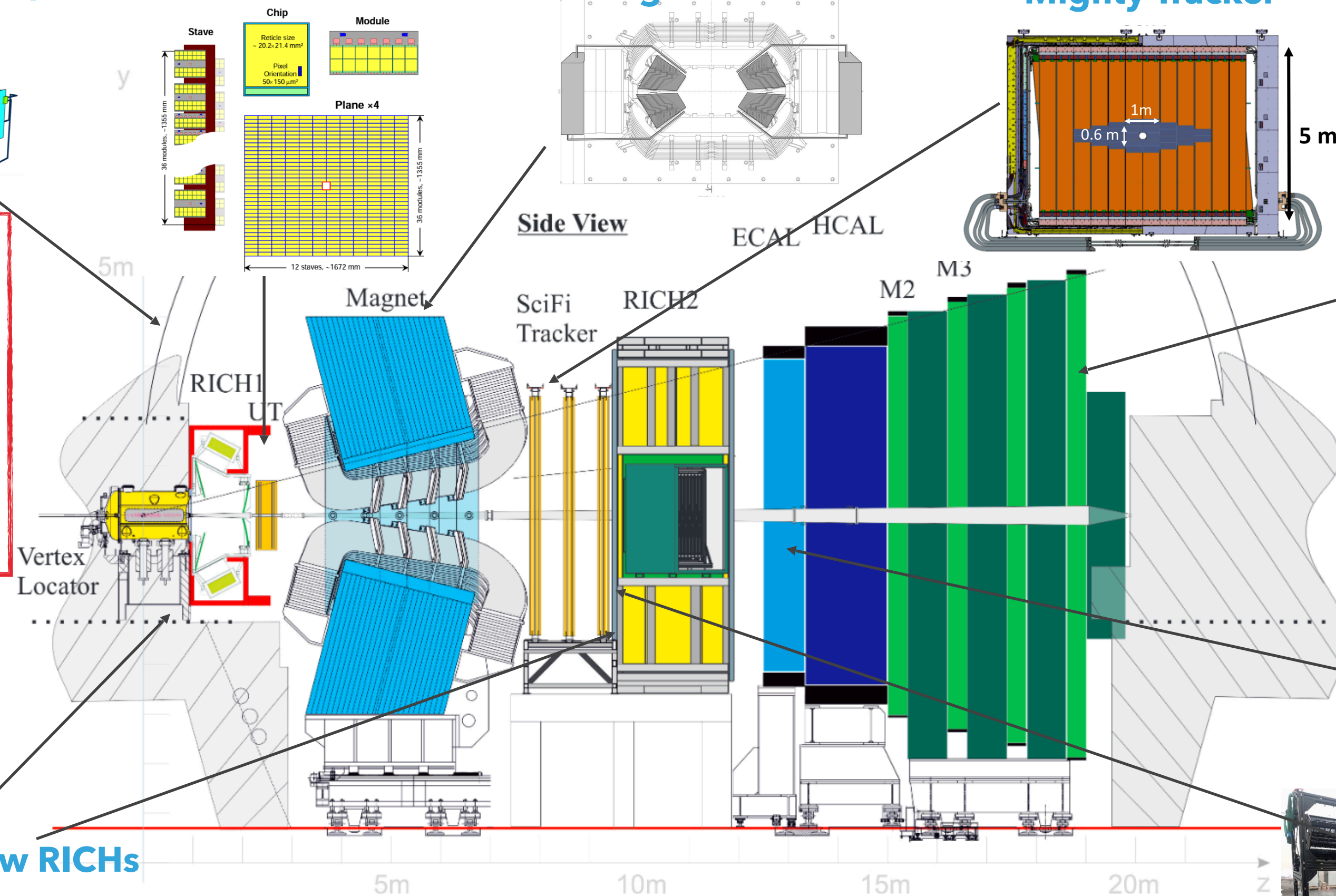
RUN5 CONFIGURATION

Muon station

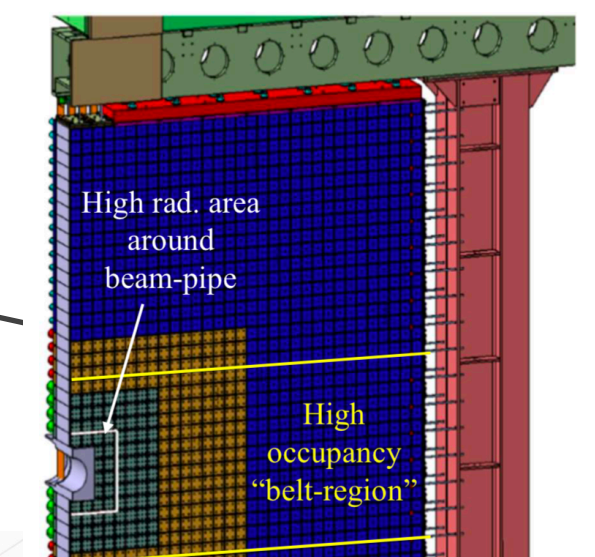
Polarized target



R&D phase supported by LHCb, still not approved



ECal



LHCspin project: R&D has started!

- Compact dipole magnet static → transverse field.
- Superconductive coils + iron yoke configuration fits in the space constraints.
- $B = 300 \text{ mT}$, $\Delta B/B \approx 10 \%$, with polarity inversion.
- Achievable Luminosity (HL-LHC): $\sim 8 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

New RICHs

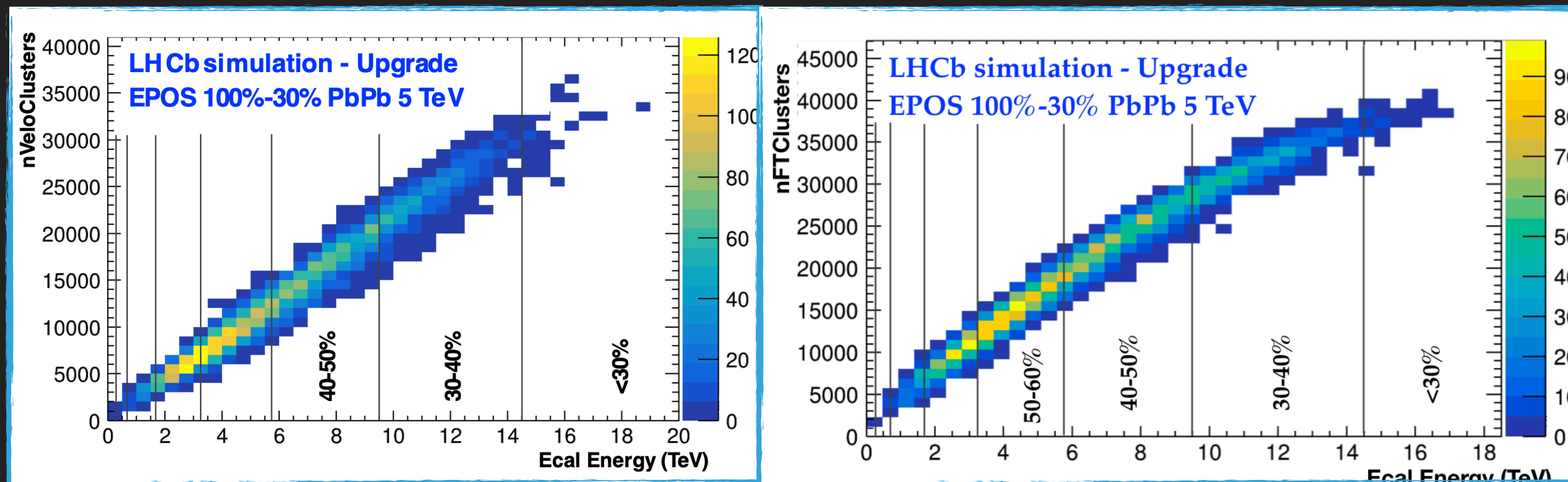
TORCH



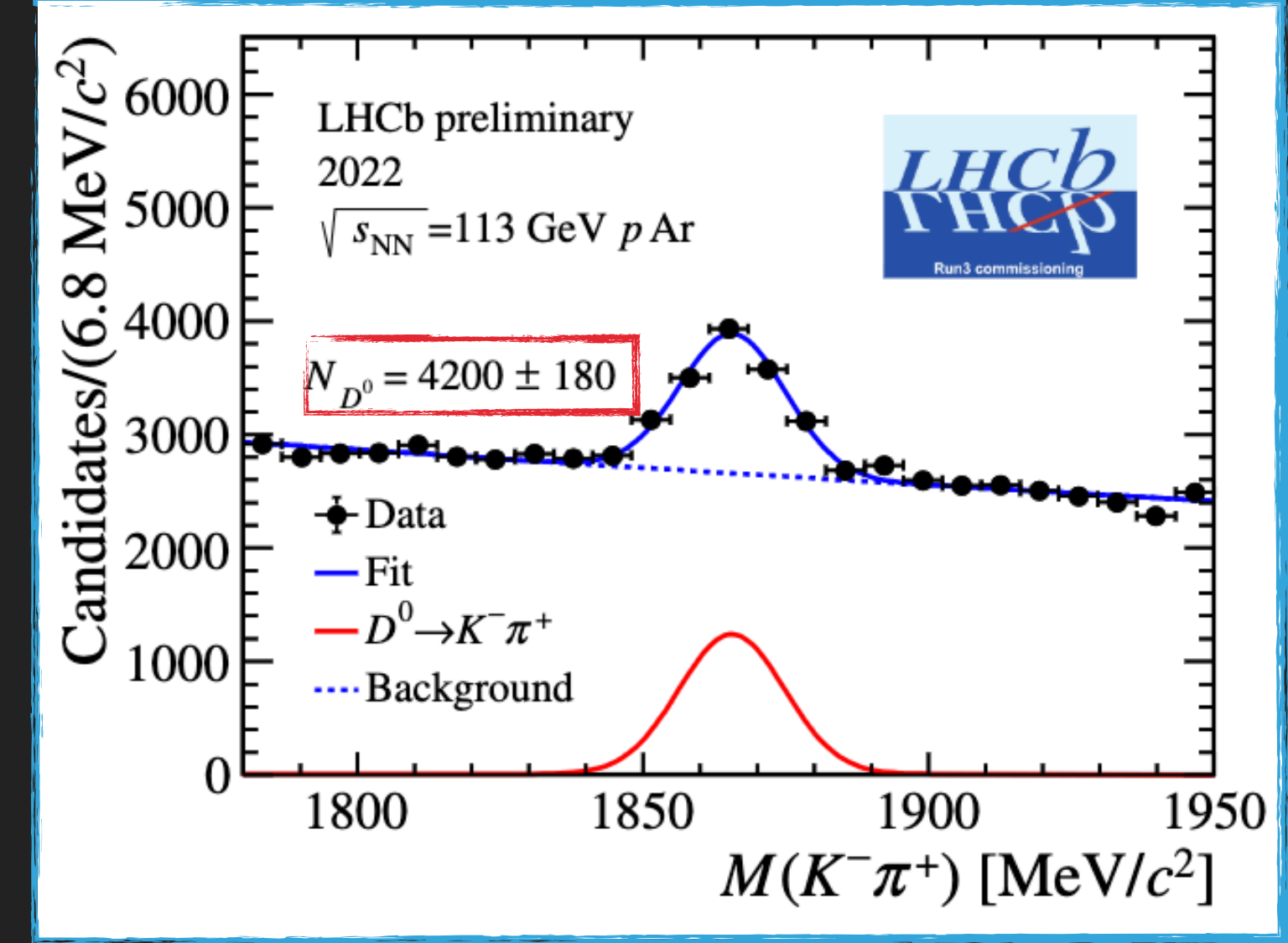
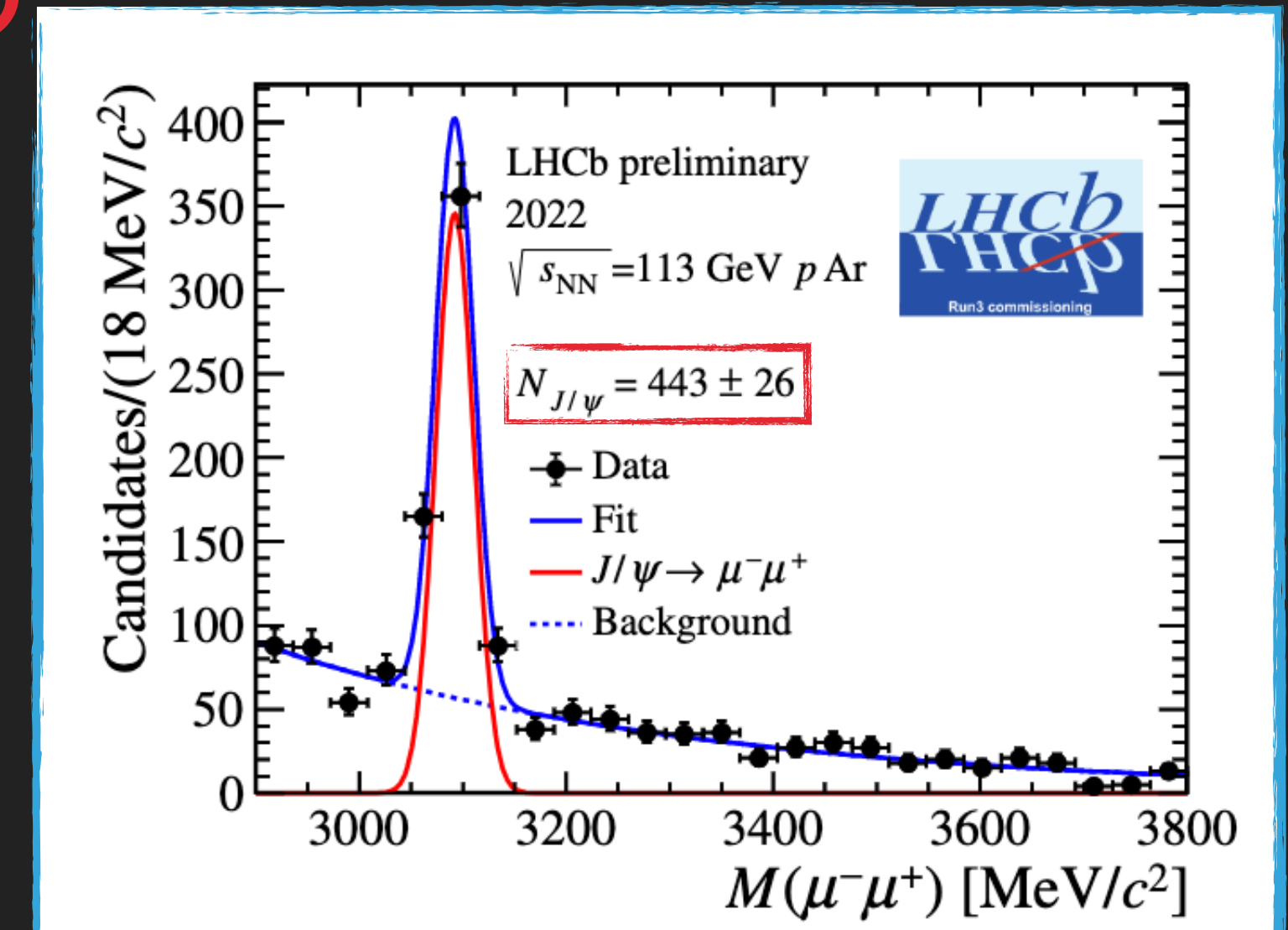
CONCLUSIONS

SMOG2

- ▶ Many interesting results shown coming from LHCb Run2
- ▶ LHCb participate in heavy-ion collisions in a successful way
- ▶ Only fixed-target experiment at LHC
- ▶ **Many more results will come with Run3 data!**



No saturation up to 30% centrality!



18 mins of data taking!

BACK UP

D^0 PRODUCTION IN $p\text{Pb}$ COLLISIONS AT $\sqrt{s} = 8.16$ TeV

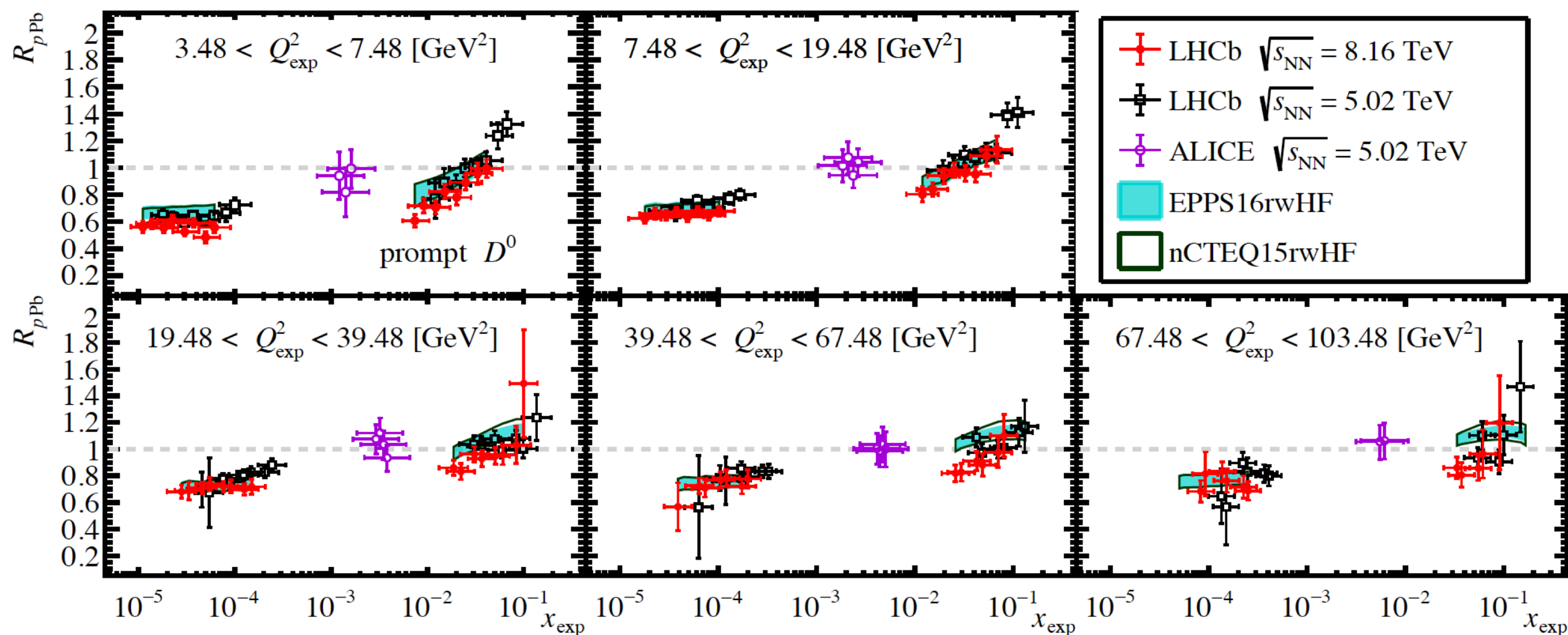
- ▶ Use experimental proxies for x and Q^2
- ▶ Data consistent at 5 and 8 TeV
- ▶ Trend seems smooth over wide x range
- ▶ nPDF undershoot the data at large x_{exp} and Q_{exp}^2

$$Q_{exp}^2 \equiv m_{D^0}^2 + p_T^2$$

$$x_{exp} \equiv 2 \frac{Q_{exp}}{\sqrt{s_{NN}}} e^{-y^*}$$

FORWARD

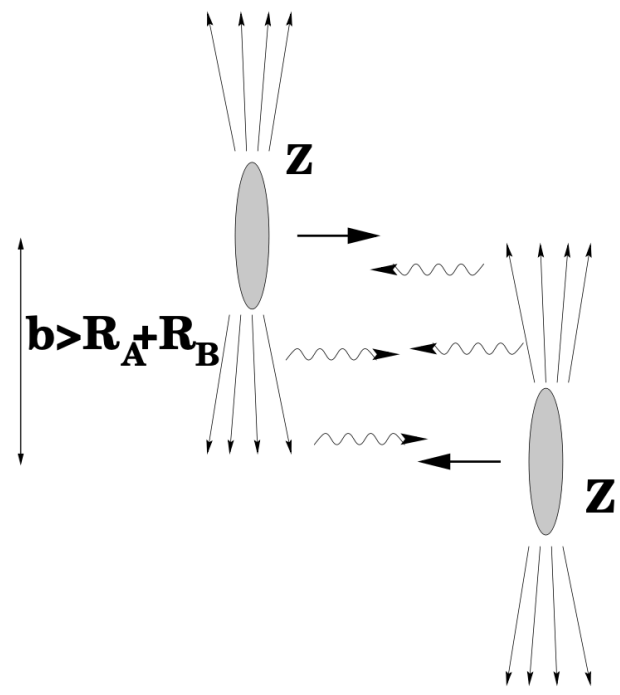
BACKWARD



CHARMONIUM PRODUCTION IN UPC PbPb AT $\sqrt{s} = 5$ TeV

ArXiv:2206.08221, submitted to JHEP

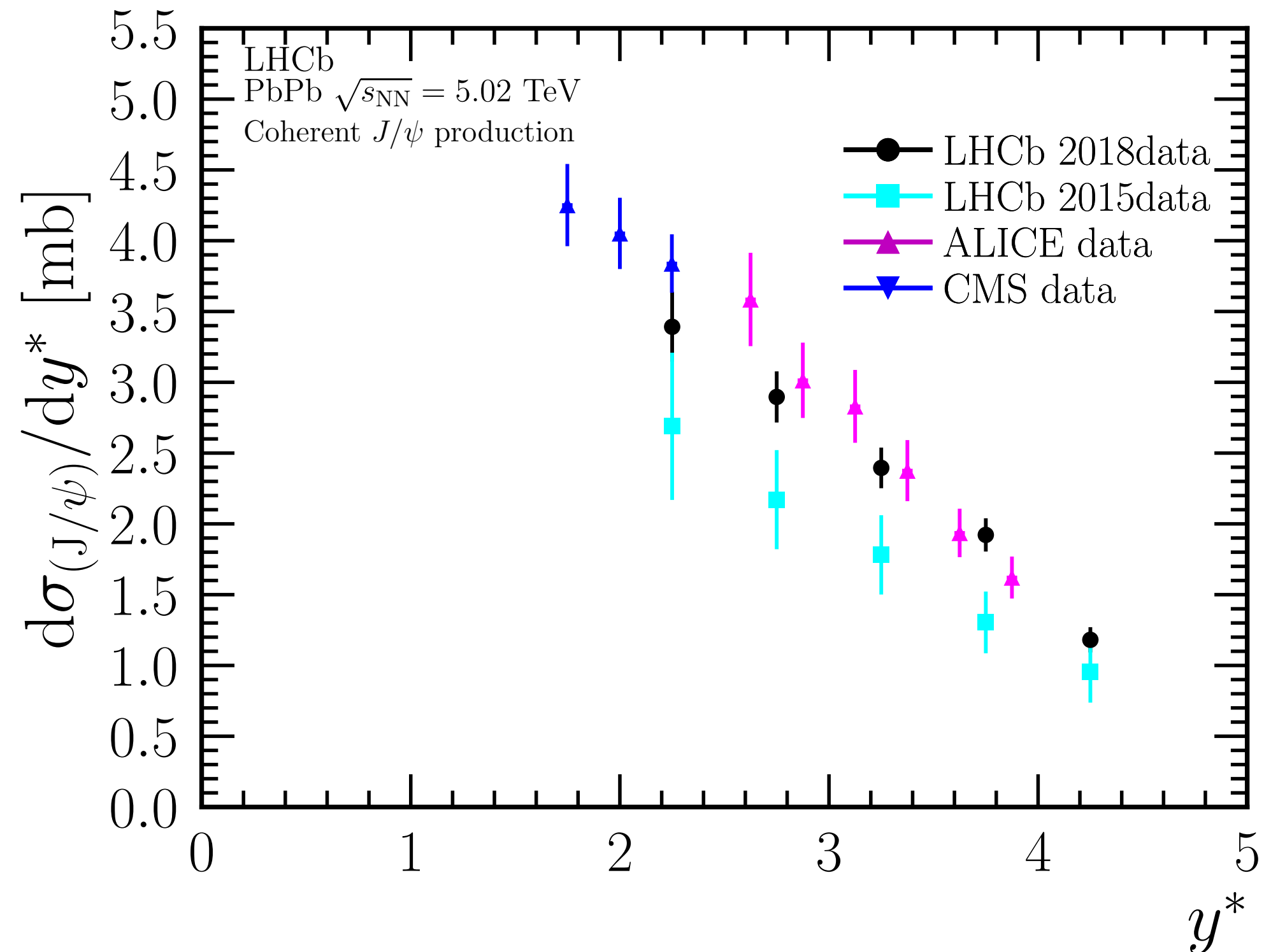
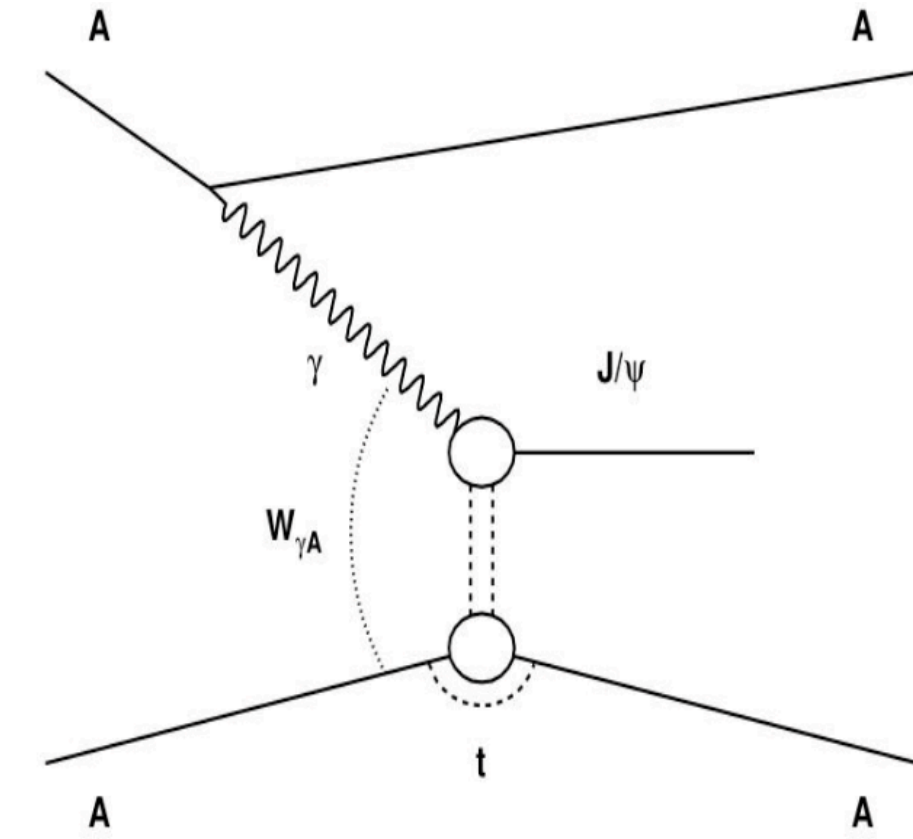
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▶ Ultra-peripheral lead-lead collisions:

- ▶ Impact parameter $b > R_A + R_B$
- ▶ **Coherent charmonia** produced by interaction between photon and pomeron
- ▶ Probe for the **gluon density distribution functions**

coherent photo-production



▶ Comparison with ALICE and CMS results