HP2024

NAGASAKI

STRANGENESS STUDIES IN LHC*b* FIXED-TARGET COLLISIONS

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on behalf of the LHCb Collaboration

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THE LHC*b* EXPERIMENT

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

- Single arm forward spectrometer originally devoted to ***heavy flavour*** physics, now a **general purpose** experiment with ***unique*** coverage $2 < \eta < 5$

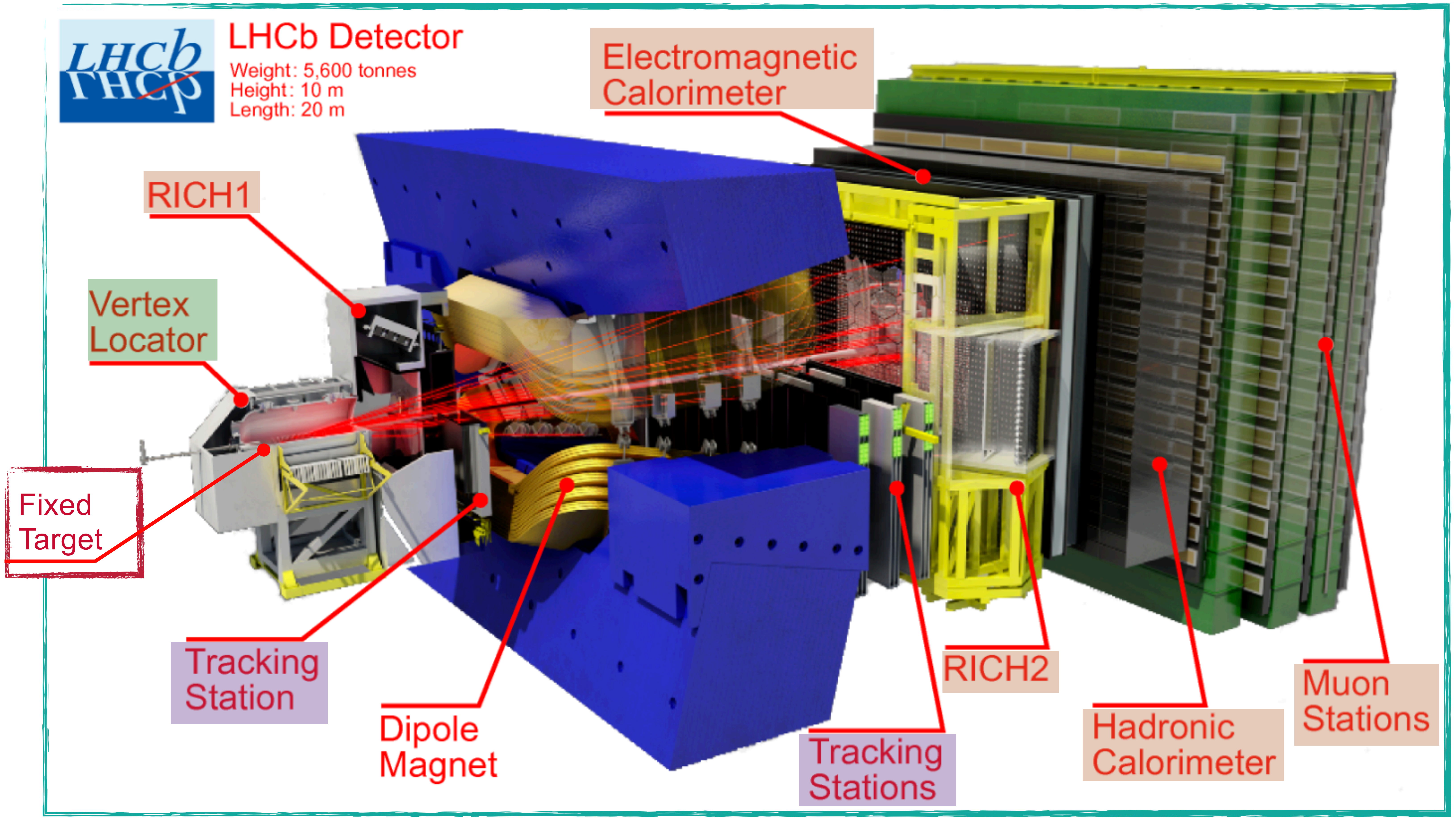
- *pp*/*p*Pb/PbPb and fixed-target modes available

- ***Excellent vertexing***, ***tracking*** down to very low p_T and ***Particle Identification***

  → momentum resolution of 0.5% – 1.0% for 5-200 GeV/c

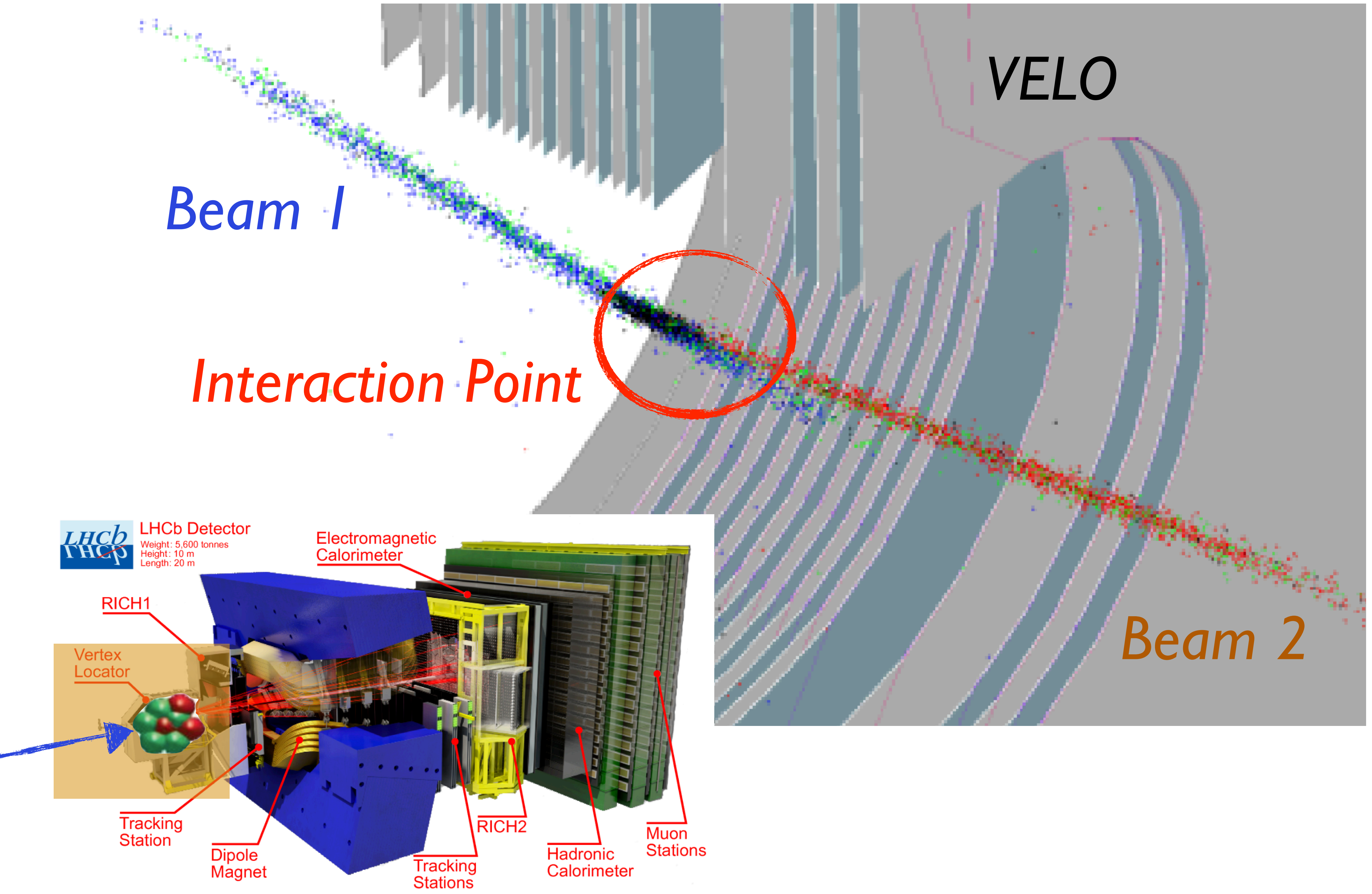
  → high precision e, μ, π, K, p, γ PID

Large variety of possible measurements!



FIXED-TARGET COLLISIONS AT LHC*b*

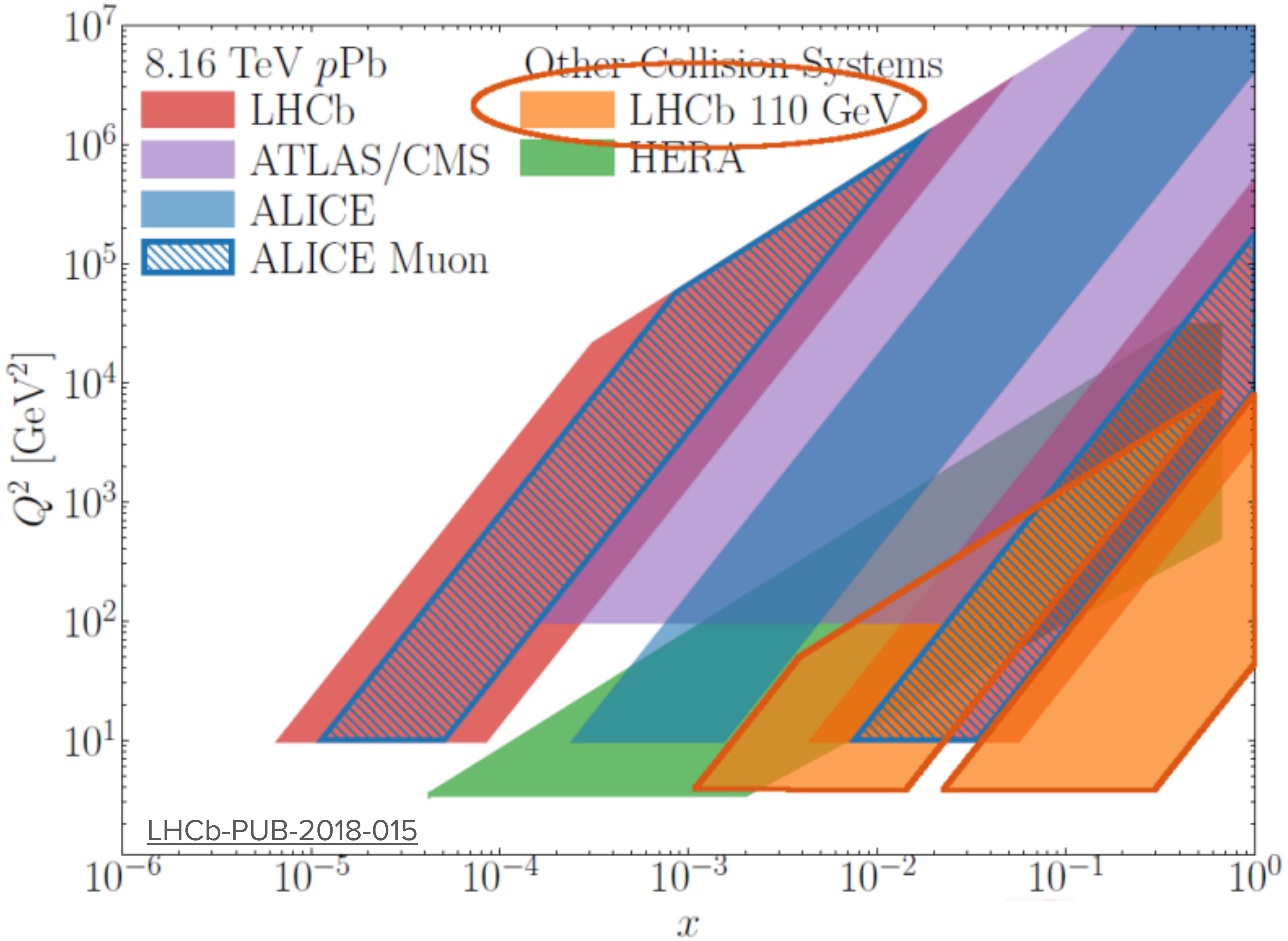
JINST 9 (2014) 12005



- SMOG: System for Measuring Overlap with Gas
  - **Noble gases (He, Ar, Ne) injected** into the LHC beam pipe around the Interaction Point (IP), pressure $\sim 10^{-7}$ mbar
  - Can run ***simultaneously*** with the main collision mode
  - **Highest-energy** fixed-target experiment ever built!

UNIQUE energy coverage at $\sqrt{s_{NN}}$ = 68.5-110 GeV
bridge between SPS and RHIC

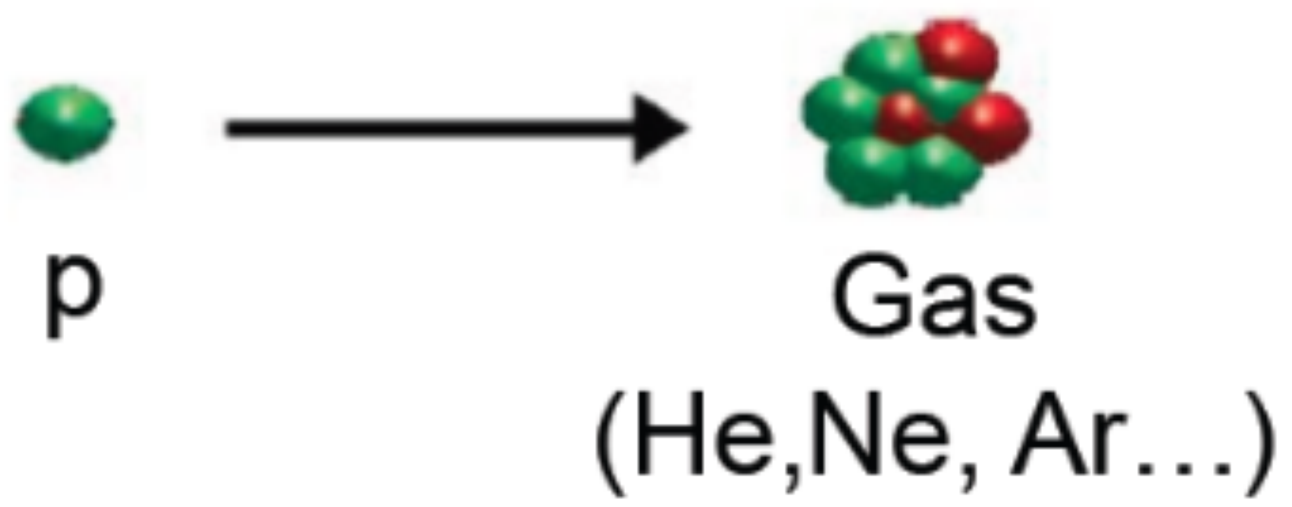
- Investigates the **high-x** of the nucleon target at **intermediate** Q^2 mostly ***unexplored*** by previous experiments

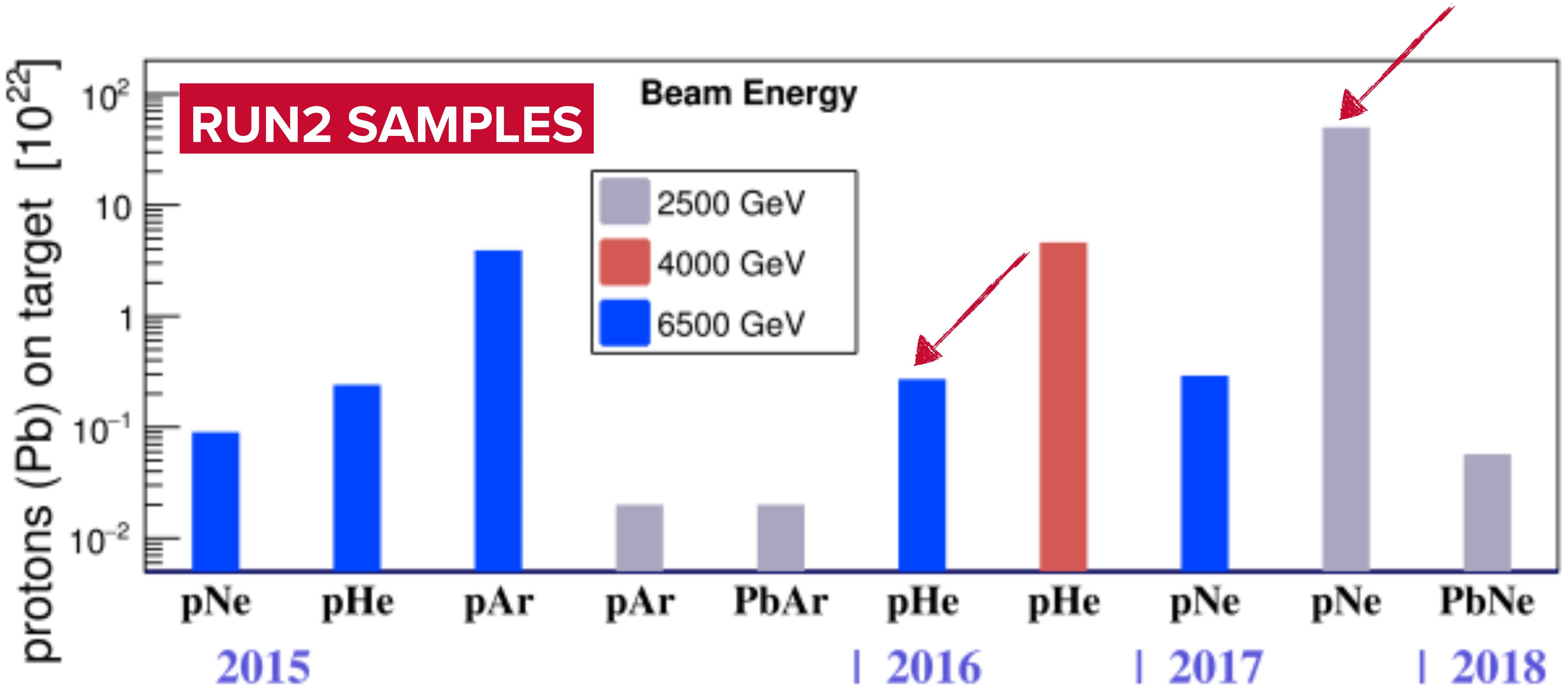


TODAY'S MENU

✓ **Fixed-Target collisions**:

- Measurement of the ϕ meson production in fixed-target pNe collisions at $\sqrt{s_{NN}}$ = 68.5 GeV NEW!
  LHCb-PAPER-2024-036, in preparation
- Λ^0 transverse polarization measurement in fixed-target pNe collisions at $\sqrt{s_{NN}}$ = 68.5 GeV at LHCb
  arXiv:2405.11324, accepted by JHEP
- Detached antiprotons in pHe at $\sqrt{s_{NN}}$ = 110 GeV
  EPJ C83, 543 (2023)-036

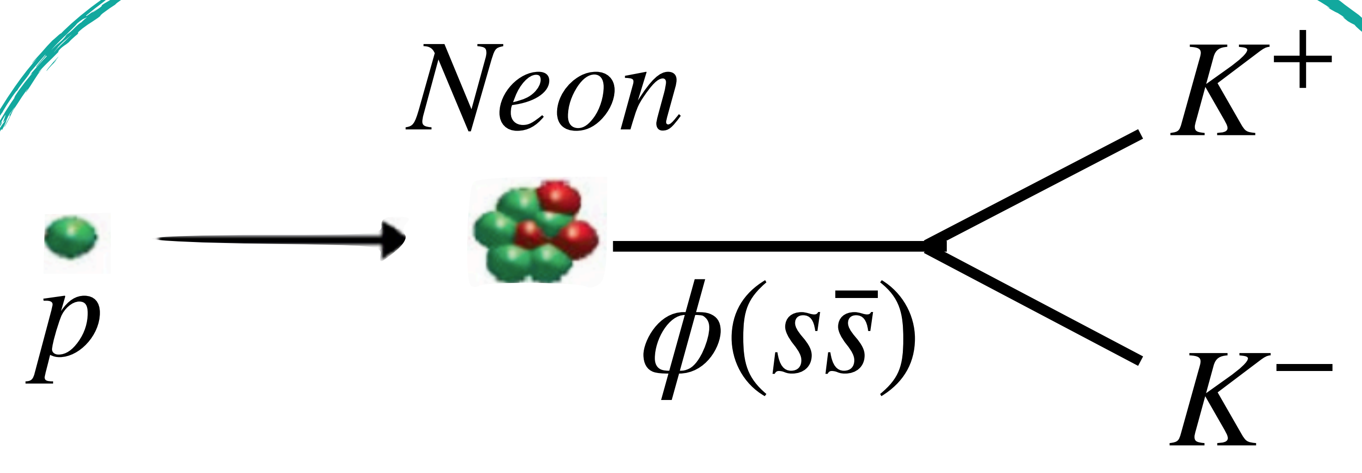




ϕ MESON PRODUCTION IN pNe COLLISIONS

NEW!

MOTIVATION



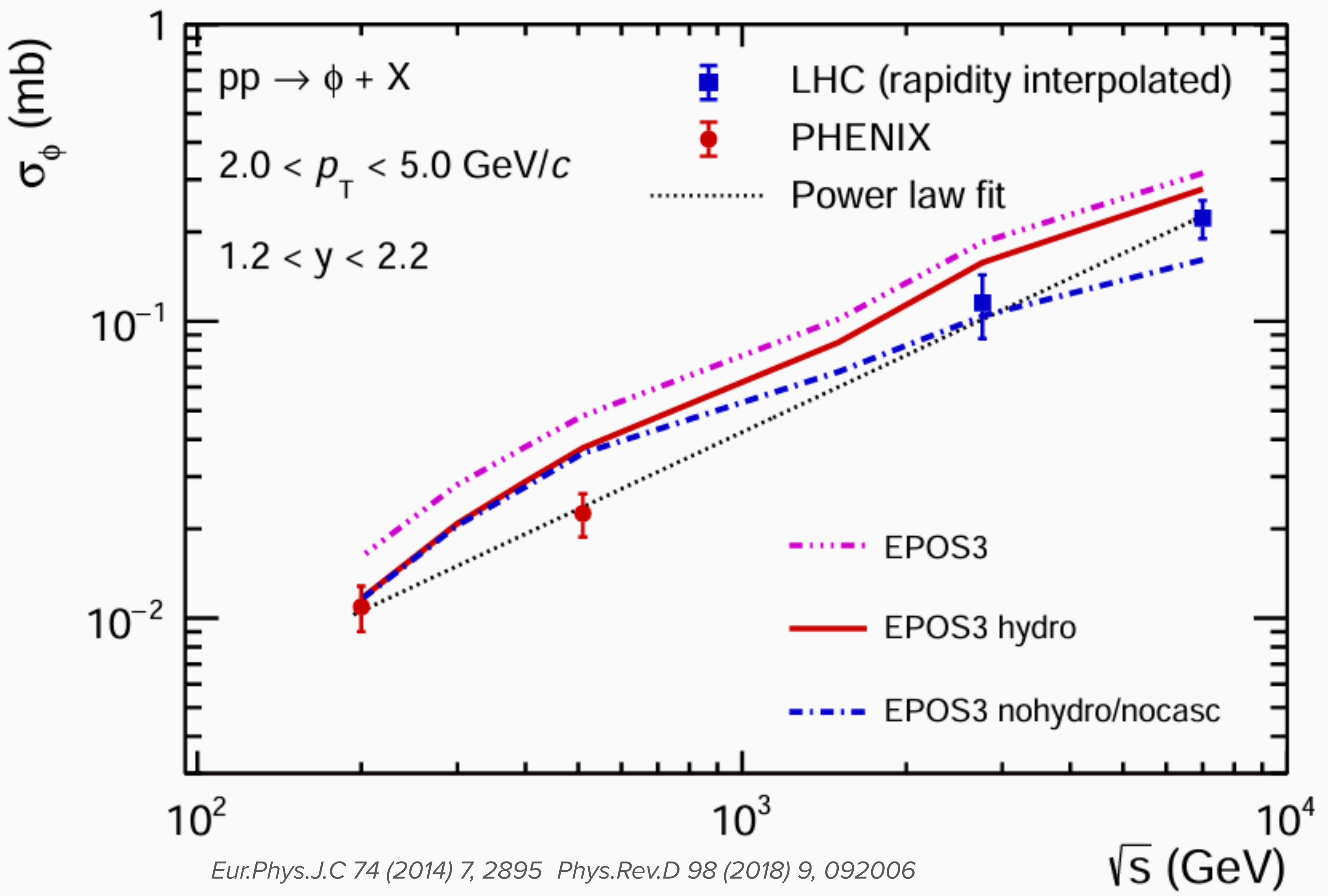
BR = (49.1 ± 0.5) %
PDG2024

- *Proton-nucleus collisions*:
  → ***baseline*** for Quark-Gluon Plasma formation
  → characterisation of CNM effects

NEW!

- *ϕ meson*: $M_\phi = 1019.461 \pm 0.016$ MeV/c^2
  → lightest bound state of $s\bar{s}$
  → abundantly produced
  → good probe to study strangeness production
  → in **larger** systems (*e.g.* heavy-ion collisions), ***strangeness enhancement*** is a good signature of QGP
  → in **smaller** systems (*e.g.* proton-nucleus), ***Cold Nuclear Matter*** effects produce effects similar to QGP

- *Previous measurements:*



Eur.Phys.J.C 74 (2014) 7, 2895 Phys.Rev.D 98 (2018) 9, 092006
Phys. Rev. C 89, 064903 (2014)

ANALYSIS STRATEGY

LHCb-PAPER-2024-036, in preparation

- *First* measurement of the ϕ production cross-section per nucleon in $p_T, y*$ in pNe collisions at $\sqrt{s_{NN}}$ = 68.5 GeV

NEW!

- ***Observable***: $$\frac{d^2\sigma(p_T, y^*)}{dp_T\, dy^*} = \frac{N^{\phi}(p_T, y^*)\ \zeta}{\mathscr{L}\ \mathrm{BR}\ \epsilon_{tot}(p_T, y^*)\ \Delta p_T\ \Delta y^*\ A_{Ne}}$$

pp contamination factor

Eur. Phys. J. C 83 (2023) 541

$\mathscr{L}$ = 21.7 ± 1.4 nb^{-1}

Eur. Phys. J. C 83 (2023) 541

$$\epsilon^i_{tot} = \epsilon^i_{acc} \times \epsilon_{PV} \times \epsilon^i_{reco\&sel} \times \epsilon^i_{PID} \times \epsilon_{trig} / \epsilon_{\mathrm{match}}$$

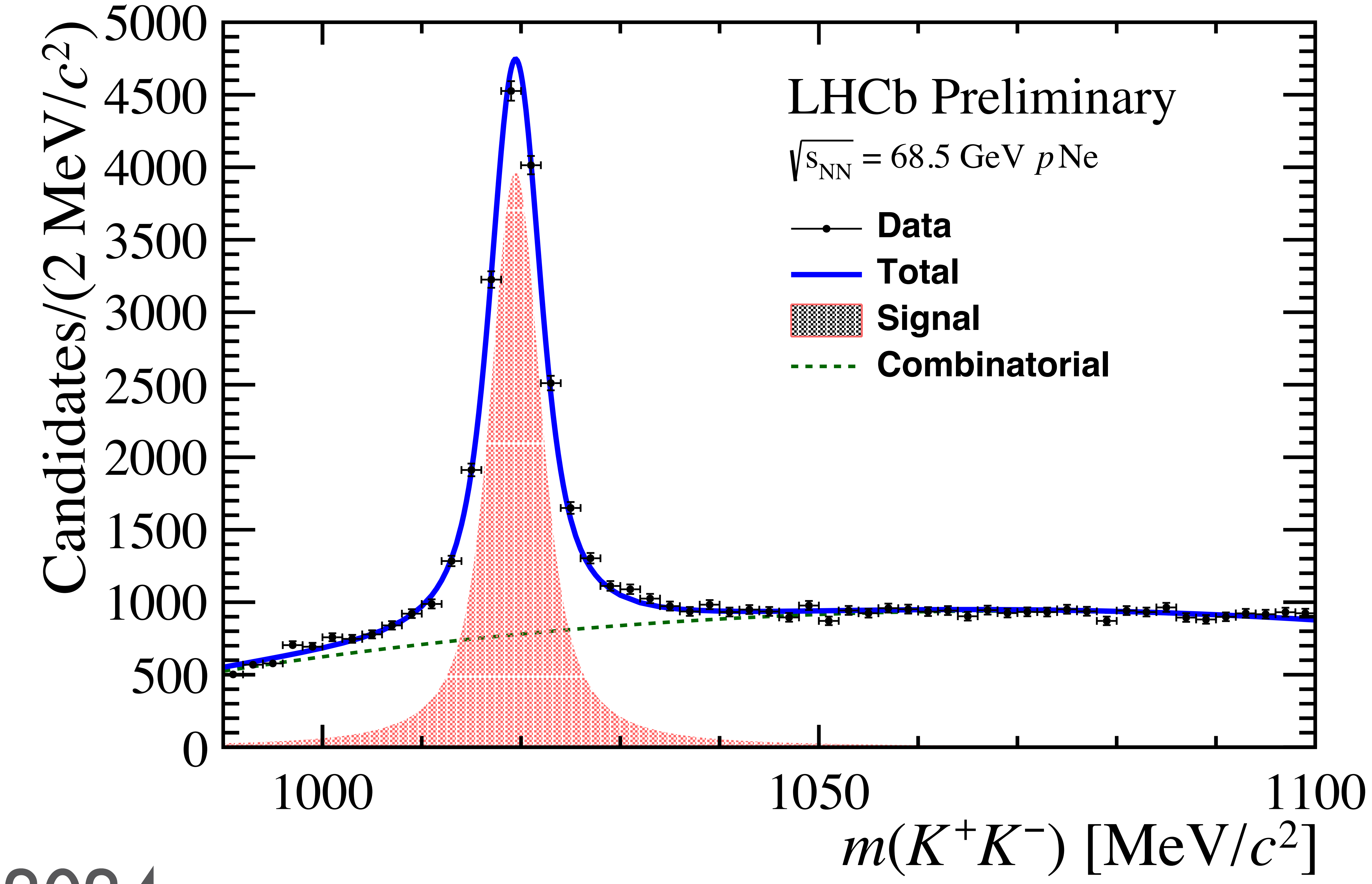
- Total of **16560 ϕ candidates**
- ϕ signal is extracted in $p_T, y*$ **regions**

p_T **[MeV/c]: 800, 1050, 1200, 1350, 1550, 1850, 6500**

$y*$ **: -1.8, -1.3, -1.0, -0.7, 0**

Fixed-target kinematics covers the $y*$ central and negative emisphere only

2.5 TeV proton beam implies a boost of Δy = 4.29



ANALYSIS STRATEGY

- *First* measurement of the ϕ production cross-section per nucleon in $p_T, y*$ in pNe collisions at $\sqrt{s_{NN}}$ = 68.5 GeV

NEW!

- ***Observable***: $$\frac{d^2\sigma(p_T, y^*)}{dp_T\, dy*} = \frac{N^\phi(p_T, y^*)\ \zeta}{\mathscr{L}\,\mathrm{BR}\,\epsilon_{tot}(p_T, y^*)\,\Delta p_T\,\Delta y*A_{Ne}}$$

- ***Total Efficiency***: $$\epsilon^i_{tot} = \epsilon^i_{acc} \times \epsilon_{PV} \times \epsilon^i_{reco\&sel} \times \epsilon^i_{PID} \times \epsilon_{trig}$$

Particle identification

Geometrical acceptance

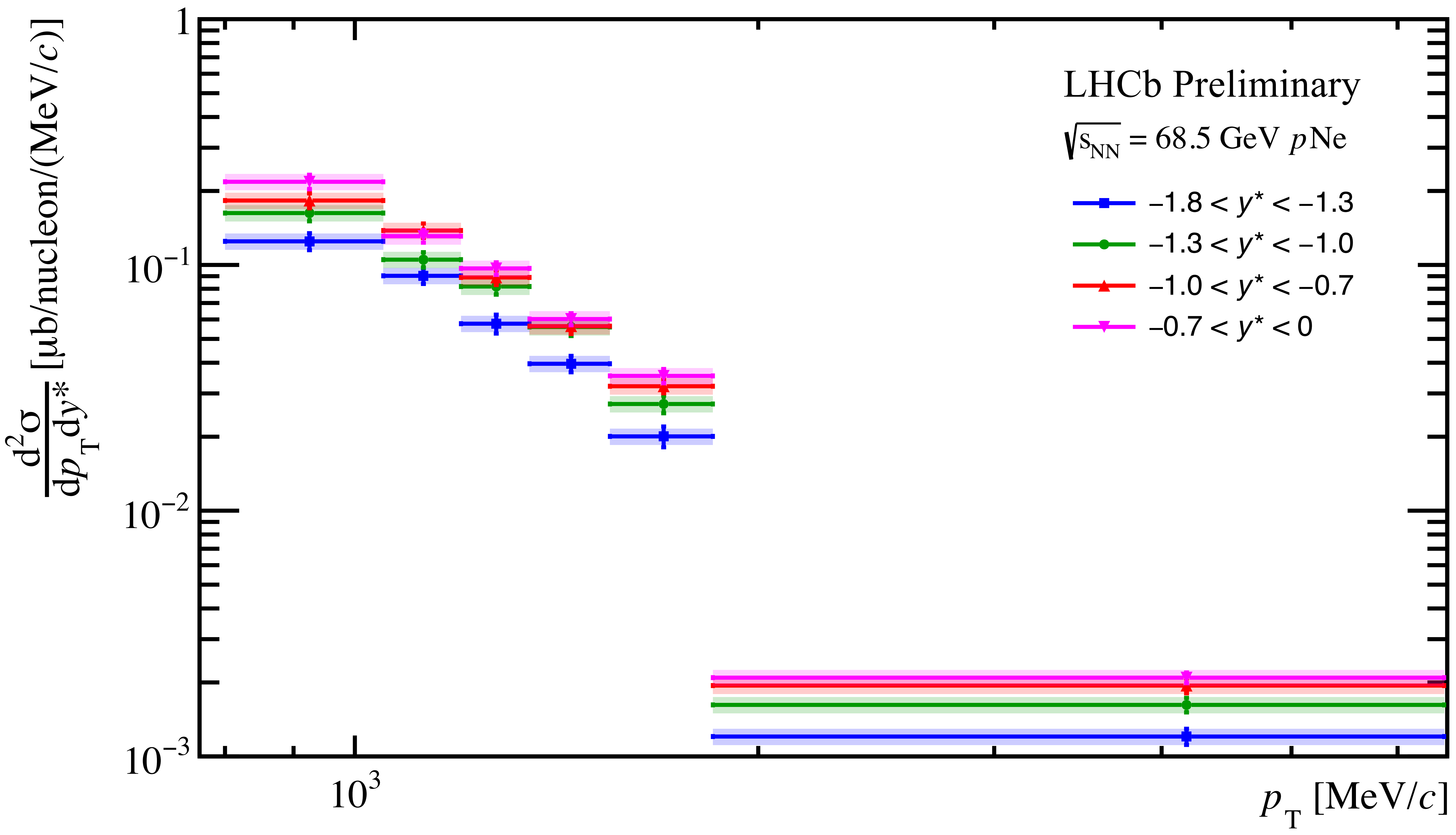
PV reconstruction

Reconstruction and selection

Trigger

- Evaluated on multiplicity-weighted Monte Carlo with data corrections on PID, PV and tracking
  $\rightarrow$ simulated sample with ***Pythia+EPOS-LHC*** event generators *Phys. Comm. 135 (2001) 238, Phys. Rev. C92 (2015) 034906*
- Used to correct signal yields
- Mostly measured in each bin $i = (p_T, y^*)$

RESULTS



- ***Double* differential cross-section per nucleon:**

  NEW!

  → Bars: statistical+uncorrelated uncertainties

  → Filled areas: correlated uncertainties

- ***compatible*** with rough extrapolation of LHC and RHIC results although in different collision systems and kinematic regions

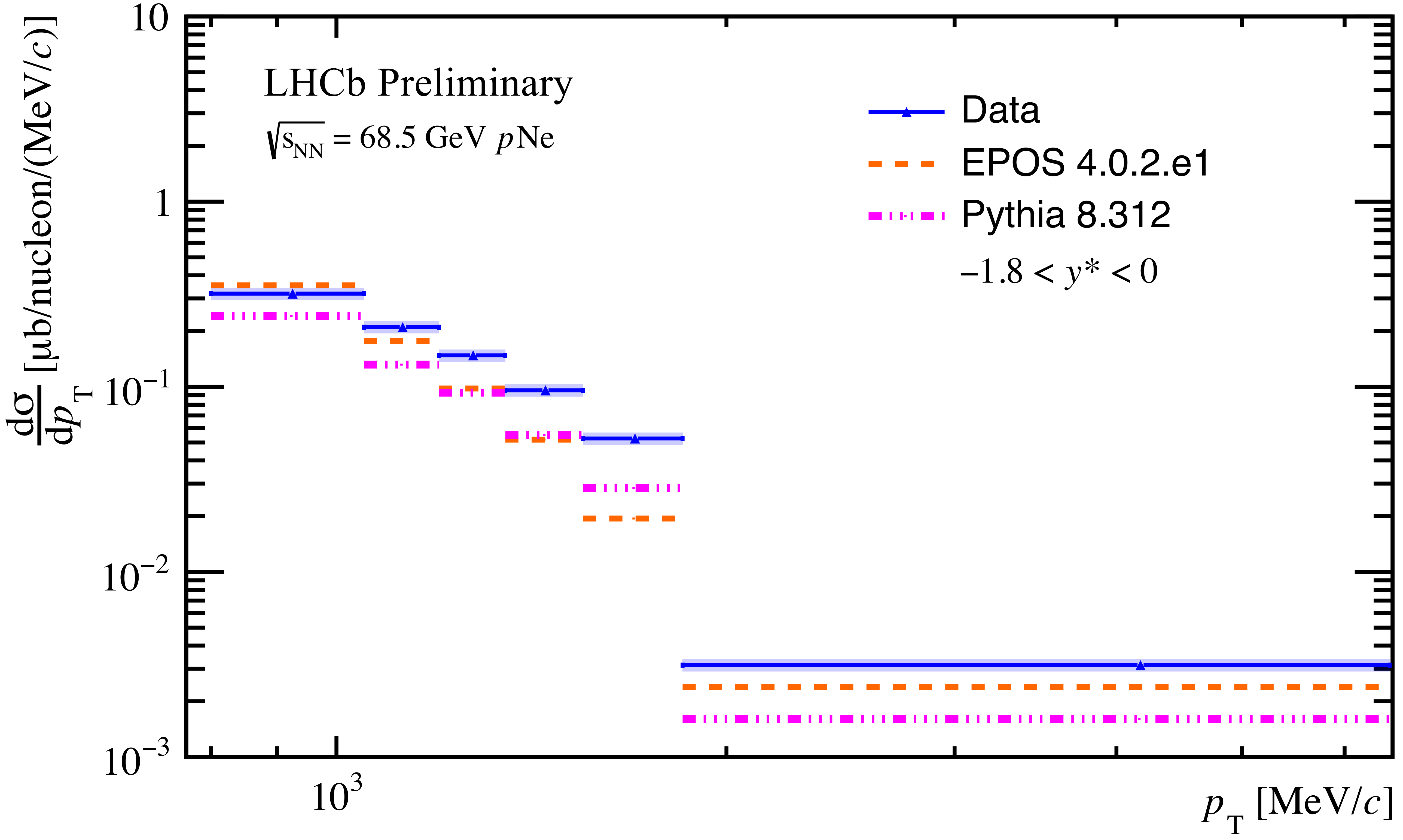
- Total cross-section per nucleon evaluated by integrating over y^*_{tot} in $[-1.8,\ 0]$ and $p_{T,tot}$ in $[800,\ 6500]$ MeV/c

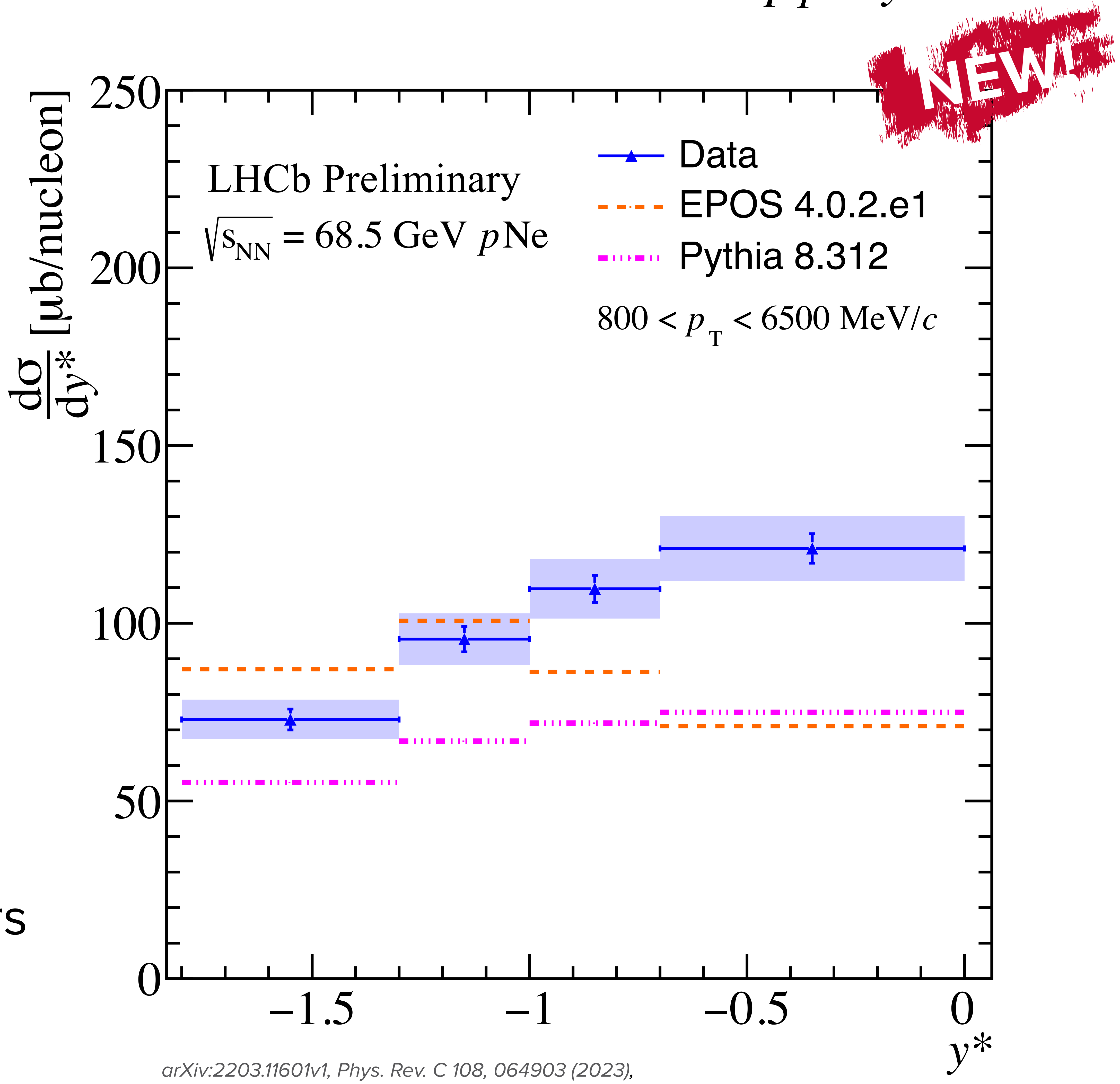
$$\sigma^{\phi}_{y,\ p_T} = 182.8 \pm 2.6\ \text{(stat)} \pm 14.2\ \text{(syst)}\ \mu\text{b/nucleon}$$

RESULTS

LHCb-PAPER-2024-036, in preparation

- By integrating over p_T or y^*, we obtain the ***single differential cross-sections per nucleon:*** $\frac{d\sigma}{dp_T}, \frac{d\sigma}{dy^*}$





- Theoretical predictions from the most common MC generators ***slightly underestimate*** the result in p_T and high y^* regions

arXiv:2203.11601v1, Phys. Rev. C 108, 064903 (2023), Phys. Rev. C 108, 034904 (2023), Phys. Rev. C 109, 034918 (2024), Phys. Rev. C 109, 014910 (2024)

Λ^0 TRANSVERSE POLARIZATION IN pNe COLLISIONS

MOTIVATION

- **Transverse Λ^0 polarization:** discovered in 1976 in pBe collisions using 300 GeV unpolarized beam

- Polarization effects **not expected** in particle production from unpolarised beams at ***high energy***

  → Indicates that ***spin effects*** play an important role even in high energy collisions

- **Common features** observed up to now:

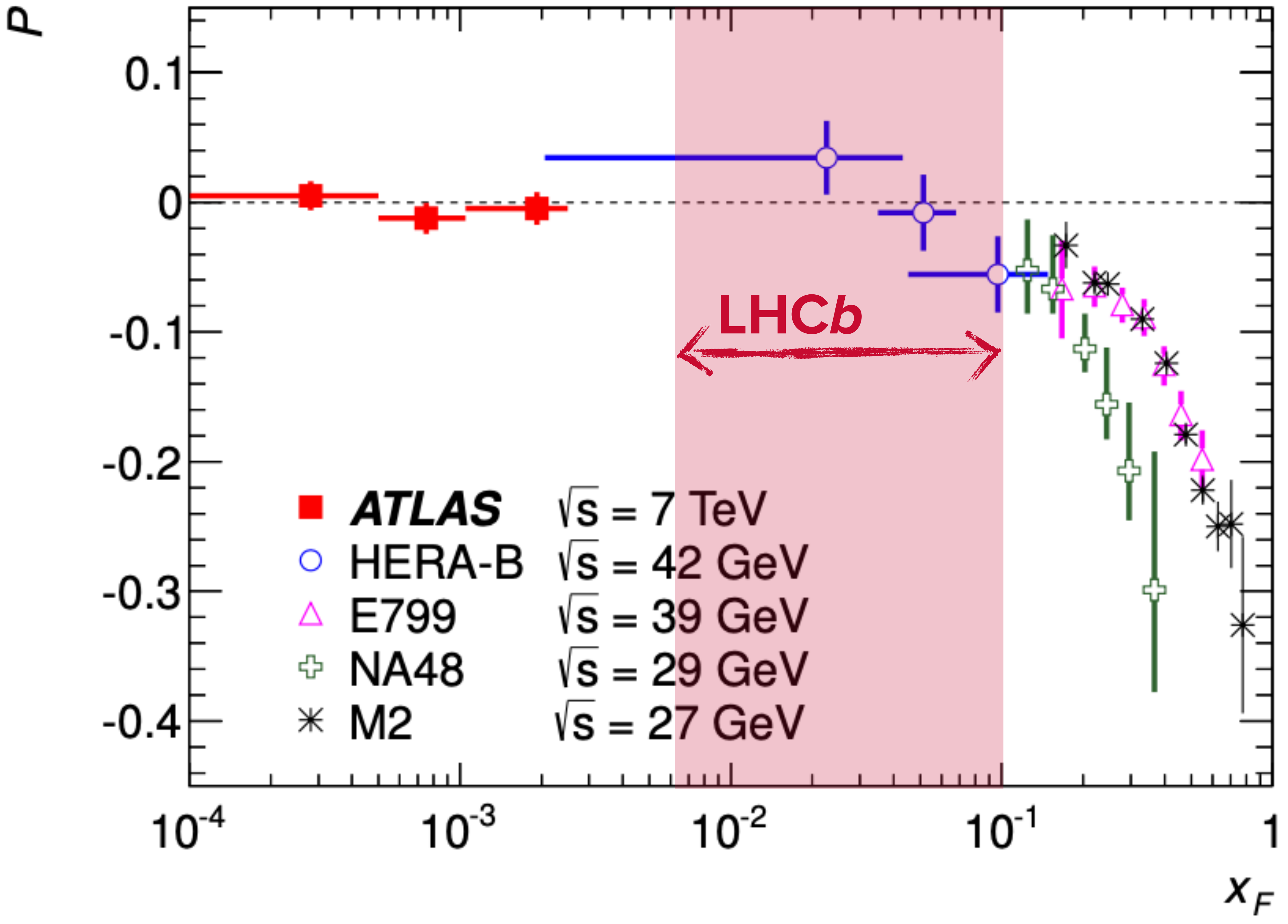
  $$\nearrow \frac{2 \cdot p_L}{\sqrt{s_{NN}}}$$

  - Polarization value ***increases with increasing*** x_F ***and*** p_T up to few GeV

  - Roughly ***independent*** of the beam energy and the atomic mass number of the colliding nuclei

- *Most recent measurements*

Phys. Rev. D 91, 032004 (2015)

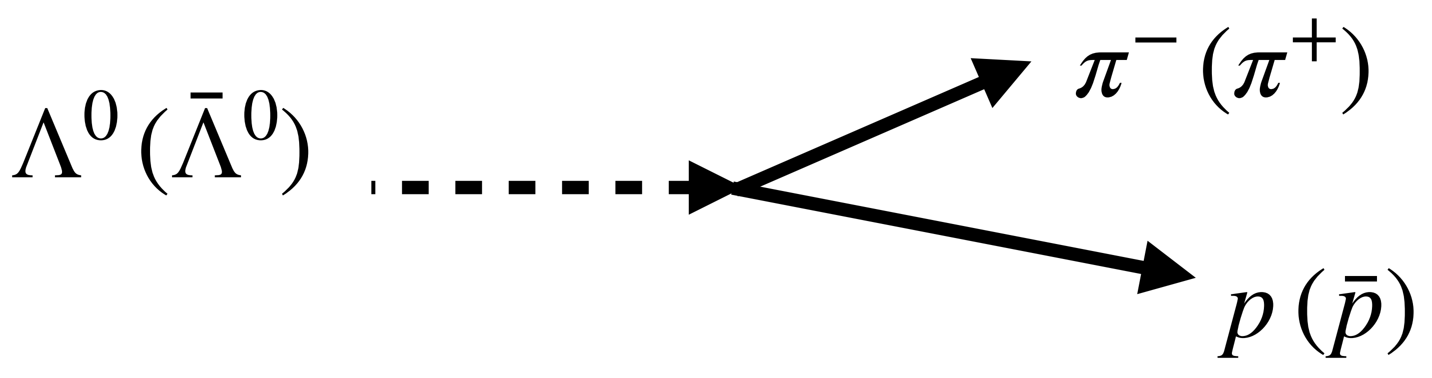


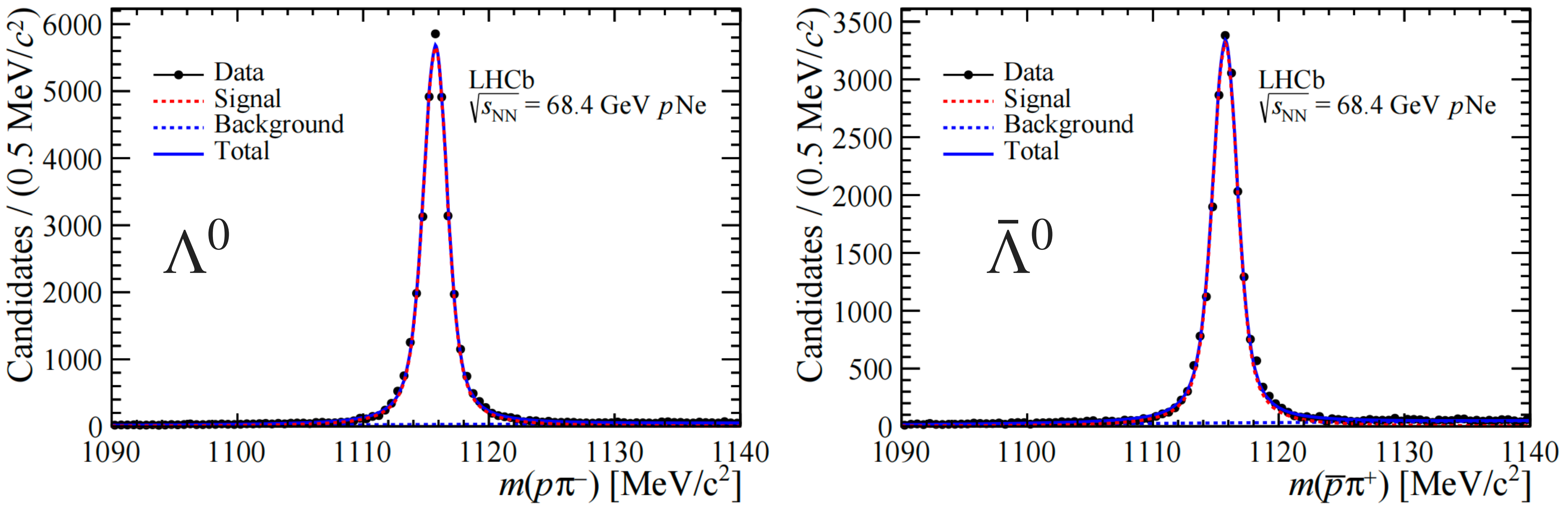
Despite many theories and experiments performed, still *not a clear explanation*!

ANALYSIS STRATEGY

arXiv:2405.11324, accepted by JHEP

- Polarization measured in the 2017 *p*Ne sample
- Decay protons preferentially emitted along the spin direction of the Λ in its rest frame





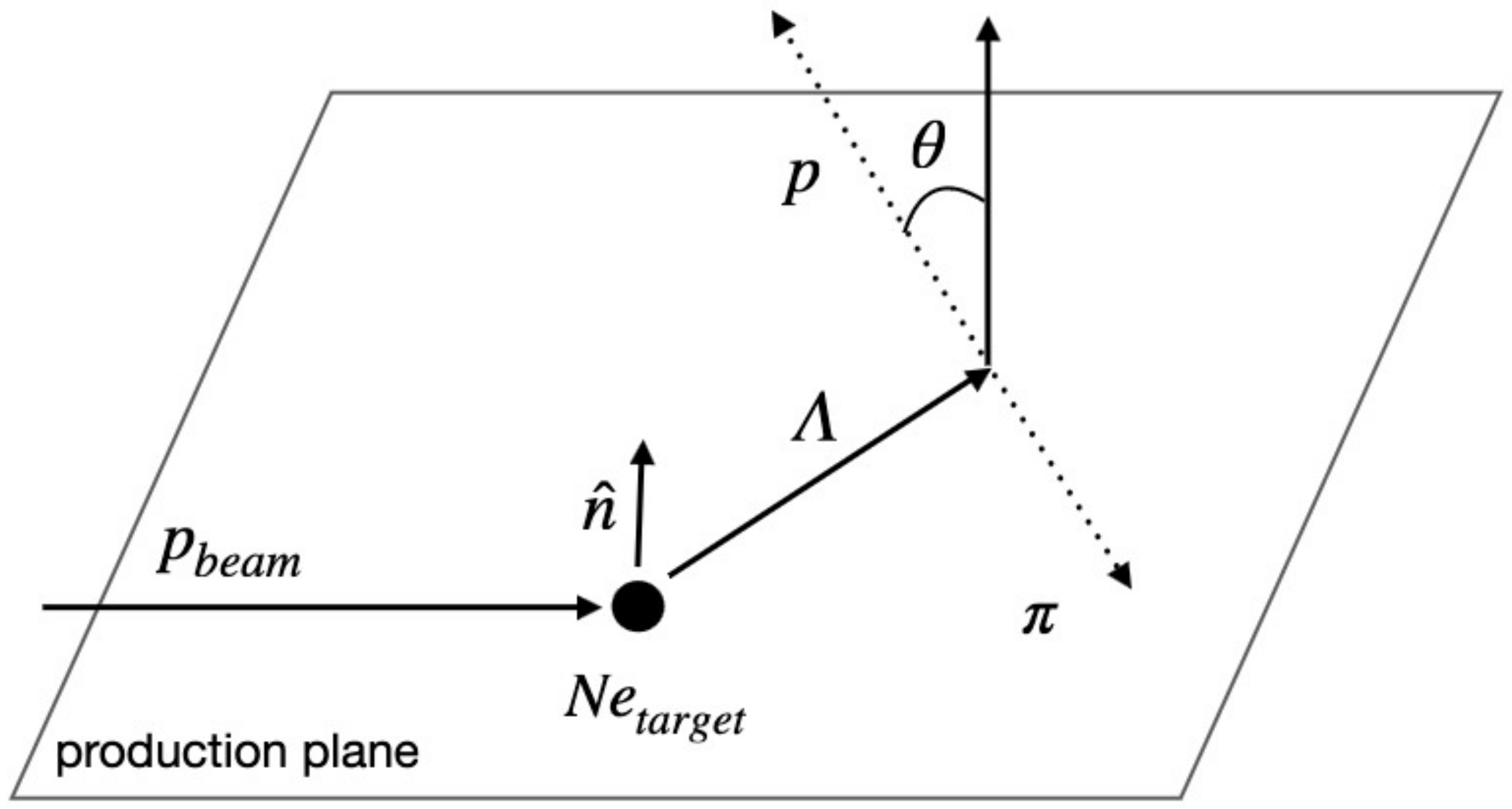
- Measuring the ***asymmetry in the proton's angular distribution***

  → if present, would provide access to the Λ^0 polarization

$$\frac{dN}{d\Omega} = \frac{dN_0}{d\Omega}(1 + \alpha P_n^{\Lambda} \cos\theta)$$

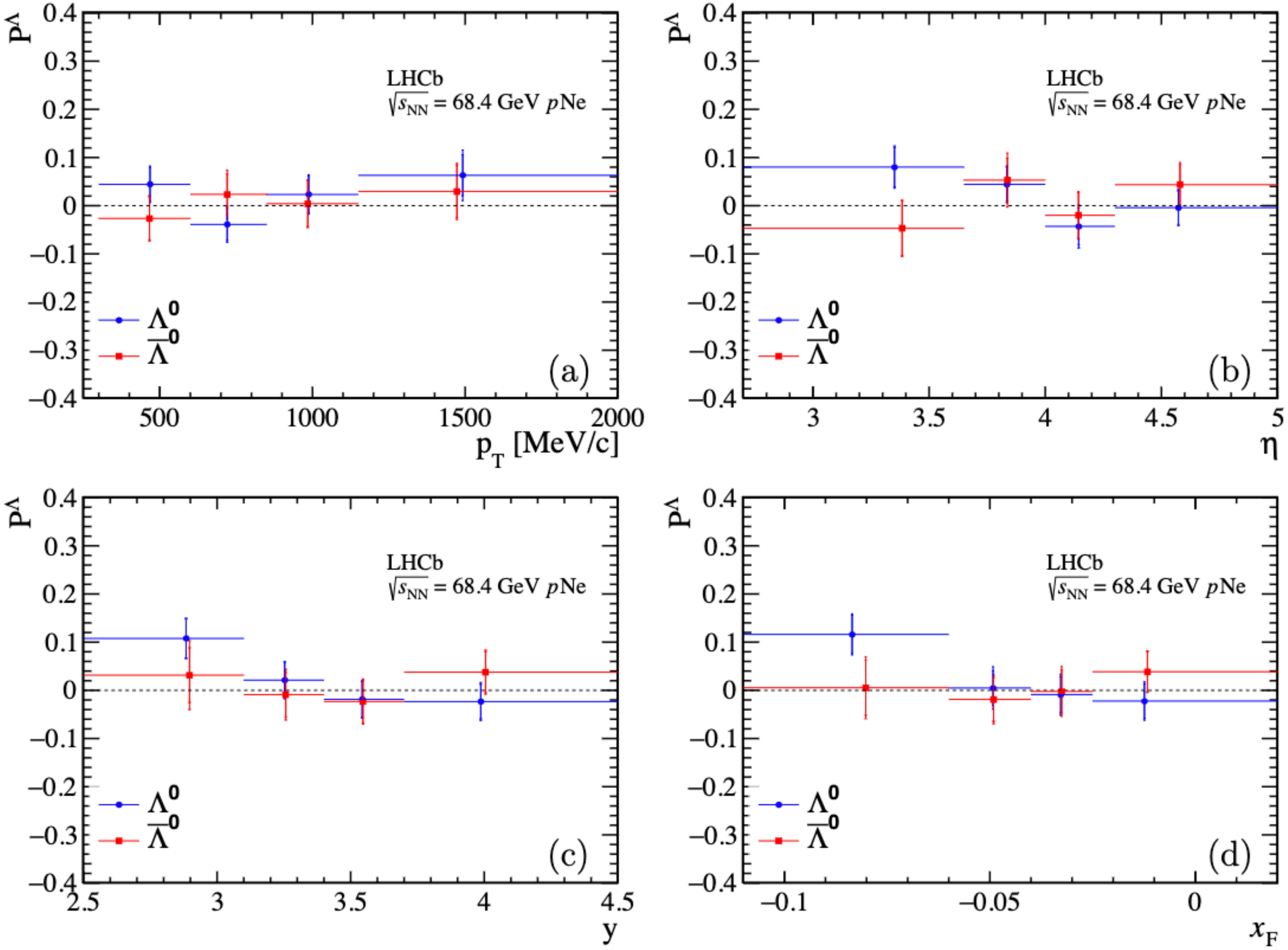
α parity-violating decay asymmetry for Λ^0

- ***Polarization extracted from the angular coefficient*** of the angular distribution



RESULTS

arXiv:2405.11324, accepted by JHEP



- **Polarization** obtained in kinematical range:
  - → **300 < p_T < 3000 MeV/c**
  - → **2 < η < 5**

$$P(\Lambda) = 0.029 \pm 0.019 \pm 0.012$$

$$P(\bar{\Lambda}) = 0.003 \pm 0.023 \pm 0.014$$

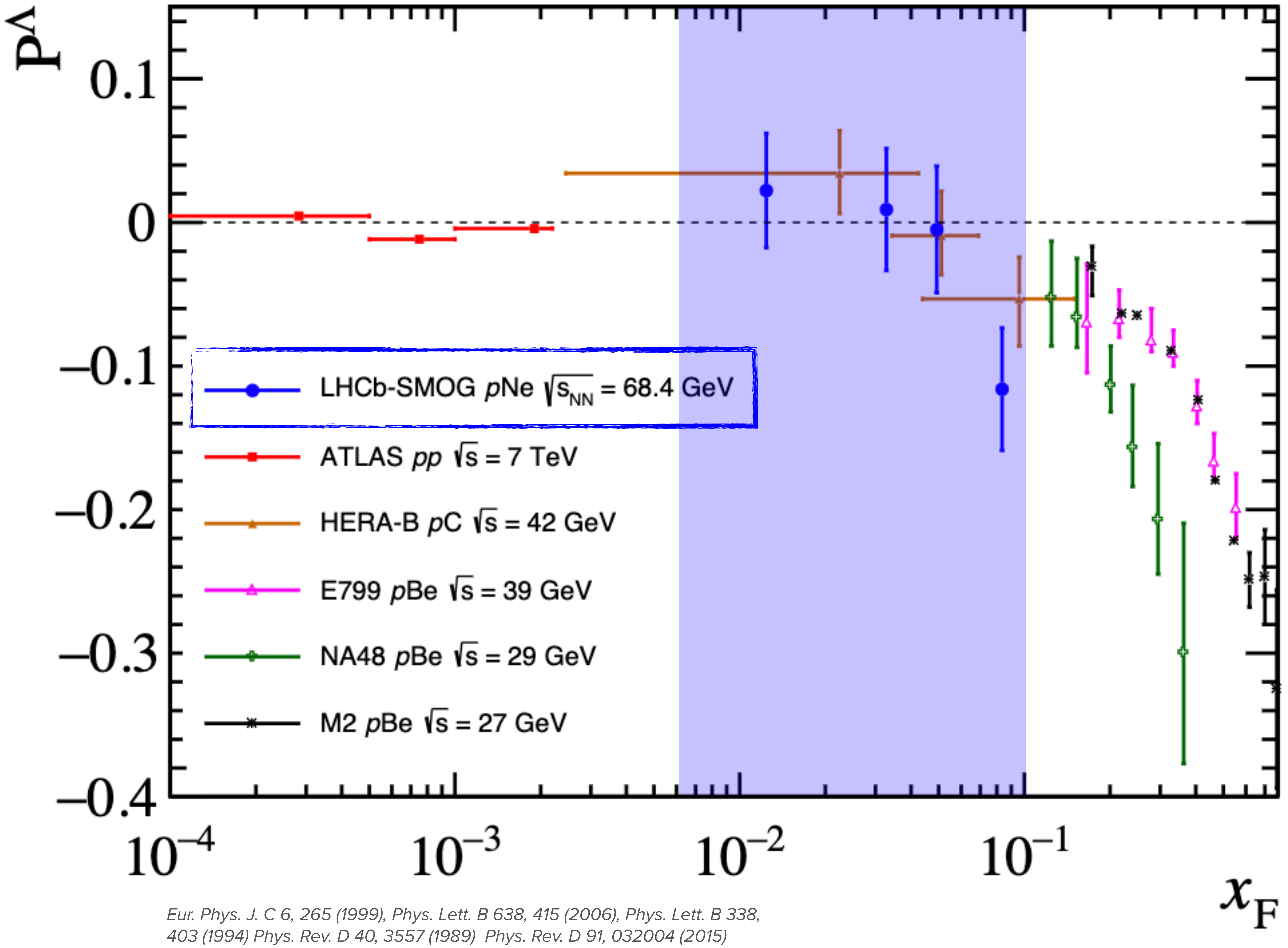
- Polarization studied as a function of

  (a) p_T (b) η
  (c) y (d) x_F

- Error bars convolution of statistical and systematic uncertainties

RESULTS

arXiv:2405.11324, accepted by JHEP



Eur. Phys. J. C 6, 265 (1999), Phys. Lett. B 638, 415 (2006), Phys. Lett. B 338, 403 (1994) Phys. Rev. D 40, 3557 (1989) Phys. Rev. D 91, 032004 (2015)

- **Λ^0 polarization vs x_F**

  → Comparison with results from other experiments in different kinematical regions and collision systems

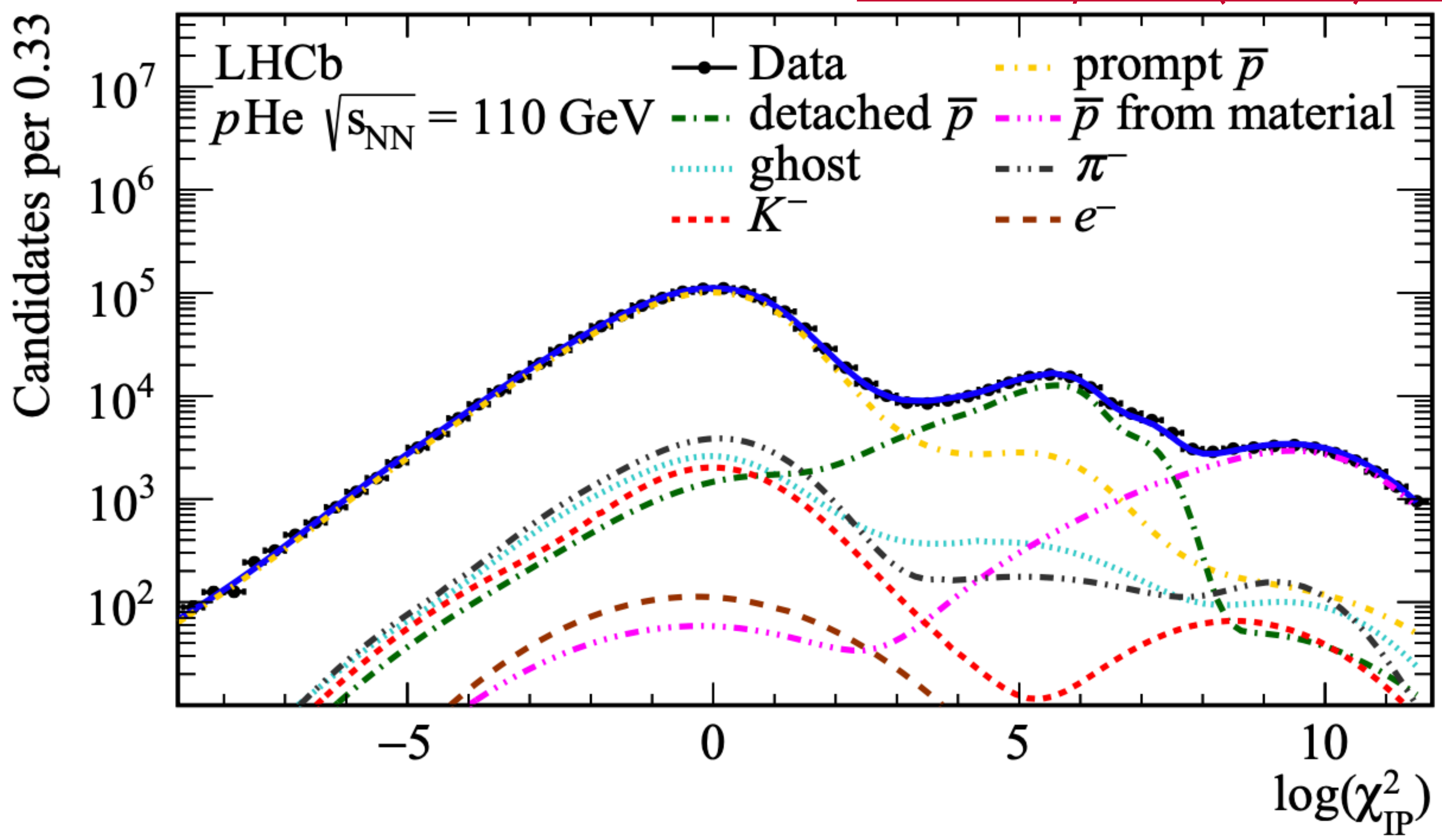
- Very good agreement in the polarization
- Results in a poorly explored kinematic region!

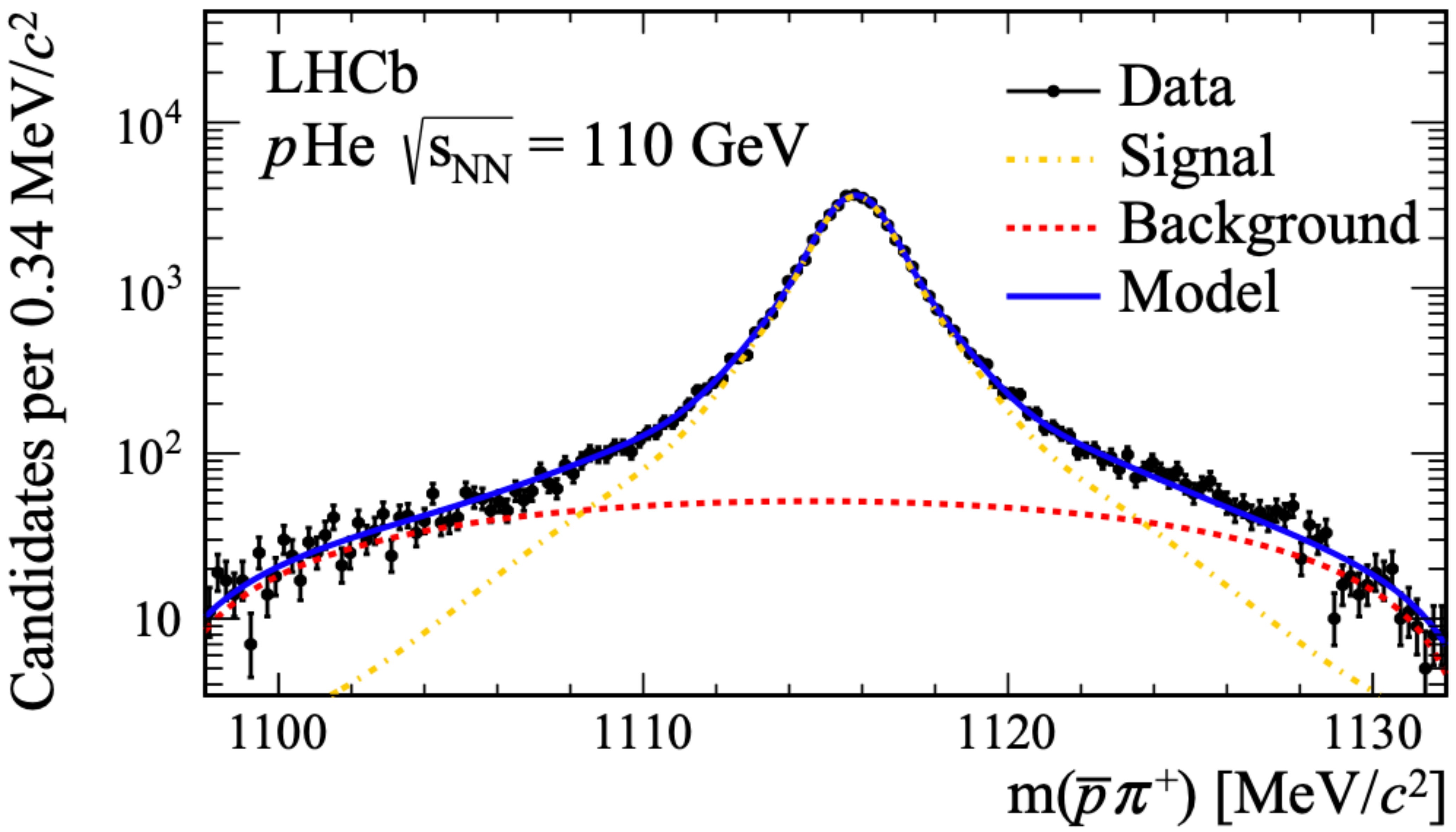
DETACHED ANTIPROTONS IN *p*He COLLISIONS

MOTIVATION AND ANALYSIS STRATEGY

EPJ C83, 543 (2023)-036

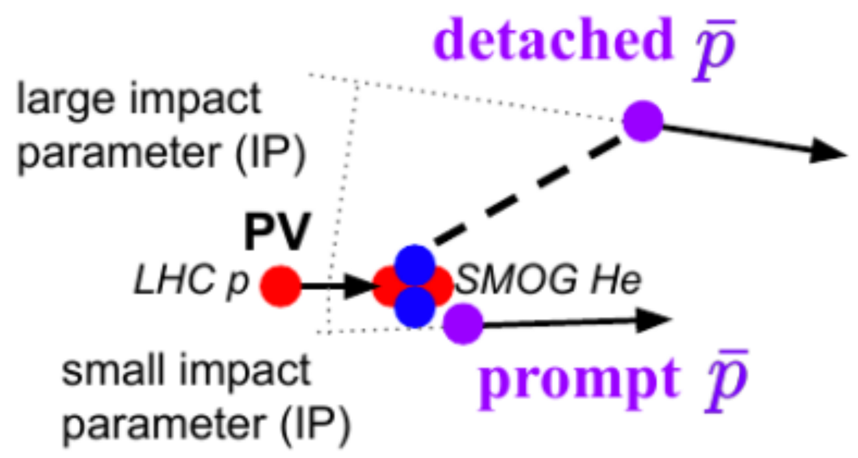
- *p*He @ 110 GeV ($\mathscr{L}$ ~0.5 nb^{-1}) mimic CR-interstellar medium collisions at energy scale relevant for AMS-02 measurements of antimatter in space (and dark matter?)
- ***Prompt*** $\bar{p}$ measurement already ***constrained*** models of secondary cosmic $\bar{p}$ PRL 121 (2018) 222001
-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





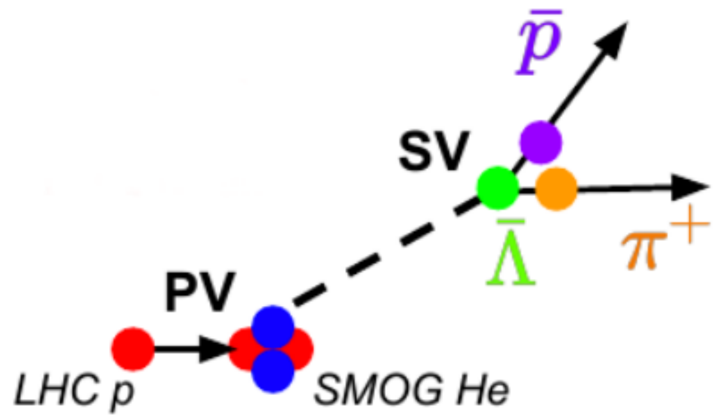
- ***Two*** complementary ***approaches*** performed

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



  → ***Exclusive*** measurement of the dominant contribution

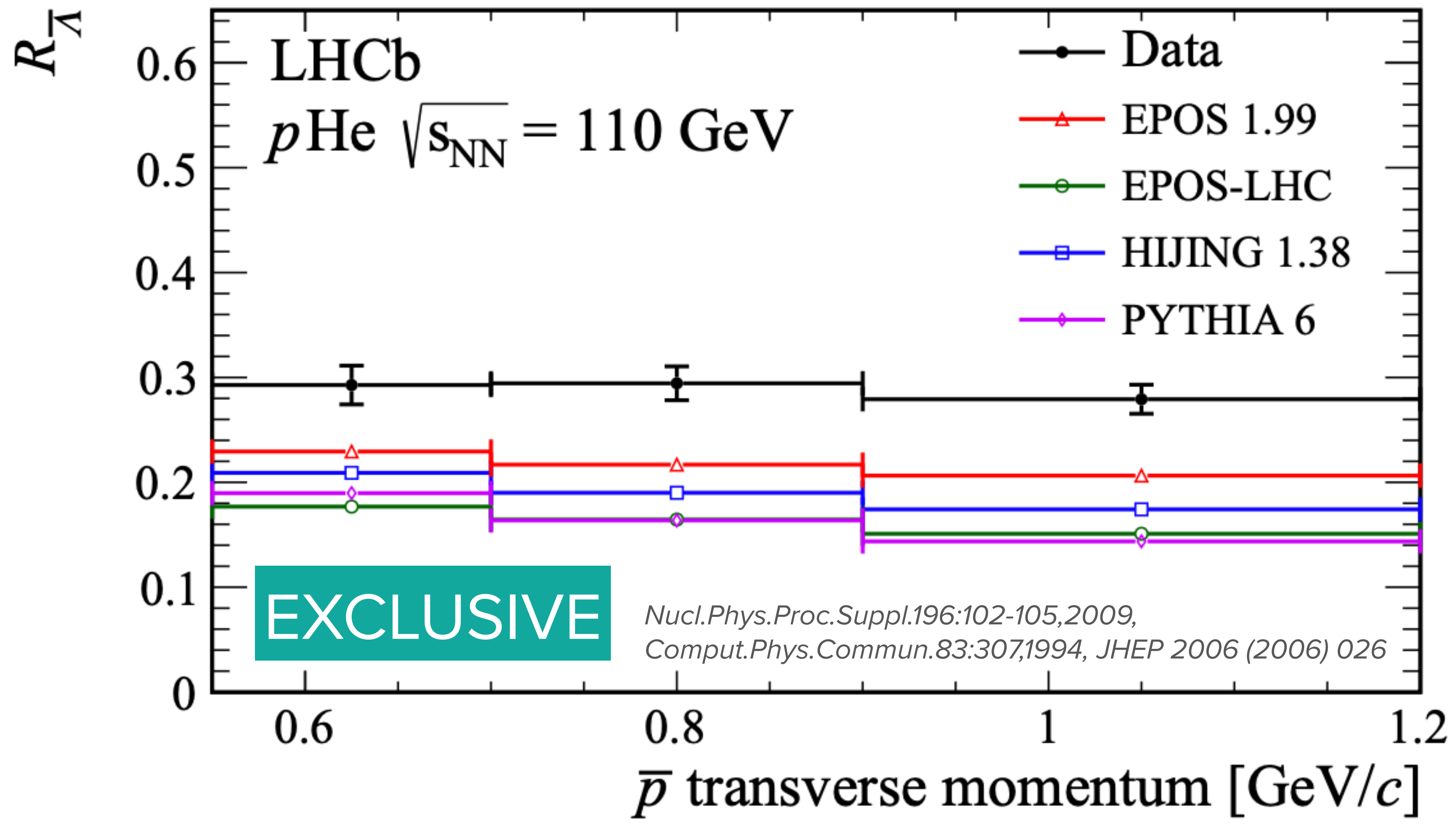
$$\bar{\Lambda} \rightarrow \bar{p}\pi^{+}$$



RESULTS

EPJ C83, 543 (2023)-036

- 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)

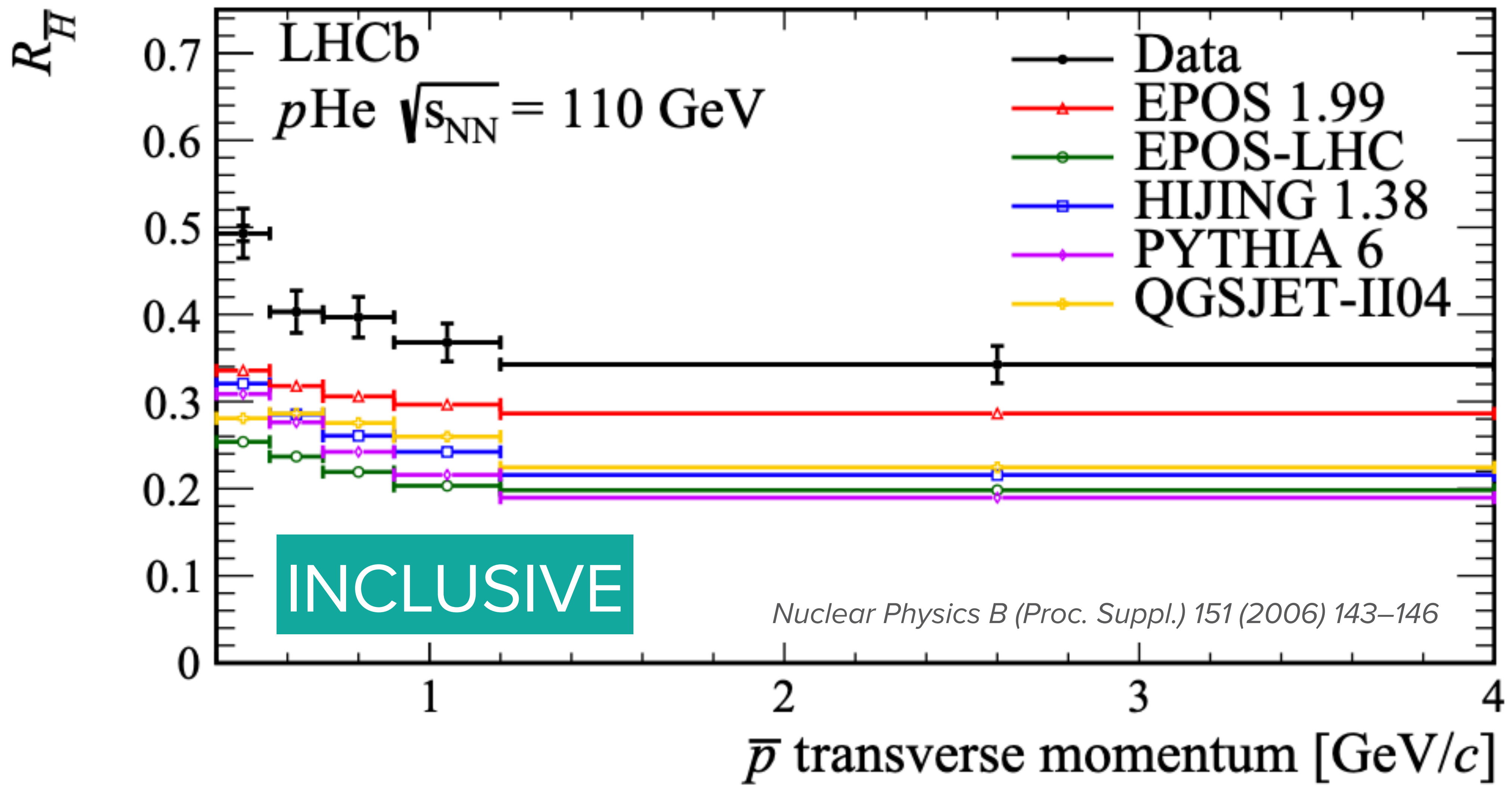


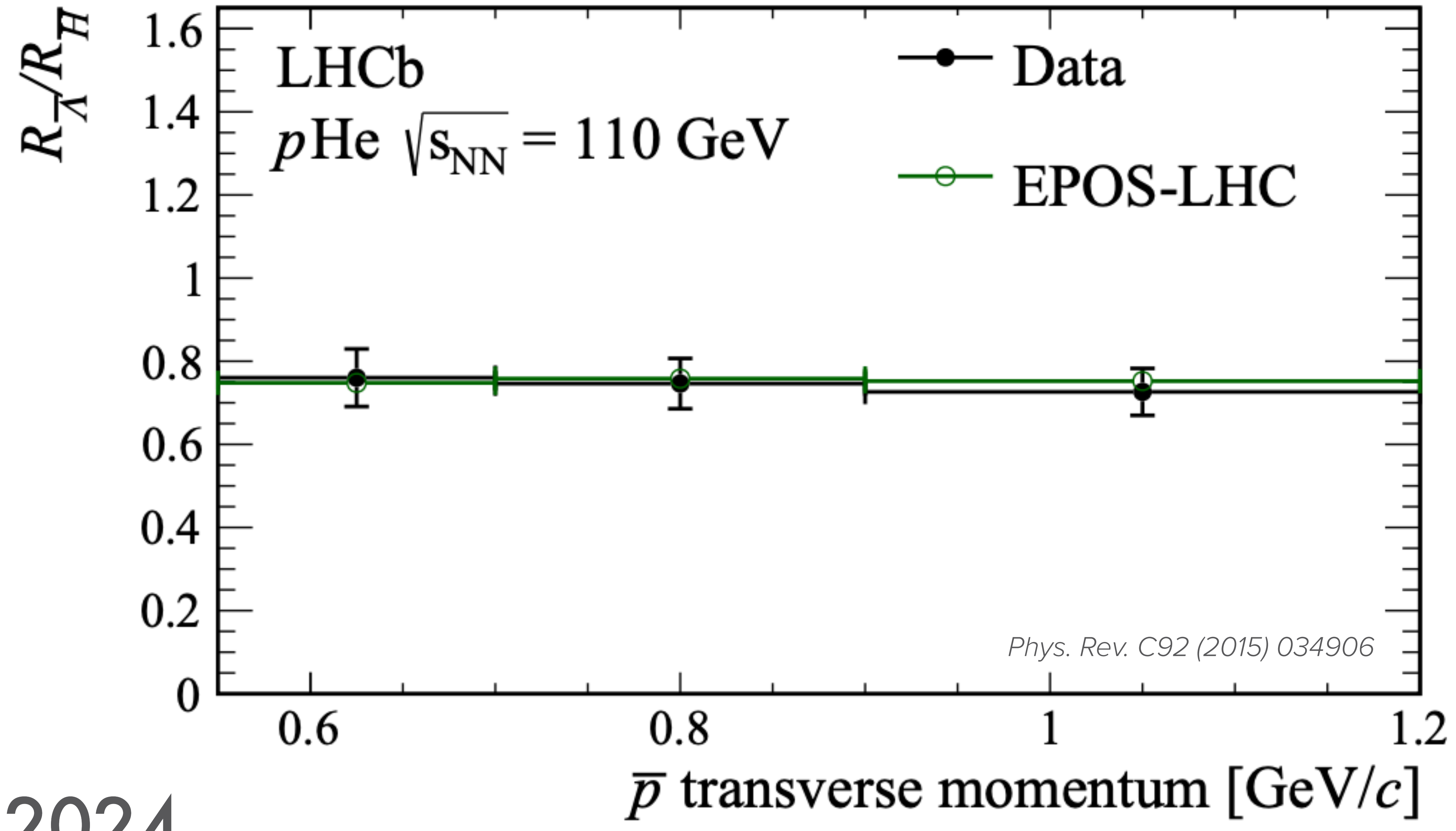
$$R_{\bar{\Lambda}} \equiv \frac{\sigma(p\text{He} \to \bar{\Lambda}X \to \bar{p}\pi^+X)}{\sigma(p\text{He} \to \bar{p}_{\text{prompt}}X)}$$

PRL 121 (2018) 222001

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

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





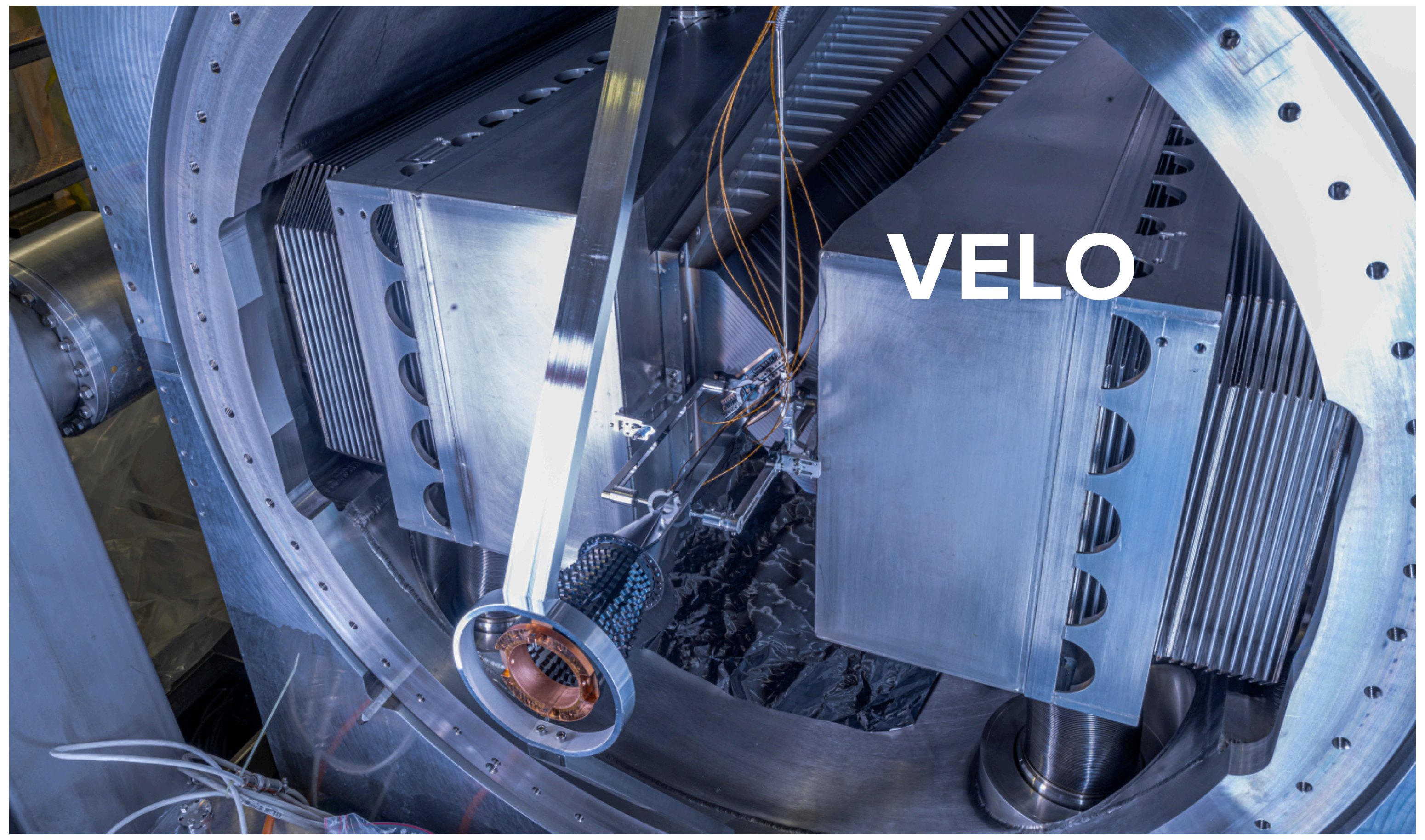
FIXED-TARGET PHYSICS AT LHC*b*: SMOG2

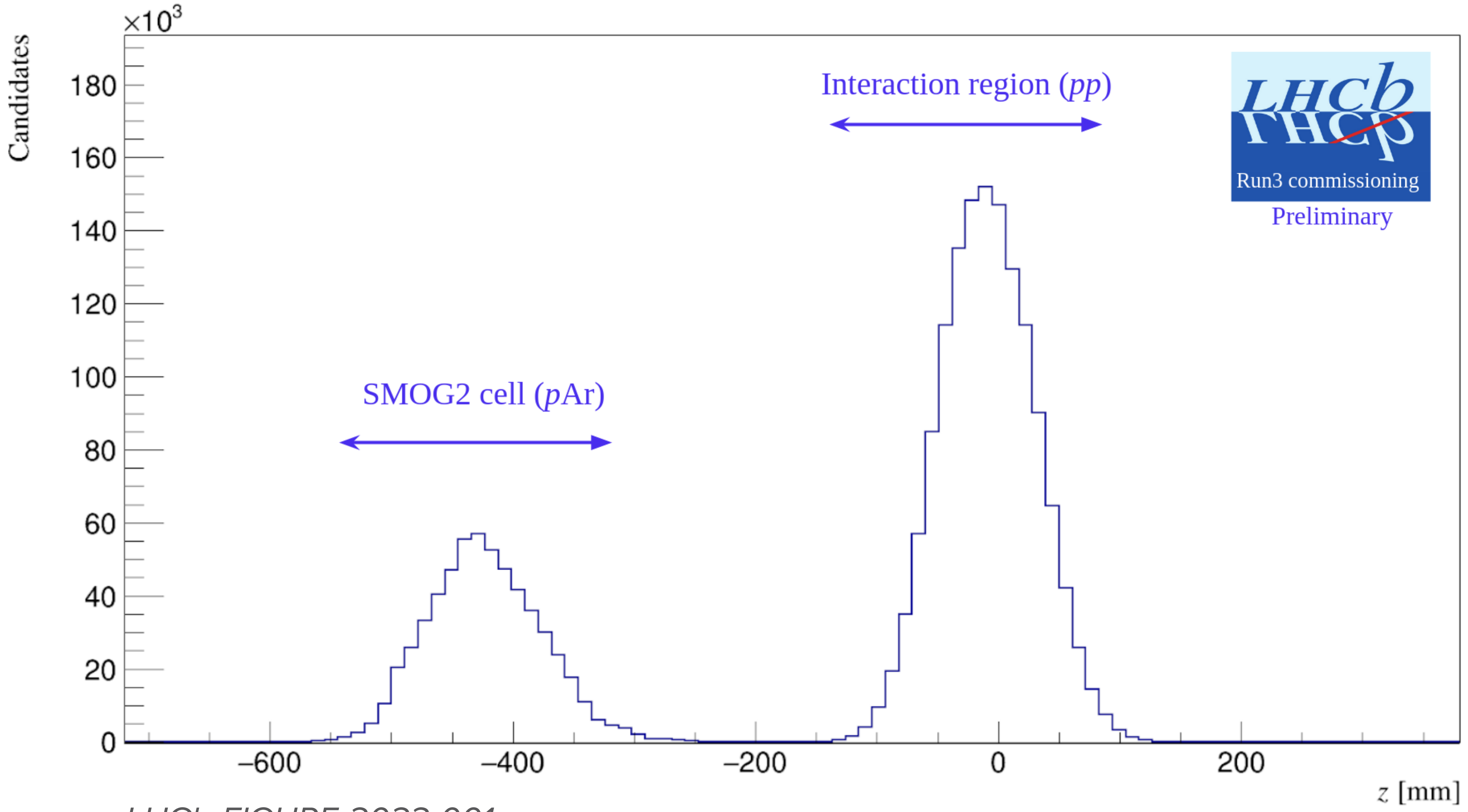
SMOG2

RUN3 CONFIGURATION

arXiv:2407.14200, in print on Physics Review Accelerators and Beams

- **SMOG2:** gas confined in a 20 cm long **storage cell**
- **Higher areal density** than SMOG (luminosity increased up to ~ x 100)
- **Wider choice of gases to be injected:** He, Ne, Ar, H_2, D_2, N_2, O_2, Kr, Xe
- **Simultaneous beam-beam beam-gas data-taking**

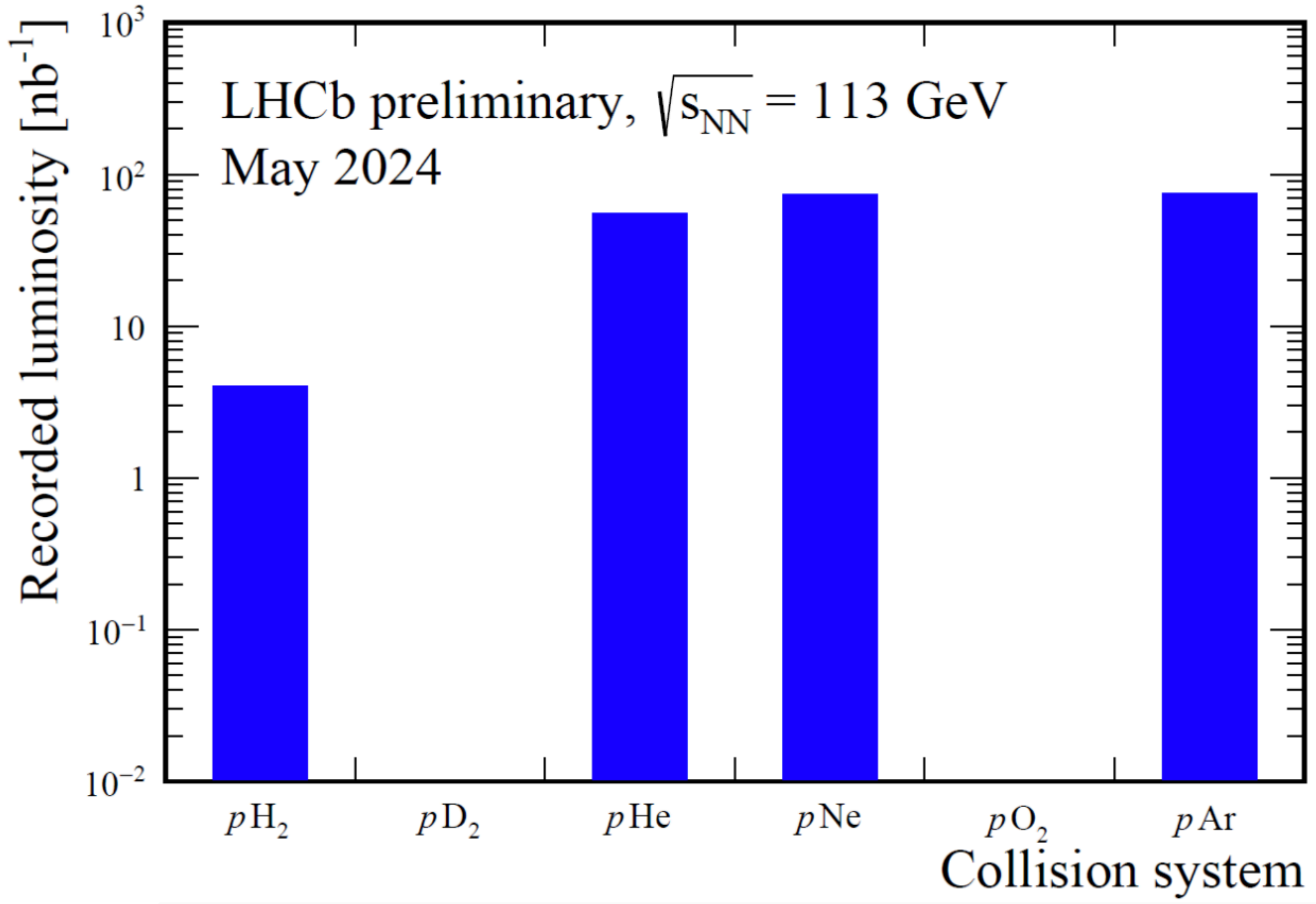




LHCb-FIGURE-2023-001

- **Possibility to improve the fixed-target analyses:**
  - **Much higher luminosity → better statistical resolution**

→ *See SMOG2 poster and Oscar Boente Garcia's talk for more*



CONCLUSIONS

- ***Most recent*** **strange production results from Run2 fixed-target data in LHCb!**
- ***New*** measurement of the ϕ meson ***production*** in fixed-target *p*Ne collisions at $\sqrt{s_{NN}}$ = 68.5 GeV

NEW!

- Measurement with the fixed-target system helps understanding the long-standing challenge of the transverse Λ ***polarization*** explanation
- Measurement of ***detached-to-prompt*** $\bar{p}$ ***production*** in *p*He collisions gives ***crucial inputs*** to models of antimatter production in space
- Many more unique results will come with **SMOG2** data!

Stay Tuned!

THANK YOU!! 💃

BACKUP

SYSTEMATIC UNCERTAINTIES

LHCb-PAPER-2024-036, in preparation

- ***Observable***: $\frac{d^2\sigma(p_T, y^*)}{dp_T\, dy^*} = \frac{N^\phi(p_T, y^*)\ \zeta}{\mathscr{L}\ \text{BR}\ \epsilon_{tot}(p_T, y^*)\, \Delta p_T\, \Delta y^*\, A_{Ne}}$

- Summary of all ***contributions*** to the systematic uncertainties

NEW!

Systematic uncertainties	
Uncorrelated among kinematic regions	
Signal determination	$(<0.1 - 5.0)\%$
Geometrical acceptance	$(<0.1 - 1.8)\%$
Multiplicity corrections	$(0.2 - 3.6)\%$
PID efficiency	$(2.3 - 4.4)\%$

- Signal extraction with alternative modelling
- Limited size of the MC sample
- Alternative MC weighting with number of tracks
- Limited size of the PID efficiency sample

Correlated among kinematic regions	
PV reconstruction	1.2%
Reconstruction and selection efficiency	3.2%
pp contamination	2.0%
$\mathcal{B}(\phi \to K^+K^-)$	1.0%
Luminosity	6.5%

- Limited size of the PV efficiency sample
- Accounts for tracking reconstruction within LHC*b* and for kaons interactions with detector material
- Uncertainty on the ghost factor due to *pp* contamination
- Luminosity evaluated from the $p - e^-$ scattering:
  $$\mathscr{L} = 21.7 \pm 1.4\ \text{nb}^{-1}$$

Eur. Phys. J. C 83 (2023) 541 Phys. Rev. Lett. 121 (2018) 222001