SQM2024

The 21st International Conference on Strangeness in Quark Matter

3-7 June 2024, Strasbourg, France

Strangeness production in fixed-target collisions at LHCb

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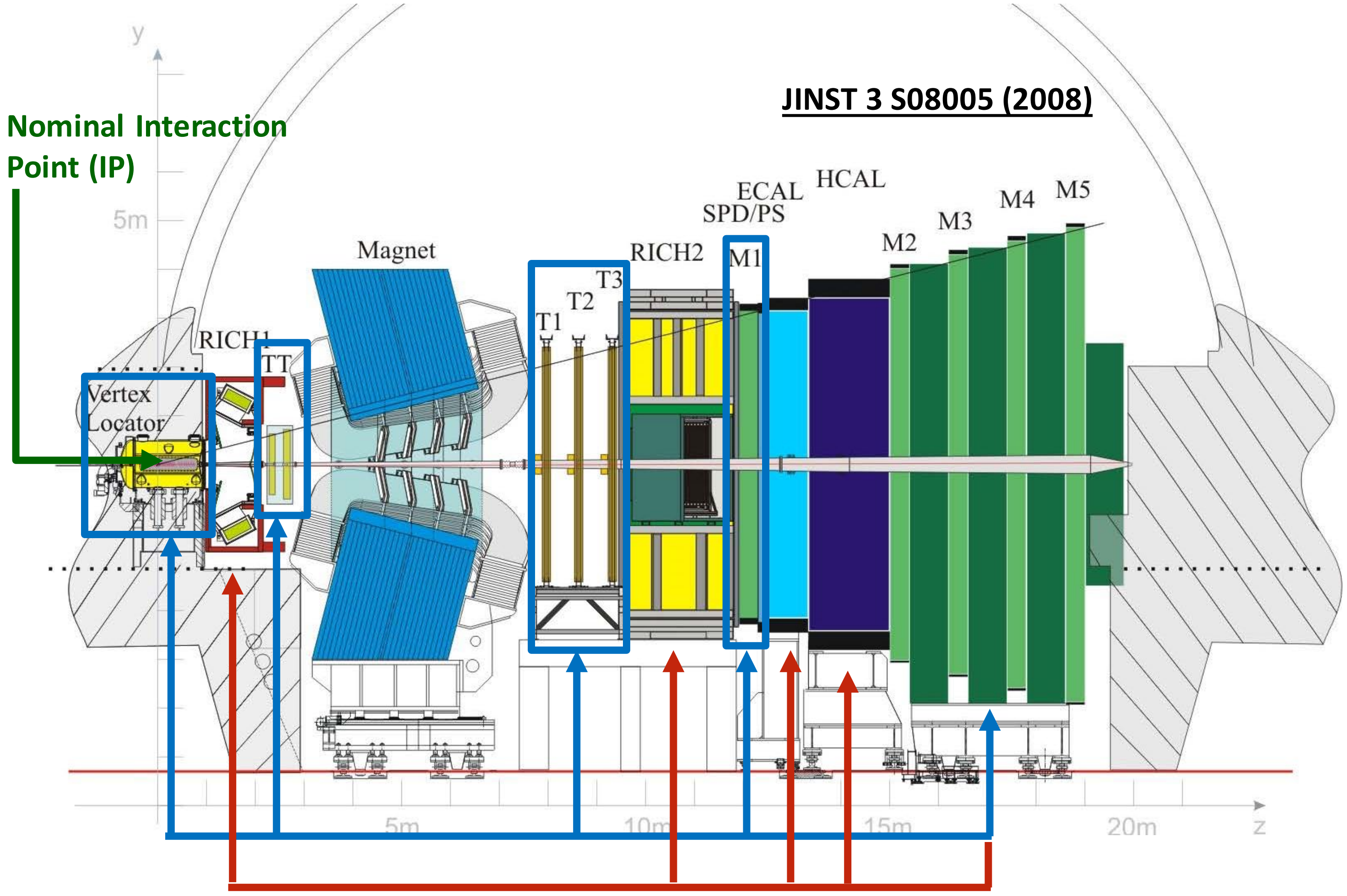
on behalf of the LHCb collaboration

SQM 2024, 5 June 2024, Strasbourg

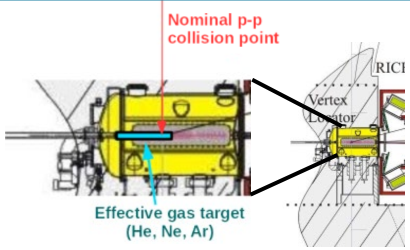
The LHCb experiment

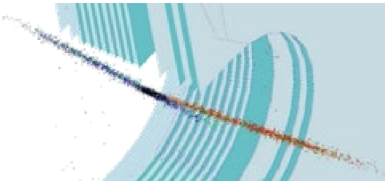


The LHCb is a general-purpose experiment in the forward direction:

- **Single-arm forward spectrometer**: optimized for $b\bar{b}$ production, $2 < \eta < 5, \Theta \in [10, 250]$ mrad.
- **Tracking:** excellent vertexing, IP resolution: 15+29/p_T [GeV] µm, momentum resolution: $\Delta p/p = 0.5\% - 1.0\%$.
- **Particle Identification (PID):** excellent separation among K, π and p with momentum in [10, 110] GeV/c range.
- **Trigger:** flexible and versatile, bandwidth up to 15 kHz to disk.
- Its forward geometry is very well suited for **fixed-target physics.**

LHCb fixed-target apparatus

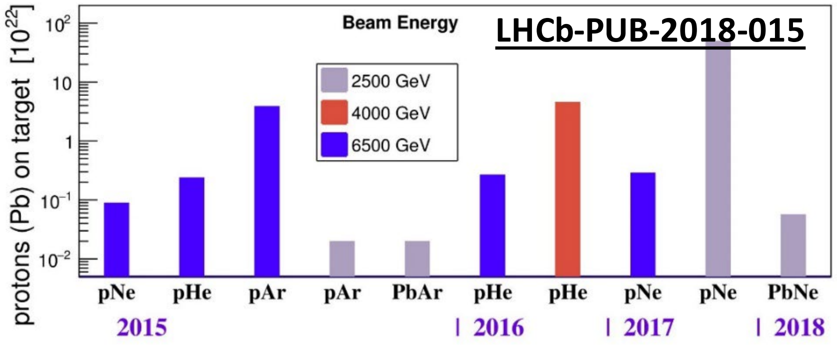




JINST 9 (2014) P12005

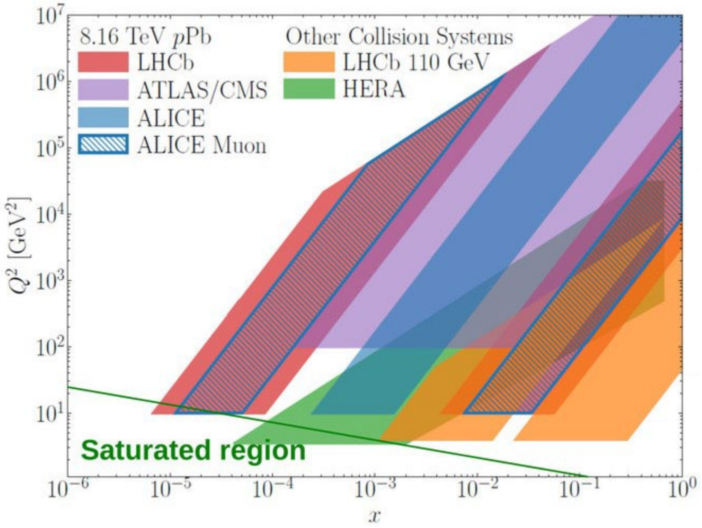
SMOG: The *System for Measuring Overlap with Gas*

- Inject nobel gases (He, Ne, Ar) in LHC beam pipe around (±20 m) the LHCb IP, pressure of **2x10^{-7} mbar** (x100 nominal LHC vacuum)
- Since 2015, exploited for LHCb fixed-target physics programme: **highest-energy fixed-target experiment ever.**



Unique physics opportunities at the LHC

- Unexplored **intermediate energy** to SpS and LHC: $\sqrt{s_{NN}} \in [30, 115]$ GeV
- **Large target Bjorken-*x* at intermediate Q^2**
- Collisions with **targets of mass number A intermediate** between *p* and Pb



- **Cold nuclear-matter effects** for QGP studies
- **Nuclear PDFs at high-*x*** and strange hadronization process
- **Hadron production** and spectra measurements for CRs physics
- **Polarization studies** in baryon production

Antiproton production from antihyperon decays

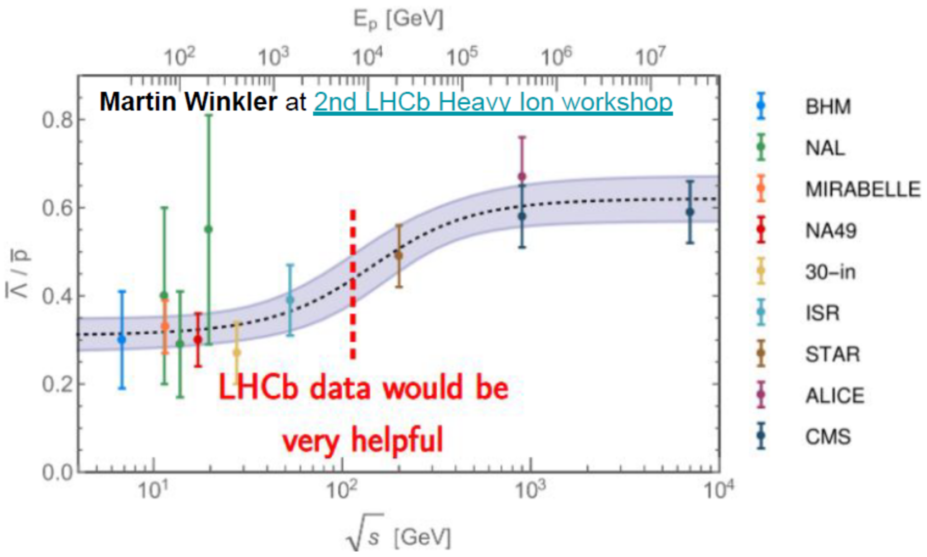
Detached antiproton production

- Interpretation of $\bar{p}$ flux in CRs measurement (indirect DM searches) limited by models of $\bar{p}$ production in CRs collisions with the interstellar medium (H, He)
- Dedicated measurement to the component from anti-hyperon decays in *p*He, extending first LHCb result only dealing with the prompt processes → Around **20-30% of $\bar{p}$ production** comes from anti-hyperon decays:

$$\bar{\Lambda}^0_{\text{prompt}} \to \bar{p}\pi^+ \qquad \bar{\Sigma}^- \to \bar{p}\pi^0 \qquad \bar{\Xi}^+ \to \bar{\Lambda}\pi^+ \qquad \bar{\Xi}^0 \to \bar{\Lambda}\pi^0 \qquad \bar{\Omega}^+ \to \bar{\Lambda}K^+$$

- Available data indicate strangeness enhancement but **large spread among different theoretical models**

→ **LHCb SMOG measurement can constrain the models**



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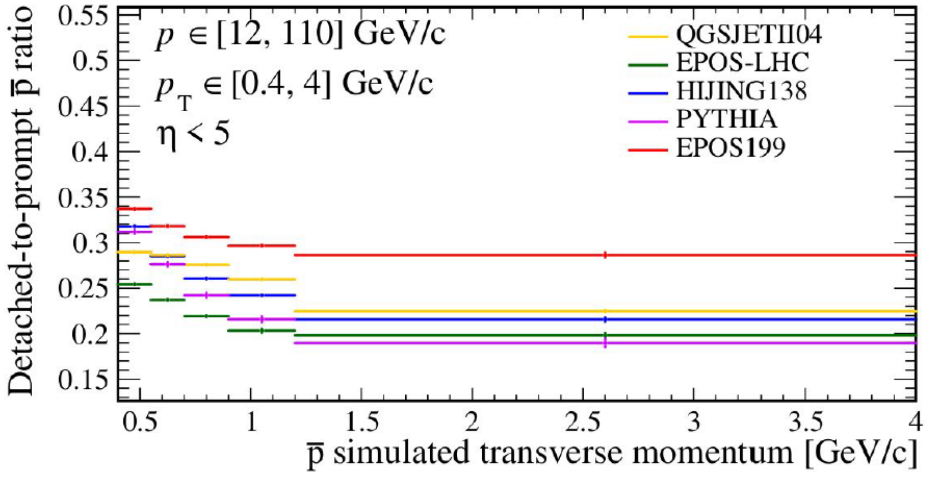
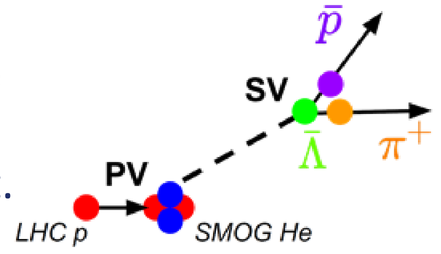


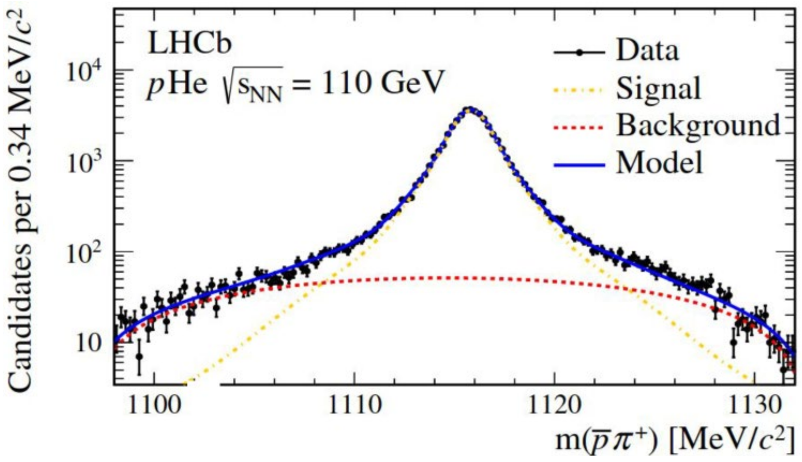
Analysis strategy

Eur. Phys. J. C83 (2023) 543

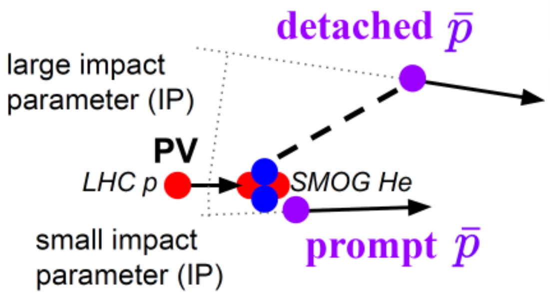
Analysis for secondary-to-primary $\bar{p}$ ratio $\boldsymbol{R = \sigma_{sec}/\sigma_{prim}}$ following **two complementary approaches**:

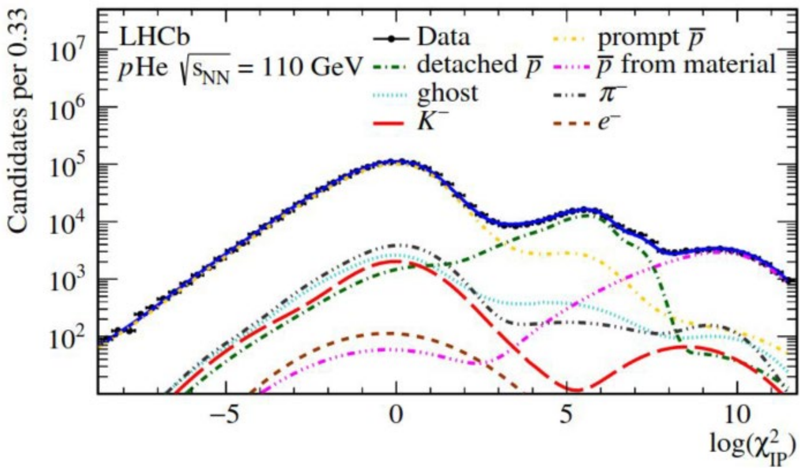
- **Exclusive approach**: $R_{\bar{\Lambda}} = \dfrac{\sigma(\text{pHe} \to (\bar{\Lambda}_{\text{prompt}} \to \bar{p}\pi^+)X)}{\sigma(\text{pHe} \to \bar{p}_{\text{prompt}}\, X)}$
  - Measure $\boldsymbol{\bar{\Lambda} \longrightarrow \bar{p}\pi^+}$, dominant detached component.
  - Identifying decay exploiting LHCb **excellent mass resolution** (no PID info): event selection via **kinematic description in the Armenteros plot** and **impact parameters**.
  - Most systematic uncertainties (luminosity, reco, …) **cancel in the ratio**.





- **Inclusive approach**: $R_{\bar{H}} \equiv \dfrac{\sigma(\text{pHe} \to \bar{H}X \to \bar{p}X)}{\sigma(\text{pHe} \to \bar{p}_{\text{prompt}} X)}$, $\bar{H} = \bar{\Lambda}, \bar{\Sigma}, \bar{\Xi}, \bar{\Omega}$
  - Focused on **all detached components.**
  - Selecting $\boldsymbol{\bar{p}}$ **with tight PID cuts**
  - Distinguishing between prompt, detached and secondary $\bar{p}$ via a **fit to the *p*He data impact parameter** with the composition of templates.





Results

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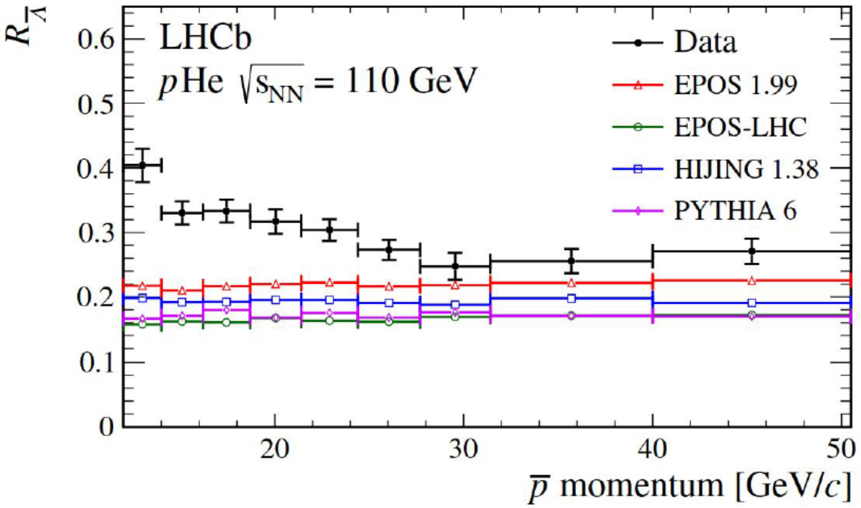
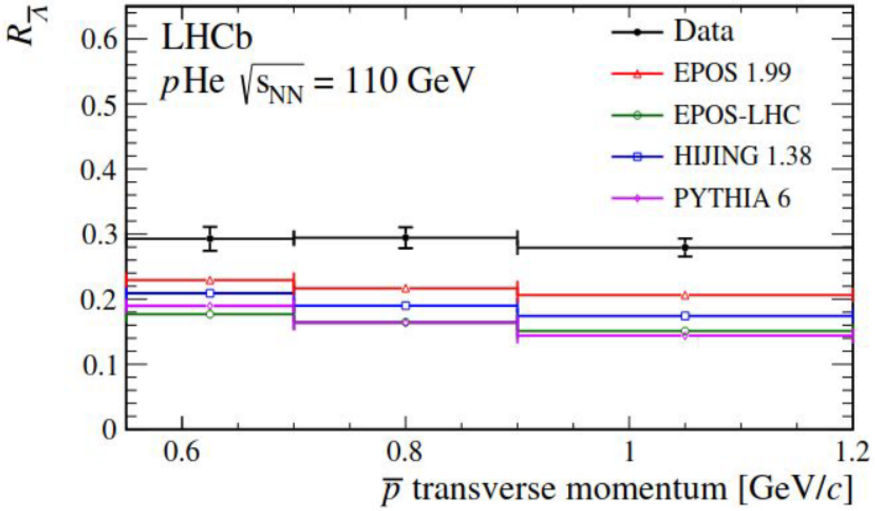
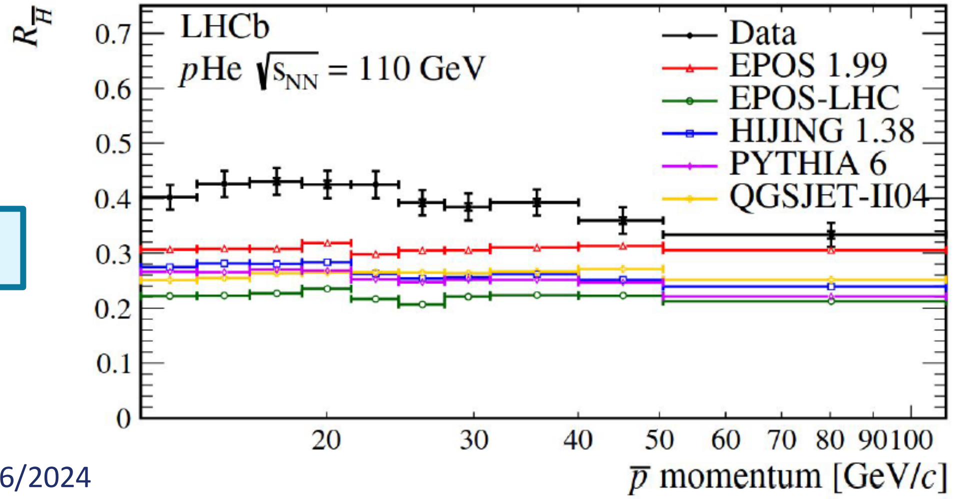
Larger contribution measured wrt all most widely used theoretical models

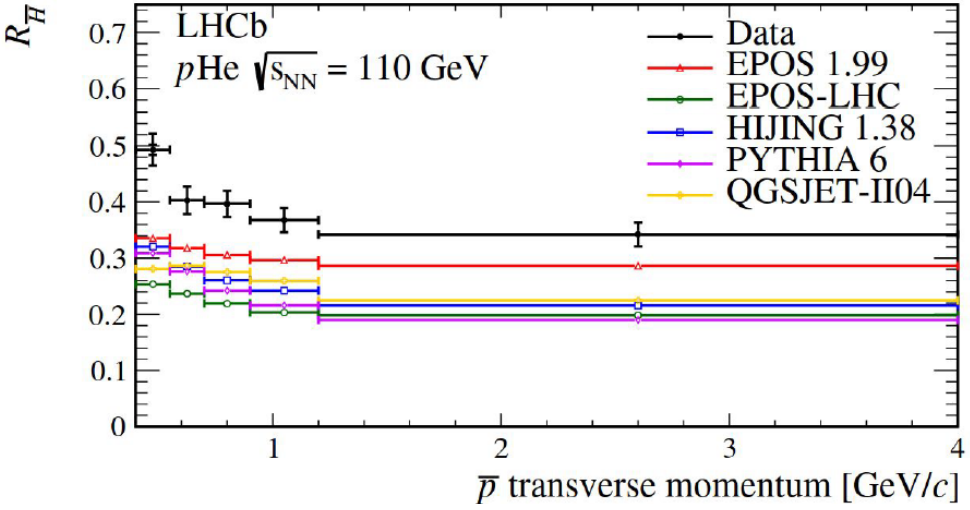
Exclusive





Inclusive





Comparison between the approaches

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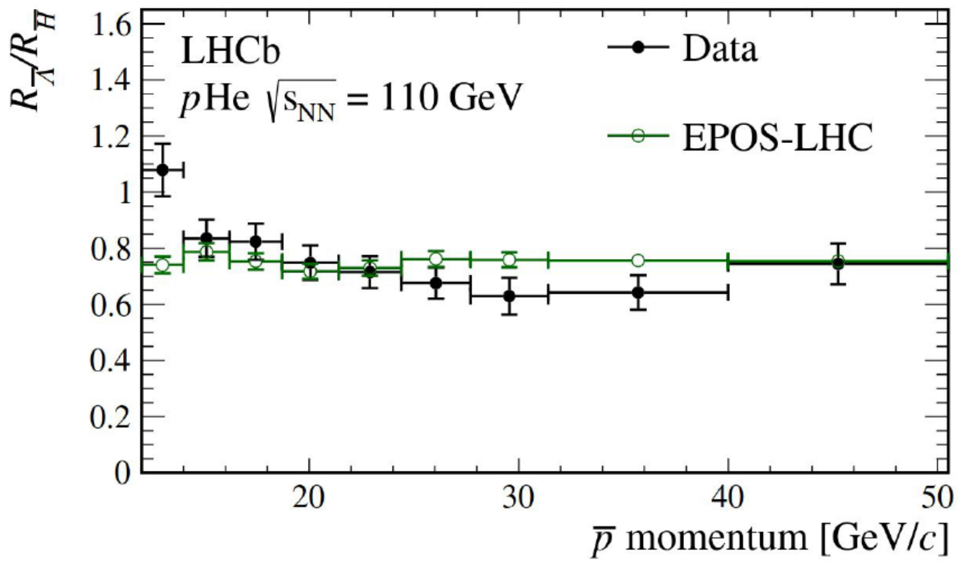
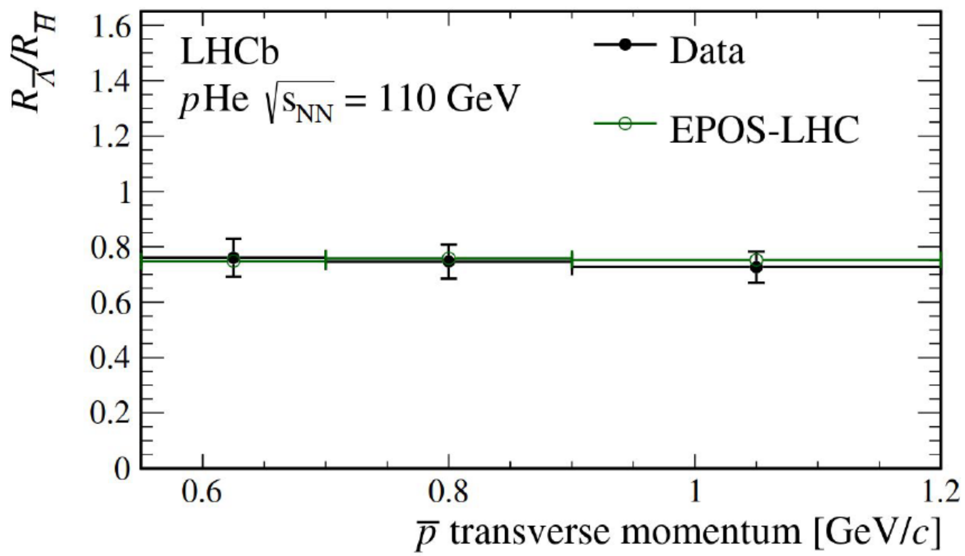
- Ratio of the results is expected to be **predicted more reliably** than the single terms (depends only on the hadronization).
- Results mutually cross-checked since found to be **consistent with EPOS-LHC prediction.**





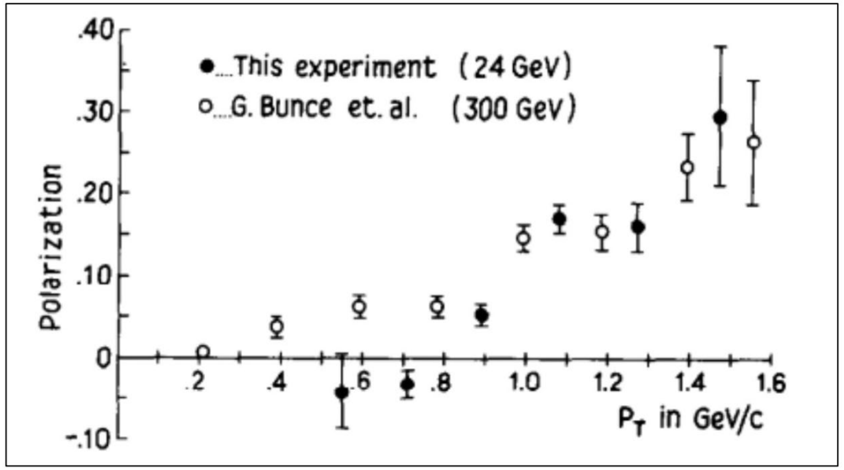
Λ^0 transverse polarization

Λ^0 transverse polarization: experimental data

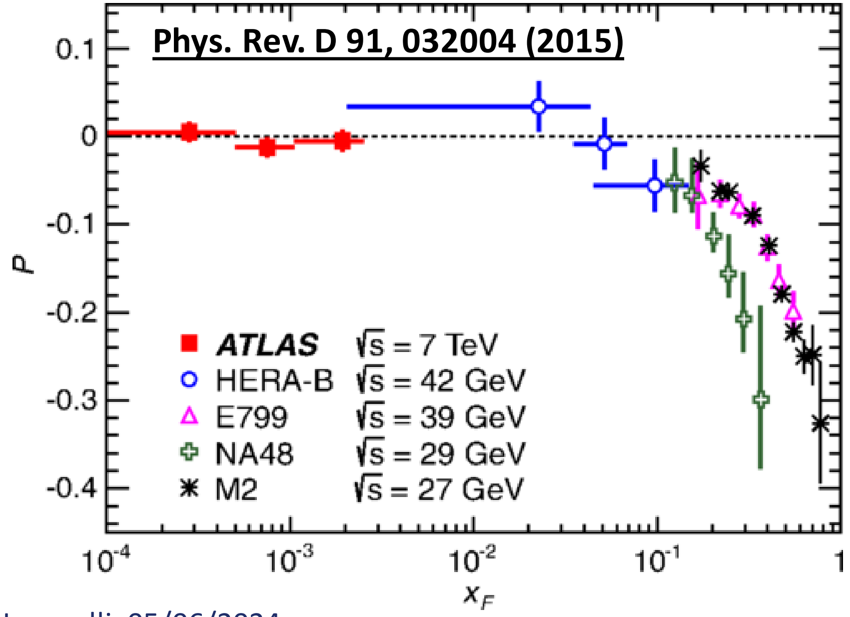
In 1976, first observation of Λ^0 transverse polarization: inclusive production by 300 GeV unpolarized *p* beam on Be target.

- Leading order perturbative QCD predicts small polarization for light quark, decreasing with momentum → No polarization effects expected in particle production with high energy unpolarised beam

Phys. Rev. Lett. 36, 1113 (1976)



<u>New result</u>: non perturbative spin effects contribute significantly even in high energy collisions



Several experimental measurements highlighted common features:

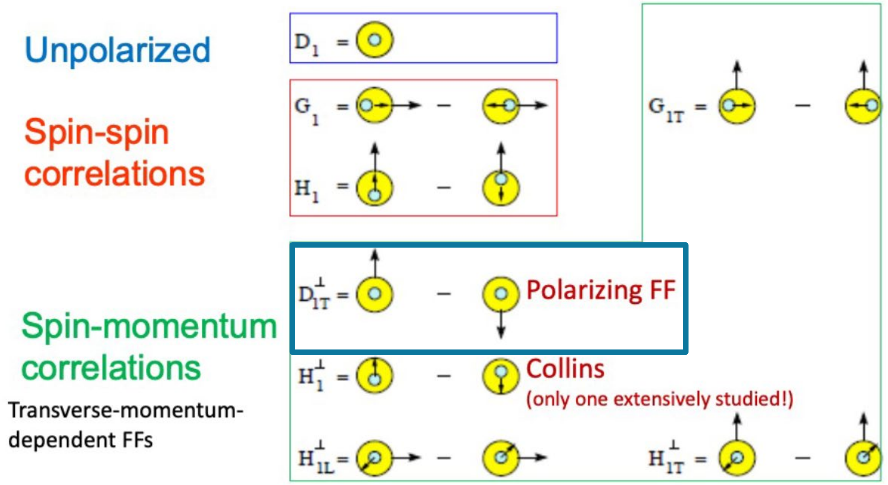
- **Same magnitude** of polarization observed **for other hyperons** (Ξ^0, $\Xi^\pm$, $\Sigma^\pm$)
- Polarization **increases with x_F and p_T** up to few GeV
- Roughly **independent of beam energy** and colliding system

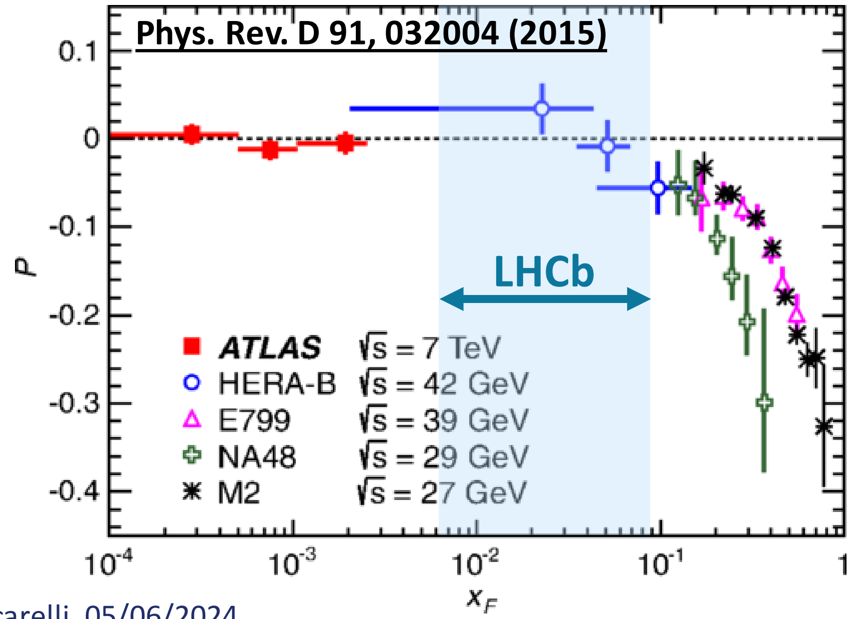
Λ^0 transverse polarization: theoretical explanation

Phenomenological approach in explaining the hyperon polarized production:
TMD fragmentation functions (FF)

Polarizing fragmentation function $D_{1T}^{\perp}$: fragmentation of unpolarized quark into transverse polarized hadron accounting for spin and momentum correlations at soft level.

→ Difficult to calculate from first principle, extracted from data





Several experiments, still not clear explanation reached

Study polarization in *p*Ne $\sqrt{s_{NN}}$=68 GeV

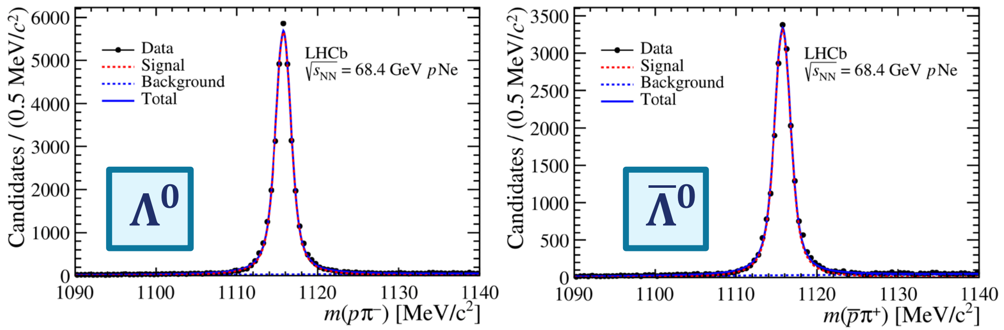
Same x_F coverage as HERA-B but higher energy
→ Study energy (in)dependence of polarization

Analysis strategy

arXiv:2405.11324, submitted to JHEP

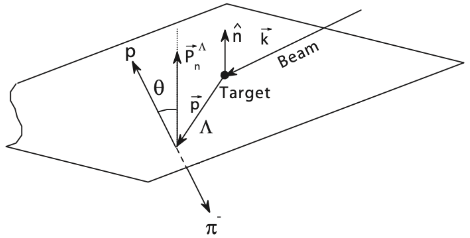
Λ^0 transverse polarization searches exploits the self-analyzing decays

$$\boldsymbol{\Lambda^0 \longrightarrow p\pi^-}$$
$$\boldsymbol{\overline{\Lambda}^0 \longrightarrow \overline{p}\pi^+}$$



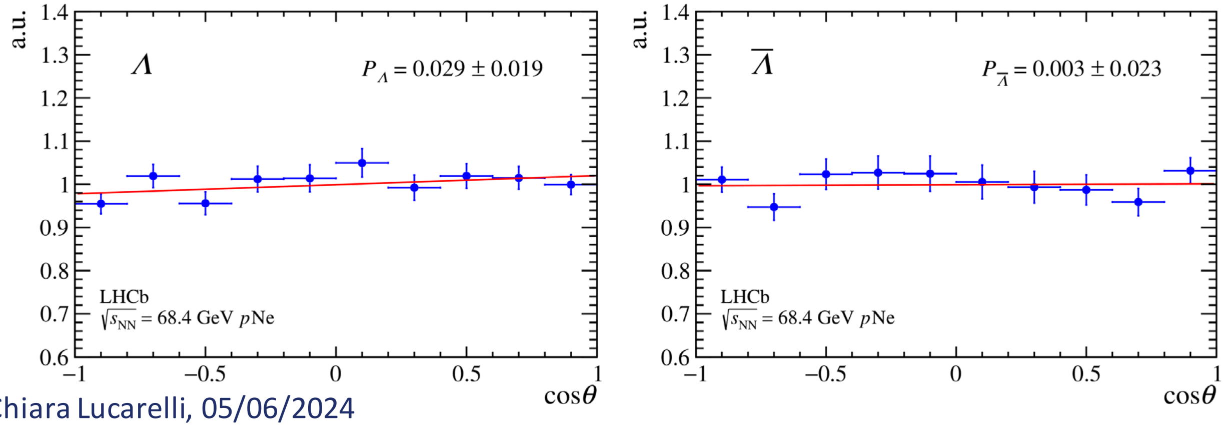
Strong parity violation: *p* preferentially emitted along the Λ^0 spin direction in its rest frame.

→ Protons angular distribution depends on the Λ^0 polarization P^{Λ^0}:



$$\frac{dN}{d\Omega} = \frac{dN_0}{d\Omega}\left(1 + \alpha P^{\Lambda^0} \cos\theta\right)$$

$\frac{dN_0}{d\Omega}$: decay distribution for unpolarized Λ^0
α : parity-violating decay asymmetry for Λ^0, fixed to world average
θ : angle between $\bar{p}_p$ and $\hat{n}$ normal to production plane

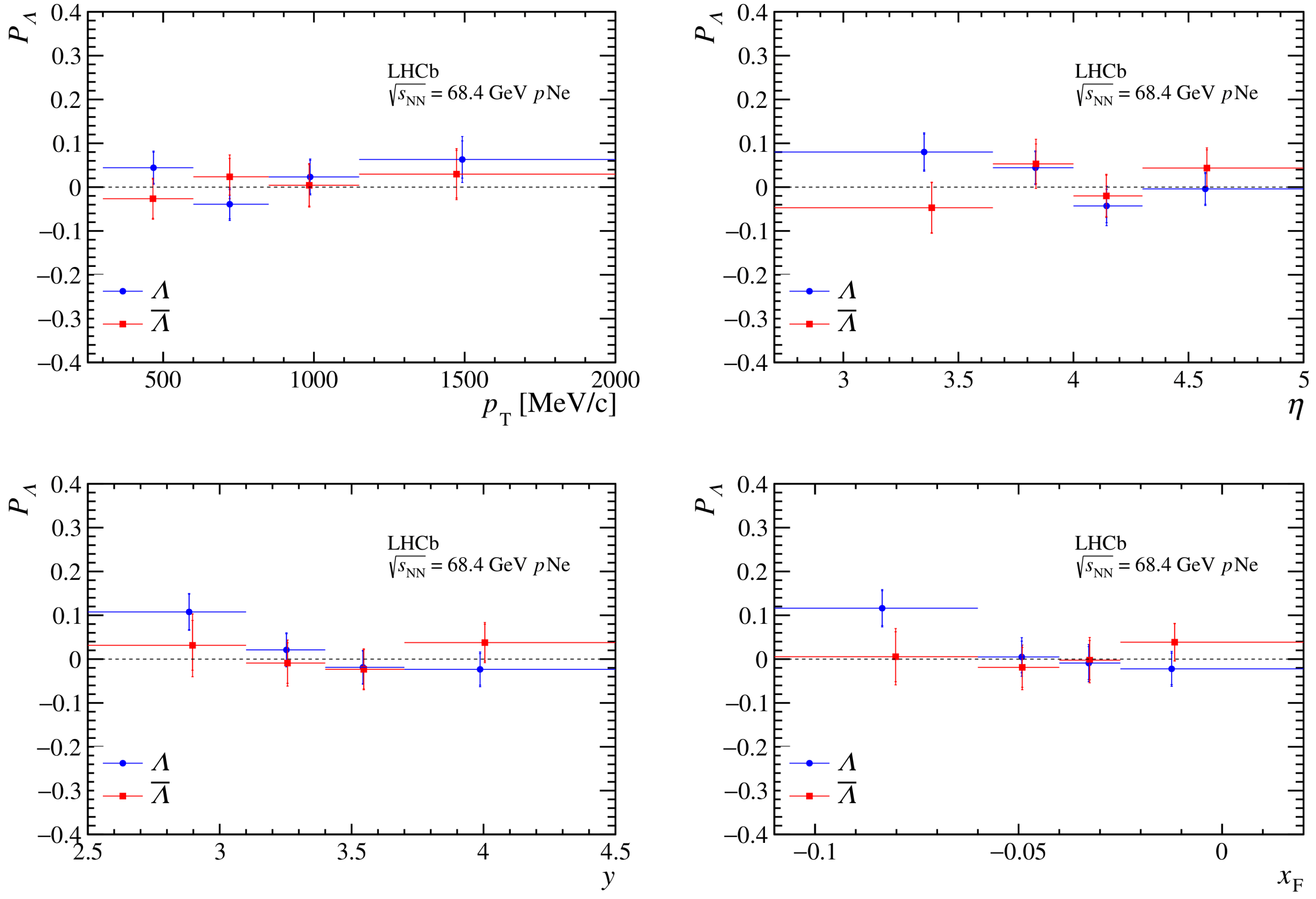


P^{Λ^0} from linear fit of *p* angular distribution in bin of cos*θ*

Polarization studied as a function of the Λ^0 p_T, η, *y* and x_F considering dependence observed in previous studies.

Results

arXiv:2405.11324, submitted to JHEP



Kinematic range: 300< p_T <3000 MeV/c & 2<η<5

$P(\Lambda^0)$ = 0.029 ± 0.019 ± 0.012

$P(\bar{\Lambda}^0)$ = 0.003 ± 0.023 ± 0.014

Uncertainty dominated by limited statistic.

Study performed in bins of p_T , η, *y* and x_F :

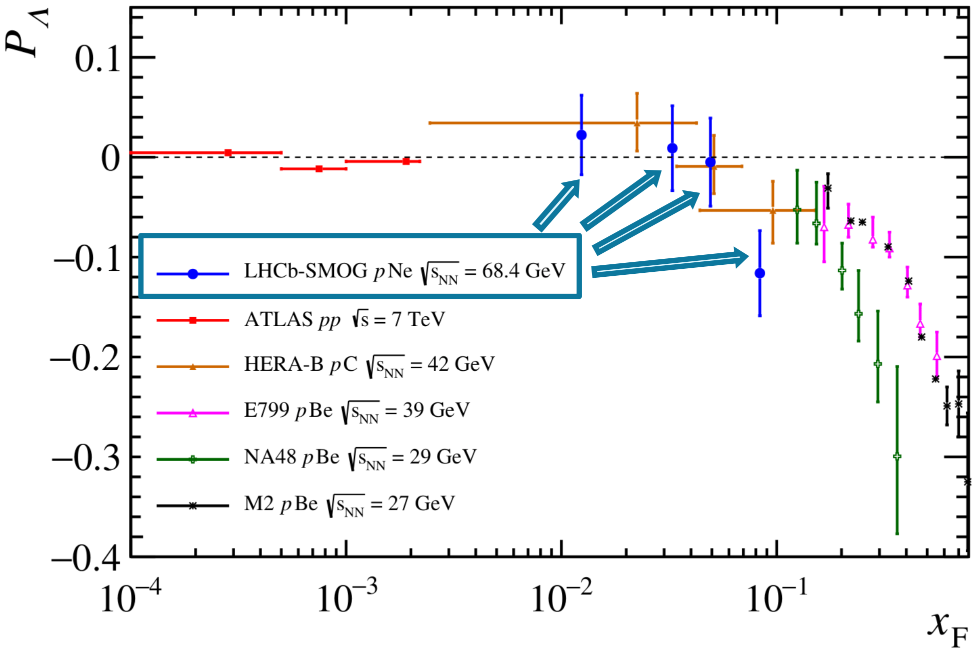
- Λ^0: **increasing trend** in polarity as **a function of x_F and p_T**, as observed by previous experiments.
- $\bar{\Lambda}^0$: **flat distribution compatible with 0**
  → Compatible with previous experiments, in contrast with theoretical expectations.

Comparison with other experiments

arXiv:2405.11324, submitted to JHEP

Comparison of results as a function of x_F with previous experiments:

- Different kinematical regions and collision systems
- **Very good agreement in polarization values**.

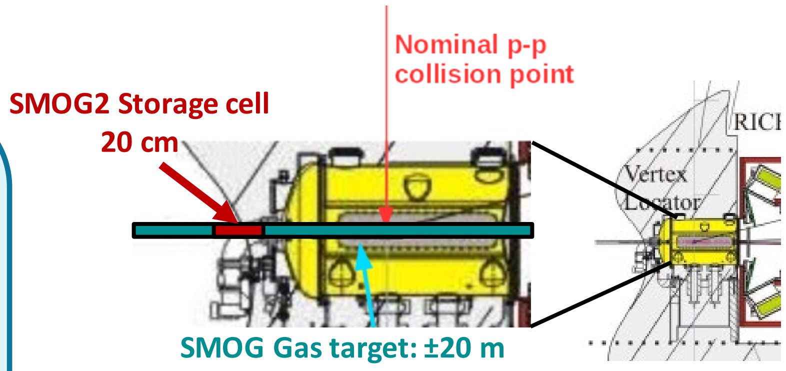


Fixed-target upgrade for Run 3

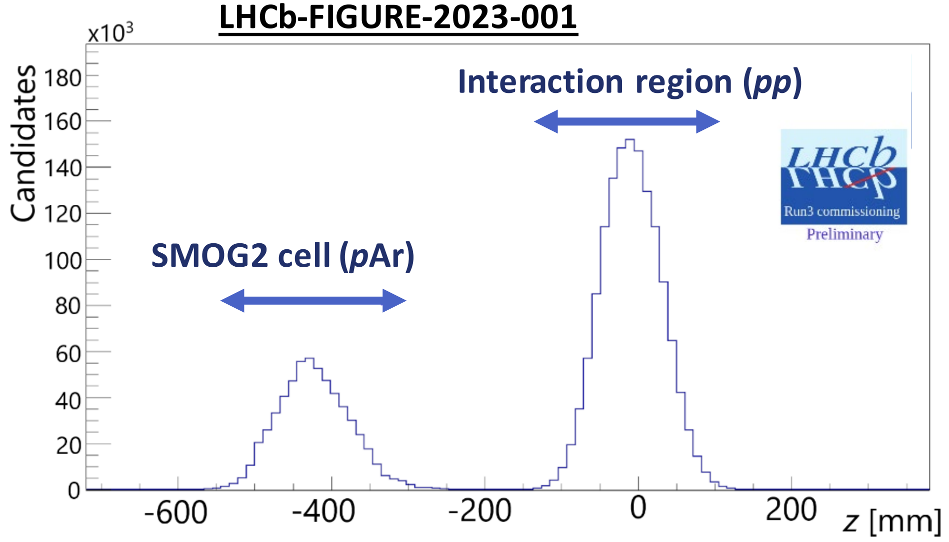
SMOG upgrade: SMOG2

SMOG2: gas confined in a 20 cm long storage cell upstream the interaction point:

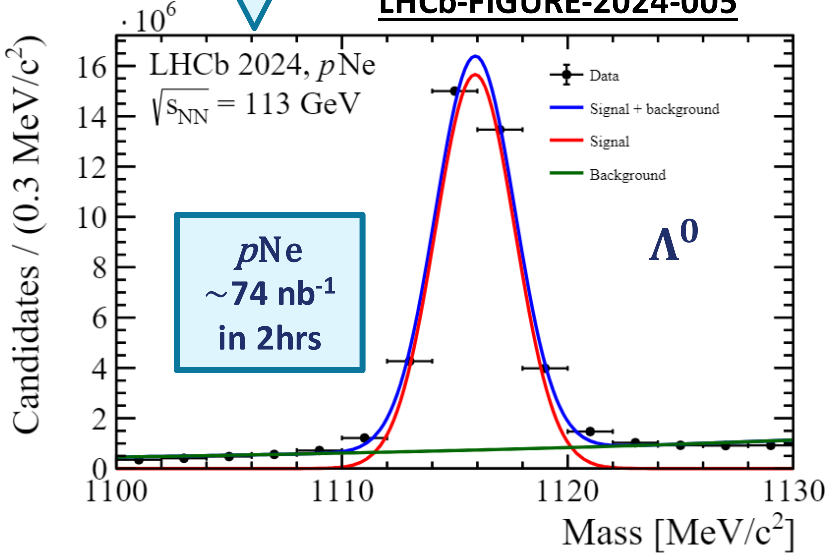
- **x100 average pressure** with same gas flow
- Direct and precise gas pressure and temperature measurement
- **Simultaneous *pp* + fixed-target data taking**
- Wider choice of injectable gases: $\mathbf{H_2}$, $\mathbf{D_2}$, $\mathbf{N_2}$, $\mathbf{O_2}$, Kr, Xe (+He, Ne, Ar)



LHCb-FIGURE-2023-001



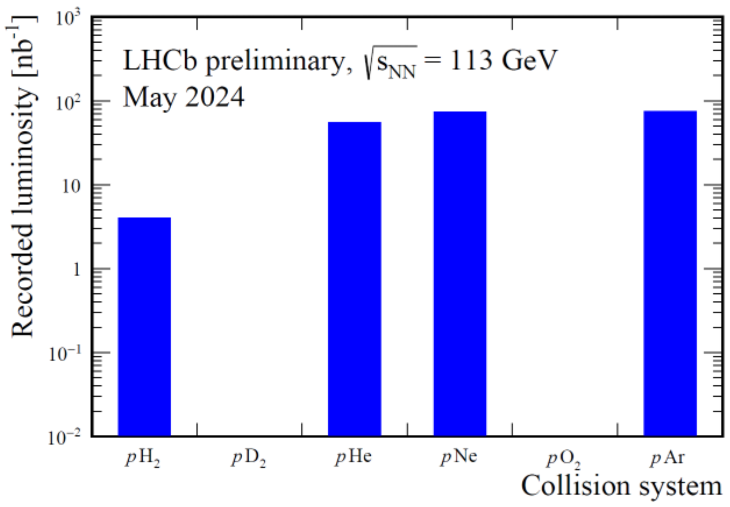
LHCb-FIGURE-2024-005

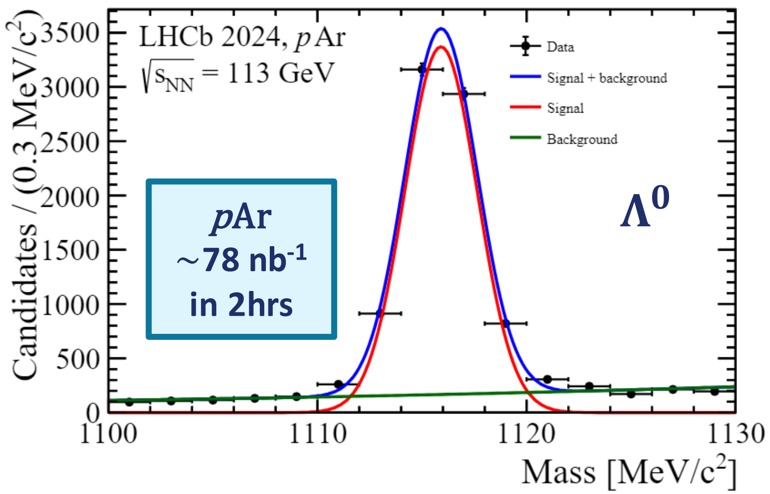


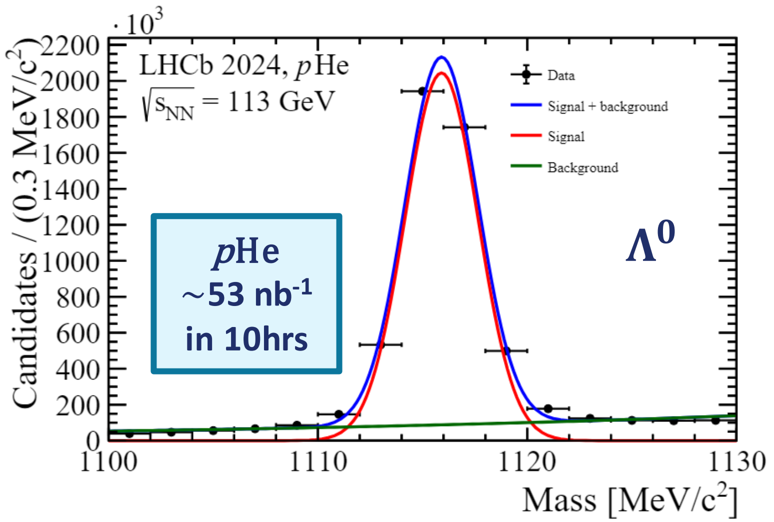
SMOG upgrade: SMOG2

LHCb-FIGURE-2024-005

Data samples collected during April and May 2024 with all available gases!

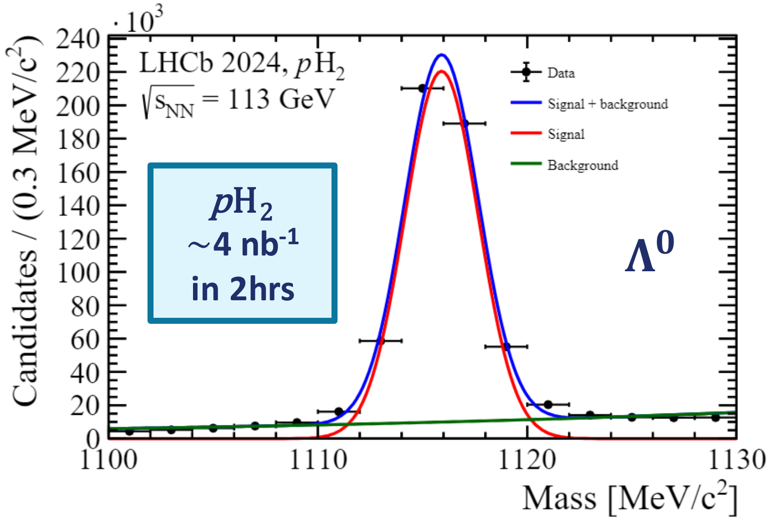






Unique physics opportunities never explored at LHC:

- **Strange-to-charm production ratio** from H_2 to Kr to constrain baseline for QGP effects
- *p*H_2, *p*He and *p*D_2 collisions to extend **modelling of secondary productions in CR-Interstellar Medium collisions**
- **Transverse polarization measurement** as a function of the beam energy and mass target



Conclusions

First strange production results from Run2 fixed-target data in LHCb

- **Measurement of detached-to-prompt $\bar{p}$ production in *p*He collisions**
    - Together with prompt $\bar{p}$ production measurement, anti-hyperon contribution to $\bar{p}$ production crucial input to models of antimatter production in space

- **First LHCb Λ^0 polarization measurement in *p*Ne collisions**
    - Unexplored kinematic region, contributing to understand the long-standing challenge of the transverse Λ^0 polarization explanation.

Many more interesting results in store with SMOG2 data samples!

Thanks for the attention!

BACKUP

Prompt antiproton production

PRL 121 (2018) 222001

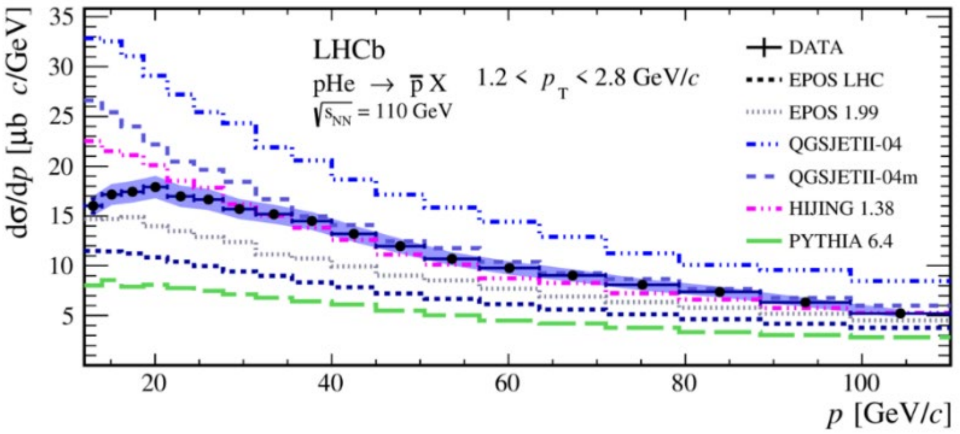
First measurement of $\boldsymbol{\sigma(pHe \longrightarrow \bar{p}_{prompt}X)}$ at $\sqrt{s_{NN}} = 110\ GeV$:

- $\bar{p}$ reconstructed in the kinematic region $p \in [12{,}110]\ GeV/c$, $p_t \in [0.4, 4]\ GeV/c$ to optimize reconstruction and particle identification efficiencies.
- **Only $\bar{p}$ promptly produced** considered; detached component reduced cutting on the impact parameter wrt the primary vertex.
- $\bar{p}$ number from a simultaneous fit to the PID variables in (p, p_t) bins.
- Luminosity from $\boldsymbol{pe}$ **elastic scattering** with gas atomic electrons.

→ **Dominant contribution to systematic:**

- **Luminosity measurement: injected gas pressure not precisely measured.**
- **Particle identification performance: poor calibration statistics.**

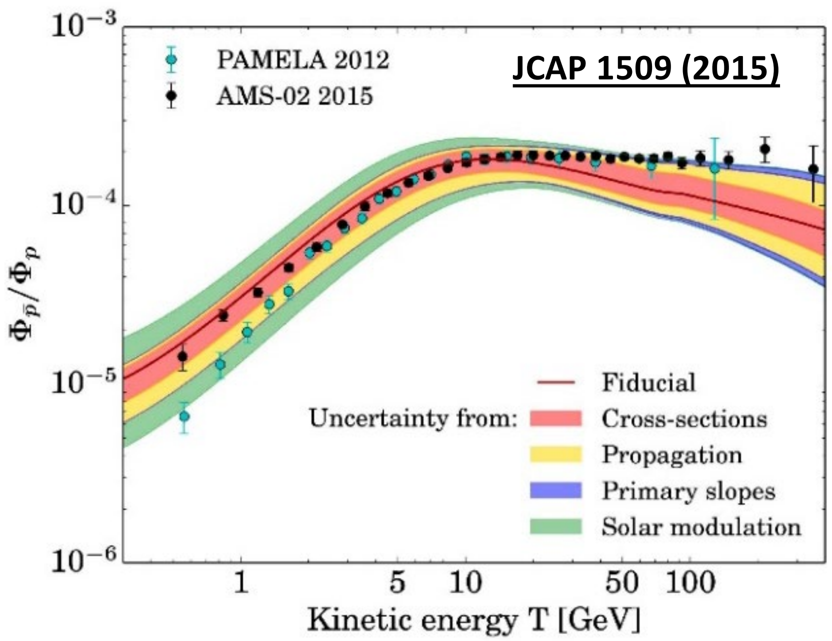
- Result on XS is compared to different MC event generator.
- **Experimental uncertainties (<10%) are lower than the spread among theoretical models.**

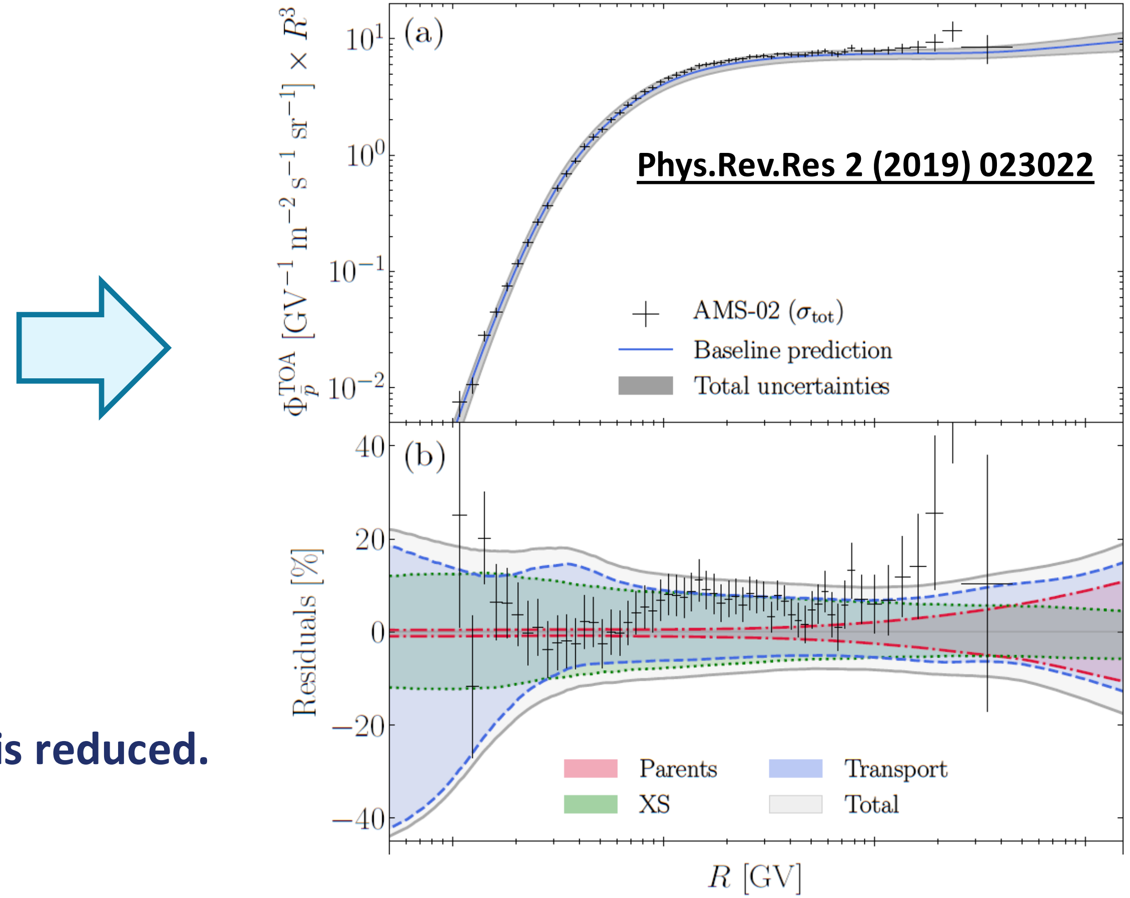


Impact of the measurement

Important contribution to the improvement of the secondary $\overline{p}$ flux prediction:

- Validation of the extrapolation of the cross section from pp to pHe.
- Validate models for the cross section energy evolution (violation of Feynman scaling above 50 GeV).





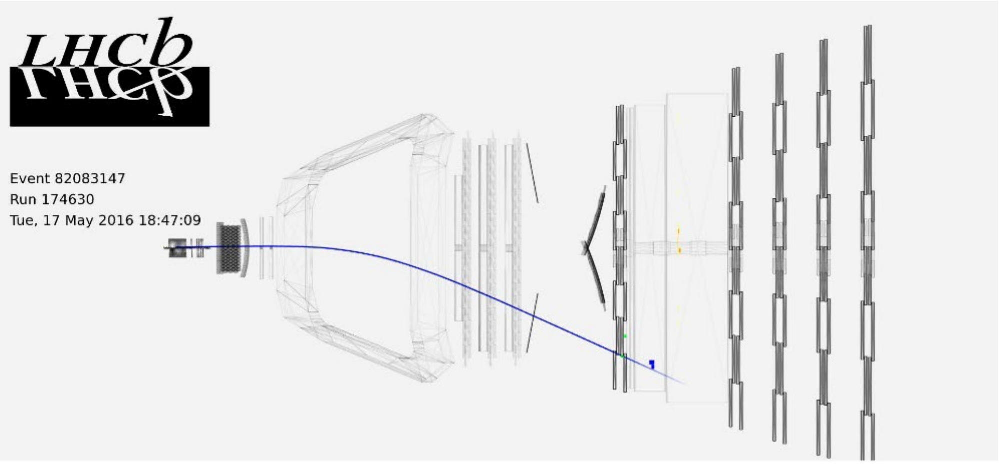
- **The uncertainty on the predicted secondary $\overline{p}$ flux is reduced.**
- **Room for exotic contribution heavily reduced**

Luminosity measurement in SMOG data samples

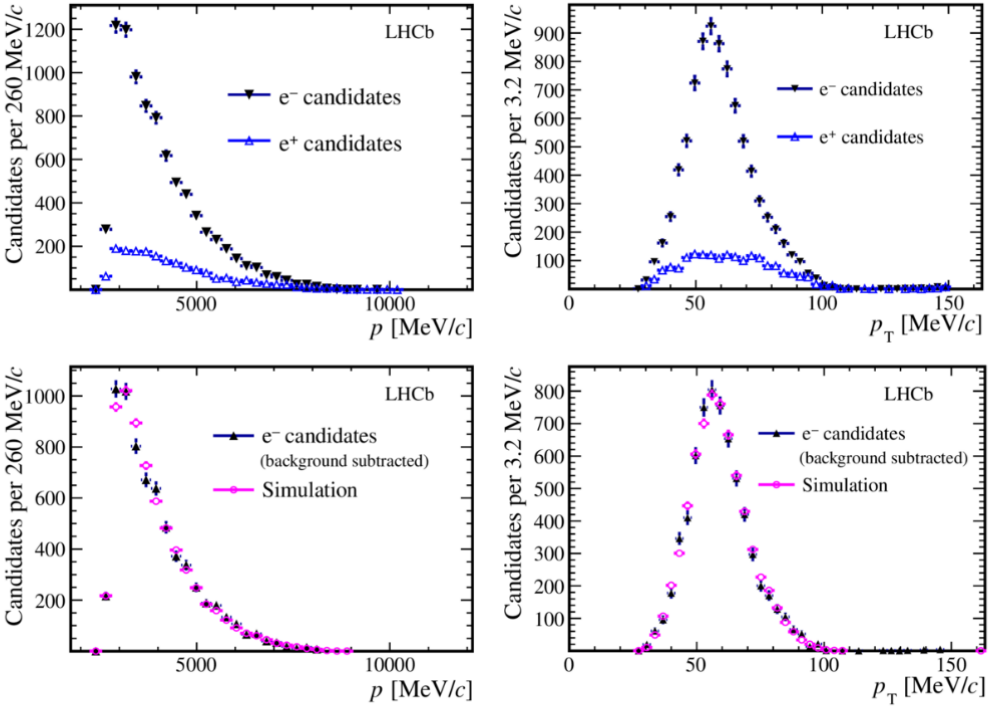
PRL 121 (2018) 222001

SMOG is not equipped with precise gauges for the gas pressure:

→ Luminosity is determined through $\boldsymbol{pe}$ **elastic scattering** with gas atomic electrons.



- pe events are identified as an isolated low-energy electron track.
- Charge symmetric background is evaluated through positron yield and subtracted from electron yield.
- Poor electron reconstruction efficiency (16%) → 6% uncertainty on luminosity



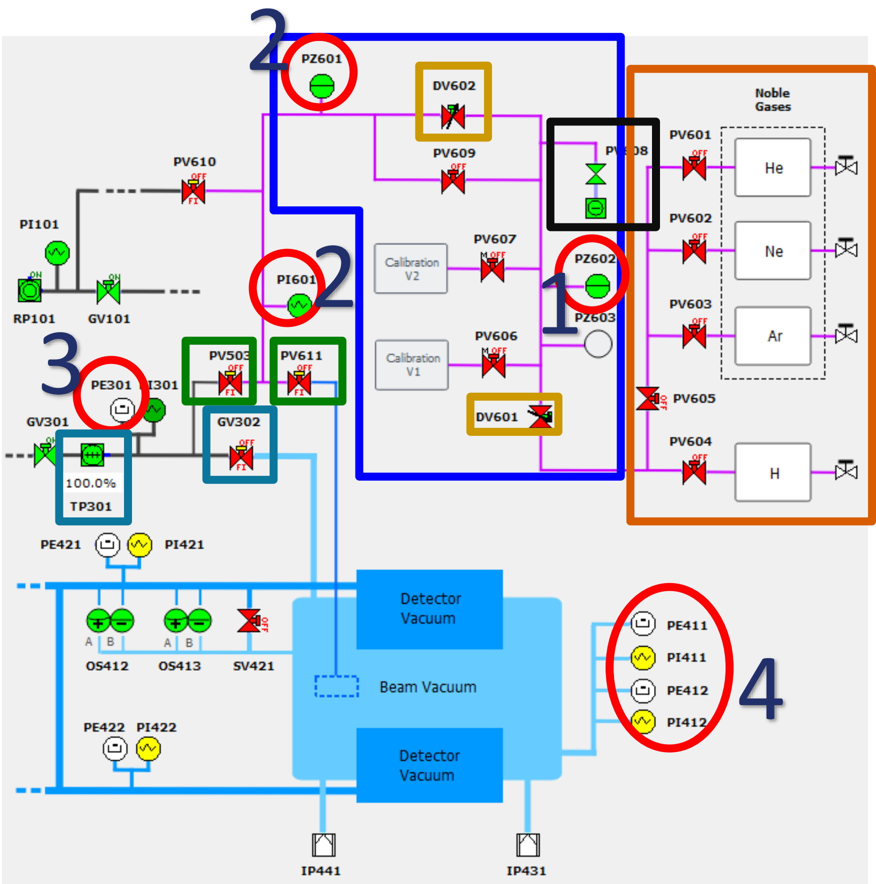
<u>**Dominant contribution to systematic uncertainty on σ!**</u>

GFS and injection

Gas injected into cell or VELO tank through the Gas Feed System:

- Four gas reservoirs (3 noble gases + 1 non getterable line), used to fill the calibrated volumes V1 and V2, controlled by dosing valve DV601
- Table with calibrated volumes used during injection, pumping group to clean line and dosing valve DV602 to control injected flux.
- Gas feed line to feed either the VELO tank (PV503) or the cell (PV611)
- Turbo pump TP301 connected to VELO tank through GV302 (open during SMOG2 operations) to provide pumping when ion pumps off.

- Multiple gauges to measure pressure along the line and in the VELO tank:
  1. PZ602: pressure at calibration volumes, around 10 mbar when full.
  2. PZ601 and PI601: pressure at the beginning and end of GF line, O(0.01) mbar for SMOG2, O(0.001) mbar a-la-SMOG (PI601 under sensibility).
  3. PE301: pressure at the turbo pump TP301 (SMOG injection point), O(1e-8) mbar for SMOG2, O(1e-6) mbar a-la-SMOG.
  4. PE411 and PE412: pressure in the VELO tank in Ne equivalent, O(1e-8) mbar.

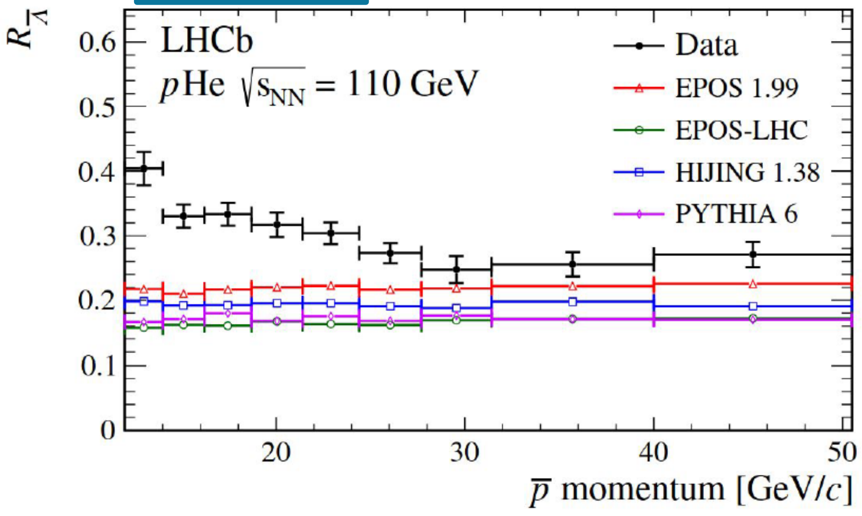


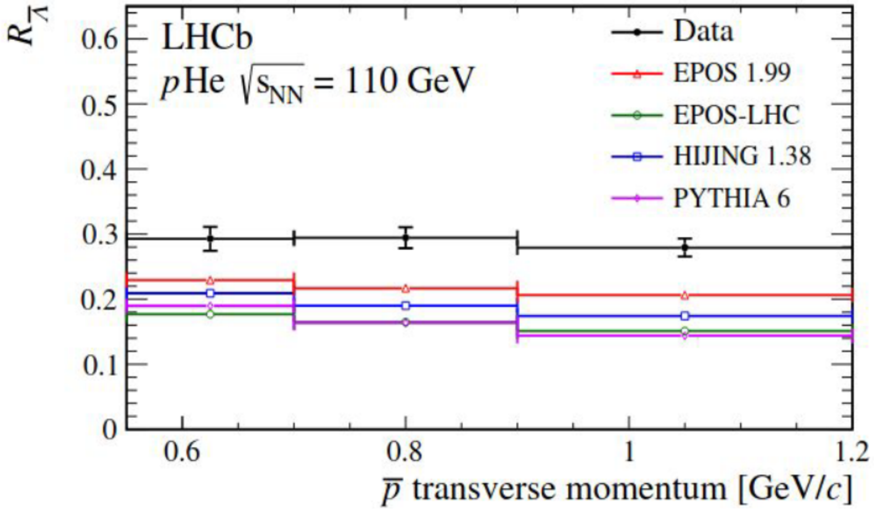
Results

Eur. Phys. J. C83 (2023) 543

Larger contribution measured wrt all most widely used theoretical models

Exclusive





EPOS 1.99: Nuclear Physics B.2009.09.017
EPOS-LHC: Phys. Rev. C 92,034906
HIJING 1.38: Computer Physics Communications 83 (1994) 307-331
PYTHIA 6: JHEP 05 (2006) 026

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