Contributions from the fixed target program of the LHCb experiment to the understanding of antimatter in cosmic rays: status and prospects

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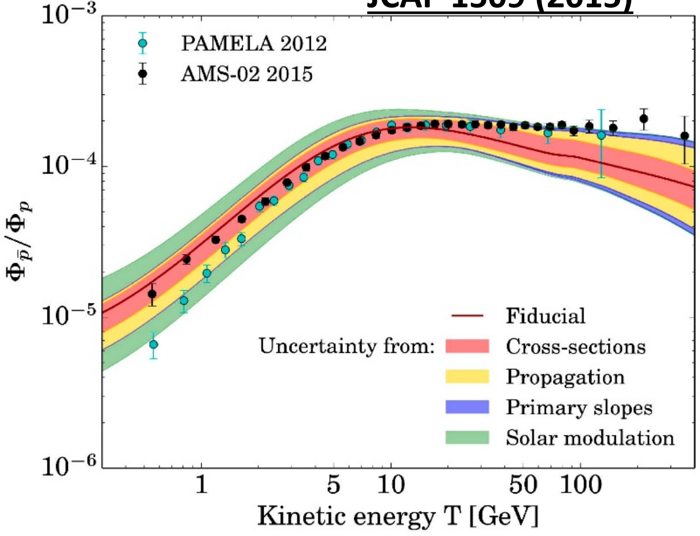
Prelude

Astroparticle physics has reached a new **high-precision** era.

BUT

The interpretation of some measurements is still limited by the understanding of the CRs interactions during their propagation (i.e. uncertainties on the hadronic production cross-sections (XS)).

JCAP 1509 (2015)



i.e.

In 2015 AMS-02 observed a hint for an **excess of high-energy antiprotons ($\overline{p}$)** wrt to the expected production in CRs-Interstellar Medium (ISM, mainly H and He) collisions.

→ It could be an **hint of Dark Matter** annihilation or decay process.

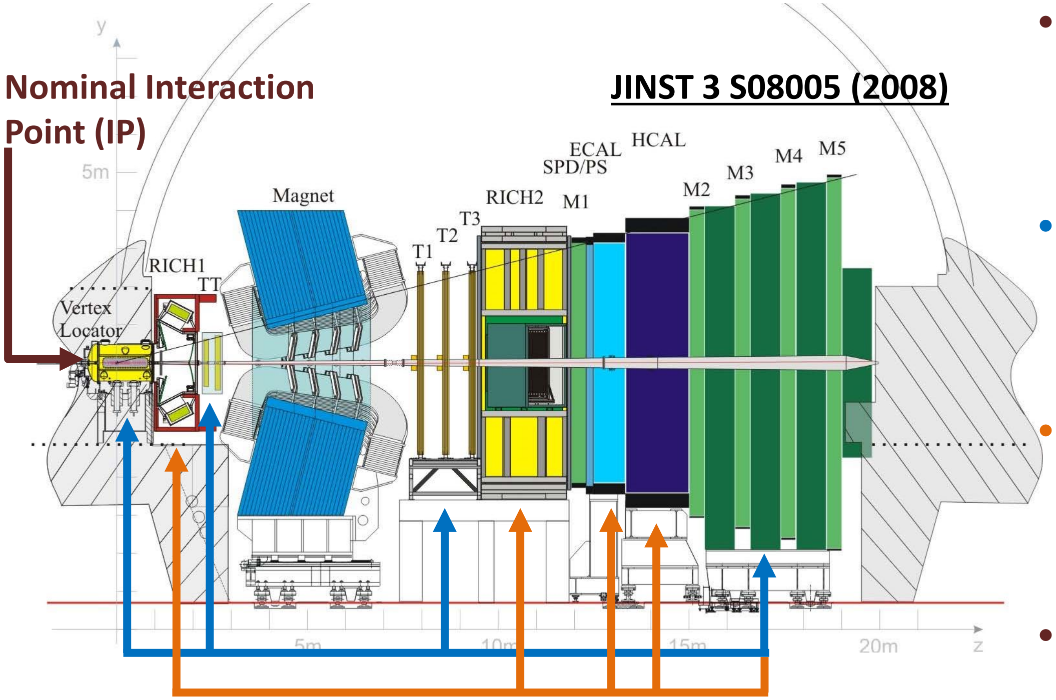
BUT

→ The interpretation is limited by **poor knowledge of hadronic production XS**.

Accelerator experiments can complement the CRs investigations

The LHCb experiment

The LHCb detector is a single-arm forward spectrometer originally optimized for heavy flavour physics.



- **Forward geometry**: optimized for $b\bar{b}$ production, $2 < \eta < 5$, $\Theta \in [10, 250]$ mrad.
- **Tracking:** excellent vertexing, IP resolution and 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, bandwith up to 15 kHz to disk.

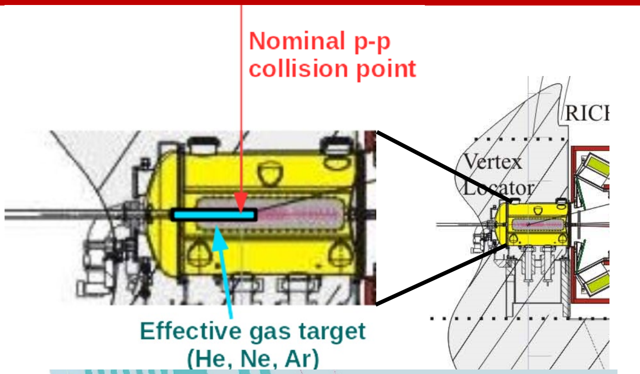
Its capabilities extend beyond the original expectations:

→ Currently it is a general purpose experiment in the forward direction.

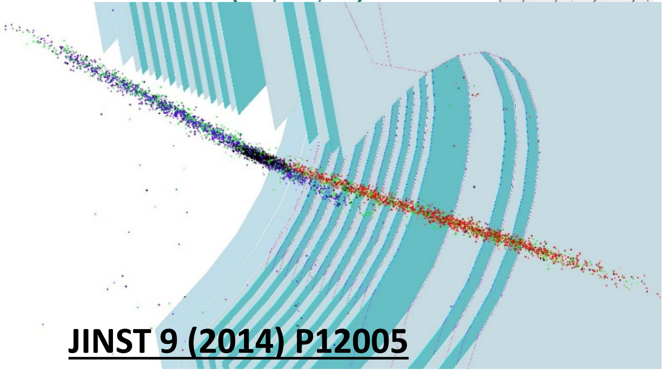
→ Its forward geometry is very well suited for **fixed-target physics.**

LHCb fixed-target configuration: SMOG

The *System for Measuring Overlap with Gas* (**SMOG**) can inject small amount of gas in LHC beam pipe around (±20 m) the LHCb IP.



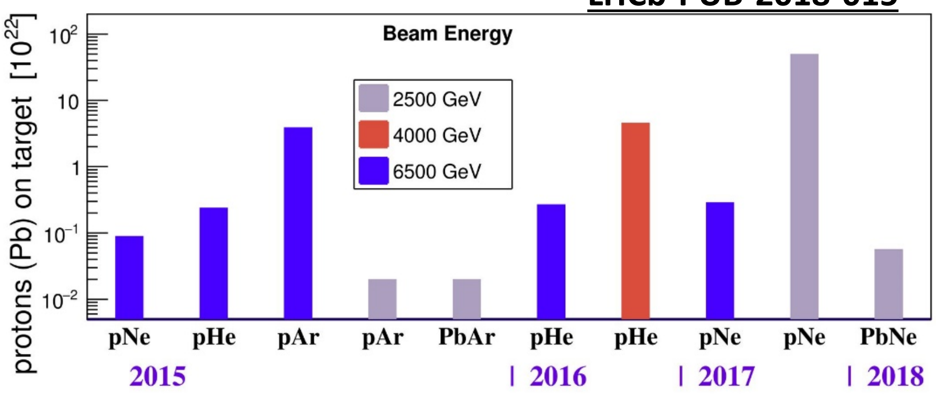
Originally it was conceived for precise luminosity measurements through **Beam-Gas Imaging**.



JINST 9 (2014) P12005

For machine safety, **only noble gases** with a maximum pressure of **2x10^{-7} mbar** (x100 nominal LHC vacuum) can be injected → Luminosity: $\mathcal{L} \sim \mathcal{O}(10^{29}\ cm^{-2}s^{-1})$.

LHCb-PUB-2018-015



In 2015-2018, LHCb collected physics samples in fixed-target configuration with different targets and different centre of mass energies.

SMOG physics opportunities

SMOG opens the possibility to access physics opportunities unique at the LHC:

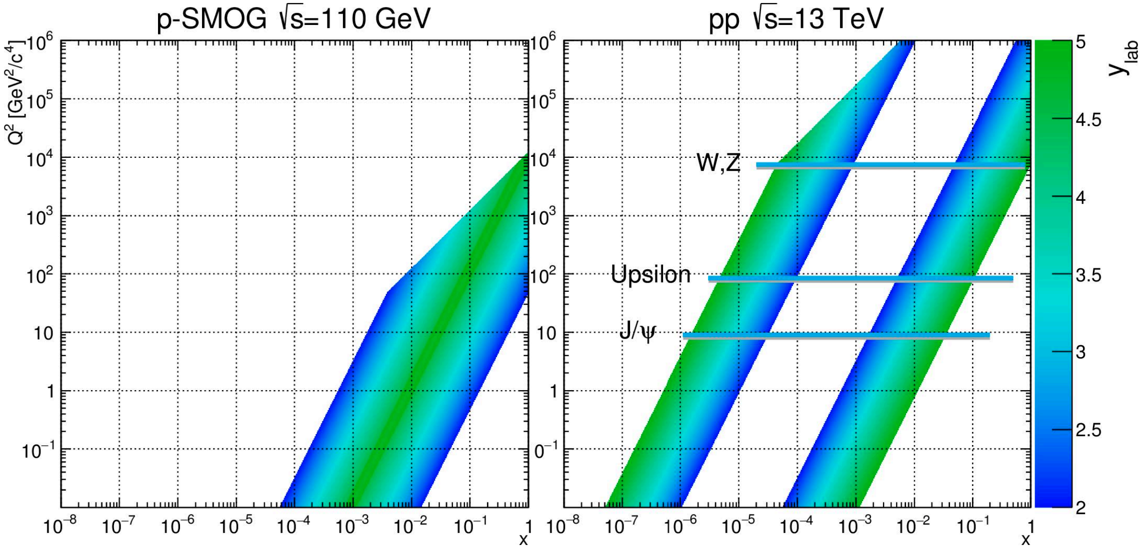
- Collisions with **targets of mass number A intermediate** between p and Pb.
- **Energy range** $\sqrt{s_{NN}} \in [30, 115]\ GeV$ for beam energy in $[0.45, 7]\ TeV$ (**unexplored gap** between SpS and LHC/RHIC).

  → $\boldsymbol{pHe}$ collisions reproduce **CRs interactions** in the ISM, important to understand the **secondary production of antimatter**.

  → $\boldsymbol{pNe}$ collisions can provide useful inputs to the **modelling of** the Ultra High Energy (**UHE**) atmospheric showers.

- Access to **large target Bjorken-x values at low Q²** (PDF is poorly constrained)

  → Study nuclear PDFs at large x; charm PDF important to understand **background to neutrino astronomy** from UHE atmospheric showers.



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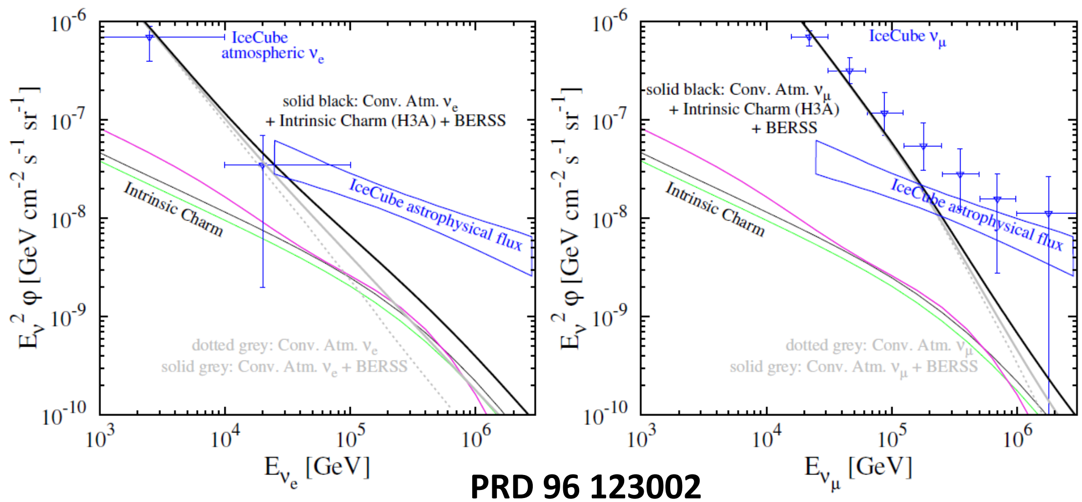
Charm production measurements for CRs

In neutrino astronomy, the **main background** to the high-energy neutrino flux comes from neutrinos produced in **decays of charmed hadrons** in UHE atmospheric showers.

The background prediction is based on charm production measurement at LHCb in pp collisions, that are not sensitive to high-x PDF (possible intrinsic charm contribution).

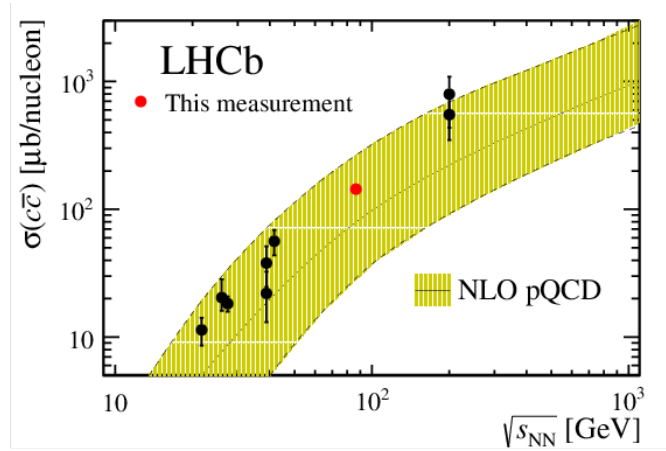
Fixed-target and/or high Q^2 pp measurements are needed.



PRD 96 123002

Charm production in fixed-target data

PRL 122 (2019) 132002



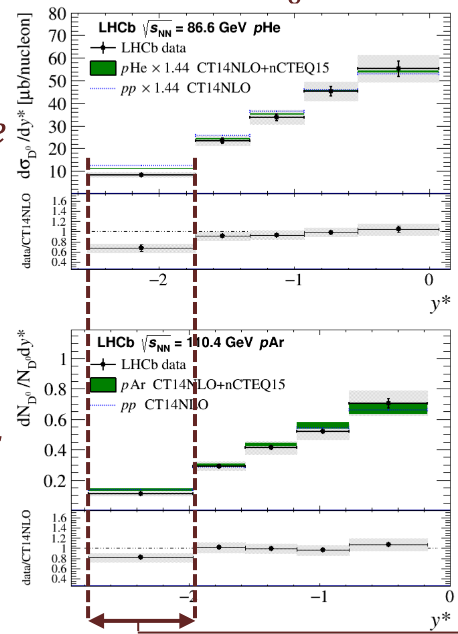
First charm production studies at LHC fixed-target:

- 86 GeV pHe ($7.6 \pm 0.5\ nb^{-1}$) and 110 GeV pAr (few nb^{-1}).
- With the luminosity measurement for pHe sample, the **first $c\bar{c}$ XS at 100 GeV** is obtained, an **unexplored energy scale**.
- Rapidity distributions at y*<0 (high x) consistent with prediction with no nucleon intrinsic charm effects, but **limited by high statistic uncertainty**.

D_0

pHe

pAr



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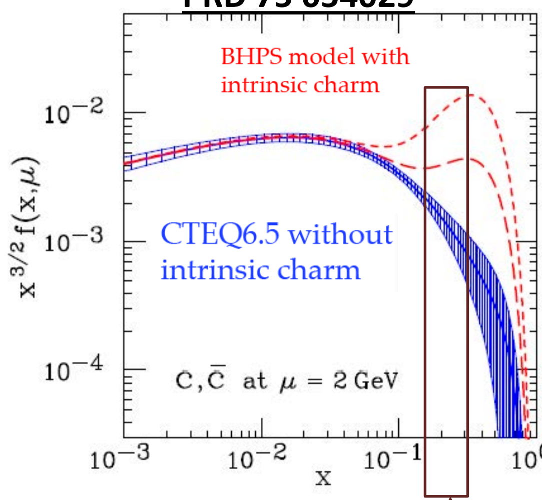
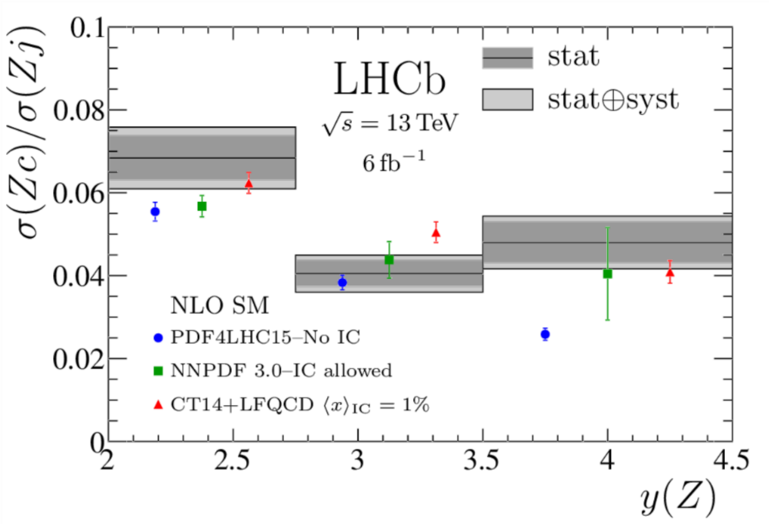


Charm production in pp at high Q^2

arXiv:2109.08084

Hint of intrinsic charm from $pp \longrightarrow Z + Charm$ measurement in the forward region:

- Zc production is at high Q^2 → Small hadronic uncertainties, sensitive to high-x charm PDF.
- pp at $\sqrt{s} = 13\ TeV$ for an integrated luminosity of $6\ fb^{-1}$.
- The fraction of Z+c-jet events is measured (less affected by systematics): $\mathcal{R}_j^c = \sigma(Zc)/\sigma(Zj)$.



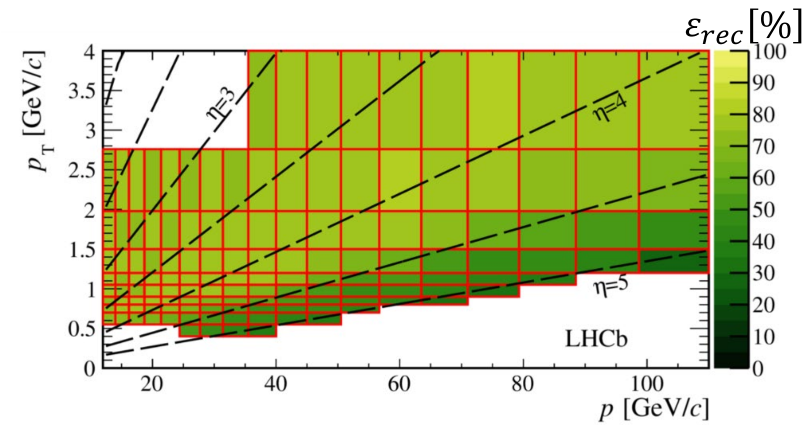
The observed $\mathcal{R}_j^c$ spectrum exhibits a sizable **enhancement** in the forward-most Z rapidity bin, **in comparison to NLO SM calculations** → Hint of possible intrinsic charm contribution to proton PDF.

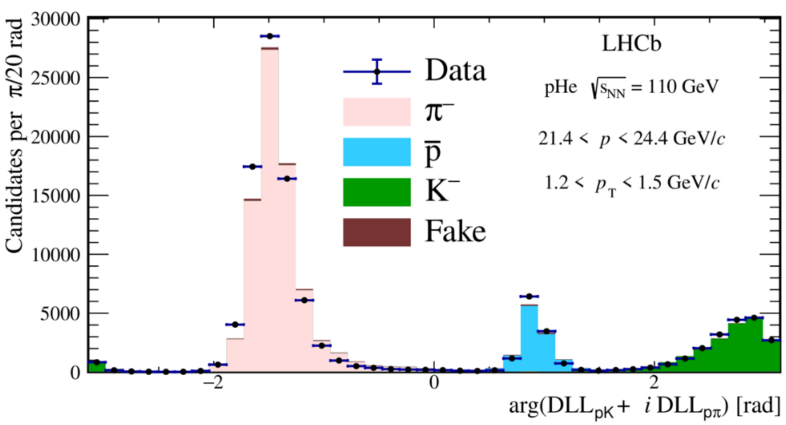
Antiproton production measurement (1)

PRL 121 (2018) 222001

First measurement of $\sigma(pHe \rightarrow \bar{p}_{prompt}X)$ 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.



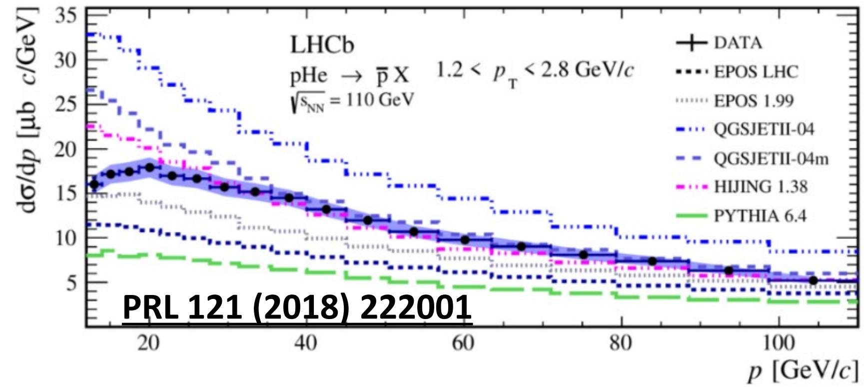


- **Only $\bar{p}$ promptly produced** considered; detached component reduced cutting on the impact parameter wrt the primary vertex.
- $\bar{p}$ number from a simultaneous fit to the PID variables in (p, p_t) bins.
- Luminosity from ***pe*** **elastic scattering** with gas atomic electrons (SMOG is not equipped with precise gauges for the gas pressure).

  → **Dominant contribution to systematic uncertainty on σ!**

Antiproton production measurement (2)

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

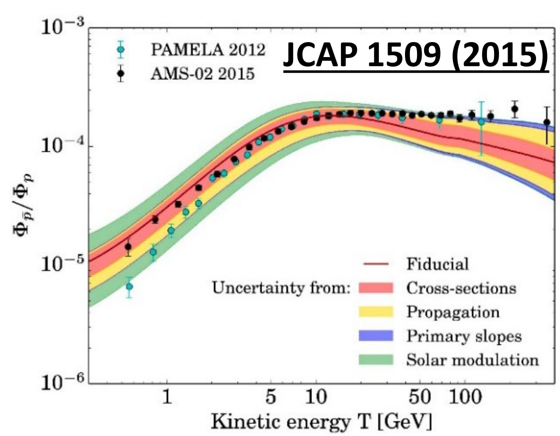


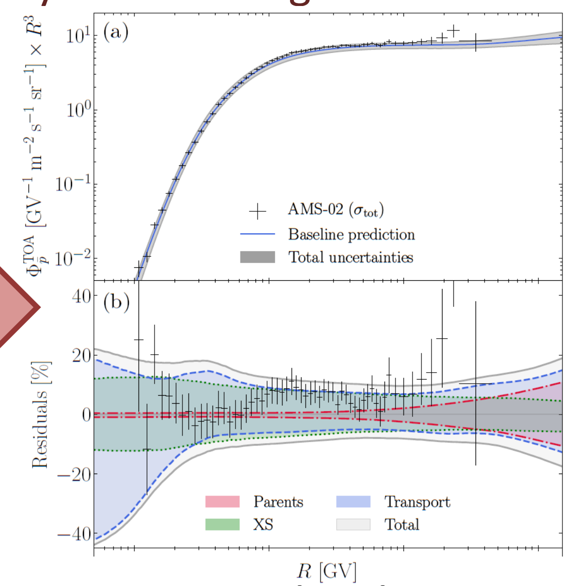
Important contribution to the improvement of the secondary $\bar{p}$ flux prediction:

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

<u>**CR impact:**</u>

Thanks to LHCb and NA61 (pp) data, the **uncertainty** on the predicted secondary $\bar{p}$ flux is **reduced.**





Phys.Rev.Res 2 (2019) 023022

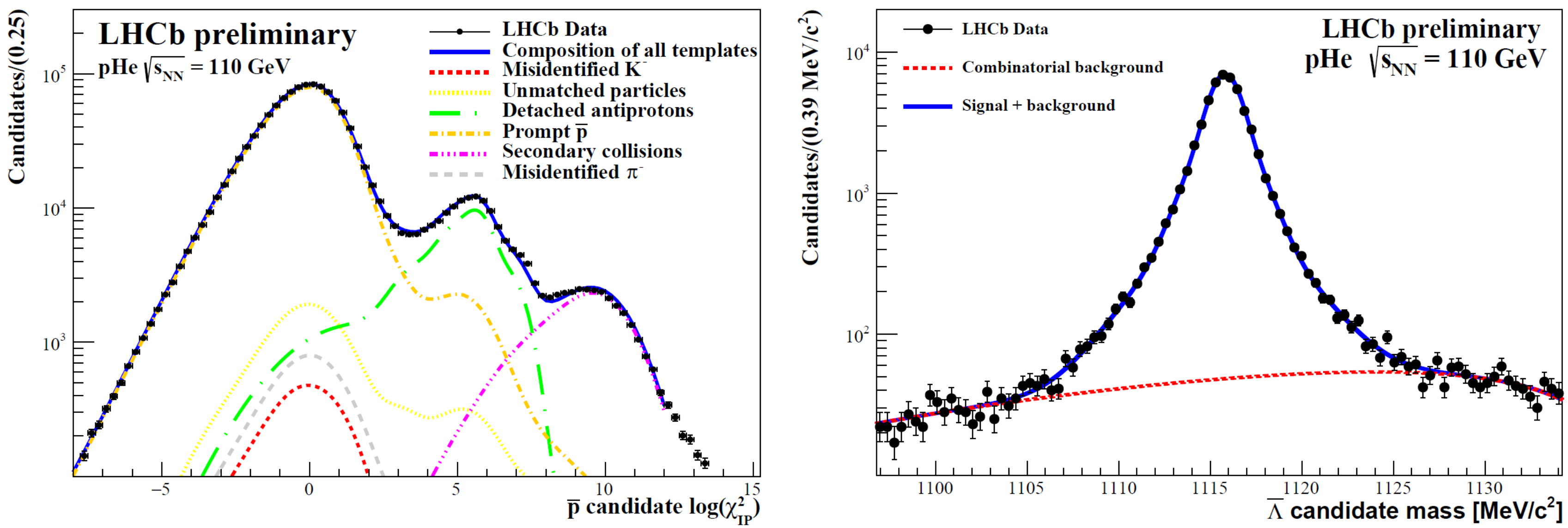
Extensions of the Run2 programme (1)

Analysis on Run2 data samples is ongoing:

- Around 20-30% of $\bar{p}$ production comes from anti-hyperon decays:

  → Analysis for secondary-to-primary $\bar{p}$ ratio $\boldsymbol{R = \sigma_{sec}/\sigma_{prim}}$ is ongoing:

  - Exploiting the IP separation between prompt and detached $\bar{p}$, **inclusive measurement** of the non prompt $\bar{p}$ yield from all anti-hyperons.
  - Measure $\boldsymbol{\bar{\Lambda} \longrightarrow \bar{p}\pi^{+}}$ **exclusive production**, exploiting LHCb excellent mass resolution.



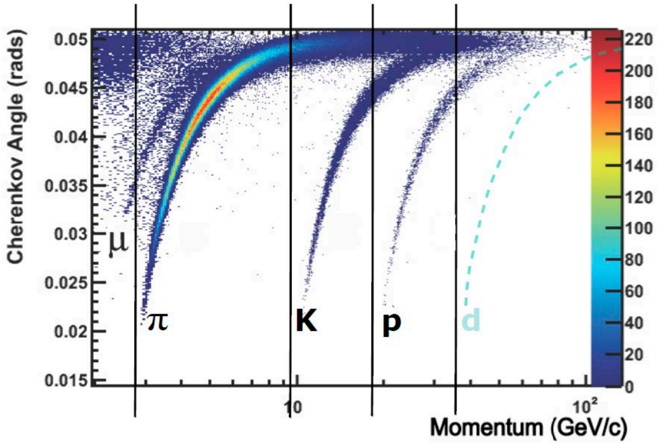
LHCb-FIGURE-2020-004

Extensions of the Run2 programme (2)

The secondary flux predictions of light anti-nuclei (i.e. antideuteron, $\bar{d}$) in CRs is limited by the absence of direct measurements of production in:

- The **interesting energy range** ($p_{lab} \in [10, 10^4]\ GeV/c$)
- The **same experimental conditions as $\bar{p}$**.

→ Searching $\bar{d}$ in the $pHe(\sqrt{s_{NN}} = 110\ GeV)$ sample.



- The RICHs can in principle identify $\bar{d}$ above 35 GeV/c.
  - From study performed for pp collisions, expected one $\bar{d}$ per $10^4\ \pi$, at the limit of LHCb PID capabilities; it can be **improved with machine learning techniques** (arXiv:2110.10259).

- The TOF between the Velo and the OT can in principle identify $\bar{d}$ in [2, 10] GeV/c range.
  - Starting from EPOS-LHC $pHe(\sqrt{s_{NN}} = 110\ GeV)$ simulation, assuming the analytic coalescence model to produce $\bar{d}$ and normalizing to the number of $\bar{p}$ observed in the data, expected $\sim$300 $\bar{d}$ in the TOF kinematic region, before PID.

Limitations of SMOG during Run2

The SMOG gas spread (±20 m) is a limiting factor:

- **Only noble gases at low pressure** can be injected to keep the beamline contamination low.
- **Limited statistics** because of short dedicated data-taking periods (overlap between the SMOG and pp luminous regions).
- **No direct $\mathcal{L}$ measurement** due to the lack of precise gauges for injected gas P.
- Injection system equipped with only **one gas bottle**.

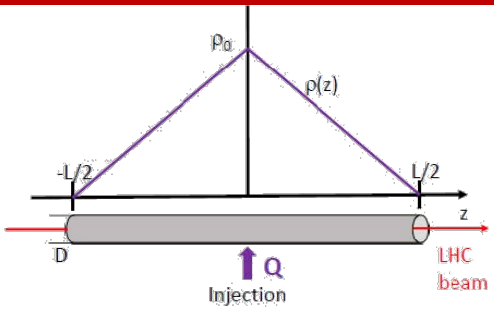
→ **Direct luminosity measurement** would reduce the dominant experimental uncertainty.

→ Separating the luminous regions facilitates **simultaneous data-taking**.

→ A gas injection system with more than one gas recipient and controlled gas flux would make possible to more easily change the gas target.

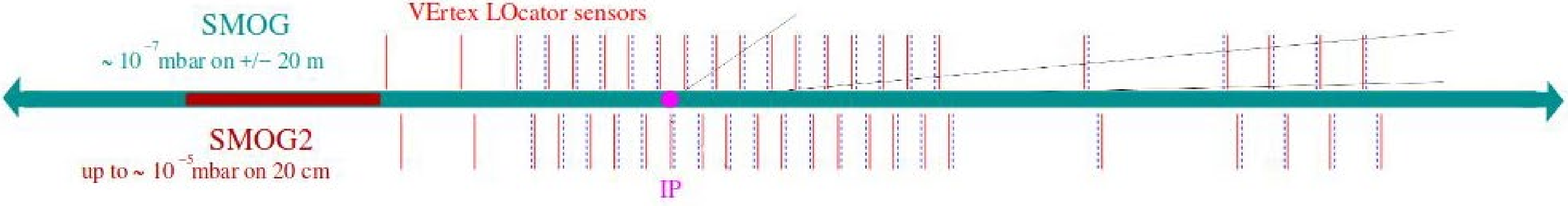
The SMOG2 upgrade

SMOG2: fixed-target LHCb programme upgraded with the installation of a **gas confinement cell upstream the IP** in the [-500, -300] mm region.



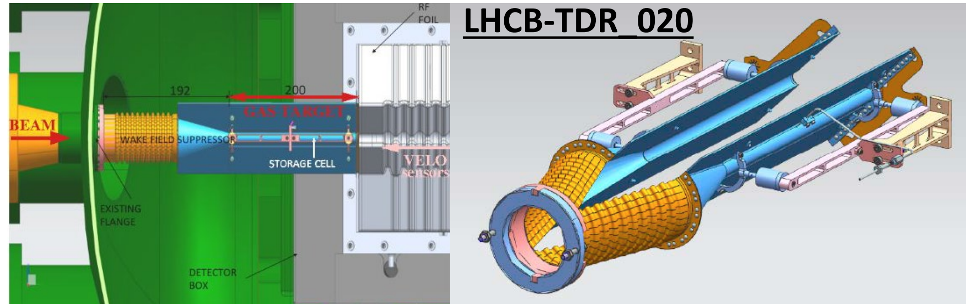
LHCB-TDR_020

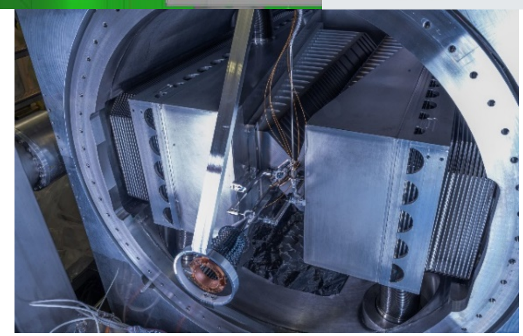
- The average gas density (and **luminosity**) will **increase up to two orders of magnitude** with the same gas flow as SMOG.
- The **gas pressure** will be **precisely measured** and finely controlled, reducing the uncertainty on luminosity.
- **More injectable gases** (pending the machine approval), like H_2, D_2, O_2, N_2, Kr, Xe.
- **Simultaneous data-taking** with pp will be possible, exploiting the separation wrt IP.

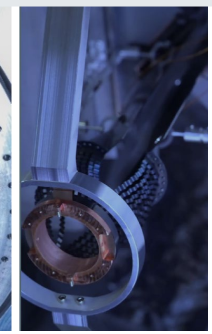


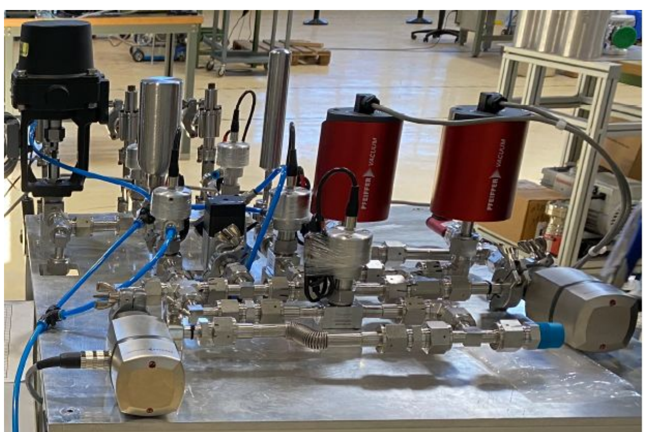
SMOG2 upgrade status

- The cell is a 20 cm long cylinder of 5 mm of radius around the beam; it is made of two halves connected to the VELO.
- The storage cell has been **installed** in the LHCb cavern **in august 2020** and the alignment and calibration have been accomplished.









<u>TO-DO list → on going:</u>

- **Install the new gas feed system** with pressure sensors (accuracy ~ 2%) and 4 gas lines to guarantee fast switch between gas species.
- **Implement the simultaneous *pp*-SMOG2 data-taking setup** within the challenging real-time event reconstruction foreseen for LHCb Run 3.

SMOG2 upgrade performance

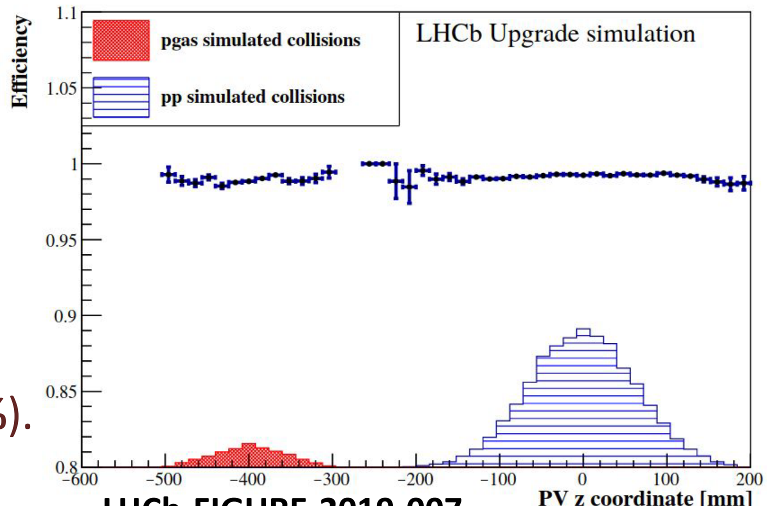
To maximize physics output, **simultaneous data-acquisition** for all bunches in LHC beam (same online software reconstruction and selection): **studies ongoing**.

→ The gas presence must not disturb the pp core physics programme.

→ $pgas$ collisions are largely displaced from the IP and they are challenging to reconstruct.

Simulation studies:

- The **reconstructed vertex** in pp and $pgas$ collisions are **separated**.
- The tracking efficiencies shows **similar performances** between pp and $pgas$.
- The beam partial lifetime largely exceed the typical duration of a fill (**lifetime reduction <2%**).
- The **gas presence doesn't affect** the pp physics program.



LHCb-FIGURE-2019-007

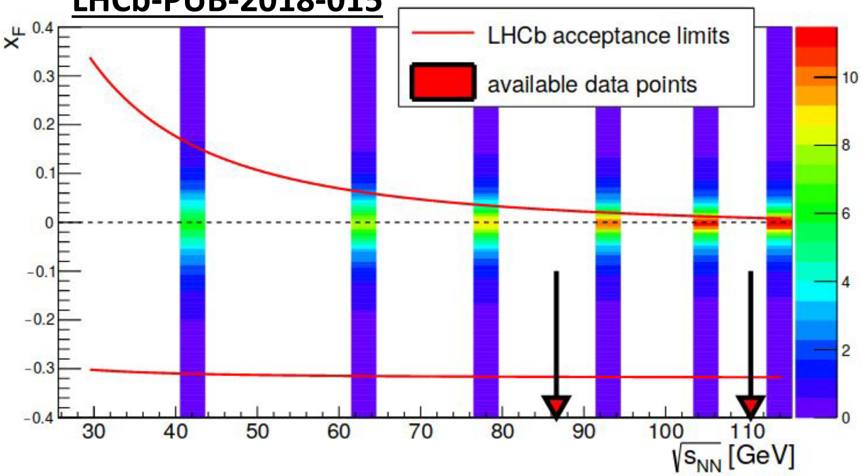
(Some) SMOG2 physics opportunities (1)

The increase in statistics (aiming at 100 pb^{-1}), in the injectable gas species and the expected higher accuracy will further widen LHCb-SMOG accessible physics scenario.

$\bar{p}$ measurement will largely benefit from SMOG programme upgrade:

- Extension towards lower energy to test **scaling violation** (starting with Run2 pHe at $\sqrt{s_{NN}} = 86\ GeV$ sample) and access **forward region** (Feynman-x>0).
- With **H_2 injection**: $\boldsymbol{\sigma(pp \longrightarrow \bar{p}X)}$ and $\boldsymbol{\sigma(pHe \longrightarrow \bar{p}X)/\sigma(pp \longrightarrow \bar{p}X)}$ to constrain the production cross section.

LHCb-PUB-2018-015



- With **D_2 injection**: $\boldsymbol{\sigma(pD \longrightarrow \bar{p}X)/\sigma(pp \longrightarrow \bar{p}X)}$ to test for isospin violation and constrain the $\bar{n}$ production.
- Explore the possibility for measurement of **light anti-nuclei production**.

(Some) SMOG2 physics opportunities (2)

The increase in statistics (aiming at 100 pb^{-1}), in the injectable gas species and the expected higher accuracy will further widen LHCb-SMOG accessible physics scenario.

LHCb-PUB-2018-015

	SMOG published result pHe@87 GeV	SMOG largest sample pNe@69 GeV	SMOG2 example pAr@115 GeV
Integrated luminosity	7.6 nb^{-1}	$\sim$ 100 nb^{-1}	$\sim$ 45 pb^{-1}
syst. error on J/ψ x-sec.	7%	6 - 7%	2 - 3 %
J/ψ yield	400	15k	15M
D^0 yield	2000	100k	150M
Λ_c^+ yield	20	1k	1.5M
$\psi(2S)$ yield	negl.	150	150k
$\Upsilon(1S)$ yield	negl.	4	7k
Low-mass Drell-Yan yield	negl.	5	9k

Important experimental inputs to heavy ion and high-x parton PDFs studies (**intrinsic charm contribution**), that impact the understanding of the development of UHE atmospheric shower:

- Study nuclear effects in **charm production in different collision systems**.
- Study **baryon and K production in pN and pO** to understand muon production off-axis in extensive showers.

Conclusions

LHCb is the first fixed-target experiment exploiting the energy and the intensity of LHC, providing unique measurements of interest to CR physics.

- Thanks to its forward geometry, its excellent vertexing, tracking and PID performances and the possibility to inject gas in LHC beam pipe, LHCb is developing a **pioneering fixed-target programme in a mostly unexplored kinematic regime**.
- The **charm production studies at LHC fixed-target collisions and pp at high Q^2** are helpful to the modelling of atmospheric neutrino production at UHE.
- The **measurement at fixed-target of $\boldsymbol{\sigma(pHe \longrightarrow \overline{p}X)}$** with a 6.5 TeV proton beam helped to improve the secondary $\bar{p}$ flux predictions.
- The **analysis on the Run2 samples are still ongoing**.
- The LHCb fixed-target programme **upgrade SMOG2** will overcome many difficulties of the current system, operating with up to x100 gas pressure and more gas species.
- Preliminary results indicate that **LHCb could be the first LHC detector running in collider and fixed target mode at the same time.**

Backup

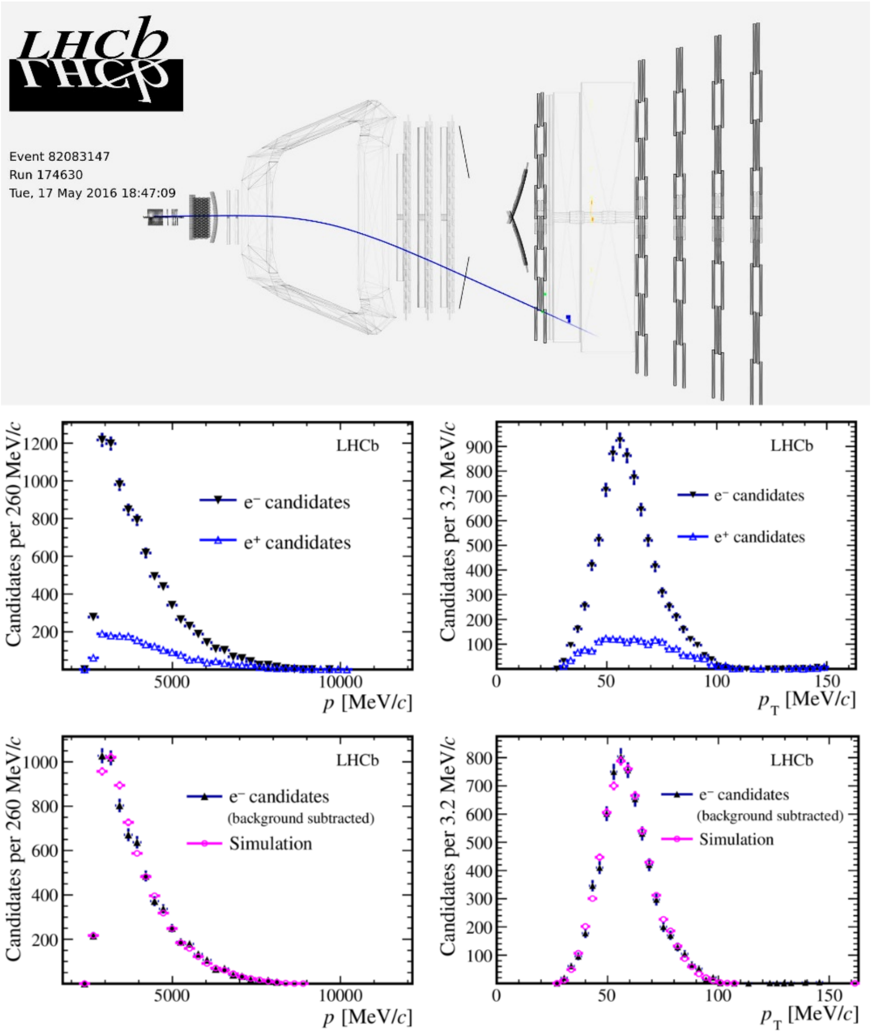
Antiproton production measurement

PRL 121 (2018) 222001

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

→ Luminosity is determined through pe **elastic scattering** with gas atomic electrons.

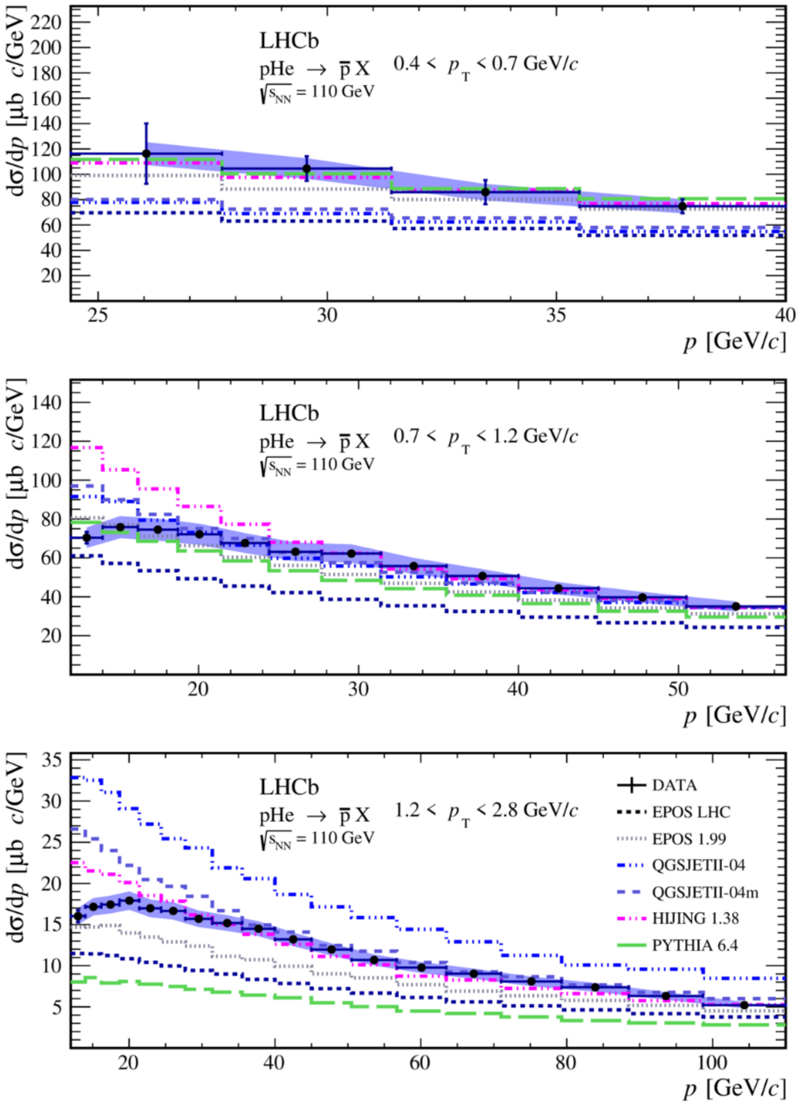
- pe events are identified as an isolated low-energy electron track.
- Charge symmetric background is evaluated through positron yield and subtracted from electron yield.
- Poor electron reconstruction efficiency (16%) → 6% uncertainty on luminosity



Dominant contribution to systematic uncertainty on σ!

(Uncertainty is still lower than the spread among models)

Antiproton production measurement



PRL 121 (2018) 222001

- Result on cross section is compared to **EPOS-LHC**, **EPOS-1.99**, **QGSJETII**, **HIJING 1.38**, **PYTHIA6**.
- Experimental uncertainties (<10%) are lower than the spread among theoretical models.
- Large excess is observed over EPOS-LHC (used for simulation).
- The total visible cross section is still consistent with the simulation:

$$\sigma_{vis}^{LHCb}/\sigma_{vis}^{EPOS-LHC} = 1.08 \pm 0.07 \pm 0.03$$

- The measured excess is due to underestimated antiproton multiplicity.

Anti-nuclei production

PRD 88 023014

$\bar{d}$ formation is described via the coalescence of a $\bar{p}$ - $\bar{n}$ pair:

$$\gamma_{\bar{d}} \frac{d^3 N_{\bar{d}}}{d^3 k_{\bar{d}}}(\vec{k}_{\bar{d}}) = \frac{4}{3}\pi p_0^3 \cdot \gamma_{\bar{p}} \gamma_{\bar{n}} \frac{d^3 N_{\bar{p}} d^3 N_{\bar{n}}}{d^3 k_{\bar{p}} d^3 k_{\bar{n}}} \left(\frac{\vec{k}_{\bar{d}}}{2}, \frac{\vec{k}_{\bar{d}}}{2}\right) \quad (1)$$

Factorization hypothesis and *isospin invariance* hypothesis:

$$\gamma_{\bar{d}} \frac{\mathrm{d}N_{\bar{d}}}{\mathrm{d}^3 k_{\bar{d}}}(\vec{k}_{\bar{d}}) = R_n(\sqrt{s + m_{\bar{d}}^2 - 2\sqrt{s}E_{\bar{d}}}) \cdot \frac{4}{3}\pi p_0^3 \cdot \left[\gamma_{\bar{p}} \frac{\mathrm{d}N_{\bar{p}}}{\mathrm{d}^3 k_{\bar{p}}}\left(\frac{\vec{k}_{\bar{d}}}{2}\right)\right]^2 \quad (2)$$

where R_n is associated to the reduction of the phase space after the production of the first nucleon.

For an anti-nucleon with mass number A, under the same hypotesis:

$$\gamma_A \frac{\mathrm{d}N_A}{\mathrm{d}^3 k_A}(\vec{k}_A) = R_n(\sqrt{s + m_A^2 - 2\sqrt{s}E_A}) \cdot \left(\frac{4\pi}{3} p_0^3\right)^{(A-1)} \cdot \left[\gamma_{\bar{p}} \frac{\mathrm{d}N_{\bar{p}}}{\mathrm{d}^3 k_{\bar{p}}}\left(\frac{\vec{k}_A}{A}\right)\right]^A \quad (3)$$

Alternative parameter: $B_A = \frac{A}{m_p^{A-1}} \left(\frac{4\pi}{3} p_0^3\right)^{A-1}$ **PRD 96 103021**