Antiproton production cross-section measurement in pHe at LHCb

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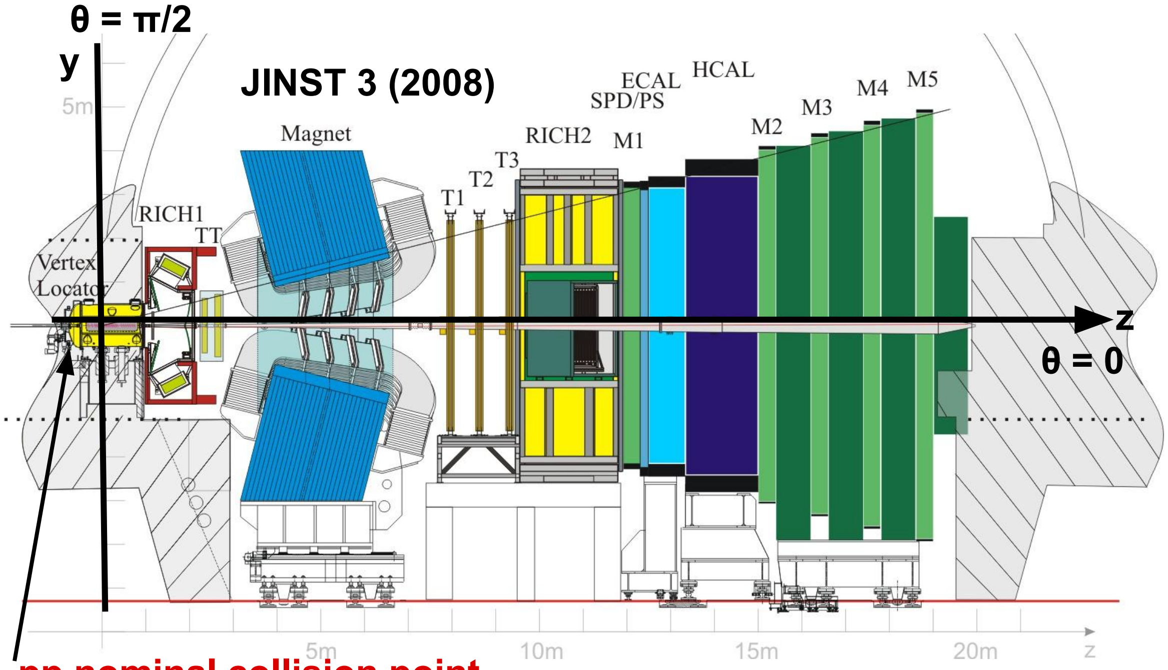
Outline

- **The LHCb experiment.**
  - Generalities and sub-detectors.
  - The SMOG system and the fixed-target programme.
- **Antiproton production cross section measurement in *pHe.***
  - Motivations: Cosmic Rays - InterStellar Medium collisions.
  - Measurement strategy and results.
- **Future prospects**
  - Upgrade of the fixed-target programme: SMOG2.
  - Plans for the antiproton measurement.
- **Conclusions.**

The LHCb Experiment

The LHCb detector

- Among the LHC detectors, dedicated to the study of **flavour physics in b sector**.

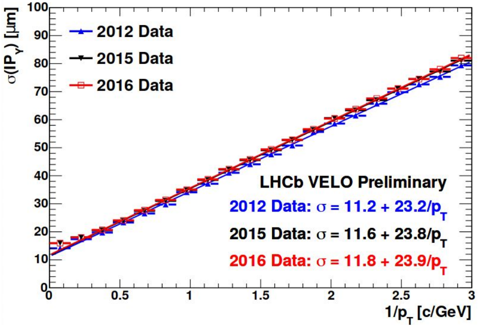


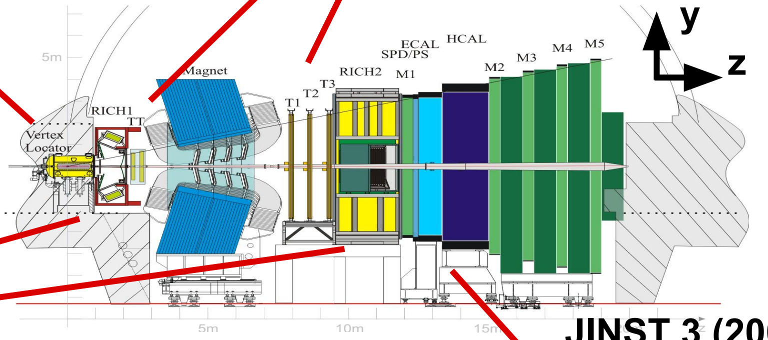
- **Single-arm spectrometer** covering the forward direction ($\Theta \in [10, 250]\ mrad$), where the production of $b\bar{b}$ is maximum.

- Now a **general-purpose** experiment in the forward direction (b and c physics, QCD, EW and Higgs, Heavy Ion…) .

The LHCb sub-detectors

- **VELO**: excellent **vertices and IP resolutions,** fundamental to distinguish long-lived particles.
- **Tracking system**: excellent **momentum resolution.**





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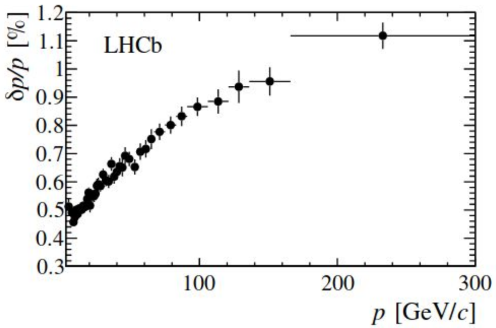
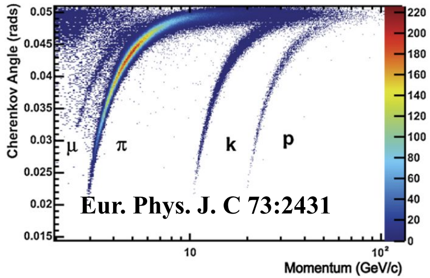


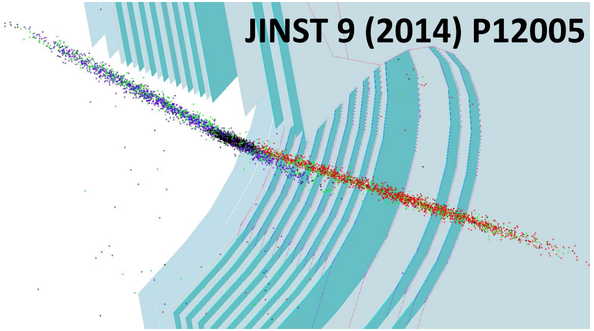
- **RICH**: excellent **separation** among kaons, pions and protons with a momentum between 10 and 110 GeV/c.



- Flexible and versatile **trigger system** with a very high efficiency and bandwidth (up to 15 kHz).

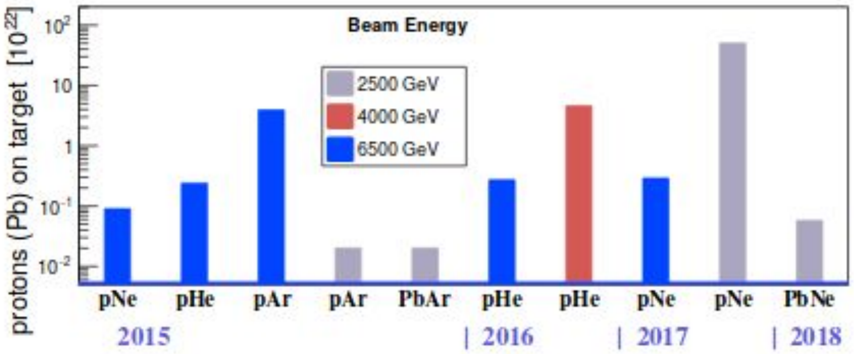
The fixed-target LHCb: SMOG

- **Luminosity** uncertainties reduced complementing VdM scans with **Beam Gas Imaging.**



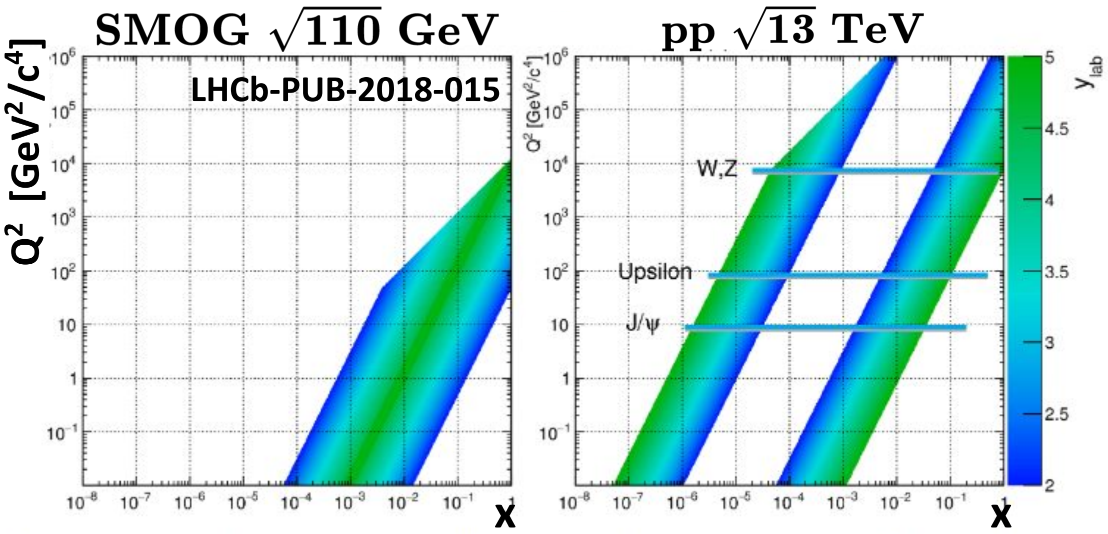
- **SMOG (System for Measuring Overlap with Gas)**: system allowing the gas injection in the LHC beam pipe between ± 20 m from the nominal collision point.
- For machine safety, only some **noble gases** allowed with a maximum pressure of $2 \times 10^{-7}\ mbar$, two orders of magnitude higher than the LHC vacuum.

- Starting from 2015, LHCb can operate as a **fixed-target experiment** too!
- Wide variety of physics samples collected with different center-of-mass energies.



SMOG physics opportunities

- LHCb fixed-target configuration offers unique possibilities:
  - **Wide choice** of the collision system.
  - **Luminosity**: with 10^{14} protons per beam and one meter of gas, $\mathcal{L} \sim 6 \times 10^{29} cm^{-2} s^{-1}$
  - **Energy** range $\sqrt{s_{NN}} \simeq \sqrt{2E_N M_N} \in [41, 115]\ GeV$ for beam energy in $[0.9, 7]\ TeV$, filling the gap between SpS and LHC *pp* collisions results.



- Access to **large negative values** of the Feynman-x, the fraction of the target longitudinal momentum in the cm frame:

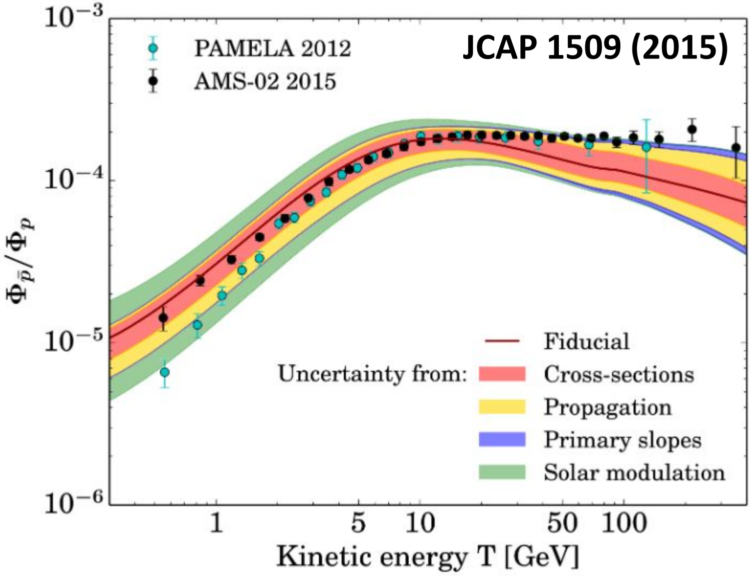
$$x_F = \frac{p_L^*}{|max(p_L^*)|} \sim x_1 - x_2$$

being x the Bjorken-x.

The Antiproton Production Cross Section Measurement

Motivations

- **Antimatter study in Cosmic Rays** (CRs) is one of the most promising experimental techniques for indirect Dark Matter annihilation or decay process searches.

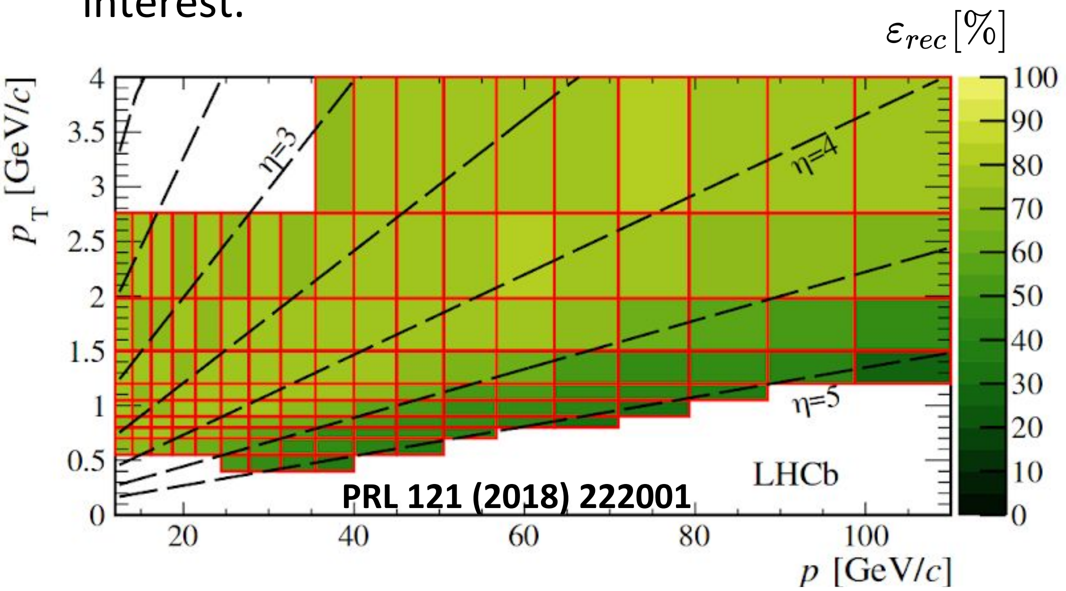


- In 2015, AMS-02 observed a hint for an **excess of high-energy antiprotons** wrt the expected production at that time in CRs - Interstellar Medium (ISM, mainly *H* and *He*) collisions.
- Interpretation limited by the poor knowledge of hadronic production cross-sections:
  - Poor data for $\sigma(pp \to \bar{p}X)$
  - No data at all for $\sigma(pHe \to \bar{p}X)$

→ • See the next talk for all the details!

Measurement strategy

- **First measurement** of $\sigma(pHe \to \bar{p}X)$ analysing a data-sample of *pHe* collisions acquired in 2016 with a beam energy of $E_{beam} = 7\ TeV$.
- Corresponding **centre-of-mass per nucleon energy**, $\sqrt{s_{NN}} = 110\ GeV$, matches the AMS-02 interest.



- Antiproton candidates reconstructed in the kinematic region:

$$p \in [12, 110]\ GeV/c$$

$$p_T \in [0.4, 4]\ GeV/c$$

- Only antiprotons **promptly** produced at the primary vertex considered in the analysis.

Measurement strategy (II)

- The secondary component, corresponding to 25-30%, is reduced cutting on the antiproton **impact parameter** wrt the primary vertex.

$$\bar{\Lambda}^0 \rightarrow \bar{p}\pi^+$$
$$\bar{\Sigma}^- \rightarrow \bar{p}\pi^0$$

- **Analysis for secondary-to-primary antiproton ratio R=σ_{sec}/σ_{pr} ongoing!**

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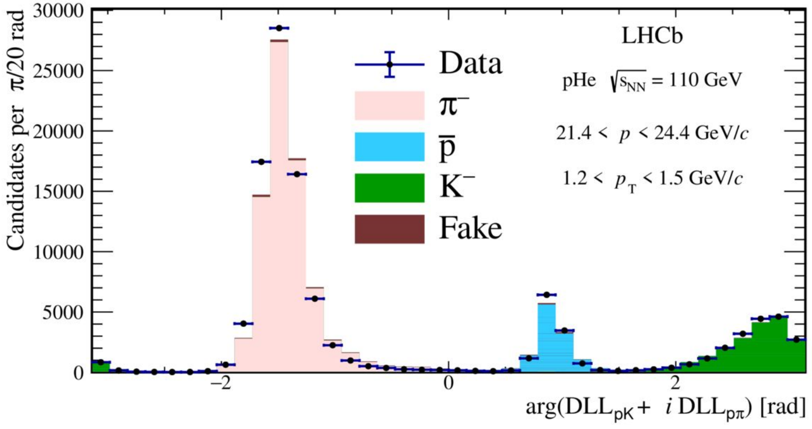
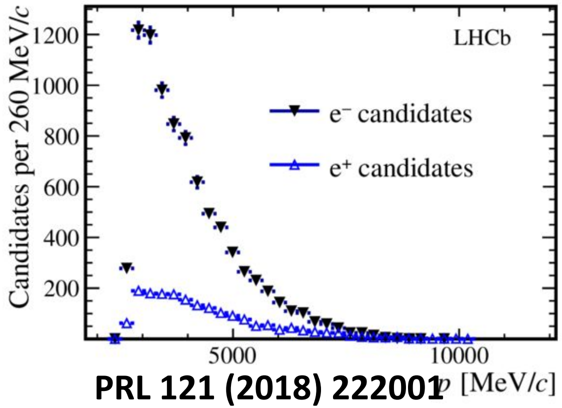


- In each kinematic bin antiprotons are selected with a fit to the **differences of the log-likelihood** functions for the different particle hypotheses.
- **Templates** taken from both *pp* and *pgas* data and from *pgas* simulations depending on the kinematic bin.

Luminosity



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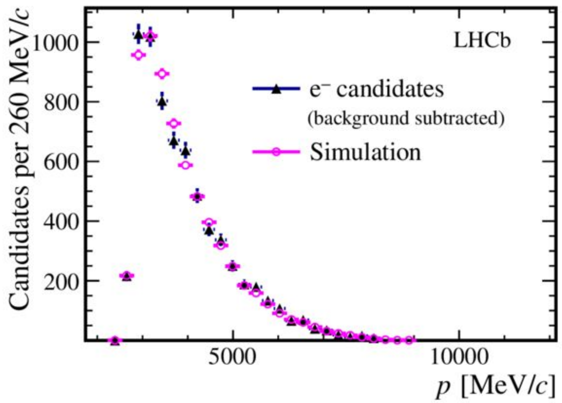
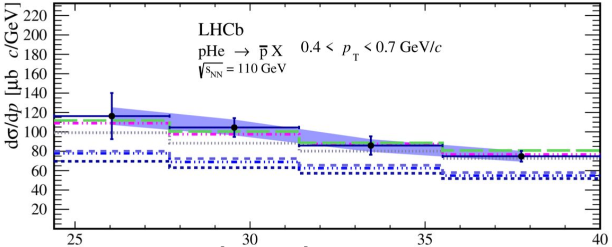


- **Luminosity** can not be directly measured because of the **lack of precise gauges** for the injected gas pressure.
- **Proton elastic scattering with gas atomic electrons**, reconstructible in the detector as an isolated low-energy electron track, used to indirectly measure the luminosity.
- **Charged-symmetric** background evaluated via positron yield and subtracted from the total electron one.
- Due to the poor electron reconstruction efficiency, luminosity measured with a 6% uncertainty, propagated as the **dominant contribution to systematic uncertainty** on σ:

$$\mathcal{L} = 484 \pm 7 \pm 29 \ \mu b^{-1}$$

Results



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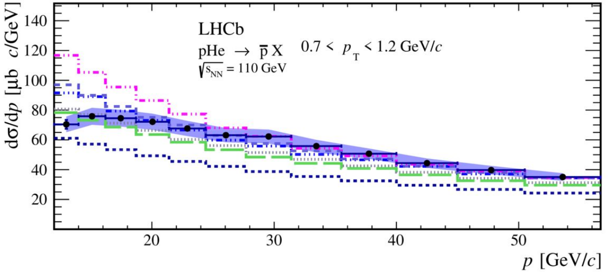

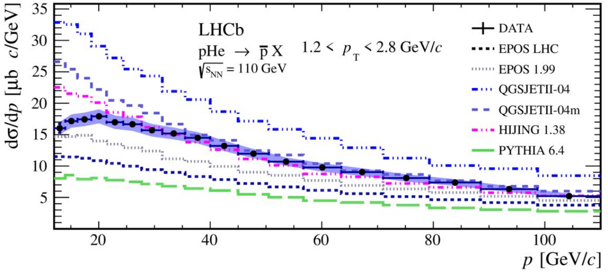

- Measured cross section compared to **EPOS-LHC, EPOS 1.99**, **QGSJETII**, **HIJING 1.38**, **PYTHIA6.**
- Experimental uncertainties, **below 10%** in most kinematic bins, lower than the spread among theoretical models.
- **Large excess** observed over EPOS-LHC, the generator used for the simulation.
- But, total visible cross section consistent with expectations:

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

- Measured excess over EPOS-LHC due to underestimated **antiproton multiplicity.**

(Taste of the) measurement impact

- 2017 preliminary results already well received by the theoretical community:
  - Constraint of the **extrapolation** of the cross section from a proton to a helium target.
  - Choice of the parametrization for the cross-section energy evolution **(scaling violation)**.

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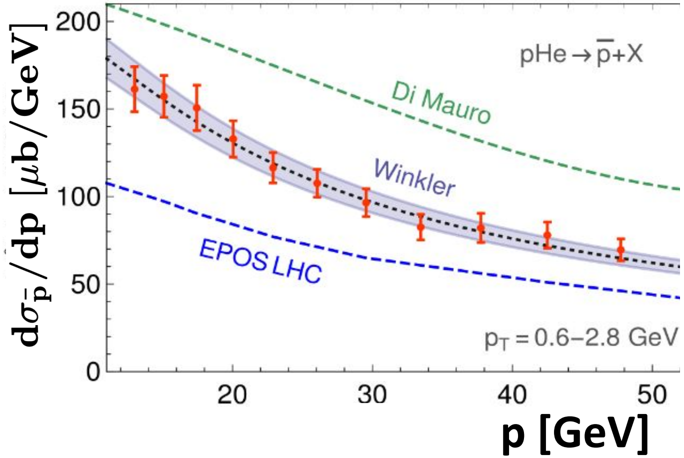

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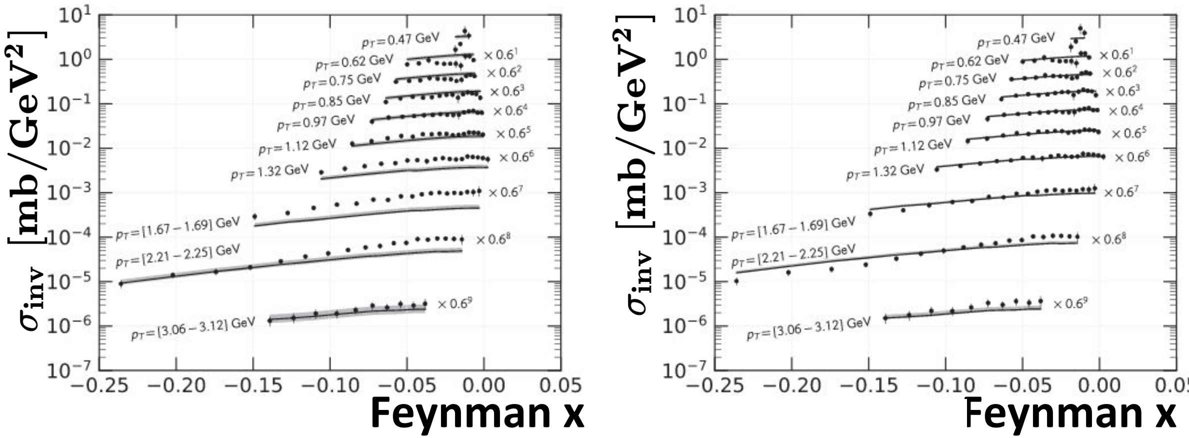


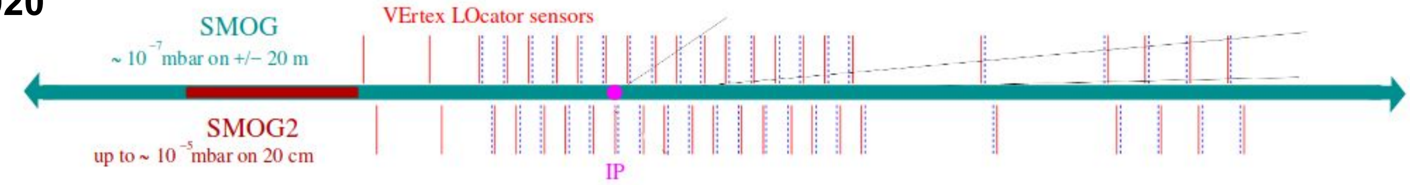
Future Prospects

SMOG programme upgrade

- **SMOG2** : **upgrade** of the fixed-target LHCb programme for 2021 data-taking with the installation of a gas confinement cell upstream the interaction point ([-500, -300] *mm*).
- pgas collisions produced by the **LHC beam crossing the cell**.

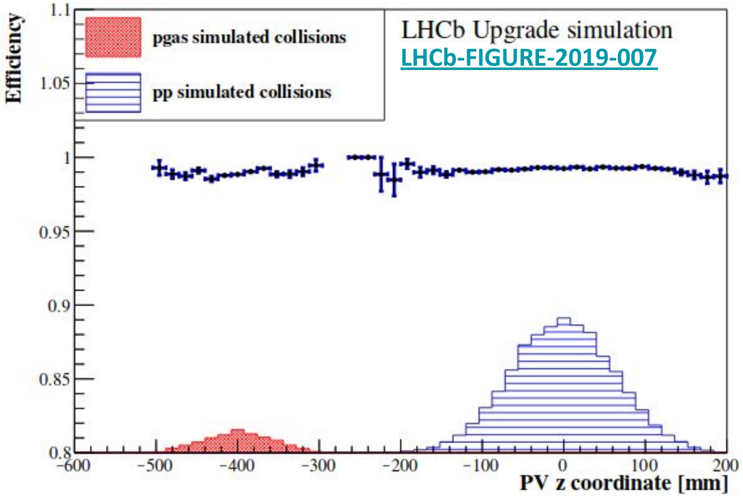
LHCB-TDR-020

- Possible to increase the **gas density** (and the luminosity) up of **two orders of magnitude** with the same gas flow as current SMOG.
- Gas pressure **precisely measured**, decreasing the dominant systematic uncertainty on cross-section measurements.
- **More gases** (with machine approval) can be injected (like H, O, N…)
- Possible to have a **simultaneous data-taking** with *pp* being the interaction region displaced wrt nominal IP.



SMOG2 data-taking

- **Data-taking strategy** definition depends on two key topics:
  - **Efficiency**: pgas collisions are largely displaced from the nominal interaction point and challenging to reconstruct because of their low multiplicity and forward direction.
  - **Disturbance**: gas presence must not disturb the *pp* core physics programme wrt both physics (inducing background) and timing (consuming bandwidth).



- Preliminary results for tracking efficiencies show **similar performances** between *pp* and *pgas.*
- Ongoing studies to address the above questions.

- Our best (and up to now possible) scenario employs *pp* and *pgas* data-taking with all LHC bunch-crossings!

(non-exhaustive) SMOG2 physics opportunities

- **Luminosity increase** and **target variety** open new measurements possibilities of keen interest of the community! → See e.g. last LHCb Heavy Ion and Fixed Target workshop!

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

1. Extension of the current Heavy Ion programme addressing measurements like **quarkonium suppression, hydrodynamic observables, Drell-Yan di-muon, particle photoproduction**.
2. Extension of the measurements of **interest to CRs physics** (next slide).
3. Detailed studies of the **gluon and heavy-quark PDFs.** Studies on the PDF p_T dependence as an intermediate step towards a **nucleon complete tomography**?

Prospects for antiprotons in space

- Antiproton measurement will largely benefit from the SMOG programme upgrade!

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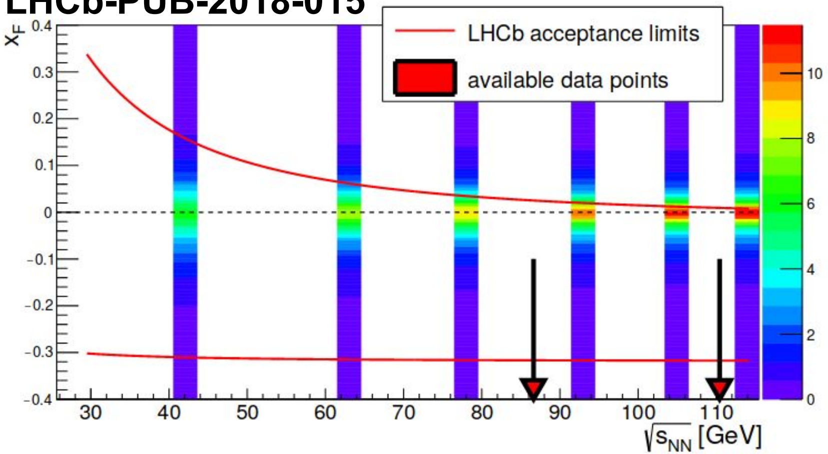


- Extension of the measurement towards **lower energy** (scaling violation?) already started in Run2 with a *pHe* sample collected with an energy of $\sqrt{s_{NN}} = 87\ GeV$.
- Lower beam energies (possibly up to 0.9 TeV) are sensitive to **positive Feynman-x** regime.

- With the hydrogen injection, $\sigma(pHe \to \bar{p}X)/\,\sigma(pp \to \bar{p}X)$ measurement, much less prone to systematic uncertainty, can further constrain the production cross sections.
- With the deuterium injection , the $\sigma(pD \to \bar{p}X)/\,\sigma(pp \to \bar{p}X)$ measurement can constrain the anti-neutron production (**isospin violation**).

Conclusions

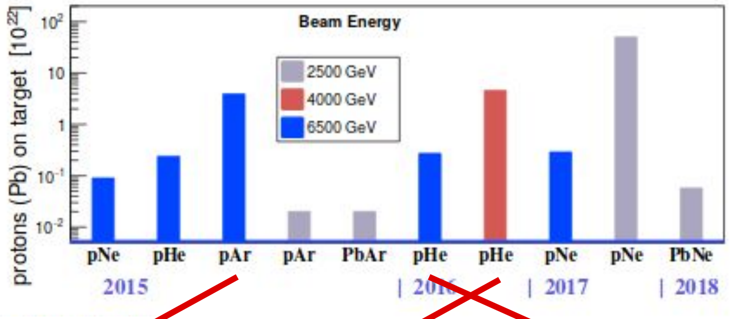
Conclusions

- Thanks to its excellent vertexing, tracking and PID performances, its forward geometry and the possibility to inject gas into the LHC beam pipe, the LHCb experiment is conducting a pioneering fixed-target programme.
- **First measurement** ever of $\sigma(pHe \rightarrow \bar{p}X)$ with a proton beam of 7 TeV energy on at-rest *He* nuclei presented.
- **Measurement uncertainty much lower** than theoretical model spread.
- Results already well received by the theoretical cosmic rays community and used to constrain the cross section evolution with the energy.
- **LHCb fixed-target programme upgrade**, SMOG2, will overcome many difficulties of the current system and will allow to further widen the LHCb physics objectives.

Thanks for your attention!

Backup

Run2 measurements of CRs interest



PRL 122, (2019) 132002

- First Measurement of **charm production** in its Fixed-Target configuration at the LHC.
- Addressing the possible **intrinsic PDF charm contribution** at large x.
- **Neutrino production** in ultra high-energy (UHE) atmospheric showers.

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- Measurement of **antiproton production** cross section in *pHe* collisions.
- Antiproton production in CRs - ISM collisions, main background for space-borne experiments **dark matter** searches.

Background from vacuum contamination

- Given the low injected gas pressure (order $2 \cdot 10^{-7}$ *mbar*), the **LHC vacuum contamination** (order 10^{-9} *mbar*) is not negligible.
- Static contamination measured with **Rest Gas Analysis** and dominant contamination found by hydrogen.
- **Beam-induced outgassing** can contain heavier contaminants, with larger σ than *He*.

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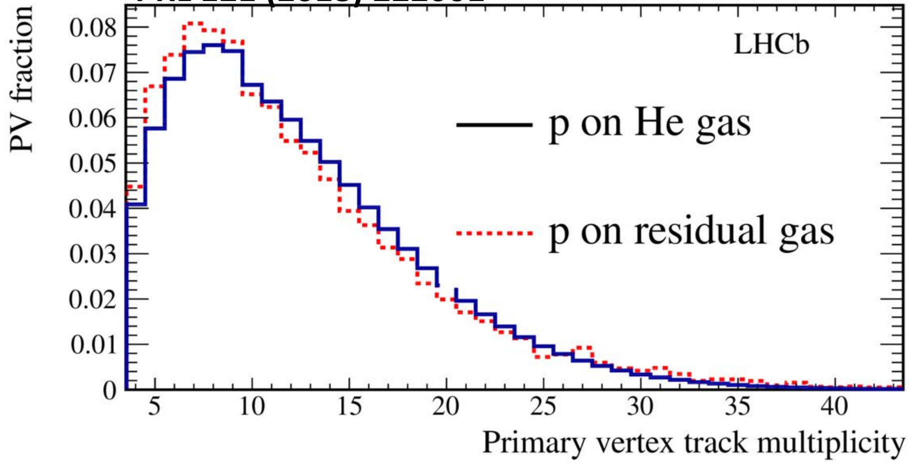
- Fraction of the events acquired with the SMOG system in place, but with **no gas**.
- PV track multiplicity on residual gas on average lower than on *He*: dominant **hydrogen** contribution.



Systematic uncertainty

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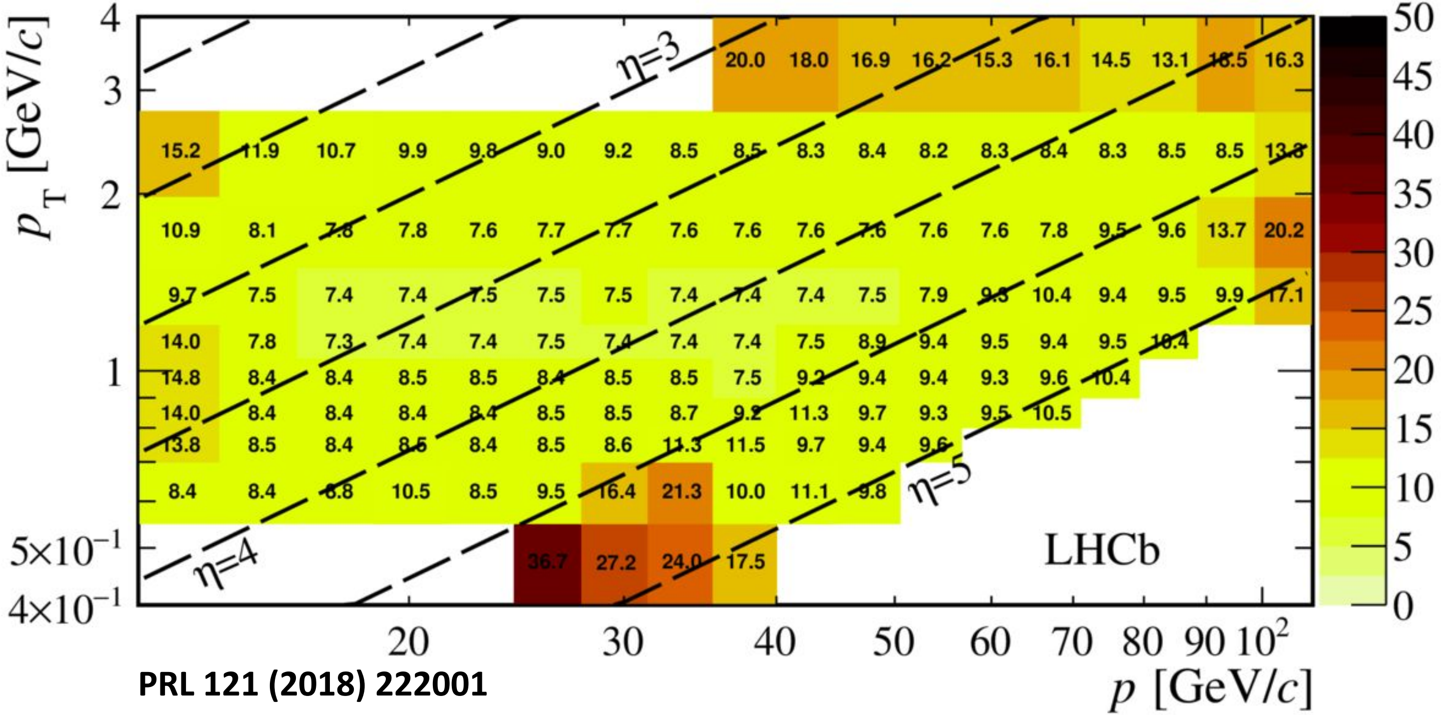
Statistical	
$\overline{p}$ yields	$0.5 - 11\%$ ($< 2\%$ for most bins)
Luminosity	$1.5 - 2.3\%$
Correlated systematic	
Luminosity	6.0%
Event and PV selection	0.3%
PV reconstruction	$0.4 - 2.9\%$
Tracking	$1.3 - 4.1\%$
Non-prompt background	$0.3 - 0.5\%$
Target purity	0.1%
PID	$3.0 - 6.0\%$
Uncorrelated systematic	
Tracking	1.0%
IP cut efficiency	1.0%
PV reconstruction	1.6%
PID	$0 - 36\%$ ($< 5\%$ for most bins)
Simulated sample size	$0.4 - 11\%$ ($< 2\%$ for most bins)

- Uncertainty in most kinematic bins **lower than 10%.**
- Dominant contribution from **luminosity** measurement: motivation for SMOG2 upgrade
- Sub-dominant PID contribution: started activity to increase the templates coverage with a **machine learning application**.

Measurement total uncertainty in bins



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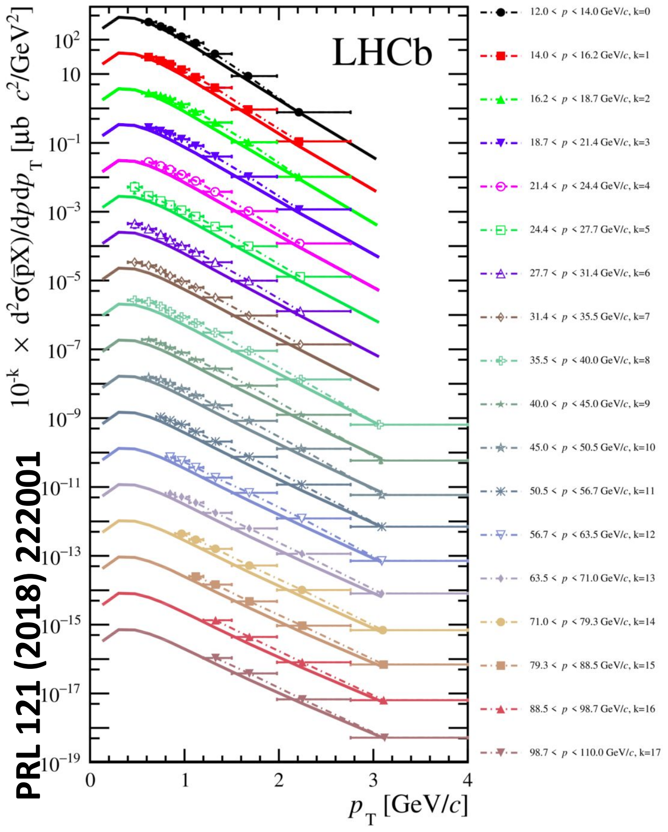
- Total uncertainty **lower than the 10%** in most bins.

Measurement results



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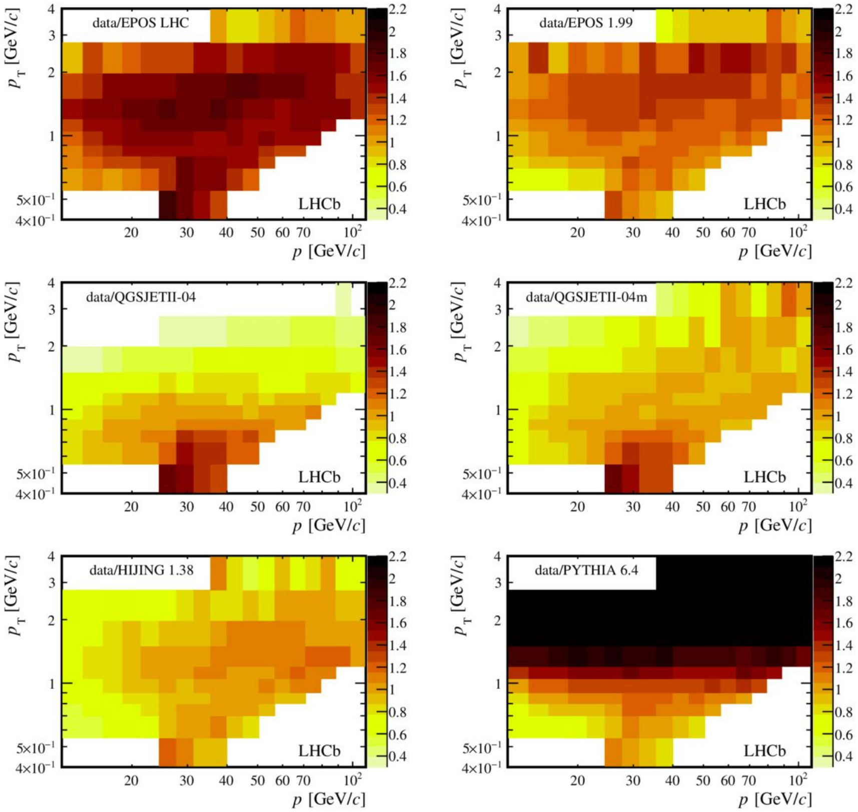
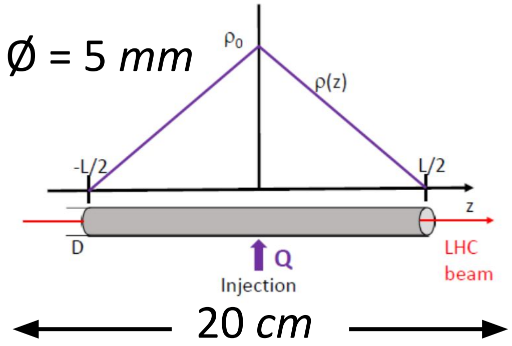
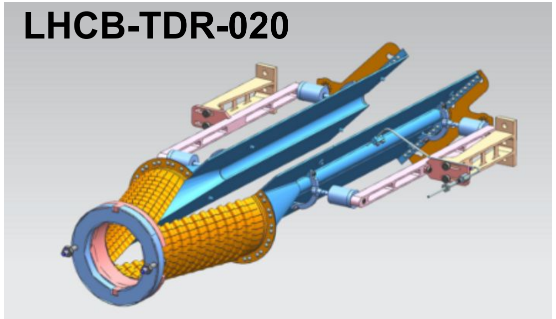


SMOG2 cell





- **Gas injection** in the cell from its half, thus the gas pressure follows a triangular profile.
- System composed of **two retractable halves** to follow the Velo closing procedure.
- Light and thin material, to keep low the **material budget** and appropriately **coated** to prevent electron clouds to form.
- **Electrical connectivity** ensured by the wake field suppressor.
- Approved by the LHCC, installation foreseen in **December**.

SMOG wishlist

- From the talk by Winkler during the Second LHCb Heavy Ion workshop:

  - LHCb SMOG wishlist:

    1) $\mathrm{p\,He} \rightarrow \bar{\Lambda}, \bar{\Sigma}$ from existing run

    2) $\mathrm{p\,p}\,(\mathrm{H_2}) \rightarrow \bar{\mathrm{p}}$ to test scaling violation in forward hemisphere

    3) $\mathrm{p\,d} \rightarrow \bar{\mathrm{p}}$ to test isospin effects

    4) $\mathrm{p\,p},\ \mathrm{p\,He} \rightarrow \bar{\mathrm{d}},\ \overline{\mathrm{He}}$ to determine coalescence momentum

    5) $\mathrm{p\,p},\ \mathrm{p\,He} \rightarrow \pi,\ \mathrm{K}$ to model positron source term

Prospects for particles interacting in atmosphere

- Studies of **ultra high-energy neutrinos** currently limited by the poor knowledge of charm particles production cross sections.

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- After the first charm production cross section measurement in *pgas* with Run2 data, SMOG2 will allow to further constrain the **charm PDF intrinsic contribution**.

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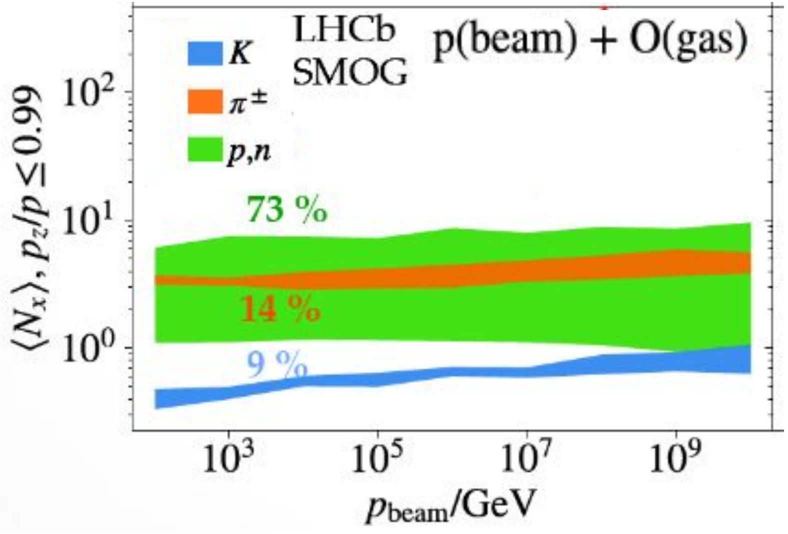

- Studies of CRs-induced atmospheric showers are currently limited by the **poor knowledge of meson and baryon production cross sections**.
- Injecting O or N in SMOG2, the models spread could be remarkably reduced.
- Proposal to perform a **LHC run with oxygen beams**. Injecting hydrogen in SMOG2, access to the extreme forward direction.

CERN-LPCC-2018-07