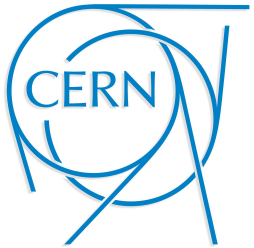
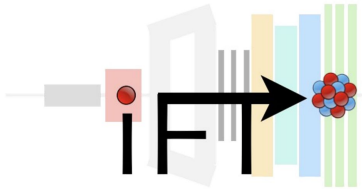




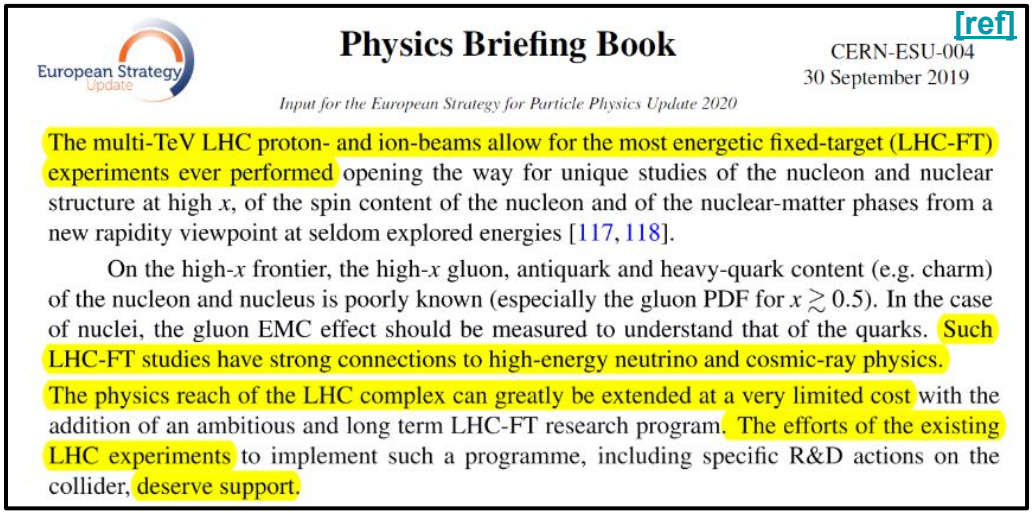
Fixed-target LHCb measurements contributing to cosmic rays physics

Saverio Mariani
CERN
On behalf of the LHCb collaboration

52nd International Symposium on Multiparticle Dynamic, 21/08/2023

Introduction

- While measurements for Cosmic Rays (CRs) are becoming more and more precise, their interpretation mostly relies on **poor experimental data** and limits the possibility to draw conclusions
  - **Antimatter production in the galaxy** → antimatter production cross-sections?
  - **Atmospheric CRs propagation** → interactions in non-perturbative regime?
  - **Photon and neutrino astronomy** → π^0, charm cross-sections?



European Strategy Update

Physics Briefing Book

CERN-ESU-004
30 September 2019

Input for the European Strategy for Particle Physics Update 2020

[ref]

The multi-TeV LHC proton- and ion-beams allow for the most energetic fixed-target (LHC-FT) experiments ever performed opening the way for unique studies of the nucleon and nuclear structure at high x, of the spin content of the nucleon and of the nuclear-matter phases from a new rapidity viewpoint at seldom explored energies [117, 118].

On the high-x frontier, the high-x gluon, antiquark and heavy-quark content (e.g. charm) of the nucleon and nucleus is poorly known (especially the gluon PDF for $x \gtrsim 0.5$). In the case of nuclei, the gluon EMC effect should be measured to understand that of the quarks. Such LHC-FT studies have strong connections to high-energy neutrino and cosmic-ray physics.

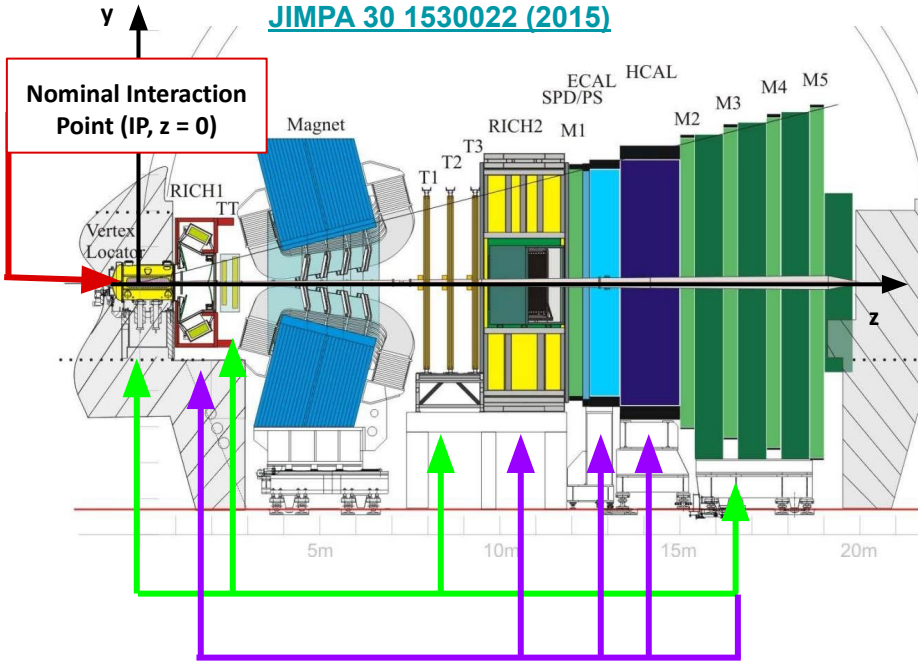
The physics reach of the LHC complex can greatly be extended at a very limited cost with the addition of an ambitious and long term LHC-FT research program. The efforts of the existing LHC experiments to implement such a programme, including specific R&D actions on the collider, deserve support.

- CERN community acknowledges fixed-target configuration @ LHC can provide **unique contributions to theoretical models**
- … and LHCb is pioneering this since 2015!

The LHCb experiment

- **Single-arm spectrometer**, nowadays a **general purpose experiment** covering η ϵ [2, 5] (QCD, SM, **heavy ion and fixed-target**)

JINST 3 08005 (2008)
JIMPA 30 1530022 (2015)

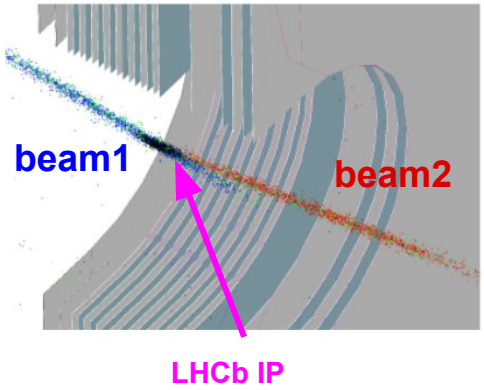


- **Complementary** wrt other LHC experiments
- Tracking system: **VErtex LOcator** + tracking stations and a dipole magnet
  - 0.5-1% *p* resolution for *p* < 300 GeV/c
  - 10-80 μm IP resolution
- Particle identification (PID): Two **Cherenkov detectors (RICH)** + calorimeters and muon
- **Flexible and versatile trigger**

JINST 8 04022 (2013)

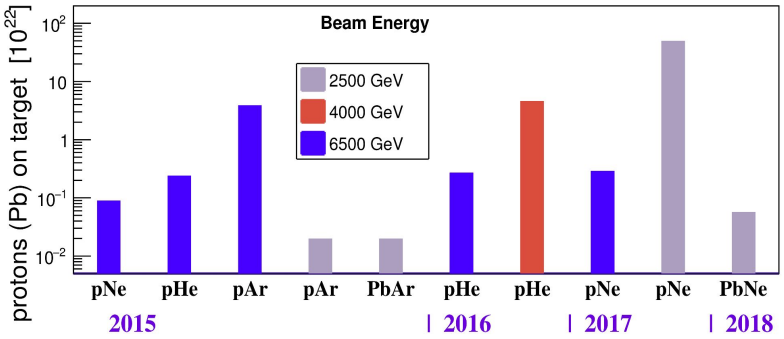
The LHCb SMOG system

JINST 9 (2014) 12005



- Since 2011, LHCb **System for Measuring Overlap with Gas (SMOG)**
  - LHC beam collisions with the small quantity of injected gas (10^{-7} mbar) used to reconstruct the **beams transverse profiles**
- Forward detector + gas target = **highest-energy fixed-target ever!**

LHCb-PUB-2018-015



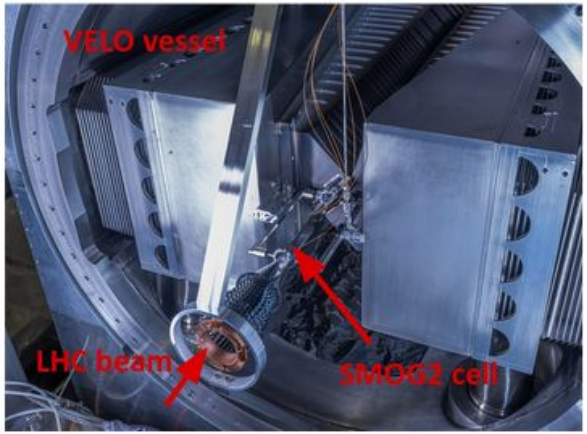
- Several *p*A and PbA fixed-target samples collected
- **Unique energy scale**: $\sqrt{s_{\mathrm{NN}}} \in [68.5, 110]$ GeV
- **Access to the high-x and intermediate Q^2** kinematic region, mostly unexplored by previous experiments

→ **Unique experimental inputs** to models

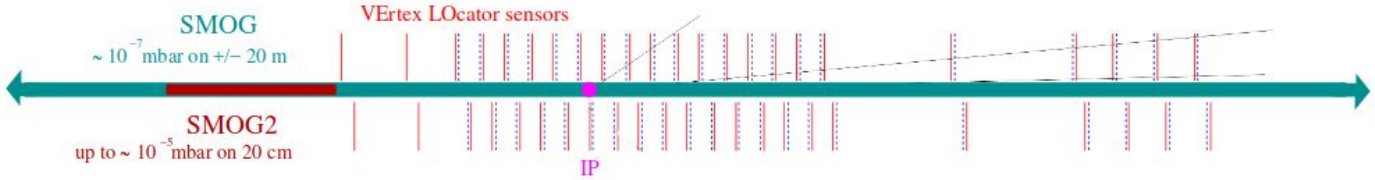
SMOG upgrade as SMOG2

- For LHC Run3, major LHCb upgrade ⇒ full tracker, full electronics and DAQ channels replaced + hardware trigger removed [LHCb-DP-2022-002]

[LHCb-TDR-020]
[LHCb-PUB-2018-015]



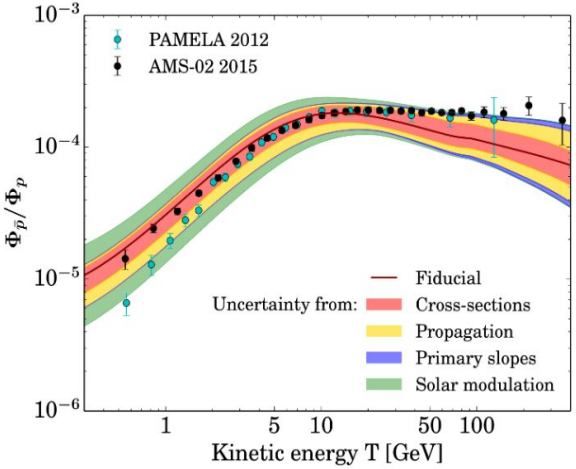
- **SMOG2: gas confinement in a cell upstream of the LHCb IP** (z ϵ [-541, -341] mm)
  - Up to x100 **pressure wrt SMOG for the same gas flow**
  - **Simultaneous beam-beam beam-gas data-taking**
  - **Heavy noble (Kr, Xe) and non-noble gases (H_2, D_2, O_2, N_2 …)** can be injected
- **New Gas Feed System**
  - Precise flow control ⟶ **direct lumi measurement**
  - More gas recipients ⟶ **fast gas replacement**

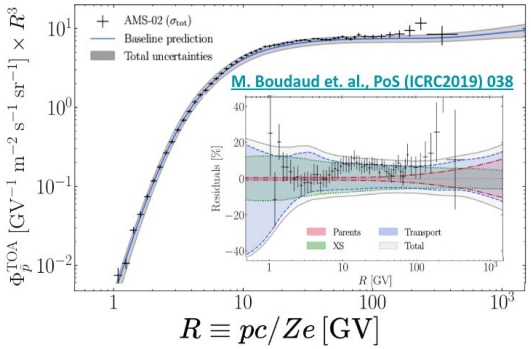


Antimatter production in the galaxy

The role of cross-section for antiproton production

Giesen *et. al.*, JCAP 1509 (2015)





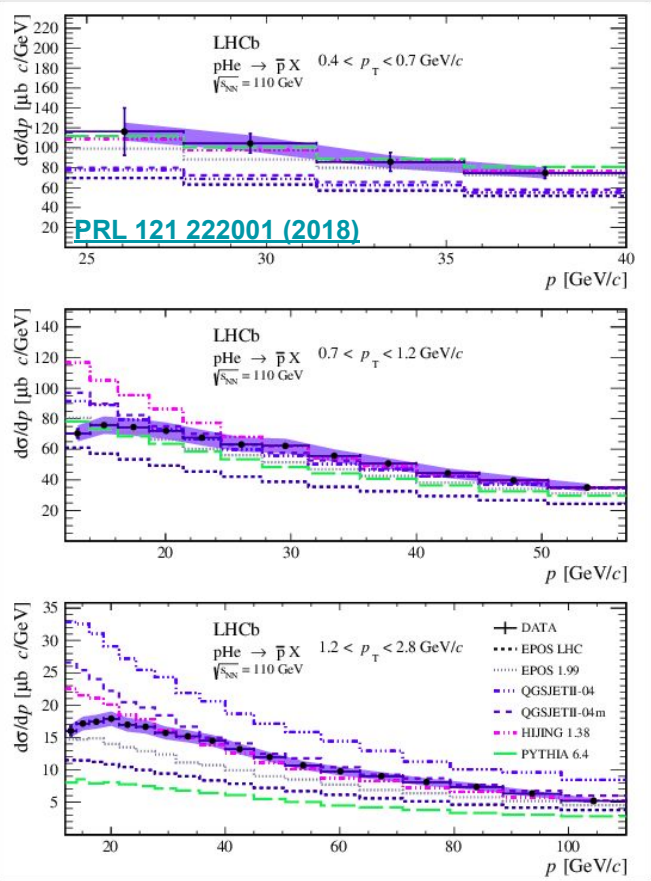
- Antiprotons in space can (could) be produced:
  - **CRs - Interstellar Medium** (mostly H, He) collisions
  - Exotic sources, maybe **Dark Matter (DM) annihilation** in proton-antiproton?

- Back to 2015, AMS-02 data compared to secondary only production model gave **hint of an excess → DM?**
- **Inconclusive interpretation** because of the uncertainties, dominated by **antiproton production cross-sections**

- With new models, significance for an exotic contribution to the antiproton flux **strongly reduced** M. Boudaud et. al., PoS (ICRC2019) 038
- Interpretation of data **still limited** by the knowledge of the **antiproton production cross-sections**

LHCb prompt antiproton production results

PRL 121 222001 (2018)



- **By injecting helium through SMOG**, LHCb published in 2018 the first measurement ever of prompt antiproton production in *p*He collisions @ 110 GeV

  - Uncertainties dominated by **lack of direct luminosity measurement** (no precise pressure gauges) + **proton identification**
  - Still, result uncertainties are **lower wrt to the spread of theoretical models**

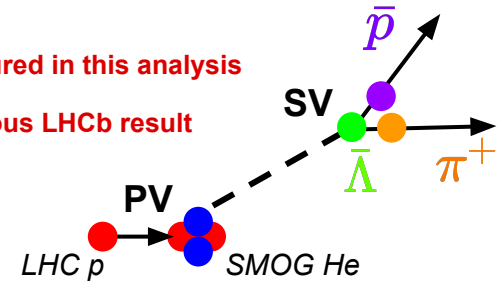
LHCb secondary antiproton production results

EPJC 83, 543 (2023)

- Measurement extended in 2022 to **anti-hyperon produced antiprotons** following two complementary approaches

- **Exclusive approach**: $R_{\bar{\Lambda}} = \dfrac{\sigma(p\mathrm{He} \to (\bar{\Lambda}_{\mathrm{prompt}} \to \bar{p}\pi^+)X)}{\sigma(p\mathrm{He} \to \bar{p}_{\mathrm{prompt}}X)}$ → measured in this analysis; → previous LHCb result

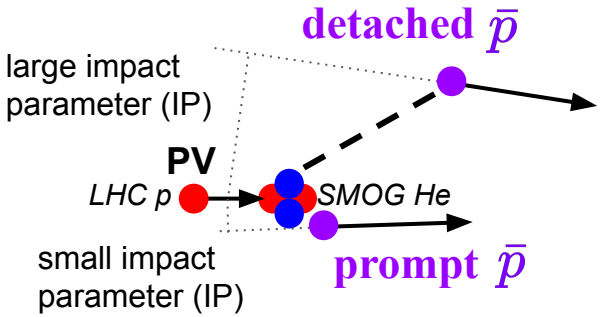
  - ➔ Addressing the **dominant detached component**
  - ➔ **Not using PID** information



- **Inclusive approach**: $R_{\bar{H}} \equiv \dfrac{\sigma(p\mathrm{He} \to \bar{H}X \to \bar{p}X)}{\sigma(p\mathrm{He} \to \bar{p}_{\mathrm{prompt}}X)}$

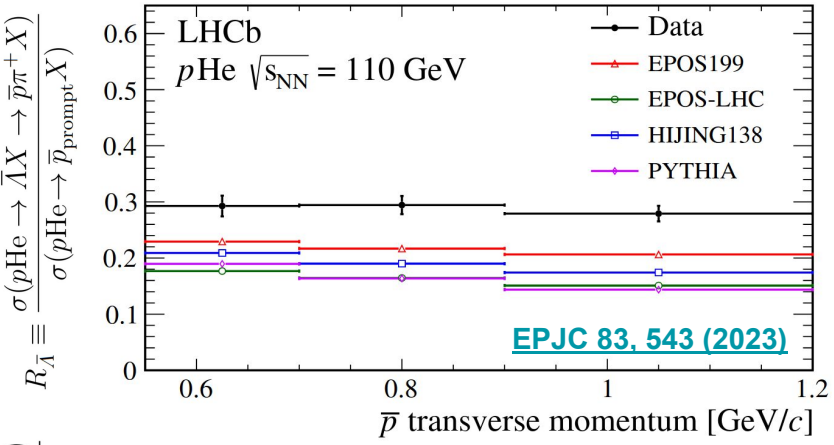
$$\bar{H} = \bar{\Lambda}, \bar{\Sigma}, \bar{\Xi}, \bar{\Omega}$$

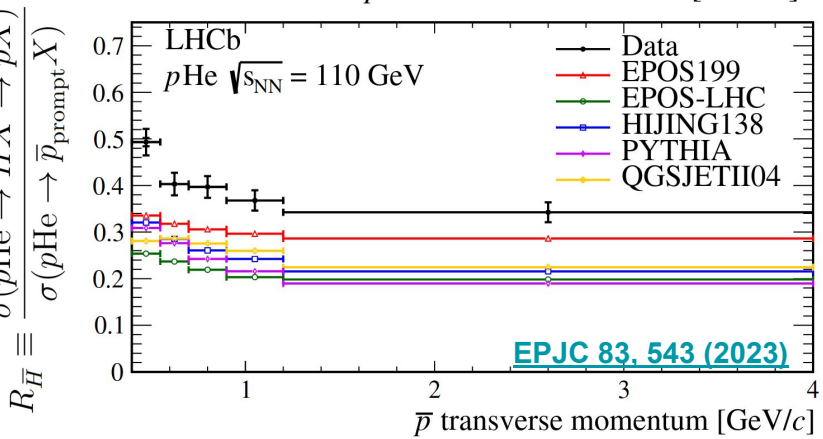
  - ➔ Addressing all **detached antiprotons**
  - ➔ **Selecting antiproton with PID** information and distinguishing between prompt and secondary via the **excellent VELO IP resolution**



LHCb secondary antiproton production results (2)

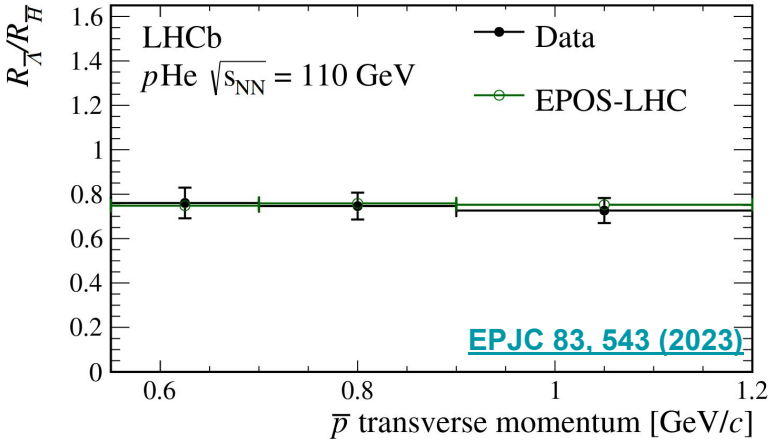
EPJC 83, 543 (2023)





- Models **largely underestimate the secondary contributions** to the total antiproton yield
- **Dependence on kinematic observed,** but usually neglected in models
- Double-ratio **consistent with predictions**, only dependent on hadronization

Becattini et al, EPJC 66, 377–386 (2010)



What's in the pipeline

- Theoreticians of the field already demonstrated **a keen interest in our results**!

- LHCb SMOG wishlist:
  1) p He $\rightarrow \bar{\Lambda}, \bar{\Sigma}$ from existing run → Done for 110 GeV, TODO @ 87 GeV
  2) p p (H_2) $\rightarrow \bar{p}$ to test scaling violation in forward hemisphere → Possible with SMOG2
  3) p d $\rightarrow \bar{p}$ to test isospin effects → Possible with SMOG2
  4) p p, p He $\rightarrow \bar{d}, \bar{He}$ to determine coalescence momentum → Nuclei identification @ LHCb proved to work…**stay tuned for EPS and Quark Matter**
  5) p p, p He $\rightarrow \pi$, K to model positron source term → Effort ongoing on available data, see next slides

Martin Winkler at 2nd LHCb Heavy Ion workshop

Searches for dark matter and primordial antimatter		
In p-H_2, p-He, p-D_2: production of $\bar{d}/\overline{He}$, $\bar{p}$, e^+, $\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$	LHCb SMOG2, AMBER, NA61	Desirable: LHC run at 450 GeV

Luca Orusa at Padova QCD challenged workshop

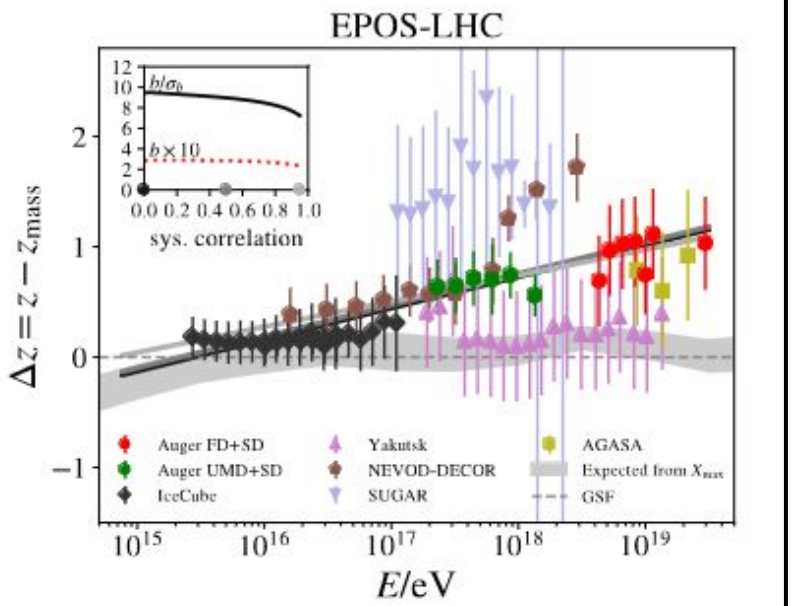
CR showers development in the atmosphere

The role of cross-section for atmospheric showers

- **Ultra-high energy CRs** are measured by ground-based experiments, after full development of the **shower in the atmosphere**
- **Muon puzzle**: observed a muon excess with respect to model predictions

Astr and Space Science, 367, 27 (2022)

Astr and Space Science, 367, 27 (2022)

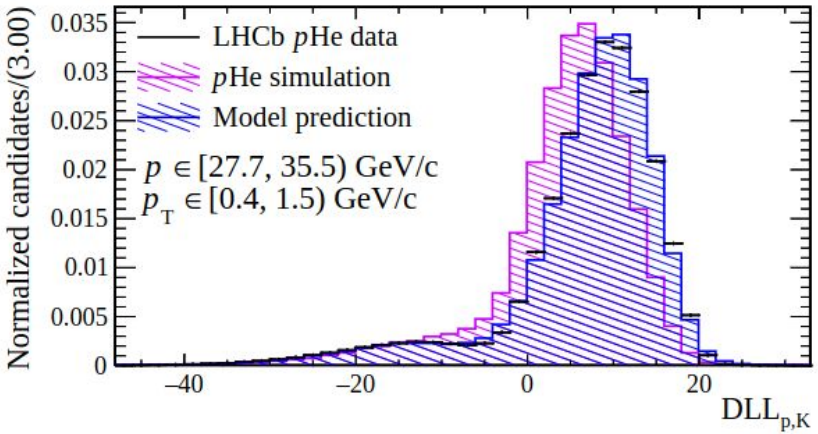


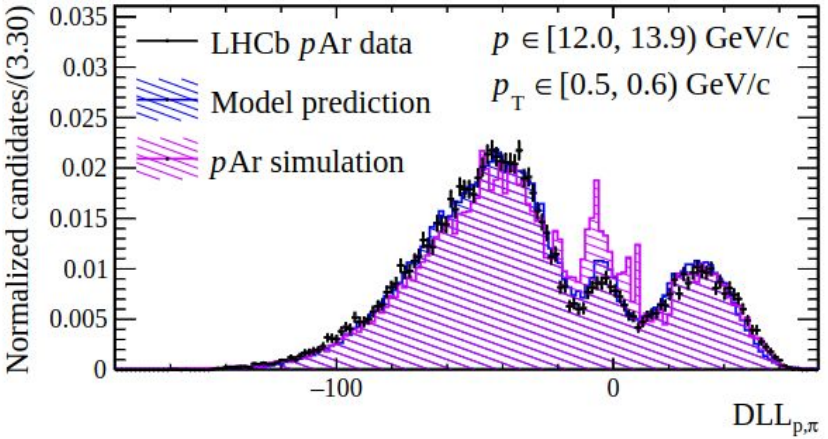
- Modelling of the hadronic interactions in non-perturbative regime require **more precise and more various experimental data**
- LHC fixed-target initiative, accessing the poorly explored **high-*x* and intermediate Q^2 region**, can give a unique contribution

Ongoing measurements with SMOG data

- **Production of prompt particles (π, K, p)** being measured in all the data samples collected in 2015 - 2018 ⟶ not public results yet, stay tuned!
- **Main limitation is particle identification**, suffering from the poor calibration statistics available in fixed-target data
- Been tackled by developing a **data-driven machine-learning approach** *JINST* 17 P02018

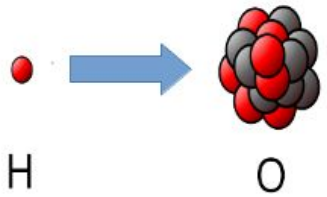
$$\mathrm{DLL}_{h1,h2} = log\left(\frac{\text{h1 likelihood}}{\text{h2 likelihood}}\right)$$



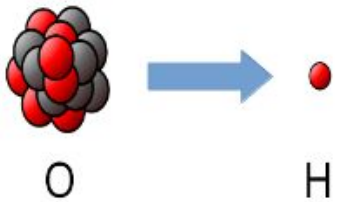


- By-eye **improvement of the data quality description**

Prospects with SMOG2



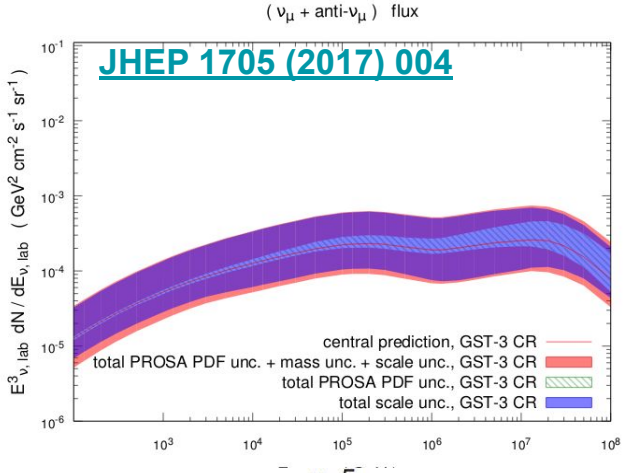
- **Injection in SMOG2 of oxygen and nitrogen** exactly reproduces the CR particle impinging on the atmosphere (with $-2.8 < y^* < 0.2$)

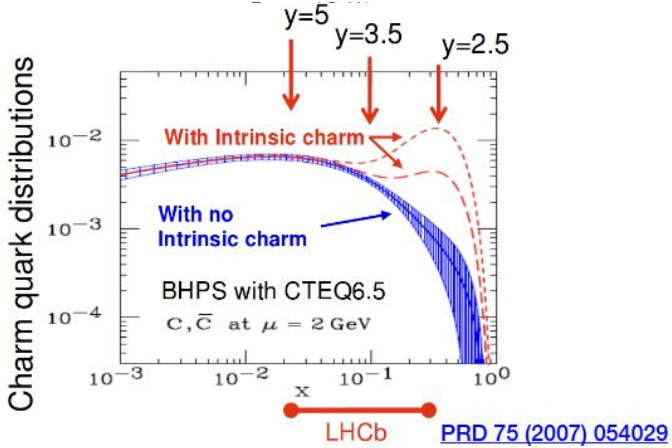


- **Oxygen-Oxygen and proton-oxygen runs** foreseen in 2024
- By injecting oxygen in SMOG2, LHCb can simultaneously collect OO collisions at two different energy scales
- By injecting hydrogen, possible to acquire proton on oxygen with rapidities $-0.5 < y^* < 2.5$

Impact of charm production measurements for neutrino astronomy

Charm decays as background to neutrino





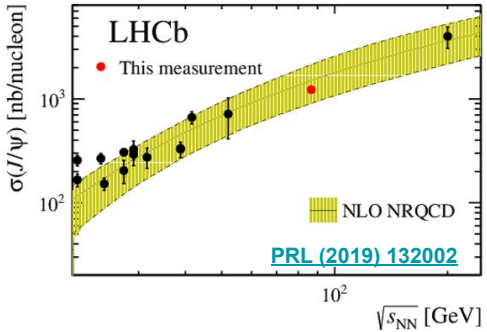
- Large volume **neutrino** telescopes (IceCube, KM3NET) are observing high-energy neutrinos up to the PeV scale
- Main background: forward decay of **charm states** originated from CRs interactions with the atmosphere.
- Need **experimental data covering several orders of magnitude** in energy to be used in the PDF fits and to reduce QCD uncertainties
- … LHCb fixed-target data, sensitive to possible intrinsic charm nucleon content, can give **unique contributions**

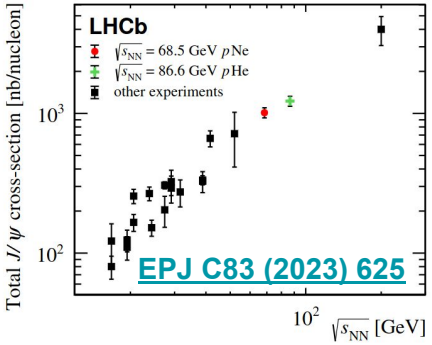
LHCb recent measurements with SMOG

PRL (2019) 132002

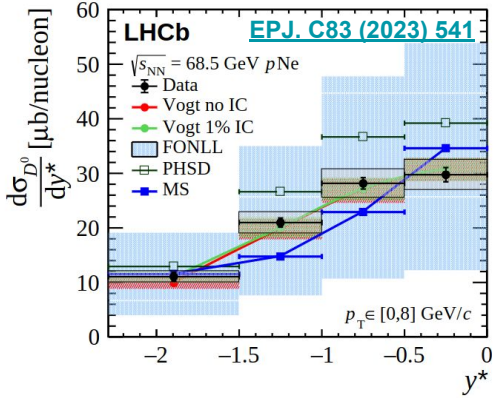
- Open charm and charmonia states measured in *p*Ar, *p*He and *p*Ne/PbNe samples

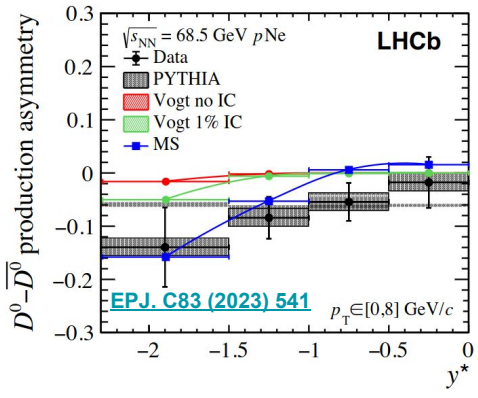
EPJ C83 (2023) 541
EPJ C83 (2023) 625
EPJ C83 (2023) 658





- Measurements filling a gap in energy
- Access to heavier states statistically limited → motivation to SMOG2!

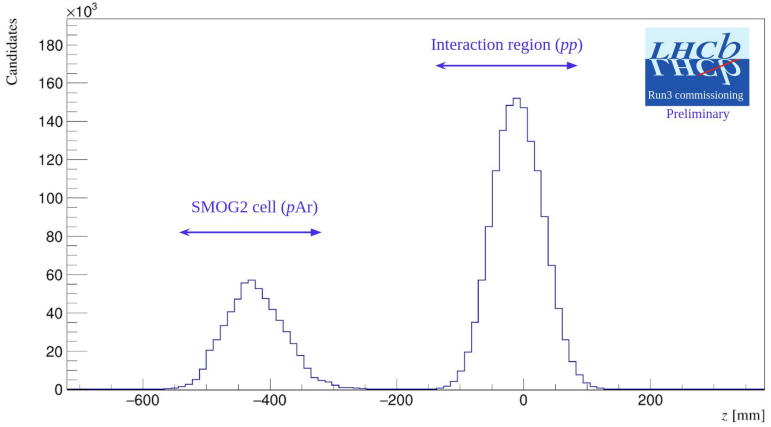


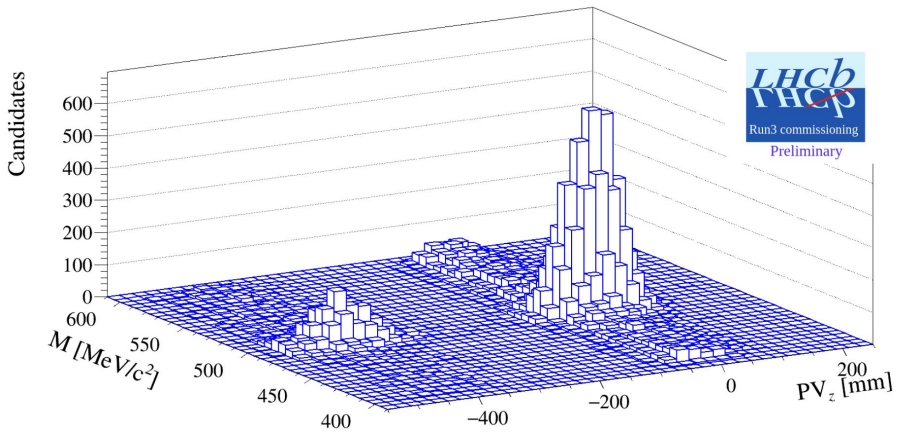


- Description of cross-section trends and asymmetries with models including **no** or 1% intrinsic charm
  Vogt, PRC 103.035204
- **More statistics is needed** to distinguish between the two!

SMOG2 in action

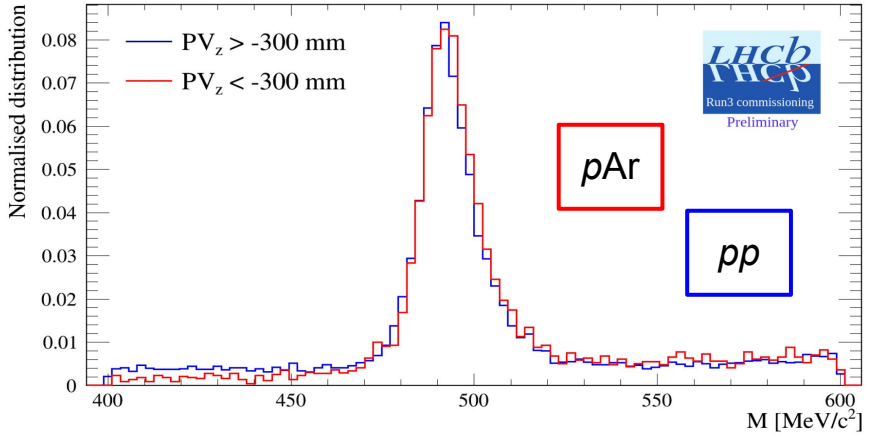
Commissioning figures of merit (I)





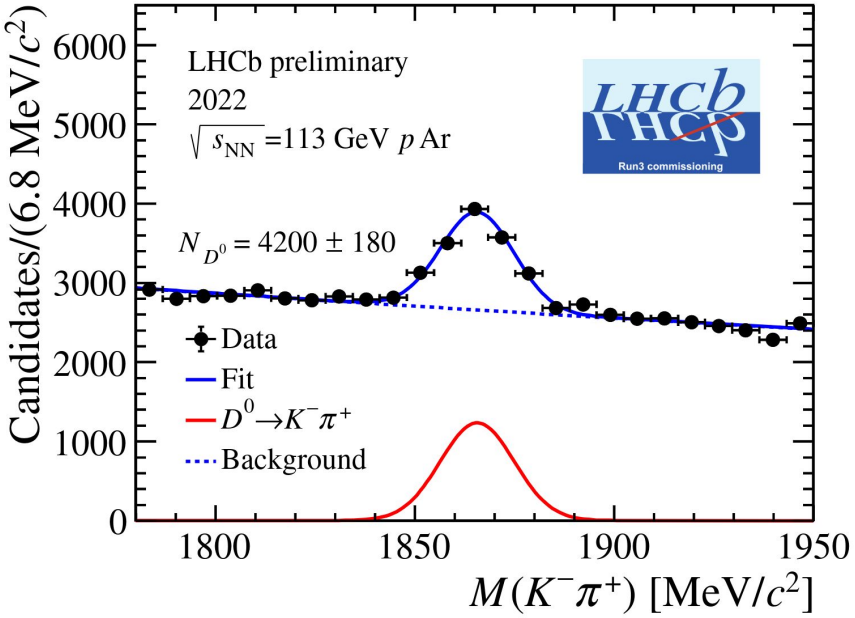
LHCb-FIGURE-2023-001

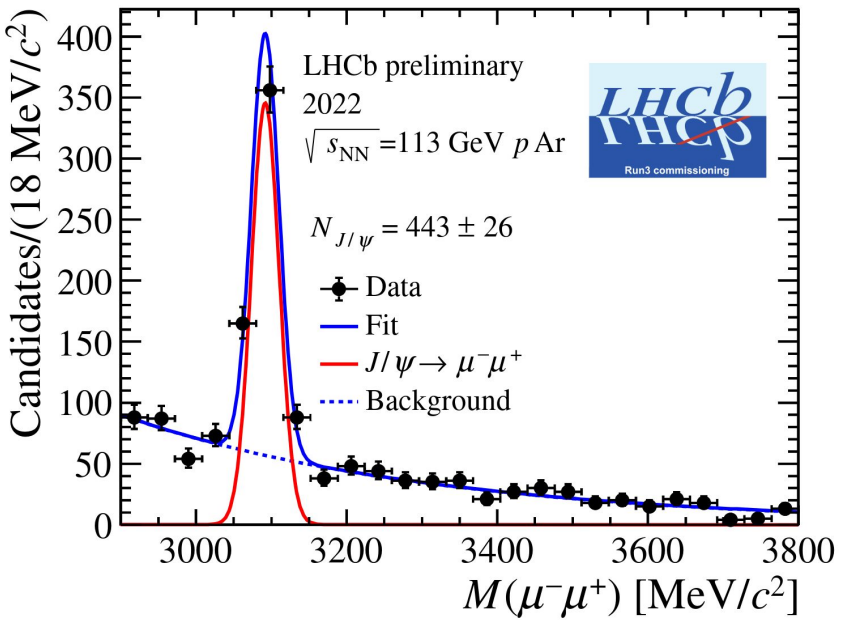
- From first data collected in 2022, LHCb was operating with **two independent collision points**
- **Reconstruction of composite particles**, with same resolution as for pp collisions, obtained



Commissioning figures of merit (II)

- Full analysis chain validated with **reconstruction of charm states**
  - Plots obtained with 18 minutes of *pp* + *p*Ar data-taking





- **A unique laboratory for QCD studies at the LHC!**

Conclusions

- While **cosmic rays measurements** are more and more precise, their interpretation relies on models built on scarce and imprecise experimental data
- Fixed-target physics at LHC offers **unique possibilities**, as pioneered by LHCb since 2015
  - **Antiproton production** measurements, contributing to constrain **antimatter production in the galaxy** theoretical models
  - **Prompt particle production** measurements, relevant to improve the modelling of **cosmic rays atmospheric shower** development
  - **Charm production** measurements, useful to constrain the main background for **astro-neutrino observations**
- SMOG and its upgrade SMOG2 are **a unique laboratory for measurements relevant for cosmic rays physics**

Thanks for your attention!

Want to follow up? saverio.mariani@cern.ch