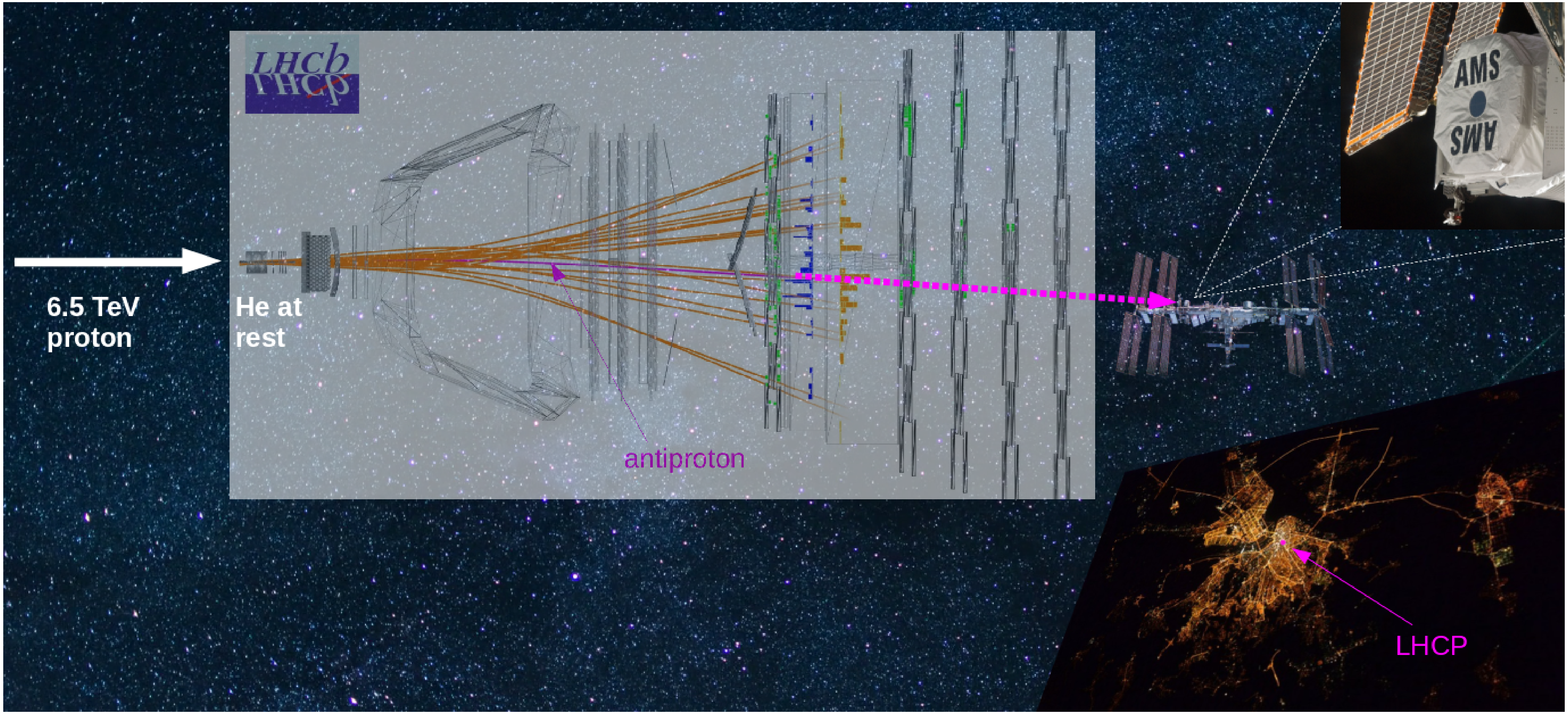
Fixed-target measurements contributing to cosmic rays studies



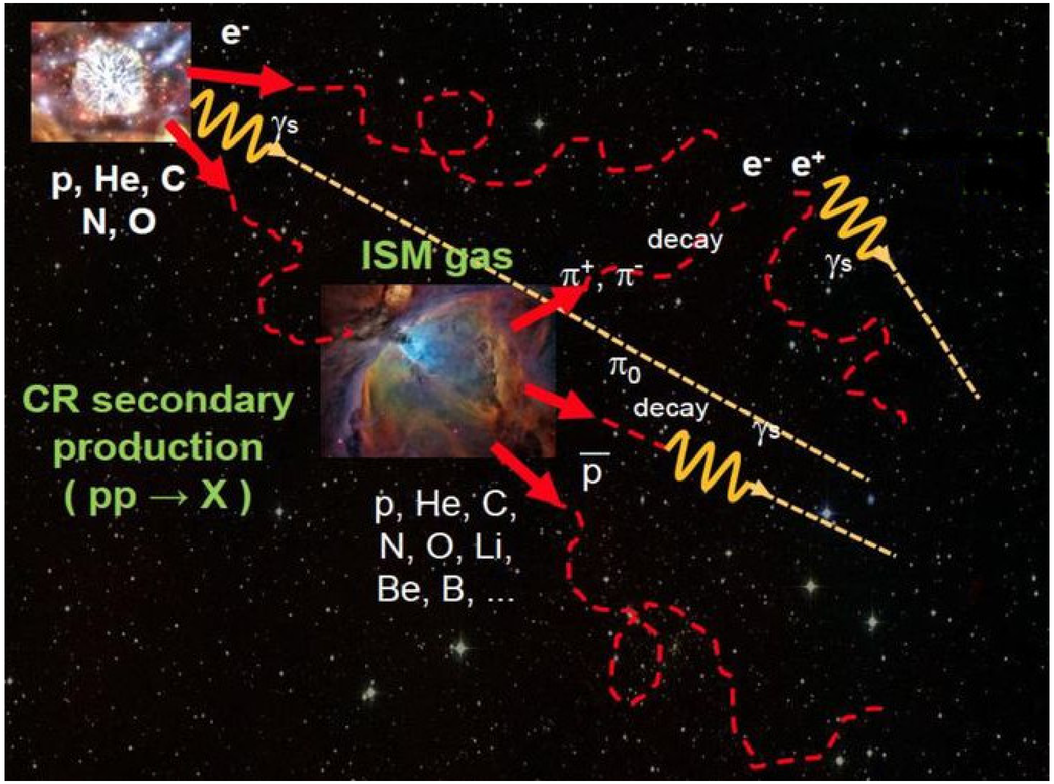
Giacomo Graziani (INFN Firenze)
on behalf of the LHCb Collaboration

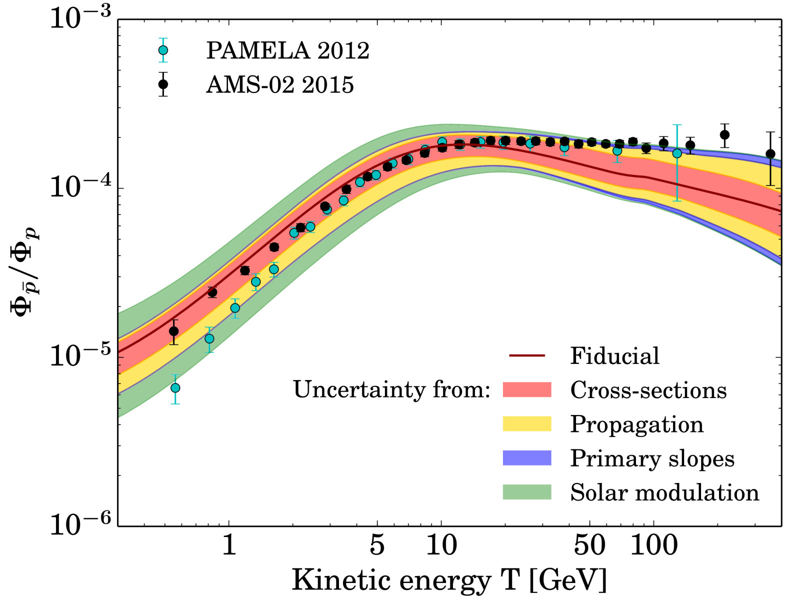
LHCP 2023, Belgrade, May 22, 2023

Cross sections for Astroparticle Physics

Experimental astroparticle physics recently entered a precision era with a variety of probes, calling for an improved understanding of interactions of cosmic rays during their propagation.
Accelerator data are much needed to complement many observations:

- Antimatter in cosmic rays ➡ background from CR interactions in the inter-stellar medium
- Gamma astronomy ➡ γ background from CR interactions
- Birth of Neutrino astronomy ➡ background from charm decays in cosmic atm. showers
- UHE CR from extensive showers in the atmosphere ➡ hadronic interactions in non-perturbative regime





AMS-02 $\overline{p}/p$ data vs model for secondary production in 2015

Giesen et al., JCAP 1509, 023

Fixed-target Physics at the LHC

Concluding slide from C. Vallée (convener of the PBC forum) at EPS 2019 (ECFA session)

CERN Physics Beyond Colliders

THE MAIN PBC MESSAGES TO THE EPPSU

FOR CERN PROJECTS

LHC Fixed-Target opens a worldwide unique domain to both SF and QGP measurements

Requires support for full exploitation of its potential on the LHC lifetime

from ESPP Update 2020

European Strategy Update

Physics Briefing Book

CERN-ESU-004
30 September 2019

Input for the European Strategy for Particle Physics Update 2020

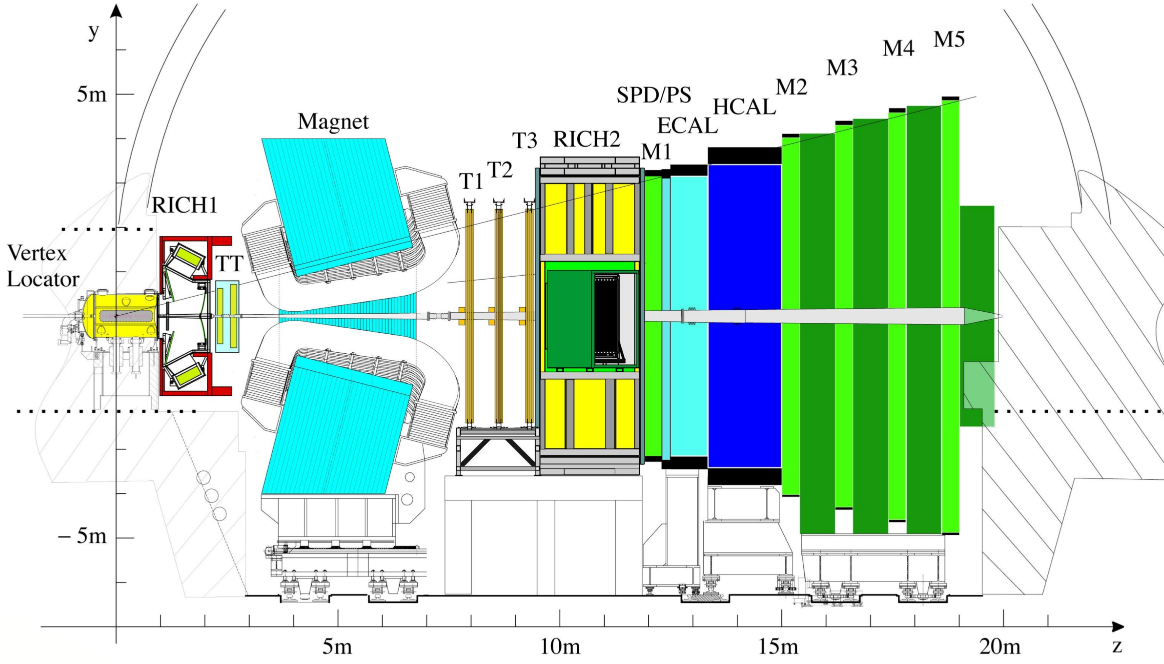
The multi-TeV LHC proton- and ion-beams allow for the most energetic fixed-target (LHC-FT) experiments ever performed opening the way for unique studies of the nucleon and nuclear structure at high x, of the spin content of the nucleon and of the nuclear-matter phases from a new rapidity viewpoint at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

The LHCb experiment

LHCb is the experiment devoted to heavy flavours in pp collisions at the LHC.



JINST 3, (2008) S08005

Int.J.Mod.Phys.A30 (2015) 1530022

Detector requirements:

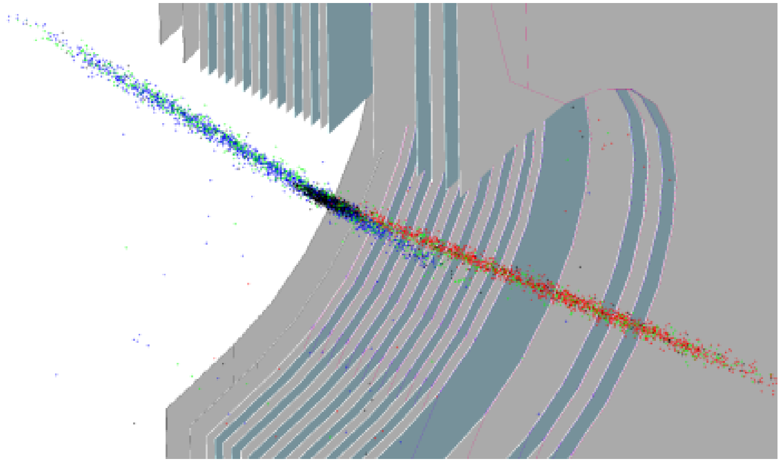
Forward geometry (pseudorap. $2 < \eta < 5$) optimises acceptance for $b\bar{b}$ pairs

Tracking : best possible proper time and momentum resolution

Particle ID : excellent capabilities to select exclusive decays

Trigger : high flexibility and bandwidth (up to 15 kHz to disk)

LHCb pioneered fixed-target physics@LHC during Run 2 thanks to SMOG



The System for Measuring Overlap with Gas

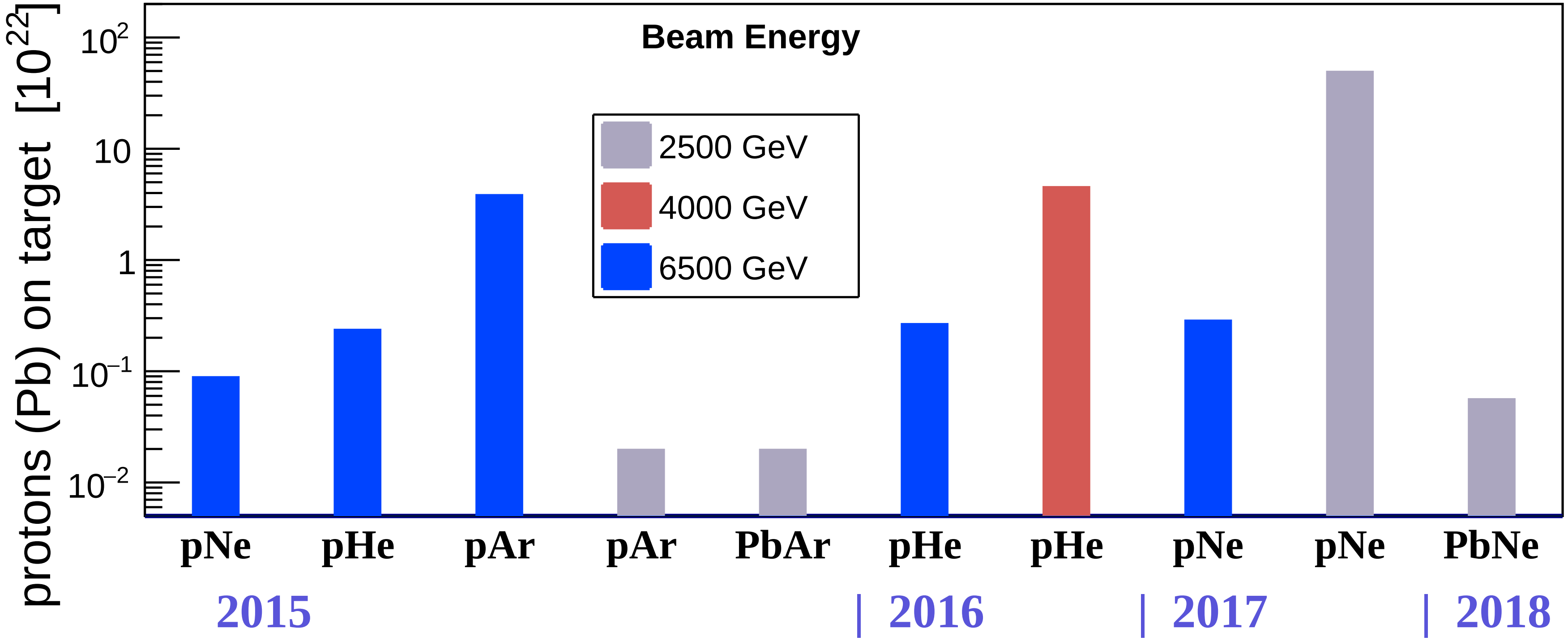
JINST 9 (2014) P12005

can inject small amount of noble gas in the LHC beam pipe around ($\sim \pm 20$ m) the LHCb collision region.

Possible targets: **He, Ne, Ar**, and more in the future

Gas pressure $\sim 2 \times 10^{-7}$ mbar ➡ $\mathcal{L} \lesssim 6 \times 10^{29}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Fixed-target Run2 datasets



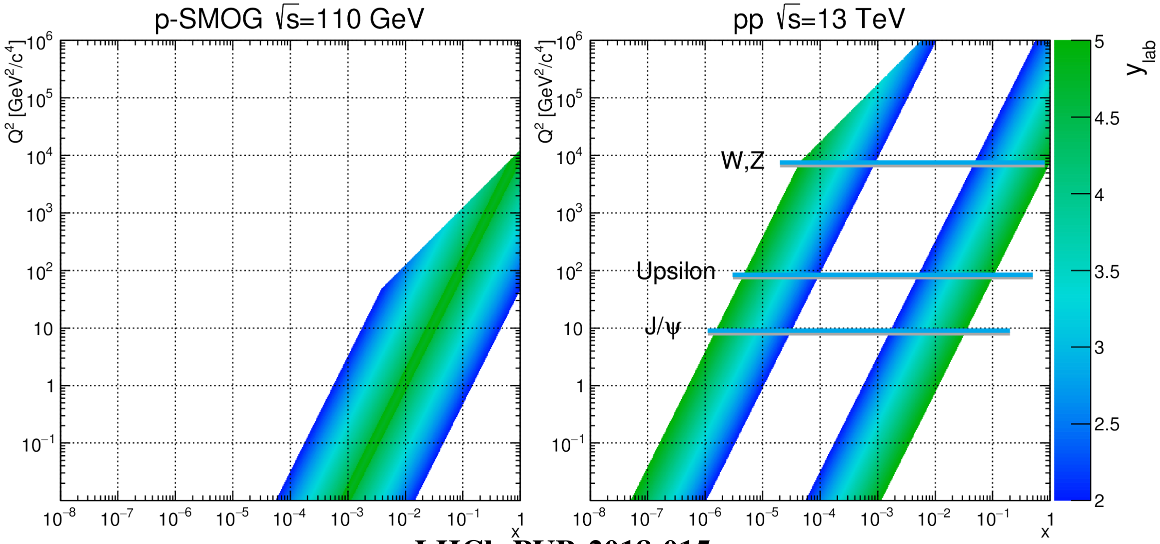
(at nominal SMOG pressure, 10^{22} POT correspond to 5/nb for 1 m of gas)

- First papers from first physics runs in 2015 and 2016
- Larger samples of pNe collisions ($\sim 100\ \mathrm{nb}^{-1}$) and PbNe collisions at same energy collected in 2017 and 2018

LHCb FT and cosmic rays

The fixed-target configuration offers some unique possibilities for hadronic/nuclear physics, with relevant applications to astroparticle physics:

- accessing **large** x region in the target, not accessible in collider mode
  ➡ charm PDF at large x, possible **intrinsic charm** contribution and nuclear effects
  Charm PDF at large x important to understand neutrino production in UHE atmospheric showers, background to emerging neutrino astronomy



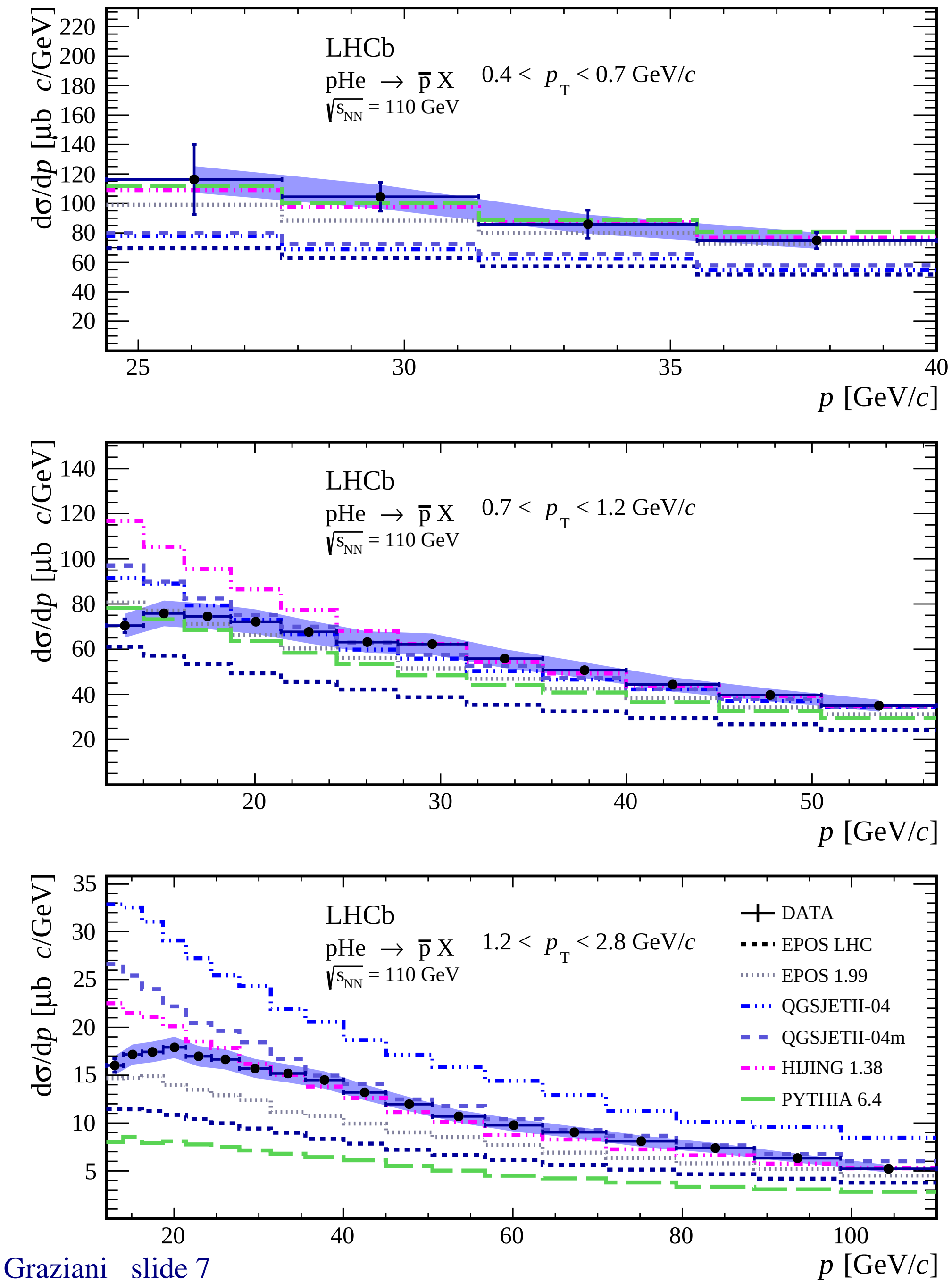
LHCb-PUB-2018-015

Several charm production results obtained from Run2 data, constraining intrinsic charm.

See Oscar Boente Garcia's talk tomorrow (heavy ion/flavour session)

- p**He collisions** (pH and pD probably possible in the future) reproduce **cosmic ray interactions in the interstellar medium** at the energy scale $\sqrt{s_{\rm NN}} \sim 100$ GeV, relevant for current experiments in space, notably for antimatter production
- p**Ne collisions** (pN and pO probably possible in the future) can provide useful measurements to understand development of UHE showers in the atmosphere

Prompt antiproton production in pHe



PRL 121 (2018), 222001

Result for **prompt** production (excluding weak decays of hyperons), compared to

EPOS LHC **PRC92 (2015) 034906**

EPOS 1.99 **Nucl.Phys.Proc.Suppl. 196 (2009) 102**

QGSJETII-04 **PRD83 (2011) 014018**

QGSJETII-04m **Astr. J. 803 (2015) 54**

HIJING 1.38 **Comp. Phys. Comm. 83 307**

PYTHIA 6.4 (2pp + 2pn) **JHEP 05 (2005) 026**

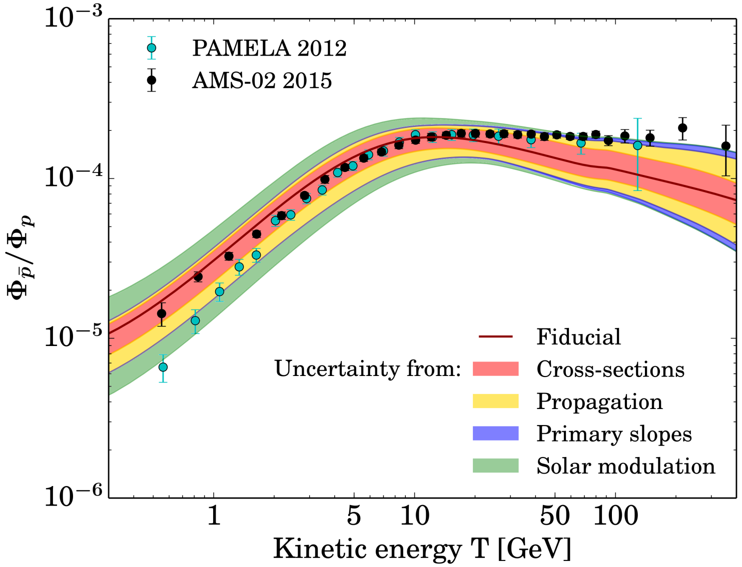
The "visible" inelastic cross section (yield of events reconstructible in LHCb) is compatible with simulation based on EPOS LHC:

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

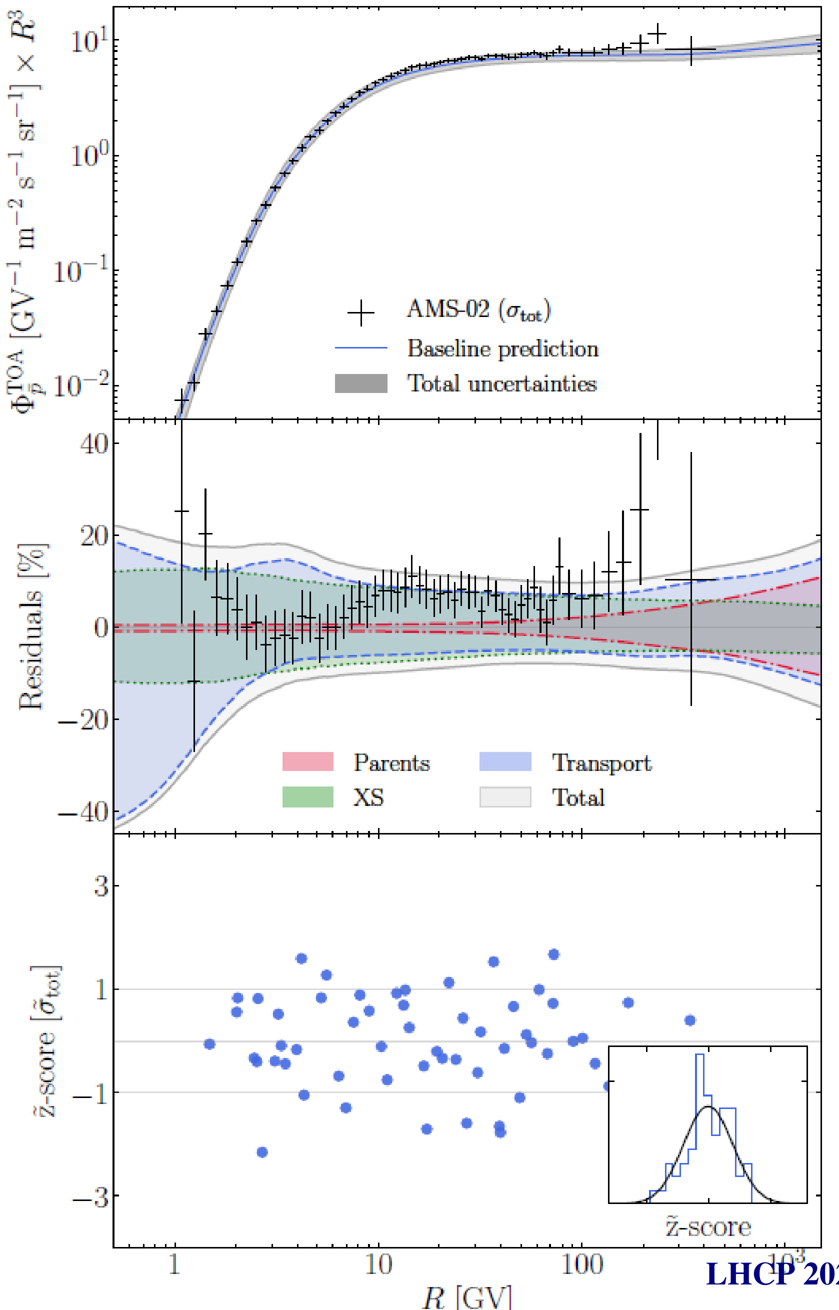
➡ excess of $\overline{p}$ yield over EPOS LHC (by factor ~ 1.5) mostly from $\overline{p}$ multiplicity

Implications for cosmic antiprotons

2015 Giesen et al., JCAP 1509, 023



2019 Boudad et al., arXiv:1906.07119



- Significant shrinking of uncertainty for the predicted secondary antiproton flux from the use of LHCb and NA61 (pp) new data (plus other improvements)
- Models now in better agreement with AMS data, notably at high energy
- Cross-section uncertainty still limiting:
  - contribution of non-prompt $\overline{p}$ (from anti-hyperons) now measured!
  - contribution of $\overline{p}$ from antineutrons (isospin violation) could be constrained using H, D targets

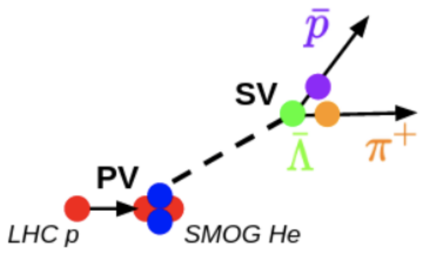
Antiprotons from antihyperons in pHe @110 GeV

LHCb-PAPER-2022-006, accepted by EPJC

- Analysis recently extended to detached $\overline{p}$ from anti-hyperon decays
- Two complementary approaches followed

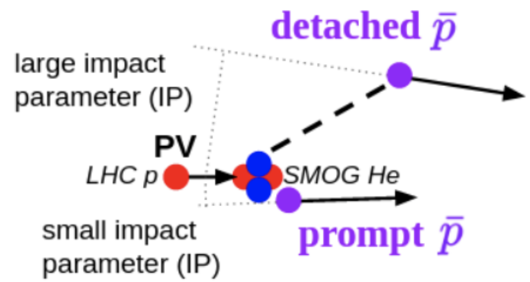
Exclusive approach

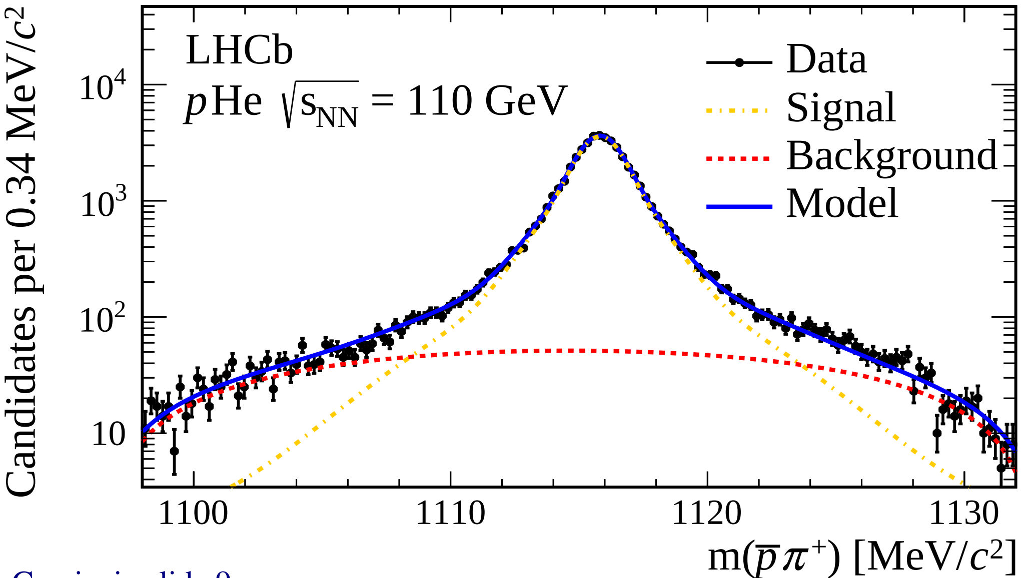
$$R_{\bar{\Lambda}} = \frac{\sigma(p\mathrm{He} \to (\bar{\Lambda}_{\mathrm{prompt}} \to \bar{p}\pi^+)X)}{\sigma(p\mathrm{He} \to \bar{p}_{\mathrm{prompt}}\, X)}$$

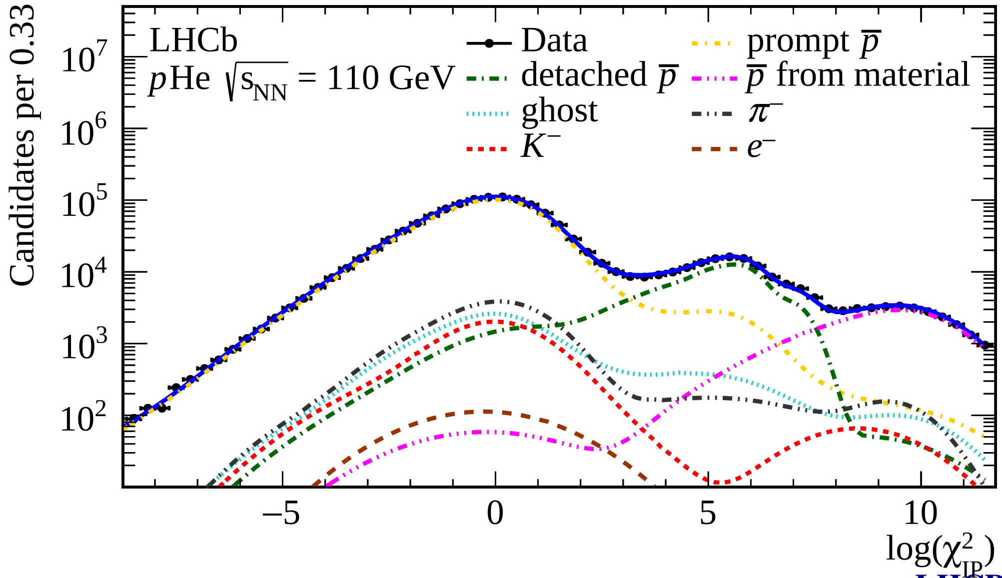


Inclusive approach

$$R_{\bar{H}} \equiv \frac{\sigma(p\mathrm{He} \to \bar{H}X \to \bar{p}X)}{\sigma(p\mathrm{He} \to \bar{p}_{\mathrm{prompt}} X)} \qquad \bar{H} = \bar{\Lambda}, \bar{\Sigma}, \bar{\Xi}, \bar{\Omega}$$





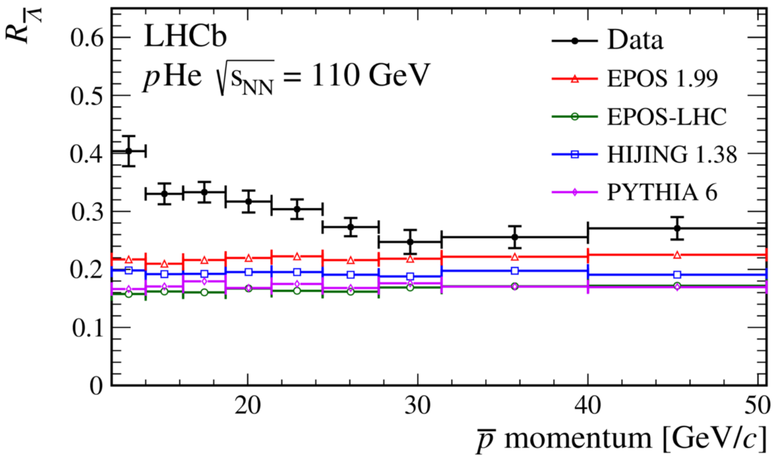


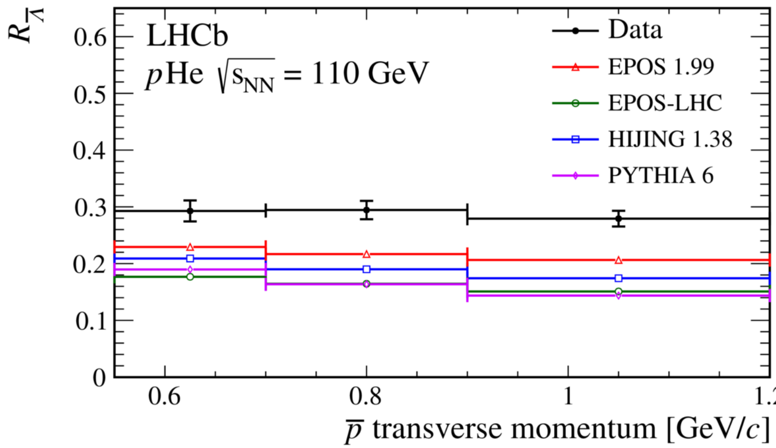
Detached Antiprotons in pHe: results

LHCb-PAPER-2022-006, accepted by EPJC

Exclusive approach

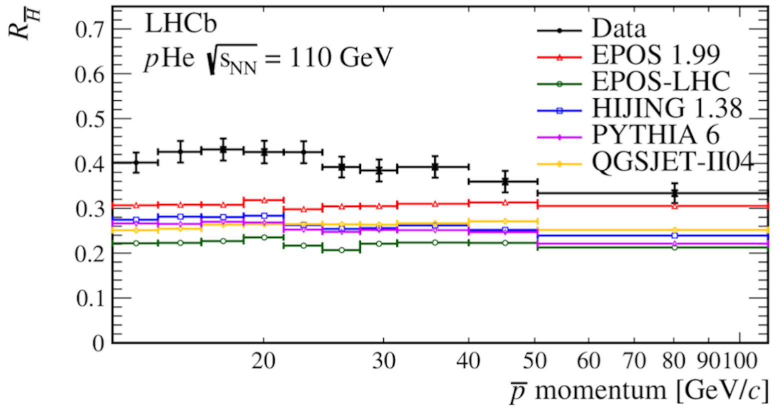
$$R_{\bar{\Lambda}} = \frac{\sigma(p\text{He} \to (\bar{\Lambda}_{\text{prompt}} \to \bar{p}\pi^+)X)}{\sigma(p\text{He} \to \bar{p}_{\text{prompt}}\, X)}$$

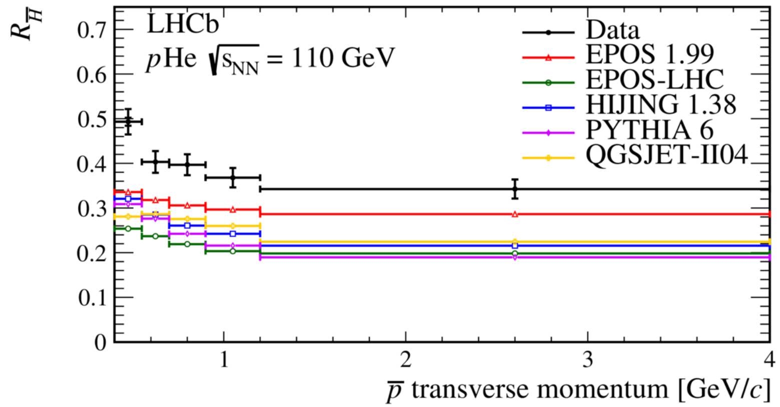




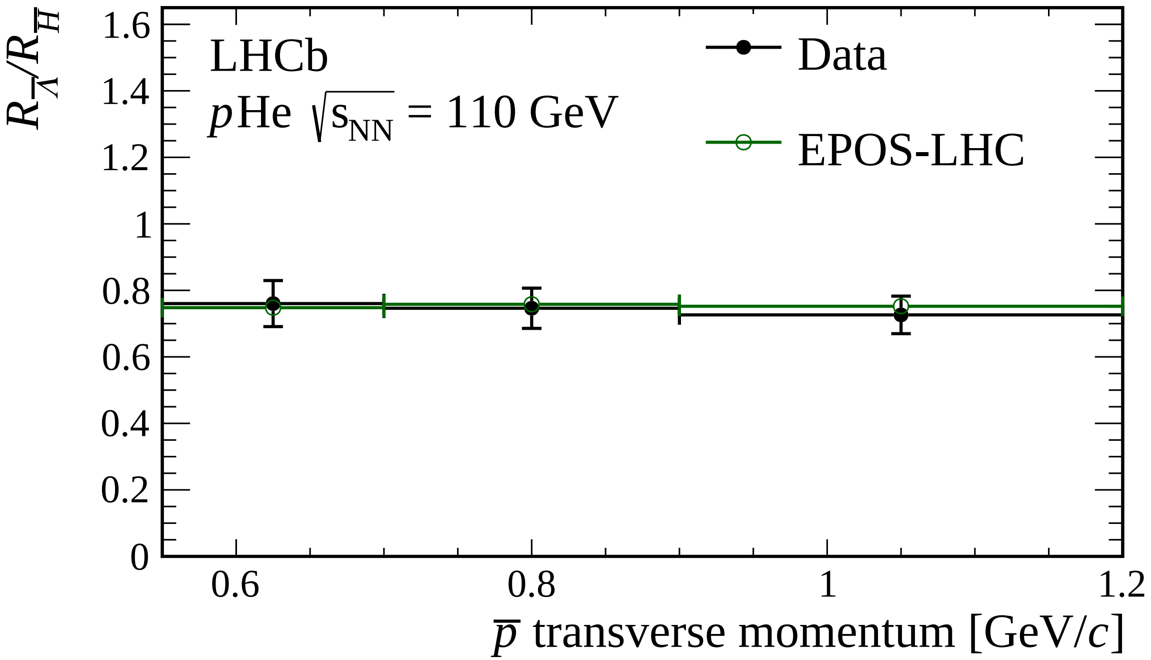
Inclusive approach

$$R_{\bar{H}} \equiv \frac{\sigma(p\text{He} \to \bar{H}X \to \bar{p}X)}{\sigma(p\text{He} \to \bar{p}_{\text{prompt}}X)} \quad \bar{H} = \bar{\Lambda}, \bar{\Sigma}, \bar{\Xi}, \bar{\Omega}$$



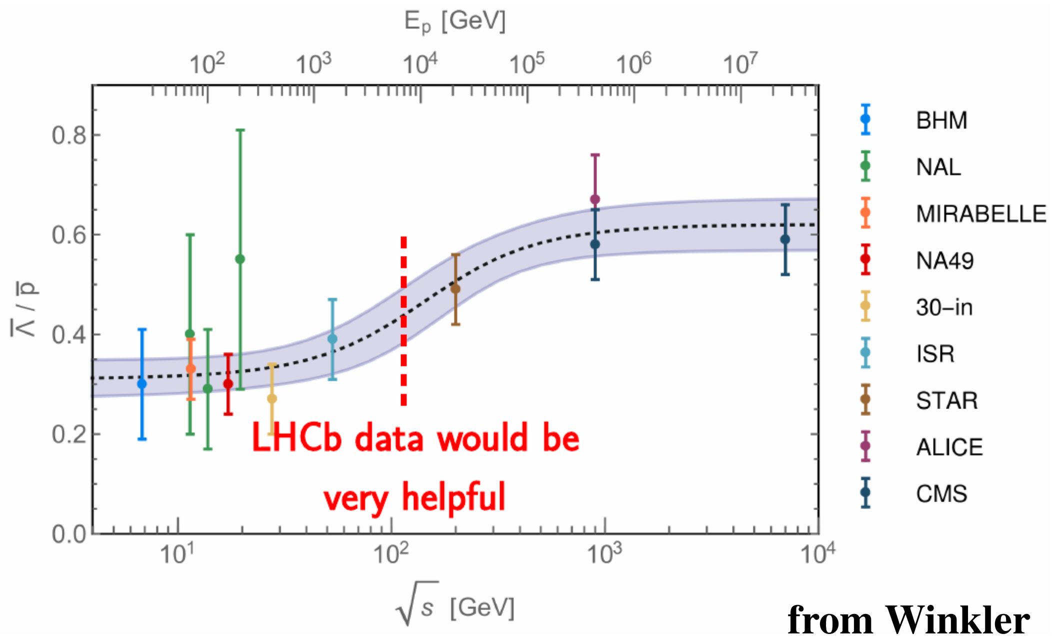


Both approaches indicate larger antihyperon production than predicted by most commonly used hadronic models



- Nice agreement of the excl.$\overline{\Lambda}$/incl.antihyperon ratio with theoretical expectations

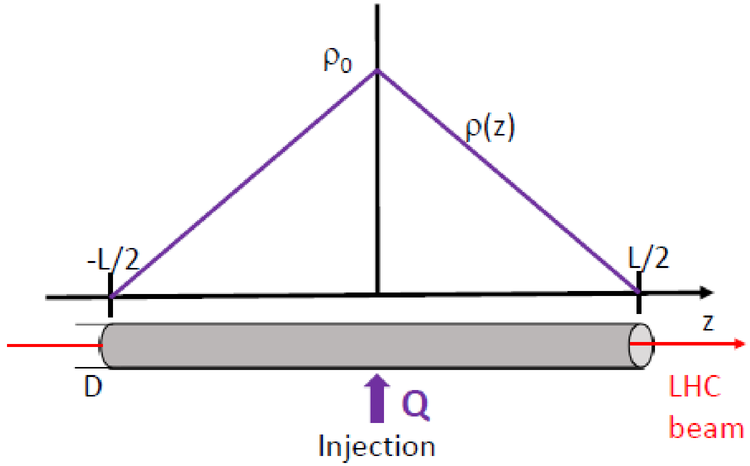
- Precise results at 100 GeV scale, at the onset of strangeness enhancement (observed at colliders)
- Significant dependence on kinematics observed (usually neglected in cosmic secondary $\overline{p}$ calculations)

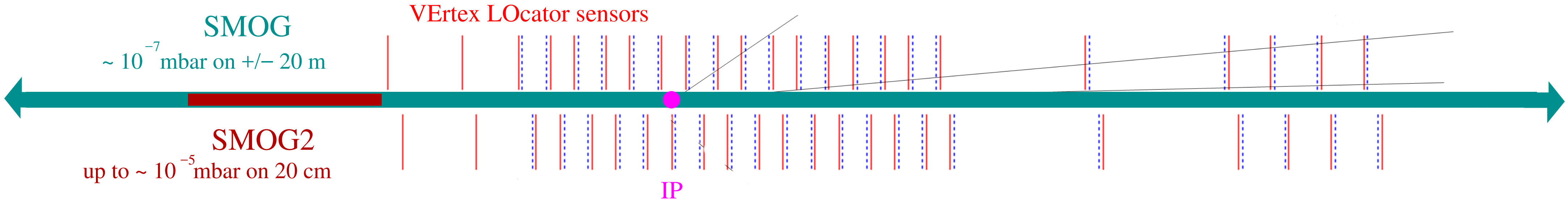


from Winkler

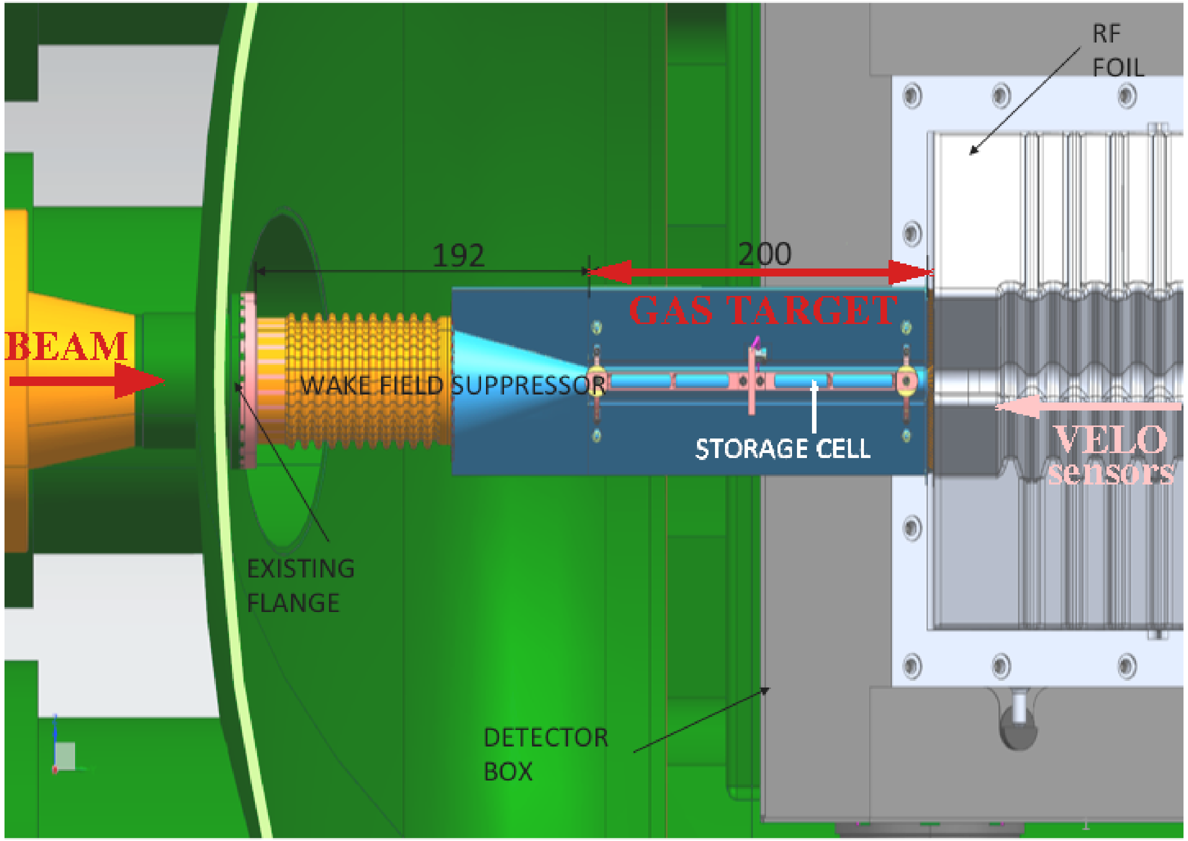
The gas target upgrade

- Major LHCb detector upgrade for the LHC Run 3, including upgraded VErtex LOcator (microstrip $\rightarrow$ pixel)
- The new VELO integrates a new fixed target device SMOG2, based on a storage cell:
  - increase effective luminosity with same gas flow
  - possibly inject other gas species, as **H**, **D**, **N**, **O**, Kr, Xe
  - precise control of the gas density (improved accuracy on luminosity determination)
  - spatial separation between beam-gas and beam-beam collision regions
    ➡ easier **simultaneous data-taking**





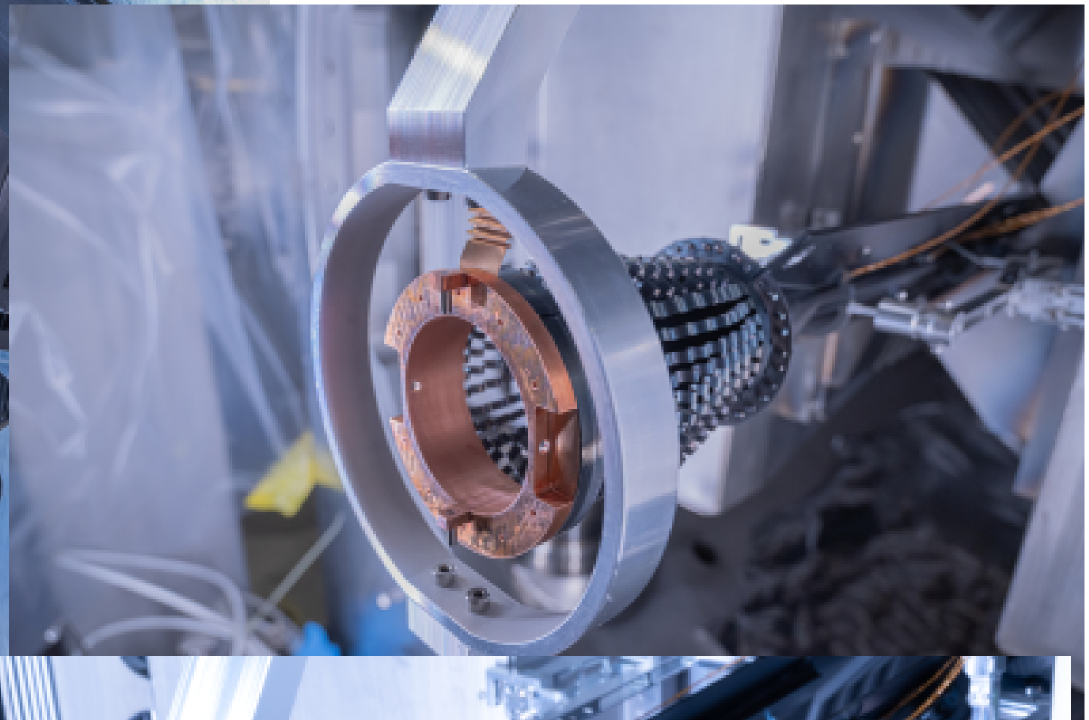
The SMOG2 gas target



- TDR approved by LHCC in 2019 **CERN-LHCC-2019-005l**
- Installed in the LHCb cavern on august 2020

- 20-cm long storage cell, 5 mm radius around the beam, just up-stream the LHCb VErtex LOcator
- Made of two rectractable halves as the rest of VELO
- Up to x100 higher gas density with same gas flow of current SMOG
- Gas density measured with $\sim$ 2% accuracy via Gas Feed System
- Fast switch between gas species

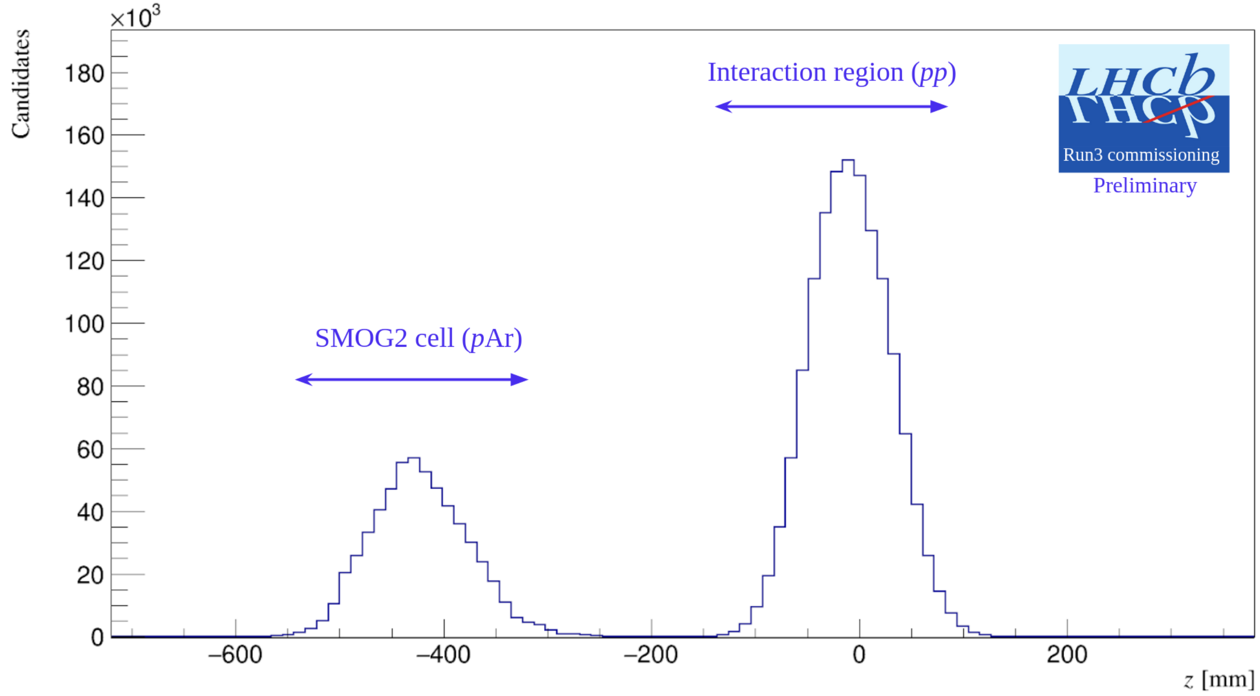
SMOG2 installation

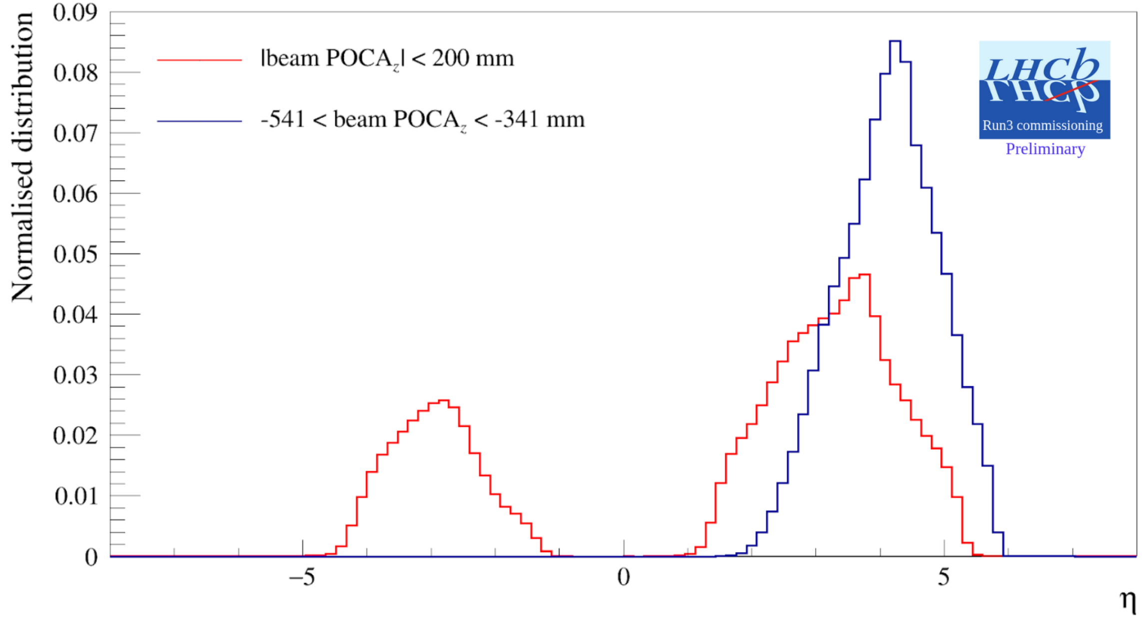


https://cds.cern.ch/record/2727007

First SMOG2 operations in 2022

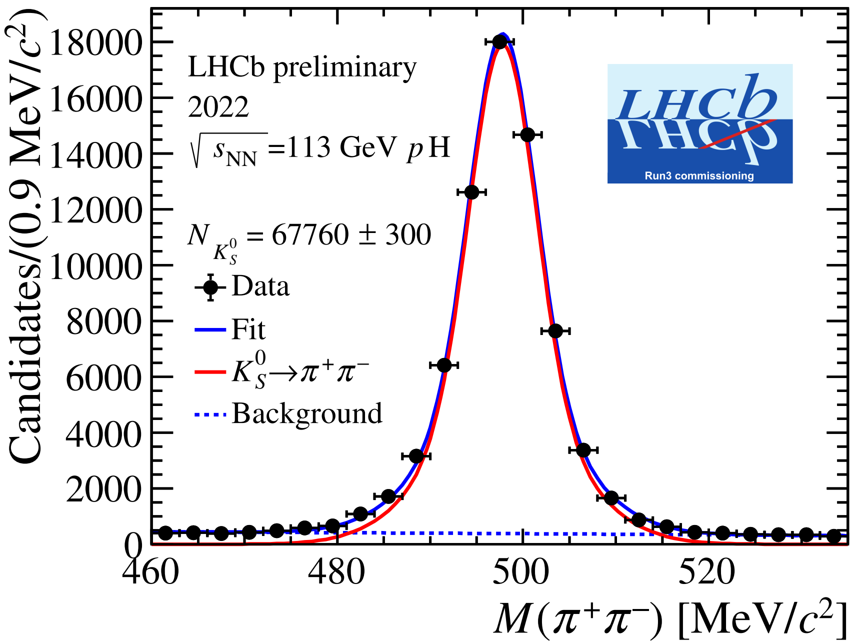
- 2022 has been a commisioning year for the upgraded LHCb detector
- SMOG2 has been succesfully tested with 4 gas species (**H**, He, Ne, Ar)
- first reconstructed primary vertices of simultaneous beam-gas and beam-beam collisions, obtained online through novel Real Time Reconstruction fully software trigger

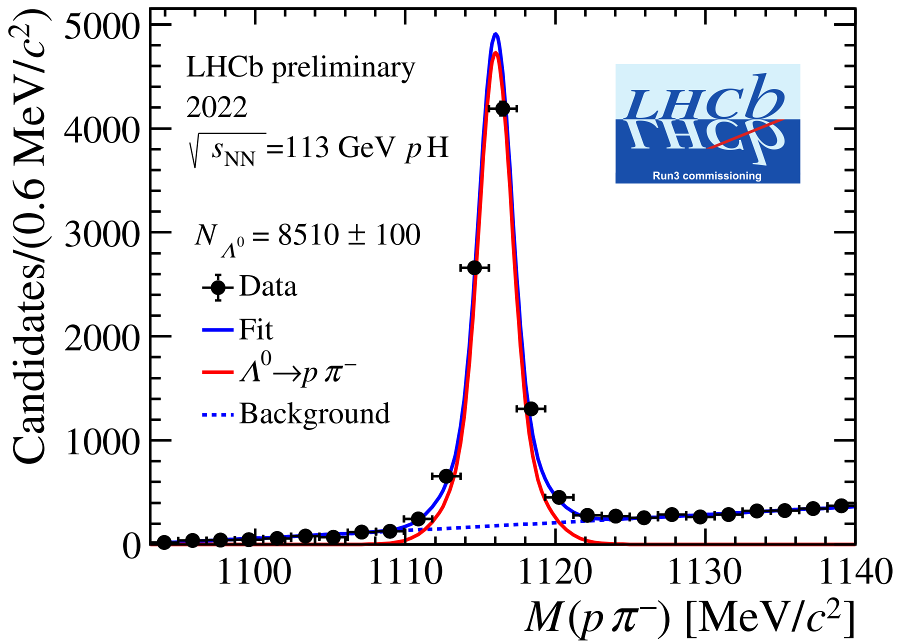




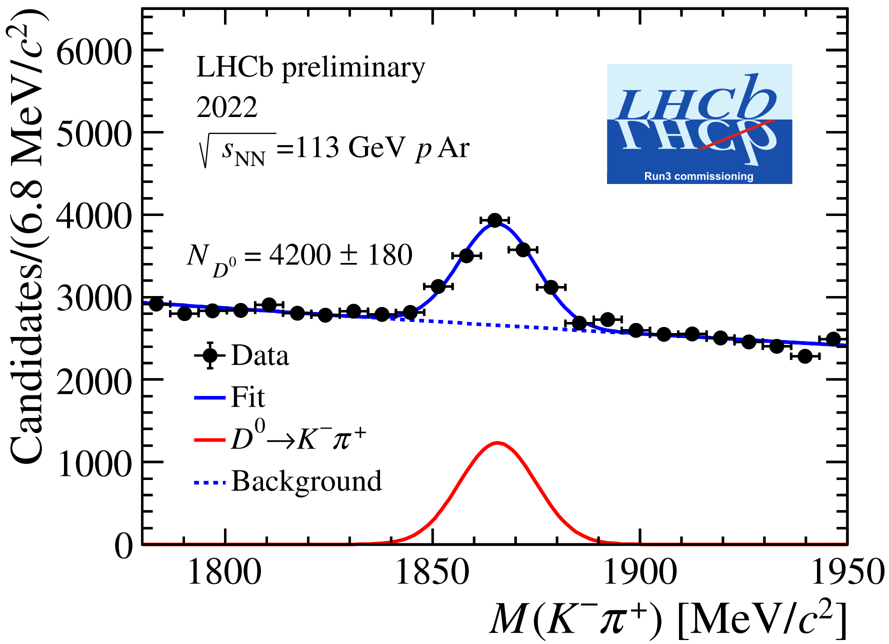
Physics signals in SMOG2 commissioning data!

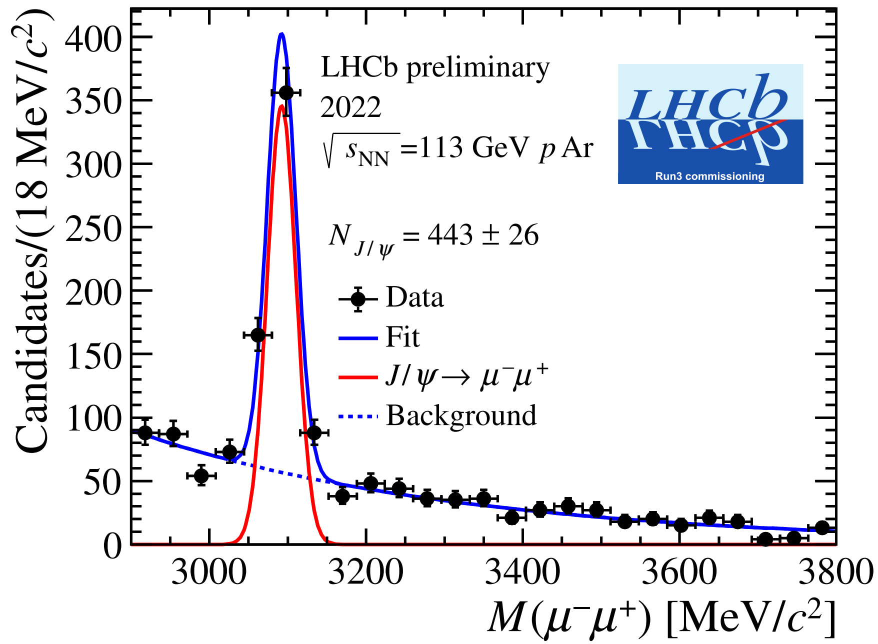
pH
20’ run!





pAr
18’ run!

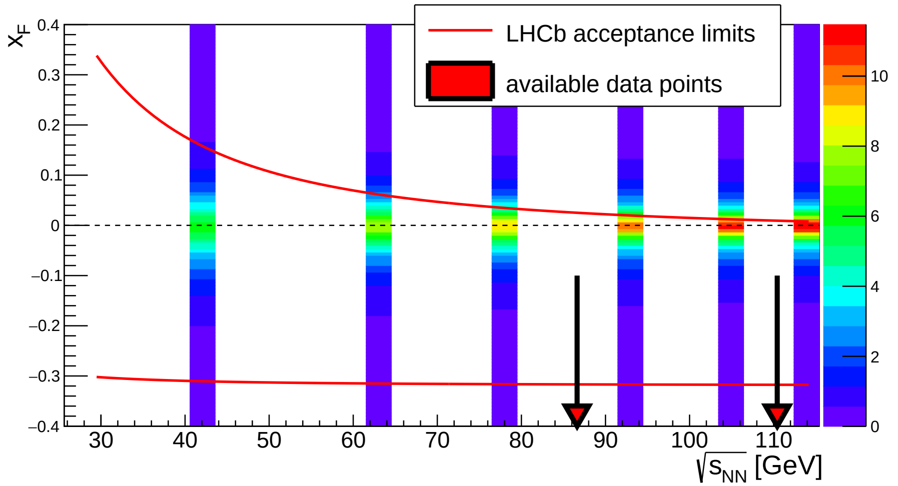




Prospects for Cosmic Rays with SMOG2

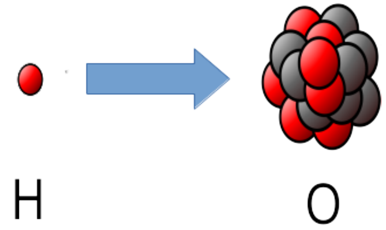
LHCB-PUB-2018-015

- Possibility to complete the cosmic $\overline{p}$ study:
  H target to also measure $pp \to \overline{p}X$ and ratios with pHe
  D target to test isospin violation (relevant for antineutron production)
  Data at lower energy to measure evolution with energy (scaling violations) and access forward region (Feynman-$x > 0$). LHCb requested to the machine a special run at injection energy with squeezed beams (mandatory to close the vertex detector)

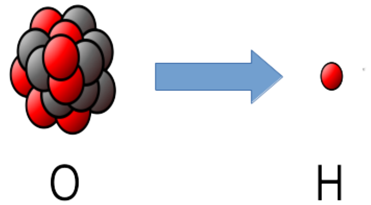


Feynman-x distribution for $\overline{p}$ vs $\sqrt{s_{\rm NN}}$ and accessible region to LHCb

- Possibility to inject Oxygen and Nitrogen to reproduce collisions in atmospheric showers at $\sqrt{s_{\rm NN}} = 113$ GeV and $-2.8 \lesssim y^* \lesssim 0.2$

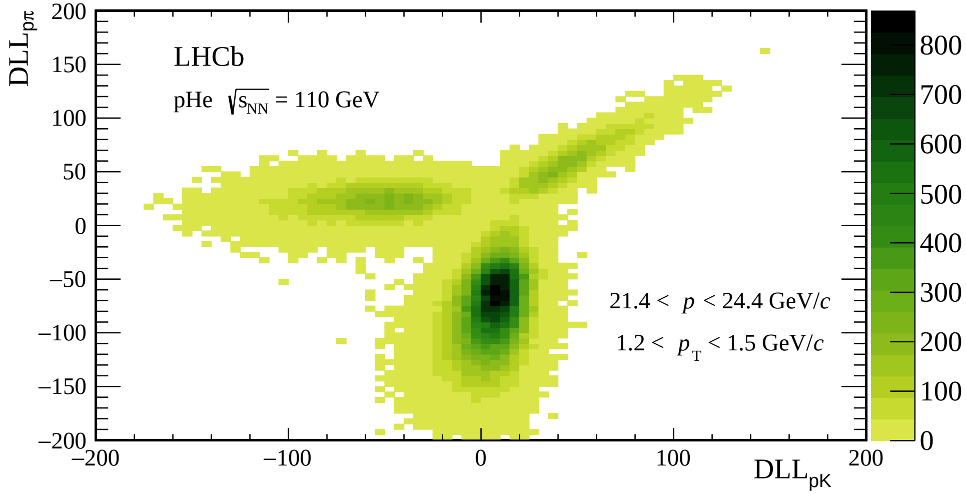


- During the oxygen-oxygen run (foreseen in 2024), inject hydrogen to measure proton on oxygen at $\sqrt{s_{\rm NN}} = 80$ GeV and $-0.5 \lesssim y^* \lesssim 2.5$

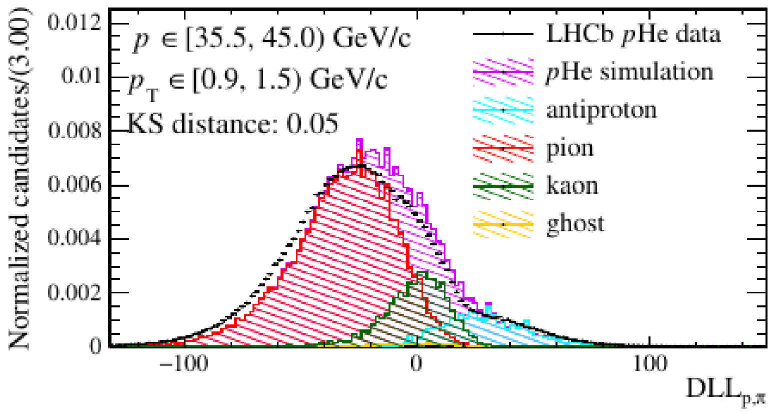


... and more with SMOG

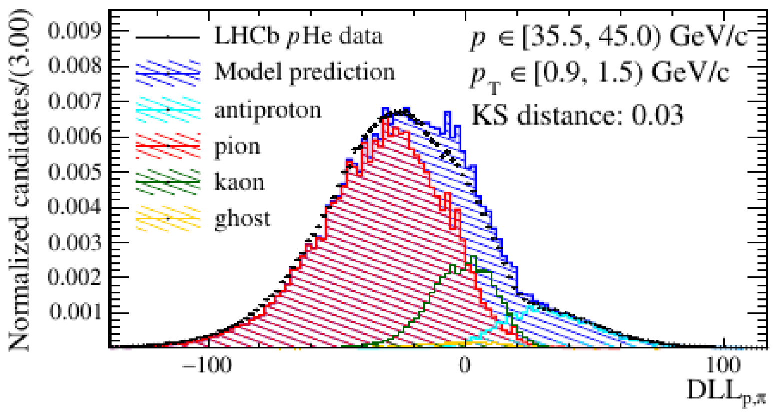
- Measure production of π, K, p from the various SMOG samples (He, Ne, Ar targets).



MC-driven model



Data-driven model



Specific ML-based tools have been developed to model the PID response in fixed-target data

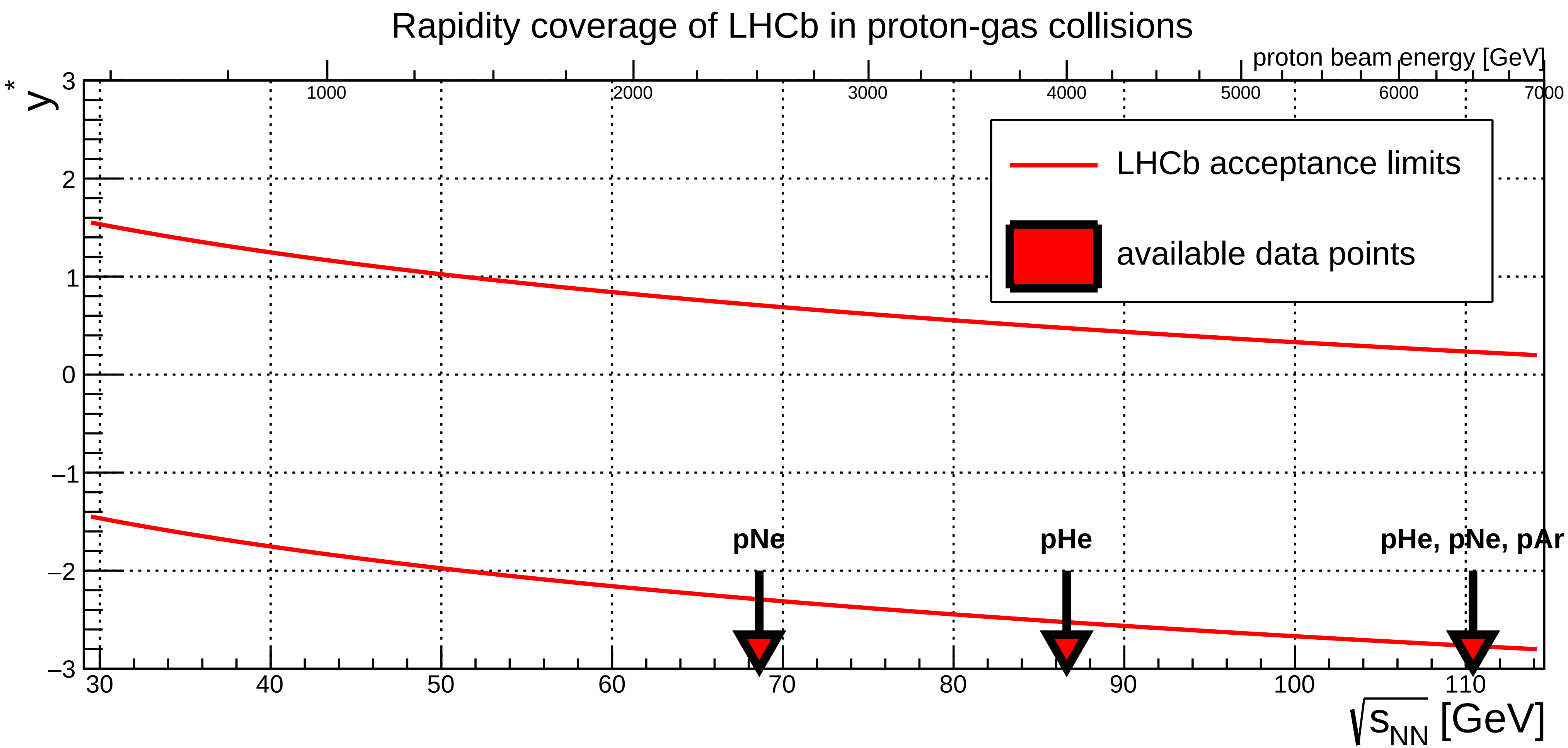
JINST 17 P02018 (2021)

- antiproton study in pHe data at 4 TeV beam energy ($\sqrt{s_{\mathrm{NN}}}$ =86 GeV)
- Effort ongoing to study production of light (anti)nuclei (D, He3) exploiting some "unplanned" dE/dx and TOF capabilities of the Run2 detector
  ➡ study coalescence at the $\sqrt{s_{\mathrm{NN}}} \sim 100$ GeV scale, relevant to AMS

Bright near future for
the LHCb "Space mission"

Additional Material

Fixed Target Acceptance



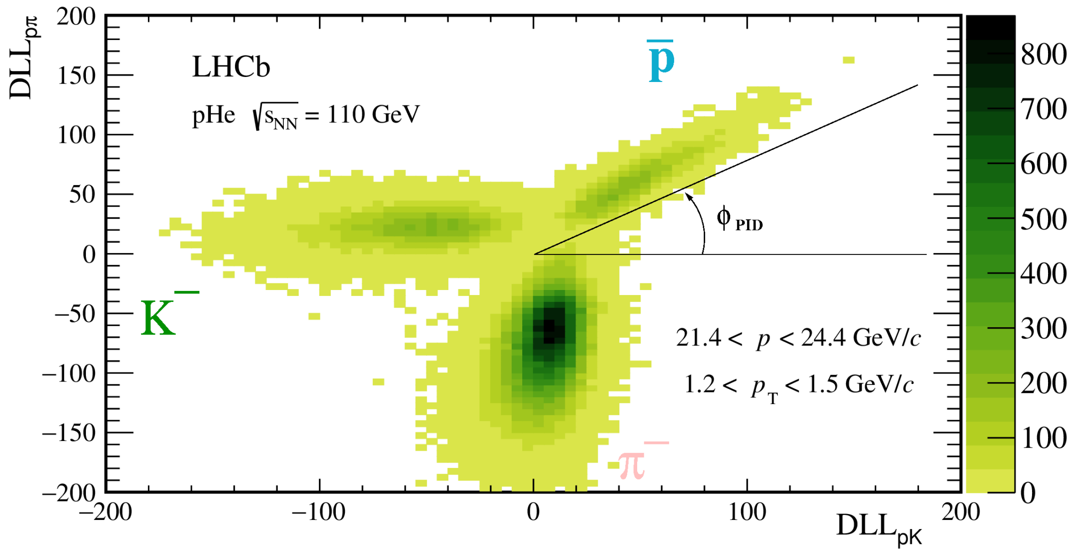
Antiprotons from pHe collisions

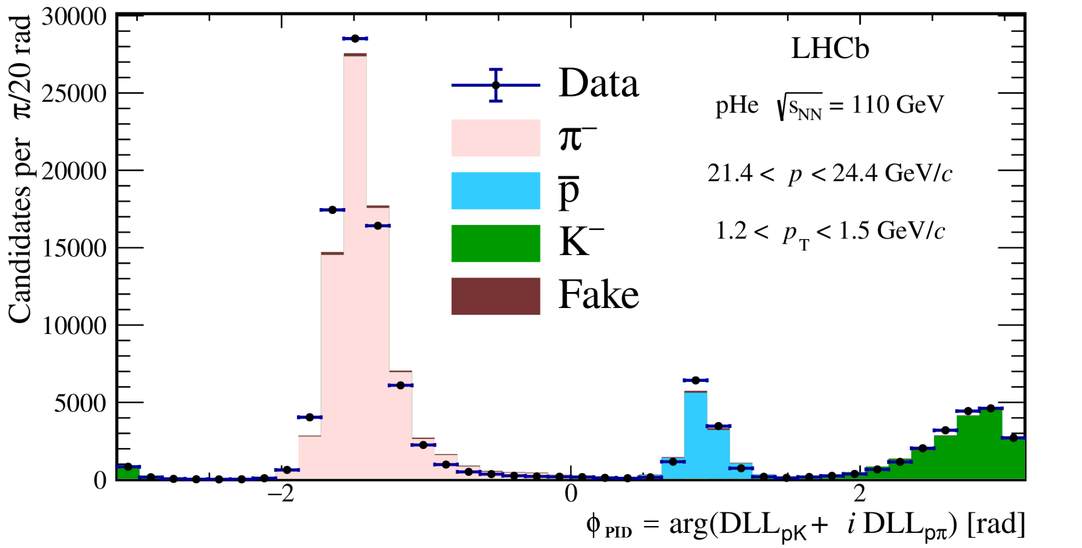
PRL 121 (2018), 222001

- First measurement of $p\text{He} \to \bar{p}X$ cross-section, the process accounts for $\sim 40\%$ of secondary cosmic $\bar{p}$
- Data collected in May 2016, with proton energy 6.5 TeV, $\sqrt{s_{\text{NN}}} = 110$ GeV, mostly from a single LHC fill (5 hours)
- Minimum bias trigger, fully efficient on candidate events
- Exploit **excellent particle identification** (PID) capabilities in LHCb to count antiprotons in $(p,\, p_{\text{T}})$ bins within the kinematic range

$$12 < p < 110\,\text{GeV}/c, \quad p_{\text{T}} > 0.4\,\text{GeV}/c$$

  (good match with PAMELA/AMS-02 capabilities)
- Exploit excellent vertexing capabilities to select **prompt production**.
  (anti-hyperon component will be measured in a dedicated analysis)

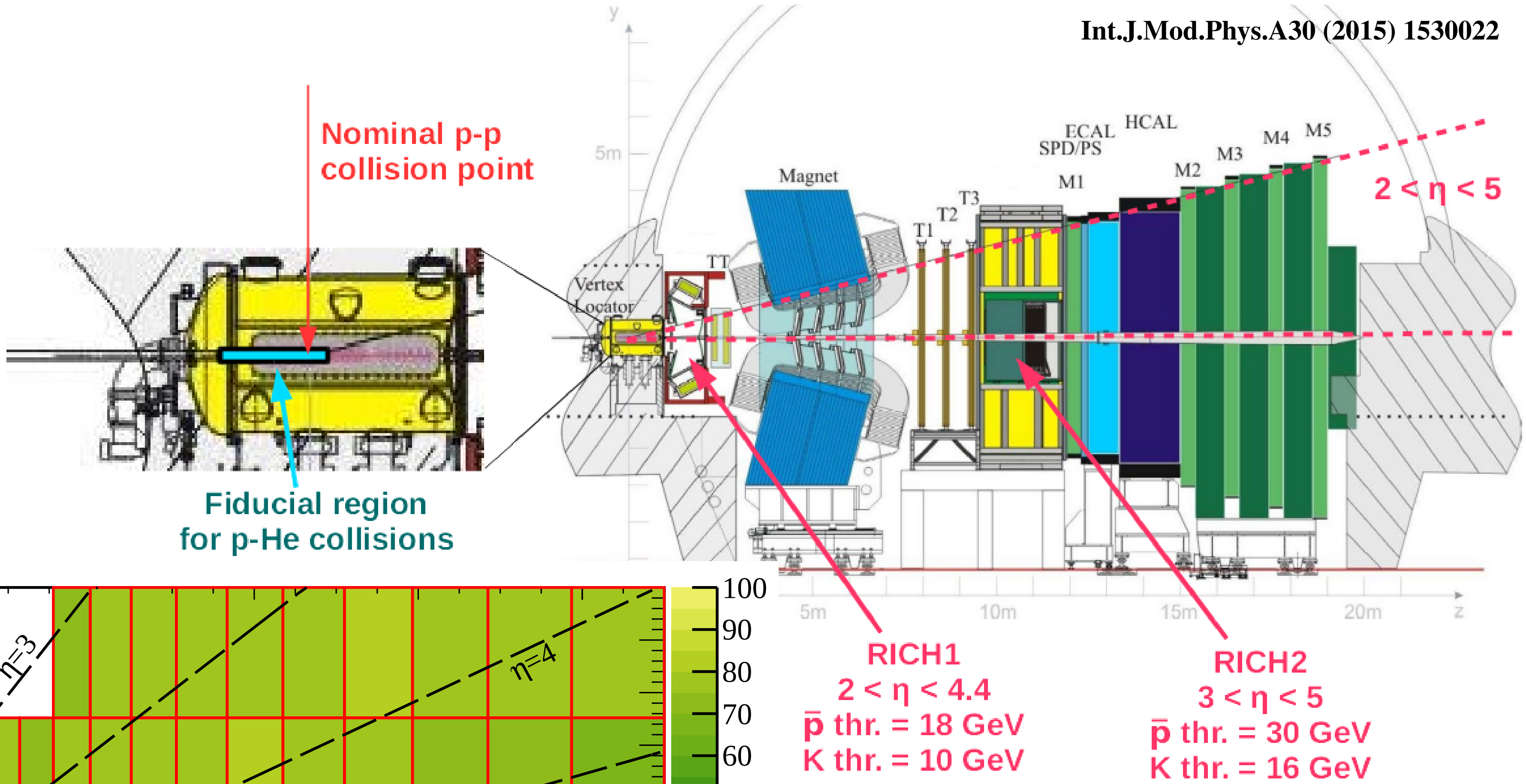


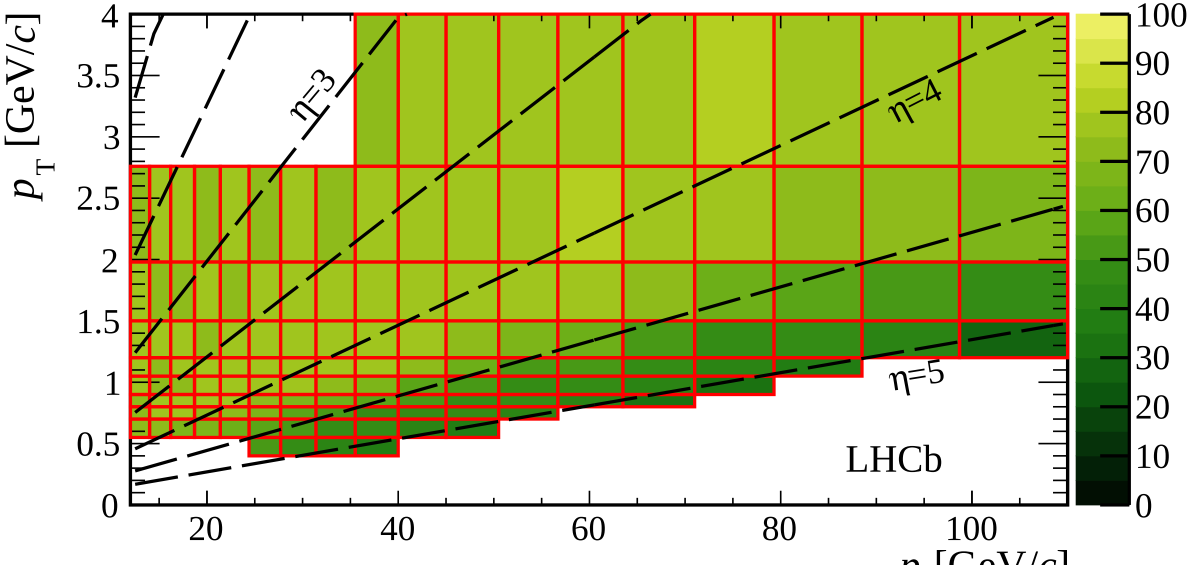


Acceptance for antiprotons in pHe collisions

JINST 3, (2008) S08005

Int.J.Mod.Phys.A30 (2015) 1530022





PRL 121 (2018), 222001

Acceptance × reconstruction efficiency for antiprotons

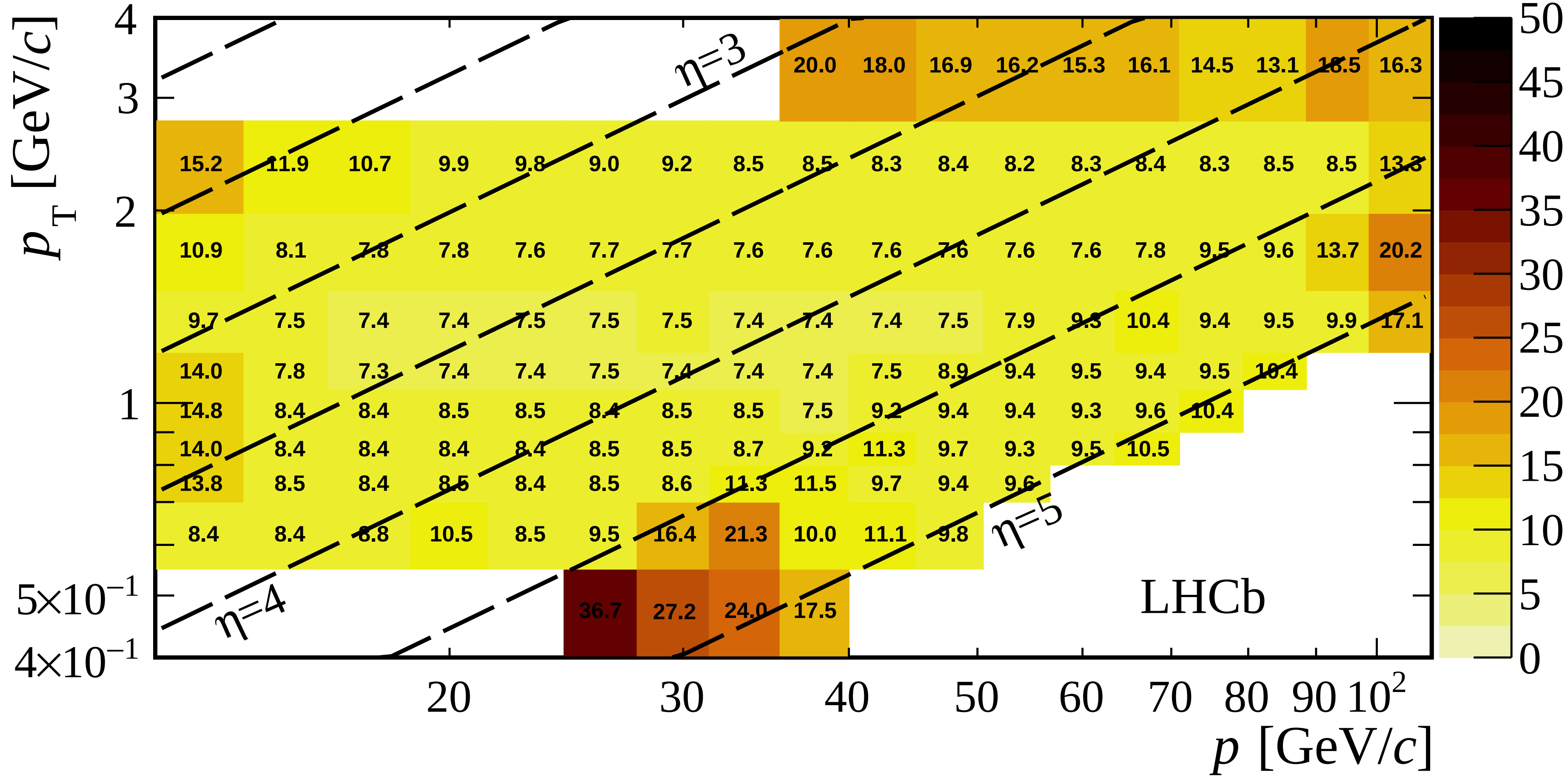
Rapidity in c.m.s. system:

$$y^* \sim -2.8 \text{ - } 0.2$$

x-Feynman $\frac{2p_L^*}{\sqrt{s_{NN}}} \sim -0.25 \text{ - } 0.$

$p\mathrm{He} \to \bar{p}X$: relative uncertainty per bin (in per cent)

PRL 121 (2018), 222001



- Dominated by systematics
- Largest correlated uncertainty is the 6% from luminosity
- Largest uncorrelated uncertainty from PID analysis

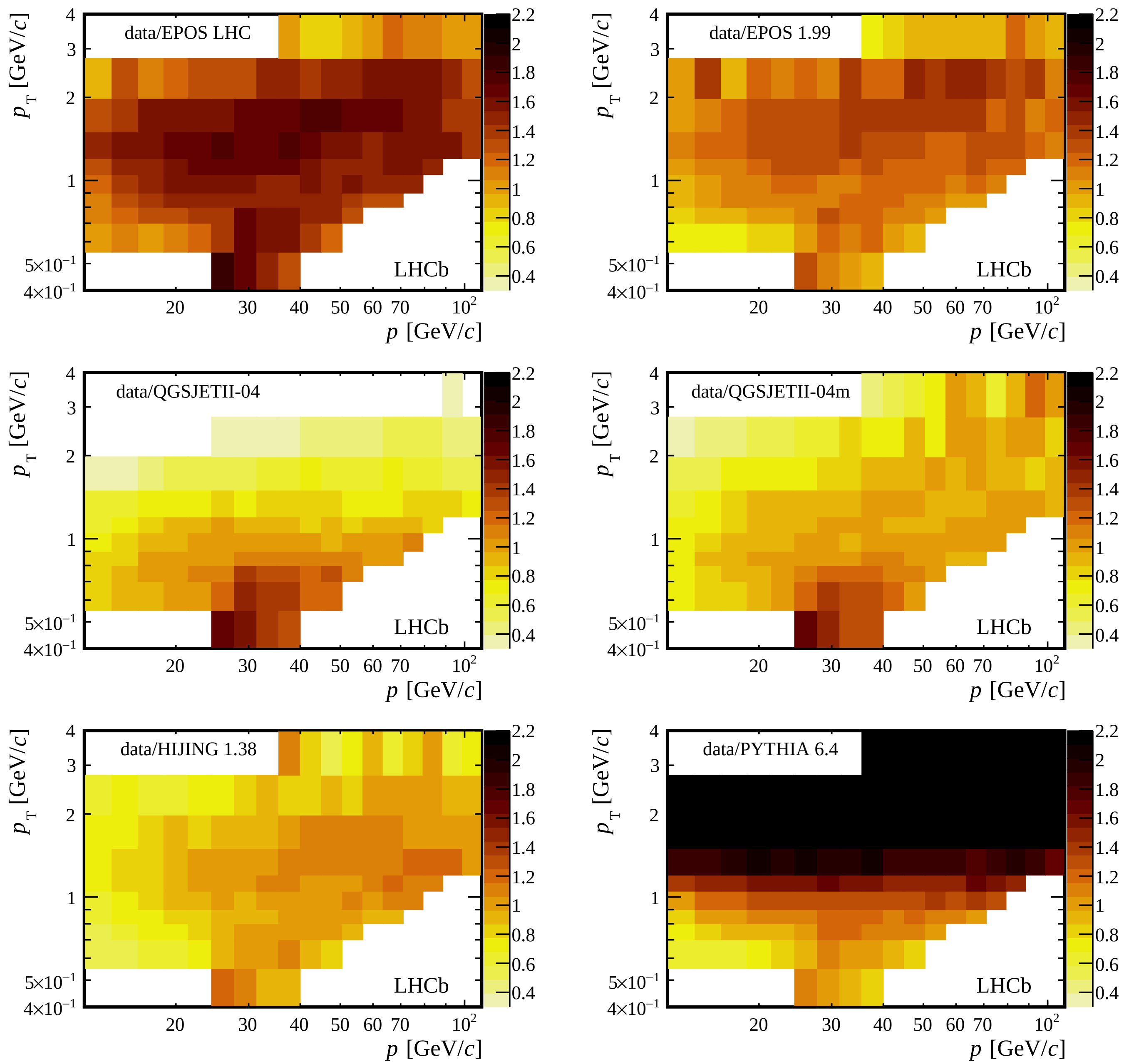
pHe $\rightarrow \overline{p}X$ result: uncertainties (relative)

PRL 121 (2018), 222001

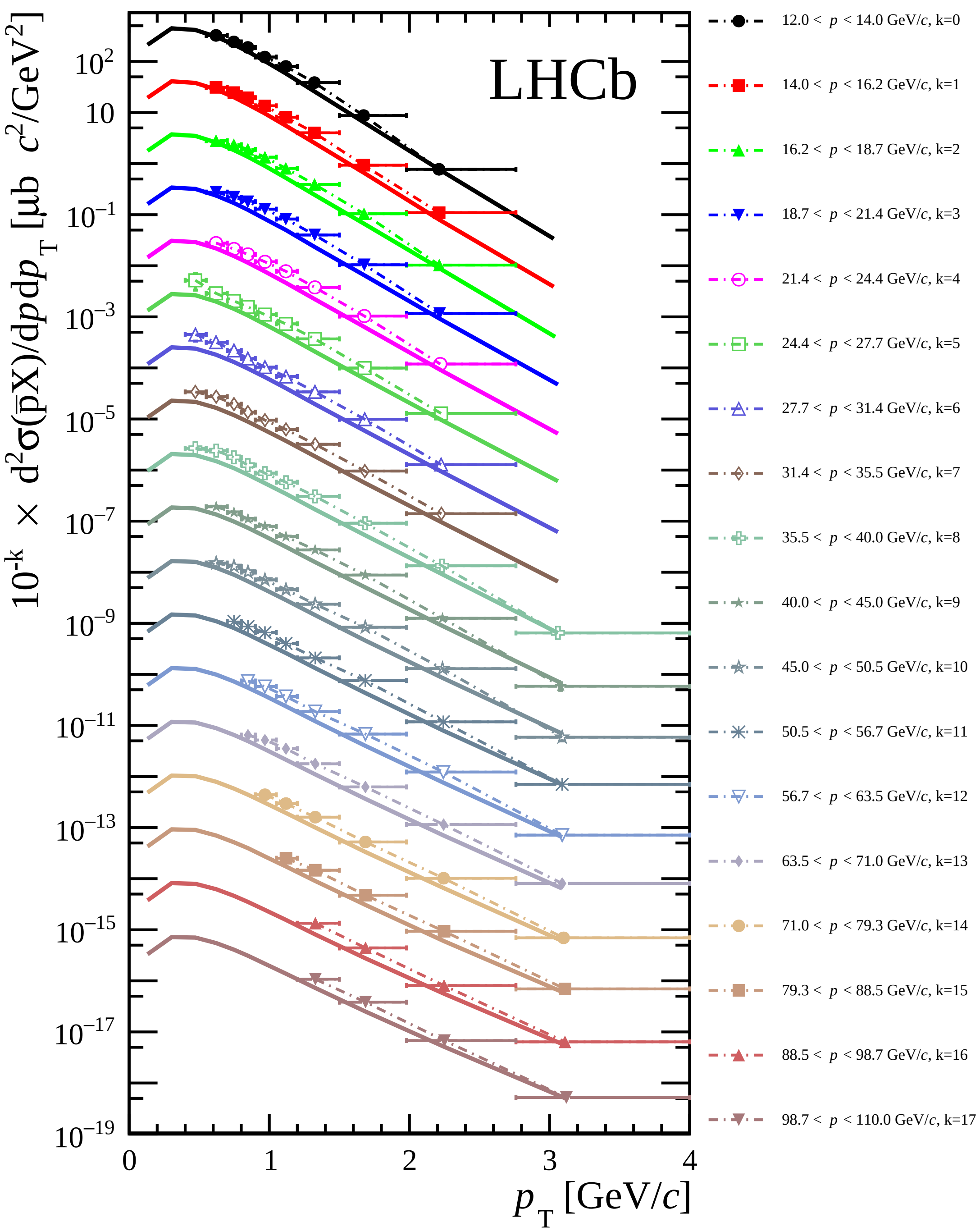
Statistical	
$\overline{p}$ yields	$0.5 - 11\%$ ($< 2\%$ for most bins)
Luminosity	$1.5 - 2.3\%$
Correlated systematic	
Luminosity	6.0%
Event and PV selection	0.3%
PV reconstruction	$0.4 - 2.9\%$
Tracking	$1.3 - 4.1\%$
Non-prompt background	$0.3 - 0.5\%$
Target purity	0.1%
PID	$3.0 - 6.0\%$
Uncorrelated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

pHe $\to \bar{p}X$ result: comparison with models

PRL 121 (2018), 222001



$\bar{p}$ production in pHe @ 110 GeV

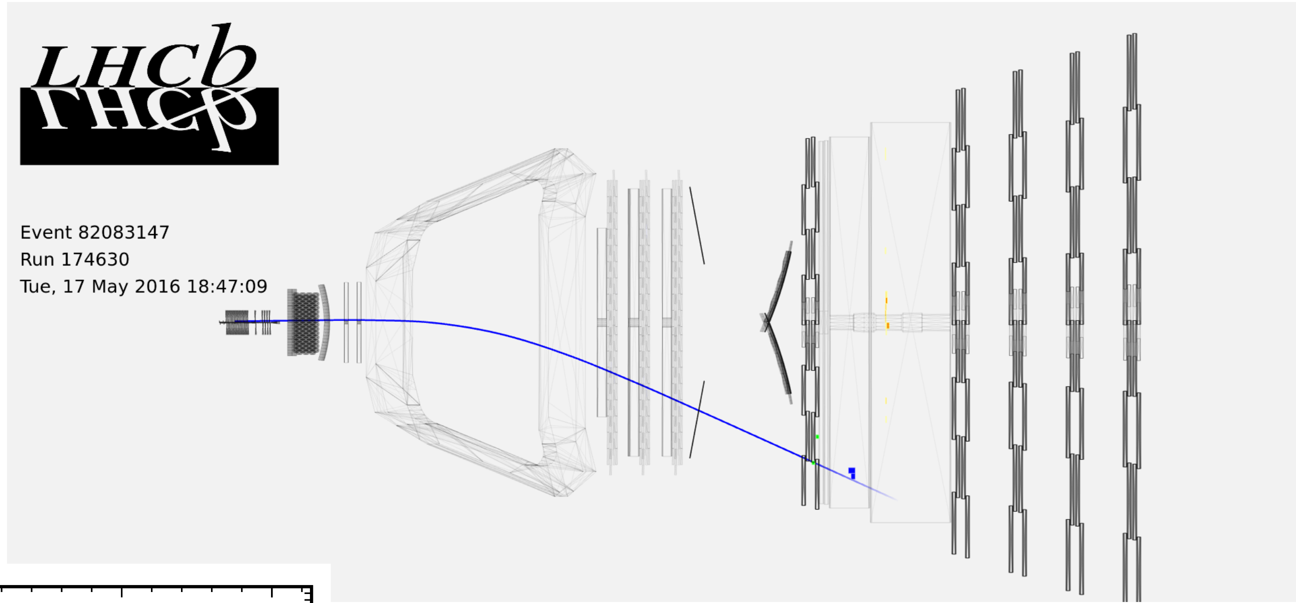


Data
(points with error bars)
vs
EPOS LHC (curves)

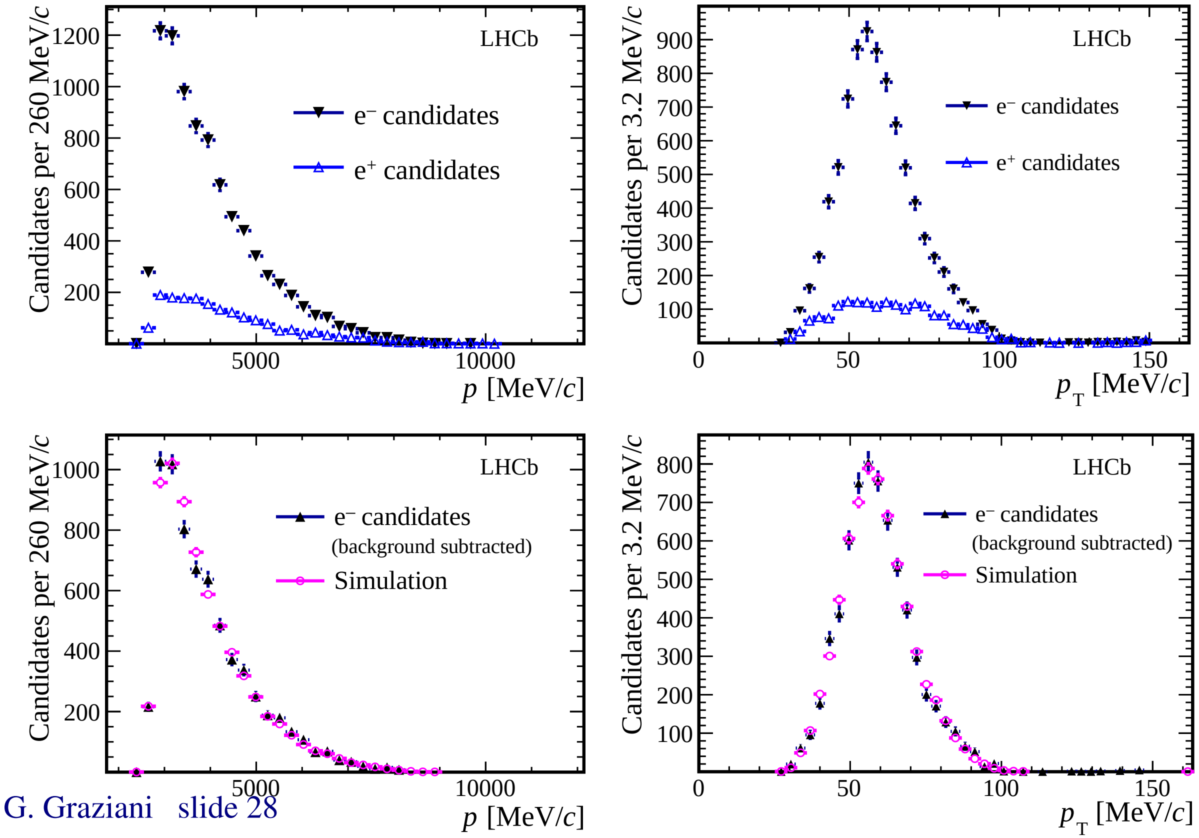
PRL 121 (2018), 222001

Fixed-target Luminosity

PRL 121 (2018), 222001



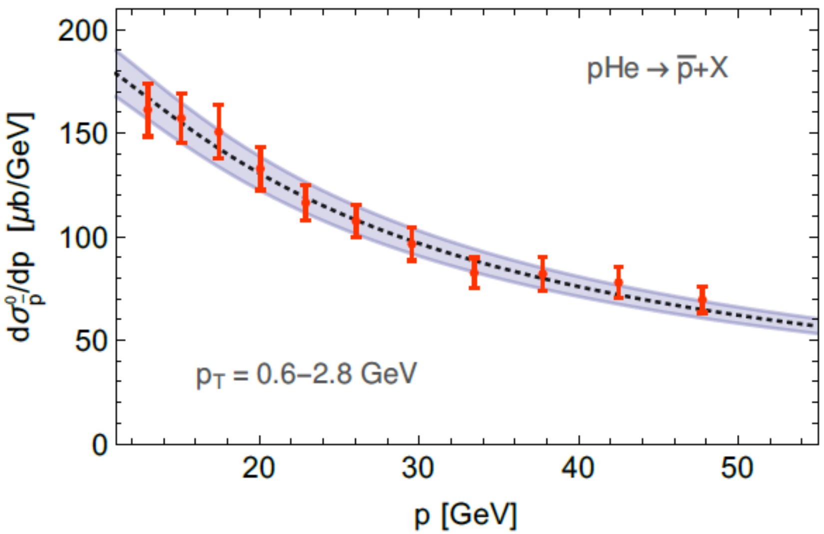
- SMOG gas pressure not precisely known. Absolute cross sections normalized to $p\,e^-$ elastic scattering



- Background measured from data, using events with single positive track
- Systematic uncertainty of 6%, due to low electron reconstruction efficiency ($\sim 16\%$)

Implications of LHCb results for cross section scaling

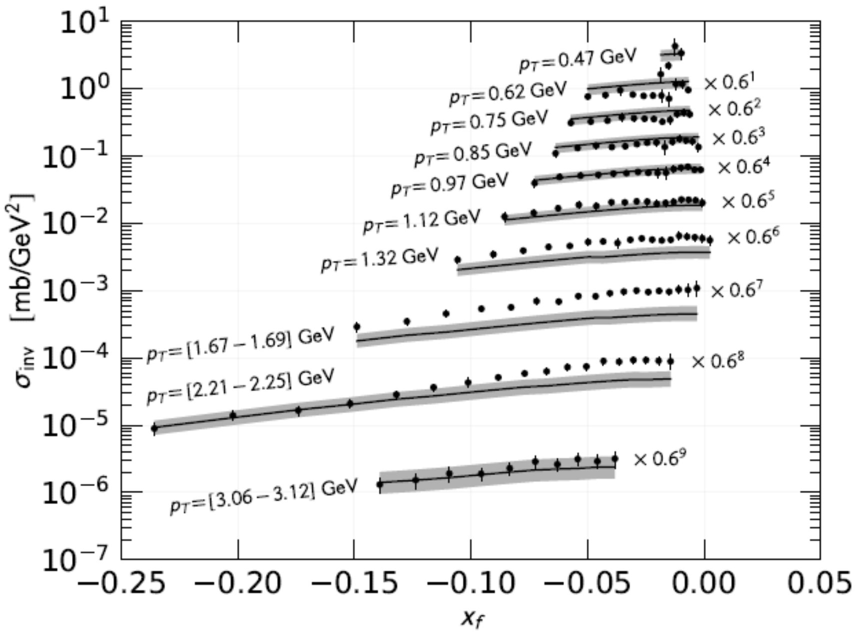
Reinert and Winkler, JCAP 1801 (2018) 055

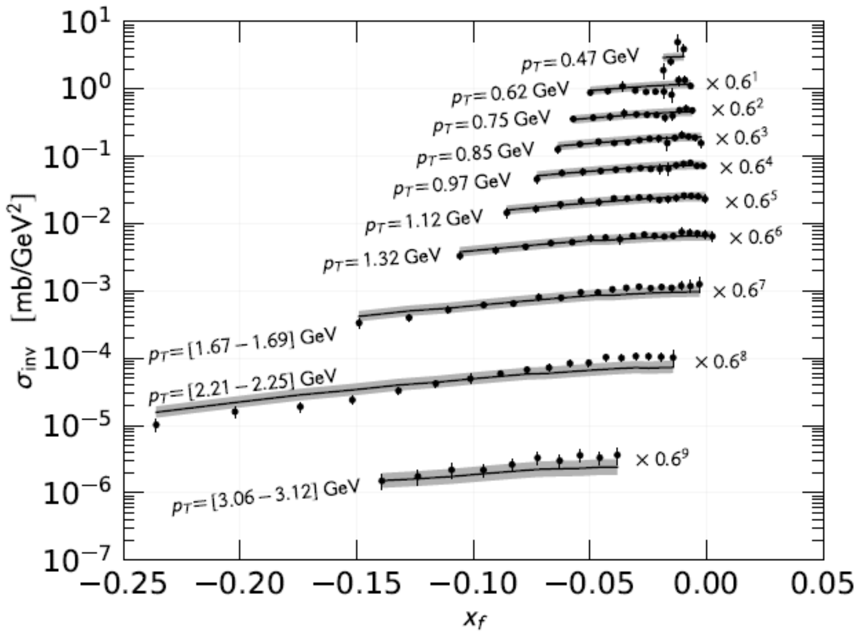


The preliminary results of this study (released in 2016) was used to validate

- extrapolations from pp data to pHe cross-sections
- empirical parametrizations for scaling violation of cross-sections

Korsmeier, Donato, Di Mauro, PRD97 (2018) 103019

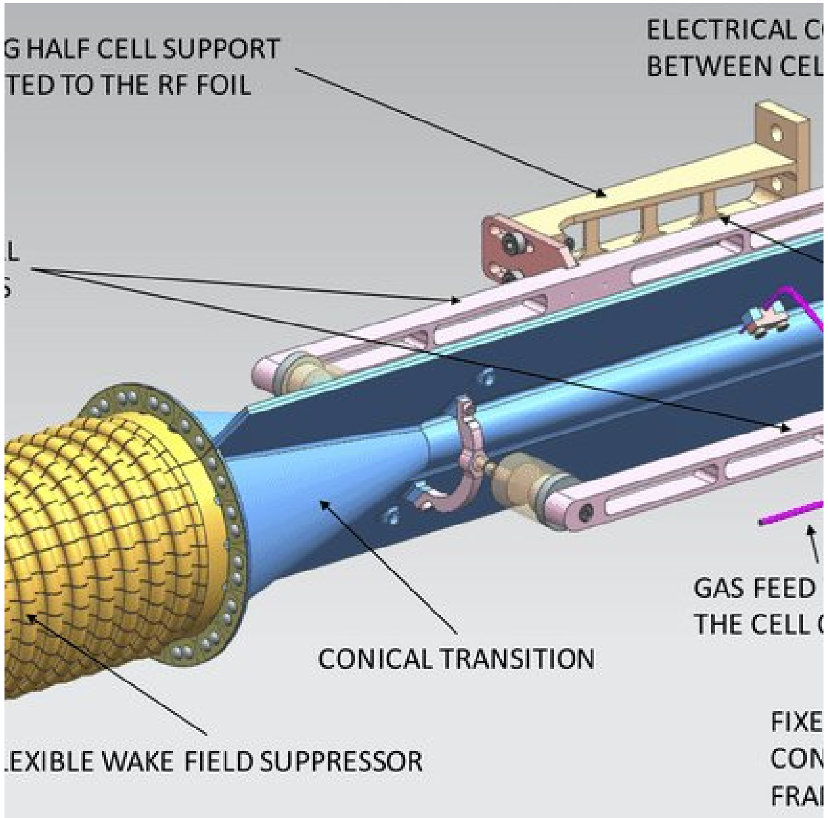


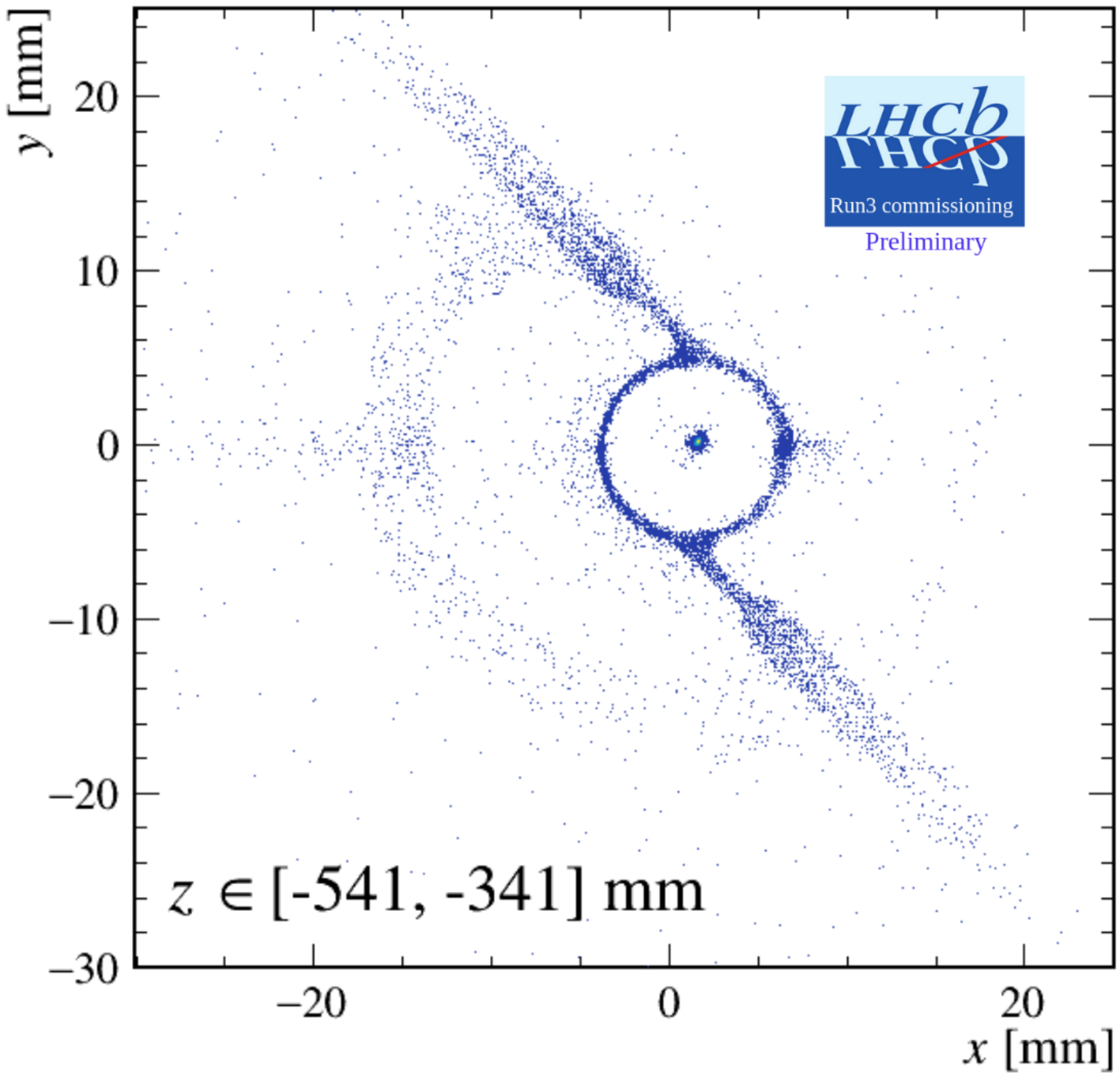


comparing data with different parameterizations for scaling

SMOG2 radiography

Reconstructed collisions vertices in the SMOG2 region





Give peace a chance

Rajko Mitić Stadium, Belgrade, March 17, 2022