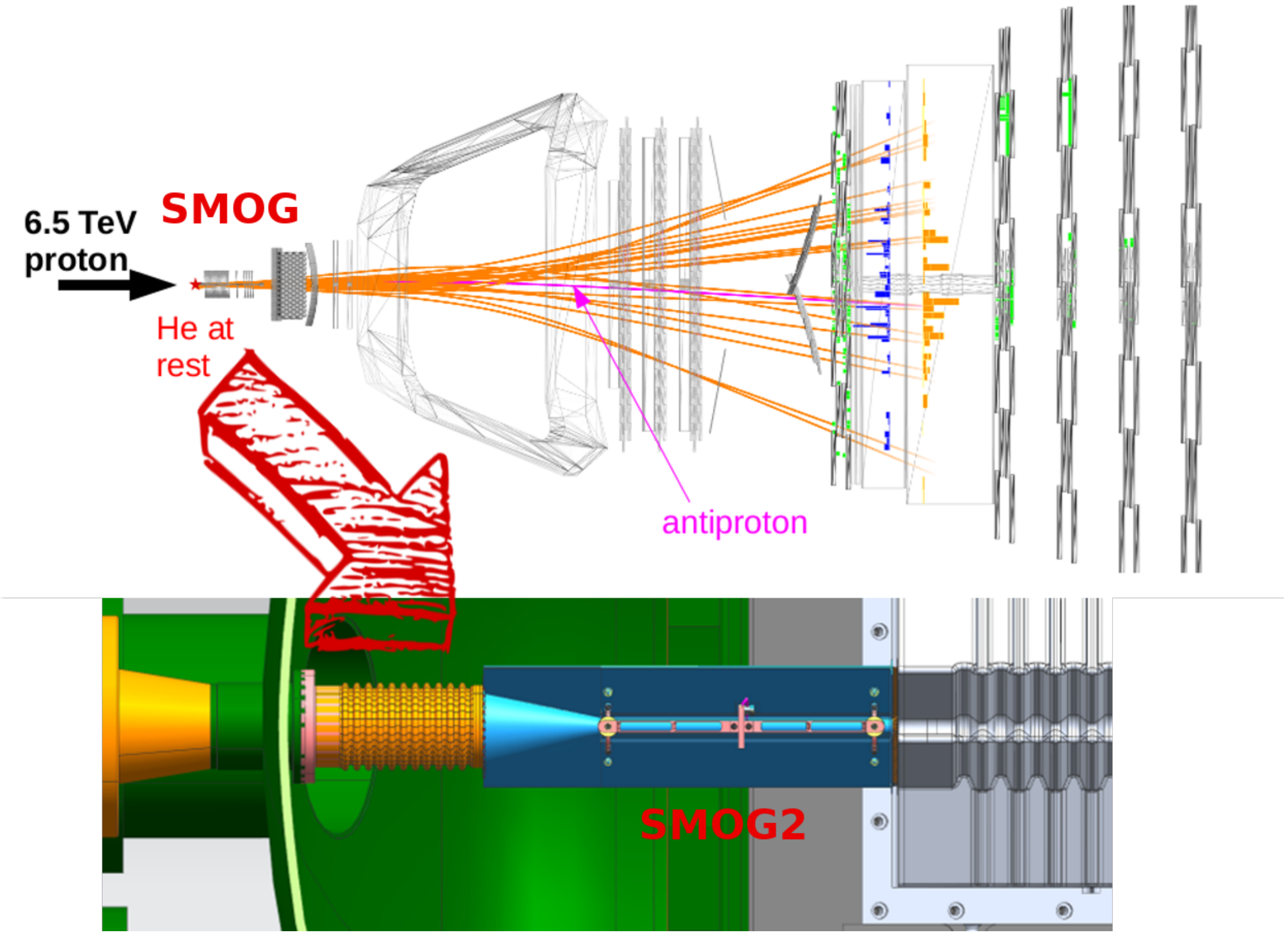
LHCb as a fixed-target experiment: introduction and cosmic-ray related studies



Giacomo Graziani (INFN Firenze)

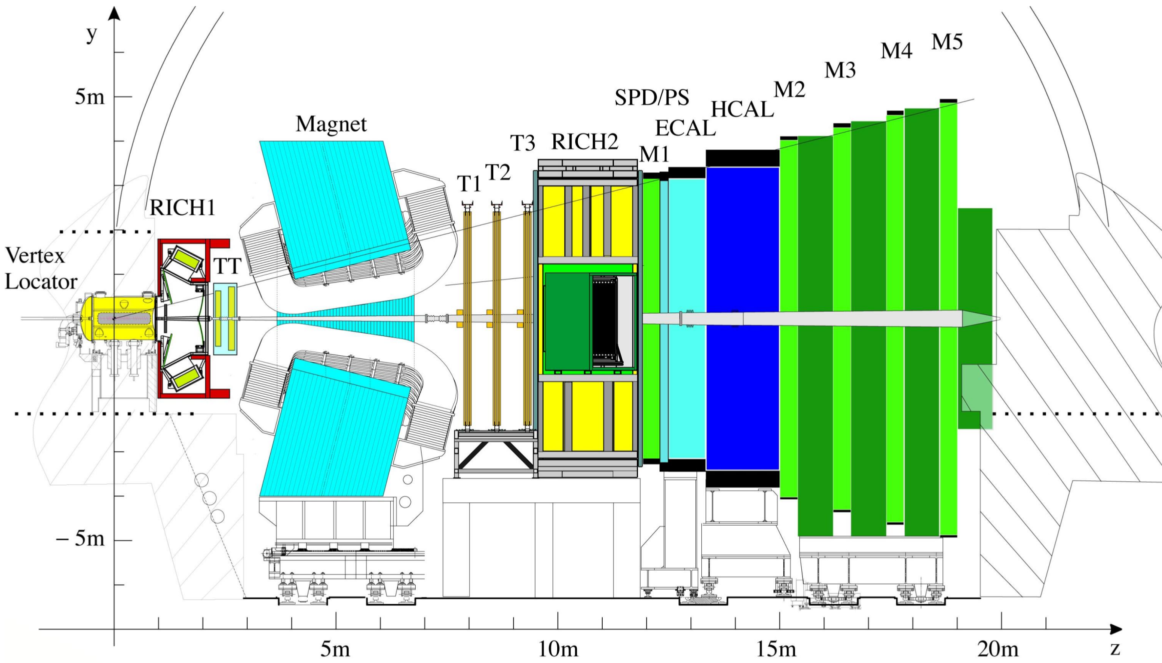
FTE@LHC & NLOAccess STRONG 2020 Kickoff Meeting
Nov 07, 2019

Istituto Nazionale di Fisica Nucleare

The LHCb experiment

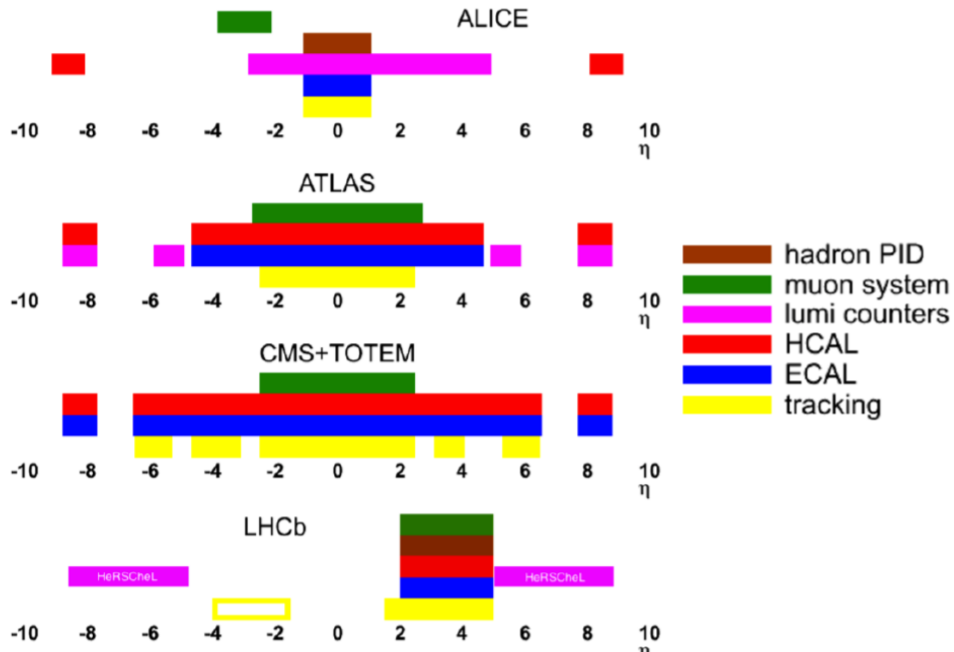
LHCb is the experiment devoted to heavy flavours in *pp* collisions at the LHC.

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)



JINST 3, (2008) S08005
Int.J.Mod.Phys.A30 (2015) 1530022

Unique forward acceptance, complementary to other LHC detectors



SMOG, the first LHCb gas target

Forward geometry is well suited for fixed-target collisions.

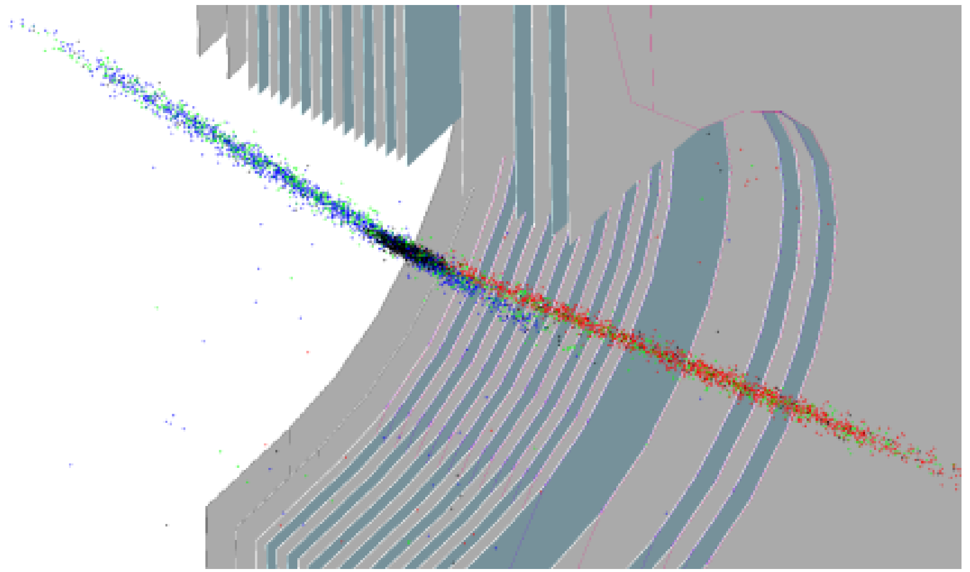
The System for Measuring Overlap with Gas (SMOG) can inject small amount of noble gas in the LHC beam pipe around ($\sim \pm 20$ m) the LHCb collision region.

Originally conceived for the luminosity determination with beam gas imaging

JINST 9, (2014) P12005

allows the most precise luminosity determination (1.2%) among the LHC experiments

Turns LHCb into a fixed-target experiment!



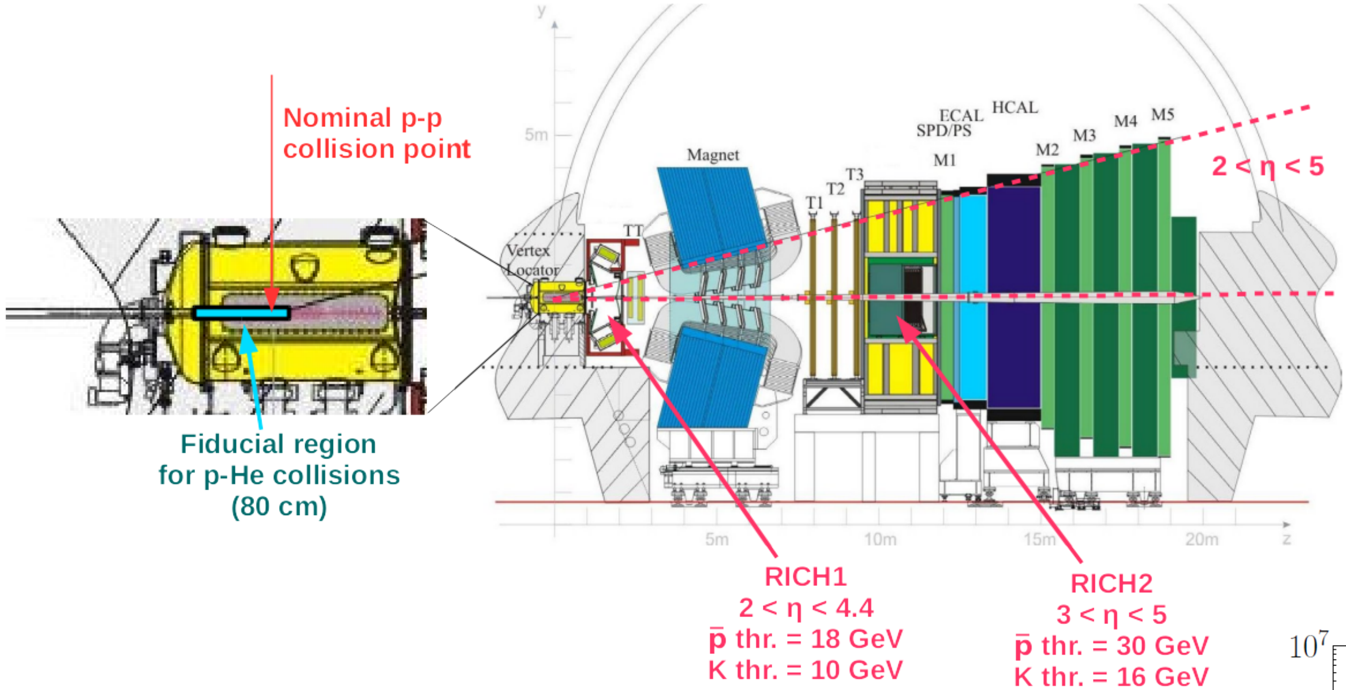
Possible targets: **He, Ne, Ar**, and more in the future

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

Beam energy up to 7 TeV ($\sqrt{s_{\text{NN}}}$ = 110 GeV)

Physics with SMOG

LHCb as a fixed target experiment, thanks to the SMOG internal gas target

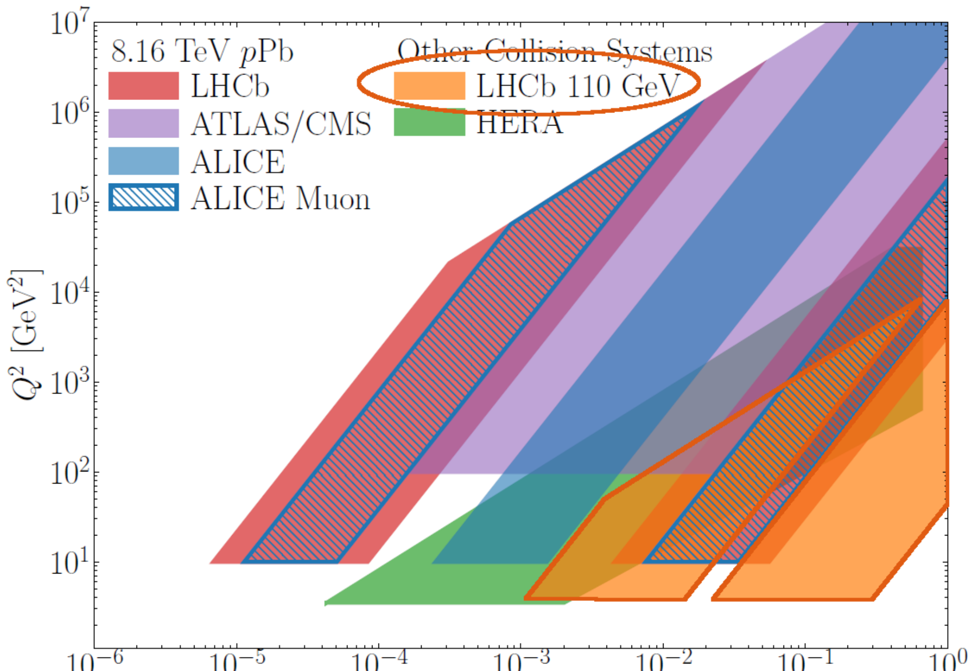


JINST 3, (2008) S08005

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

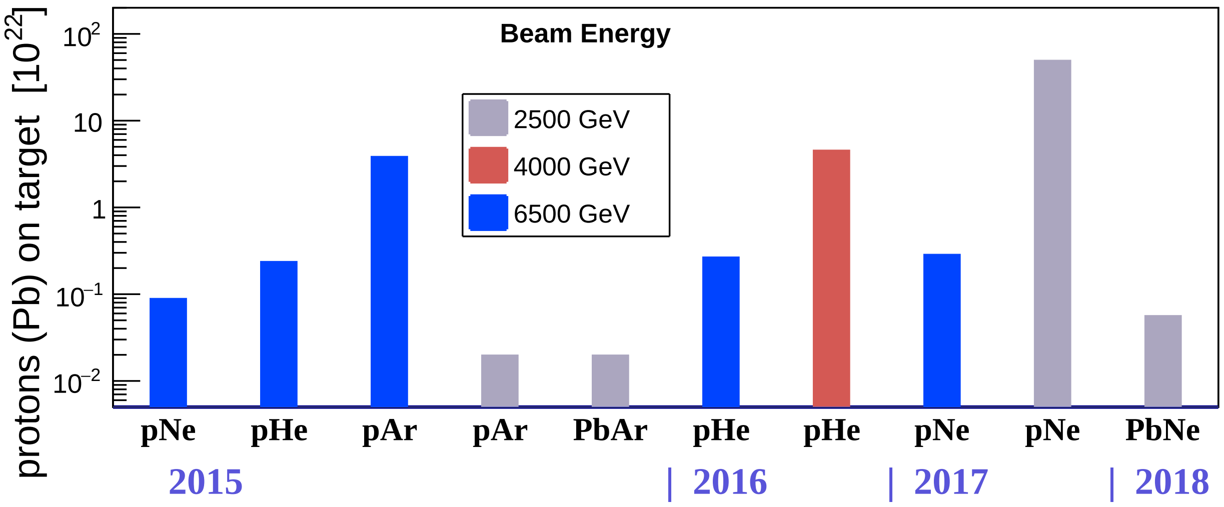
- pA collisions at unique energy scale

  $\sqrt{s_{NN}} \sim 100$ GeV
- Unique coverage for (n)PDF at large x
- Exploiting LHCb specific features
  - forward geometry
  - extreme vertexing performance + complete particle identification : ideal for heavy flavours



SMOG data samples

Final summary of fixed-target samples acquired with SMOG in Run 2



$$\int \mathcal{L}dt \sim 5\ \text{nb}^{-1} \times \frac{pot}{10^{22}} \times \frac{p_{gas}}{2 \times 10^{-7}\text{mbar}} \times \text{Exp\_Efficiency}$$

Largest sample (pNe 2017) $\sim 100\ \text{nb}^{-1}$

Main physics goals:

- charm production to investigate nuclear effects and (n)PDF at large x;
- studies of hadron production in novel kinematic regime and collision systems (notably proton - Helium), bringing crucial inputs to cosmic ray physics.

First two physics results published during the last year:

antiprotons in pHe, PRL 121 (2018), 222001

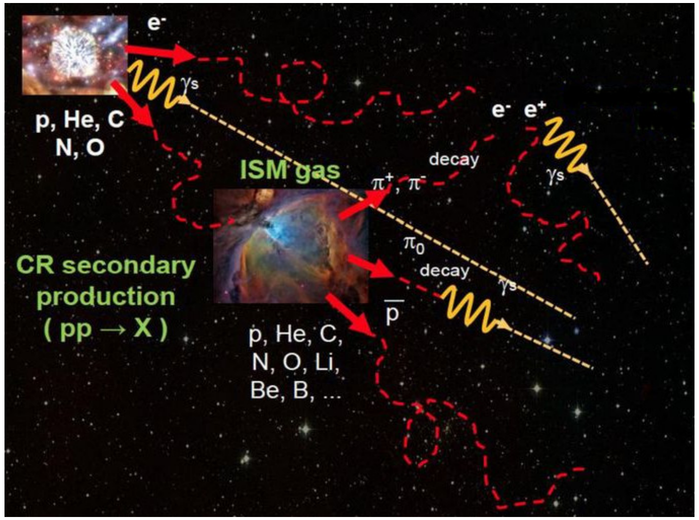
charm production in pHe and pAr, PRL 122 (2019) 132002

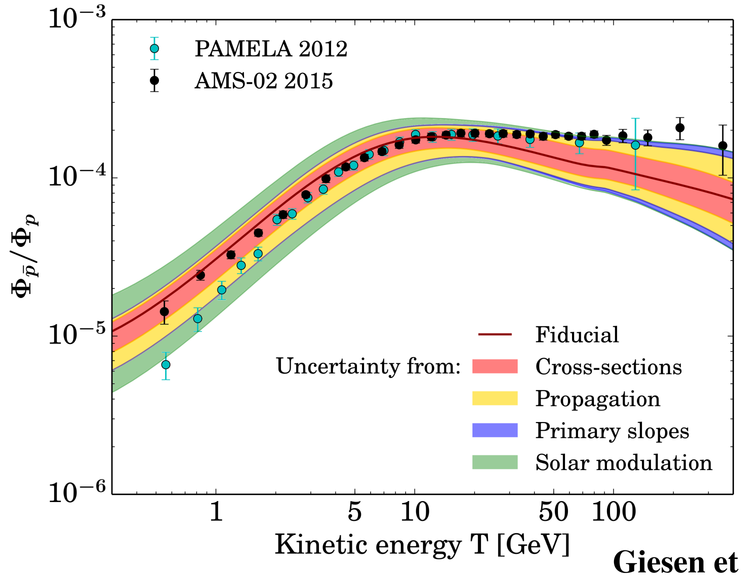
LHCb FT for astroparticle physics

The precision era reached in astroparticle physics with a variety of probes requires improved understanding of interactions of cosmic rays during their propagation.

the LHCb fixed-target configuration can contribute with unique production studies:

- charm production in fixed-target ➡ understanding background to Neutrino astronomy (high-x charm PDF)
- production studies (antiprotons and more) in proton-helium collisions
  ➡ secondary CR production in the ISM





Giesen et al., JCAP 1509, 023

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

- identified hadrons in proton-gas collisions (gas=He, Ne, Ar)
  ➡ help models of extensive showers in the atmosphere, particularly to address the radial profile of muons

Antiprotons in pHe collisions

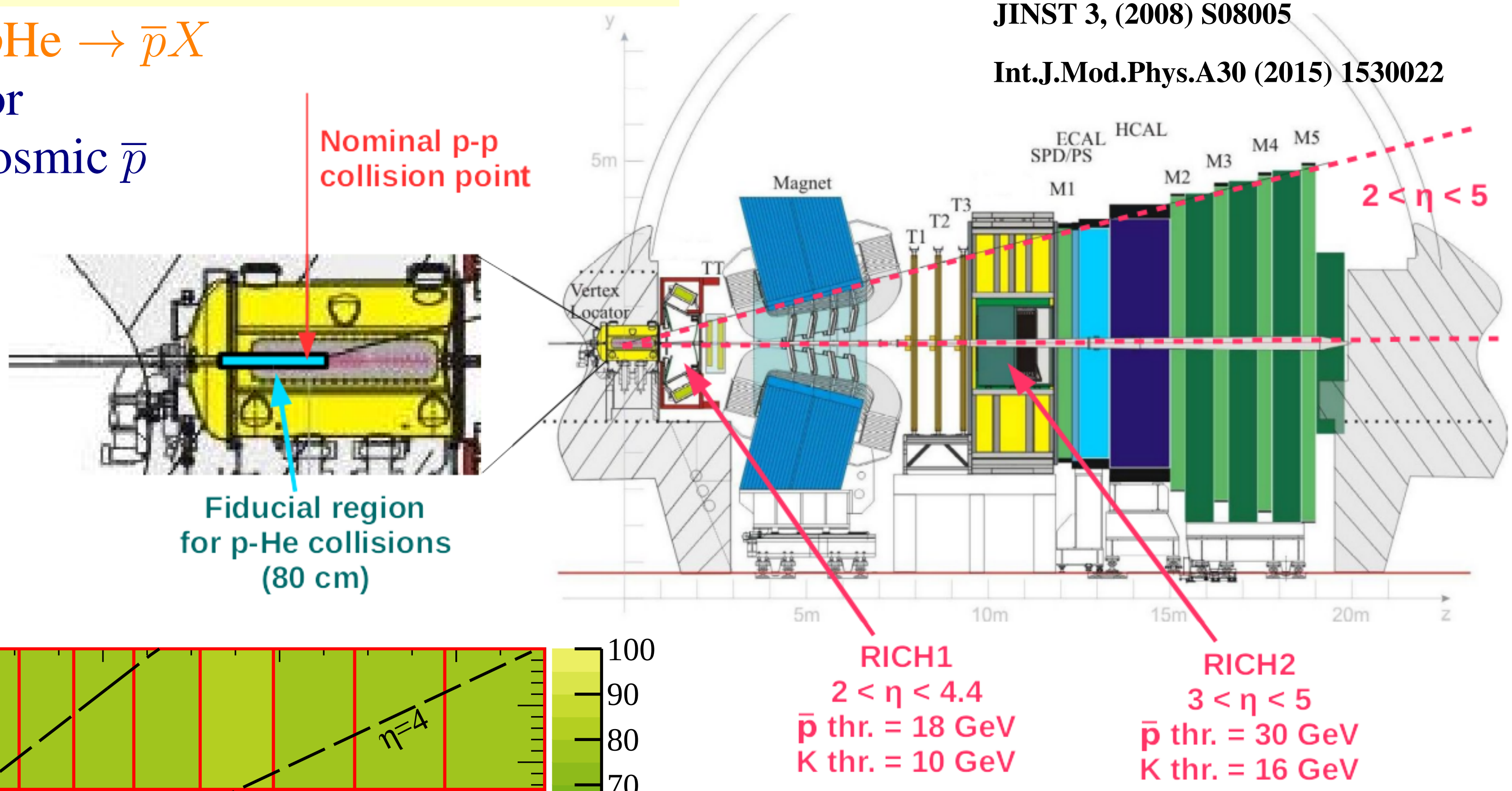
First measurement of $p\text{He} \to \overline{p}X$

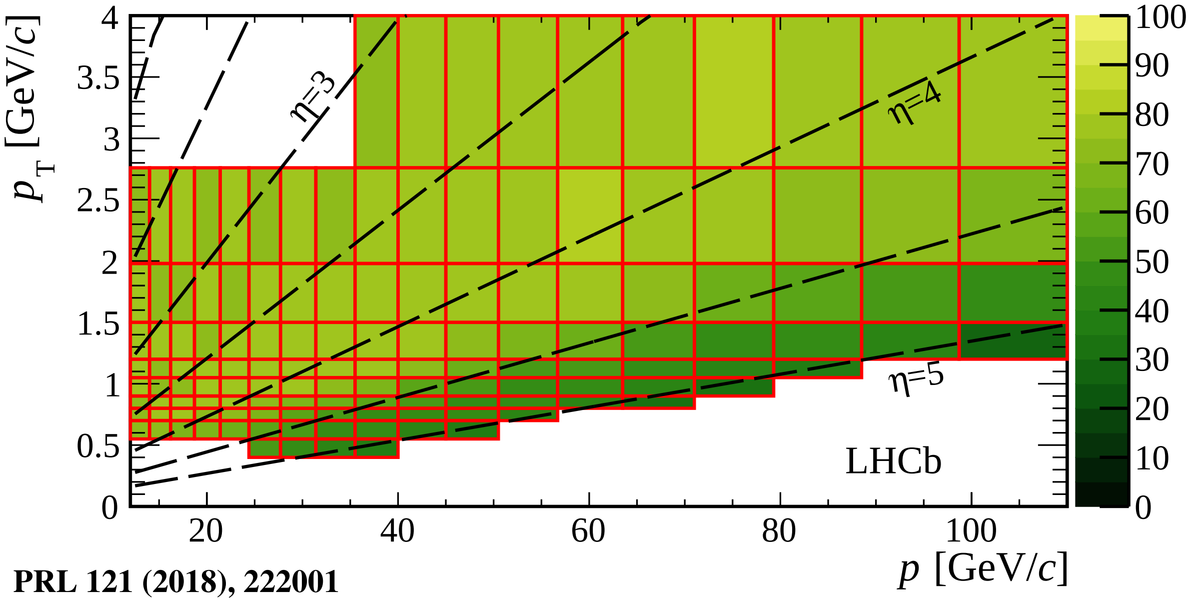
the process accounts for

$\sim 40\%$ of secondary cosmic $\overline{p}$

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:

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

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

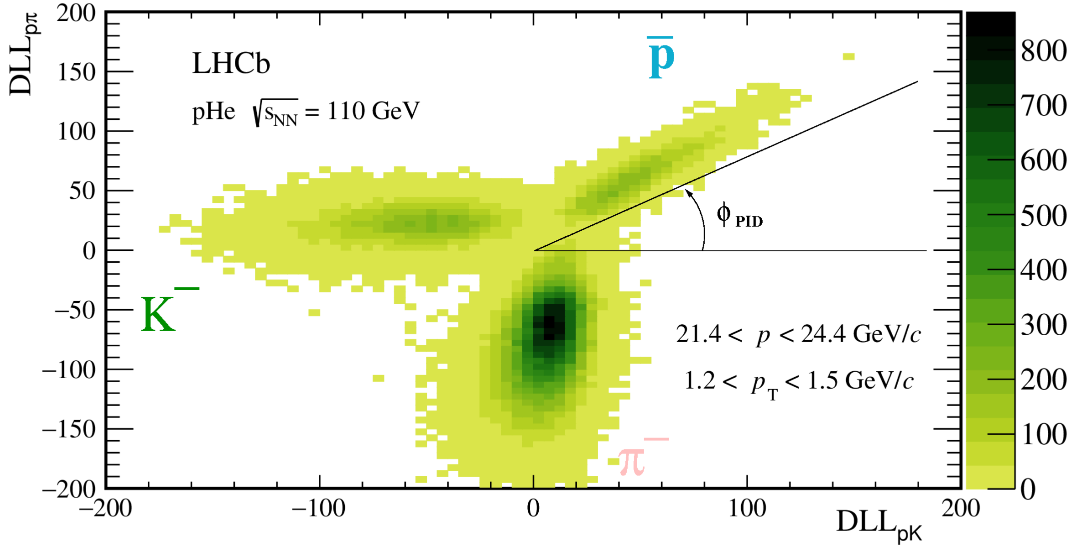
Data sample and particle identification

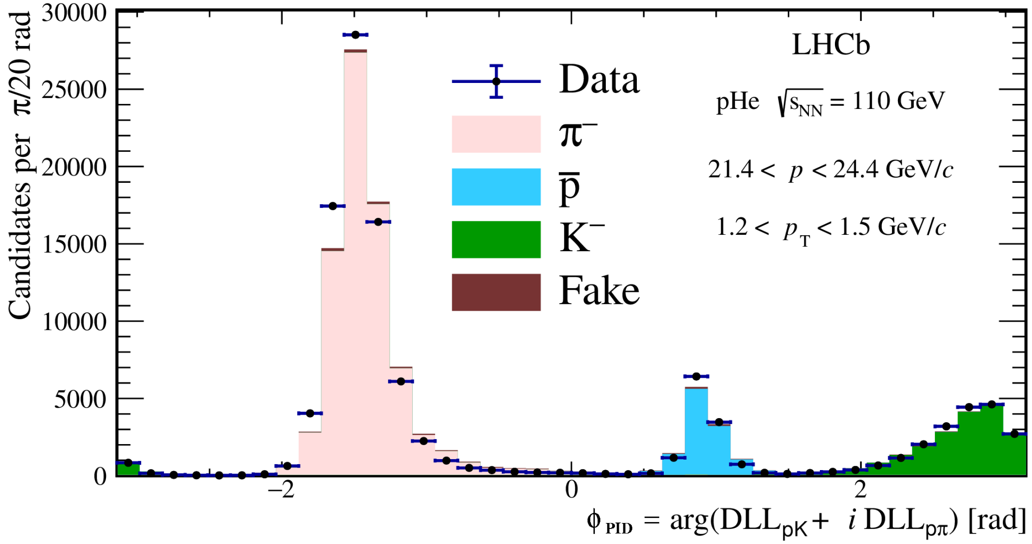
PRL 121 (2018), 222001

- Data collected in May 2016, with proton energy 6.5 TeV, $\sqrt{s_{NN}} = 110$ 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 $(p,\ p_T)$ bins within the kinematic range

$$12 < p < 110\,\mathrm{GeV}/c, \quad p_T > 0.4\,\mathrm{GeV}/c$$

(good match with PAMELA/AMS-02 capabilities)

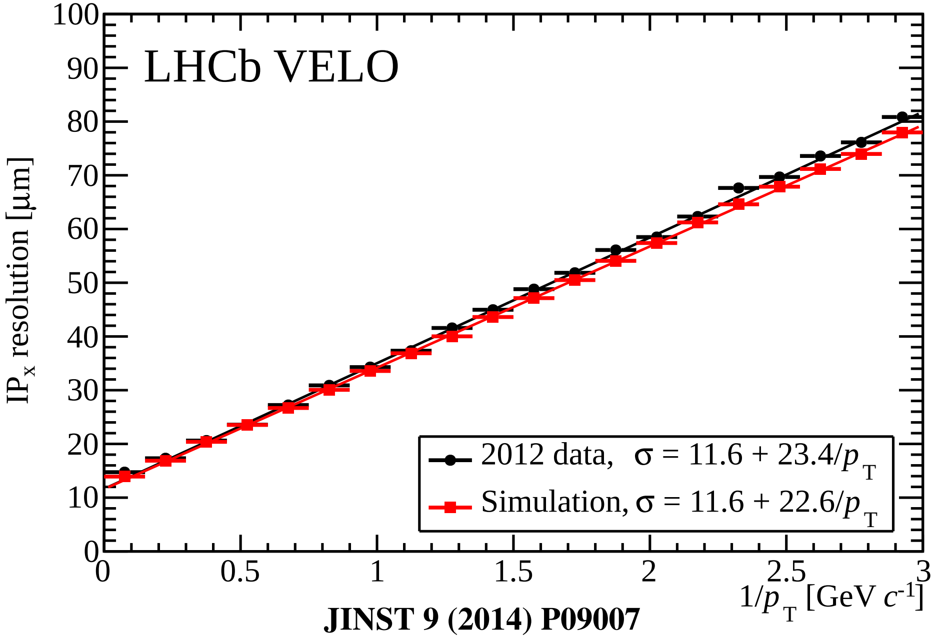




Antiprotons from weak hyperon decays

PRL 121 (2018), 222001

- Excellent impact parameter (IP) resolution provides good separation of prompt and detached $\overline{p}$ production



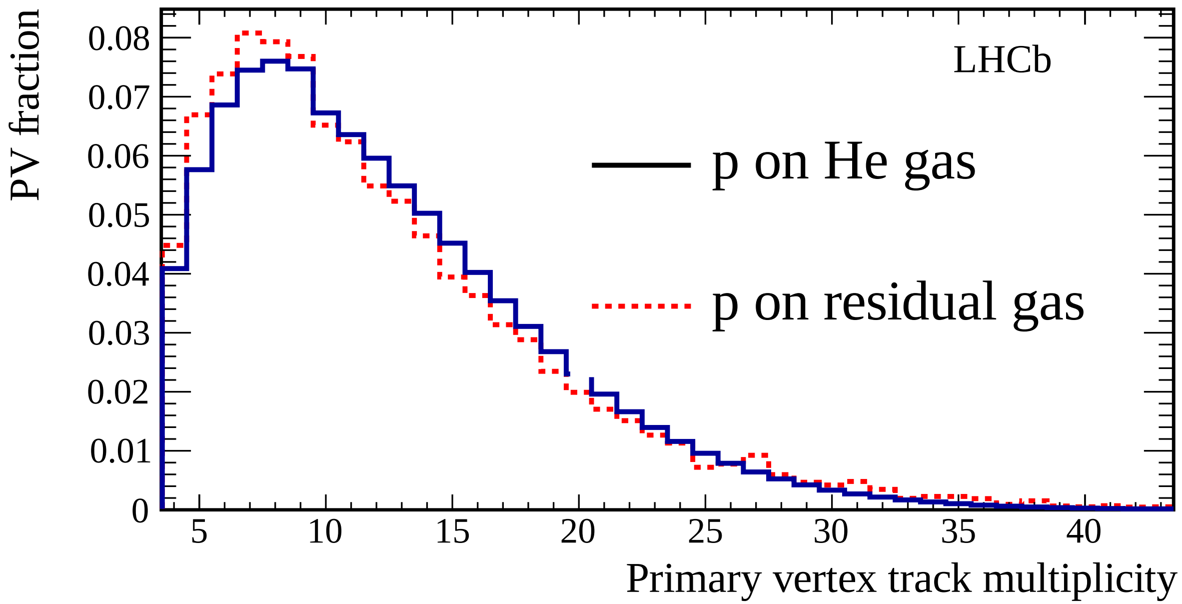
JINST 9 (2014) P09007

- Only prompt $\overline{p}$ component measured so far
- Residual detached component (after low IP requirement) estimated to be $(2.4 \pm 0.5)\%$ and subtracted
- Ongoing dedicated studies to determine the secondary component: measuring both inclusive non-prompt $\overline{p}$ yield and $\overline{\Lambda} \to \overline{p}\pi^+$ exclusive decays

Background from residual gas

PRL 121 (2018), 222001

- Residual vacuum in LHC is not so small ($\sim 10^{-9}$ mbar) compared to SMOG pressure
- Can be a concern, especially for heavy contaminants (larger cross section than He), and beam-induced local outgassing
- Direct measurement in data: about 15% of delivered protons on target acquired before He injection (but with identical vacuum pumping configuraton)

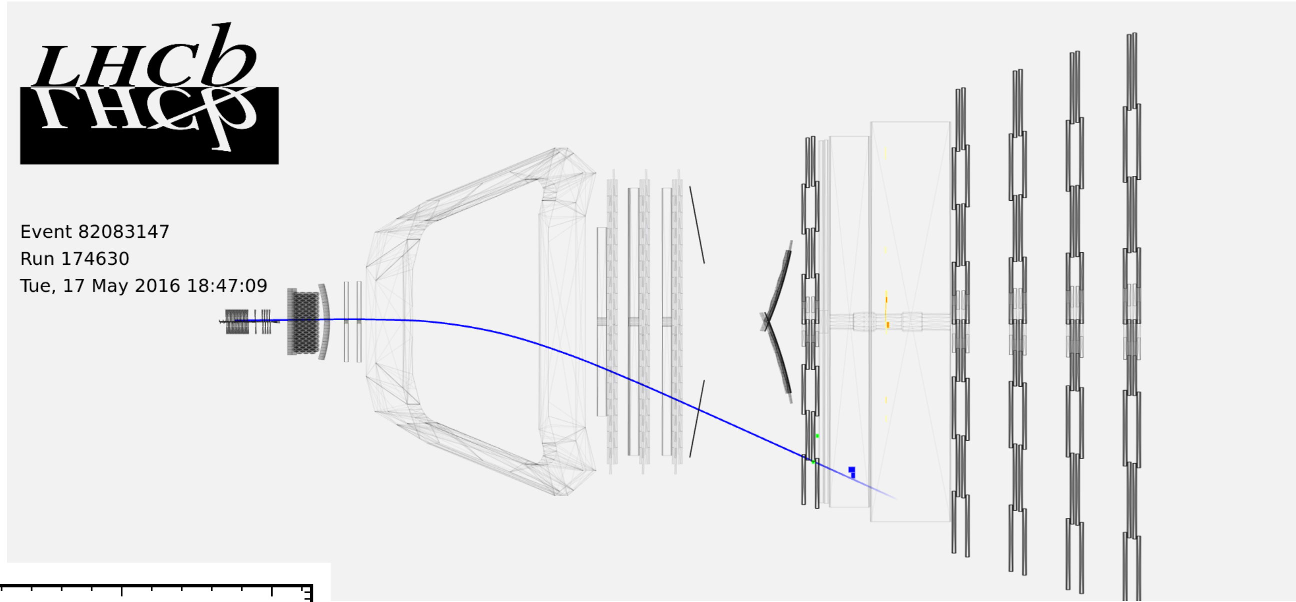


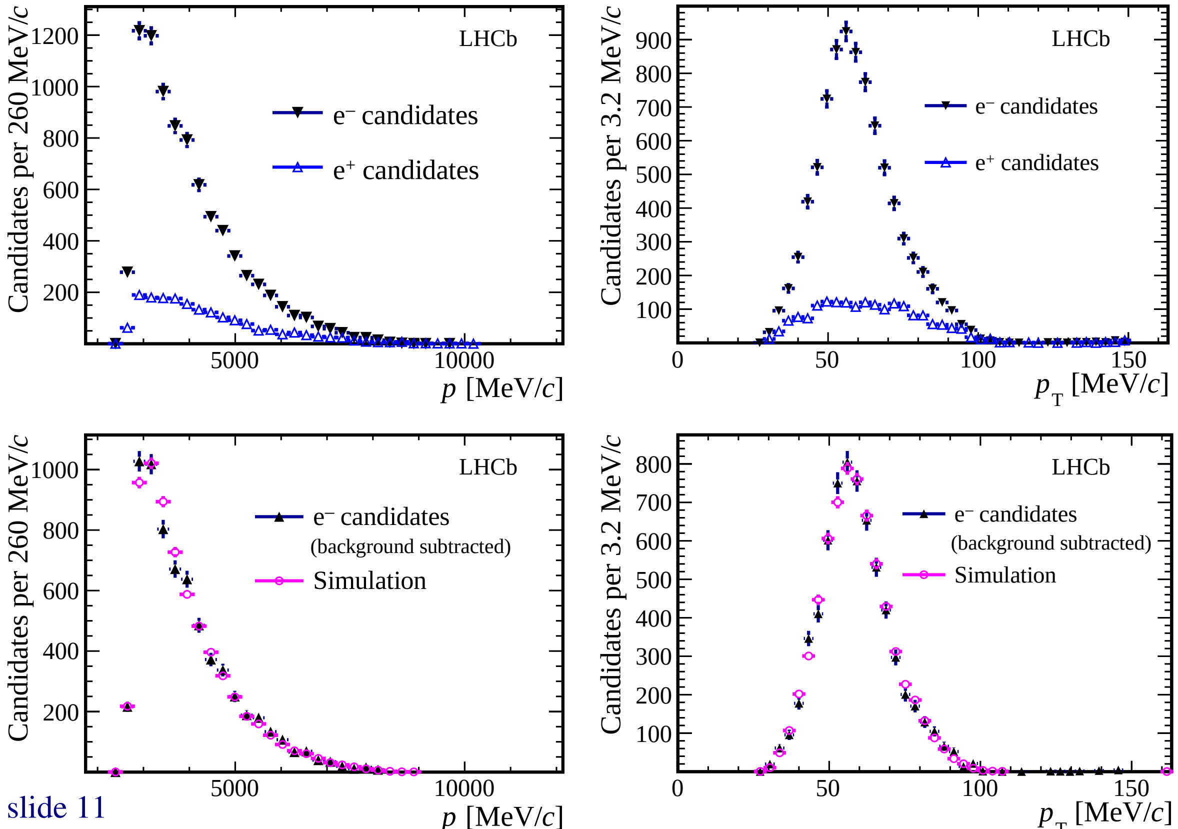
- Contribution from gas impurity found to be small: $0.6 \pm 0.1\%$
- PV multiplicity in residual vacuum events is **lower** than in He events, but has longer tails ➡ confirm findings from Rest Gas Analysis that residual vacuum is mostly H_2, with small heavy contaminants

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 ($\sim 16\%$)

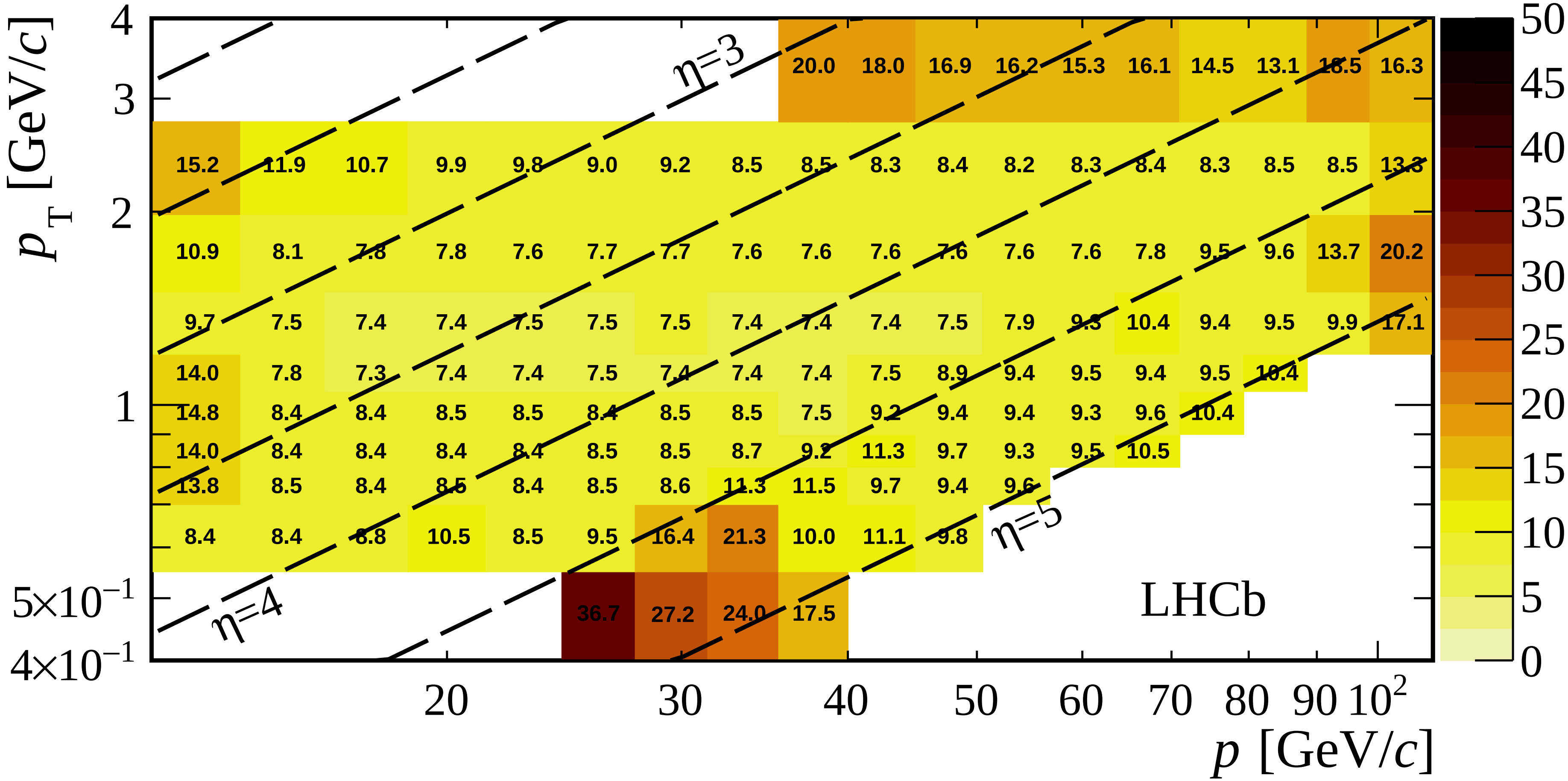
pHe $\to \overline{p}X$ result: uncertainties (relative)

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)

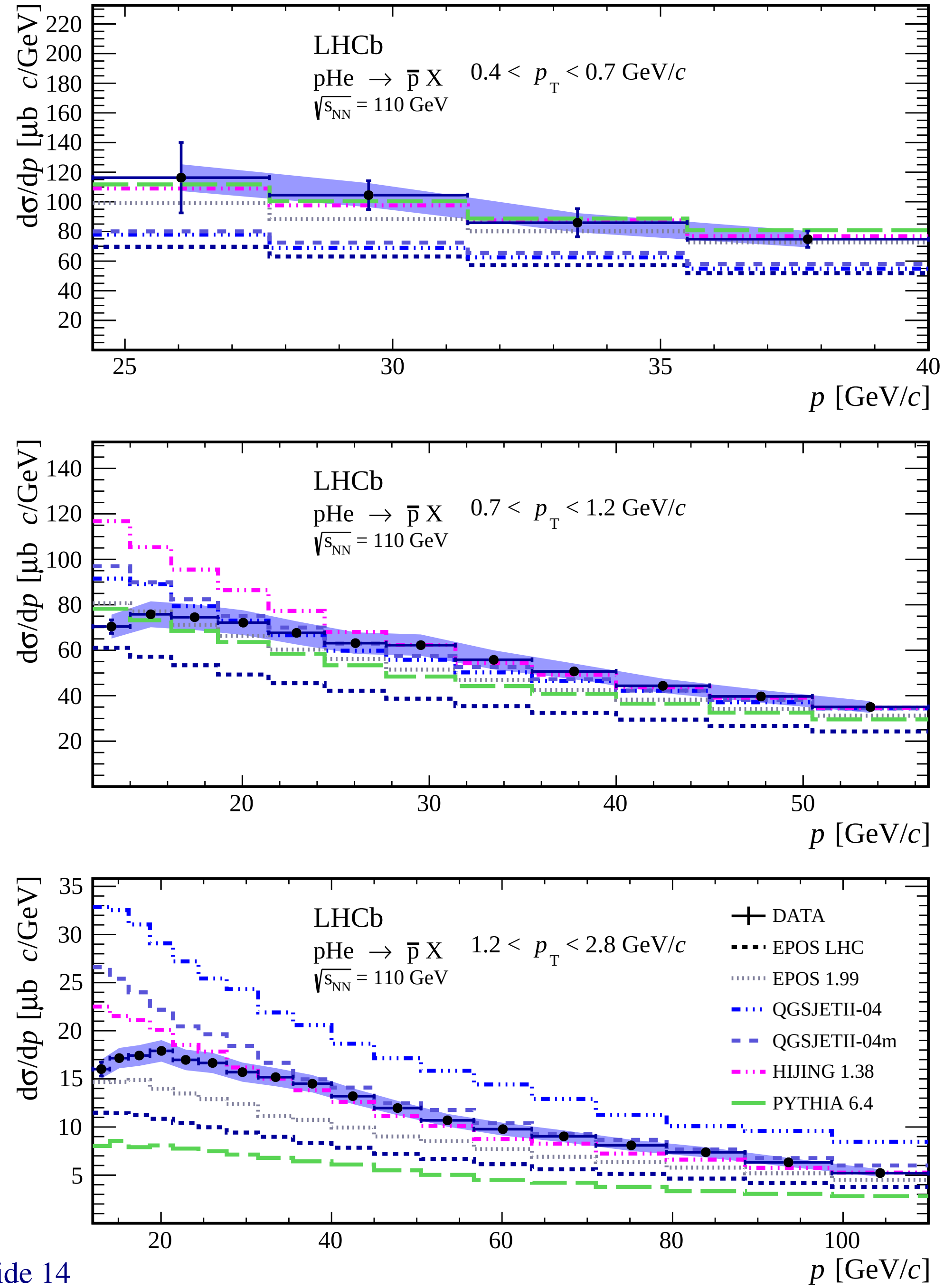
Total relative uncertainty per bin, in per cent

PRL 121 (2018), 222001



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

Result for cross section, compared with models



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**

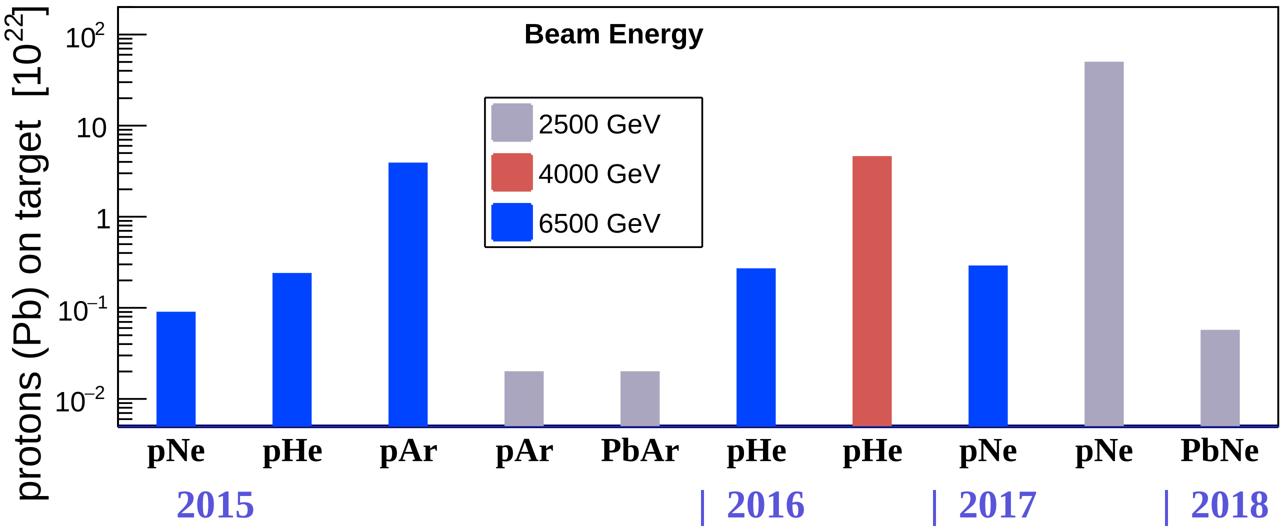
The "visible" inelastic cross section (yield of events reconstructable in LHCb) is compatible with simulation based on EPOS LHC:

$$\sigma_{\rm vis}^{\rm LHCb} / \sigma_{\rm vis}^{\rm EPOS-LHC} = 1.08 \pm 0.08$$

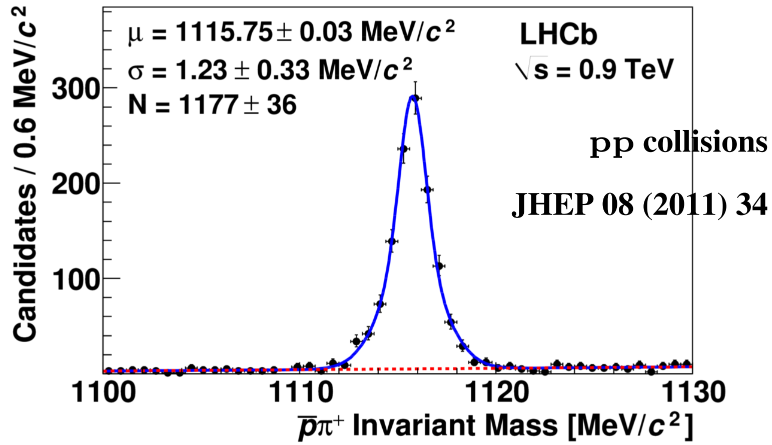
➡ excess of $\overline{p}$ yield over EPOS LHC (by factor ~ 1.5) mostly from $\overline{p}$ multiplicity

Prospects: Exploitation of current samples

Samples acquired during Run 2, up to $\int \mathcal{L} dt \sim 100\,\mathrm{nb}^{-1}$ (pNe)



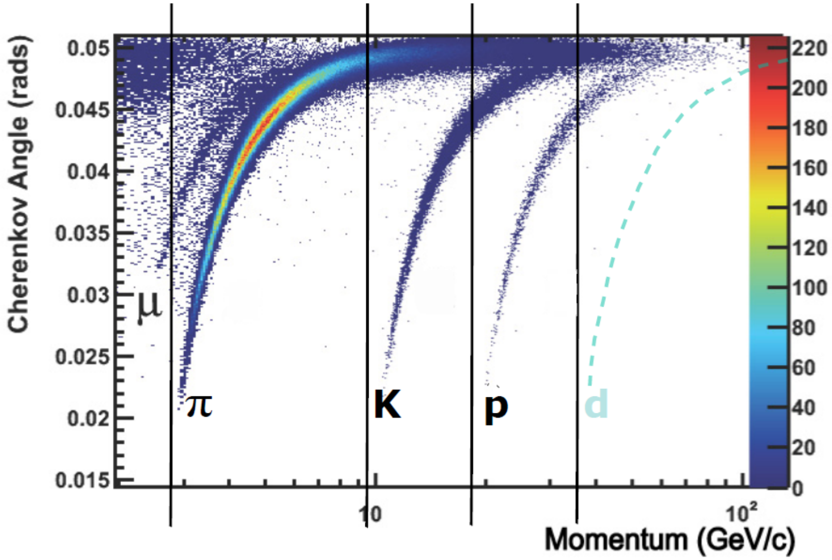
- More precise charm measurements, including other states (*e.g.* Λ_c^+)
- pHe data at 4 TeV beam energy ($\sqrt{s_{\mathrm{NN}}}$ =86 GeV) ➡ energy evolution of the cross-section



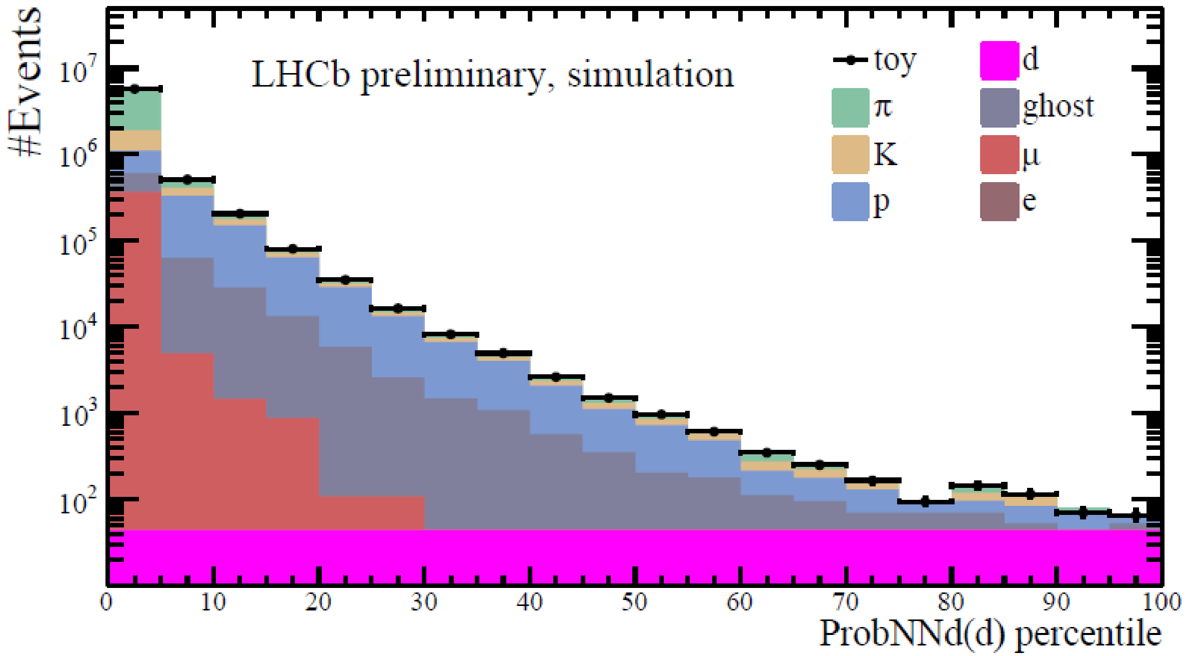
- Extend the study to $\bar{p}$ produced by anti-hyperon decays (∼20-30% of $\bar{p}$ production)
  - Measure $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ exclusive production
  - Inclusive measurement of detached antiprotons
- Measure production of π, K, p from the various SMOG samples (He, Ne, Ar targets) ➡ estimate **positron** production

Antideuterons?

- Nuclear fragment identification capabilities have not been foreseen in LHCb
- But RICHs can in principle identify (anti)deuterons above 35 GeV
- A study has been performed for *pp* collisions, modeling deuteron production with coalescence model tuned on ALICE data **PRD92, 069903 (2015)**



➡ expect 1 deuteron per 10^4 pions, at the limit of LHCb PID capabilities



Simulated template fit on neural network classifier for deuterons identification in pp collisions at 13 TeV

- Could be tried also on fixed target data in the future, if suitable trigger selection can be developed

The next steps

Physics Briefing Book

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].

...

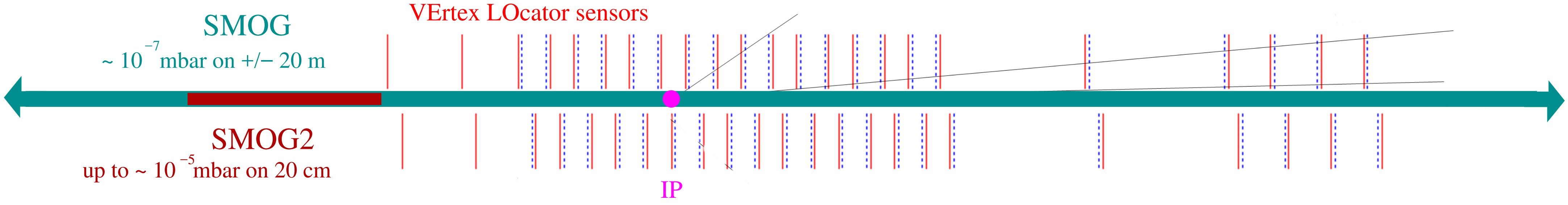
The physics reach of the LHC complex can greatly be extended at a very limited cost with the addition of an ambitious and long term LHC-FT research program. The efforts of the existing LHC experiments to implement such a programme, including specific R&D actions on the collider, deserve support.

Physics Goals for LHC Run 3/4

Develop physics with unpolarised gas targets:

- **Increase data size**: better accuracy, access rarer states (including $b\overline{b}$, DY)
  ➡ strong impact on PDFs at large x, QGP studies in PbA
- Extend target choice:
  - **Hydrogen** and **Deuterium** would provide pp reference measurements, studies of GPDs/TMDs (through unpolarized observables), more $\overline{p}$ production for CR in space (production in pp and isospin violation)
  - **Nitrogen/Oxygen** for atmospheric CR
  - **Heavier** gas (Kr, Xe?). Upgraded LHCb detector (from Run 3) will allow better reconstruction of central event

thanks to an upgraded gas target device: **SMOG2**



New target setups:

- Polarised gas target
- Bent crystal for MDM/EDM measurements

(see next talks)

Antiprotons with SMOG2

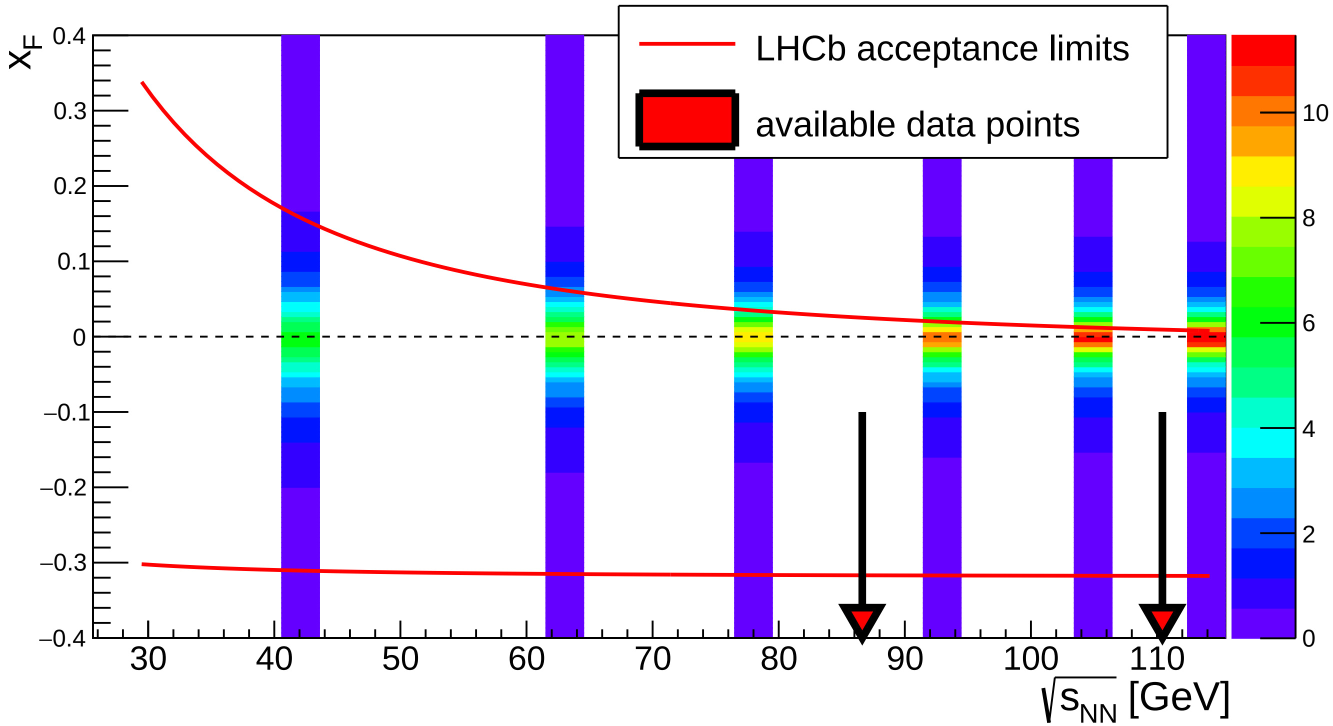
LHCB-PUB-2018-015

- 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)

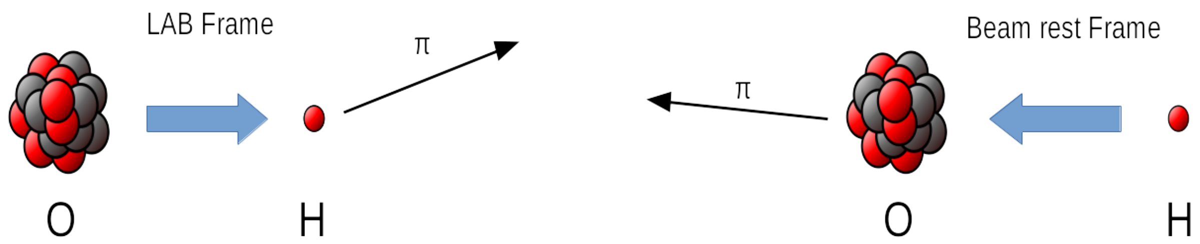
  Data at lower energy to measure evolution with energy (scaling violations) and access forward region (Feynman-$x > 0$)

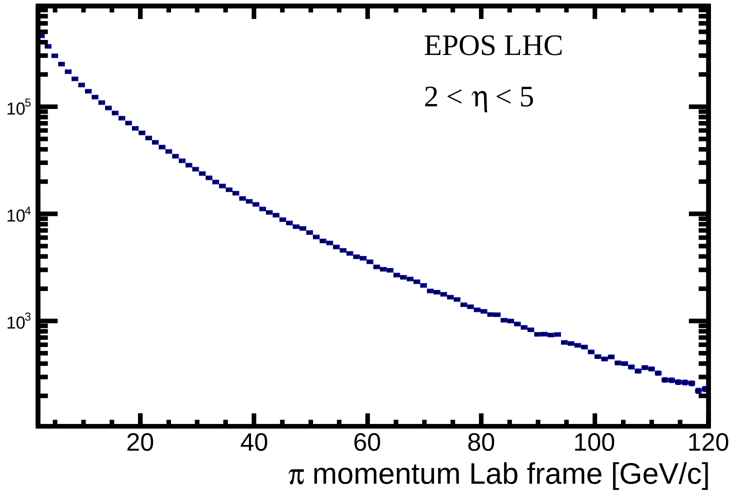


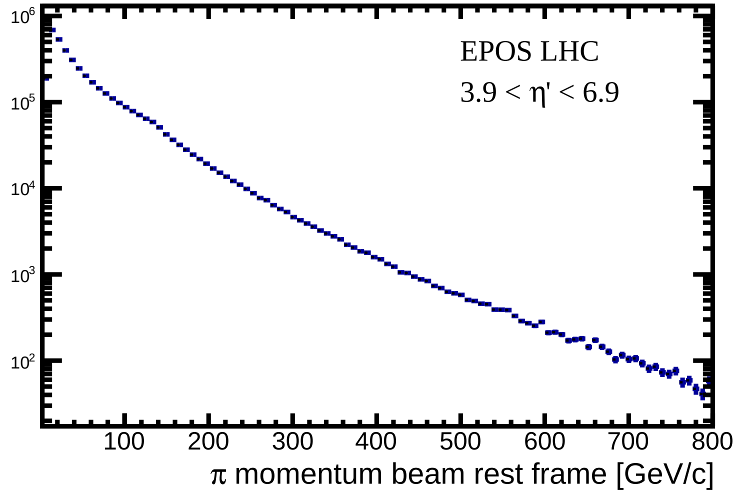
Feynman-x distribution for $\overline{p}$ vs $\sqrt{s_{\rm NN}}$ and accessible region to LHCb

"Atmospheric" cross-sections with SMOG2

- Large statistics to study nuclear effects in charm production, and possibly disentangle intrinsic charm with H target
- Possibility to inject nitrogen and oxygen. Baryon and kaon production in pN and pO is a key input to understand muon production off-axis in extensive showers
- For Run 3 and beyond: a special run with oxygen beam is foreseen(**CERN-LPCC-2018-07**):
  - study pO collisions up to $\sqrt{s_{\mathrm{NN}}} = 9.9$ TeV with forward acceptance
  - oxygen beams on H target give access to very forward particles in pO (up to $\eta = 6.9$) at $\sqrt{s_{\mathrm{NN}}} \sim 100$ GeV







Conclusions

- LHCb demonstrated the potential for fixed target physics at the LHC using internal gas targets in existing detectors
- First two physics results on PRL, more to come from Run 2 samples
- SMOG2 upgrade approved by LHCC and being installed
  ➡ great possibilities for a substantial increase of data size and choice of target gas species wrt the current SMOG program already from Run3
- and several ambitious proposals for the future