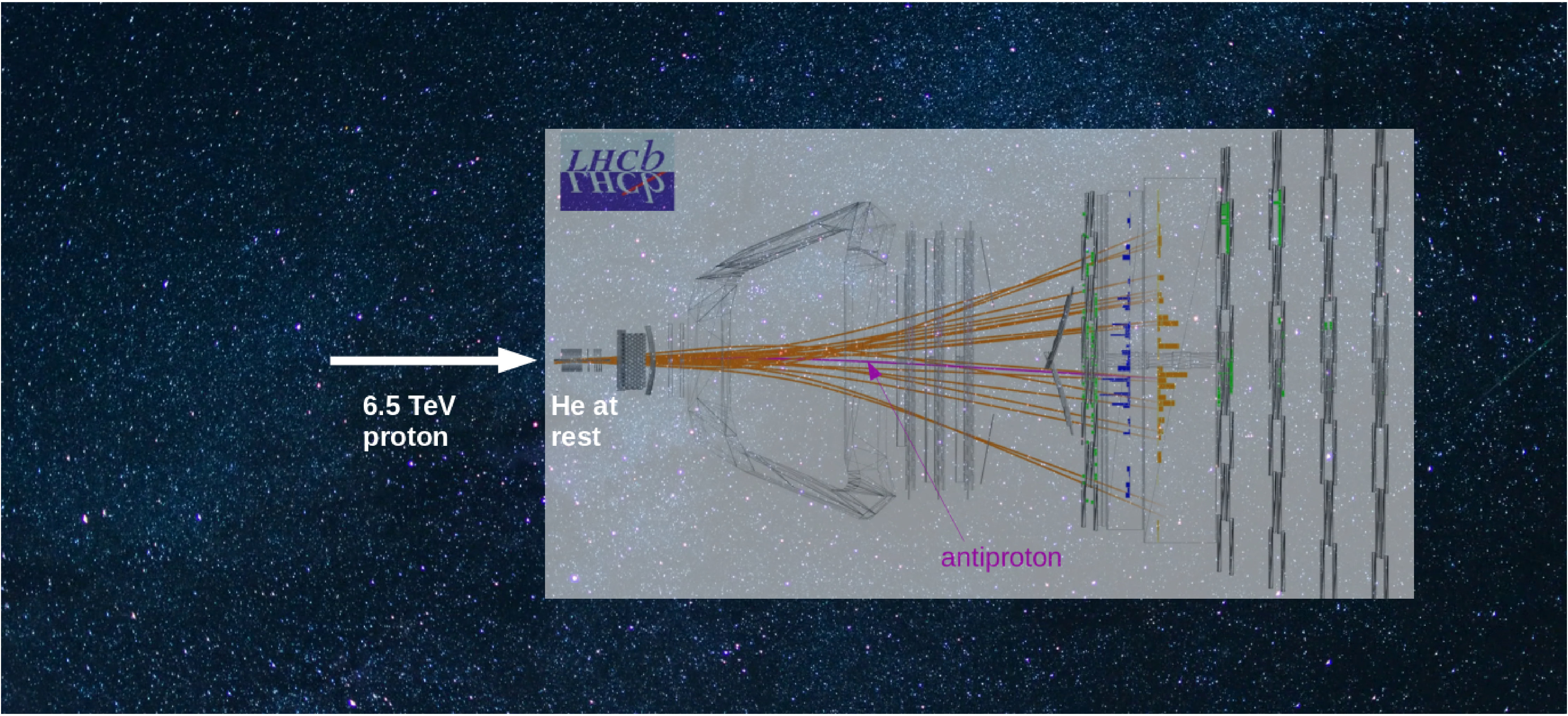
Antiproton and charm production in proton-nucleus collisions with LHCb and prospects



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

XSCRC2019: Cross sections for Cosmic Rays @ CERN
November 15, 2019

LHCb and astroparticle physics

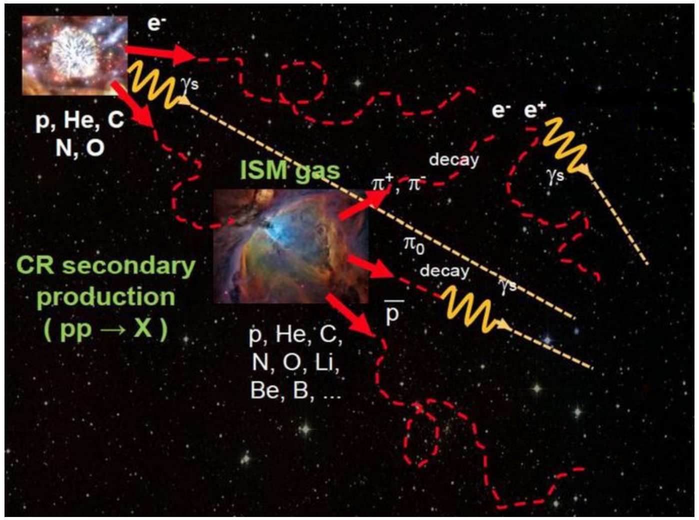
The precision era reached in astroparticle physics with a variety of probes requires improved understanding of interactions of cosmic rays during their propagation.

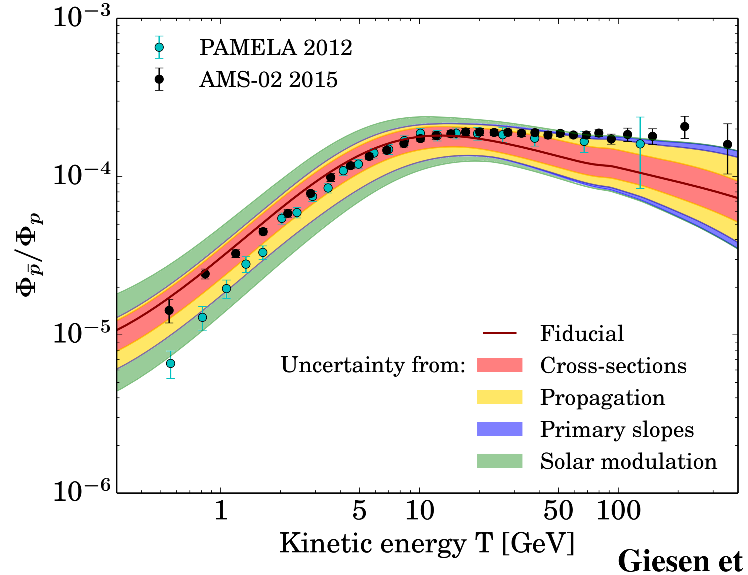
LHCb can contribute with novel production studies, exploiting two distinctive features:

- the unique coverage of forward geometry at the LHC
- the unique possibility to use LHC beams on fixed targets

Most notably:

- charm in pp, pPb and fixed-target ➡ understanding background to Neutrino astronomy
- 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 pp, pPb and proton-gas collisions (gas=He, Ne, Ar)
  - ➡ help models of extensive showers in the atmosphere

The LHCb experiment

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

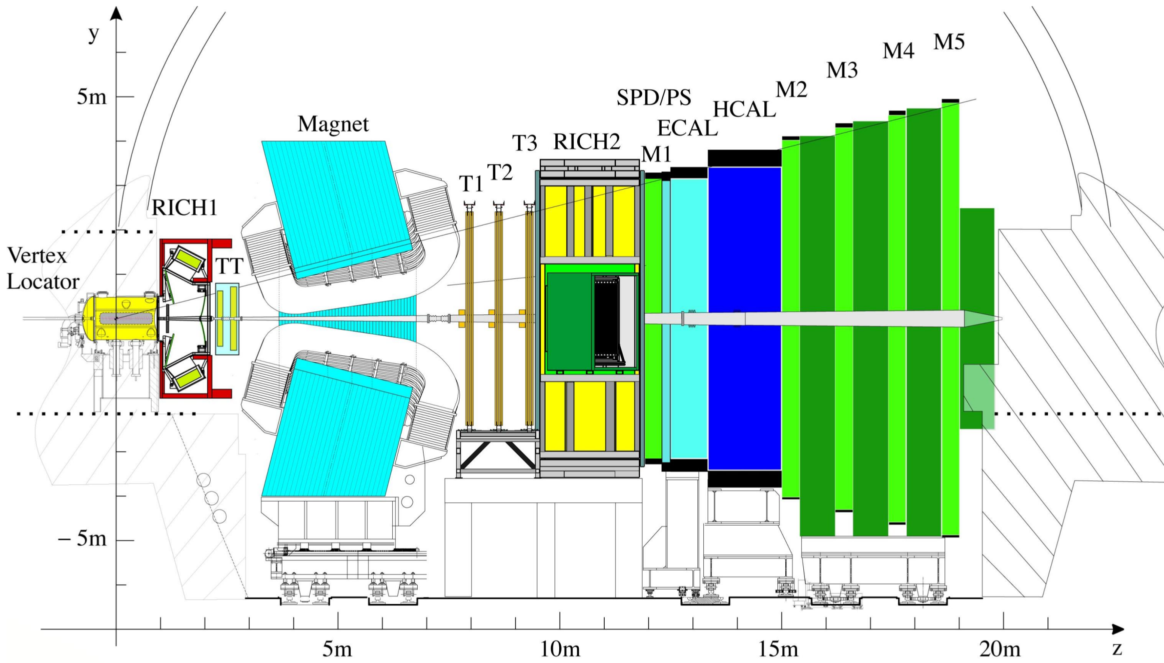
Detector requirements:

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

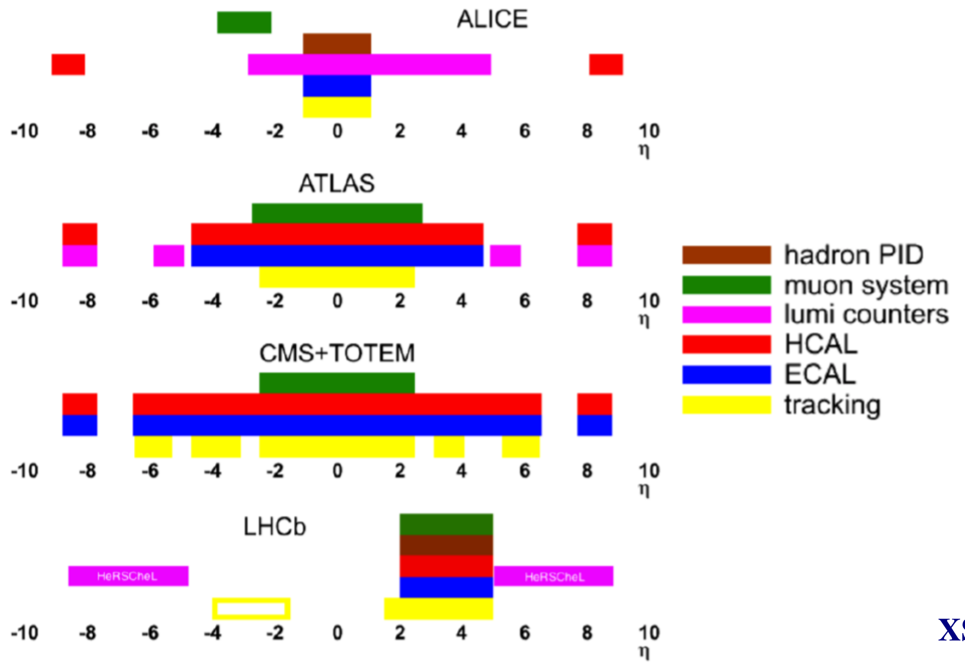
Trigger : high flexibility and bandwidth (up to 15 kHz to disk)



JINST 3, (2008) S08005

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

Unique forward acceptance, complementary to other LHC detectors



The LHCb gas target

Forward geometry is well suited for fixed-target collisions.

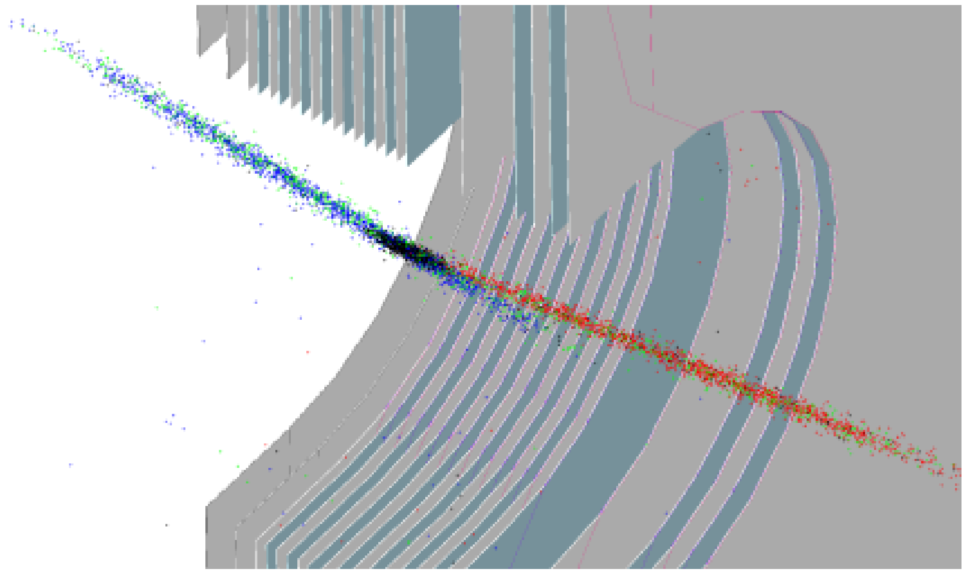
The System for Measuring Overlap with Gas (SMOG) can inject small amount of noble gas in the LHC beam pipe around ($\sim \pm 20$ m) the LHCb collision region.

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!



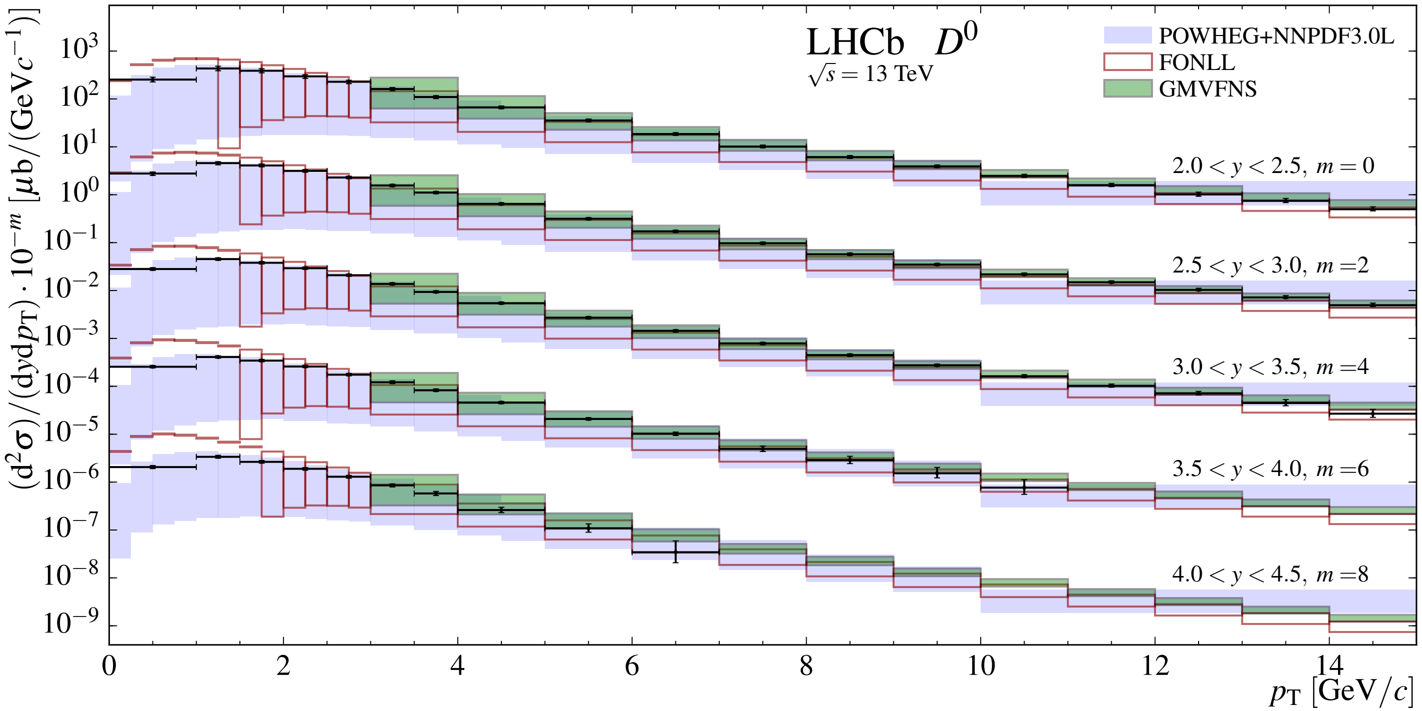
Possible targets: **He, Ne, Ar**, and more in the future

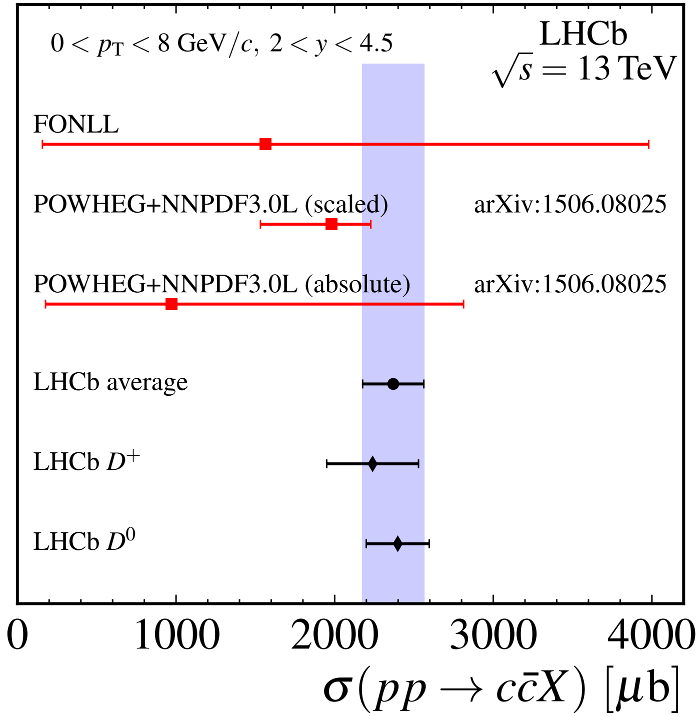
Gas pressure $\sim 2 \times 10^{-7}$ mbar ➡ $\mathcal{L} \lesssim 6 \times 10^{29} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

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

Charm production in pp collisions

- LHCb data provide measurements in the forward direction at the highest available energy at accelerators
- Exclusive measurements of D^0, D^+, D_s^+, D^*, Λ_c^+ for $7 \leq \sqrt{s} \leq 13$ TeV
- Data are remarkably more precise than theoretical uncertainty, notably at low p_T





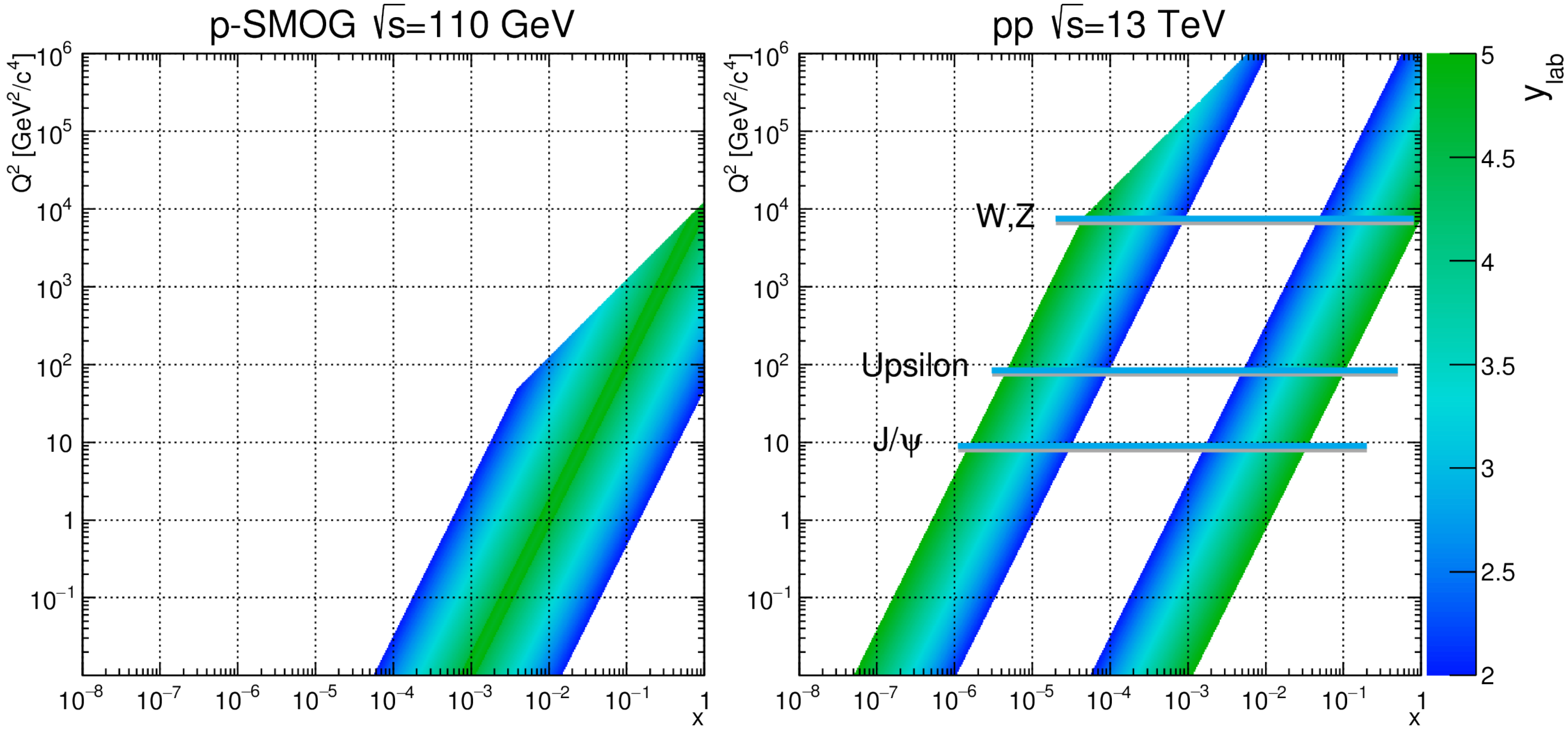
JHEP 03 (2016) 159, erratum JHEP 05 (2017) 074

- Main input to PDF fits and current predictions of atmospheric high-energy neutrino flux (see e.g. **PROSA collaboration JHEP 1705 (2017) 004**)

Charm production in fixed-target data

The fixed-target configuration offers some unique possibilities:

- accessing **large** x region in the target,
  not accessible in collider mode
  ➡ charm PDF at large x, possible **intrinsic charm** contribution and nuclear effects

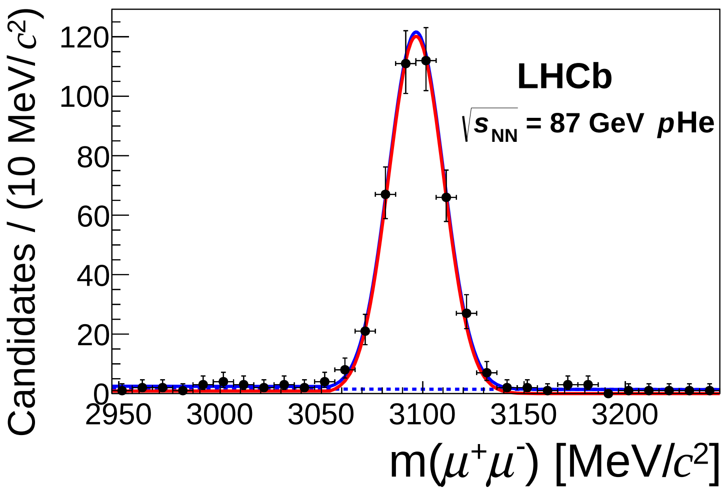


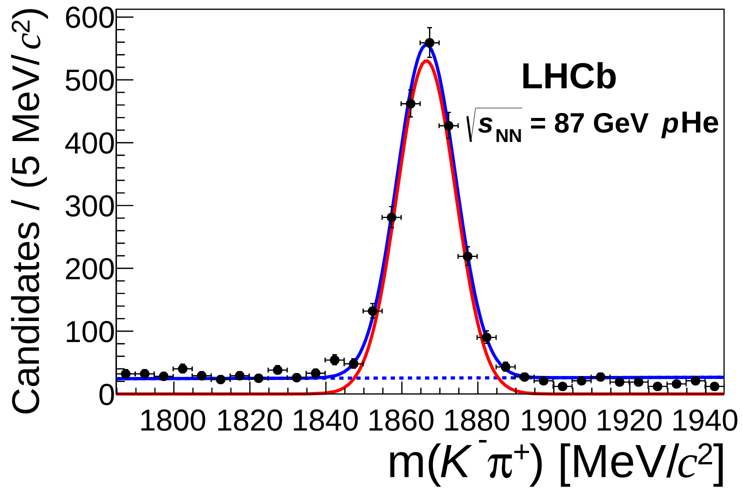
LHCb-PUB-2018-015

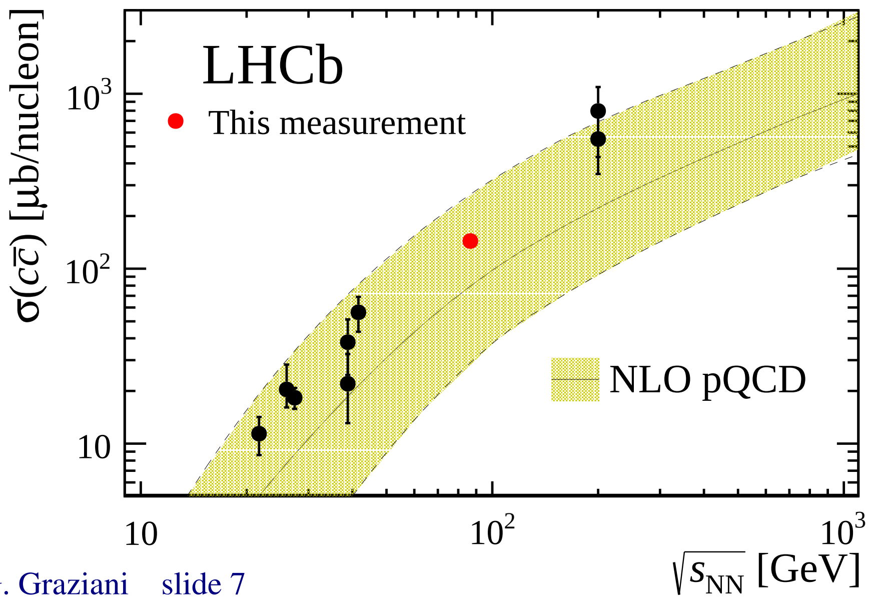
First charm signals in fixed-target data

PRL 122 (2019) 132002, Erratum to appear

- First charm samples from pHe @86 GeV (7.6 ± 0.5 nb^{-1}) and pAr @110 GeV (few nb^{-1})
- Charm cross section measured from ~ 400 $J/\psi \rightarrow \mu^+\mu^-$ and ~ 2000 $D^0 \rightarrow K\pi$ decays from pHe data (and differential shapes from similar statistics in pAr)

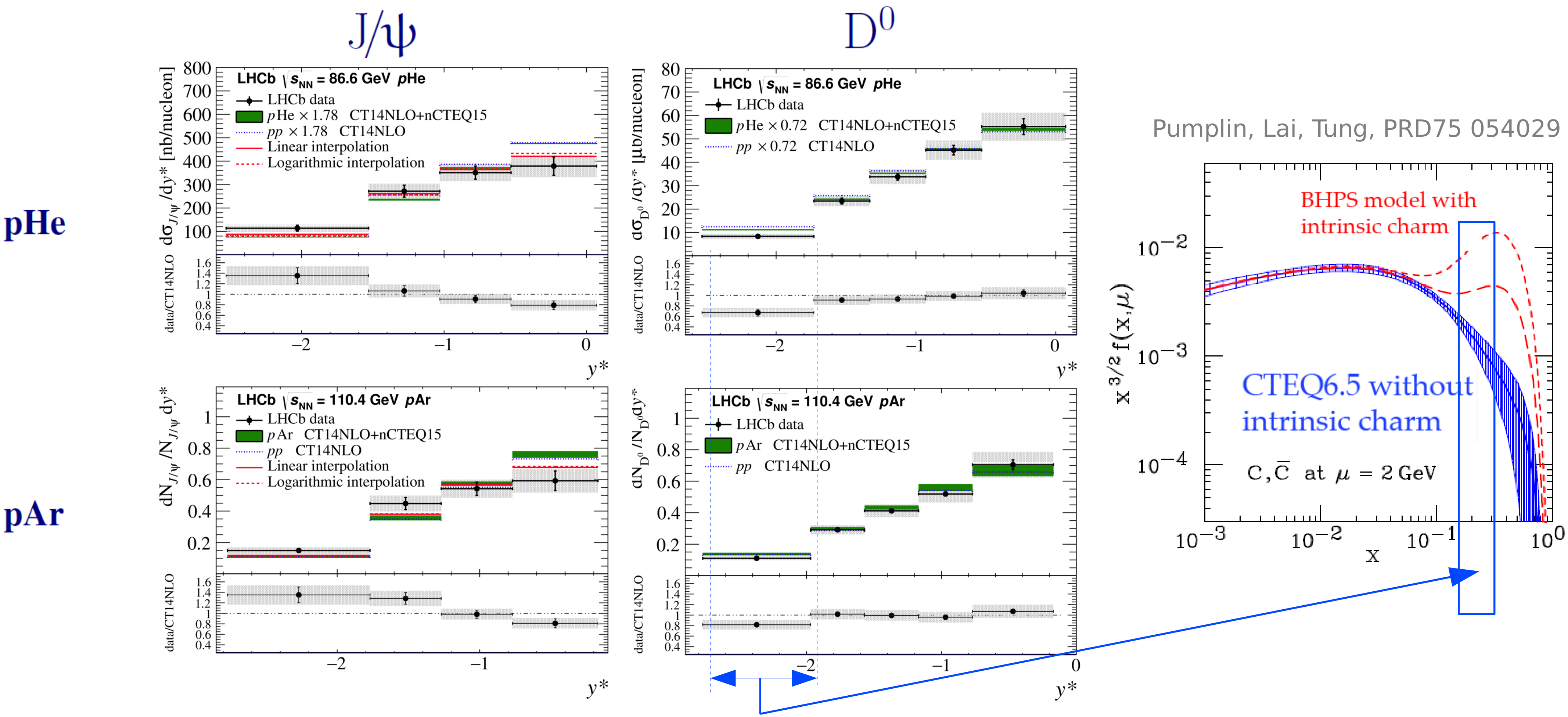






- First determination of $c\bar{c}$ cross-section at this energy scale

PRL 122 (2019) 132002



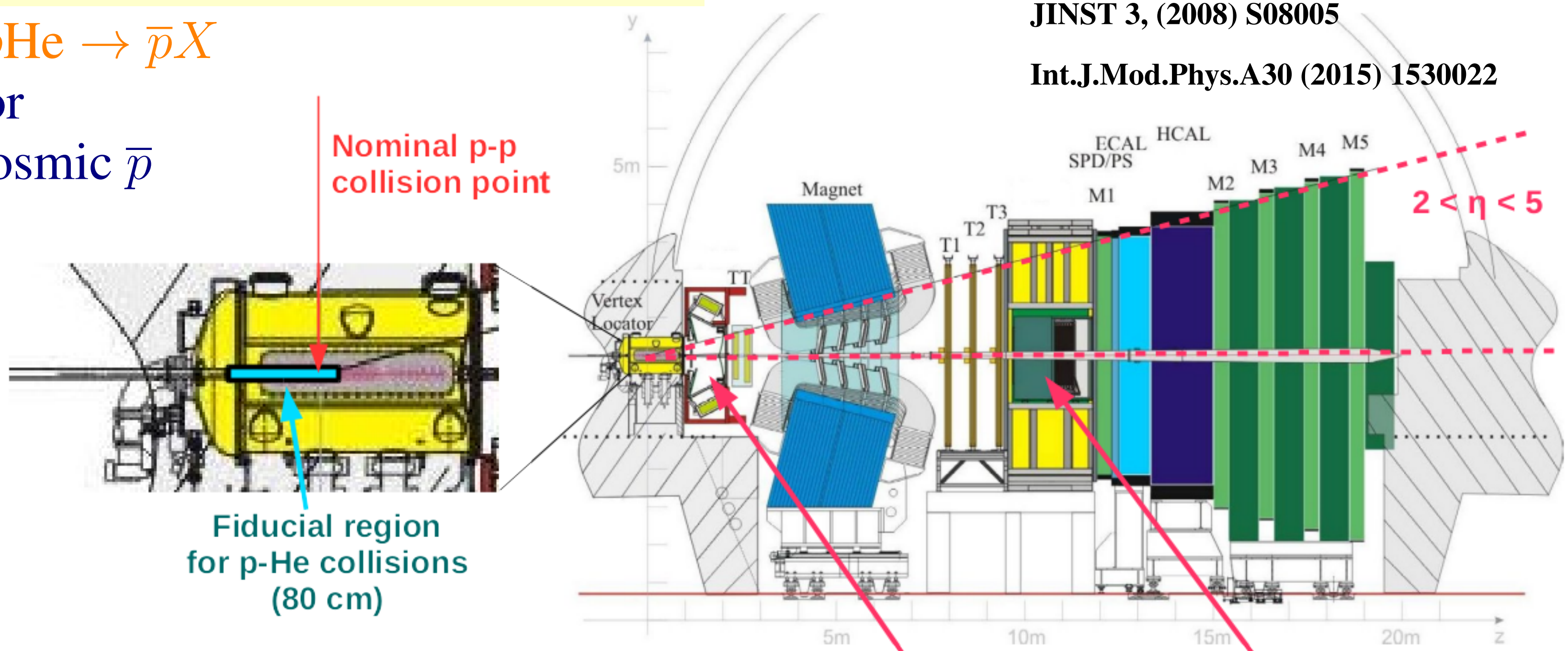
- Rapidity distributions in backward region compatible with predictions without Intrinsic Charm from the HELAC-ONIA model [Lansberg and Shao, EPJC 77 (2017) 1] in both pHe and pAr samples.
  ➡ no evidence for large IC contributions (unless tricky cancellations with nuclear effects)
- More to come from larger samples on tape ($\sim 100\ \mathrm{nb}^{-1}$ pNe)

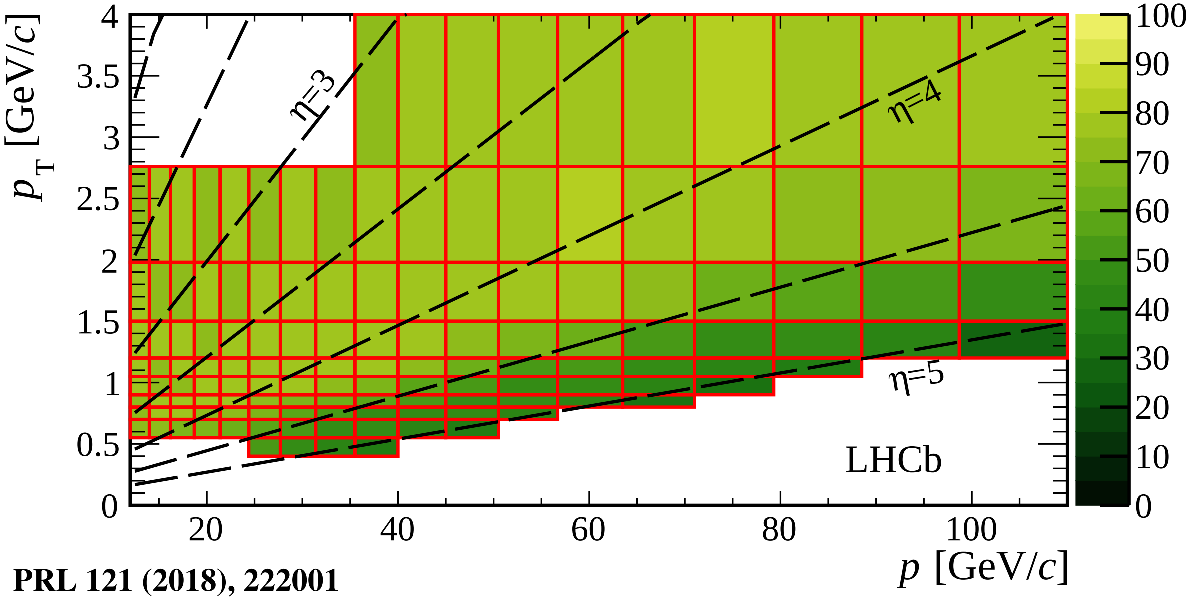
Antiprotons in pHe collisions

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

the process accounts for

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





PRL 121 (2018), 222001

Acceptance × reconstruction efficiency for antiprotons

Rapidity in c.m.s. system:

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

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

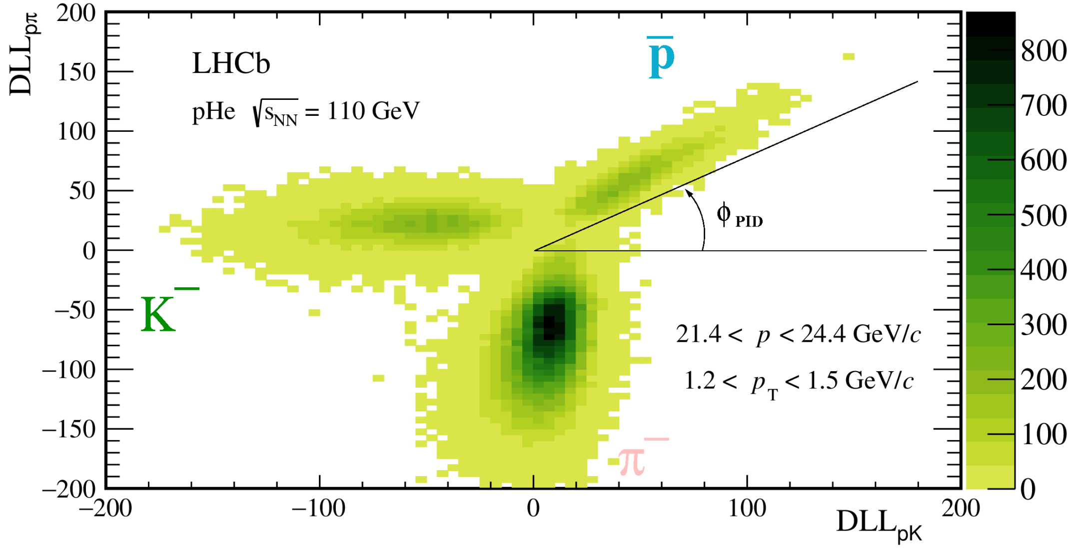
Data sample and particle identification

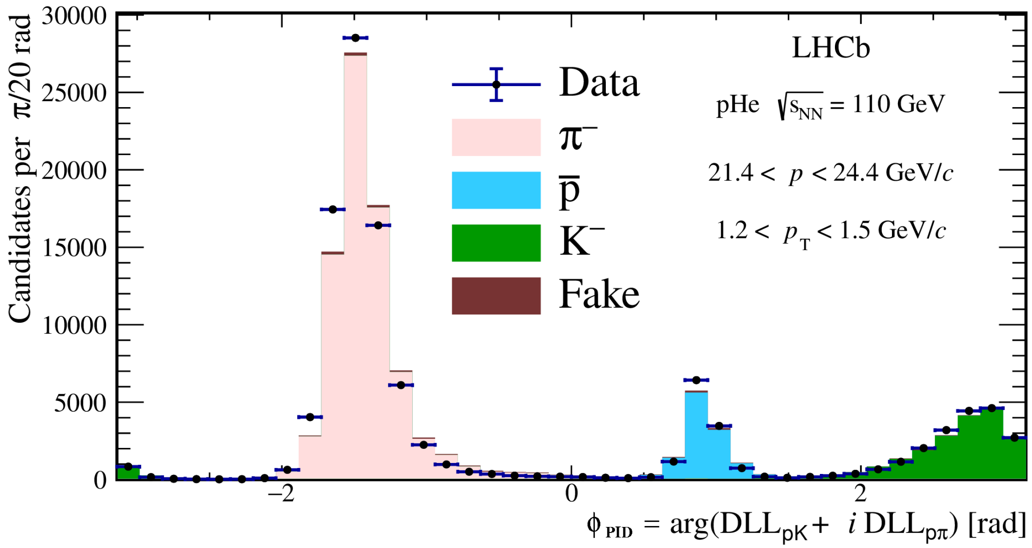
PRL 121 (2018), 222001

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

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

(good match with PAMELA/AMS-02 capabilities)

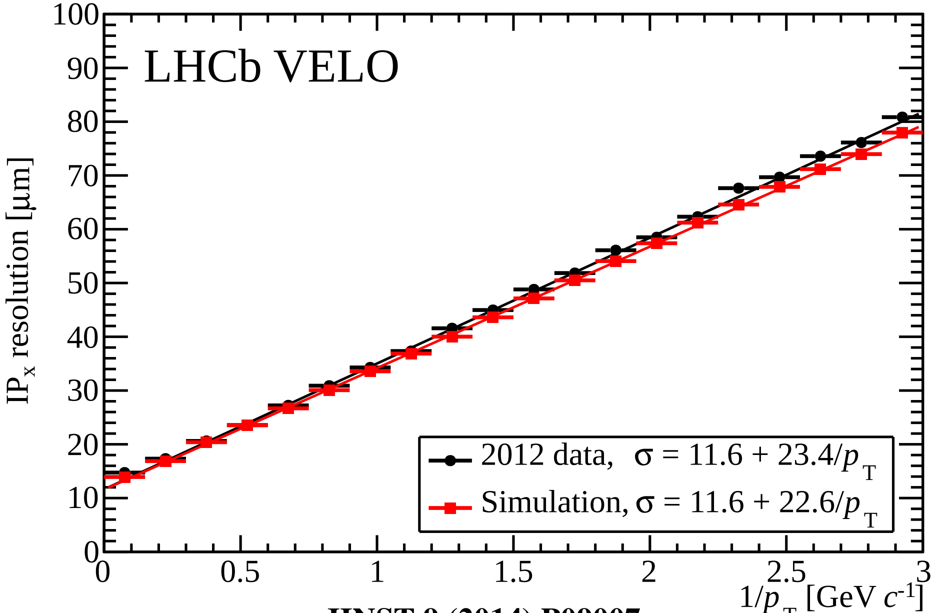




Antiprotons from weak hyperon decays

PRL 121 (2018), 222001

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



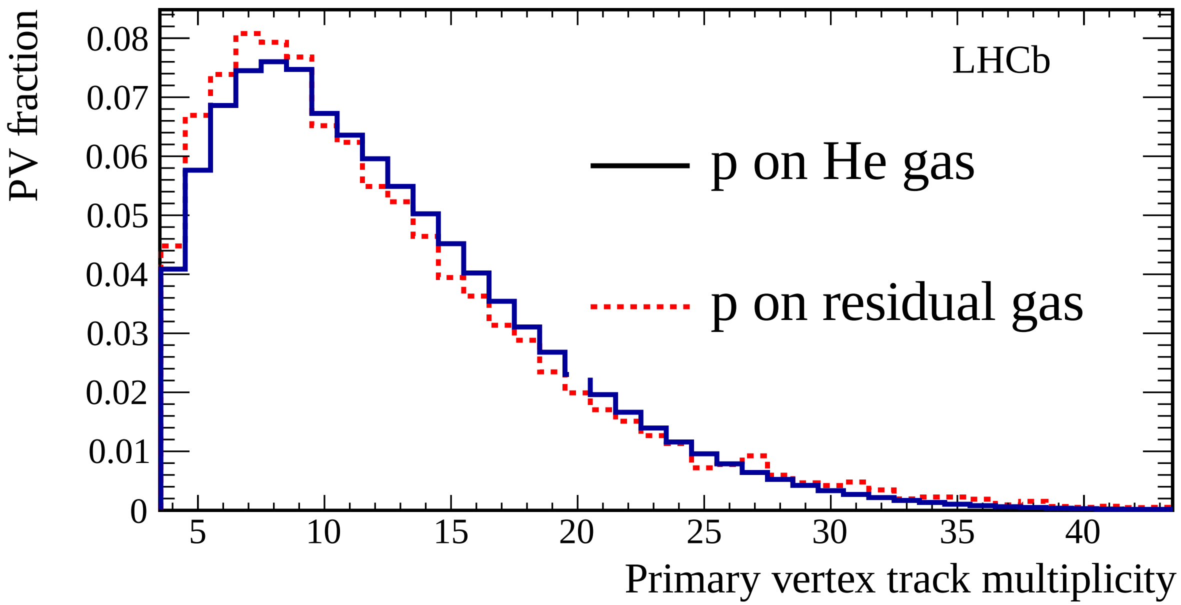
JINST 9 (2014) P09007

- 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

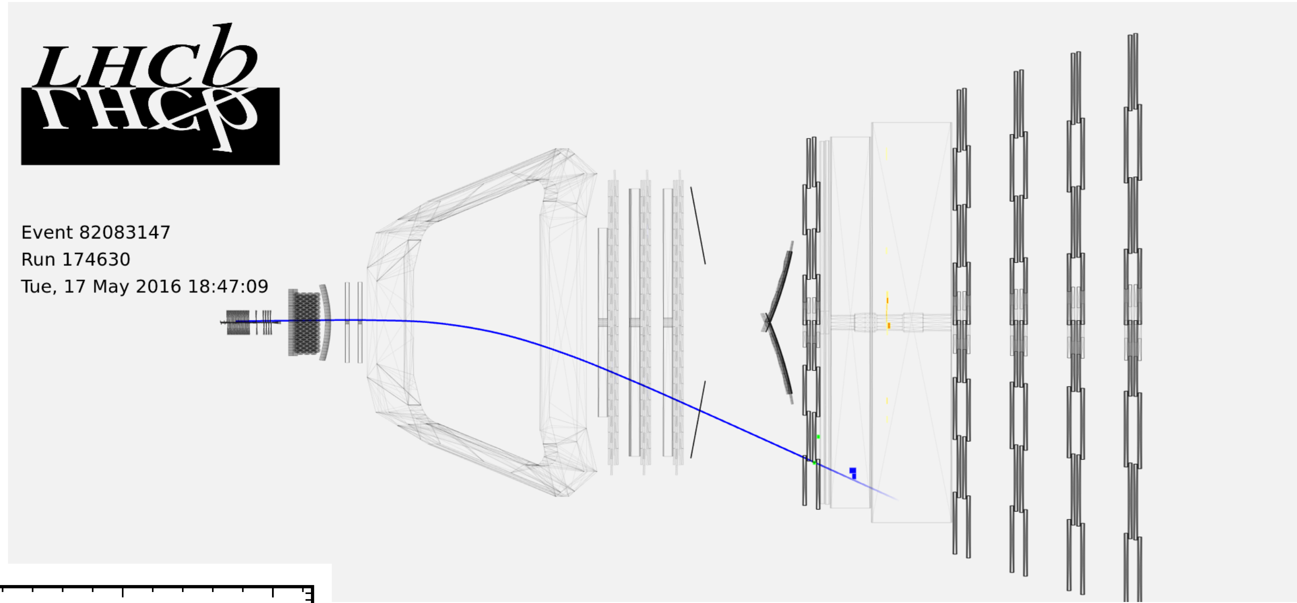
- Residual vacuum in LHC is not so small ($\sim 10^{-9}$ mbar) compared to SMOG pressure
- Can be a concern, especially for heavy contaminants (larger cross section than He), and beam-induced local outgassing
- Direct measurement in data: about 15% of delivered protons on target acquired before He injection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



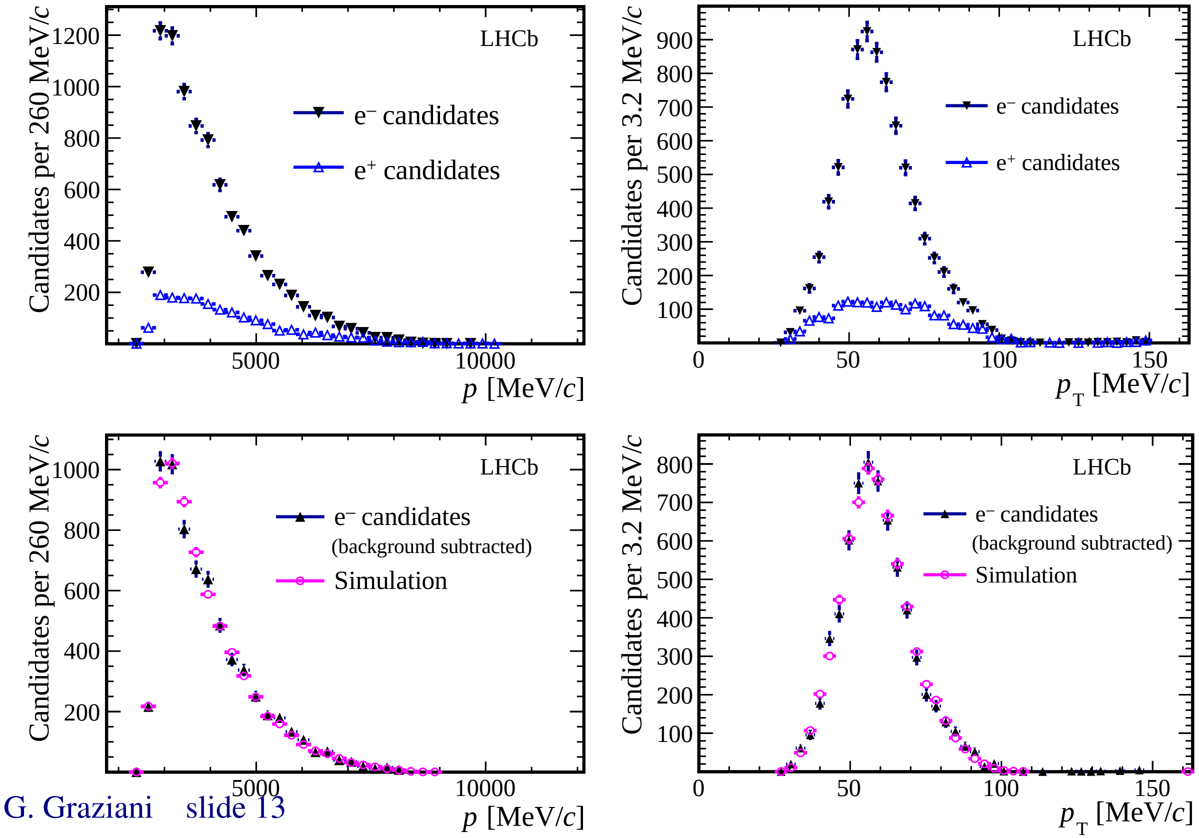
- Contribution from gas impurity found to be small: $0.6 \pm 0.1\%$
- PV multiplicity in residual vacuum events is **lower** than in He events, but has longer tails ➡ confirm findings from Rest Gas Analysis that residual vacuum is mostly H_2, with small heavy contaminants

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 ($\sim 16\%$)

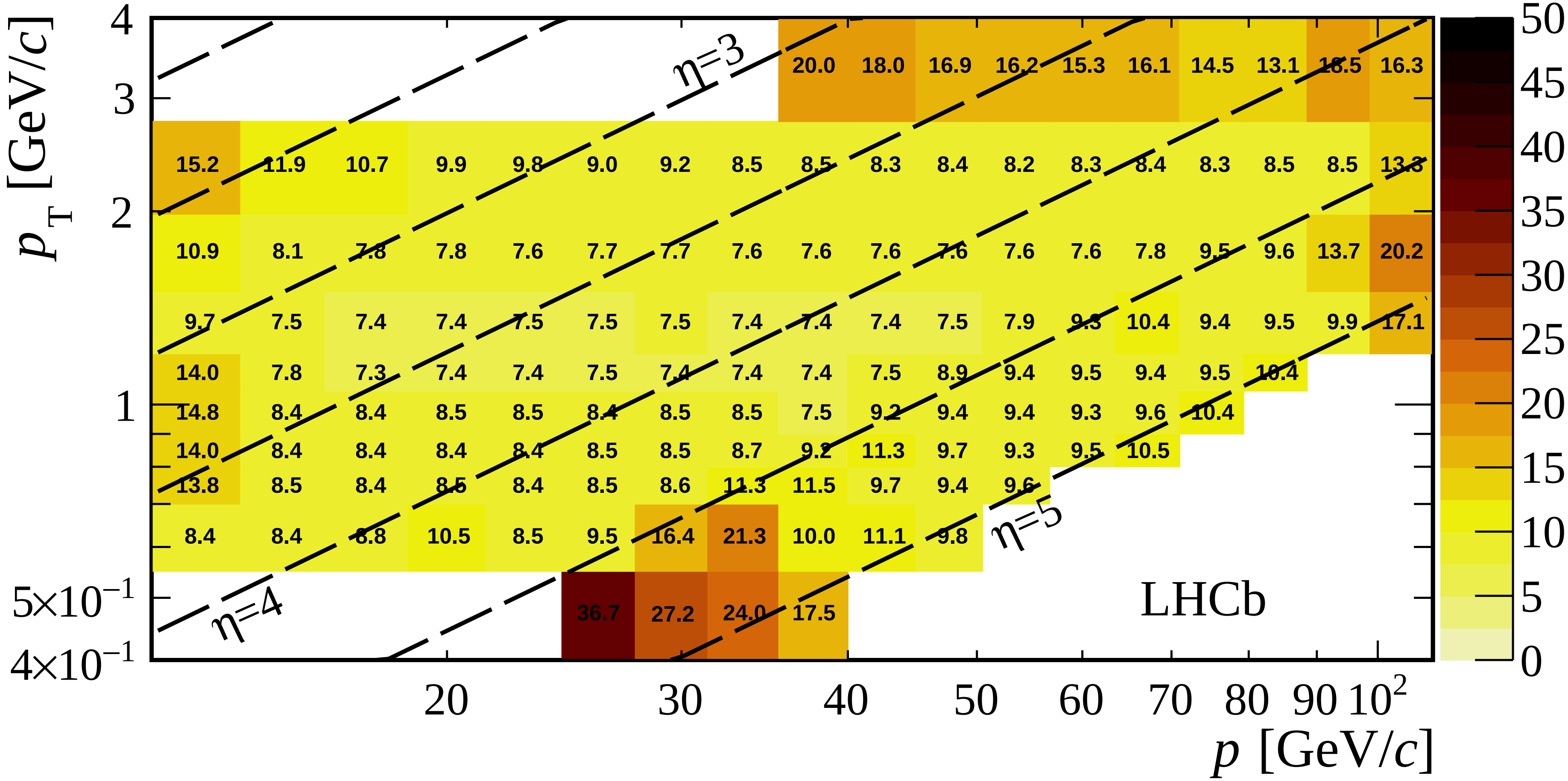
pHe $\rightarrow \overline{p}X$ result: uncertainties (relative)

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)

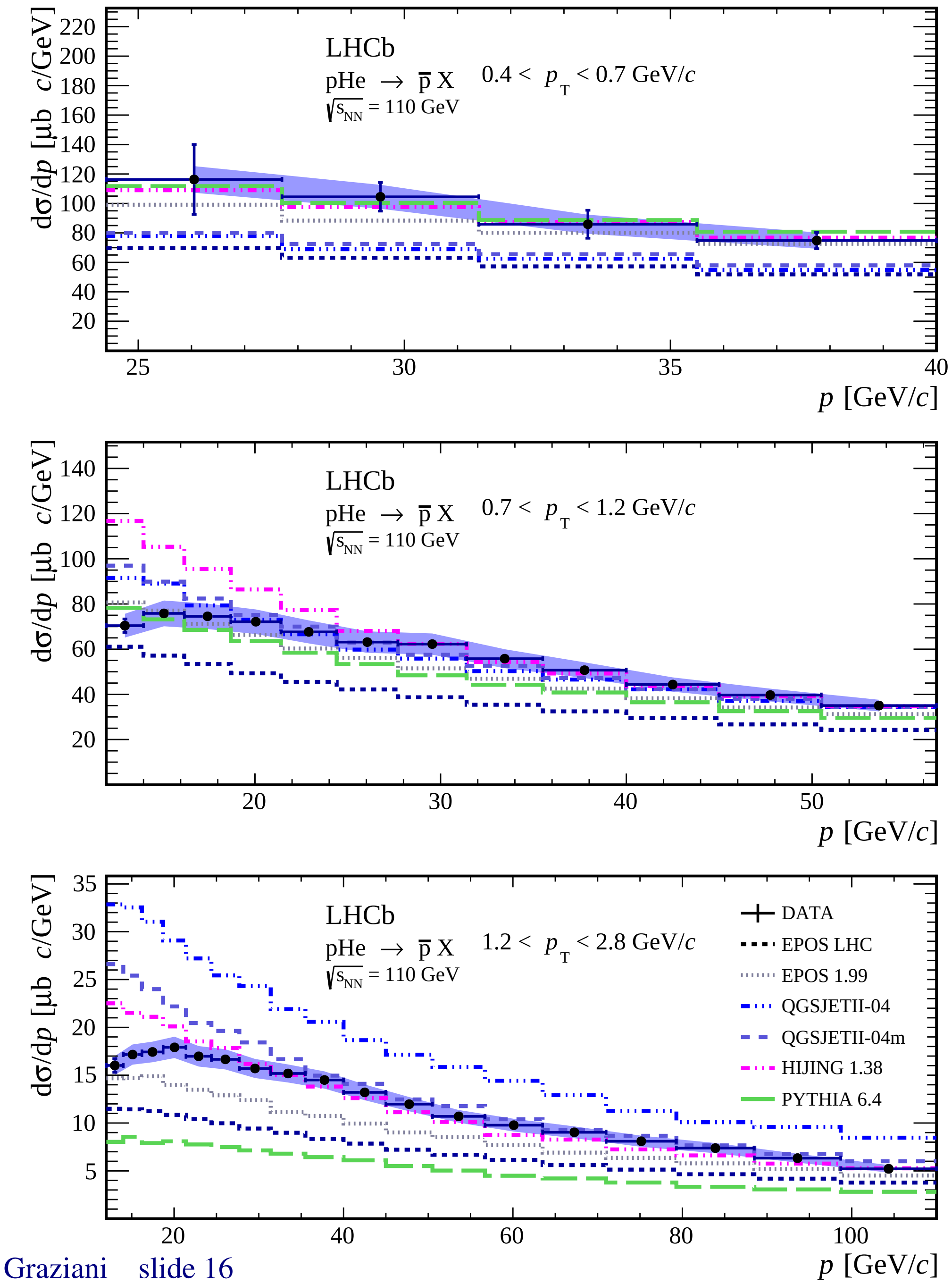
Total relative uncertainty per bin, in per cent

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**

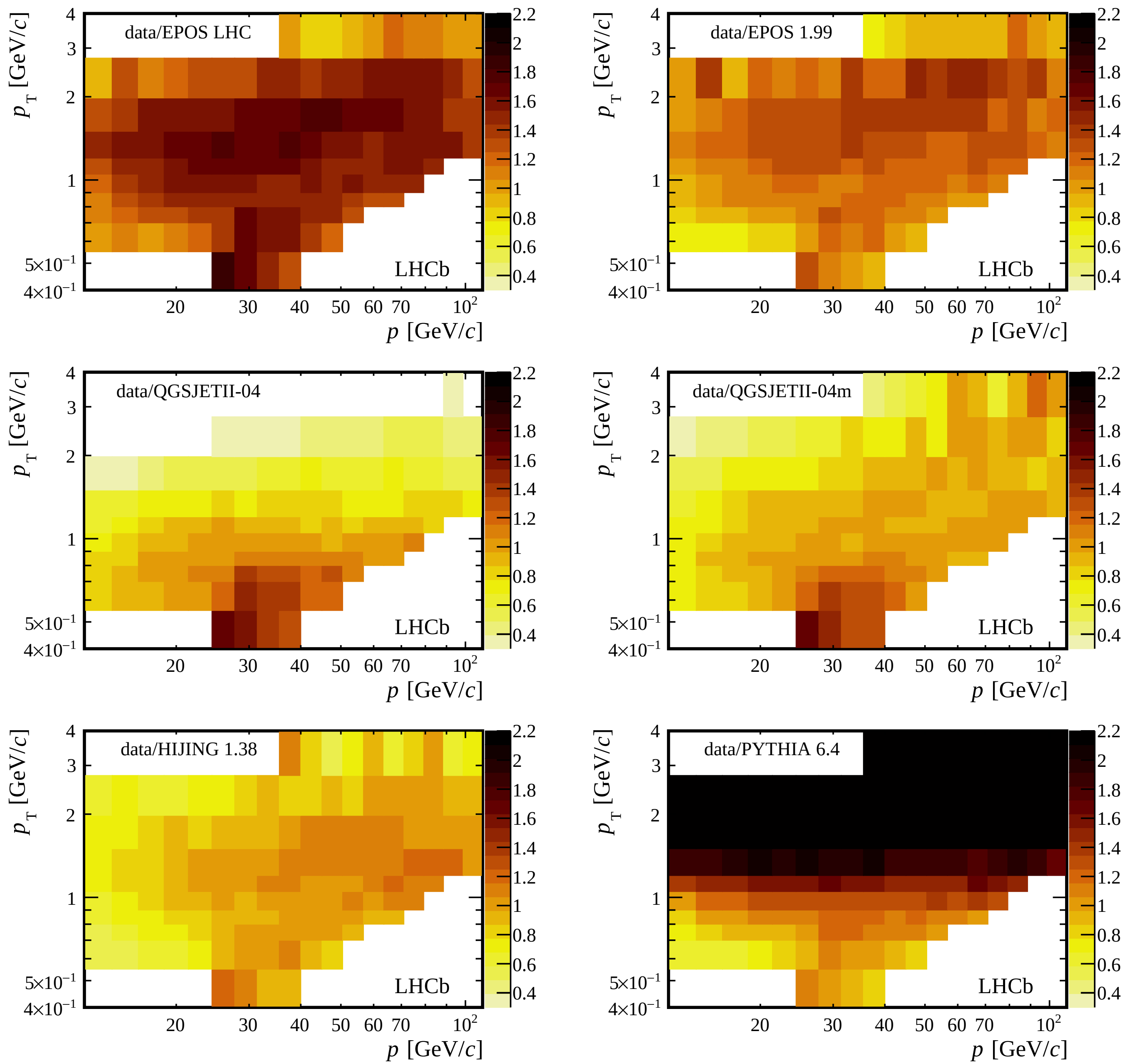
The “visible” inelastic cross section (yield of events reconstructable in LHCb) is compatible with simulation based on EPOS LHC:

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

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

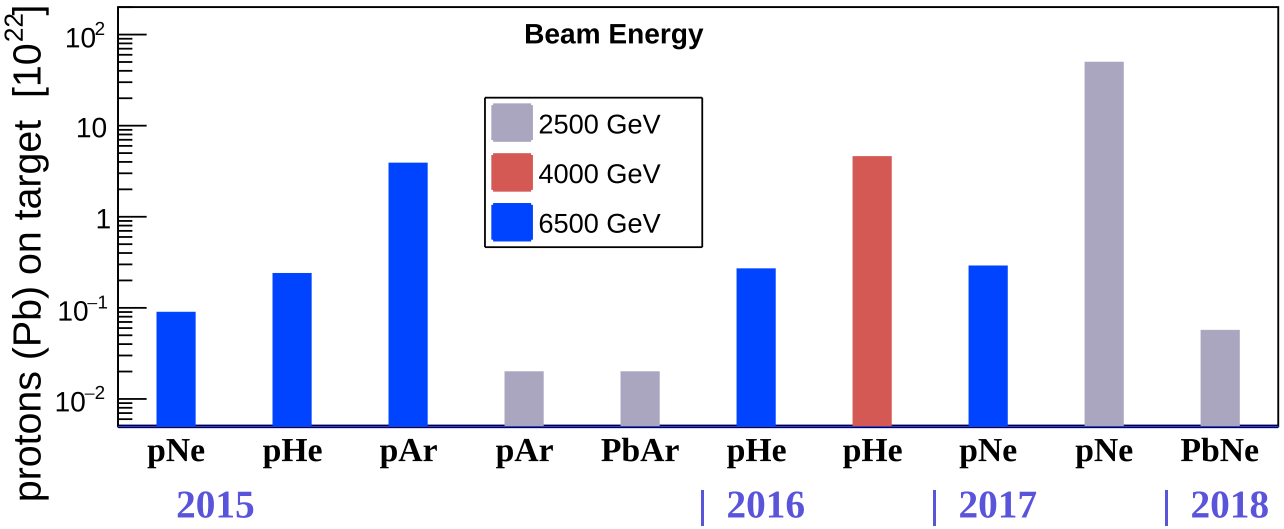
$p\mathrm{He} \to \bar{p}X$ result: ratio with models

PRL 121 (2018), 222001



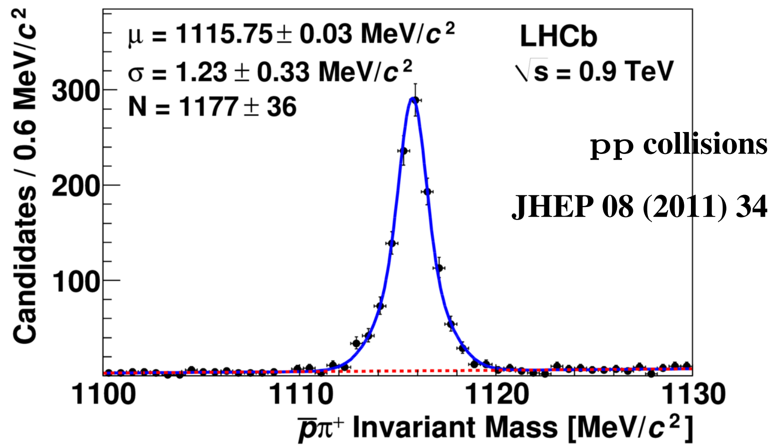
Prospects: Exploitation of current samples

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



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

- Extend the study to $\overline{p}$ produced by anti-hyperon decays (~20-30% of $\overline{p}$ production)
  - Measure $\overline{\Lambda} \rightarrow \overline{p}\pi^+$ exclusive production
  - Inclusive measurement of detached antiprotons

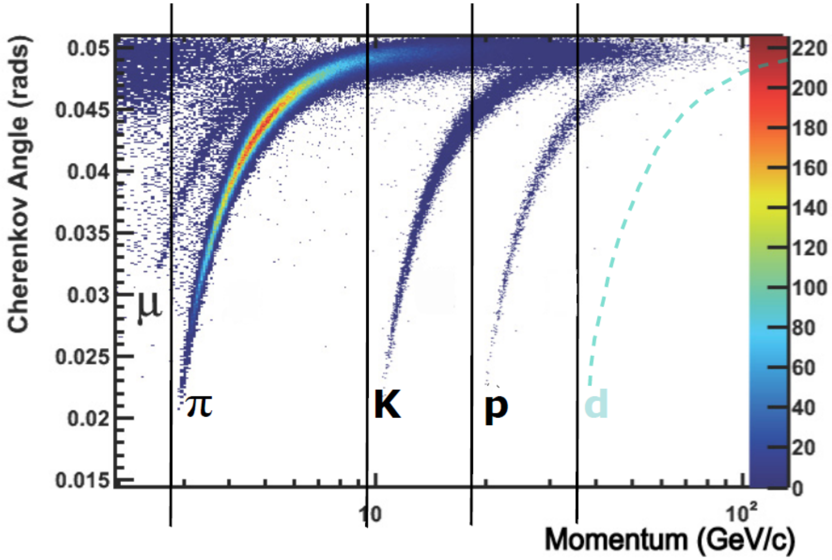


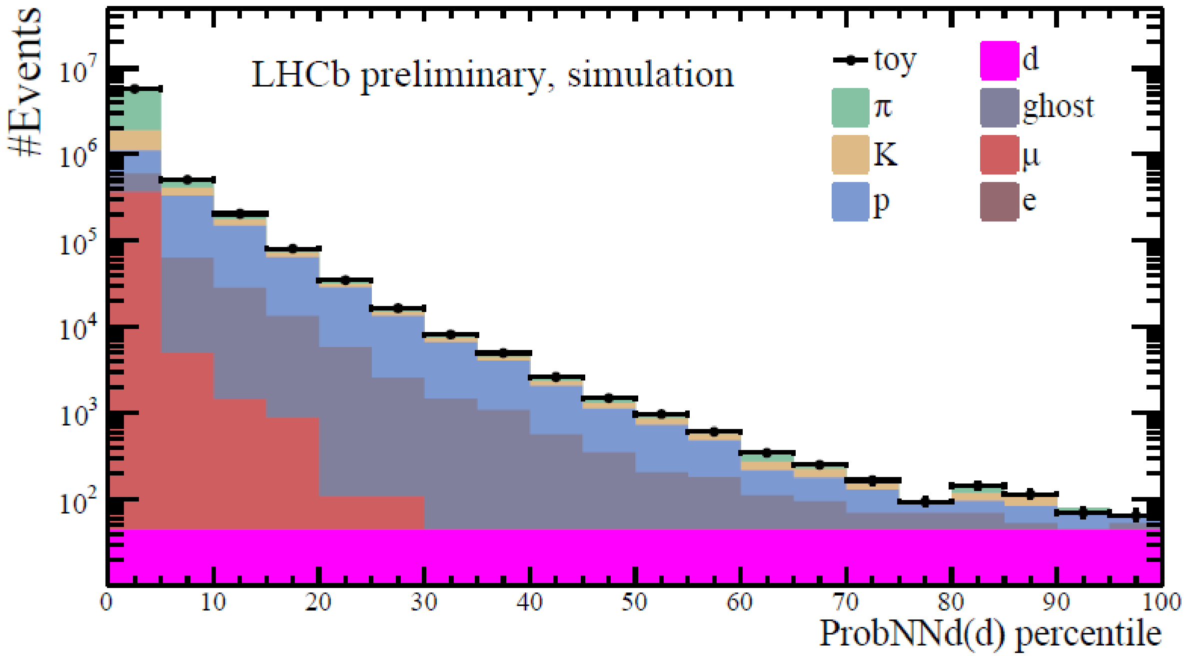
- Measure production of π, K, p from the various SMOG samples (He, Ne, Ar targets) ➡ estimate **positron** production

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





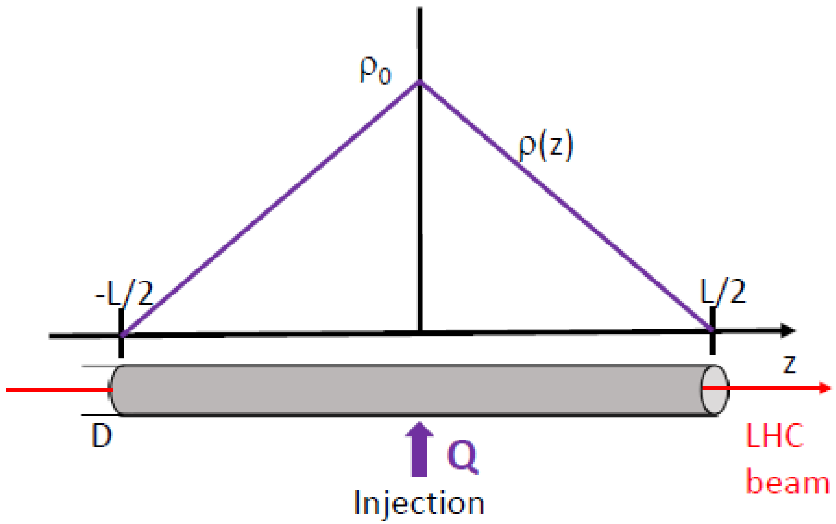
Simulated template fit on neural network classifier for deuterons identification in pp collisions at 13 TeV

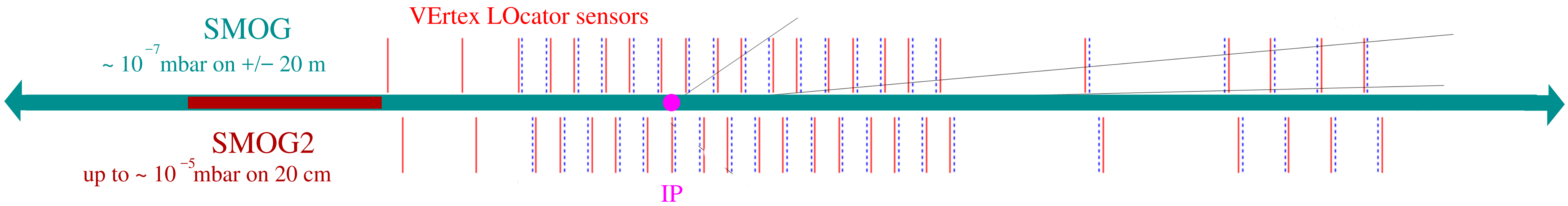
- Could be tried also on fixed target data in the future, if suitable trigger selection can be developed

Gas target upgrade

A substantial development of the fixed-target program is expected already from the LHC Run 3 (starting in 2021), thanks to a new gas target: SMOG2

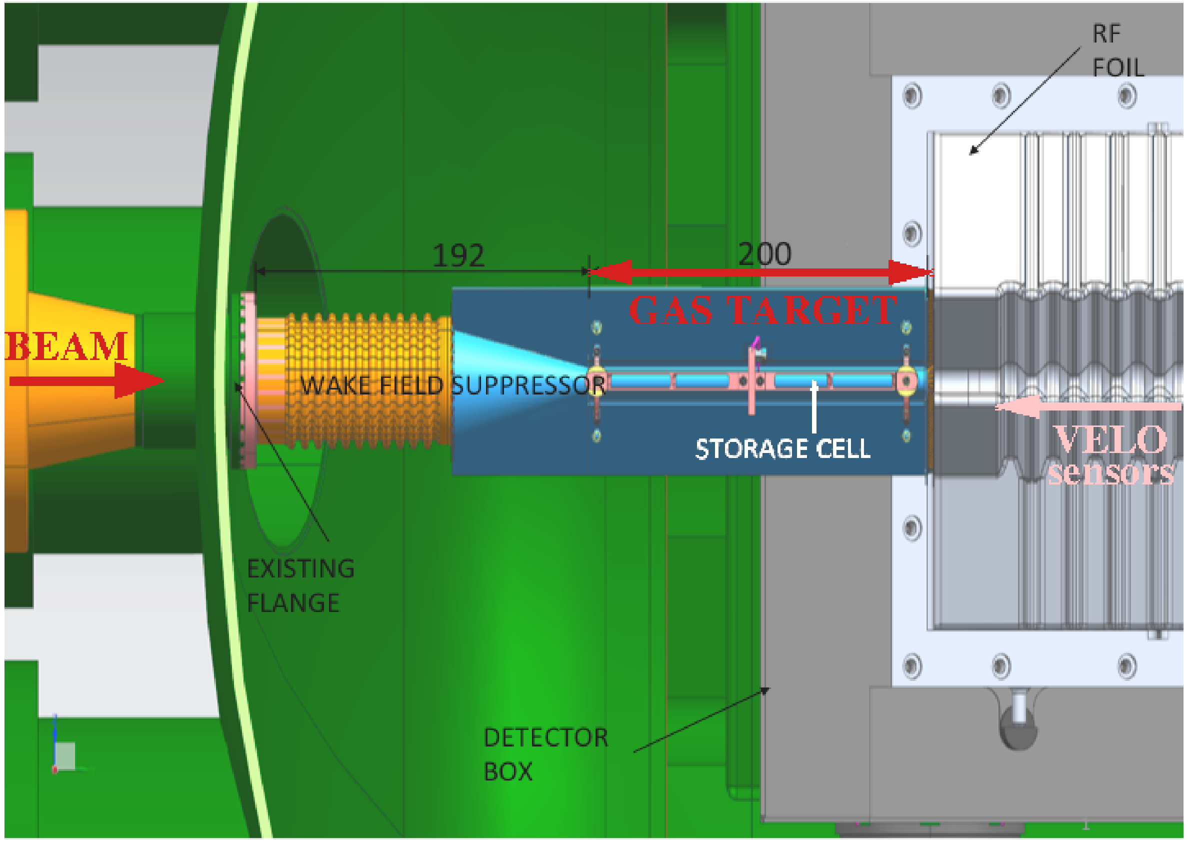
- contain gas in 20 cm long storage cell ➡ up to x100 increase of target density for same gas flow;





- lower contamination of beam line ➡ more gas species possible, as H, D, N, O
- better control over injected gas density (better accuracy on absolute cross sections).

The SMOG2 gas target



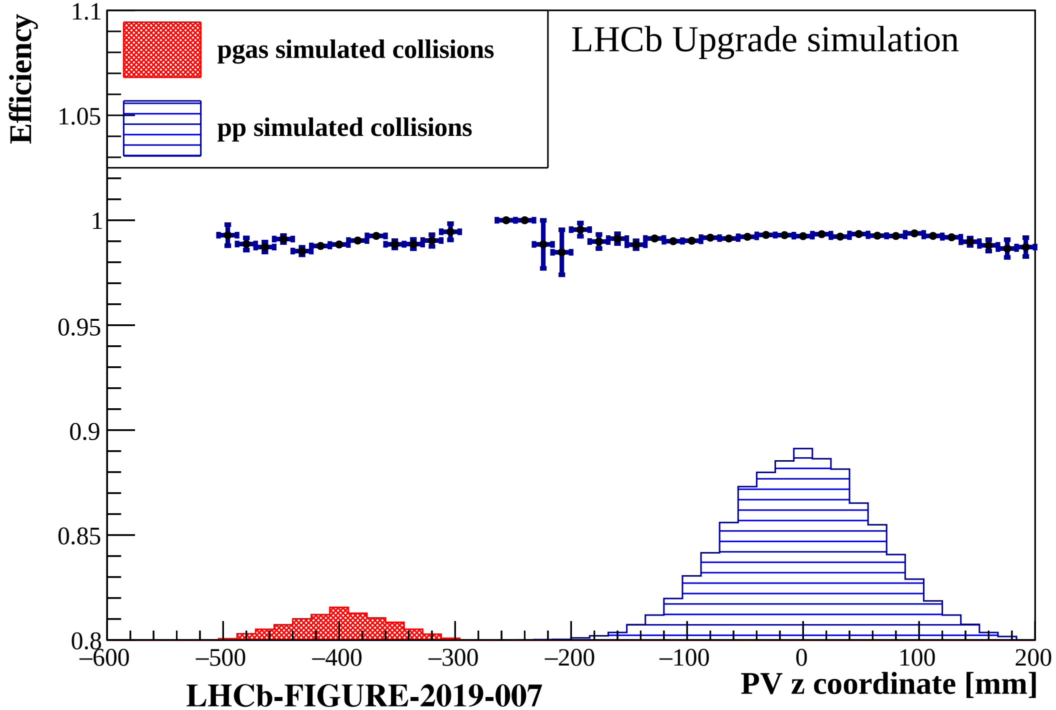
- Approved by LHCC **CERN-LHCC-2019-005l**
- Installation due in january 2020, to be operational from the start of LHC Run 3

- 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 feed system measures the gas density with $\sim 2\%$ accuracy

Data-taking scenario

- Fixed-target data-taking should not affect the core LHCb *pp* program
- Gas flow limited by machine safety (notably for hydrogen and heavy gas)
- To maximize physics output, we aim at acquiring beam-gas events simultaneously with *pp* events, using all bunches in the LHC beam
  ➡ include beam-gas events in the extremely challenging online software reconstruction and selection foreseen for the LHCb upgrade: 30 MHz with 5 visible *pp* interaction per bunch crossing

Tracking efficiency vs longitudinal vertex position



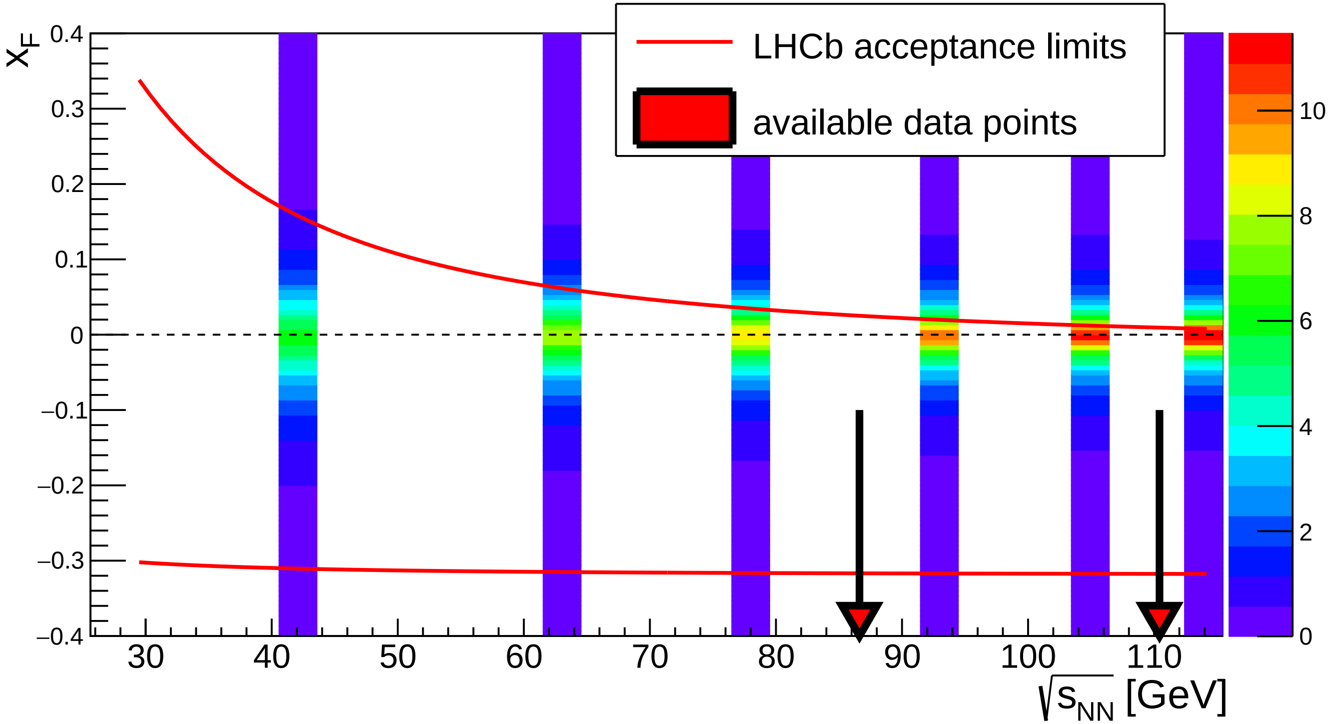
LHCb-FIGURE-2019-007

- Ongoing work shows promising performance for simultaneous data-taking

Antiprotons with SMOG2

LHCB-PUB-2018-015

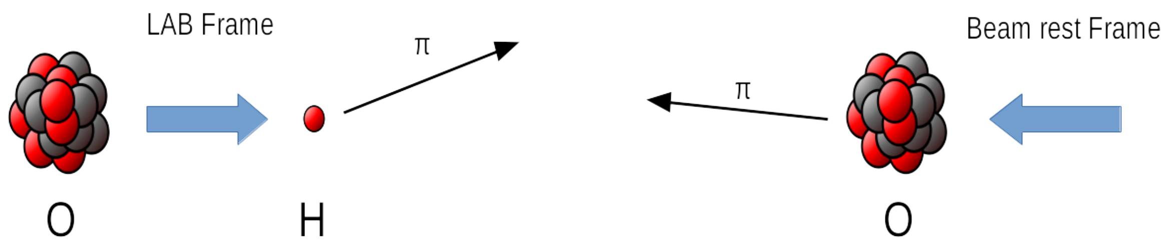
- Possibility to complete the cosmic $\overline{p}$ study:
  H target to also measure $pp \to \overline{p}X$ and ratios with pHe
  D target to test isospin violation (relevant for antineutron production)
  Data at lower energy to measure evolution with energy (scaling violations) and access forward region (Feynman-$x > 0$)

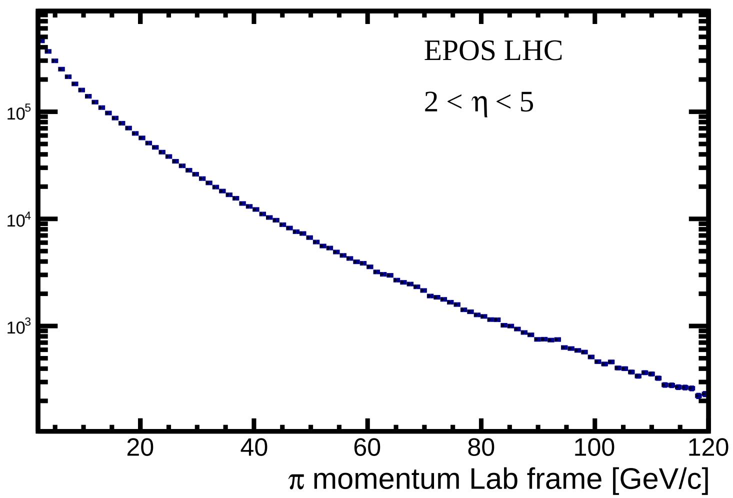


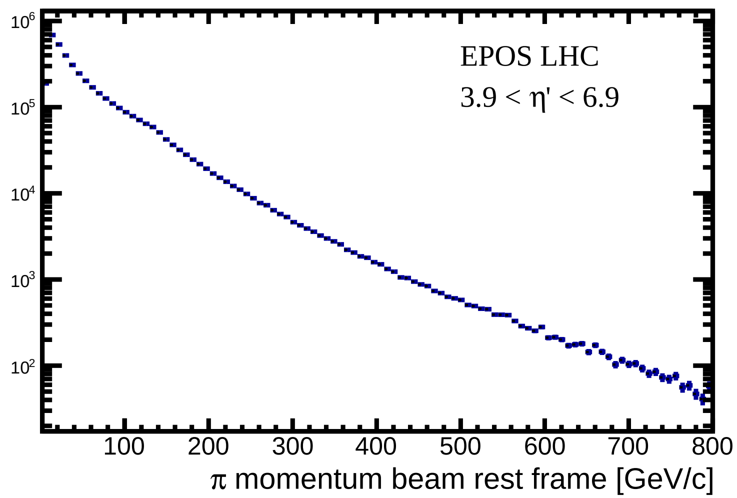
Feynman-x distribution for $\overline{p}$ vs $\sqrt{s_{\rm NN}}$ and accessible region to LHCb

"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 $\sqrt{s_{\rm NN}} = 9.9$ TeV with forward acceptance
  - oxygen beams on H target give access to very forward particles in pO (up to $\eta = 6.9$) at $\sqrt{s_{\rm NN}} \sim 100$ GeV







Conclusions

- Thanks, notably, to its fixed-target program, LHCb became an unexpected contributor to cosmic ray physics!
- Many new measurements will be possible with the gas target upgrade already from Run 3 (starting in 2021)
- Great support from **CERN** and the **HEP community**
- Inputs/feedback from the **astroparticle community** is a key ingredient (pHe program proposed by O. Adriani, F. Donato *et al*)

The LHCb space mission is reaching new heights!

Opening talk at Hard Probes (Eckhard Elsen)

Welcome to Hard Probe 2018

Eckhard Elsen

Director Research and Computing

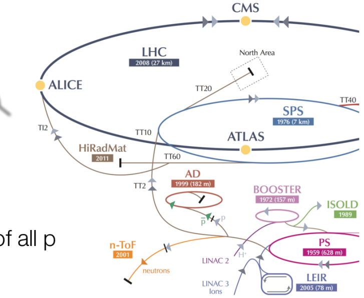
The conference is focused on experimental and theoretical developments on perturbative probes of hot and dense QCD matter as studied in high-energy nucleus-nucleus, proton-nucleus and proton-proton collisions, including: (i) nuclear Parton Distribution Functions and early-time dynamics, (ii) jets and high-pT hadrons, (iii) heavy quarks (charm, bottom, top), and quarkonia, (iv) high-pT photons and electroweak bosons, and (v) future experimental and new theoretical developments in associated topics.

Hard Probes 2018. International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions, Aix-Les-Bains, Oct 1, 20

LHC and its injector chain

- LHC
  - ongoing Run 2 @ 13 TeV
- Injectors supporting
  - Fixed target programme
  - ISOLDE (isotopes)
  - n-ToF
  - AD-programme

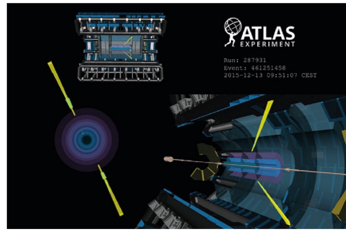
75% of all p

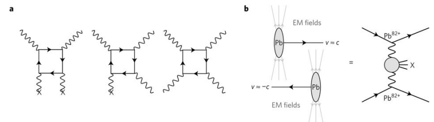


ATLAS

Light by light scattering in Heavy Ion Scattering

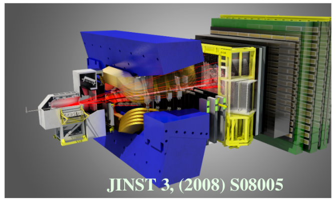
- Heavy Ion acts as a copious source of photons
- ATLAS Collaboration Nature Physics 13, 852–858 (2017) doi:10.1038/nphys4208

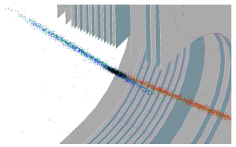




LHCb in Fixed Target mode

- System for Measuring Overlap with Gas (SMOG) allows to inject small amount of noble gas (He, Ne, Ar,…) inside the LHC beam around (±20 m) the LHCb collision region
- pressure ~ 2 × 10^{-7} mbar
- In the meantime used for fixed target physics simultaneously with pp-mode.
- Further plans for PBC-study

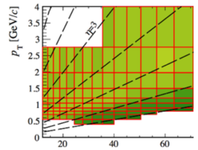


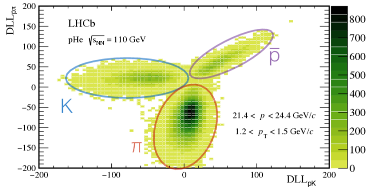


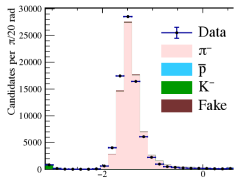
LHCb

pHe scattering using gas target

- Measurement of prompt antiproton production in pHe collisions
  - PID from RICH detector response
  - 3 templates built from simulated samples
- 2-d binned extended ML fit and cut-and-count method used to determine antiproton fraction



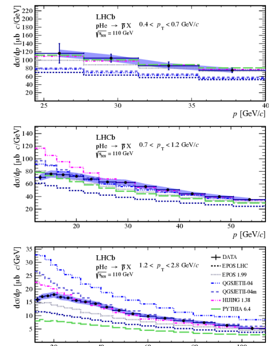




LHCb

$\bar{p}$ production in pHe interactions at $\sqrt{s} = 110\,\mathrm{GeV}$

- Antiproton production cross section shown (integrated over different kinematic regions)
- Uncertainty lower than 10% for most bins
  - Lower than spread between predictions from various theoretical models
- Improves the precision of secondary antiproton cosmic ray flux predictions



Message from "Physics Beyond Colliders"

Concluding slide from C. Vallée (PBC convener) at EPS (ECFA session)

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

A SPS Beam Dump Facility would cover a worldwide unique domain for hidden sector searches complementary to high-energy colliders and non-accelerator experiments
A mid-size project now mature for an implementation decision

FOR PROJECTS OUTSIDE CERN

Support is required to fully exploit the potential of National Labs for both non-accelerator projects (e.g. IAXO) and precision physics (e.g. pEDM R&D)

The particle physics potential of the new European facilities such as ESS and DESY XFEL requires support to be fully exploited in the long term.

C. Vallée, ECFA-EPS, 13 July 2019 Physics Beyond Colliders 23

Message from the European Strategy Group

CERN-ESU-004
30 September 2019

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].

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.

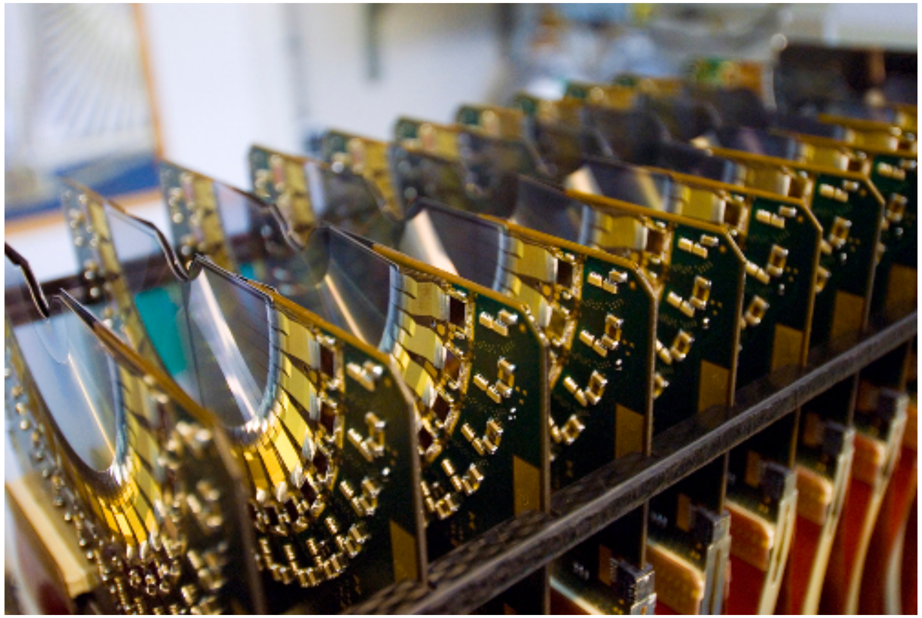
. . .

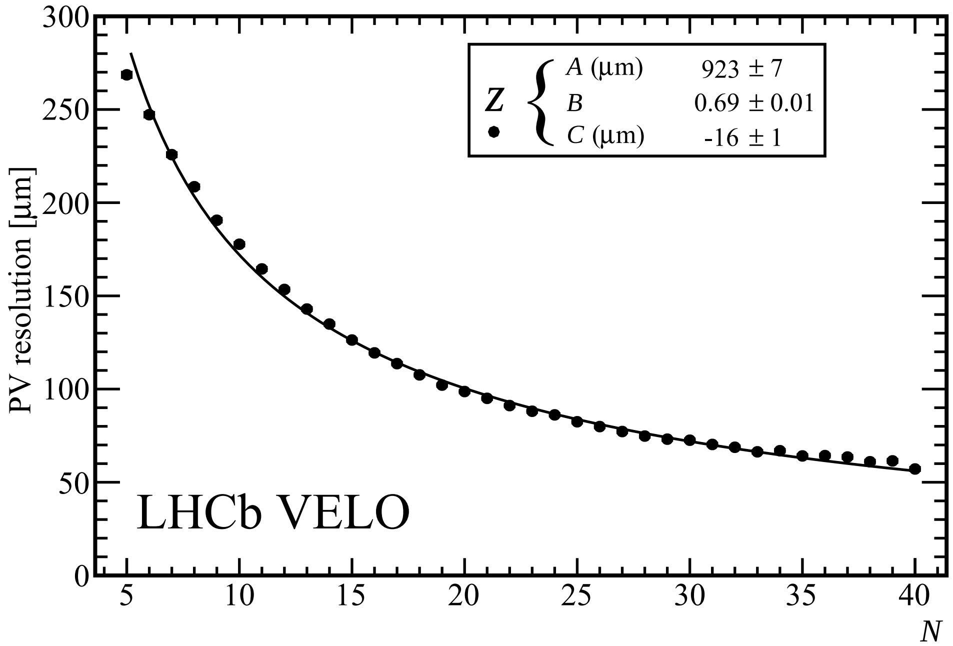
The physics reach of the LHC complex can greatly be extended at a very limited cost with the addition of an ambitious and long term LHC-FT research program. The efforts of the existing LHC experiments to implement such a programme, including specific R&D actions on the collider, deserve support.

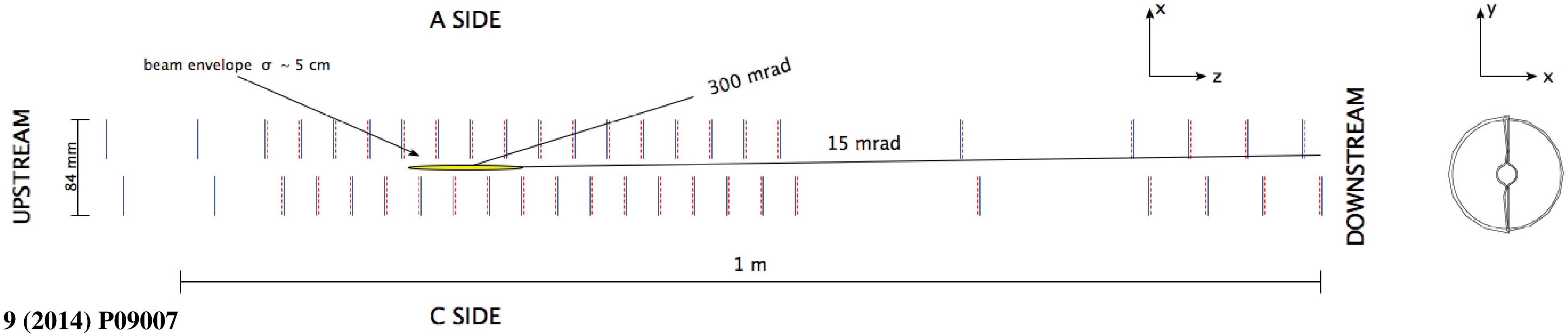
Additional Material

the VErtex LOcator

- Excellent LHCb vertexing capabilities, optimized for forward particles, allow to distinguish prompt and secondary particles from weak decays



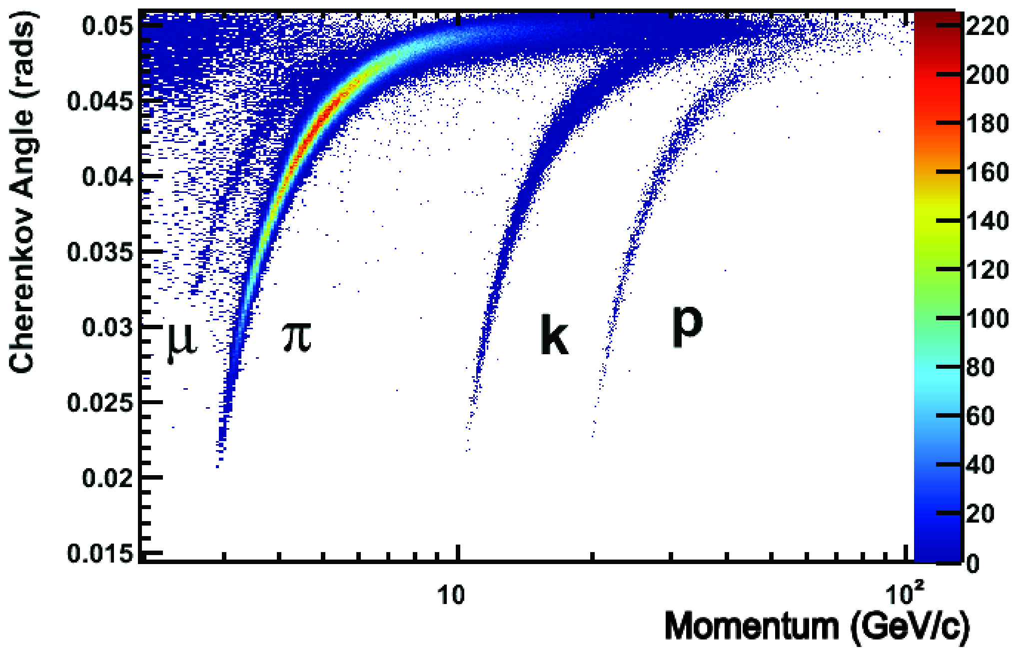




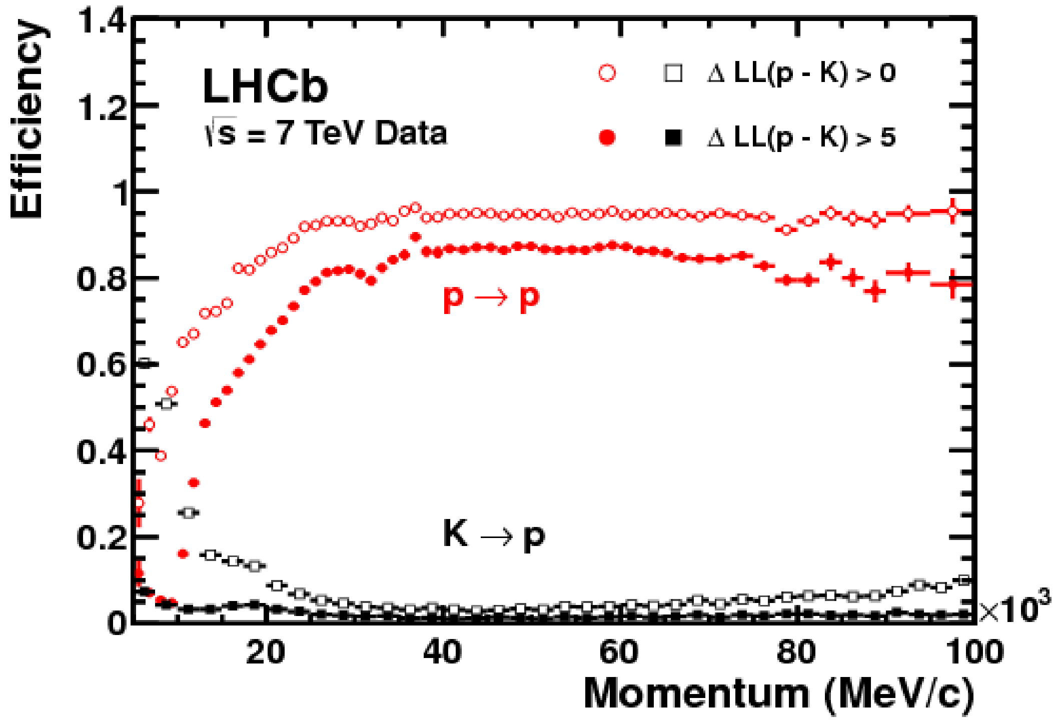
JINST 9 (2014) P09007

RICH Performance

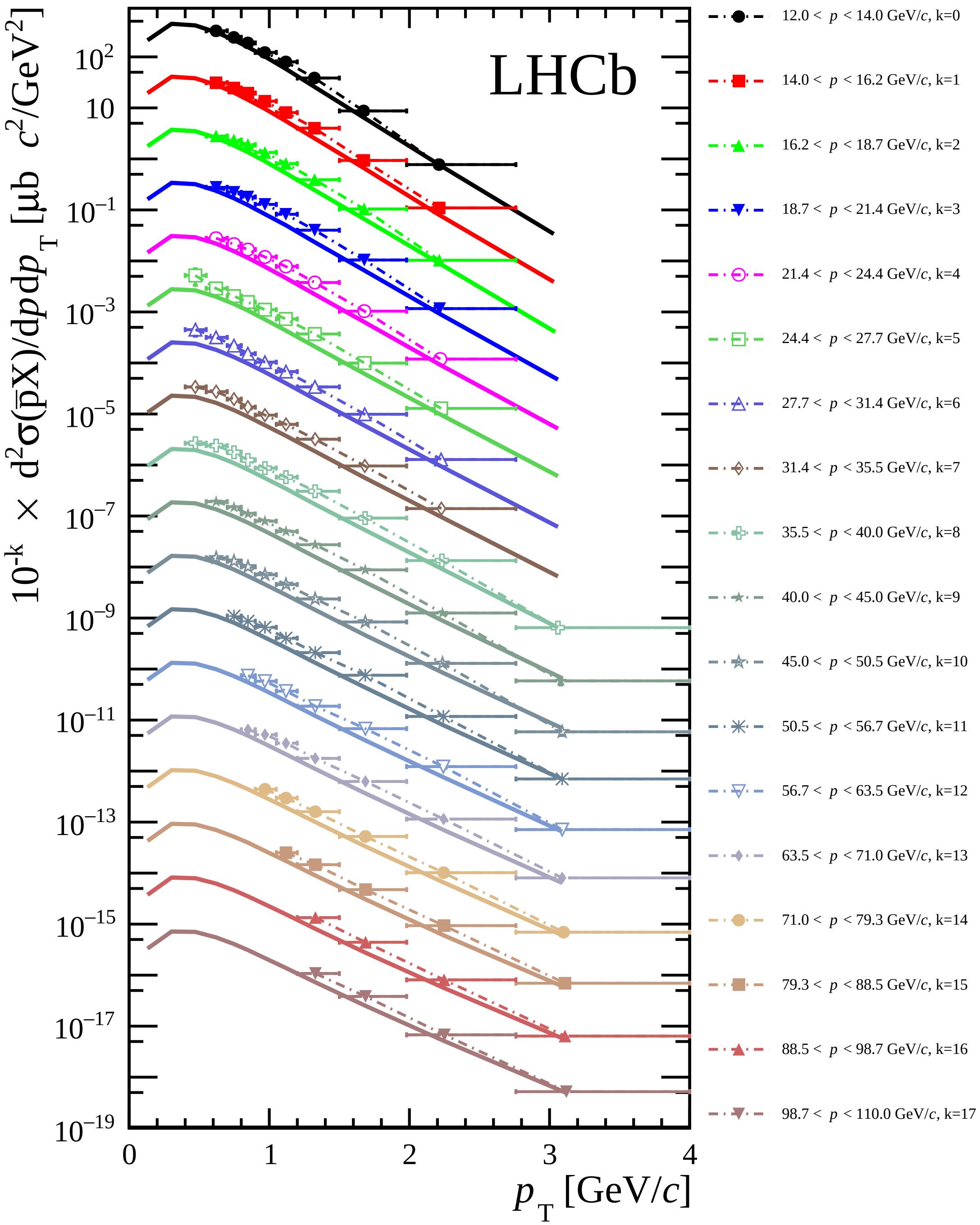
Eur. Phys. J. C 73 (2013) 2431



Particle separation in RICH1



K/p separation vs momentum



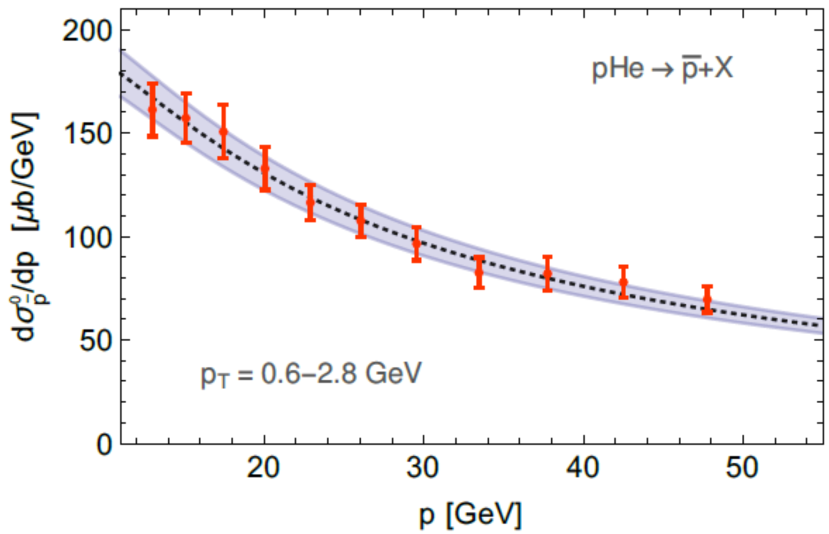
$\bar{p}$ production in pHe @ 110 GeV

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

PRL 121 (2018), 222001

pHe $\to \bar{p}X$: Implications for cosmic antiprotons

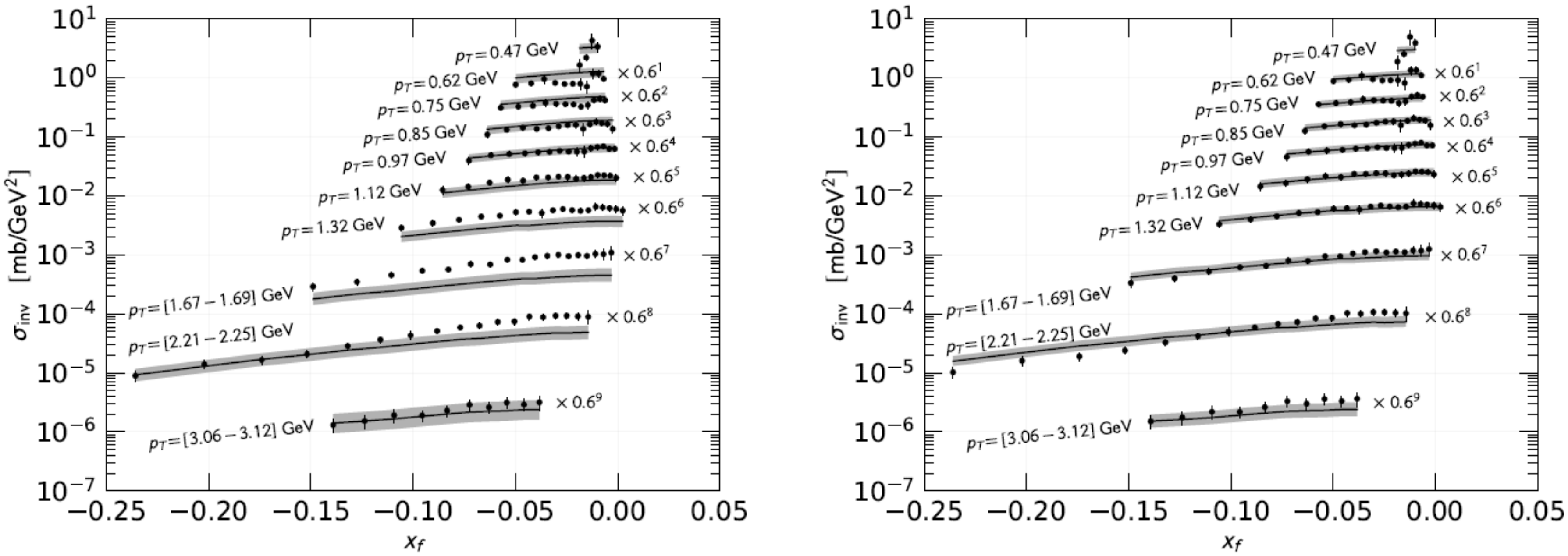
Reinert and Winkler, JCAP 1801 (2018) 055



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

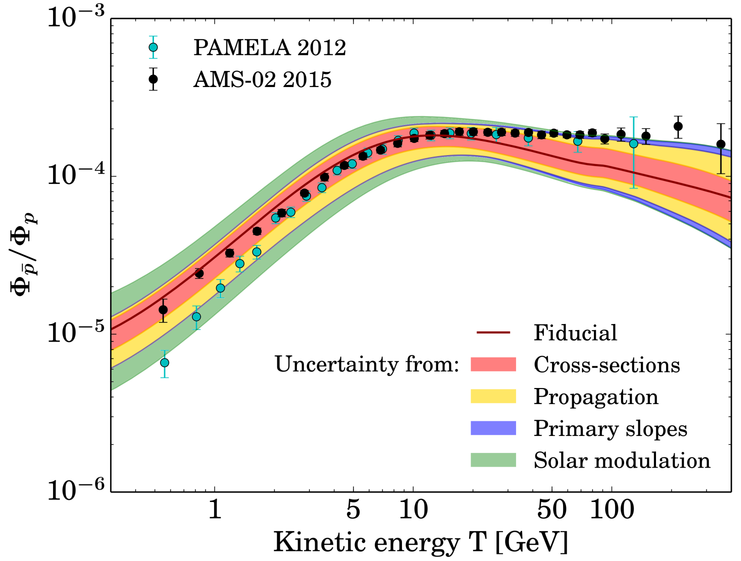
- extrapolations from pp data to pHe cross-sections
- empirical parametrizations for scaling violation of cross-sections

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

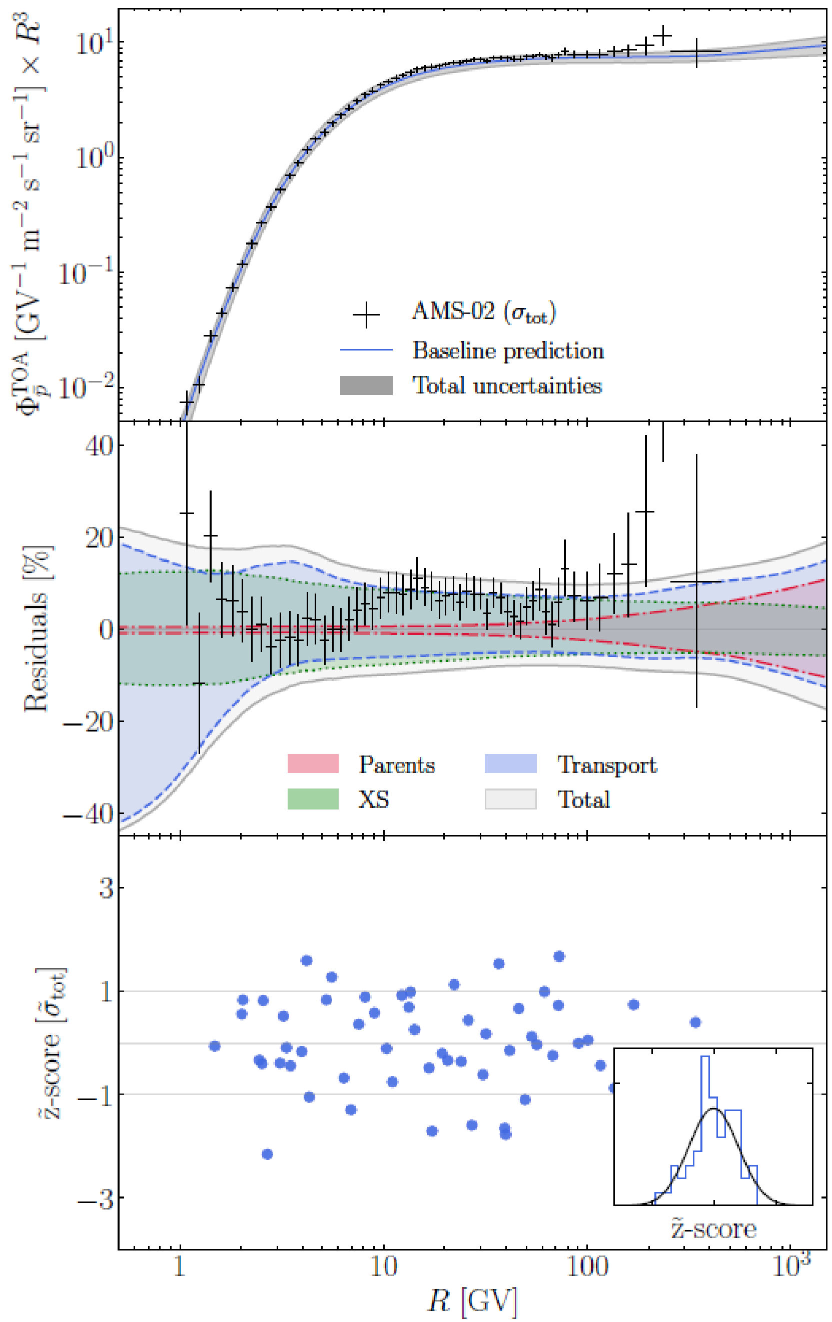


comparing data with two different parameterizations for scaling

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)
- Other studies still suggest a possible excess from dark matter annihilation

e.g. **Cuoco et al, arXiv:1903.01472**: $\sim 3\sigma$ significance in the $40-130\,\mathrm{GeV}$ range