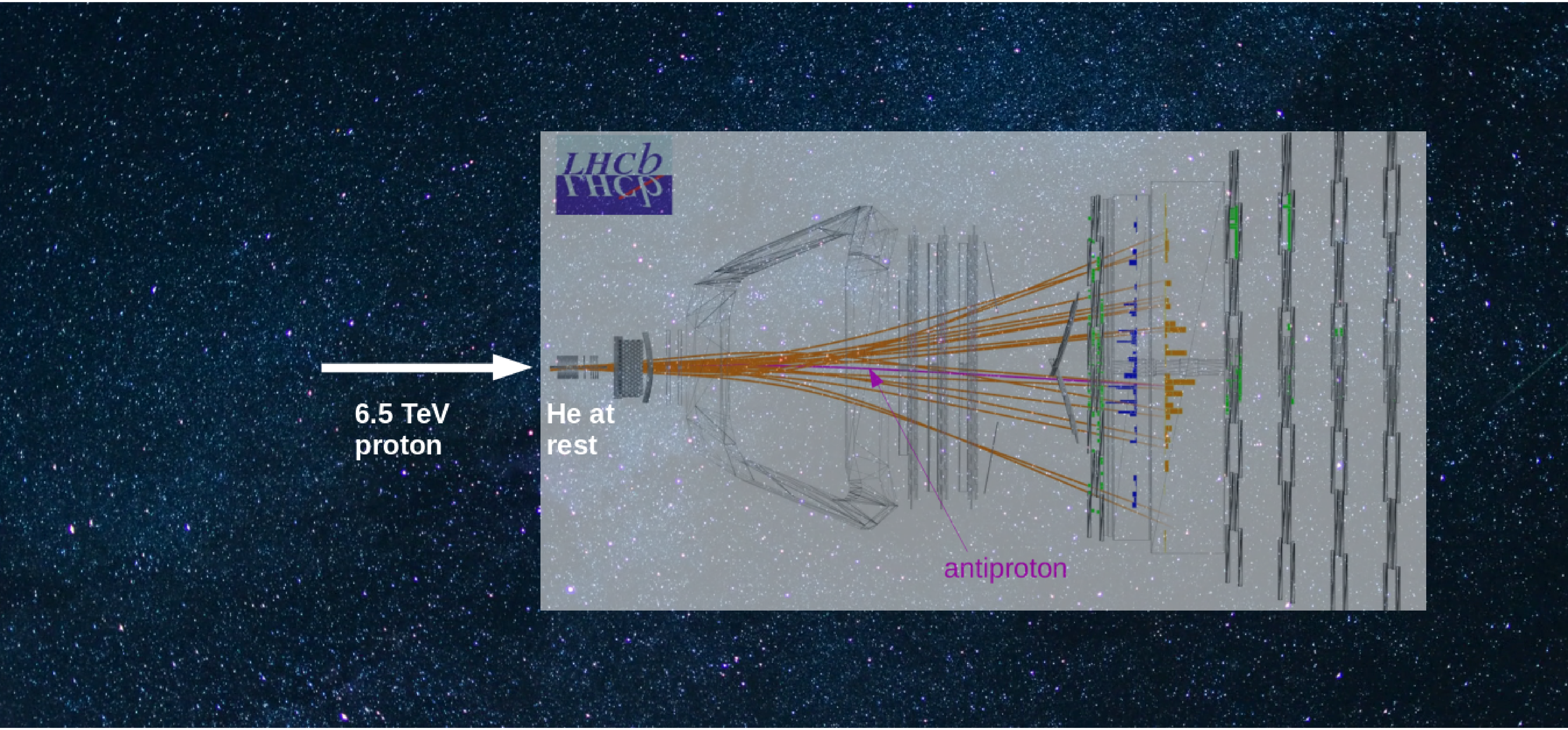
LHCb inputs to astroparticle physics



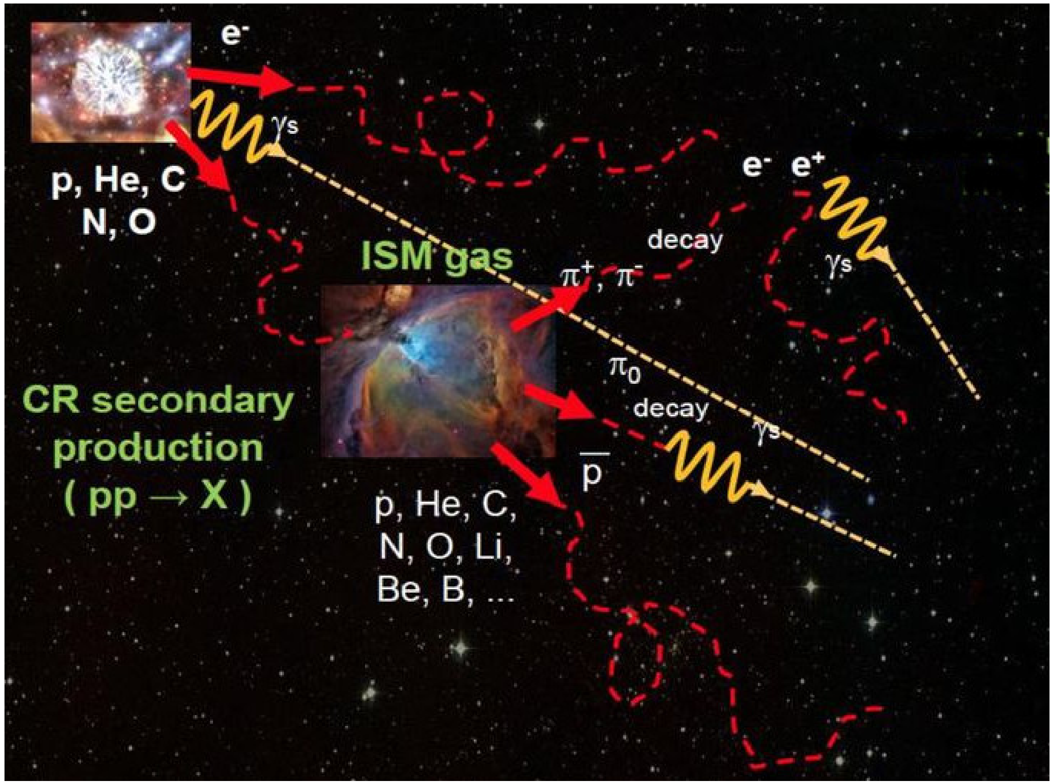
Giacomo Graziani (INFN Firenze)
on behalf of the LHCb Collaboration

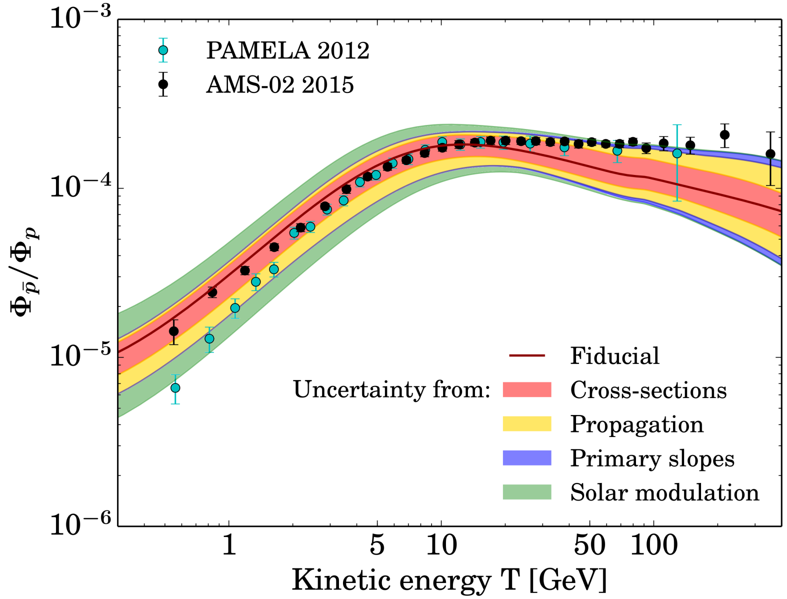
EPS-HEP Conference 2019
July 11, 2019

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:

- Birth of Neutrino astronomy ➡ background from charm decays in cosmic atm. showers
- Gamma astronomy ➡ γ background from CR interactions
- Antimatter in cosmic rays ➡ background from CR interactions in the inter-stellar medium
- 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

The LHCb experiment

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

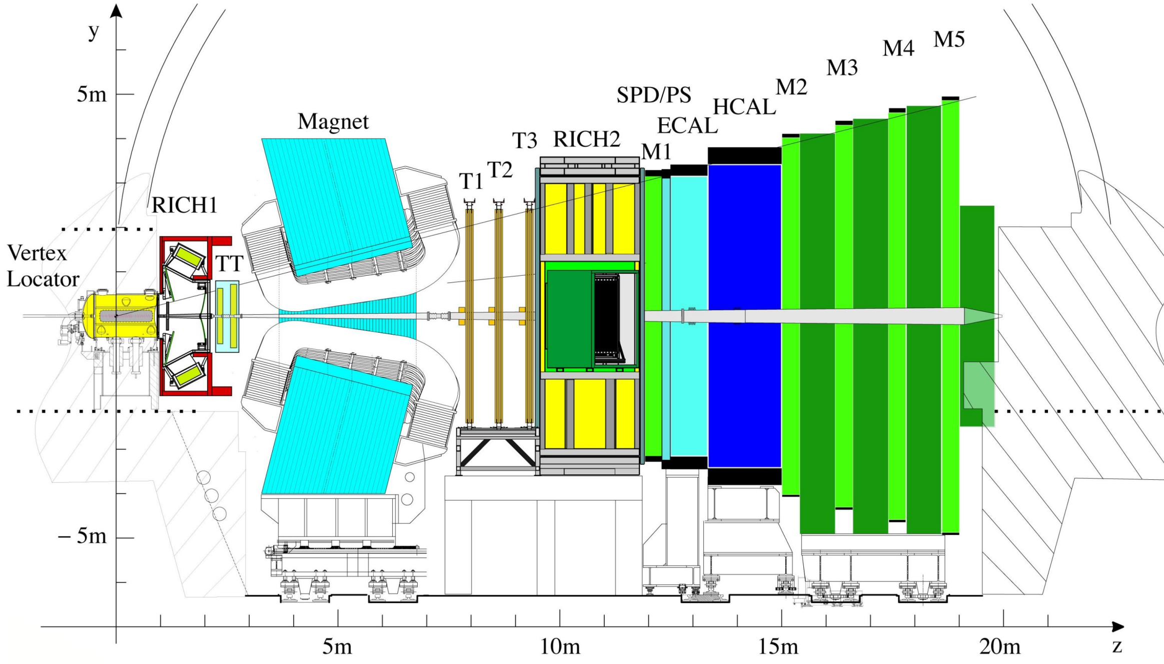
Detector requirements:

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

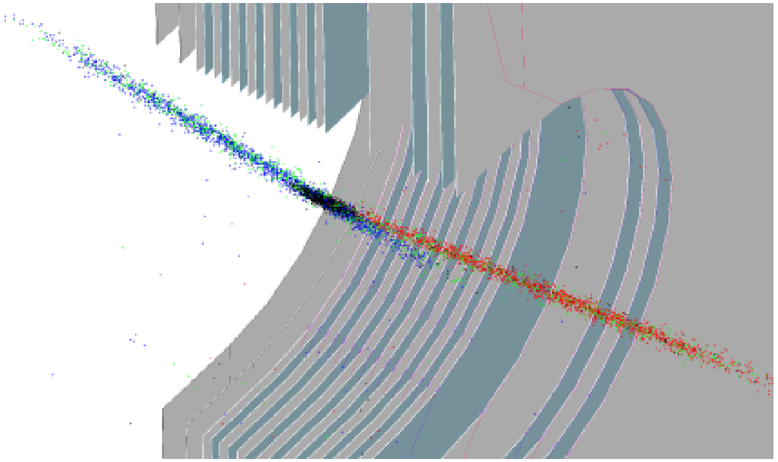
Trigger : high flexibility and bandwidth (up to 15 kHz to disk)



JINST 3, (2008) S08005

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

"Fixed-target like" geometry very well suited for. . . fixed-target physics!



The System for Measuring Overlap with Gas (SMOG)

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.

Turns LHCb into a fixed-target experiment!

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

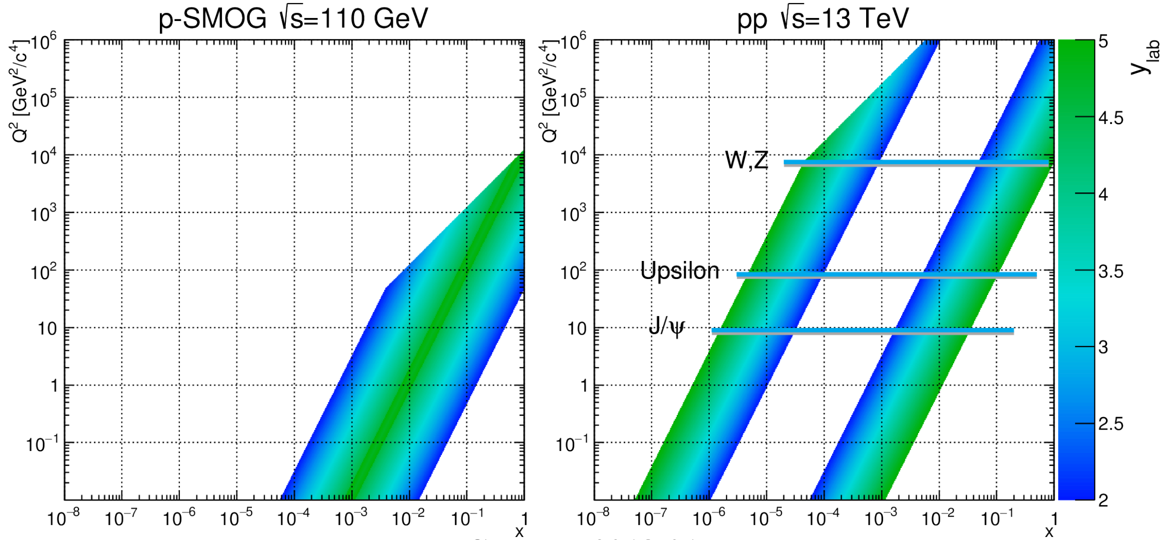
Gas pressure $\sim 2 \times 10^{-7}$ mbar ➡ $\mathcal{L} \lesssim 6 \times 10^{29} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

LHCb and cosmic rays: Outline

- The experiment provides the most accurate measurements of **charm production** at the highest energy achievable at accelerators in pp collisions, important to understand neutrino production in UHE atmospheric showers

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

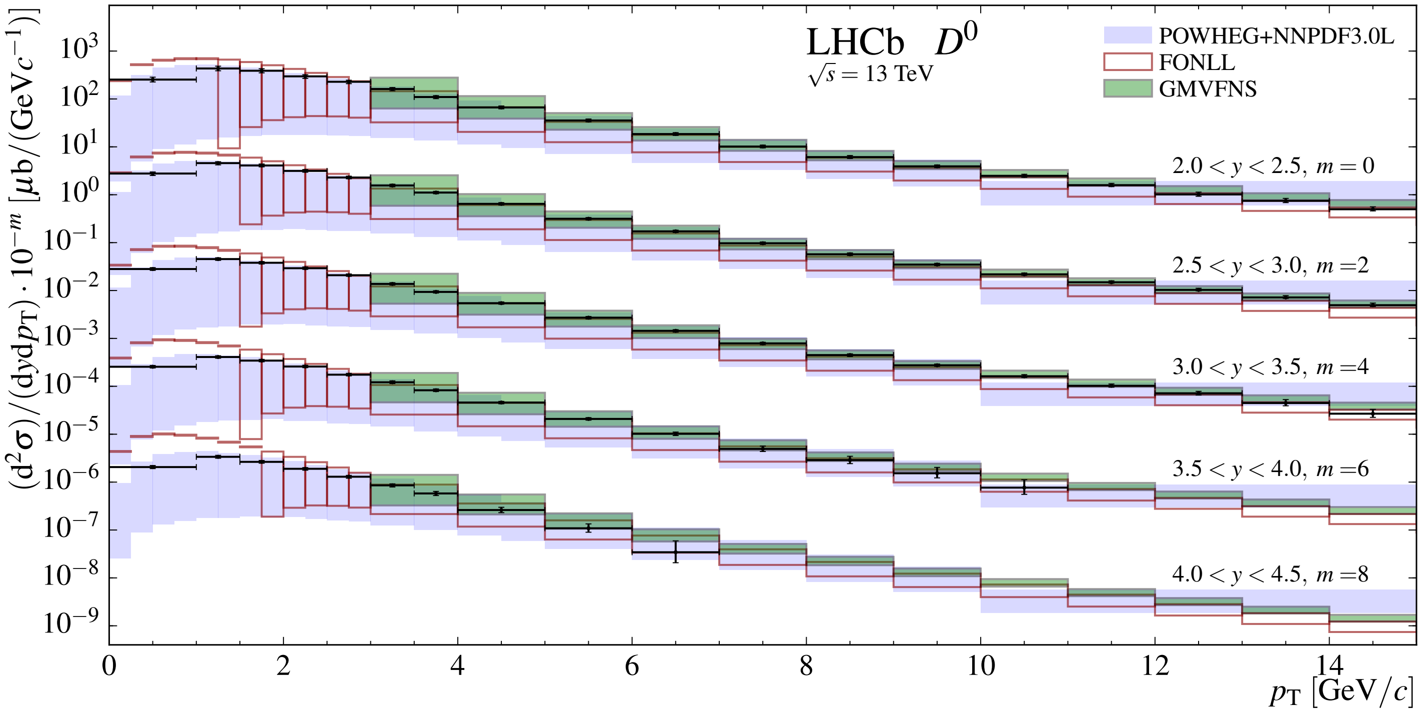


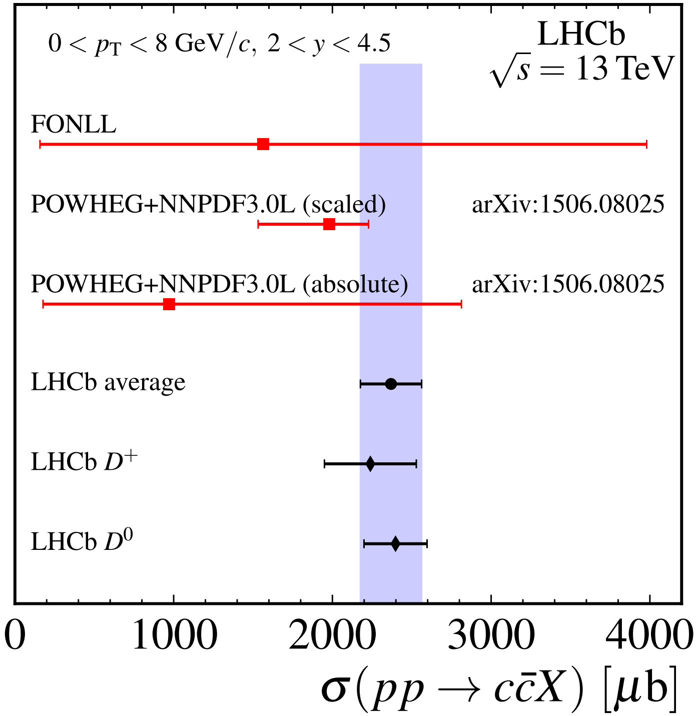
LHCb-PUB-2018-015

- p**He collisions** (pH and pD probably possible in the future) reproduce **cosmic ray interactions in the interstellar medium** at the energy scale $\sqrt{s_{\mathrm{NN}}} \sim 100$ 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

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}





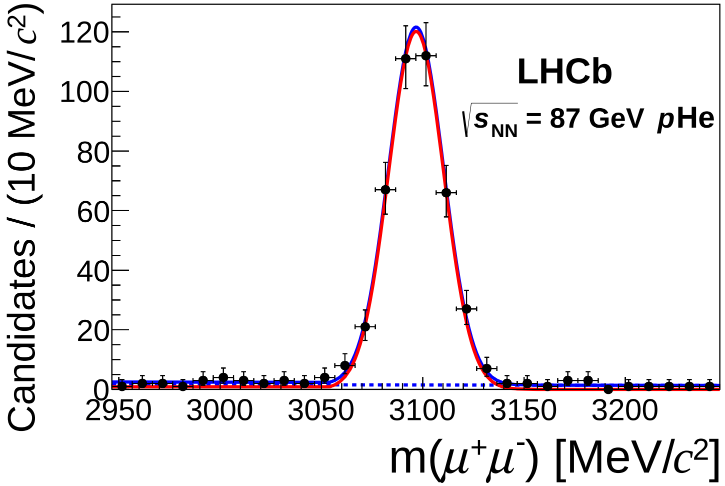
JHEP 03 (2016) 159, erratum JHEP 05 (2017) 074

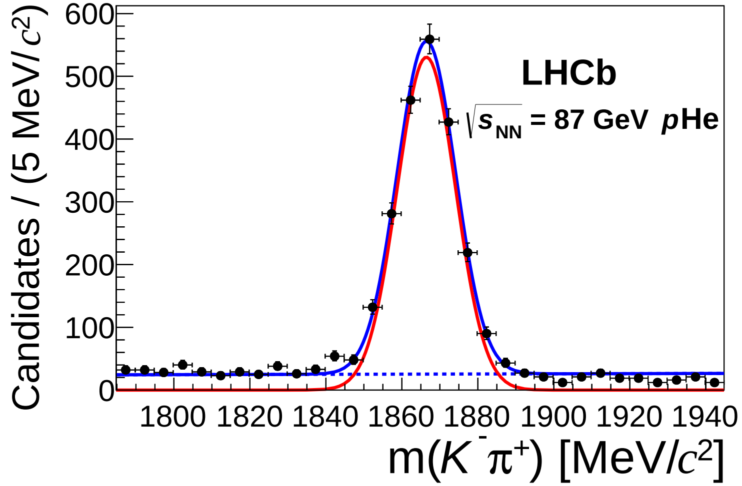
- Main input to PDF fits and current predictions of atmospheric high-energy neutrino flux (see e.g. **PROSA collaboration JHEP 1705 (2017) 004**)

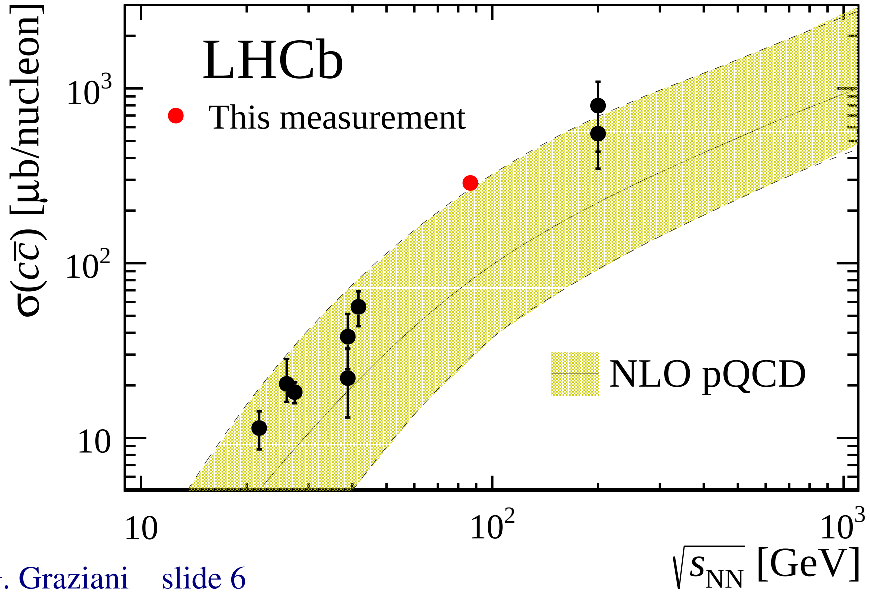
Charm production in fixed-target data

PRL 122 (2019) 132002

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





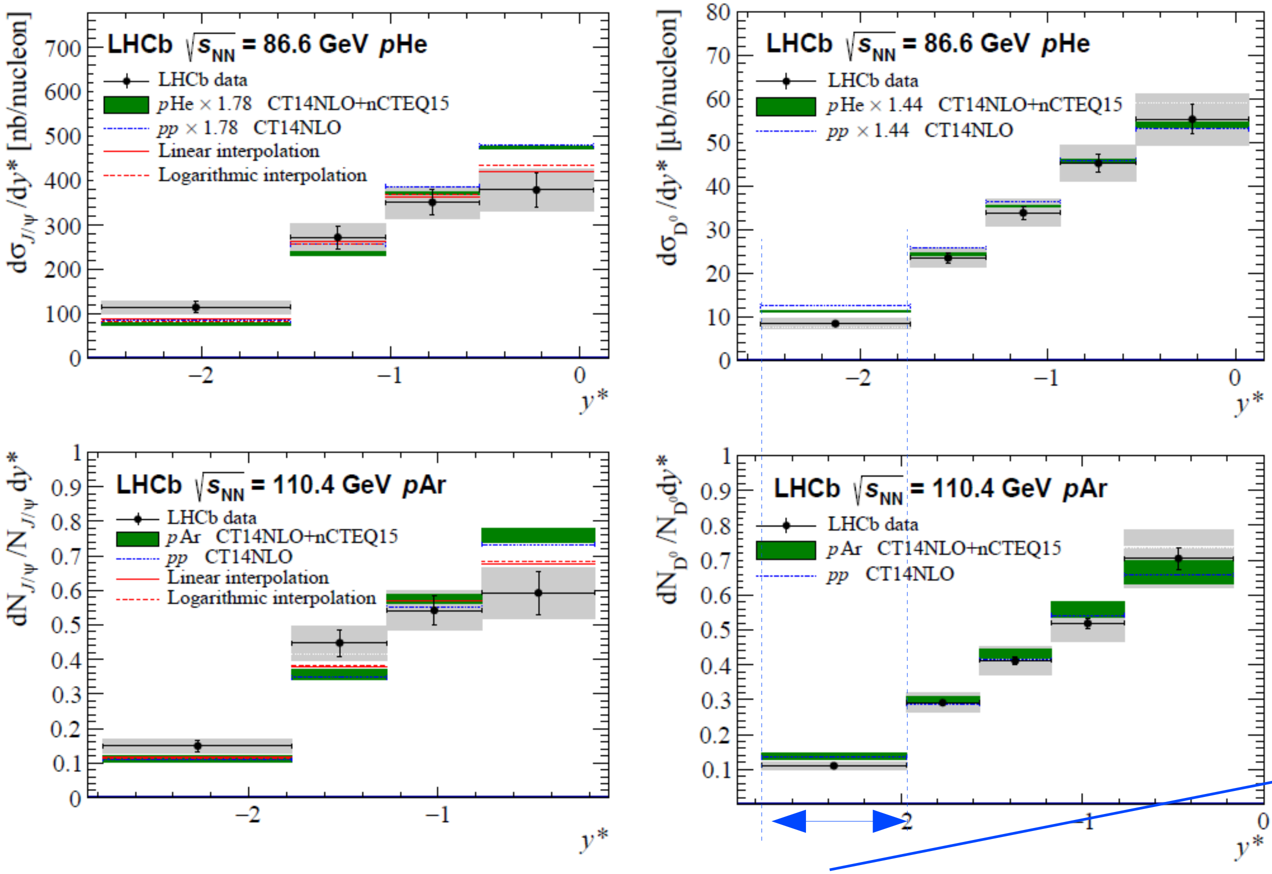


- First determination of $c\bar{c}$ cross-section at this energy scale

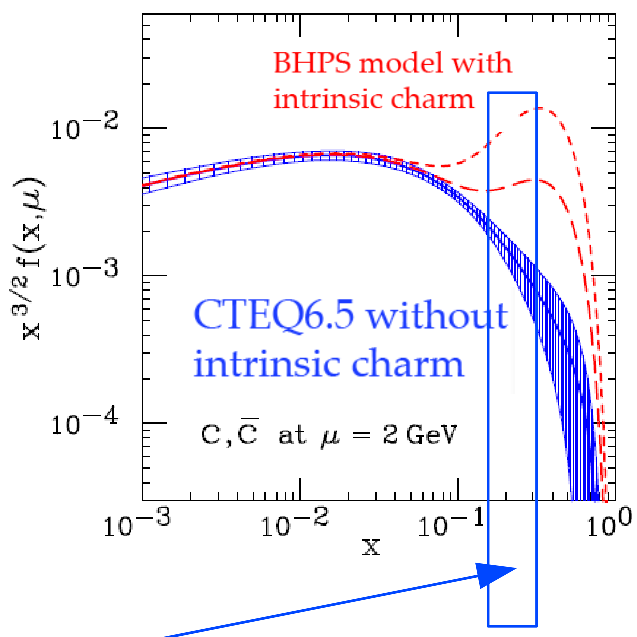
J/ψ D^0

pHe

pAr



Pumplin, Lai, Tung, PRD75 054029



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

More details in Felipe Garcia's talk tomorrow (heavy ion session)

Antiprotons from pHe collisions

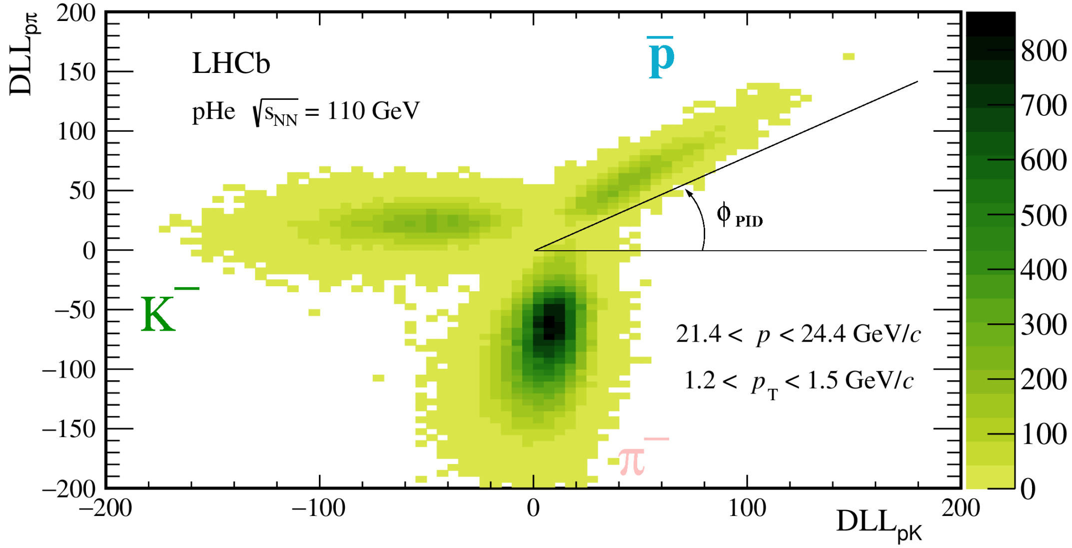
PRL 121 (2018), 222001

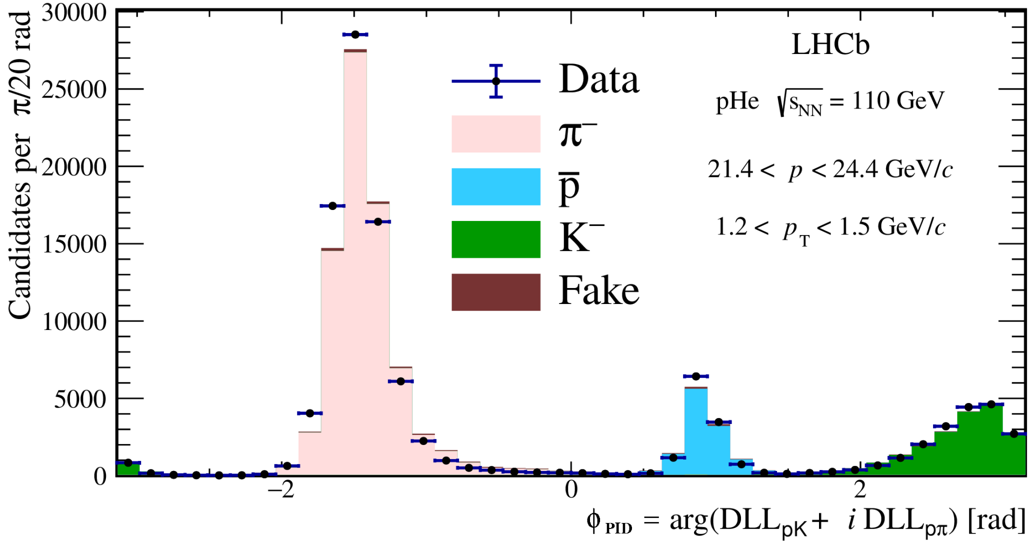
- First measurement of $p\text{He} \to \bar{p}X$ cross-section, the process accounts for $\sim 40\%$ of secondary cosmic $\bar{p}$
- Data collected in May 2016, with proton energy 6.5 TeV, $\sqrt{s_{\rm NN}}$ = 110 GeV, mostly from a single LHC fill (5 hours)
- Minimum bias trigger, fully efficient on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

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

(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)

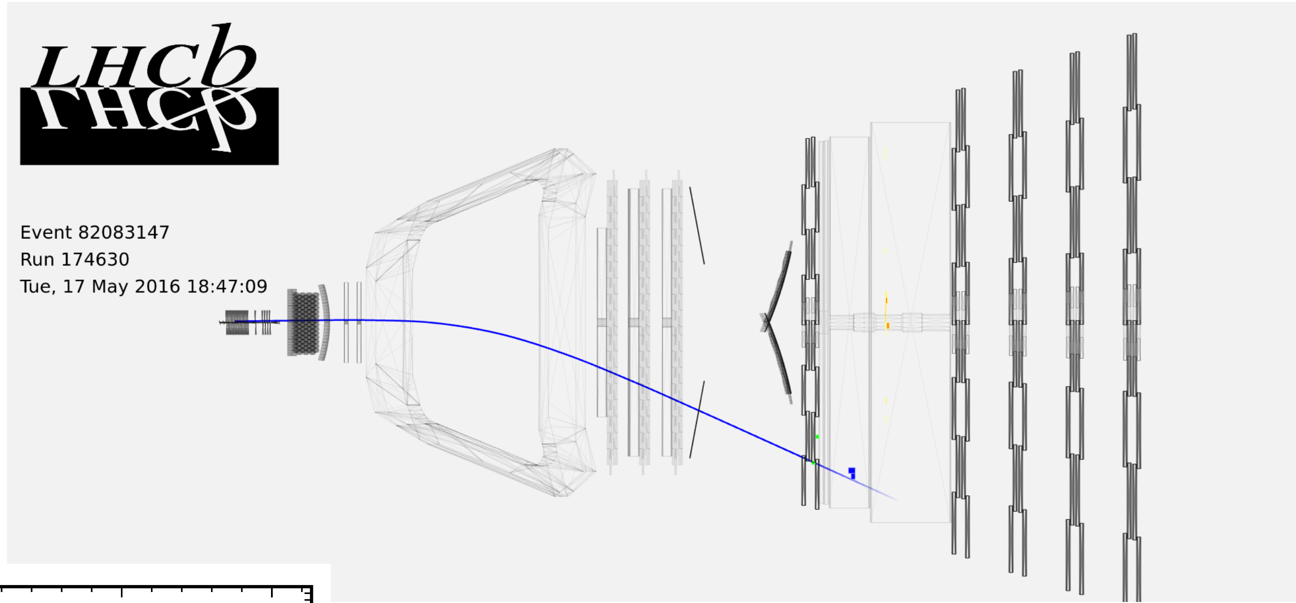


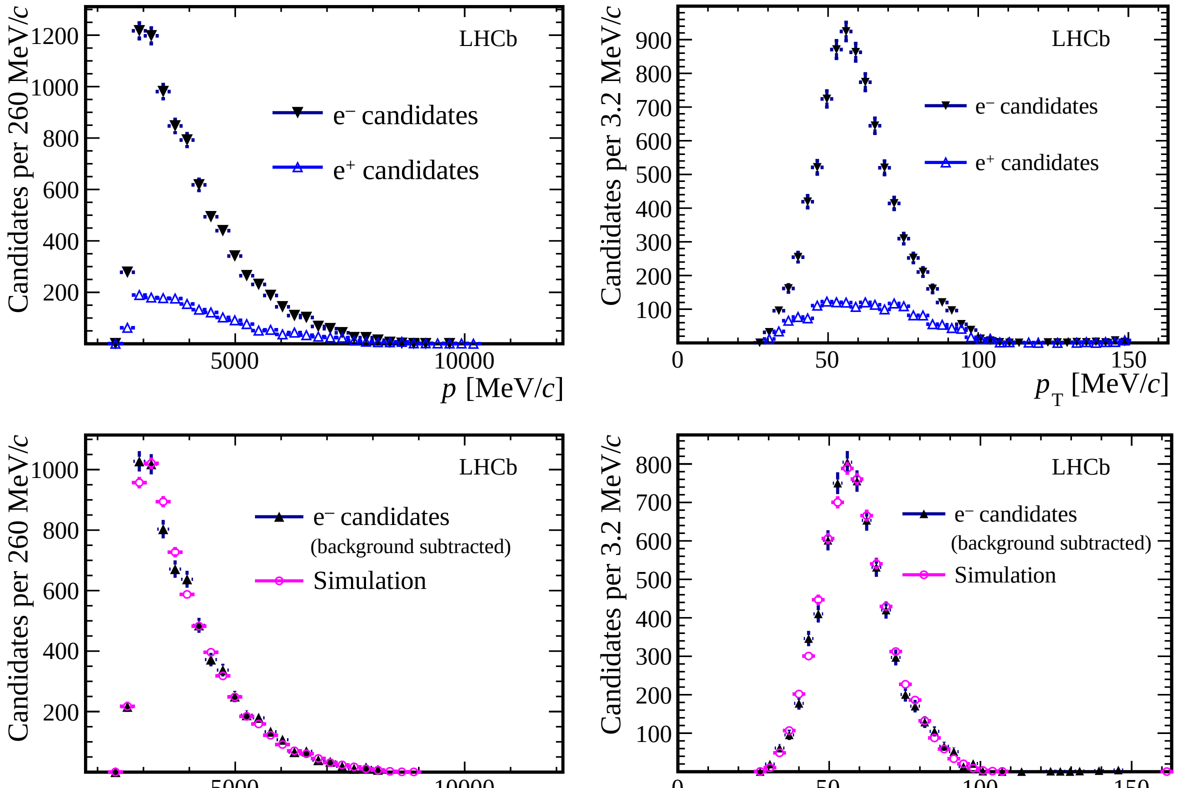


Fixed-target Luminosity

PRL 121 (2018), 222001

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

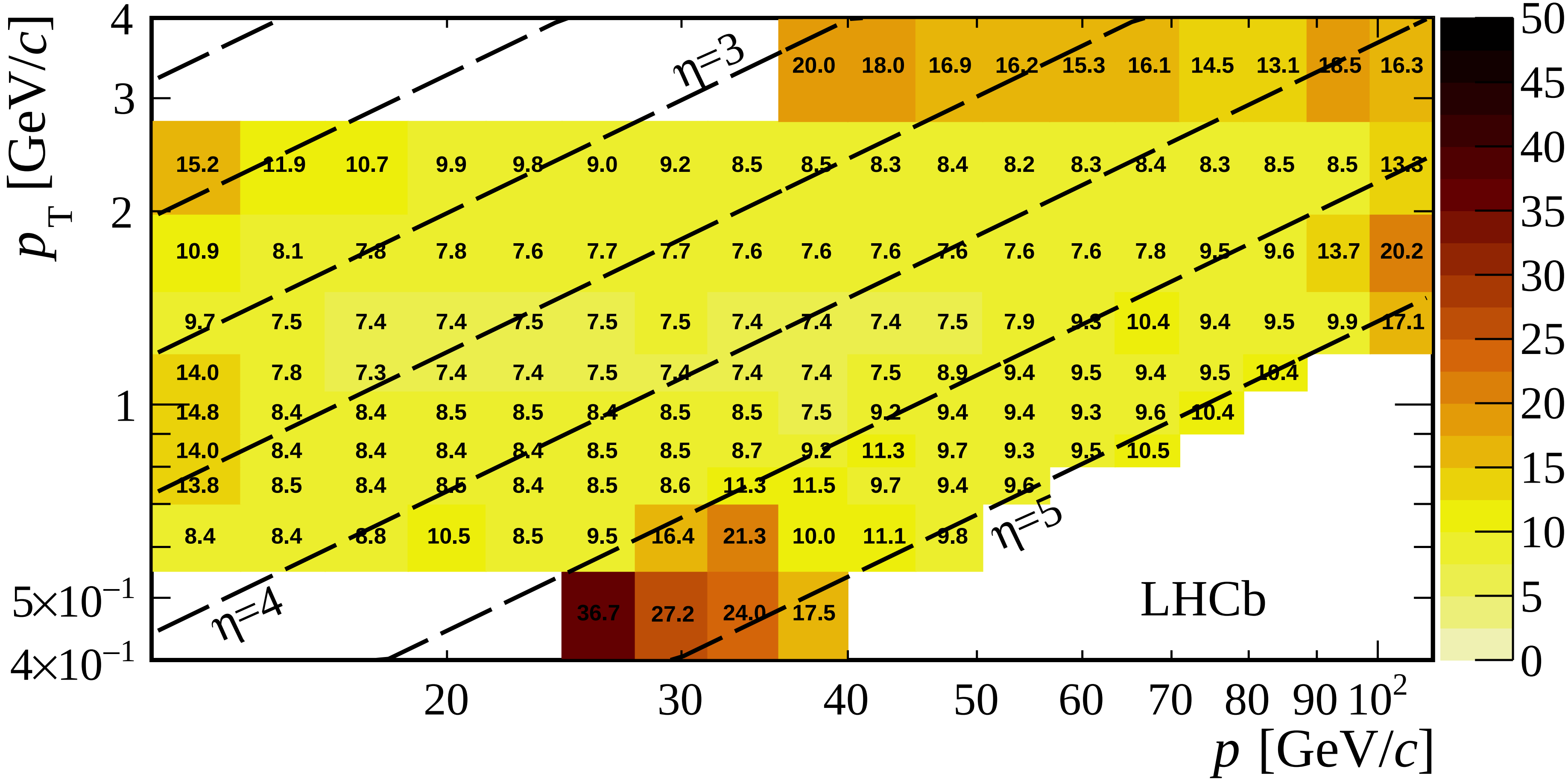




- Background measured from data, using events with single positive track
- Systematic uncertainty of 6%, due to low electron reconstruction efficiency ($\sim 16\%$)

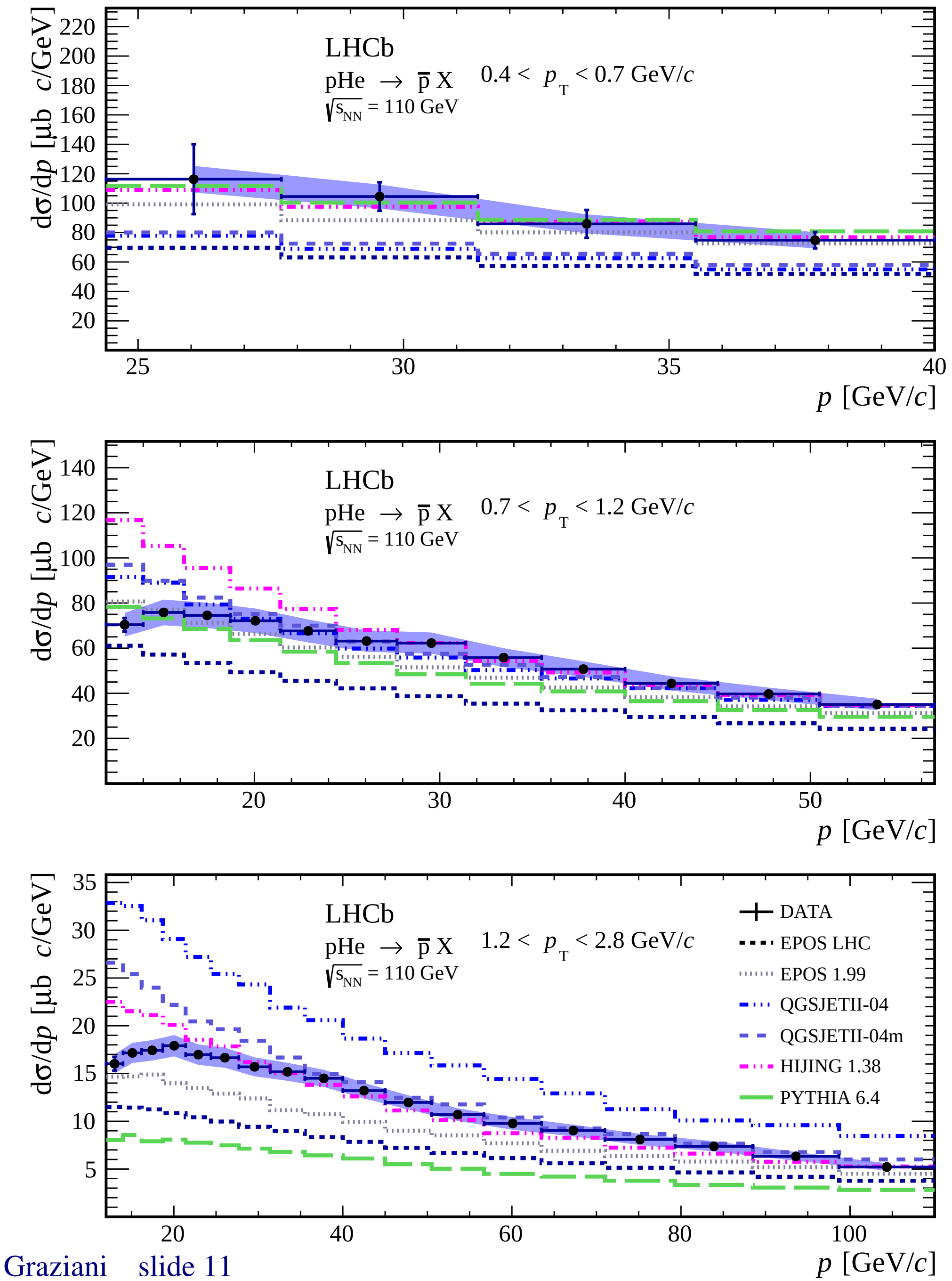
Total relative uncertainty per bin, in per cent

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:

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

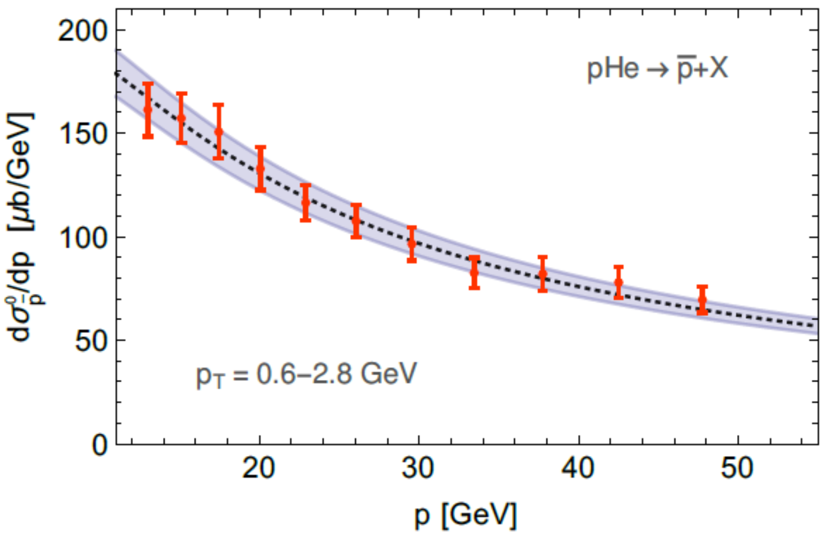
➡ excess of $\overline{p}$ yield over EPOS LHC (by factor ~ 1.5) mostly from $\overline{p}$ multiplicity

Implications for cosmic antiprotons

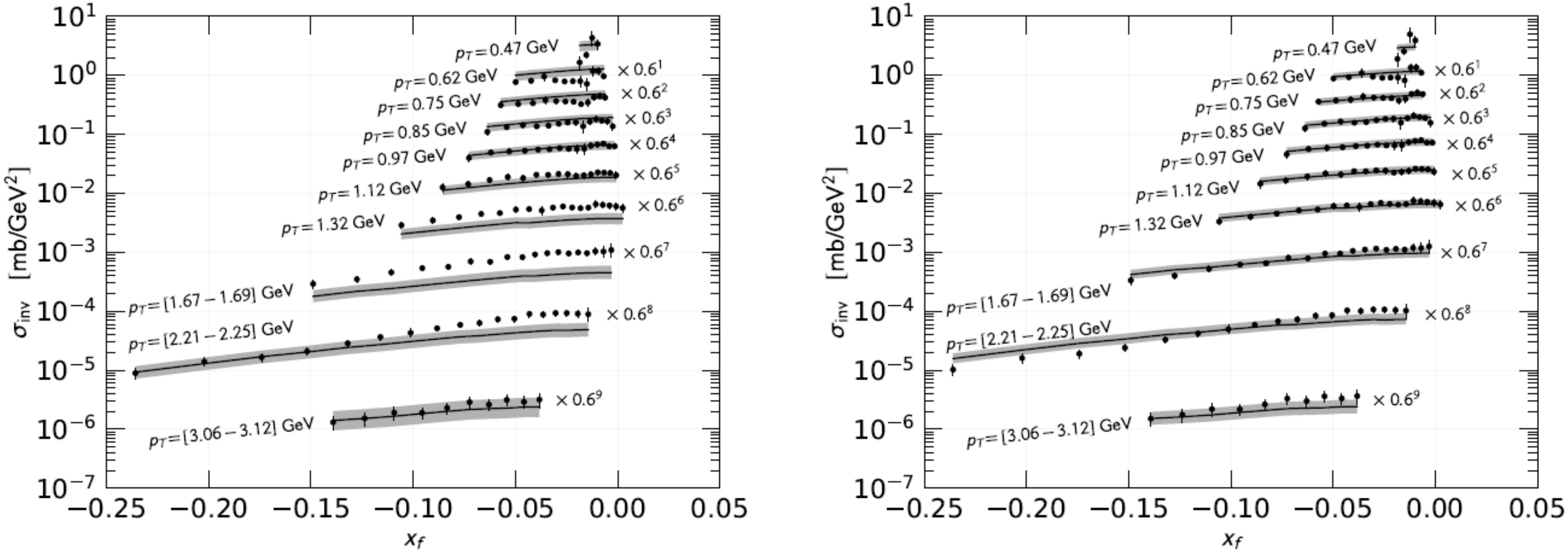
The preliminary results of this study (released in 2016) was used to validate

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

Reinert and Winkler, JCAP 1801 (2018) 055

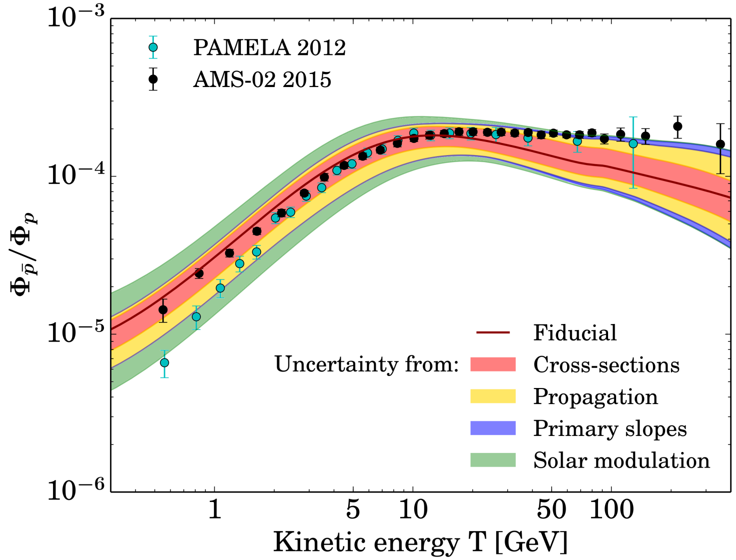


Korsmeier, Donato, Di Mauro, PRD97 (2018) 103019

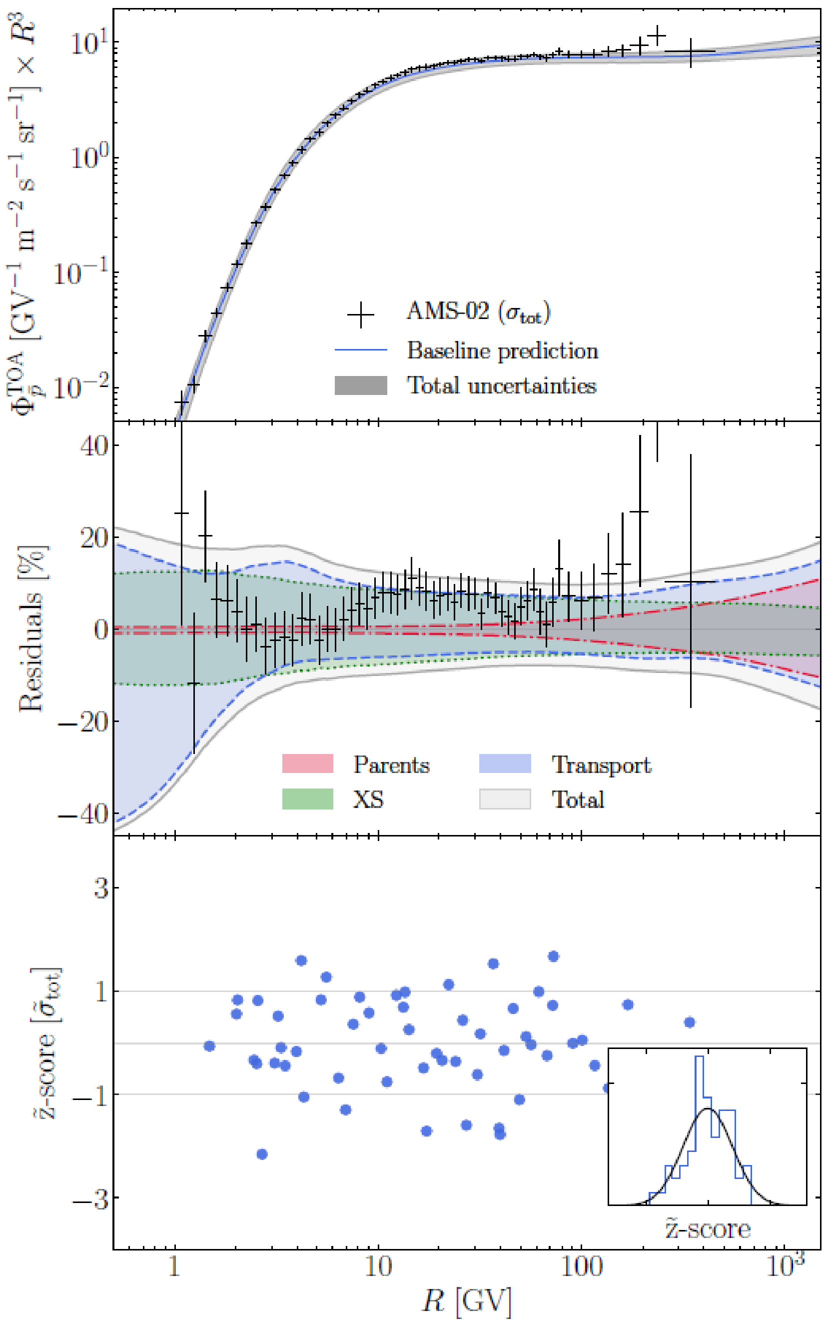


comparing data with different parameterizations for scaling

2015 Giesen et al., JCAP 1509, 023

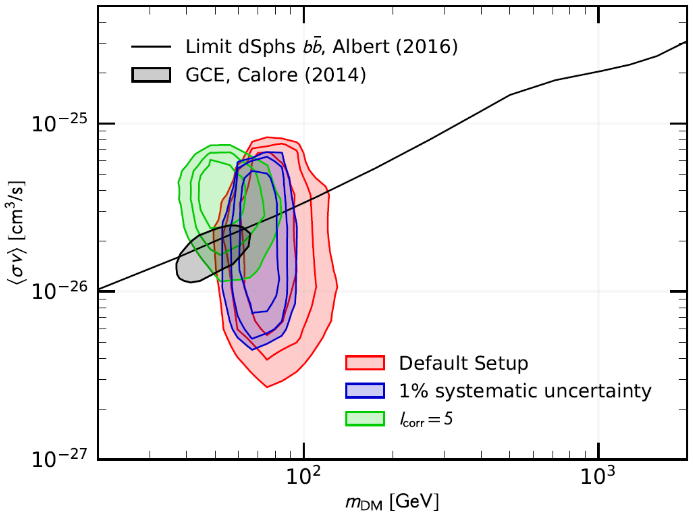


2019 Boudad et al., arXiv:1906.07119



- 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

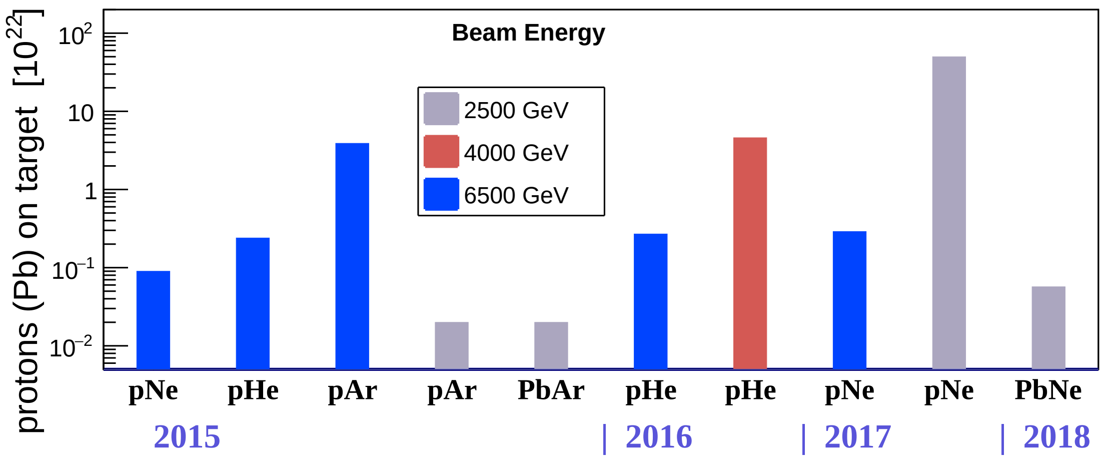
e.g. **Cuoco et al, arXiv:1903.01472**: $\sim 3\sigma$ significance in the $40 - 130\,\text{GeV}$ range



Prospects

Exploitation of current samples

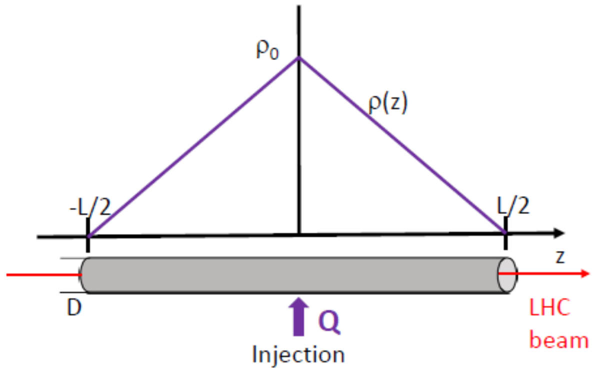
Samples acquired during Run 2, up to $\int \mathcal{L}dt \sim 100\,\mathrm{nb}^{-1}$ (pNe)

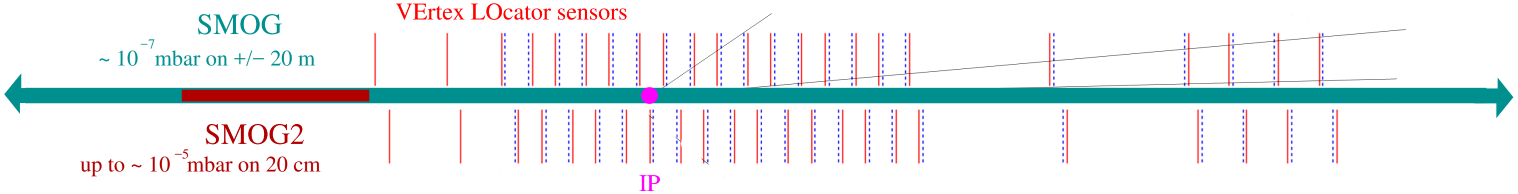


- pHe data at 4 TeV beam energy ($\sqrt{s_{\mathrm{NN}}}$ =86 GeV)
- Extend the study to $\overline{p}$ produced by anti-hyperon decays (∼20-30% of $\overline{p}$ production)
- Measure production of π, K, p from the various SMOG samples (He, Ne, Ar targets).

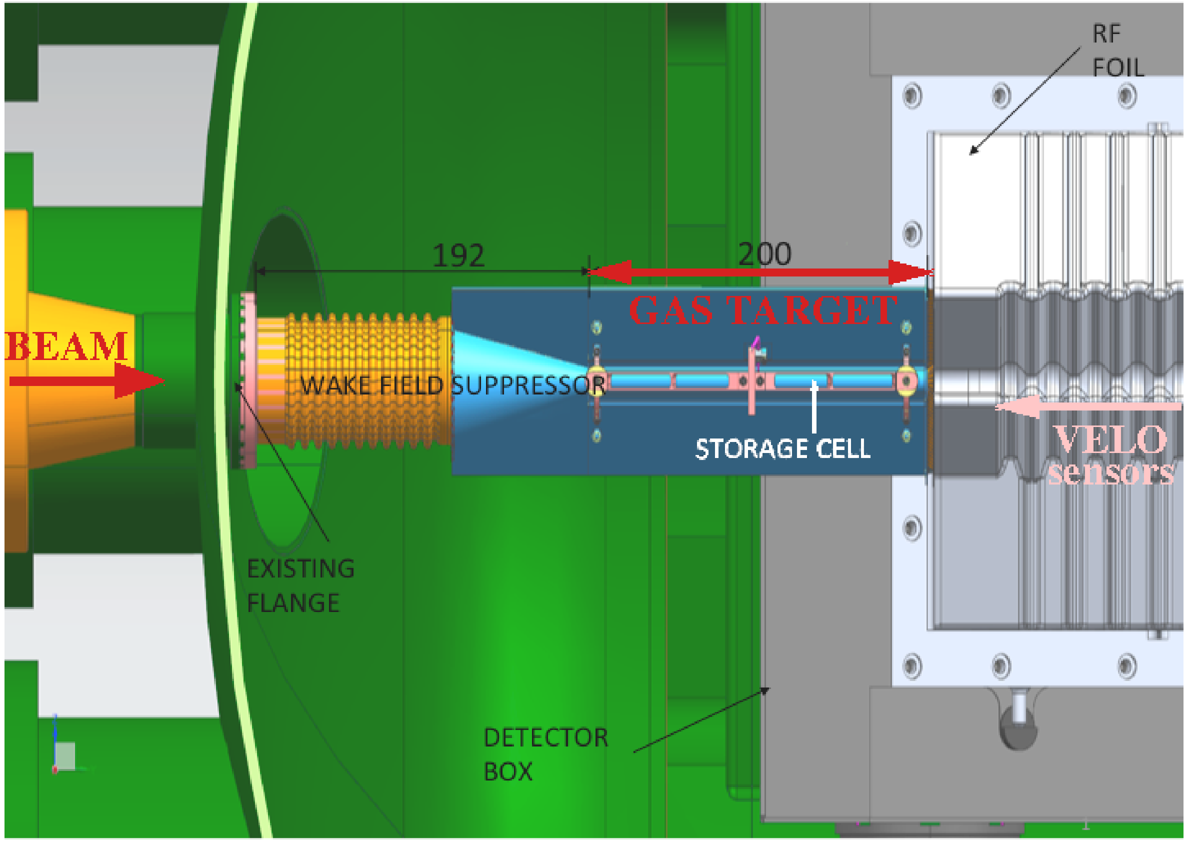
Gas target upgrade

- The fixed-target program will be developed from LHC Run 3 thanks to a new gas target SMOG2, based on a storage cell:
  - increase instantaneous luminosity
  - possibly inject other gases as H, D, N, O
  - precise control of the gas density





The SMOG2 gas target



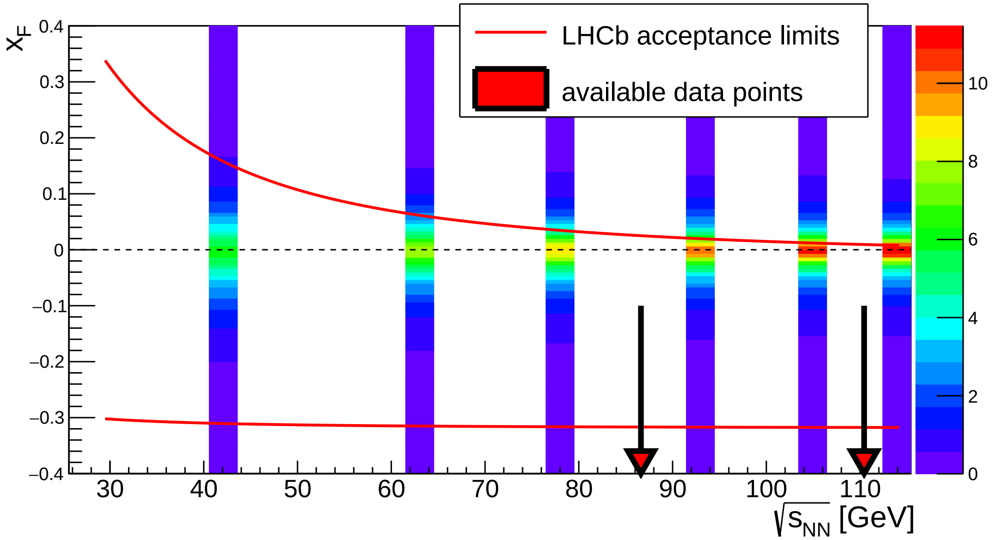
- 20-cm long storage cell, 5 mm radius around the beam, just up-stream the LHCb VErtex LOcator
- Made of two rectractable halves as the rest of VELO
- Up to x100 higher gas density with same gas flow of current SMOG
- Gas feed system measures the gas density with $\sim 2\%$ accuracy

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

Prospects 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 $\sqrt{s_{NN}}$ and accessible region to LHCb

- 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
- Huge statistics to study nuclear effects in charm production, and disentangle intrinsic charm with H target
- For Run 3 and beyond: proposal to have short runs with oxygen beams (CERN-LPCC-2018-07):
  - study pO collisions up to $\sqrt{s_{NN}} = 9.9$ TeV with forward acceptance
  - oxygen beams on H target give access to very forward particles in pO (up to $\eta = 7.6$) at $\sqrt{s_{NN}} \sim 100$ GeV

Conclusions

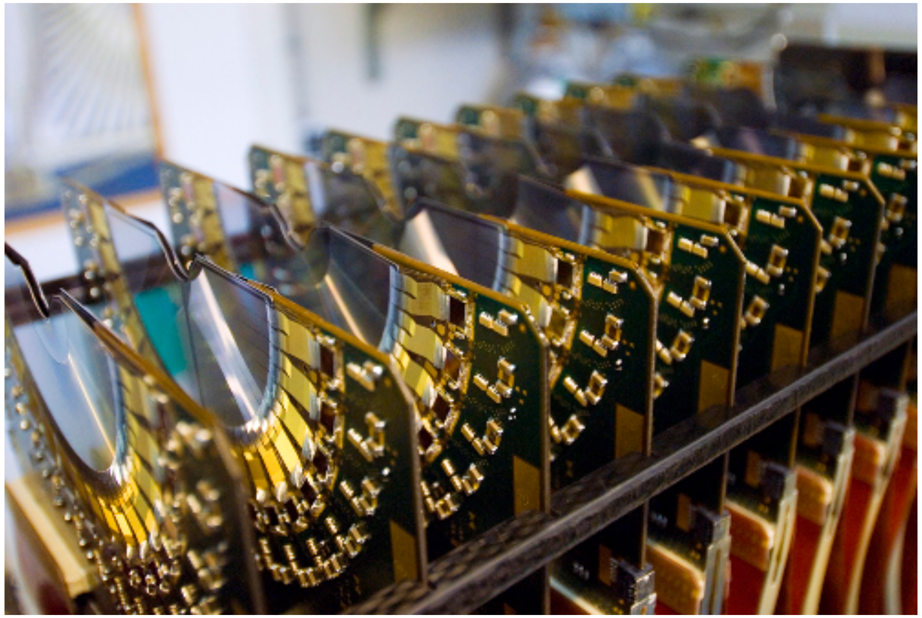
- Thanks, notably, to its fixed-target program, LHCb became an unexpected contributor to cosmic ray physics!
- Fruitful collaboration with the astroparticle community (pHe program proposed by O. Adriani, F. Donato *et al*)
- Many new measurements will be possible with the gas target upgrade already from Run 3

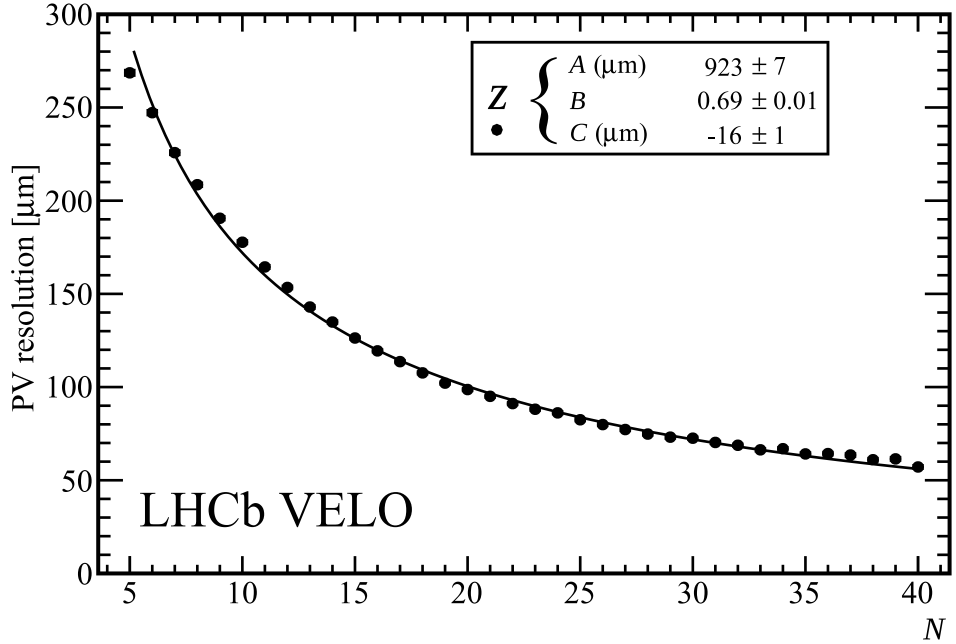
The LHCb space mission is reaching new heights!

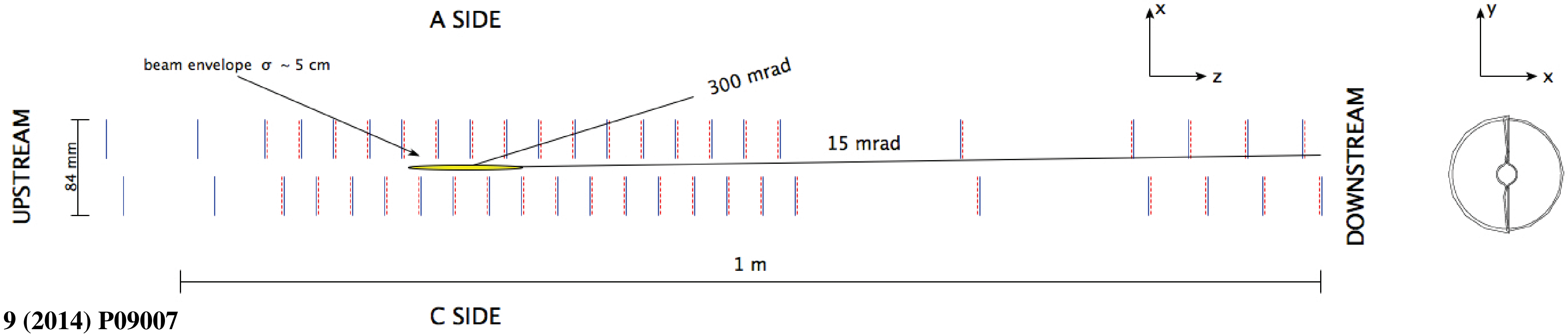
Additional Material

the VErtex LOcator

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



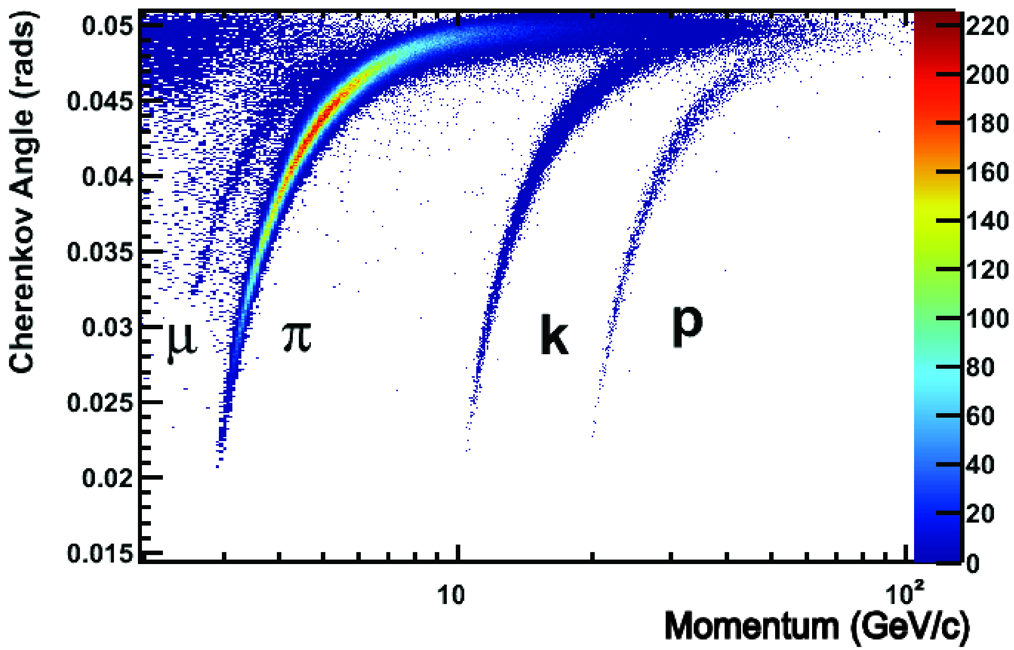




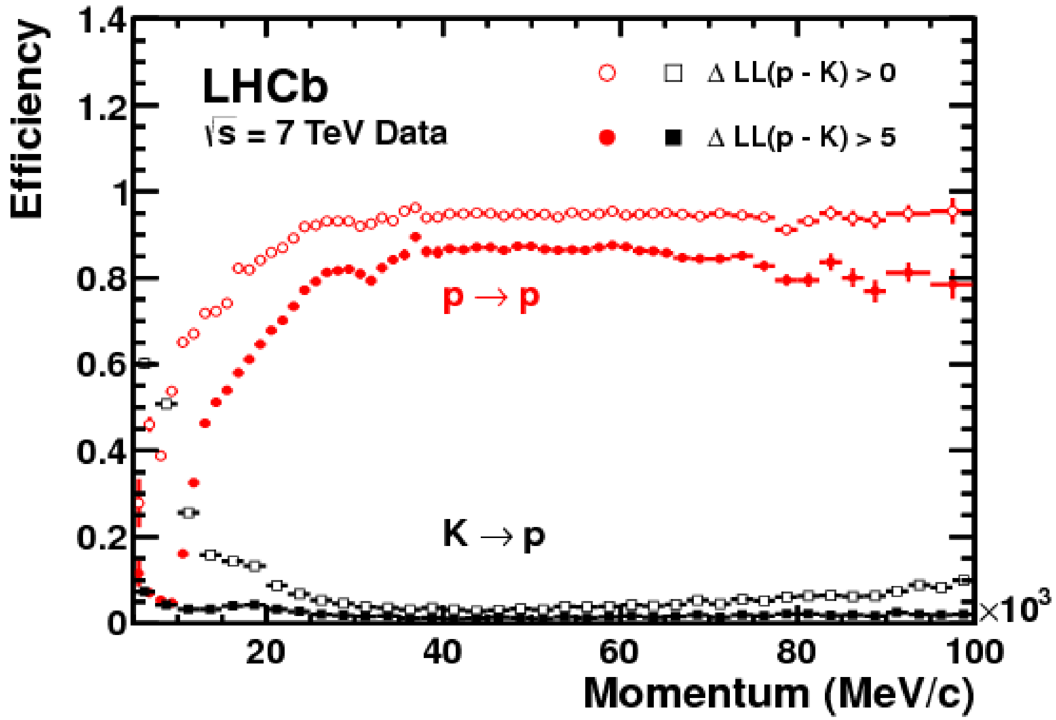
JINST 9 (2014) P09007

RICH Performance

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



Particle separation in RICH1

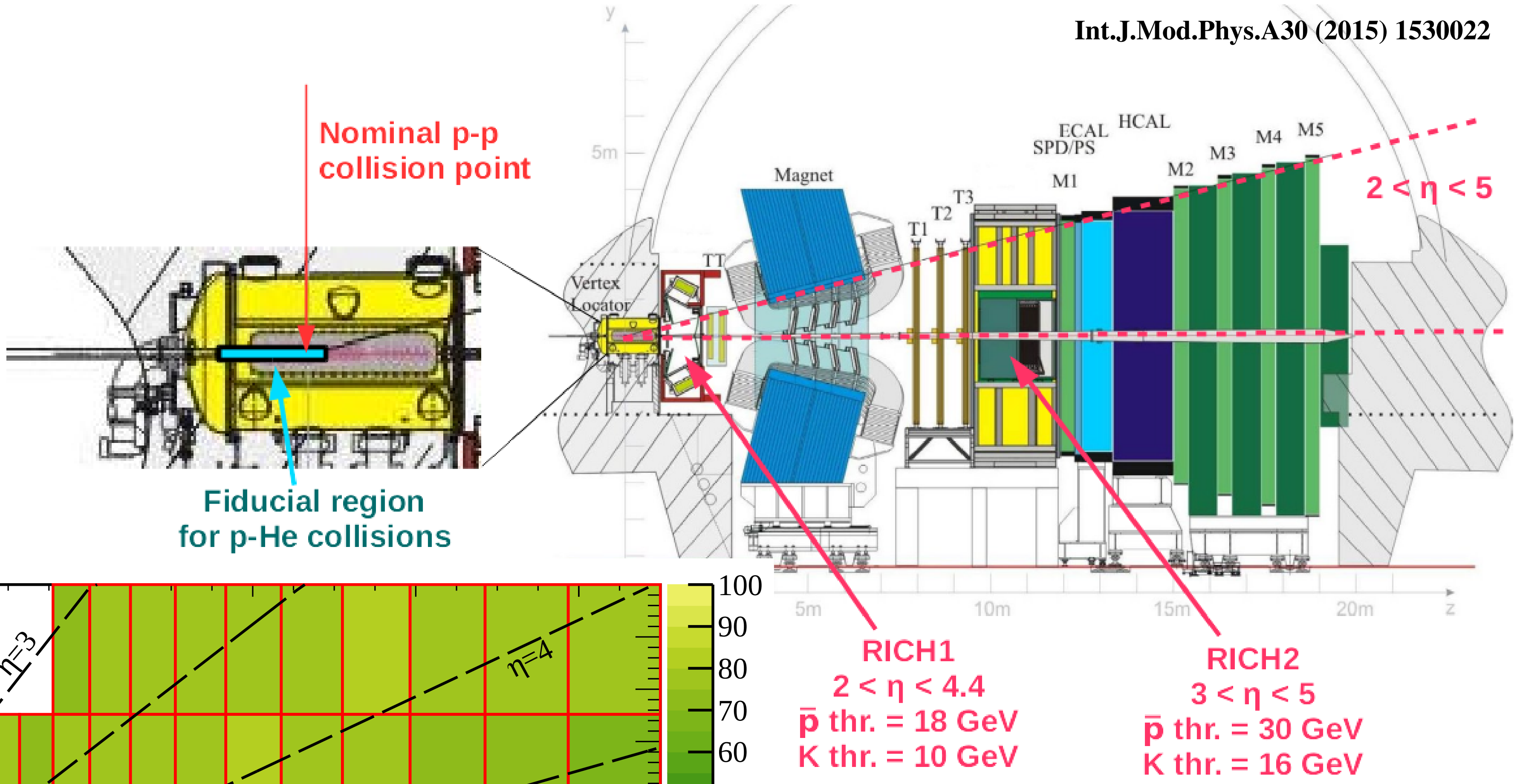


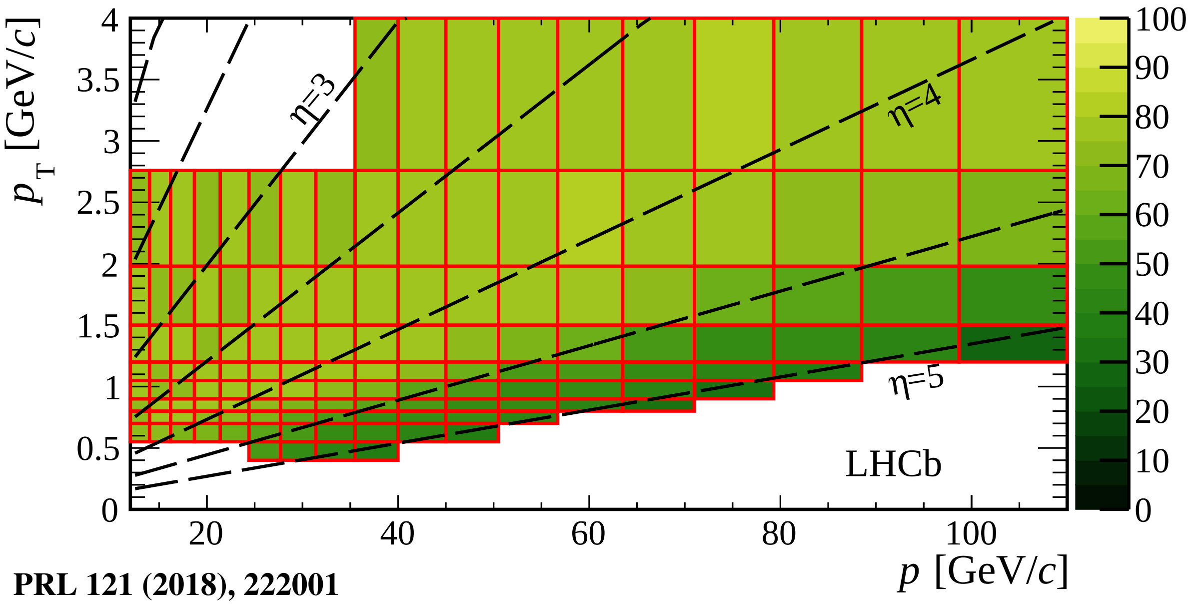
K/p separation vs momentum

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:

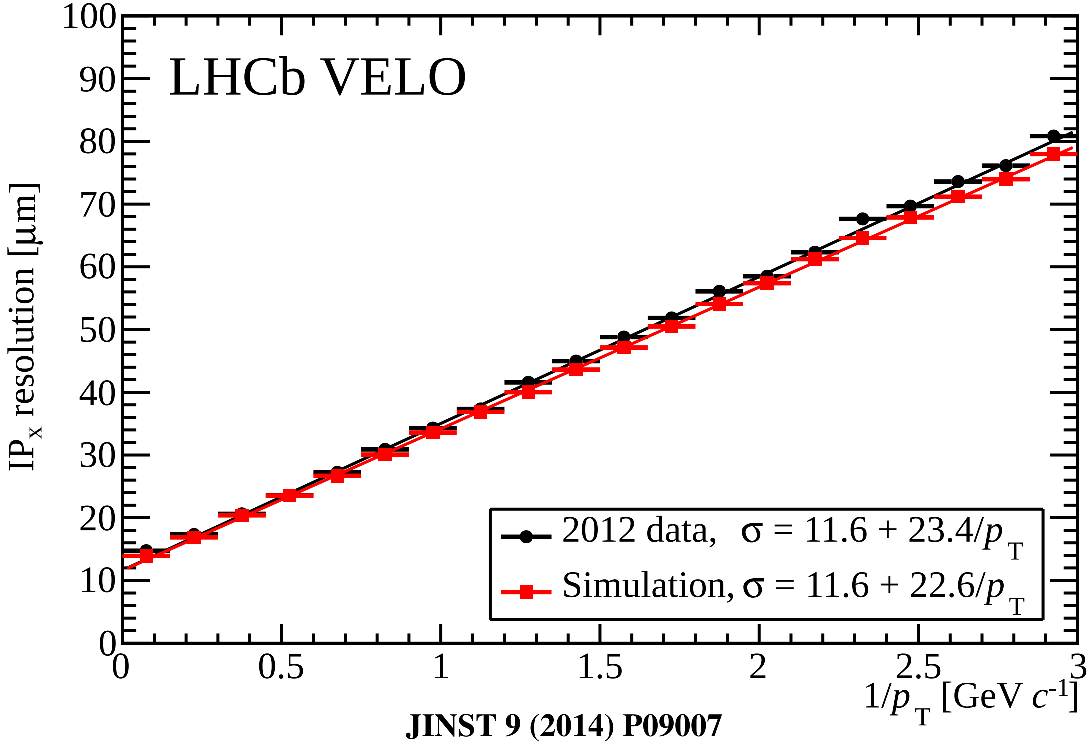
$$y^* \sim -2.8 \text{ - } 0.2$$

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

Antiprotons from weak hyperon decays

- only prompt $\overline{p}$ component measured so far, detached component from weak decays of hyperons is treated as a background (will be determined in a separate study)

- suppressed by requiring small impact parameter (IP)

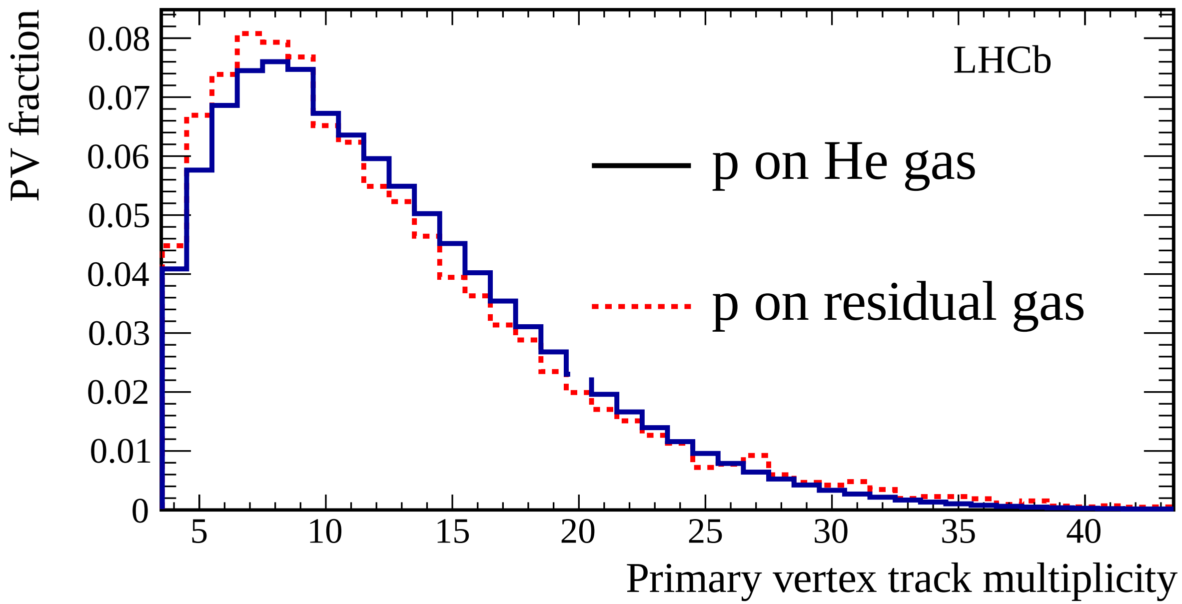


JINST 9 (2014) P09007

- Residual detached component estimated to be $(2.4 \pm 0.5)\%$ and subtracted
- Systematic uncertainty estimated from data/MC comparison of IP tails

Background from residual gas

- 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)



PRL 121 (2018), 222001

- 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

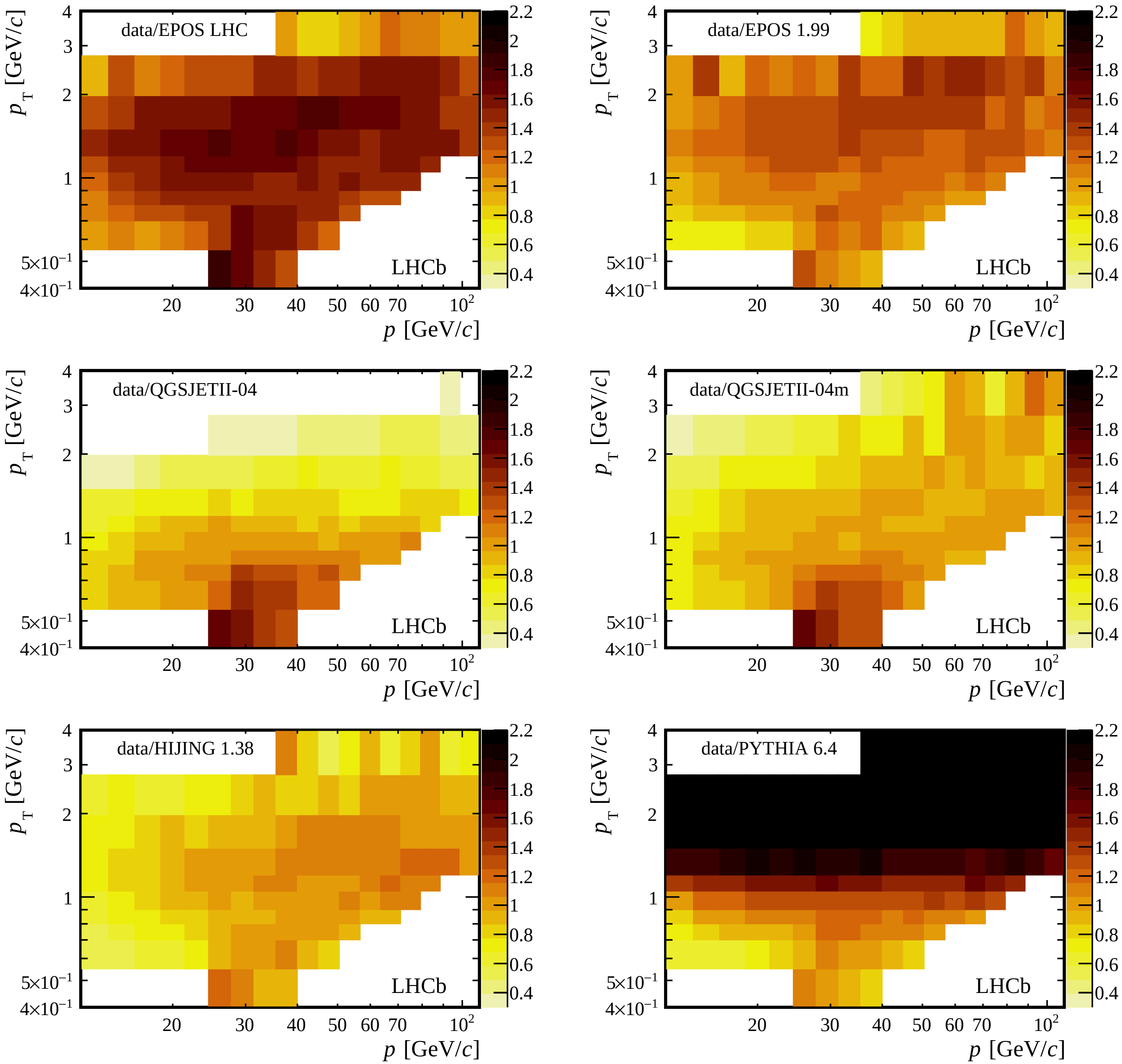
$p\text{He} \to \overline{p}X$ result: uncertainties (relative)

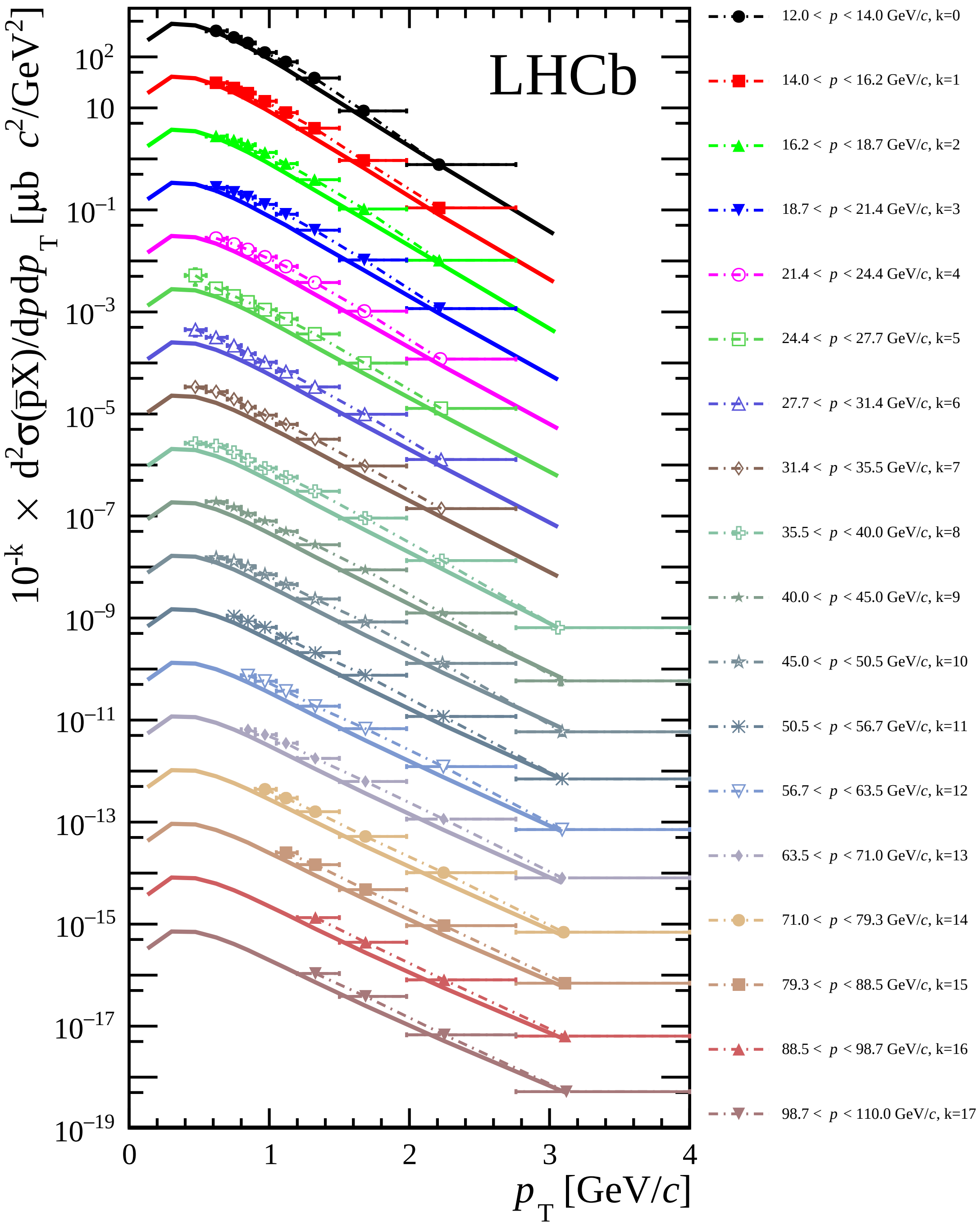
PRL 121 (2018), 222001

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)

pHe $\to \bar{p}X$ result: ratio 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