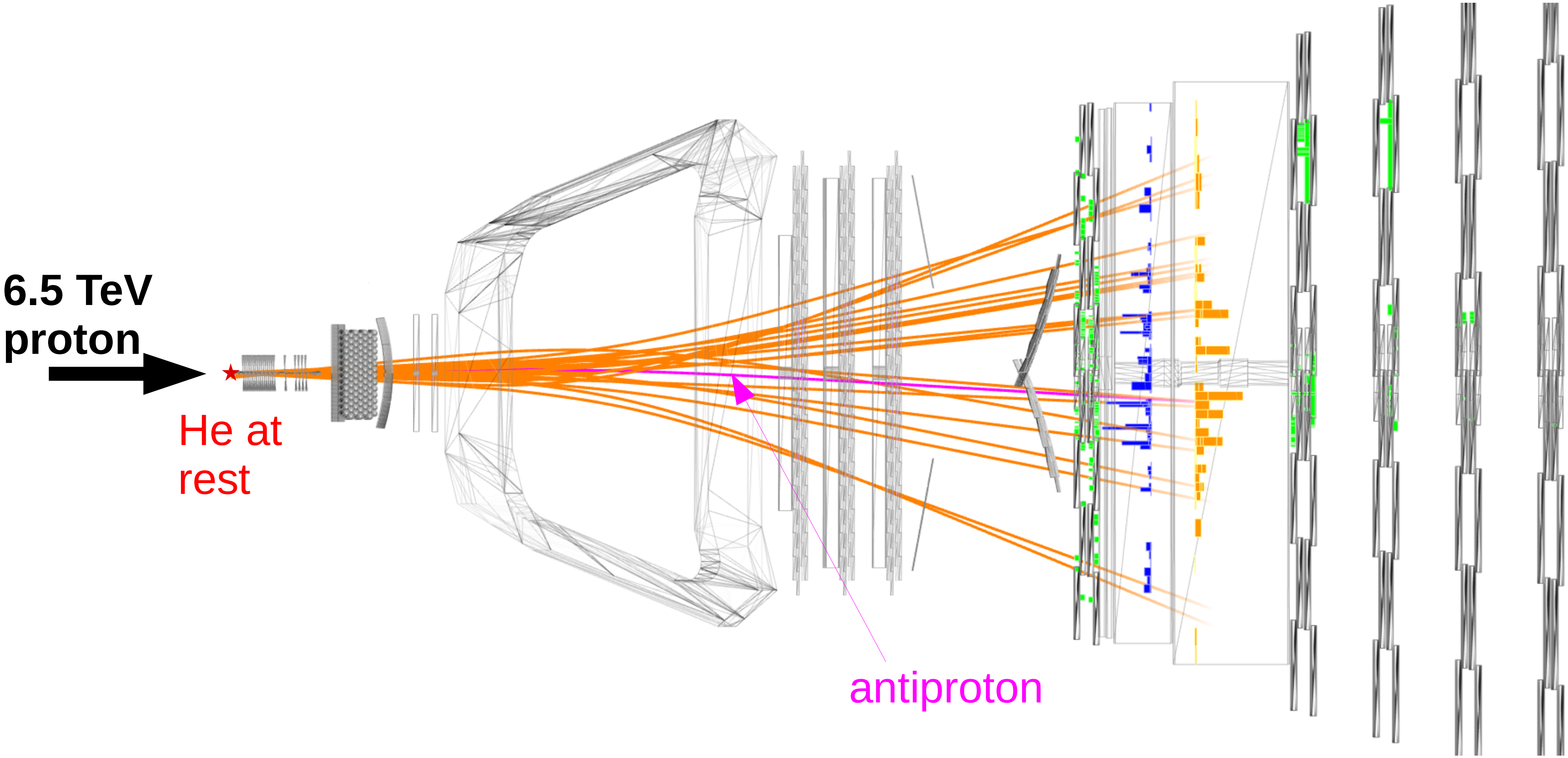
LHCb as a fixed-target experiment

Status and short-term prospects

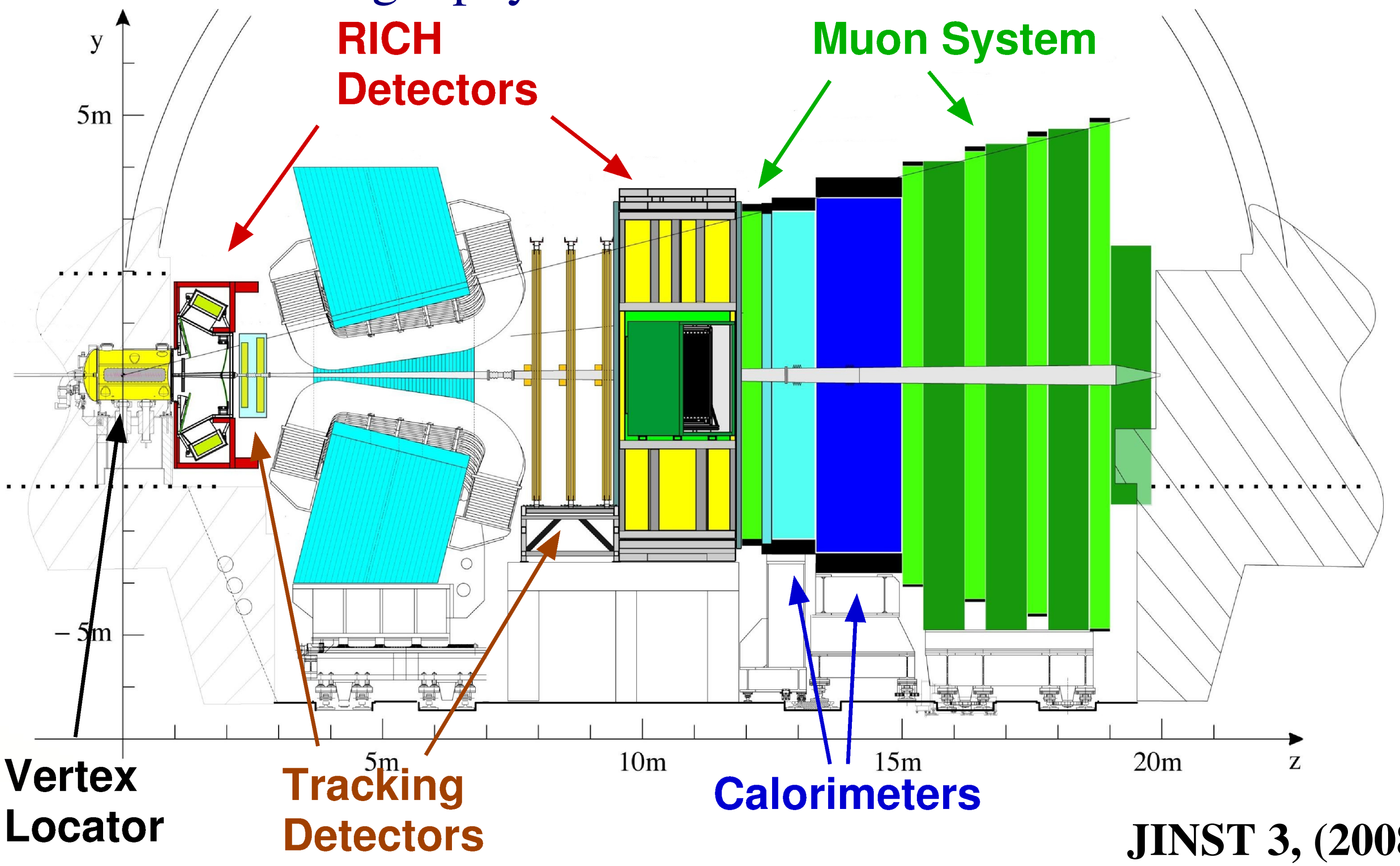


Giacomo Graziani (INFN Firenze)
on behalf of the LHCb Collaboration

Physics Beyond Colliders Annual Workshop
November 21, 2017

The LHCb Detector

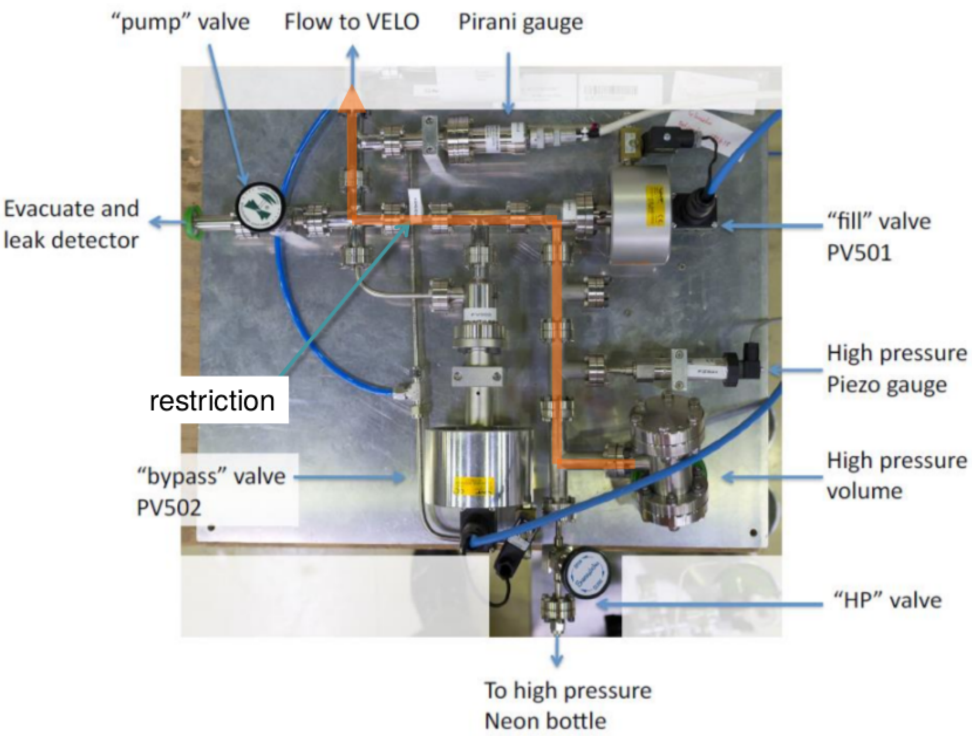
- LHCb is the LHC experiment with "fixed-target like" geometry very well suited for... fixed target physics!



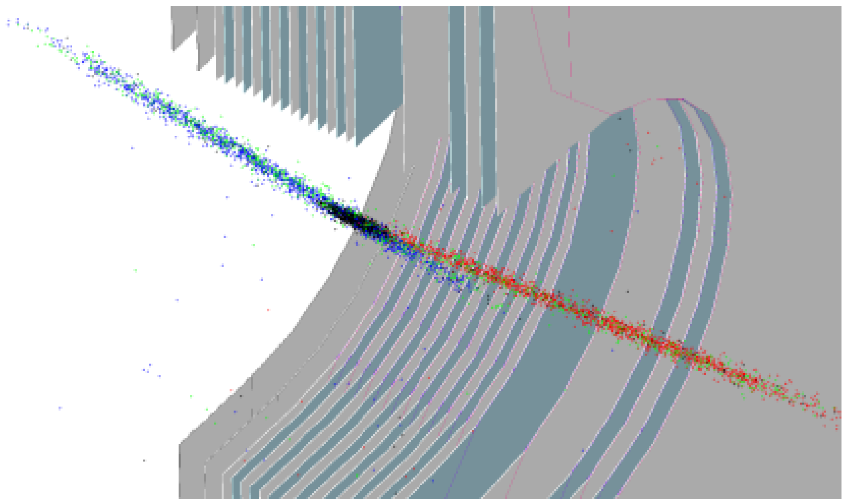
JINST 3, (2008) S08005

- fully instrumented in the pseudorapidity range $\mathbf{2} < \eta < \mathbf{5}$
- excellent vertexing, tracking, PID
- flexible trigger with high bandwidth: hardware level up to 1 MHz, software level with offline-quality event reconstruction

SMOG: the LHCb internal gas target



- The System for Measuring Overlap with Gas (SMOG) allows to inject small amount of noble gas (He, Ne, Ar, ...) inside the LHC beam around ($\sim \pm 20$ m) the LHCb collision region
  Expected pressure $\sim 2 \times 10^{-7}$ mbar



- Originally conceived for the luminosity determination with beam gas imaging **JINST 9, (2014) P12005**
- Became the LHCb internal gas target for a rich and varied fixed target physics program

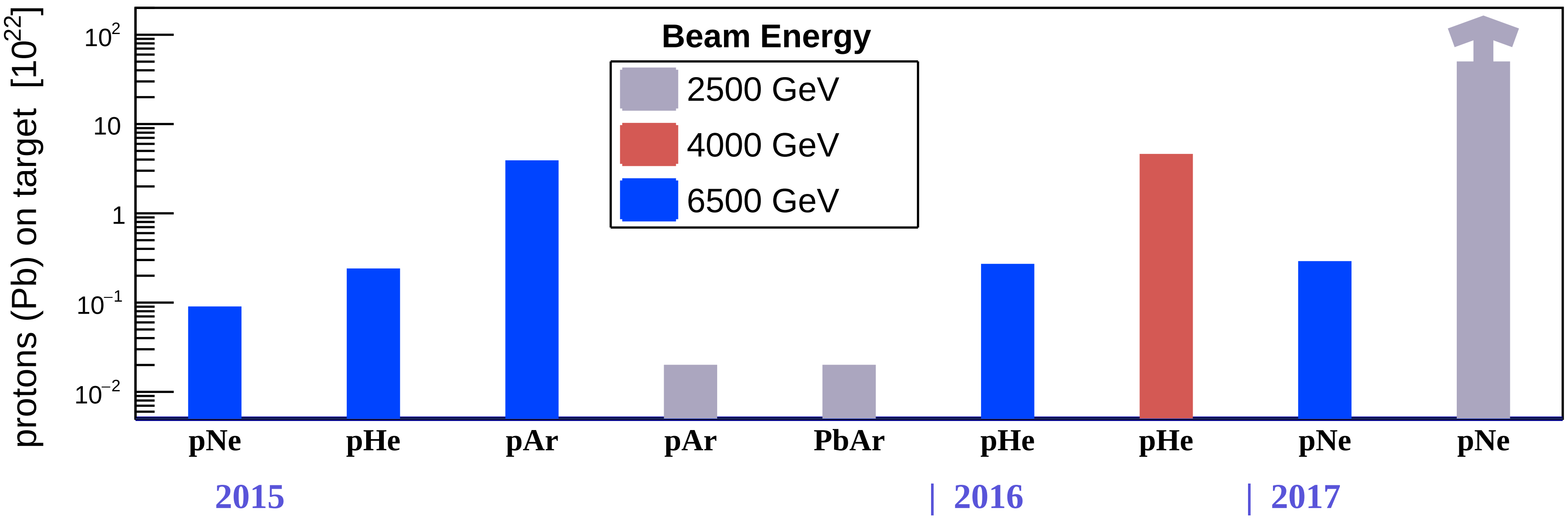
SMOG samples on tape

2012 First pilot runs with p and Pb beams on Neon

2015 Several data samples with He, Ne and Ar targets acquired during **special runs** (e.g. VdM scans) with **limited beam intensity** and without interference with pp data taking

2016 Other special runs with helium gas

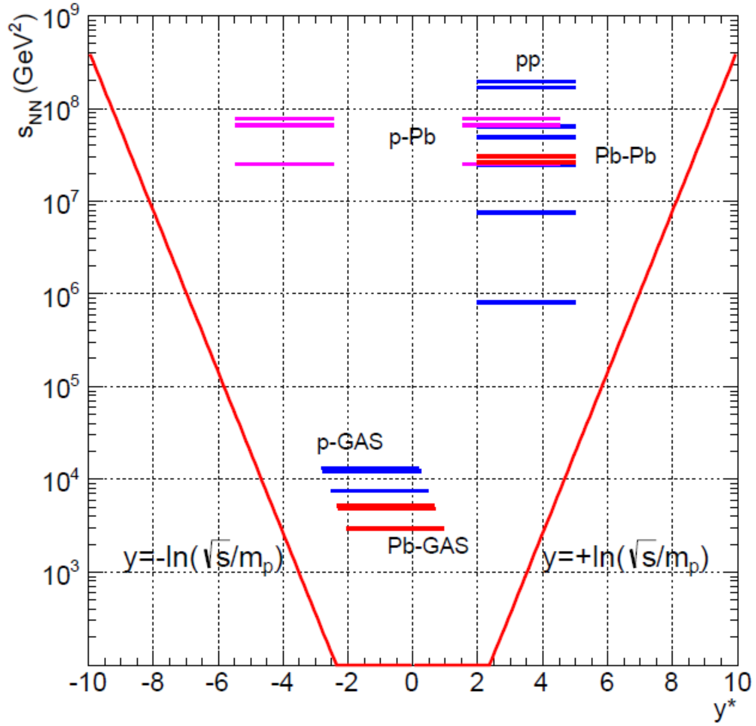
2017 First **high-intensity** SMOG run currently ongoing, with proton beam of nominal intensity on Neon. Acquiring **simultaneously** beam-gas collision (when beam1 bunches cross the detector without colliding) and beam-beam collisions for standard LHCb physics (up to 742 non colliding and 1094 colliding bunches)

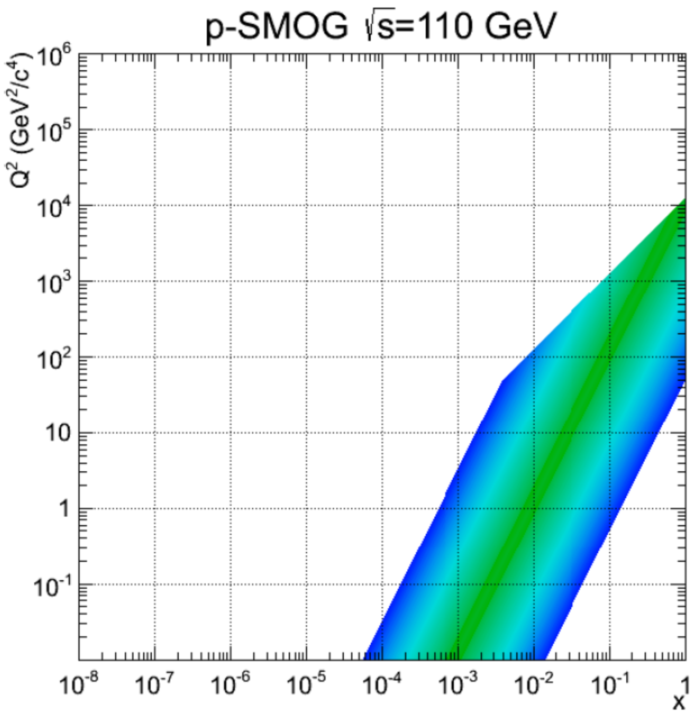


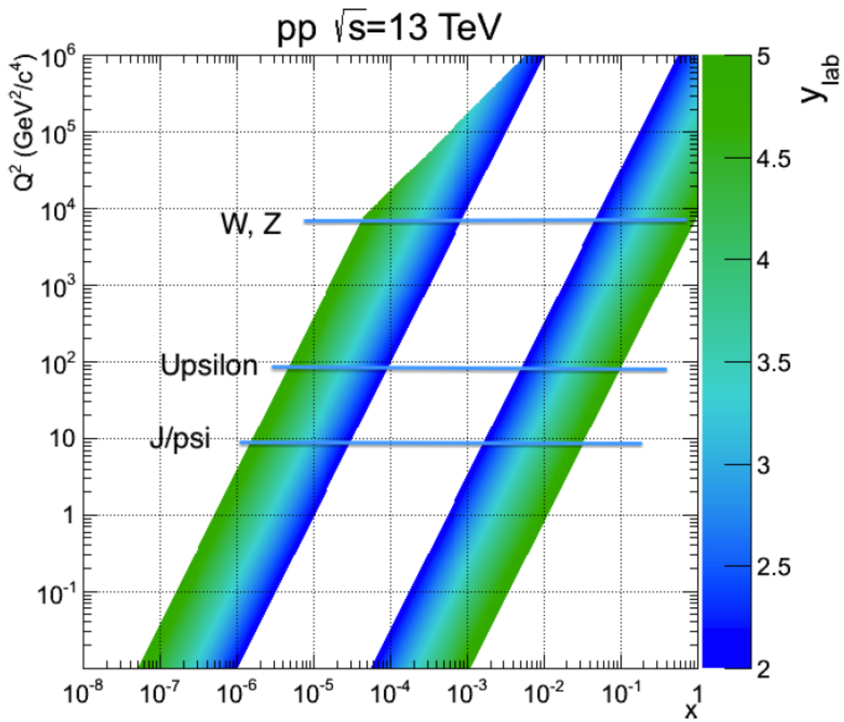
$$\mathcal{L} \sim 5\,\mathrm{nb}^{-1} \times \frac{pot}{10^{22}} \times \frac{p_{gas}}{2 \times 10^{-7}\,\mathrm{mbar}} \times \mathrm{Exp\_Efficiency}$$

The pros of fixed target

- Study **different collisions systems** at different energy scales **within the same experiment**
- Access to large-x region also at moderate Q^2







Physics Menu

Unique measurements already achievable with few/nb:

- Study charm production at $\sqrt{s_{\mathrm{NN}}} \sim 100$ GeV on different nuclei
  ➡ Cold Nuclear Matter effects, sensitivity to (n)PDFs at large x
- production measurements in soft QCD realm at $\sqrt{s_{\mathrm{NN}}} \sim 100$ GeV
  large model uncertainties, great interest for Cosmic Rays physics

The first two preliminary results from SMOG released during 2017

Future:

- several ideas for improved targets under study, which could greatly widen the physics program:
  - larger density
  - wider range of nuclei
  - possible target polarization
  - crystal targets

See talks by

P. Di Nezza (LHCSpin)

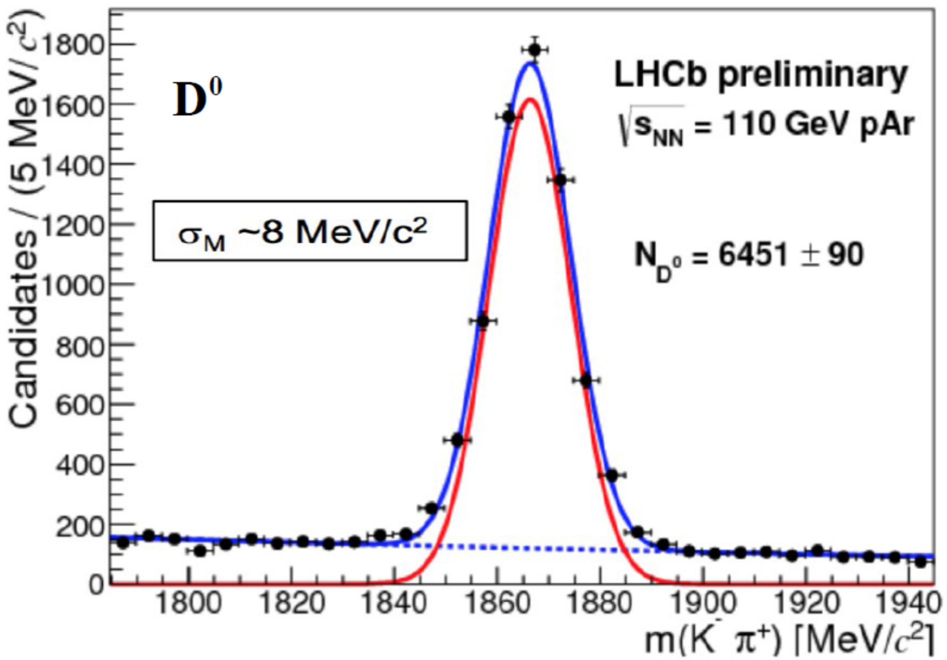
J.-P. Lansberg (AFTER)

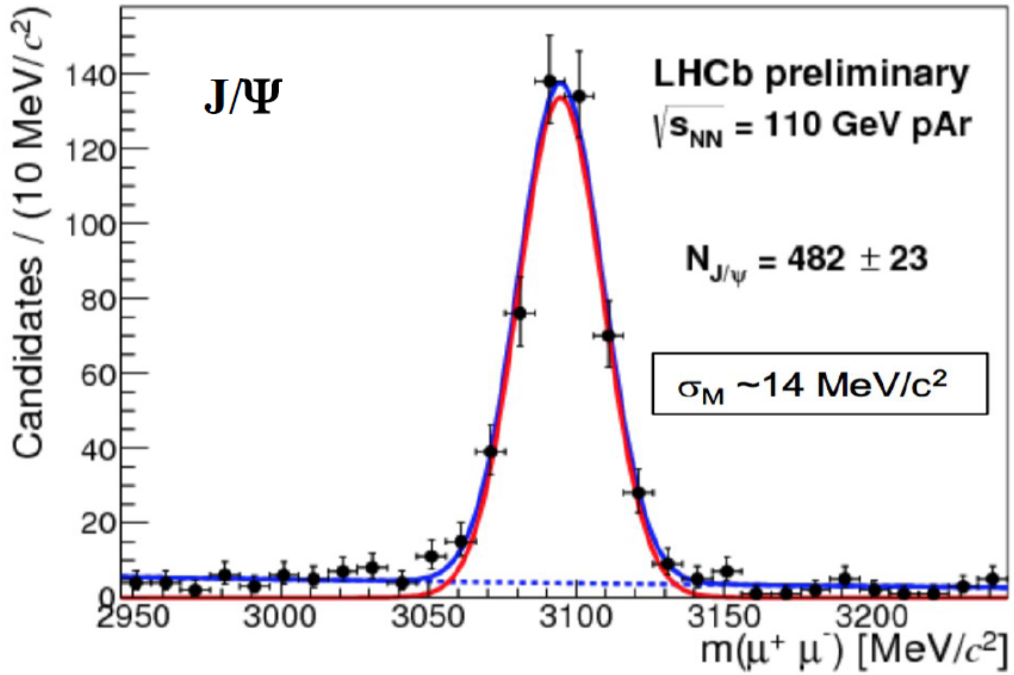
A. Stocchi (Crystal exps)

M. Ferro Luzzi (LHC FT)

First charm in LHC fixed target

LHCb-CONF-2017-001



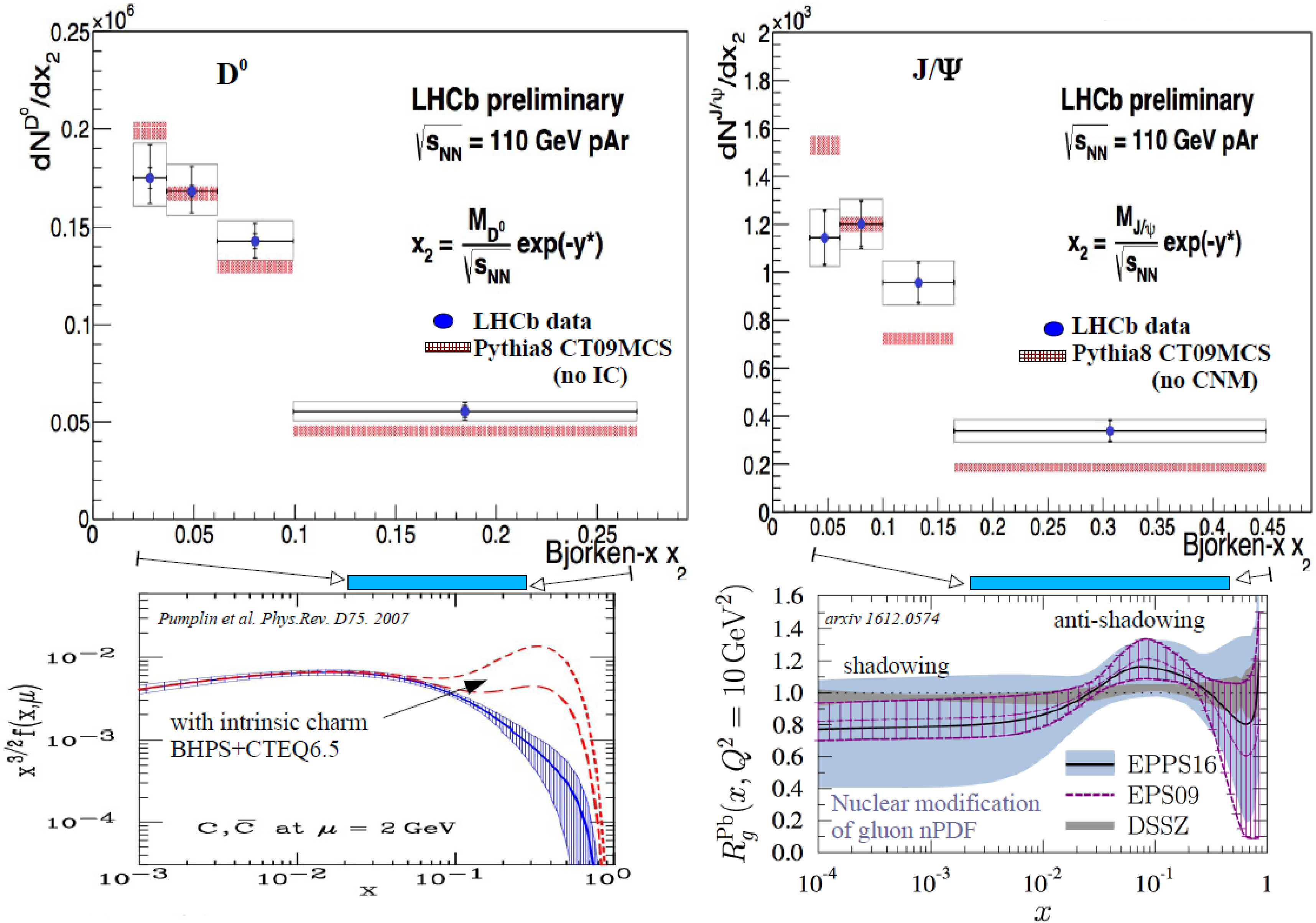


- Obtained from the first small (few nb^{-1}) p-Ar data sample acquired in 2015
- First demonstration analysis, but differential shapes (y, p_{T}, x_F) expected to constrain models
- more theoretical predictions needed!

Acessing high-x region

LHCb-CONF-2017-001

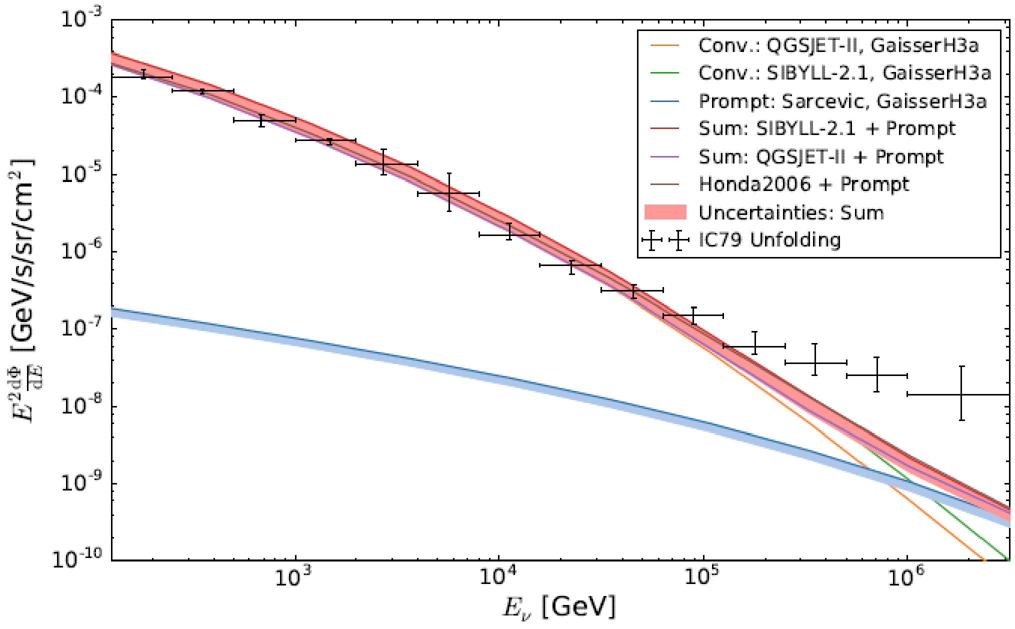
Distributions of $x_2 \equiv (Me^{-y^*})/\sqrt{s_{\rm NN}}$



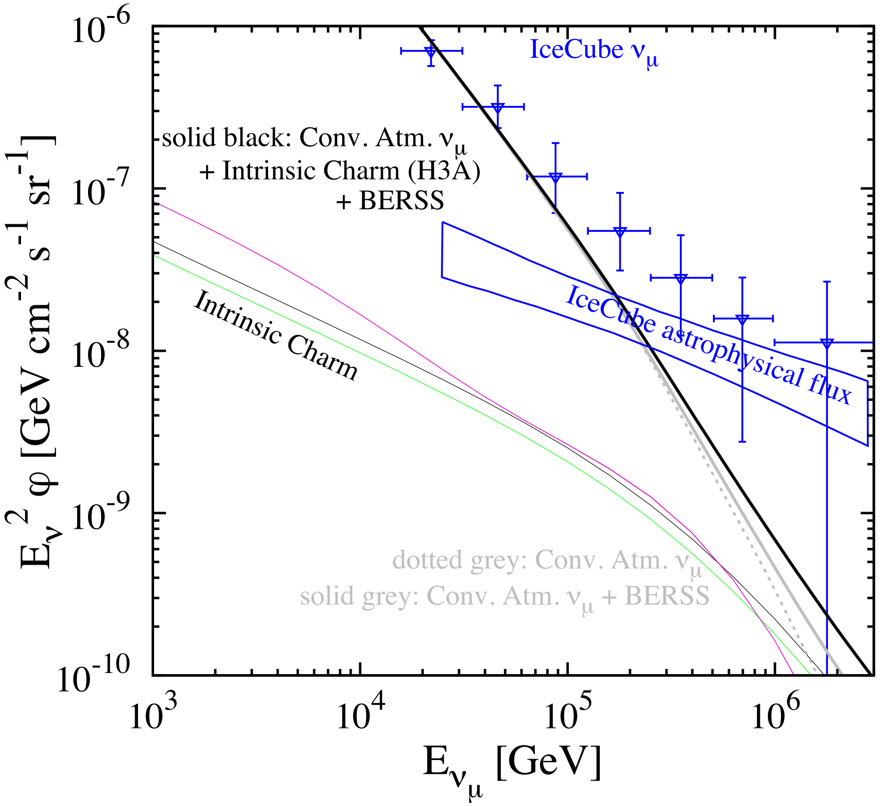
Possibility to constrain **Intrinsic charm** and antishadowing in nPDFs.

Inputs to Cosmic Ray Physics I

- Intrinsic charm important for **high-energy neutrino astrophysics**: background for the ICECUBE experiment is dominated by open charm production in atmospheric showers
- predictions are based on measurements at $x_F \sim 0$ (like pp collisions in LHCb)
- possible relatively large contribution from intrinsic charm



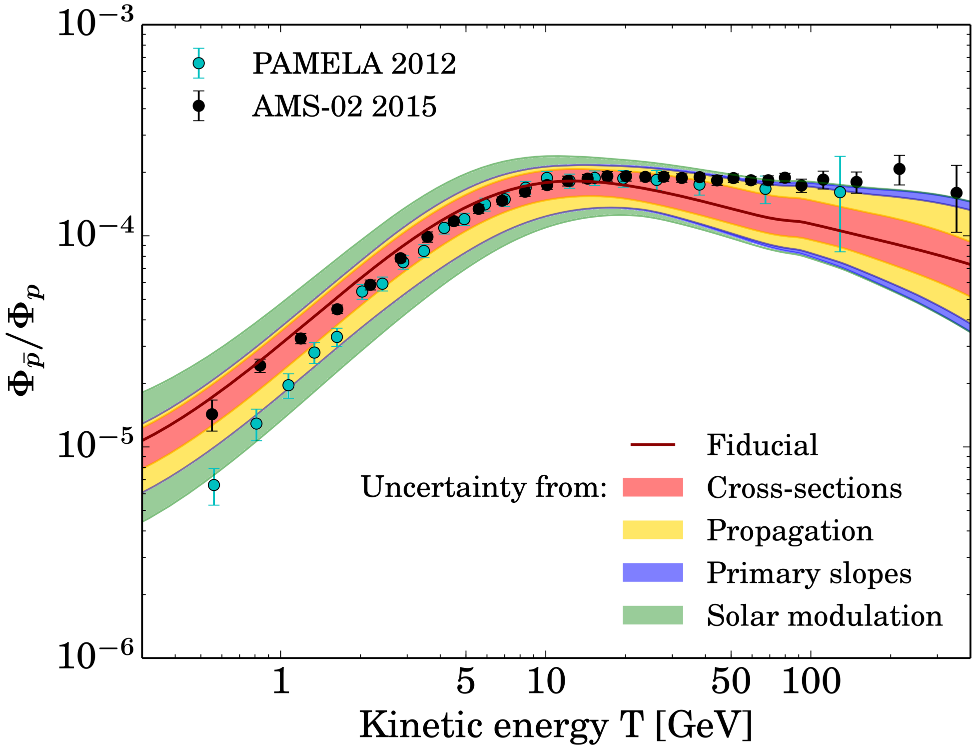
IceCube, arXiv:1705.07780



Laha and Brodsky, arXiv:1607.08240

Inputs to Cosmic Ray Physics II

- AMS02 results provide unprecedented accuracy for measurement of $\overline{\mathrm{p}}/\mathrm{p}$ ratio in cosmic rays at high energies **PRL 117, 091103 (2016)**
- hint for a possible excess, and milder energy dependence than expected
- prediction for $\overline{\mathrm{p}}/\mathrm{p}$ ratio from spallation of primary cosmic rays on intestellar medium (H and He) is **presently limited by uncertainties on $\overline{\mathrm{p}}$ production cross-sections, particularly for p-He**
- no previous measurement of $\overline{\mathrm{p}}$ production in p-He, current predictions vary within a factor 2
- the LHC energy scale and LHCb +SMOG are very well suited to perform this measurement



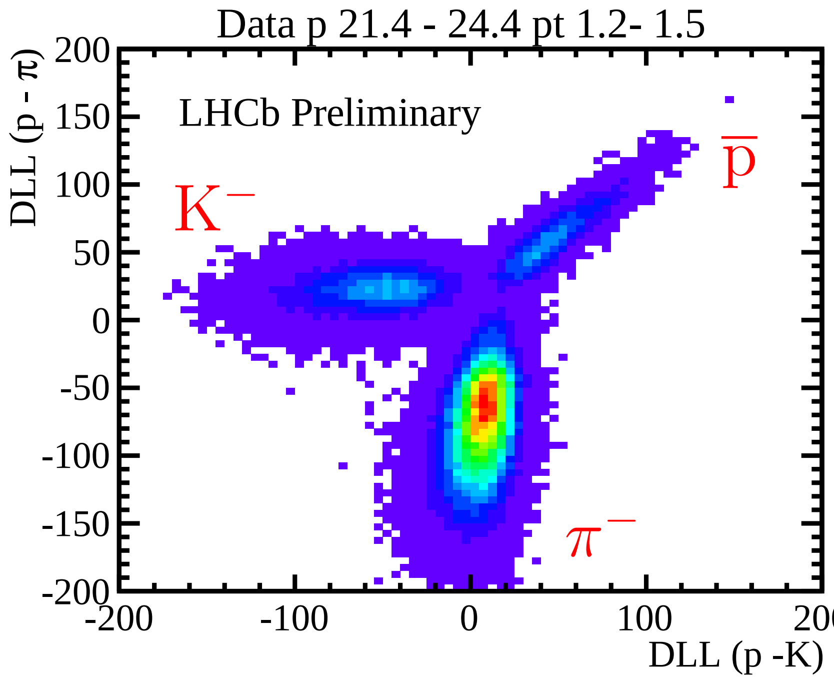
Giesen et al., JCAP 1509, 023 (2015)

Antiprotons in p-He

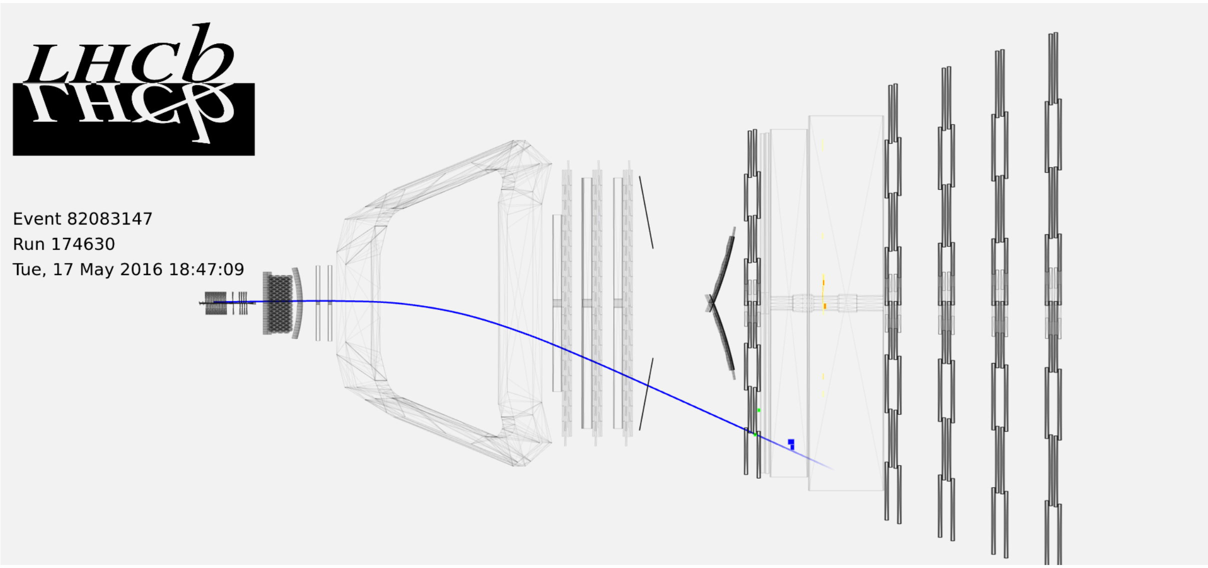
LHCb-CONF-2017-002

- Data collected in May 2016, with proton energy 6.5 TeV, $\sqrt{s_{NN}} = 110$ GeV
- Most data 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

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



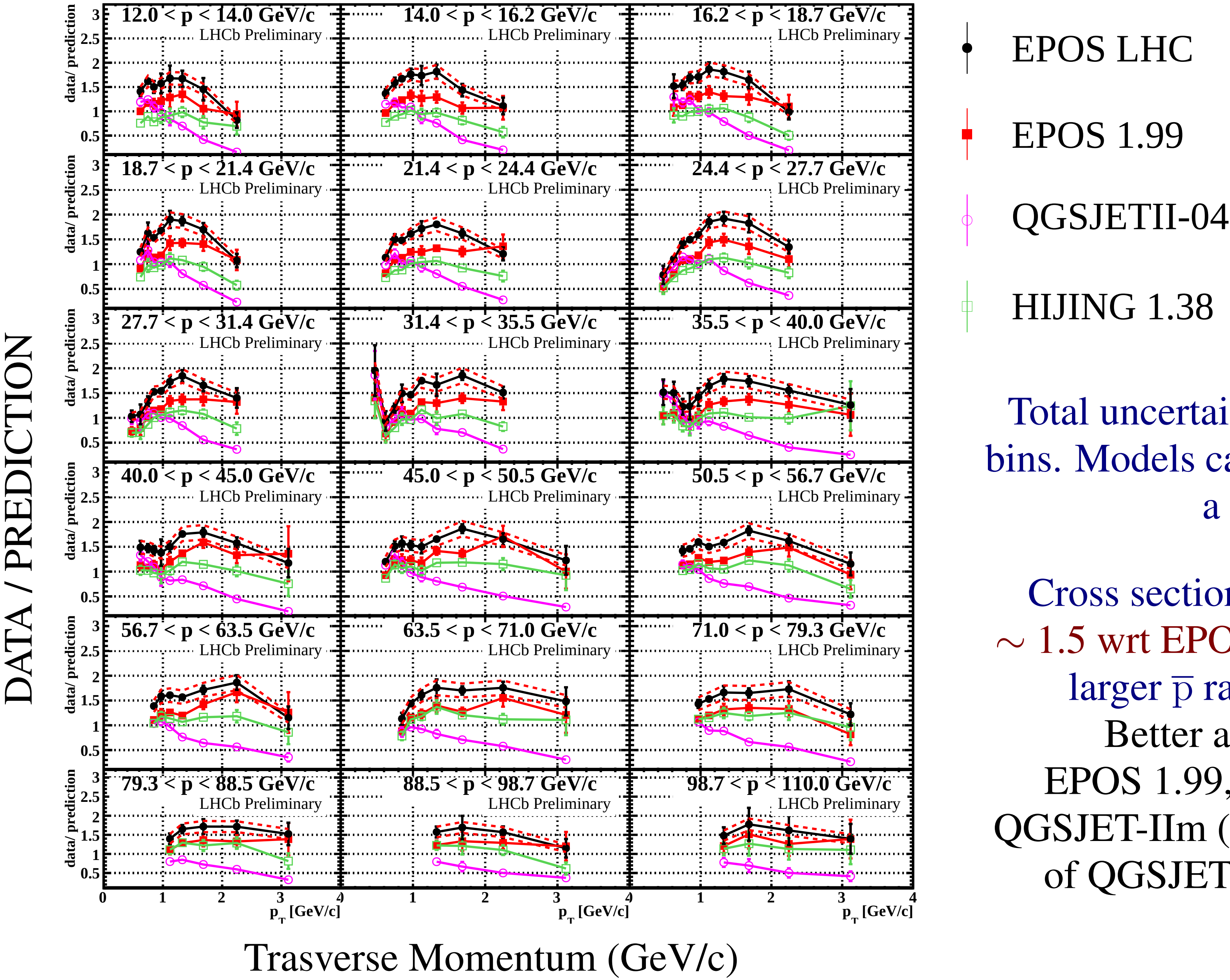
- Normalization from **p-e⁻ elastic scattering**



- Exploit excellent vertexing capabilities to **separate prompt and detached components**. Only the prompt component included in this preliminary result (analysis of component from hyperon decays will follow).
- Background from gas contamination **measured** to be $0.6 \pm 0.2\%$

Result for cross section, ratio with models

LHCb-CONF-2017-002

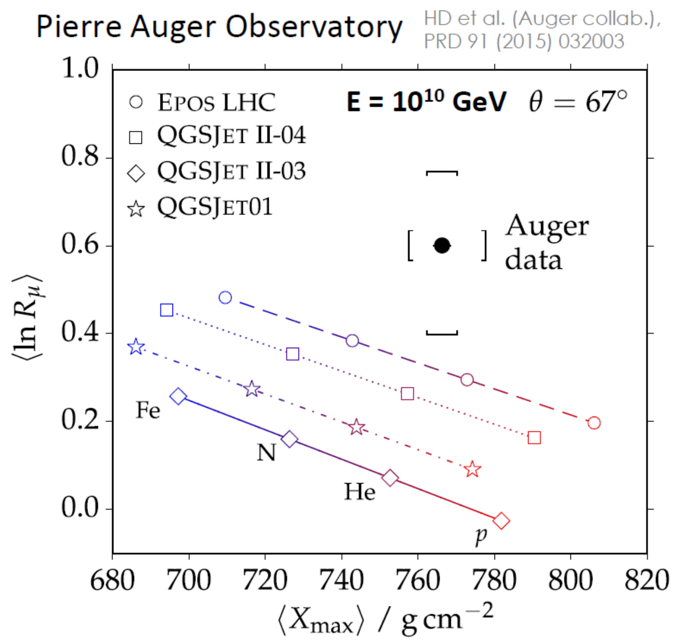


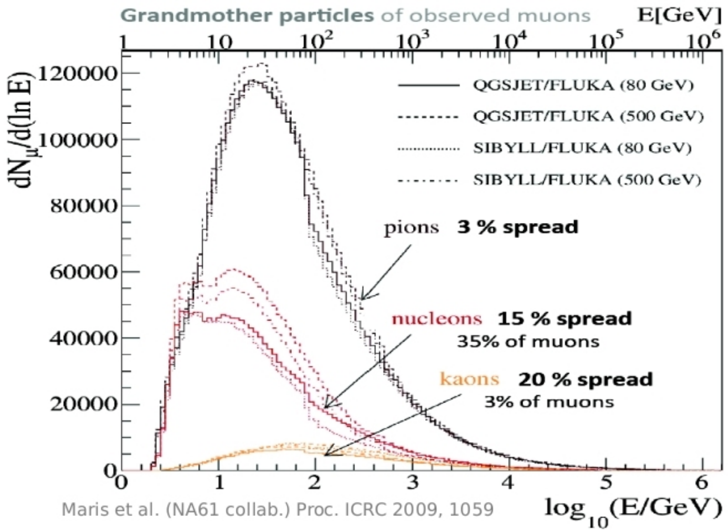
Total uncertainty ~ **10%** for most bins. Models can differ by more than a factor 2.

Cross section is larger by factor ~ 1.5 wrt EPOS LHC (mostly from larger $\overline{p}$ rate per collision). Better agreement with EPOS 1.99, HIJING 1.38 and QGSJET-IIm (low energy extension of QGSJET-II-04, not shown)

Inputs to Cosmic Ray Physics III

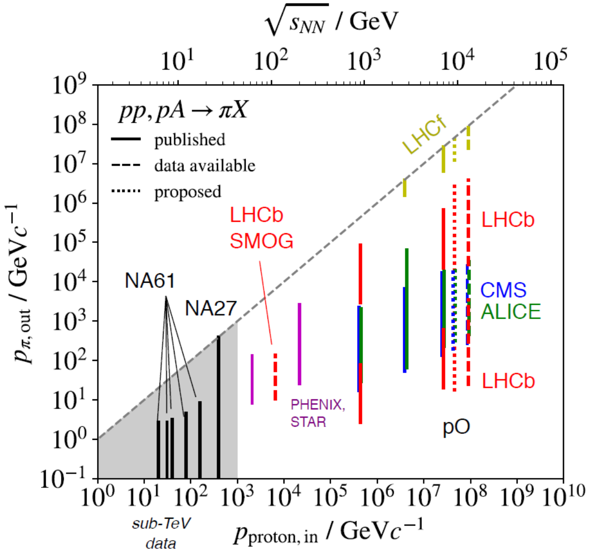
- **Muon puzzle** in the understanding of UHECR atmospheric showers: yield and lateral profile of muons are used as proxy of impinging particle mass, but are not well predicted by current models





- muon yield at given energy is critically dependent on production of nucleons and kaons
- large uncertainties from nuclear effects since data with nitrogen and oxygen targets are sparse

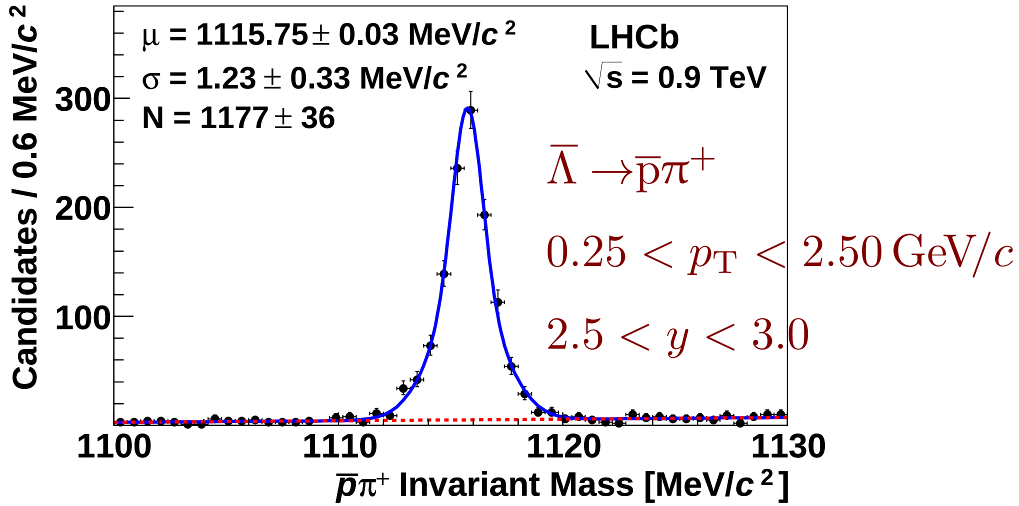
- **proton-Neon SMOG data provide a good model for interaction in air**, energy corresponds to 3rd to 4th interaction for a 10^{10} GeV shower. Measurement at mid-rapidity useful to model lateral shower development
- Use of nitrogen target not excluded in the future



Prospects for soft QCD

- production of charged hadrons (p/$\overline{\text{p}}$, $\pi^{\pm}$, $K^{\pm}$) is also being measured for the three different targets (He, Ne, Ar). Ratios of particle species, not affected by uncertainty on luminosity, can provide precise constraints to soft QCD models

- We plan to extend the study of $\overline{\text{p}}$ production to hyperon decays (accounting for 20-30% of the production). LHCb can cleanly select decays of $\overline{\Lambda}$



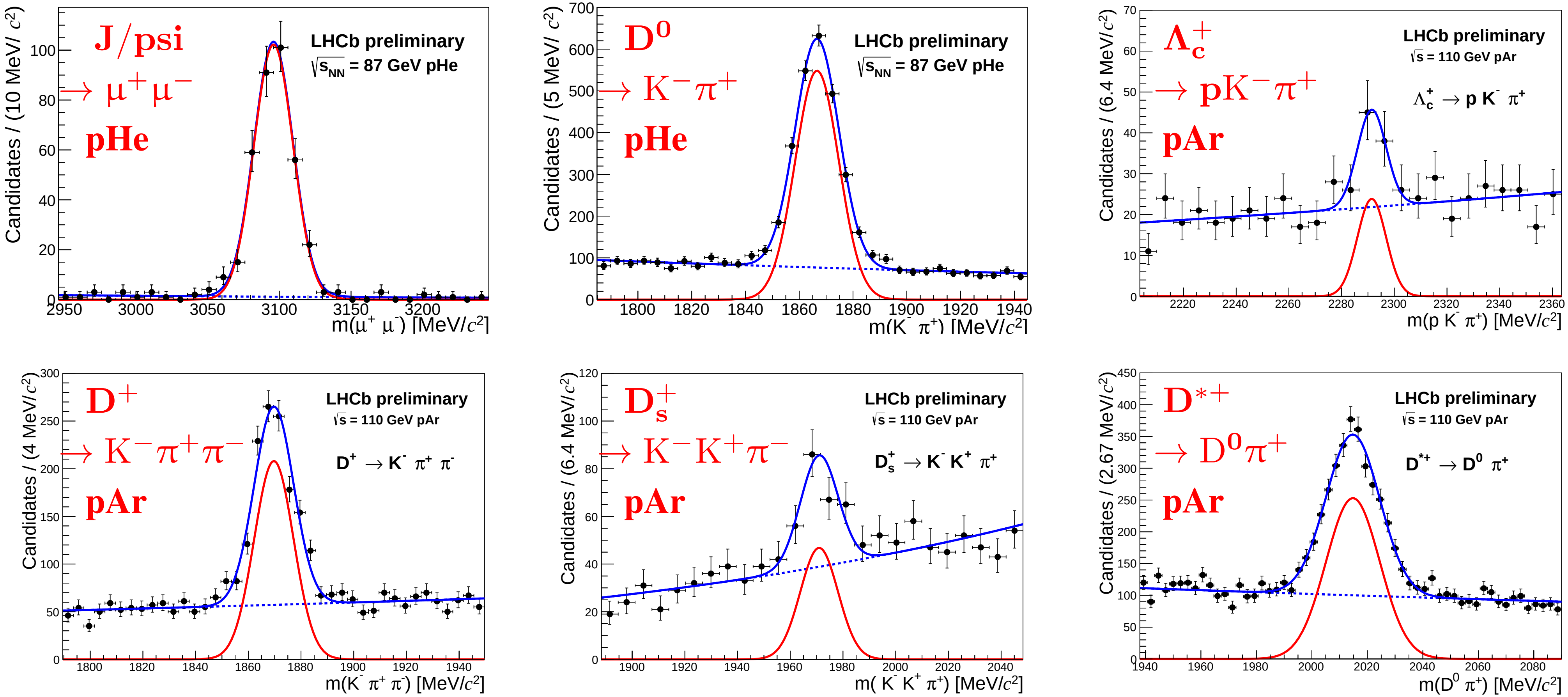
JHEP 1108 (2011) 034

- Another p-He run was performed in november 2016 with a 4 TeV beam ($\sqrt{s_{\text{NN}}}$ =87 GeV) ➡ scaling violation can be constrained

- investigating our potential for antinuclei $\overline{d}$, $\overline{t}$ and $\overline{^{3}He}$

Prospects for heavy flavours

- A rich charm harvest expected from data on tape: comparison of different targets, study other states (Λ_c^+ baryons, D_s^+, ...)



- Large gain in statistics (factor 10-100) expected from currently ongoing **high-intensity run** , despite larger backgrounds from ghost collisions and beam-induced residual gas
  ➡ higher accuracy, extend study to $\psi(2S)$, ...

Conclusions

- Big progress with LHCb fixed target program during the last year
- First results demonstrate physics potential
  - Charm production in fixed target data expected to provide crucial inputs to understand CNM effects and Intrinsic Charm
  - LHCb became an unexpected contributor to cosmic ray physics!

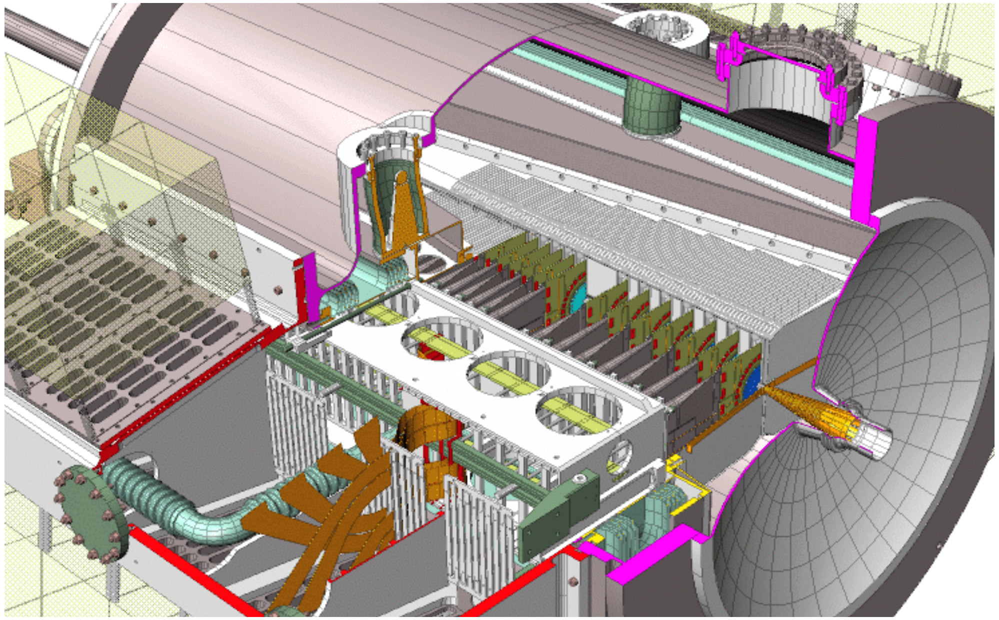
- Improving the hardware: new calibrated pressure gauge installed during last winter shutdown ➡ cross-check of the luminosity determination

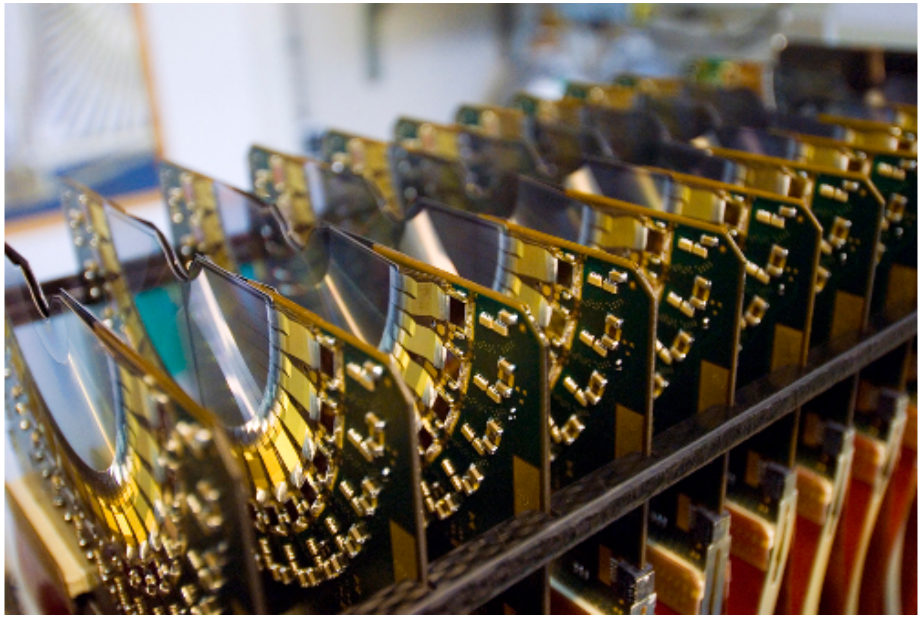
- Setting the ground for future fixed target programs at LHCb
  - evaluating several proposals for new targets ➡ talks in this workshop

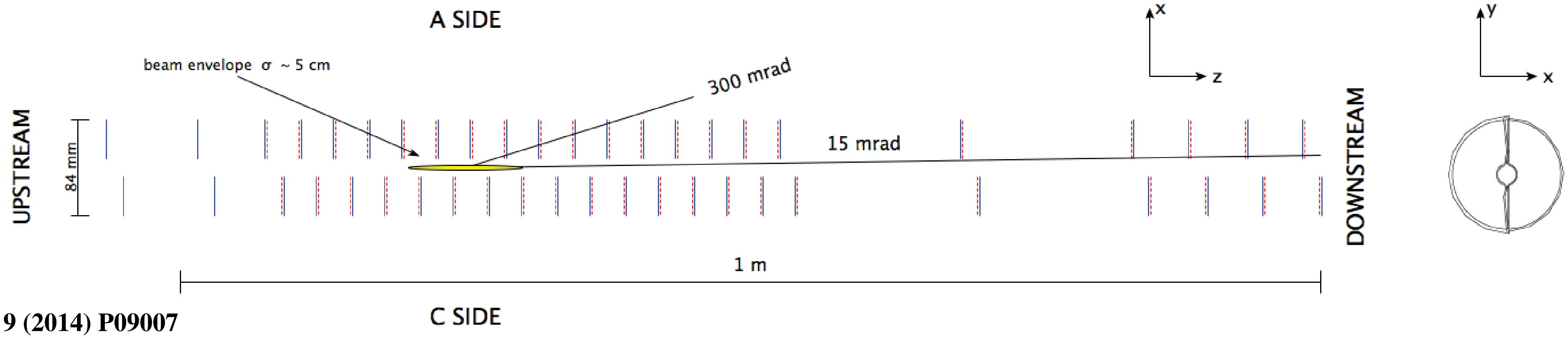
Additional Material

the VErtex LOcator

- Crucial detector for all SMOG studies
- optimized for forward tracks, allowing impact parameter resolution of $15 + 29/pT(GeV)\ \mu m$





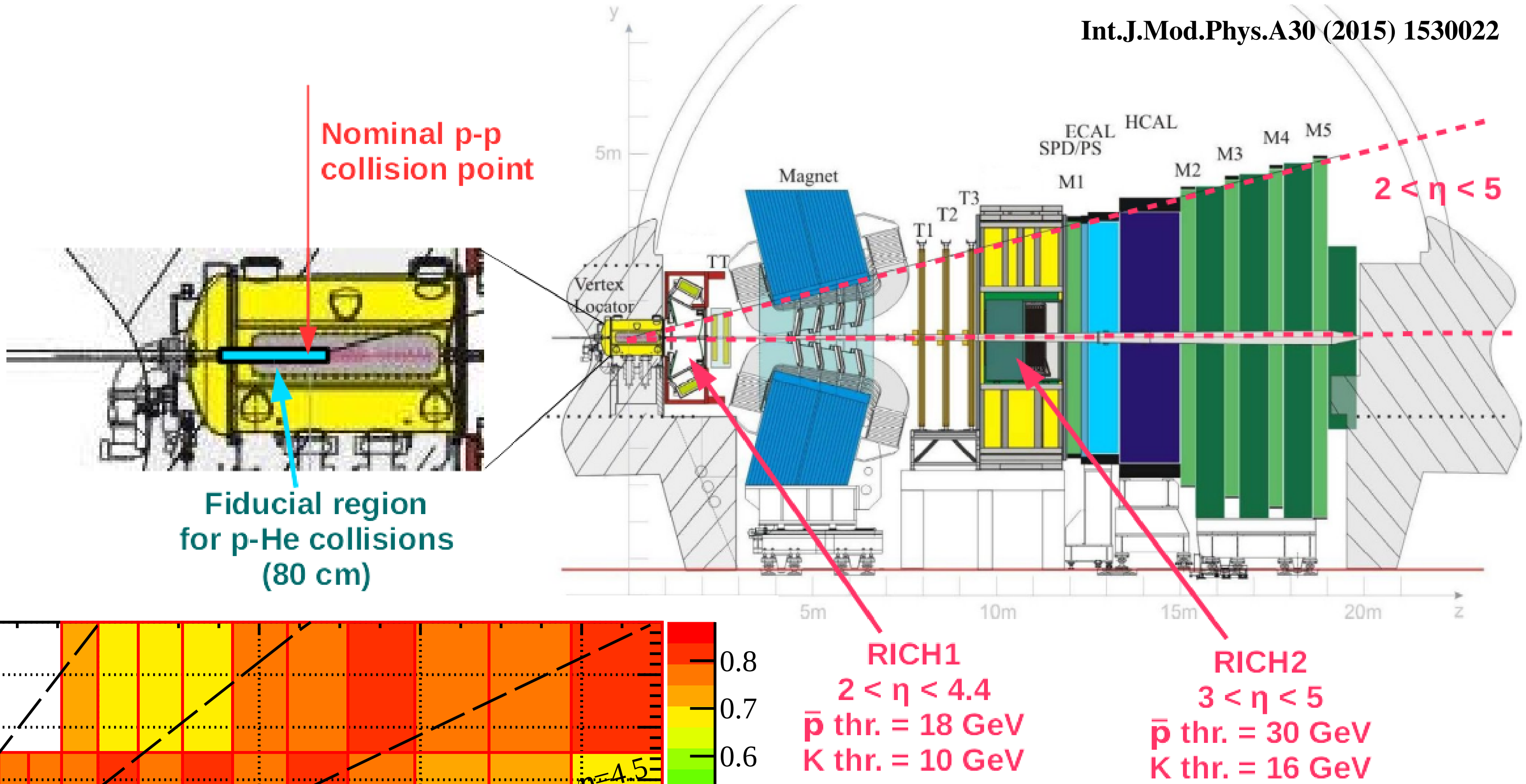


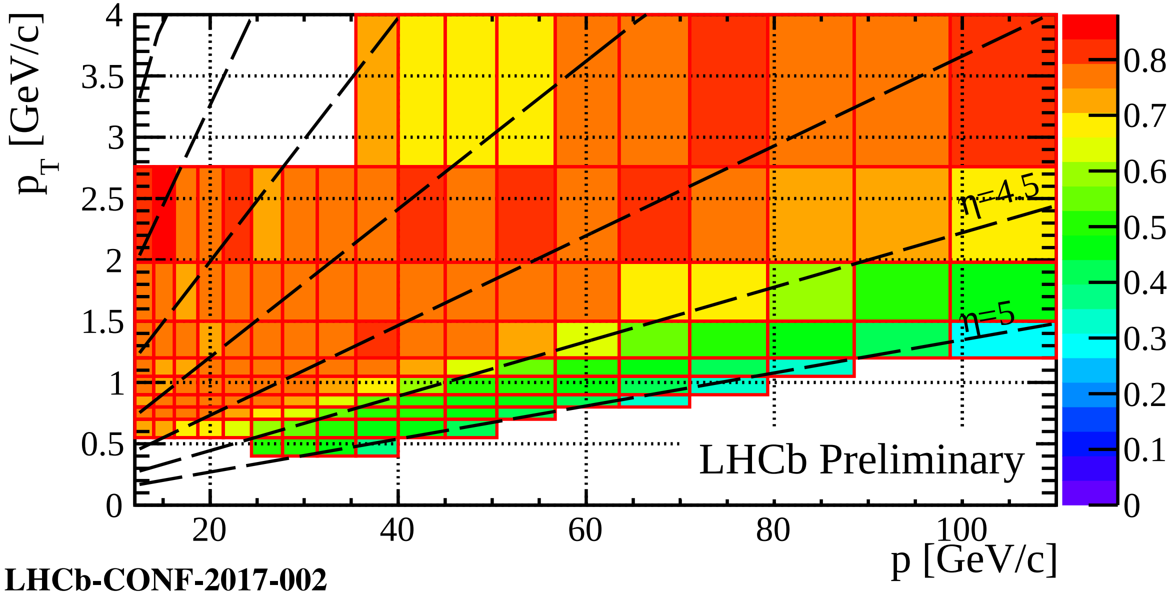
JINST 9 (2014) P09007

Acceptance for SMOG events

JINST 3, (2008) S08005

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





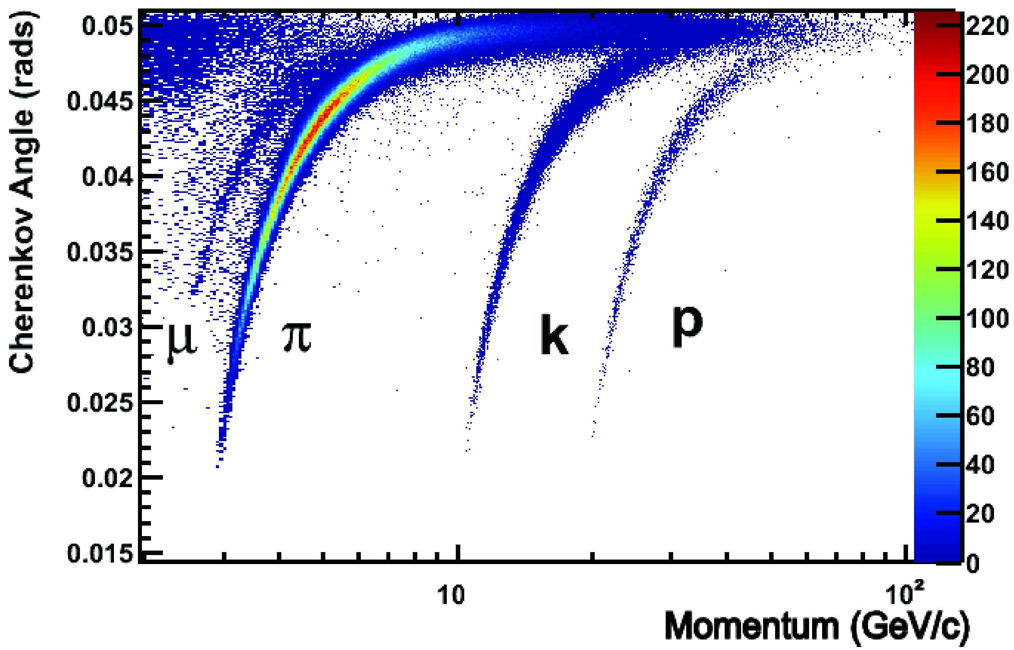
LHCb-CONF-2017-002

Total acceptance × reconstruction efficiency for antiprotons

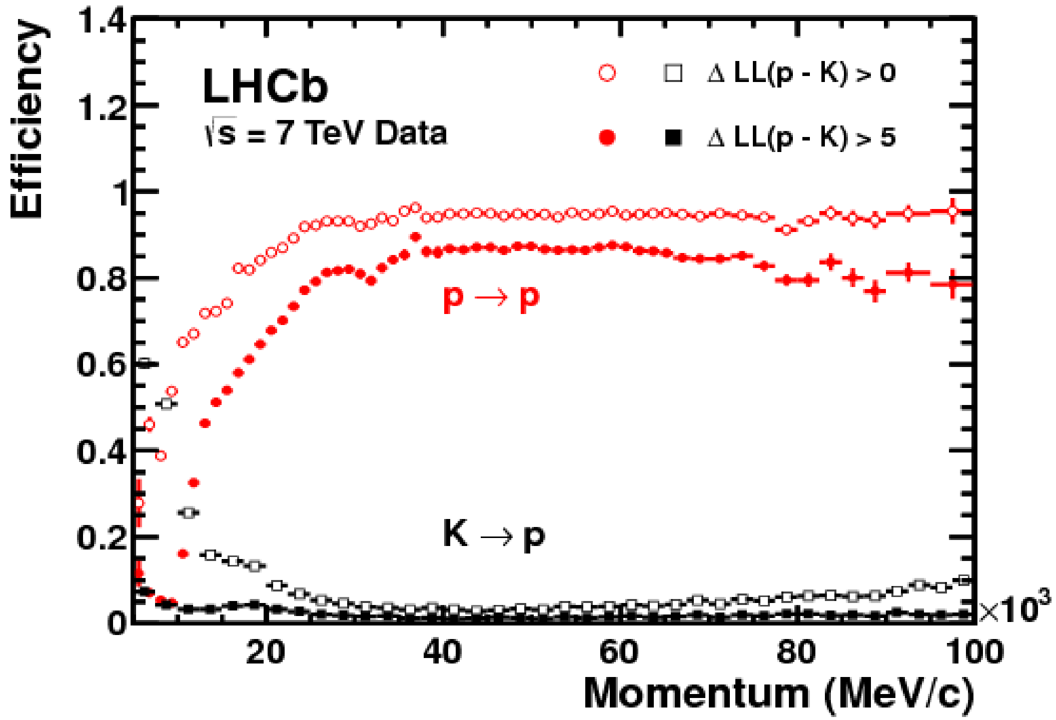
Tracking efficiency estimated from simulation, validated on (pp) data

RICH Performance

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



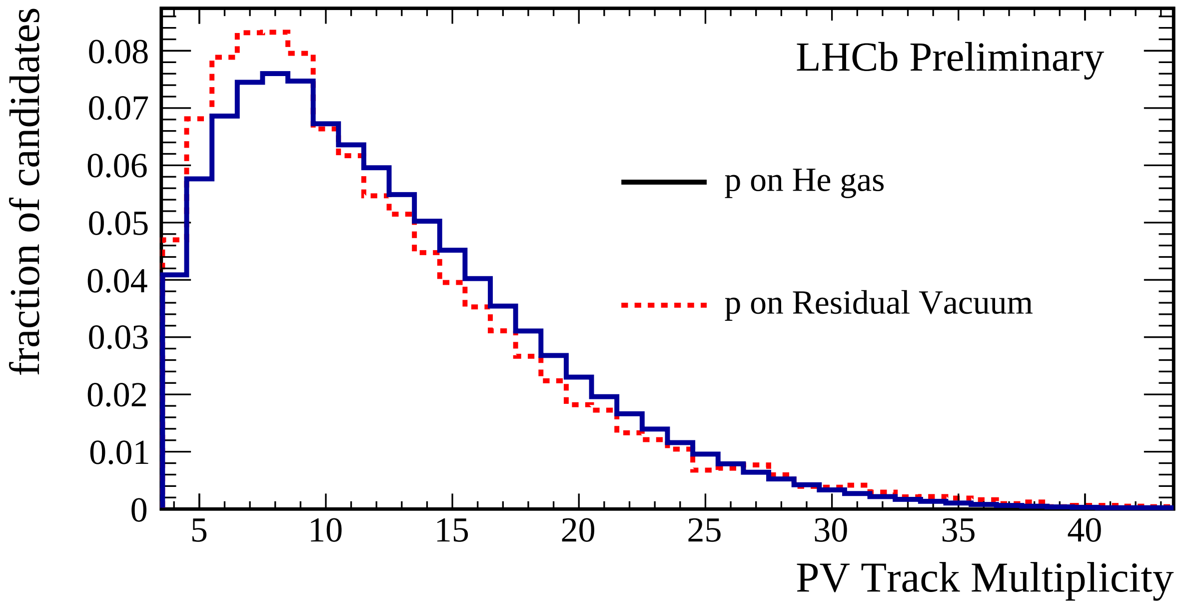
Particle separation in RICH1



K/p separation vs momentum

Background from Residual Vacuum

- 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)



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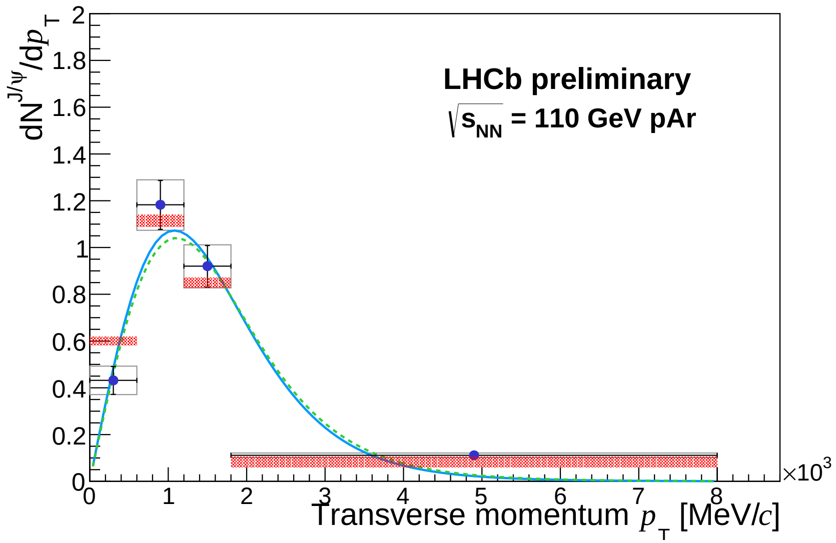
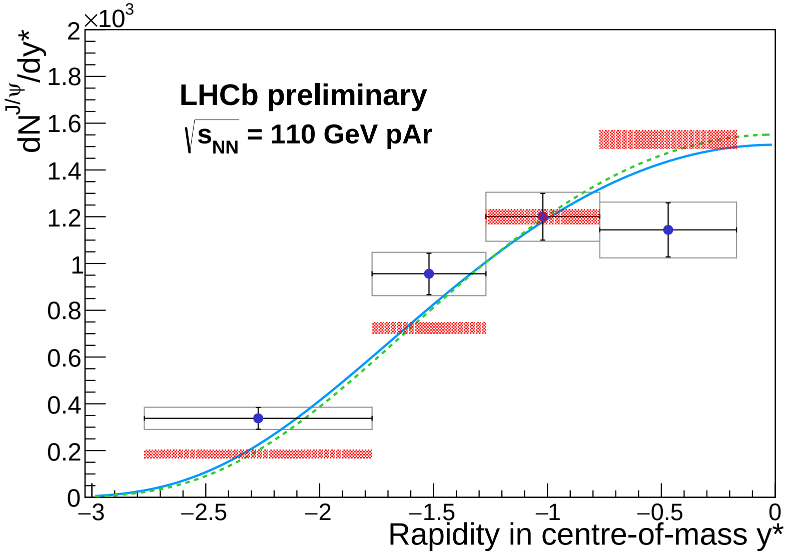
- Gas impurity found to be small: $0.6 \pm 0.2\%$
- PV multiplicity in residual vacuum events is **lower** than in He events, but has longer tails ➨ confirm findings from Rest Gas Analysis that residual vacuum is mostly H_2, with small heavy contaminants

Results for D^0 and J/ψ

LHCb-CONF-2017-001

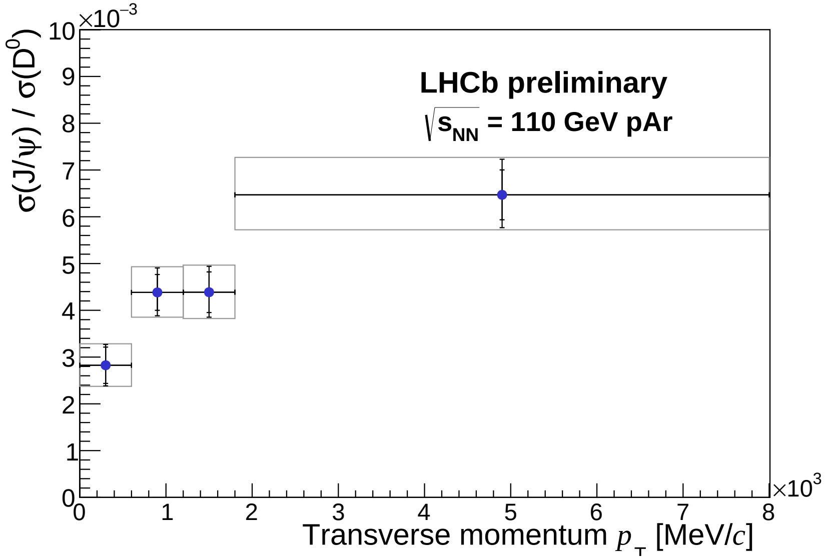
p_T and y^* spectra for J/ψ

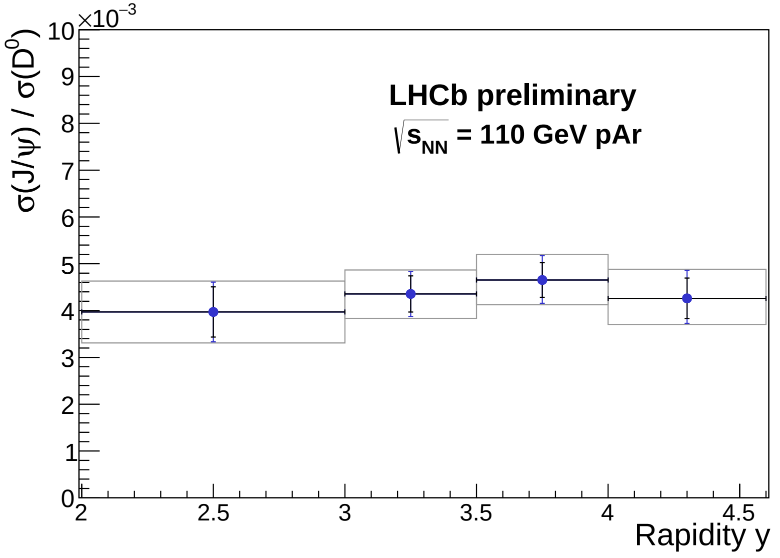




compared to Pythia8 predictions and phenom. parameterizations in arXiv:1304.0901

J/ψ / D^0 Ratios

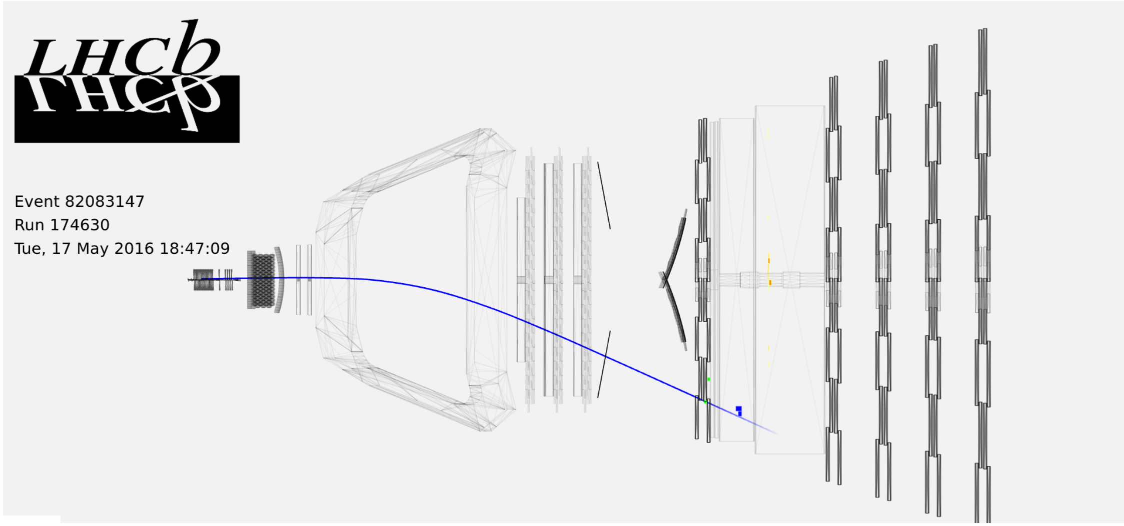


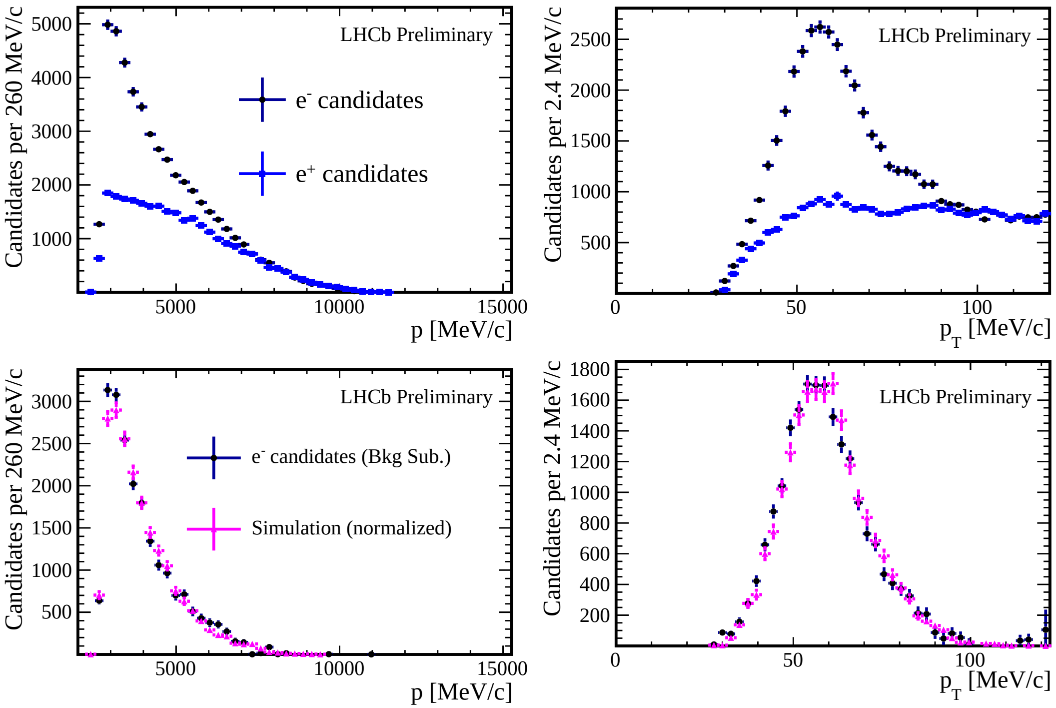


SMOG luminosity determination

LHCb-CONF-2017-002

- Gas target density not precisely known
  ➡ using **p-e$^-$ elastic scattering**
- distinct signature with single low-p and very-low-p_{T} electron track, and nothing else
- residual background charge symmetric to good approximation ➡ data-driven background subtraction





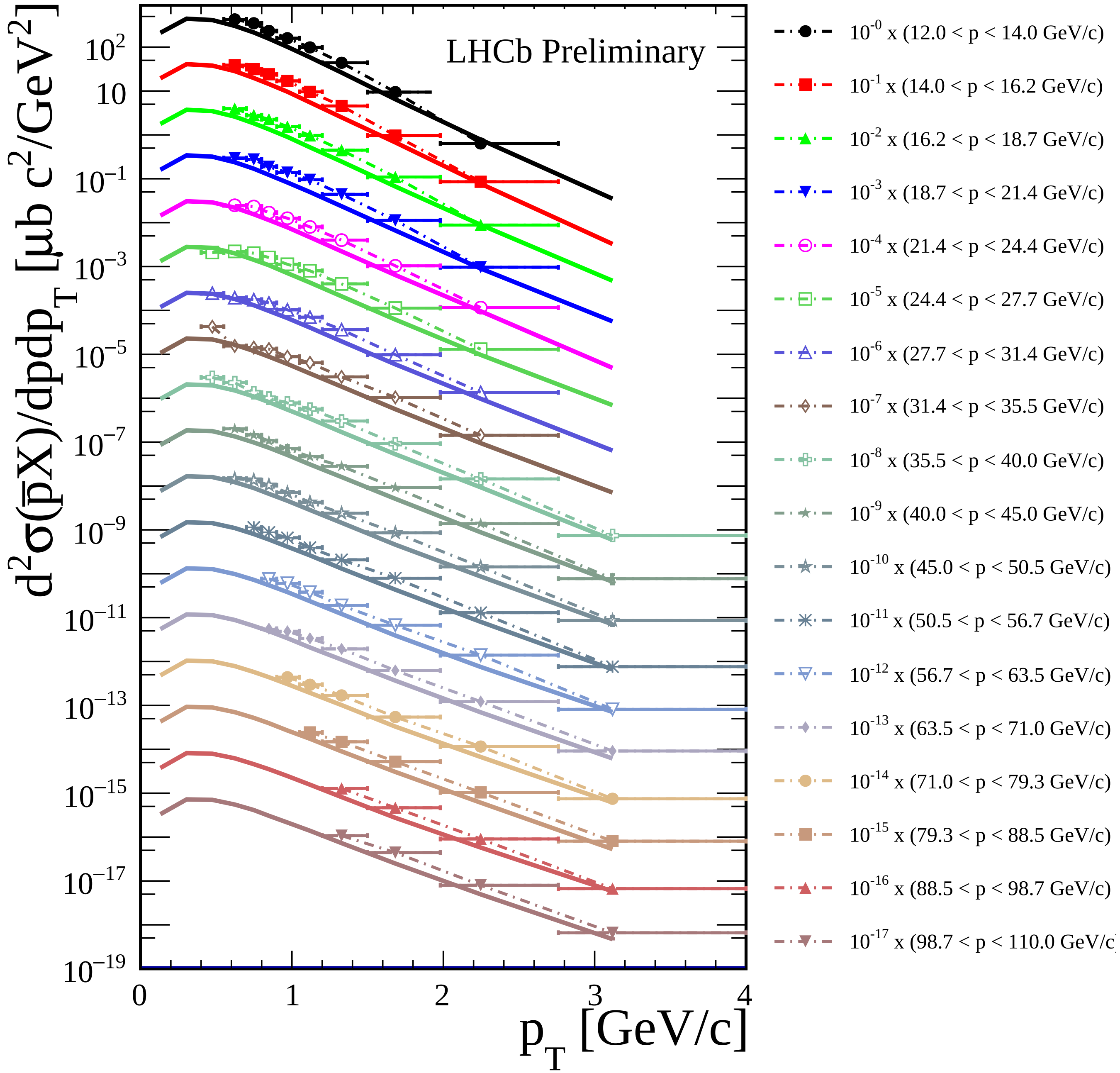
- Very good agreement with simulation of single scattered electrons

$$\mathcal{L} = \mathbf{0.443 \pm 0.011 \pm 0.027}\,\mathrm{nb}^{-1}$$

- equivalent gas pressure is 2.4×10^{-7} mbar, in agreement with the expected level in SMOG
- 6% systematic from absolute reconstruction efficiency

Result for $\overline{p}$ cross section, compared with EPOS LHC

LHCb-CONF-2017-002



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

The total inelastic cross section is also measured to be

$$\sigma_{inel}^{LHCb} = (140 \pm 10)\ \mathrm{mb}$$

The EPOS LHC prediction

[T. Pierog at al, Phys. Rev. C92 (2015), 034906]

is 118 mb, ratio is 1.19 ± 0.08.