LHCb fixed-target results and prospects

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on behalf of the LHCb collaboration

EPS-HEP, 28/07/2021, (unfortunately still) virtual

Prelude

[Ref]

Physics Briefing Book

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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.

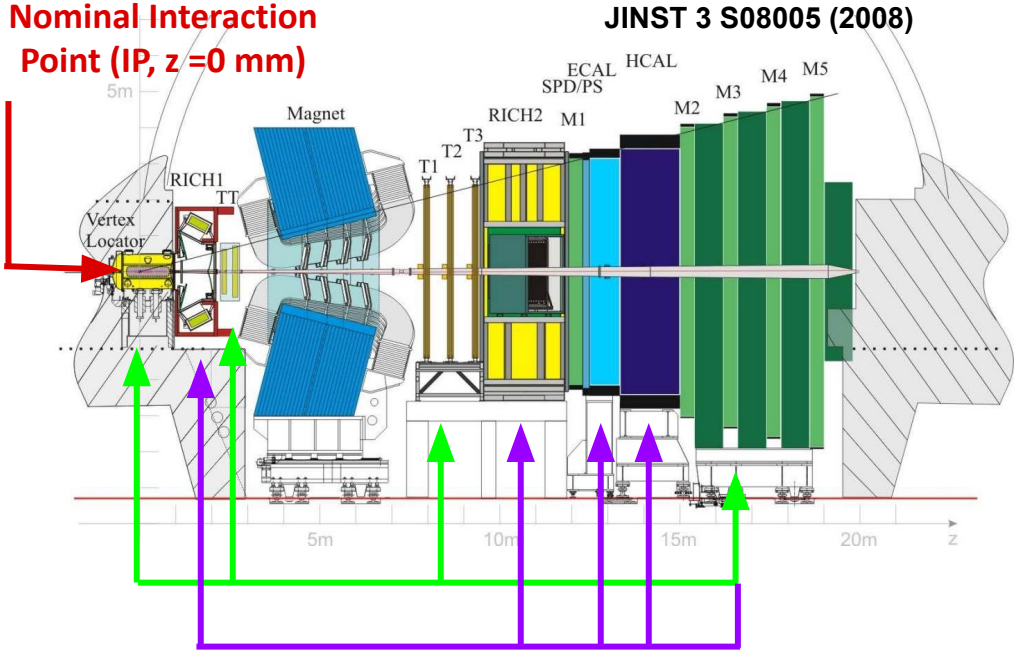
The physics reach of the LHC complex can greatly be extended at a very limited cost with the addition of an ambitious and long term LHC-FT research program. The efforts of the existing LHC experiments to implement such a programme, including specific R&D actions on the collider, deserve support.

- As stressed in the **2020 ESPP update**, the **diversity of the LHC physics reach** also relies on fixed-target experiments. At LHCb, **we are pioneering this from 2015** in parallel to *pp* physics.

The LHCb experiment in its fixed-target configuration

The LHCb experiment

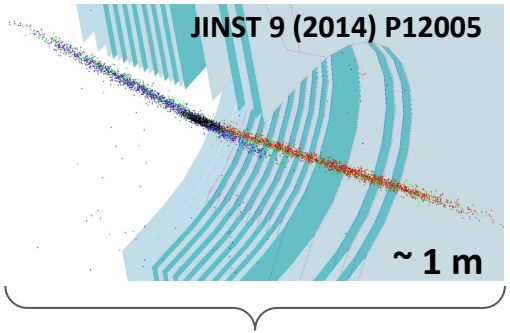
- Originally dedicated to ***heavy flavour*** **physics measurements,** evolving to a **general-purpose experiment** in $\Theta \in [10, 250]\ mrad$ (QCD, SM, heavy ion and **fixed-target program**)



- **Single-arm spectrometer** geometry maximizes acceptance for $b\bar{b}$ pairs, also **optimal for fixed-target** physics
- Same *onion-like* structure as all HEP experiments with **tracking** and **particle identification** sub-detectors
- Excellent momentum resolution, vertexing and PID performance
- Flexible and versatile **trigger system** with high efficiency and bandwidth

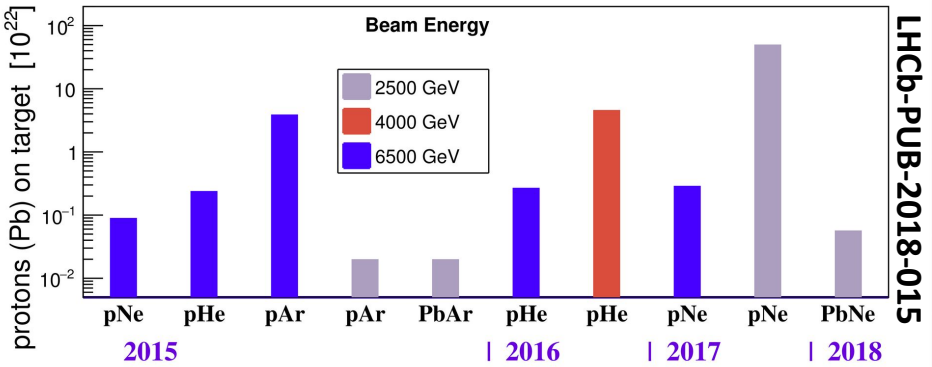
The LHCb fixed-target program, SMOG

- **Luminosity** uncertainties reduced complementing VdM scans with **Beam Gas Imaging,** *ie* the reconstruction of the beam profiles with proton-gas collisions**.**



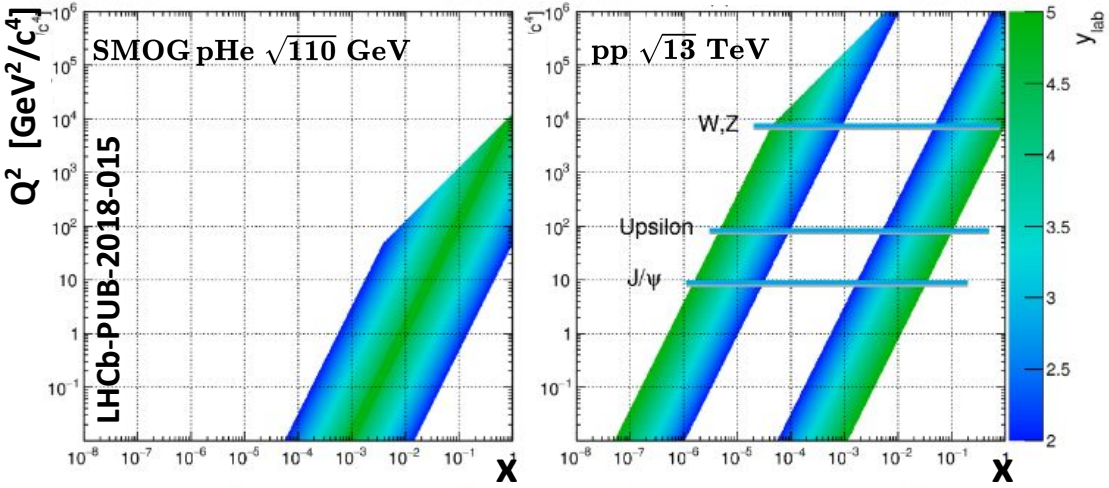
- **SMOG (System for Measuring Overlap with Gas)**: gas injection in the LHC beam-pipe in ± 20 m from the nominal *pp* collision point
- For machine safety, only some **noble gases** with a maximum pressure of $2 \times 10^{-7}\ mbar$, *x*100 wrt the threshold LHC vacuum

- Starting from 2015, LHCb is being exploited as a **fixed-target experiment** too!
- Physics samples with different *cm* energies and systems collected in 2015-18



SMOG physics opportunities

- The LHCb-SMOG accessible physics scenario **is unique at the LHC**:
  - **Wide choice** of the collision system, with intermediate *A* between *p* and *Pb*.
  - **Energy** range $\sqrt{s_{NN}} \simeq \sqrt{2E_N M_N} \in [41, 115]\ GeV$ for beam energy in $[0.9, 7]\ TeV$, filling an **unexplored gap** between SpS and LHC/RHIC results.



  - Access to **large target Bjorken-x values at low Q^2, a poorly PDF constrained region**

The Run2 SMOG results and operations

(Two examples of) Run2 results

- **First charm production study at LHC fixed-target** at 86 GeV *pHe* and 110 GeV *pAr*
- J/ψ → μμ and D^0 → Kπ result at y*<0 consistent with prediction with no **nucleon intrinsic charm.**

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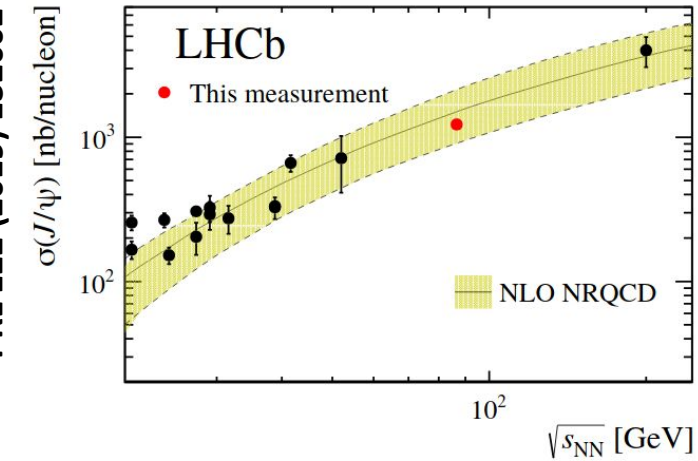
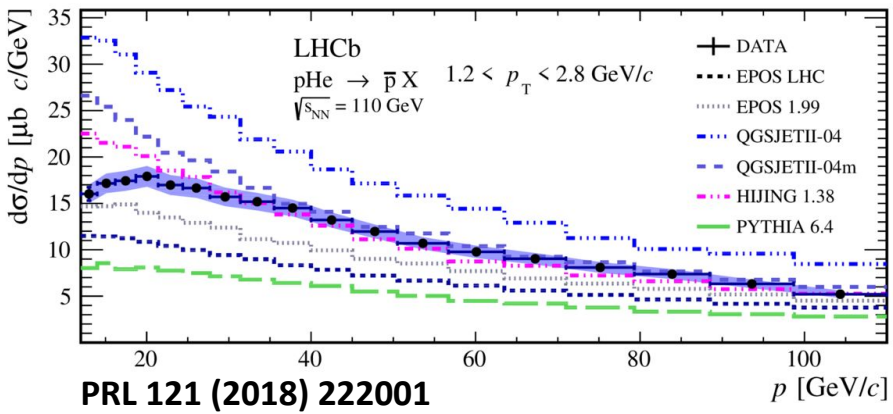


- J/ψ → μμ result at **unique energy scale.**

- **First measurement** of $\sigma(pHe \to \bar{p}_{prompt} X)$ at $\sqrt{s_{NN}} = 110\,GeV$
- **Only prompt $\bar{p}$ considered**
- Uncertainty dominated by lumi (SMOG not equipped with precise gauges for the gas pressure → ***pe* scatterings used**), still lower than the spread among models



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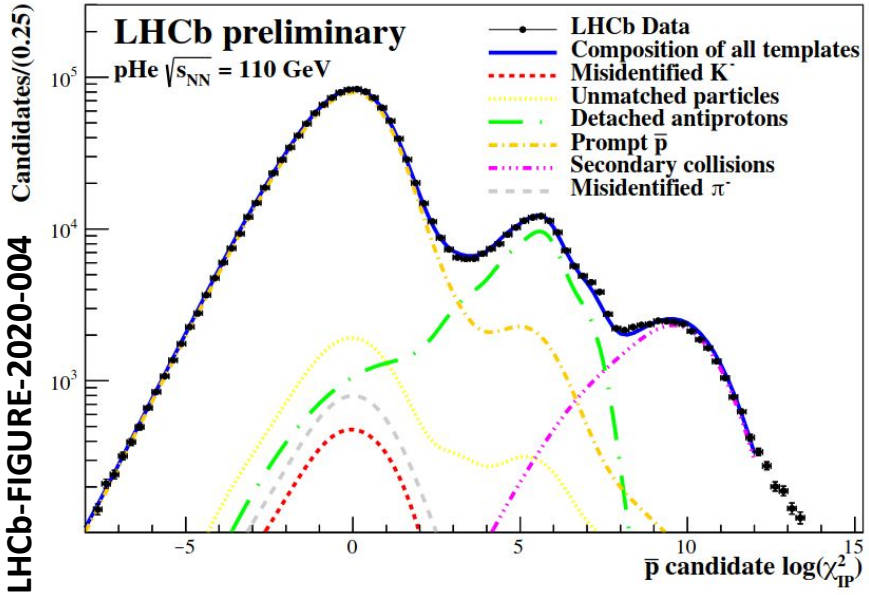
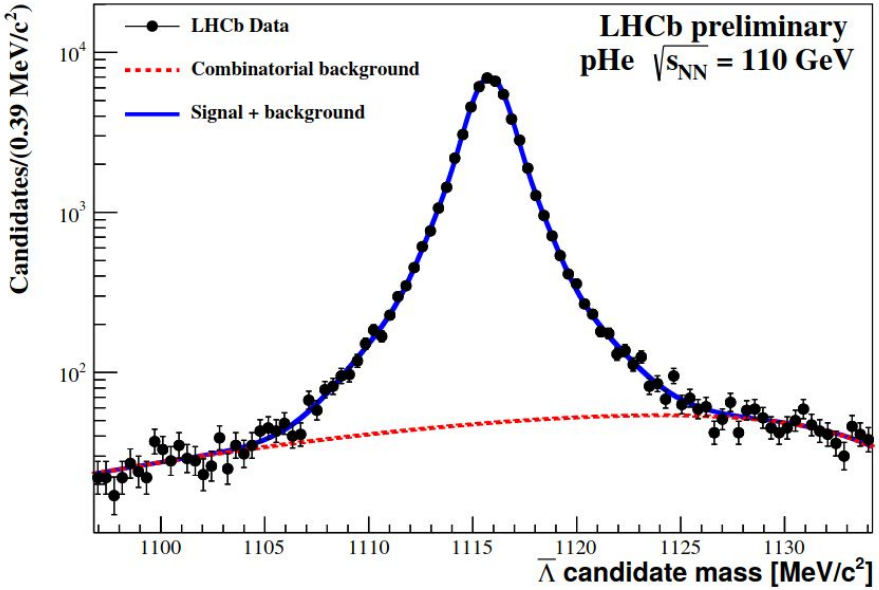
Extensions of the Run2 programme

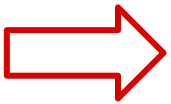
- **Charm in *pNe*** (D^0, Λ_c, quarkonia) and **light hadron productions and spectra** ongoing
- E.g., $\bar{\Lambda} \to \bar{p}\pi^+$ and $\bar{\Sigma} \to \bar{p}\pi^0$ antiproton production exploiting the IP separation wrt prompt and, for the former, the **exclusive decay reconstruction → analysis in review**





Limitations of the Run2 programme (and how to mitigate them)

- The **SMOG gas spread in ± 20m** is a limiting factor, requiring:
  - **Only (some) noble gases at p *O*(10^{-7} mbar),** to keep the beam contamination low
  - Mostly **short and dedicated data-taking periods**, because of the overlap between the *pp* and SMOG luminous regions



- ❏ Measurements **limited by statistics and by data-driven description** of tracking/PID with calibration channels in data
- ❏ For PID, **machine learning approach** trained on highest-statistics SMOG sample and able to predict PID for lower ones developed → **publication soon**

- **Direct luminosity measurement** would reduce the dominant experimental uncertainty
- A gas injection system with **more than one gas recipient** and a controlled gas flux would make possible **to measure ratios** with different injected gases

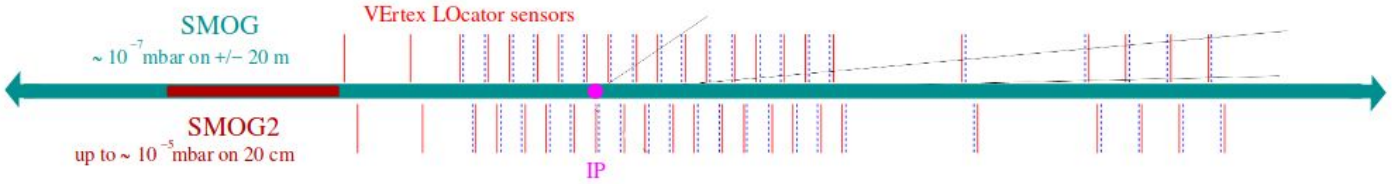
The SMOG2 upgrade

SMOG2 upgrade overview

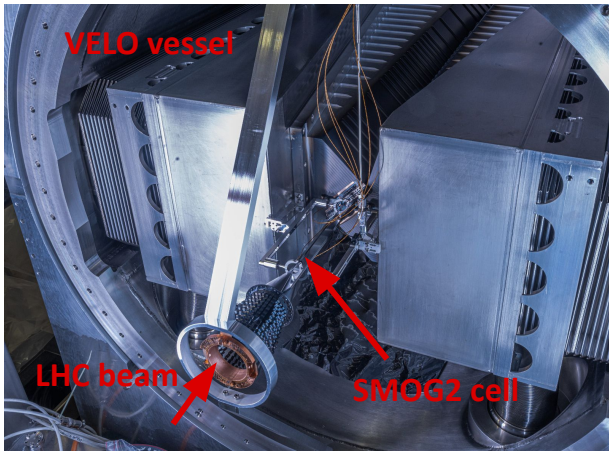
LHCB-TDR-020

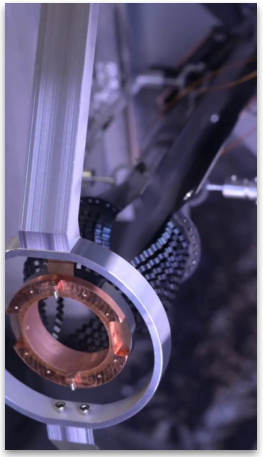
- **SMOG2** : fixed-target LHCb programme upgrade from Run3 on with the installation of a **gas confinement cell upstream the interaction point** ($z \in [-500, -300]$ *mm*)

- Average **gas density** (and luminosity) will increase up to **two orders of magnitude** with the same gas flow as SMOG
- Gas pressure **precisely measured** and finely controlled → **removes lumi error.**
- **More injectable gases** (pending the machine approval): H, O, N, Kr, Xe...
- **Simultaneous data-taking** with *pp* possible, exploiting the separation wrt IP

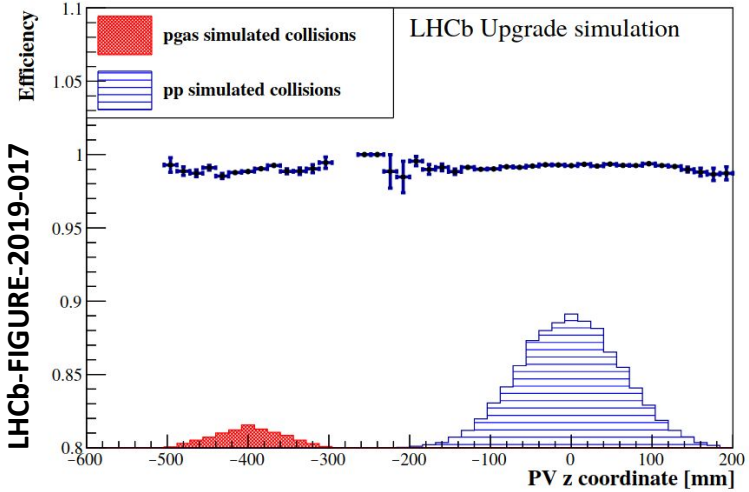


Status of the SMOG2 installation





X10 faster



- **SMOG2** cell installed in August and alignment and calibration accomplished
- Cell made up of two halves opening and closing (as the VELO does to protect its sensors outside data-taking)

- Work currently ongoing to:
  - **Calibrate and install the new gas feed system**, with p sensors and 4 gas lines
  - Prove that **the simultaneous pp-SMOG2 data-taking is feasible** (no showstoppers found)

SMOG2 physics opportunities

LHCb-PUB-2018-015

	SMOG largest sample p–Ne@68 GeV	SMOG2 example p–Ar@115 GeV
Integrated luminosity	$\sim 100\ \text{nb}^{-1}$	$100\ \text{pb}^{-1}$
syst. error on J/ψ x-sec.	6–7%	2–3 %
J/ψ yield	15k	35M
D^0 yield	100k	350M
Λ_c yield	1k	3.5M
$\psi(2S)$ yield	150	400k
$\Upsilon(1S)$ yield	4	15k
Low-mass ($5 < M_{\mu\mu} < 9$ GeV/c^2) Drell-Yan yield	5	20k

- The expected **increase in statistics, in the injectable gas species** and the expected higher accuracy will further **widen the LHCb-SMOG accessible physics scenario**

- **Charmonia spectra** in different collision systems**, b and low-mass Drell Yan states**
- Extension of the $\bar{\mathbf{p}}$ **production towards lower energies**; study of **isospin violation** with $\sigma(pD \to \bar{p}X)/\sigma(pH \to \bar{p}X)$, of **cosmic showers** with *N, O*; addressing **nuclei**?
- Study of **high-x parton PDFs and nucleon structure**
- High-statistics ultra-peripheral ρ, ω, charmonia and bottomonia states with **high-Z targets**

A unique laboratory for QCD!

Conclusions

Conclusions

- By injecting gas in the LHC, LHCb is developing a **pioneering fixed-target programme**
- SMOG2 will operate from 2022 with up to x100 **gas pressure and more species (H, N, O…)**
- Preliminary results indicate that **LHCb could be the first LHC detector running in collider and fixed-target mode at the same time!**
- Physics accessible scenario further widened and covering nucleon structure, cosmic-rays and heavy-ion measurements, a **unique laboratory for QCD at the LHC**

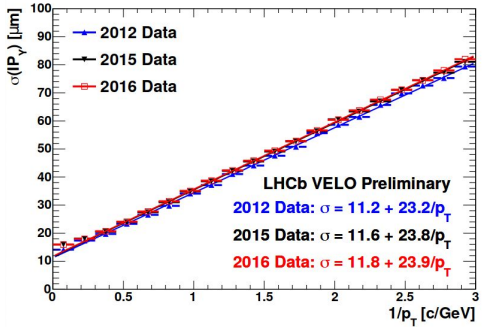
- In parallel, **R&D to inject polarized gases**[ref], **include a solid target**[ref] **or use crystals**[ref] **in the future** (not yet official LHCb programs, but support for the R&Ds)

Thanks for your attention!

Follow up? saverio.mariani@cern.ch

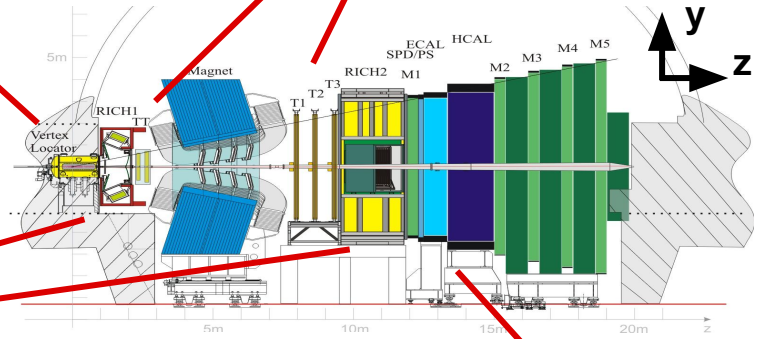
The LHCb sub-detectors

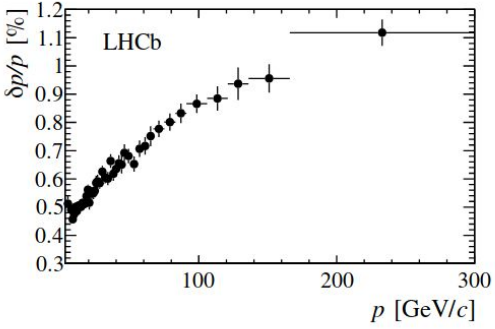
- **VELO**: excellent **vertices and IP resolutions,** fundamental to distinguish long-lived particles.



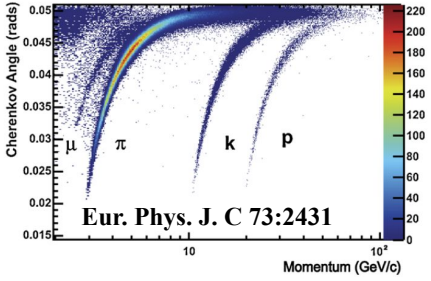
- **Tracking system**: excellent **momentum resolution.**

JINST 3 S08005 (2008)





- **RICH**: excellent **separation** among kaons, pions and protons with a momentum between 10 and 110 GeV/c.



- Flexible and versatile **trigger system** with a very high efficiency and bandwidth (up to 15 kHz).

Charm production measurement

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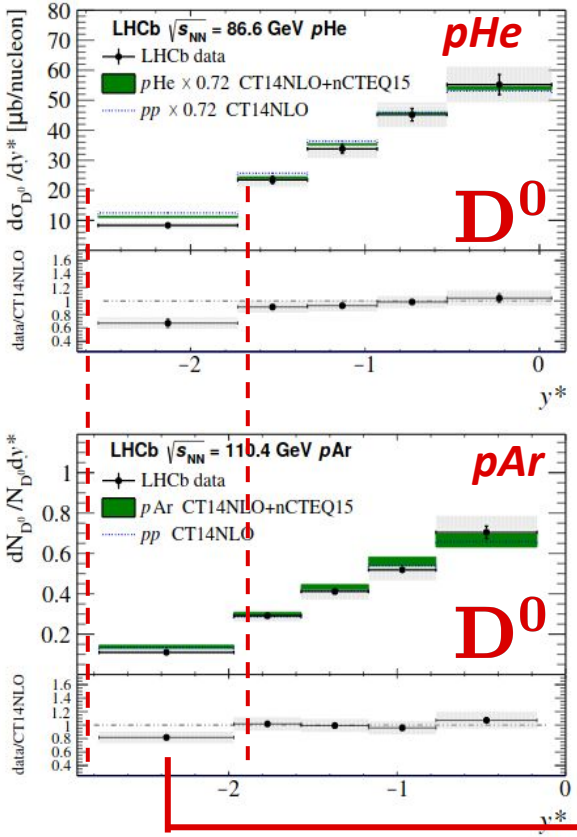
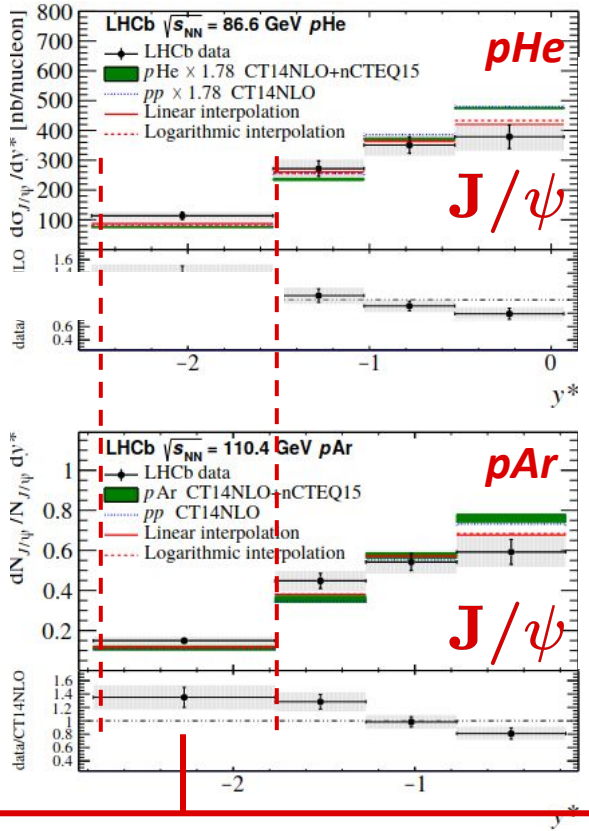
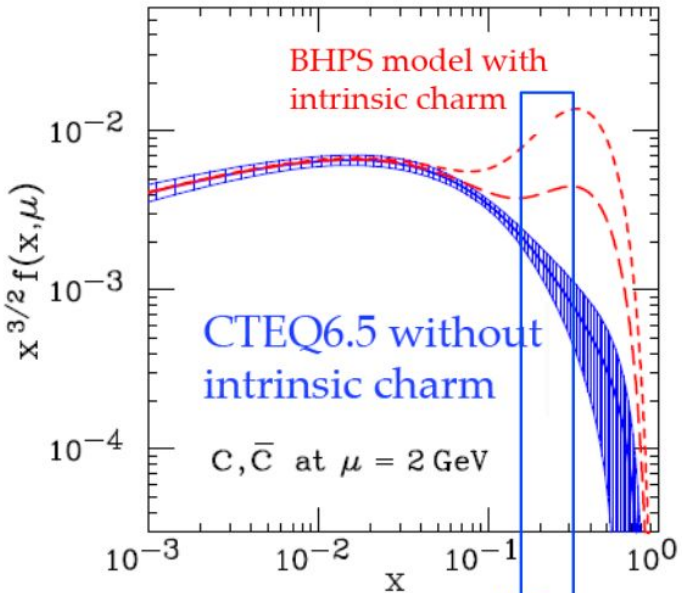


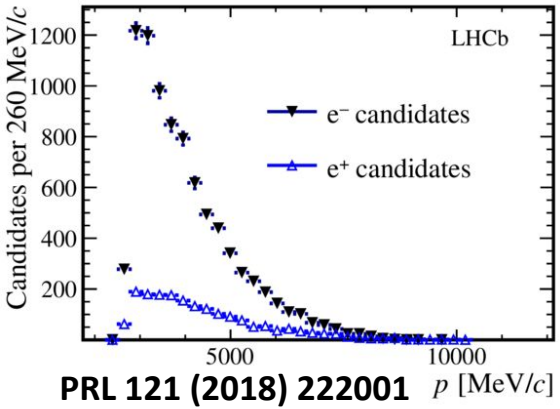


Pumplin, Lai, Tung, PRD75 054029



-2.53 < y* < -1.73
0.17 < x < 0.37

The pHe luminosity measurement



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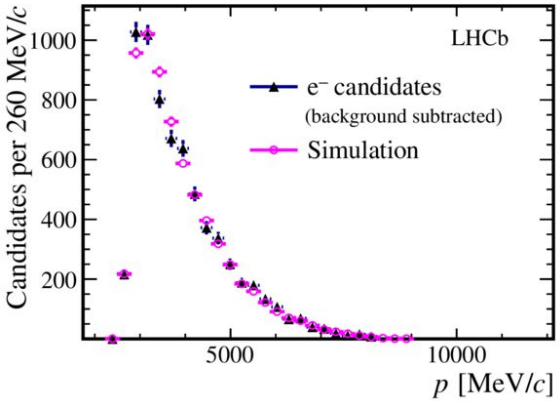
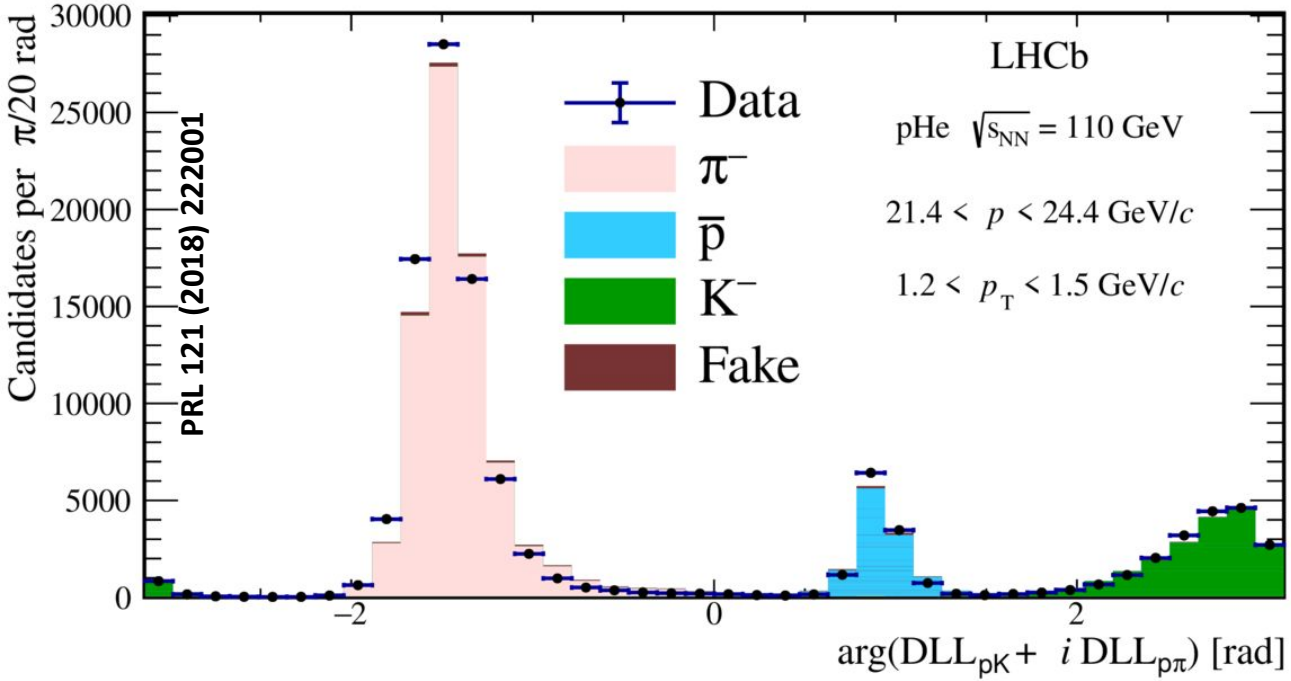


- **SMOG lacking of precise gauges** for the injected gas pressure ⟶ lumi to be indirectly measured
- **p-e scattering with gas atomic electrons**, reconstructible in the detector as an isolated low-energy electron track, used
- **Charged-symmetric** background evaluated via positron yield and subtracted from the total electron one.
- Poor electron reconstruction efficiency ⟶ , lumi affected by 6% uncertainty, **dominating the σ one**

PID for SMOG samples



- Data-driven modelling with calibration channels suffering from the **poor available statistics**
- **Machine learning approach developed** to predict templates of low-statistic samples

Antiproton measurement: systematics

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)

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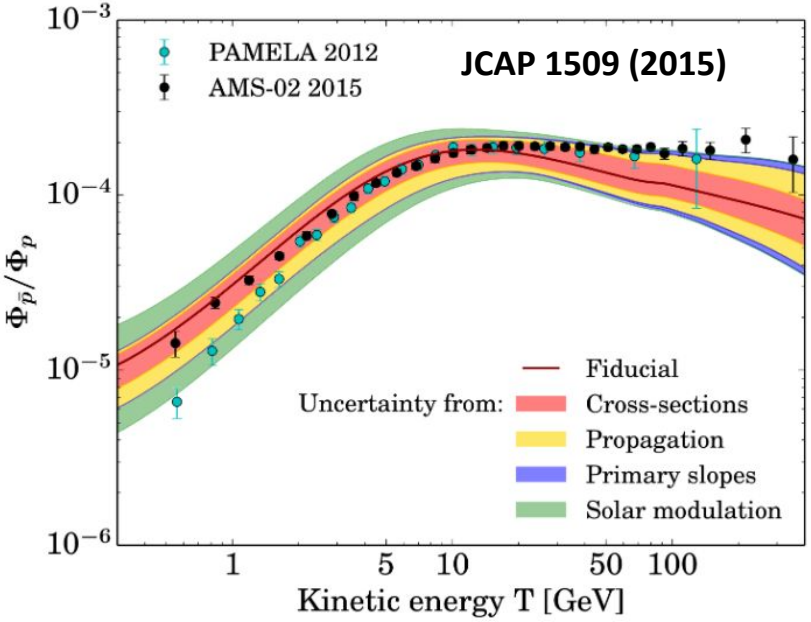
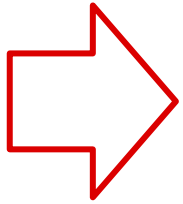
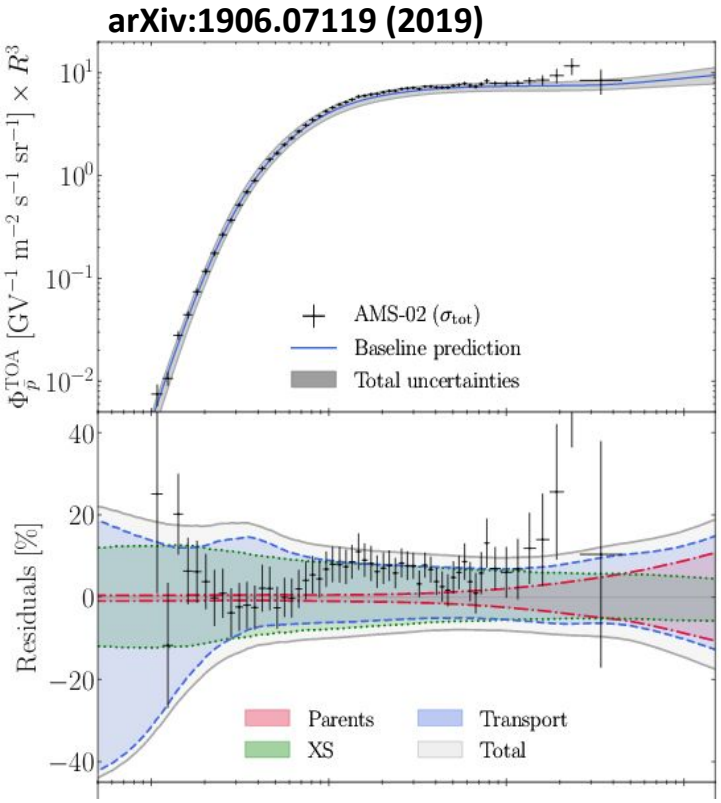
- Dominant contribution from **luminosity** measurement: motivation for SMOG2 upgrade
- PID contribution sub-dominant: machine learning approach developed.

Antiproton in CRs predictions







- Prediction improved **(also) thanks to LHCb result**
- **Uncertainties on the antiproton production XS still dominant**

The LHCb upgrade - overview

- LHCb is currently facing **a major upgrade**, *de facto* will be **a brand-new experiment**
- The hardware trigger level will be removed and the **full detector read-out, calibration and alignment and the events reconstruction and selection will be in real time**
- **The first software trigger level will completely run on GPUs**, a novelty in large experiments