Fixed-target physics at LHCb: Results and prospects

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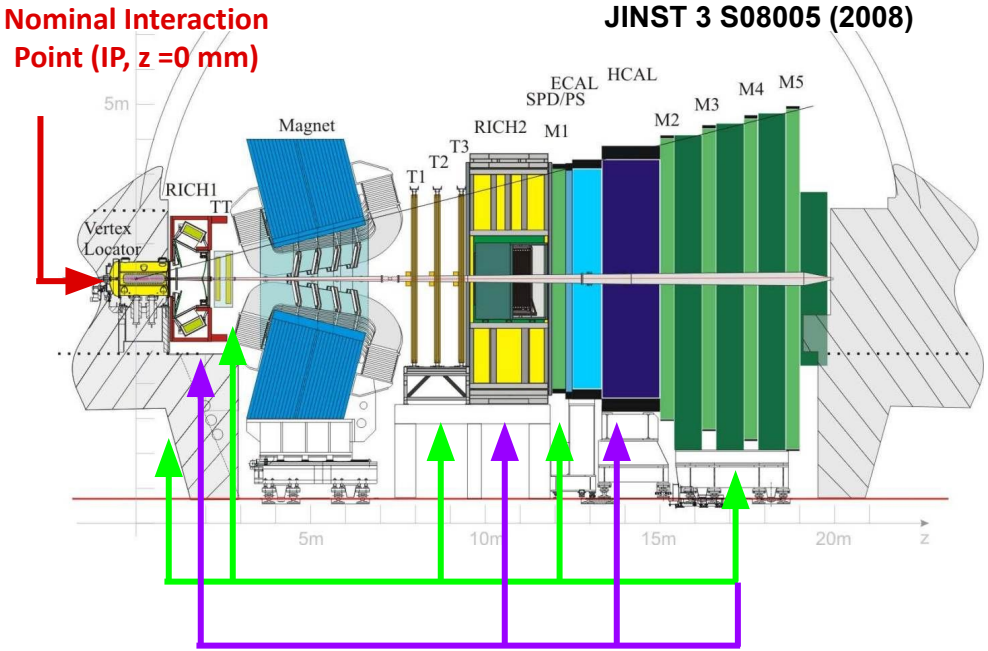
on behalf of the LHCb collaboration

The LHCb experiment in its fixed-target configuration

The LHCb experiment

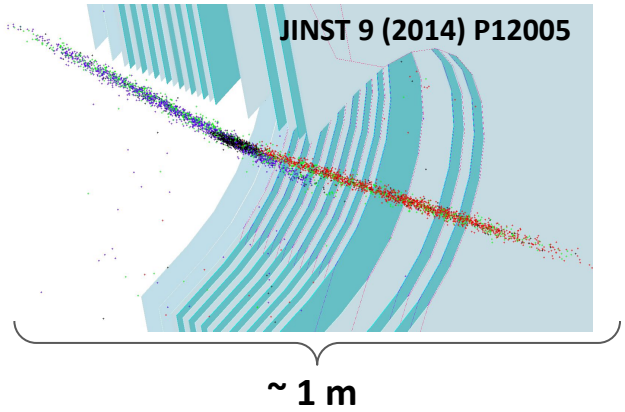
- Originally devoted to ***b* physics measurements,** now a **general-purpose experiment** in the forward direction (c, QCD and SM physics and a **pioneering fixed-target program**)



- **Single-arm spectrometer** covering the forward direction ($\Theta \in [10, 250]\ mrad$), where the $b\bar{b}$ production is maximum.
- Same *onion-like* structure as general-purpose experiments made up of **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.**



- **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

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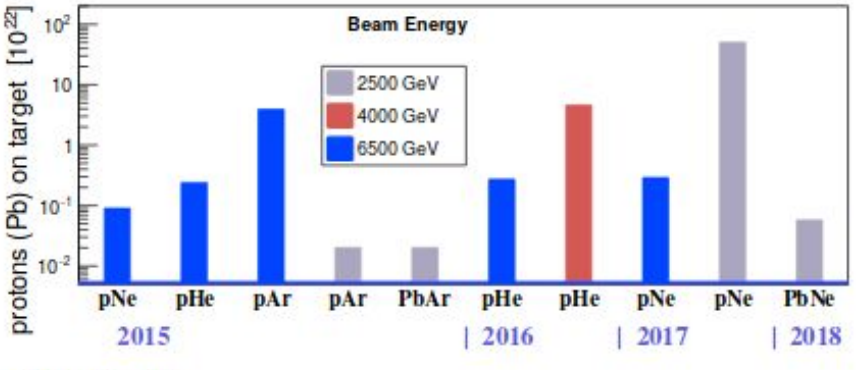

SMOG physics opportunities

- The LHCb-SMOG accessible physics scenario **is unique at the LHC**:
  - **Wide choice** of the collision system, with intermediate *A* between *p* and *Pb*.
  - **Luminosity**: with 10^{14} protons per beam and one meter of gas, $\mathcal{L} \sim 6 \times 10^{29} cm^{-2} s^{-1}$
  - **Energy** range $\sqrt{s_{NN}} \simeq \sqrt{2E_N M_N} \in [41, 115]\ GeV$ for beam energy in $[0.9, 7]\ TeV$, filling a **mostly unexplored gap** between SpS and LHC collisions results.

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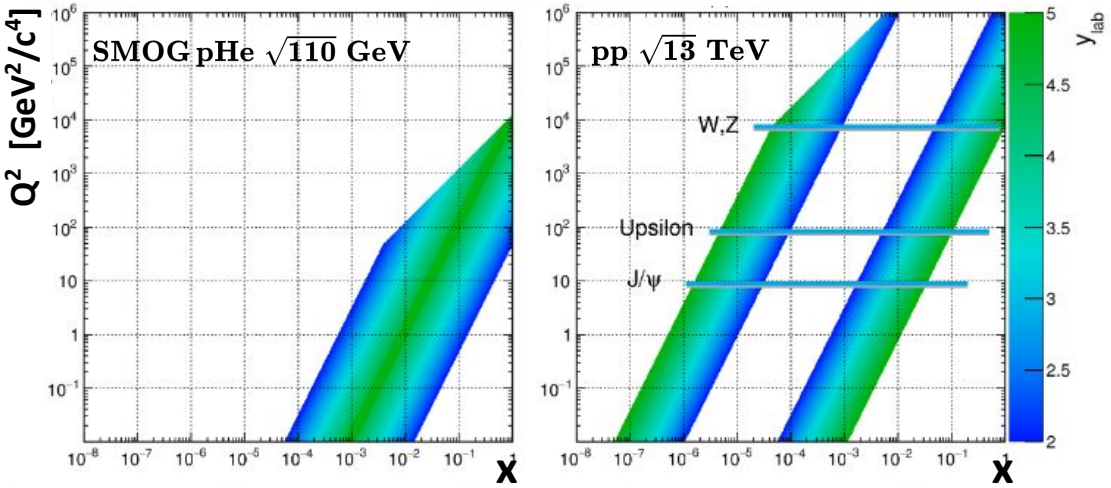


- Access to **large target Feynman-*x***, the fraction of the longitudinal target momentum in the cm frame:

$$x_F = \frac{p_L^*}{|max(p_L^*)|} \sim x_1 - x_2$$

x being the Bjorken-x.

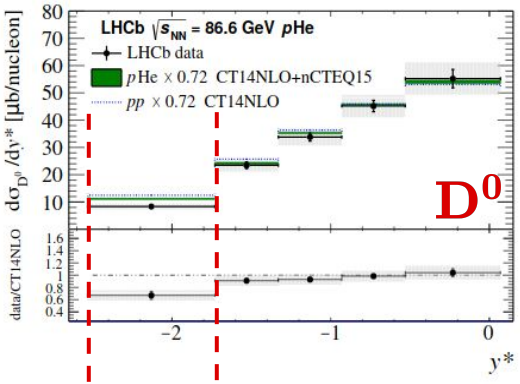
Run2 results and operations

Charm production measurement

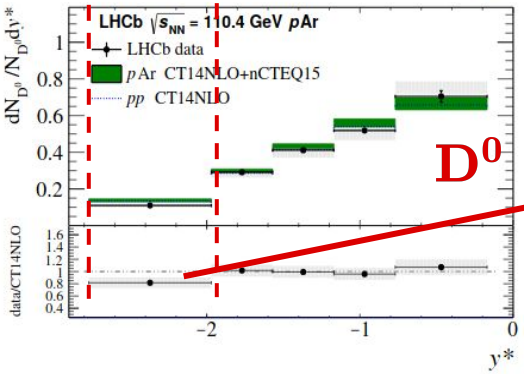
- Among the published results with Run2 data, 86 GeV *pHe* (7.6 ± 0.5 nb^{-1}) and 110 GeV *pAr* (few nb^{-1}) samples exploited to the **first charm production studies at LHC fixed-target**

PRL 122 (2019) 132002

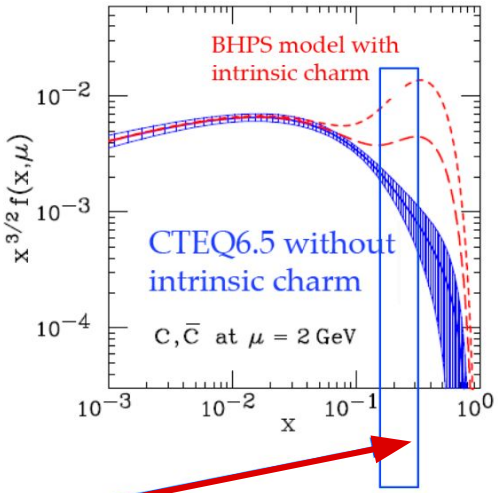
pHe



pAr



Pumplin, Lai, Tung, PRD75 054029



- $J/\psi \to \mu\mu$ and $D^0 \to K\pi$ decays reconstructed and selected in *pHe* and *pAr* data
- Precise luminosity measurement only available in *pHe* via *p-e* elastic scatterings studies (now ongoing for all SMOG samples)

-2.53 < y* < -1.73
0.17 < x_2 < 0.37

- **No evidence for strong intrinsic charm effects**

Charm production measurement (II)

- With the luminosity measurement for the *pHe* sample, obtained the **first $c\bar{c}$ cross-section at 100 GeV energy scale**
- **Extremely precise measurement** at an unexplored energy scale

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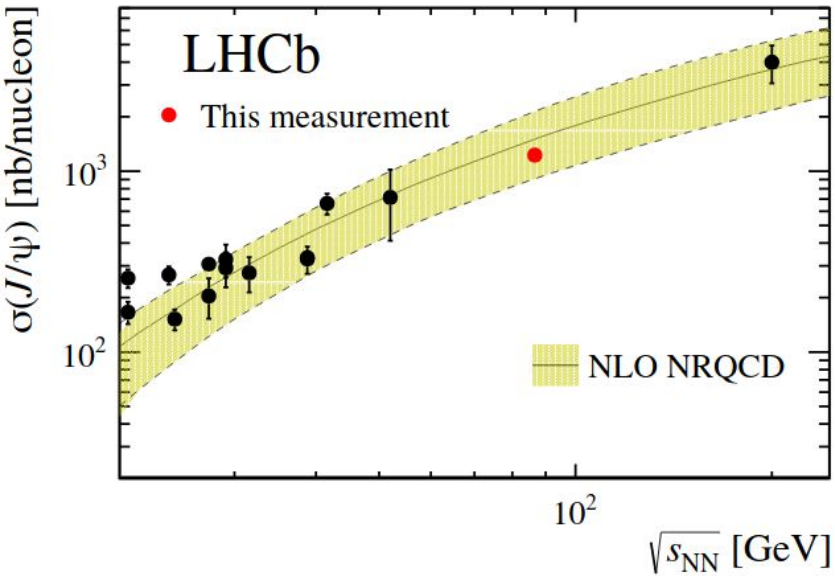
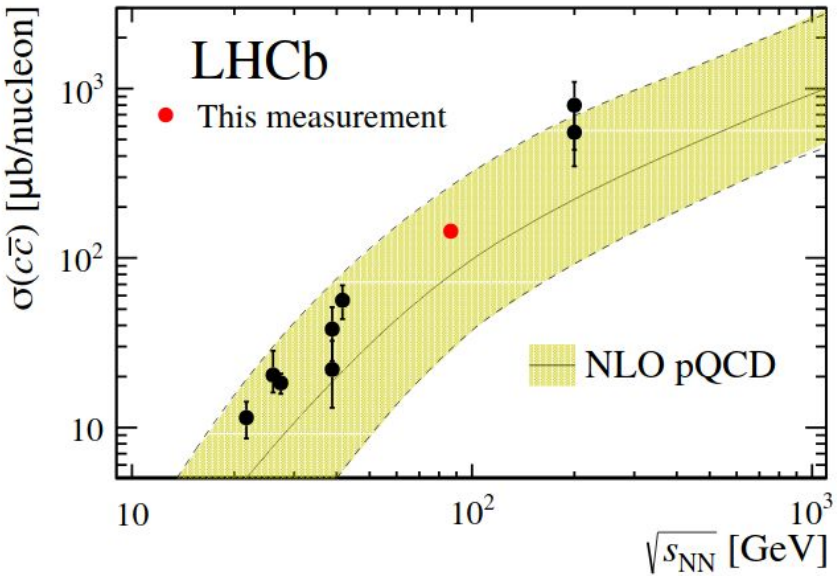




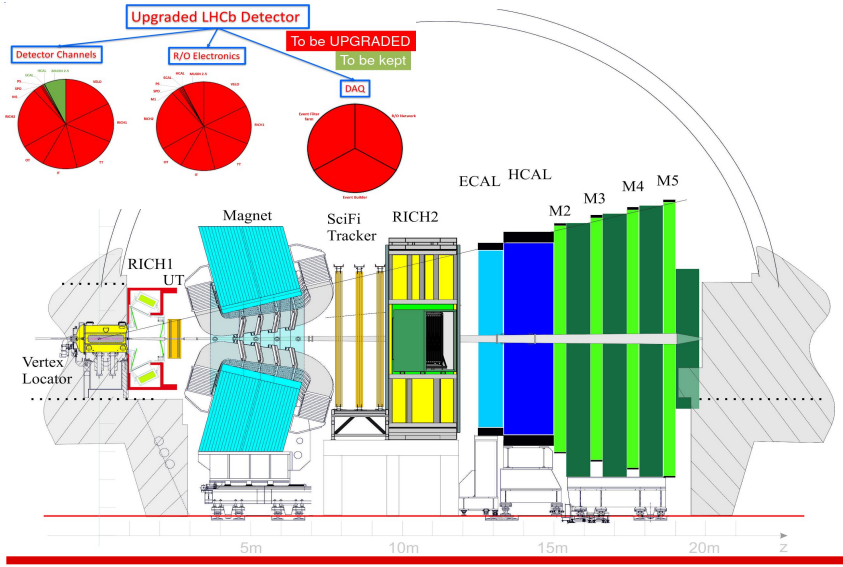
Limitations of the Run2 SMOG program

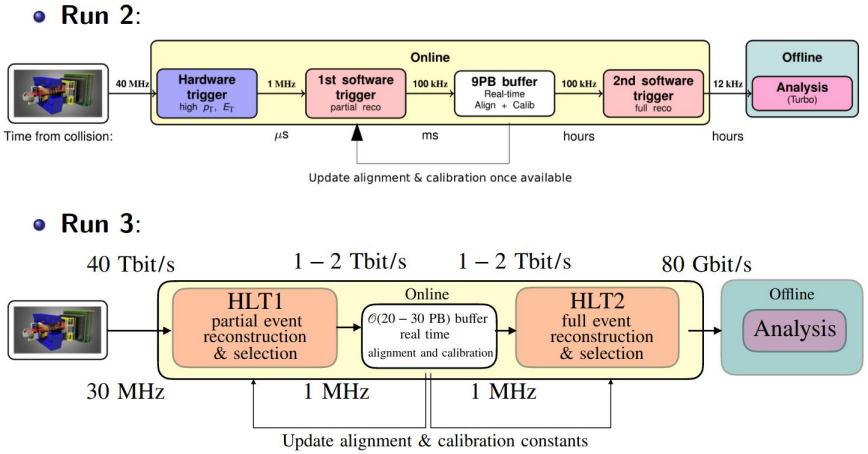
- Not originally conceived for production measurements, **the spread of the gas in ± 20m with SMOG in Run2 was a limiting factor**:
  - **Only noble gases at a moderate pressure** could be injected, to keep the beam contamination low
  - The overlap between the *pp* and SMOG luminous regions **disfavoured a simultaneous data-taking** and most of the SMOG samples were collected in dedicated short periods, limiting the statistics
- The absence of precise enough gauges for the injected gas pressure explains the **lack of a direct luminosity measurement**, this representing one of the dominant contributions to the experimental uncertainty
- The gas injection system equipped with **only one gas bottle**, this requiring one intervention to switch the gas, and a **fixed flux value**

Prospects for Run3

The LHCb upgrade - overview

- LHCb is currently facing **a major upgrade**, *de facto* **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



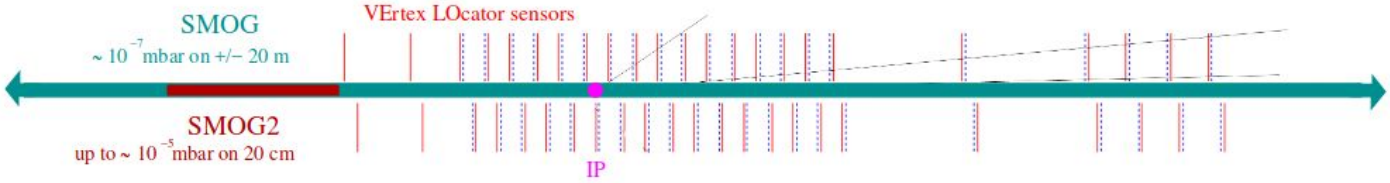


The SMOG upgrade: SMOG2

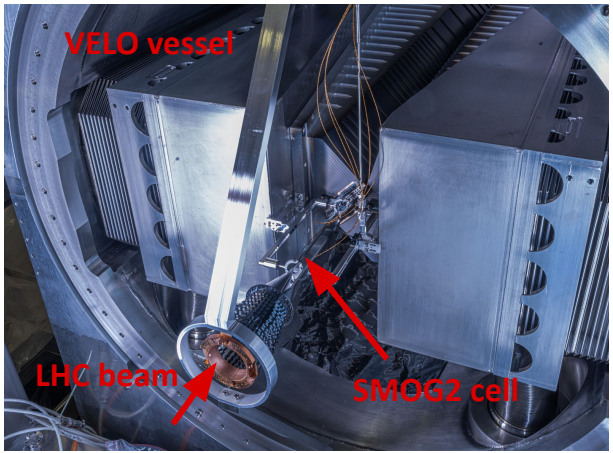
- **SMOG2** : **upgrade** of the fixed-target LHCb program for 2022 data-taking with the installation of a **gas confinement cell upstream the interaction point** ([-500, -300] *mm*).

LHCB-TDR-020

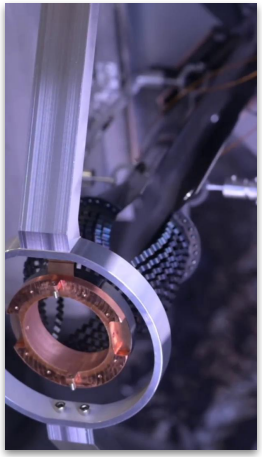
- Possible to increase the average **gas density** (and the luminosity) up of **two orders of magnitude** with the same gas flow as current SMOG.
- Gas pressure **precisely measured**, decreasing the dominant systematic uncertainty on cross-section measurements, and finely controlled.
- **More gases** (with machine approval) can be injected (like H, O, N, Kr, Xe…)
- Possible to have a **simultaneous data-taking** with *pp,* being the interaction region displaced wrt nominal IP.

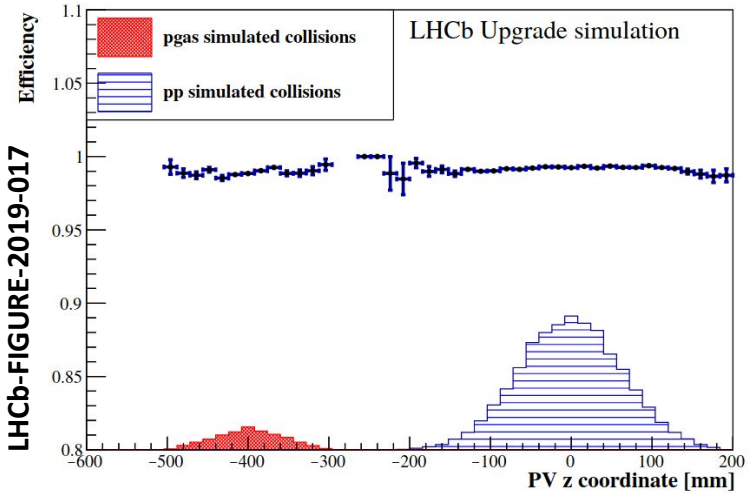


SMOG2 upgrade status



x10 faster





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

- Work currently ongoing to:
  - **Calibrate and install a new gas feed system**, equipped with sensors for the gas pressure and 4 gas bottles
  - Prove that **a simultaneous pp-SMOG2 data-taking is feasible**

SMOG2 physics opportunities

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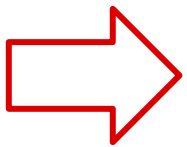
	SMOG largest sample p–Ne@68 GeV	SMOG2 example p–Ar@115 GeV
Integrated luminosity	~ 100 nb^{-1}	100 pb^{-1}
syst. error on J/ψ x-sec.	6–7%	2–3 %
J/ψ yield	15k	35M
D^0 yield	100k	350M
Λ_c yield	1k	3.5M
ψ(2S) yield	150	400k
Υ(1S) yield	4	15k
Low-mass ($5 < M_{\mu\mu} < 9$ GeV/c^2) Drell-Yan yield	5	20k

- The expected **increase in statistics and in the gas species** that can be injected will further widen the LHCb-SMOG accessible physics scenario

- Together with the expected decrease of the systematic uncertainties thanks to the **direct luminosity determination**, accurate measurements of the **charmonia spectra in different collision systems** will be achievable
- Production of ***b* and low-mass Drell Yan states** can also be accessed



- Important experimental inputs to **Heavy Ion and high-x parton PDFs** studies

SMOG2 physics opportunities (II)

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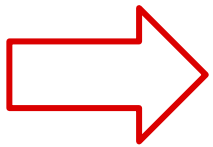
- Other results in different fields can be accessed with SMOG2:
  - High-statistics **ultra-peripherical-produced** ρ and ω and charmonia and bottomonia are expected, especially with **high-Z targets**.
  - Studies of **antiproton production in *p-gas* collisions**, key input to **cosmic rays physics** and already started in Run2, will continue constraining the **evolution with the energy and including H or D targets**
  - The quark, antiquark and gluon content in nucleons can be studied, aiming at a **3D tomography of the nucleon structure**



- All of this results in a **unique laboratory for QCD!**

Conclusions

Conclusions (I)

- Opportunities acknowledged in the **update of the european strategy for particle physics**

Physics Briefing Book

CERN-ESU-004
30 September 2019

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.

- In parallel to the SMOG2 project, **R&D to inject polarized gases in the future**
(not yet an official LHCb program, but strong support for the R&D)

Conclusions (II)

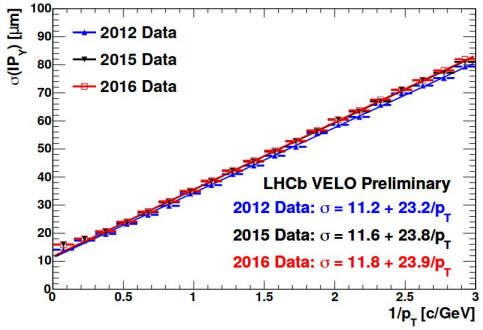
- With the gas injection in the LHC beam-pipe, the LHCb experiment is developing a **pioneering fixed-target program**
- Wide variety of samples with different collisions systems and cm energies collected in 2015-2018, opening a **unique and mostly unexplored kinematic scenario**
- The SMOG2 upgrade will operate with a x100 **gas pressure and with more gas species**
- Preliminary results for the preparation to Run3 data acquisition indicate that **LHCb could be the first detector running in collider and fixed-target mode at the same time!**
- Physics accessible scenario further widened and covers nucleon structure, cosmic-rays and heavy-ion measurements, a **unique laboratory for QCD at the LHC**

Thanks for your attention!

Follow up? saverio.mariani@cern.ch

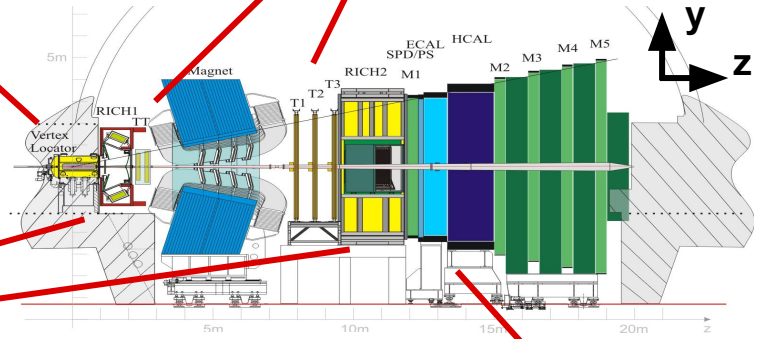
The LHCb sub-detectors

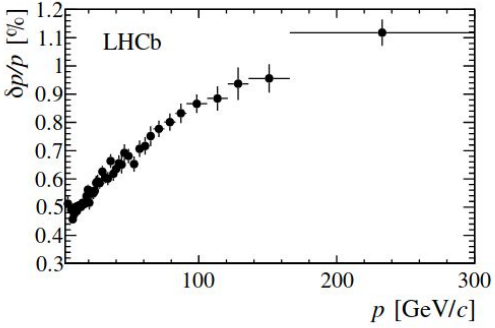
- **VELO**: excellent **vertices and IP resolutions,** fundamental to distinguish long-lived particles.



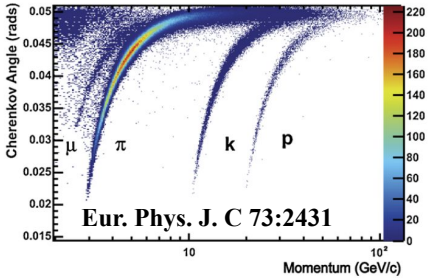
- **Tracking system**: excellent **momentum resolution.**

JINST 3 S08005 (2008)



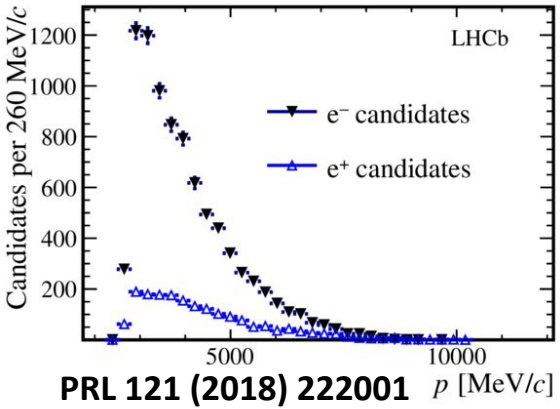


- **RICH**: excellent **separation** among kaons, pions and protons with a momentum between 10 and 110 GeV/c.

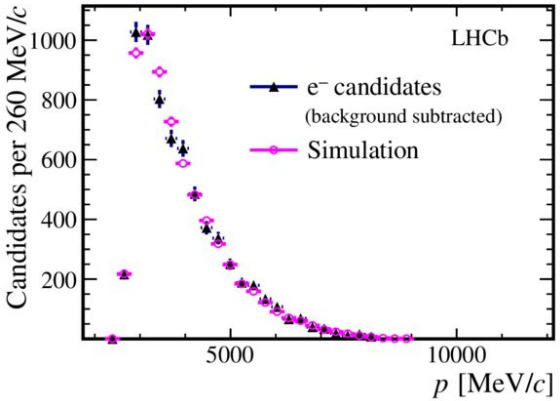


- Flexible and versatile **trigger system** with a very high efficiency and bandwidth (up to 15 kHz).

The pHe luminosity measurement



PRL 121 (2018) 222001



- **SMOG luminosity** can not be directly measured because of the **lack of precise gauges** for the injected gas pressure.
- **Proton elastic scattering with gas atomic electrons**, reconstructible in the detector as an isolated low-energy electron track, used to indirectly measure the luminosity.
- **Charged-symmetric** background evaluated via positron yield and subtracted from the total electron one.
- Due to the poor electron reconstruction efficiency, luminosity measured with a 6% uncertainty, one of the **dominant contributions to systematic uncertainty** on σ