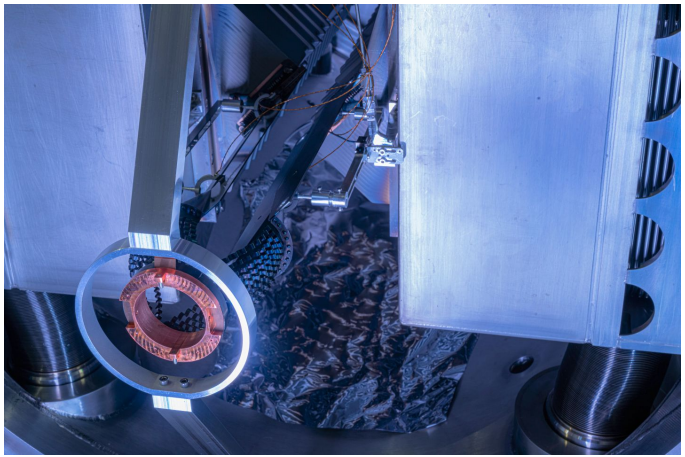
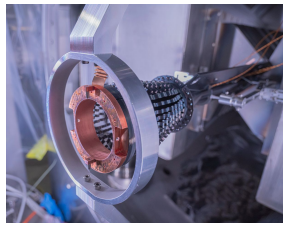




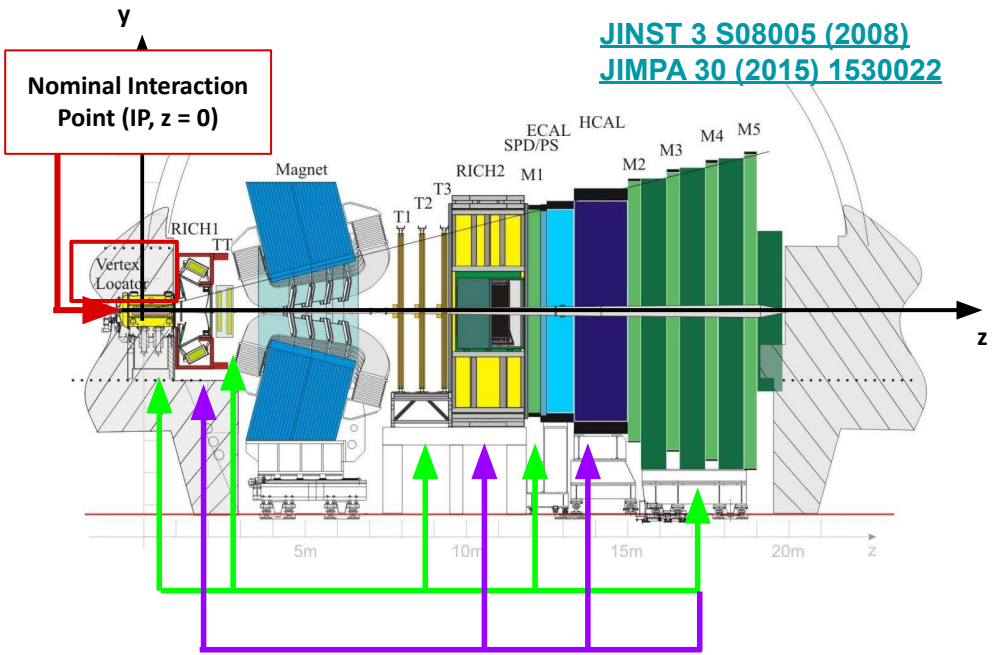
The SMOG2 experience at LHC: technical challenges, implementation and lessons (I) learned

Saverio Mariani
CERN

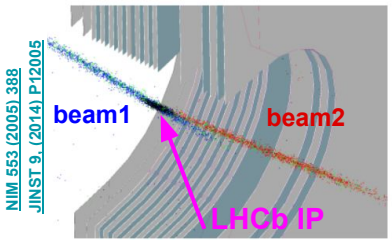
Stony Brook University, 29/09/2025

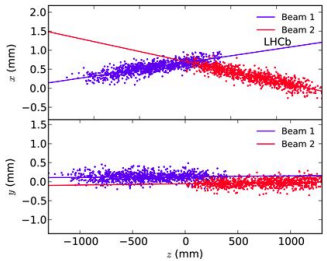
The LHCb experiment in its fixed-target mode

- A **general-purpose** single-arm spectrometer (η ϵ [2, 5]) with very precise tracking and vertexing, full PID, and **the only one at LHC equipped with a fixed-target facility**



- A **System for Measuring Overlap with Gas** (SMOG) at LHCb from 2011, originally only to improve the collider-mode luminosity measurement
- Proton distribution in the beams imaged by reconstructing the **beam-gas vertices** (BGI), as well as the tiny quantity of **debunched protons** (ghosts) → **leading lumi precision**



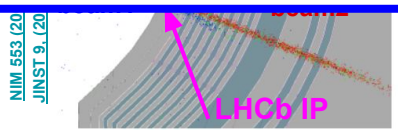


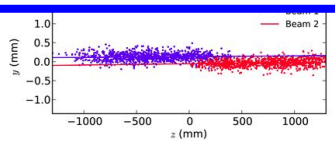
The LHCb experiment in its fixed-target mode

- A **general-purpose** single-arm spectrometer (η ϵ [2, 5]) with very precise tracking and vertexing, full PID,

- I will mostly cover today the aspects and lesson for SMOG(2) as a standalone physics experiment, but let me stress here how this has always been as well **a fundamental tool for LHCb collider mode**, enabling:
  - the beam-gas-imaging and ghost-charge measurements → **1.12% lumi uncertainty**
  - studies on the beam quality (satellite charges, ion transmutation, vacuum quality…)
  - advanced (re)commissioning of the LHCb subdetectors, e.g. increasing their activity during the beam ramping-up phase
  - tests of the reconstruction/trigger algorithms in an orthogonal configuration wrt collider mode, with very precious debugging

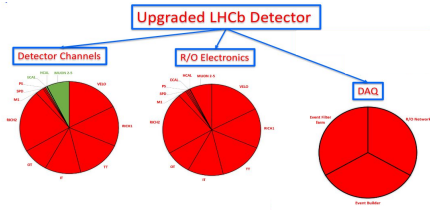
- **All of this would be of critical importance for a FIX experiment at EIC**





The LHCb Upgrade I detector

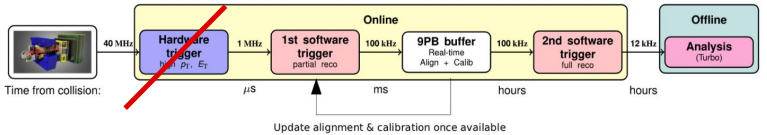
Comp Softw Big Sci 4, 7



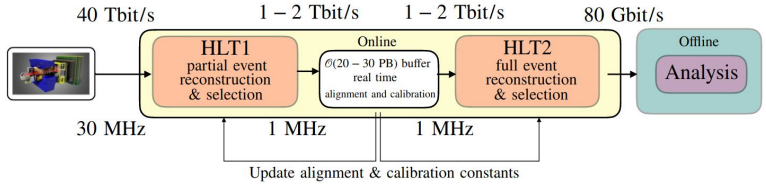
Removed/replaced

Kept from Run2

- **Run 2**:



- **Run 3**:



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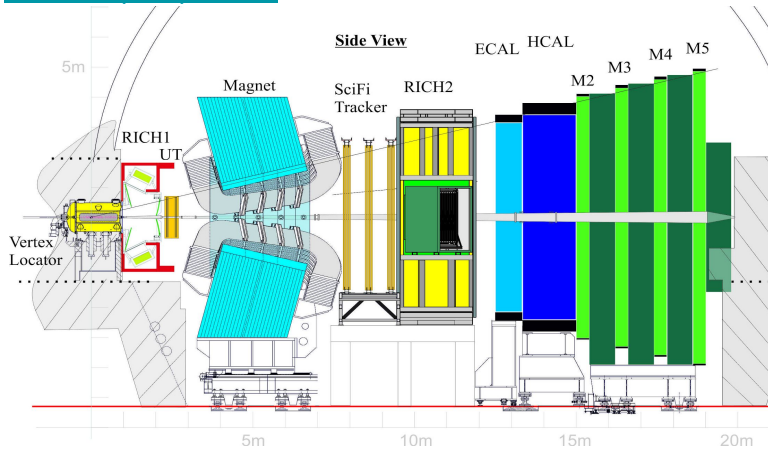
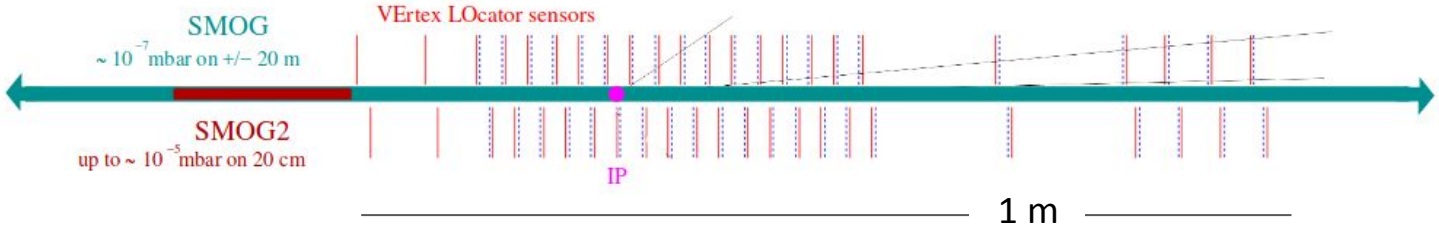
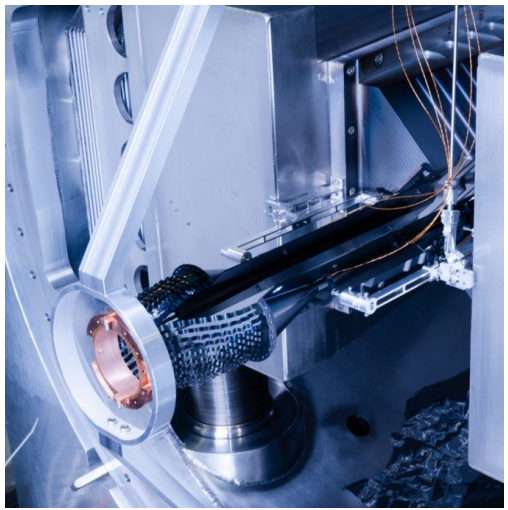


- **Almost a new detector**: increased granularity
- **Hardware trigger removed**. **Fully software detector read-out, calibration, alignment and event reconstruction and selection in real-time**
  - This means in particular **trigger on physics reconstructed objects** (tracks, vertices…)

The SMOG2 fixed-target upgrade





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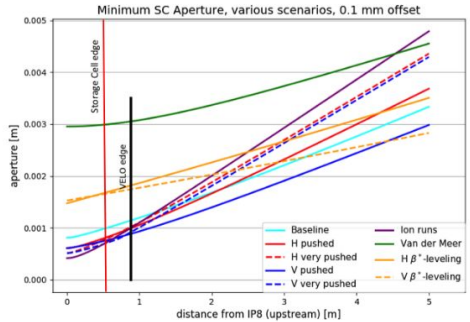
- **SMOG:** Gas was injected in the VELO vessel for a pressure $\mathcal{O}(10^{-7}$ mbar), and no dedicated precise gauges for the gas flow/pressure available
  - Overlap with the *pp* IP and luminosity measurement precision (6%) dominant on cross-section measurements
- **SMOG2:** **confinement of the gas in a cell** (1 cm diameter) made up of two movable halves **(40 ± 10) cm upstream of the LHCb IP**
  - **In the LHC primary vacuum!**
  - Up to x100 gas **pressure wrt SMOG for the same gas flow**
  - Cell detachment wrt IP enables **simultaneous data-taking**!
  - New **Gas Feed System** now equipped with **precise gas flow measurement**, enabling direct luminosity measurement

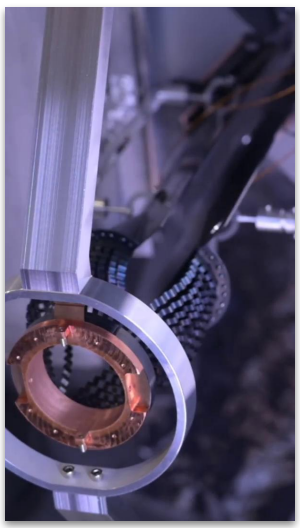
SMOG2 technical challenges - the cell



LHCb-TDR-020

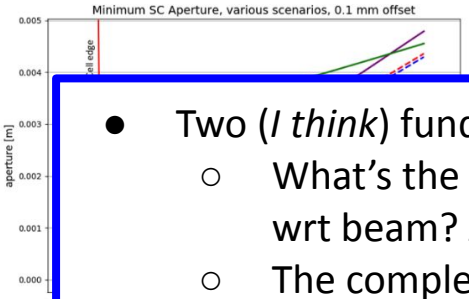
- **Aperture**: in its closed position, a worst-case scenario aperture during the Van Der Meer scans of 3 mm required → 5 mm choice
- **Flexibility**: the VELO has a minimum 3.5 mm (5 mm for the sensors) distance from the beam, which moves by $\mathcal{O}$(mm) fill by fill
  - The SMOG2 cell made of two movable halves to follow the VELO, one rigidly connected and the other one via a spring to ensure sealing and allowing closure on the fill-specific position

x10 wrt reality



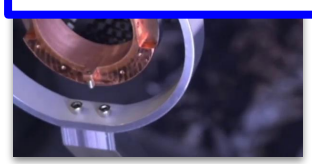
- All details of the (negligible) **beam-gas collisions impact on the accelerator and on the detectors hardware** required several and different studies
  - Beam lifetime reduction, impedance and electrical continuity, coating and secondary electron yield (see Pasquale's talk today and LHCb-TDR-020 + Phys. Rev. Accel. Beams 27 (2024) 111001)

SMOG2 technical challenges - the cell



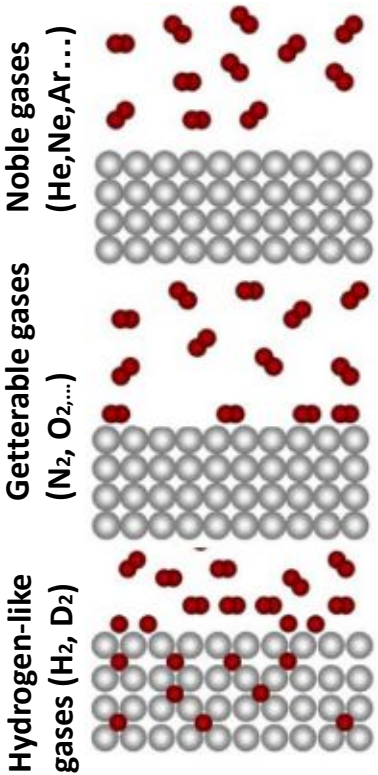
x10 wrt reality

- Two (*I think*) fundamental lessons here to keep in mind
  - What's the beam reproducibility, and how to ensure the cell closing is always centered wrt beam? **A dedicated vertexing/beam monitoring detector is needed**
  - The complexity of operating a gas storage cell in the LHC primary vacuum is such that all aspects must be under control of the project
    - **Involvement of machine experts** (vacuum, impedance, aperture…) **is crucial**



LHCb-TDR-020 + Phys. Rev. Accel. Beams 27 (2024) 111001)

SMOG2 technical challenges - gas species



- SMOG physics goals (see next) requiring both heavy noble gases, maximising heavy-probes production cross-sections, and non-noble light ones
- **Gas interaction with detector coating** studied in details
  - Light noble gases are unlimited and safe, heavier ones (Kr, Xe) could accumulate to the cold-to-warm LHC magnet transitions and being investigated
  - Getterable non-hydrogen like gases (O_2, N_2) stick to the surface, and saturate its pumping capabilities → $\mathcal{O}$(10 h) maximum injection time
  - Getterable hydrogen-like gases (H_2, D_2) partly stick to the surface, but also can penetrate it → $\mathcal{O}$(100 h) maximum injection time
    - Coating peel-off or embrittlement (substrate cracking) can happen for larger fluxes than $\mathcal{O}$(40 mbar l/s), negligible at the SMOG2 flux points $\mathcal{O}(10^{-4}$ mbar l/s)

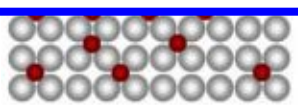
SMOG2 technical challenges - gas species

- Despite we all like samples as uniform as possible, operations **alternating periods with noble and non-noble injections** are needed, in order to allow for coating relaxation
- Also, noble and getterable gases must **not mix in the Gas Feed System**, which has to be designed with redundancy and clear protections for the two gas types

Noble gases

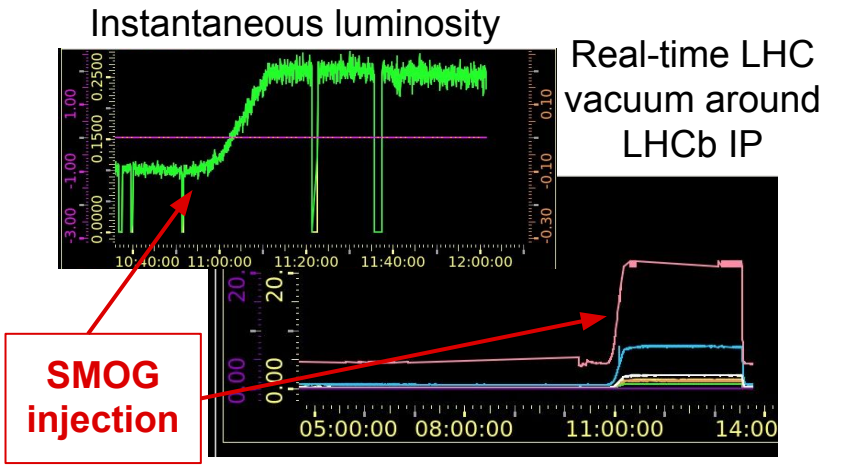
Getterable gases

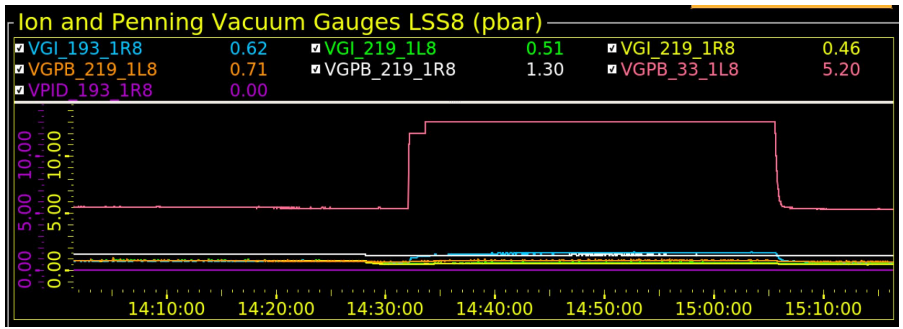
Hydrogen-like gases (H



points $\mathcal{O}(10^{-4}$ mbar l/s)

The SMOG2 commissioning



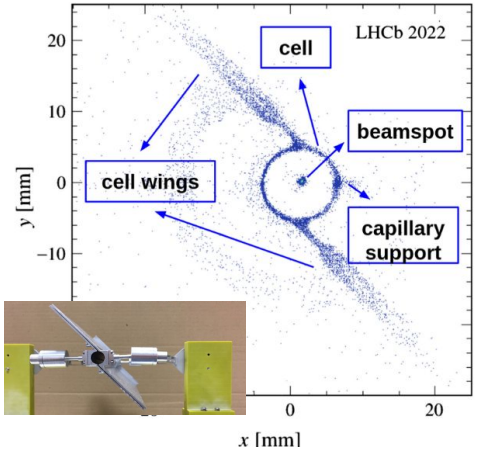


- In June 2022, with 450 GeV beams, first injections **through the open SMOG2 cell**, allowing CERN vacuum experts to **set the injection procedure**

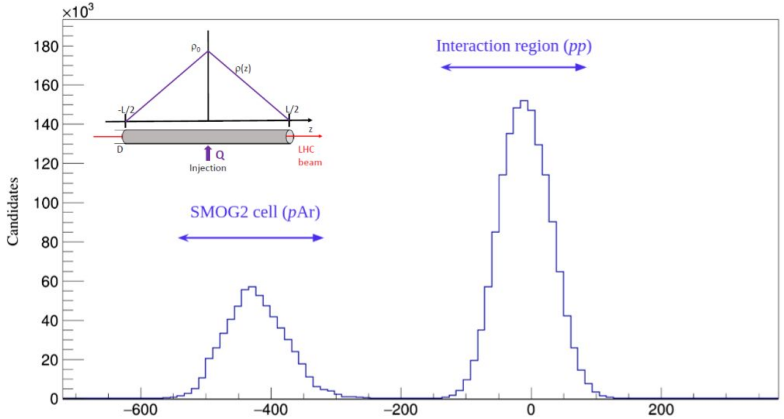
- **01/11:** First injection in the closed cell
- **Very stable operations:** with injected Ar with a pressure 6.5 times lower wrt Run 2, already **achieved a x5.5 higher inst. luminosity**!
- In 11/2022, injected He, Ne, Ar and, **for the first time ever**, H_2

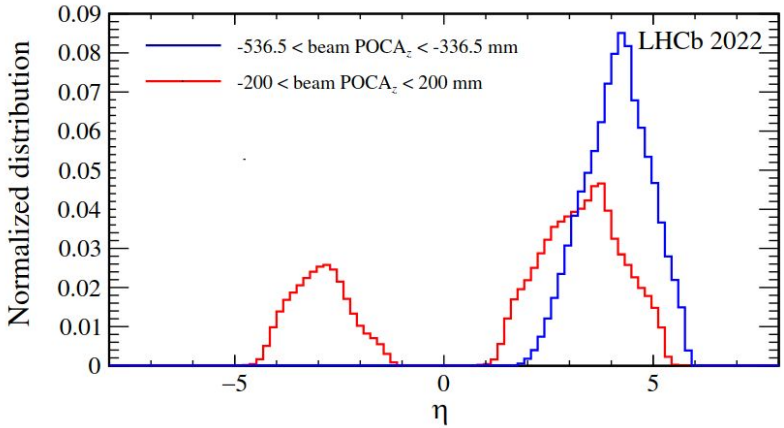
GFS fully and successfully commissioned

The SMOG2 commissioning (II)



- Hardware and software commissioning
  - SMOG2 cell imaged by reconstructing material interaction vertices, to verify design positions and alignment
  - Verified beam-gas and beam-beam PV separation and particle distributions
- **LHCb can and is running since 2024 with two simultaneous IPs**





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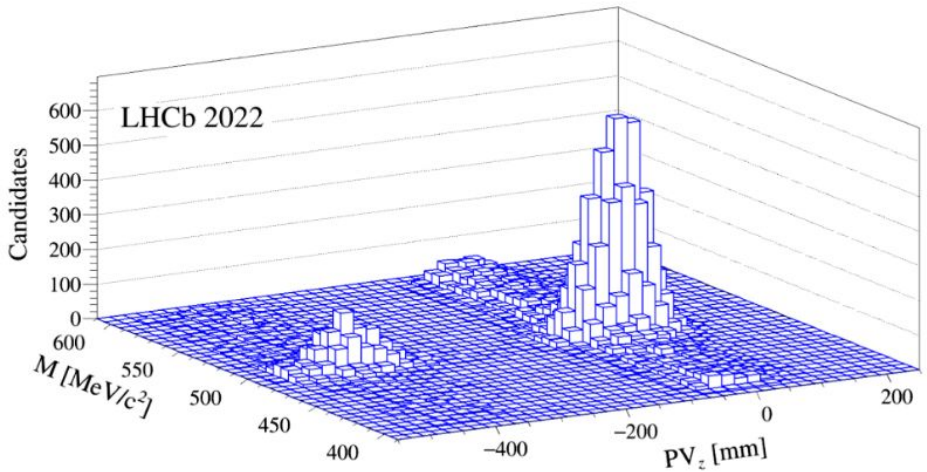
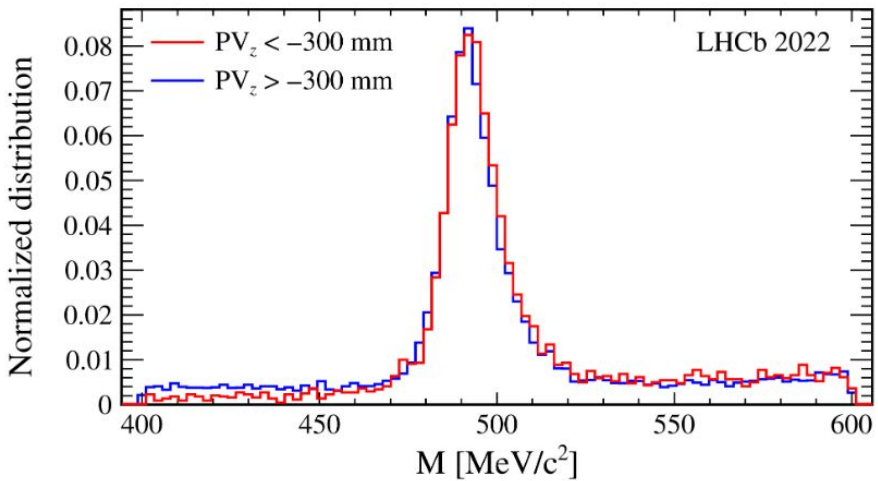
The SMOG2 commissioning (III)

- **LHCb can and is running since 2024 with two simultaneous and independent IPs**
  - First ingredient is **precision**: LHCb momentum resolution and to a good extent efficiency do not depend on the z





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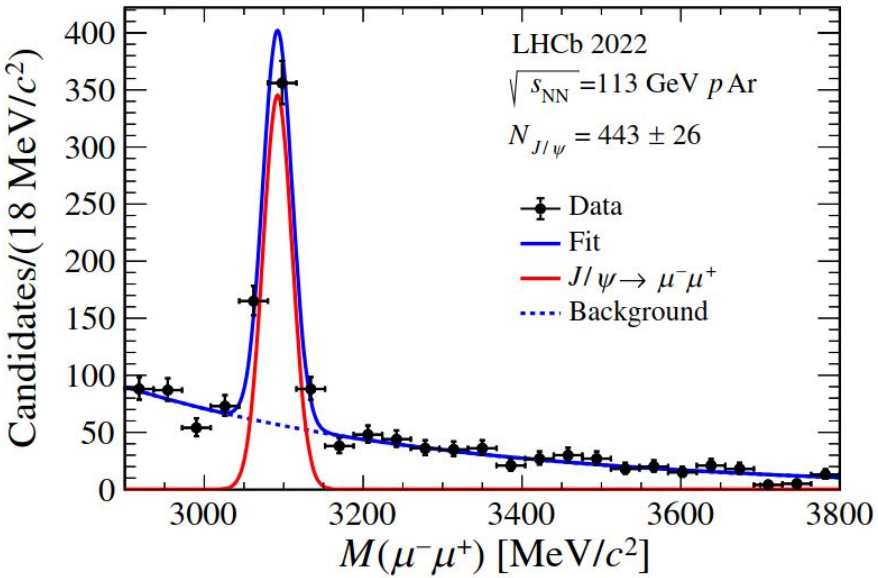
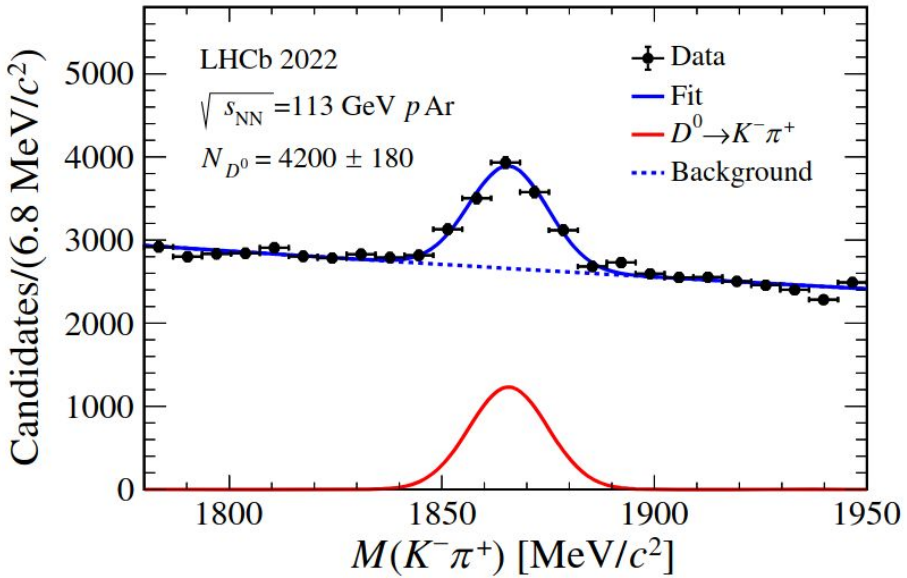
The SMOG2 commissioning (IV)

- **LHCb can and is running since 2024 with two simultaneous and independent IPs**
  - First ingredient is **precision**: LHCb momentum resolution and to a good extent efficiency do not depend on the z
  - Second ingredient is the **samples size**: with 18 minutes of *p*Ar, clear charm signals appearing!





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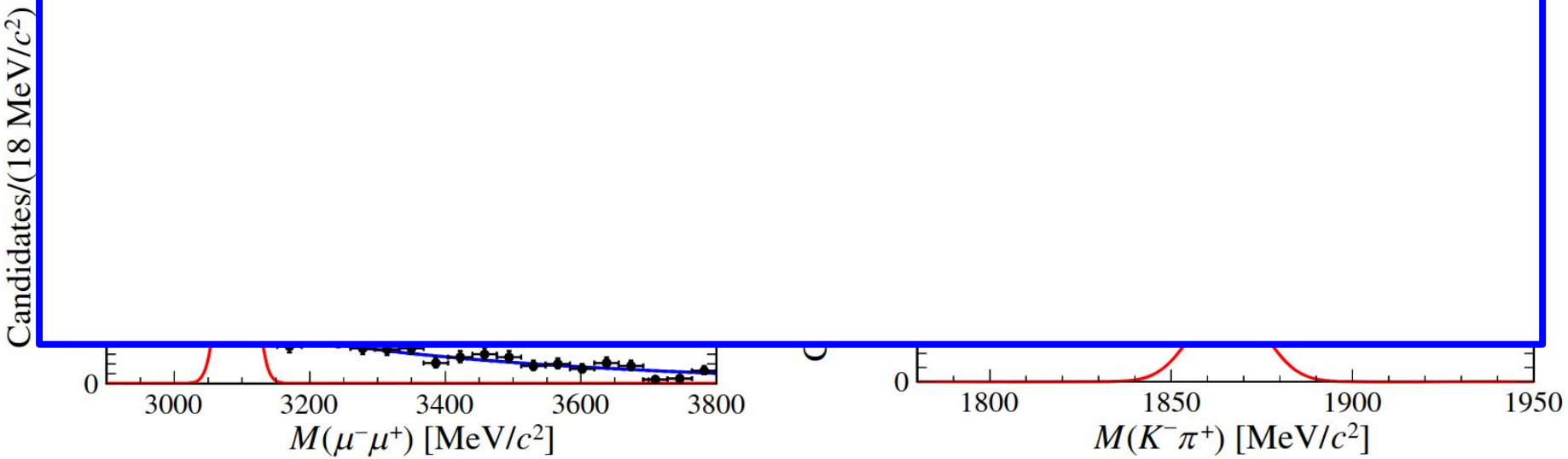
The SMOG2 commissioning (IV)

- **LHCb can and is running since 2024 with two simultaneous and independent IPs**
  - First ingredient is **precision**: LHCb momentum resolution and to a good extent efficiency do not

- **A dedicated trigger system selection is needed** to decouple beam-gas and beam-beam collisions ⟶ need physics objects, e.g. tracks coming from or reconstructed vertices in the SMOG2 cell; level-0 thresholds would not be discriminative enough!



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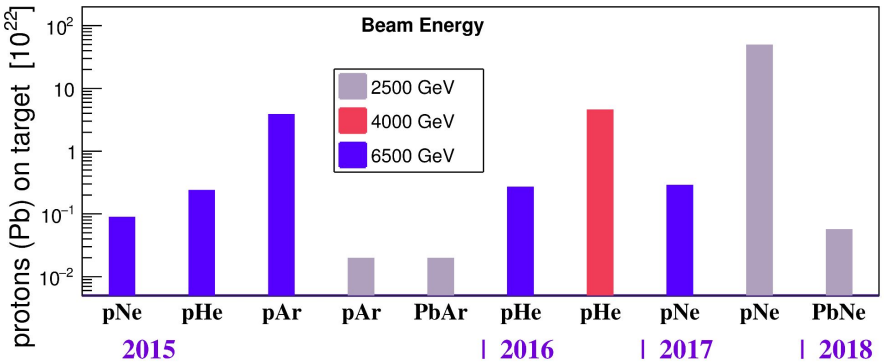
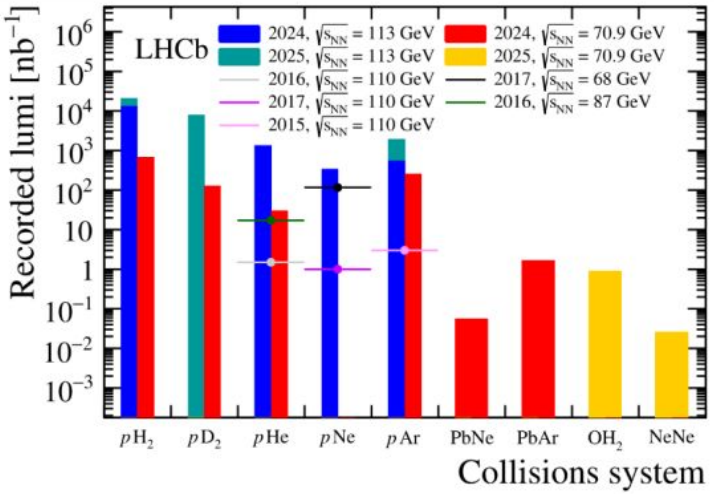
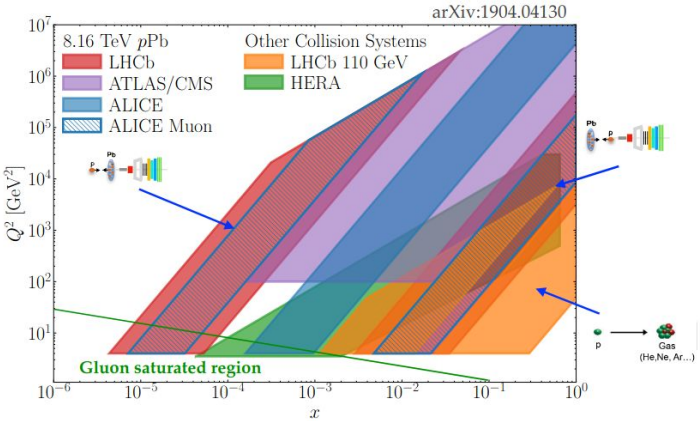
…and it's working so well!



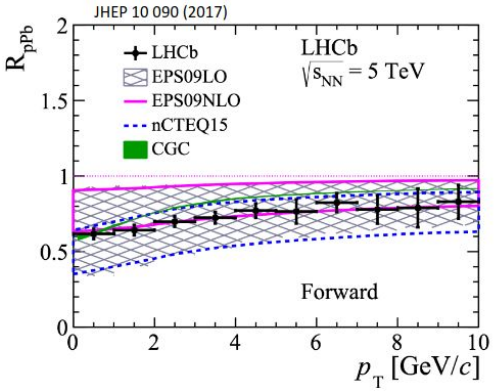


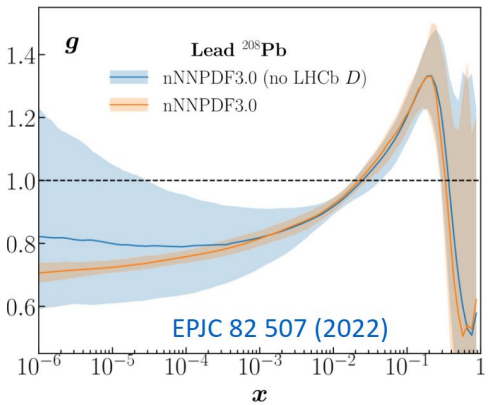
- While the Run2 SMOG has pioneered fixed-target physics at LHC, with SMOG2 the only 2024 + 2025 **give up to x1000 statistics** and an expansion of the available gas to inject
- Keep extending the programme, owing to new gases (H_2 and D_2) and new ion species → system size scan!

LHCb Bjorken-x coverage



- By combining *p*Pb, UPC PbPb and fixed-target data, LHCb is able to cover a **very wide region in Bjorken-x**:
  - With *p*Pb/Pb*p*, reaching Bjorken-x ~ 10^{-6}
  - With *p*A in SMOG, exploring the **high-x at moderate Q^2 region**, mostly unexplored by previous experiments

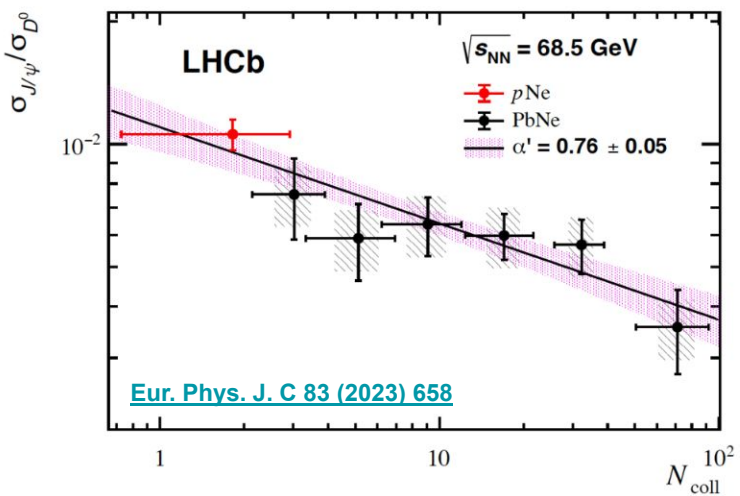




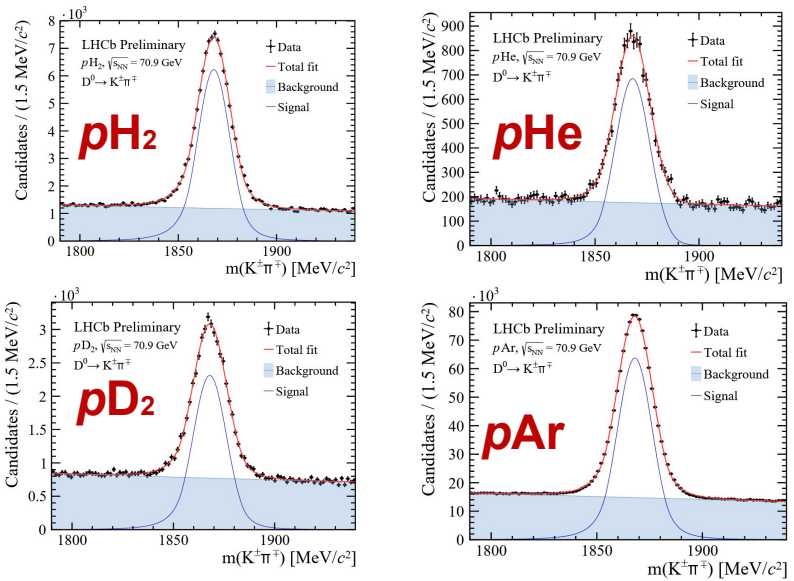
- **Dramatic impact of our measurements in constraining low-x nuclear PDFs**, while high-x region still mostly unconstrained

LHCb SMOG as a high-x nucleon imager

- Multiple open-charm and charmonium measurements available with SMOG data (*p*He, *p*Ar, *p*Ne, PbNe) → **onset of nuclear effects and transition to QGP** as a function of system size
  - No J/ψ anomalous observation seen in PbNe
  - Measurements suffering available statistics. With SMOG2, a **high-precision study of the high-x nPDF** will be possible!

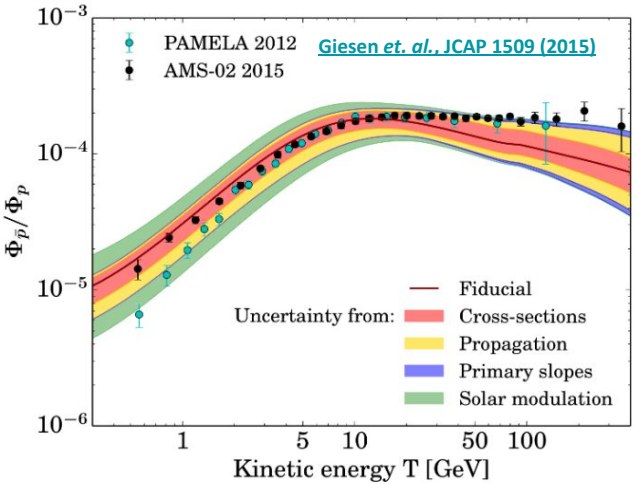


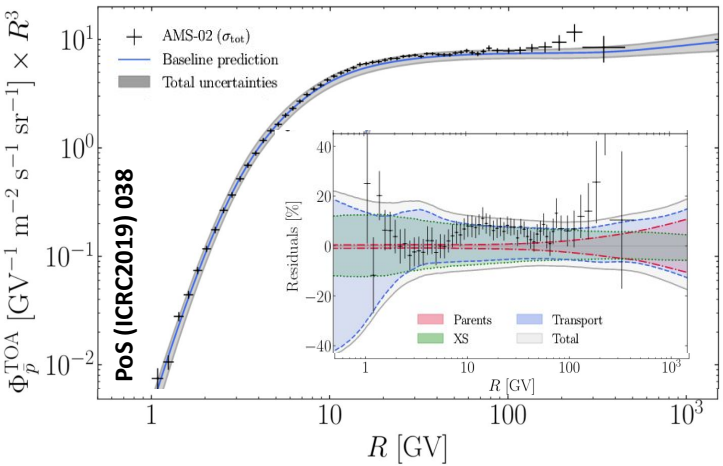
LHCb-FIGURE-2025-013



Antimatter production in cosmic rays

- Intensive programme ongoing since a few years to **constrain antimatter production** in beam-gas SMOG collisions, reproducing a Cosmic Ray impinging on the Interstellar Medium (ISM, 90% H_2 + 10% He)
- **Crucial inputs for Dark Matter decays** to particle-antiparticle final states by satellite experiments (AMS)





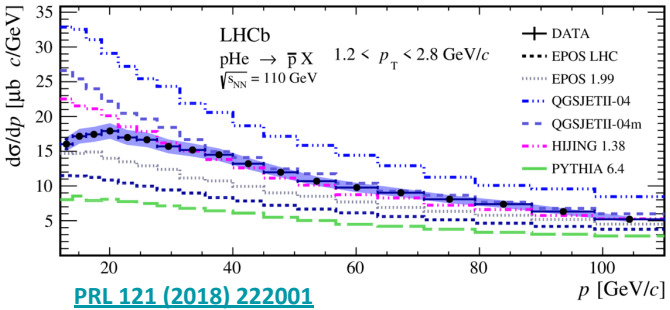
- For antiprotons, update of the theoretical models (also including LHCb results!, see next slide) makes antiproton fluxes measured by AMS consistent with CR-ISM hypothesis only (so, **no DM yet**).
- **Cross-section uncertainties are still dominant**, and more cross-section measurements for sqrt(sNN) ϵ [10, 200] GeV are needed [arXiv:2503.16173]

LHCb SMOG on a space mission

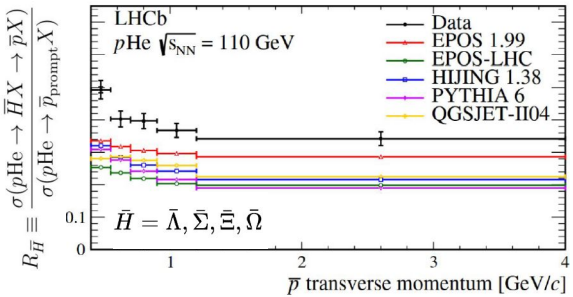
Physics report on XS needs for CR (including NASA)

- LHC beam collisions on the SMOG gas reproducing a cosmic ray impinging on the Interstellar Medium (*p*He, *p*H_2, *p*D_2) or on the atmosphere (OH_2)
- Measured in particular prompt and from-strange-decays antiproton production in 2016 *p*He collisions, constraining antimatter fluxes in cosmic rays, background to indirect Dark Matter searches (AMS)
  - For both prompt and secondary production, first measurements ever in that system!
  - Extension with *p*H_2 and *p*D_2 collisions in SMOG2 ongoing
- Recently, also developed a new time-of-flight-based technique for **(anti)deuteron identification in SMOG** → will test fragmentation vs nuclear coalescence
- **All of this was absolutely not foreseen at LHCb**

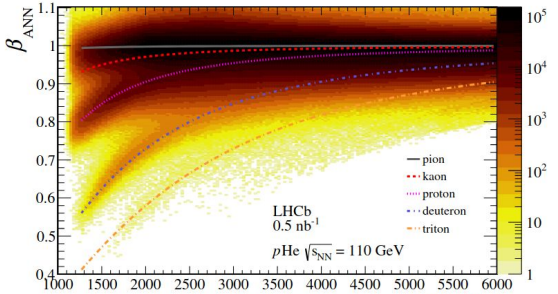
NEW



PRL 121 (2018) 222001



Eur. Phys. J. C83 (2023) 543

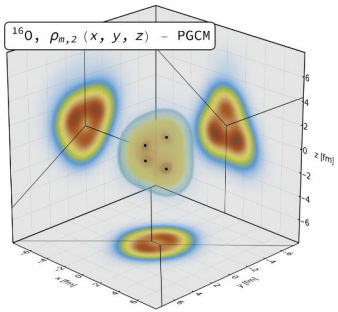


arXiv:2508.06305

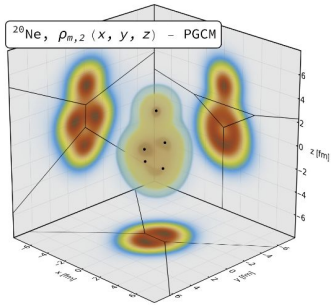
LHCb SMOG as a bowling alley (I)

- A central question in the field is what's the **impact of the initial state geometry to the medium evolution** ⇒ 2025 OO/NeNe runs (similar nuclear effects, but different geometry)

Phys. Rev. Lett. 135, 012302



Phys. Rev. Lett. 134, 082301



- Actually, SMOG2 already **uniquely** provides us a bowling alley, allowing comparison between neon and spherical nuclei like argon
- Can we provide **first experimental evidence** of the Ne shape?

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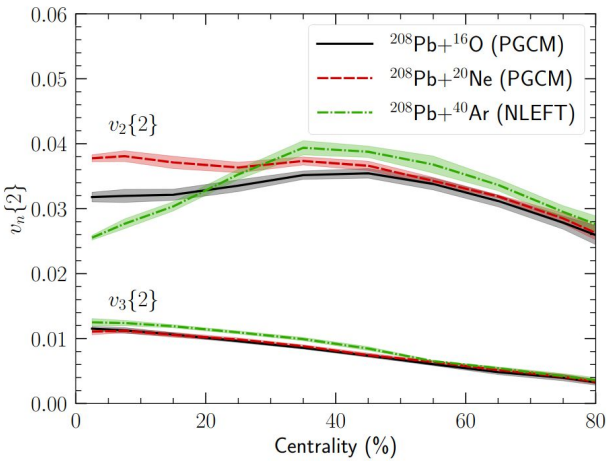

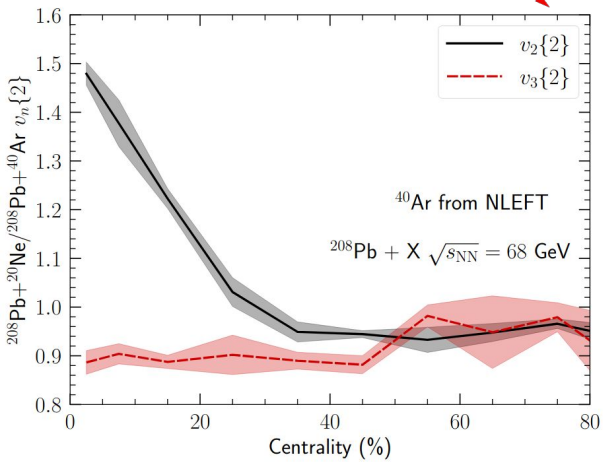

- **A significant connection** between the initial-state geometry and the final-state flow observables expected
- In central collision, PbNe to PbAr ratio up to 1.5!

LHCb SMOG as a bowling alley (II)

NEW

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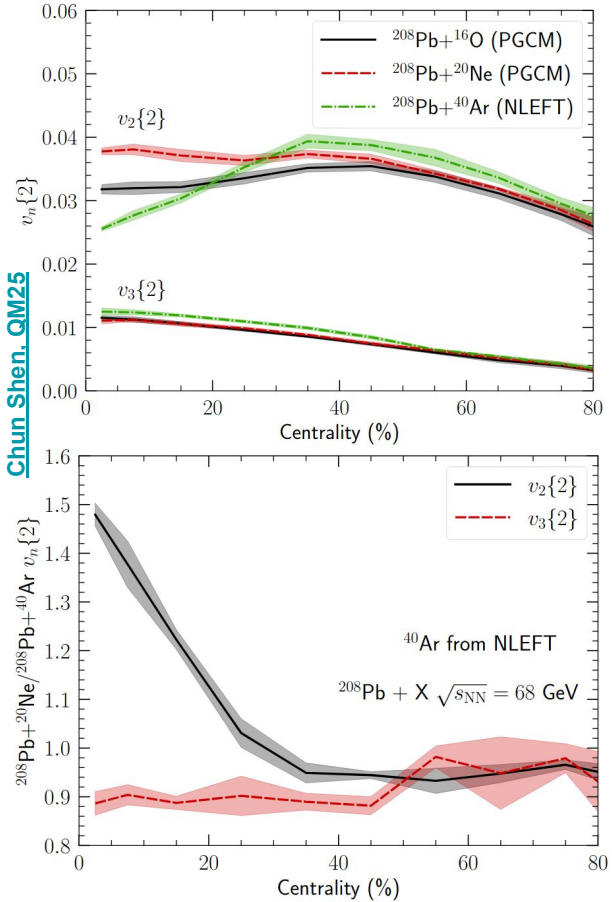

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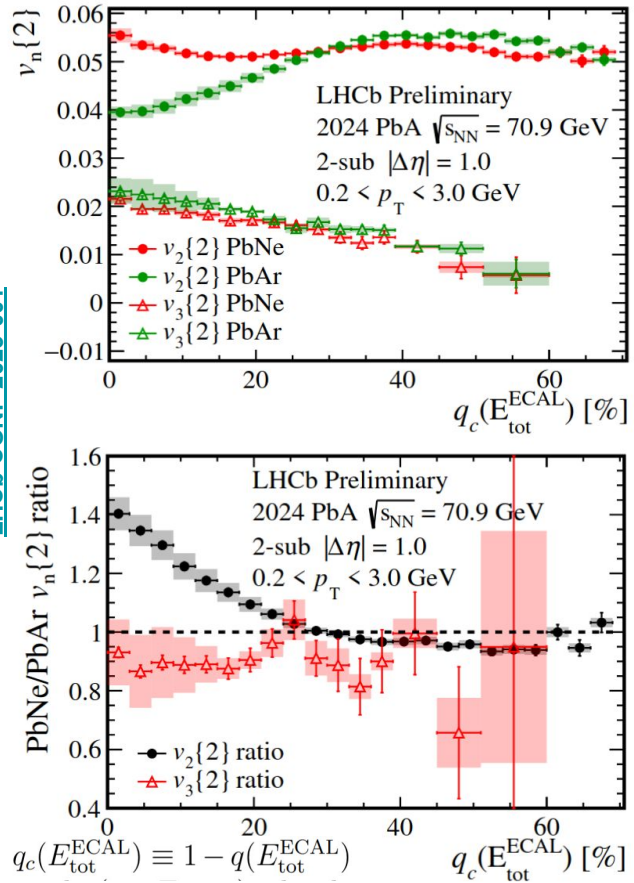

- Results as a function of a proxy for the centrality (ECAL energy percentile) show an evident flatter $v_2\{2\}$ values for PbNe than PbAr, and a similar $v_3\{2\}$
- This is **clearly consistent with the predicted Ne bowling-pin shape**, and confirms its **major effect on the collective dynamics**
- p_T-differential results as a function of centrality will follow

Conclusions

- **The SMOG(2) system at LHCb pioneered fixed-target physics at LHC**, and is now a(n unexpected!) core part of its physics programme
  - Just a few examples today for **high-x nPDF** studies, **probes for cosmic rays physics, flow…** and so much more I was not able to cover!
- The SMOG2 implementation presented several challenges on the machine (aperture, impedance, coating…) and on the data acquisition (new trigger!) side
  - I am incredibly proud that we can now stand as an example of how to solve this, and, hopefully, **see more fixed-target physics in the future**!

Thanks for your attention!

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