Measurement of strangeness production in OH_2 and pNe collisions using SMOG2

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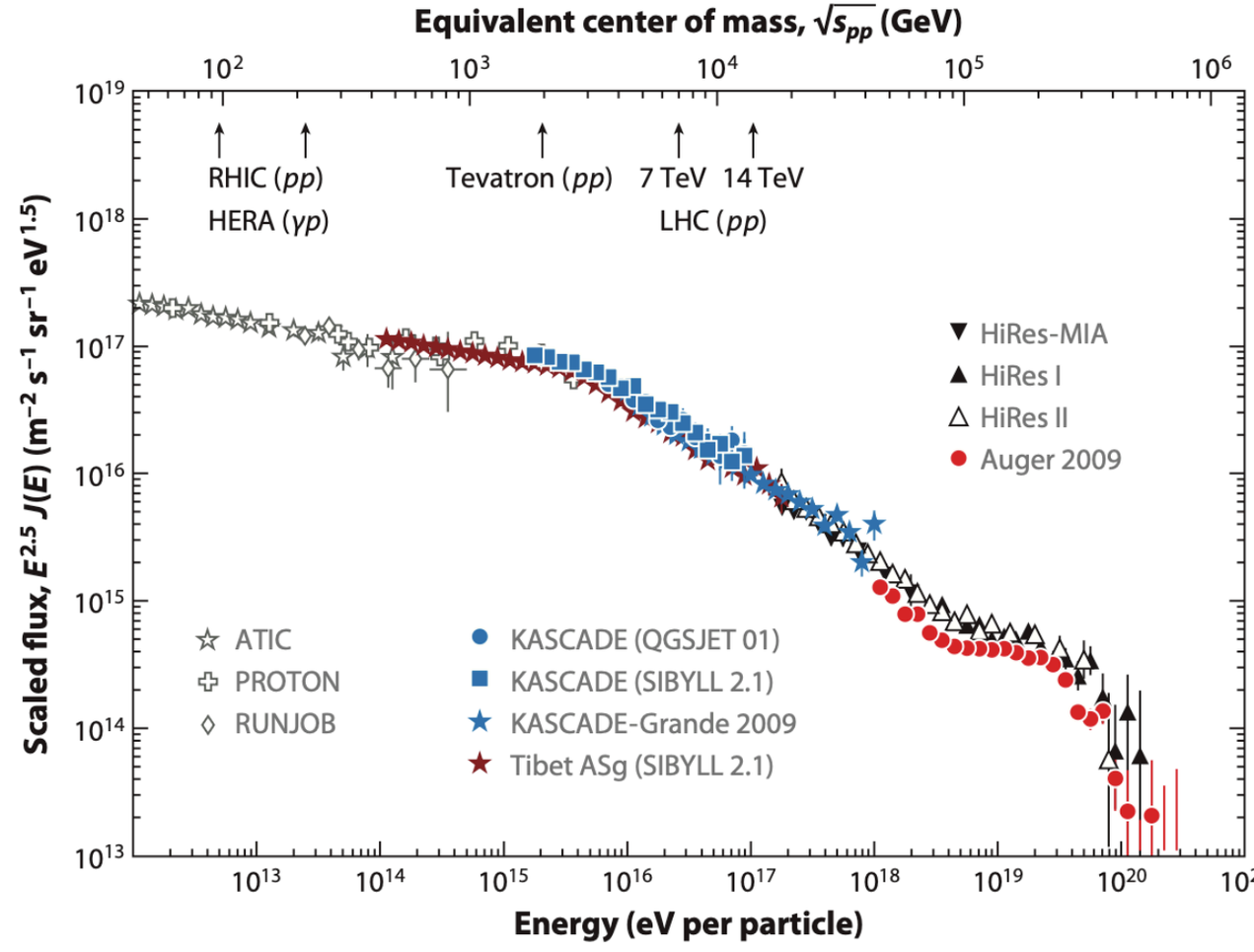
Herbstschule HEP 2026, 09.09.2026

Cosmic rays

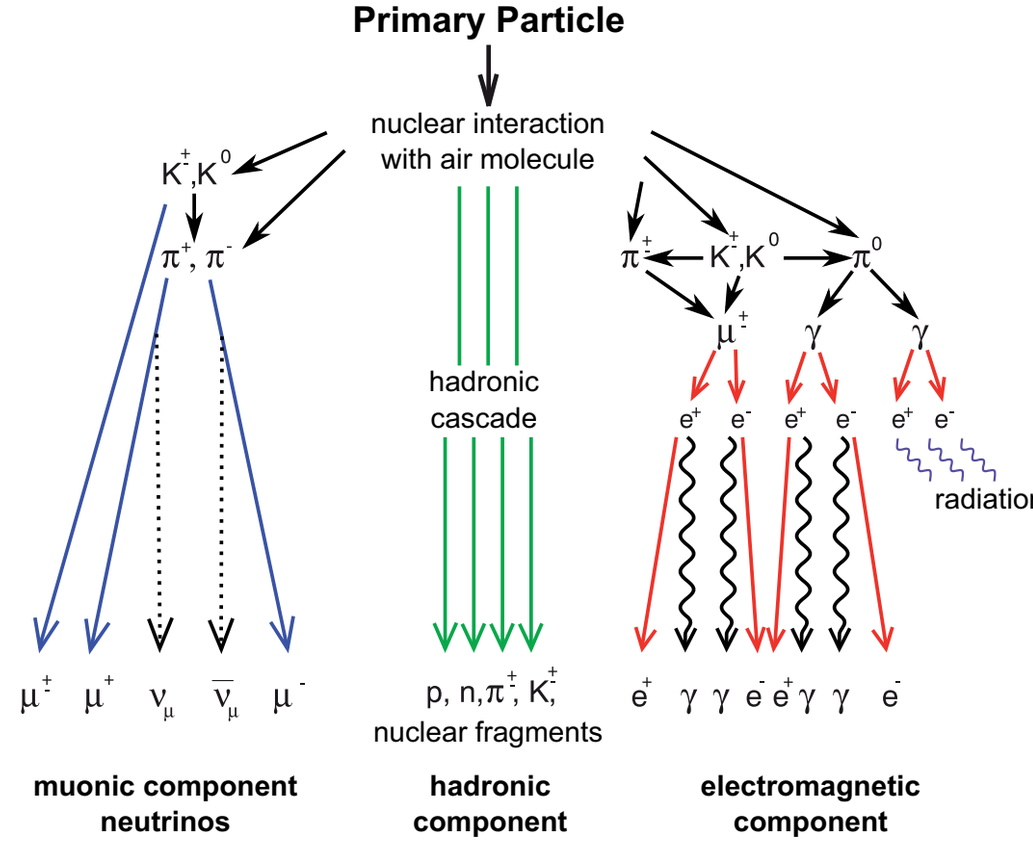
- Highly energetic particles coming from the universe
- Energies of up to 10^{20} eV
- Cosmic ray spectrum poorly understood at highest energies
- Need better measurements to understand spectrum, composition, origins etc.



R. Engel et al., Annu. Rev. Nucl. Part. Sci 61 (2011) 467

Air showers

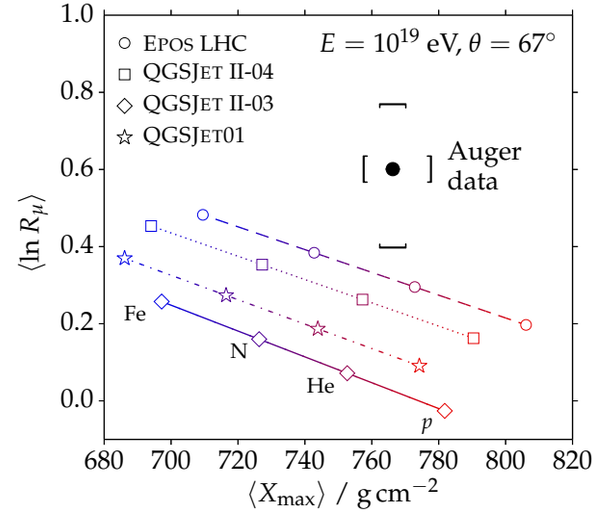
- Enable indirect measurements of highest energy cosmic rays
- Reconstructed using ground-based observatories, e.g. Pierre Auger Observatory
- Measure energy of primary particle via shower depth and number of muons
- Need simulations of air showers which require effective, data-driven models of hadronic interactions



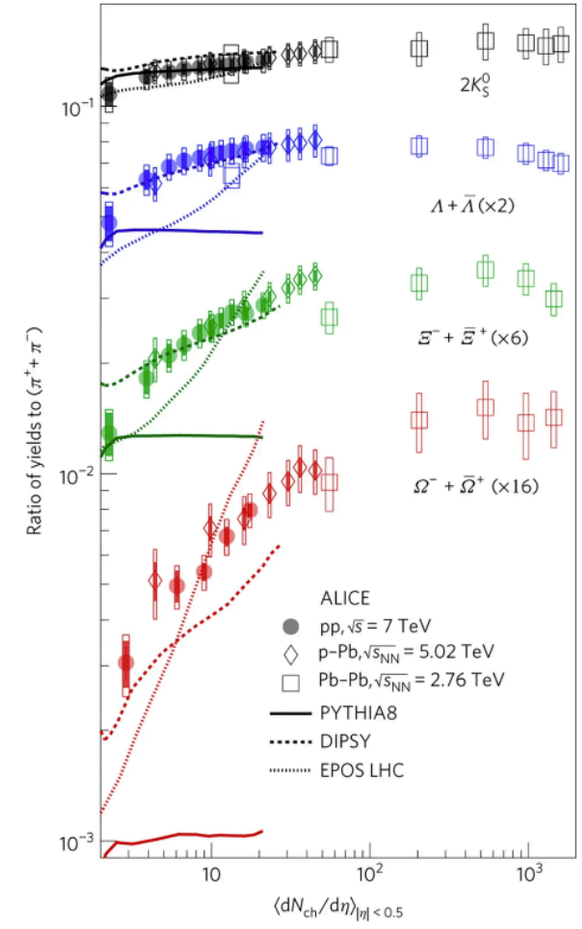
KCDC - The KASCADE Cosmic-ray Data Centre, PoS ICRC2023 (2023)

Muon puzzle

- Simulations predict too few muons at high energies → muon puzzle
- Proposed solution: enhanced strangeness production
- Increase of strange-hadron production in high-multiplicity events observed by ALICE
- Need to test this in forward rapidity region relevant for air-showers



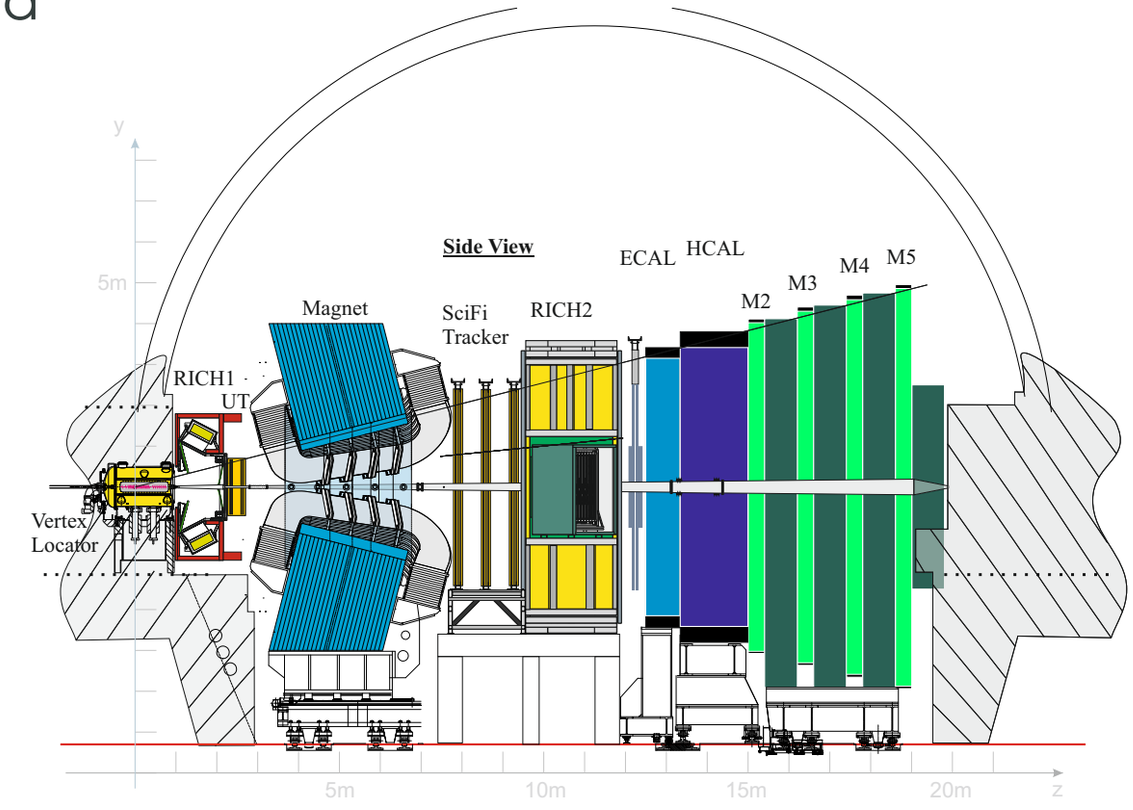
Pierre Auger Collaboration, Phys. Rev. D 91



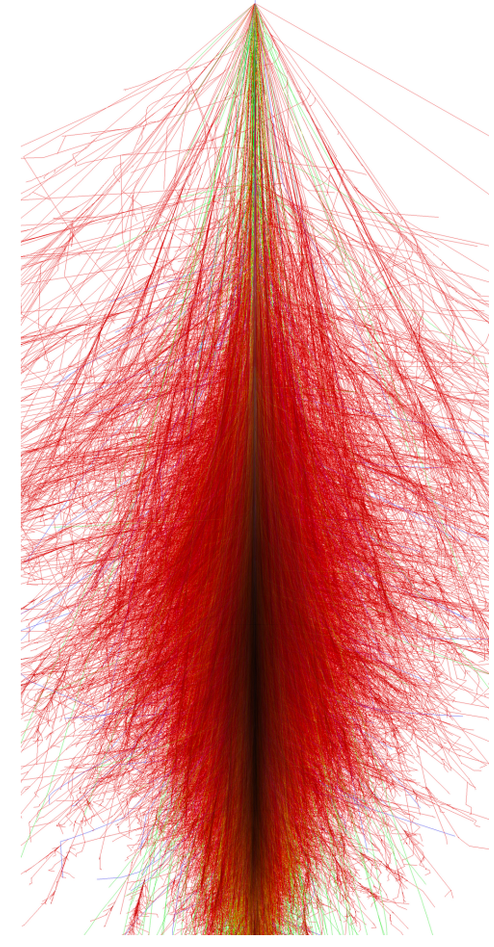
Alice Collaboration, Nat. Phys. 13 (2017) 535.

LHCb and air showers

- Forward layout optimised for studies of B mesons
- Suitable for fixed-target studies
- Run 3 LHCb has a fixed-target mode (SMOG2)
- Acceptance region relevant for air shower physics



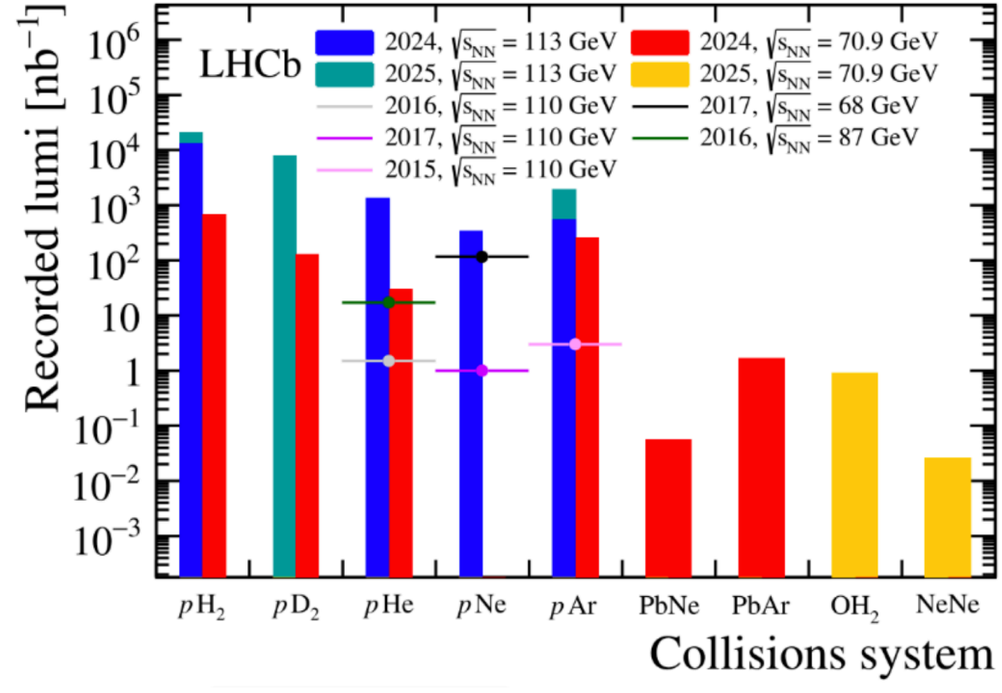
The LHCb Upgrade I, LHCb collaboration, JINST 19 (2024)



CORSIKA Shower Images: Iron Showers

SMOG2 at LHCb

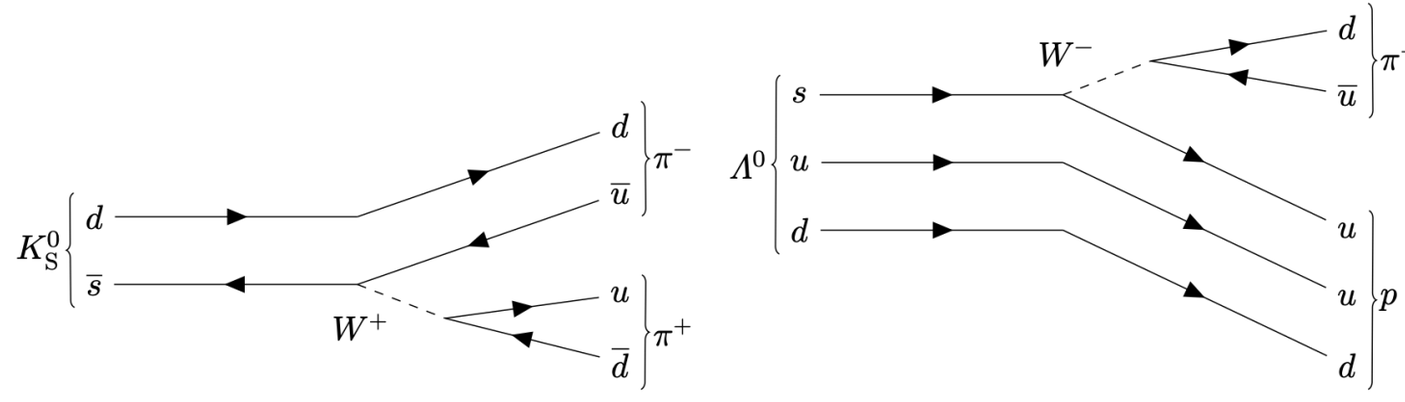
- Gas injections in front of VELO
- Enables various collision systems
- Data for this analysis: 2025 OH_2 and 2024 pNe collisions from SMOG2
- Unique samples that match the actual conditions in air showers
- Non-perturbative QCD: The hadronic interaction models rely on input from experimental data



LHCb collaboration (Internal)

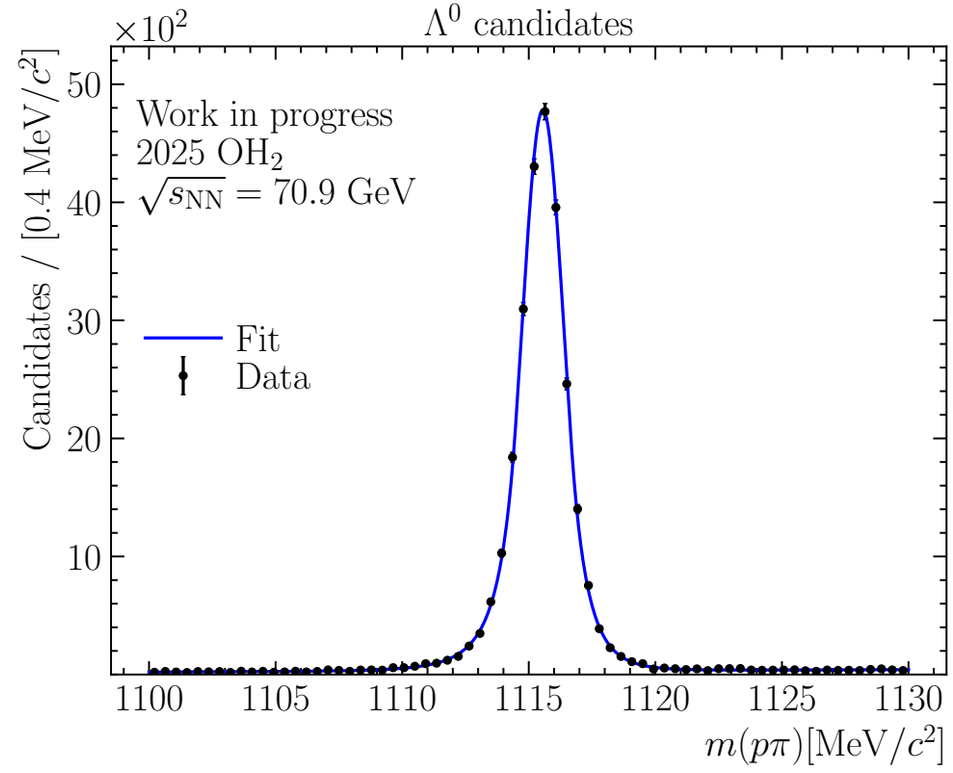
Goal of the analysis

- Measure the production cross-section ratios R of V^0 particles (strange, neutral hadrons)
- Abundantly produced, easy to reconstruct, many uncertainties cancel in ratio
- $R(\bar{\Lambda}^0, \Lambda^0)$ tests how well the models describe hadronization in the strange hadron sector
- The baryon/meson ratios $R(\bar{\Lambda}^0, K_S^0)$ and $R(\Lambda^0, K_S^0)$ are sensitive to the muon number in air showers



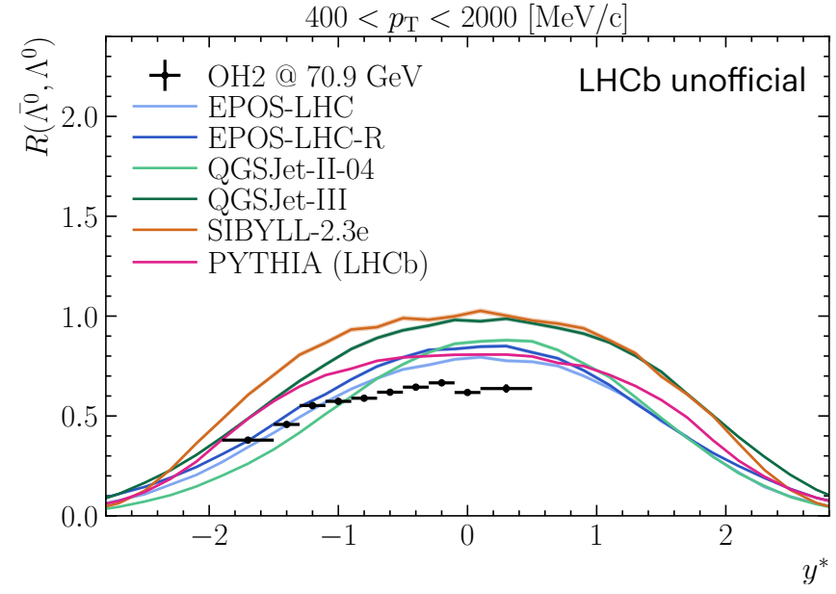
Analysis steps overview

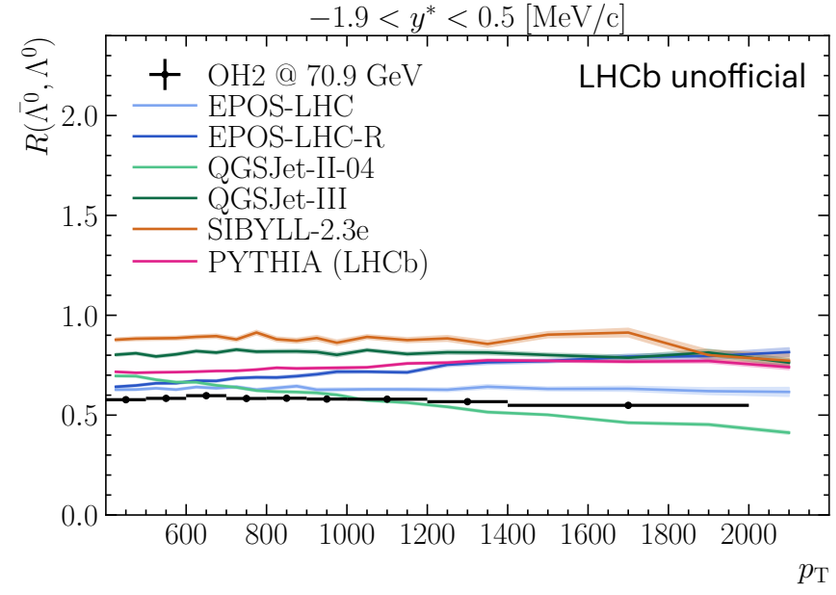
- Obtain the raw yields from LHCb data
- Use MC simulations to determine detector efficiencies
- Calculate the V^0 ratios including all corrections
- Run various hadronic interaction models to obtain their predictions for the ratios



Current results (1/3)

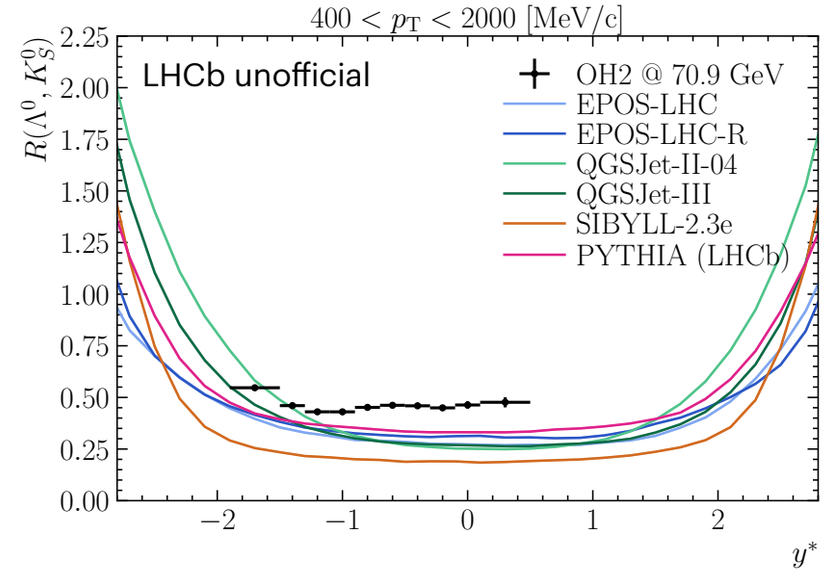
- Compare oxygen data with the common models EPOS, QGS-JET, SIBYLL and PYTHIA
- Differential measurement in center-of-mass rapidity y^* and transverse momentum p_T
- The measured $R(\bar{\Lambda}^0, \Lambda^0)$ ratio lies below the model predictions

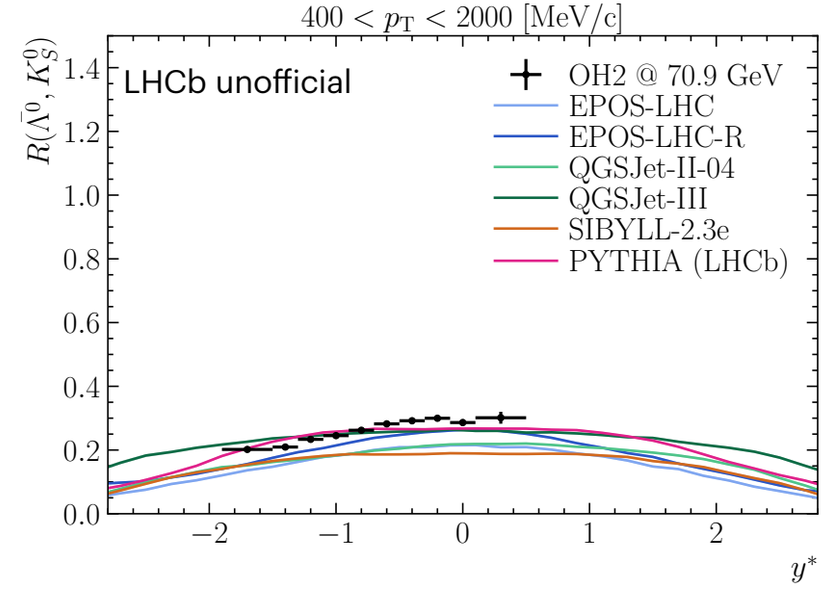




Current results (2/3)

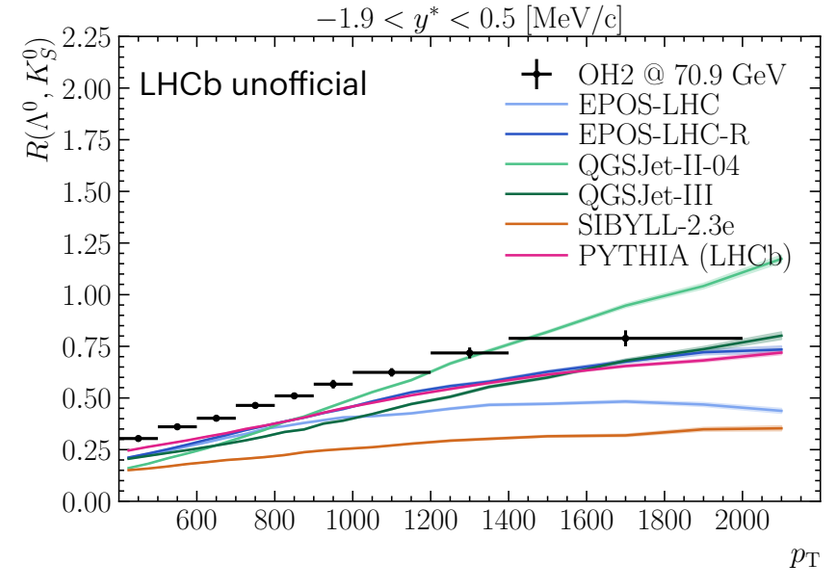
- Significant Λ^0 enhancement is visible in the baryon/meson ratio
- The model shapes seem to match the data shape at least partially
- The increased baryon production would help to enhance the muon number in air shower simulations

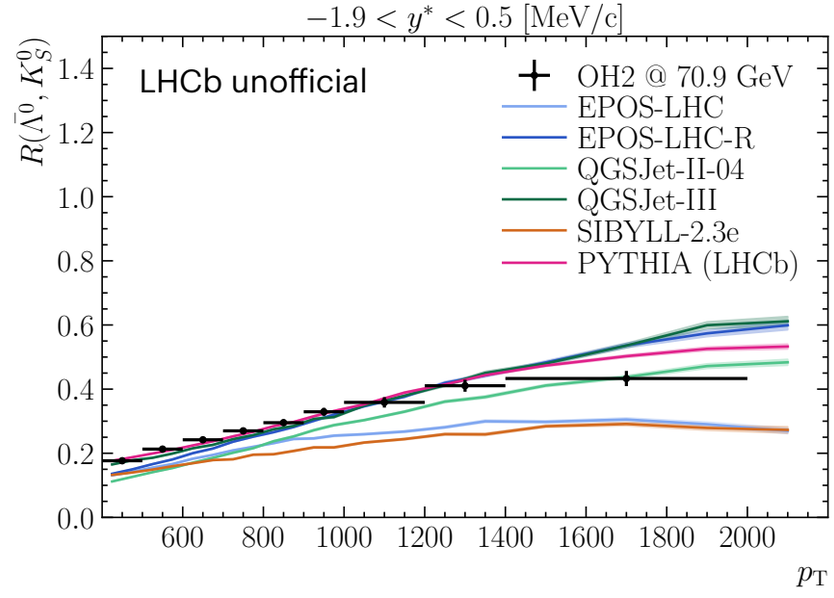




Current results (3/3)

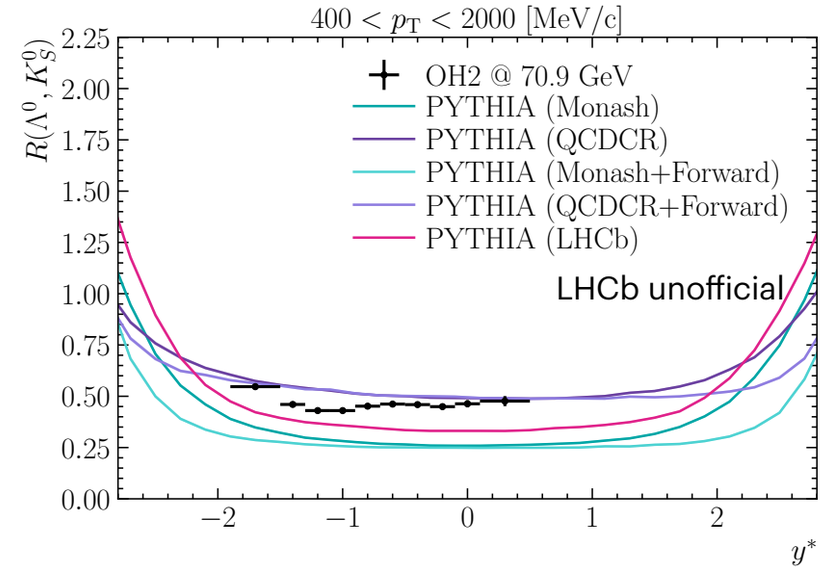
- Some models are more accurate regarding the absolute value, but others model the shape better
- No model can correctly describe Λ^0 and $\bar{\Lambda}^0$ production simultaneously
- Further model tuning seems necessary

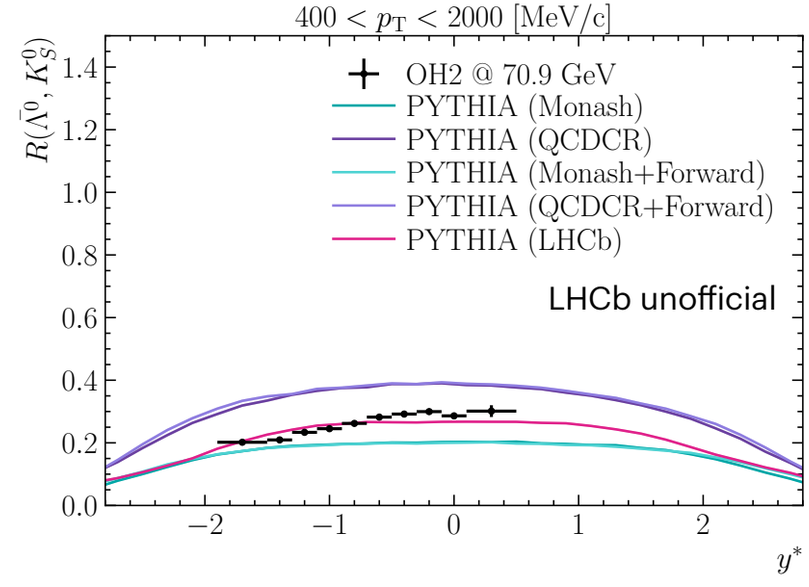




Testing PYTHIA tunes

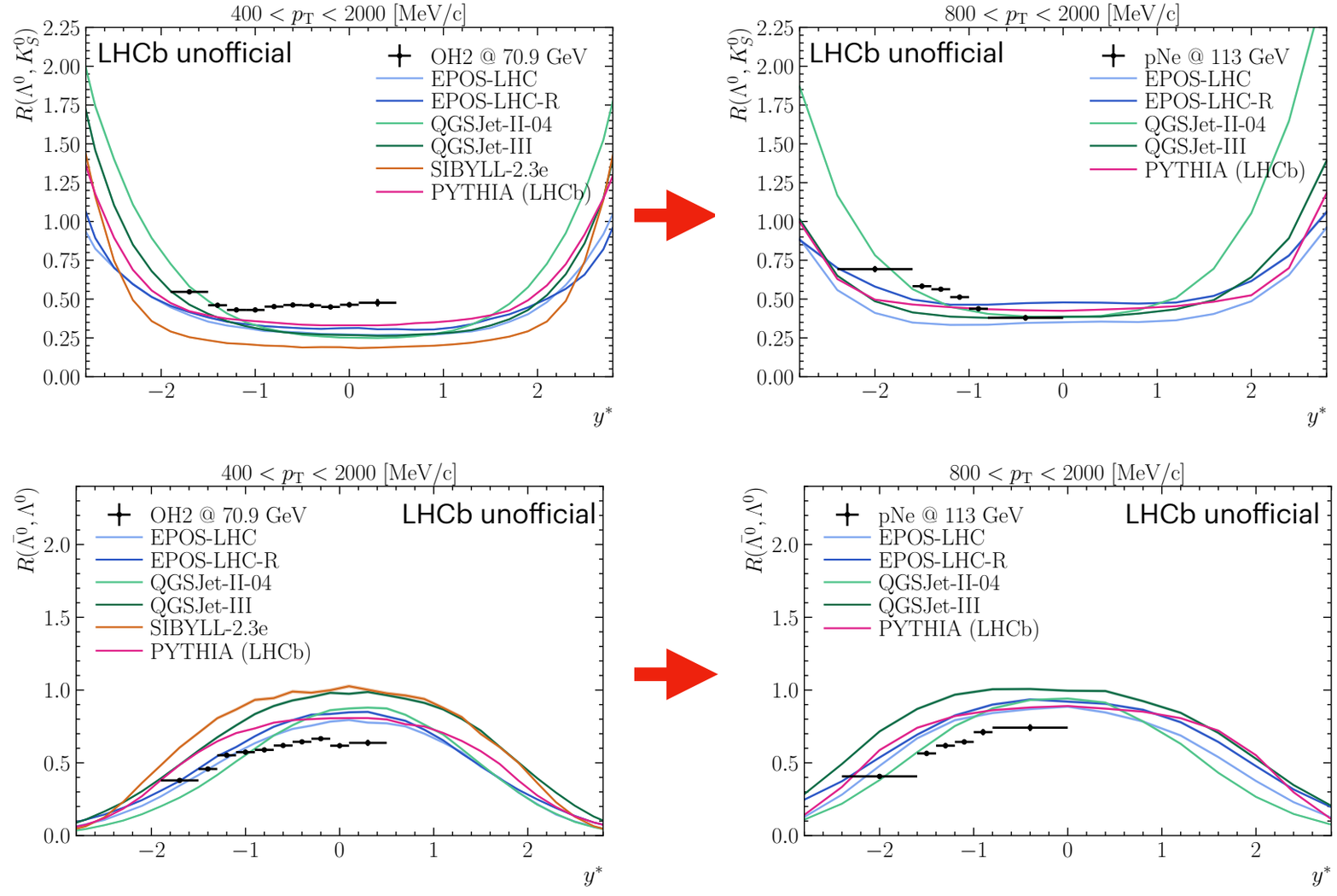
- PYTHIA has many tunes available, depending on the application
- Base (Monash), color reconnection (CR) and LHCb tune tested
- Λ^0 excess better modelled with CR, but overestimated regarding $\bar{\Lambda}^0$
- Forward tune using LHCf data has minimal impact





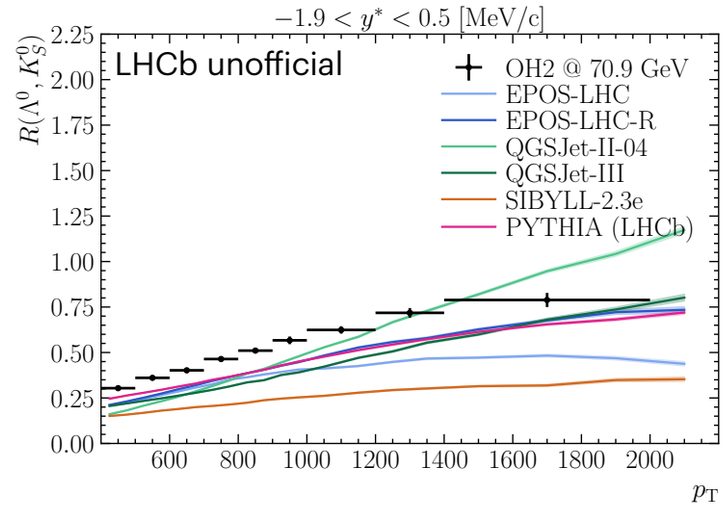
Comparing with pNe (1/2)

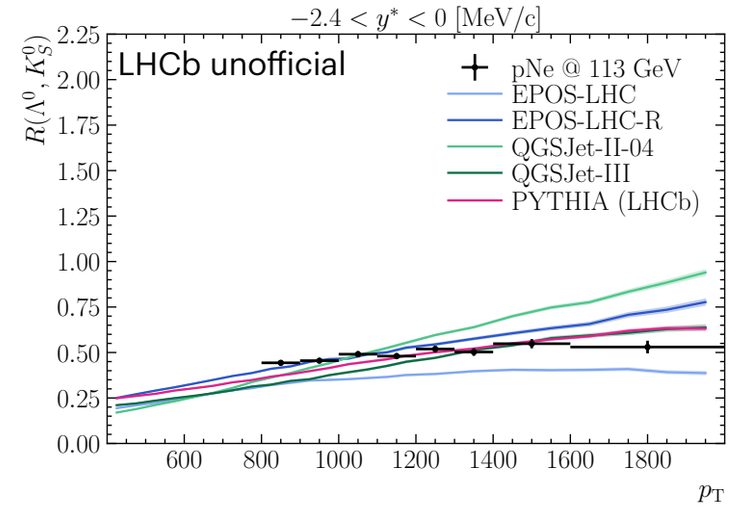
- pNe probes the neon side, while OH_2 probes the proton side
- pNe and OH_2 measurement at slightly different energies
- In pNe, the Λ^0 excess is less pronounced

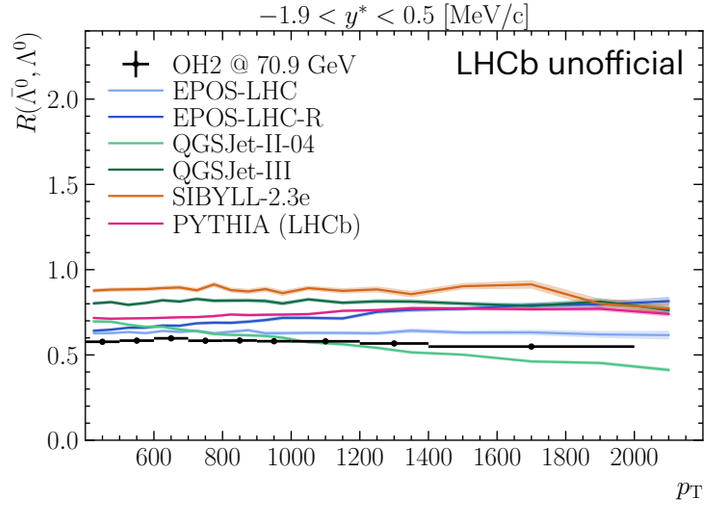


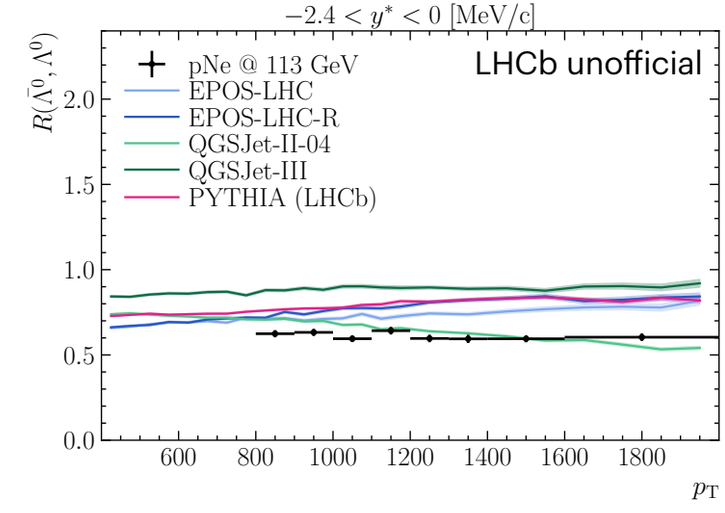
Comparing with pNe (2/2)

- No visible p_T dependence of Λ^0 excess in both
- Adding more collision systems to the study could test the impact of the nucleus



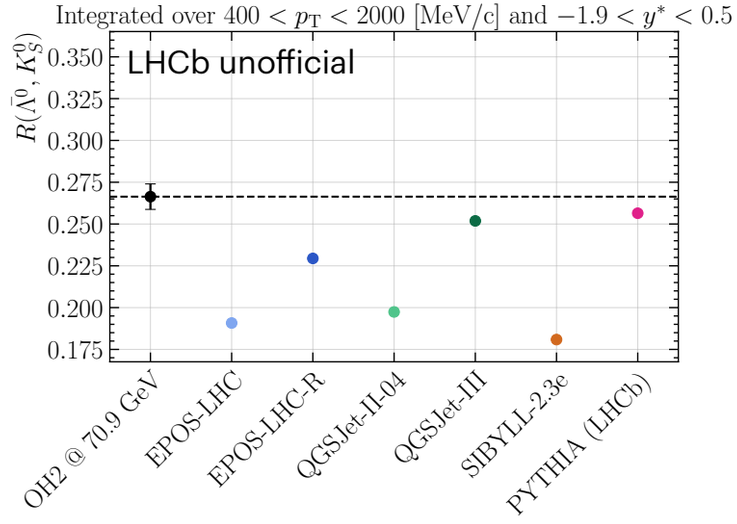


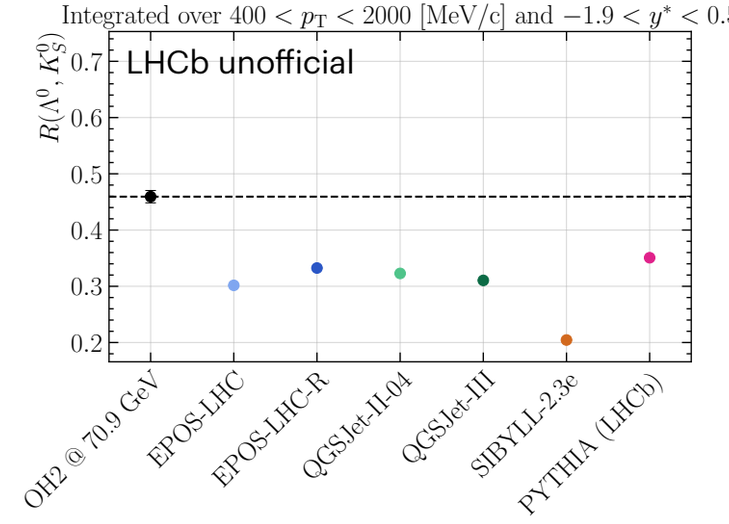


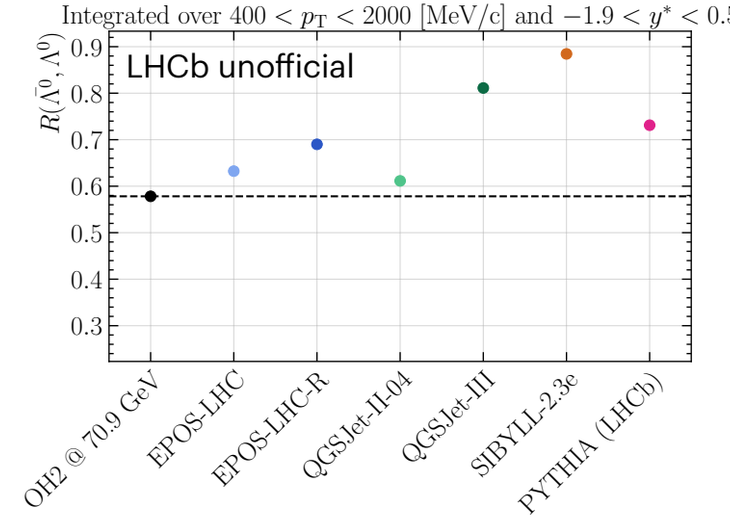


The next steps

- A few additional studies of corrections and uncertainties are still needed
- Enter internal review process next month
- Aiming for publication early next year



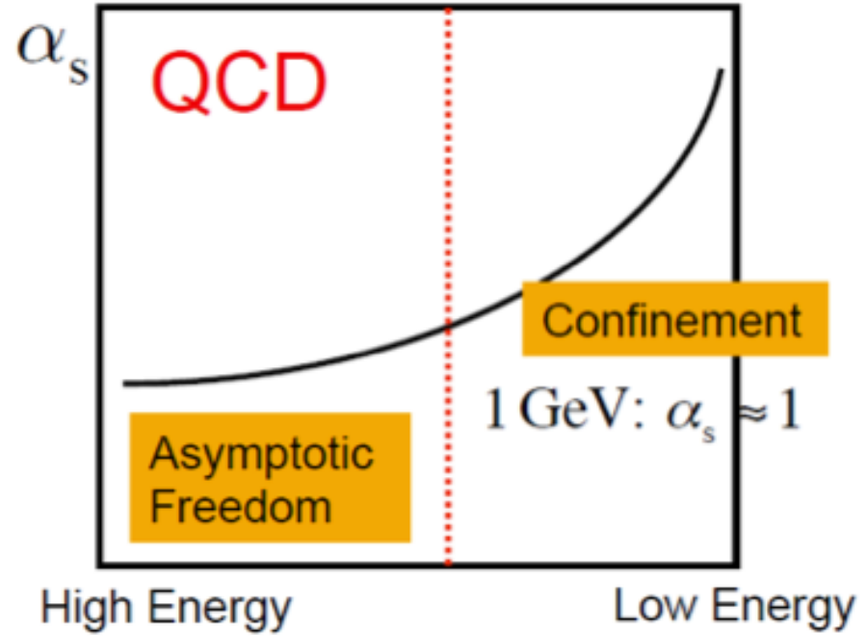




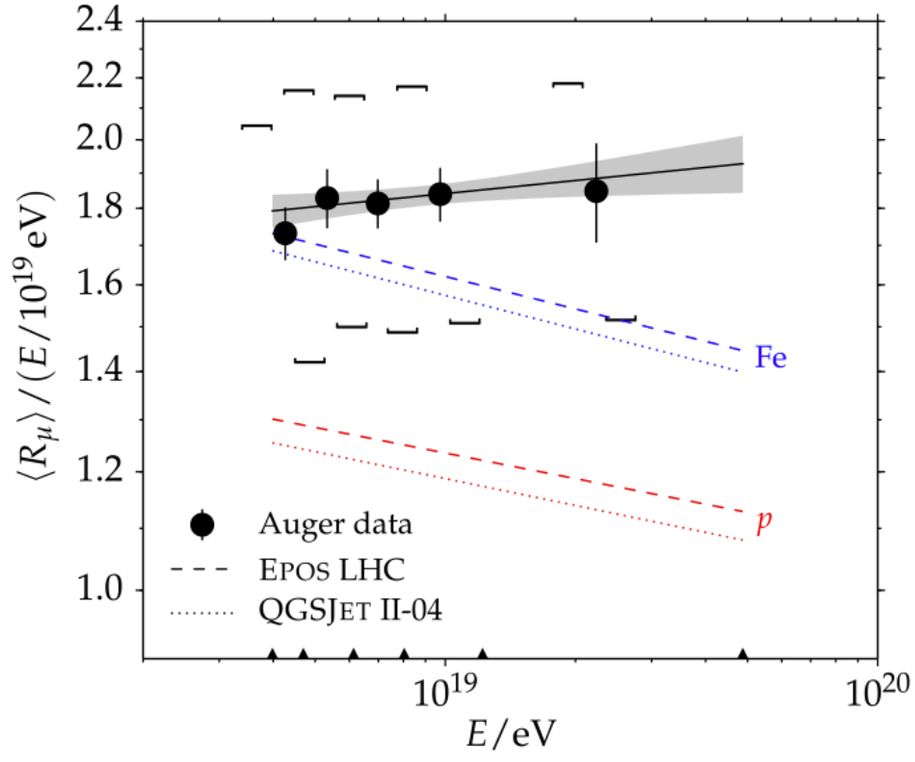
Thanks for your attention :)

Backup

QCD coupling

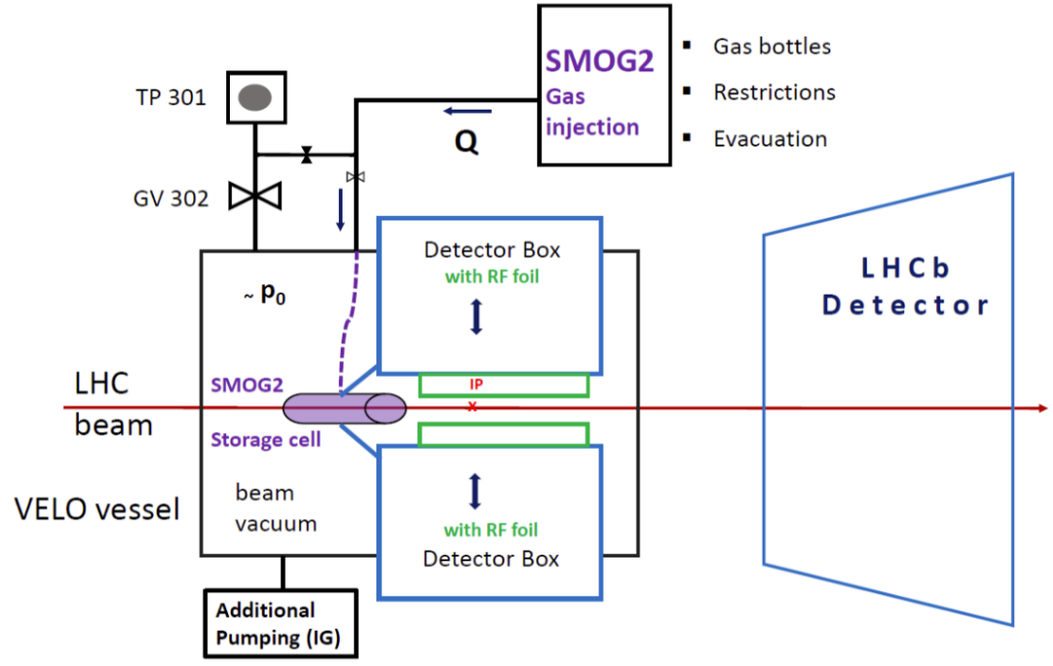


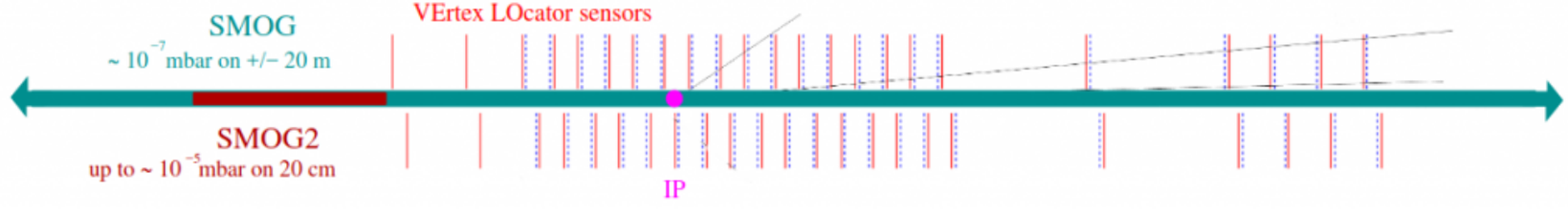
Muon puzzle



Muons in air showers at the Pierre Auger Observatory:
Mean number in highly inclined events,
Pierre Auger Collaboration,
Phys. Rev. D 91

SMOG and SMOG2





More on the SMOG system, LHCb outreach