Measurements of hadron production in LHCb and their impact on modeling of extensive air showers

Felix Riehn[a] on behalf of the LHCb collaboration

a: TU Dortmund University

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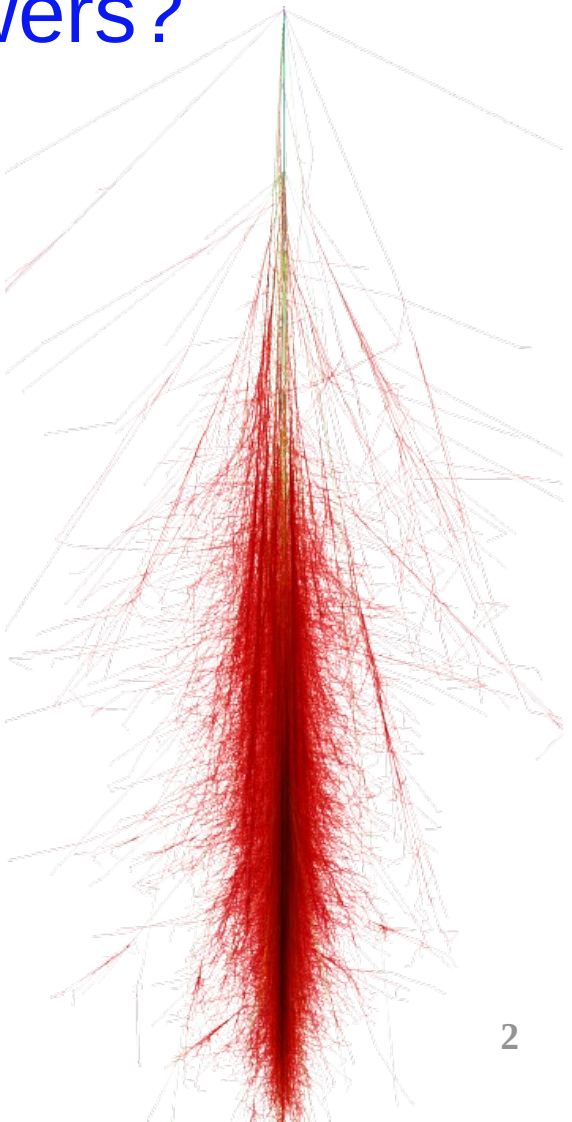
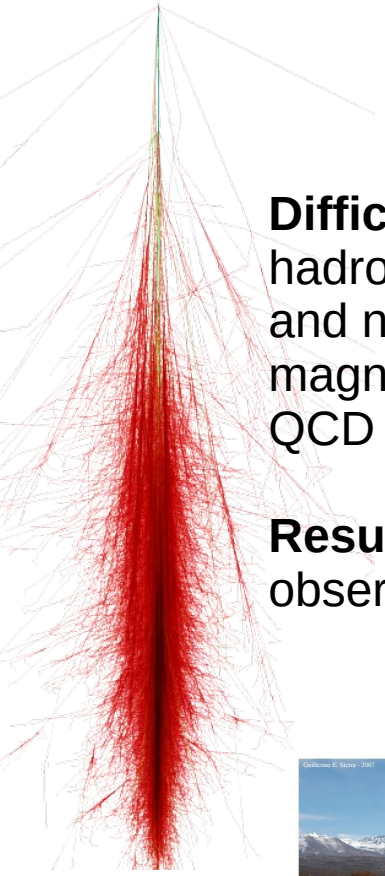
What are extensive air showers?

- Cascade of particle interactions in Earth's atmosphere initiated by
  - Ultra-high energy protons/nuclei (up to 100 EeV)
  - High energy photons (up to 300 TeV)

- Air showers play a role in **all** ground-based astroparticle experiments (signal or background), e.g.
  - *Pierre Auger Observatory*
  - Cherenkov Telescope Array Observatory
  - IceCube Neutrino Telescope



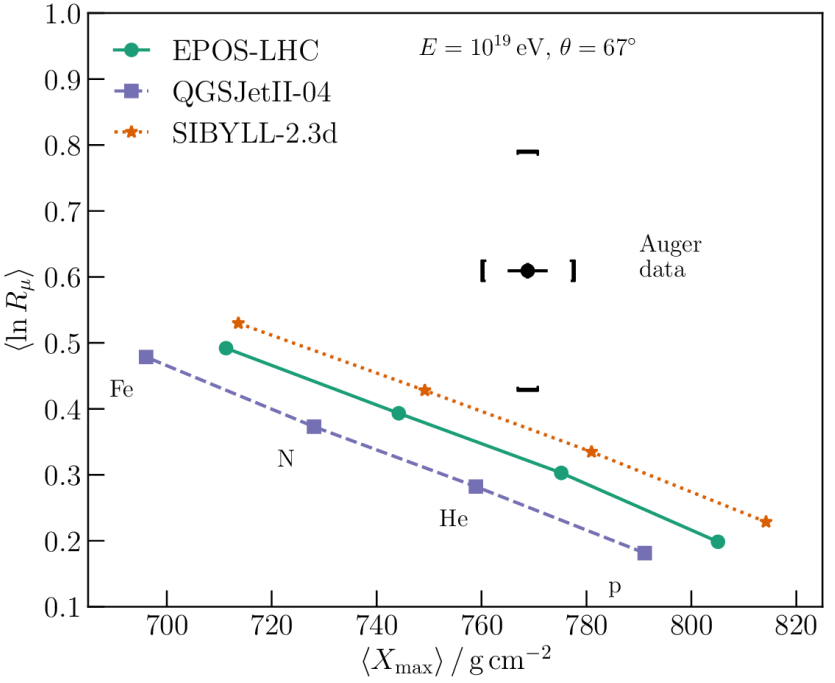
The problem: air showers not correctly modeled



Difficulty: Need a fully inclusive model of hadronic interactions of pions, kaons, protons and nuclei with nuclei over 10 orders of magnitude in energy ! → non-perturbative QCD

Result: inconsistent results between observables, in-particular ground based

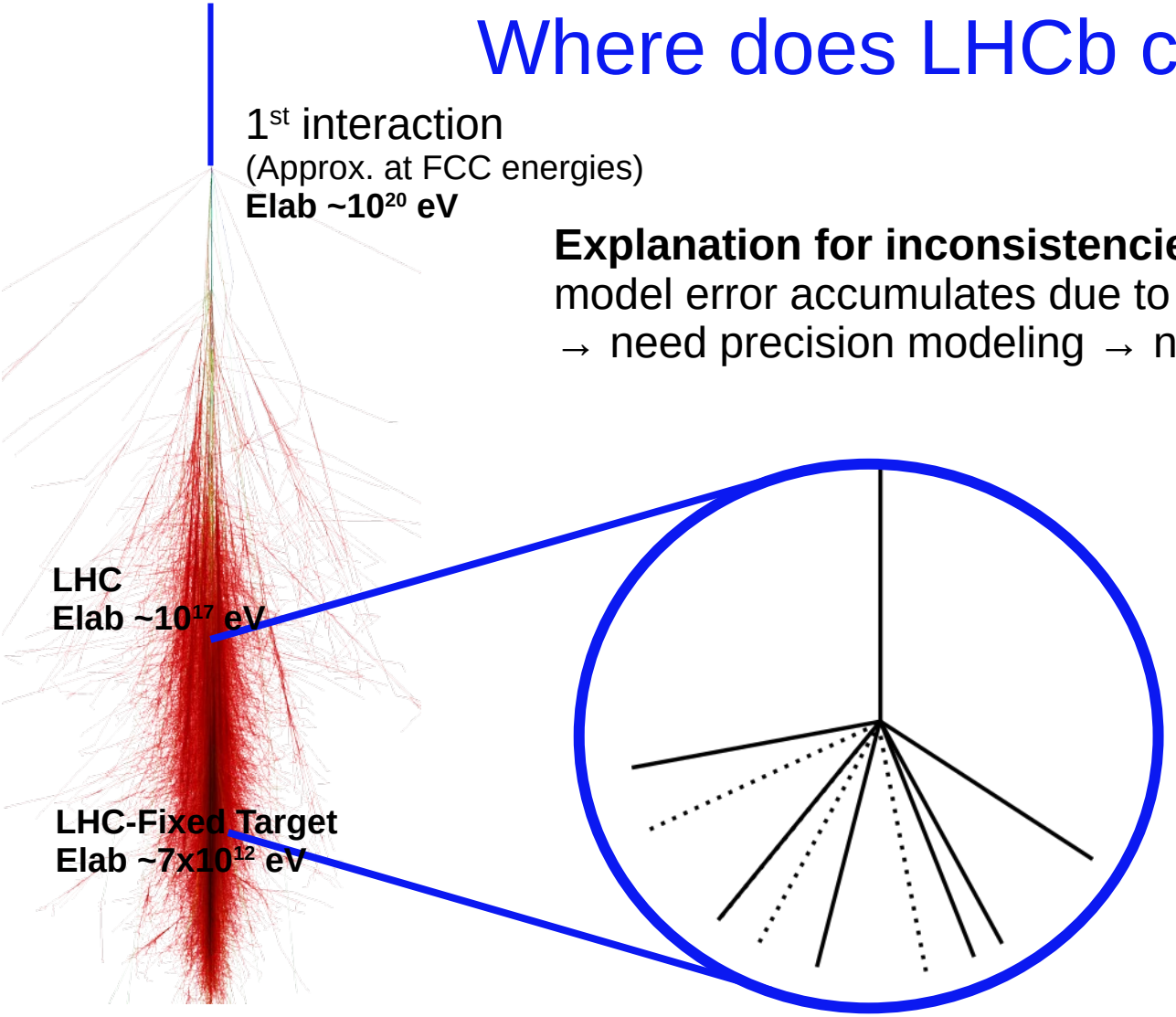
(PRL 126, 152002 (2021))



Where does LHCb come in?

1st interaction
(Approx. at FCC energies)
Elab ~10^{20} eV

Explanation for inconsistencies:
model error accumulates due to cascade
→ need precision modeling → need precision data



LHCb allows **precision measurements** of proton-proton **and** proton-nucleus interactions in a **broad energy range** covering the bulk of the shower development

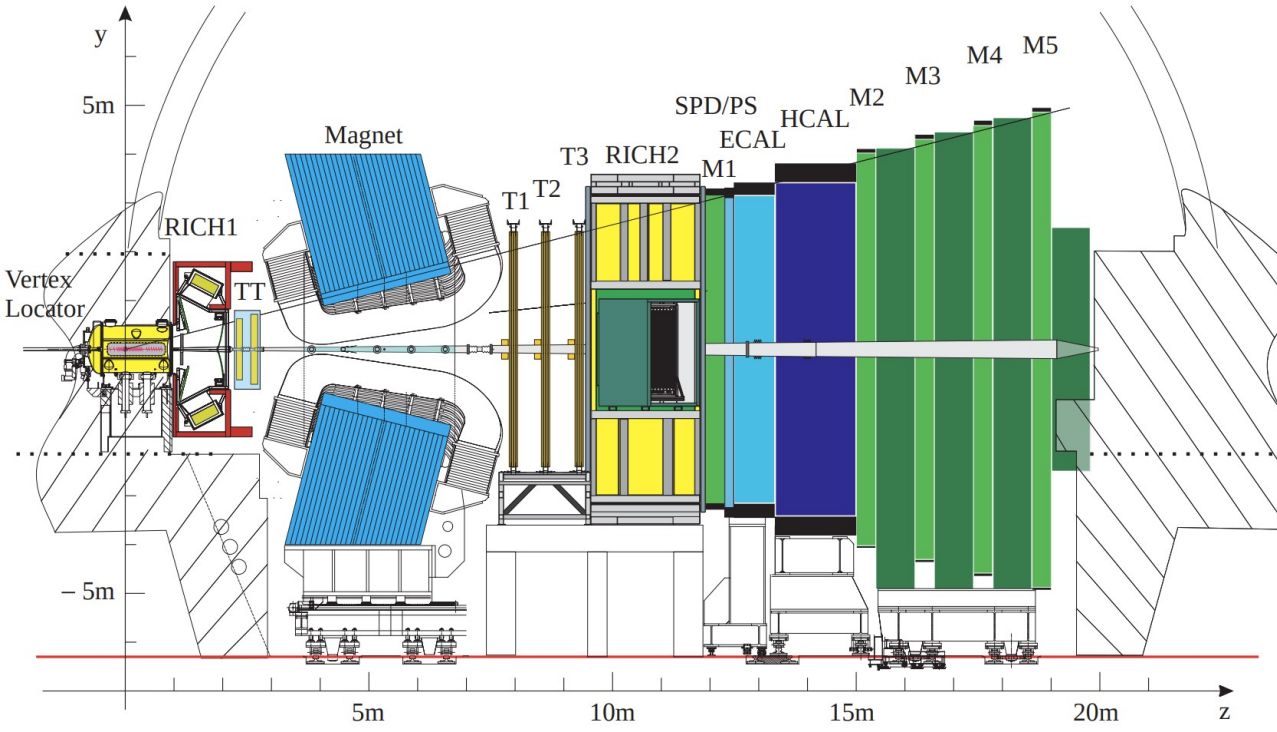
LHCb

- single arm forward spectrometer covering 2<eta<5

  (Int. J. Mod. Phys. A 30, 1530022 (2015))

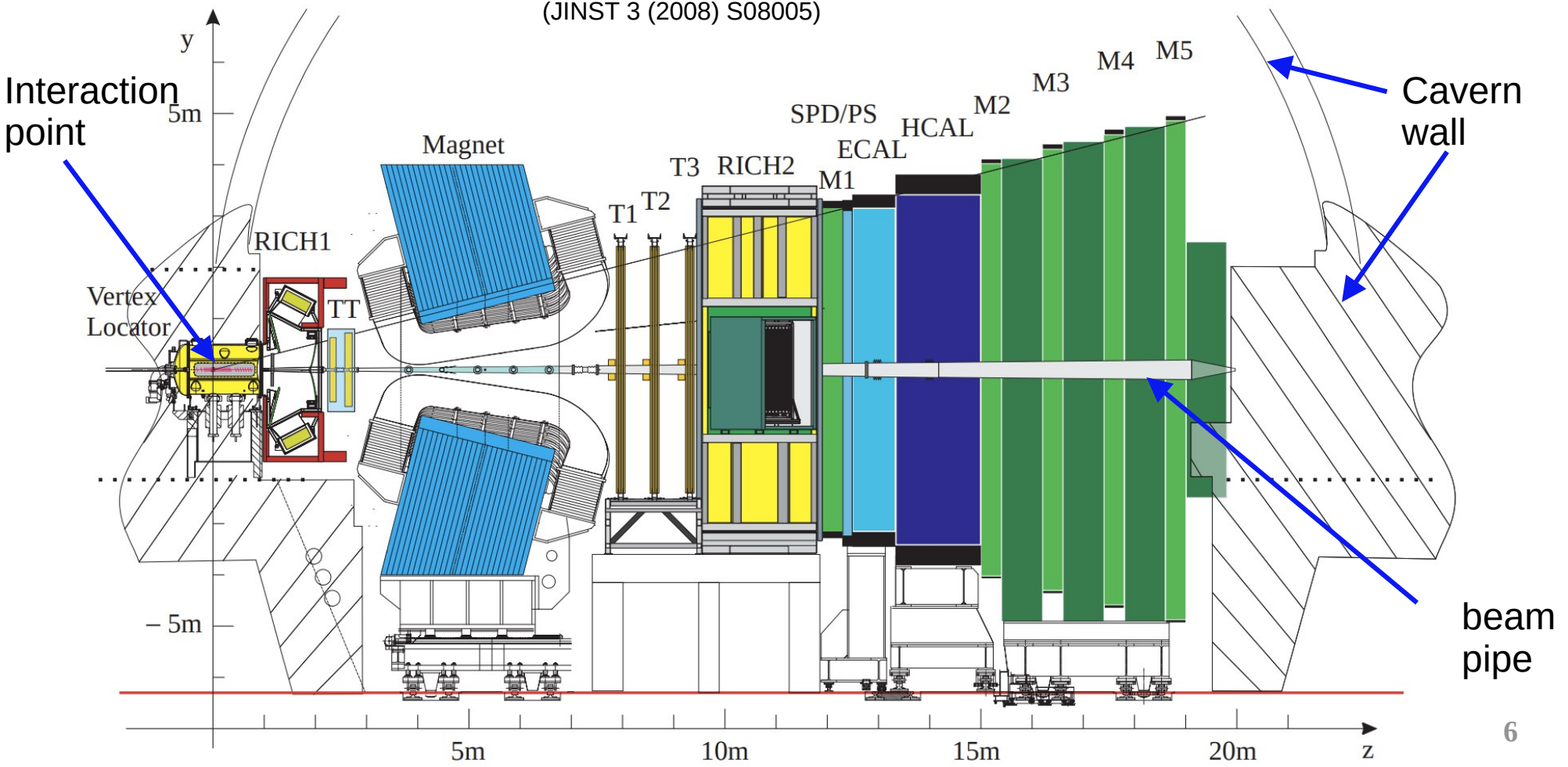
- designed to study CP violation, flavour oscillations & rare decays in beauty-hadron (and *charm-hadron*) decays
  - Particle identification: pions, Kaons, protons, electrons, muons, deuterium
  - Momentum resolution from 0.5% at low momentum to 1.0% at 200 GeV/c
  - Vertex resolution: 10-50μm IP resolution

(JINST 3 (2008) S08005)

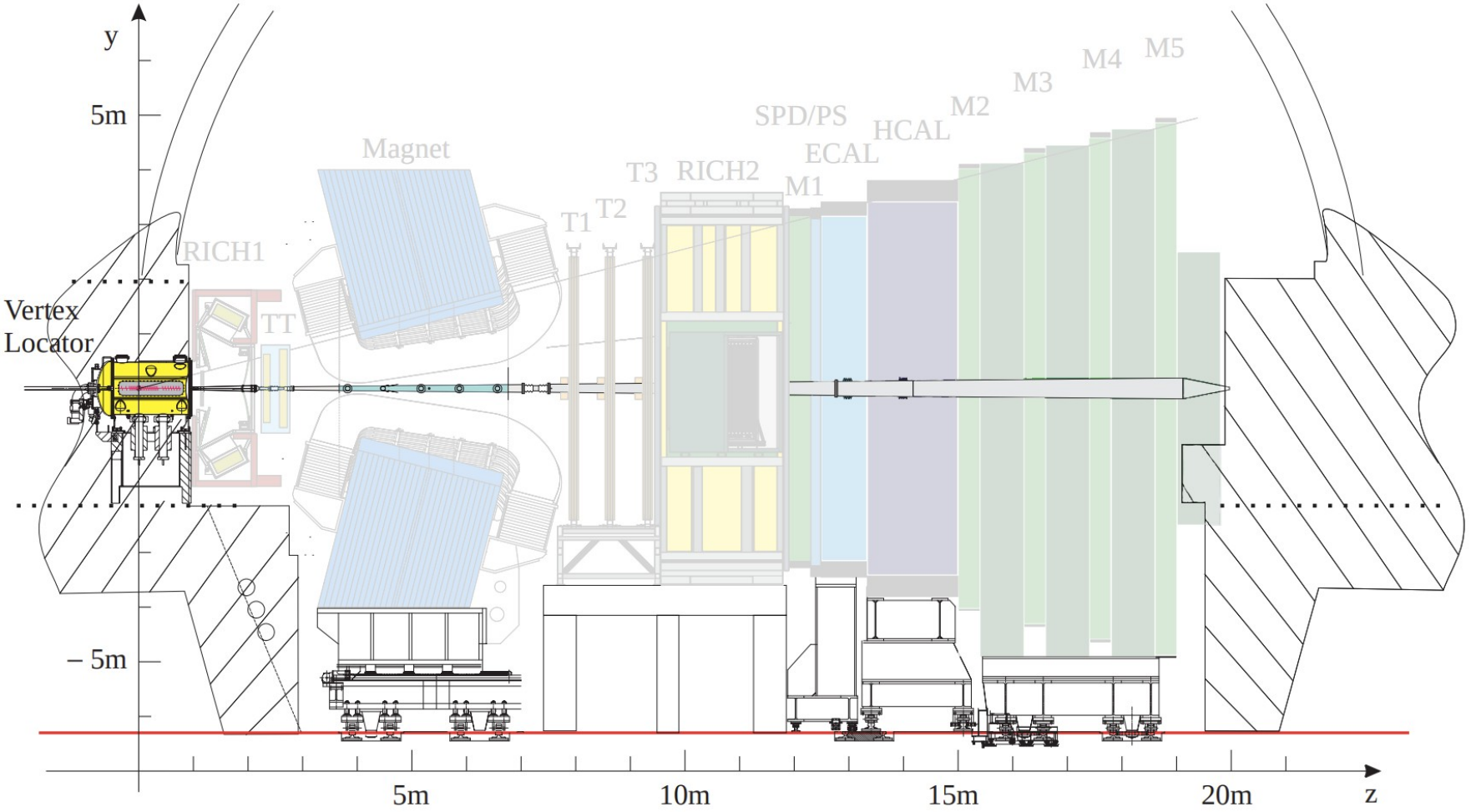


The LHCb detector: schematic side-view

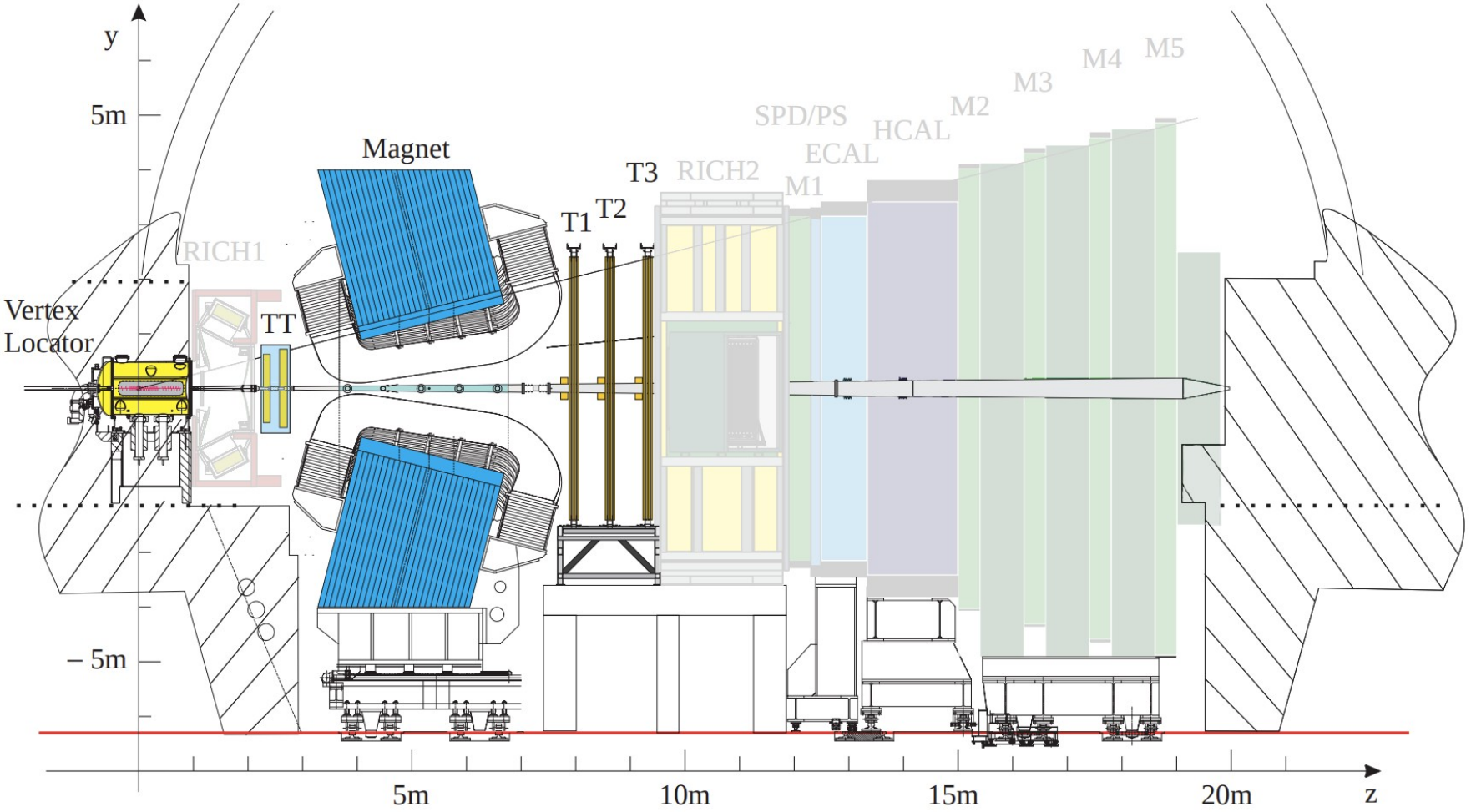
(JINST 3 (2008) S08005)



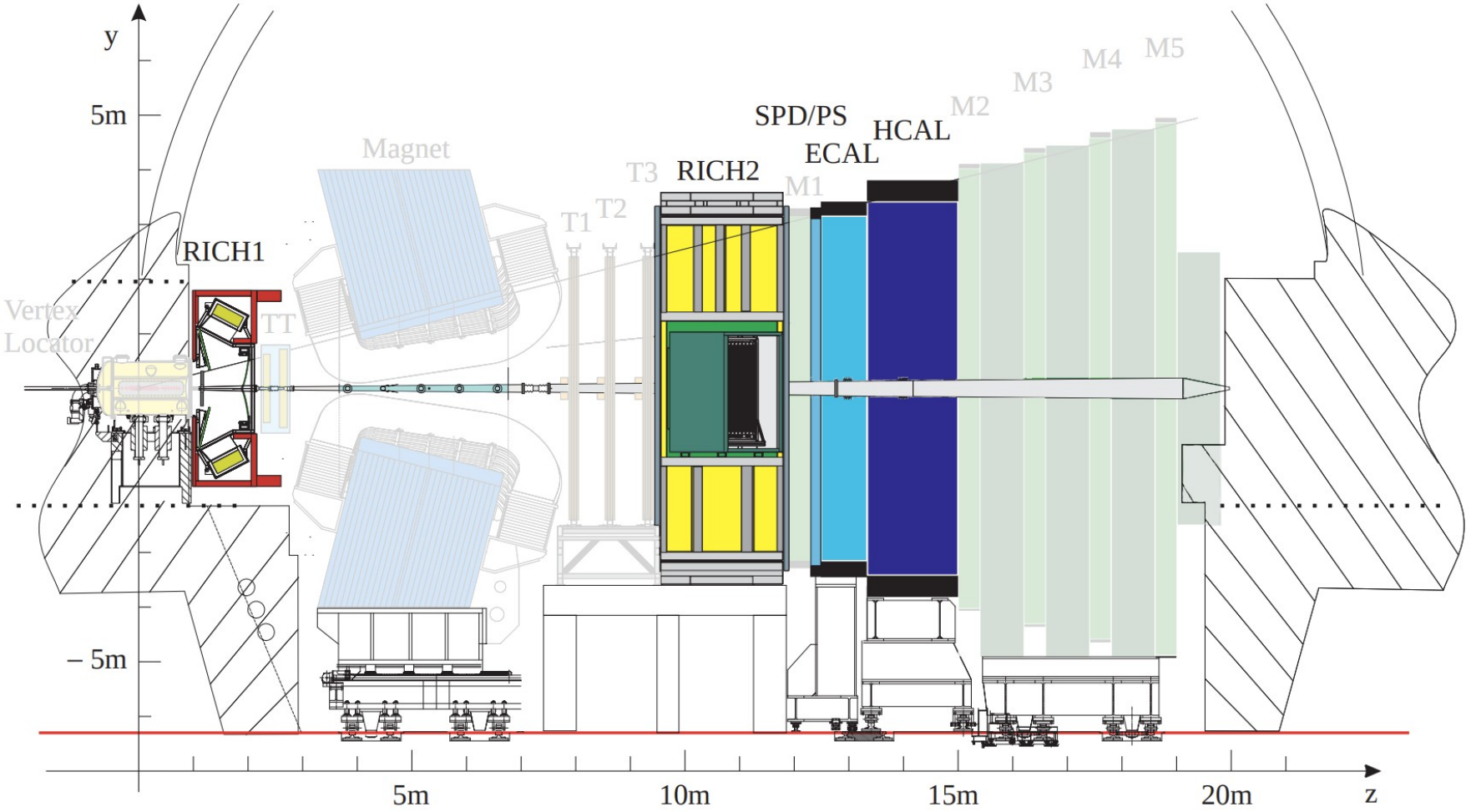
The LHCb detector: vertex locator



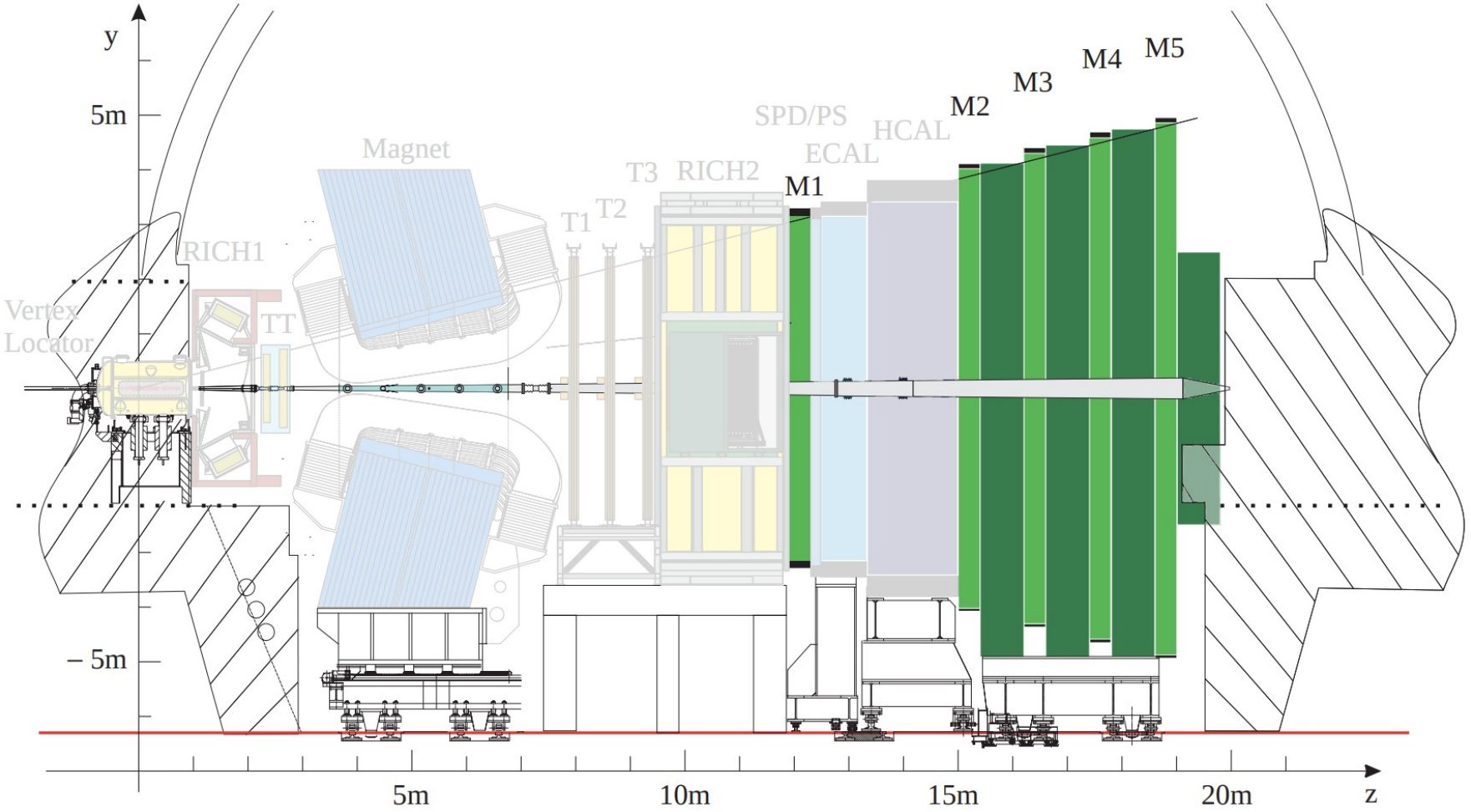
The LHCb detector: tracking system



The LHCb detector: particle identification



The LHCb detector: muon chambers

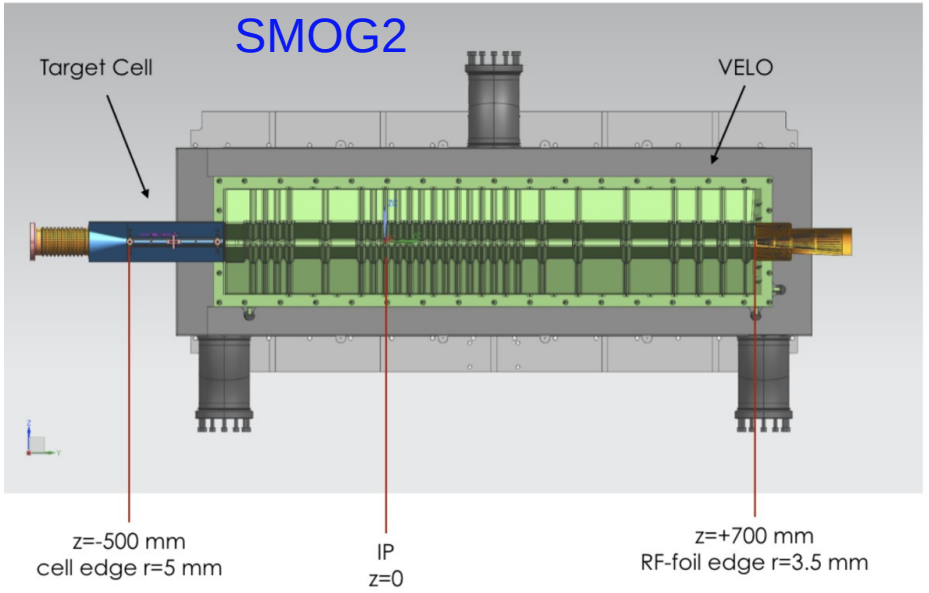


LHCb fixed target mode: SMOG system

- Beam-gas interactions
- Energy range: 70 – 115 GeV
- Rapidity range: mid-rapidity in CM
- Varying targets

SMOG (gas flow through vertex locator)
- Low luminosity
- Only Noble gases (He, Ne, Ar)

SMOG 2 (dedicated injection device)
- 100x SMOG luminosity
- Noble and non-Noble gases (H_2, D_2, maybe others)



(LHCB-TDR-020)

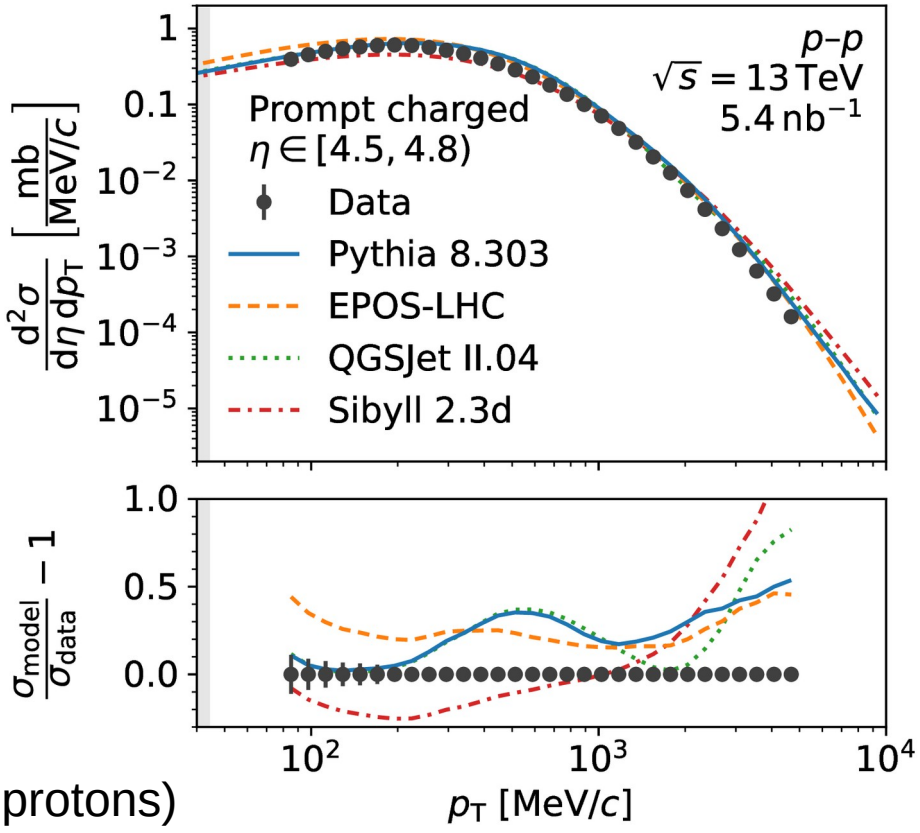
Prompt charged particle production in pp

Measure double-differential Cross-section of prompt production of *long-lived* charged particles in proton-proton collision

Long lived: $\tau \geq 30$ ps ,
charged : e −, μ−, π +, K +, p, Σ +, Σ − and Ω−

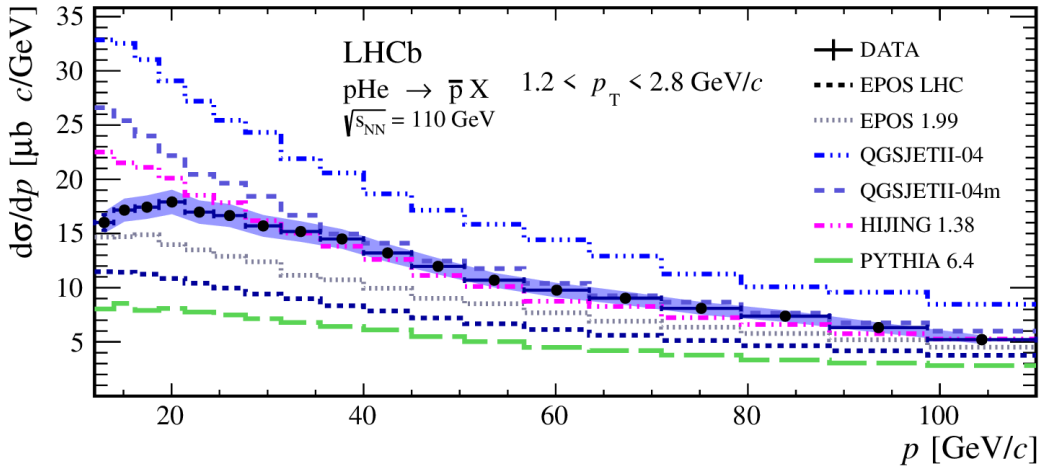
Dominant systematic: background tracks
- interactions with detector material
- fake tracks
- strange hadron decays

(JHEP 01 (2022) 166)



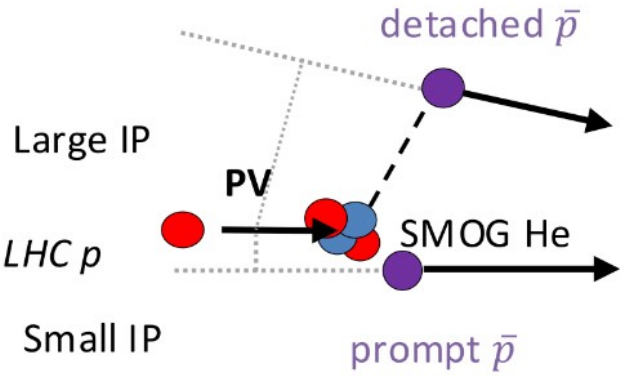
Measurement of identified spectra (pion, kaon, protons) on-going.. similar precision expected..

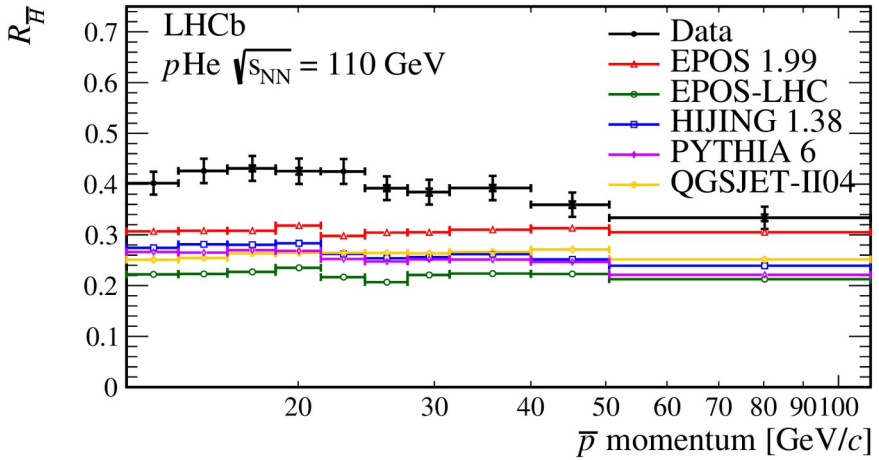
Anti-proton production in p-Helium using SMOG



(Phys. Rev. Lett. 121, 222001)

prompt





Non-prompt (hyperon decays)/prompt

Impact of this measurement on CR propagation shown in talk by K-H. Kampert on Monday

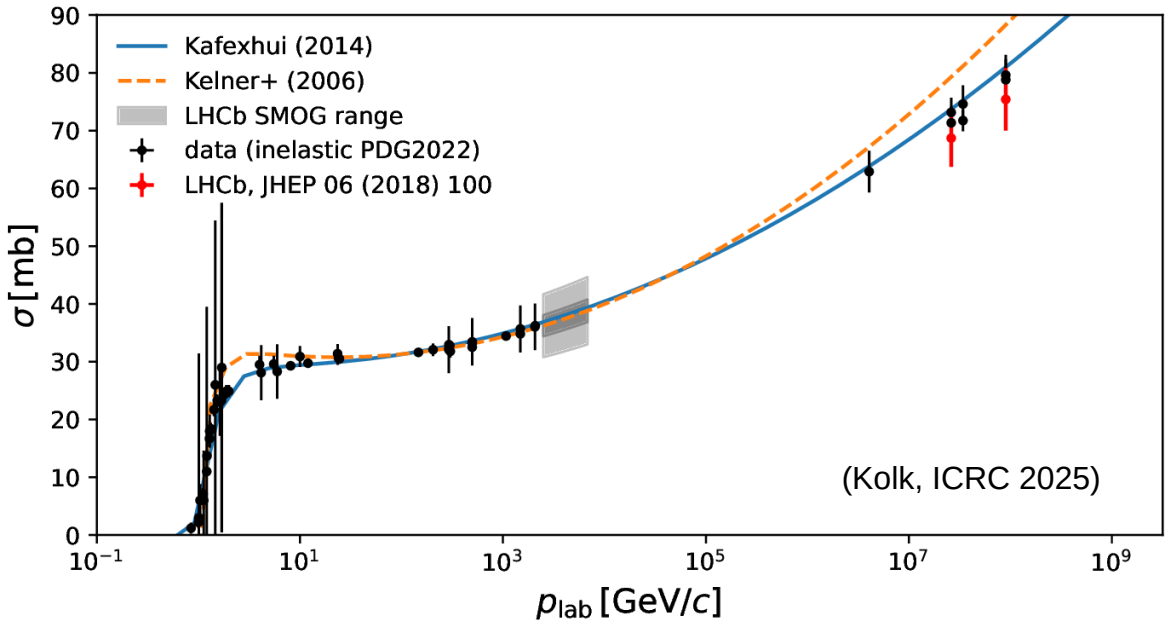
(Eur. Phys. J. C83 (2023) 543)

Inelastic proton proton cross section

(JHEP 06 (2018) 100)

LHCb measurements of inelastic pp cross-section

- $\sqrt{s}$ = 7 TeV :
  sigma-inel = 68.7 ± 2.1 exp ± 4. 5 extr mb
- $\sqrt{s}$ = 13 TeV :
  sigma-inel = 75.4 ± 3.0 (exp) ± 4. 5 extr mb



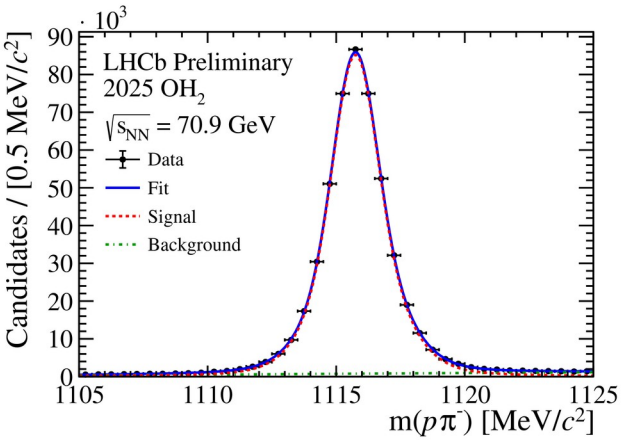
Based on track multiplicity (zero-counting)

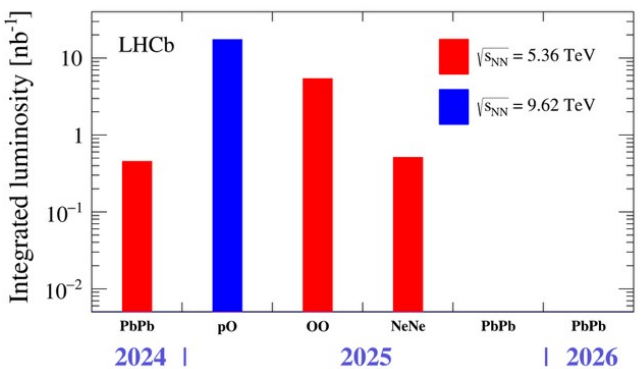
Dominant systematic: extrapolation from fiducial to full phase space,
2nd dominant: luminosity

Future measurements with LHCb

Probing the air shower configuration

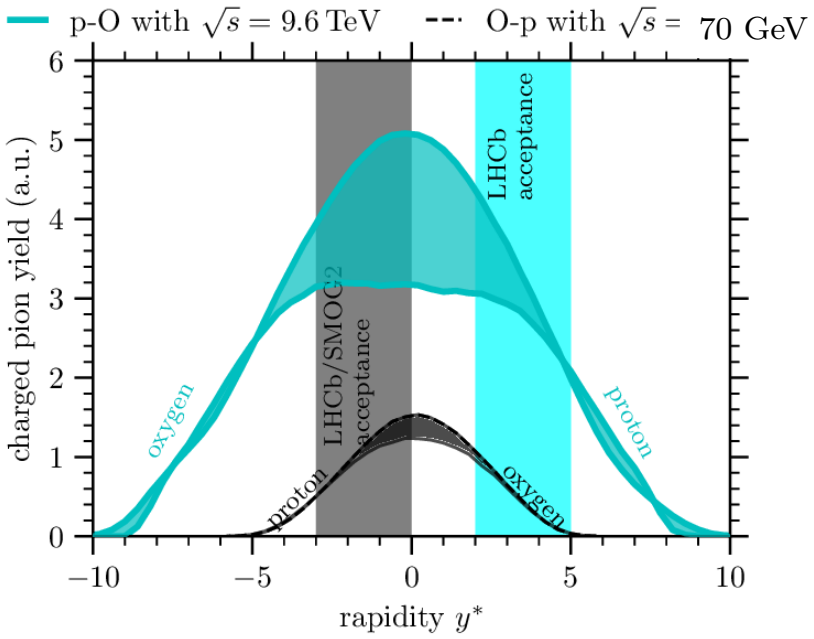
- Light-ion run at LHC in July 2025 delivered proton-Oxygen collisions at 9.6 TeV!
- During Oxygen-Oxygen run, LHCb operated SMOG2 with H2 ==> fixed target collisions of proton-Oxygen at 70 GeV!
- Scan over proton-light-ions (H_2, D_2, He, Ne + maybe others) with SMOG2

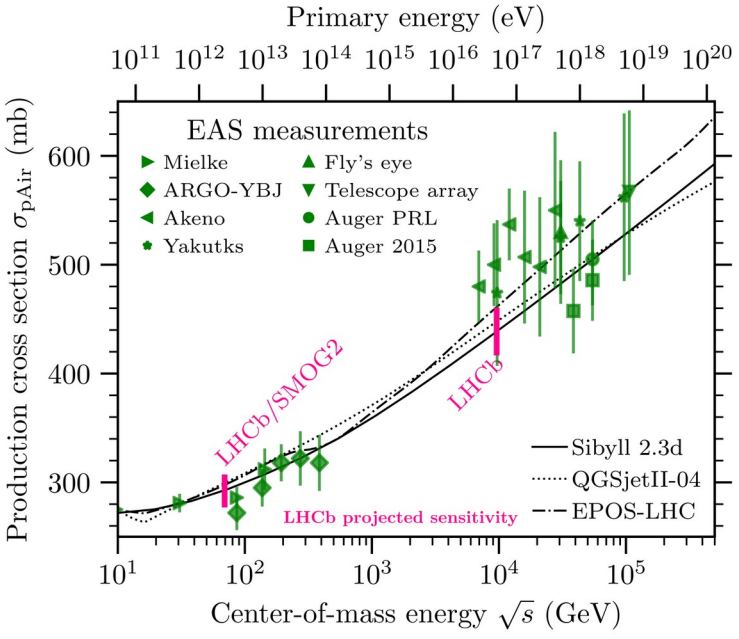




Future measurements with LHCb

Probing the air shower configuration





+ scan A dependence for light-ions !

Summary

- Modeling of air showers at the moment is incomplete/inconsistent
  - → dominant systematic uncertainty in many astroparticle experiments
  - → need more **accurate models**, need more **precision data**
- LHCb provides **precision** measurements of particle production in various configurations useful for air shower modeling
  - Charged particles in pp at 13 TeV (identified spectra on-going)
  - Anti-proton production in p-Helium at 110GeV
  - Inelastic cross section
- Thanks to light-ion run in 2025, LHCb will be able to provide precision measurements that **directly constrain** air shower modeling.