pO collisions for cosmic ray physics at the LHC

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HL-HLC Workshop, 1 Nov 2017

In a Nutshell

- Why pO?
  - **Cosmic rays** interact with Earth's atmosphere and produce **air showers**
  - Experiments need **accurate simulation** of air showers
  - pO collisions at LHC reproduce **first interaction** of cosmic ray with atmosphere

- What to measure?
  - **π, K, p** for cosmic ray experiments
    - Inclusive production, (eta, pT) spectra
    - Multiplicity distributions
  - D mesons for IceCube
    - Inclusive production, (eta, pT) spectra

- Required luminosity
  - **1 nb^{-1}** for **π, K, p, D** (500M events)

- Data of interest for several experiments
  - **LHCb: full hadron PID for 2 < eta < 5**
  - LHCf: gammas and neutrons at eta > 8.4
  - ALICE, CMS, CASTOR, TOTEM ...

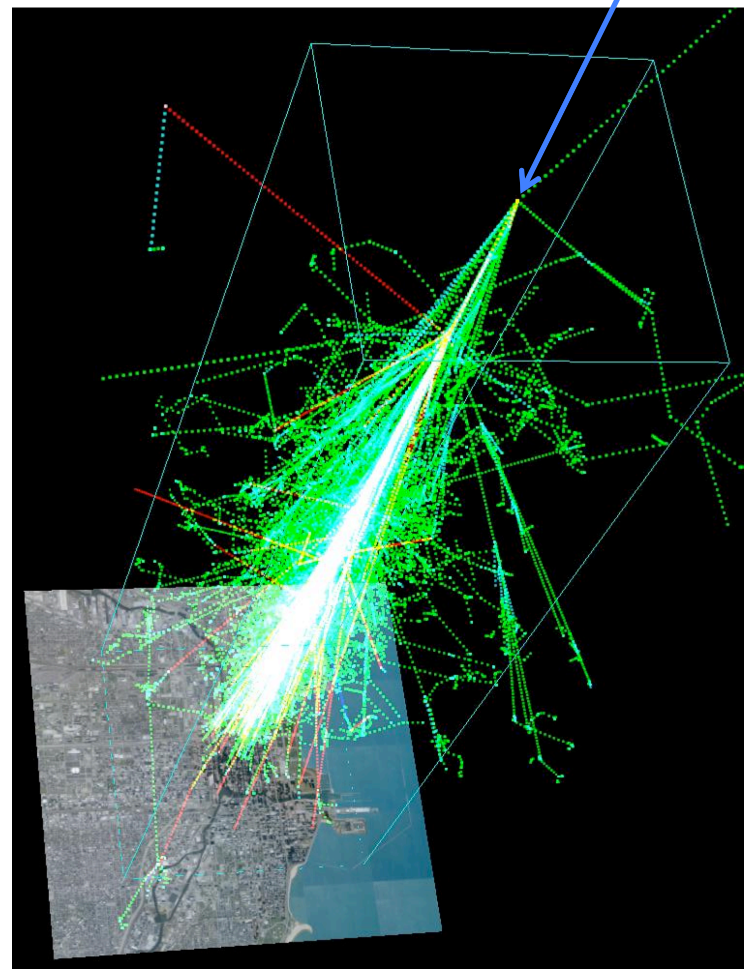
Air showers

Not this

CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=53806520

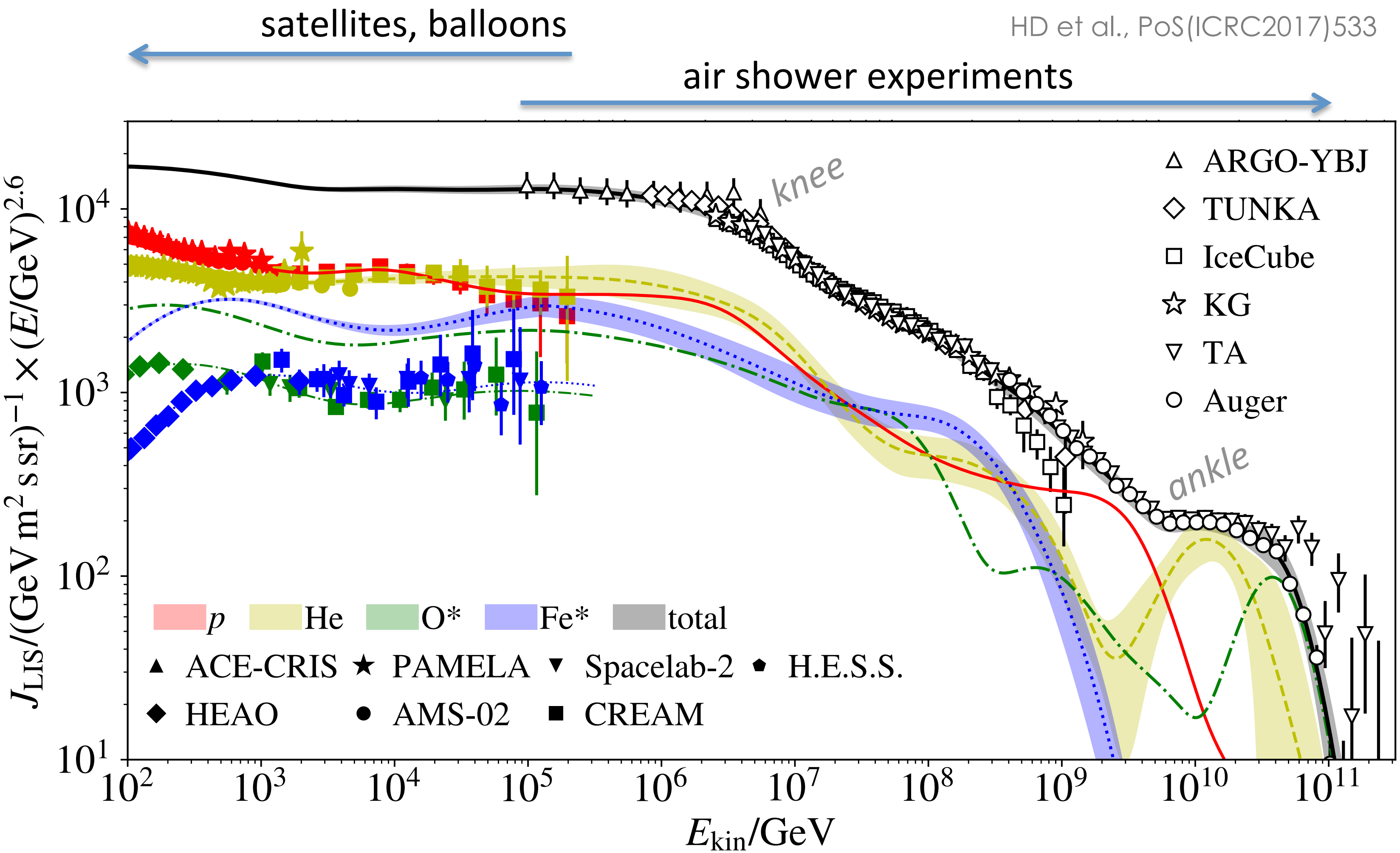
This

cosmic ray



http://astro.uchicago.edu/cosmus/projects/aires/

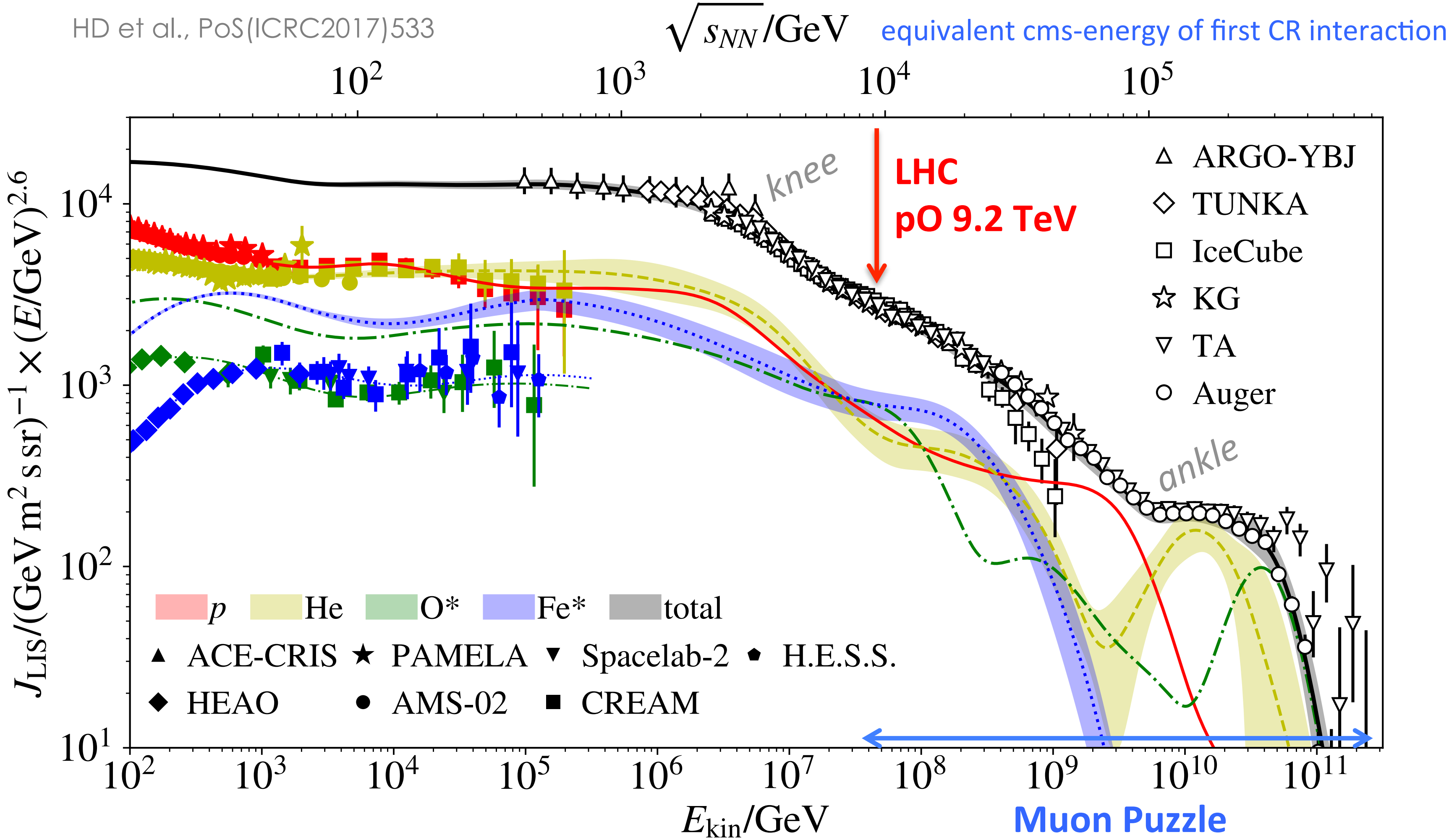
Cosmic rays



Cosmic rays: naked high-energy nuclei from outer space

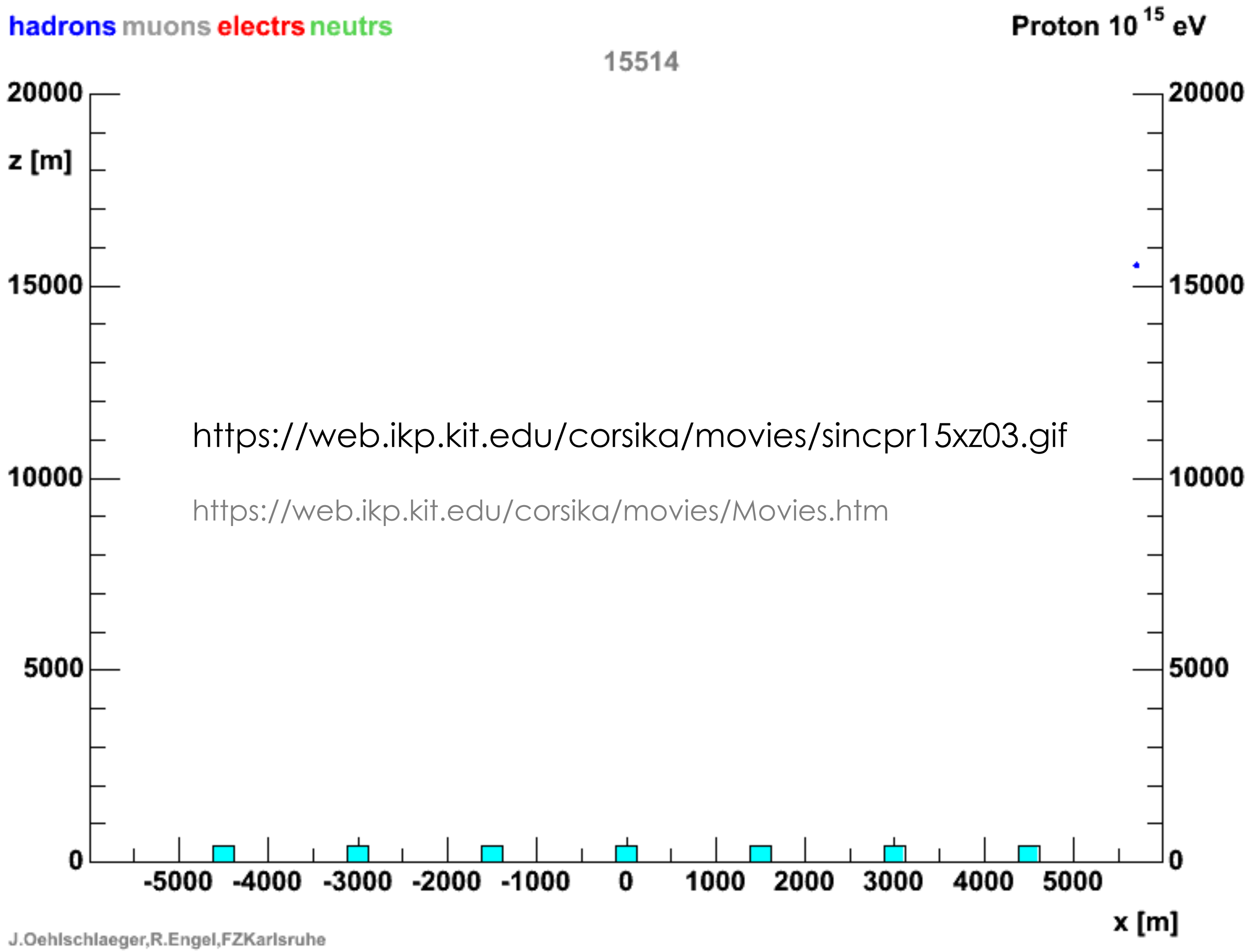
- Below 10^5 GeV: elemental composition of cosmic rays well known
- Above 10^5 GeV: elemental composition uncertain, inferred from observing **air showers**

Cosmic rays



- Air shower simulations needed to connect observables to cosmic ray properties
- Muons wrong in simulations, preventing better understanding: the **Muon Puzzle**

Air shower animation

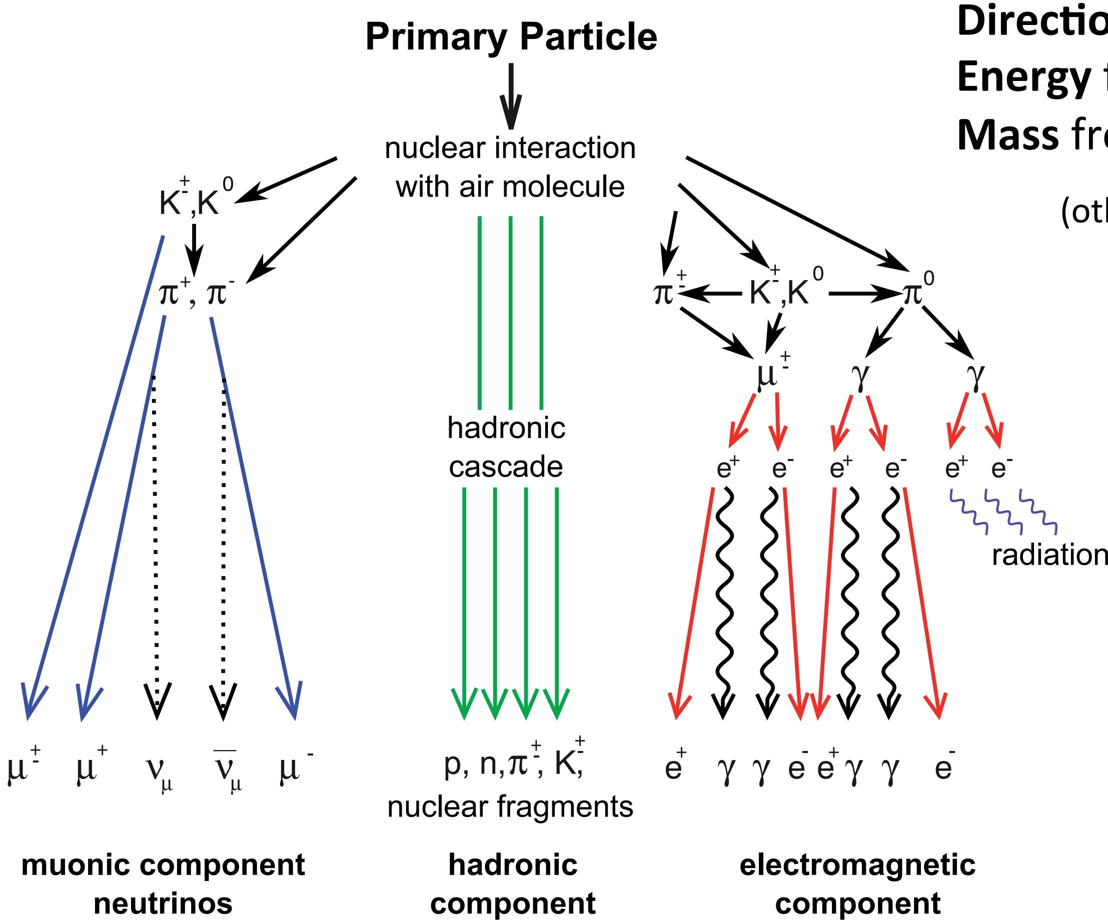


https://web.ikp.kit.edu/corsika/movies/sincpr15xz03.gif

https://web.ikp.kit.edu/corsika/movies/Movies.htm

Air shower observables

Haungs et al., JoP Conf. Ser. 632 (2015) 012011



mass proxy

energy proxy

Direction from particle arrival times

Energy from size of **eγ component**

Mass from size of **muonic component**

(other mass proxies also exist)

Muons and Mass

Iron-induced showers produce **40 % more muons** than proton-induced showers **at the same energy**

Bottleneck for a field: the mass

Test CR origin theories...

...with arrival directions

- **Strongly discriminating, if point source**
- Weakly discriminating, if anisotropy
- **No point sources found**

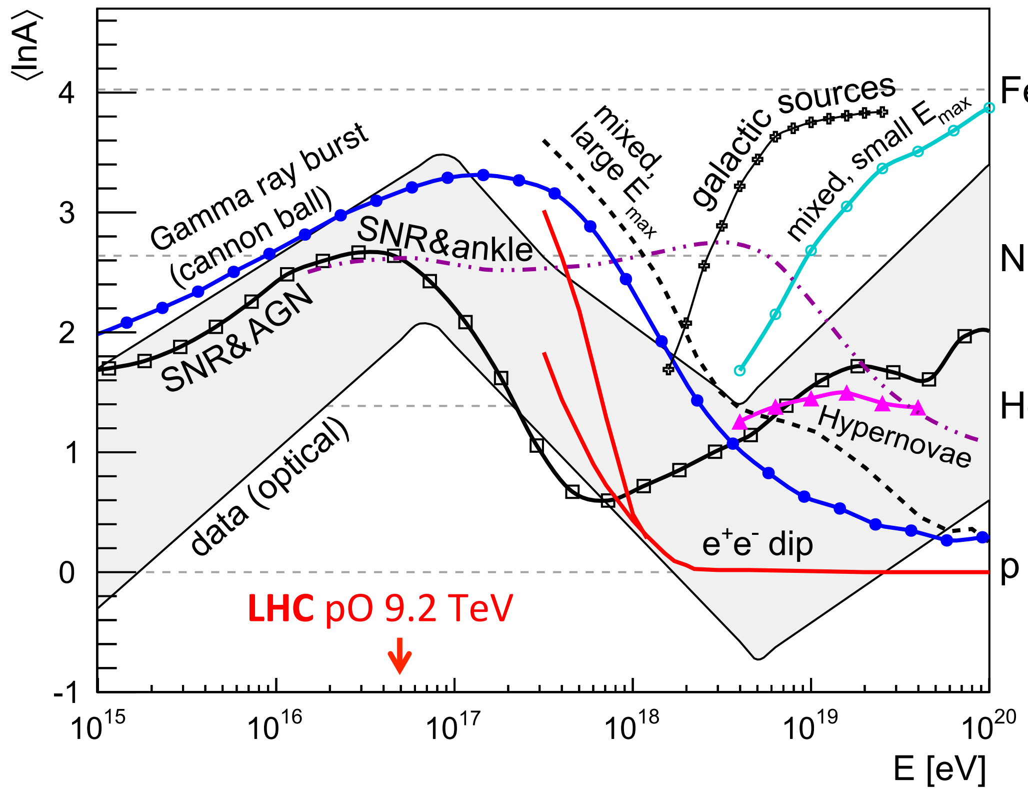
...with energy spectrum

- Weakly discriminating
- Small uncertainties

...with mass composition

- **Strongly discriminating**
- **Large uncertainties (so far)**

Adapted from: Kampert & Unger, Astropart. Phys. 35 (2012) 660–678



SNR ... Super Nova Remnant
ankle ... Feature in cosmic-ray flux

AGN ... Active Galactic Nucleus
E_{max} ... maximum energy of cosmic accelerators

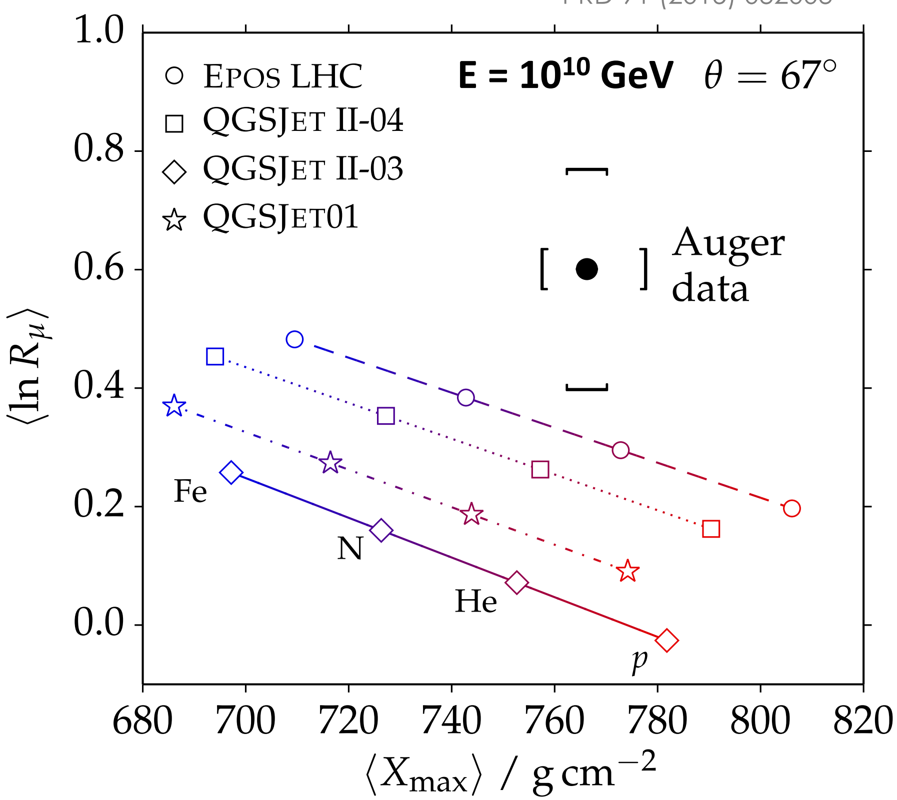
- Mass composition **differs a lot** in astrophysical theories about cosmic ray origin
- But: measurement accuracy poor, because of **uncertainties in air shower models**

Muon Puzzle

Muon number in simulated air showers inconsistent with air shower data

Pierre Auger Observatory

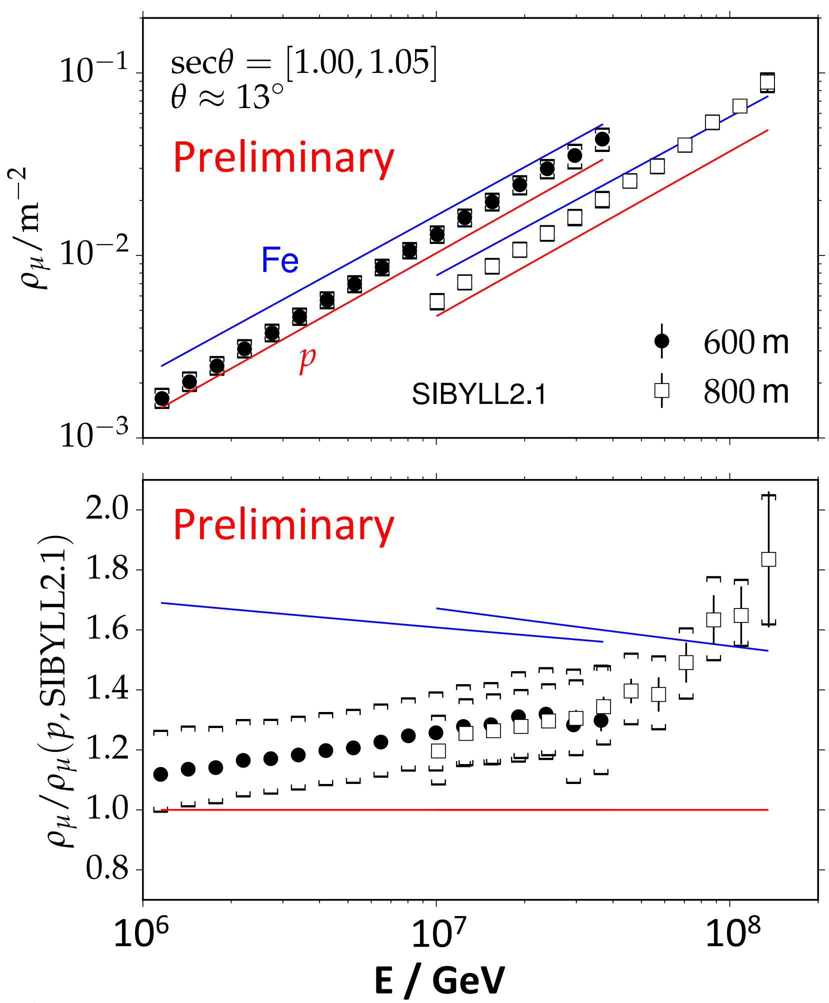
HD et al. (Auger collab.), PRD 91 (2015) 032003



Muon number in data **20 % higher** than closest model (EPOS-LHC)

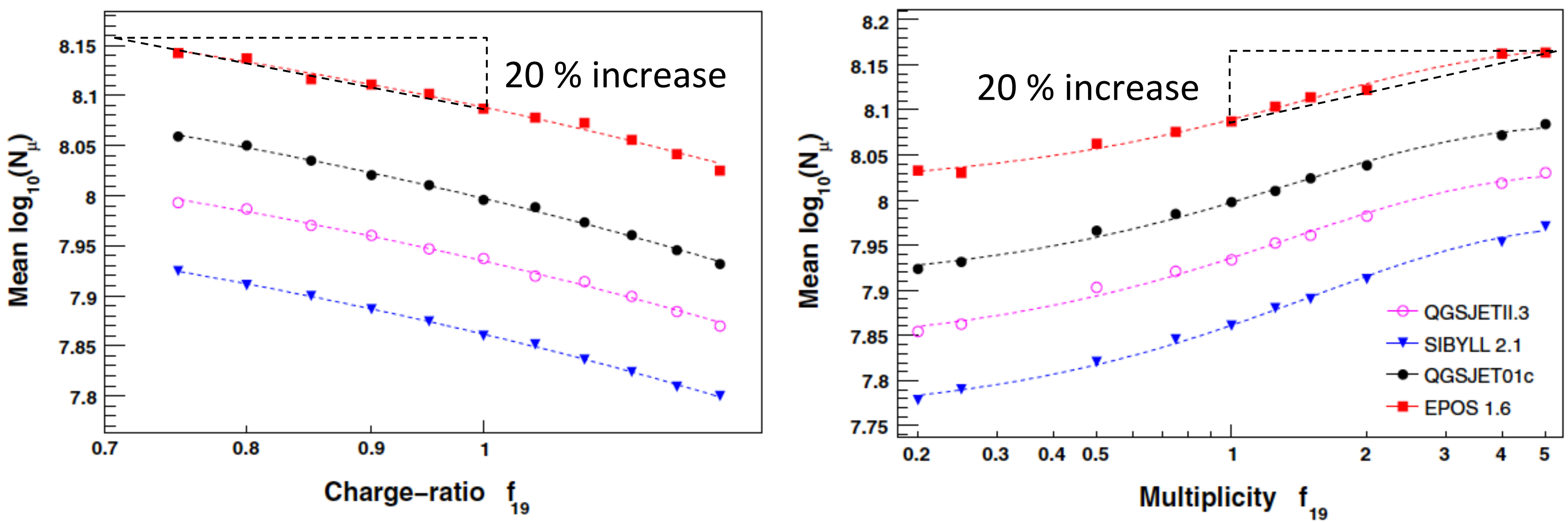
IceCube/IceTop

HD et al. (IceCube collab.), EPJ WoC 145 (2017) 01003



Air shower simulations

Ulrich et al., PRD 83 (2011) 054026

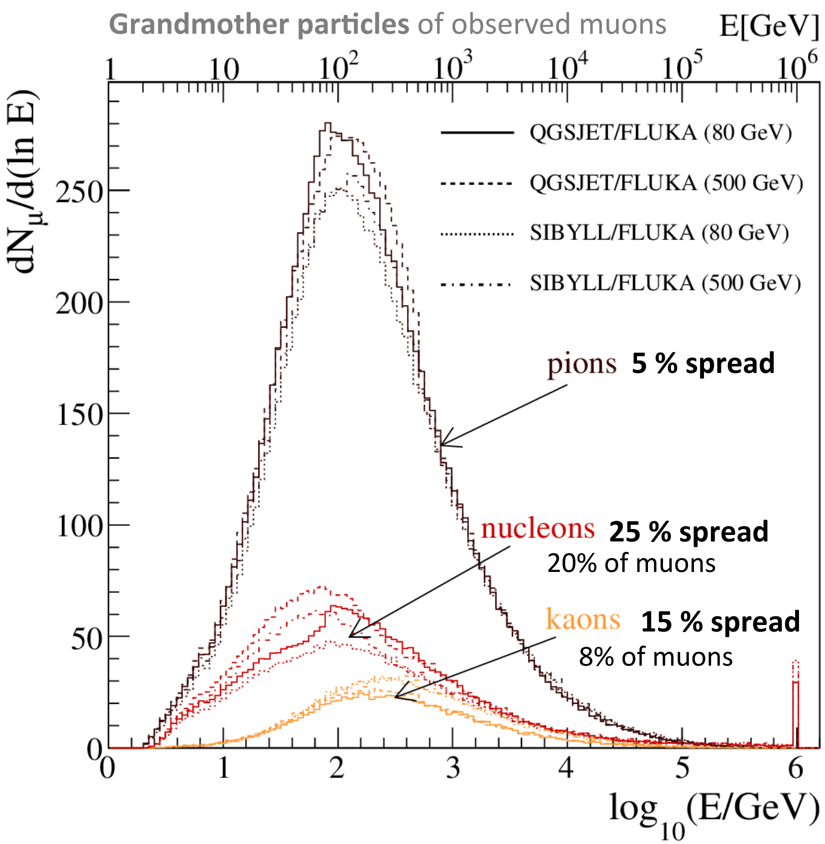


- MC study using modified hadronic interaction models
  - Hadron production properties adjusted with energy-dependent factor $\mathbf{f_{19}}$
- Muon number…
  - **very sensitive** to ratio of charged to neutral pions in forward direction
  - **sensitive** to particle multiplicity
- **Extreme changes** required to increase muon number by observed 20 %

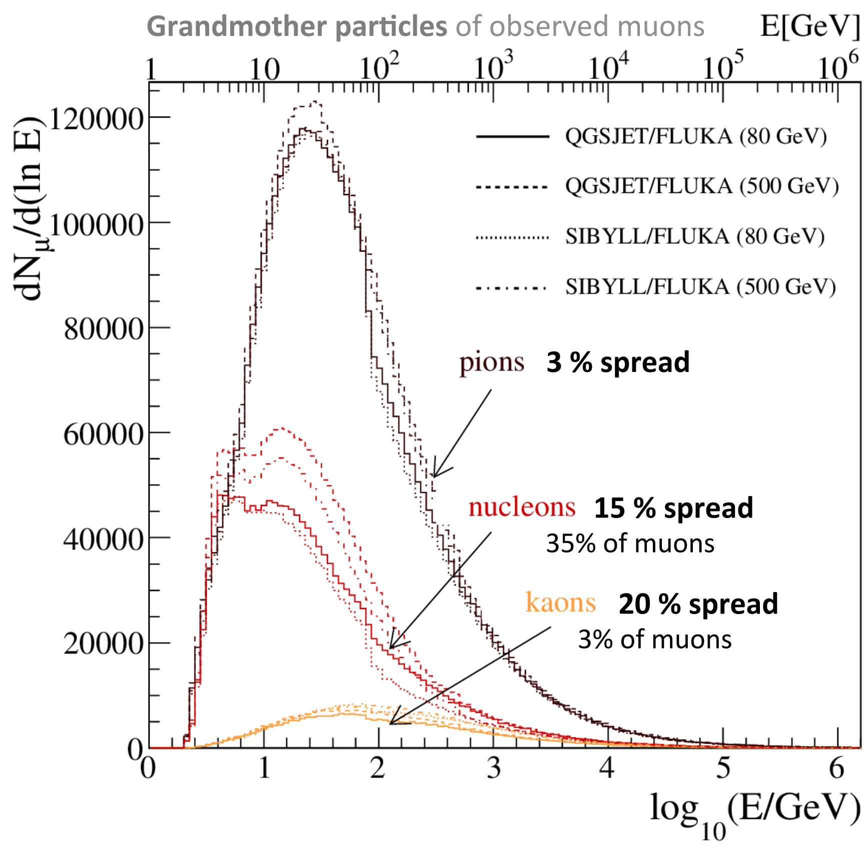
LHC: Particles to investigate

Typical muons in air shower experiments — Maris et al. (NA61 collab.) Proc. ICRC 2009, 1059

- Are of 10 – 100 GeV energies, not collimated with the shower axis, produced late in shower
- Interesting parent/grandmother particles: **pions, kaons, protons**



KASCADE: E_0 = 1 PeV, r = 20-200 m

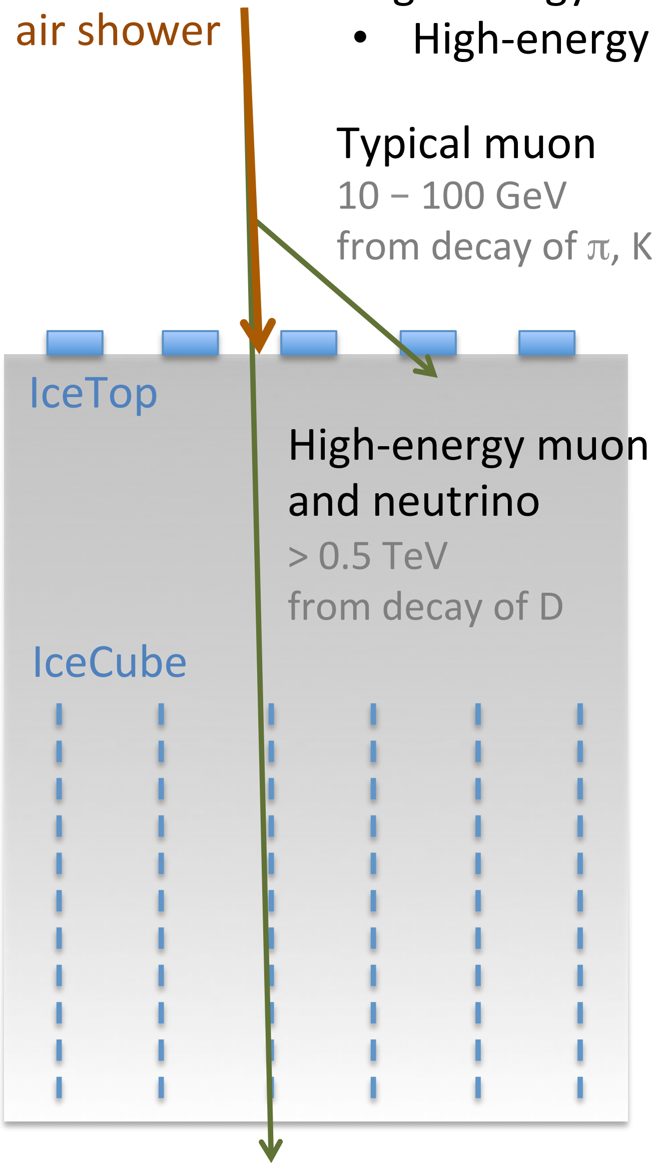


Pierre Auger, E_0 = 10 EeV, r = 1000 m

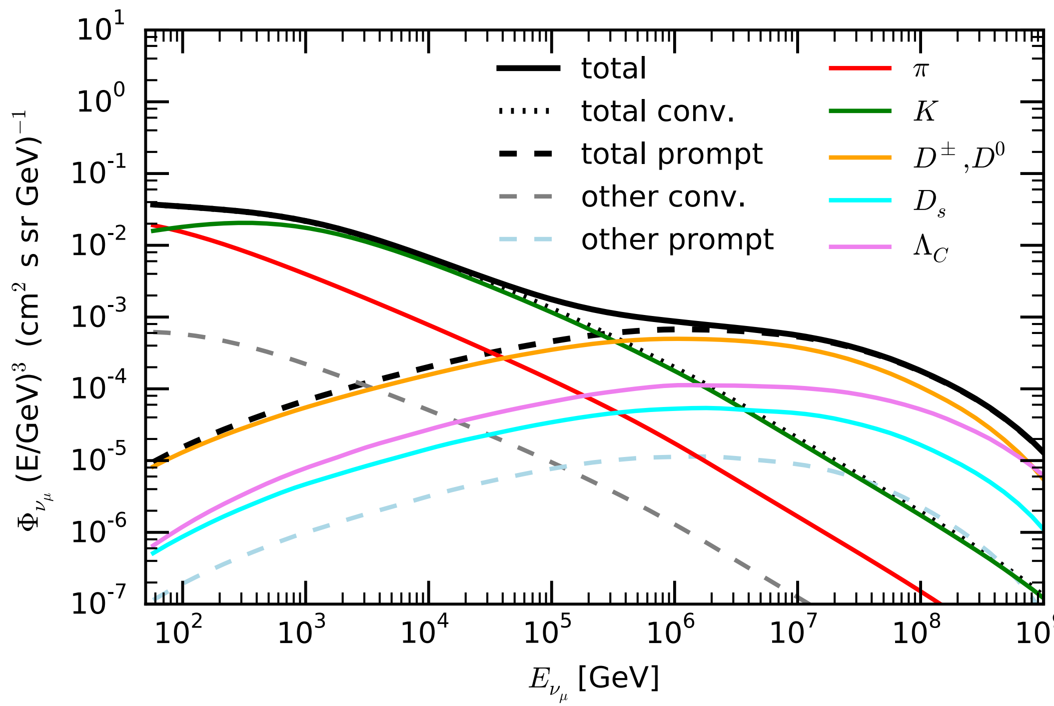
LHC: Particles to investigate

High-energy neutrinos from air showers main background for IceCube

- High-energy muon neutrino flux dominantly from **D meson** decays



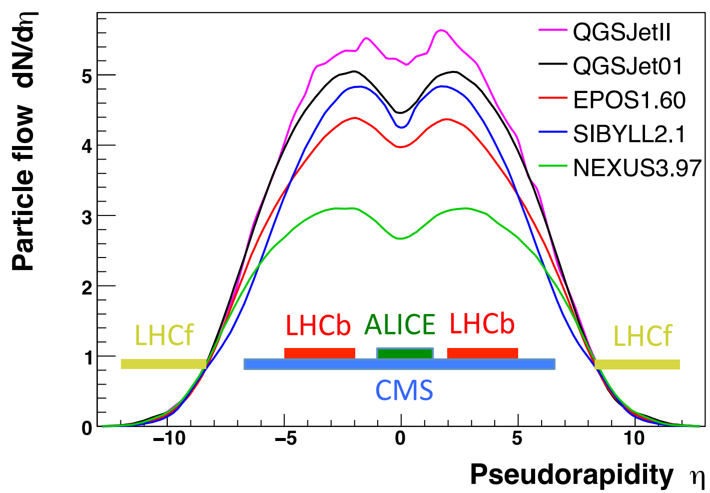
A. Fedynitch, EPJ Web Conf. 99 (2015) 08001



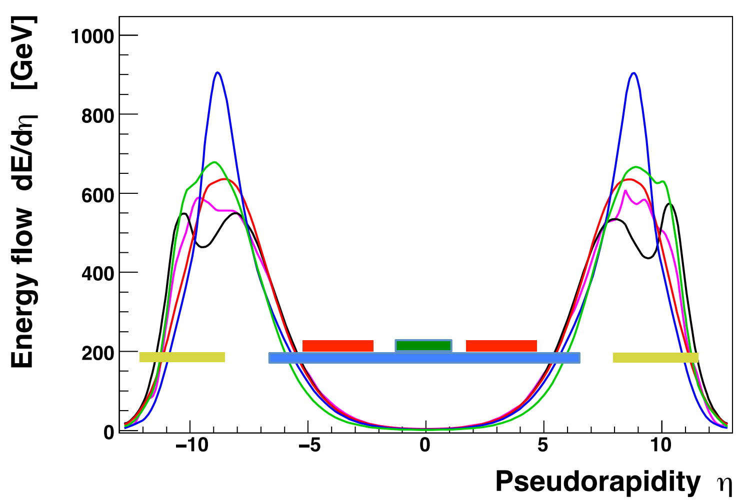
Complementarity of LHC experiments

pp @ √s = 14 TeV

Particle flow
(charged)



Energy flow
(all particles)



Exploit pO collisions with **multiple** experiments, maximize impact:

Hadron PID up to mid rapidity

- **LHCb,** ALICE

Charged spectra up to mid rapidity

- CMS+CASTOR

Inelastic cross-section

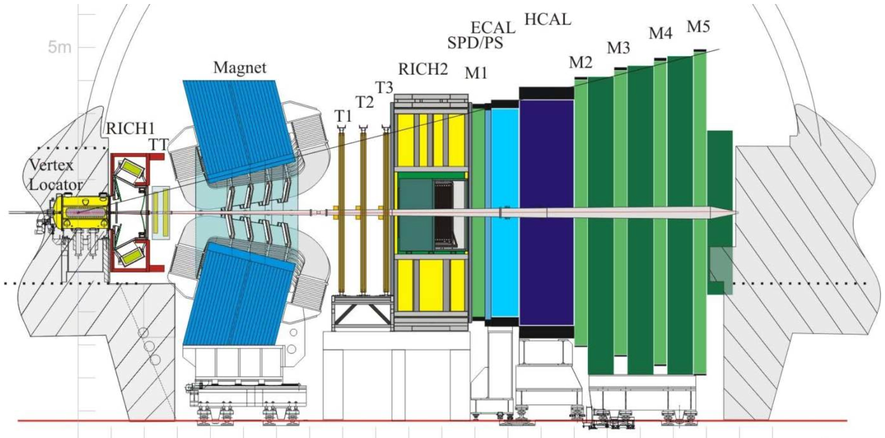
- TOTEM

Energy flow in extreme forward

- LHCf

LHCb

Only LHC detector with **hadron PID** in **forward rapidity**

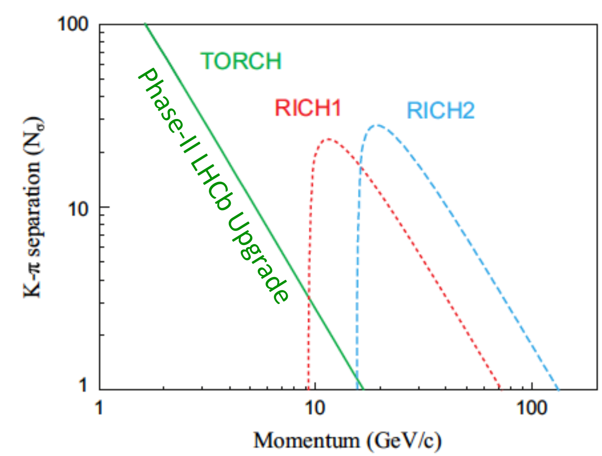


LHCb collab., JINST 3 (2008) S08005
LHCb collab., IJMP A 30 (2015) 1530022

Forward spectrometer fully instrumented in **$2 < \eta < 5$**

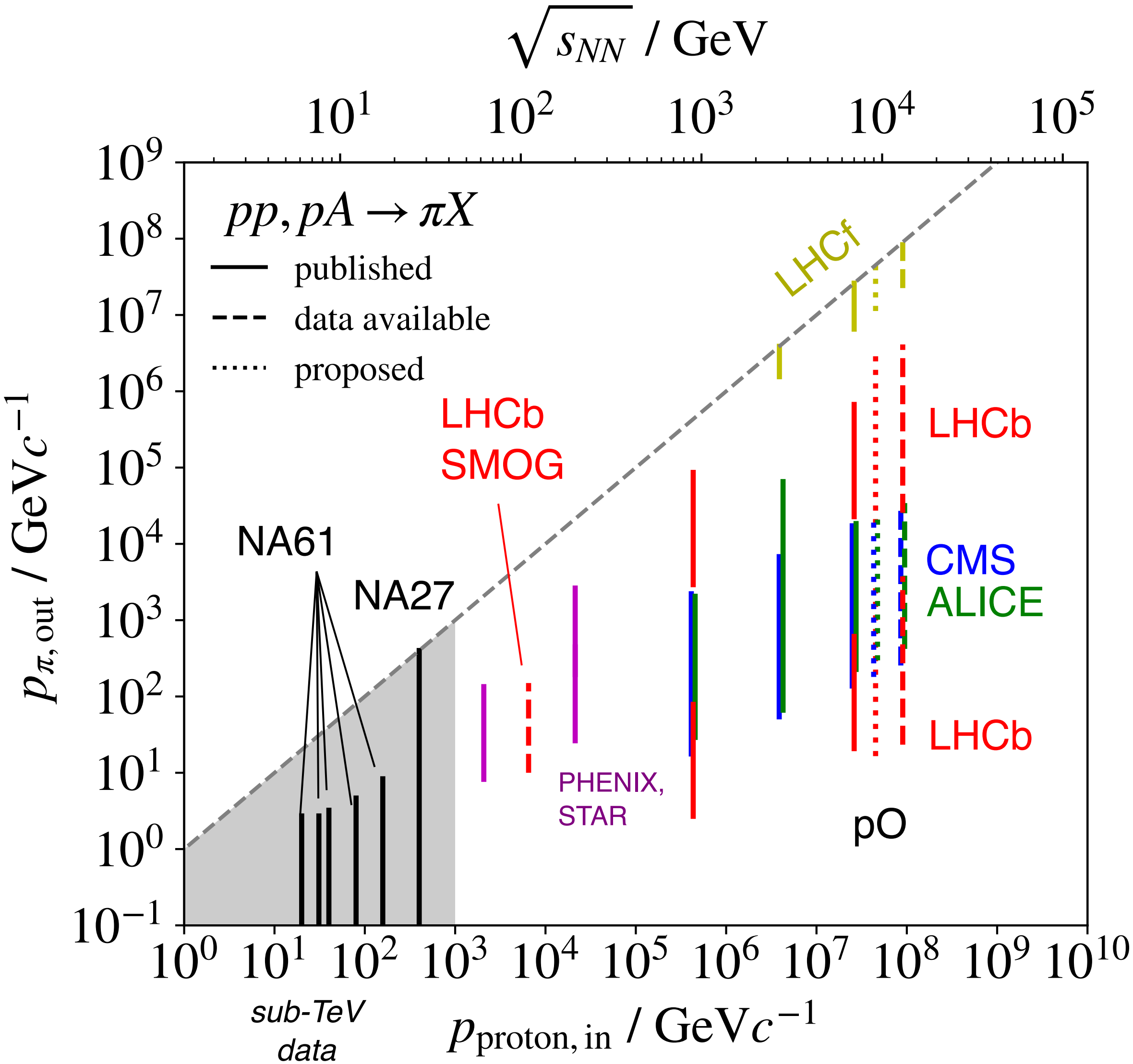
- Very good momentum and vertex resolution
  - $\delta p/p < 1$ % for $2 < p < 200$ GeV/c, $\delta x \sim 20$ μm for high p_T tracks
- **Good particle identification**
  - K: ~90 % efficiency, mis-ID < 5 %
  - μ: ~97 % efficiency, mis-ID ~ 1-3 %
- **Optimal**: μ, **p, K^{+-}, π^{+-}** produced inside Vertex Locator
- **Ok**: K^0_S, Λ^0, γ, e, π^0
- **Challenging**: stable neutral hadrons

Hadron PID (Kaon-Pion separation)



RICH: PID for p > 10 GeV/c
TORCH: proposed to extend PID to p < 10 GeV/c

Data on pion spectra

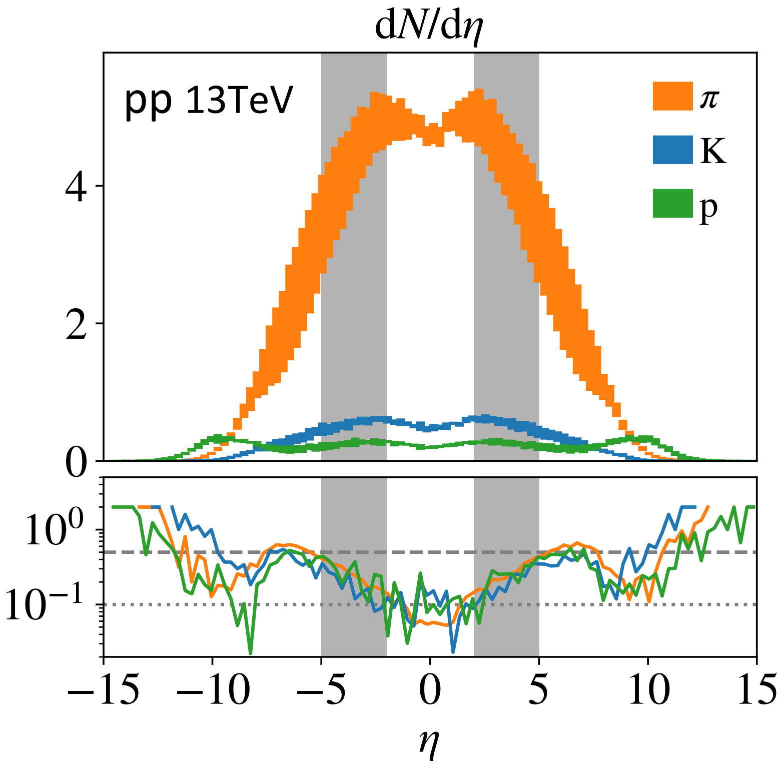


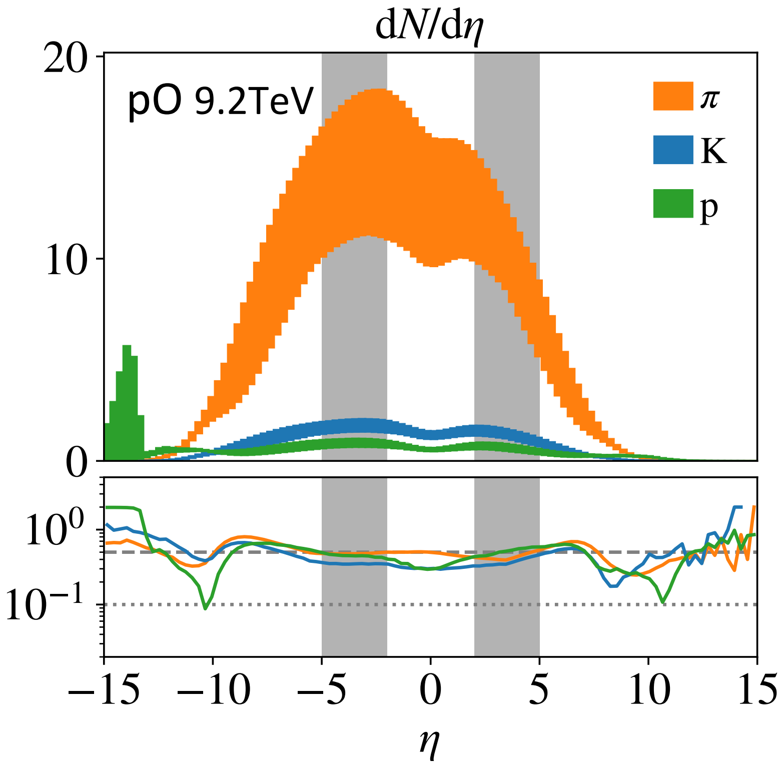
Phase space of air shower interactions as covered by various experiments
(beam-beam collisions transformed to equivalent fixed-target system)

LHCb significantly increases coverage

Why pO if we have pp?

Model spread: EPOS-LHC, QGSJet-II.04, SIBYLL-2.3 CRMC: R. Ulrich et al. https://web.ikp.kit.edu/rulrich/crmc.html





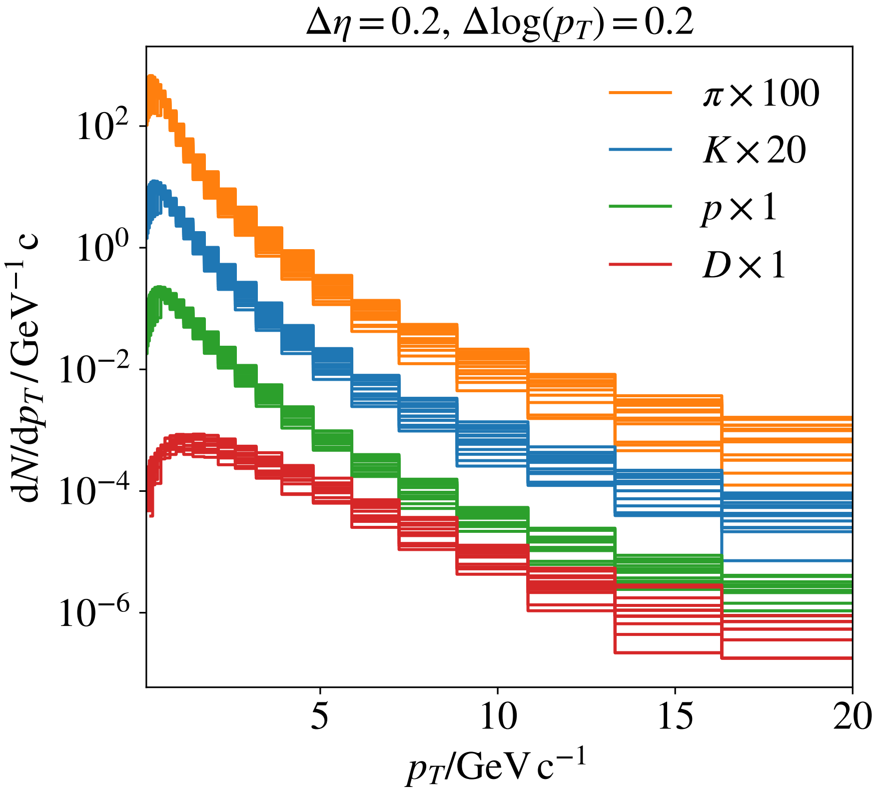
Models mostly tuned to pp data at |eta| < 1

- |eta| < 1: pp 10 % model spread, **pO 50 %** model spread
- eta = 5: **pp and pO 50 %** model spread

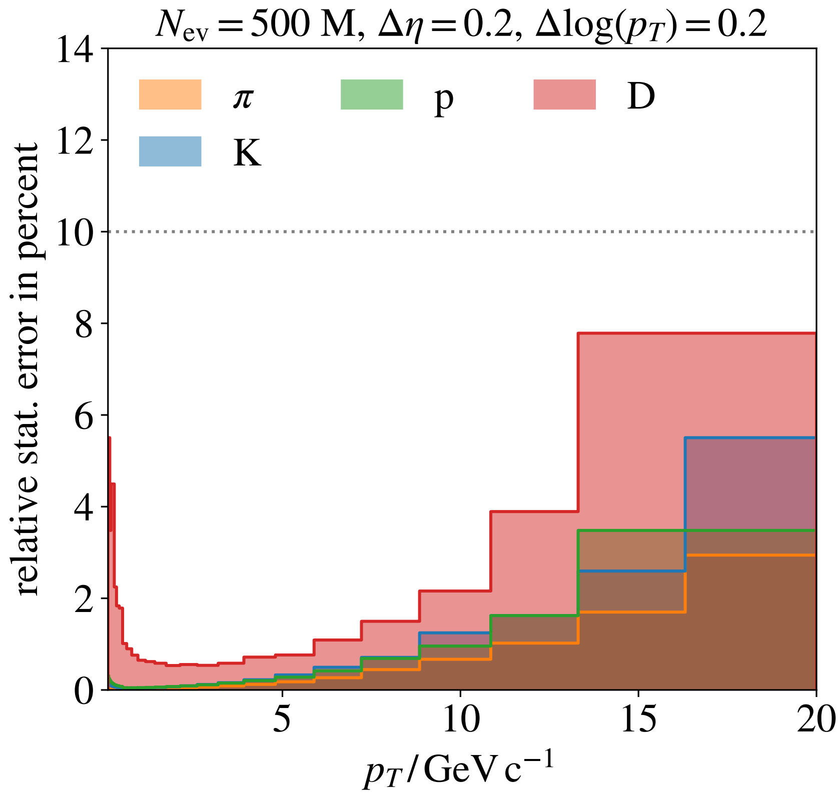
Required luminosity (LHCb)

Mix of EPOS-LHC, QGSJet-II.04, SIBYLL-2.3 CRMC: R. Ulrich et al. https://web.ikp.kit.edu/rulrich/crmc.html
LHCb acceptance: p > 10 GeV/c, 2 < eta < 5

Raw pT spectra in eta bins



Projected stat. error for **500M events**

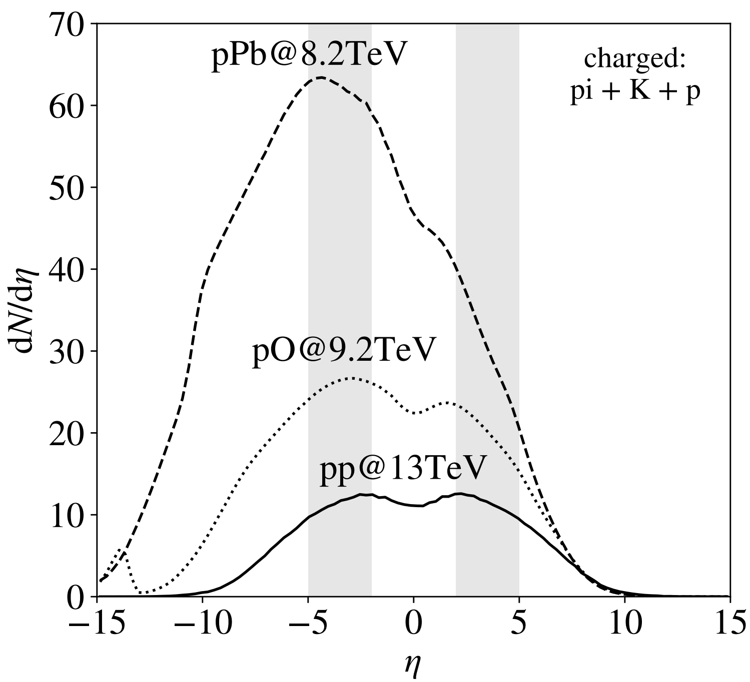


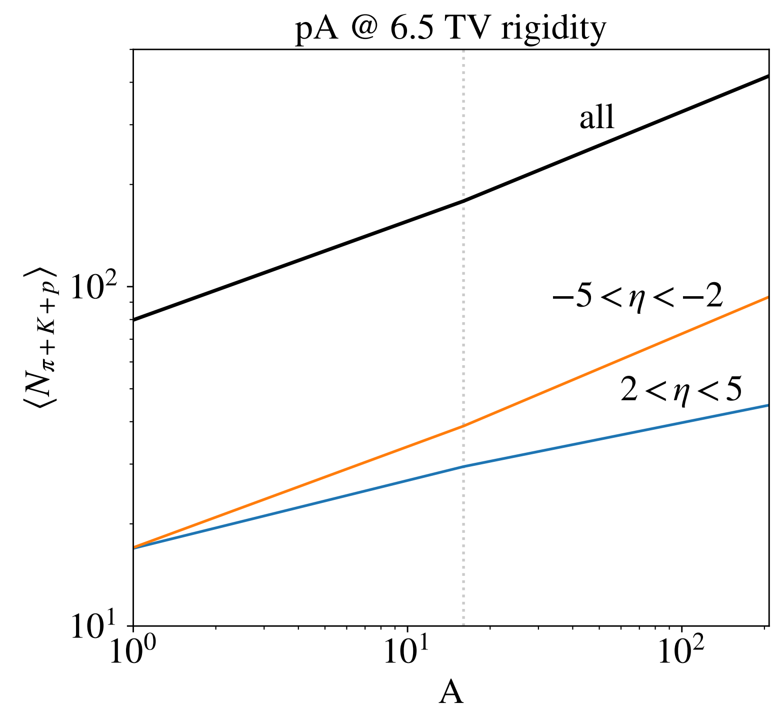
500M events (1 nb^{-1} for pO) sufficient even with fine binning in eta and pT

pO and heavy-ion physics

EPOS-LHC model

CRMC: R. Ulrich et al. https://web.ikp.kit.edu/rulrich/crmc.html





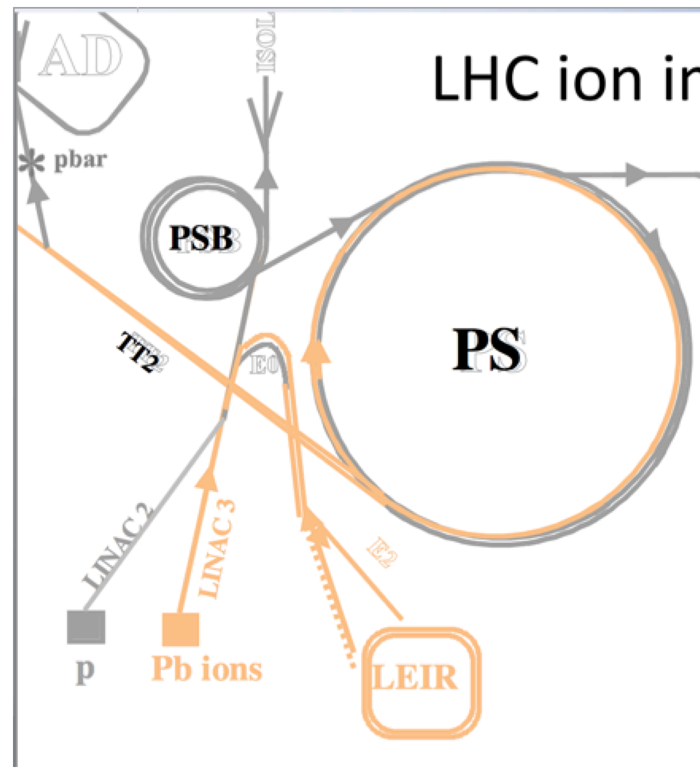
pp pO pPb

- log(Multiplicity) scales with log(A) in pA: pO intermediate system between pp and pPb
- Investigate onset of collectivity and other phenomena observed in high multiplicity events

Feasibility of pO collisions at LHC

- Initial study by D. Mangluki in 2012
  - CERN can provide light nucleon beams
  - Collisions can be pA and AA
- ECR source can "deliver anything", but takes time to commission the whole chain (LEIR/PS/SPS)
  - Oxygen already support gas for lead
- Required luminosity 1 nb^{-1} can be acquired in a short time
- Strong support from cosmic ray community at this year's Int. Cosmic Ray Conference
  Karl-Heinz Kampert, Tanguy Pierog, Ralph Engel, Anatoli Fedynitch...

A. de Roeck, highlight talk, ICRC 2017

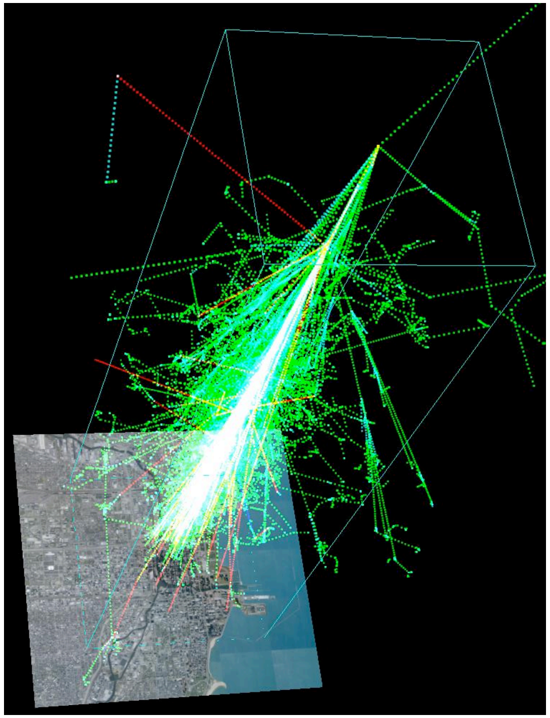


Interesting facts about the ECR source: http://alicematters.web.cern.ch/?q=DetlefKuchler

Summary

- Why pO?
  - **Cosmic rays** (nuclei, proton to iron) interact with Earth's atmosphere and produce **air showers**
  - pO collisions at LHC reproduce **first interaction** in **50 000 TeV cosmic ray**
  - Experiments rely on **accurate simulation** of air showers; **goal: 10 % model spread**
  - Only data on pp at these energies, no data on pO; **50 % model spread**
  - What about HeO ... FeO? HeO ... FeO predictions relative to pO seem ok, pO can fix all!

- What to measure?
  - **π, K, p** to solve Muon Puzzle
    - Inclusive production, (eta, pT) spectra
    - Multiplicity distributions
  - **D** mesons for IceCube
    - Inclusive production, (eta, pT) spectra



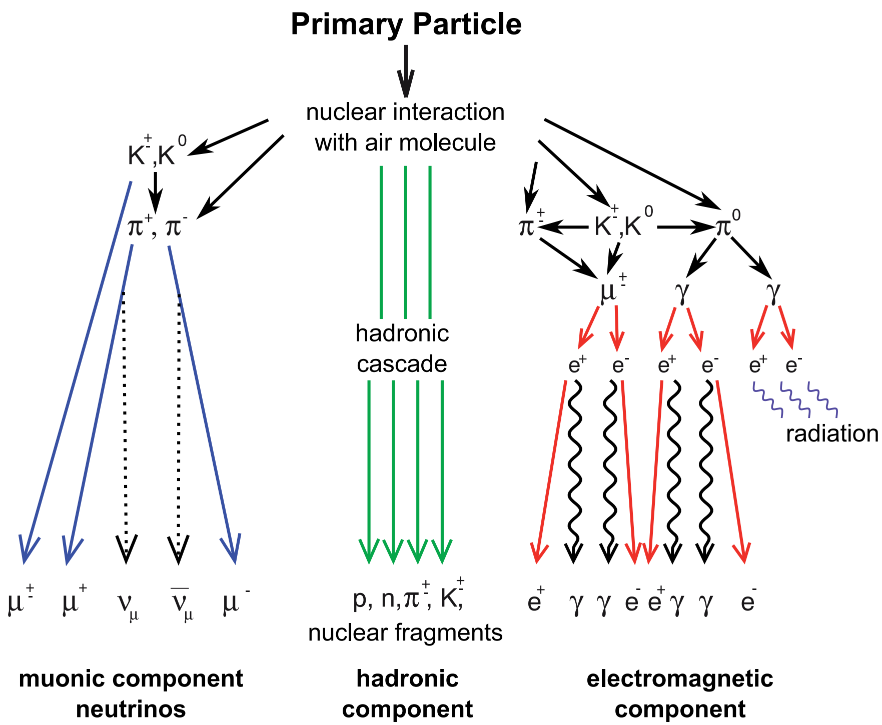
- Luminosity
  - **1 nb^{-1}** for **π, K, p, D** (500M events)

- Exploit data with multiple experiments
  - **LHCb: hadron PID for 2 < |eta| < 5**
  - ALICE: hadron PID for |eta| < 1
  - LHCf: gammas and neutrons for |eta| > 8.4
  - TOTEM: total inelastic cross-section
  - CMS+CASTOR: charged spectra |eta| < 6.6

BACKUP

Air showers and arrays

Haungs et al., JoP Conf. Ser. 632 (2015) 012011



mass proxy

energy proxy

Energy from size of **eγ component**

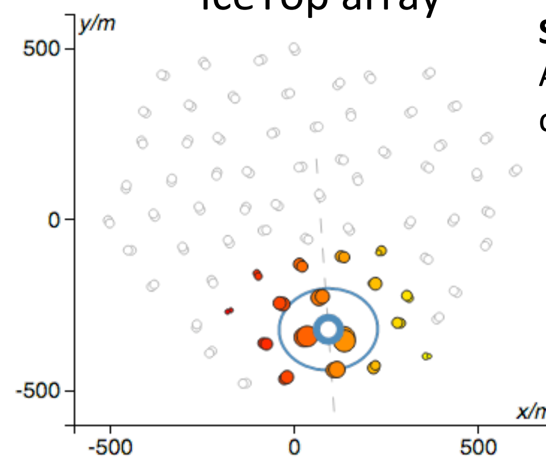
Mass from size of **muonic component**

(other mass proxies also exist)

HD et al. (IceCube collab.), PoS(ICRC2015)576

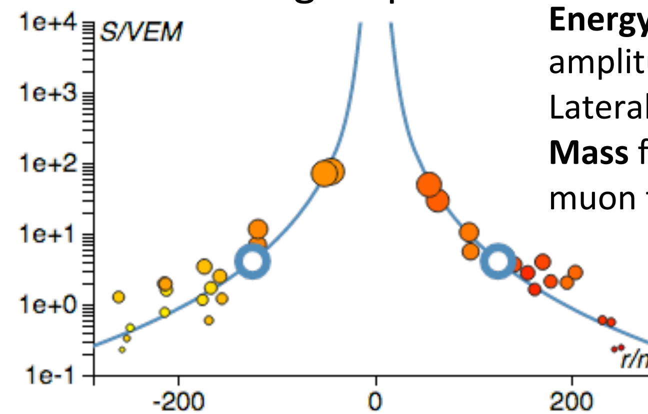
http://icecube.wisc.edu/viewer/icetop

IceTop array



Shower axis from Arrival times and core position

Lateral signal profile

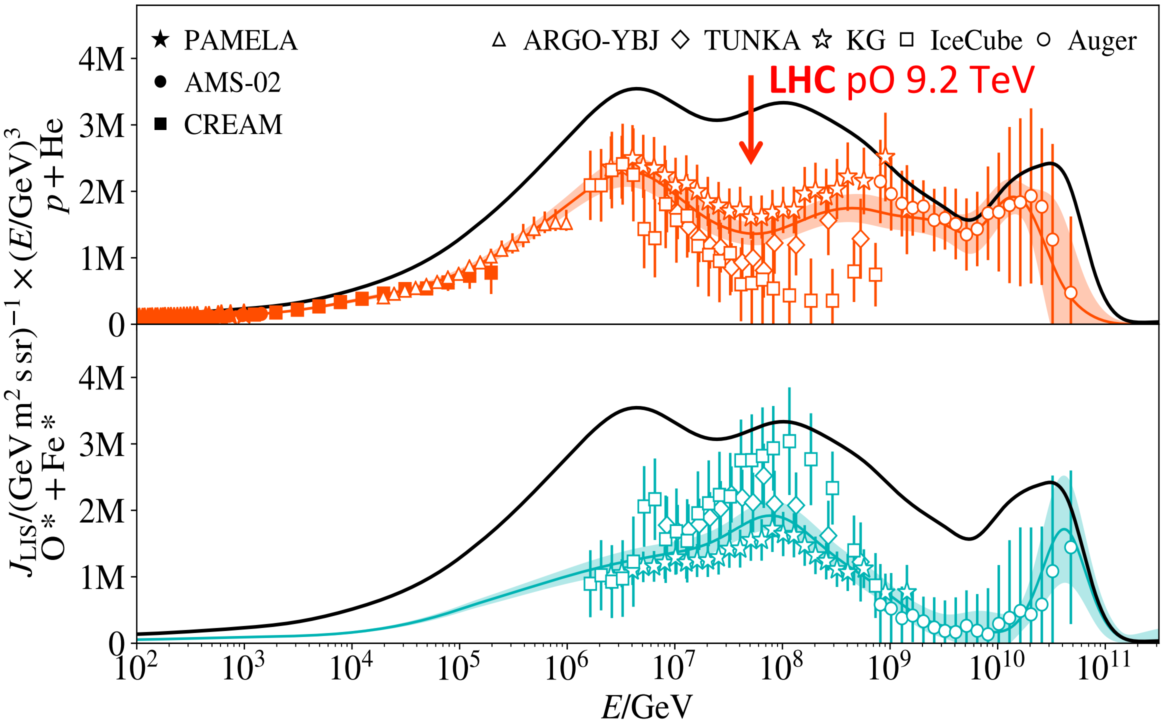


Energy from amplitude of Lateral signal profile

Mass from muon fraction

Mass uncertainty

HD et al., PoS(ICRC2017)533

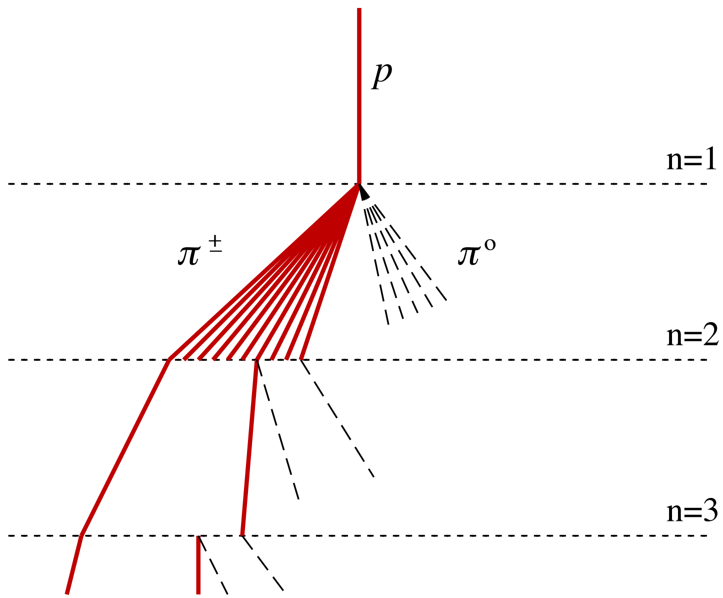


- **Mass** inferred from number of muons
  - Relationship **muons <-> mass** taken from **air shower simulations**
  - Uncertainties of air shower simulations dominated by soft-QCD physics
  - Only phenomenological models (EPOS, ...), need **collider data** for tuning
  - Inferred cosmic-ray mass composition limited by **model accuracy**

- **pO runs:** lab measurement of first interaction in a **5x10^7 GeV air shower**

Matthews-Heitler model of air shower

Matthews, Astropart.Phys. 22 (2005) 387-397



- Only pions produced: $N_{ch} + N_0$
- Charged pions interact if $E_\pi > \xi_c^\pi$

  ξ_c^π *... critical energy*
- No. of muons = No. of charged pions at *critical energy*

$$E_\pi \stackrel{!}{=} \xi_c^\pi \rightarrow n_c = \frac{\ln[E_0/\xi_c^\pi]}{\ln[N_{ch} + N_0]}$$

n_c ... cascade steps until decay to muons, typical 4 to 5

$$N_\mu = {N_{ch}}^{n_c} = \left(\frac{E_0}{\xi_c^\pi}\right)^{\overbrace{\frac{\ln[N_{ch}]}{\ln[N_{ch}+N_0]}}^{\beta}}$$

No. of muons very sensitive to **"energy loss"** from neutral pions

Muons and Mass $N_\mu(E, A) \stackrel{\text{superposition model}}{=} A\, N_\mu\left(\frac{E}{A}, 1\right) = A^{1-\beta}\, N_\mu(E, 1) \rightarrow N_\mu(\text{Fe}) \approx 1.4 N_\mu(p)$

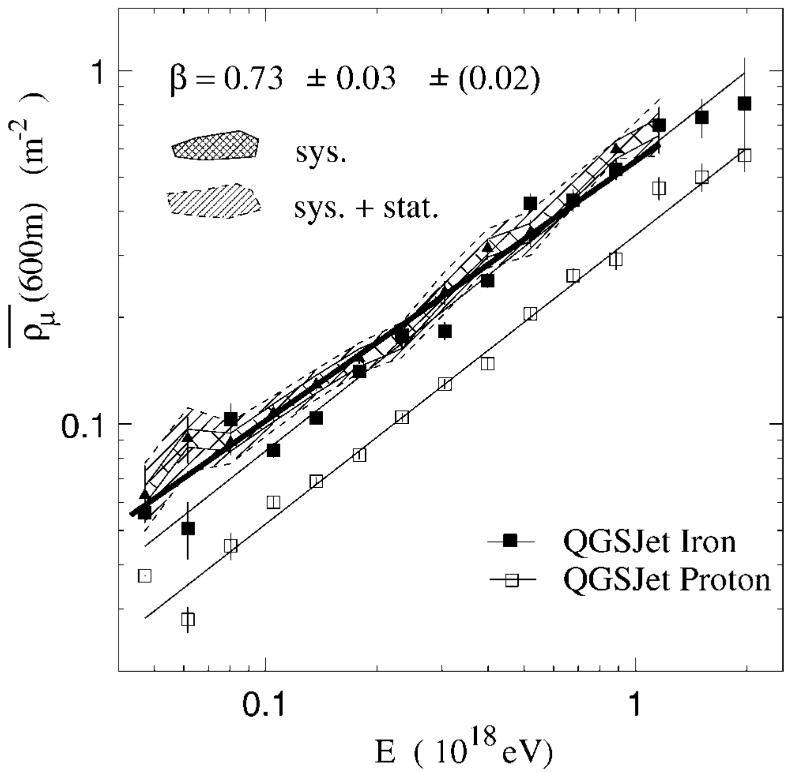
Whole shower development relevant for final **muon number**

Important properties of shower secondaries: **multiplicities, IDs, energy distribution**

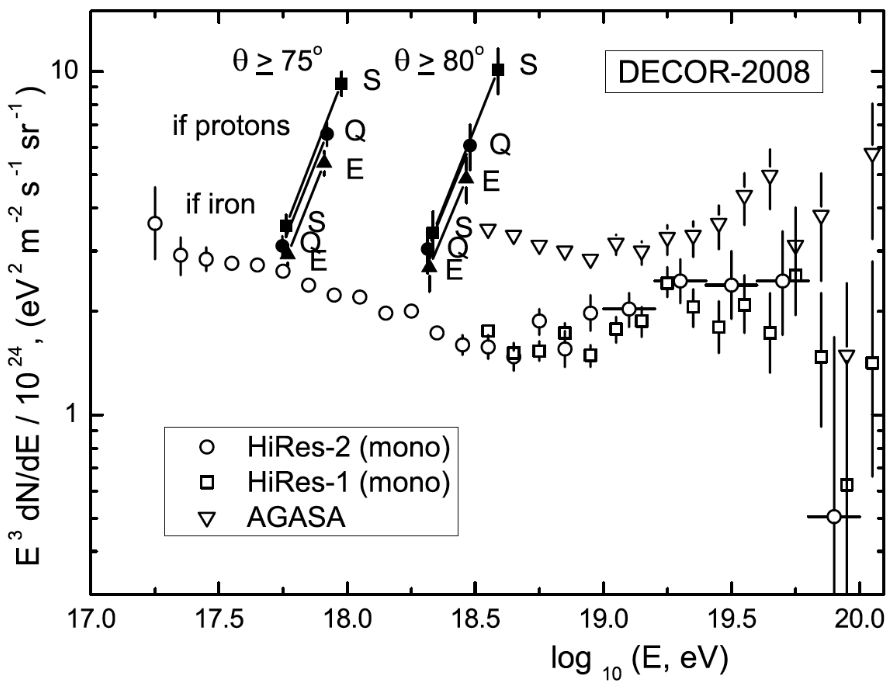
Muon Puzzle

Muon number in simulated air showers inconsistent with data

HiRes-MIA collab. PRL 84, no. 19 (2000) 4276



Kokoulin et al. Nucl. Phys. B Proc. Suppl. 196 (2009) 106

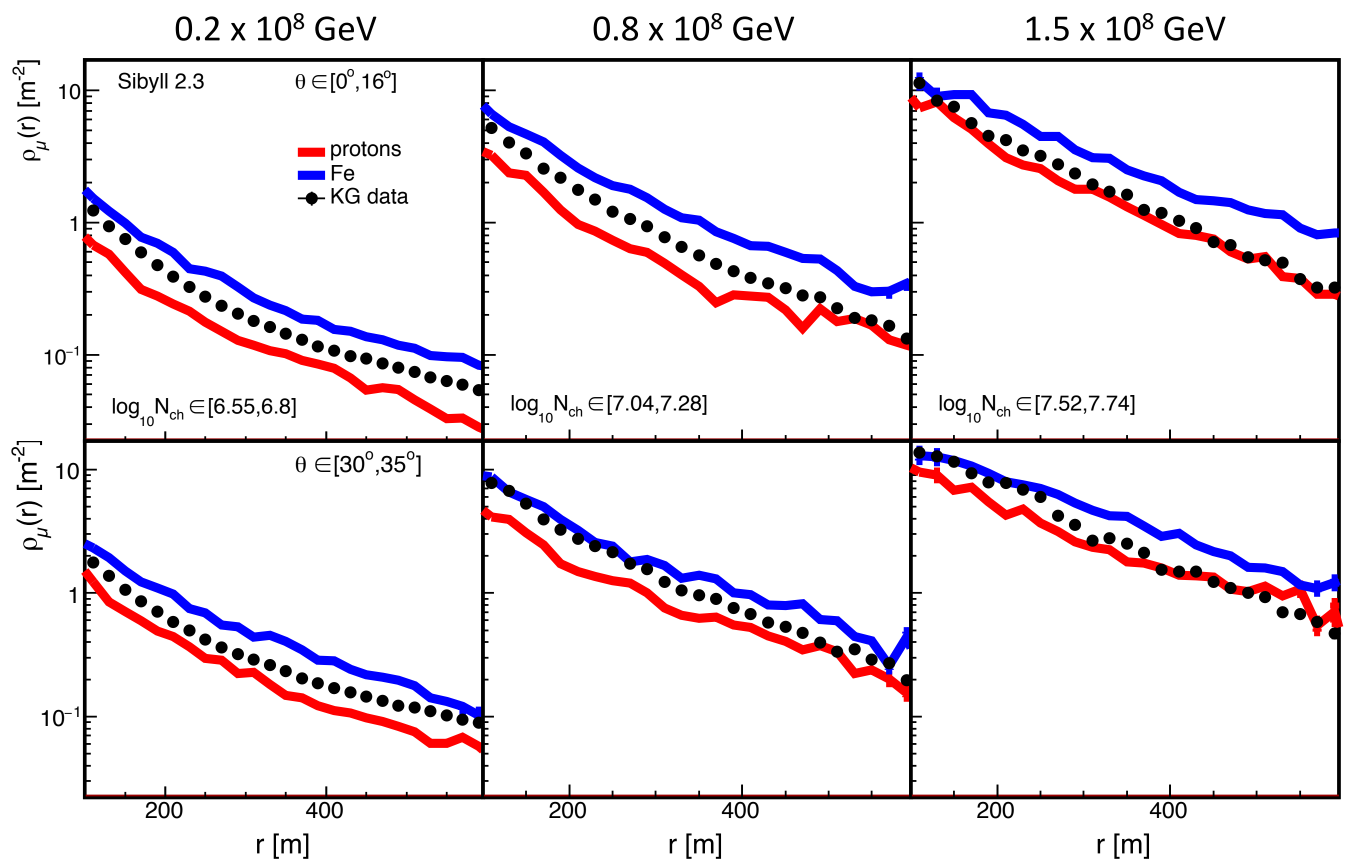


- Muon Puzzle confirmed by several experiments at small and large zenith angles
- Discrepancies in **old** and **latest** models

Muon Puzzle

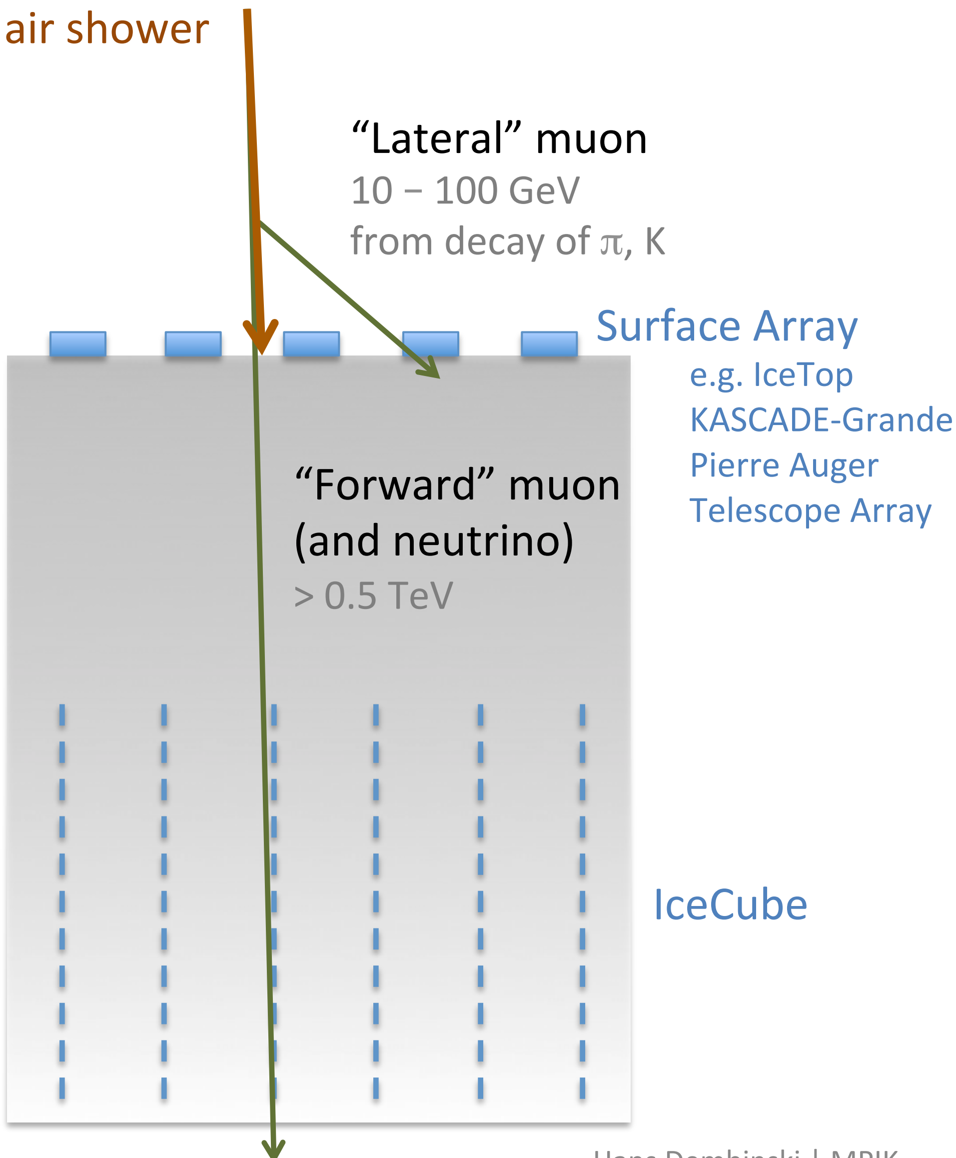
μ-LDF (Lateral Density Function) shape differs from simulations

Ateaga-Velazquez et al. (KASCADE-Grande collab.), PoS(ICRC2017)316



Discrepancy in μ-LDF larger at higher energies and near shower axis

Muon Puzzle: Particles to investigate



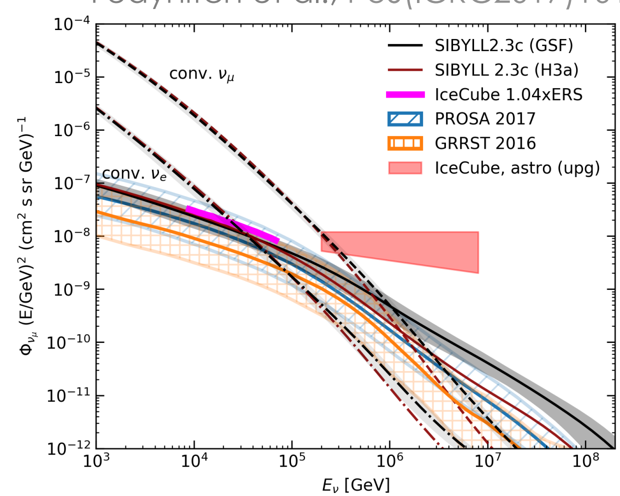
“Lateral” muons

- Air shower arrays only sensitive to lateral muons
- **Muon Puzzle** is about them

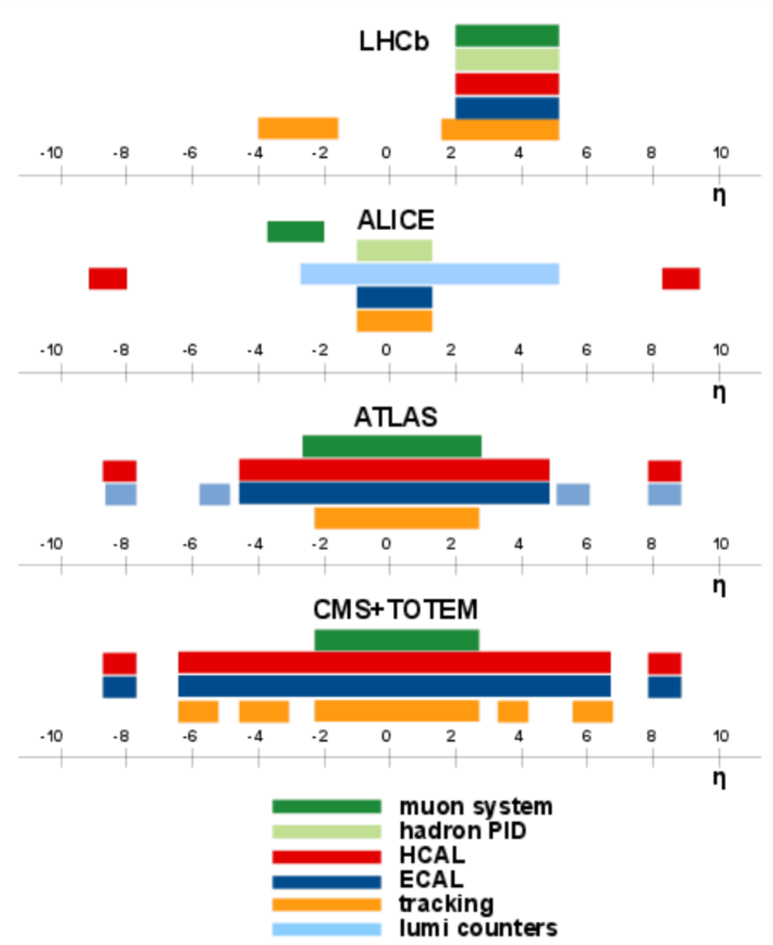
“Forward” muons

- Only IceCube is sensitive
- Forward muon neutrinos are **important background** to astrophysical neutrinos
- D mesons dominant

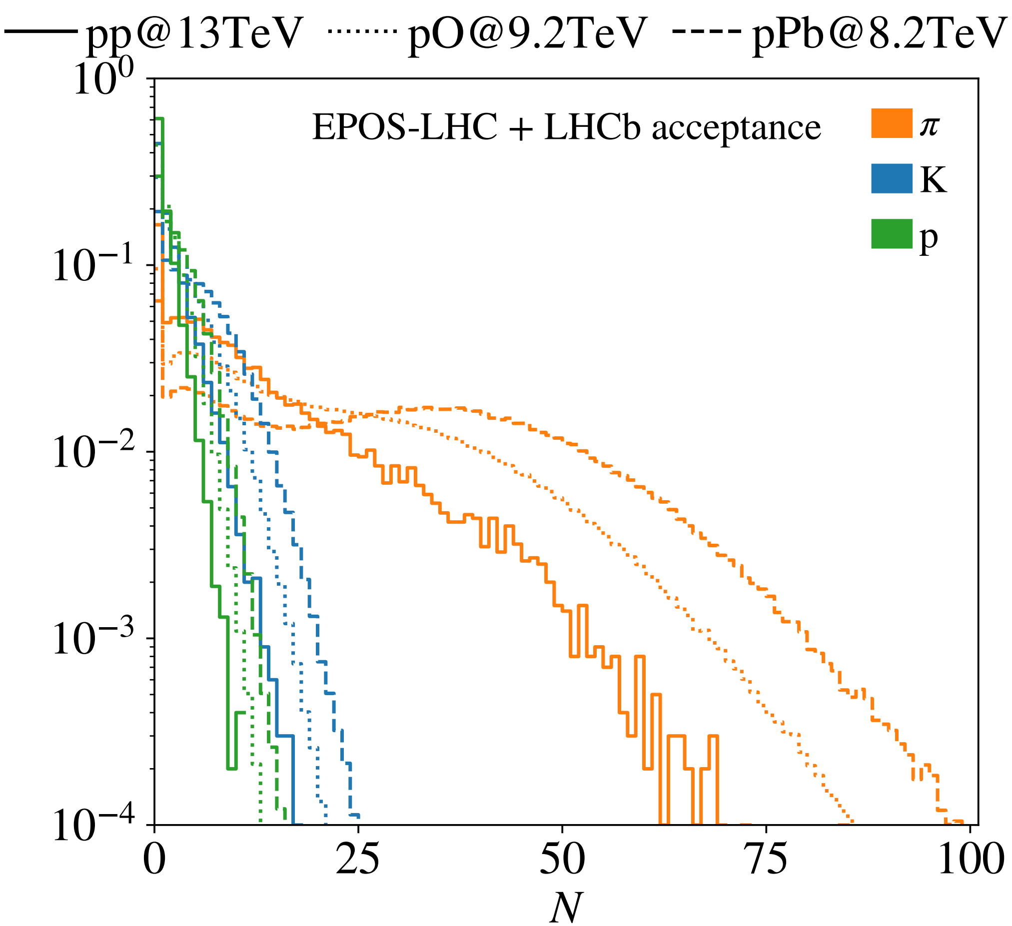
Fedynitch et al., PoS(ICRC2017)1019



LHC detectors



Multiplicities of individual particles



SMOG

pHe(gas) @ 6.5 TeV
Model spread: EPOS-LHC, QGSJet-II.04, SIBYLL-2.3