LHC and the Muon Puzzle in Extensive Air Showers

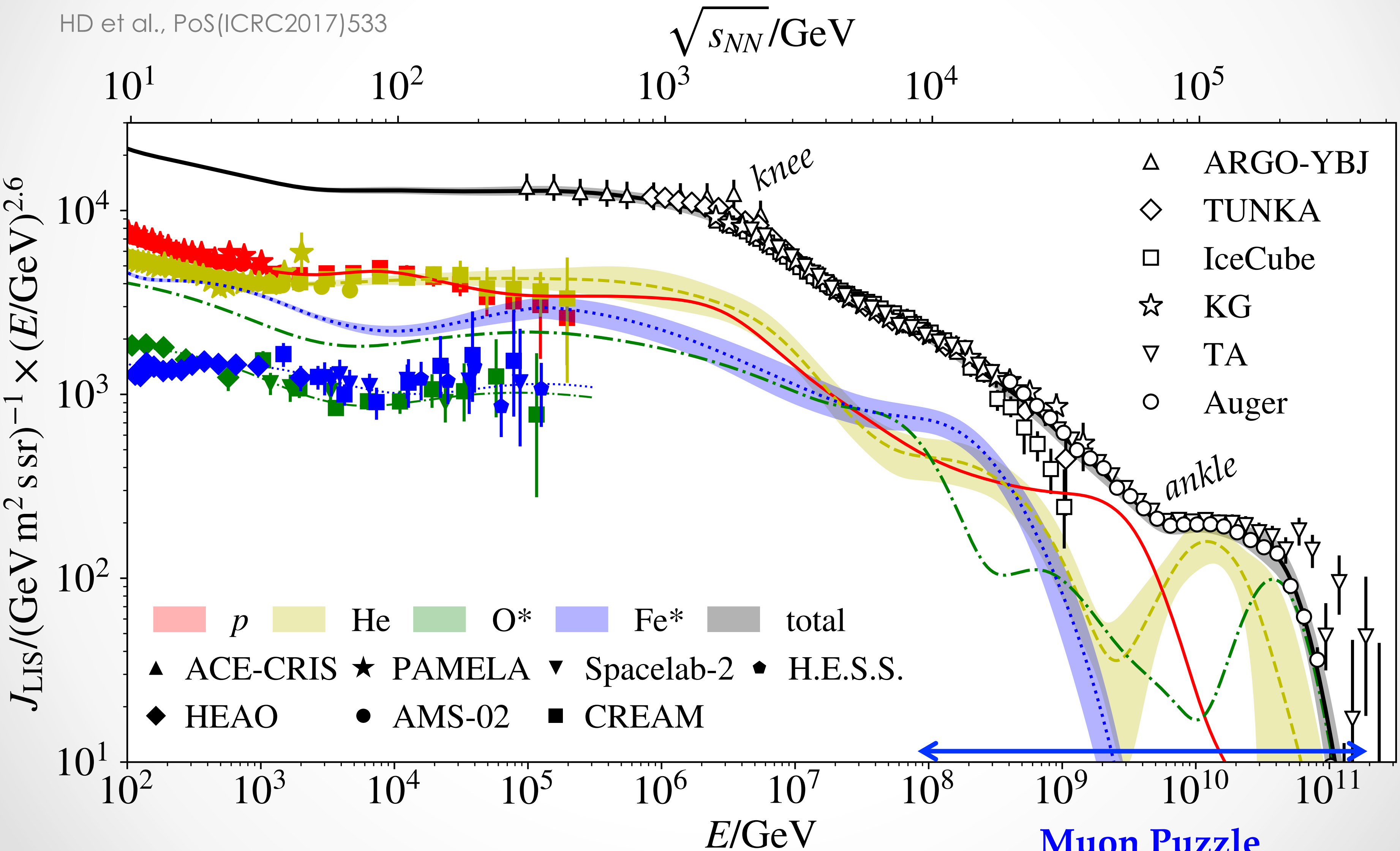
Hans Dembinski

FSP Meeting, Siegen, 5. Oct 2017

MPIK LHCb group
Michael Schmelling, HD, Tatsiana Klimkovich, Dmitry Popov,
Mikhael Zavertyaev,

Cosmic rays

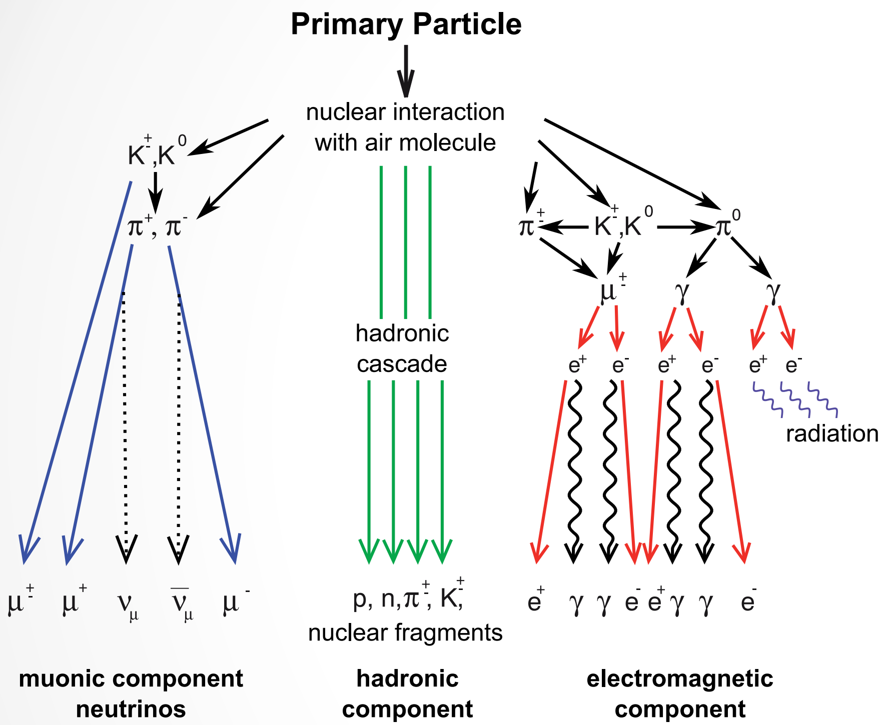
HD et al., PoS(ICRC2017)533



Muon Puzzle

Air showers in arrays

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



mass proxy

energy proxy

Energy from size of **eγ component**

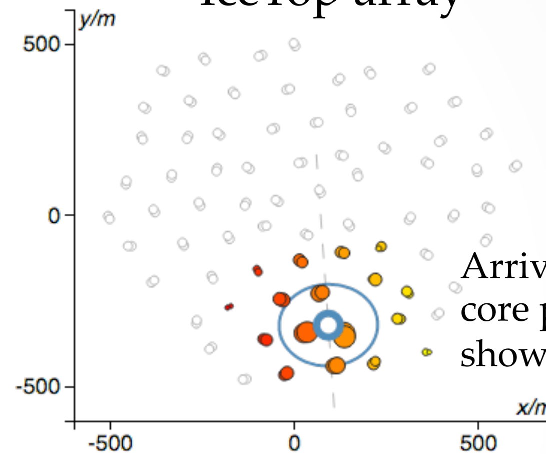
Mass from size of **muonic component**

(other mass proxies also in use, e.g. X_{max})

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

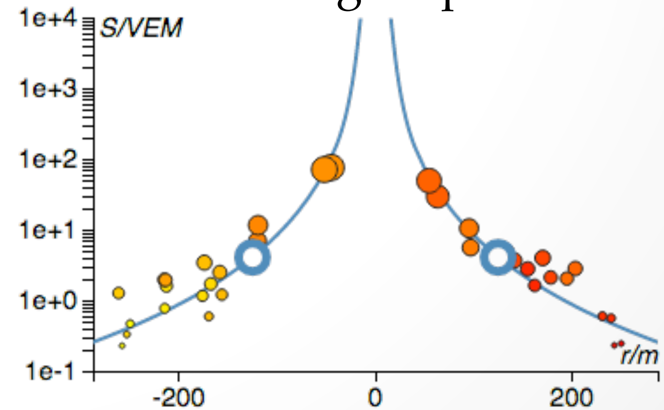
http://icecube.wisc.edu/viewer/icetop

IceTop array



Arrival times and core position: shower axis/direction

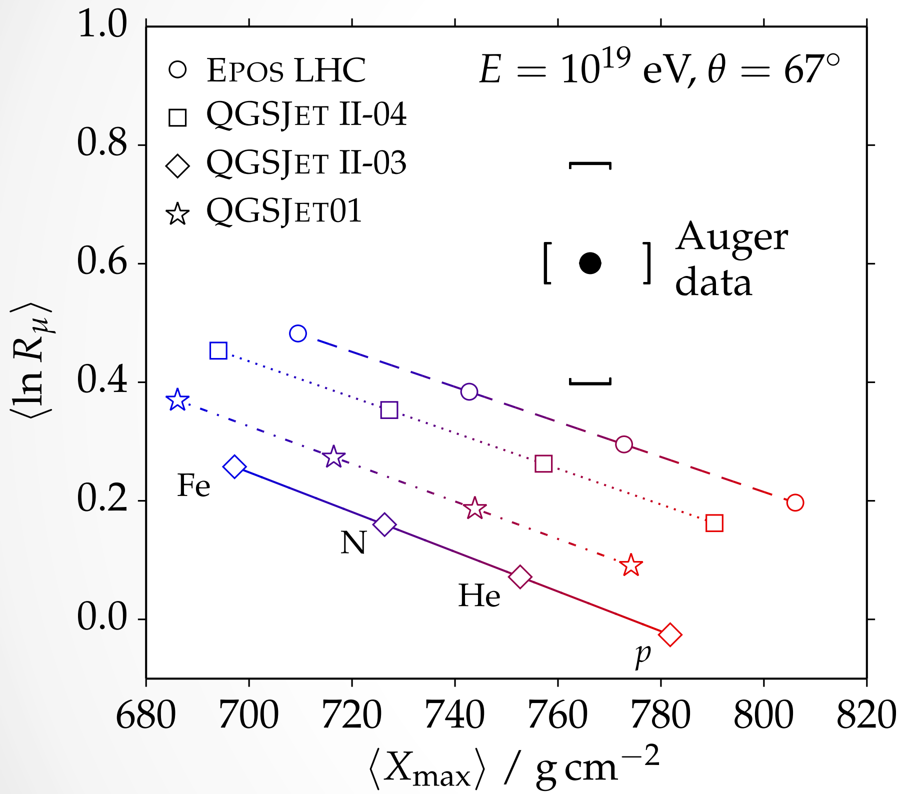
Lateral signal profile



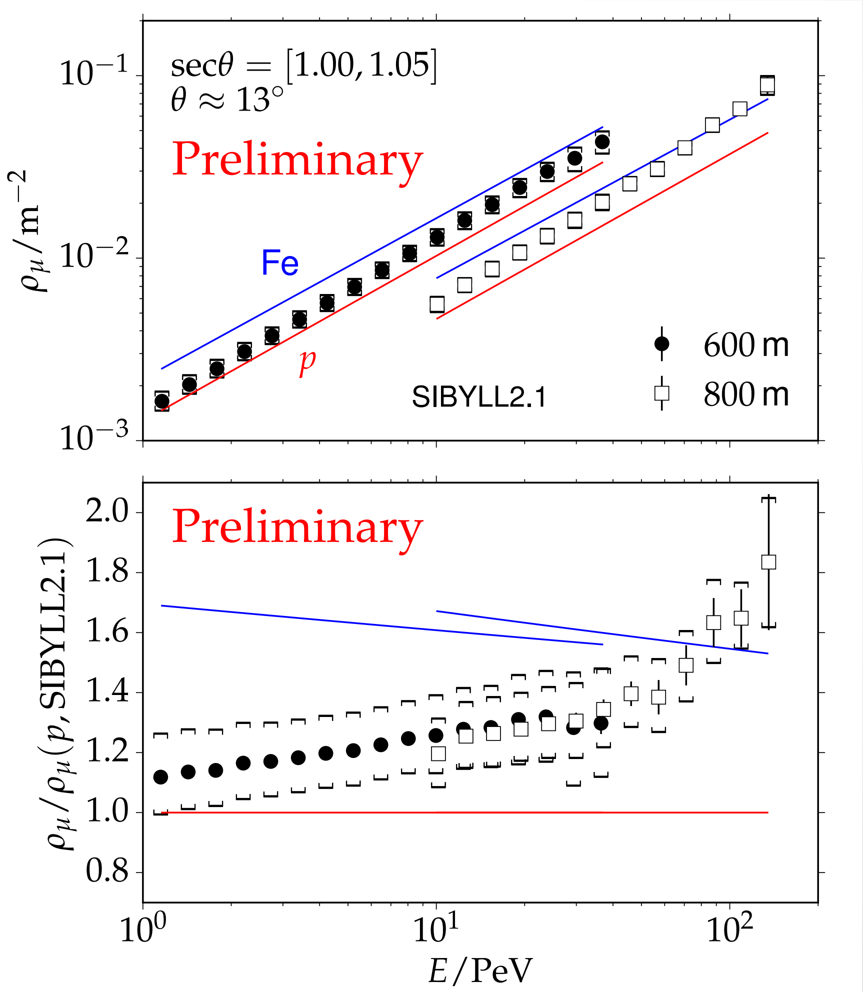
Muon Puzzle

Muon deficit in simulated air showers for cosmic rays above 10^8 GeV

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



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

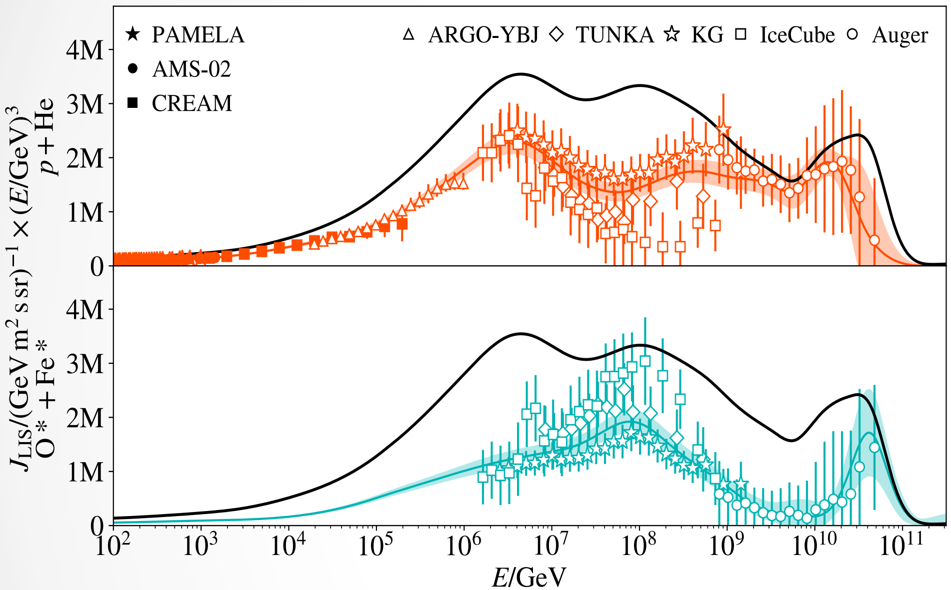


Muon number in data **20 % higher** than closest model (EPOS-LHC)

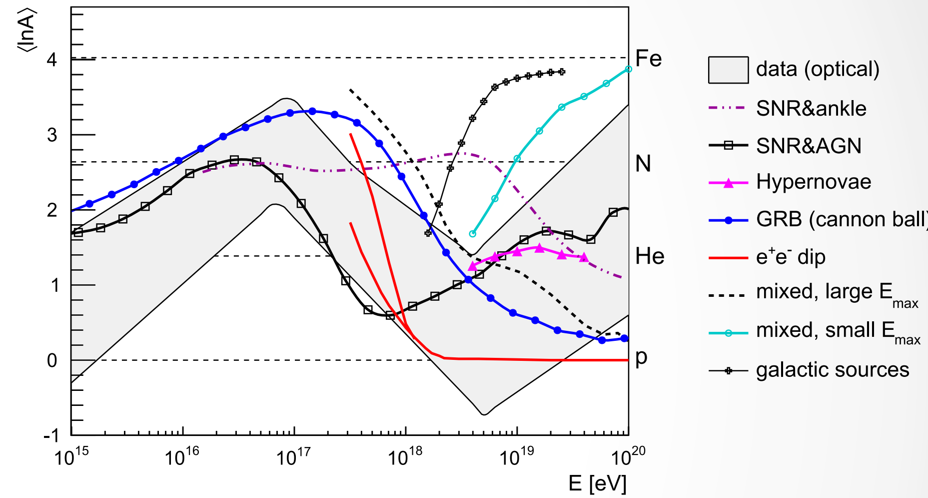
Why fix muons?

To resolve large uncertainties in cosmic-ray composition above the knee

HD et al., PoS(ICRC2017)533



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



Data **not precise enough** to exclude models (data band represents optical measurements)

Many mass composition measurements above the knee based on μ-component: IceTop/IceCube, KASCADE-Grande, Haverah Park, AGASA…

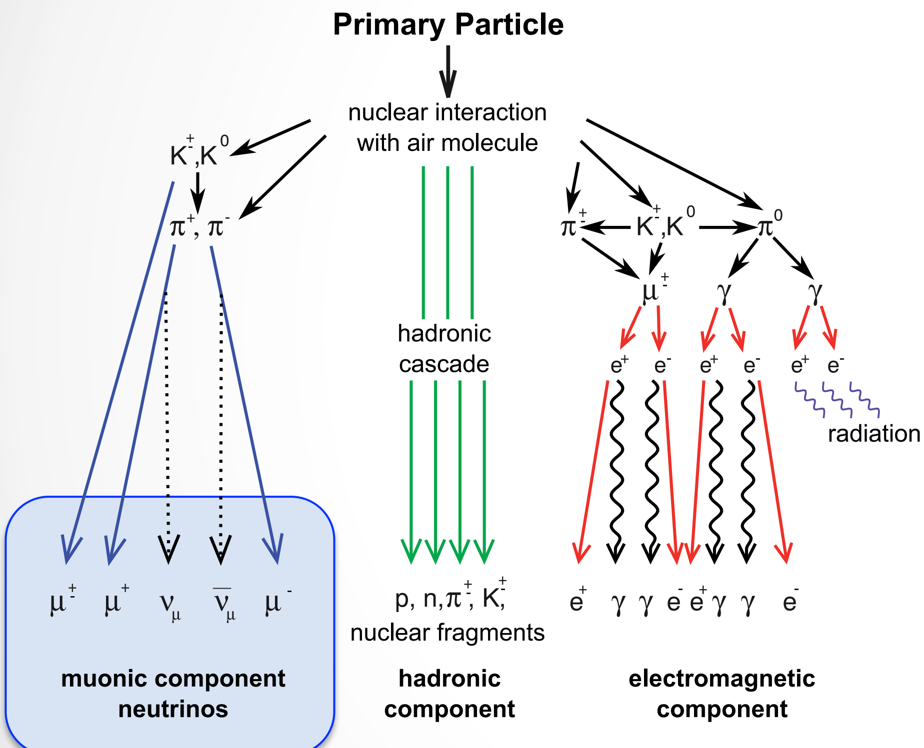
Two recent leading experiments differ above the knee, likely because of model

- IceTop/IceCube: μ-component interpreted with SIBYLL 2.1 (old)
- KASCADE-Grande: μ-component interpreted with EPOS-LHC (new)

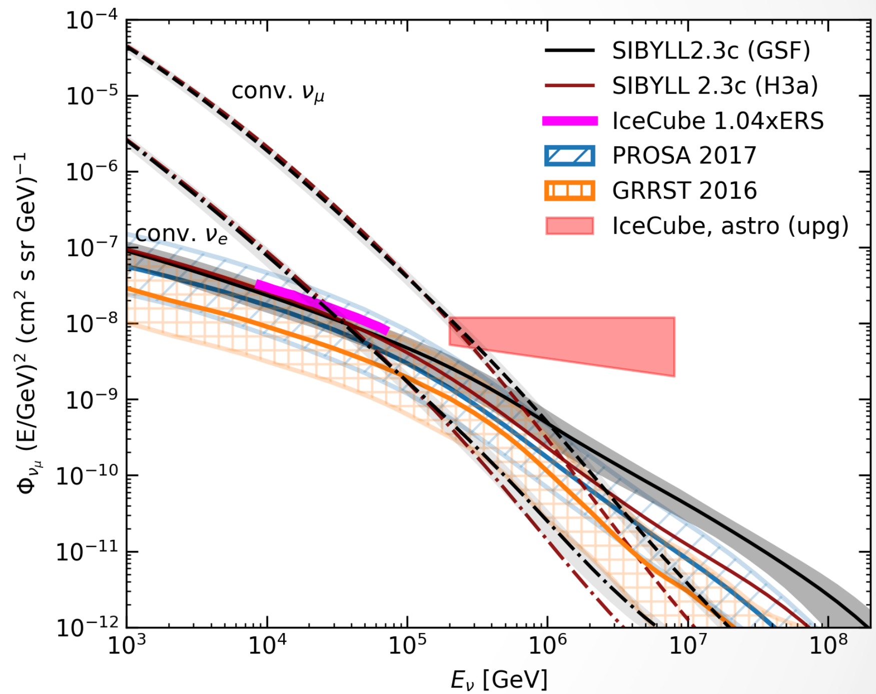
Why fix muons?

To get better predictions of atm. neutrino background for neutrino observatories

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



Fedynitch et al., PoS(ICRC2017)1019



Muon production and **neutrino** production in air showers **coupled**
Wrong number of muons = wrong prediction of atm. neutrino background

Relevant particles

CRMC simulation, model spread: EPOS-LHC, QGSJet-II-04, SIBYLL-2.3

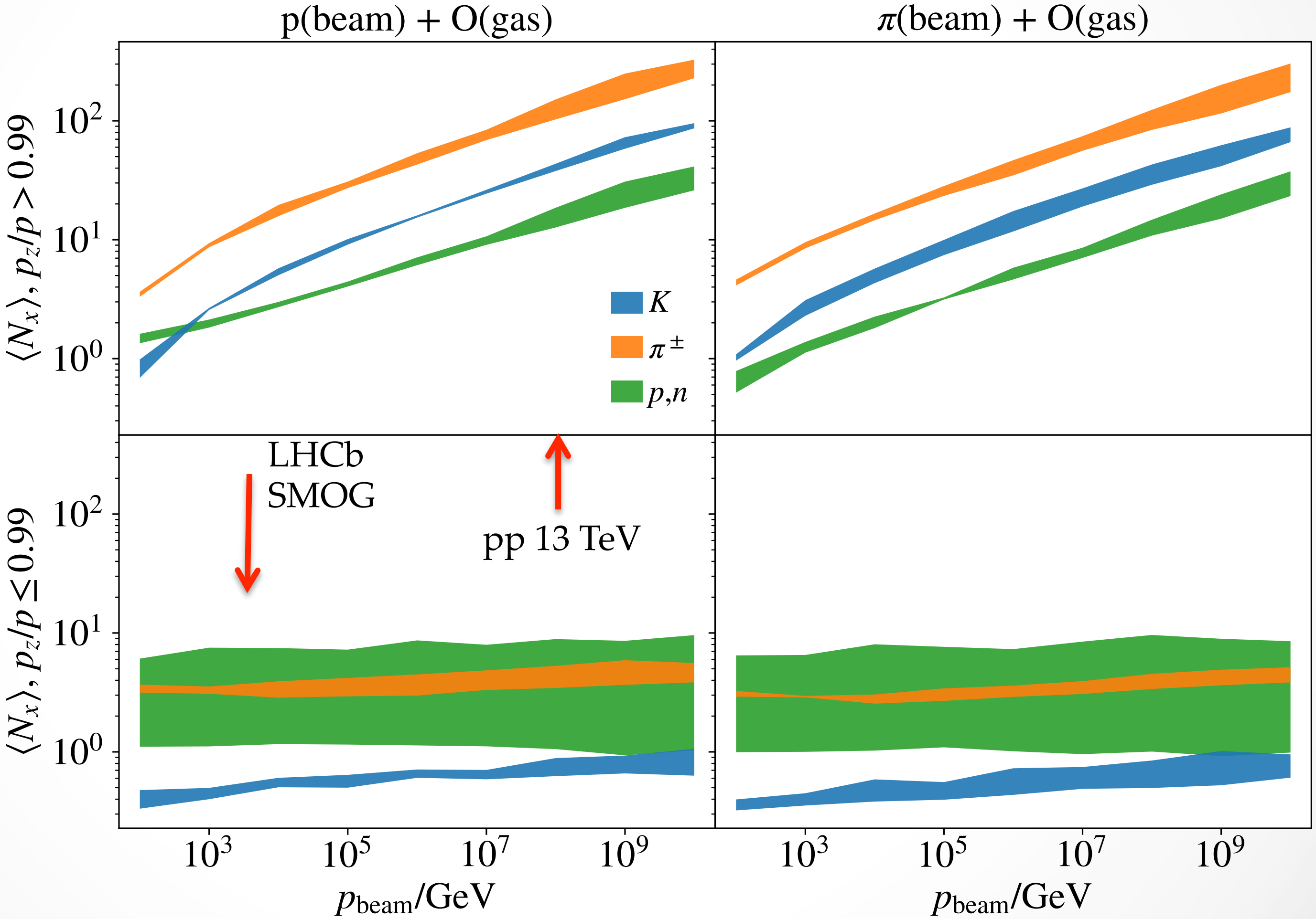
CRMC: R. Ulrich et al. https://web.ikp.kit.edu/rulrich/crmc.html

forward production, energy transfer

LHCf
CASTOR

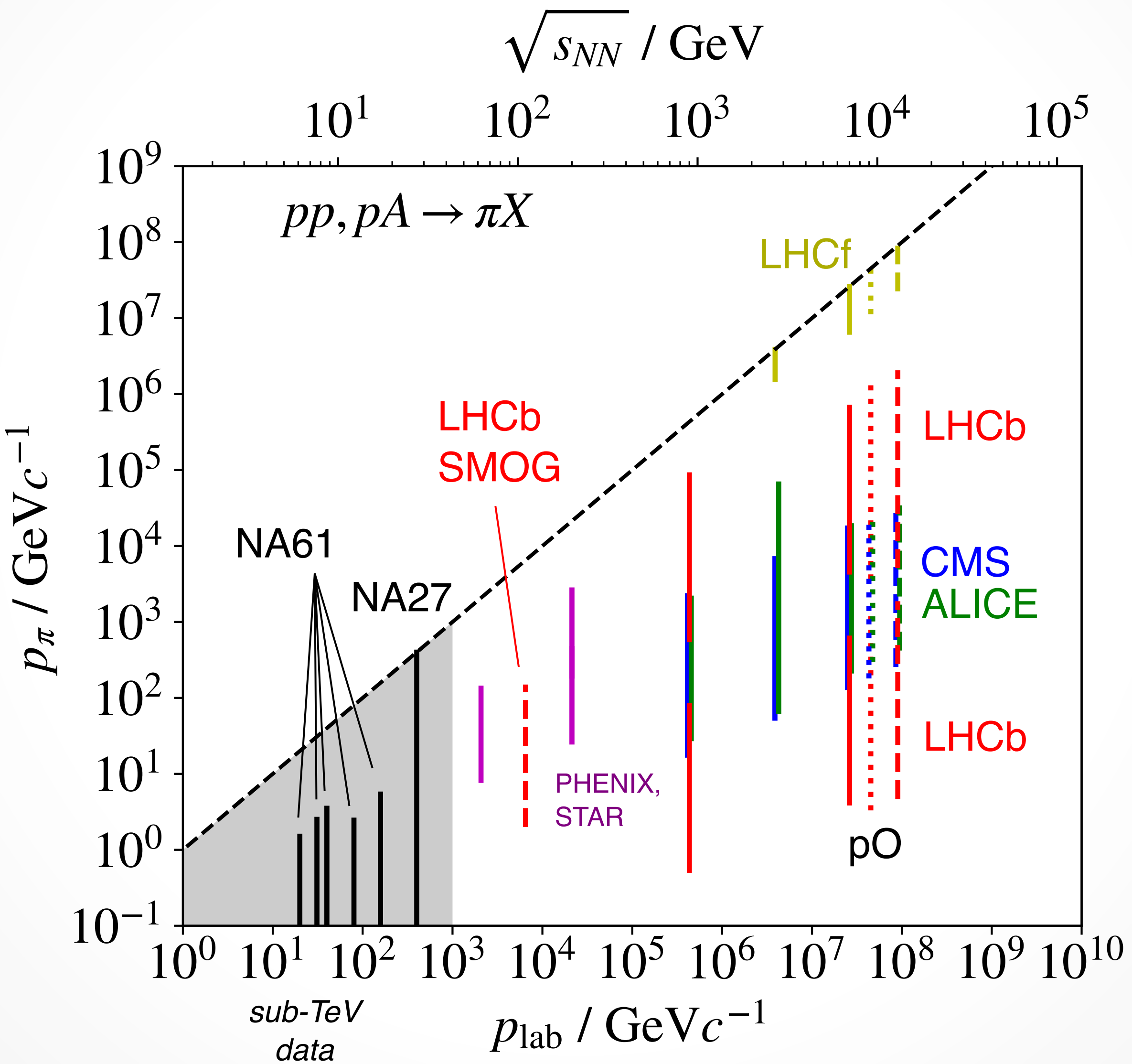
lateral production, observable muons

LHCb
ALICE
CMS



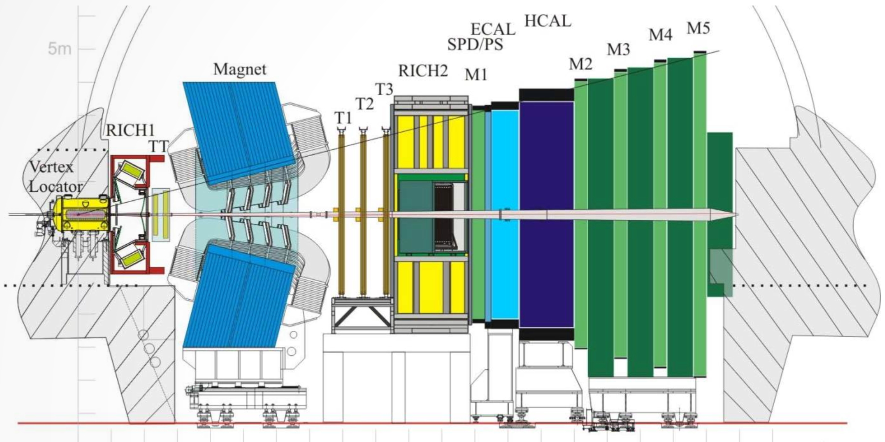
Kaons do not contribute significantly to observable muons, but transport energy

Data on pion spectra

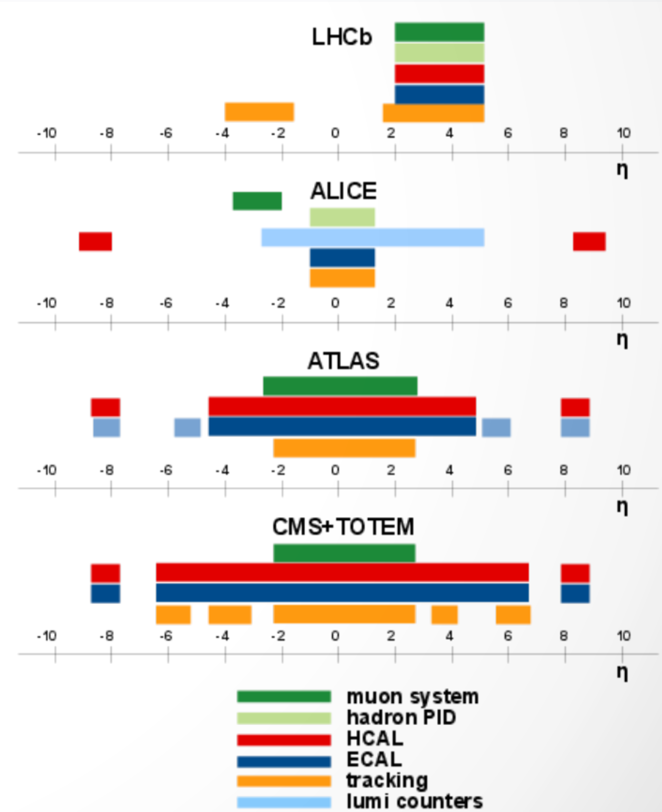


LHCb

Favored LHC detector for this work: **forward geometry** with excellent **particle ID**



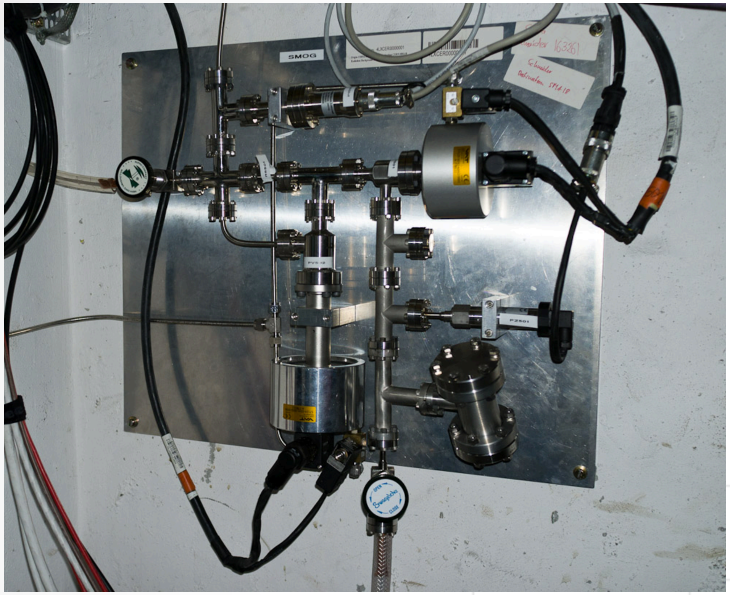
LHCb collab., JINST 3 (2008) S08005
LHCb collab., IJMP A 30 (2015) 1530022



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

- Very good momentum and vertex resolution
  - $\delta p/p < 1$ % for $0 < p < 200$ 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 n, K^0_L

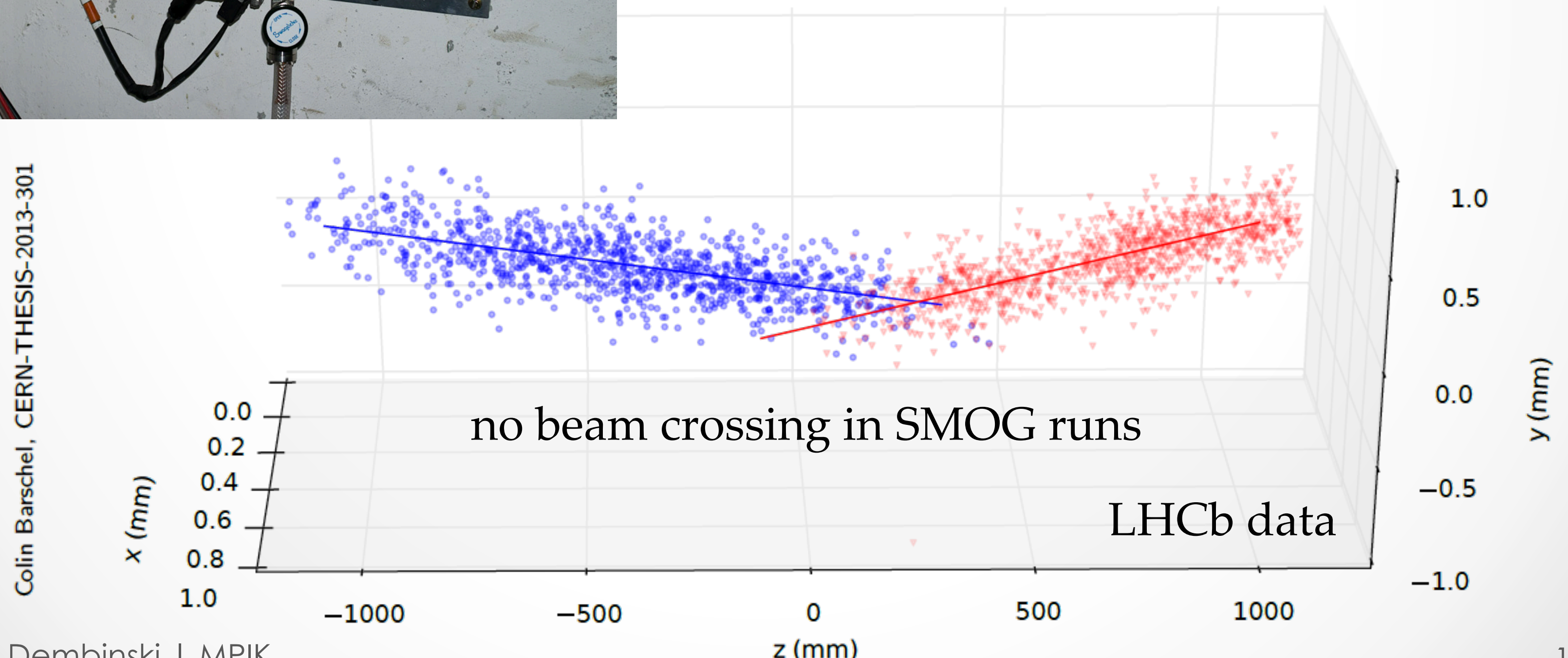
LHCb-SMOG: Gas target



LHCb collab., JINST 9 (2014) P12005

System for **M**easuring **O**verlap with **G**as

- Inject He, Ne, Ar into beam pipe at ~2x10^{-7} mbar
- Enabled best luminosity measurement at LHC
- Allows data taking in **fixed target mode**: **unique feature!**



Science Objectives

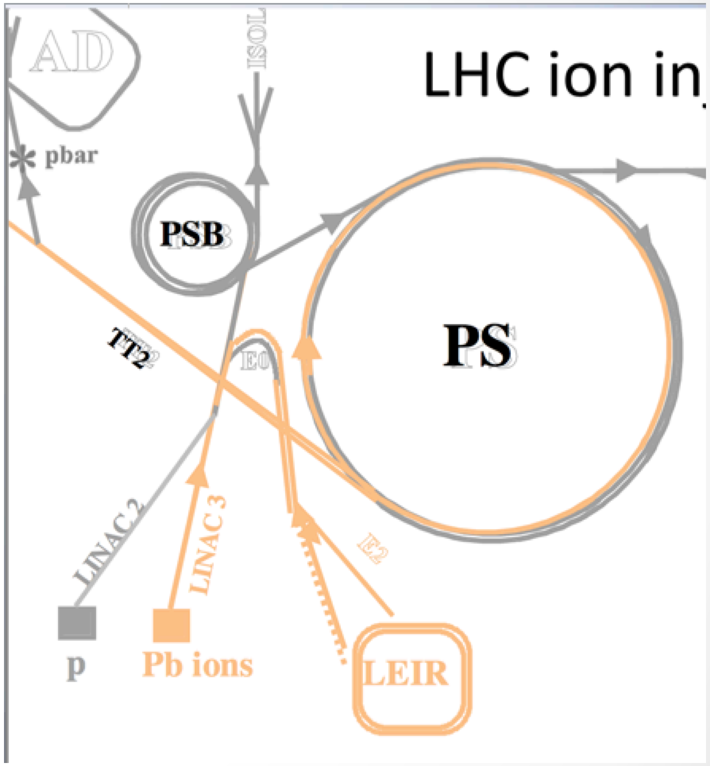
- Solve Muon Puzzle
  - Investigate hadron production to understand **amplitude** and **shape** of **μ-LDF**
  - Study forward and lateral hadron production at LHC
- Forward production: study pp $\sqrt{s}$ = 13 TeV
  - Study forward-physics near first interaction in air shower
  - Cover forward range relevant for energy transfer and **μ-LDF amplitude**
  - Relevant for energy transfer: pions (charged and neutral), kaons, nucleons
  - **Measure:** gamma/pi-charged ratio; spectra of pions, kaons, protons, neutrons
- Lateral production: study p(6.5 TeV) on gas (He, Ne) with LHCb-SMOG
  - pO in between pHe and pNe, test Glauber model predictions
  - LHCb covered mid-rapidity range relevant for **μ-LDF shape**
  - Relevant for muon production: pions, protons
  - **Measure:** spectra of pions, protons
- Push for dedicated pO collisions in Run 3 (2020-2022)
  - Objectives and measurements as in pp + test Glauber model predictions
  - pO $\sqrt{s}$ = 9.2 TeV; measure and interpolate pp $\sqrt{s}$ = 8, 13 TeV to compare

Backup

pO collisions at LHC

A. de Roeck, highlight talk, ICRC 2017

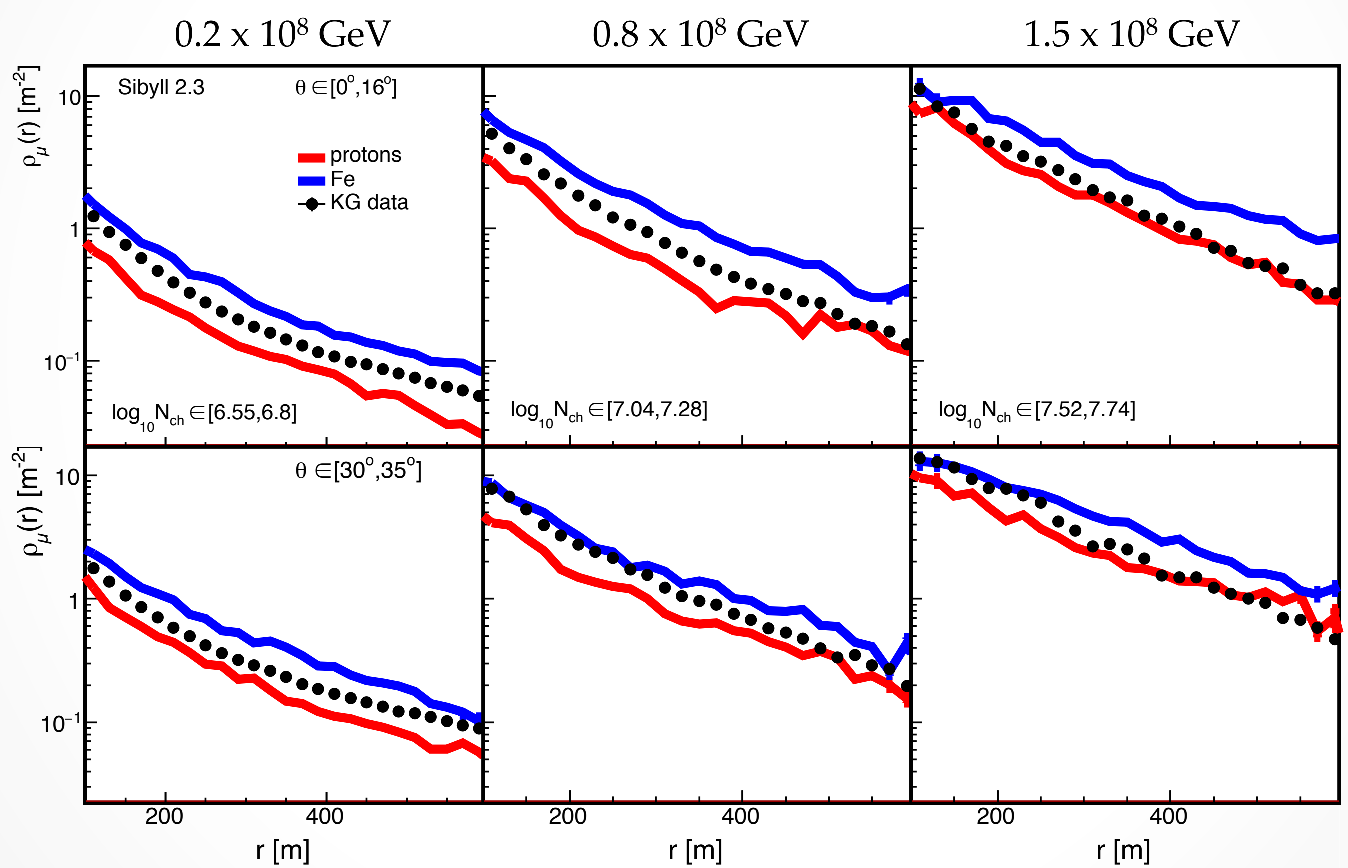
- Initial study by D. Mangluki in 2012
  - CERN can provide light nucleon beams
  - Collisions can be pA, AA, and AB
- ECR source can "deliver anything", but takes time to commission the whole chain (LEIR/PS/SPS)
- O is already support gas for Pb
- Required luminosity can be acquired in a short time
- Strong support from the cosmic ray community



Muon Puzzle

μ-LDF (Lateral Density Function) **steeper** than in simulations

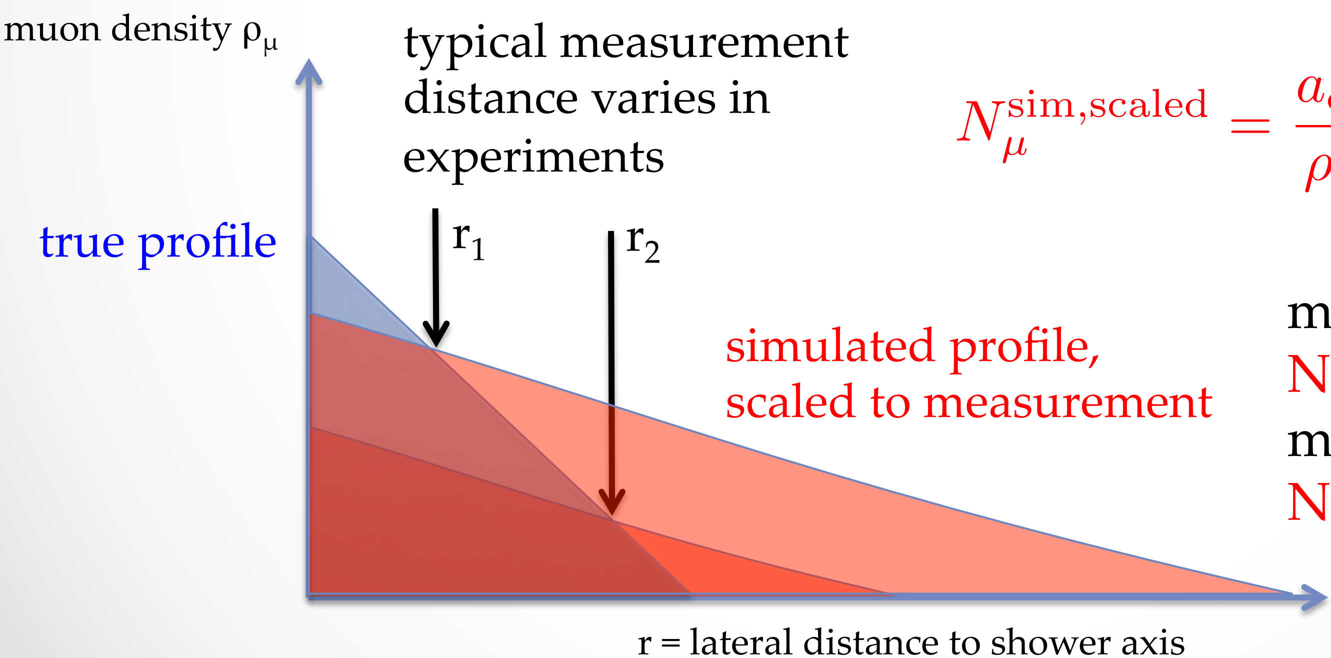
Ateaga-Velazquez et al. (KASCADE-Grande collab.), PoS(ICRC2017)316



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

Muon Puzzle: Summary

- Muon deficit in simulated air showers above 10^8 GeV
- Muon deficit shows up in old and recent models (although less in recent models)
- μ-LDF steeper than in simulations (KASCADE-Grande)
- Muon deficit due to wrong μ-LDF? It depends…



$$N_\mu^{\text{sim,scaled}} = \frac{a_{\text{data}}(r_0)}{\rho_\mu^{\text{MC}}(r_0)} \times \int \rho_\mu^{\text{MC}}(r)$$

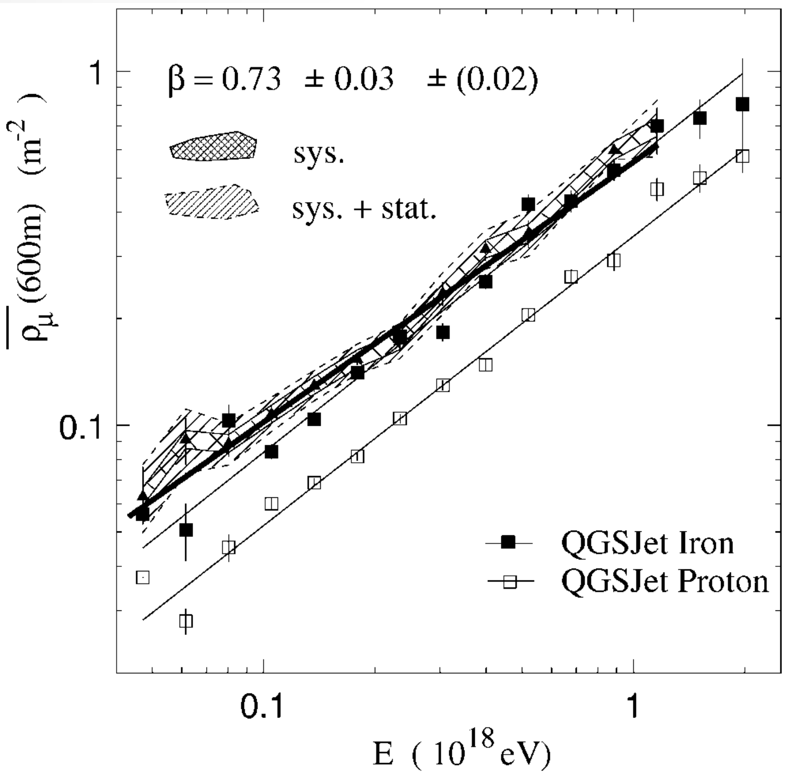
measurement @ r_1:
$N_\mu^{\text{sim,scaled}} > N_\mu^{\text{true}}$

measurement @ r_2:
$N_\mu^{\text{sim,scaled}} < N_\mu^{\text{true}}$

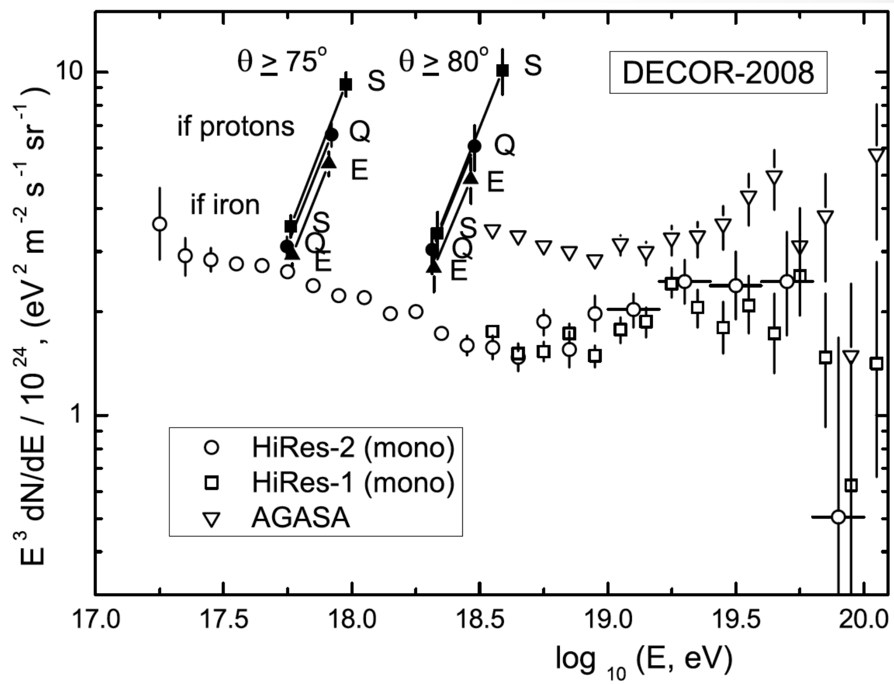
Muon Puzzle

Muon deficit in simulated air showers for cosmic rays above 10^8 GeV

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



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



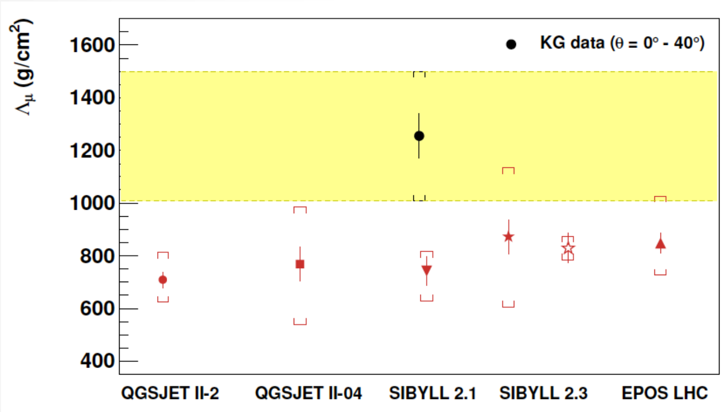
- Effect seen by several experiments at small and large zenith angles
- Effect seen in old and latest models, but latest models caught up

Extended Muon Puzzle

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

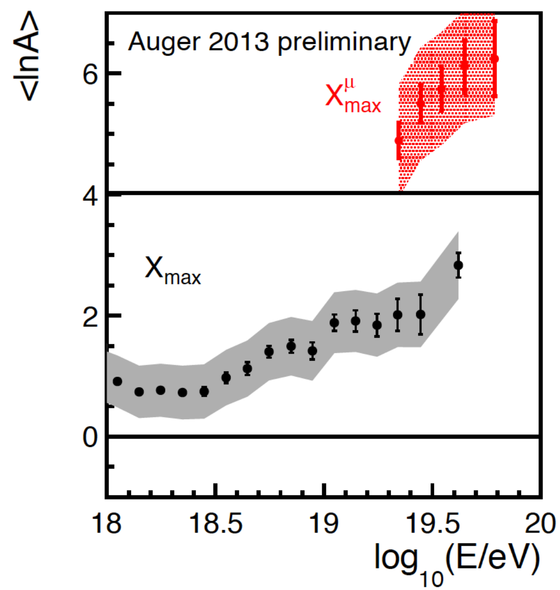
Letessier-Selvon et al. (Pierre Auger collab.), Brazilian J. of Physics 44 (2014) 560–570

μ-attenuation rate

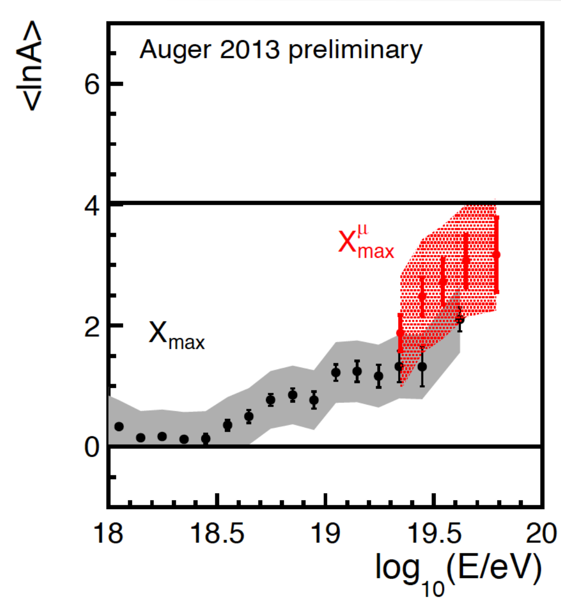


$$N_\mu(\theta) = N_\mu^\circ e^{-X_0 \sec(\theta)/\Lambda_\mu}$$

EPOS-LHC



QGSJetII-04

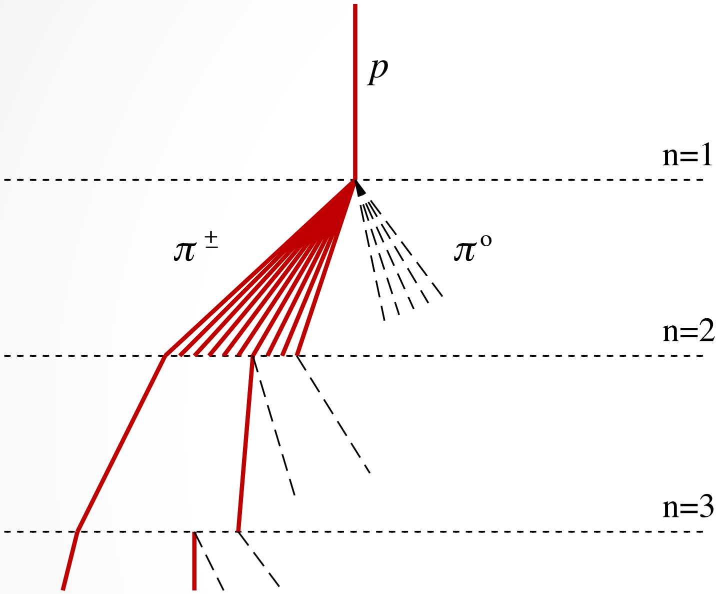


μ-attenuation rate **higher**, all models equally too low

Muon production depth **higher** than expected for EPOS-LHC, which is otherwise closest to data

Matthews-Heitler model

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



- Only pions produced: $N_{ch} + N_0$
- Charged pions re-interact until they reach critical energy
- No. of muons = No. of charged pions at critical energy

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

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

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

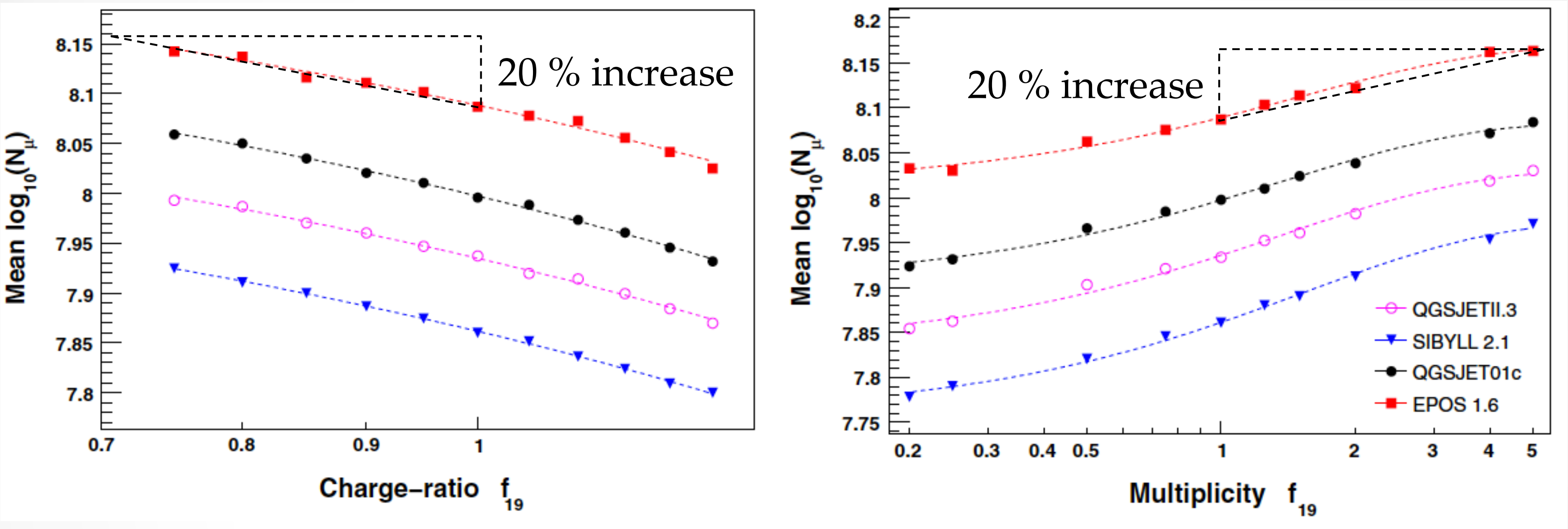
$$N_\mu = {N_{ch}}^{n_c} = \left(\frac{E_0}{\xi_c^\pi}\right)^{\overbrace{\frac{\ln[N_{ch}]}{\ln[N_{ch}+N_0]}}^{}_{\beta}}$$

Mass sensitivity $N_\mu(A) = A^{1-\beta} \times N_\mu(p) \rightarrow N_\mu(\text{Fe}) \approx 1.4\, N_\mu(p)$

- **No. of muons:** whole shower history relevant
- **μ-LDF:** near (far) part dominated by high (low) energy muons $\alpha_\mu \propto 1/E_\mu$

Full 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 $\mathbf{f_{19}}$
- Matthews-Heitler model confirmed, muon number…
    - **very sensitive** to pion charge ratio $N_0/(N_{ch} + N_0)$
    - **sensitive** to particle multiplicity
- **Extreme changes** required to increase muon number by observed 20 %

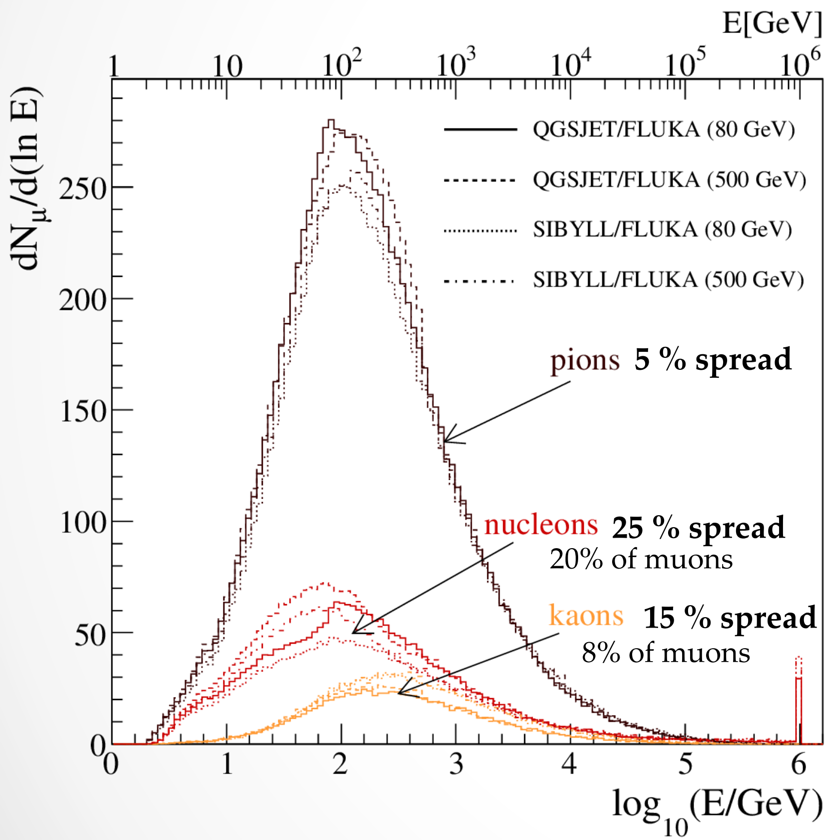
Relevant particles I

Who are the **grandmothers** of observable muons?

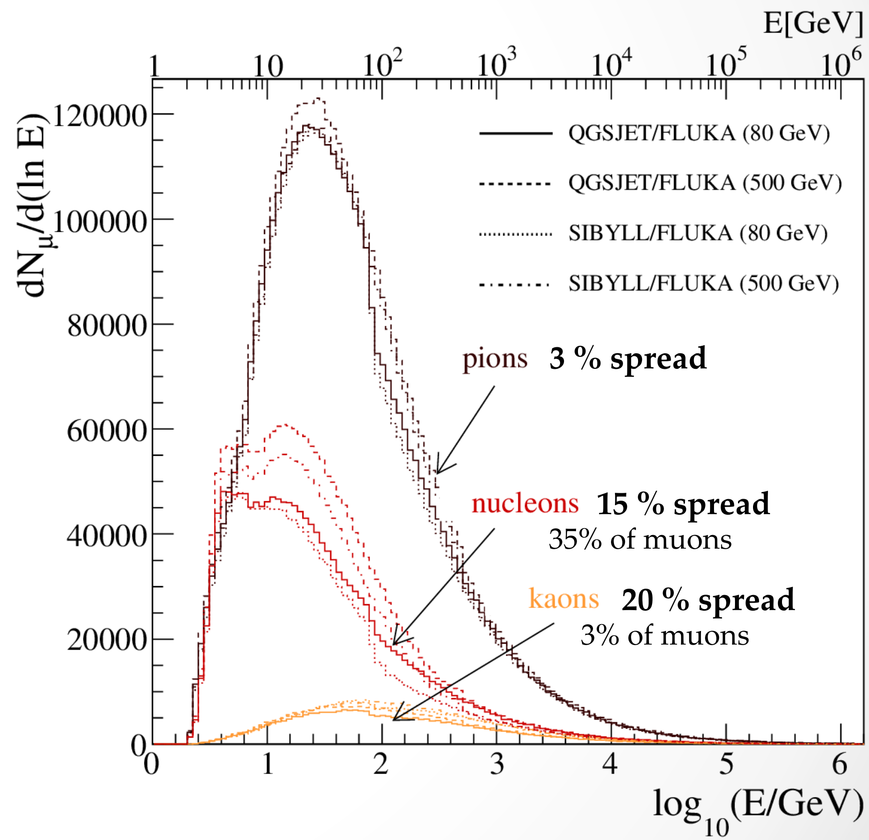
air shower arrays are insensitive to extreme-forward muons

$$\boxed{\text{hadron}} + \text{air} \rightarrow \text{meson} + X$$
$$\rightarrow \boxed{\mu} + \nu_\mu + \nu_e$$

Maris et al. (NA61 collab.) Proc. ICRC 2009, 1059



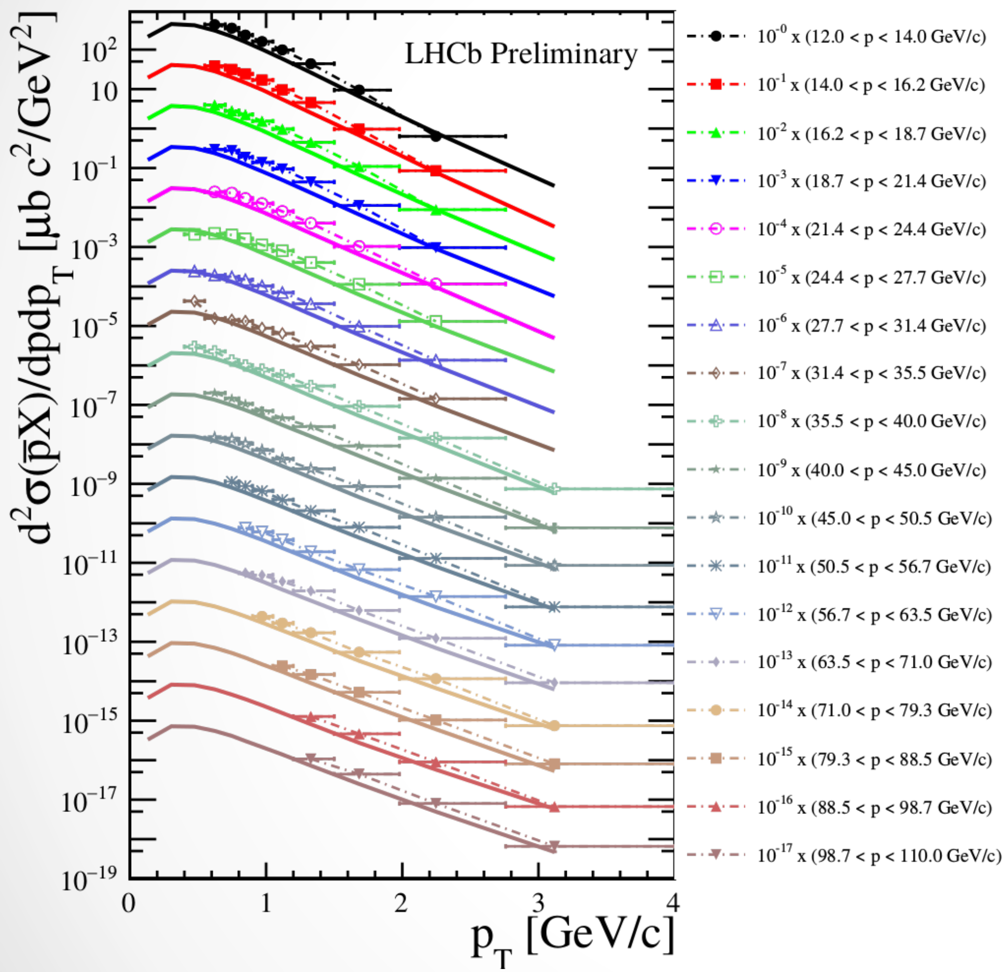
KASCADE: E_0 = 1 PeV, r = 20-200 m



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

Related work

p+He$_{(fixed)}$: anti-proton spectra



LHCb-CONF-2017-002

Prompt production at $\sqrt{s_{NN}}$ = 110 GeV

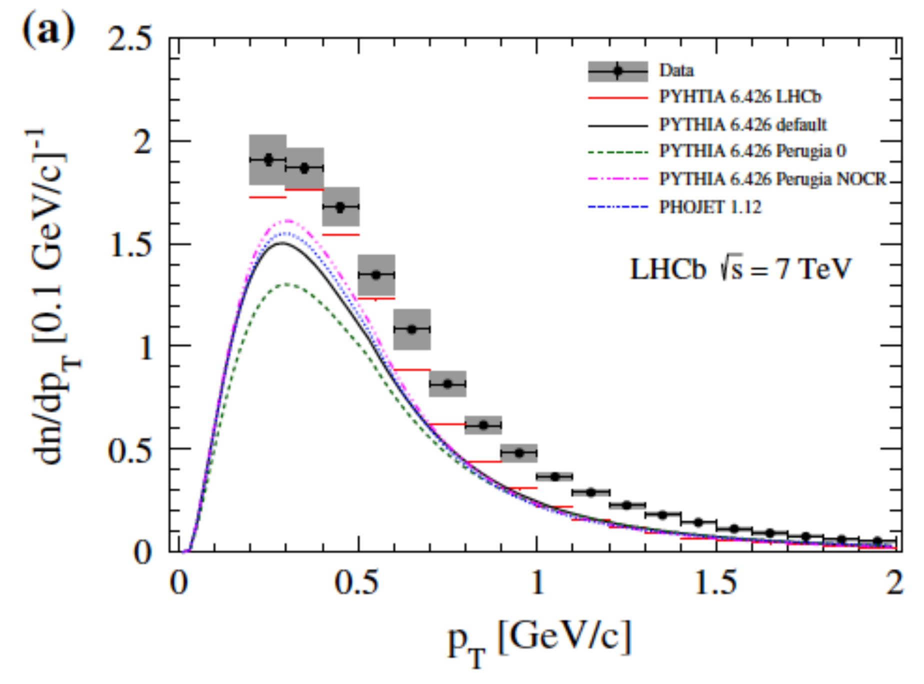
EPOS-LHC: data/MC ~ 1.5

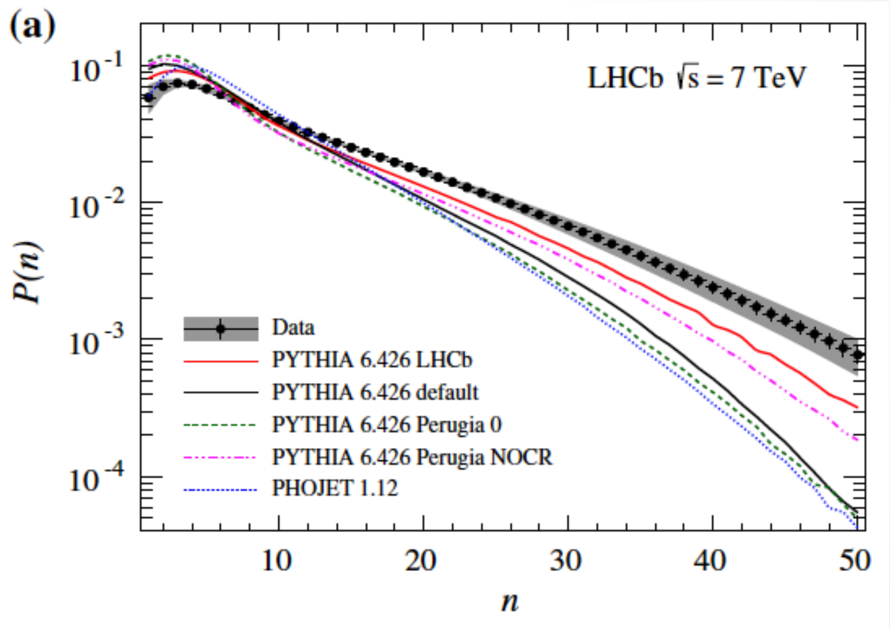
Plans to also…

- measure p-bar from strange decays
- analyze data from 4 TeV p beam

Charged particle multiplicity and density at 7TeV

LHCb collab., EPJC 74 (2014) 2888





Soft-QCD group

- Inelastic pp cross-section at $\sqrt{s}$ = 5, 13 TeV
- Charge ratios in pA, Ap, pp
- Production of (anti-)Λ
- Charged particle multiplicities and densities at $\sqrt{s}$ = 7 TeV
- V0 cross-sections at $\sqrt{s}$ = 2.76, 7 TeV
- Forward energy flow
- Ridge study in pp collisions at $\sqrt{s}$ = 13 TeV