Core-Corona Effect and Air Showers

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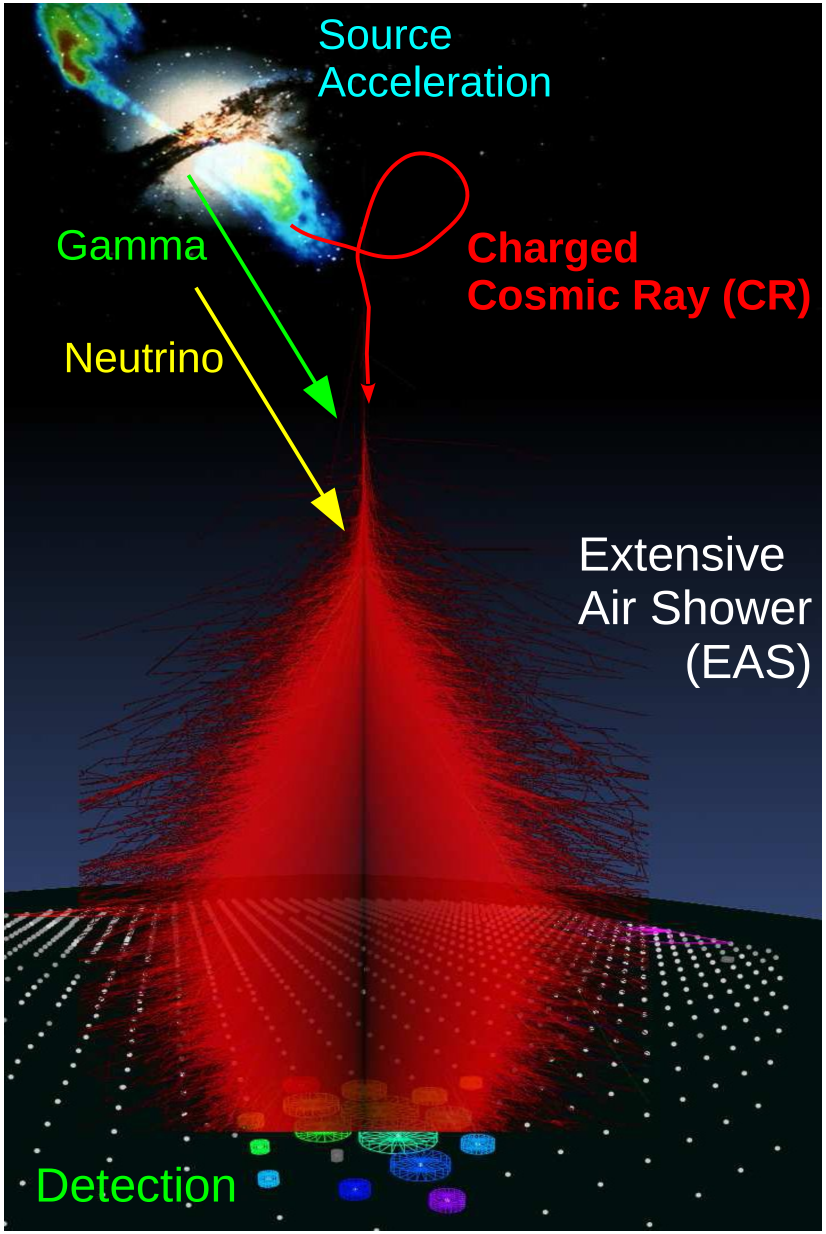
Outline

- **Introduction**
- **Extensive Air Showers (EAS)**
  - ➜ Muon deficit in simulations
- **Hadronizations**
  - ➜ Simple vs complex environment
  - ➜ Core-corona approach
- **Core-corona and EAS**
  - ➜ Qualitative tests

Recent LHC data combined with the result of air shower experiment meta-analysis provide a possible explanation of the muon deficit in air shower simulations : QGP-like hadronization could be more common than thought until now.

Astroparticles



From R. Ulrich (KIT)

- **Astronomy with high energy particles**
  - gamma (straight but limited energy due to absorption during propagation)
  - neutrino (straight but difficult to detect)
  - charged ions (effect of magnetic field)
- **Measurements of charged ions**
  - source position (only for light and high E)
  - energy spectrum (source mechanism)
  - mass composition (source type)
    - light = hydrogen (proton)
    - heavy = iron (A=56)
  - test of hadronic interactions in EAS via correlations between observables.

mass measurements should be consistent and lying between proton and iron simulated showers if physics is correct

Hadronic Models for Air Showers

- **EAS simulations necessary to study high energy cosmic rays**
  - complex problem: identification of the primary particle from the secondaries

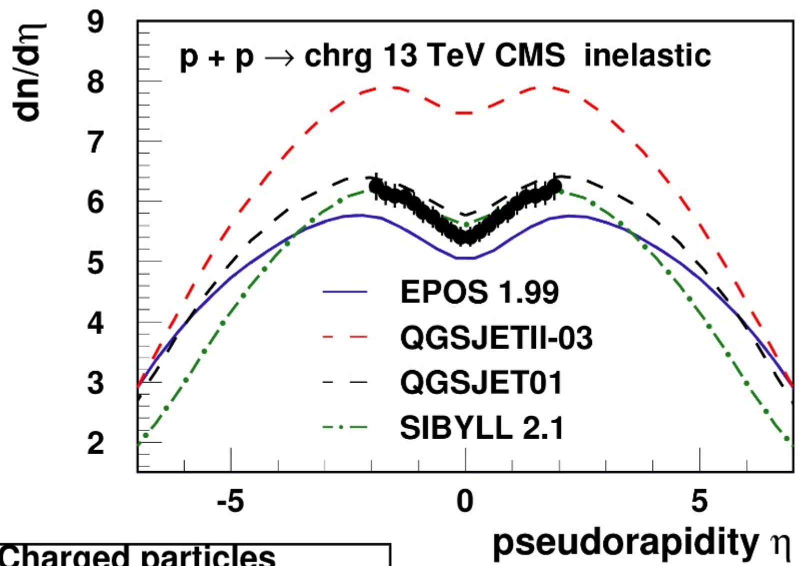
- **Hadronic models are the key ingredient !**
  - follow the standard model (QCD)
    - but mostly non-perturbative regime (phenomenology needed)
  - main source of uncertainties

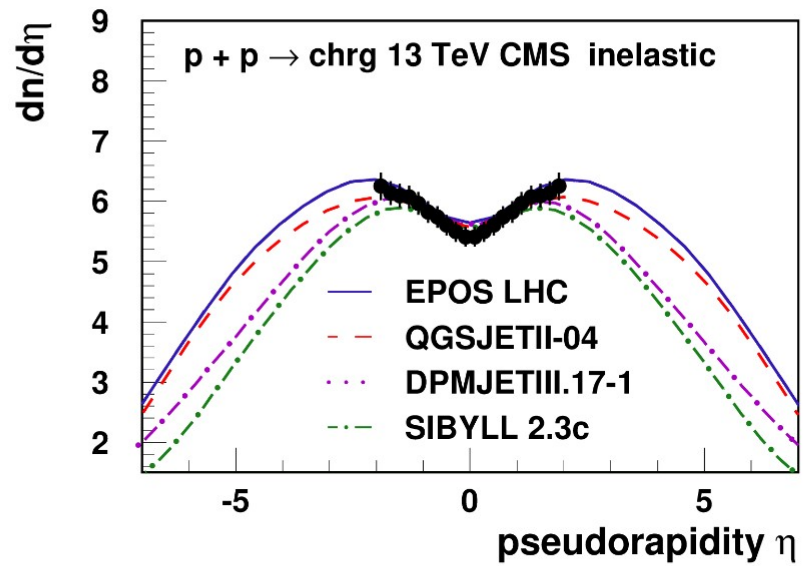
- **Which model for CR ?** **(alphabetical order)**
  - **DPMJETIII.17-1/19-1** by S. Roesler, A. Fedynitch, R. Engel and J. Ranft
  - **EPOS (1.99/LHC/3/4/LHCR)** by T. Pierog and K.Werner. et al.
  - **QGSJET** (01/II-03/II-04/III) by S. Ostapchenko (starting with N. Kalmykov)
  - **Sibyll (2.1/(2.3c/)2.3d)** by E-J Ahn, R. Engel, R.S. Fletcher, T.K. Gaisser, P. Lipari, F. Riehn, T. Stanev
    - All tuned on early LHC data from 10 years ago !

Models Uncertainties

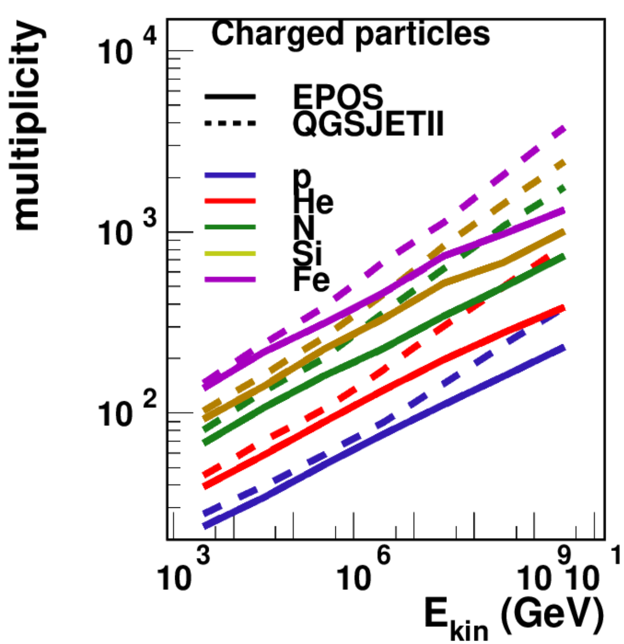
Significant improvement require new data (light ion and higher energy)

Pre - LHC





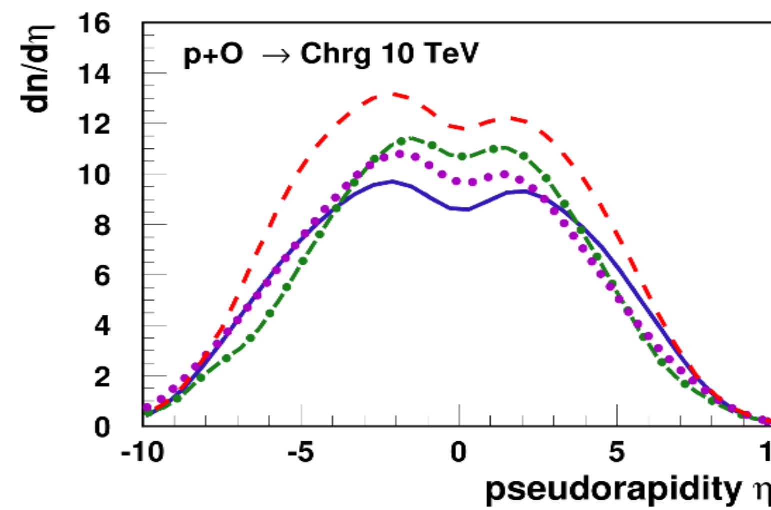
Post - LHC



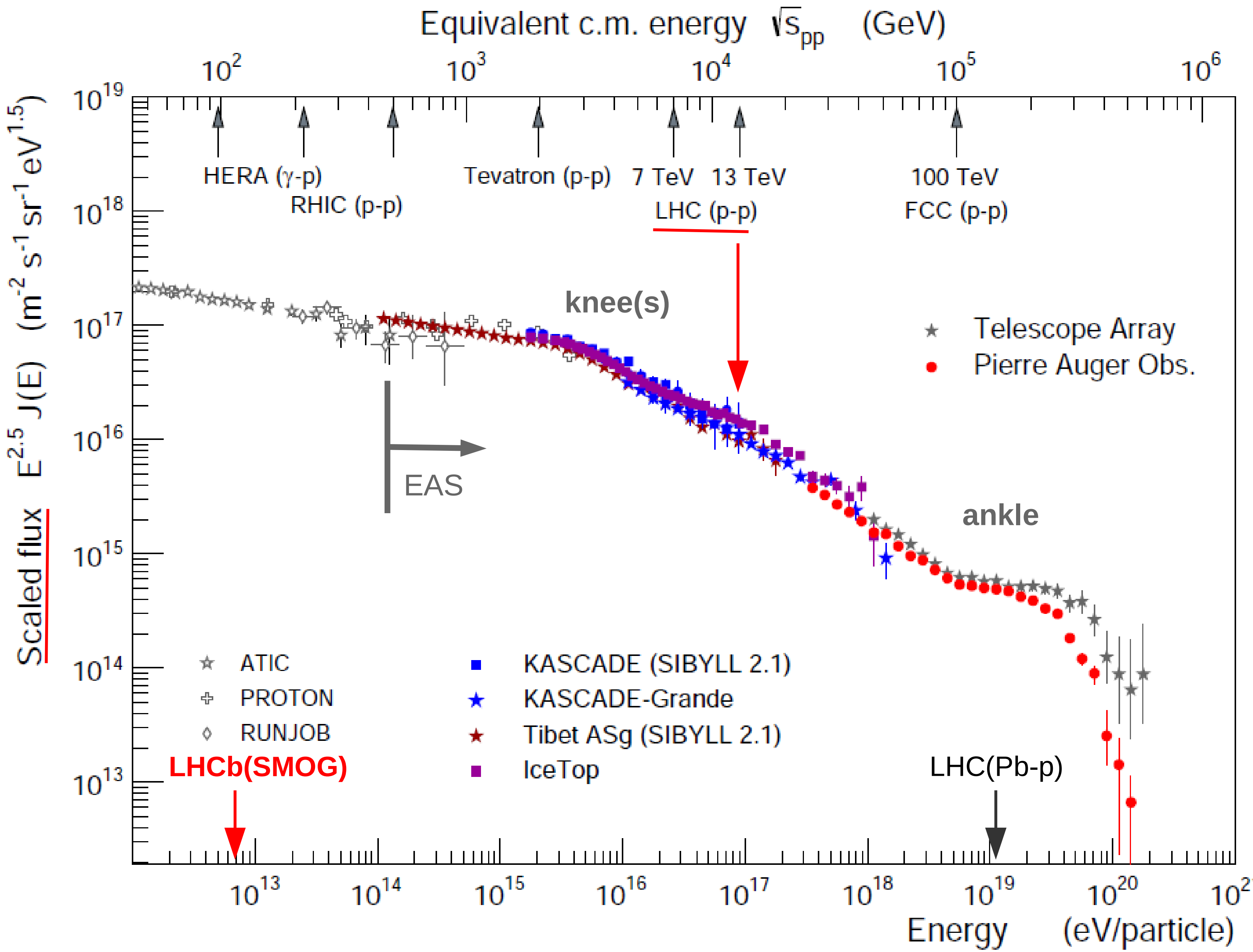
After LHC, most of the model difference appear in nuclear collisions : ideal tests using p-O and O-O collisions

2024 !

Post - LHC



Energy Spectrum

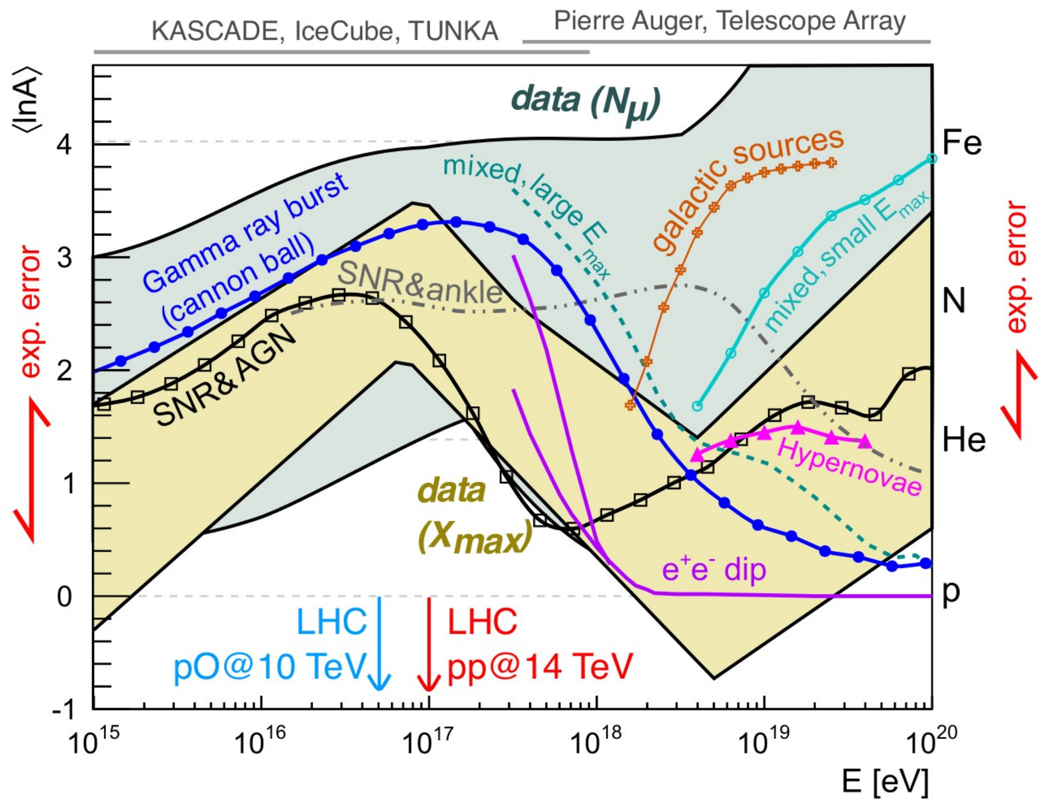


R. Engel (KIT)

UHECR Composition

With muons current CR data are impossible to interpret

- Very large uncertainties in model predictions
- Mass from muon data incompatible with mass from X_{max}

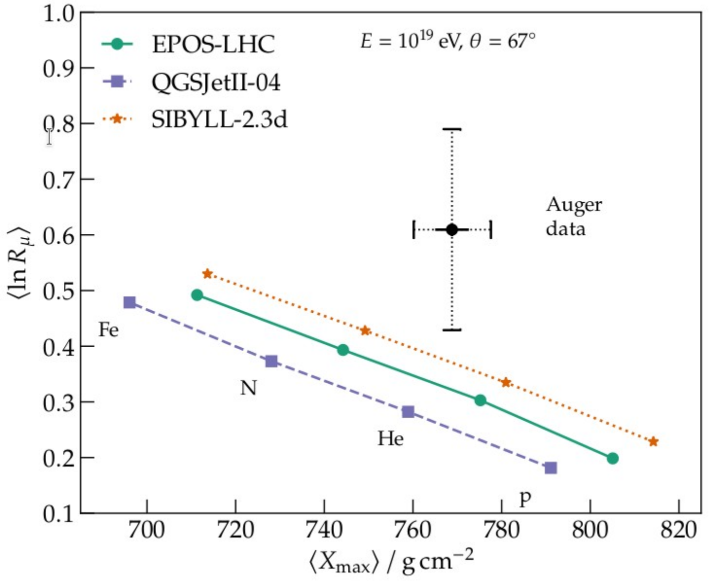


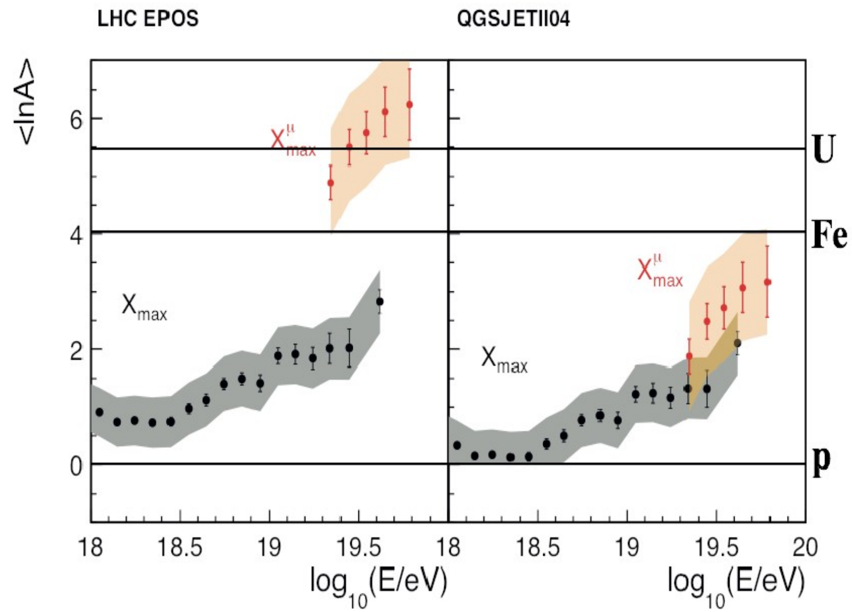
Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

H. Dembinski UHECR 2018 (WHISP working group)

Hybrid Measurements

- **Degeneracy between mass composition and hadronic interactions**
  - With unknown mass composition, hybrid type of measurements are a must to test hadronic interactions in EAS
  - Various types of measurements (number of muons, muon produdction depth (MPD), X_{max}, rise time, ...) and their correlations
  - Independent measurements of EM and muon component : results not consistent



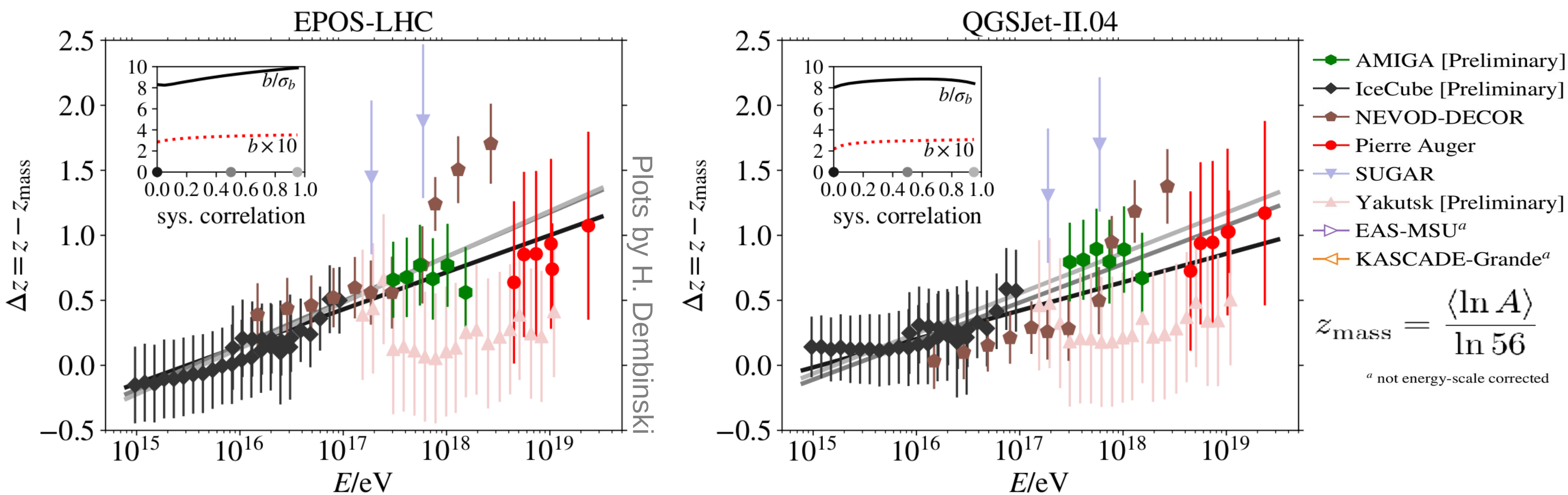


- **Different observable = different type of hadronic interactions**
  - X_{max} = first interaction
  - Muon Productin Depth = pion interactions
  - Muons = hadronization at all energies
  - ...

WHISP Meta-Analysis

$$z = \frac{\ln N_{\mu}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}{\ln N_{\mu,\mathrm{Fe}}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}$$

- **Global analysis of muon measurements in EAS :**
  - Clear muon excess in data compared to simulation
  - Different energy evolution between data and simulations
    - Significant non-zero slope (>8σ)



- **Different energy or mass scale cannot change the slope**
  - Different property of hadronic interactions at least above 10^{16} eV

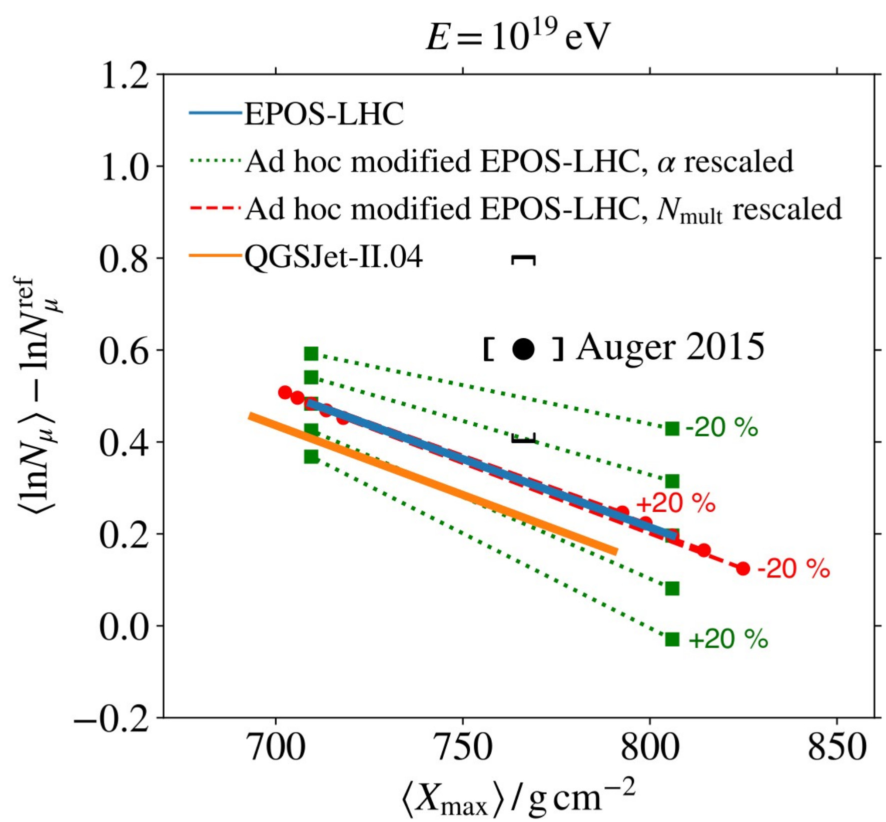
Constraints from Correlated Change

- **One needs to change energy dependence of muon production by ~+4%**

$$N_\mu = A^{1-\beta}\left(\frac{E}{E_0}\right)^\beta$$

$$X_{max} \sim \lambda_e \ln\left(E_0/(2.N_{mult}.A)\right) + \lambda_{ine}$$

- **To reduce muon discrepancy β has to be change**
  - ➡ X_{max} alone (composition) will not change the energy evolution
  - ➡ β changes the muon energy evolution but not X_{max}



Plot by H. Dembinski

- $$\beta = \frac{\ln(N_{mult} - N_{\pi^0})}{\ln(N_{mult})} = 1 + \frac{\ln(1-\alpha)}{\ln(N_{mult})}$$
  - ➡ +4% for β ➤ -30% for $\alpha = \frac{N_{\pi^0}}{N_{mult}}$

Possible Particle Physics Explanations

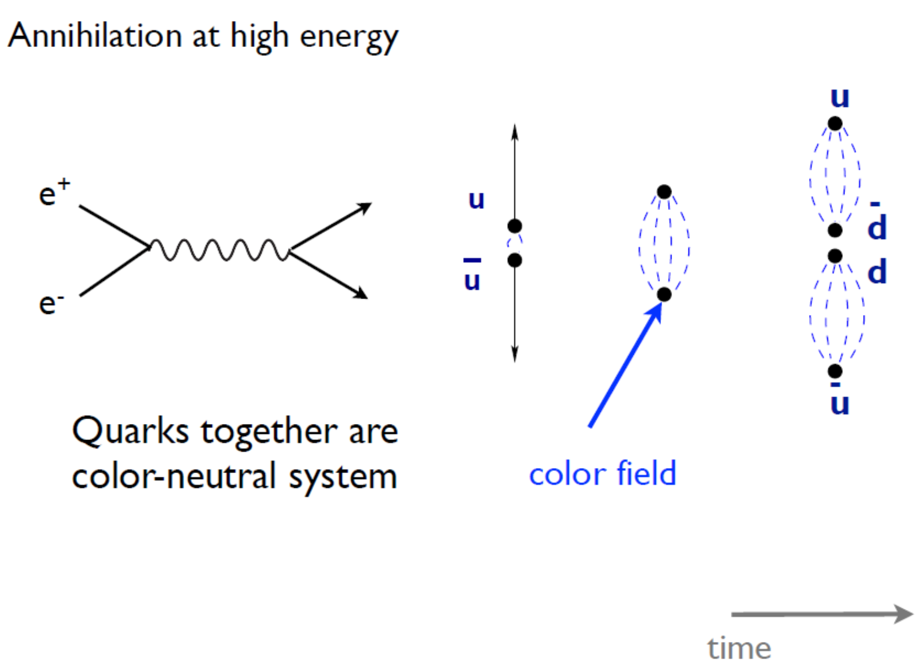
A 30% change in particle charge ratio ($\alpha = \frac{N_{\pi^0}}{N_{mult}}$) is huge !

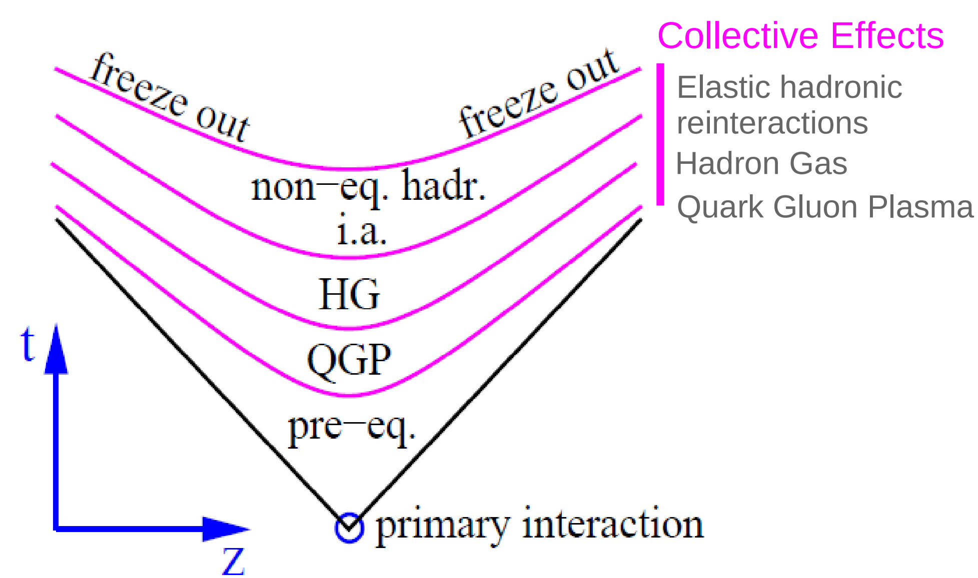
- Possibility to increase N_{mult} limited by X_{max}
- New Physics ?
  - Chiral symmetry restoration (Farrar et al.) ?
  - Strange fireball (Anchordoqui et al., Julien Manshanden) ?
  - String Fusion (Alvarez-Muniz et al.) ?
    - Problem : no strong effect observed at LHC (~10^{17} eV)
- Unexpected production of Quark Gluon Plasma (QGP) in light systems observed at the LHC (at least modified hadronization)
  - Reduced α is a sign of QGP formation (enhanced strangeness and baryon production reduces relative π^0 fraction. Baur et al., arXiv:1902.09265) !
  - α depends on the hadronization scheme
    - How is it done in hadronic interaction models ?

Hadronization Models

2 models well established for 2 extreme cases

➡ String Fragmentation vs Collective hadronization (statistical models)





In dilute systems… CORONA
→ “high” π^0 fraction

In dense systems… CORE
→ “low” π^0 fraction

➡ What to do in between ? For proton-proton, hadron-Air, ...

Hadronization in Simulations

- **Historically (theoretical/practical reasons) string fragmentation used in high energy models (Pythia, Sibyll, QGSJET, …) for proton-proton.**

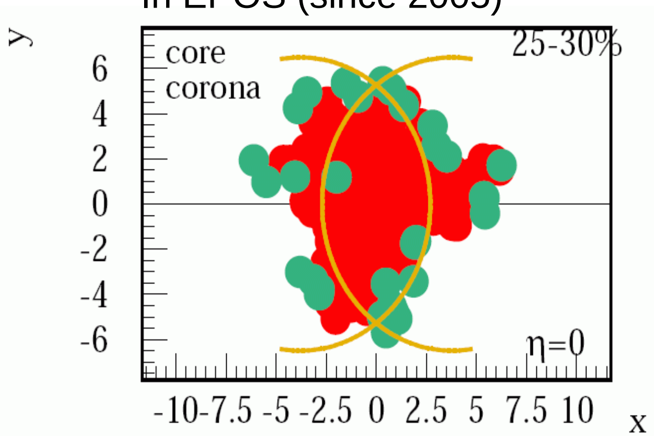
  - Light system are not “dense”
  - Works relatively well at SPS (low energy)
  - But problems already at RHIC, clearly at Fermilab, and serious at LHC :
    - Modification of string fragmentation needed to account for data
    - Various phenomenological approaches :
      - Color reconnection
      - String junction
      - String percolation, …
    - Number of parameters increased with the quality of data …

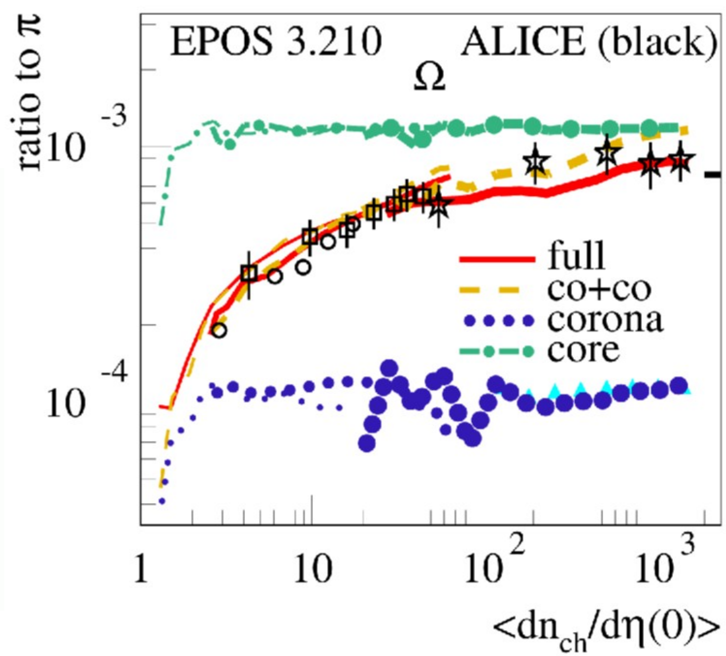
- **Statistical model only used for heavy ion (HI) in combination with hydrodynamical evolution of the dense system : QGP hadronization**
  - Account for flow effects, strangeness enhancement, particle correlations...

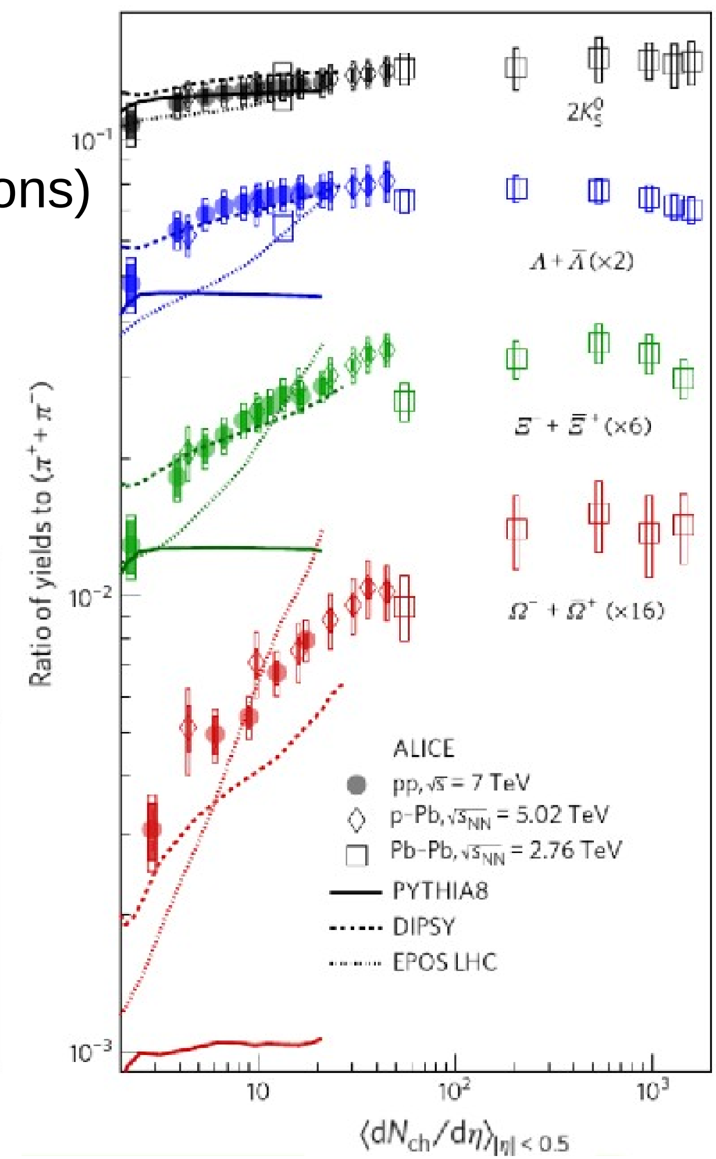
Core-Corona Approach

- **Mixing of core and corona hadronization needed to achieve detailed description of p-p data (EPOS)**
  - Evolution of particle ratios from pp to PbPb
  - Particle correlations (ridge, Bose Einstein correlations)
  - Pt evolution, …
- **Both hadronizations are universal but the fraction of each change with particle density**
- **2 simultanous source of particles**

In EPOS (since 2005)



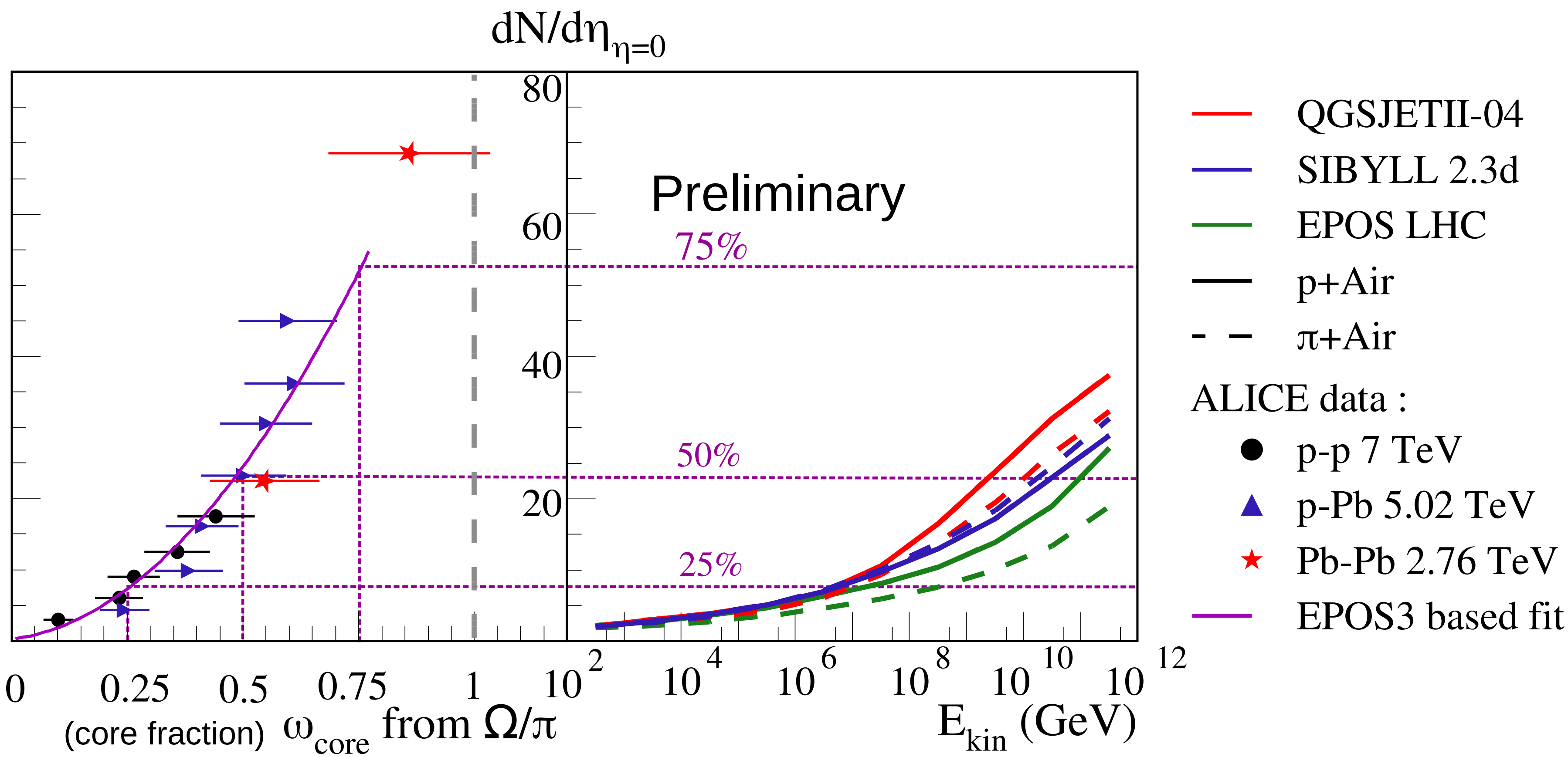




Particle Densities in Air Showers

Is particle density in air shower high enough to expect core formation ?

- Core formation start quite early according to ALICE data
- Cosmic ray primary interaction likely to have 50% core at mid-rapidity !



Core-Corona appoach and CR

To test if a QGP like hadronization can account for the missing muon production in EAS simulations a core-corona approach can be artificially apply to any model

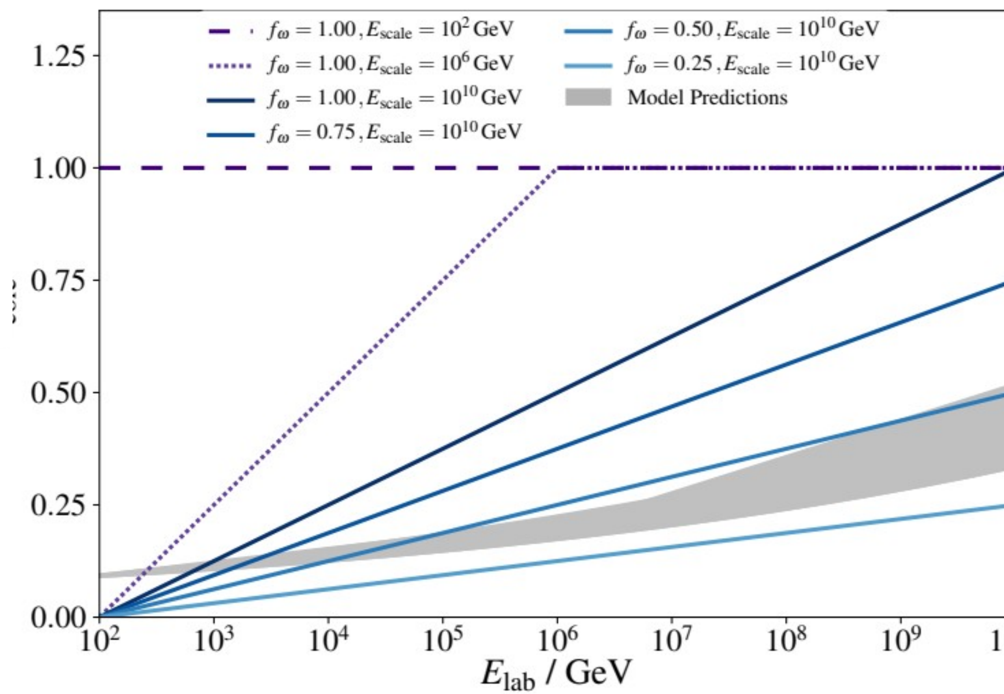
- Particle ratios from statistical model are known (tuned to PbPb) and fixed : core
- Initial particle ratios given by individual hadronic interaction models : corona
- Using CONEX, EAS can be simulated mixing corona hadronization with an arbitrary fraction ω_{core} of core hadronization: $N_i = \omega_{\text{core}}\, N_i^{\text{core}} + (1 - \omega_{\text{core}})\, N_i^{\text{corona}}$

$$\omega_{\text{core}}(E_{\text{lab}}) = f_\omega \underbrace{F(E_{\text{lab}}; E_{\text{th}}, E_{\text{scale}})}_{\frac{\log_{10}(E_{\text{lab}}/E_{\text{th}})}{\log_{10}(E_{\text{scale}}/E_{\text{th}})} \text{ for } E_{\text{lab}} > E_{\text{th}}}$$

$$E_{\text{th}} = 100\,\text{GeV}$$

Different scenarii can be studied playing with f_ω and E_{scale}.

Note : the leading particle is NOT modified (projectile remnant)

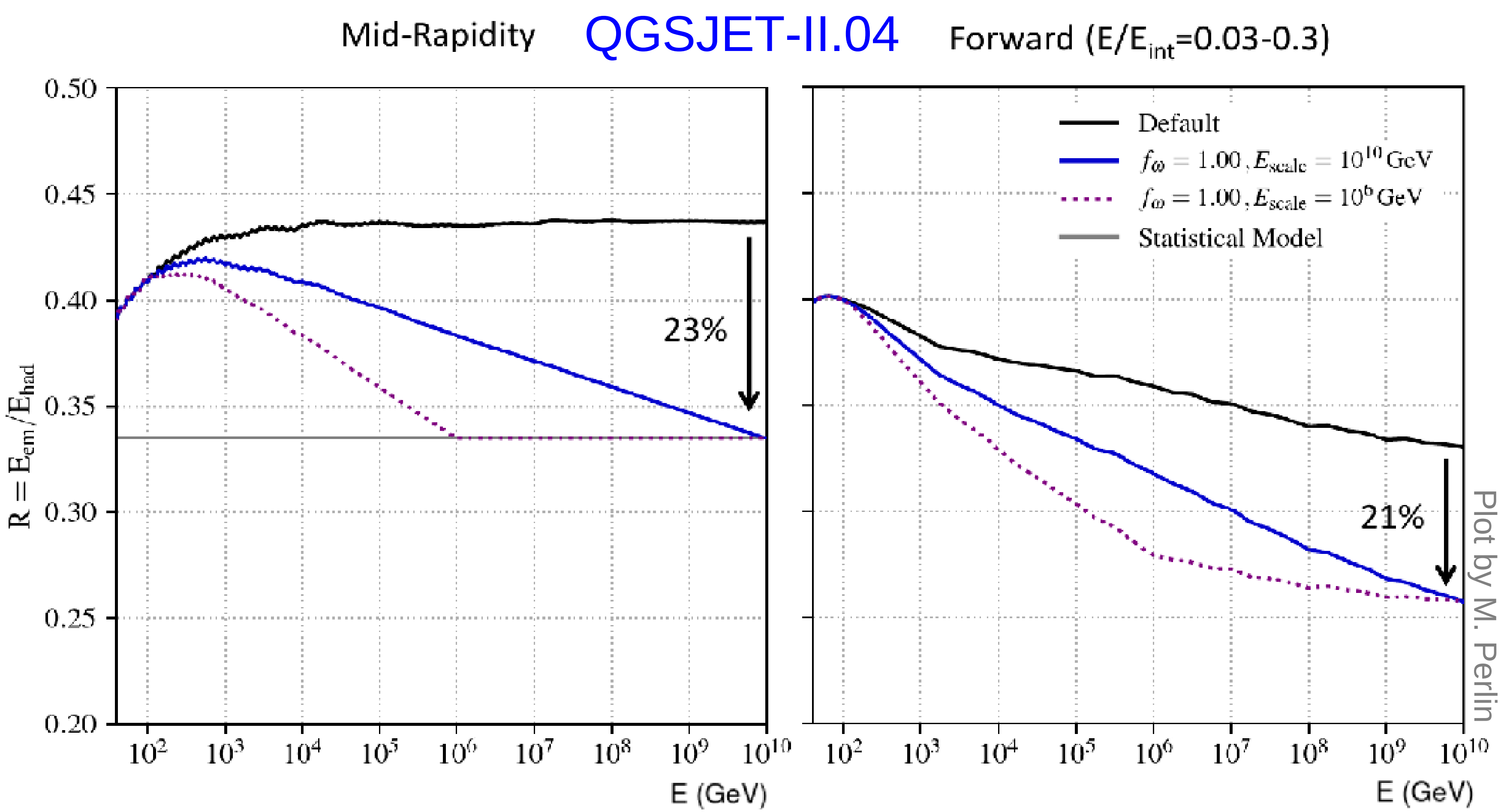


Plot by M. Perlin

Evolution of hadronization from core to corona

The relative fraction of π^0 depends on the hadronization scheme

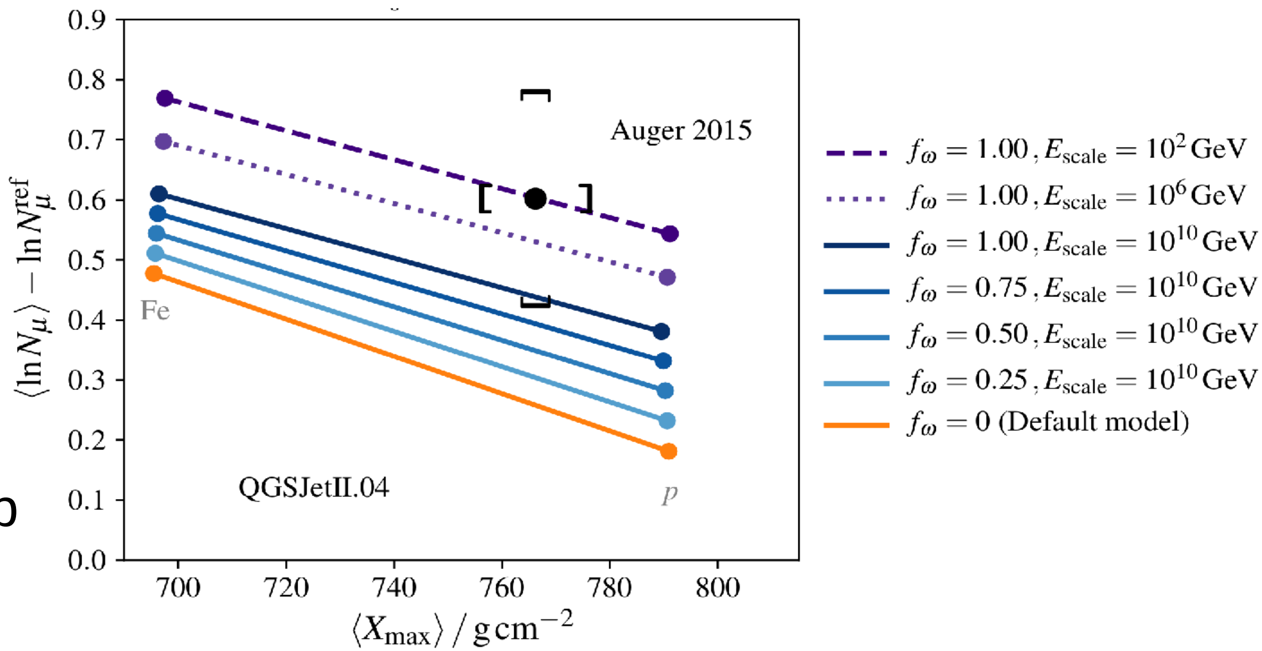
➡ Change of ω_{core} with energy change $\alpha = \frac{N_{\pi^0}}{N_{mult}}$ or $R(\eta) = \frac{\langle \mathrm{d}E_{\mathrm{em}}/\mathrm{d}\eta \rangle}{\langle \mathrm{d}E_{\mathrm{had}}/\mathrm{d}\eta \rangle}$ which define the muon production in air showers.

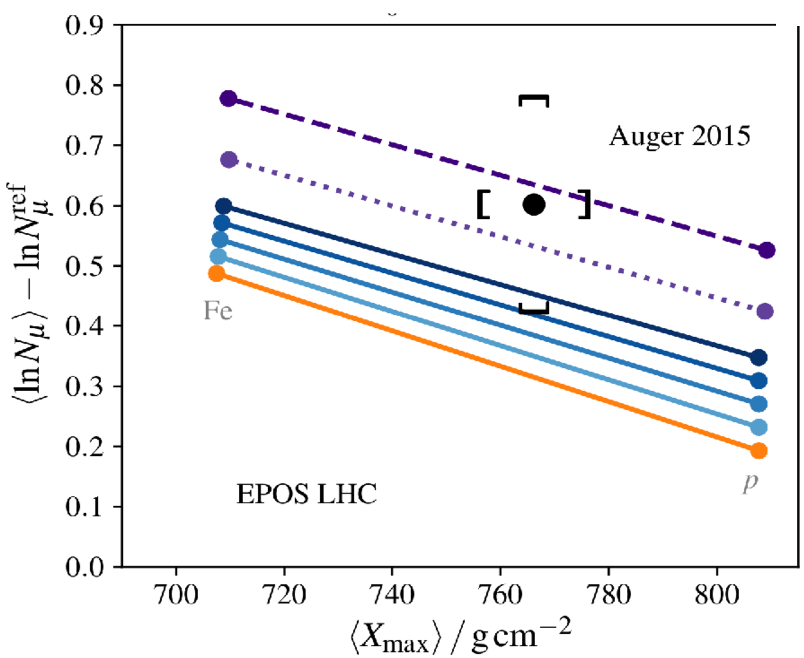


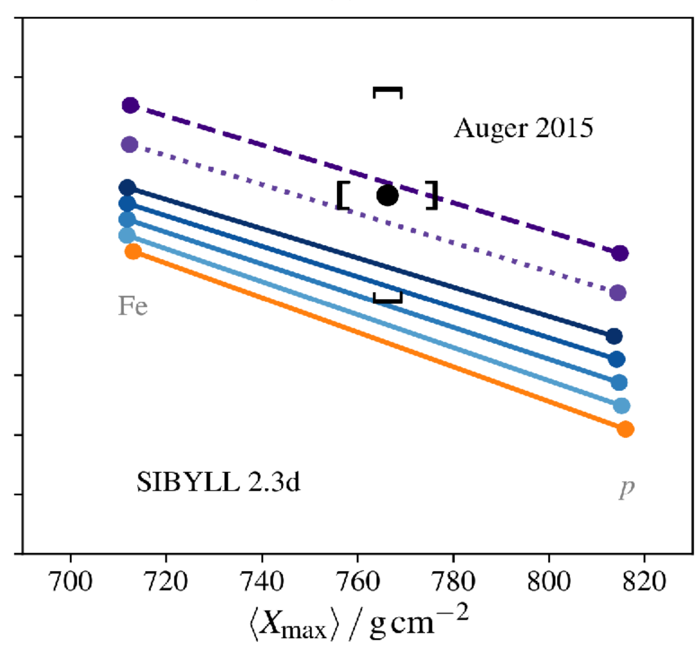
Results for X_{max}-N_{mu} correlation

Significant effect observed

- No change in X_{max}
- Needs a large part of core hadronization at maximum energy to reach Auger point
- Sibyll with higher mass (deep X_{max}) need less

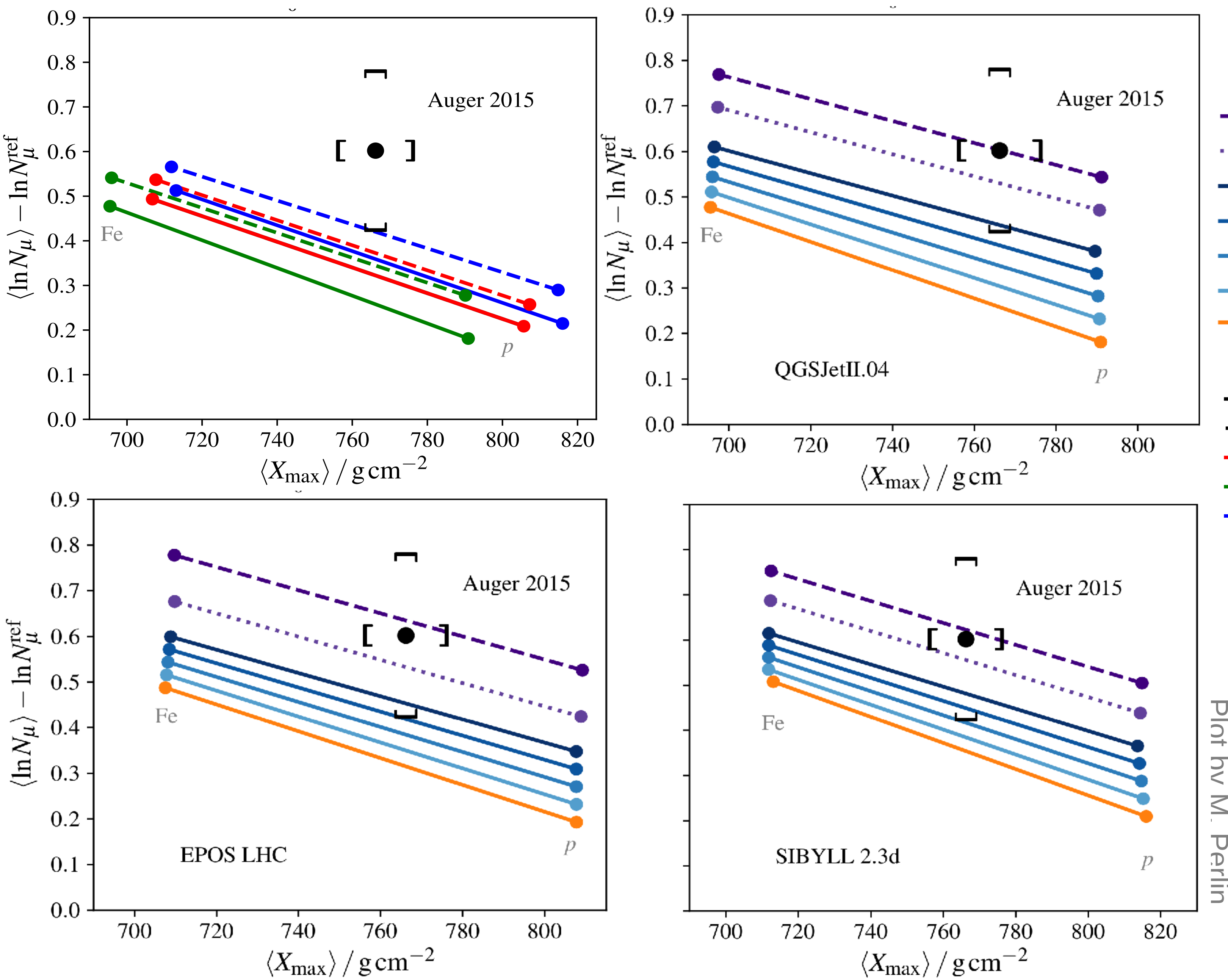


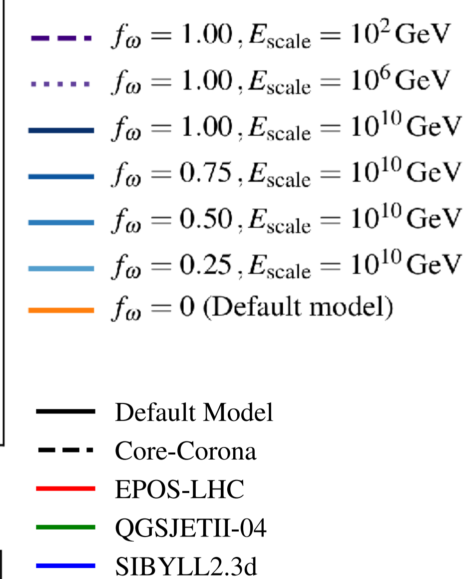




Plot by M. Perlin

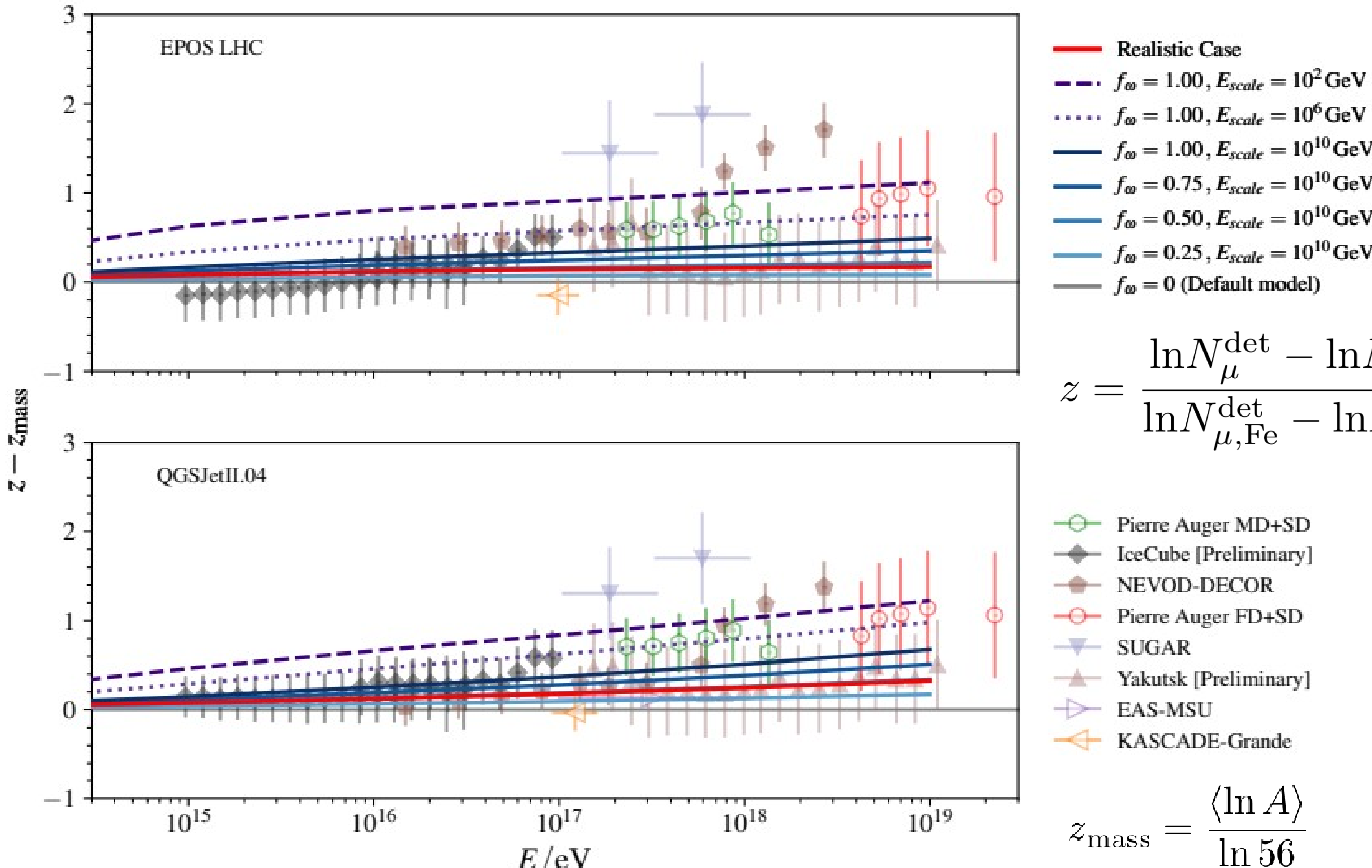
Results for X_{max}-N_{mu} correlation





Forward core fraction unknown and not necessarily lower that at mid-rapidity (saturation effect)

Results for z-scale



$$z = \frac{\ln N_\mu^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}{\ln N_{\mu,\mathrm{Fe}}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}$$

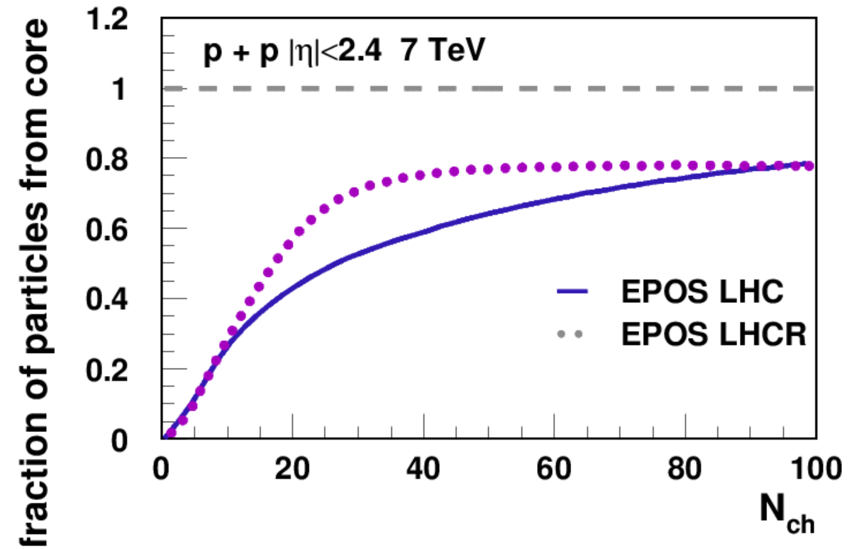
$$z_{\mathrm{mass}} = \frac{\langle \ln A \rangle}{\ln 56}$$

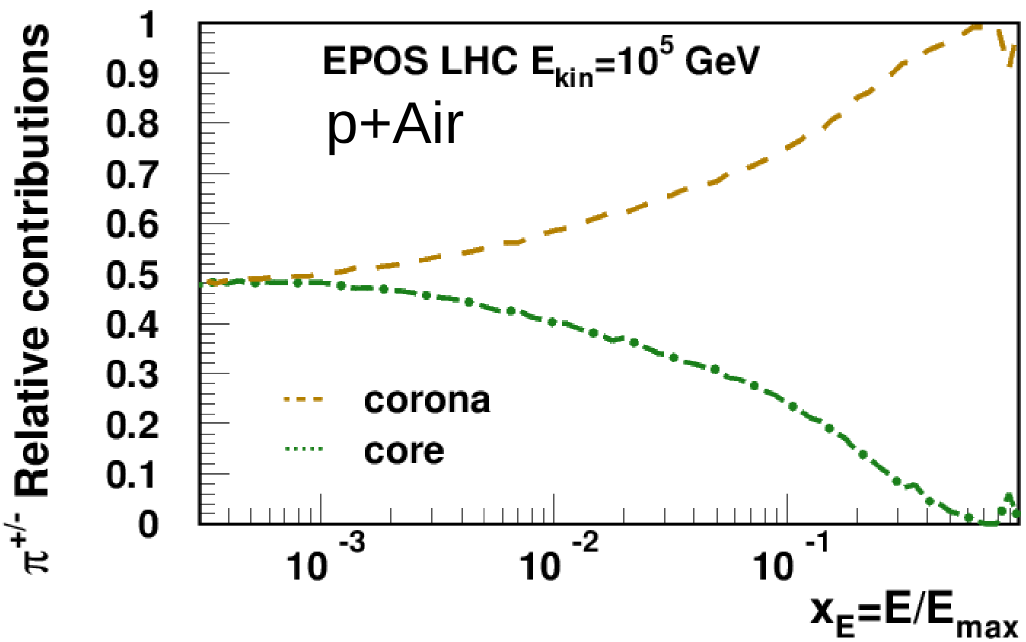
Plot by M. Perlin

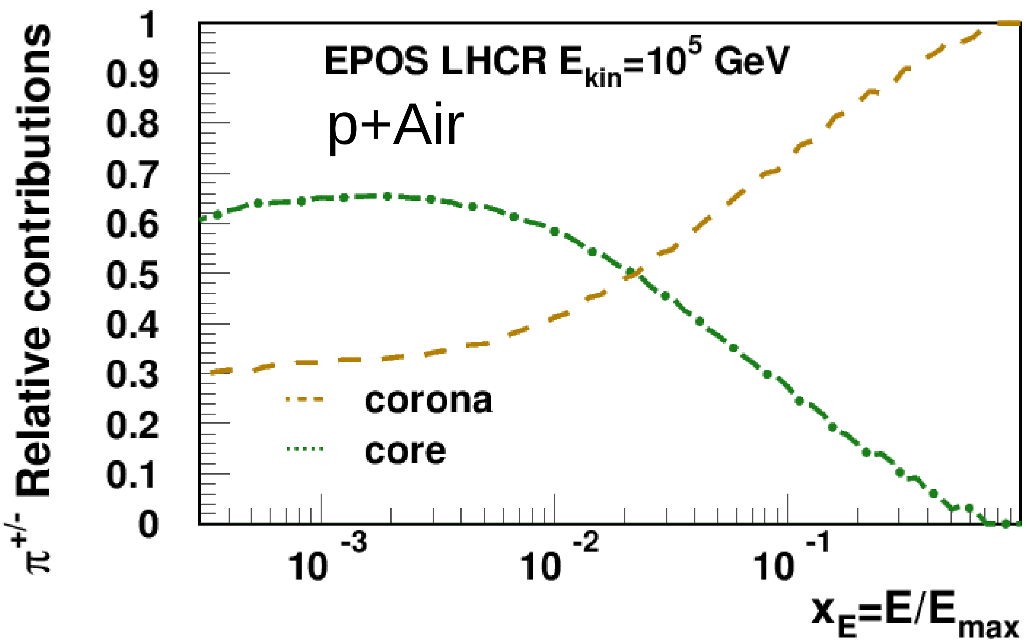
Interactions in Air Showers

Update of EPOS (LHCR) to reproduce ALICE data

- Lower condition (particle density) to form core
- More core and more forward
- Possible impact on muon production in air showers (lower π^0 fraction)







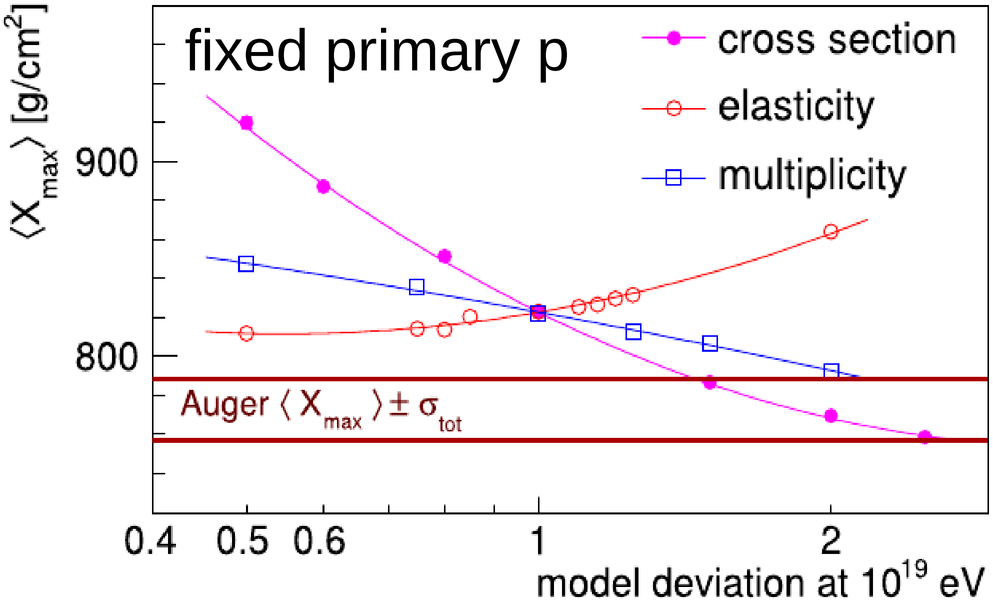
Summary

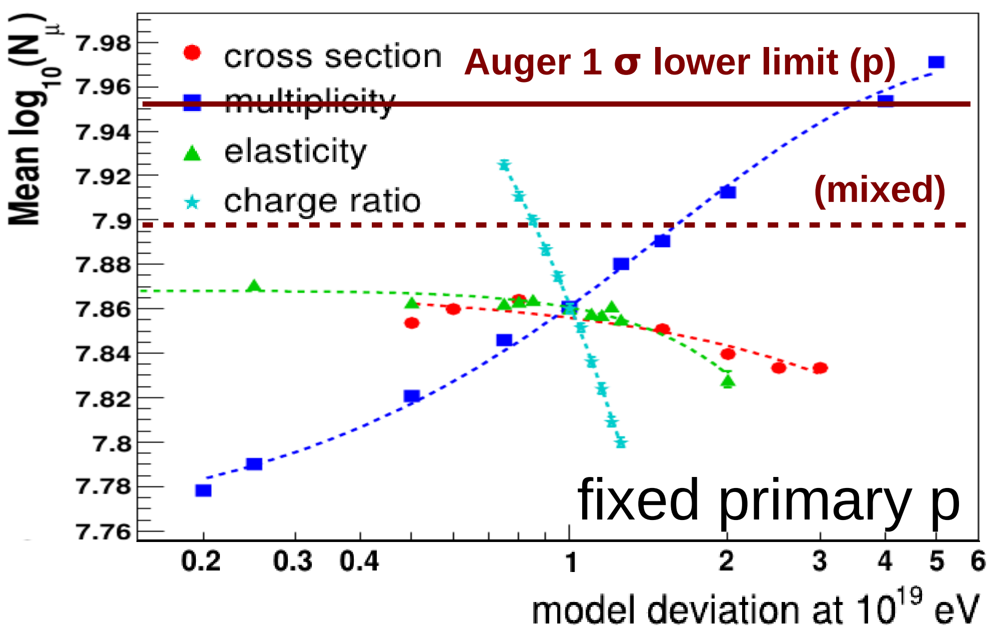
- **WHISP working group clearly established a muon production deficit in air shower simulations.**
  - ➔ Exact scale not known (dependent on energy and mass)
  - ➔ Deficit has a continuous increase above 10^{16} eV
    - ➔ No sudden increase
  - ➔ Zenith angle, muon energy, radial distance effect still to be studied
- **Most "natural" explanation given by a change in electromagnetic to hadronic energy ratio.**
  - ➔ Other possibilities limited by X_{max} (multiplicity, inelasticity)
- **Large change needed for a well constrained observable.**
  - ➔ Different type of hadronization
    - ➔ extended range for QGP-like hadronization could be sufficient with current global uncertainties (energy, X_{max}, ...)
  - ➔ New physics still needed ?
- **Not all relevant CERN data taken into account in model yet.**

Recent LHC data combined with the result of air shower experiment meta-analysis provide a possible explanation of the muon deficit in air shower simulations : QGP-like hadronization could be more common than thought until now.

Thank you !

Sensitivity to Hadronic Interactions





From R. Ulrich (KIT)

- **Air shower development dominated by few parameters**
  - ➡ mass and energy of primary CR
  - ➡ cross-sections (p-Air and (π-K)-Air)
  - ➡ (in)elasticity
  - ➡ multiplicity
  - ➡ charge ratio and baryon production
- **Change of primary = change of hadronic interaction parameters**
  - ➡ cross-section, elasticity, mult. ...

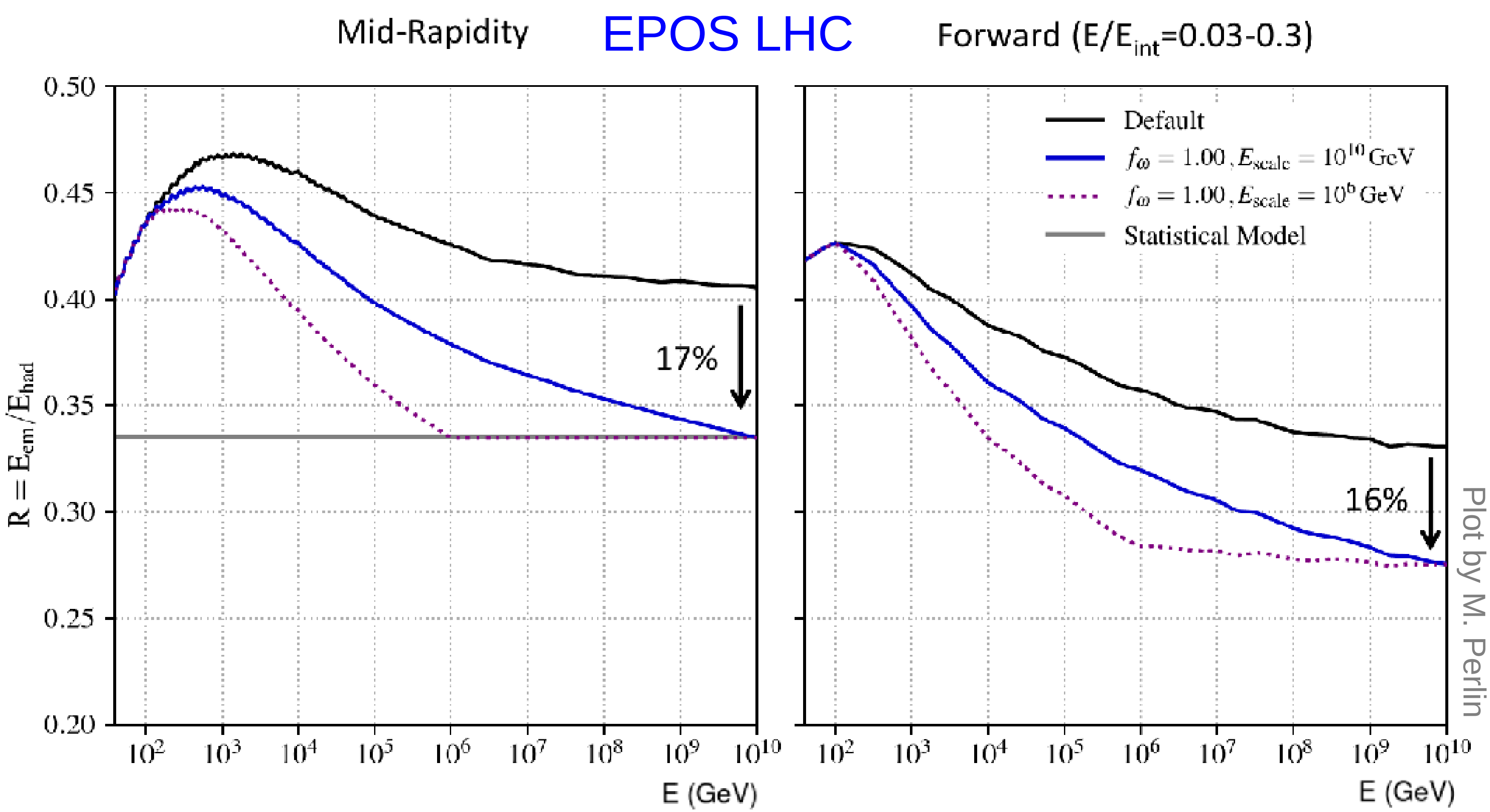
With unknown mass composition hadronic interactions can only be tested using various observables which should give consistent mass results

Evolution of hadronization from core to corona

The relative fraction of π^0 depends on the hadronization scheme

- Change of ω_{core} with energy change $\alpha = \frac{N_{\pi^0}}{N_{mult}}$ or $R(\eta) = \frac{\langle \mathrm{d}E_{\mathrm{em}}/\mathrm{d}\eta \rangle}{\langle \mathrm{d}E_{\mathrm{had}}/\mathrm{d}\eta \rangle}$

  which define the muon production in air showers.



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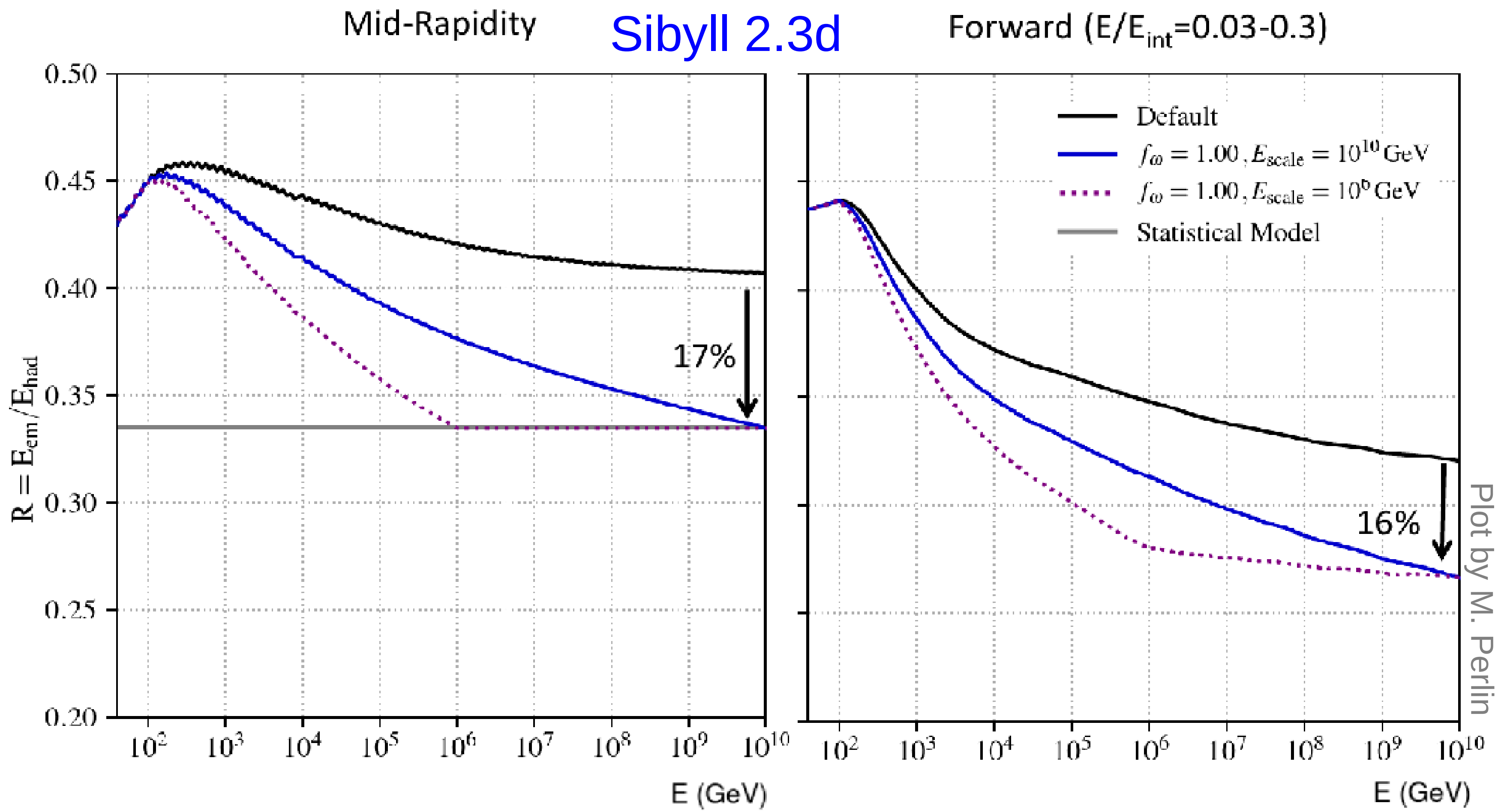
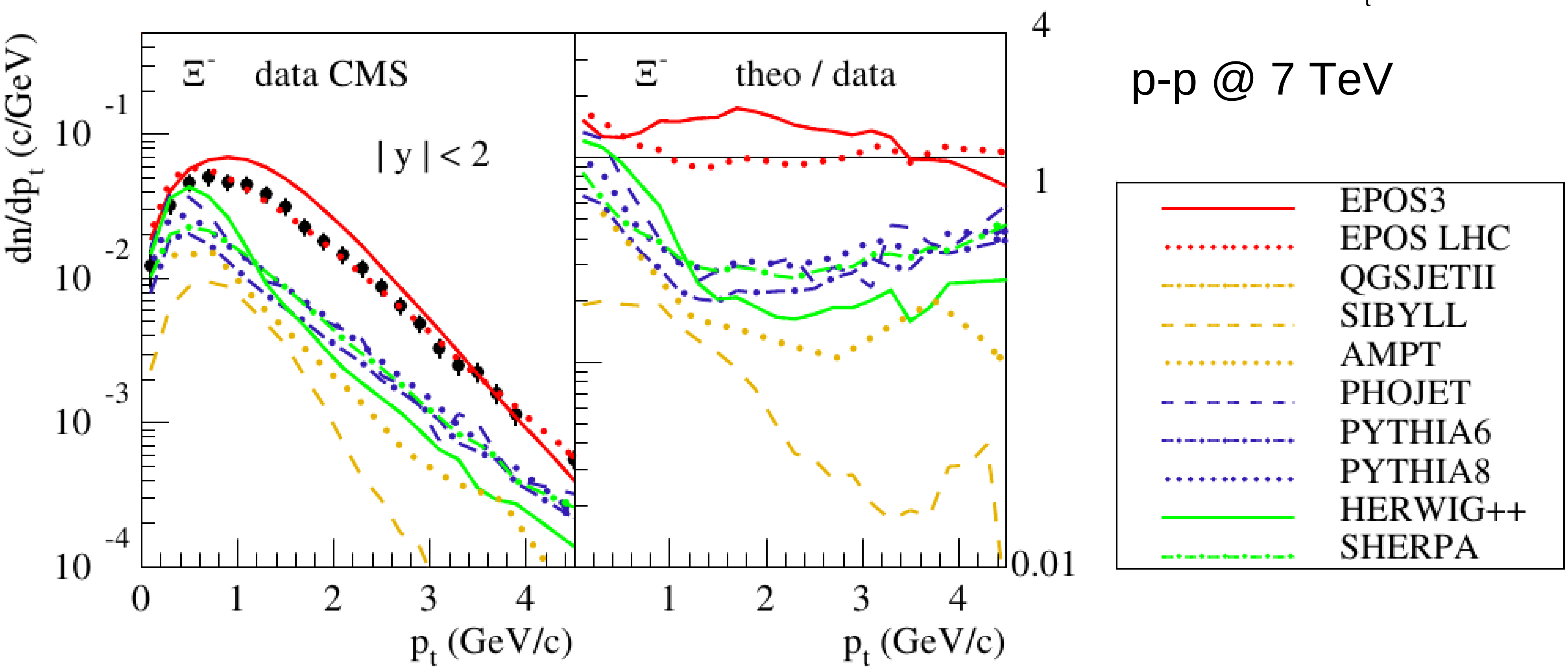


Core in p-p (early LHC data)

Detailed description can be achieved with core in pp

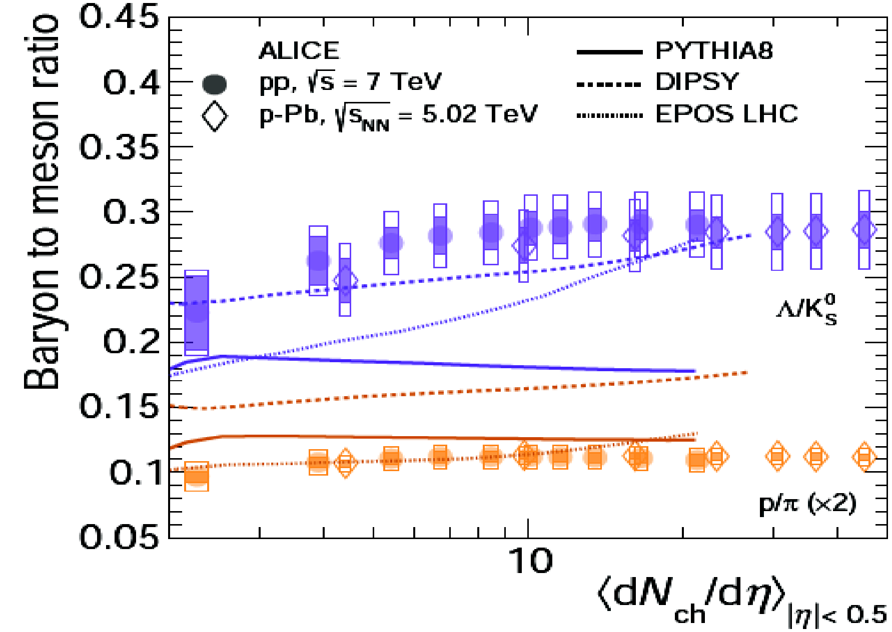
- identified spectra: different strangeness between string (low) and stat. decay (high)
- p_t behavior driven by collective effects (statistical hadronization + flow)
  - larger effect for multi-strange baryons (yield AND <p_t>)

p-p @ 7 TeV

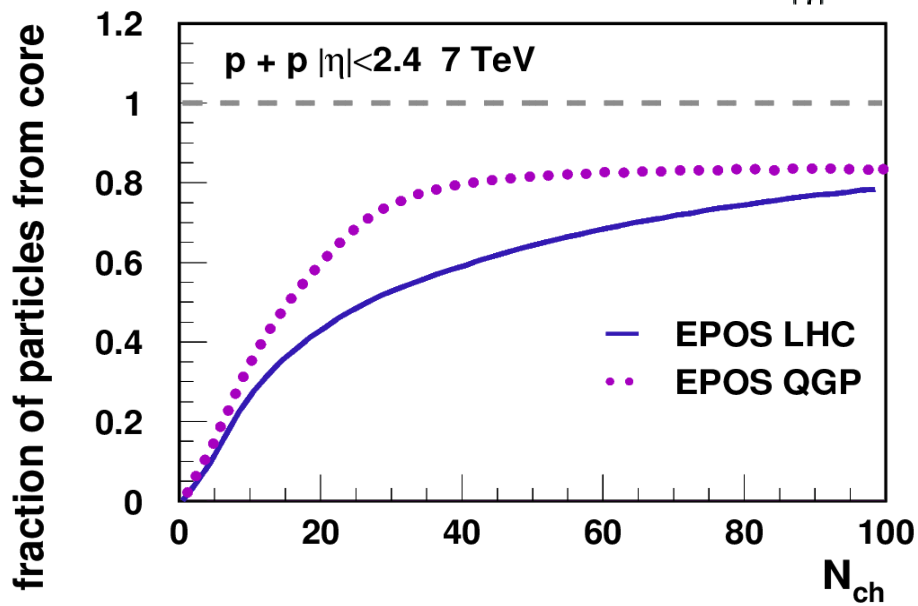


Modified EPOS with Extended Core

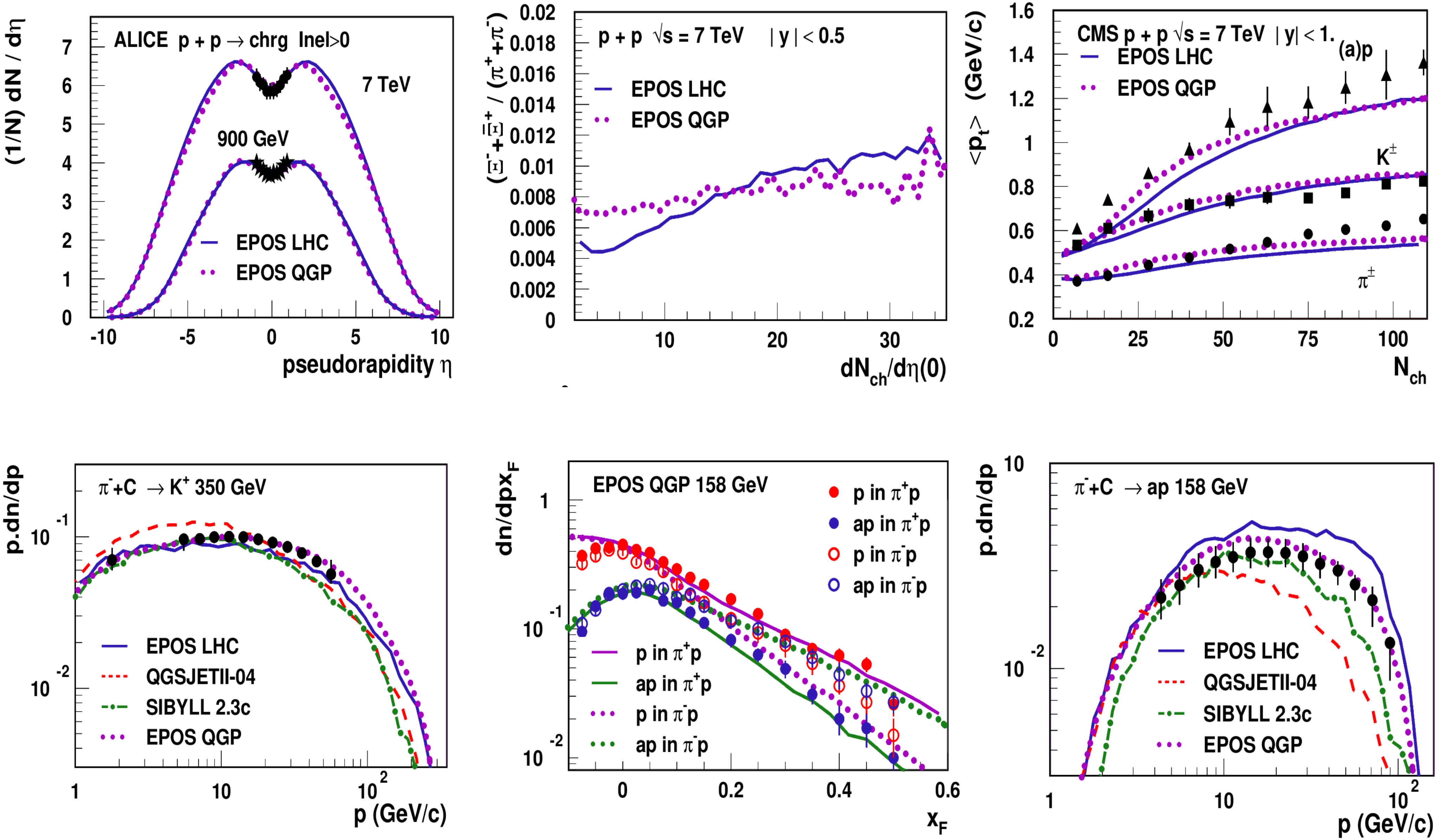
- **Core in EPOS LHC appear too late**
  - ➡ Recent publication show the evolution of chemical composition as a function of multiplicity
  - ➡ Large amount of (multi)strange baryons produced at lower multiplicity than predicted by EPOS LHC



- **Create a new version EPOS QGP with more collective hadronization**
  - ➡ Core created at lower energy density
  - ➡ More remnant hadronized with collective hadronization
  - ➡ Collective hadronization using grand canonical ensemble instead of microcanonical (closer to statistical decay)



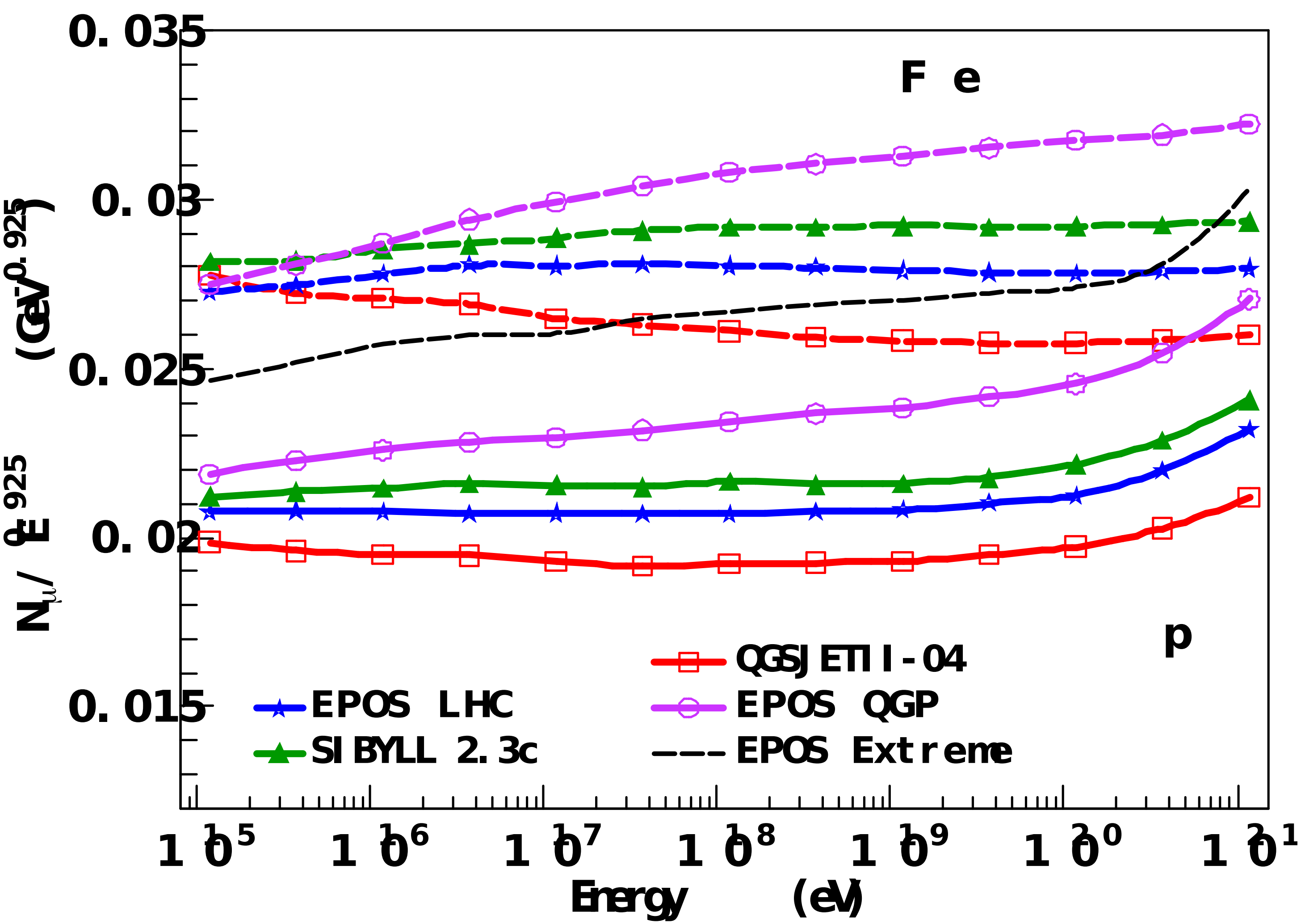
Preliminary Version with Minimum Constraints

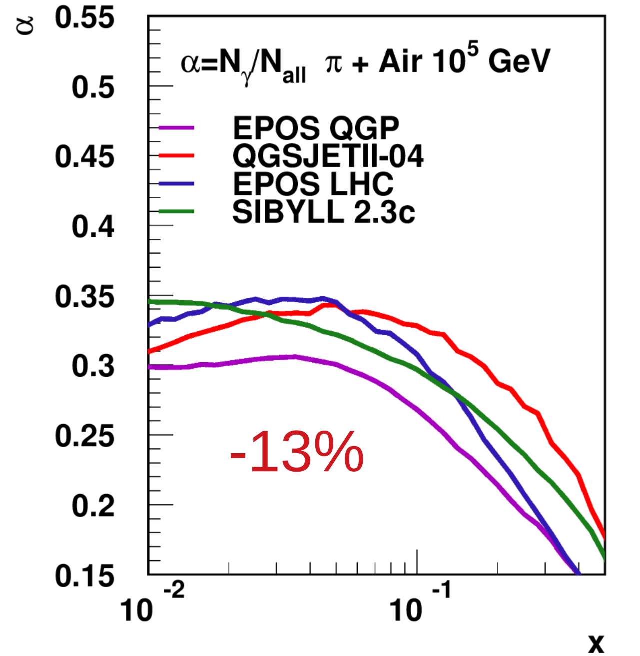


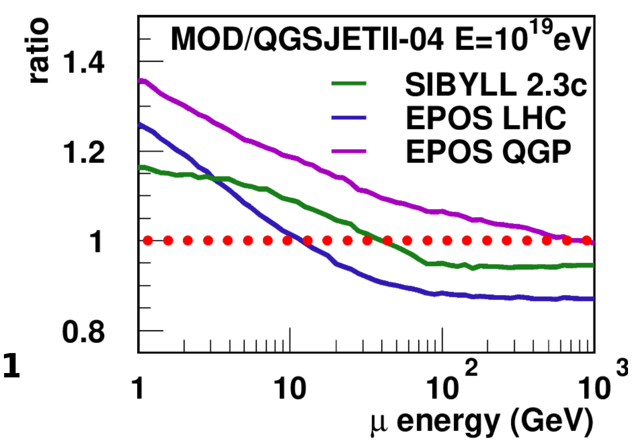
Results for Air Showers

Large change of the number of muons at ground

➡ Different slope as expected from the change in α



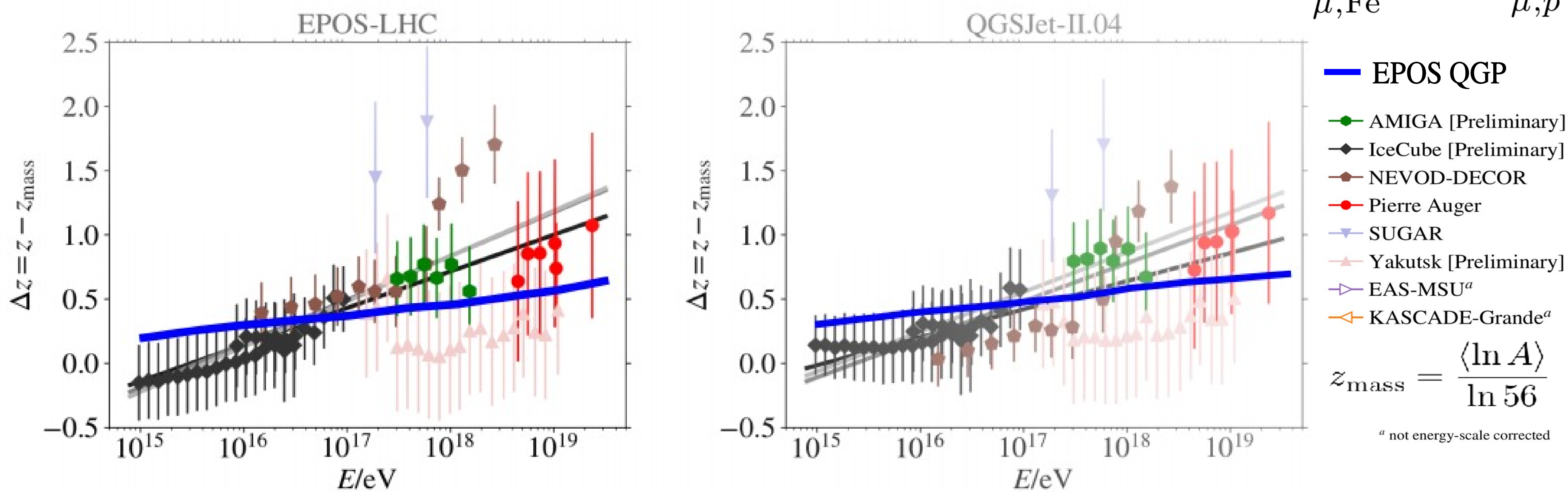




Comparison with Data

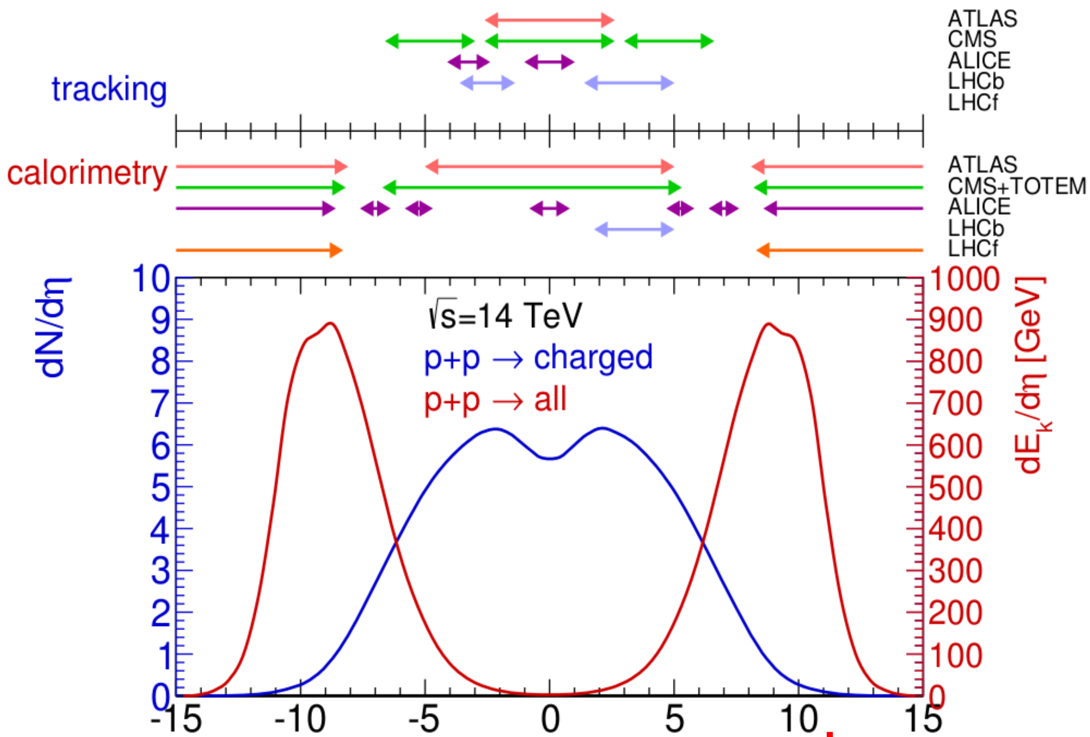
- **Collective hadronization gives a result compatible with data**
  - ➜ Still different energy evolution between data and simulations
    - ➜ Very similar to CONEX study

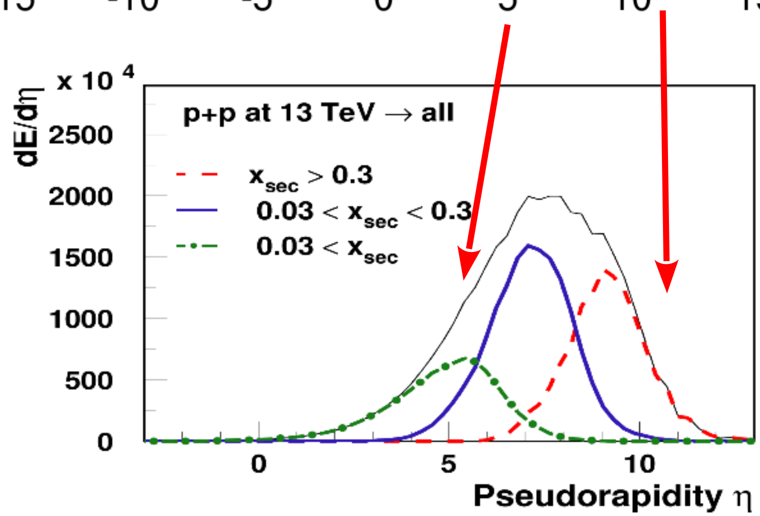
$$z = \frac{\ln N_{\mu}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}{\ln N_{\mu,\mathrm{Fe}}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}$$



- **Probably tension at low energy (too many muons)**
  - ➜ Ideally a larger slope would be needed … what kind of hadronization possible ?
  - ➜ QGP with large chemical potential (Anchordoqui et al.) ?

LHC acceptance and Phase Space

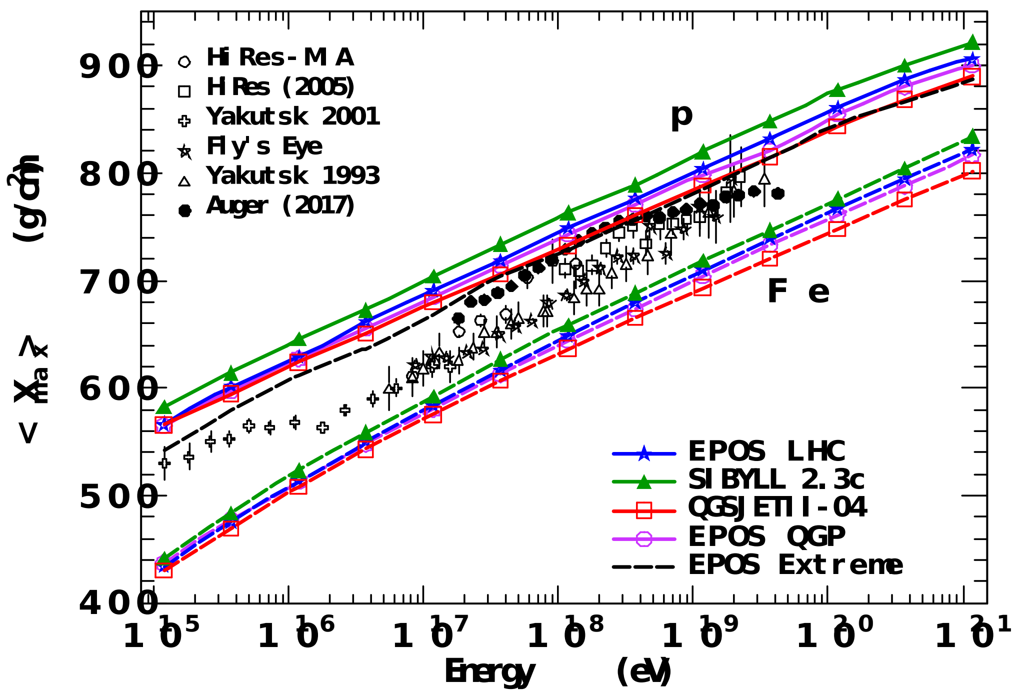


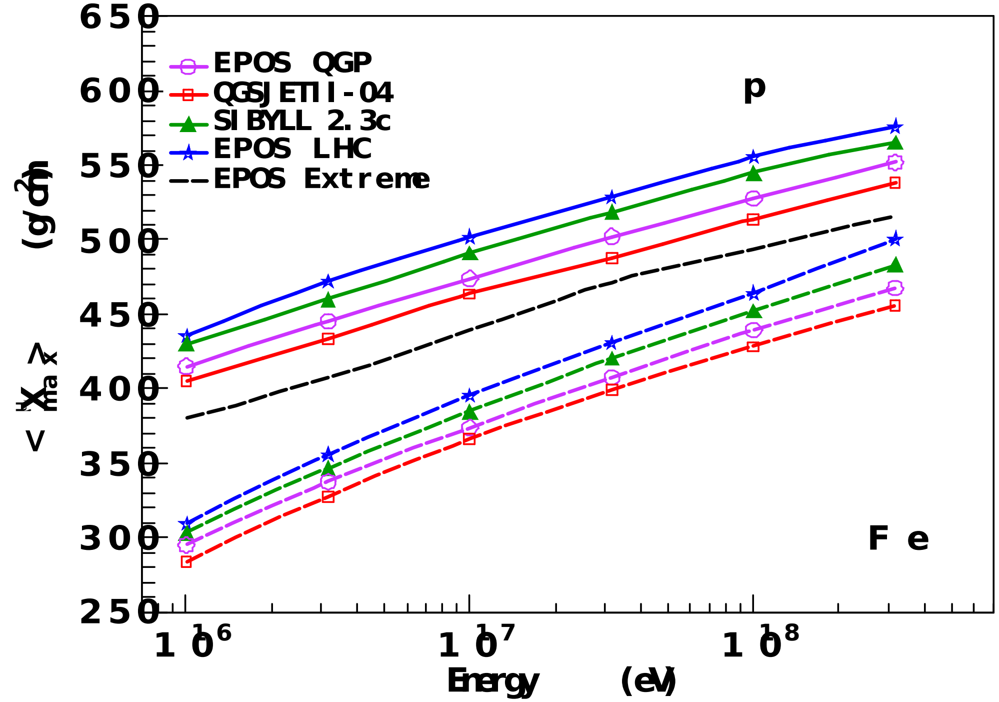


- **p-p data mainly from “central” detectors**
  - pseudorapidity η=-ln(tan(θ/2))
  - θ=0 is midrapidity
  - θ>>1 is forward
  - θ<<1 is backward
- **Different phase space for LHC and air showers**
  - most of the particles produced at midrapidity
    - important for models
  - most of the energy carried by forward (backward) particles
    - important for air showers

Results for Air Showers

- Small change for <X_{max}> as expected
- Significant change of <X^{μ}_{max}>
- Comparison with extreme case (almost only grand canonical hadron.)
  - ➡ maximum effect using this approach
  - ➡ not compatible with accelerator data





WHISP Working Group

- **Lots of muon measurements available**
  - ➡ Auger, EAS-MSU, KASCADE-Grande, IceCube/IceTop, HiRes-MIA, NEMOD/DECOR, SUGAR, TA, Yukutsk
- **Working group (WHISP) created to compile all results together. Analysis led and presented on behalf of all collaborations by H. Dembinski at UHECR 2018 :** **H. Dembinski (LHCb, Germany),**

L. Cazon (Auger, Portugal), R. Conceicao (AUGER, Portugal), F. Riehn (Auger, Portugal), T. Pierog (Auger, Germany),

Y. Zhezher (TA, Russia), G. Thomson (TA, USA) , S. Troitsky (TA, Russia), R. Takeishi (TA, USA),

T. Sako (LHCf & TA, Japan), Y. Itow (LHCf, Japan),

J. Gonzales (IceTop, USA), D. Soldin (IceCube, USA),

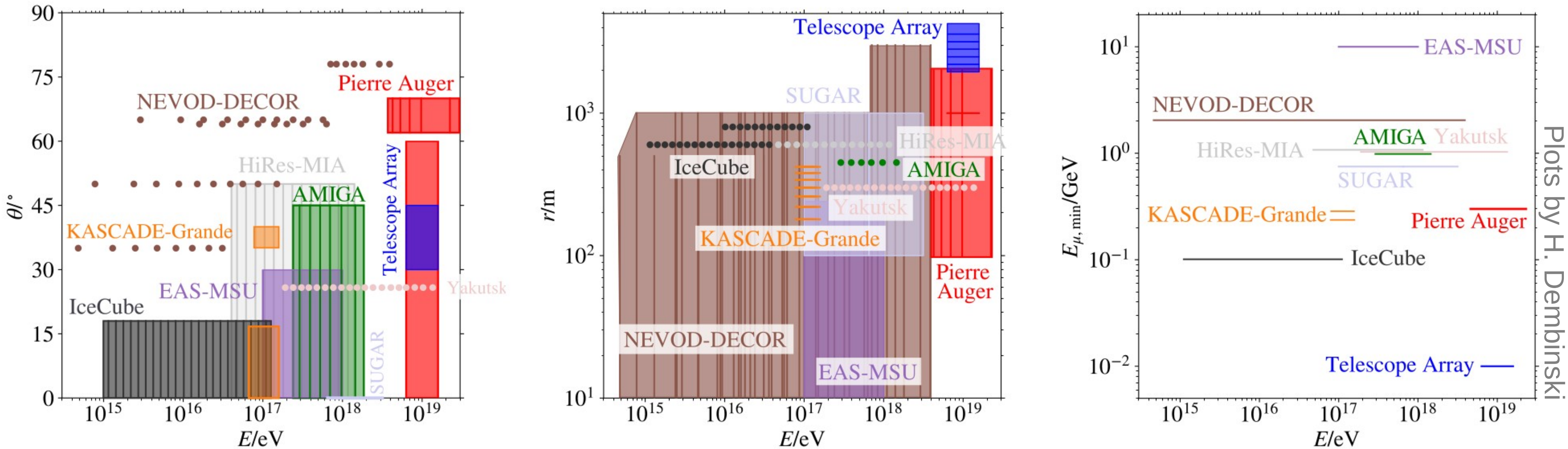
J.C. Arteaga (KASCADE-Grande, Mexico),

I. Yashin (NEMOD/DECOR, Russia). E. Zadeba (NEMOD/DECOR, Russia)

N. Kalmykov (EAS-MSU, Russia) and I.S. Karpikov (EAS-MSU, Russia)

Common Representation

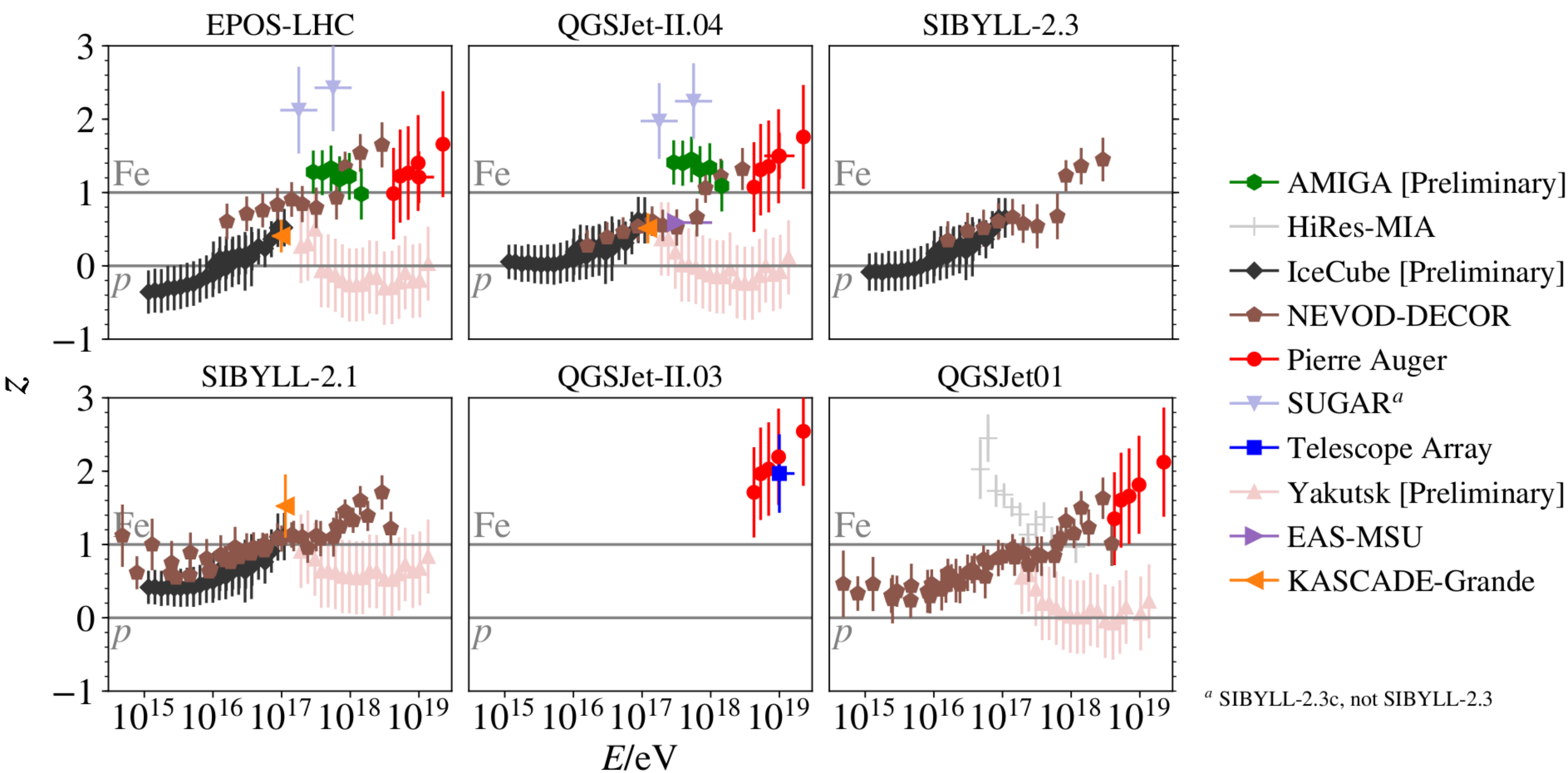
- **Experiments cover different phase space**
  - ➡ Distance to core, zenith angle, energy …



- **Define a unified scale (z) to minimize differences :**

$$z = \frac{\ln N_\mu^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}{\ln N_{\mu,\mathrm{Fe}}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}$$

Raw Data


EPOS-LHC
QGSJet-II.04
SIBYLL-2.3
SIBYLL-2.1
QGSJet-II.03
QGSJet01
Fe
p
z
E/eV
AMIGA [Preliminary]
HiRes-MIA
IceCube [Preliminary]
NEVOD-DECOR
Pierre Auger
SUGAR[a]
Telescope Array
Yakutsk [Preliminary]
EAS-MSU
KASCADE-Grande
[a] SIBYLL-2.3c, not SIBYLL-2.3

Renormalization

- **Define a unified scale (z) to minimize differences :**

$$z = \frac{\ln N_{\mu}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}{\ln N_{\mu,\mathrm{Fe}}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}$$

- **From a simple (Heitler) model, the energy and mass dependence of the muon number is given by :**

$$N_{\mu} = A\left(\frac{E}{AE_0}\right)^{\beta} = A^{1-\beta}\left(\frac{E}{E_0}\right)^{\beta}$$

  ➡ Where β~0.9 is link to hadronic interaction properties

- **To extract proper relative behavior between data and model :**

  ➡ unique energy scale

  ➡ estimation of mass evolution

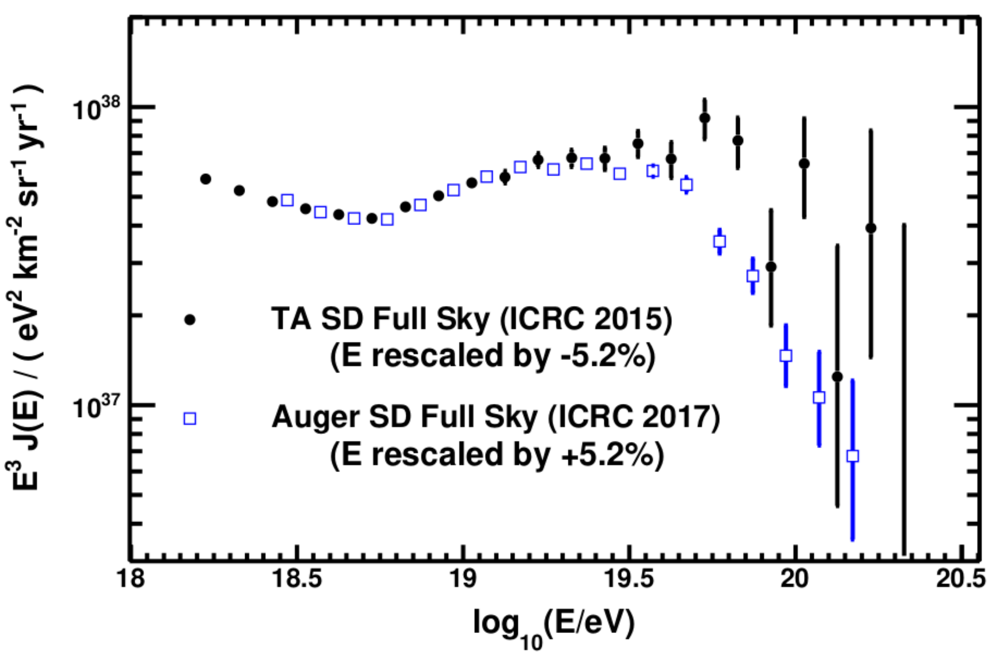
Using an external data based model !

Energy Scale

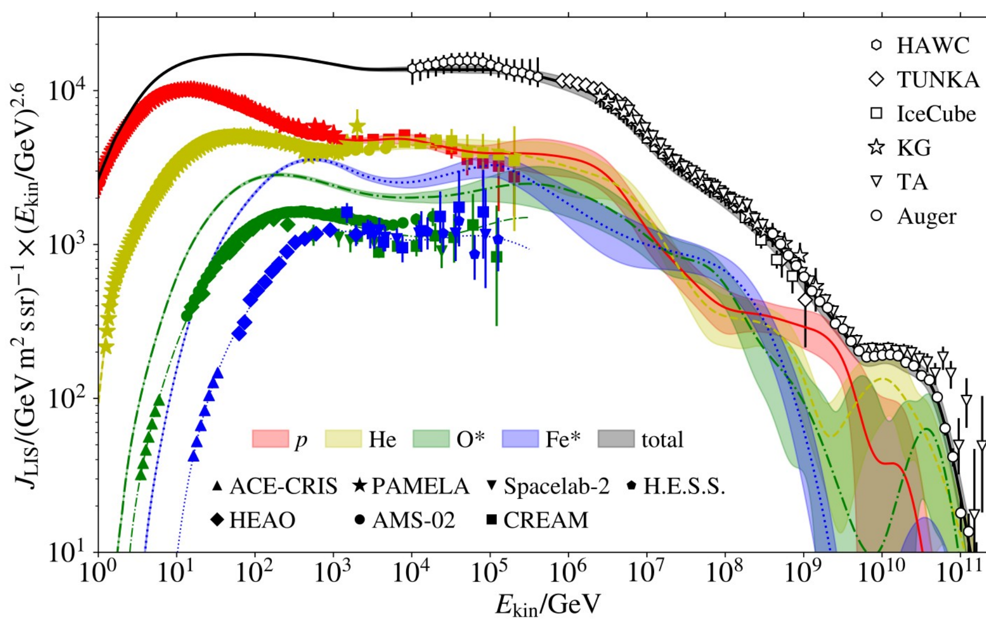
Unique energy scale obtained mixing

- Combine Auger/TA spectrum
- Relative factors between other experiment using the Global Spline Fit (GSF) from H. Dembinski (PoS(ICRC 2017)533)

Experiment	$E_{\mathrm{data}}/E_{\mathrm{ref}}$
EAS-MSU	unknown
IceCube Neutrino Observatory	1.19
KASCADE-Grande	unknown
NEVOD-DECOR	1.08
Pierre Auger Observatory & AMIGA	0.948
SUGAR	0.948
Telescope Array	1.052
Yakutsk EAS Array	1.24

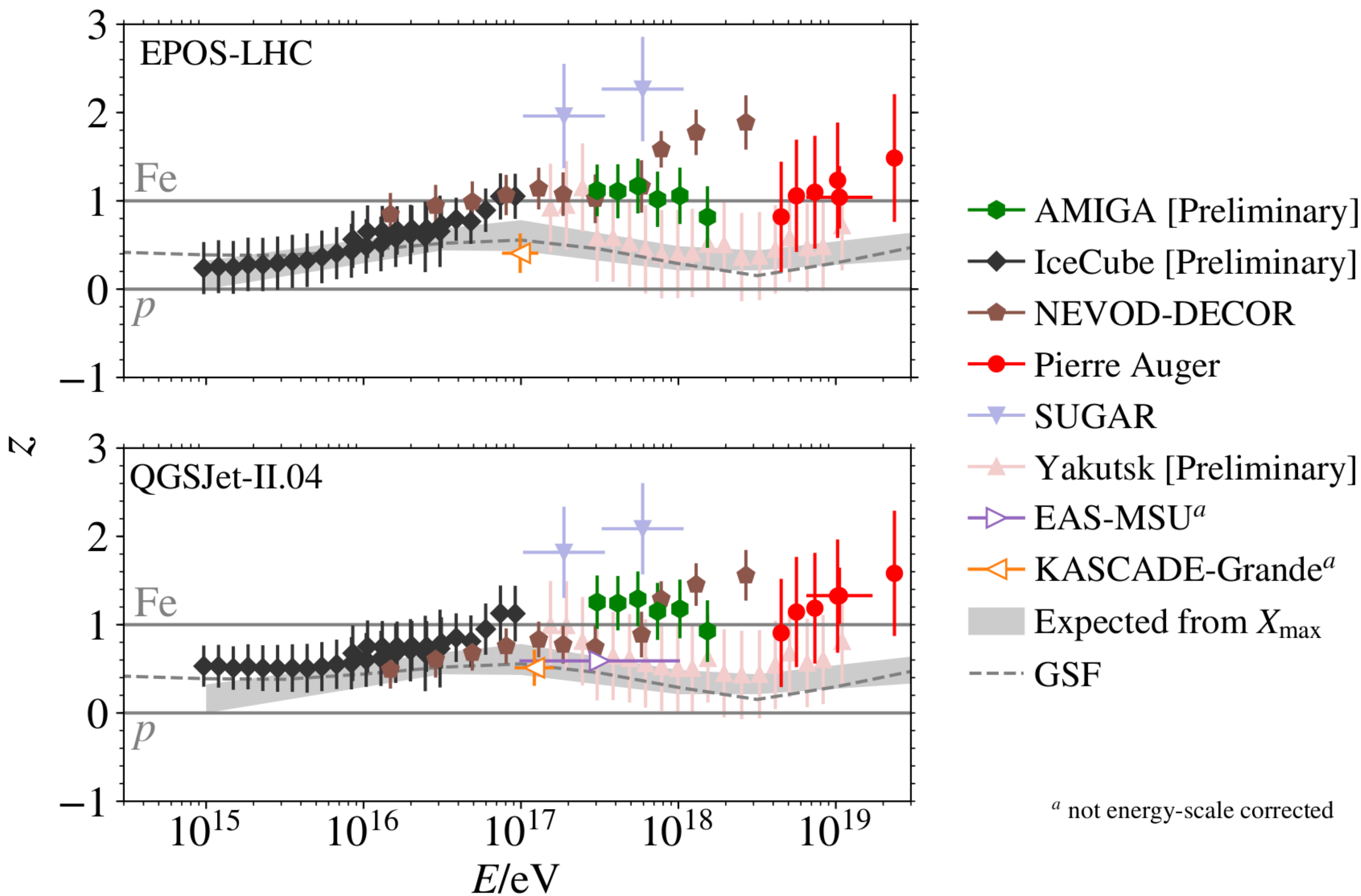


GSF

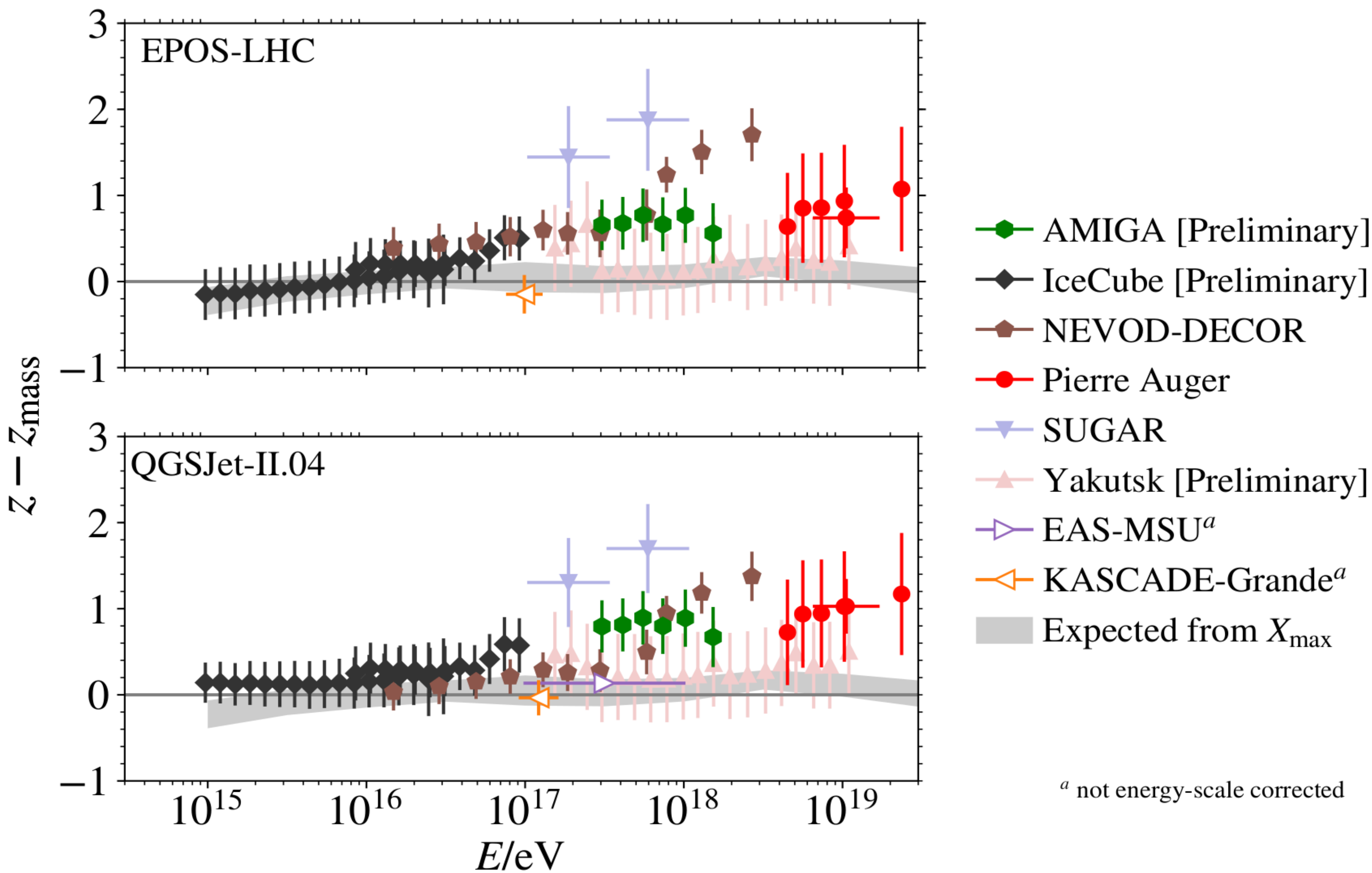


H. Dembinski

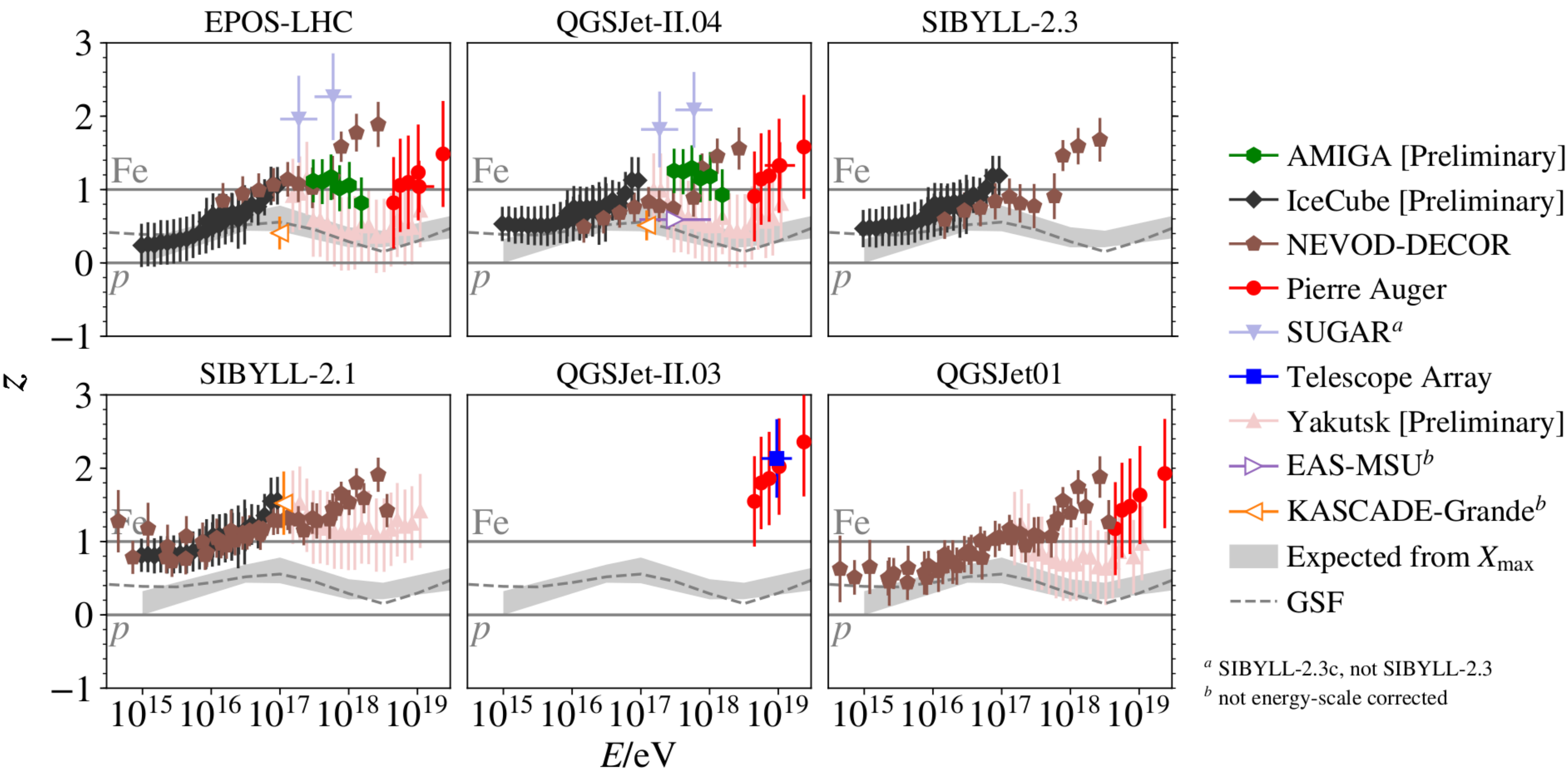
Rescaled Data



Rescaled Data with Mass Correction

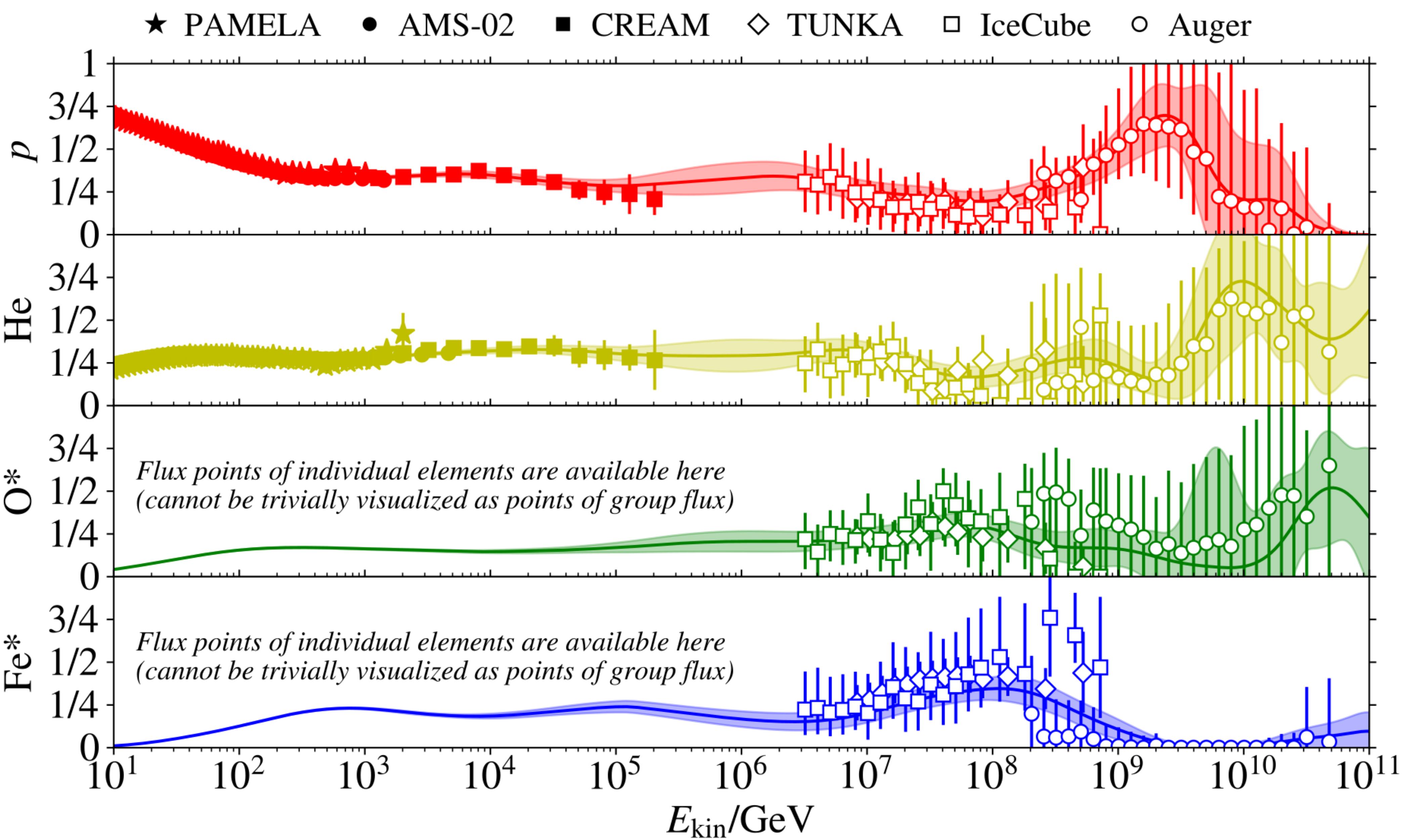


Data Rescaled



[a] SIBYLL-2.3c, not SIBYLL-2.3
[b] not energy-scale corrected

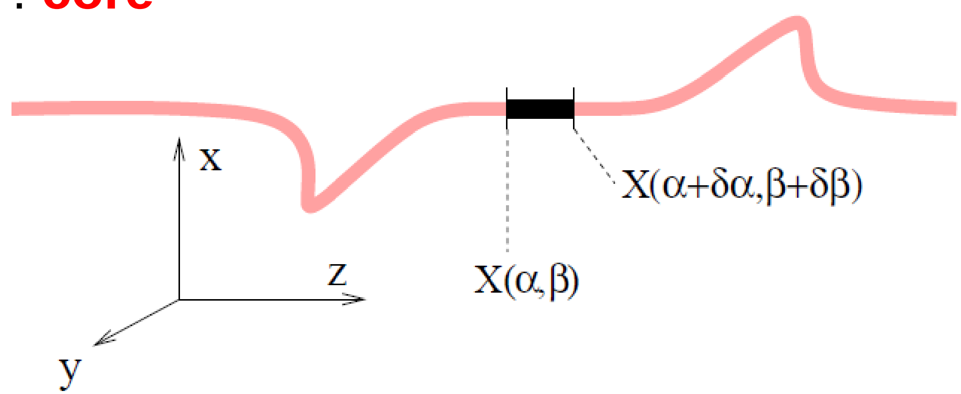
GSF Composition Details



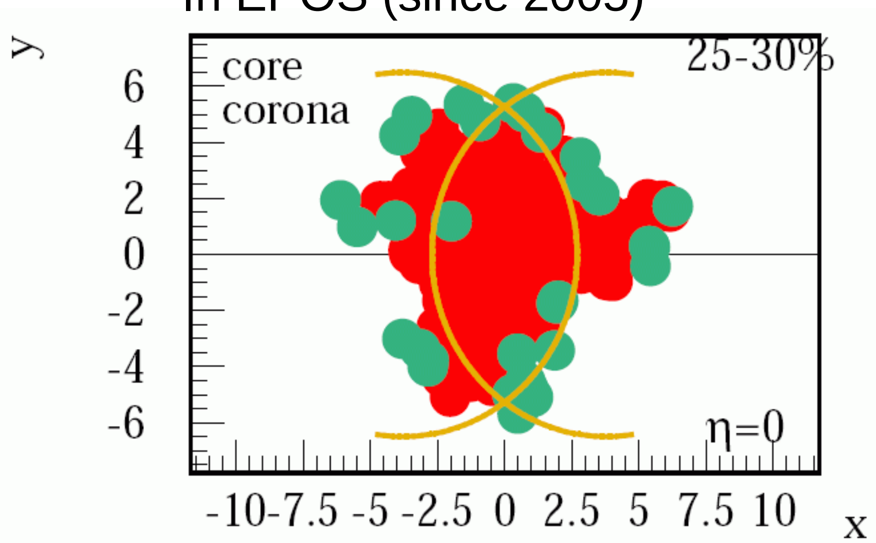
A 3rd way : the core-corona approach

Consider the local density to hadronize with strings OR with QGP:

- First use string fragmentation but modify the usual procedure, since the density of strings will be so high that they cannot possibly decay independently : **core**



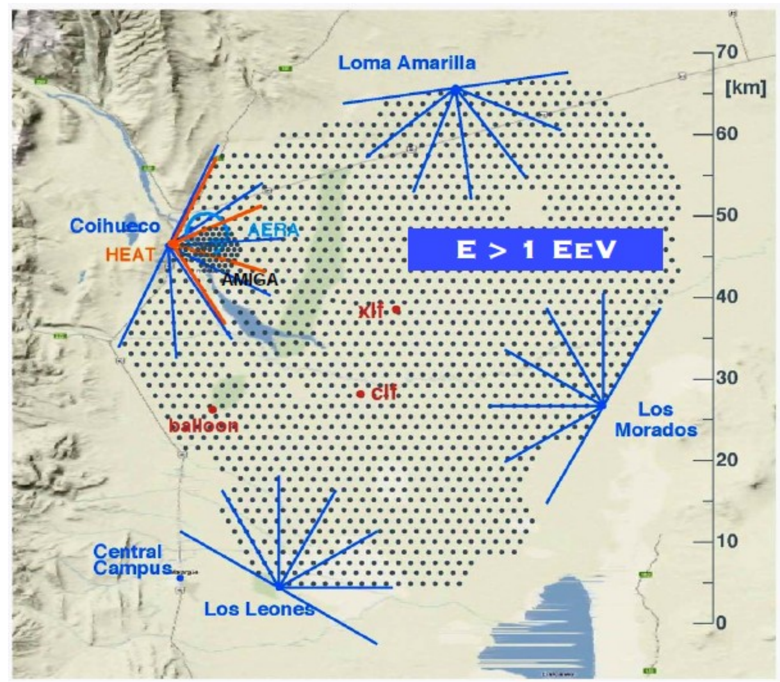
In EPOS (since 2005)

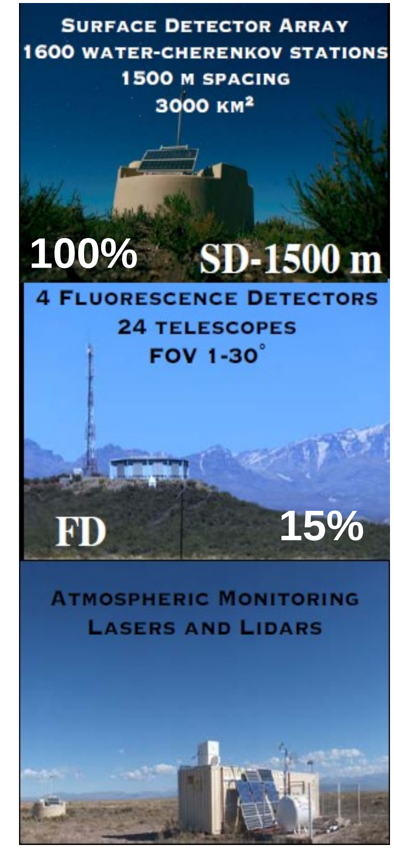


- Each string cut into a sequence of string segments, corresponding to widths δα and δβ in the string parameter space
- If energy density from segments high enough
  - segments fused into core
    - flow from hydro-evolution
    - statistical hadronization
- If low density (corona)
  - segments remain hadrons

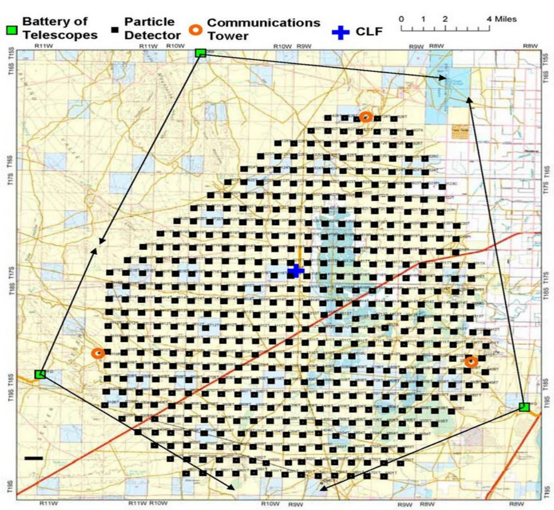
PAO/TA

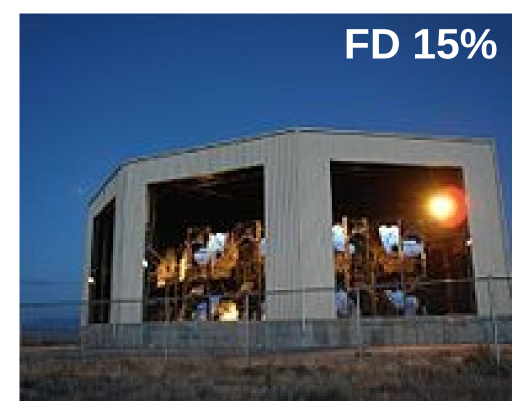
- **Pierre Auger Observatory (PAO)**
  - Mendoza, Argentina
  - Southern Hemisphere
  - 3000 km^2: 32000 km^2/sr/yr



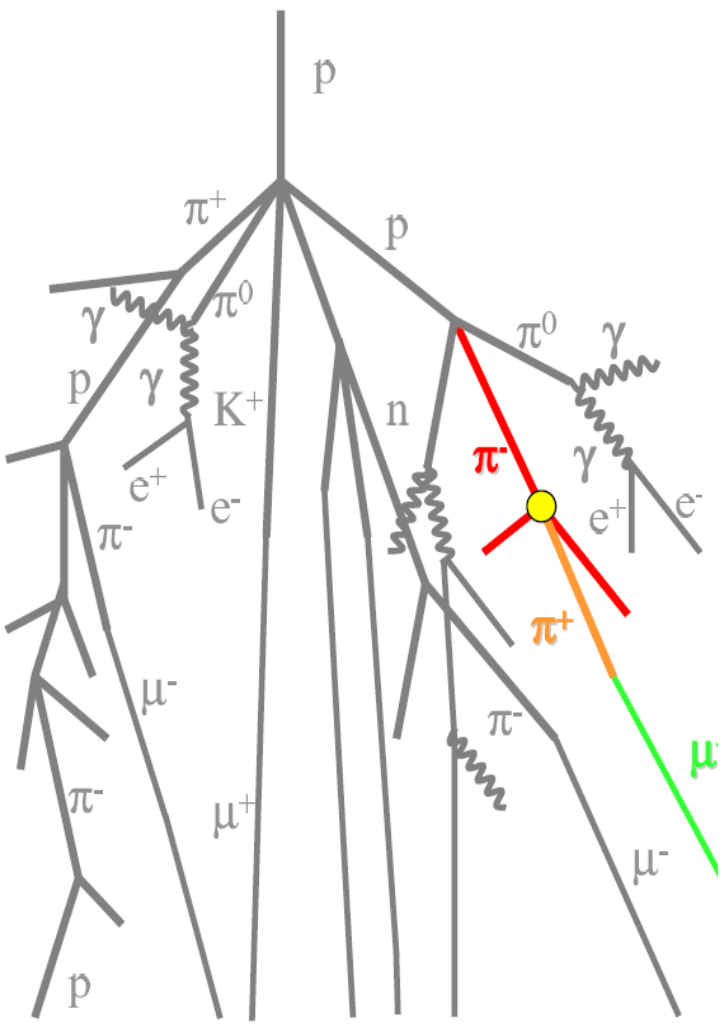


- **Telescope Array (TA)**
  - Utah, USA
  - Northern Hemisphere
  - 680 km^2: 3700 km^2/sr/yr

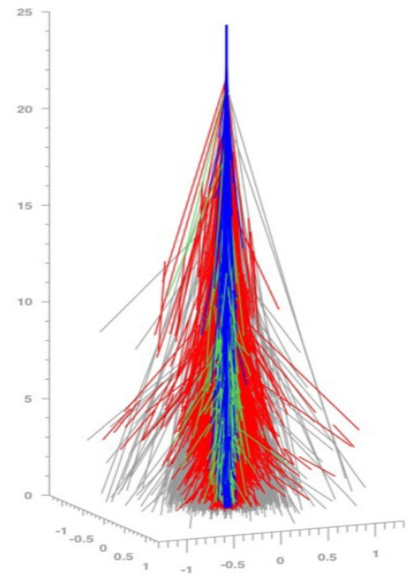




Extensive Air Shower



From R. Ulrich (KIT)



$$A + air \rightarrow \text{hadrons}$$
$$p + air \rightarrow \text{hadrons}$$
$$\pi + air \rightarrow \text{hadrons}$$

hadronic physics

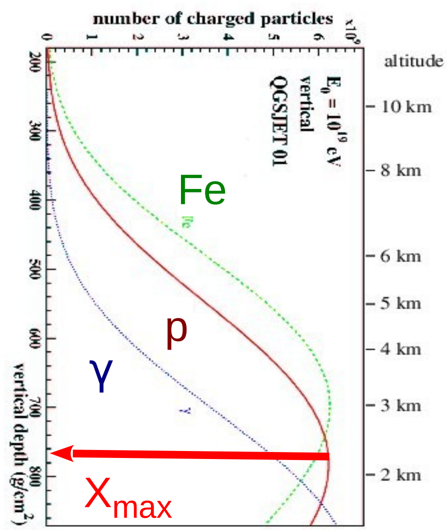
initial γ from π^0 decay

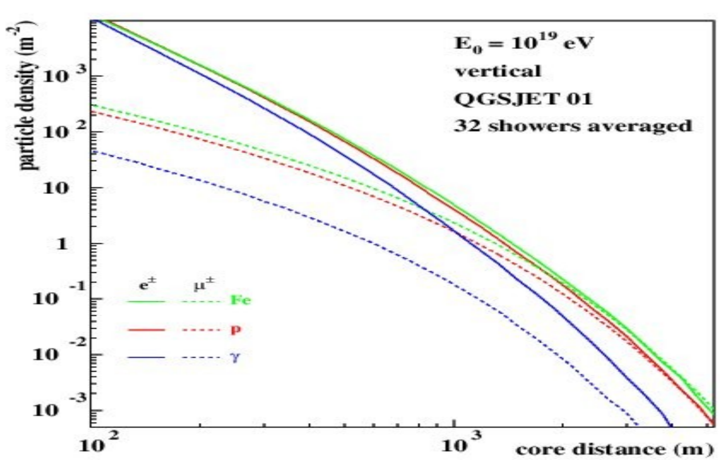
$$e^\pm \rightarrow e^\pm + \gamma$$
$$\gamma \rightarrow e^+ + e^-$$

well known QED

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu / \bar{\nu_\mu}$$

Cascade of particle in Earth's atmosphere





X_{max}

+/- 20g/cm² is a realistic uncertainty band but :

- minimum given by QGSJETII-04 (high multiplicity, low elasticity)
- maximum given by Sibyll 2.3c (low multiplicity, high elasticity)
- anything below or above won't be compatible with LHC data