

# Muon Puzzle in Air Showers

Tanguy Pierog

Karlsruhe Institute of Technology,  
Institute for Astroparticle Physics, Karlsruhe, Germany



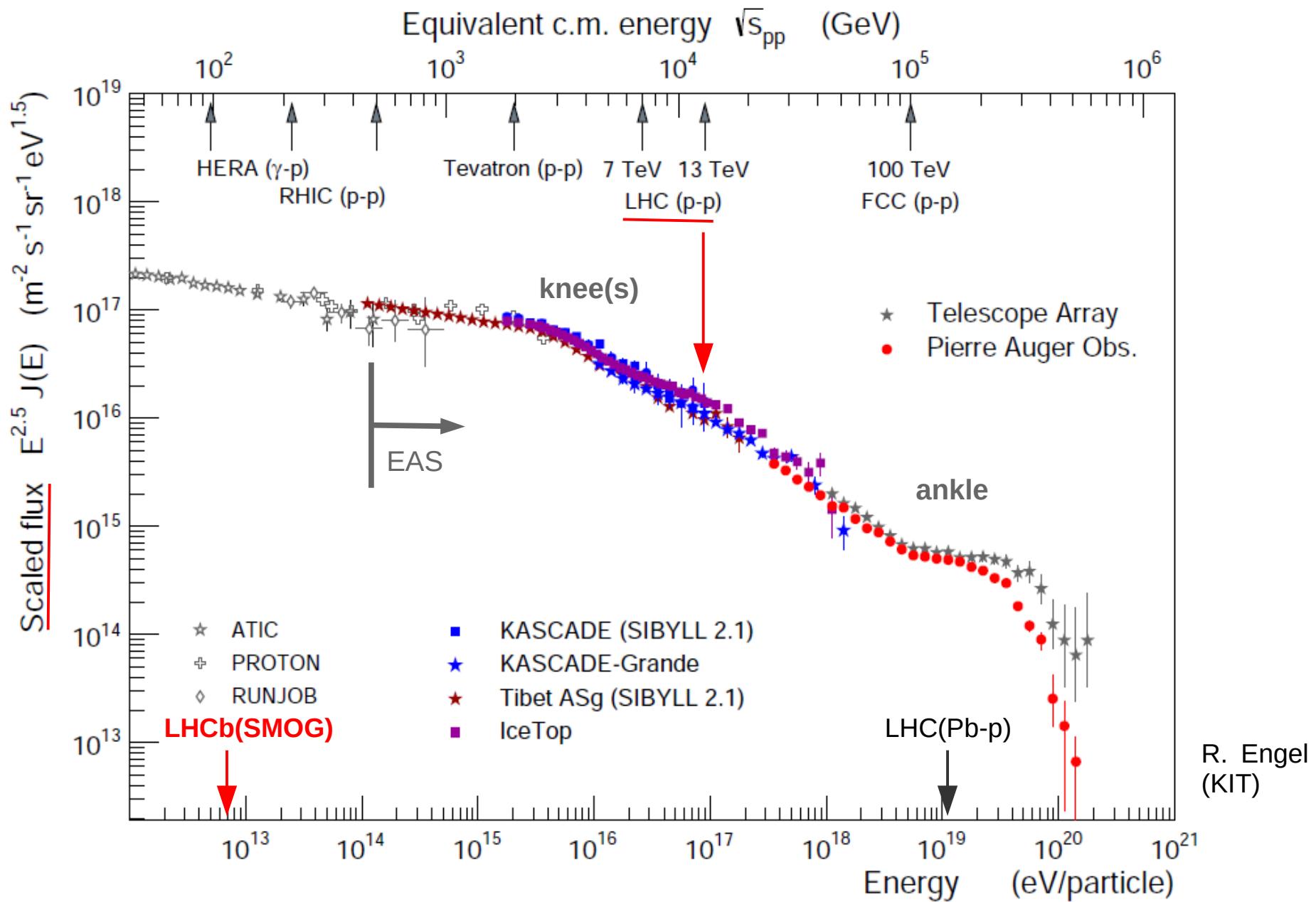
**QCD Challenges from pp to AA collisions, Padova, Italy**  
**February the 13<sup>th</sup> 2023**

# Outline

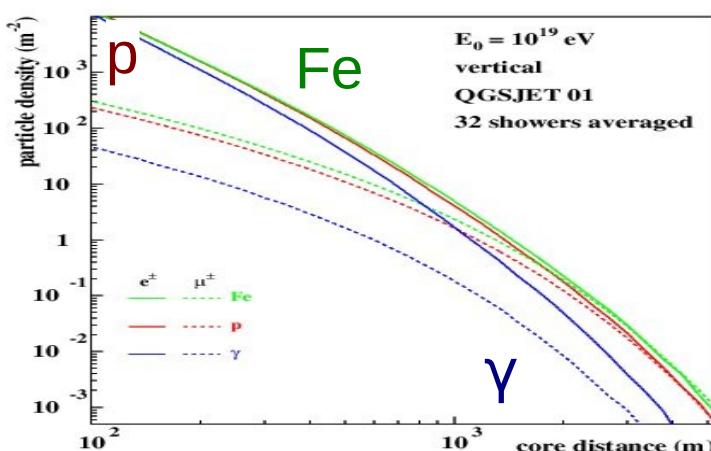
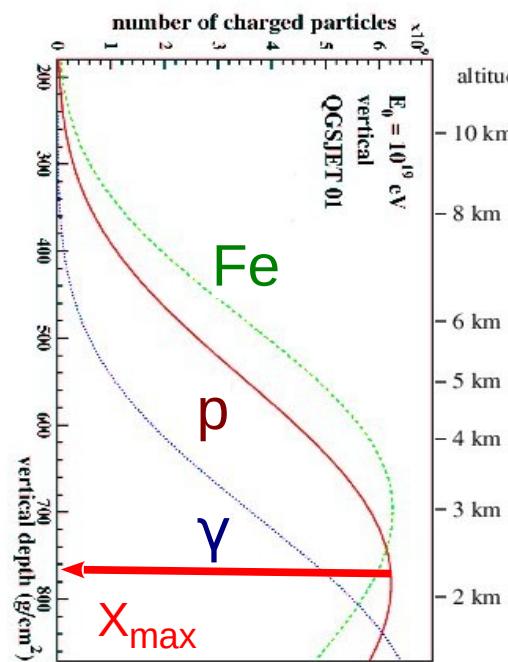
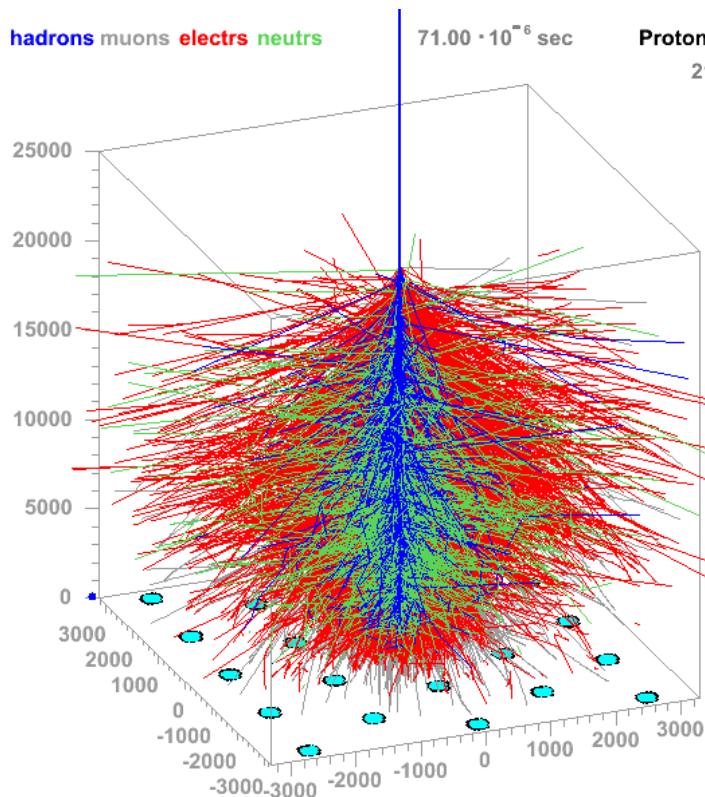
- **Introduction**
- **Muon “puzzle”**
  - WHISP: Global view of the muon excess compared to simulations
- **Hadronizations**
  - Simple vs complex environment
- **Quark Gluon Plasma and Cosmic Rays**
  - Qualitative tests
- **Xmax ?**

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

# Energy Spectrum



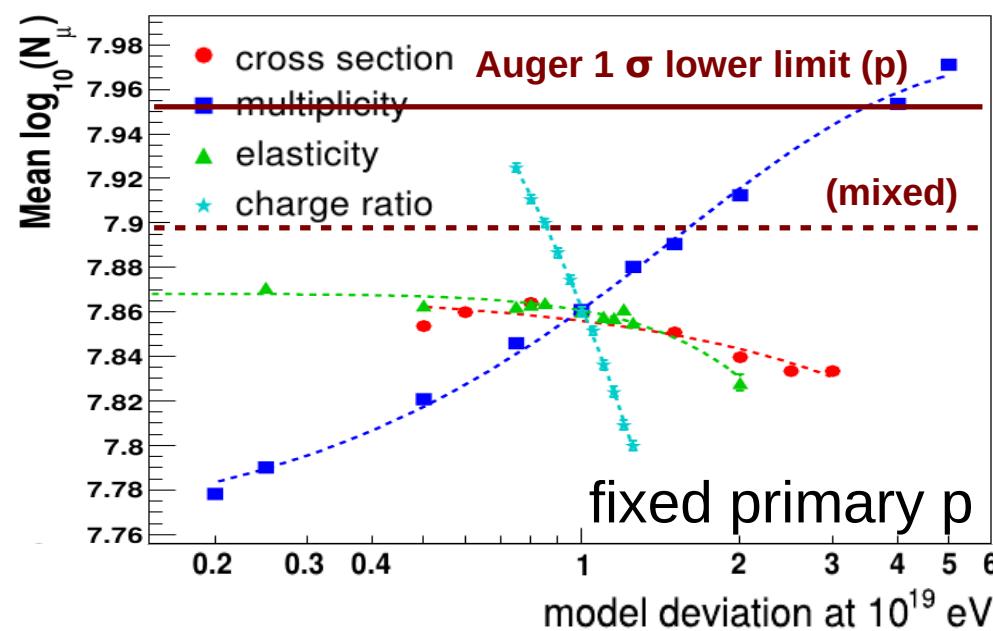
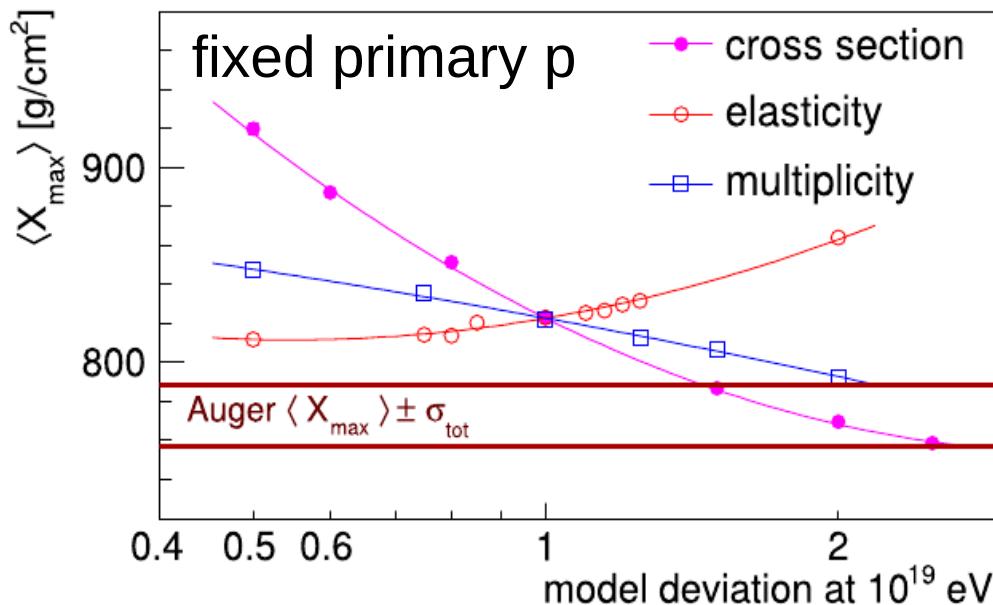
# Extensive Air Shower Observables



- **Longitudinal Development**
  - number of particles vs depth
 
$$X = \int_h^{\infty} dz \rho(z)$$
  - Larger number of particles at  $X_{\text{max}}$
  - For many showers
    - ◆ mean :  $\langle X_{\text{max}} \rangle$
    - ◆ fluctuations : RMS  $X_{\text{max}}$
    - ◆ depends on primary mass
    - ◆ depends on Hadr. Inter.

- **Lateral distribution function (LDF)**
  - particle density at ground vs distance to the impact point (core)
  - can be muons or electrons/gammas or a mixture of all.
- **Others: Cherenkov emissions, Radio signal**

# Sensitivity to Hadronic Interactions



- Air shower development dominated by few parameters
  - ➔ mass and energy of primary CR
  - ➔ cross-sections (p-Air and  $\pi$ -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 observable which should give consistent mass results

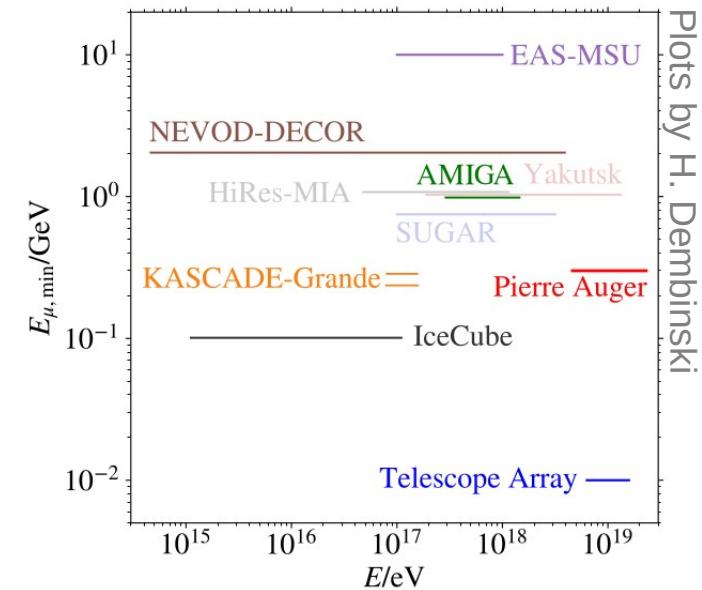
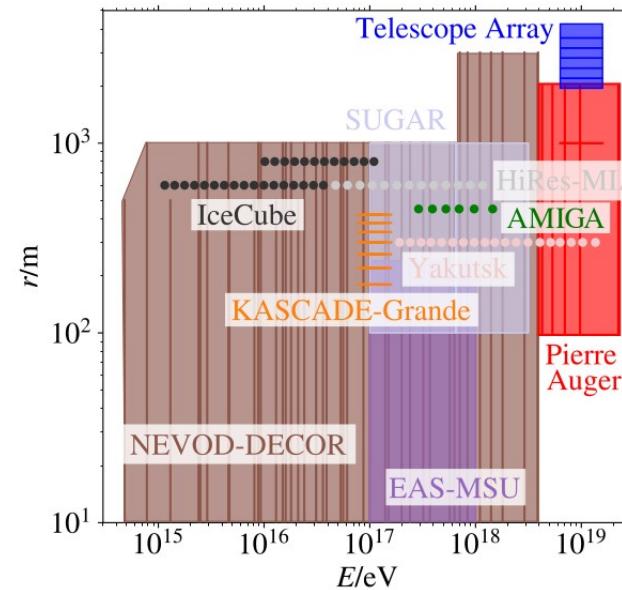
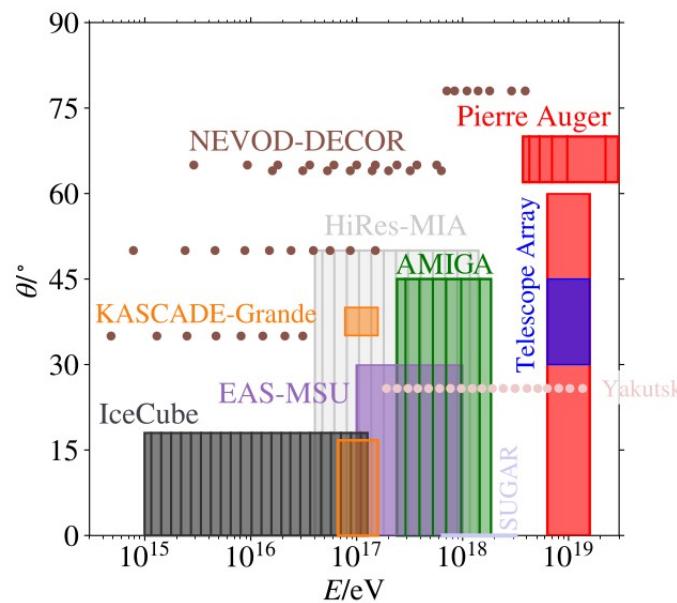
# WHISP Working Group

- Meta-analysis of all muon measurement from air showers

AGASA, Auger, EAS-MSU, KASCADE-Grande, IceCube/IceTop,  
HiRes-MIA, NEMOD/DECOR, SUGAR, TA, Yakutsk

- Experiments cover different phase space

→ Distance to core, zenith angle, energy, energy scale ...



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

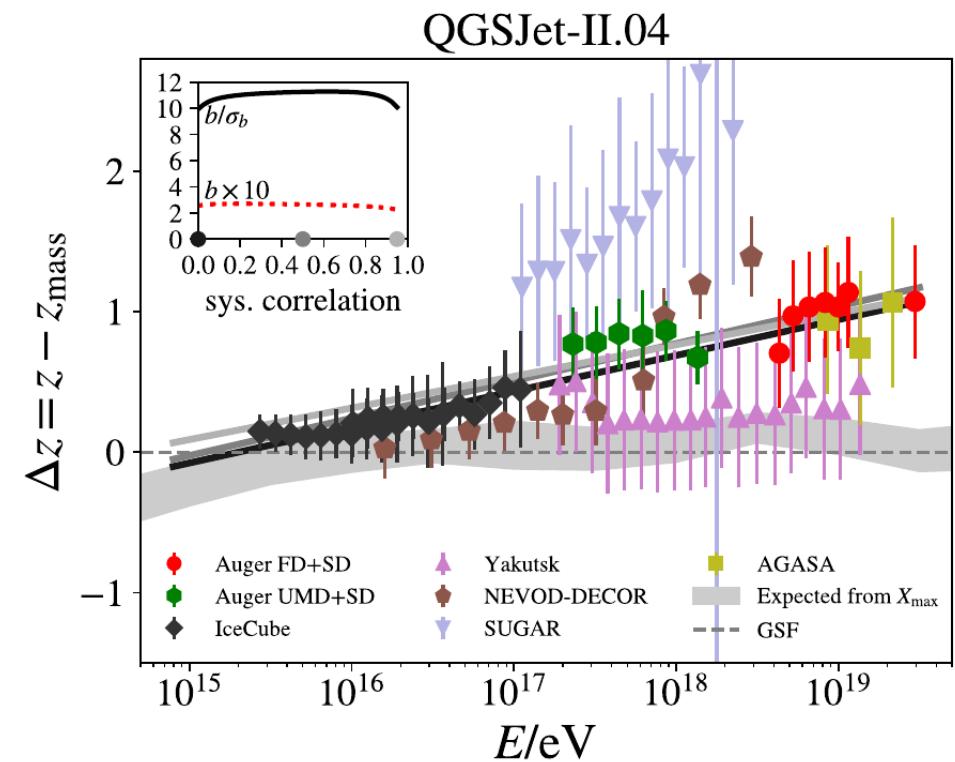
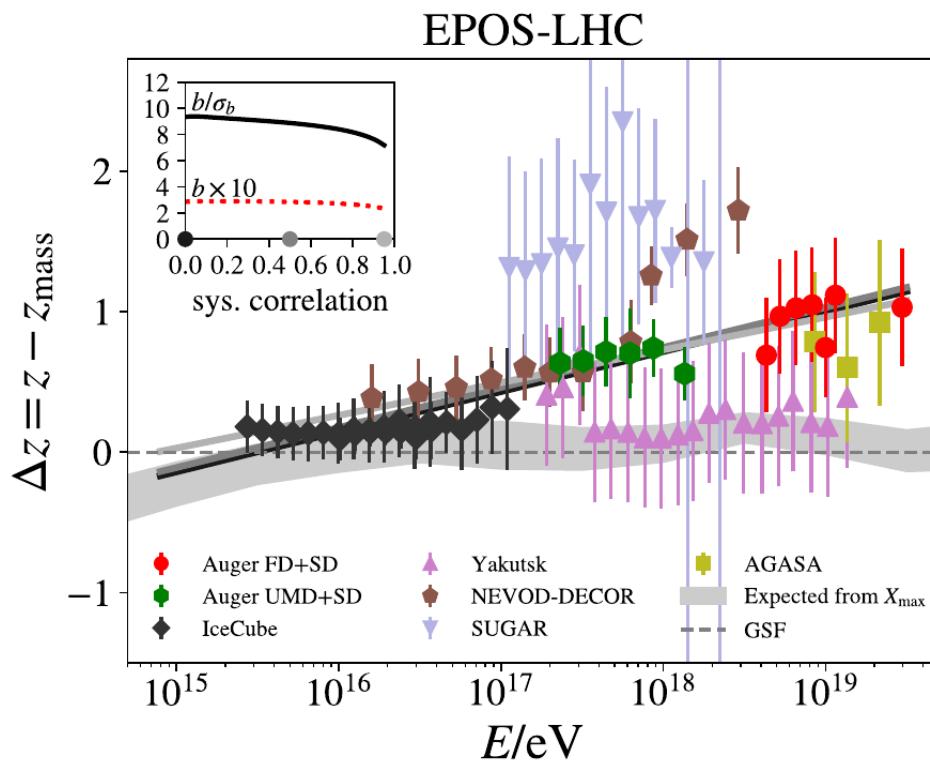
$$z = \frac{\ln N_{\mu}^{\text{det}} - \ln N_{\mu,p}^{\text{det}}}{\ln N_{\mu,\text{Fe}}^{\text{det}} - \ln N_{\mu,p}^{\text{det}}}$$

# Global Behavior after Corrections

- Clear muon excess in data compared to simulation
  - Different energy evolution between data and simulations
    - Significant non-zero slope ( $>8\sigma$ )

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

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



- Different energy cannot change the slope
  - Different property of hadronic interactions at least above  $10^{17}$  eV

# Constraints from Correlated Change

- One needs to change energy dependence of muon production by  $\sim +4\%$

- To reduce muon discrepancy  
 $\beta$  has to be change

→  $X_{\max}$  alone (composition) will not change the energy evolution

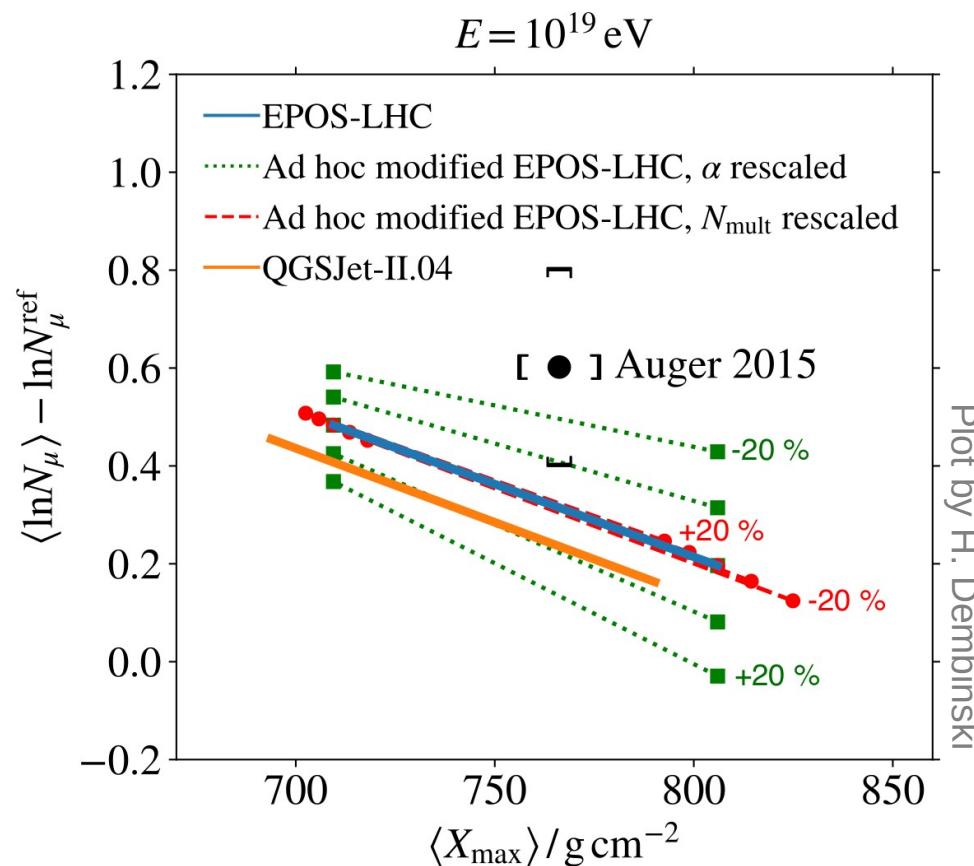
→  $\beta$  changes the muon energy evolution but not  $X_{\max}$

$$\beta = \frac{\ln(N_{mult} - N_{\pi^0})}{\ln(N_{mult})} = 1 + \frac{\ln(1 - \alpha)}{\ln(N_{mult})}$$

→ +4% for  $\beta$  → -30% for  $\alpha = \frac{N_{\pi^0}}{N_{mult}}$

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

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



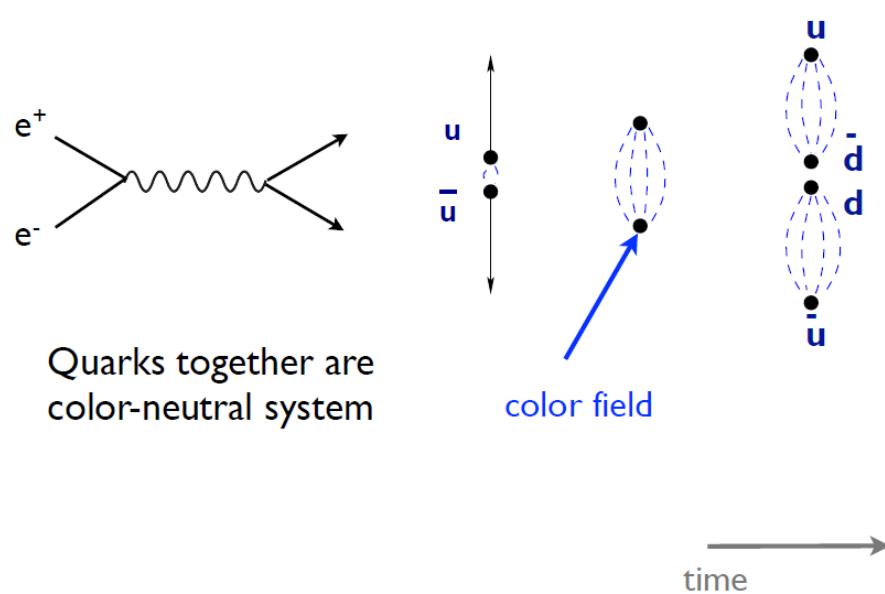
# Hadronization Models

2 models well established for 2 extreme cases

→ String Fragmentation

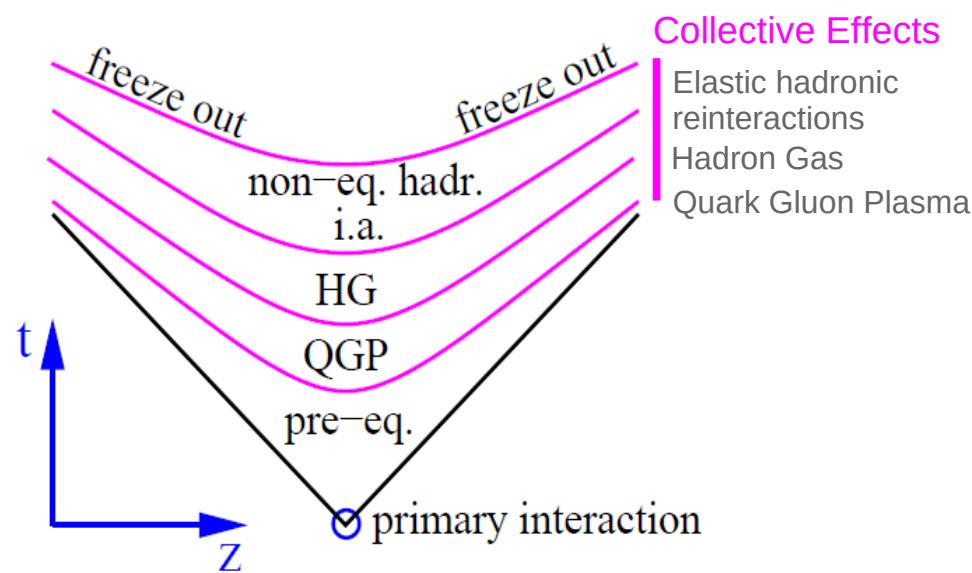
vs Collective hadronization (statistical models)

Annihilation at high energy



Quarks together are color-neutral system

In dilute systems... CORONA  
→ “high”  $\pi^0$  fraction

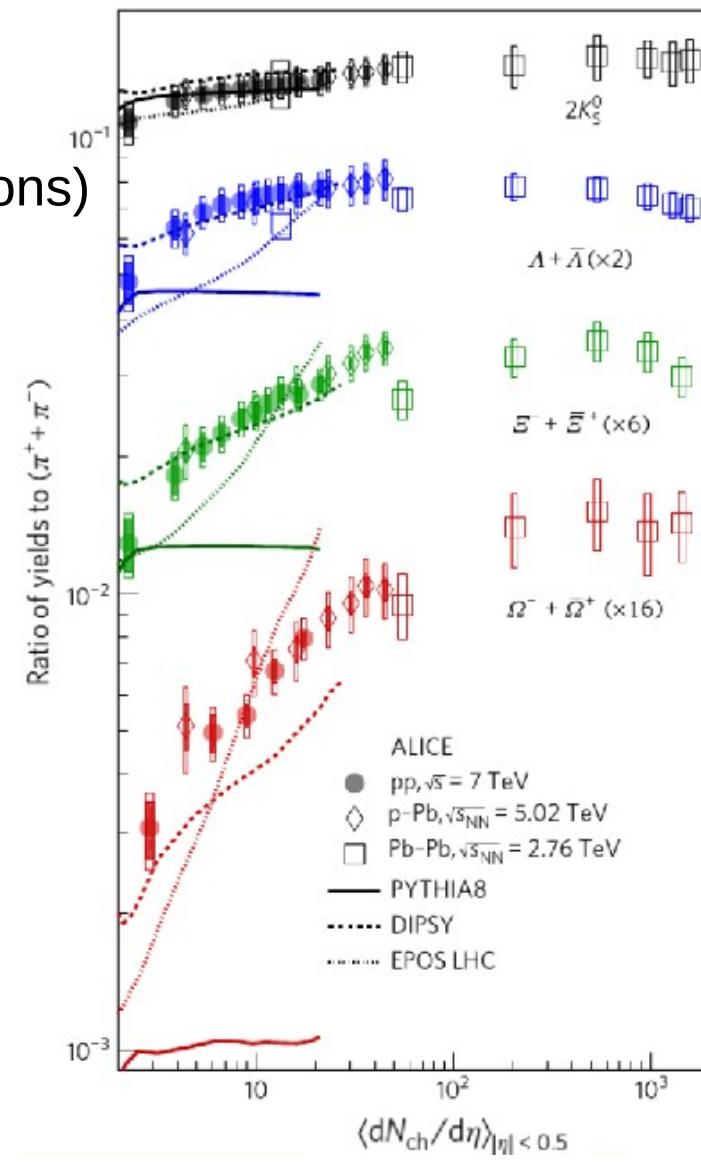
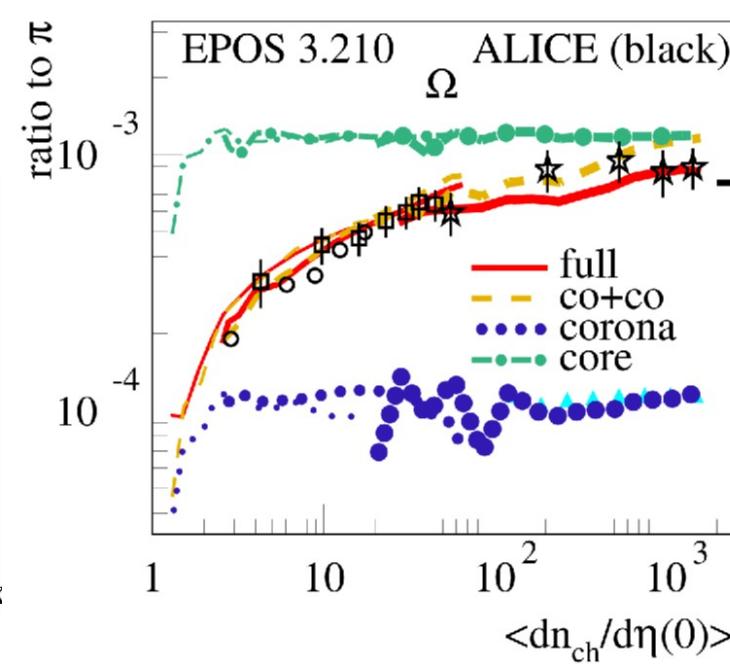
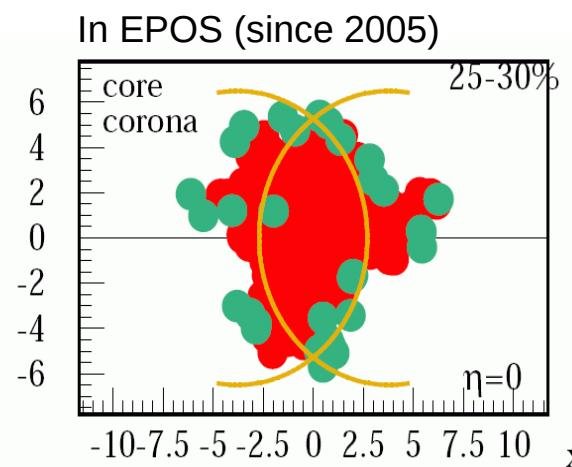


In dense systems... CORE  
→ “low”  $\pi^0$  fraction

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

# Core-Corona at LHC

- 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 simultaneous source of particles



# Core-Corona approach 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  $\omega_{\text{core}}$  of core hadronization:  $N_i = \omega_{\text{core}} N_i^{\text{core}} + (1 - \omega_{\text{core}}) N_i^{\text{corona}}$

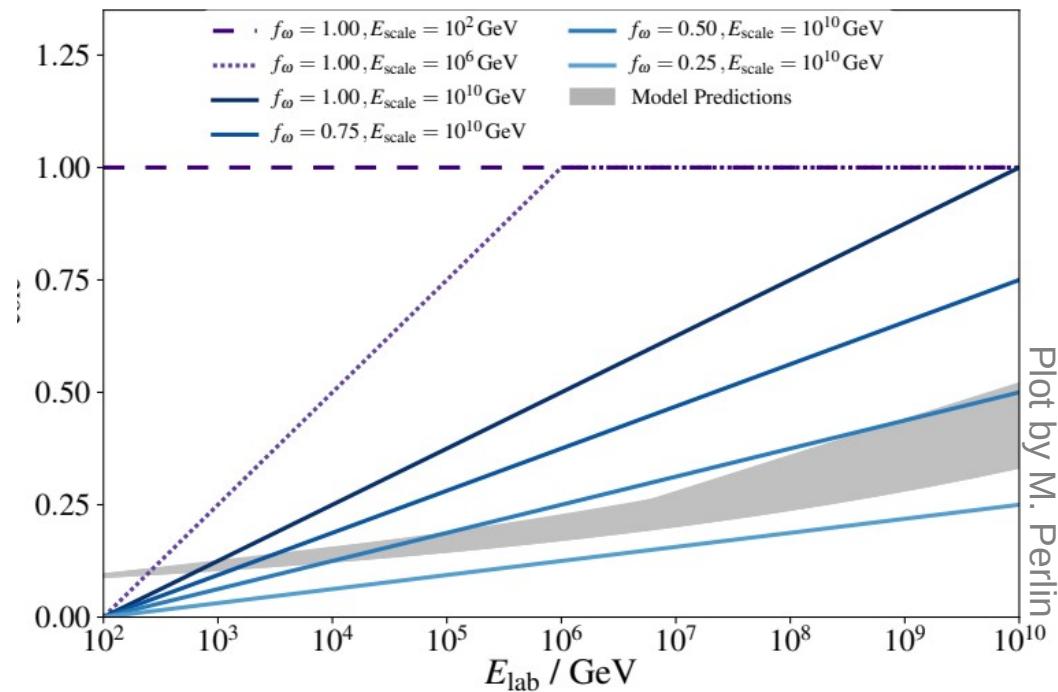
$$\omega_{\text{core}}(E_{\text{lab}}) = f_{\omega} \underbrace{F(E_{\text{lab}}; E_{\text{th}}, E_{\text{scale}})}_{}$$

$$\frac{\log_{10}(E_{\text{lab}}/E_{\text{th}})}{\log_{10}(E_{\text{scale}}/E_{\text{th}})} \text{ for } E_{\text{lab}} > E_{\text{th}}$$

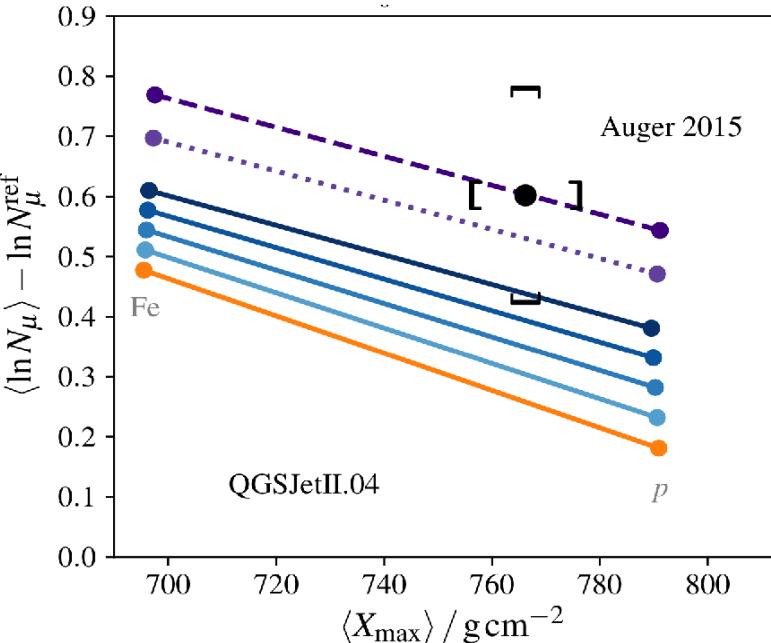
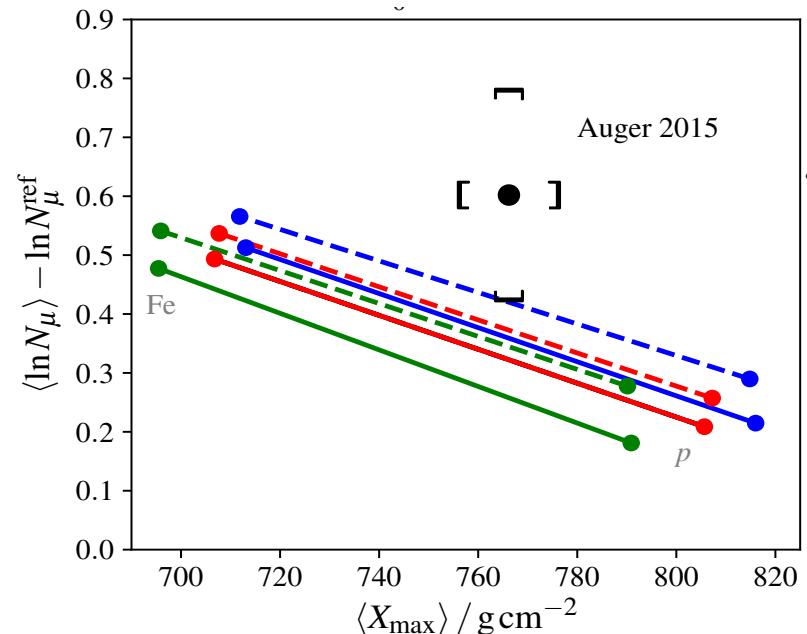
$$E_{\text{th}} = 100 \text{ GeV}$$

Different scenarii can be studied playing with  $f_{\omega}$  and  $E_{\text{scale}}$ .

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

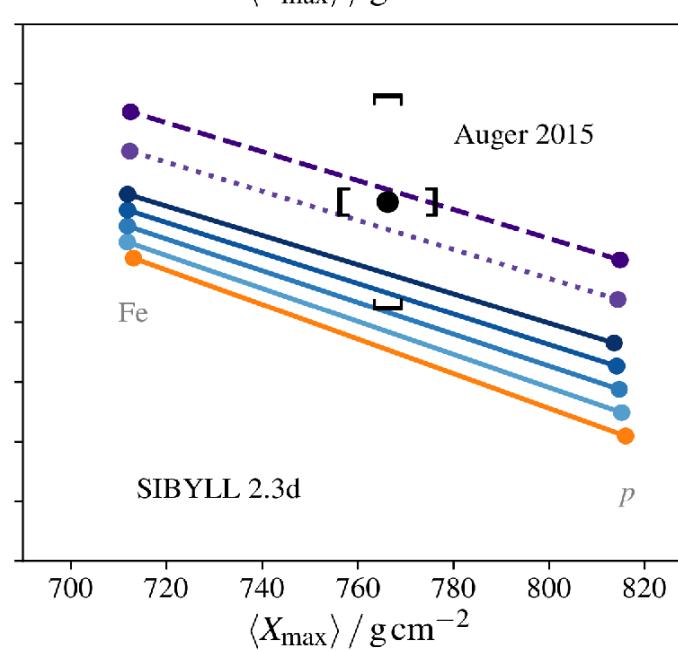
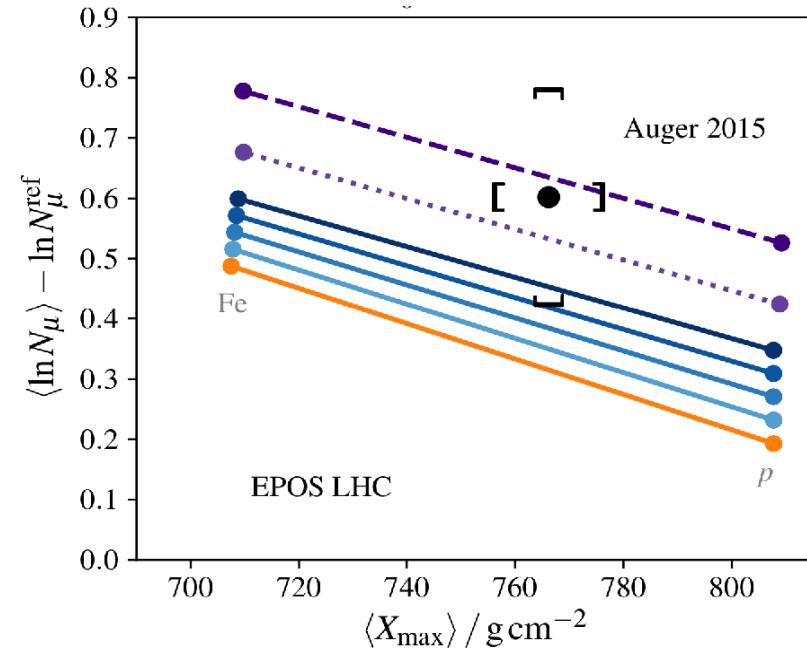


# Results for $X_{\max}$ - $N_{\mu}$ correlation



- $f_\omega = 1.00, E_{\text{scale}} = 10^2 \text{ GeV}$
- $f_\omega = 1.00, E_{\text{scale}} = 10^6 \text{ GeV}$
- $f_\omega = 1.00, E_{\text{scale}} = 10^{10} \text{ GeV}$
- $f_\omega = 0.75, E_{\text{scale}} = 10^{10} \text{ GeV}$
- $f_\omega = 0.50, E_{\text{scale}} = 10^{10} \text{ GeV}$
- $f_\omega = 0.25, E_{\text{scale}} = 10^{10} \text{ GeV}$
- $f_\omega = 0$  (Default model)

- Default Model
- - Core-Corona
- EPOS-LHC
- QGSJETII-04
- SIBYLL2.3d

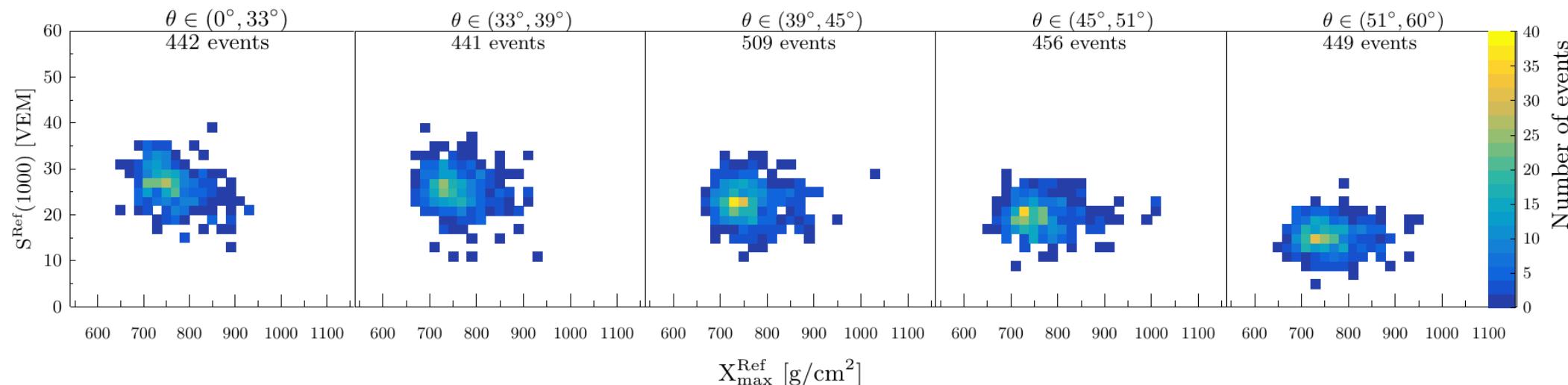


Forward core fraction unknown  
and not necessarily lower  
than at mid-rapidity  
(saturation effect)

Plit hv M. Perljin

# X<sub>max</sub>-S(1000) correlation

Hybrid measurements allows to test model consistency in more details



$$X_{\max}^{\text{Ref}} \equiv \widehat{X_{\max}^{\text{Ref}}} + \Delta X_{\max},$$

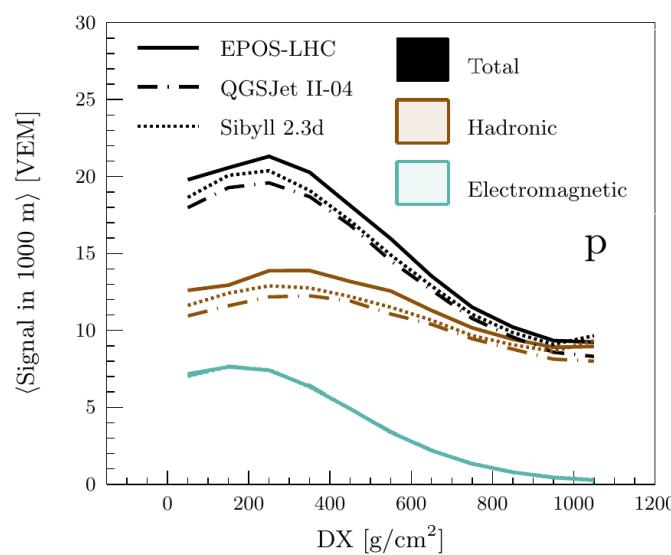
$$S^{\text{Ref}}(1000) \equiv \widehat{S^{\text{Ref}}(1000)} \cdot f_{SD}(\theta)$$

Parameters:

$$\Delta X_{\max}, R_{\text{Had}}, R_{\text{em}}, \xi_1, \xi_2, \xi_3$$

Describe the 4 mass fractions

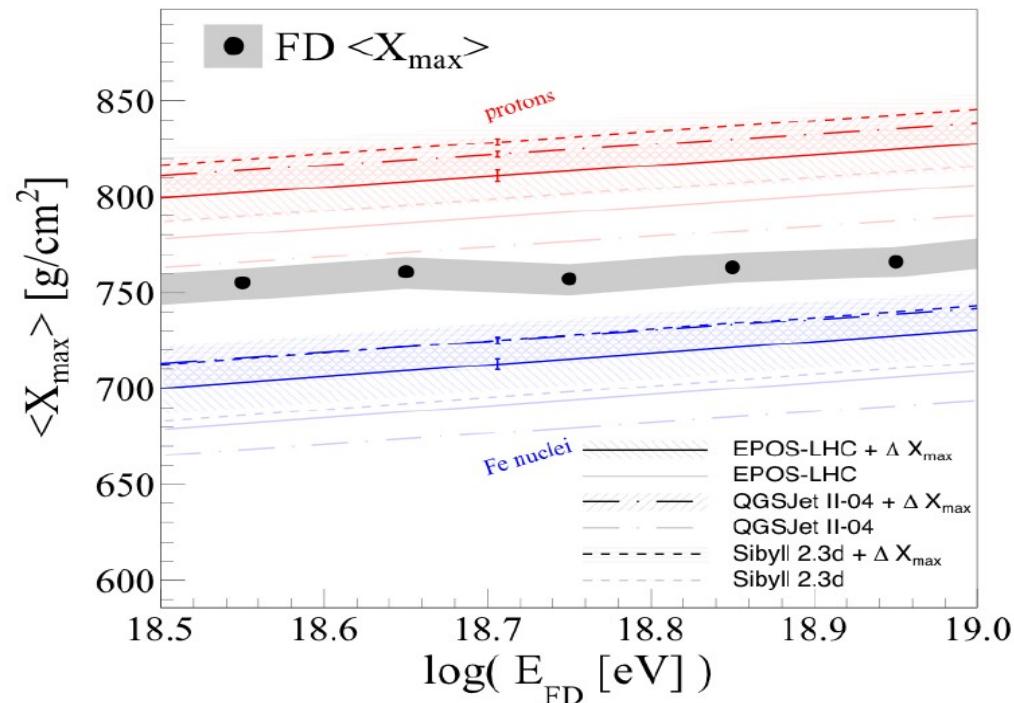
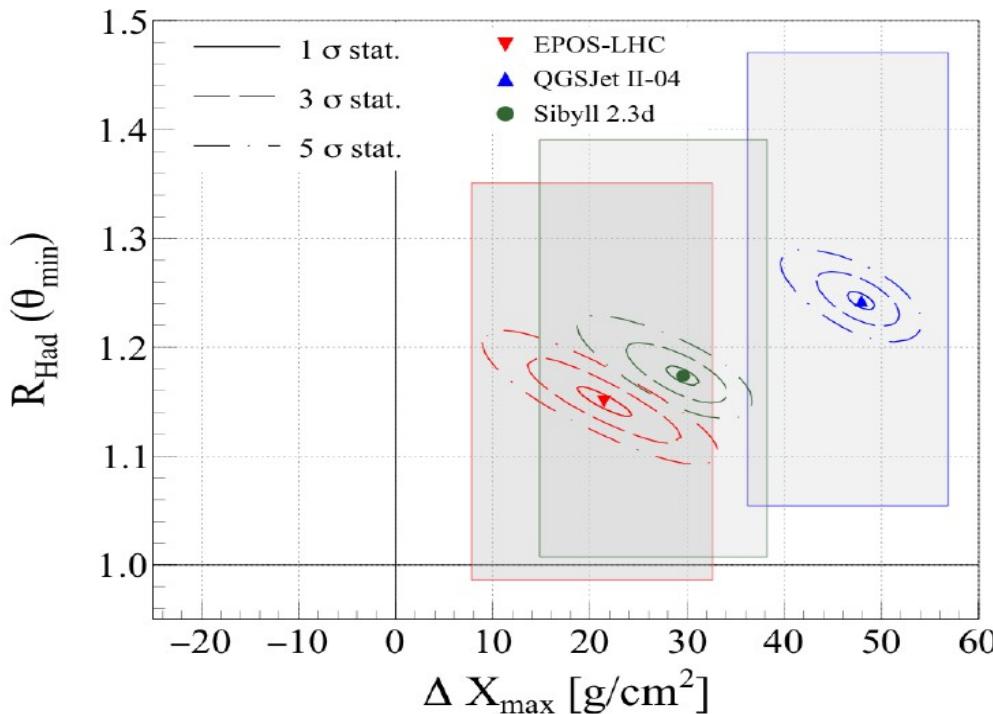
$$\phi = c \cdot f_{\text{Gumbel}}(X_{\max}^{\text{Ref}}) \cdot f_{\text{Gauss}}(X_{\max}^{\text{Ref}}, S^{\text{Ref}}(1000))$$



The final MC templates are a sum of templates of the form of  $\phi$  of individual primary species weighted by their relative fractions.

# Modifications of $X_{\max}$ and signal at ground

- Best fit of data require multiple changes in hadronic models
  - Rescaling (increase) of muons (hadronic component → confirmed)
  - Shift in  $X_{\max}$  toward higher mass (electromagnetic component → new)
- Might imply a change in mass composition
  - Importance of LHC data to improve models (pO data to reduce  $X_{\max}$  and muon (core-corona ?) uncertainties)



# Model Improvement

- But a number of new data since model release could be used to improve the models :

- Update of the p-p cross sections (ALFA)
- Data at 13 TeV (CMS, ATLAS)
- More detailed p-Pb measurements (fluctuations) CMS
- Particle yields as a function of multiplicity (ALICE, LHCb)
  - Very important to understand the mechanism behind particle production

X<sub>max</sub>

N<sub>μ</sub>

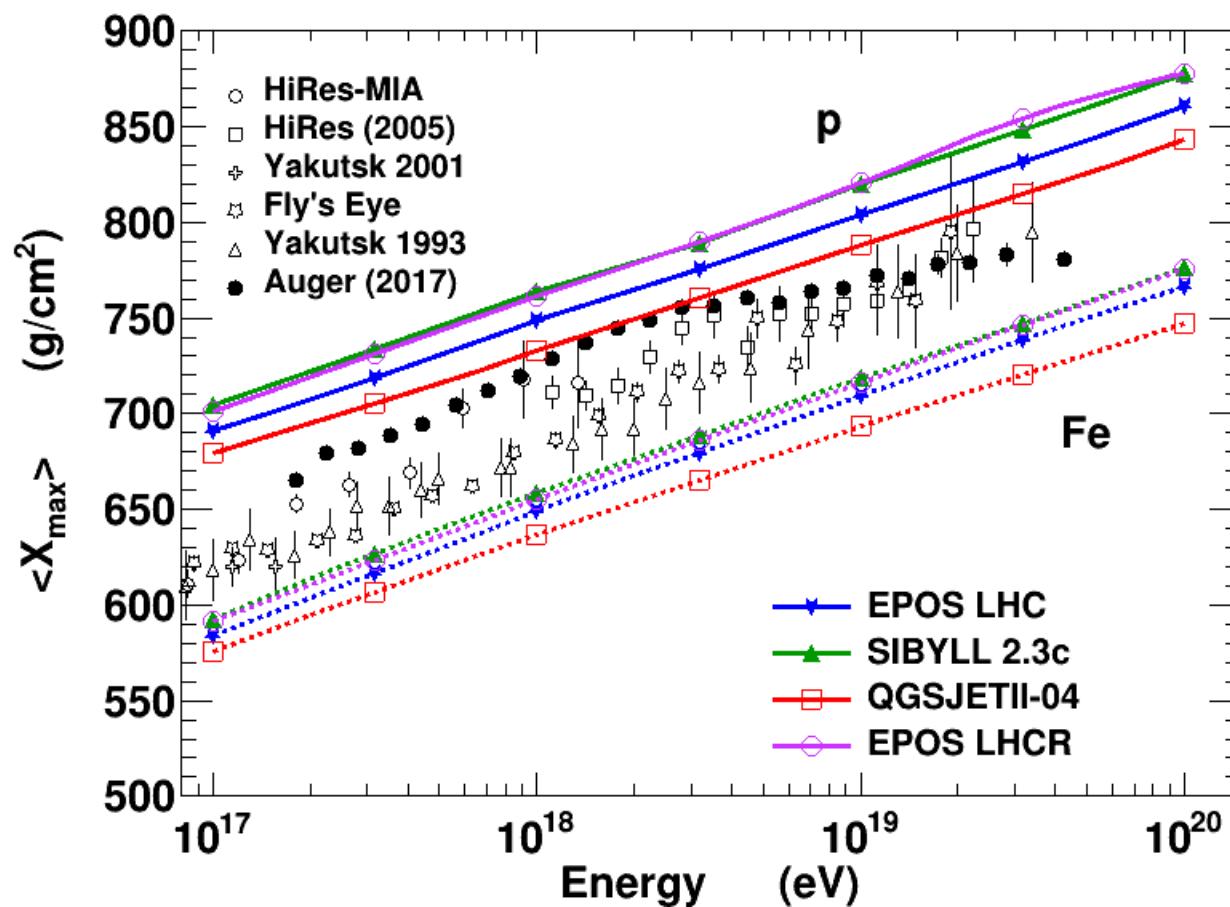
- Update of EPOS LHC → **EPOS LHC-R**

- New EPOS 4 available soon for heavy ion physics but not usable for air showers (yet)
- Modify EPOS LHC to take into account new data and new knowledge accumulated with EPOS 4
- **Very preliminary results !**

**X<sub>max</sub>**

+/- 20g/cm<sup>2</sup> was realistic uncertainty band :

- minimum given by QGSJETII-04 (high multiplicity, low elasticity) ?
- maximum given by Sibyll 2.3c/d (low multiplicity, high elasticity) ?
- Taking into account new data, EPOS shifted by +15g/cm<sup>2</sup> (=Sibyll)



Correction of  
nuclear  
fragmentation in  
EPOS :  
 $X_{\max}$  RMS Fe  
LHC=20g/cm<sup>2</sup>  
LHCR=22g/cm<sup>2</sup>  
SIB=25g/cm<sup>2</sup>  
QII=25g/cm<sup>2</sup>

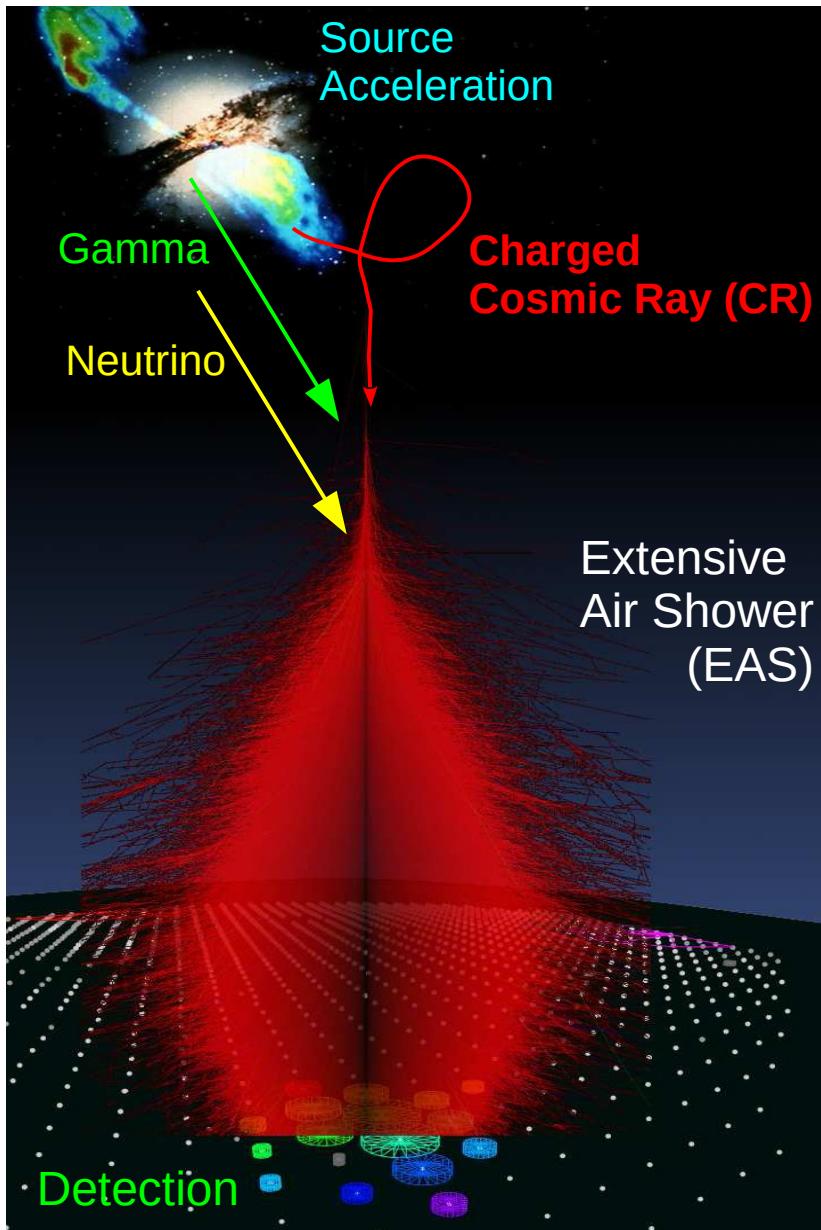
# Summary

- WHISP working group clearly established a muon production deficit in air shower simulations.
  - Exact scale not known (dependent on energy and MASS)
  - Continuous increase of difference above  $10^{16}$ - $10^{17}$  eV
    - No sudden increase
  - Zenith angle, muon energy, radial distance effect still to be studied
- Most “natural” explanation given by a **change in neutral pion 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 uncertainties
  - New physics still needed ?
    - Other LHC data could affect  $X_{\max}$  and then the measured mass of primary cosmic rays (heavier → reduction of muon deficit)

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

Thank you !

# Astroparticles



- **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 observable.

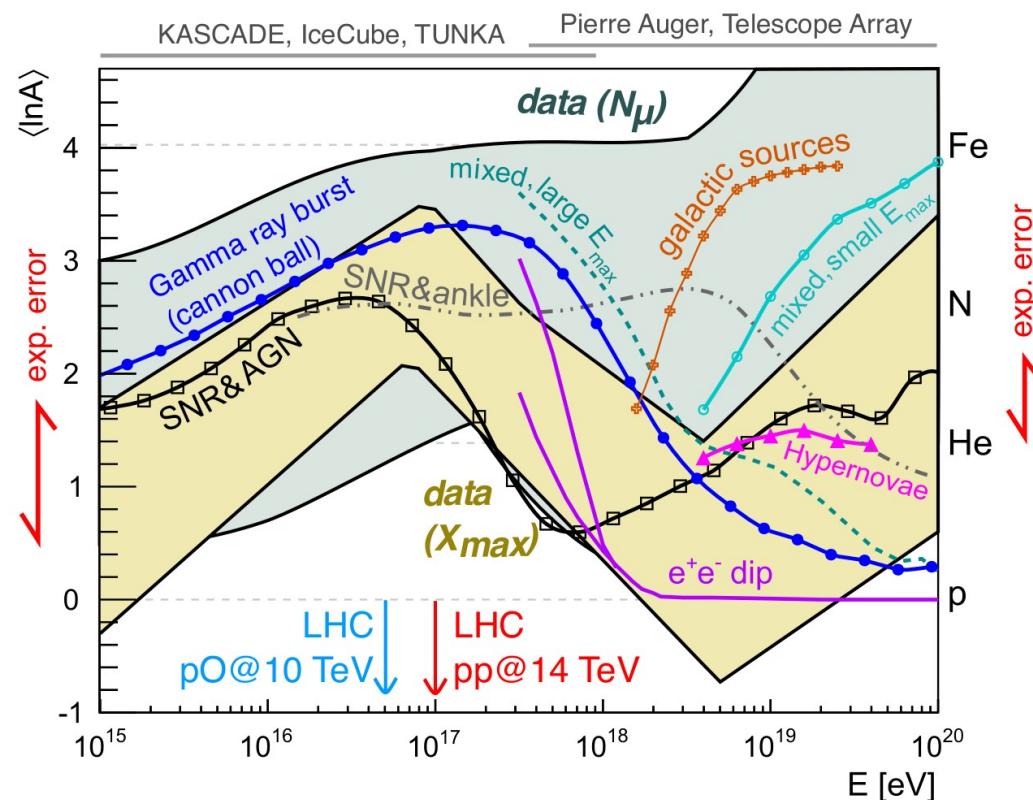
**mass measurements should be consistent  
and lying between proton and iron  
simulated showers if physics is correct**

From R. Ulrich (KIT)

# UHECR Composition

With muons current CR data are impossible to interpret

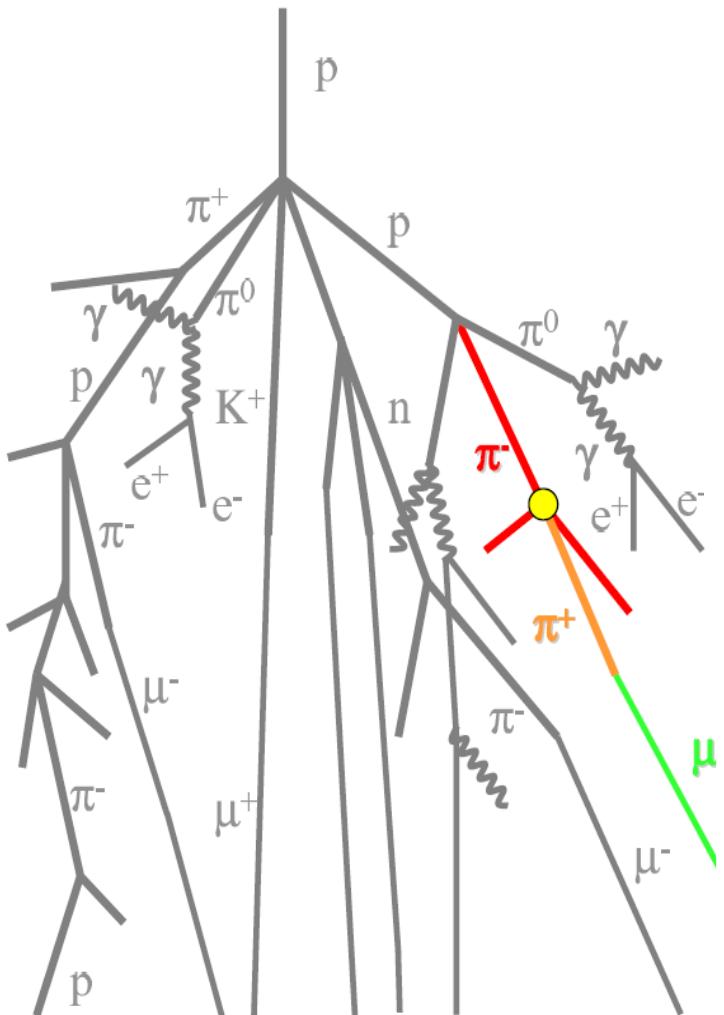
- Very large uncertainties in model predictions
- Mass from muon data incompatible with mass from  $X_{\max}$



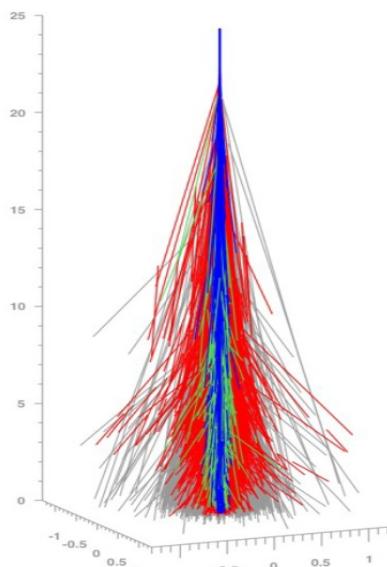
Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

H. Dembinski UHECR 2018 (WHISP working group)

# Extensive Air Shower



From R. Ulrich (KIT)



$A + \text{air} \rightarrow \text{hadrons}$   
 $p + \text{air} \rightarrow \text{hadrons}$   
 $\pi + \text{air} \rightarrow \text{hadrons}$   
initial  $\gamma$  from  $\pi^0$  decay  
 $e^\pm \rightarrow e^\pm + \gamma$   
 $\gamma \rightarrow e^+ + e^-$

hadronic physics

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

well known  
QED

## Cascade of particle in Earth's atmosphere

Number of particles at maximum

- 99,88% of electromagnetic (EM) particles
- 0.1% of muons
- 0.02% hadrons
- Energy
- from 100% hadronic to 90% in EM + 10% in muons at ground (vertical)

# Cosmic Ray Analysis from 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

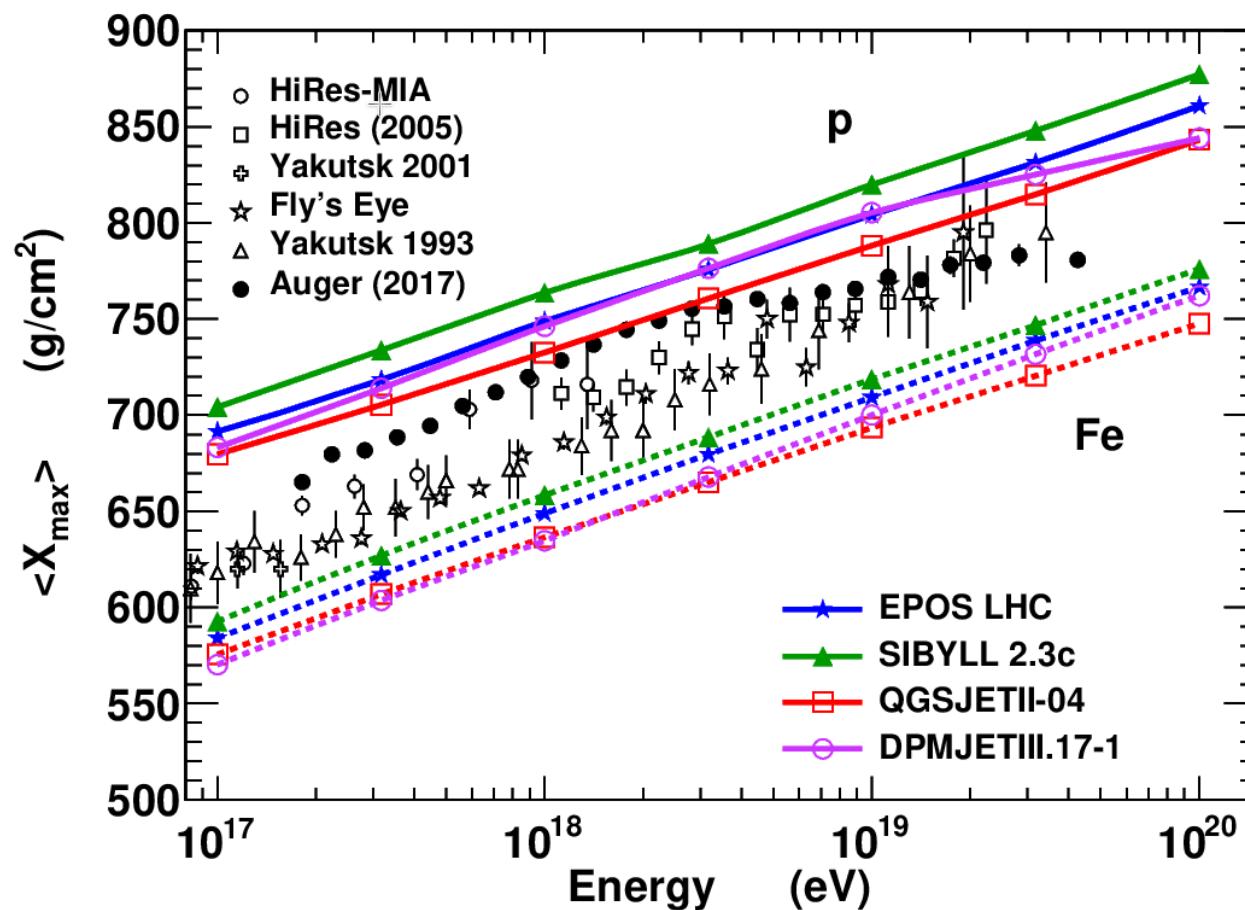
- Which model for CR ? (alphabetical order)

- **DPMJETIII.(17-1/19-1)** by S. Roesler, A. Fedynitch, R. Engel and J. Ranft
  - **EPOS (1.99/LHC/3/4)** (from VENUS/NEXUS before) by T. Pierog and K.Werner.
  - **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

$X_{\max}$

$\pm 20 \text{ g/cm}^2$  is a realistic uncertainty band but :

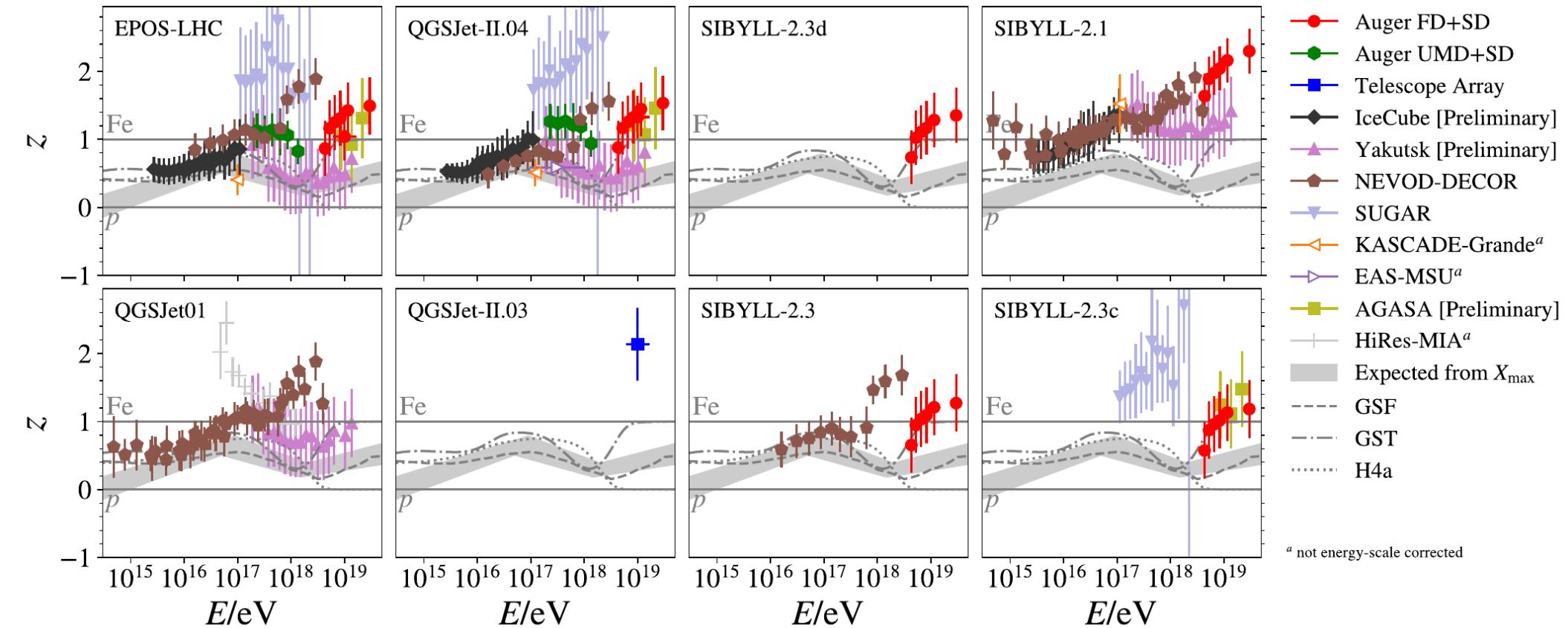
- minimum given by QGSJETII-04 (high multiplicity, low elasticity)
- maximum given by Sibyll 2.3c (low multiplicity, high elasticity)
- Used to define the mass of the primary cosmic ray



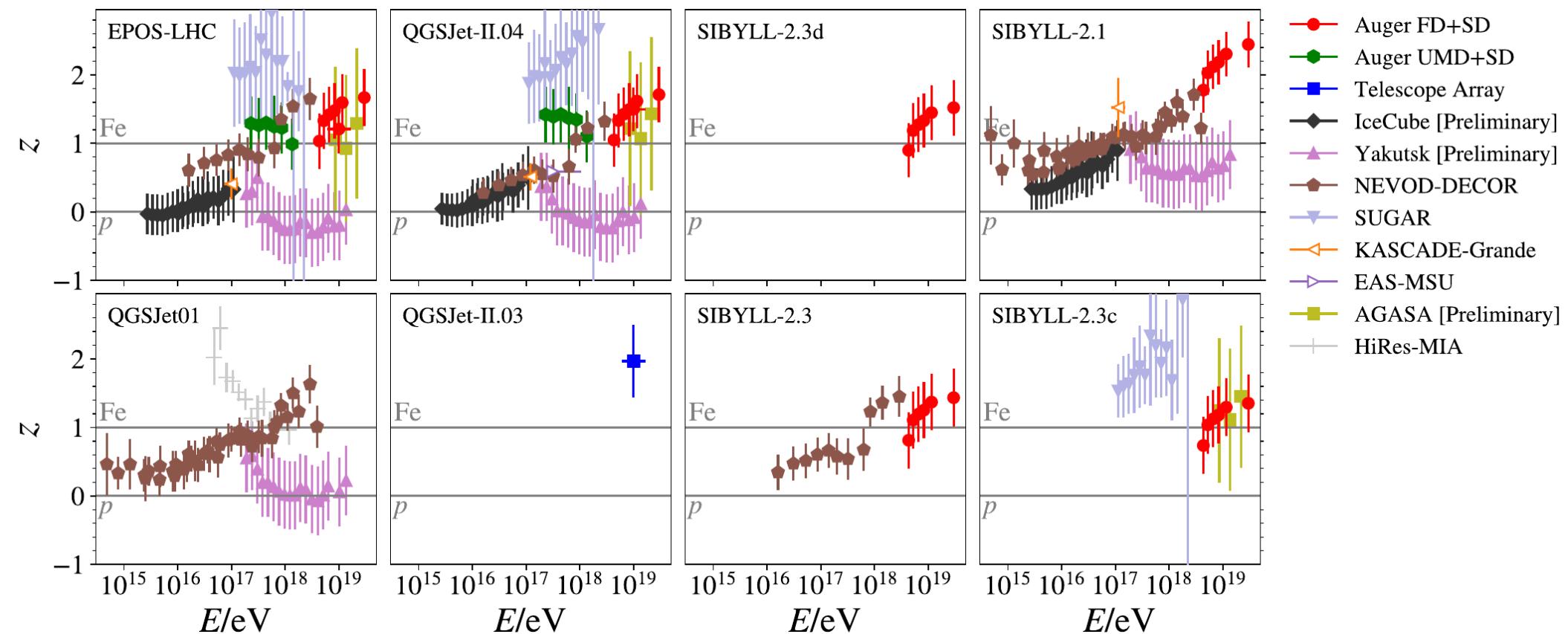
# WHISP Working Group

- Lots of muon measurements available
  - ➔ AGASA, Auger, EAS-MSU, KASCADE-Grande, IceCube/IceTop, HiRes-MIA, NEMOD/DECOR, SUGAR, TA, Yakutsk
- Working group (**WHISP**) created to compile all results together.  
Analysis led and presented first time 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)

# Rescaled Data



# Raw Data



# Renormalization

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

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

- 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  $\beta \sim 0.9$  is link to hadronic interaction properties
- To extract proper relative behavior between data and model :
  - unique energy scale
  - estimation of mass evolution
    - Based on model and  $X_{\max}$

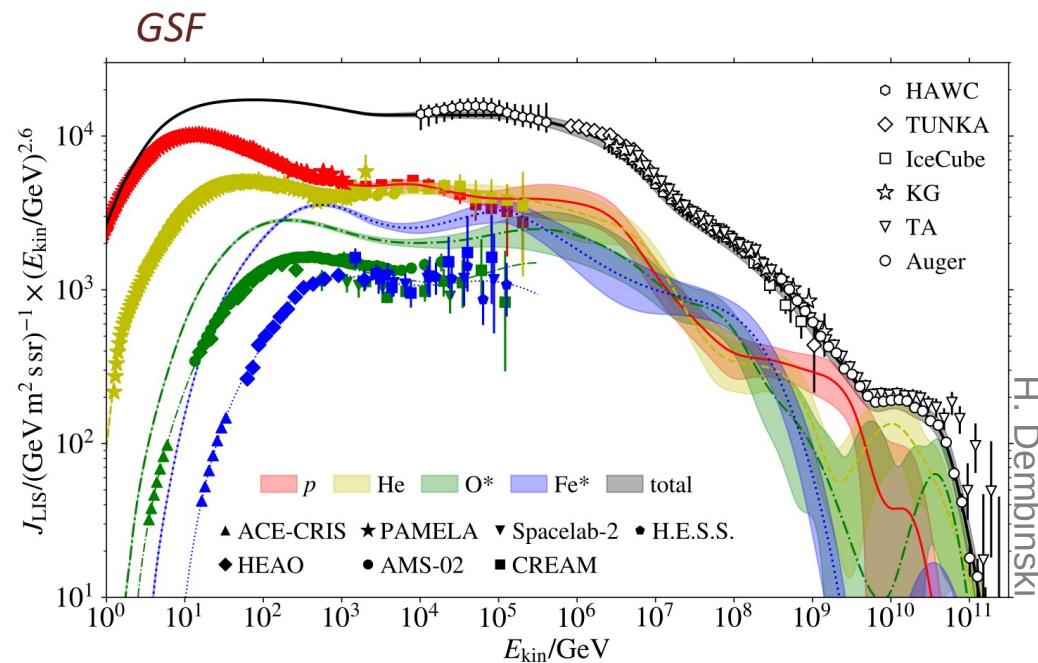
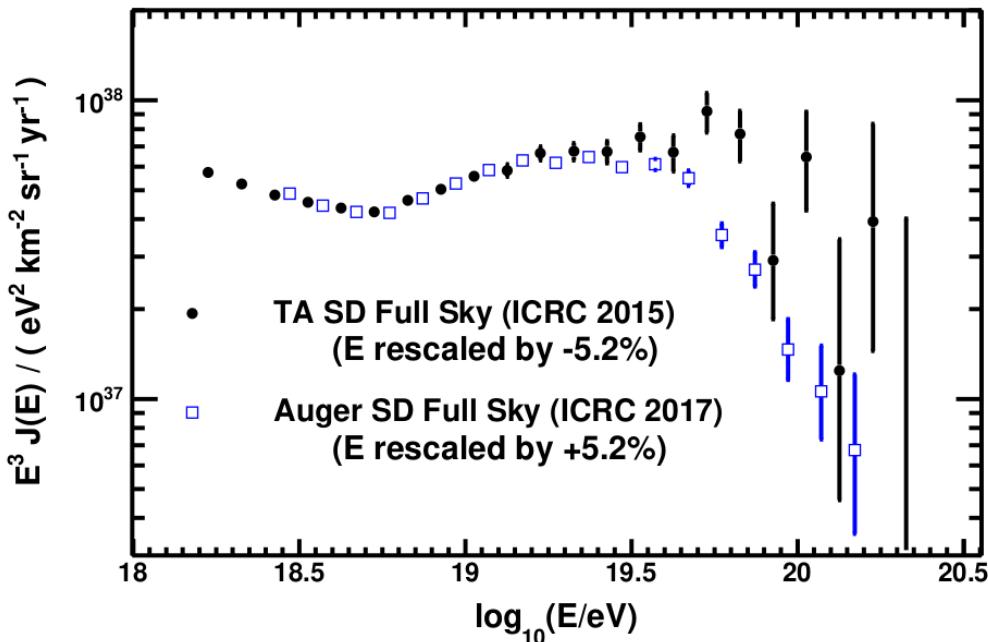
Using an external  
data based model !

# 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	$E_{\text{data}}/E_{\text{ref}}$
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



# 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.) ?
- String Fusion (Alvarez-Muniz et al.) ?

→ Problem : no strong effect observed at LHC ( $\sim 10^{17}$  eV)

→ Unexpected production of Quark Gluon Plasma (QGP) in light systems observed at the LHC (at least modified hadronization)

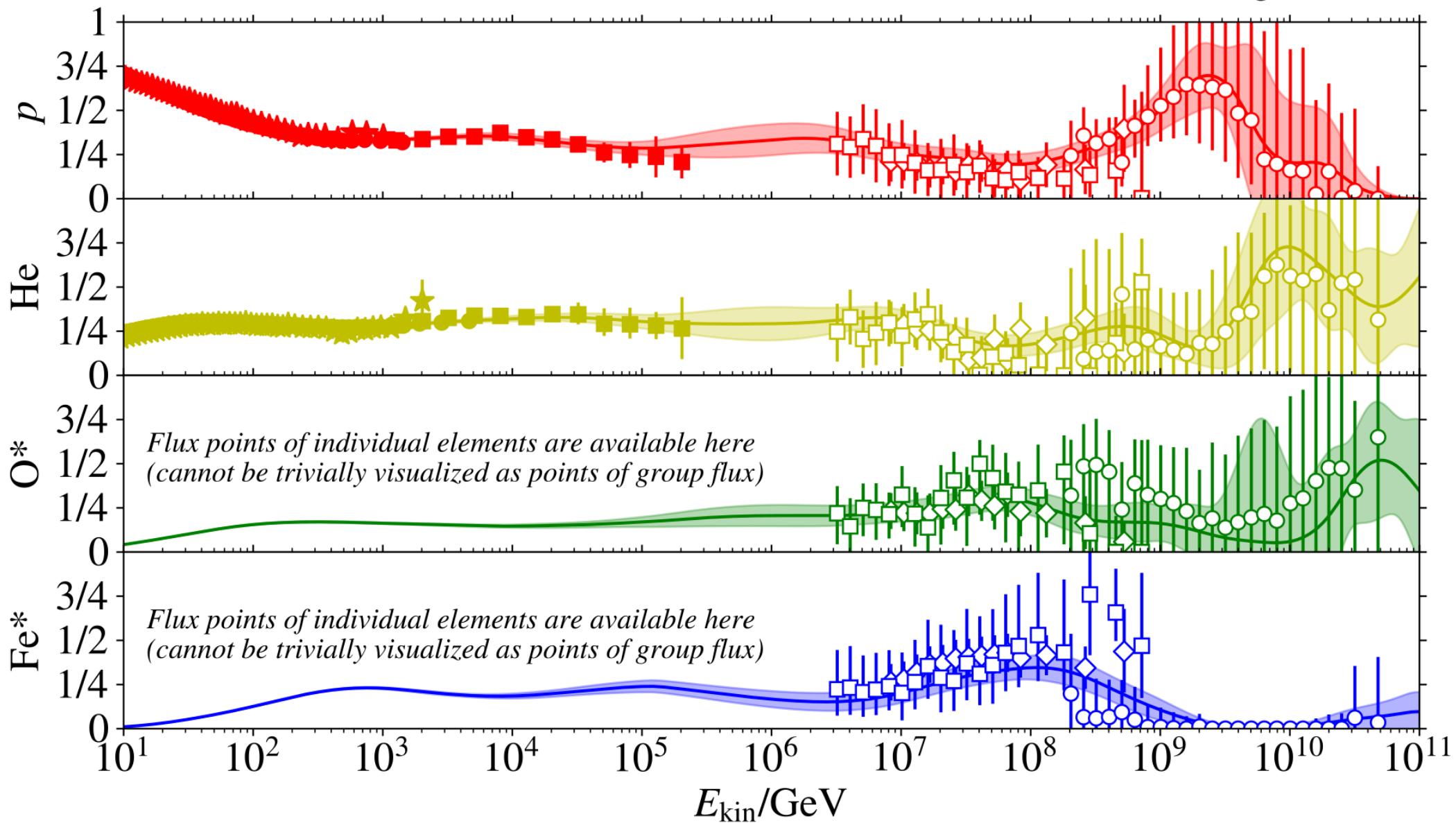
- Reduced  $\alpha$  is a sign of QGP formation (enhanced strangeness and baryon production reduces relative  $\pi^0$  fraction. Baur et al., arXiv:1902.09265) !
- $\alpha$  depends on the hadronization scheme
  - How is done in hadronic interaction models ?

# Hadronization in Simulations

- Historically (theoretical/practical reasons) string fragmentation used in high energy models (Pythia, Sibyll, QGSJET, ...) for proton-proton.
  - ➔ Light systems 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 used for Heavy Ion only in combination with hydrodynamical evolution of the dense system : QGP hadronization
  - ➔ Account for flow effects, strangeness enhancement, particle correlations...

# GSF Composition Details

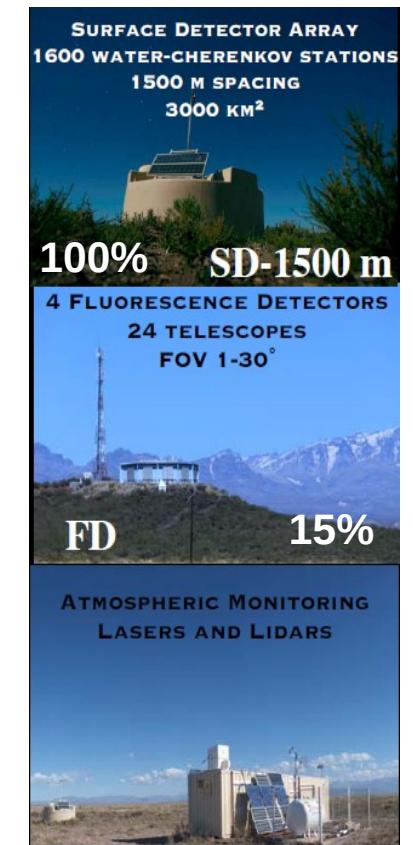
★ PAMELA • AMS-02 ■ CREAM ◇ TUNKA □ IceCube ○ Auger



# PAO/TA

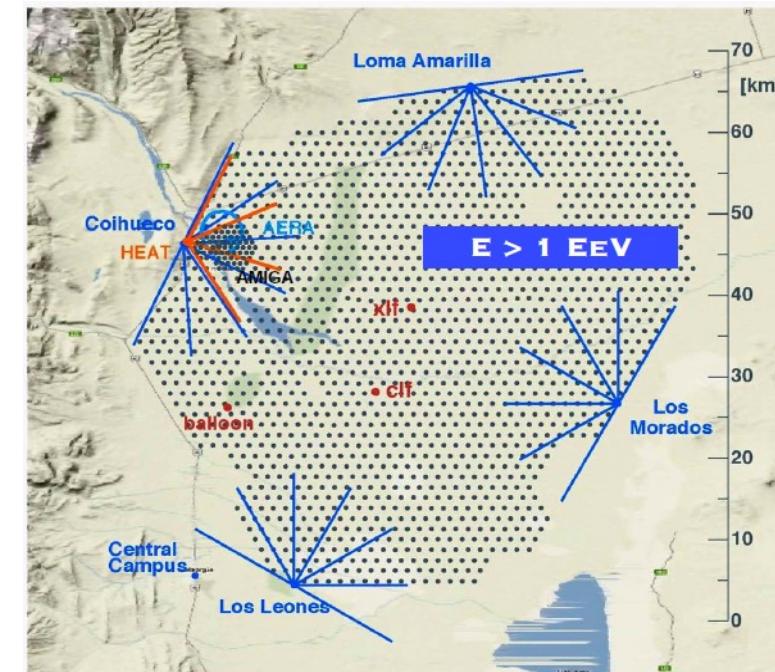
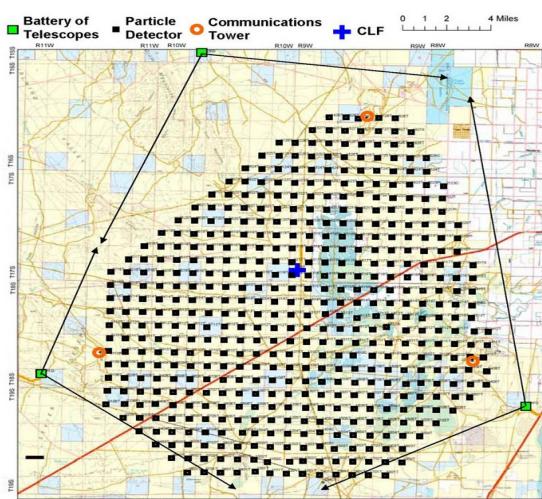
## ● Pierre Auger Observatory (PAO)

- Mendoza, Argentina
- Southern Hemisphere
- $3000 \text{ km}^2$ :  $32000 \text{ km}^2/\text{sr}/\text{yr}$



## ● Telescope Array (TA)

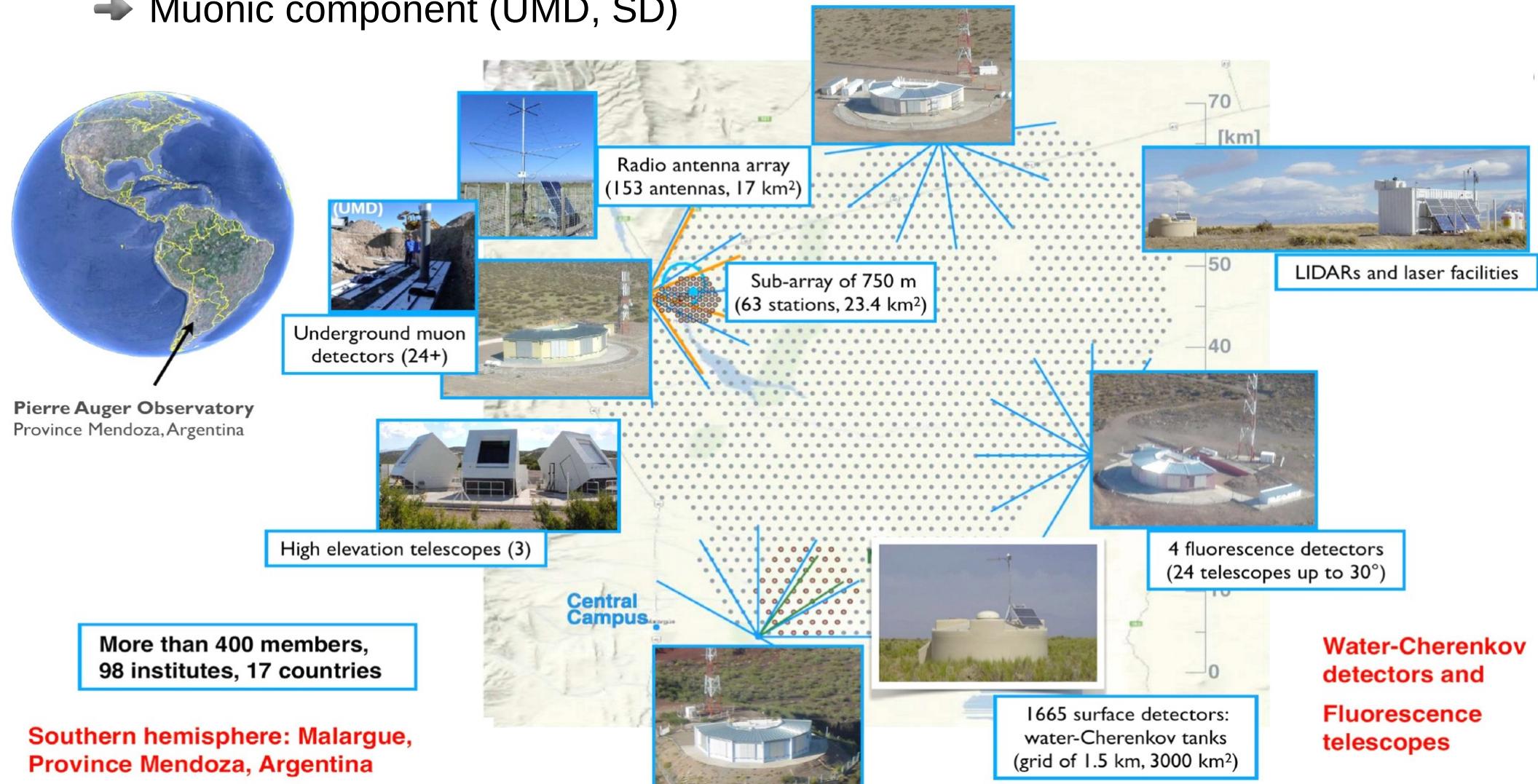
- Utah, USA
- Northern Hemisphere
- $680 \text{ km}^2$ :  $3700 \text{ km}^2/\text{sr}/\text{yr}$



# The Pierre Auger Observatory

## Multicomponent (hybrid) detector

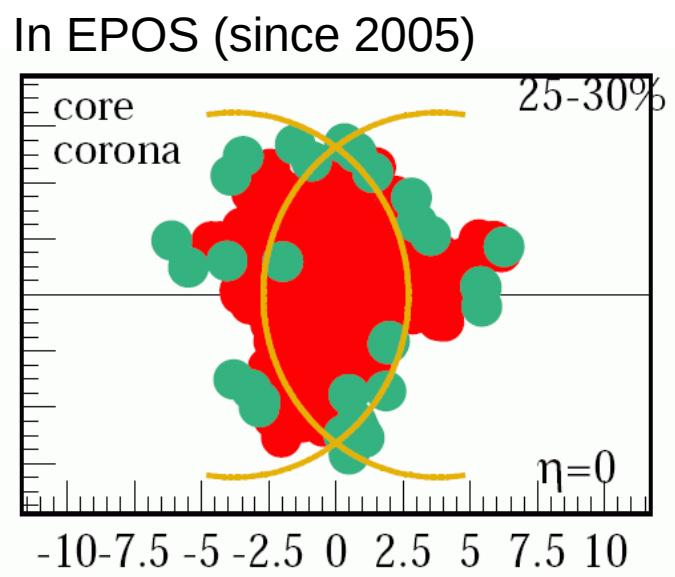
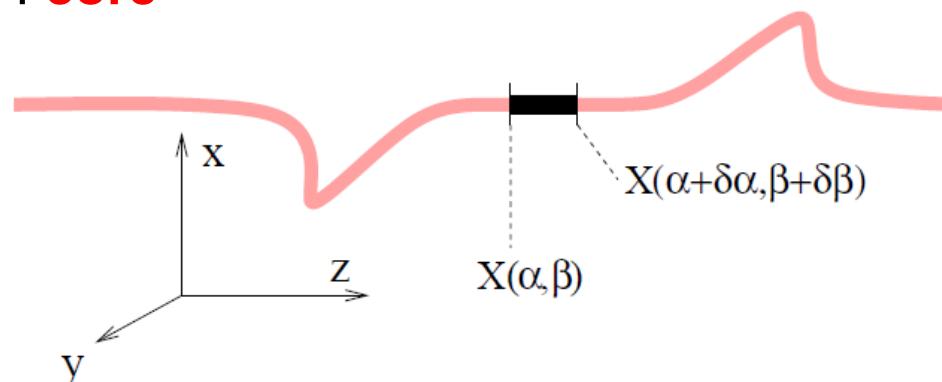
- Electromagnetic component (FD, RD, SD)
- Muonic component (UMD, SD)



# A 3<sup>rd</sup> 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**

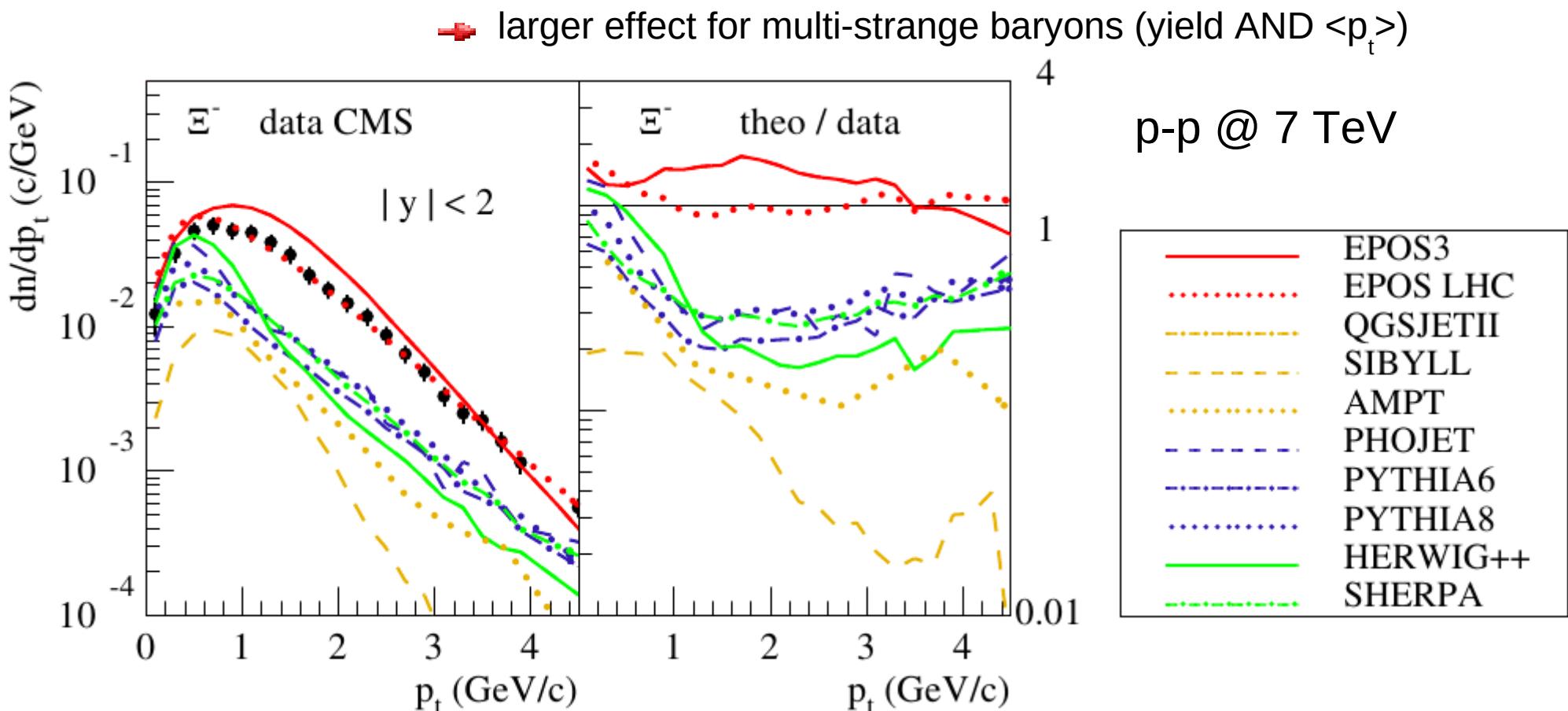


- Each string cut into a sequence of string segments, corresponding to widths  $\delta\alpha$  and  $\delta\beta$  in the string parameter space
- If energy density from segments high enough
  - ◆ segments fused into core
    - flow from hydro-evolution
    - statistical hadronization
- If low density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

# Core in p-p (early LHC data)

Detailed description can be achieved with core in pp

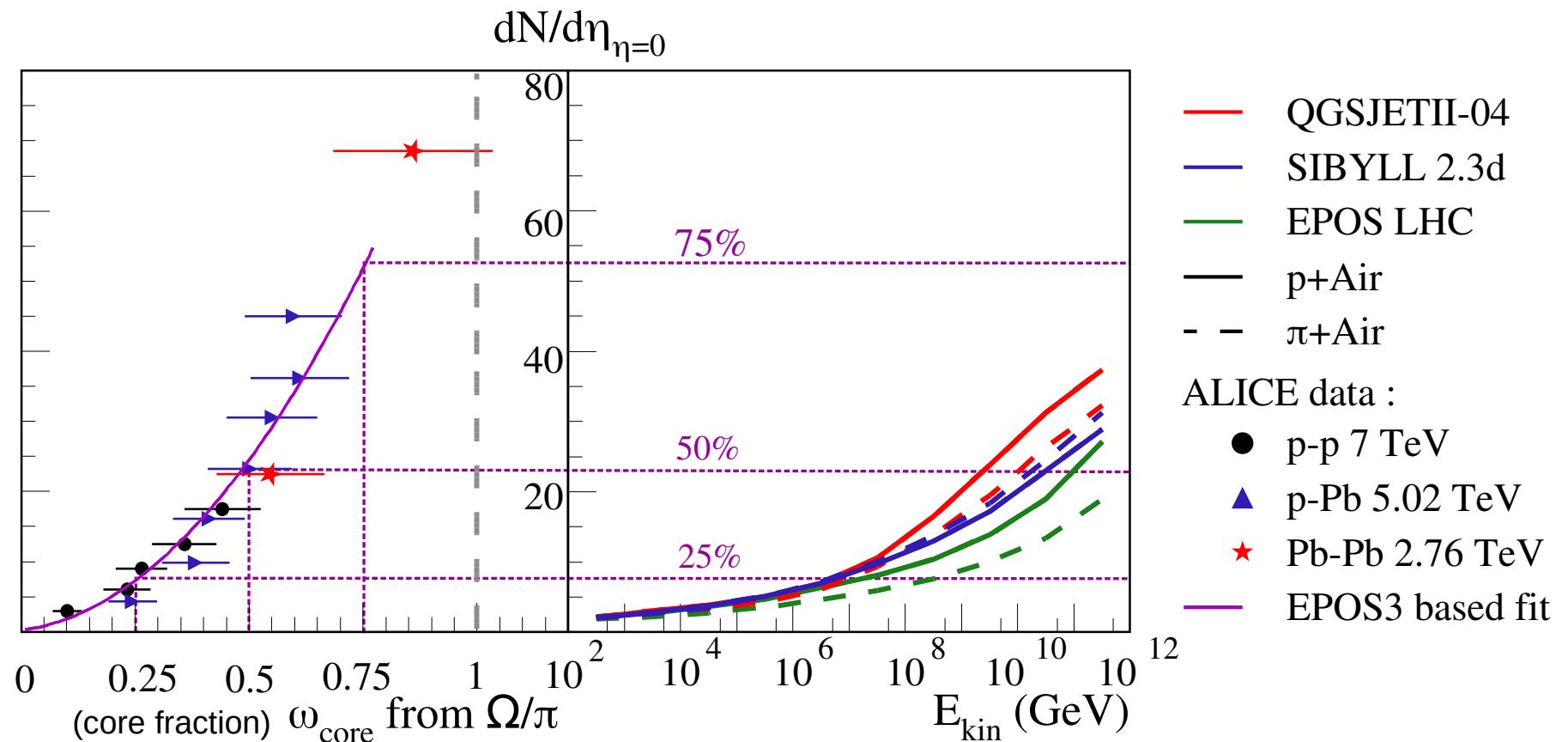
- identified spectra: different strangeness between string (low) and stat. decay (high)
- $p_t$  behavior driven by collective effects (statistical hadronization + flow)



# 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 !

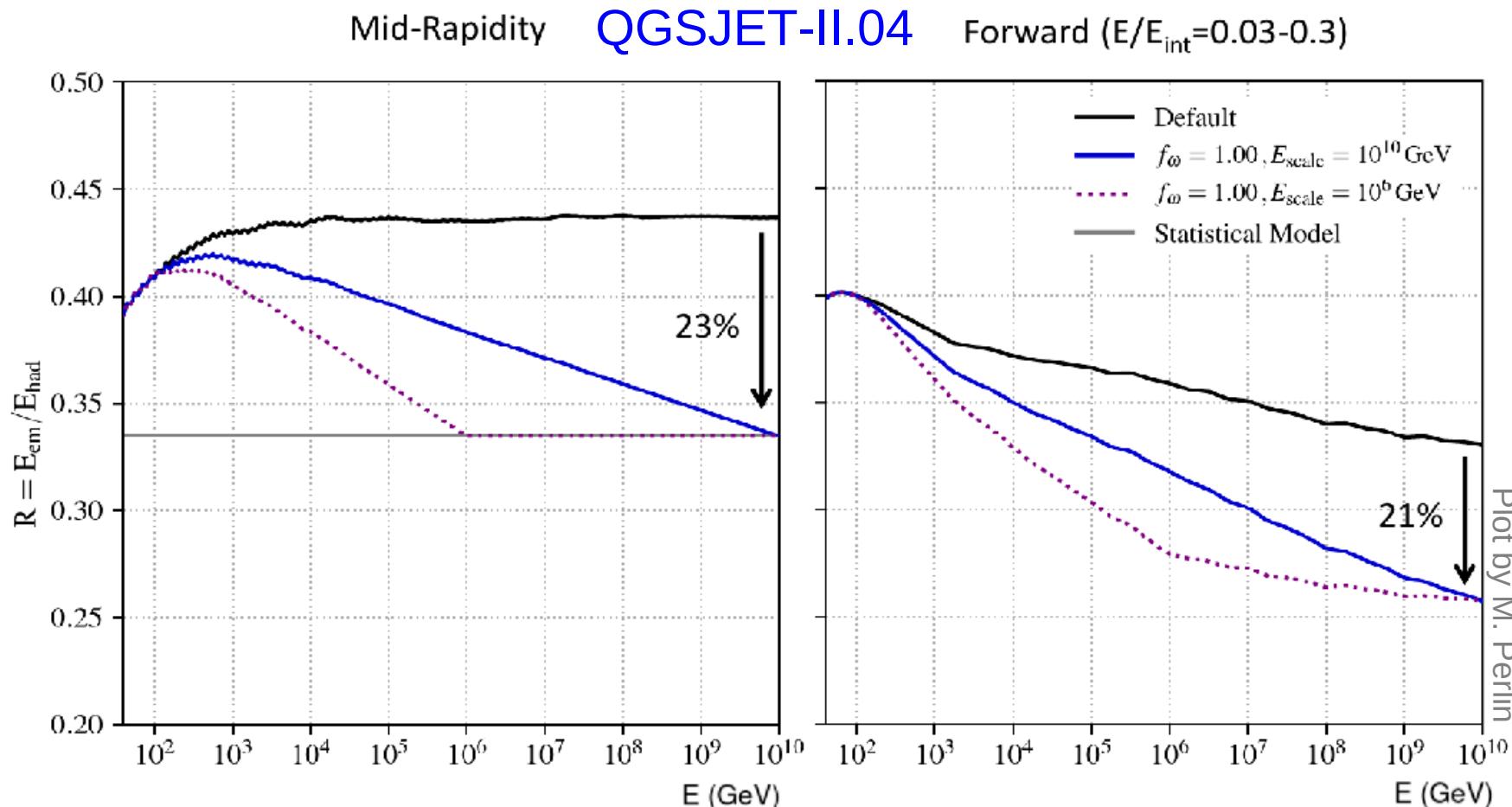


# Evolution of hadronization from core to corona

The relative fraction of  $\pi^0$  depends on the hadronization scheme

→ Change of  $\omega_{\text{core}}$  with energy change  $\alpha = \frac{N_{\pi^0}}{N_{\text{mult}}}$  or  $R(\eta) = \frac{\langle dE_{\text{em}}/d\eta \rangle}{\langle dE_{\text{had}}/d\eta \rangle}$

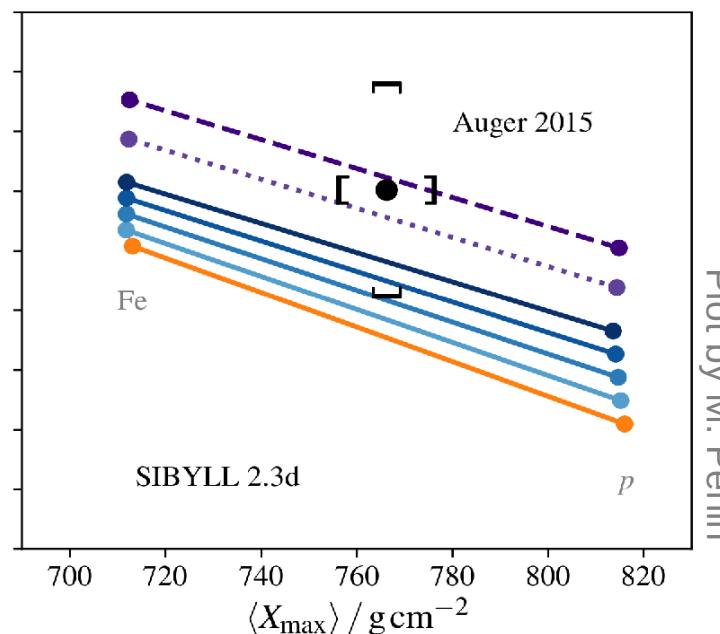
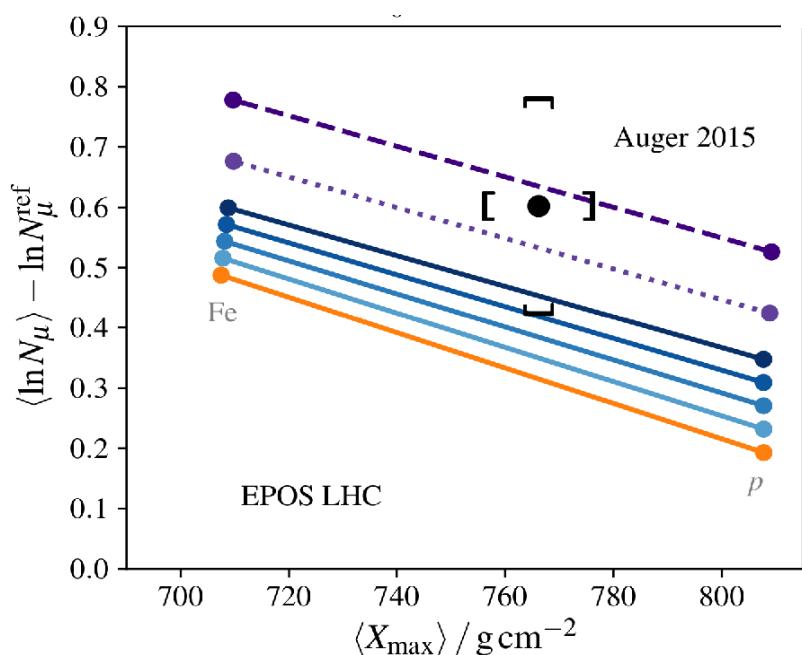
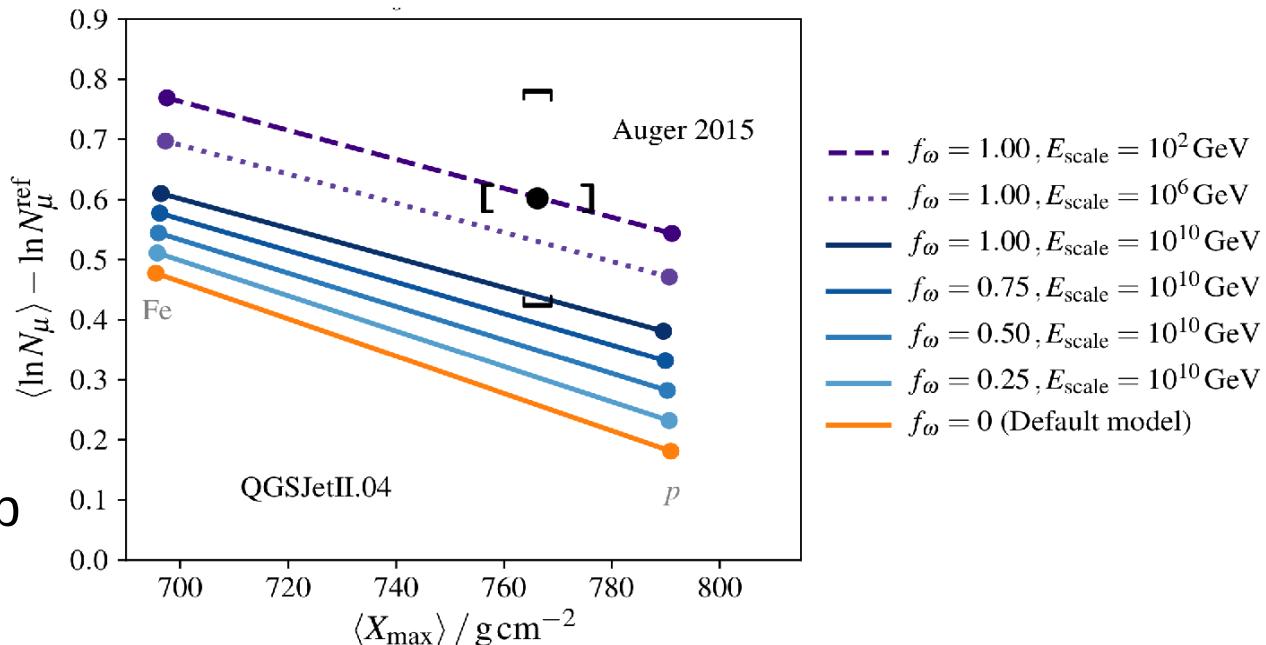
which define the muon production in air showers.



# 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

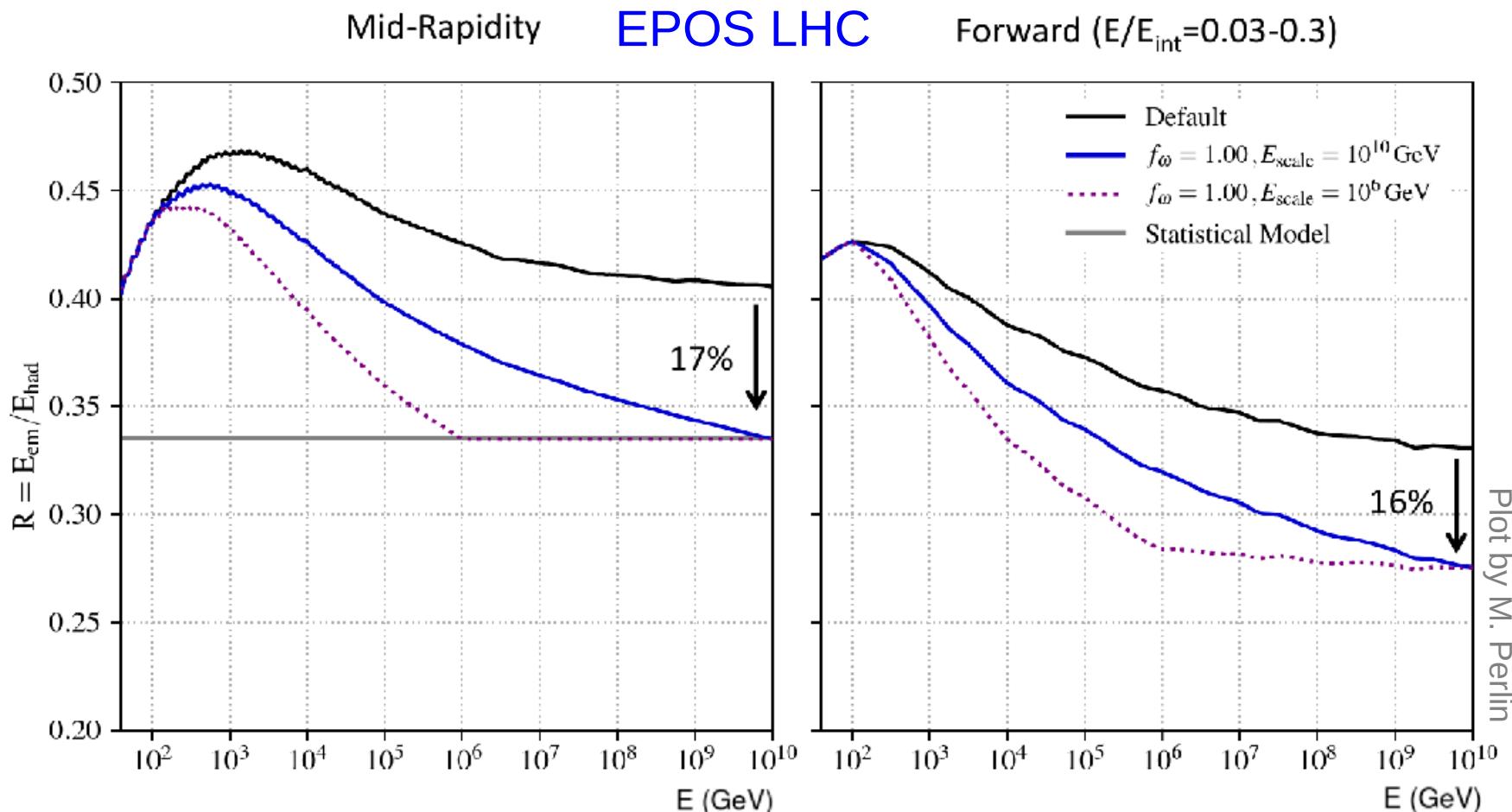


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which define the muon production in air showers.

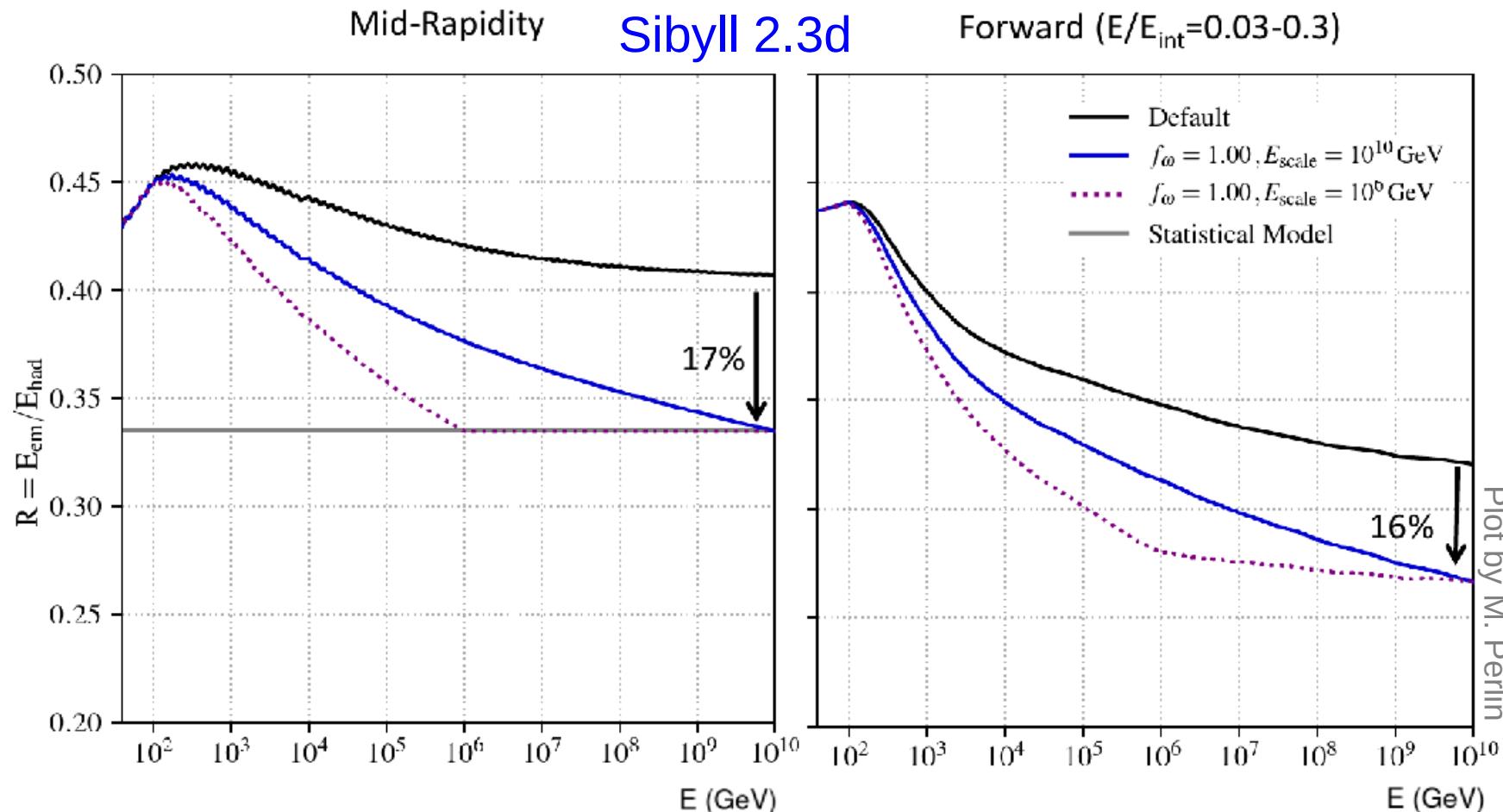


# Evolution of hadronization from core to corona

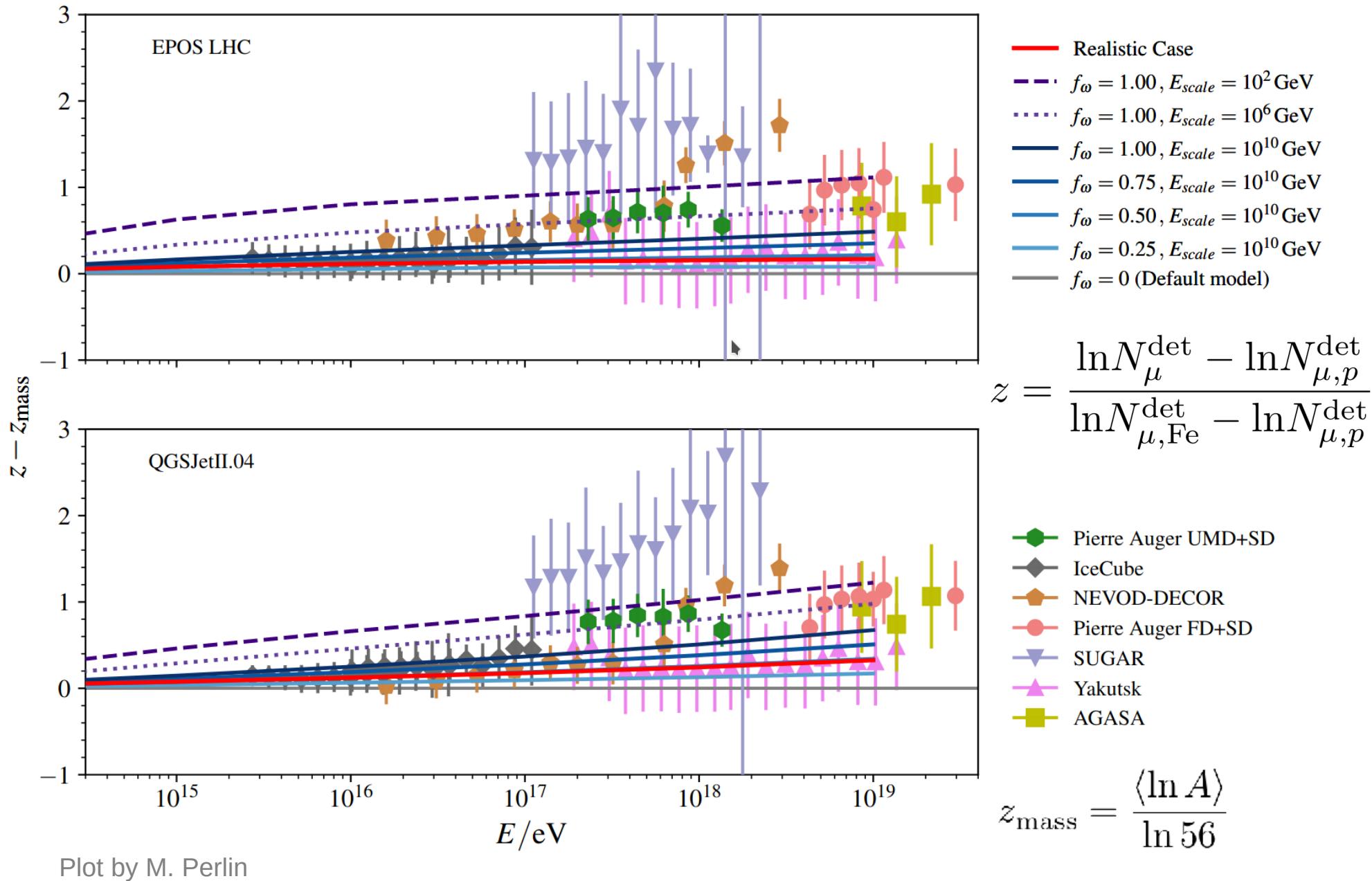
The relative fraction of  $\pi^0$  depends on the hadronization scheme

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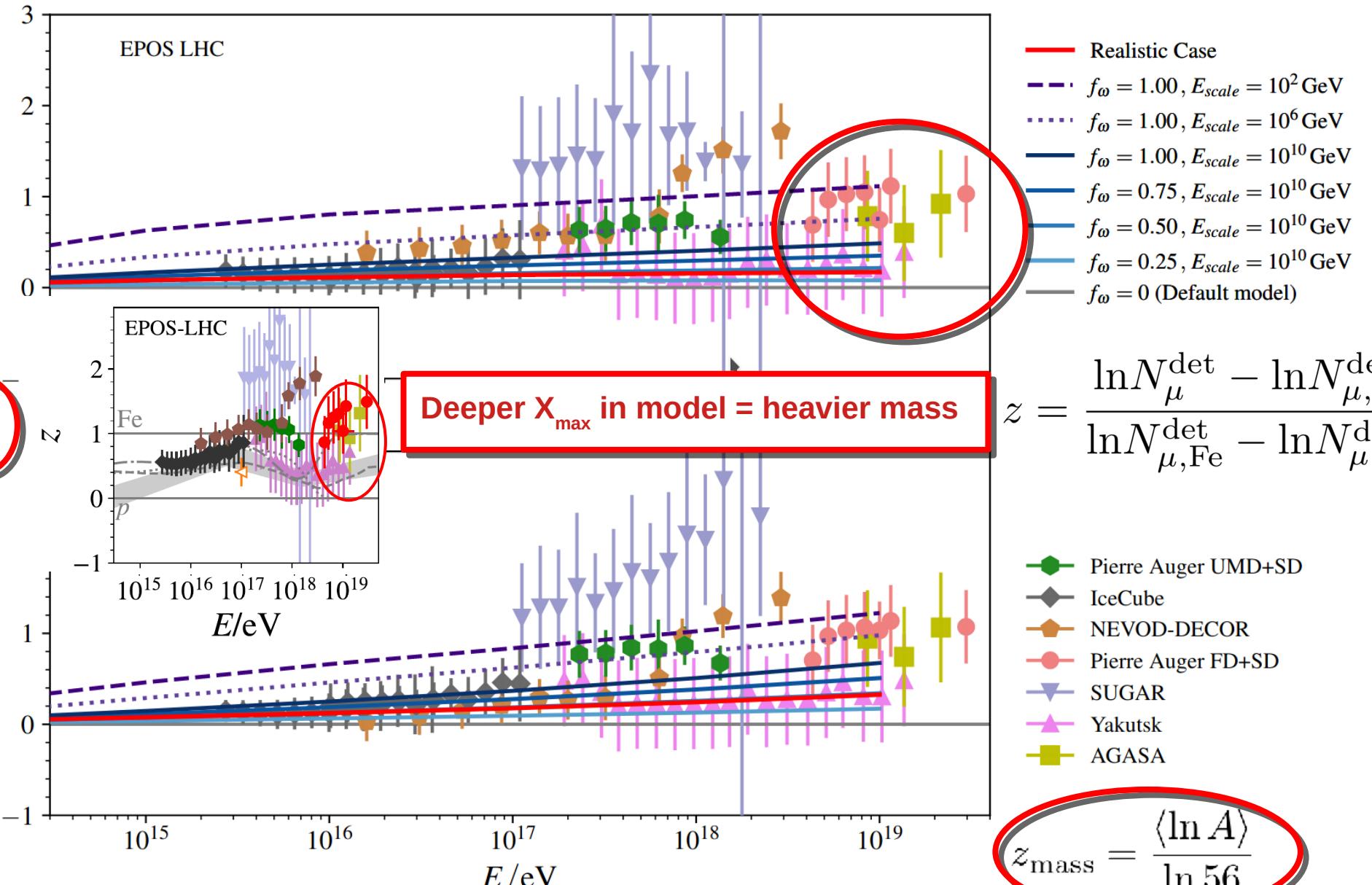
which define the muon production in air showers.



# Results for z-scale

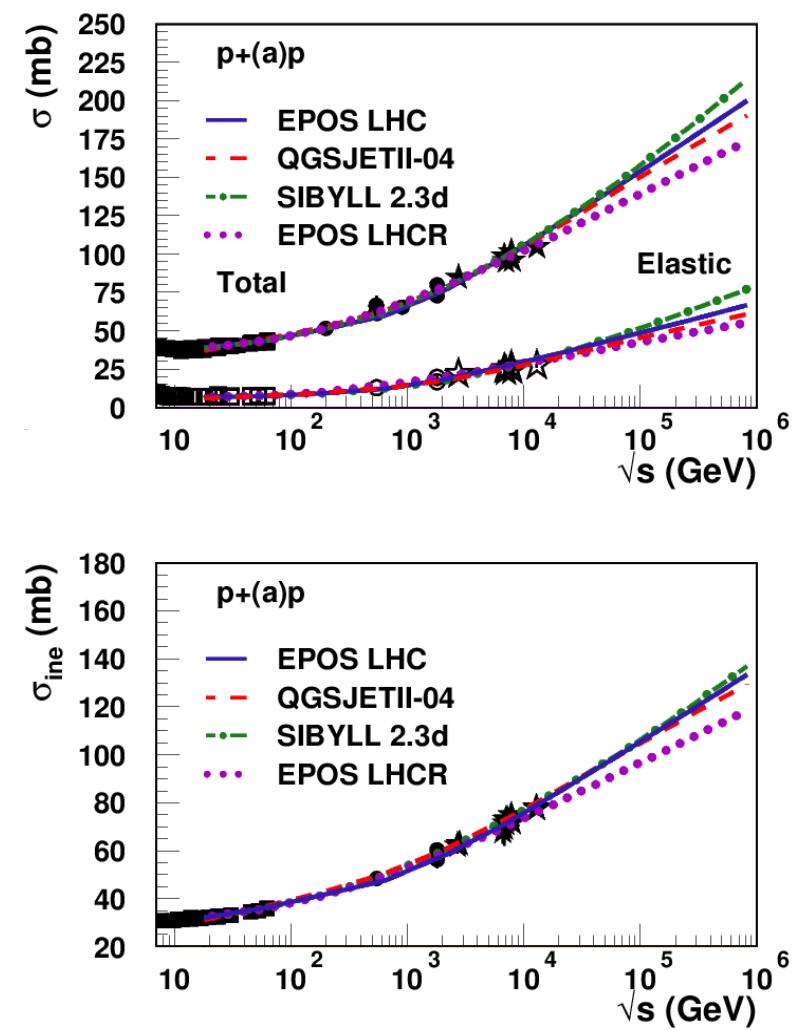
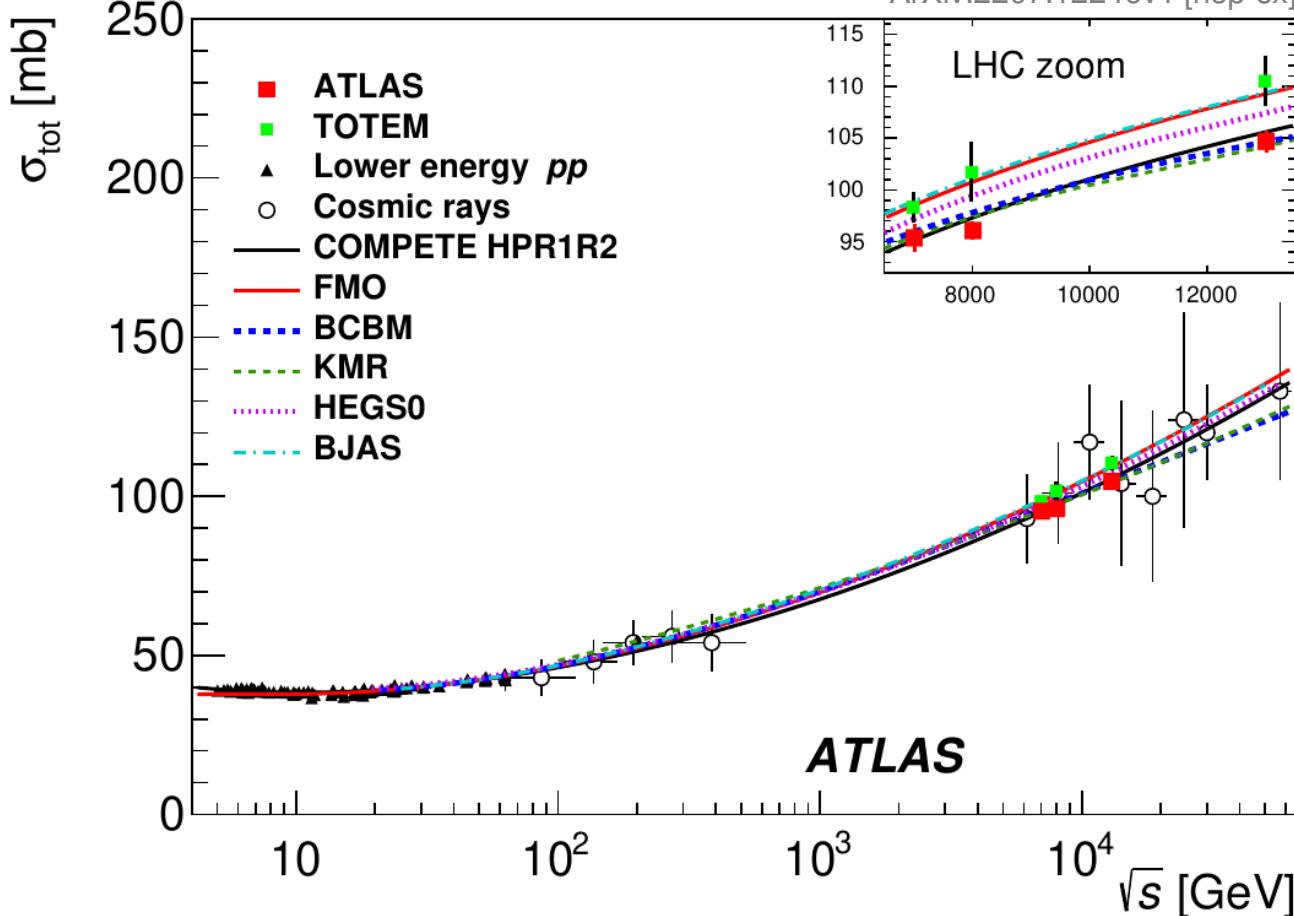


# Results for z-scale



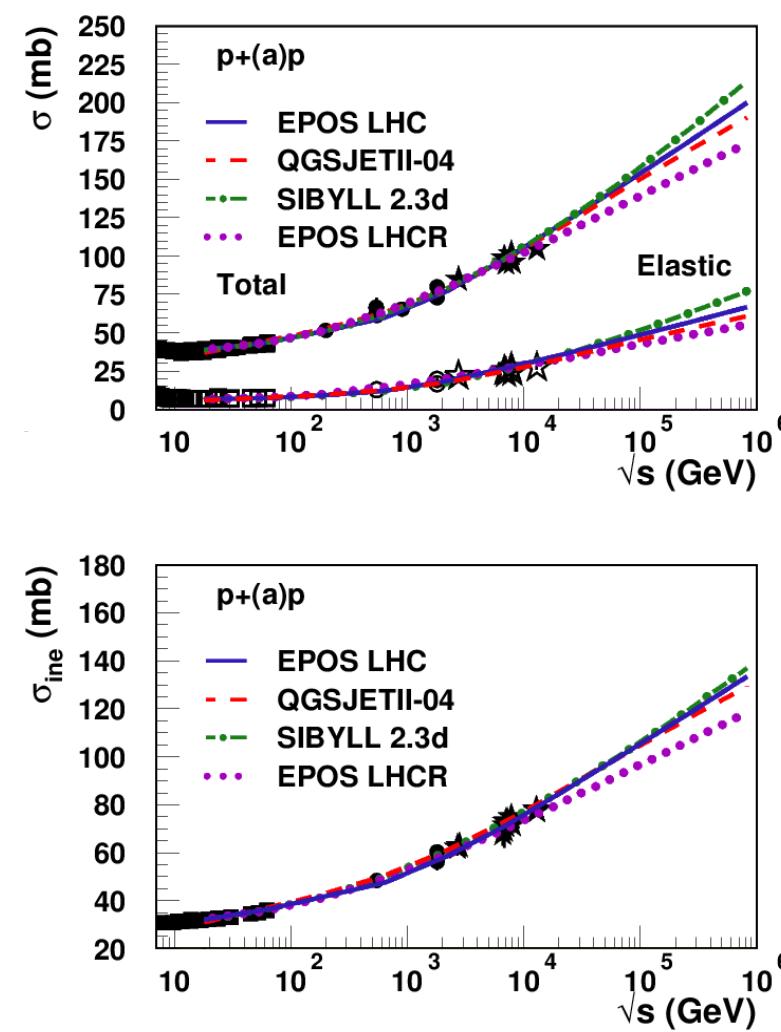
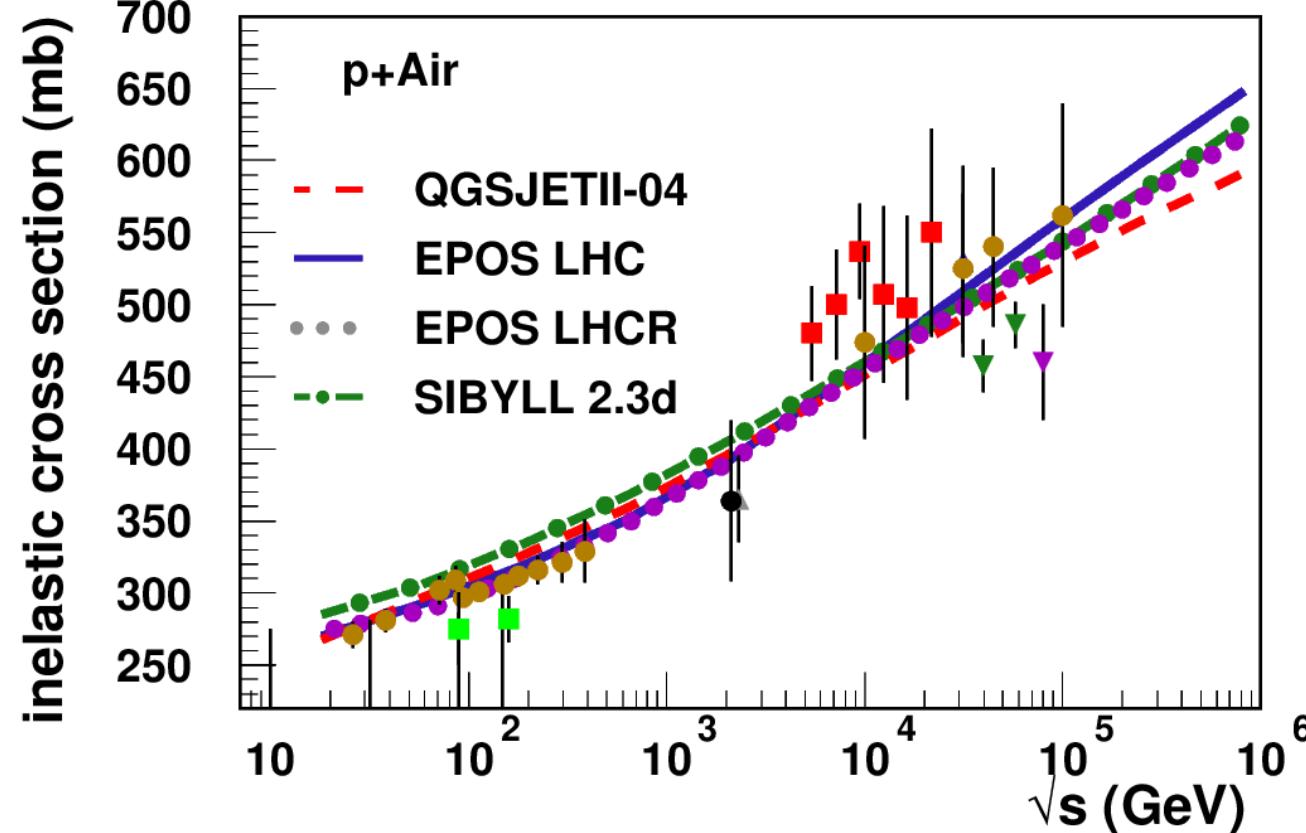
# Inelastic Cross-Section

- Probability for the particle to interact : directly related to  $X_{\max}$
- After TOTEM (CMS), new measurements by ALFA (ATLAS) with higher precision
  - p-p cross-section too high in all models



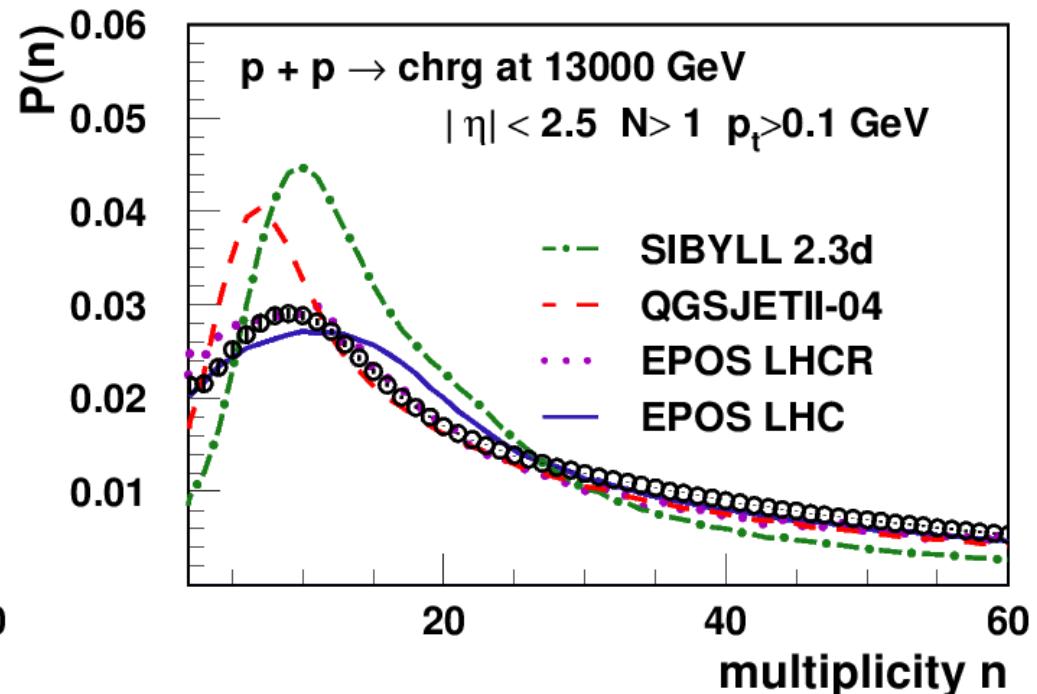
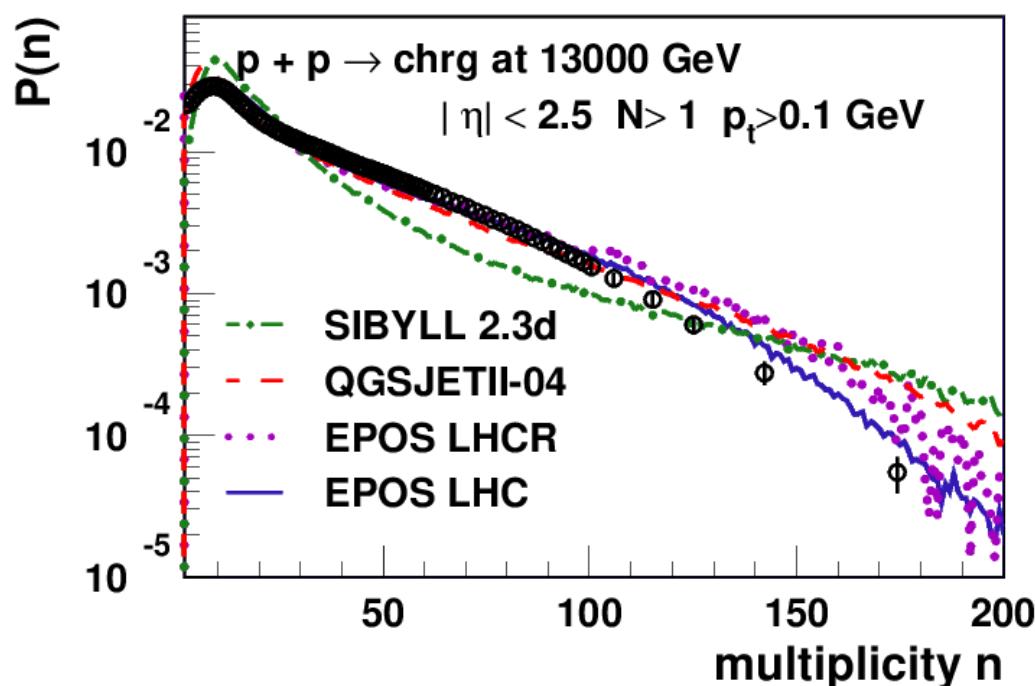
# Cross-Section Reduced

- Probability for the particle to interact : directly related to  $X_{\max}$
- After TOTEM (CMS), new measurements by ALFA (ATLAS) with higher precision
  - p-p cross-section too high in all models
  - Change by -15% at the highest energy



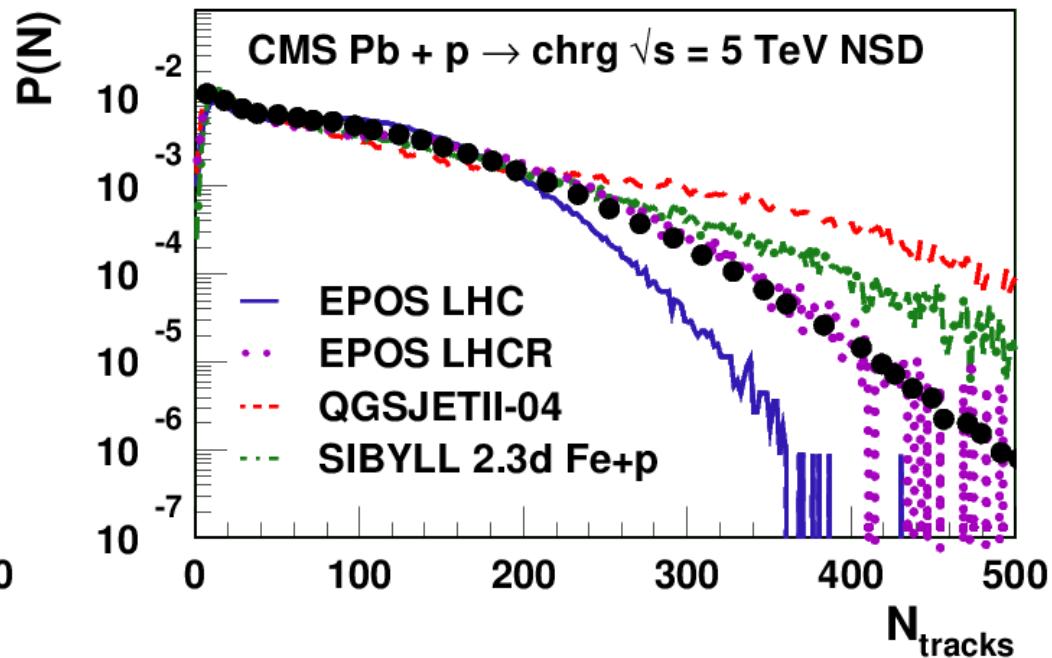
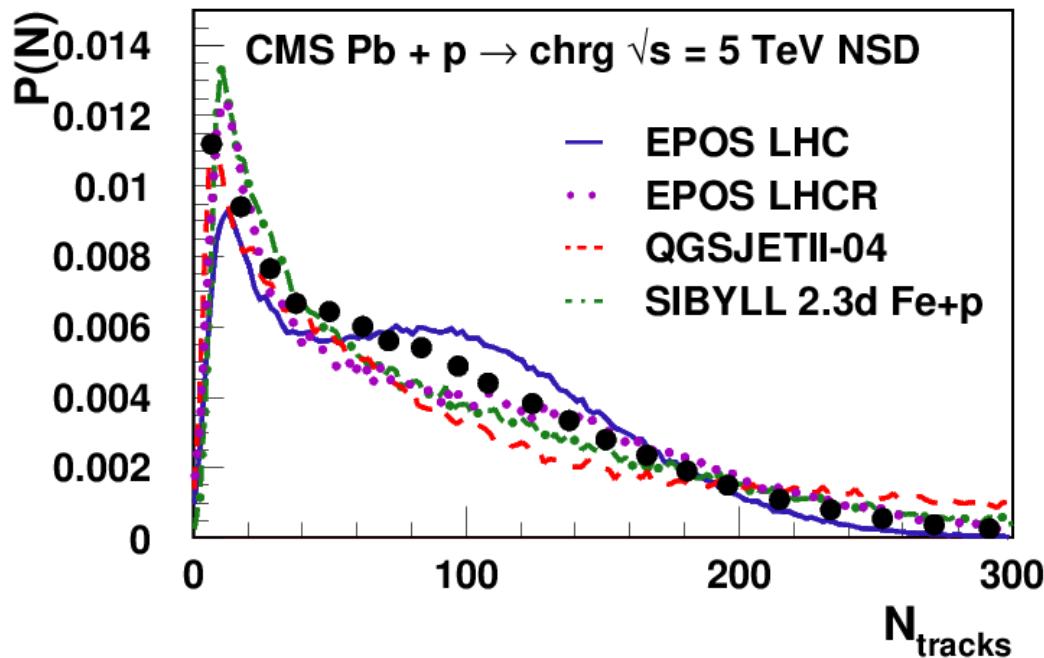
# Multiplicity 13 TeV

- **Probability of a given multiplicity**
- New data at 13 TeV in p-p
  - Not well reproduced by models except EPOS (energy sharing)
  - More attention should be payed to low multiplicities (high elasticity)
    - ➡ Problem was already here at 7 TeV but increasing

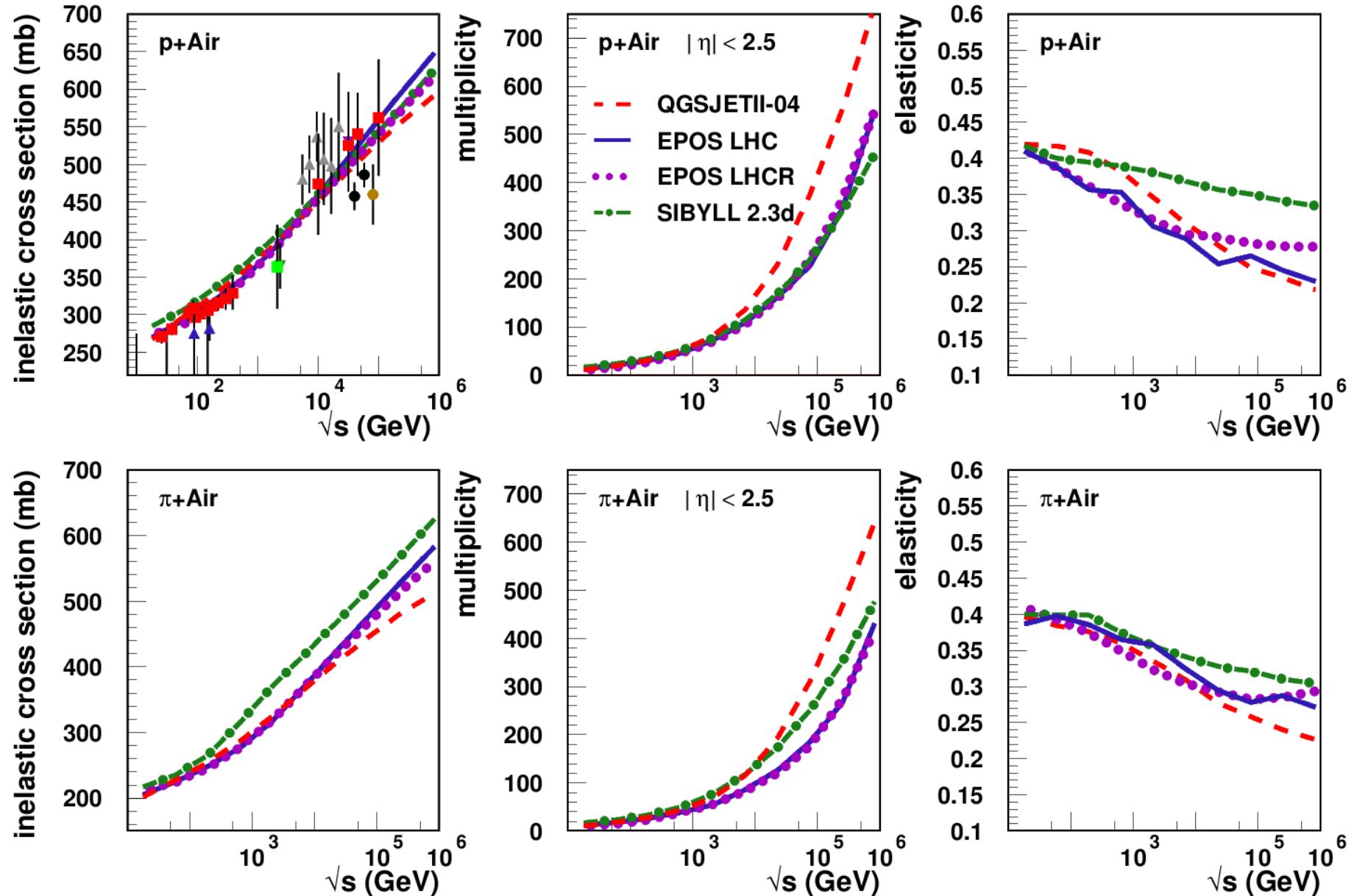


# Multiplicity 5 TeV p-Pb

- **Probability of a given multiplicity**
- New data at 5 TeV in Pb-p
  - Not well reproduced by any model (not possible have lead for Sibyll)
  - A new QCD process has to be introduced in EPOS to reproduce data
    - Color transparency = fluctuation of the number of Fock states
    - Produce more elastic events (low multiplicity)

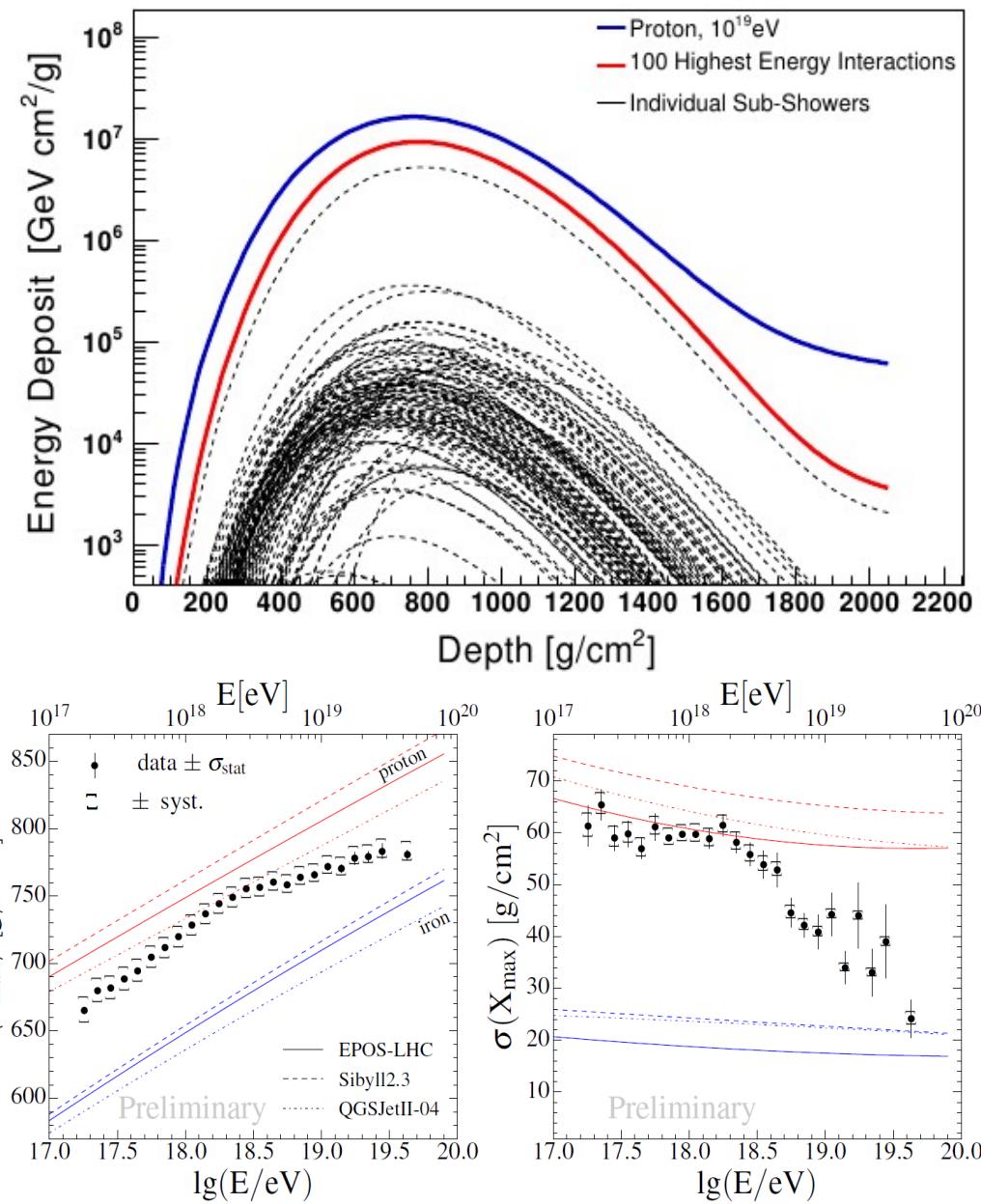


# EPOS LHCR interaction with Air



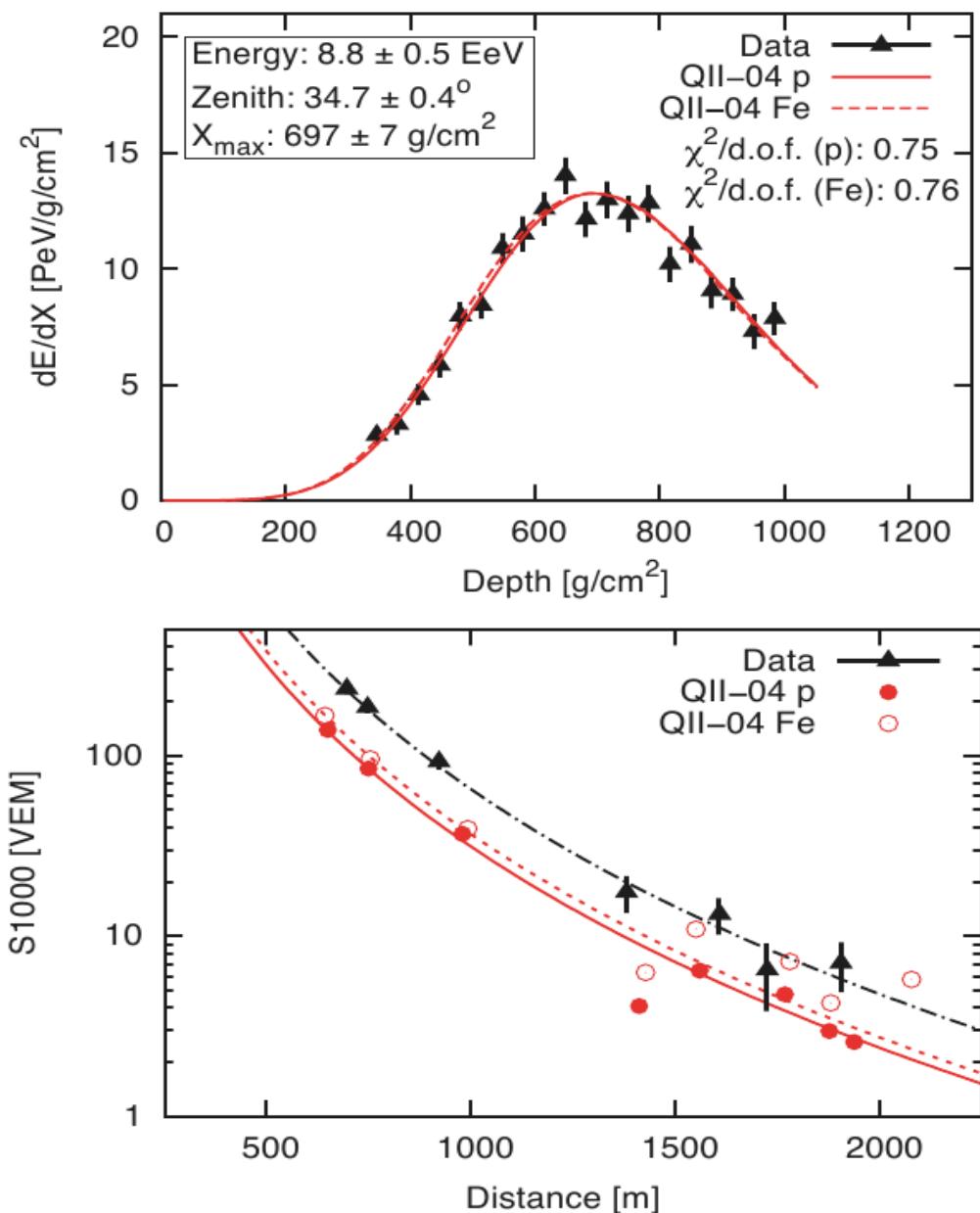
# Fluorescence Detector (FD)

From R. Ulrich (KIT)



- **Most direct measurement**
  - ➔ dominated by first interaction
- **Reference mass for other analysis**
  - ➔ <math>\langle \ln A \rangle</math> from <math>\langle X\_{\max} \rangle</math> and RMS
- **Possibility to use the tail of <math>X\_{\max}</math> distribution to measure p-Air inelastic cross-section.**
  - ➔ require no contamination from photon induced showers (independent check)
  - ➔ correction to “invisible” cross-section using hadronic models
  - ➔ conversion to p-p cross-section using Glauber model.

# Hybrid Analysis



- Analysis based on 411 Golden Hybrid Events

- find simulated showers reproducing each FD profile for all possible models and primary masses (p, He, N, Fe),
- decompose ground signal into pure electromagnetic ( $S_{EM}$ ) and muon dependent signal ( $S_\mu$ ),
- rescale both component separately ( $R_E$  and  $R_\mu$ ) to reproduce SD signal for each showers,
- for mixed composition, give weight according to  $X_{max}$  distribution.

$$S_{\text{resc}}(R_E, R_\mu)_{i,j} \equiv R_E S_{EM,i,j} + R_E^\alpha R_\mu S_{\mu,i,j}$$

# Muon Rescaling

- Simulations don't reproduce FD and SD signal consistently

→  $R = S_{1000}^{\text{observed}} / S_{1000}^{\text{predicted}}$  increase with zenith angle

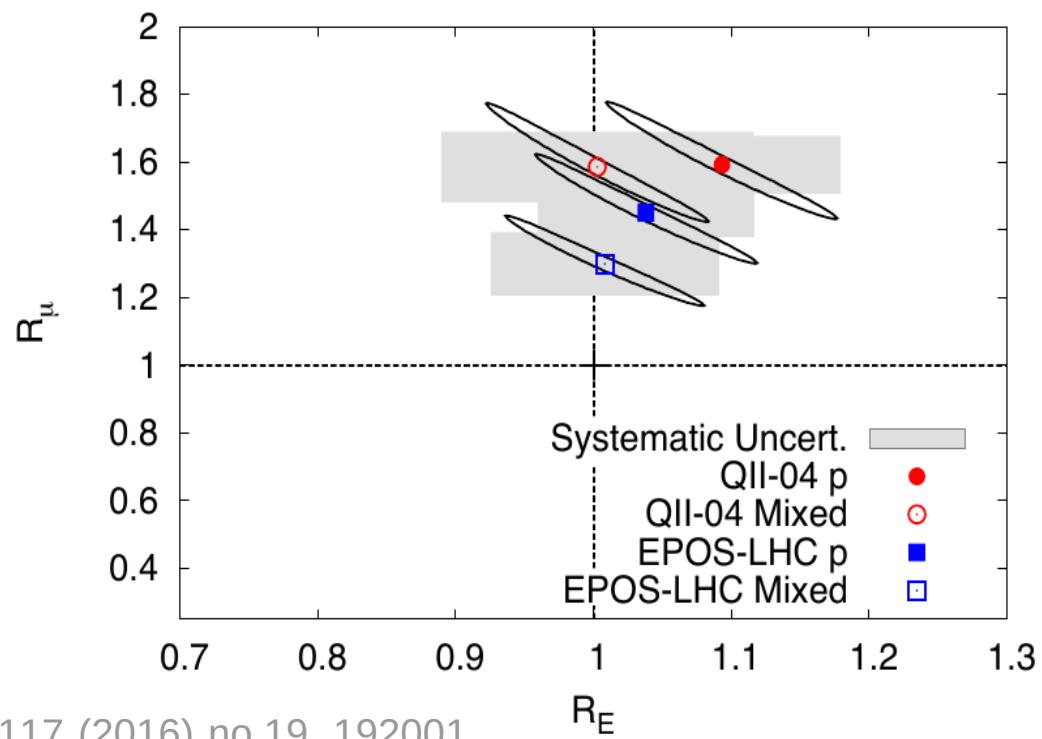
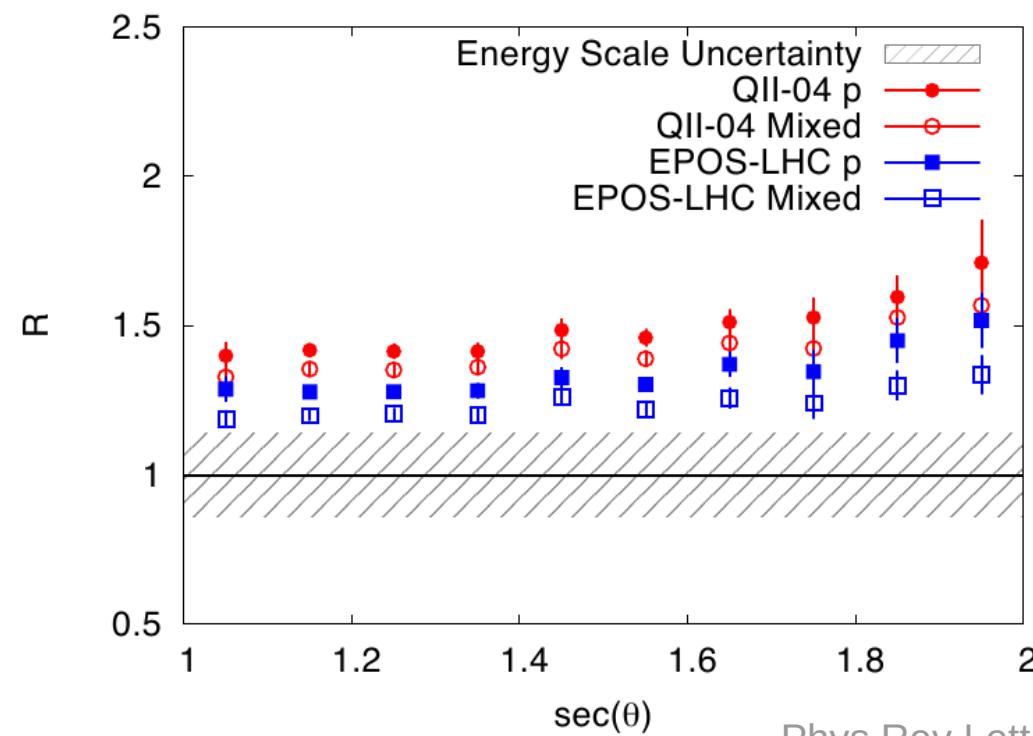
→ EPOS-LHC Iron could be (almost) compatible with data, but  $X_{\max}$  data are NOT pure Iron (but mixed).

- To reproduce data simulations have to be rescaled

→ for mixed composition, only muon component has to be changed

→ correct energy scale

→ 30% muon deficit for EPOS-LHC and 59% for QGSJETII-04.

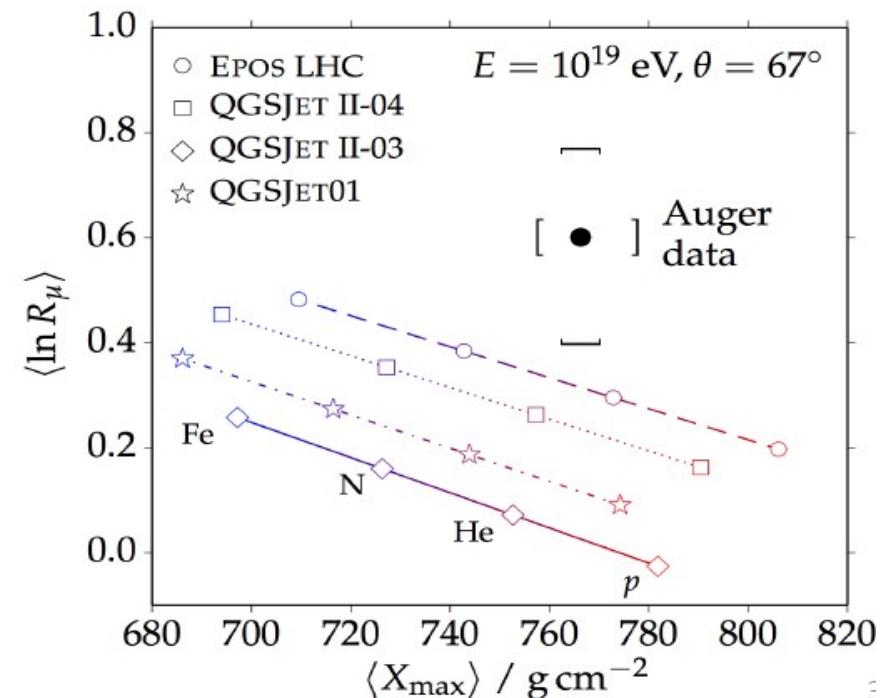
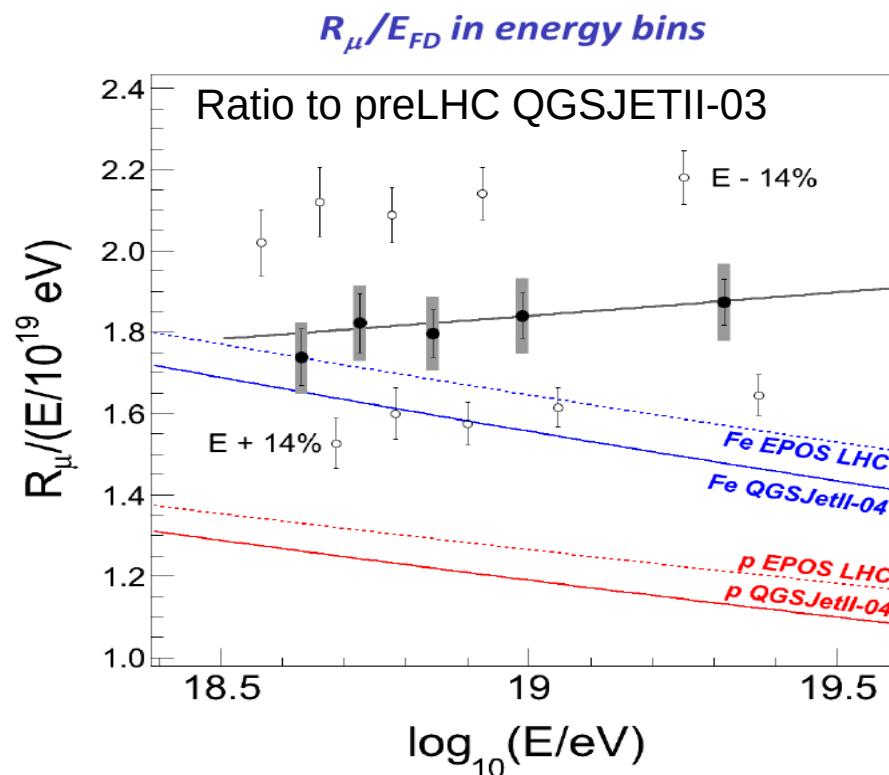
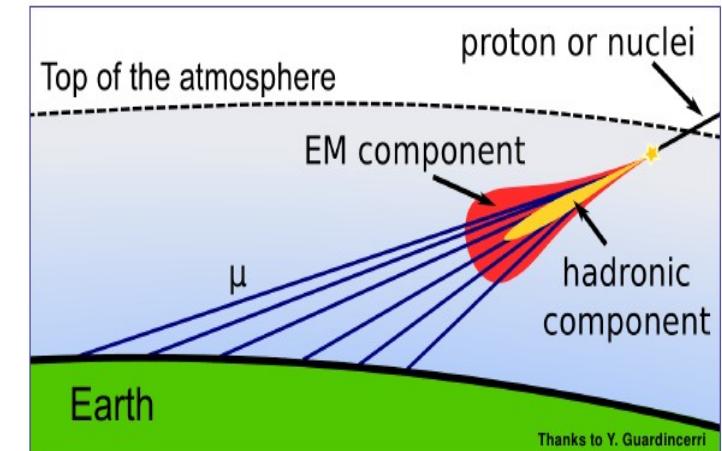


Phys.Rev.Lett. 117 (2016) no.19, 192001

# Direct Muon Measurement

- Old showers contain only muon component

- direct muon counting with very inclined showers ( $>60^\circ$ ) by comparing to simulated muon maps (geometry and geomagnetic field effects)
- EM halo accounted for
- correction between true muon number and reconstructed one from map by MC (<5%)



# Muon Production Depth

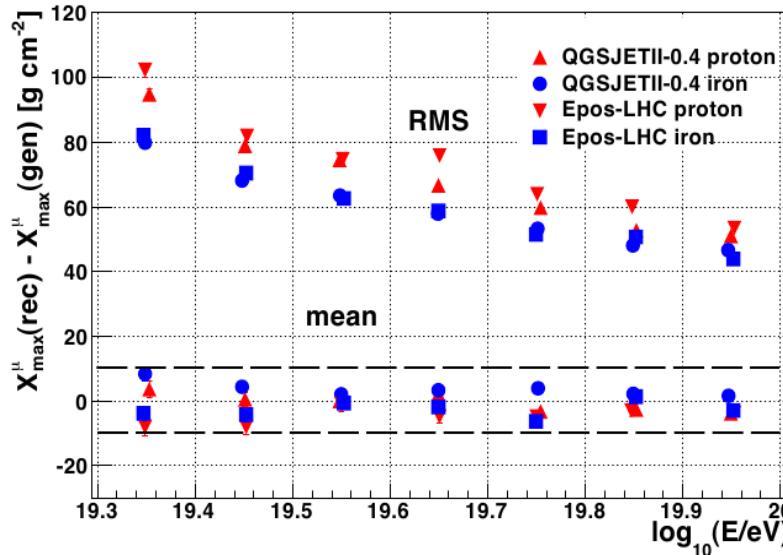
- Independent SD mass composition measurement
  - geometric delay of arriving muons

$$\begin{aligned} c \cdot t_g &= l - (z - \Delta) \\ &= \sqrt{r^2 + (z - \Delta)^2} - (z - \Delta) \end{aligned}$$

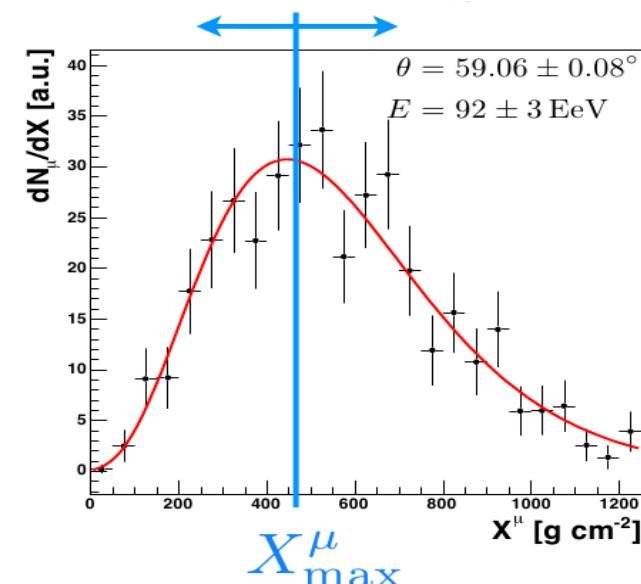
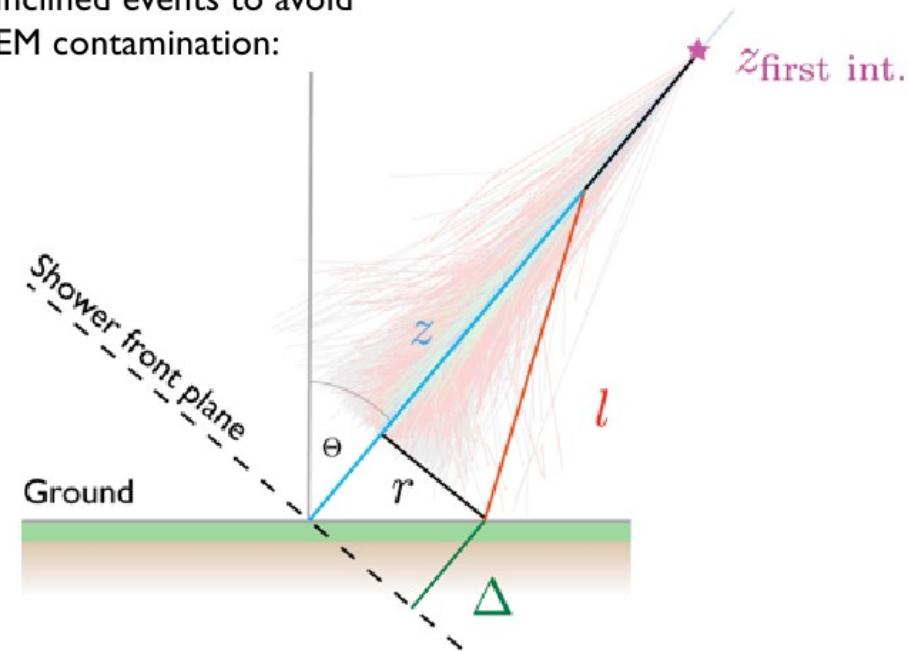
- mapped to muon production distance

$$z = \frac{1}{2} \left( \frac{r^2}{ct_g} - ct_g \right) + \Delta$$

- decent resolution and no bias

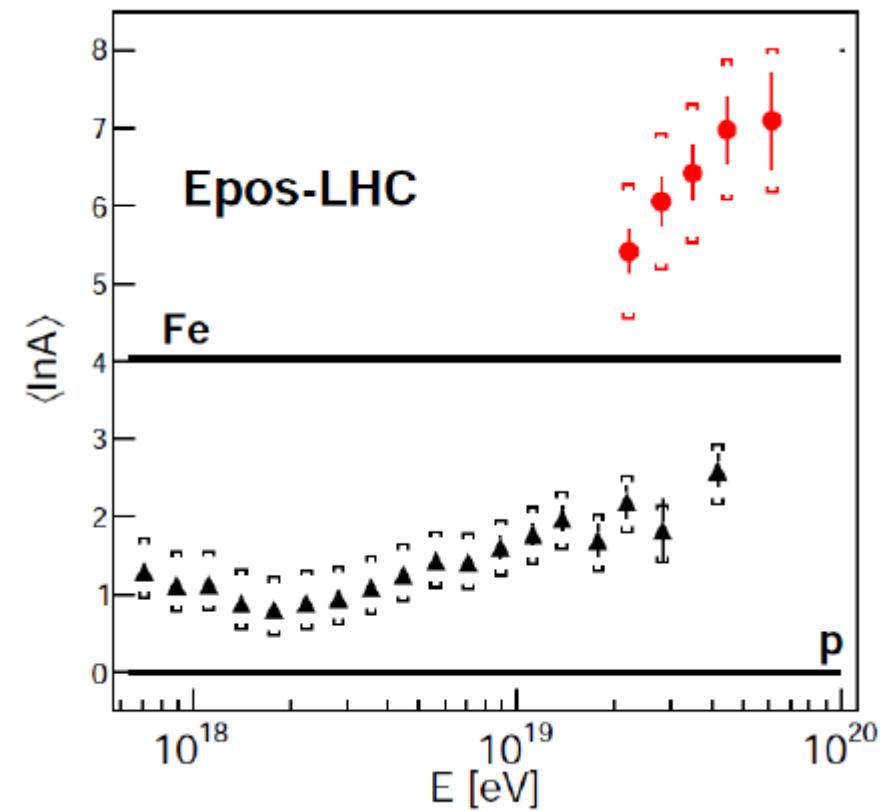
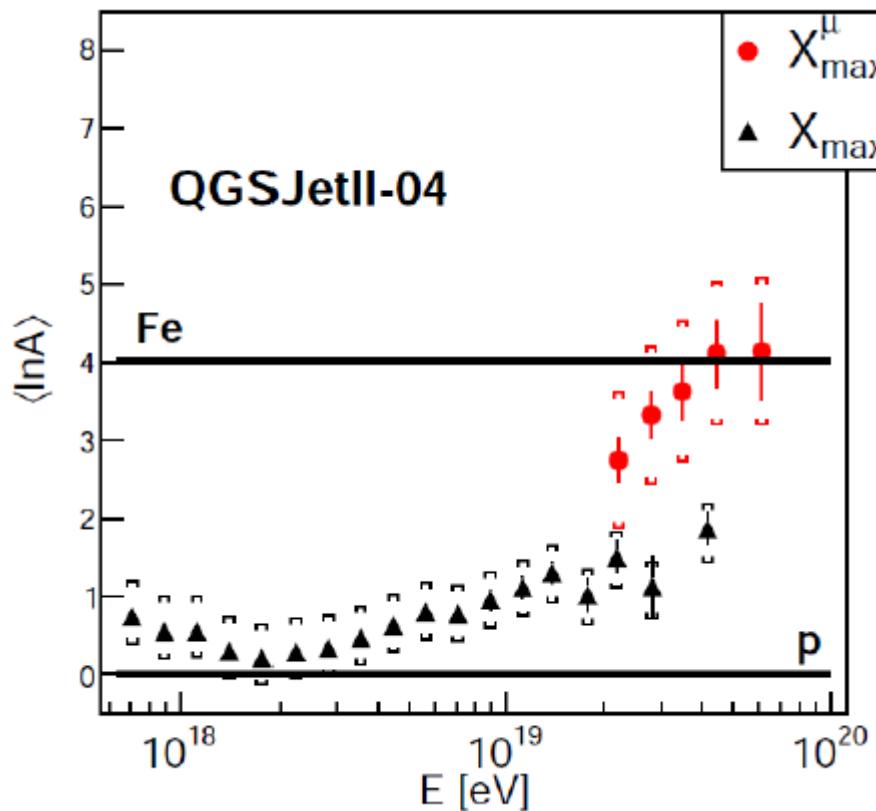


Inclined events to avoid EM contamination:



# MPD and Models

- 2 independent mass composition measurements
  - both results should be between p and Fe
  - both results should give the same mean logarithmic mass for the same model
  - problem with EPOS appears after corrections motivated by LHC data (low mass diffraction) and model consistency (forward baryon production at high energy): **direct constraint on hadronic interactions.**

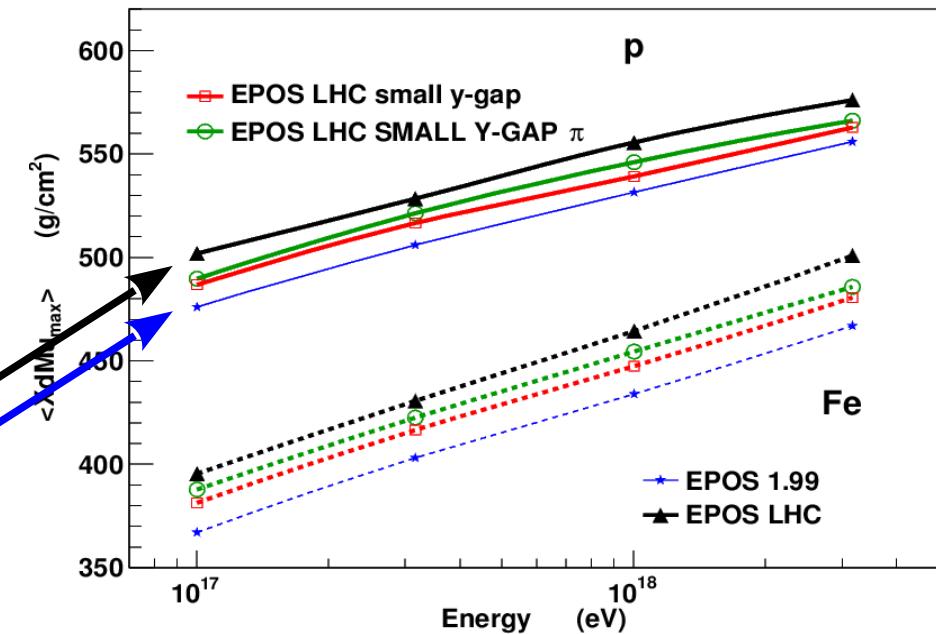
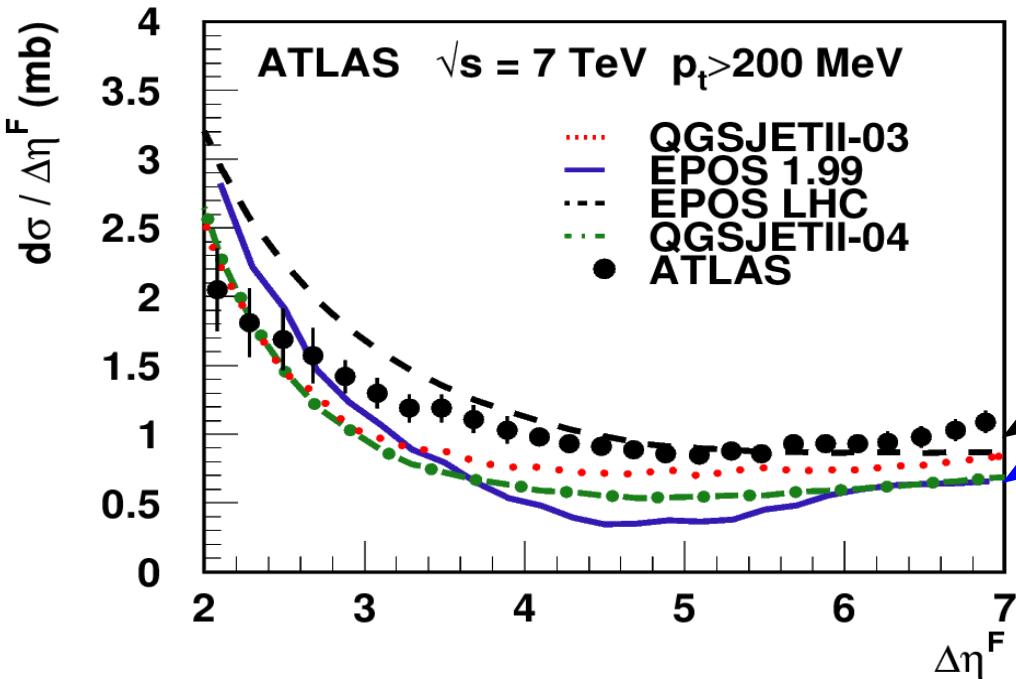


# MPD and Diffraction

## Inelasticity linked to diffraction (cross-section and mass distribution)

- weak influence on EM  $X_{\max}^\mu$  since only 1st interaction really matters
- cumulative effect for  $X_{\max}^\mu$  since muons produced at the end of hadr. subcasc.
- rapidity-gap in p-p @ LHC not compatible with measured MPD
- harder mass spectrum for pions reduce  $X_{\max}^\mu$  and increase muon number !

**different diffractive mass distribution for mesons and baryons !**



# Correlation between $X_{\max}^*$ and $S^*(1000)$

- in data correlation is significantly negative

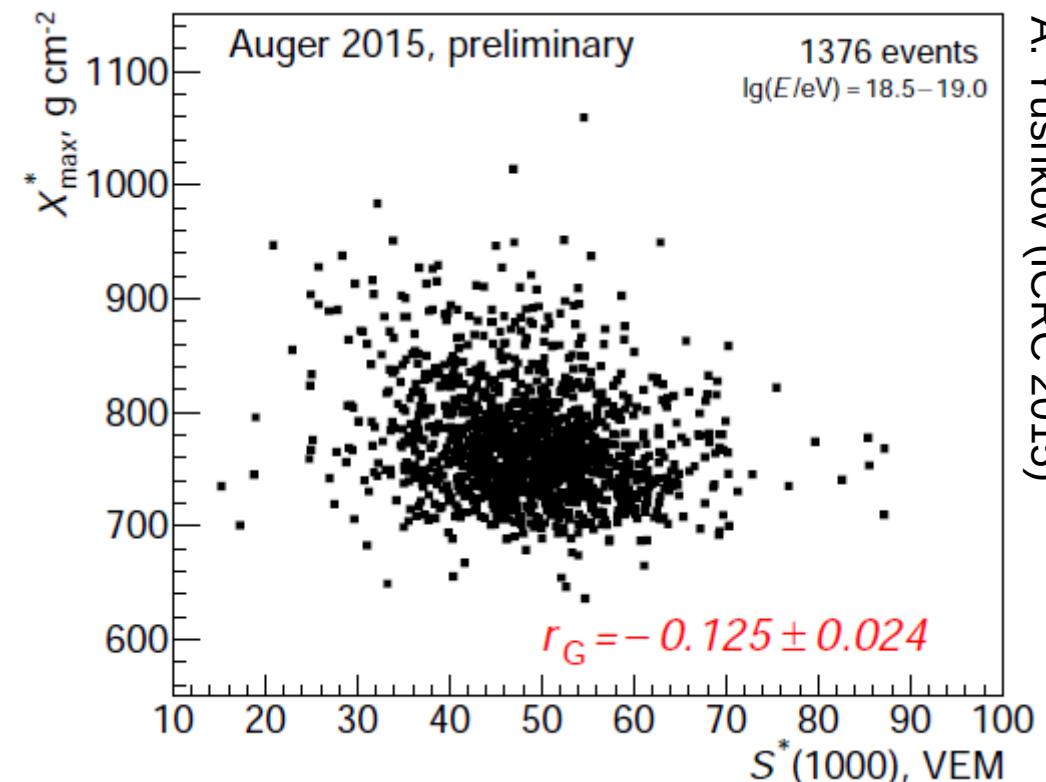
$$\rightarrow r_G = -0.125 \pm 0.024$$

- $r_G(X_{\max}^*, S^*(1000))$  for p

- EPOS-LHC : 0.00 ( $5\sigma$  to data)
- QGSJetII-04 : +0.08 ( $8\sigma$  to data)
- Sibyll 2.1 : +0.07 ( $7.5\sigma$  to data)

- difference is larger for other pure beams

primary composition  
near the 'ankle' is  
mixed

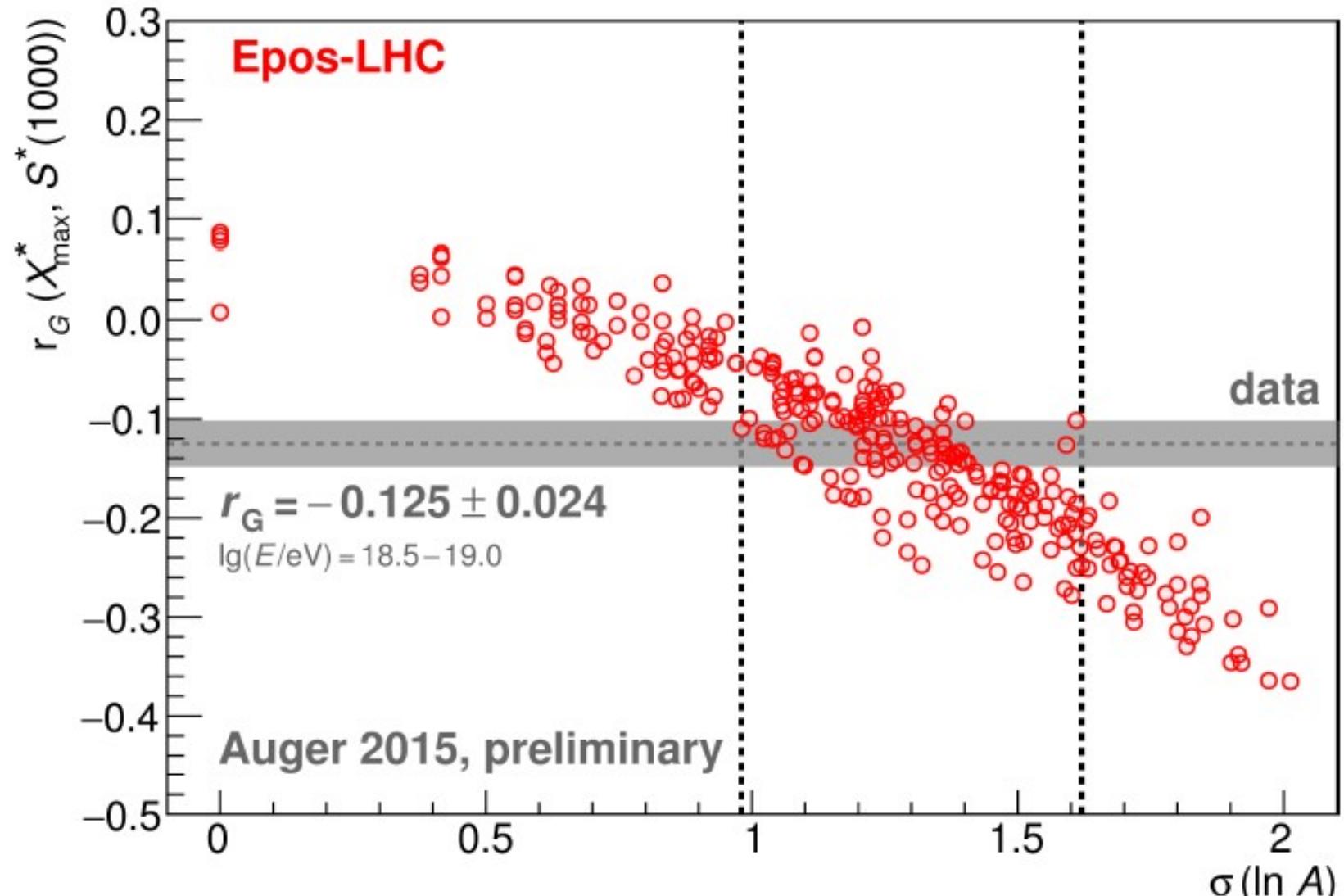


$r_G$  - rank correlation coefficient introduced in R. Gideon, R. Hollister, JASA 82 (1987) 656

- test of “exotic” models fails

# Dispersion of Masses in Data

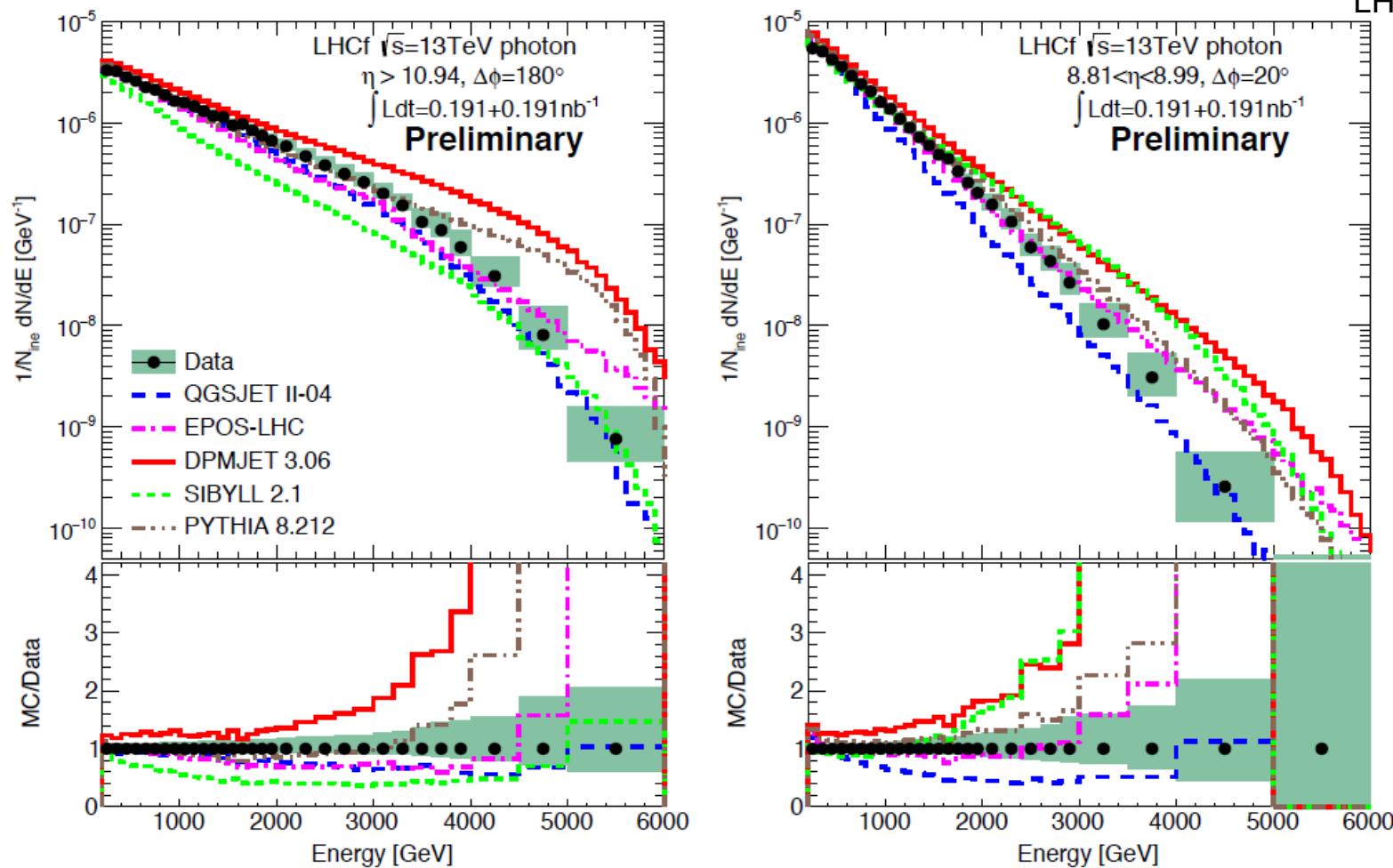
A. Yushkov (ICRC 2015)



# Comparison with LHCf

- LHCf favor not too soft photon spectra (EPOS LHC, SIBYLL 2.3) : deep  $X_{\max}$
- No model compatible with all LHCf measurements : room for improvements !
- Can p-Pb data be used to mimic light ion (Air) interactions ?

T.Sako for the  
LHCf collaboration



# Baryons in Pion-Carbon

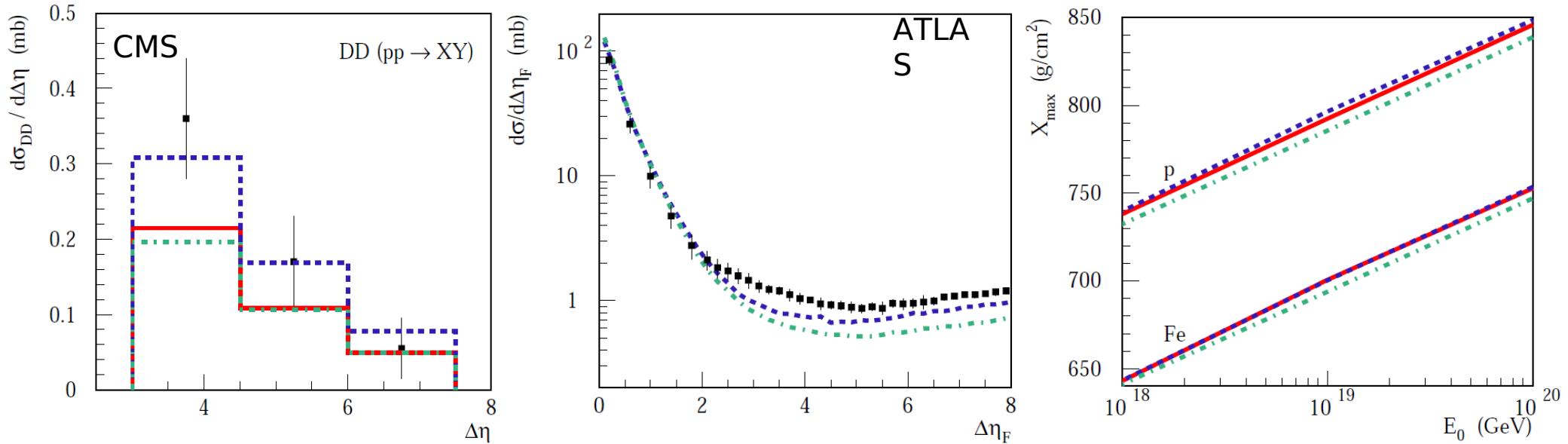
- Very few data for baryon production from meson projectile, but for all :
    - strong baryon acceleration (probability ~20% per string end)
    - proton/antiproton asymmetry (valence quark effect)
    - target mass dependence
  - New data set from NA49 (G. Veres' PhD)
    - test  $\pi^+$  and  $\pi^-$  interactions and productions at 158 GeV with C and Pb target
    - confirm large forward proton production in  $\pi^+$  and  $\pi^-$  interactions but not for anti-protons
      - ◆ forward protons in pion interactions are due to strong baryon stopping  
(nucleons from the target are accelerated in projectile direction)
      - ◆ strong effect only at low energy
- EPOS overestimate forward baryon production at high energy

# Diffraction measurements

- TOTEM and CMS diffraction measurement not fully consistent
- Tests by S. Ostapchenko using QGSJETII-04 (PRD89 (2014) no.7, 074009)
  - SD+ option compatible with CMS
  - SD- option compatible with TOTEM

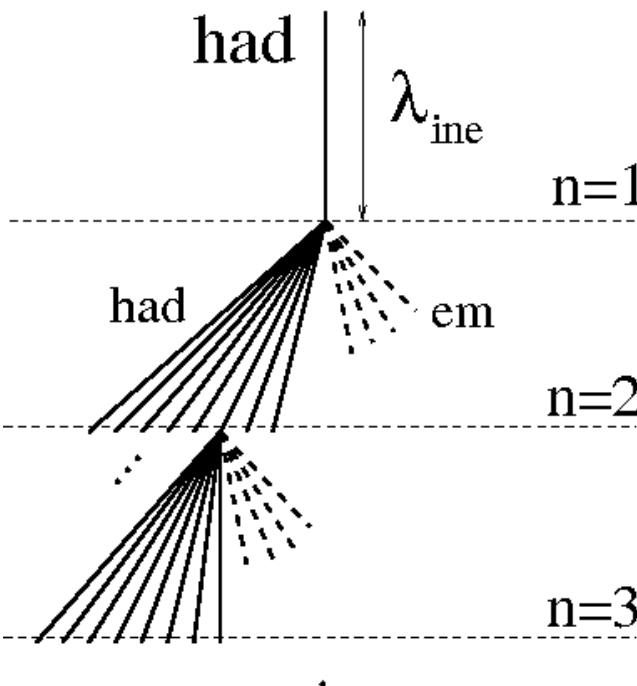
$M_X$ range	< 3.4 GeV	3.4 – 1100 GeV	3.4 – 7 GeV	7 – 350 GeV	350 – 1100 GeV
TOTEM [13, 24]	$2.62 \pm 2.17$	$6.5 \pm 1.3$	$\simeq 1.8$	$\simeq 3.3$	$\simeq 1.4$
QGSJET-II-04	3.9	7.2	1.9	3.9	1.5
option SD+	3.2	8.2	1.8	4.7	1.7
option SD-	2.6	7.2	1.6	3.9	1.7

→ difference of  $\sim 10$  gr/cm $^2$  between the 2 options



# Simplified Shower Development

Using generalized Heitler model and superposition model :



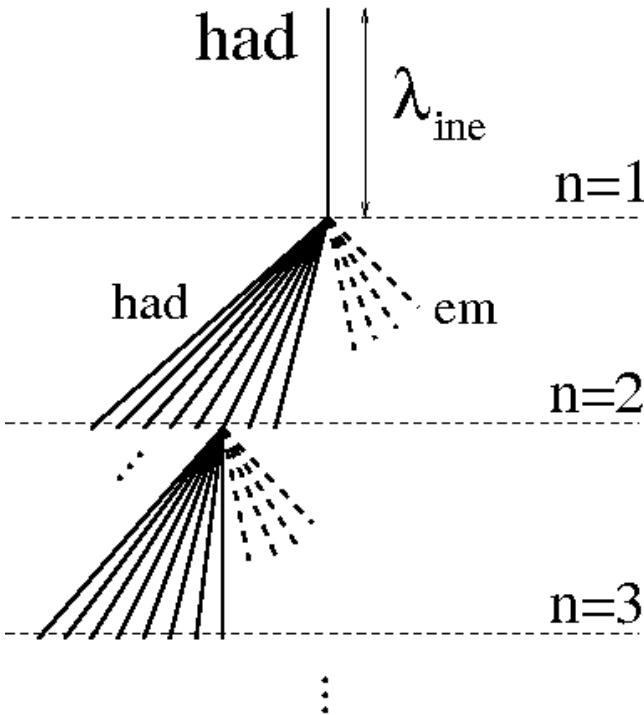
$$N_{tot} = N_{had} + N_{em}$$

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

$$X_{max} \sim \lambda_e \ln \left( (1-k) \cdot E_0 / (2 \cdot N_{tot} \cdot A) \right) + \lambda_{ine}$$

- Model independent parameters :
  - $E_0$  = primary energy
  - $A$  = primary mass
  - $\lambda_e$  = electromagnetic mean free path
- Model dependent parameters :
  - $k$  = elasticity
  - $N_{tot}$  = total multiplicity
  - $\lambda_{ine}$  = hadronic mean free path (cross section)

# Toy Model for Hadronic Cascade



**Primary particle : hadron**  
**Muons produced after many had. generations**

$N_{\text{had}}^n$  particles  
can produce  
muons after  $n$   
interactions

$N_{\text{tot}}^n$  particles  
share  $E_0$  after  $n$   
interactions

$$N(n) = N_{\text{had}}^n$$

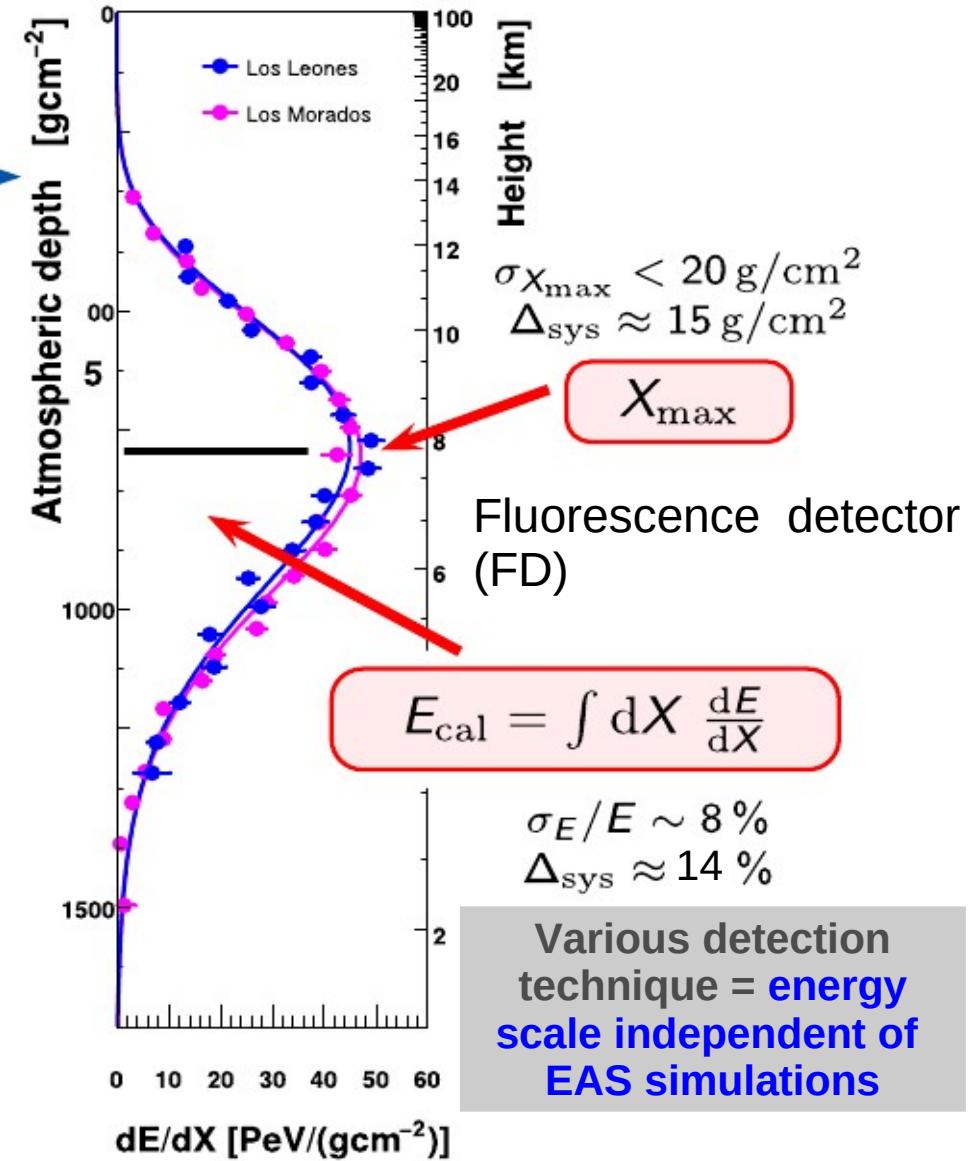
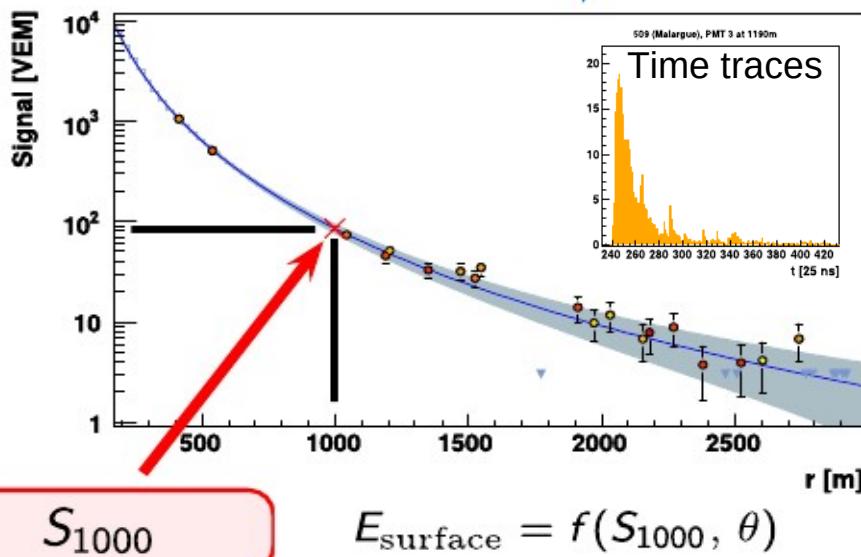
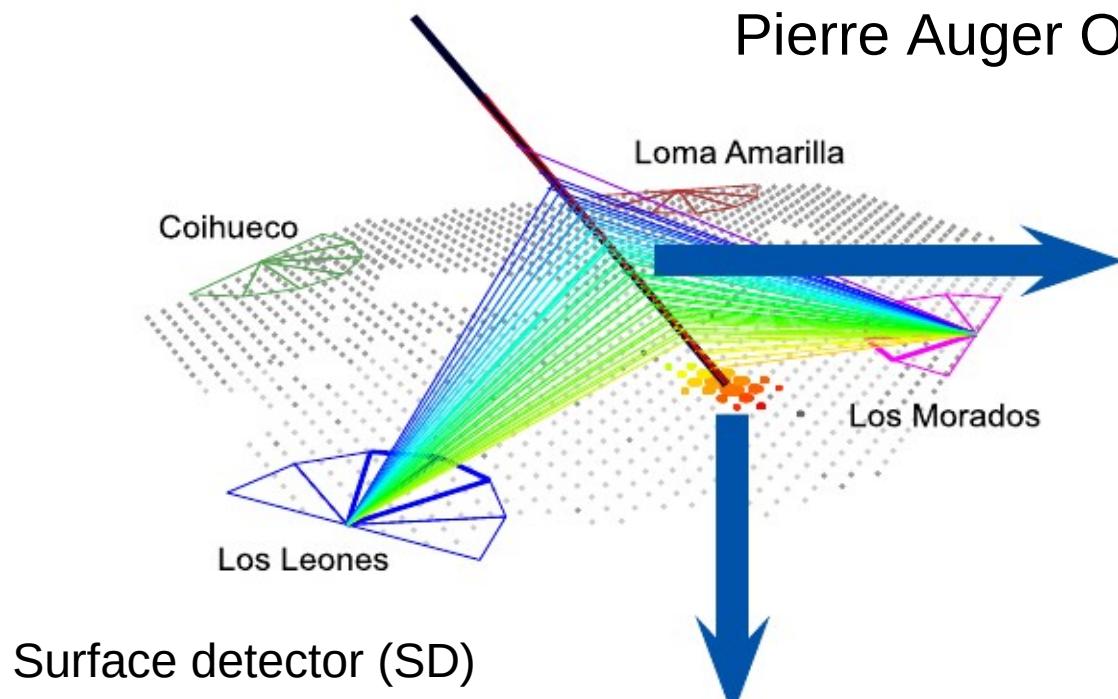
$$E(n) = E_0 / N_{\text{tot}}^n$$

**Assumption:** particle decay to muon when  $E$   
 $= E_{\text{dec}}$  (critical energy) after  $n_{\text{max}}$  generations

$$E_{\text{dec}} = E_0 / N_{\text{tot}}^{n_{\text{max}}} \quad n_{\text{max}} = \frac{\ln(E_0/E_{\text{dec}})}{\ln(N_{\text{tot}})} \quad \ln(N_{\mu}) = \ln(N(n_{\text{max}})) = n_{\text{max}} \ln(N_{\text{had}})$$

# Hybrid Detection

Pierre Auger Observatory / Telescope Array



# When does a projectile interact ?

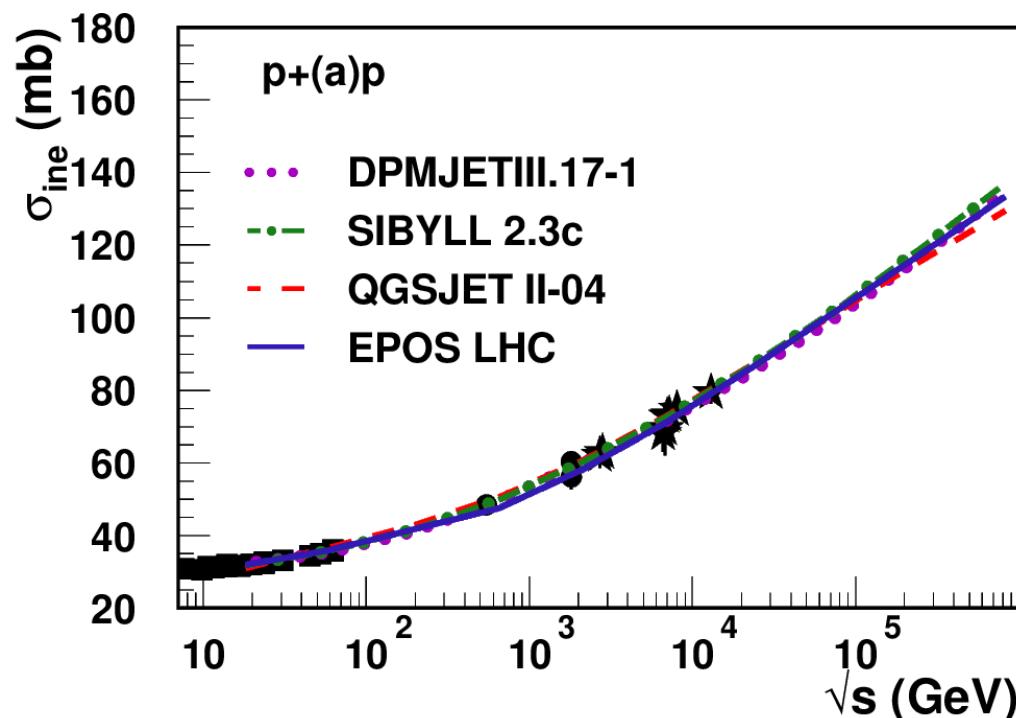
For all models cross-section calculation based on optical theorem

→ total cross-section given by elastic amplitude

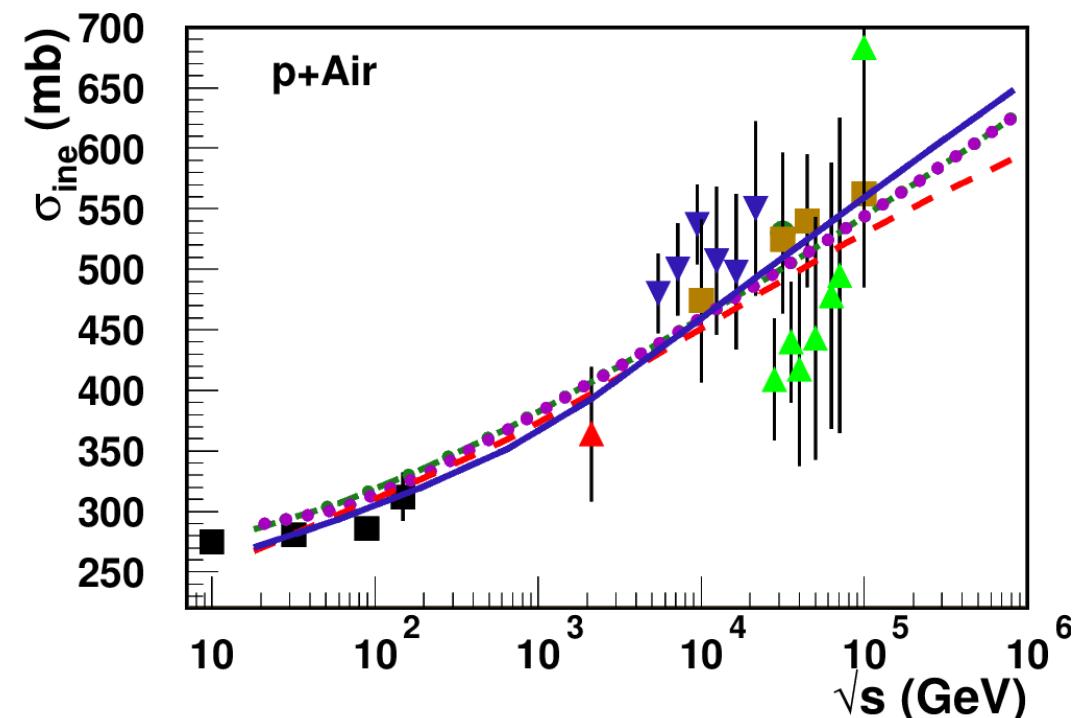
ide most generally defi

- different amplitudes in the models but free parameters set to reproduce all p-p cross-sections
- basic principles + high quality LHC data = same extrapolation

pp



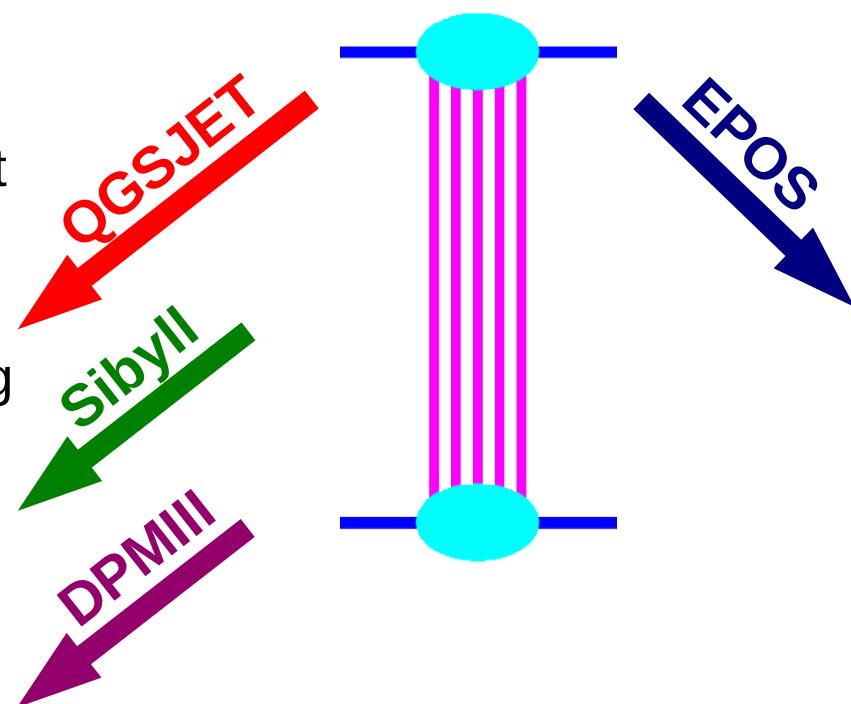
p-Air



# How does the projectile interact ?

- Field theory : scattering via the exchange of an excited field
  - parton, hadron, quasi-particle (= Reggeon or Pomeron (vacuum excitation))
- Gribov-Regge Theory and cutting rules : multiple scattering associated to cross-section via sum of inelastic states
  - different ways of dealing with energy conservation

- sum all scatterings with full energy to get cross-section
- get number of elementary scattering without energy sharing (Poissonian distribution)
- share energy between scattering afterwards

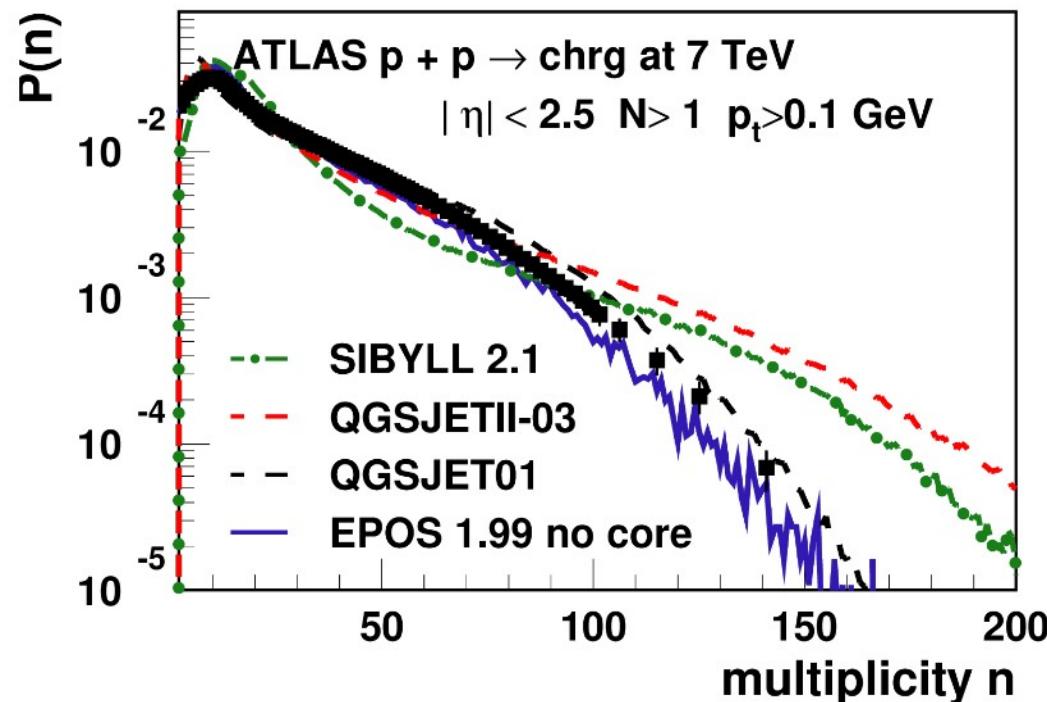


- cross-section calculated with energy sharing
- get the number of scattering taking into account energy conservation
- consistent approach

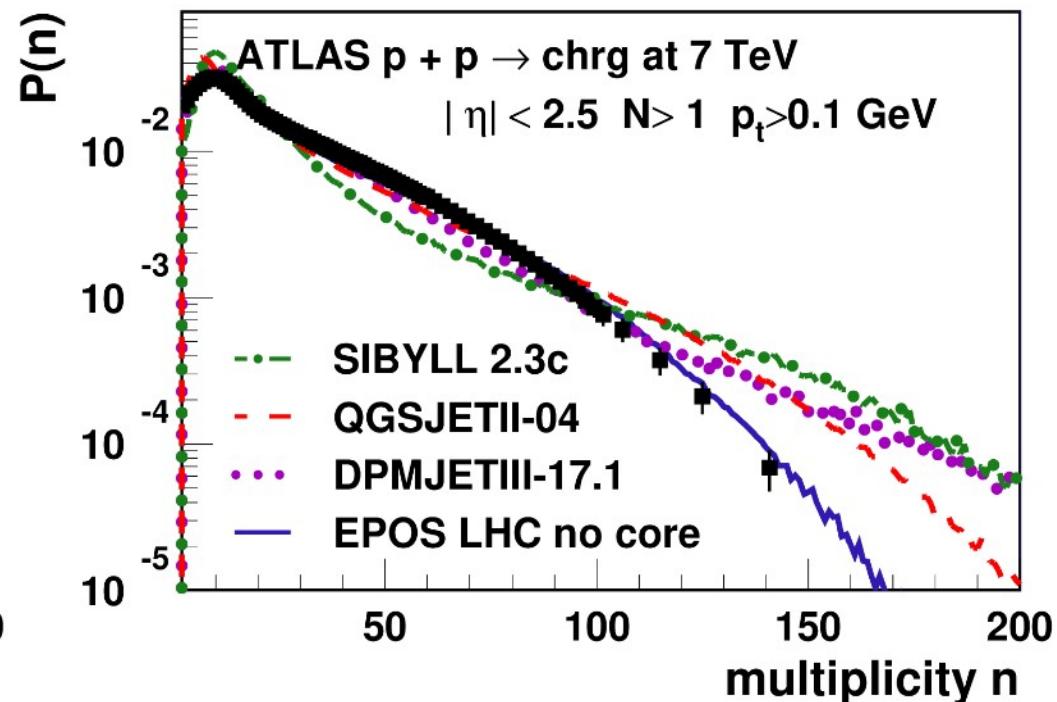
# Does energy sharing order matter ?

- Field theory : scattering via the exchange of an excited field
  - parton, hadron, quasi-particle = Reggeon or Pomeron (vacuum excitation)
- Gribov-Regge Theory and cutting rules : multiple scattering associated to cross-section via sum of inelastic states
  - different ways of dealing with energy conservation

Pre - LHC



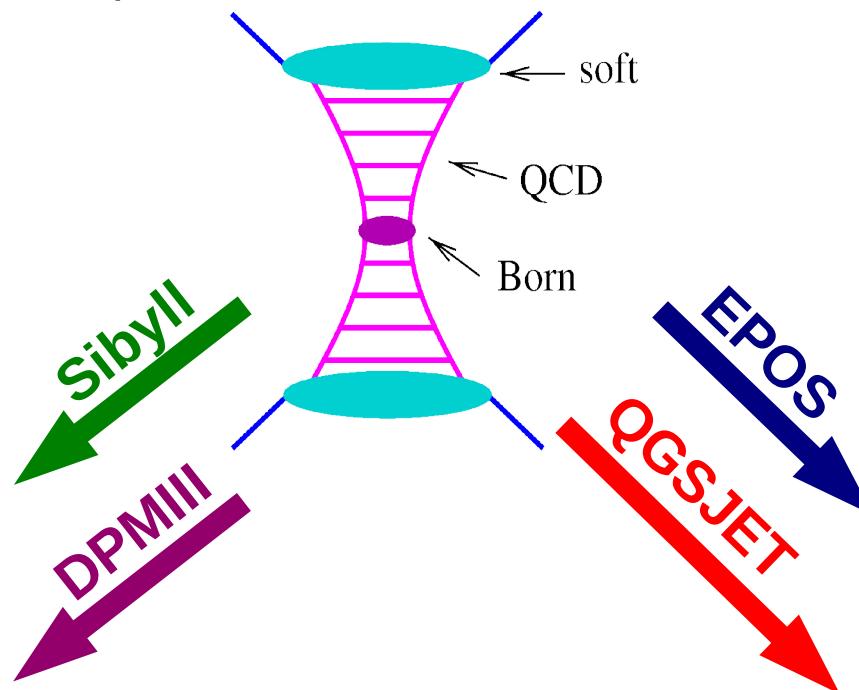
Post - LHC



# How to build the amplitude ?

- Field theory : scattering via the exchange of an excited field
  - parton, hadron, quasi-particle = Reggeon or Pomeron (vacuum excitation)
- QCD based theory : at high energy, perturbative QCD can be used to build the field amplitude (amplitude used for the cross-section)
  - all **minijet based** (parton cascade and pQCD born process hadronized using string fragmentation) but different definitions

- soft+hard in different components
- external parton distribution functions (**GRV98,cteq14**)
- connection to projectile/target with small “x”

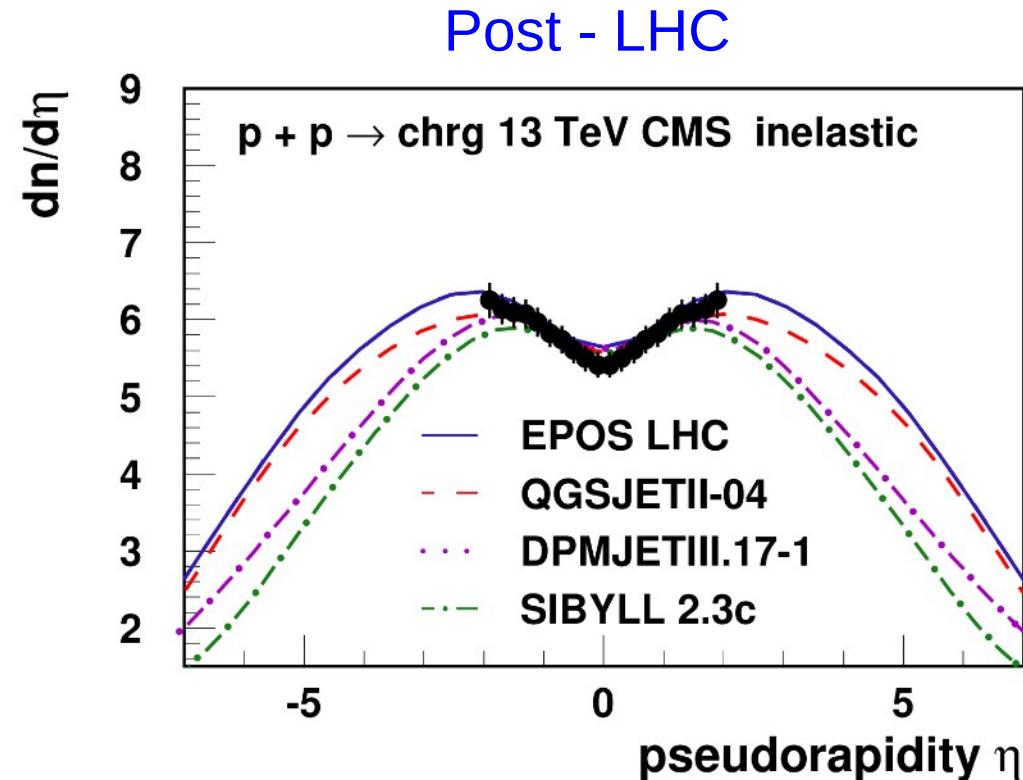
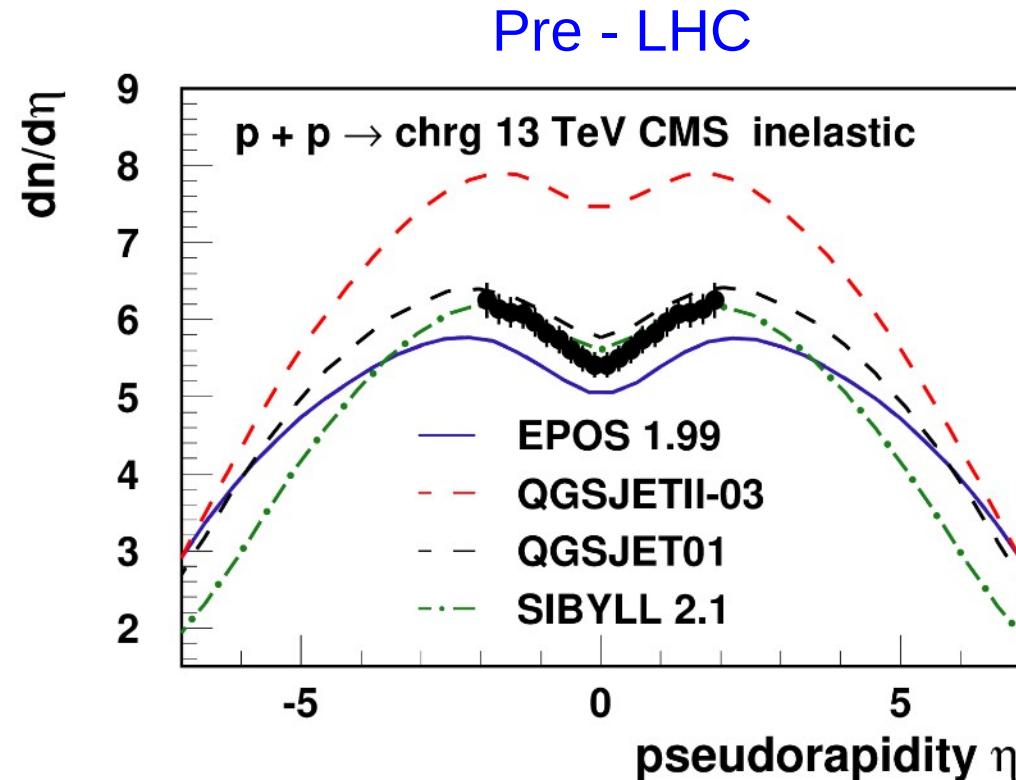


- soft+hard in the same amplitude
- own parton distribution function compatible with HERA data (not for QGSJET01: pre-HERA time)
- connection to projectile/target with large “x”

Ostapchenko et al. Phys.Rev. D94 (2016) no.11, 114026

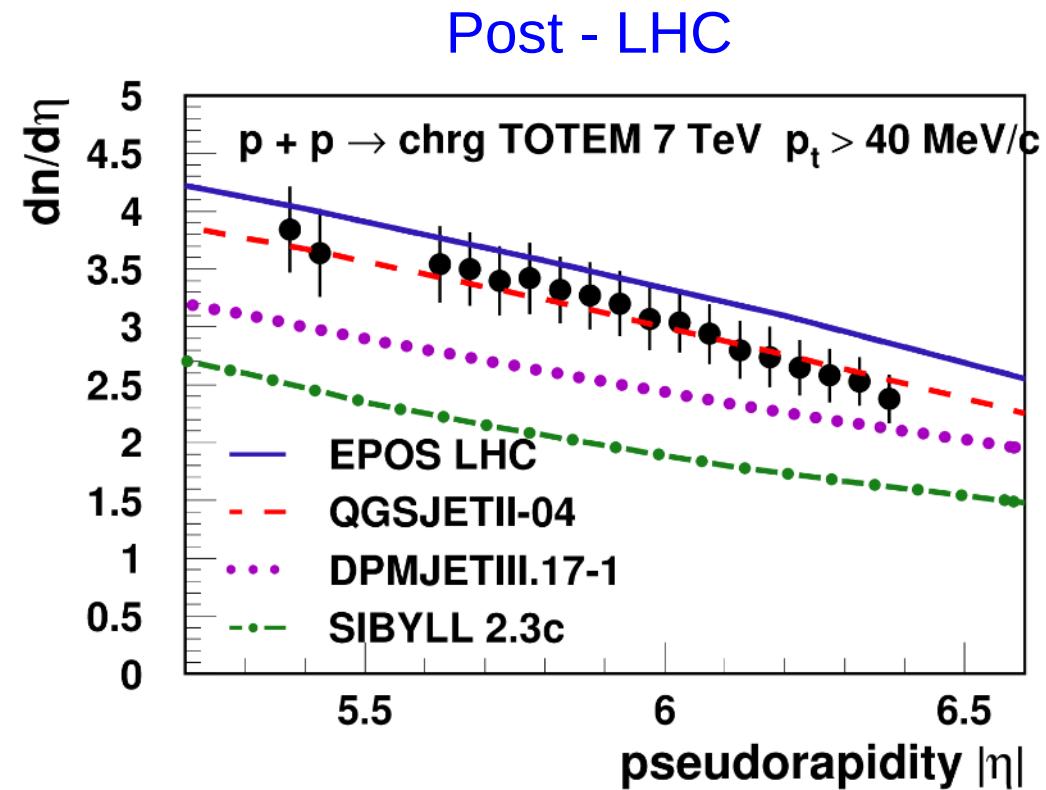
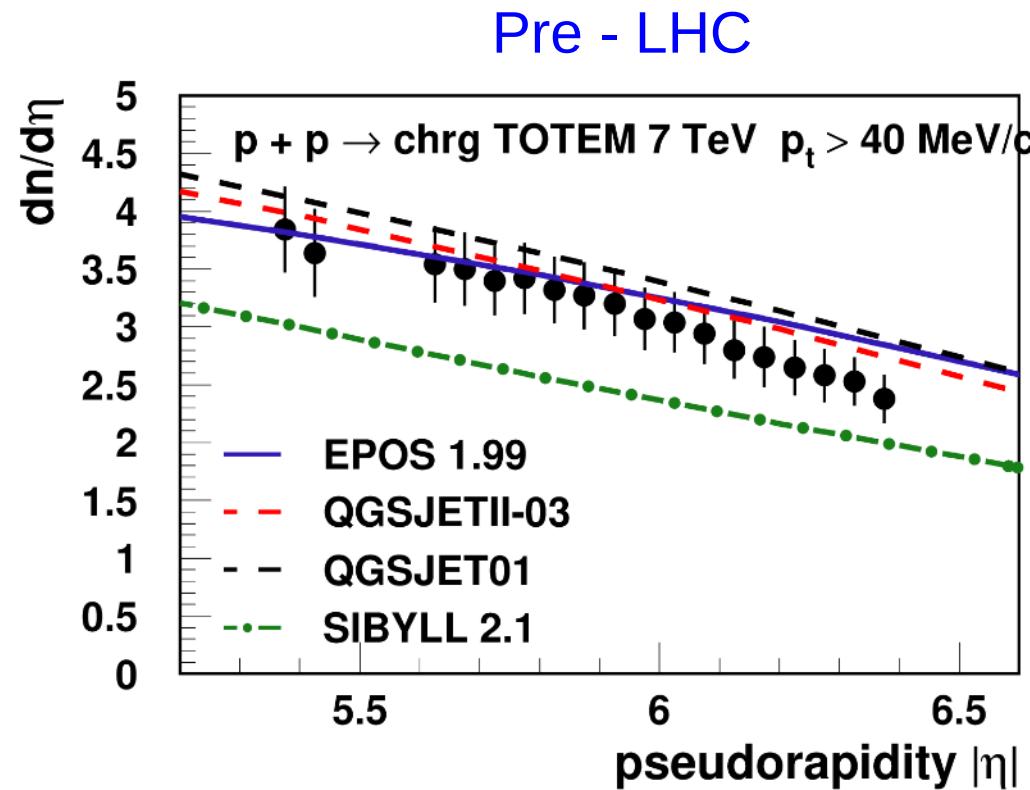
# Does the minijet definition matter ?

- Field theory : scattering via the exchange of an excited field
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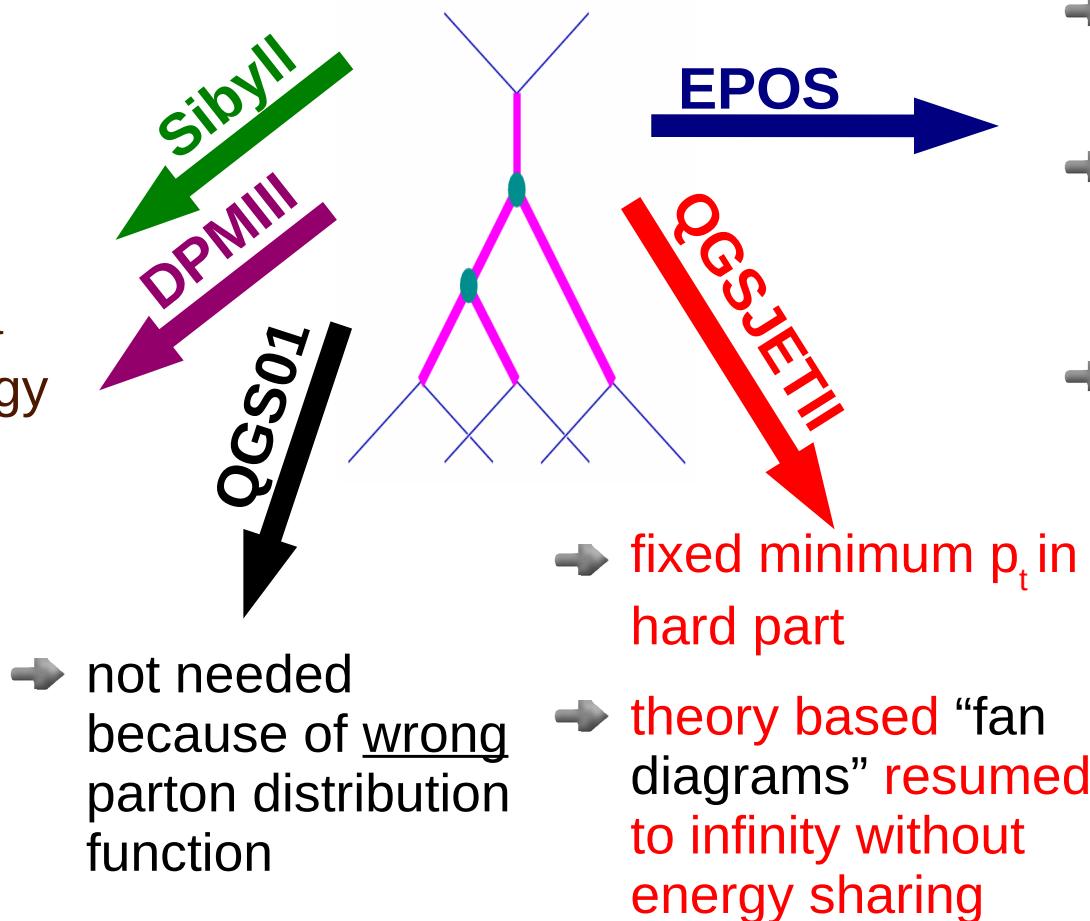


# How to take into account energy evolution ?

- Multiple scattering not enough to reconcile pQCD minijet cross-section and total cross-section
  - non-linear effects should be taken into account (interaction between scatterings)

## Solution depends on amplitude definition

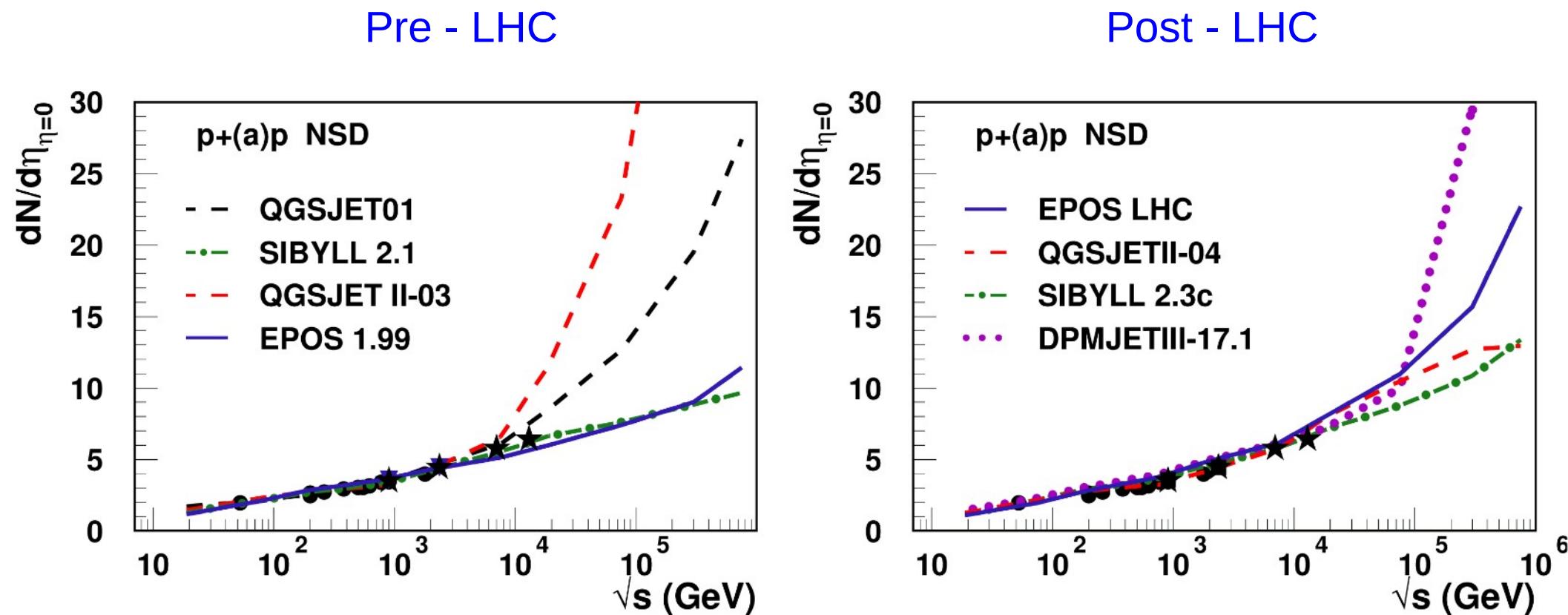
- hard amplitude depend on minimum  $p_t$
- parametrize minimum  $p_t$  as a function of energy
- fit to data (multiplicity and cross-section)



- fixed minimum  $p_t$  in hard part
- enhanced diagrams not compatible with energy sharing
- modification of vertex function to take into account non linear effects (data driven phenomenological approach)

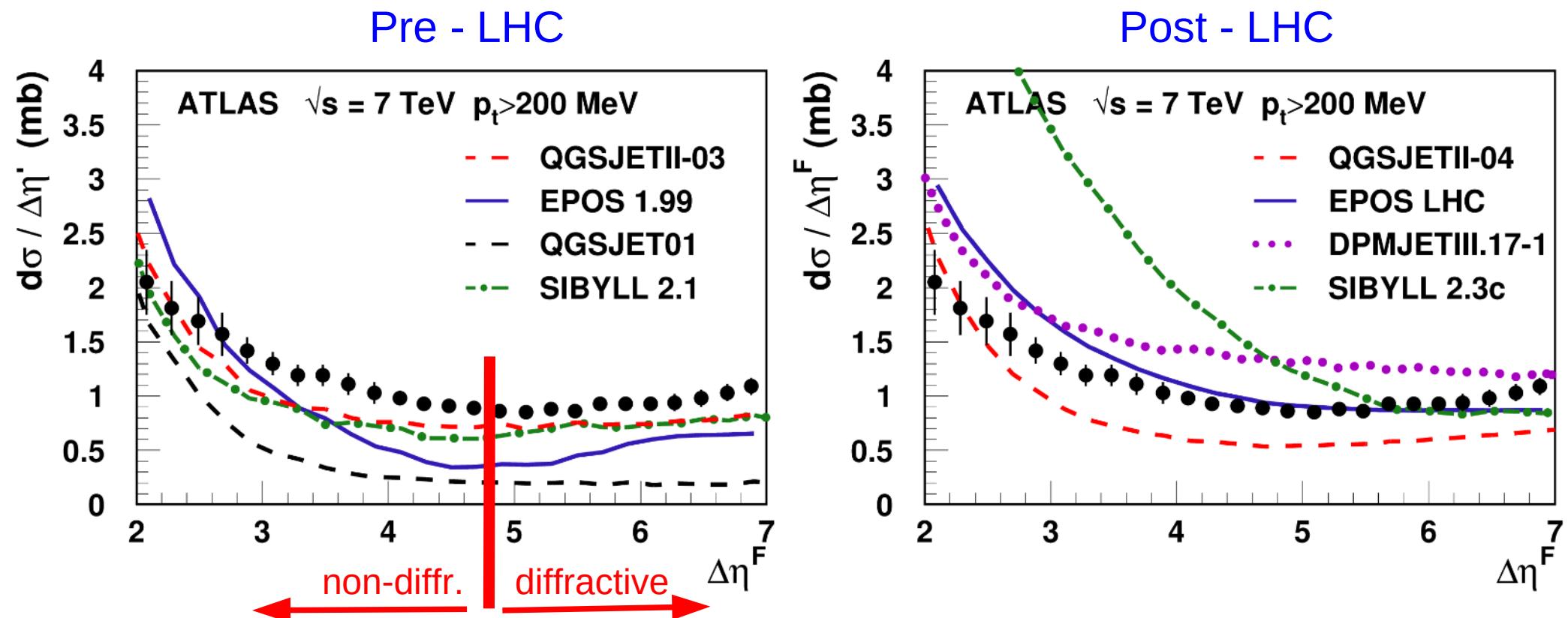
# Do non linear effects matters ?

- Multiple scattering not enough to reconcile pQCD minijet cross-section and total cross-section
  - non-linear effect should be taken into account (interaction between scatterings)
- Solution depends on amplitude definition
  - large uncertainties at high energy but reduced after LHC



# What if only energy is transferred ?

- In most of the cases, the projectile is destroyed by the collision
  - non-diffractive scattering : high energy loss for leading particle, high multiplicity
- In 10-20% of the time, the projectile have a small energy loss (high elasticity) and is unchanged
  - diffractive scattering : low energy loss, low multiplicity on target side
- Model difference mostly at technical level (and choice of data for tuning)

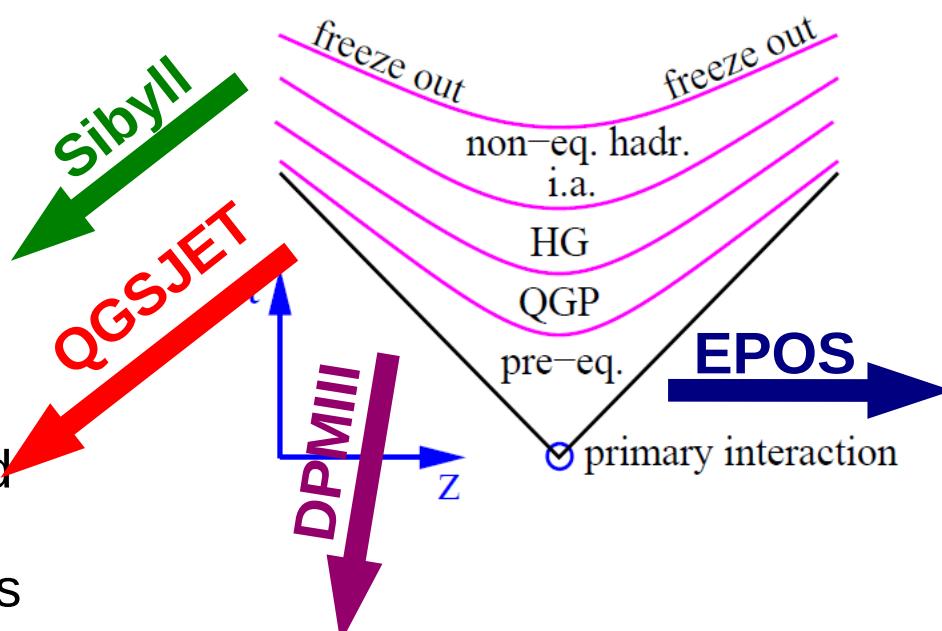


# Should everything be taken into account ?

Models have different philosophies !

- number of parameters increase with data set to reproduce
- predictive power may decrease with number of parameters
- predictive power increase if we are sure NOT to neglect something

- models for CR only
- fast and not suppose to describe everything
- no detailed hard scattering or collective effects

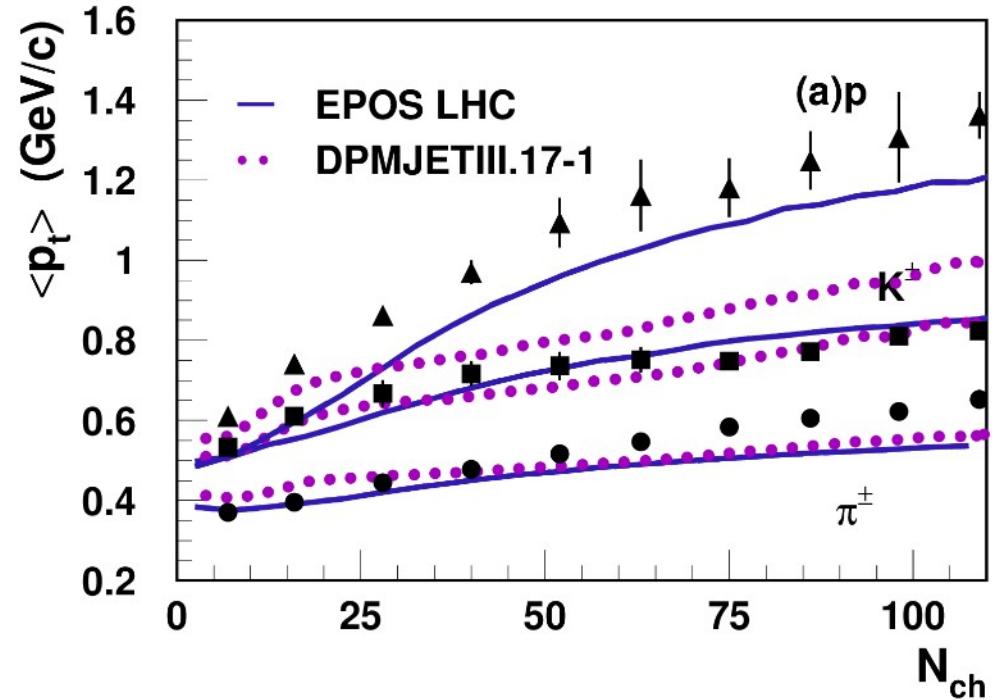
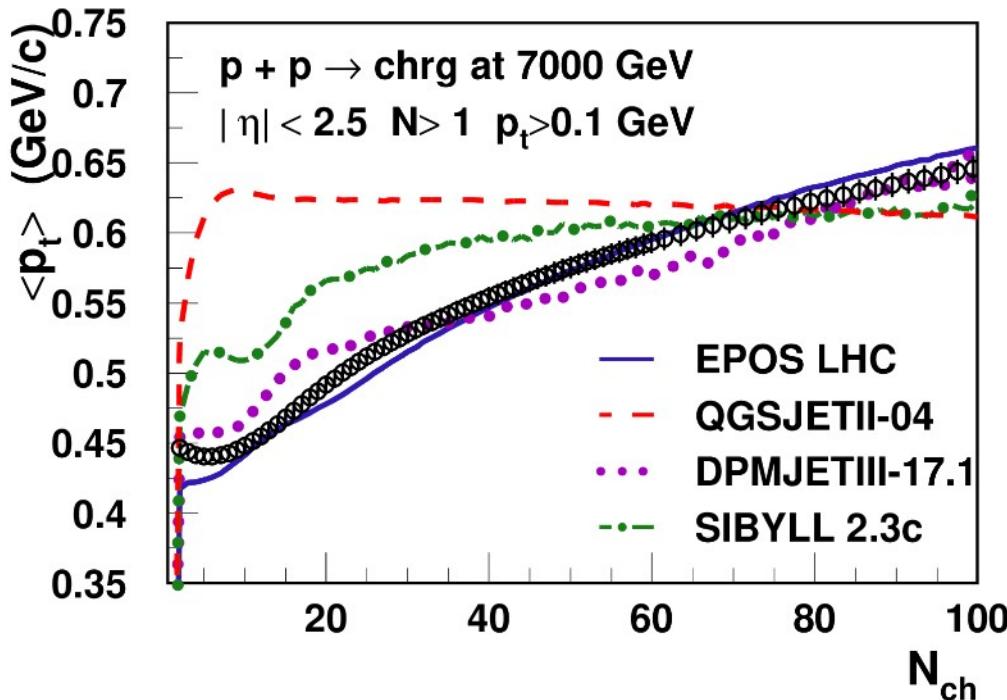


- heavy ion model intended to be used for high energy physics
- limited development for collective effects but correct hard scattering

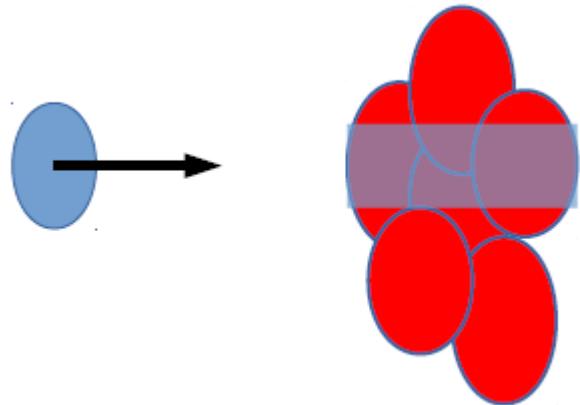
- developed first for heavy ion interactions
- detailed description of every possible “soft” observable (not good for hard scattering yet)
- sophisticated collective effect treatment (real hydro for EPOS 2 and 3)
- very large complete data set (LEP, HERA, SPS, RHIC, LHC, ...)

# Should everything be taken into account ?

- Models have different philosophies !
  - number of parameters increase with data set to reproduce
  - predictive power may decrease with number of parameters
  - predictive power increase if we are sure not to neglect something
- No direct influence on air showers but different parameters and extrapolations ?



# How to do nuclear interactions ?

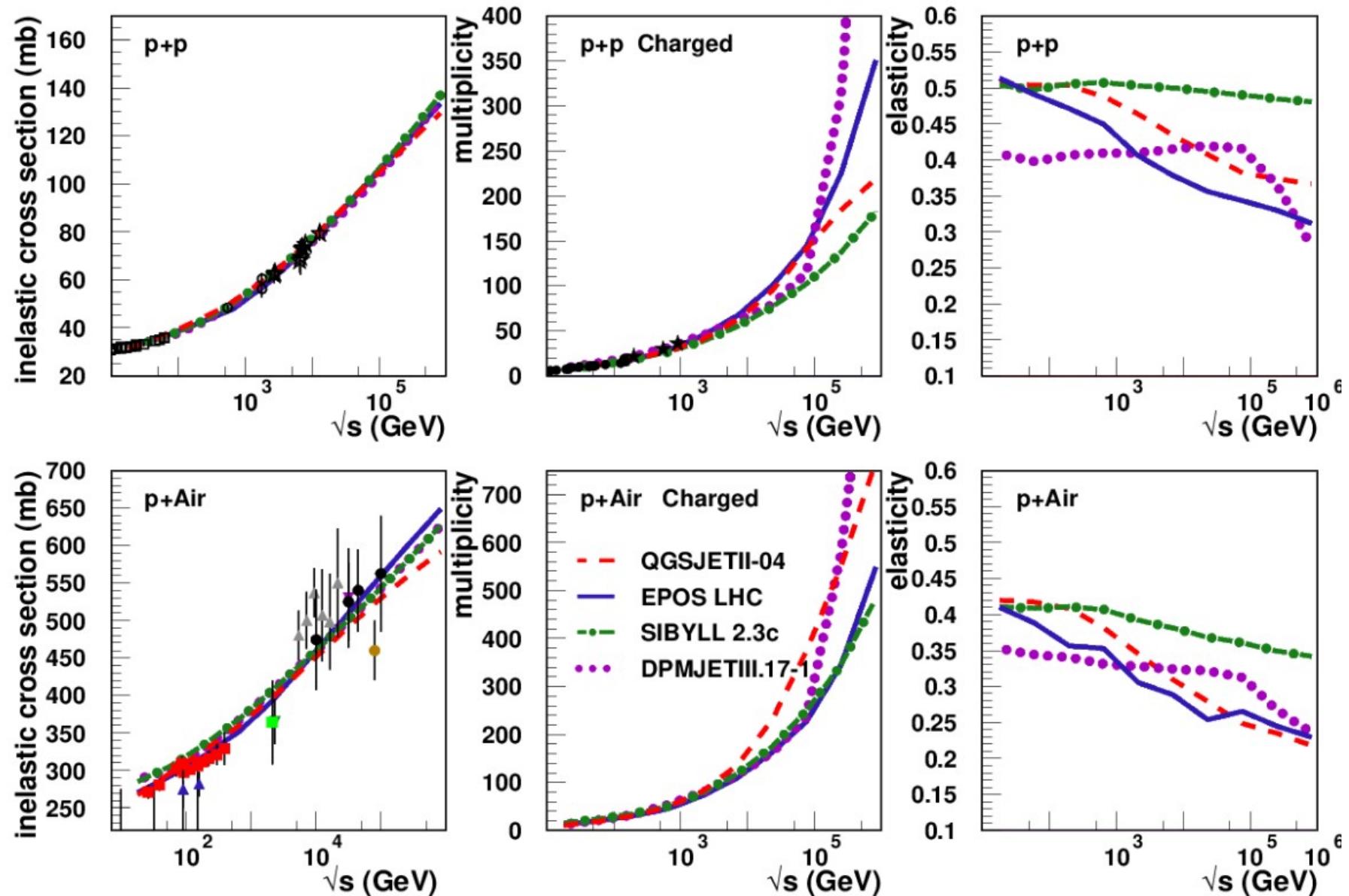


## Main source of uncertainty in extrapolation :

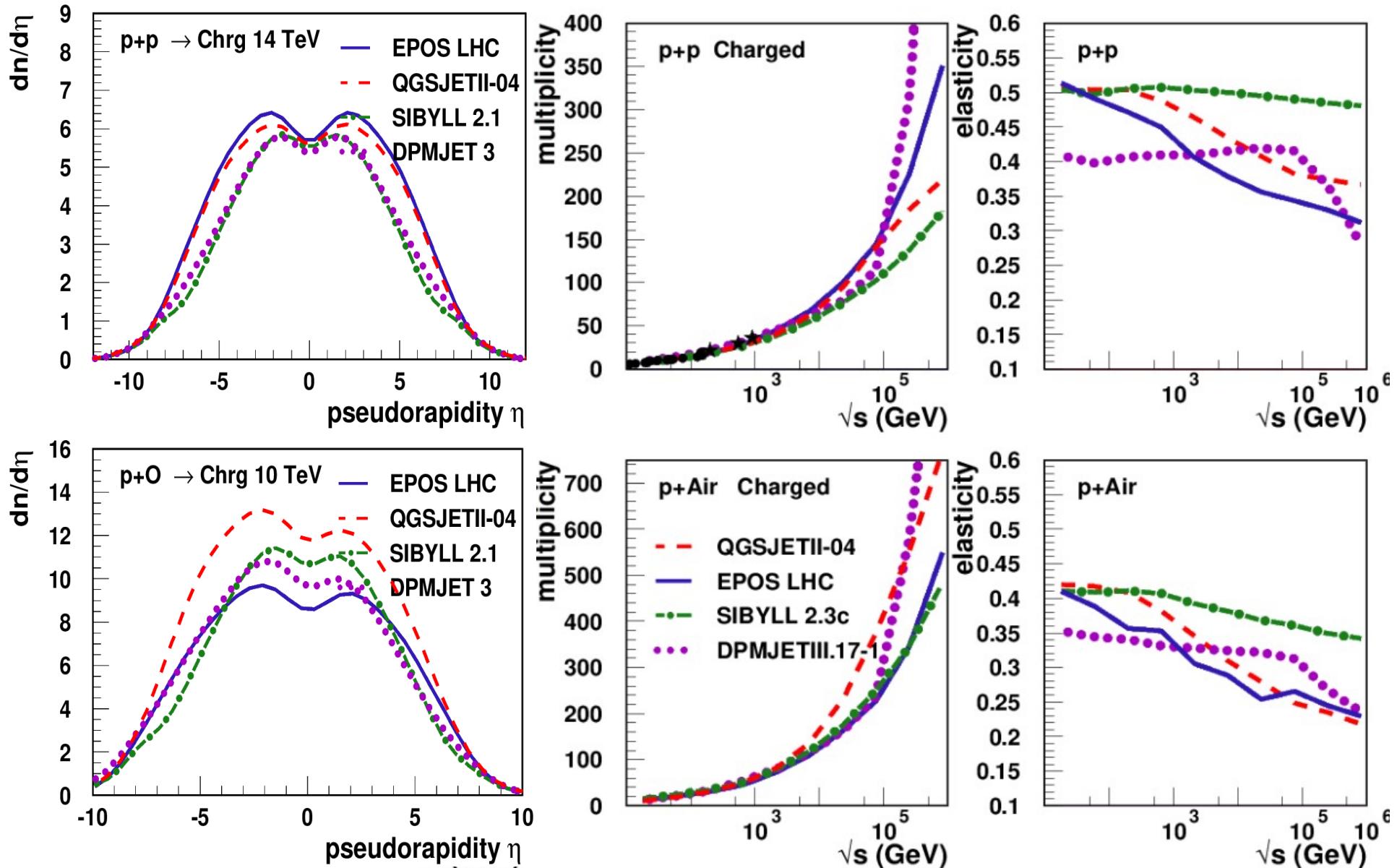
- very different approaches
- limited available data set
- limited models capabilities

- **Sibyll** (light ion only)
  - corrected Glauber for pA ( $A/B=\#$  of nucleons)
  - superposition model for AB ( $A \times pB$ )
- **QGSJETII** (all masses but not all data)
  - Scattering configuration based on A projectile nucleon and B target nucleons
  - Nuclear effect due to multi-leg Pomerons
- **DPMJETIII (all masses)**
  - Glauber
  - limited collective effects treatment
- **EPOS** (all masses)
  - Scattering configuration based on A projectile nucleons and B target nucleons
  - screening corrections depend on nuclei
  - final state interactions (core-corona approach and collective hadronization with flow for core)

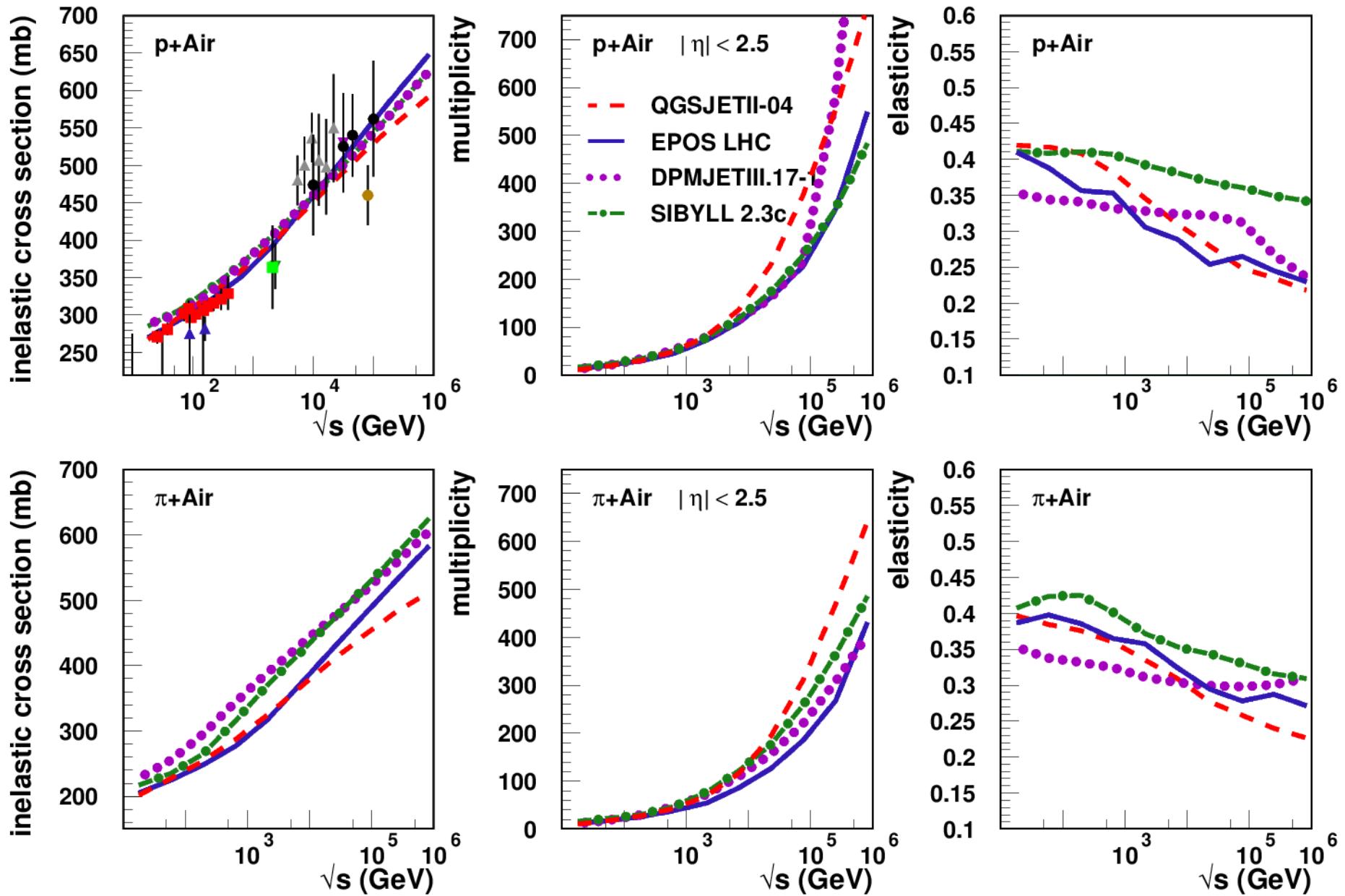
# Ultra-High Energy Hadronic Model Predictions p-Air



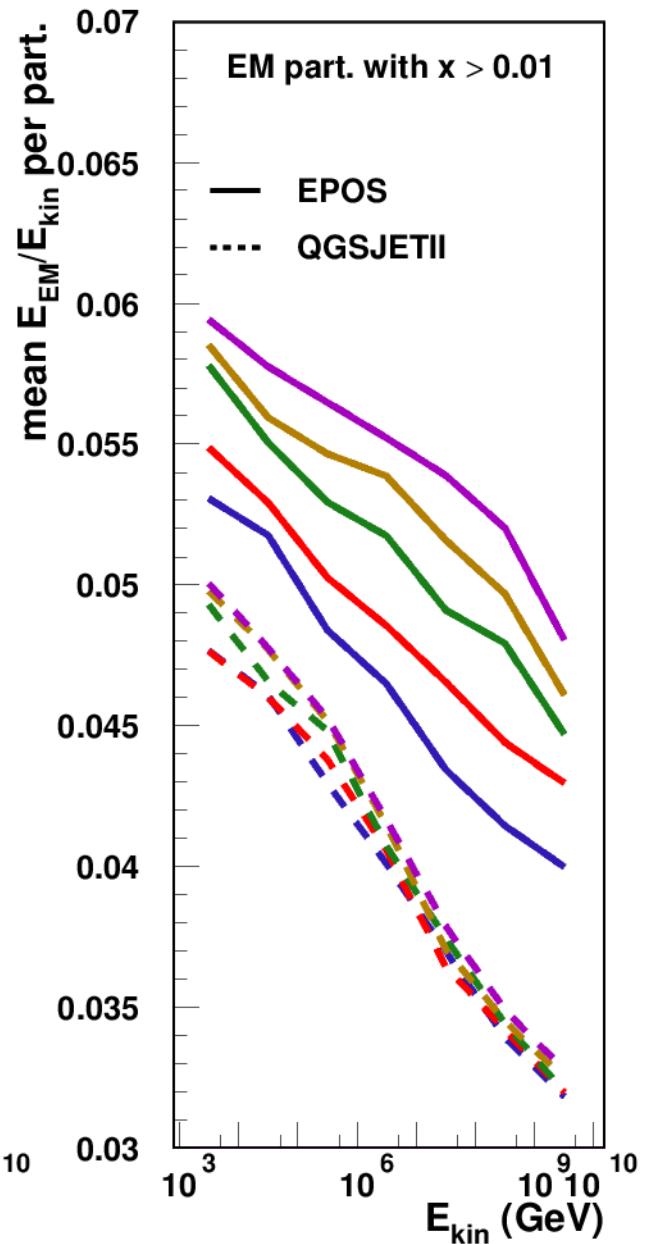
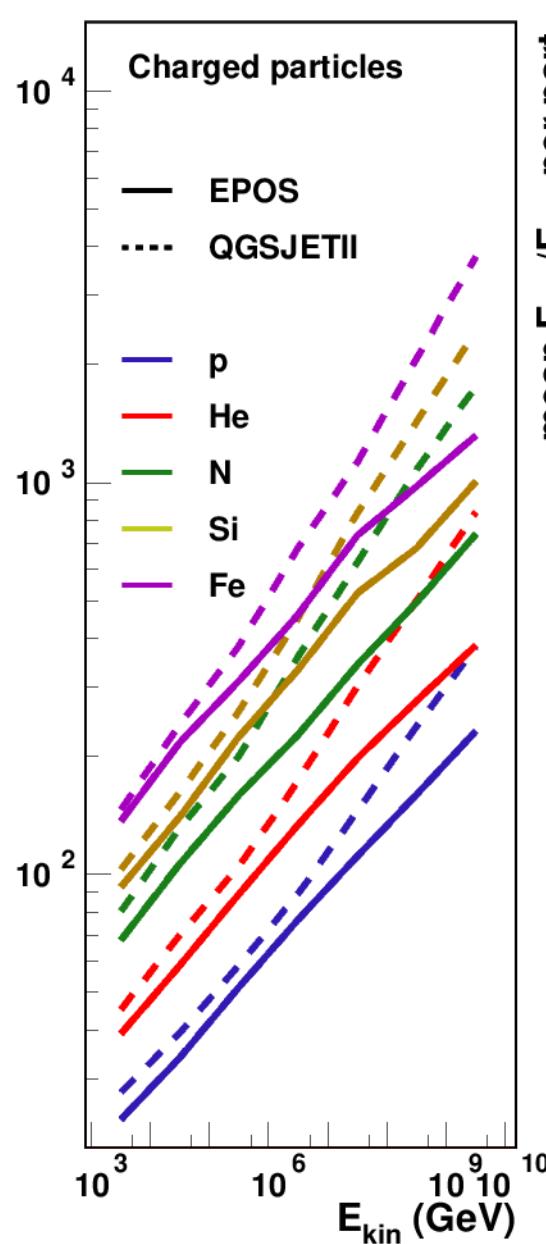
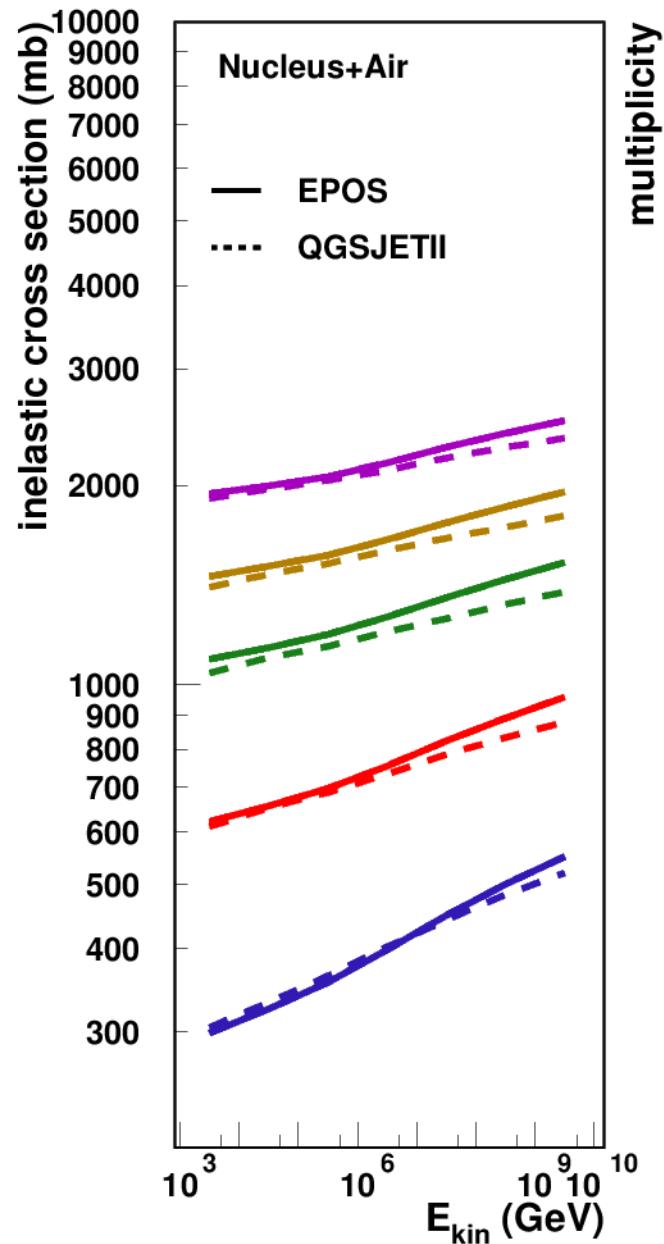
# Ultra-High Energy Hadronic Model Predictions p-Air



# Ultra-High Energy Hadronic Model Predictions $\pi$ -Air



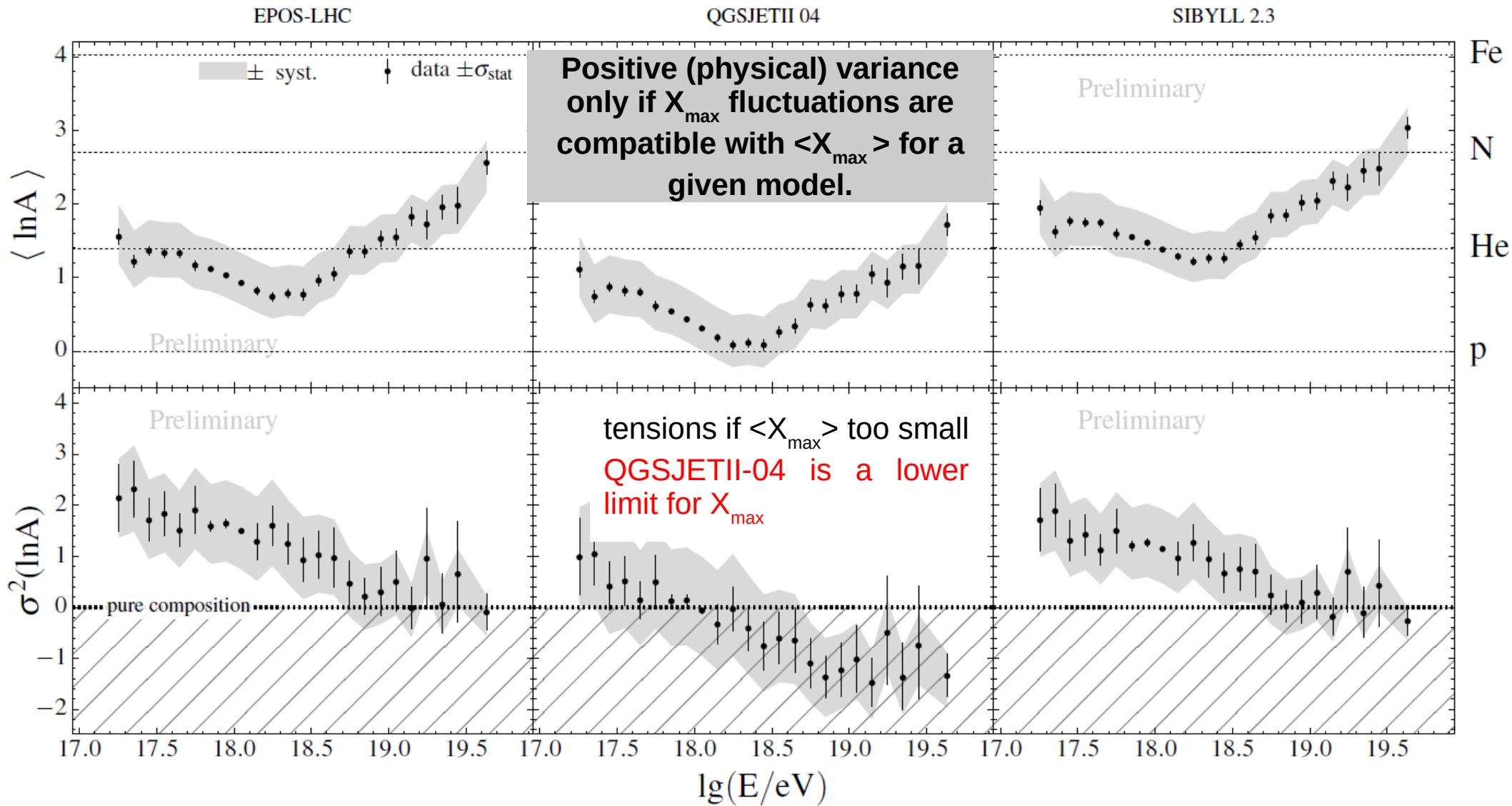
# Ultra-High Energy Hadronic Model Predictions A-Air



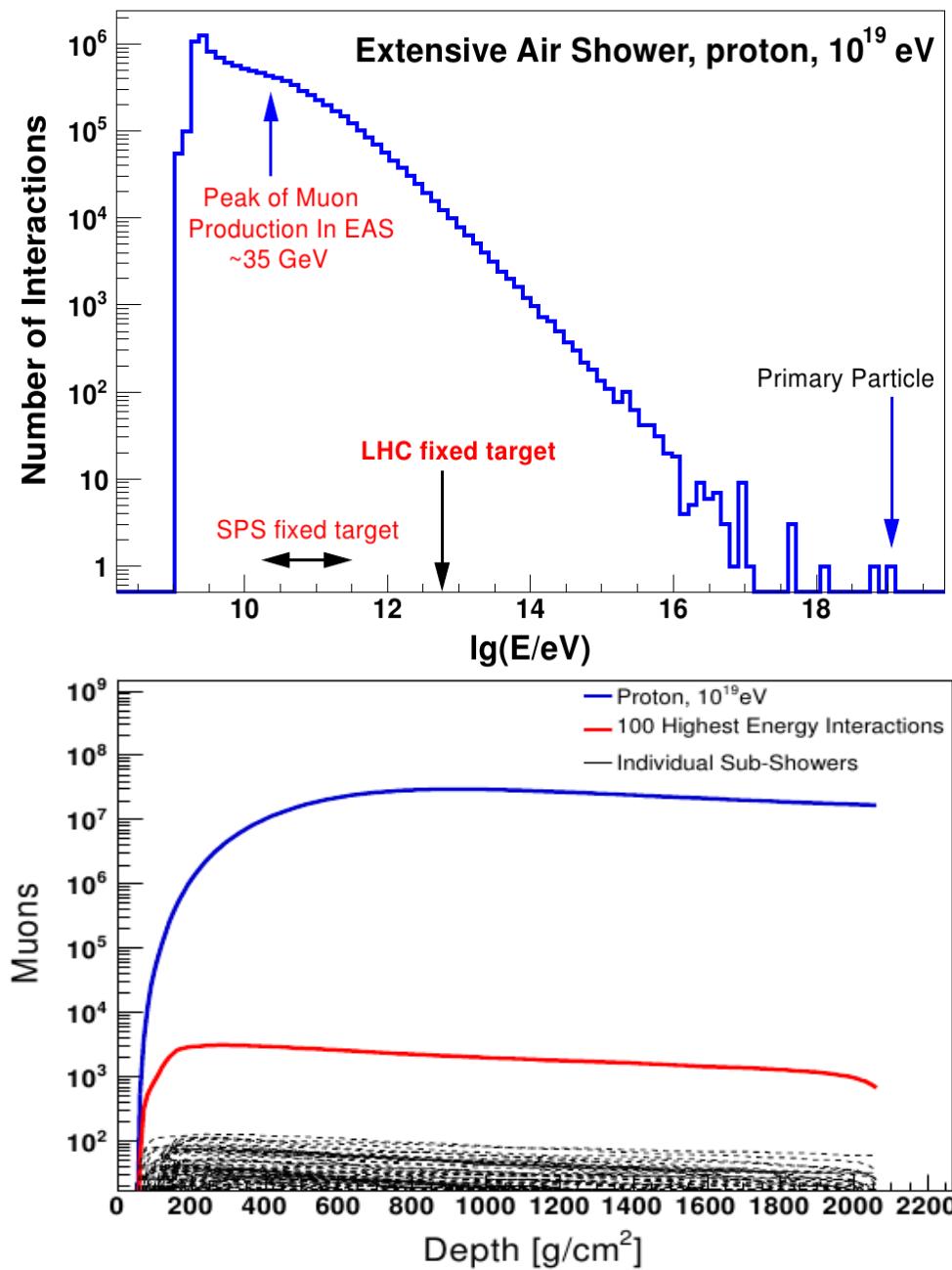
# Model Consistency using Electromagnetic Component

## Study by Pierre Auger Collaboration (ICRC 2017)

→ std deviation of  $\ln A$  allows to test model consistency.



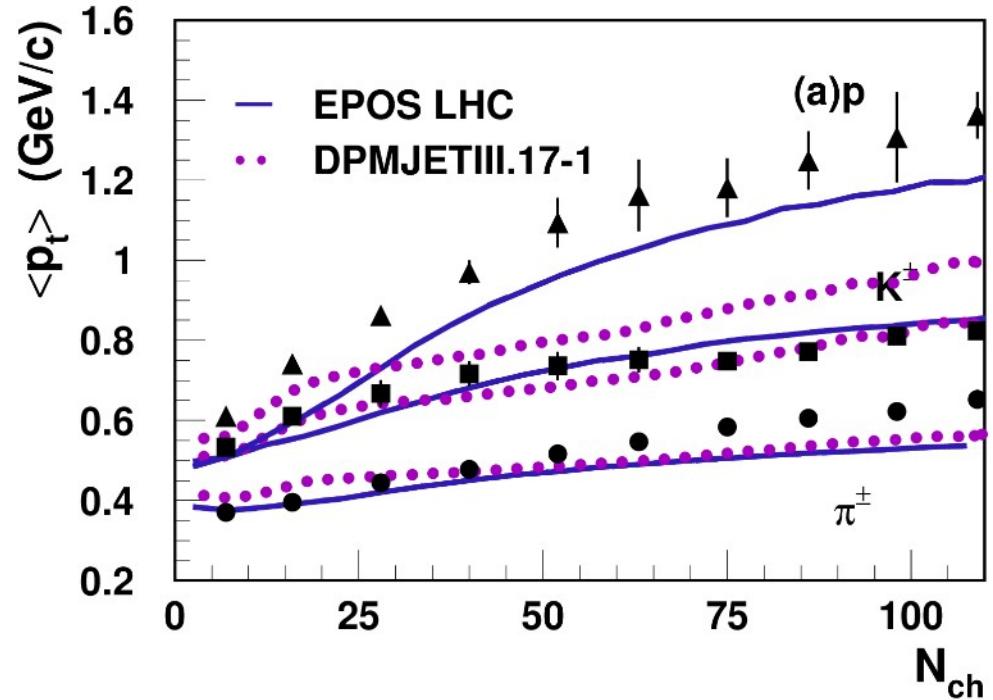
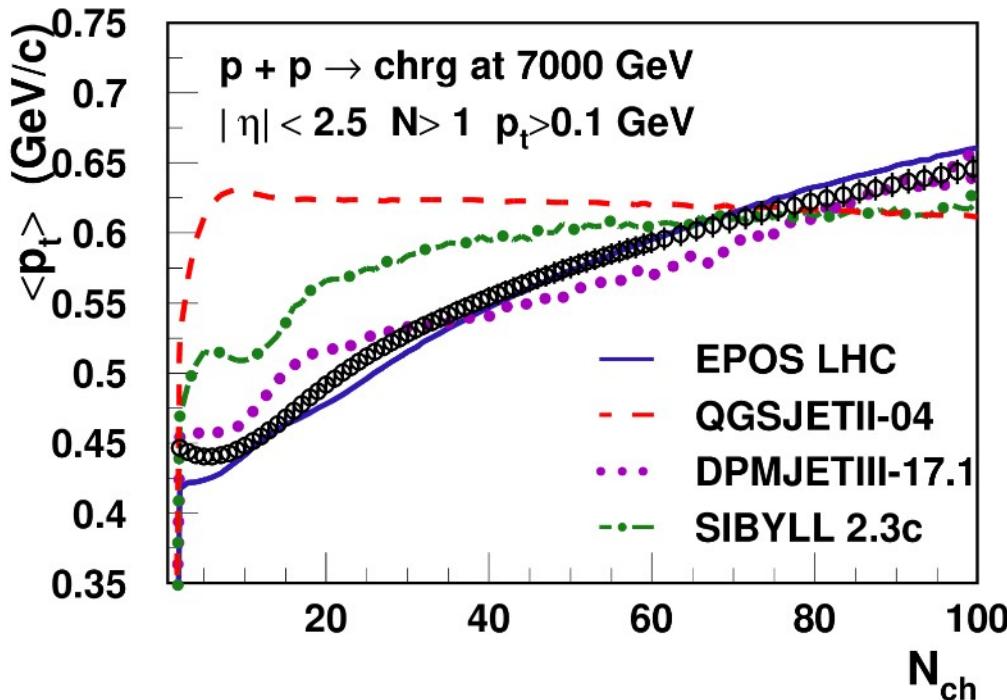
# Surface Detectors (SD)



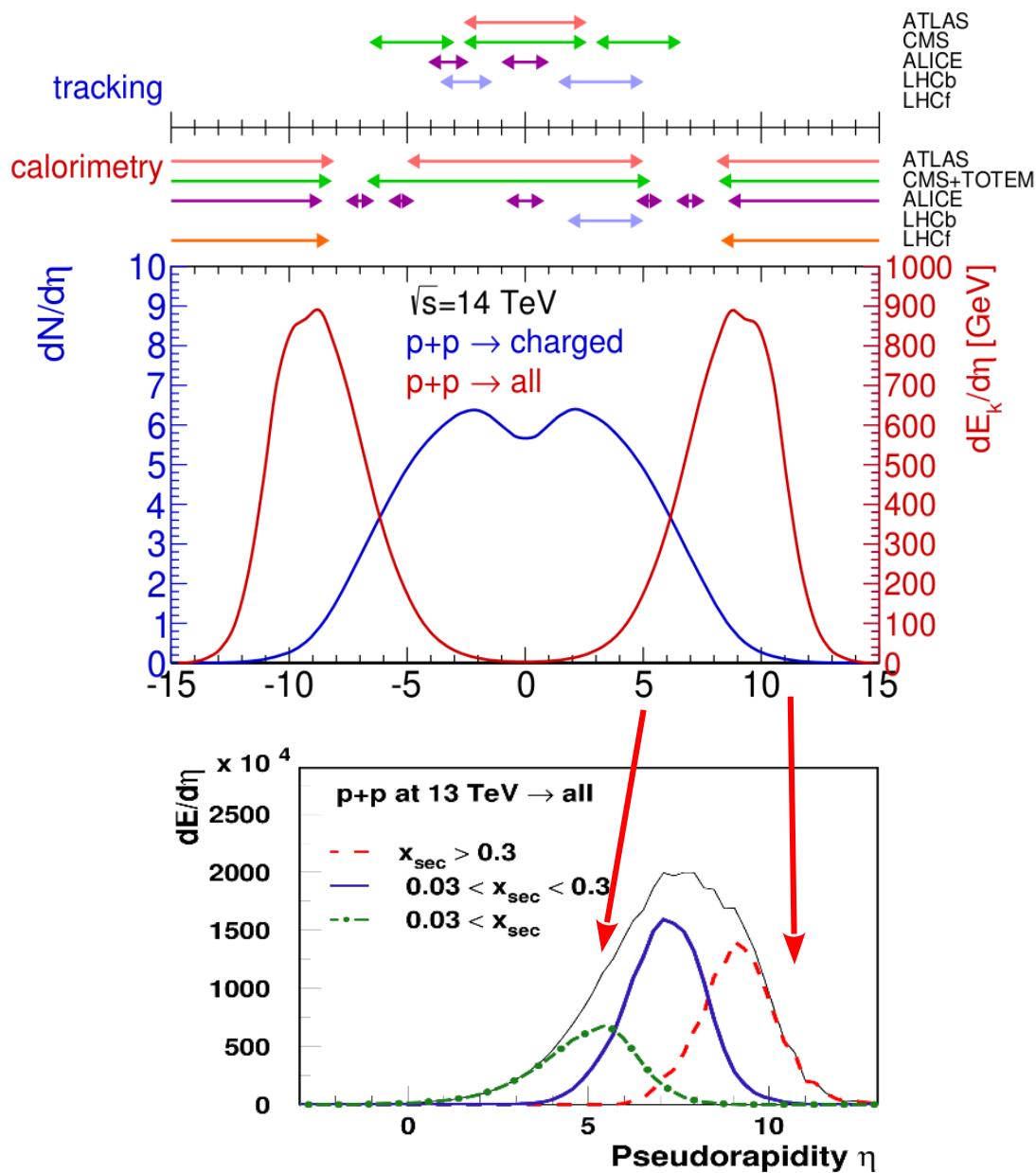
- SD detector sensitive to
  - electromagnetic particles (EM)
  - muons
- Particles at ground produced after many generations of hadronic interactions
  - most of EM particles from pure EM (universal) shower (depend on high (first) energy hadronic interactions)
  - muons produced at the end of hadronic cascade (depend on low energy hadronic interactions)
  - small fraction of EM (at large r) produced by last hadronic generation
- EM and muons give different signal in Cherenkov detector.
  - property of time traces

# Should everything be taken into account ?

- Models have different philosophies !
  - number of parameters increase with data set to reproduce
  - predictive power may decrease with number of parameters
  - predictive power increase if we are sure not to neglect something
- No direct influence on air showers but different parameters and extrapolations ?



# LHC acceptance and Phase Space



- p-p data mainly from “central” detectors
  - pseudorapidity  $\eta = -\ln(\tan(\theta/2))$
  - $\theta=0$  is midrapidity
  - $\theta>>1$  is forward
  - $\theta<<1$  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