QCD Challenges in Air Shower Measurements

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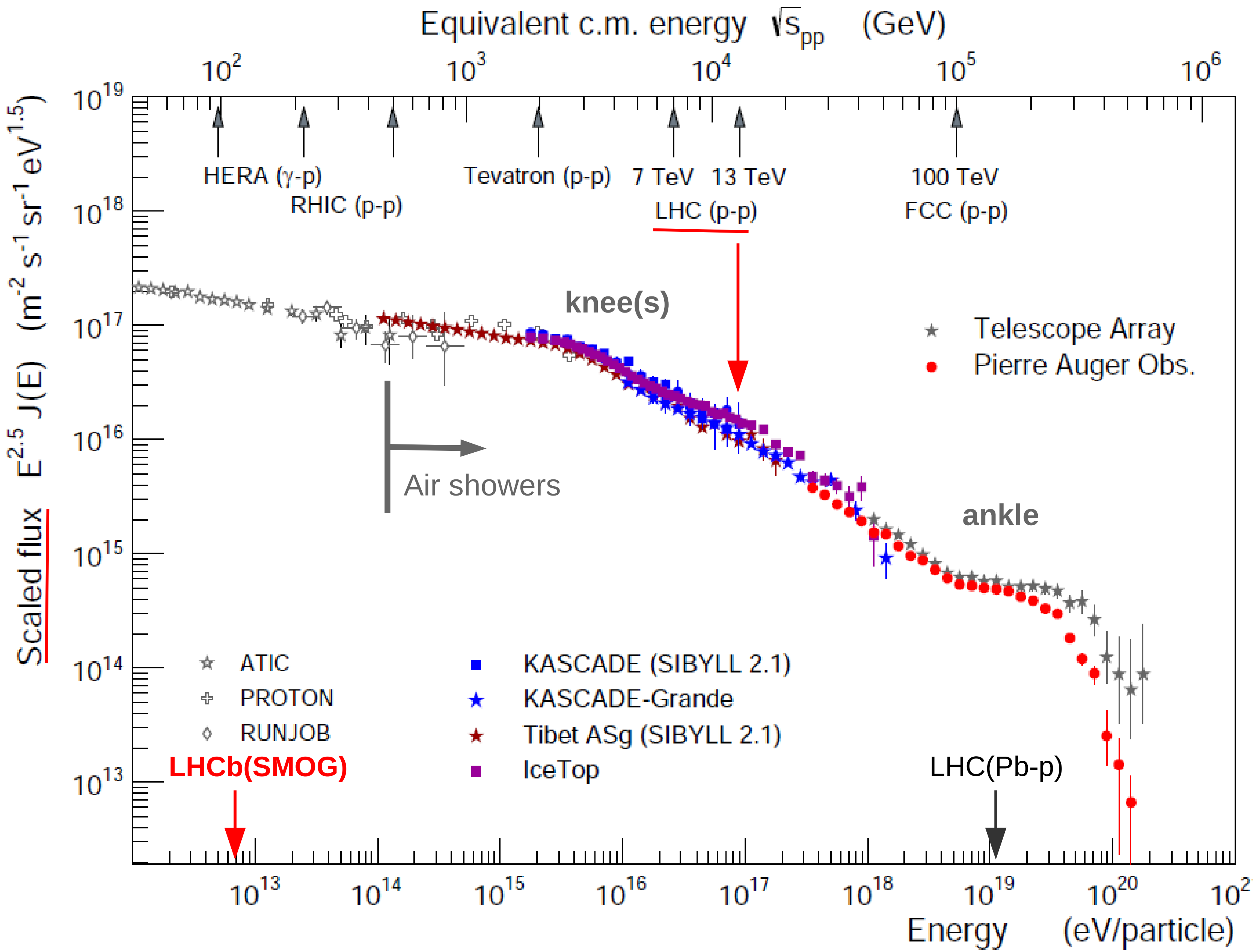
Outline

- **Introduction**
- **Air shower physics**
- **X_{max}**
- **Muons**
  - ➔ Isospin symmetry
  - ➔ Hadronizations

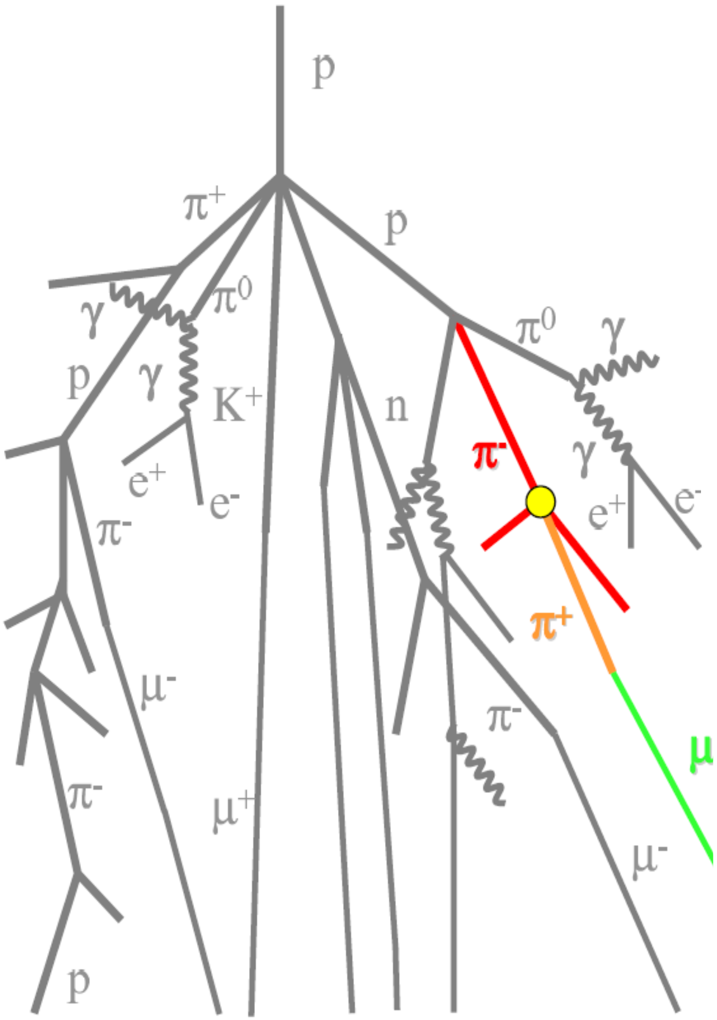
LHC data provide important constraints on models changing X_{max}
Details on hadronization could be more important than thought until now, impacting the muon production, and need careful study at LHC in particular with pO data.

Energy Spectrum

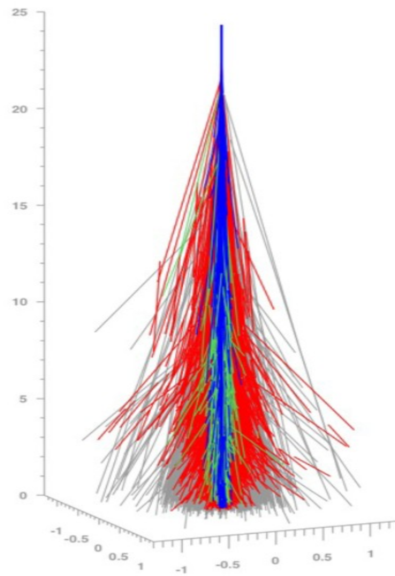


R. Engel (KIT)

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

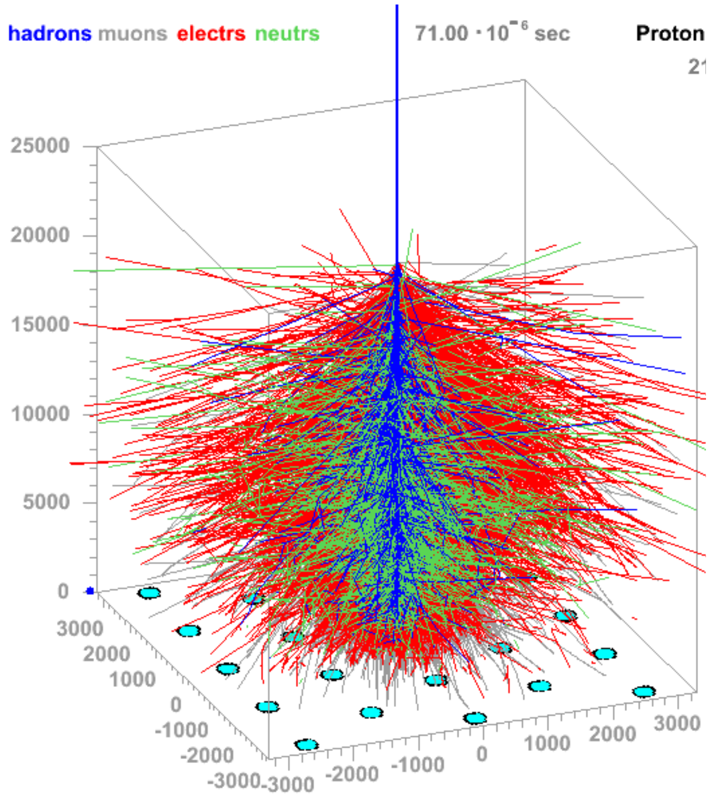
Number of particles at maximum

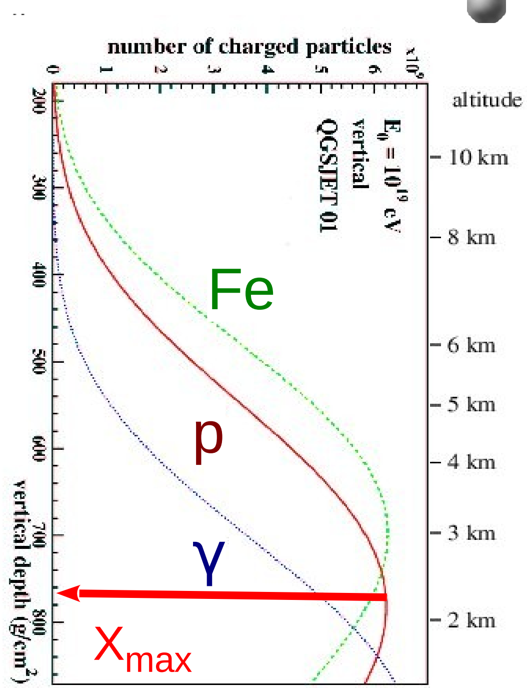
- 99,88% of electromagnetic (EM) particles
- 0.1% of muons
- 0.02% hadrons

Energy

- from 100% hadronic to 90% in EM + 10% in muons at ground (vertical)

Extensive Air Shower Observables



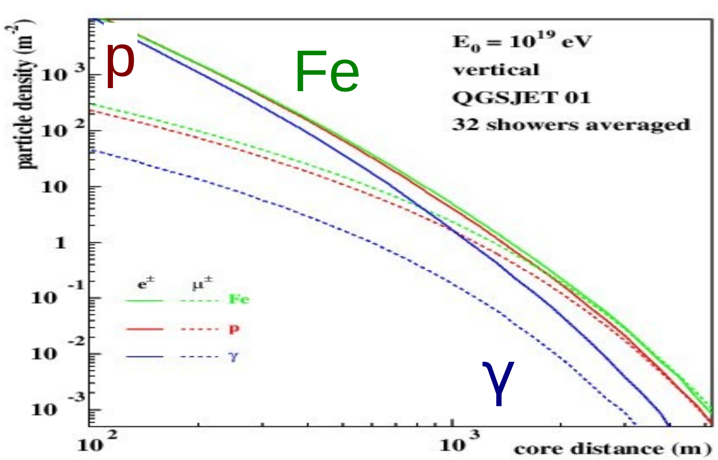


- **Longitudinal Development**
  - number of particles vs depth

    $$X = \int_h^\infty dz\, \rho(z)$$

  - Larger number of particles at X_{max}

    For many showers
    - mean : $\langle X_{max} \rangle$
    - fluctuations : RMS X_{max}
    - depends on primary mass
    - depends on Hadr. Inter.



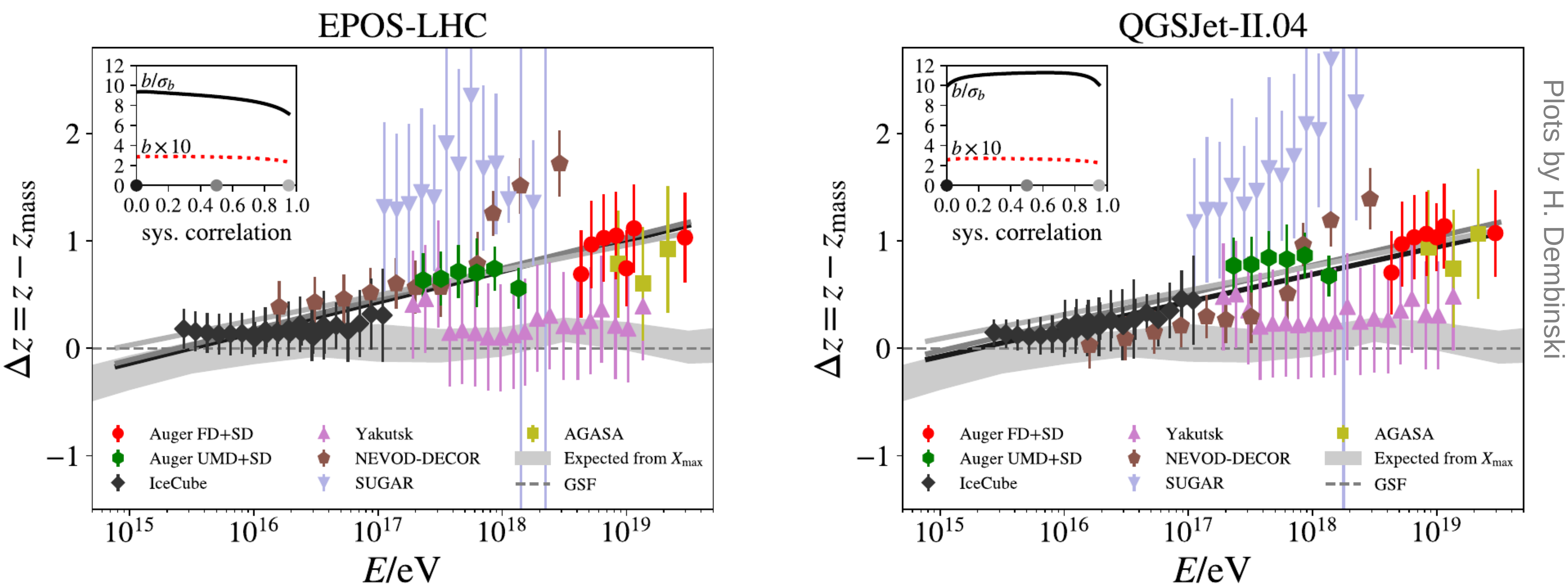
- **Lateral distribution function (LDF)**
  - particle density at ground vs distance to the impact point (core)
  - can be muons or electrons/gammas or a mixture of all.
- **Others: Cherenkov emissions, Radio signal**

WHISP Meta-Analysis (2021)

- **Clear muon excess in data compared to simulation**
  - ➡ Different energy evolution between data and simulations
  - ➡ Significant non-zero slope (>8σ)

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

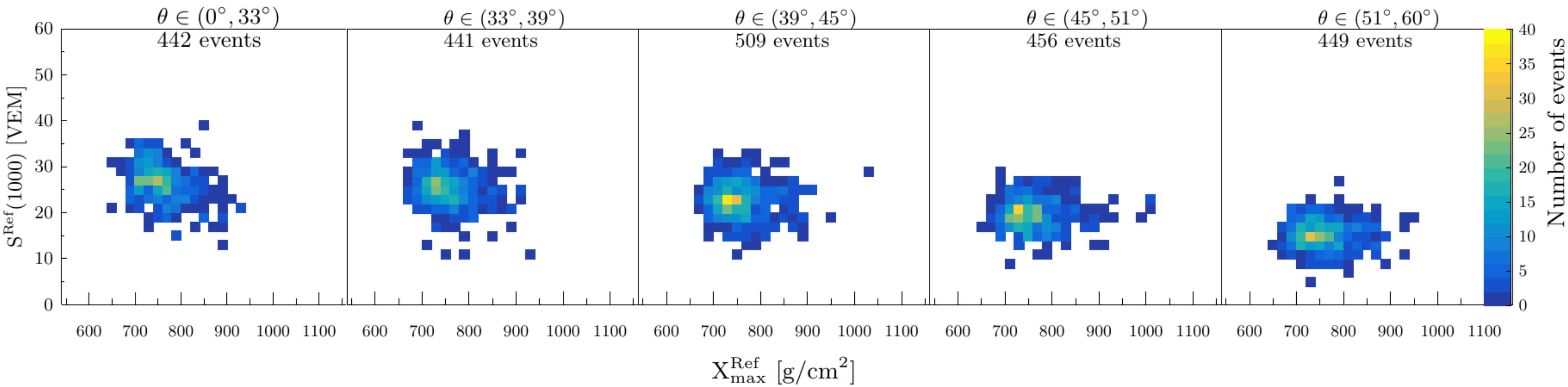
$$z_{\rm mass} = \frac{\langle \ln A \rangle}{\ln 56}$$



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

X_{max}-S(1000) correlation

Hybrid measurements allows to test model consistency in more details

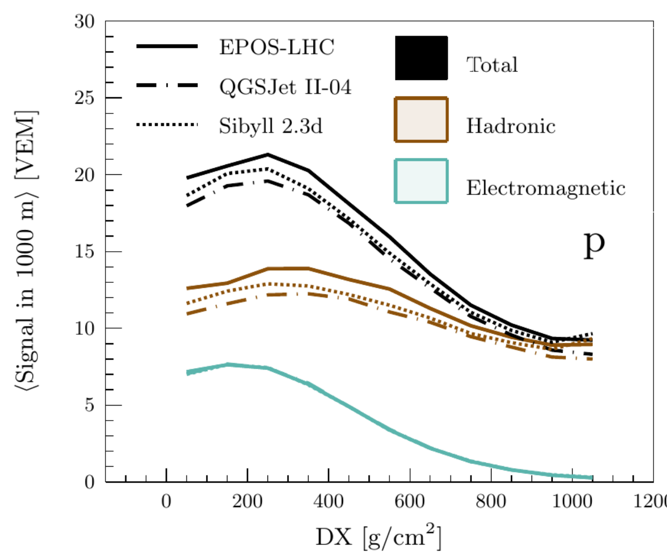


$$X^{\rm Ref}_{\rm max} \equiv \widehat{X^{\rm Ref}_{\rm max}} + \Delta X_{\rm max},$$
$$S^{\rm Ref}(1000) \equiv \widehat{S^{\rm Ref}(1000)} \cdot f_{\rm SD}(\theta)$$

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

Describe the 4 mass fractions

$$\phi = c \cdot f_{Gumbel}\left(X^{Ref}_{max}\right) \cdot f_{Gauss}\left(X^{Ref}_{max}, S^{Ref}(1000)\right)$$

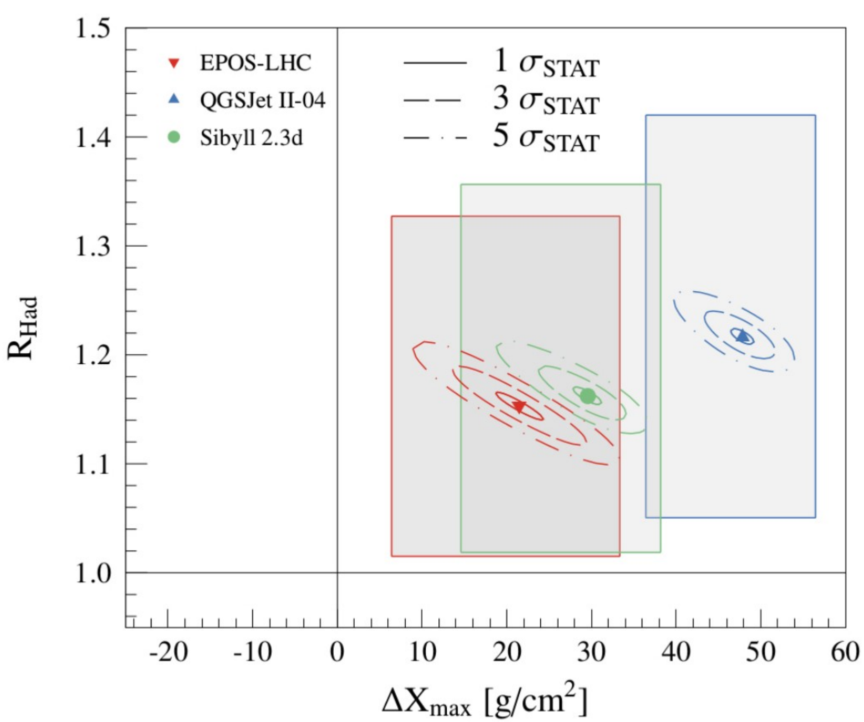


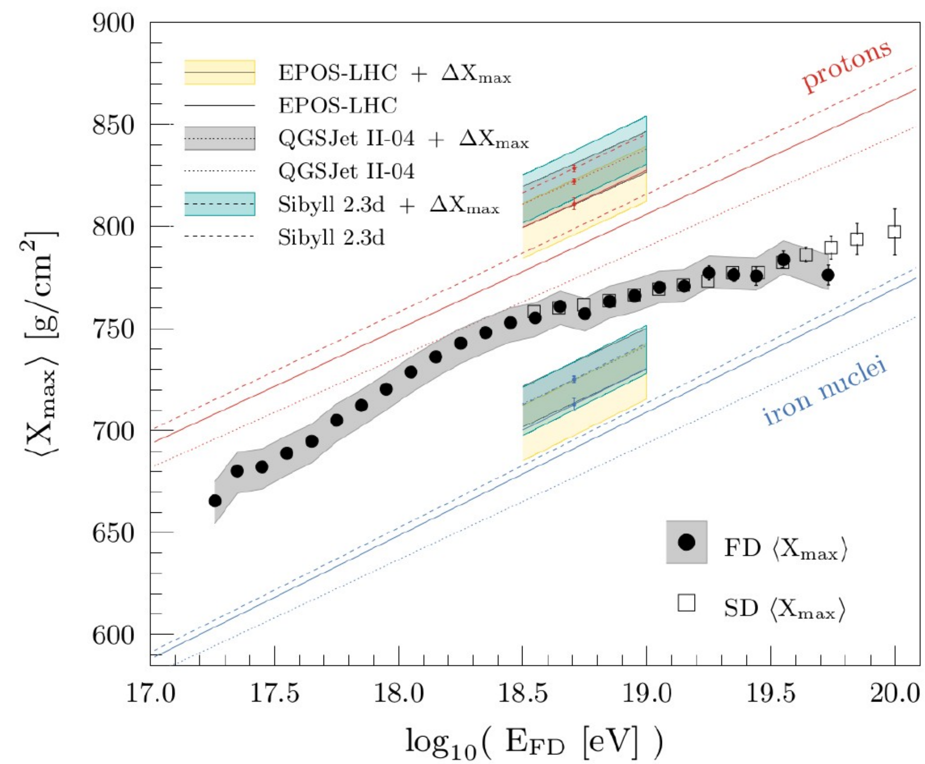
The final MC templates are a sum of templates of the form of Φ of individual primary species weighted by their relative fractions.

EPJ Web Conf. 283 (2023) 02012

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 and forward data to reduce X_{max} and muon uncertainties)





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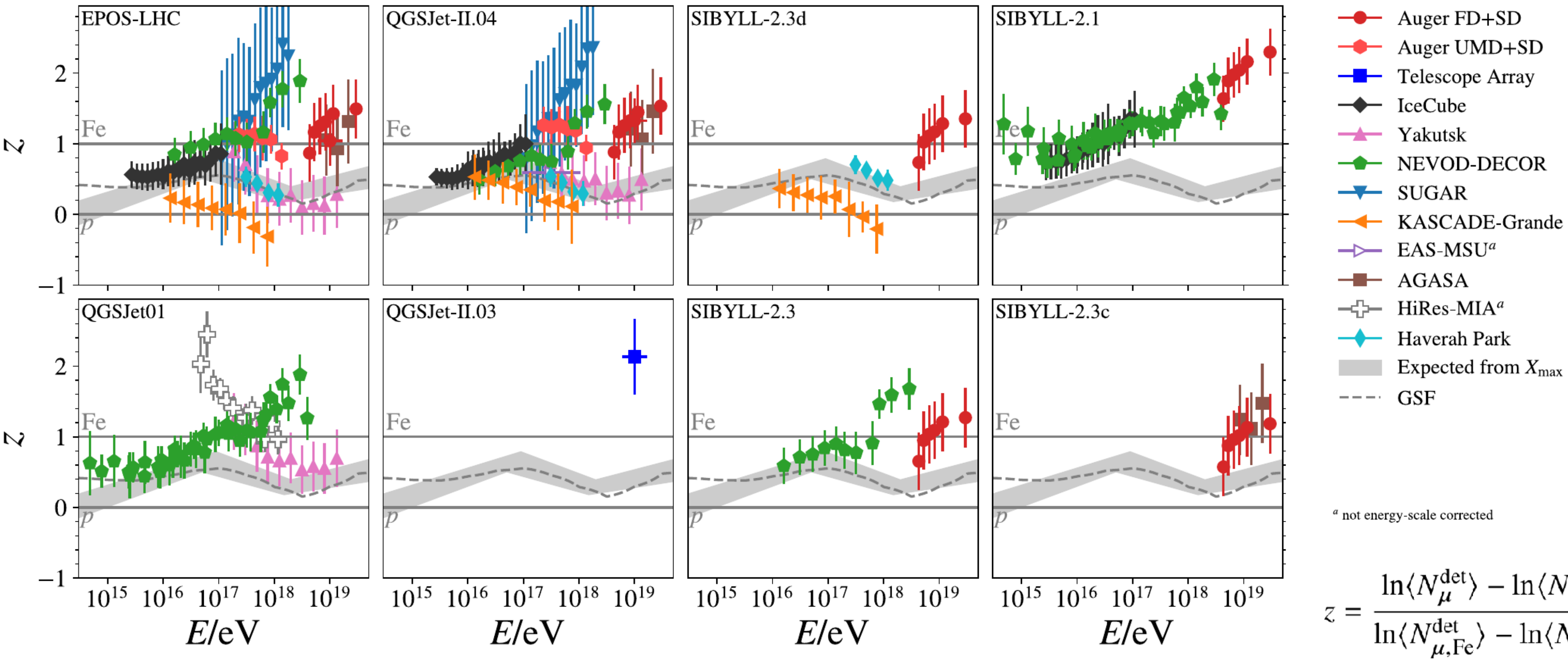
Blurry Picture.

- **"Muon Puzzle" (<N$_\mu$>) depends on energy measurement technique**
  - ➡ Update of WHISP analysis (2023)

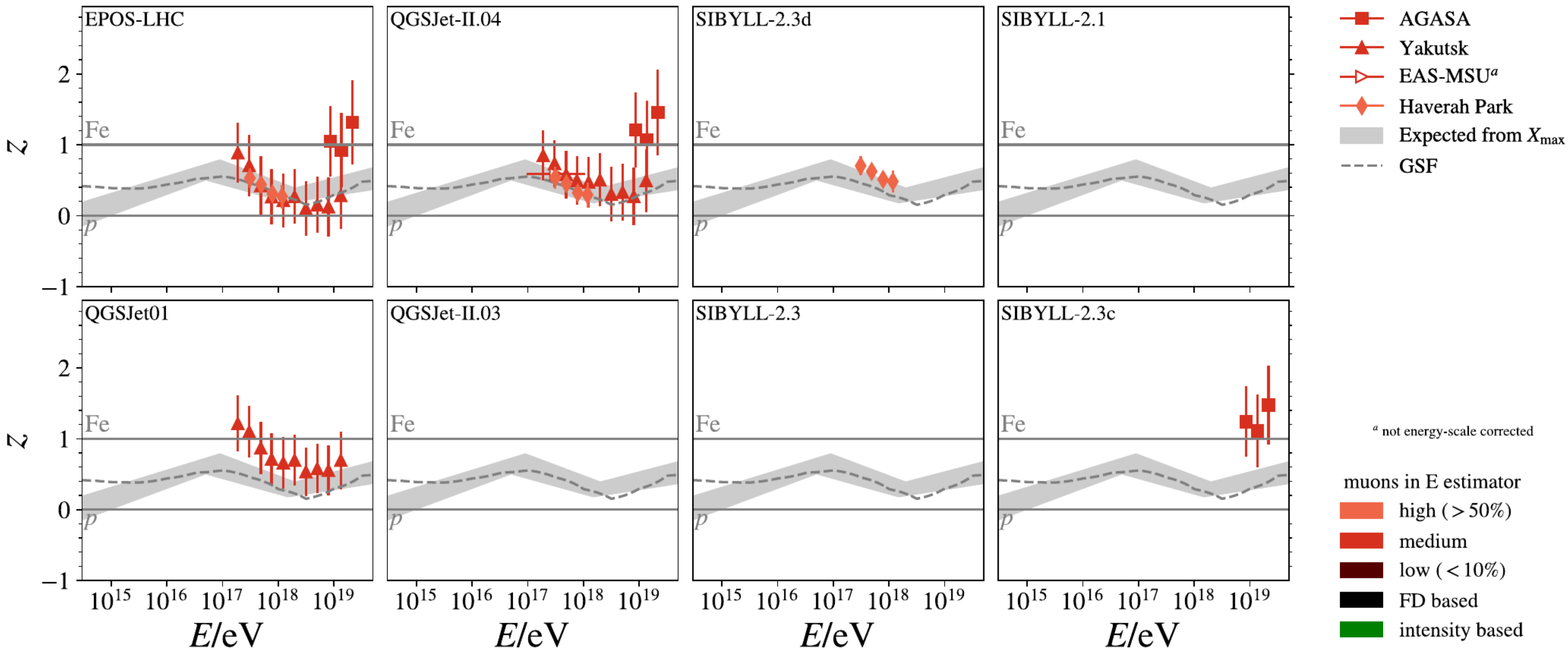


$$z = \frac{\ln\langle N_\mu^{det}\rangle - \ln\langle N_{\mu,p}^{det}\rangle}{\ln\langle N_{\mu,Fe}^{det}\rangle - \ln\langle N_{\mu,p}^{det}\rangle}$$

J.C. Arteaga-Update on the combined analysis of μ data ICRC 2023, Nagoya, Japan 11

Blurry Picture..

- **"Muon Puzzle" (<N_μ>) depends on energy measurement technique**
  - ➡ High muon fraction in energy estimator
    - ➡ No muon excess observed in data



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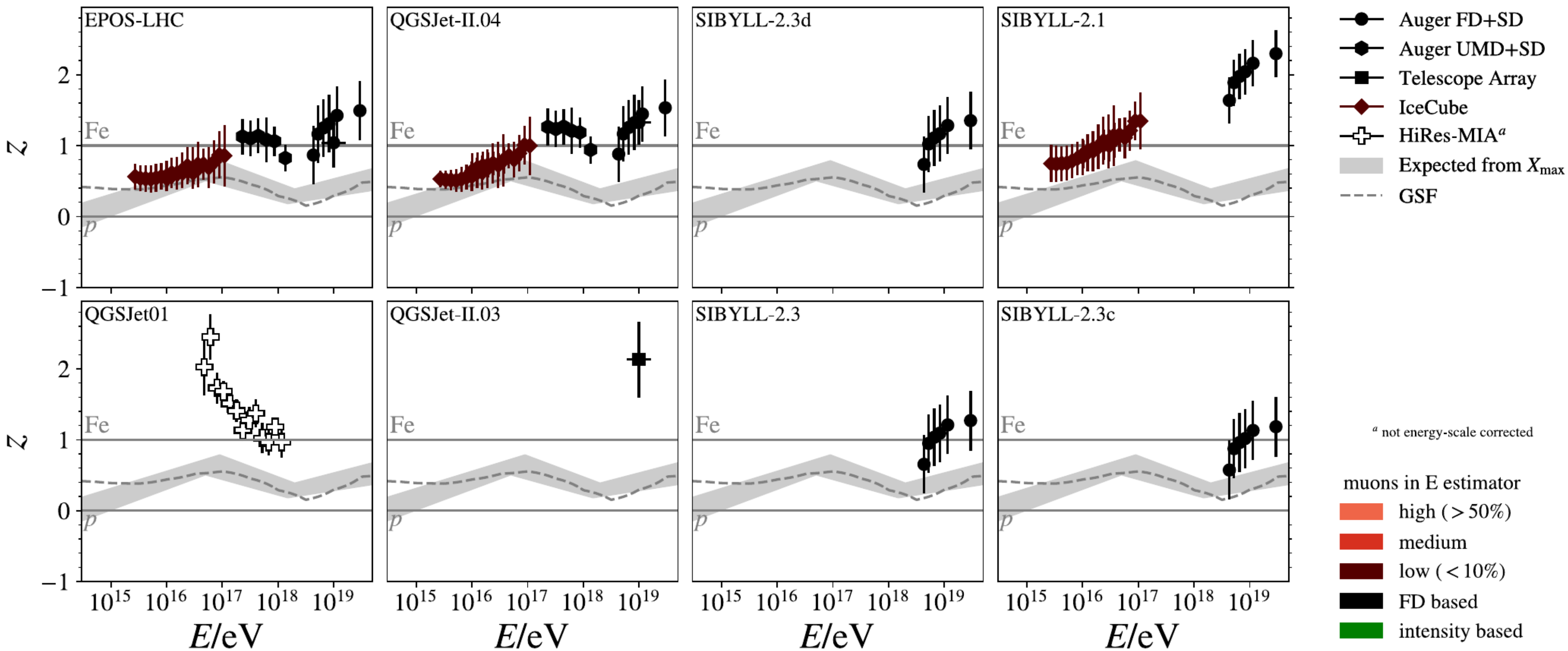
Blurry Picture...

- **"Muon Puzzle" (<N_μ>) depends on energy measurement technique**
  - ➡ Low muon fraction in energy estimator
    - ➡ Large muon deficit in simulations



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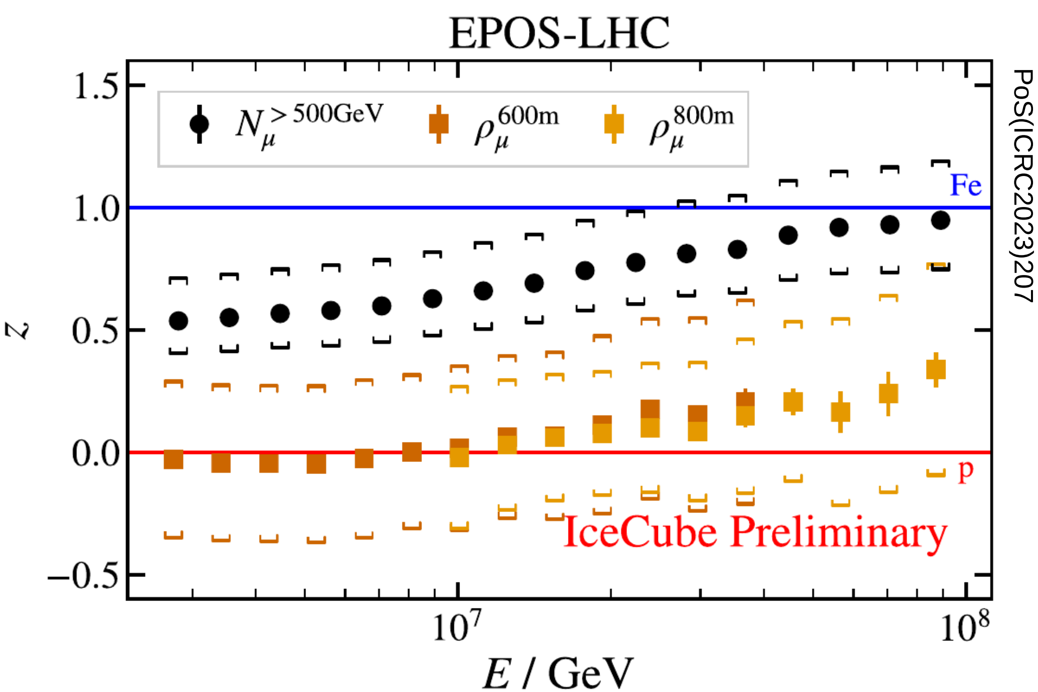
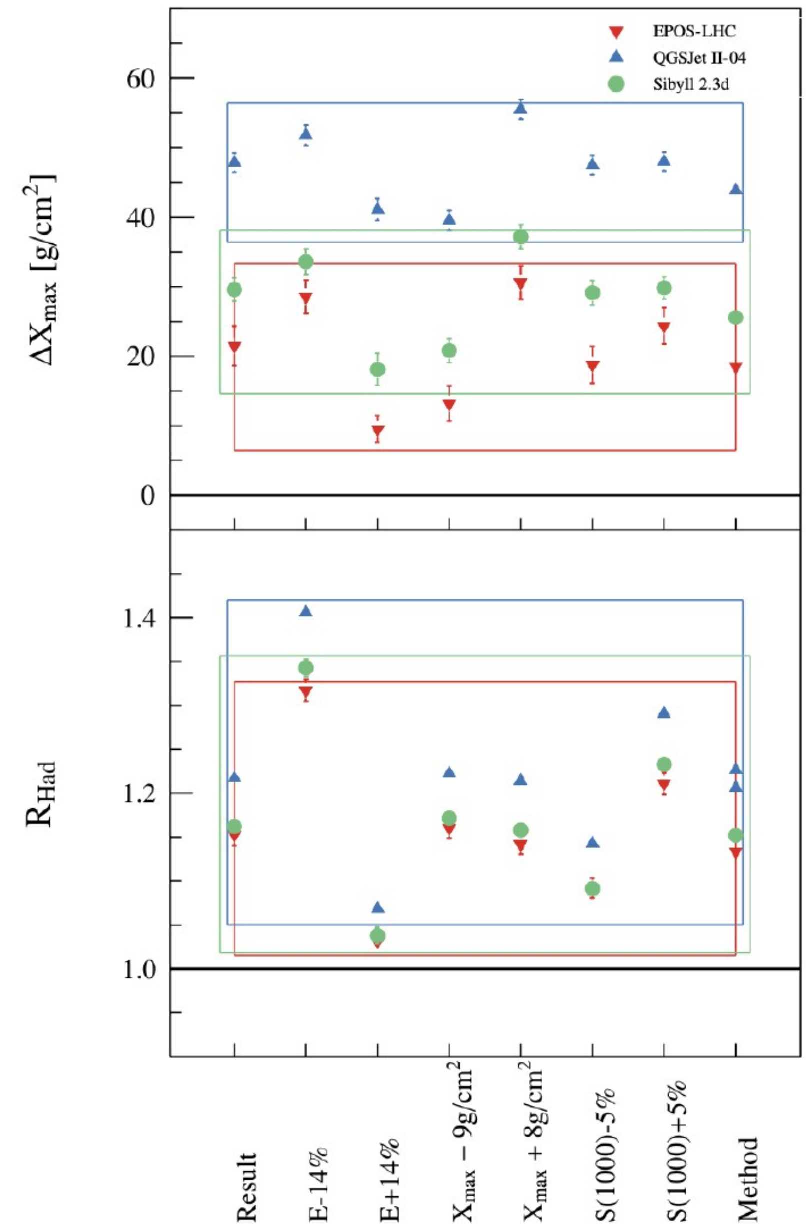
… but more evidences

- **Air shower measurement suffer from large energy scale uncertainties**
  - ➡ But discrepancy remains within errors
- **Different muon energies are not equally reproduced**





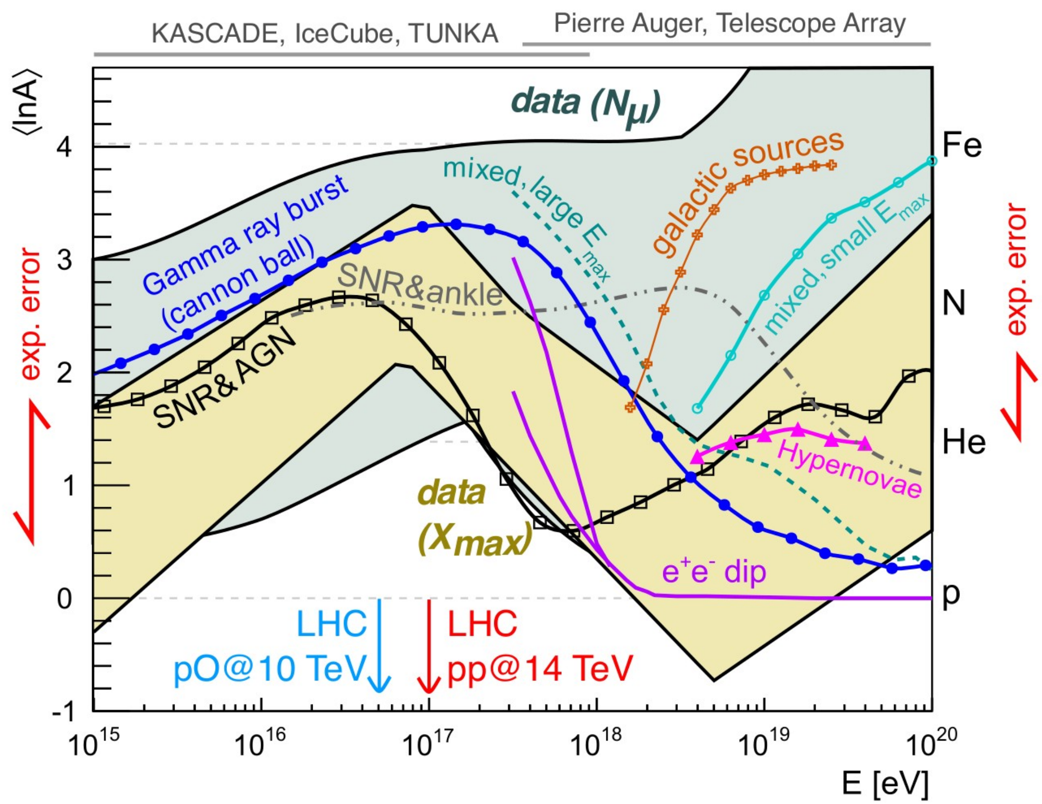
- **Other variables not well reproduced**
  - ➡ Zenith angle dependence, muon production height, ...

UHECR Composition

With current models, CR data are impossible to interpret

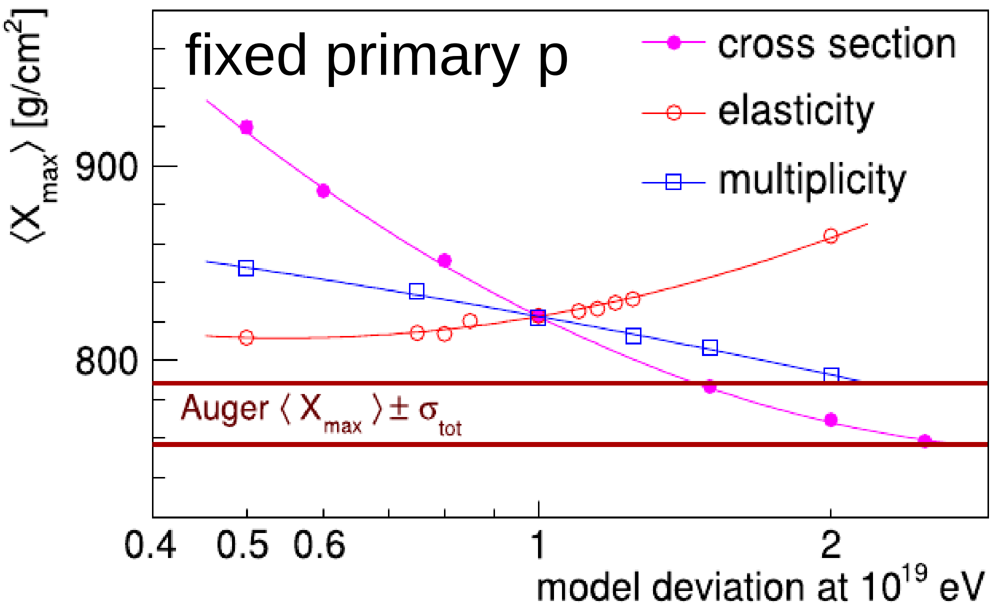
- Very large uncertainties in model predictions
- Mass from muon data incompatible with mass from X_{max}

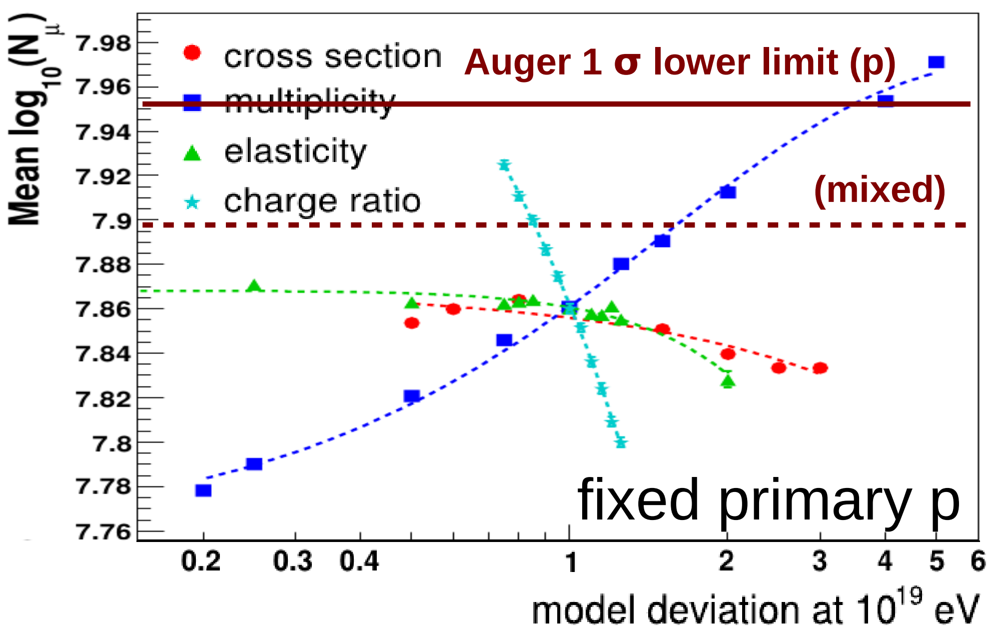
→ Need better hadronic interaction models



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

Sensitivity to Hadronic Interactions





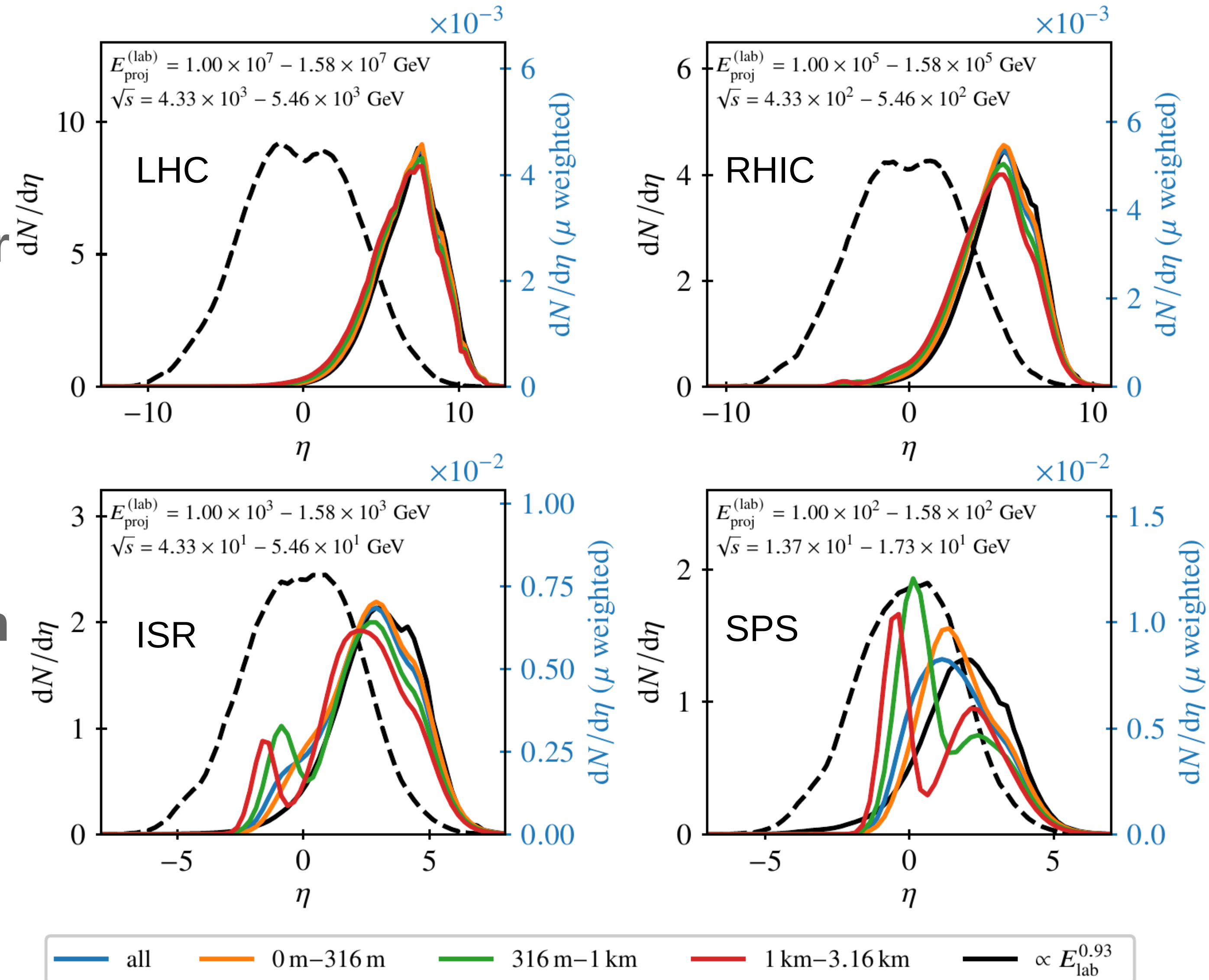
From R. Ulrich (KIT)

- **Air shower development dominated by few parameters**
  - ➡ mass and energy of primary CR
  - ➡ cross-sections (p-Air and (π-K)-Air)
  - ➡ (in)elasticity
  - ➡ multiplicity
  - ➡ Hadronization (π^0, baryon, str.,...)
- **Change of primary = change of hadronic interaction parameters**
  - ➡ cross-section, elasticity, mult. ...

Good measurements at LHC constrain hadronic interaction parameters and improve mass resolution !

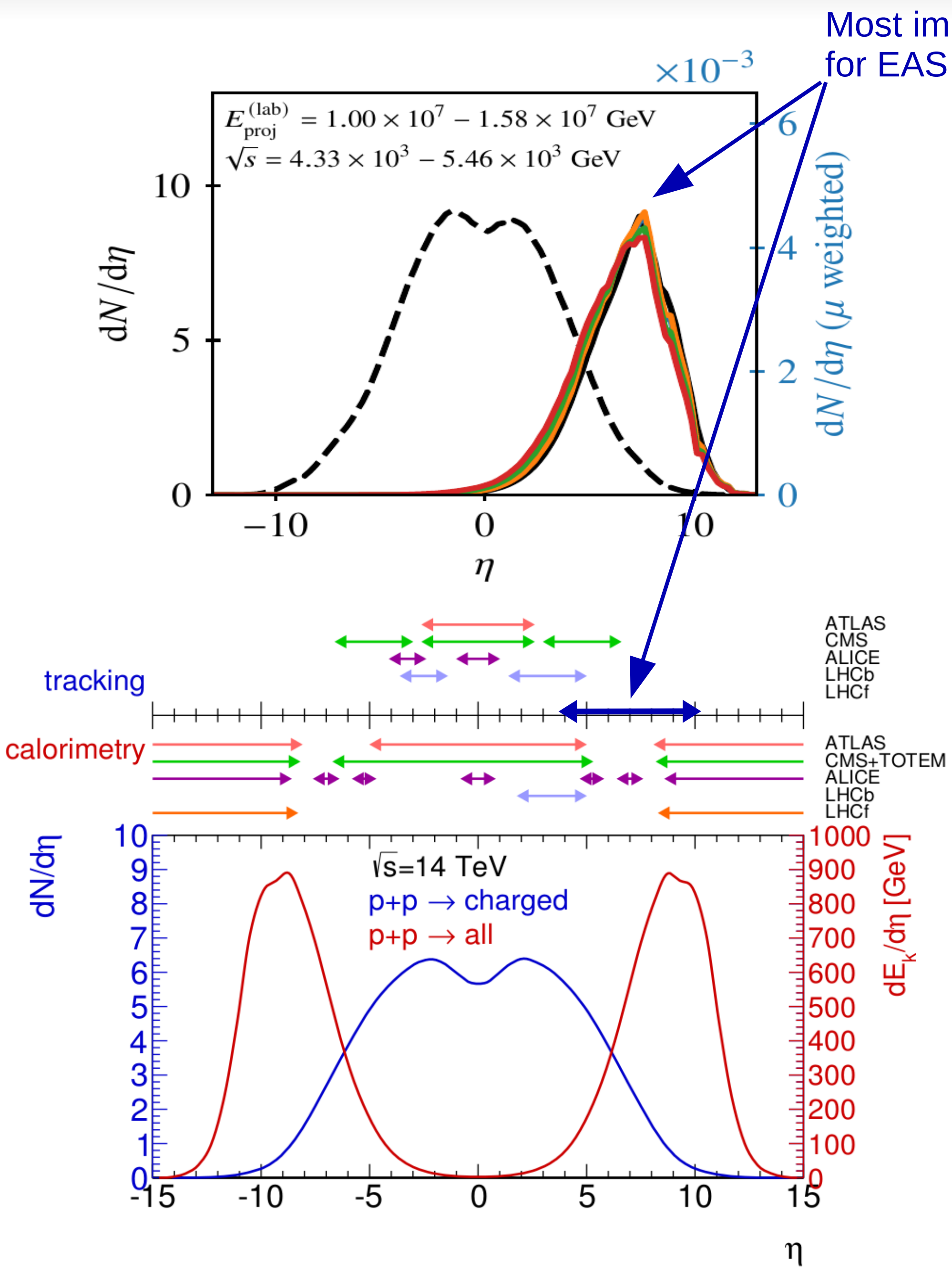
Relevant Phase Space in Air Showers

- **X_{max} dominated by cross-section and elasticity of the 1st int.**
- **Muon production in air showers dominated by forward produced particles**
  - ➔ True at high energy
- **Midrapidity production important in the last generations and for muon at large distances from the shower core**
  - ➔ Low energy data as important than high energy data



Maximilian Reininghaus, ICRC2021

LHC acceptance



- p-p data of central detectors used to reduce uncertainty by factor ~2. How to do more ?
  - p-Pb difficult to compare to CR models (only EPOS)
  - special centrality selection
  - p-O !
- **Maximum energy flow relevant for EAS**
  - η~5-8 (muons)
  - η>9 (X_{max})
- **Limited forward measurements**
  - Only calorimetric (EM)
    - LHCf
  - With particle identification
    - LHCb

Data to Improve Models

- **A number of new data could be use to improve the models :**
  - ➡ p-p and p-A cross-sections
  - ➡ Multiplicity (with proton tagging ?)
  - ➡ More detailed p-A measurements (fluctuations, fragmentation)
  - ➡ Inelasticity (beam remnant energy loss)
  - ➡ Particle yields as a function of multiplicity
    - Very important to understand the mechanism behind particle production
  - ➡ Electromagnetic to hadronic energy ratio

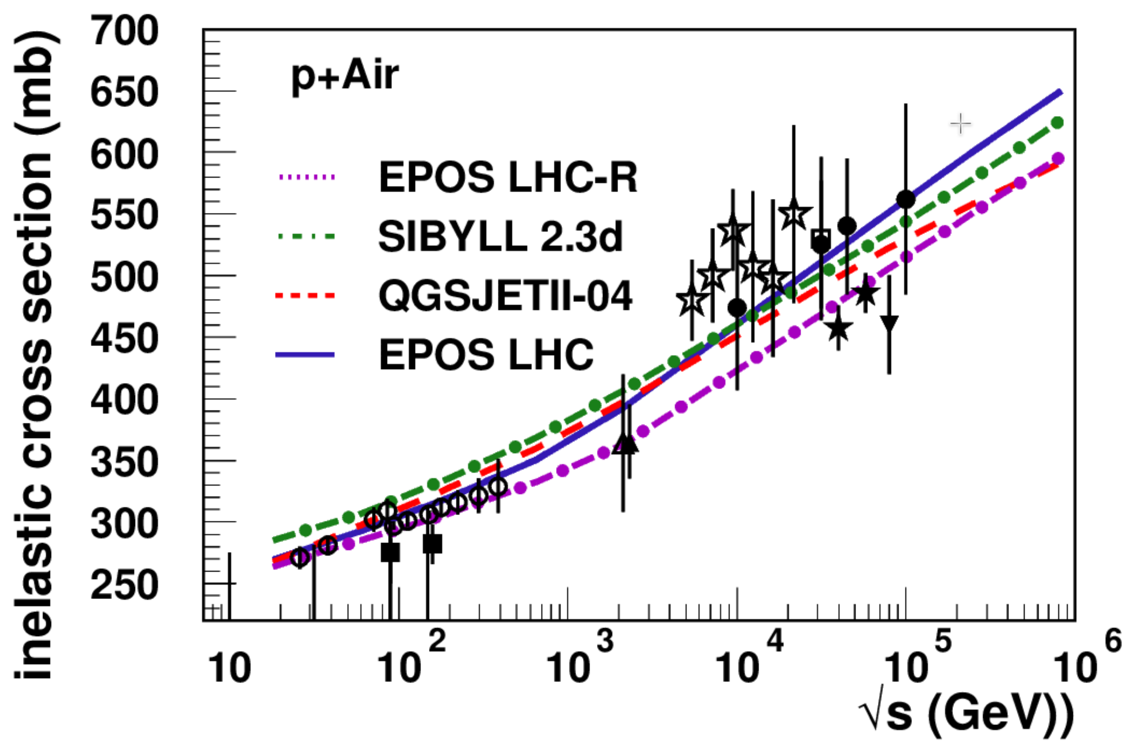
X_{max} (multiplicity, p-A measurements, inelasticity)

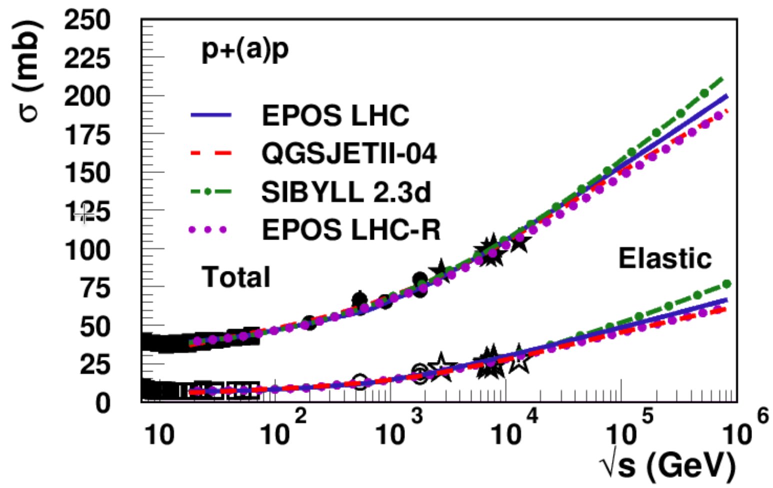
N_{μ} (particle yields, electromagnetic to hadronic energy ratio)

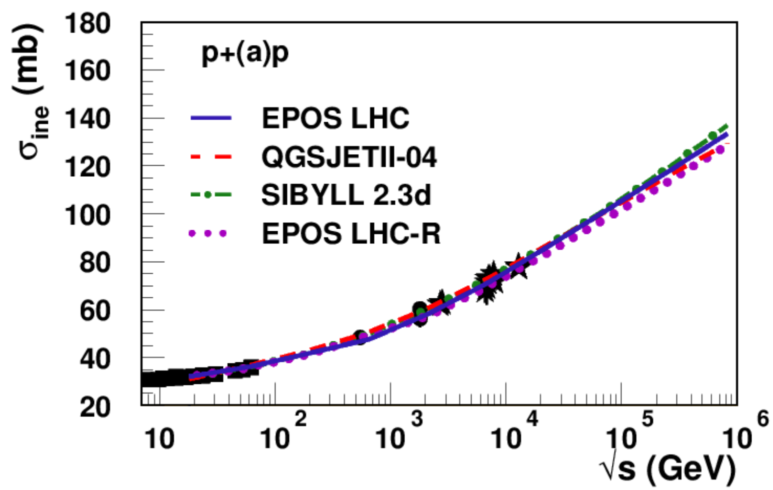
- **Example : Update of EPOS LHC → EPOS LHC-R**
  - ➡ New EPOS 4 available soon for heavy ion physics but not usable for air showers (yet)
  - ➡ Modify EPOS LHC to take into account new data and new knowledge accumulated with EPOS 4
  - ➡ Very preliminary results for illustration !

Cross-Sections

- **Key measurement : 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 up to -15% at the highest energy using most recent CR based measurements

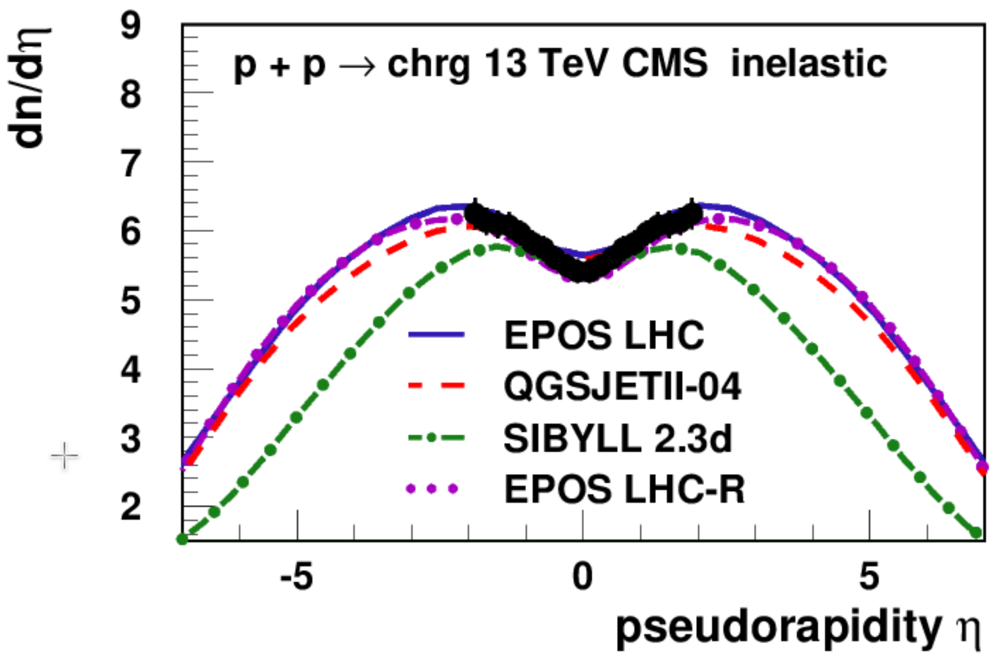


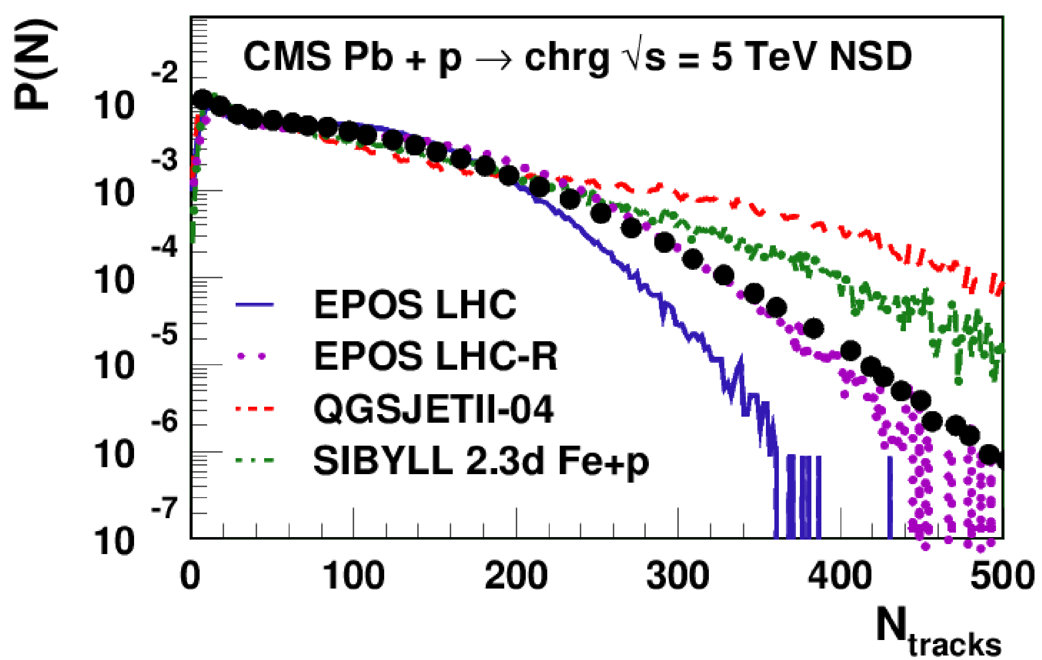




Pseudorapidity

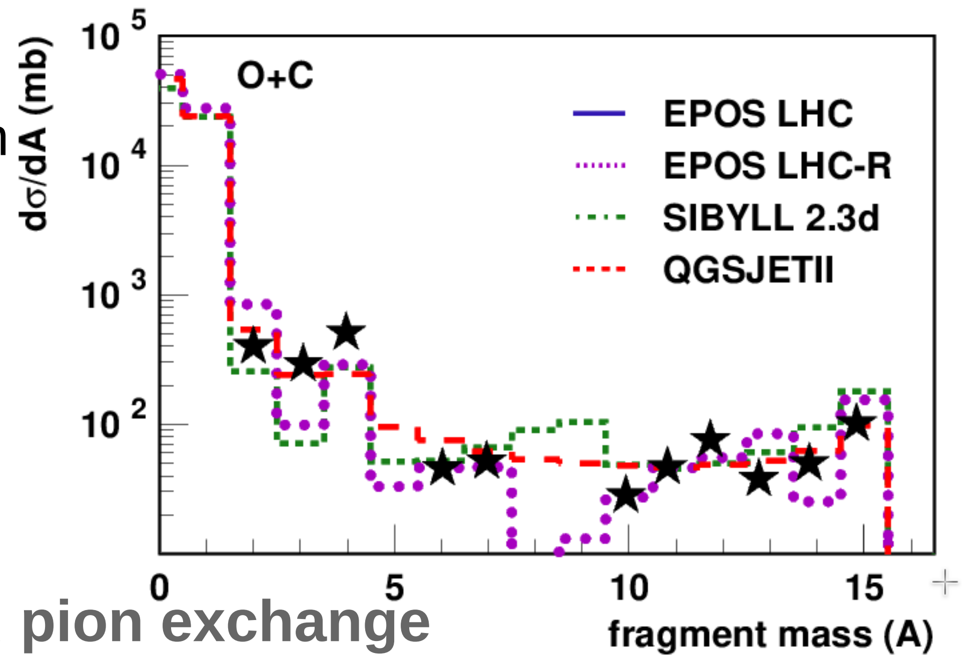
- **Simple (basic) measurement still important !**
- **New data at 13 TeV in p-p**
  - ➜ Test extrapolation with different triggers
  - ➜ Sibyll has a clear difference with other models (and data) : too narrow !
- **Detailed data at 5 TeV for p-Pb**
  - ➜ Wrong multiplicity distributions in all models (before retune)



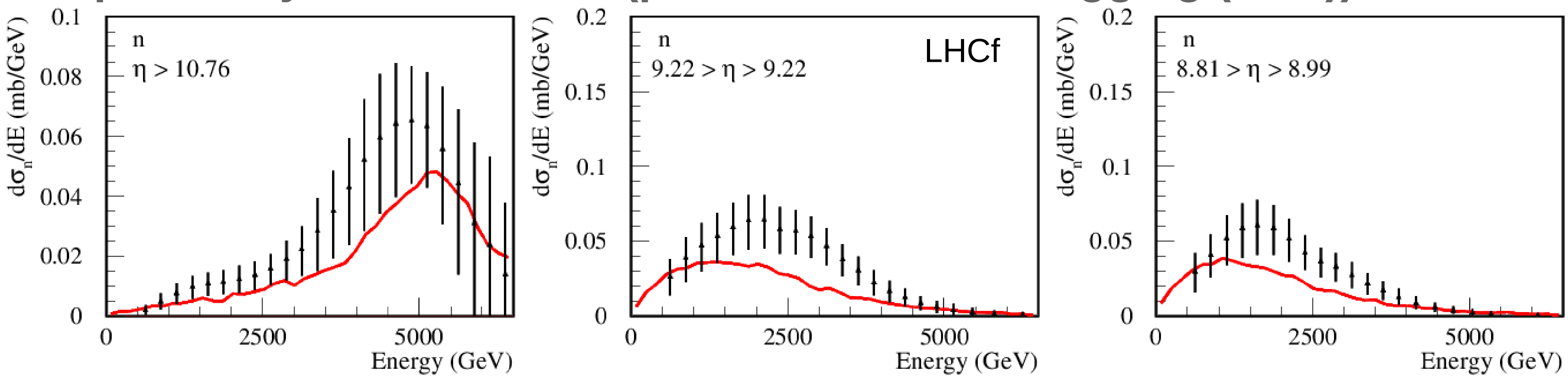


Other Type of Forward Measurements

- **Beam remnant very important in air shower development**
- **Nuclear fragments in EPOS LHC**
  - Correction of initial too simple approach
    - Now similar to other models
    - Significant impact on X_{max} fluctuations for nuclei
  - Measurement @LHC ?

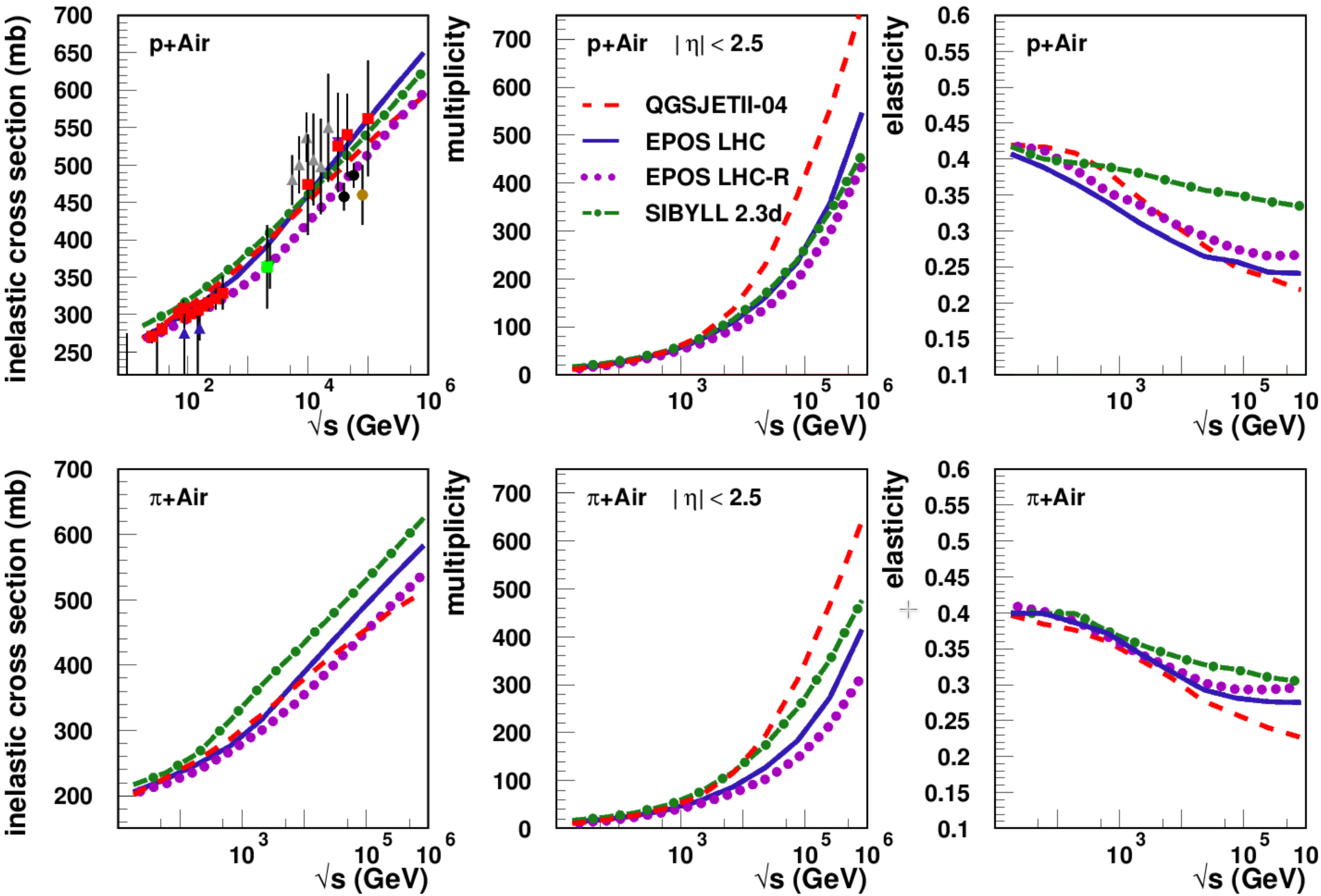


- **Simplified high mass diffraction and pion exchange replaced by real emission (proton or neutron tagging (ZDC))**



EPOS LHC-R interaction with Air

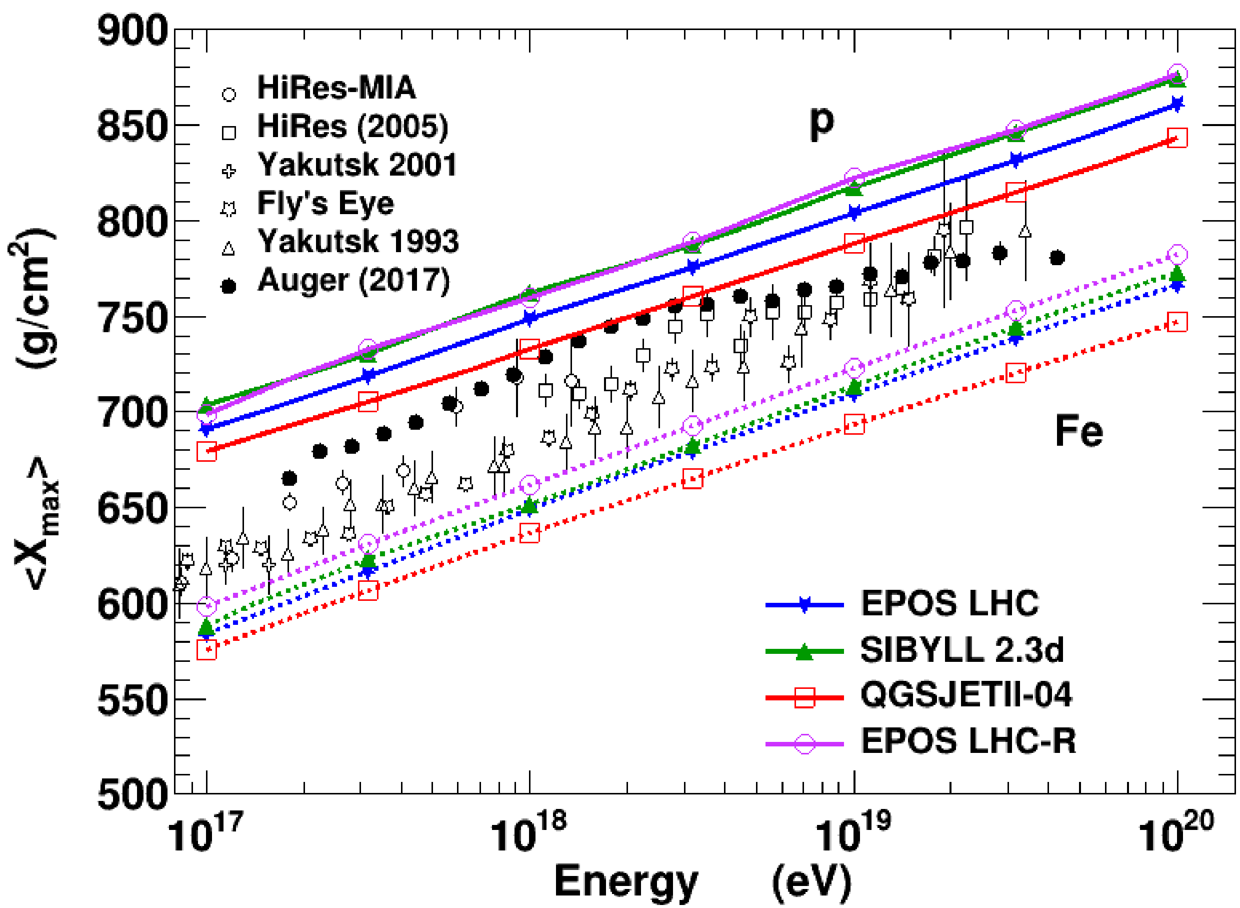
(preliminary)



X_{max}

+/- 20g/cm² is a realistic uncertainty band where is the center ?

- minimum given by QGSJETII-04 ((too) high multiplicity, low elasticity) ?
- maximum given by Sibyll 2.3d (low multiplicity, high elasticity) ?
- Taking into account new data, now EPOS shifted by +15g/cm² (=Sibyll for p)



Higher <lnA> !

Correction of nuclear fragmentation in EPOS :
X_{max} RMS Fe
LHC=20g/cm2
LHC-R=24g/cm2
SIB=25g/cm2
QII=25g/cm2

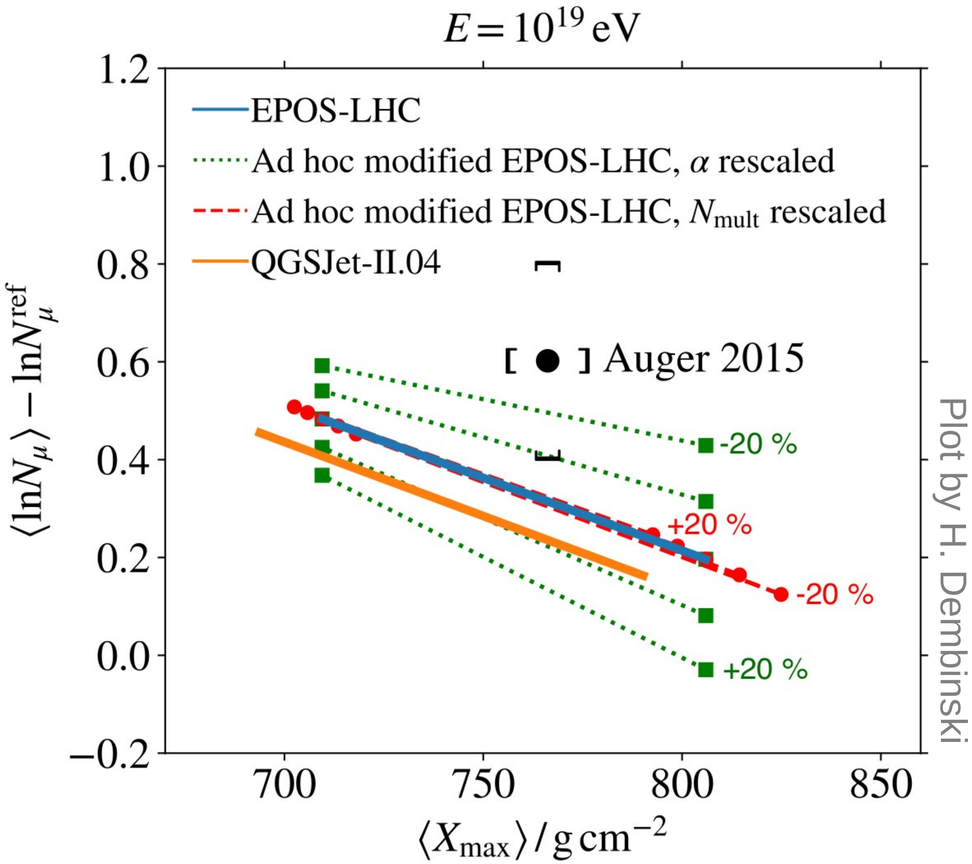
Muon Production

- **From WHISP, one needs to change energy dependence of muon production by ~+4%**

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

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

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



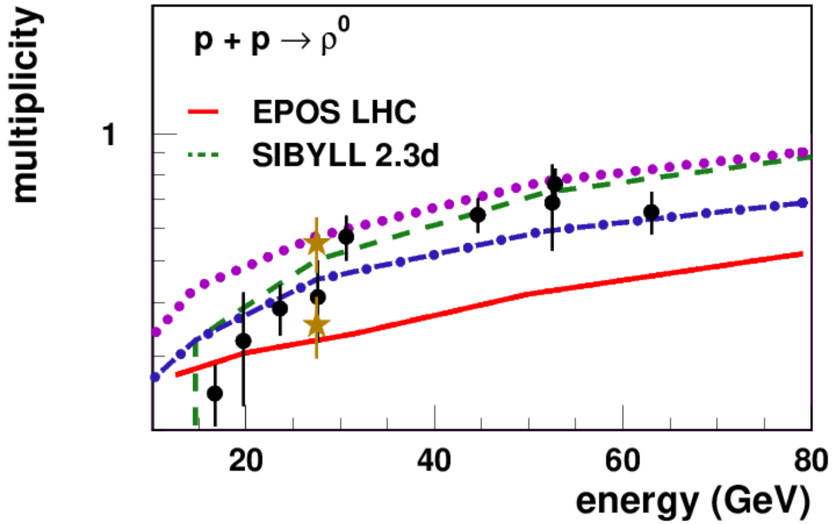
- $$\beta = \frac{\ln\left(N_{mult} - N_{\pi^0}\right)}{\ln\left(N_{mult}\right)} = 1 + \frac{\ln\left(1-\alpha\right)}{\ln\left(N_{mult}\right)}$$
  - +4% for β ➤ -30% for $\alpha = \frac{N_{\pi^0}}{N_{mult}}$
  - Measure@LHC : $R = \frac{E_{e/m}}{E_{had}} \approx \frac{c}{1-c}$

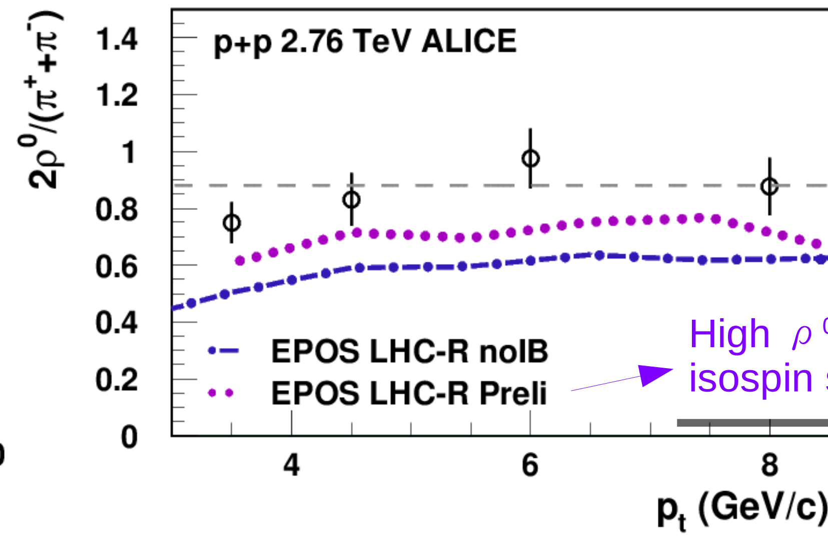
Isospin Symmetry and Resonances

- **Isospin symmetry used as an argument in models to justify 1:1:1 ratios in π or ρ mesons** (or equal neutron/proton production)
  - ➔ But true only if u and d quarks have the same mass !
- **Pions can be produced directly or via ρ resonance decay**
  - ➔ Ratio $\pi^0/\pi^{+/-}$ very important for muon production
    - ➔ More π^0 means less μ production
  - ➔ But ρ^0 decay in $\pi^{+/-}$
    - ➔ More ρ^0 means more μ production
  - ➔ Are π mesons mostly produced through ρ mesons ?
- **Isospin symmetry broken in multiparticle hadronization ?**
  - ➔ Sea u and d quark assymmetry observed in proton parton distribution function (Phys.Rev.D 71 (2005) 012003)
  - ➔ Particle masses are slightly different !
  - ➔ Can the 1:1:1 ratio be broken in particular for ρ mesons (and baryons) ?
  - ➔ What do we see in data ?

Resonance Production

➡ In proton-proton interactions, ratio 1:1:1 is not observed and high ρ ...

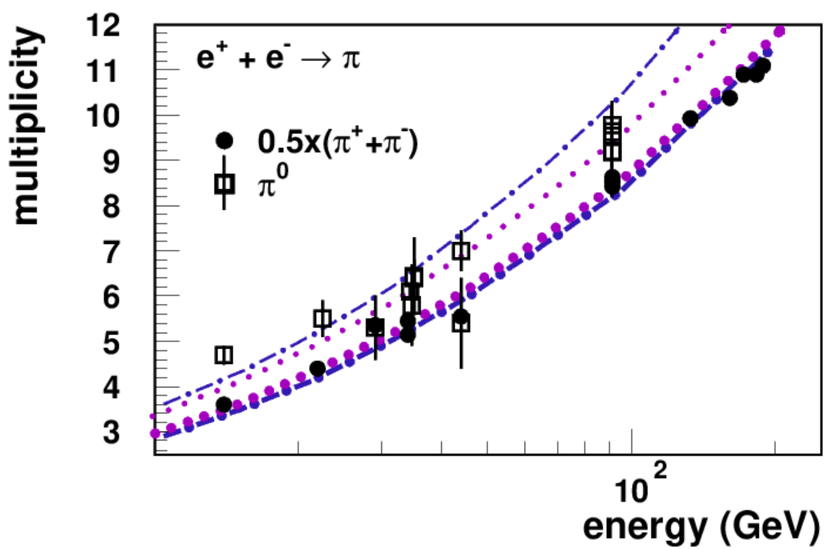


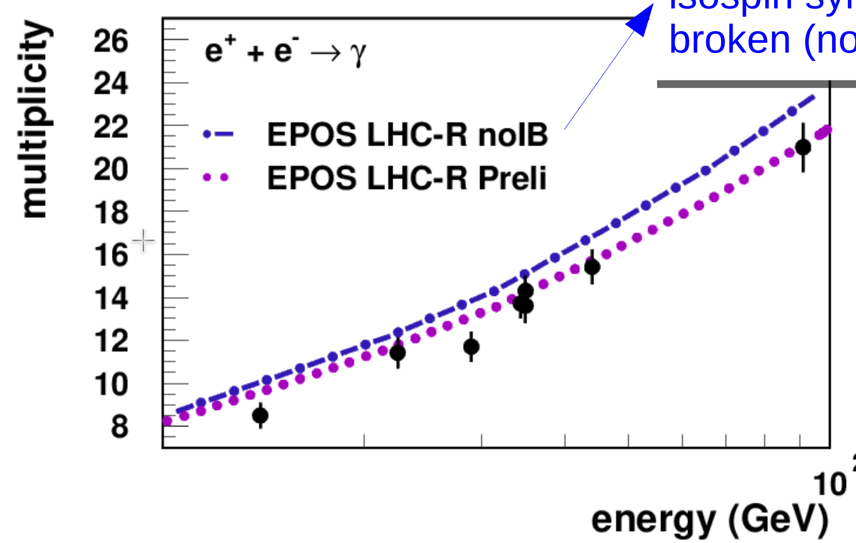


High ρ^0 fraction and isospin sym. broken

➡ Both favored in electron-positron data !

Low ρ fraction and isospin sym. NOT broken (noIB)

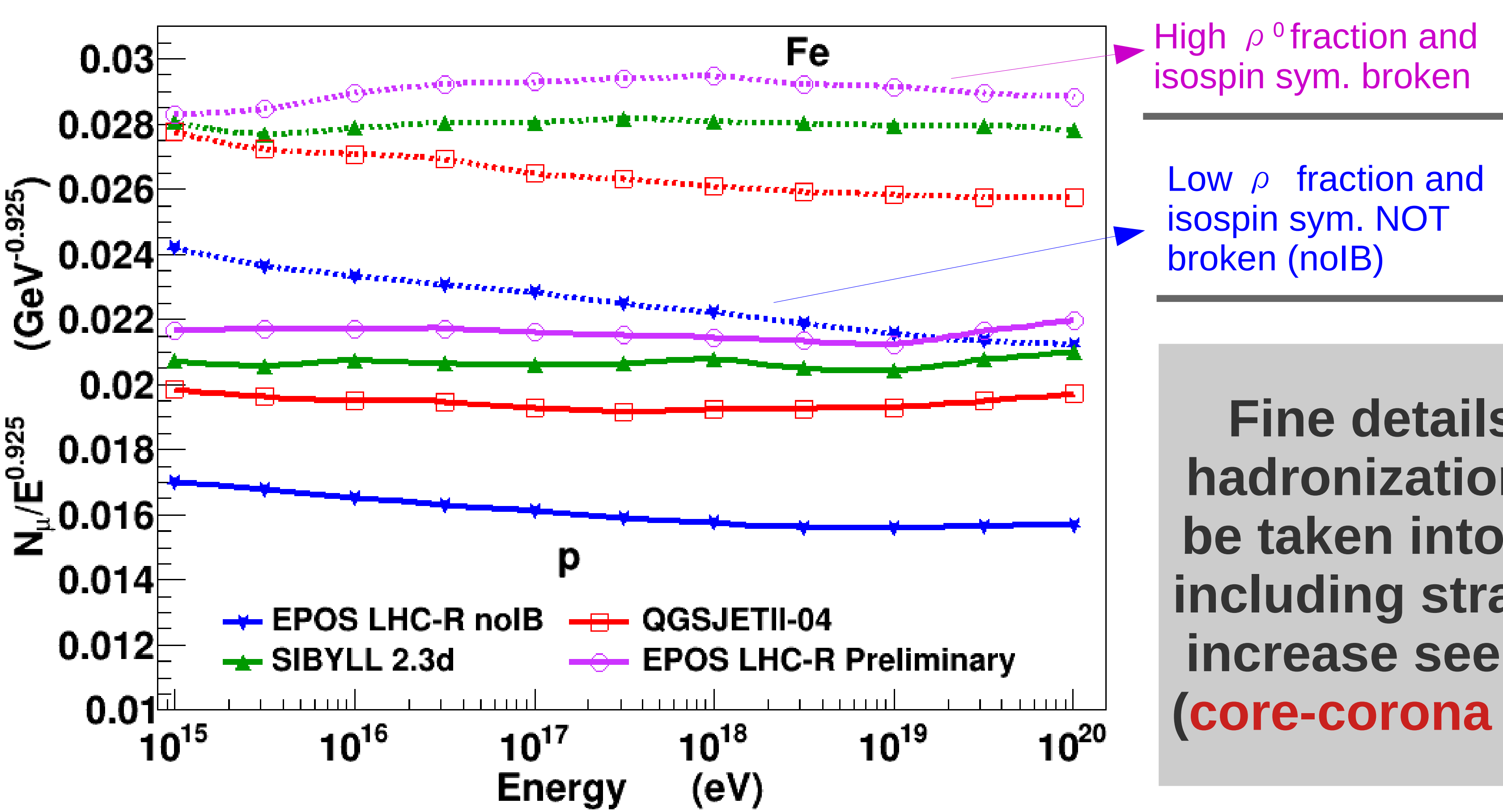




N_μ

Very large differences depending on resonances (meson and baryon) :

- minimum given by low content of resonances and isospin symmetry
- maximum given by high content of resonances with isospin symmetry breaking
- Accelerator data seem to favor the 2nd option (EPOS LHC-R preliminary)



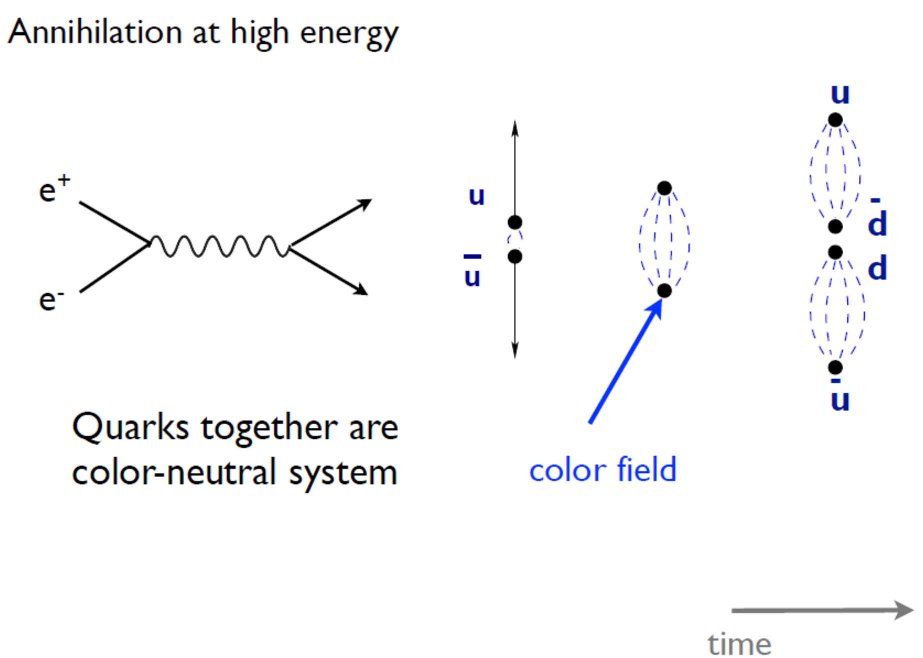
30% !

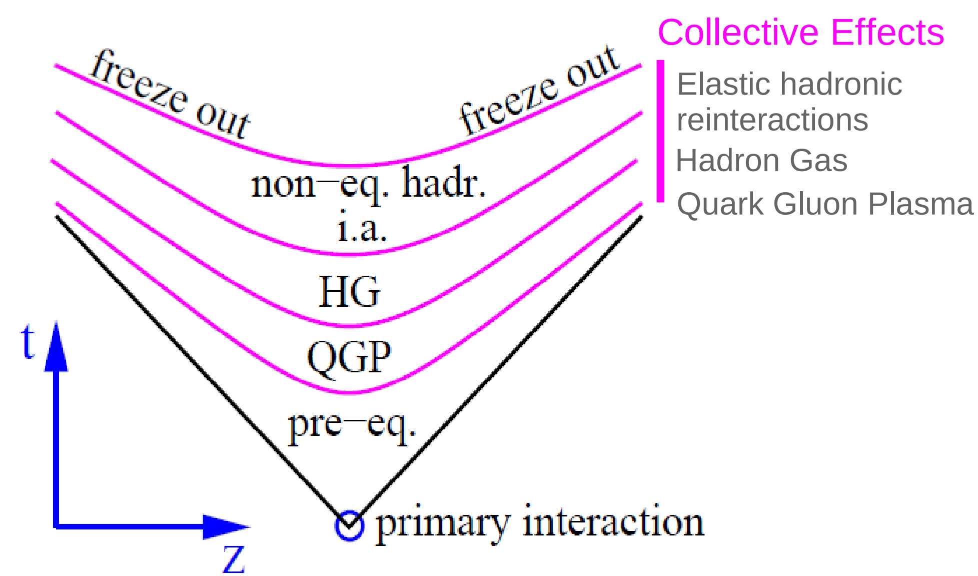
Fine details of the hadronization should be taken into account including strangeness increase seen at LHC (core-corona not here)

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 → less muons

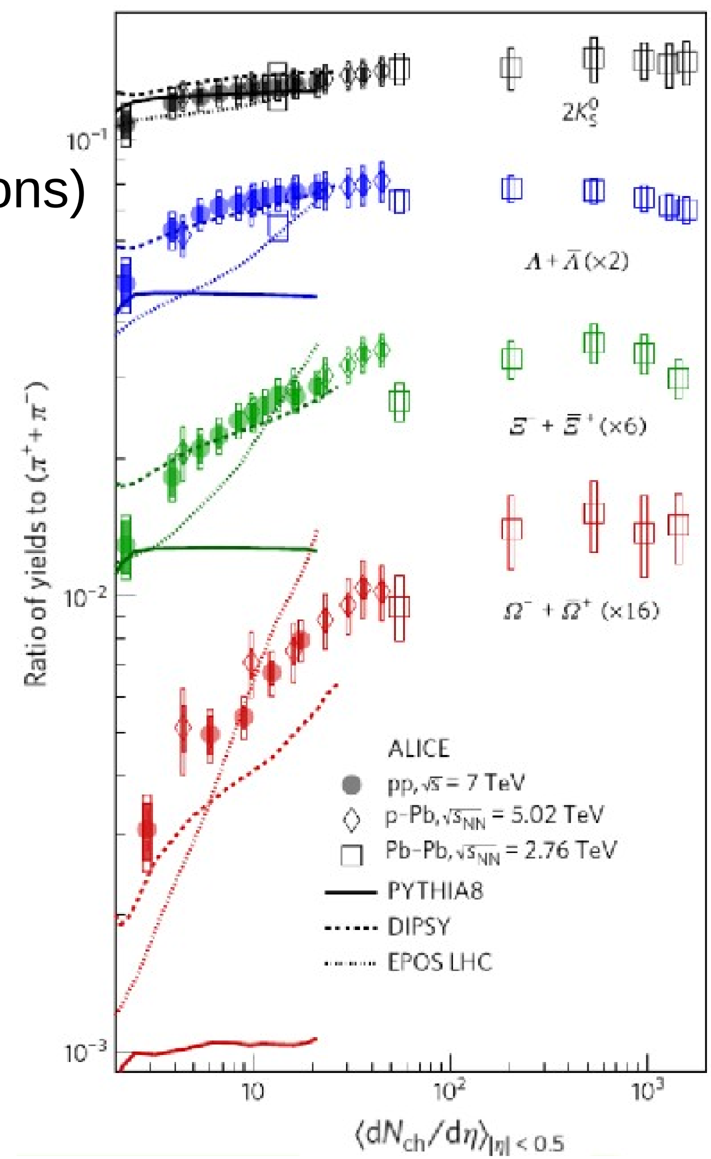
In dense systems… CORE
→ "low" π^0 fraction → more muons

➡ Core-corona → transition from one regime to the other (strangeness vs mult.)

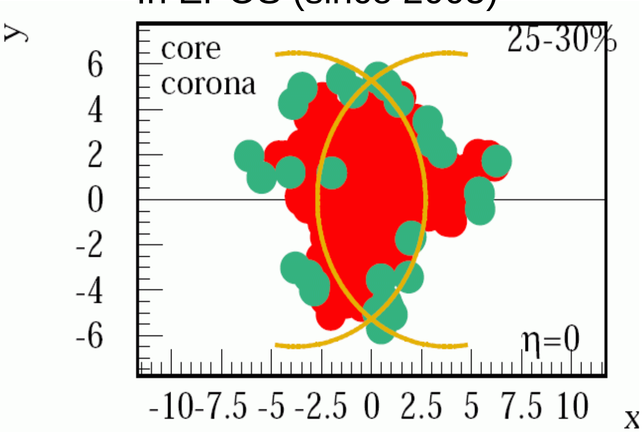
➡ Different hadronization = different muon production in air showers !

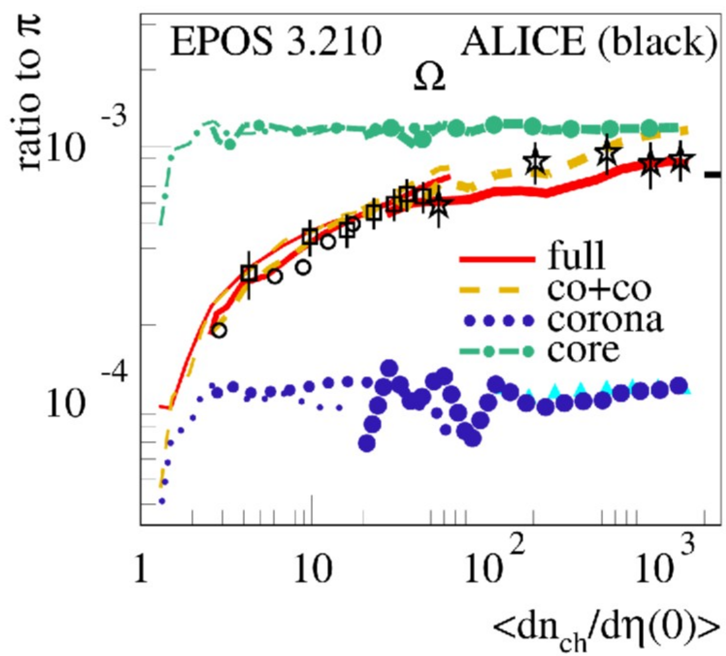
Core-Corona at LHC

- 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



In EPOS (since 2005)





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

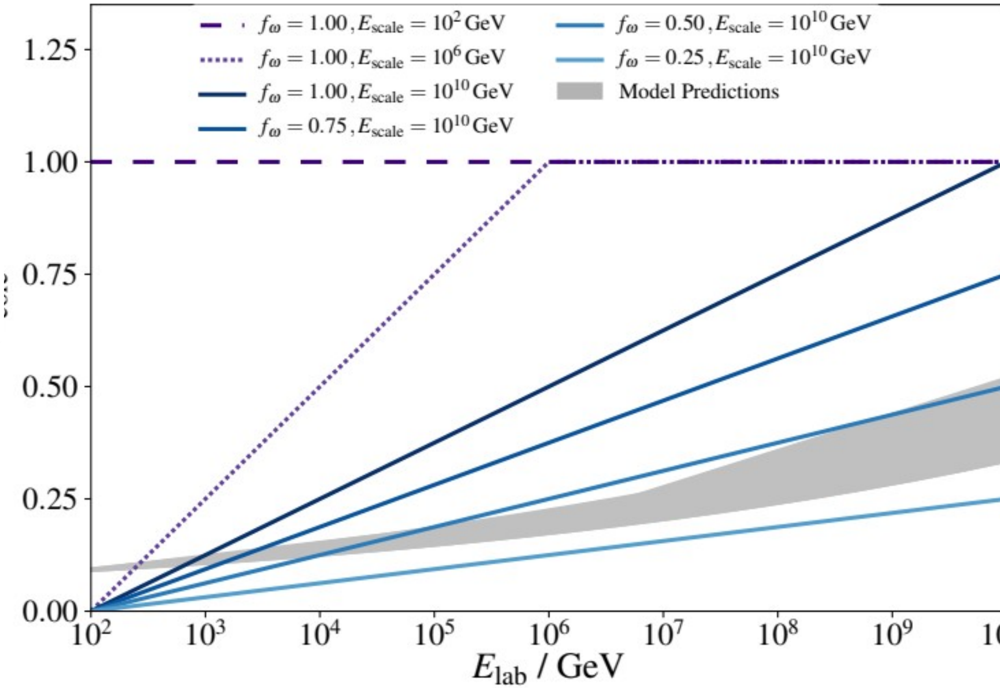
- Particle ratios from statistical model are known (tuned to PbPb) and fixed : core
- Initial particle ratios given by individual hadronic interaction models : corona
- Using CONEX, EAS can be simulated mixing corona hadronization with an arbitrary fraction ω_{core} of core hadronization: $N_i = \omega_{\text{core}}\,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

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

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

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

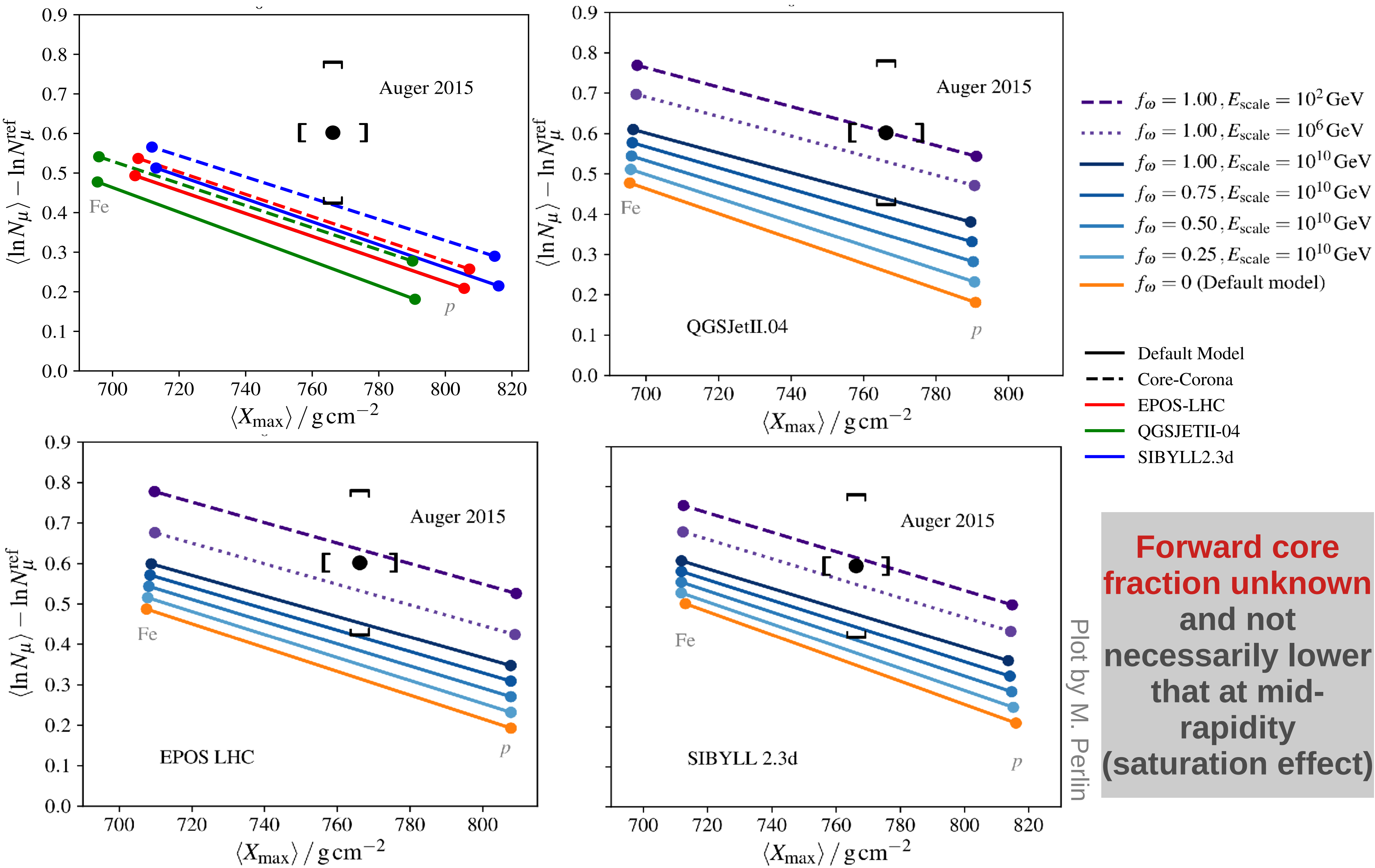
Note : the leading particle is NOT modified (projectile remnant)



Plot by M. Perlin

Phys.Rev.D 107 (2023) 9, 094031 1902.09265 [hep-ph]

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



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

Summary

- **Not all relevant CERN data taken into account in model yet**
  - 10 more years of LHC data including LHCf dedicated measurements
  - Room for more data in particular with pO beam and correlated measur.
    - Very forward measurement important for x-section and elasticity
- **Updated results of cross-sections and diffraction**
  - Significant impact on X_{max}
  - Larger <lnA>
- **Details of hadronization matters to solve “muon puzzle”**
  - Important role of resonance with sparse data = large uncertainty
    - Is Isospin symmetry broken in multiparticle production ?
  - Evolution of strangeness with multiplicity
    - Different type of hadronization (“core-corona”)
  - Carefully study “standard” physics before going to “new” physics
    - Check number of μ + energy spectra + production height (time)

LHC data provide important constraints on models changing X_{max}

Details on hadronization could be more important than thought until now, impacting the muon production, and need careful study at LHC in particular with pO data.

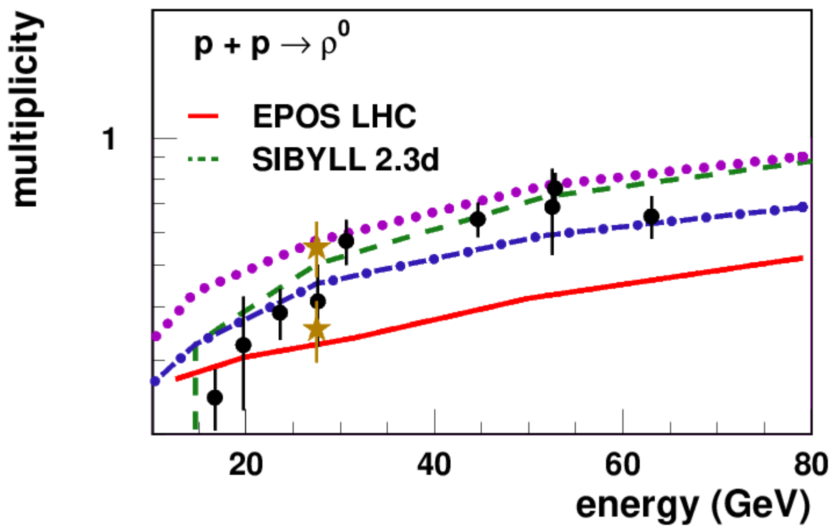
Thank you !

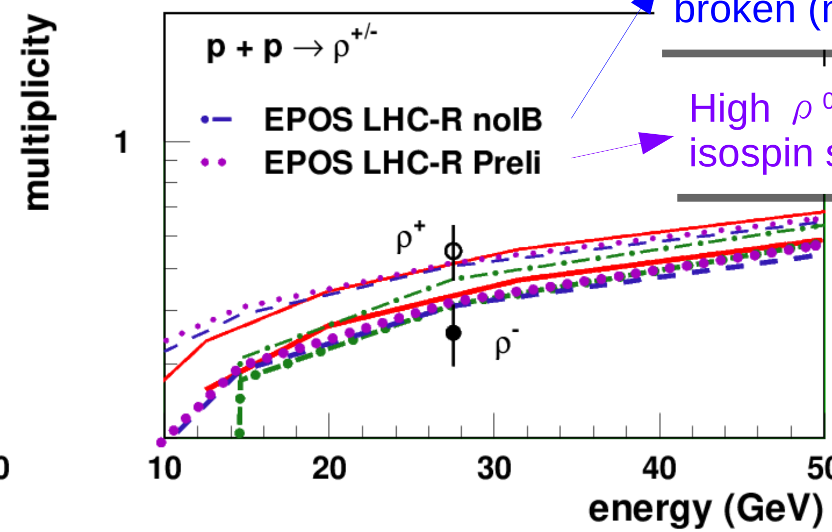
Resonance Production

➡ In proton-proton interactions, ratio 1:1:1 is not observed !

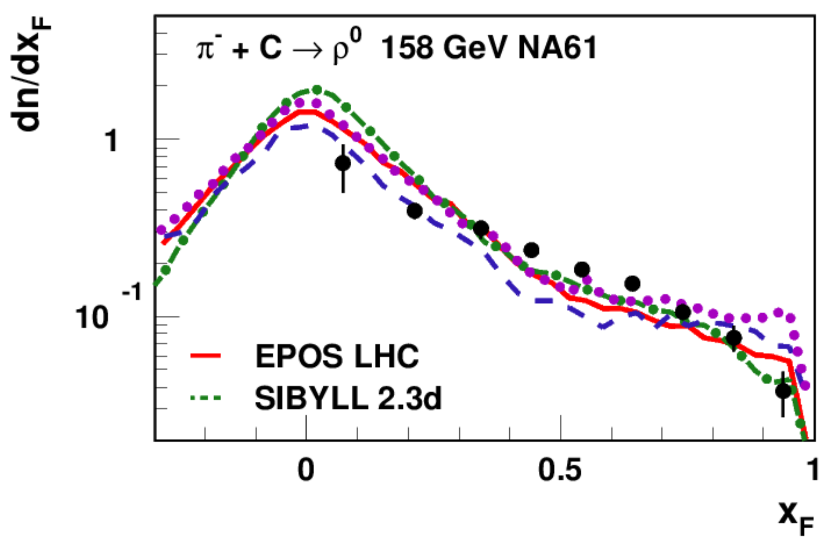
Low ρ fraction and isospin sym. NOT broken (noIB)

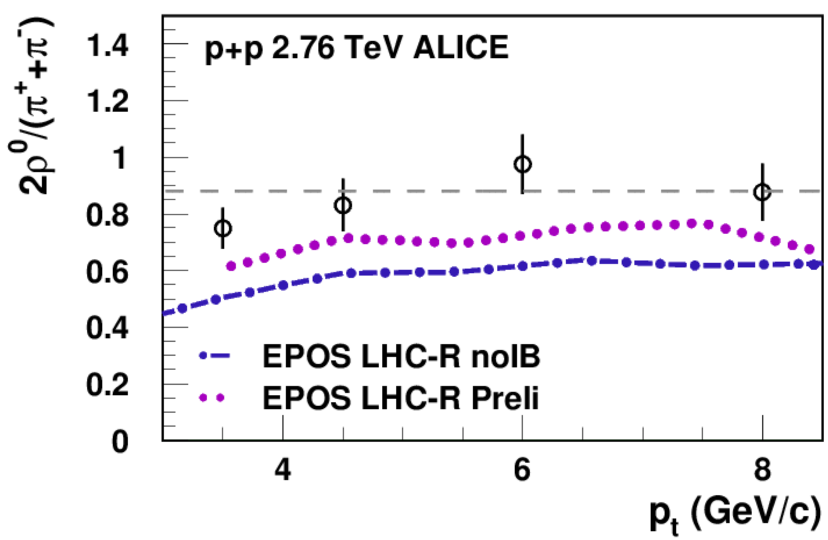
High ρ^0 fraction and isospin sym. broken



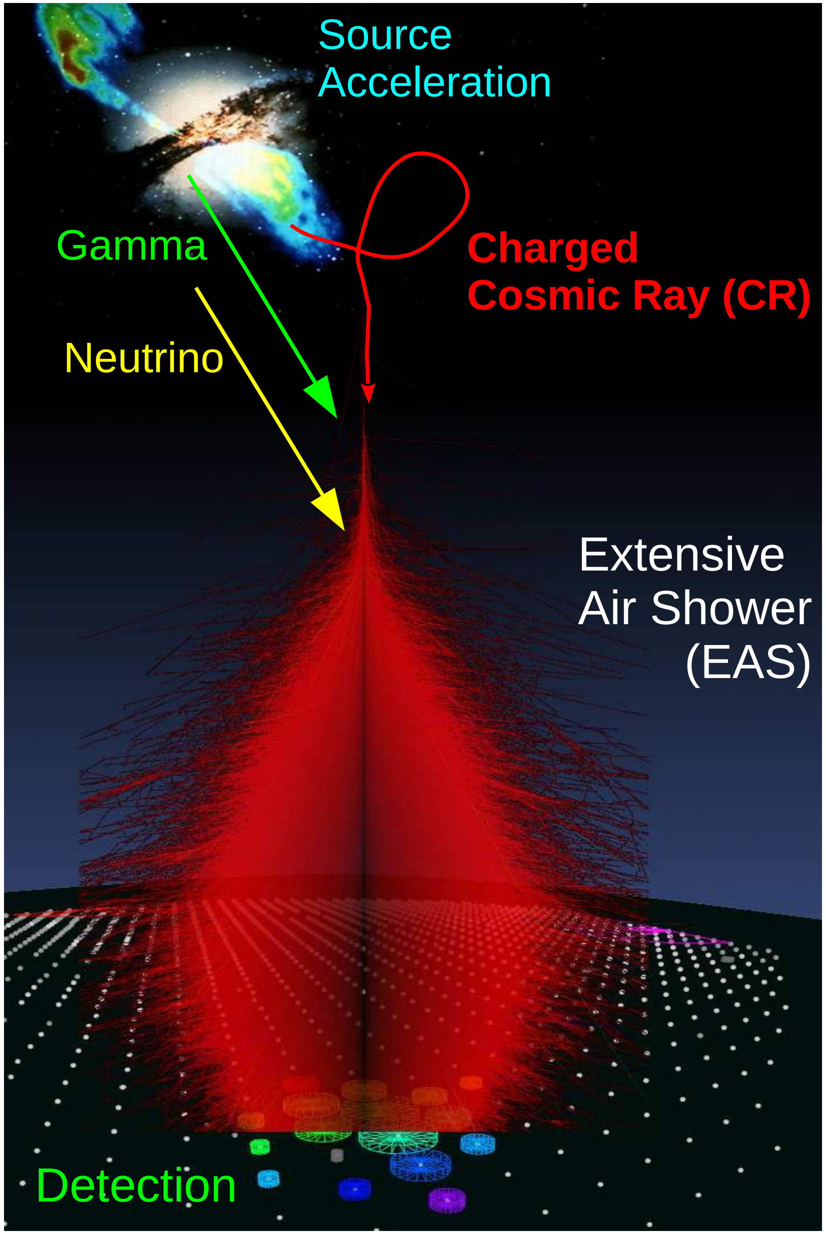


➡ AND high resonance fraction is favored !





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 observable.

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

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

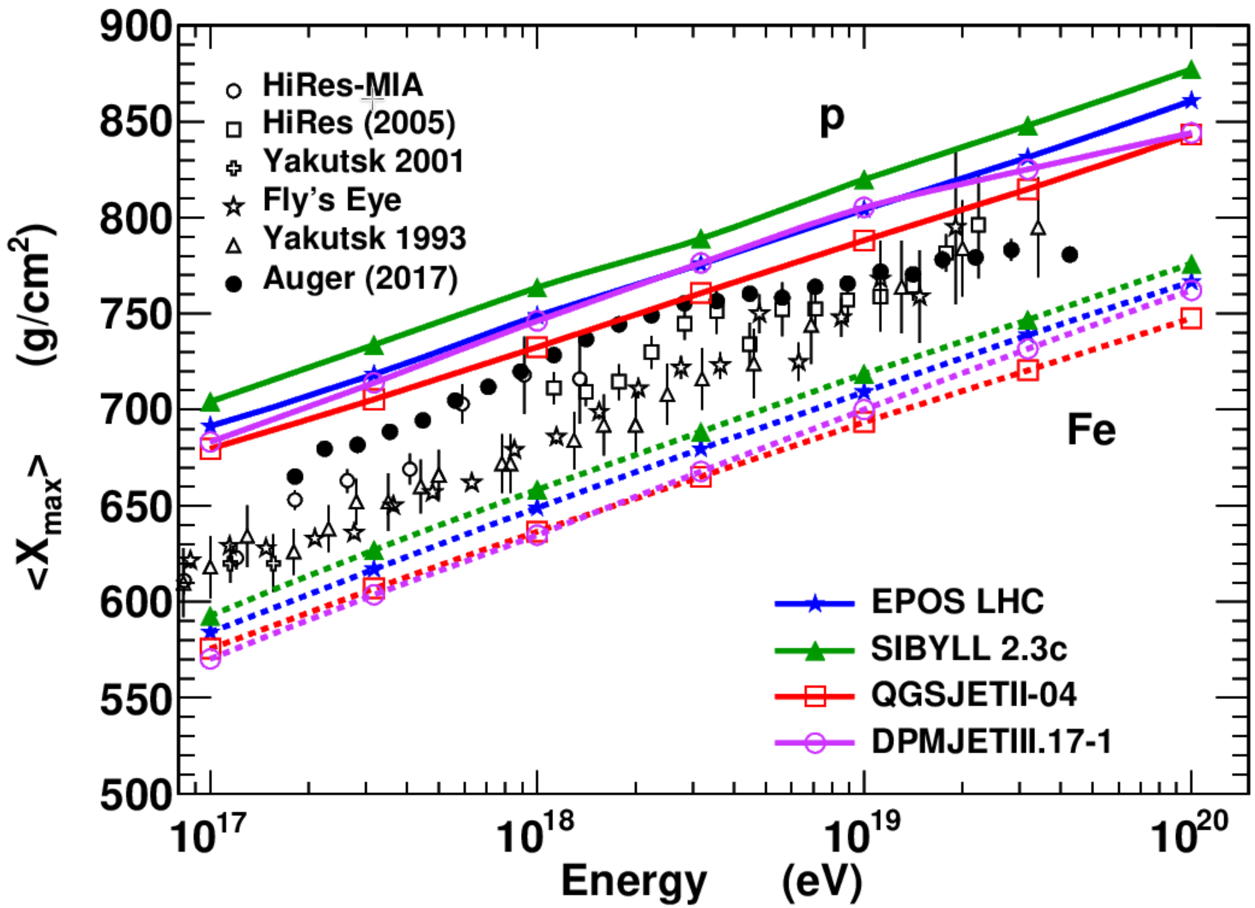
- **Hadronic models are the key ingredient !**
  - ➔ follow the standard model (QCD)
    - ➔ but mostly non-perturbative regime (phenomenology needed)
  - ➔ main source of uncertainties

- **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}

+/- 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)
- 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)

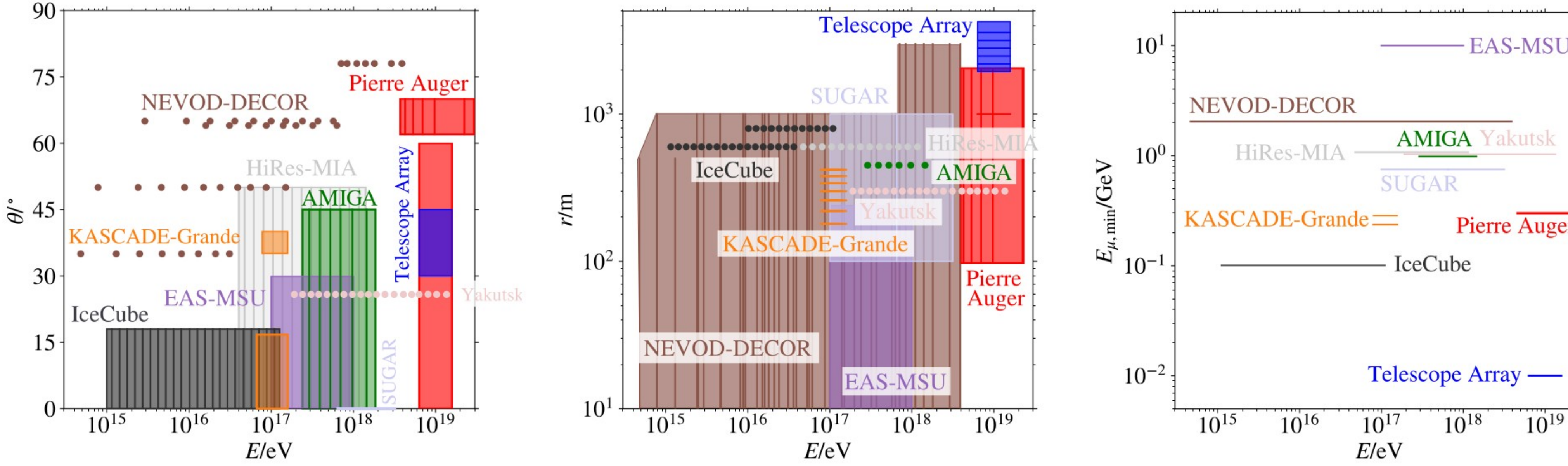
  N. Kalmykov (EAS-MSU, Russia) and I.S. Karpikov (EAS-MSU, Russia)

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 …



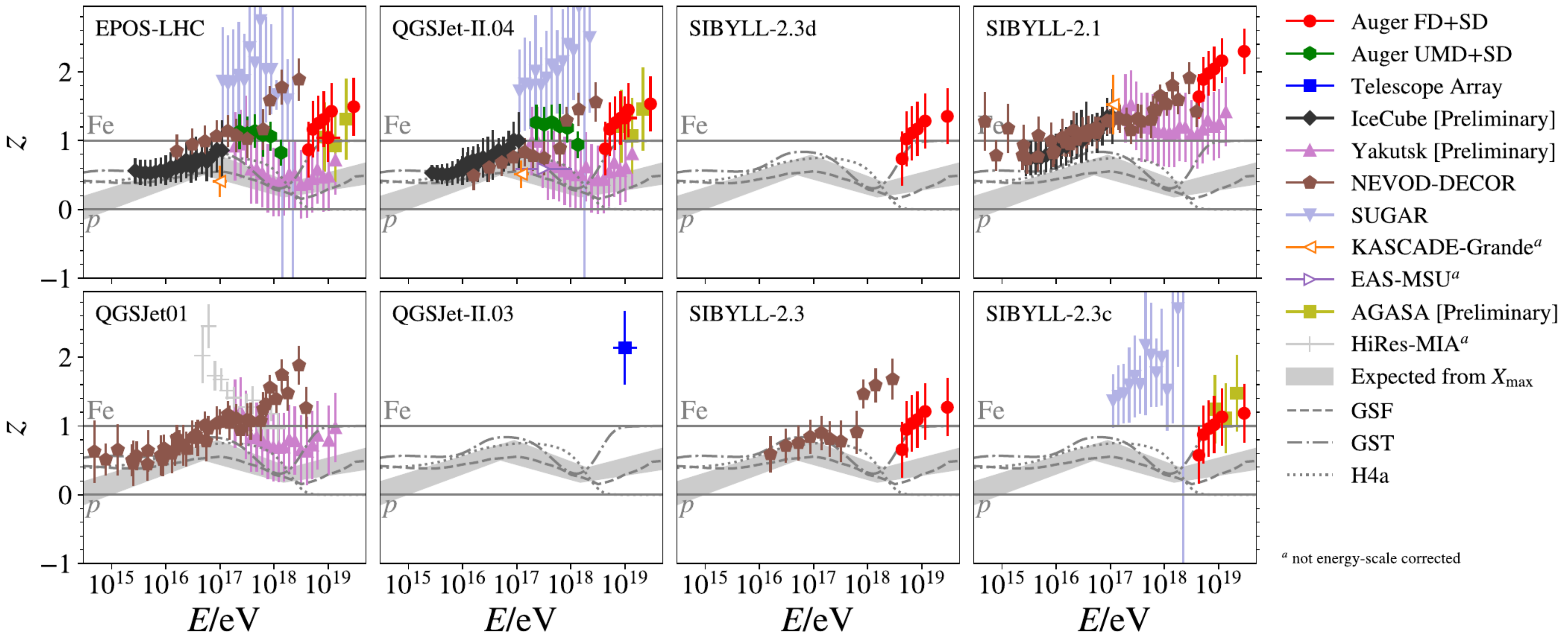
Plots by H. Dembinski

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

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

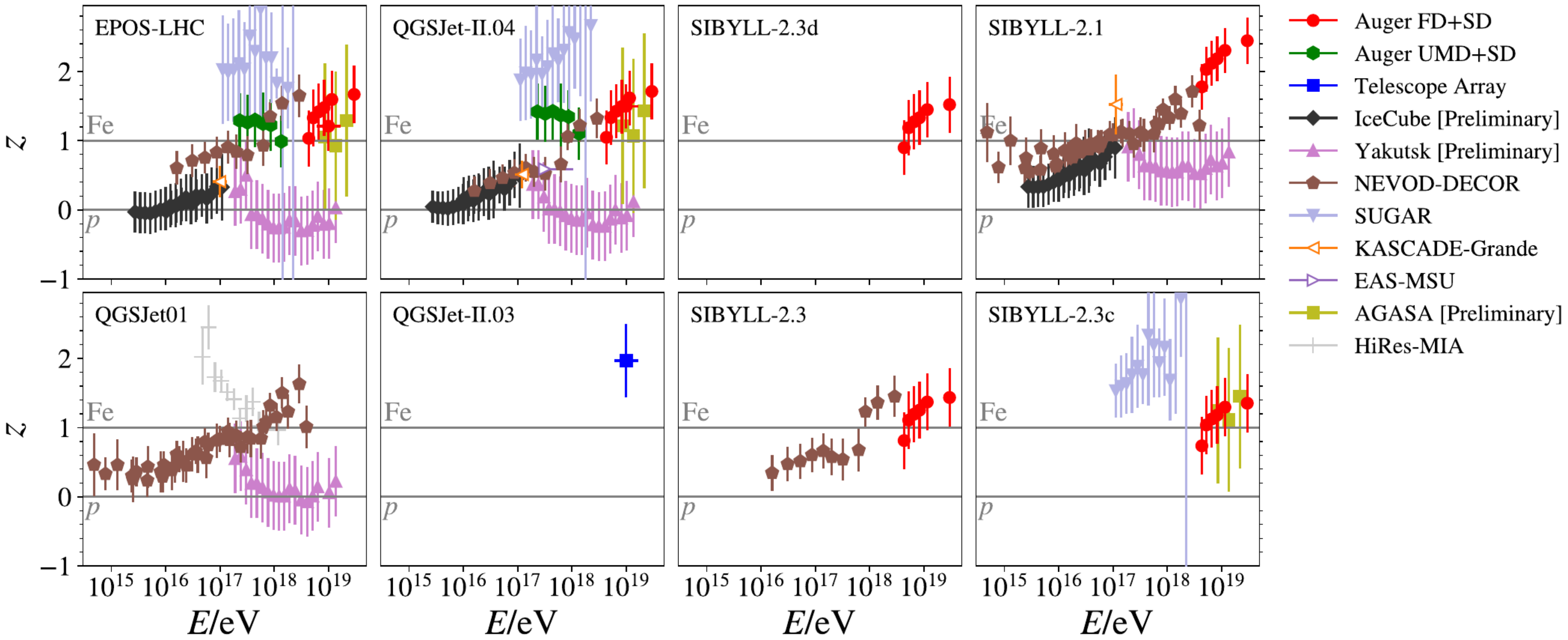
H. Dembinski UHECR 2018 (WHISP working group)

Rescaled Data



H. Dembinski UHECR 2018 (WHISP working group)

Raw Data



H. Dembinski UHECR 2018 (WHISP working group)

Renormalization

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

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

- **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
    - ➔ Based on model and X_{max}

Using an external data based model !

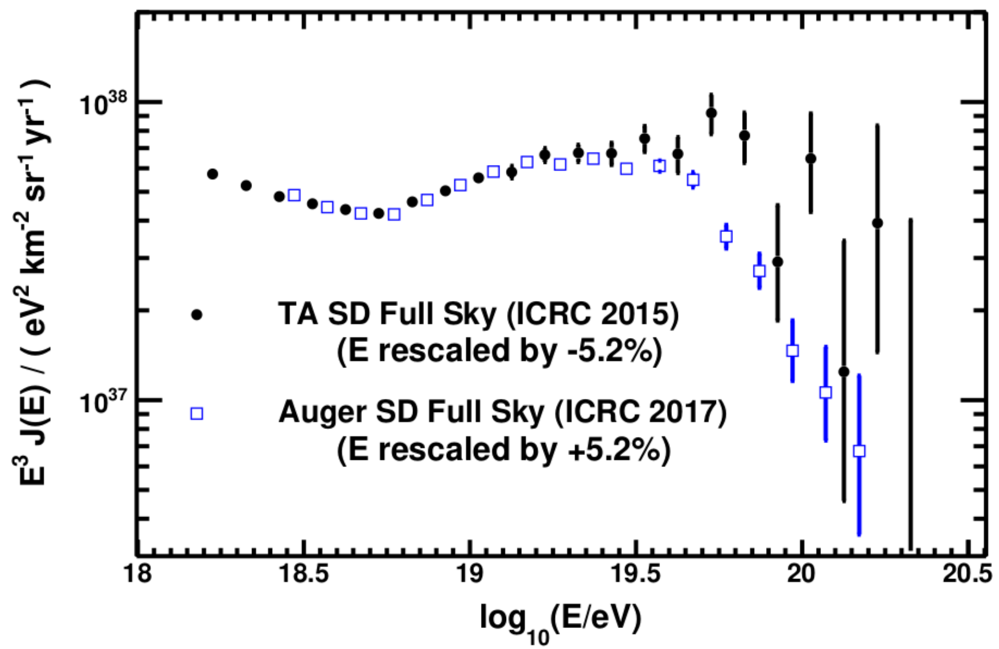
H. Dembinski UHECR 2018 (WHISP working group)

Energy Scale

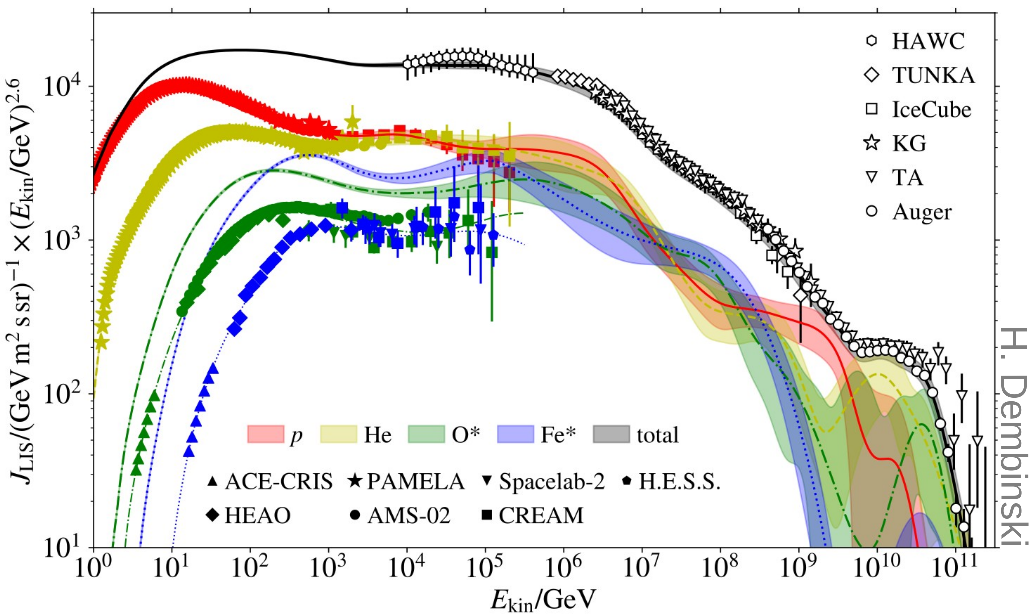
Unique energy scale obtained mixing

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

Experiment	E_{data}/E_{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 UHECR 2018 (WHISP working group)

Possible Particle Physics Explanations

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

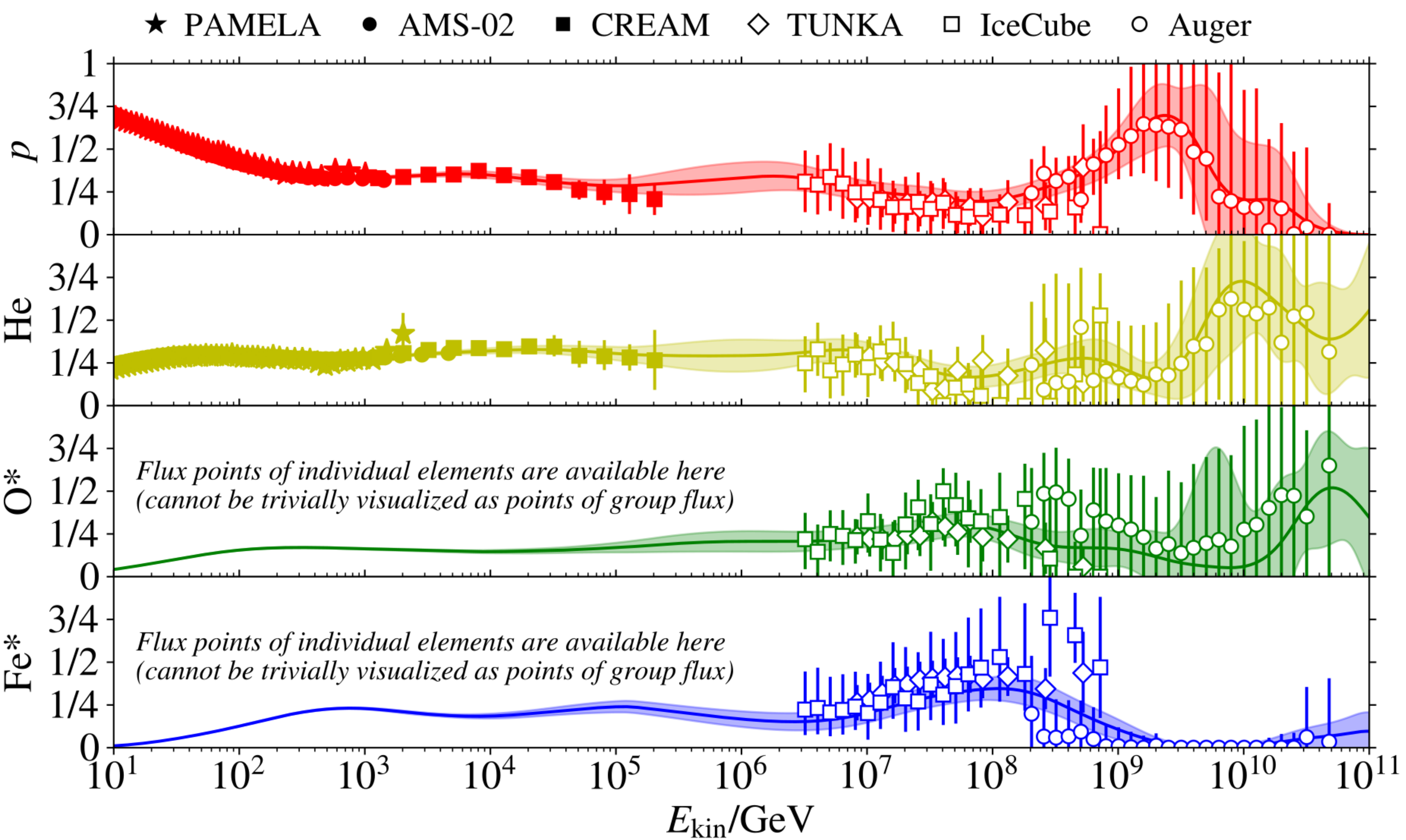
- Possibility to increase N_{mult} limited by X_{max}
- New Physics ?
  - Chiral symmetry restoration (Farrar et al.) ?
  - Strange fireball (Anchordoqui et al.) ?
  - String Fusion (Alvarez-Muniz et al.) ?
    - Problem : no strong effect observed at LHC (~10^{17} eV)
- Unexpected production of Quark 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 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 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 …

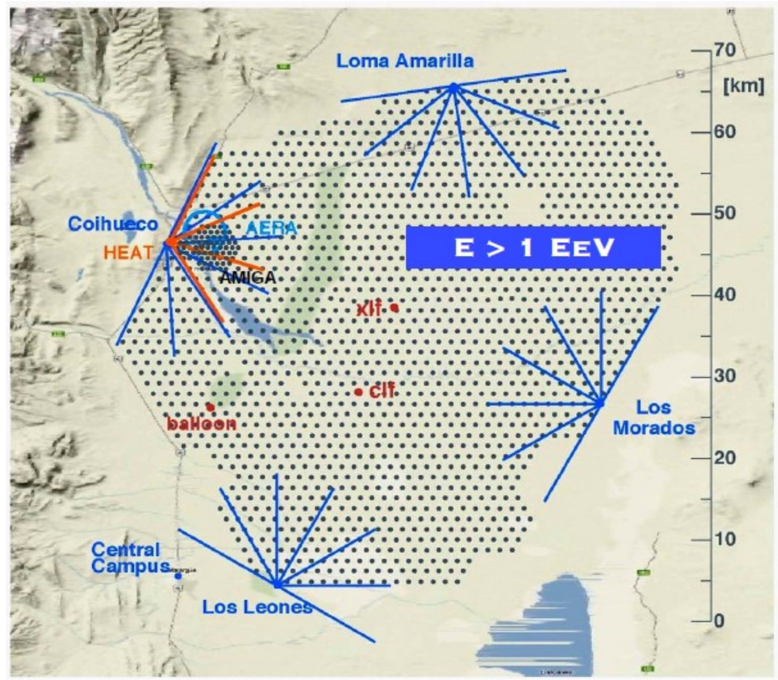
- **Statistical model used for Heavy Ion only in combination with hydrodynamical evolution of the dense system : QGP hadronization**
  - ➜ Account for flow effects, strangeness enhancement, particle correlations...

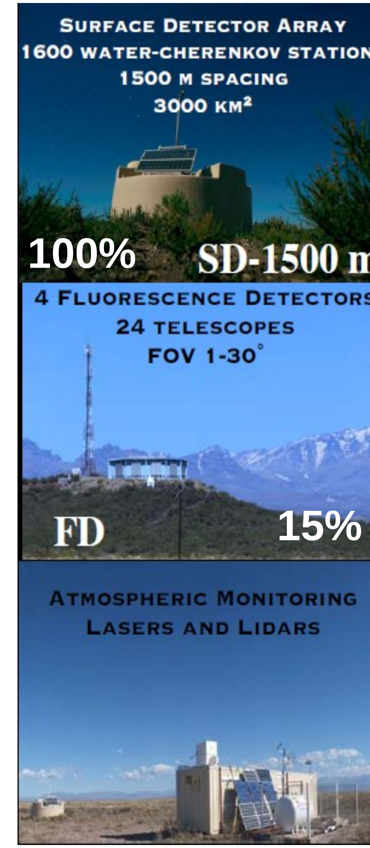
GSF Composition Details



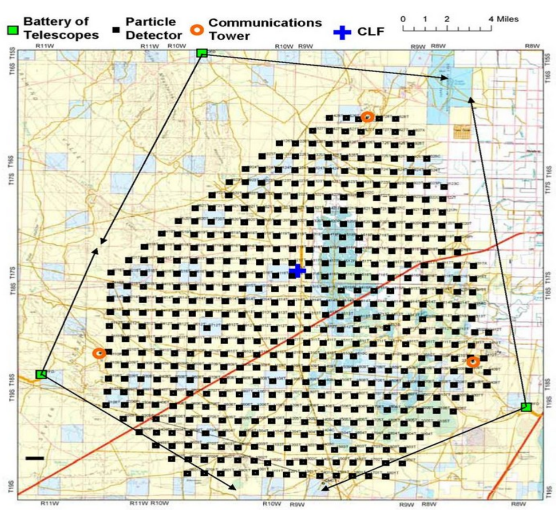
PAO/TA

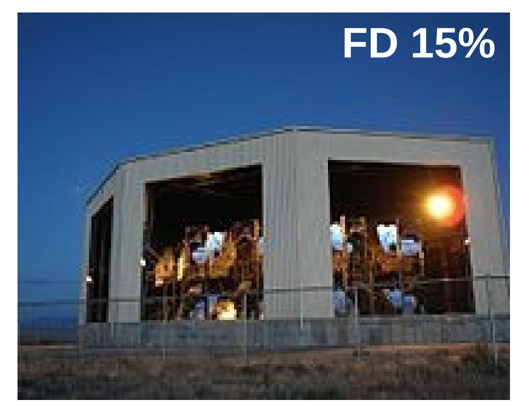
- **Pierre Auger Observatory (PAO)**
  - Mendoza, Argentina
  - Southern Hemisphere
  - 3000 km^2: 32000 km^2/sr/yr





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

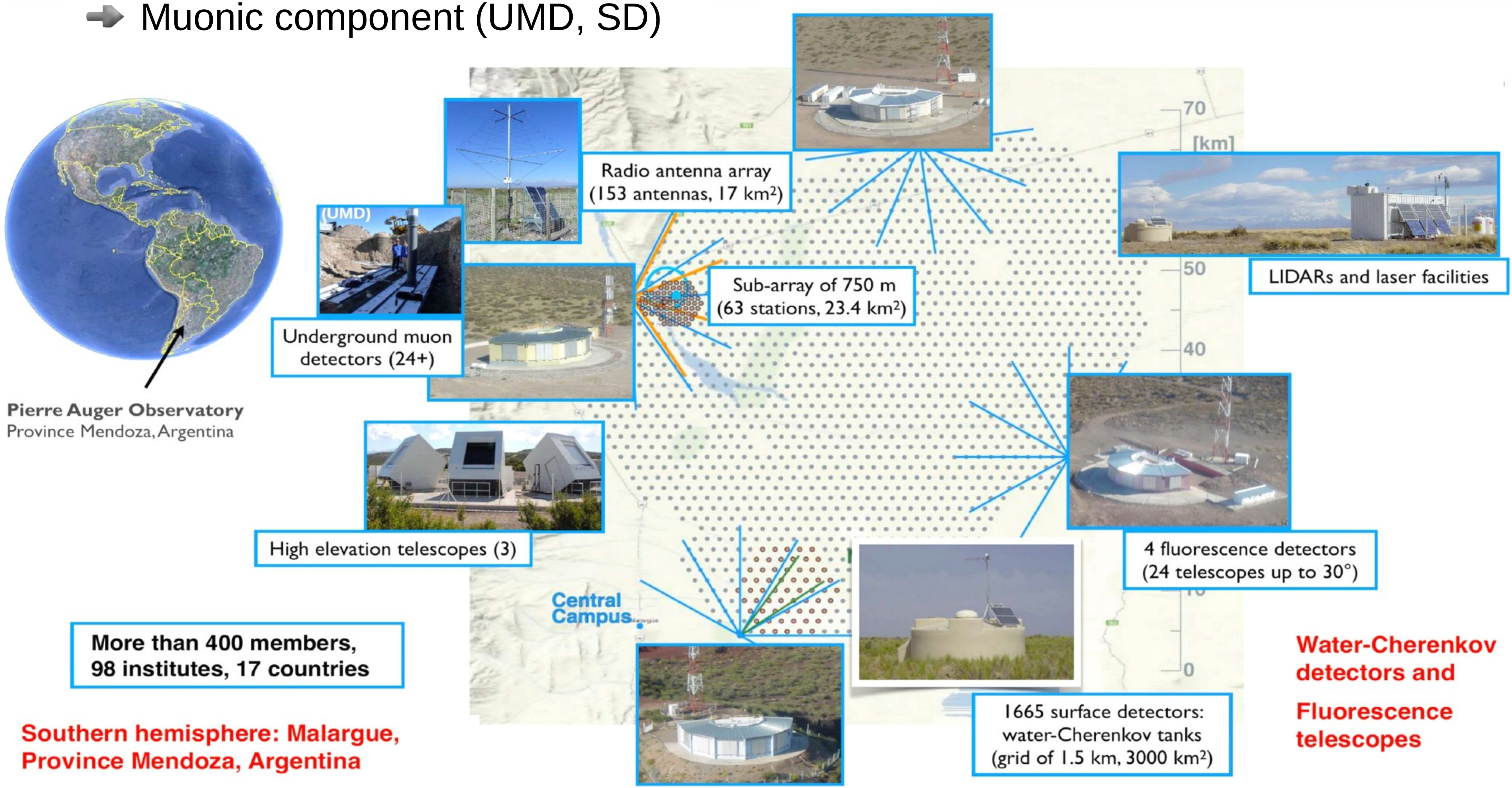




The Pierre Auger Observatory

Multicomponent (hybrid) detector

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



More than 400 members, 98 institutes, 17 countries

Southern hemisphere: Malargue, Province Mendoza, Argentina

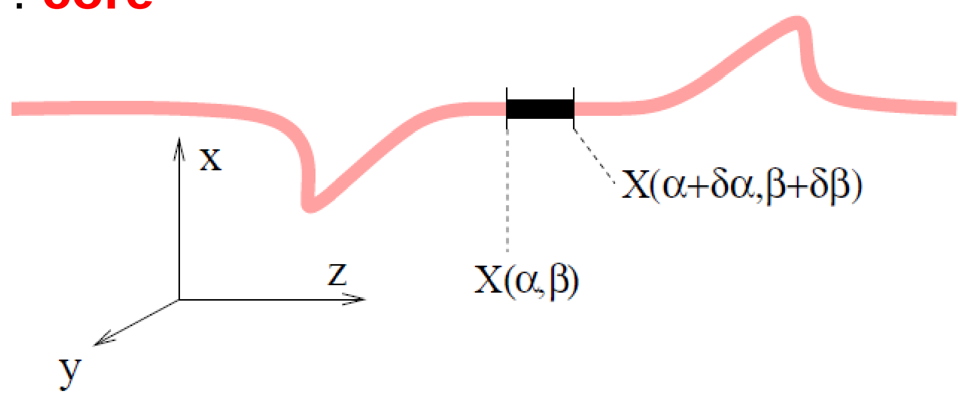
Water-Cherenkov detectors and

Fluorescence telescopes

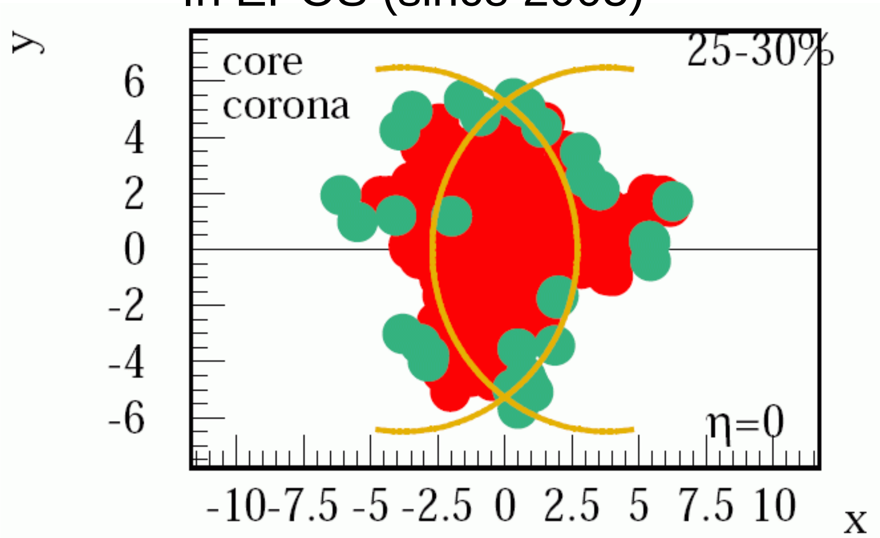
A 3rd way : the core-corona approach

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)

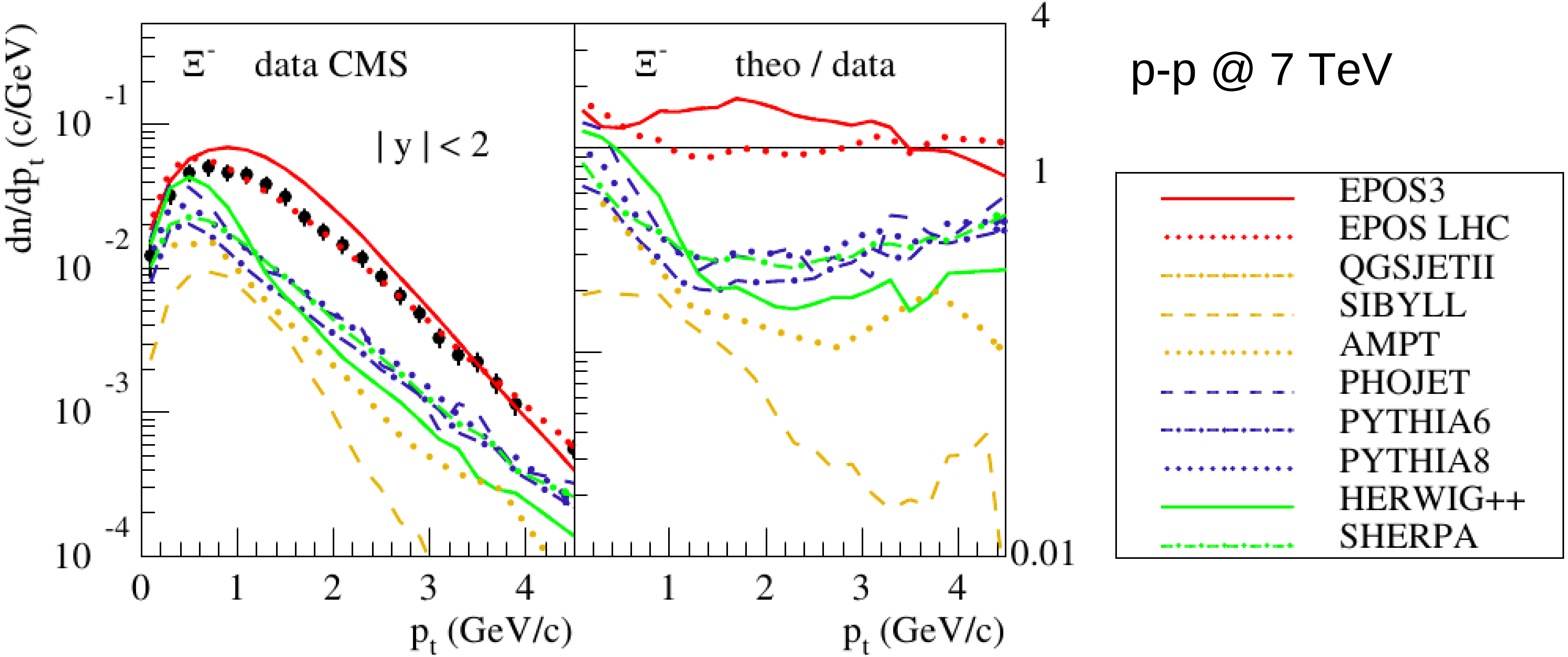


- Each string cut into a sequence of string segments, corresponding to widths δα and δβ in the string parameter space
- If energy density from segments high enough
  - segments fused into core
    - flow from hydro-evolution
    - statistical hadronization
- If low density (corona)
  - segments remain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

Core in p-p (early LHC data)

Detailed description can be achieved with core in pp

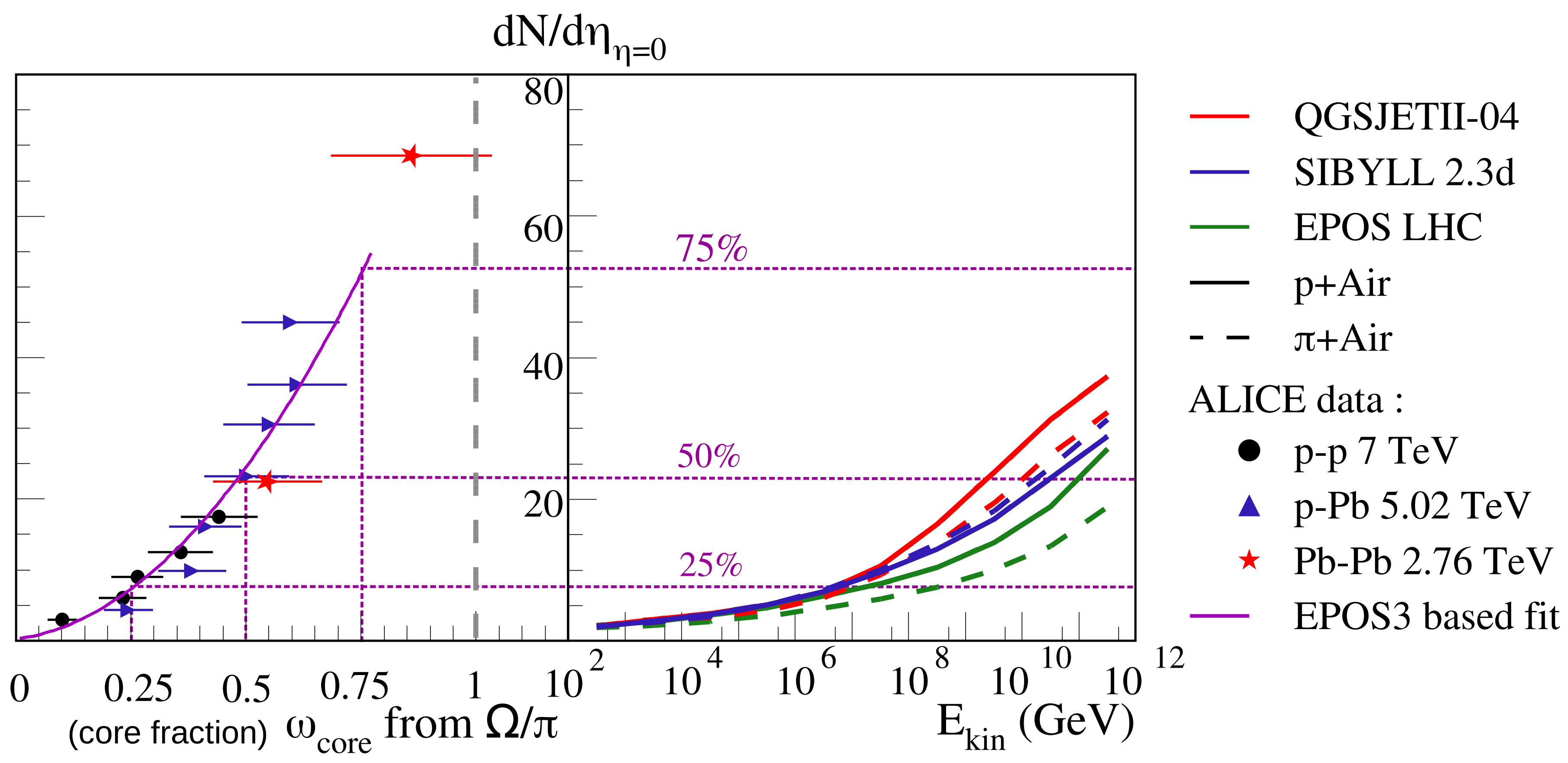
- identified spectra: different strangeness between string (low) and stat. decay (high)
- p_t behavior driven by collective effects (statistical hadronization + flow)
  - larger effect for multi-strange baryons (yield AND $<p_t>$)



Particle Densities in Air Showers

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

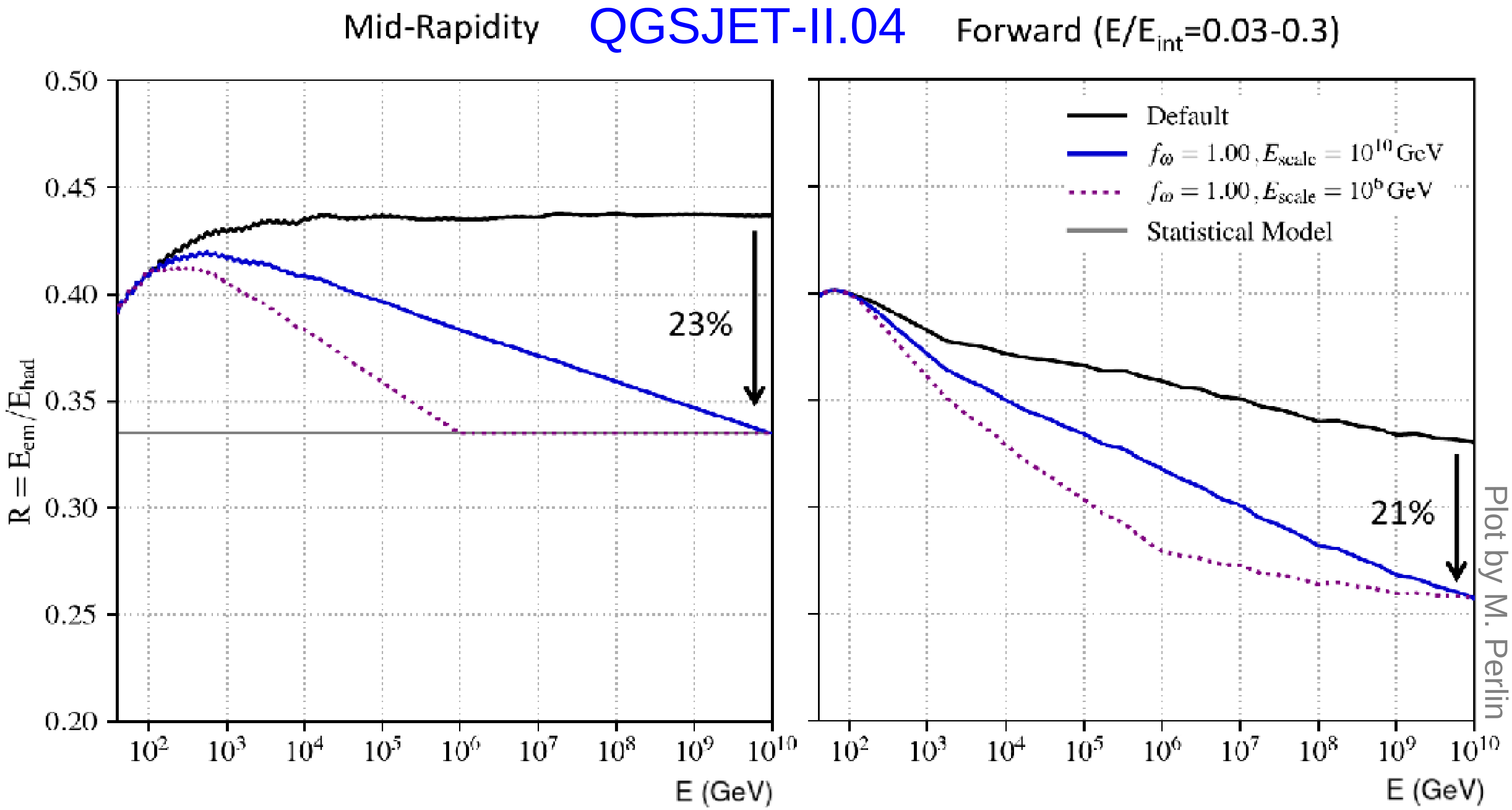
- Core formation start quite early according to ALICE data
- Cosmic ray primary interaction likely to have 50% core at mid-rapidity !



Evolution of hadronization from core to corona

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

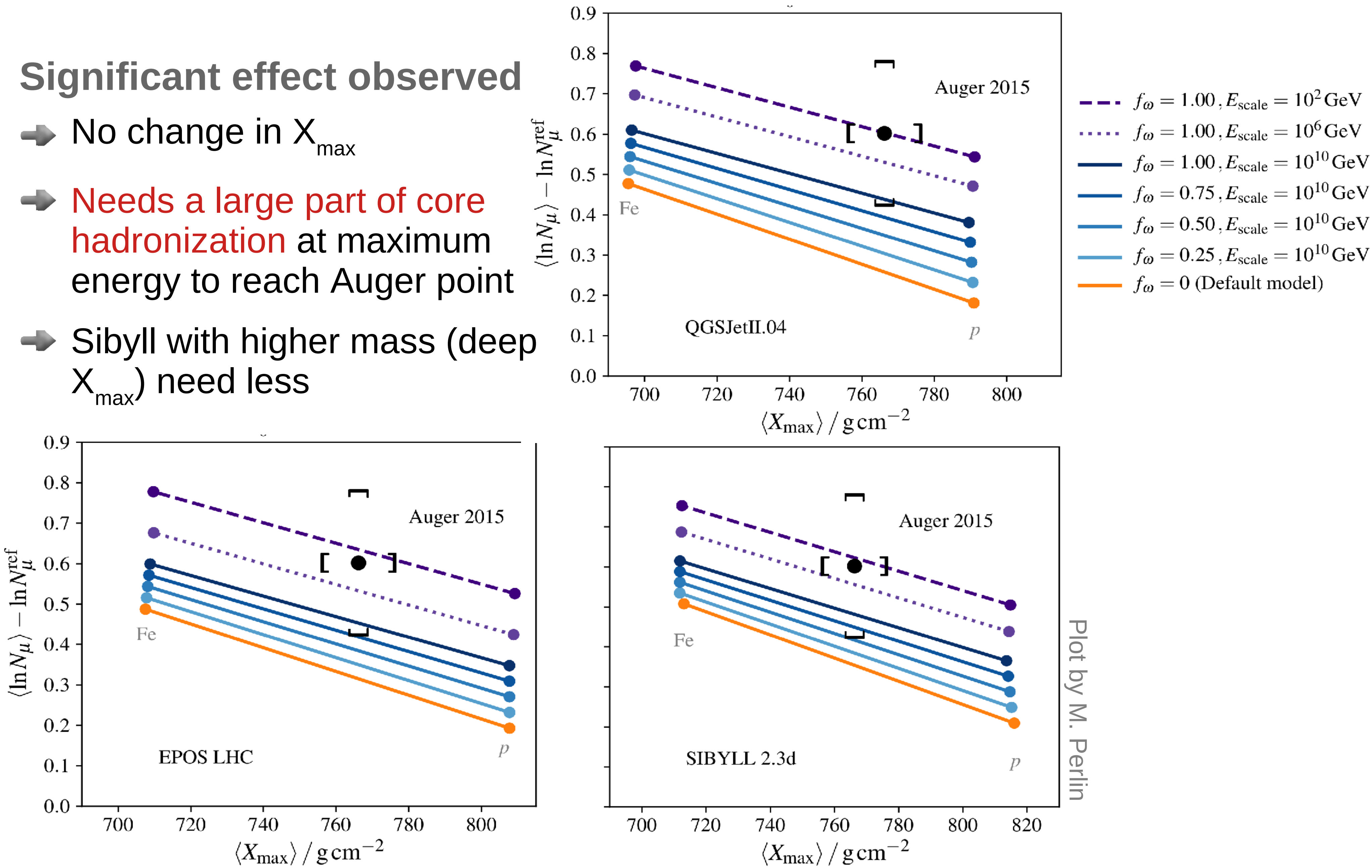
➡ Change of ω_{core} with energy change $\alpha = \frac{N_{\pi^0}}{N_{mult}}$ or $R(\eta) = \frac{\langle dE_{em}/d\eta \rangle}{\langle dE_{had}/d\eta \rangle}$ which define the muon production in air showers.



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



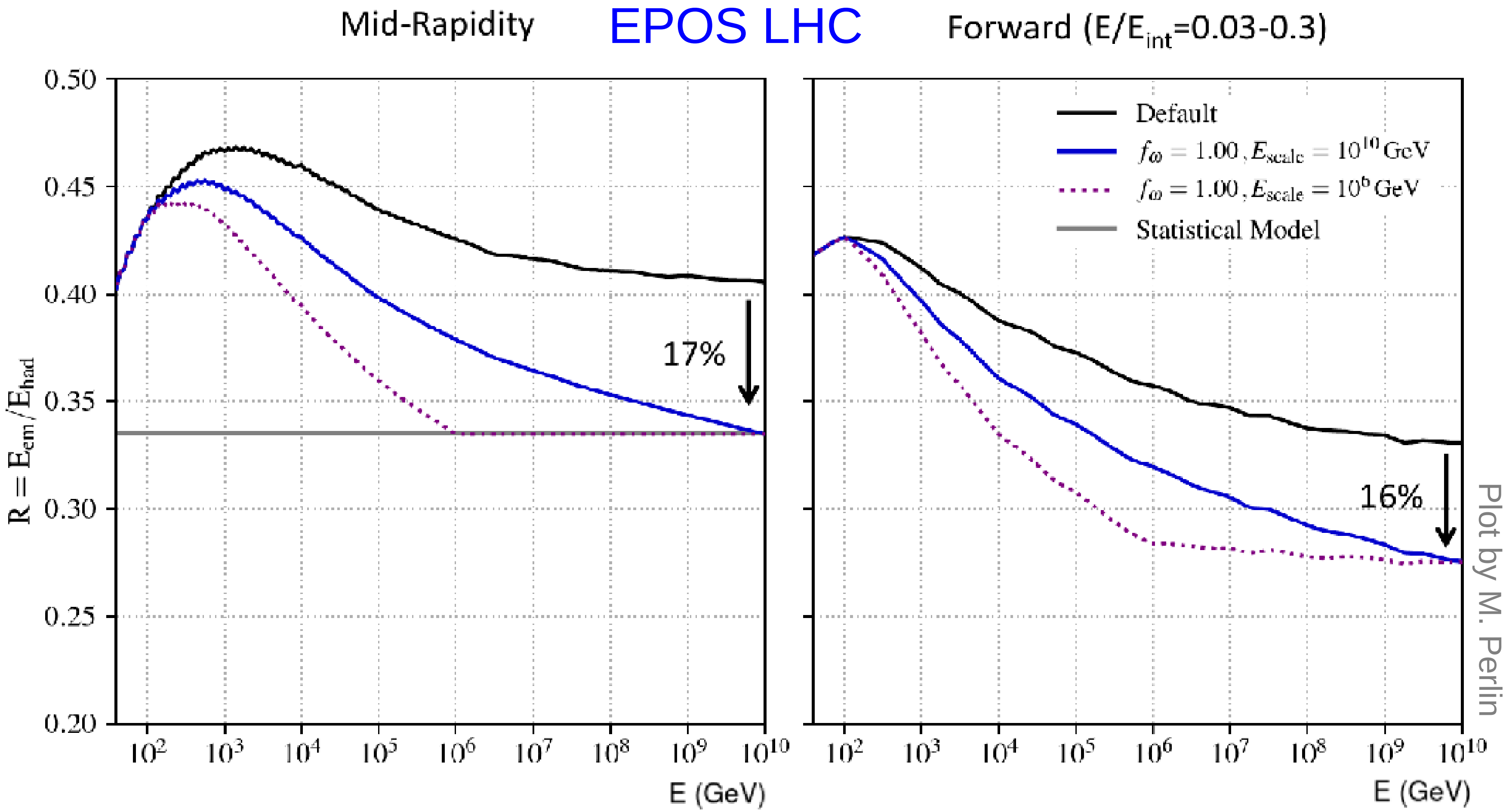
Plot by M. Perlin

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 $R(\eta) = \frac{\langle dE_{em}/d\eta \rangle}{\langle dE_{had}/d\eta \rangle}$

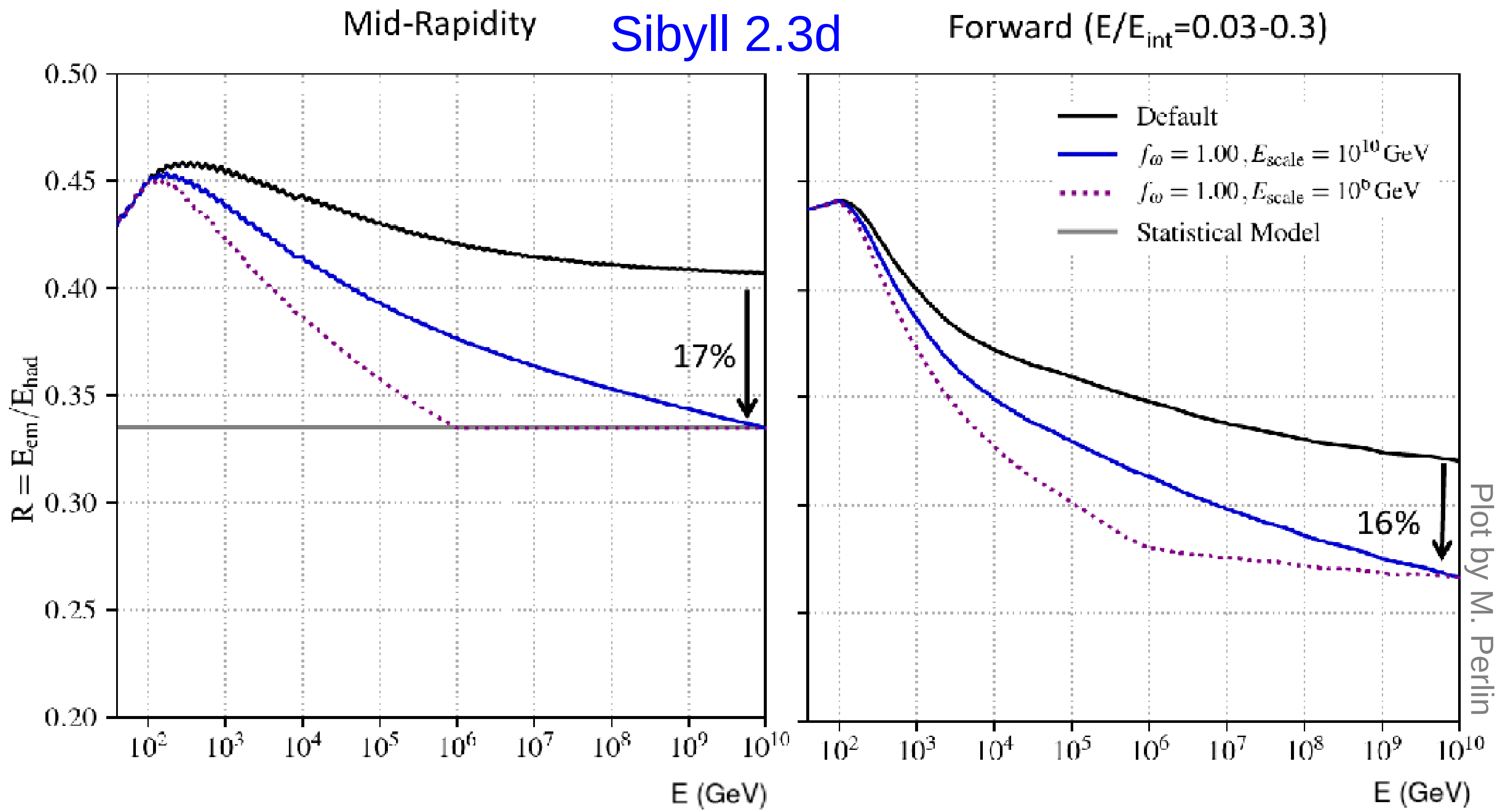
  which define the muon production in air showers.



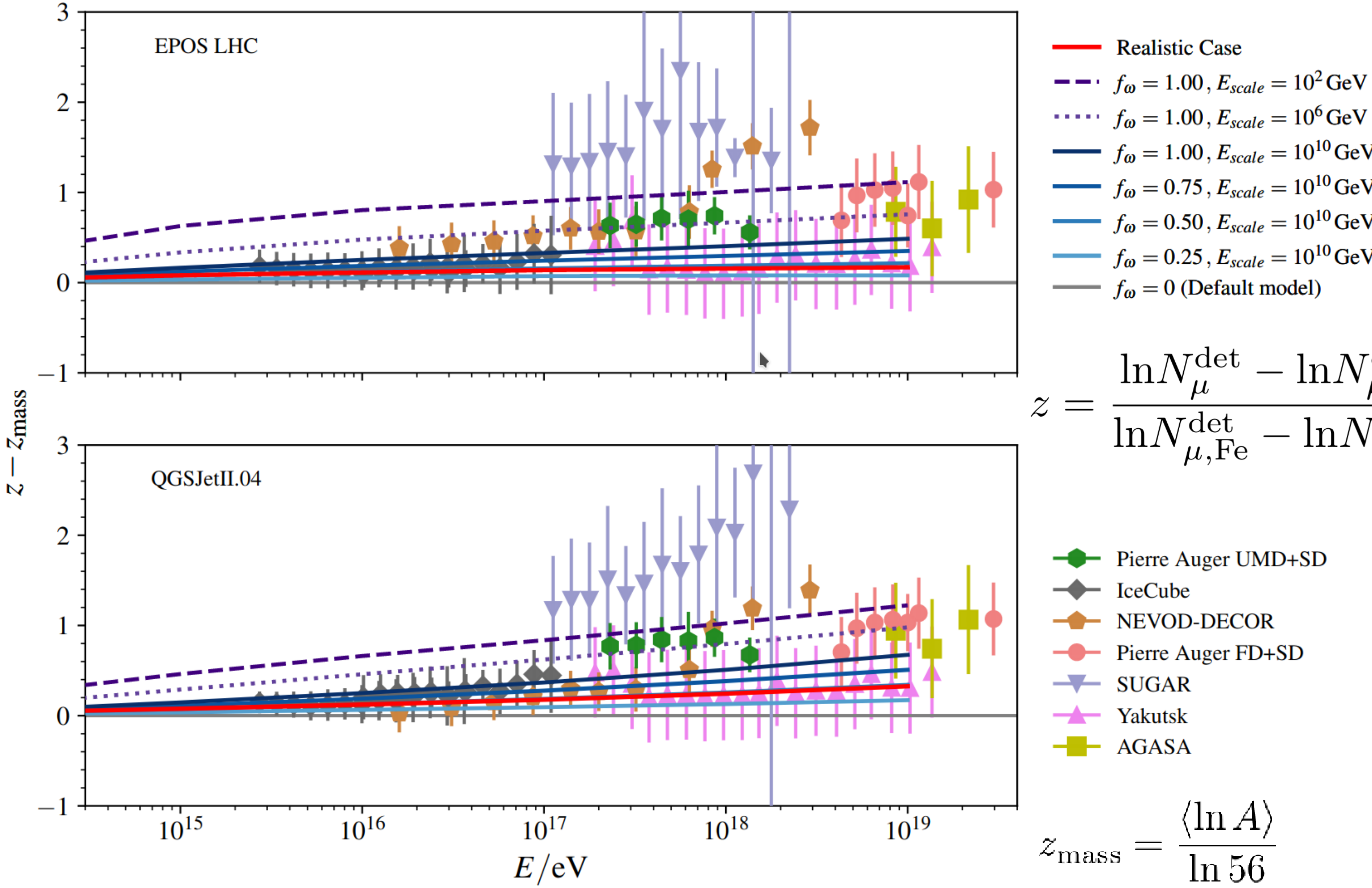
Evolution of hadronization from core to corona

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 z-scale

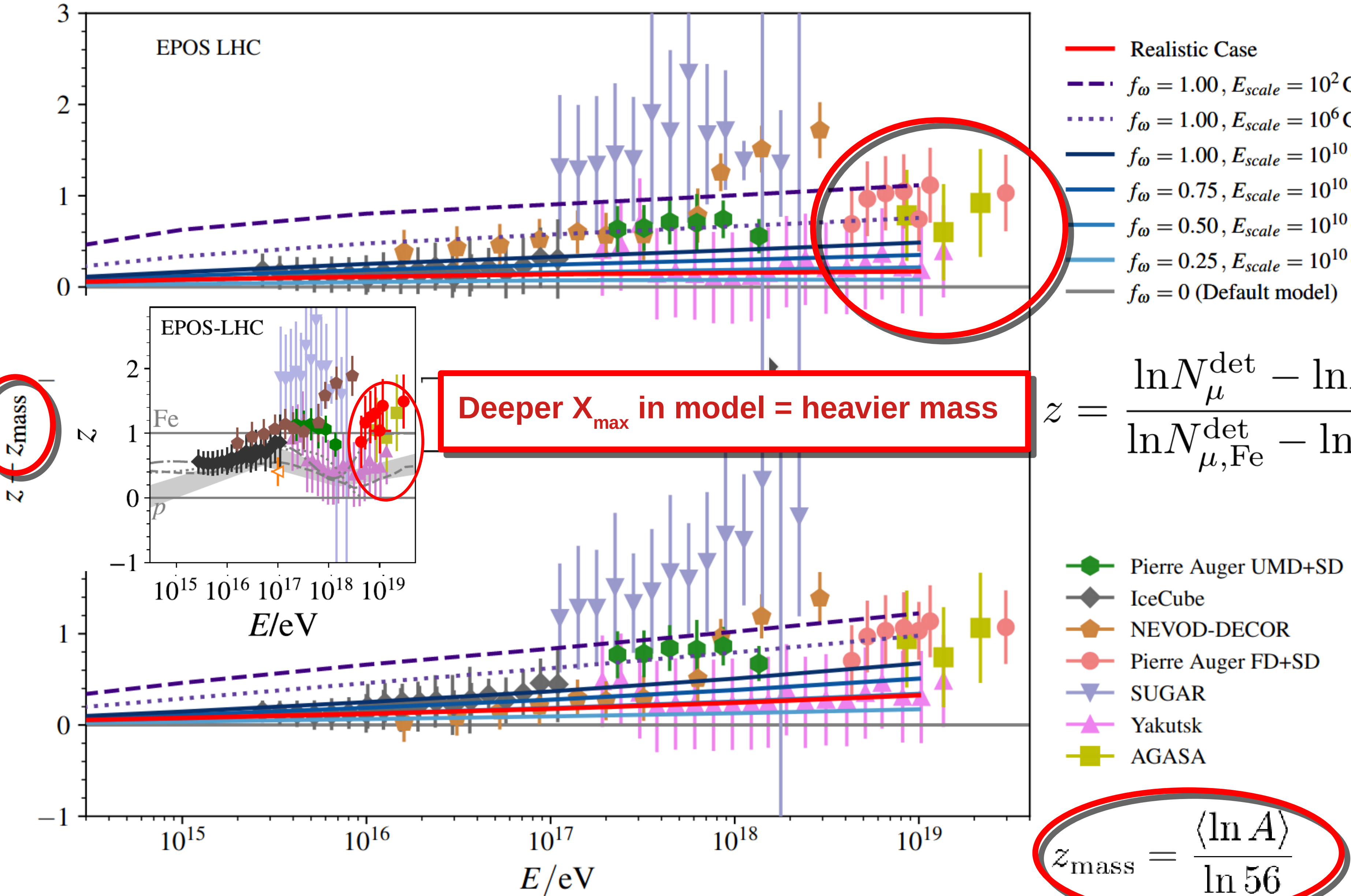


$$z = \frac{\ln N_{\mu}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}{\ln N_{\mu,\mathrm{Fe}}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}$$

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

Plot by M. Perlin

Results for z-scale



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

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

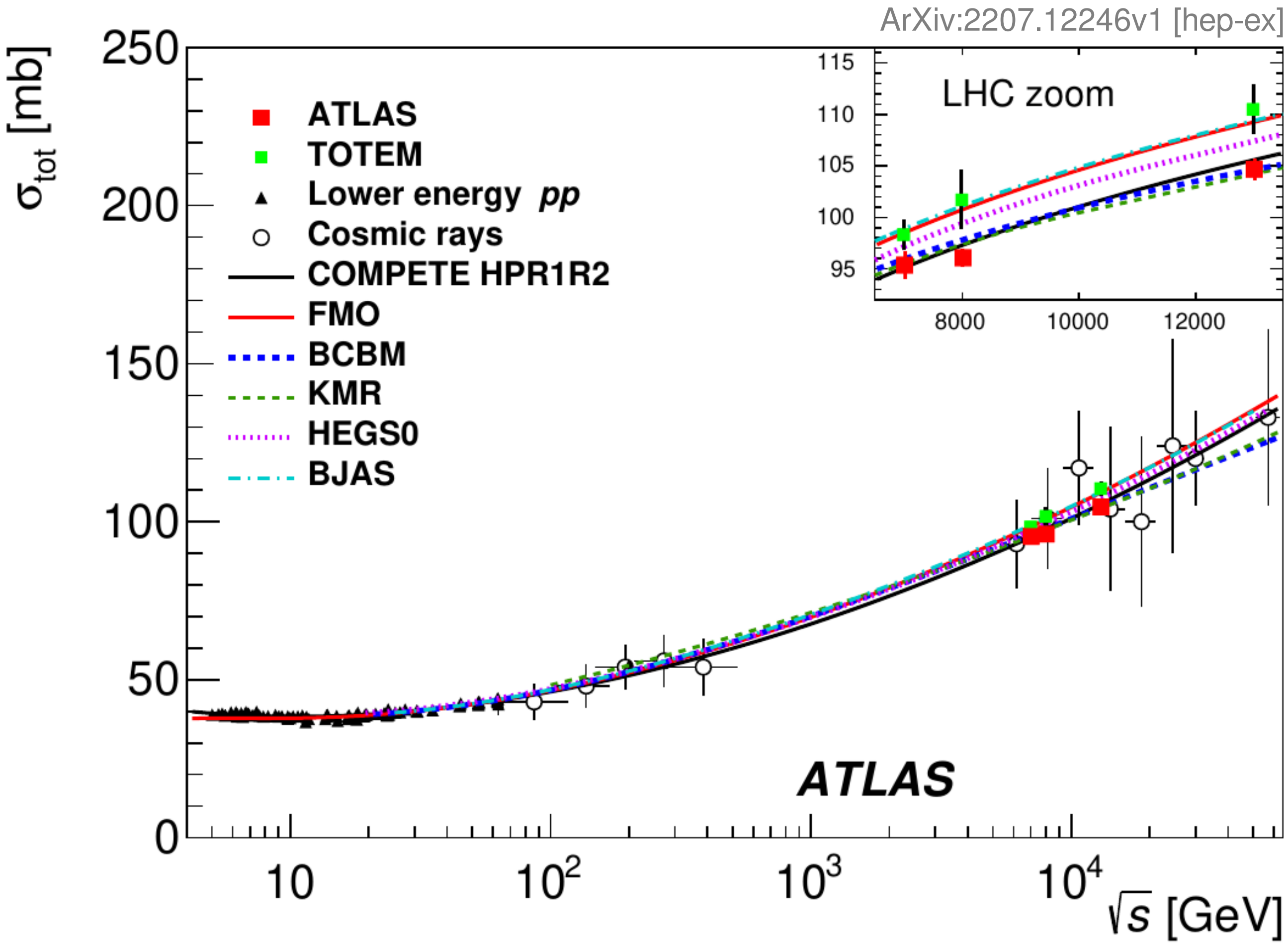
Plot by M. Perlin

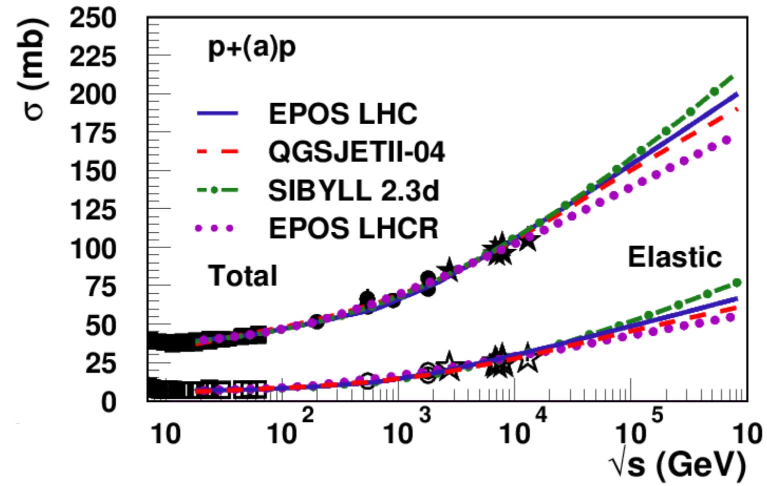
Inelastic Cross-Section

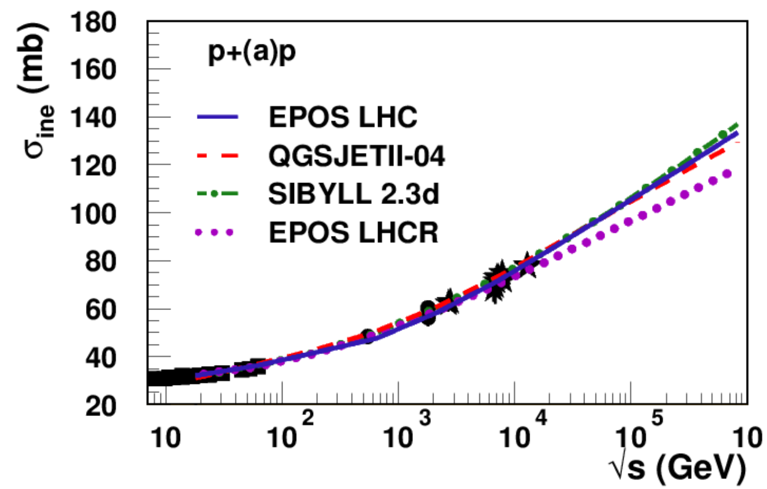
- **Probability for the particle to interact : directly related to X_{max}**
- **After TOTEM (CMS), new measurements by ALFA (ATLAS) with higher precision**

➔ p-p cross-section too high in all models

ArXiv:2207.12246v1 [hep-ex]

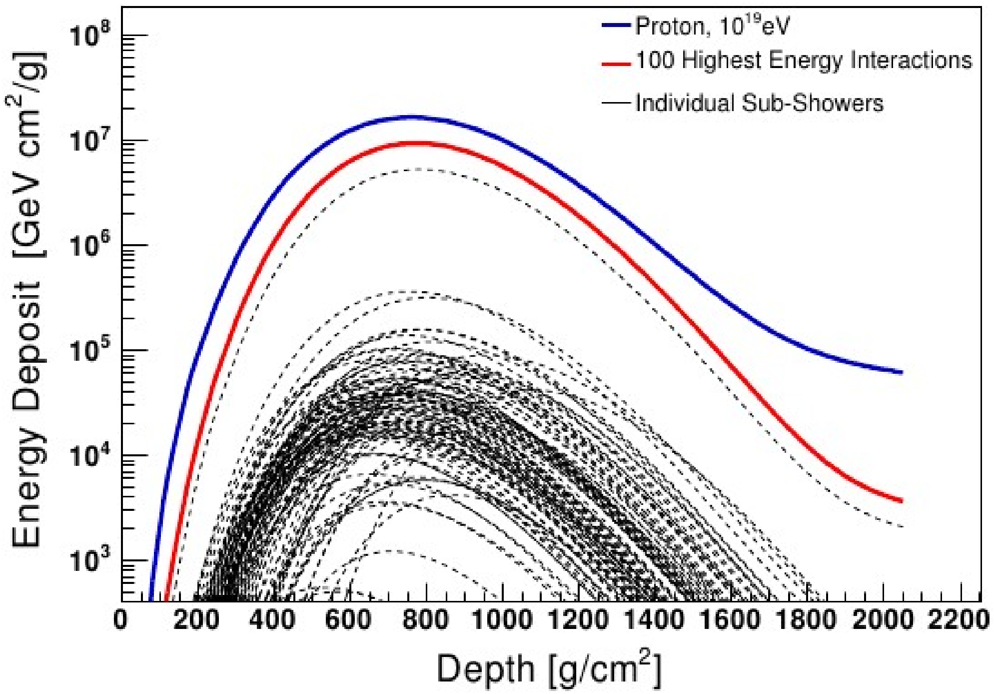


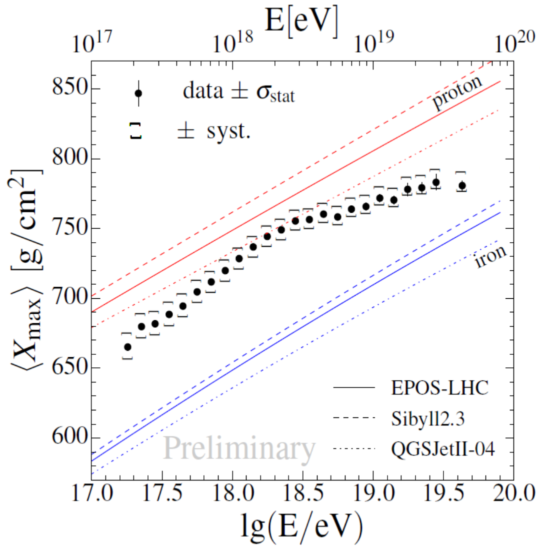


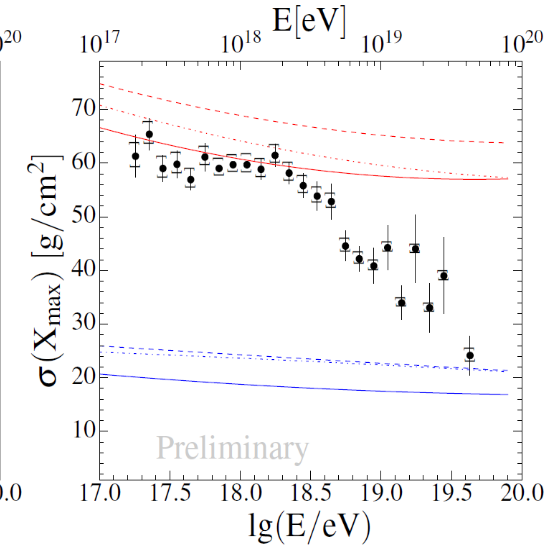


Fluorescence Detector (FD)

From R. Ulrich (KIT)

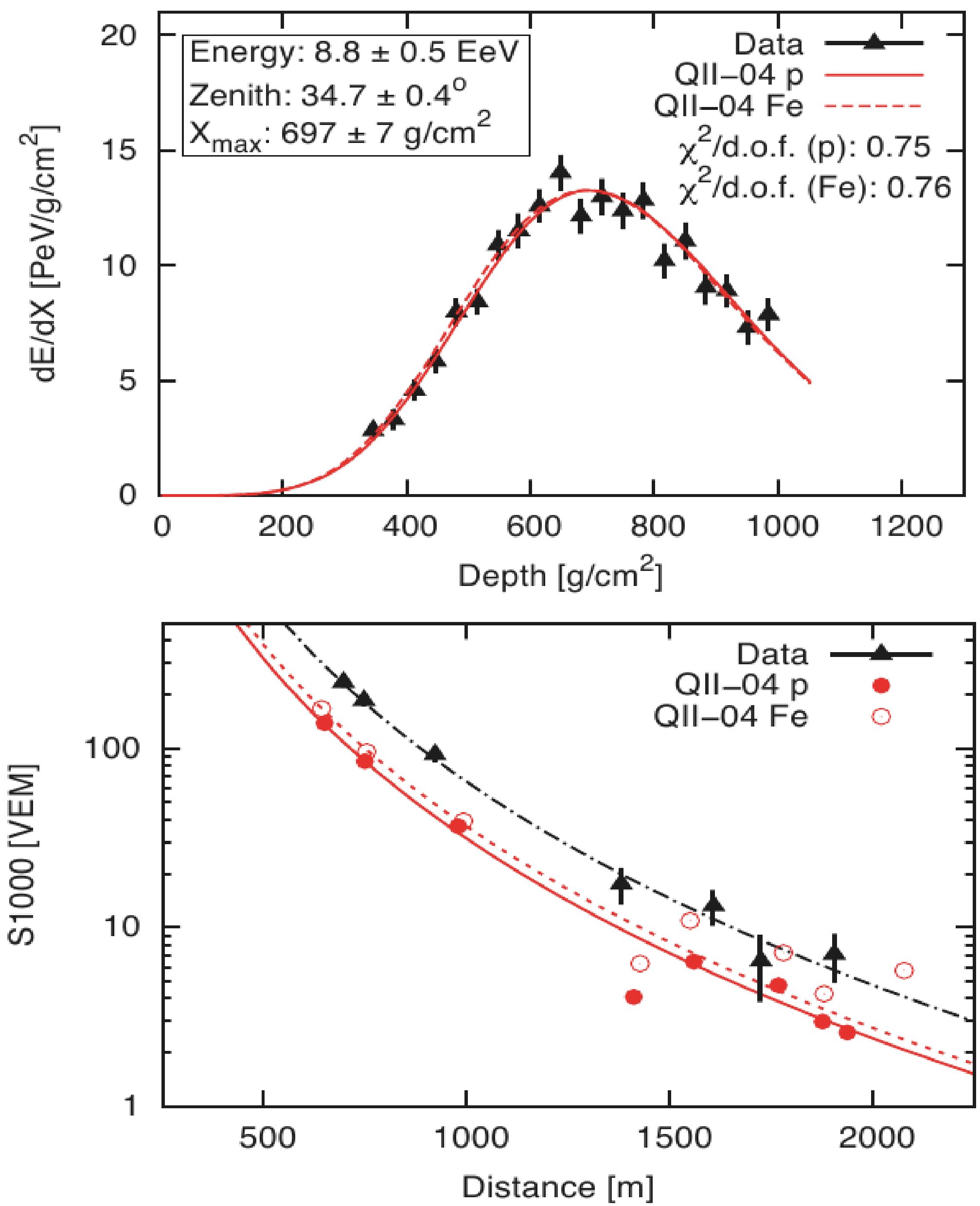






- **Most direct measurement**
  - dominated by first interaction
- **Reference mass for other analysis**
  - <lnA> from <X_{max}> and RMS
- **Possibility to use the tail of X_{max} distribution to measure p-Air inelastic cross-section.**
  - require no contamination from photon induced showers (independent 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_μ),
  - rescale both component separately (R_E and R_μ to reproduce SD signal for each showers,

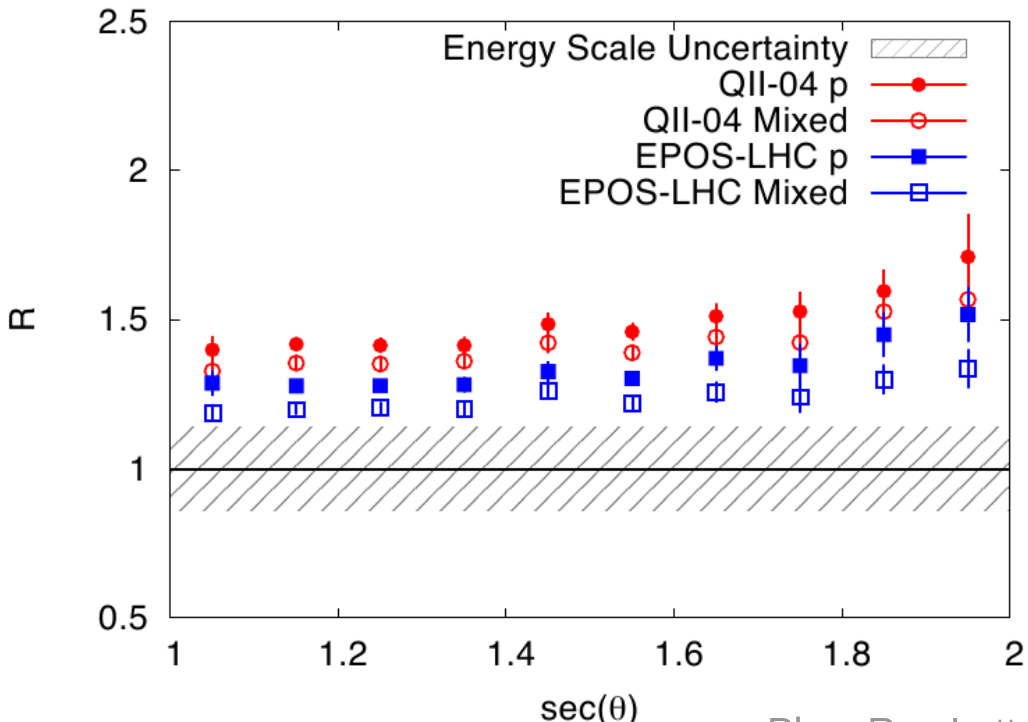
$$S_{\rm resc}(R_E, R_\mu)_{i,j} \equiv R_E\, S_{EM,i,j} + R_E^\alpha R_\mu\, S_{\mu,i,j}$$

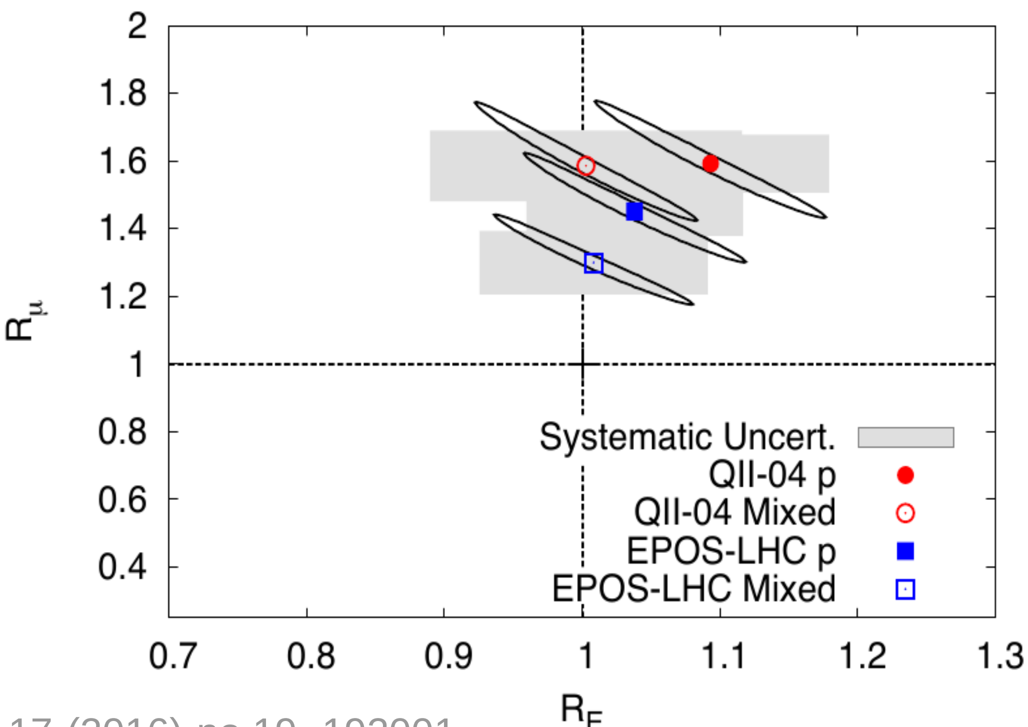
  - for mixed composition, give weight according to X_{max} distribution.

Muon Rescaling

- **Simulations don't reproduce FD and SD signal consistently**
  - $R = S_{1000}^{observed} / S_{1000}^{predicted}$ 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.

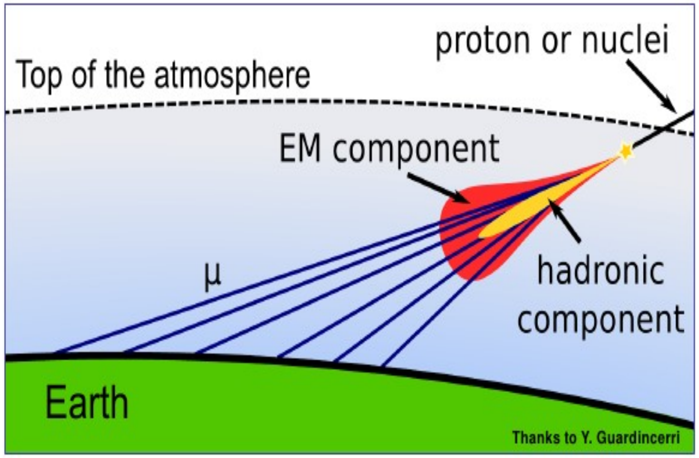




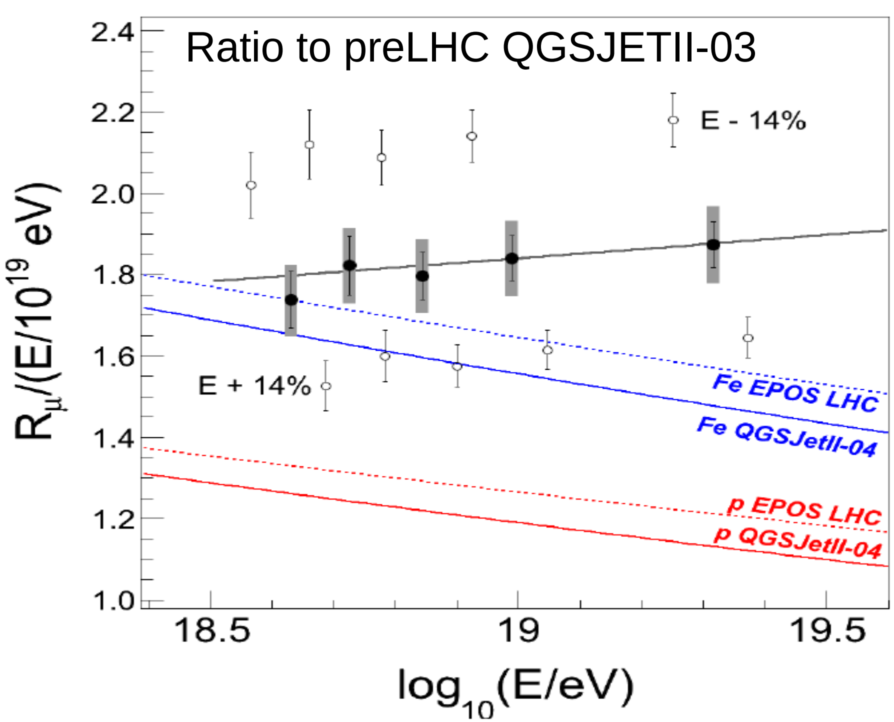
Phys.Rev.Lett. 117 (2016) no.19, 192001

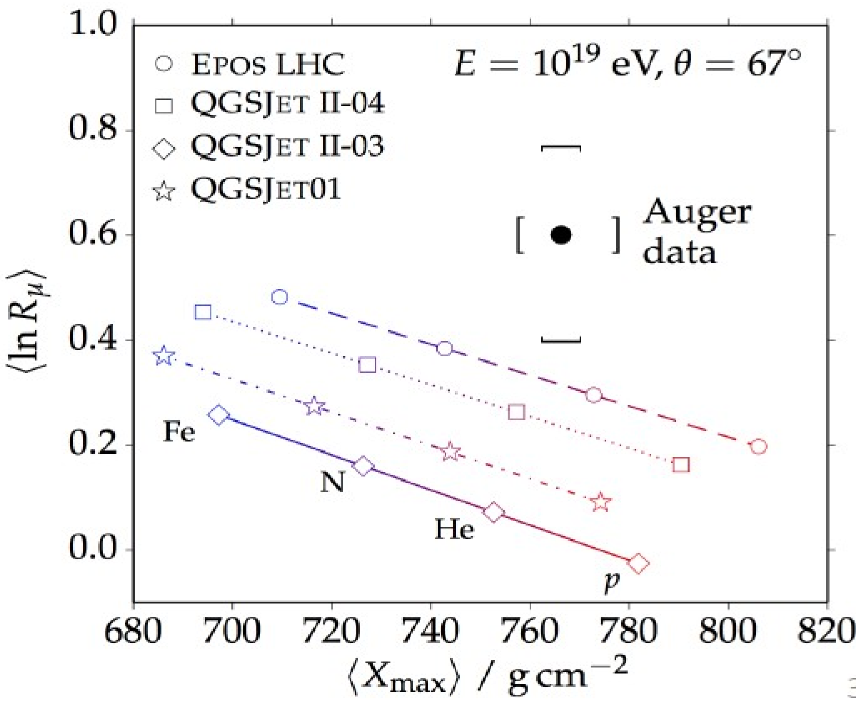
Direct Muon Measurement

- **Old showers contain only muon component**
  - direct muon counting with very inclined showers (>60°) 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%)



R_μ/E_{FD} in energy bins





Muon Production Depth

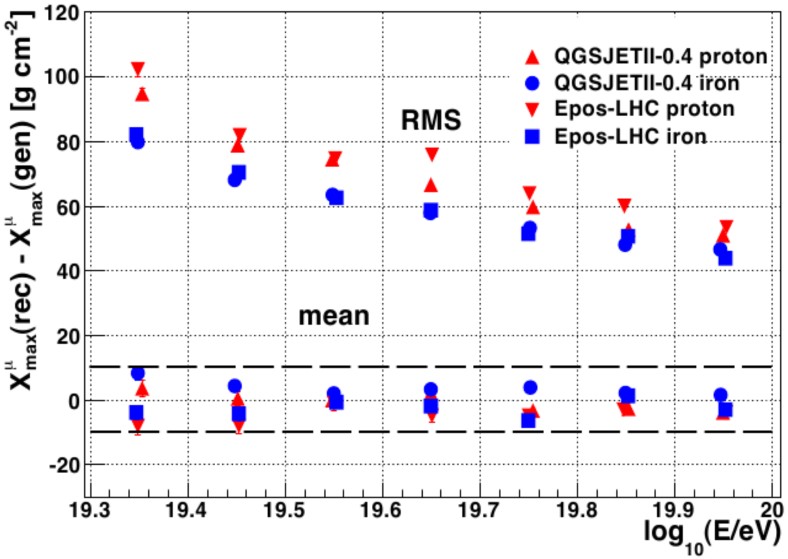
- **Independent SD mass composition measurement**
  - geometric delay of arriving muons

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

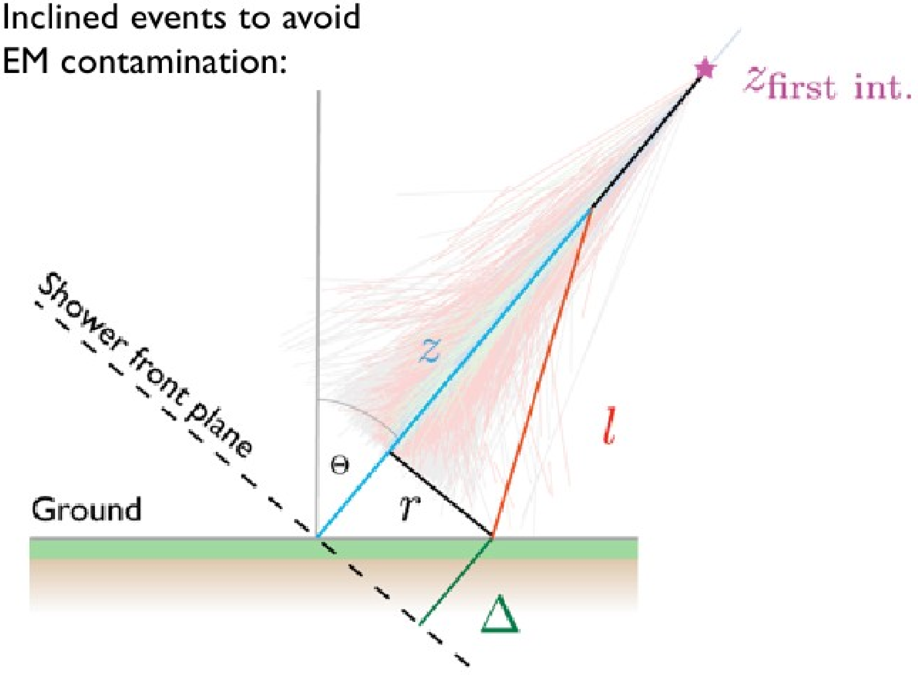
  - mapped to muon production distance

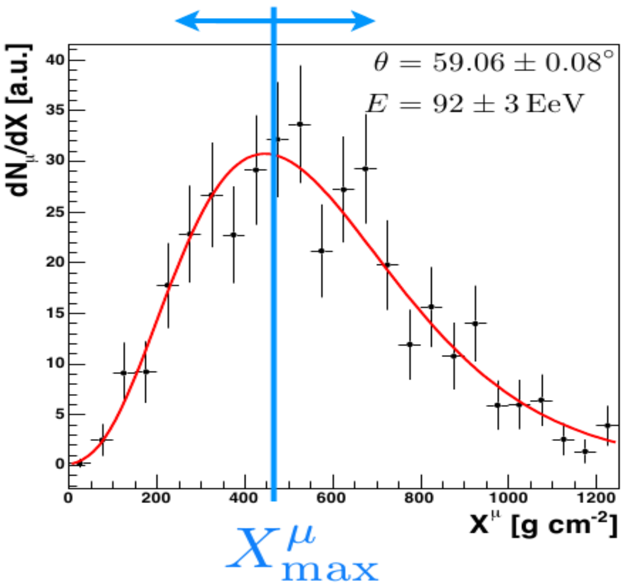
$$z = \frac{1}{2}\left(\frac{r^2}{ct_g} - ct_g\right) + \Delta$$

  - decent resolution and no bias



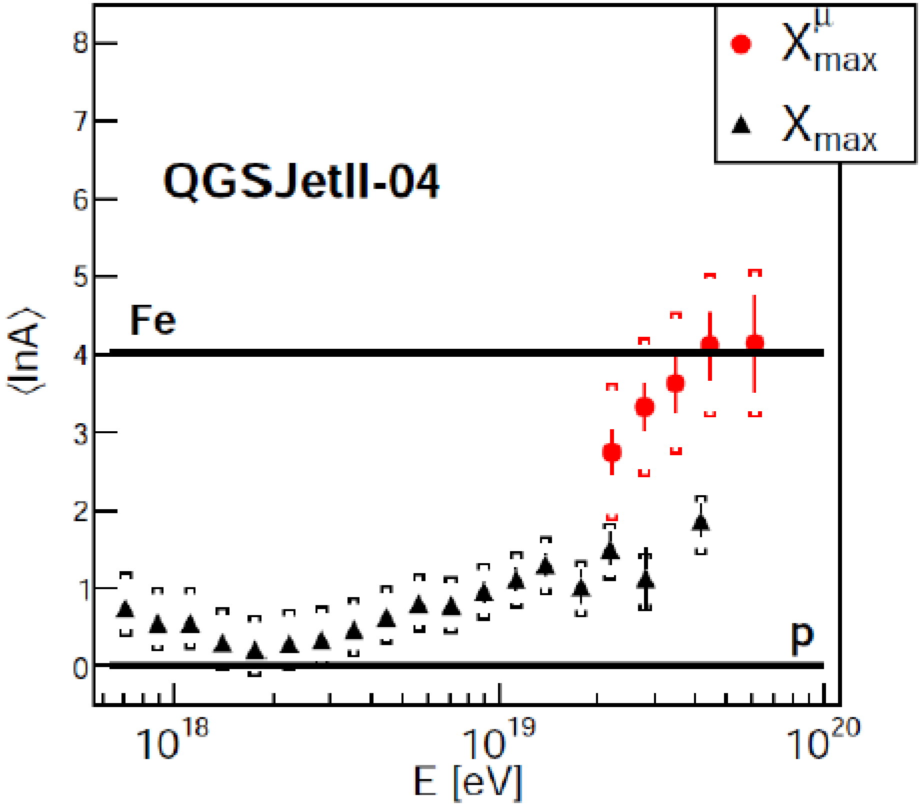
Inclined events to avoid EM contamination:

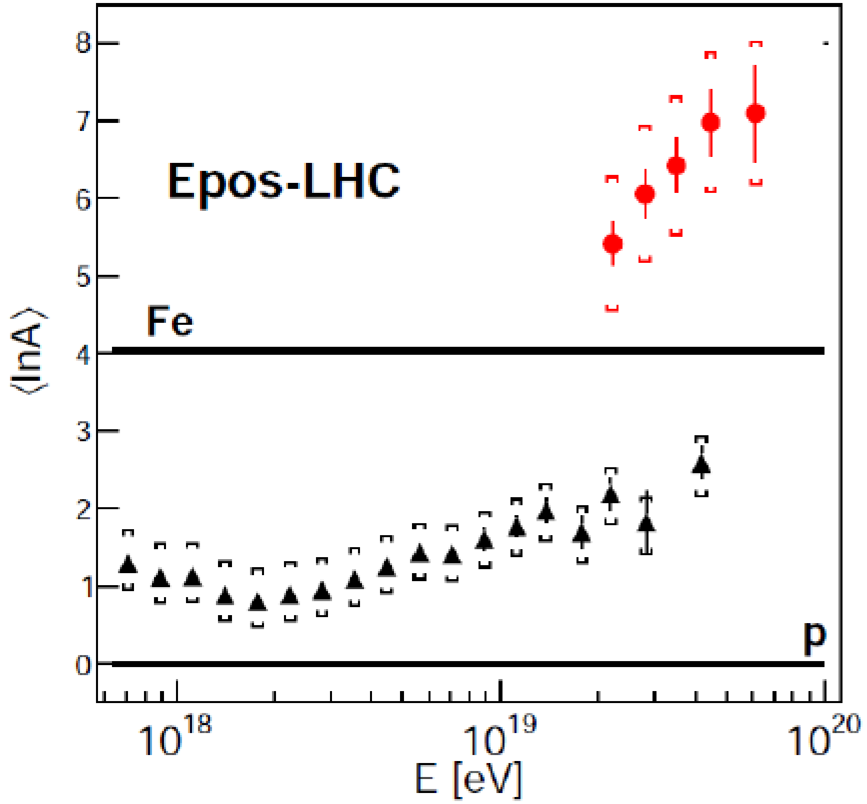




MPD and Models

- **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.



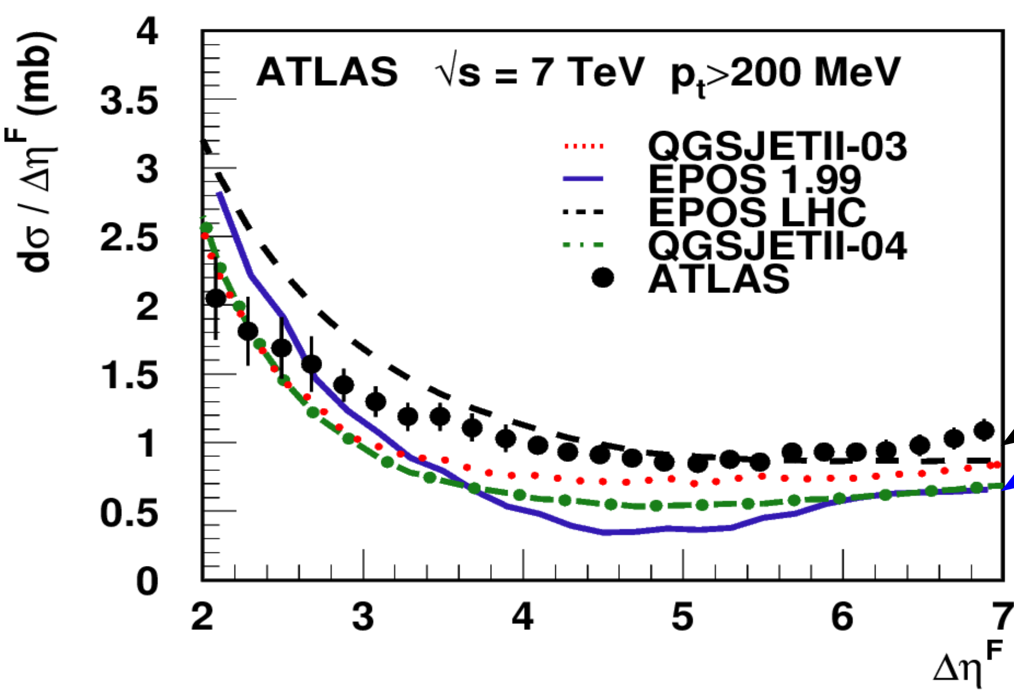


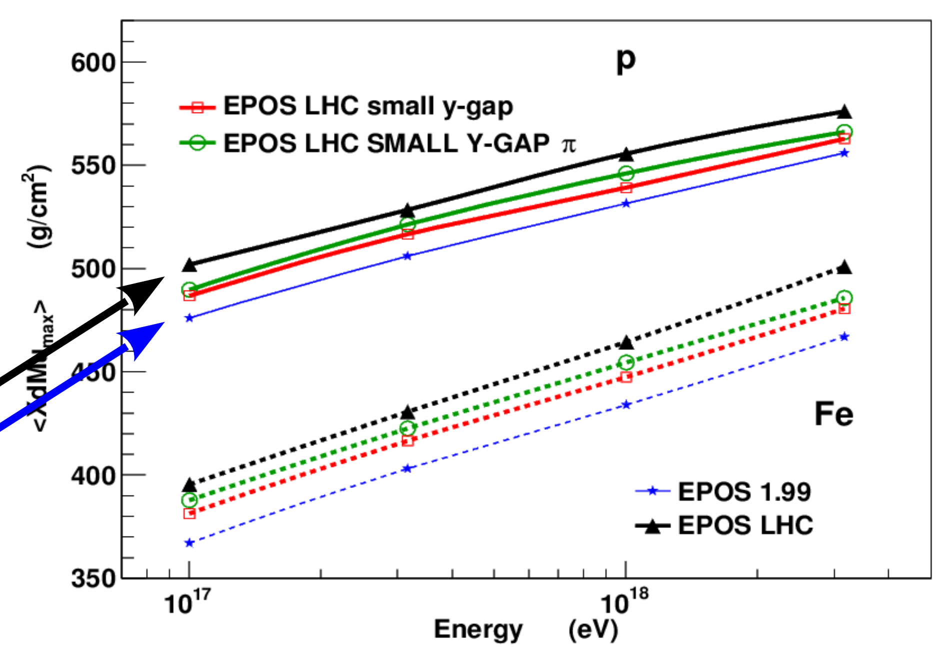
MPD and Diffraction

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

- weak influence on EM X_{max} since only 1st interaction really matters
- cumulative effect for X^{μ}_{max} 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^{μ}_{max} and increase muon number !

different diffractive mass distribution for mesons and baryons !





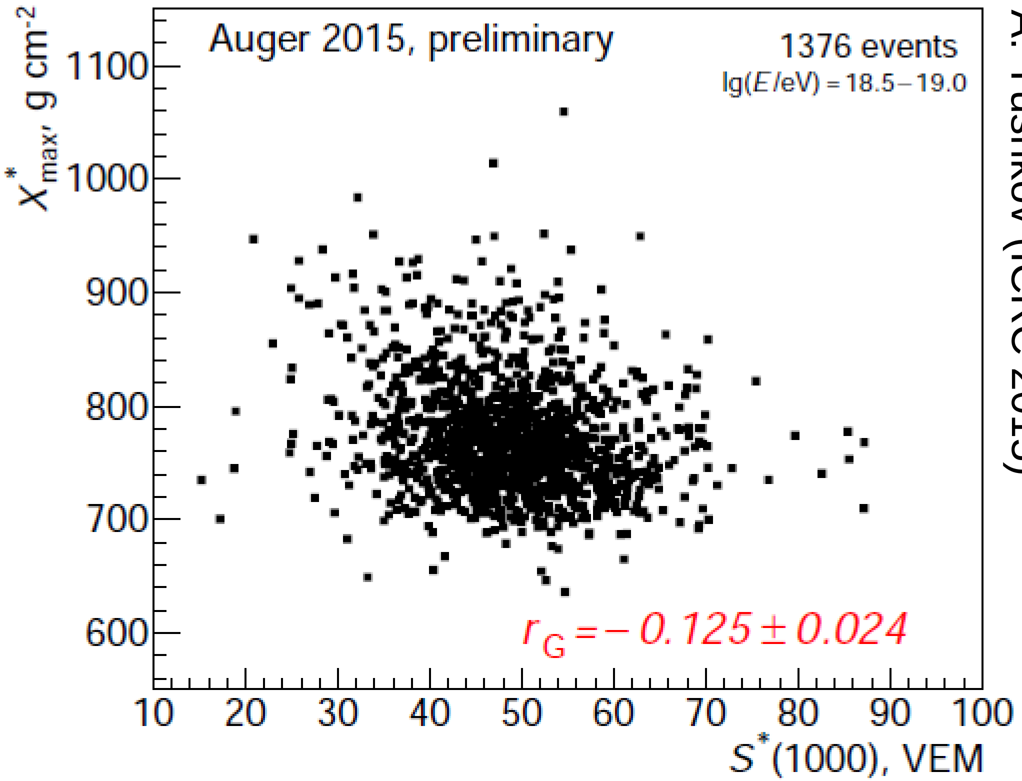
Correlation between X^*_{max} and $S^*(1000)$

- **in data correlation is significantly negative**

  ➔ $r_G = -0.125 \pm 0.024$

- **$r_G(X^*_{max}, S^*(1000))$ for p**
  - ➔ EPOS-LHC : 0.00 (5σ to data)
  - ➔ QGSJetII-04 : +0.08 (8σ to data)
  - ➔ Sibyll 2.1 : +0.07 (7.5σ to data)
- **difference is larger for other pure beams**

primary composition near the `ankle' is mixed

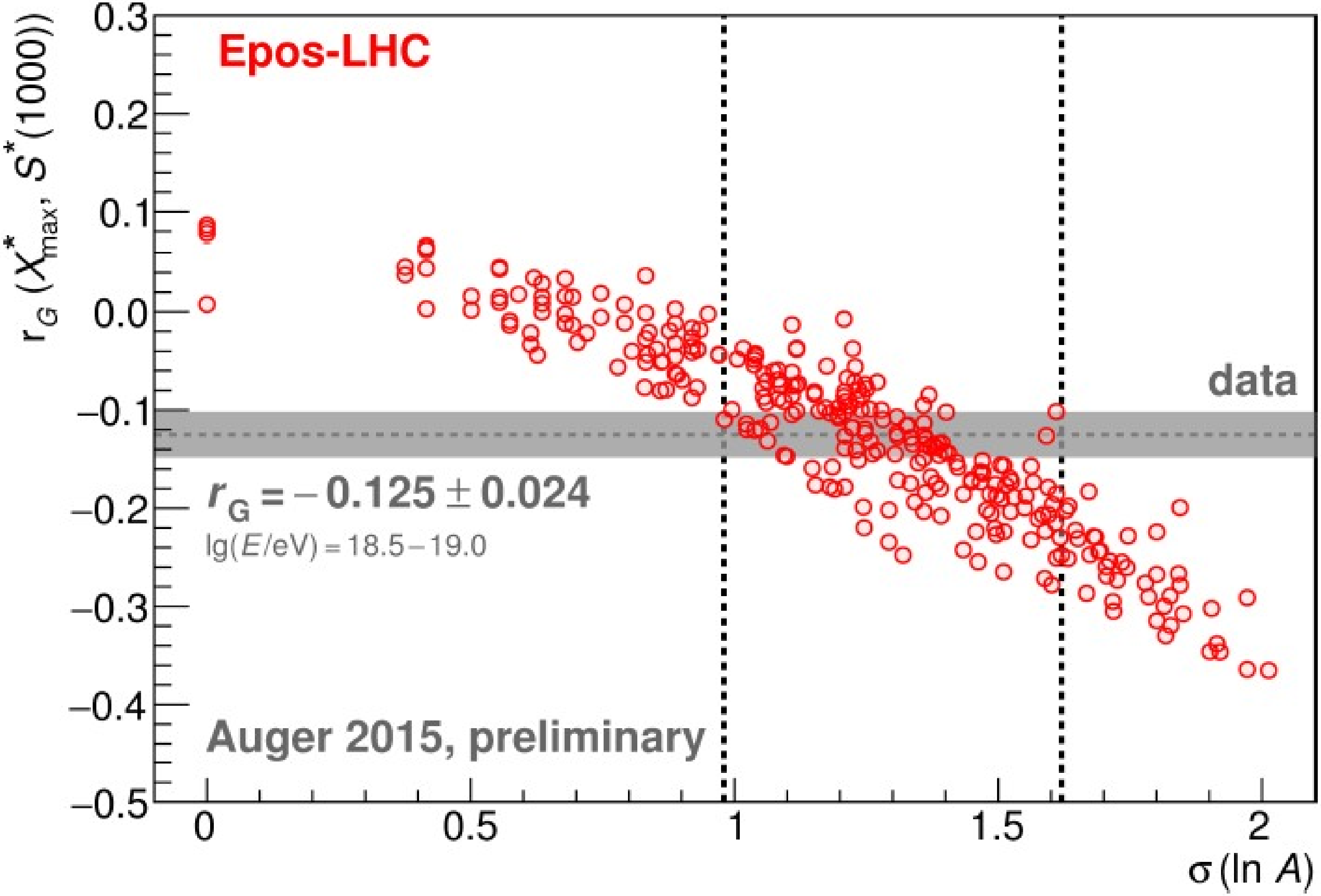


A. Yushkov (ICRC 2015)

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



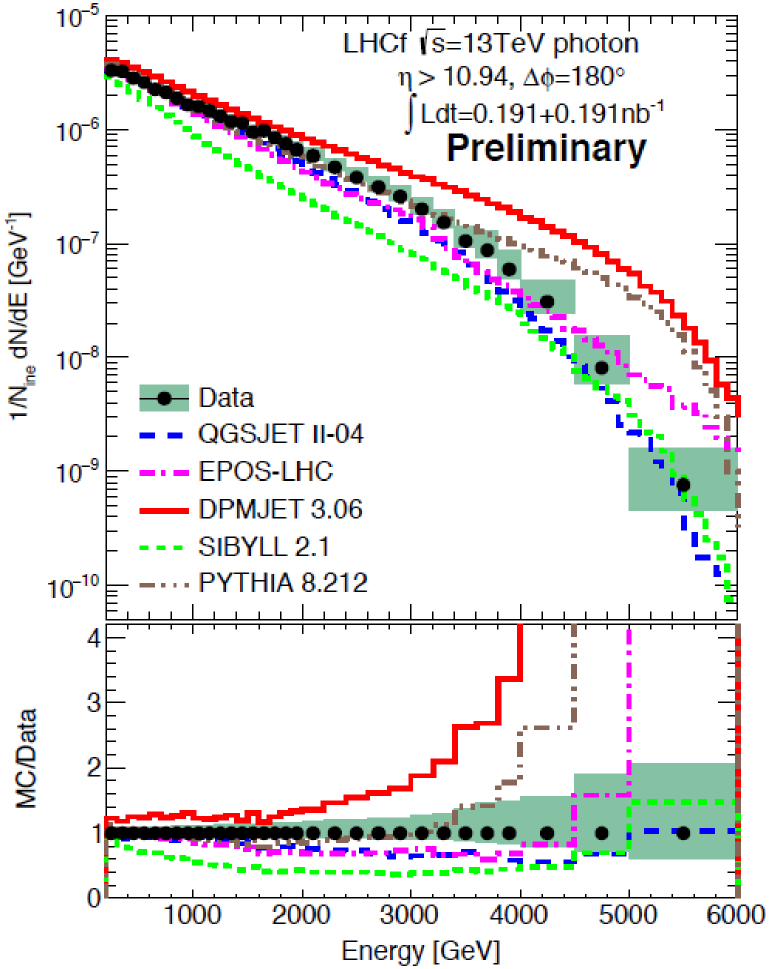
A. Yushkov (ICRC 2015)

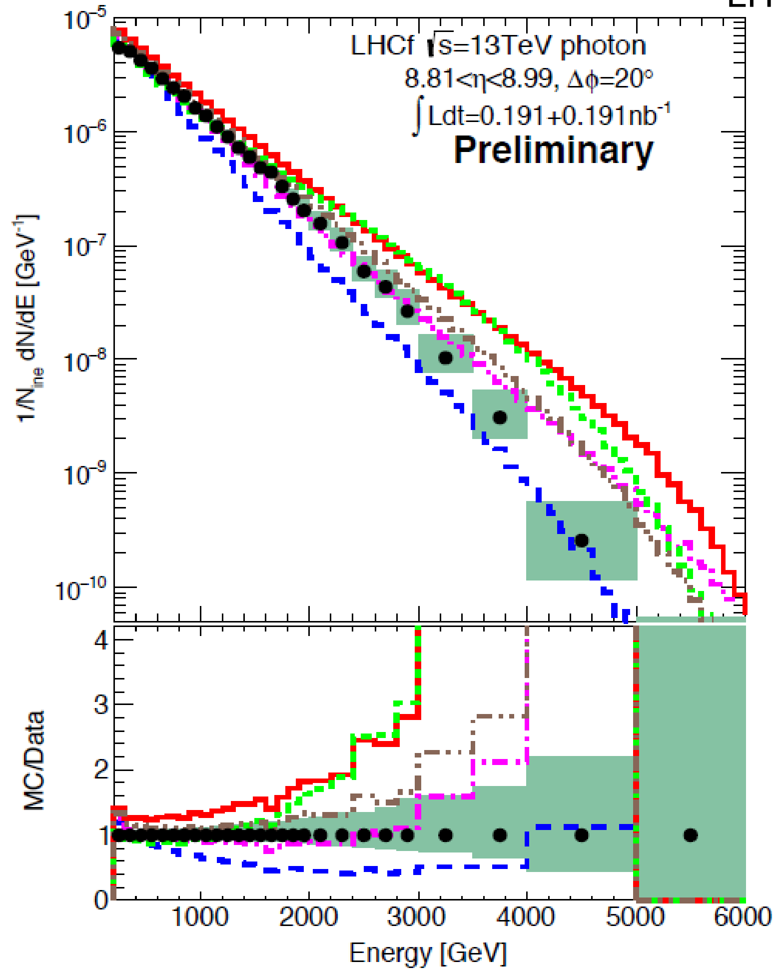
data are compatible with 1.0 ≲ σ(ln A) ≲ 1.7

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 improvments !
- 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 π^+ and π^- interactions and productions at 158 GeV with C and Pb target
  - ➜ confirm large forward proton production in π^+ and π^- 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

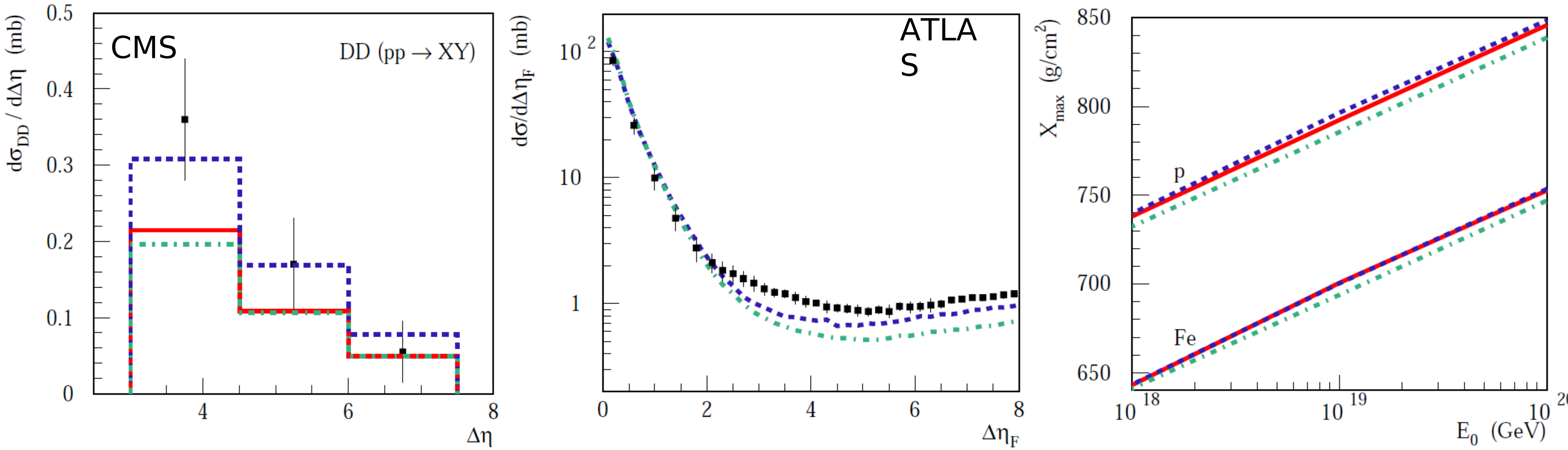
➜ EPOS overestimate forward baryon production at high energy

Diffraction measurements

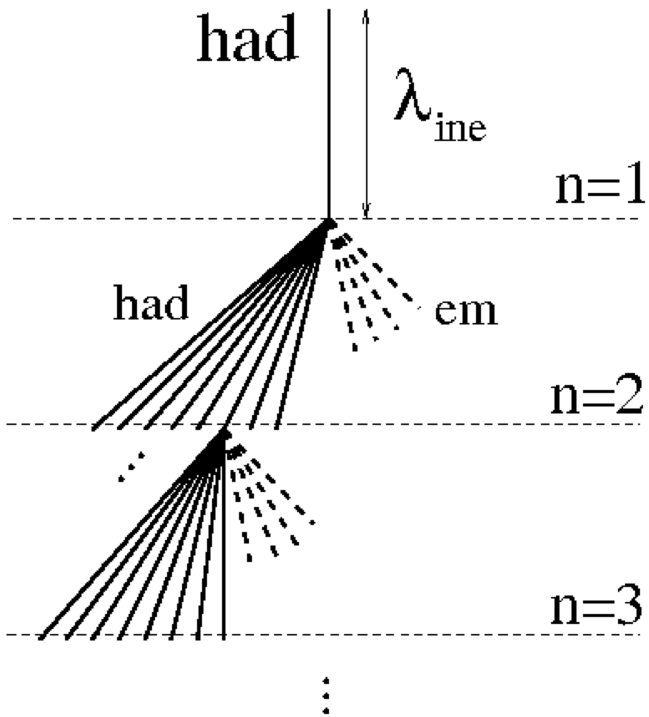
- **TOTEM and CMS diffraction measurement not fully consistent**
- **Tests by S. Ostapchenko using QGSJETII-04 (PRD89 (2014) no.7, 074009)**
  - ➔ SD+ option compatible with CMS
  - ➔ SD- option compatible with TOTEM

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 ± 2.17	6.5 ± 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 ~10 gr/cm^2 between the 2 options



Simplified Shower Development



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

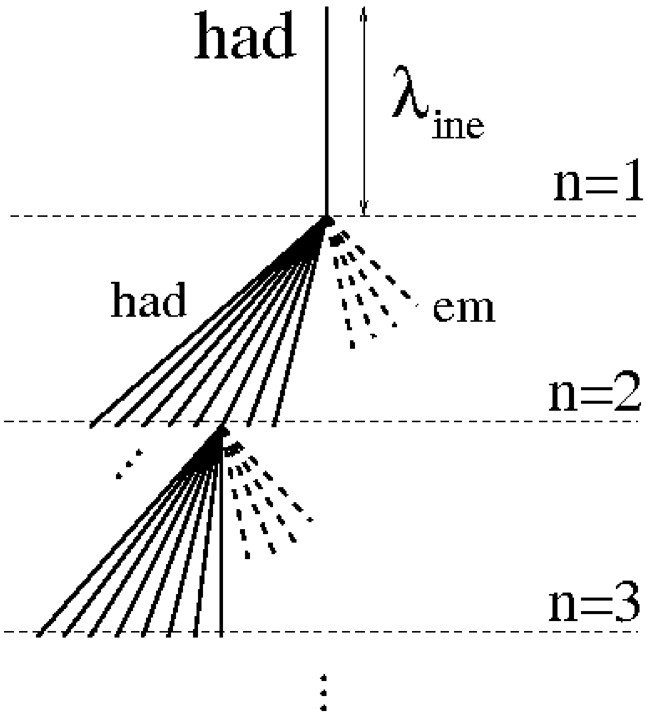
J. Matthews, Astropart.Phys. 22 (2005) 387-397

Using generalized Heitler model and superposition model :

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

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

Toy Model for Hadronic Cascade



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

Primary particle : hadron
Muons produced after many had. generations

N_{had}^{n} particles can produce muons after *n* interactions

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

N_{tot}^{n} particles share E_0 after *n* interactions

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

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

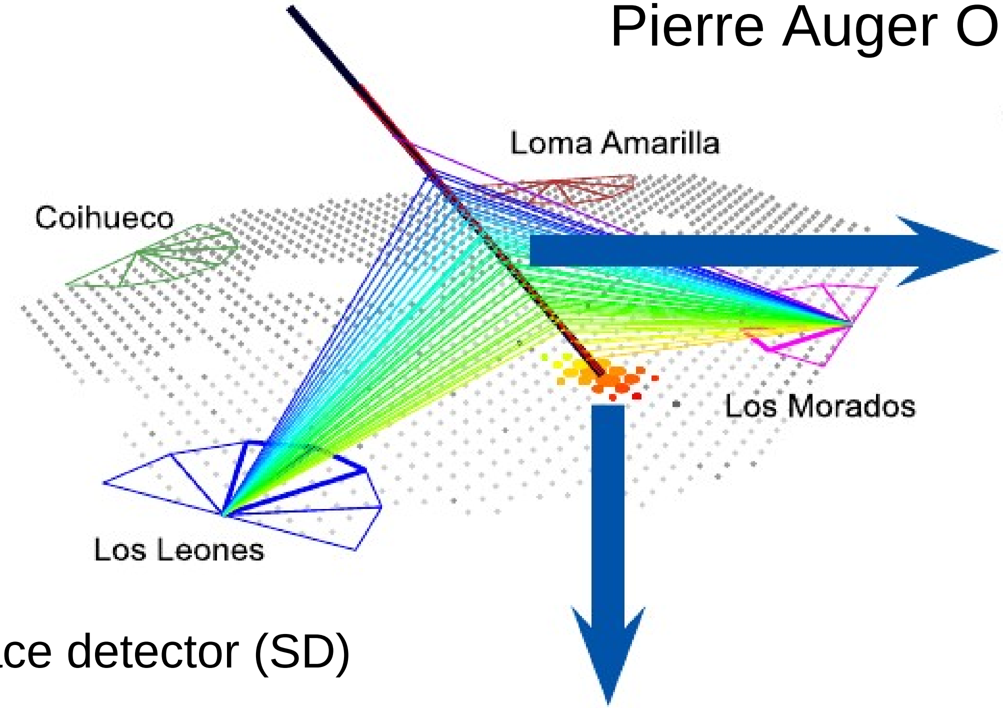
$$E_{dec} = E_0 / N_{tot}^{n_{max}}$$

$$n_{max} = \frac{\ln(E_0/E_{dec})}{\ln(N_{tot})}$$

$$\ln(N_\mu) = \ln(N(n_{max})) = n_{max} \ln(N_{had})$$

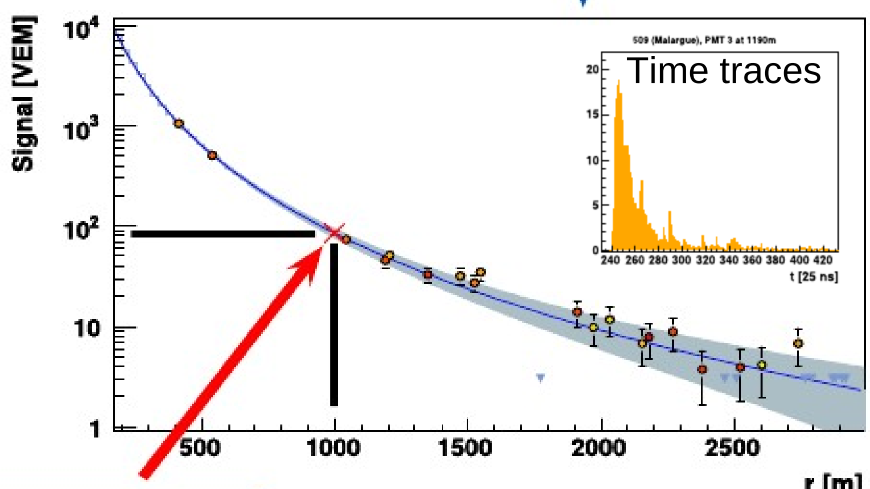
Hybrid Detection

Pierre Auger Observatory / Telescope Array



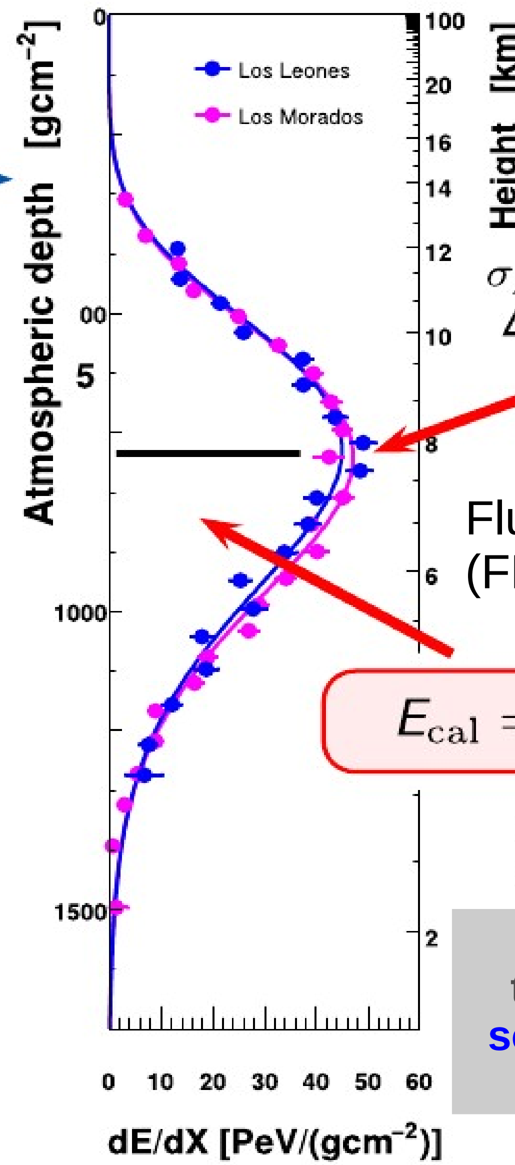
Surface detector (SD)

From R. Ulrich (KIT)



S_{1000}

$E_{\rm surface} = f(S_{1000},\ \theta)$



$\sigma X_{\rm max} < 20\,{\rm g/cm^2}$
$\Delta_{\rm sys} \approx 15\,{\rm g/cm^2}$

$X_{\rm max}$

Fluorescence detector (FD)

$E_{\rm cal} = \int {\rm d}X\ \frac{{\rm d}E}{{\rm d}X}$

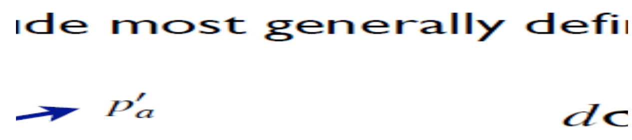
$\sigma_E/E \sim 8\,\%$
$\Delta_{\rm sys} \approx 14\,\%$

Various detection technique = energy scale independent of EAS simulations

When does a projectile interact ?

For all models cross-section calculation based on optical theorem

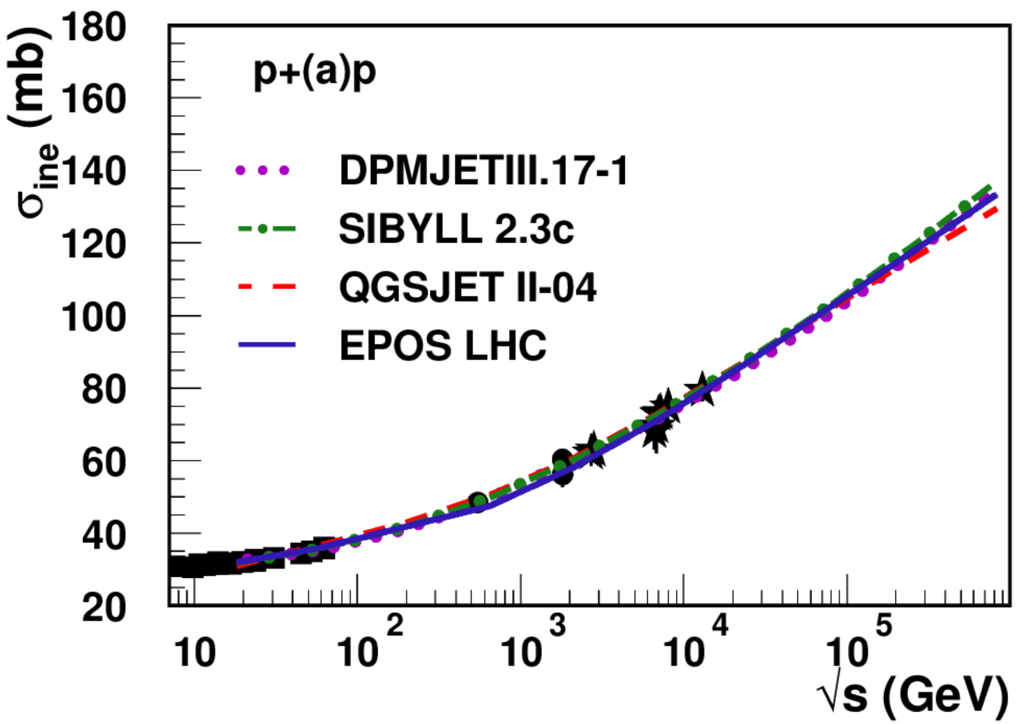
- total cross-section given by elastic amplitude



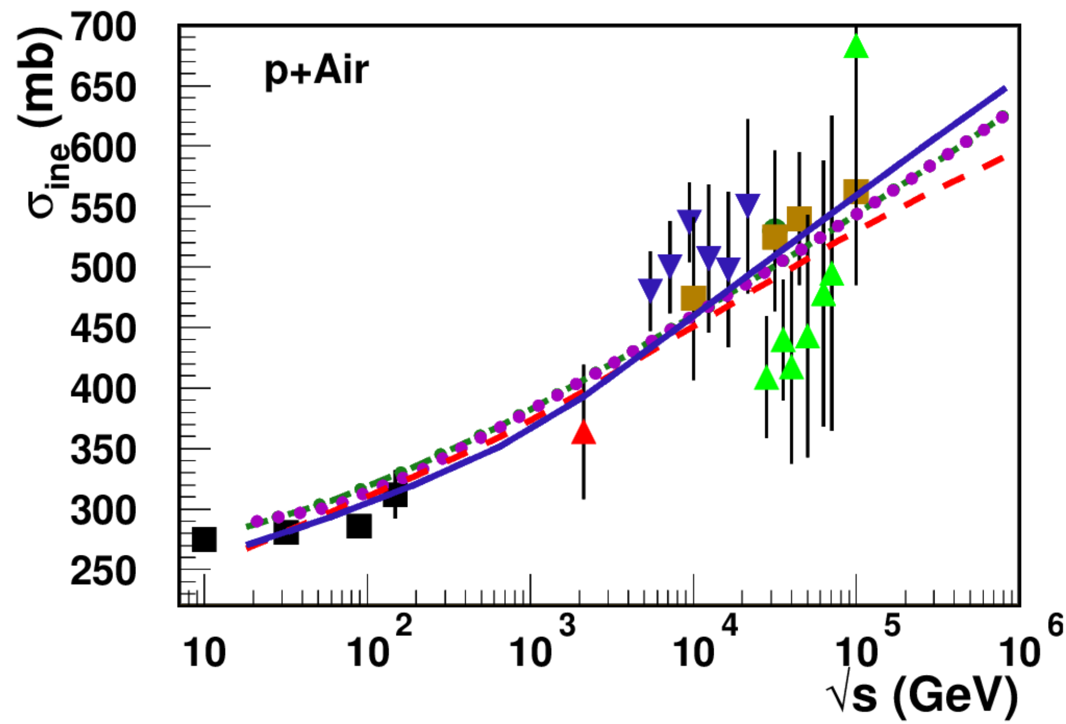
- different amplitudes in the models but free parameters set to reproduce all p-p cross-sections

- basic principles + high quality LHC data = same extrapolation

pp



p-Air



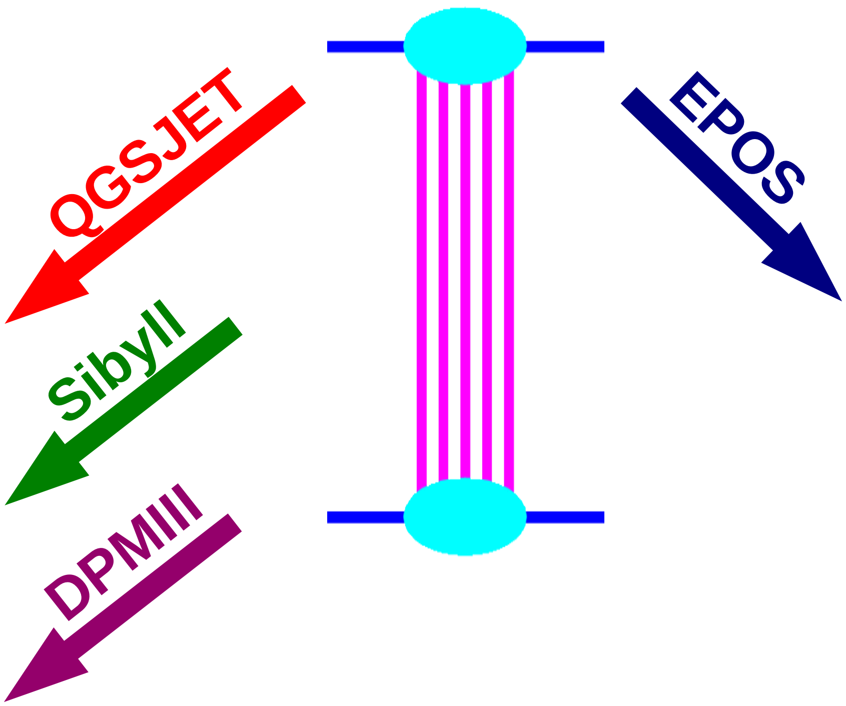
How does the projectile interact ?

- **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

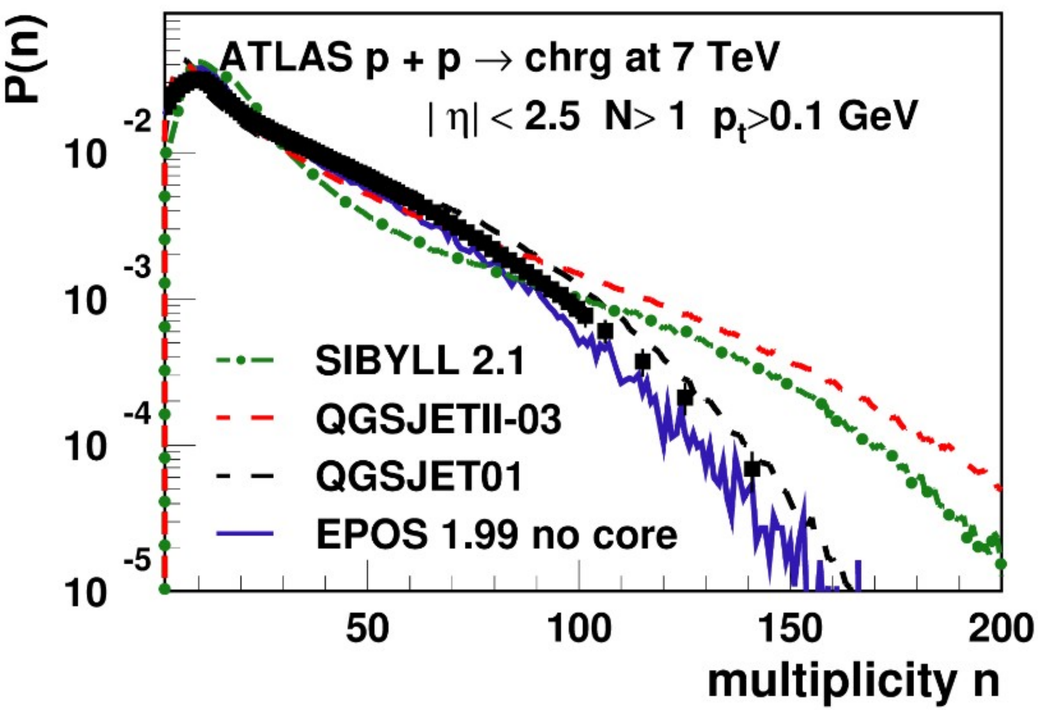
➔ get the number of scattering taking into account energy conservation

➔ consistent approach

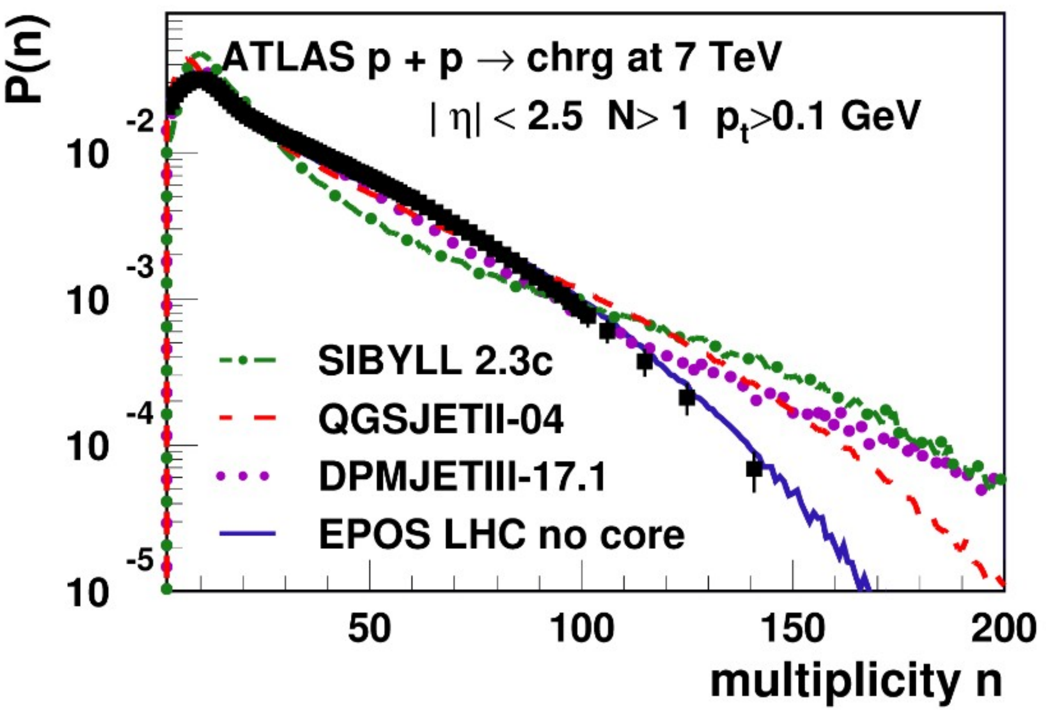
Does energy sharing order matter ?

- **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



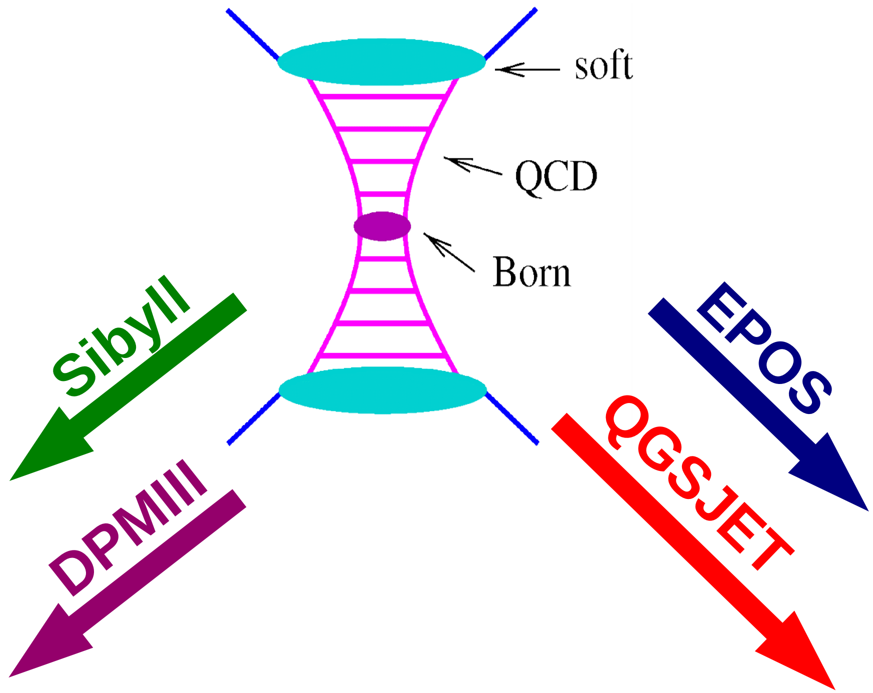
How to build the amplitude ?

- **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**
  - ➔ parton, hadron, quasi-particle = Reggeon or Pomeron (vacuum excitation)
- **QCD based theory so at high energy, perturbative QCD can be used to build the field amplitude (amplitude used for the cross-section)**
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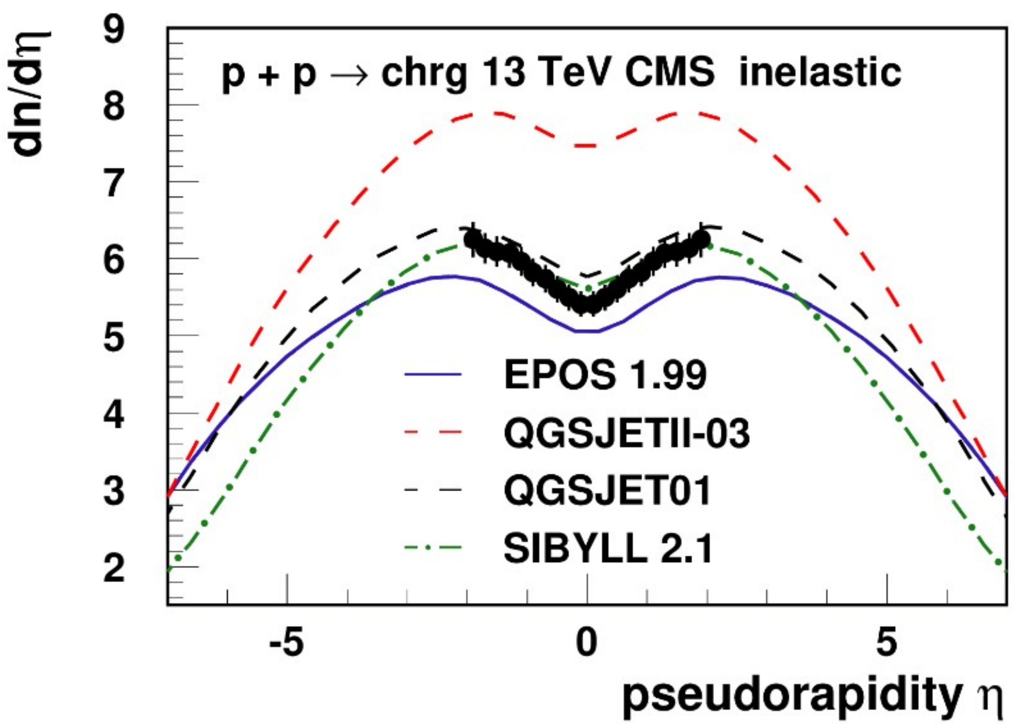
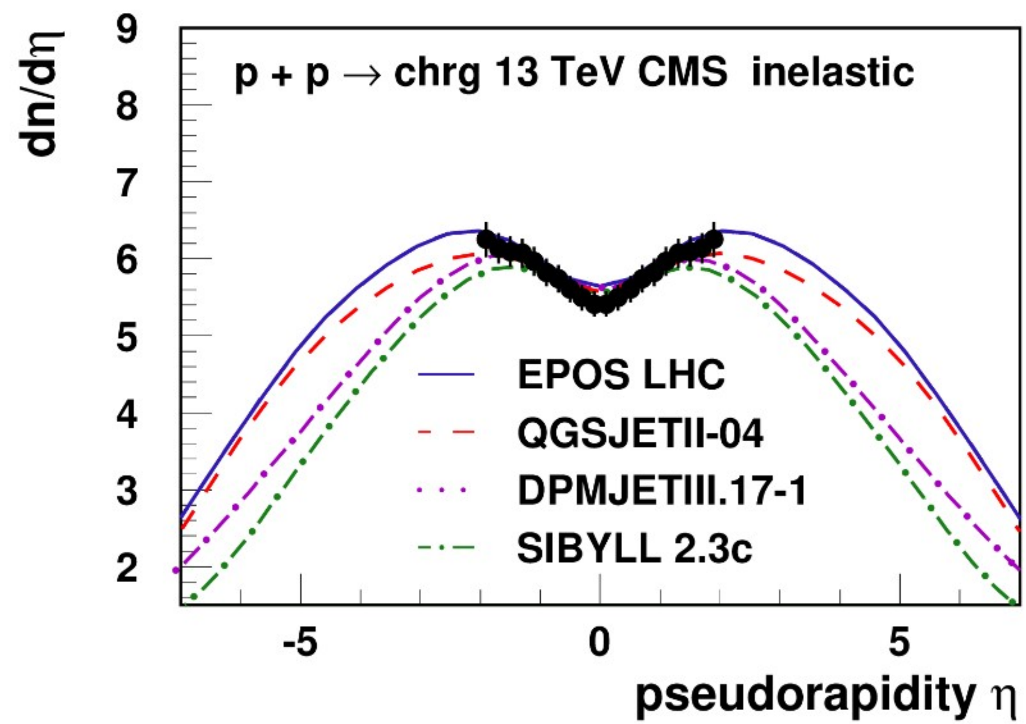
Pre - LHC



Post - LHC



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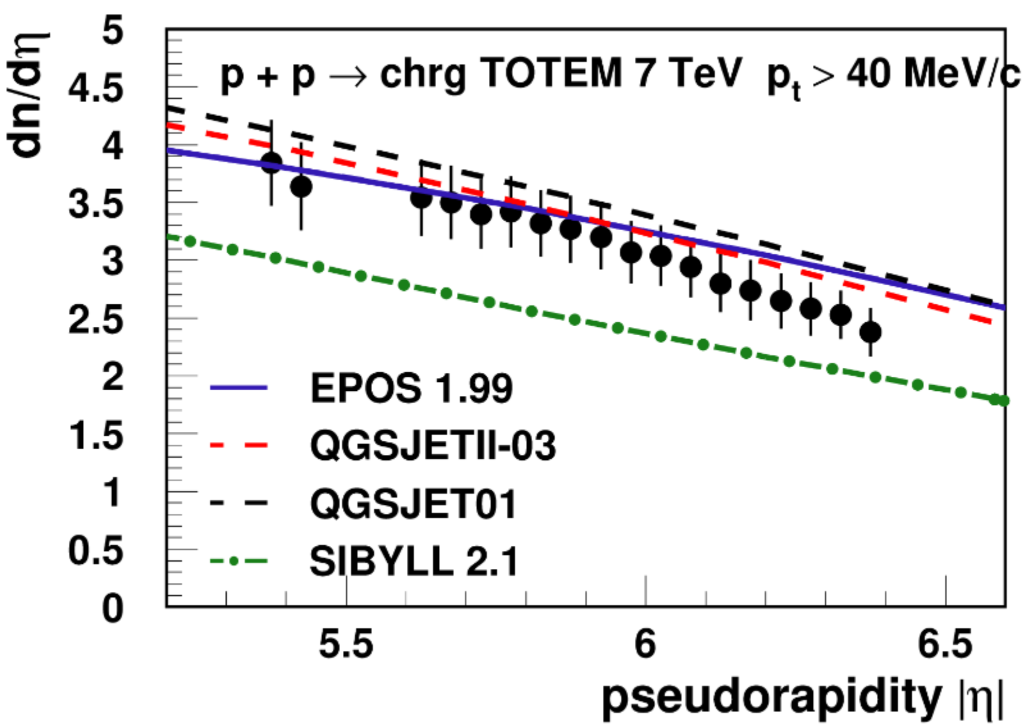
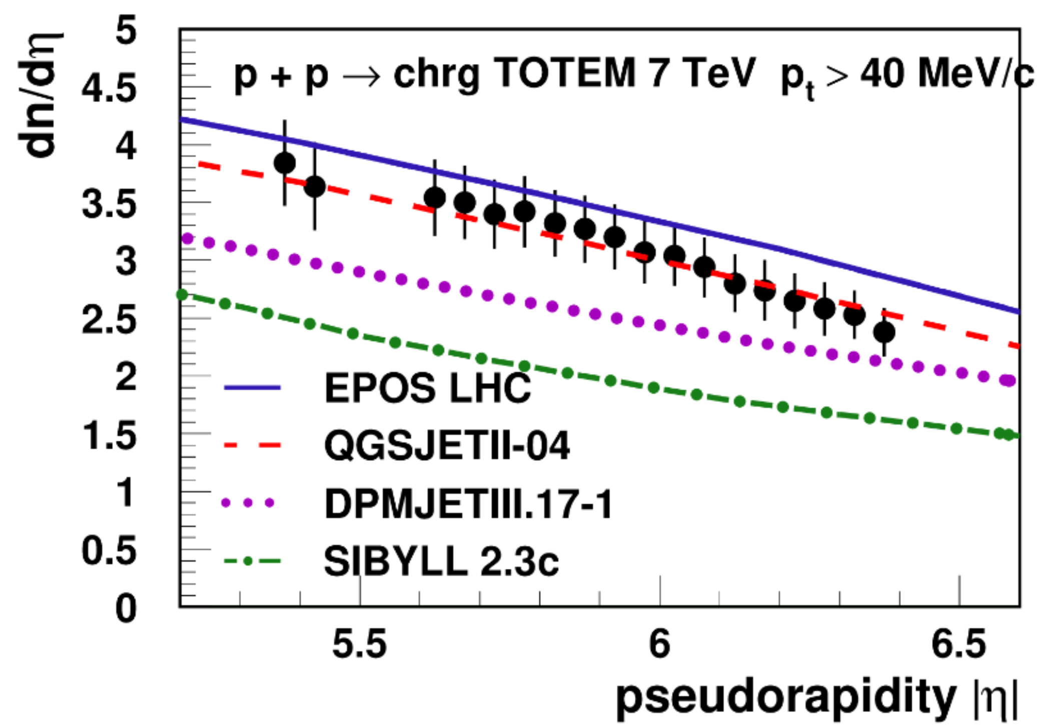
Pre - LHC

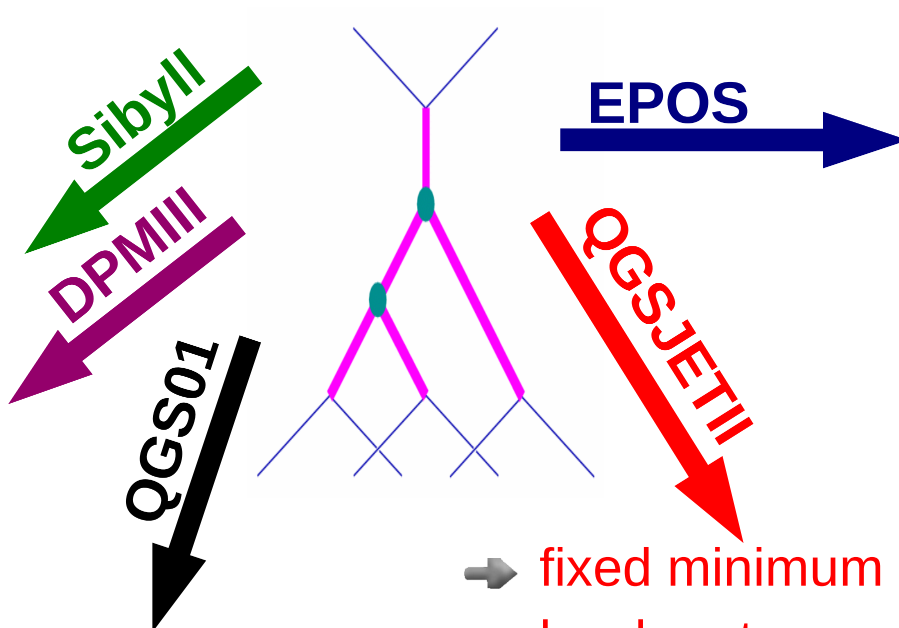


Post - LHC



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)

- ➔ not needed because of <u>wrong</u> parton distribution function

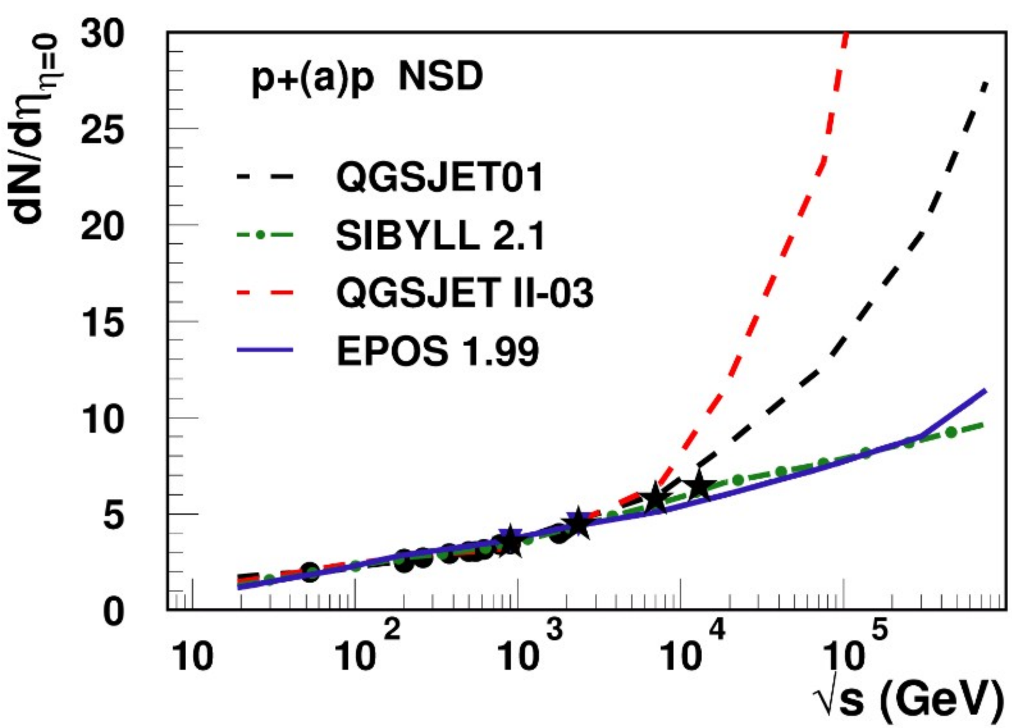
- ➔ fixed minimum p_t in hard part
- ➔ theory based "fan diagrams" resumed to infinity without energy sharing

- ➔ 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)

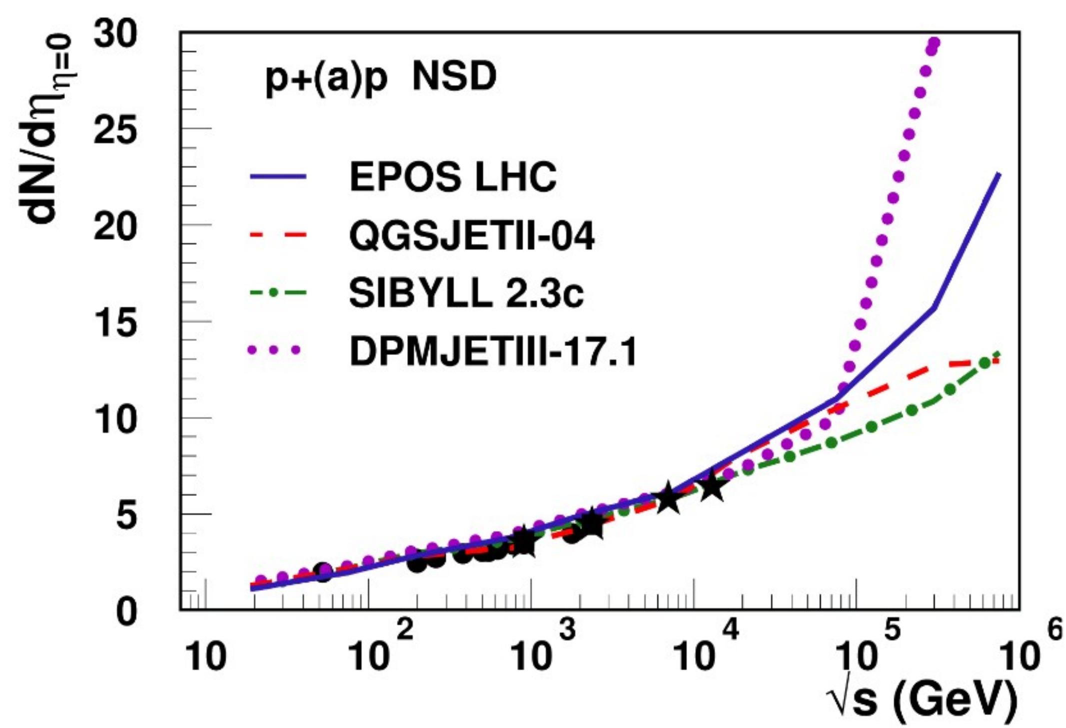
Do non linear effects matters ?

- **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

Pre - LHC



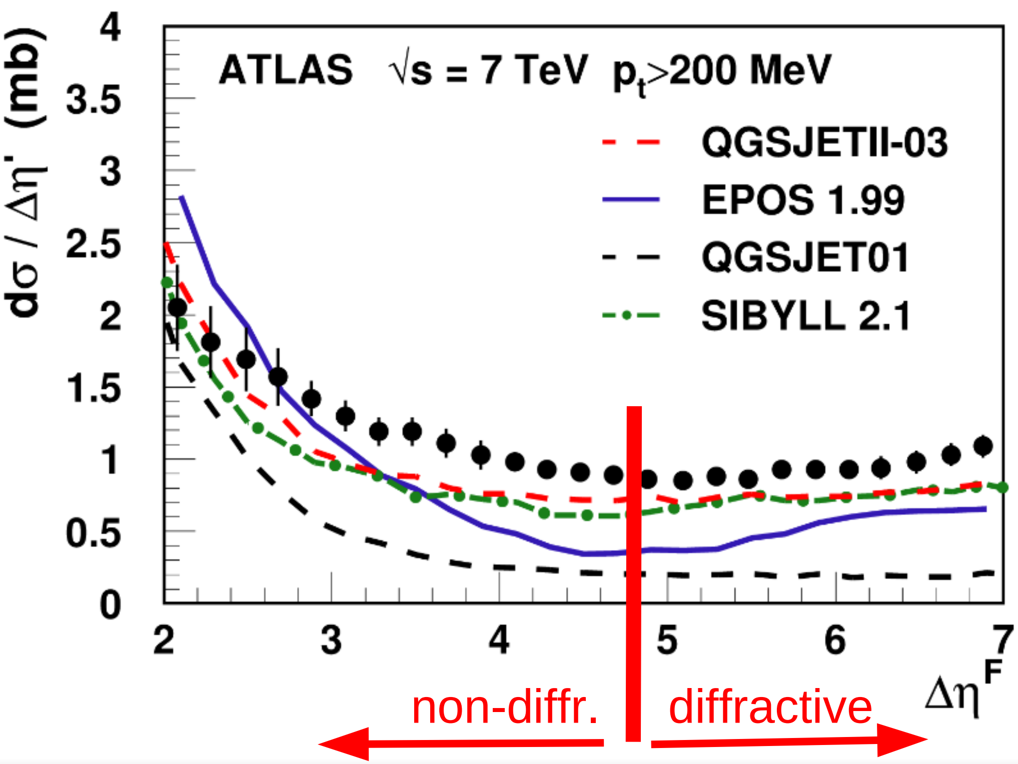
Post - LHC



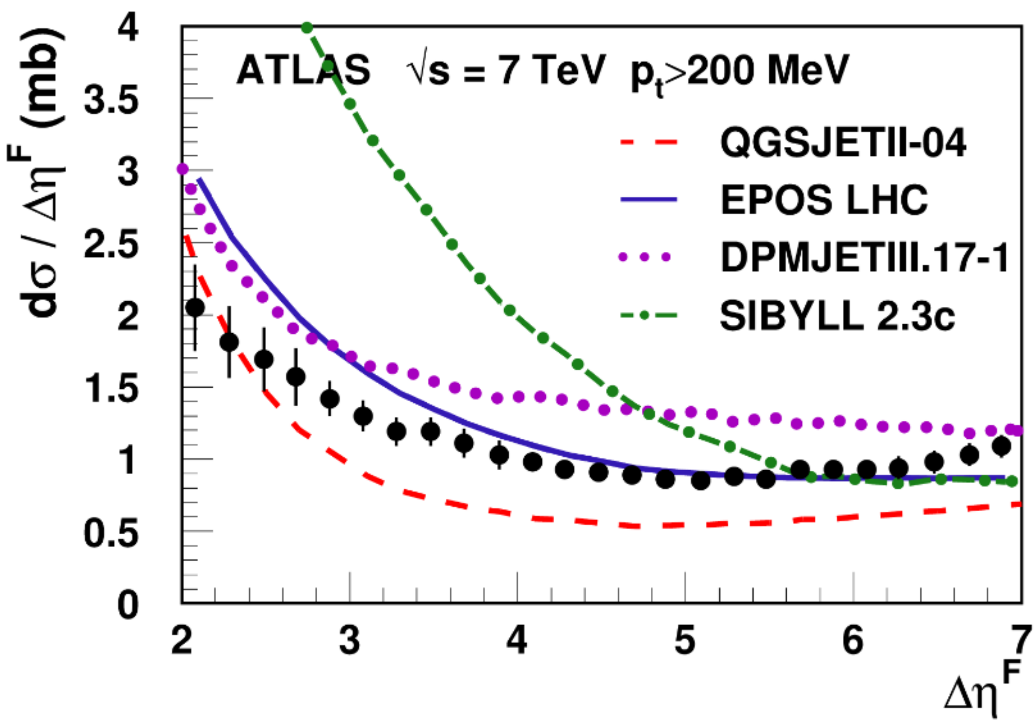
What if only energy is transferred ?

- **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)**

Pre - LHC



Post - LHC

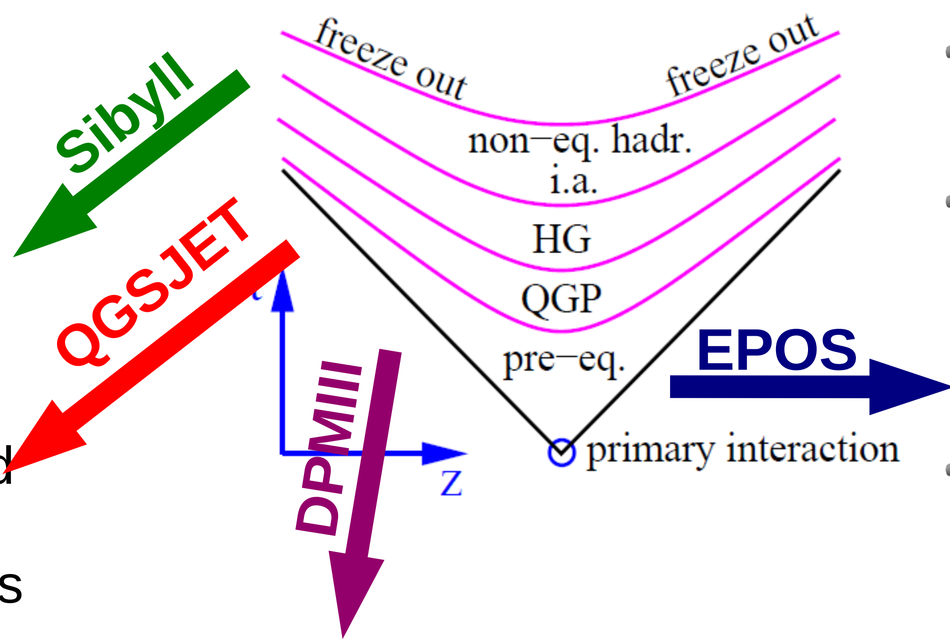


Should everything be taken into account ?

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

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

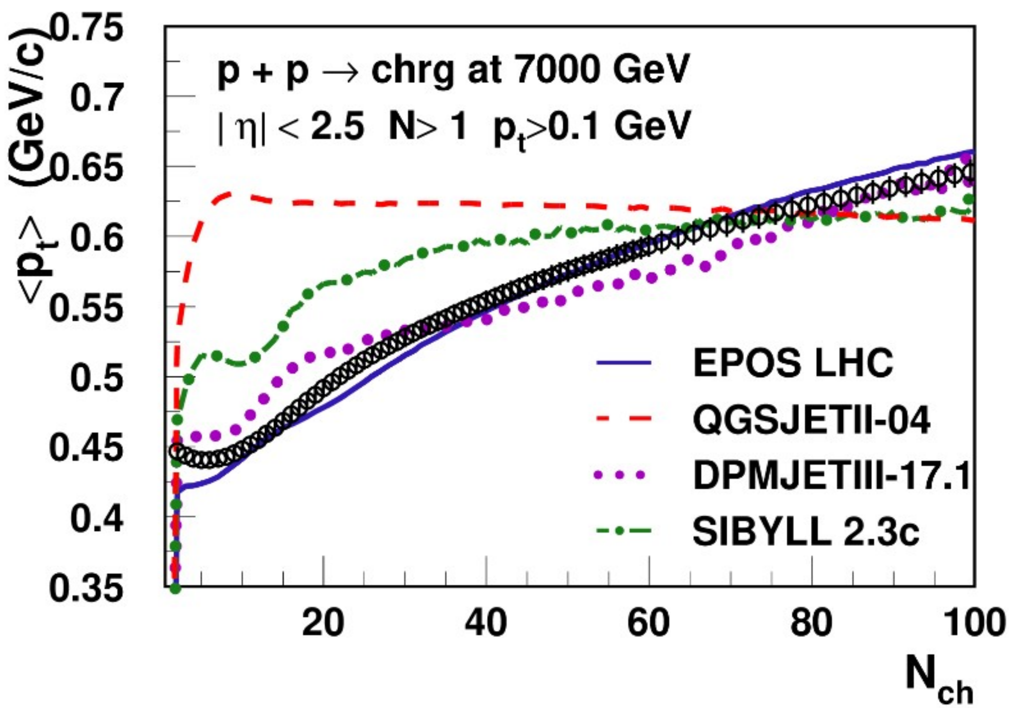


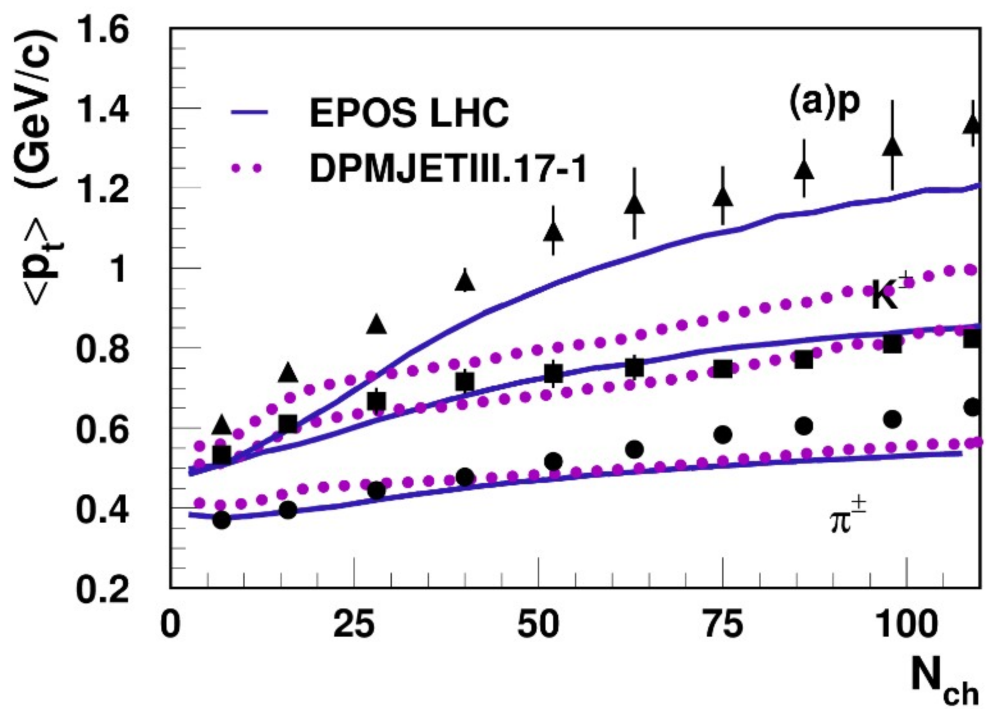
- developed first for heavy ion interactions
- detailed description of every possible “soft” observable (not good for hard scattering yet)
- sophisticated collective effect treatment (real hydro for EPOS 2 and 3)
- very large complete data set (LEP, HERA, SPS, RHIC, LHC, ...)

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

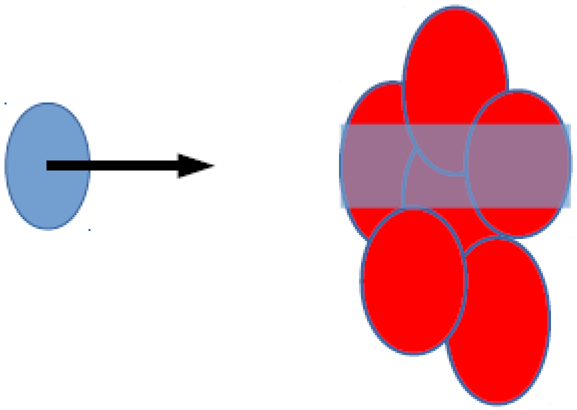
Should everything be taken into account ?

- **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 ?**





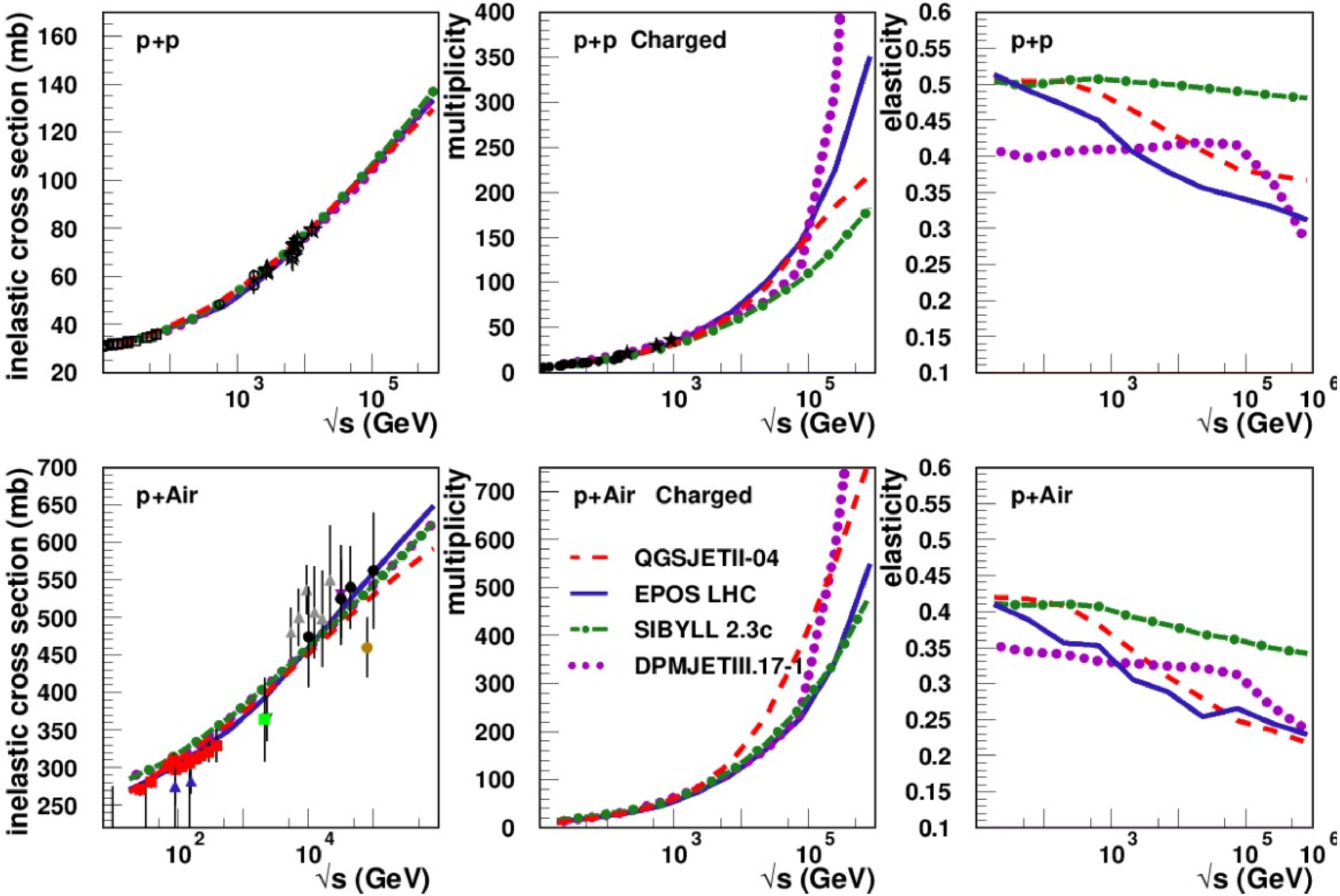
How to do nuclear interactions ?



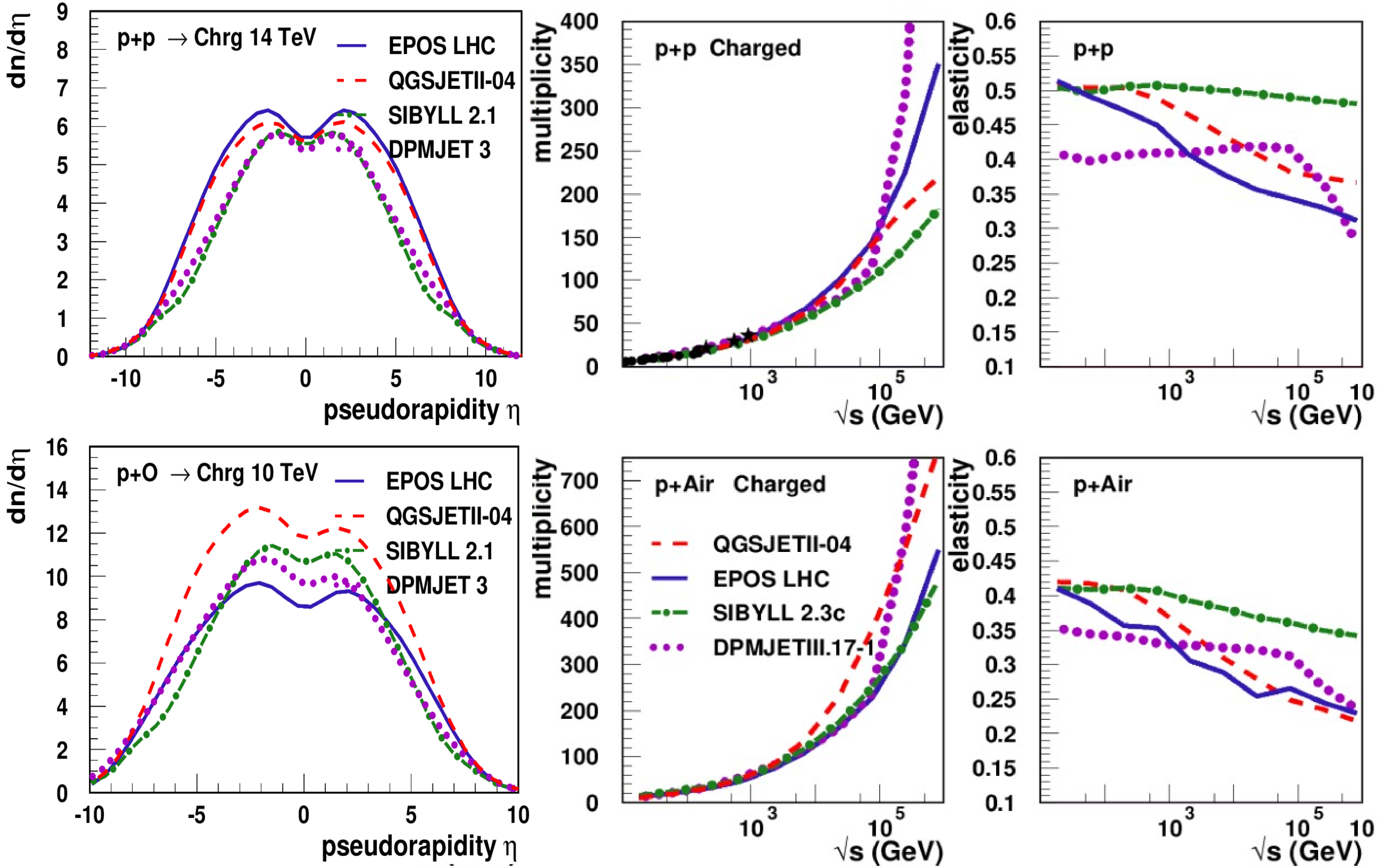
Main source of uncertainty in extrapolation :
- **very different approaches**
- **limited available data set**
- **limited models capabilities**

- **Sibyll** (light ion only)
  - corrected Glauber for pA (A/B=# of nucleons)
  - superposition model for AB (A x 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)

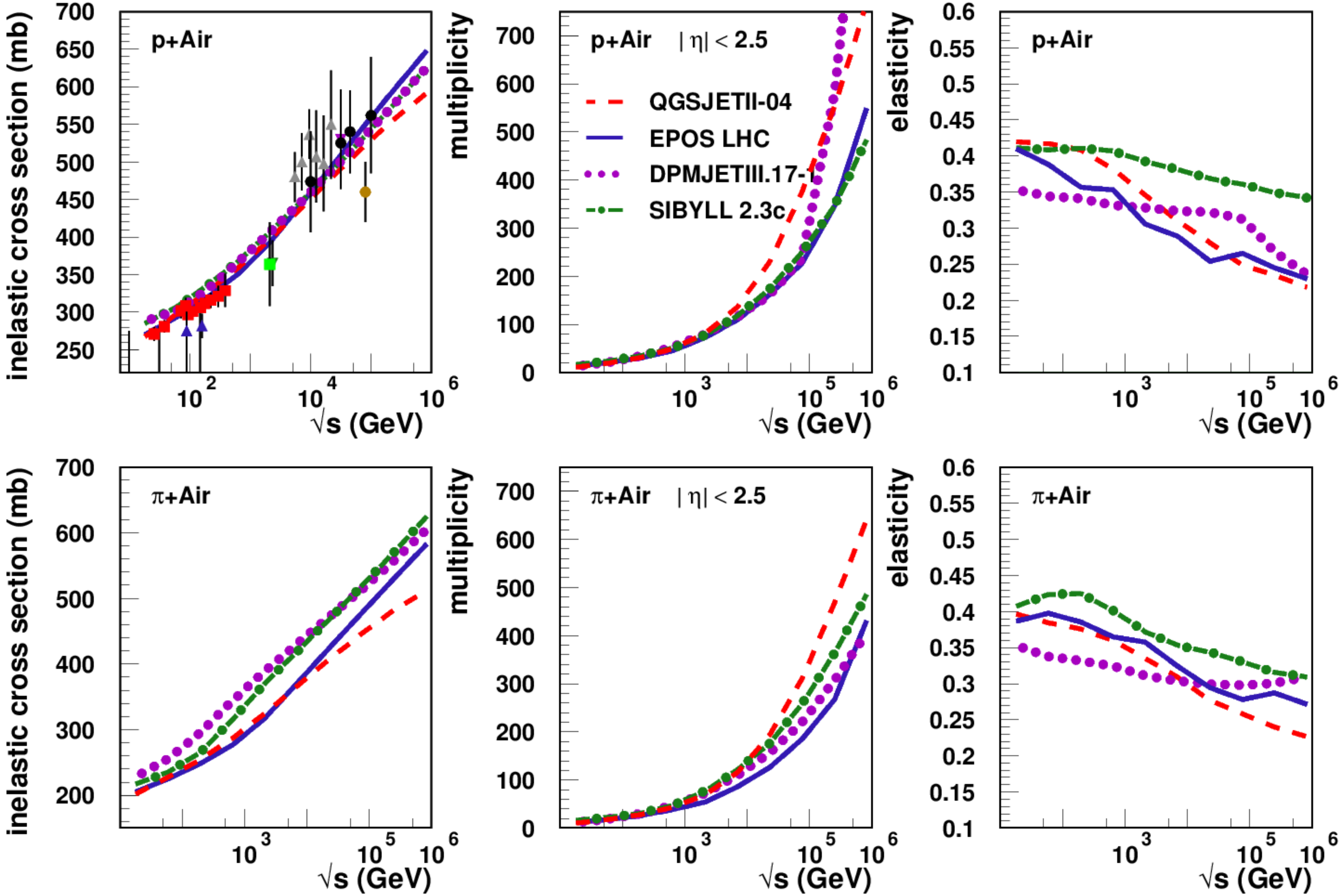
Ultra-High Energy Hadronic Model Predictions p-Air



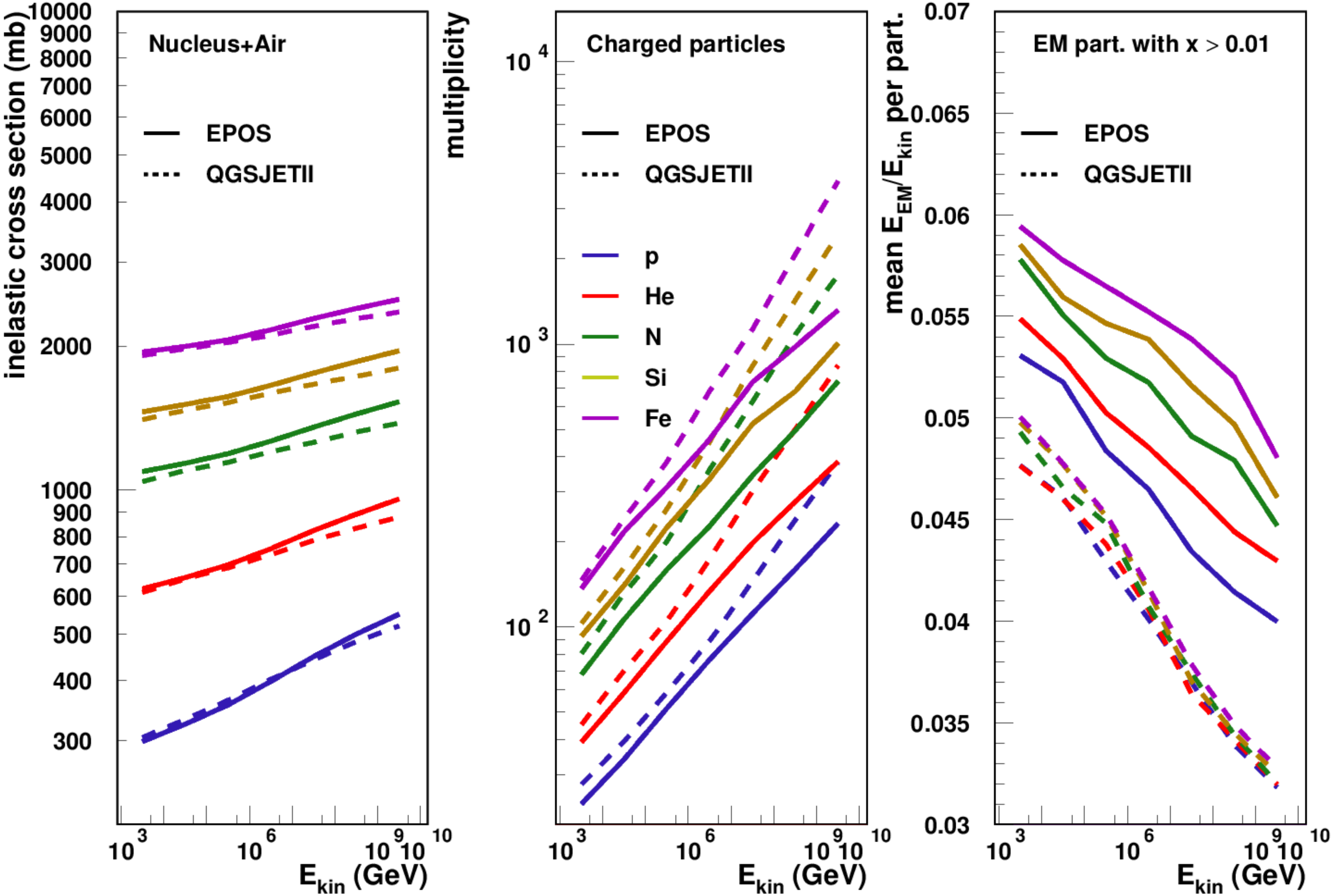
Ultra-High Energy Hadronic Model Predictions p-Air



Ultra-High Energy Hadronic Model Predictions π-Air



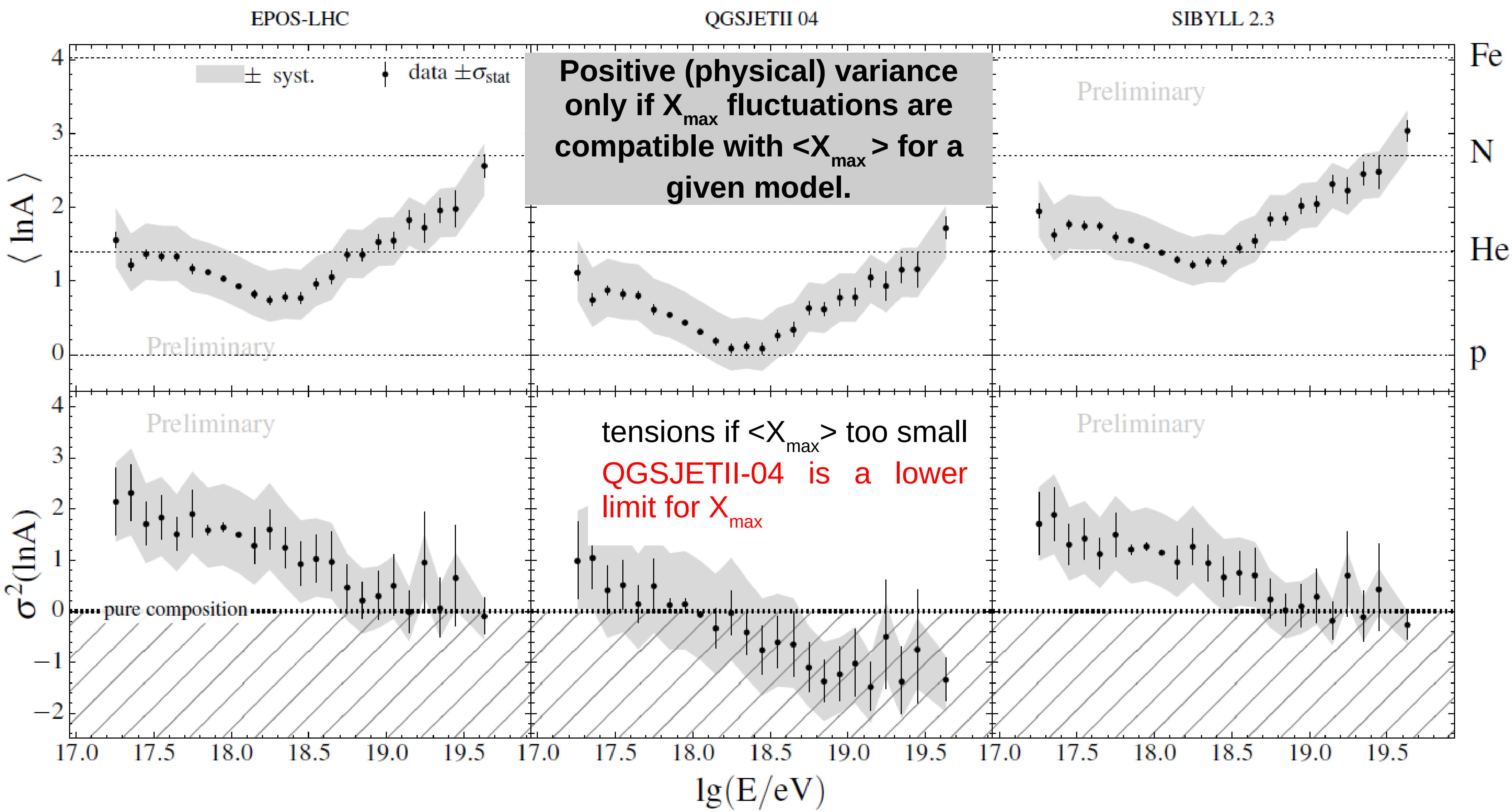
Ultra-High Energy Hadronic Model Predictions A-Air



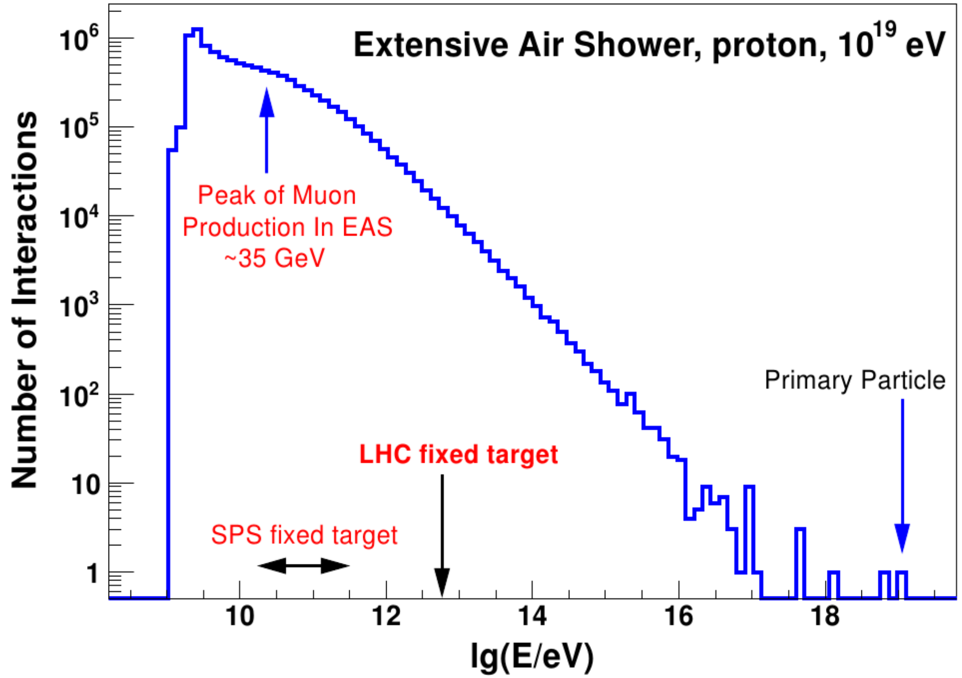
Model Consistency using Electromagnetic Component

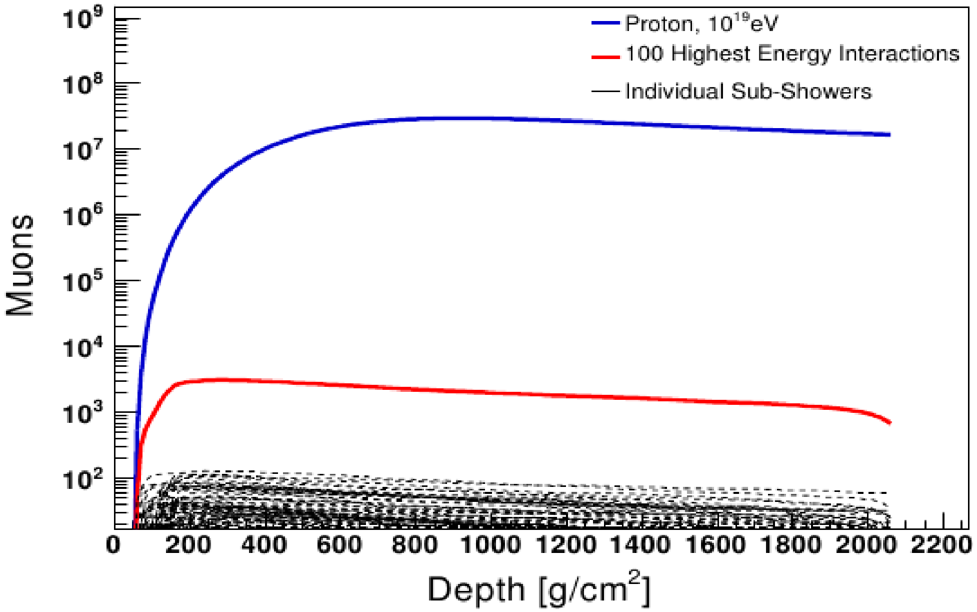
Study by Pierre Auger Collaboration (ICRC 2017)

- ➡ std deviation of lnA allows to test model consistency.



Surface Detectors (SD)

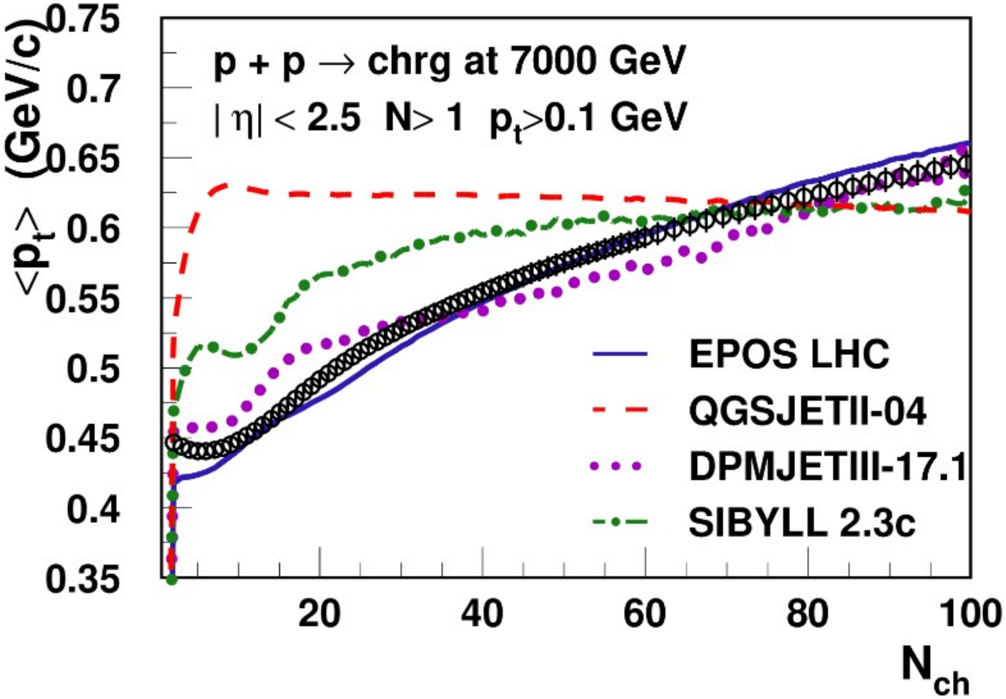


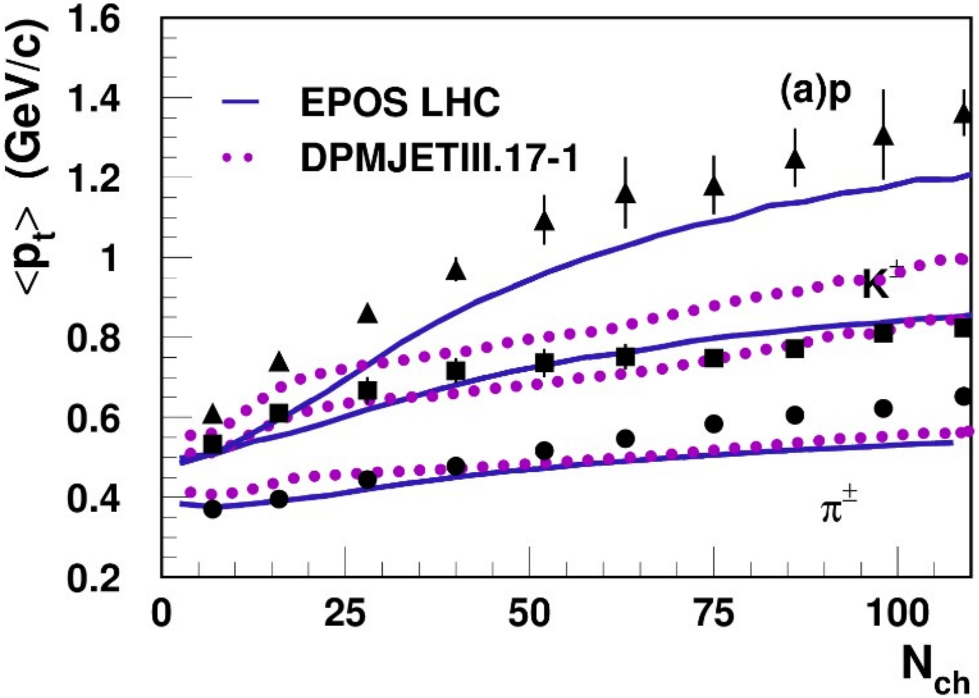


- **SD detector sensitive to**
  - electromagnetic particles (EM)
  - muons
- **Particles at ground produced after many generations of hadronic interactions**
  - most of EM particles from pure EM (universal) shower (depend on high (first) energy hadronic interactions)
  - muons produced at the end of 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

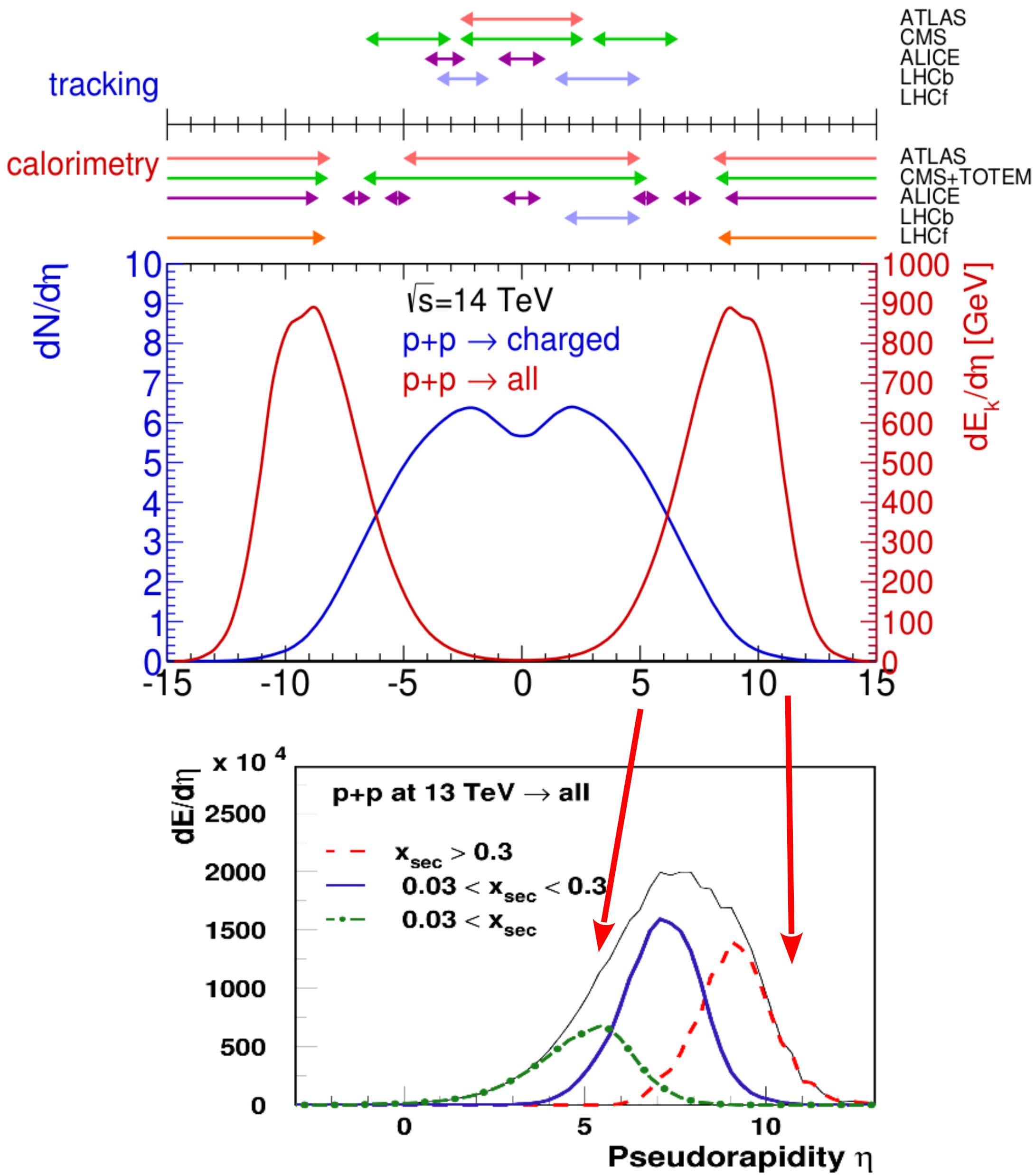
Should everything be taken into account ?

- **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 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