Hadronic Interactions Studies at LHC

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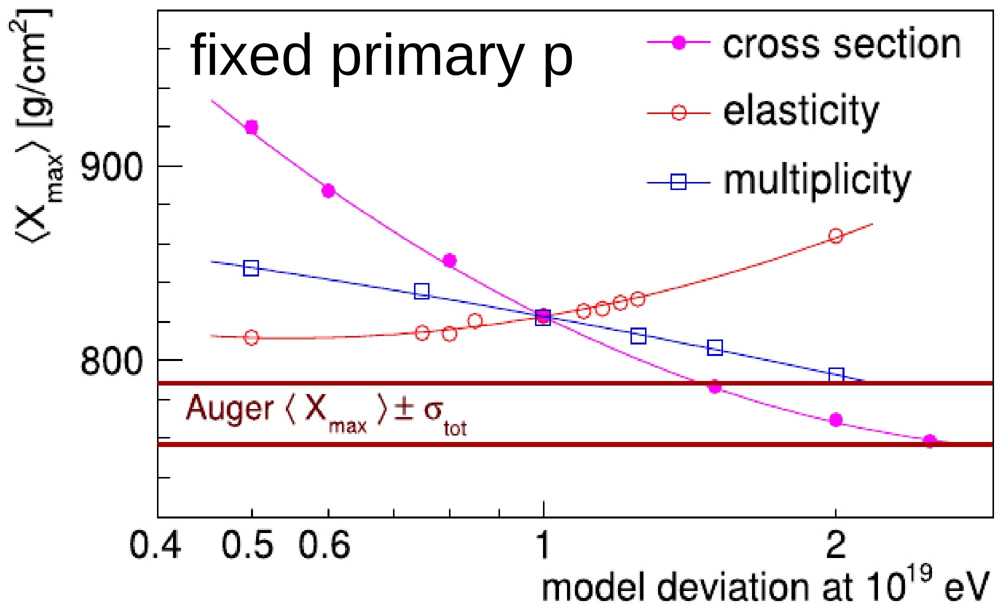
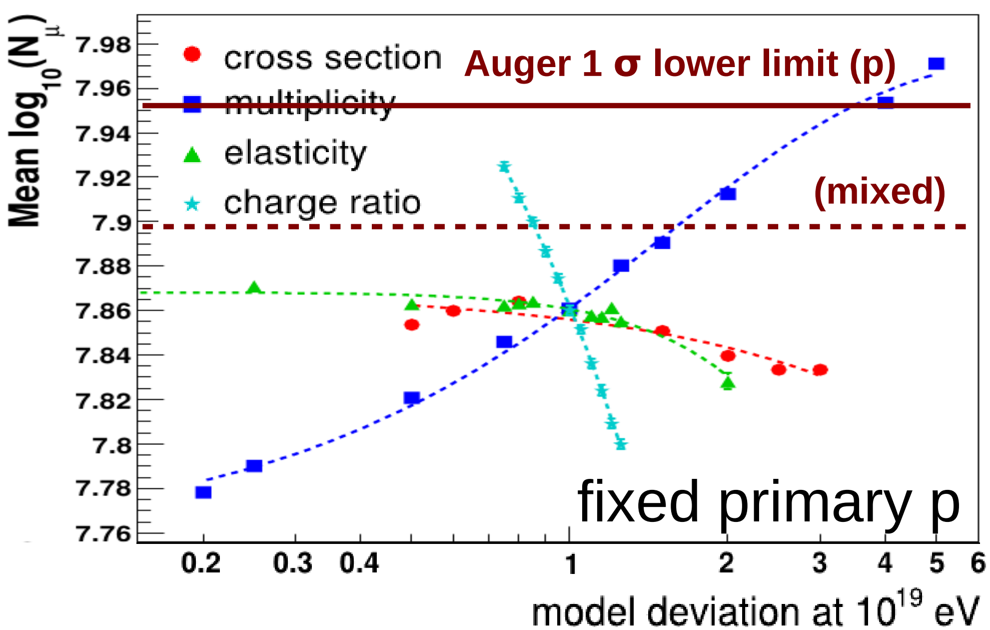
Outline

- **Introduction**
- **Cross-section and Multiplicity**
  - ALFA
  - Fluctuations in p-Pb by CMS
- **Impact on X_{max}**
- **ALICE, Core-corona and EAS**
  - Qualitative tests

Recent LHC data provide new constraints on models changing X_{max} and Quark Gluon Plasma (QGP)-like hadronization could be more common than thought until now which will impact muon production.

Sensitivity to Hadronic Interactions





From R. Ulrich (KIT)

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

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

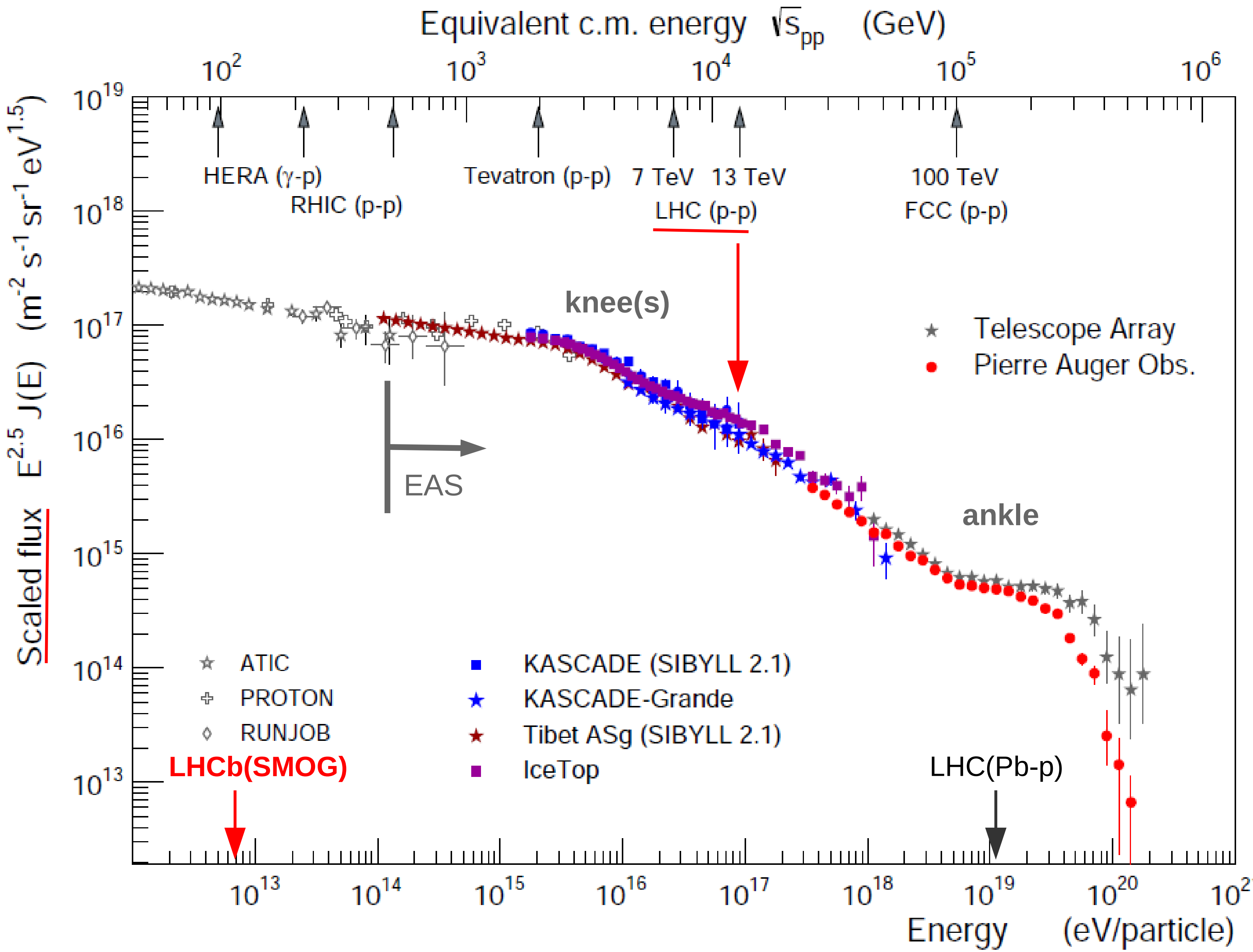
Hadronic Models for Air Showers

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

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

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

Energy Spectrum

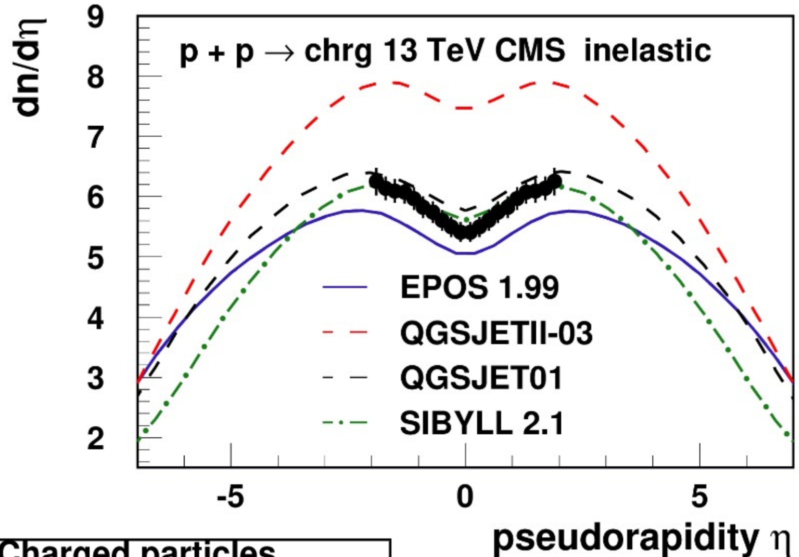


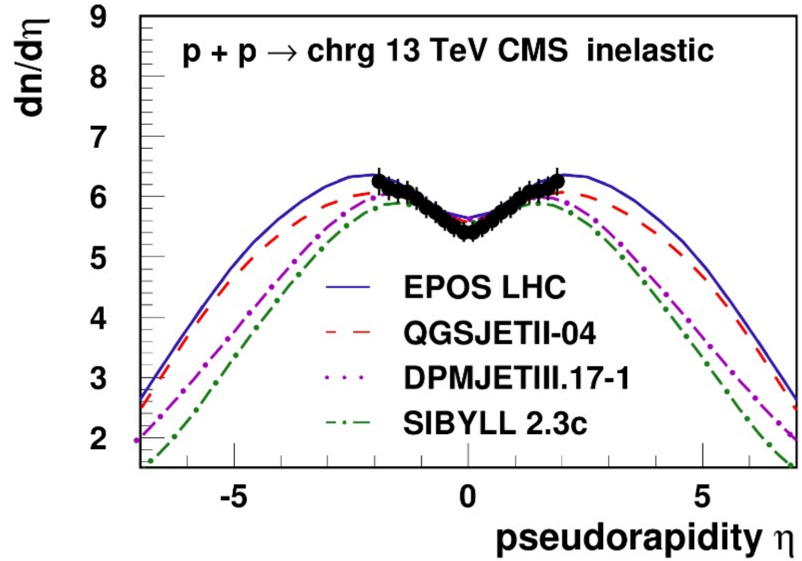
R. Engel (KIT)

Models Uncertainties

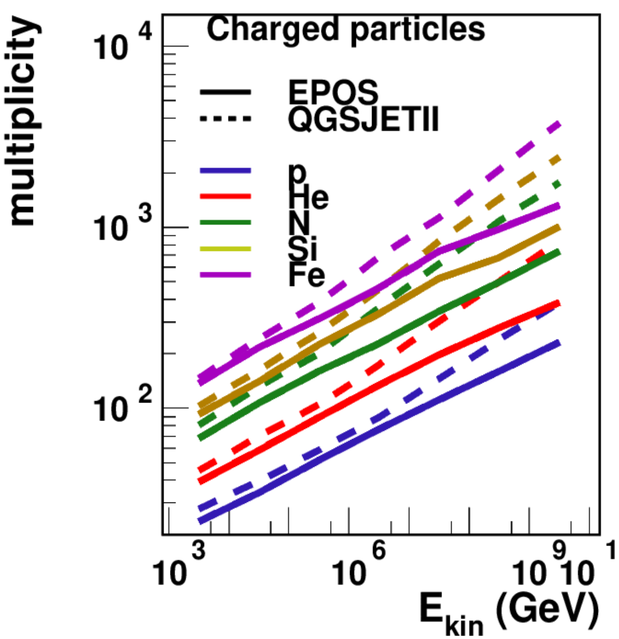
Significant improvement require new data (light ion and higher energy)

Pre - LHC





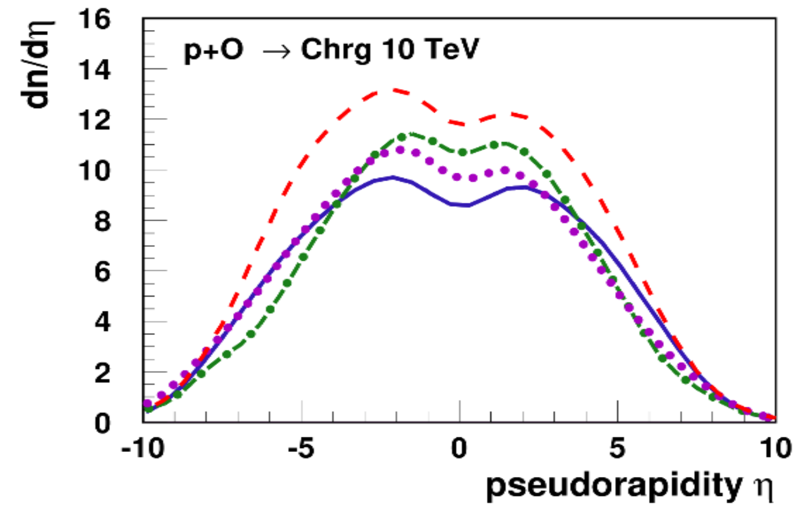
Post - LHC



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

2024 !

Post - LHC



Model Improvement

- **But a number of new data since model release could be use 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

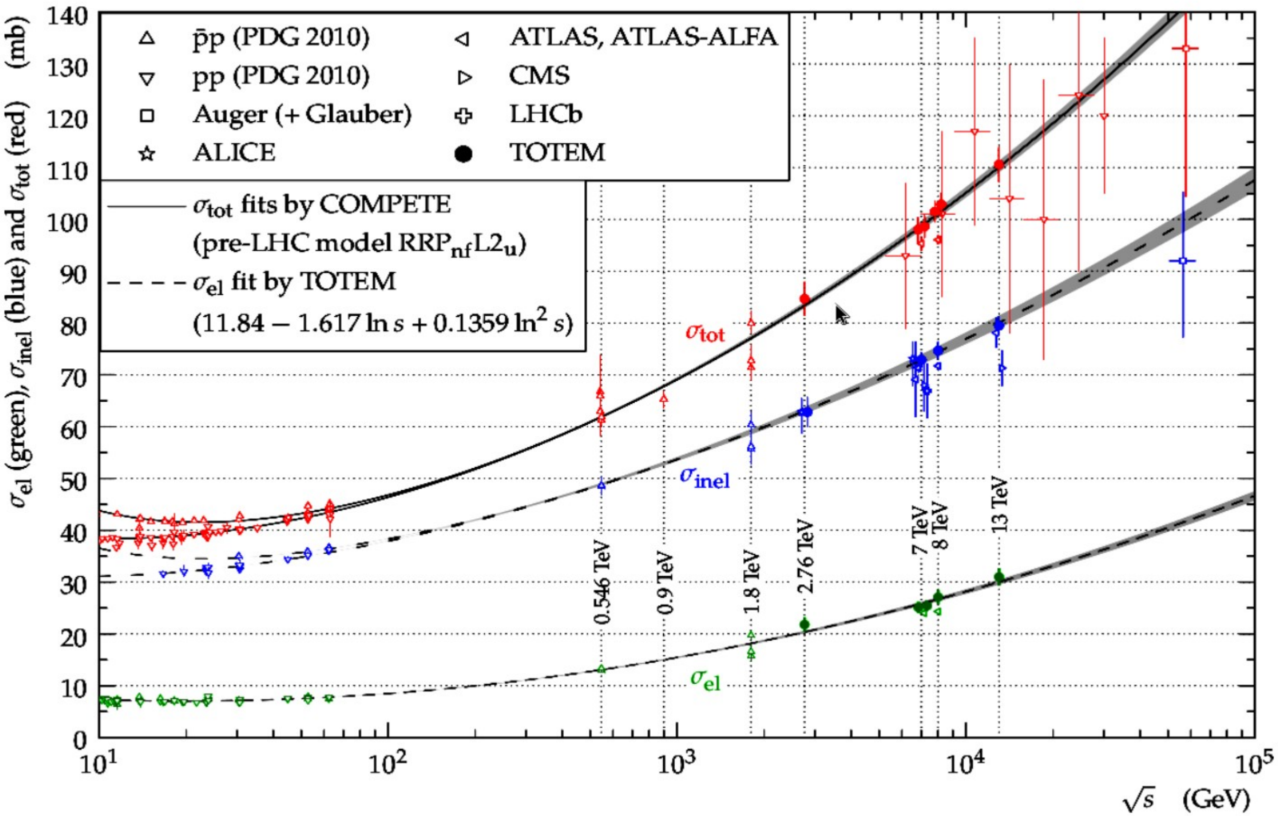
X_{max}

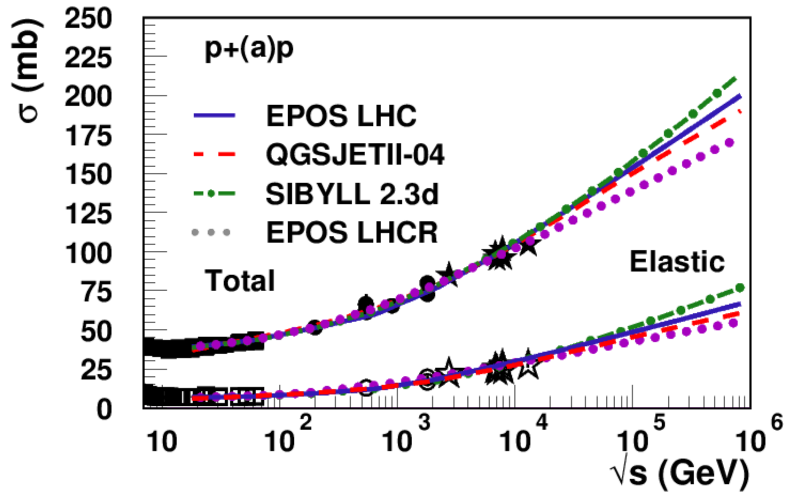
N_{μ}

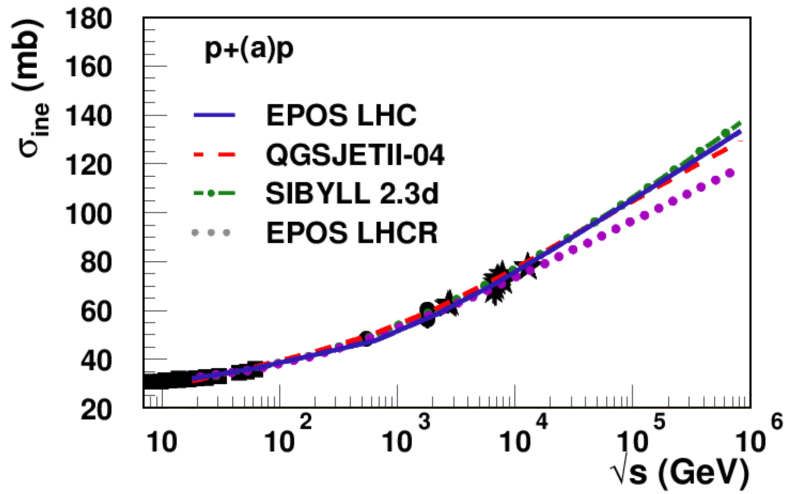
- **Update of EPOS LHC → EPOS LHCR**
  - New EPOS 4 available soon for heavy ion physics but not usable for air showers (yet)
  - Modify EPOS LHC to take into account new data and new knowledge accumulated with EPOS 4
  - Very preliminary results !

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

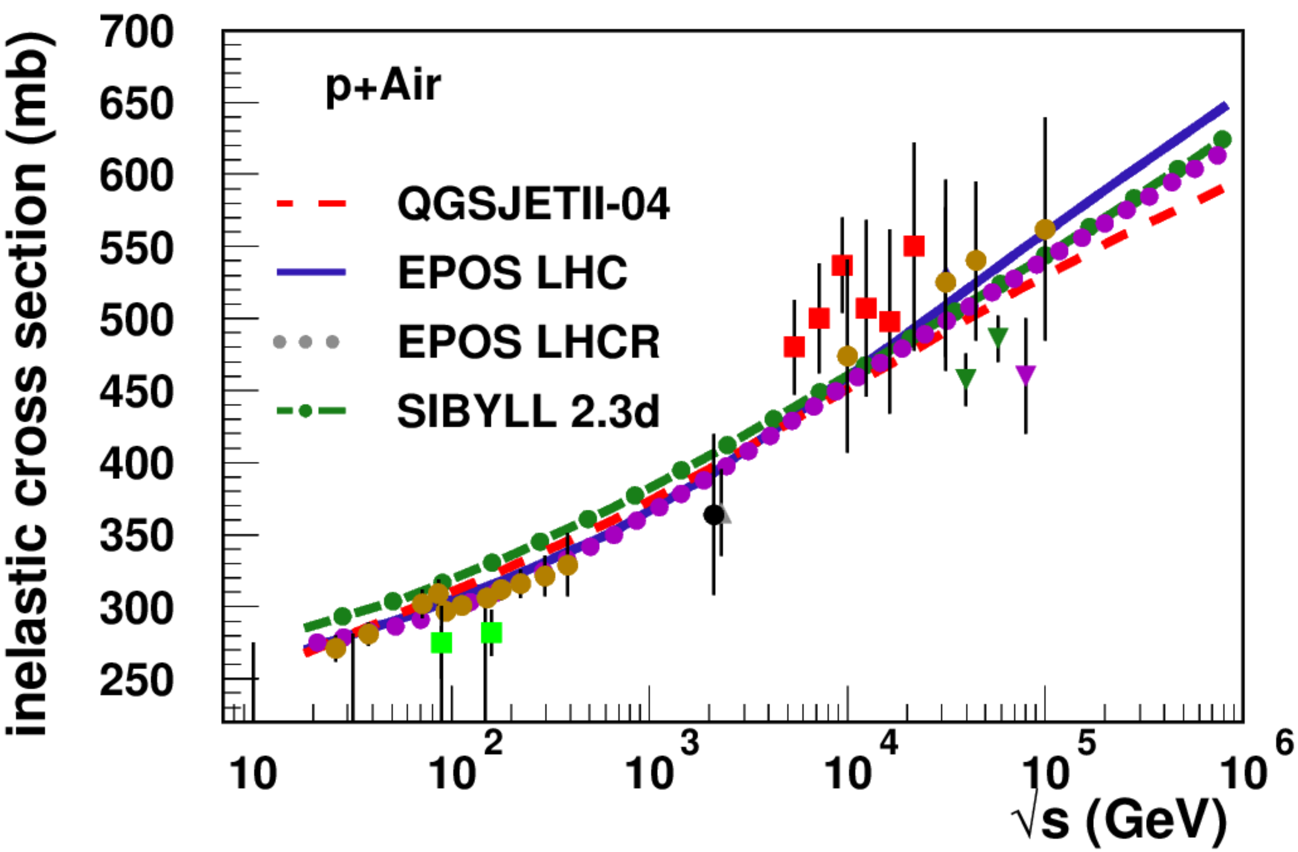


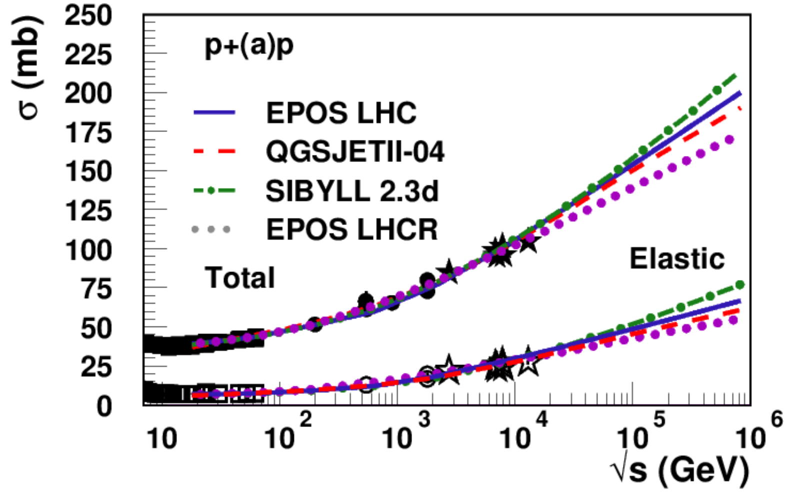


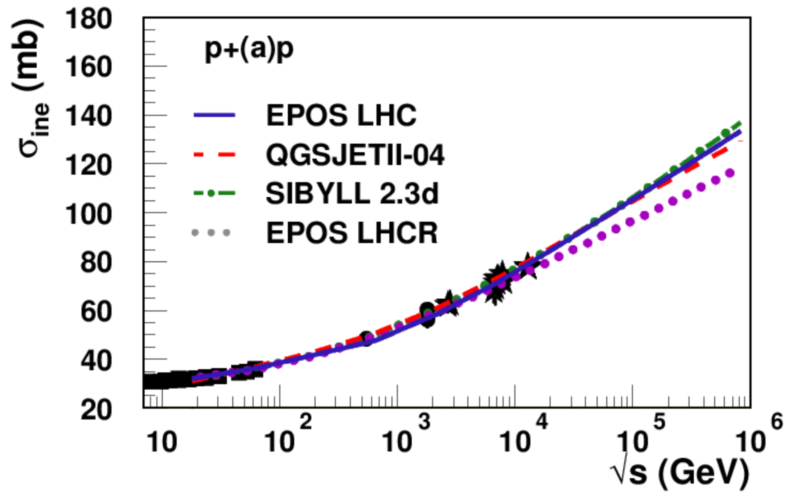


Cross-Section Reduced

- **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

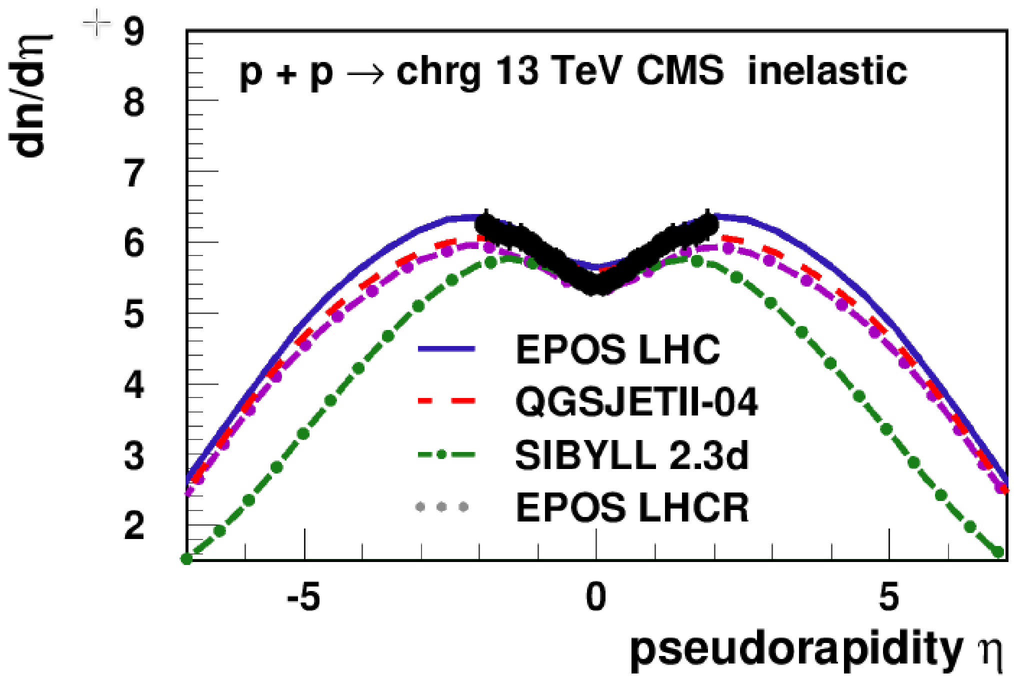


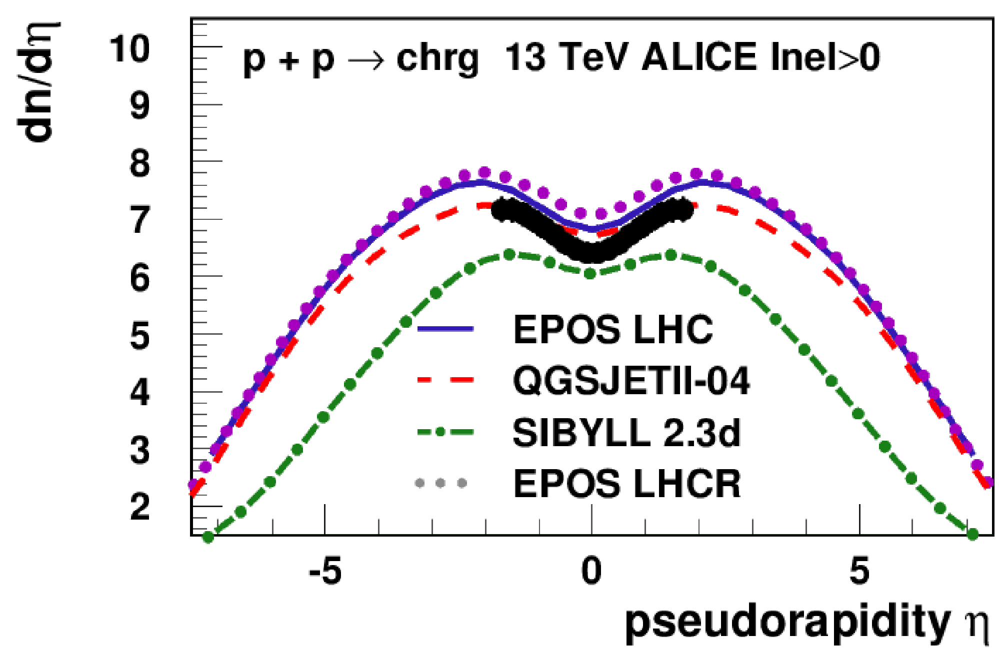




Pseudorapidity 13 TeV

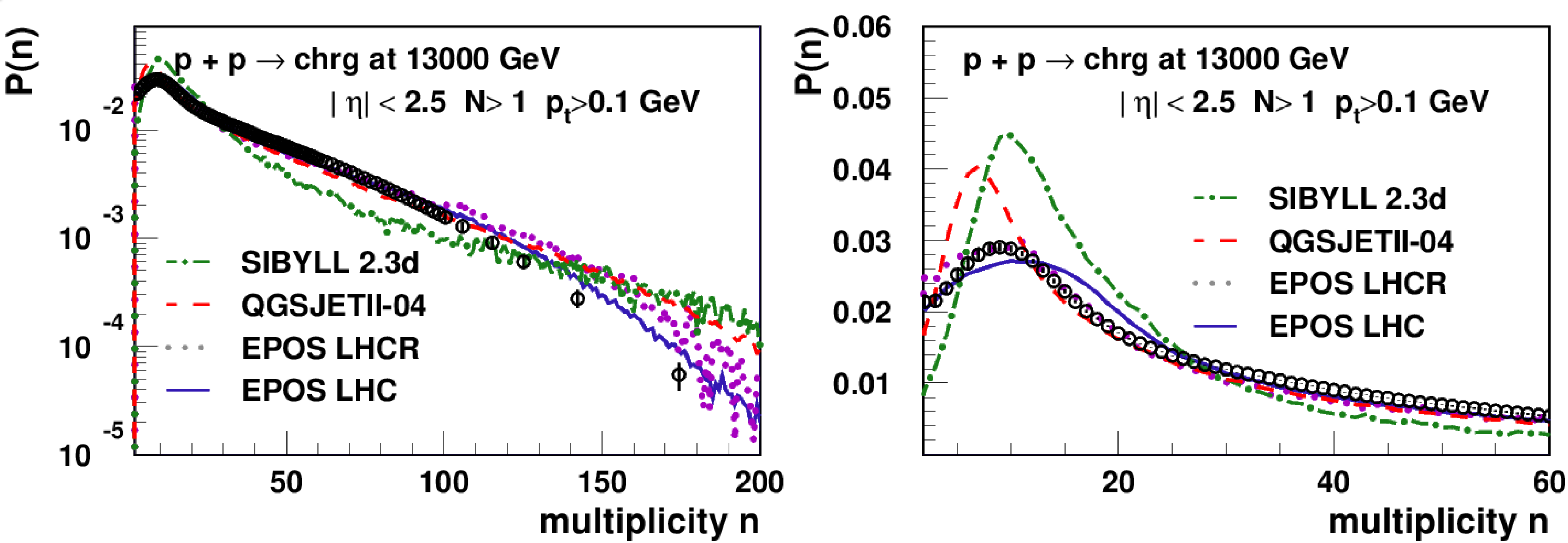
- **Angular distribution of newly produced particles**
- **New data at 13 TeV in p-p**
  - ➜ Test extrapolation
  - ➜ Different triggers
  - ➜ Sibyll has a clear difference with other models (and data)





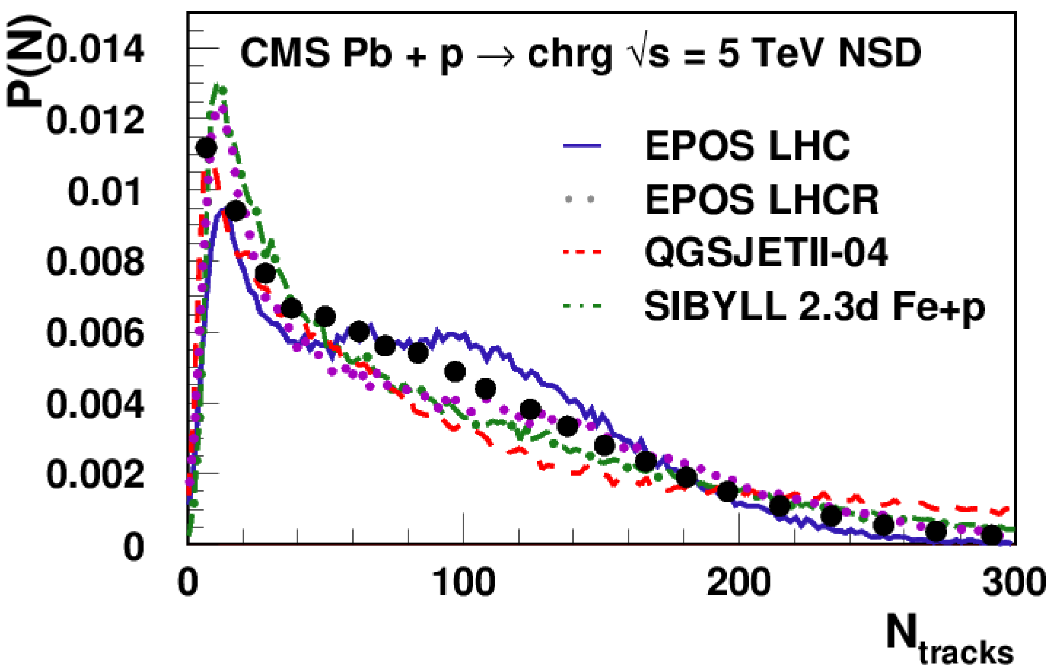
Multiplicity 13 TeV

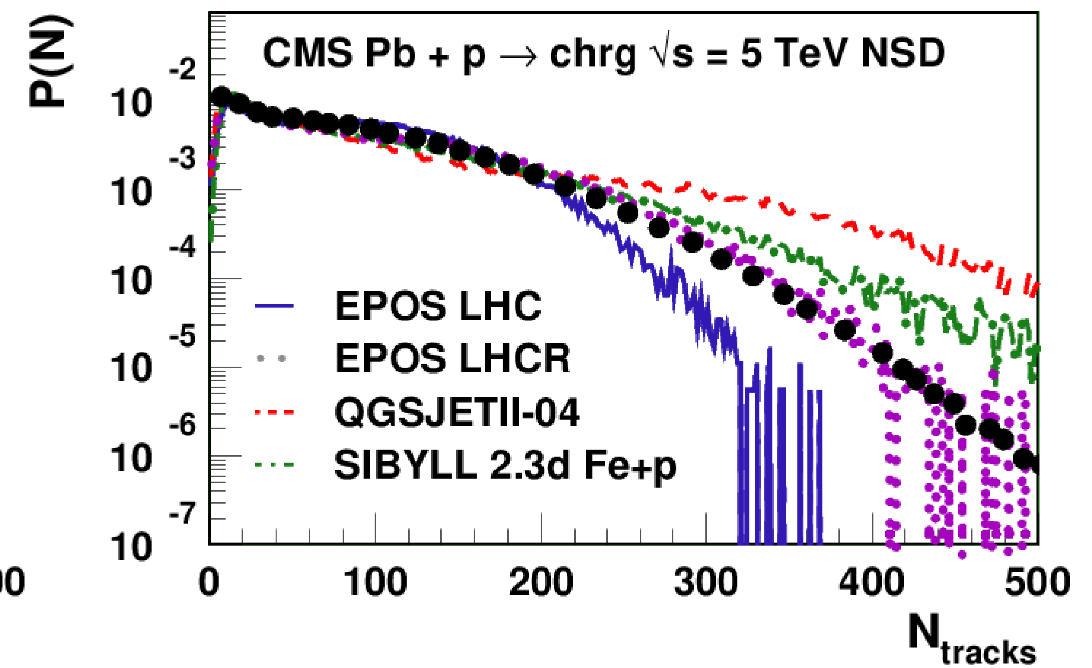
- **Probability of a given multiplicity**
- **New data at 13 TeV in p-p**
  - Not well reproduced by models except EPOS (energy sharing)
  - More attention should be payed to low multiplicities (high elasticity)
    - Problem was already here at 7 TeV but increasing



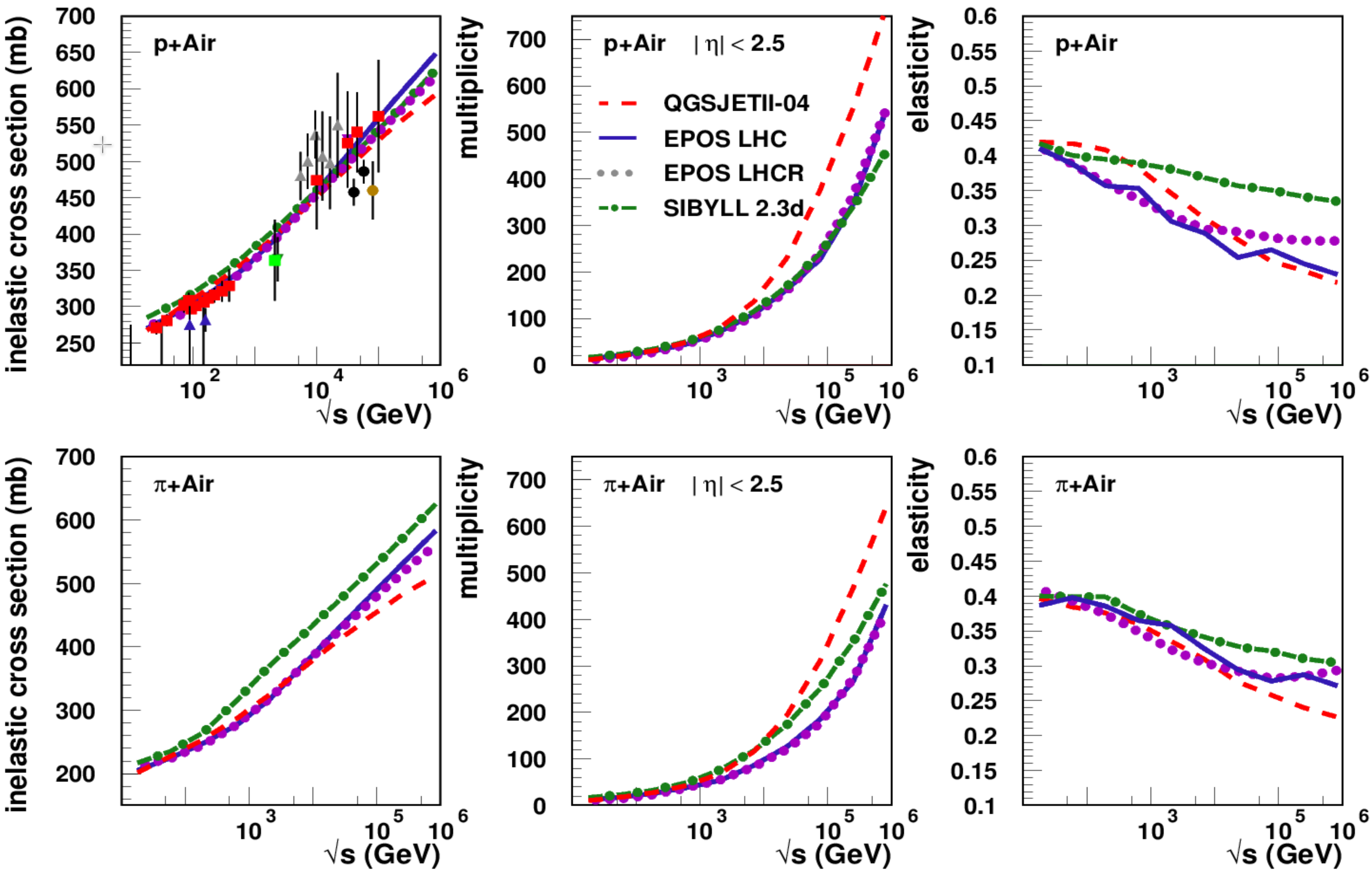
Multiplicity 5 TeV p-Pb

- **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)





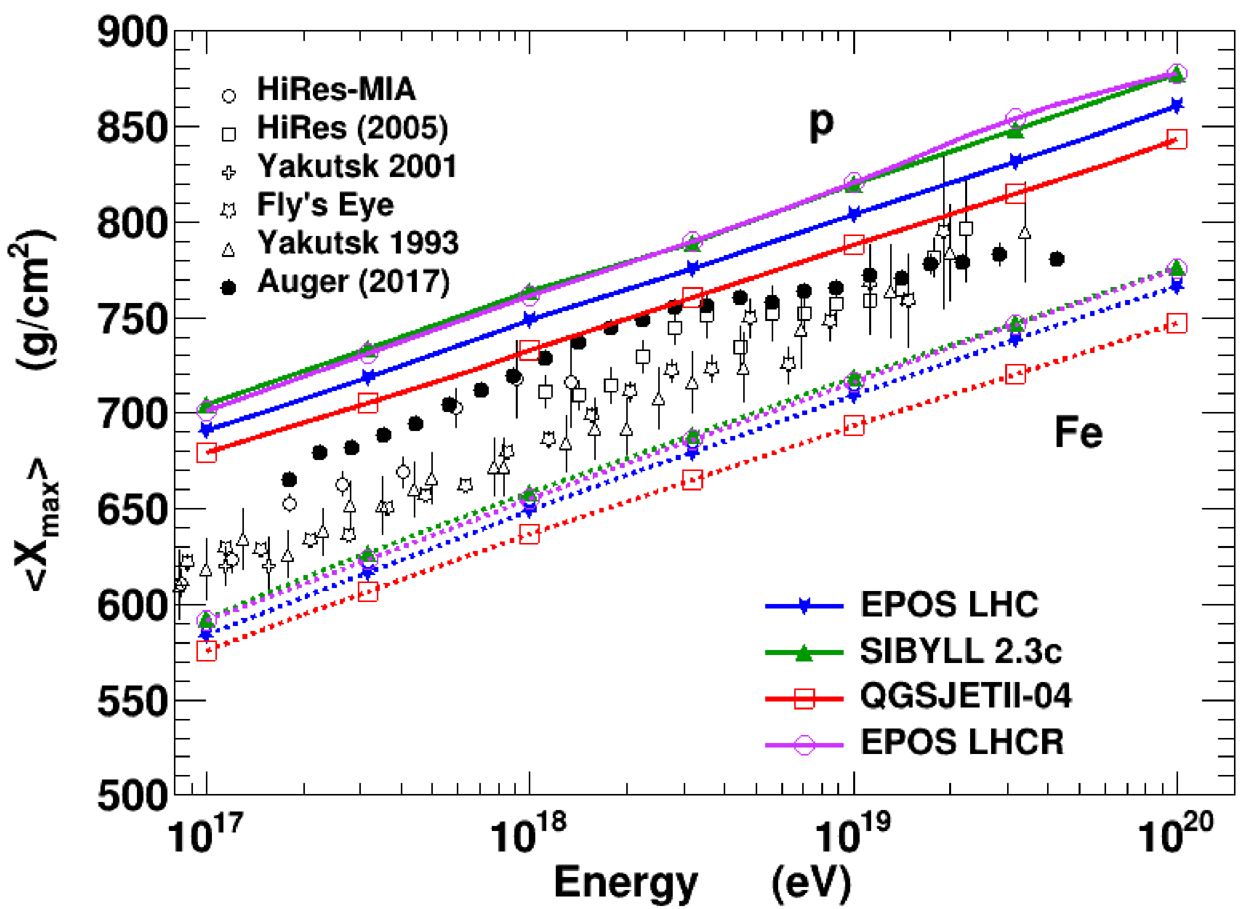
EPOS LHCR interaction with Air



X_{max}

+/- 20g/cm² 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/cm² (=Sibyll)

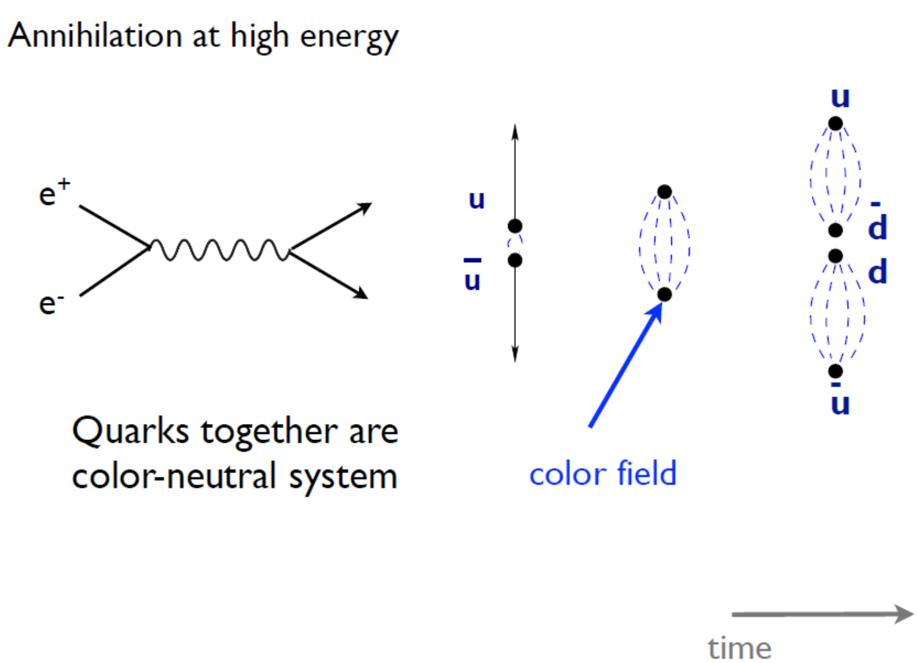


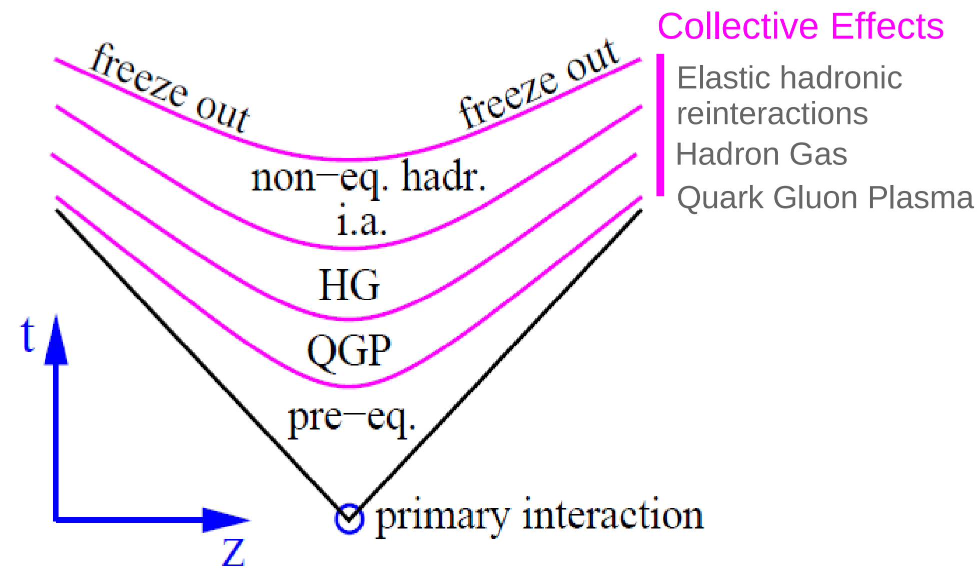
Correction of nuclear fragmentation in EPOS :
X_{max} RMS Fe
LHC=20g/cm2
LHCR=22g/cm2
SIB=25g/cm2
QII=25g/cm2

Hadronization Models

2 models well established for 2 extreme cases

- String Fragmentation vs Collective hadronization (statistical models)





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

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

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

Hadronization in Simulations

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

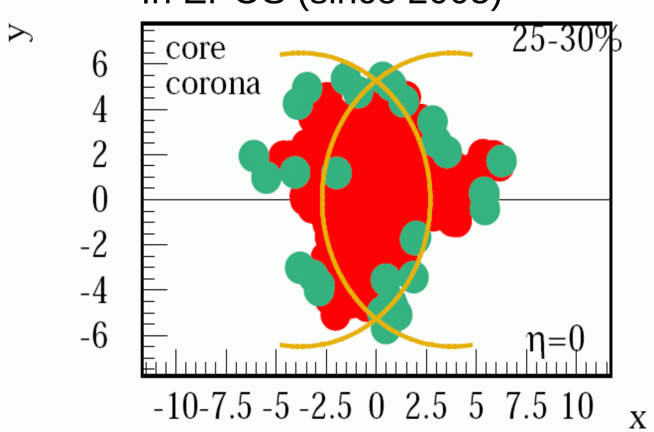
  - ➡ Light system are not “dense”
  - ➡ Works relatively well at SPS (low energy)
  - ➡ But problems already at RHIC, clearly at Fermilab, and serious at LHC :
    - Modification of string fragmentation needed to account for data
    - Various phenomenological approaches :
      - ➡ Color reconnection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

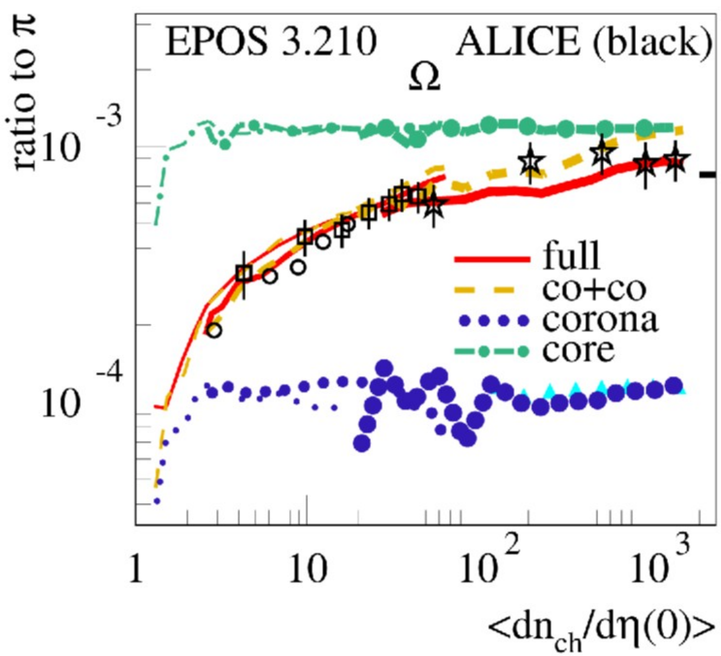
- **Statistical model only used for heavy ion (HI) in combination with hydrodynamical evolution of the dense system : QGP hadronization**
  - ➡ Account for flow effects, strangeness enhancement, particle correlations...

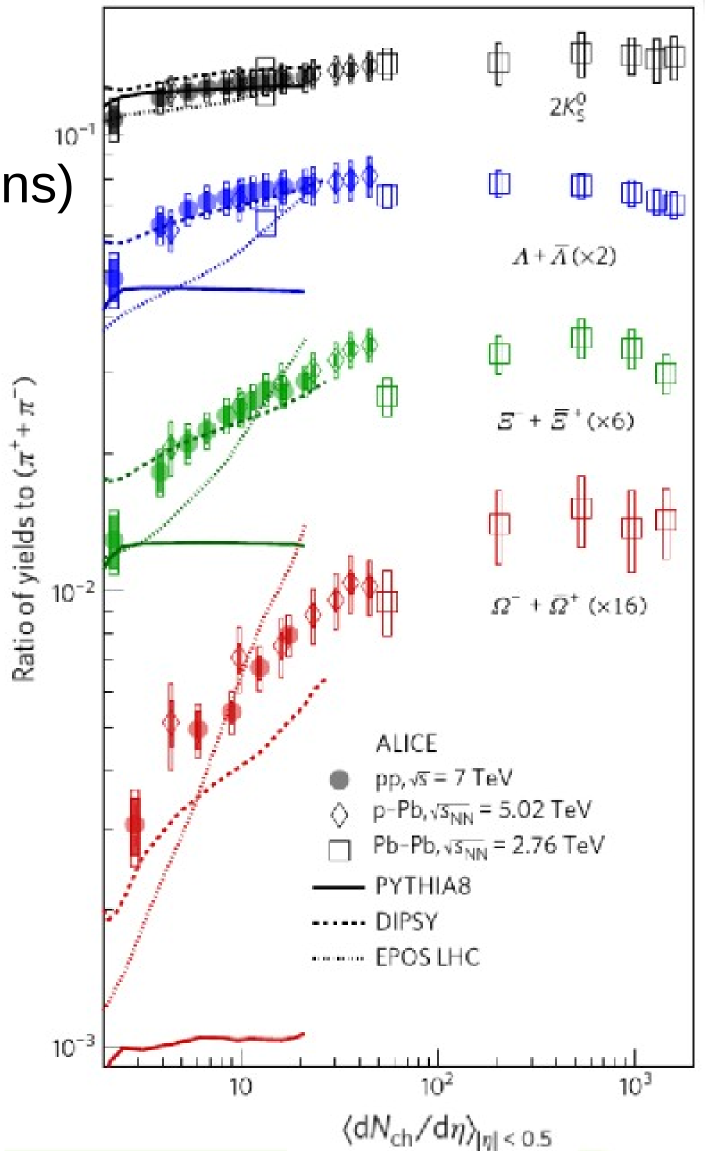
Core-Corona Approach

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

In EPOS (since 2005)



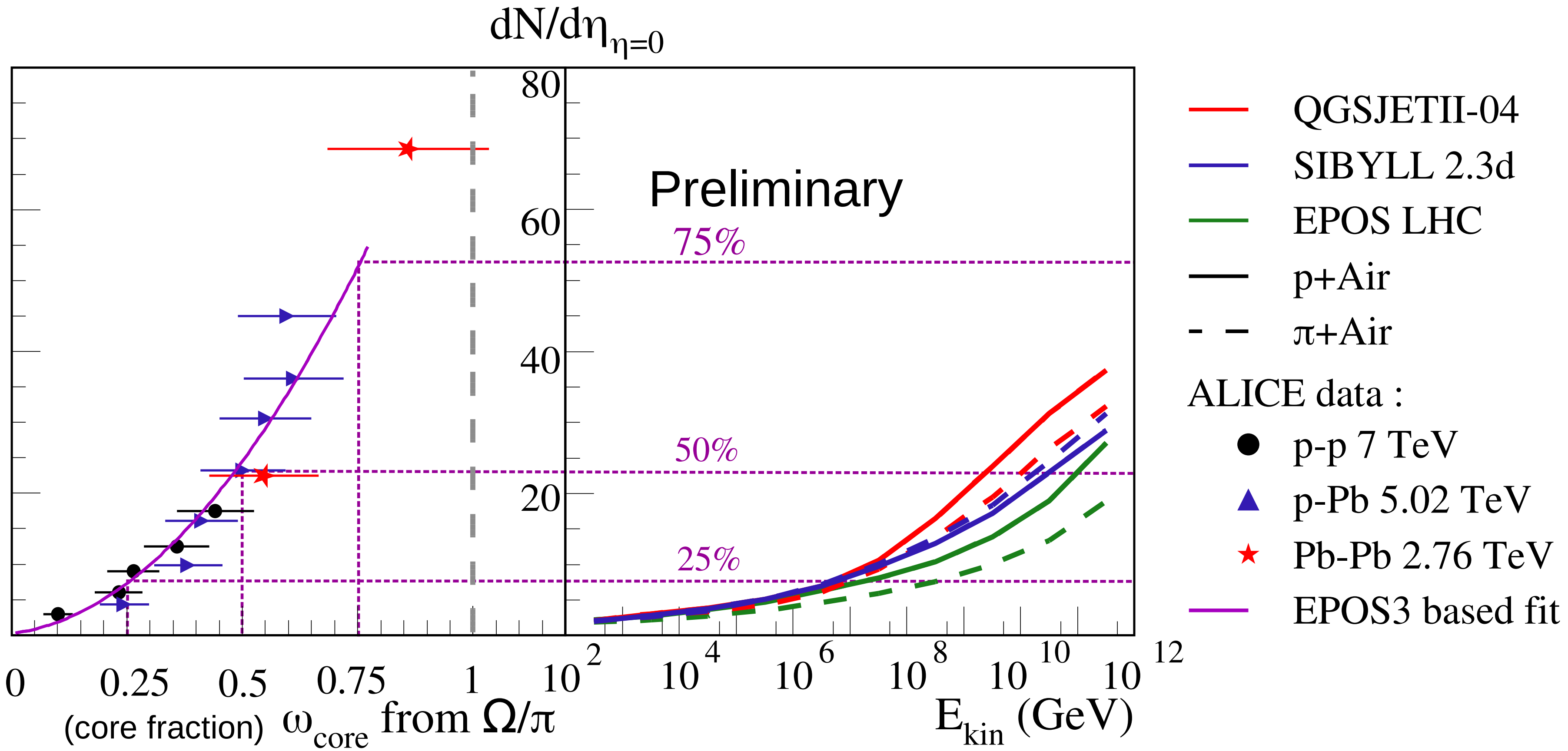




Particle Densities in Air Showers

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

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



Core-Corona appoach and CR

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

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

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

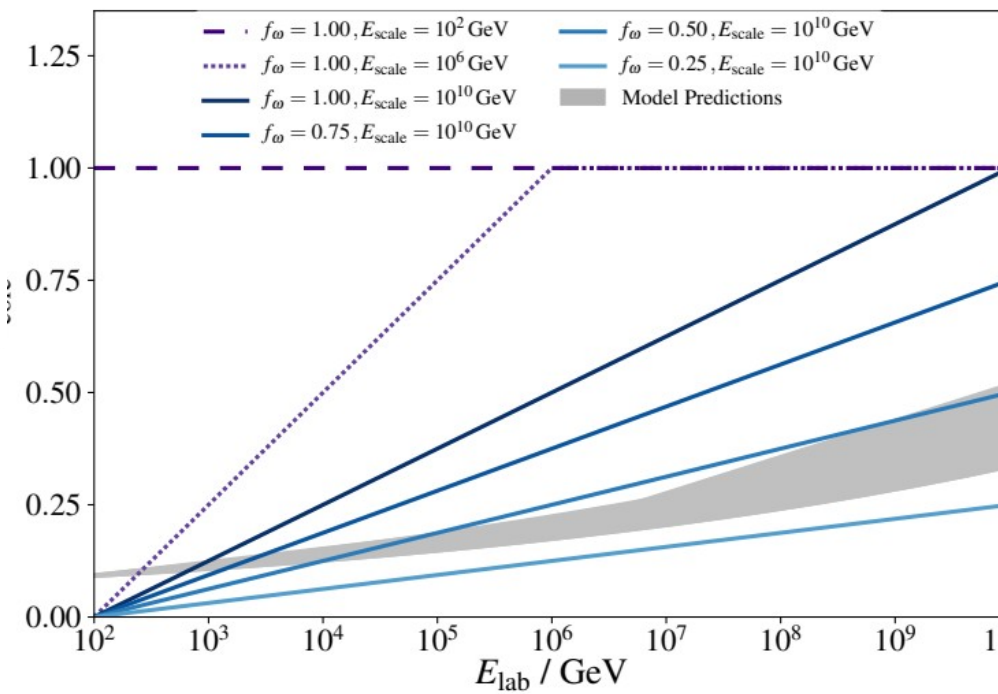
$$\frac{\log_{10}(E_{\text{lab}}/E_{\text{th}})}{\log_{10}(E_{\text{scale}}/E_{\text{th}})} \quad \text{for } E_{\text{lab}} > E_{\text{th}}$$

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

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

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

arXiv:1902.09265

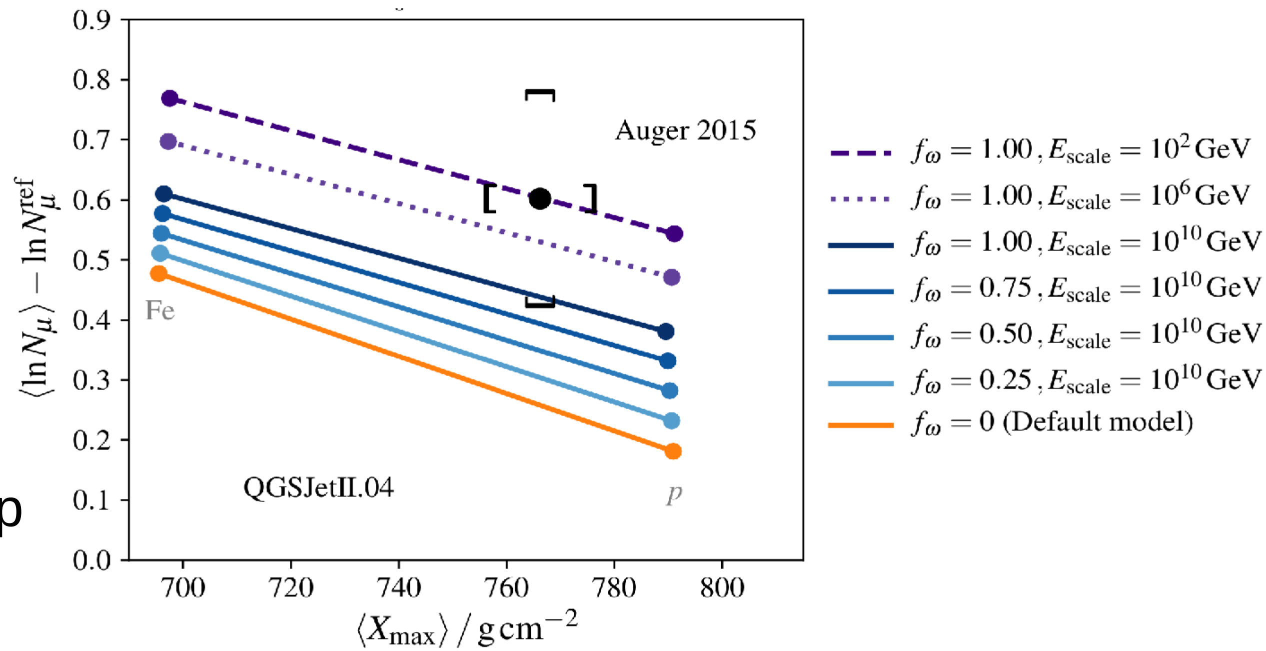


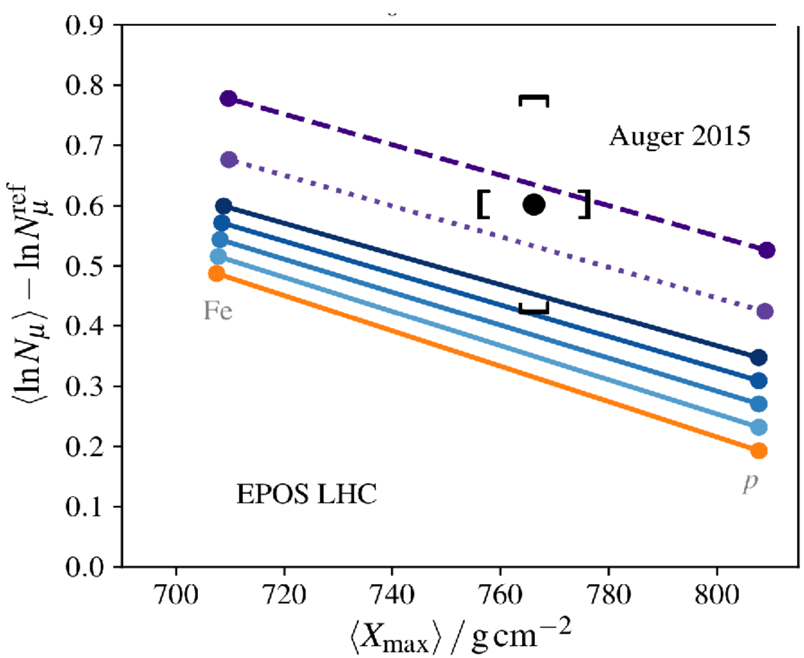
Plot by M. Perlin

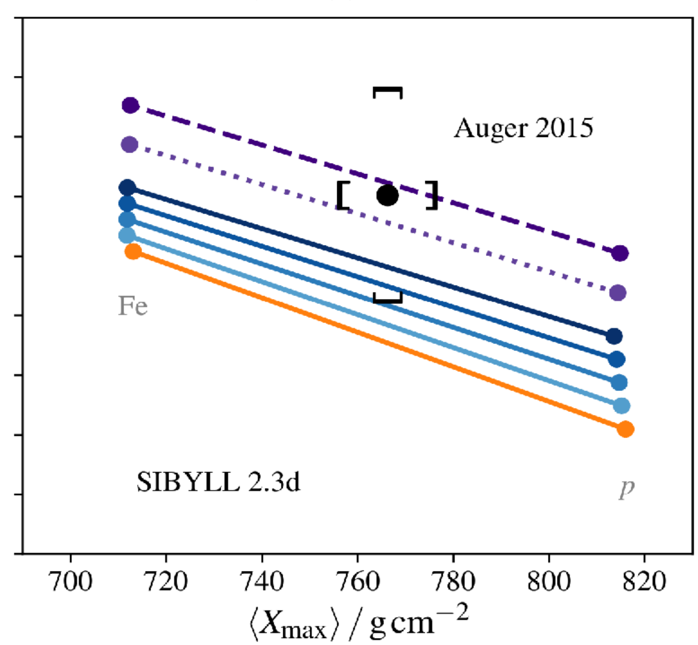
Results for X_{max}-N_{mu} correlation

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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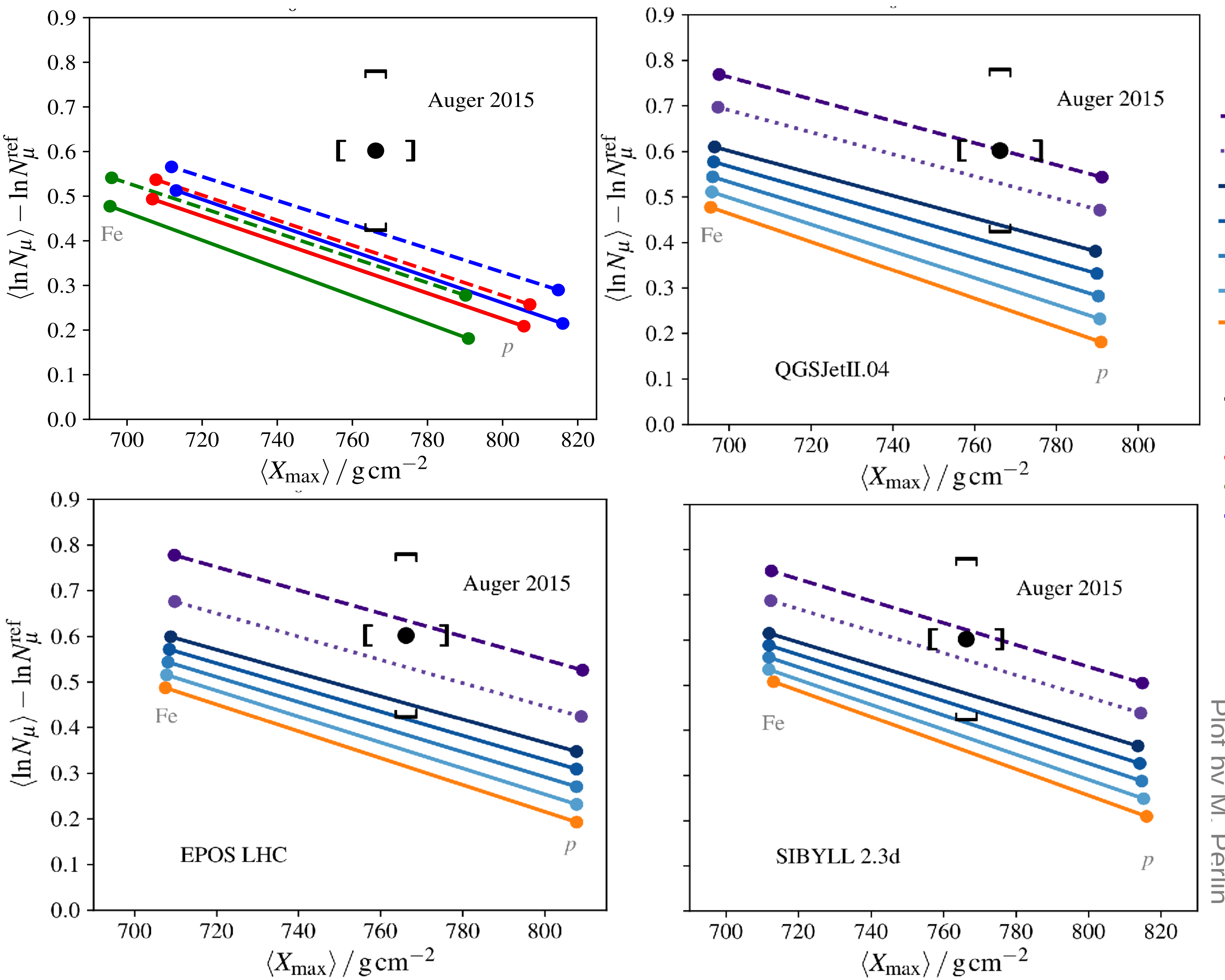
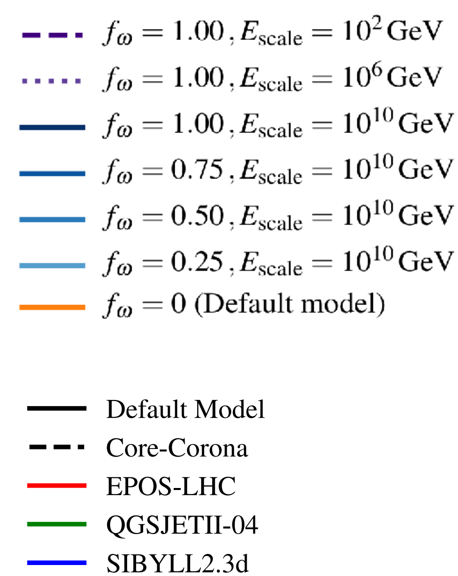


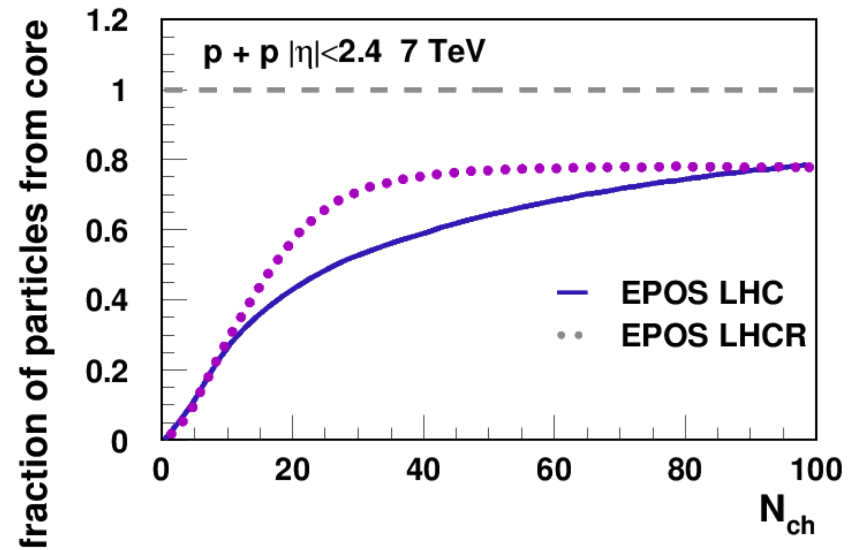


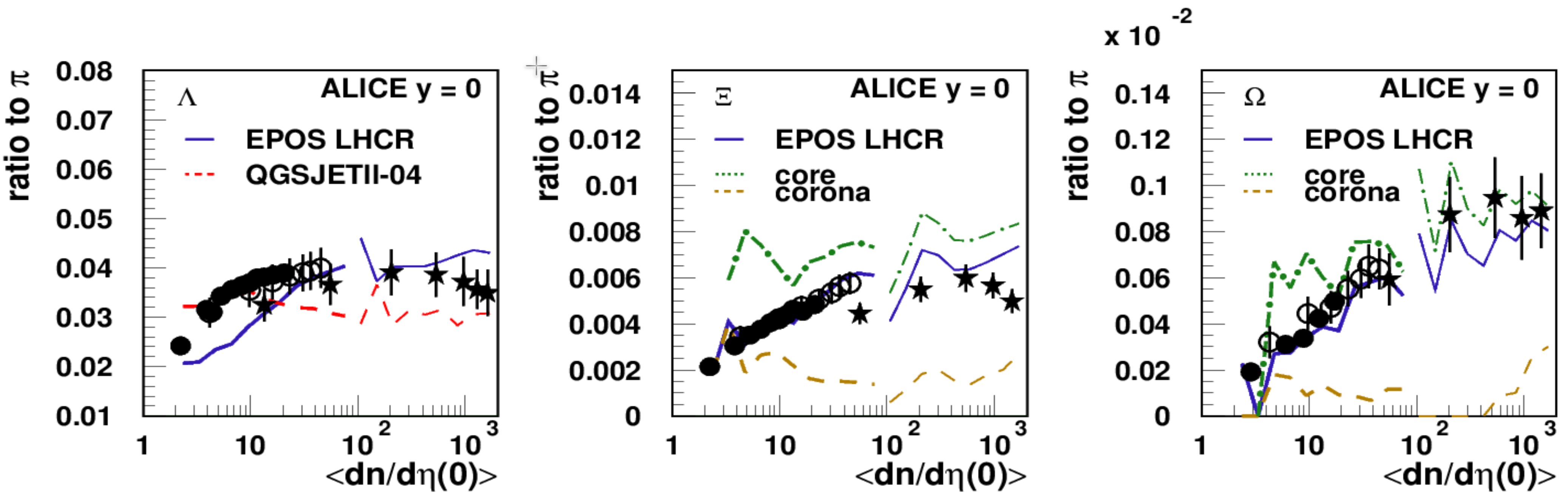
Forward core fraction unknown and not necessarily lower that at mid-rapidity (saturation effect)

ALICE data

Update of EPOS to reproduce ALICE data

- Lower condition (particle density) to form core
- More core

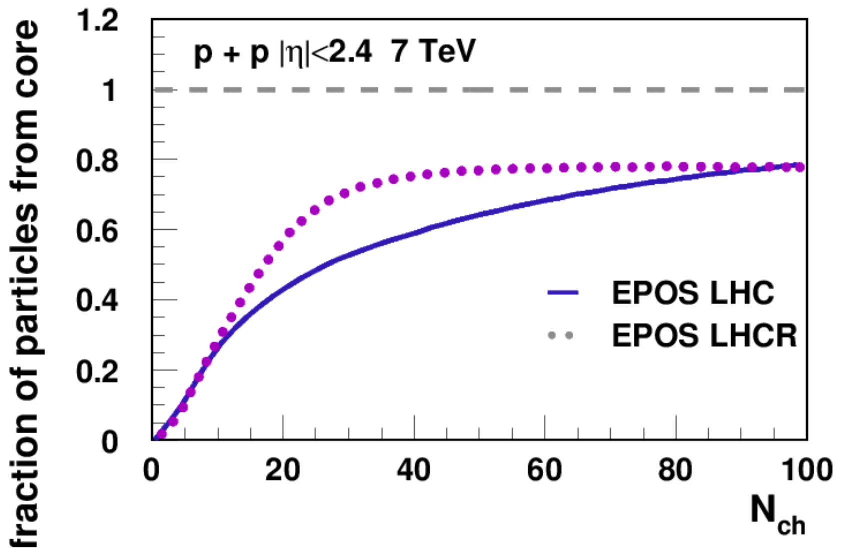


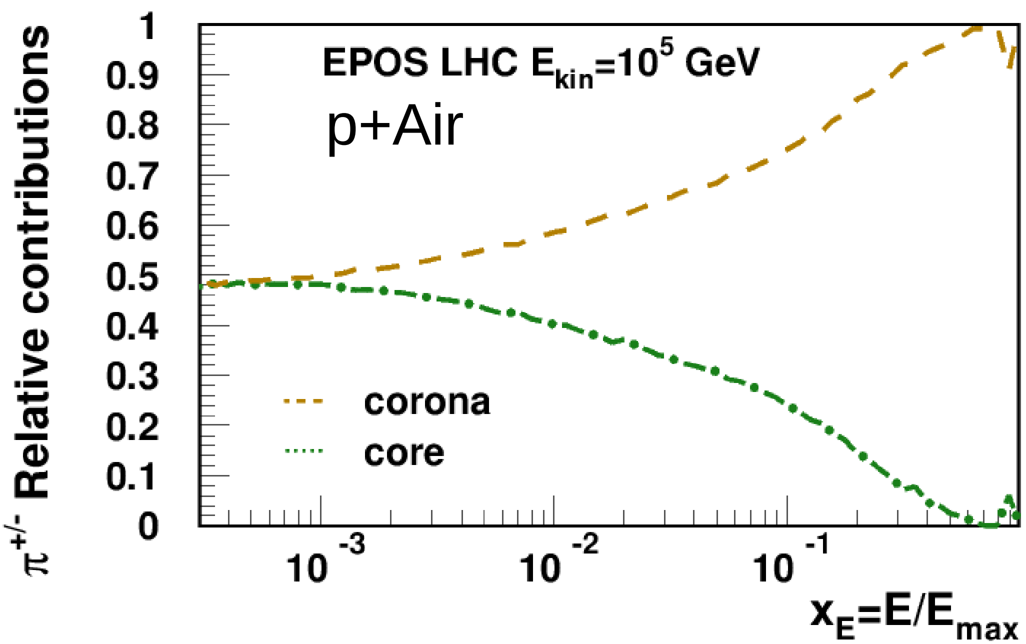


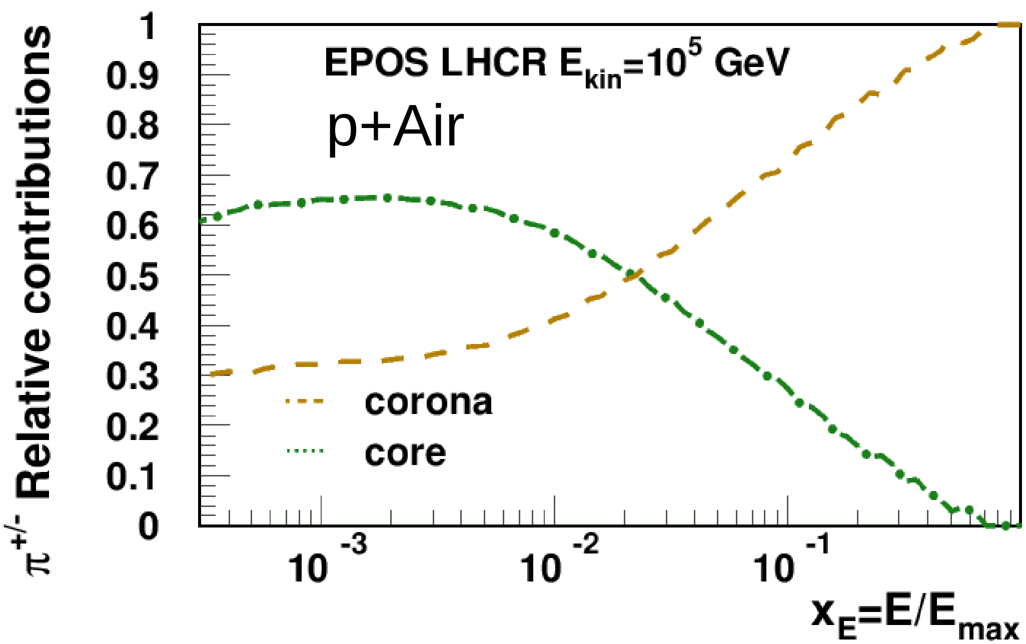
Interactions in Air Showers

Update of EPOS to reproduce ALICE data

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







Summary

- **Not all relevant CERN data taken into account in model yet.**
  - 10 more years of LHC data
  - New results from SPS (NA61 - 2209.10561 [nucl-ex])

- **Updated results of cross-sections and multiplicity fluctuations**
  - Significant impact on X_{max}
  - Larger <lnA>

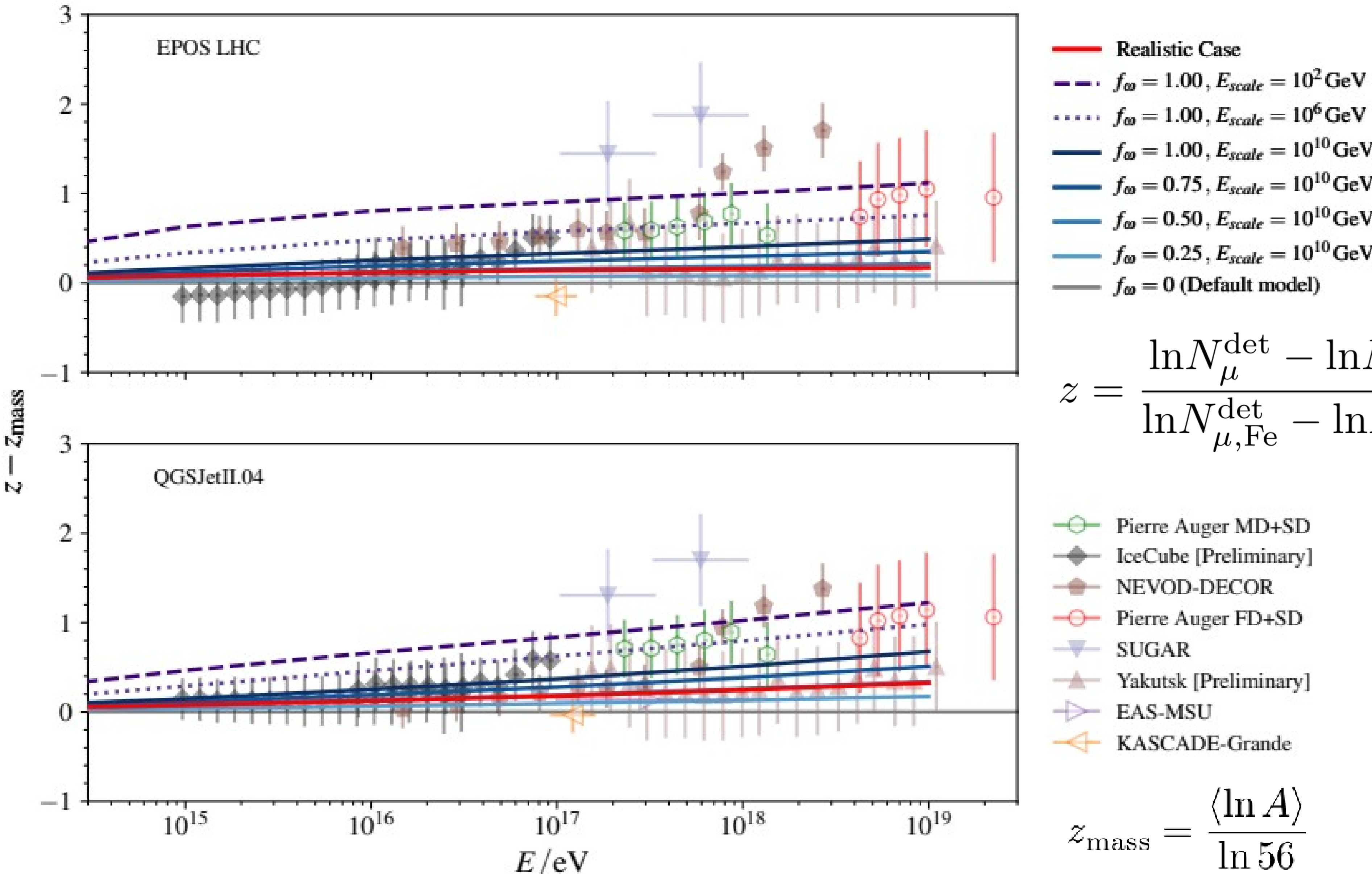
- **Evolution of strangeness with multiplicity**
  - Different type of hadronization
    - extended range for QGP-like hadronization could be sufficient with current global uncertainties to solve the muon puzzle ? (energy, X_{max}, ...)
  - New physics still needed ?

- **Updated EPOS LHCR to be released before next ICRC**

Recent LHC data provide new constraints on models changing X_{max} and QGP-like hadronization could be more common than thought until now which will impact muon production.

Thank you !

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

Constraints from Correlated Change

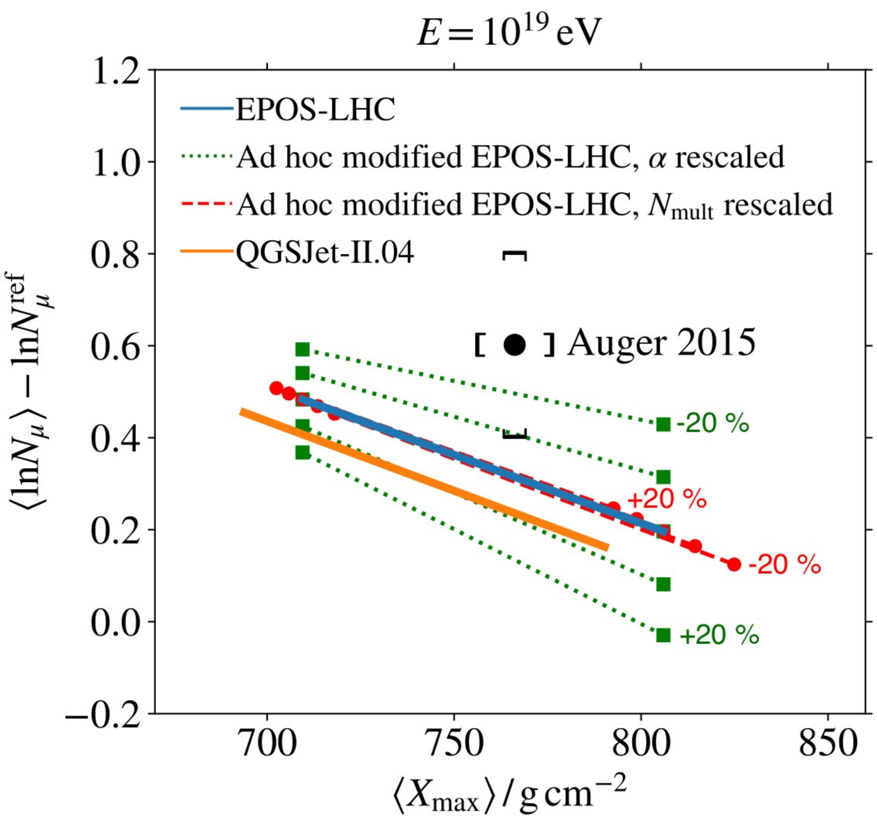
- **One needs to change energy dependence of muon production by ~+4%**

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

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

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

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



Plot by H. Dembinski

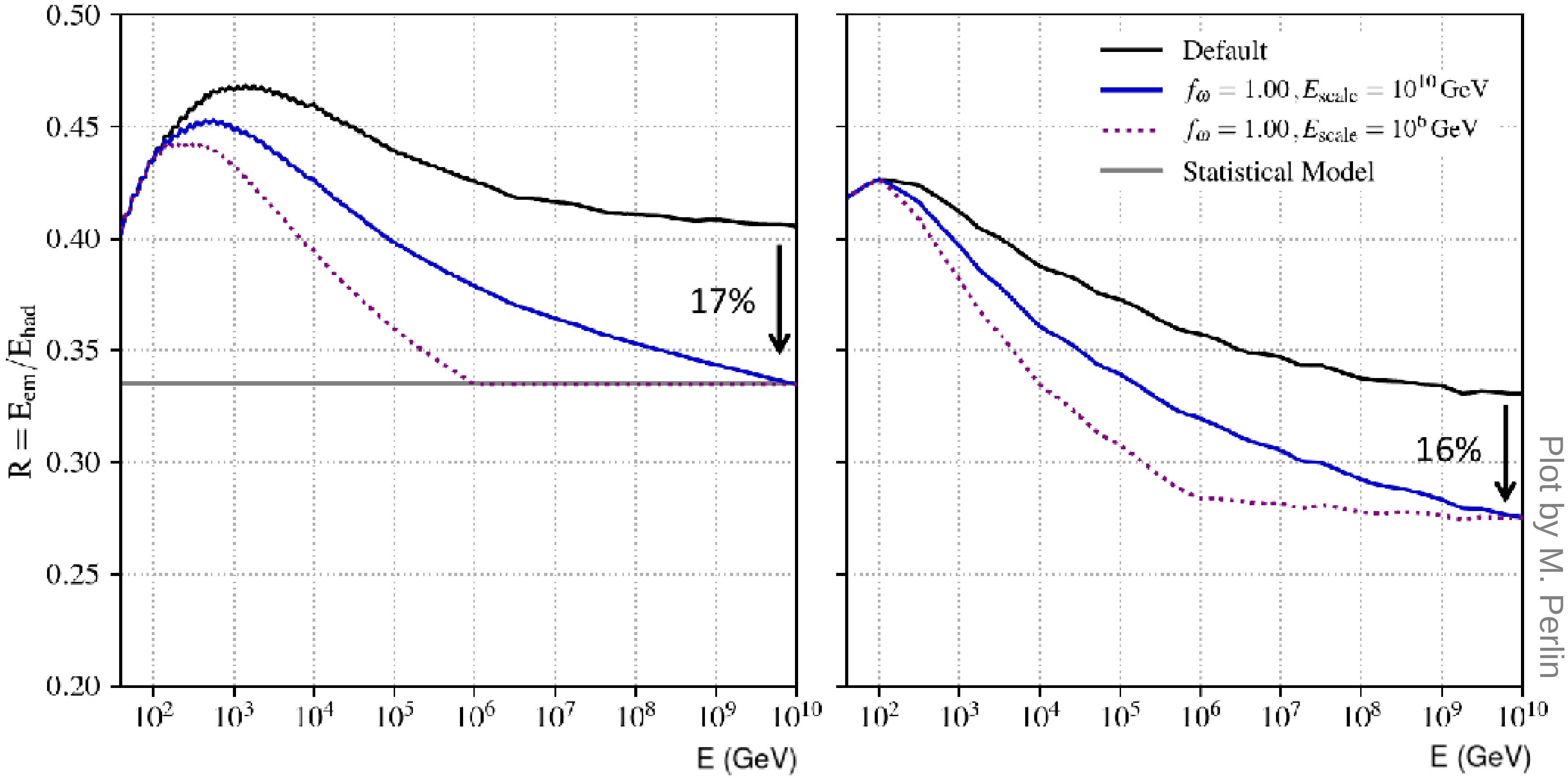
Evolution of hadronization from core to corona

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.

Mid-Rapidity EPOS LHC Forward (E/E_{int}=0.03-0.3)



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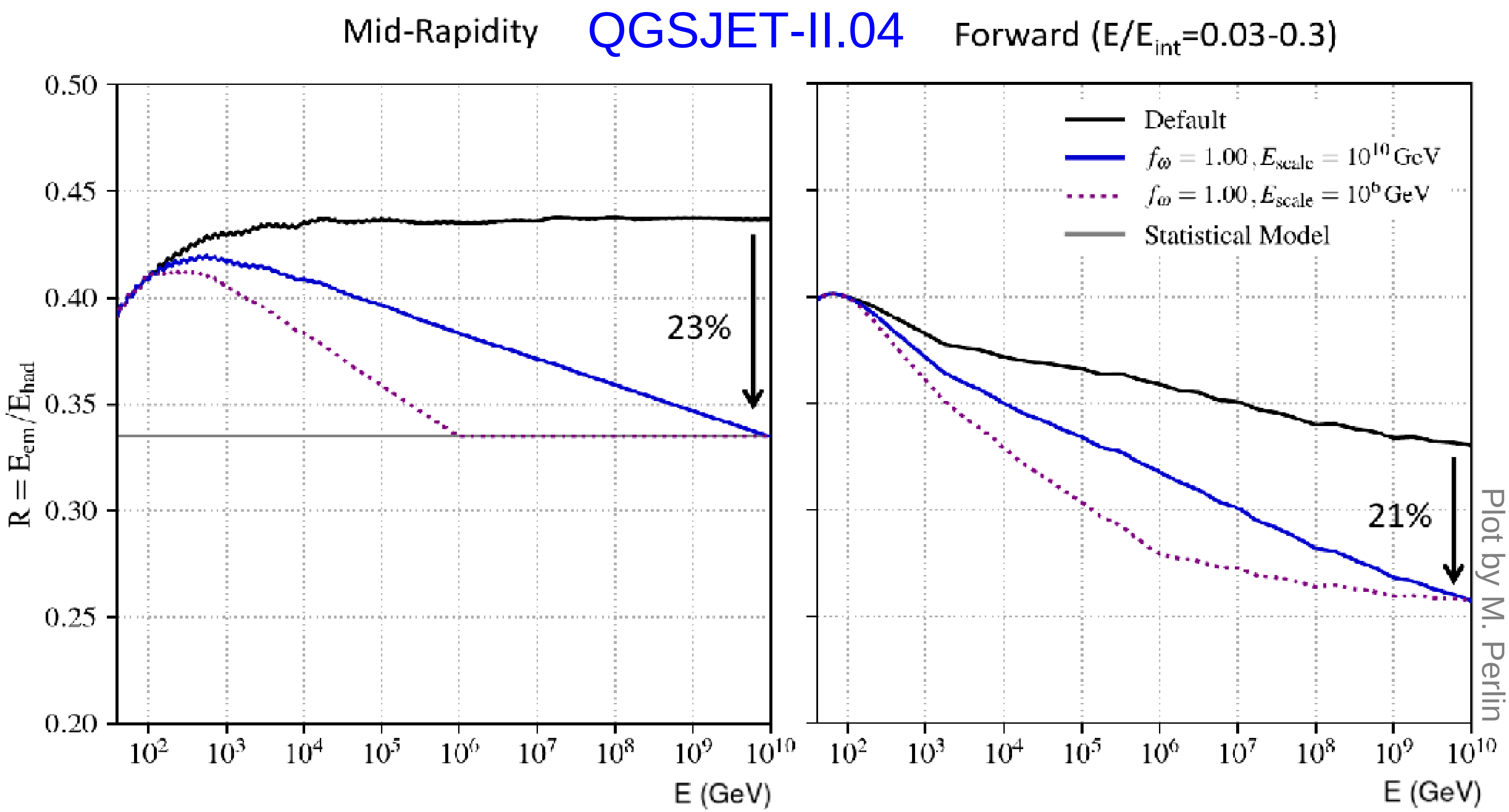

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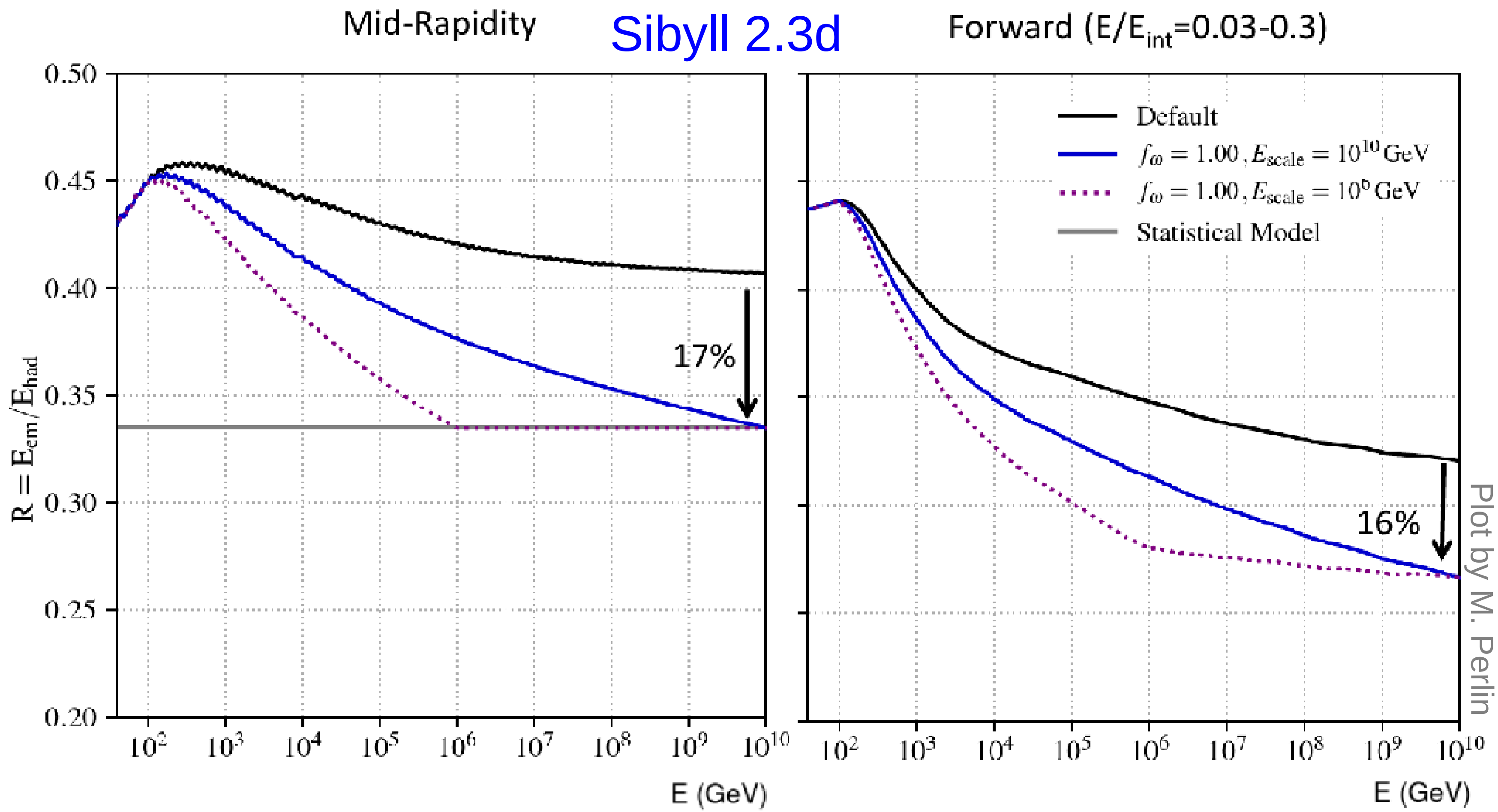
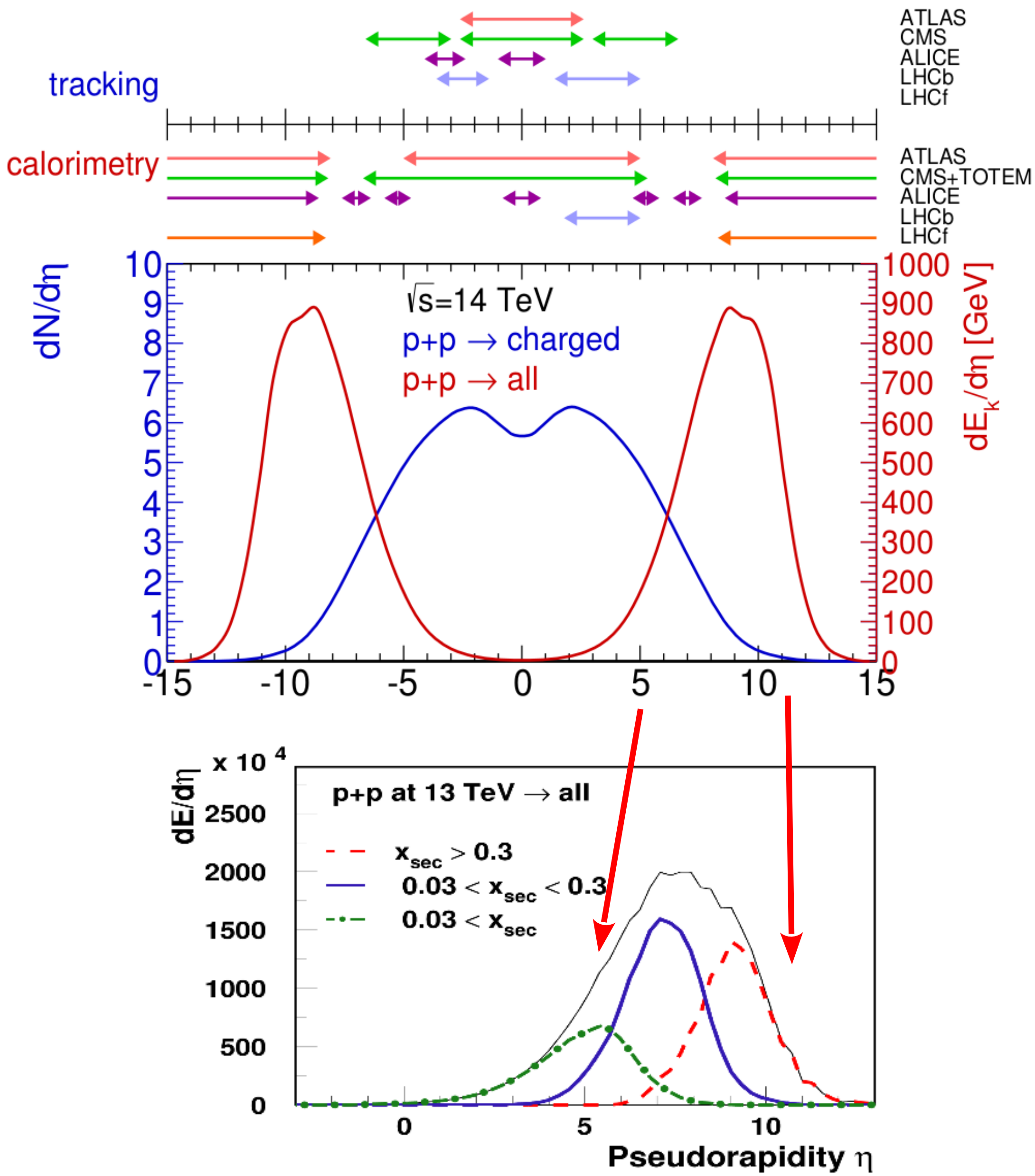


Possible Particle Physics Explanations

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

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

LHC acceptance and Phase Space

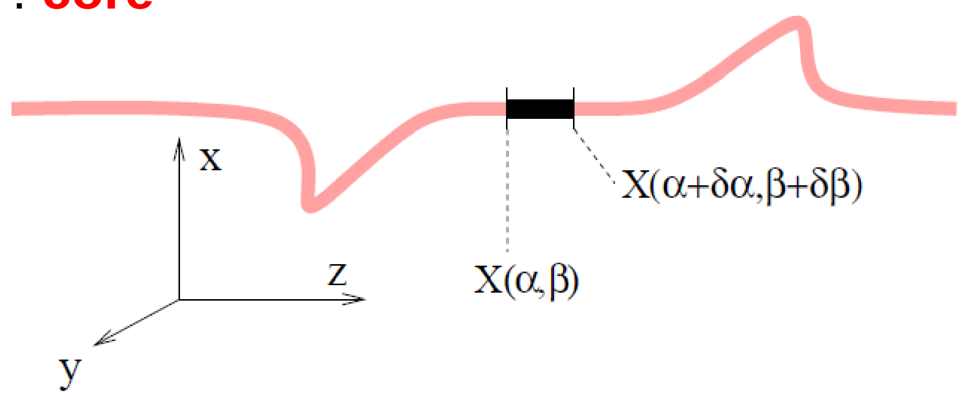


- **p-p data mainly from "central" detectors**
  - pseudorapidity $\eta = -\ln(\tan(\theta/2))$
  - $\theta = 0$ is midrapidity
  - $\theta >> 1$ is forward
  - $\theta << 1$ is backward
- **Different phase space for LHC and air showers**
  - most of the particles produced at midrapidity
    - important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

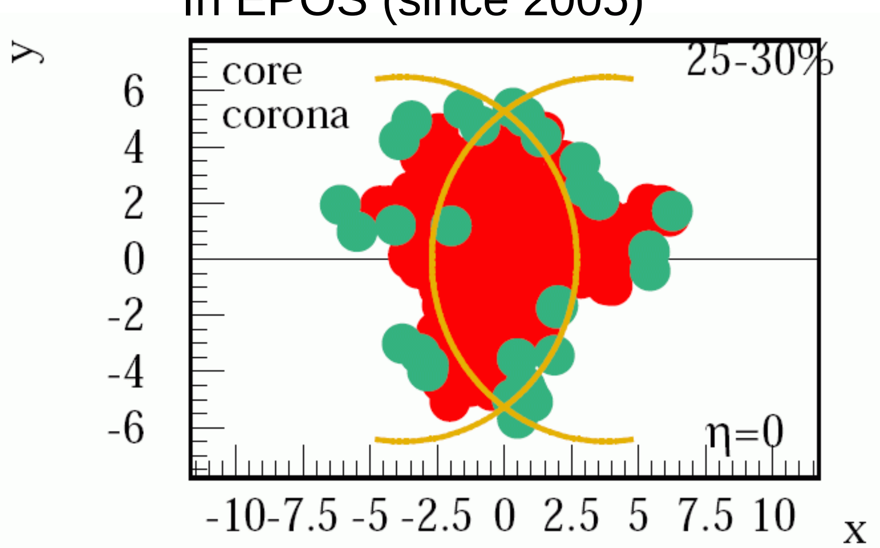
A 3rd way : the core-corona approach

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