Hadronic High Energy Interactions and Atmospheric Cascades

Tanguy Pierog and Ralph Engel

Karlsruhe Institute of Technology, Institut für Kernphysik,
Karlsruhe, Germany

Karlsruhe Institute of Technology

Ultra-High Energy Cosmic Ray, Nagoya

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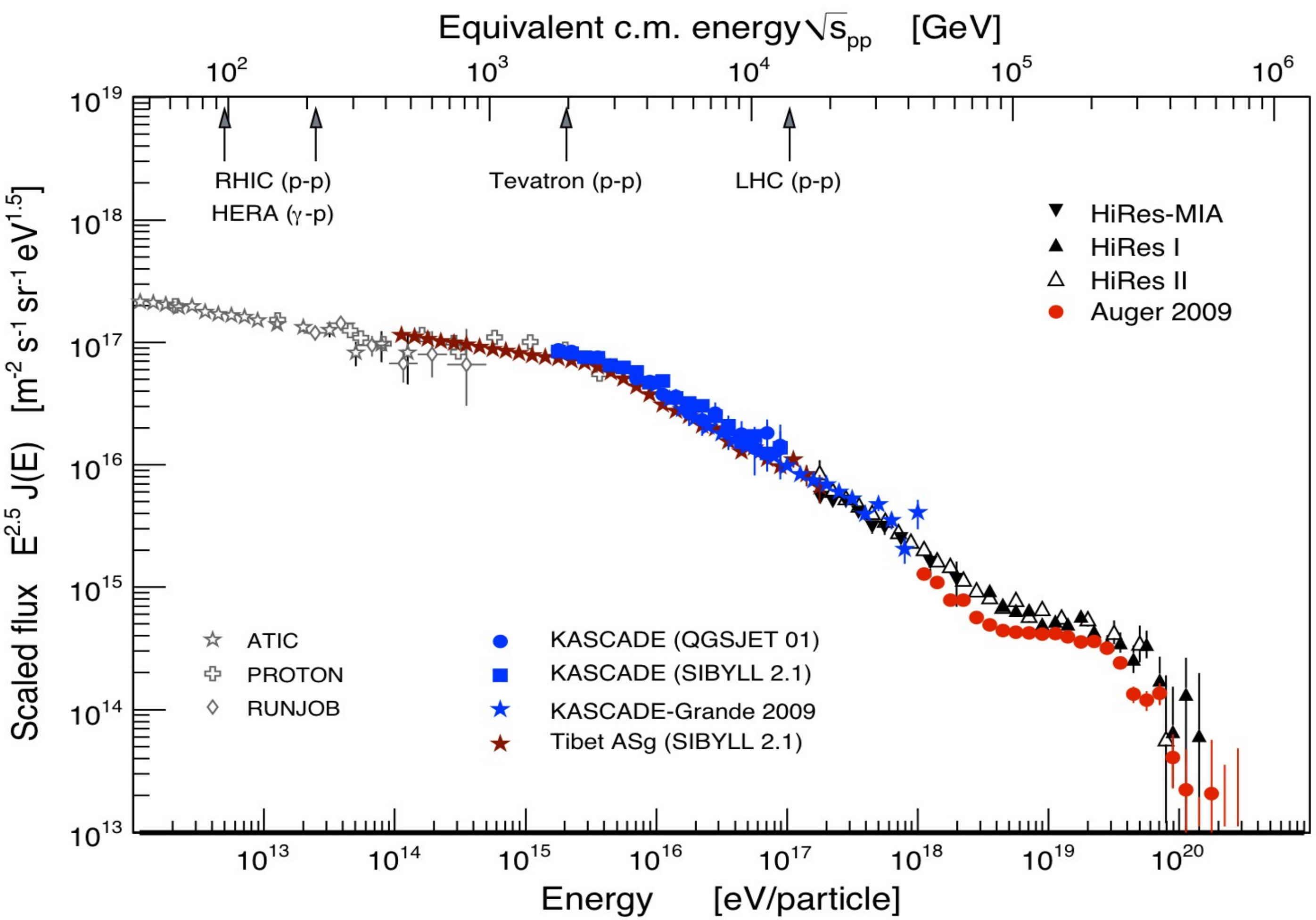
Introduction

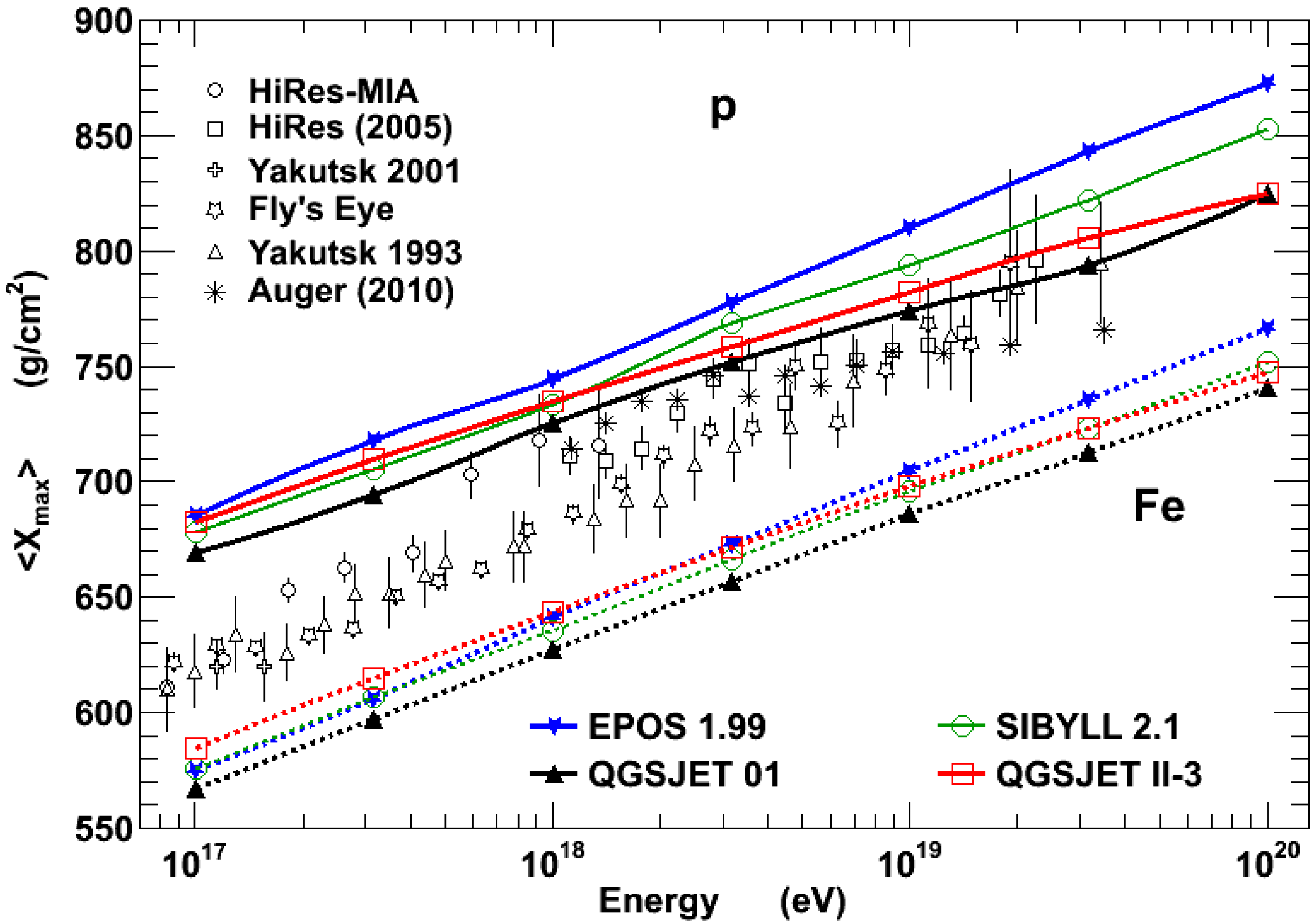


- **Most of analysis based on simulations**
  - CORSIKA
  - AIRES
  - COSMOS
  - CONEX, ...
- **Particle Physics in unknown regions**
  - Ultra-high energies
  - Small x (forward kinematic)

Outline

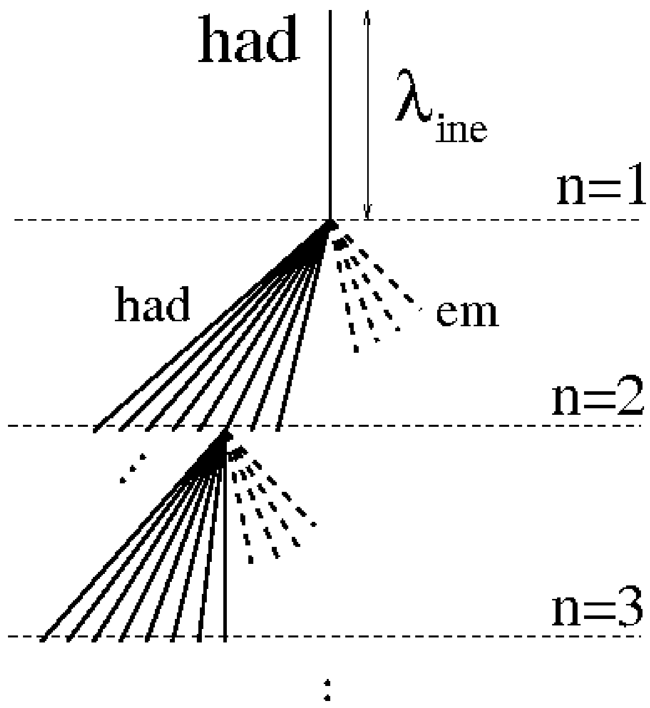
- **<Xmax>**
  - Elongation rate
  - Fluctuations
- **Energy scale**
  - FD vs SD
  - Muon number
- **Model Validity**
  - Theory
  - LHC comparison

<Xmax>



Large spread of model predictions !

<Xmax> Theory



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

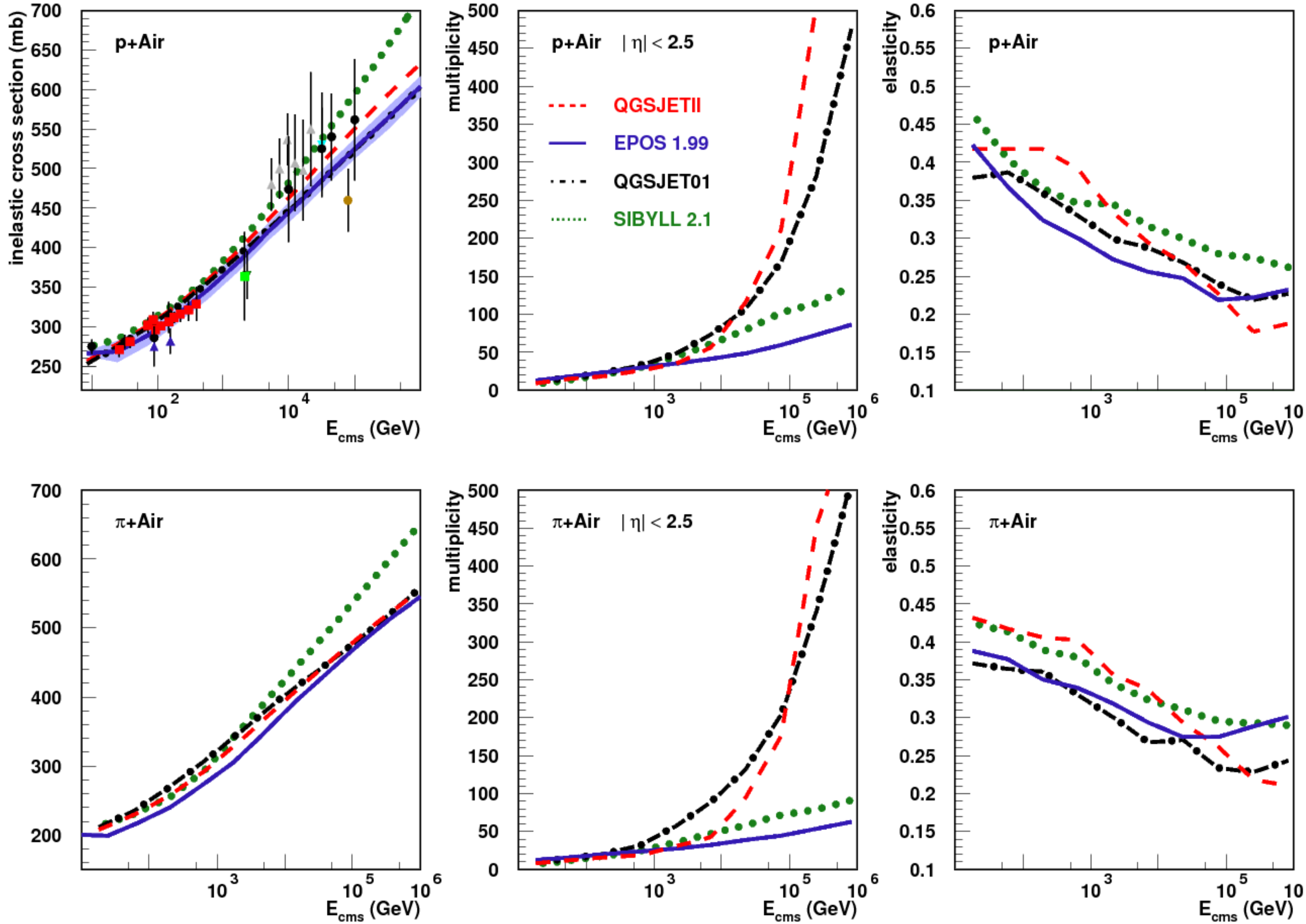
J. Matthews, Astropart.Phys. 22 (2005) 387-397

- **Using generalized Heitler model and superposition model :**

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

- 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

Hadronic Model Predictions

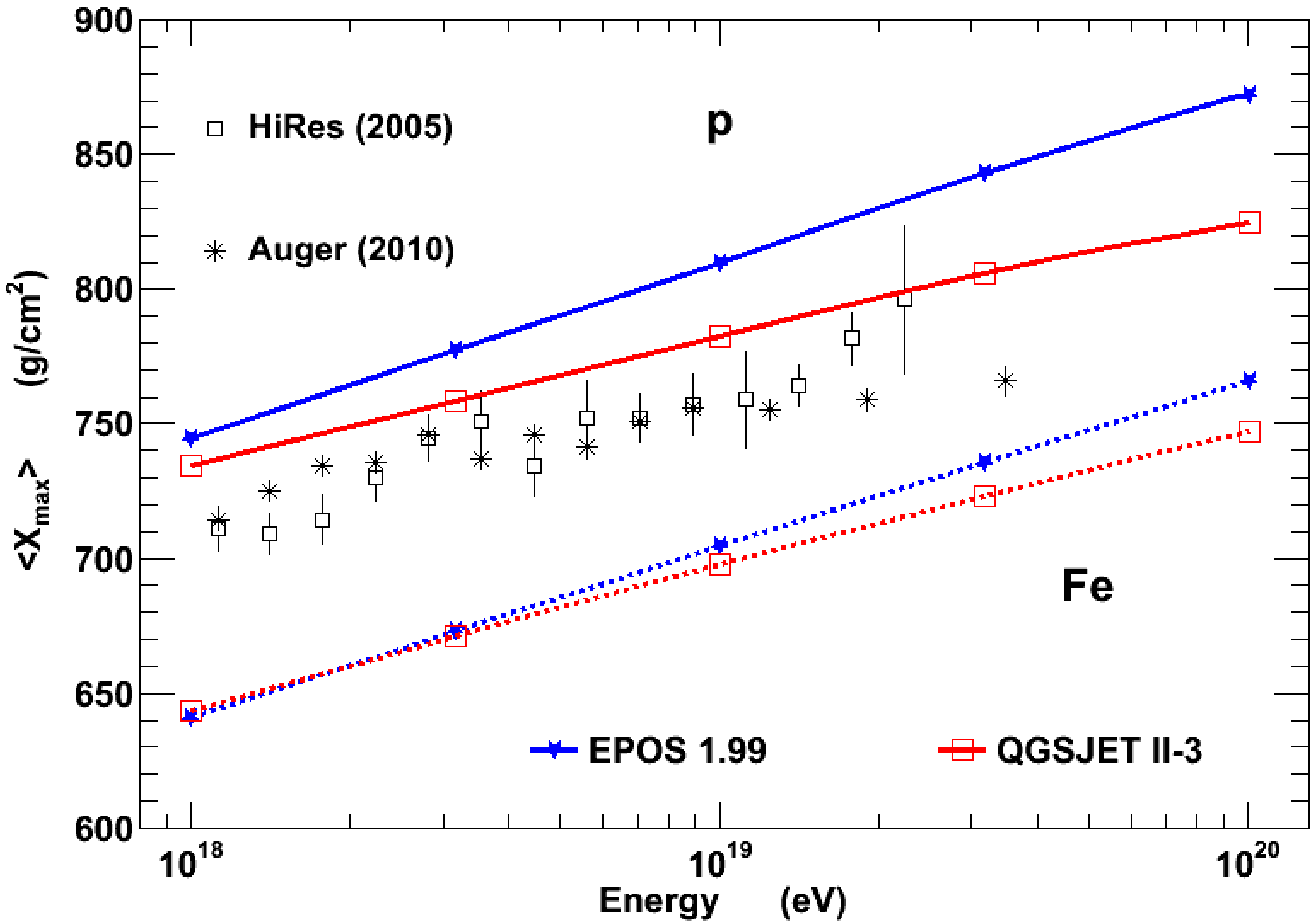


Mass composition from <Xmax>

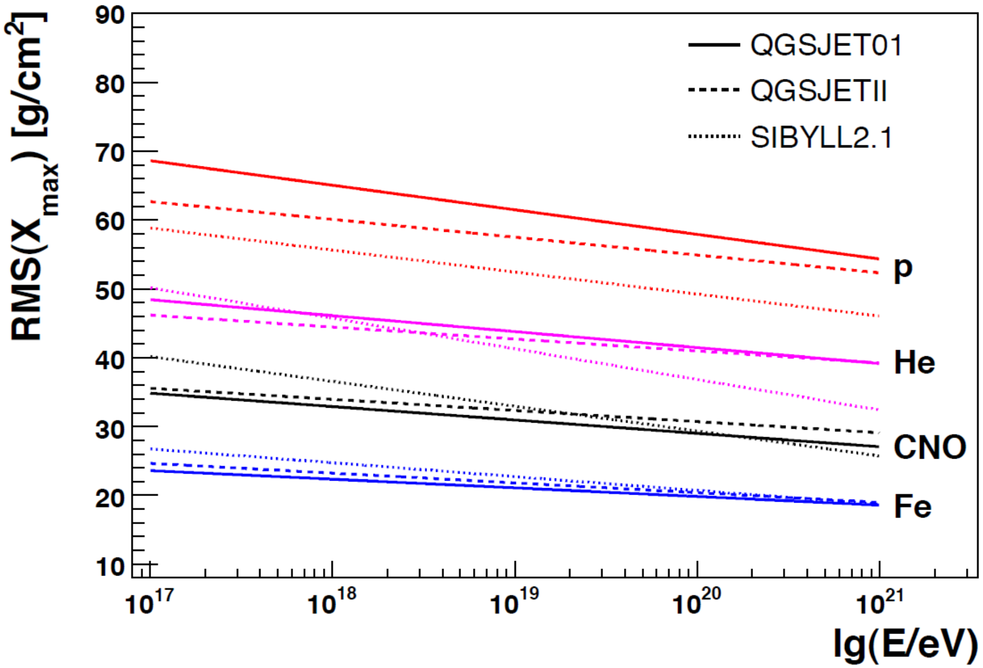
Discrepancy (cross section and multiplicity) between models

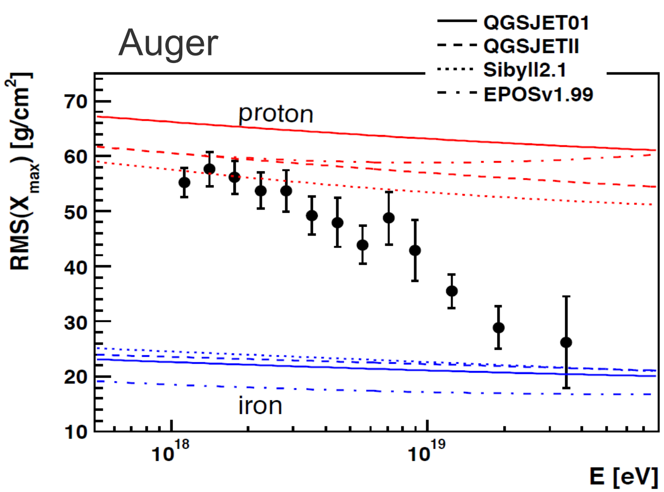
=

Large source of uncertainty for mass composition

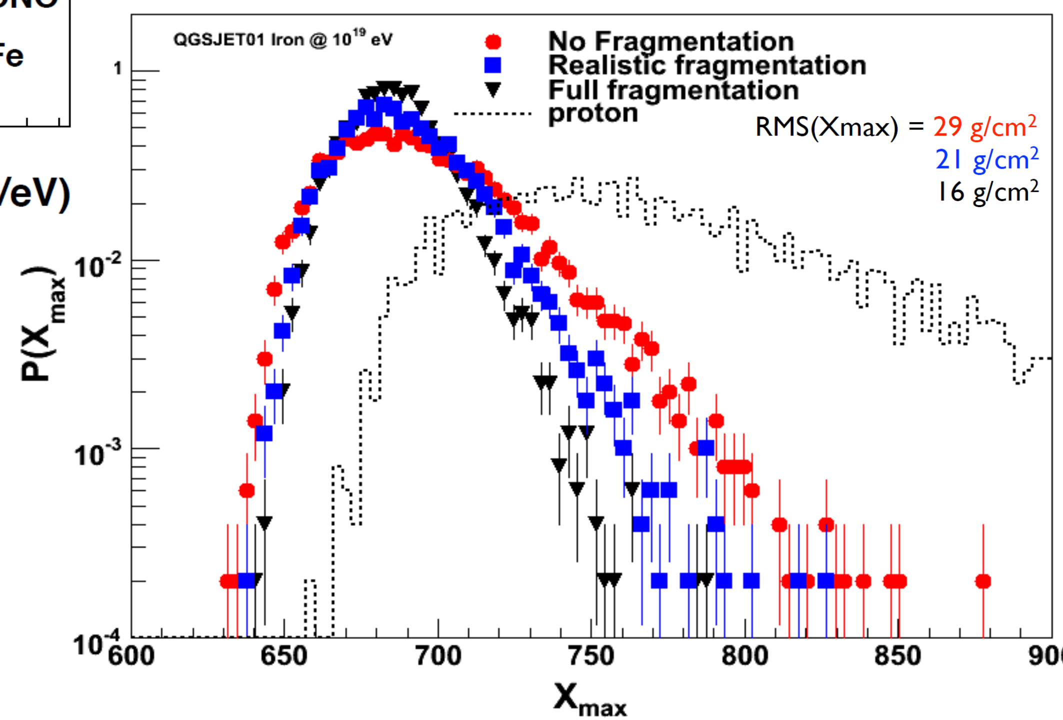


Xmax Fluctuations



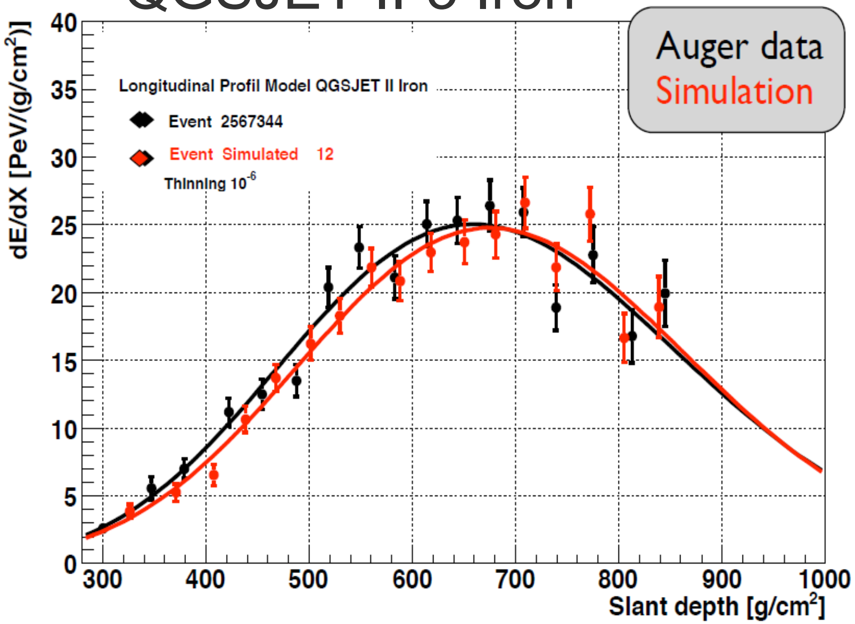


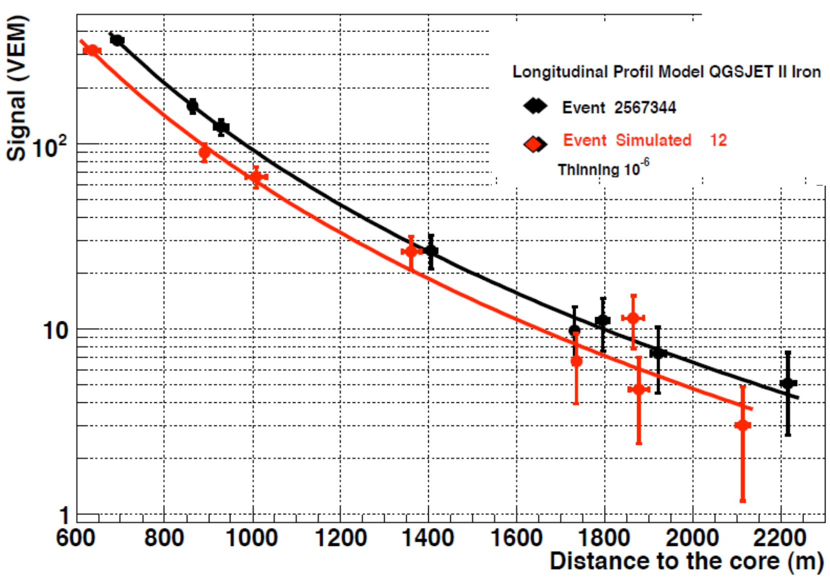
- **Much smaller differences between models**
  - RMS for heavy primary very stable
  - Reduced uncertainties for data analysis



FD and SD mismatch

QGSJET II-3 Iron





AUGER

- Comparison event-by-event
  - Fix simulated FD profile with data
  - Compare measured SD signal with simulated one

SD systematically lower in simulation : ~25 % shift in energy scale + ~50 % deficit in muon number (for QGSJETII-03)

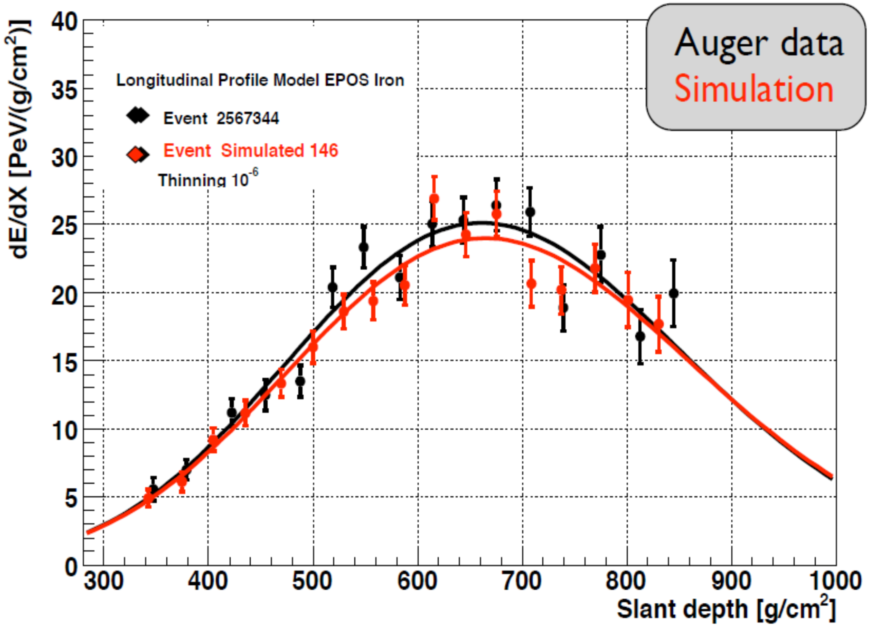
TA

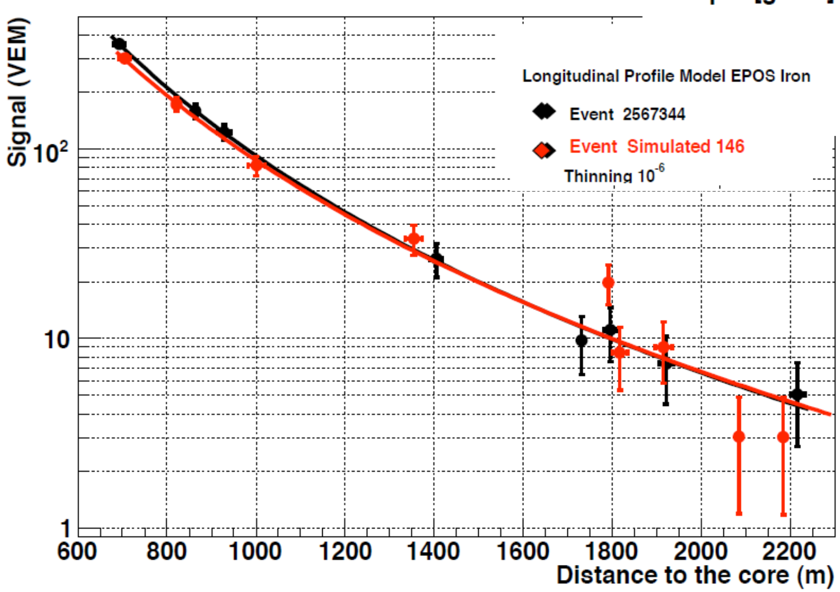
- Spectrum reconstruction
  - Spectrum using QGSJETII-03 for energy reconstruction
  - Renormalize energy using event seen by FD and SD using FD energy as reference

27 % shift in energy scale needed

FD and SD mismatch

EPOS 1.6 Iron





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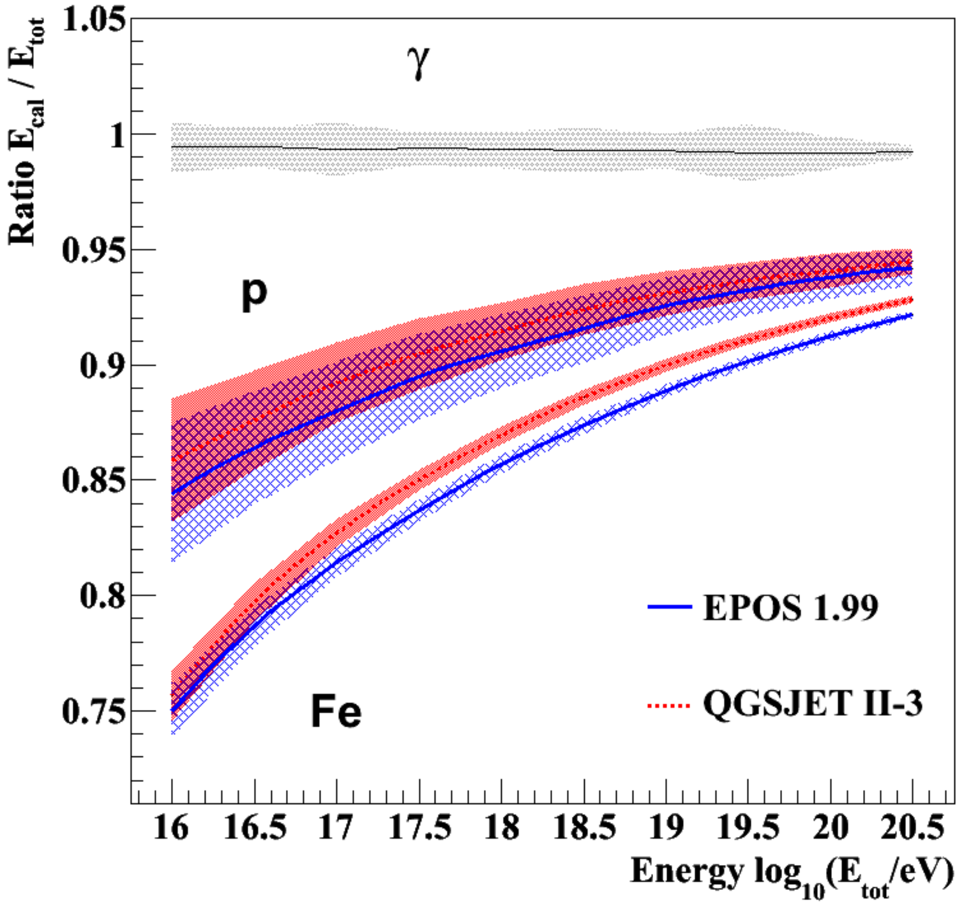
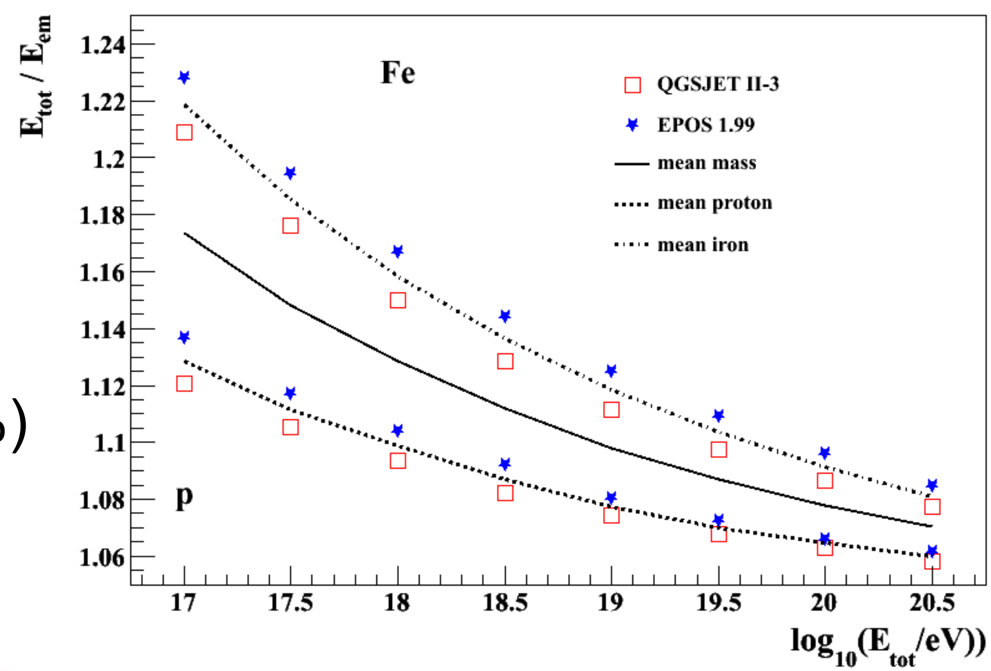
Energy Deposit



- **From Heitler model**

$$E_{em} = \left[1 - \left(\frac{N_{em}}{N_{tot}}\right)^{n(A)}\right] E_0$$

- **Energy deposit depends on muon number**
  - Primary mass dependent
  - Hadronic model dependent



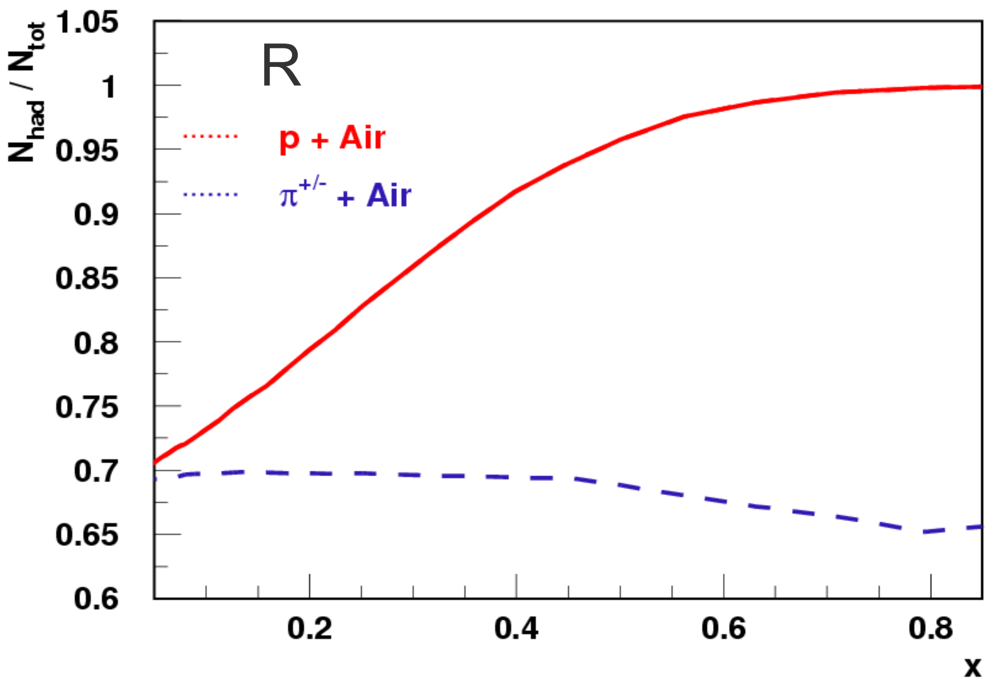
- **Average value used**
  - Small error due to models (~1-2%)
  - Main uncertainty from unknown mass (~5-2%)

Muon Number

- **From Heitler**

$$N_\mu = \left(\frac{E_0}{E_{dec}}\right)^\alpha, \quad \alpha = \frac{\ln N_{\pi^{ch}}}{\ln(N_{\pi^{ch}} + N_{\pi^0})}$$

➜ In real shower, not only pions : Kaons and (anti)Baryons (but 10 times less ...)



$$\alpha = \frac{\ln(N_{had})}{\ln(N_{tot})} = 1 + \frac{\ln(R)}{\ln(N_{tot})}$$

$$R = \frac{N_{had}}{N_{tot}} \approx \frac{N_{\pi^{ch}} + N_B}{N_{\pi^{ch}} + N_B + N_{\pi^0}}$$

Very important :
in (a)Baryon-Air interactions, no leading neutral pion !
R~1

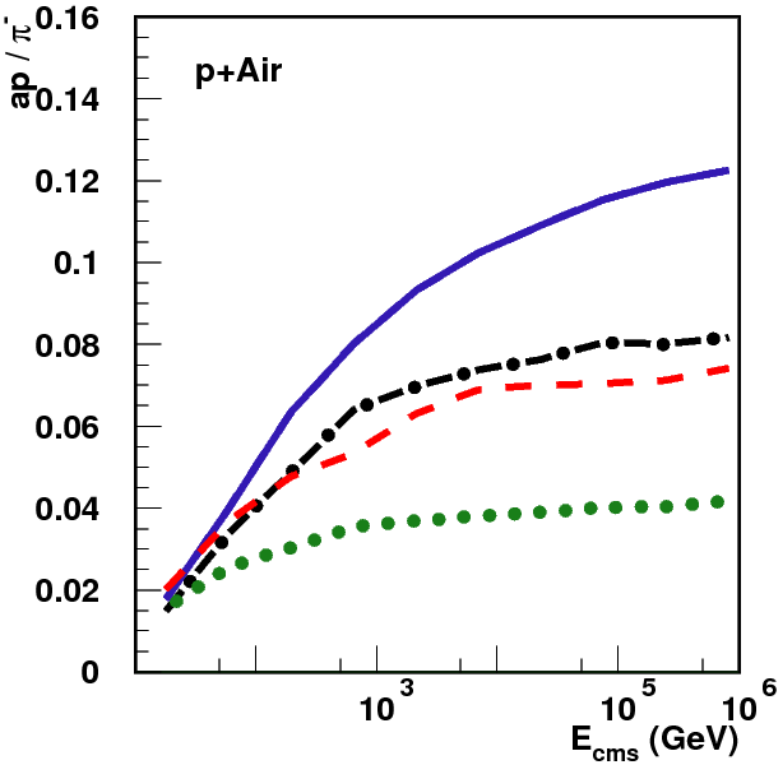
R depends on the number of (anti)B in p- or π-Air interactions

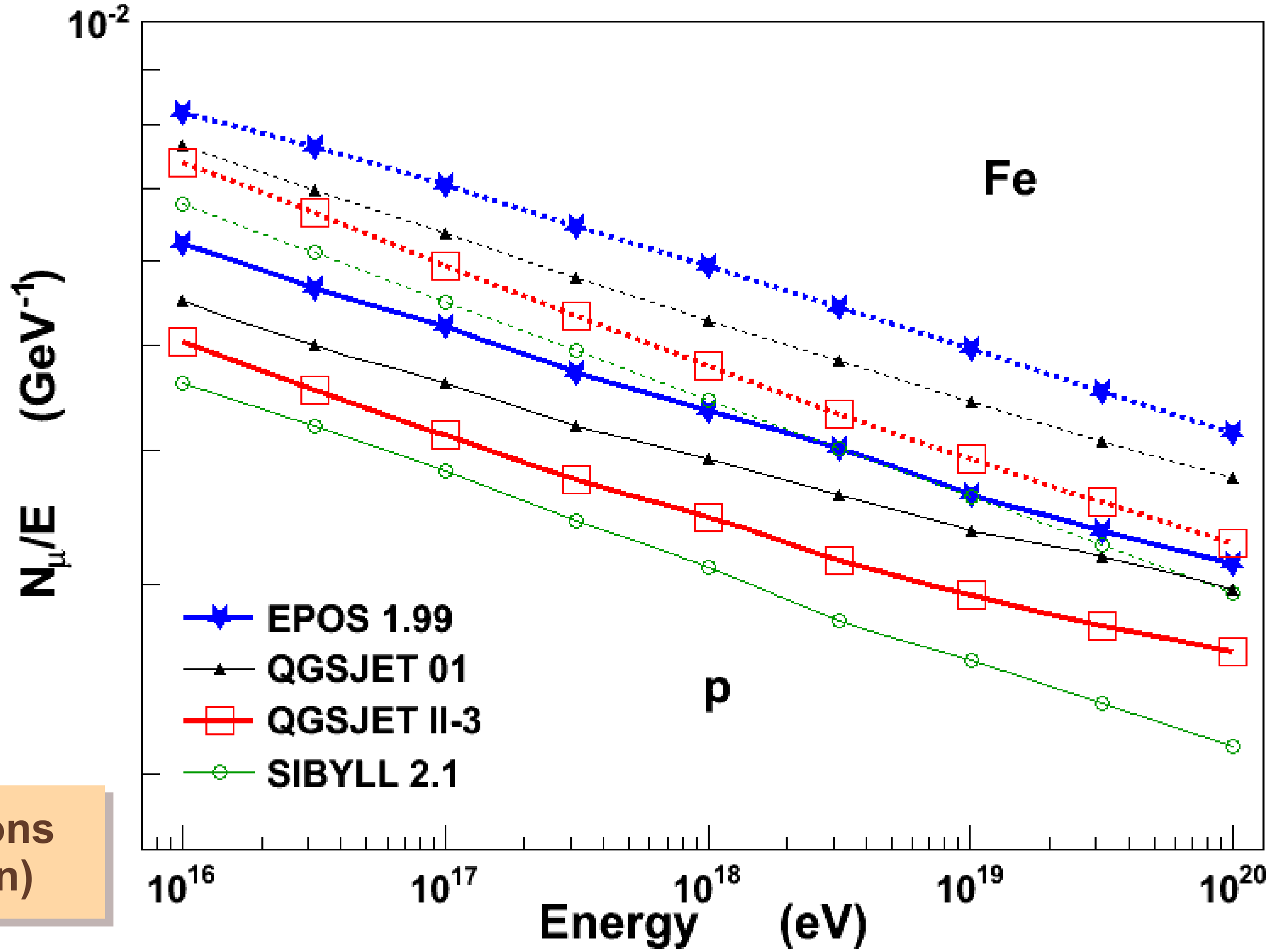
More fast (anti)baryons = $\alpha \rightarrow 1$ = more muons

T. Pierog et al.,Phys.Rev.Lett. 101 (2008) 171101

Total Number of Muons

Discrepancy (baryon and pion spectra) between models
=
Large differences in the number of muons





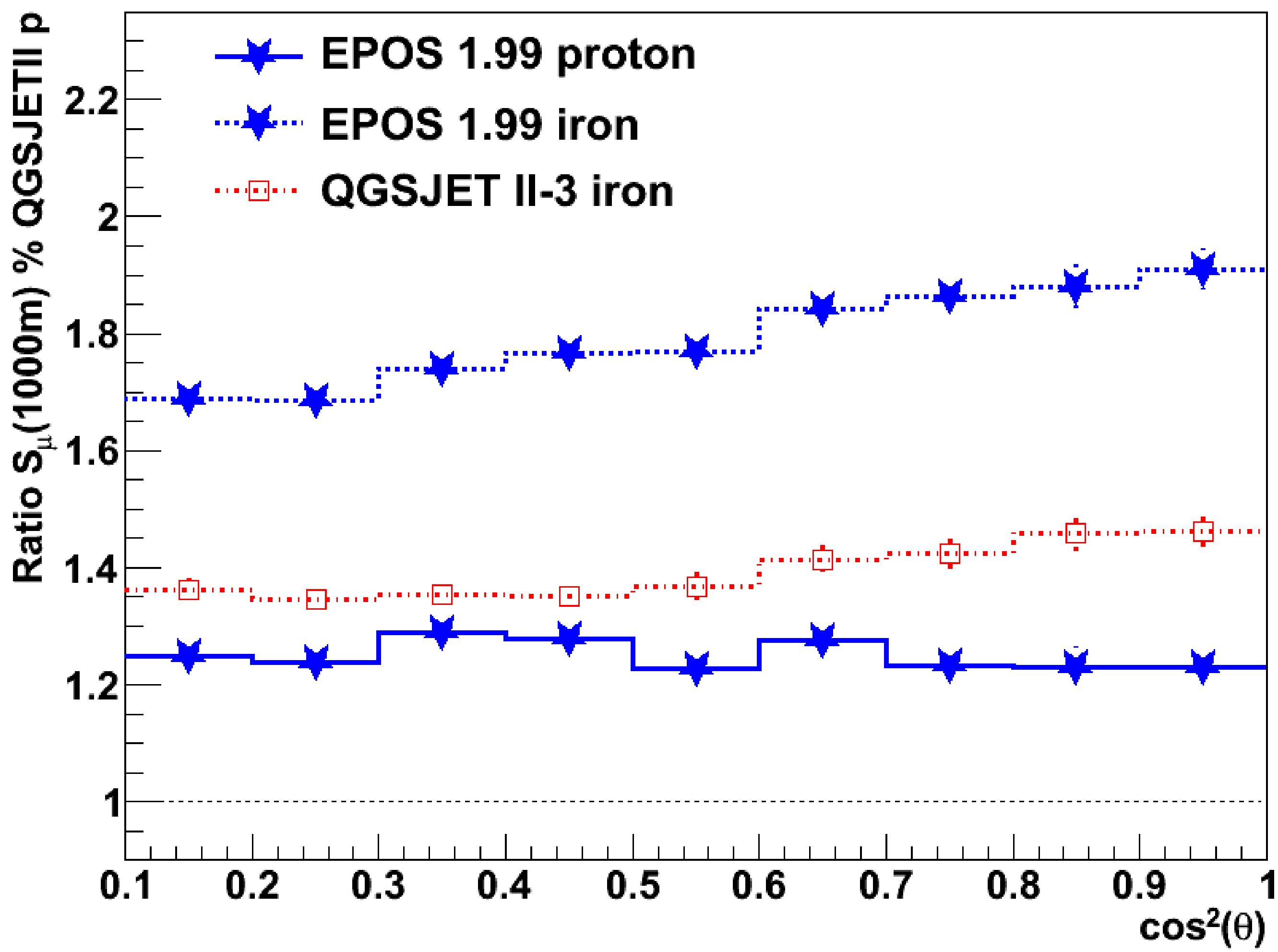
2 times less baryons = 35 % less muons (~difference between proton and iron)

Muon Density @ 1000 m

Discrepancy (baryon and pion spectra) **between models**

=

source of uncertainty for mass composition and energy



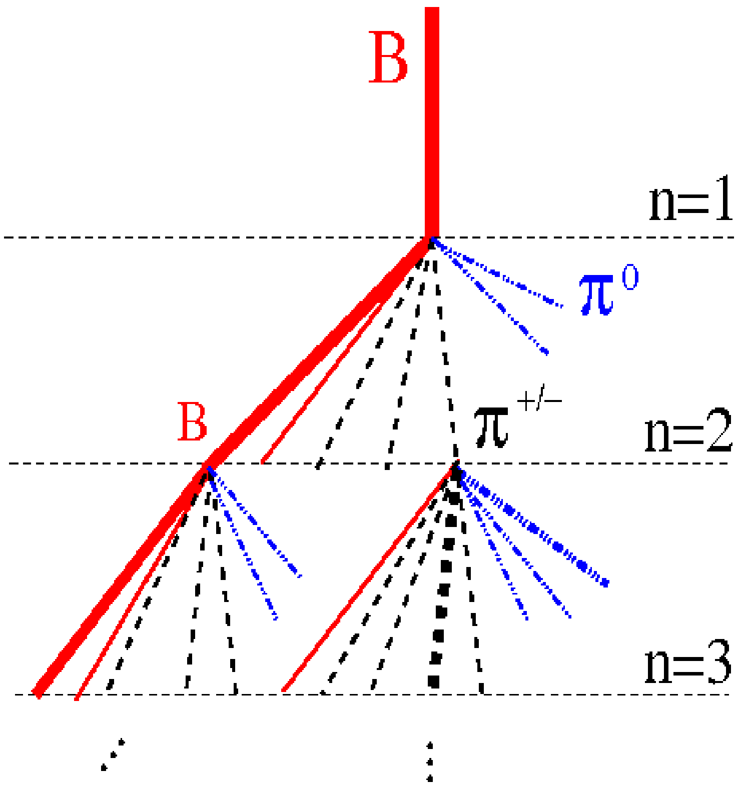
PAO observable

Models for Air Shower Simulation

Realistic approach :

Proper energy transfer from hadronic particles to electromagnetic one (π^0) :

Particle Physics



Thickness = amount of energy

- **Hadronic models for simulations :**
  - mainly soft physics + diffraction (forward region)
  - should handle p-, π-Air, K-Air and A-Air interactions
  - should be able to run at 10^6 GeV center-of-mass energy
  - models used for EAS analysis :
    - QGSJET01/II
    - SIBYLL 2.1
    - EPOS
    - DPMJET III

Hadronic Interaction Models

- **Theoretical basis :**
  - pQCD
  - Gribov-Regge
  - energy conservation

Pb : CR physic dominated by soft interactions

Pb : Gribov-Regge do not take into account energy conservation ...

- **Phenomenology (models) :**
  - string fragmentation
  - diffraction
  - higher order effects

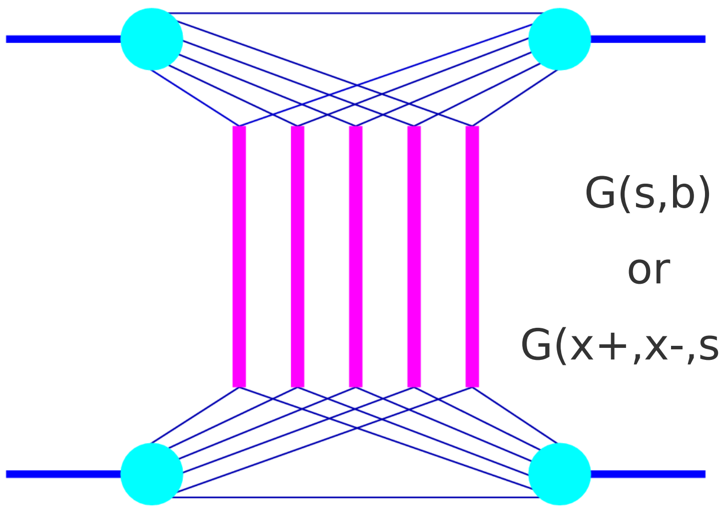
Need Parameters !

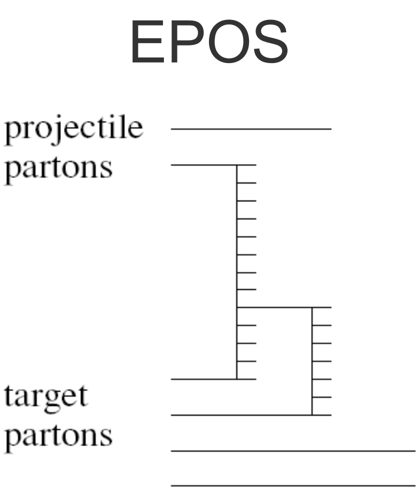
- **Comparison with data to fix parameters :**
  - the more parameters, the more data you need

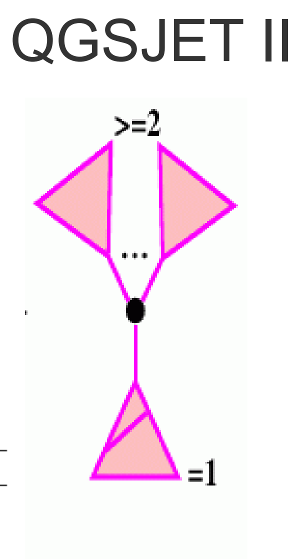
... or ...

  - the more data, the more parameters you need !

Differences between Models



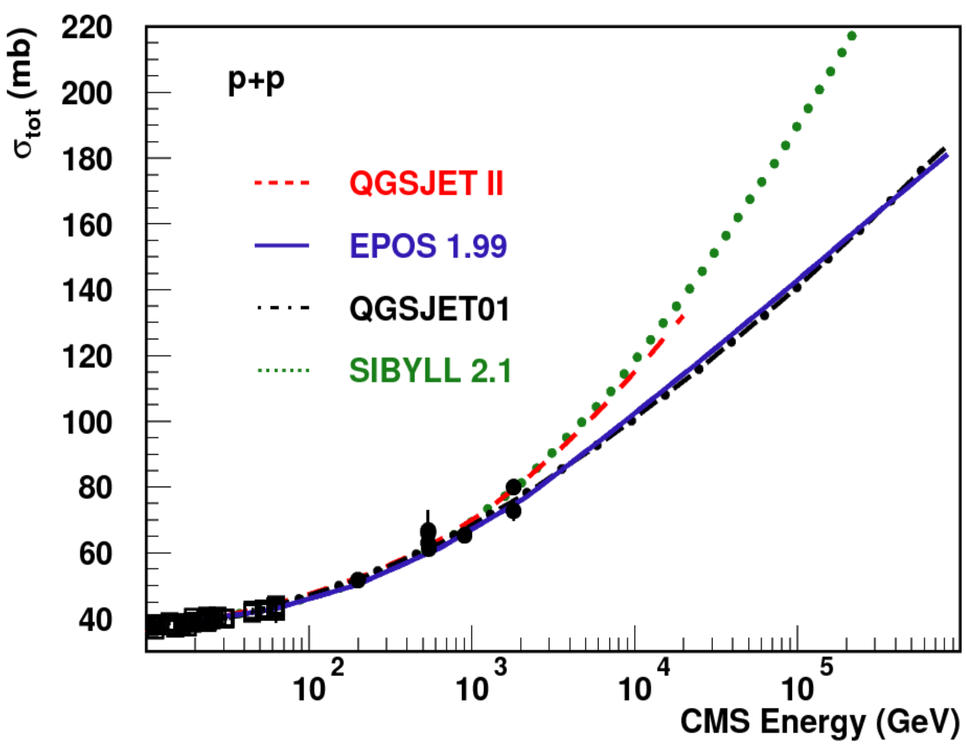


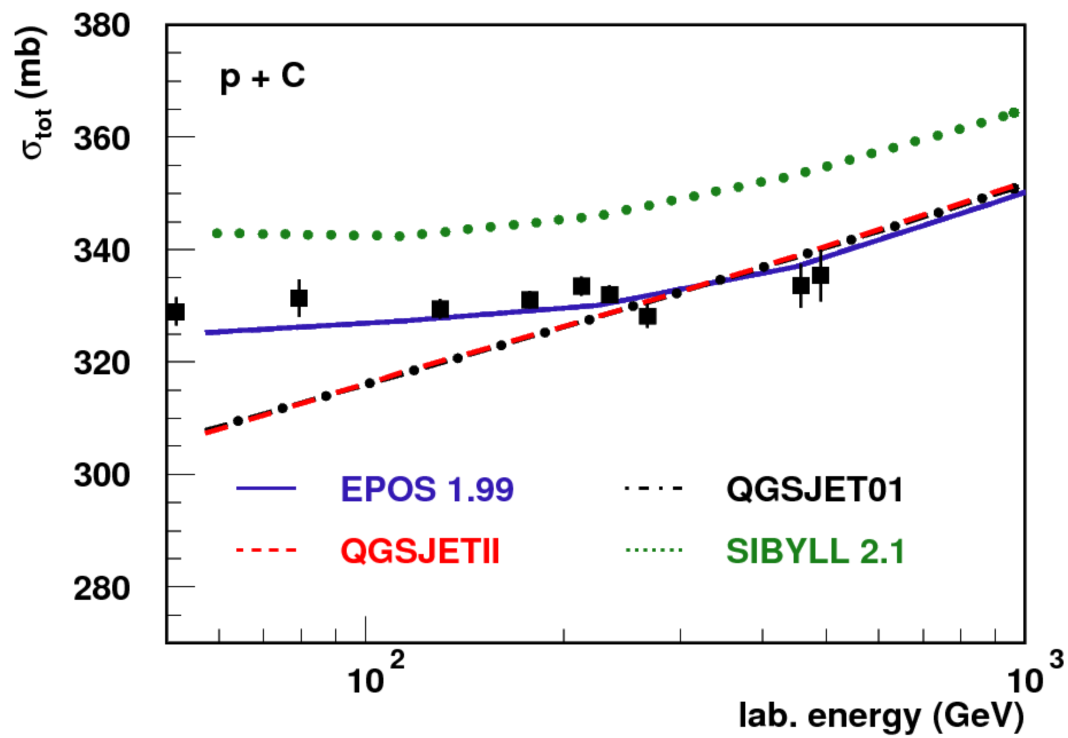


- **Gribov-Regge and optical theorem**
  - Basis of all models but
    - Classical approach for QGSJET and SIBYLL (no energy conservation for cross section calculation)
    - Parton based Gribov-Regge theory for EPOS (energy conservation at amplitude level)
- **pQCD**
  - Minijets with cutoff in SIBYLL
  - Same hard Pomeron (DGLAP convoluted with soft part : not cutoff) in QGS and EPOS but
    - No enhanced diagram in Q01
    - Generalized enhanced diagram in QII
    - Simplified non linear effect in EPOS
      - Phenomenological approach

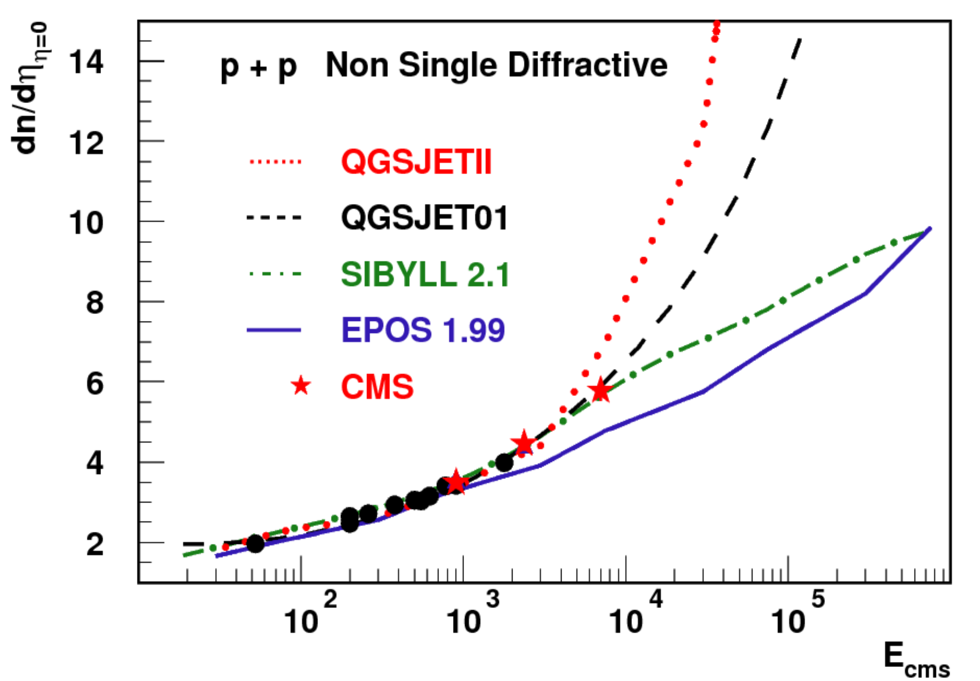
Cross Section

- Same cross section at pp level and low energy (data)
- extrapolation to pA or to high energy
  - different amplitude and scheme : different extrapolations

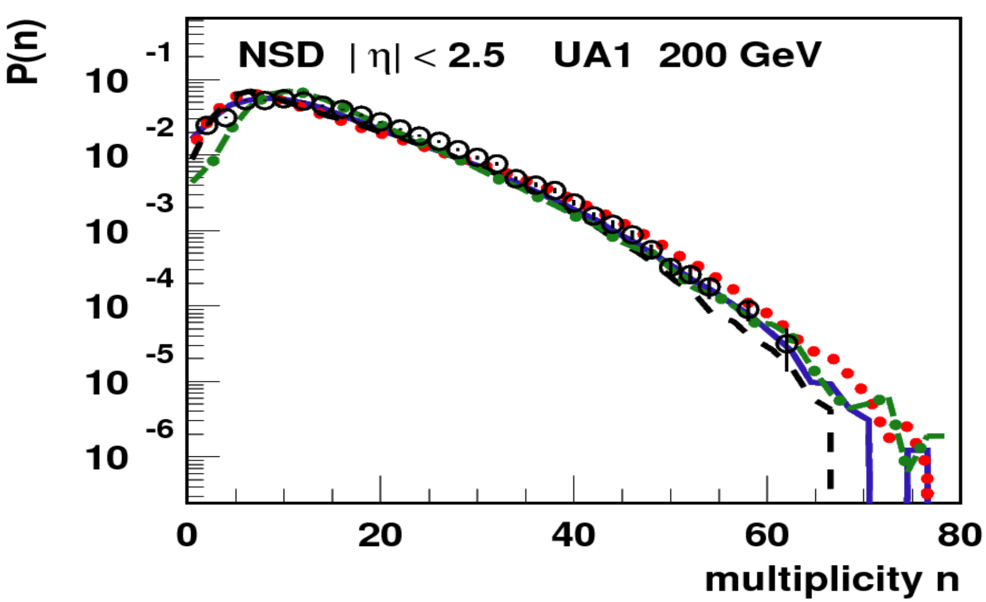


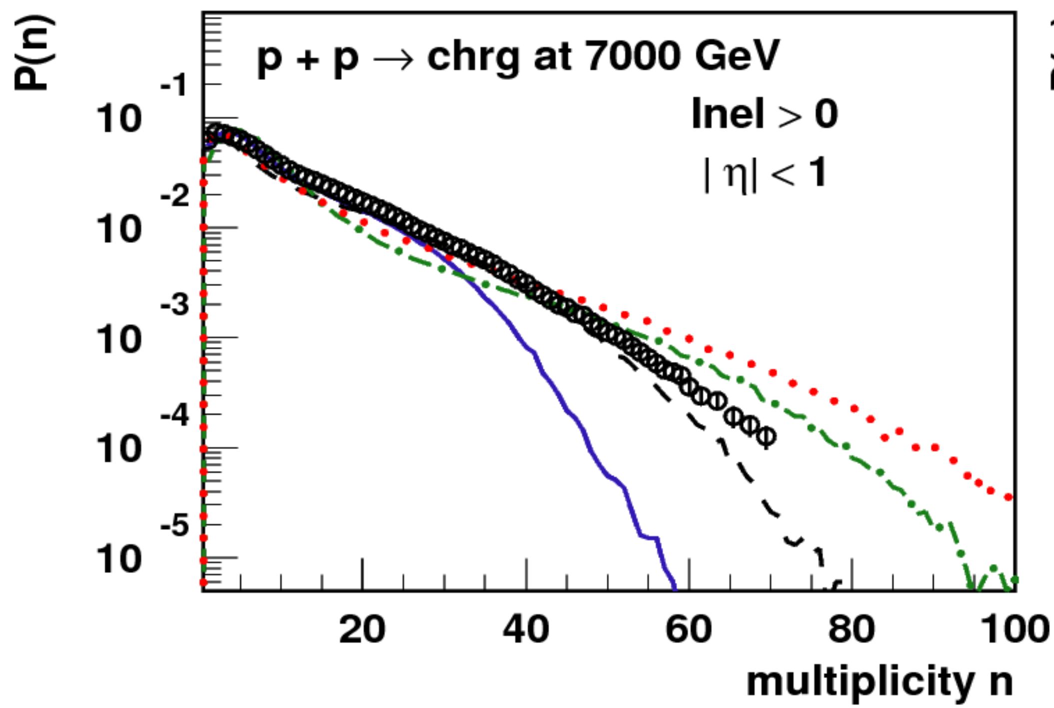


Multiplicity

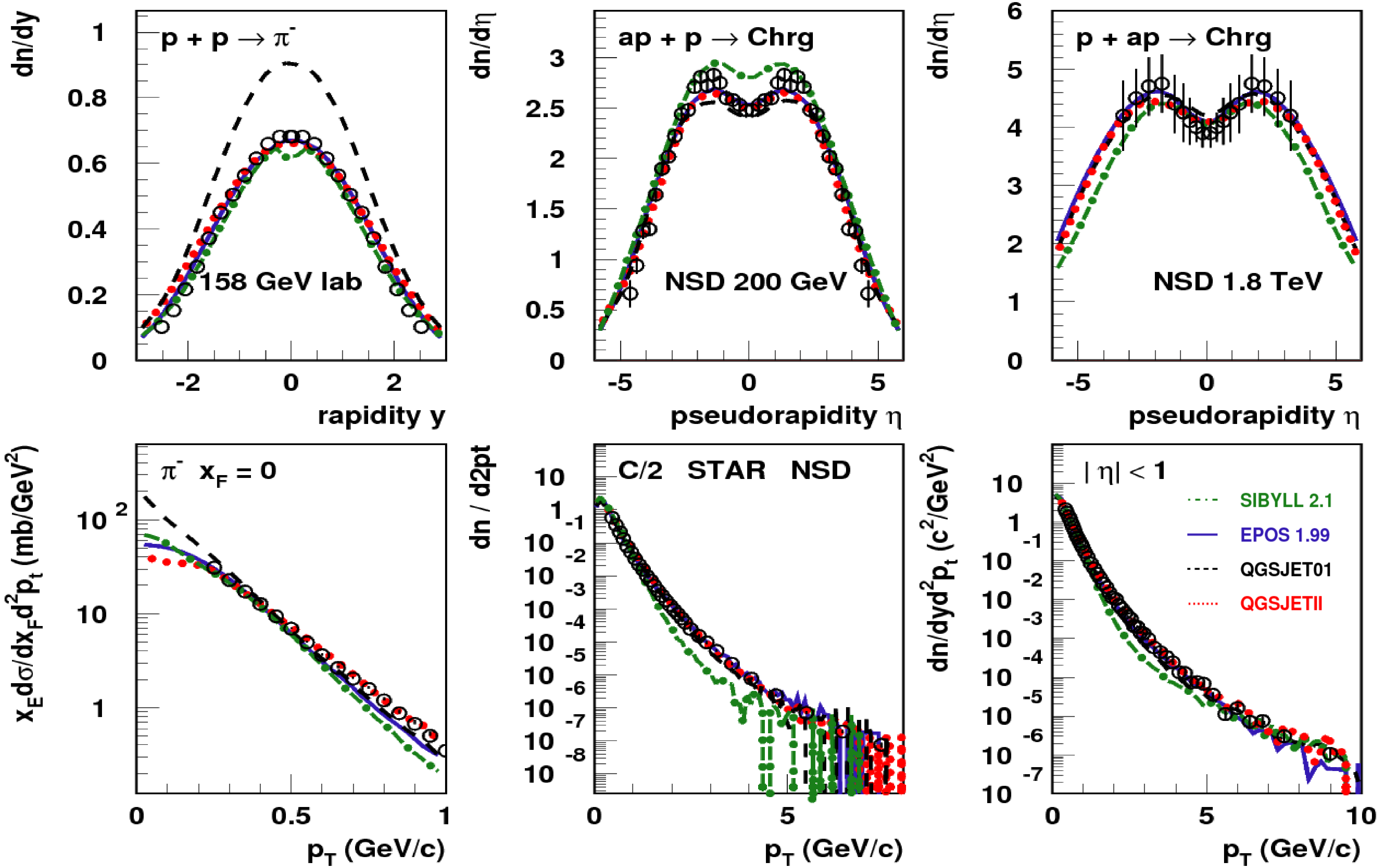


- More than linear increase
- Shape of distribution correct
- large differences at LHC

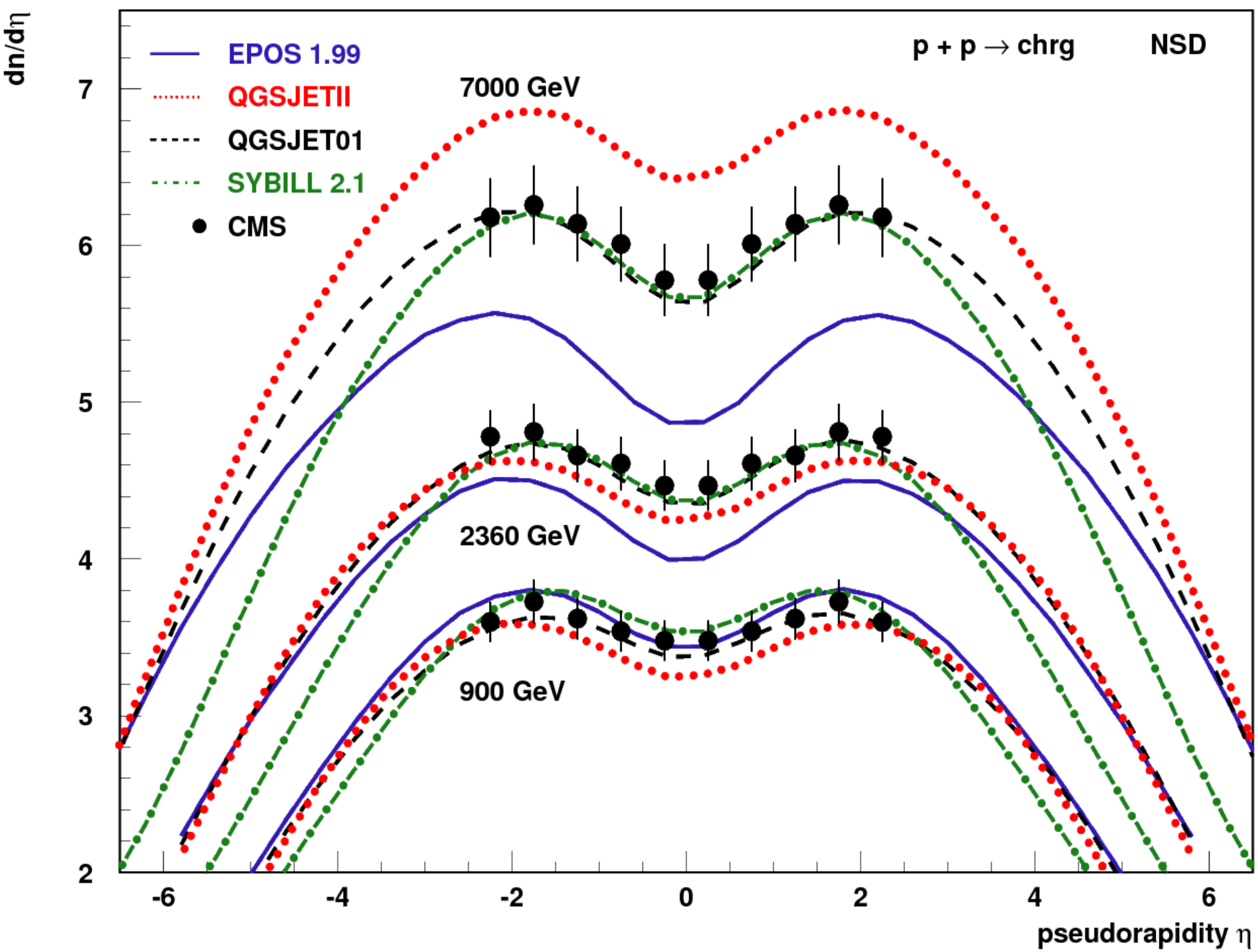




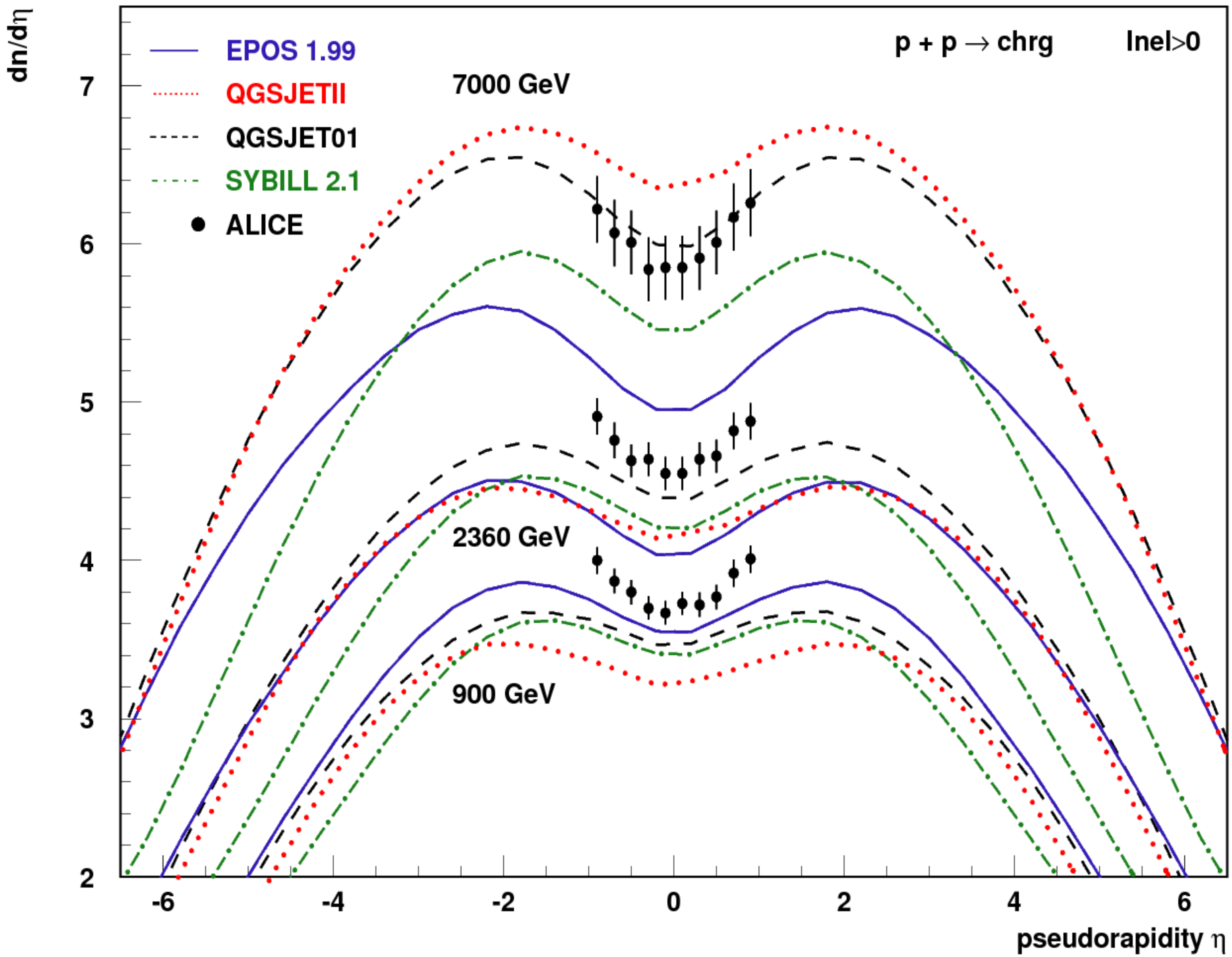
Pre-LHC Pseudorapidity and p_T



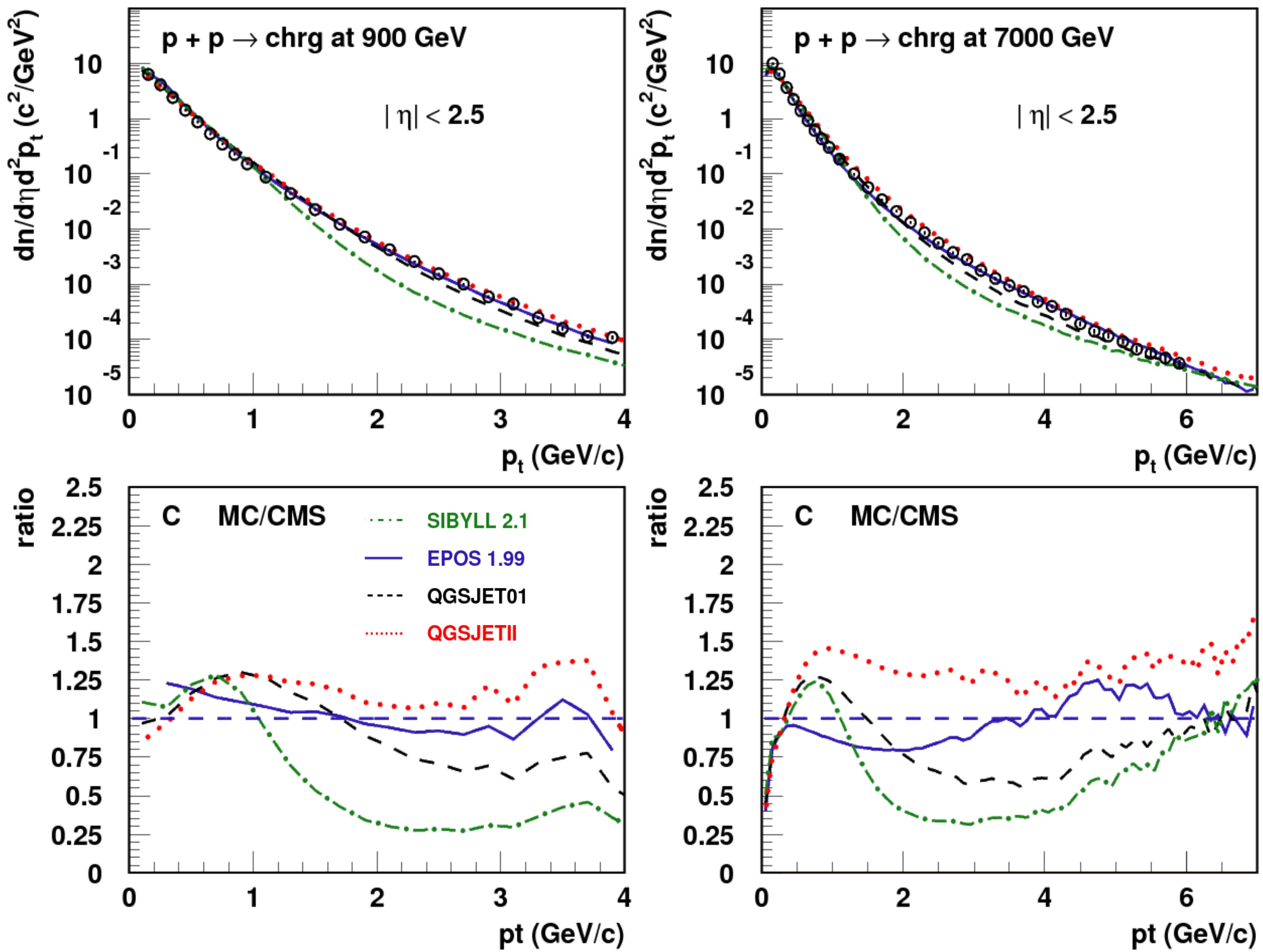
Pseudorapidity NSD CMS



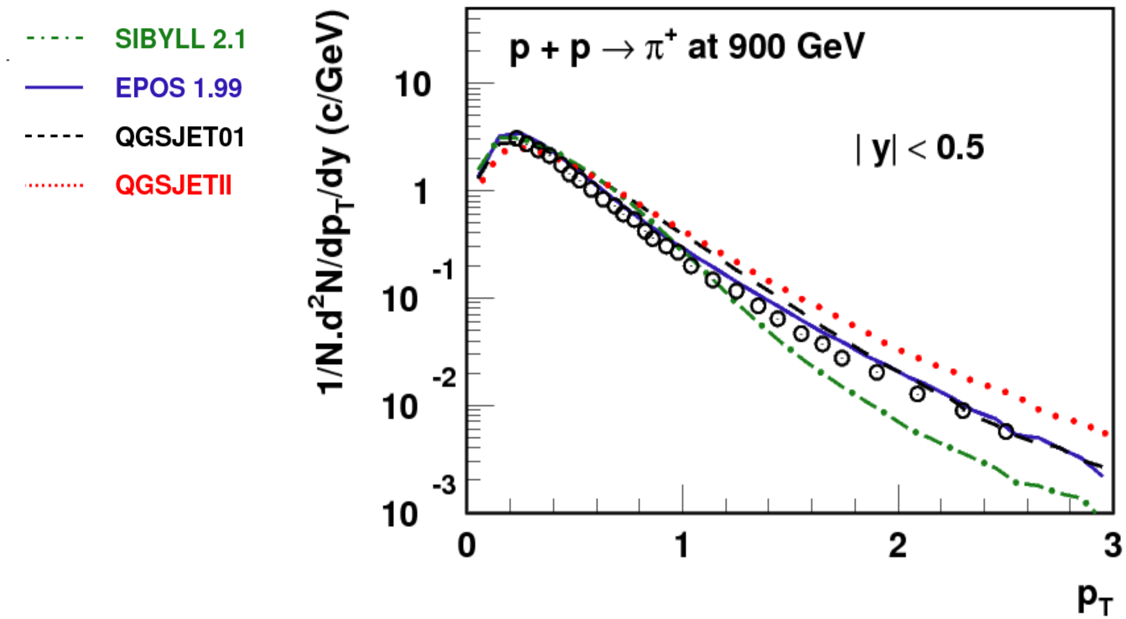
Pseudorapidity ALICE Inel>0

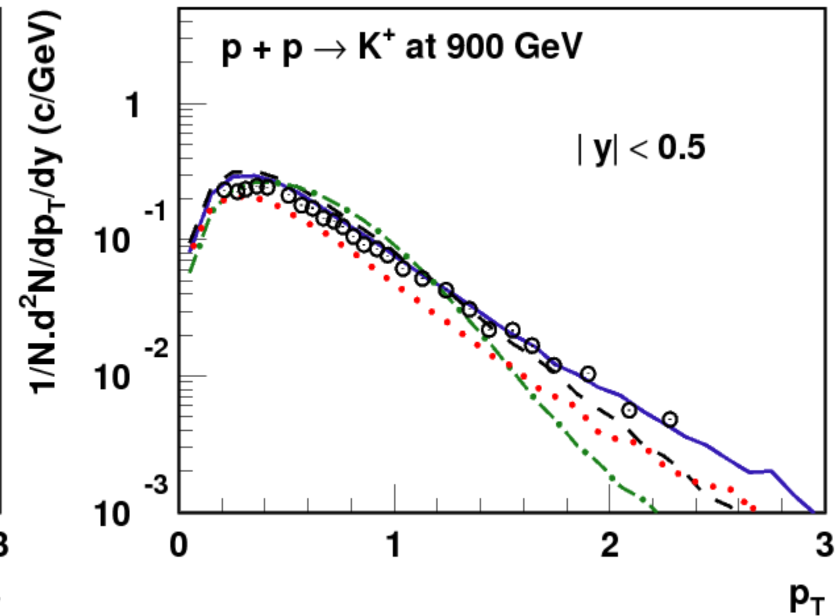


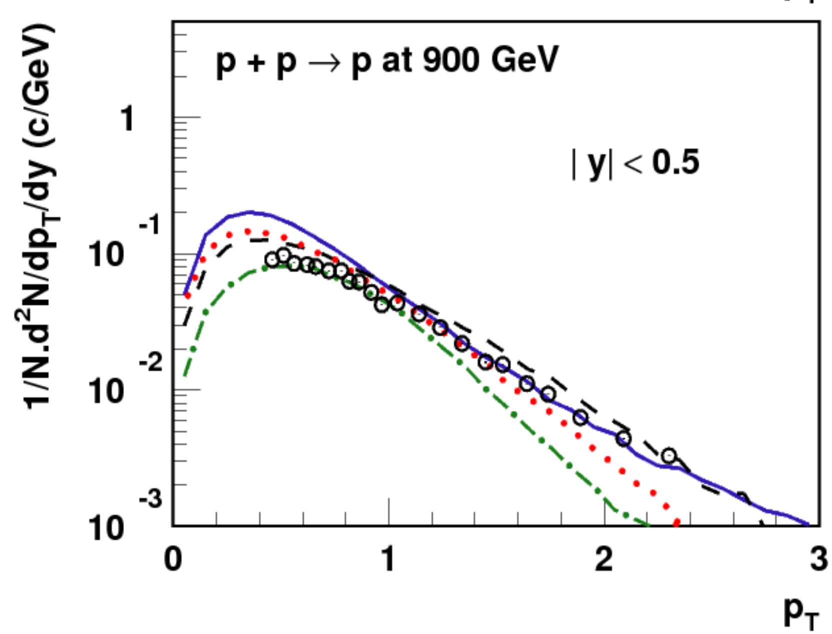
CMS Transverse Momentum p_T



ALICE Identified Spectra 900 GeV

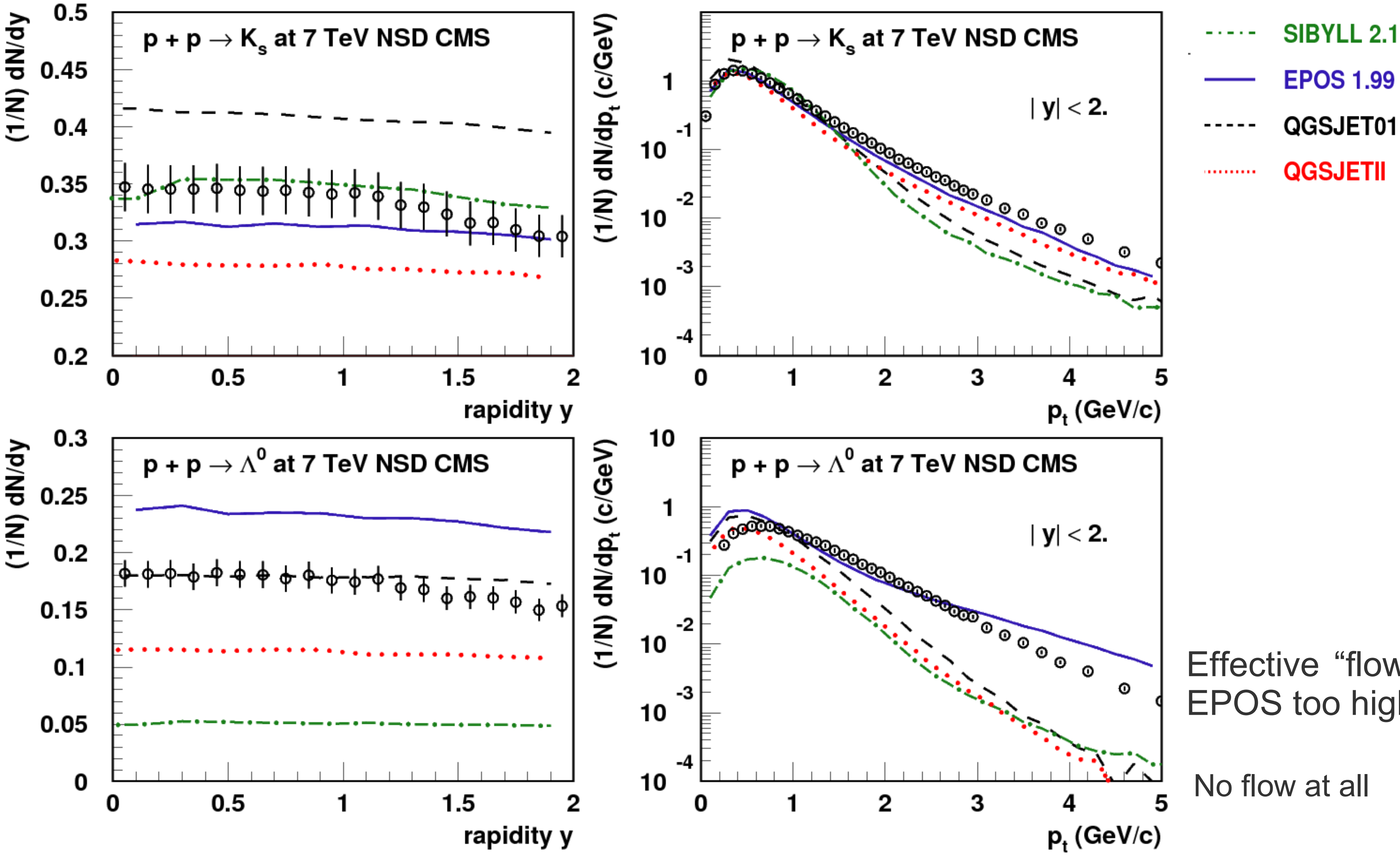






- **Individual particles**
  - EPOS OK (proton ?)
  - QGSJET01 OK !
  - QGSJETII Pion mean p_T too large

CMS Strangeness 7 TeV

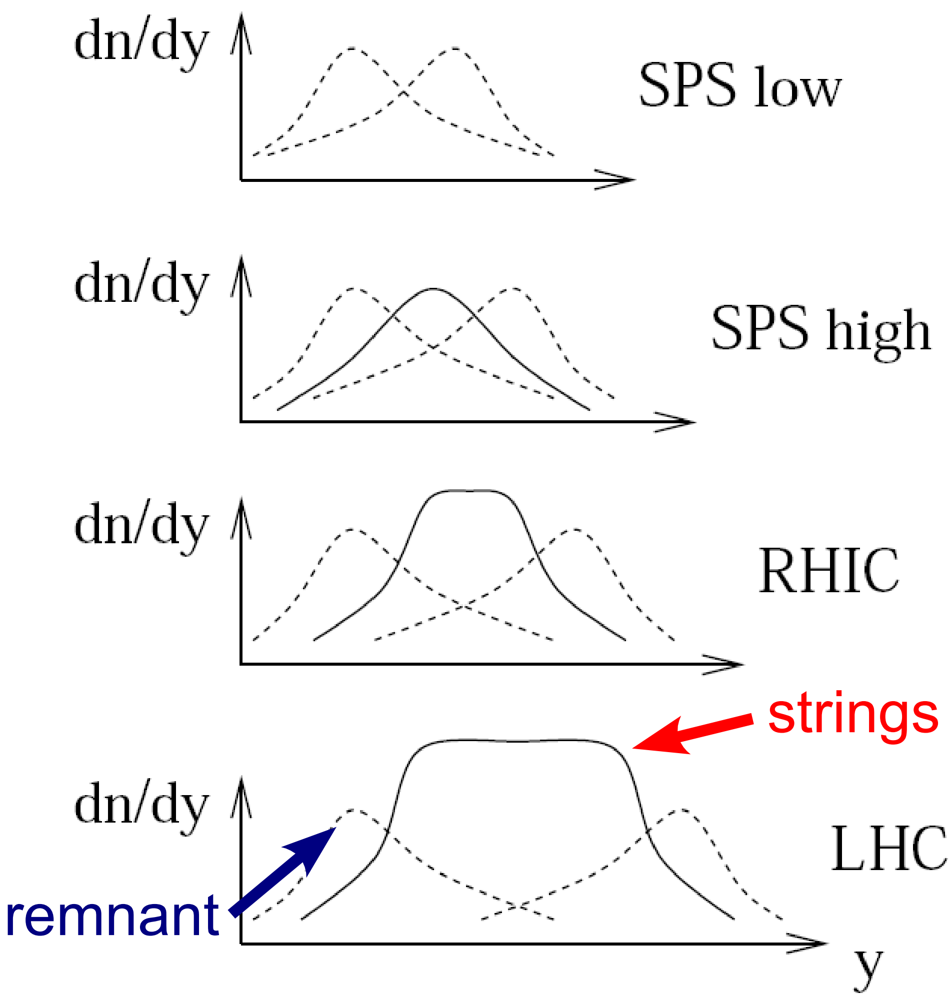


Effective “flow” in EPOS too high

No flow at all

Forward Spectra

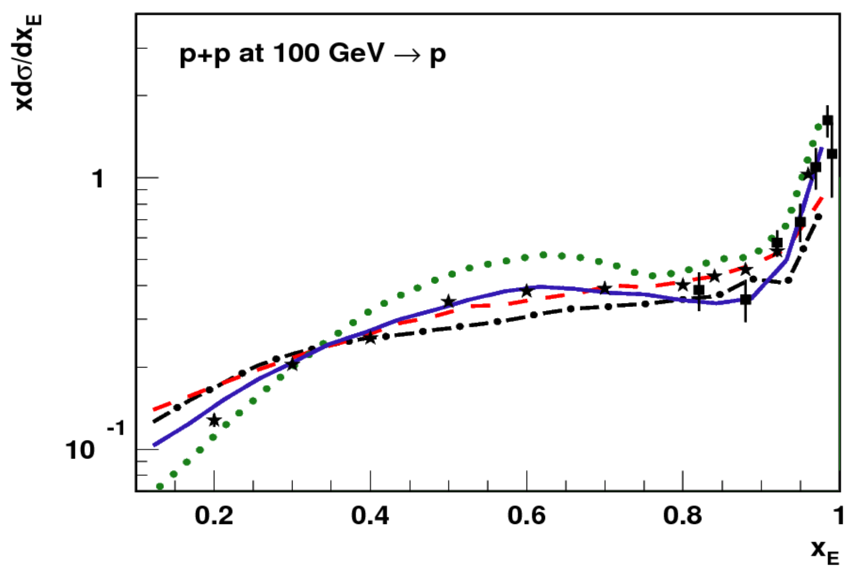
Forward particles mainly from projectile remnant

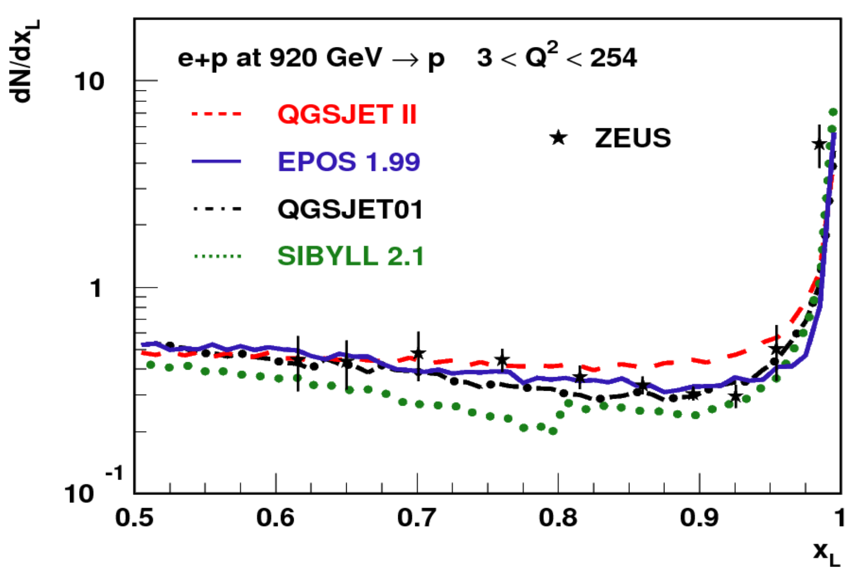


The inelasticity is closely related to diffraction and forward spectra

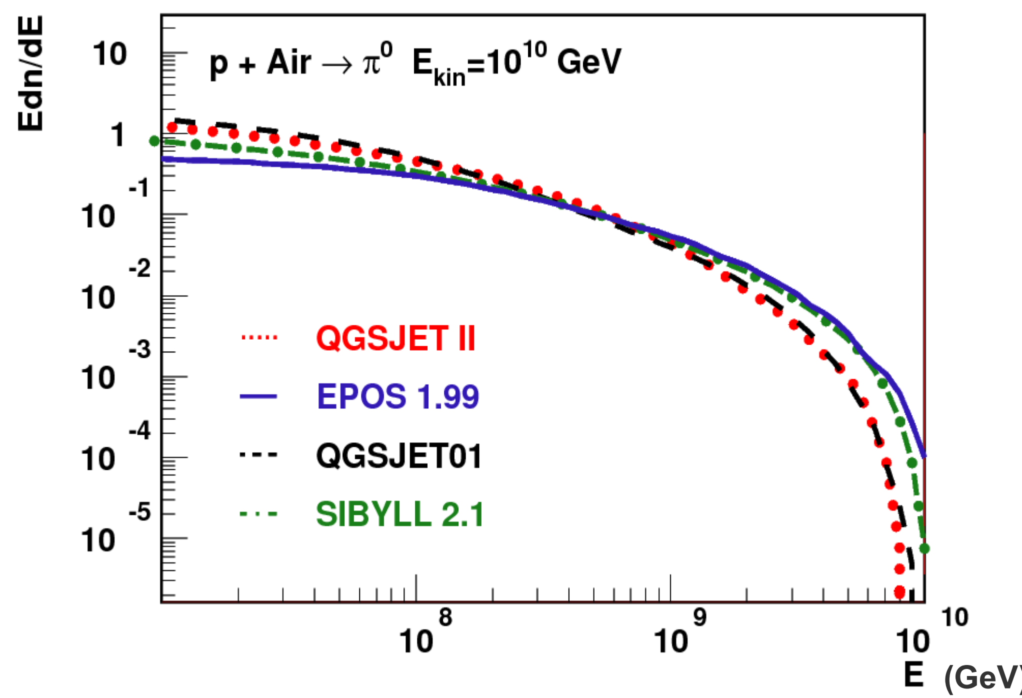
- SIBYLL
  - No remnant except for diffraction
  - Leading particle from string ends
- QGSJET
  - Low mass remnants
  - Low inelasticity at low energy
  - Lot of strings
- EPOS
  - Low and high mass remnants
  - Limited number of strings
  - Special hadronization

Diffraction and x Distributions



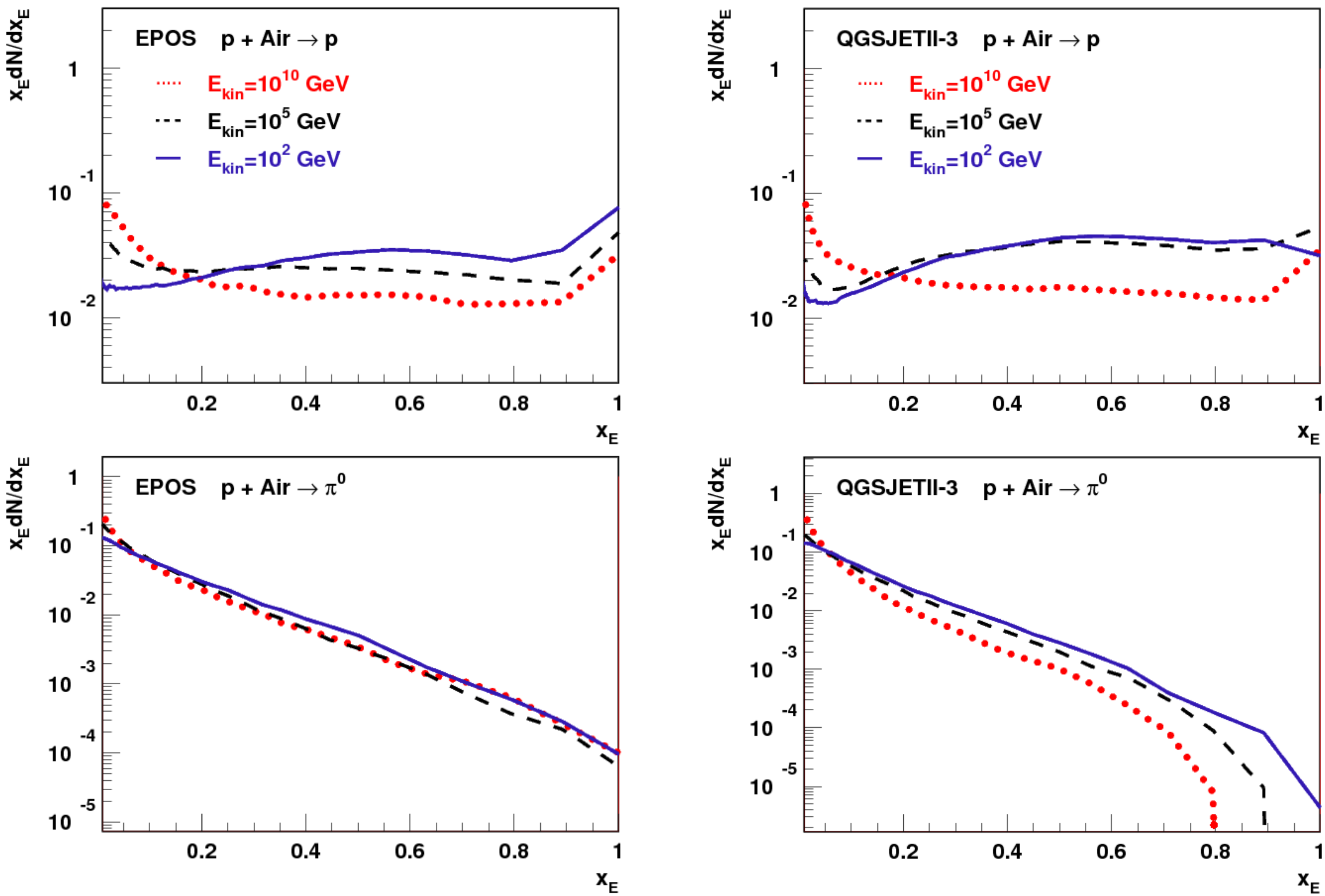


- most of the data at low energy (fixed target experiment)
- extrapolation tested with HERA data
- But large differences at CR energies

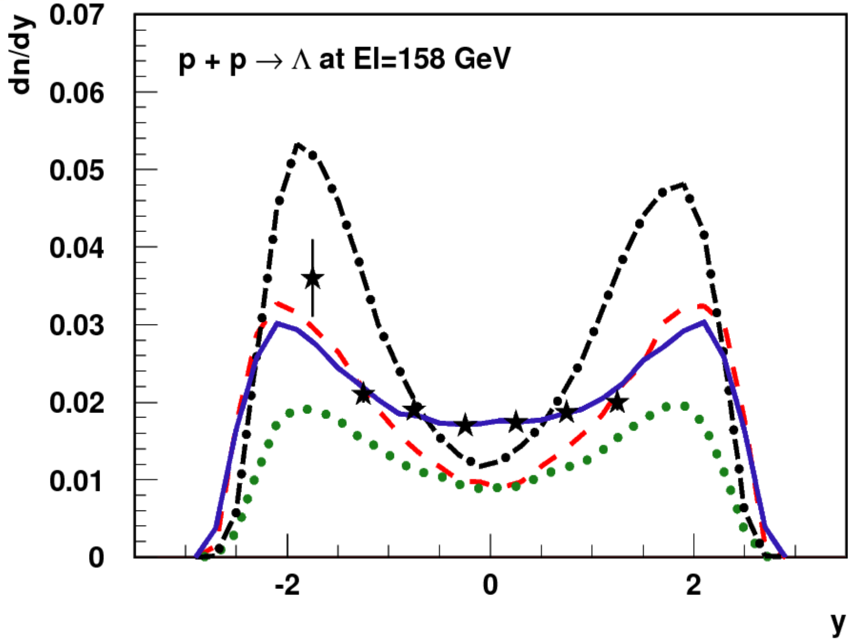


LHCf results very important

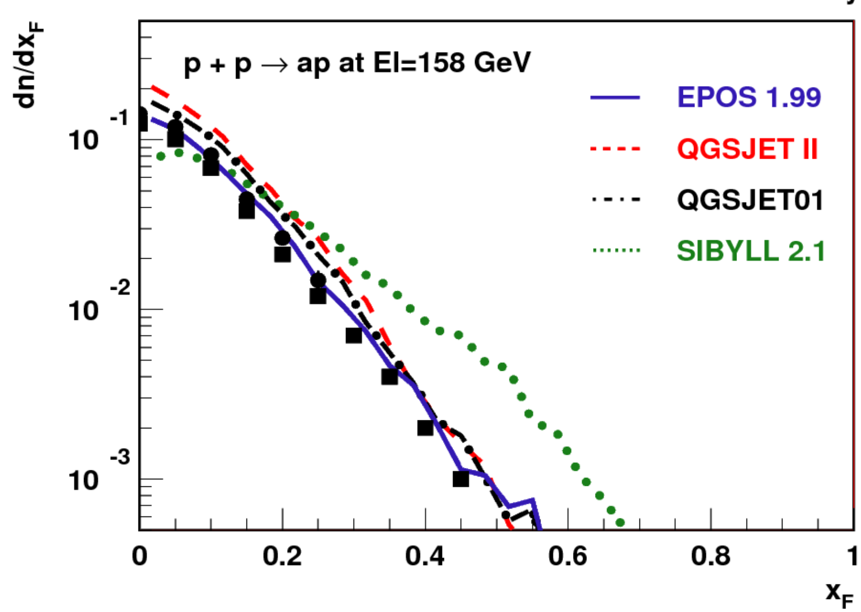
Scaling with Energy

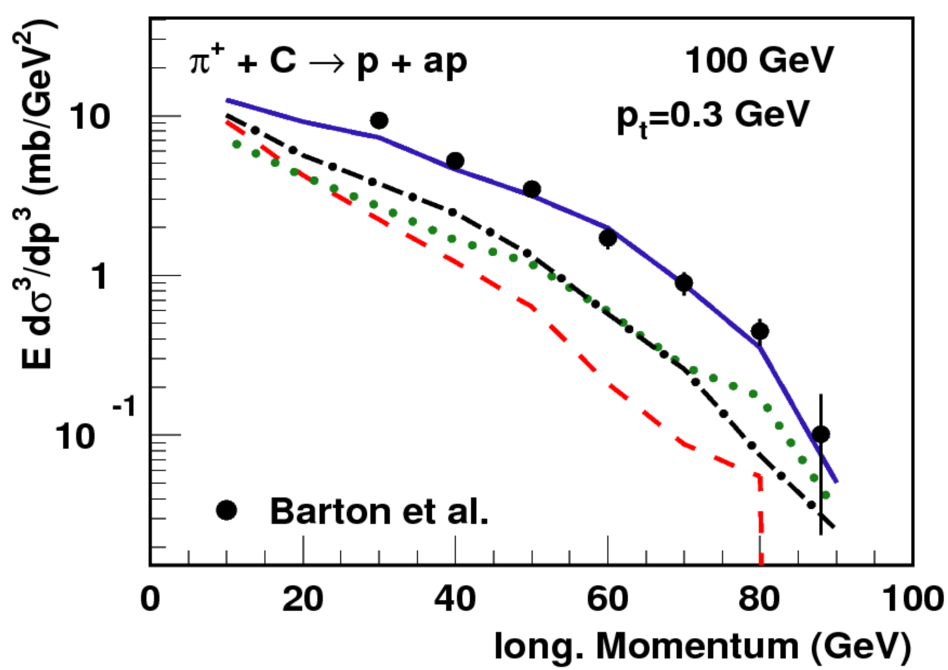


Baryon Forward Spectra

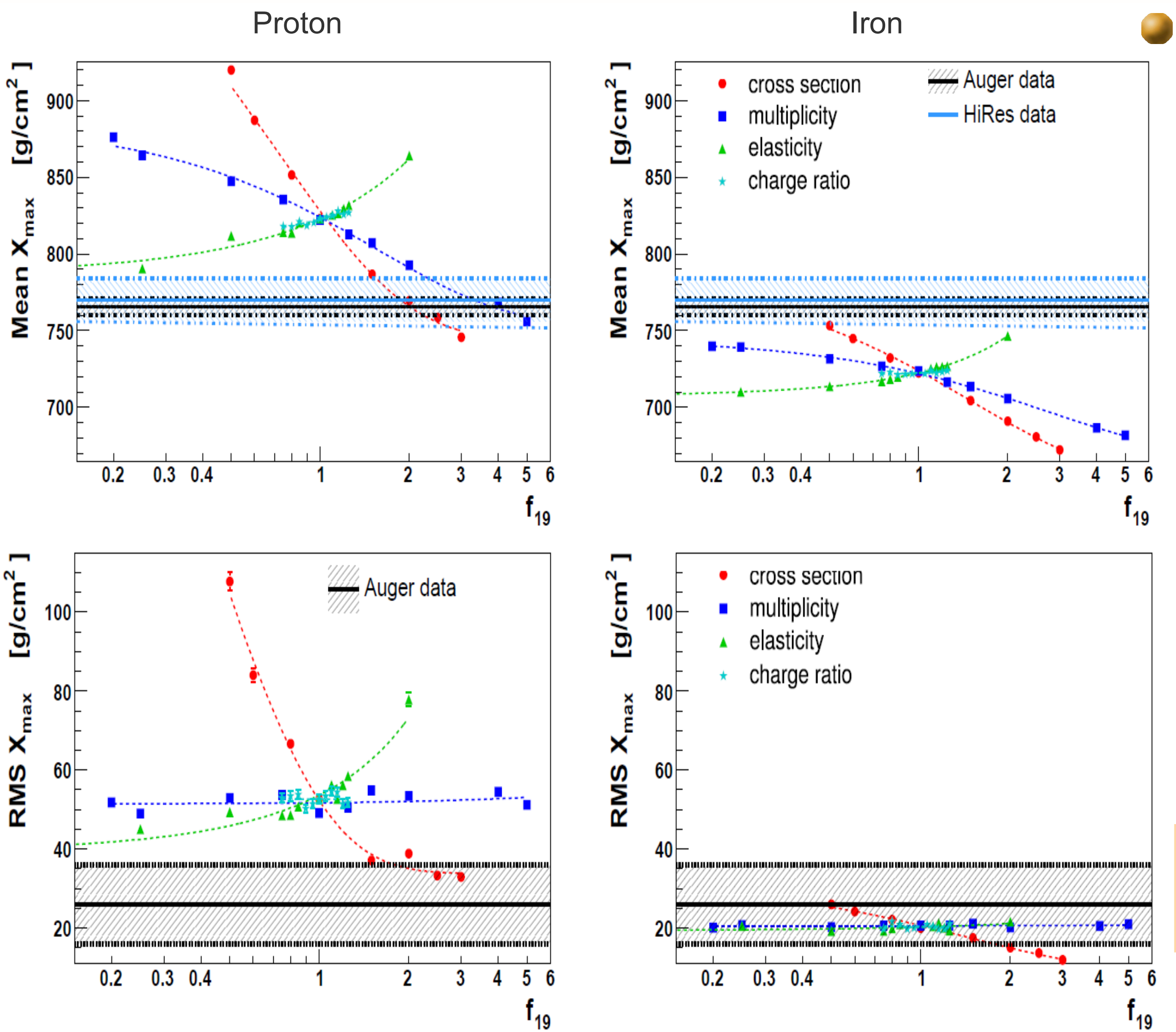


- Large differences between models
- Need a new approach for a complete description (EPOS)
- Problems even at low energy
- Production most likely energy dependent





Uncertainties in Model Extrapolation



Plots by R. Ulrich (KIT)

Variation of basic parameters

- SIBYLL 2.1
- Original parameters for $E<10^{15}$ eV
- Logarithmic change up to $E=10^{19}$ eV
- Correlation between parameters not taken into account
- Baryon not taken into account in charge ratio (effect can be much larger)

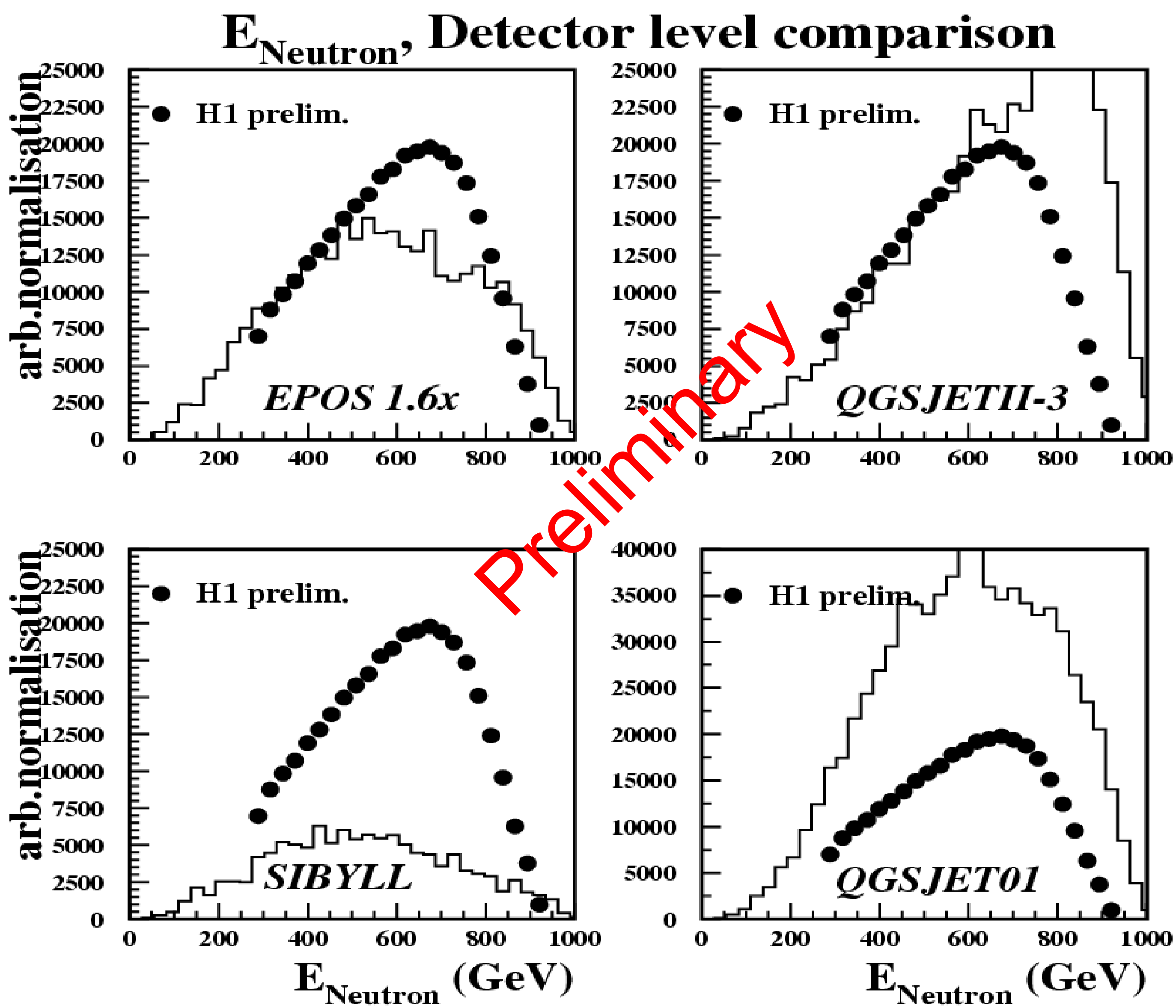
Large uncertainties will be reduced by LHC

Summary

- **Even in the range of existing data, hadronic interaction models have different predictions :**

  - Large uncertainties in EAS simulations due to hadronic models.
  - Cosmic ray analysis, in particular for mass composition, has to be done carefully (at least with 2 different hadronic interaction models).
  - Extrapolation p-p to p-A or π-A and forward region: need more h-A data.
  - Future particle physics measurement at CERN (NA61 and LHC) will provide more constraints on hadronic models.
    - Update of models in 2011
  - Except EPOS, models dedicated to cosmic rays.
  - Low energy model important especially far from the core (large relative transverse momentum)

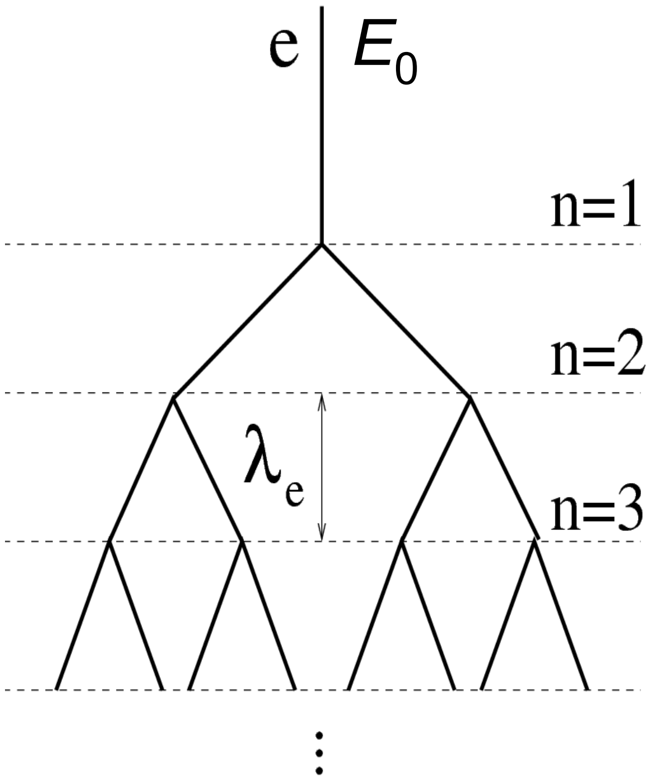
Forward Neutron Distributions



Analysis by A. Bunyatian

Toy Model for Electromagnetic Cascade(skip)

Primary particle : photon/electron



Heitler toy model :

- 2 particles produced with equal energy

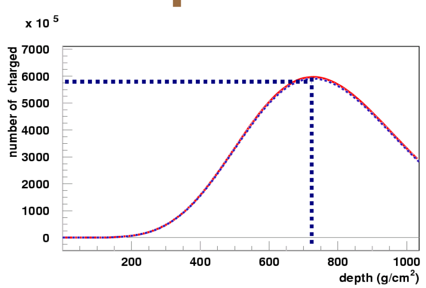
2ⁿ particles after *n* interactions

$n = X/\lambda_e$

$N(X) = 2^n = 2^{X/\lambda_e}$

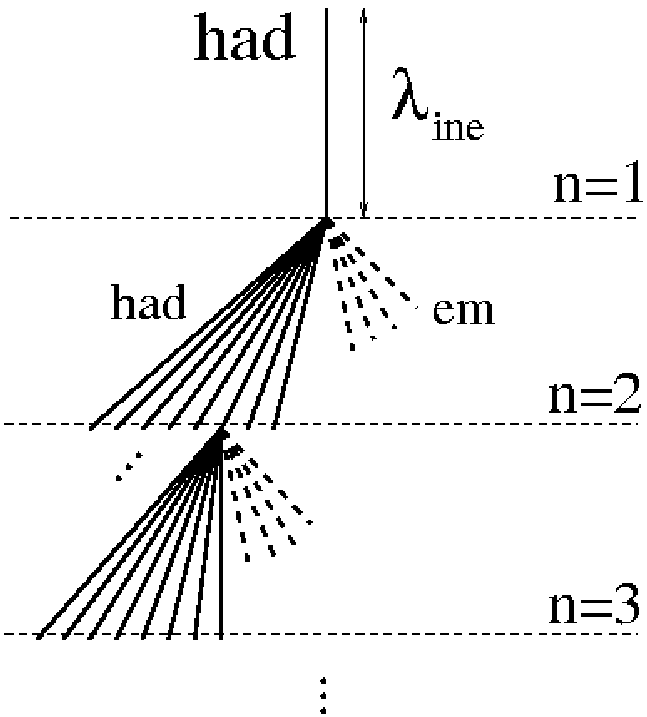
$E(X) = E_0/2^{X/\lambda_e}$

Assumption: shower maximum reached if *E(X)* = E_c (critical energy)



$N_{max} = E_0/E_c$ $\quad X_{max} \sim \lambda_e \ln(E_0/E_c)$

Toy Model for Hadronic Cascade



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

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

$$N_\mu = \left(\frac{E_0}{E_{dec}}\right)^\alpha, \quad \alpha = \frac{\ln N_{had}}{\ln N_{tot}}$$

Primary particle : hadron

Using a simple generalized Heitler model to understand EAS characteristics :

- fixed interaction length
- equally shared energy
- 2 types of particles :
  - N_{had} continuing hadronic cascade until decay at E_{dec} producing muons (charged pions).
  - N_{em} transferring their energy to electromagnetic shower (neutral pions).

Lessons From Heitler Model

Important hadronic interaction parameters :

- **For X_{max} :**
  - Cross section
  - Multiplicity
- **For the number of muons :**
  - Multiplicity
  - π^0 to all particles ratio and baryons
- **For Energy deposit :**
  - π^0 to all particles ratio

Cross check using modified realistic simulations.

Energy Transfer : Energy Deposit

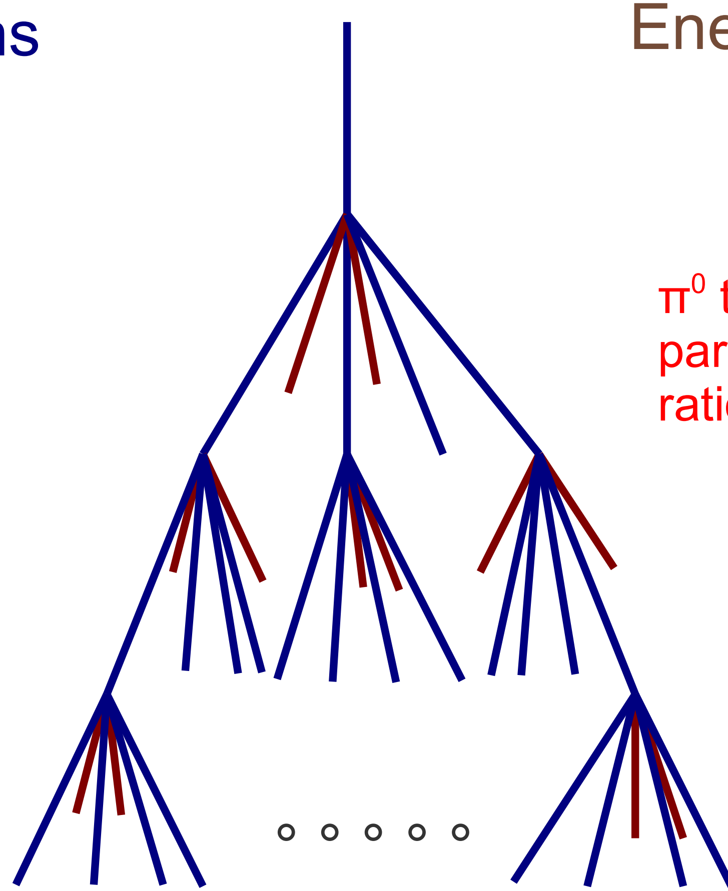
Energy of all hadrons

E_0

$\frac{2}{3} E_0$

$\frac{2}{3}\left(\frac{2}{3} E_0\right)$

After *n* generations



Energy of all em. particles

0

π^0 to all particles ratio → $\frac{1}{3} E_0$

$\frac{1}{3} E_0 + \frac{1}{3}\left(\frac{2}{3} E_0\right)$

$$E_{had} = \left(\frac{2}{3}\right)^n E_0$$

Energy in em. ~ 90 %

(n=5, E_{had} ~12%
n=6, E_{had} ~8%)

$$E_{em} = \left[1 - \left(\frac{2}{3}\right)^n\right] E_0$$