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Test of Interaction Models via Accelerator Data

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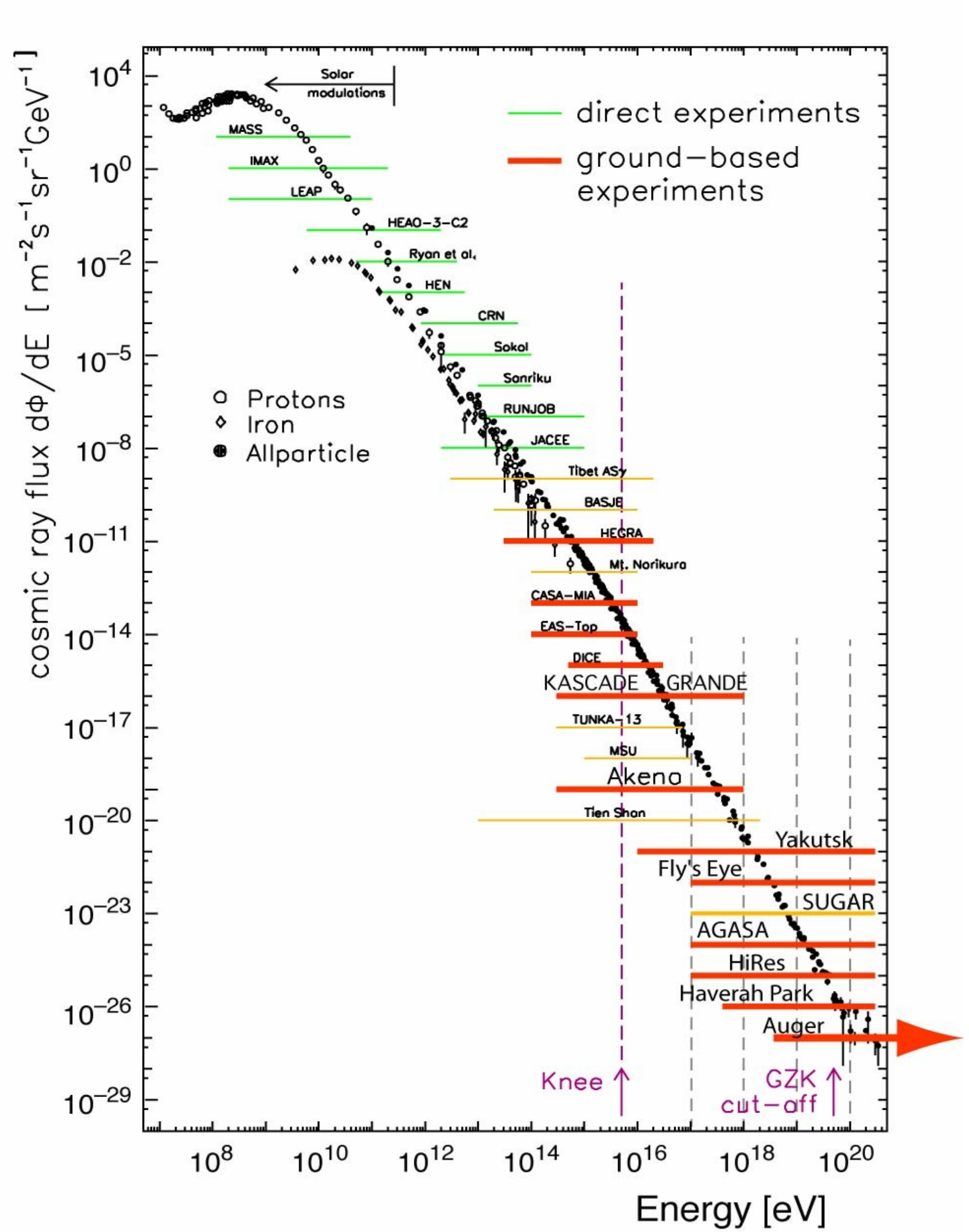
Outline

- Cosmic rays
- Extended Air Shower (EAS) phenomenology
- Hadronic interaction models
- Relevant data for EAS
- Uncertainties in EAS simulations
- Summary

Cosmic Rays



cosmic ray flux dΦ/dE [m^-2 s^-1 sr^-1 GeV^-1]
Solar modulations
direct experiments
ground-based experiments
Protons
Iron
Allparticle
MASS
IMAX
LEAP
HEAO-3-C2
Ryan et al.
HEN
CRN
Sokol
Sanriku
RUNJOB
JACEE
Tibet ASγ
BASJE
HEGRA
Mt. Norikura
CASA-MIA
EAS-Top
DICE
KASCADE
GRANDE
TUNKA-13
MSU
Akeno
Tien Shan
Yakutsk
Fly's Eye
SUGAR
AGASA
HiRes
Haverah Park
Auger
Knee
GZK cut-off
Energy [eV]

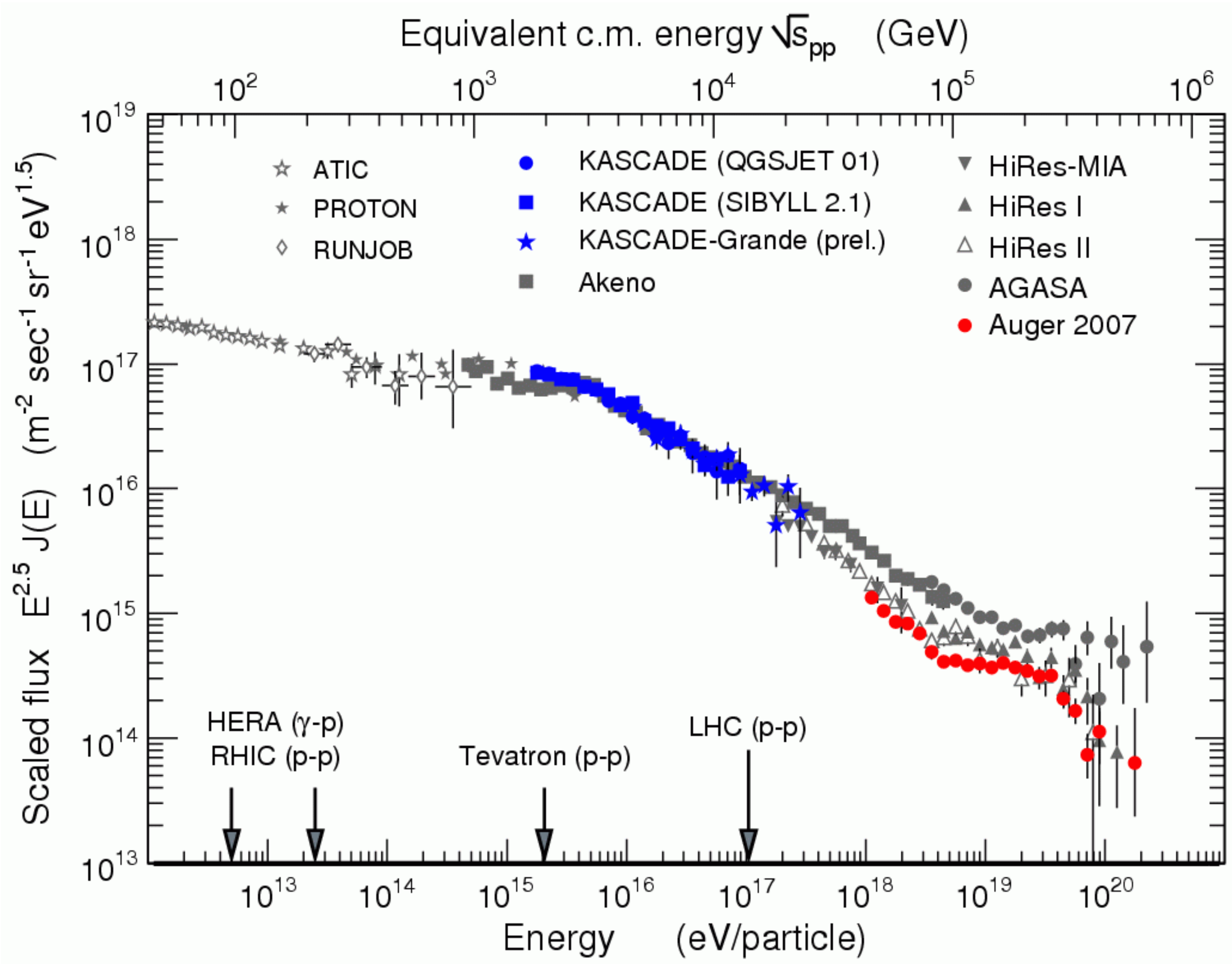
Cosmic Rays

Measurements need hadronic models for :

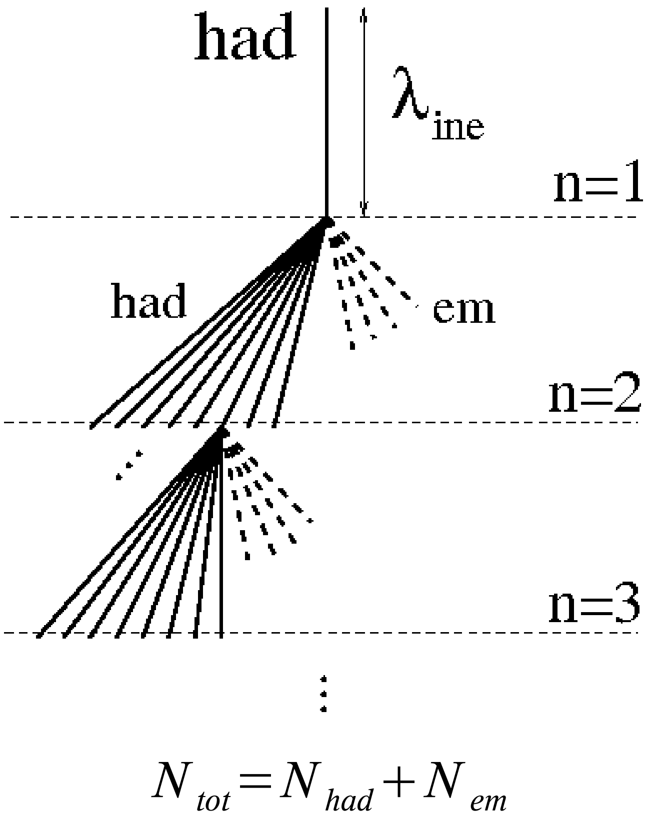
- Mass (always)
- Energy (sometimes)

Maximum mass limited to iron :

- Constraints on models



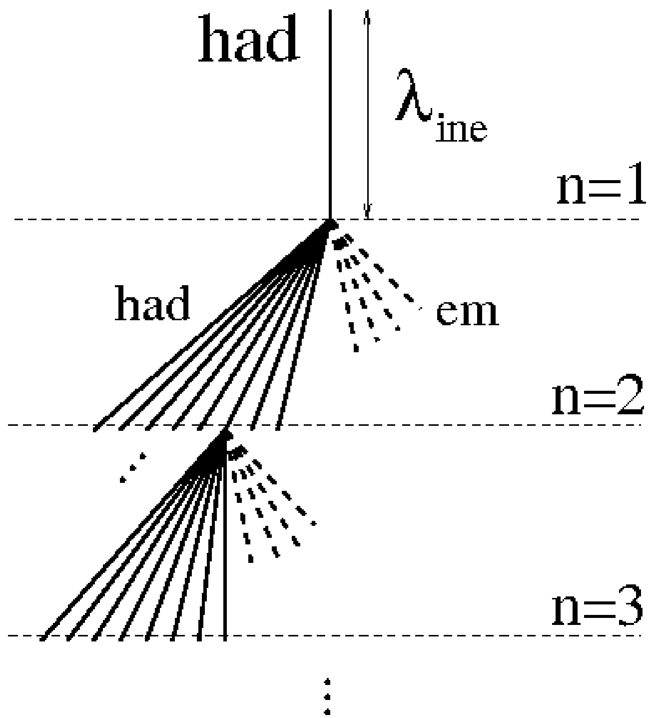
Generalized Heitler Model



Using a simple generalized Heitler model to understand EAS characteristics :

- Only 2 types of hadronic 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).
- equally shared energy
- fixed interaction length

Generalized Heitler Model



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

Results : $E(X) = E_0/(N_{tot})^n \rightarrow E_{dec}$

N_μ is then given by : $N_\mu = N_{had}^n = \left(\frac{E_0}{E_{dec}}\right)^\alpha$

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

$$R = \frac{N_{had}}{N_{tot}} \approx \frac{N_{\pi^{ch}}}{N_{\pi^{ch}} + N_{\pi^0}} = \frac{2}{3}$$

Fixed if only pions

$$N_\mu = \left(\frac{E_0}{E_{dec}}\right)^\alpha, \quad \alpha = \frac{\ln N_{had}}{\ln N_{tot}} \approx 0.82 \ldots 0.95$$

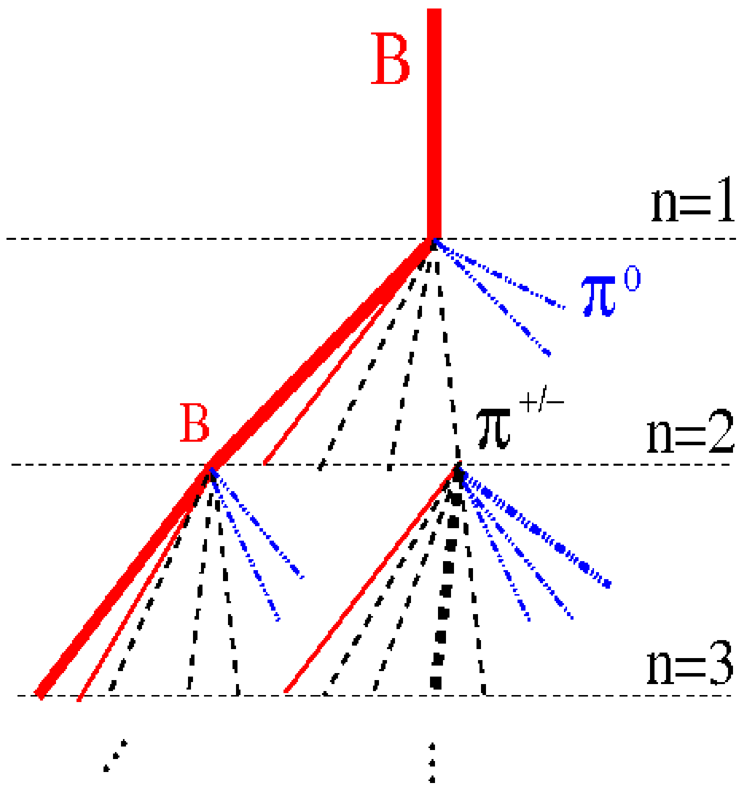
X_{max} is then given by :

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

Hadronic Model dependent !

Air Shower Simulation

More realistic approach implies to take into account the proper energy transfer from hadronic particles to electromagnetic one (via neutral pions) : MC : CORSIKA, AIRES, CONEX, ... using realistic hadronic interaction models.



Thickness = amount of energy

- models for minimum Bias simulation : mainly soft physic + diffraction (forward region).
- should handle p-, π-Air, K-Air and A-Air interactions
- should be able to run at 10^6 GeV cms.

Dedicated models : QGSJET(01 or II) and SYBILL 2.1

Models used for RHIC and CR : EPOS (and DPMJET III)

Needs for Hadronic Interaction Models

Models used for EAS simulation should describe for p-Air and pi-Air interactions :

- For Xmax :
- Inelastic cross section
- Inelasticity
- Total multiplicity
- diffraction
- For the number of muons :
- Multiplicity in the forward region
- energy spectra of pi^0 and antibaryons at large xF

Problem : not so many data in that range ...
... max energy for the last item : 100 GeV lab !

Ingredient of Hadronic Models

Theoretical basis :

- QCD
- Gribov-Regge (MPI)
- 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 !

Hadronic Interaction Models for Cosmic Rays

(HDPM)

Old generation : QGSJET01 SIBYLL DPMJET 2 VENUS

All Glauber based

But differences in hard, remnants, diffraction …

semi–hard

soft

NEXUS

Attempt to get everything describe in a consistent way (energy sharing)

New generation : QGSJET II (DPMJET III) EPOS

Theory ++ :

–**Fan diagrams**

–**diffraction**

–**optimized for CR**

Phenomenology ++ :

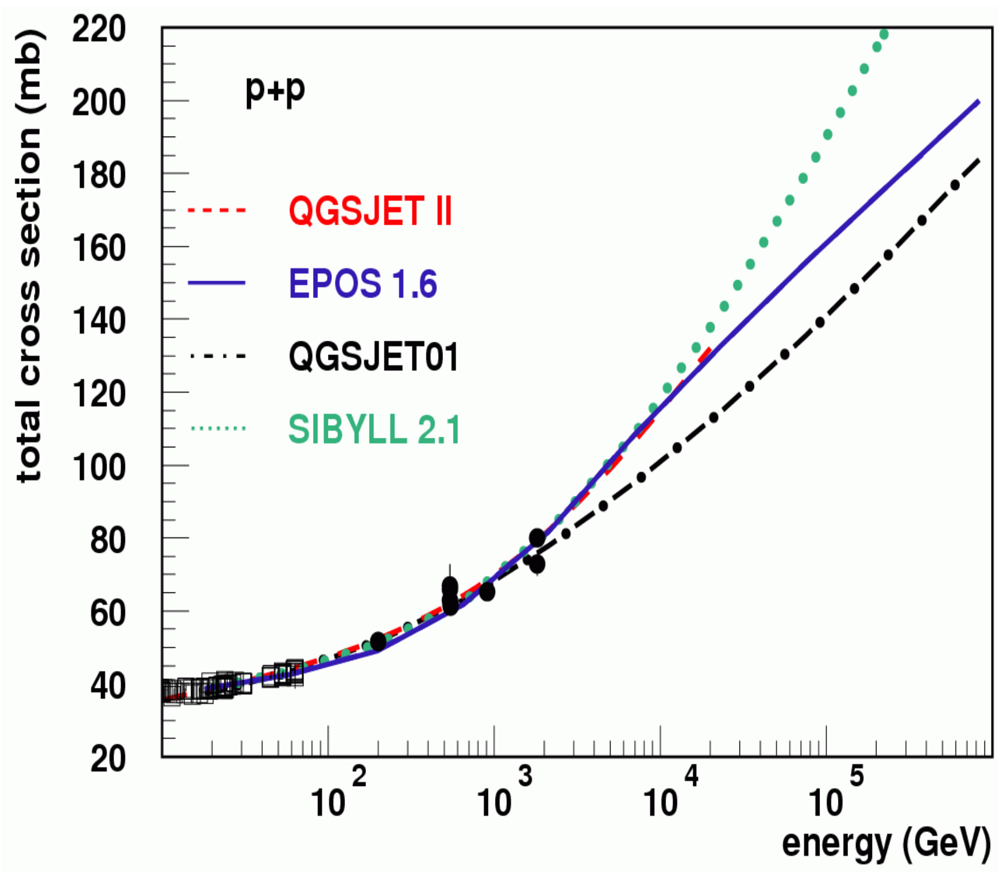
–**Nuclear effect**

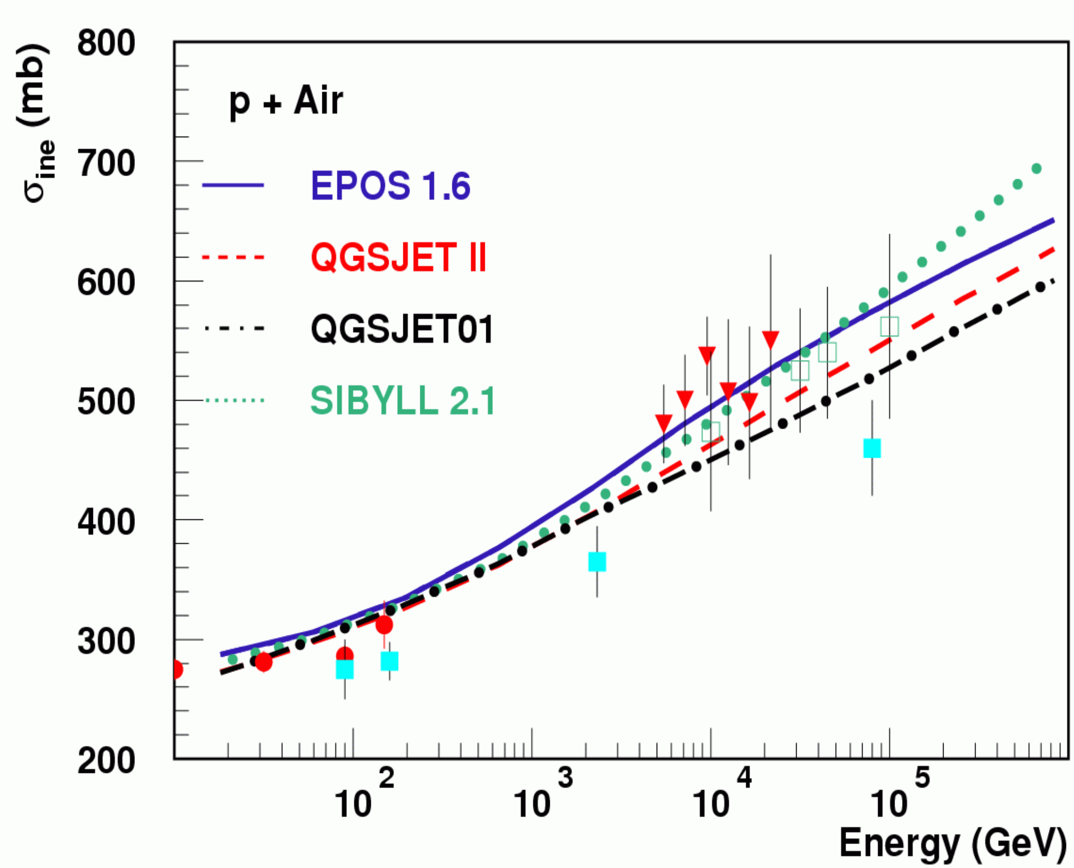
–**High density effect (QGP)**

–**all type of data studied**

Inelastic Cross Section

- Consistent cross section and particle production at pp level.
- extrapolation to pA using Glauber
  - Nuclear effects neglected in cross section !





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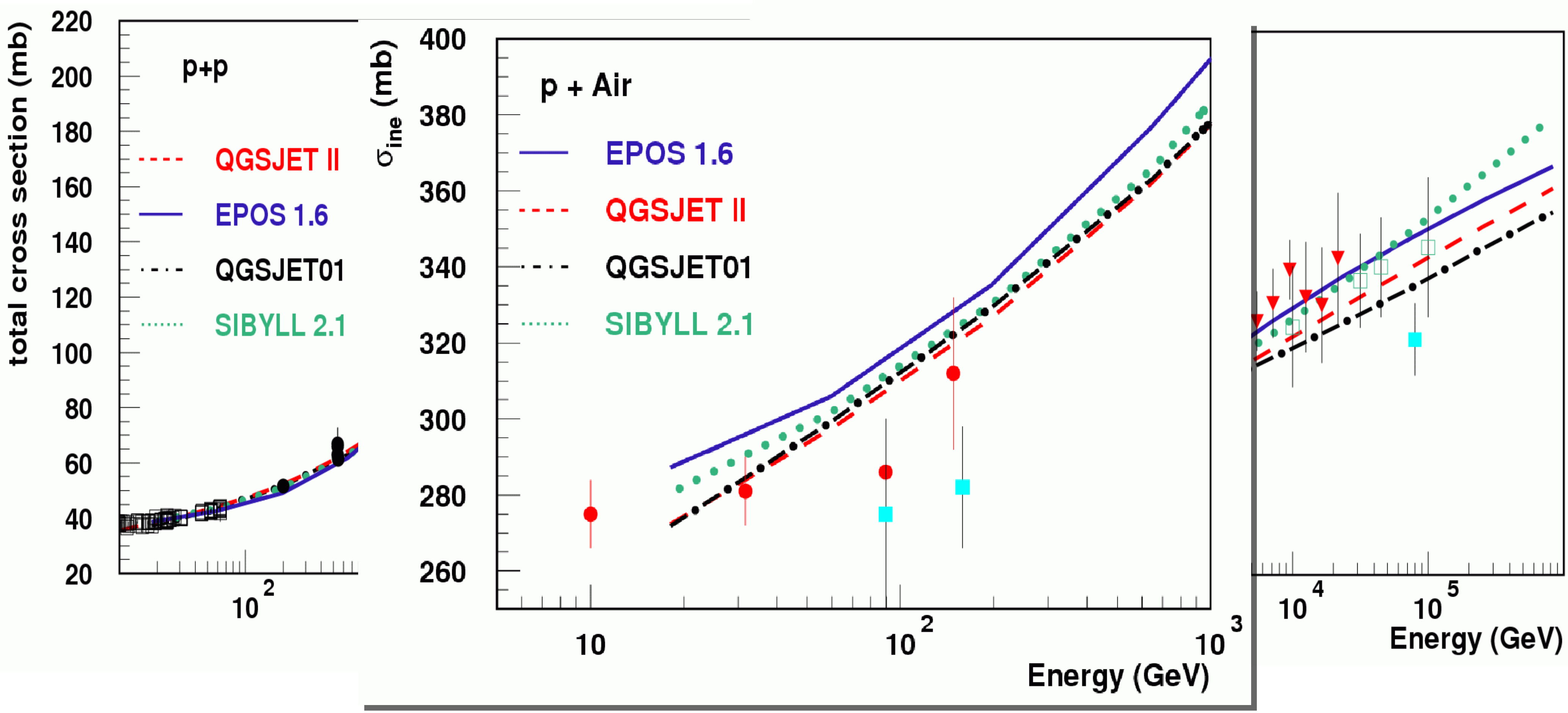
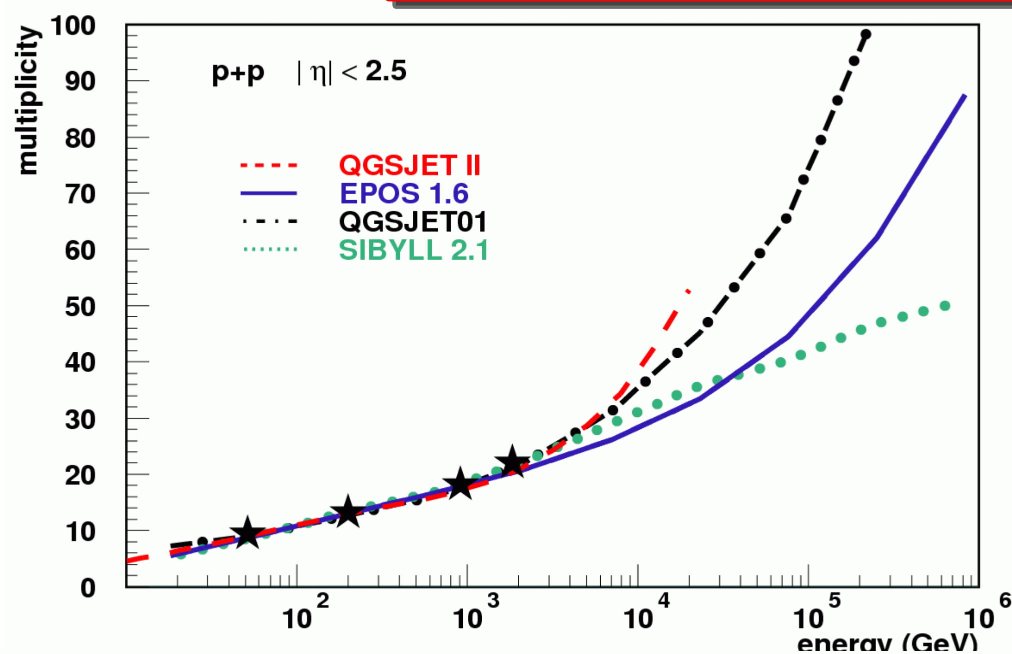
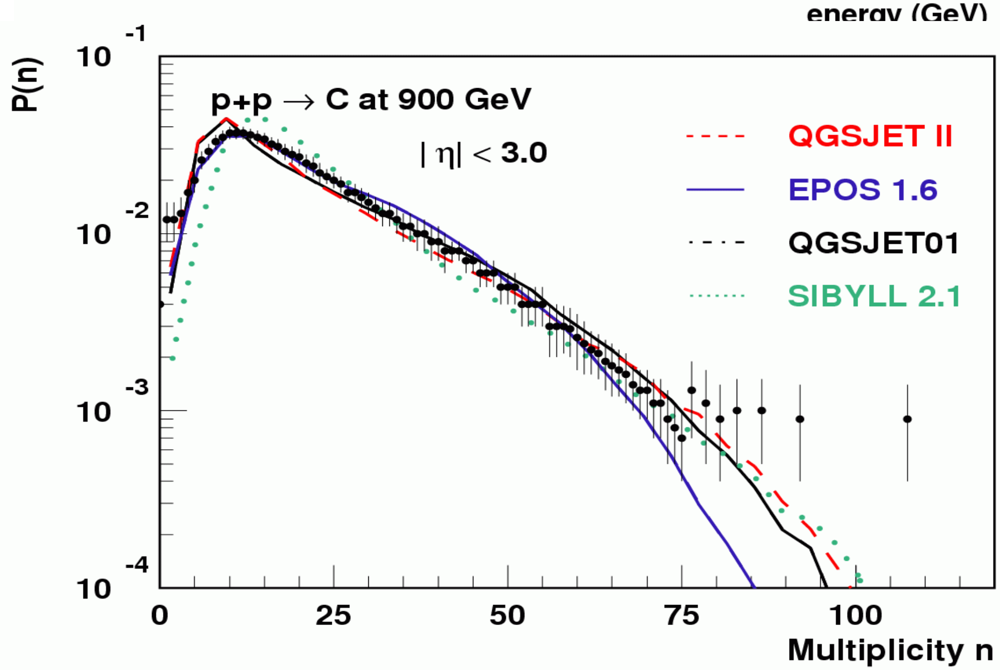
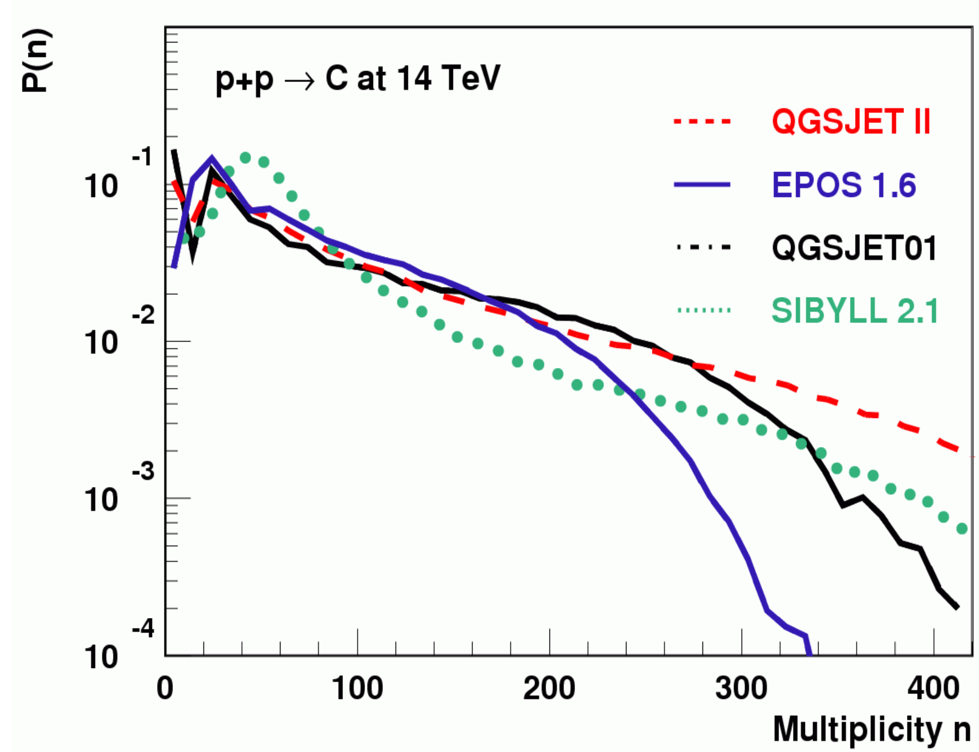


Multiplicity

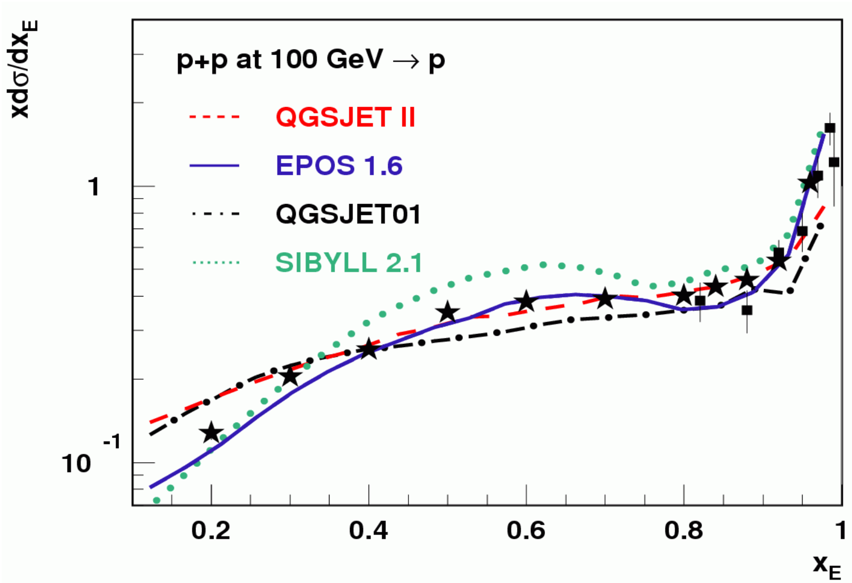


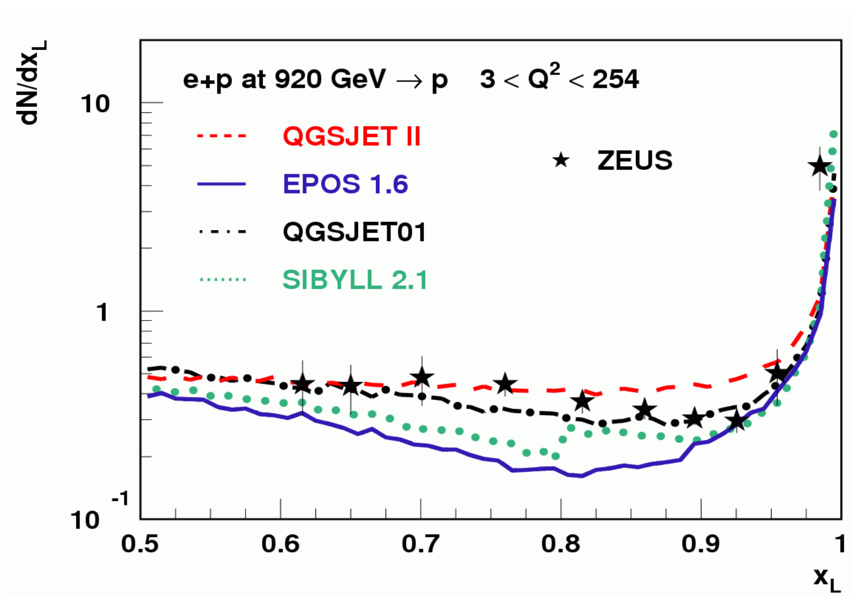


- More than linear increase
- Shape of distribution correct
- large differences at LHC

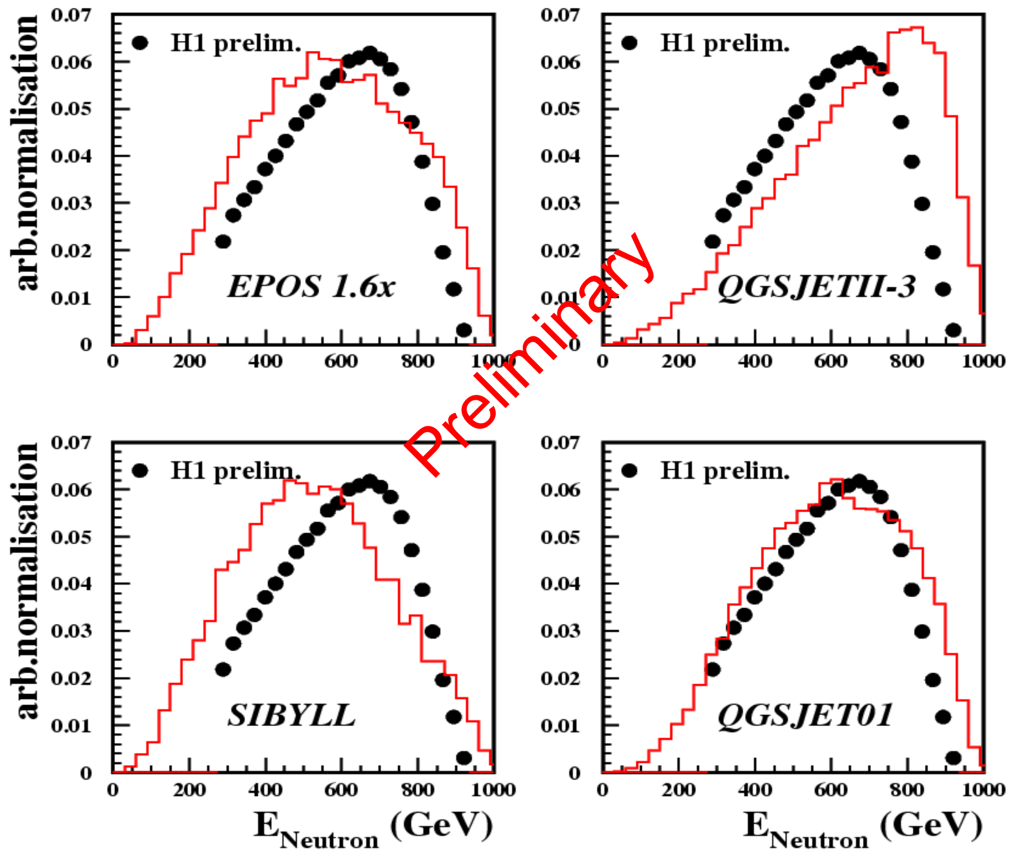


Diffraction and xf Distribution



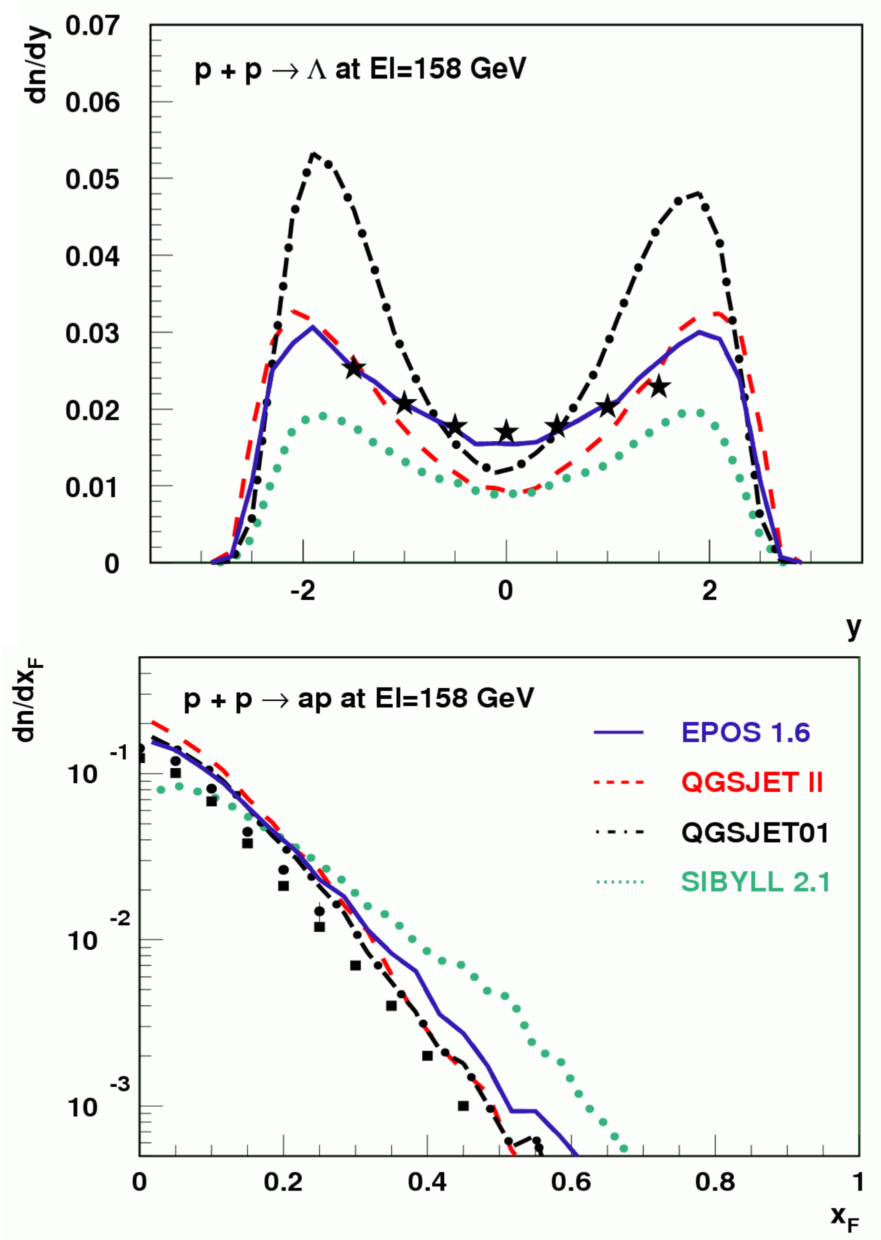


- data at low energy (fixed target experiment)
- extrapolation tested with HERA data

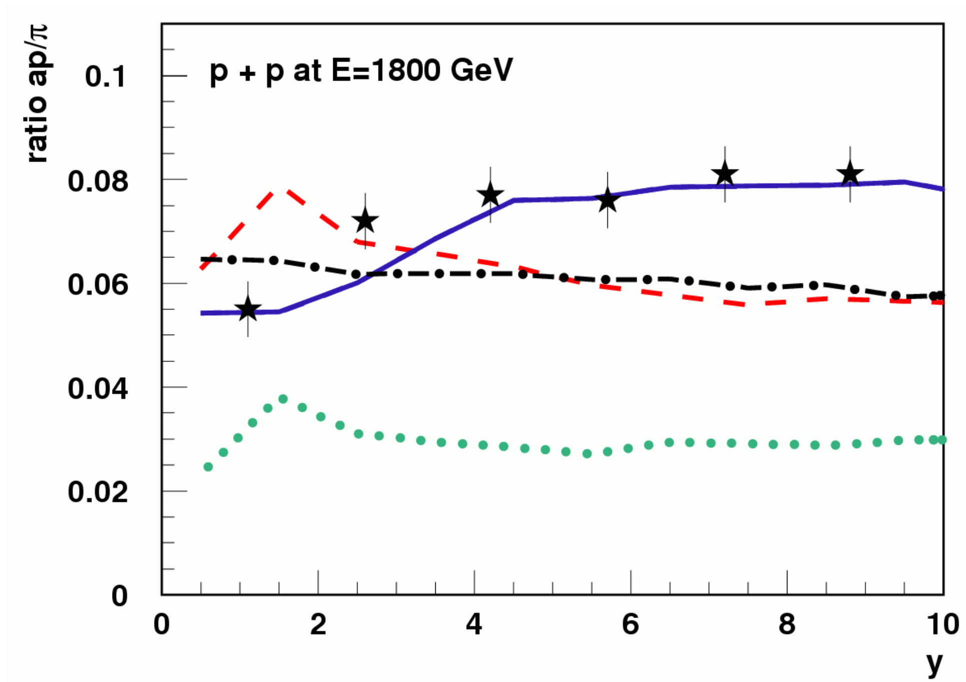


Analysis by A. Bunyatian

Baryon Production



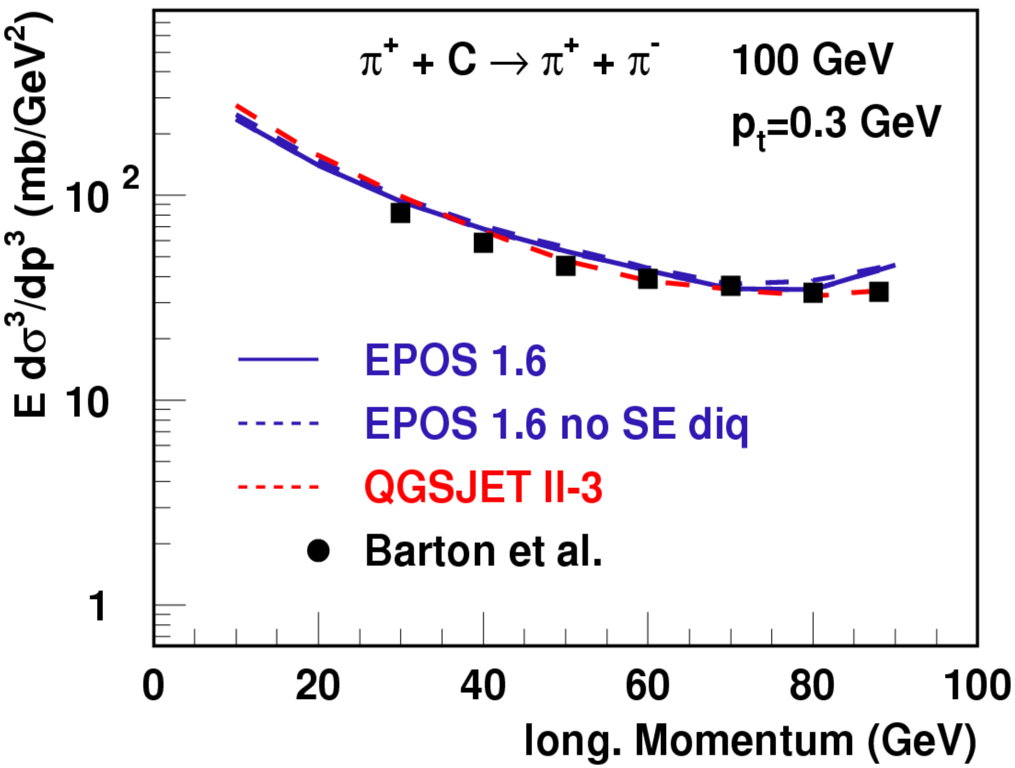
- Need a new approach for a complete description
- problem even at low energy
- production most likely energy dependent

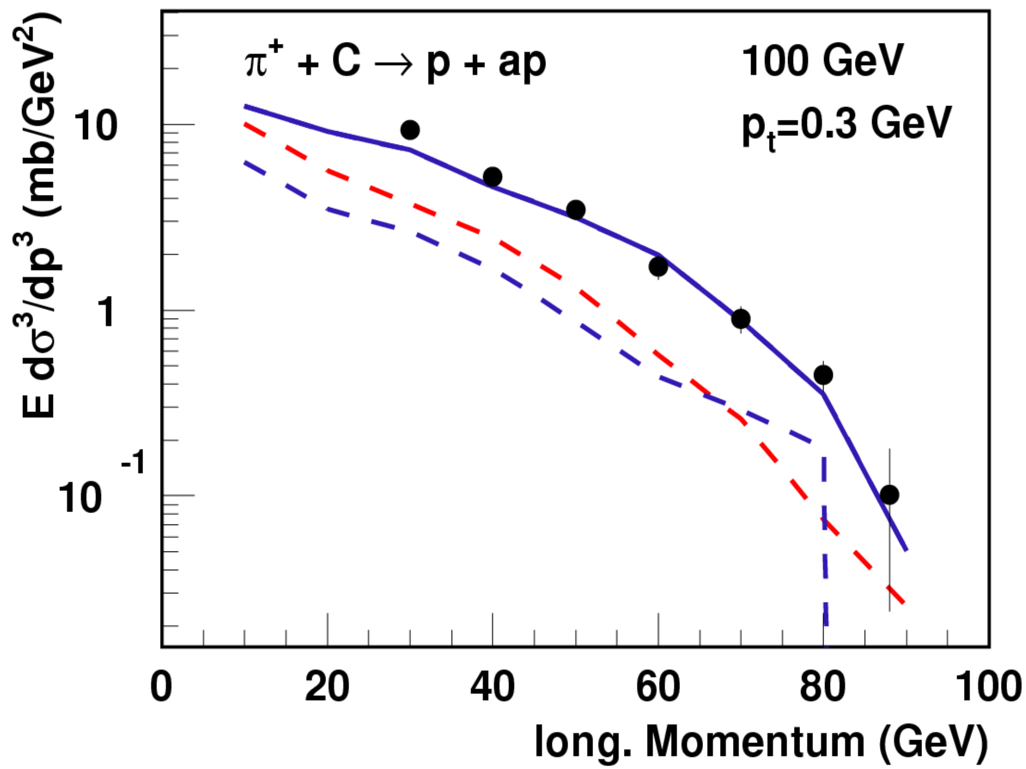


Baryons from Pion-Carbon

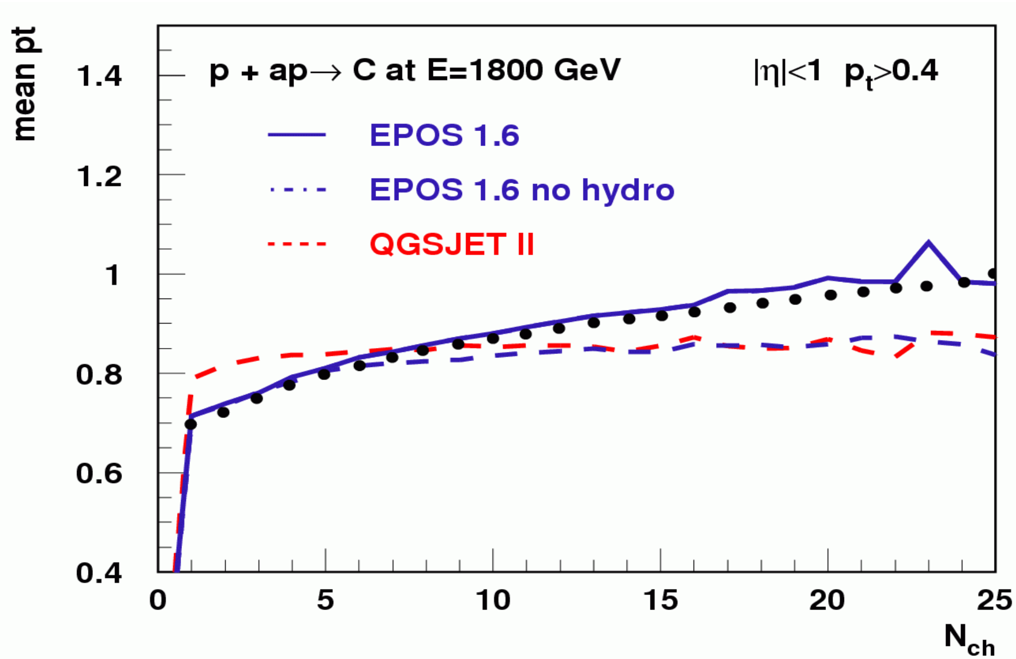
Very few data for baryon production from meson projectile, but for all :

- strong baryon acceleration (probability ~20% per string end)
- proton/antiproton asymmetry (valence quark effect)
- target mass dependence

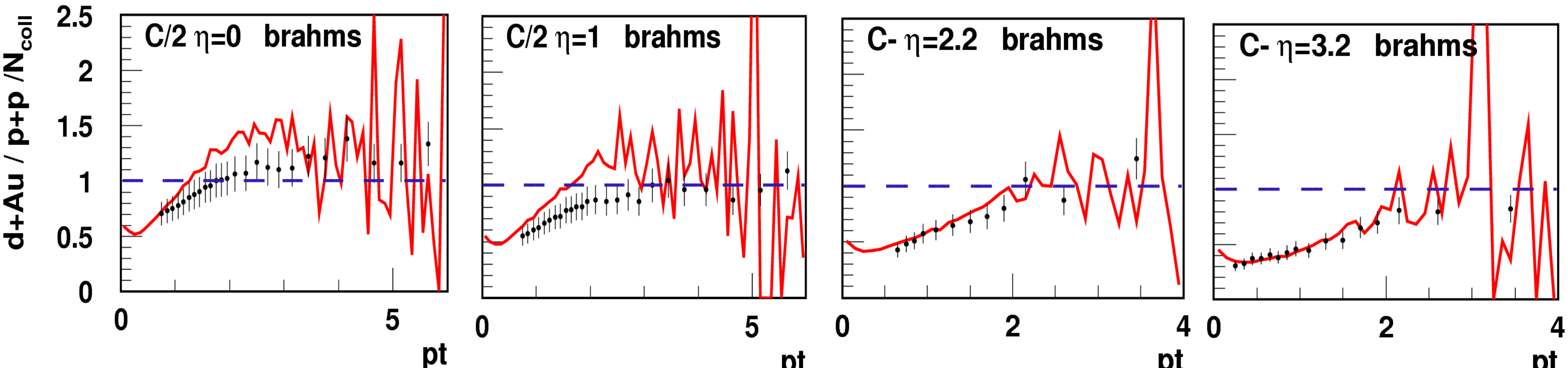




Simplified Models ?



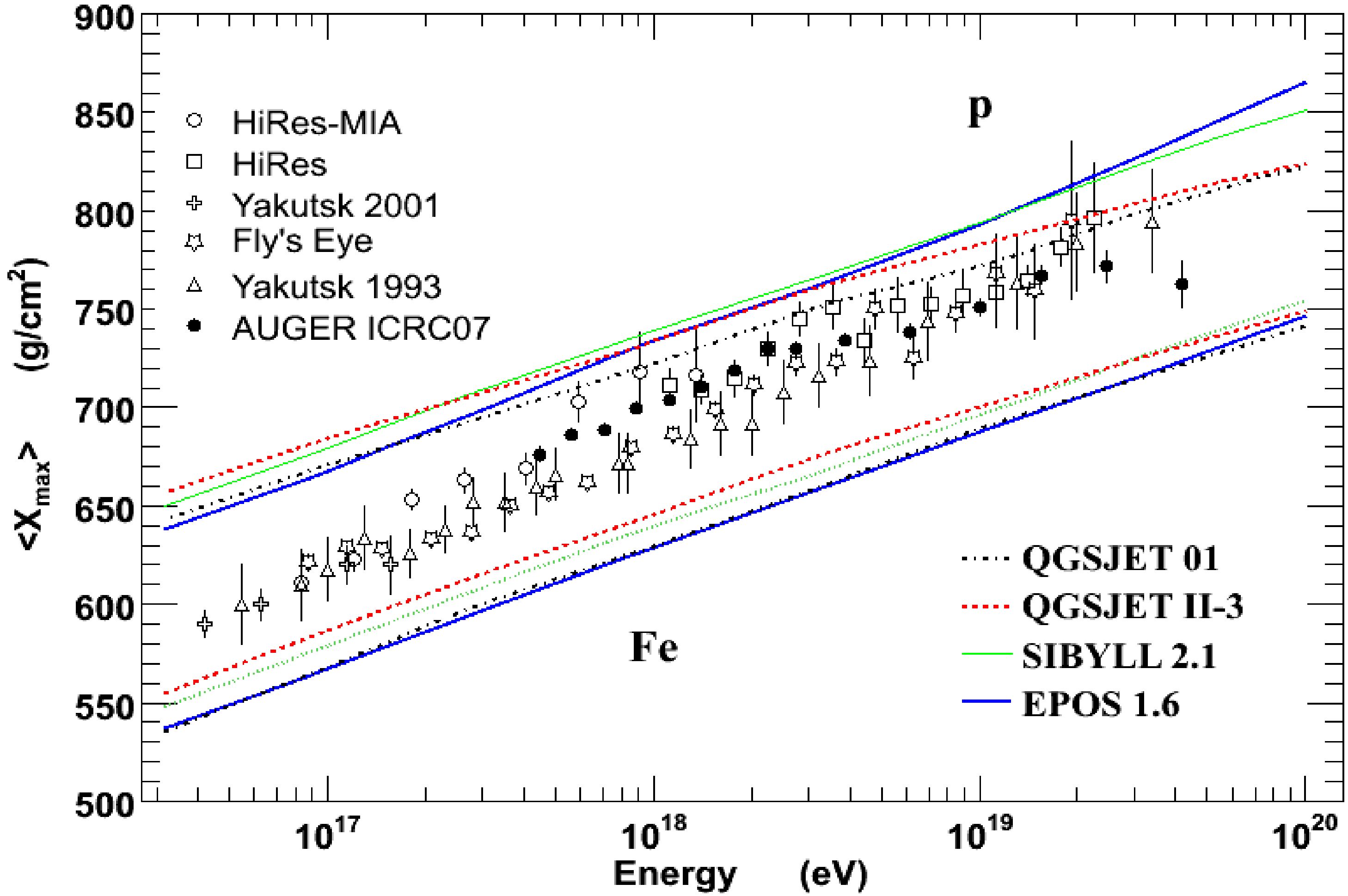
- hydro in pp ?
- limited fragmentation
  - remnant fragmentation
- pt suppression at large eta
  - not trivial (QGSJET II flat)
  - CGC not the only solution



EPOS – no CGC

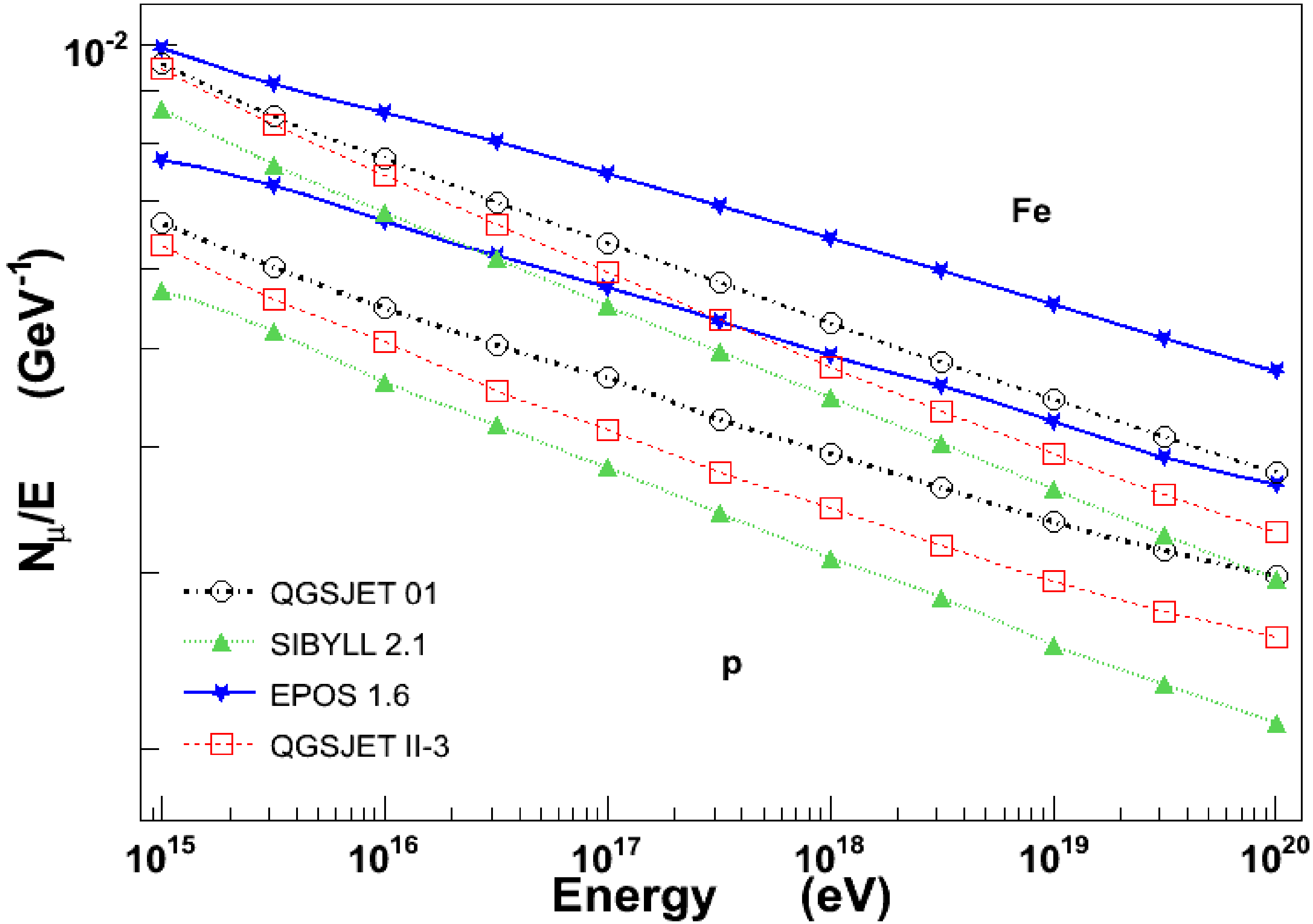
Uncertainty in EAS Simulations (Xmax)

Discrepancy (cross section and multiplicity) between models
=
source of uncertainty for mass composition



Uncertainty in EAS Simulations (muons)

Discrepancy (baryon and pion spectra) between models
=
source of uncertainty for mass composition and energy



Summary

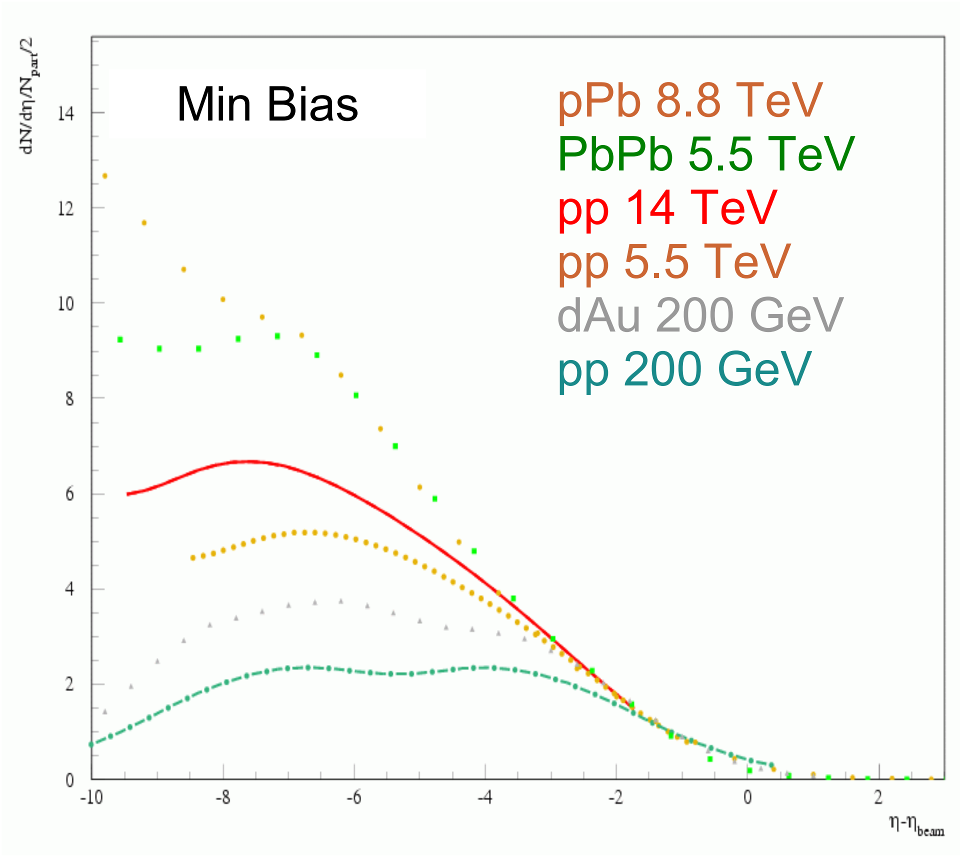
Even in the range of existing data, models have different predictions :

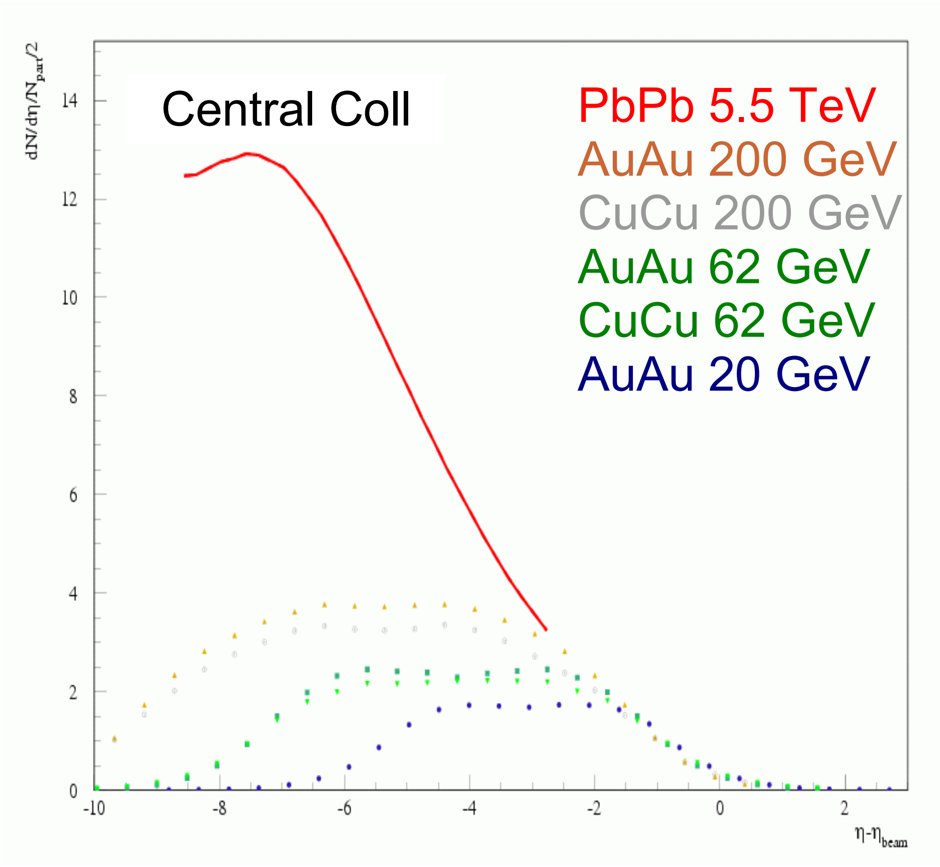
- Extrapolation p-p to p-A or π-A and forward region: need more h-A data (NA61, LHC)
- Except EPOS, models dedicated to CR : need more models used by both community (DPMJET III, ???)
  - better test (baryon, strangeness, ...)
  - different approach (CGC relevant for EAS ...)
- Except EPOS, no future evolution of the models

  (SO : “QGSJET II is now complete”)
  - new model please !
- Next version of EPOS will take into account what we can learn from air showers (KASCADE experiment Ne-Nh-Nμ correlations) and can be used for LHC (min bias)

Limited Fragmentation

Simulations with EPOS 1.6





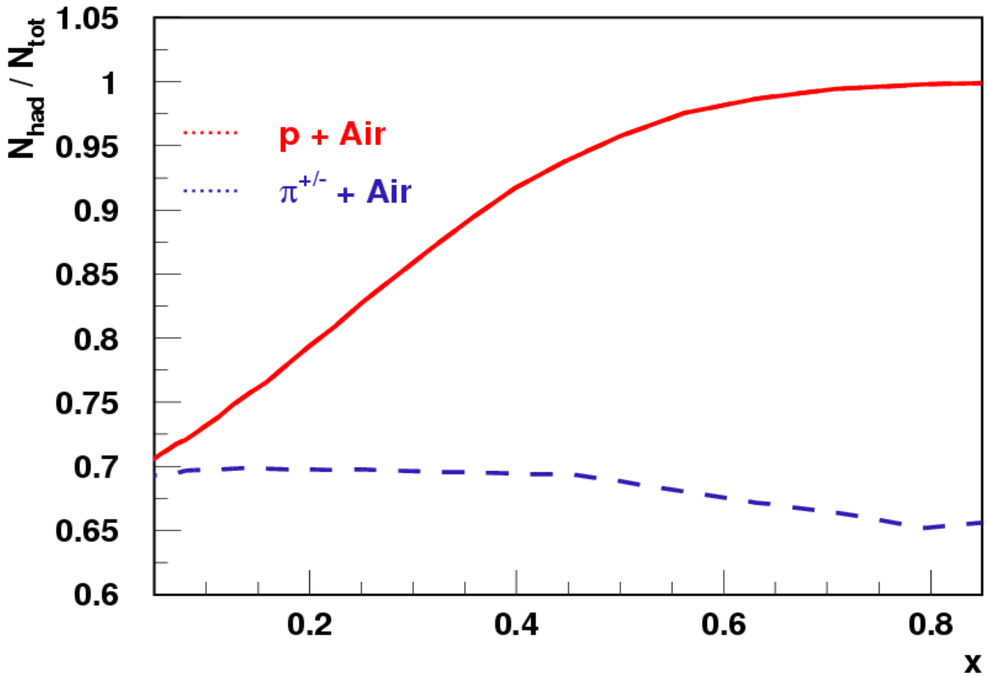
Similar results with QGSJET

Realistic Approach

But in real shower, not only pions : Kaons and (anti)Baryons

(but 10 times less ...)

➔ and mainly fast (leading) particles important for the cascade



Very important :

in (a)B-Air interactions, no leading neutral pion !

R~1

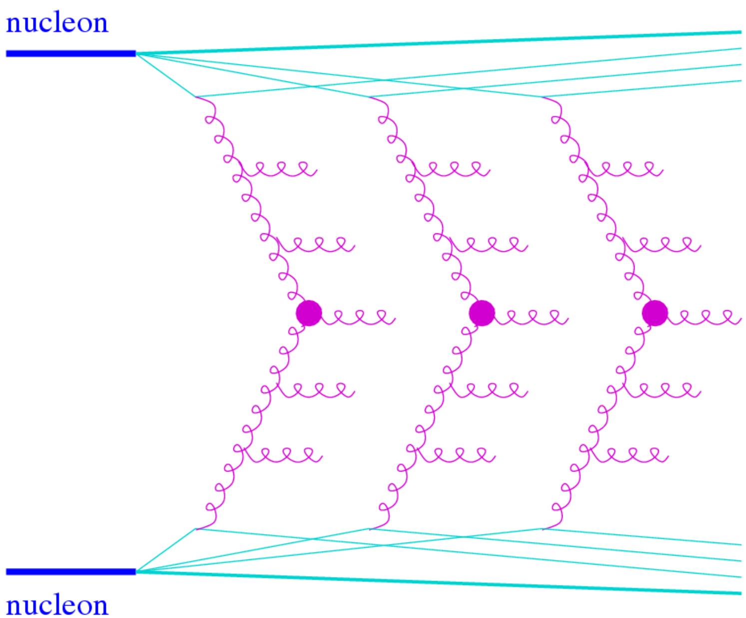
p induced sub-showers produces 30% more muons than pion induced sub-showers ...

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

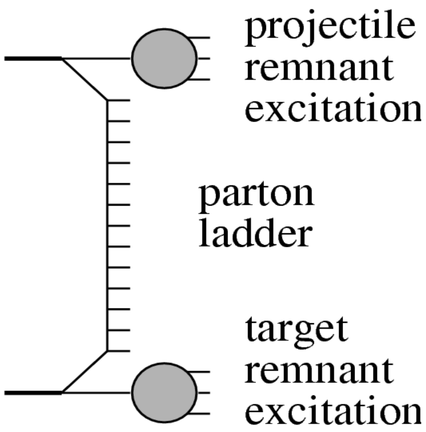
More fast (anti)baryons = $\alpha \to 1$ = more muons

Ref : astro-ph/0611311

EPOS and Parton-Based Gribov Regge Theory



EPOS is a parton model, with many binary parton-parton interactions, each one creating a parton ladder.



- Energy-sharing :
  - for cross section calculation AND particle production
- Multiple scattering (interference term)
- All ladder similar
  - valence quark in remnants
- Screening and shadowing via unitarization and splitting
- Ladder = soft + hard = field = string

Remnants

In EPOS : Diquark transfer between string ends and remnants

- Baryon number can be removed from nucleon remnant :
  - Baryon stopping
- Baryon number can be added to pion/kaon remnant :
  - Baryon acceleration