Model Comparisons with Accelerator and EAS data

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Outline

- **Hadronic Interaction Models in CORSIKA**
  - references
  - CPU time
- **Accelerator data**
  - excitation functions
  - distributions
- **EAS data**
  - fluorescence light
  - particles at ground

Models in CORSIKA

- **High-energy models in CORSIKA (Elab > 80 GeV)**
  - DPMJET II.55
  - EPOS 1.99
  - neXus 3.97
  - QGSJET 01
  - QGSJET II-3
  - SIBYLL 2.1
- **Low-energy models in CORSIKA**
  - FLUKA 2008
  - GHEISHA 2002
  - UrQMD 1.3

References for High Energy Models

- **DPMJET II.55**
  - J. Ranft, Phys. Rev. D51 (1995) 64; hep-ph / 9911213; hep-ph / 9911232
- **EPOS 1.99**
  - K. Werner et al., Phys. Rev. C74 (2006) 044902
  - T. Pierog et al., ICRC 2009 Proceedings
- **neXus 3**
  - H.J. Drescher et al., Phys. Rep. 350 (2001) 93
  - T. Pierog et al., QM2002 Proceedings
- **QGSJET 01**
  - N.N. Kalmykov et al., Nucl. Phys. B (Proc. Suppl.) 52B (1997) 17
- **QGSJET II-3**
  - S. Ostapchenko, Phys. Rev. D74 (2006) 014026
  - Nucl. Phys. B (Proc. Suppl.) 151 (2006) 143 & 147
- **SIBYLL 2.1**
  - R. Engel et al., Proc. 26th ICRC (Salt Lake City) 1 (1999) 415

References for Low Energy Models

- **FLUKA**
  - Fass`o A. et al., Report CERN-2005-10 (2005);
  - Computing in High Energy and Nuclear Physics 2003 Conference (CHEP2003), (paper MOMT005);
  - hep-ph / 0306267; http://www.fluka.org/
- **GHEISHA**
  - Fesefeldt H., PITHA-85/02 (RWTH, Aachen) (1985);
  - correction patches: Cassell R.E. and Bower G., private comm. (2002)
- **UrQMD 1.3**
  - Bass S.A. et al., Prog. Part. Nucl. Phys. 41 (1998) 225;
  - Bleicher M. et al., J. Phys. G: Nucl. Part. Phys. 25 (1999) 1859
  - http://www.th.physik.uni-frankfurt.de/ ˜urqmd/

CPU Time for Low Energy Models

model	100 000 collisions at 10 GeV p-air	100 000 collisions at 10 GeV π-air	1 shower[1] 10^{19} eV $\varepsilon = 10^{-6}$
FLUKA	208	190	72 800
GHEISHA 2002	124	117	33 500
UrQMD 1.3c	(≈1 200)	(≈1 200)	(≈95 000)
QGSJET 01	101	100	

[1] QGSJET 01, vertical, $w_{em} < 10^4$, $w_h < 10^2$, 1450 m a.s.l., $E_h > 300$ MeV, $E_\mu > 100$ MeV, $E_{em} > 250$ keV

CPU times (sec) for 1 GHz Pentium.

CPU Time for High Energy Models

model	10 000 collisions at 1 PeV p-^{14}N	10 000 collisions at 1 PeV π-^{14}N	100 p-showers 1 PeV only NKG [1]	100 p-showers 100 PeV with THIN [2]
DPMJET II.55	312	367	(2 170)[3]	(87 051)[3]
EPOS 1.6	1 789	936	13 414 [4]	280 000 [4]
neXus 3.97	2 202	884	8 950 [4]	413 950 [4]
QGSJET 01	189	336	4 490 [4]	40 540 [4]
QGSJET II-3	1 283	1 122	5 784 [4]	93 878 [4]
SIBYLL 2.1	214	240	4 348 [4]	43 200 [4]

[1] vertical, $E_h > 300$ MeV, $E_\mu > 300$ MeV

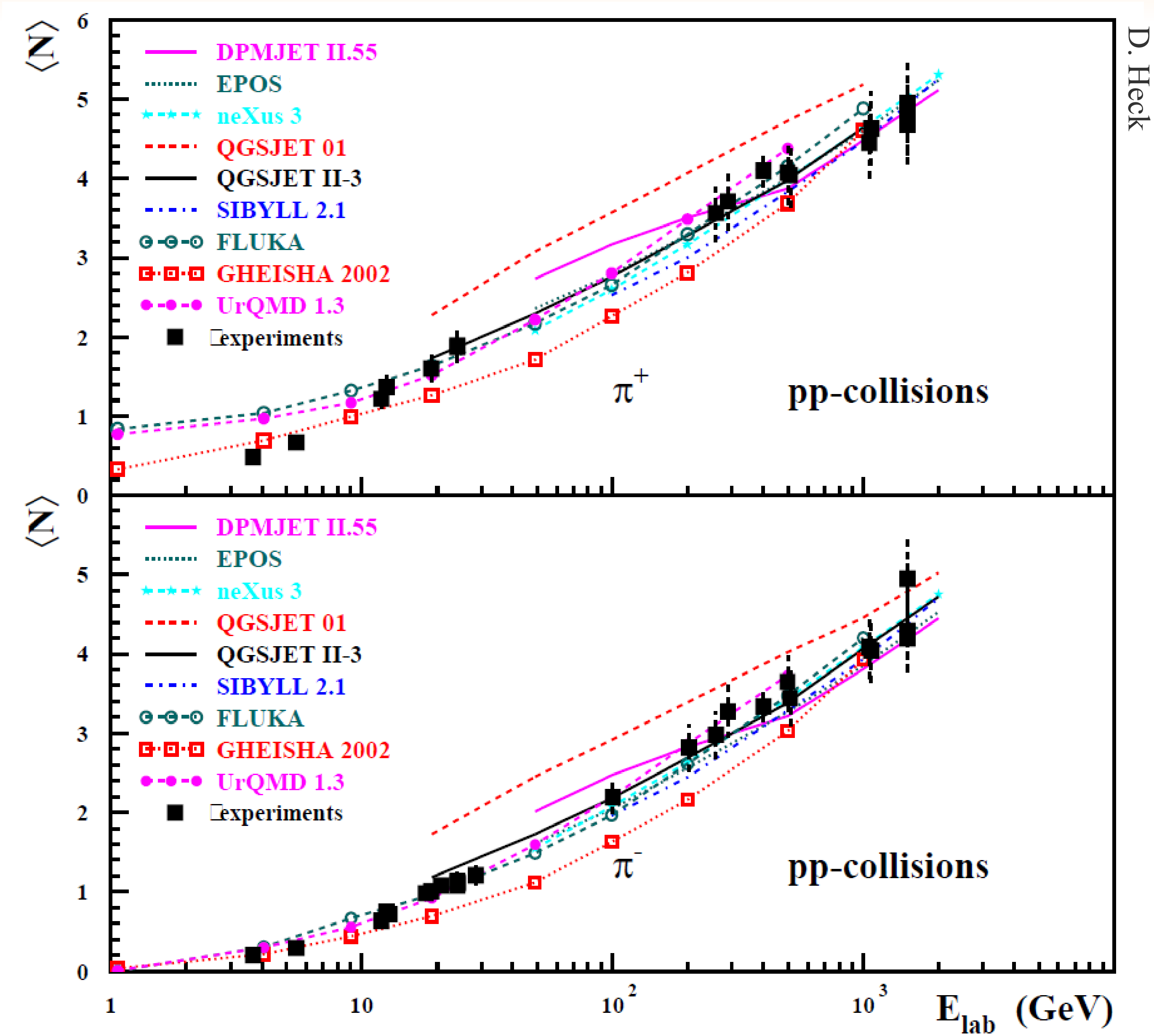
[2] vertical, $E_h > 100$ MeV, $E_\mu > 100$ MeV, $E_{em} > 0.1$ MeV, $\varepsilon = 10^{-5}$

[3] with low energy model GHEISHA 2002

[4] with low energy model FLUKA

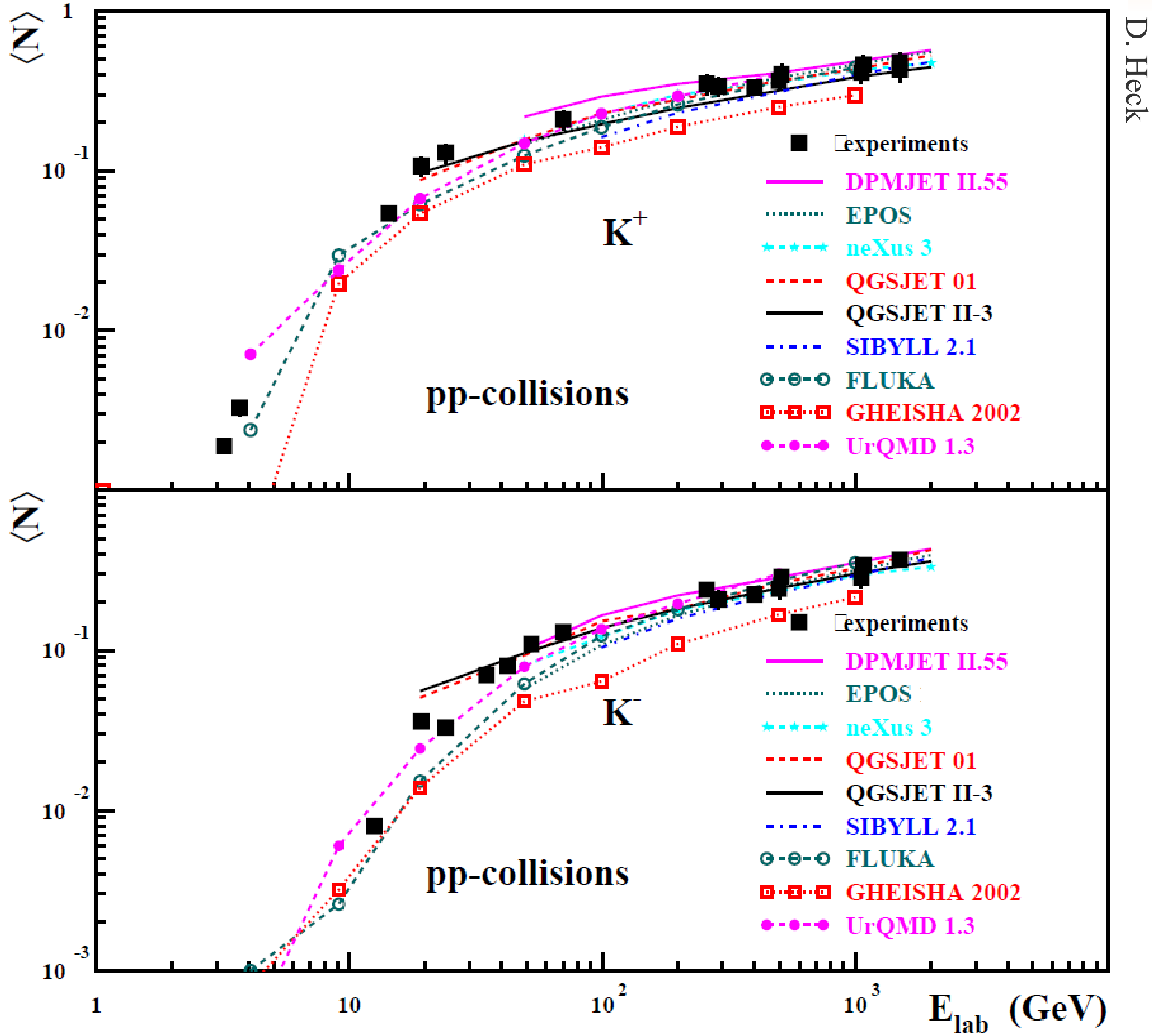
CPU times (sec) for 1 GHz Pentium.

Excitation function : Charged Pions



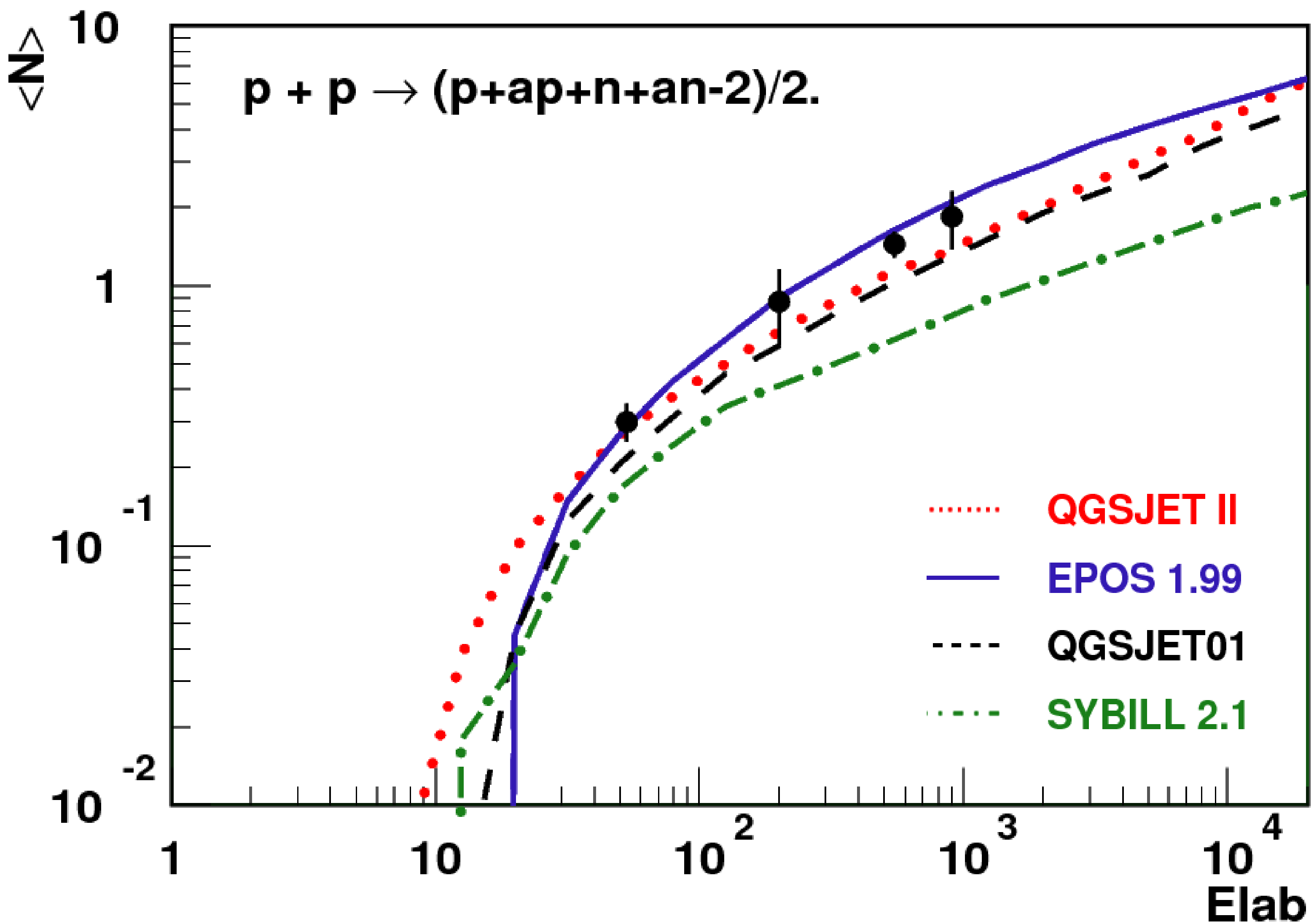
$\pi^{\pm}$ multiplicities in pp-collisions as function of energy.

Excitation function : Charged Kaons



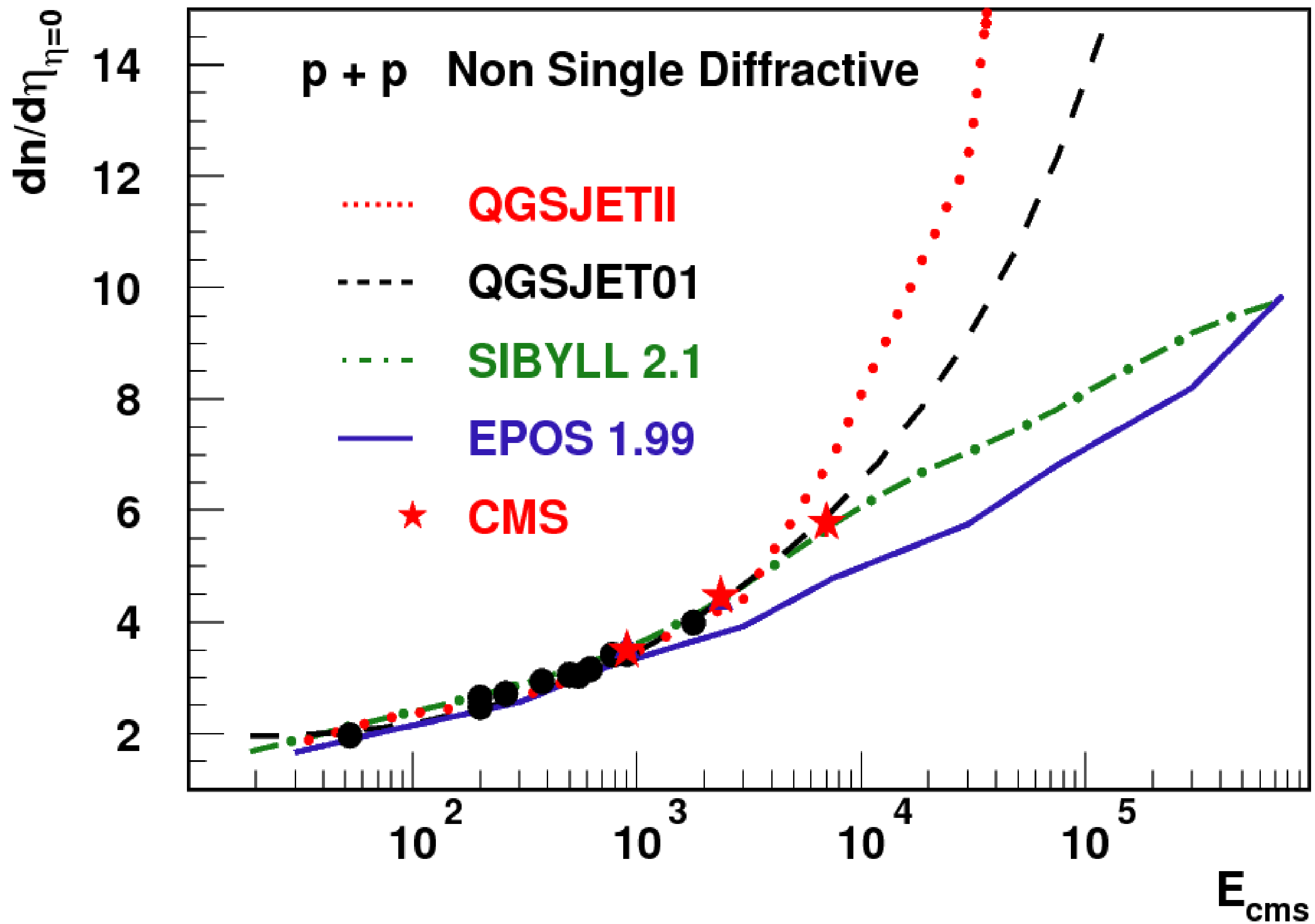
$K^{\pm}$ multiplicities in pp-collisions as function of energy.

Excitation function : Anti-protons



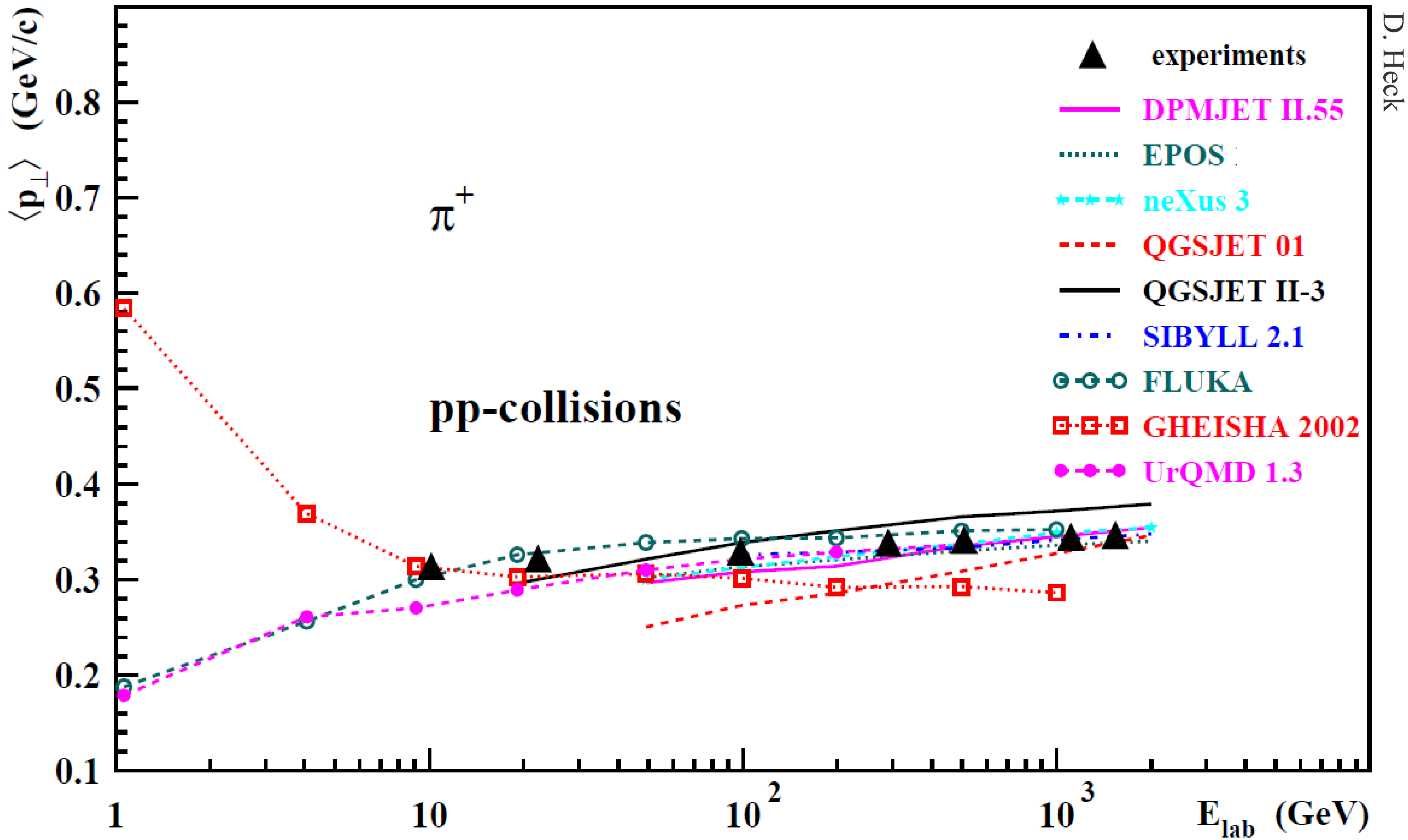
nucleon multiplicities in pp-collisions as function of energy.

Excitation function : Charged



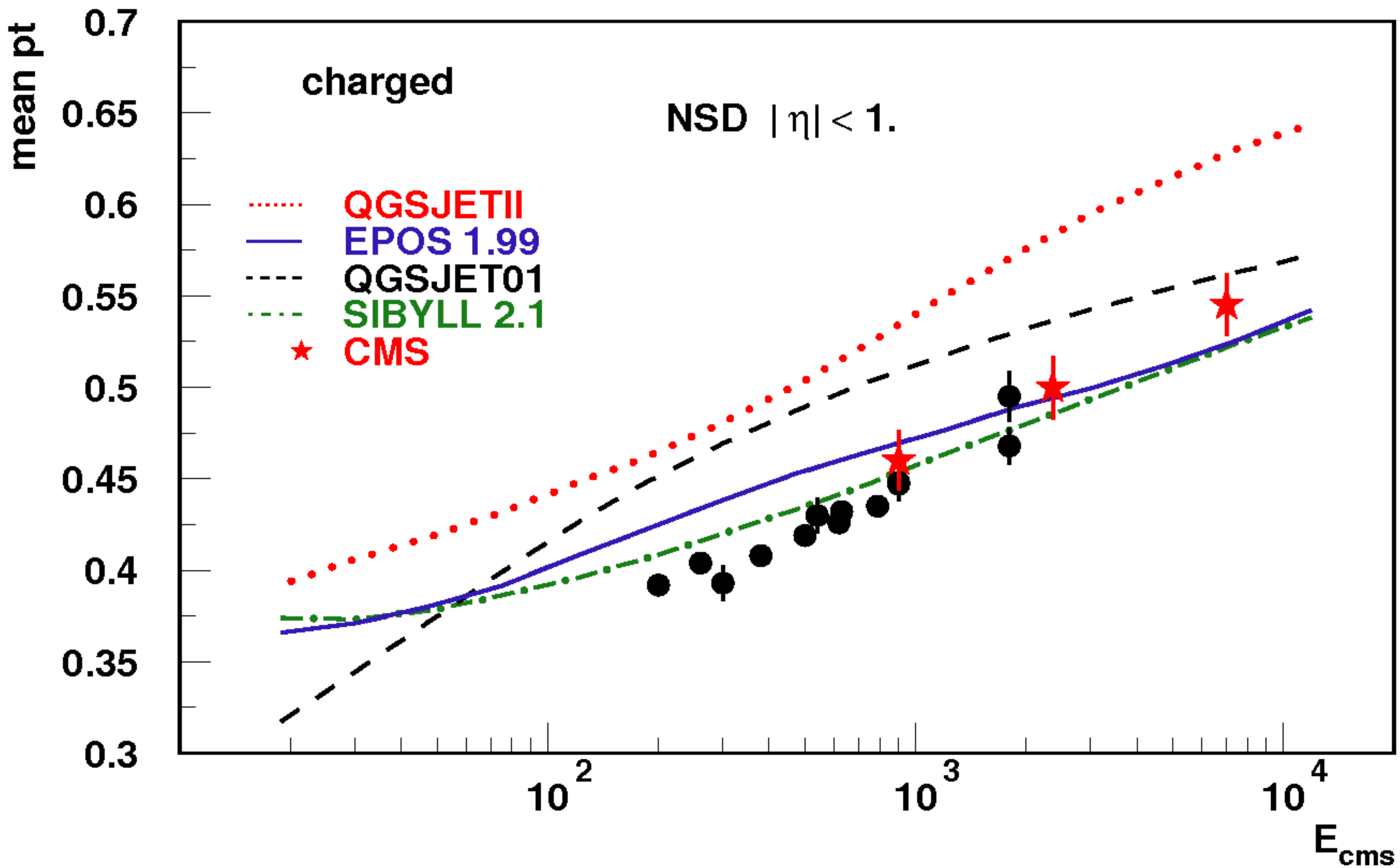
Charge particles multiplicities in pp-collisions as function of energy.

Pion <Pt>



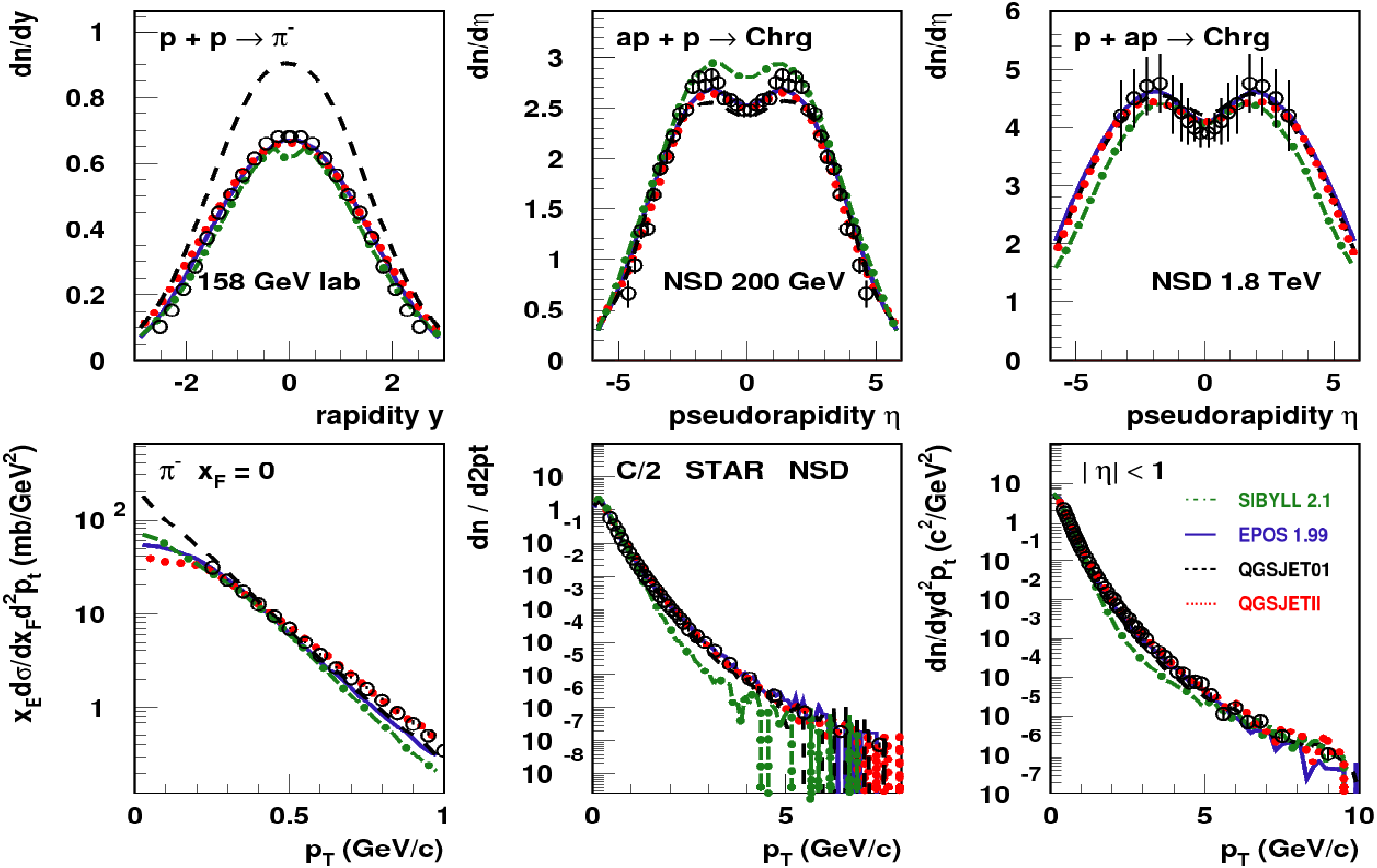
Charged pions mean transvers momentum in pp-collisions as function of energy.

<Pt>

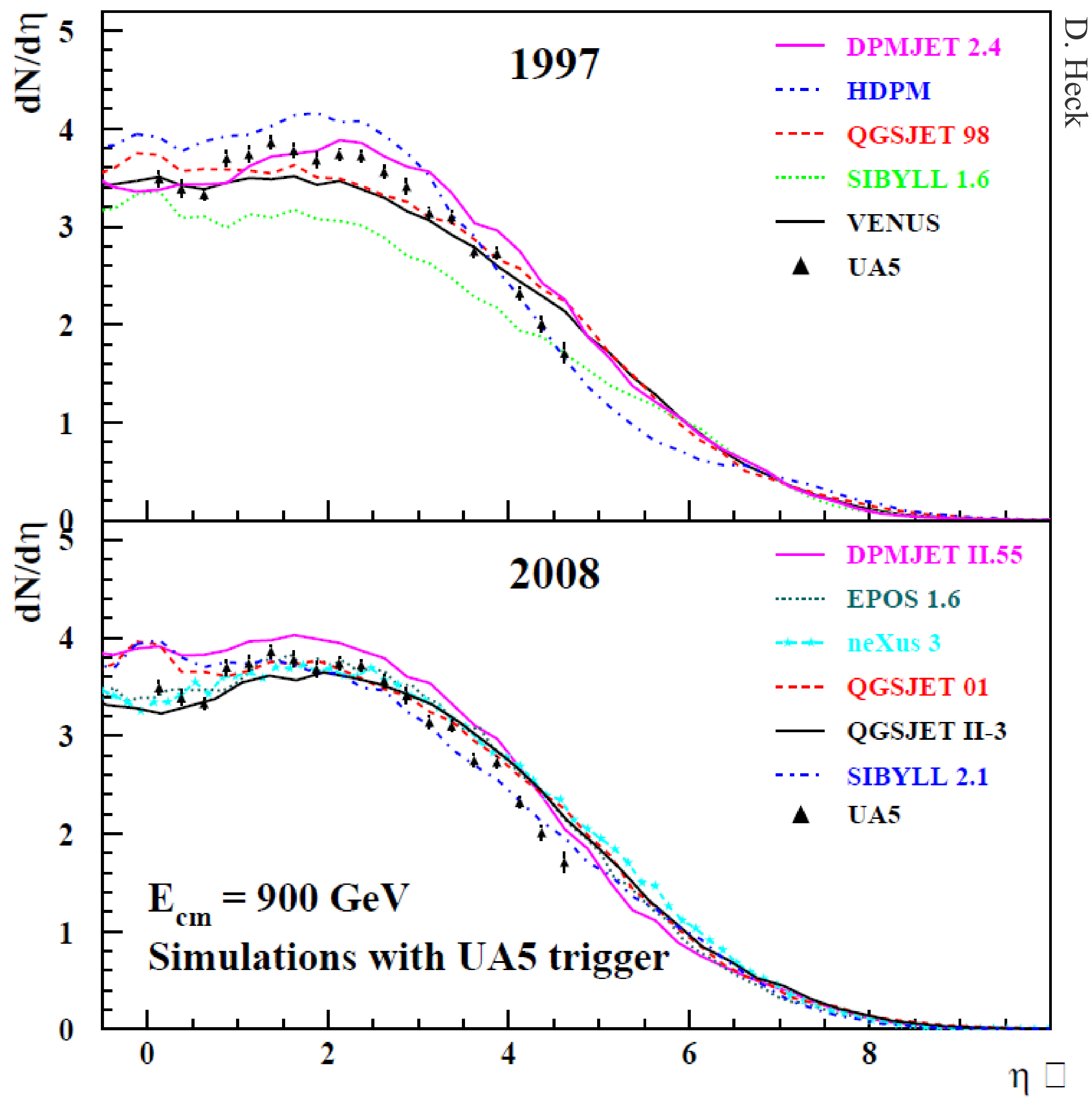


Charged pions mean transvers momentum in pp-collisions as function of energy.

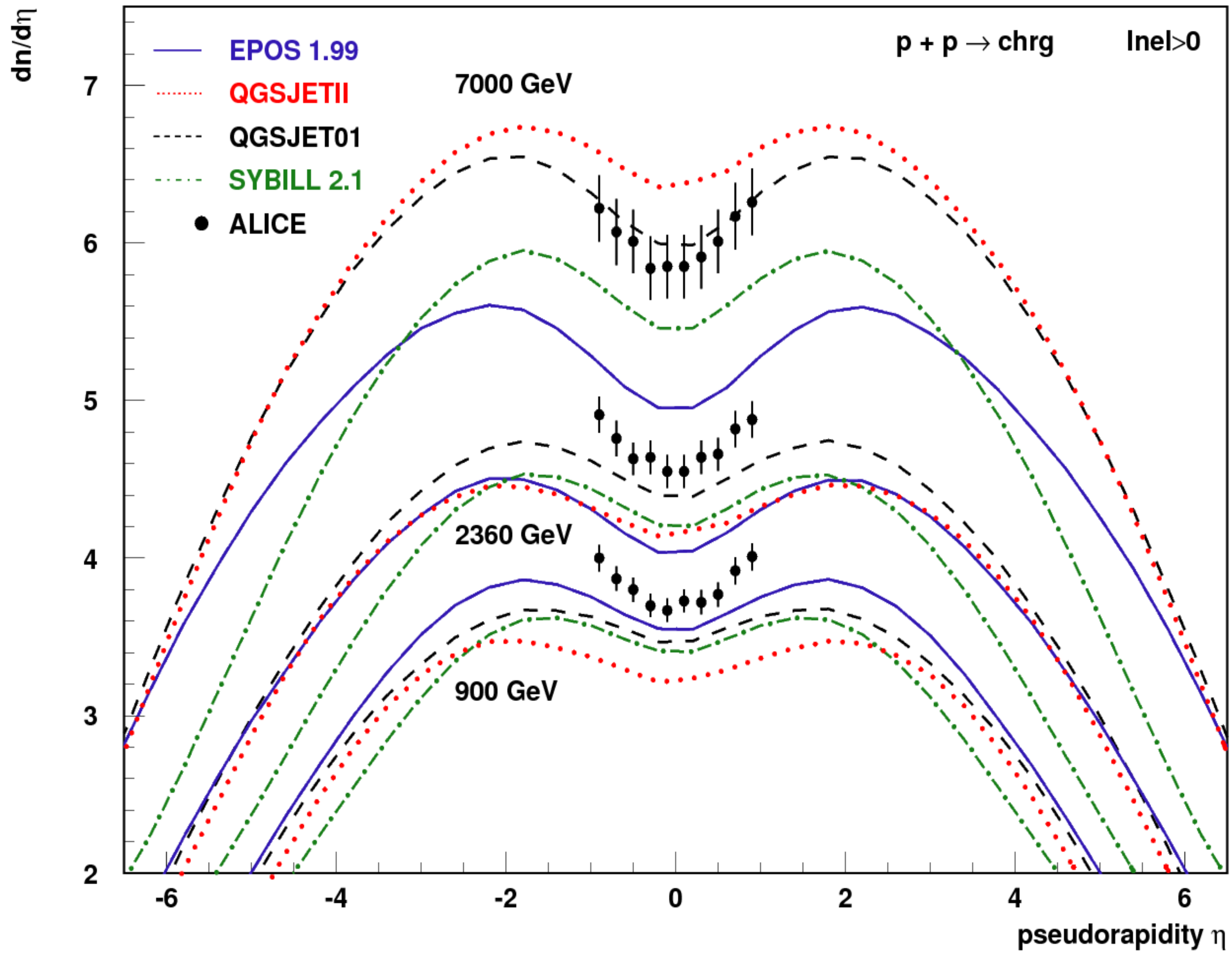
Distributions



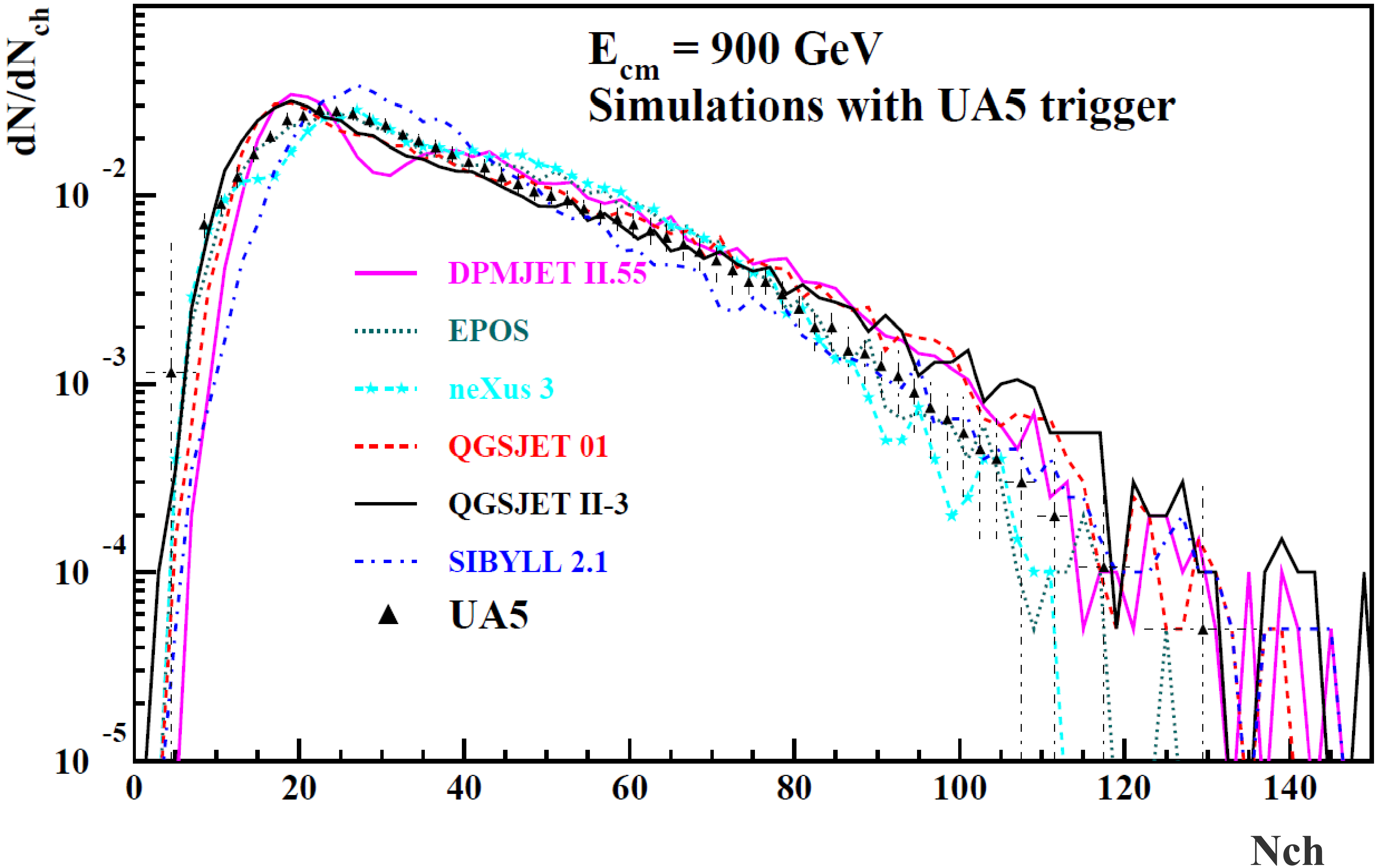
Pseudorapidity p-ap 900 GeV



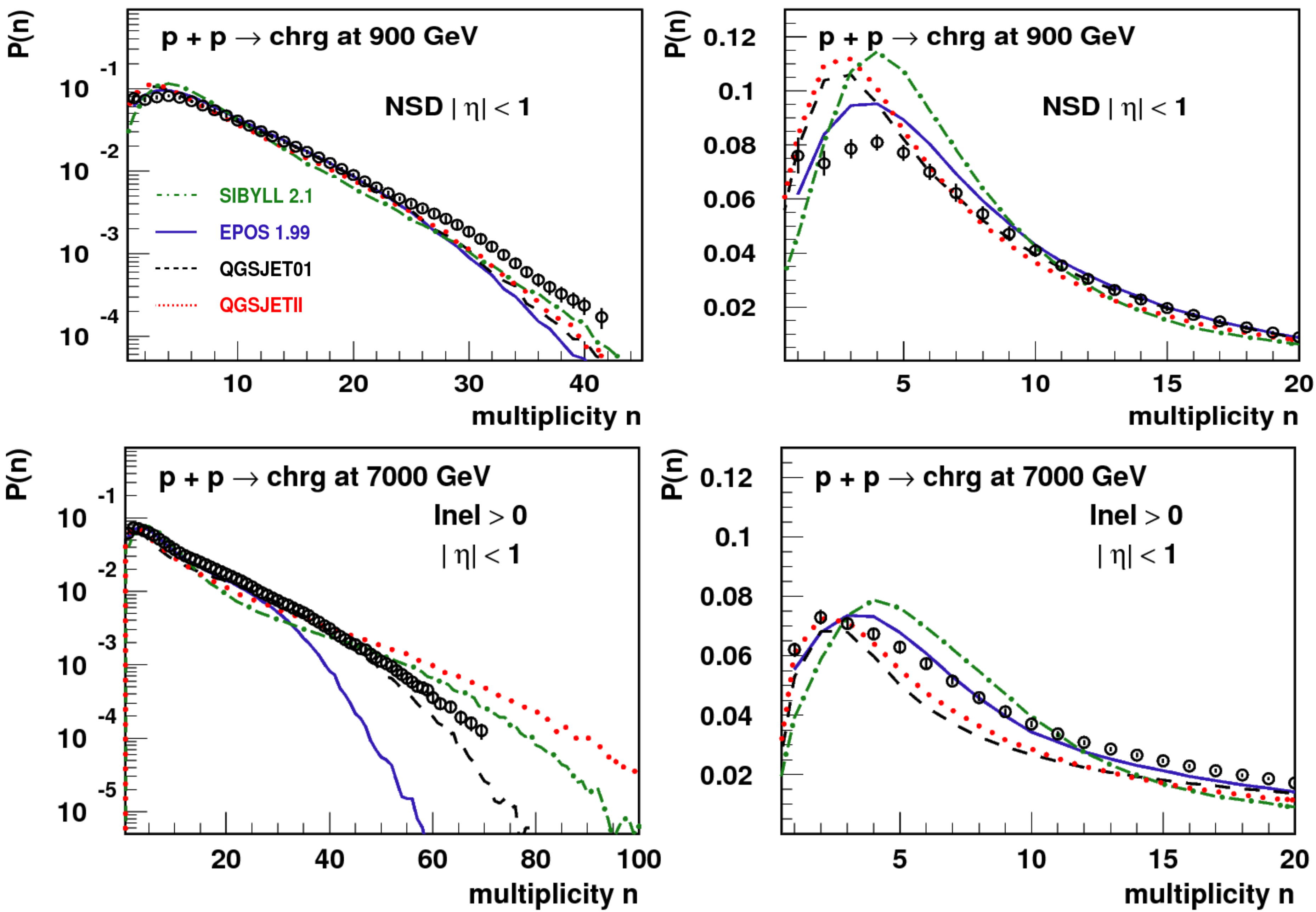
Pseudorapidity ALICE Inel>0



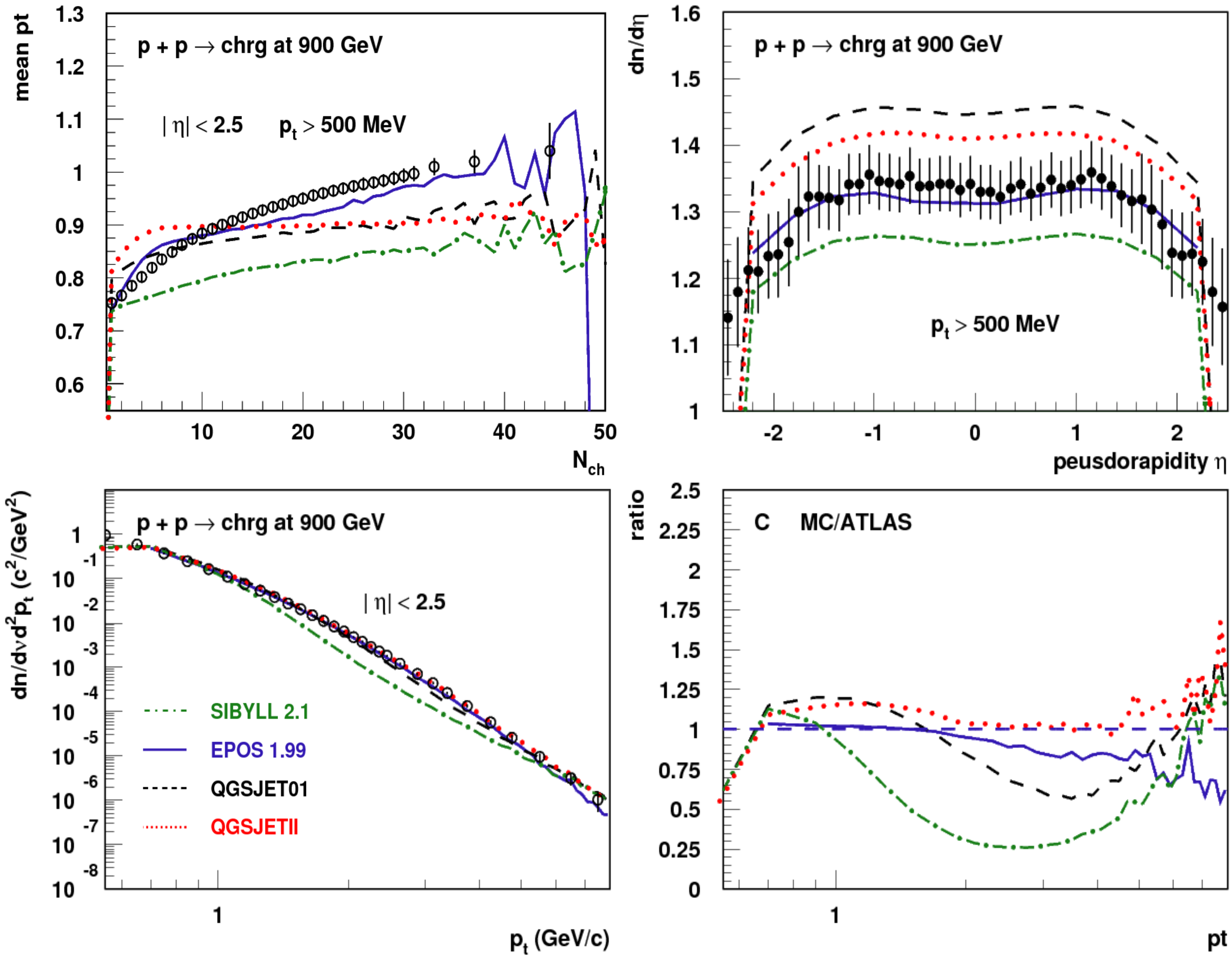
Multiplicity Distribution 900 GeV



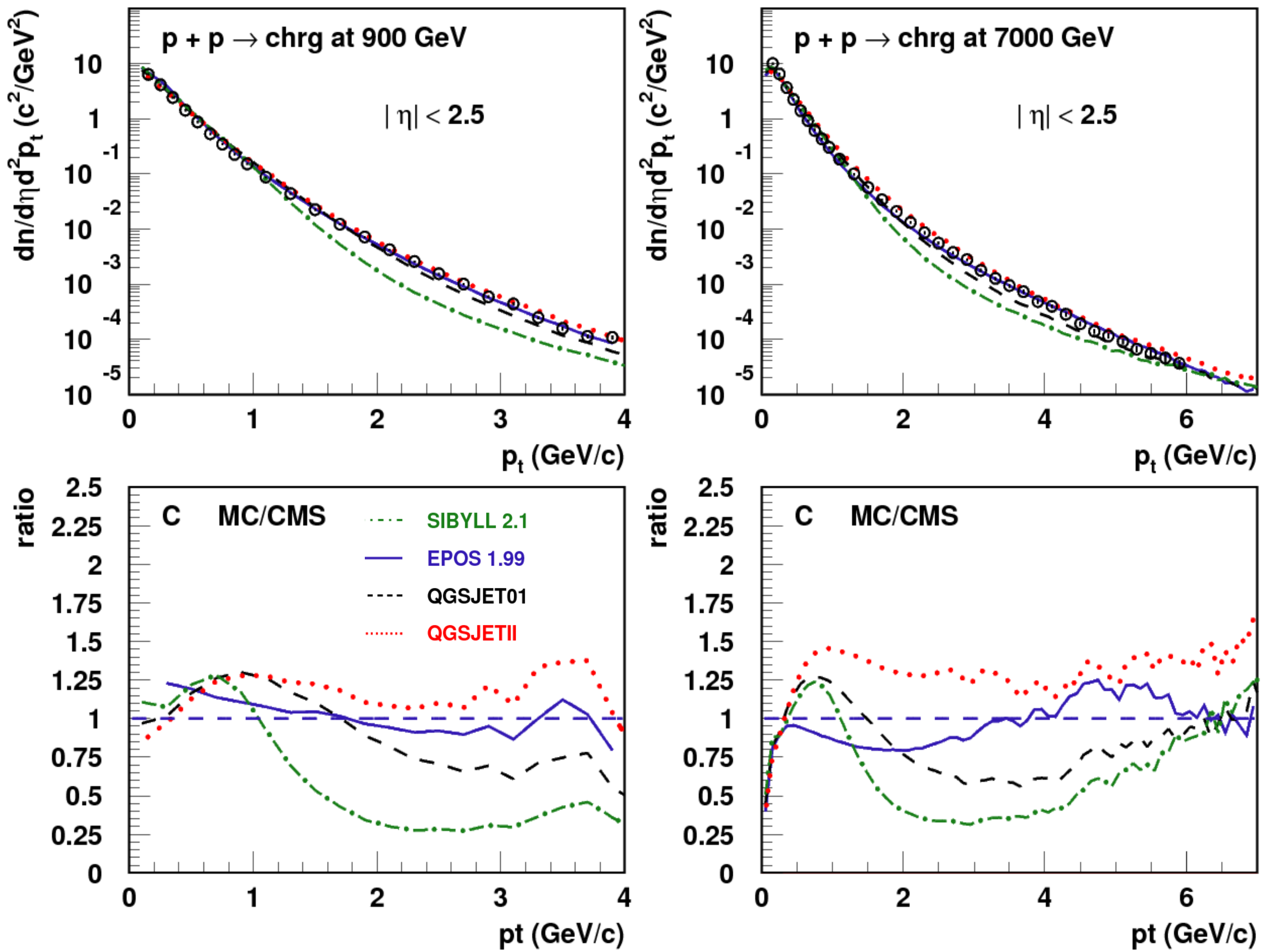
ALICE Multiplicity Distributions



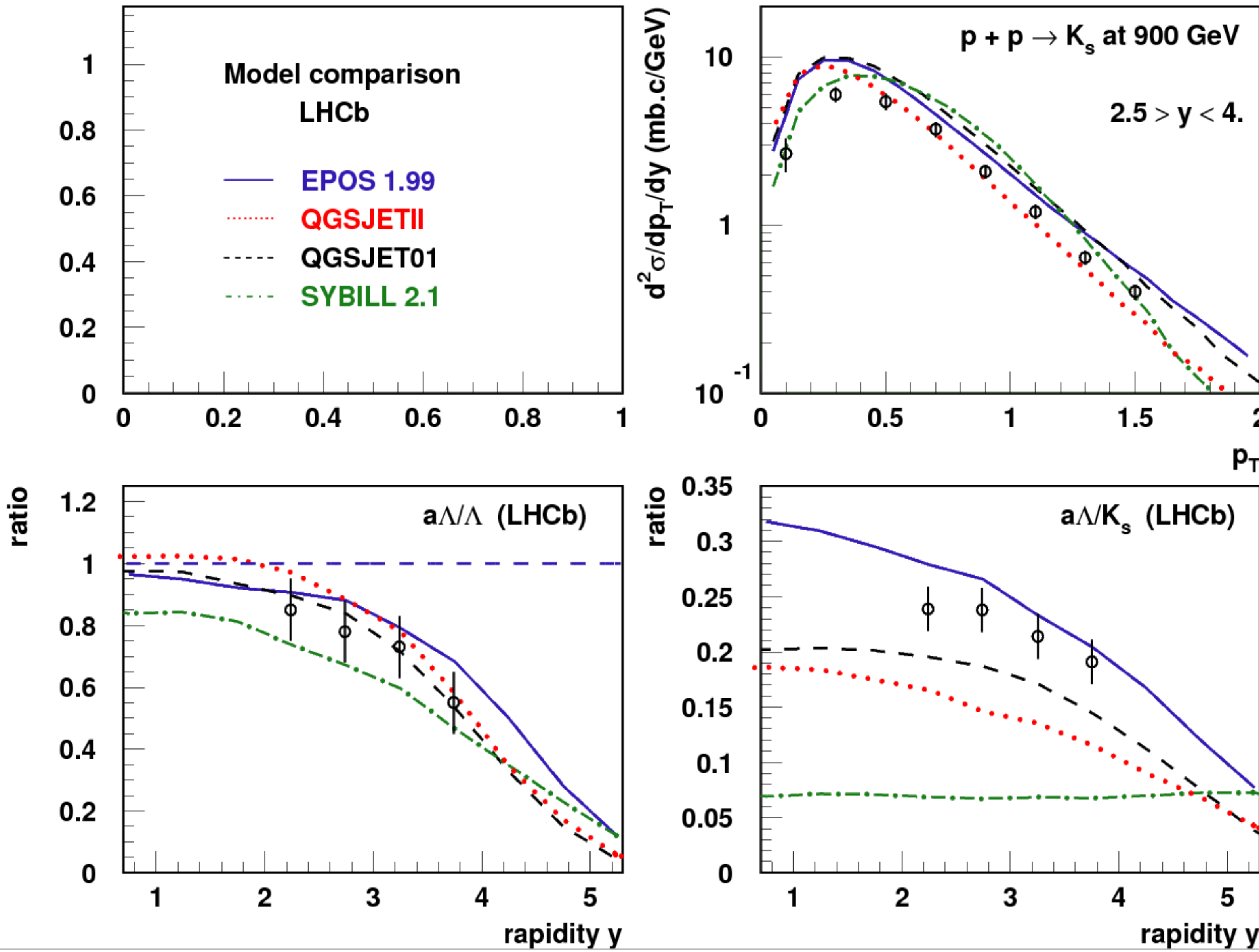
ATLAS Distributions



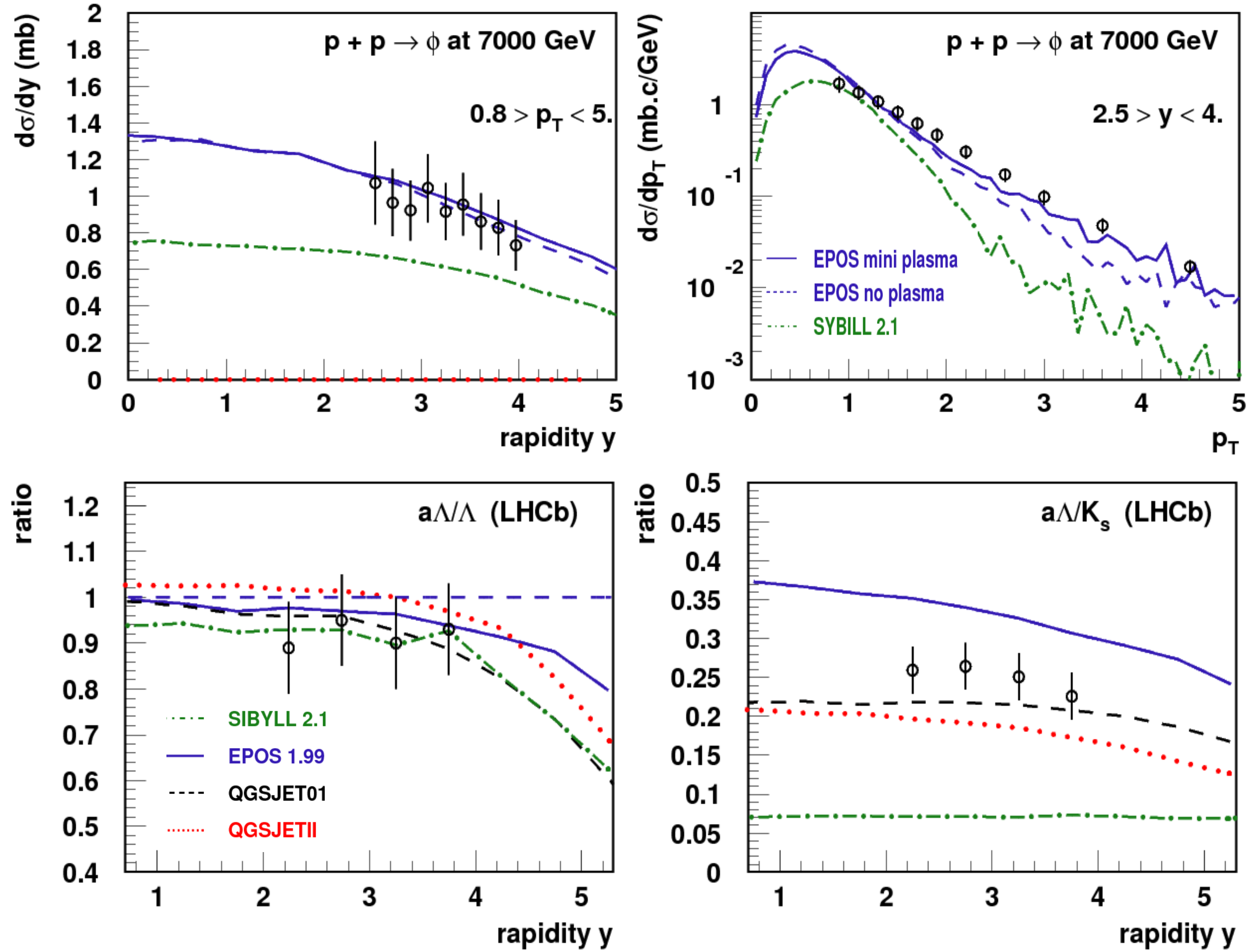
CMS Transverse Momentum Pt



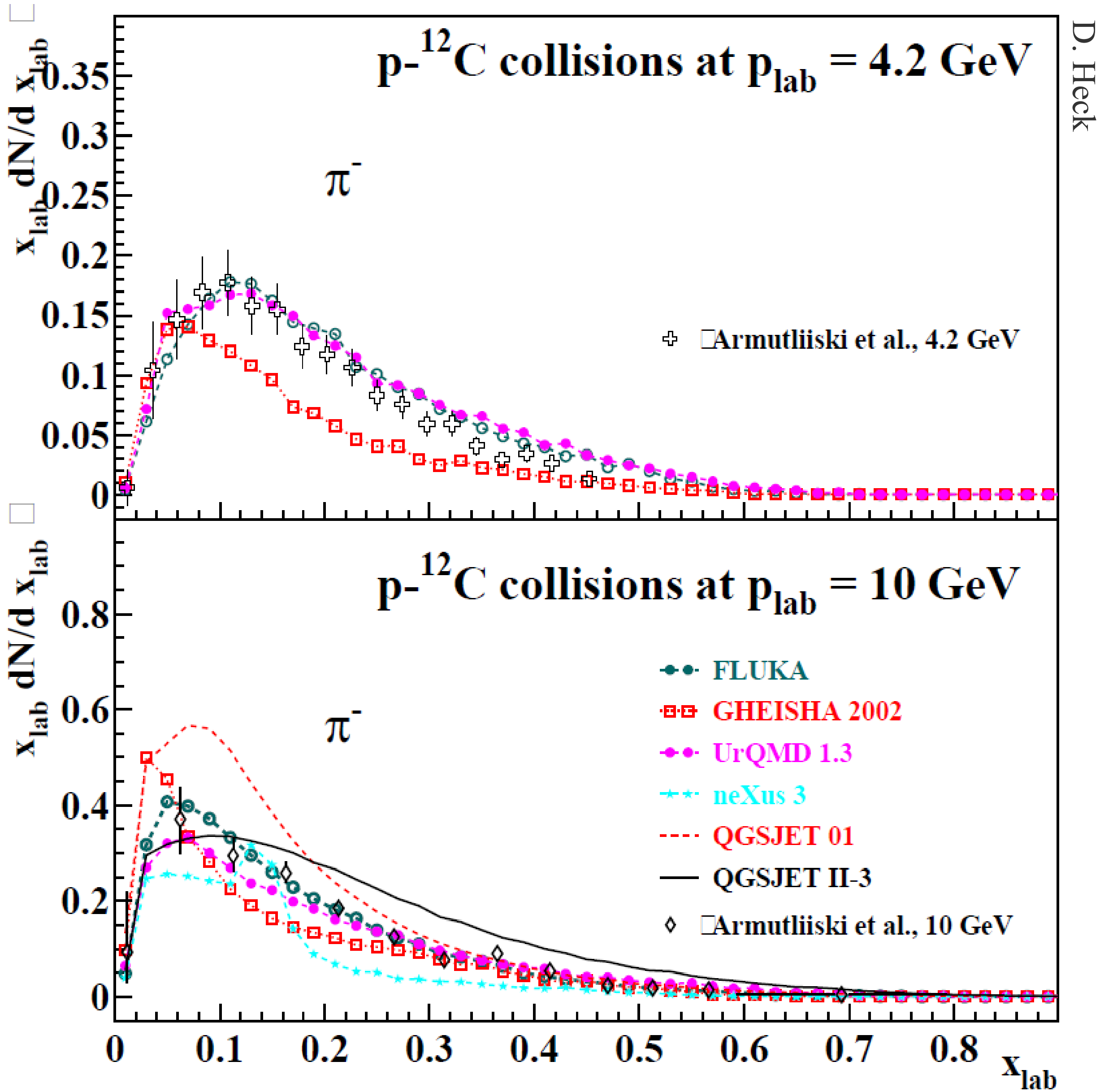
LHCb 900 GeV


Model comparison
LHCb
EPOS 1.99
QGSJETII
QGSJET01
SYBILL 2.1
p + p → K_s at 900 GeV
2.5 > y < 4.
$d^2\sigma/dp_T/dy$ (mb.c/GeV)
p_T
ratio
aΛ/Λ (LHCb)
rapidity y
aΛ/K_s (LHCb)

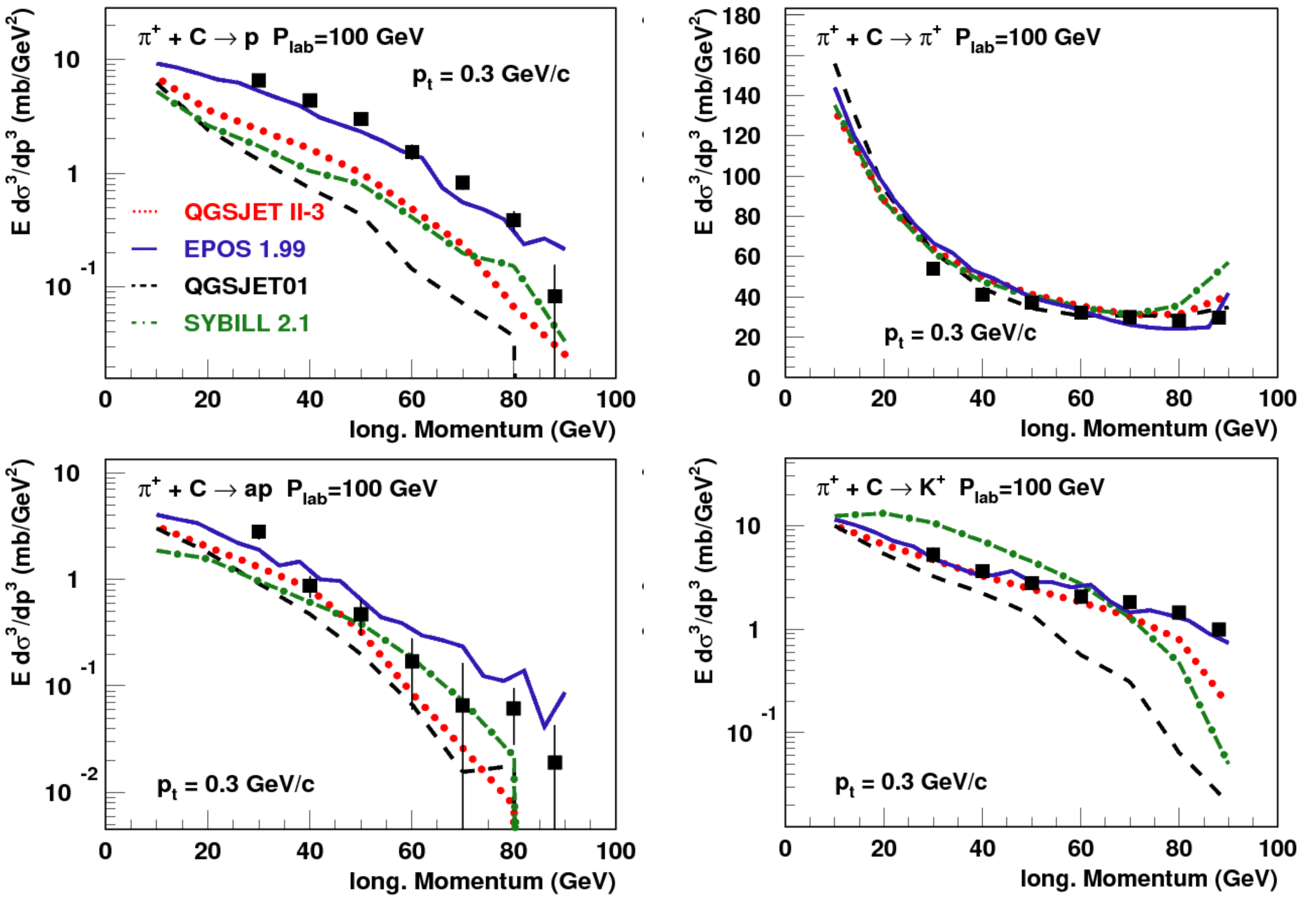
LHCb 7 TeV


p + p → φ at 7000 GeV
0.8 > pT < 5.
dσ/dy (mb)
rapidity y
p + p → φ at 7000 GeV
2.5 > y < 4.
dσ/dpT (mb.c/GeV)
pT
EPOS mini plasma
EPOS no plasma
SYBILL 2.1
aΛ/Λ (LHCb)
ratio
SIBYLL 2.1
EPOS 1.99
QGSJET01
QGSJETII
rapidity y
aΛ/Ks (LHCb)
ratio
rapidity y

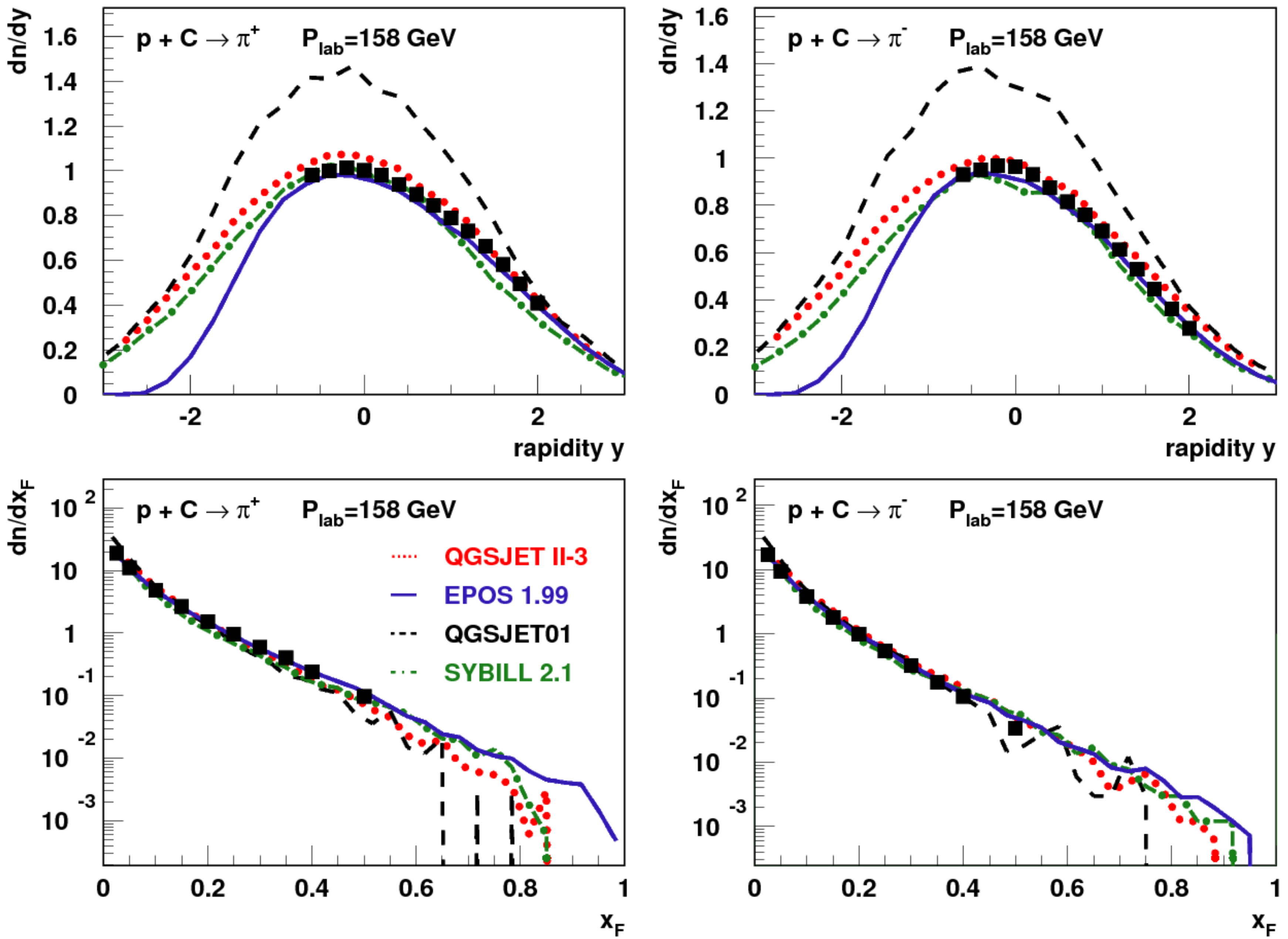
proton-Carbon x distributions



pion-Carbon Pl distributions



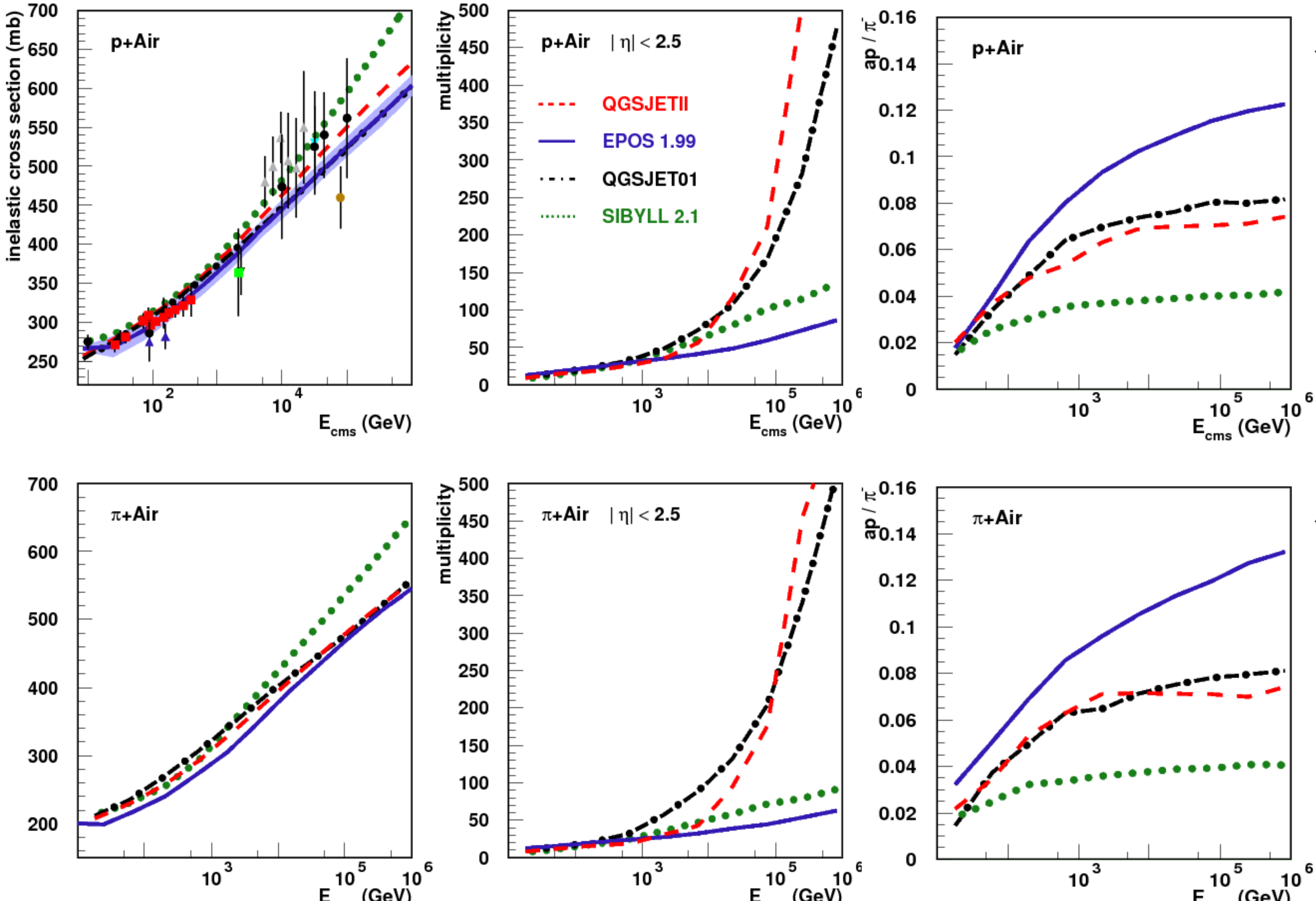
proton-Carbon distributions



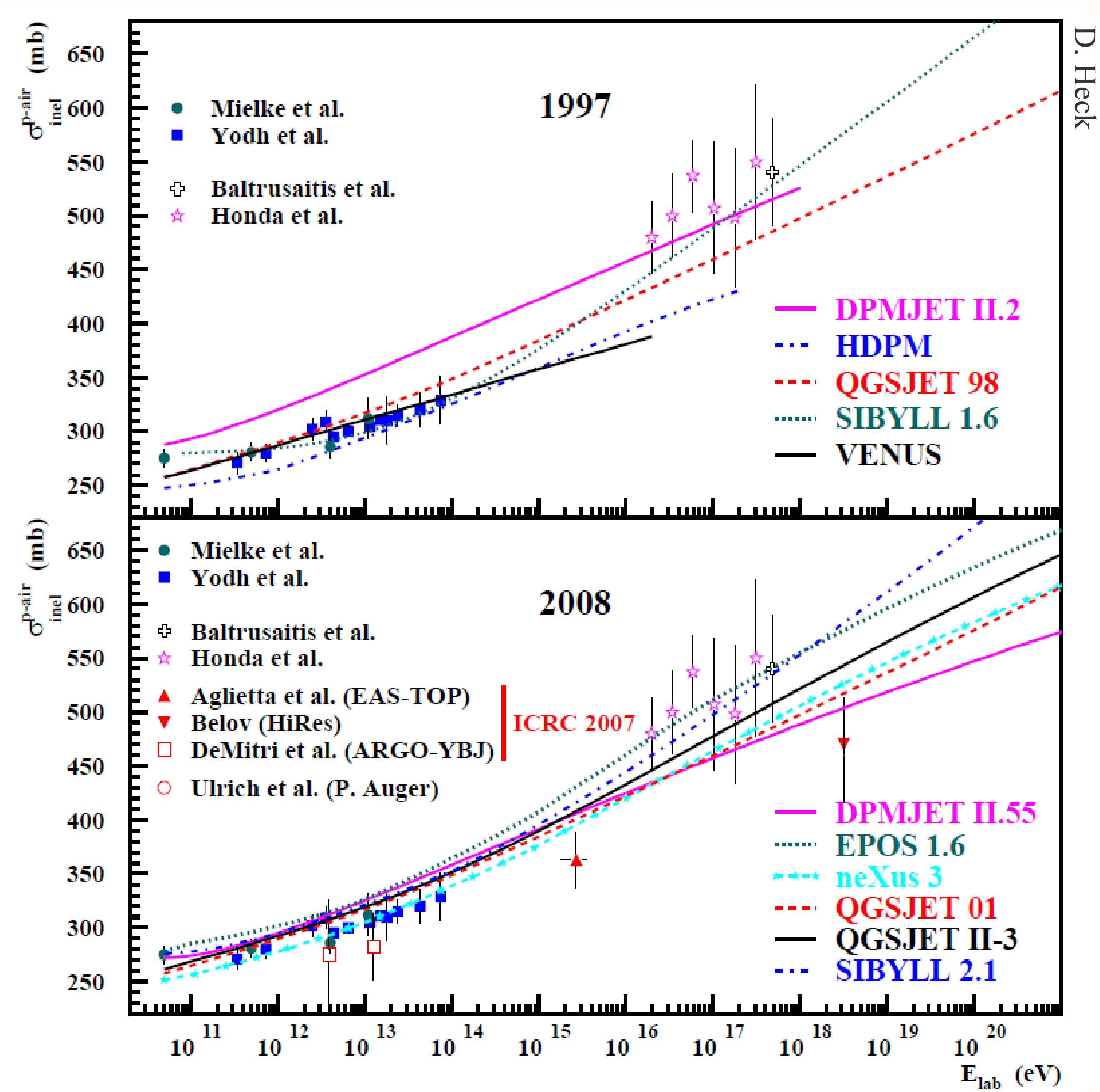
Summary for Single Interactions

- **EPOS 1.99**
  - not enough low-X pions at E > 10^{15} eV
  - too large Pt for baryons at high energy
- **QGSJET 01**
  - too many low-X pions at low energy
  - much high-mass diffraction at E > 10^{16} eV
  - low elasticity in pion-induced interactions
  - baryons a bit low at high energy
- **QGSJET II-3**
  - too many low-X mesons
  - high elasticity for p-N with 10^{12} < E < 10^{17} eV
  - not enough baryons at high energy
- **SIBYLL 2.1**
  - high elasticity and high cross section at E > 10^{17} eV
  - very few baryons

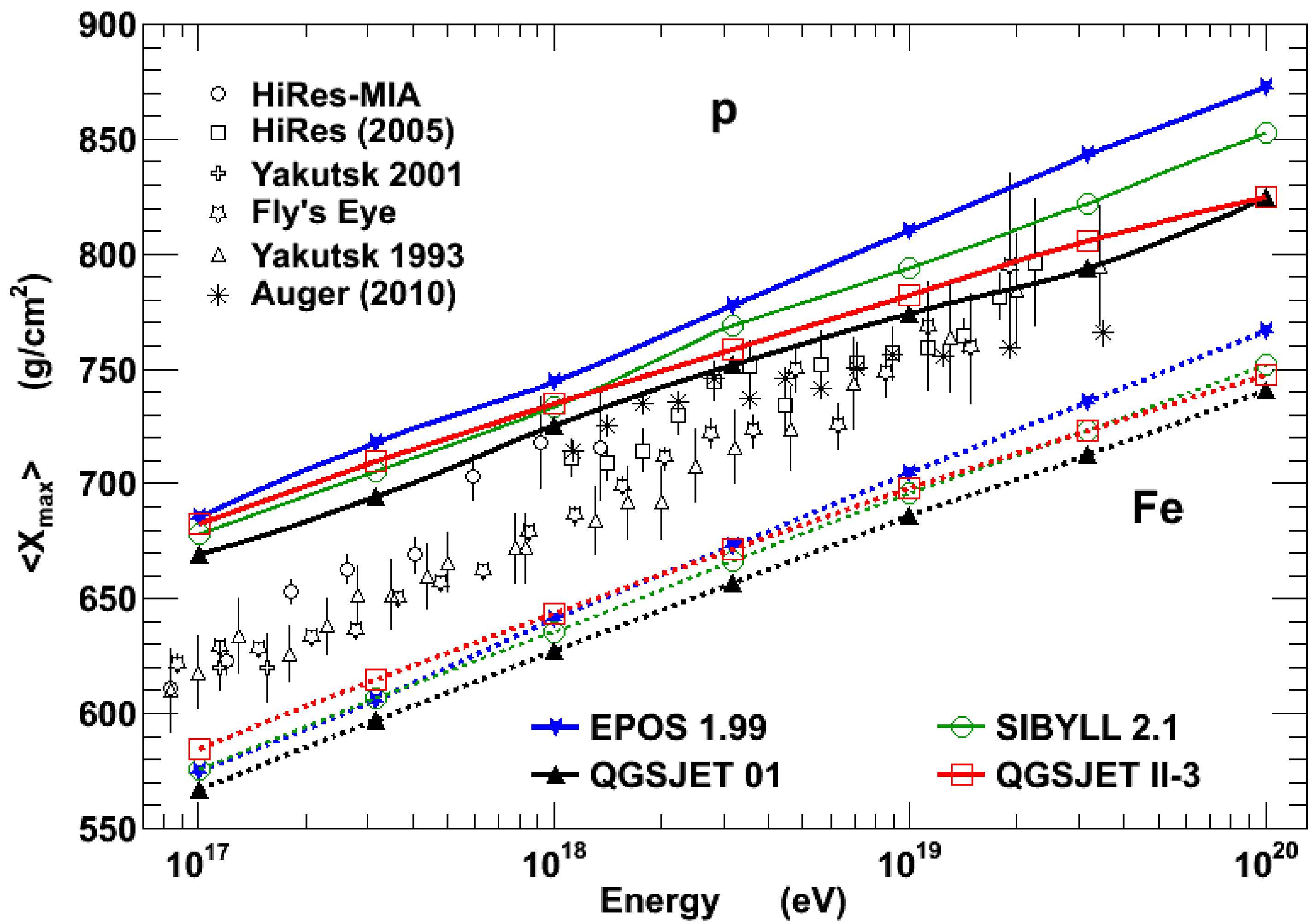
Hadronic Model Predictions



Inelastic p-Air Cross Section

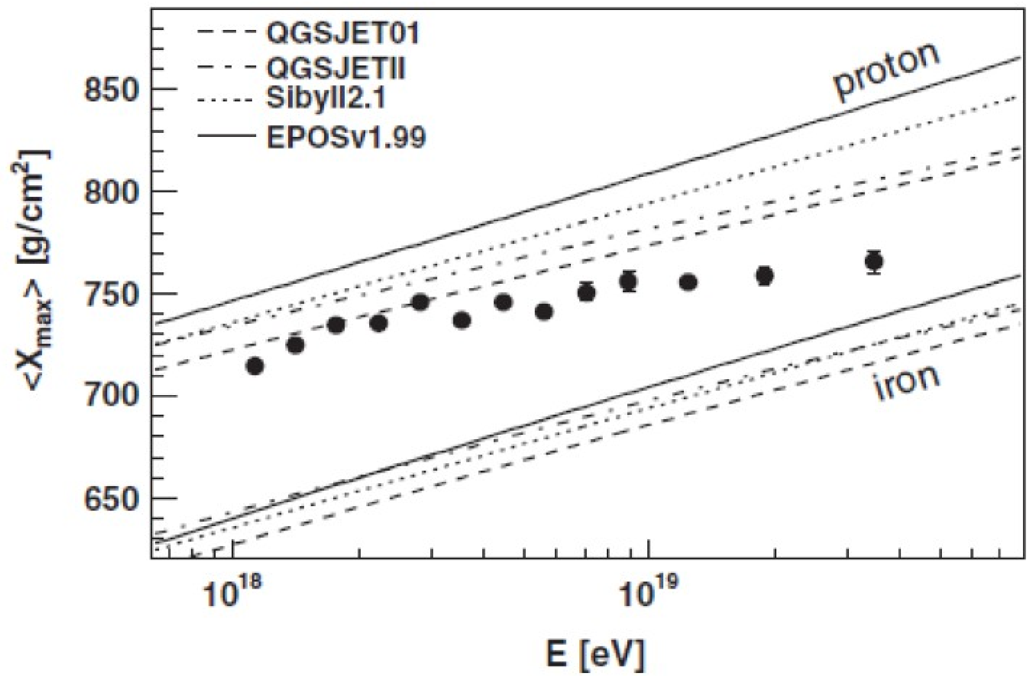


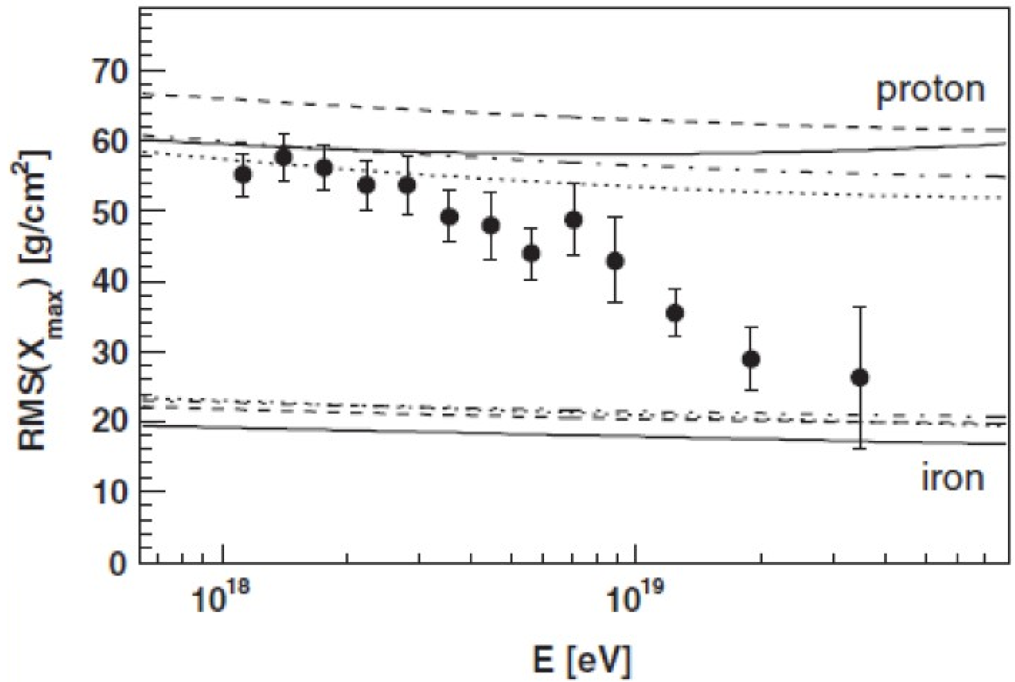
<Xmax>



Large spread of model predictions !

Xmax Auger





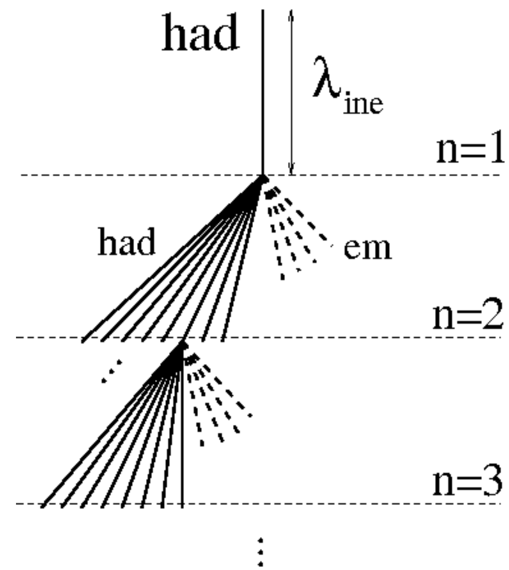
- **EPOS and SIBYLL (almost)**
  - consistent light mix to heavy mix <Xmax> and RMS
- **QGSJETII**
  - very light at low E, but inconsistent <Xmax> and RMS at high E
- **QGSJET01**
  - inconsistent description of <Xmax> and RMS

Generalized Heitler Model

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).

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

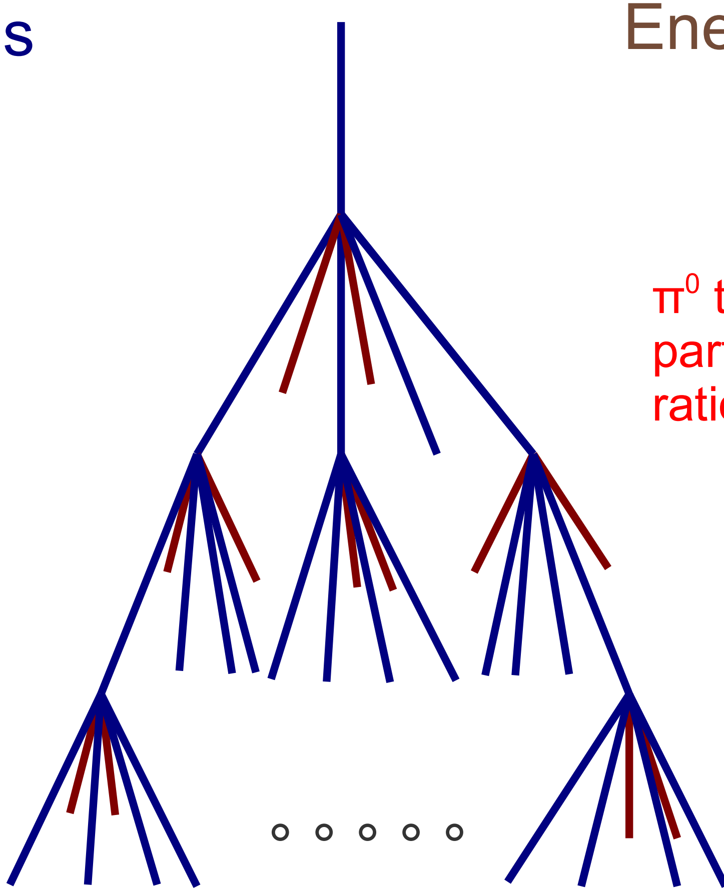


$$N_{tot} = N_{had} + N_{em}$$

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

- Model independent parameters :
  - E_0 = primary energy
  - λ_e = electromagnetic mean free path
- Model dependent parameters :
  - N_{tot} = total multiplicity
  - λ_{ine} = hadronic mean free path

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

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

Energy of all em. particles

0

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

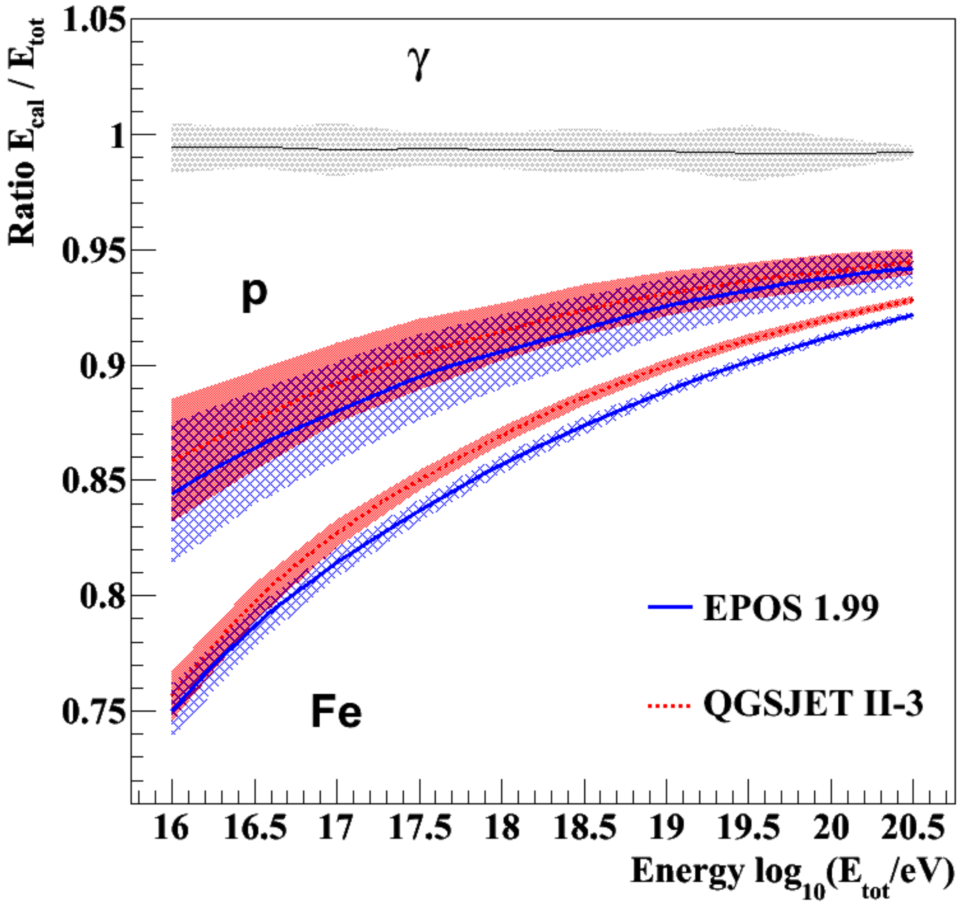
$\frac{1}{3} E_0 + \frac{1}{3}\left(\frac{2}{3} E_0\right)$

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

Energy in em. ~ 90 %

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

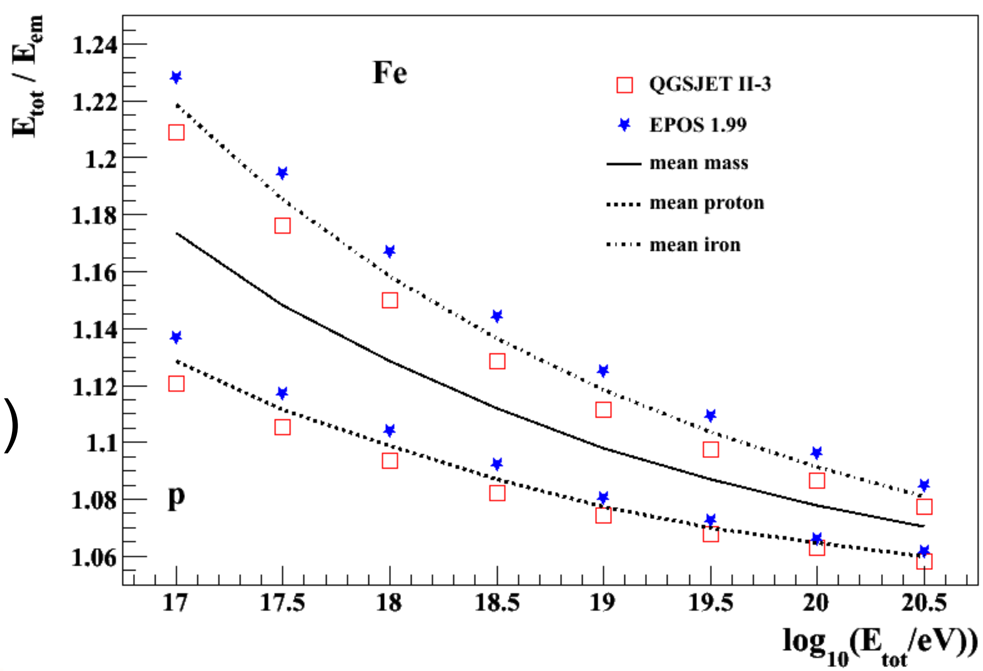
Conversion Factor



- **From Heitler model**

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

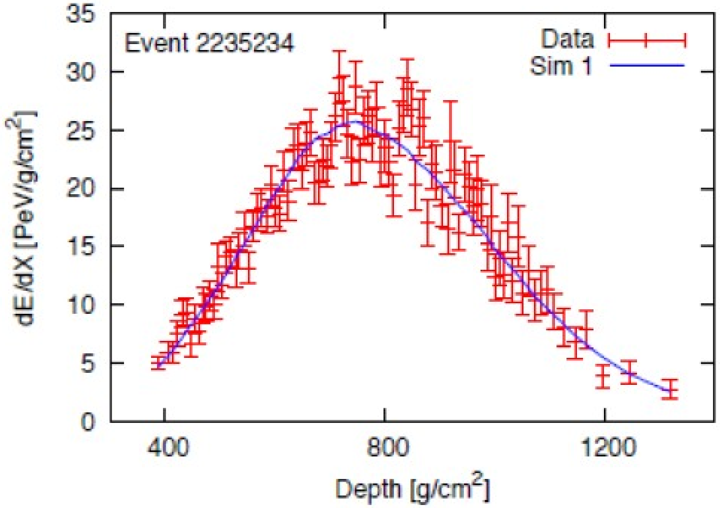
- **Energy deposit depends on muon number**
  - Primary mass dependent
  - Hadronic model dependent



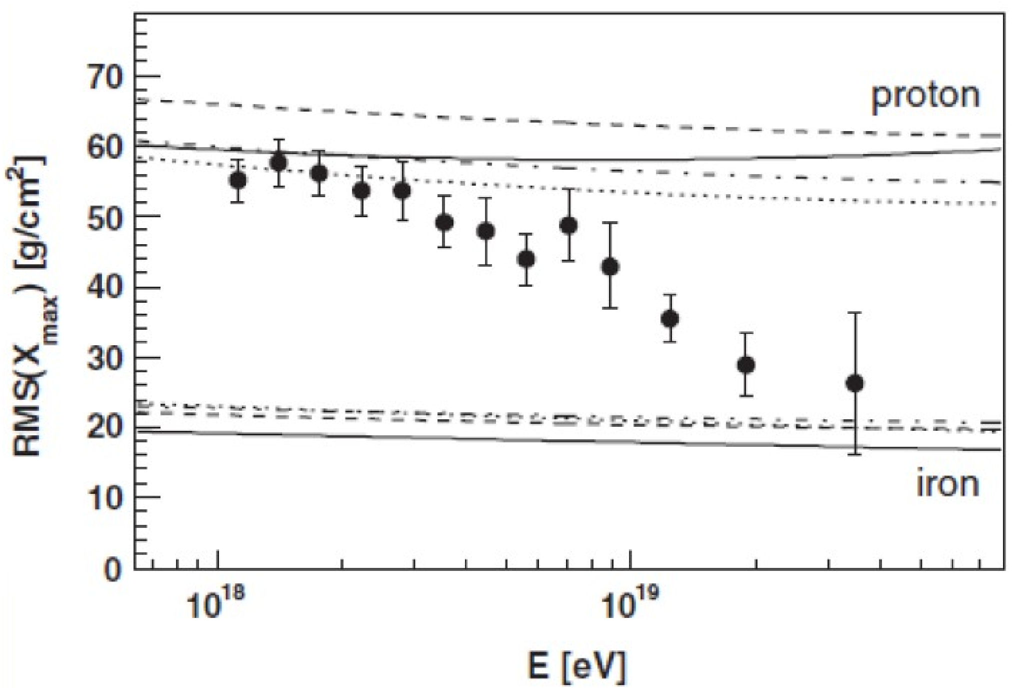
- **Average value used**
  - Small error due to models (~1-2%)
  - Main uncertainty from unknown mass (~5-2%)

Energy from FD

- **Energy from longitudinal development**
  - integration of energy deposit
  - measure of calorimetric energy
  - conversion factor to get primary energy

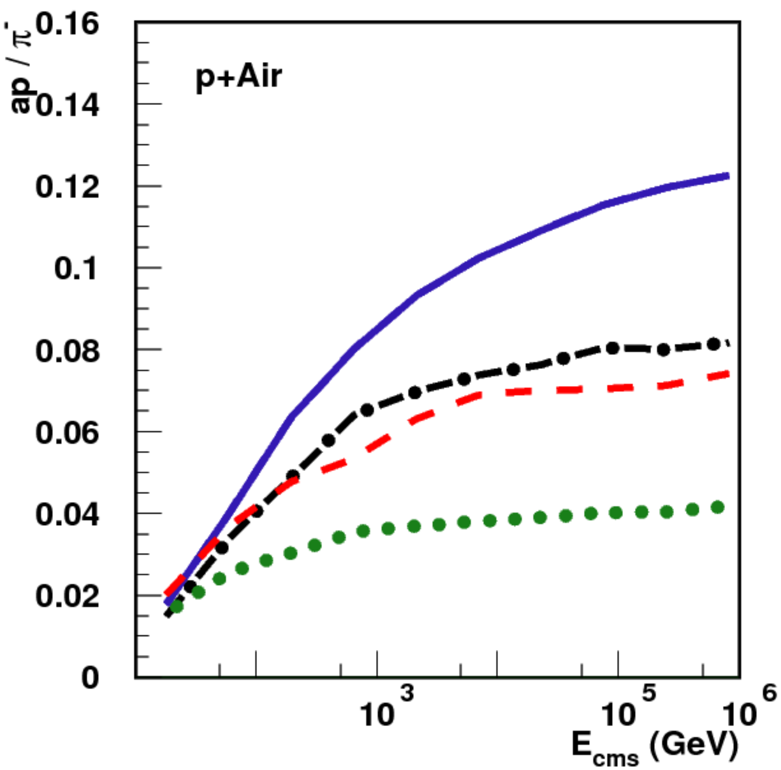


- **Change in composition**
  - conversion factor is mass dependent
  - energy scale can be changed by ~5%

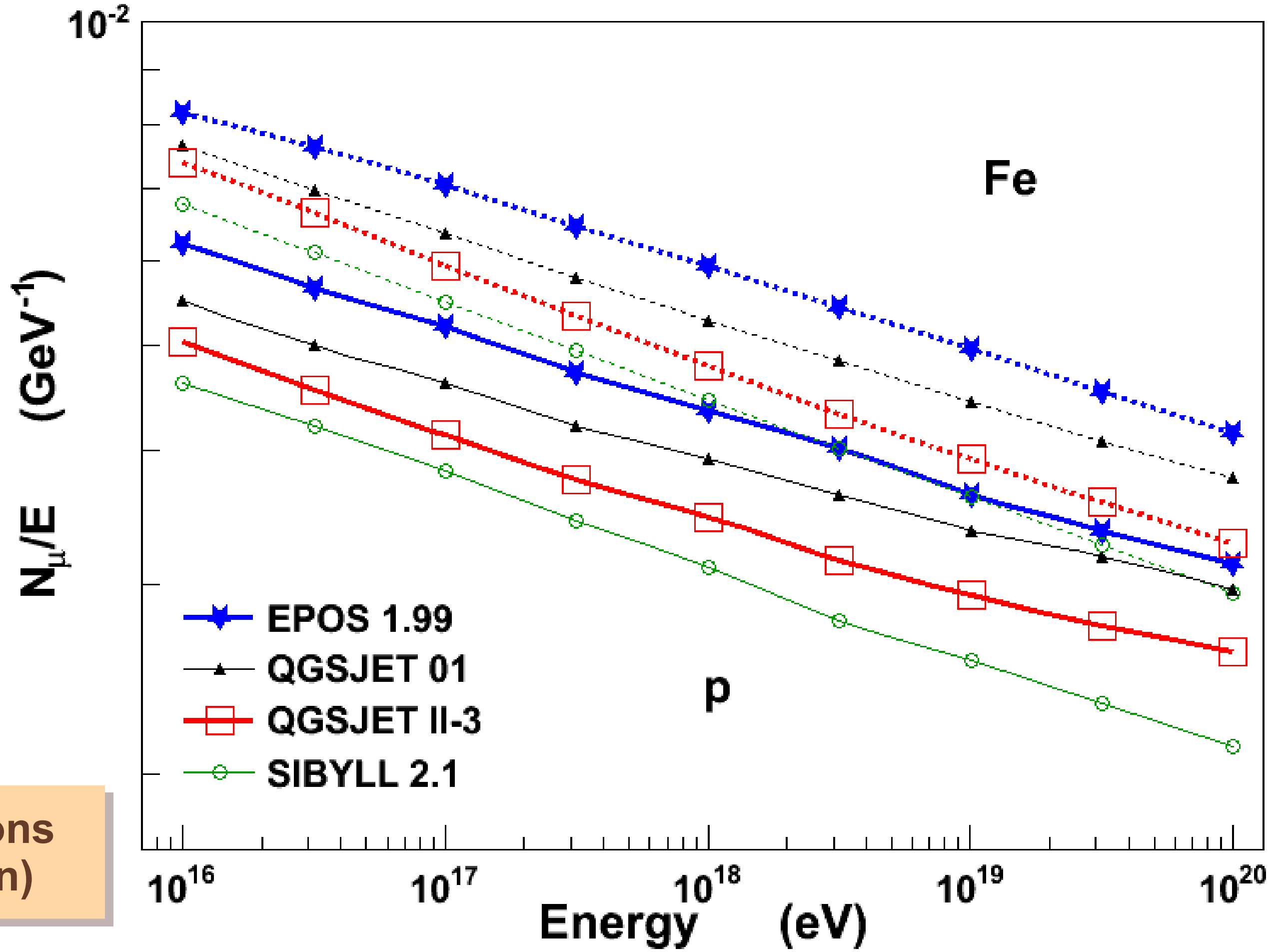


Total Number of Muons

Discrepancy (baryon and pion spectra) between models
Much more muons in EPOS



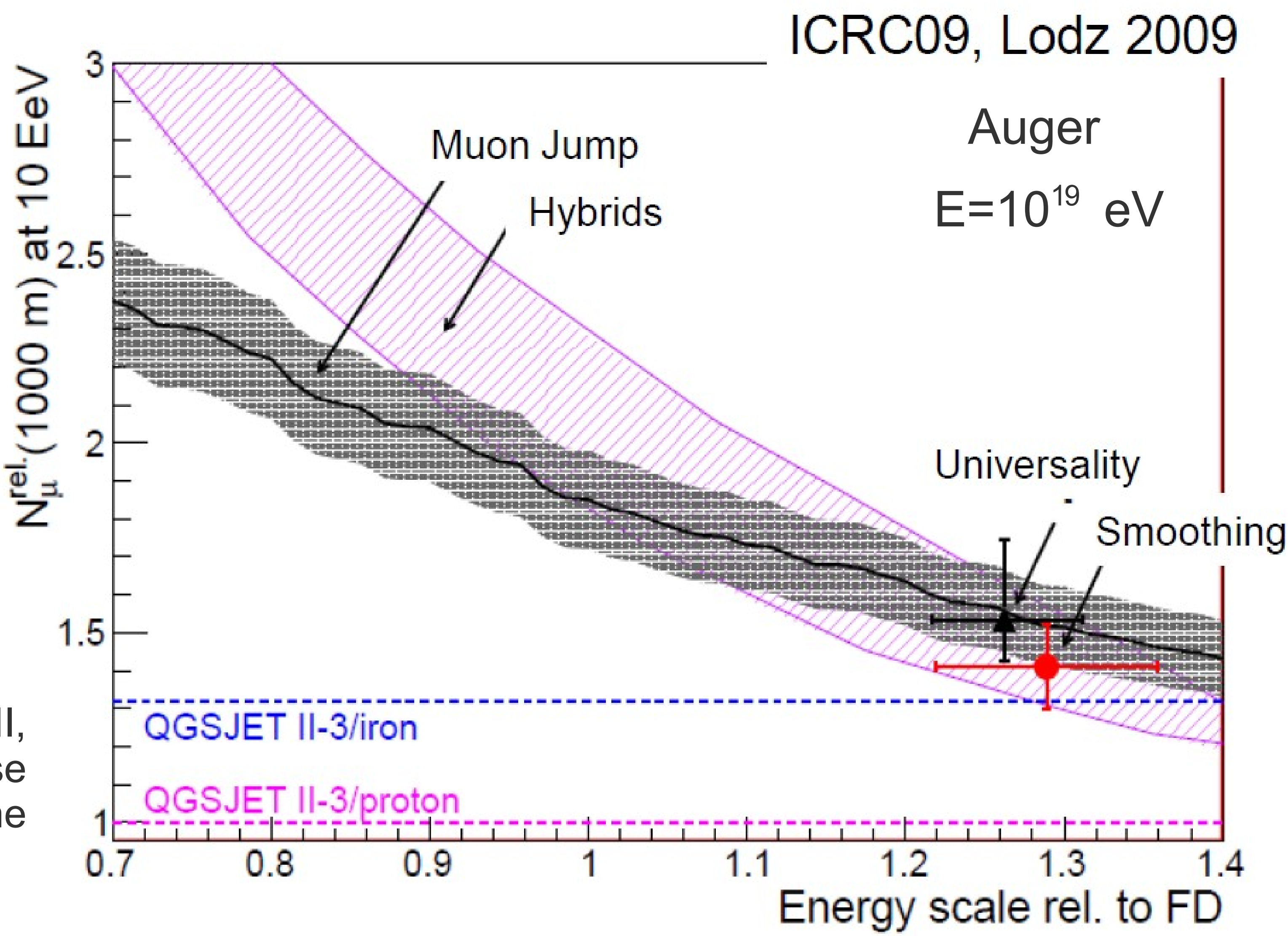
3 times less baryons = 40 % less muons
(~difference between proton and iron)



Muons in Data

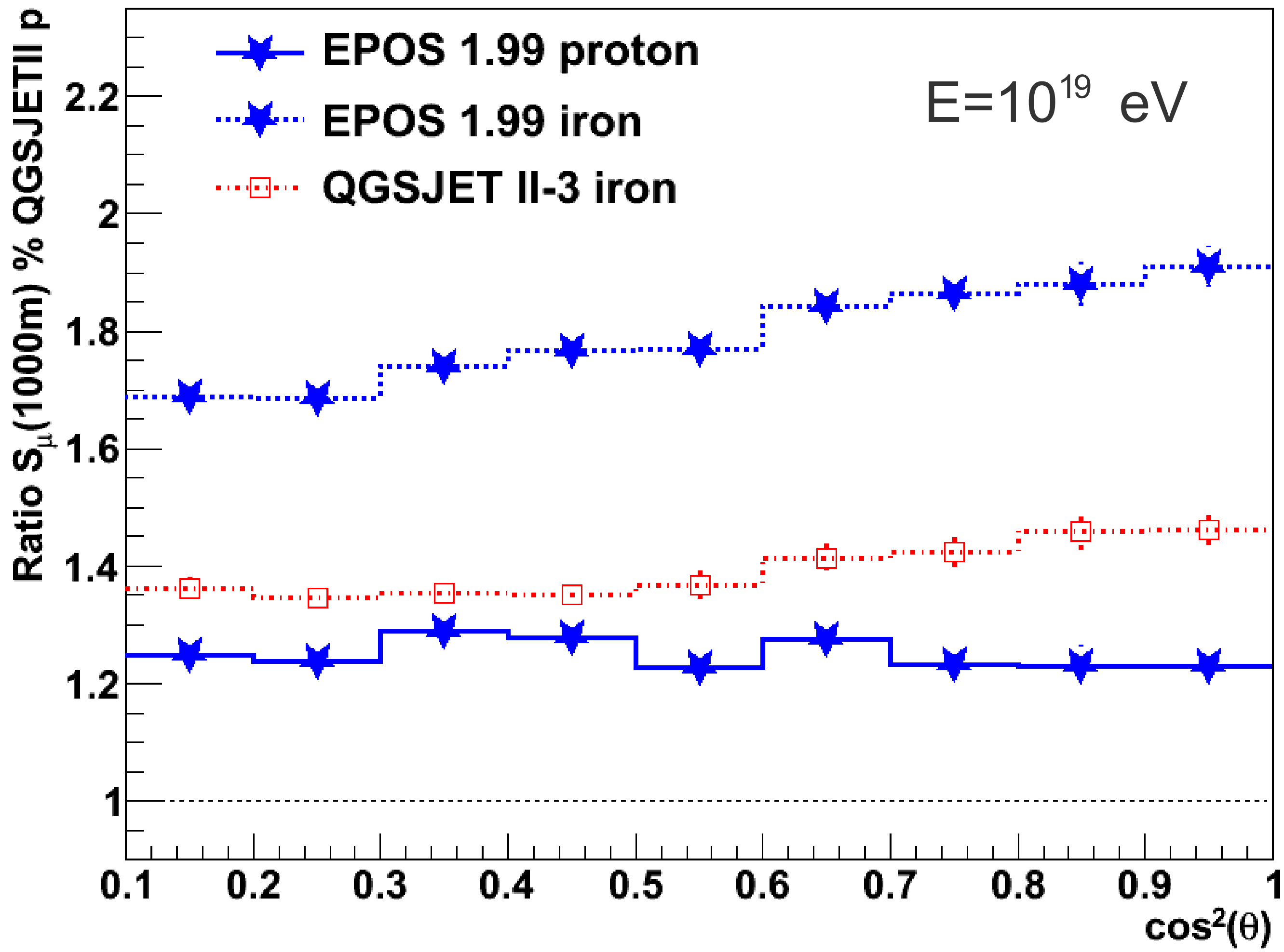
Is the problem seen using QGSJETII-3 with muons general ?

For QGSJETII, <Xmax> close to proton line



Muon Density @ 1000 m

- **EPOS consistent with Auger data**
  - ➜ intermediate mass needed both for <Xmax>, RMS Xmax and muons
- **QGSJETII underestimate the number of muons**



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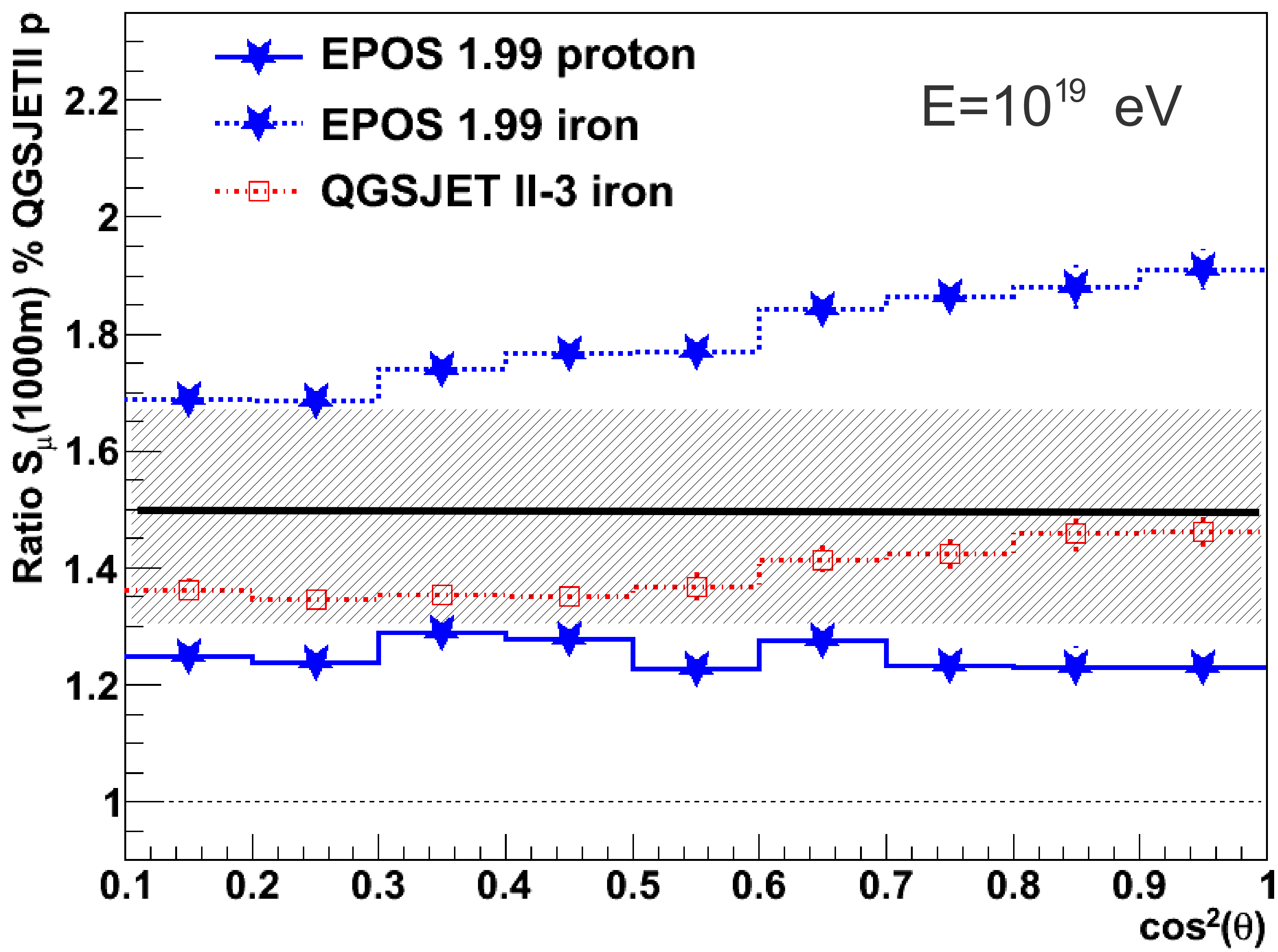
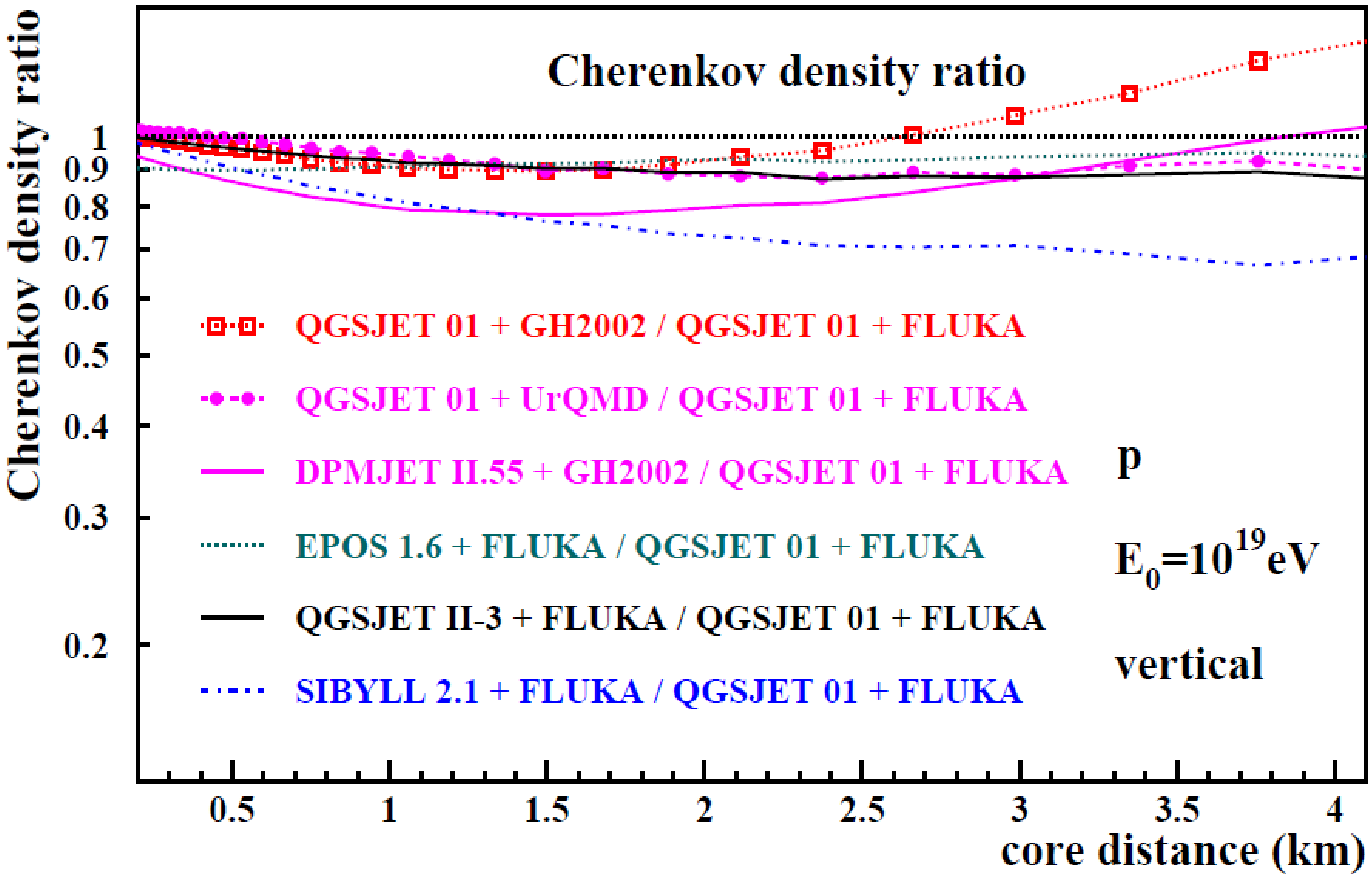


PAO data

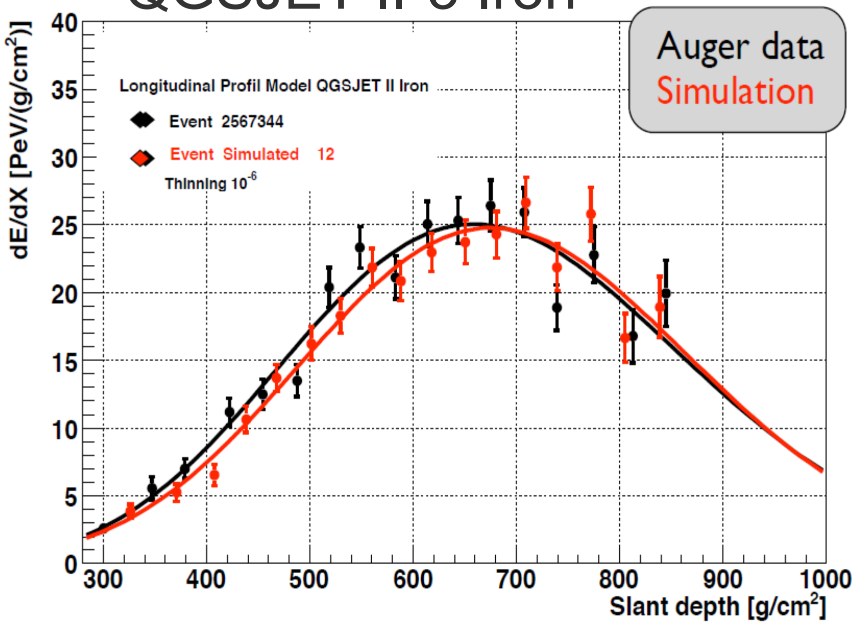
Effect of Low Energy Model

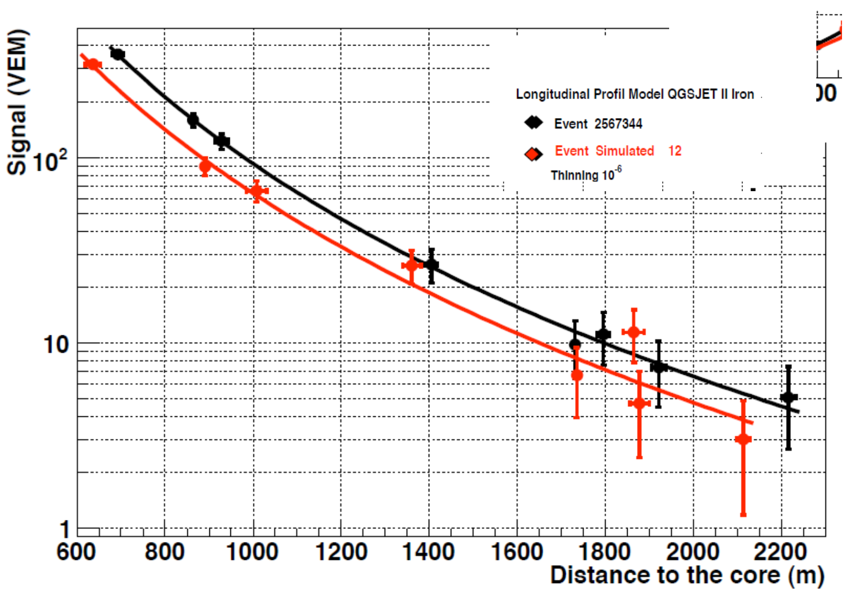


Lateral distribution of the Cherenkov density ratios relative to QGSJET 01 + FLUKA.

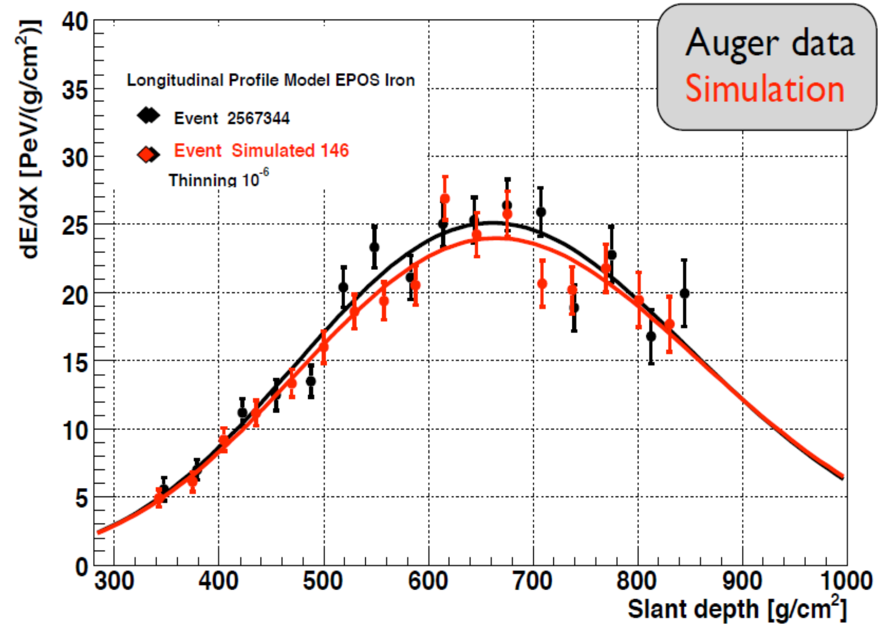
Auger Event-by-Event $E \sim 10^{19}$ eV

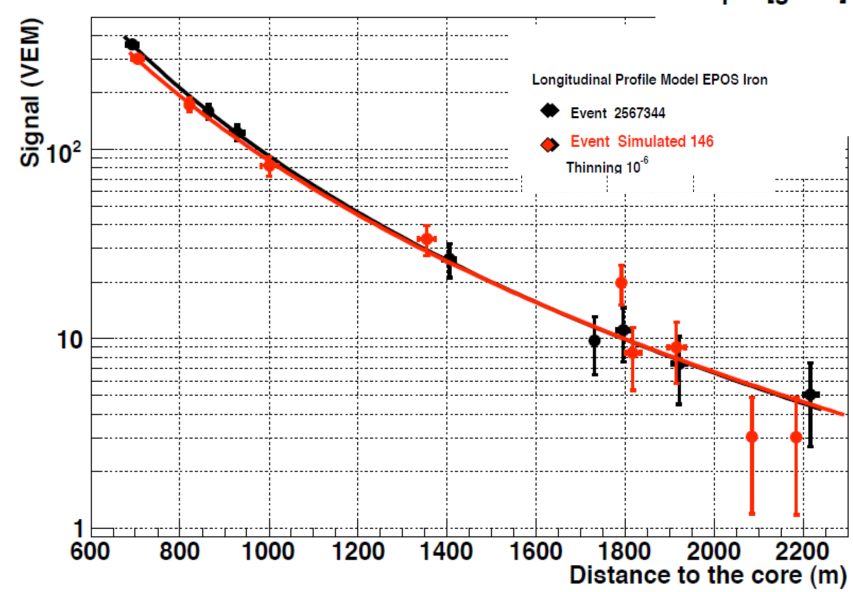
QGSJET II-3 Iron





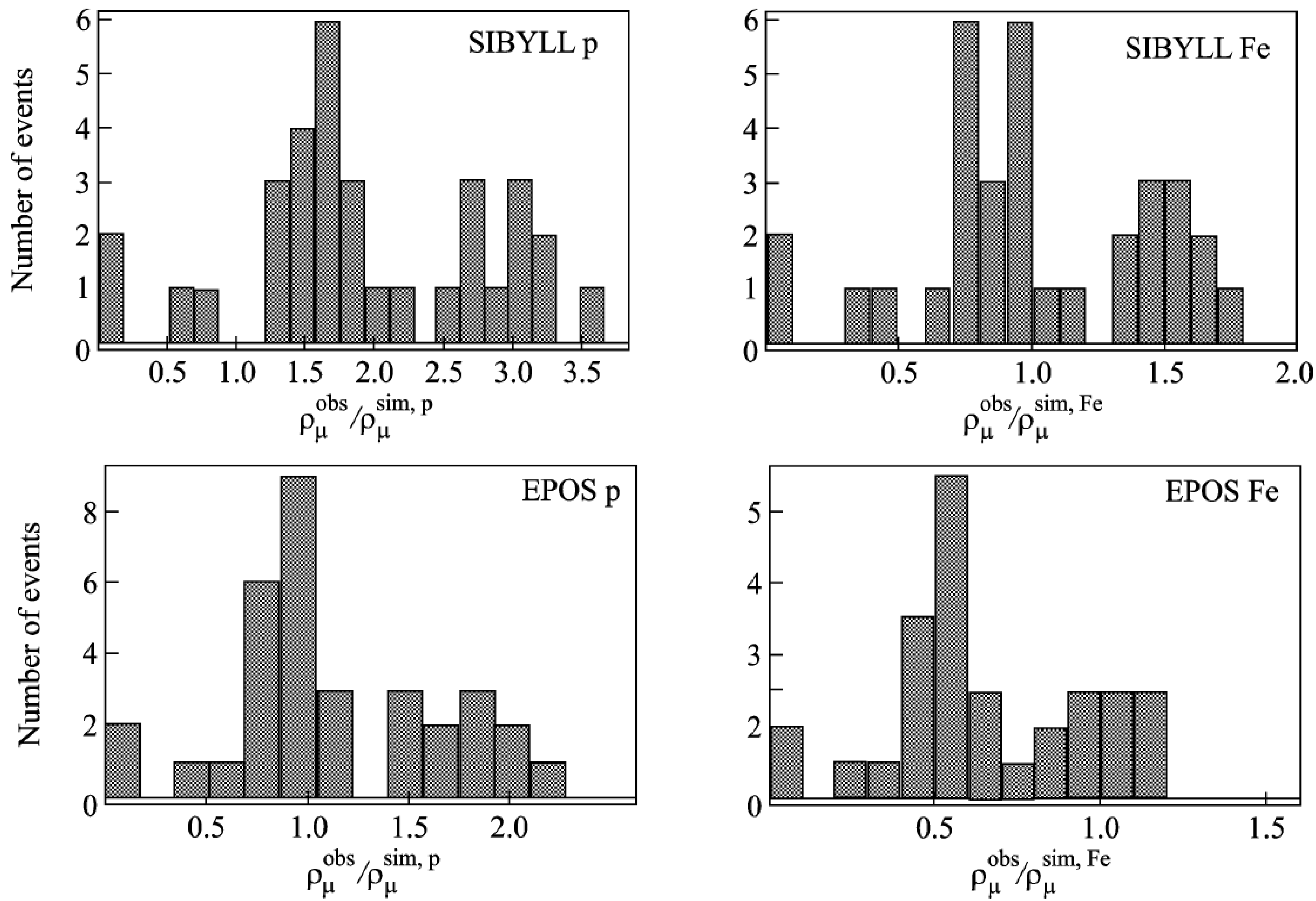
EPOS 1.6 Iron





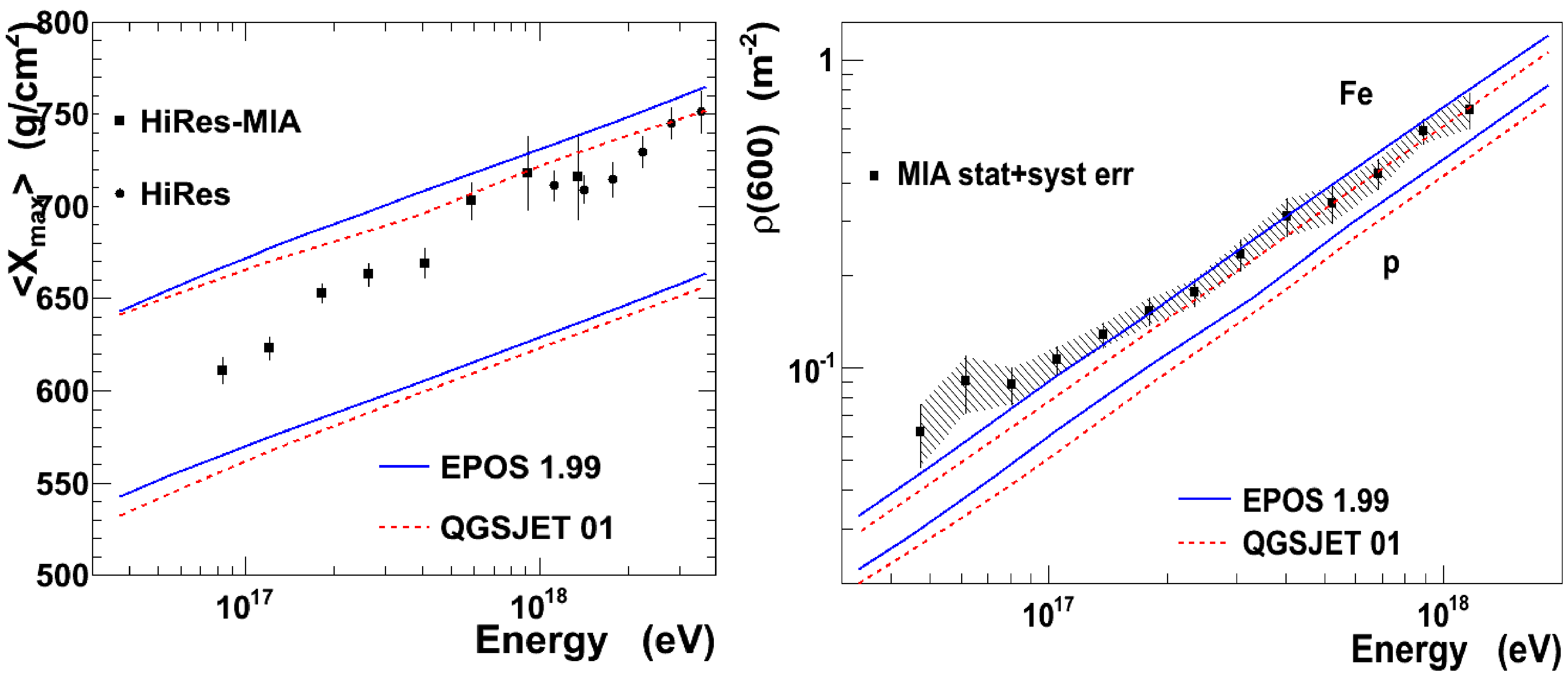
Yakutsk E>10^{19} eV

- Analysis on 33 events recontructed with the same geometry



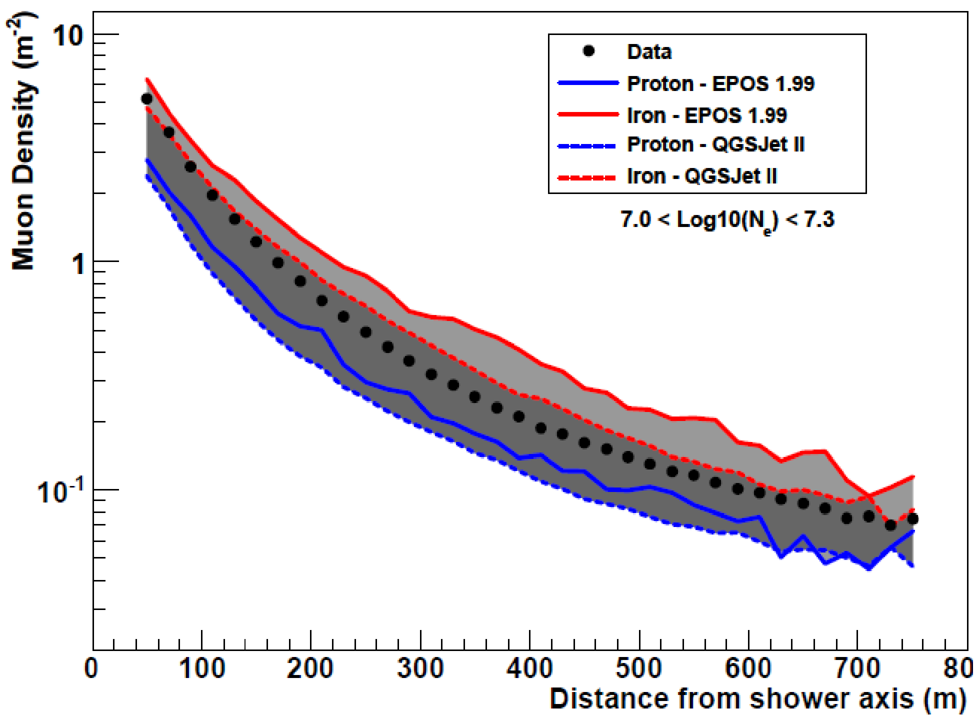
HiRes-Mia

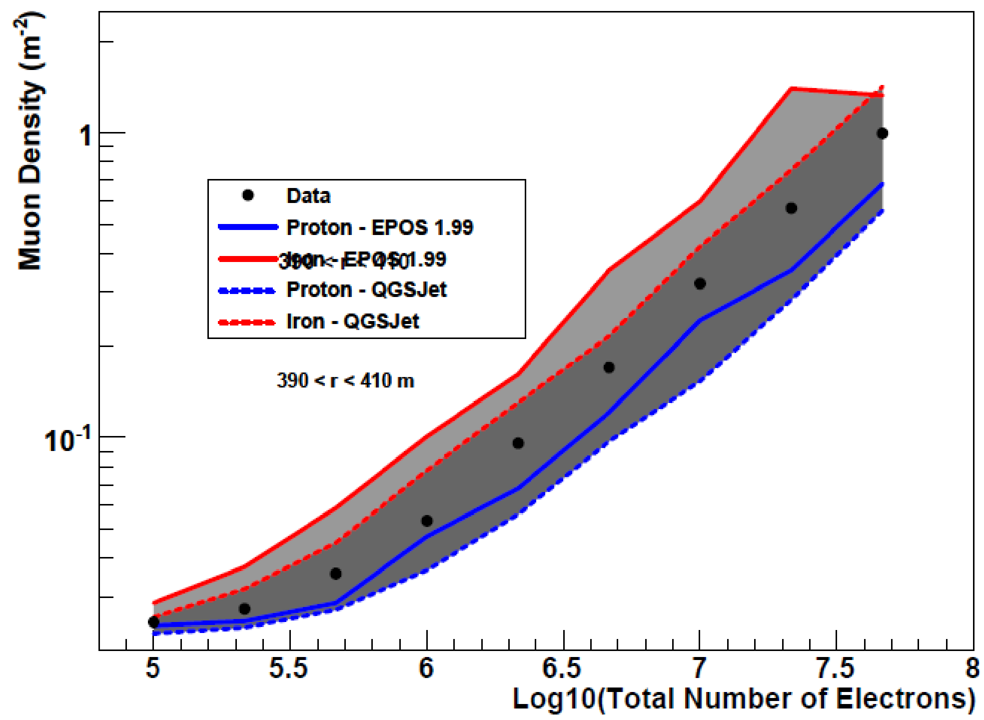
- **EPOS much closer to the data than QGSJET01**
  - ➔ may be even not enough ?



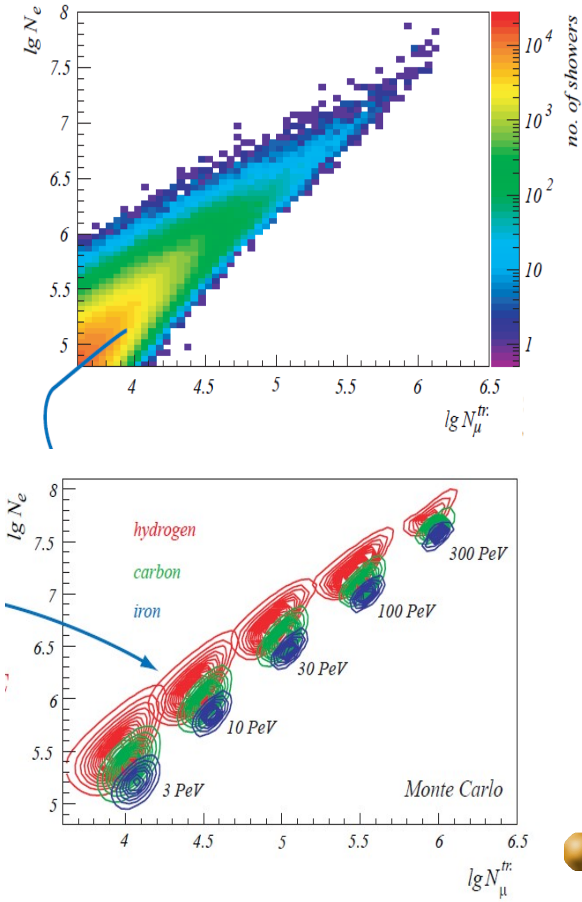
KASCADE-Grande

- **Muon density indicates a high number of muon**
  - ➜ EPOS consistent with data
  - ➜ QGSJETII too low close to the core
- **Shape of LDF for charged particles seems to indicate the same.**





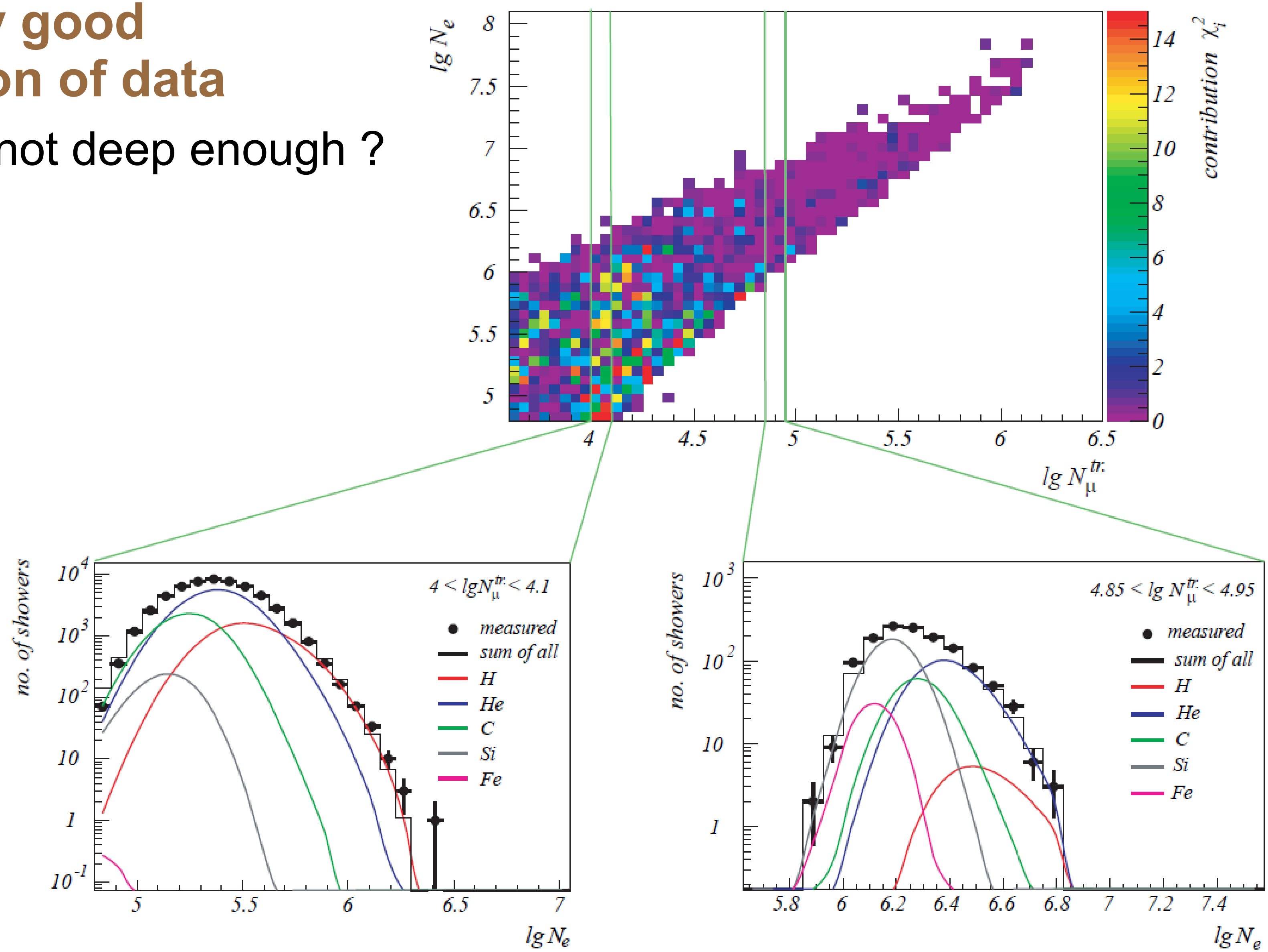
KASCADE



- **Utilize correlations between Ne and Nmu to determine the mass spectra**
  - absolute normalization not very important (for this analysis)
    - degeneracy mass/model
  - low number of muons can be compensated by low number of electrons
  - high number of muons has to be compensated by high number of electrons
  - cross check with correlation with hadrons
- **Different experiment in same energy range can provide complementary informations**

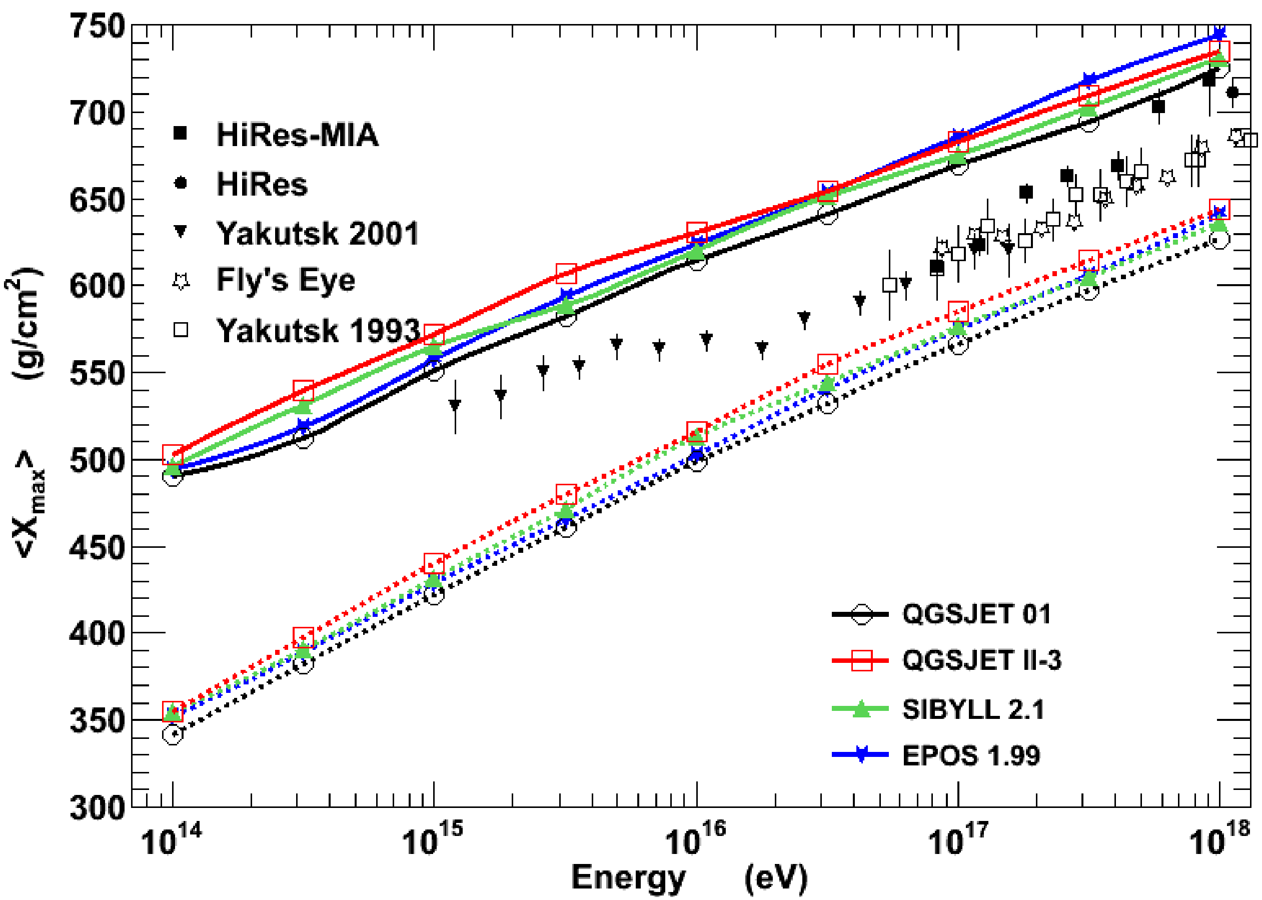
Ne-Nmu QGSJET01

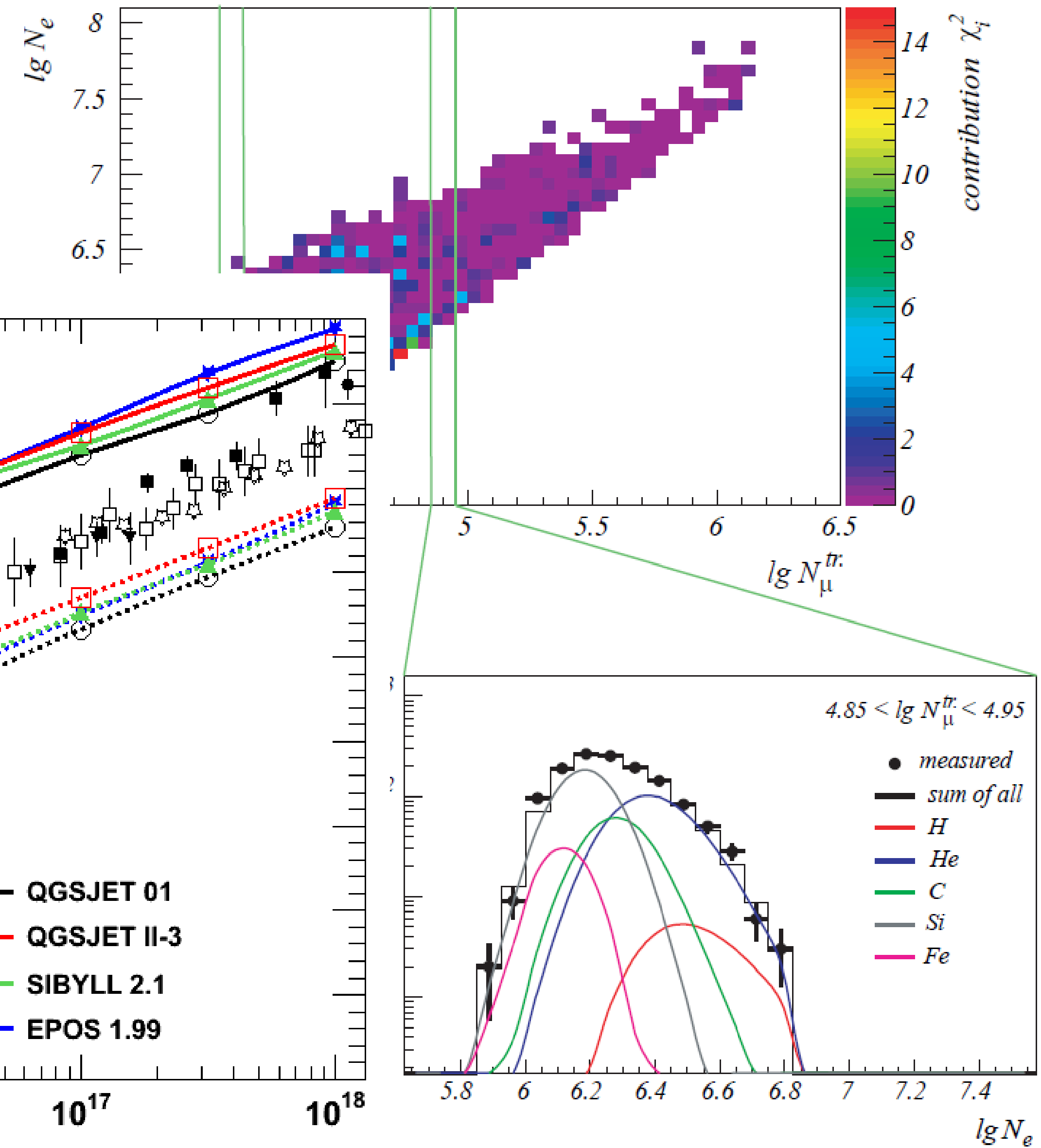
- **Relatively good description of data**
  - ➔ shower not deep enough ?



Ne-Nmu QGSJET01

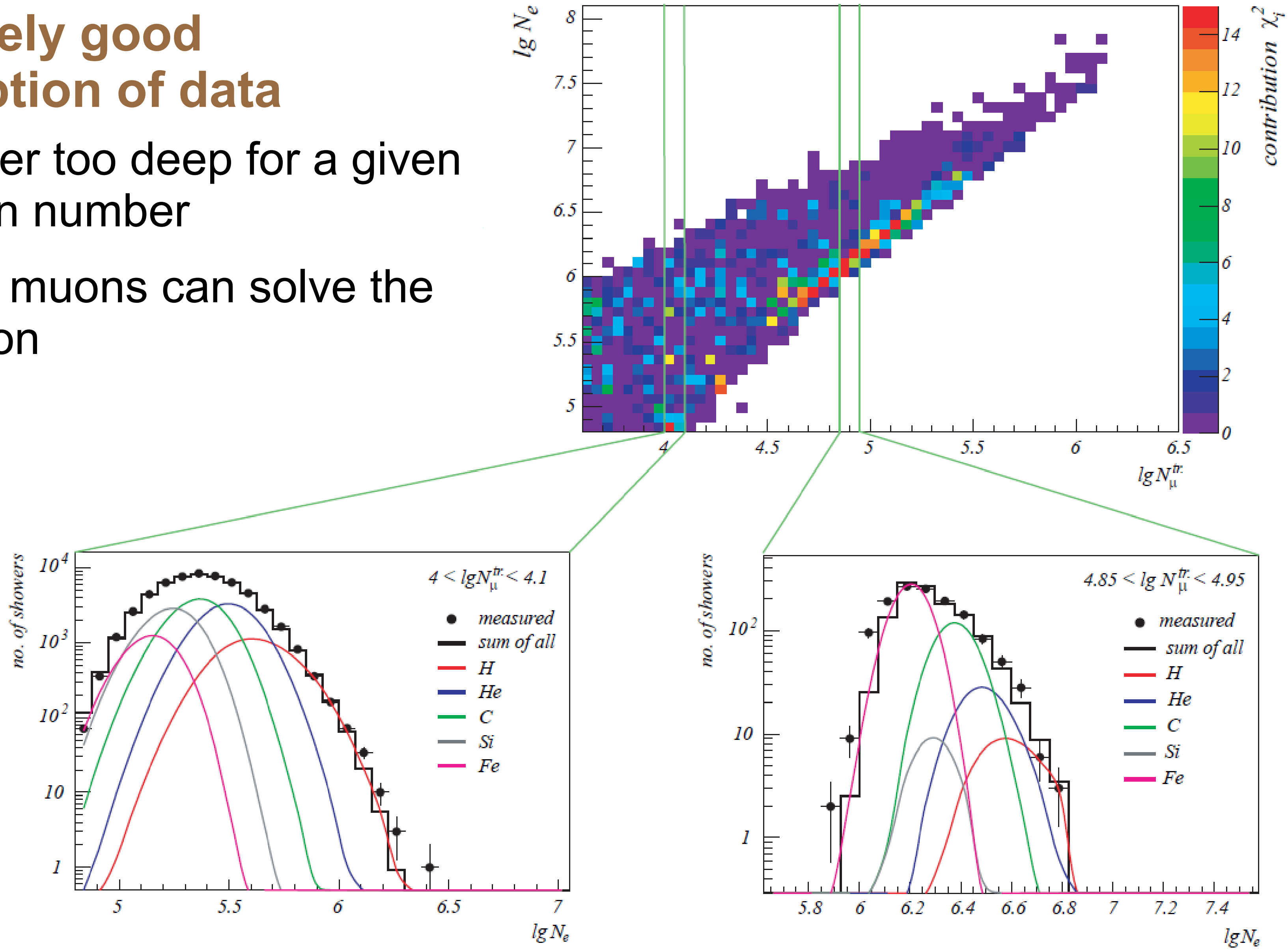
- **Relatively good description of data**
  - ➜ shower not deep enough ?





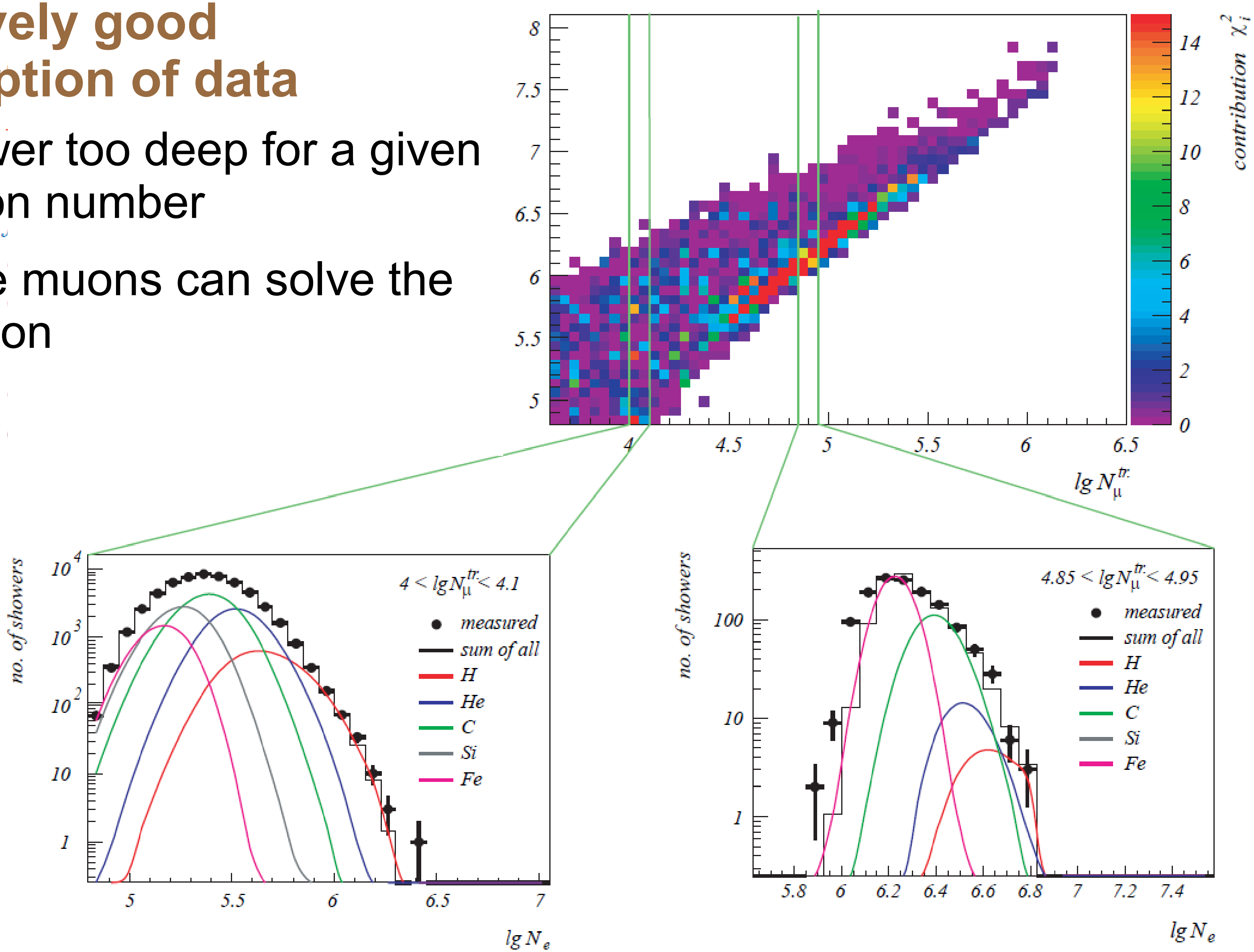
Ne-Nmu QGSJETII

- **Relatively good description of data**
  - shower too deep for a given muon number
  - more muons can solve the tension

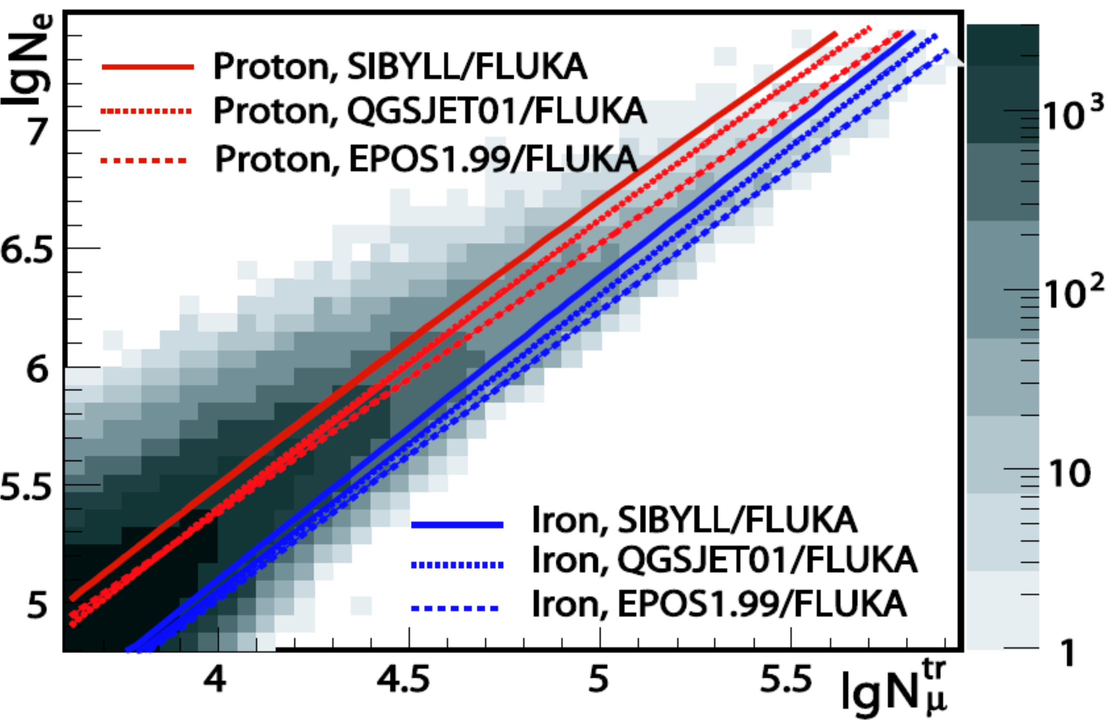


Ne-Nmu Sibyll

- **Relatively good description of data**
  - shower too deep for a given muon number
  - more muons can solve the tension



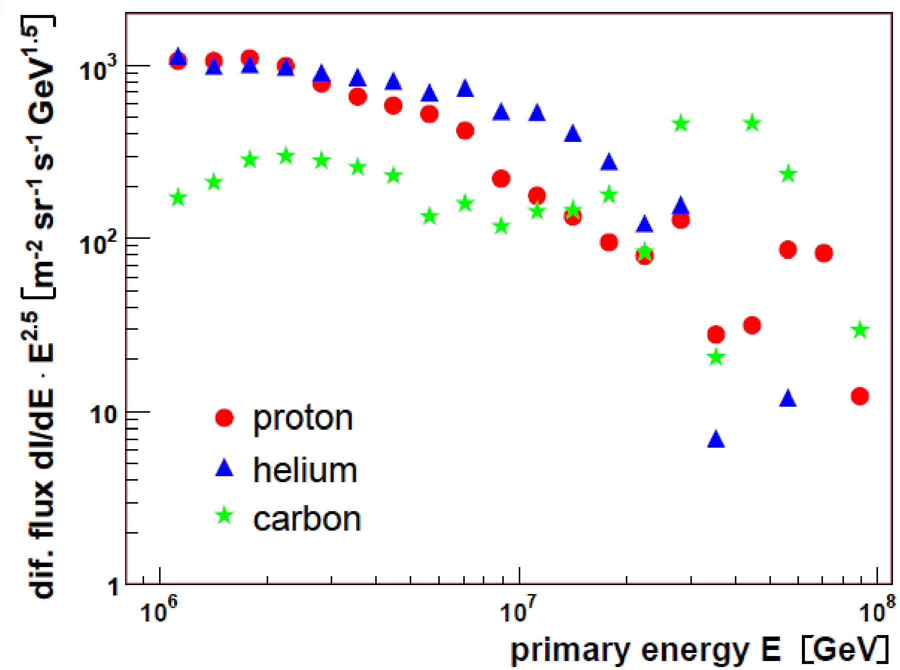
Ne-Nmu EPOS 1.99

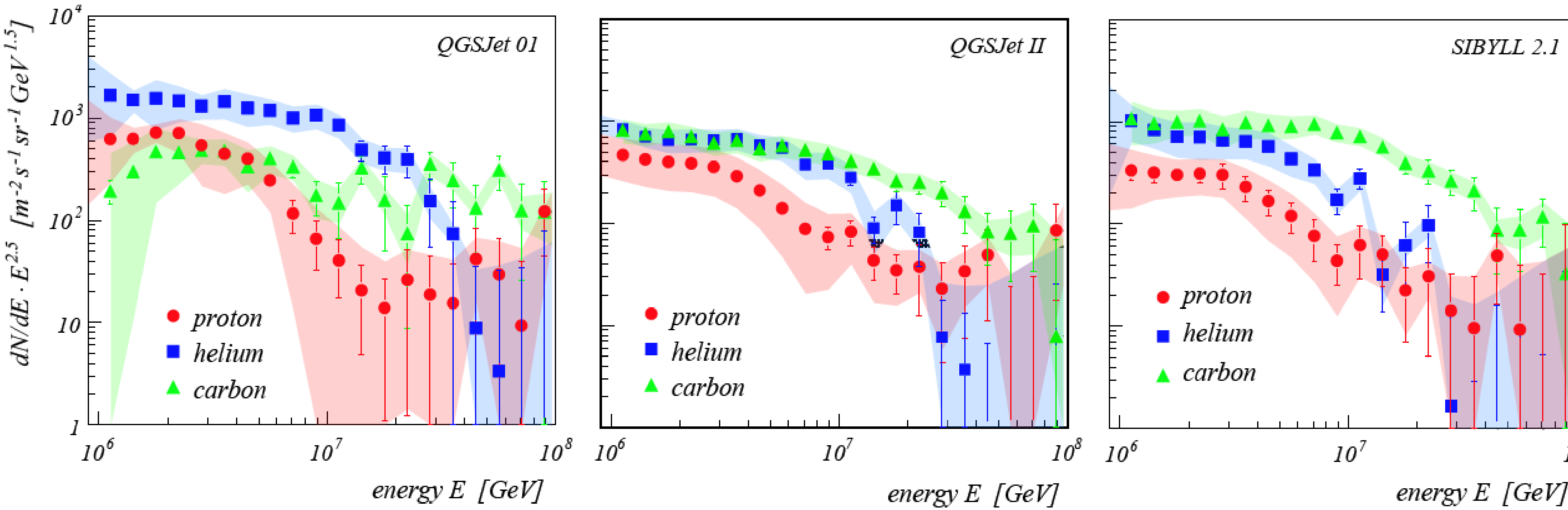


- **Reasonable description of data too but**
  - too many muons
  - or not enough electrons (not deep enough showers

Ne-Nmu

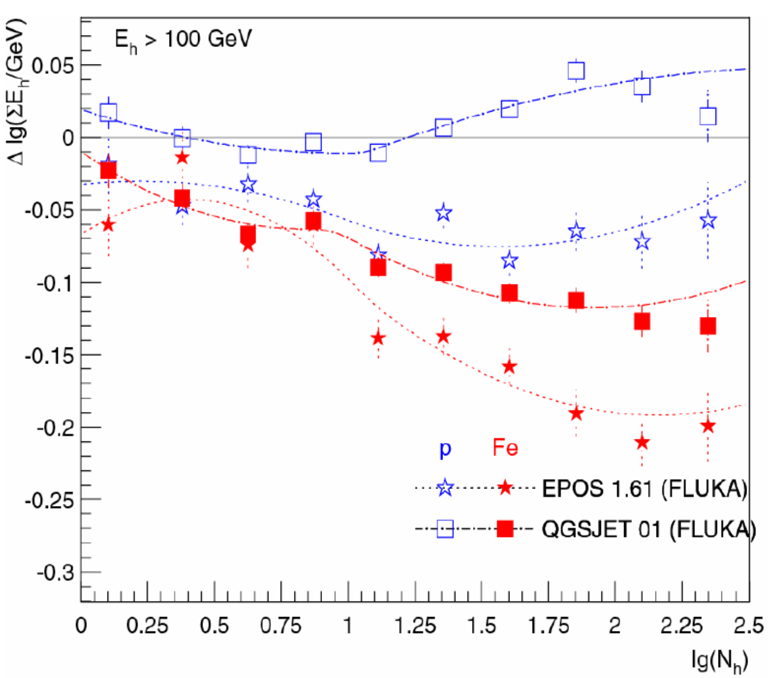
- **Different mass spectra**
  - Sibyll/QGSJETII : lot of Carbon and few protons
  - QGSJET01 : more Helium and low Carbon
  - EPOS : same proton and Helium flux, Carbon very low

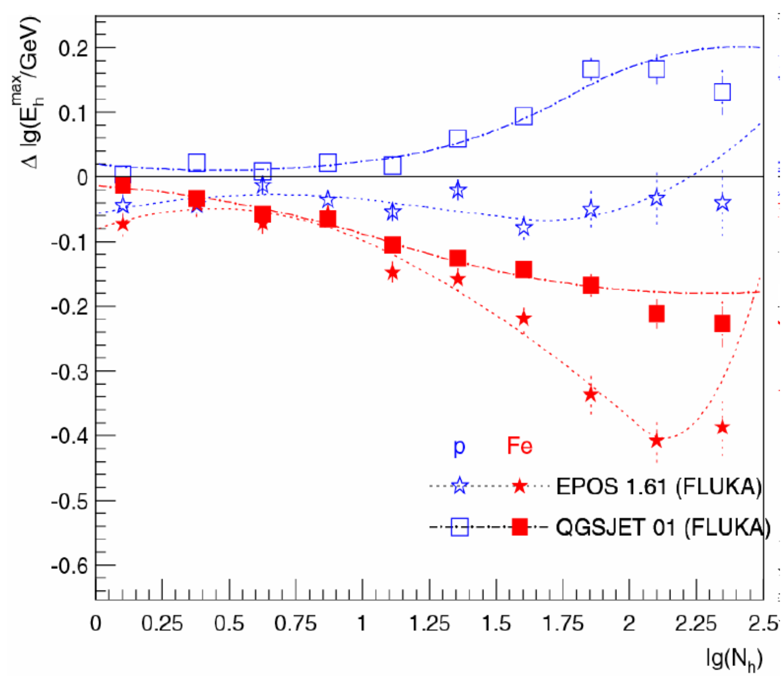




Hadron Correlation (1)

- **EPOS 1.6 Problem**
  - showers not deep enough (cross section and remnant break-up)
- **EPOS 1.99**
  - OK (on-going full analysis)

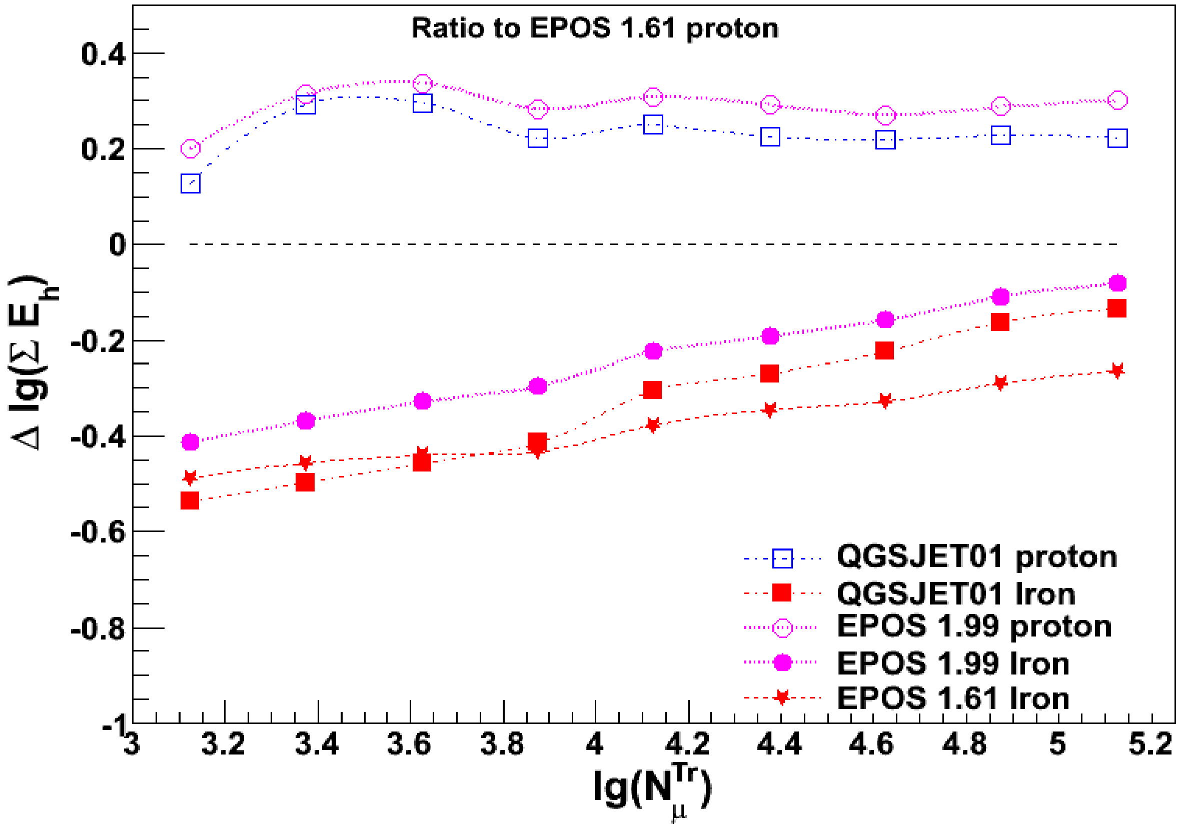




→ energy per hadron too small

Hadron Correlation (2)

- **EPOS 1.6 Problem**
  - showers not deep enough (cross section and remnant break-up)
- **EPOS 1.99**
  - OK (on-going full analysis)



Hadron Correlation (3)

Jörg R. Hörandel, RU Nijmegen
Jens Milke, IWR, FZK

- EPOS 1.6 is not compatible with KASCADE measurements
  → can not be recommended for air shower simulations
- QGSJET-II has some deficiencies
  → should be used for simulations with care
- QGSJET 01 and SIBYLL 2.1 still most compatible models

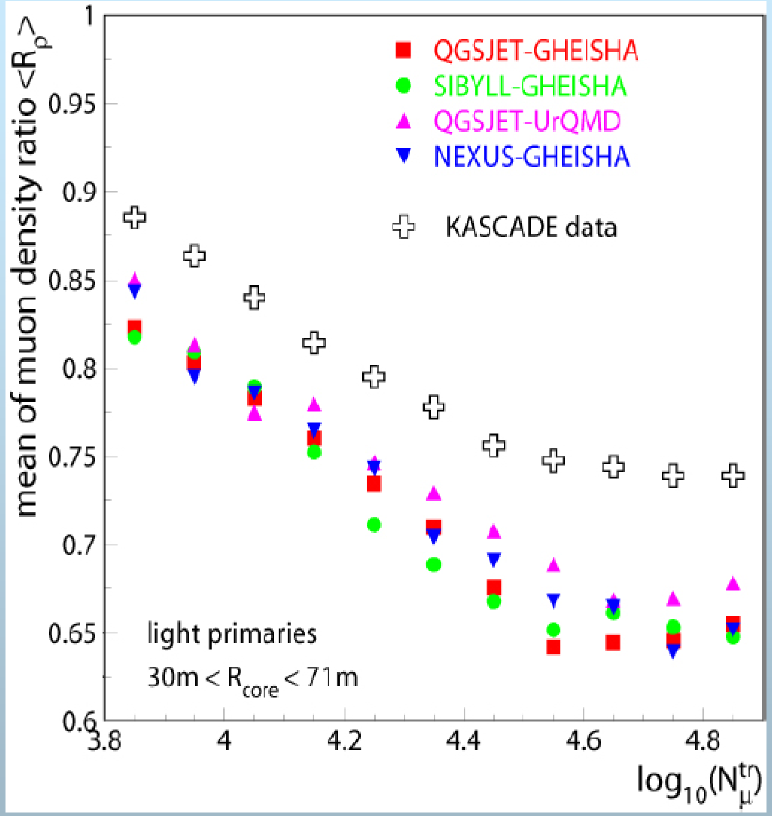
QGSJET 98
~~VENUS~~
~~SIBYLL 1.6~~

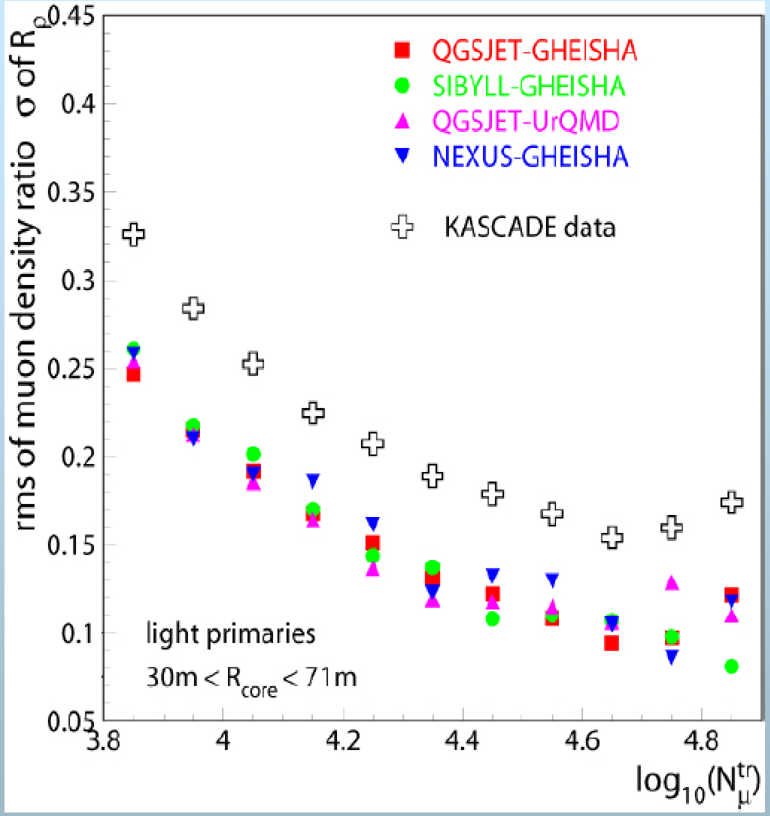
~~DPMJET II.5~~
DPMJET II.55
QGSJET 01
SIBYLL 2.1
~~NEXUS 2~~

~~EPOS 1.6~~
(QGSJET II)

- **EPOS 1.99**
  - results should come soon
  - preliminary tests OK.

KASCADE Direct Muons





Results:

-) inconsistencies for all investigated model combinations

-) problem with the muon energy spectrum predicted by the models?

A.Haungs for KASCADE-Grande, 28th ICRC Tsukuba Japan (2003)

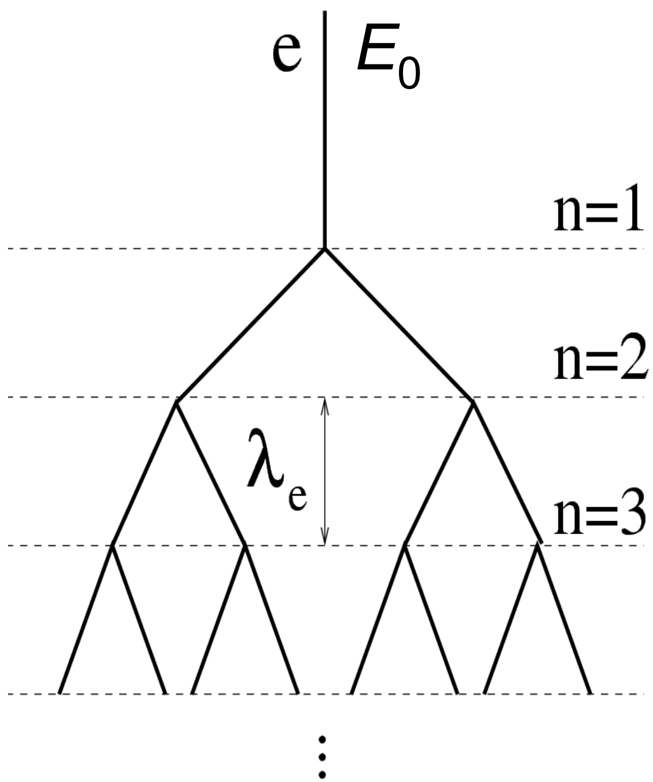
Summary

- **In single collisions some programs show deficits**
  - multiplicities, xlab, Pt, …
    - LHC
  - Still more data needed, especially for pion-projectiles
    - NA61
- **Measurable shower parameters (longitudinal, lateral)**
  - high-energy model : main contribution
  - low-energy model : finer details (~10%)
- **No consistent description of all cosmic ray experiment**
  - QGSJET01 not to bad in average but certainly fail at Auger
    - Pb : no supported by the author ...
  - SIBYLL/QGSJETII not enough muons
  - EPOS consistent description of data above KASCADE
    - too many muons or shower not deep enough ?

Recommandations for Simulations

- **High-energy models:**
  - DPMJET II.55 to be replaced by DPMJET 3 (to come ...)
  - EPOS 1.99 very long CPU-times, but only one with high muon content
  - neXus 3 long CPU-times, to be replaced by EPOS
  - QGSJET 01 fast, high transition energy recommended
  - QGSJET II-3 replaces QGSJET 01, but slower
  - SIBYLL 2.1 fast, (too) low muon content
- **Low-energy models:**
  - FLUKA describes experiments best, if suitable objectfile available
  - GHEISHA 2002 is now obsolete, despite improvements still insufficient in kinematic
  - UrQMD 1.3 needs long CPU times

Toy Model for Electromagnetic Cascade



Primary particle : photon/electron

Heitler toy model :

- 2 particles produced with equal energy

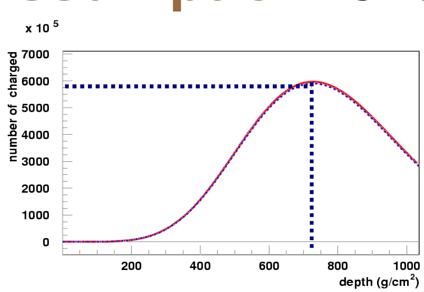
2^n particles after *n* interactions

$$n = X/\lambda_e$$

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

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

Assumption: shower maximum reached if $E(X_{max}) = E_c$ (critical energy)



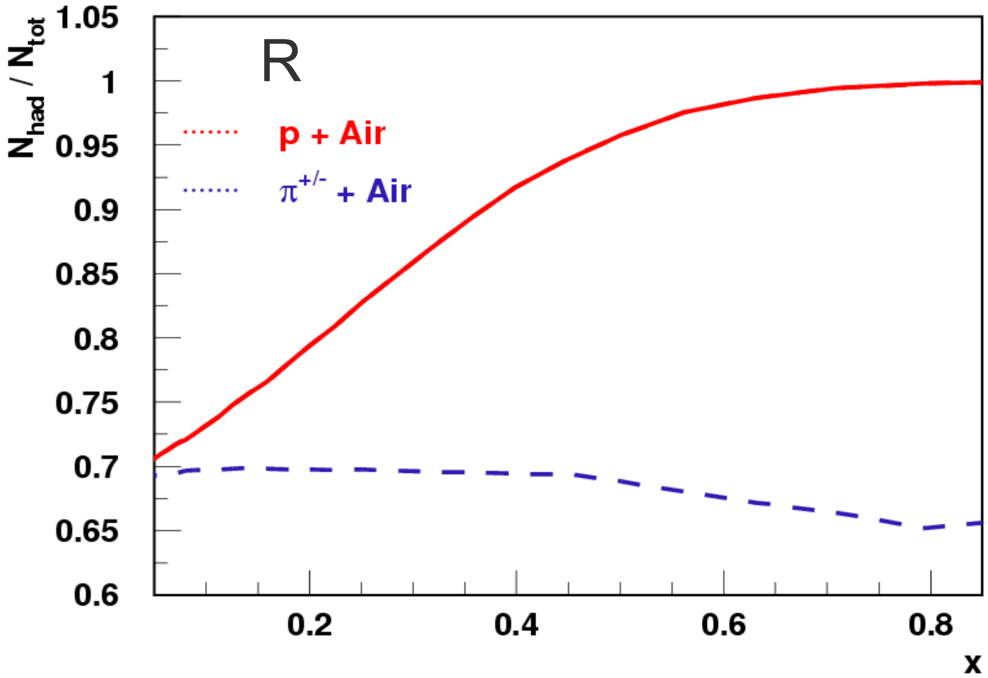
$$N_{max} = E_0/E_c \qquad X_{max} \sim \lambda_e \ln(E_0/E_c)$$

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 (anti)Baryon-Air interactions, no leading neutral pion !

R~1

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

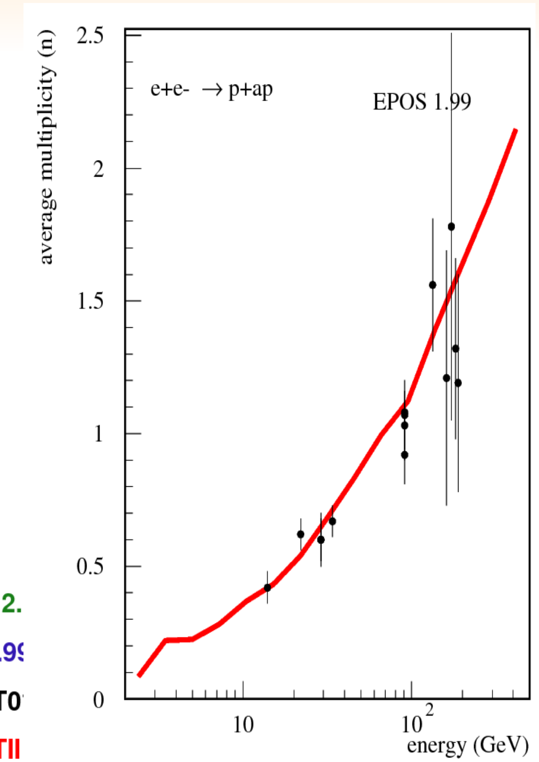
More fast (anti)baryons = $\alpha \rightarrow 1$ = more muons

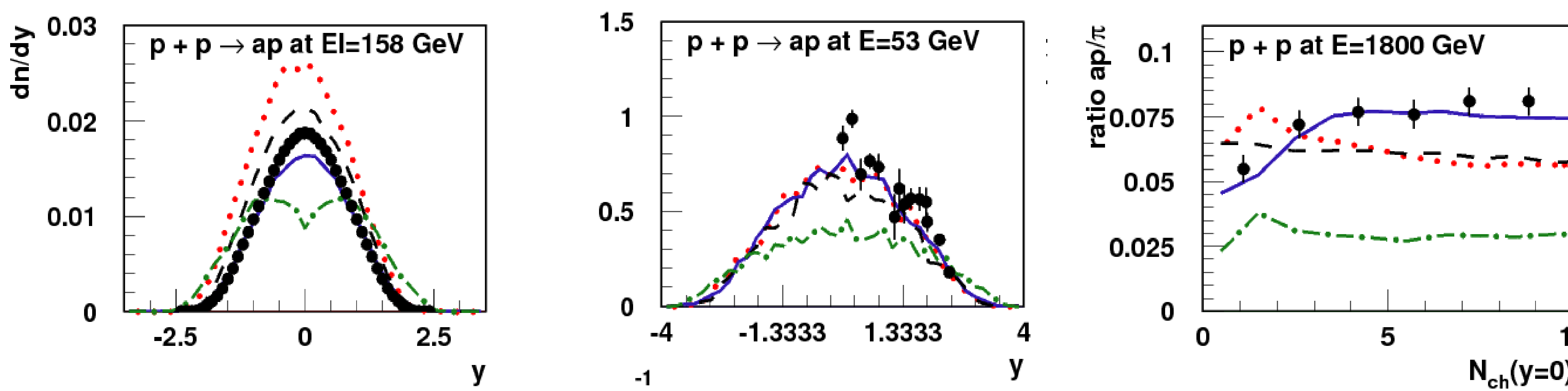
T. Pierog et al.,Phys.Rev.Lett. 101 (2008) 171101

Baryon Production

Baryon production at different level

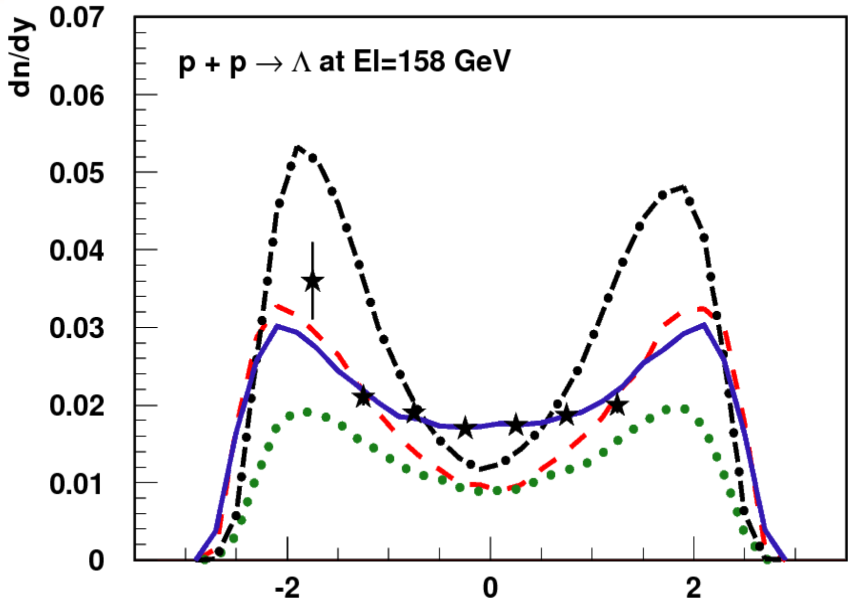
- diquark pair during string fragmentation
  - tested in e+e-
  - do not reproduce energy evolution observed in pp
    - different string tension for gluon jet in EPOS
- diquark pair as string end
  - diquark only in string
  - diquark between remnant and string
    - only EPOS



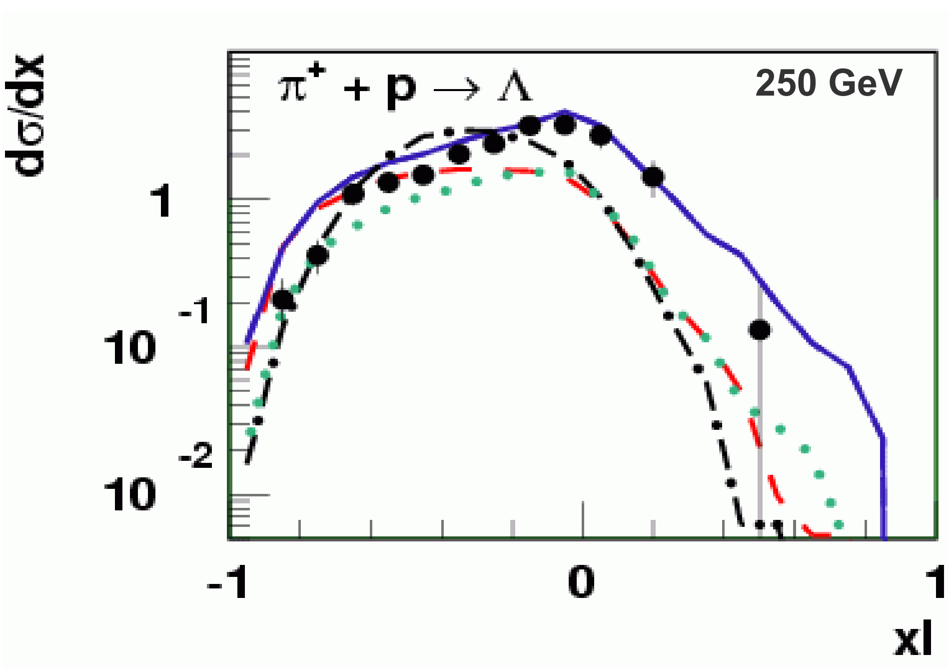


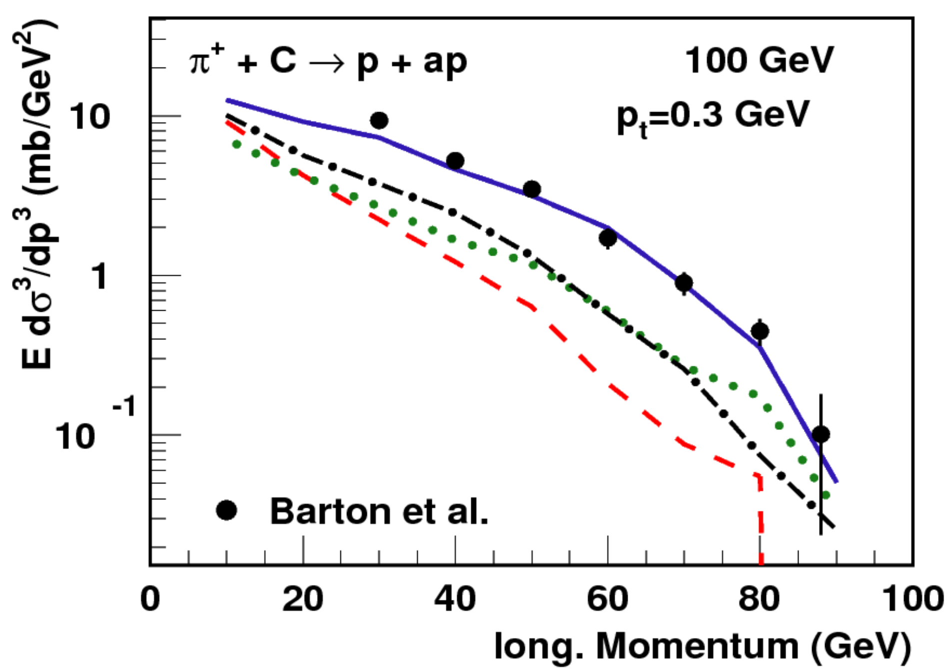
more baryons at high energy in EPOS

Baryon Forward Spectra

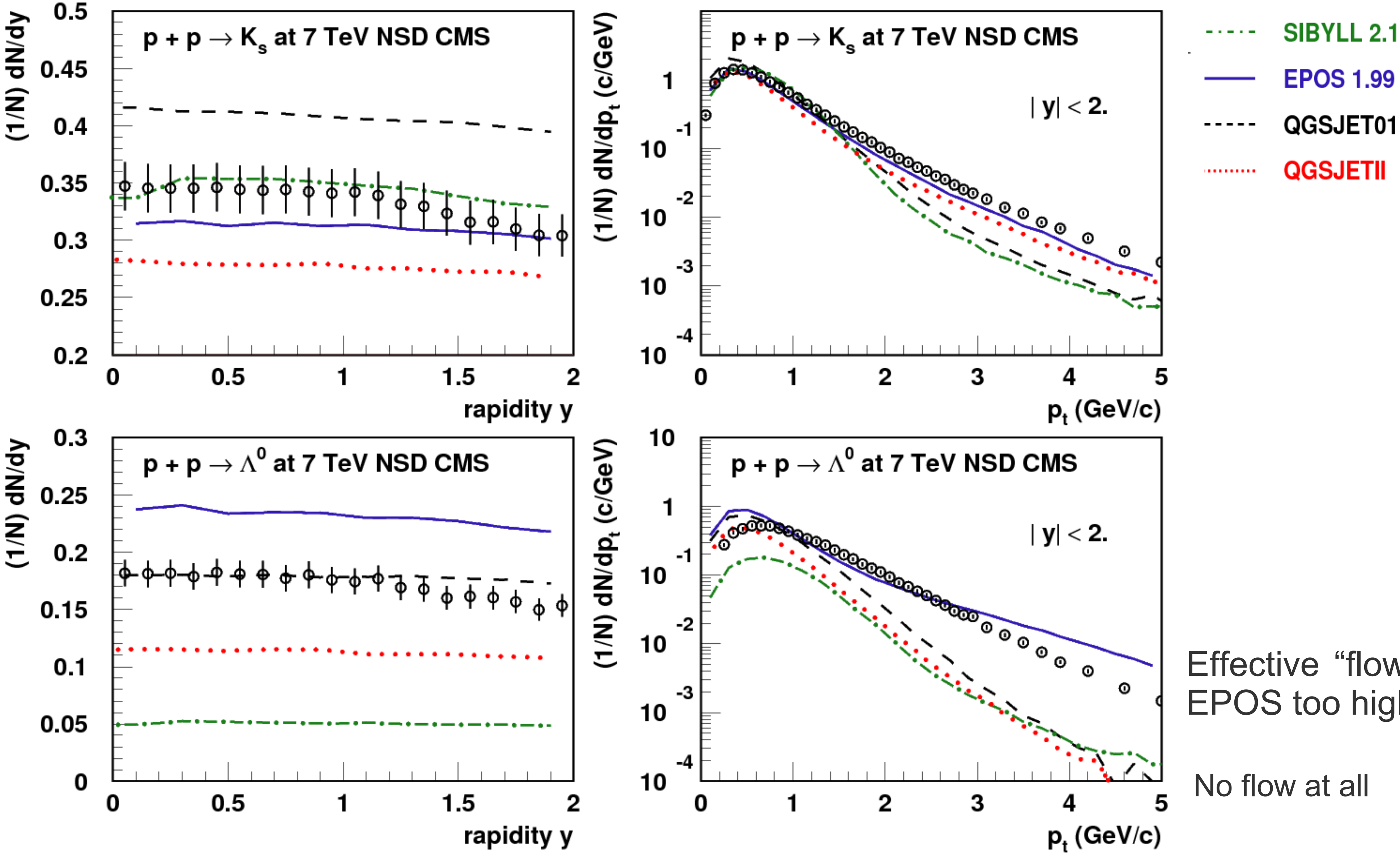


- Large differences between models
- Need a new remnant approach for a complete description (EPOS)
- Problems even at low energy
- No measurement at high energy !





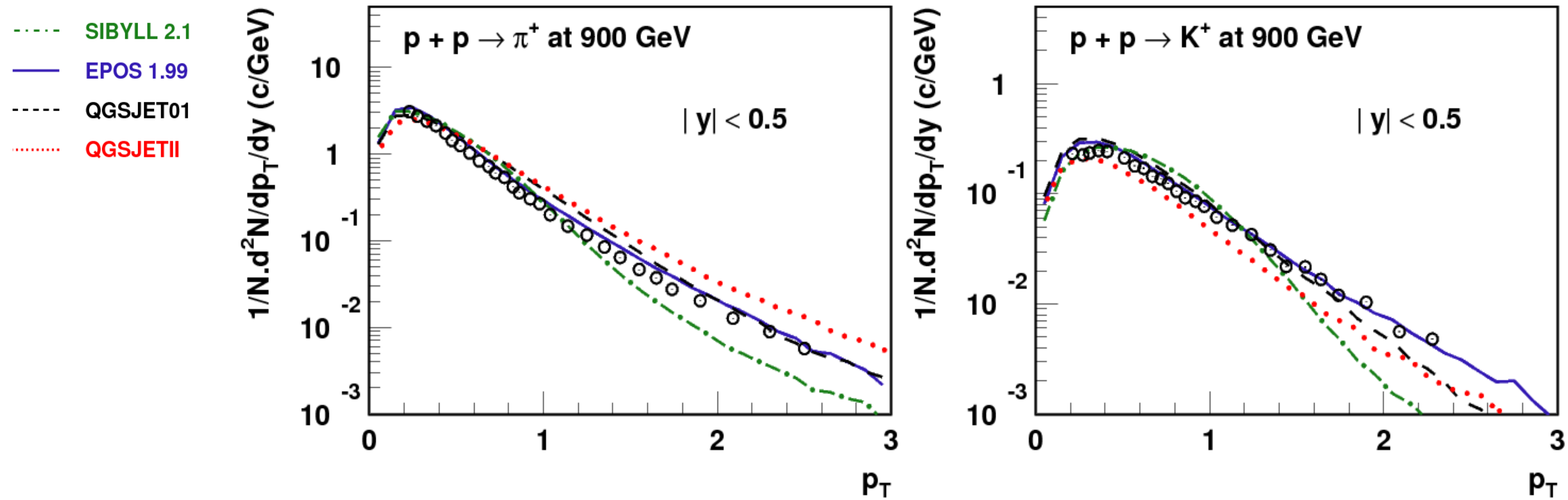
CMS Strangeness 7 TeV

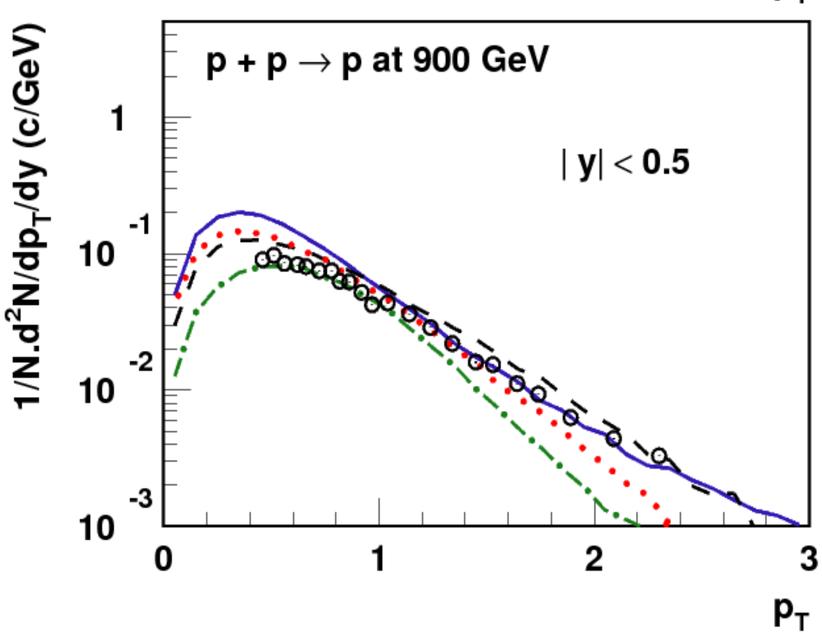


Effective “flow” in EPOS too high

No flow at all

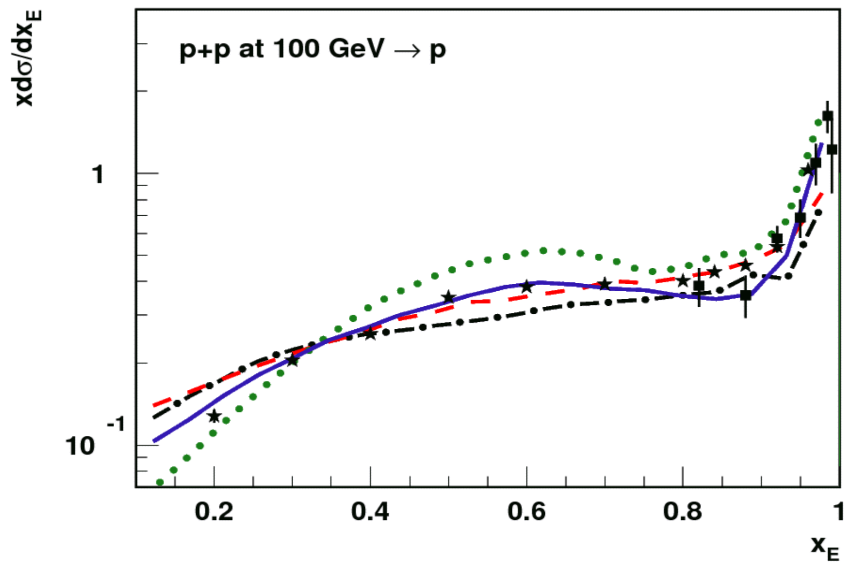
ALICE Identified Spectra 900 GeV

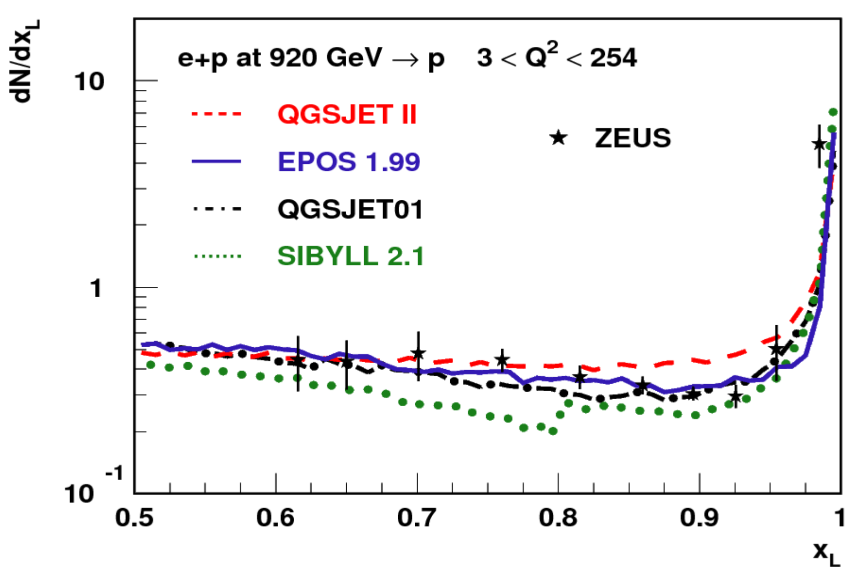




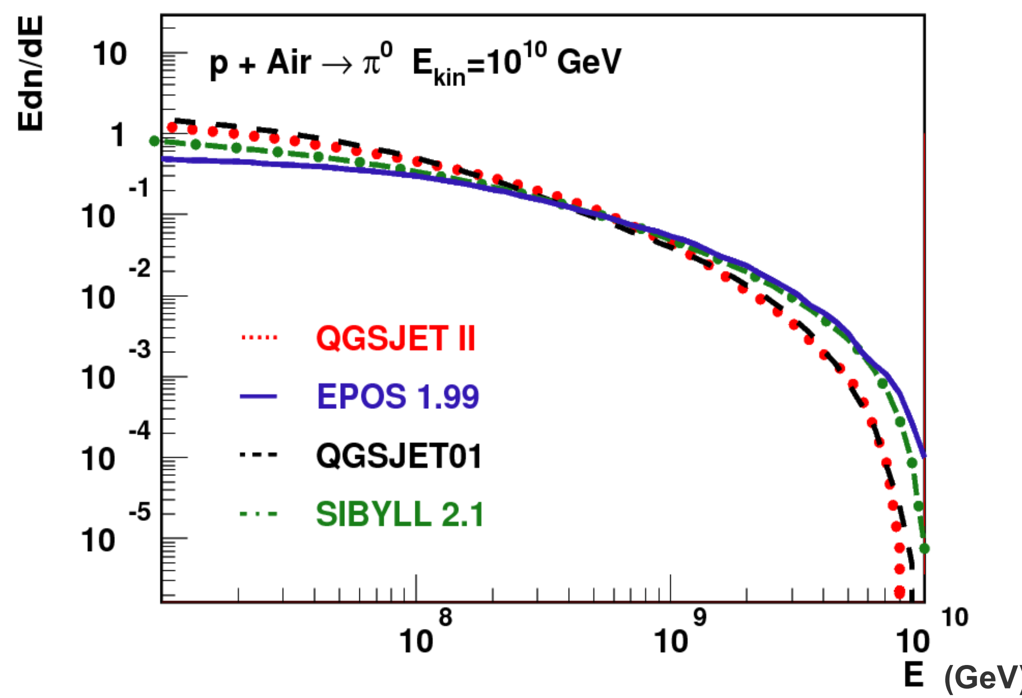
- **Individual particles**
  - EPOS OK (proton ?)
  - QGSJET01 OK !
  - QGSJETII Pion mean p_T too large

Diffraction and x Distributions



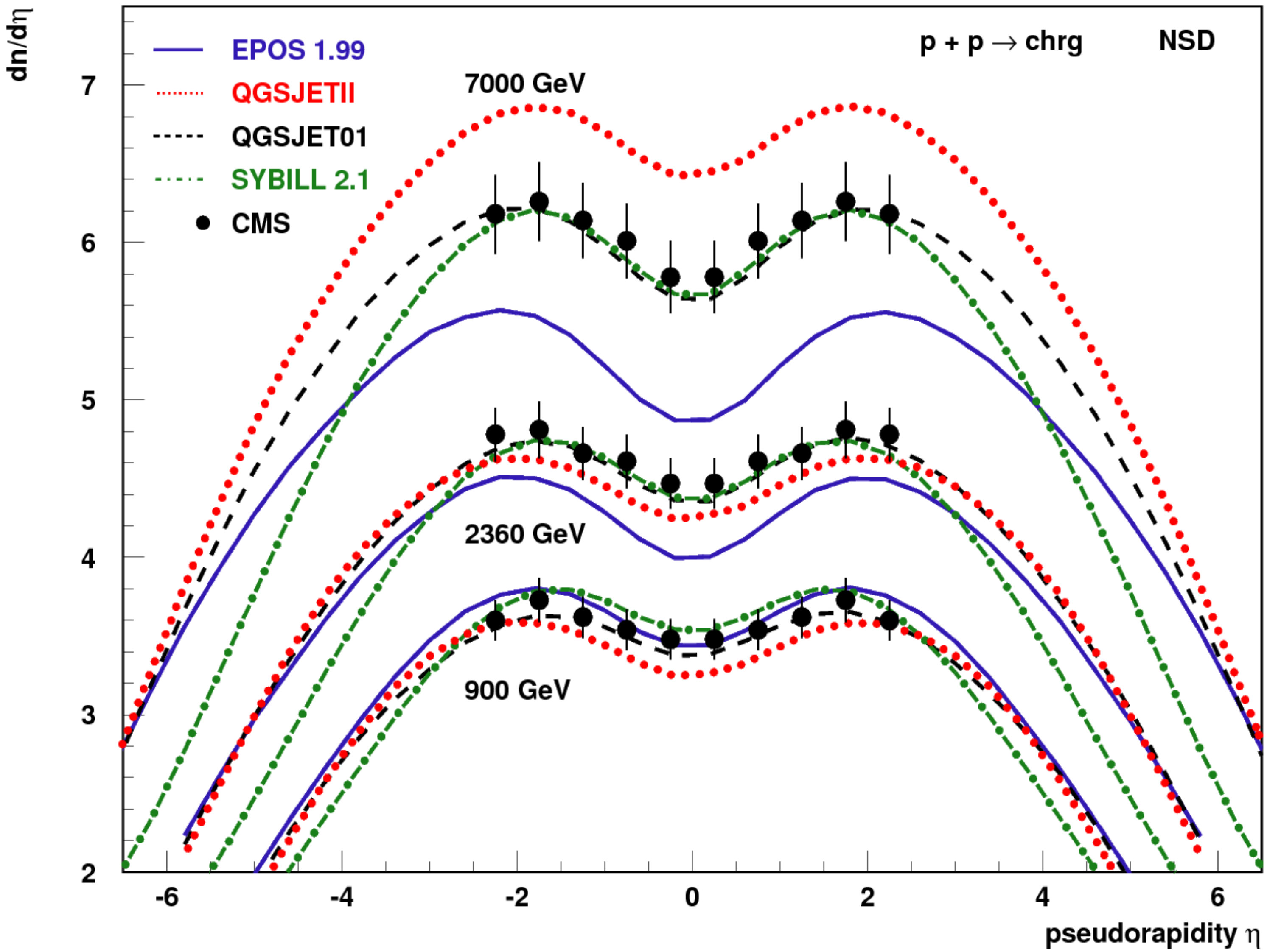


- most of the data at low energy (fixed target experiment)
- extrapolation tested with HERA data
- But large differences at CR energies



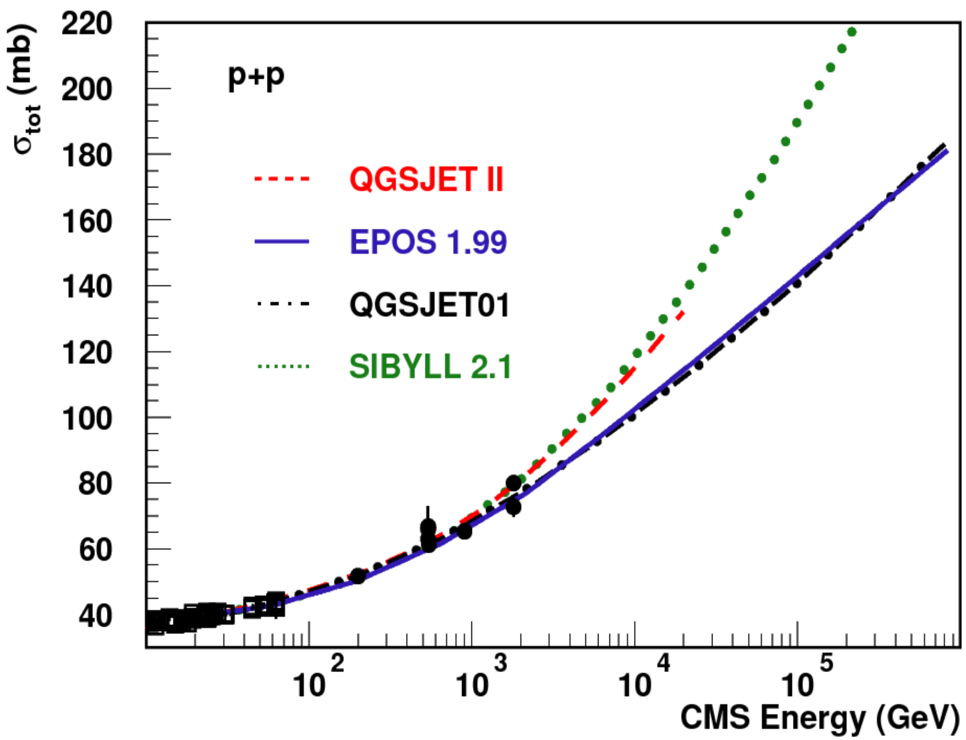
LHCf results very important

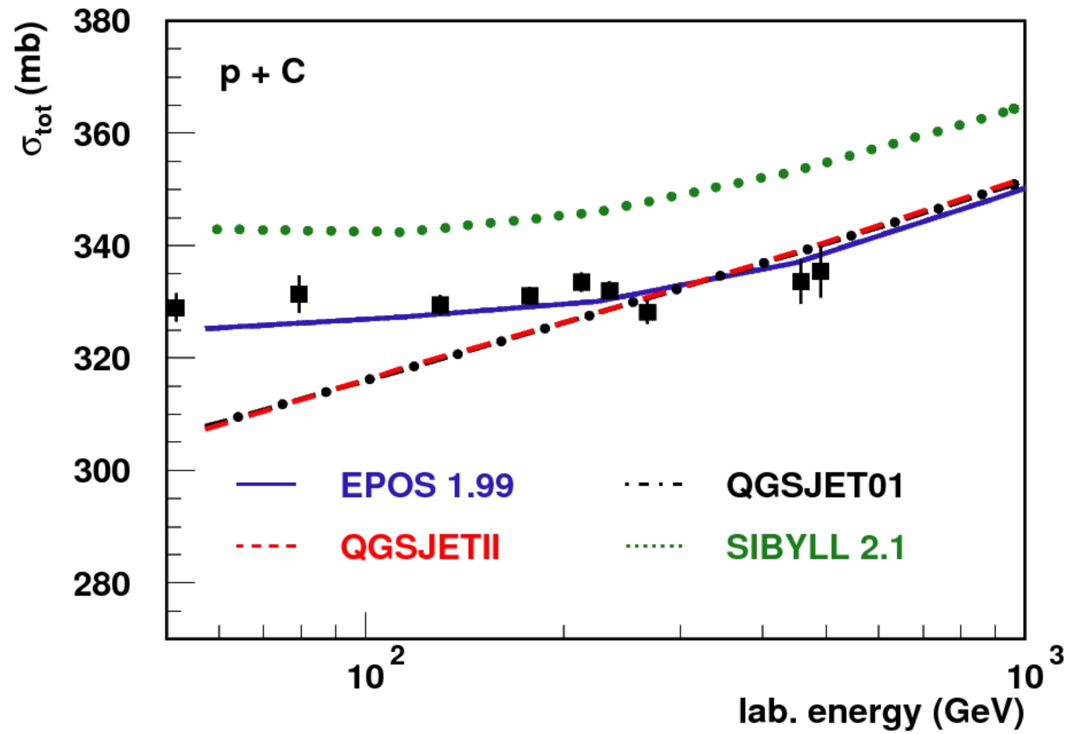
Pseudorapidity NSD CMS



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





Low cross section in EPOS