Hadronic interactions and EAS

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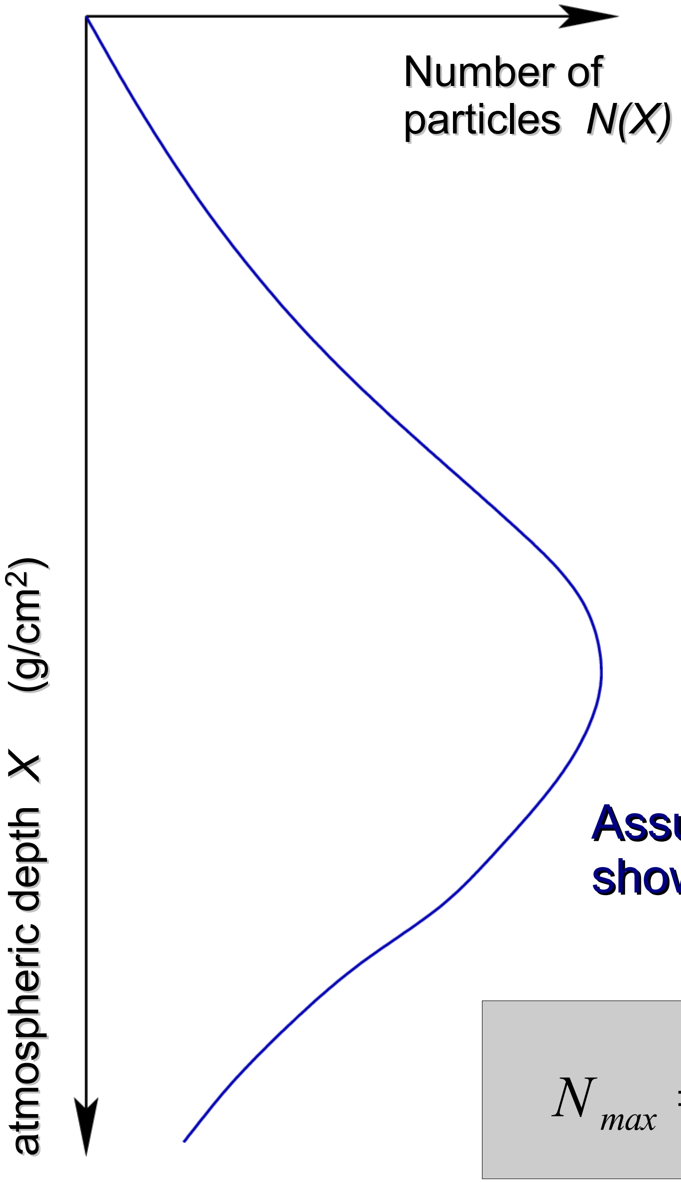
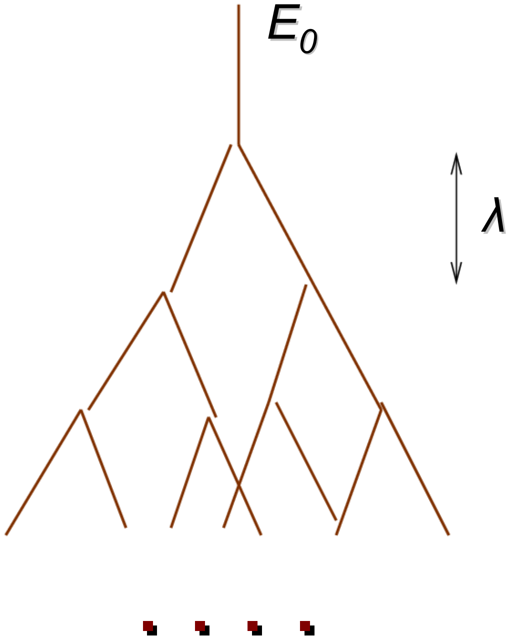
Outline

- Toy model: important parameters of had. interactions
- Predictions of interaction models (hadron-air)
- Constraints from theory & accelerator data:
  - Differences of predictions realistic
  - Uncertainty range properly reflected
- Air shower predictions:
  - Impact on energy and composition measurements
  - Detector optimization

Heitler's model of em. showers





Primary particle: photon

2^n particles after n interactions

$$n = X/\lambda$$

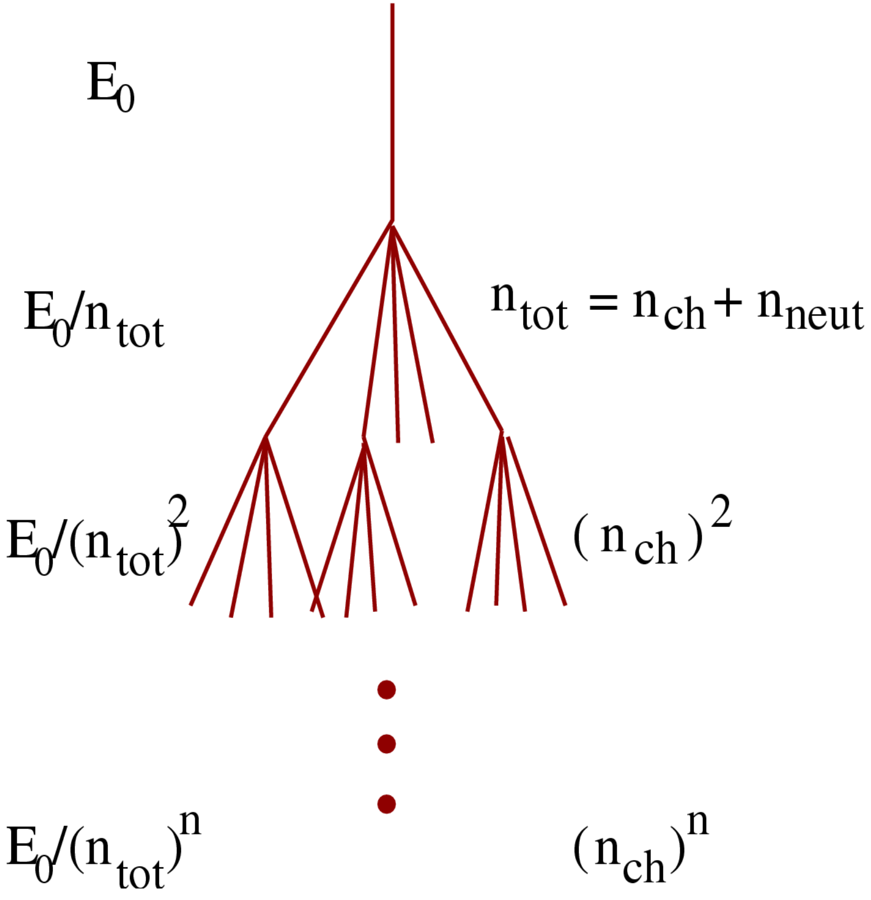
$$N(X) = 2^n = 2^{X/\lambda}$$

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

Assumption:
shower maximum reached if $E(X) = E_c$

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

Muon production in had. showers



E_0

E_0/n_{tot} $\quad n_{tot} = n_{ch} + n_{neut}$

$E_0/(n_{tot})^2$ $\quad (n_{ch})^2$

$E_0/(n_{tot})^n$ $\quad (n_{ch})^n$

Primary particle: proton

π^0 decay immediately

Only charged pions initiate new hadronic cascades

Cascade ends with decay at energy E_{dec}

$$E(X) = E_0/(n_{tot})^n = E_{dec}$$

$$N_\mu = (n_{ch})^n$$

$$\boxed{N_\mu = \left(\frac{E_0}{E_{dec}}\right)^\alpha, \quad \alpha = \frac{\ln n_{ch}}{\ln n_{tot}} \approx 0.82\ldots0.95}$$

Application: superposition model

Proton shower characteristics:

$$N_{max} = E_0 / E_c$$

$$X_{max} = \lambda_e \ln(E_0)$$

$$N_\mu = \left(\frac{E_0}{E_{dec}} \right)^\alpha$$

Assumption:

nucleus of mass *A* and energy E_0 acts
like *A* independent nucleons with energy $E_n = E_0/A$

$$N^A_{max} = A\ E_n / E_c = E_0 / E_c$$

$$X^A_{max} \sim \lambda_e \ln(E_0 / A)$$

$$N^A_\mu = A \left(\frac{E_0 / A}{E_{dec}} \right)^\alpha = A^{1-\alpha} N_\mu$$

Toy model parameters

Hadronic interaction model

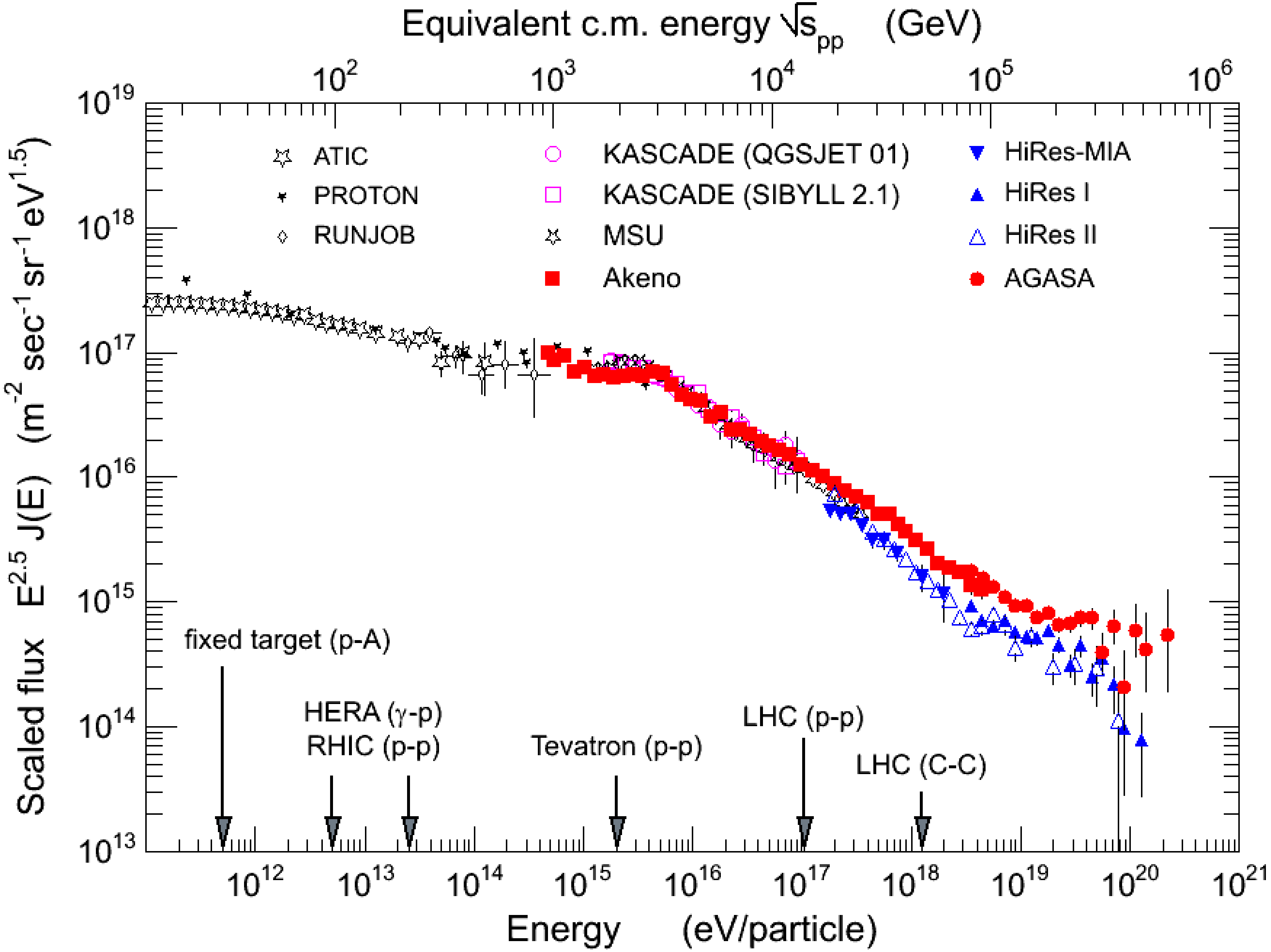
- interaction cross section
- multiplicity of secondary particles
- ratio of neutral to charged pion / kaon multiplicities

Atmosphere as target and calorimeter

- critical energy
- density: typical pion / kaon decay energy

Number of shower particles proportional to energy

Comparison of energies



Comparison of model predictions

Cosmic ray hadronic interaction models

High energy models:

DPMJET II.5 and III (Ranft / Roesler, RE & Ranft)

neXus 2.0 and 3.0 (Drescher, Hladik, Ostapchenko, Pierog & Werner)

QGSJET 98 and 01 (Kalmykov & Ostapchenko)

SIBYLL 1.7 and 2.1 (Engel / RE, Fletcher, Gaisser, Lipari & Stanev)

- Gribov-Regge type models, minijets
- Parametrizations of data

Low/intermediate energy models:

GHEISHA (Fesefeldt)

Hillas' splitting algorithm (Hillas)

FLUKA (Fasso, Ferrari, Ranft & Sala)

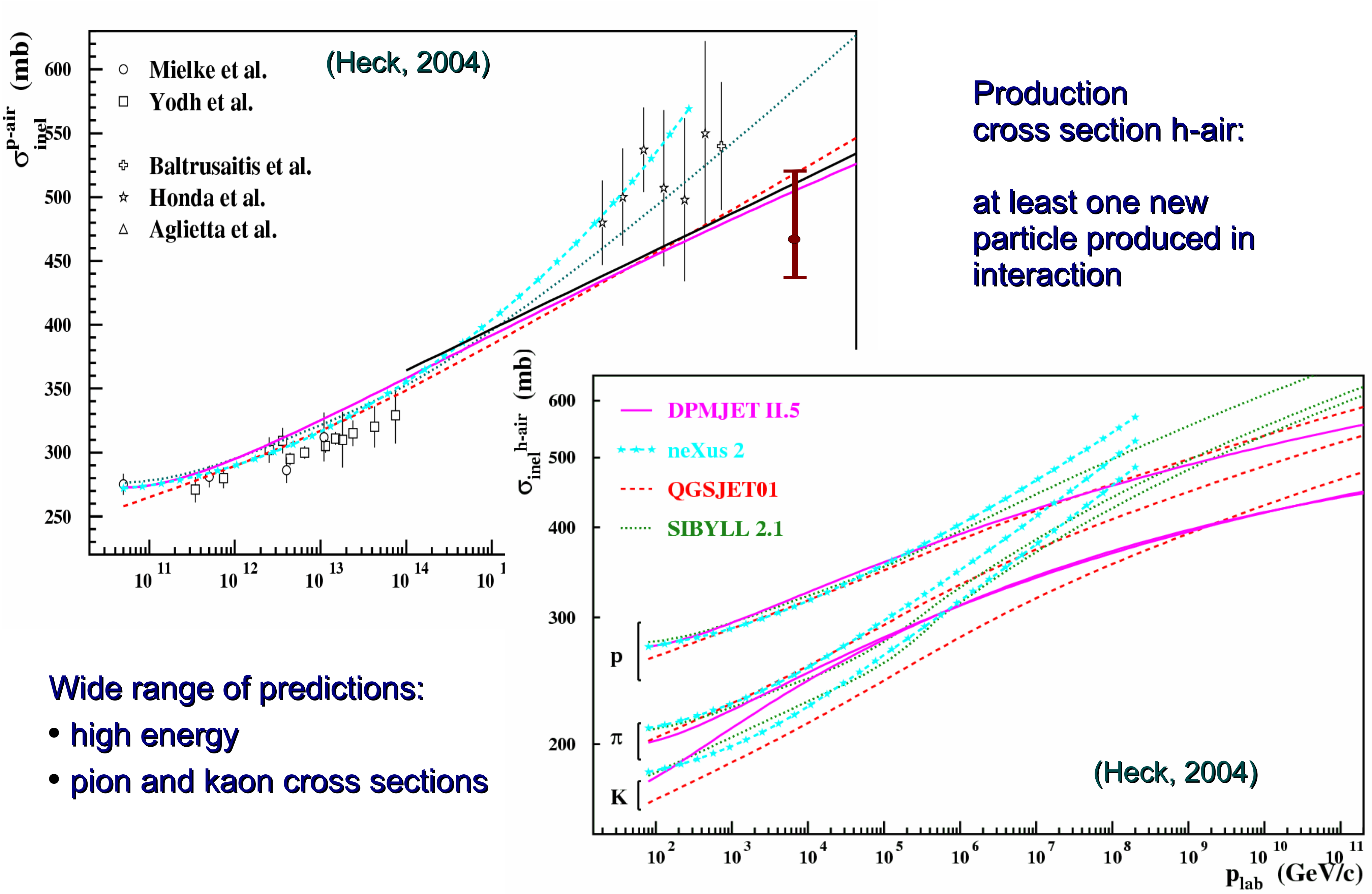
UrQMD (Bass, Bleicher et al.)

TARGET (RE, Gaisser, Protheroe & Stanev)

HADRIN/NUCRIN (Hänßgen & Ranft)

SOPHIA (Mücke, RE, Rachen, Protheroe, Stanev)

Cross section predictions



Production
cross section h-air:

at least one new
particle produced in
interaction

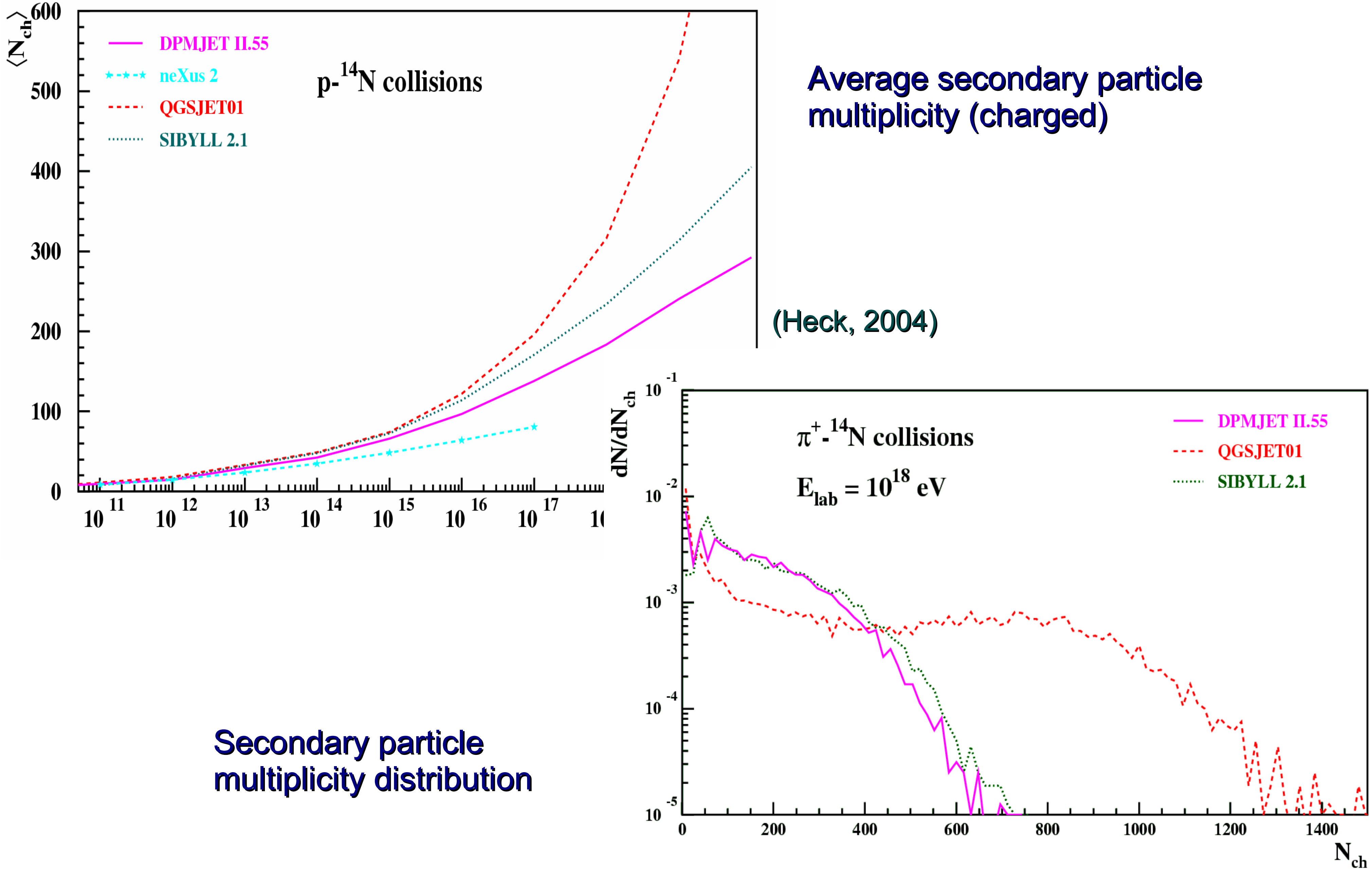
Wide range of predictions:

- high energy
- pion and kaon cross sections

Multiplicity predictions

Average secondary particle multiplicity (charged)

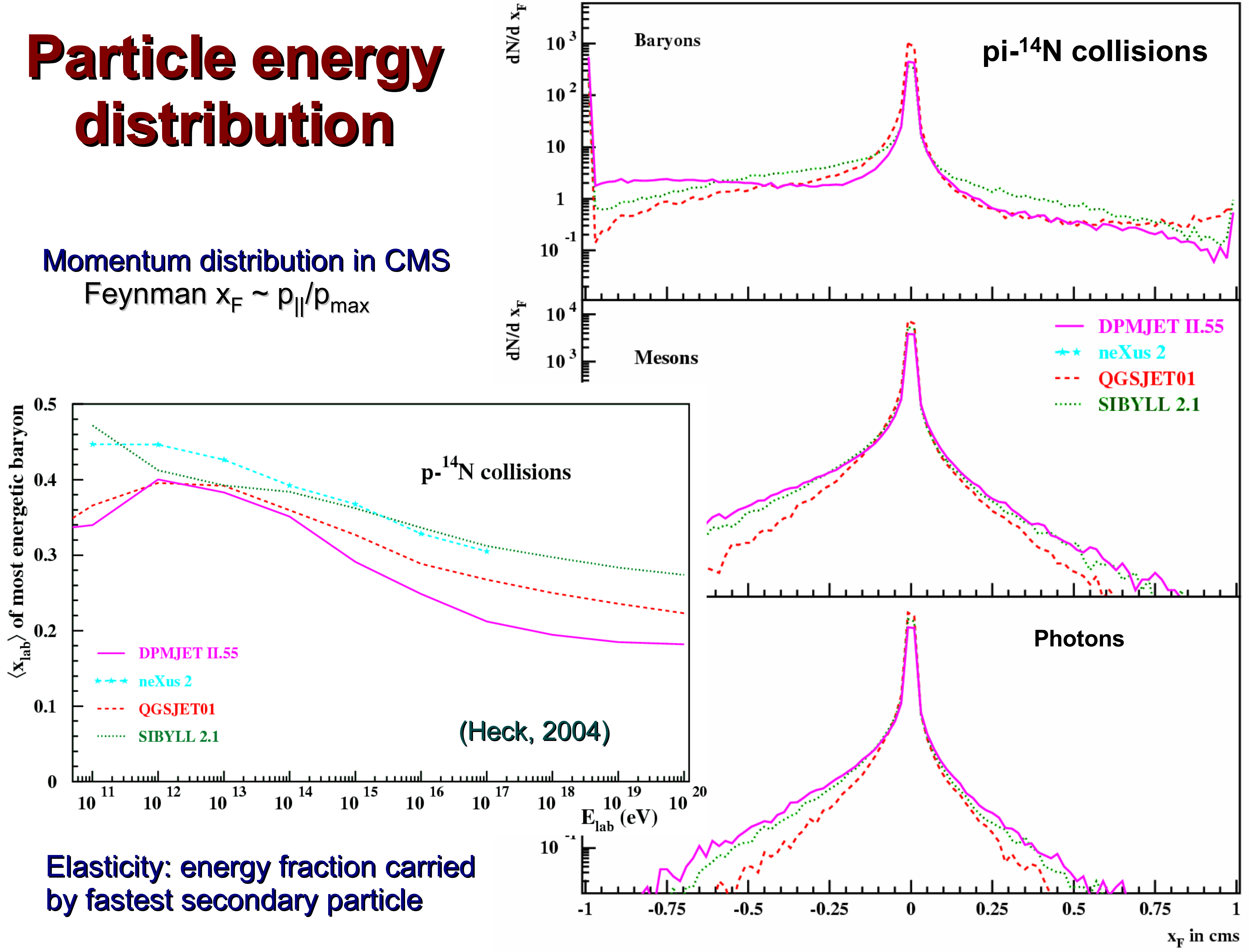
(Heck, 2004)



Secondary particle multiplicity distribution

Particle energy distribution

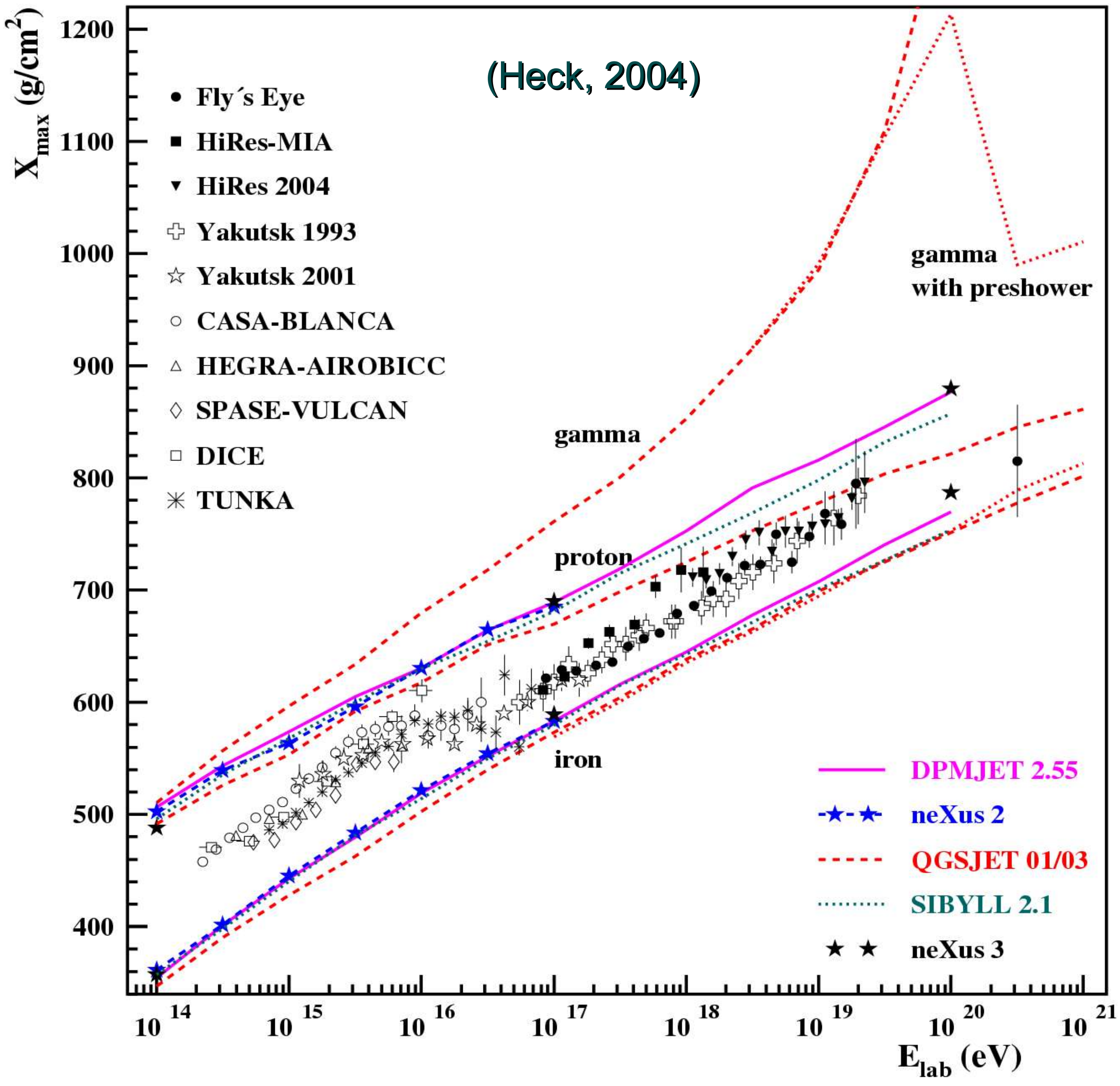
Momentum distribution in CMS
Feynman $x_F \sim p_{||}/p_{max}$



(Heck, 2004)

Elasticity: energy fraction carried by fastest secondary particle

Mean depth of shower maximum



Superposition model:

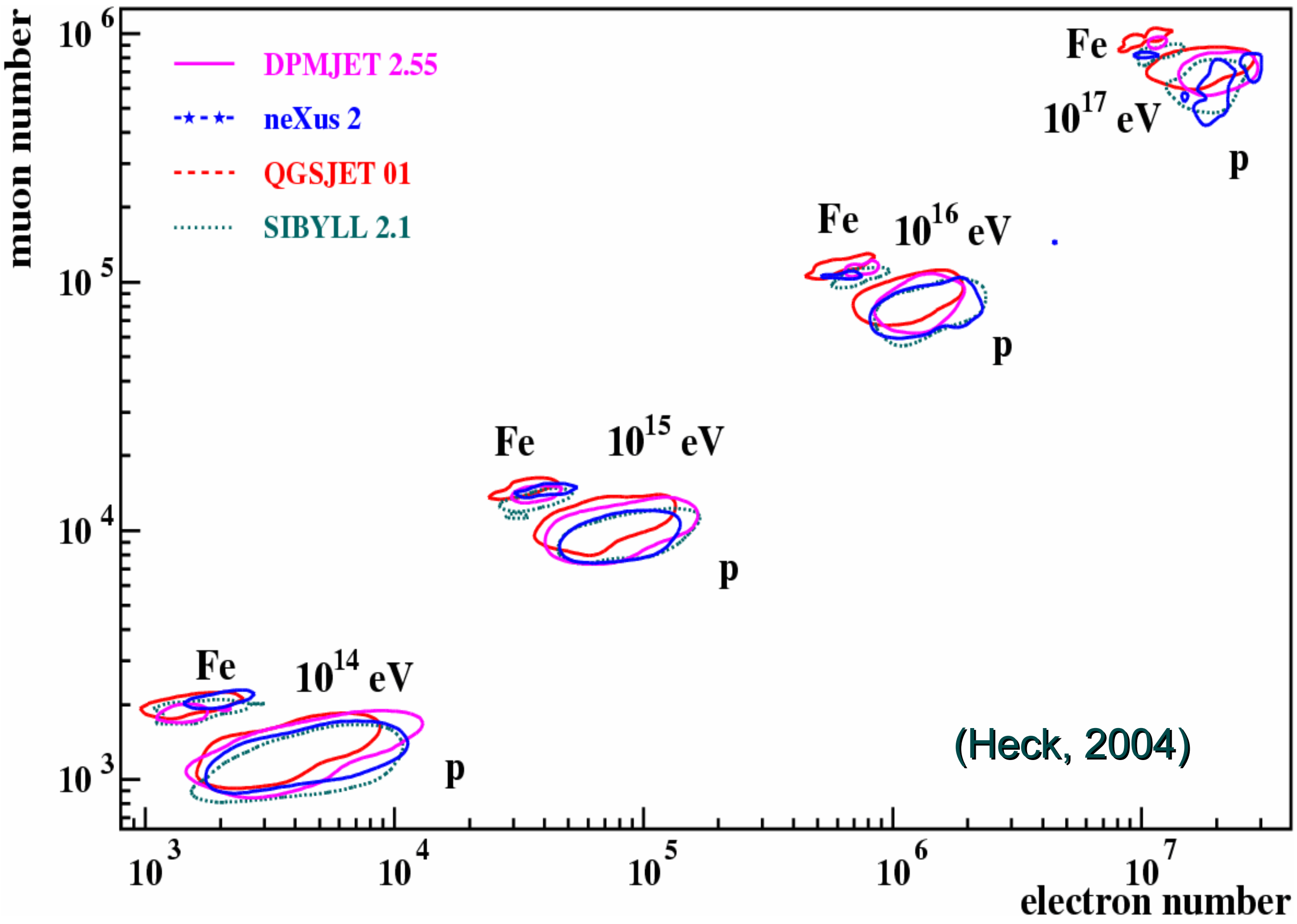
$$X^A_{max} \sim \lambda_e \ln(E_0/A)$$

MC simulation (CORSIKA):

Predictions depend on had. interaction model

Partial compensation of various effects (cross section - inelasticity)

Shower size: N_e-N_μ correlation



Curves: full width at half maximum

Good agreement with superposition model:

$$N_\mu^A = A^{1-\alpha}\left(\frac{E_0}{E_{dec}}\right)^\alpha$$

Model dependence strongly increasing with energy

Are the differences between the predictions reasonable?

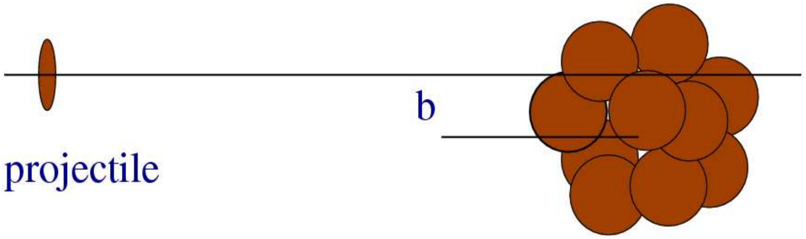
(i) Description of existing (accelerator) data

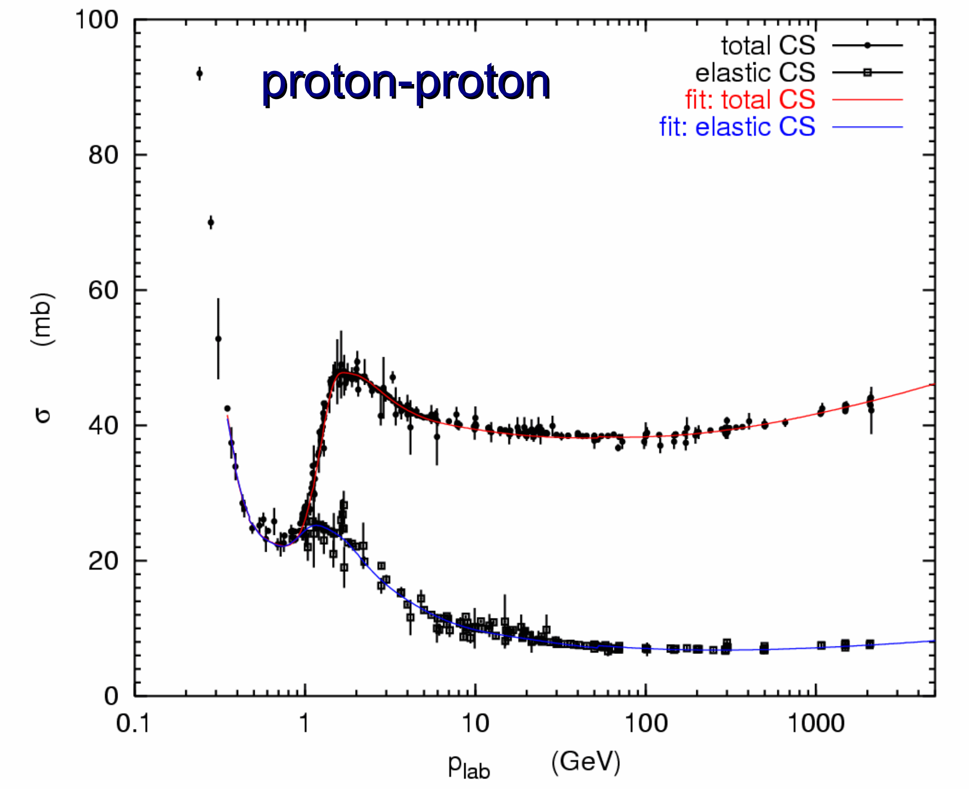
(ii) Theoretically sound basis of extrapolation

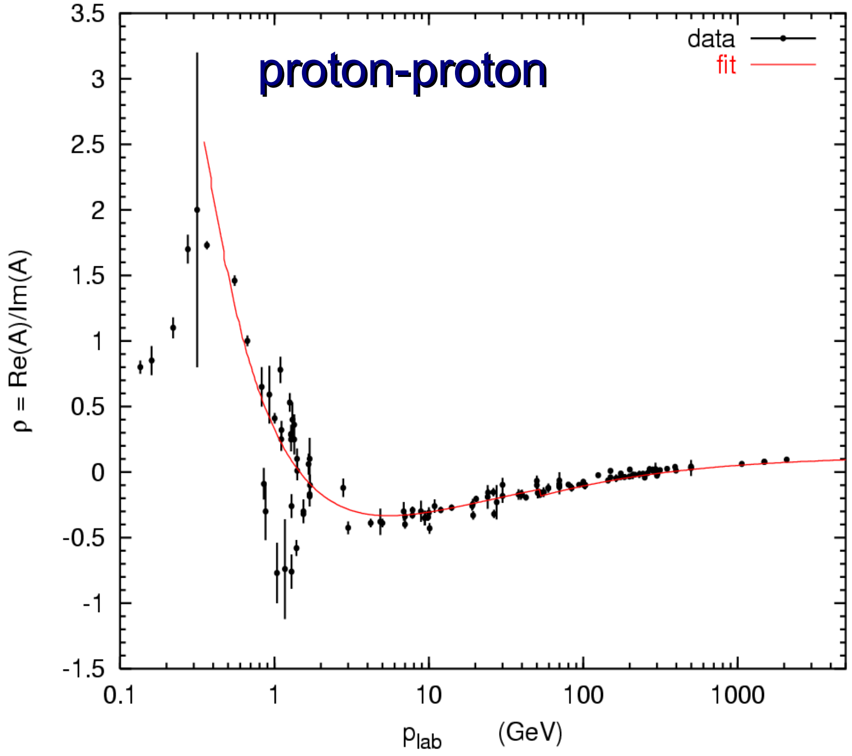
Cross section calculation (i)

Gribov-Glauber approximation

$$\sigma_{\text{inel}}^{(\text{pA})} \approx \pi \int db^2 \left(1 - \exp\left[-\sigma_{\text{tot}}^{(\text{pp})} T_A(b)\right]\right)$$







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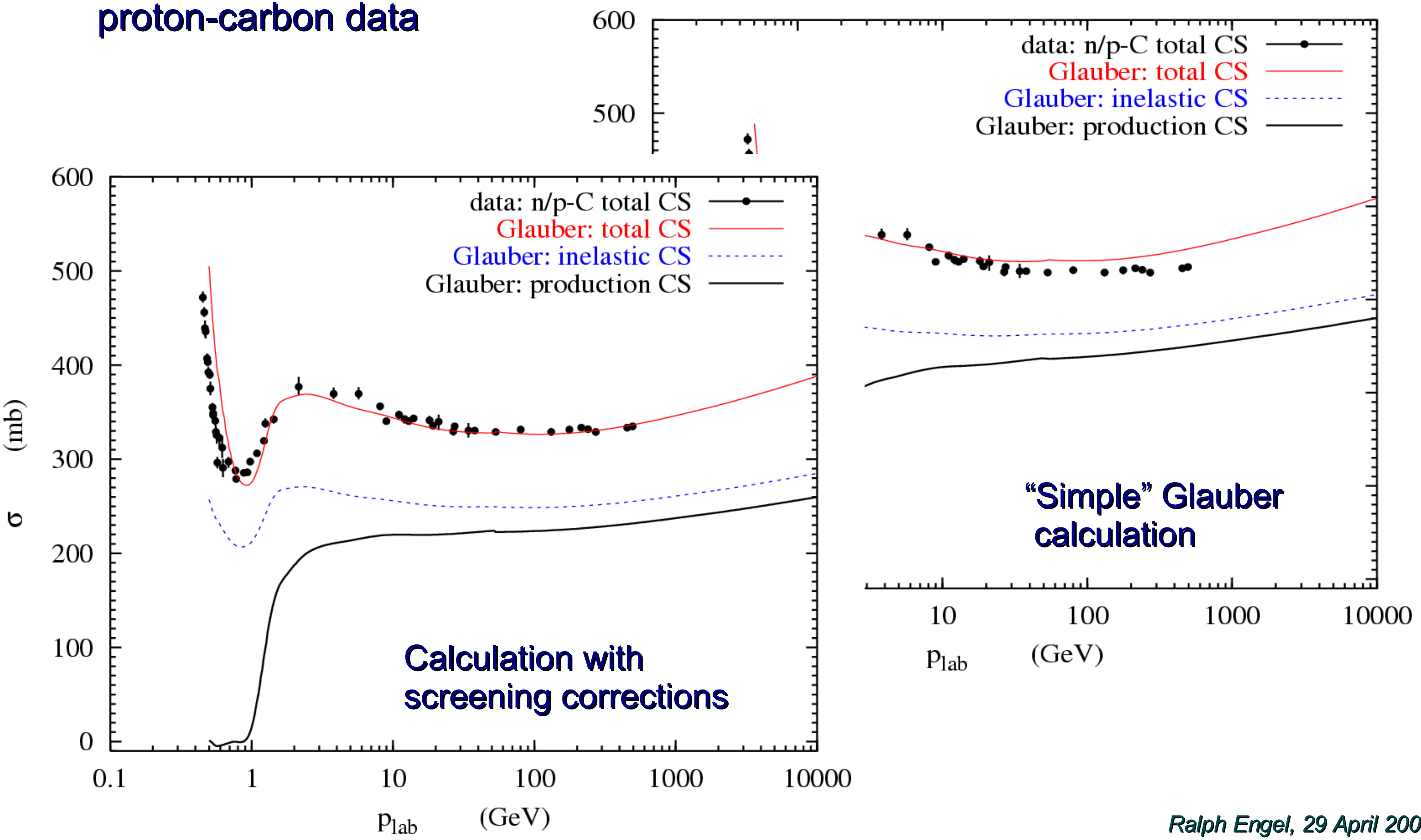
Cross section calculation (ii)

Reliability test:
proton-carbon data



Calculation with screening corrections

“Simple” Glauber calculation

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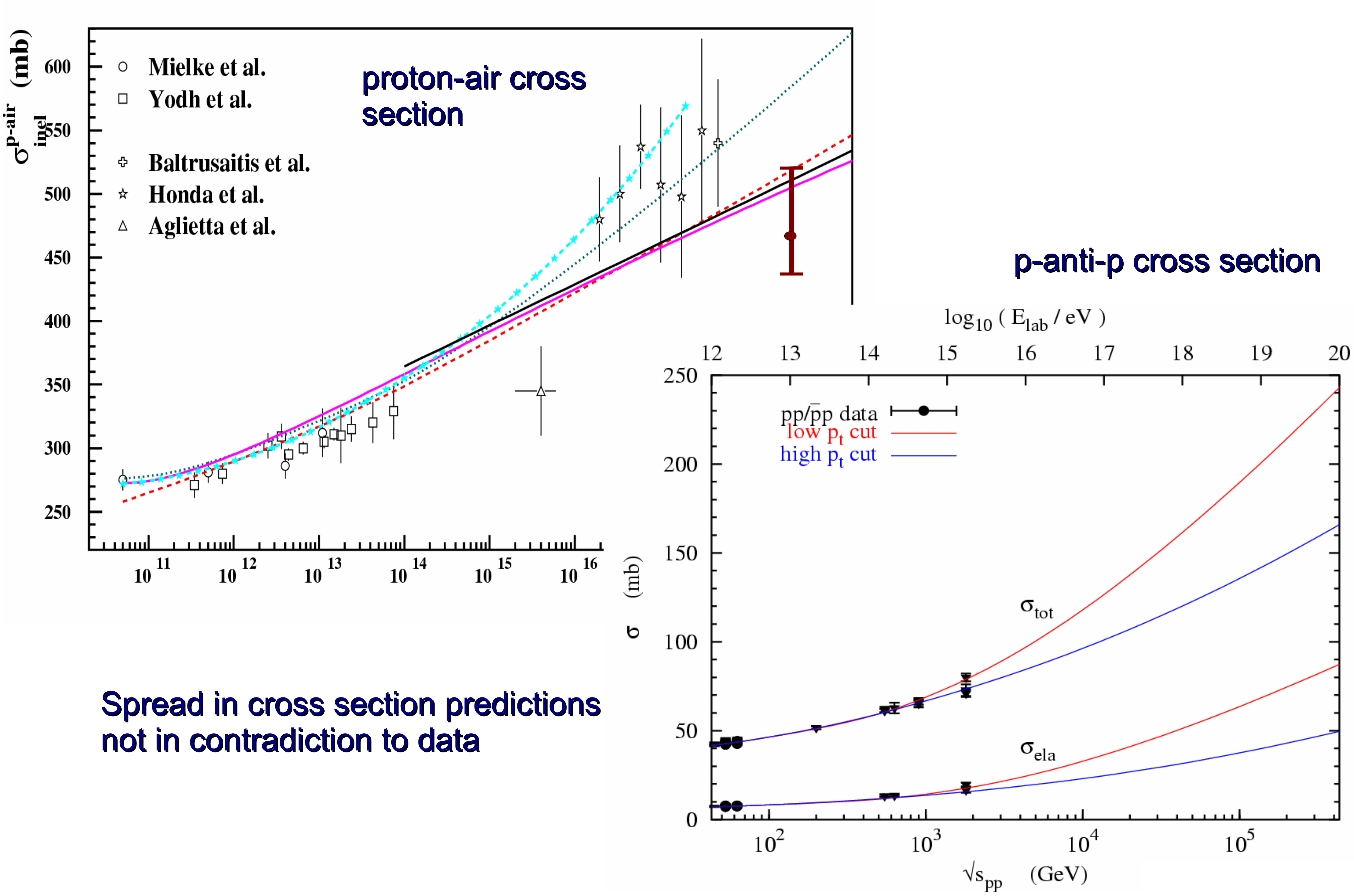
Cross section calculation (iii)

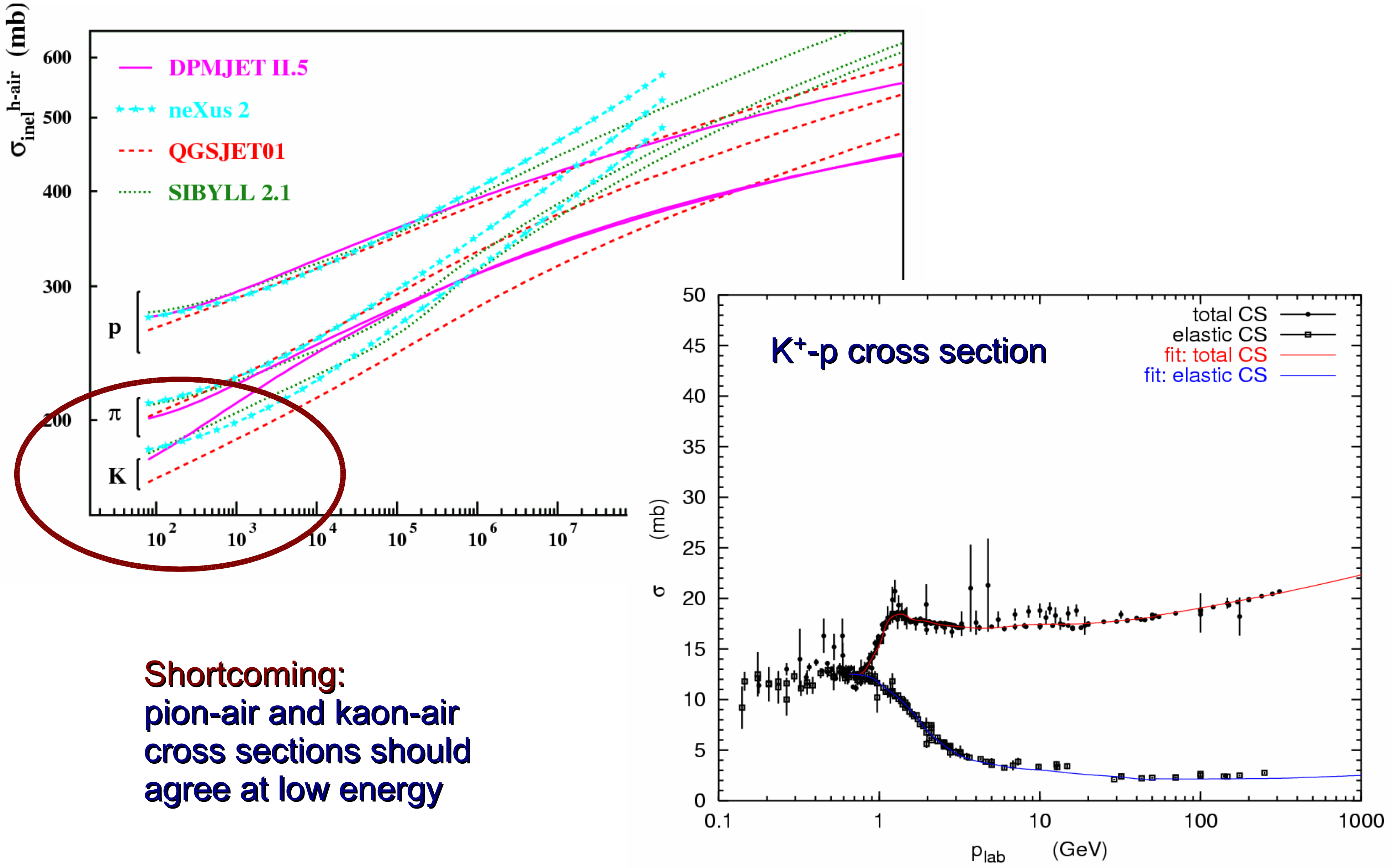


proton-air cross section

p-anti-p cross section

Spread in cross section predictions not in contradiction to data

Cross section calculation (iv)



Shortcoming:
pion-air and kaon-air cross sections should agree at low energy

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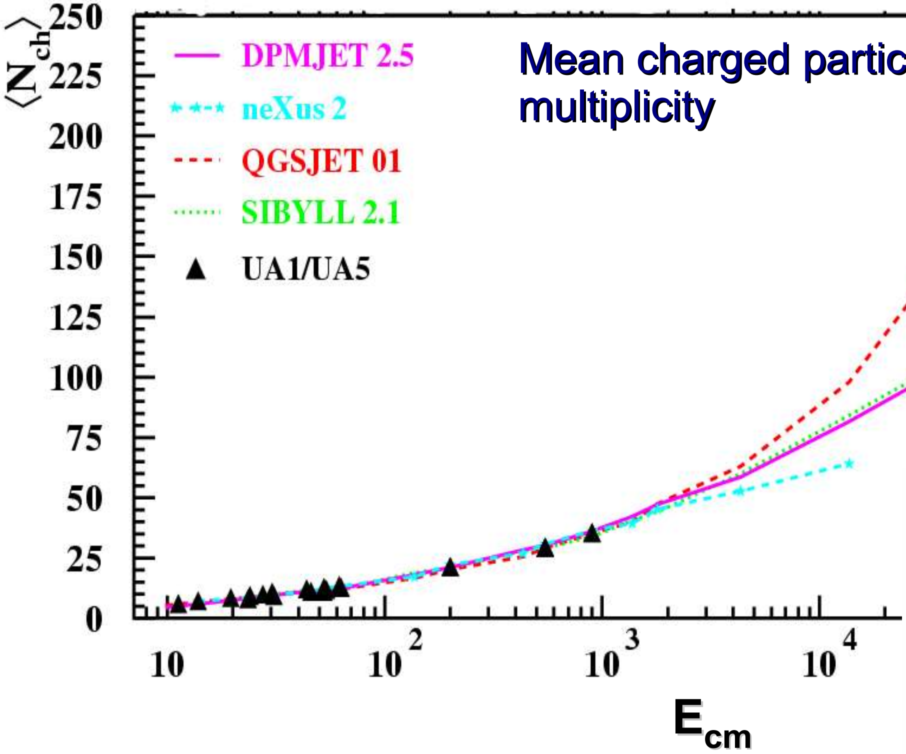
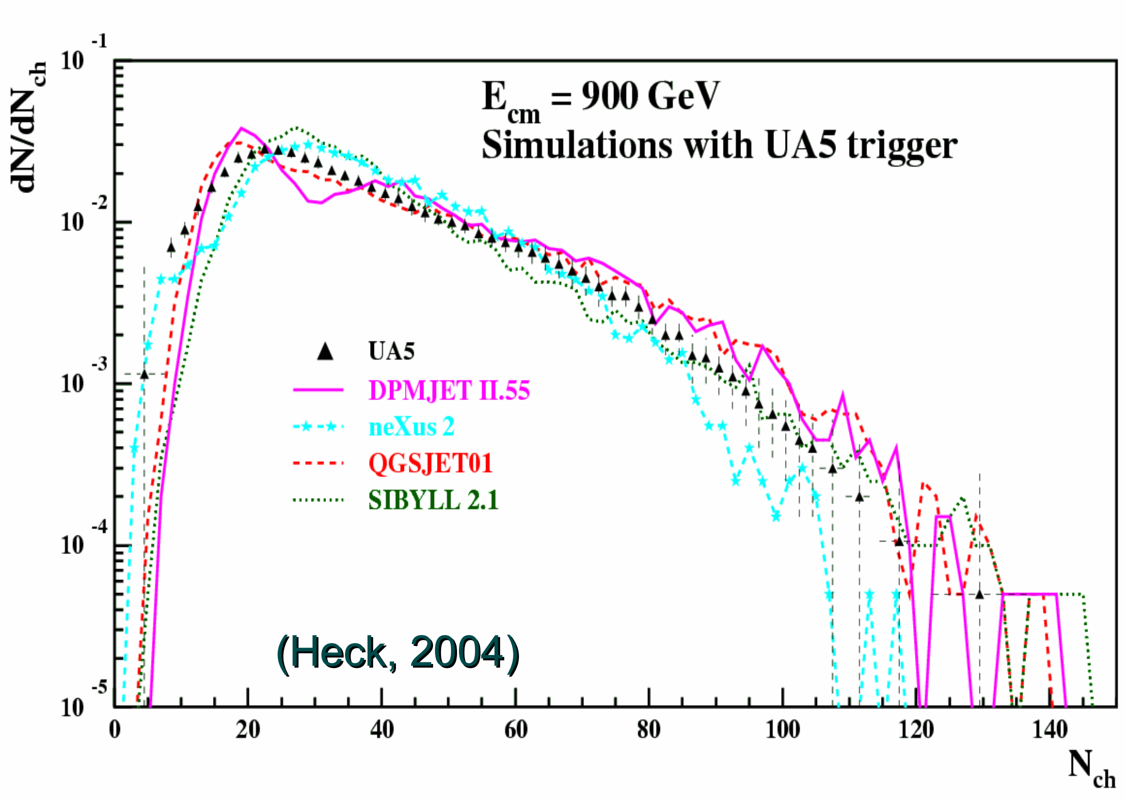
Secondary particle multiplicity



Mean charged particle multiplicity

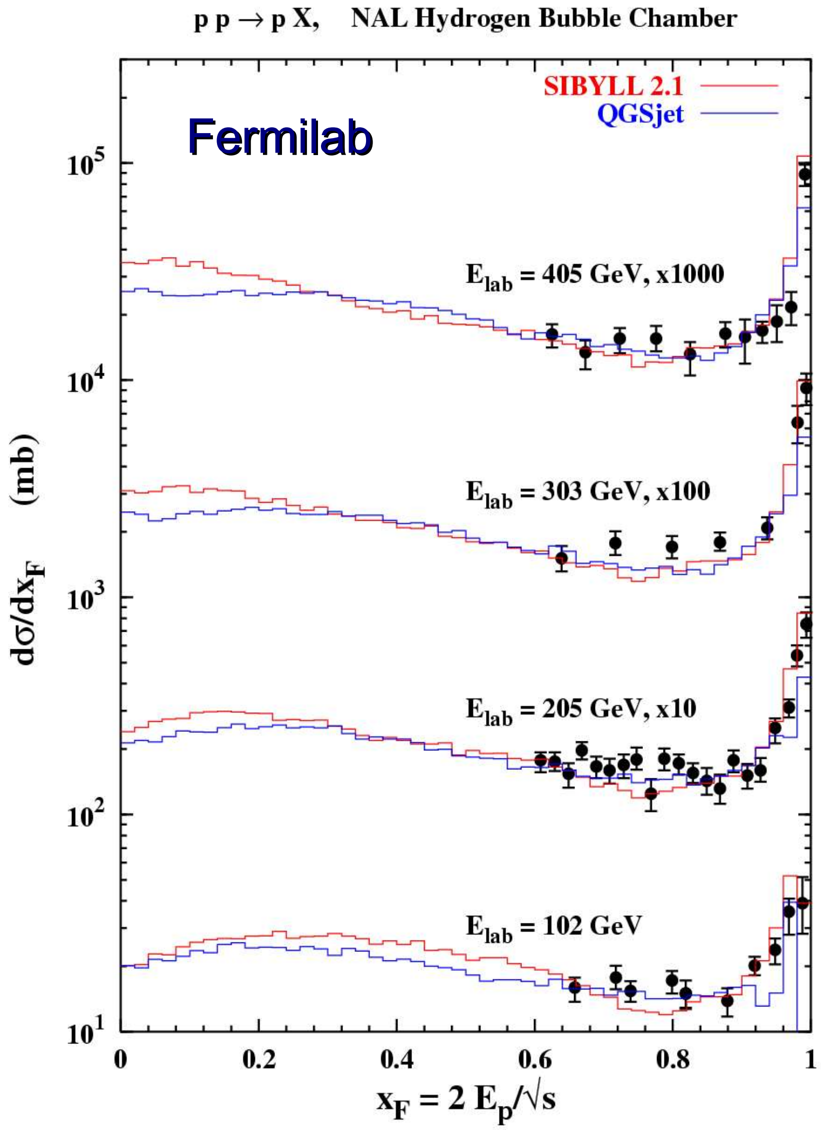
Proton-antiproton at CERN SPS & Tevatron

Multiplicity distribution



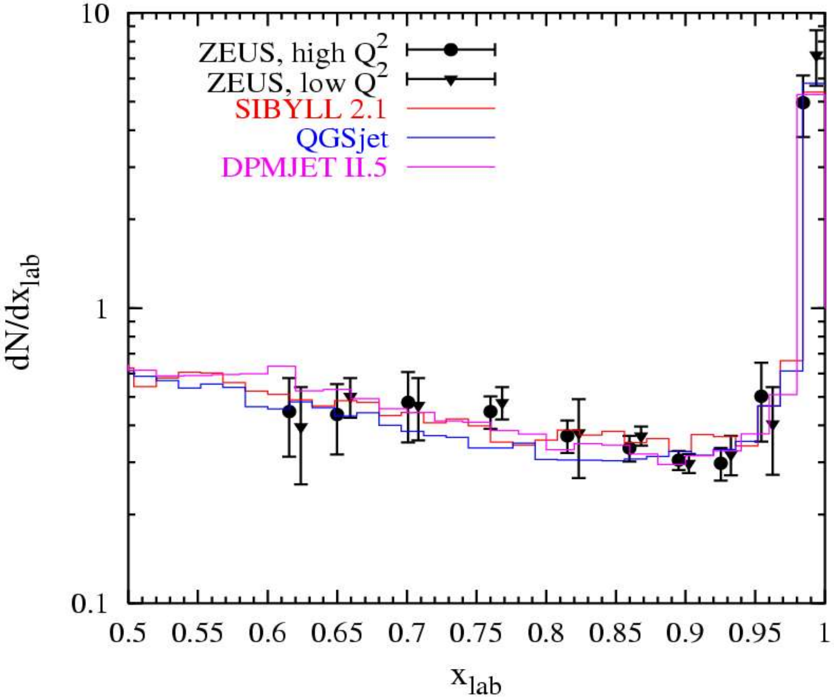
(Heck, 2004)

Leading particle production (i)



E_{lab} ~ $4x10^{11}$ eV

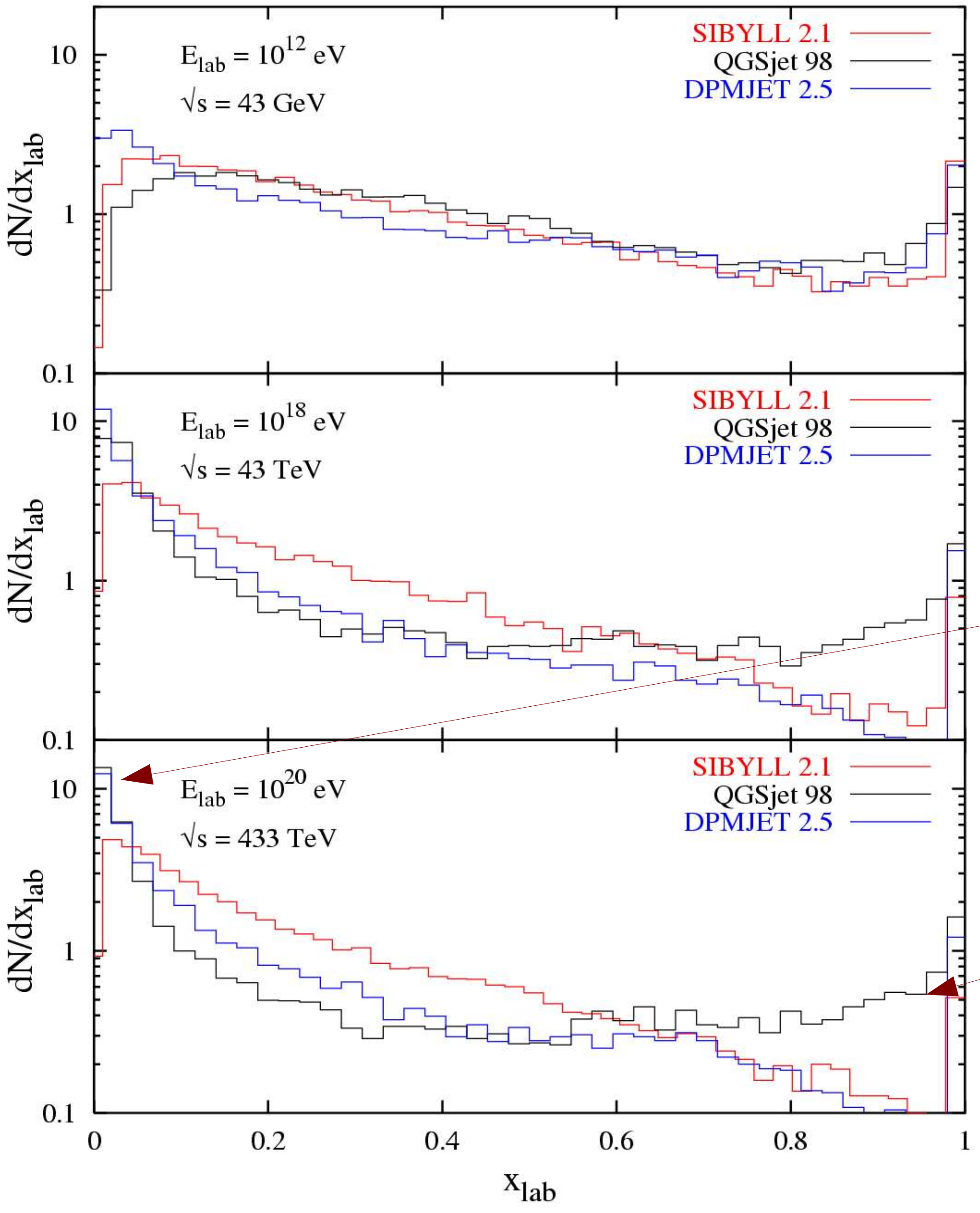
HERA: *p-$\gamma \rightarrow p/n$ X*



E_{lab} ~ $2x10^{13}$ eV

No indications of significant scaling violation of leading particle distributions

Leading particle production (ii)



Distribution of momentum fraction of leading baryon

p-air → p/n X

Extremely inelastic events

Nearly elastic events

Overview of model assumptions

	DPMJET 2.55 / 3	neXus	QGSJET01	SIBYLL 2.1
Parton densities	GRV94 / GRV98	fit	outdated	GRV98
Profile function	Gaussian	Gaussian	Gaussian	Dipole FF
Saturation	energy-dependent pt cutoff			energy-dep. pt cutoff
	triple pomeron graphs	triple pomeron graphs		
Cross section extraploation	black disk	grey disk	grey disk	black disk
Others	string fusion nuclear fragmentation, evaporation	consistent amplitude		consistent nuclear diffraction
low energy mult.	good	good	too high	too low

Do the different model predictions exhaust the uncertainty range?

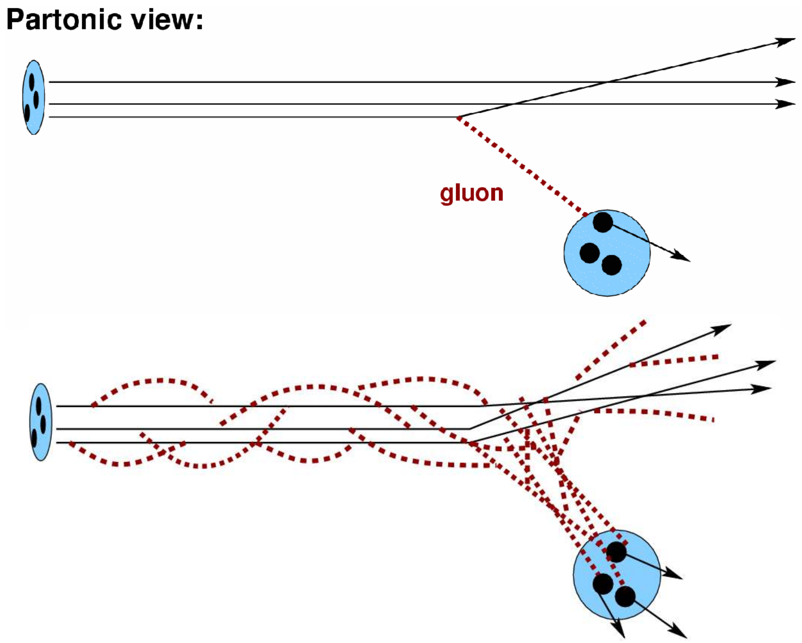
There can be only one answer: NO

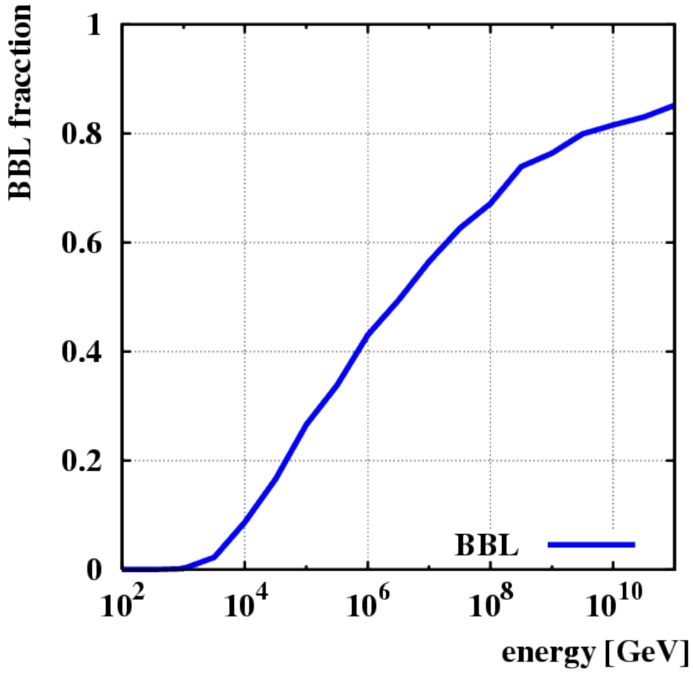
One counter-example sufficient ...

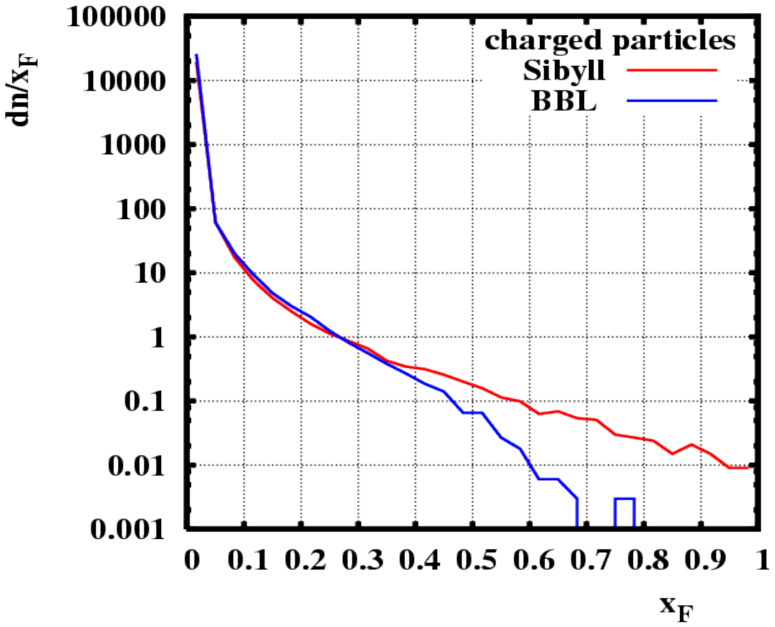
Parton density saturation (RHIC)?

Low energy:
pronounced leading
particle effect

High energy & central collision:
black disk limit,
no leading particles!!!

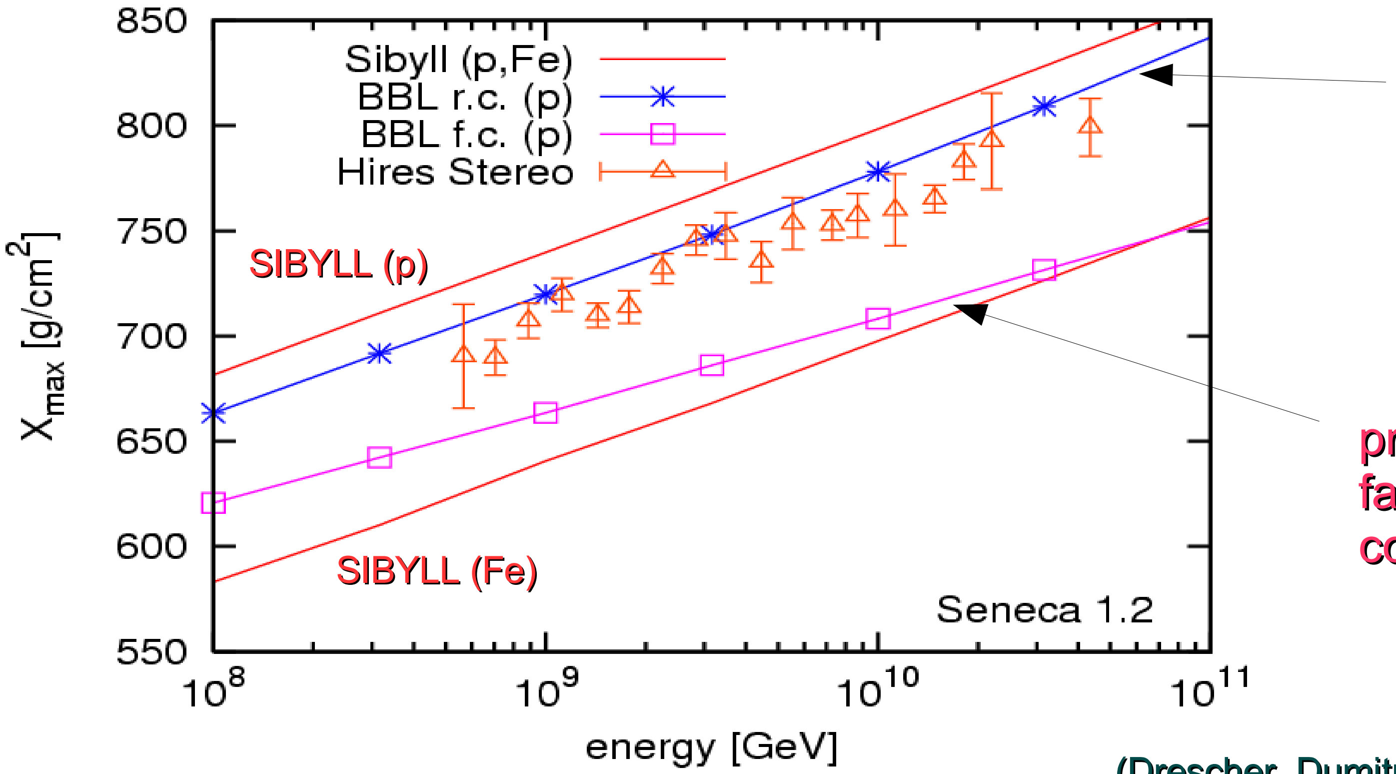






Model by Drescher, Dumitru, Strikman, hep-ph/0408073

Parton density saturation scenarios



proton showers:
moderate growth of
gluon density

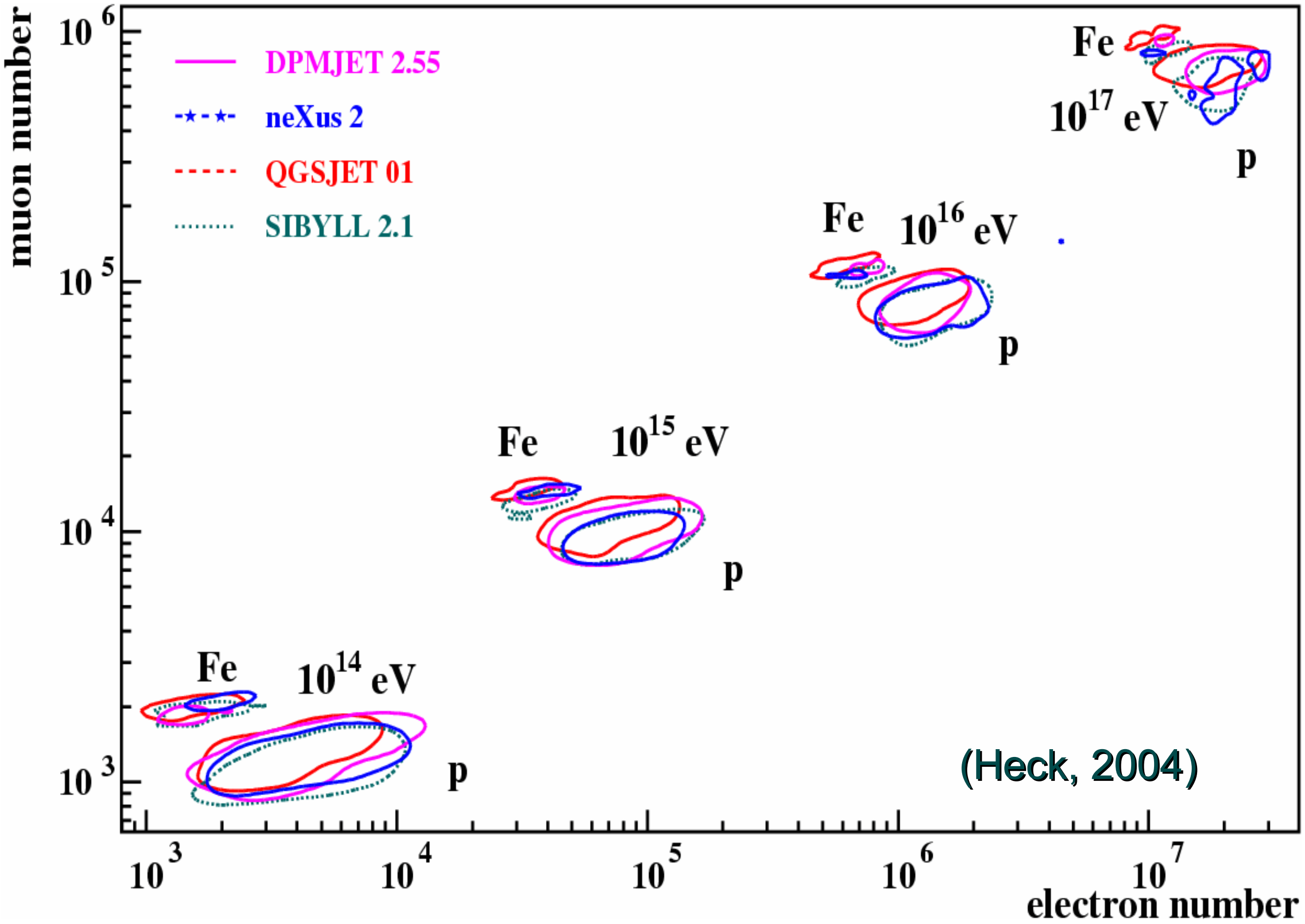
proton showers::
fast growth of gluon density:
contradiction to data

(Drescher, Dumitru,
Strikman, hep-ph/0408073)

Leading particle distribution:
air shower predictions very sensitive,
extreme case: protons might look like iron!

Implications on energy / composition reconstruction

Energy/composition: N_e-N_μ correlation



(Heck, 2004)

Curves: full width at half maximum

Further development and tuning of models will reduce spread somewhat

No significant reduction of uncertainty expected without new accelerator data

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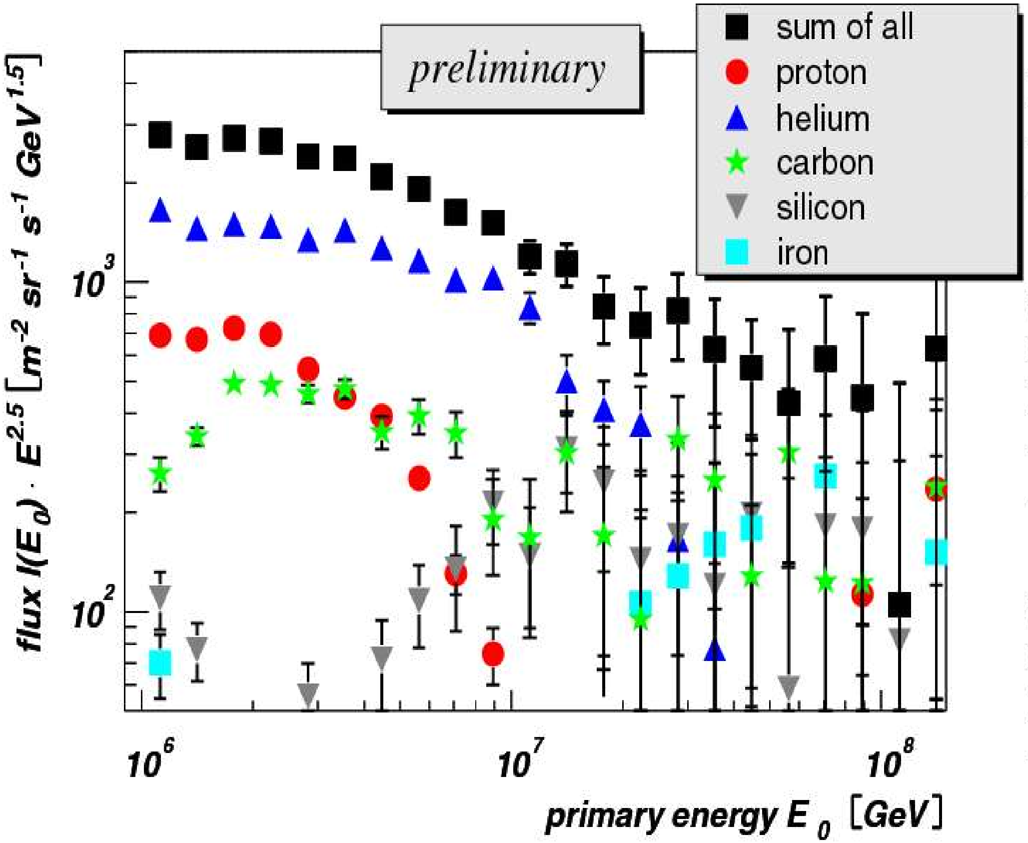
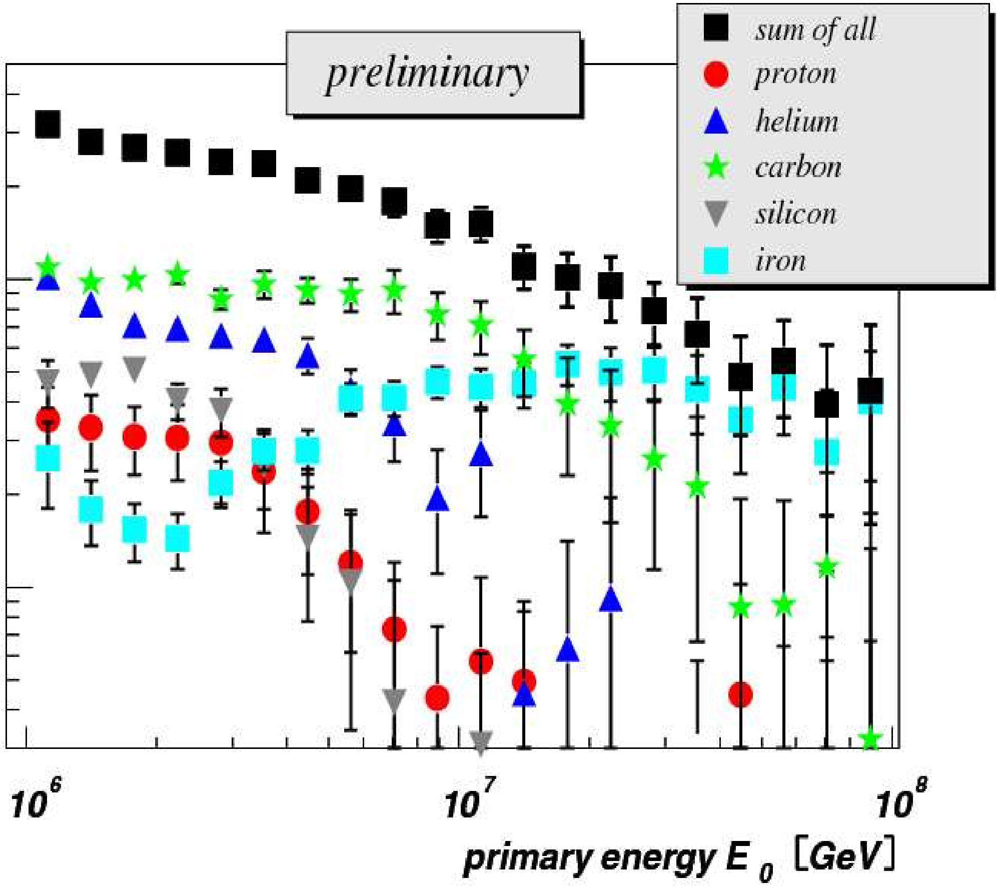
Example: KASCADE composition



QGSJET 01

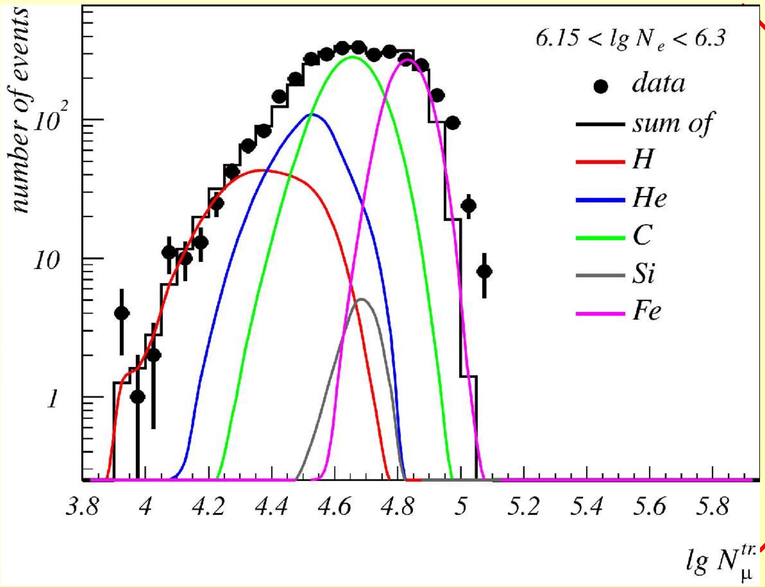


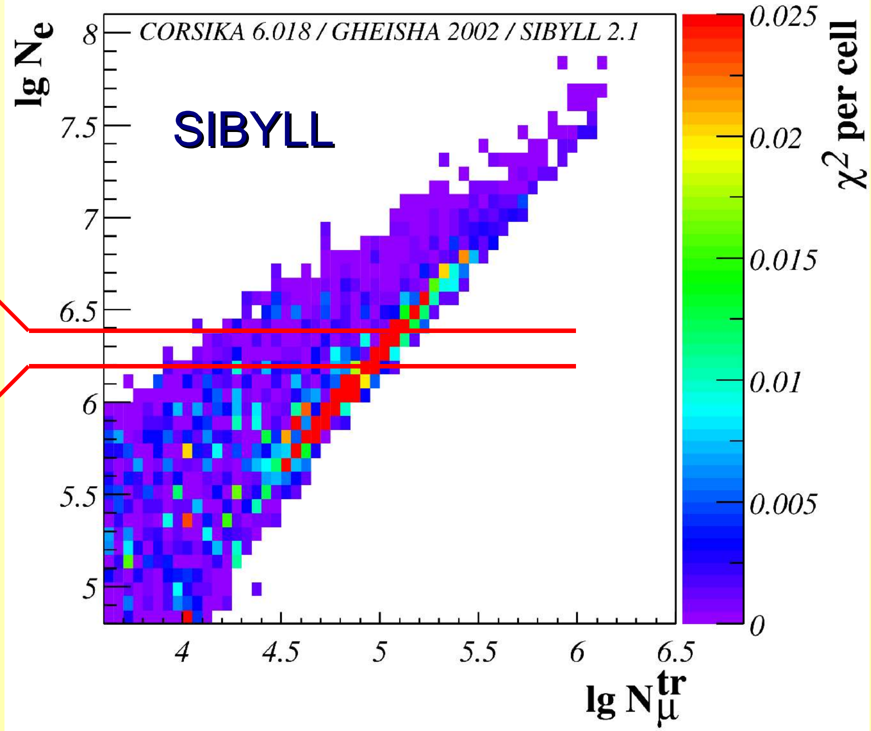
SIBYLL 2.1

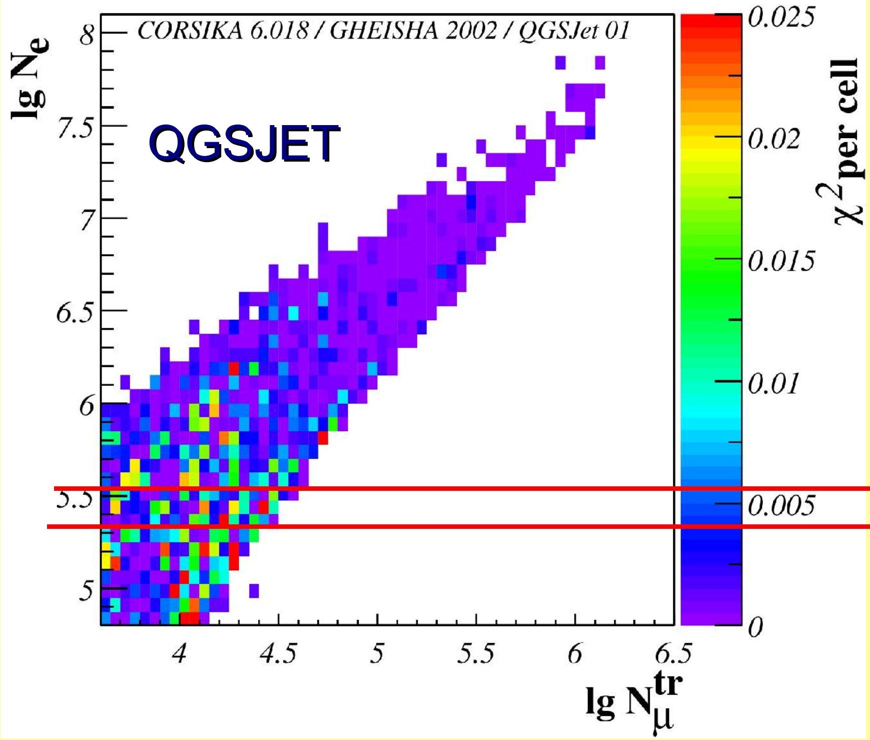
KASCADE: high resolution/precision data, analysis limited by model uncertainties

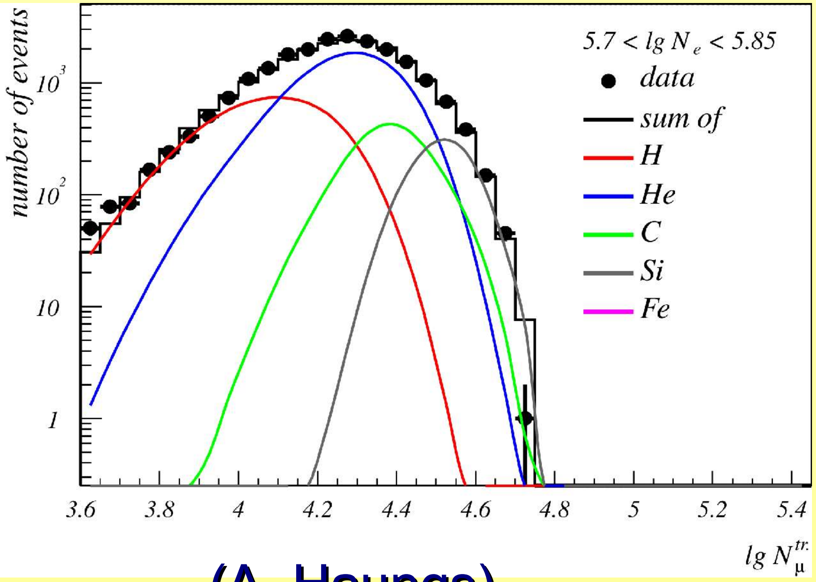
Energy spectra KASCADE

quality of description of data



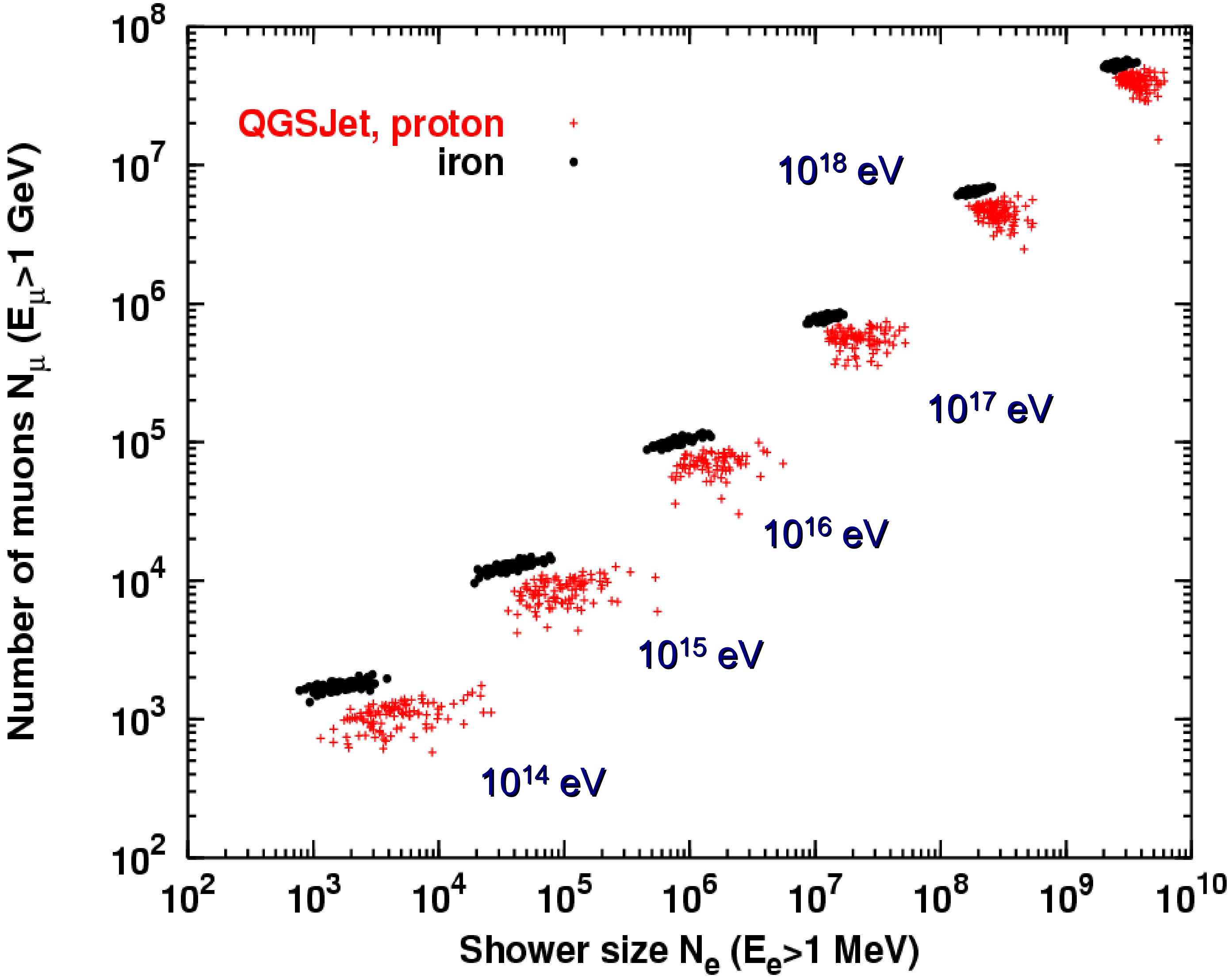






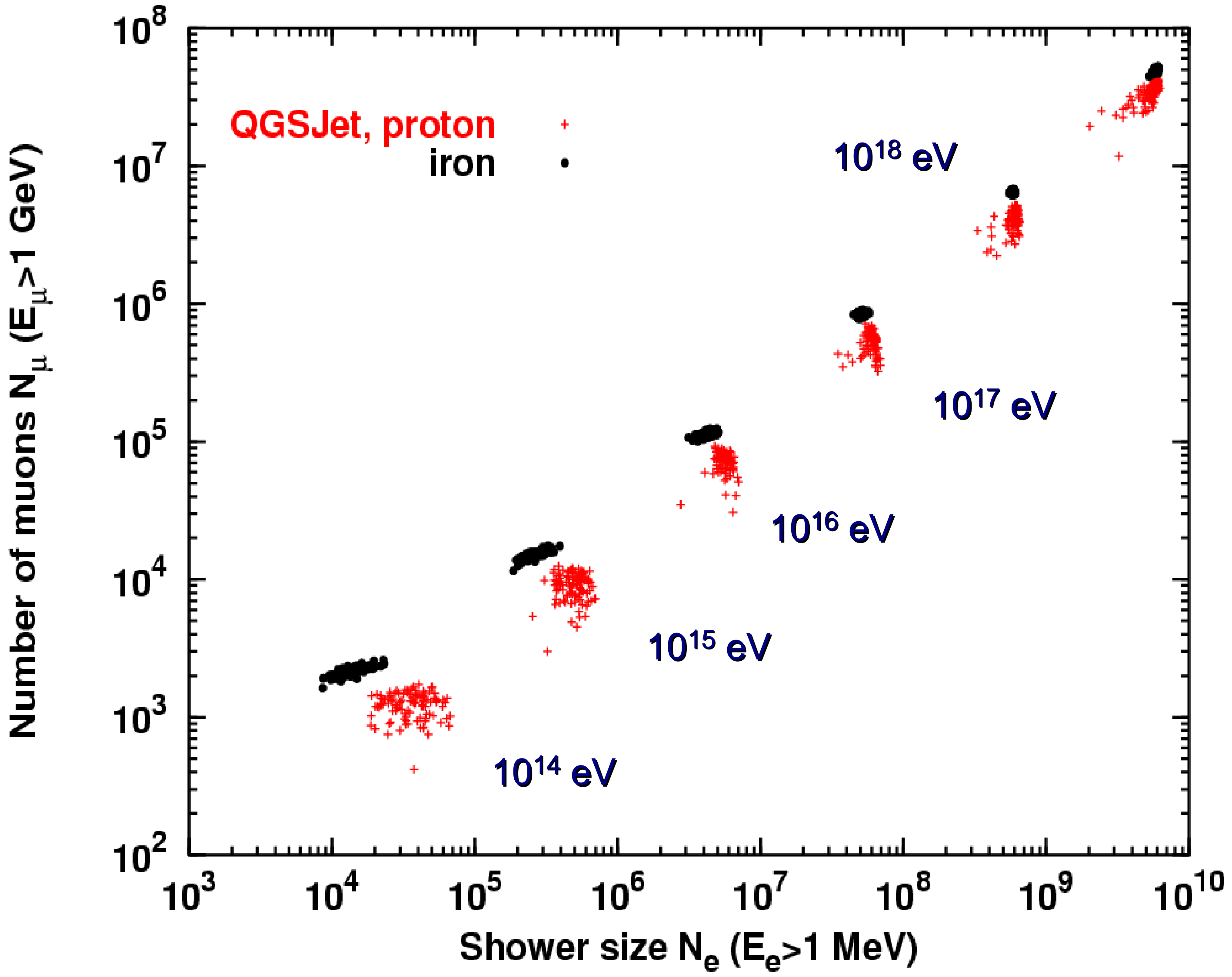
(A. Haungs)

Detector design optimization (i)



- Sea level
- Low-energy muons
- Single model

Detector design optimization (ii)



- Mountain altitude
- Low-energy muons
- Single model

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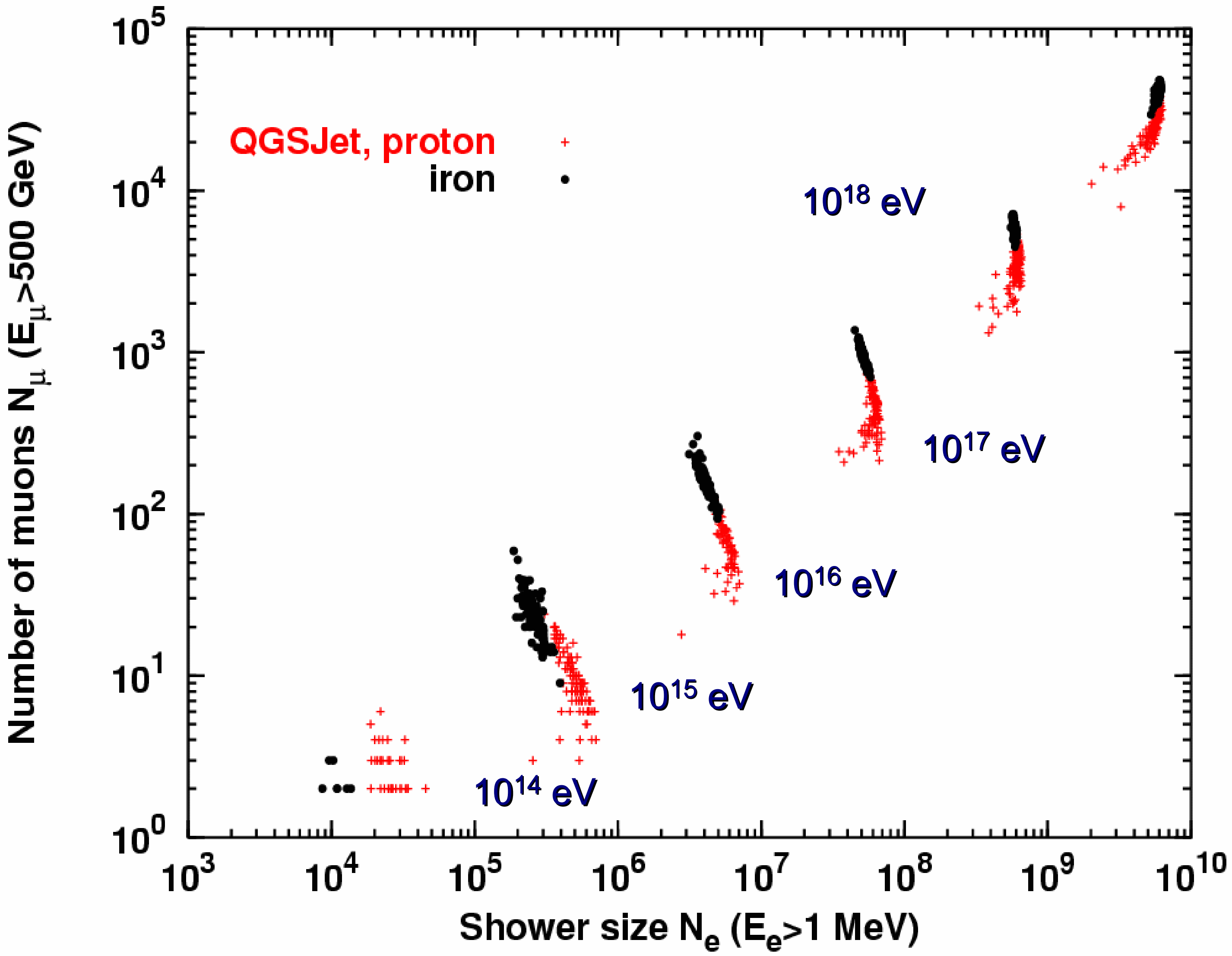
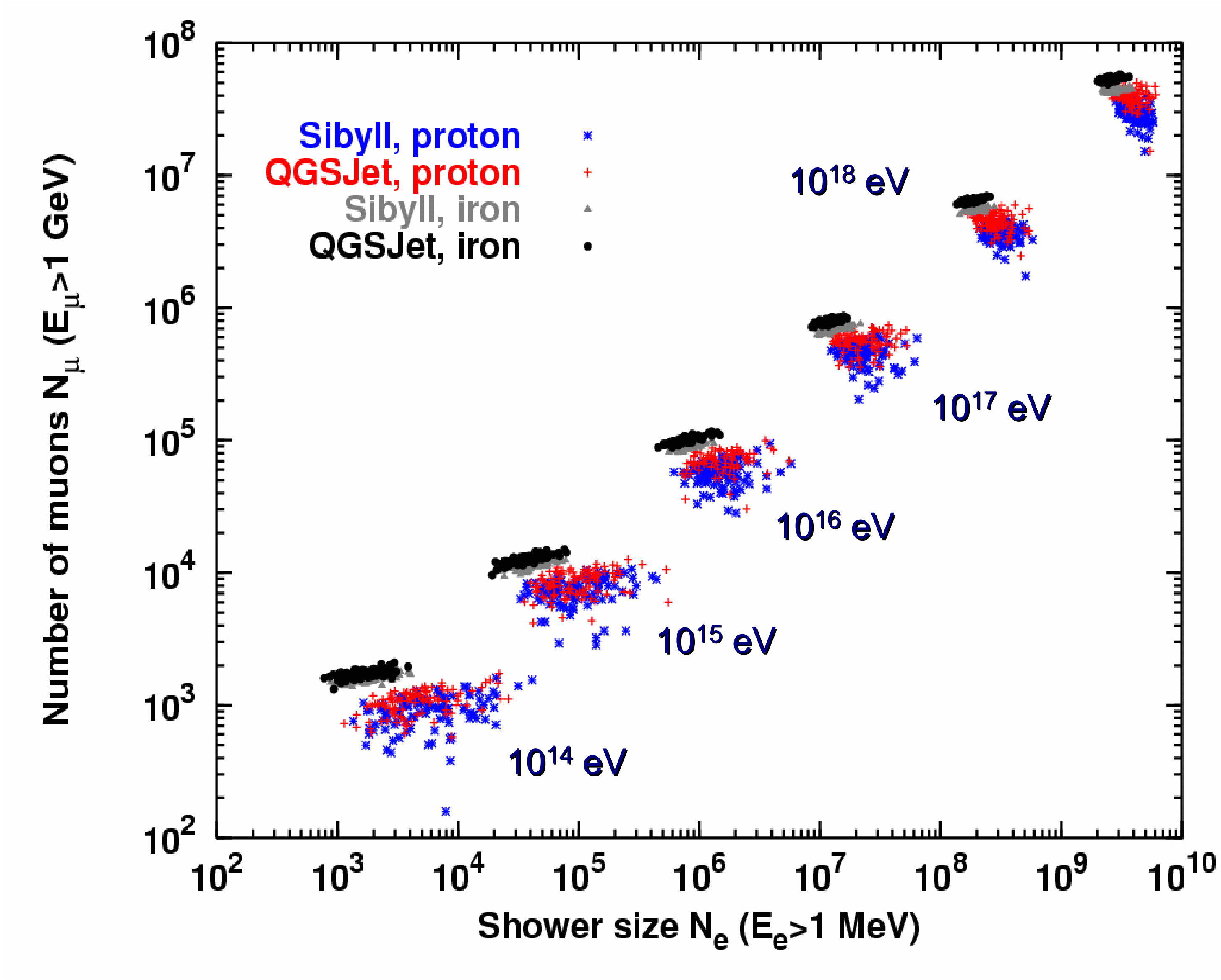
Detector design optimization (iii)



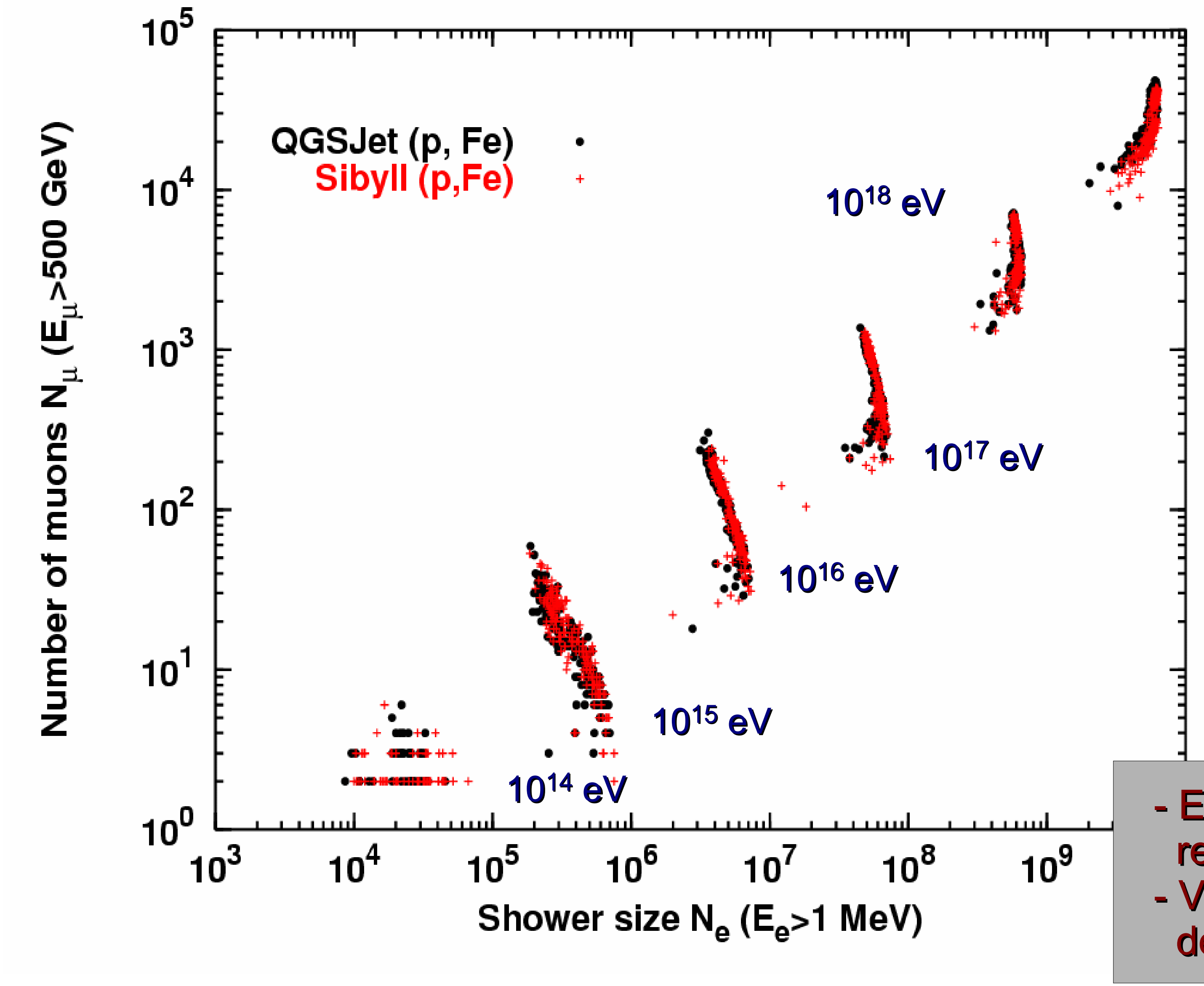
- Mountain altitude
- High-energy muons
- Single model

Detector design optimization (vi)



- Sea level
- Low-energy muons
- Several models

Detector design optimization (v)



- Mountain altitude
- Low-energy muons
- Several models

- Excellent energy resolution ~10%
- Virtually no model dependence

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Fluorescence detector: energy (i)

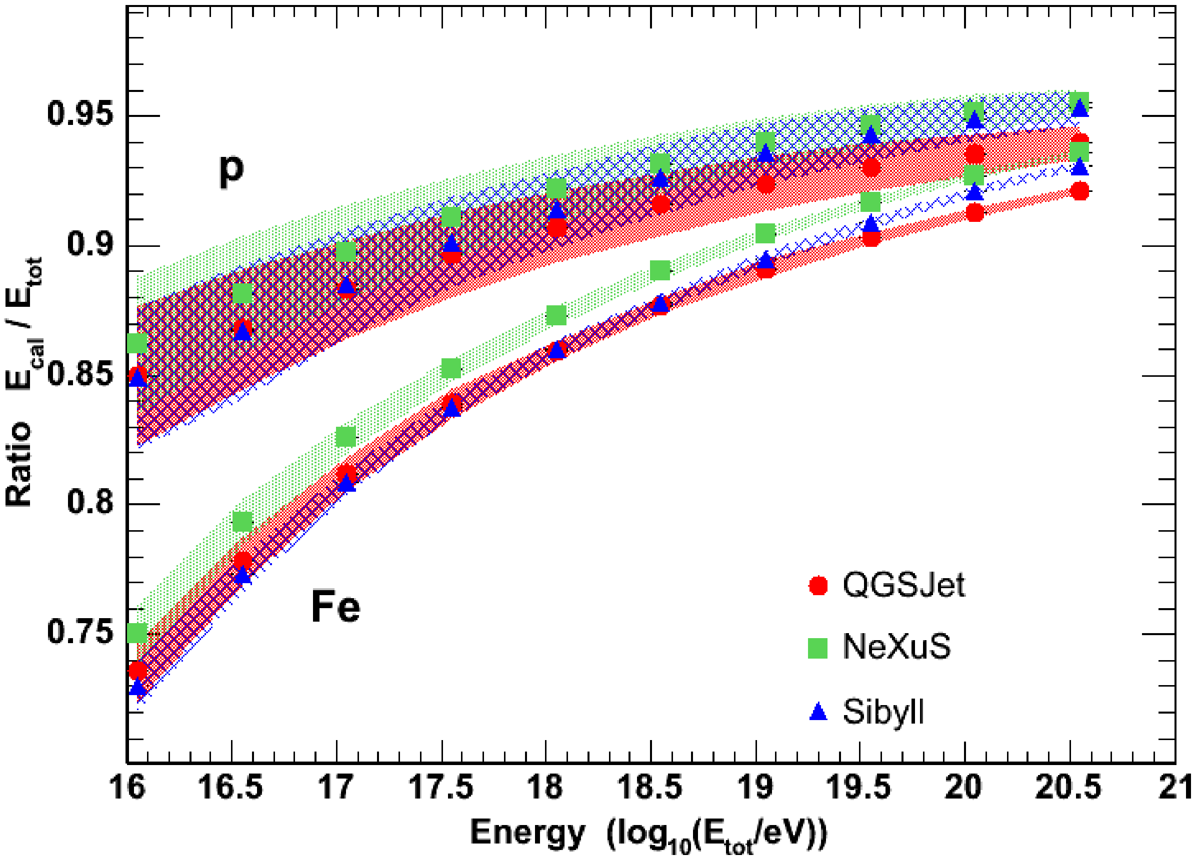
Simulation:

- Ecal: ionization deposit in atmosphere
- perfect shower profile measurement assumed

Fluorescence technique at low energy:

- visible energy correction strongly composition dependent
- best energy resolution ~15%

(Karlsruhe Auger Group: Unger, Pierog et al.)



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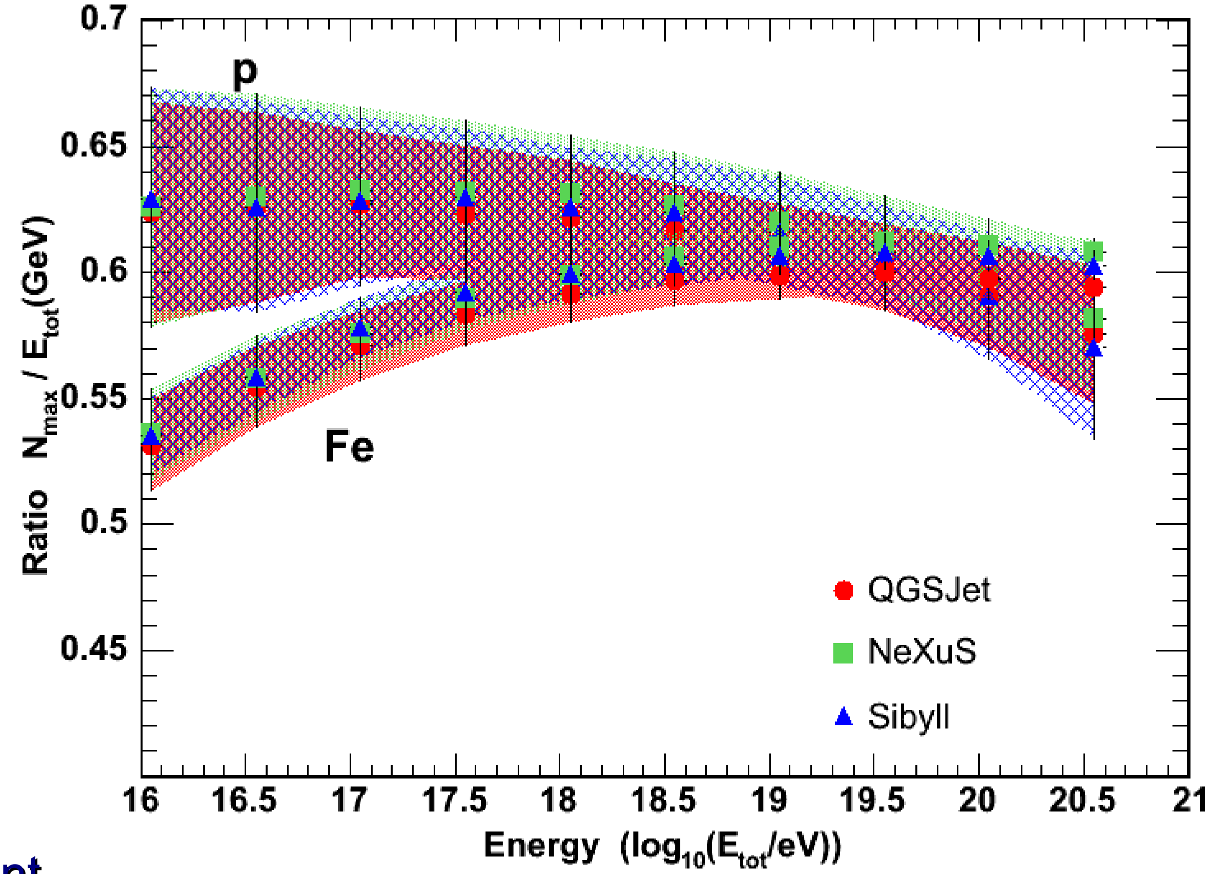
Fluorescence detector: energy (ii)

Simulation:

- Nmax: shower size at maximum (E>1 MeV)
- perfect shower profile measurement assumed

(Karlsruhe Auger Group: Unger, Pierog et al.)



Fluorescence technique at low energy:

- visible energy correction strongly composition dependent
- fluctuations for known composition stronger
- best energy resolution ~20%

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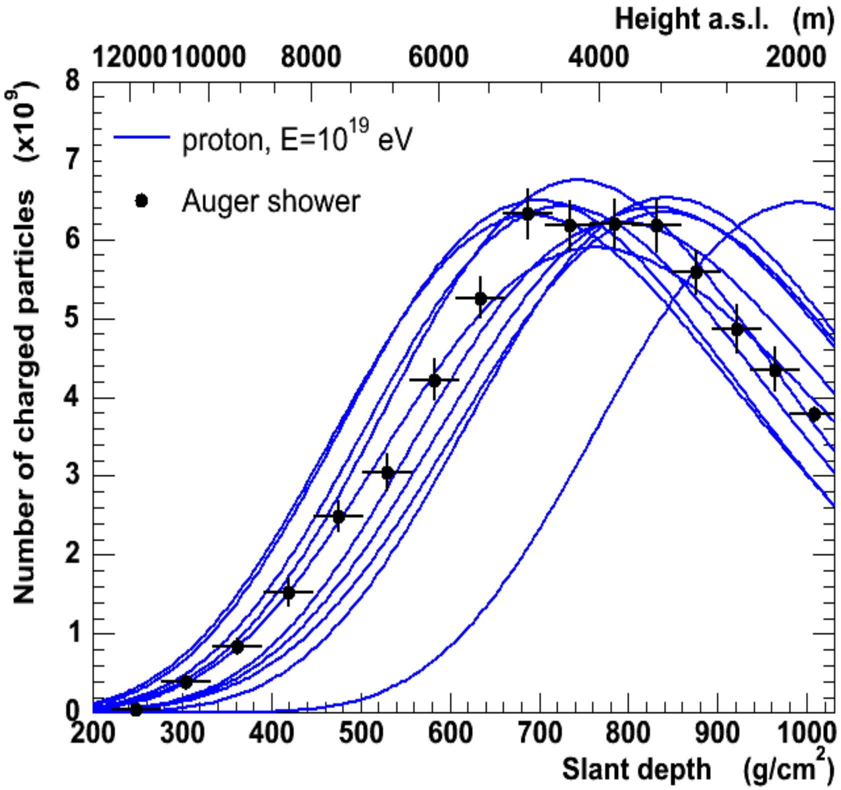
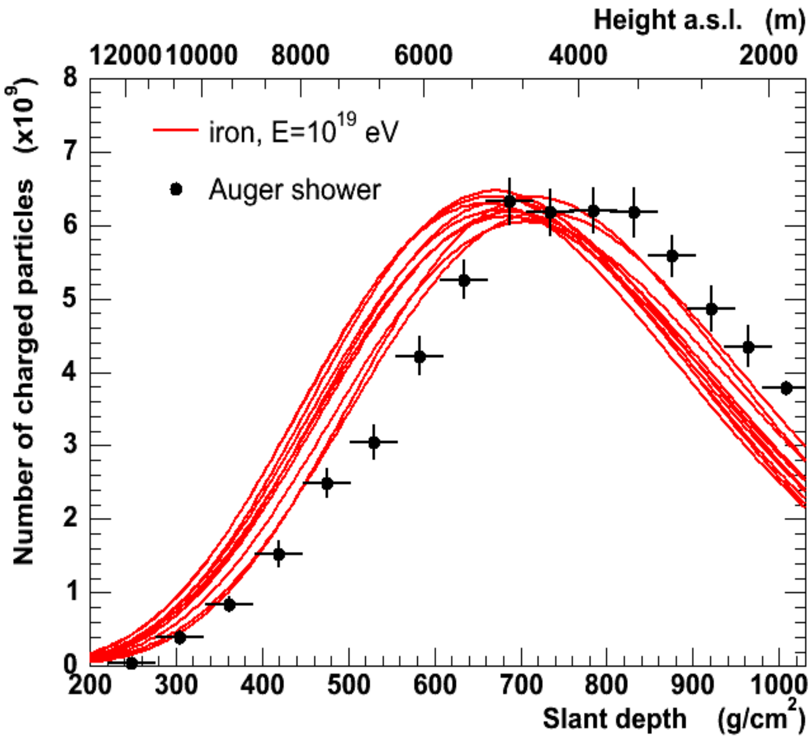
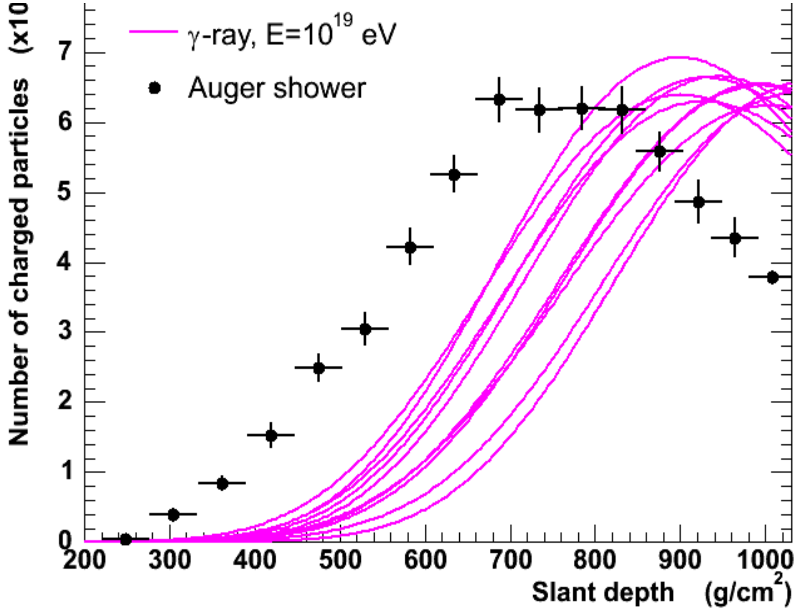
Fluorescence detector: composition (i)

Detailed MC simulation: 10 showers
zenith angle 35°, QGSJET







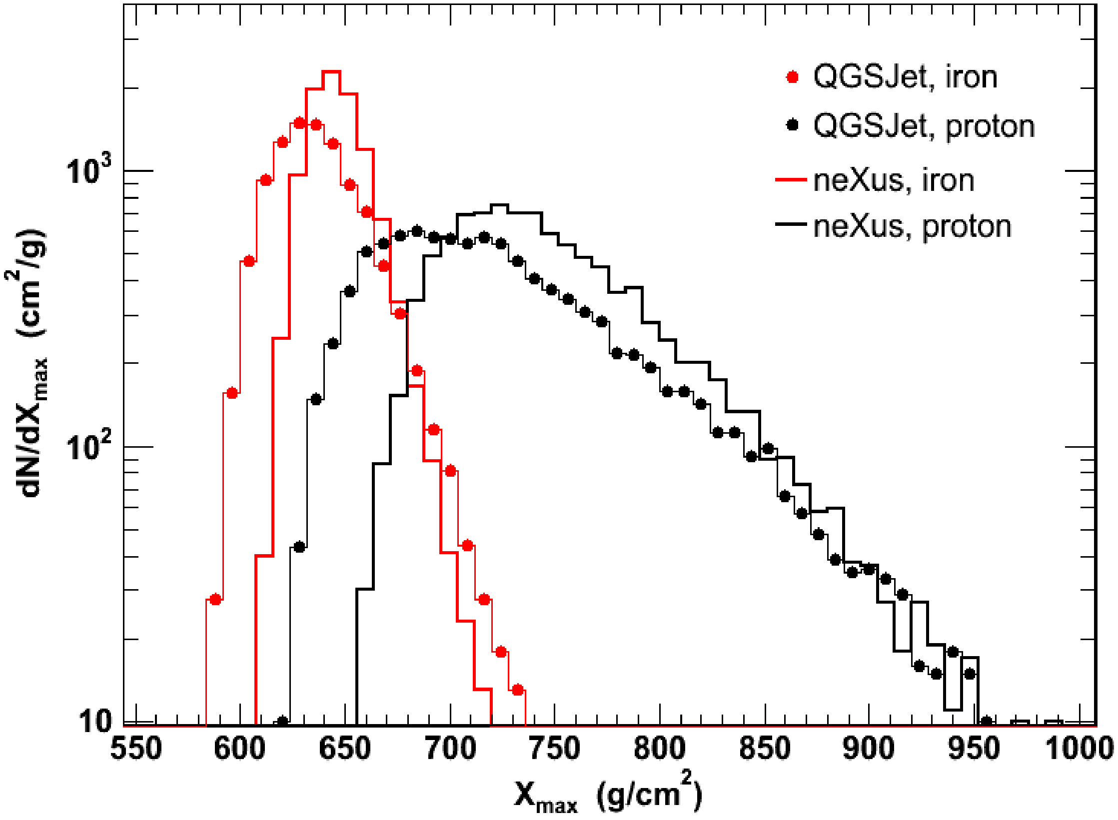
Fluctuations of shower profile important

Fluorescence detector: composition (ii)

(Karlsruhe Auger Group: Unger, Pierog et al.)

Simulation:

- CONEX hybrid simulation code
- 10,000 showers for each component
- model: neXus
- E = 10^{18} eV



Expectation: similar problems and uncertainties as for N_e-N_μ correlation method

Conclusions & outlook

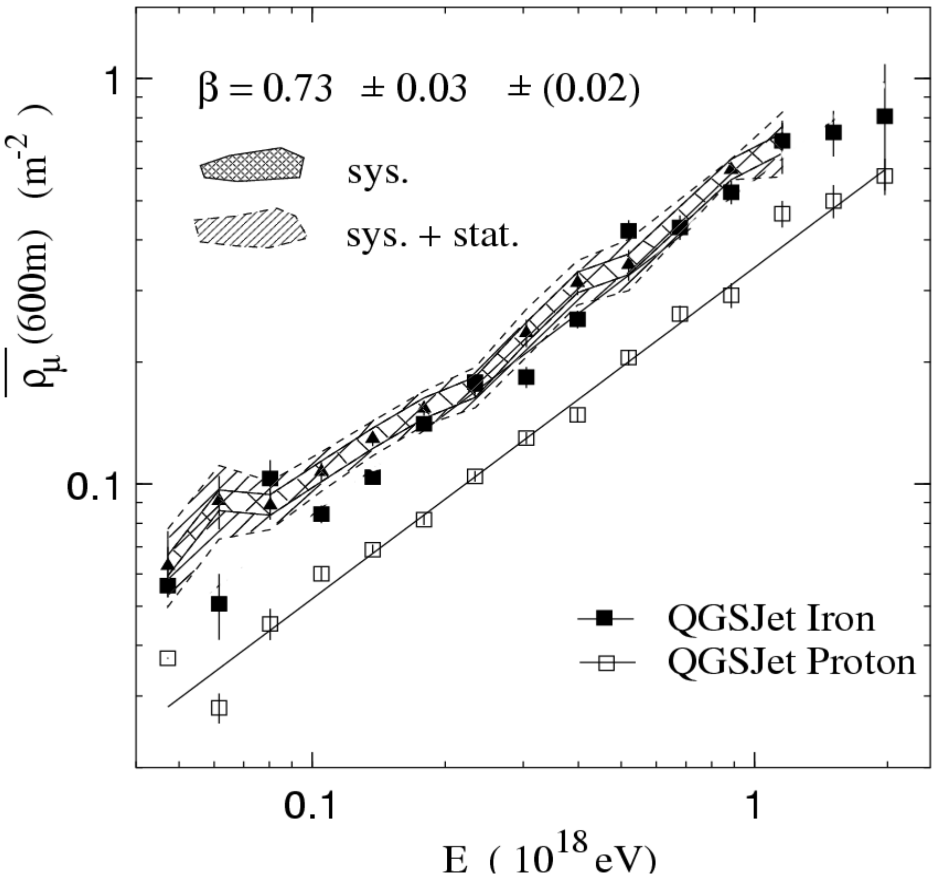
- **Model uncertainties in first approximation reasonable**
- **Uncertainties do not exhaust theoretically expected range**
- **No significant improvement without new accelerator data**

- **N_e-N_μ and fluorescence of comparable resolution if**
  - high altitude detector (600 – 700 g/cm^2)
  - low- and high-energy muons are measured simultaneously
- **Excellent energy resolution of IceTop/IceCube detector possible**

- **Model uncertainties seem impossible to estimate reliably**
- **Need multi-component / hybrid detectors for checking model uncertainties** (calorimetry, electrons, muons, X_{max})

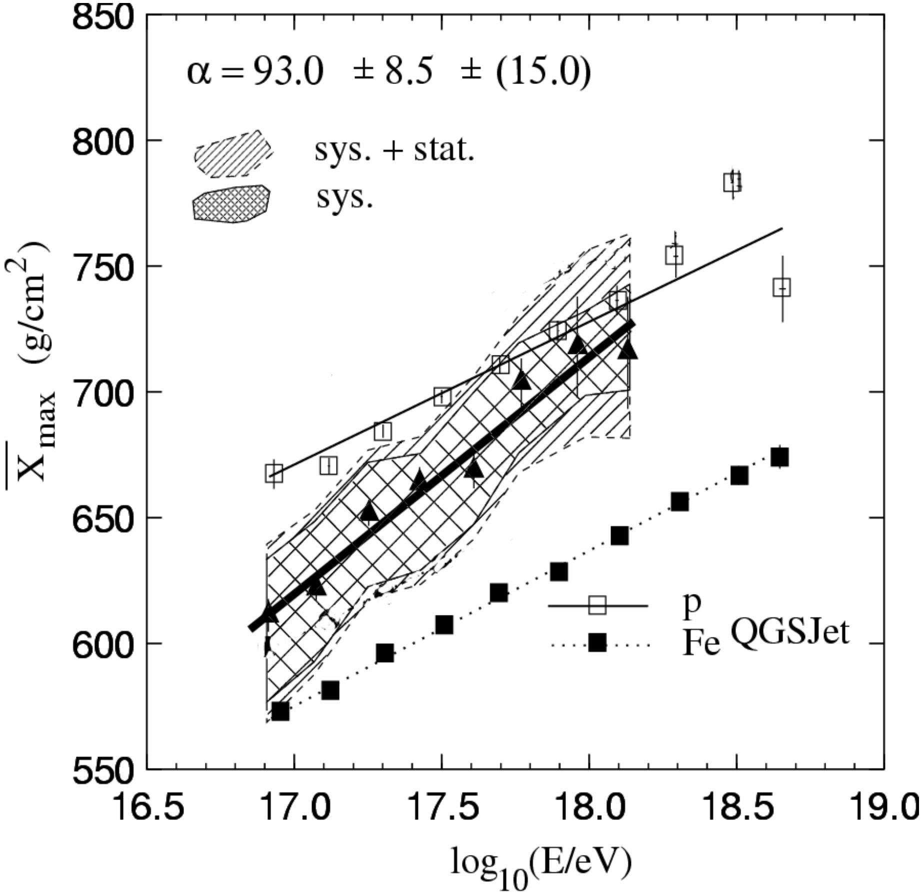
Example: HiRes-MIA measurement

MIA: muon density at 600m



Composition iron dominated,
no significant change with energy

HiRes: depth of shower maximum



Composition changes to proton
dominated one

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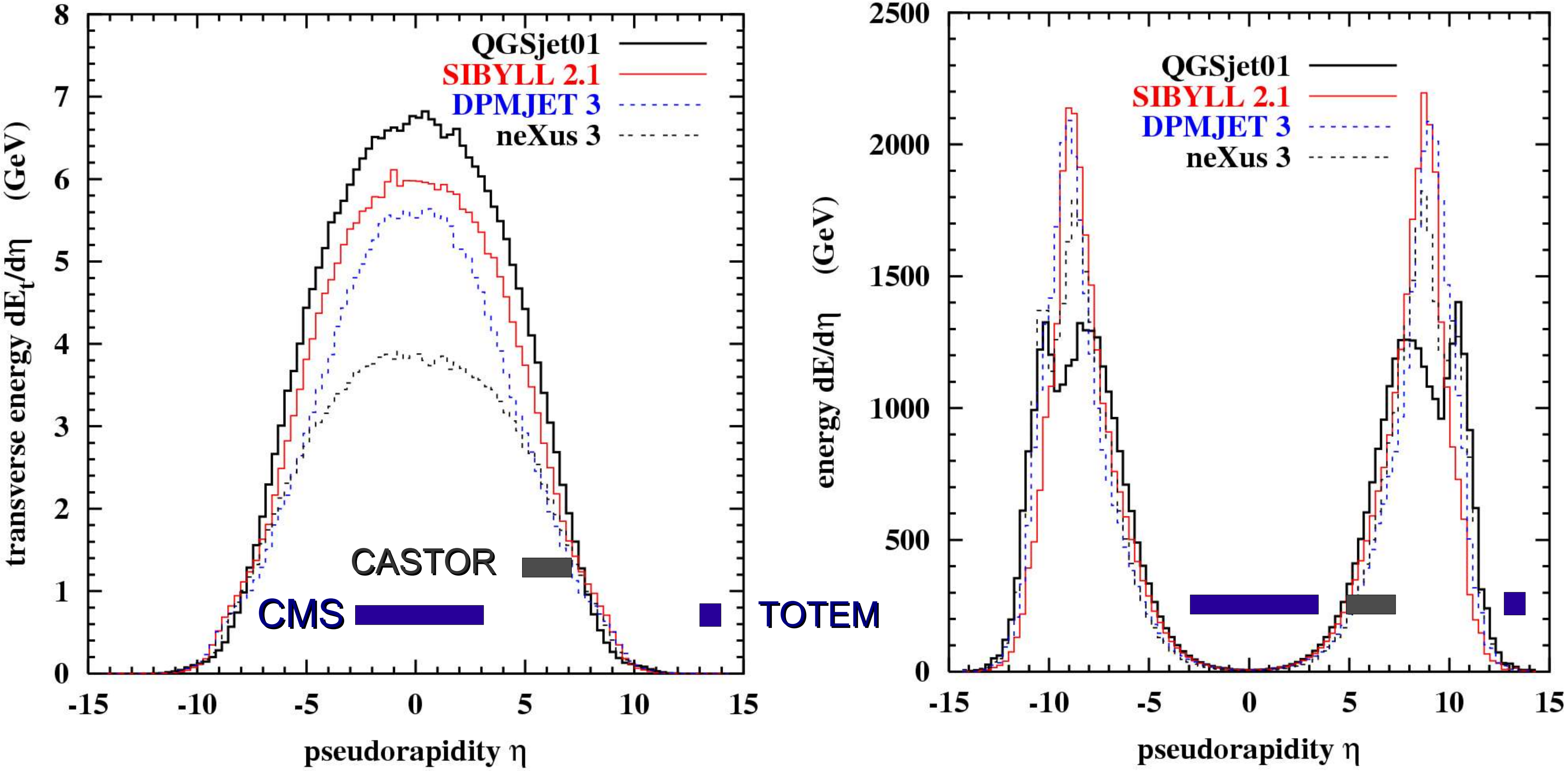
Discrimination potential of LHC (i)



- p-p collisions at LHC at √s = 14 TeV
- major experiments consider to do CR relevant measurements (for example, CMS / CASTOR / TOTEM)