Modelling of hadronic showers

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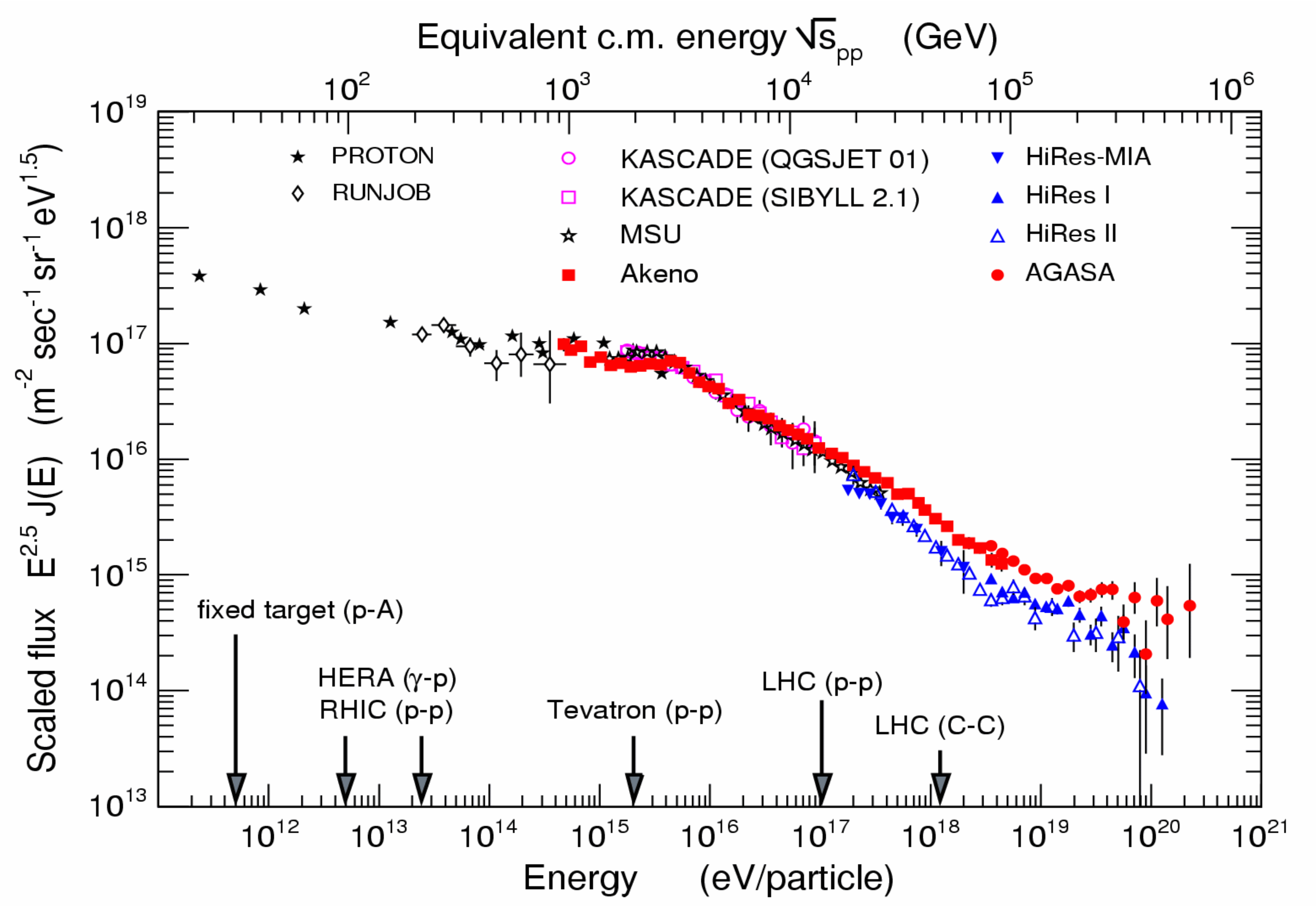
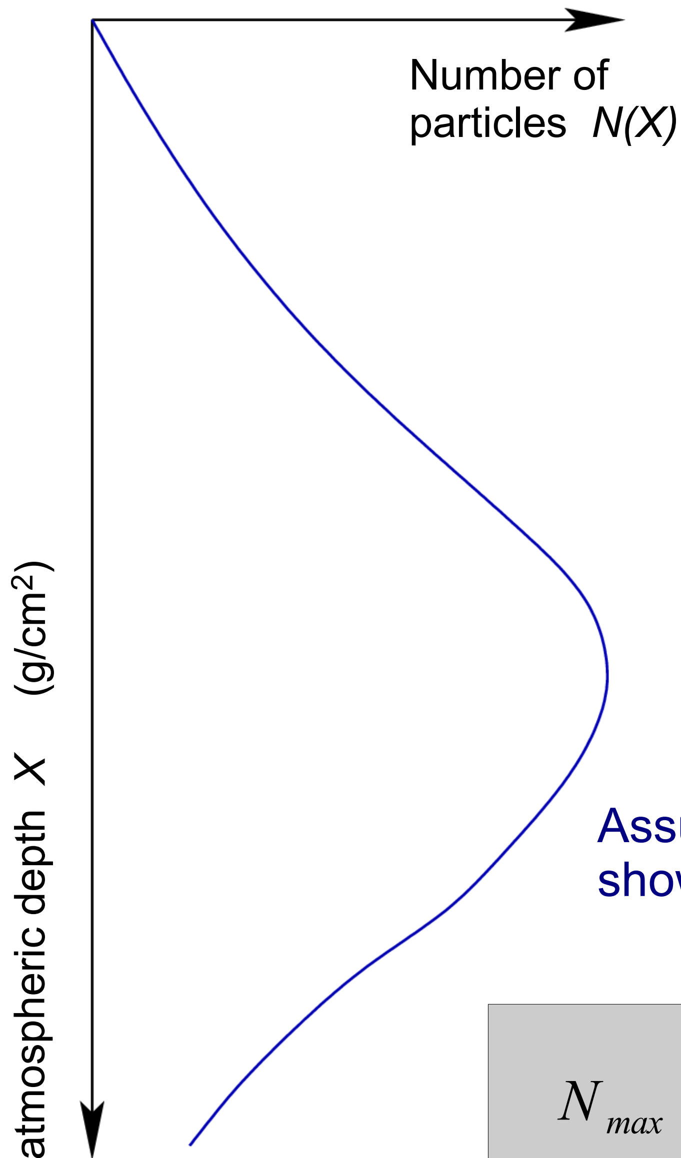
Comparison of energies

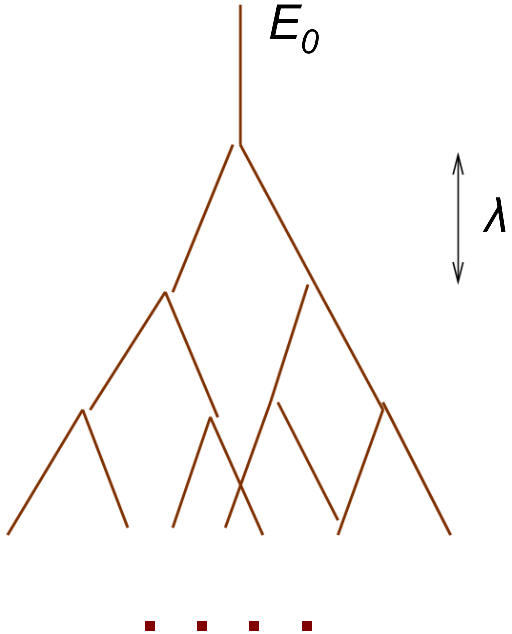


Outline

- Air showers and hadronic interactions
- Modelling of hadronic interactions
- Constraints from accelerator measurements
- Information from cosmic-ray data
- Possible interaction scenarios at ultra-high energy

Heitler's model of em. showers





Primary particle: photon

2^n particles after n interactions

$$n = X/\lambda$$

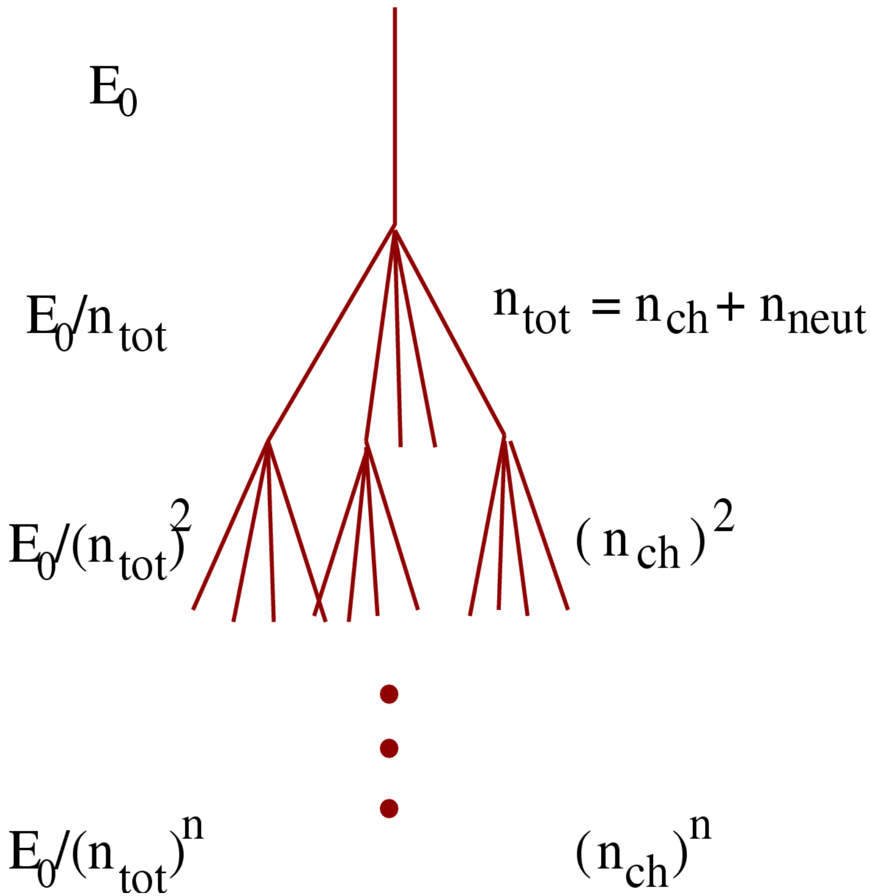
$$N(X) = 2^n = 2^{X/\lambda}$$

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

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



Primary particle: proton

π^0 decay immediately

Only charged pions initiate new hadronic cascades

Cascade ends with decay at energy E_{dec}

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

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

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

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 $E_n = E_0/A$

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

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

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

Toy model parameters

Hadronic interaction model

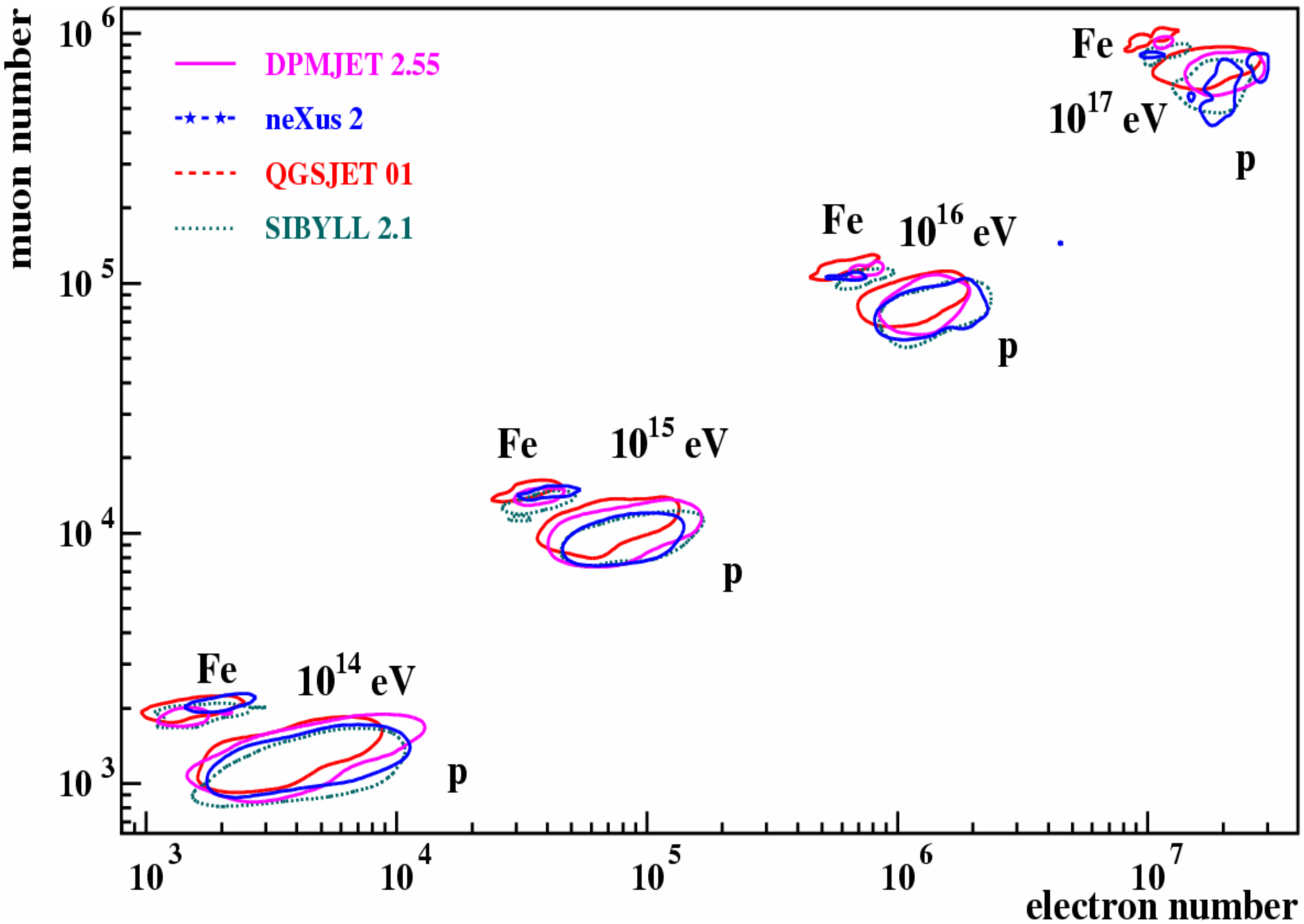
- interaction cross section
- multiplicity of secondary particles
- ratio of neutral to charged pion multiplicity

Atmosphere as target and calorimeter

- critical energy
- typical pion decay energy

Number of shower particles proportional to energy

Energy/composition: N_e-N_μ correlation



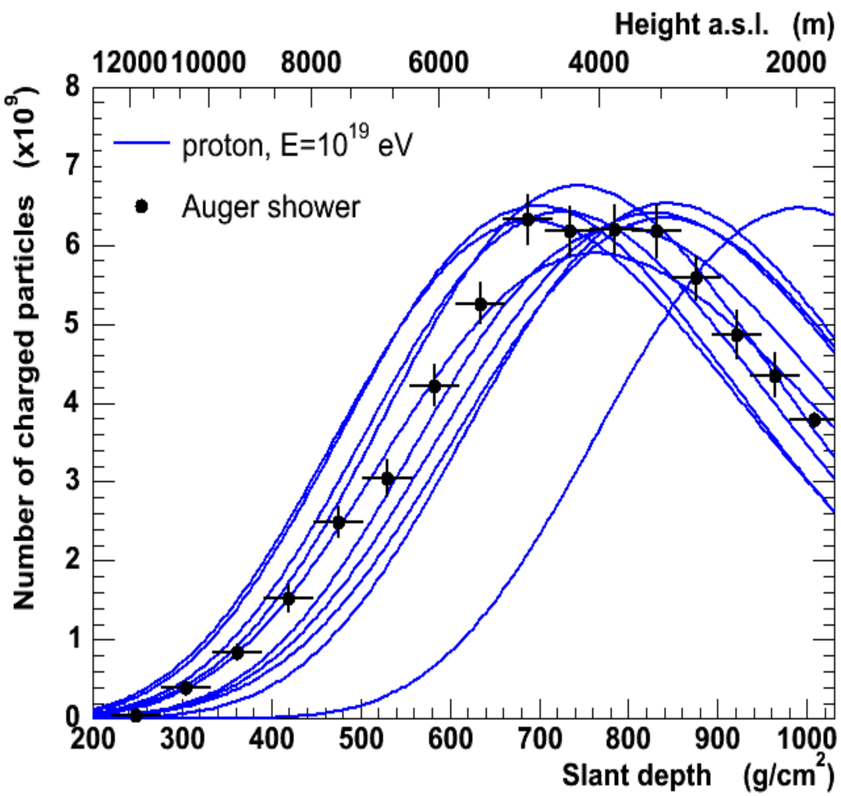
Standard method
for surface detector
arrays

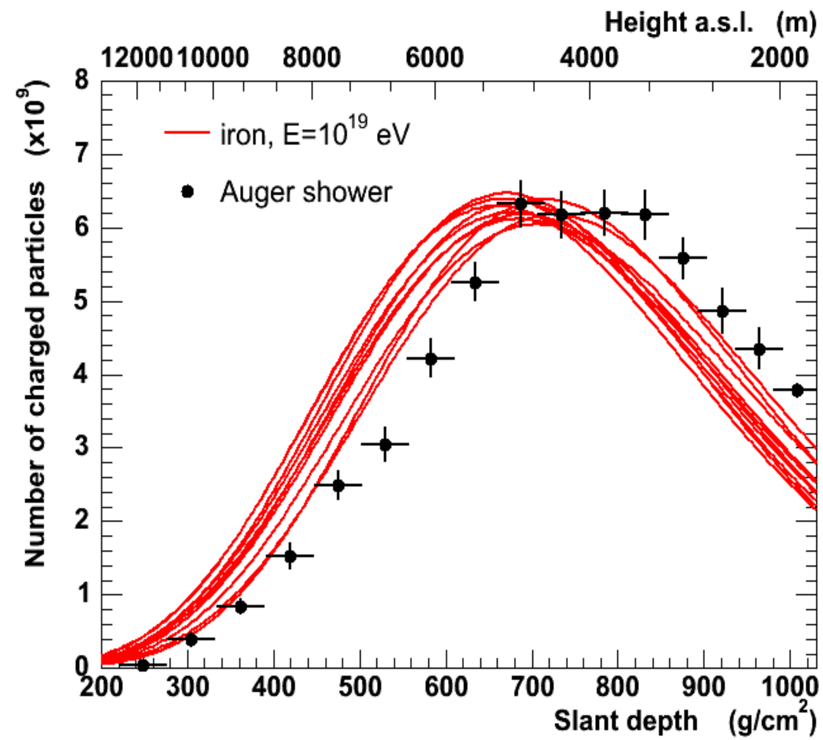
$$N_\mu^A = A^{1-\alpha}\left(\frac{E_0}{E_{dec}}\right)^\alpha$$

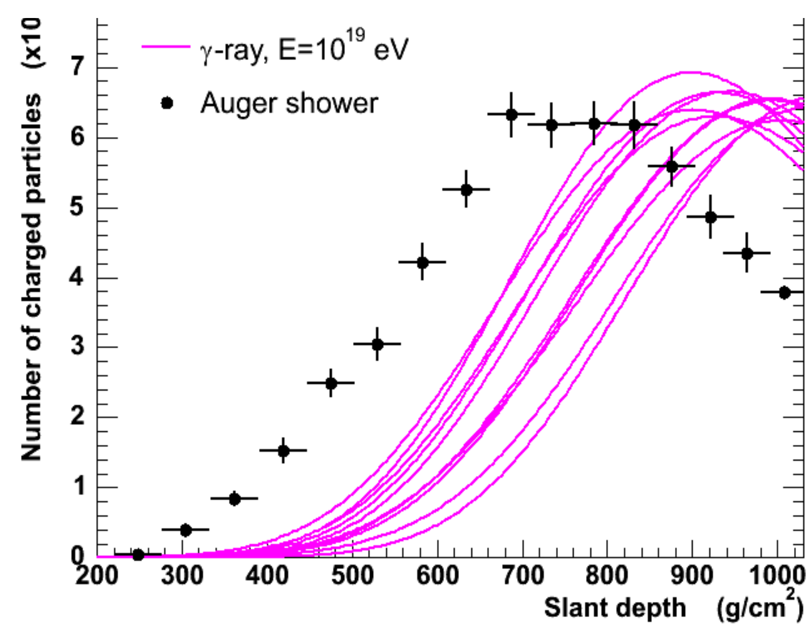
Model dependence increasing with energy

Energy/composition: shower profile

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

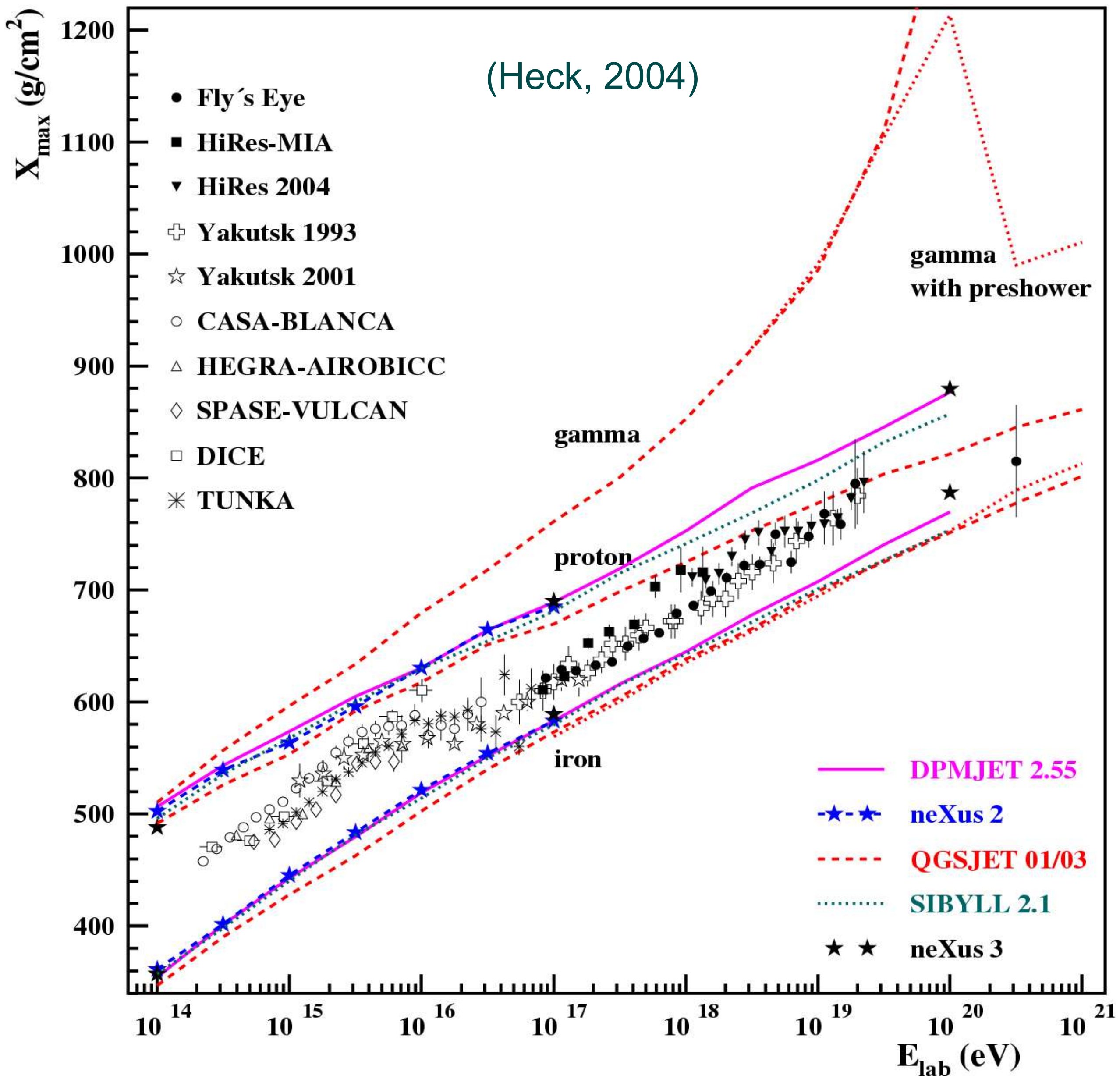






$$N_{max}^{A} = N_{max}, \qquad X_{max}^{A} \sim \lambda_e \ln(E_0 / A)$$

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 used for simulation

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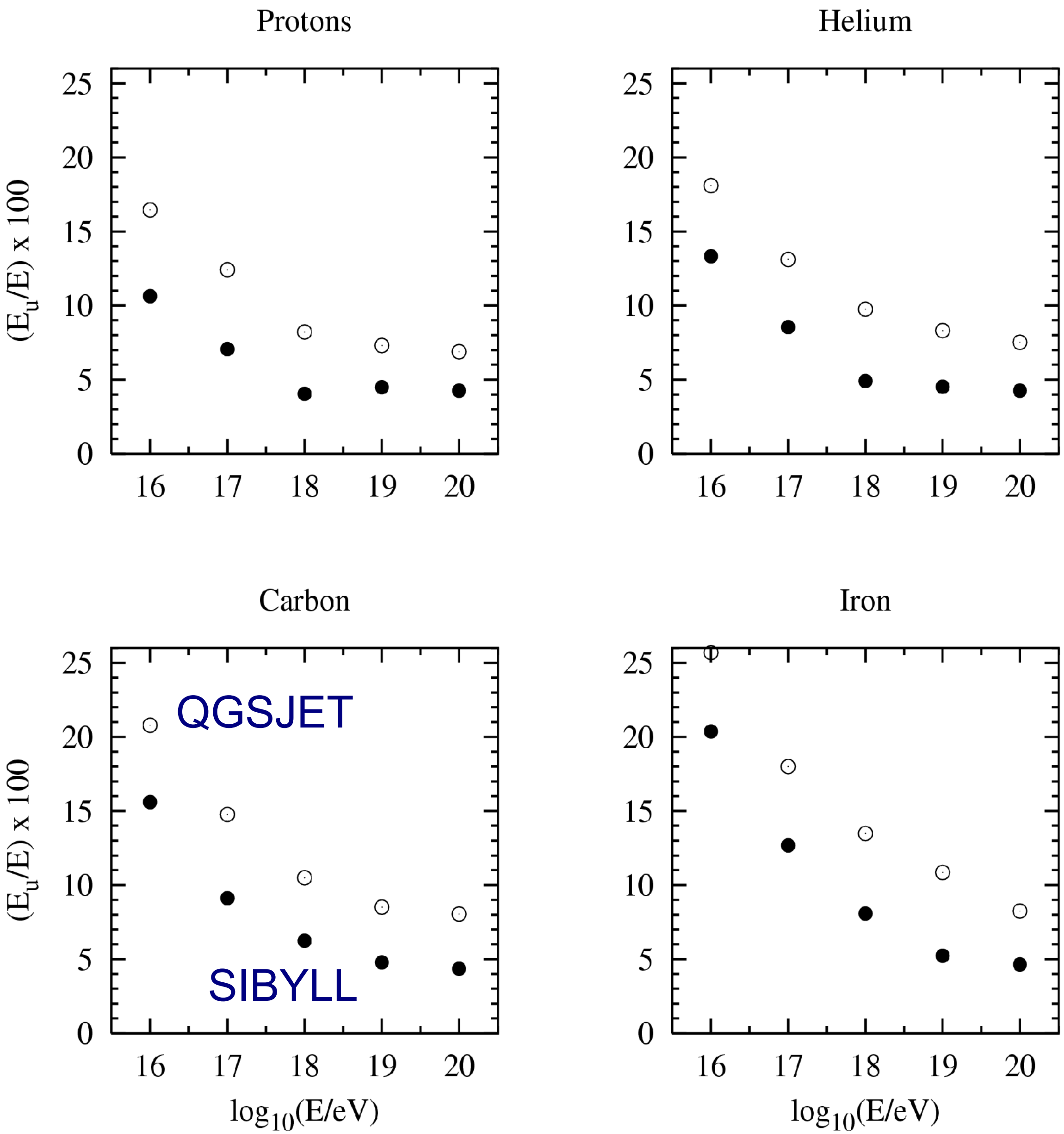
Energy reconstruction: fluorescence technique



Fraction of “unseen” energy E_u

$$E = E_{\mathrm{cal}} + E_u$$

The higher the energy of the primary particle the smaller the fraction of unseen energy

(Alvarez-Muniz et al., PRD69 (2004) 103003)

Hadronic interaction models

Requirements:

- simulation of π, K, p, n, ..., Fe collisions with air nuclei (C,N,O, Ar)
- coverage of full energy range from production threshold to $\sqrt{s}$ ~ 400,000 GeV
- minimum bias event simulation
  - central and peripheral collisions
  - diffractive and non-diffractive interactions
- optimal description of high-energy secondary particles

- tuned to existing fixed-target and collider data

- variable projectile/target combinations
- variable collision energy
- fast simulation

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)

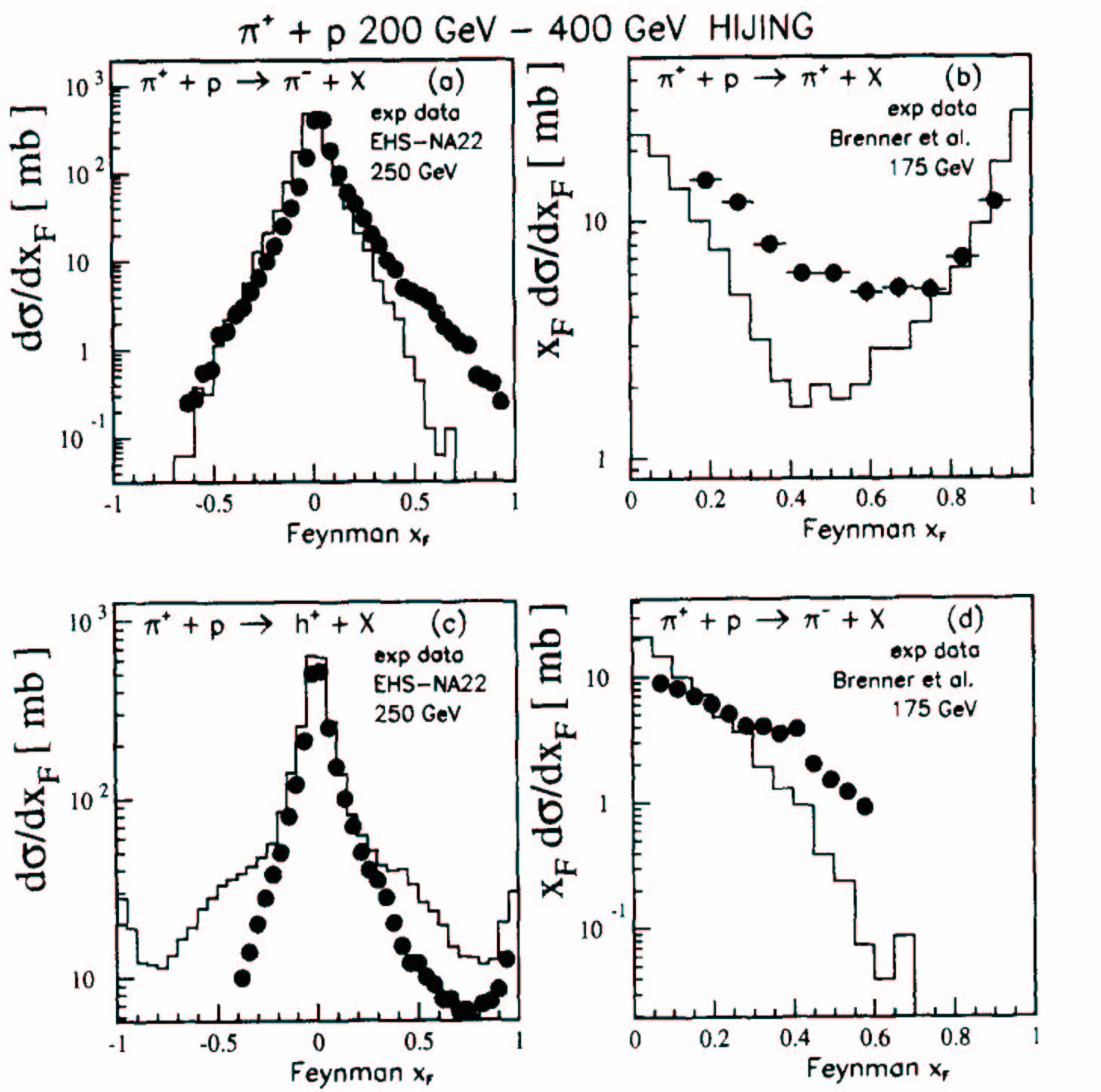
SOPHIA (Mücke, RE, Rachen, Protheroe, Stanev)

Why not PYTHIA, HERWIG, HIJING, ... ?

Most models not designed/tuned for simulating forward particle production

Most models cannot handle different projectiles/targets and energies

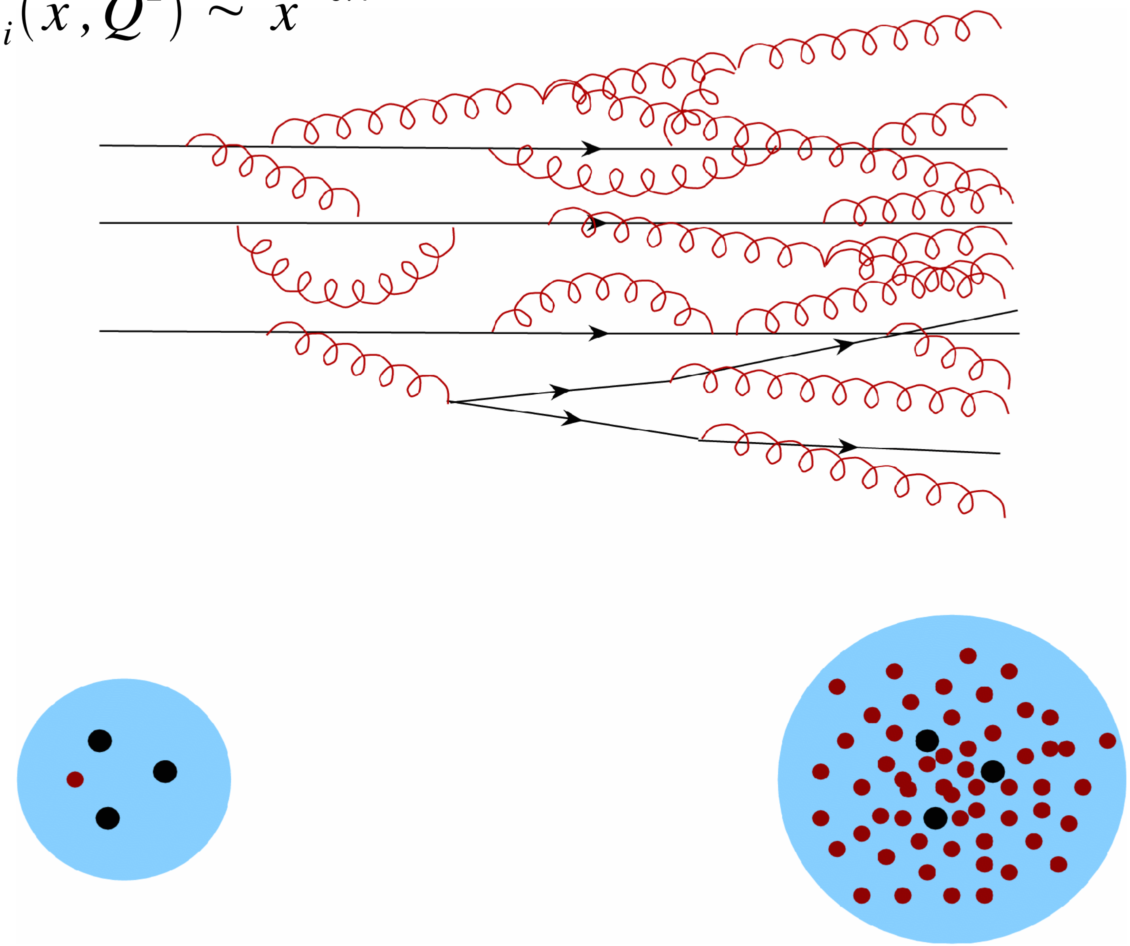
Example: comparison of HIJING to fixed target data



(Pop, Gyulassy & Rebel, Astropart. Phys. 10 (1999) 211)

Geometric view of hadron

$$f_i(x, Q^2) \sim x^{-0.4}$$



Hadron at low energy

Hadron at high energy

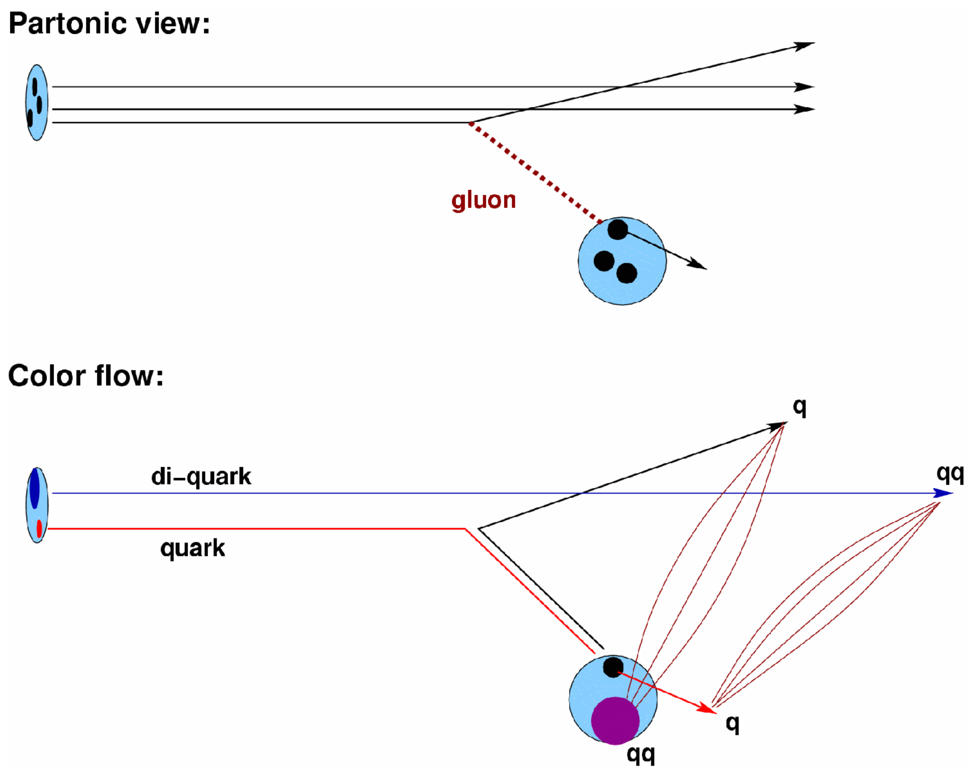
Total cross section:

number and spacial distribution of gluons

Fast secondaries:

quarks/gluons with large momentum fraction *x*

Low energy: two-string models



Basics:

- hadrons built up of quarks, gluons
- quarks, gluons carry color

  interactions lead to color transfer

String fragmentation
from e+e- data

Regge parametrizations: Mueller diagrams

Momentum fraction of quark in nucleon: $f_{\mathrm{DPM}}(x_q) = x_q^{-1/2}(1-x_q)^{3/2}$

Momentum fraction of quark in pion: $f_{\mathrm{DPM}}(x_q) = x_q^{-1/2}(1-x_q)^{-1/2}$

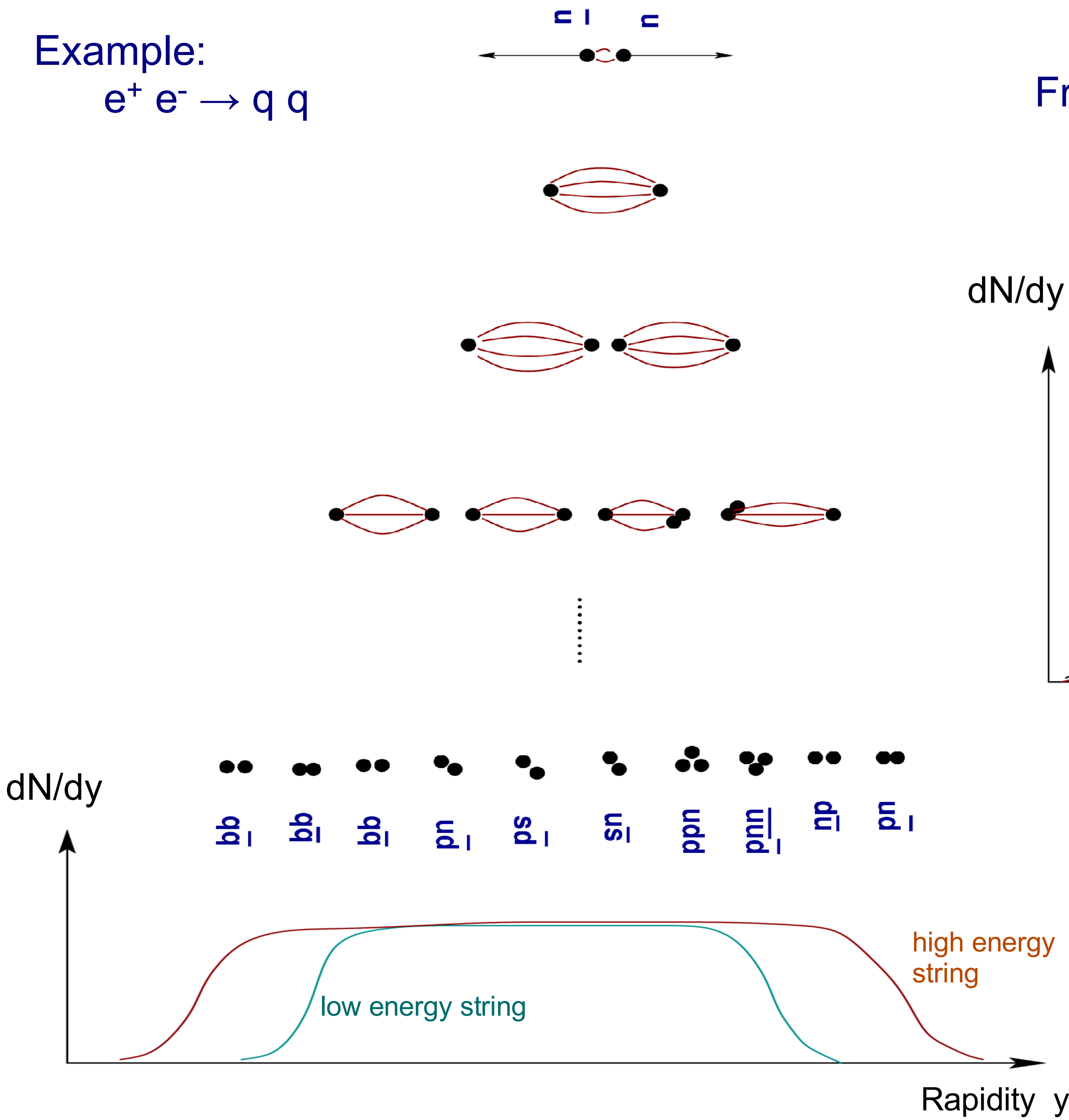
String fragmentation process

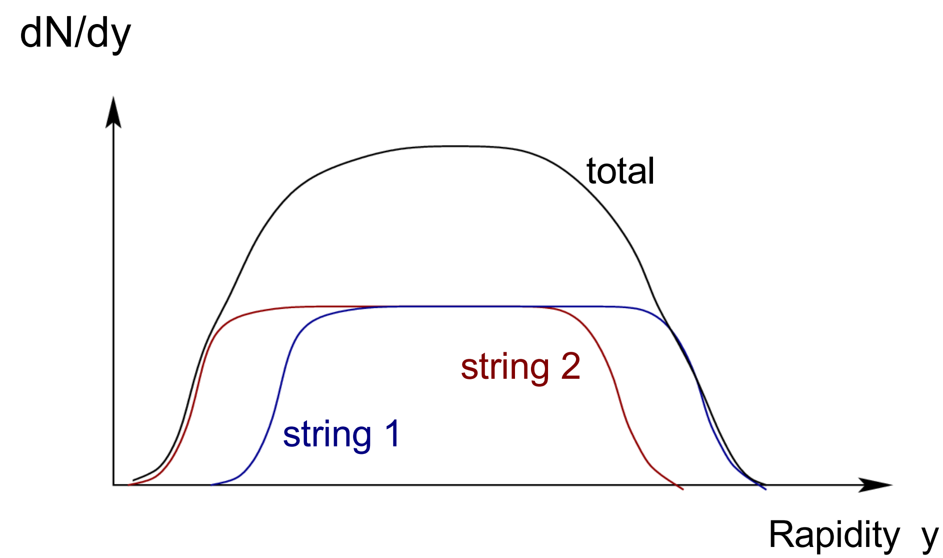
Example:

$e^+ e^- \rightarrow q\,q$

Fragmentation:

assumed to be universal



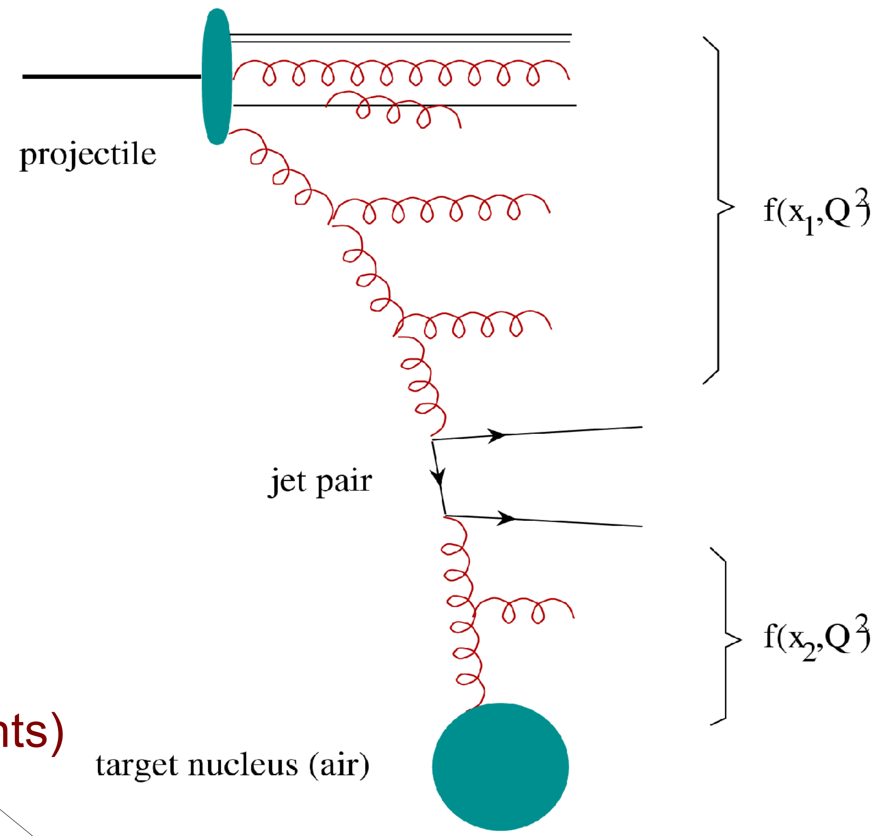


Rapidity plateau independent of energy:
Feynman scaling

High energy: QCD minijet production

QCD parton model:

colinear factorization
DGLAP evolution Eqs.

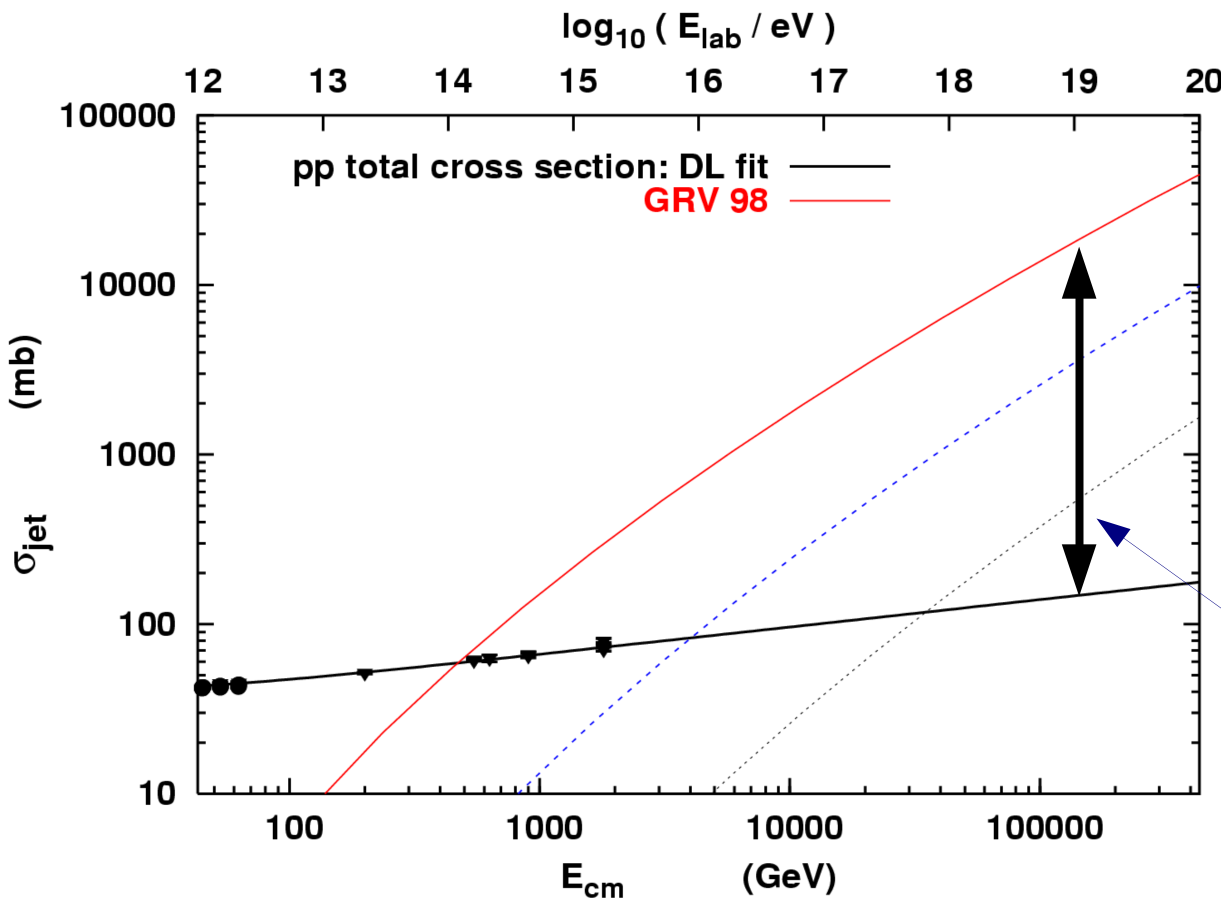


Transverse momentum cutoff: $p_T > p_T^{\text{cutoff}}$

Parton densities
(HERA measurements)

$$\sigma_{\text{jet}} = \sum_{i,j,k,l} \int_{p_T^{\text{cutoff}}} dp_T \int dx_1 dx_2 \; f_i(x_1, Q^2) \; f_j(x_2, Q^2) \; \frac{d\sigma_{i,j \to k,l}}{dp_T}$$

Inclusive minijet cross section



$p_T^{\text{cutoff}} = 2\,\text{GeV}$

$p_T^{\text{cutoff}} = 4\,\text{GeV}$

$p_T^{\text{cutoff}} = 8\,\text{GeV}$

~150 jet pairs per single p-p collision

$$<n_{\text{jet}}> = \frac{\sigma_{\text{jet}}}{\sigma_{\text{ine}}}$$

Transverse momentum cutoff p_t^{cutoff} : QCD gives no prediction

(a) value at a given energy

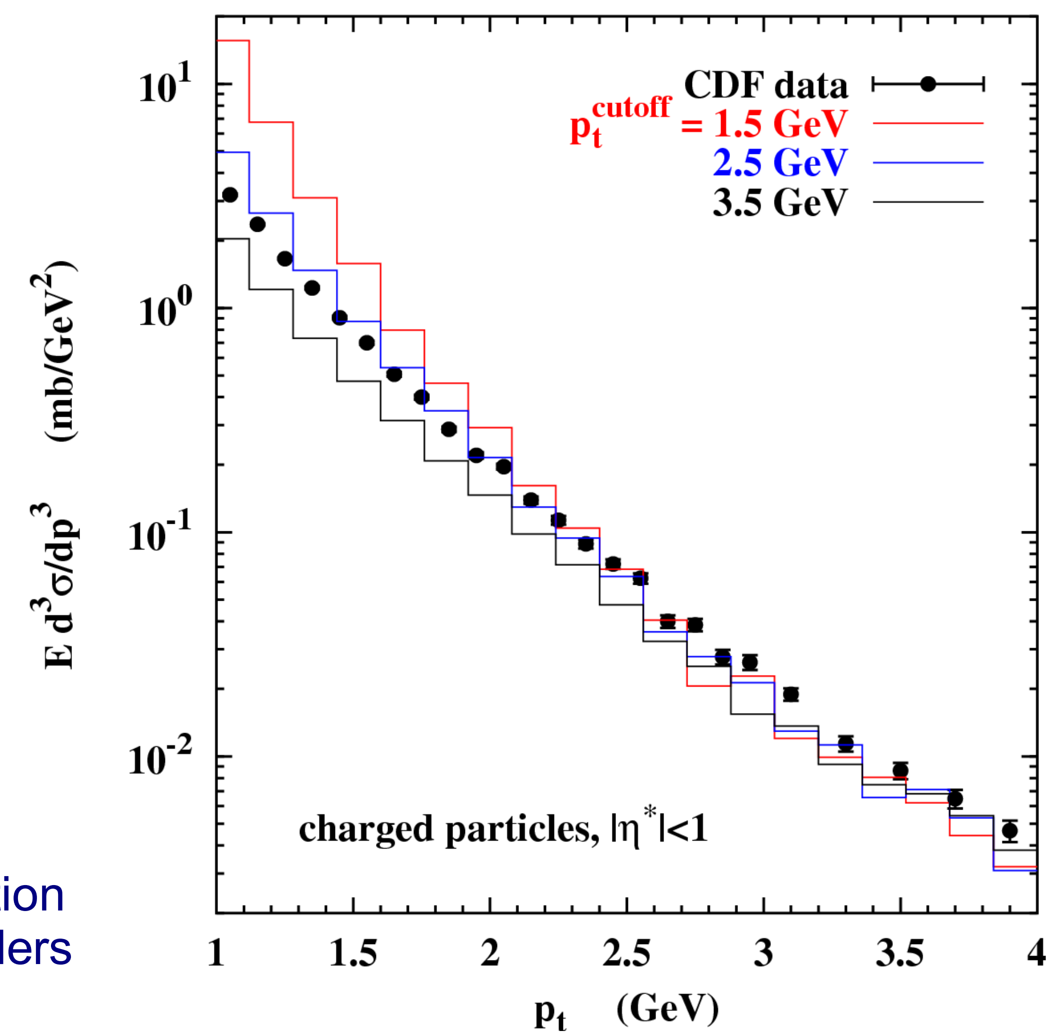
(b) dependence on energy, projectile/target, ...

Transverse momentum cutoff

HERA data:
small p_T^{cutoff} ~1.5 GeV

Tevatron data:
slightly larger p_T^{cutoff} ~ 3 GeV

Energy-dependence of transverse momentum cutoff?

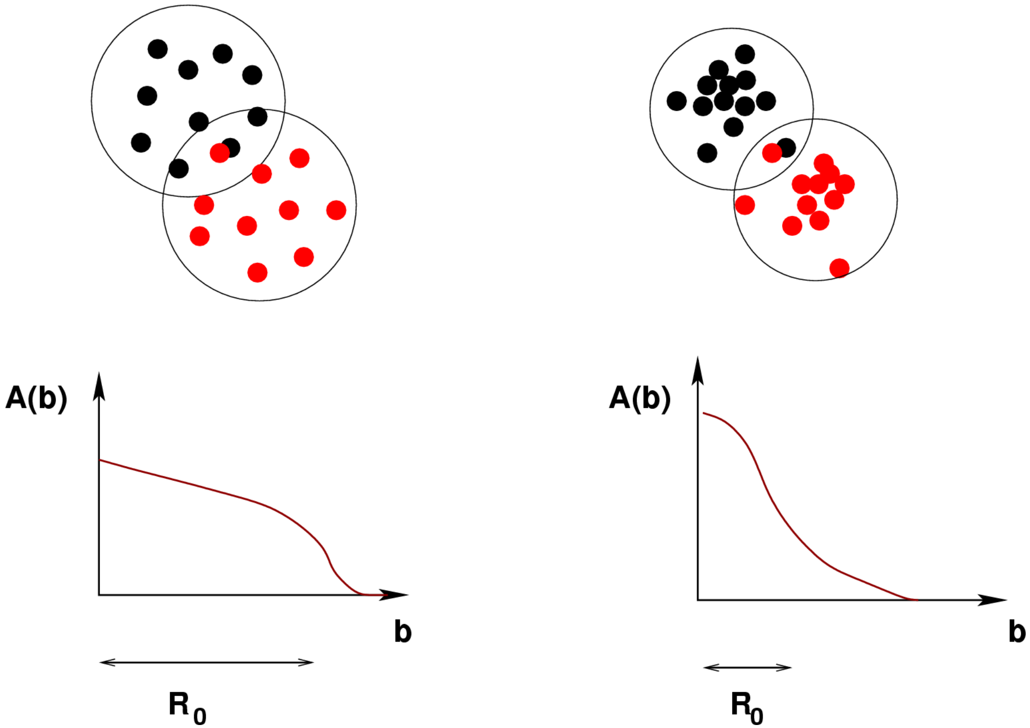


QGSJET II: energy-independent transverse momentum cutoff, summation of soft multi-pomeron graphs to all orders

SIBYLL: energy-dependent transverse momentum cutoff

$$p_T^{cutoff} = p_T^0 + 0.065\,\mathrm{GeV}\exp\left(0.9\sqrt{\ln s}\right)$$

Calculation of total cross section



QCD: prediction of inclusive cross section (number of partons)

Total cross section: profile function *A(b)* needed

QGSJET: gaussian distribution

SIBYLL: em. form factor

Example: eikonal model

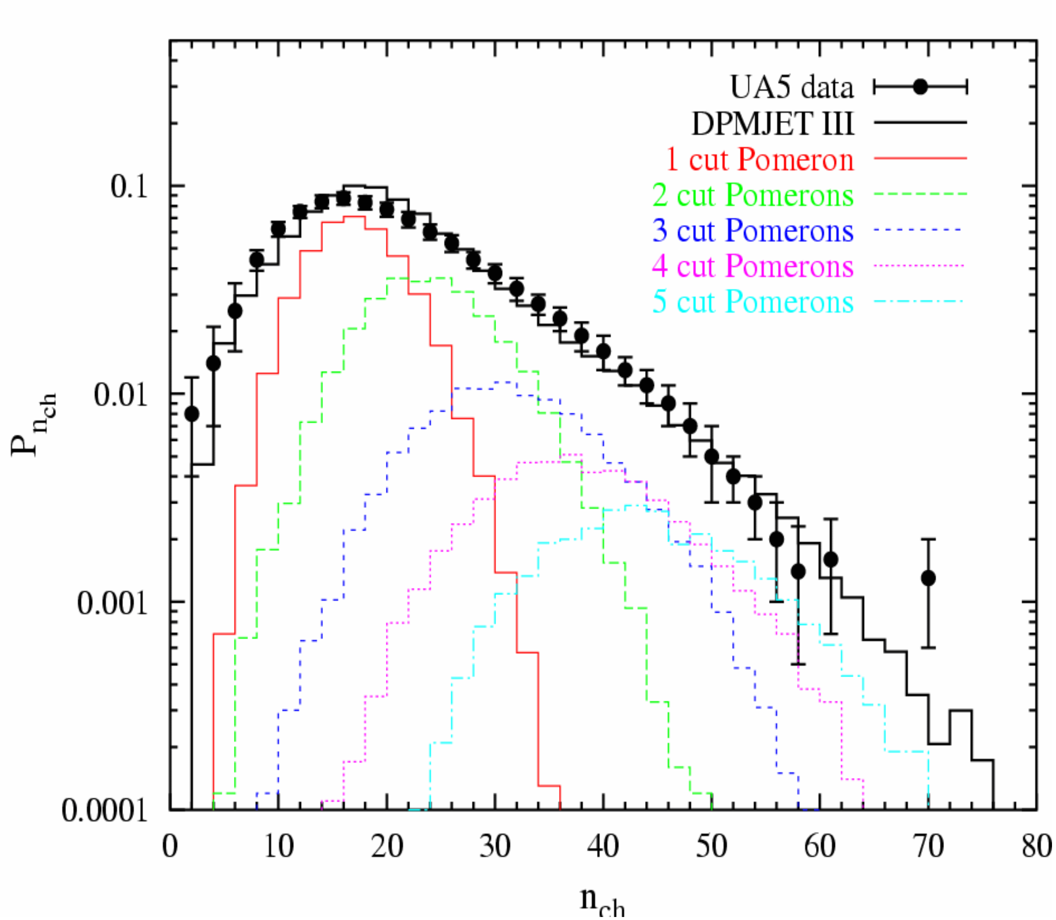
$$\sigma_{\mathrm{ine}} = \pi \int db^2 \left(1 - \exp\left[-\sigma_{\mathrm{jet}} A(b) - \sigma_{\mathrm{soft}} A_s(b)\right]\right)$$

Resummation according to topologies

Analytical resummation of inelastic cross section (eikonal only):

partial cross sections for *n* hard/soft partonic interactions (cut pomerons)

$$\sigma_{\text{inel}}^{(n)} = \int d^2 b \frac{(2\chi)^n}{n!} \exp(-2\chi)$$



$$\chi = \chi_{\text{soft}} + \chi_{\text{hard}}$$

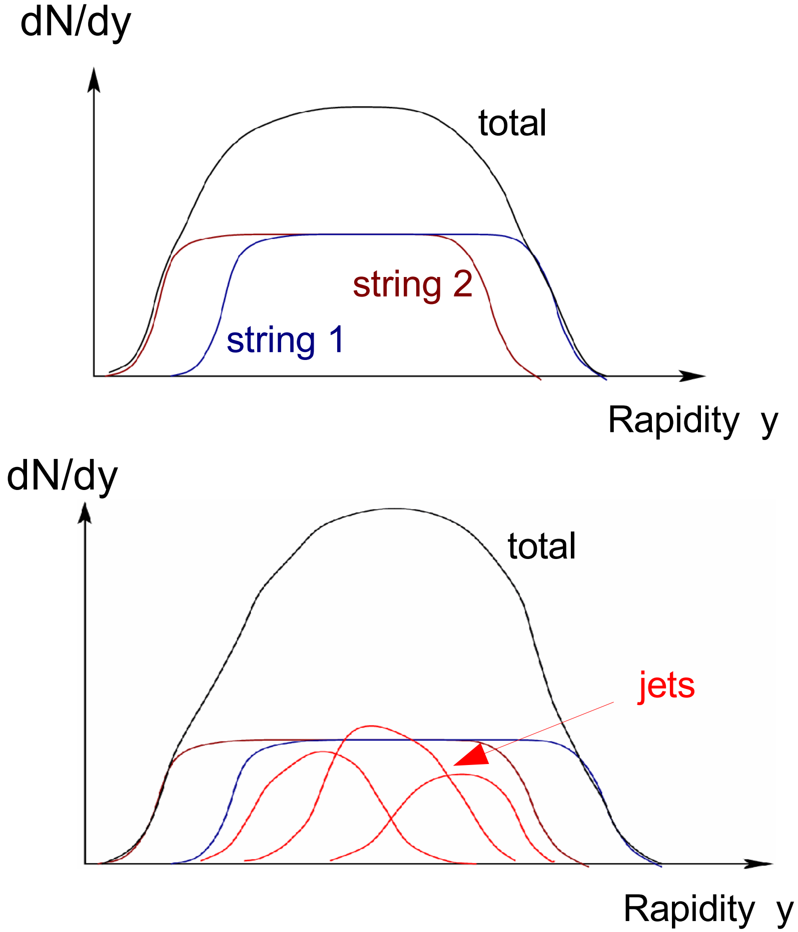
$$\chi_{\text{soft}} = \sigma_{\text{soft}} \; A_{\text{soft}}(s, b)$$

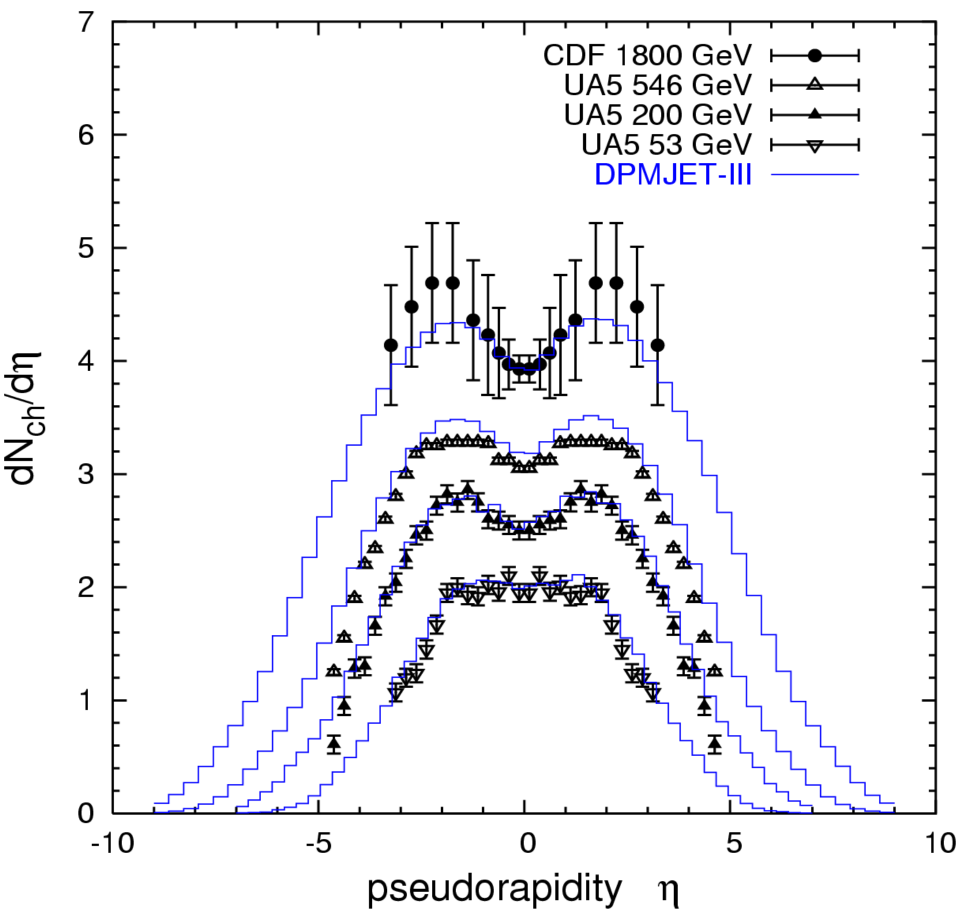
$$\chi_{\text{jet}} = \sigma_{\text{jet}} \; A_{\text{jet}}(s, b)$$

(AGK cutting rules)

Violation of Feynman scaling

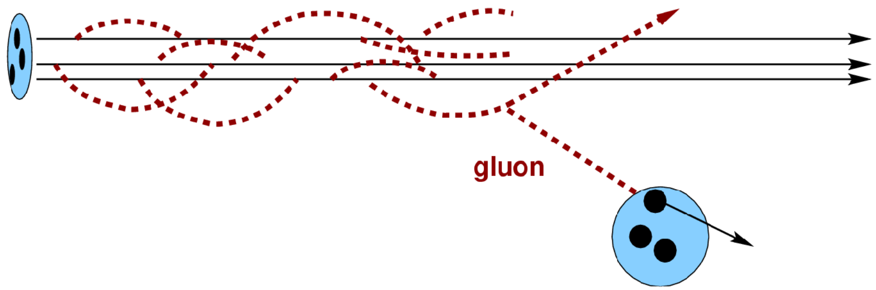
Multiple partonic interactions lead to increase of rapidity plateau





Leading particle production

Partonic view:



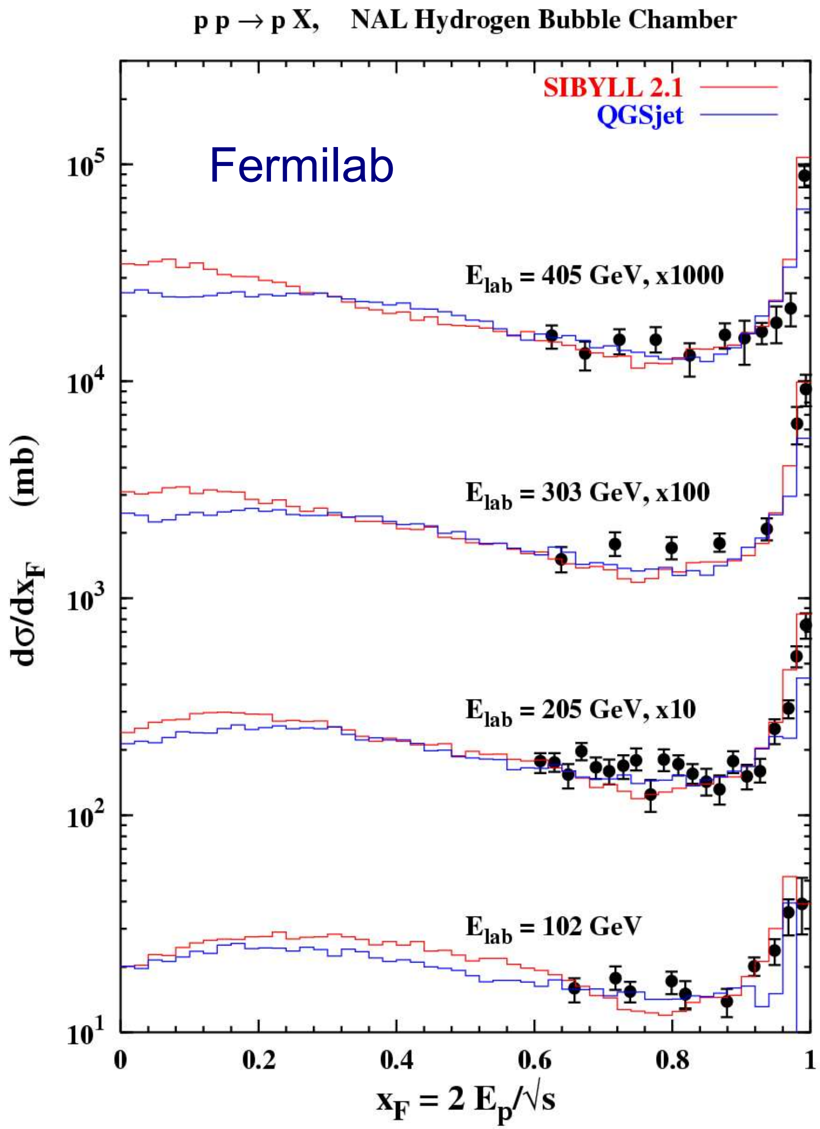
Parametrizations:

scaling assumed (energy-independent)

$$f_{\mathrm{DPM}}(x_q) = x_q^{-1/2}(1-x_q)^{3/2}$$

$$f_{\mathrm{SIB}}(x_q) = \left(x_q + \mu^2/s\right)^{-1/4}(1-x_q)^3$$

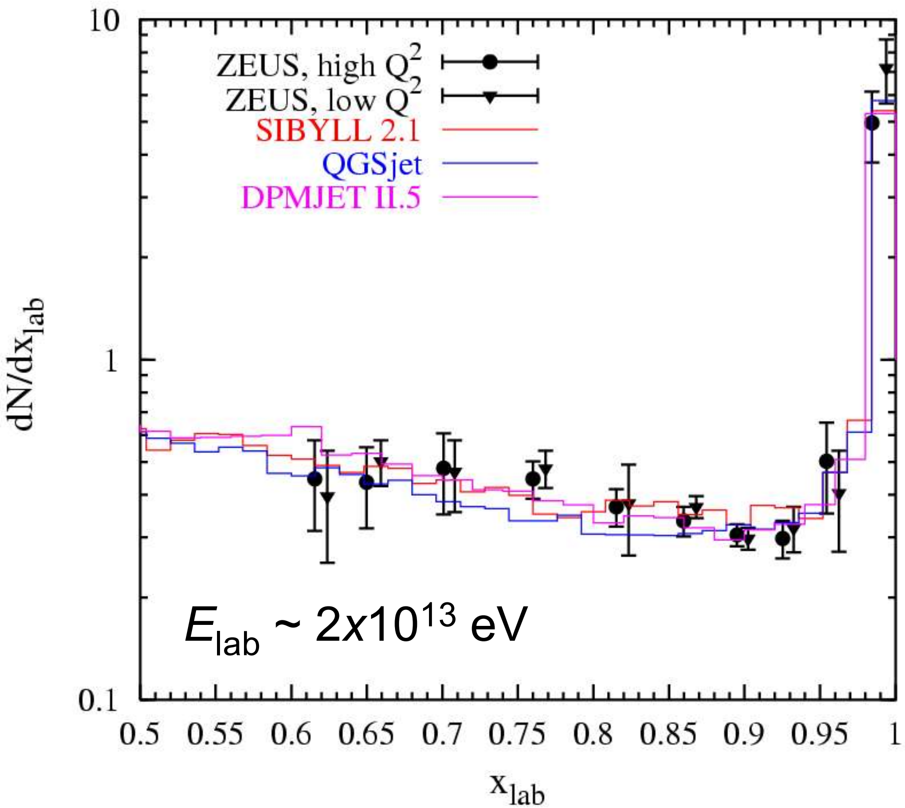
energy-momentum conservation



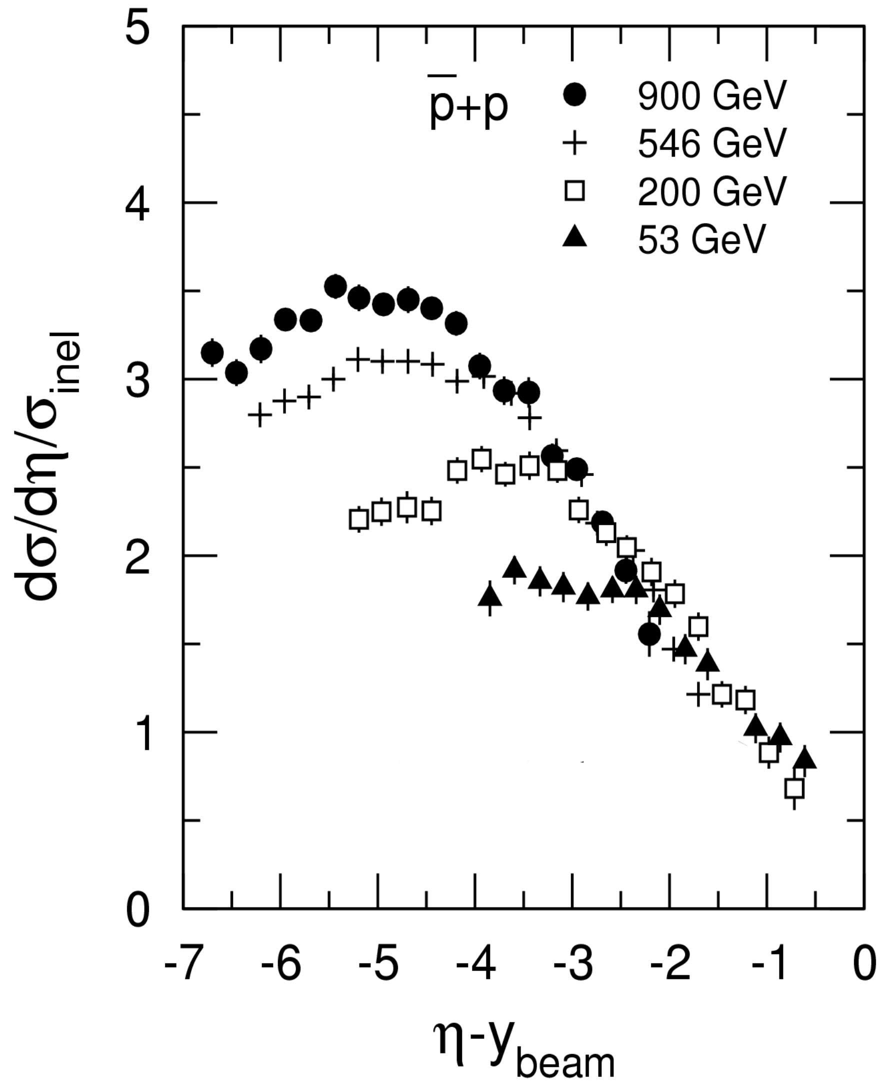
$E_{\mathrm{lab}} \sim 4x10^{11}$ eV

Extrapolation of leading particle production

HERA: *p-γ → p/n X*



CERN: limiting fragmentation

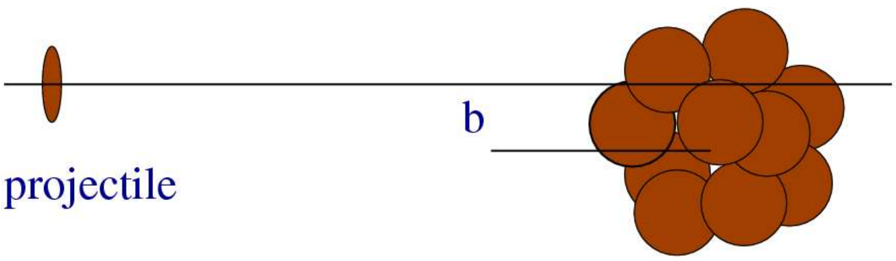


No indications of scaling violation of leading particle distributions

Nuclear projectiles & targets

Nuclear effects:

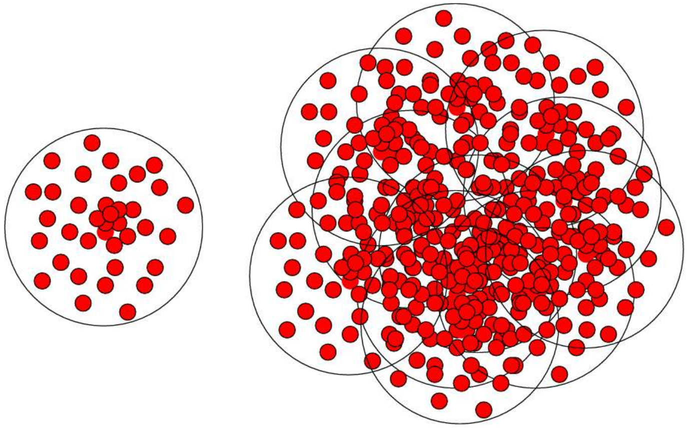
Gribov-Glauber approximation



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

Saturation effects expected to be even more important:

- String fusion and percolation
- Triple and multiple pomeron interactions
- Non-linear parton density evolution equations



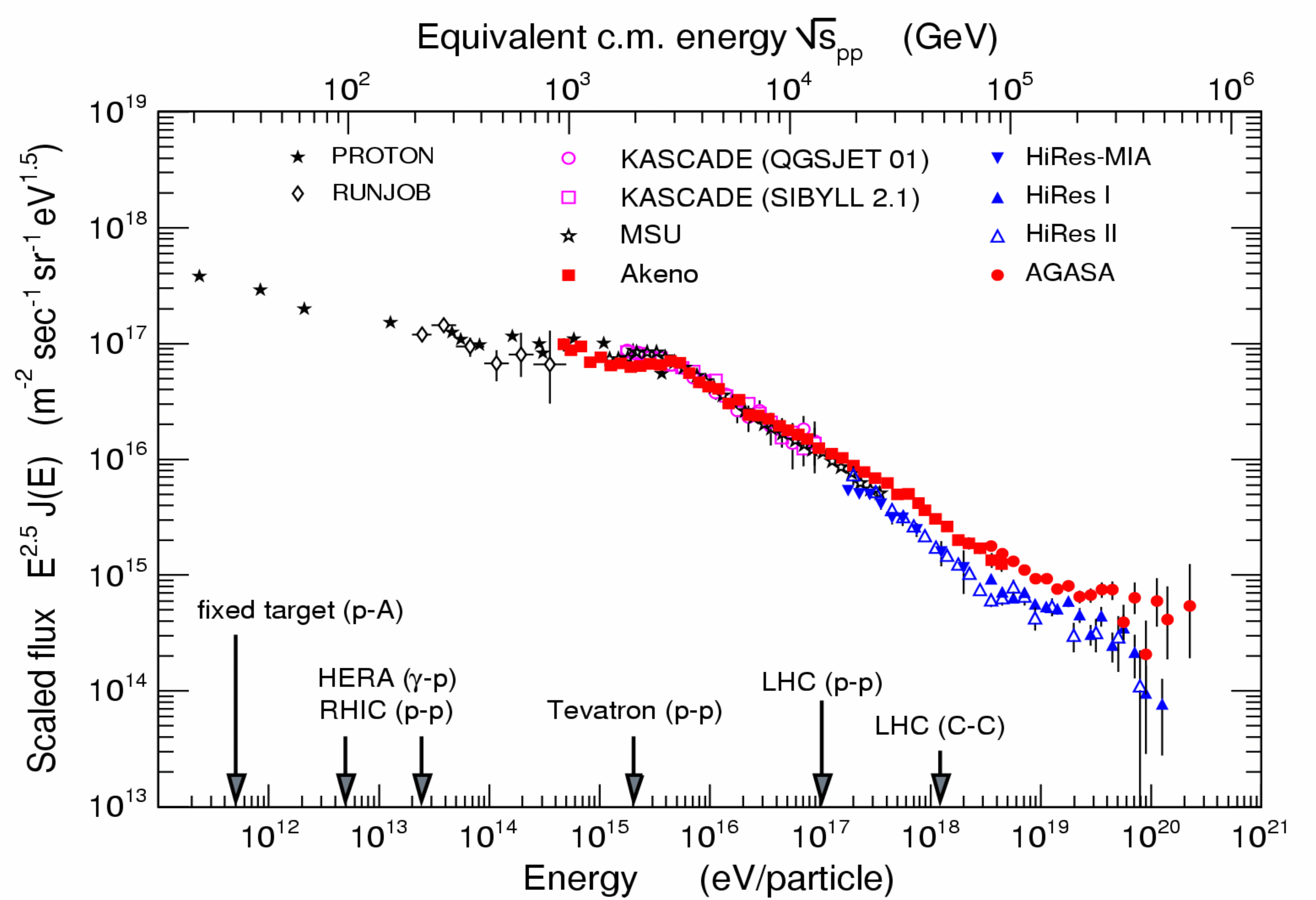
- Color Glass Condensate Model

RHIC data!

Main sources of uncertainty

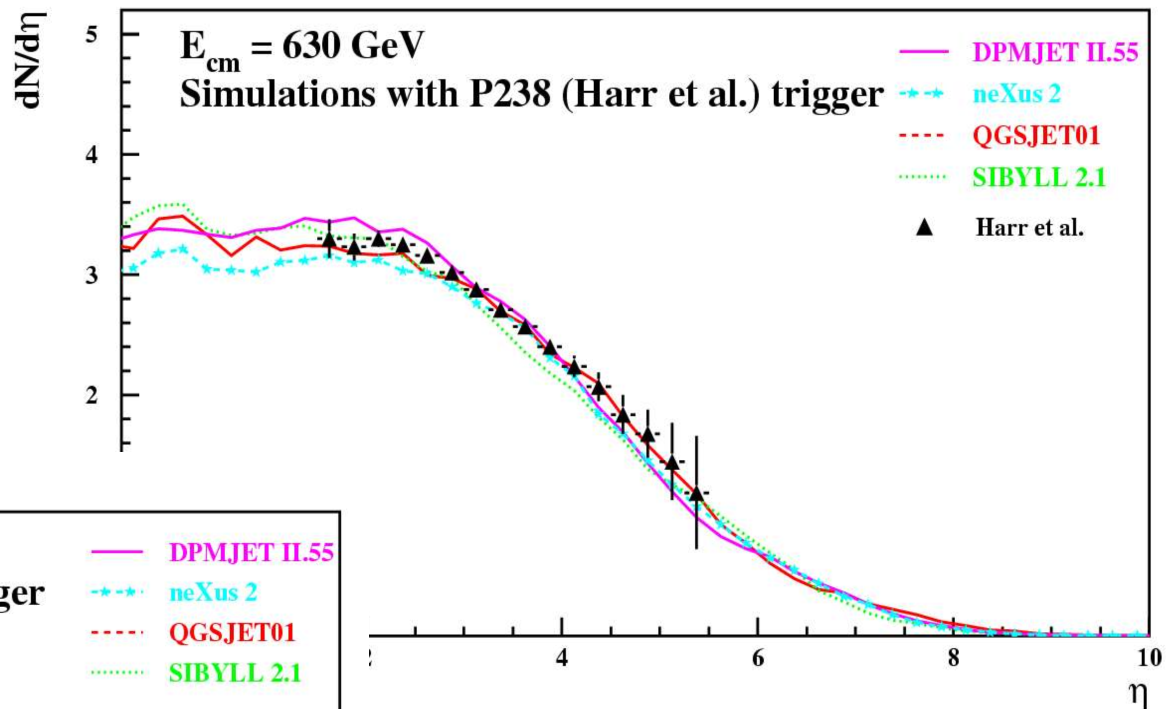
- Minijet cross section (parton densities, range of applicability)
- Transverse profile function (total cross section, multiplicity distribution)
- Energy dependence of leading particle distribution
- Role of nuclear effects (saturation, stopping power, QGP)

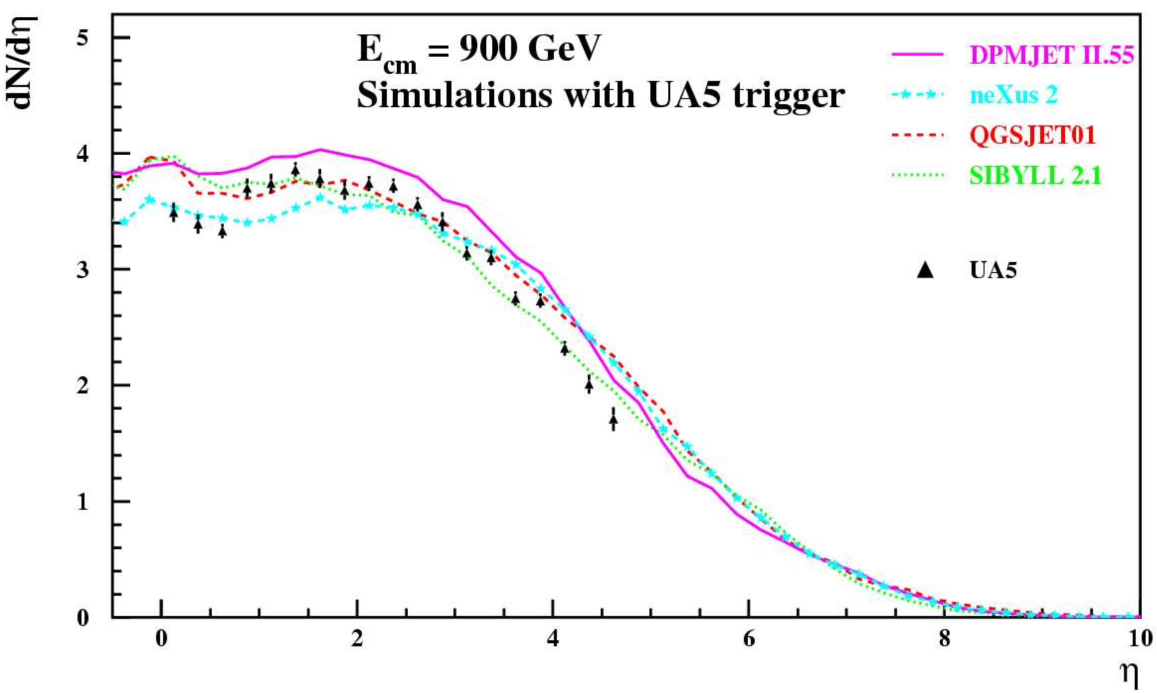
Tuning to accelerator measurements



Tuning to accelerator data (i)

Proton-antiproton at CERN SPS

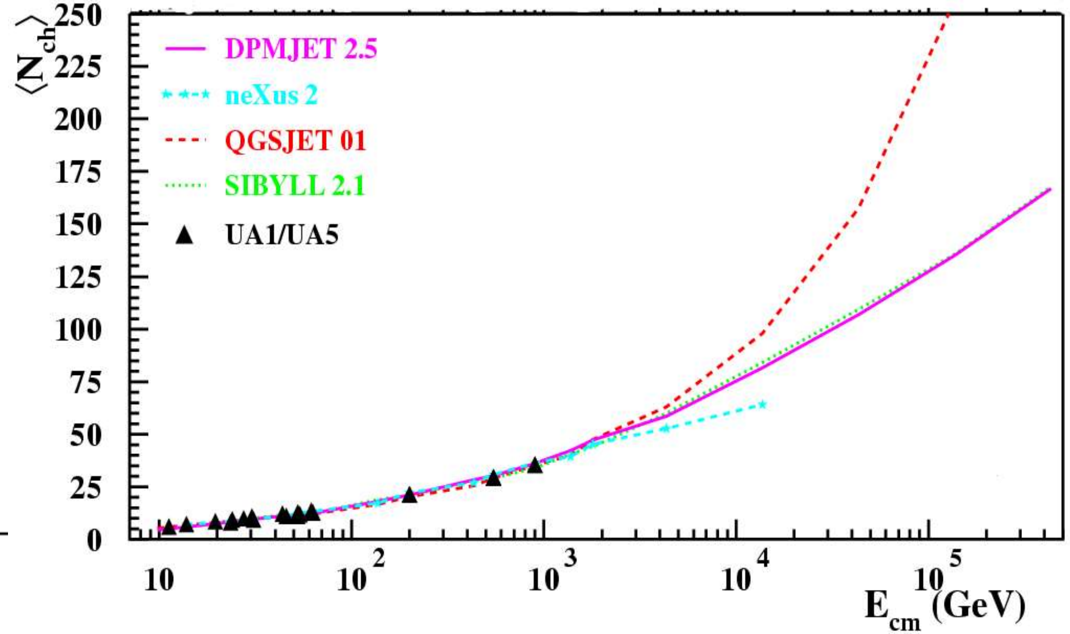




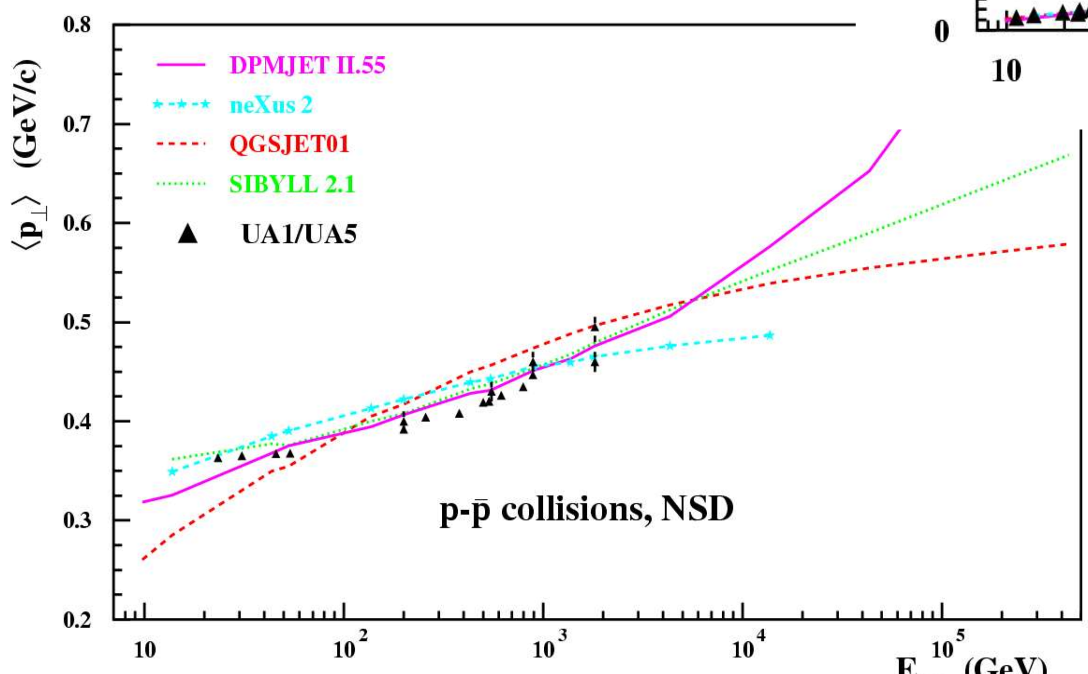
Pseudorapidity distribution of charged particles

Tuning to accelerator data (ii)

Mean charged particle multiplicity

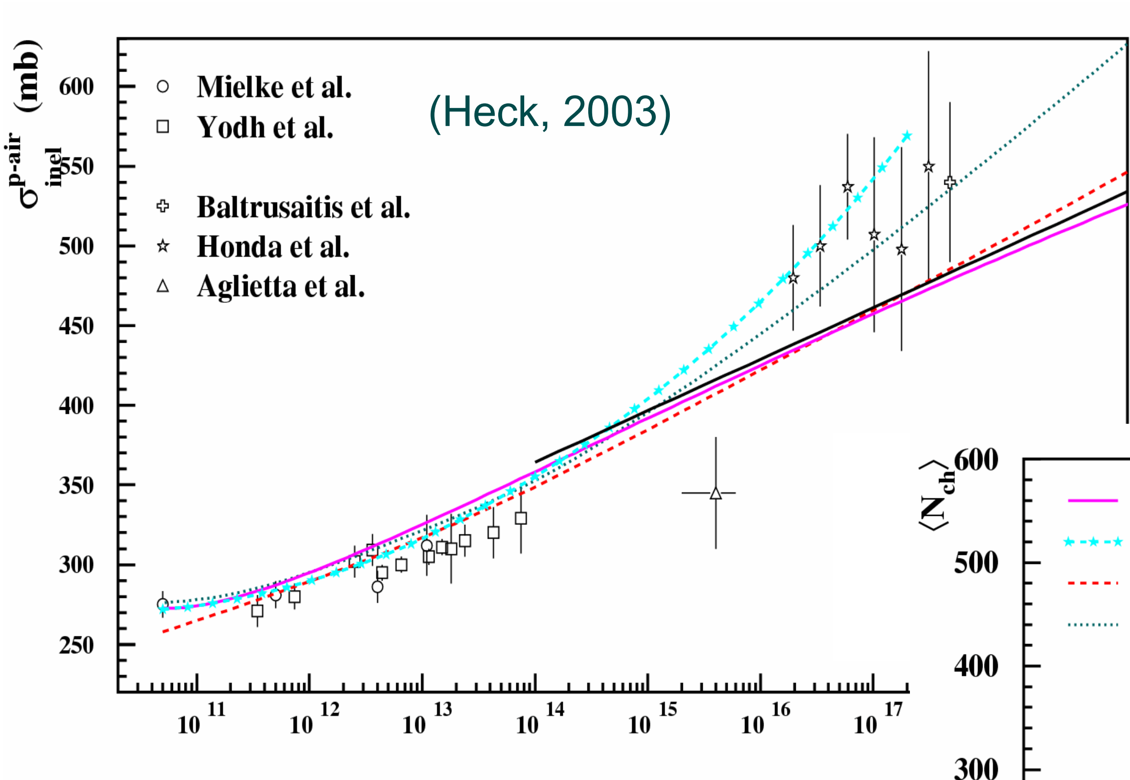


Mean transverse momentum



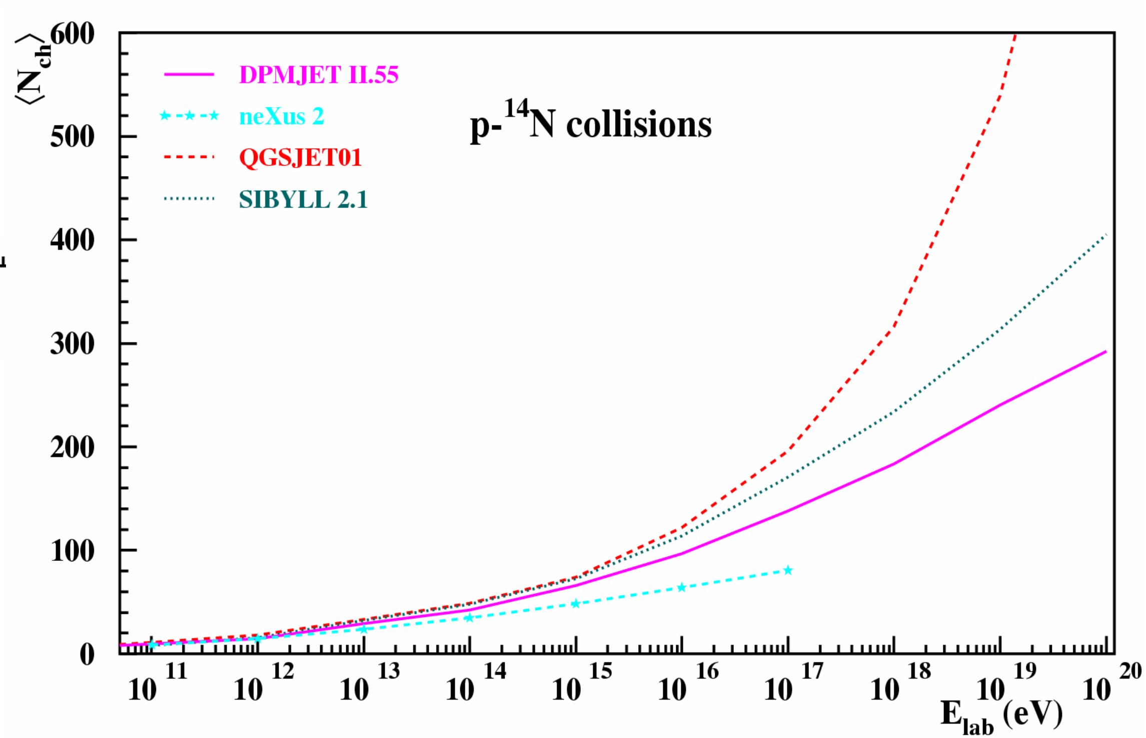
Proton-antiproton at CERN SPS & Tevatron

Hadronic interaction model predictions



Production cross section p-air

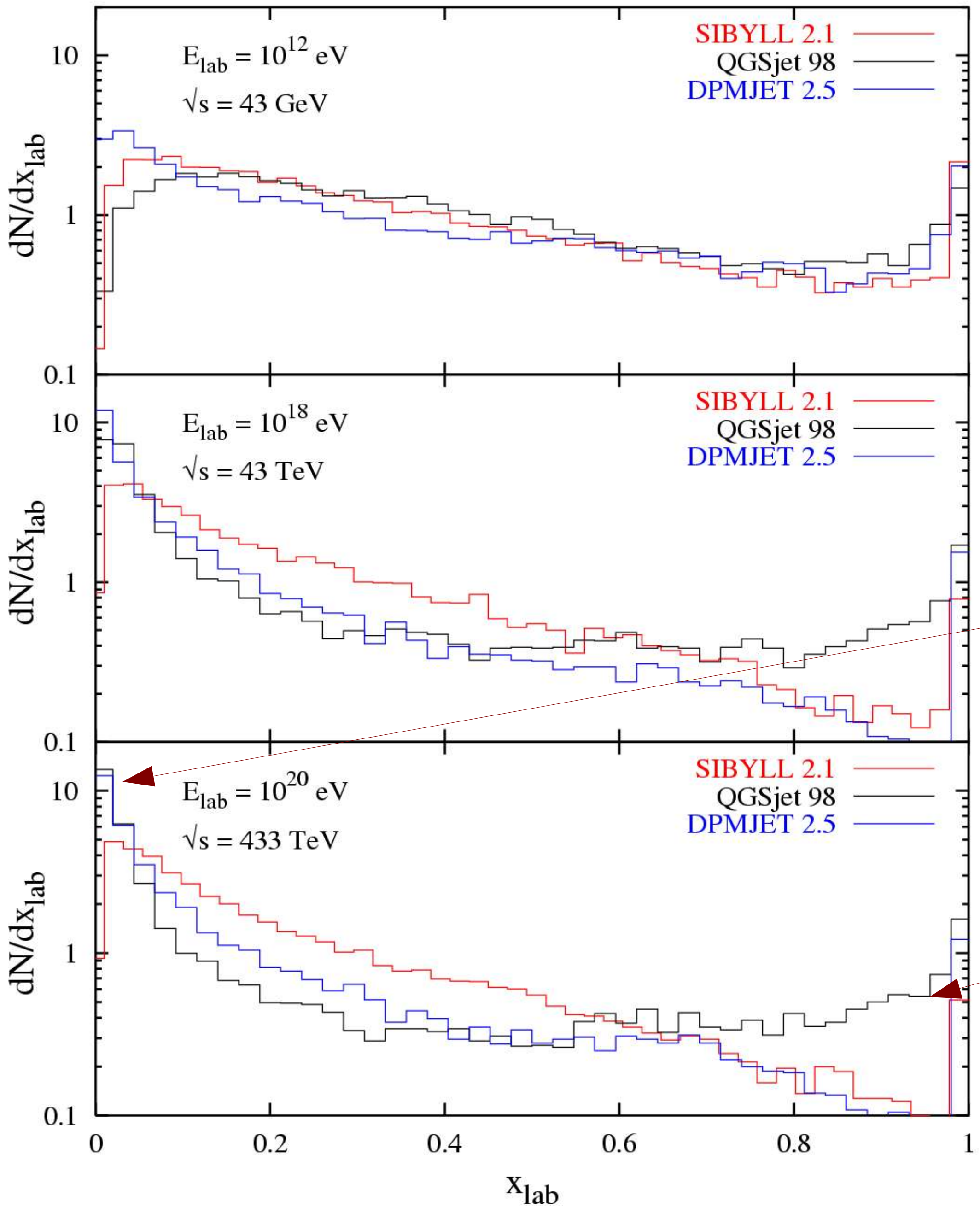
Secondary particle multiplicity (charged)



Wide range of predictions:

- Air showers rather insensitive
- Correlation of cross section and multiplicity: partial compensation

Extrapolation of leading particle production



Distribution of momentum fraction of leading baryon

p-air → p/n X

Extremely inelastic events

Nearly elastic events

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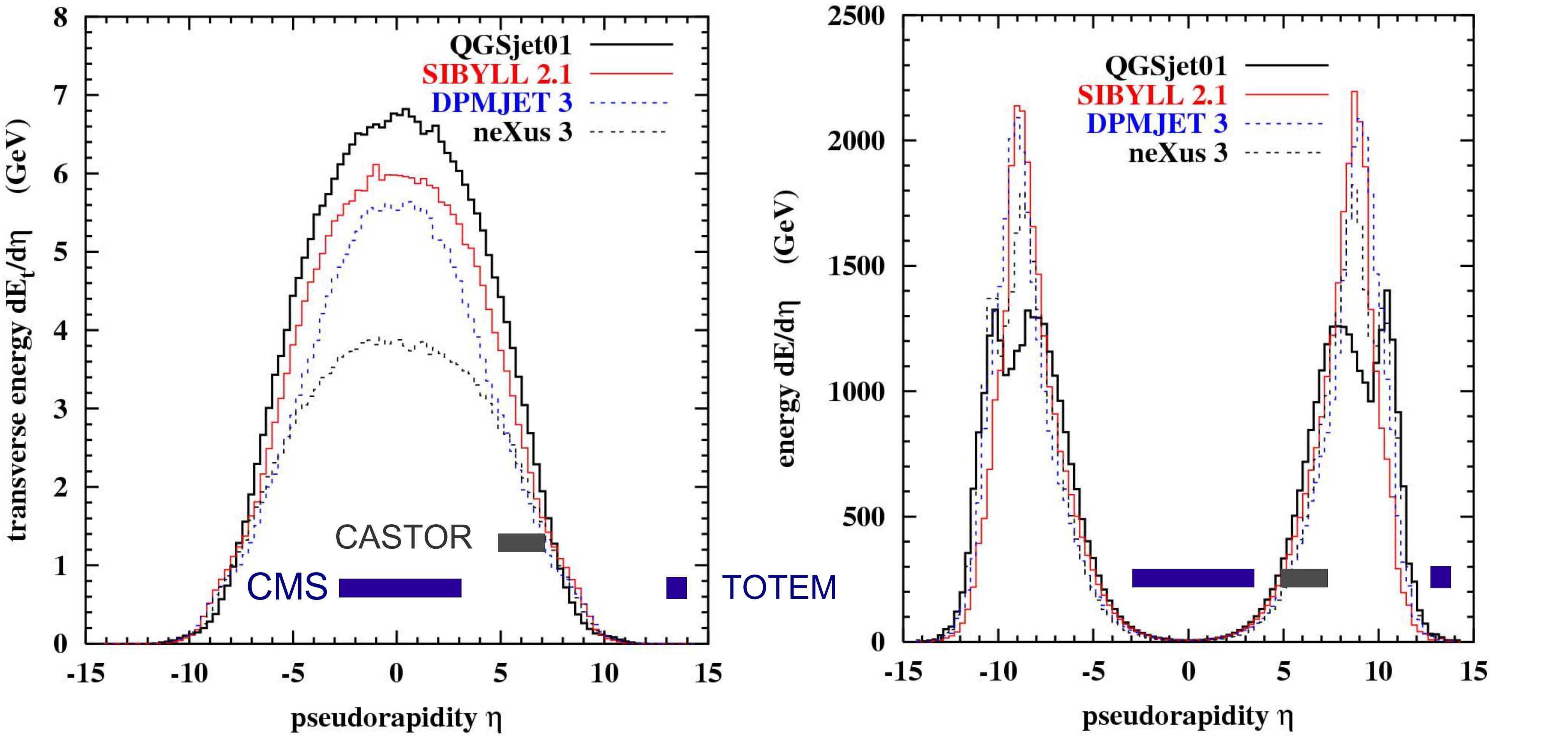
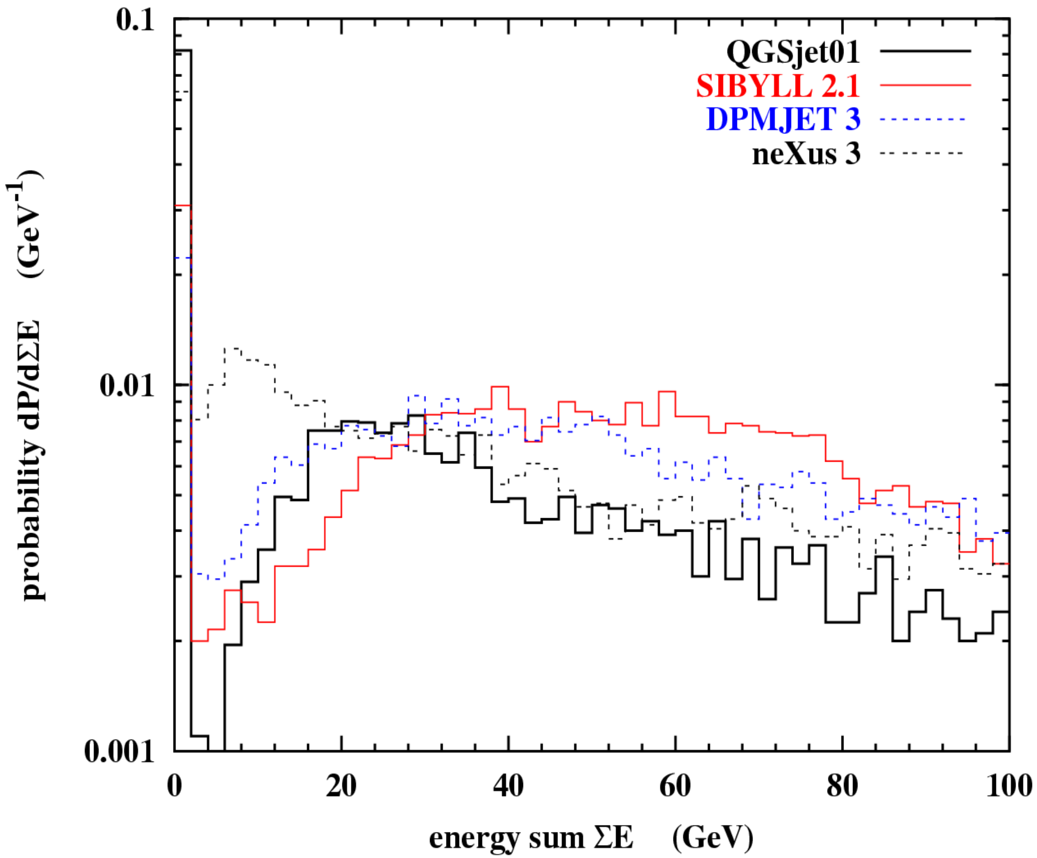
Discrimination potential of LHC (i)

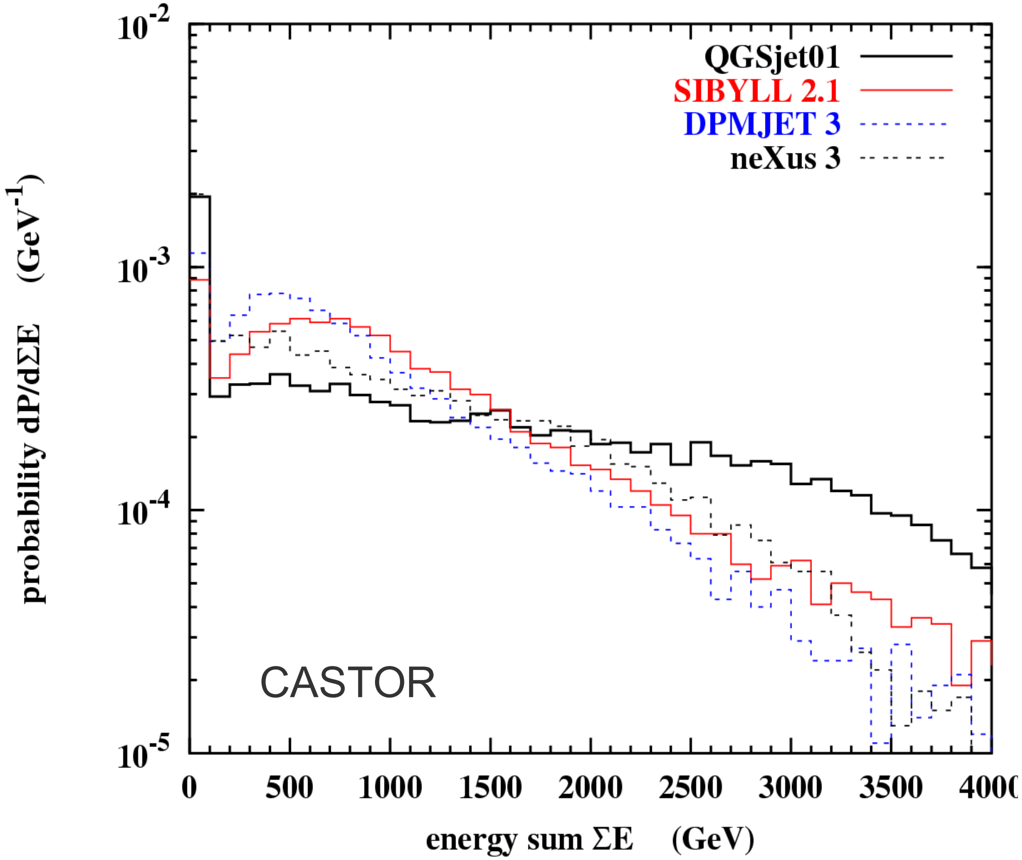


- p-p collisions at LHC at $\sqrt{s}$ = 14 TeV
- major experiments consider to do CR relevant measurements (for example, CMS / CASTOR / TOTEM)

Discrimination potential of LHC (ii)

Total energy sum in different detector parts:





Central detector: -3 < η < 3

Forward detector: 5 < η < 7

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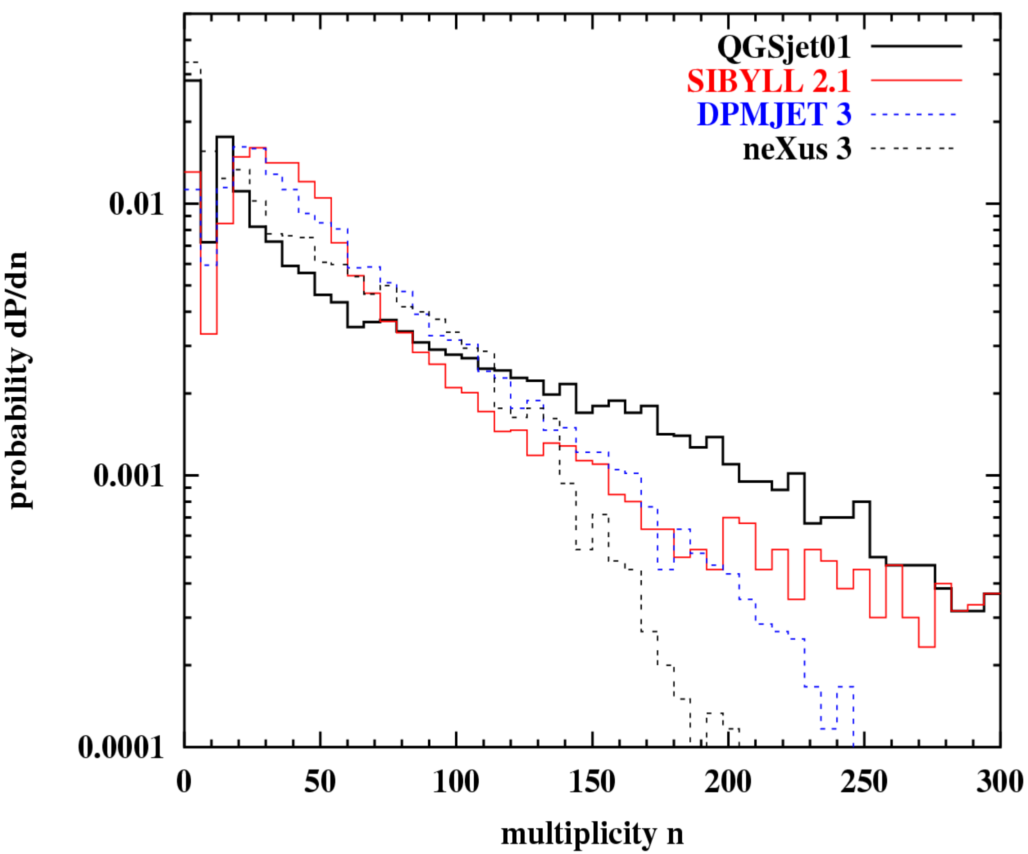
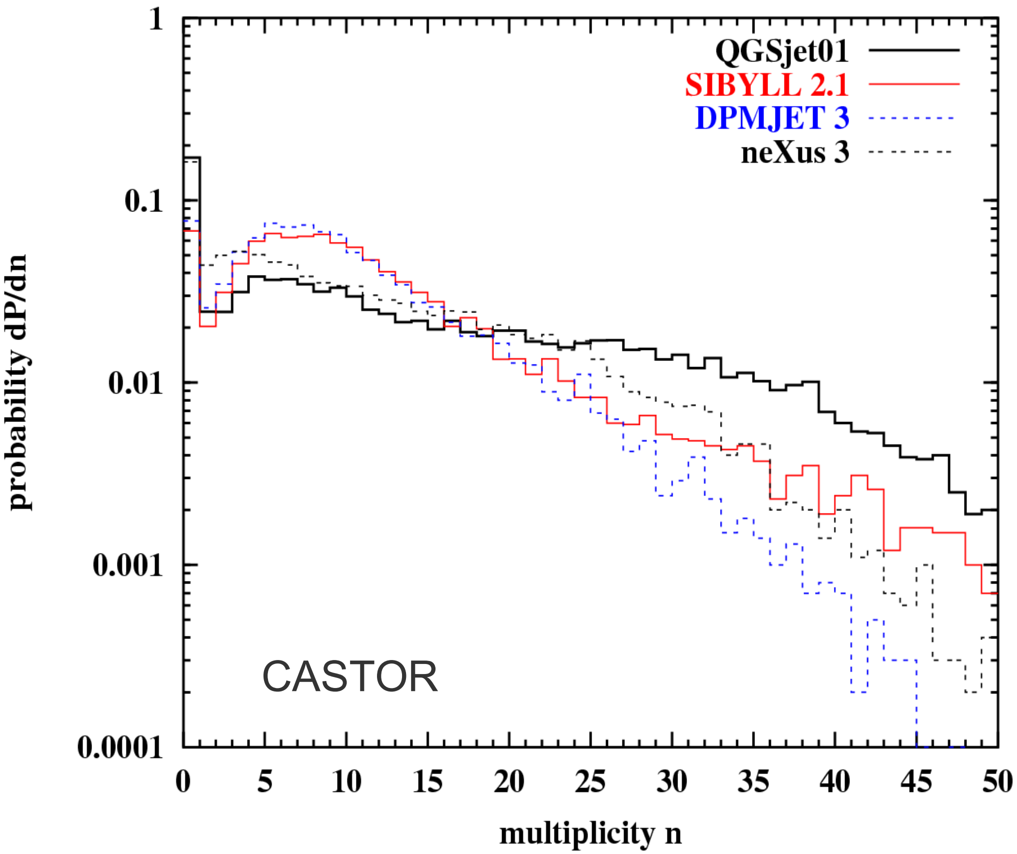
Discrimination potential of LHC (iii)

Total multiplicity in different detector parts:





Central detector: $-3 < \eta < 3$

Forward detector: $5 < \eta < 7$

Constraints from cosmic ray data

Difficulties with cosmic ray beams:

- no direct measurement of interaction
- primary energy unknown
- primary particle unknown

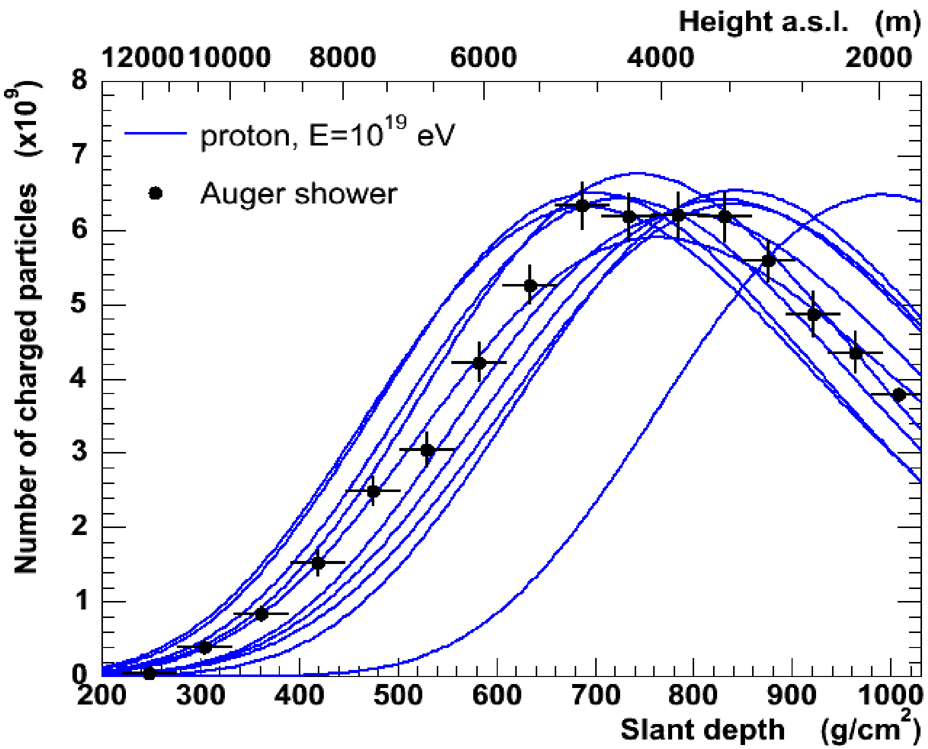
Possible methods of constraining models:

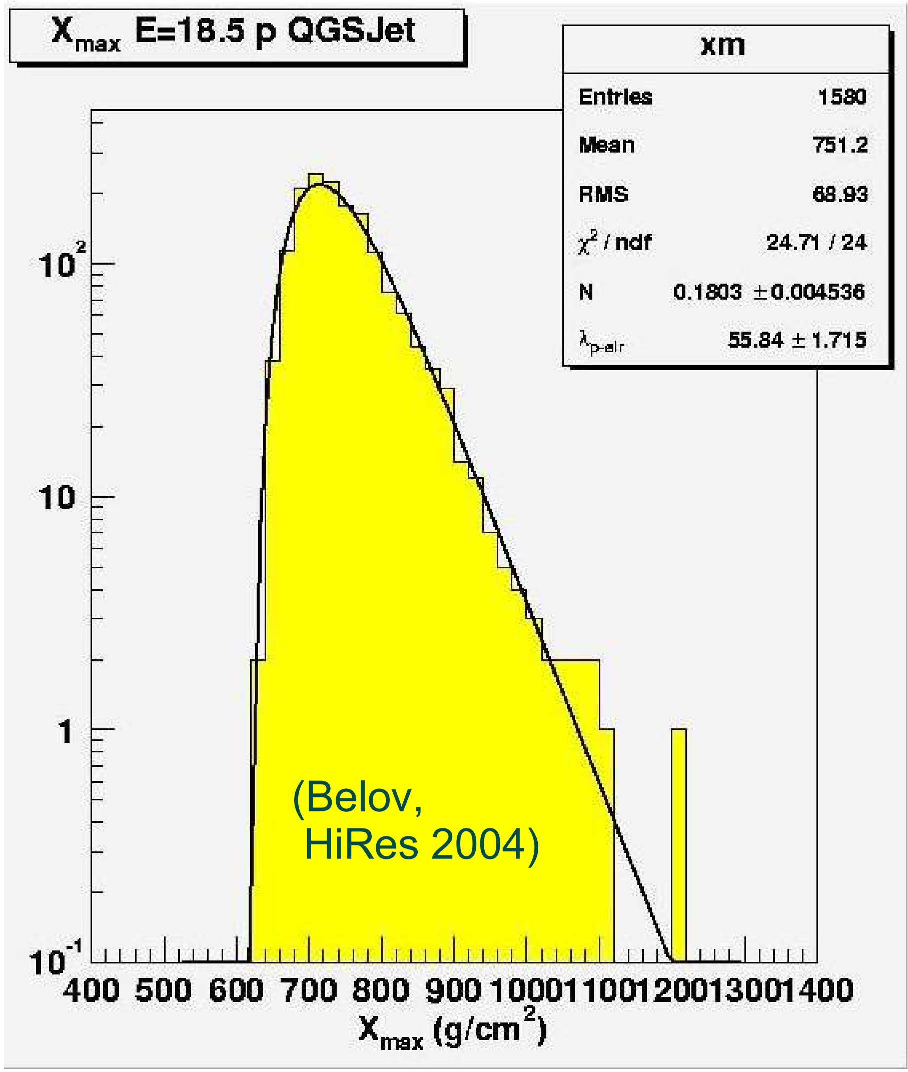
- comparison of measurements to simulated showers assuming a primary energy spectrum and composition
- consistency checks within limits given by expected primary composition
- multiparameter measurements: check of parameter correlations

Model-independent limits on interaction characteristics impossible

Cross section measurement

Correlation between first interaction point and depth of shower maximum



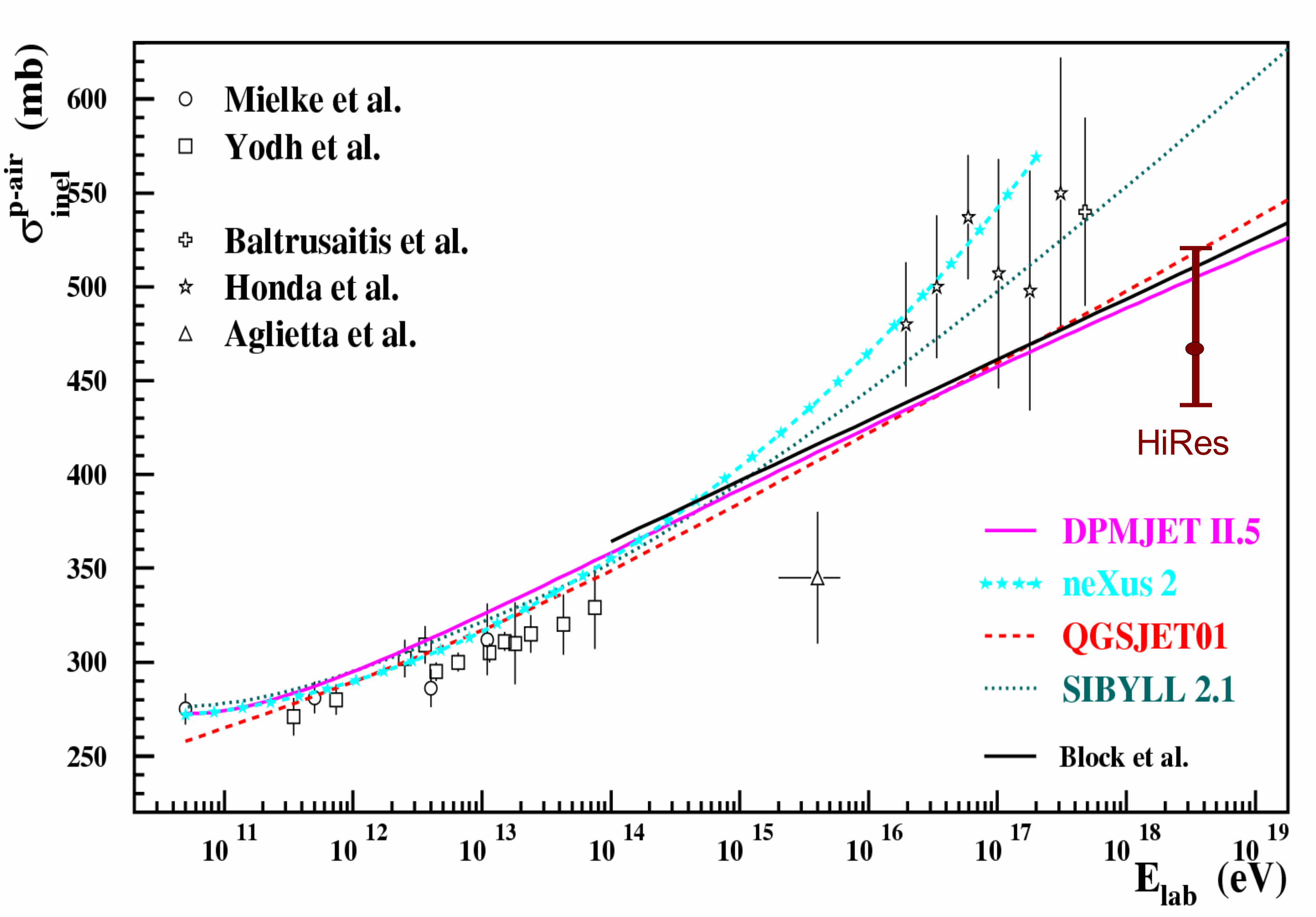


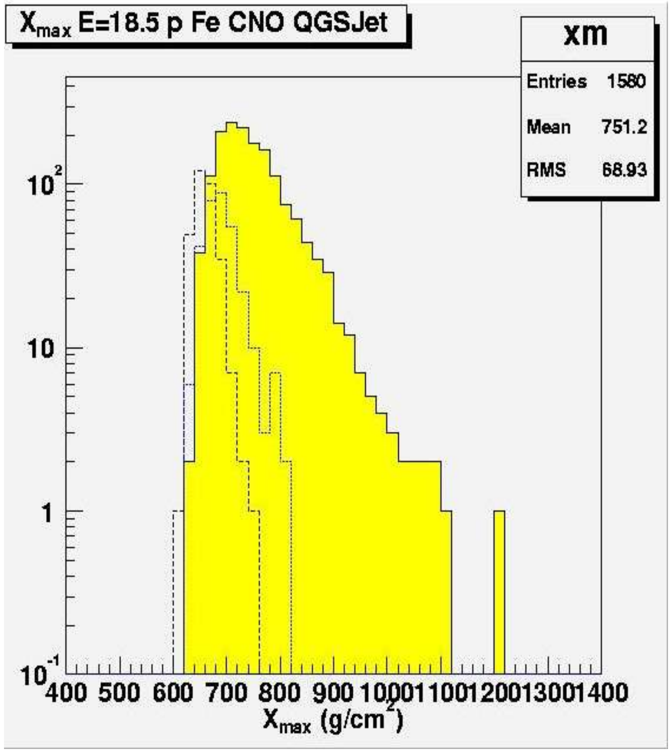
Slope in X_{max} distribution related to interaction length

- selection of proton showers
- selection by energy

HiRes cross section measurement

HiRes result on p-air production cross section





$$\sigma_{in}^{p-Air} = 456 \pm 17\,(stat) + 39(sys) - 11(sys)\ mb$$

possible influence of heavier primaries and gamma-rays

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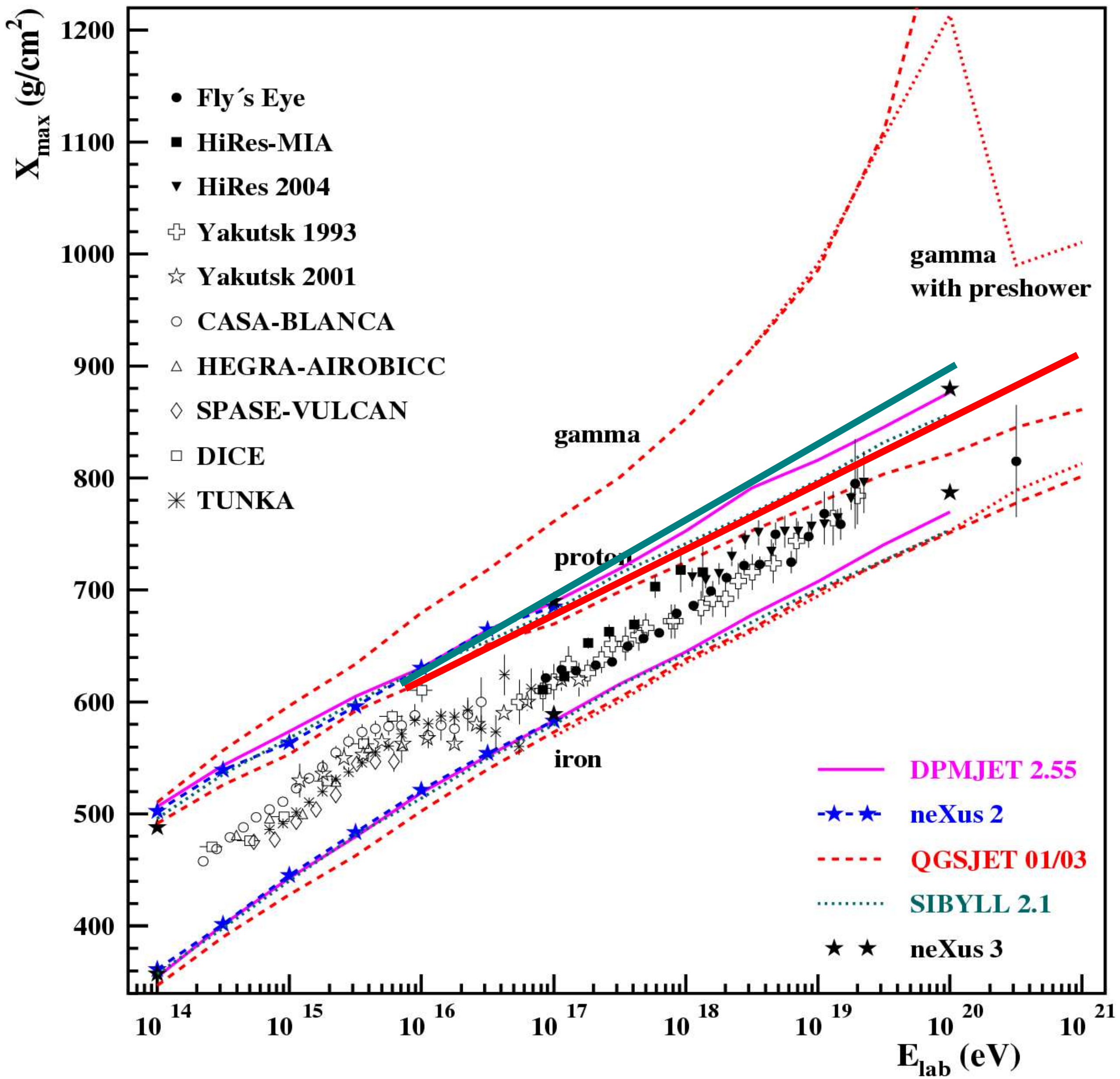
Implications of HiRes measurement



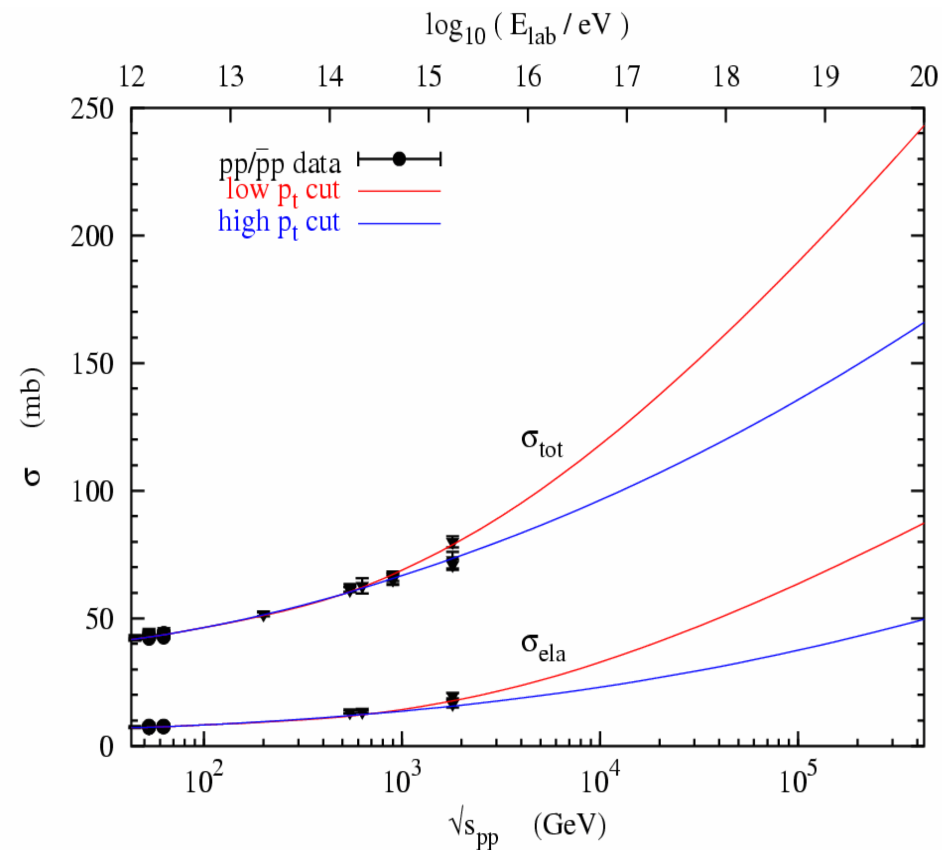
Toy model:

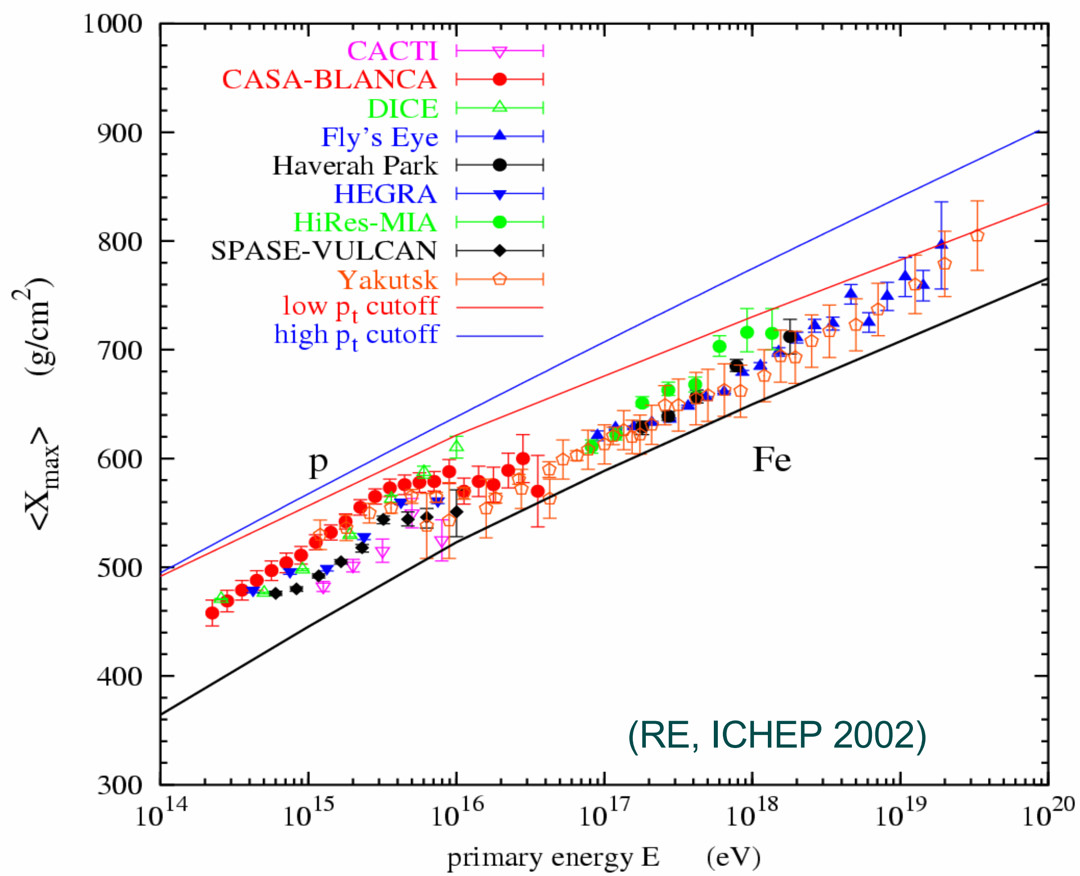
- only cross section of models is re-scaled to fit HiRes measurement
- depth of maximum of proton showers would increase by 25 – 35 g/cm^2
- almost no change for iron showers
- data would correspond to mixed composition for all models

Ralph Engel, 19 Feb 2005

Upper cross section bound ?

Realistic model with steep cross section extrapolation (CDF-like)





- CDF-like extrapolation still consistent with data
- exclusion of extreme increase of cross section possible (but with caveats)

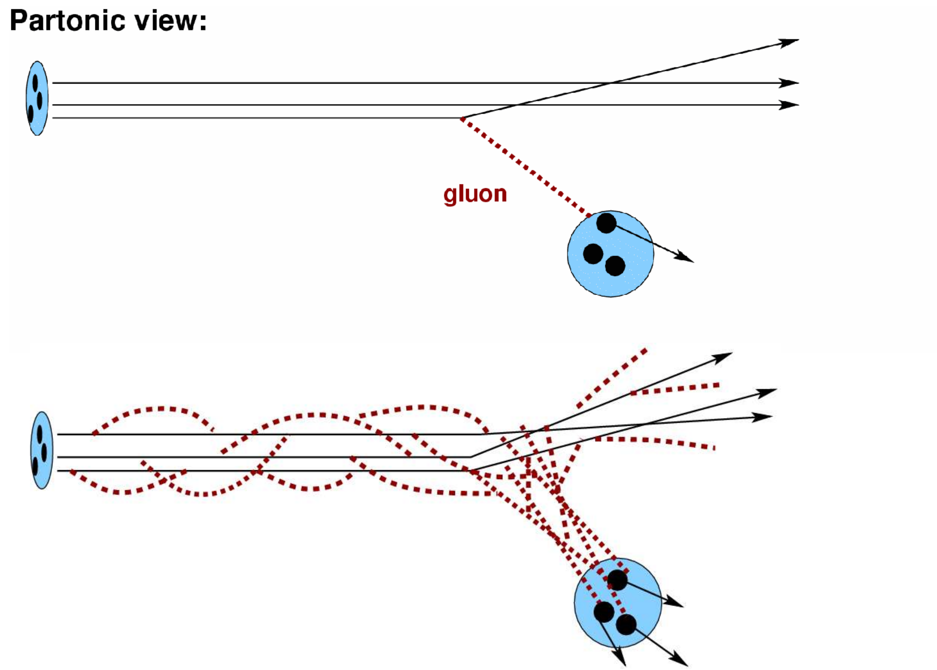
RHIC: parton density saturation?

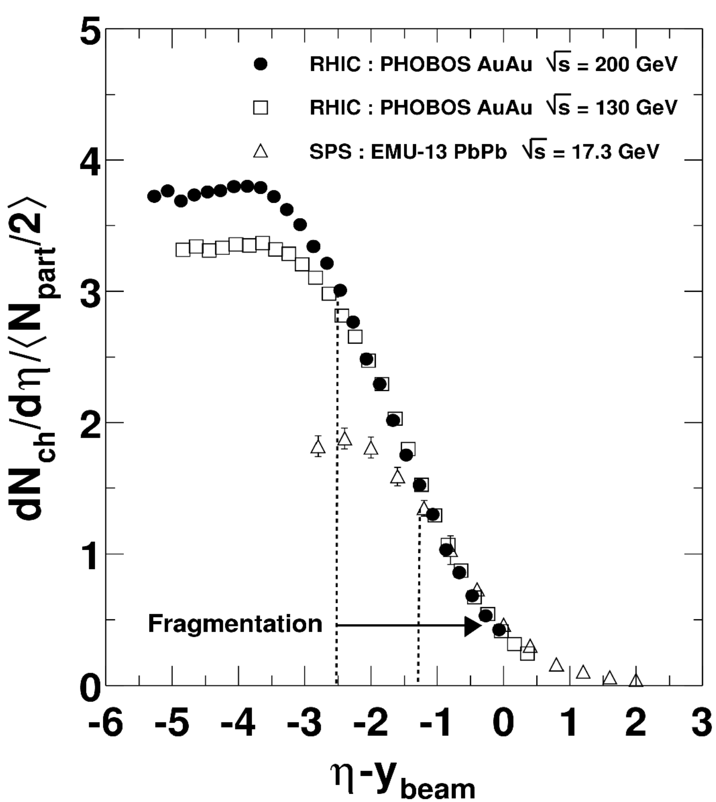
Low energy:

pronounced leading particle effect

High energy & central collision:

black disk limit,
no leading particles

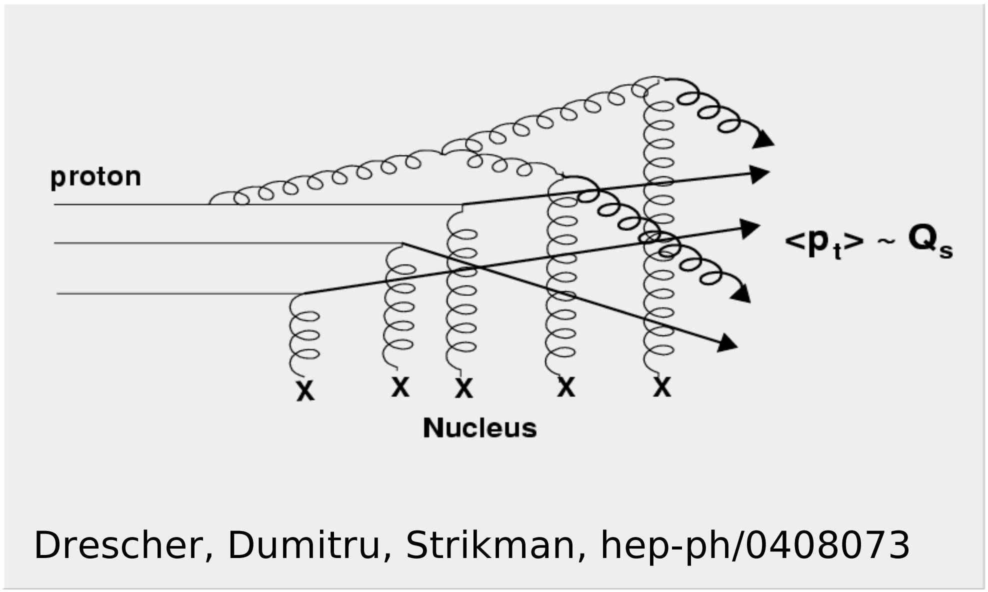


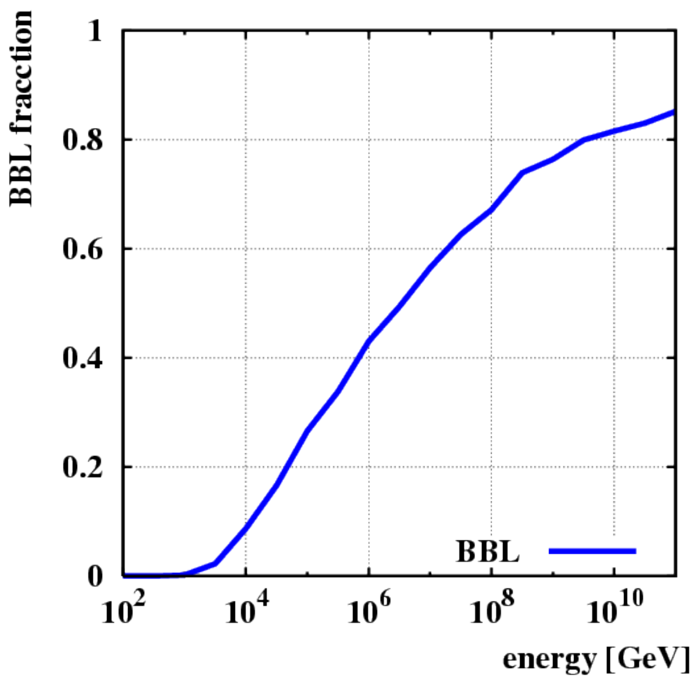


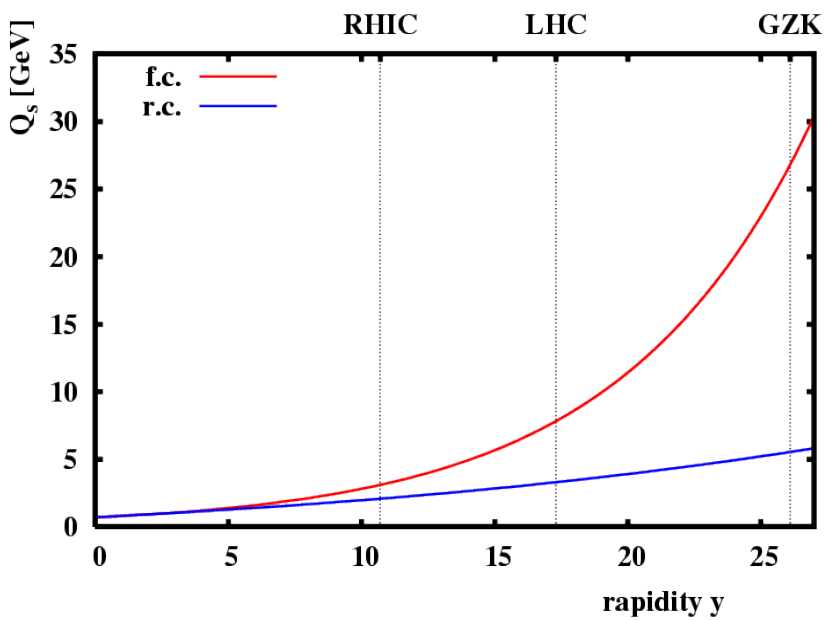
Limiting fragmentation:

no scaling violations seen
in phase space region
accessible with RHIC detectors

Implications of black disk limit







fixed-coupling BFKL:

$$Q_s^2(x, A) = Q_0^2(A)\left(\frac{x_0}{x}\right)^{\lambda}$$

running coupling BFKL:

$$Q_s^2 = \Lambda^2 \exp\left(\log\left(Q_0^2/\Lambda^2\right)\sqrt{1+2c\,\alpha_s\,y}\right)$$

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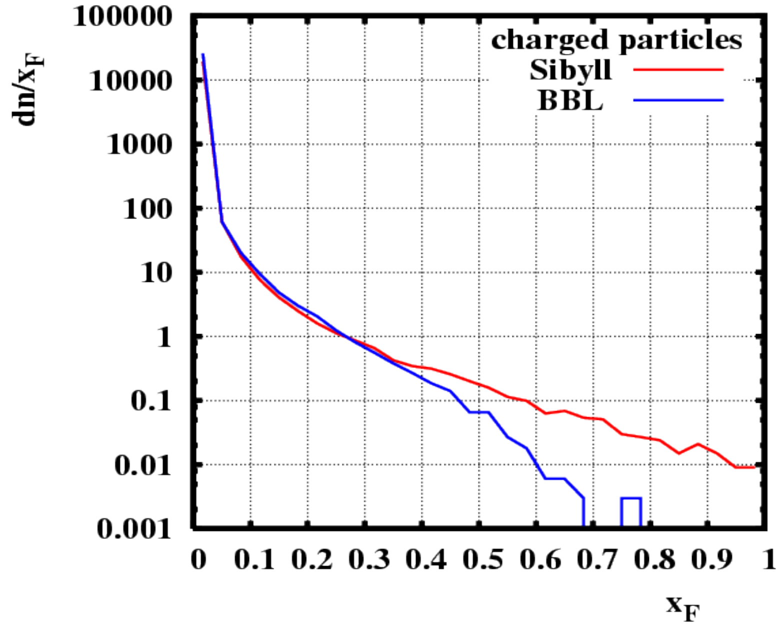
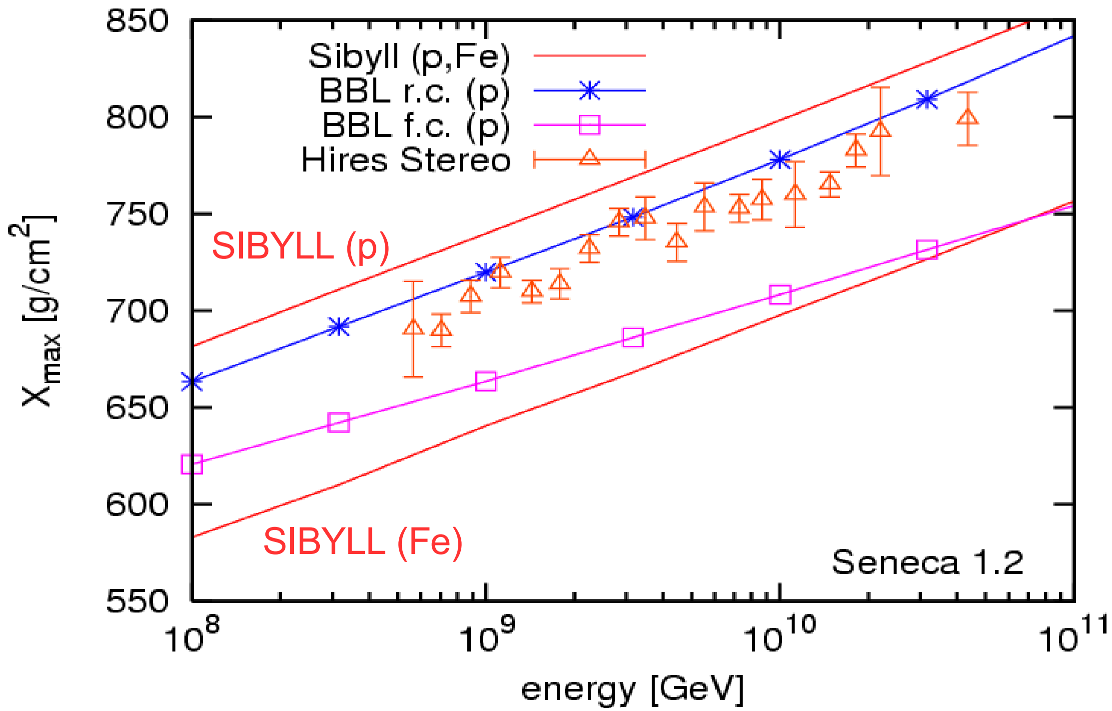
Different saturation scenarios



Leading particle distribution:
air shower predictions sensitive to saturation scale mainly through leading particle effect



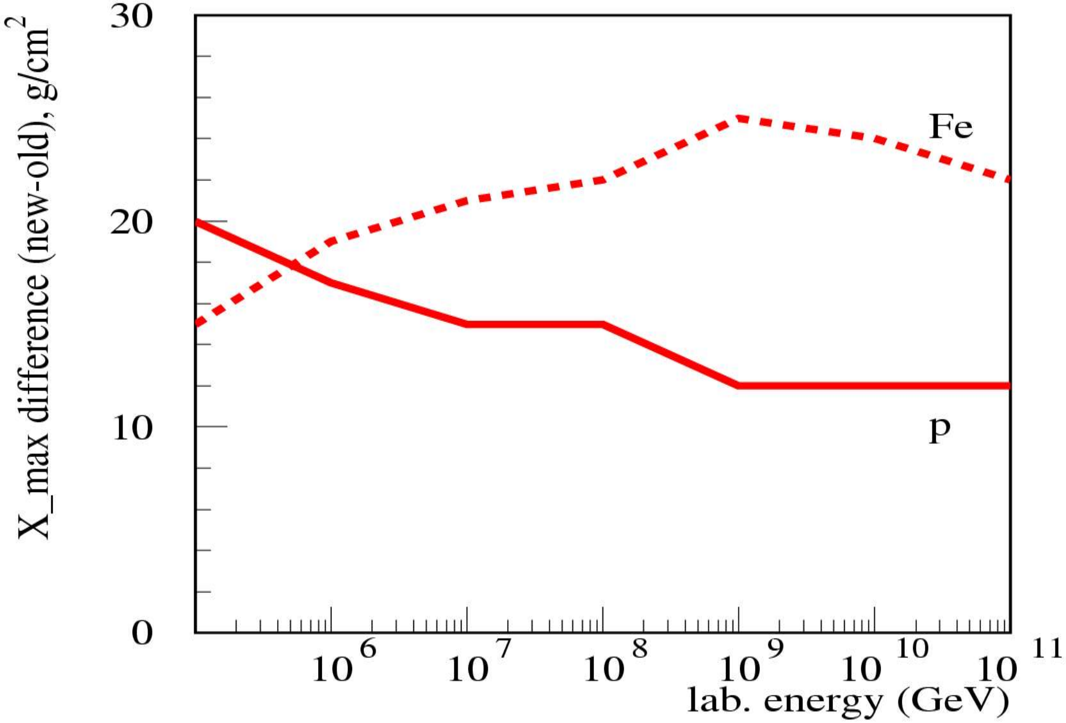
running coupling BFKL:
moderate growth of gluon density

fixed-coupling BFKL:
fast growth of gluon density:
contradiction to data

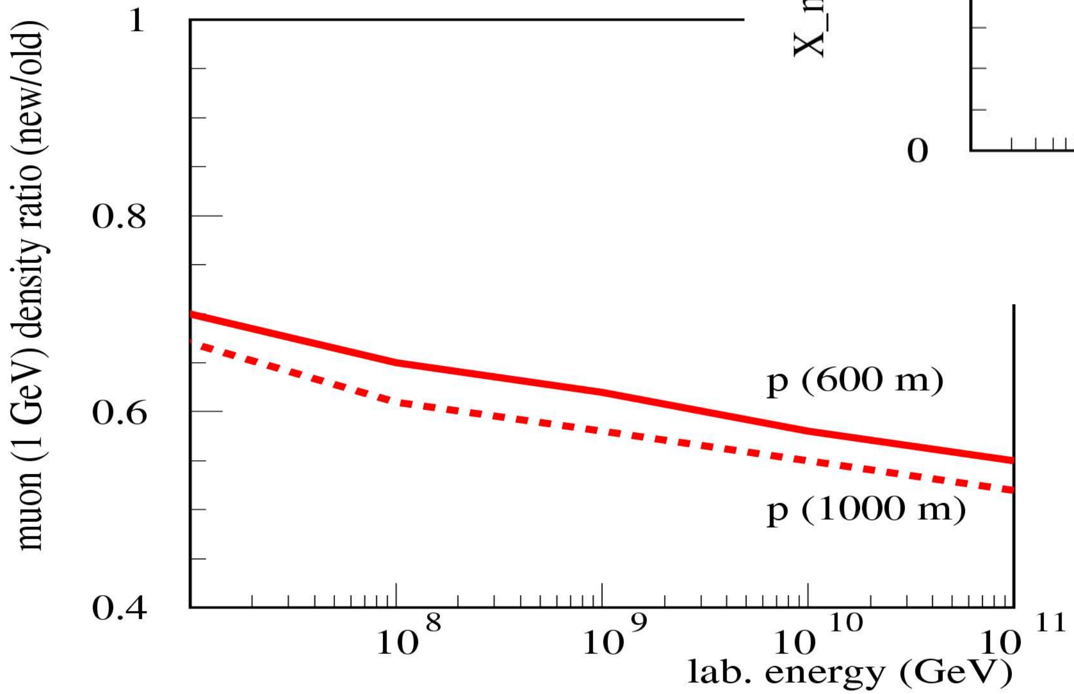
(Drescher, Dumitru, Strikman, hep-ph/0408073)

Preview: new version of QGSJET

QGSJET I:
"standard candle" for simulations
QGSJET II:
- new parton densities
- summation of enhanced pomeron graphs



Muon density (> 1 GeV) ratio



Changes important:
- proton showers more like SIBYLL
- iron showers different
- no superposition model

Summary

- Cosmic rays and extensive air showers

  - air showers rather insensitive to many hadron production details
  - detailed predictions strongly model dependent

- Modelling of hadronic multiparticle production at high energy

  - attempt to formulate self-consistent models (unitarity)
  - large uncertainties due mainly to
    - minijet cross section (p_T cutoff, saturation, ...)
    - relation between inclusive vs. exclusive cross sections
    - leading particle distributions (scaling/scaling violation)
    - nuclear effects

- Accelerator measurements: very important, in particular forward direction

- Information from air shower data:

  - cross section measurement
  - indications for moderate growth of gluon density