Perturbative QCD Predictions and Giant Air Showers

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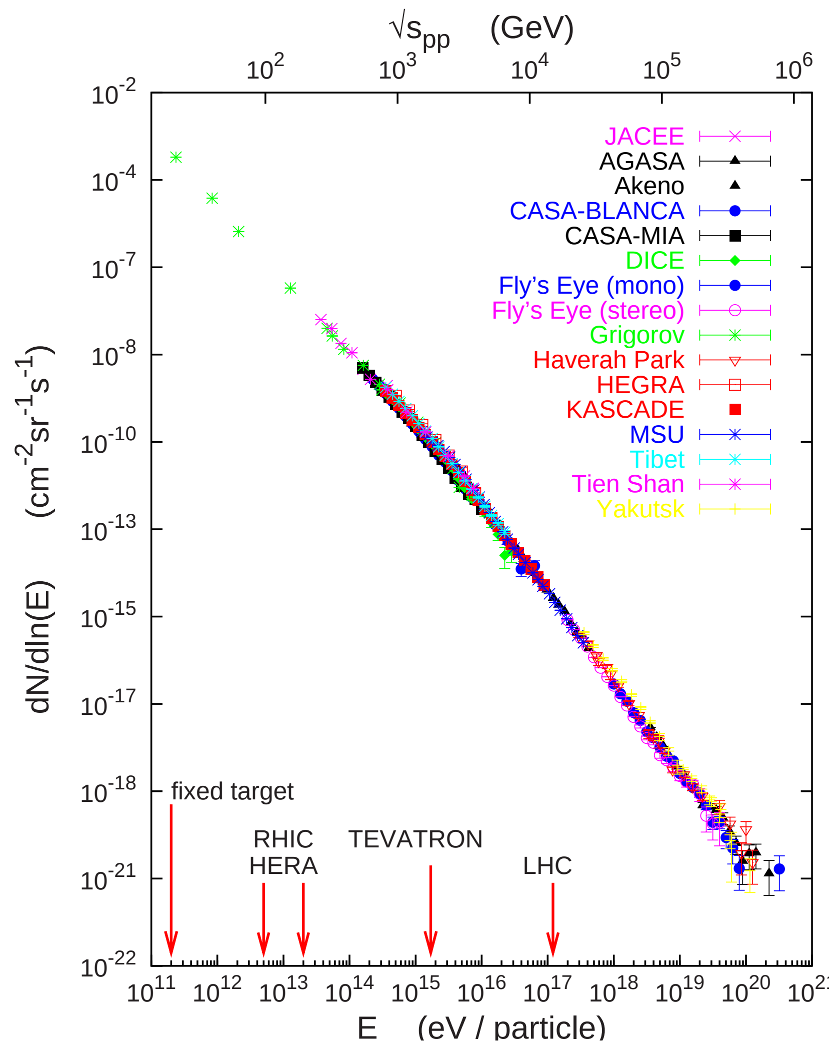
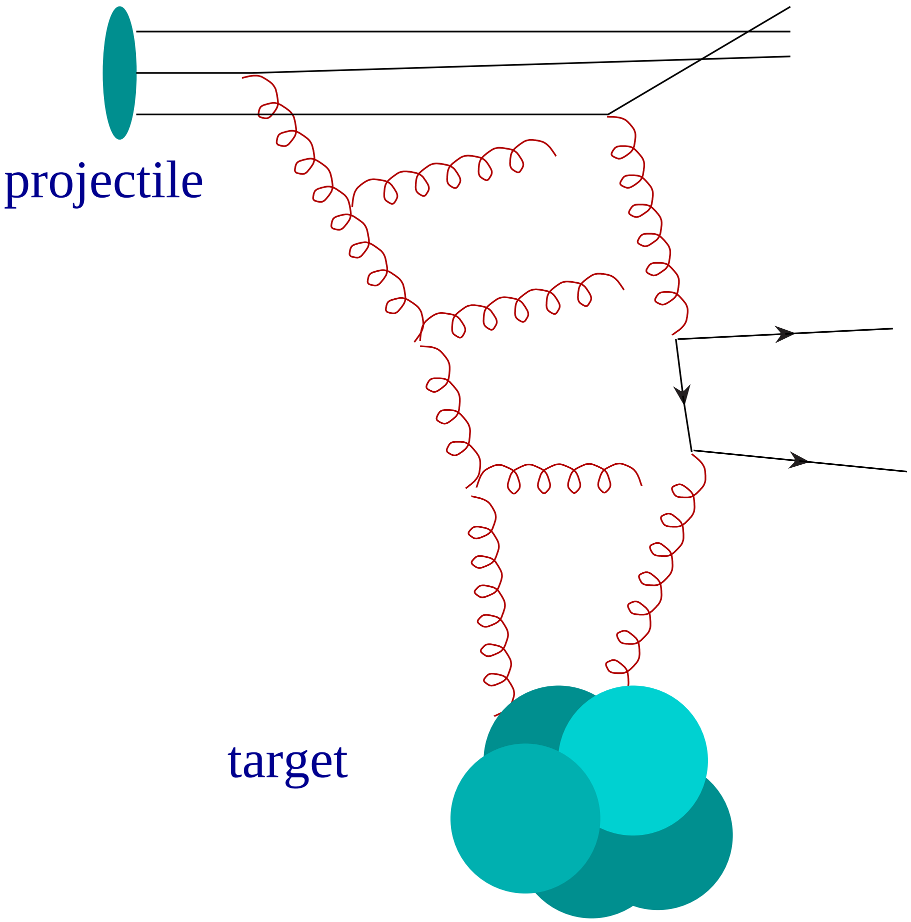
Extensive air showers: energy range comparison

- measured flux extends to $\sqrt{s} \sim 400$ TeV
- highest energy particles extremely rare
- still unexplained: sources, knee, ankle ...
- existence of GZK cutoff at $E \sim 7 \times 10^{19}$ eV ?
- EAS: highly indirect method of measurement which relies on detailed shower simulation



Partonic view: structure of QCD inspired models

- model for nucleon-nucleon interaction
  - central particle production (soft interactions, minijet production)
  - leading particle production (projectile remnant, diffraction dissociation)
- generalization to hadron-nucleus and nucleus-nucleus interactions
- fragmentation and hadronization
- intranuclear cascade, etc.



Are minijets important for EAS simulations?

- NO:
  - high-$p_\perp$ hadrons are rare
  - jets cannot be resolved as subshowers at sea level (however high altitude experiments)
  - particles from jet fragmentation are slow in target rest frame
- YES:
  - minijet cross section dominant contribution at high energy: total cross section
  - leading particle distributions affected by energy-momentum conservation
  - low-energy muons are produced by decay of slow partons

Reliability of minijet phenomenology

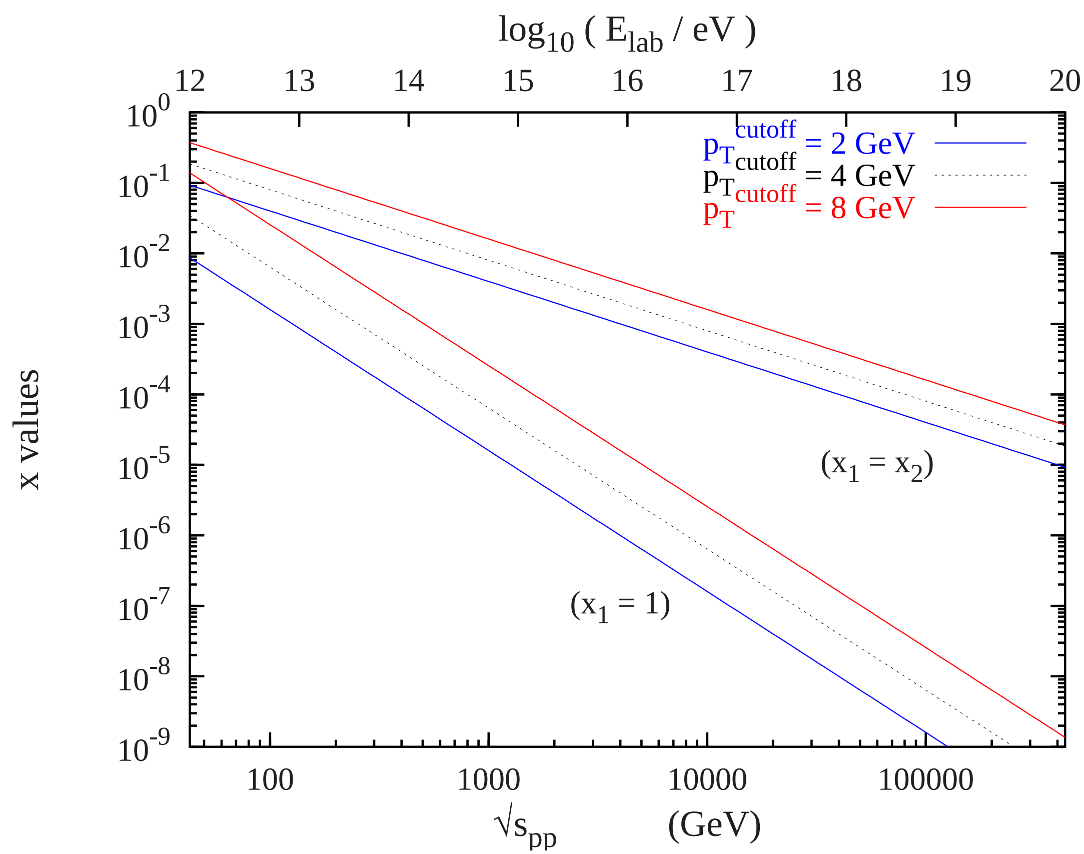
- kinematics:

$$x_1 x_2 \geq \frac{4p_\perp^2}{s}$$

- minijet cross section depends on $p_\perp^{\text{cutoff}}$

- parton densities measured in limited x, Q^2 range

- higher order corrections

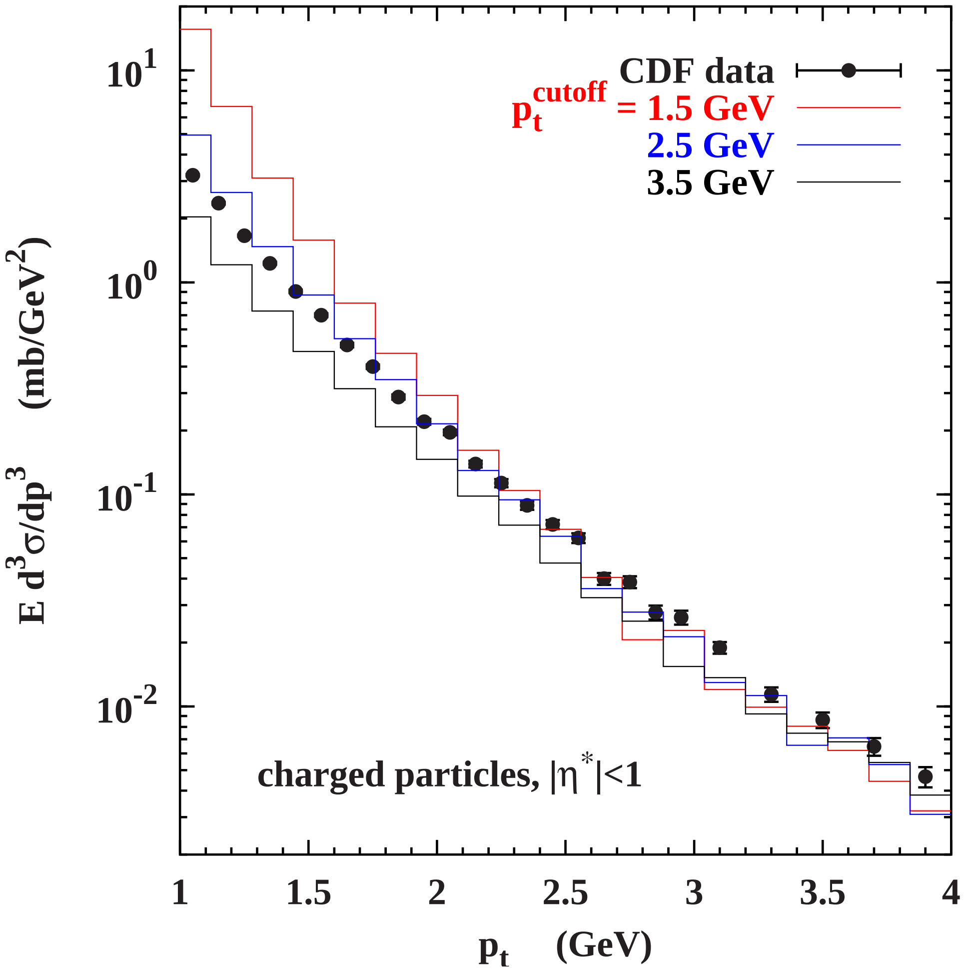


- Tevatron data ideal for cross check:

important range of x, Q^2 covered by HERA

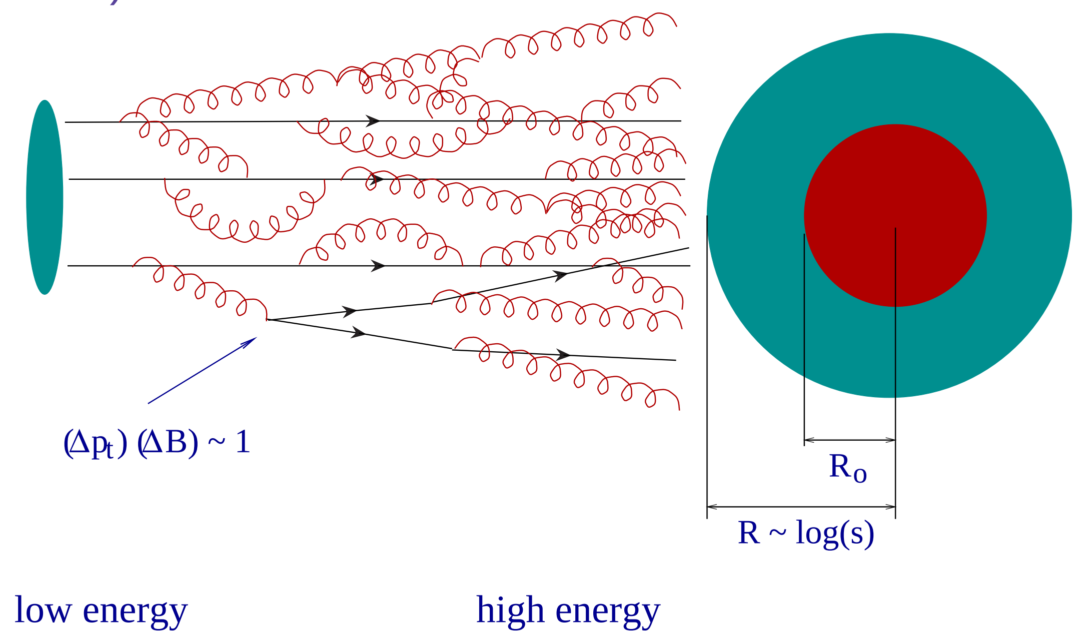
Comparison with Tevatron data

- low-energy data favours $p_\perp^{\text{cutoff}} \sim 1.5 \ldots 2\text{GeV}$
- k-factor of $k = 2$ used
- inclusive cross section not affected by unitarity corrections



Parton density screening/saturation effects

- predicted already in 1983 (Gribov, Levin, Ryskin)
- intuitive (geometric picture):



- saturation scale:

$$Q_s^2 \simeq \alpha_s(Q_s^2) \frac{xG(x, Q_s^2)}{\pi R^2}$$

Saturation: energy-dependent transverse momentum cutoff

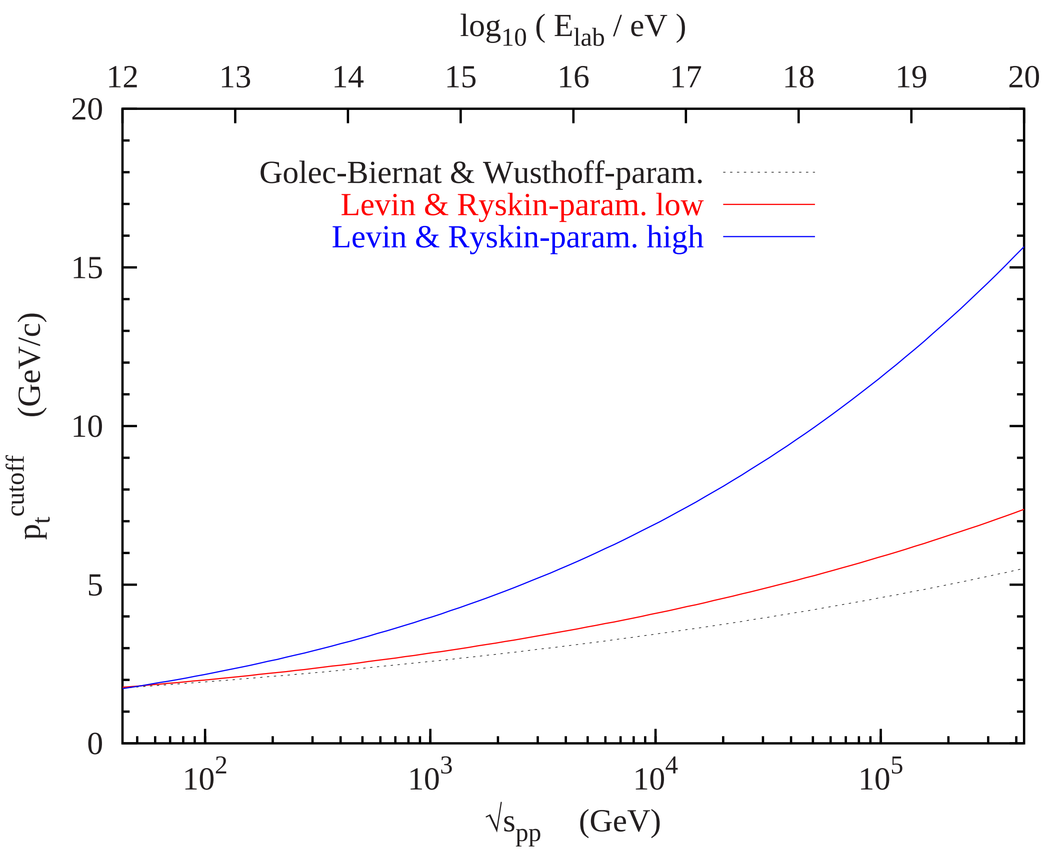
- Gribov, Levin & Ryskin (1983), Levin & Ryskin (1990)

$$p_\perp^{\text{cutoff}} = p_\perp^0 + \Lambda \exp\left\{ c\sqrt{\ln s} \right\}$$

- Golec-Biernat & Wüsthoff (1998)

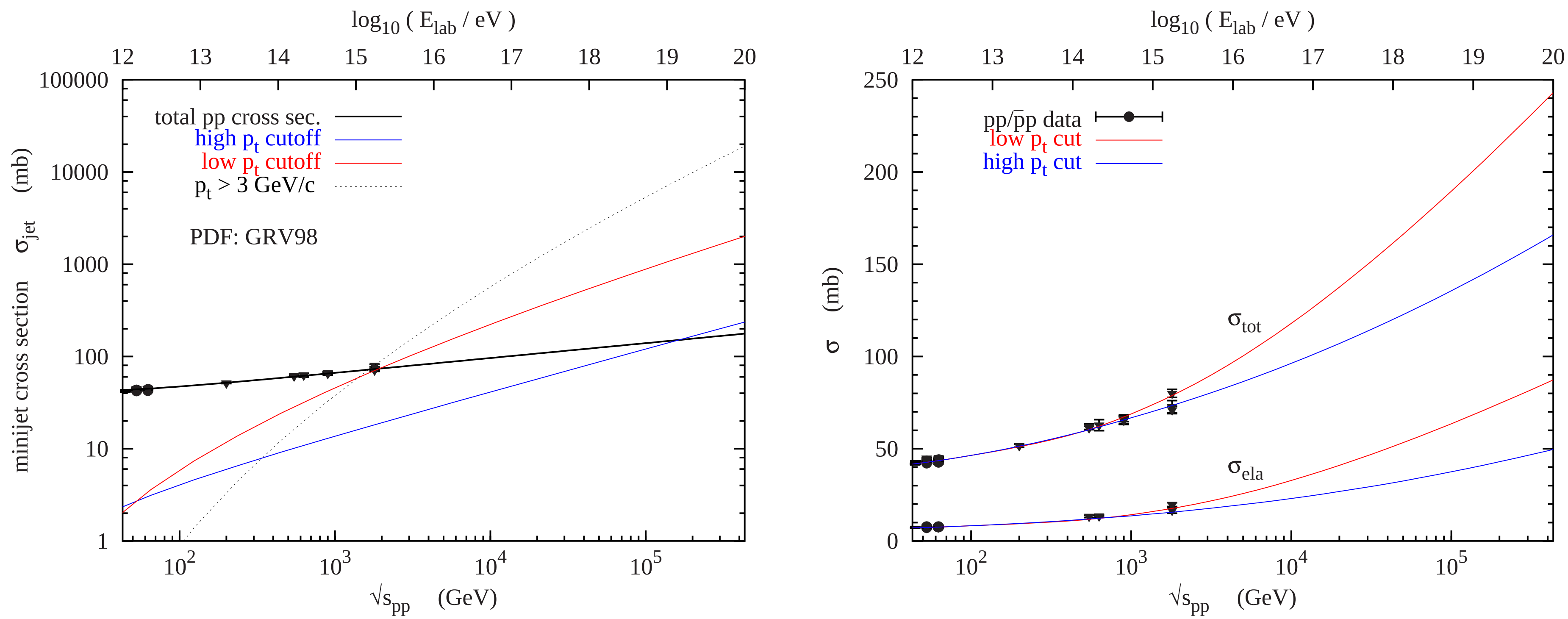
$$p_\perp^{\text{cutoff}} = p_\perp^0 \left(\frac{s}{s_0} \right)^{\lambda/4}$$

- parameters not well constrained by data



Construction of hadronic interaction model

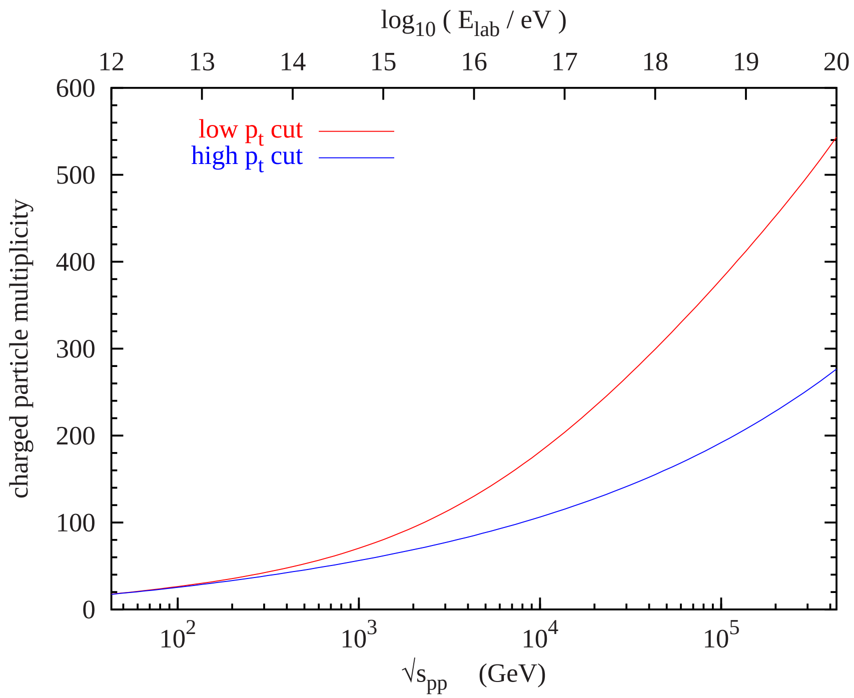
- SIBYLL is used as model with different minijet cross sections

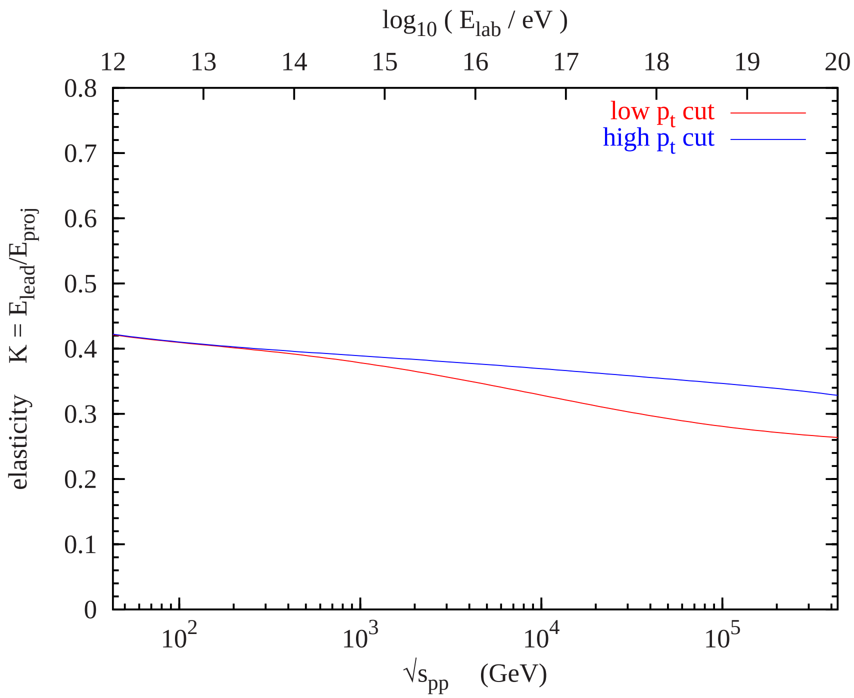


- difference in p-p cross sections reduced due to unitarization
- difference in p-air cross sections small due to geometric size of air nucleus
- model with larger cross section predicts higher multiplicity

Extrapolation of model predictions: p-air collisions

- Gribov-Glauber formalism used to model p-air interactions from p-p collisions

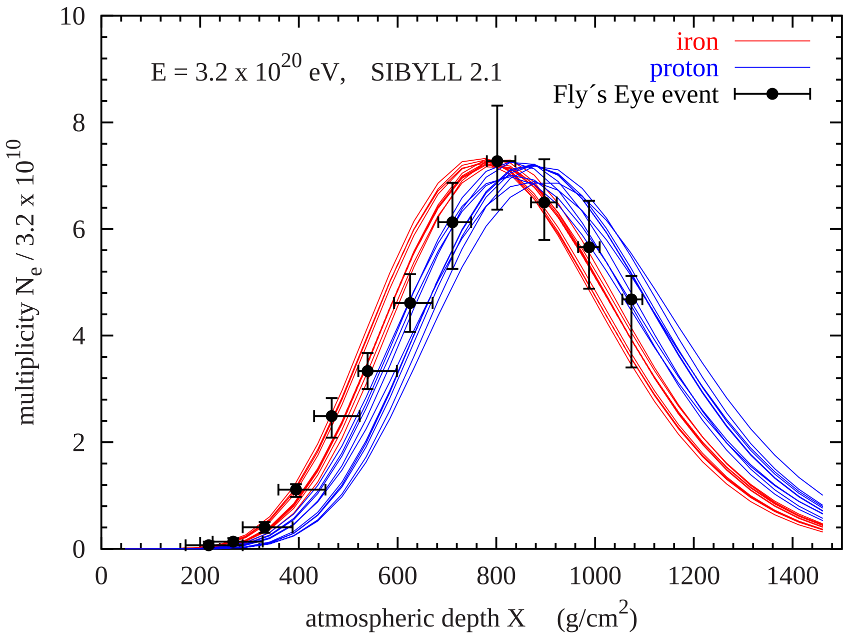




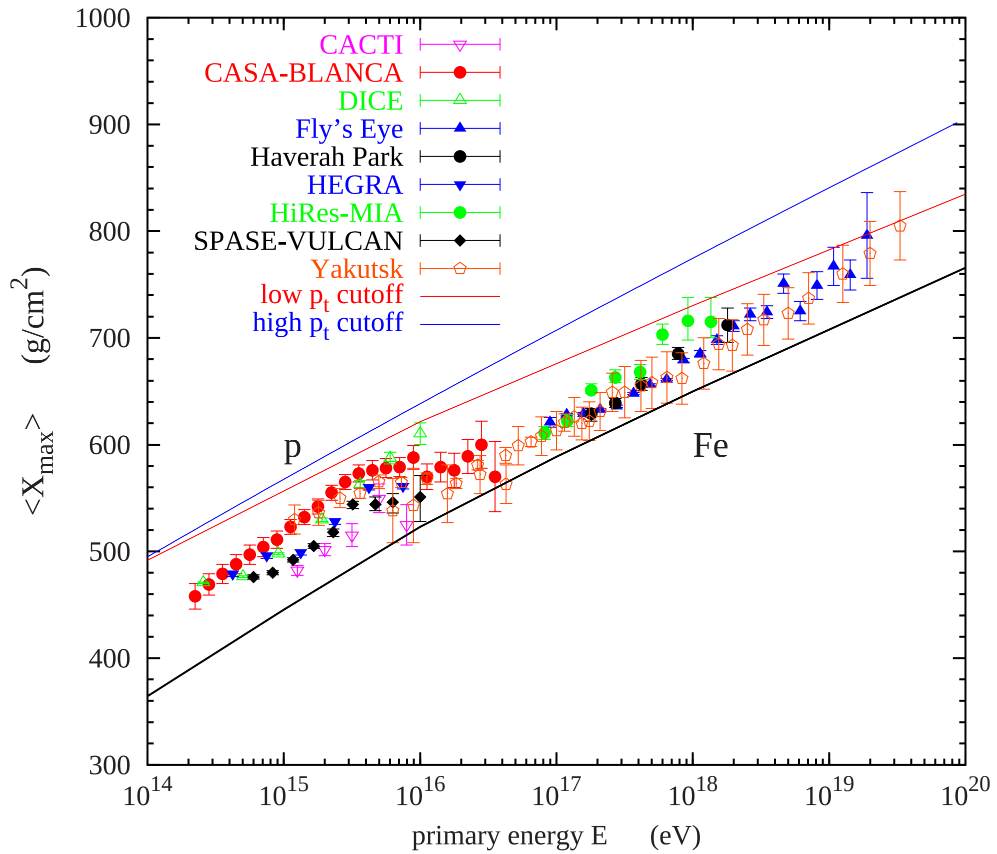
- large difference in predicted secondary particle multiplicity
- multiplicity influences elasticity via energy conservation

Extensive air shower predictions (i)

- longitudinal shower profile:



- depth of shower maximum:

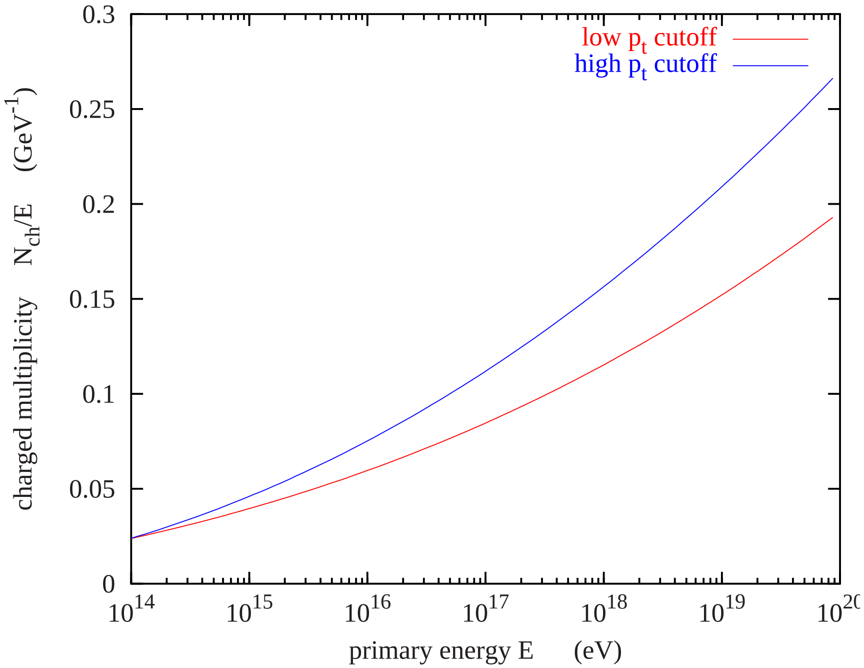


- depth of shower maximum depends mainly on cross section and elasticity

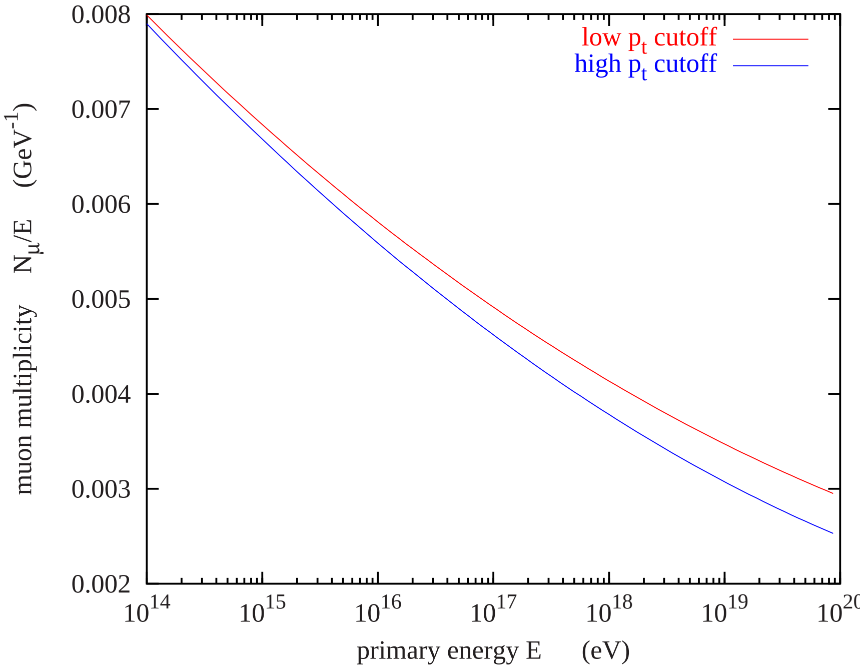
Extensive air shower predictions (ii)

- multiplicities at observation level (CORSIKA, Auger altitude, $\theta = 45^\circ$)

- charged particle multiplicity (mostly $e^\pm$):



- muon multiplicity ($E_\mu > 300$ MeV):



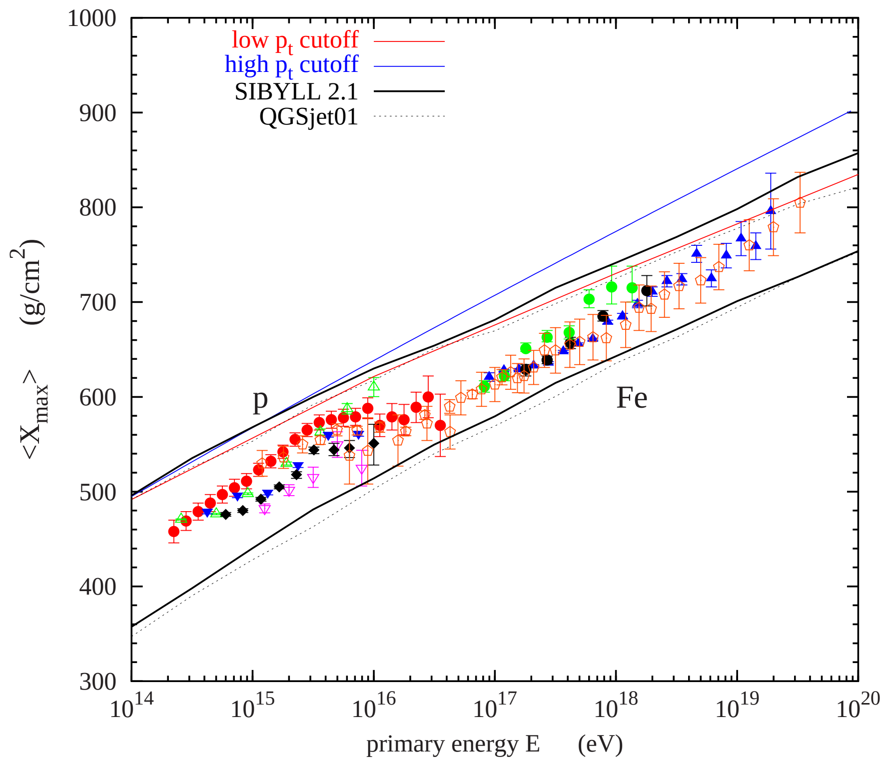
- anticorrelation between N_μ and $N_{e^\pm}$ also typical for transition to heavy primaries
- number of particles at shower maximum independent of model

Summary & conclusions

● extrapolation using HERA data only possible with parton screening / saturation

● minijet cross section is source of important uncertainties in EAS simulations

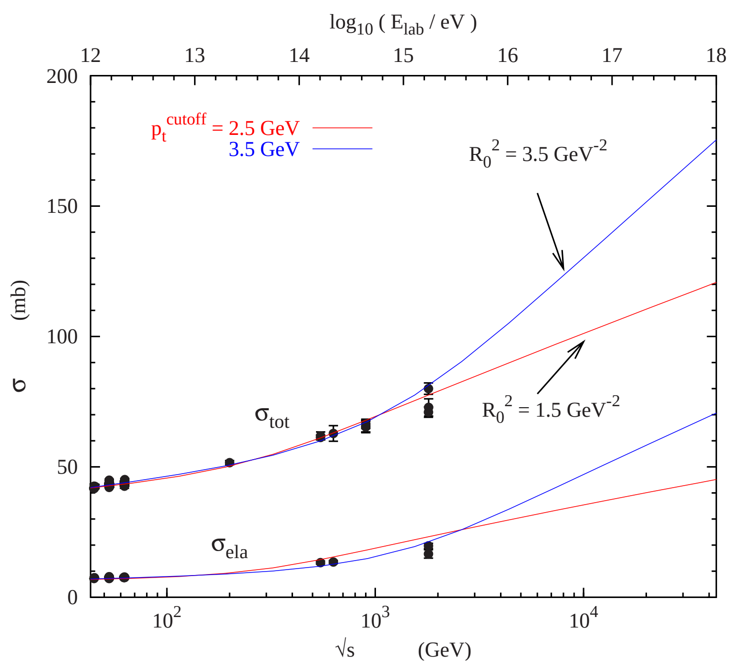
● study of reliability and range of applicability of QCD minijet predictions needed

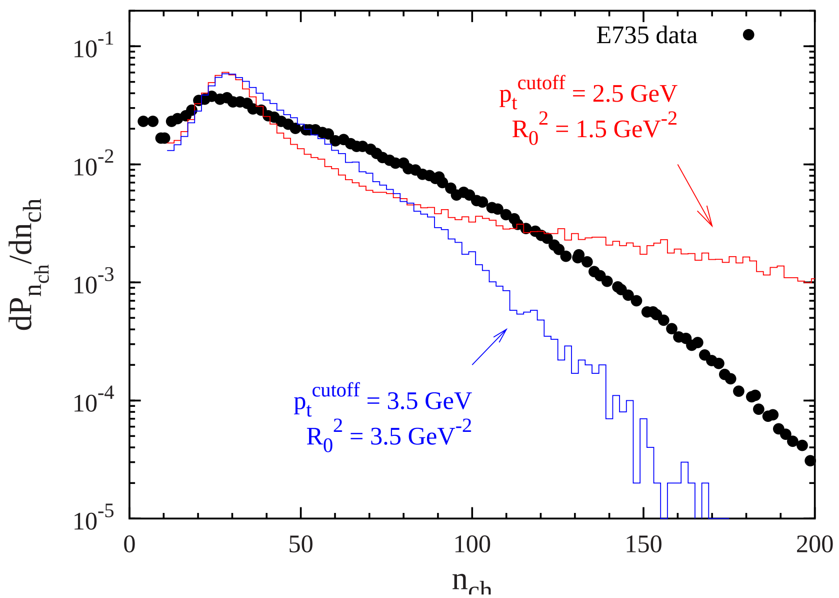


● multi-component EAS measurements can help to exclude extreme low- or high-multiplicity extrapolations

● detailed analysis of primary high-energy interaction characteristics impossible due to complex relation to shower parameters

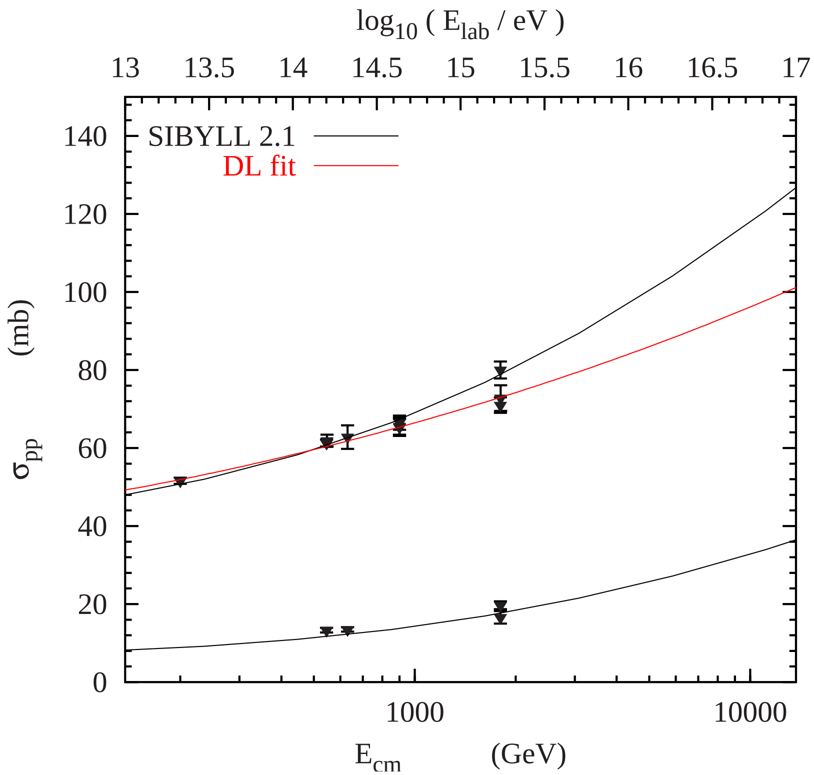
Relation between multiplicity and total cross section

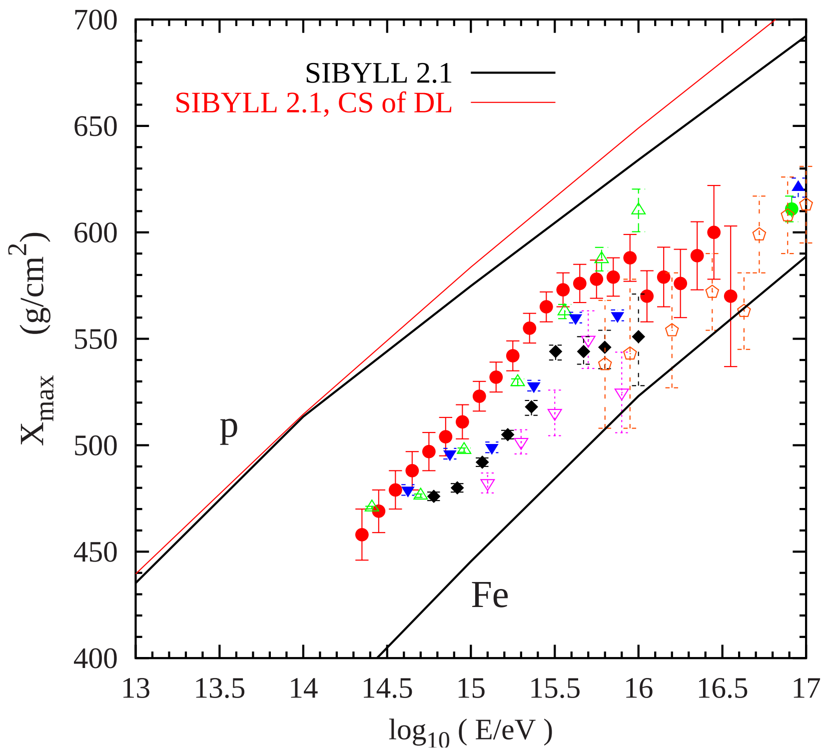




- correlation between eikonal function and multiplicity distribution / total cross section
- small transverse size: large fluctuations and small cross section
- large transverse size: small fluctuations and large cross section

Importance of Tevatron cross section measurement





- simulations with SIBYLL 2.1 using two different cross section extrapolations