Theory of Hadronic Interactions and Its Application to Modeling of Cosmic Ray Hadronic Showers

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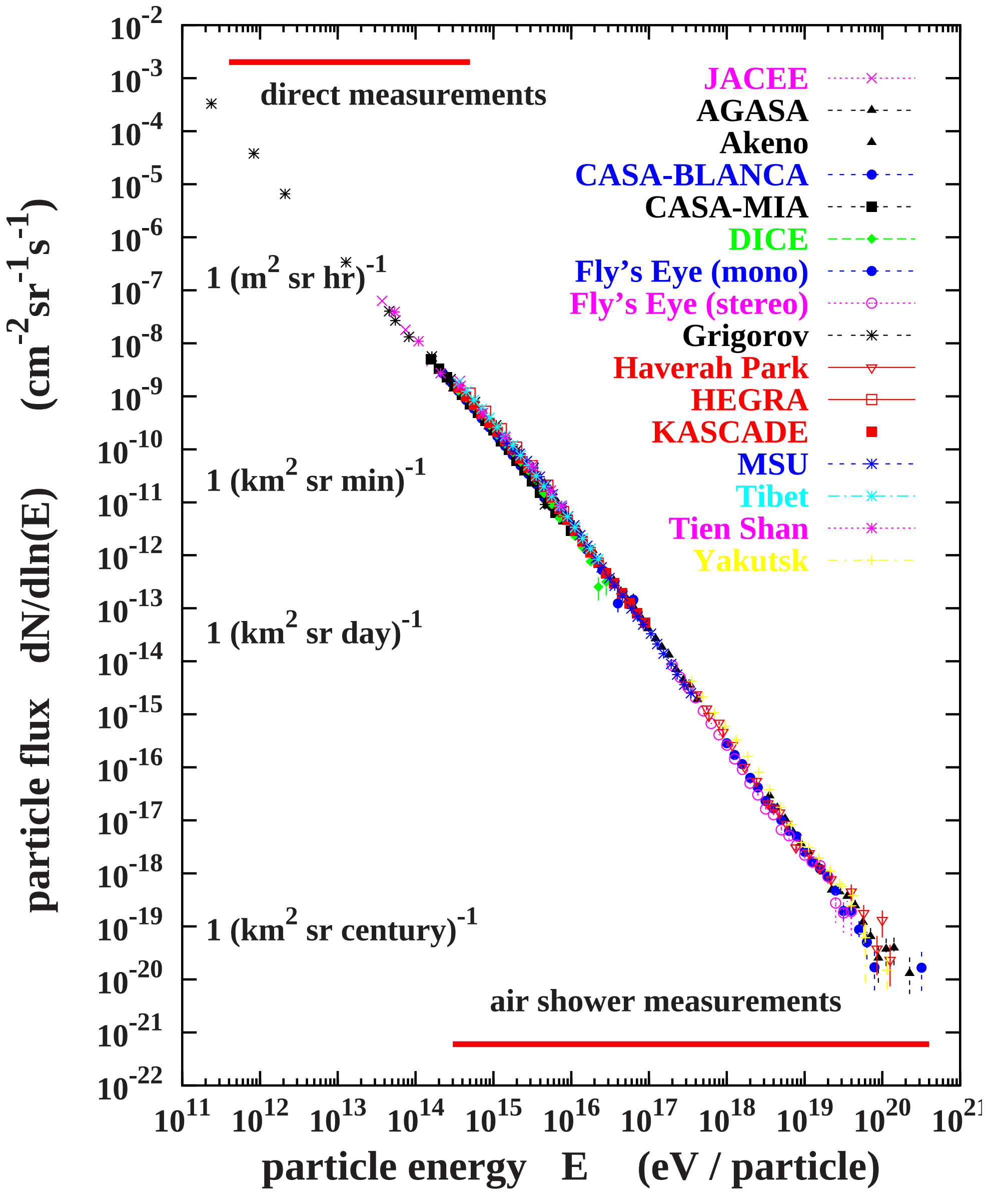
Outline

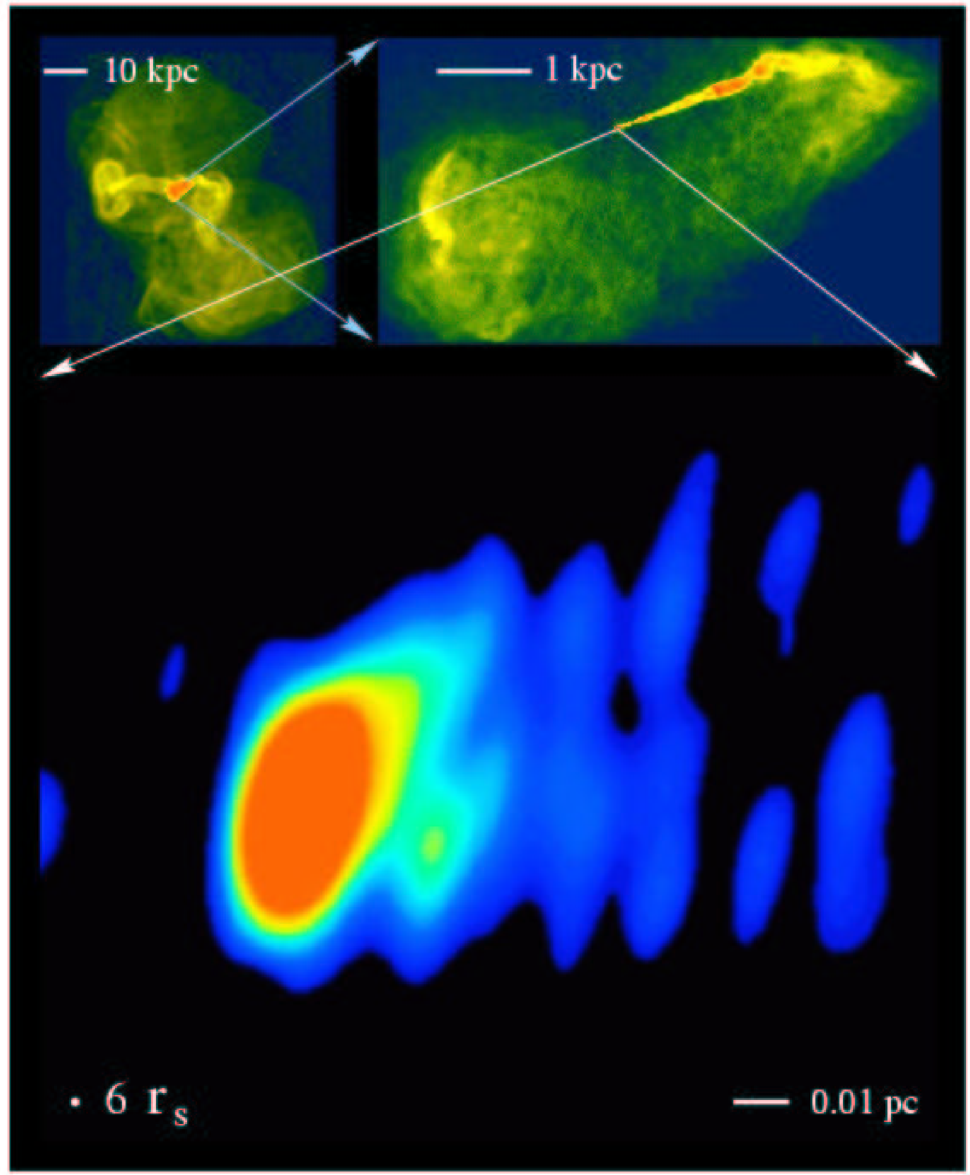
- cosmic ray flux and energies
- physics of air showers
  - physics of air showers and their characteristics
  - basic methods for measuring energy and composition
- hadronic interaction models
  - pomeron interpretation, minijets and parton densities
  - unitarization and cross sections
  - leading particle production
  - generalization to nuclear projectiles and targets
- predictions for LHC (central and forward)
- constraints from cosmic ray data

Local interstellar cosmic ray flux

- all energies refer to total particle energy
- measured flux extends to $E_{\mathrm{lab}} \approx 3 \times 10^{20}$eV
- highest energy particles extremely rare
- still unexplained: sources, knee, ankle ...
- existence of GZK cutoff at $E \sim 5 \ldots 7 \times 10^{19}$ eV ?
- hypothetical sources:
  – below ankle: galactic
  – above ankle: extra-gal.



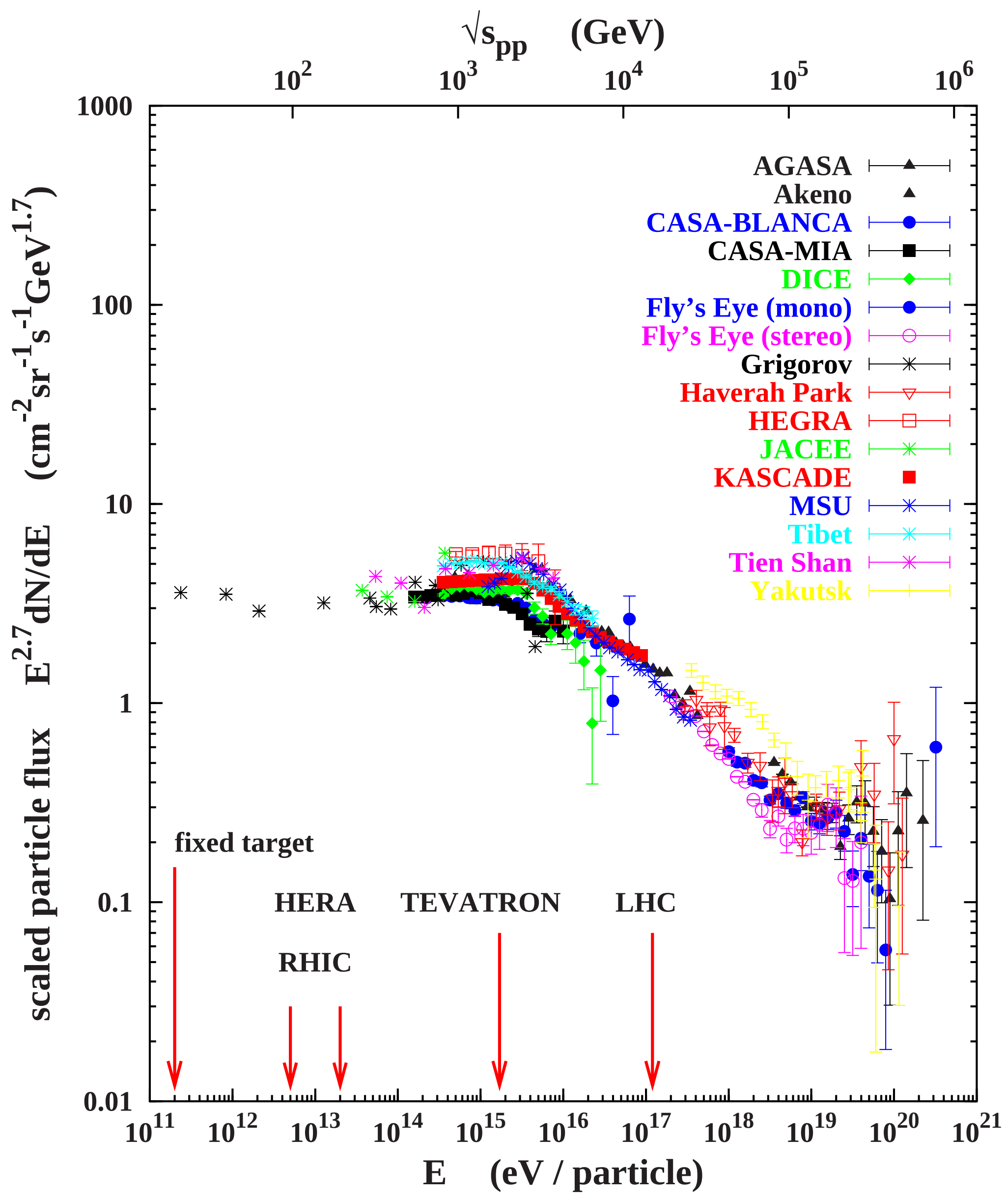
Hypothetical sources of high-energy cosmic rays

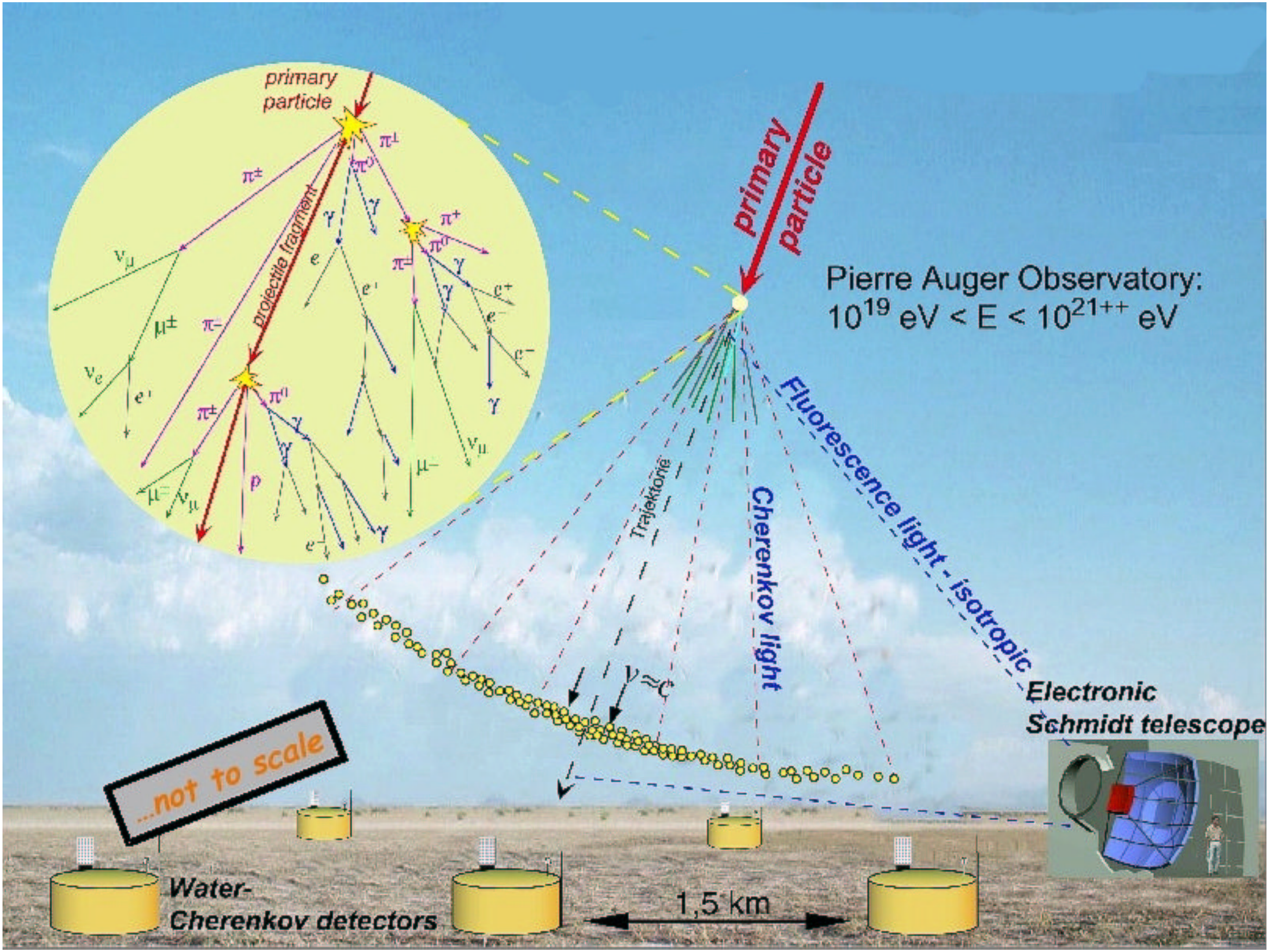


Crab Nebula (SNR) and M87 (AGN)

Cosmic ray flux: energy comparison

- power-law spectra
  - low-energy index: -2.7
  - high-energy index: -3.1
- particle type
  - low energy:
    mainly H .... Fe ions
  - high energy:
    unknown
- measured flux extends to $\sqrt{s_{pp}} \sim$ 400 TeV
- knee coincides with Teva-tron energy
- ankle above LHC energy





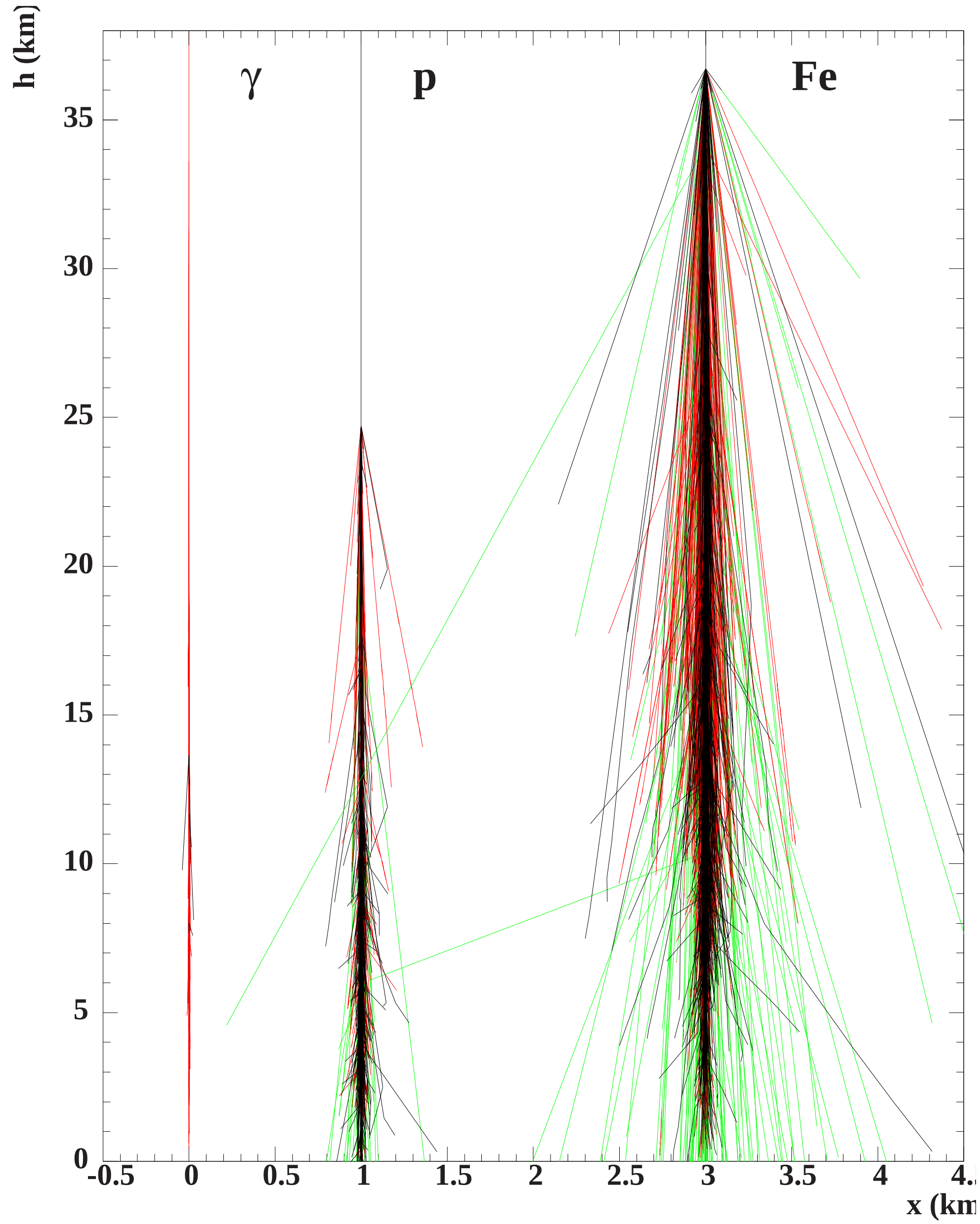
primary particle
π±
π0
γ
π+
π−
νμ
μ±
νe
e
e+
e−
p
projectile fragment
primary particle
Pierre Auger Observatory:
10^19 eV < E < 10^21++ eV
Fluorescence light - isotropic
Cherenkov light
Trajektorie
v≈c
Electronic
Schmidt telescope
...not to scale
Water-
Cherenkov detectors
1,5 km

Simulation of extensive air showers

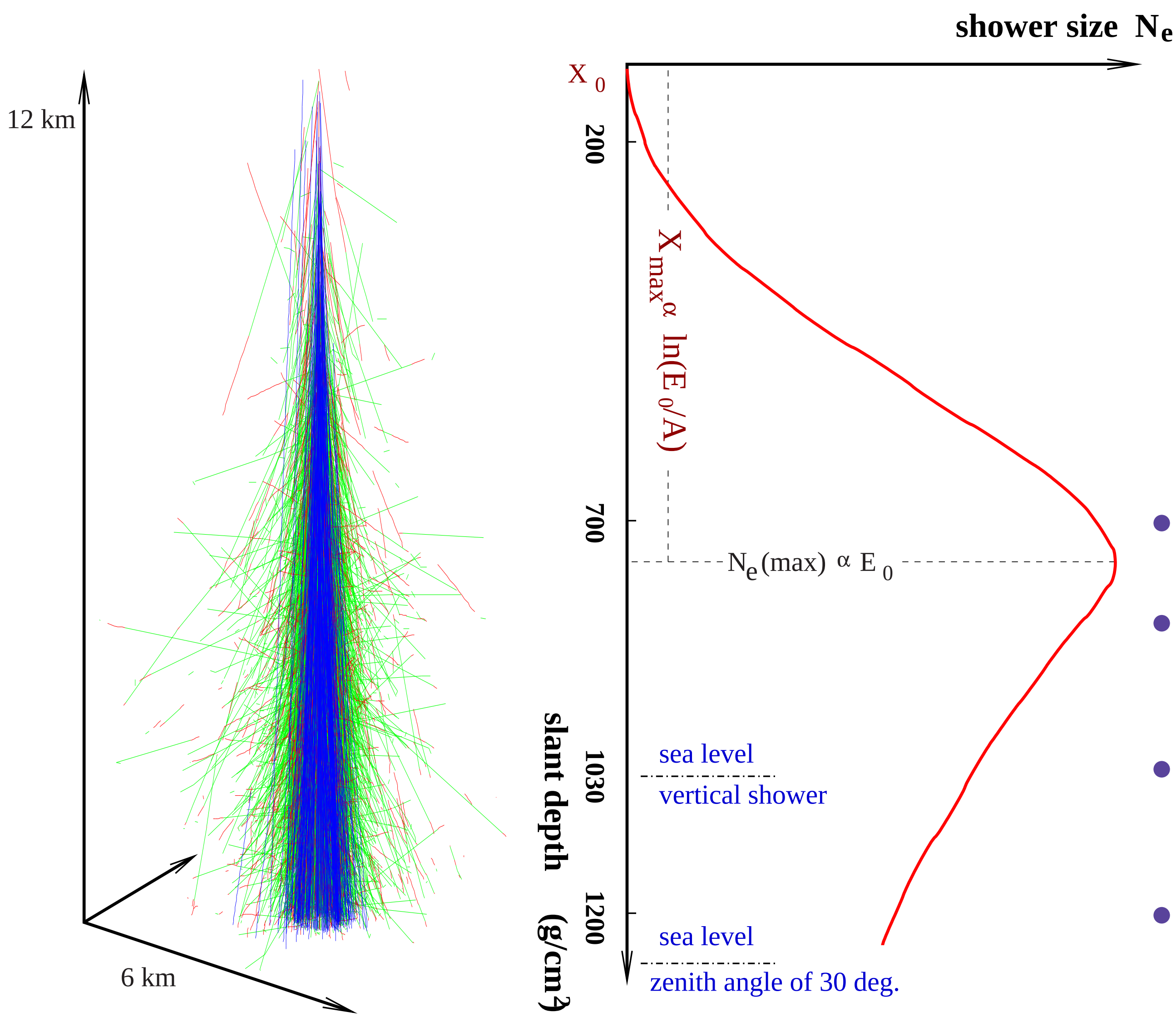
- particle production (hadronic, electroweak)
- propagation, decay
- energy loss and deflection in geomag. field
- public MC codes:

  CORSIKA (Heck et al.)
  AIRES (Sciutto et al.)
  SENECA (Drescher et al.)

- problematic: simulation and extrapolation of hadronic multiparticle production



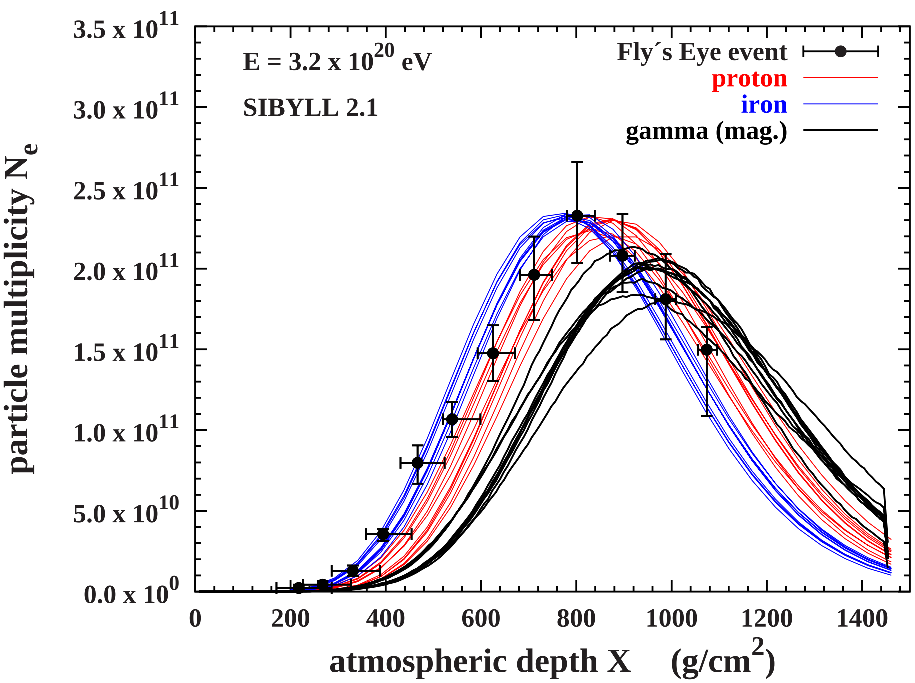
Characterization of extensive air showers



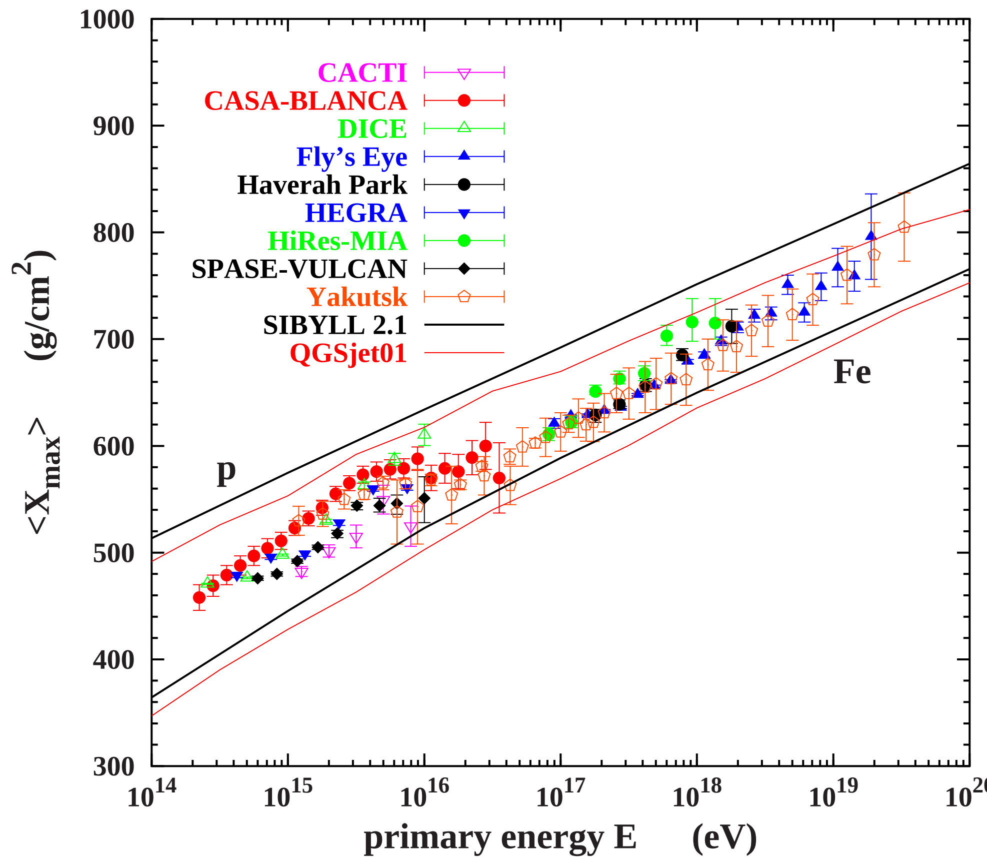
- secondaries mainly $e^{\pm}, \gamma$
- π^0's transfer energy to em. component
- mean particle energy at maximum 0.6 GeV
- 70 . . . 80% of primary energy converted to ionization energy

Model-dependence: energy/composition via shower profile

- simulation of shower profile:



- mean depth of shower maximum:



- strong dependence on hadronic interaction model

Model-dependence: energy/composition via N_e-N_μ

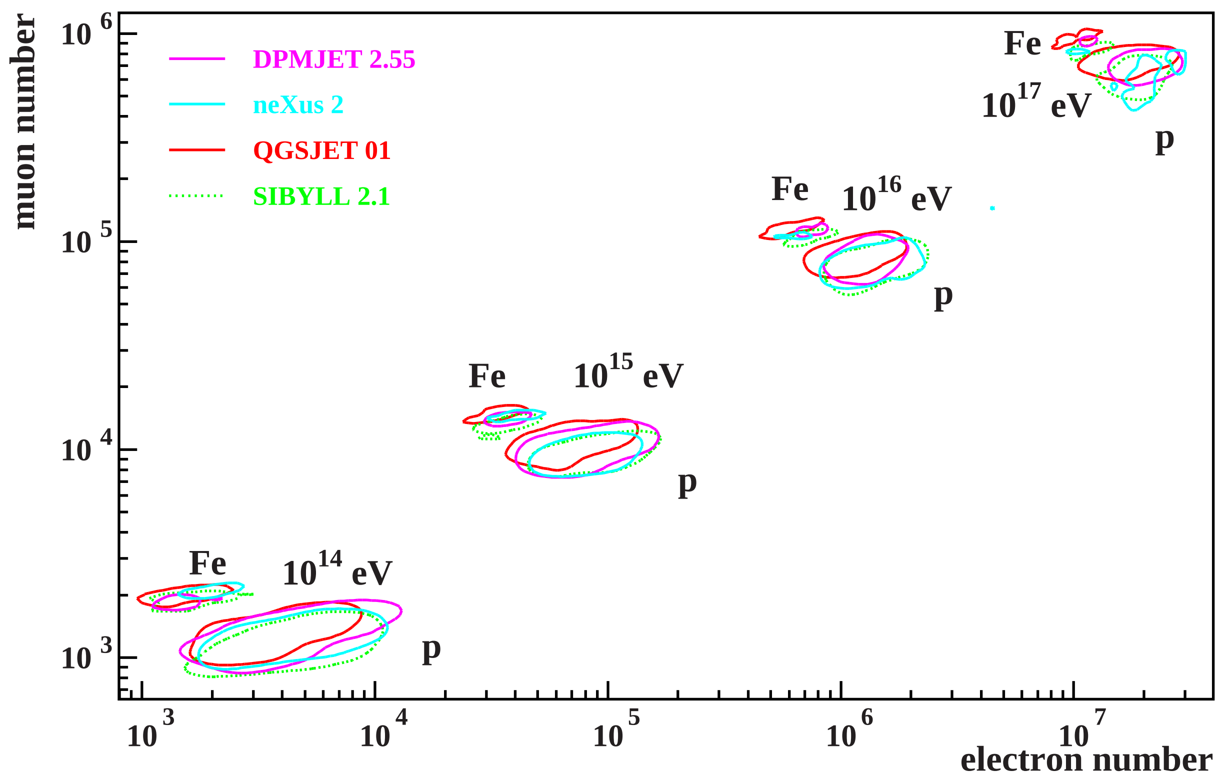
superposition model:

- proton of energy E

$$N_\mu \sim E^{0.89}$$
$$N_e \sim E \ln E$$

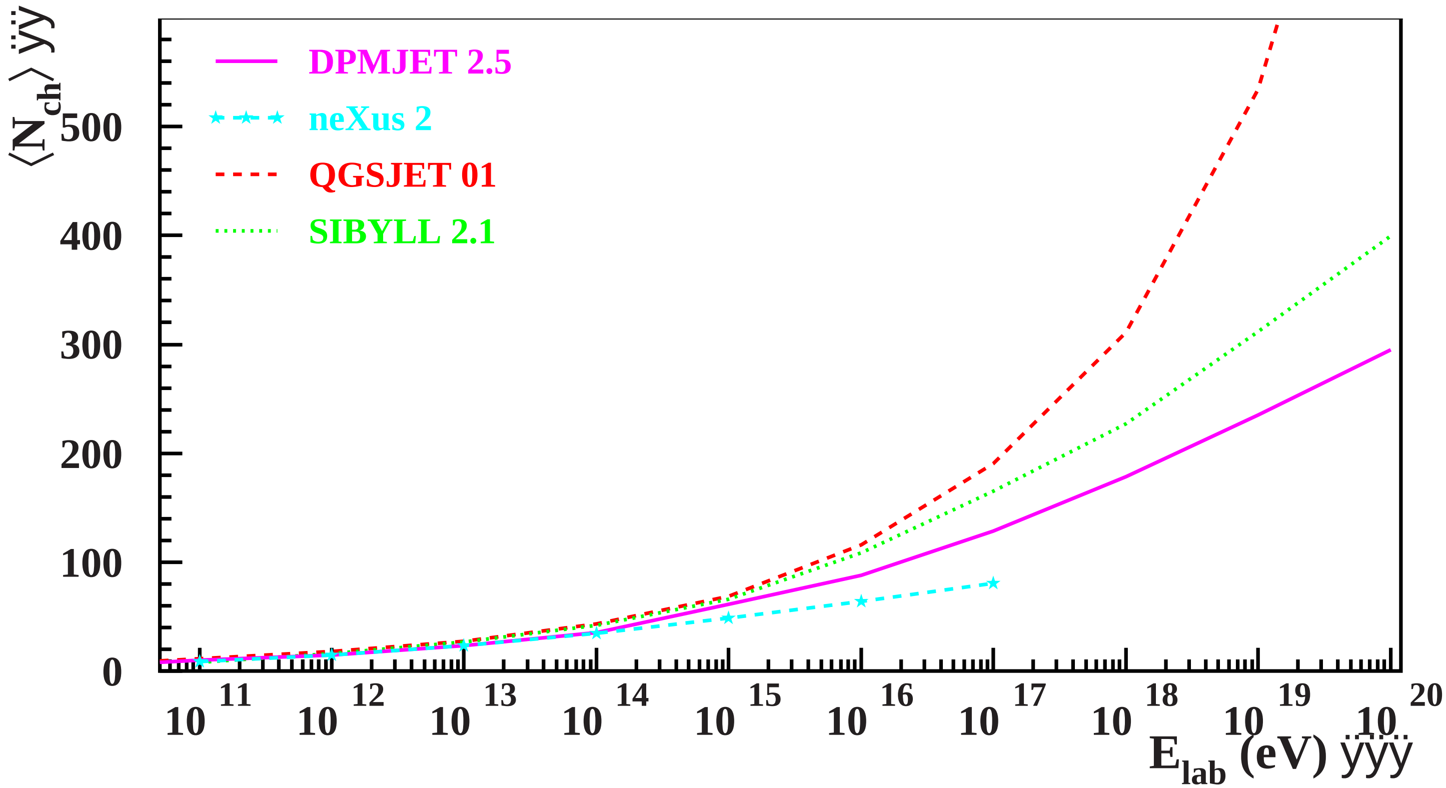
- nucleus of energy E and mass number A

$$N_\mu \sim A(E/A)^{0.89}$$
$$N_e \sim E \ln(E/A)$$



(D. Heck, ICRC 2001)

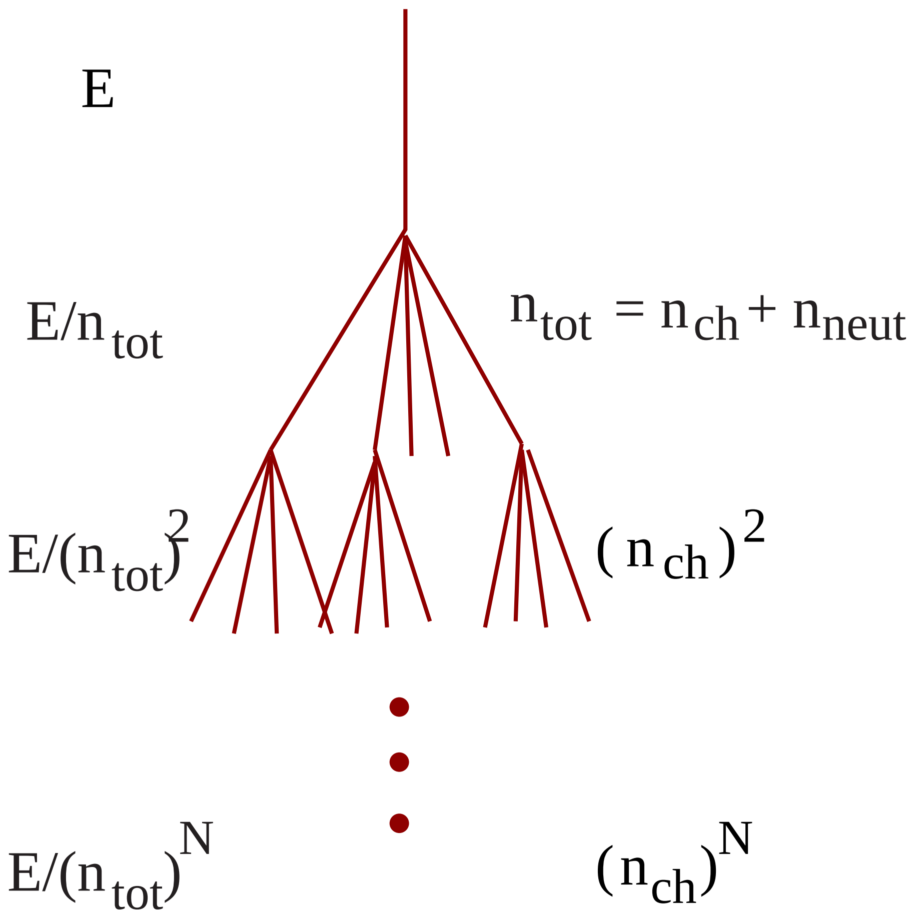
Models: charged particle multiplicity in p-N collisions



(D.Heck, ICRC 2001)

- model predictions by more than factor 2 at high energy
- similar differences for π-N collisions
- mean muon multiplicities of showers differ only by 20%

Muon production: Heitler's model



- only charged secondaries initiate new cascades
- decay if critical energy E_c is reached

$$E_c = E/(n_{\text{tot}})^N$$

- charged particles decay producing one muon

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

- eliminating N gives

$$N_\mu = \left(\frac{E}{E_c}\right)^\alpha$$

$$\alpha = \frac{\ln n_{\text{ch}}}{\ln n_{\text{tot}}} \approx 0.85 \ldots 0.92$$

- showers have reduced sensitivity to high energy interactions

Requirements on hadronic interaction models

- physics requirements:
  - simulation of p, π, K, ... collisions with air nuclei
  - coverage of full energy range from production threshold to $\sqrt{s} \sim 400$ TeV
  - minimum bias event simulation
  - tuned to give optimal description of energetic secondary particles

- technical requirements:
  - variable projectile/target combinations
  - variable energy simulation
  - fast simulation code

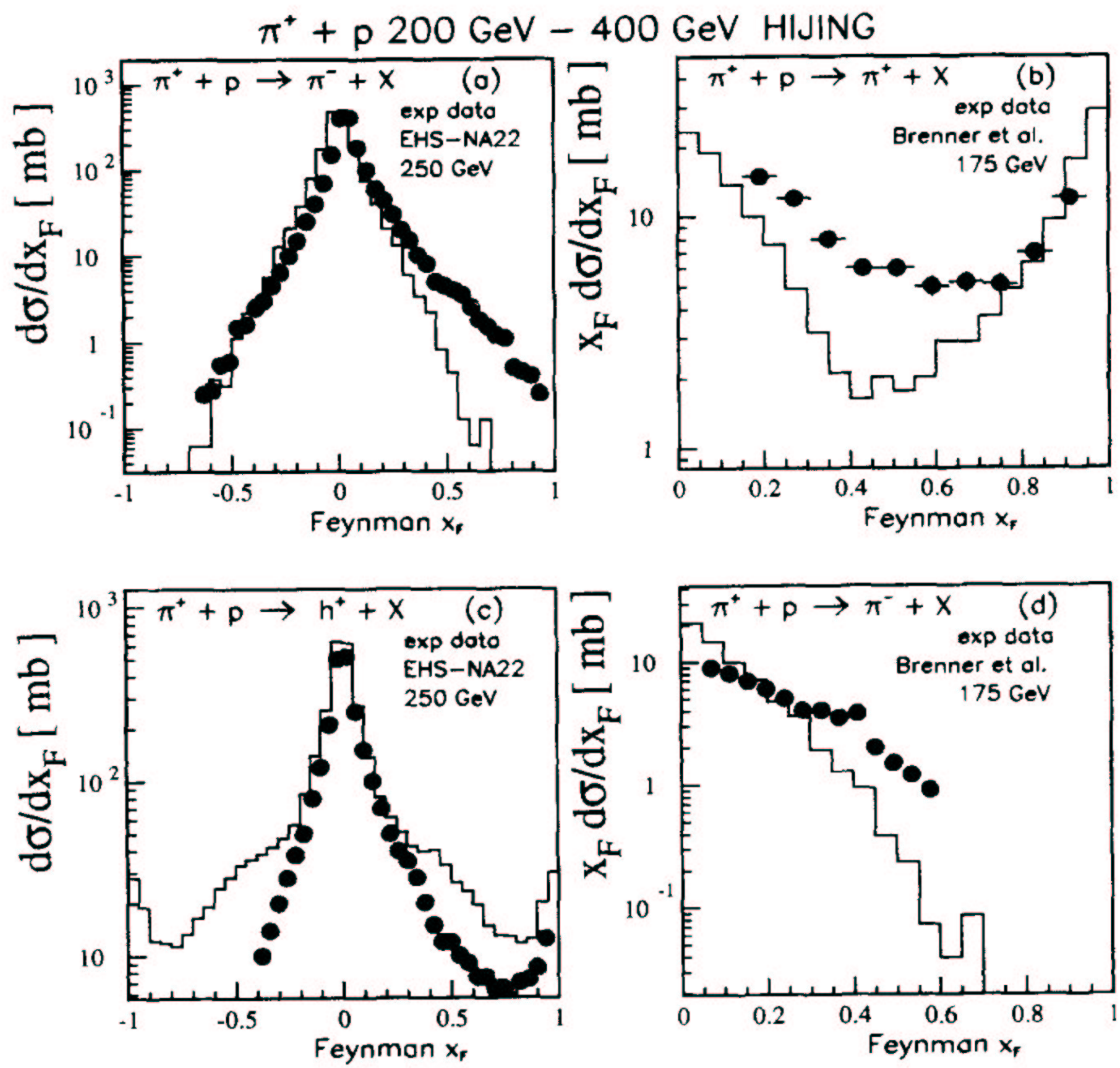
Cosmic ray hadronic interaction models

- 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)
- all QCD-inspired models (minijets)

- low-energy models:
  - GHEISHA/GEANT (Fesefeldt)
  - Hillas' splitting algorithm (Hillas)
  - FLUKA (Fasso, Ferrari, Ranft, Sala)
  - UrQMD (Bass, Bleicher et al.)
  - TARGET (RE, Gaisser, Protheroe & Stanev)
  - HADRIN/NUCRIN (Hänßgen & Ranft)
- mostly parametrizations of data

What about PYTHIA, HIJING, . . . ?

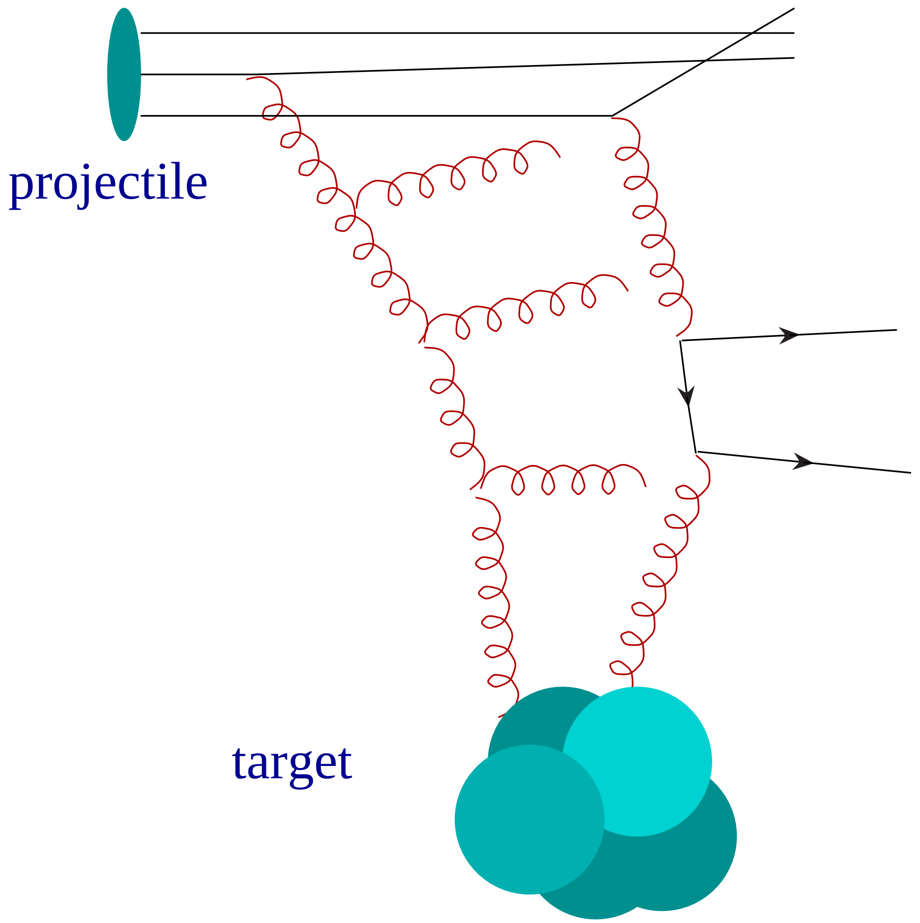
- most HEP models not designed for leading particle production
- other models lack completeness
- example: HIJING predictions and bubble chamber data



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

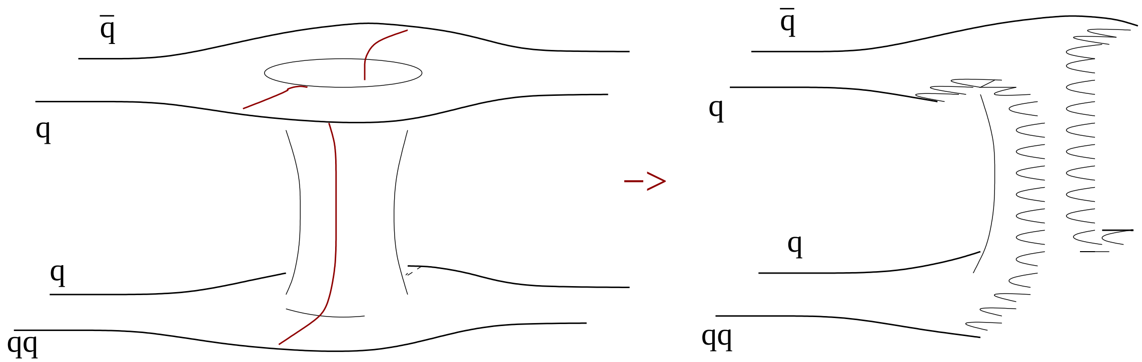
Partonic view: structure of QCD inspired models

- 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.

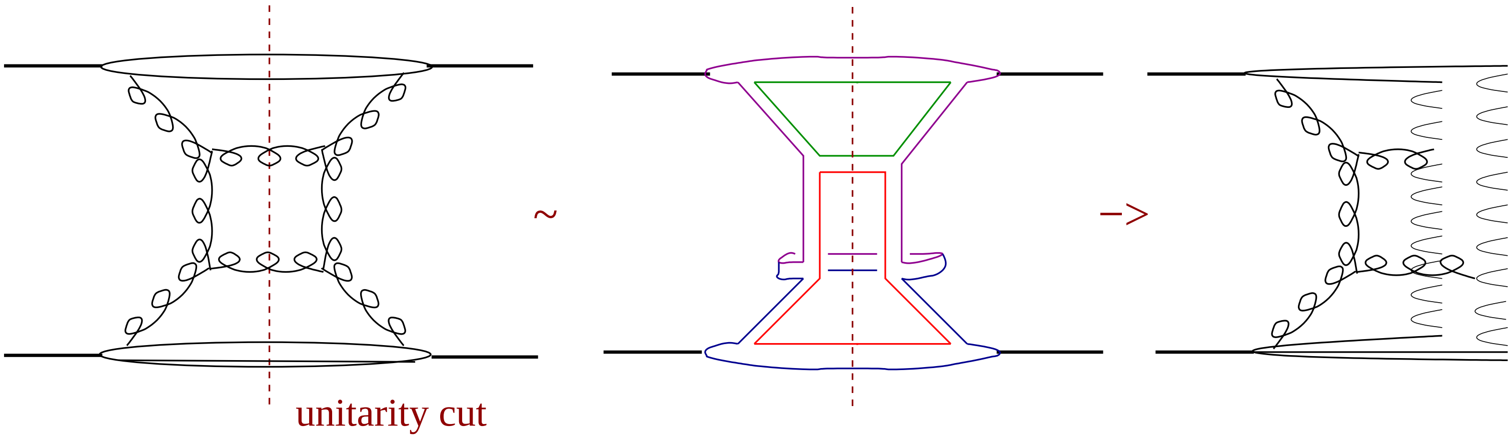


Nucleon-nucleon scattering: pomeron description

- color dipole scattering, exchange of vacuum quantum numbers: pomeron



- two-gluon scattering in QCD-improved parton model:



Perturbative QCD: hard part of the pomeron

- conventional phenomenology: two-gluon scattering and collinear factorization

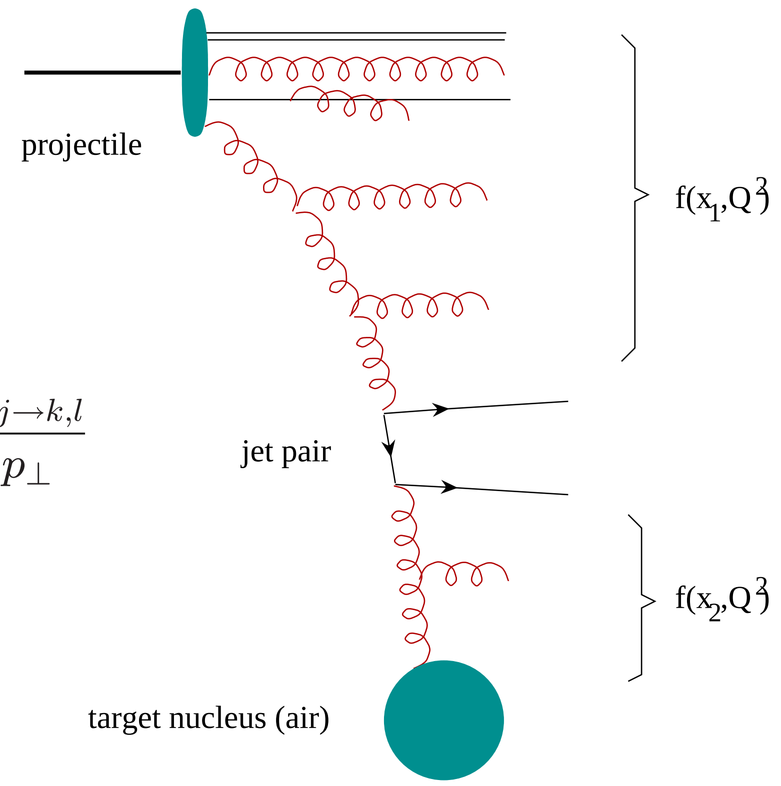
- inclusive jet-pair cross section:

$$\frac{\sigma_{\rm jet}}{d^2p_\perp} = \sum_{i,j,k,l} \frac{1}{1+\delta_{kl}} f_A(x_1,Q^2) \otimes f_B(x_2,Q^2) \otimes \frac{d\hat{\sigma}_{i,j\to k,l}}{d^2p_\perp}$$

- parton density evolution (DGLAP):

$$\frac{df(x,Q^2)}{dlogQ^2} = \frac{\alpha_s(Q^2)}{2\pi} P(x/y) \otimes f(y,Q^2)$$

- factorization: parton densities are universal



Minijet cross section: energy and cutoff dependence

- QCD expectation:

$$f(x, Q^2) \sim 1/x^{1+\Delta}$$

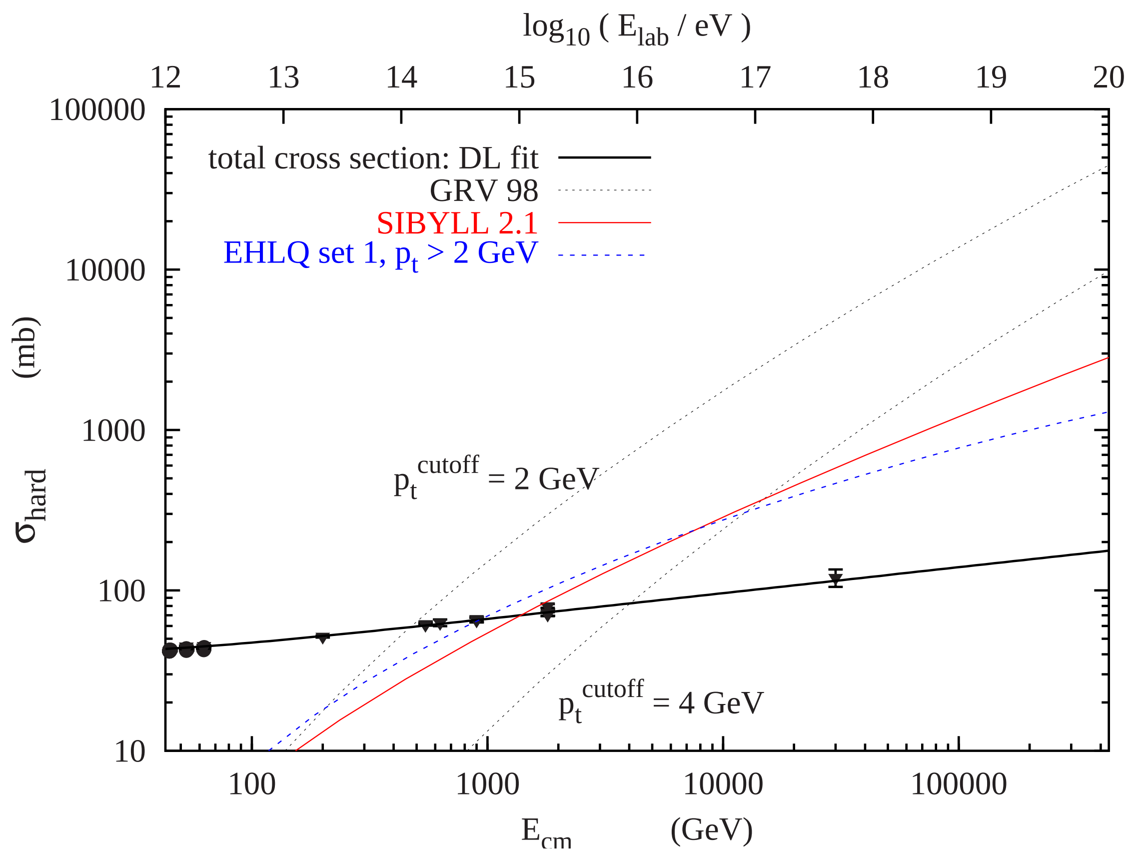
$$\sigma_{\rm jet} \sim s^{\Delta}\ \ln s$$

- old extrapolations:

$\Delta \sim 0 \ldots 0.2$

- HERA measurements:

$\Delta \sim 0.3 \ldots 0.4$

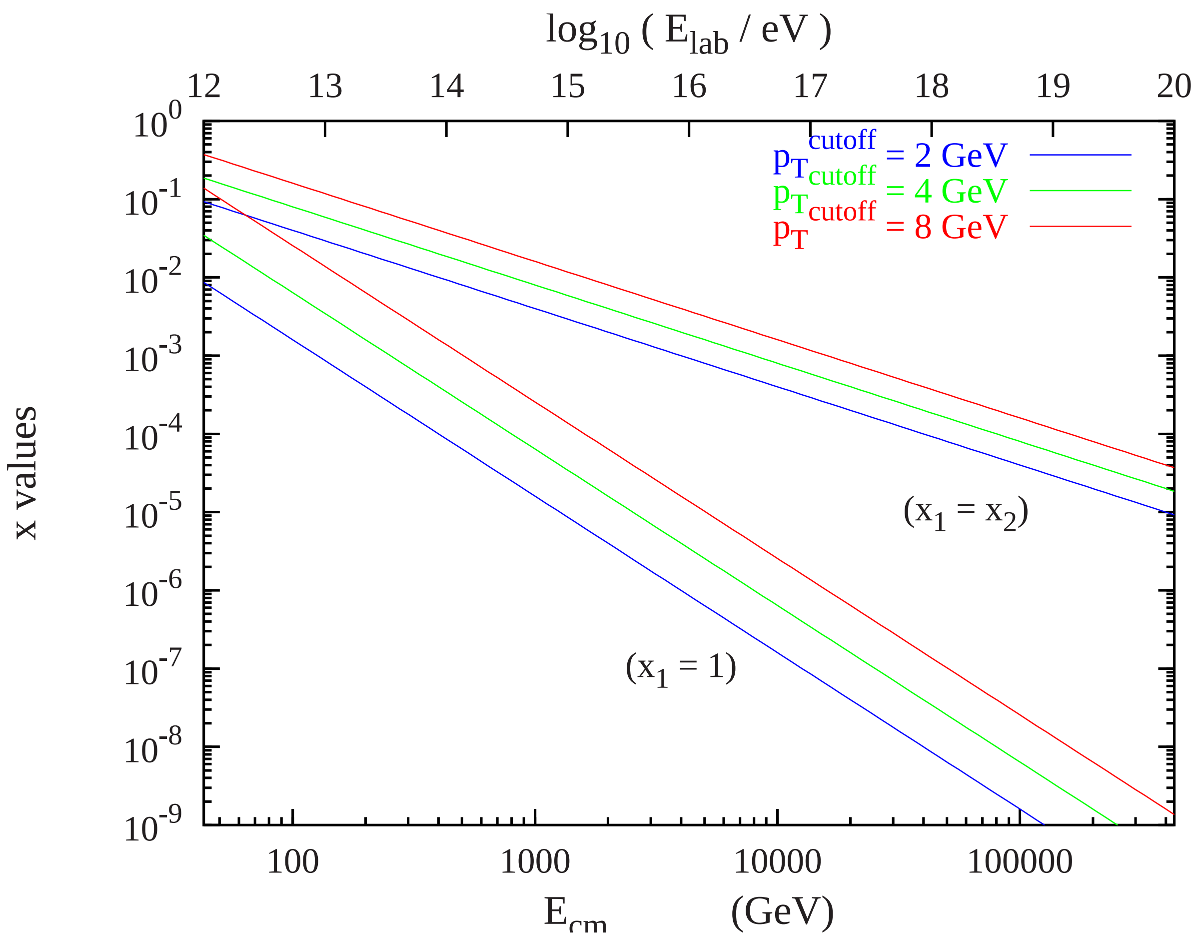


- inclusive cross section exceeds total cross section:

  many minijet pairs produced per p-p collision $\quad \sigma_{\rm jet} = \langle n_{\rm jet} \rangle \sigma_{\rm inel}$

Reliability of minijet phenomenology

- kinematics:
  $x_1 x_2 \geq 4p_\perp^2/s$
- parton densities measured in limited x, Q^2 range
- higher order corrections (k-factor)
- parton density saturation effects



Model implementations of hard scattering

- QGSjet: pre-HERA parton densities, no saturation
- DPMJET III: energy-dependent transverse momentum cutoff
  (summation of lowest-order enhanced diagrams, string fusion)

$$p_\perp^{\text{cutoff}}(\sqrt{s}) = p_\perp^0 + 0.12\text{GeV}\left(\log_{10}\frac{\sqrt{s}}{50\text{GeV}}\right)^3$$

- SIBYLL: energy-dependent transverse momentum cutoff

$$p_\perp^{\text{cutoff}}(\sqrt{s}) = p_\perp^0 + 0.065\text{GeV}\exp\left\{0.9\sqrt{\ln(s)}\right\}$$

- numerically similar to Golec-Biernat & Wüsthoff model

$$Q_s^2(x) = Q_0^2\left(\frac{x}{x_0}\right)^\lambda \simeq Q_0^2\left(\frac{s}{s_0}\right)^{\lambda/2} \qquad \lambda \simeq 0.25\ldots 0.37$$

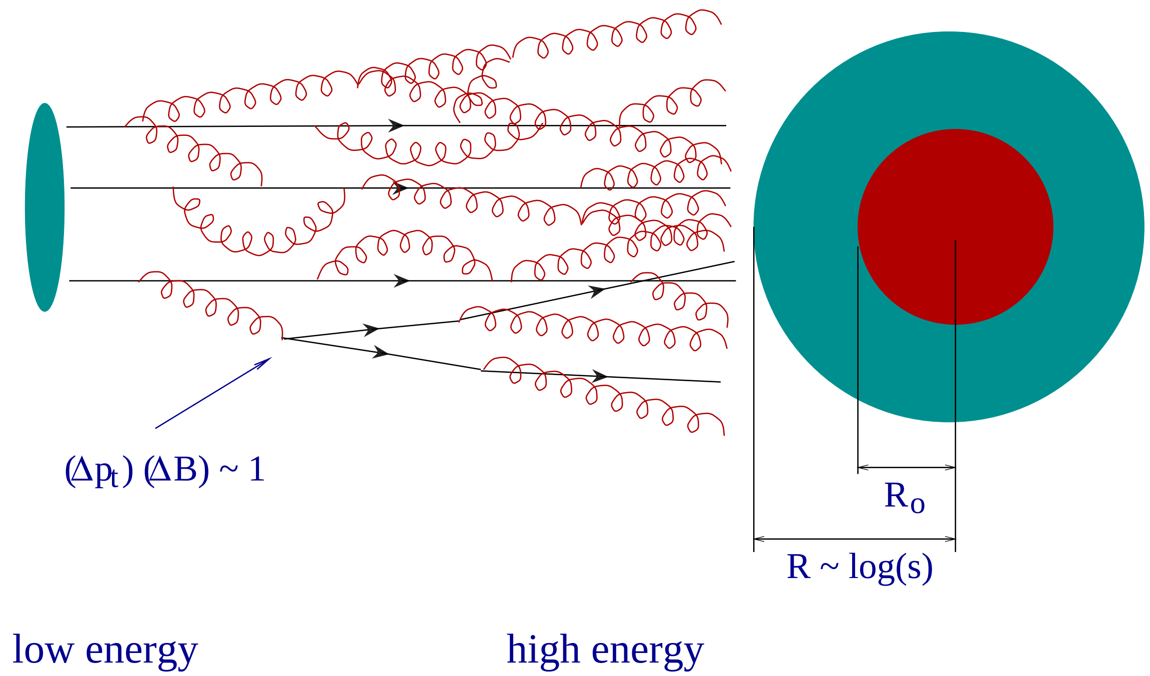
Unitarization: eikonal approximation

- standard in literature: two-component eikonal models

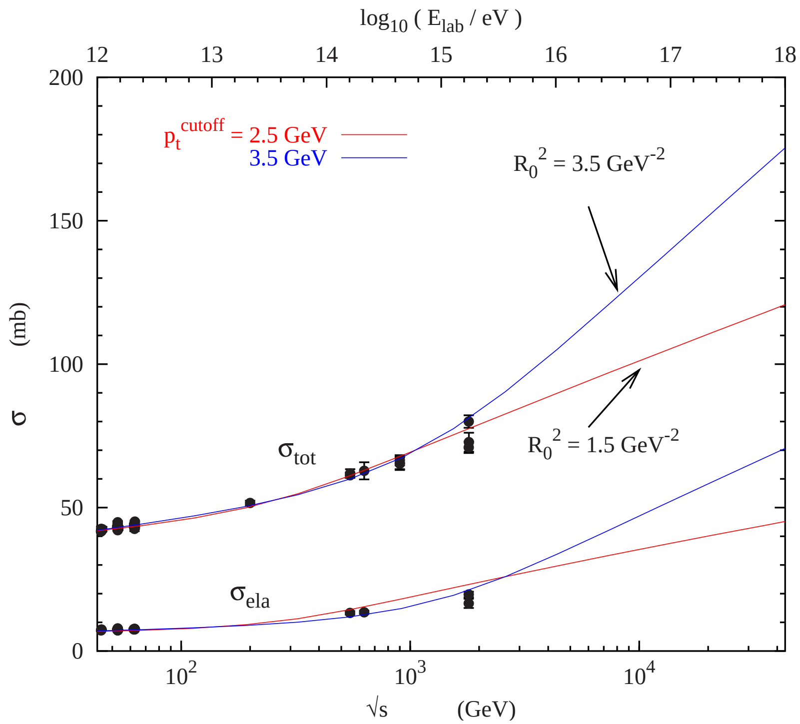
$$\sigma_{\text{inel}} = \int d^2\vec{b}\ \left(1 - \exp\{-2\chi_s - 2\chi_h\}\right)$$

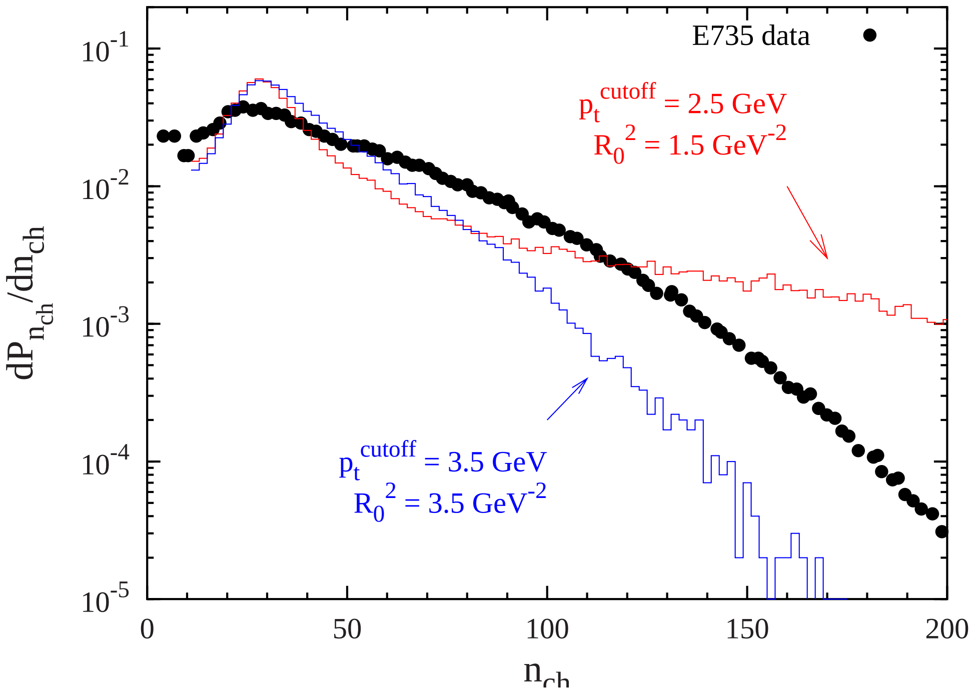
$$\chi_{s/h}(s,\vec{b}) = \sigma_{s/h} A(s,\vec{b}) \quad \text{with} \quad \int d^2\vec{b}\ A(s,\vec{b}) = 1$$

- profile function $A(s,\vec{b})$



Cross section fits: model parameters





- reasonable cross section fits possible for many parameter combinations
- correlation between eikonal function and multiplicity distribution

Resummation according to unitarity cuts (AGK)

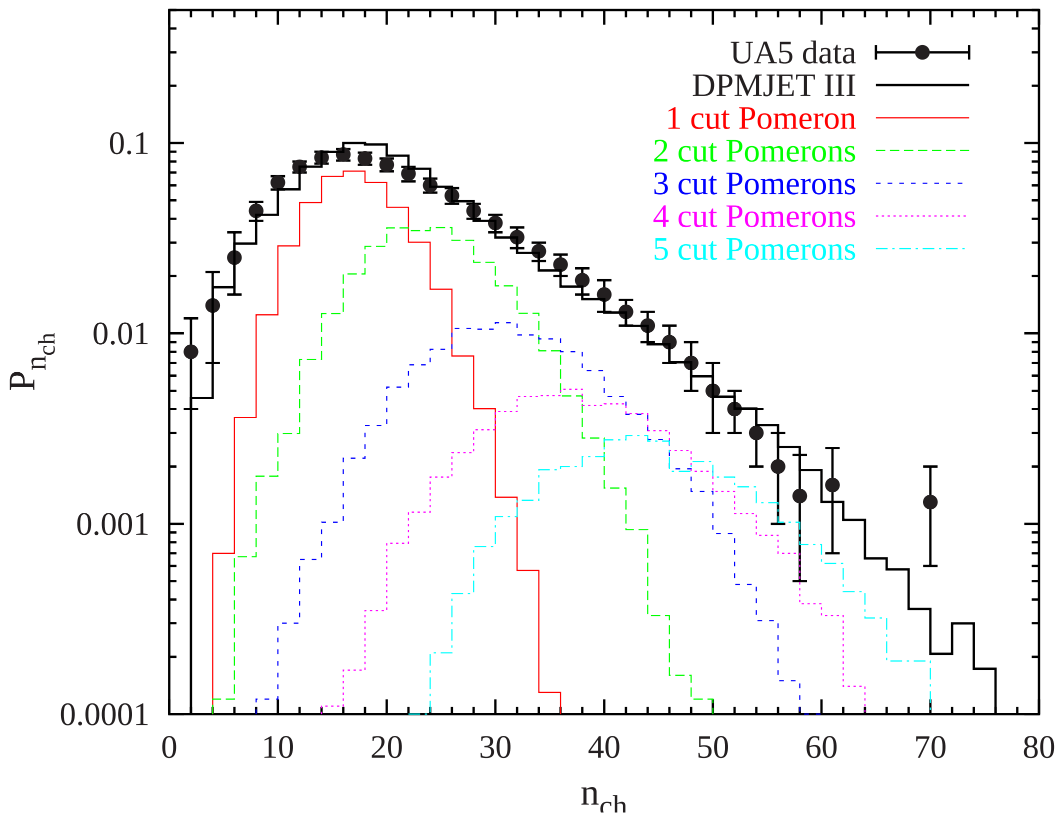
- analytical resummation possible for eikonal-type models

- cross section for n cut pomerons (i.e. n partonic interactions)

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

- inelastic cross section

$$\sigma_{\text{inel}} = \sum_{n=1}^{\infty} \sigma_{\text{ine}}^{(n)}$$

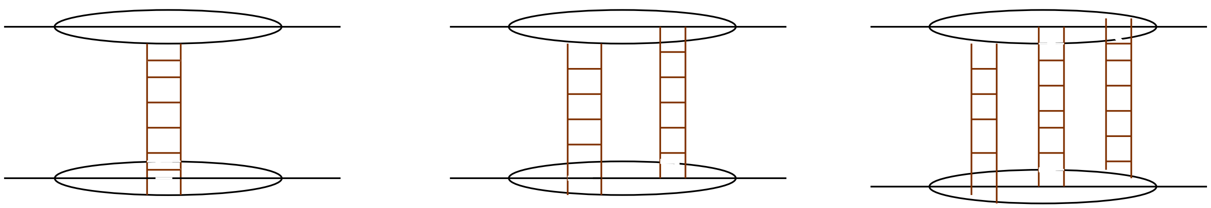


Interpretation of the eikonal approximation

- unitarized amplitude

$$a(s,\vec{b}) \;=\; \frac{i}{2}\left(1-e^{-\chi(s,\vec{b})}\right)$$

$$\sim\;\chi(s,\vec{b})\;-\;\frac{1}{2!}\left[\chi(s,\vec{b})\right]^2\;+\;\frac{1}{3!}\left[\chi(s,\vec{b})\right]^3\;\ldots$$



- problem: energy-momentum sharing not considered at amplitude level

- neXus: explicit calculation with energy-momentum conservation

Partonic view: structure of QCD inspired models

- model for nucleon-nucleon interaction
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    (soft interactions, minijet production)
  - leading particle production
    (projectile remnant, diffraction dissociation)
- generalization to hadron-nucleus and nucleus-nucleus interactions
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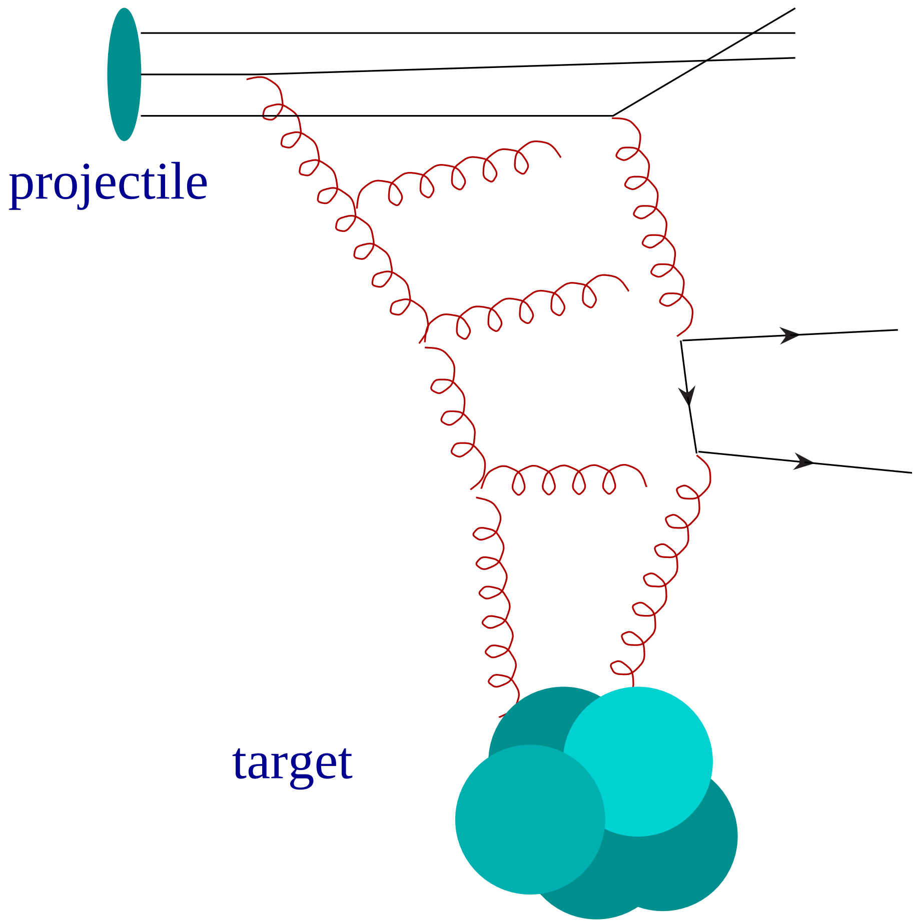


Leading particle production: models

- DPMJET, QGSjet: leading particle distributions determined by pomeron/reggeon parameters (Mueller diagrams)

$$f_{\mathrm{nuc}}^{\mathrm{DPM}}(x) \sim x_q^{-1/2}(1-x_q)^{3/2}, \qquad f_{\mathrm{mes}}^{\mathrm{DPM}}(x) \sim x_q^{-1/2}(1-x_q)^{1/2}$$

- neXus, SIBYLL: fits to data

$$f_{\mathrm{nuc}}^{\mathrm{SIB}}(x) \sim (x_q^2 + \mu^2/s)^{-1/4}(1-x_q)^3$$

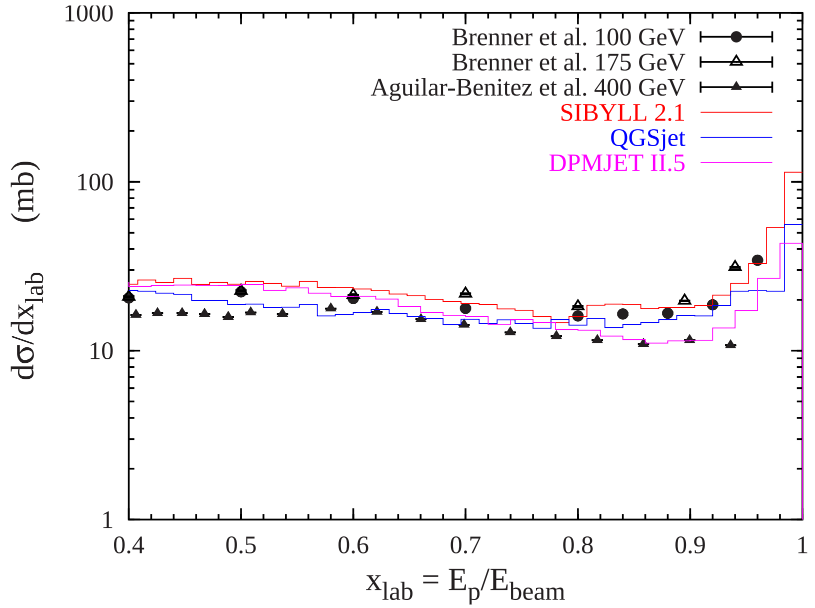
- distributions assumed to be energy-independent

- energy-momentum conservation influences distributions

Leading particle production: data

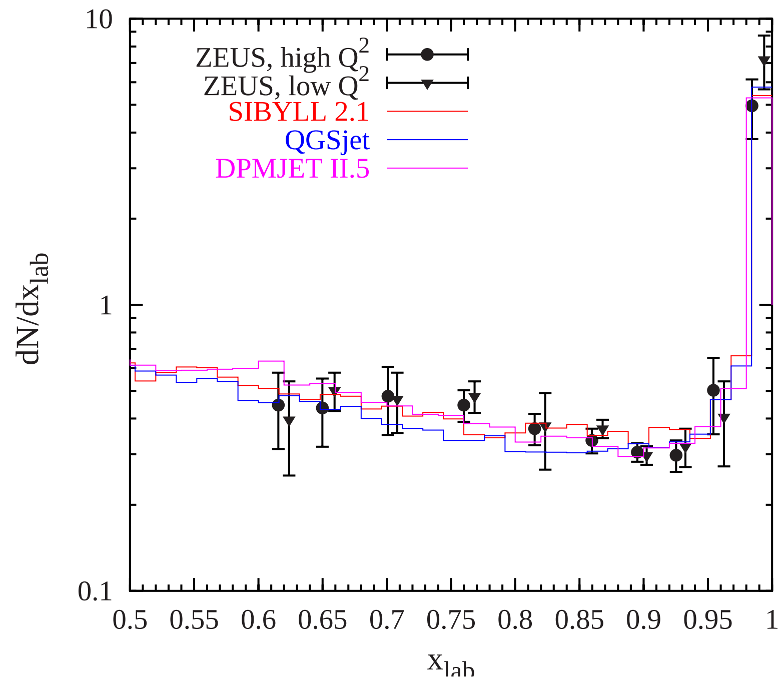
- fixed target experiments:

  $E_{\text{lab}} \leq 5 \times 10^{11}$ eV



- HERA collider:

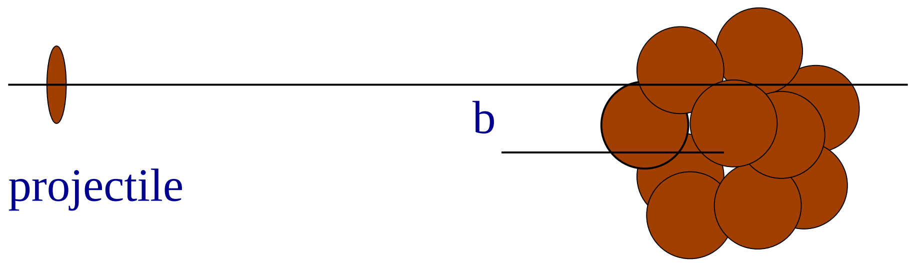
  $\sqrt{s_{\gamma p}} \approx 200$ GeV, $E_{\text{lab}} \approx 2 \times 10^{13}$ eV



- different parametrizations work well at low energy, however substantial differences in extrapolation

Gribov-Glauber approximation

- geometric picture:



- target (and its fluctuations) interact coherently with several nucleons

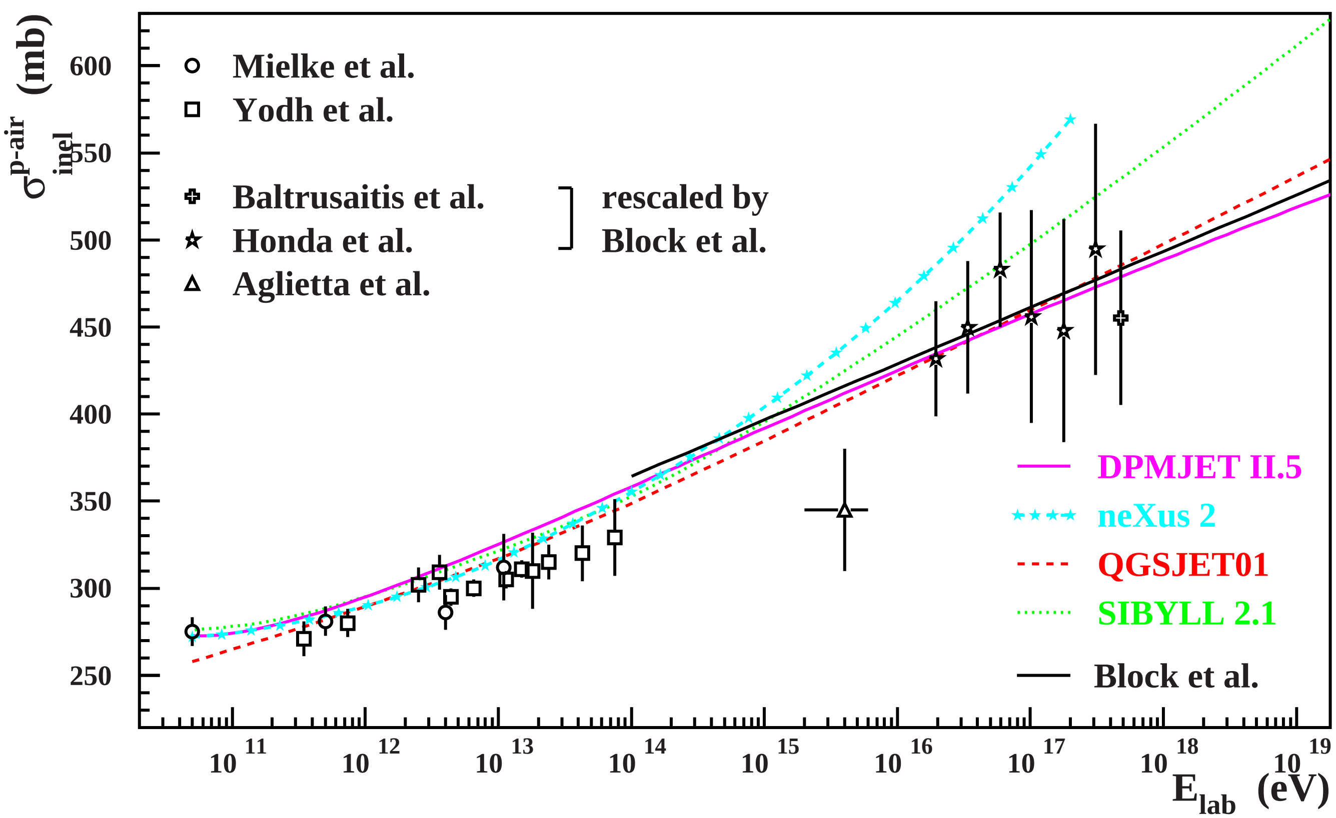
$$\sigma_{\text{inel}} = \int d^2\vec{b} \left[1 - \prod_{k=1}^{A} \left(1 - \sigma_{\text{tot}}^{\text{NN}} T_N(\vec{b} - \vec{s}_k)\right)\right] \approx \int d^2\vec{b} \left[1 - \exp\left\{\sigma_{\text{tot}}^{\text{NN}} T_A(\vec{b})\right\}\right]$$

$$\sigma_{\text{prod}} \approx \int d^2\vec{b} \left[1 - \exp\left\{\sigma_{\text{ine}}^{\text{NN}} T_A(\vec{b})\right\}\right]$$

- known not to be a good approximation for central collisions

- first investigations of string fusion by Santiago group and Ranft show small impact on shower predictions

Current status of predictions: proton-air cross sections



(D. Heck)

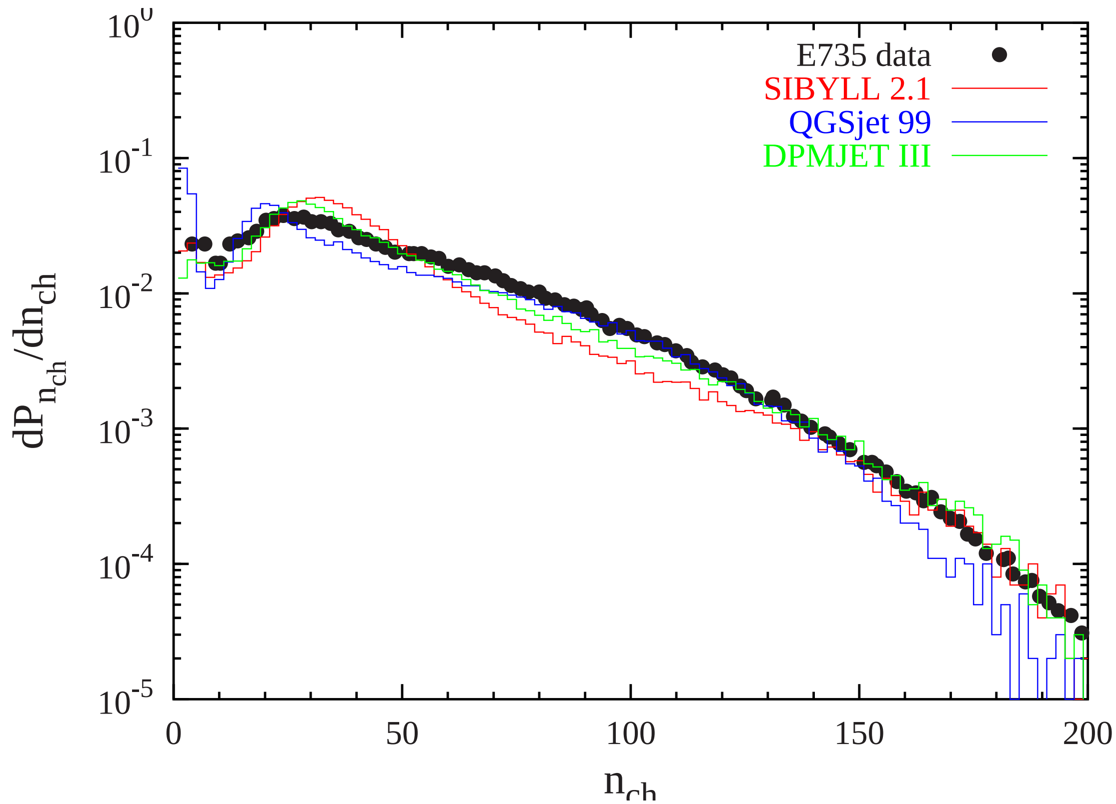
- difference QGSjet - SIBYLL: profile function $A(s, \vec{b})$
- difference neXus - QGSjet: pre- and post-HERA parton densities

Current status of predictions: multiplicity distributions

- charged particle multiplicity distribution
- p-p̄ collisions:

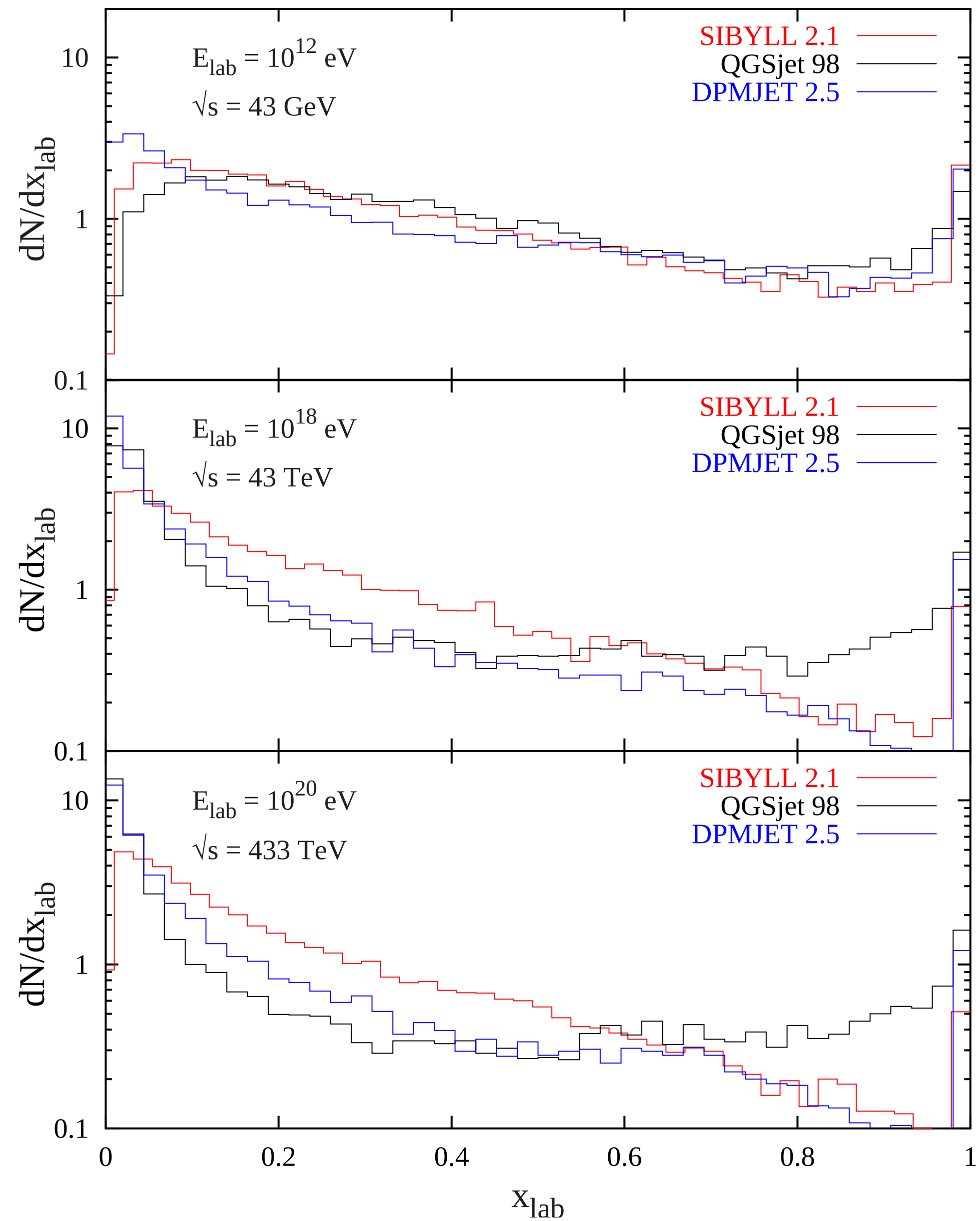
  $\sqrt{s} = 1800$ GeV,

  $E_{\text{lab}} \approx 1.7 \times 10^{15}$ eV
- data became available only recently (no model tuning)
- crucial test of consistency of model parameters and cross sections

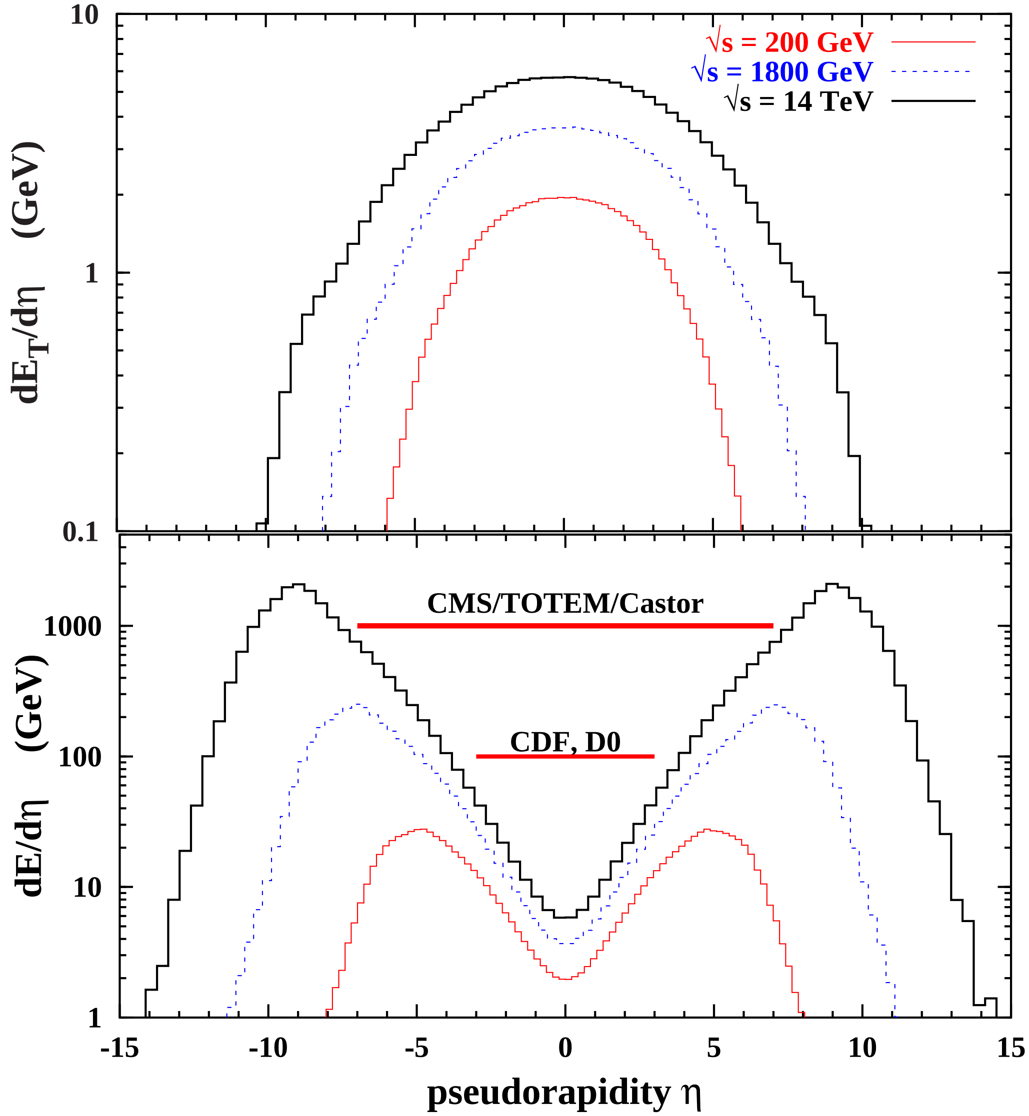


Current status of predictions: leading particle distributions

- leading hadron distribution in p-air collisions
- model predictions similar at low energy
- significant divergence at high energy
- extremely inelastic collisions related to
  - high multiplicity events
  - popcorn-type effect

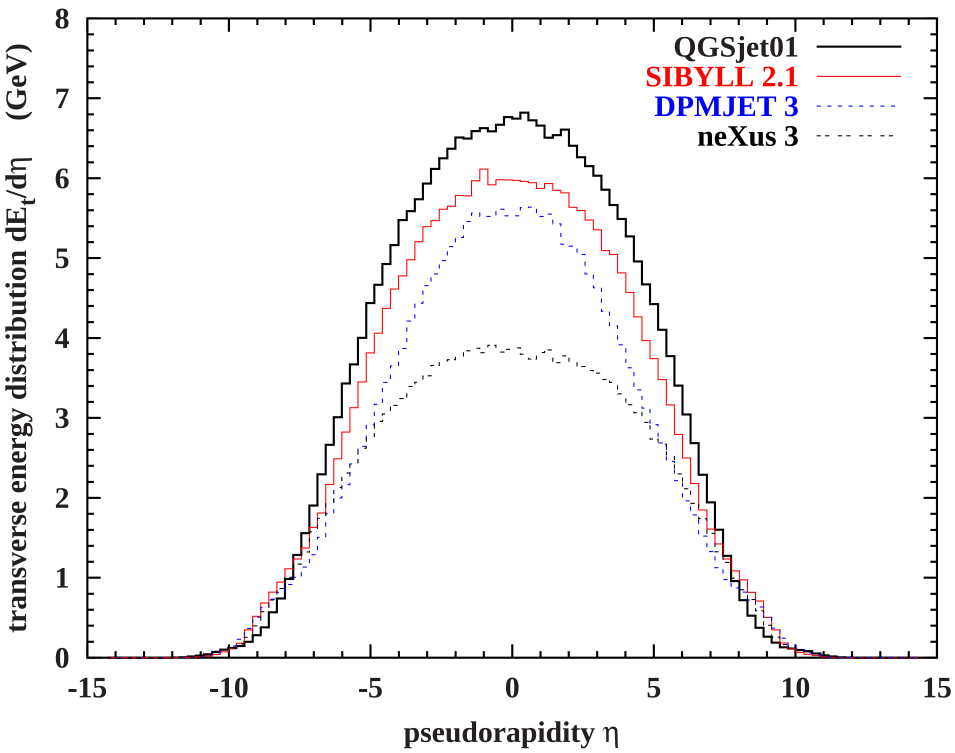


Model tuning: important phase space regions

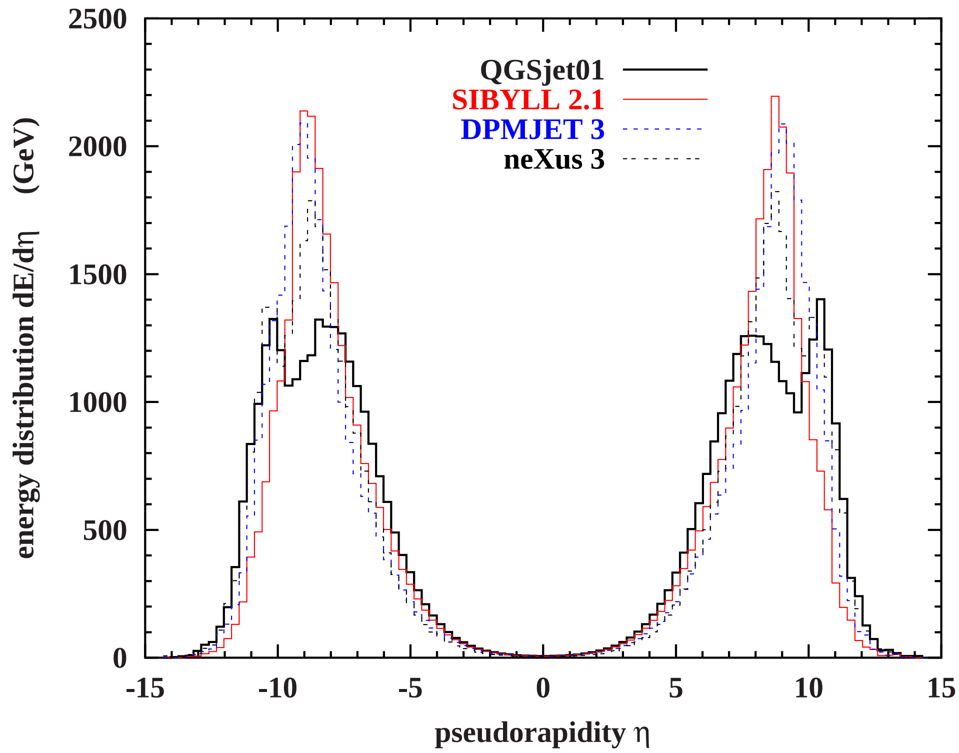


- HEP:
  - high-$p_\perp$ jets and secondaries
  - transverse energy
  - leptonic secondaries
- air shower physics:
  - total/inelastic cross section
  - fraction of diff. dissociation
  - energy flow
  - particle multiplicity distribution
  - hadronic secondaries

Model predictions: proton-proton at LHC

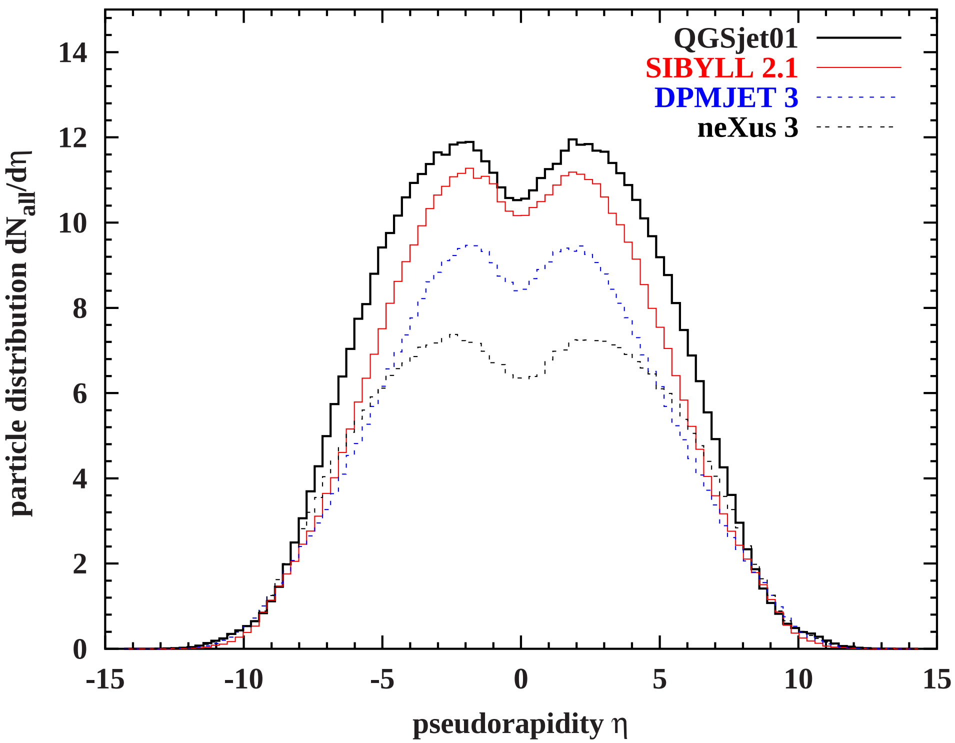


transverse energy

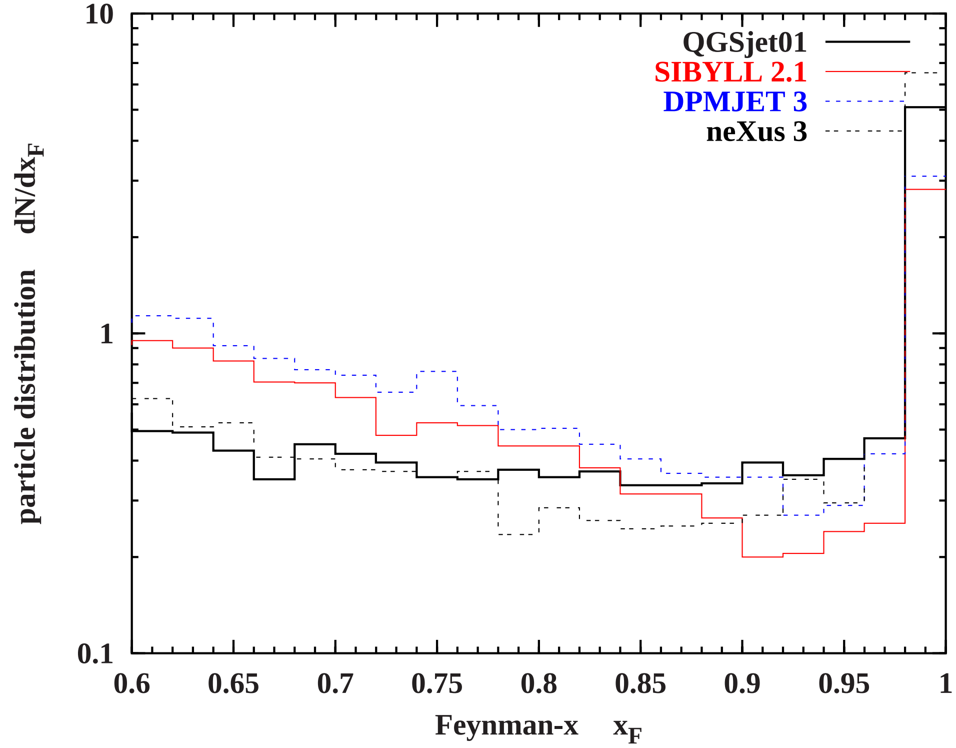


total energy

Model predictions: central vs. forward region



particle multiplicity

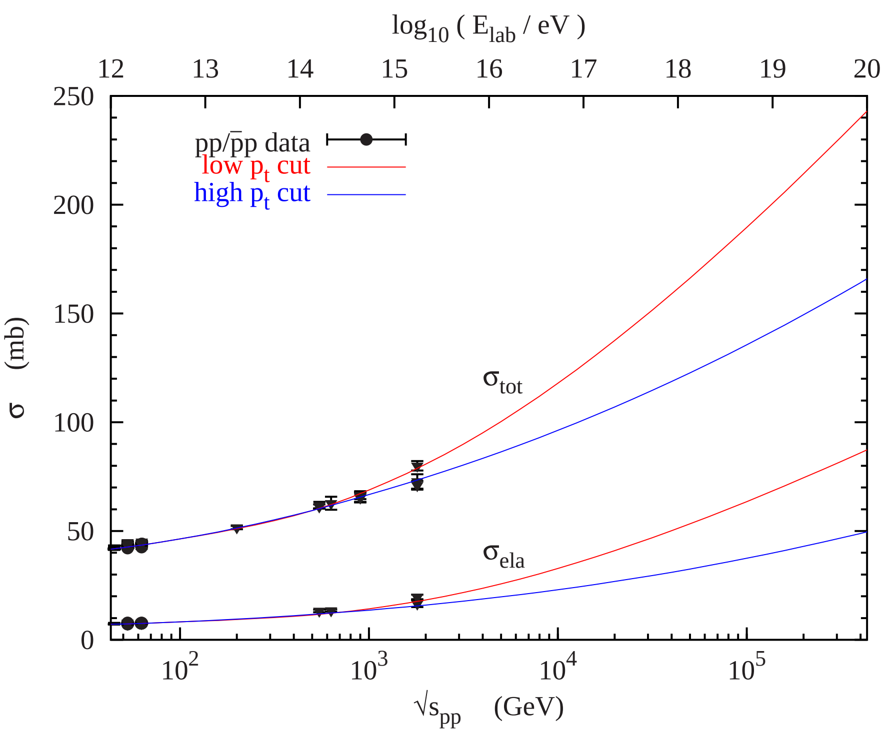


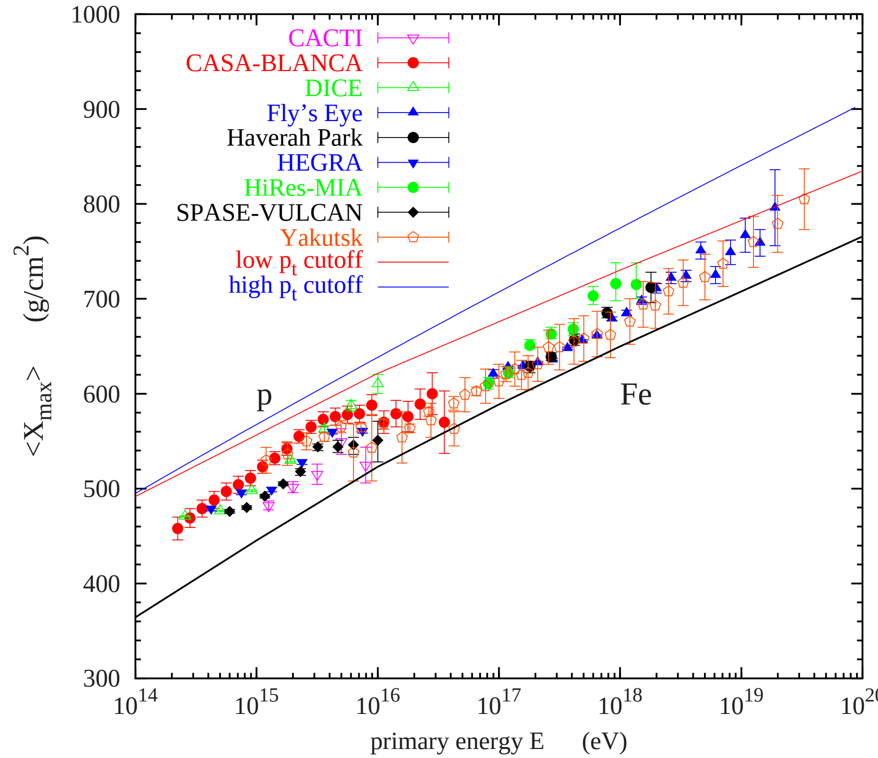
particle multiplicity

Constraints from cosmic ray data

- difficulties with cosmic ray beams:
  - no direct measurement of interactions possible
  - selection of showers of fixed energy
  - selection of showers of desired primary
- possible methods to constrain models:
  - comparison of shower measurements to simulated showers assuming an energy spectrum and primary composition
  - consistency checks within limits given by possible composition
  - multiparameter measurements: check of parameter correlation
- model-independent limits on interaction characteristics impossible

Example: upper cross section bound?





- realistic model with steep cross section extrapolation (RE, ICHEP 2002)
- comparison of prediction with measurement (assumption: no photon primaries)
- shown example (based on CDF-like extrapolation) consistent with data
- exclusion of extreme cross section rise possible (but caveats)

Summary & conclusions

- cosmic rays and their interactions:
  - interesting field of physics, many open questions
  - measurements rely on detailed simulations
- hadron-nucleon interactions:
  - models with high degree of self-consistency
  - considerable uncertainty in extrapolation and reliability of minijet cross section
  - no good theory of leading particle production
- hadron- and nucleus-nucleus interaction: need to understand RHIC data
- current phenomenology relies on forward hadron production data
- predictions for LHC
  - central and forward particle production not directly correlated
  - need measurements of central and forward region
- model-independent limits difficult to derive from cosmic ray data

Acknowledgments

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D. Heck, J. Alvarez-Muñiz, T.K. Gaisser, A. Haungs, S. Ostapchenko, J. Ranft, S. Roesler, and T. Stanev

Unitarity and optical theorem

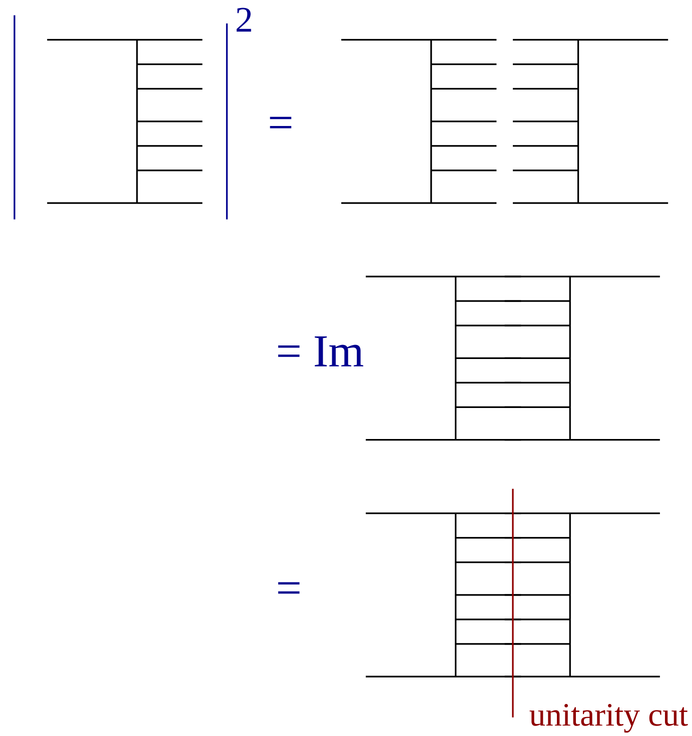
total cross section:

$$\sigma_{\text{tot}} = \frac{1}{\Phi}\int dP_X\, |M_{pp\to X}|^2$$
$$= \frac{1}{\Phi}\int dP_X\, M_{pp\to X} M^{+}_{pp\to X}$$

phase space integration

$$\frac{d^3k}{2E} = \delta(k^2 - m^2)d^4k$$
$$\sim \Im m \left(\frac{1}{k^2 - m^2 + i\epsilon}\right) d^4k$$

results in particle propagators



optical theorem:

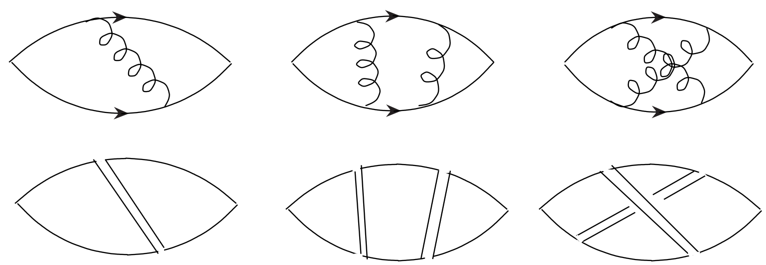
$$\frac{1}{s}\Im m\, A_{pp\to pp}(s, t=0) = \frac{1}{\Phi}\int dP_X\, |M_{pp\to X}|^2 = \sigma_{\text{tot}}$$

Topological expansion of QCD

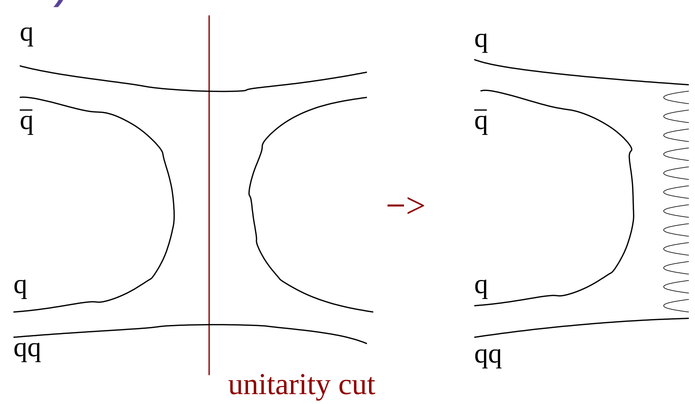
- limit $N_c \to \infty$, $N_c/n_f = \text{const.}$, $g^2 N_c^2 \sim 1$

  ('t Hooft, Veneziano, Witten)

- example:



- planar graph (reggeon):

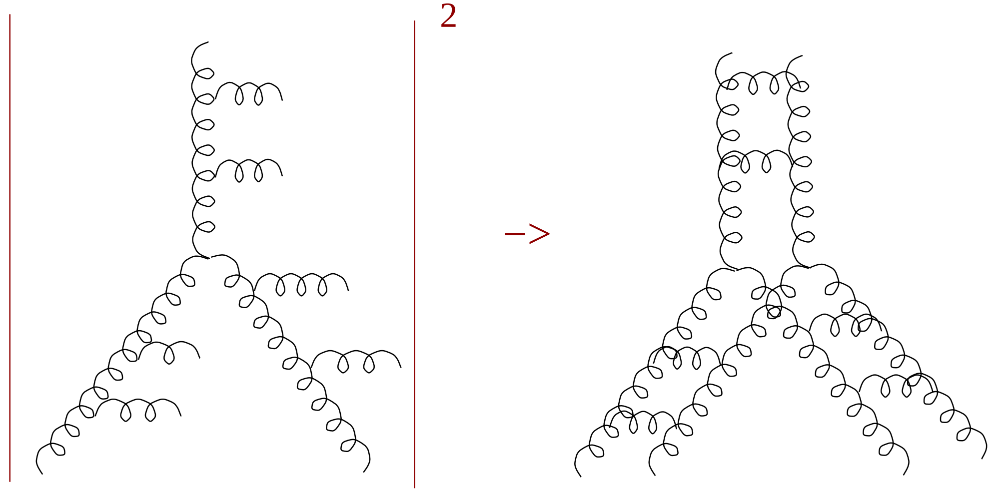


Enhanced pomeron diagrams

- method of calculating gluon-gluon fusion

- different unitarity cuts possible: hard diffraction

- example: triple-pomeron graph



- resummation to all orders very difficult due to cancellations