Models for Cosmic Ray Interactions

S. Ostapchenko

Institut für Kernphysik, Forschungszentrum Karlsruhe

From Colliders to Cosmic Rays

Prag, September 07-13 2005

- Introduction: from colliders to cosmic rays
- Mini-jets and multiple scattering:
  from “hard” to “soft” or from “soft” to “hard”?
- “Dense” partonic systems: non-linear effects
- Air shower characteristics and related quantities
- Cosmic ray interactions: remaining puzzles
- Outlook

Introduction: from colliders to cosmic rays

Hadronic MC models at colliders and in CRs:

- planning new experiments
- analysis & interpretation of data
- testing theoretical ideas

Contemporary model constructions - guided by accelerator data, e.g.,

- energy increase of cross sections
- Feynman scaling violations for particle spectra
- copious mini-jet production

Model parameters - tuned to accelerator data

But: models for colliders or models for CRs?

Model $\equiv$ approximation of the reality; has to mimic its essential features

Essential for colliders:

- detailed simulation of the interaction pattern
- close detailed agreement with experimental data

Possible simplifications:

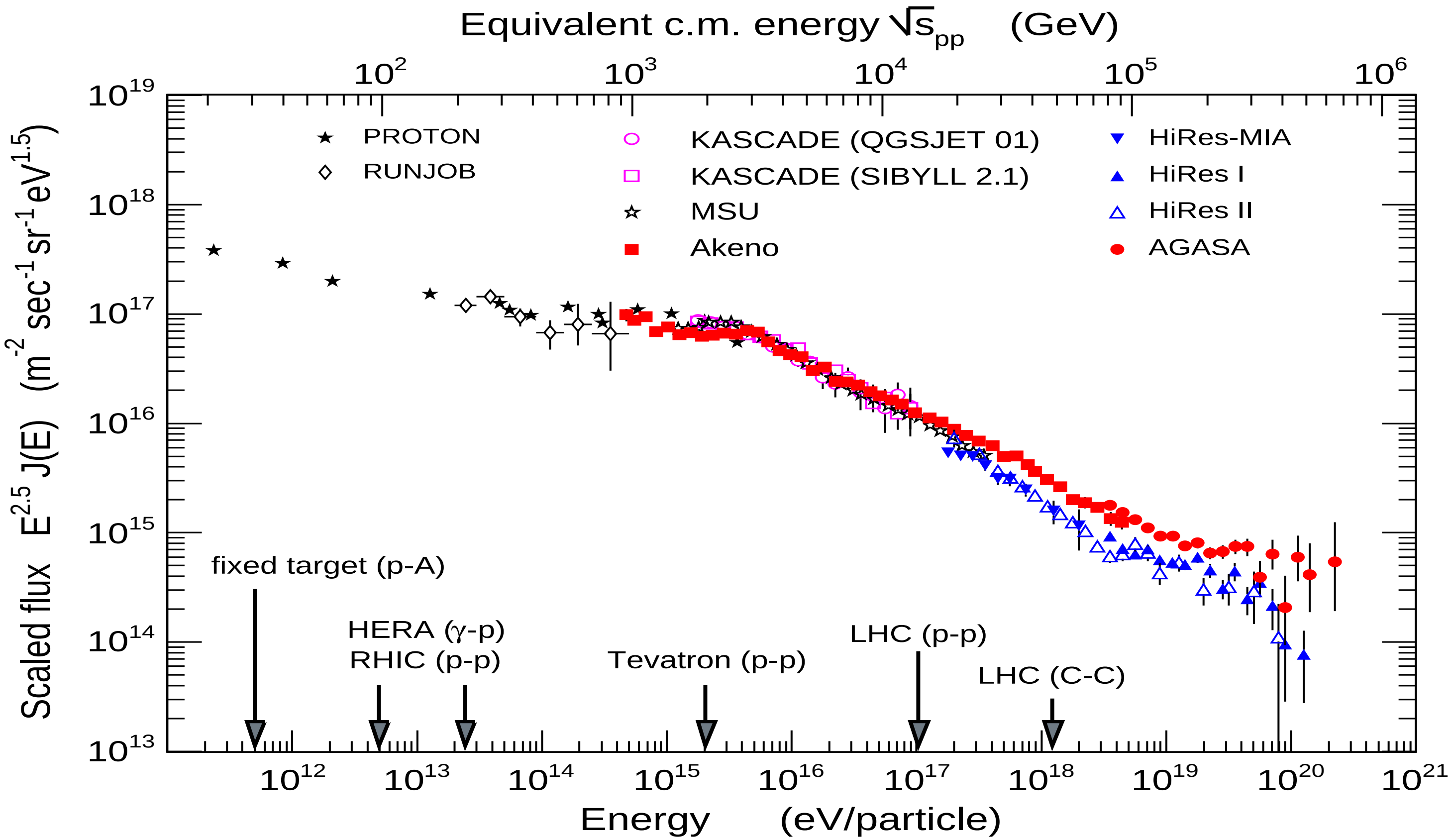
- models applicable to particular (not all) event classes, e.g.,
  - high p_t jet triggered
  - central heavy ion collisions
- models can be re-tuned for a particular experiment

Representative models:

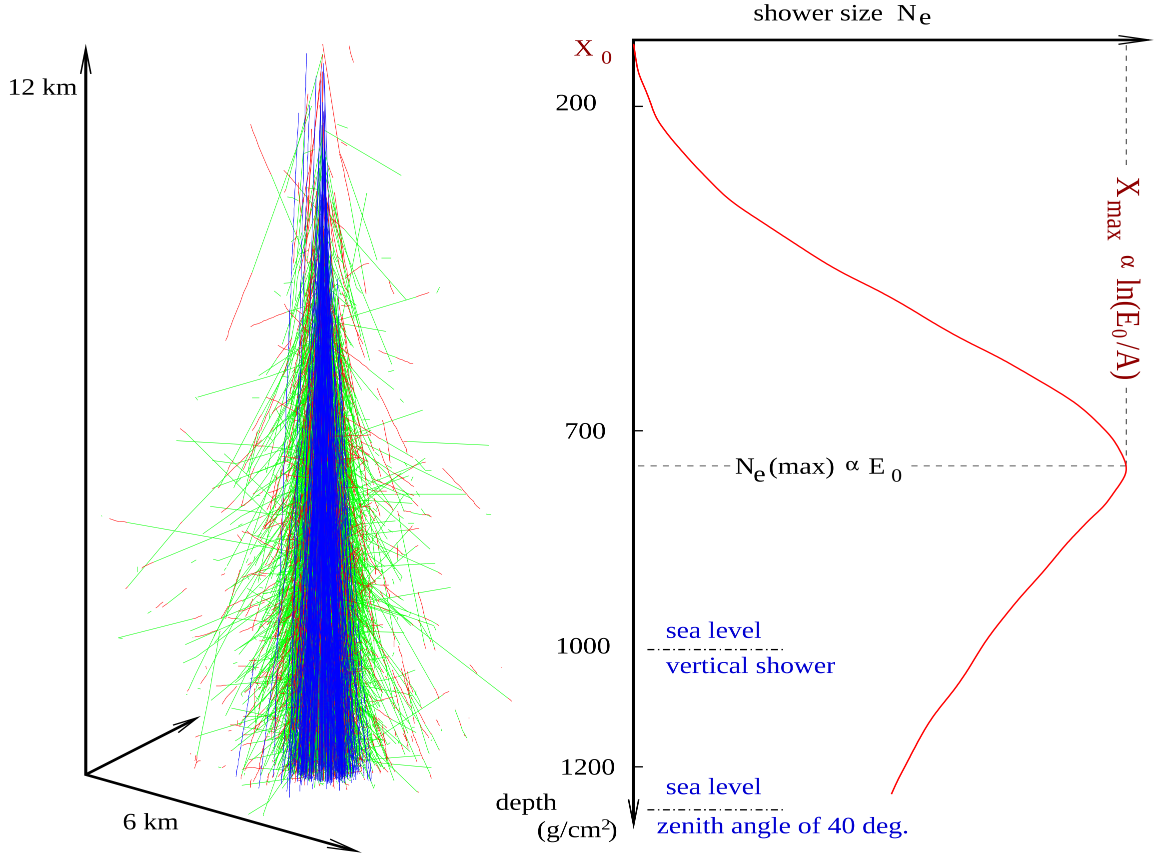
- PITHYA (Sjostrand et al.)
- HERWIG (Webber et al.)
- HIJING (Wang & Gyulassy)

High energy cosmic ray spectrum:

- steeply falling down: $\sim E^{-2.7}$ ($E^{-3.1}$) before (after) the "knee" ($\sim 4 \cdot 10^{15}$ eV)
- $\Rightarrow$ very few particles at highest energies



Detection: extensive air showers (EAS)



(Pryke, Auger Project)

Observed quantities:

- result from multi-step cascade process
- generally different from ones for fixed energy cascades

Requirements to CR interaction models:

- cross section predictions
- description of minimum bias hA- and AA-collisions
- importance of "forward" region
- predictive power (to extrapolate over many energy decades)

But: low sensitivity to "fine" details (smoothed by EAS development)

Representative models:

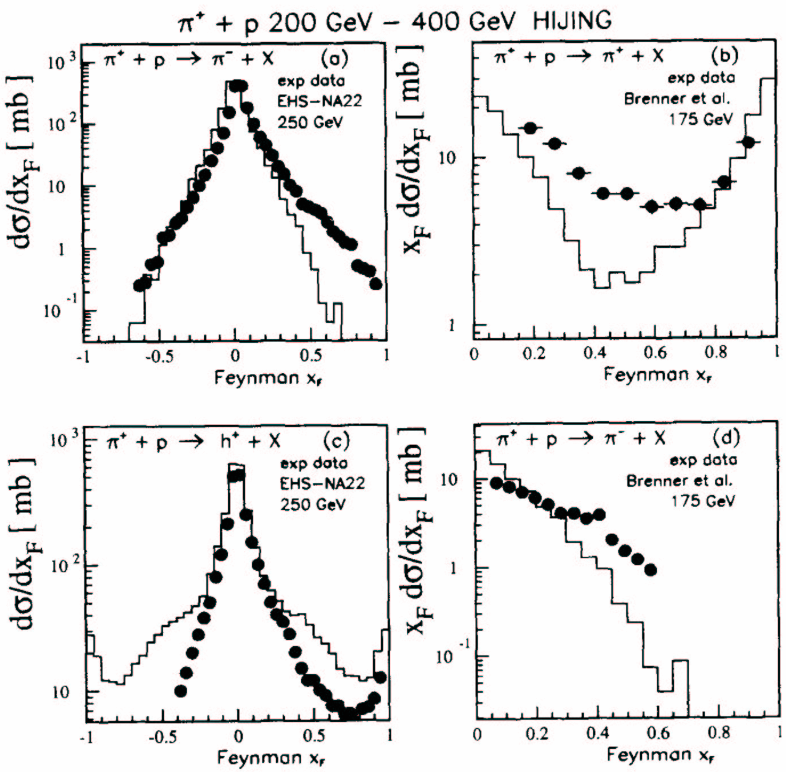
- DPMJET (Engel, Ranft & Roesler)
- neXus (Drescher, Hladik, SO, Pierog & Werner)
- QGSJET (Kalmykov & SO)
- SIBYLL (Engel, Gaisser, Lipari & Stanev)

Why not PYTHIA, 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)

Mini-jets and multiple scattering:
from "hard" to "soft" or from "soft" to "hard"?

From "hard" to "soft" - "pure QCD" models: PITHYA, HIJING, SIBYLL, ...

What "pure QCD" tells us?

- (mini-)jet production ($p_t > p_t^{\min} = Q_0$) - increases with energy
- small coupling ($\alpha_s(p_t^2)$) - compensated by large logarithms $\ln \frac{x_i}{x_{i+1}}$, $\ln \frac{p_{t_{i+1}}^2}{p_{t_i}^2}$

$\Rightarrow$ "leading-log" re-summations (n-parton "ladders"): $\sum_n \Pi_{i=1}^n \left(\int \alpha_s \frac{dx_i}{x_i}\right)$; $\sum_n \Pi_{i=1}^n \left(\int \alpha_s \frac{dp_{t_i}^2}{p_{t_i}^2}\right)$

QCD "collinear" factorization $\Rightarrow$ inclusive (leading-log) jet-pair cross section:

$$\sigma_{ad}^{\rm jet}(s,Q_0^2) = \sum_{I,J=q,\bar{q},g} \int_{p_t^2>Q_0^2} dp_t^2 \int dx^+ dx^- \frac{d\sigma_{IJ}^{2\to 2}(x^+x^-s,p_t^2)}{dp_t^2} f_{I/a}(x^+,M_F^2)\; f_{J/d}(x^-,M_F^2)$$

$d\sigma_{IJ}^{2\to 2}/dp_t^2$ - differential parton-parton cross section;

$f_{I/a}(x^+,Q^2)$ - parton I momentum distribution, "probed" at scale Q^2

pQCD tells nothing about

- jet production in an individual event
- interaction cross sections
- "soft" (low p_t) particle production, e.g., about leading particles

$\Rightarrow$ Mini-jet scheme (Gaisser & Halsen, Pancheri & Srivastava):

- "soft" physics $\equiv$ scaling
- energy increase of $\sigma_{ad}^{\rm tot}(s)$, $N_{ad}^{\rm ch}(s)$ - due to mini-jet production
- multiple scattering - eikonal approach

"Hard" eikonal:

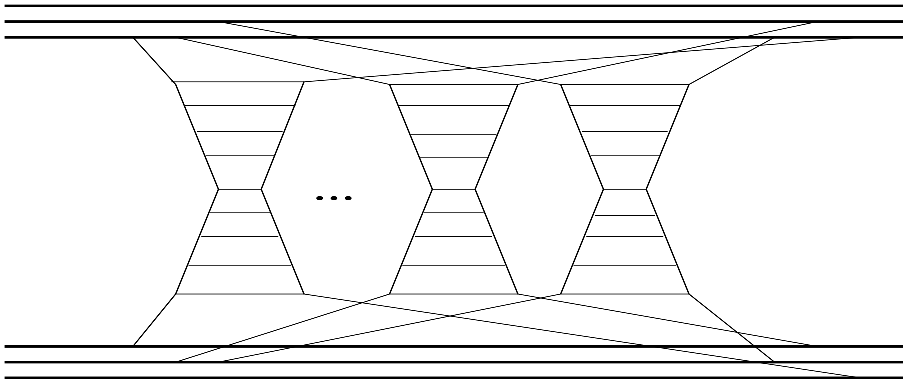
$$\chi_{ad}^{\rm hard}(s,b) = \frac{1}{2}\sigma_{ad}^{\rm jet}(s,Q_0^2)\,A_{ad}(b) \equiv \frac{1}{2}\langle n_{ad}^{\rm jet}(s,b)\rangle$$

$A_{ad}(b) = \int d^2s\; T_a^{e/m}(\vec{s})\, T_d^{e/m}(|\vec{b}-\vec{s}|)$ - hadronic overlap function

Number of jet pairs per event (for given b) - Poisson:

$$W(n_{\rm jet}) = \frac{\left[2\chi_{ad}^{\rm hard}(s,b)\right]^{n_{\rm jet}}}{n_{\rm jet}!}\exp\left(-2\chi_{ad}^{\rm hard}(s,b)\right)$$

Most general: each hard process accompanied by initial & final state parton emission $\Rightarrow$ represented by a parton ladder:



To get cross sections - also "soft" eikonal:

$$\chi_{ad}^{\text{soft}}(s,b) = \frac{1}{2}\sigma_{ad}^{\text{soft}}(s)\, A_{ad}(b)$$

$\Rightarrow$ inelastic cross section:

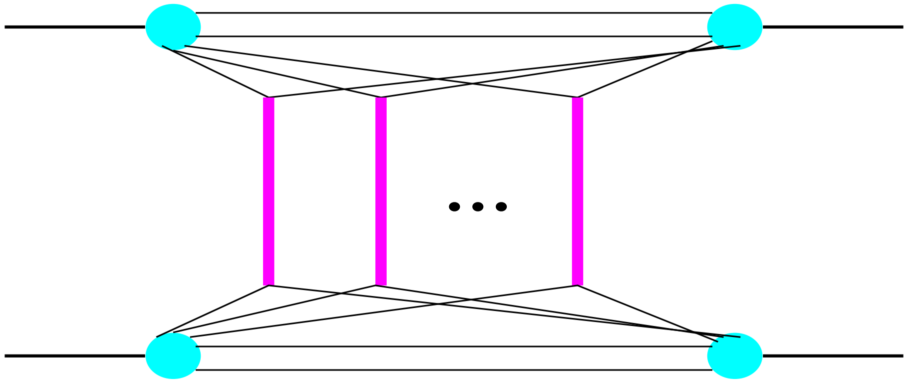
$$\sigma_{ad}^{\text{inel}}(s) = \int d^2b \left[1 - e^{-2\chi_{ad}^{\text{soft}}(s,b) - 2\chi_{ad}^{\text{hard}}(s,b)}\right]$$

Conversion of partons into hadrons:

- color field connections between final partons
- hadronization: string or cluster procedures

Let us look from the other side:
from “soft” to “hard” - Reggeon approach (Gribov, 1968)

elementary interaction = parton cascade ≡ Pomeron exchange



Pomeron amplitude:

$$f_{ab}^{\mathrm{P}}(s,b) = \frac{i\gamma_a\gamma_b s^{\alpha_{\mathrm{P}}(0)}}{\lambda_{ab}(s)} \exp\left(\frac{-b^2}{4\lambda_{ab}(s)}\right) \equiv i\chi_{ab}^{\mathrm{P}}(s,b)$$

$$\lambda_{ab}(s) = R_a^2 + R_b^2 + \alpha'_{\mathrm{P}}(0)\,\ln s$$

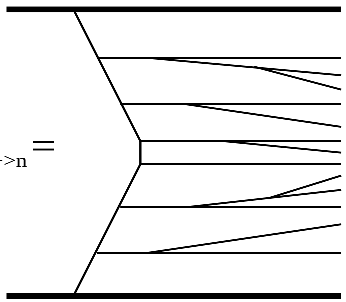
Pomeron intercept $\alpha_{\mathrm{P}}(0) > 1$ - energy increase

Pomeron slope $\alpha'_{\mathrm{P}}(0)$ - increasing spatial size of the interaction

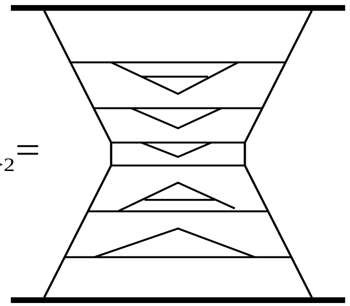
Cross sections & particle production

Elementary interaction - inelastic&elastic amplitudes:

$\mathbf{A}_{2->n} =$



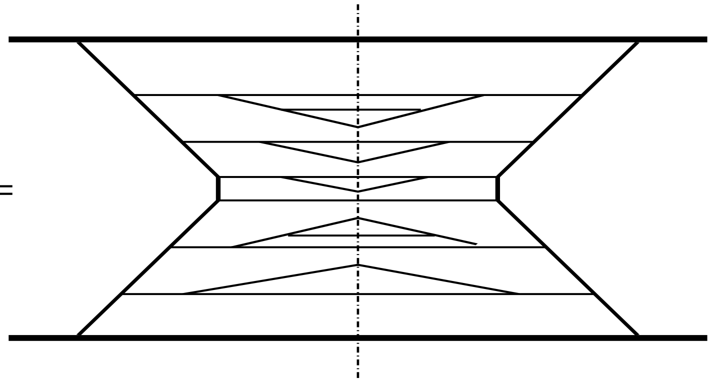
$\mathbf{A}_{2->2} =$



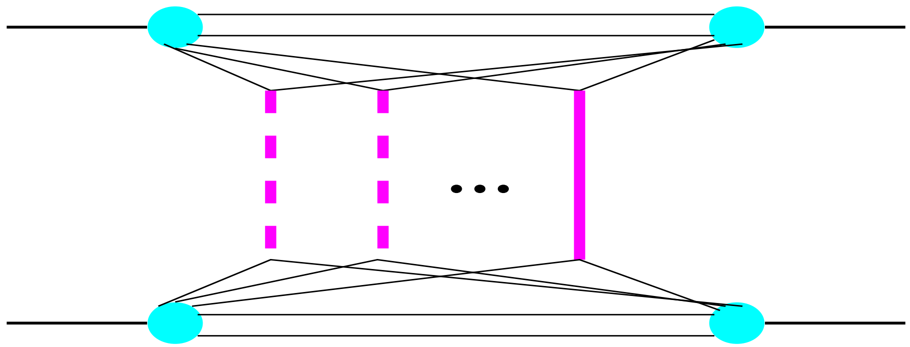
Cross section - optical theorem:

$$\sigma_{\rm tot} = \sum_n \int d\tau_n \; A_{2\to n} \cdot A^*_{2\to n} = 2{\rm Im}\, A_{2\to 2}$$

$\boldsymbol{\sigma}_{\mathbf{tot}} =$



Multiple scattering ⇒ AGK cutting rules (Abramovskii, Gribov & Kancheli):
no interference between different classes of the interaction ⇒ cross sections:



$$\sigma_{ab}^{\rm tot}(s) \; = \; 2\int d^2b \left[1 - e^{-\chi_{ab}^{\rm P}(s,b)}\right]$$

$$\sigma_{ab}^{\rm inel}(s) \; = \; \int d^2b \left[1 - e^{-2\chi_{ab}^{\rm P}(s,b)}\right]$$

"Topological" cross section (n "cut" Pomerons):

$$\sigma_{ab}^{(n)}(s) = \int d^2b \, \frac{\left[2\chi_{ab}^{\rm P}(s,b)\right]^n}{n!} e^{-2\chi_{ab}^{\rm P}(s,b)}$$

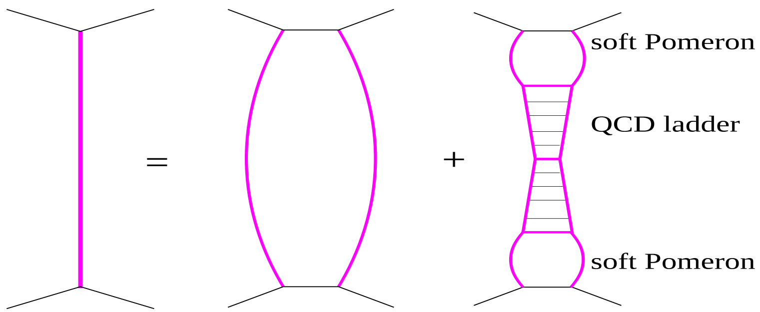
Particle production (Capella et al.; Kaidalov & Ter-Martyrosyan):
"cut" Pomeron ⇒ string formation & break up ⇒ hadronization

Matching with QCD - "semi-hard Pomeron" scheme (QGSJET, neXus):

- introduce a "threshold" scale Q_0^2
- use "soft" Pomeron below Q_0^2
- use DGLAP ladder for $|p_t^2| > Q_0^2$

The same picture as before but based on a "general Pomeron":

$$\chi_{ab}^{\mathrm{P}}(s,b) = \chi_{ab}^{\mathrm{P_{soft}}}(s,b) + \chi_{ab}^{\mathrm{P_{sh}}}(s,b)$$



⇒ similar to the mini-jet approach

Important differences:

- parton (particle) production extends to "soft" (low p_t) region
- low-x partons - distributed over larger transverse area

Presently: no sharp border between mini-jet / semi-hard Pomeron approaches:

- SIBYLL 2.1 - multiple "soft" interactions
- DPMJET - each mini-jet process accompanied by "soft" Pomeron exchange

Important: in both schemes elementary processes proceed independently

Rapidly comes to its limits: realistic parton momentum distributions (PDFs)
$\Rightarrow$ too rapid energy growth of cross sections & hadron multiplicities

Energy-dependent p_t-cutoff: $p_t^{\min} \equiv Q_0 = Q_0(s)$? Why?

“Dense” partonic systems: non-linear effects

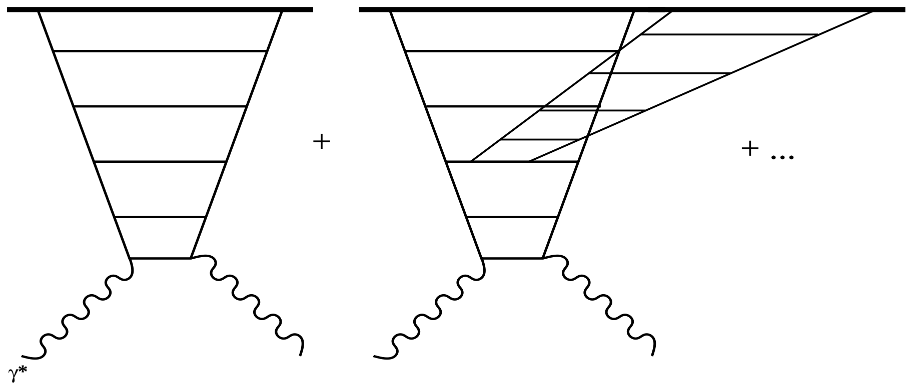
Independent interaction picture is inadequate for large s, small b, large A:

- many partons closely packed
- $\Rightarrow$ expected to interact with each other

QCD approach (Gribov, Levin & Ryskin) - asymptotic picture:

- parton saturation at some scale $Q^2_{\rm sat}(x) \Rightarrow$ “soft” contribution suppressed
- QCD parton dynamics for $p_t^2 > Q^2_{\rm sat}(x)$
- non-linear effects - interaction between QCD ladders

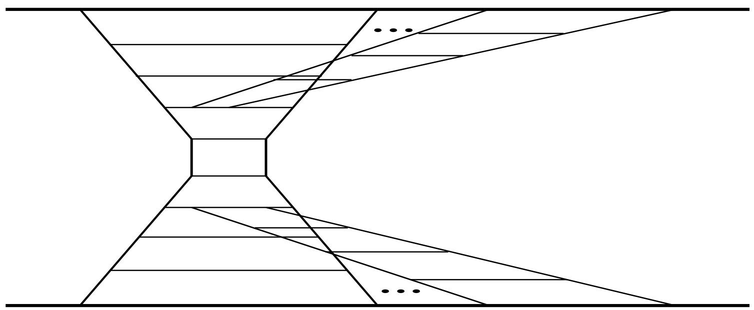
Structure function (SF) $F_2(x)$, $x \to 0$:



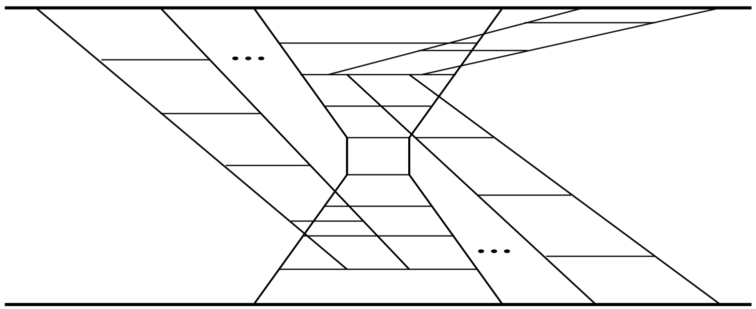
Provides formal justification for the energy-dependent p_t-cutoff:
saturation-based picture; $Q_0^2 = Q_0^2(s)$ - effective saturation scale

However: no explicit connection to GLR - ad hoc parameterizations

GLR - responsible for the factorizable contribution to the eikonal:
convolution of screened parton SFs:



But non-factorizable contributions - impossible to account for:

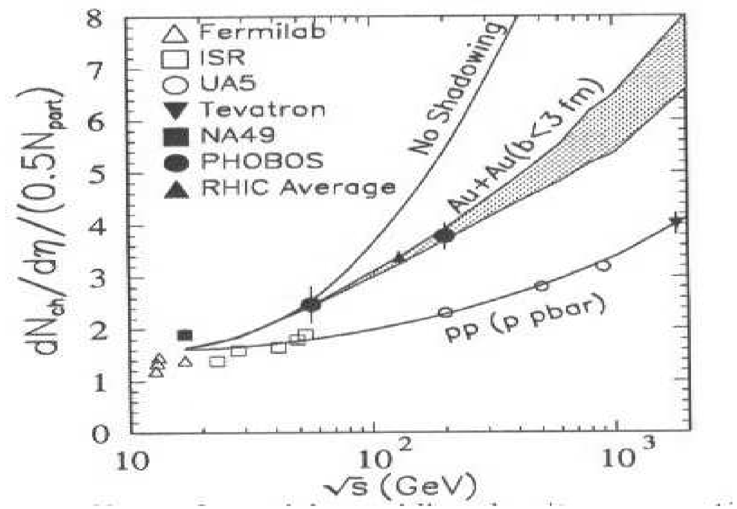


No account for:

- no saturation in peripheral interactions
- saturation being different in $hh-$, $hA-$, $AA-$collisions
- screening effects in non-saturation regime (shadowing)

Partly attempted in HIJING - parameterized nuclear shadowing of PDFs:

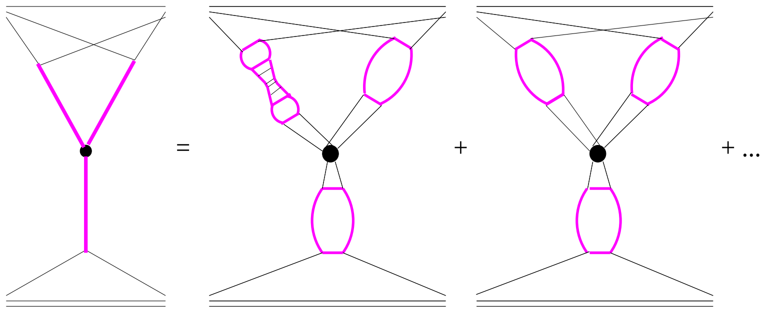
$$f_{I/A} = f_{I/A}(x, Q^2, b, A)$$



In general: treatment of realistic (not asymptotic) conditions needed!

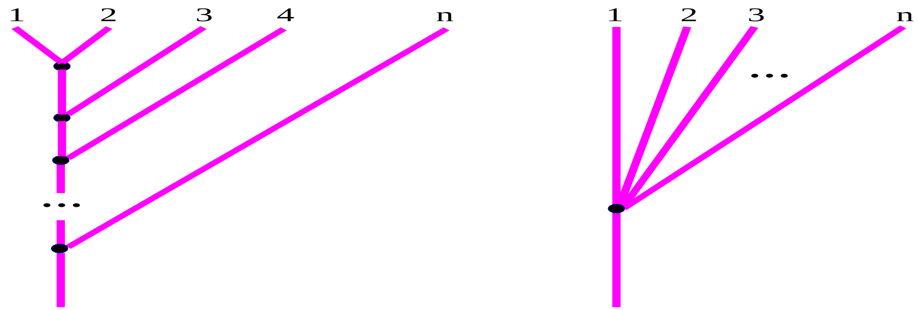
Alternative approach - QGSJET-II model (SO, 2004) :

- assumes no saturation at a fixed Q_0^2 scale
- $\Rightarrow$ non-linear effects = interactions between "soft" Pomerons
- $\Rightarrow$ can be described using Gribov's Reggeon scheme

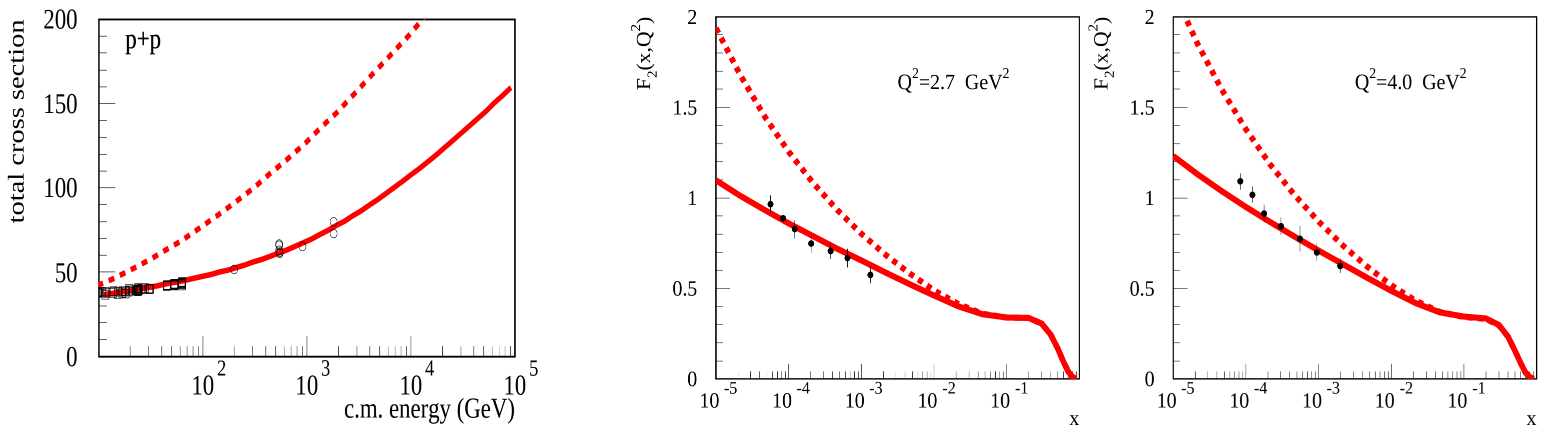


Main problem: all orders are to be accounted for:

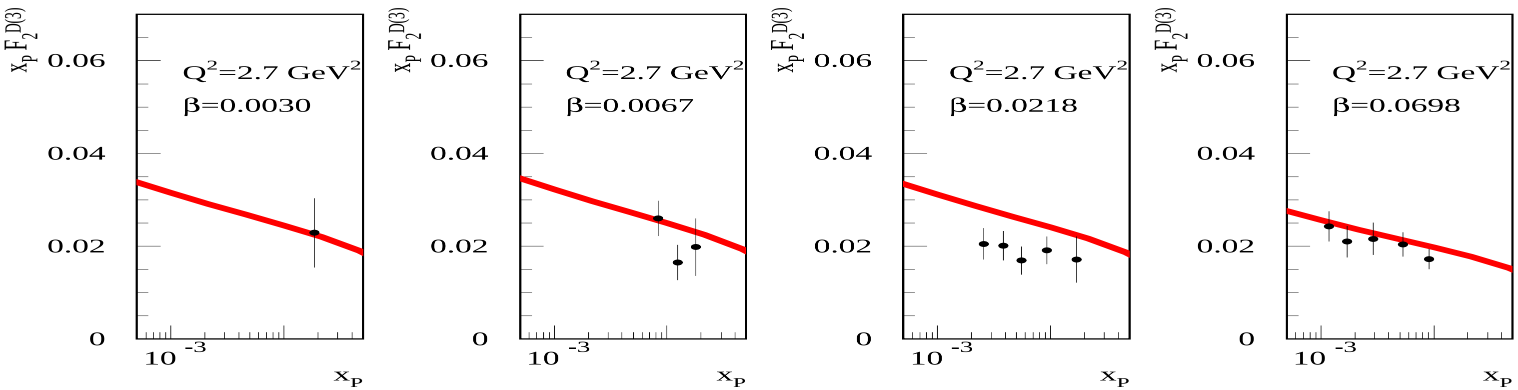
$$\Delta\chi_{ab}^{\rm fan} = \Sigma_{n=1}^{\infty}\, \Delta\chi_{ab}^{\rm fan} \sim \Sigma_{n=1}^{\infty}\, r_{3\mathbb{P}}^{n}\, \left[-\chi_{\mathbb{P}}(s)\right]^{n+1}, \quad \chi_{\mathbb{P}}(s) \sim s^{\alpha_{\mathbb{P}}(0)-1}$$



Total cross section and SF $F_2(x, Q^2)$ with (without) enhanced graphs:

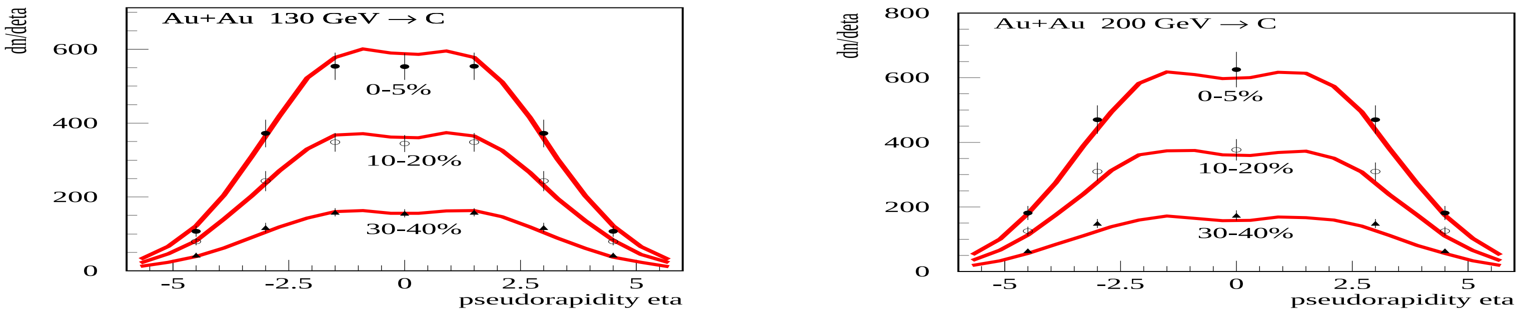


Triple-Pomeron vertex - can be inferred from "hard" diffraction data at HERA:



hA, AA: "fans" include connections to different nucleons
$\Rightarrow$ A-enhancement of screening effects

Charged multiplicity for different centralities at RHIC:



Main differences to the linear scheme:

- screening of the "soft" particle production
- in the "dense" limit (large s, small b, large A) -
  re-normalization of the "soft" Pomeron intercept: $\alpha_{\mathrm{P}}(0) \longrightarrow \tilde{\alpha}_{\mathrm{P}}(0) < 1$
  $\Rightarrow \chi_{ab}^{\mathrm{P}_{\mathrm{soft}}}(s,b)$ - decreasing with s - saturation at the Q_0^2 scale!
- $\Rightarrow$ approaches "mini-jet" picture in the "dense" limit

Drawback: does not treat screening & saturation effects at $p_t^2 > Q_0^2$!

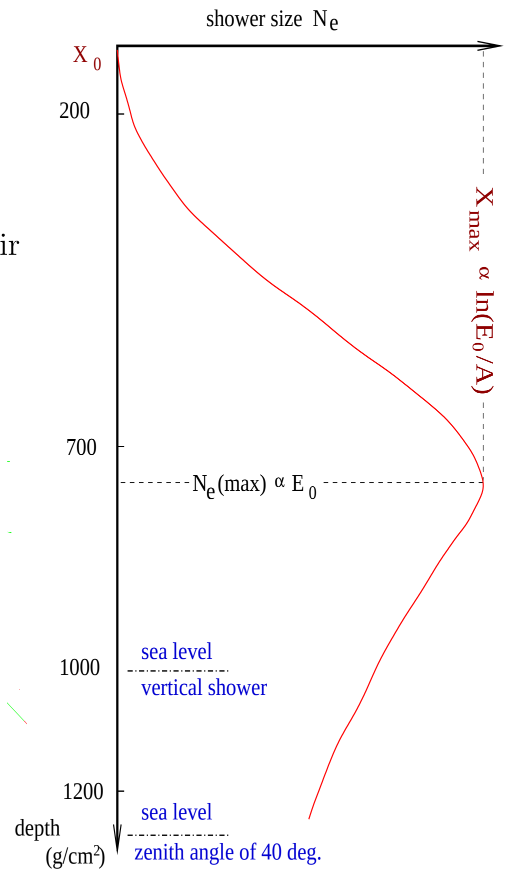
Air Shower Predictions

Basic EAS characteristics - sensitivity to hadronic interactions:

- $X_{\max}$ - mainly defined by $\sigma^{\rm inel}_{h-\rm air}$, $K^{\rm inel}_{h-\rm air}$
  a) position of the first interaction X_0: $\sigma^{\rm inel}_{p-\rm air}$
  b) profile shape: $K^{\rm inel}_{p-\rm air}$ (also $\sigma^{\rm inel}_{\pi-\rm air}$, $K^{\rm inel}_{\pi-\rm air}$)
  c) $X_{\max}$ fluctuations: mainly from X_0, $K^{\rm inel}_{p-\rm air}$

- N_e - correlated with $X_{\max}$ (parallel shift)

- N_μ - depends on $N^{ch}_{h-\rm air}$ (especially, $N^{ch}_{\pi-\rm air}$)



Energy (mass) dependence:

- $X_{\max} \sim \ln(E_0/A)$
- $N_e \sim A\ (E_0/A)^{\alpha_e}$, $\alpha_e > 1$
- $N_\mu \sim A\ (E_0/A)^{\alpha_\mu}$, $\alpha_\mu < 1$

Münchhausen's problem: disentangle energy, mass, and hadronic models

Let us compare models...

SIBYLL 2.1:

- mini-jet approach + multiple "soft" Pomerons
- GRV PDFs + floating p_t-cutoff $(Q_0(s))$

QGSJET:

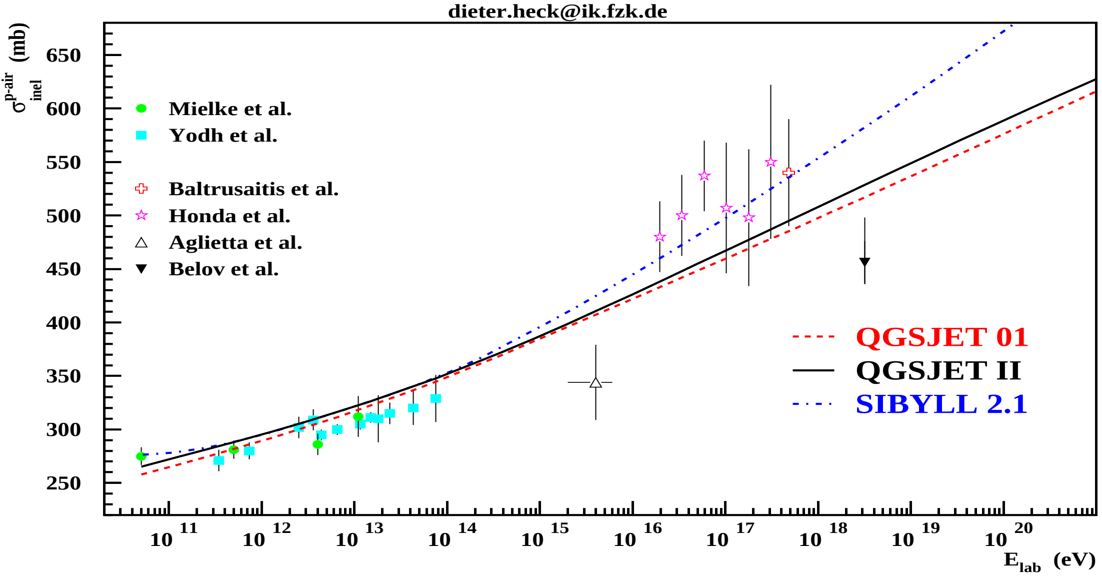
- multiple "soft" and "semi-hard" Pomerons
- "flat" (pre-HERA) PDFs

QGSJET-II / QGSJET:

- bigger Pomeron intercept (1.18 instead of 1.07)
- steeper PDFs (now in agreement with HERA)
- non-linear screening effects (multi-Pomeron vertices)

Impact on $\sigma^{\rm inel}_{h-{\rm air}}$, $K^{\rm inel}_{h-{\rm air}}$, $N^{ch}_{h-{\rm air}}$?

Proton-air cross section



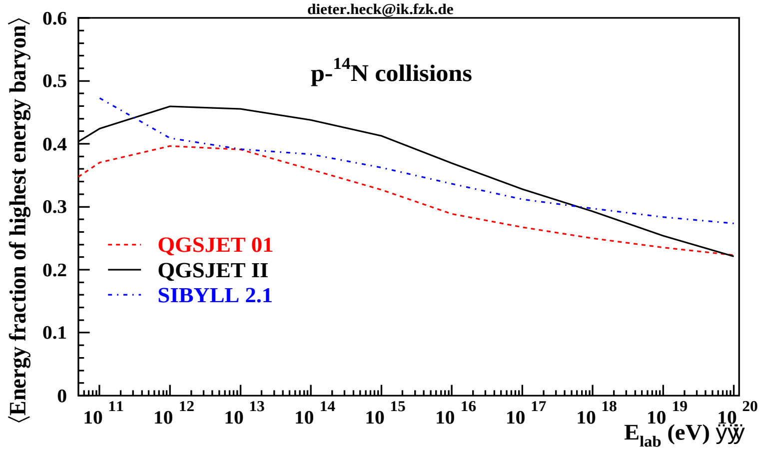
200 GeV fixed target: $\sigma^{\rm inel(exp)}_{n-{}^{12}C} = 237 \pm 2$ mb; $\sigma^{\rm inel}_{p-{}^{12}C} = 241$ mb (QGSJET-II)

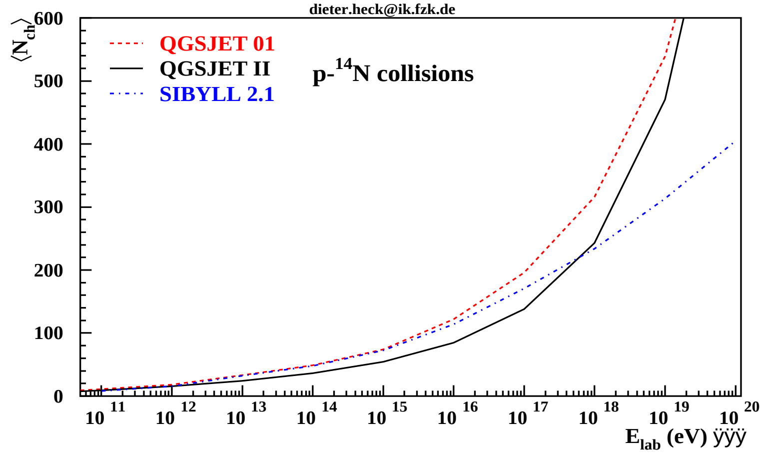
SIBYLL / QGSJET - faster energy increase:

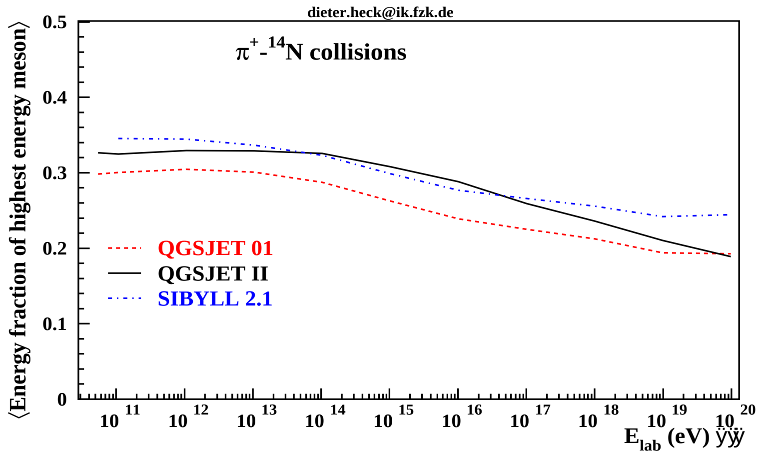
- steeper PDFs in SIBYLL
- inelastic screening in QGSJET
- beware: also depends on the $Q_0(s)$-parameterization & parton b-distribution

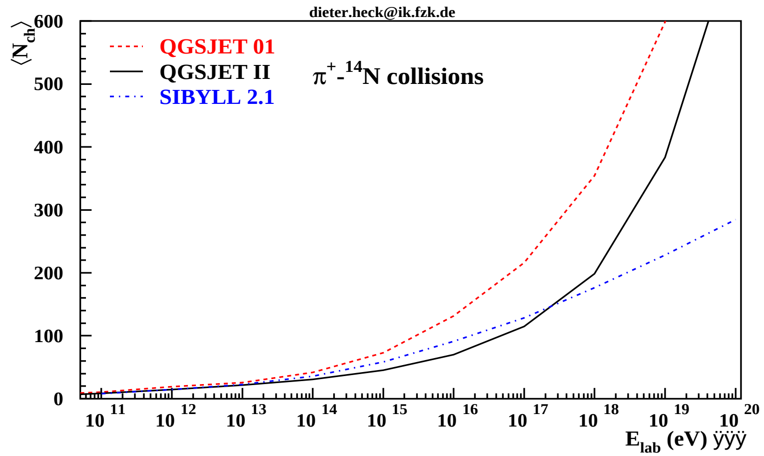
QGSJET-II / QGSJET: steeper PDFS compensated by screening effects

Leading baryon (meson) energy share $(1 - K^{\text{inel}}_{h-\text{air}})$ and charged multiplicity $(N^{ch}_{h-\text{air}})$ in $p - {}^{14}N$ $(\pi - {}^{14}N)$ collisions









QGSJET / SIBYLL: "soft" parton production in addition to mini-jets

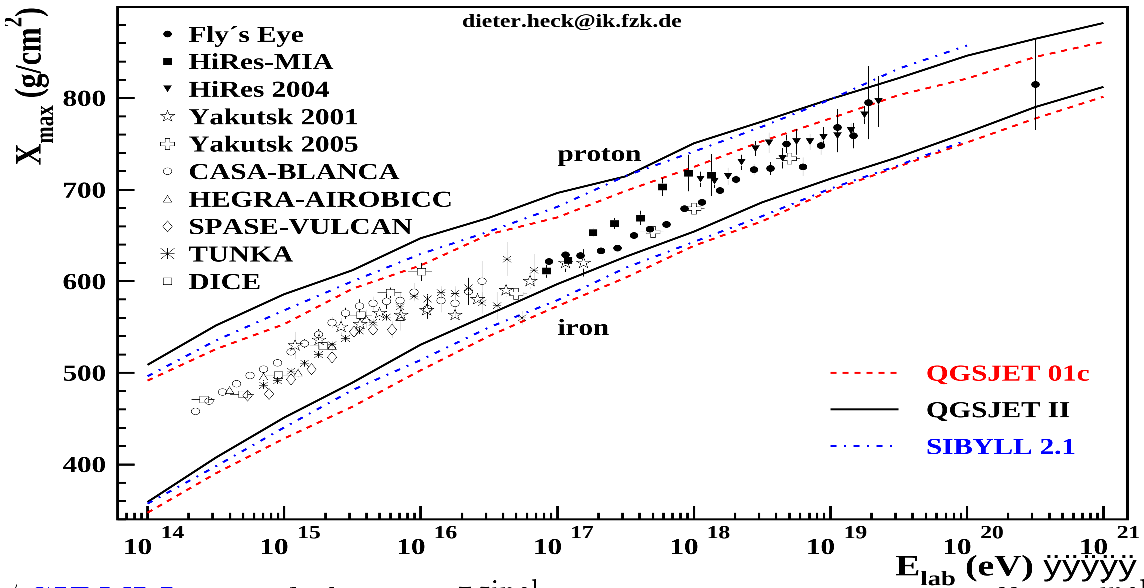
- $\Rightarrow$ faster energy increase of $K^{\rm inel}_{h-{\rm air}}$, $N^{ch}_{h-{\rm air}}$ in QGSJET

QGSJET-II / QGSJET: strong reduction of "soft" production in the "dense" limit

- $\Rightarrow$ much smaller $K^{\rm inel}_{h-{\rm air}}$, $N^{ch}_{h-{\rm air}}$ in QGSJET-II

QGSJET-II / SIBYLL:

- "soft" Pomeron contribution reduced $\Rightarrow$ same effect
- highest energies - faster increase of $K^{\rm inel}_{h-{\rm air}}$, $N^{ch}_{h-{\rm air}}$ in QGSJET-II:
  too strong $Q_0(s)$ growth in SIBYLL or absence of GLR-effects in QGSJET-II?



QGSJET / SIBYLL: much larger $K^{\text{inel}}_{p-\text{air}}$ over-compensates smaller $\sigma^{\text{inel}}_{p-\text{air}}$

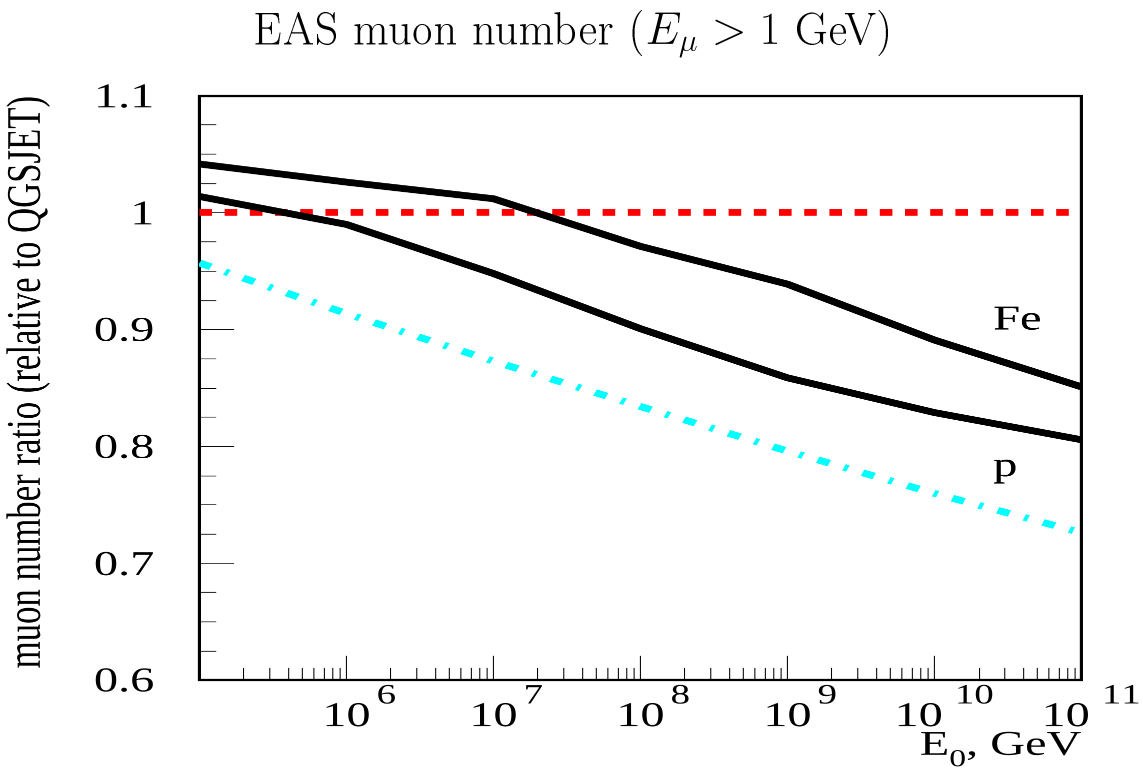
- $\Rightarrow$ higher shower maximum

QGSJET-II / QGSJET: even bigger difference for $K^{\text{inel}}_{p-\text{air}}$; similar $\sigma^{\text{inel}}_{p-\text{air}}$

- $\Rightarrow$ much deeper $X_{\max}$ (by $\sim 20 \div 25$ g/cm^2)

QGSJET-II / SIBYLL:

- smaller $K^{\text{inel}}_{p-\text{air}}$, $\sigma^{\text{inel}}_{p-\text{air}} \Rightarrow$ deeper $X_{\max}$
- highest energies: smaller $\sigma^{\text{inel}}_{p-\text{air}}$ compensated by larger $K^{\text{inel}}_{p-\text{air}}$



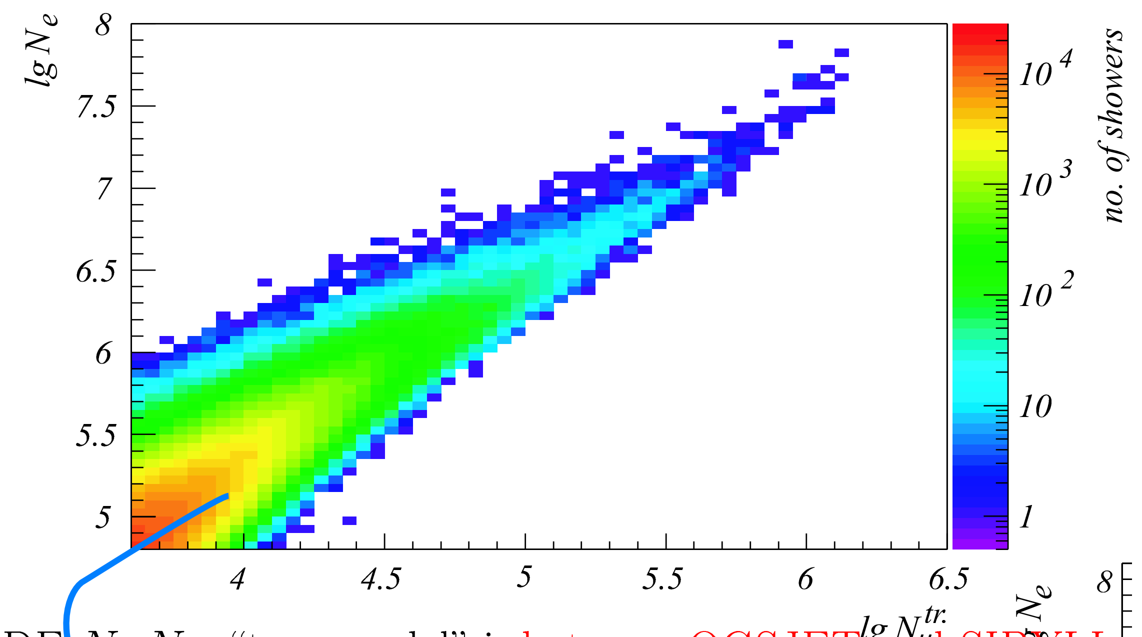
SIBYLL / QGSJET: factor of 2 difference in $N^{ch}_{p-\mathrm{air}} \Rightarrow$ 30% difference in N_μ

QGSJET-II: reduction of $N^{ch} \Rightarrow$ smaller N_μ (only 10% bigger than in SIBYLL)

Cosmic ray interactions: remaining puzzles

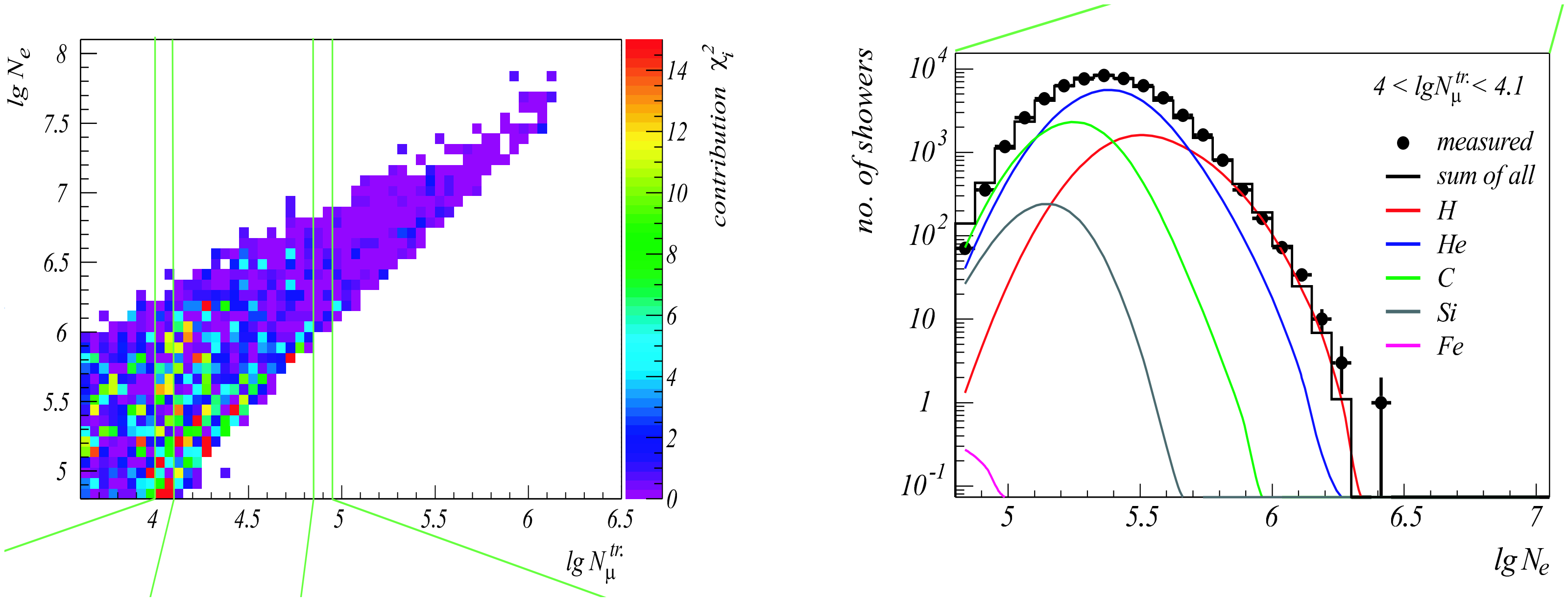
Model discrimination - solving Münchhausen's problem?

- studies of correlations between air shower observables



KASCADE N_e-N_μ: "true model" is between QGSJET and SIBYLL

- either smaller N_μ than in QGSJET (larger than in SIBYLL)
- or bigger N_e?



Smaller N_μ solves the problem?

No! Calculated distributions too smooth (wide) compared to data

$\Rightarrow$ smaller EAS fluctuations needed $\Rightarrow$ deeper $X_{\max}$ (bigger N_e)

QGSJET-II goes in the right direction...

but too far...

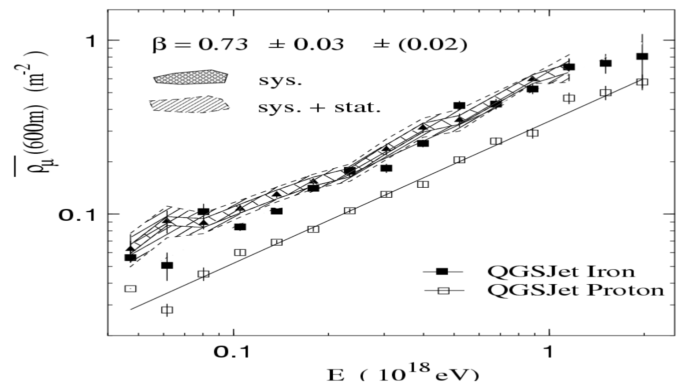
Now few possibilities:

- bigger $K^{\rm inel}_{h-{\rm air}}$, increasing with E_0 - supported by RHIC data (baryon stopping), theoretical ideas (diquark breaking, junction & saturation)
- larger cross section - possible, but in variance with HIRES result
- "exotic" option: even smaller cross section but significantly larger multiplicity

Difficult to accept but could help to solve composition puzzle at higher energies:

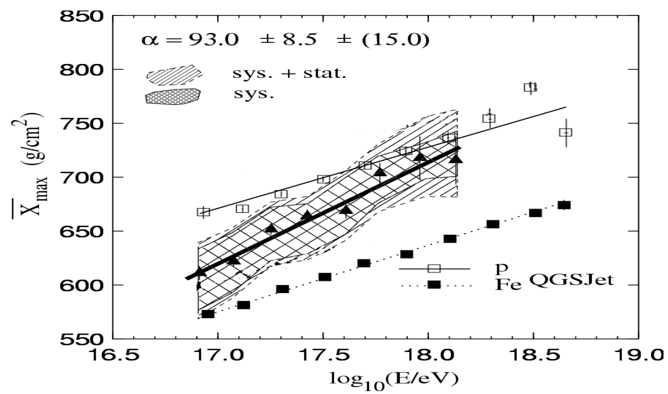
Example: HiRes-MIA measurement

MIA: muon density at 600m



Composition iron dominated, no significant change with energy

HiRes: depth of shower maximum



Composition changes to proton dominated one

Outlook

Contemporary models - generally good description of EAS physics

Theoretical challenge:
consistent description of both "soft" and "hard" screening (saturation) effects

CR experiments can test general consistency and particular features of models:

- studies of correlations of basic air shower observables
- determination of proton-air cross section
- inclusive muon flux measurements
- studies of muon bundles
- ...

But Münchhausen's problem? $\Rightarrow$ accelerator experiments are of great help:

- LHC measurement of $\sigma_{pp}^{\rm tot}$ and $B_{pp}^{\rm el}$ would resolve cross section uncertainty
- RHIC studies of baryon "stopping" for different "centralities" may give insight into hadronic leading state behavior
- proton-nucleus?, pion-nucleus?, ... (from HARP to UHE-HARP?!)