Simulations of Cosmic Ray Interactions: Past, Present, and Future

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Physics at the End of the Galactic Cosmic Ray Spectrum

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Outline:

1) Historical trend
2) High energy interactions - basic approach
3) Matching with QCD?
4) Non-linear effects
5) Air shower predictions
5) Model uncertainties
6) Future prospects

Historical Trend

Simulations of CR interactions - 50 year history

(G.Zatsepin, M.Hillas, M.Dedenko, and others)

Early approaches - semi-inclusive:

- sampling of K^{inel}, $N_{\pi^{\pm}}$, $N_{\pi^{0}}$
- simple parameterizations of inclusive spectra for given K^{inel}, $N_{\pi^{\pm}}$, $N_{\pi^{0}}$

Microscopic MC models (around 90s):

requested by the increased accuracy of CR experiments

Evolution of physics picture:

- first simple scaling: $\sigma_{\mathrm{inel}}(s) = \mathrm{const}$, $K^{\mathrm{inel}}(s) = \mathrm{const}$, $N_{\pi}(s) = \mathrm{const}$
- but $\sigma_{\mathrm{inel}}(s)$ - increasing with s
- $N_{\pi}(s)$ - also increasing
- finally, the inelasticity grows with s

Presently: phenomenological MC models

High energy models ($> 10 \div 100$ GeV):

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

Low-energy models:

- GHEISHA/GEANT (Fesefeldt)
- Splitting algorithm (Hillas)
- FLUKA (Fasso, Ferrari, Ranft, Sala)
- UrQMD (Bass, Bleicher et al.)
- TARGET (Engel, Gaisser, Protheroe, Stanev)
- HADRIN/NUCRIN (Hanssgen, Ranft)

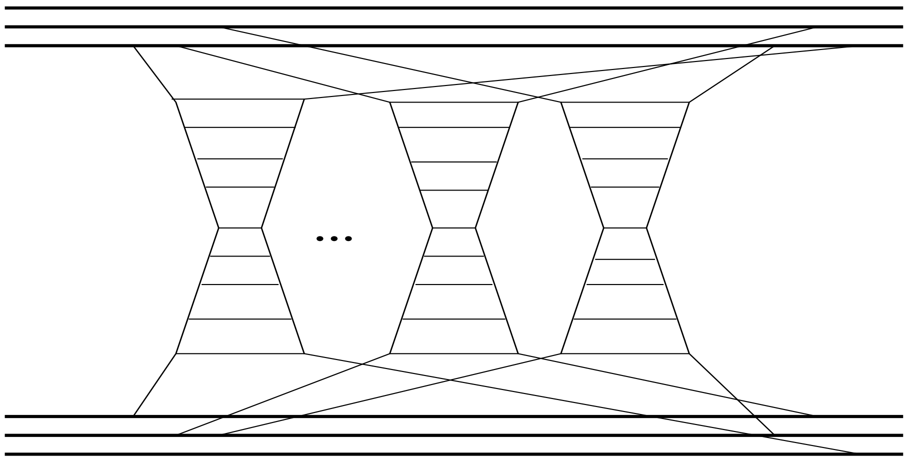
Current and future progress - due to closer link to QCD

But: (most likely) the models will remain phenomenological

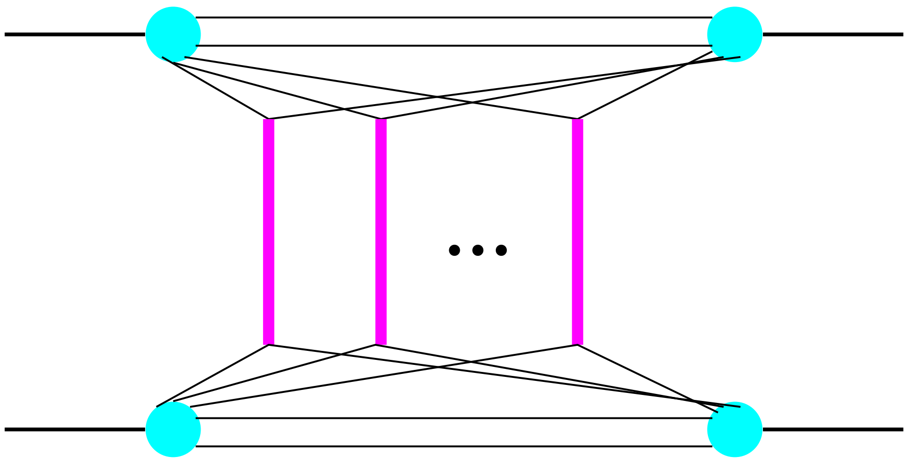
Basic Approach

High energy interactions - multiple scattering scheme:

- required by unitarization
- inclusive cross sections increase faster than total ones
- describes diffraction dissociation



Elementary interaction = parton cascade ≡ Pomeron exchange



Pomeron amplitude:

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

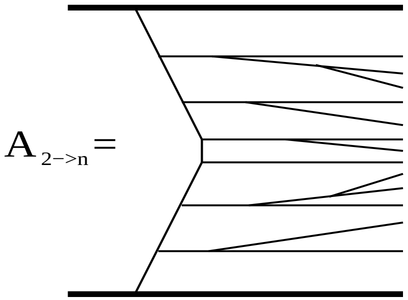
$$\lambda_{ab}(s) = R_a^2 + R_b^2 + \alpha'_{\mathrm{P}}(0)\,\ln s$$

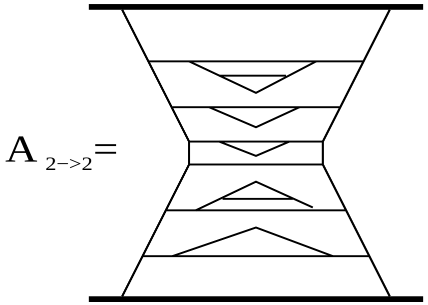
Pomeron intercept $\alpha_{\mathrm{P}}(0) > 1$ - energy increase

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

Cross sections & particle production

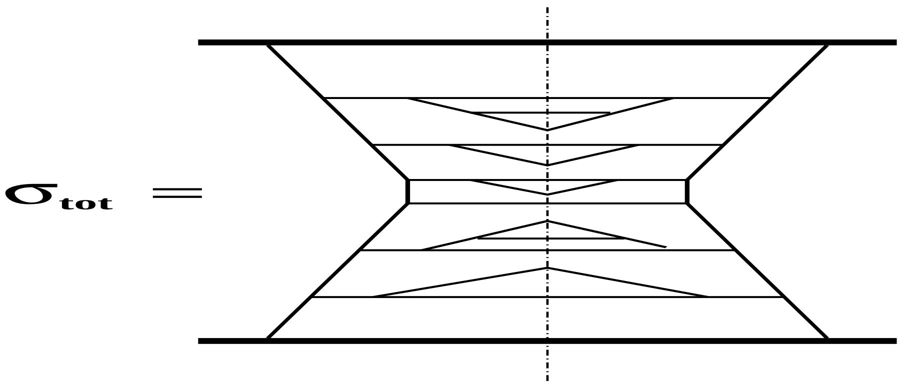
Elementary interaction - inelastic&elastic amplitudes:





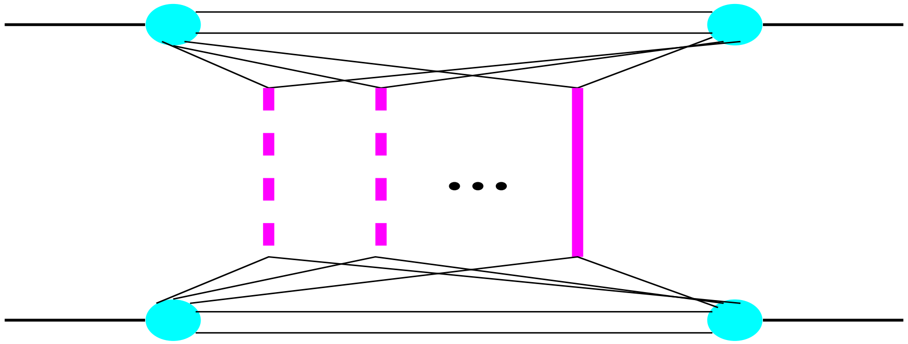
Cross section - optical theorem:

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



AGK cutting rules (V.Abramovskii, V.Gribov, O.Kancheli, 1973):

no interference between different classes of the interaction $\Rightarrow$ cross sections:



$$\sigma_{ab}^{\rm tot}(s) = 2\sum_{i,j} C_i^a\, C_j^b \int d^2b \left[1 - e^{-\lambda_i^a\,\lambda_j^b\,\chi_{ab}^{\rm P}(s,b)}\right]$$

$$\sigma_{ab}^{\rm inel}(s) = \sum_{i,j} C_i^a\, C_j^b \int d^2b \left[1 - e^{-2\lambda_i^a\,\lambda_j^b\,\chi_{ab}^{\rm P}(s,b)}\right]$$

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

$$\sigma_{ab}^{(n)}(s) = \sum_{i,j} C_i^a\, C_j^b \int d^2b\, \frac{\left[2\lambda_i^a\,\lambda_j^b\,\chi_{ab}^{\rm P}(s,b)\right]^n}{n!} e^{-2\lambda_i^a\,\lambda_j^b\,\chi_{ab}^{\rm P}(s,b)}$$

C_i^a, λ_i^a - relative weights and strengths of diffraction eigenstates of hadron a

Important: diffraction and inelastic screening - related to each other:
higher diffraction $\Rightarrow$ larger inelastic screening
$\Rightarrow$ smaller cross sections at higher energies and on nuclei

Dual Parton Model (A.Capella et al., 1979),
Quark-Gluon String model (A.Kaidalov, K.Ter-Martyrosyan, 1982):

"cut" Pomeron $\Rightarrow$ string formation & break up $\Rightarrow$ hadronization

Remarkably simple picture:

- elementary processes - Pomeron exchanges
- small number of adjustable parameters
- generalization to hA, AA - parameter free

Experimental data on $\sigma^{\rm tot}$, $\sigma^{\rm el}$, $\sigma^{\rm difr}$, $B^{\rm el}$ $\Rightarrow$ fixing Pomeron parameters
Experimental data on particle production $\Rightarrow$ fixing hadronization parameters

Drawbacks:

- high energy behavior governed by the Pomeron intercept, not by QCD
- no space for high p_t physics

Matching with QCD?

Present approaches:

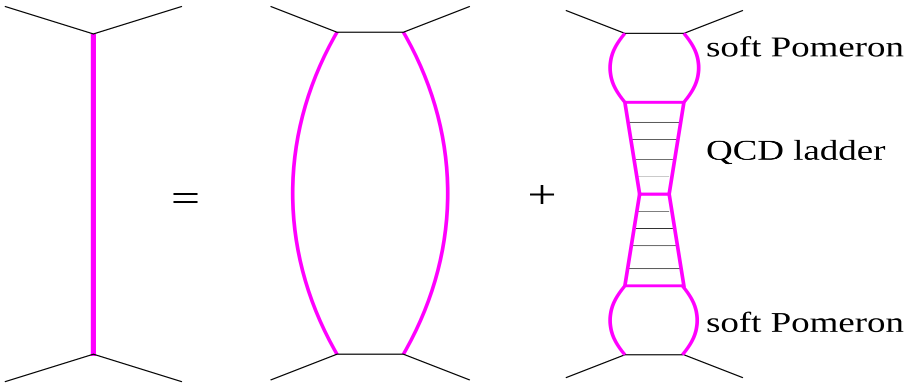
- "mini-jet" scheme - SIBYLL model (R.Fletcher et al., 1994; R.Engel et al., 1999), PYTHIA model (T.Sjostrand, 1987), others
- "semi-hard Pomeron" scheme - QGSJET model (N.Kalmykov, SO, A.Pavlov, 1994, 1997), neXus model (H.Drescher et al., 2001)

"Semi-hard Pomeron" approach:

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

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

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



"Mini-jet" approach - without "soft" Pomeron (no "soft pre-evolution")

$\Rightarrow$ implies screening mechanism: $Q_0^2 = Q_0^2(s)$

(to suppress non-perturbative parton evolution)

In general, Pomeron physics is complicated:

- QCD parton evolution
- string formation and break-up
- fragmentation into hadrons

Interaction physics - simple and transparent:

- a number of elementary processes - Pomeron (QCD ladder) exchanges
- small number of adjustable parameters
- generalization to hA, AA - parameter free
- high energy asymptotics - governed by pQCD

Important: elementary processes proceed independently

Rapidly comes to its limits - cross sections and hadron multiplicities increase too fast for realistic parton structure functions (SFs)

Non-Linear Effects

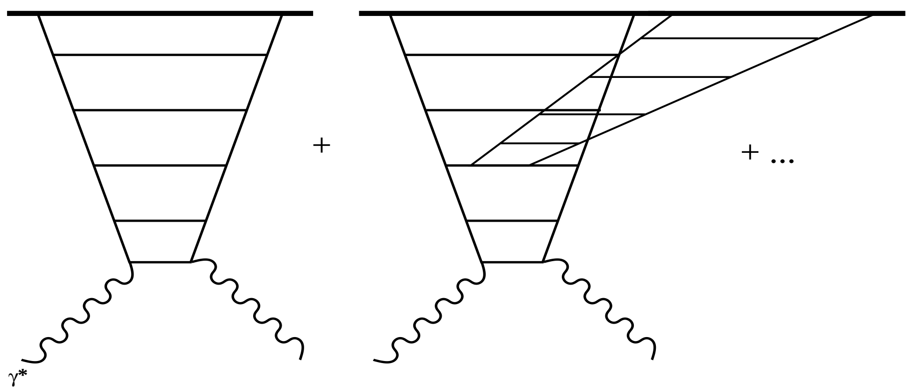
Independent interaction picture is inadequate for large s, small b, large A:

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

QCD approach (L.Gribov, E.Levin, M.Ryskin, 1983) - asymptotic picture:

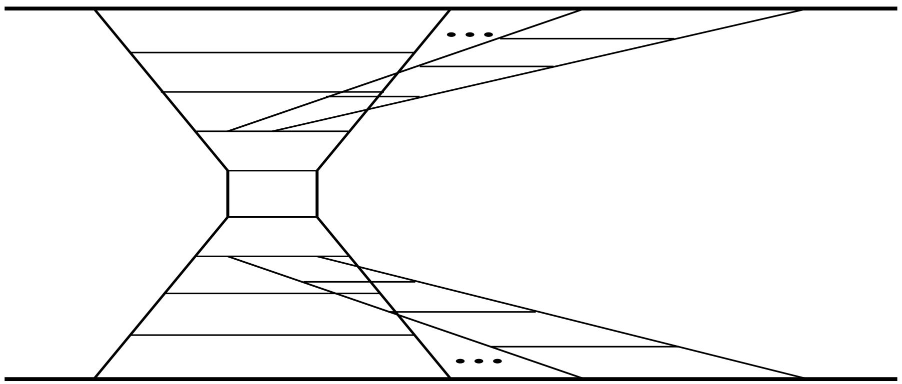
- parton saturation at some scale $Q^2_{\rm sat}(x) \Rightarrow$ “soft” contribution suppressed
- QCD parton dynamics for $Q_i^2 > Q^2_{\rm sat}(x)$
- non-linear effects - interaction between QCD ladders

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

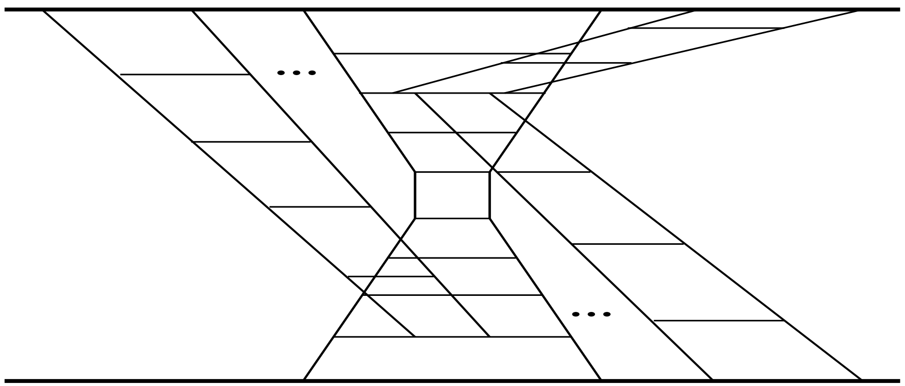


Provides formal justification for the "mini-jet" approach:
saturation-based picture; $Q_0^2 = Q_0^2(s)$ - effective saturation scale

Factorizable contribution to the eikonal - convolution of screened parton SFs:



But also non-factorizable contributions - impossible to account for:



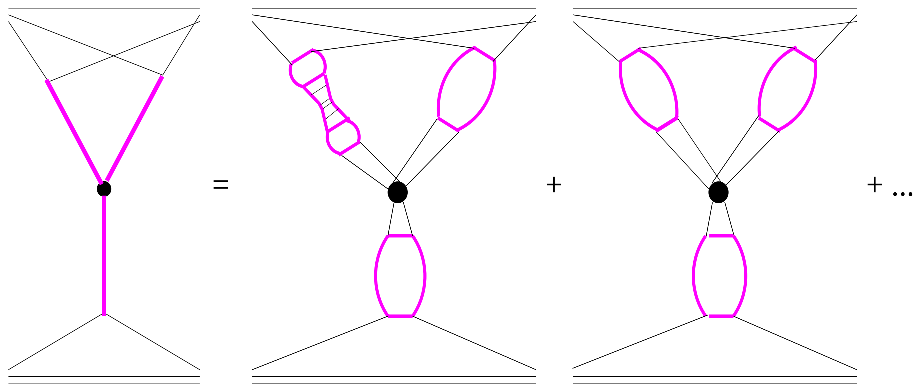
Does not account for:

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

$\Rightarrow$ Treatment of realistic (not asymptotic) conditions needed!

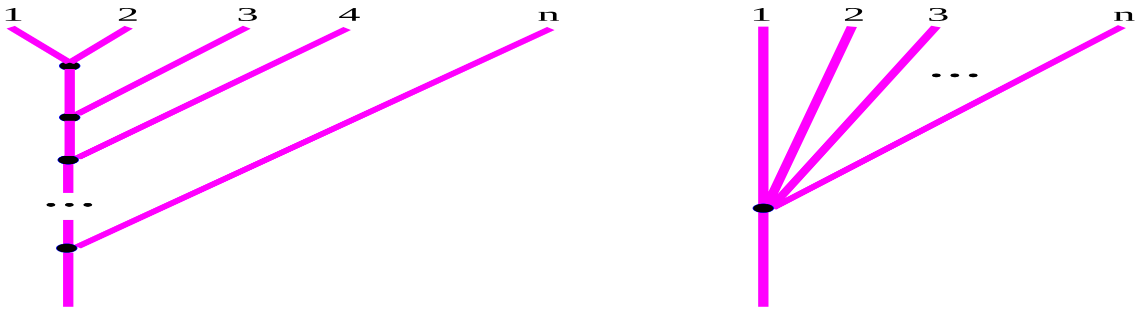
QGSJET-II model (SO, 2004) - alternative approach:

- 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



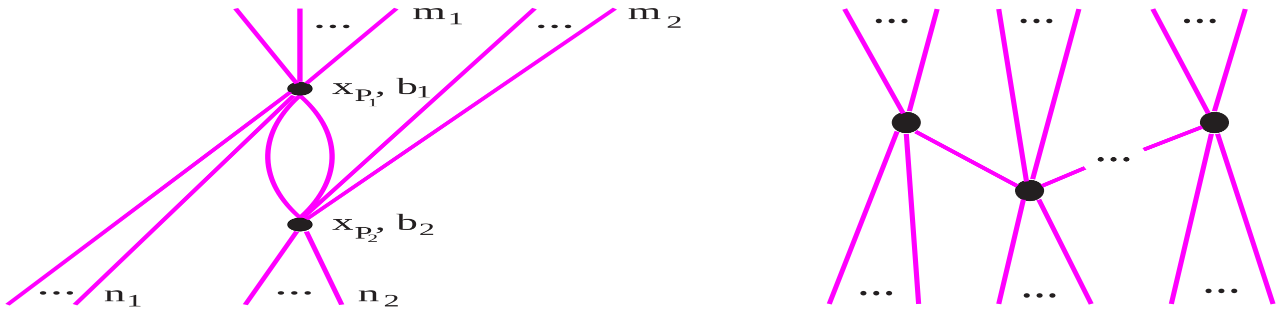
Main problem: all orders are to be accounted for!

Example: "fan" contributions with n "legs":



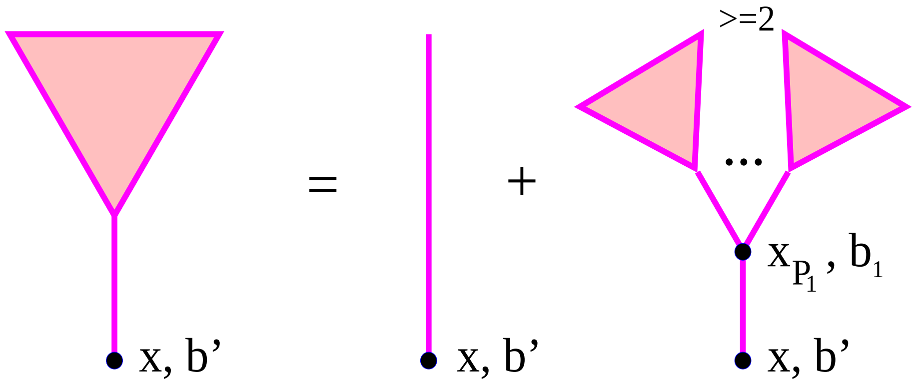
$$\Delta\chi_{ab}^{\rm fan} = \sum_{n=1}^{\infty} \Delta\chi_{ab}^{\rm fan} \sim \sum_{n=1}^{\infty} r_{3\rm P}^{n} \, \left[-\chi_{\rm P}(s)\right]^{n+1} , \quad \chi_{\rm P}(s) \sim s^{\alpha_{\rm P}(0)-1}$$

Still one can neglect "loop" and "chess-board" diagrams:

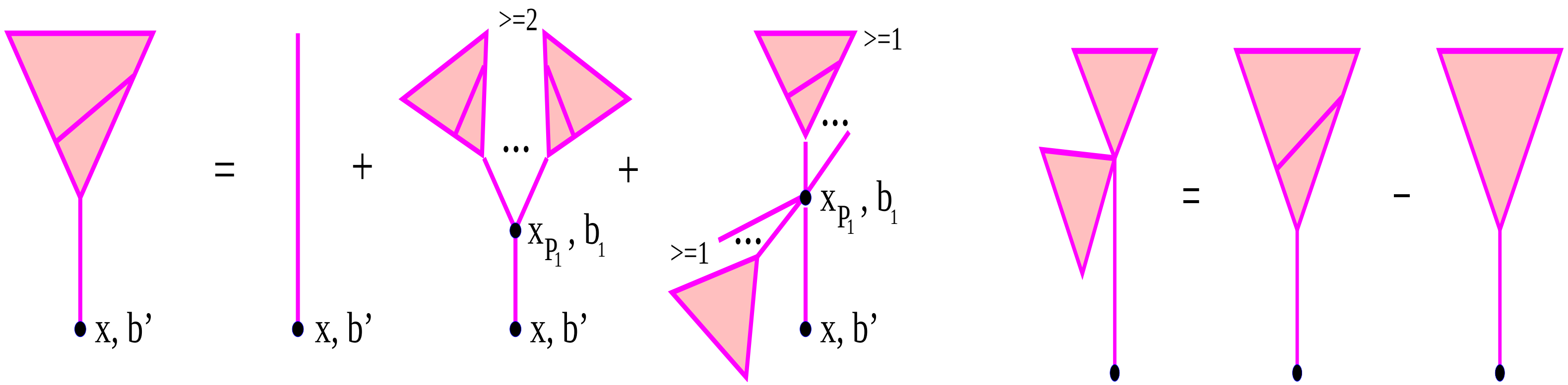


And re-sum all others ...

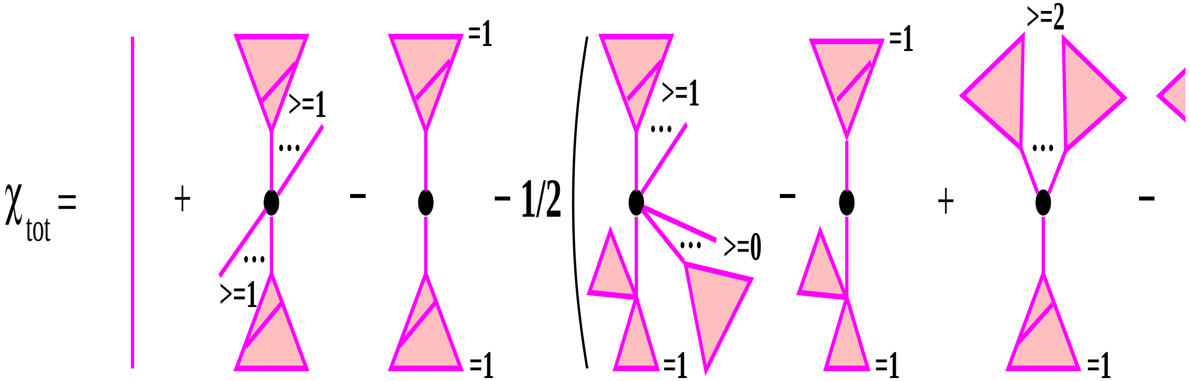
Elementary building blocks - "fan" contributions:



Introduce "generalized fans" and the difference:



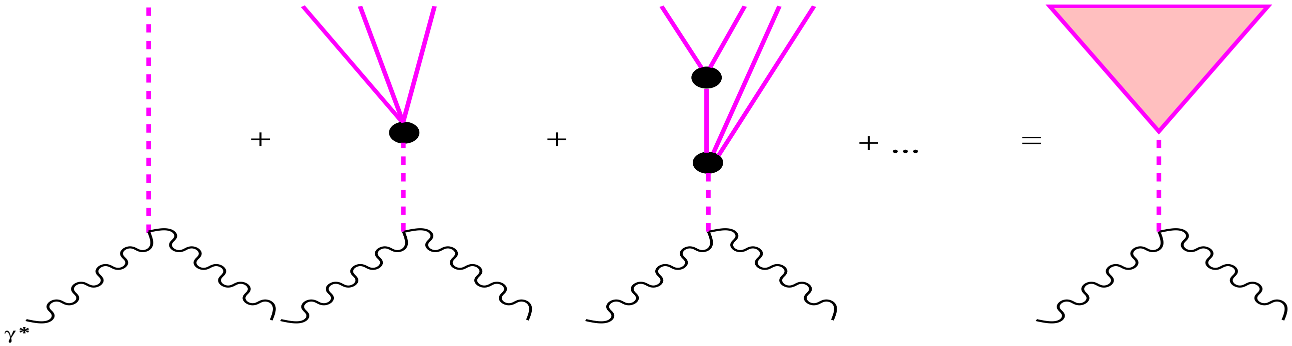
Now total eikonal:



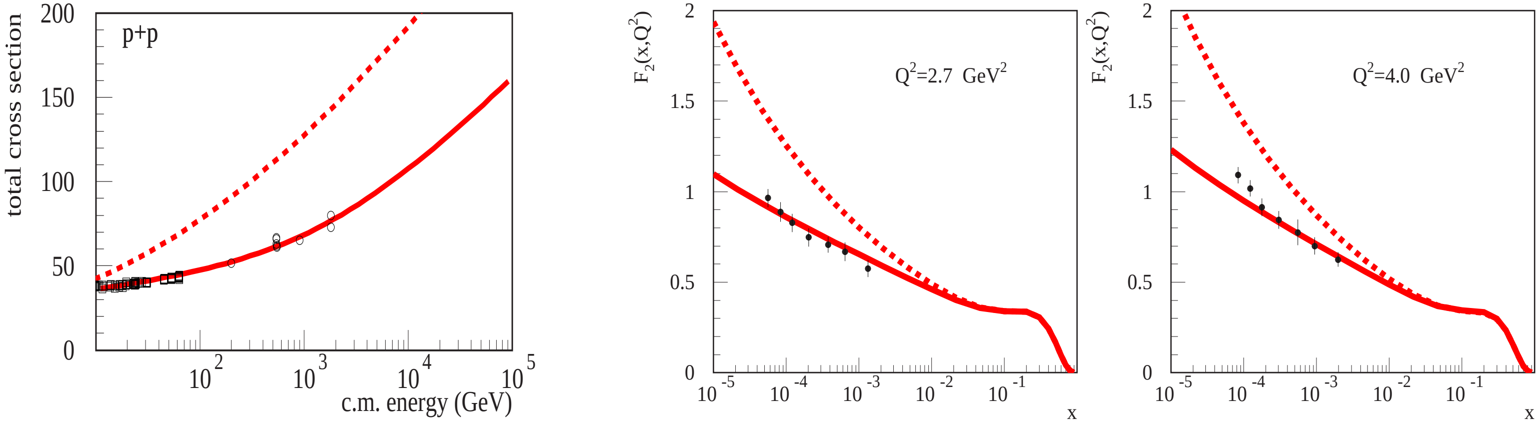
hA, AA - similar; "fans" include connections to different nucleons
$\Rightarrow$ A-enhancement of screening effects

Cross sections - the same formulas as before but with the full eikonal $\chi_{ab}^{\rm tot}(s,b)$

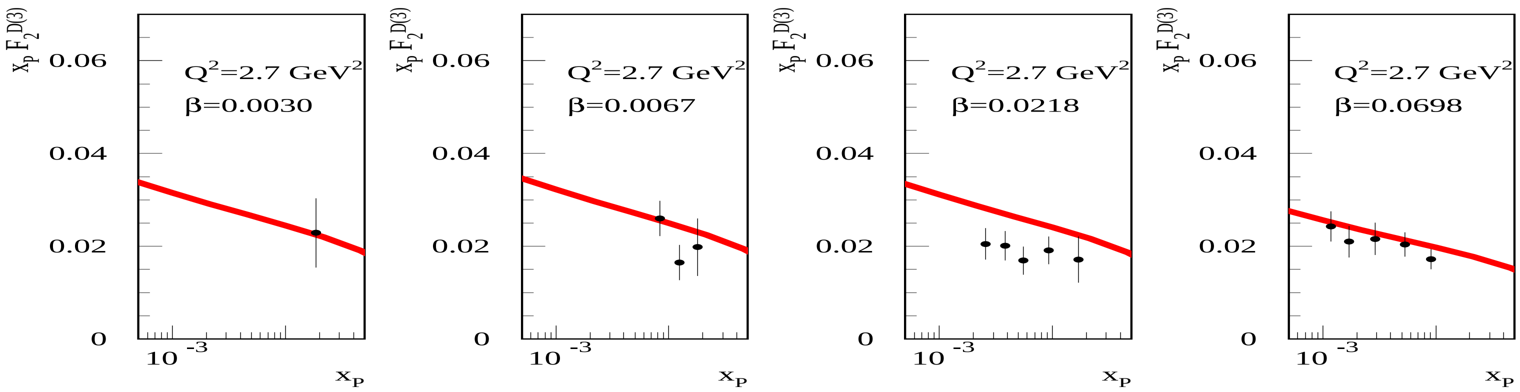
Proton SF $F_2(x,Q^2)$, $x \to 0$ - just a "fan":



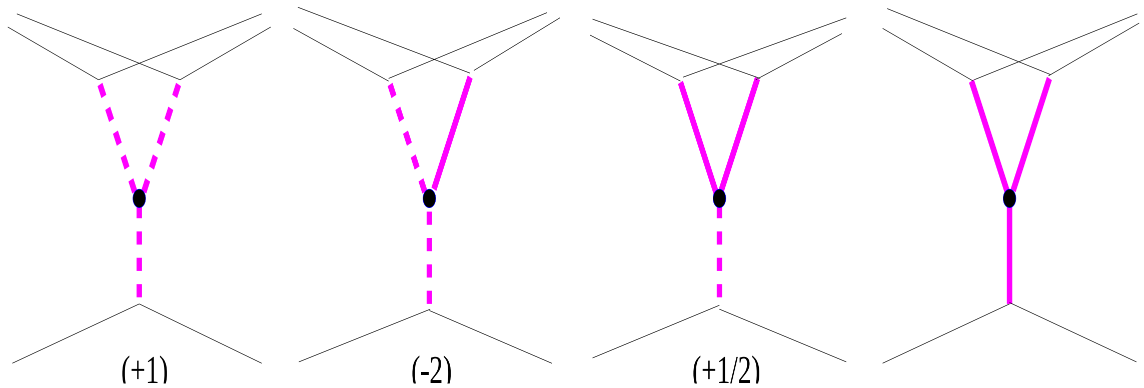
Total cross section and SF $F_2(x, Q^2)$ with (without) enhanced graphs ($Q_0^2 = 2.5$ GeV^2, $\alpha_{\mathbb{P}}(0) = 0.18$):



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



Not yet the end - one needs "cut" diagrams for particle production:



Total "cut" contribution can be obtained similarly

Finally we are back: physics of the interaction - (almost) simple and transparent

- a number of elementary processes (Pomeron + multi-Pomeron graph exchanges)
- small number of adjustable parameters
- generalization to hA, AA - parameter free
- high energy asymptotics - governed by pQCD
- parameters can be fixed using cross sections, total and diffractive SFs, particle production

Main differences to the linear scheme:

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

Drawback of the scheme:

- can not treat screening & saturation effects at $Q^2 > Q_0^2$!

Air Shower Predictions

Basic EAS characteristics:

- $X_{\max}$ - mainly defined by $\sigma^{\rm inel}_{h-{\rm air}}$, $K^{\rm inel}_{h-{\rm air}}$ (especially, $\sigma^{\rm inel}_{p-{\rm air}}$, $K^{\rm inel}_{p-{\rm air}}$)
- N_e - correlated with $X_{\max}$
- N_μ - strongly depends on $N^{ch}_{h-{\rm air}}$ (especially, $N^{ch}_{\pi-{\rm air}}$), however, also depends on the spectra

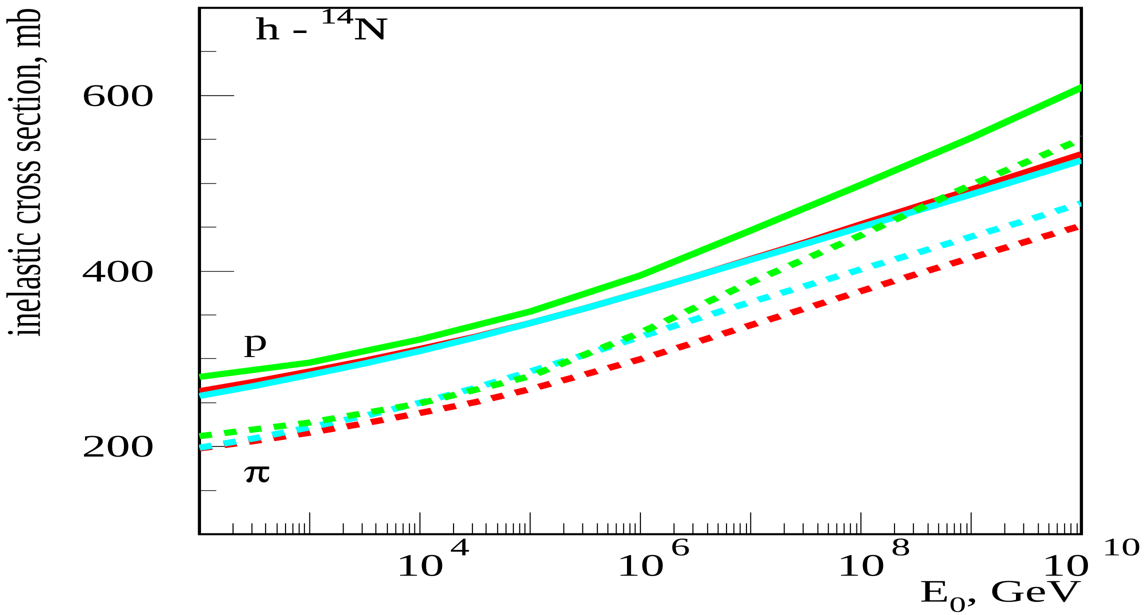
Inelastic cross sections ($\sigma^{\rm inel}_{h-{\rm air}}$) - no new parameters compared to $h-p$

- depend on Pomeron parameters / parton momentum distributions
- depend on the inelastic screening (related to the diffraction dissociation)
- depend on non-linear screening effects (stronger than for $\sigma^{\rm inel}_{h-p}$)

$\pi-$ air / $p-$ air:

- stronger inelastic screening
- stronger non-linear effects (larger relative weight, stronger parton "packing")

QGSJET-II / QGSJET-I / SIBYLL

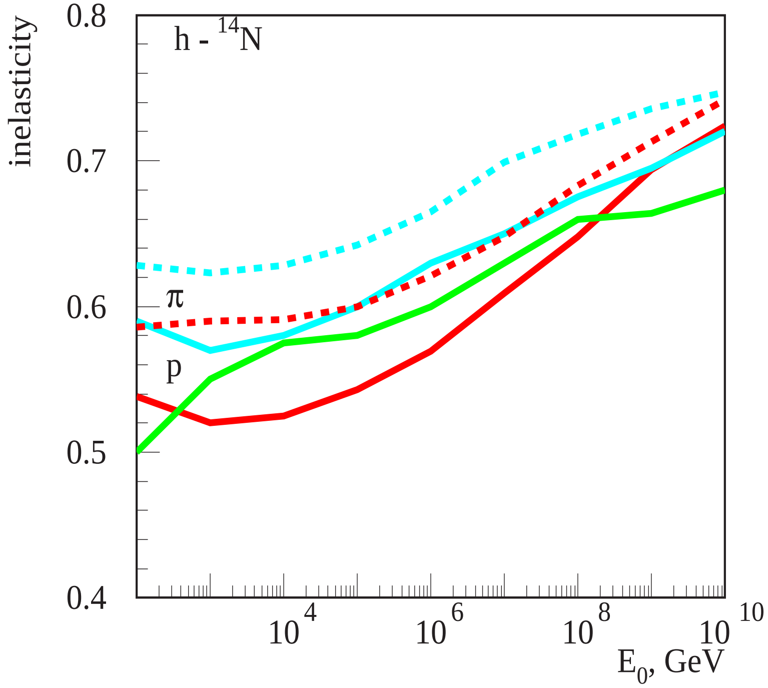


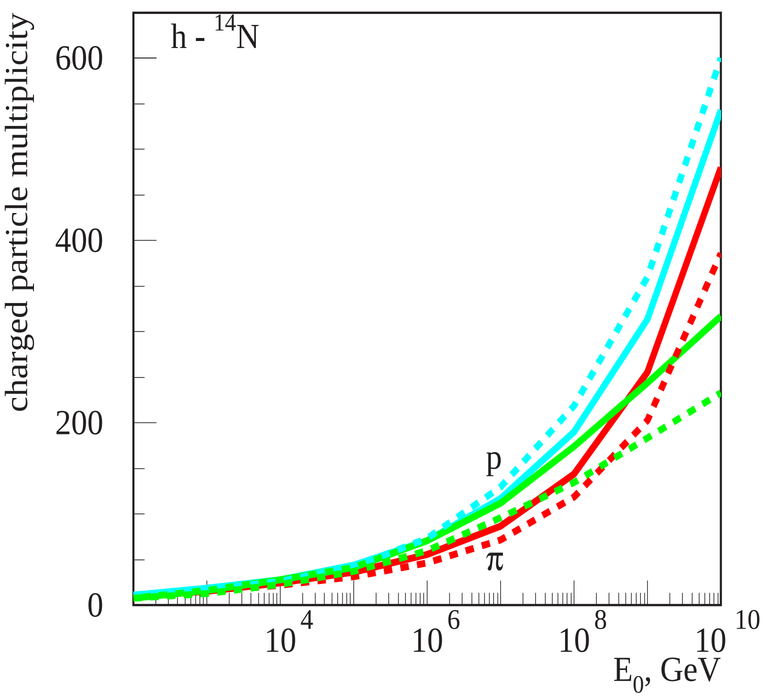
$E_0 = 200$ GeV ($\sigma^{\mathrm{inel(exp)}}_{n-^{12}C}$ - T.Roberts et al., 1979;
$\sigma^{\mathrm{abs(exp)}}_{h-^{12}C}$ - A.Carroll et al., 1979)

- $\sigma^{\mathrm{inel}}_{p-^{12}C} = 241$ mb, $\sigma^{\mathrm{inel(exp)}}_{n-^{12}C} = 237 \pm 2$ mb
- $\sigma^{\mathrm{abs}}_{p-^{12}C} = 232$ mb, $\sigma^{\mathrm{abs(exp)}}_{p-^{12}C} = 225 \pm 7$ mb
- $\sigma^{\mathrm{abs}}_{\pi-^{12}C} = 170$ mb, $\sigma^{\mathrm{abs(exp)}}_{\pi^{+}-^{12}C} = 171 \pm 5$ mb

Inelasticity $(K^{\rm inel}_{h-\rm air})$ and multiplicity $(N^{ch}_{h-\rm air})$:
strongly reduced by screening effects in the "soft" component
(especially for $\pi - \rm air$)

QGSJET-II / QGSJET-I / SIBYLL

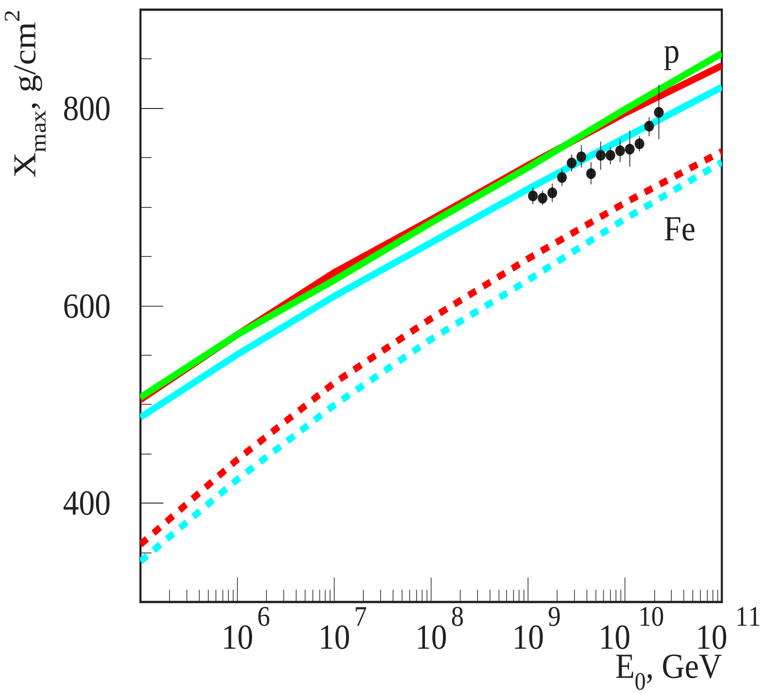


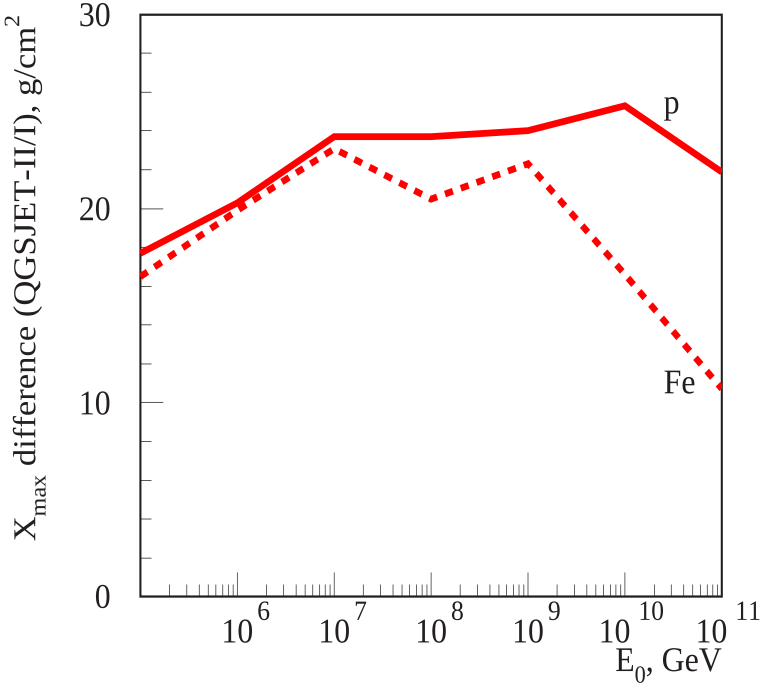


Shower maximum position ($X_{\max}$):

- systematically shifted deeper by screening effects (by ~ 20 g/cm^2)
- $\Rightarrow$ will lead to a heavier composition
- agreement between QGSJET-II and SIBYLL

QGSJET-II / QGSJET-I / SIBYLL vrs. HIRES data (R.Abbasi et al., 2004)

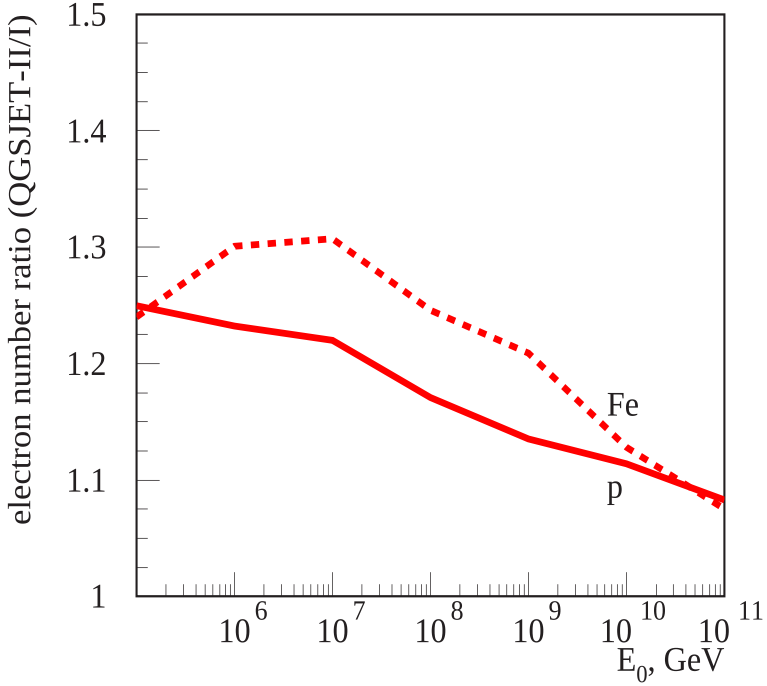


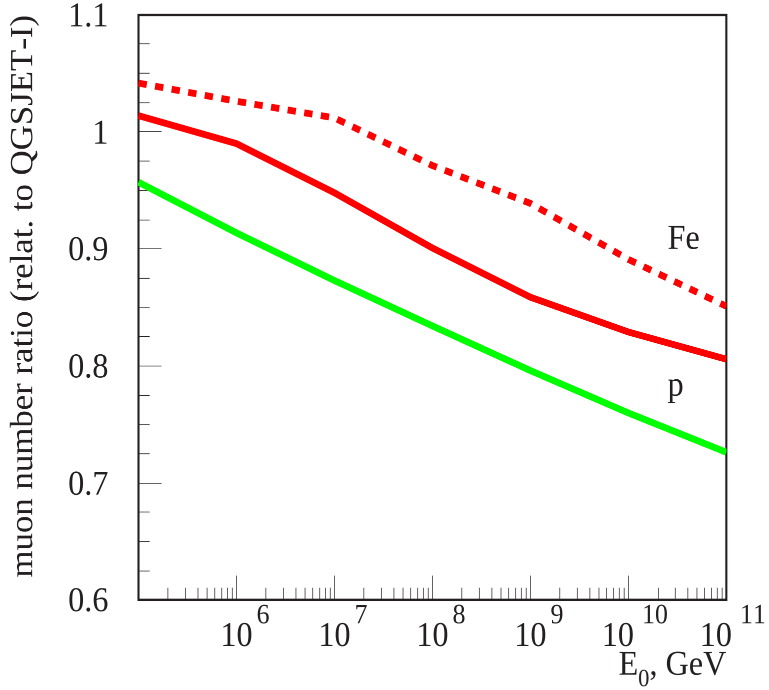


Electron (N_e) and muon (N_μ, E_μ>1 GeV) number ratios:

- $N_\mu(N_e)$ - significantly increasing
- $\Rightarrow$ again leads to a heavier composition

QGSJET-II (SIBYLL) relative to QGSJET-I



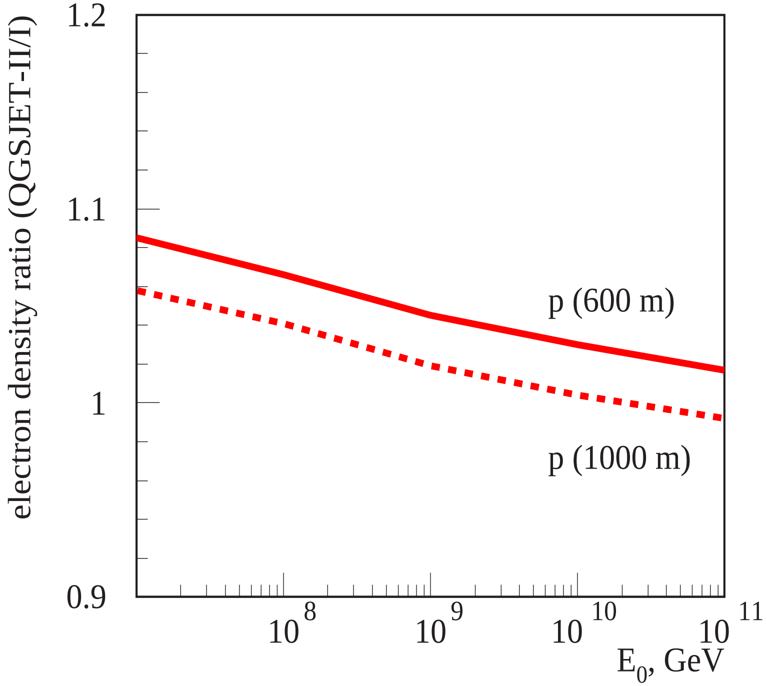


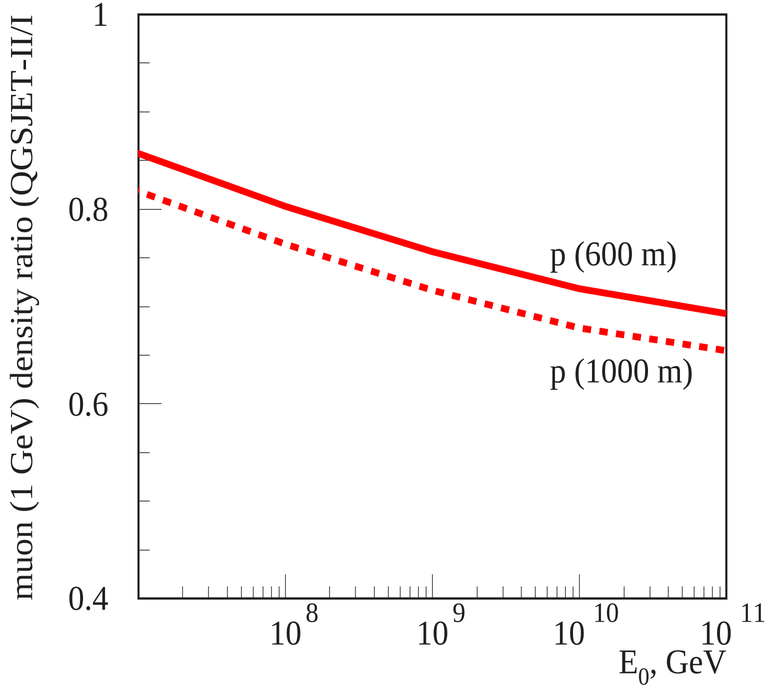
Energy determination

EAS profile: N_e^{max} ratio - within 3%

Electron (ρ_e) and muon (ρ_μ, E_μ>1 GeV) densities at 600 and 1000 m:

- energy estimations depend on the muon contribution (water tanks?)





Model Uncertainties

From experimental data:

- calibration - mainly on hp, mainly at fixed target energies
- hA, AA data scarce
- central heavy ion collisions - provide only general guidance (may include new physics, e.g., QGP effects)
- $\sigma_{pp}^{\rm tot}(\sqrt{s} = 1800$ GeV) - two contradictory measurements
- $\sigma_{hA}^{\rm inel}$ - only at fixed target energies

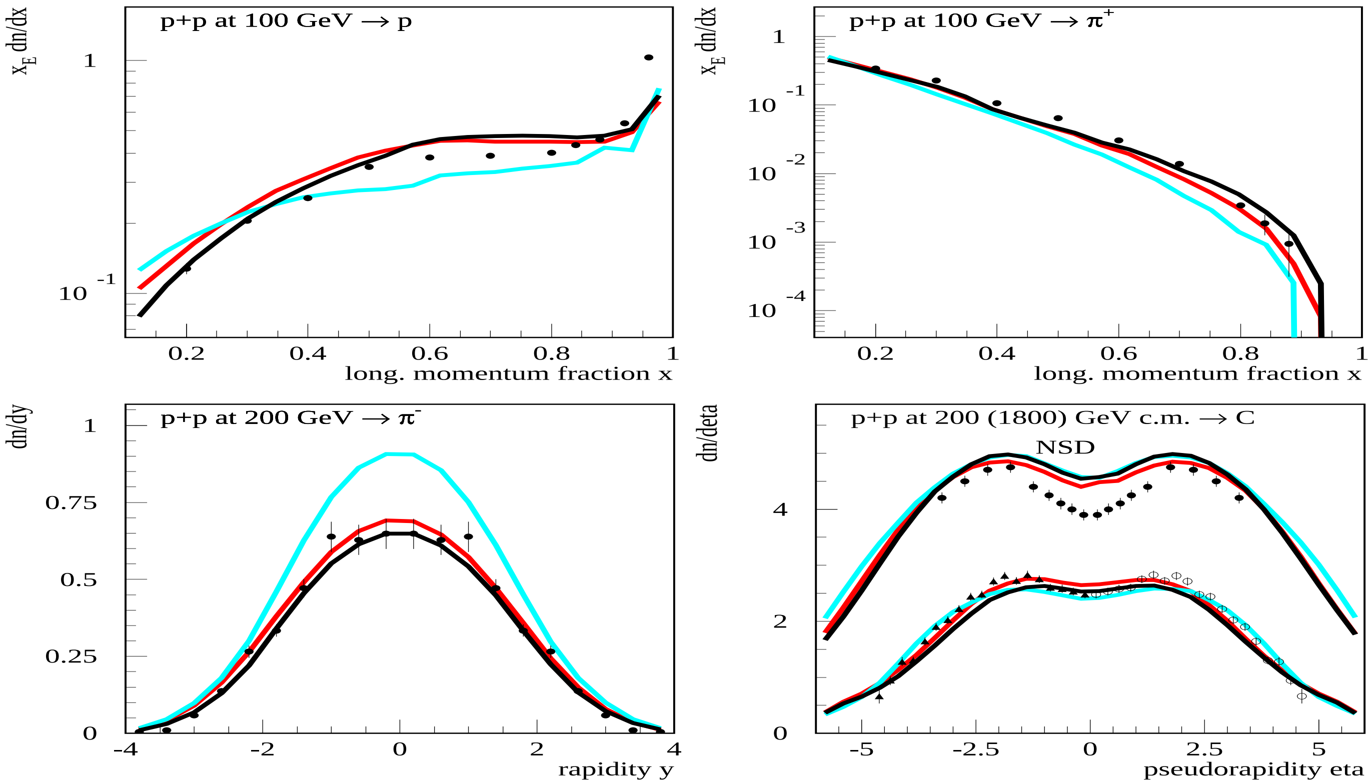
Model parameter & algorithm freedom:

- treatment of leading states & string ends ("valence-like" or "sea-like")
- treatment of low mass diffraction $\Rightarrow$ inelastic screening
- choice of Q_0^2 (saturation effects)
- choice of parton SFs at the Q_0^2 scale (factorization scale, "resolved photon" contribution, etc.)
- possible loss of coherence of leading states (H.Drescher et al., 2004)

Before - tests of parameter freedom with QGSJET-I
(M.Zha, J.Knapp, SO, 2002)

Here - only 1st option (string end momentum distribution)

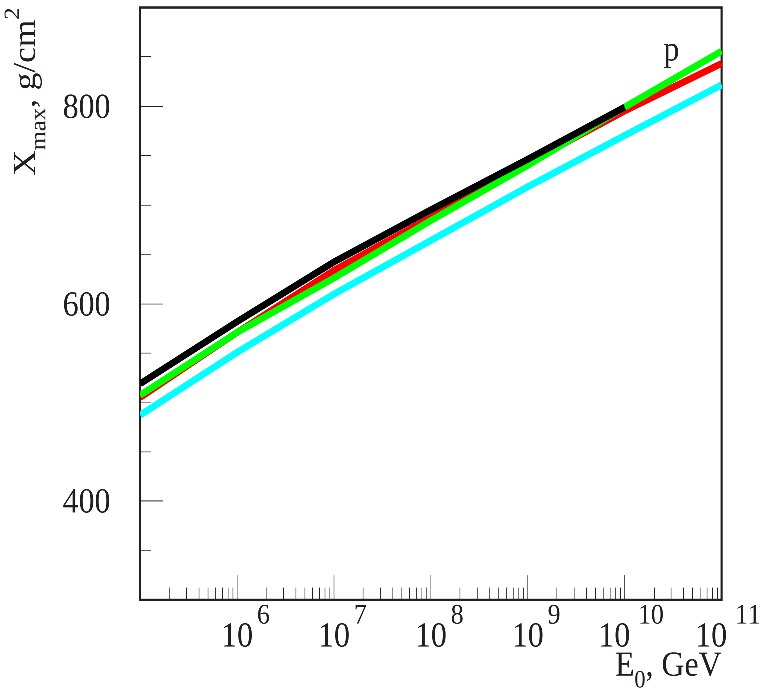
QGSJET-II / QGSJET-I / QGSJET-IIm

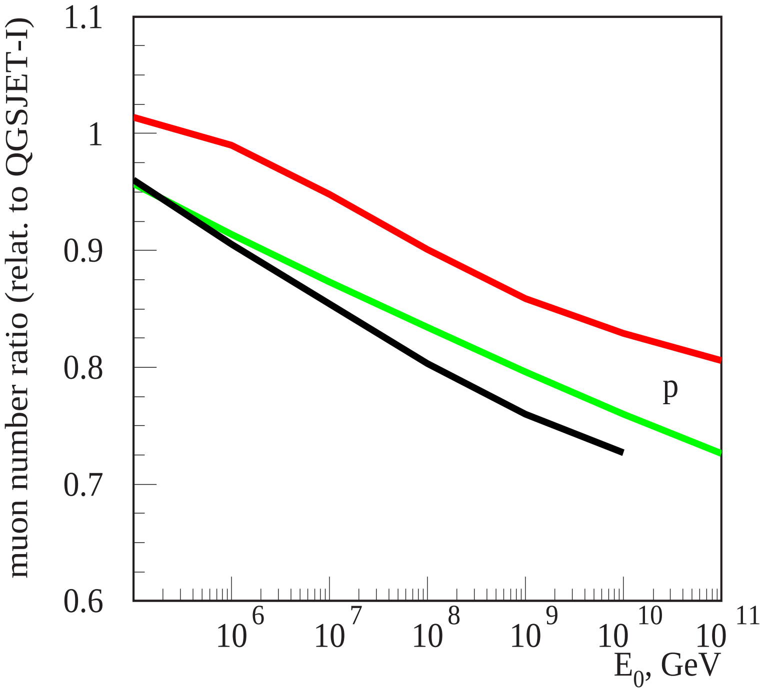


More "sea-like" string ends $\Rightarrow$ smaller multiplicity & inelasticity in hA (AA)

$\Rightarrow$ deeper $X_{\rm max}$, smaller N_μ

QGSJET-II / QGSJET-I / SIBYLL / QGSJET-IIm





Future Prospects

Largely expected from QCD:

- progress with BFKL Pomeron & NLL QCD
- perturbative treatment of screening & saturation effects

$\Rightarrow$ reliable calculations of high energy asymptotics of scattering amplitudes

What QCD can not do (always non-perturbative):

- hadronization
- treatment of leading states

But a lot can be fixed with new experimental data:

- on particle production in $hh-$, $hA-$, $AA-$collisions (RHIC, LHC)
- on total and diffraction cross sections (Tevatron?, LHC)

And present models are not bad:

- describe cross sections & particle production for different hadronic processes
- describe perturbative observables:
  high p_t particle spectra, SFs, hard diffraction
- converge in EAS predictions

And can be further improved on the phenomenological level

Considerable progress can be made and is made with CR data:

- studies of correlations of EAS observables discriminate between models (example, KASCADE)
- measurements of $\sigma^{\rm inel}_{h-{\rm air}}$ (example, HIRES)
- penetrating hadrons - sensitive to $\sigma^{\rm inel}_{h-{\rm air}}$, $\sigma^{\rm difr}_{h-{\rm air}}$
- muon spectra & bundles - sensitive to $N^{ch}_{h-{\rm air}}$, hadron spectra

We made a big progress!
Things will further improve in future!