Hadronic MC generators for colliders and cosmic rays

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QCD at Cosmic Energies - II

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- Introduction: models for colliders and models for cosmic rays
- Conventional structure:
  - Gribov's Reggeon approach and multiple scattering
  - QCD and hard processes
  - color connections and hadronization
- "Dense" partonic systems: non-linear effects
- Air shower characteristics and related quantities
- Cosmic ray interactions: remaining puzzles
- Outlook

Introduction: models for colliders and models for cosmic rays

MC generators at colliders and in CRs:

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

Contemporary models:

- similar physics input
- guided by 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
- high p_t physics of special importance (pQCD tests, background for new physics)

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

Typical collider models:

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

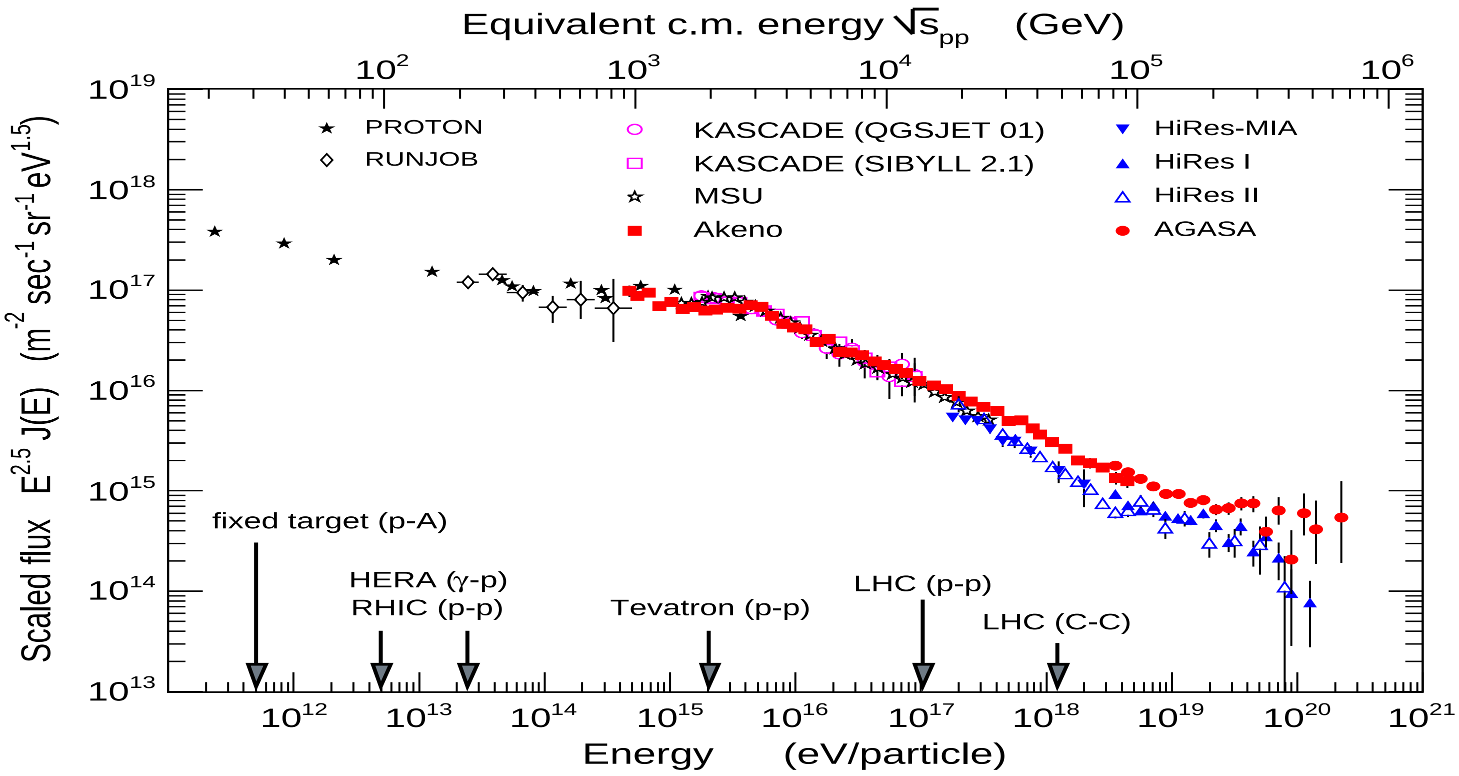
Representative CR models:

- DPMJET (Engel, Ranft & Roesler)
- neXus (Drescher et al.)
- QGSJET (Kalmykov & SO)
- SIBYLL (Engel, Gaisser, Lipari & Stanev)

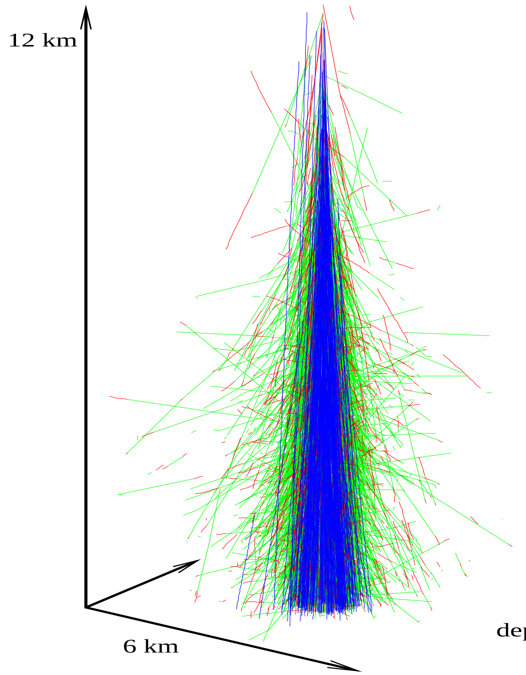
What is different?

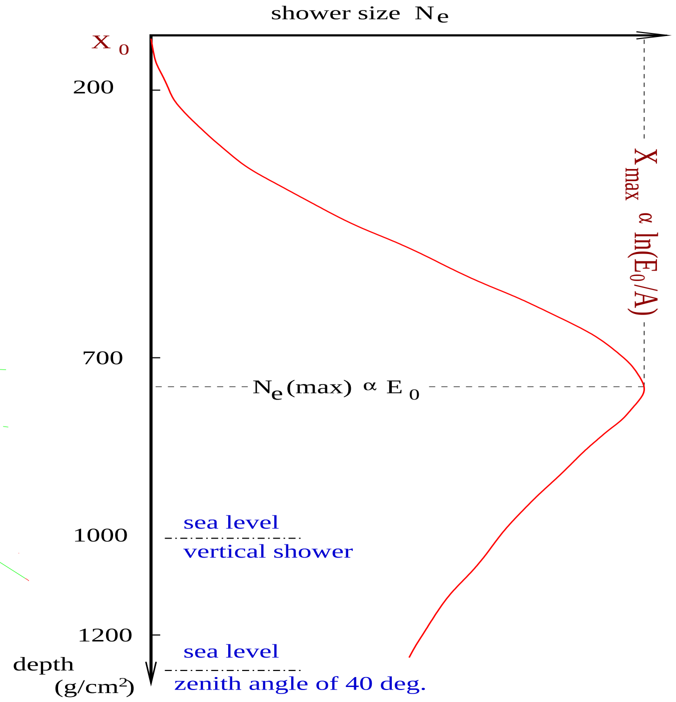
High energy cosmic ray spectrum:

- extends over 10 energy decades!
- 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)





EAS development:

- guided by few interactions of the initial (fastest secondary) particle
  $\Rightarrow$ main source of fluctuations (interaction point X_0, energy loss $K_{\rm inel}$)
- many sub-cascades of secondaries $\Rightarrow$ well averaged

$\Rightarrow$ 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:

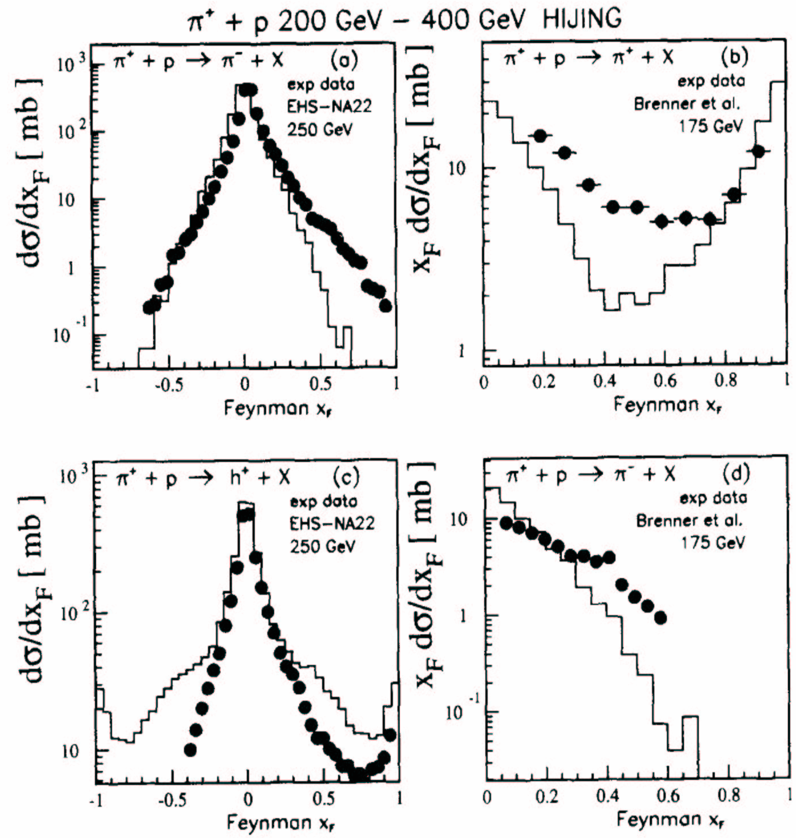
- low sensitivity to "fine" details (smoothed by EAS development)
- high p_ts - irrelevant, e.g., $p_t = 10$ GeV, $E_0 = 10^5$ GeV $\Rightarrow \Theta \simeq p_t/E_0 = 10^{-4}$
- charm, bottom, ... new rare processes - also irrelevant:
  - much smaller inclusive cross sections
  - produced mainly at central rapidities

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

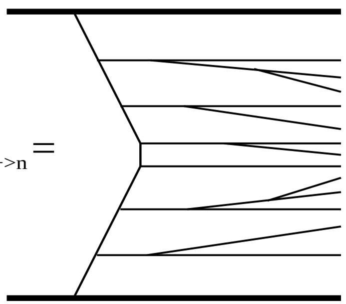


(Pop, Gyulassy & Rebel, Astropart. Phys. 10 (1999) 211)

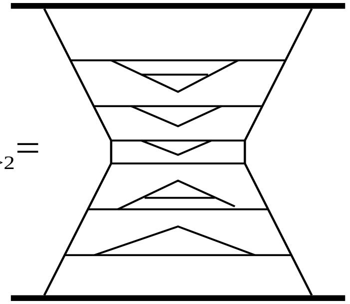
Gribov's Reggeon approach and multiple scattering

Elementary interaction - inelastic&elastic amplitudes:

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



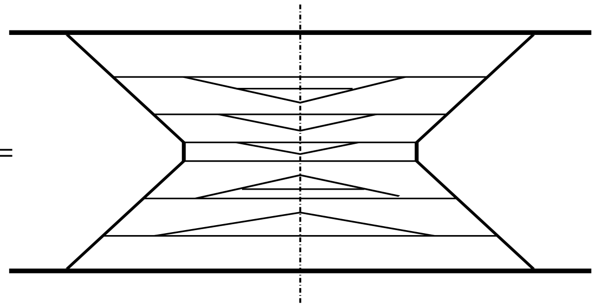
$\mathbf{A}_{2->2} =$



Cross section - optical theorem:

$$\sigma_{\rm tot} = \sum_n \int d\tau_n \; A_{2\to n} \cdot A^*_{2\to n} = \frac{1}{2s} 2{\rm Im}\, A_{2\to 2}\Big|_{t=0}$$

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



Pomeranchuk: elementary interaction $\equiv$ Pomeron exchange

Pomeron amplitude:

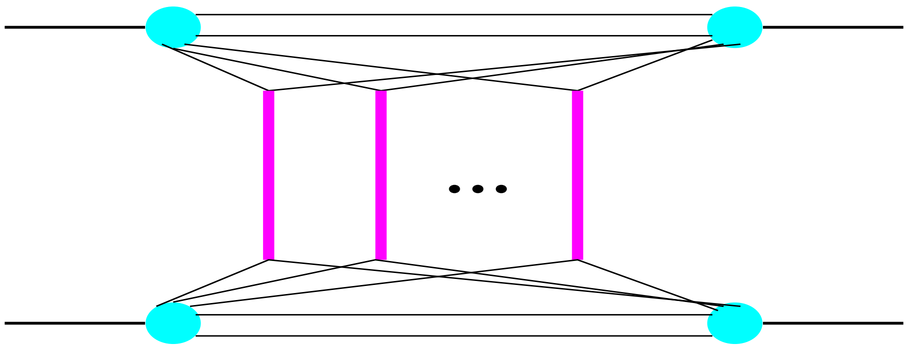
$$f_{ad}^{\rm P}(s,t) = 8\pi i \gamma_a \gamma_d \, s^{\alpha_{\rm P}(0)} \exp(-\lambda_{ad}(s) t)$$
$$\lambda_{ad}(s) = R_a^2 + R_d^2 + \alpha'_{\rm P}(0) \, \ln s$$

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

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

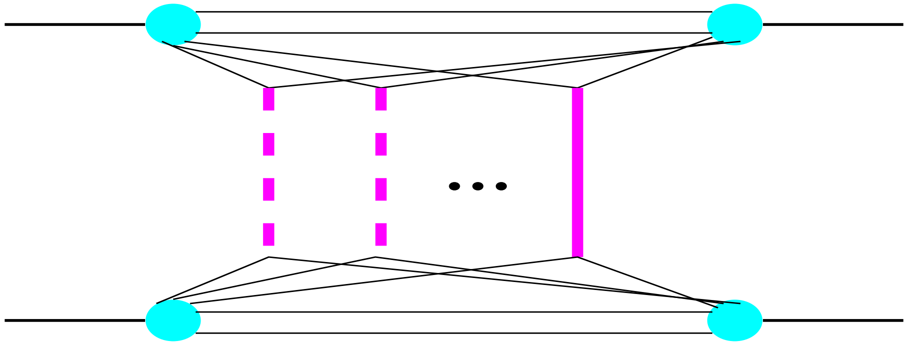
$\sigma_{ad}^{\rm P}(s) = \frac{1}{2s} 2{\rm Im}\, f_{ad}^{\rm P}(s,0) \sim s^{\alpha_{\rm P}(0)}$ - violates unitarity bound?

$\Rightarrow$ multiple scattering (multi-Pomeron exchange):



$$\sigma_{ad}^{\rm tot}(s) = 2 \int d^2 b \left[1 - e^{-\chi_{ad}^{\rm P}(s,b)}\right] \sim \ln^2 s, \quad s \rightarrow \infty$$
$$\chi_{ad}^{\rm P}(s,b) = \frac{1}{8\pi^2 s} \int d^2 q_\perp \, e^{-i \vec{q}_\perp \vec{b}} \, {\rm Im} f_{ad}^{\rm P}(s, q_\perp^2) = \frac{\gamma_a \gamma_d \, s^{\alpha_{\rm P}(0)-1}}{\lambda_{ad}(s)} \exp\left(\frac{-b^2}{4\lambda_{ad}(s)}\right)$$

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



⇒ "topological" cross sections (n "cut" Pomerons):

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

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

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

QCD and hard processes

What QCD tells us about high energy interactions?

- (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:

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

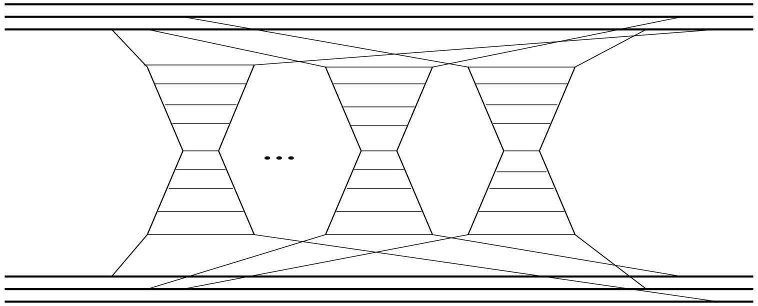
$d\sigma_{IJ}^{2\to 2}/dp_t^2$ - differential parton-parton cross section;
$f_{I/a}(x^+, Q^2)$ - parton I momentum distribution, "probed" at scale Q^2

Not sufficient to construct a MC model: 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
- $\sigma_{ad}^{\rm jet} > \sigma_{ad}^{\rm tot} \Rightarrow$ multiple scattering - eikonal approach



"Hard" eikonal - product of $\sigma_{ad}^{\rm jet}(s,Q_0^2)$ and hadronic overlap function $A_{ad}(b)$:

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

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

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

$$W(n_{\rm jet}) = \frac{1}{n_{\rm jet}!}\left[2\chi_{ad}^{\rm hard}(s,b)\right]^{n_{\rm jet}} \exp\left(-2\chi_{ad}^{\rm hard}(s,b)\right)$$

To get cross sections - also “soft” eikonal:

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

$\Rightarrow$ inelastic cross section:

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

Conversion of partons into hadrons:

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

Employed in PITHYA, HERWIG, HIJING, SIBYLL,...

Main differences to Gribov's scheme:

- high energy scattering - dominated by “hard” eikonal
  $\Rightarrow$ (believed to be) governed by pQCD
- multiple scattering - only due to “semi-hard” ($p_t > Q_0$) processes
- initial state emission - starts at $p_t = Q_0$ (or a similar scale)

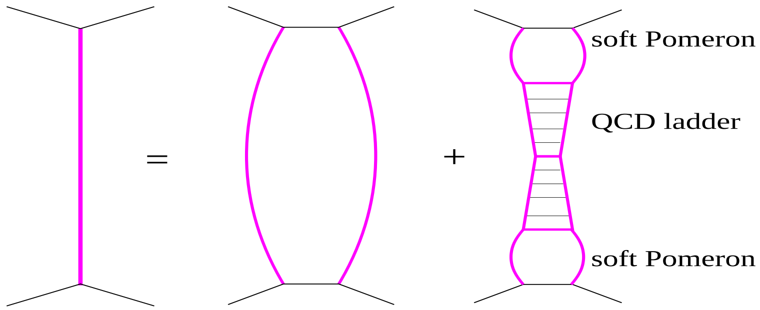
Alternative: matching Gribov's scheme with QCD

⇒ "semi-hard" ("heterotic") Pomeron scheme (Levin & Tan, Kalmykov & SO):

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

⇒ Gribov's scheme 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

Employed in QGSJET, neXus

Differences from the mini-jet scheme:

- multiple scattering - due to both "soft" and "semi-hard" Pomerons
- parton (particle) production extends to "soft" (low p_t) region ("soft pre-evolution")
- low-x partons - distributed over larger transverse area

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

- SIBYLL 2.1 - multiple "soft" interactions ("soft" Pomerons)
- DPMJET - each mini-jet process accompanied by "soft" Pomeron exchange
- PITHYA - hardest scattering is color connected to valence quarks & diquarks
  $\Rightarrow$ mimics "soft pre-evolution"
- HERWIG - initial state emission may (optionally) continue till $\Lambda_{\rm QCD}$ scale

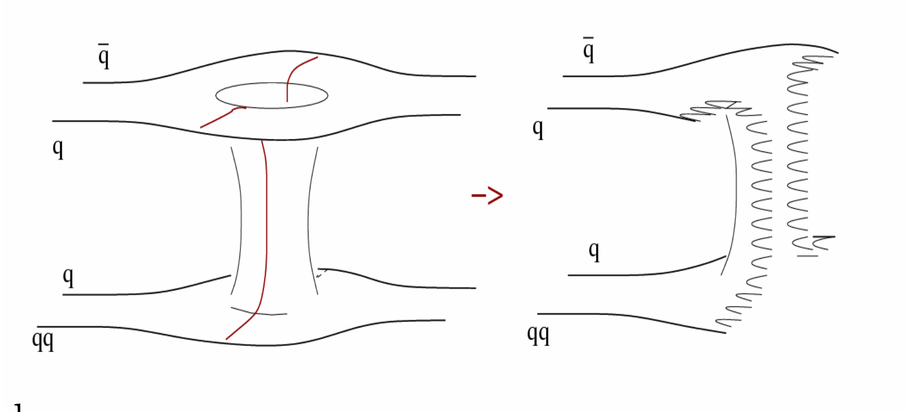
Important: in both schemes elementary processes proceed independently

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

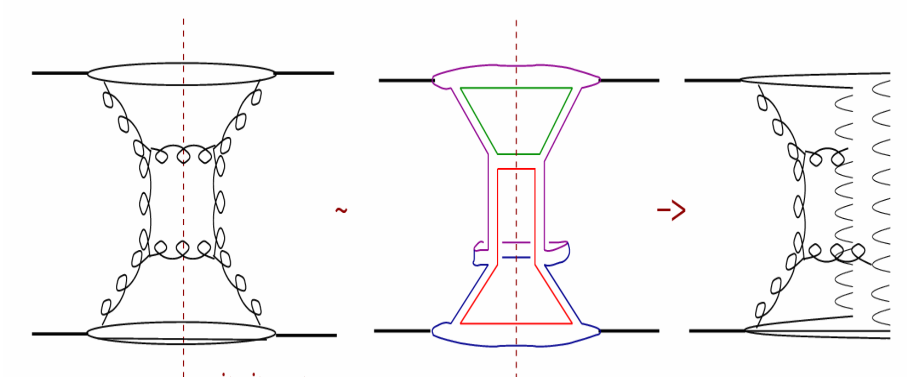
Energy-dependent p_t-cutoff: $p_t^{\rm min} \equiv Q_0 = Q_0(s)$? Why?

Color connections and hadronization

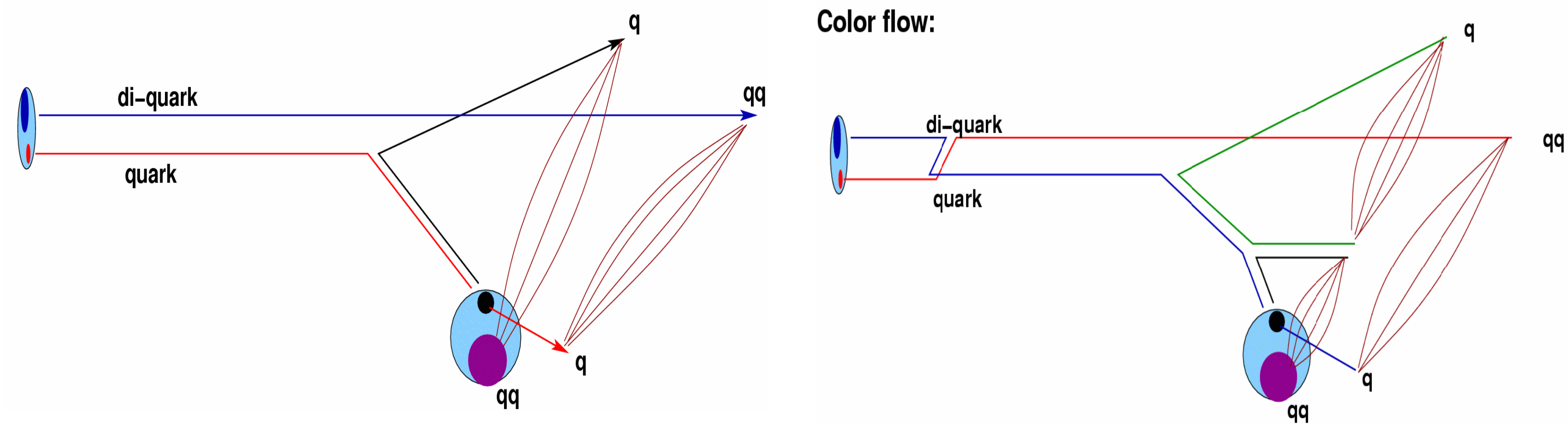
Dual topological unitarization scheme, $N_c \to \infty$, $N_f \to \infty$ (Veneziano):
Pomeron ≡ cylinder
⇒ "cut" Pomeron ≡cut cylinder ⇒ 2 chains of secondaries:



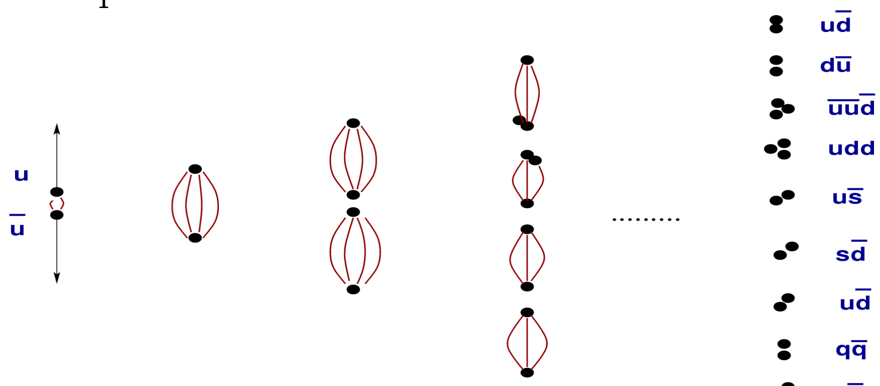
Or via gluon exchange:



Can be used to establish string picture of hadronization (Capella et al., Kaidalov & Ter-Martyrosyan):



String fragmentation procedure:



Mostly LUND fragmentation procedures used - “area law” decay (PITHYA, HIJING, DPMJET, SIBYLL,...)

HERWIG: $g \longrightarrow \bar{q}q$ splittings and isotropic cluster decays
recently - fission of long clusters (similar to string procedure)

QGSJET: fragmentation of string-end partons ($q(\bar{q})$, qq,...);
parameters - Regge intercepts (Kaidalov)

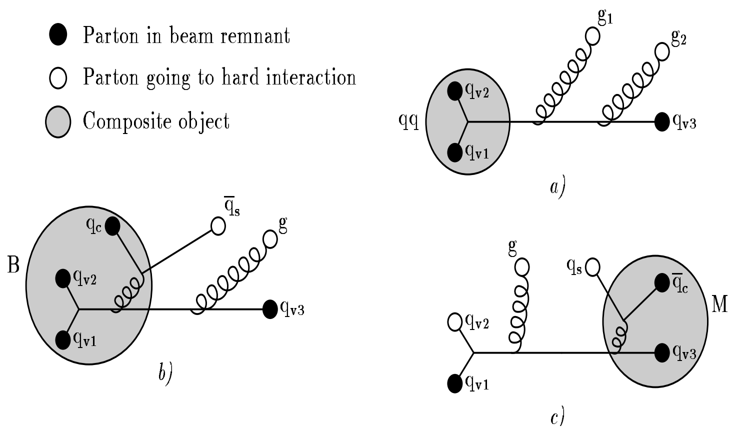
Important aspect - hadronic “remnants”:

- PITHYA:
  - 1st (“hardest”) process is color-connected to valence q, qq
  - all other hard processes decoupled
  - composite remnants (new option): may contain many (anti-)quarks
  - if no quarks left $\Rightarrow$ remnant = gluon
- HERWIG:
  - all hard processes decoupled
  - “soft” processes = “soft” gluon emission (also decoupled)

- HIJING:
  - all hard processes decoupled
  - "soft" processes = (multiple) longitudinal remnant excitation (dM^2/M^2)
- SIBYLL: similar to PITHYA but with multiple "soft" Pomeron exchanges
- DPMJET: multiple "soft" and "hard" interactions coupled to remnants
- QGSJET: multiple "soft" and "semi-hard" Pomerons coupled to constituent (valence and sea) (anti-)quarks ($f_{q(\bar{q})}(x) \sim 1/\sqrt{x}$)

Additional baryon stopping - "diquark splitting" (junction) (PITHYA, HIJING)

Also black disk limit (BDL) stopping mechanism (Drescher, Dimitru & Strikman)



“Dense” partonic systems: non-linear effects

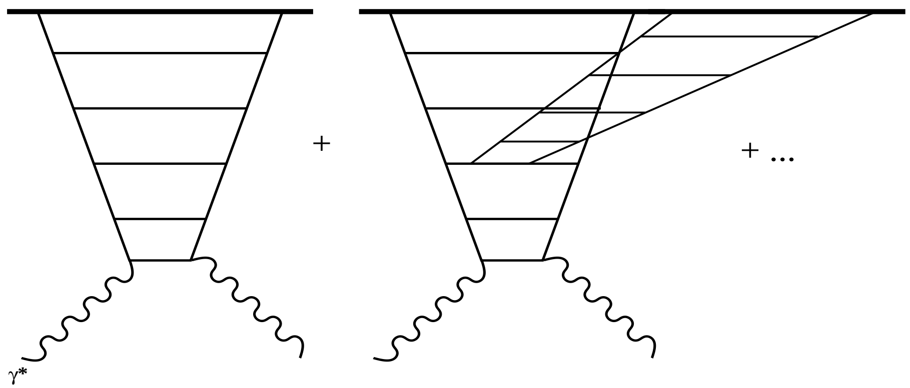
Independent interaction picture is inadequate for large s, small b, large A:

- 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 (QCD) $\Rightarrow$ loss of predictive power
ad hoc parameterizations:

- SIBYLL: $Q_0(s) = p_t^{\min}(s) = 1 + 0.065\ \exp\left[0.9\sqrt{\ln s}\right]$ (GLR-inspired)
- PITHYA: $p_t^{\min}(s) \sim \sqrt{s}^{0.25}$ ("like Pomeron intercept")
- HERWIG: $p_t^{\min}$ - free parameter
- HIJING: $p_t^{\min}(s) = 3.91 - 3.34\ \ln(\ln\sqrt{s}) + 0.98\ \ln^2(\ln\sqrt{s}) + 0.23\ \ln^3(\ln\sqrt{s})$

Still no account for:

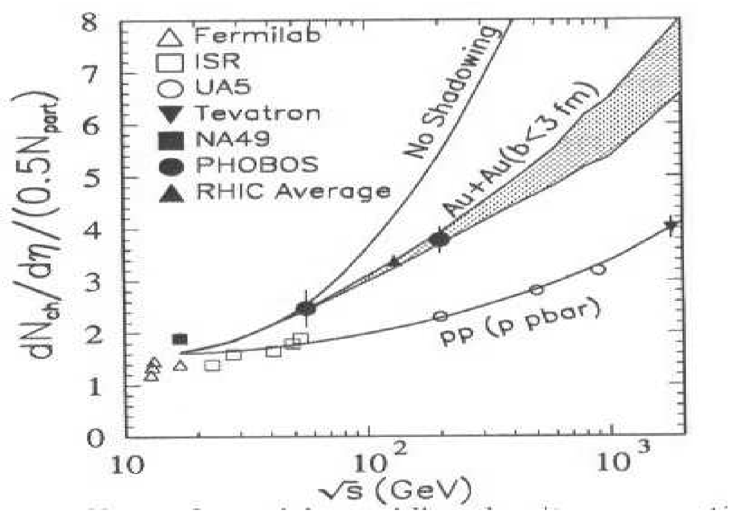
- no saturation in peripheral interactions
- saturation being different in $hh-$, $hA-$, $AA-$collisions
- screening effects in non-saturation regime (shadowing)

Additional non-linear effects may be introduced at particle production level, e.g., color re-arrangement in PITHYA, HERWIG (optional)

HIJING (Li & Wang, 2001): parameterized nuclear shadowing of PDFs, e.g.

$$\begin{aligned} f_{g/A}(x, Q^2, b, A) &= A\, f_{g/p}(x, Q^2)\, \Big[1 + 1.19\, \ln^{1/6} A\, (x^3 - 1.2\, x^2 + 0.21\, x) \\ &- s_g(b)\, (A^{1/3} - 1)^{0.6} (1 - 1.5\, x^{0.35})\, \exp(-x^2/0.004)\Big] \\ s_g(b) &= (0.24 \div 0.28)\, \frac{5}{3} (1 - b^2/R_A^2) \end{aligned}$$

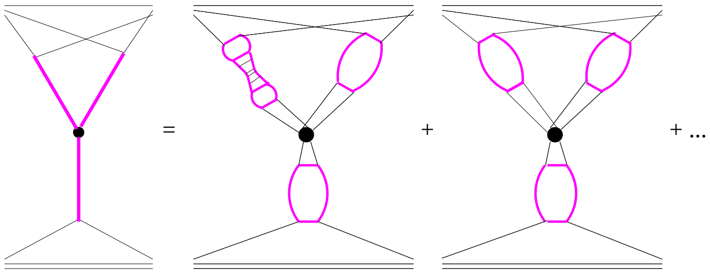
appears to be decisive to get agreement with RHIC:



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

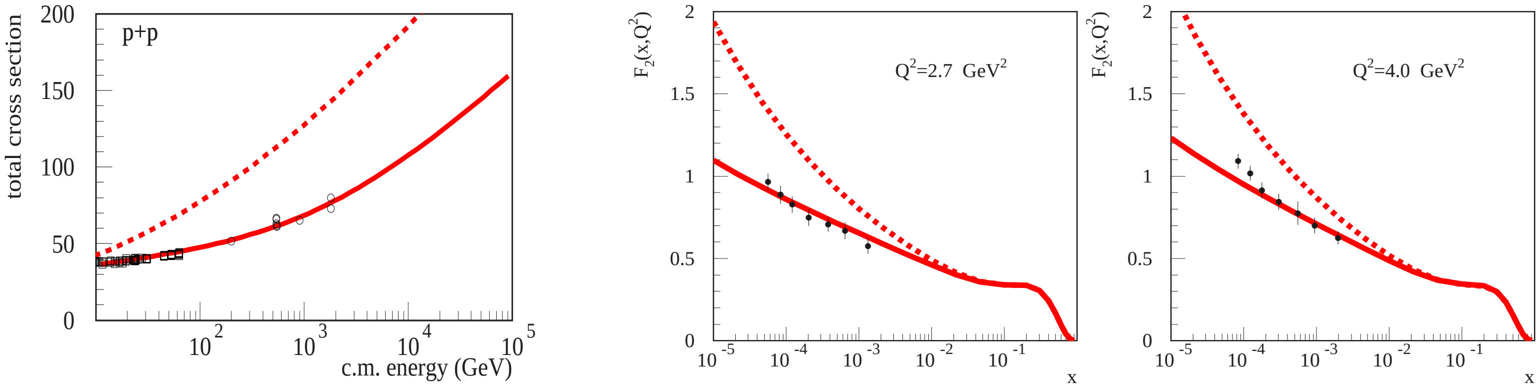
Alternative approach - QGSJET-II model (SO, 2004) :

- assumes no saturation at a fixed Q_0^2 scale
- $\Rightarrow$ non-linear effects = interactions between "soft" Pomerons



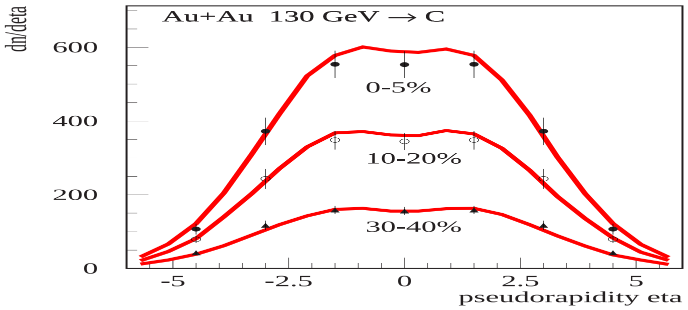
- $\Rightarrow$ Gribov's Reggeon scheme (all order re-summation of "enhanced" graphs)

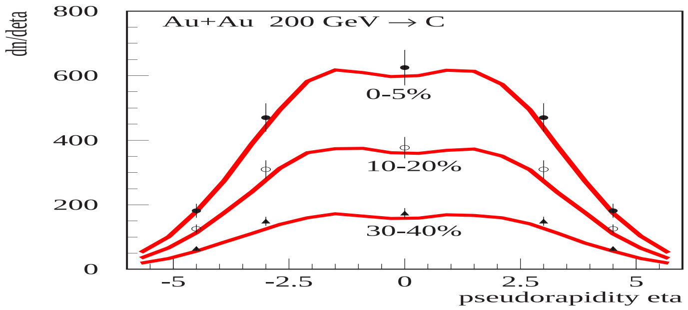
Total cross section and SF $F_2(x, Q^2)$ with (without) enhanced graphs:



hA, AA: "enhanced" (multi-Pomeron) graphs connected to different nucleons
$\Rightarrow$ A-enhancement of screening effects

Charged multiplicity for different centralities at RHIC:





Main differences to the linear scheme:

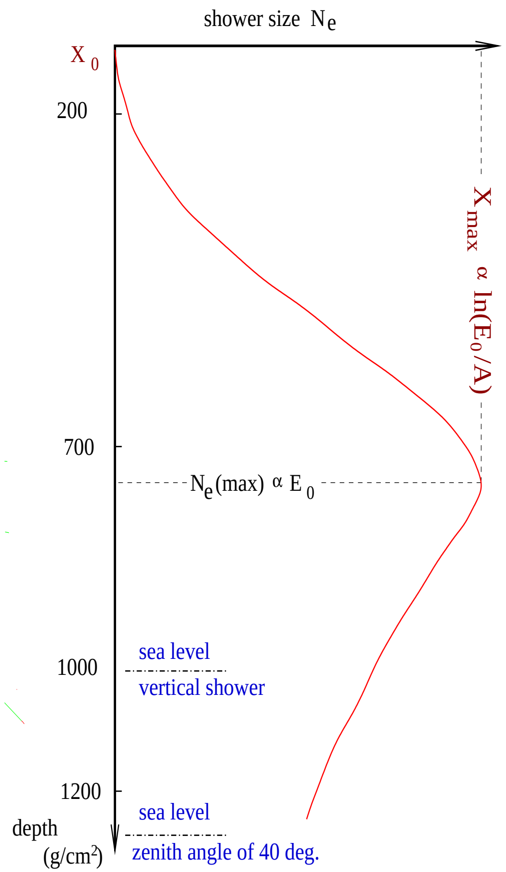
- screening of the "soft" particle production
- in the "dense" limit (large s, small b, large A) -
  re-normalization of the "soft" Pomeron intercept: $\alpha_{\mathrm{P}}(0) \longrightarrow \tilde{\alpha}_{\mathrm{P}}(0) < 1$
  $\Rightarrow \chi_{ab}^{\mathrm{P_{soft}}}(s,b)$ - decreasing with s - saturation 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 $\sigma^{\rm inel}_{h-{\rm air}}$, $K^{\rm inel}_{h-{\rm air}}$
  - position of the first interaction X_0: $\sigma^{\rm inel}_{p-{\rm air}}$
  - profile shape: $K^{\rm inel}_{p-{\rm air}}$, $\sigma^{\rm inel}_{\pi-{\rm air}}$, $K^{\rm inel}_{\pi-{\rm air}}$
  - $X_{\max}$ fluctuations: mainly from X_0, $K^{\rm inel}_{p-{\rm air}}$
- N_e - correlated with $X_{\max}$
- N_μ - depends on $N^{ch}_{h-{\rm air}}$ (especially, $N^{ch}_{\pi-{\rm air}}$)



Energy (mass) dependence:

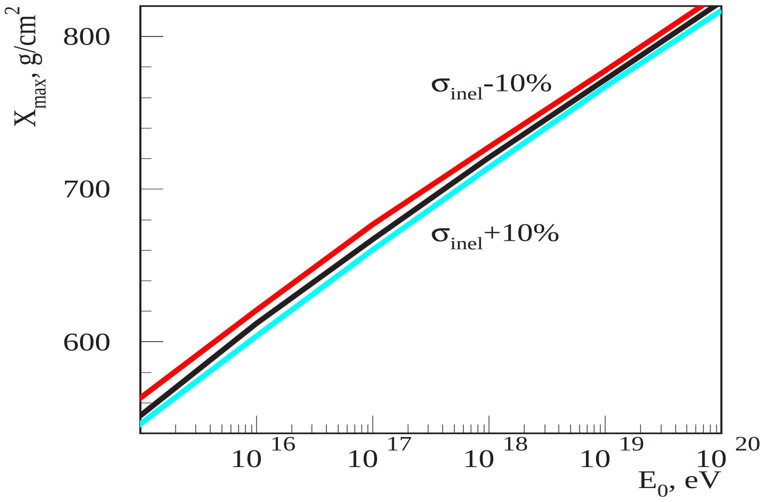
- $X_{\max} \sim \ln{(E_0/A)}$
- $N_e \sim A\ (E_0/A)^{\alpha_e}$, $\alpha_e > 1$
- $N_\mu \sim A\ (E_0/A)^{\alpha_\mu}$, $\alpha_\mu < 1$

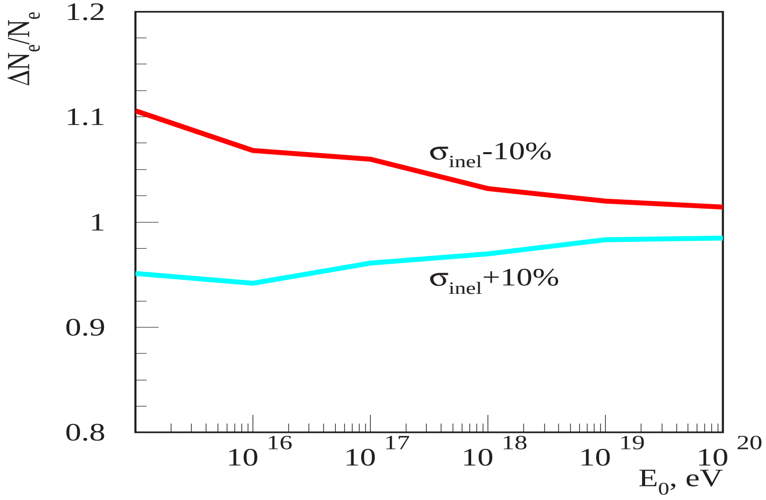
Münchhausen's problem: disentangle energy, mass, and hadronic models

Let us make simple tests...

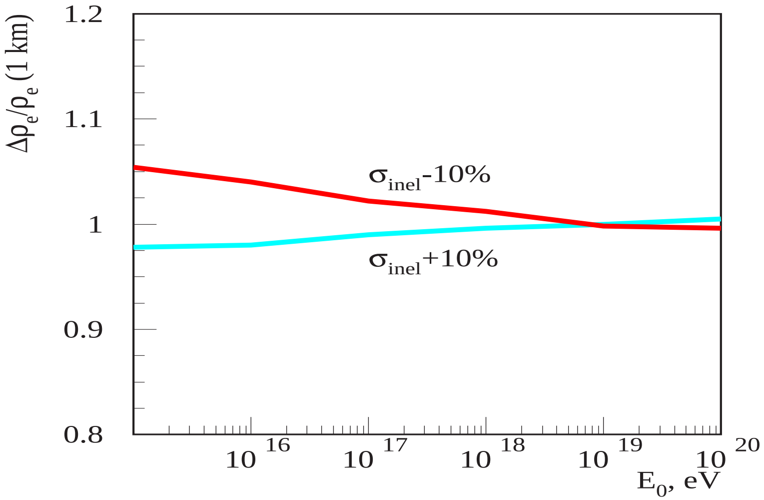
Change $\sigma_{p-\mathrm{air}}^{\mathrm{inel}}$ by $\pm 10\%$:

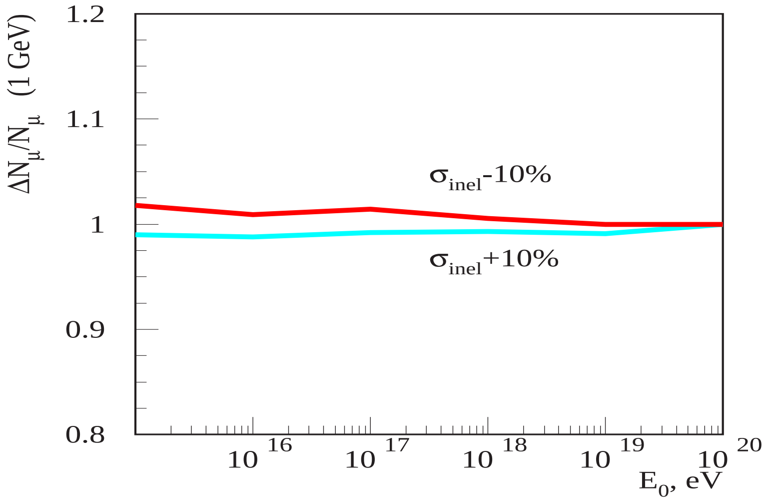
- $X_{\max}$ changes by $\pm 5 \div 10$ g/cm^2
- electron number at ground - by $\pm 5 \div 10\%$



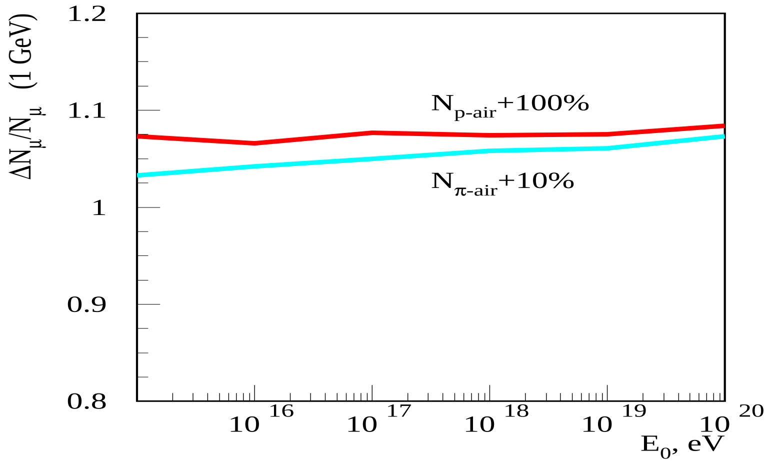


But electron density at large distance (1 km) and muon number - more stable





Now we increase $p -$ air multiplicity by 100% or $\pi -$ air multiplicity by 10%
- nearly same effect at highest energies



Let us compare models...

SIBYLL 2.1:

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

QGSJET:

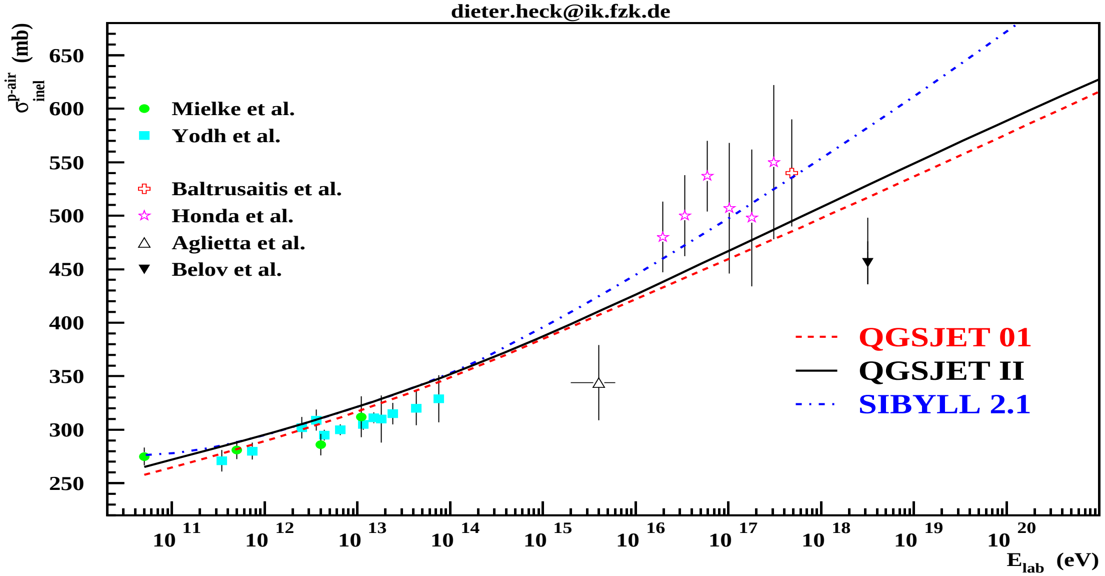
- multiple “soft” and “semi-hard” Pomerons
- “flat” (pre-HERA) PDFs & fixed p_t-cutoff (2 GeV)

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

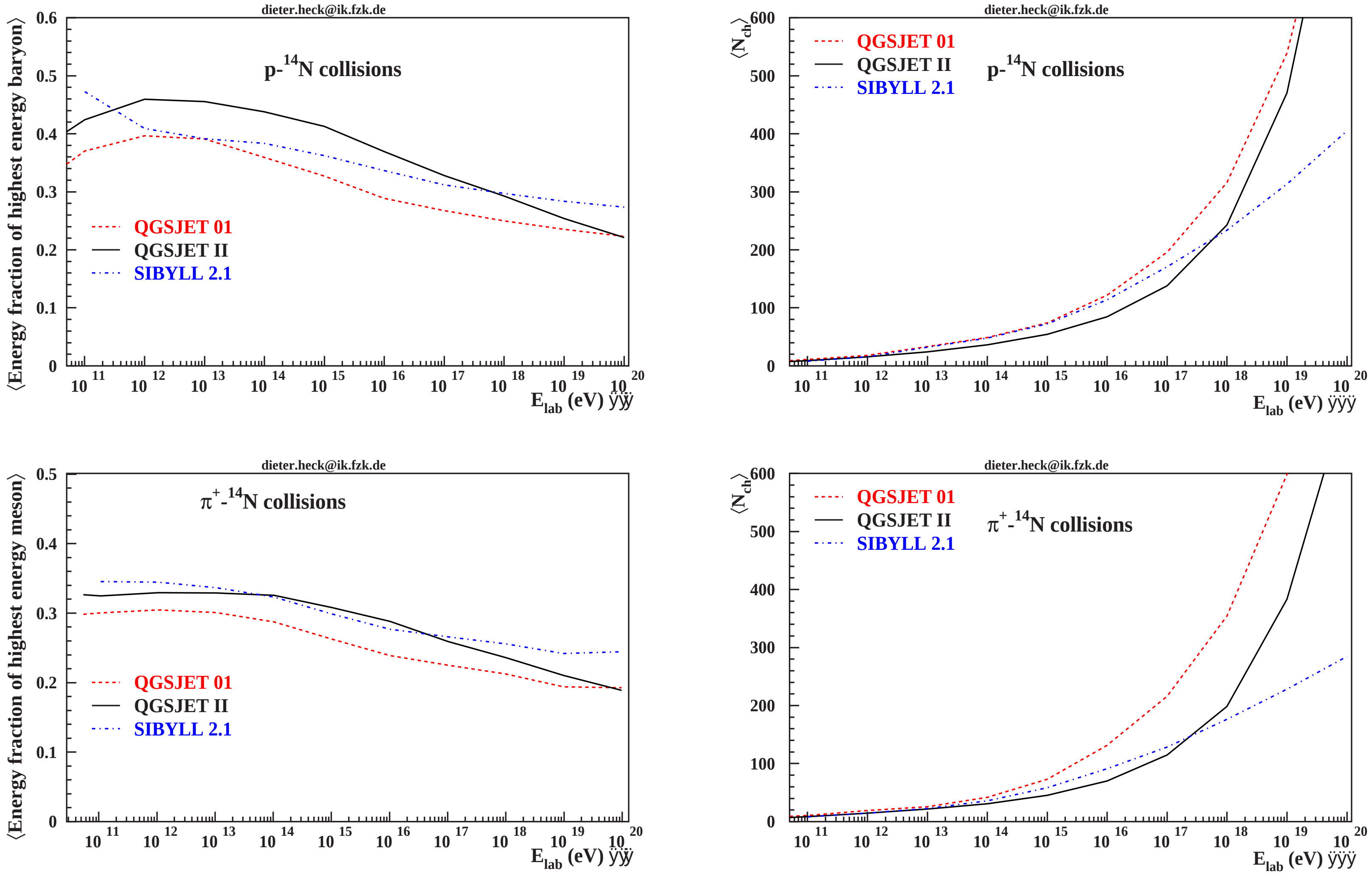


SIBYLL / QGSJET - faster energy increase:

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

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

Leading baryon (meson) energy share $(1 - K^{\rm inel}_{\rm h-air})$ and charged multiplicity



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

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

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

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

QGSJET-II / SIBYLL: same effect

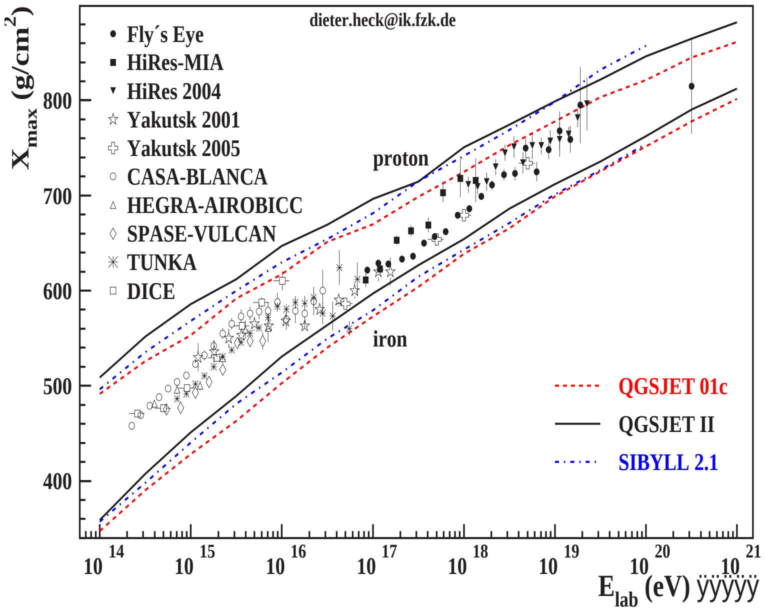
At highest energies - faster increase of $K^{\rm inel}_{\rm h-air}$, $N^{\rm ch}_{\rm h-air}$ in QGSJET-II:

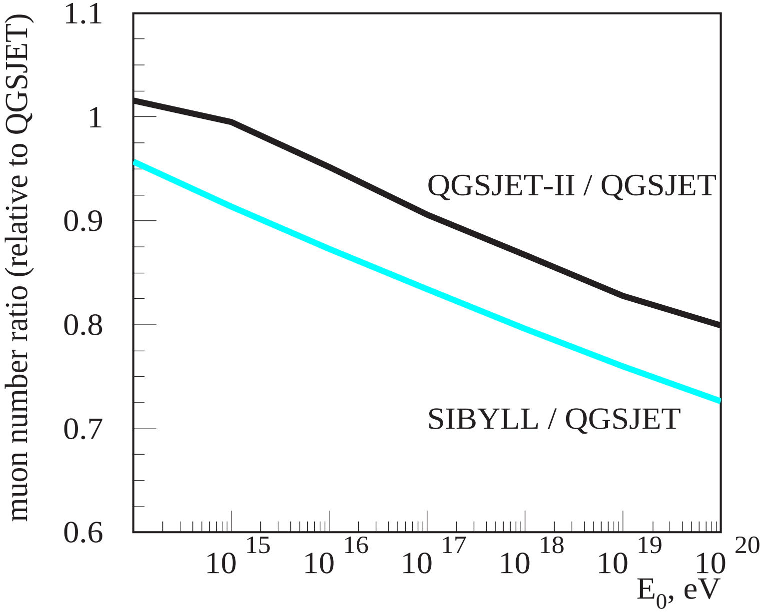
too strong $Q_0(s)$ increase in SIBYLL or absence of GLR-effects in QGSJET-II?

Summary of model differences

- $\sigma^{\rm inel}_{h-{\rm air}}$: increasing with energy, reaching 10-15% at $10^{19} - 10^{20}$ eV
- $K^{\rm inel}_{h-{\rm air}}$: 10-20% between QGSJET / SIBYLL over the whole energy range
- $N^{ch}_{h-{\rm air}}$ - increasing with energy, up to a factor of 2 at $10^{19} - 10^{20}$ eV

Shower maximum position ($X_{\max}$) and muon number N_μ ($E_\mu > 1$ GeV)





QGSJET:

- largest $K^{\rm inel}_{\rm h-air} \Rightarrow$ highest shower maximum
- much bigger $N^{ch}_{h-{\rm air}}$ compared to SIBYLL $\Rightarrow$ higher N_μ (up to 30% at 10^{20})

QGSJET-II / QGSJET - strong reduction of $K^{\rm inel}_{\rm h-air}$, $N^{ch}_{h-{\rm air}}$

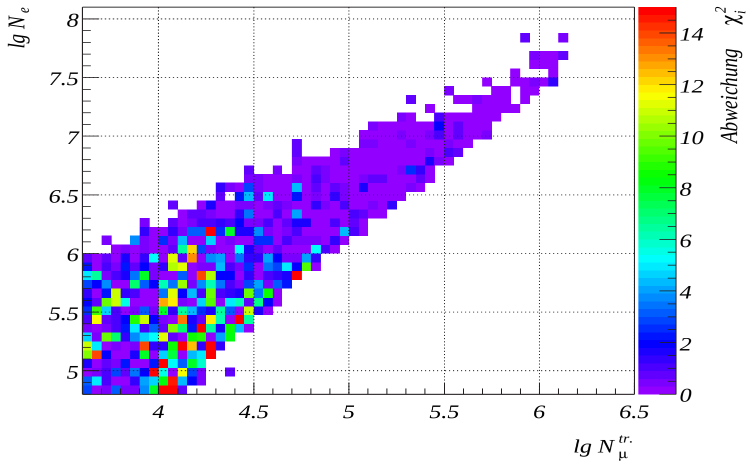
$\Rightarrow$ deeper $X_{\max}$, smaller N_μ (only 10% difference with SIBYLL)

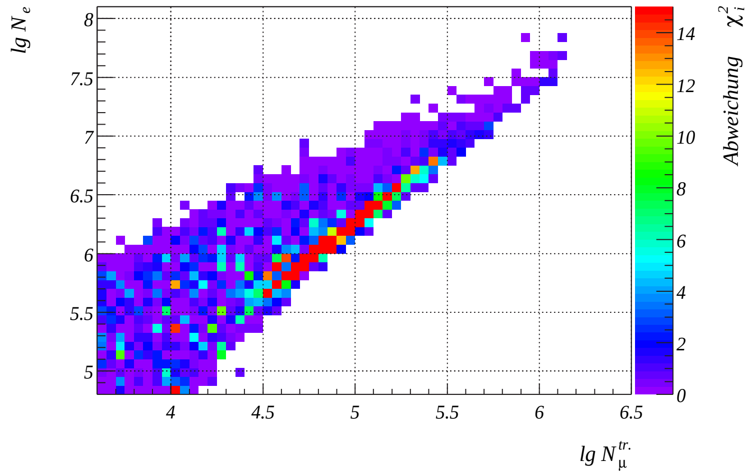
Remaining puzzles

Solving Münchhausen's problem - KASCADE studies of N_e-N_μ correlations:

- reconstruction of CR spectra and composition using a hadronic MC model
- testing model consistency with the obtained spectra

(H. Ulrich et al., 2005)

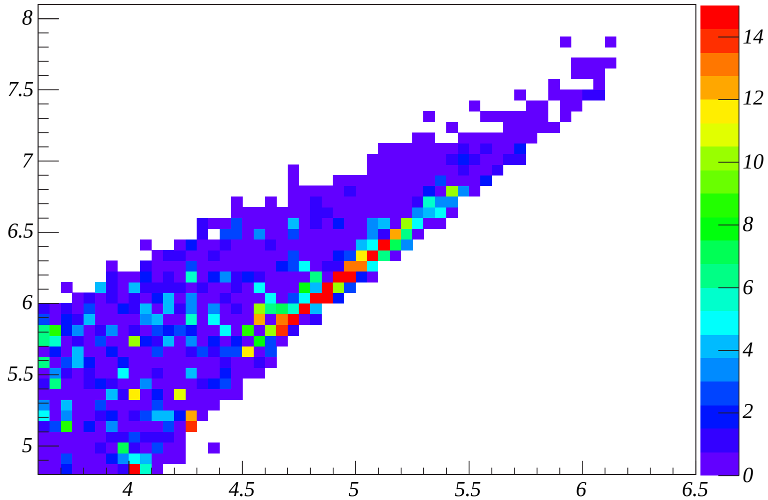


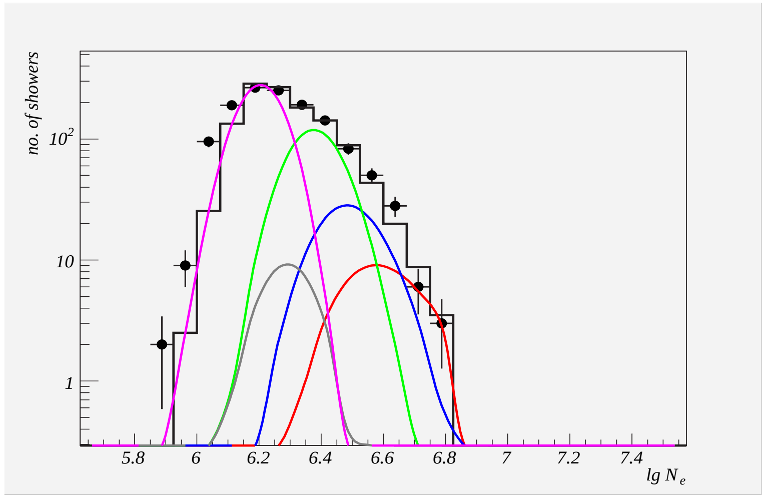


Result: "true" model is between QGSJET and SIBYLL:

- either smaller N_μ than in QGSJET
- or (more probable) bigger $N_e \Rightarrow$ deeper $X_{\max}$?

QGSJET-II goes in the right direction... but too far:





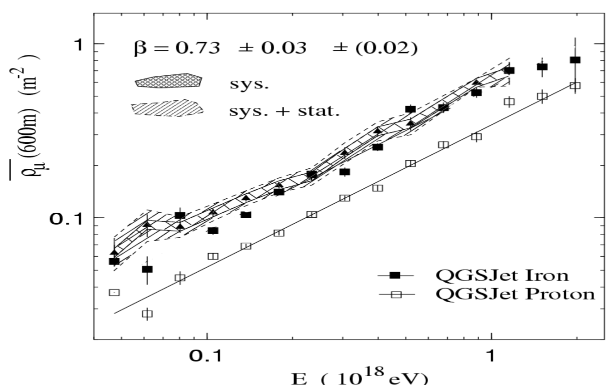
Now few possibilities:

- larger $K^{\rm inel}_{\rm h-air}$, increasing with energy - supported by RHIC (baryon stopping) & theoretical ideas (diquark breaking (baryon junction), BDL-scenario,...)
- larger cross section
- "exotic" option: significantly bigger multiplicity (how to accommodate with RHIC data?)

The last option could help solving composition puzzles at higher energies

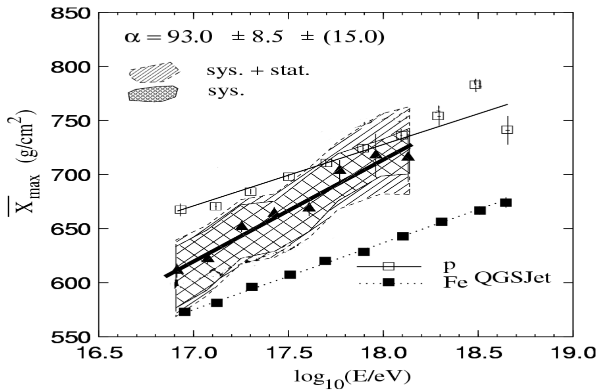
Example: HiRes-MIA measurement

MIA: muon density at 600m



Composition iron dominated,
no significant change with energy

HiRes: depth of shower maximum



Composition changes to proton
dominated one

Seems to be a general problem:

- ground arrays favor iron-dominated composition
- fluorescence arrays: light (proton-dominated) composition

Way to solve: deeper $X_{\max}$ and large N_μ ($\Rightarrow$ huge multiplicity)

May be we don't understand πA-interaction?

Outlook

Contemporary models - "conventional" structure well established

Still significant technical differences

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

Hadronic leading states - phenomenological approaches $\Rightarrow$ data should decide

CR experiments can test general model consistency

Accelerator data are of great help to solve Münchhausen's problem:

- LHC measurements of $\sigma_{pp}^{\rm tot}$, $B_{pp}^{\rm el}$ could resolve cross section uncertainty $\Rightarrow X_{\rm max}$
- LHC measurements of $N_{pp}^{\rm ch}$, $N_{pA}^{\rm ch}$ $\Rightarrow$ key to the multiplicity problem $\Rightarrow N_{\rm mu}$
- RHIC studies of baryon "stopping" for different "centralities"
  $\Rightarrow$ insight into hadronic leading state behavior

Can πA-interaction be very different from pA? Any ideas?