Non-linear effects in high energy hadronic interactions

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"QCD at cosmic energies", Erice, 29.08-05.09.04

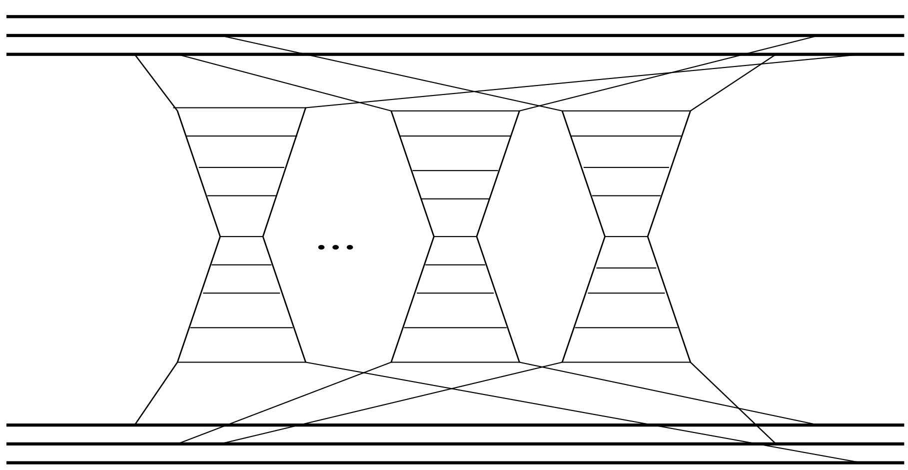
EAS: shower maximum position $X_{\max}$
- depends on $\sigma^{\rm inel}_{h-\rm air}$, $K^{\rm inel}_{h-\rm air}$

Is it sufficient to know PDFs to calculate $\sigma^{\rm inel}_{h-\rm air}$?

Imagine ideal scheme:

- pQCD applicable down to Λ_{QCD}
- or intrinsic hadronic "hard" scale Q_0

Eikonal picture:

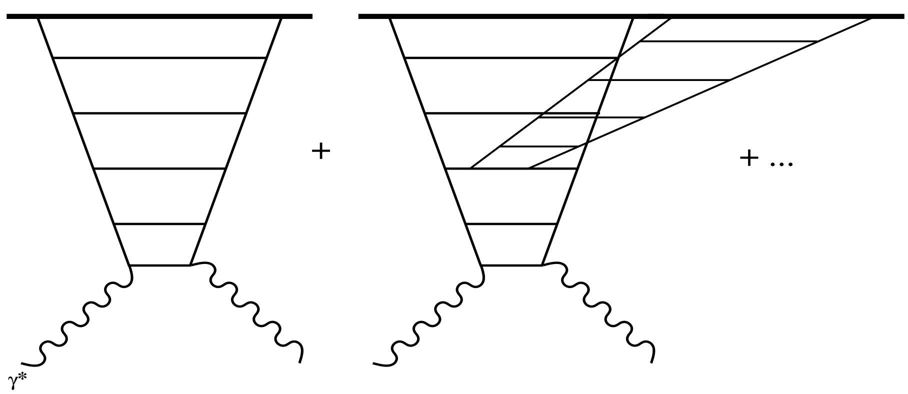


High energy (small b, large A) $\Rightarrow$ many ladders

$\Rightarrow$ non-linear effects

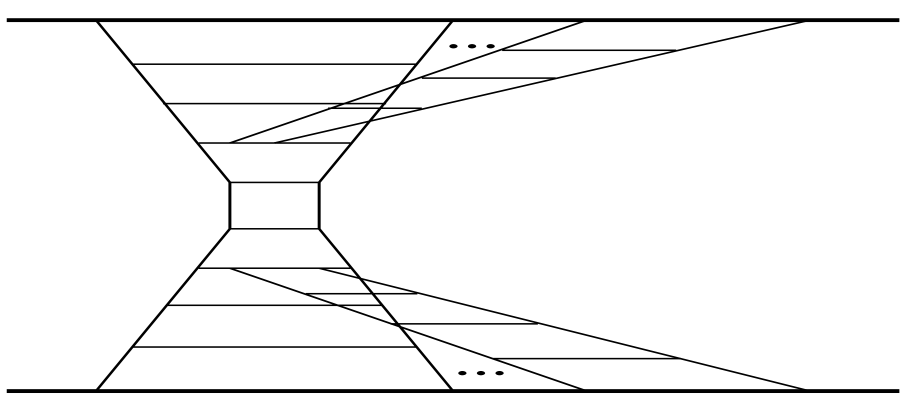
GLR (L.Gribov et al., 1983)

$\Rightarrow$ PDFs: $G(x, Q^2, b)$, $q(\bar{q})(x, Q^2, b)$

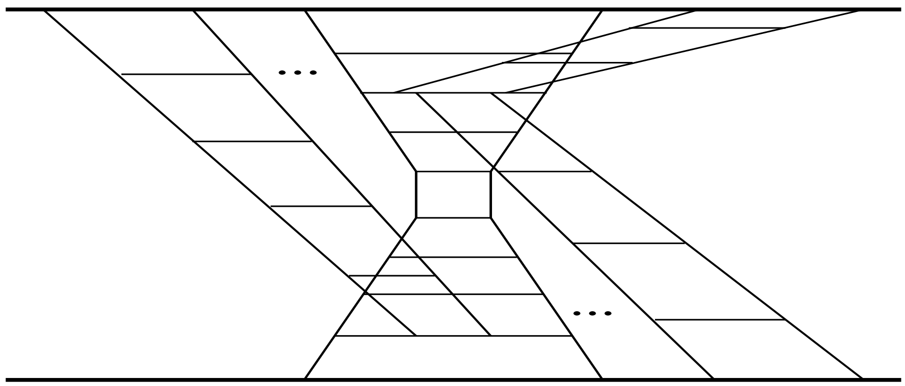


Factorized contribution to pp-eikonal:

$$\Delta\chi_{pp}^{\rm fact}(s,b) = \sum_{i,j=q,\bar{q},G} \int_{p_t^2>Q_0^2} dp_t^2 \int dx^+ dx^- \, \frac{d\sigma^{2\rightarrow 2}}{dp_t^2} \times \int d^2b' \; f_i(x^+, b', p_t^2) \; f_j(x^-, |\vec{b}-\vec{b'}|, p_t^2)$$



But also non-factorizable contributions:

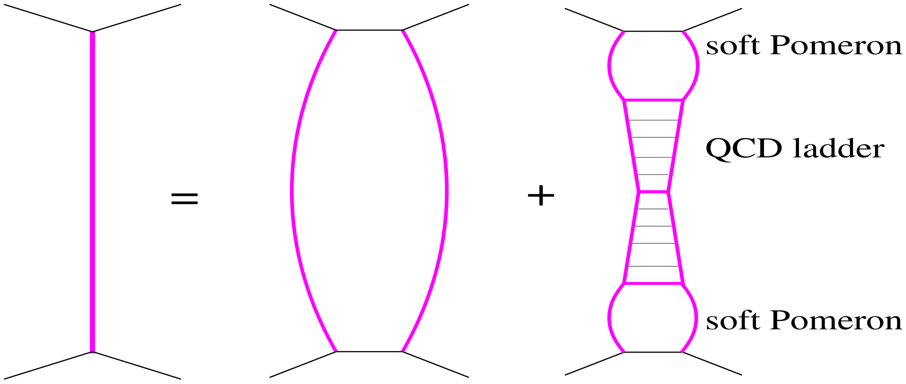


⇒ Full Reggeon scheme needed!

Phenomenological approach (neXus, QGSJET-II):

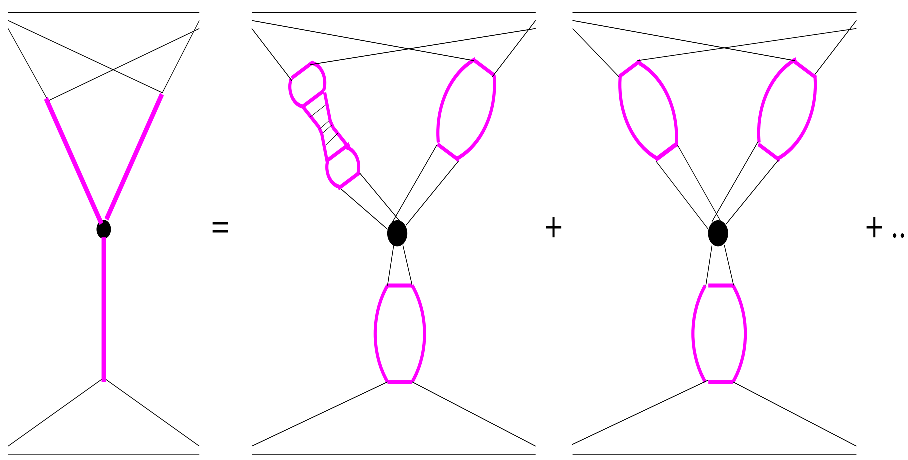
- introduce a "linearity" scale Q_0^2
- use "soft" Pomeron below Q_0^2
- use DGLAP for $|q^2| > Q_0^2$

General "Pomeron":

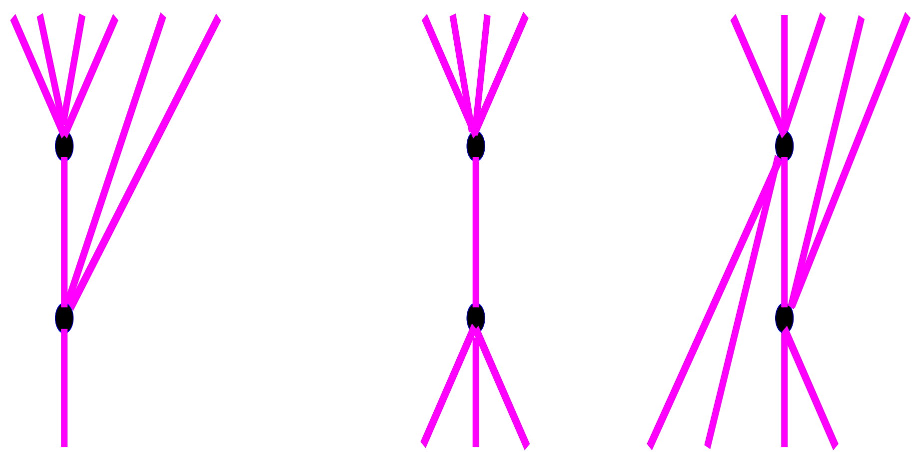


By definition: non-linear effects

- interactions between "soft" Pomerons

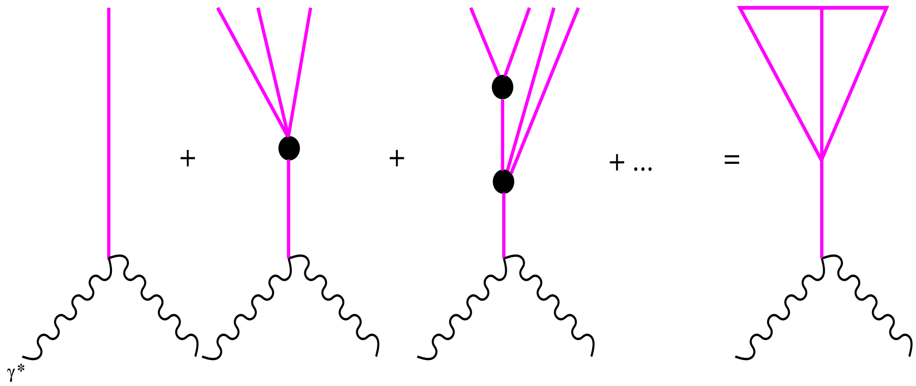


QGSJET-II - dominant contributions re-summed to all orders

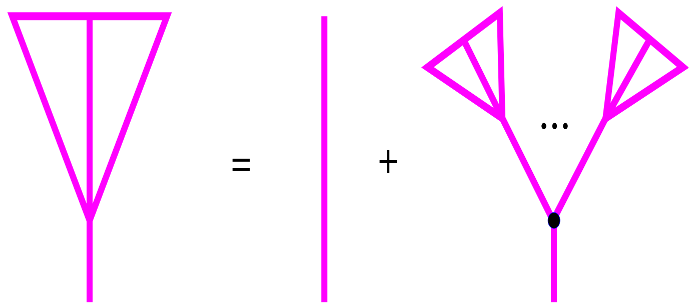


Non-factorizable diagrams:

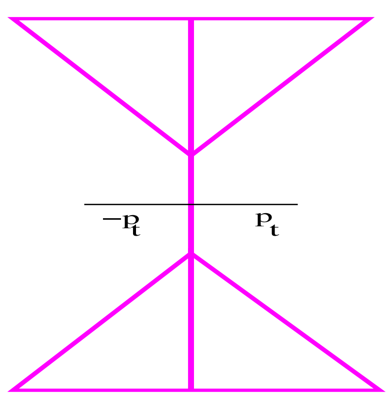
- not appear in SFs



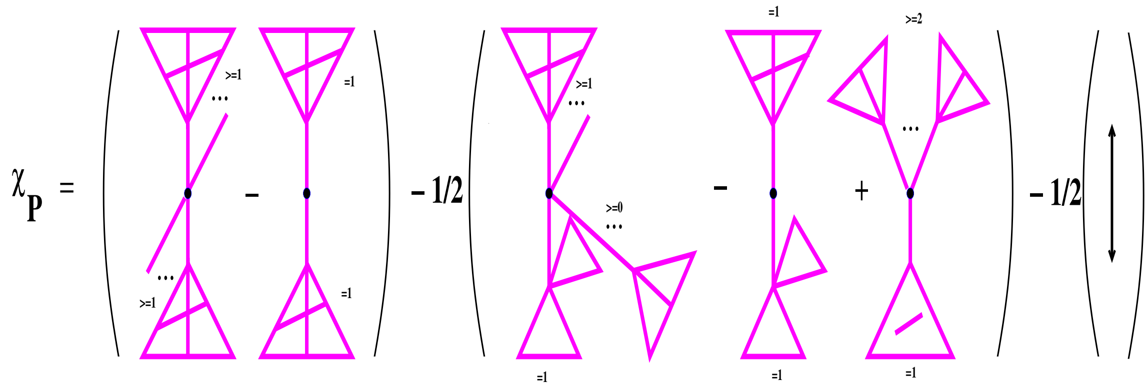
"Fan" contribution:

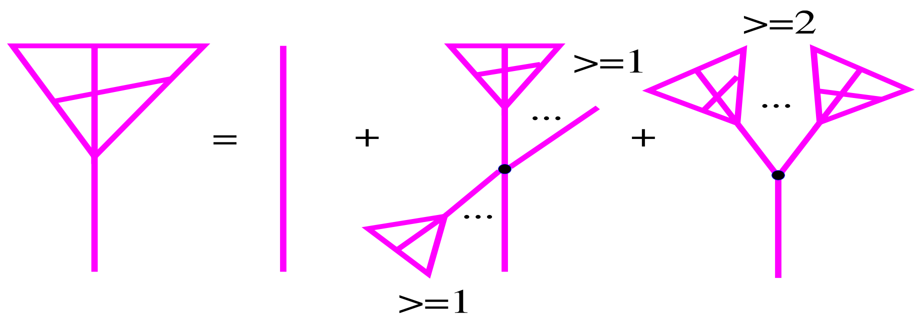


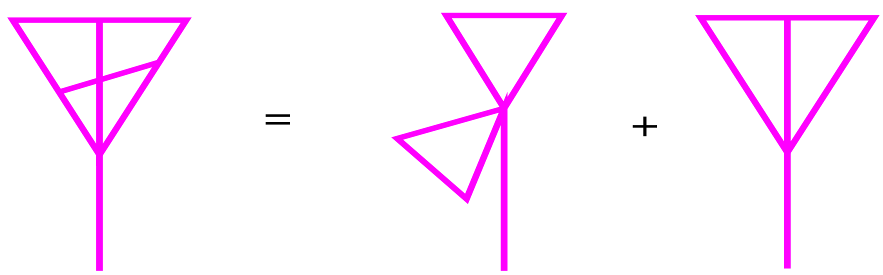
- not contribute to jet spectra (assuming AGK)
  ⇒ QCD factorization

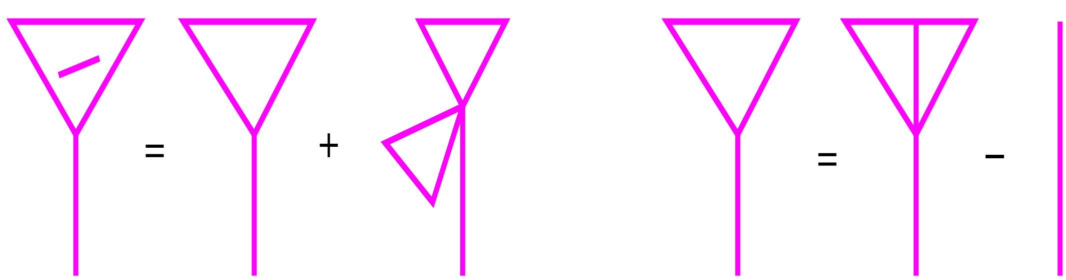


- significantly contribute to pp-eikonal

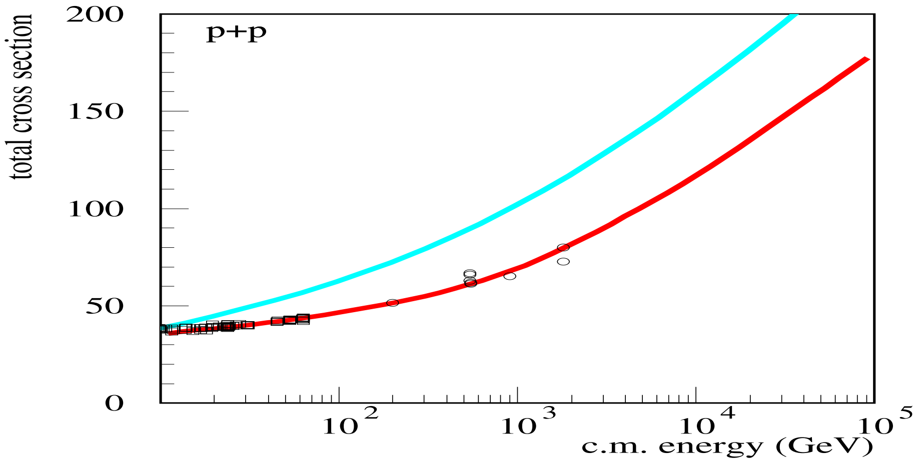






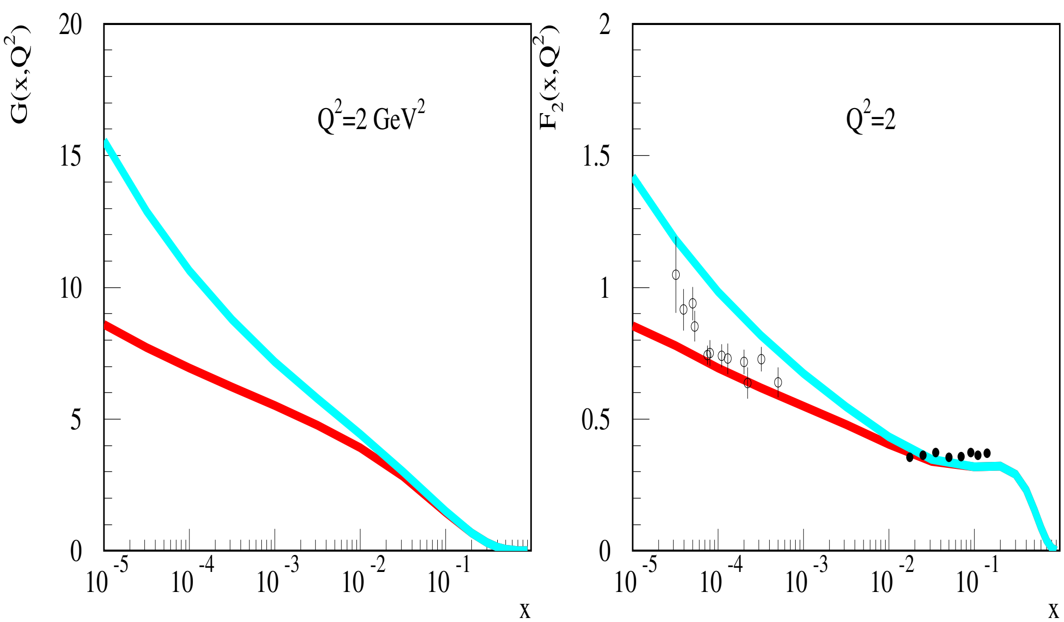


Cross section with (without) enhanced graphs:



Important aspect:

- "Fan" contributions - natural saturation limit in "dense" regime ($s \to \infty,\ b \sim 0,\ A \gg 1$)
- integrated (over b) contributions - still far from the saturation:



Cross sections reduced stronger due to non-factorizable contributions to the eikonal:

- in the "dense" regime "soft" Pomeron intercept re-normalized (A. Kaidalov et al., 1986) $\alpha_{\rm P}(0) \to \tilde{\alpha}_{\rm P}(0)$
- here (in QGSJET-II): $\tilde{\alpha}_{\rm P}(0) < 1$ $\Rightarrow$ "full screening" limit for "soft" Pomerons

"Old" QGSJET:

- always "semi-hard" and "soft" Pomerons
- always "soft pre-evolution" in "semi-hard" Pomerons

QGSJET-II:

in the "dense" regime "soft" pieces "shrink" due to the screening

$$\chi_{pp}^{{\rm P}_{\rm soft}}(\hat{s}, b)\Big|_{\rm screened} \sim \hat{s}^{\tilde{\alpha}_{\rm P}(0)-1}$$

Compared to "old" QGSJET:

- smaller inelasticity
- smaller multiplicity

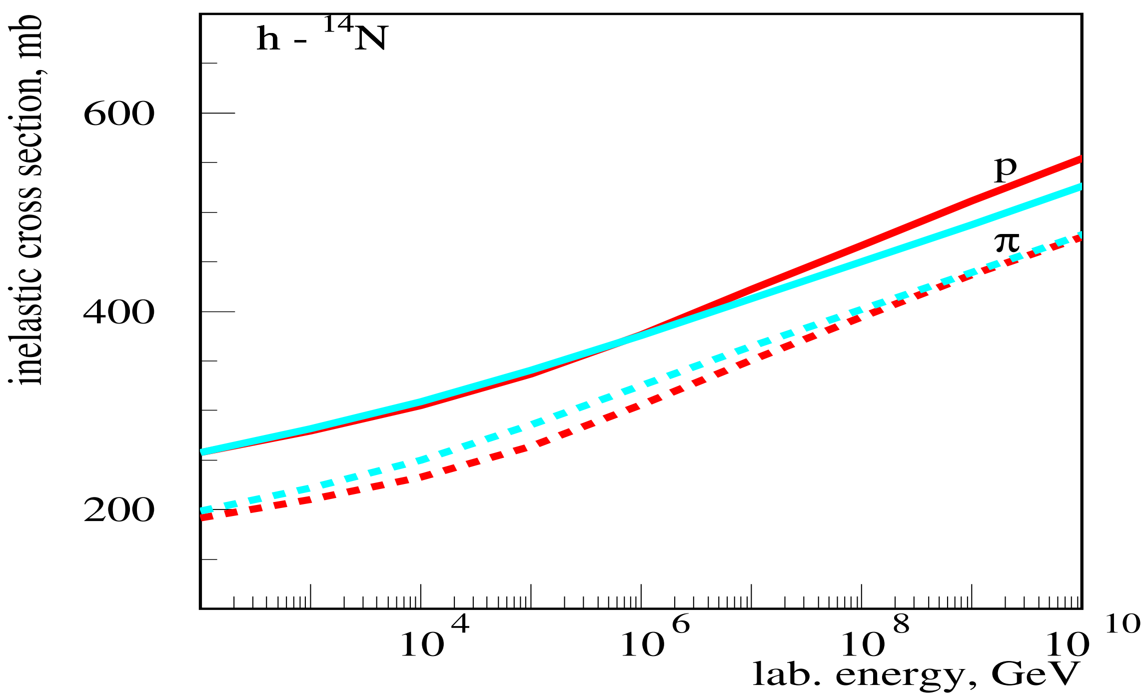
Comparisons between new and old QGSJET

Basic EAS characteristics:

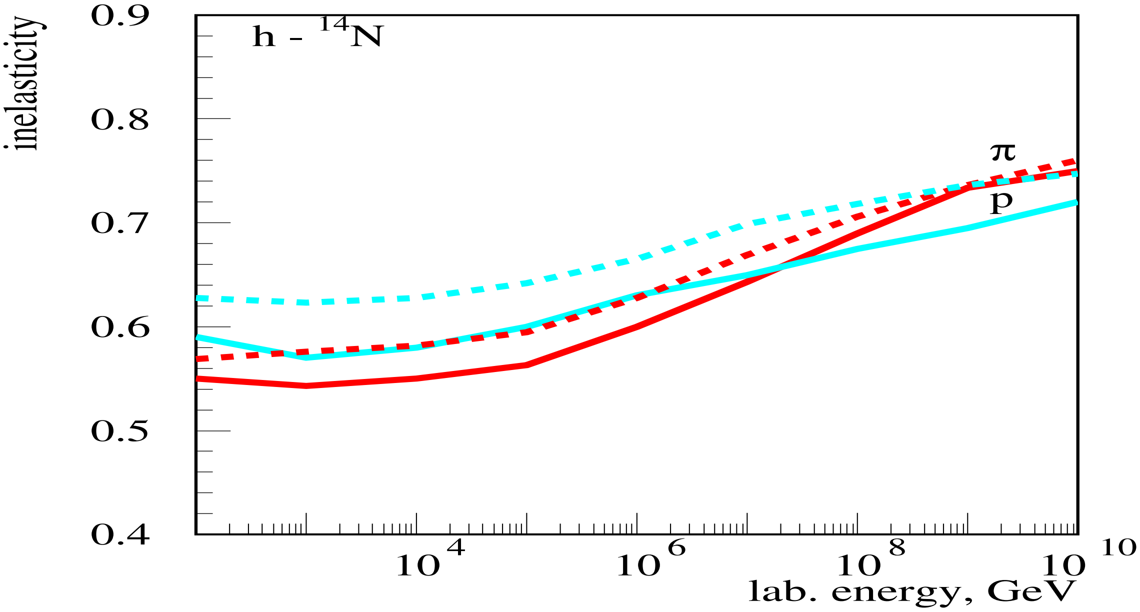
- $X_{\max}$ - mainly defined by $\sigma^{\rm inel}_{h-{\rm air}}$, $K^{\rm inel}_{h-{\rm air}}$
- N_e - correlated with $X_{\max}$
- N_μ - strongly depends on $N^{ch}_{h-{\rm air}}$

Inelastic cross sections ($\sigma^{\rm inel}_{h-{\rm air}}$)

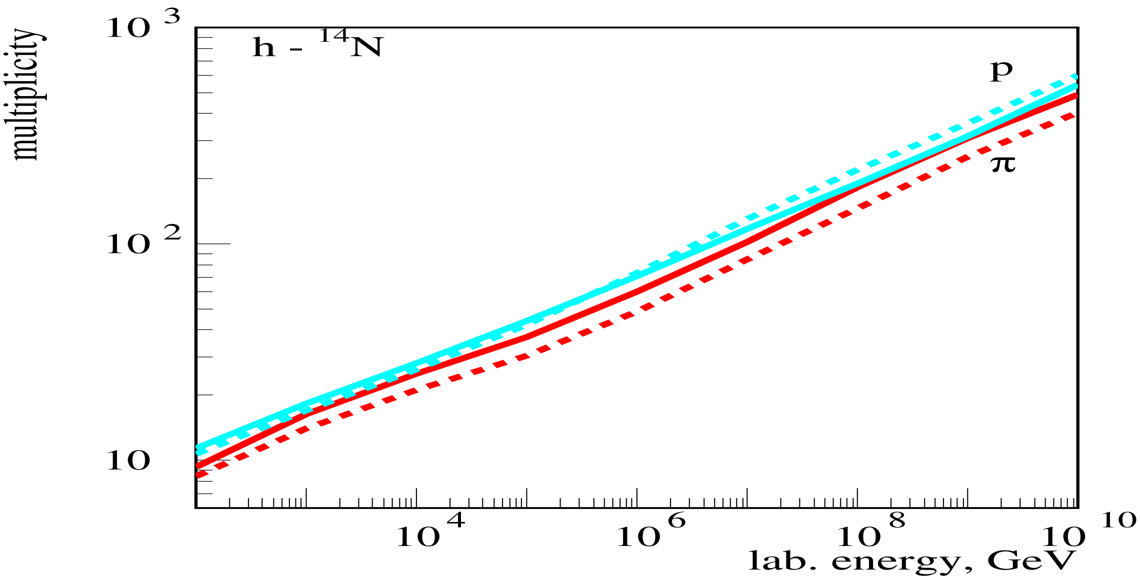
- increase faster for $p-$air
  (steeper parton distributions)
- compensated by the screening for $\pi-$air



Inelasticity ($K^{\rm inel}_{h-{\rm air}}$) suppressed by the screening:

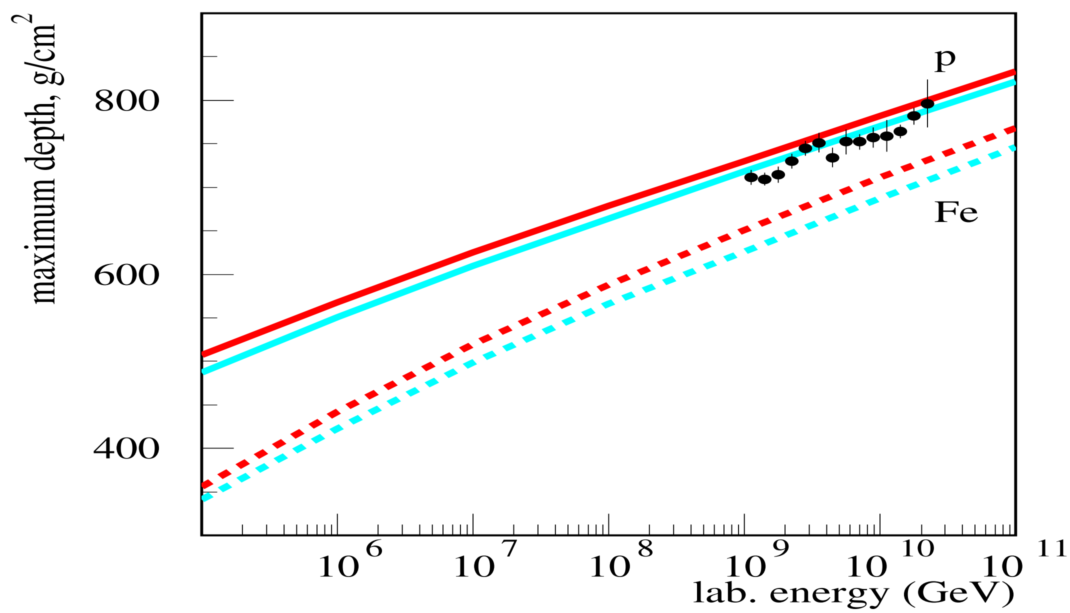


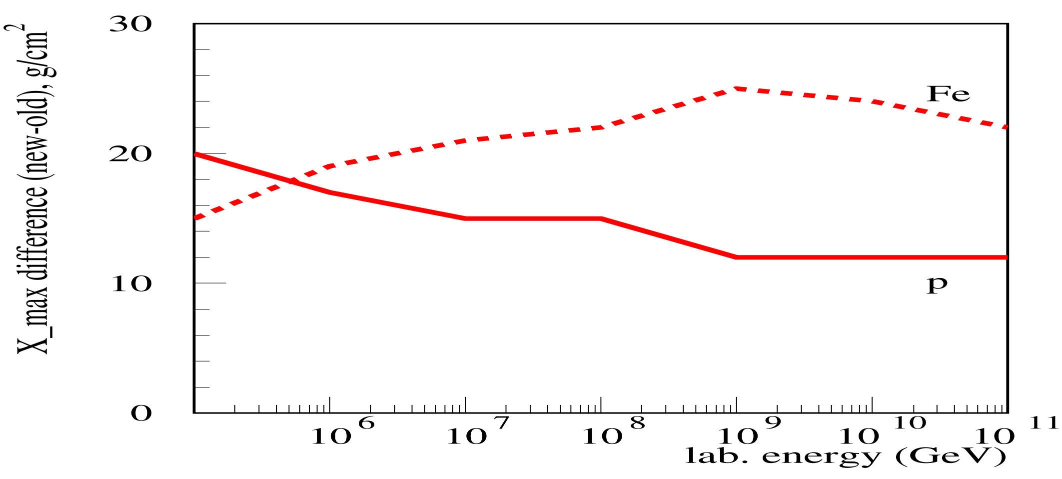
Multiplicity ($N^{ch}_{h-{\rm air}}$) - reduced ("soft" particle production suppressed by the screening):



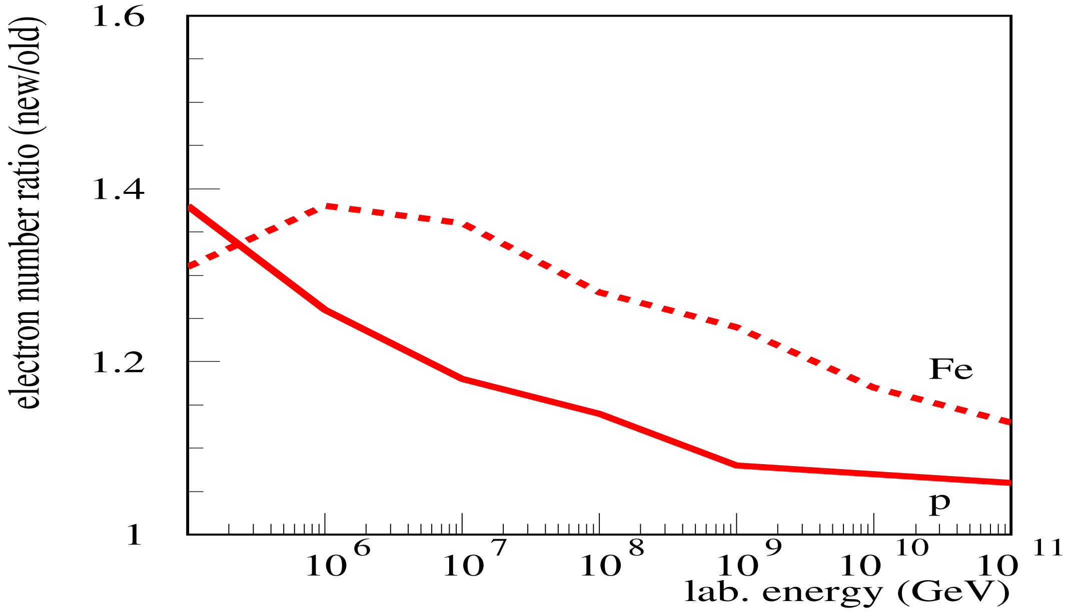
Shower maximum position ($X_{\max}$):

- systematically shifted deeper by screening
- p: ~ 10 g/cm^2 effect at VHE
- Fe: stronger non-linear effects, increasing with energy $\Rightarrow$ superposition picture invalid!

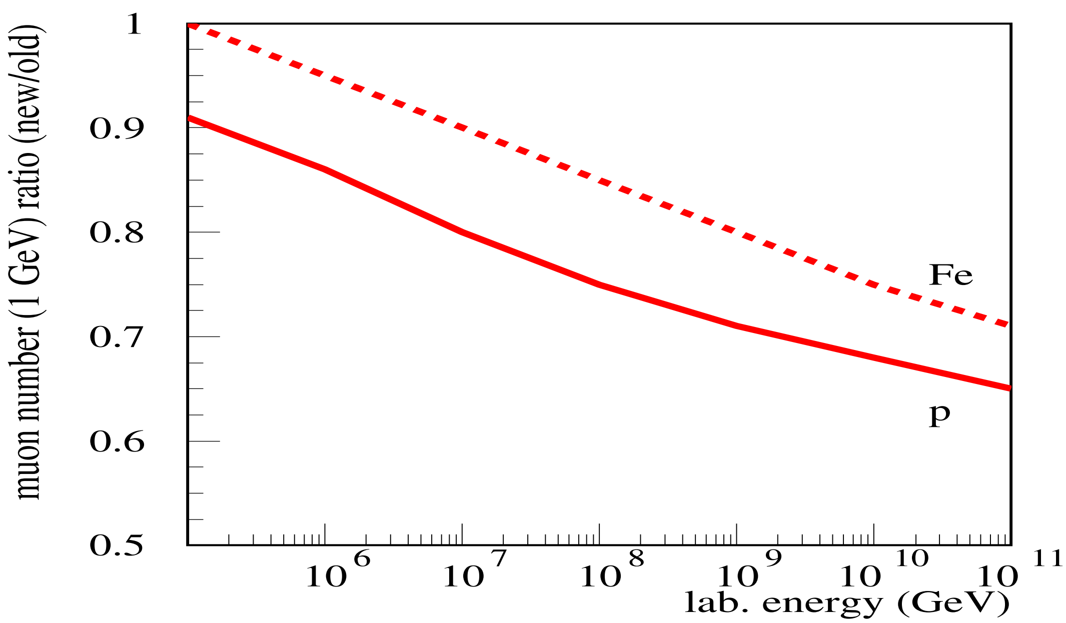




Electron number (N_e) ratio (new/old):



Muon number (N_μ, E_μ>1 GeV) ratio (new/old):



Conclusions

- non-linear effects - of great importance at high energies
- provide non-factorizable contributions to the semi-hard eikonal
- resolve contradiction between SFs and cross sections

QGSJET-II / QGSJET-I:

- smaller $K_{h-\mathrm{air}}^{\mathrm{inel}}$
- smaller $N_{h-\mathrm{air}}^{ch}$

EAS characteristics:

- $X_{\max}$ - deeper ($\sim$10 g/cm^2 effect at VHE)
- N_e - larger (correlated with $X_{\max}$)
- N_μ - smaller, difference increasing with energy

Problem:

- non-linear QCD effects only at the initial scale (Q_0^2)
- but saturation already reached for small b

Increase Q_0^2? - too crude

$\Rightarrow$ GLR-mechanism ($Q_0^2 = Q_0^2(s)$) needed!