Hadronic Interaction Models: Collider - CR connection

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"Avoid models as much as you can!"

"Important issues are INPUT OF REAL DATA ..."

A. Watson

Hadronic MC generators - twofold purpose:

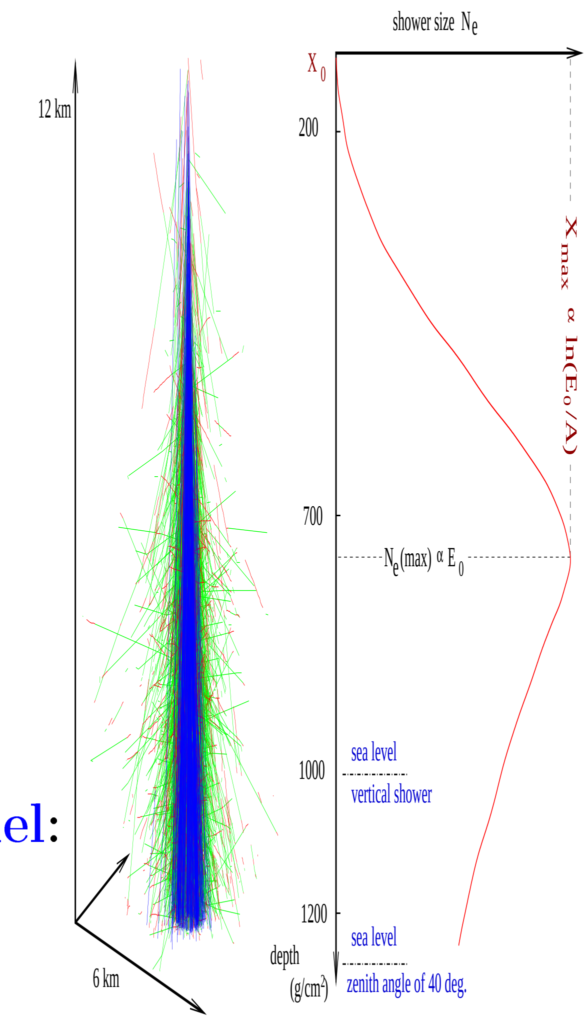
- **interpretation of CR data**
- **bridge between collider & CR studies**

EAS techniques & model requirements

High energy CR studies - via air shower (EAS) development

Basic measured quantities:

- shower maximum position $X_{\max}$
  - mainly sensitive to $\sigma^{\rm inel}_{p-{\rm air}}$ $(\sigma^{\rm non-diffr}_{p-{\rm air}})$, $K^{\rm inel}_{p-{\rm air}}$
- number of charged particles at ground N_e
- number of muons at ground N_μ
  - mainly depends on $N^{\rm ch}_{\pi-{\rm air}}$



Energy dependence:

- $X^p_{\max}(E_0) \simeq {\rm const} + ER \cdot \lg E_0$
- $N^p_e(E_0) \sim E_0^{\alpha_e}$, $\alpha_e \simeq 1.1$
- $N^p_\mu(E_0) \sim E_0^{\alpha_\mu}$, $\alpha_\mu \simeq 0.9$

Projectile mass dependence - 'superposition' model:

- $X^A_{\max}(E_0) = X^p_{\max}(E_0/A) \simeq X^p_{\max}(E_0) - ER \cdot \lg A$
- $N^A_{e/\mu}(E_0) = A \cdot N^p_{e/\mu}(E_0/A) \sim A^{1-\alpha_{e/\mu}} \cdot E_0^{\alpha_{e/\mu}}$,

$\Rightarrow$ CR composition studies

Model requirements for cosmic ray applications

- cross section predictions
- description of minimum bias hA- and AA-collisions
- $\Rightarrow$ importance of 'forward' region
- predictive power (no re-tuning possibilities)

Representative models:

- SIBYLL (Engel, Gaisser, Lipary & Stanev): 'minijet'-type model
- EPOS (Pierog & Werner): Reggeon approach + energy sharing
- QGSJET(-II) (Kalmykov & SO): Reggeon approach, 'enhanced' graphs

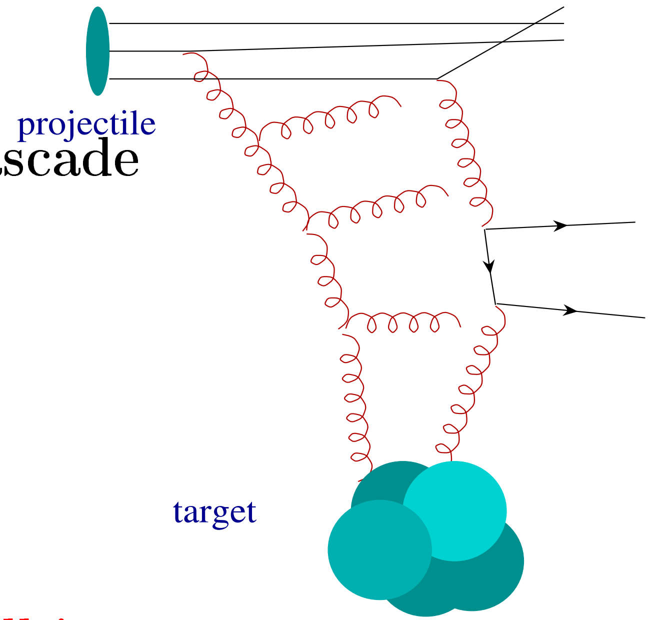
Same physics:

- 'soft' & 'hard' processes
- multiple scattering
- 'central' & peripheral collisions
- nonlinear effects (screening, saturation ...)

Differences: in the implementation, amount of input assumptions, etc.
$\Rightarrow$ in the predictions

High energy interactions: qualitative picture

Hadronic interactions - multiple scattering processes (parton cascades):



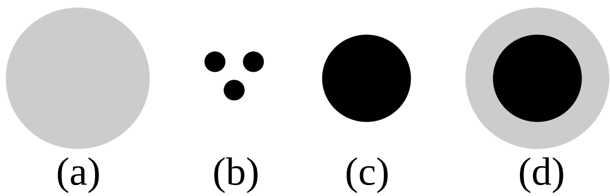
Single scattering:

- (a) 'soft' (all $|q^2| \sim p_t^2 < Q_0^2$, $Q_0 \sim 1$ GeV^2) cascade
  - large effective area ($\Delta b^2 \sim 1/|q^2|$)
  - slow energy rise

  $\Rightarrow$ dominant at relatively low energies
- (b) cascade of 'hard' partons (all $|q^2| \gg Q_0^2$)
  - small effective area
  - rapid energy rise

  $\Rightarrow$ important at very high energies and small impact parameters
- (c) 'semihard' scattering (some $|q^2| > Q_0^2$)
  - large effective area
  - rapid energy rise

  $\Rightarrow$ dominates at high energies and over a wide b-range



Lessons:

- 'soft' processes important (for peripheral & 'semihard' interactions)
  $\Rightarrow$ nonperturbative treatment
- 'hard' processes important (for 'central'/quasi-peripheral collisions)
- high parton density reached over large phase volume
  $\Rightarrow$ nonlinear effects important

General model strategy:

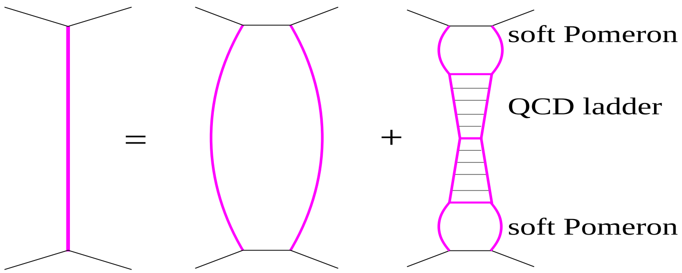
- describe 'elementary' interactions (parton cascades)
  - scattering amplitude
  - hadronization procedure (conversion of partons into hadrons)
- apply Reggeon approach to treat multiple scattering processes
- describe particle production as superposition of 'elementary' processes

'Elementary' interaction

Possible phenomenological approach - 'QCD-improved' Reggeon scheme:

- Q_0^2 - cutoff between 'soft' and perturbative physics
- 'soft' interactions (all $|q^2|$ - small $\Rightarrow \alpha_s(q^2) > 1$):
  - pQCD is inapplicable $\Rightarrow$ Regge pole amplitude ('soft' Pomeron)
- 'semihard' processes ($|q^2| > Q_0^2 \Rightarrow \alpha_s(q^2) \ll 1$)
  - 'soft' Pomeron for $\left|p_t^2\right| < Q_0^2$
  - QCD parton ladder for $\left|p_t^2\right| > Q_0^2$

General interaction $\Rightarrow$ 'general Pomeron':



- particle production: DGLAP cascade + string hadronization

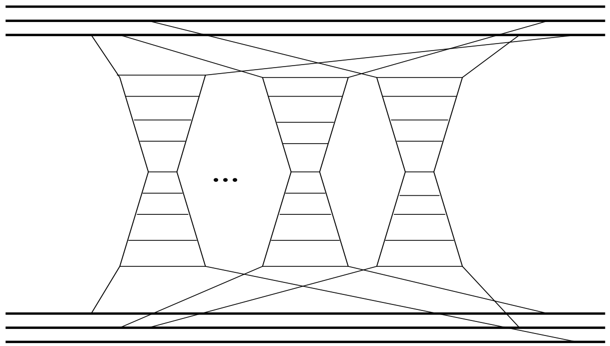
Alternatively ('minijet' scheme):

$Q_0^2 = Q_{\rm sat}^2$ - saturation scale; no parton production @ $p_t < Q_0$

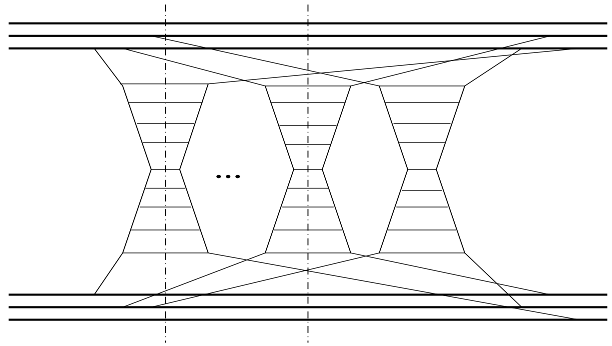
Gribov's reggeon calculus

General interaction - superposition of many 'elementary' processes:

$\sigma_{ad}^{\mathrm{tot}} = \quad \mathrm{Im}$

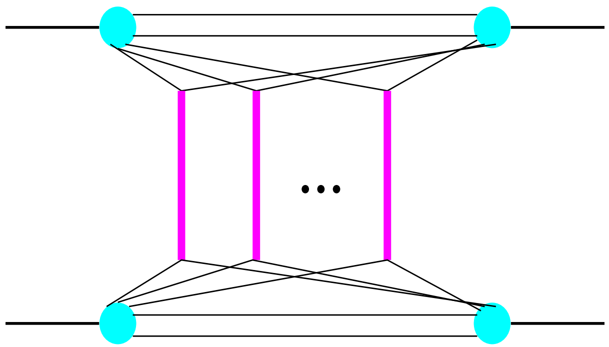


$= \sum$

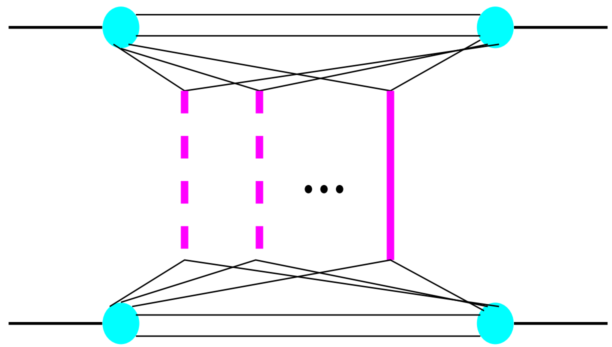


Or (Abramovskii-Gribov-Kancheli cutting rules):

$\sigma_{ad}^{\mathrm{tot}} = \quad \mathrm{Im}$



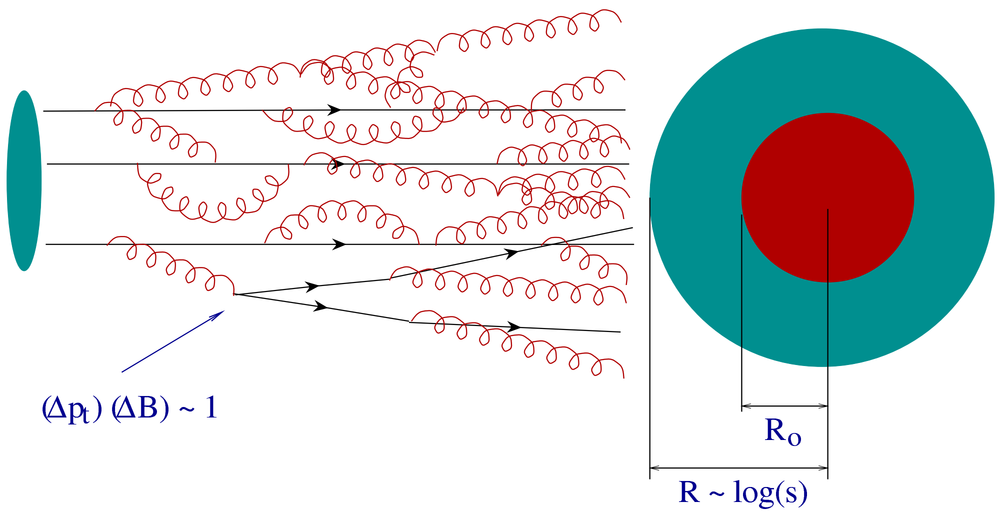
$= \sum$



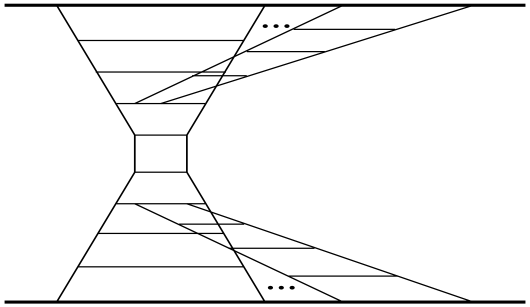
Non-linear effects

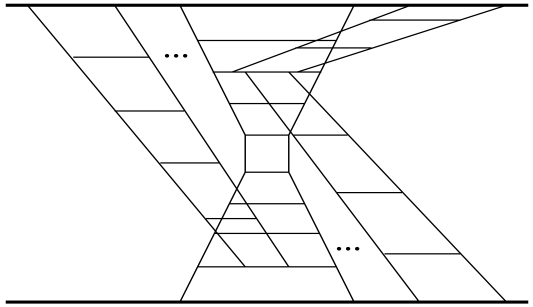
Large s, small b, large A:

- many partons closely packed
- $\Rightarrow$ parton cascades overlap and interact with each other
- $\Rightarrow$ parton shadowing (slower rise of parton density)
- saturation (maximal possible density reached)



Non-linear effects in QCD - interaction between parton ladders:





Model implementations

- traditional (e.g., SIBYLL model):
  - $Q_0^2 = Q_{\rm sat}^2(s)$ - parametrized saturation scale
  - no parton production @ $p_t < Q_0$

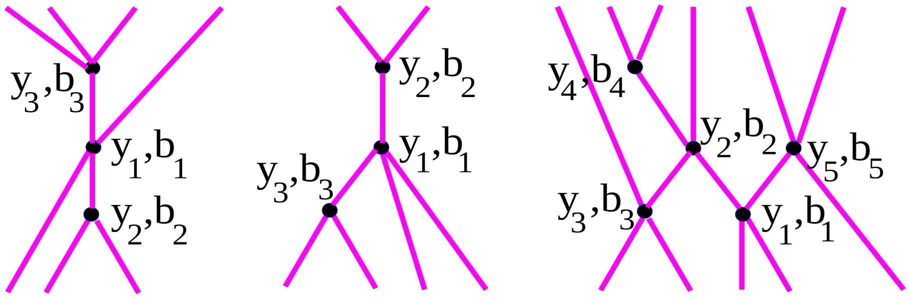
  actually, there exist parton production in the saturated region

- EPOS:
  - effective 'damping' of the amplitude (eikonal)
  - particle production in the 'saturation' region - QGP treatment
  - still based on parametrizations...

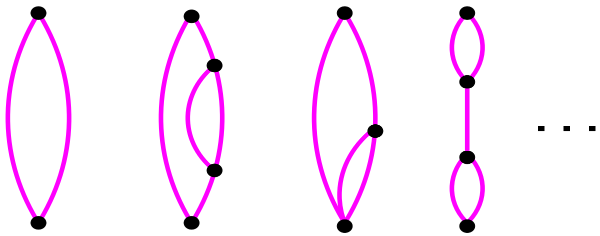
- QGSJET-II - Pomeron approach, 'enhanced' graphs

Pomeron approach: non-linear effects $\equiv$ Pomeron-Pomeron interactions

- all order re-summation of arbitrary Pomeron 'nets' (SO, 2006)

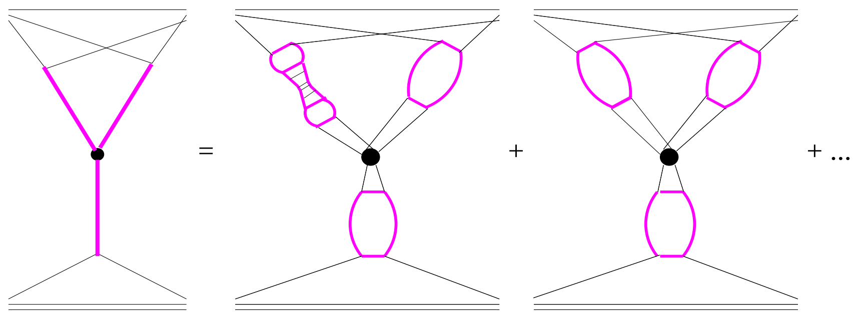


- also 2-point 'loop' corrections (SO, 2008)



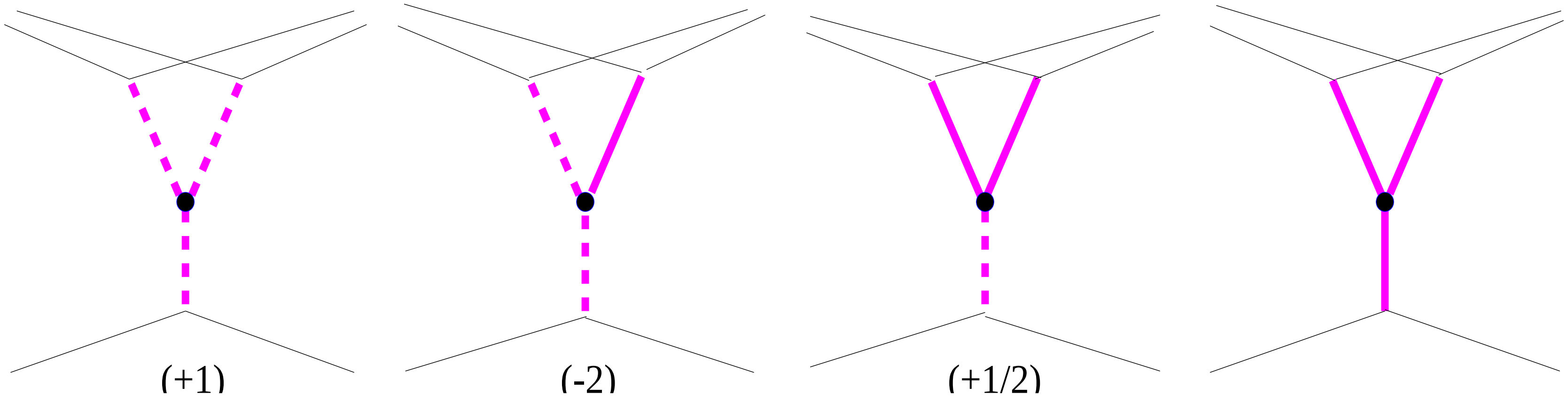
Basic assumptions:

- neglect saturation effects above a fixed Q_0^2 scale
- Pomeron-Pomeron coupling - only at $|q|^2 < Q_0^2$
- $\Rightarrow$ only 'soft' Pomeron coupling
- eikonal multi-Pomeron vertices

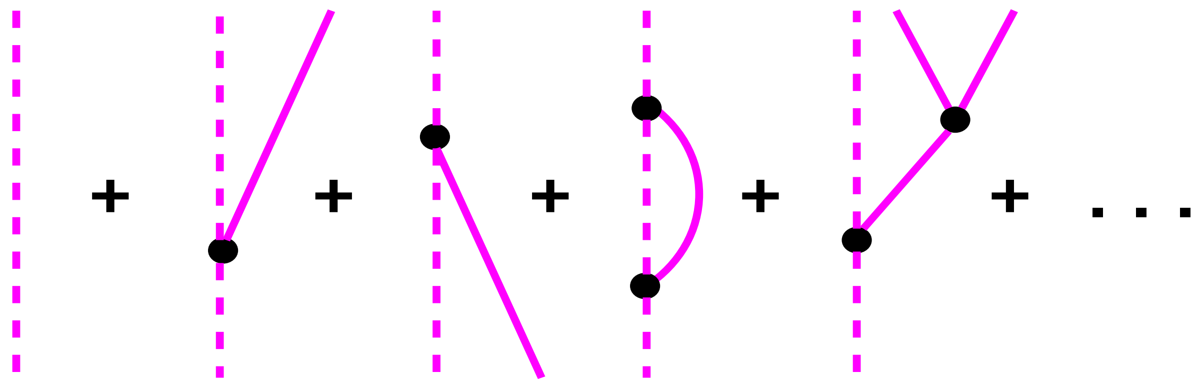


Final states $\Rightarrow$ resummation of unitarity cuts

Example:



Simpliest contribution (single inelastic process):



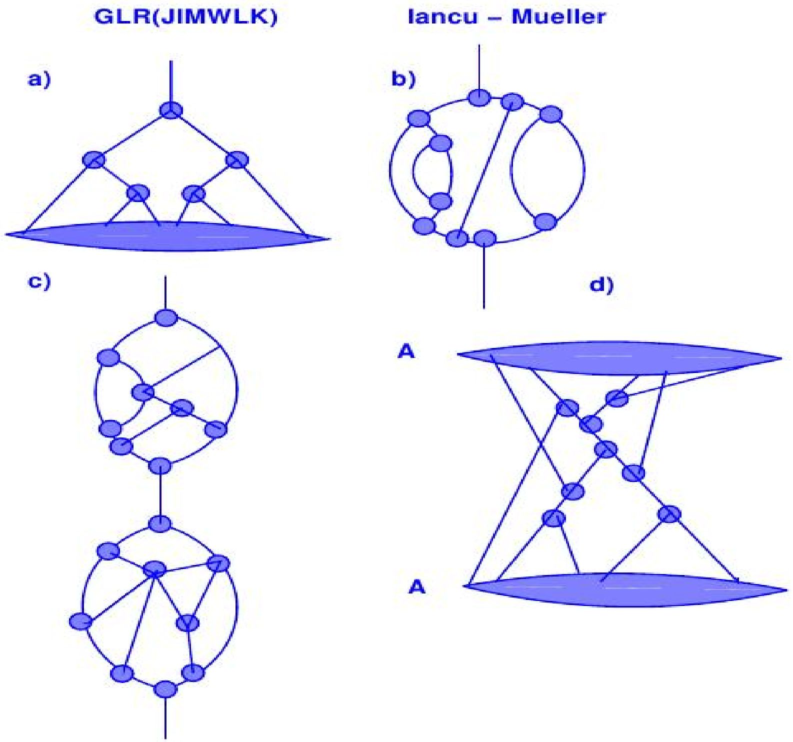
Final results - Schwinger-Dyson recursive representations
$\Rightarrow$ easy implementation in a MC procedure

QCD prospect: color glass condensate approach

Evident positive aspect: QCD-based picture

What diagrams are actually considered?

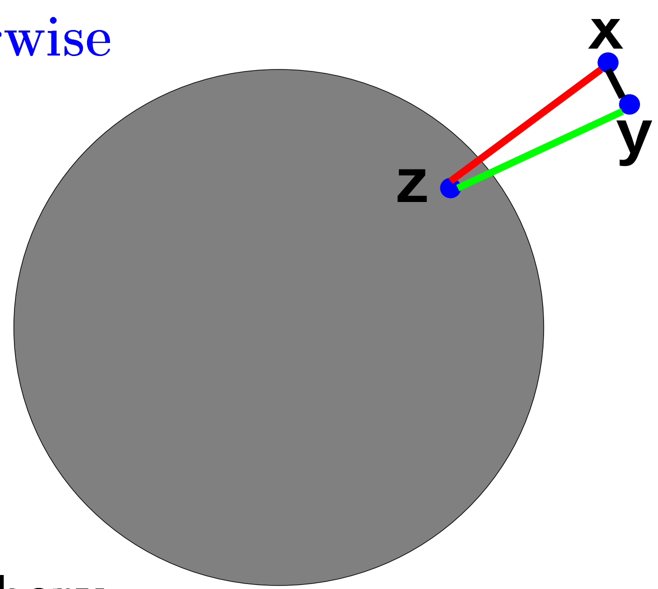
Significant progress reported but the evolution kernel is yet incomplete *(figure from Levin & Lublinsky, 2005)*:



General final states - impossible without cut diagram resummation!

Expansion of the black disk *(Kovner & Wiedermann, 2002):*

- well defined where $Q_{\rm sat}$ is well defined
- dominated by emission of large dipoles otherwise
- $\Rightarrow$ violates Froissar bound!



To properly describe the evolution of the periphery

- either use CGC / dipole approach with additional assumptions *(Ferreiro, Iancu, Itakura & McLerran, 2002; Avsar, 2008)*
- or 'glue' it to a nonperturbative treatment

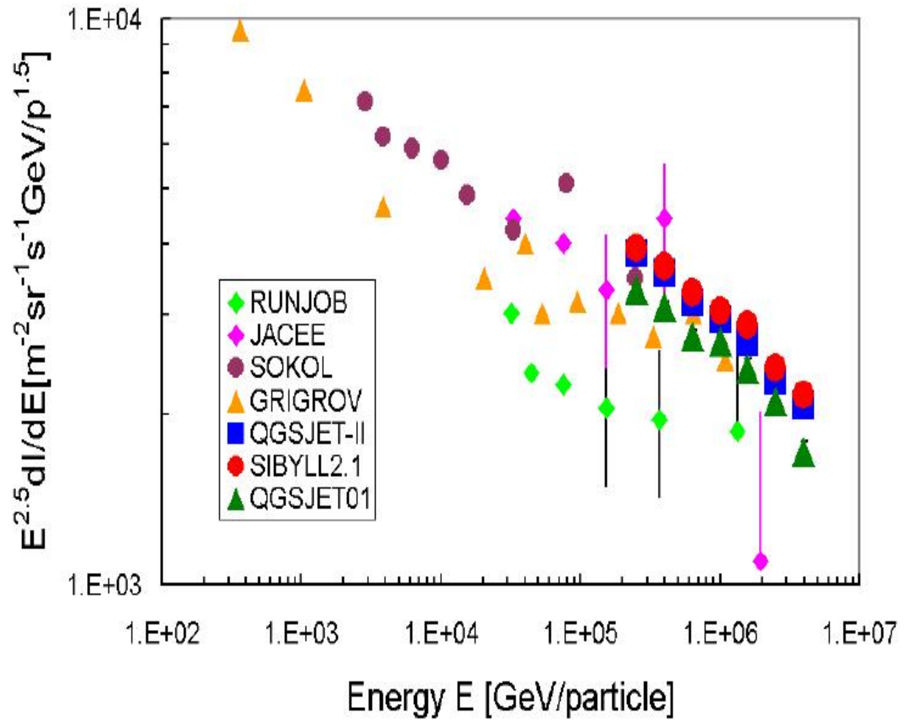
Both cases involve phenomenology

$\Rightarrow$ have to be proven competitive with presently used phenomenology

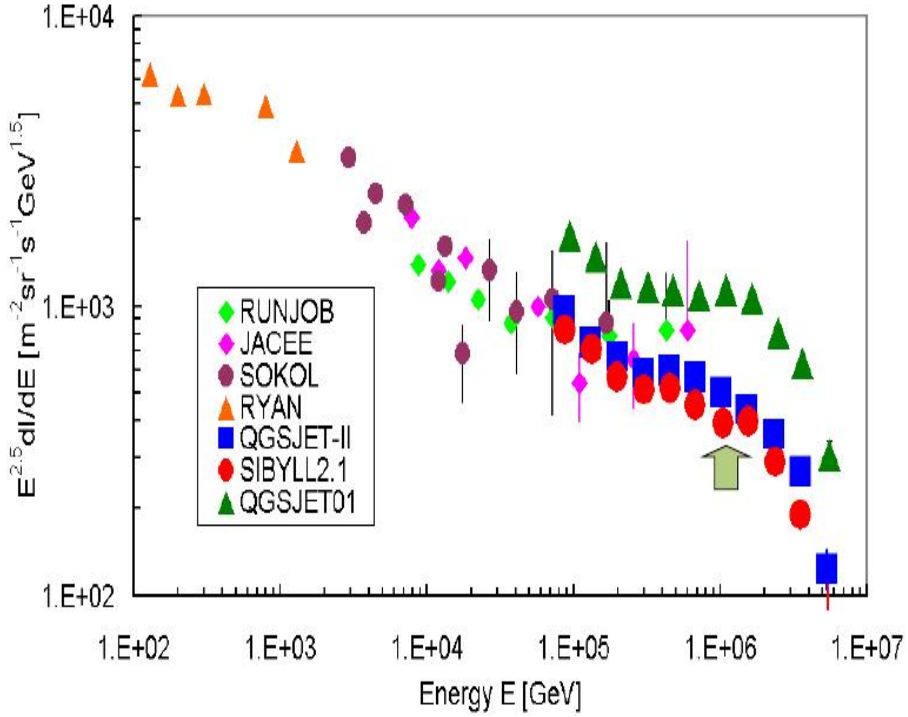
Models & EAS development: the knee and beyond

Grapes data analized with SIBYLL, QGSJET-II *(Gupta, ISVHECRI-08)*: reasonable match with direct measurements

All-particle spectrum



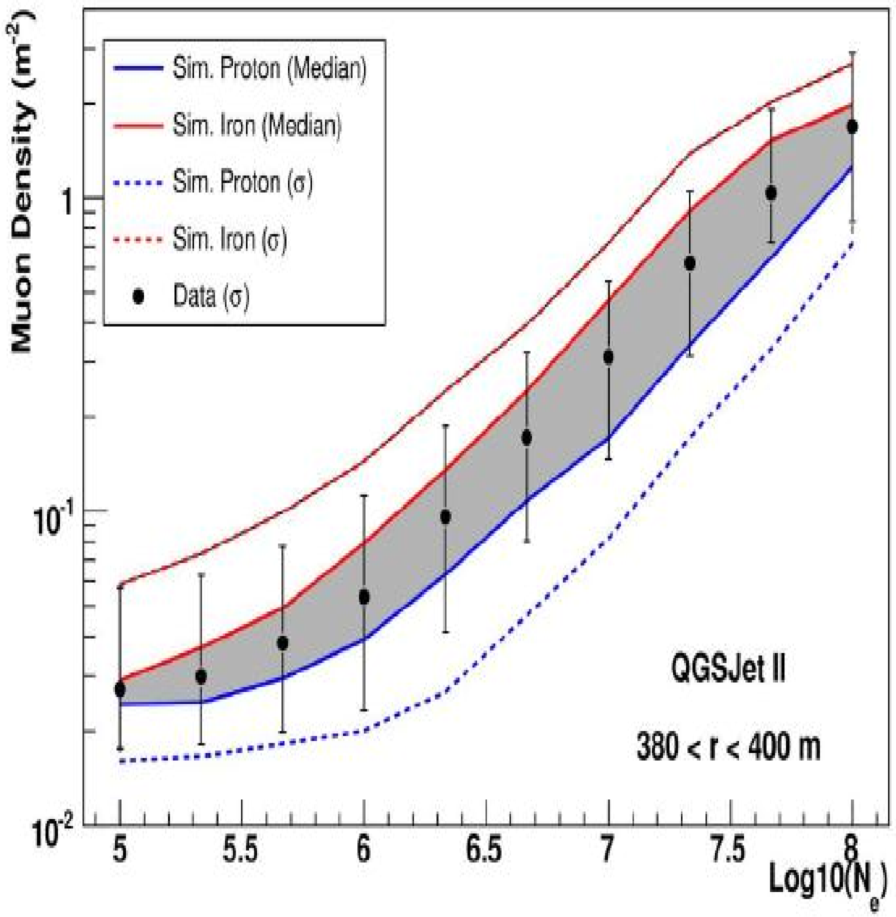
Proton spectrum

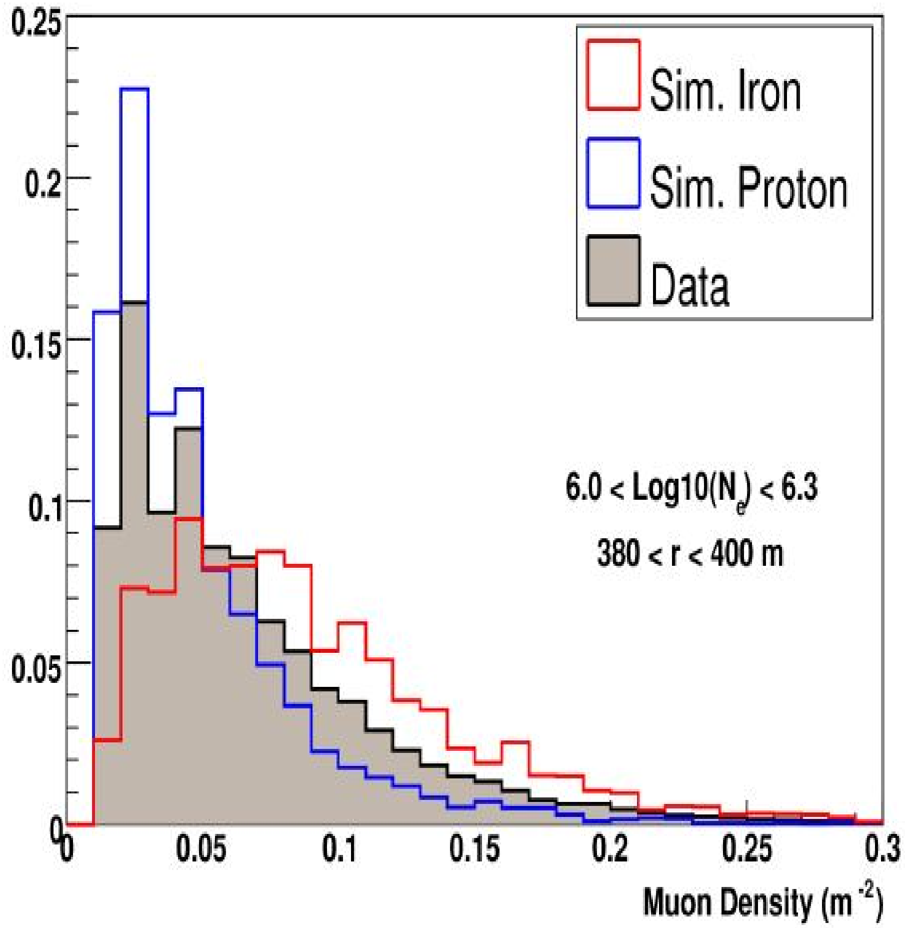


- QGSJET01 → QGSJET-II ⇒ improved agreement for proton spectra

Contemporary CR interaction models seem to work well up to 10^{18} eV

Example: $N_e - N_\mu$ correlation in QGSJET-II / KASCADE-Grande data *(de Souza, ICRC-2007)*:



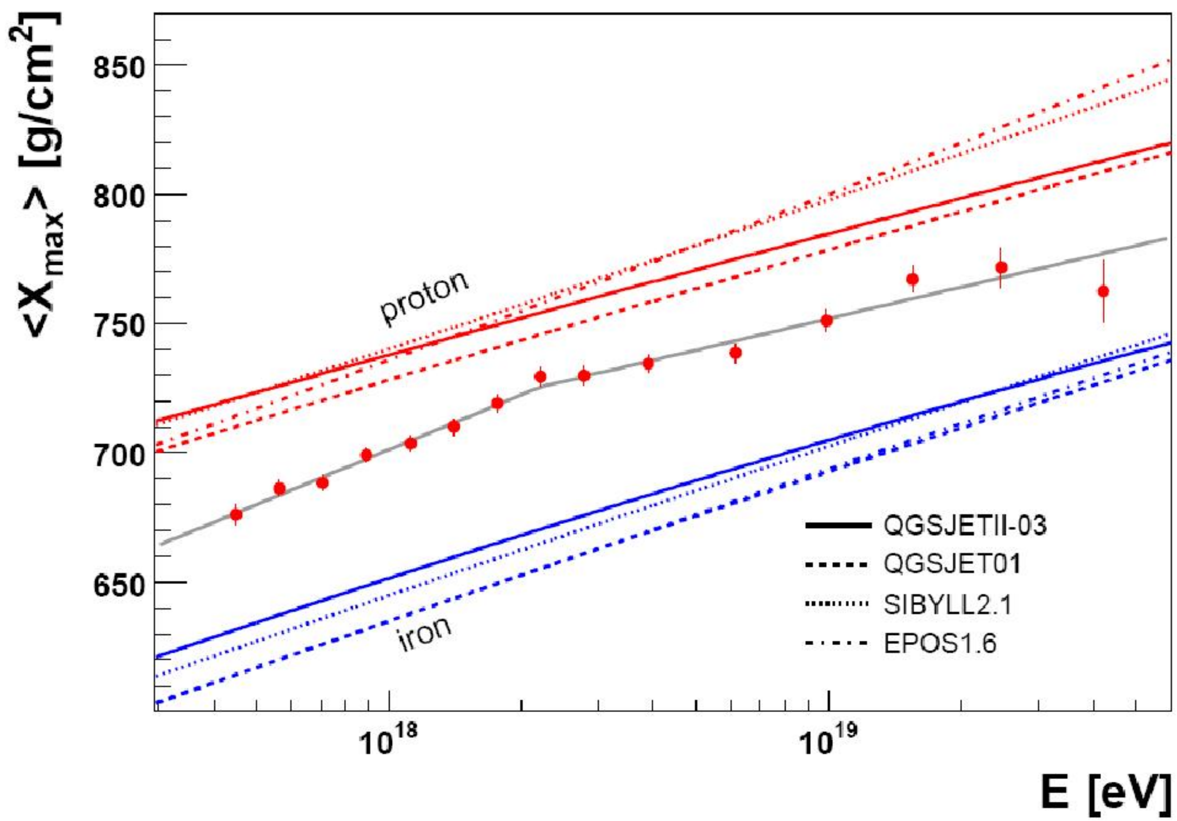


- data are 'bracketed' by the model predictions for p & Fe!

UHECR: model challenge

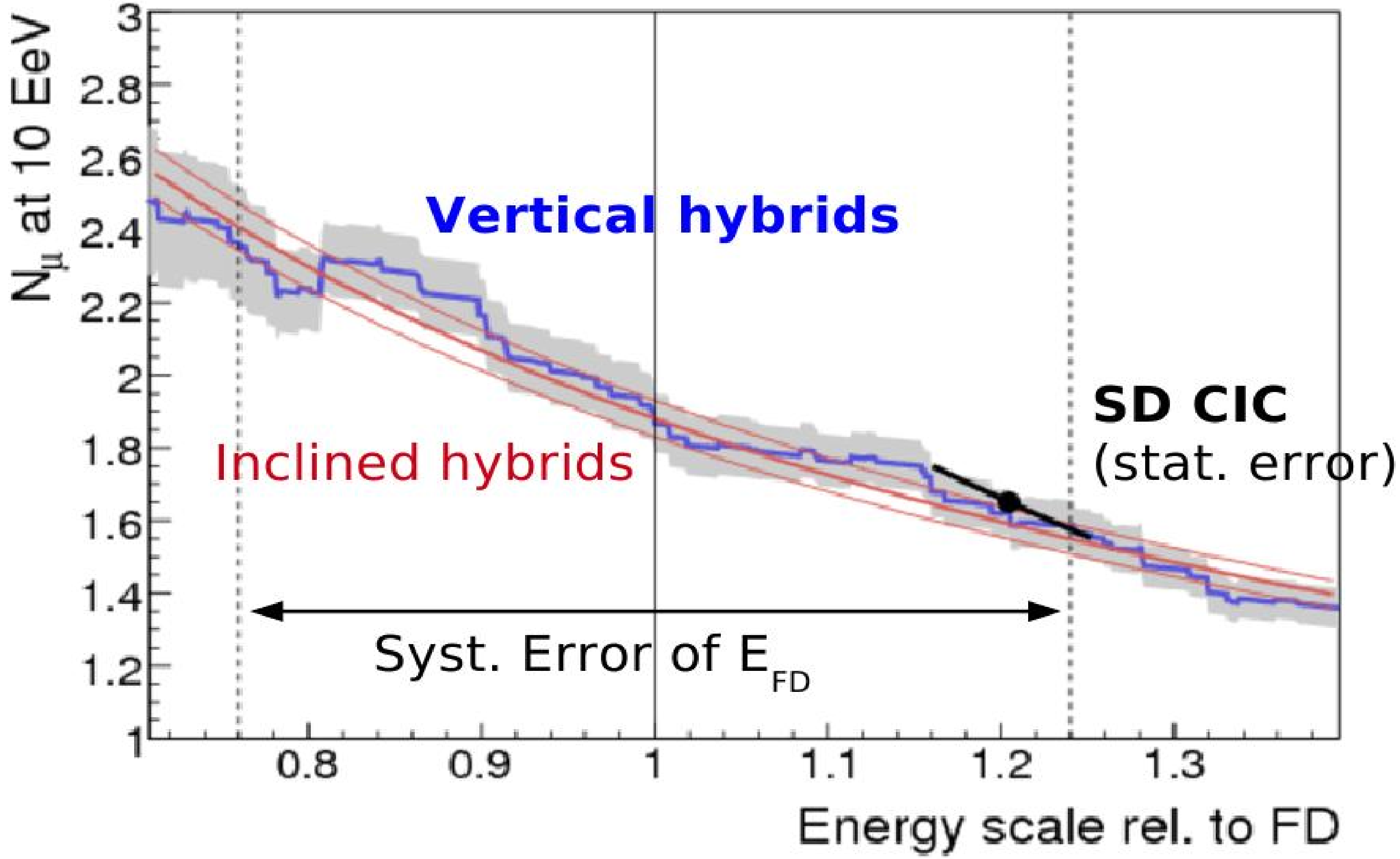
- angular correlation of Auger events with nearby AGNs
  $\Rightarrow$ strongly supports proton primaries above 10^{19} eV

- contradicts the interpretation of Auger $X_{\max}$ data *(Unger, ICRC-2007)*:



\- present models indicate a 'mixed' composition (protons & nuclei)!

• contradiction with Auger muon data *(Schmidt, ISVHECRI-08)*:



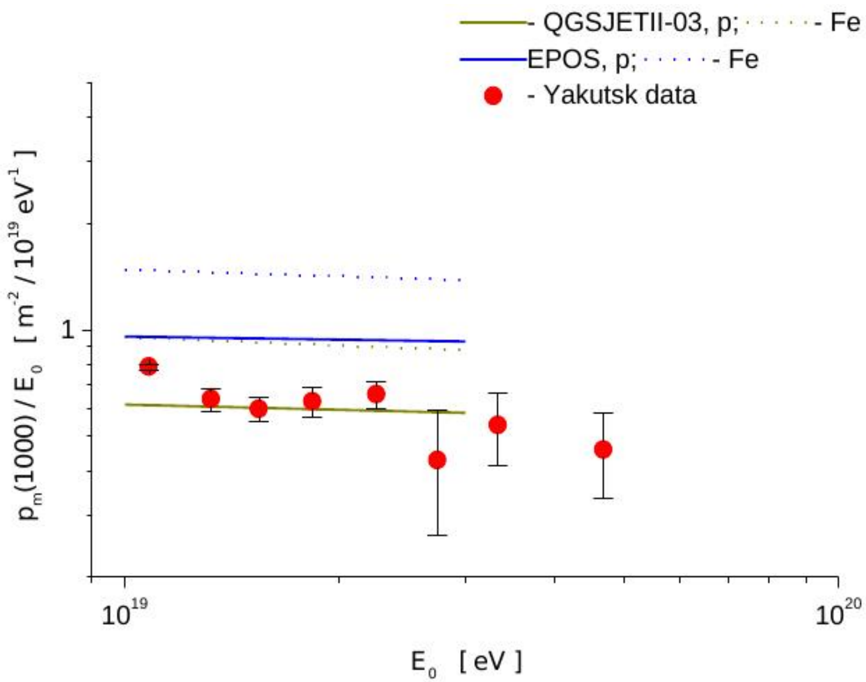
• $\langle N_\mu^{\rm Auger}(10^{10}\,{\rm GeV})\rangle$ / N_μ^p**(QGSJET-II) = 1.62 +0.20/-0.10**

• confirmed by 3(!) independent methods:
- CIC (based on EAS 'universality')
- 'hybrid' events
- inclined showers

• surprisingly steep rise of N_μ over one energy decade (KG $\rightarrow$ Auger)?

• challenged by Yakutsk data *(**Knurenko, ISVHECRI-08**)*:

$$N_\mu^{\rm exp} \sim N_\mu^{p({\rm QGSJET-II})}$$



• HiRes $X_{\rm max}$ - consistent with p-dominance *(**Sokolsky, ISVHECRI-08**)*:

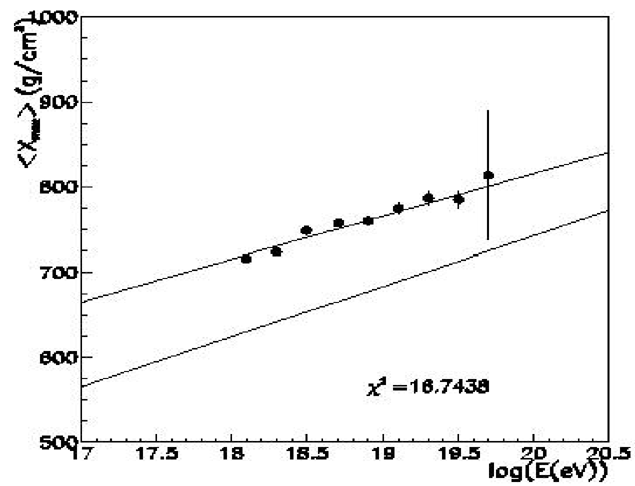


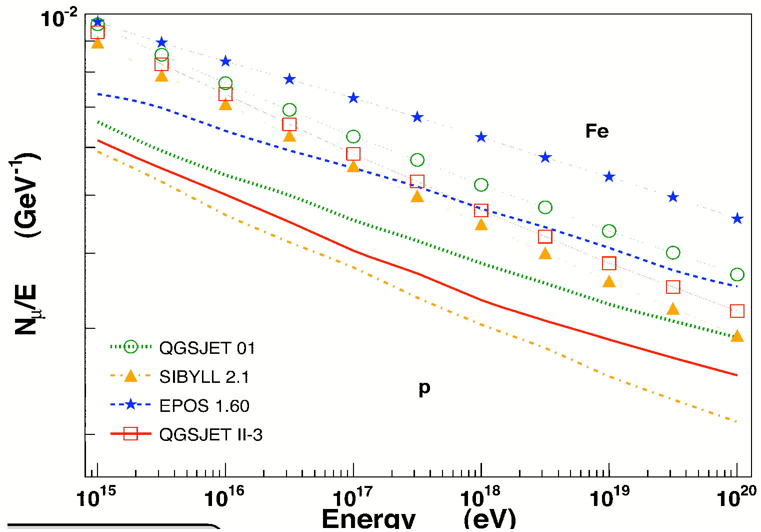
Figure 39: Bias-corrected $<X_{max}>$ in HiRes stereo data, after energy cuts. The χ^2 shown is *not* the result of a fit, but of a direct comparison with the QGSJET01 proton rail for the Gaussian-in-age parametrization.

Let's concentrate on Auger: can a 'conventional' model explain the data?

EPOS model *(Pierog, & Werner, 2006)*

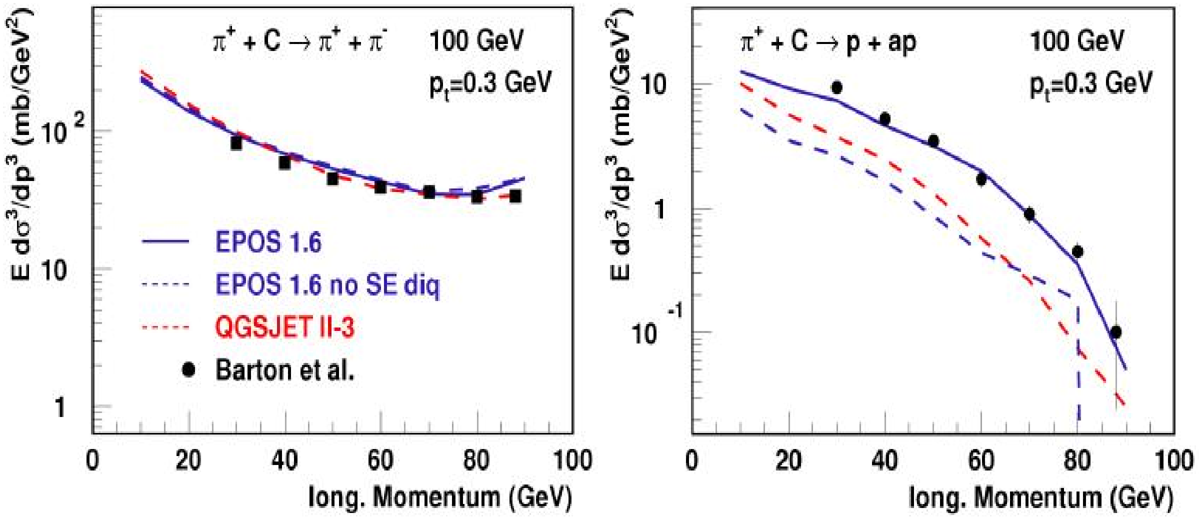
- enhanced muon production in EAS:

$N_\mu^{p(\mathrm{EPOS})} = N_\mu^{\mathrm{Fe(QGSJET-II)}}$ @ 10^{18} eV!

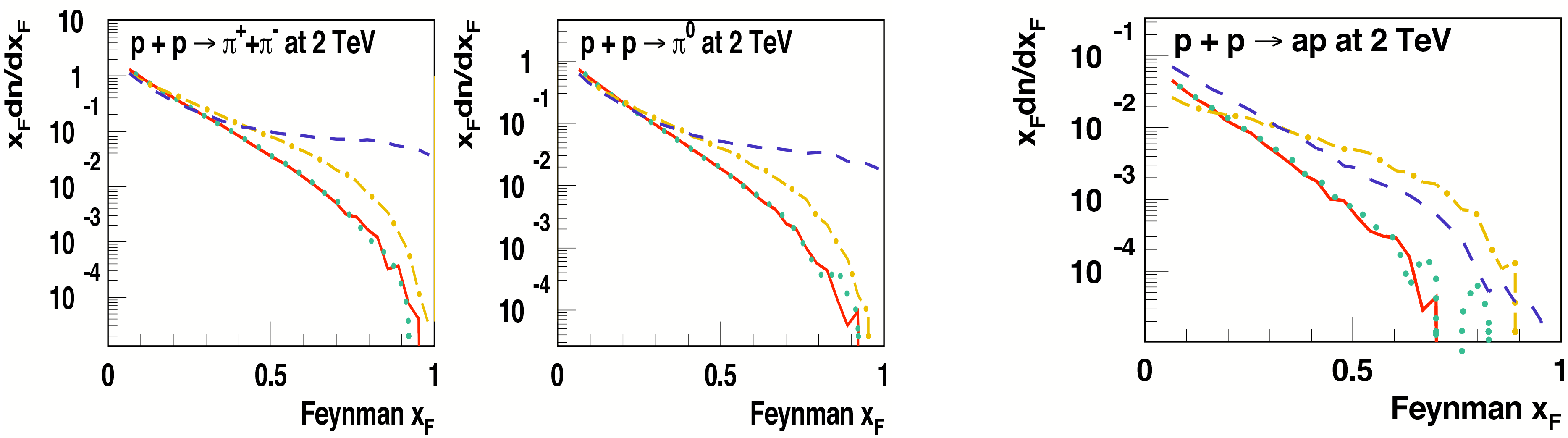


Why?

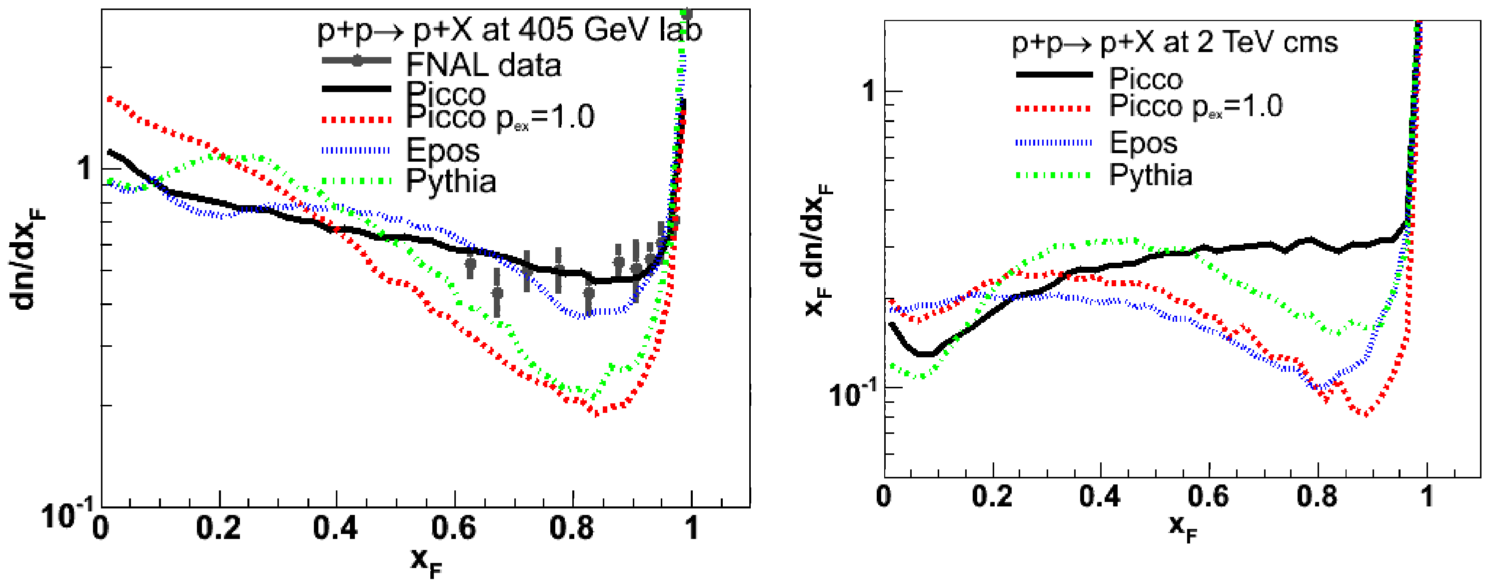
- enhanced (anti-)baryon production *(Pierog, ISVHECRI-08)*



- harder spectra of secondaries



- special treatment of 'remnants' ⇒ higher K_{inel} *(from H. Drescher, 2008)*

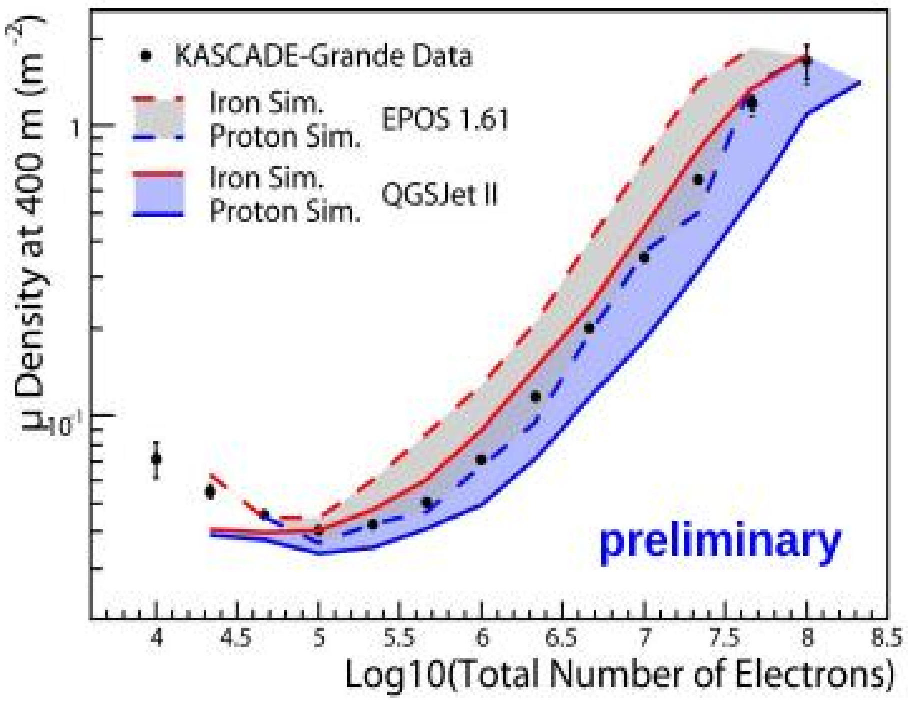


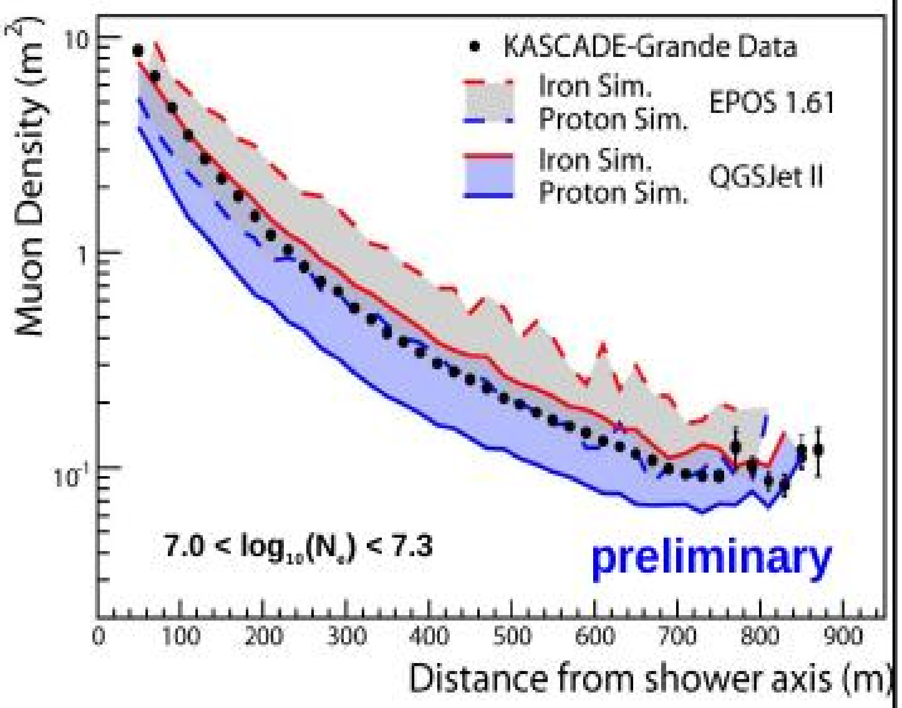
However:

- insufficient to resolve Auger muon puzzle *(Schmidt, ISVHECRI-08)*:
  $\langle N_\mu^{\rm Auger}(10^{10}\ {\rm GeV})\rangle / N_\mu^p({\bf EPOS}) \sim 1.2 \div 1.5$
  ('additional' muons - of low energies $\Rightarrow$ decay in inclined EAS)
  $\Rightarrow$ lesson for Auger people!
- does not solve $X_{\rm max}$-contradiction

On the other hand

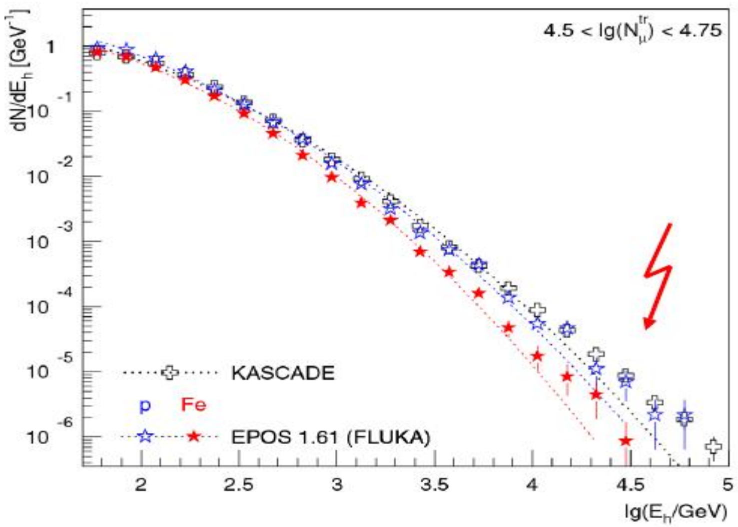
- hardly consistent with N_μ in KG *(Haungs, ISVHECRI-08)*

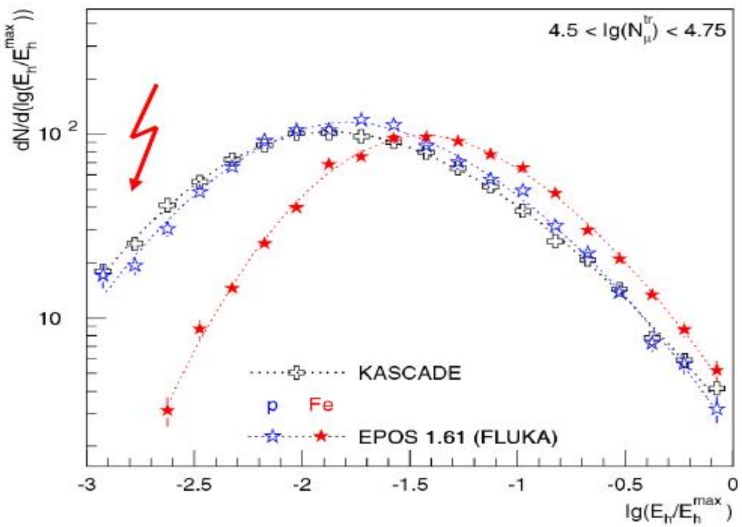




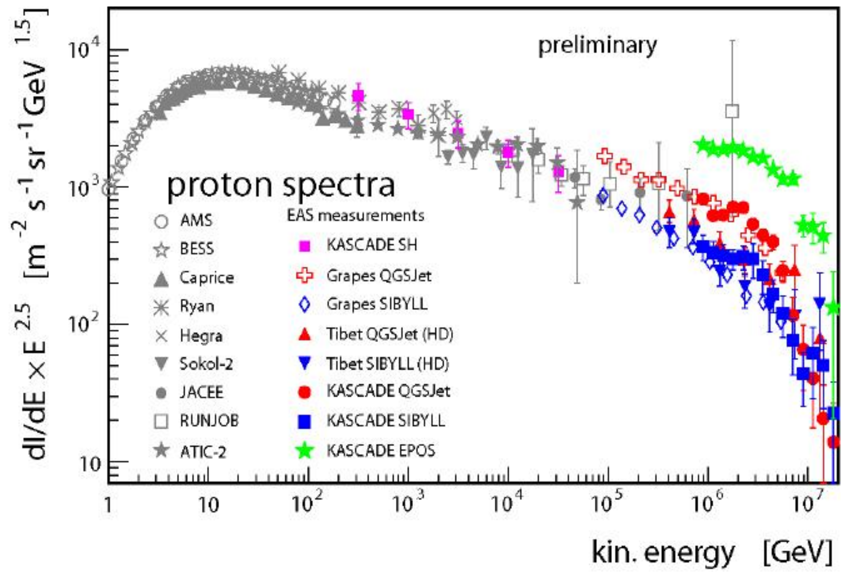
- contradiction with KASCADE hadrons *(Horandel, ISVHECRI-08)*:

Hadron energy spectrum **E_h / E_h^{max}**



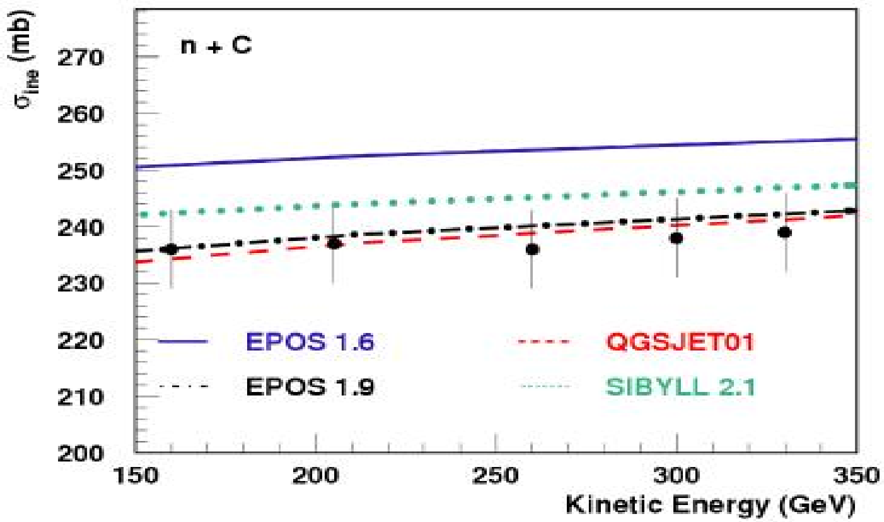


- primary proton spectrum is off... *(Haungs, ISVHECRI-08)*

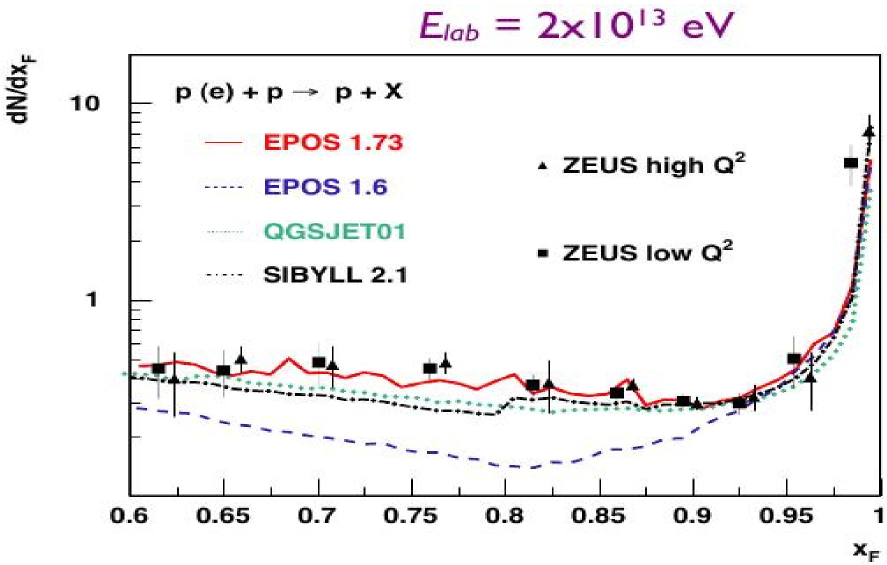


Current problems with EPOS understood:

- neglected nuclear effects on $\sigma_{pA}^{\mathrm{inel}}$ ***(Pierog, ISVHECRI-08):***



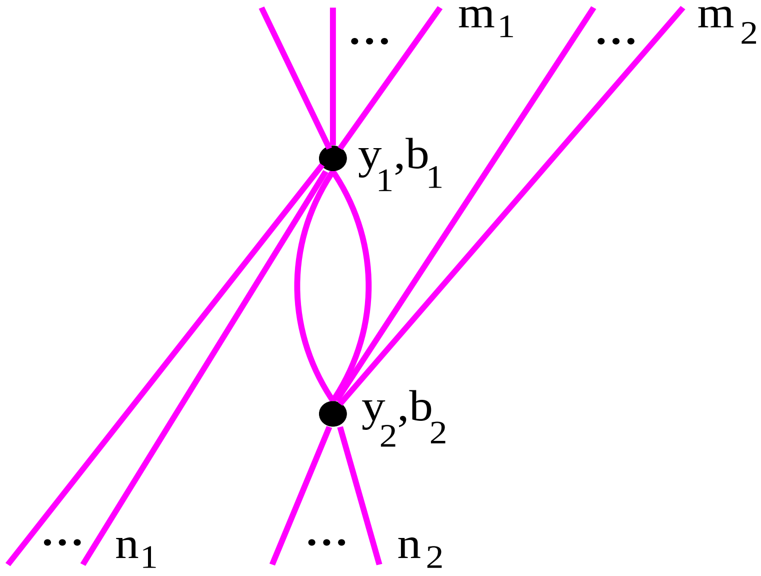
- quick rise of K_{inel} contradicts HERA data ***(Engel, INT Workshop-2008)***:



Recent model updates

QGSJET II-04: account for Pomeron 'loops':

- small at low parton density ($\sim G^2_{3\mathbb{P}}$)
- suppressed at high density:
  $\sim \sum_{n_1=0}^{\infty} \frac{(-\chi^{\mathbb{P}}_{d\mathbb{P}}(s_0 e^{y_1}, b_1))^{n_1}}{n_1!} = e^{-\chi^{\mathbb{P}}_{d\mathbb{P}}(s_0 e^{y_1}, b_1)}$



- Still a finite correction at large b
- Required for s-channel unitarity - all inelastic final states should have positive probabilities (e.g., double high mass diffraction was ill-defined)
- Most important: different energy / (projectile or target) mass dependence of screening corrections

Re-summation technique: SO, PRD2008

Adding 'loops' $\Rightarrow$ additional screening corrections to fit same data on σ_{pp}^{tot}
$\Rightarrow$ smaller 3P-coupling

Consequences:

1) smaller diffraction (smaller $G_{3\mathbb{P}}$, suppression of peripheral collisions)

2) smaller nuclear screening effects (smaller $G_{3\mathbb{P}}$)

3) smaller screening effects for πp & πA (Kp & KA)

EAS characteristics - small but finite changes:

- shift of $X_{\max}$ position - up to 10 g/cm^2
- up to 10% changes of N_e (below 10^{17} eV)
- up to 5% changes of N_μ

Model development completed now

$\Rightarrow$ will stay in contradiction with Auger data

EPOS 1.9 ***(Pierog, ISVHECRI-08)*** - problems understood & corrected

- high N_μ prediction preserved
- smaller N_e & deeper $X_{\max}$ predicted
- $\Rightarrow$ may resolve KASCADE-Grande / Auger inconsistency!
- can not resolve the $X_{\max}$ puzzle

Still a lot to do with EPOS

- role of inelasticity (similar effect on electron than cross section but change muon and hadron number)
  - correlations Ne-Eh
- different approach for saturation effect in EPOS
- more conservative approach for remnants in EPOS
- new hydrodynamical treatment of high density region (QGP)
- soon comparison to LHC ...

(Pierog, ISVHECRI-08)

What is needed to reproduce Auger data with protons?

- to get higher $X_{\max}$:
  - higher $\sigma^{\rm inel}_{p-{\rm air}}$
  - or higher $K^{\rm inel}_{p-{\rm air}}$ ('stopping power')?
- to get higher N_μ:
  - higher $N^{\rm ch}_{\pi-{\rm air}}$
  - somewhat 'harder' pion spectra?

Can CGC do that?

- high parton density in the saturation region $\Rightarrow$ high multiplicity
- rapid rise of $B^{\rm el}_{pp}$ $\Rightarrow$ of $\sigma^{\rm tot}$, $\sigma^{\rm inel}$
- independent parton fragmentation $\Rightarrow$ high 'stopping power' ***(Drescher, Dumitru & Strikman, 2004)***

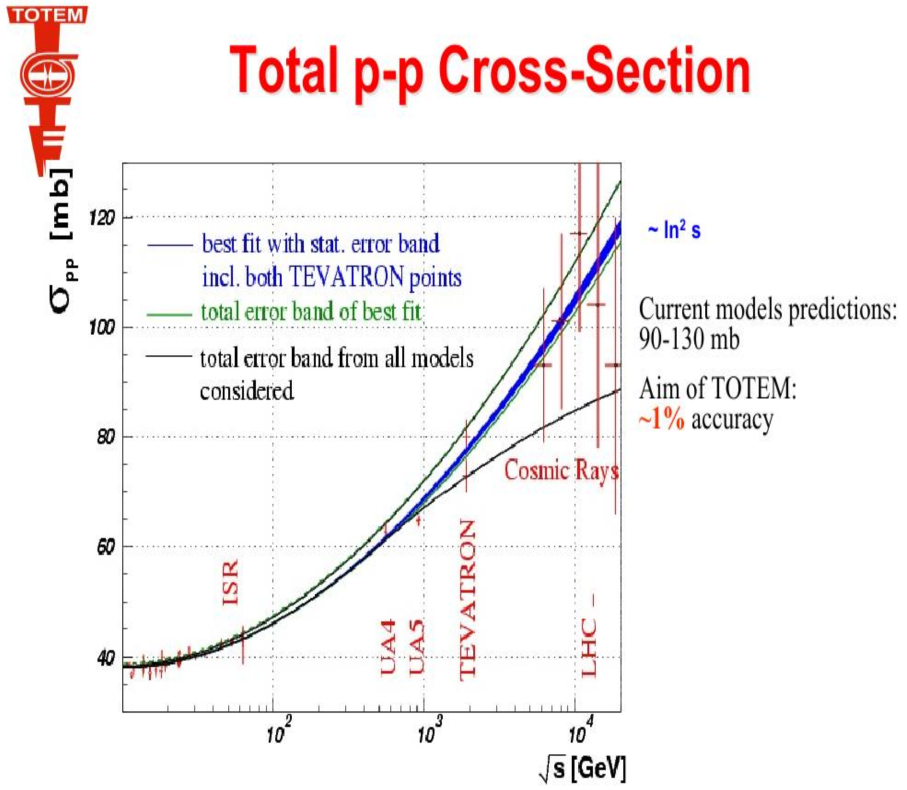
Main problem: what one needs is

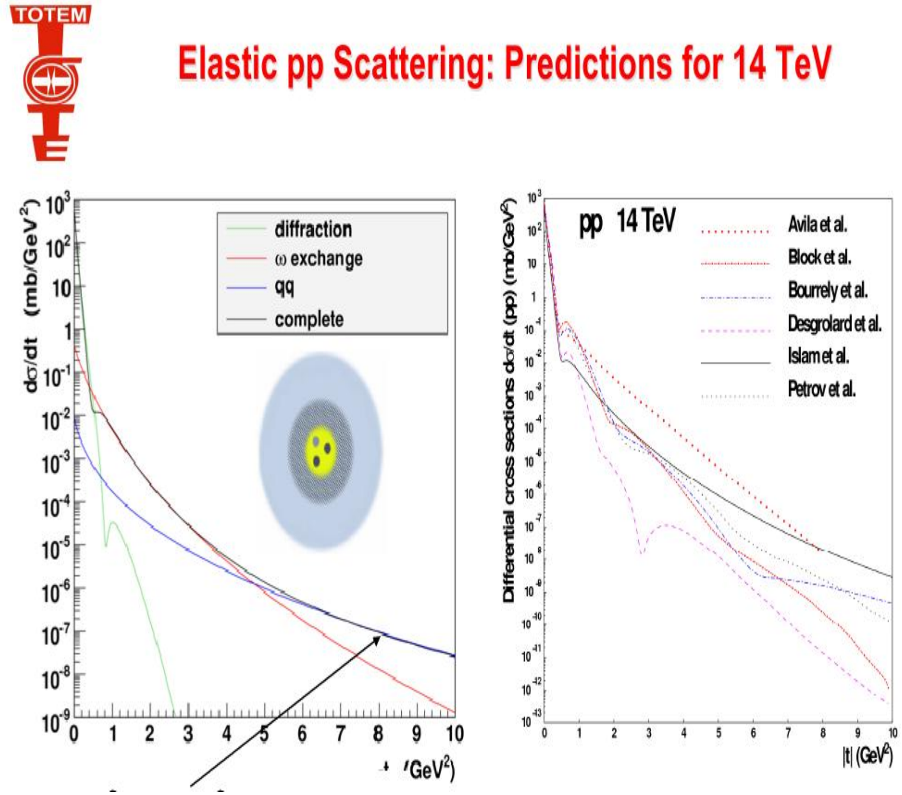
- not an explanation (fit) of the data
- but a reliable prediction!

$\Rightarrow$ self-consistent & coherent model approach is awaited!

Substantial progress may be assured by the forthcoming LHC data

E.g., by TOTEM studies of $\sigma_{pp}^{\rm tot}$, $\sigma_{pp}^{\rm diffr}$, $d\sigma_{pp}^{\rm el}/dt$ ***(Eggert, ISVHECRI-08)***:





Measurement of total cross section:

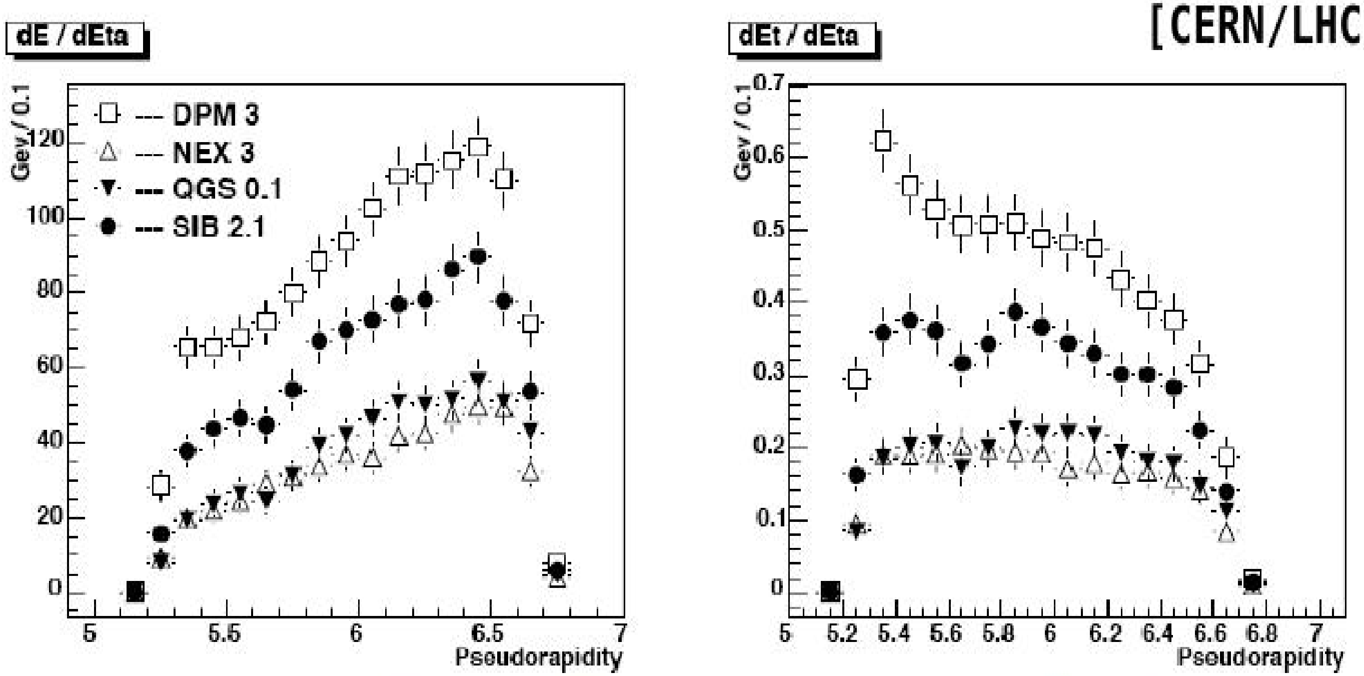
- allows to discriminate current model predictions for $\sigma_{pp}^{\rm tot} \Rightarrow \sigma_{pA}^{\rm inel}$, $\sigma_{AA}^{\rm inel}$ - given also $B_{pp}^{\rm el}$ (beware, inelastic screening is model-dependent)
- significantly constrains model results for $K_{hA}^{\rm inel}$, $N_{hA}^{\rm ch}$

Measurement of $\sigma_{pp}^{\rm diffr}$ - significantly constrains $K_{pp}^{\rm inel} \Rightarrow K_{hA}^{\rm inel}$

Measurement of $d\sigma_{pp}^{\rm el}/dt$ = information on the interaction profile $\sigma_{pp}(b)$
$\Rightarrow$ allows to test saturation models

Indirect information on $K_{\rm inel}$ & saturation scale:
CASTOR measurements *(McCauley, ISVHECRI-08)*:

[CERN/LHCC 2006-039]



Energy flow and transverse energy flow in CASTOR for diffractive events

Outlook

Contemporary CR interaction models (e.g., QGSJET-II):

- seem to work well up to Auger energies
- have serious discrepancies with Pierre Auger data

Model status:

- QGSJET-II:
  - model development finished
  - latest development - Pomeron 'loops': $\Delta X_{\rm max}$<10 g/cm^2; $\Delta N_\mu/N_\mu$<5%
  - in contradiction with Pierre Auger muon excess
- EPOS *(Pierog, ISVHECRI-08)*:
  - current problems understood and corrected
  - new version also predicts high N_μ

Promising framework for a new generation of models - CGC scheme
However, big 'to do' list for CGC people...

LHC data: crucial test for present & future models!!!