Modeling of high energy cosmic ray interactions: selected topics

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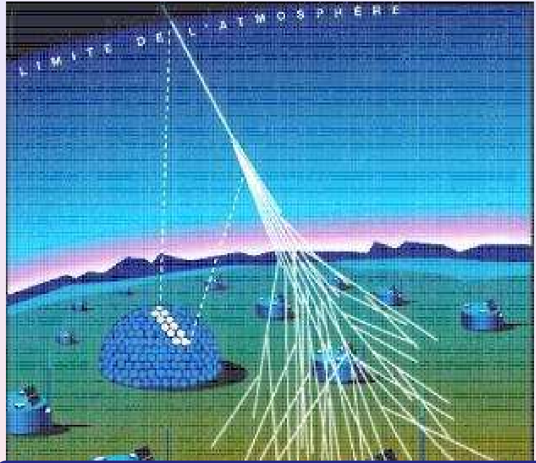
Frankfurt Institute for Advanced Studies

CORSIKA Cosmic Ray Simulation Workshop
Karlsruhe, June 18, 2019

Cosmic ray studies with Extensive Air Shower techniques



Standard practice: use the CORSIKA program for EAS simulations

- backbone of air shower – hadronic cascade
- $\Rightarrow$ hadronic MC event generators

CR interaction models

List of models available in the CORSIKA EAS simulation code

(from T. Pierog, ISVHECRI-2018)

- **Which model for CR ? (alphabetical order)**
  - **DPMJETIII.17-1** by S. Roesler, A. Fedynitch, R. Engel and J. Ranft
  - **EPOS (1.99/LHC)** (from VENUS/NEXUS before) by H.J. Drescher, F. Liu, T. Pierog and K.Werner.
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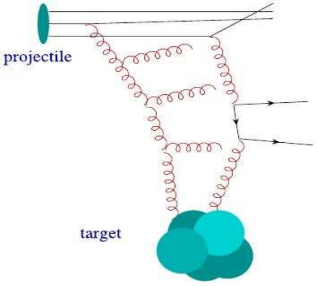
Disclaimer

- current talk: no systematic discussion of the models / comparison of predictions

Qualitative picture for all the models

- QCD-inspired: interaction mediated by parton cascades
- multiple scattering
  (many cascades in parallel)
- real cascades ⇒ particle production
- virtual cascades ⇒ elastic rescattering (momentum transfer)
- generally nonperturbative physics
  ⇒ phenomenological approaches



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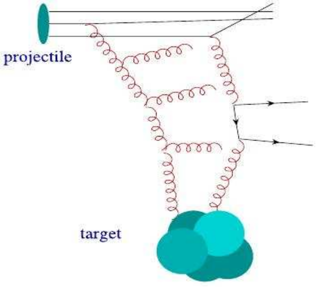

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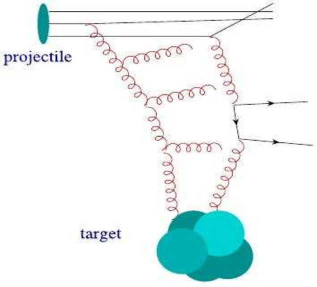

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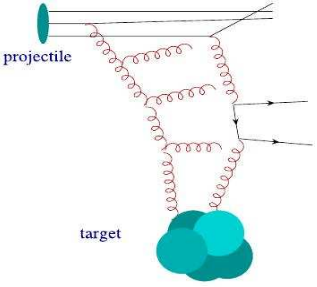

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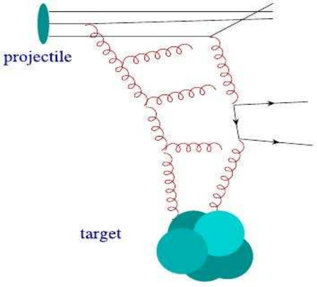

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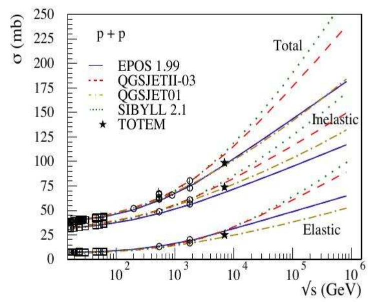
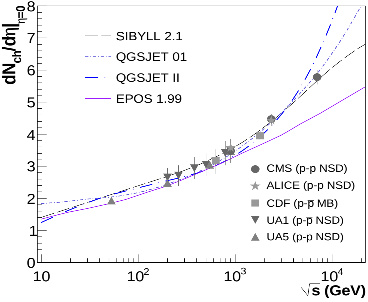
- energy-evolution of the observables (e.g. σ_{pp}^{tot}): due to a larger phase space for cascades to develop
- ⇒ smooth energy-dependence for all the observables!!!

Smooth energy-dependence for σ_{pp}^{tot}, N_{pp}^{ch}, etc.: well confirmed by collider studies, notably, at LHC

E.g. pre-LHC model predictions and experimental data





- $\Rightarrow$ extrapolation to ultra-high energies – now constrained by LHC data (within a particular model approach)

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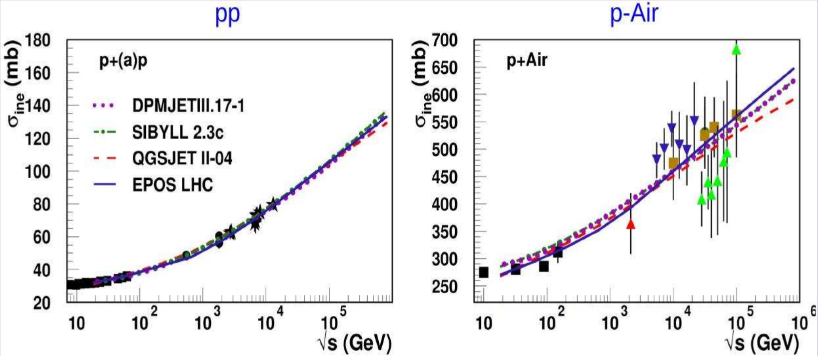
E.g. inelastic cross sections for models tuned to LHC data



[T. Pierog, ISVHECRI-2018]

Phenomenological approaches: “soft” particle production

- nonperturbative soft (small p_t) interactions: successfully treated by Reggeon Field Theory (RFT) *[Gribov, 1967]*
  - Quark-Gluon String Model *[Kaidalov & Ter-Martyrosian, 1982]*
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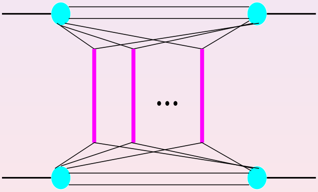

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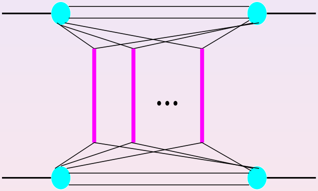

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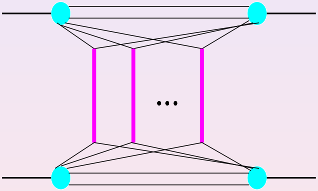

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- particle production: hadronization of quark-gluon strings

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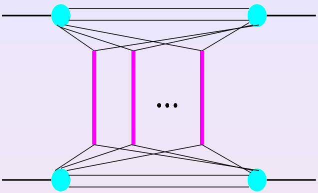

Involves minimal number of adjustable parameters (to describe Pomeron exchange eikonal)

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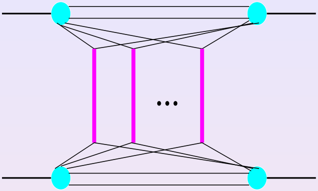

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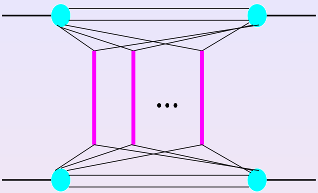

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NB: N of parameters for hadronization procedures depends on the degree of sophistication (types of secondary hadrons included, etc.)

- optionally, one may use external procedures (e.g. ISAJET used by SIBYLL & DPMJET)

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NB: additional parameters needed to describe inelastic diffraction

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- soft Pomerons to describe soft (parts of) cascades $(p_t^2 < Q_0^2)$
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- DGLAP for hard cascades
- taken together: 'general Pomeron'

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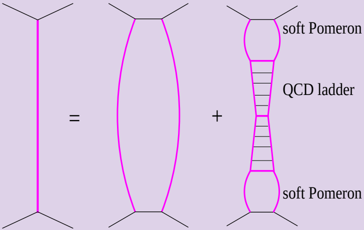

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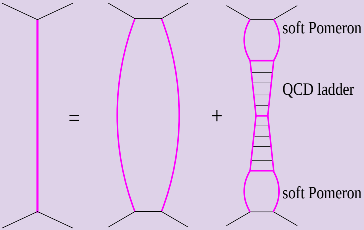

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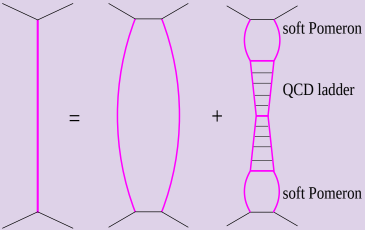

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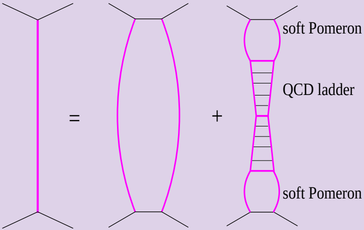

- apart from the Q_0-cutoff, involves 2 more parameters: to describe parton distributions in the soft Pomeron

Phenomenological approaches: hard processes

'Minijet' approach: define (mini-)jet production eikonal independently of soft processes (DPMJET, SIBYLL)

$$
\begin{aligned}
\chi_{pp}^{\mathrm{hard}}(s,b,p_{\mathrm{t,cut}}) &= \sigma_{pp}^{\mathrm{jet}}(s,p_{\mathrm{t,cut}})\, O_{pp}(b) \\
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&\times\; f_{I/p}(x^+,p_{\mathrm{t,cut}}^2)\, f_{J/p}(x^-,p_{\mathrm{t,cut}}^2)
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- allows one to use external PDFs $f_{I/p}(x,Q^2)$
- but: requires additional assumptions on the overlap function $O_{pp}(b)$ $\Rightarrow$ on spacial parton distributions in the proton

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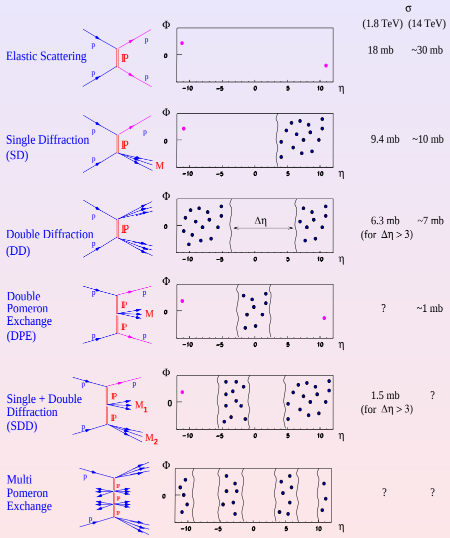
NB: Additional differences between the 'semihard Pomeron' and 'minijet' approaches arise at particle production level

Phenomenological approaches: inelastic diffraction



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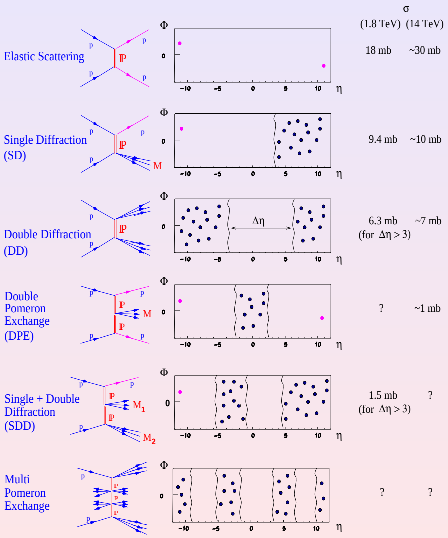

- experimentally: formation of LRG not covered by secondaries
- in many models (e.g. PYTHIA), diffraction is treated independently of ND collisions
- but: microscopically, diffractive treatment is closely related to cross sections & ND particle production (e.g. higher diffraction $\Rightarrow$ smaller σ_{pp}^{inel} & longer multiplicity tails)

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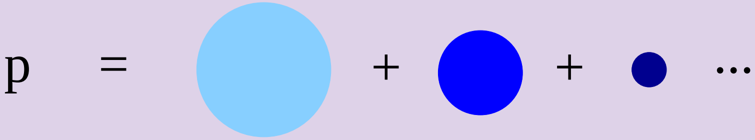
Good-Walker approach: proton is a superposition of a number of elastic scattering eigenstates: $|p\rangle = \sum_i \sqrt{C_i}\,|i\rangle$



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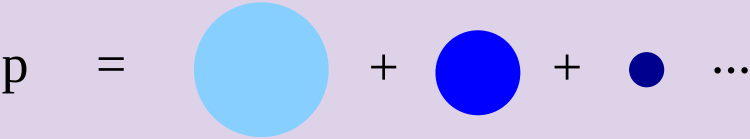

- in pp scattering, those states undergo different absoprtion: $|p\rangle = \sum_i \sqrt{C_i}\,|i\rangle \to \sum_i \sqrt{C_i'}\,|i\rangle = \alpha\,|p\rangle + \beta\,|p^*\rangle$

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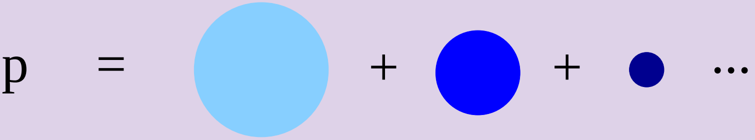

- in pp scattering, those states undergo different absoprtion: $|p\rangle = \sum_i \sqrt{C_i}\,|i\rangle \to \sum_i \sqrt{C_i'}\,|i\rangle = \alpha\,|p\rangle + \beta\,|p^*\rangle$
- $\Rightarrow$ treatment involves interaction eikonals $\chi^{\rm tot}_{pp(ij)}(s,b,Q_0^2)$ for different combinations of such states, e.g.

$$\sigma^{\rm inel}_{pp}(s,b) = \sum_{i,j} C_i\,C_j \int d^2b \, \left[1 - e^{-2\chi^{\rm tot}_{pp(ij)}(s,b)}\right]$$

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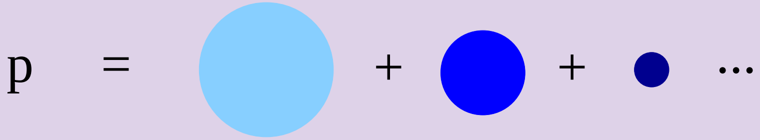

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  - 'semihard Pomeron': own values $\gamma_{p(i)}$ & $R^2_{p(i)}$ for each state $|i\rangle$
  - 'minijet' approach: one would need partial generalized parton distributions (GPDs) $G_p^{(i)}(x,b,Q^2)$ for all the states

Phenomenological approaches: nonlinear effects

- Problem: for realitic PDFS, both cross sections & multiplicity of produced hadrons rise too steeply with energy

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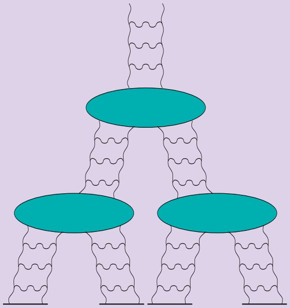
- parton cascades strongly overlap and interact with each other
- $\Rightarrow$ shadowing effects (slower rise of parton density)
- saturation: parton production compensated by fusion of partons



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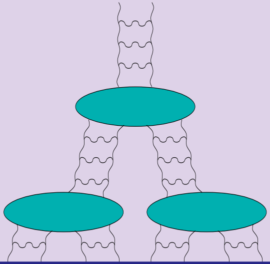
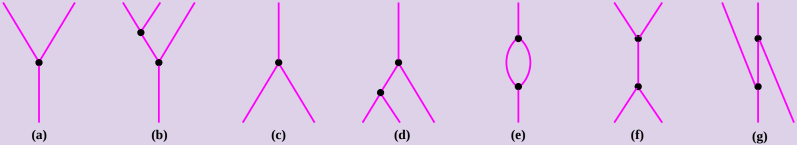


In QGSJET-II: Pomeron-Pomeron interactions (scattering of intermediate partons off the proj./target hadrons & off each other)

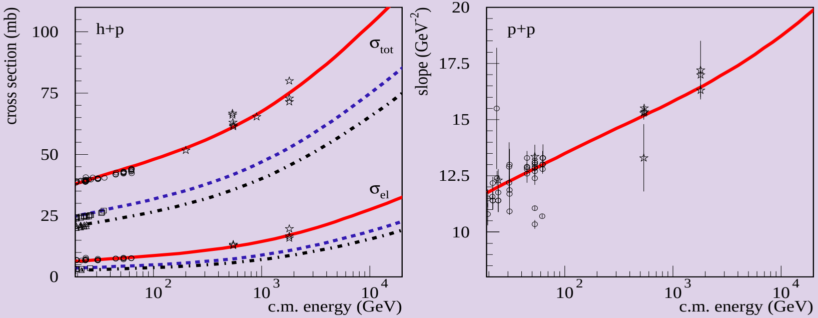


thick lines = Pomerons = 'elementary' parton cascades

- contributions resummed to all orders (sign-altering series)

QGSJET-II-04: consistent description of $\sigma_{tot/el}$ & F_2

E.g., $\sqrt{s}$-dependence of $\sigma^{tot/el}_{pp/\pi p/Kp}$ for realistic transverse profiles



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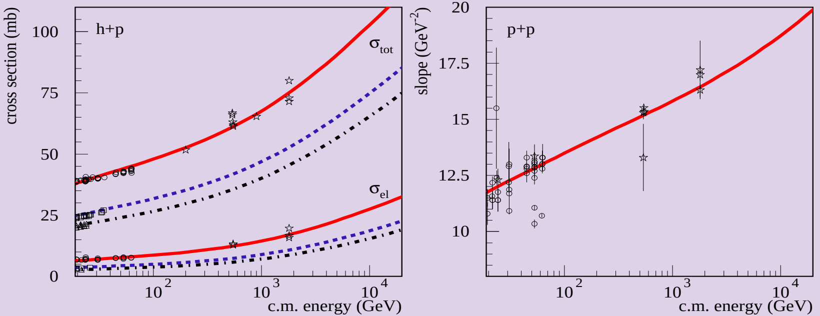
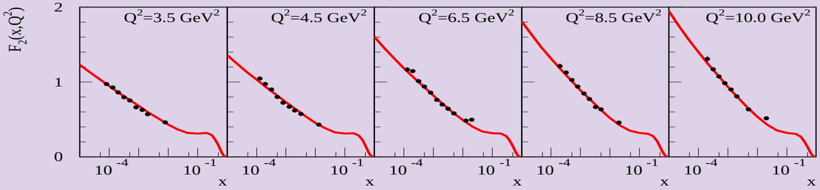


For PDFs fitting HERA data



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This is nontrivial, not being related to parton saturation

- e.g. factorizable graphs: provide corrections both to $\sigma_{tot/el}$ & PDFS
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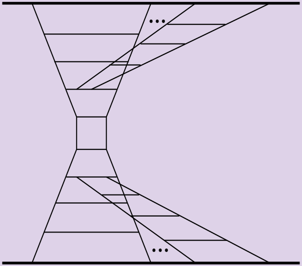

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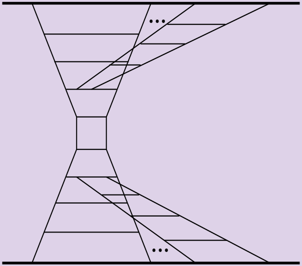

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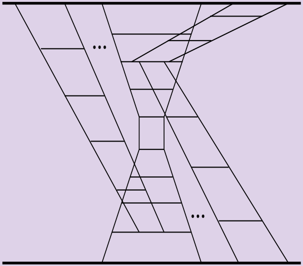

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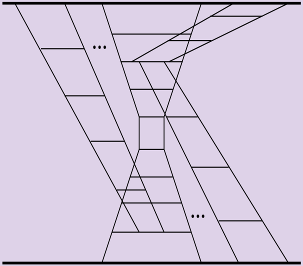

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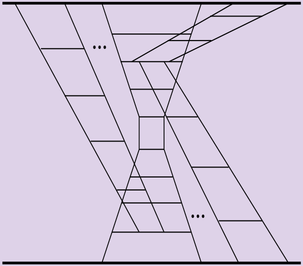

EPOS model: qualitatively similar approach but based on effective treatment of lowest order enhanced diagrams

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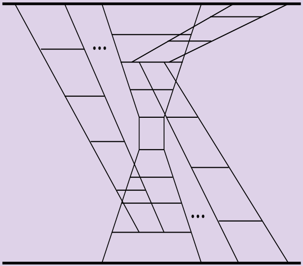

EPOS model: qualitatively similar approach but based on effective treatment of lowest order enhanced diagrams

In other models: energy dependent p_{t}-cutoff for jet production, $p_{\mathrm{t,cut}} = p_{\mathrm{t,cut}}(s)$

- is it reasonable and what kind of physics is behind?

Phenomenological approaches: higher twist (HT) effects

Any model should respect collinear factorization of pQCD

$$\sigma_{pp}^{\rm jet}(s,p_{\rm t,cut}) = \sum_{I,J=q,\bar{q},g} \int_{p_{\rm t}>p_{\rm t,cut}} dp_t^2 \int dx^+ \, dx^- \, \frac{d\sigma_{IJ}^{2\to 2}(x^+x^-s,p_t^2)}{dp_t^2} \times f_{I/p}(x^+,M_{\rm F}^2)\, f_{J/p}(x^-,M_{\rm F}^2)$$

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- ideally, p_t-cutoff should be just a technical parameter, without a strong impact on the results
- $\Rightarrow$ some important perturbative mechanism seems missing

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Collinear factorization: valid at leading twist (up to $1/Q^n$ terms)

- for small p_t^2, power corrections can be important (being suppressed as $1/(p_t^2)^n$)

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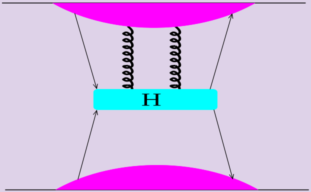

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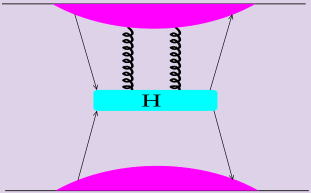

QGSJET-III: phenomenological implementation of the mechanism

- with HT effects: dependence on Q_0-cutoff strongly reduced *[SO & Bleicher, 2019]*
  - now: twice smaller cutoff for hard processes ($Q_0^2 = 1.5$ GeV^2)

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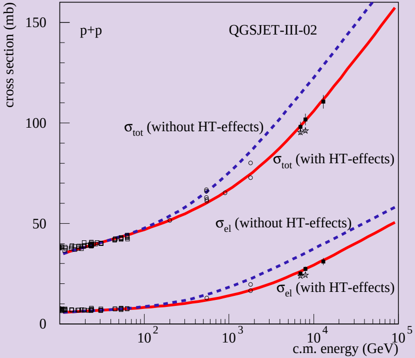
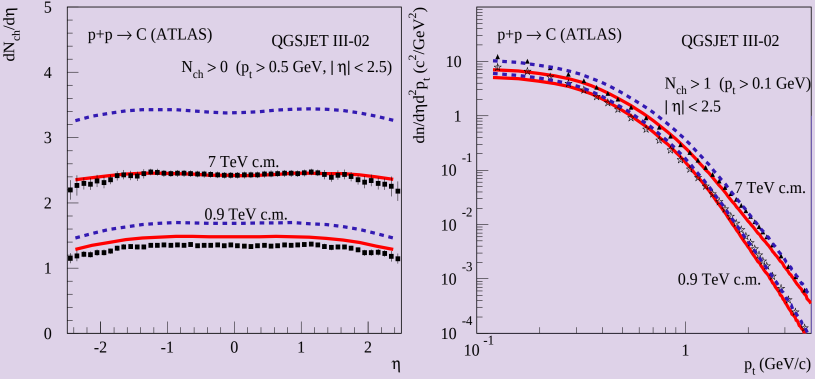
Impact on $\sqrt{s}$-dependence of $\sigma_{pp}^{tot/el}$

- significant corrections for total/elastic cross sections
  - start to be important already at $\sqrt{s} \sim 1$ TeV



Phenomenological approaches: higher twist (HT) effects

Impact on charged hadron multiplicity & p_t-spectra



- reduction of N_{ch}: stronger at higher energies
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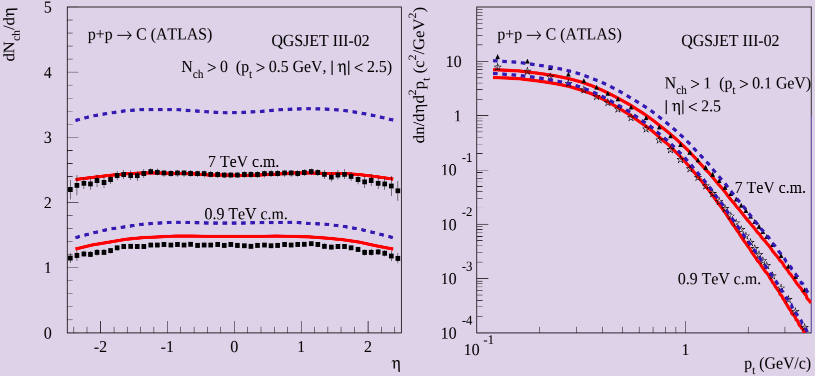

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Results for air showers: preliminary and close to QGSJET-II-04

- e.g. difference for N_μ – at percent level
- shower maximum shifted upwards by $\simeq 10$ g/cm^2 at 10^{19} eV

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NB: qualitatively, the approach mimics an energy dependent p_t-cutoff for jet production

- suppresses emission of jets of moderately small p_t
- has no impact on PDFs $\Rightarrow$ not related to parton saturation

Current approaches to the treatment of hadronic collisions: rather involved but largely phenomenological

- $\Rightarrow$ no wonder models differ from each other
- however: predictions now strongly constrained by LHC data

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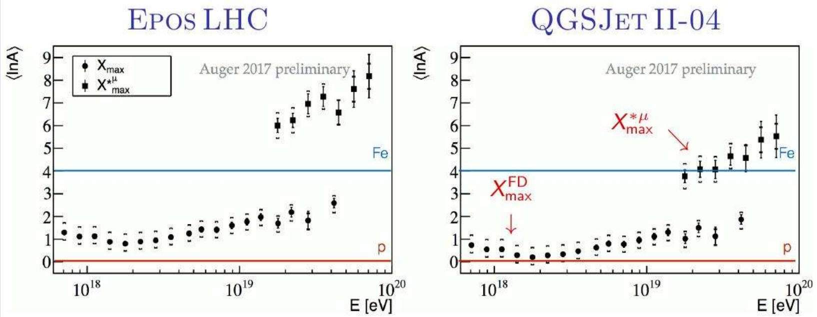
- NB: extrapolation from pp to π-air and K-air is rather constrained in a particular approach
  - is it feasible to discriminate between the approaches?
  - do some/all models do it right?
- current indications from UHECR data:
  treatment of pion-air collisions may be deficient

Interpreting PAO data on $X_{\max}$ & $X^{\mu}_{\max}$: not self-consistent

How to change models to 'marry' $X_{\max}$ & $X^{\mu}_{\max}$ composition-wise?



[R. Prado, ISVHECRI-2018]

- the two sets of data should overlap in terms of $\langle \ln A \rangle$
  - for $1 \leq A \leq 56$!

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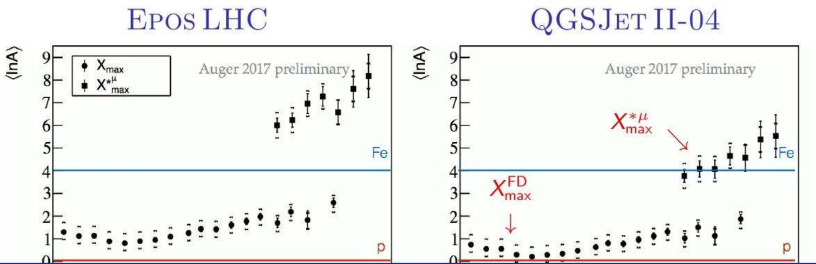

Acient Greek wisdom may help...

- change a model to modify $X_{\max}$ prediction:
  - $X^{\mu}_{\max}$ will move in the same direction!
- or vice versa

Modifying CR interaction models: which way to go?

Changing the treatment of $p-$air interactions?

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- $\Rightarrow$ not a way to reach a consistency

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Changing the treatment of $\pi-$air collisions ('Achilles & Tortoise')

- e.g., $\sigma^{\rm inel}_{\pi-{\rm air}}$, $\sigma^{\rm diffr}_{\pi-{\rm air}}$, $K^{\rm inel}_{\pi-{\rm air}}$
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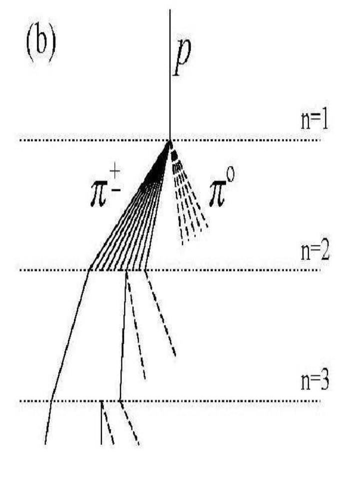

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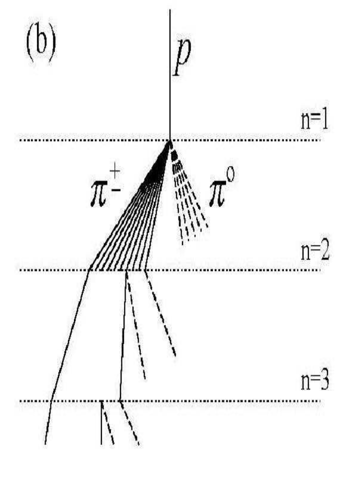

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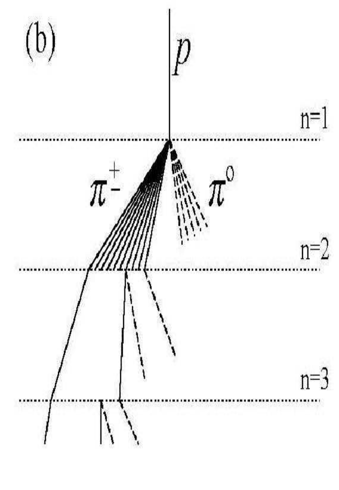
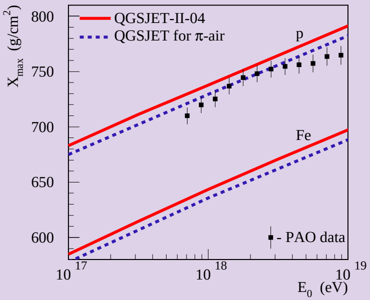
- affects every step in the multi-step hadron cascade
  - $\Rightarrow$ cumulative effect on $X^{\mu}_{\rm max}$
- but: only the first few steps in the cascade impact $X_{\rm max}$
  - after few steps, most of energy channelled into e/m cascades
  - $\Rightarrow$ much weaker effect on $X_{\rm max}$

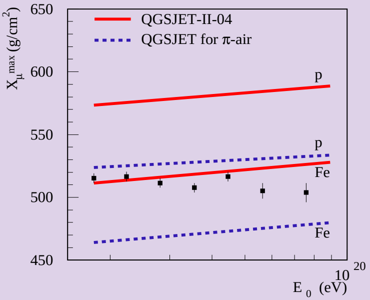


Modifying CR interaction models: which way to go?

E.g., replacing QGSJET-II by the old QGSJET, for $\pi-$air collisions

- $\Rightarrow$ higher $\sigma^{\rm inel}_{\pi-\rm air}$, larger $N^{\rm ch}_{\pi-\rm air}$ & $K^{\rm inel}_{\pi-\rm air}$



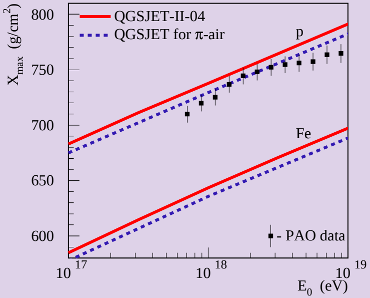


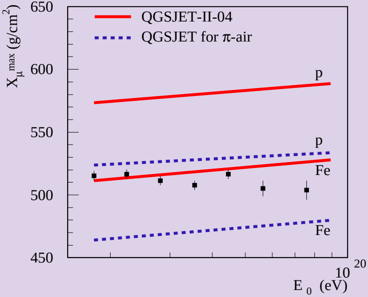
- $\Rightarrow$ nearly self-consistent interpretation

Modifying CR interaction models: which way to go?

E.g., replacing QGSJET-II by the old QGSJET, for $\pi-$air collisions

- $\Rightarrow$ higher $\sigma^{\rm inel}_{\pi-{\rm air}}$, larger $N^{\rm ch}_{\pi-{\rm air}}$ & $K^{\rm inel}_{\pi-{\rm air}}$





- $\Rightarrow$ nearly self-consistent interpretation

NB: higher $\sigma^{\rm inel}_{\pi-{\rm air}}$ & $N^{\rm ch}_{\pi-{\rm air}}$ with current models – very challenging

- old QGSJET – outdated; known to overestimate particle production in $\pi-$air collisions
- needed: drastic increase of gluon density in pions?!

Outlook

1. Current approaches to the treatment of hadronic collisions: involved but largely phenomenological
   - predictions now strongly constrained by LHC data
2. Present differences for EAS predictions:
   largely dominated by model differences for pion-air collisions
3. UHECR data indicate serious deficiences in the current treatments
4. Required modifications of the model predictions: challenging