QGSJET-III: physics, hadron production, and applications for high energy CR studies

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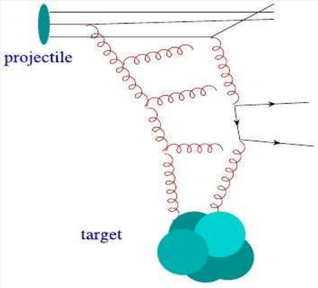
Qualitative picture for hadronic MC event generators

- 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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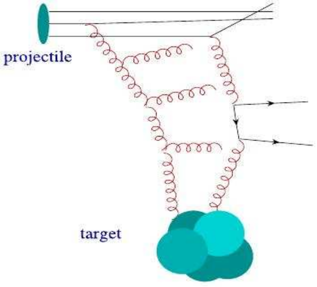

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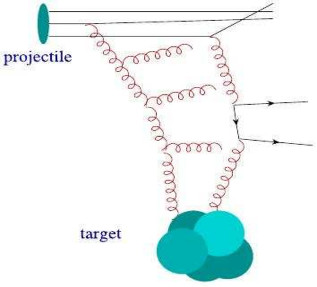

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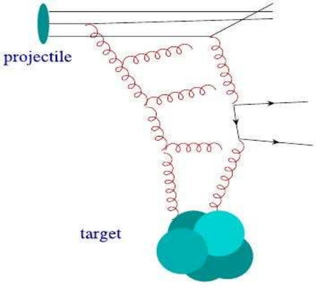

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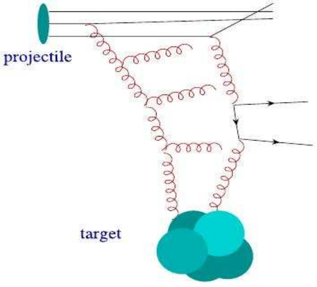

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- different hadrons (nuclei) ⇒ different initial conditions (parton Fock states) but same mechanism
- energy-evolution of the observables (e.g. σ_{pp}^{tot}): due to a larger phase space for cascades to develop
- ⇒ smooth energy-dependence for all the observables

Soft interactions & Reggeon Field Theory (RFT)

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

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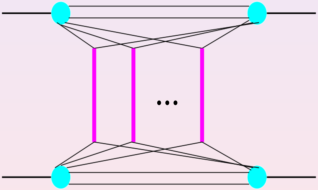

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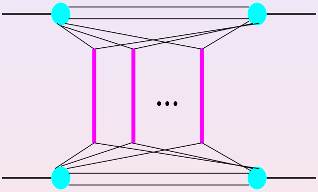

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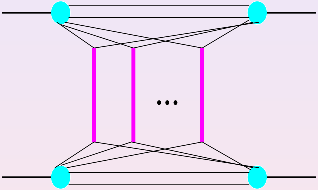

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- particle production: hadronization of quark-gluon strings

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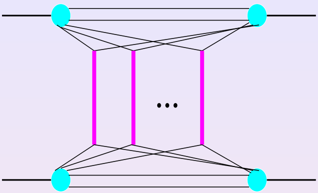

Involves minimal number of adjustable parameters
(to describe Pomeron exchange eikonal $\chi^{\mathbb{P}}_{pp}(s,b) = \mathrm{Im} f^{\mathbb{P}}_{pp}(s,b)$)

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- Pomeron intercept $\alpha_{\mathbb{P}}(0) > 1 \Rightarrow$ energy rise of parton density
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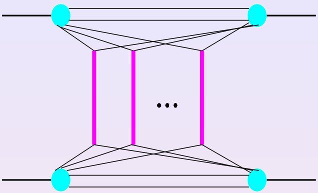

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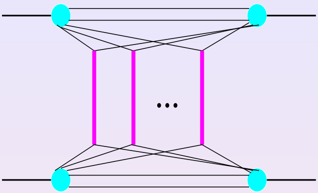

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NB: N of parameters for hadronization procedures depends on the degree of sophistication (types of secondary hadrons included, etc.)

- optionally, one may use external procedures (e.g. ones tuned to the data on e^+e^- annihilation into hadrons)

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NB: additional parameters needed to describe inelastic diffraction

- in QGSM: shower enhancement coefficients (C_{pp}, $C_{\pi p}$, C_{Kp})

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- Alternative: treat hard processes in the RFT framework
  - QGSJET *[Kalmykov, SO & Pavlov, 1997]*
  - neXus *[Drescher et al., 2001]*
  - EPOS *[Werner et al., 2006; Pierog et al., 2015]*

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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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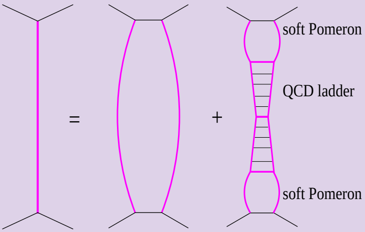

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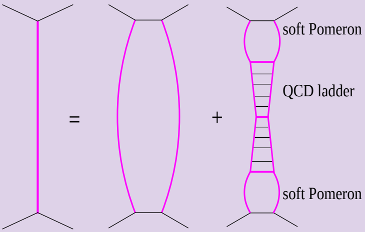

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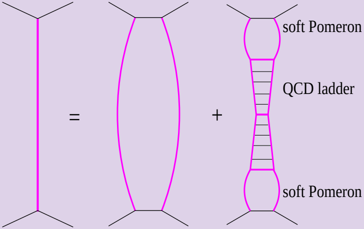

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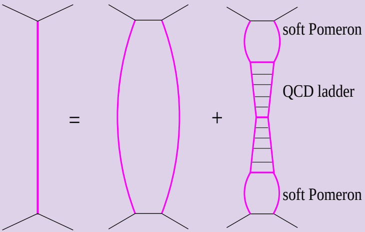
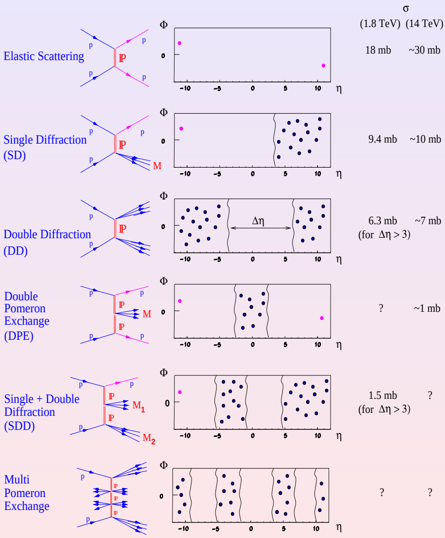


- apart from the Q_0-cutoff, involves 2 more parameters:
  to describe parton distributions in the soft Pomeron

Inelastic diffraction: Good-Walker approach and beyond



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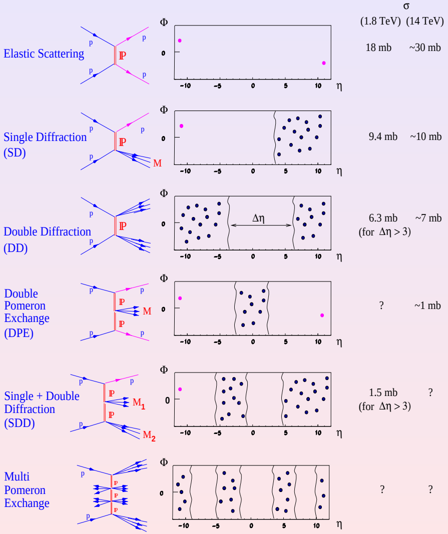

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- in many models (e.g. PYTHIA), diffraction is treated independently of ND collisions
- but: microscopically, diffractive treatment is closely related to cross sections & ND particle production (e.g. higher diffraction $\Rightarrow$ smaller σ_{pp}^{inel} & longer multiplicity tails)

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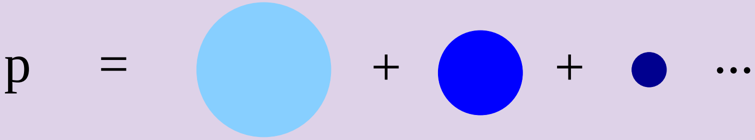

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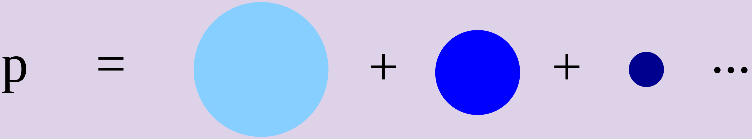

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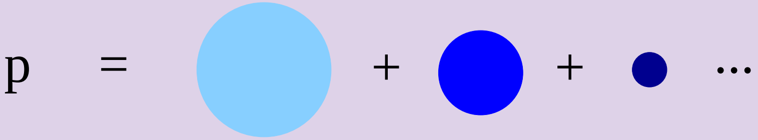

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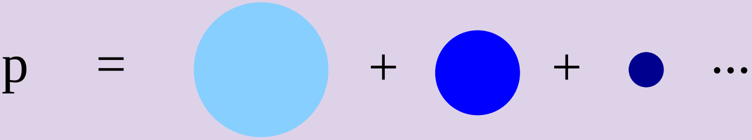

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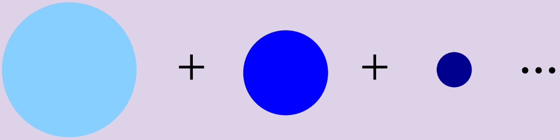

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  - for each state $|i\rangle$: its own size & parton density
  - should momentum sum rule be satisfied for each state $|i\rangle$ separately: $\sum_{I=q,\bar{q},g} \int dx\, x\, f_{I/p(i)}(x, Q^2) = 1$?!

QGSJET-II: RFT treatment of nonlinear effects *[SO, 2011]*

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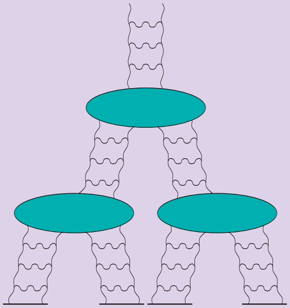
This signals the need to account for nonlinear interaction effects

When parton density becomes high (high energy and/or small b):

- 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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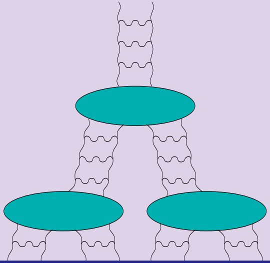
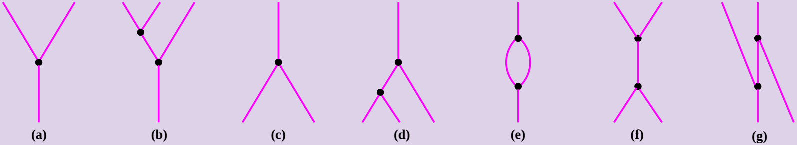


In QGSJET-II: Pomeron-Pomeron interactions (scattering of intermediate partons off the proj./target hadrons & off each other)

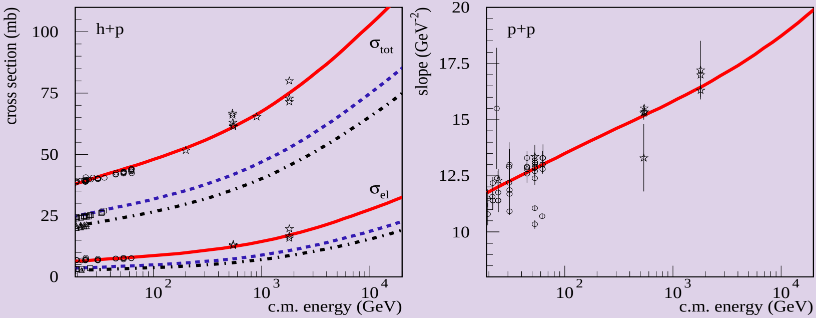


thick lines = Pomerons = 'elementary' parton cascades

- 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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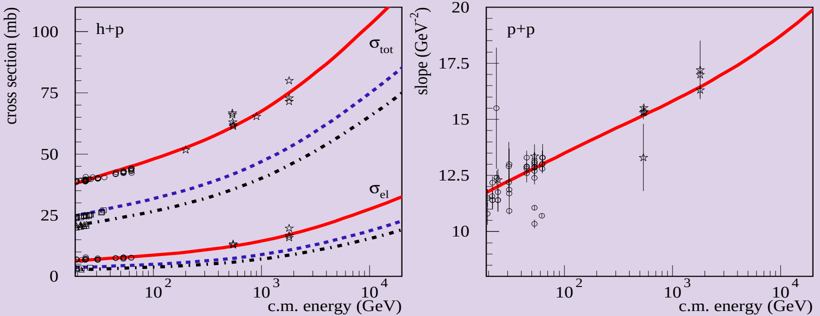
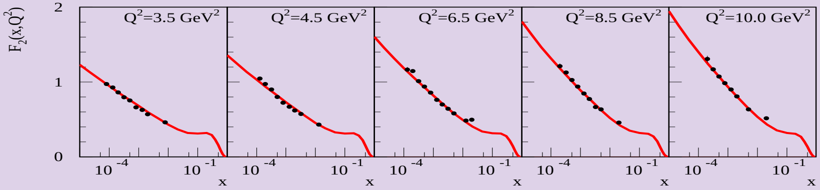


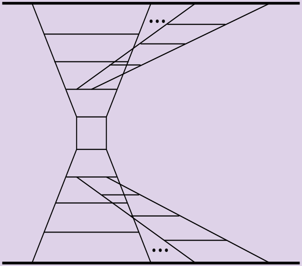
and for PDFs fitting HERA data...



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

This is nontrivial: not related to parton saturation!

- e.g. factorizable graphs: provide corrections both to $\sigma_{tot/el}$ & PDFS
- they describe parton rescattering off the parent hadrons
- but they don't play the major role



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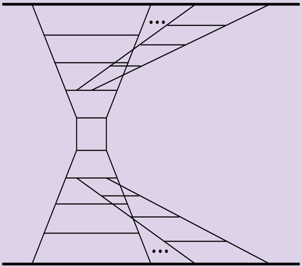

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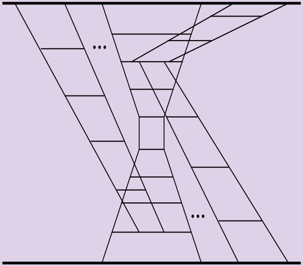

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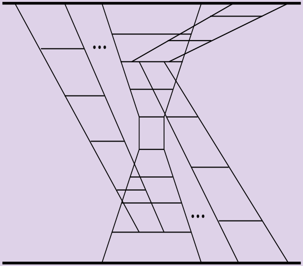

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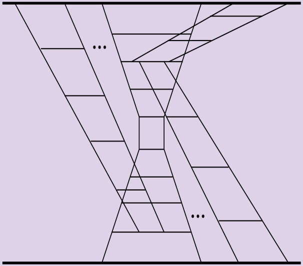

Many other models: energy dependent p_t-cutoff for jet production, $p_{t,cut} = p_{t,cut}(s)$

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

QGSJET-III: treatment of 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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  - but: pQCD should work down to $Q_0 \sim 1$ GeV?!
- ideally, p_t-cutoff should be just a technical parameter, without a strong impact on the results
- $\Rightarrow$ some important perturbative mechanism seems missing

Phenomenological approaches: higher twist (HT) effects

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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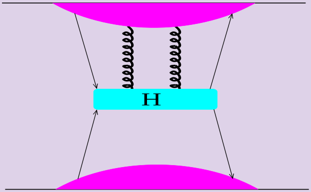
  - hard scattering involves any number of additional gluon pairs



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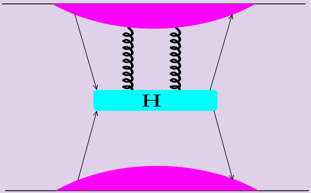

QGSJET-III: phenomenological implementation of the mechanism

- with HT effects: dependence on Q_0-cutoff strongly reduced *[SO & Bleicher, 2019]*
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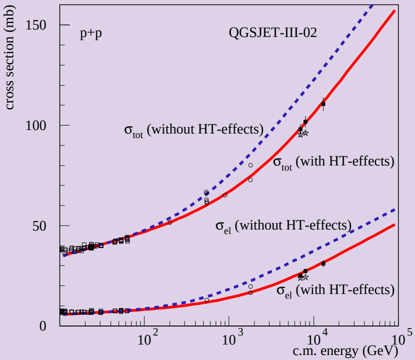
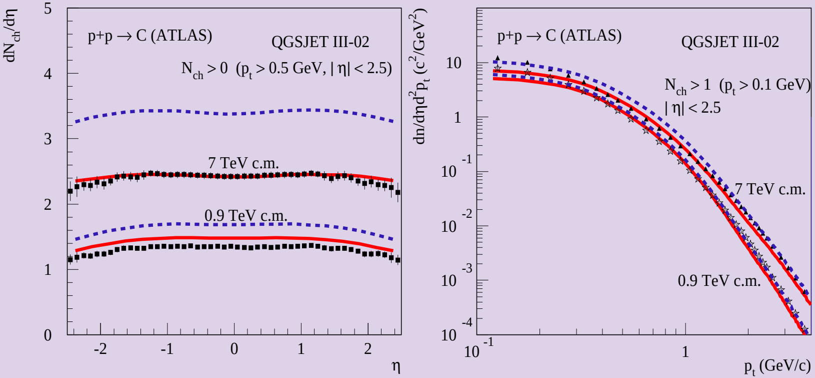
Impact on $\sqrt{s}$-dependence of $\sigma_{pp}^{tot/el}$

- 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 $N_{\rm ch}$: stronger at higher energies
- mostly for moderately small p_t:
  the effect fades away for increasing p_t ($\propto 1/p_t^2$)

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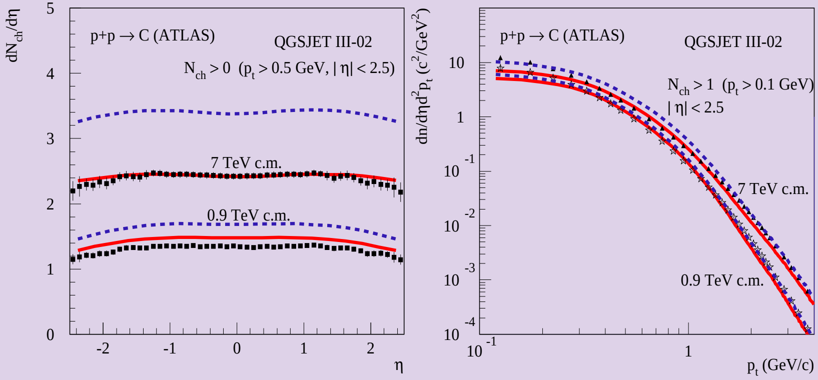

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Results for air showers: preliminary and close to QGSJET-II-04

- e.g. difference for N_μ – at percent level

Phenomenological approaches: higher twist (HT) effects

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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

QGSJET-III: number of adjustable parameters

- basic treatment (pp, πp, Kp): 15
  (soft & hard interactions; low mass diffraction)
- nonlinear effects (Pomeron-Pomeron interactions): 1
- higher twist effects: 1
- hadronization parameters: < 20

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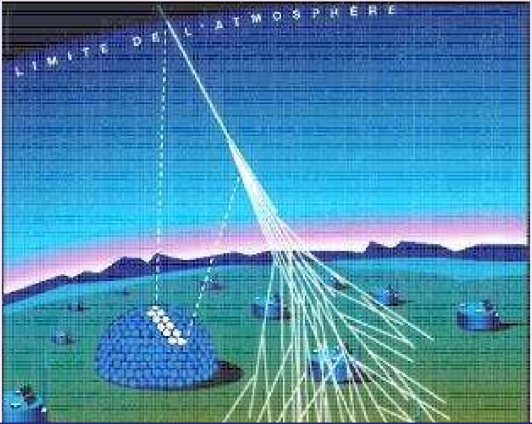
Generally: present models of hadronic collisions – rather involved but largely phenomenological

- $\Rightarrow$ no wonder models differ from each other
- however: predictions now strongly constrained by LHC data
  (using a particular model framework)

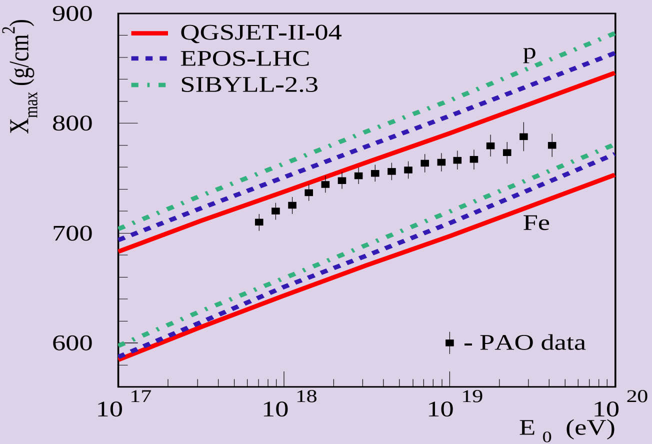
Air shower characteristics & hadronic interactions



CR composition studies – most dependent on interaction models

- e.g. predictions for $X_{\max}$: on the properties of the primary particle interaction ($\sigma^{\text{inel}}_{p-\text{air}}$, $\sigma^{\text{diffr}}_{p-\text{air}}$, $K^{\text{inel}}_{p-\text{air}}$)
- predictions for muon density: on secondary particle interactions (cascade multiplication); mostly on $N^{\text{ch}}_{\pi-\text{air}}$

Why different model predictions for $X_{\max}$?

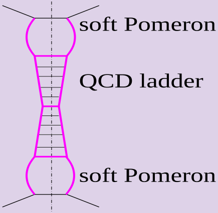


- $\sigma^{\rm inel}_{p-{\rm air}}$ – constrained by LHC studies of *pp* collisions
- uncertainties for $\sigma^{\rm diffr}_{p-{\rm air}}$: small impact ($< 10$ g/cm^2) *[SO, 2014]*
- what about $K^{\rm inel}_{p-{\rm air}}$?

Structure of constituent parton Fock states

Initial state emission (ISE) of partons doesn't stop at the Q_0-cutoff

- it is extended into nonperturbative region by the soft Pomeron
- this changes the structure of constituent parton Fock states
  (represented by end-point partons in ISE)
    - in QGSJET(-II): described by Reggeon asymptotics ($\propto x^{-\alpha_{\mathbb{R}}(0)}$, $\alpha_{\mathbb{R}}(0) \simeq 0.5$)



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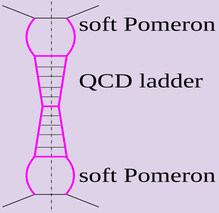

- $\Rightarrow$ observables consequences:
    - softer forward spectra (energy sharing between constituent partons)
    - forward & central particle production - strongly correlated (more activity in central detectors $\Rightarrow$ larger Fock states $\Rightarrow$ softer forward spectra)

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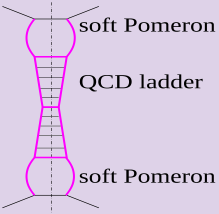

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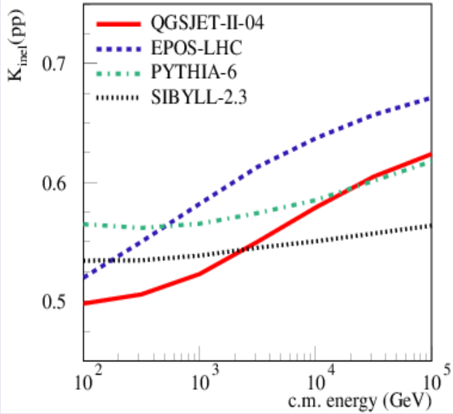
Alternative (SIBYLL & PYTHIA): no "soft preevolution"

- $\Rightarrow$ multiple scattering has small impact on forward spectra
  - Feynman scaling for forward production
  - forward & central production – decoupled from each other

Structure of constituent parton Fock states

Of importance for cosmic ray studies: $\sqrt{s}$-dependence of $K_{pp}^{\rm inel}$



- SIBYLL & PYTHIA: weak energy dependence of the nucleon 'inelasticity' (for increasing $\sqrt{s}$, mostly rise of central production)
- smaller $K^{\rm inel}$ $\Rightarrow$ stronger 'leading particle' effect
- $\Rightarrow$ slower development of CR-induced air showers

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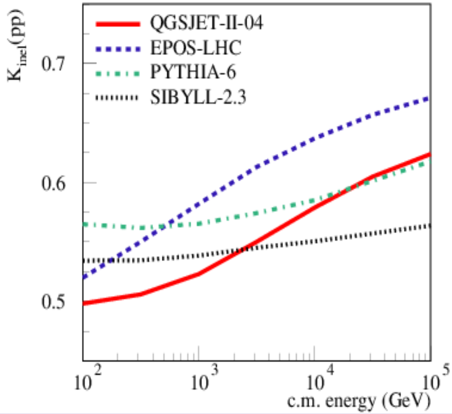

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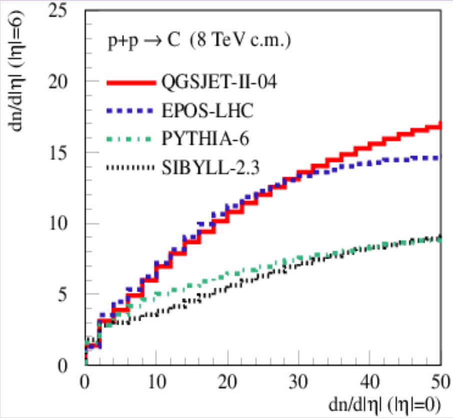
Structure of constituent parton Fock states

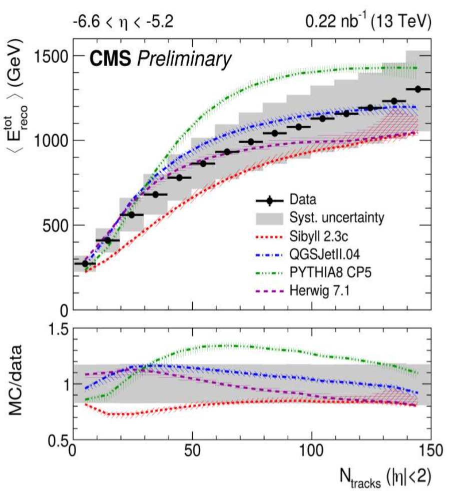
Crucial test: cross-correlation of $dN^{ch}_{pp}/d|\eta|$ at $\eta = 0$ and $\eta = 6$



- strong correlation for QGSJET-II & EPOS (apart from the tails of the N^{ch} distributions)
- twice weaker correlation for SIBYLL & PYTHIA

Structure of constituent parton Fock states

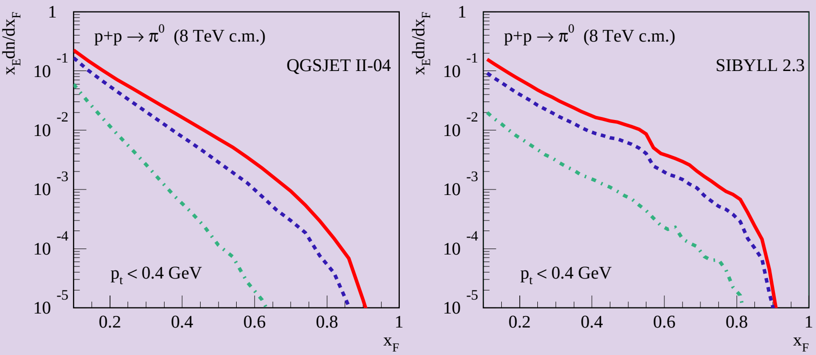
Now measured: correlation of forward energy (in CASTOR) with central activity (N of charged particle tracks) in CMS



- most important – first 3 bins ($N_{\text{tracks}} < 30$)
- very puzzling results: intermediate between QGSJET-II and SIBYLL?!
  - decisive discrimination not possible?

Further discrimination: forward hadrons by LHCf & ATLAS

Forward π^0 spectra in LHCf for different ATLAS triggers (≥ 1, 6, 20 charged hadrons of $p_t > 0.5$ GeV & $|\eta| < 2.5$)



Compare QGSJET-II-04 (left) to SIBYLL 2.3 (right)

- enhanced multiple scattering $\Rightarrow$ softer pion spectra
  - $\Rightarrow$ violation of limiting fragmentation
- nearly same spectral shape for all the triggers
  - $\Rightarrow$ perfect limiting fragmentation

What next?

What about other differences for EAS predictions?

- now largely dominated by model differences for pion-air (kaon-air) collisions *[SO & Bleicher, 2016]*

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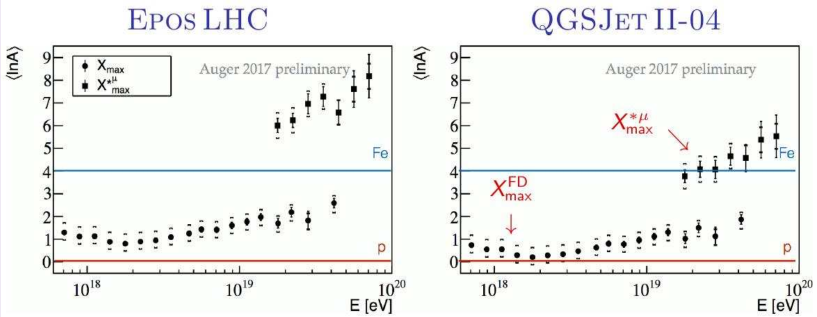
- NB: extrapolation from pp to π-air and K-air is rather constrained in a particular approach
  - do some/all models do it right?
- current indications from UHECR data ($X_{\rm max}$ & $X^{\mu}_{\rm max}$): treatment of pion-air collisions may be deficient (extra slides)

Extra slides

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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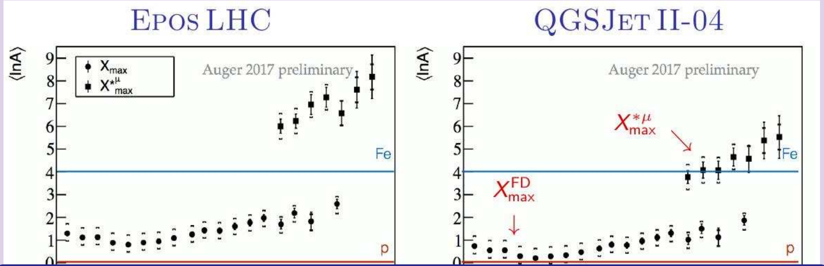

Acient Greek wisdom may help...

- 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?

- this impacts only the initial stage of EAS development
  - further cascade development – dominated by pion-air collisions

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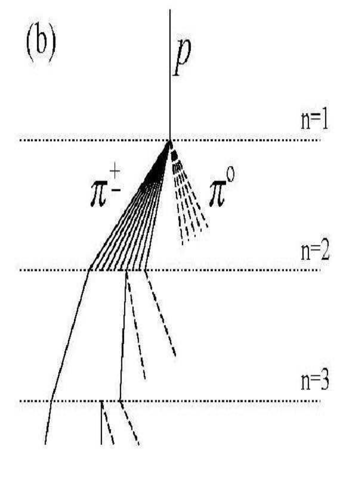
  - $\Rightarrow$ same effect on $X_{\max}$ and $X^{\mu}_{\max}$
- $\Rightarrow$ not a way to reach a consistency

Modifying CR interaction models: which way to go?

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

- e.g., $\sigma^{\rm inel}_{\pi-{\rm air}}$, $\sigma^{\rm diffr}_{\pi-{\rm air}}$, $K^{\rm inel}_{\pi-{\rm air}}$
  - $\equiv$ making special assumptions concerning the pion structure



Modifying CR interaction models: which way to go?

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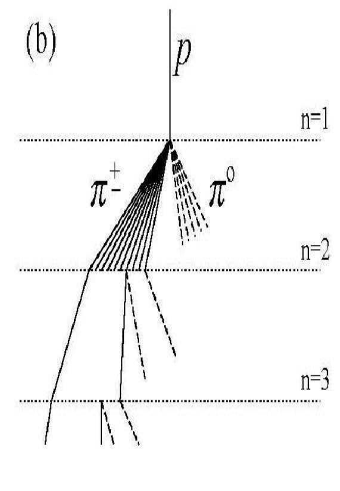

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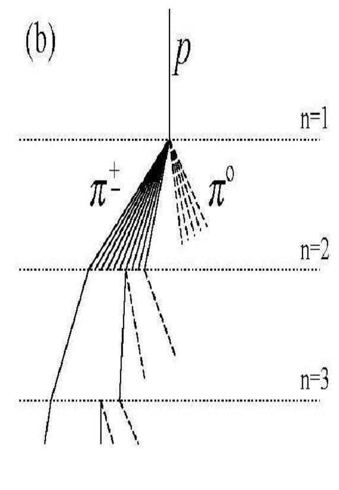
- but: only the first few steps in the cascade impact $X_{\rm max}$
  - after few steps, most of energy channelled into e/m cascades
  - $\Rightarrow$ much weaker effect on $X_{\rm max}$



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

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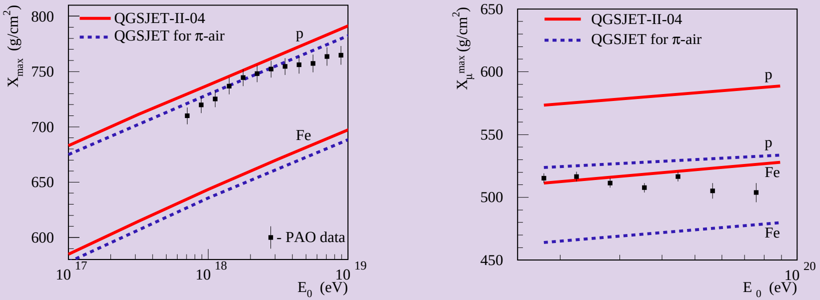

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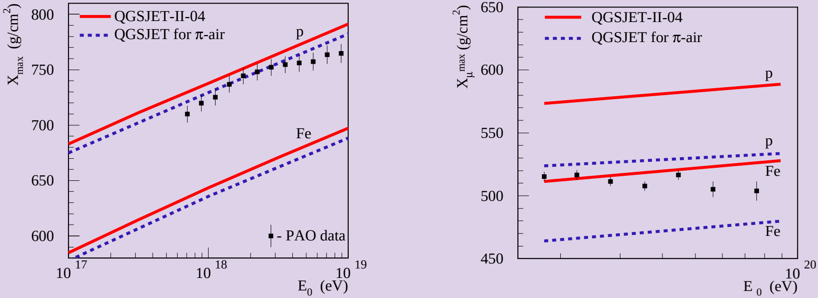

- $\Rightarrow$ nearly self-consistent interpretation

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?!