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

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ISCRA-2019
Moscow, June 25-28, 2019
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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- energy-evolution of the observables (e.g. $\sigma_{p\bar{p}}^{\text{tot}}$): 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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\sigma_{pp}^{\text{tot}}(s, b) = 2 \int d^2b \left[ 1 - e^{-\chi_{pp}^p(s,b)} \right]
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\[ s_{\text{tot}}^{pp}(s, b) = \frac{2}{Z^2 b} \left[ 1 - e^{-c_{P}^{pp}(s, b)} \right] \]
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Particle production: hadronization of quark-gluon string

Involves minimal number of adjustable parameters
(to describe Pomeron exchange eikonal \( \chi_{pp}^{P}(s, b) = \text{Im} f_{pp}^{P}(s, b) \))

\[ \chi_{pp}^{P}(s, b) = \frac{\gamma_p^2 s^{\alpha_{P}(0)-1}}{2R_p^2 + \alpha'_{P}(0) \ln s} \exp \left( \frac{-b^2 / 4}{2R_p^2 + \alpha'_{P}(0) \ln s} \right) \]

- Pomeron intercept \( \alpha_{P}(0) > 1 \) ⇒ energy rise of parton density
- Pomeron slope \( \alpha'_{P}(0) \) ⇒ parton transverse diffusion
- \( R_p \) characterizes proton size & \( \gamma_p \) – soft interaction strength
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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 $e^+ e^- \text{ annihilation into hadrons}$)
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- generalization for \( p A \) & \( A A \) collisions – parameter free

NB: additional parameters needed to describe inelastic diffraction

- in QGSM: shower enhancement coefficients (\( C_{pp}, C_{\pi p}, C_{K p} \))
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average parton $p_t$ in the cascades should rise with energy ($k_t$-diffusion)
  $\Rightarrow$ energy-dependent Pomeron intercept $\alpha_P(s)$?
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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]
Alternative: treat hard processes in the RFT framework


- soft Pomerons to describe soft (parts of) cascades \((p_t^2 < Q_0^2)\)
  - \(\Rightarrow\) transverse expansion governed by the Pomeron slope
- DGLAP for hard cascades
- taken together: 'general Pomeron'
  \[
  \chi_{pp}^{\text{tot}}(s, b, Q_0^2) = \chi_{pp}^{\text{P soft}}(s, b) + \chi_{pp}^{\text{P semihard}}(s, b, Q_0^2)
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  \]
- 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

- Experimentally: formation of LRG not covered by secondaries
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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 ⇒ smaller $\sigma_{pp}^{inel}$ & longer multiplicity tails)
Good-Walker approach: proton is a superposition of a number of elastic scattering eigenstates: \( |p⟩ = \sum_i \sqrt{C_i} |i⟩ \)
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\[ p = \frac{\text{in } pp \text{ scattering, those states undergo different absorption:}}{\text{}} \]

$|p\rangle = \sum_i \sqrt{C_i} |i\rangle \rightarrow \sum_i \sqrt{C'_i} |i\rangle = \alpha |p\rangle + \beta |p^*\rangle$
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\[ p = + + \ldots \]

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\[ \Rightarrow \] treatment involves interaction eikonals \( \chi_{pp(ij)}^{\text{tot}}(s, b, Q^2) \) for different combinations of such states, e.g.

\[
\sigma_{pp}^{\text{inel}}(s, b) = \sum_{i,j} C_i C_j \int d^2 b \left[ 1 - e^{-2\chi_{pp(ij)}^{\text{tot}}(s,b)} \right]
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for each state \( |i\rangle \): its own size & parton density
Good-Walker approach: proton is a superposition of a number of elastic scattering eigenstates: \( |p\rangle = \sum_i \sqrt{C_i} |i\rangle \)

\[
p = \begin{tikzpicture}
  \draw[fill=blue!20] (0,0) circle (1cm);
  \draw[fill=blue!60] (2,0) circle (0.5cm);
  \draw[fill=blue!80] (4,0) circle (0.3cm);
  \draw[fill=blue!90] (6,0) circle (0.2cm);
  \end{tikzpicture}
\]

- In \( pp \) scattering, those states undergo different absorption:
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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:
  \[
  \sum_{I=q, \bar{q}, g} \int dx x f_{I/p(i)}(x, Q^2) = 1?!
  \]
Problem: for realistic PDFs, both cross sections & multiplicity of produced hadrons rise too steeply with energy
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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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- saturation: parton production

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)
E.g., $\sqrt{s}$-dependence of $\sigma_{\text{tot/el}}^{\text{pp/\pi p/Kp}}$ for realistic transverse profiles
QGSJET-II-04: consistent description of $\sigma_{\text{tot/el}}$ & $F_2$

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and for PDFs fitting HERA data...
This is nontrivial: not related to parton saturation!

- e.g. factorizable graphs: provide corrections both to $\sigma_{\text{tot/el}}$ & PDFS
- they describe parton rescattering off the parent hadrons
- but they don’t play the major role
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  rescattering off the partner hadrons
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Many other models: energy dependent $p_t$-cutoff for jet production, $p_{t,\text{cut}} = p_{t,\text{cut}}(s)$

- 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

\[
\sigma_{pp}^{jet}(s,p_t,\text{cut}) = \sum_{I,J=q,\bar{q},g} \int_{p_t>p_{t,\text{cut}}} dp_t^2 \int dx^+ dx^- \frac{d\sigma_{IJ}^{2-2}(x^+ x^- s, p_t^2)}{dp_t^2} \\
\times f_I/p(x^+, M_F^2) f_J/p(x^-, M_F^2)
\]

\[\Rightarrow \sigma_{pp}^{jet}(s, Q_0^2) \propto \frac{1}{Q_0^2} s^{\Delta_{\text{eff}}} , \Delta_{\text{eff}} \simeq 0.3\]
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with PDFS \( f_{I/p}(x, Q^2) \) known from HERA data, no freedom:

\[ dN_{\text{ch}} / d\eta \bigg|_{\eta=0} \propto \sigma_{pp}^{jet} \text{ explodes at high energies for small } Q_0^2 \]
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- in QGSJET-II-04, a rather large value (3 GeV^2) is used
- with the factorization scale \( M_F^2 = p_t^2/4 \), yields \( p_t^{\text{cut}} \approx 3.4 \) GeV
- but: pQCD should work down to \( Q_0 \approx 1 \) GeV?!
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\[\Rightarrow \text{some important perturbative mechanism seems missing}\]
Collinear factorization: valid at leading twist (up to $1/Q^n$ terms)

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Phenomenological approaches: higher twist (HT) effects

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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 $\sigma_{pp}^{\text{tot/el}}$

- significant corrections for total/elastic cross sections
- start to be important already at $\sqrt{s} \sim 1$ TeV
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Impact on charged hadron multiplicity & $p_t$-spectra

- Reduction of $N_{ch}$: 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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  [SO & Bleicher, 2019]
  - now: twice smaller cutoff for hard processes ($Q_0^2 = 1.5$ GeV$^2$)

Results for air showers: preliminary and close to QGSJET-II-04
- e.g. difference for $N_\mu$ – at percent level
Phenomenological approaches: higher twist (HT) effects

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  [SO & Bleicher, 2019]
  
  - now: twice smaller cutoff for hard processes ($Q_0^2 = 1.5 \text{ GeV}^2$)

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 ($pp$, $\pi p$, $Kp$): 15
  (soft & hard interactions; low mass diffraction)
- nonlinear effects (Pomeron-Pomeron interactions): 1
- higher twist effects: 1
- hadronization parameters: $< 20$
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- but: based on phenomenological approaches
  ⇒ the model is overconstrained
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Generally: present models of hadronic collisions
– rather involved but largely phenomenological

⇒ 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 $X_{\text{max}}$: on the properties of the primary particle interaction ($\sigma_{p-\text{air}}^{\text{inel}}, \sigma_{p-\text{air}}^{\text{diff}}, K_{p-\text{air}}^{\text{inel}}$)

- predictions for muon density: on secondary particle interactions (cascade multiplication); mostly on $N_{\pi-\text{air}}^{\text{ch}}$
Air shower characteristics & hadronic interactions

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

- $\sigma_{p-\text{air}}^{\text{inel}}$ – constrained by LHC studies of $pp$ collisions
- uncertainties for $\sigma_{p-\text{air}}^{\text{dissr}}$: small impact (< 10 g/cm²) [SO, 2014]
- what about $K_{p-\text{air}}^{\text{inel}}$?
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 ($\propto x^{-\alpha_R(0)}$, $\alpha_R(0) \simeq 0.5$)
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- ⇒ observables consequences:
  - softer forward spectra (energy sharing between constituent partons)
  - forward & central particle production - strongly correlated (more activity in central detectors ⇒ larger Fock states ⇒ softer forward spectra)
Structure of constituent parton Fock states

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

- SIBYLL & PYTHIA: weak energy dependence of the nucleon 'inelasticity' (for increasing $\sqrt{s}$, mostly rise of central production)
- smaller $K^{\text{inel}} \Rightarrow$ stronger 'leading particle' effect
- $\Rightarrow$ slower development of CR-induced air showers
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Crucial test: cross-correlation of $dN_{pp}^{ch}/d|\eta|$ 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 $\pi^0$ spectra in LHCf for different ATLAS triggers ($\geq 1$, 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 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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  - do some/all models do it right?
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  - do some/all models do it right?
- current indications from UHECR data \((X_{\text{max}} \text{ & } X_{\mu \text{max}})\):
  treatment of pion-air collisions may be deficient \((\text{extra slides})\)
Interpreting PAO data on $X_{\text{max}}$ & $X_{\mu \text{max}}$: not self-consistent

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

- the two sets of data should overlap in terms of $\langle \ln A \rangle$
- for $1 \leq A \leq 56$!
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How to change models to 'marry' $X_{\text{max}}$ & $X_{\mu\text{max}}$ composition-wise?

Ancient Greek wisdom may help...

- change a model to modify $X_{\text{max}}$ prediction:
  - $X_{\mu\text{max}}$ 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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  $\Rightarrow$ parallel up/down shift of the cascade profile (same shape)

  $\Rightarrow$ same effect on $X_{\text{max}}$ and $X_{\mu\text{max}}$
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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., $\sigma_{\pi-\text{air}}^{\text{inel}}$, $\sigma_{\pi-\text{air}}^{\text{diffr}}$, $K_{\pi-\text{air}}^{\text{inel}}$
- $\equiv$ making special assumptions concerning the pion structure
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  - $\Rightarrow$ cumulative effect on $X_{\text{max}}^\mu$
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  - $\equiv$ making special assumptions concerning the pion structure
- affects every step in the multi-step hadron cascade
  - $\Rightarrow$ cumulative effect on $X_{\text{max}}$
- but: only the first few steps in the cascade impact $X_{\text{max}}$
  - after few steps, most of energy channelled into e/m cascades
  - $\Rightarrow$ much weaker effect on $X_{\text{max}}$
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E.g., replacing QGSJET-II by the old QGSJET, for $\pi -$ air collisions

- higher $\sigma_{\pi\text{-air}}^{\text{inel}}$, larger $N_{\pi\text{-air}}^{\text{ch}}$ & $K_{\pi\text{-air}}^{\text{inel}}$

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- nearly self-consistent interpretation

NB: higher $\sigma_{\pi-\text{air}}^{\text{inel}}$ & $N_{\pi-\text{air}}^{\text{ch}}$ 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?!