

Characteristics of UHECR-induced EAS: Results of QGSJET-III & model uncertainties

Sergey Ostapchenko

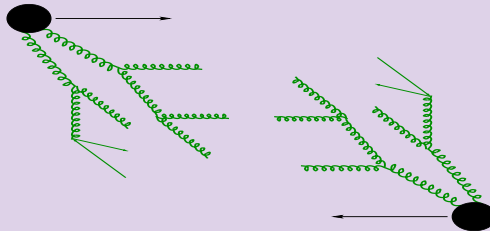
Hamburg University, II Institute for Theoretical Physics

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Hadronic interactions: qualitative picture

QCD-inspired: interactions mediated by parton cascades

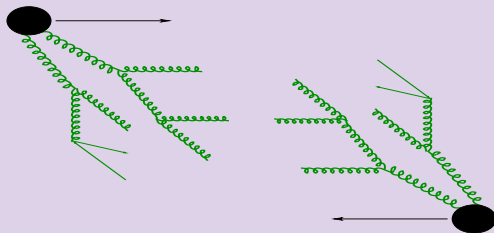
NB: hadrons form their virtual parton 'clouds' before the collision



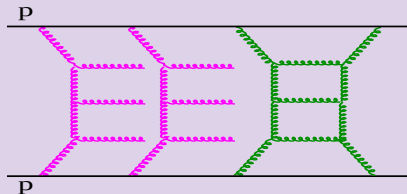
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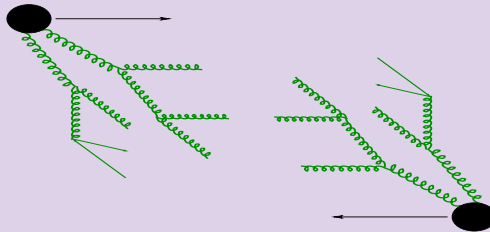
Inelastic collisions involve both 'real' & 'virtual' rescatterings



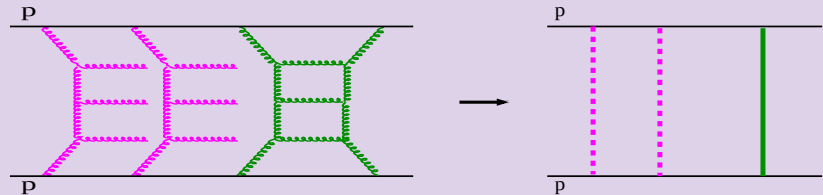
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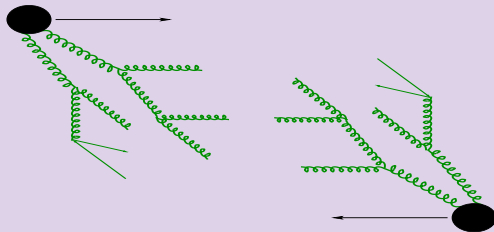
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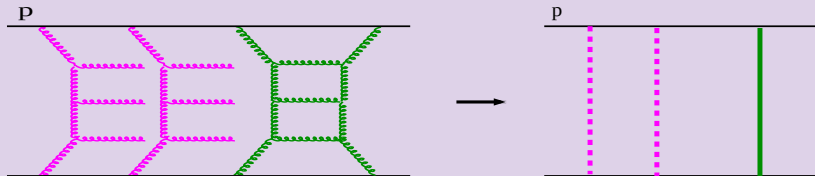
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NB: parton cascades - generally nonperturbative
(contain small p_t partons)

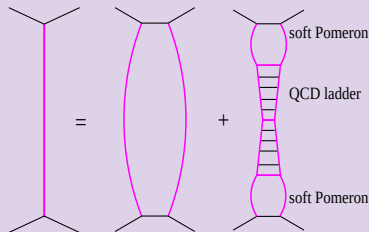
QGSJET: combined treatment of soft & hard interactions

[Kalmykov, SO & Pavlov, Nucl.Phys.Proc.Suppl. 52B (1997) 17]

'Semihard Pomeron' approach for soft & hard processes

[Drescher, Hladik, SO, Pierog & Werner, Phys.Rep. 350 (2001) 93]

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



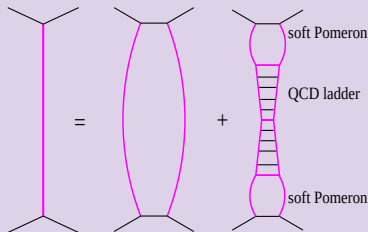
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- altogether: 'general Pomeron'
- most important:
faster energy-rise of multiple scattering ($\propto s^{\Delta_{\text{hard}}}$, $\Delta_{\text{hard}} \sim 0.3$)



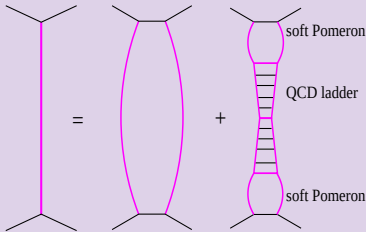
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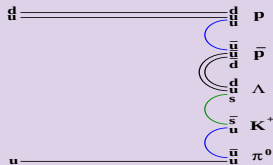
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Particle production: string fragmentation

- final partons: connected by strings of color field
- color field is neutralized via creation of $q - \bar{q}$ & $qq - \bar{q}\bar{q}$ pairs from the vacuum

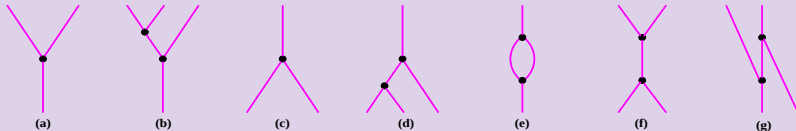


QGSJET-II: treatment of nonlinear interaction effects

[SO, PRD 74 (2006) 014026; PRD 83 (2011) 014018]

Nonlinear effects = Pomeron-Pomeron interactions (scattering of intermediate partons off the proj./target hadrons & off each other)

[SO, PLB 636 (2006) 40; PRD 77 (2008) 034009; PRD 81 (2010) 114028]



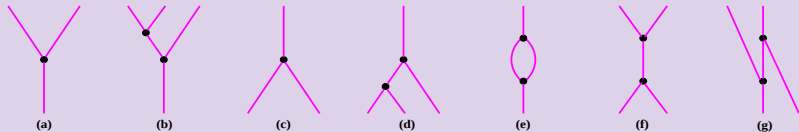
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Dynamical microscopic treatment

- consistent treatment of proton F_2 , $\sigma_{pp}^{\text{tot/inel}}$, $d\sigma_{pp}^{\text{el}}/dt$, $\sigma_{pp}^{\text{diffr}}$
- stronger screening in pA & AA
(Pomerons couple to different nucleons)
- stronger screening for central (small b) collisions
(higher parton density)
- single adjustable parameter (PPP-coupling)

QGSJET-III: higher twist corrections for hard scattering

[SO, EPJ Web.Conf. 208 (2019) 11001; Phys.At.Nucl. 84 (2021) 1017]

All current MC generators: using leading twist QCD factorization

$$\sigma_{pp}^{\text{jet}} = \sum_{I,J=g,q,\bar{q}} f_{I/p} \otimes \sigma_{IJ}^{2 \rightarrow 2} \otimes f_{J/p}$$

- involves $2 \rightarrow 2$ Born cross section for parton scattering (LO)
 - 1 projectile parton interacts with 1 target parton

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- **uncontrollable rise of minijet production in the small p_t limit**
- also: steep energy-rise of $\sigma_{pp}^{\text{jet}}(s, p_t^{\text{cut}})$ for moderately small p_t^{cut}

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- also: steep energy-rise of $\sigma_{pp}^{\text{jet}}(s, p_t^{\text{cut}})$ for moderately small p_t^{cut}
- but: **higher twist corrections potentially important at small p_t**

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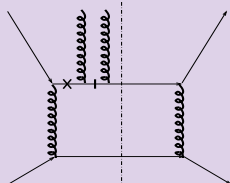
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Higher twist corrections due to coherent scattering on soft ($x_g \sim 0$) gluon pairs [*Qiu & Vitev, PRL 93 (2004) 262301; PLB 632 (2006) 507*]

- important corrections for DIS on nuclei & for jet production in pA
- hard scattering involves any number of additional gluon pairs
- $\Rightarrow$ involve multi-parton correlators



QGSJET-III: higher twist corrections for hard scattering

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Phenomenological implementation: interpreting multi-parton correlators as generalized n -PDFs [*SO & Bleicher, Universe* 5 (2019) 106]

- **strong damping of hard scattering in the small p_t limit**
(with the corrections vanishing for large p_t)
 - $\Rightarrow$ reducing the model sensitivity to (soft/hard) Q_0 -cutoff
(currently: $Q_0^2 = 2 \text{ GeV}^2$)

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- taming the energy-rise of both $\sigma_{pp}^{\text{tot/inel}}(s)$ & $N_{pp}^{\text{ch}}(s)$
- **dynamical scheme:** e.g. stronger effects in hA (AA) (scattering on soft gluons from different nucleons)
 - stronger screening for central (small b) collisions (denser gluon clouds)
- **single adjustable parameter K_{HT}** (overall normalization)

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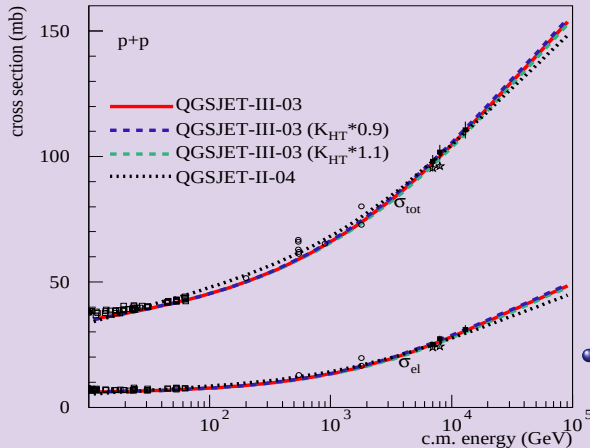
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- dynamical scheme: e.g. stronger effects in hA (AA) (scattering on soft gluons from different nucleons)
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Additionally - technical improvement in QGSJET-III:
treatment of the pion exchange process (extra slides)

QGSJET-III: higher twist corrections for hard scattering

[*SO, EPJ Web.Conf.* 208 (2019) 11001; *Phys.At.Nucl.* 84 (2021) 1017]

$\sigma_{pp}^{\text{tot/el}}(s)$ in QGSJET-III & for $\pm 10\%$ variation of K_{HT}

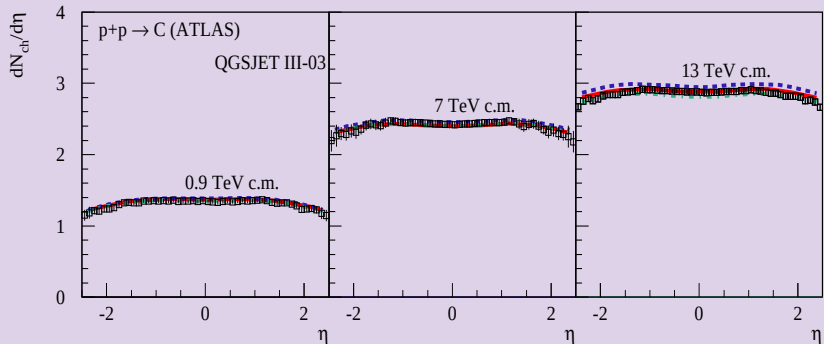


● $\sigma_{pp}^{\text{tot/el}}$: up to $\pm 1\%$ variation at the highest s

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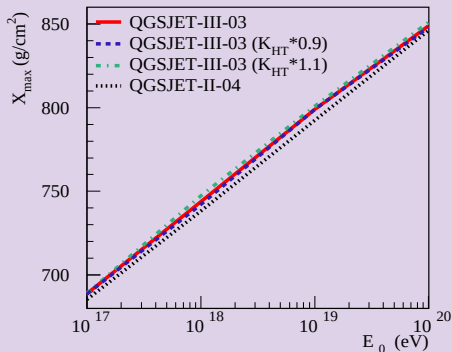
$dN_{pp}^{\text{ch}}/d\eta$ in QGSJET-III & for $\pm 10\%$ variation of K_{HT}



• $\pm 2\%$ variation at $\sqrt{s} = 13$ TeV

Results for extensive air showers

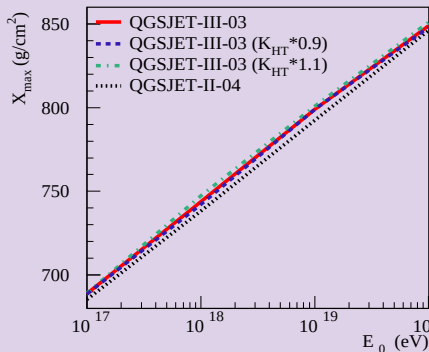
$X_{\max}$ for proton showers: QGSJET-III & $\pm 10\%$ variation of K_{HT}



- up to ± 2 g/cm² variation for $X_{\max}$

Results for extensive air showers

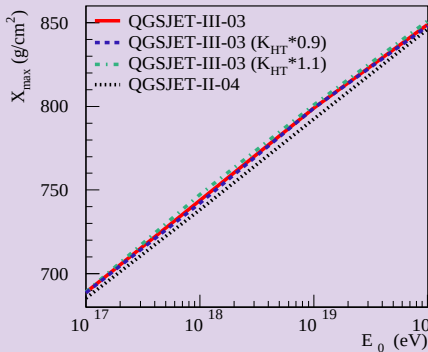
$X_{\max}$ for proton showers: QGSJET-III & $\pm 10\%$ variation of K_{HT}



- up to $\pm 2 \text{ g/cm}^2$ variation for $X_{\max}$
- $\sim 5 \text{ g/cm}^2$ difference with QGSJET-II-04
- $X_{\max}^{\mu}$: $< 5 \text{ g/cm}^2$ difference
- $\simeq 1\%$ difference for N_{μ}

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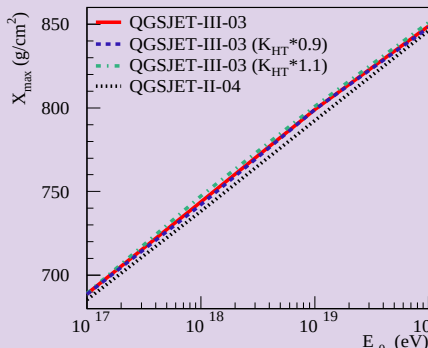
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Stability of $X_{\max}$ predictions expected IFF:

- 1 $X_{\max}$ is dominated by p -air interactions
- 2 predictions for p -air are sufficiently constrained by LHC data

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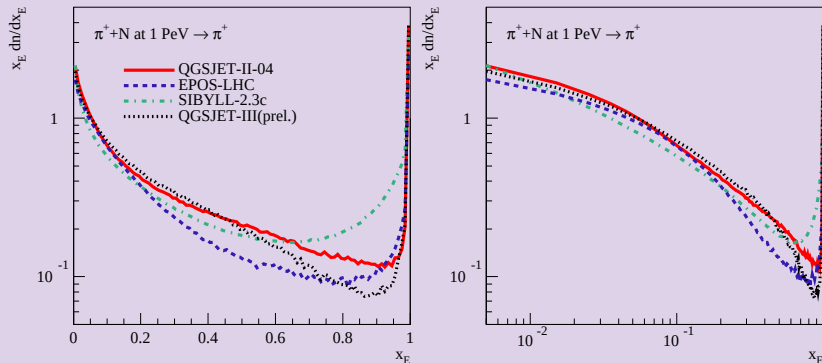
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NB: deeper $X_{\max}$ of EPOS & SIBYLL - (at least partly) due to serious inconsistencies of the models [SO & Bleicher, PRD93 (2016) 051501; SO, Bleicher, Pierog & Werner, PRD94 (2016) 114026] (see also extra slides)

Interactions of pions: impact on $X_{\max}$, $X_{\max}^{\mu}$ & N_{μ}

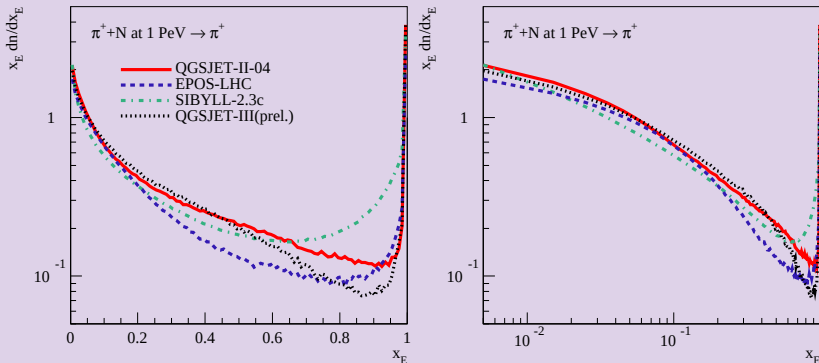
π^{+} spectrum for $\pi^{+} - {}^{14}\text{N}$ collisions at 1 PeV



- strong model dependence for $x_E \gtrsim 0.5$ (diffraction & scaling violations)
- smallest model differences at $x_E \sim 0.1$

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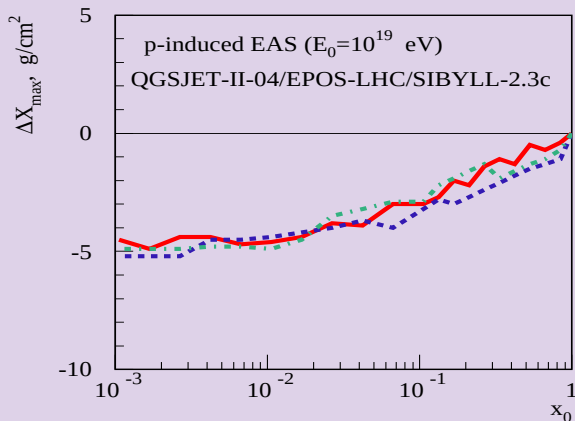


Let us change production spectra of pions for all π -air collisions

- 'splitting' each $\pi^{\pm}$, π^0 with $x_E > x_0$ into two (with 1/2 energy)
 - NB: fraction of energy going into π^0 s remains unchanged!
- e.g. for x_0 close to 1: **only diffraction affected**
- for $x_0 \rightarrow 0$: **twice higher multiplicity & much softer spectra**

Interactions of pions: impact on $X_{\max}$, $X_{\max}^{\mu}$ & N_{μ}

Impact on $X_{\max}$ ('splitting' pions with $x_E > x_0$)



- miserable dependence on pion diffraction ($\Delta X_{\max} \simeq 1$ g/cm²)
- even for extreme changes ($x_0 \rightarrow 0$): $\Delta X_{\max} \lesssim 5$ g/cm²
- $\Rightarrow X_{\max}$ is strongly dominated by p -air interactions

Interactions of pions: impact on $X_{\max}$, $X_{\max}^{\mu}$ & N_{μ}

- What about N_{μ} ? Let us neglect contributions of kaons & (anti)baryons to the hadronic cascade:

$$N_p^{\mu}(E_0) \simeq \int dx \frac{dN_{p-\text{air}}^{\pi^{\pm}}(E_0, x)}{dx} N_{\pi^{\pm}}^{\mu}(xE_0).$$

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- with $N_{\pi^{\pm}}^{\mu}(x, E) \propto E^{\alpha}$, $dN_{p-\text{air}}^{\pi^{\pm}}(E_0, x)/dx \propto x^{-1-\Delta} (1-x)^{\beta}$:

$$N_p^{\mu}(E_0) \propto E_0^{\alpha} \int_{x_{\min}}^1 dx x^{\alpha-1-\Delta} (1-x)^{\beta}.$$

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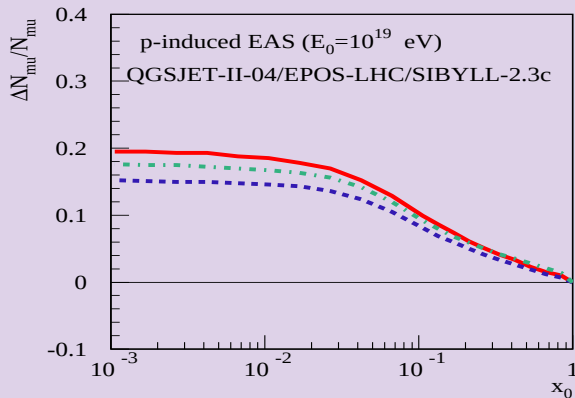
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$$N_p^{\mu}(E_0) \propto E_0^{\alpha} \int_{x_{\min}}^1 dx x^{\alpha-1-\Delta} (1-x)^{\beta}.$$

- largest contribution comes from $\langle x_{\pi} \rangle \simeq \frac{\alpha-\Delta}{\alpha+\beta-1-\Delta} \sim 0.2$
(for $\Delta \simeq 0.3$, $\alpha \simeq 0.9$, $\beta \sim 4$)
- relevant $\langle x_{\pi} \rangle$ for π -air interactions follows similarly

Interactions of pions: impact on $X_{\max}$, $X_{\max}^{\mu}$ & N_{μ}

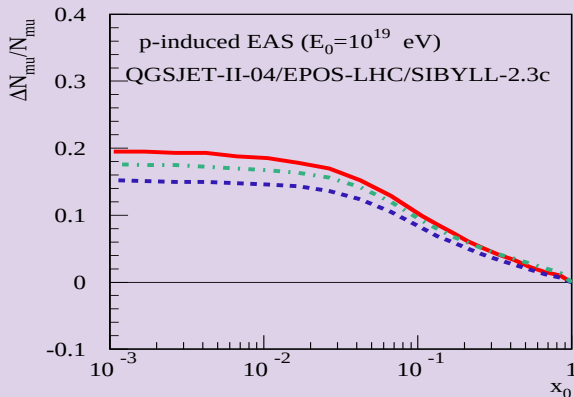
Cross check the impact on N_{μ} ('splitting' pions with $x_E > x_0$)



- extreme changes (doubling the multiplicity): $\Delta N_{\mu}/N_{\mu} \lesssim 20\%$
- main change of N_{μ} : for $x_E \sim 0.1$

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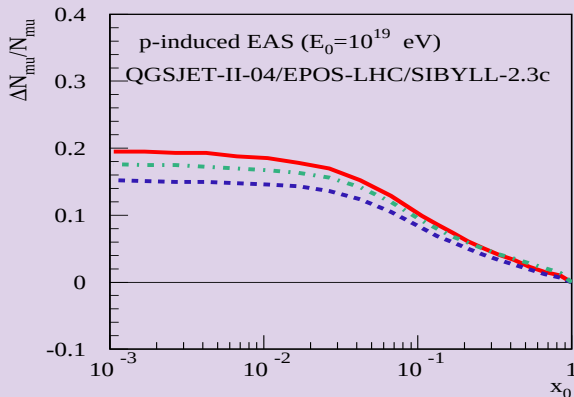
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 - pion production at $x_F \sim 0.1$: well measured at low energies

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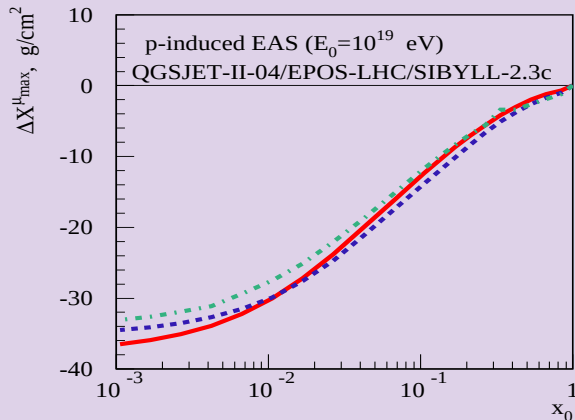
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- main change of N_{μ} : for $x_E \sim 0.1$
 - pion production at $x_F \sim 0.1$: well measured at low energies
 - energy evolution: **driven by the rise of gluon density in pion** (yet reasonably constrained for $x_F \sim 0.1$ - extra slides)

Interactions of pions: impact on $X_{\max}$, $X_{\max}^{\mu}$ & N_{μ}

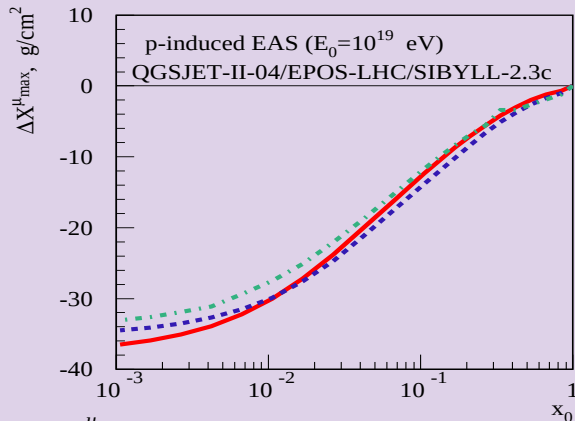
Impact on $X_{\max}^{\mu}$ ('splitting' pions with $x_E > x_0$)



- pion diffraction is irrelevant
- main change for $0.01 < x_E < 0.1$
- why?

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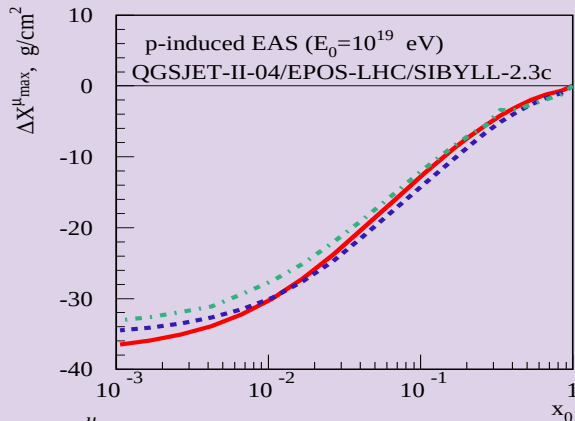


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- $X_{\max}^{\mu}$: pion interaction & decay rates become comparable
- $\sigma_{\pi\text{-air}}^{\text{inel}}$ & $\sigma_{\pi\text{-air}}^{\text{diffr}}$ impact the number of 'generations' (cascade steps) till that point

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Impact on $X_{\max}^{\mu}$ ('splitting' pions with $x_E > x_0$)

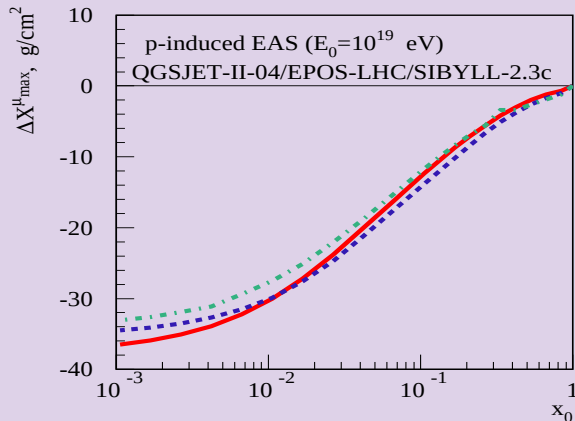


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- but: multiplicity controls the speed of pion energy decrease

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Impact on $X_{\max}^{\mu}$ ('splitting' pions with $x_E > x_0$)



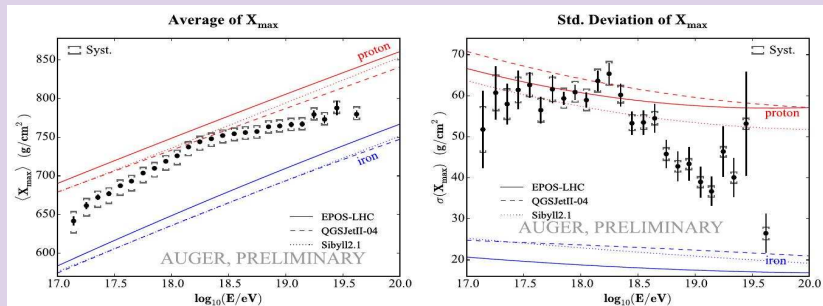
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- pion production at $0.01 < x_F < 0.1$:
well measured at fixed target energies
- energy evolution: gluon density rise in pion
- $G_{\pi}(x, q^2)$: reasonably constrained for $0.01 < x_F < 0.1$

PAO analysis of UHECR composition

[PRD 90 (2014) 12, 122006; JCAP 04 (2017) 038]

PAO data favor predictions with higher $X_{\max}$ & smaller $\sigma(X_{\max})$

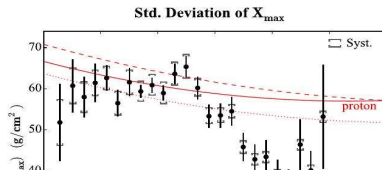
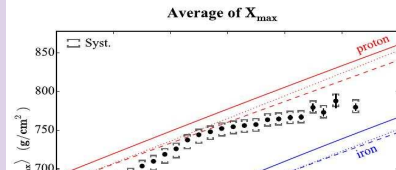


• $\Rightarrow$ data analyzed, using EPOS-LHC

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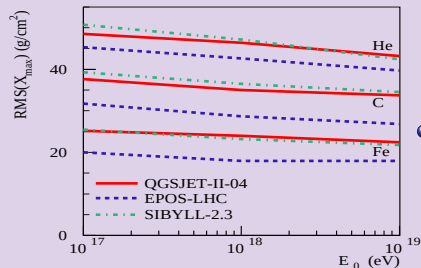
[PRD 90 (2014) 12, 122006; JCAP 04 (2017) 038]

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But: $\sigma(X_{\max})$ is very robust theoretically

[Aloisio, Berezhinsky, Blasi & SO, PRD 77 (2008) 025007; SO, AdSR 64 (2019) 2445]



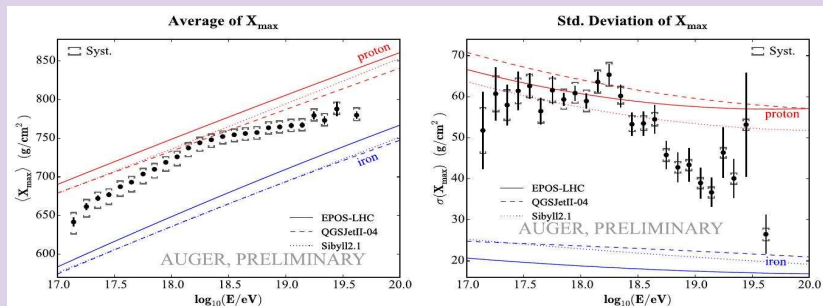
- small $\sigma(X_{\max})$ of EPOS: obviously wrong (incorrect treatment of nuclear break-up)

[SO, arXiv:1612.09461]

PAO analysis of UHECR composition

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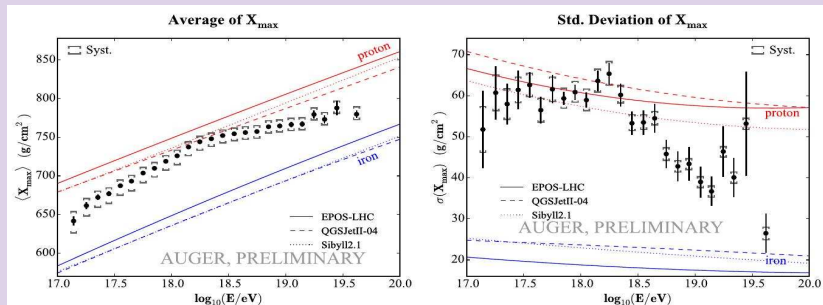
What about a deeper shower maximum?

- large $X_{\max}$ of SIBYLL:
due to inconsistent treatment of (semi)hard scattering
- EPOS-LHC: partly due to enhanced (anti)baryon production

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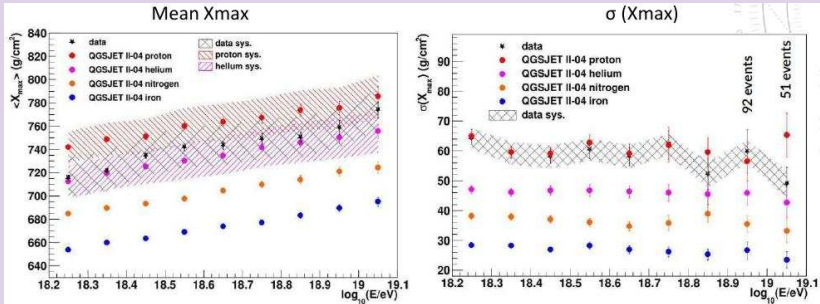


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Consistent data interpretation, if such mistakes are avoided?

UHECR composition: TA results [*H. Sagawa, talk at ISVHECRI-2022*]

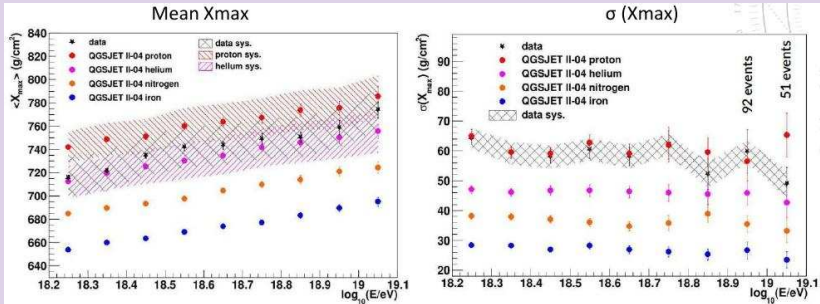
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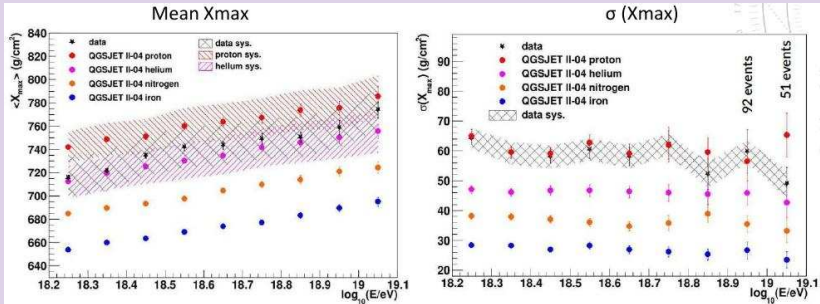
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- $X_{\max}$ & $\sigma(X_{\max})$: consistent with pure protons / light mix (in the energy range characterized by sufficient statistics)
- to discriminate: higher experimental statistics & quantitative analysis of model uncertainties for $X_{\max}$ predictions required
- crucial question: can one exclude pure proton composition at the highest energies?

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 - $\Rightarrow$ high predictive power
 - but: phenomenological treatments $\Rightarrow$ not necessarily valid

Summary

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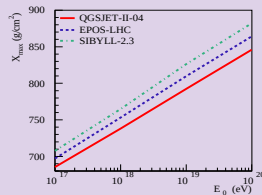
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- ❸ Quantitative analysis of uncertainties for EAS predictions?
 - but: avoiding obviously wrong approaches

Extra slides

Extensive air showers: QGSJET-III & other models

Higher $X_{\max}$ of SIBYLL-2.3: from the treatment of p -air collisions
[SO, Bleicher, Pierog & Werner, PRD94 (2016) 114026]

- arises from an inconsistent treatment of (semi)hard scattering
- leads to a contradiction with LHC data
 - $\Rightarrow$ LHC data are discriminative enough!

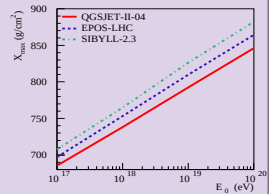


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Case of EPOS: more involved; part of the effect due to enhanced (anti)baryon production in π -air [SO & Bleicher, PRD93 (2016) 051501]

- $\Rightarrow$ important consequences for N_μ & muon spectrum
 - how reasonable it is?

Hard scattering: importance of the parton cascade

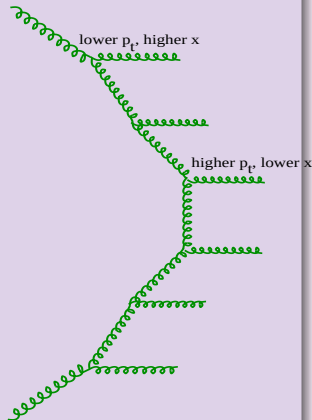
- high energies $\Rightarrow$ high p_t parton production important
 - small $\alpha_s(p_t^2)$ - compensated by infrared and collinear logs (arising from parton cascading): $\ln(x_i/x_{i+1})$, $\ln(p_{t_{i+1}}^2/p_{t_i}^2)$

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- hadron jets: typically produced in central region ($y \sim 0$) in c.m.s.
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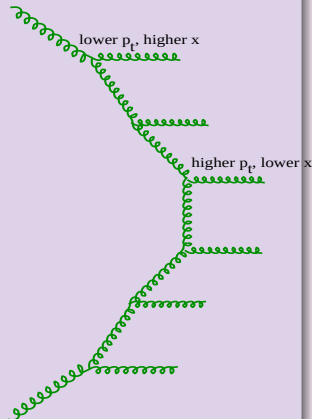


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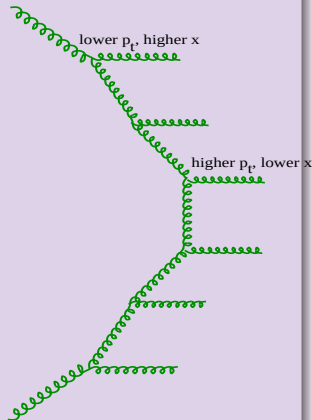


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- **start of the cascade: at which p_t & x ?**
(Q_0^2 - soft/hard separation scale)

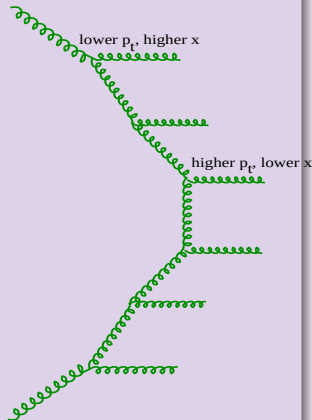


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- start of the cascade: at which p_t & x ? (Q_0^2 - soft/hard separation scale)
- QGSJET/NEXUS/EPOS: the cascade starts at $p_t < Q_0$ ($\Rightarrow$ high x)

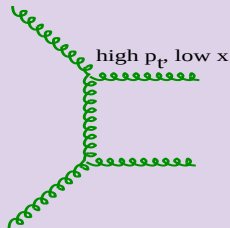


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Counterexample: SIBYLL model [*Fletcher et al.*, PRD 50 (1994) 5710; *Ahn et al.*, PRD 80 (2009) 094003; *Riehn et al.*, PRD 102 (2020) 063002]

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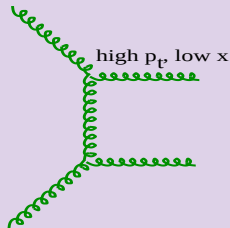


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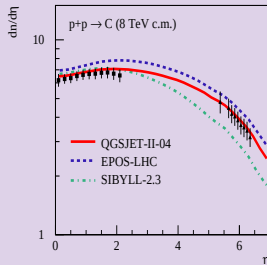


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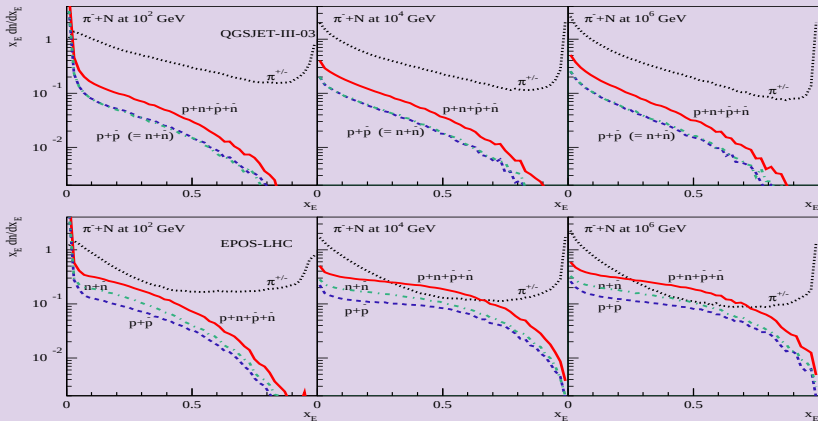
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- the model is at variance with LHC data on $dN_{pp}^{\text{ch}}/d\eta$



Energy-dependence of (anti)nucleon production

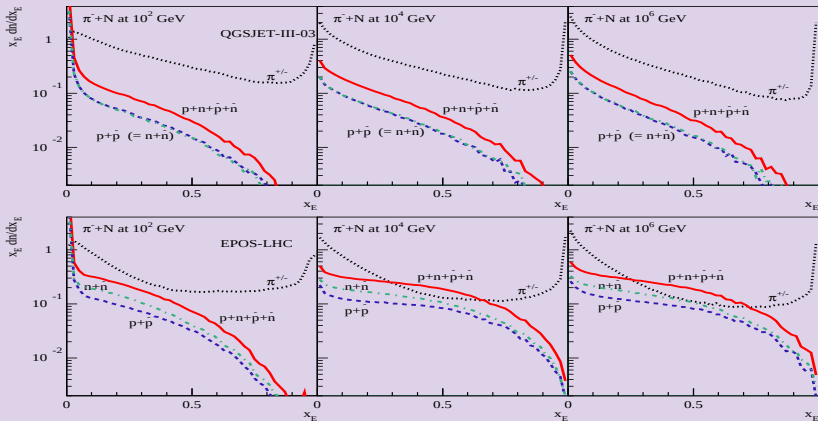
$\pi^- N$: (anti)nucleon production in QGSJET-III & EPOS-LHC



- 'hardening' of the baryon yield with energy seems artificial:
no viable theoretical mechanism

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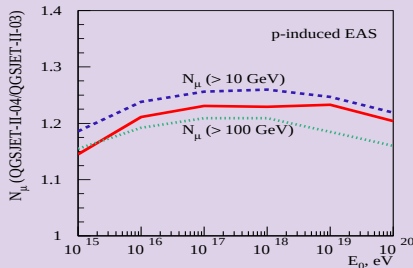
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- violation of the isospin invariance - obviously wrong (yields of $p+\bar{p}$ & $n+\bar{n}$ should coincide)

Technical improvement in QGSJET-III: pion exchange

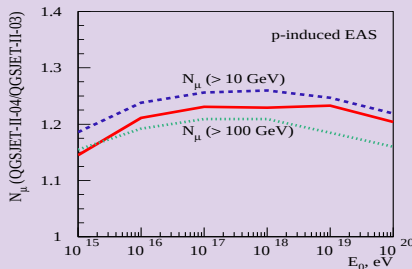
Pion exchange process in π -air: important for N_μ predictions
(due to forward ρ production) [SO, EPJ Web Conf. 52 (2013) 02001]



- $\sim 20\%$ higher $N_\mu (> 1 \text{ GeV})$
(relative to QGSJET-II-03)
- the enhancement weakly depends on E_0
- nearly same N_μ excess up to $E_\mu \sim 100 \text{ GeV}$

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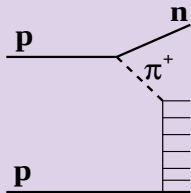
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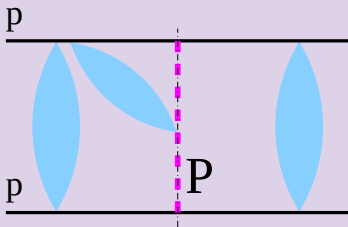
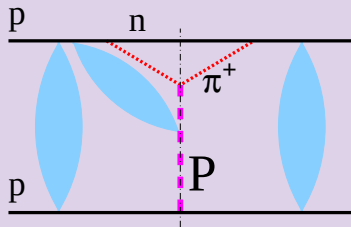
Check/tune the mechanism with forward neutron production in pp ?

- Born cross section for π -exchange - well known [e.g. Kaidalov et al., EPJC 47 (2006) 385]
- main challenge: **absorptive corrections**
 - $\Rightarrow$ energy-dependence! (see extra slides)



Technical improvement in QGSJET-III: pion exchange

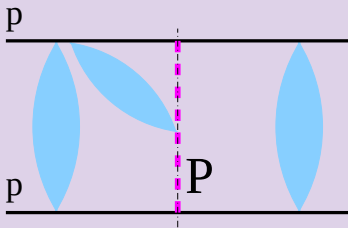
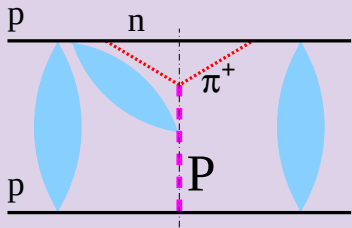
π -exchange & single cut Pomeron process: same absorptive effects



- eikonal rapidity gap suppression factor
(to exclude additional inelastic rescatterings)
- enhanced diagrams (to exclude inelastic rescattering of intermediate partons in the Pomeron)
- $\Rightarrow$ same energy-dependence for π -exchange & $1\mathbb{P}$ process

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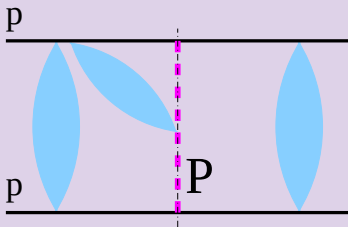
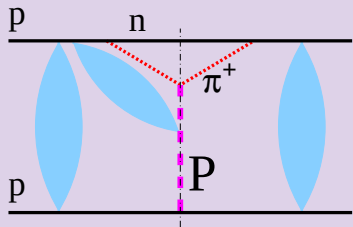
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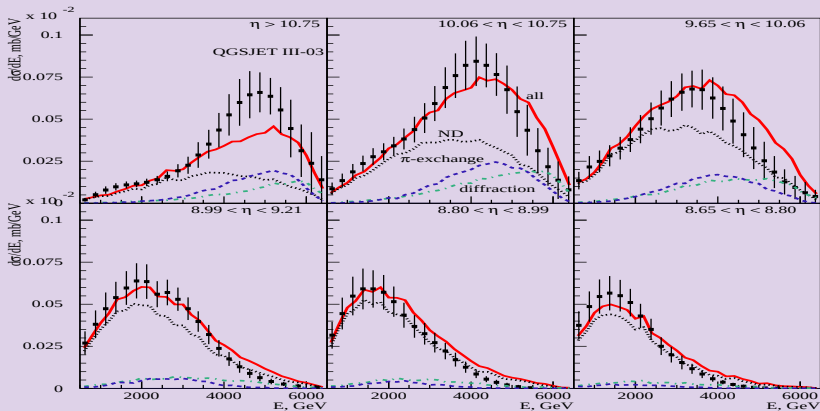


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- $\Rightarrow$ treat π -exchange as a part (probability w_π) of $1\mathbb{P}$ -exchange
 - for πp & π -air: already in QGSJET-II-04 (in a simplified way)

π -exchange process in pp scattering & LHCf data

[Adriani et al., PLB 750 (2015) 360; JHEP 1811 (2018) 073]

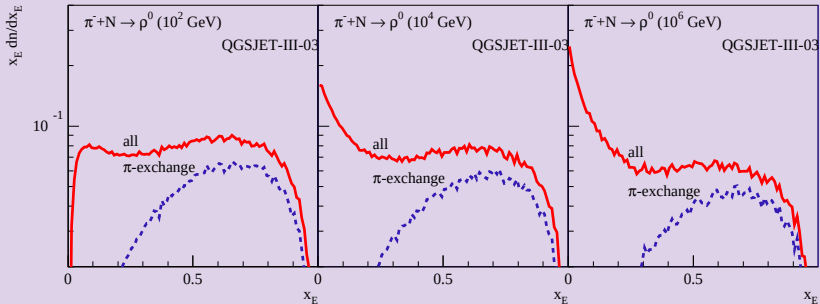
Comparison to LHCf data at $\sqrt{s} = 13$ TeV ($w_{\pi}^p = 0.25$)



- forward neutron production: **dominated by ND** (no π -exch.)
- π -exchange: important in the highest η bins
- comparable contribution from **inelastic diffraction**

π -exchange process in pion-nucleus collisions

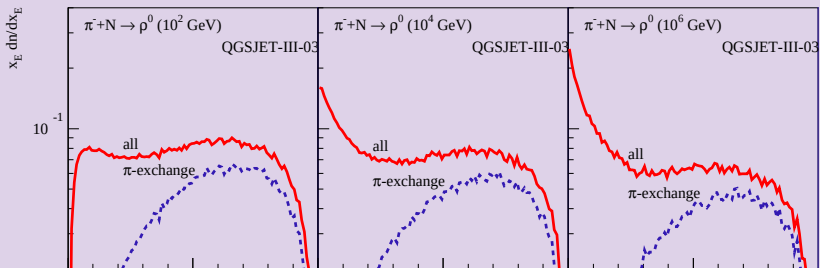
Energy-dependence of ρ^0 production in $\pi^- N$ collisions ($w_\pi^\pi = 0.4$)



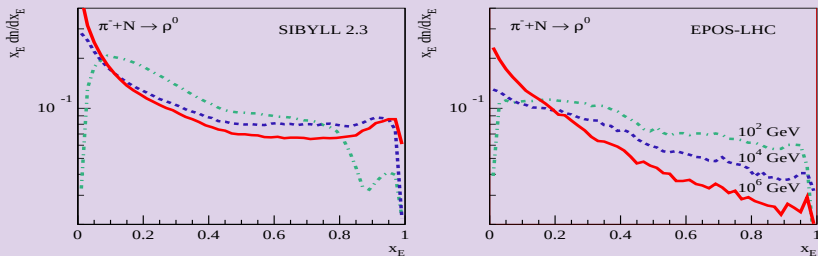
- forward ρ^0 yield: dominated by π -exchange process
- higher energies: absorptive corrections damp the π -exchange

π -exchange process in pion-nucleus collisions

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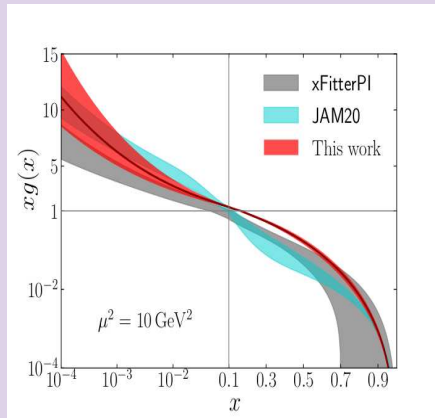


ρ^0 production in SIBYLL-2.3 & EPOS-LHC (10^2 , 10^4 & 10^6 GeV)



Gluon density in the pion

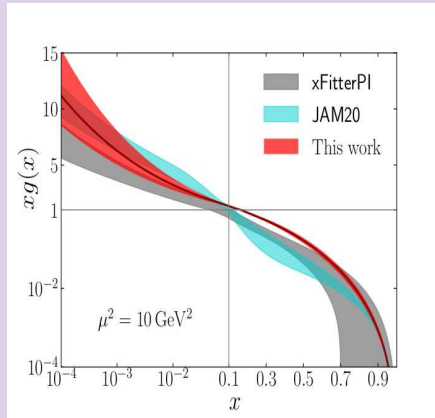
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