QGSJET-III: predictions for EAS and the corresponding uncertainties

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arXiv: 2401.06202; 2403.16106; 2404.02085

"An ignorance of a law is not a justification for violating the law"

This applies equally to the laws of physics

Main motivation for QGSJET-III

Jet production in MC generators: collinear factorization of pQCD

$$\frac{d\sigma_{pp}^{\rm jet}}{dp_t^2} = \sum_{I,J=q,\bar{q},g} f_I \otimes \frac{d\sigma_{IJ}^{2\to 2}}{dp_t^2} \otimes f_J$$

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- for $Q_0 \sim$ few GeV, soft physics irrelevant
  - $\Rightarrow$ a perturbative mechanism missing

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- for $Q_0 \sim$ few GeV, soft physics irrelevant
  - $\Rightarrow$ a perturbative mechanism missing
- are MC predictions trustworthy, without such a mechanism?

Dynamical higher twist effects in hadronic scattering

Hint: collinear factorization of pQCD valid at leading twist level

- perhaps higher twist effects do the job?
    - come into play at relatively small p_t [suppressed as $1/p_t^n$]

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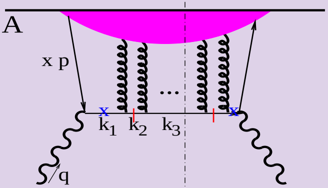
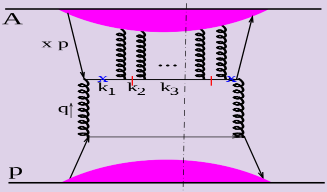
Promising: coherent multiple scattering on 'soft' gluons in $\gamma^* A/pA$

[Qiu & Vitev, PRL93 (2004) 262301; PLB632 (2006) 507]





- scattering involves any number of 'soft' gluon pairs
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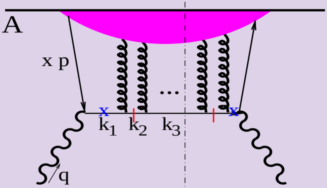

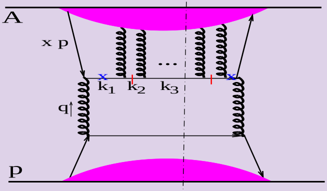

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Extrapolation to hadron-proton & light nuclei

[SO & Bleicher, Universe 5 (2019) 106; SO, arXiv: 2401.06202]

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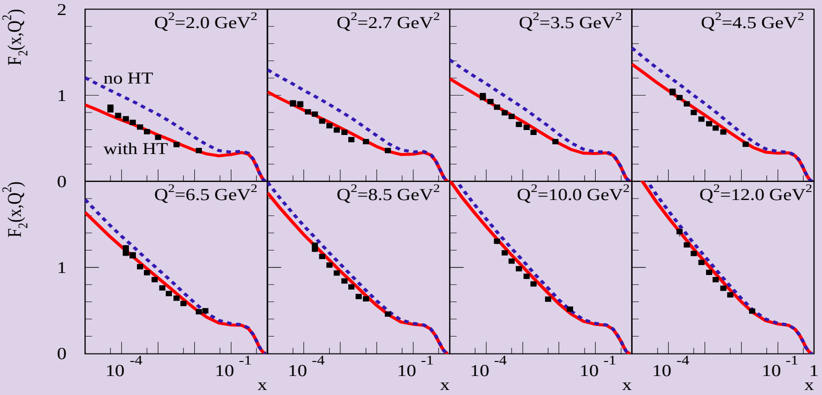
NB: only moderate HT corrections allowed by HERA data



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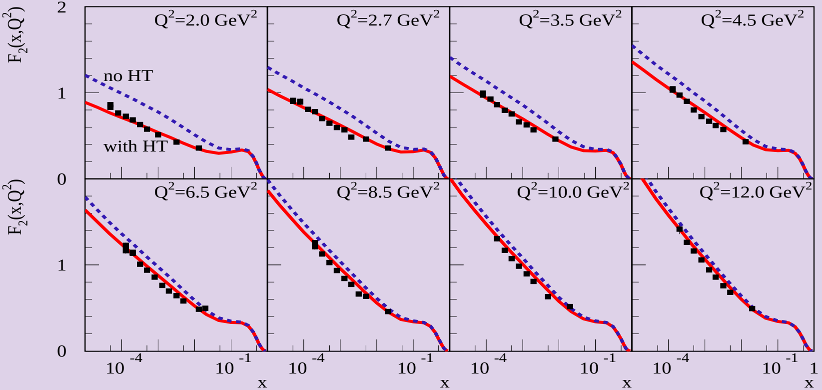

- HT corrections important at low Q^2
  - $\Rightarrow$ too strong corrections at tension with Q^2-evolution of F_2
- known fact: Q^2-evolution of F_2 is well-described by DGLAP
  - $\Rightarrow$ little space for HT or/and saturation effects

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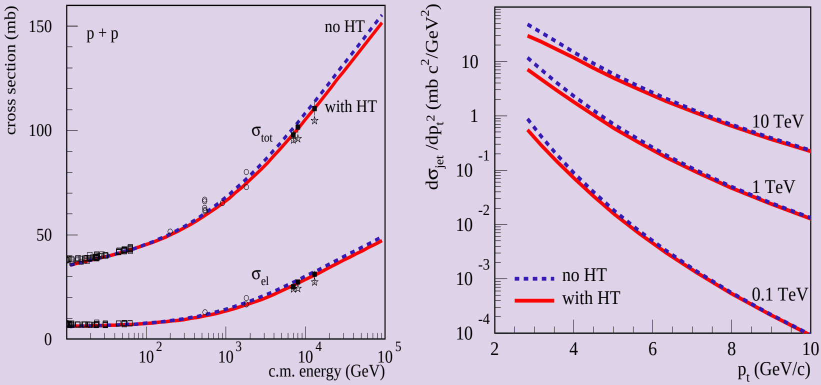
Small effect on $\sigma_{pp}^{tot/el}$ but taming the low-p_t rise of (mini)jet rates



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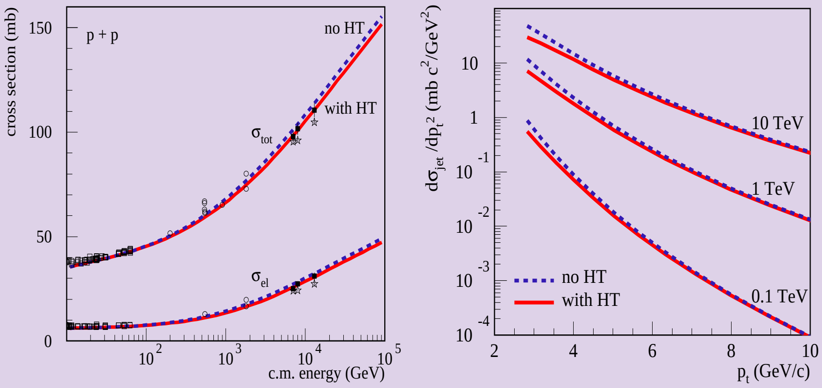


- ⇒ the mechanism does its principal job

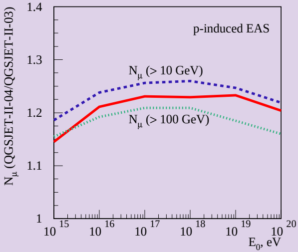
NB: this is NOT parton saturation! *[see also backup slides]*

- rather resembles LPM effect in QED

Technical improvement: π-exchange *[SO, Phys.At.Nucl. 44 (2021) 1017]*

π- over ρ-exchange dominance ⇒ ∼ 20% increase of N_μ

- why so?!



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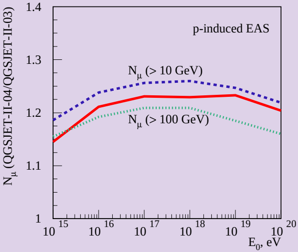

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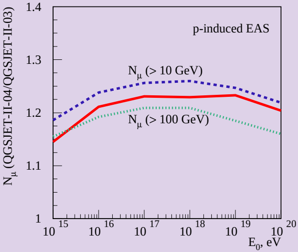

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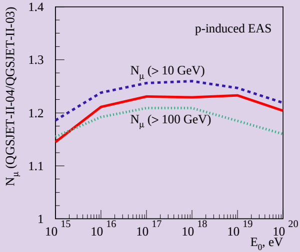

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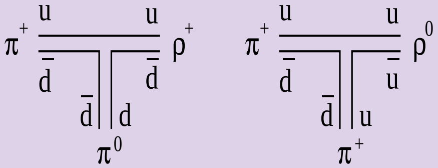

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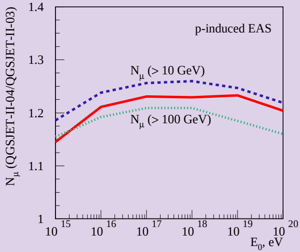

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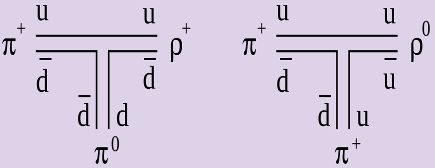

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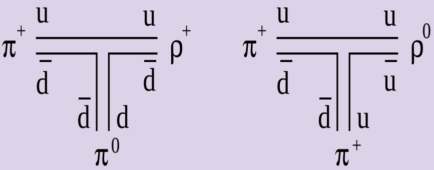

Energy-dependence: driven by absorptive corrections to the process

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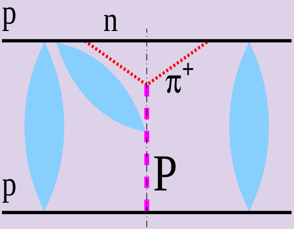

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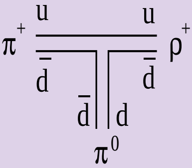

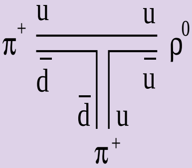

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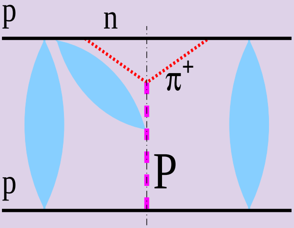
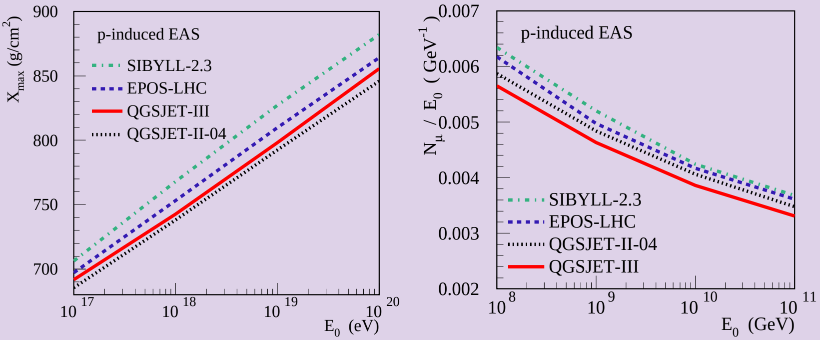
- now can be tested in $pp \to nX$ thanks to LHCf data *[backup slides]*



Results for extensive air showers

Rather small changes for X_{max} and N_μ (wrt QGSJET-II-04)



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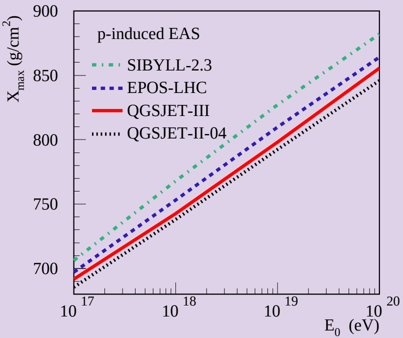

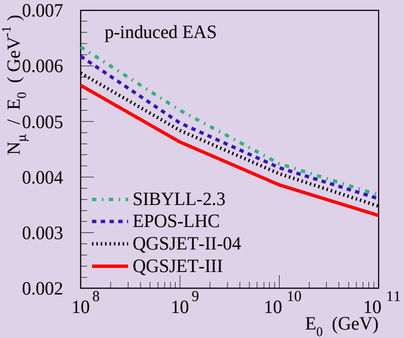

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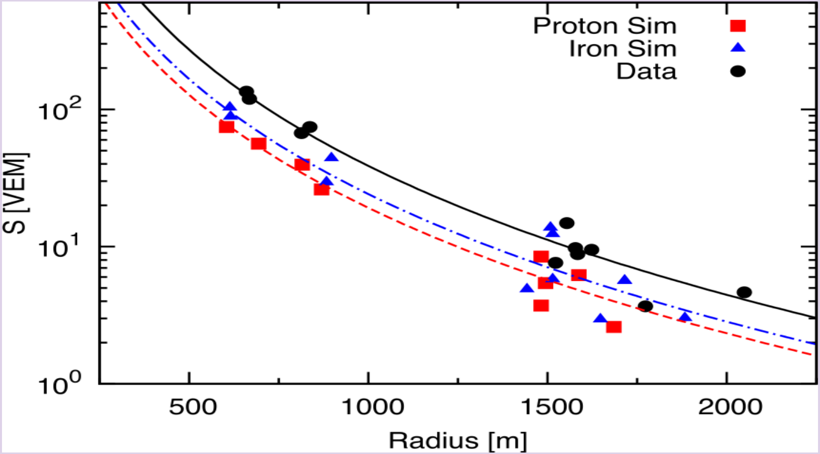
What is the reason for the stability of the predictions?

- the model sufficiently constrained by LHC data?
- or a mere consequence of a particular model approach?

UHECR puzzles

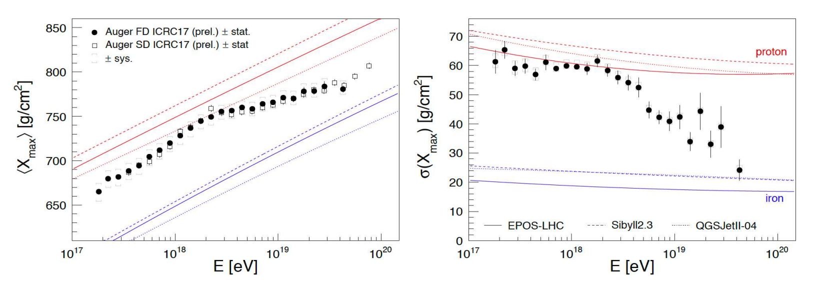
'Muon puzzle': UHECRs are dust grains?



[Pierre Auger Collab., PRL 117 (2016) 192001]

UHECR puzzles

More serious: tension between $X_{\max}$ & $\sigma(X_{\max})$



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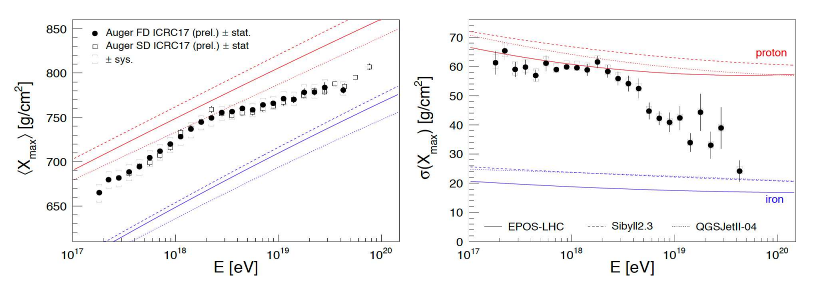

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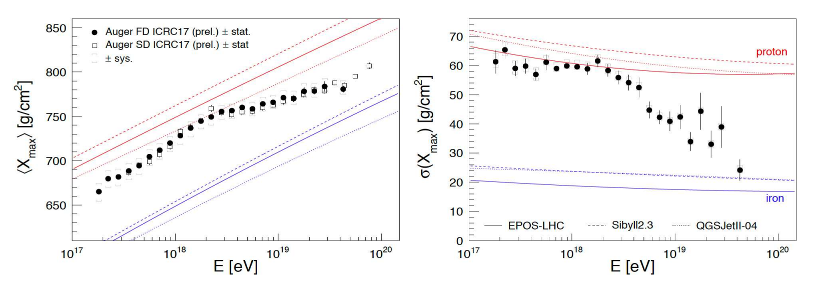

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$\sigma(X_{max})$ – theoretically robust *[Berezinsky et al., PRD 77 (2008) 025007]*

- higher elongation rate (deeper X_{max})?
  - by how much?!

UHECR puzzles

PROCEEDINGS OF SCIENCE

ONLINE ICRC 2021

Adjustments to Model Predictions of Depth of Shower Maximum and Signals at Ground Level using Hybrid Events of the Pierre Auger Observatory

Jakub Vícha[a,*] **on behalf of the Pierre Auger**[b] **Collaboration**

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- to be compatible with PAO data, $X_{\max}$ of QGSJET-II should be larger by $48 \pm 2^{+9}_{-12}$
- is it feasible, in view of available LHC data?
    - what kind of physics changes are required?

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3 'pillars' of the current study

- restrict oneself with the standard physics (no BSM effects!)
- make changes at the microscopic level
- check consequences regarding a (dis)agreement with
  accelerator & CR data

Model uncertainties for predicted N_μ *[SO & Sigl, arXiv: 2404.02085]*

Kinematic range for hadron production, relevant for N_μ predictions

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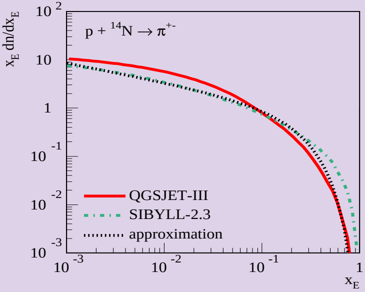
$N_p^\mu(E_0) \propto E_0^{\alpha_\mu} \int_{x_{\min}}^1 dx \, x^{\alpha_\mu - 1 - \Delta} \, (1-x)^\beta$



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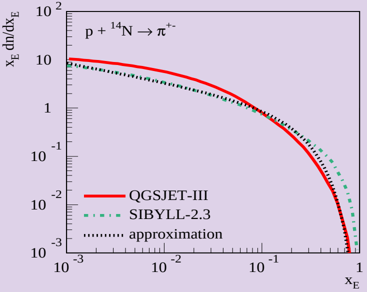
$$N_p^\mu(E_0) \propto E_0^{\alpha_\mu} \int_{x_{\min}}^1 dx\, x^{\alpha_\mu-1-\Delta}\,(1-x)^\beta$$

- largest contribution from
  $\langle x_\pi \rangle \simeq \frac{\alpha_\mu-\Delta}{\alpha_\mu+\beta-1-\Delta} \sim 0.1$
  $(\Delta \simeq 0.4,\ \alpha_\mu \simeq 0.9,\ \beta \simeq 4.5)$



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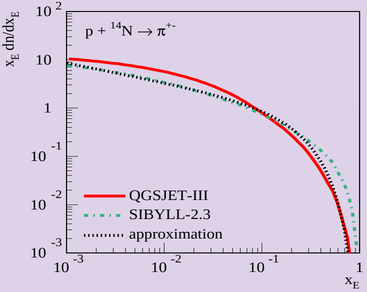
- large N_μ yields at $x \to 1$: $N^\mu_{\pi^\pm}(xE_0) \propto (xE_0)^{\alpha_\mu}$

Using an ansatz: $dN^{\pi^\pm}_{p-\mathrm{air}}(E_0,x)/dx \propto x^{-1-\Delta}\,(1-x)^\beta$

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

- largest contribution from $\langle x_\pi \rangle \simeq \frac{\alpha_\mu-\Delta}{\alpha_\mu+\beta-1-\Delta} \sim 0.1$ $(\Delta \simeq 0.4,\ \alpha_\mu \simeq 0.9,\ \beta \simeq 4.5)$
- relevant $\langle x_\pi \rangle$ for π-air interactions follows similarly



Model uncertainties for predicted N_μ *[SO & Sigl, arXiv: 2404.02085]*

Kinematic range for hadron production, relevant for N_μ predictions

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Accounting for all 'stable' hadrons ($\pi^\pm$, kaons, (anti)nucleons)

- relevant quantity for EAS muon content:
  $\sum_{h=\mathrm{stable}} \langle (x_E^h)^{\alpha_\mu} \rangle = \sum_{h=\mathrm{stable}} \int dx_E \, x_E^{\alpha_\mu} \, \frac{dN_{\pi^\pm \mathrm{air}}^h(E_0,x_E)}{dx_E}$

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- can be well approximated by $\sum_{h=\mathrm{stable}} \langle x_E^h \rangle$ ($\alpha_\mu \to 1$)
- $\Rightarrow$ N^μ is governed by the total energy fraction taken by all 'stable' hadrons (not by the multiplicity)

Model uncertainties for predicted N_μ *[SO & Sigl, arXiv: 2404.02085]*

How to increase $\sum_{h=\text{stable}} \langle x_E^h \rangle$?

- change the energy dependence of the multiplicity for $\pi^\pm$air
  - driven by the energy-rise of (mini)jet production
    $\Rightarrow$ by the gluon density of the pion

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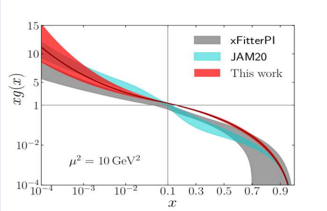
$G_\pi(x,q^2)$ - mostly constrained by the momentum sum rule



- $q_\pi^{\mathrm{v}}(x,q^2)$ - well constrained by Drell-Yan process studies
  - uncertainties for $\langle x_g \rangle$ and $\langle x_{q_{\mathrm{sea}}} \rangle$
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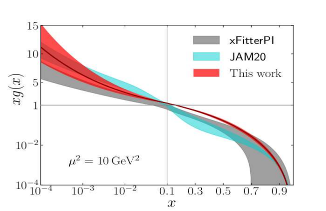

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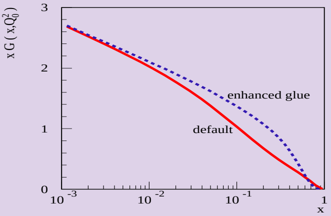
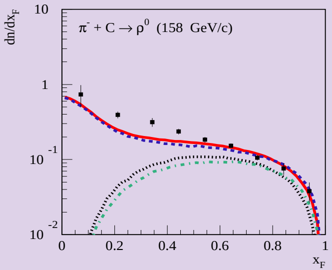
Reducing $\langle x_{q_\mathrm{v}} \rangle$ by factor 2 and enhancing $\langle x_g \rangle$ & $\langle x_{q_\mathrm{sea}} \rangle$

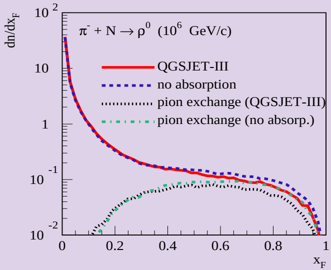


- change of N_μ: $\lesssim 1\%$
- sizable impact on π-air collisions at highest energies only (top of EAS)

Model uncertainties for predicted N_μ *[SO & Sigl, arXiv: 2404.02085]*

Neglecting absorptive corrections to the π-exchange process
⇒ higher yield of forward-produced ρ-mesons





Model uncertainties for predicted N_μ *[SO & Sigl, arXiv: 2404.02085]*

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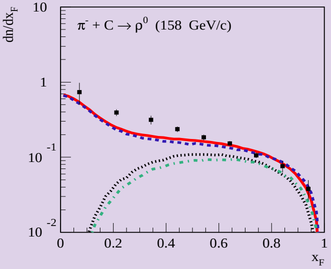
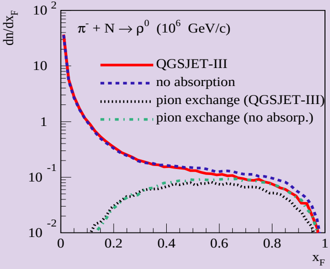
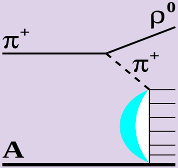
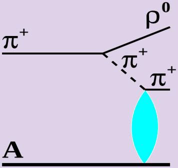




In such a case: large contribution of pion elastic scattering

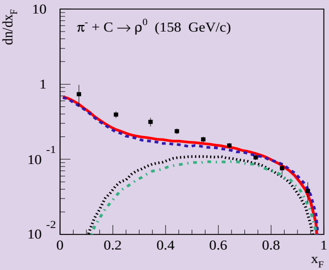


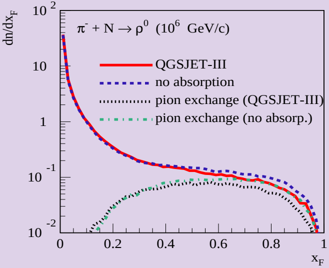


- $\sigma^{el}_{\pi-air} \to \frac{1}{2}\sigma^{tot}_{\pi-air}$ at $E_0 \to \infty$
- ⇒ scarce hadron production!

Model uncertainties for predicted N_μ *[SO & Sigl, arXiv: 2404.02085]*

Neglecting absorptive corrections to the π-exchange process $\Rightarrow$ higher yield of forward-produced ρ-mesons





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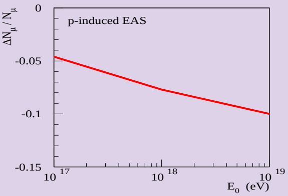
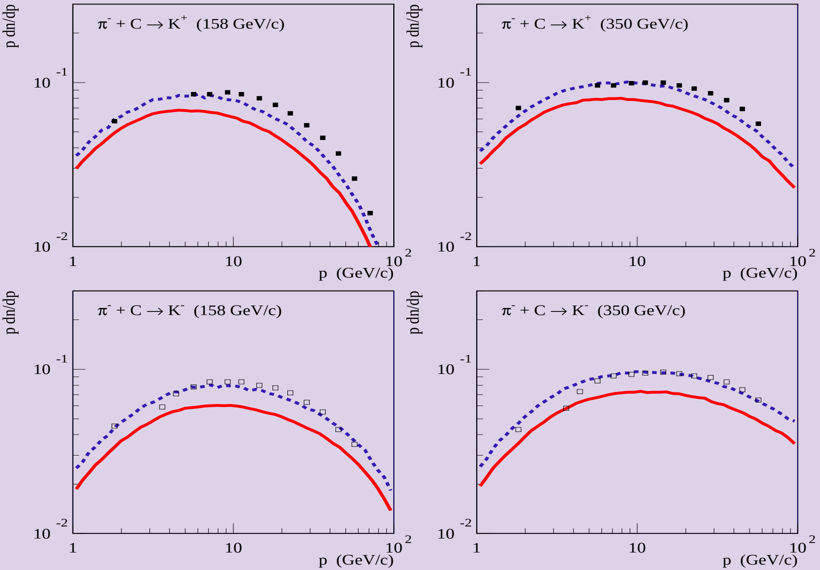


- $\sigma^{\rm el}_{\pi-{\rm air}} \to \frac{1}{2}\sigma^{\rm tot}_{\pi-{\rm air}}$ at $E_0 \to \infty$
- $\Rightarrow$ scarce hadron production!
- $\Rightarrow$ decrease of N_μ (instead of an enhancement)

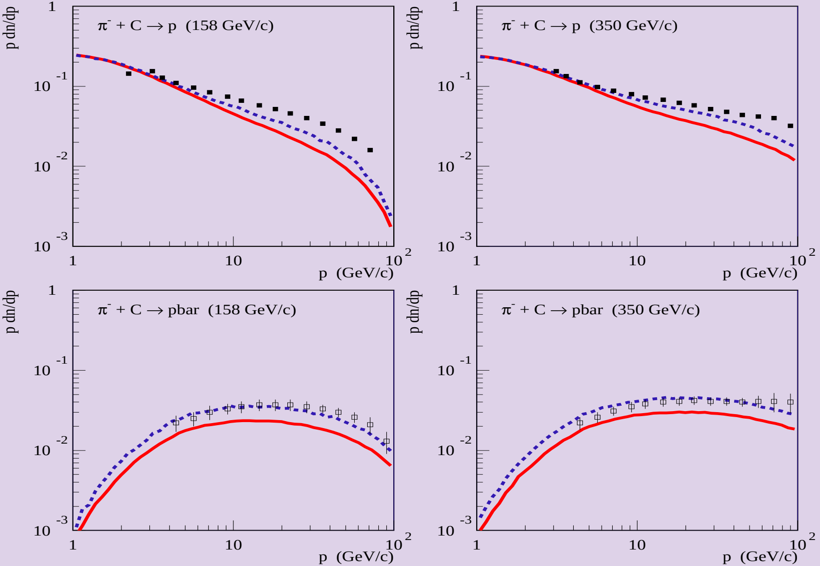
Model uncertainties for predicted N_μ *[SO & Sigl, arXiv: 2404.02085]*

Enhancing kaon production in πA collisions by 40%



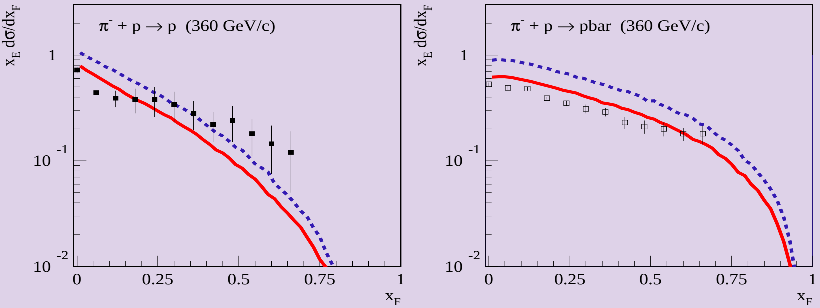
Model uncertainties for predicted N_μ *[SO & Sigl, arXiv: 2404.02085]*

Enhancing (anti)nucleon production in πA collisions by 60%



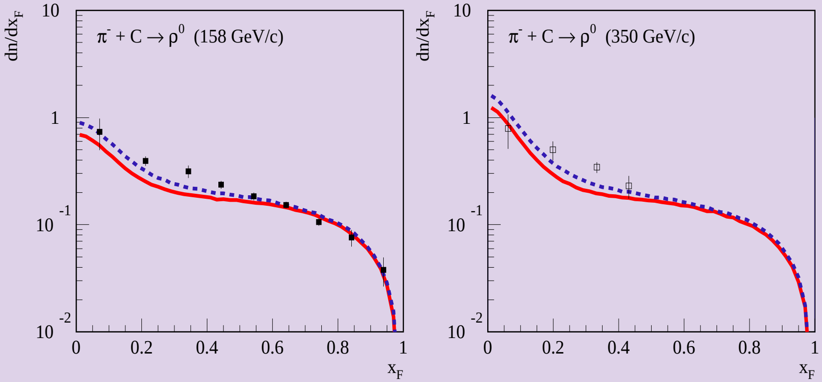
Model uncertainties for predicted N_μ *[SO & Sigl, arXiv: 2404.02085]*

NB: no kaon & (anti)nucleon 'deficit' observed in *pp* & πp



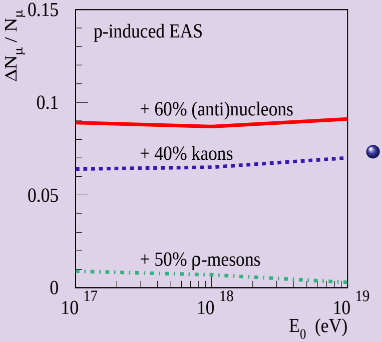
Model uncertainties for predicted N_μ *[SO & Sigl, arXiv: 2404.02085]*

Enhancing ρ-meson production in πA collisions by 50%



Model uncertainties for predicted N_μ [SO & Sigl, arXiv: 2404.02085]

Relative changes of the calculated N_μ: $\lesssim 10\%$



- small impact of the the considered enhancements on $\sum_{h=\mathrm{stable}} \langle x_E^h \rangle$

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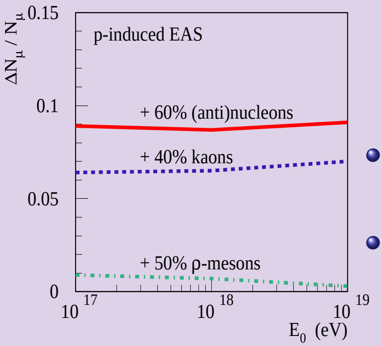

- small impact of the the considered enhancements on $\sum_{h=\text{stable}} \langle x_E^h \rangle$
- $\Rightarrow$ one can't enhance N_μ by more than $\sim 10\%$, without contradicting accelerator data!

Model uncertainties for $X_{\max}$ calculations

3 main 'switches' for changing $X_{\max}$ predictions

- inelastic proton-air cross section ($\sigma^{\rm inel}_{p-{\rm air}}$)
- inelastic diffraction rate ($\sigma^{\rm diffr}_{p-{\rm air}}/\sigma^{\rm inel}_{p-{\rm air}}$)
- inelasticity of non-diffractive interactions ($K^{\rm inel}_{p-{\rm air}}$)

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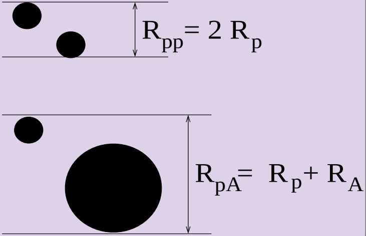
Inelastic cross section: well constrained by LHC data

- $< 3\%$ difference for $\sigma^{\rm inel}_{pp}$ between ATLAS & TOTEM (79.5 ± 1.80 & 77.41 ± 2.92 mb)
- even smaller difference for pA: $\sigma^{\rm inel}_{pp} \propto R_p^2$, $\sigma^{\rm inel}_{pA} \propto (R_p + R_A)^2$



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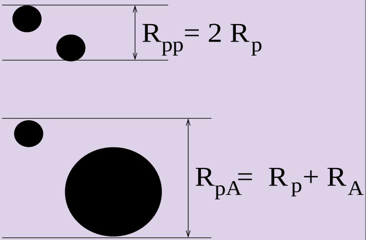

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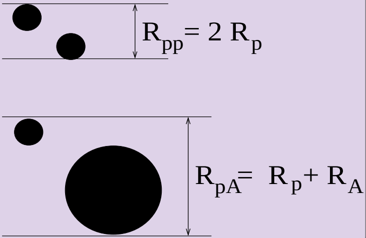

Diffraction uncertainties: $\Delta X_{\max} \lesssim 5$ g/cm^2 *[SO, PRD89 (2014) 074009]*

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The only freedom left: inelasticity for $p - \text{air}$

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  - ideally: Feynman scaling for forward spectra

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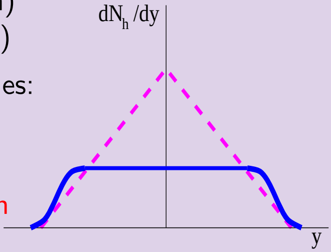
How to give less energy away to secondary hadrons?

- hadronization (string fragmentation) procedure is a 'holy cow' (universal)
- central rapidity density of secondaries: constrained by data
- main 'switch': constituent parton (string end) momentum distribution $(x^{-\alpha_q})$ *[SO, J.Phys. G29 (2003) 831]*



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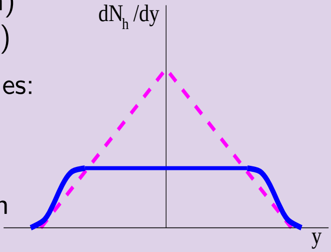

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Model uncertainties for $X_{\max}$ calculations

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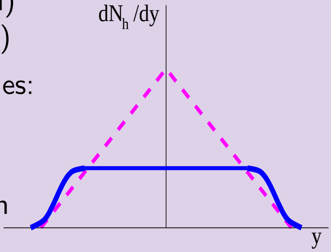
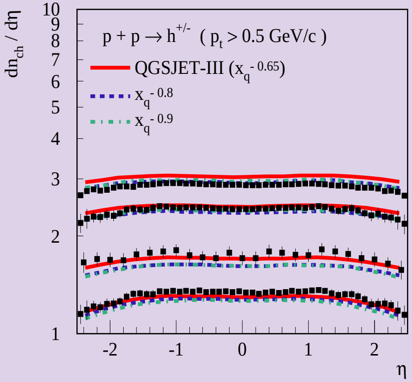


- $\alpha_q \rightarrow 1$: approximate Feynman scaling for forward spectra
- NB: may not work for semihard scattering (minijet production)

Model uncertainties for $X_{\max}$ calculations

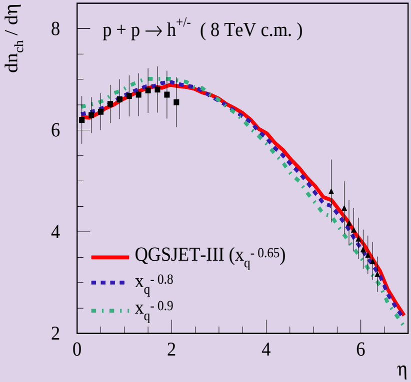
Vary the string end distributions, $x^{-\alpha_q}$: with $\alpha_q = 0.65, 0.8, 0.9$



- perform the same model tuning:
  - to fixed target data
  - and to central production at LHC

Model uncertainties for $X_{\max}$ calculations

Check with more forward data from CMS & TOTEM



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Model uncertainties for $X_{\max}$ calculations

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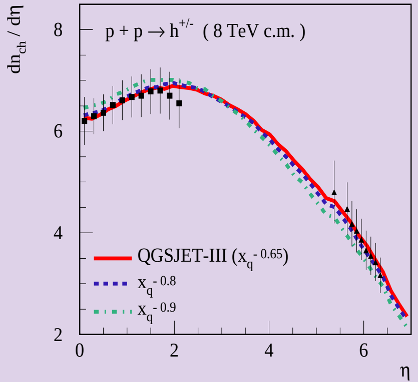

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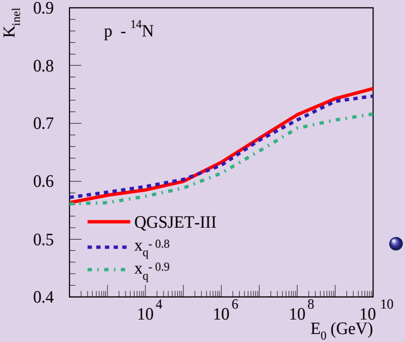
- NB: higher discrimination power expected from combined studies with central & forward detectors (e.g. LHCf & ATLAS) *[SO, Bleicher, Pierog & Werner, PRD94 (2016) 114026]*

Model uncertainties for $X_{\max}$ calculations

Choice of string end distribution ($x^{-\alpha_q}$): impact on K_{p-air}^{inel}



- up to $\simeq 6\%$ reduction of K_{p-air}^{inel}

Model uncertainties for $X_{\max}$ calculations

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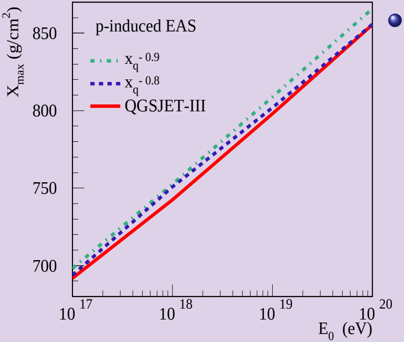
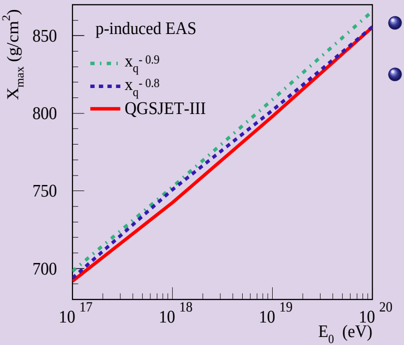


- up to $\simeq 10$ g/cm^2 shift of $X_{\max}$

Model uncertainties for $X_{\max}$ calculations

Choice of string end distribution ($x^{-\alpha_q}$): impact on $X_{\max}$



- up to $\simeq 10$ g/cm^2 shift of $X_{\max}$
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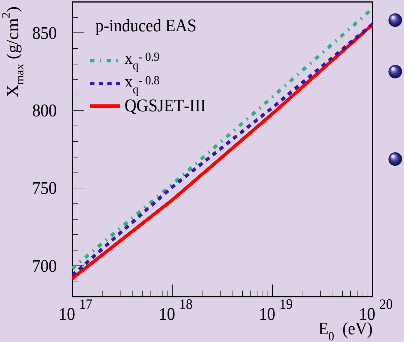
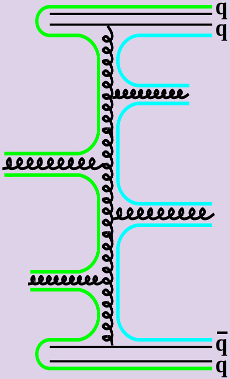


- up to $\simeq 10$ g/cm^2 shift of $X_{\max}$
- why a moderate effect on particle production & $X_{\max}$?
- 'warranted' scaling violation due to semihard scattering (energy fraction taken by perturbatively generated partons $\Rightarrow$ lower bound on $K^{\text{inel}}_{p-\text{air}}$)

Model uncertainties for $X_{\max}$ calculations

Exotic: modification of the hadronization by 'collective effects'



- standard treatment: strings of color field stretched between constituent partons and/or all perturbatively produced partons
  - $\Rightarrow$ production of partons (& hadrons) covers the full rapidity range

Model uncertainties for $X_{\max}$ calculations

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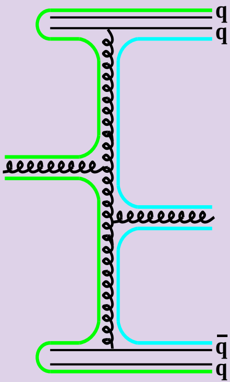

- assuming this is modified by 'collective effects' & neglecting parton cascades: strings are formed between constituent partons & highest p_t partons

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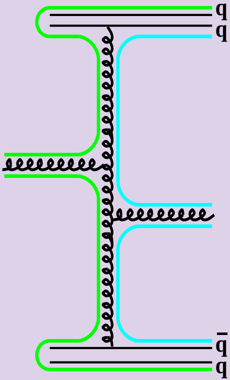

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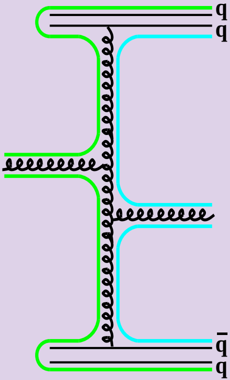

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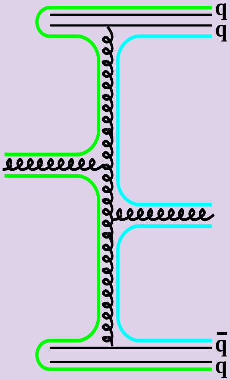

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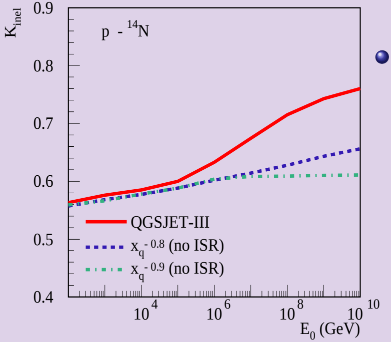
- $\alpha_q \to 1$ limit: short strings concentrated at central rapidities in c.m. frame
  - $\Rightarrow$ small impact on $K^{\text{inel}}_{p-\text{air}}$
- rather nonphysical: collective effects may be strong in central (small b) collisions only
  - $\Rightarrow$ should not have large impact on the average parton production pattern (dominated by peripheral collisions)

Model uncertainties for $X_{\max}$ calculations

Impact of string end distribution on $K^{\mathrm{inel}}_{p-\mathrm{air}}$ (no parton cascades)



- energy-dependence of $K^{\mathrm{inel}}_{p-\mathrm{air}}$ reduced drastically
  - $\alpha_q = 0.9$: $K^{\mathrm{inel}}_{p-\mathrm{air}}$ doesn't depend on energy above 1 PeV

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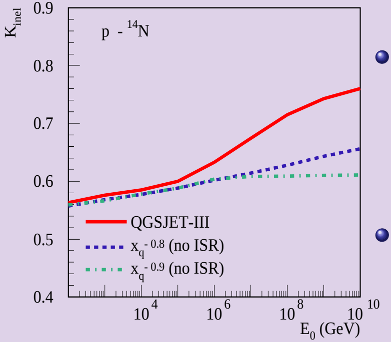

- energy-dependence of $K^{\text{inel}}_{p-\text{air}}$ reduced drastically
  - $\alpha_q = 0.9$: $K^{\text{inel}}_{p-\text{air}}$ doesn't depend on energy above 1 PeV
- $\Rightarrow$ (mini)jet production has no impact on the inelasticity in the $\alpha_q \to 1$ limit

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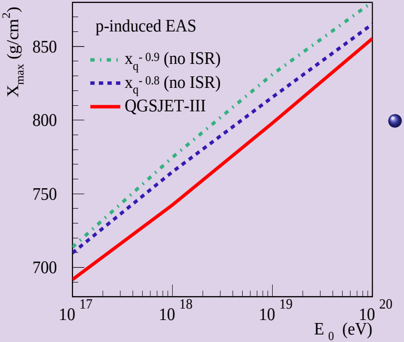

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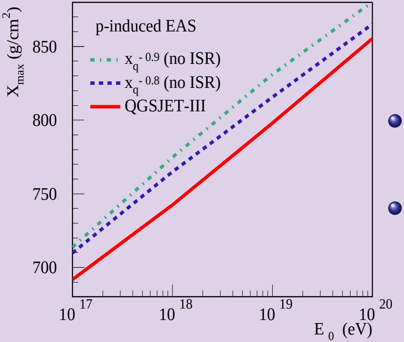
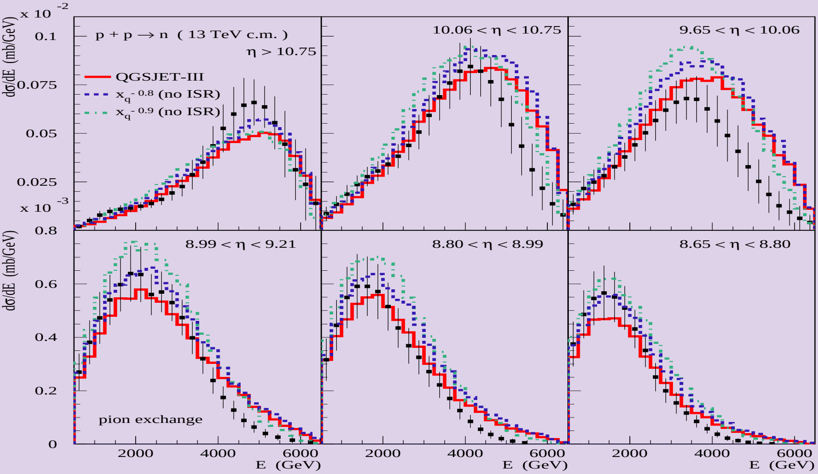


- up to $\simeq 25$ g/cm^2 shift of $X_{\max}$ ($\alpha_q = 0.9$)
- can be refuted/constrained by LHC data?

Model uncertainties for $X_{\max}$ calculations

The limit $\alpha_q \to 1$: disfavored by LHCf data on forward neutrons



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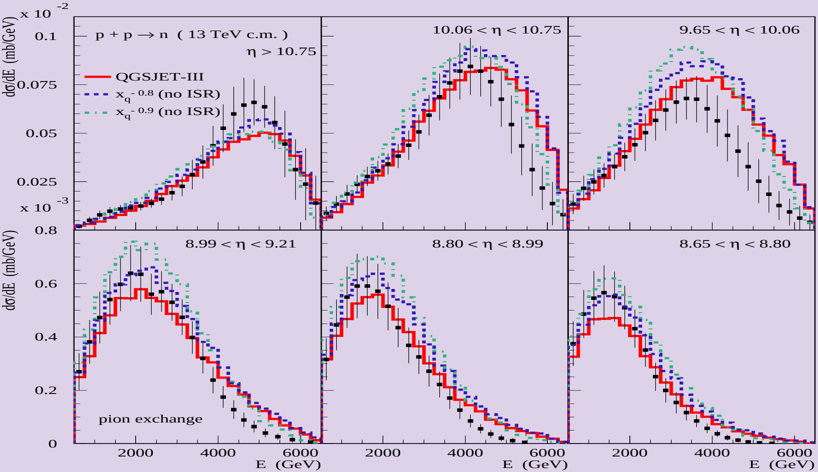

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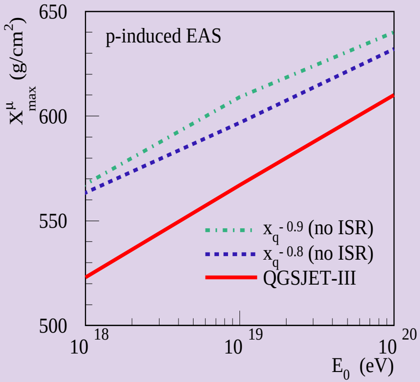
Model uncertainties for $X_{\max}$ calculations

More important constraints: from PAO measurements of $X^{\mu}_{\max}$



- any change of $X_{\max}$ $\Rightarrow$ similar (or even larger) shift of $X^{\mu}_{\max}$

  [see backup slides]

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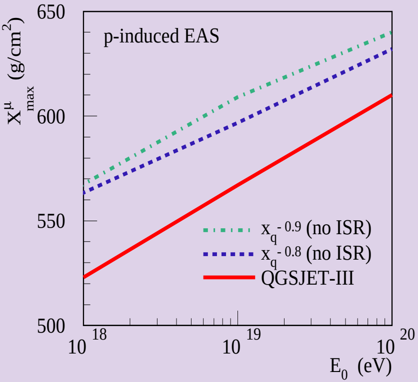

- any change of $X_{\max}$ $\Rightarrow$ similar (or even larger) shift of $X^{\mu}_{\max}$ *[see backup slides]*
- $\alpha_q \to 1$: up to ~ 30 g/cm^2 larger $X^{\mu}_{\max}$
  - $\Rightarrow$ strong tension with PAO measurements of $X^{\mu}_{\max}$

Outlook

- Major development in QGSJET-III: phenomenological treatment of HT corrections to hard scattering processes
  - tames the low p_t rise of (mini)jet rates
  - reduces the model dependence on the low p_t cutoff Q_0
- Technical improvement: treatment of π-exchange process
  - energy-dependence: due to absorptive corrections (probability not to have additional inelastic rescattering)
- Rather small changes for EAS characteristics (wrt QGSJET-II)
  - up to $\simeq 10$ g/cm^2 shift of $X_{\max}$ and up to $\simeq 5\%$ change of N_μ
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Extra slides follow

(1) Few comments on the parton saturation mechanism

Usually a picture of a crowded bus in mind

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Observable are consequences of (hard) interactions of partons

- correct argument: not too many boxing pairs at the same ring

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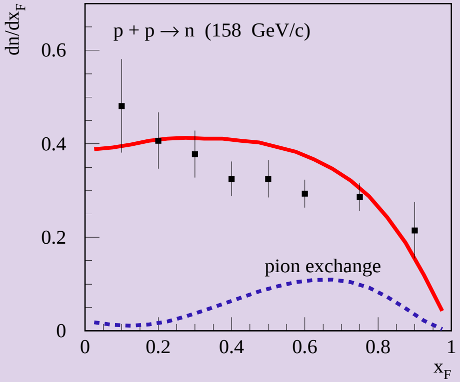
- but: one may have arbitrary many virtual boxers at the ring, if they don't fight (no problem with unitarity)
- above-discussed: mechanism preventing partons from 'fighting each other'

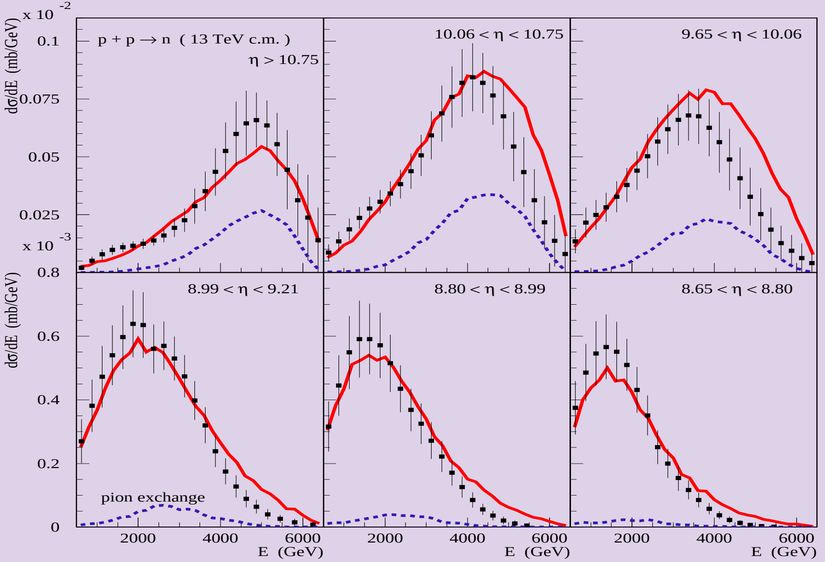
(2) Technical improvement: π-exchange process

Starting with NA49 data at 158 GeV/c



(2) Technical improvement: π-exchange process

And moving over 6 energy decades to 13 TeV c.m.



(3) Hard scattering: importance of the parton cascade

- high energies ⇒ quick rise of (mini)jet production
  - 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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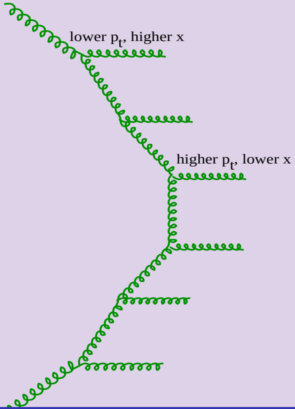

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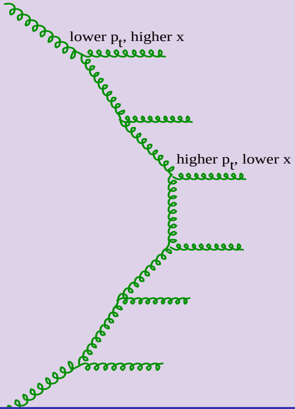

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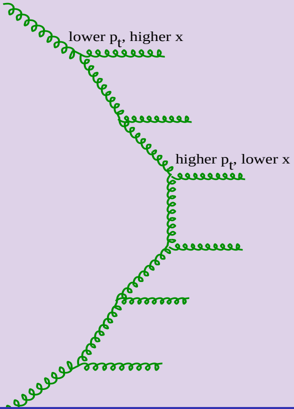

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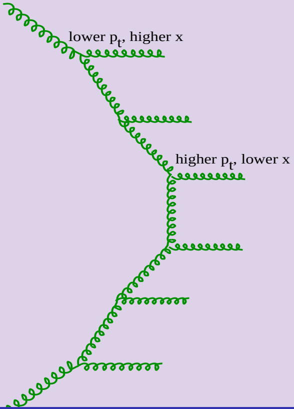
  ($f_g(x,Q_0^2) \propto x^{-1-\Delta_g}$, $\Delta_g \simeq 0.2$)
- no: *x*-distribution of those gluons is weighted with the hard scattering!



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Virtual gluons emitted by protons are indeed soft: $\propto x^{-1-\Delta_g}$

- but the probability for hard scattering: convolution with $\sigma_{gg}^{\rm hard}$

$$w_{\rm hard}(s) \propto \int dx^+ dx^- \; f_g(x^+, Q_0^2)\, f_g(x^-, Q_0^2)\; \sigma_{gg}^{\rm hard}(x^+ x^- s, Q_0^2)$$

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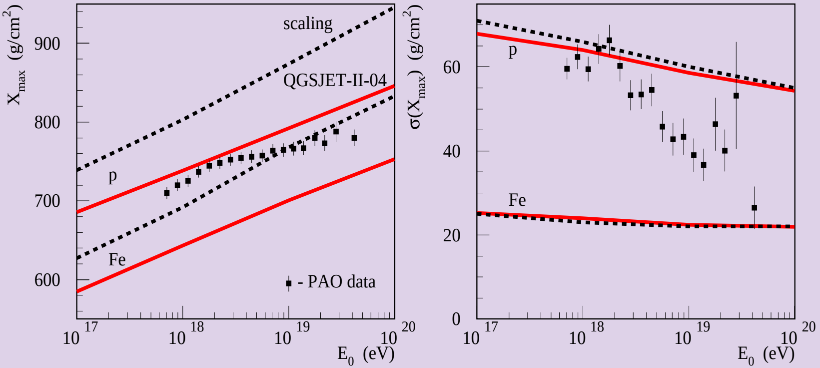
- $\sigma_{gg}^{\rm hard}(\hat{s}, Q_0^2) \propto \hat{s}^{\Delta_{\rm hard}}$ – contribution of the DGLAP 'ladder'
- $\Rightarrow$ gluons which succeed to interact have large x: $\propto x^{\Delta_{\rm hard}-\Delta_g-1}$ (iff $\Delta_{\rm hard} \simeq 0.3 > \Delta_g$)
  - i.e., first partons in a perturbative cascade are 'valence-like' (independently on our assumptions for string end distribution)

(4) PAO data: what kind of interaction physics is required?

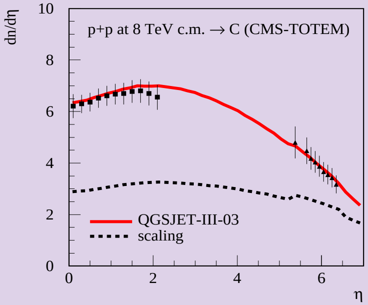
Extreme case - Feynman scaling: same $\sigma(X_{\max})$, much deeper $X_{\max}$



- $\sigma^{\rm inel}_{p-\rm air}$, $\sigma^{\rm inel}_{A-\rm air}$, $\sigma^{\rm inel}_{\pi-\rm air}$ - all kept unchanged (wrt QGSJET-II-04)
- nonlinear effects & hard scattering switched off (K-factor=0, $G_{\mathbb{PPP}} = 0$, $K_{\rm HT} = 0$)
- production spectra - frosen at 100 GeV lab.

(4) Scaling model is dead since > 50 years

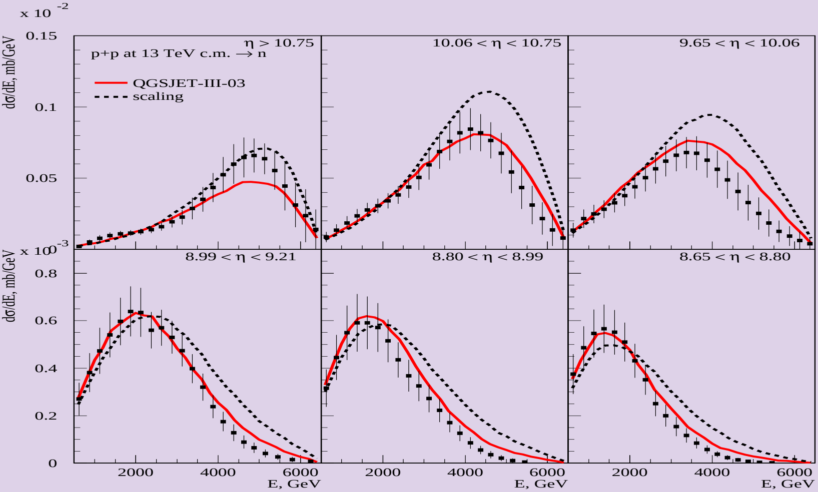
Since it misses the observed rise of the 'rapidity plato' $dN^{\rm ch}_{pp}/d\eta$



- $dN^{\rm ch}_{pp}/d\eta$ at small η: of weak importance for EAS (small $x_{\rm F}$)

(4) Scaling model is dead since > 50 years

More important: LHCf data on forward neutrons - measure of K_{pp}^{inel}

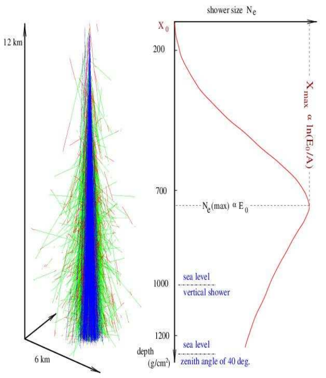


- scaling: energy loss of leading nucleons is underestimated

(4) Most general warning regarding large $X_{\max}$ predictions

Changing $X_{\max}$ implies equal or larger changes for $X_{\max}^{\mu}$

- any change of the primary interaction ($\sigma_{p-\mathrm{air}}^{\mathrm{inel}}$, $\sigma_{p-\mathrm{air}}^{\mathrm{diffr}}$, $K_{p-\mathrm{air}}^{\mathrm{inel}}$) impacts only the initial stage of EAS development



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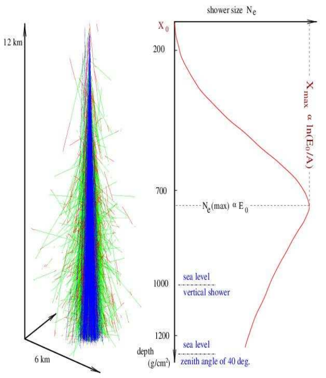

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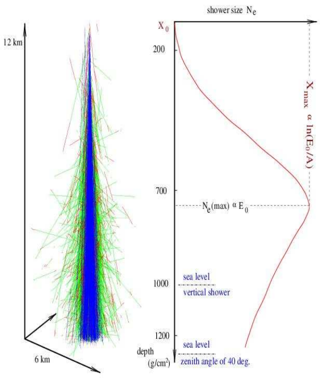
- $\Rightarrow$ parallel up/down shift of the cascade profile (same shape)
- $\Rightarrow$ same effect on $X_{\max}$ & $X^{\mu}_{\max}$



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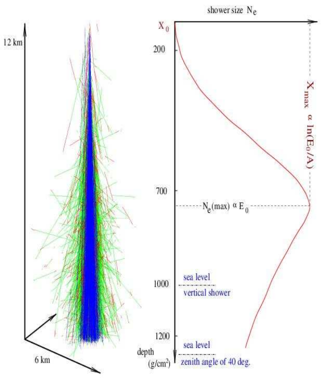
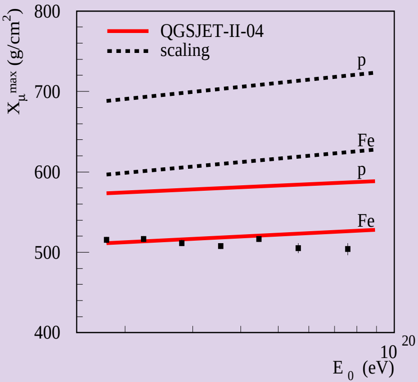
Changing $X_{\max}$ implies equal or larger changes for $X_{\max}^{\mu}$

- any change of the primary interaction ($\sigma_{p-\mathrm{air}}^{\mathrm{inel}}$, $\sigma_{p-\mathrm{air}}^{\mathrm{diffr}}$, $K_{p-\mathrm{air}}^{\mathrm{inel}}$) impacts only the initial stage of EAS development
- $\Rightarrow$ parallel up/down shift of the cascade profile (same shape)
- $\Rightarrow$ same effect on $X_{\max}$ & $X_{\max}^{\mu}$
- additionally: the corresponding change of physics impacts π-air interactions at all the steps of the cascade development
  - $\Rightarrow$ cumulative effect on $X_{\max}^{\mu}$



(4) Most general warning regarding large $X_{\max}$ predictions

Changing $X_{\max}$ implies equal or larger changes for $X^{\mu}_{\max}$



- e.g. using Feynman scaling: UHECRs are transuraniums