Extensive air shower predictions: sufficiently constrained by accelerator data?

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Hamburg University

Cosmic Rays and Neutrinos in the Multi-Messenge Era

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arXiv: 2401.06202; 2403.16106; 2404.02085; 2409.05501

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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What kind of physics is behind this cutoff?

- 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 $1/p_\mathrm{t}^n$]

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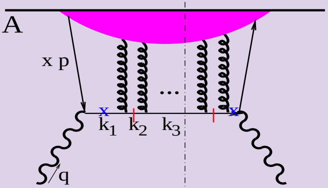
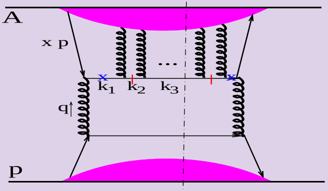
HT effects in $\gamma^* A/pA$: coherent multiple scattering on 'soft' gluons

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





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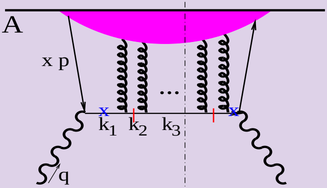

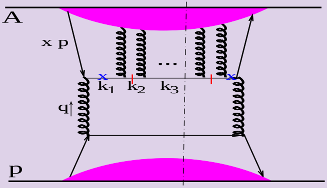

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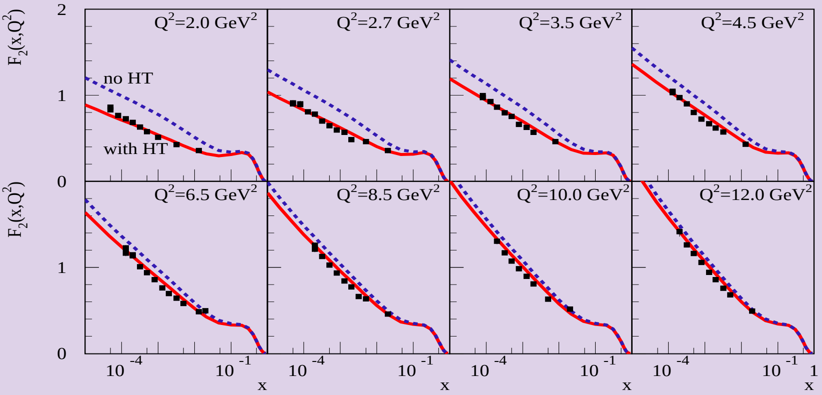
Extrapolation to hadron-proton & light nuclei

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

Dynamical higher twist effects in hadronic scattering

NB: only moderate HT corrections allowed by HERA data



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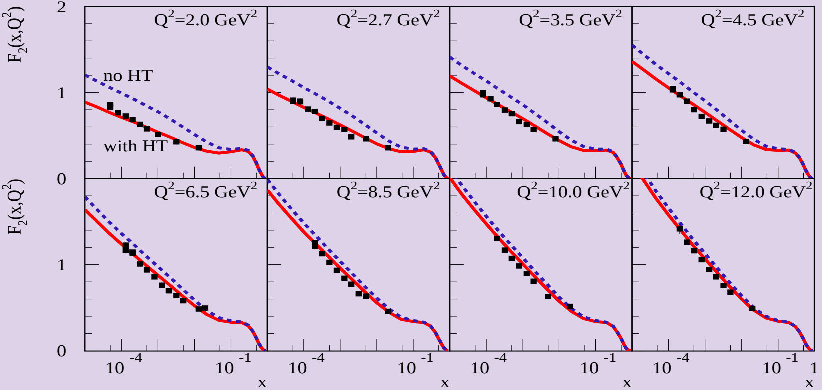
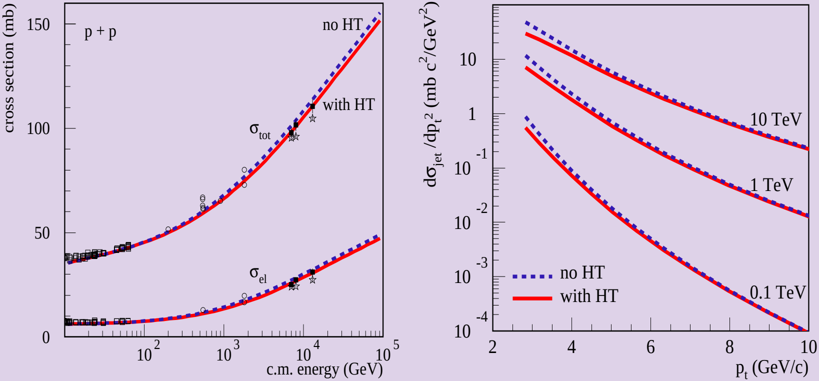


- HT corrections important at low Q^2
  - $\Rightarrow$ too strong corrections at tension with Q^2-evolution of F_2
- known fact: Q^2-evolution of F_2 is well-described by DGLAP
  - $\Rightarrow$ little space for HT or/and saturation effects

Dynamical higher twist effects in hadronic scattering

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

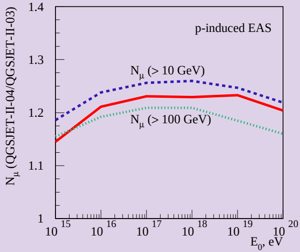


- $\Rightarrow$ the mechanism does its principal job

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

π- over ρ-exchange dominance $\Rightarrow \sim 20\%$ increase of N_μ

- why so?!



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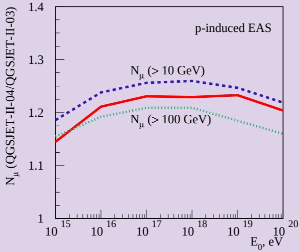

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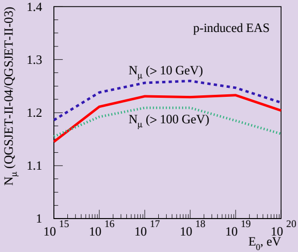

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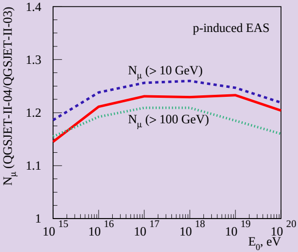

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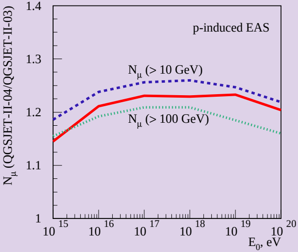

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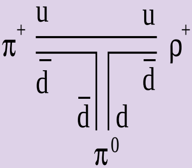

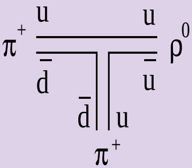

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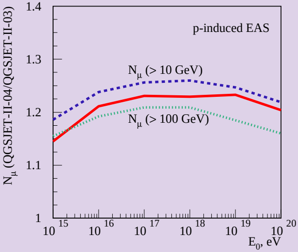

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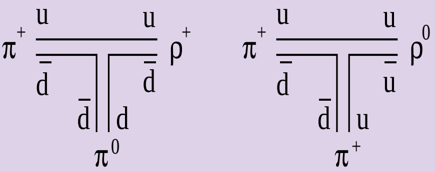

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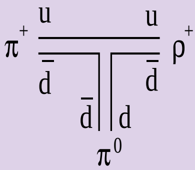

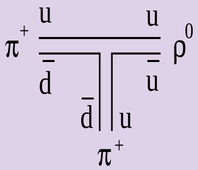

Energy-dependence: driven by absorptive corrections to the process

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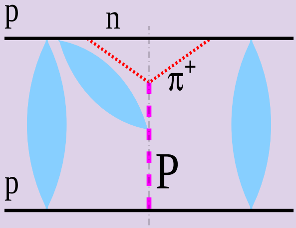

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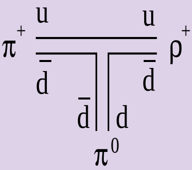

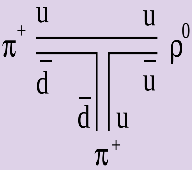

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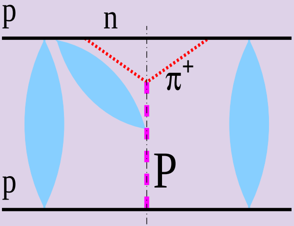
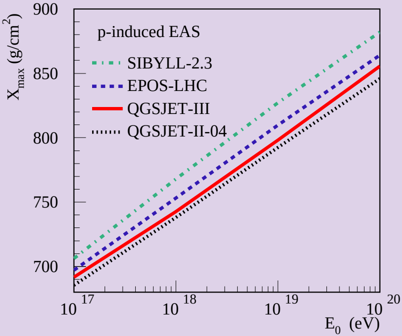
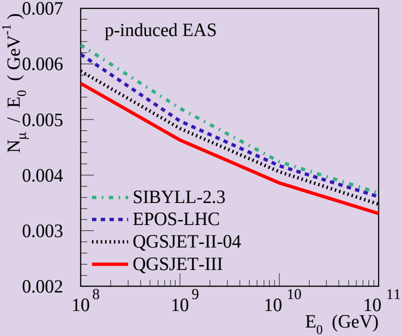
- now can be tested in $pp \to nX$ thanks to LHCf data *[backup slides]*



Results for extensive air showers *[SO, arXiv: 2403.16106]*

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





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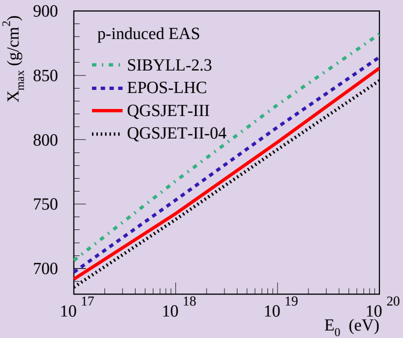

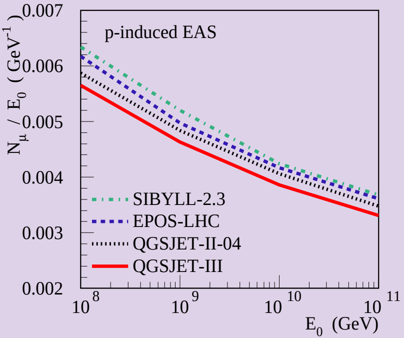

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What is the reason for the stability of the predictions?

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

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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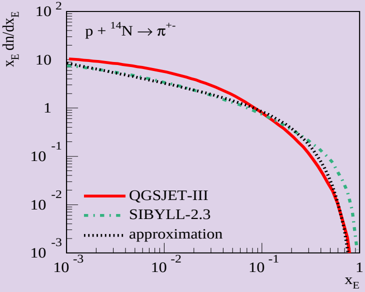

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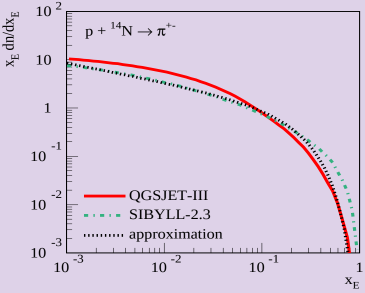
- largest contribution from $\langle x_\pi \rangle \simeq \frac{\alpha_\mu-\Delta}{\alpha_\mu+\beta-1-\Delta} \sim 0.1$
  ($\Delta \simeq 0.4$, $\alpha_\mu \simeq 0.9$, $\beta \simeq 4.5$)



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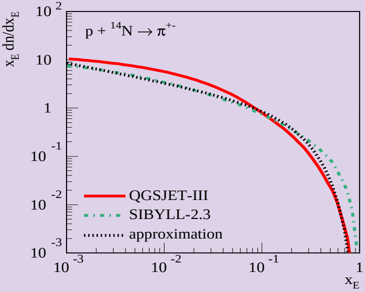
- relevant $\langle x_\pi \rangle$ for π-air interactions follows similarly



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

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

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

- relevant quantity for EAS muon content:
  $\sum_{h=\mathrm{stable}} \langle (x_E^h)^{\alpha_\mu} \rangle = \sum_{h=\mathrm{stable}} \int dx_E \, x_E^{\alpha_\mu} \, \frac{dN^h_{\pi^\pm \mathrm{air}}(E_0,x_E)}{dx_E}$
- can be well approximated by $\sum_{h=\mathrm{stable}} \langle x_E^h \rangle$ $(\alpha_\mu \to 1)$

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

Kinematic range for hadron production, relevant for N_μ predictions

- let us restrict ourselves with pion production only:
  $N_p^\mu(E_0) \simeq \int dx \, \frac{dN^{\pi^\pm}_{p-\mathrm{air}}(E_0,x)}{dx} \, N^\mu_{\pi^\pm}(xE_0)$
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- NB: $\sum_{h=\mathrm{stable}} \langle x_E^h \rangle \simeq 1 - \langle x_E^{\pi^0} \rangle$

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

How to increase $\sum_{h=\mathrm{stable}} \langle x_E^h \rangle$ (decrease $\langle x_E^{\pi^0} \rangle$)?

- change the energy dependence of the pion exchange process $\Rightarrow$ larger forward yield of ρ-mesons $\Rightarrow$ higher $\langle E_{\pi^\pm} \rangle / \langle E_{\pi^0} \rangle$

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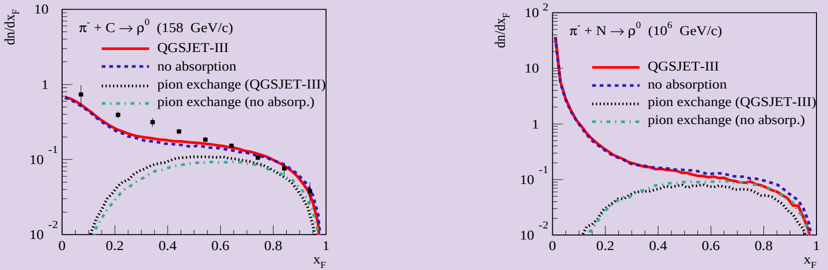
- change the model calibration (e.g. based on NA61 data): more kaons & (anti)nucleons

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

Neglecting absorptive corrections to the π-exchange process: larger forward production of ρ-mesons at higher energies



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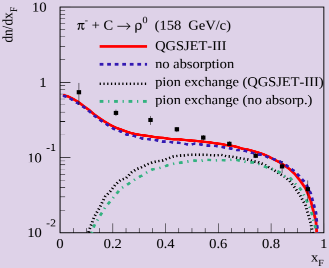
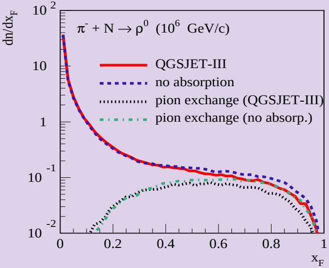
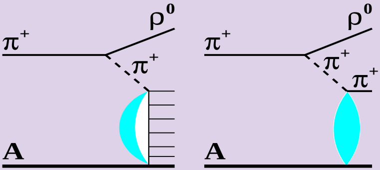




In such a case: large contribution of pion elastic scattering



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

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

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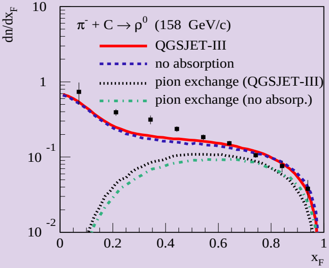

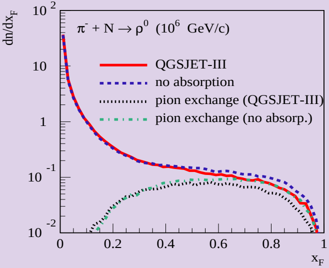

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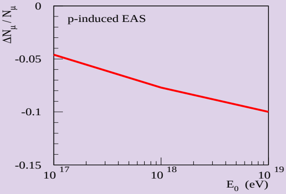
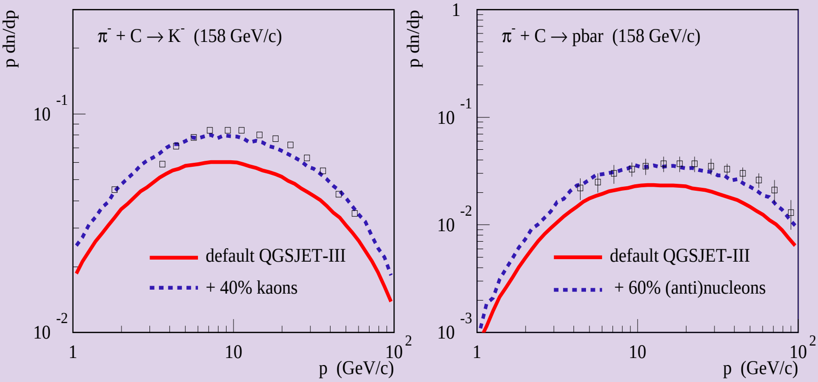


- $\sigma^{\rm el}_{\pi-{\rm air}} \longrightarrow \frac{1}{2}\sigma^{\rm tot}_{\pi-{\rm air}}$ at $E_0 \longrightarrow \infty$
- $\Rightarrow$ scarce hadron production!
- $\Rightarrow$ decrease of N_μ (instead of an enhancement)

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

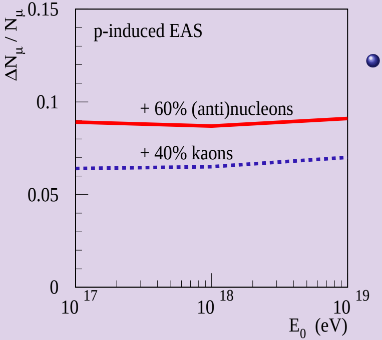
NA61 data: very high yields of kaons & (anti)protons in $\pi^- C$



- $\simeq 40\%$ more kaons & $\simeq 60\%$ more (anti)protons required
- NB: such enhancements create a tension with other data on kaon & (anti)proton production in πp & pp interactions

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

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



- why?

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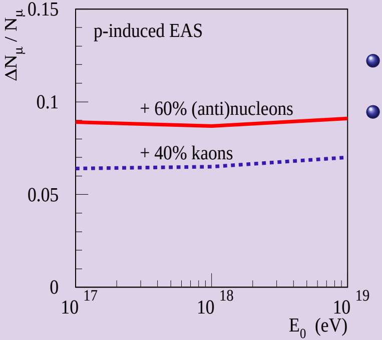

- why?
- small impact of the the considered enhancements on $\sum_{h=\text{stable}} \langle x_E^h \rangle$ (changes mostly affect central hadron production)

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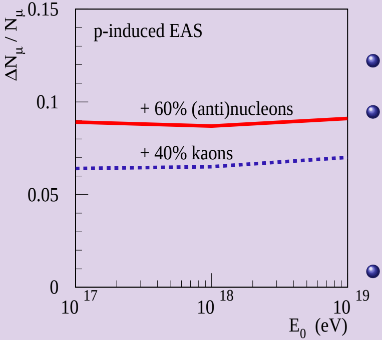

- why?
- small impact of the the considered enhancements on $\sum_{h=\text{stable}} \langle x_E^h \rangle$ (changes mostly affect central hadron production)
- $\Rightarrow$ accelerator data allow one to enhance N_μ by up to $\sim 10\%$

Model uncertainties for $X_{\max}$ *[SO & Sigl, arXiv: 2409.05501]*

Predictions for EAS maximum depth $X_{\max}$: 3 main 'switches'

- 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 for p-air 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)
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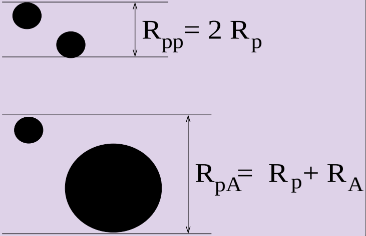

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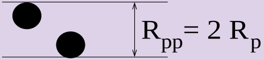

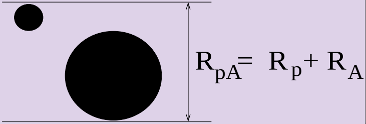

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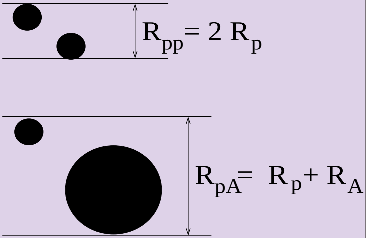

Diffraction uncertainties: $\Delta X_{\max} \lesssim 5$ g/cm^2 *[SO, PRD89 (2014) 074009]*

Model uncertainties for $X_{\max}$ *[SO & Sigl, arXiv: 2409.05501]*

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

- higher energy $\Rightarrow$ higher multiple scattering $\Rightarrow$ higher $K_{p-\text{air}}^{\text{inel}}$

Model uncertainties for $X_{\max}$ *[SO & Sigl, arXiv: 2409.05501]*

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    - ideally: Feynman scaling for forward spectra

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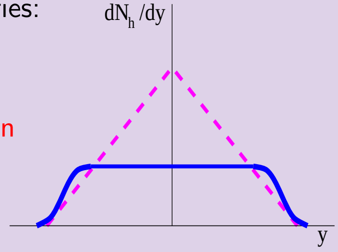
How to give less energy away to secondary hadrons?

- 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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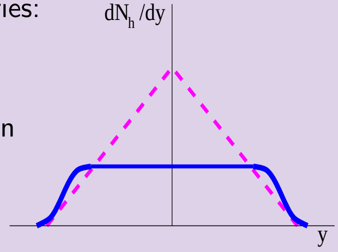
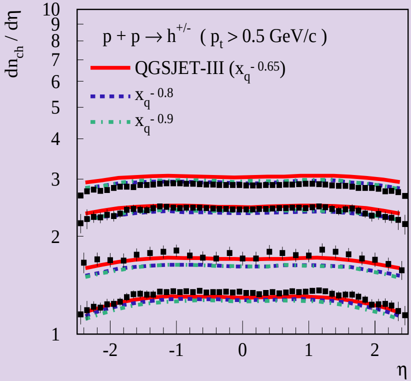


- $\alpha_q \to 1$: approximate Feynman scaling for forward spectra
- NB: may not work for semihard scattering (minijet production)

Model uncertainties for $X_{\max}$ *[SO & Sigl, arXiv: 2409.05501]*

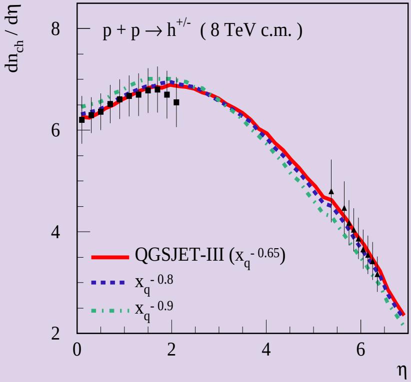
Vary the string end distributions, $x^{-\alpha_q}$: with $\alpha_q = 0.65, 0.8, 0.9$



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

Model uncertainties for $X_{\max}$ *[SO & Sigl, arXiv: 2409.05501]*

Check with more forward data from CMS & TOTEM



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Model uncertainties for $X_{\max}$ *[SO & Sigl, arXiv: 2409.05501]*

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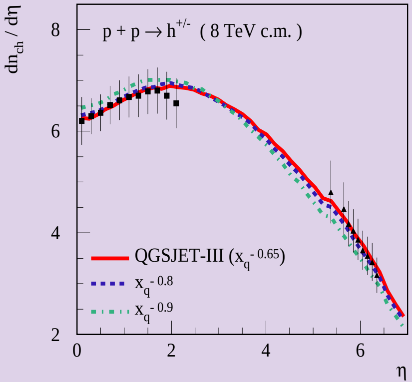
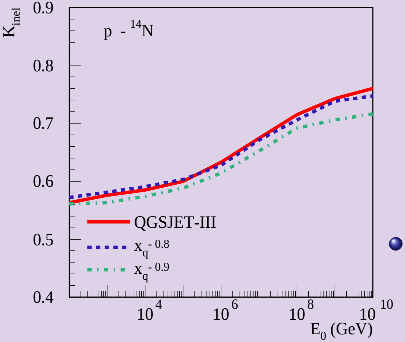


- the trend towards larger α_q not supported
- but can not yet be disproved

- 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 $X_{\max}$ *[SO & Sigl, arXiv: 2409.05501]*

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



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

Model uncertainties for $X_{\max}$ *[SO & Sigl, arXiv: 2409.05501]*

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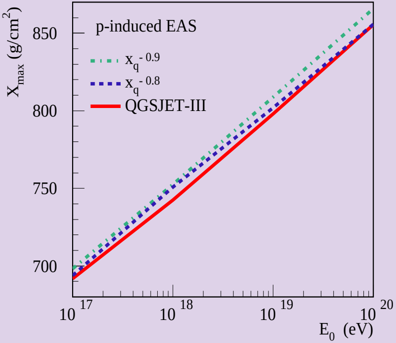

- up to $\simeq 10$ g/cm^2 shift of $X_{\max}$

Model uncertainties for $X_{\max}$ *[SO & Sigl, arXiv: 2409.05501]*

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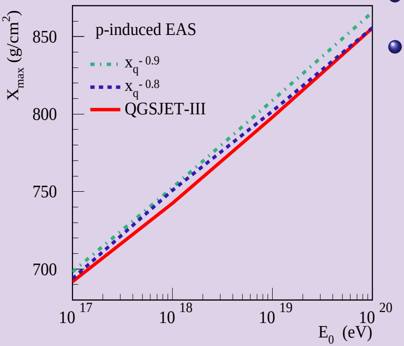

- up to $\simeq 10$ g/cm^2 shift of $X_{\max}$
- why a moderate effect on particle production & $X_{\max}$?

Model uncertainties for $X_{\max}$ *[SO & Sigl, arXiv: 2409.05501]*

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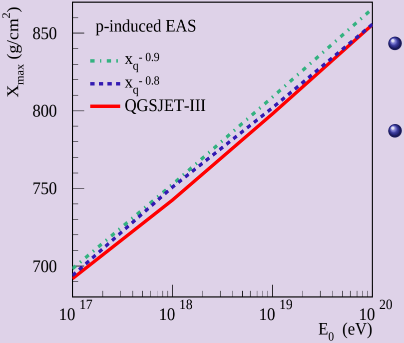
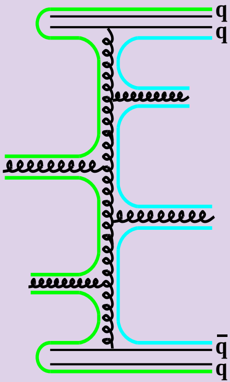


- up to $\simeq 10$ g/cm^2 shift of $X_{\max}$
- why a moderate effect on particle production & $X_{\max}$?
- 'warranted' scaling violation due to semihard scattering (energy fraction taken by perturbatively generated partons $\Rightarrow$ lower bound on $K_{p-\mathrm{air}}^{\mathrm{inel}}$)

[see backup slides]

Model uncertainties for $X_{\max}$ *[SO & Sigl, arXiv: 2409.05501]*

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

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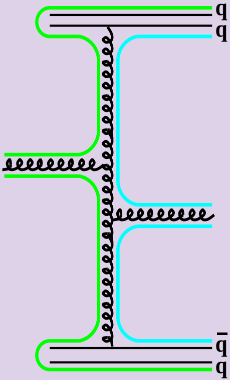

- assuming this is modified by 'collective effects' & neglecting parton cascades: strings are formed between constituent partons & highest p_t partons

Model uncertainties for $X_{\max}$ *[SO & Sigl, arXiv: 2409.05501]*

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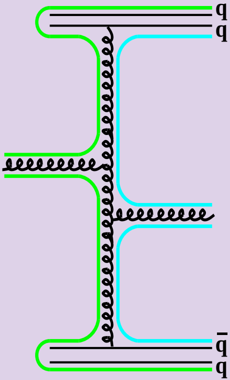

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- $\alpha_q \to 1$ limit: short strings concentrated at central rapidities in c.m. frame
  - $\Rightarrow$ small impact on $K^{\rm inel}_{p-{\rm air}}$

Model uncertainties for $X_{\max}$ *[SO & Sigl, arXiv: 2409.05501]*

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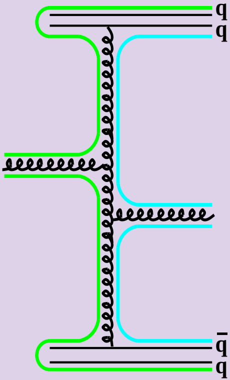

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- rather nonphysical: collective effects may be strong in central (small b) collisions only

Model uncertainties for $X_{\max}$ [SO & Sigl, arXiv: 2409.05501]

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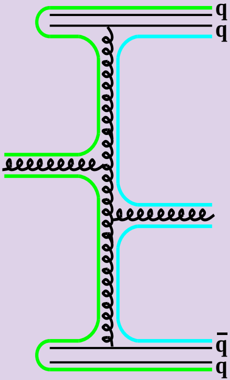

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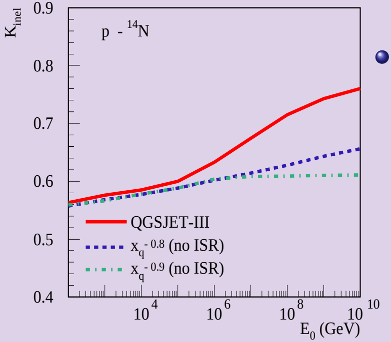
- $\alpha_q \rightarrow 1$ limit: short strings concentrated at central rapidities in c.m. frame
  - $\Rightarrow$ small impact on $K^{\text{inel}}_{p-\text{air}}$
- rather nonphysical: collective effects may be strong in central (small b) collisions only
  - $\Rightarrow$ should not have large impact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

Model uncertainties for $X_{\max}$ *[SO & Sigl, arXiv: 2409.05501]*

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



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

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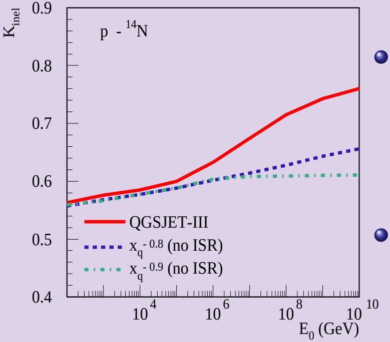
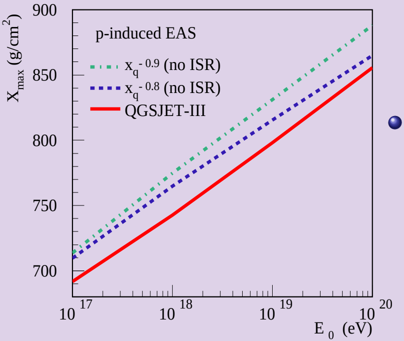


- energy-dependence of $K^{\rm inel}_{p-\rm air}$ reduced drastically
  - $\alpha_q = 0.9$: $K^{\rm inel}_{p-\rm air}$ doesn't depend on energy above 1 PeV
- $\Rightarrow$ (mini)jet production has no impact on the inelasticity in the $\alpha_q \to 1$ limit

Model uncertainties for $X_{\max}$ *[SO & Sigl, arXiv: 2409.05501]*

Impact of string end distribution on $X_{\max}$ (no parton cascades)



- up to $\simeq 30$ g/cm^2 shift of $X_{\max}$ ($\alpha_q = 0.9$)

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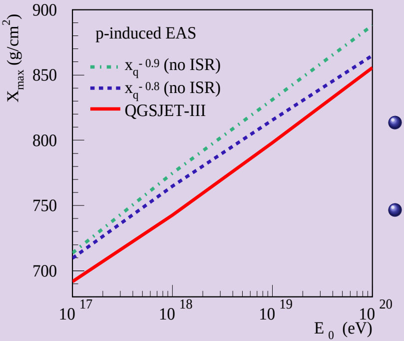

- up to $\simeq 30$ g/cm^2 shift of $X_{\max}$ ($\alpha_q = 0.9$)
- can be refuted/constrained by LHC data?

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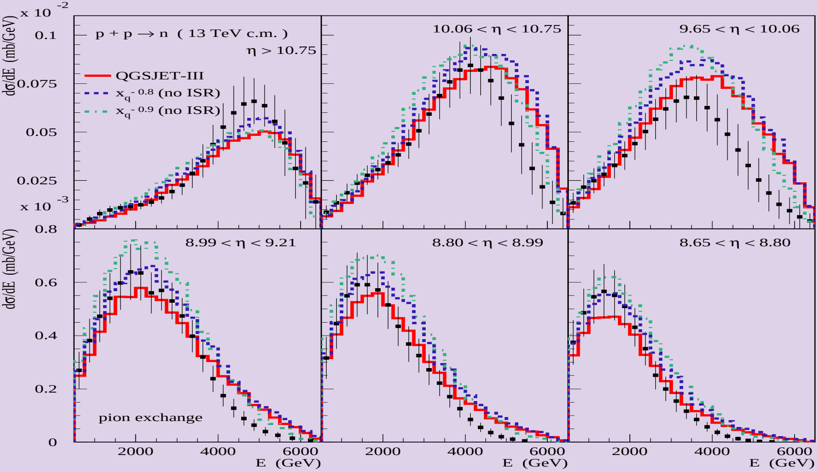
The limit $\alpha_q \to 1$: disfavored by LHCf data on forward neutrons



- $\alpha_q \to 1$: forward neutron yield exceeds the measured one

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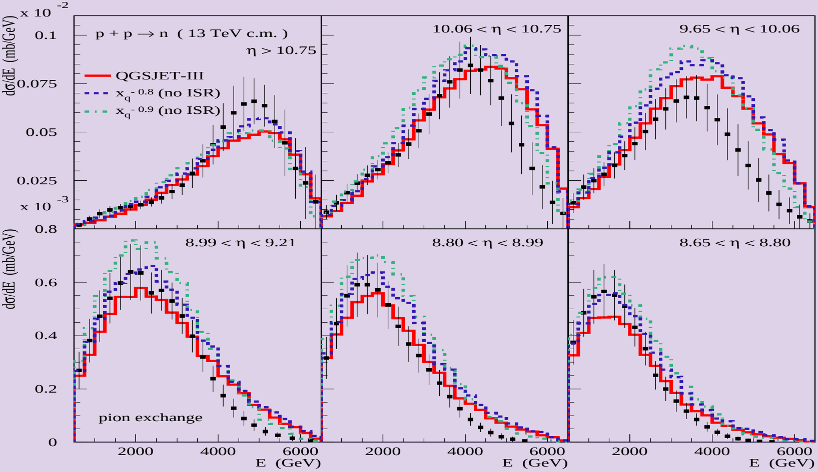
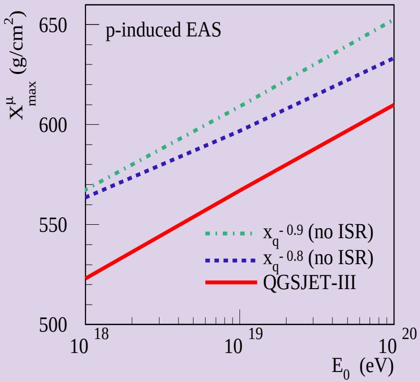


- $\alpha_q \to 1$: forward neutron yield exceeds the measured one
- $\Rightarrow$ energy loss of leading nucleons is underestimated

Model uncertainties for $X_{\max}$ *[SO & Sigl, arXiv: 2409.05501]*

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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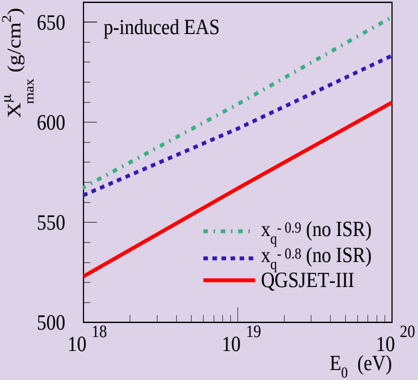

- any change of $X_{\max}$ $\Rightarrow$ similar (or even larger) shift of $X^{\mu}_{\max}$ *[see backup slides]*
- $\alpha_q \to 1$: up to ~ 40 g/cm^2 larger $X^{\mu}_{\max}$
  - $\Rightarrow$ strong tension with PAO measurements of $X^{\mu}_{\max}$

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
- Model uncertainties for N_μ: only up to $\sim 10\%$ enhancement
- Model uncertainties for $X_{\max}$: only up to ~ 10 g/cm^2 shift (using the standard interaction treatment)
- More exotic: 'collective effects' $\Rightarrow \Delta X_{\max}$ up to $\simeq 30$ g/cm^2
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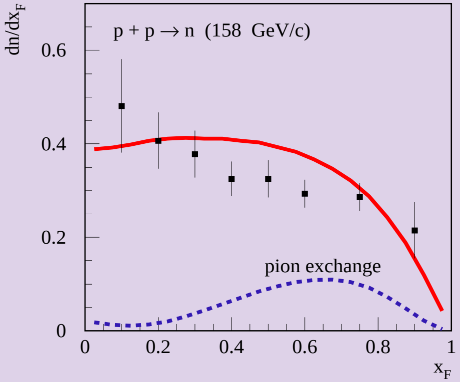
Extra slides follow

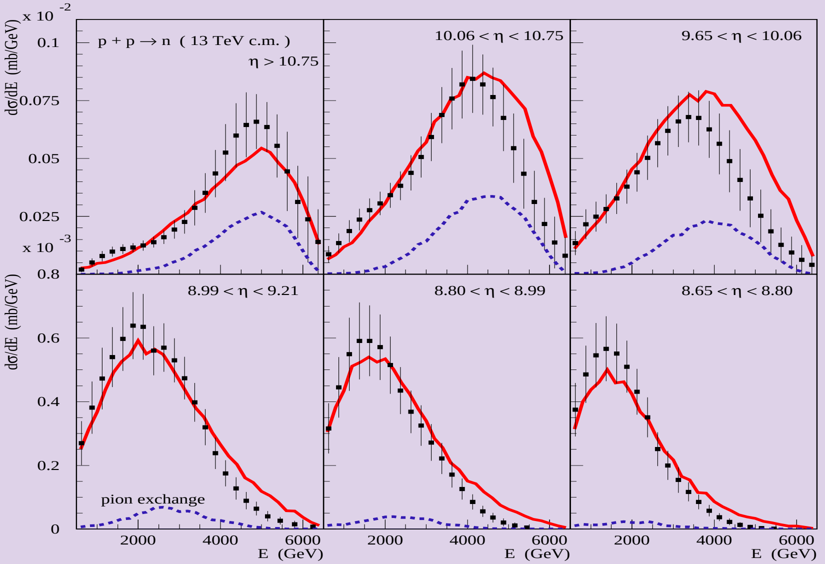
(1) Technical improvement: π-exchange process

Starting with NA49 data at 158 GeV/c



(1) Technical improvement: π-exchange process

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



(2) 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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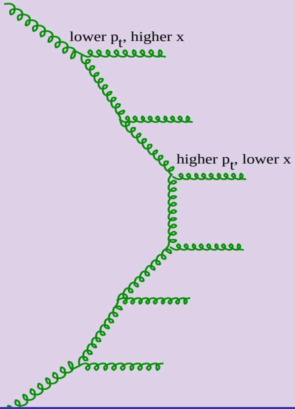
- hadron jets: typically produced in central region ($y \sim 0$) in c.m.s.
  - small impact on forward spectra



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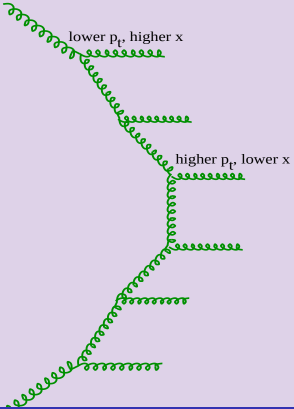
  - $\Rightarrow$ most important are first ('softest') partons in the cascade



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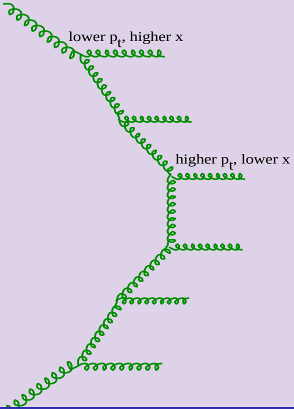

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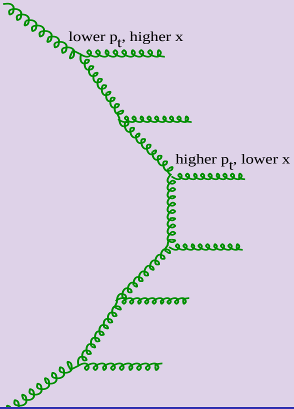
- no: *x-distribution of those gluons is weighted with the hard scattering!*



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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 $\sigma_{gg}^{\mathrm{hard}}$

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

- $\sigma_{gg}^{\mathrm{hard}}(\hat{s}, Q_0^2) \propto \hat{s}^{\Delta_{\mathrm{hard}}}$ – contribution of the DGLAP 'ladder'

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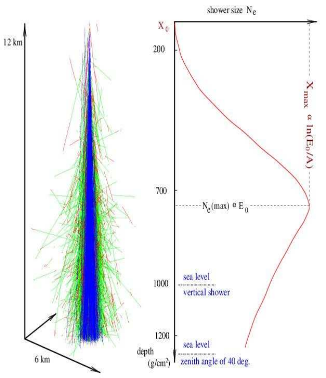
- $\sigma_{gg}^{\text{hard}}(\hat{s}, Q_0^2) \propto \hat{s}^{\Delta_{\text{hard}}}$ – contribution of the DGLAP 'ladder'
- $\Rightarrow$ gluons which succeed to interact have large x: $\propto x^{\Delta_{\text{hard}}-\Delta_g-1}$ (iff $\Delta_{\text{hard}} \simeq 0.3 > \Delta_g$)
  - i.e., first partons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

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

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

- any change of the primary interaction ($\sigma^{\rm inel}_{p-{\rm air}}$, $\sigma^{\rm diffr}_{p-{\rm air}}$, $K^{\rm inel}_{p-{\rm air}}$) impacts only the initial stage of EAS development



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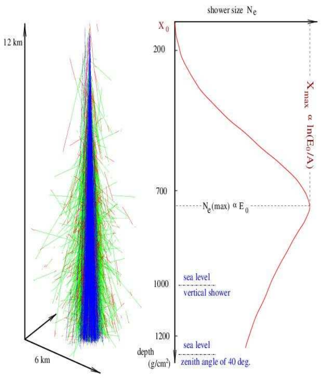

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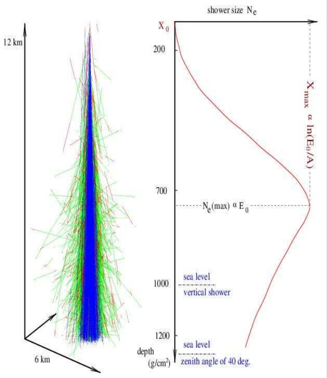

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- any change of the primary interaction ($\sigma^{\mathrm{inel}}_{p-\mathrm{air}}$, $\sigma^{\mathrm{diffr}}_{p-\mathrm{air}}$, $K^{\mathrm{inel}}_{p-\mathrm{air}}$) impacts only the initial stage of EAS development
- $\Rightarrow$ parallel up/down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