EAS predictions of QGSJET-III and model uncertainties for $X_{\max}$

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arXiv: 2208.05889; 2401.06202

Motivation

Jet production in MC generators: collinear factorization of pQCD

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

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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

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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 $p_{\rm t}$ [suppressed as $1/p_{\rm t}^n$]

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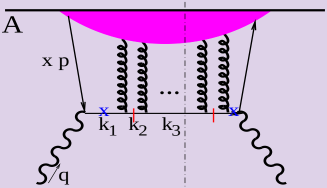
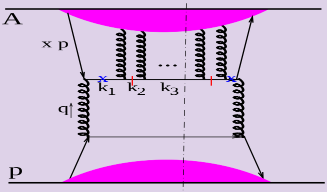
Promising: coherent multiple scattering on 'soft' gluons in $\gamma^* A/pA$

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





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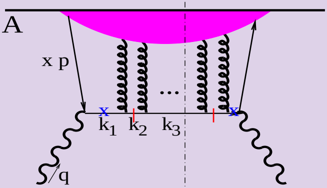

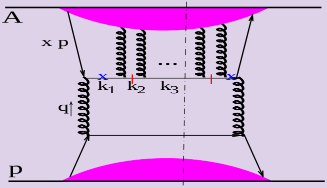

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Extrapolation to hadron-proton & light nuclei

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

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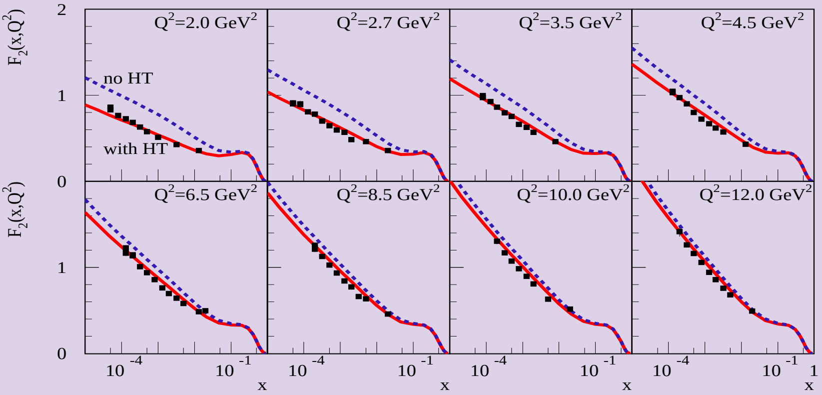
NB: only moderate HT corrections allowed by HERA data



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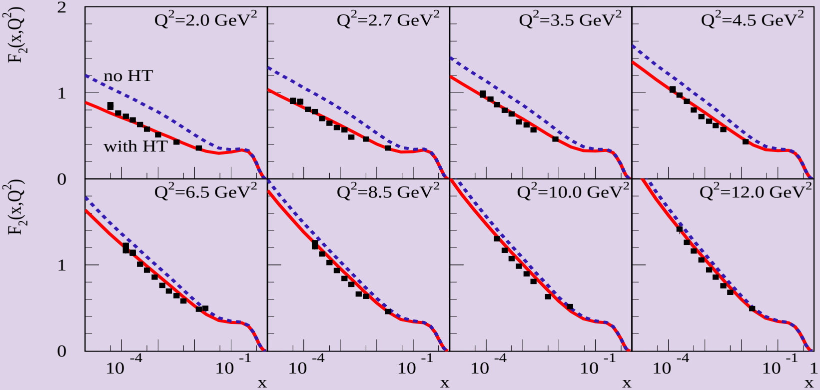
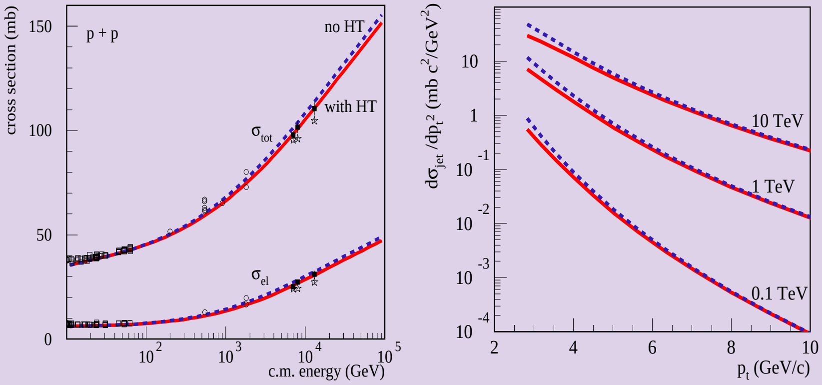


- HT corrections important at low Q^2
  - $\Rightarrow$ too strong corrections at tension with Q^2-evolution of F_2
- known fact: Q^2-evolution of F_2 is well-described by DGLAP
  - $\Rightarrow$ little space for HT or/and saturation effects

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



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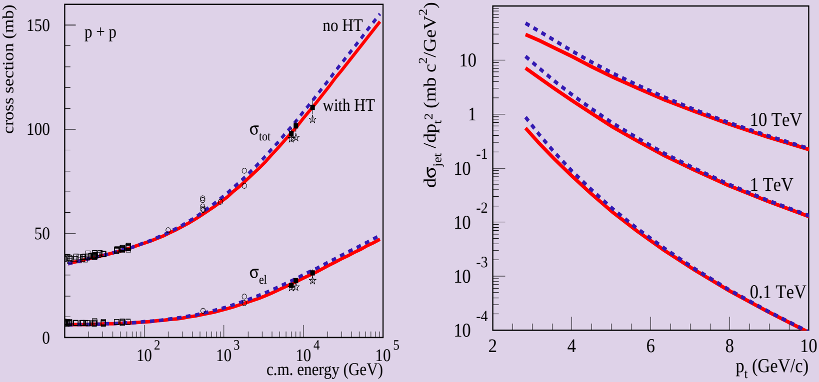

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NB: this is NOT parton saturation!

- rather resembles LPM effect in QED

Few comments on the parton saturation mechanism

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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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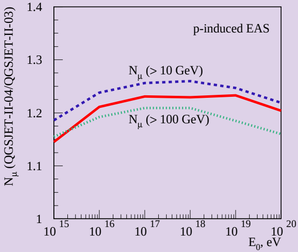
Observable are consequences of (hard) interactions of partons

- 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'

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

π- over ρ-exchange dominance $\Rightarrow \sim 20\%$ increase of N_μ
[SO, EPJ Web Conf. 52 (2013) 02001]

- why so?!



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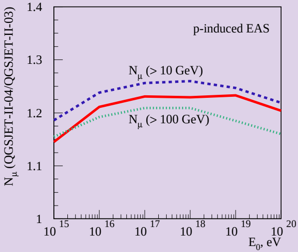

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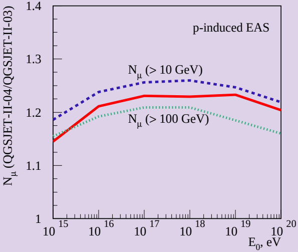

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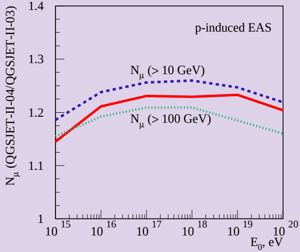
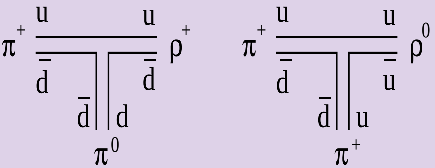


π-exchange process in $\pi^+ A$: only ρ^+ and ρ^0 produced forward

- $\Rightarrow \langle E_{\pi^\pm}\rangle : \langle E_{\pi^0}\rangle = 3:1$
- $\Rightarrow$ less energy channeled into e/m cascades



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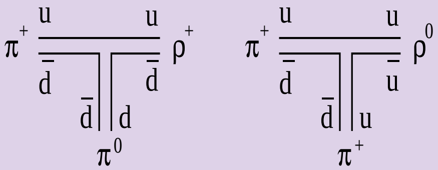
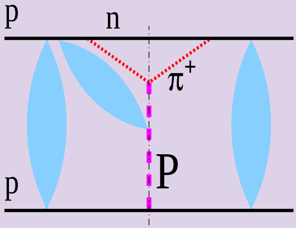


Energy-dependence: driven by absorptive corrections to the process

- high x production of ρ in $\pi^\pm p$ ($\pi^\pm A$) or of neutrons in pp: only without additional inelastic rescatterings



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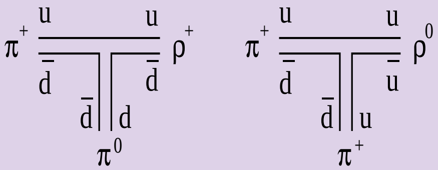
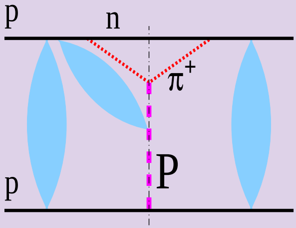


Energy-dependence: driven by absorptive corrections to the process

- high x production of ρ in $\pi^\pm p$ ($\pi^\pm A$) or of neutrons in pp: only without additional inelastic rescatterings
- now can be tested in $pp \to nX$ (thanks to LHCf data)



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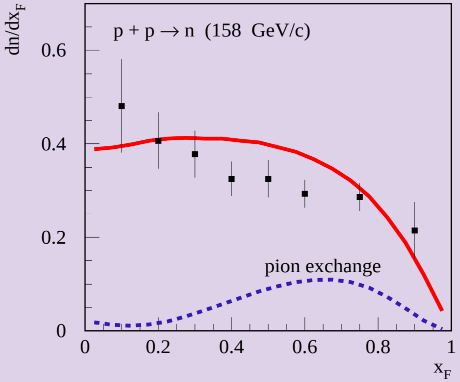
Starting with NA49 data at 158 GeV/c



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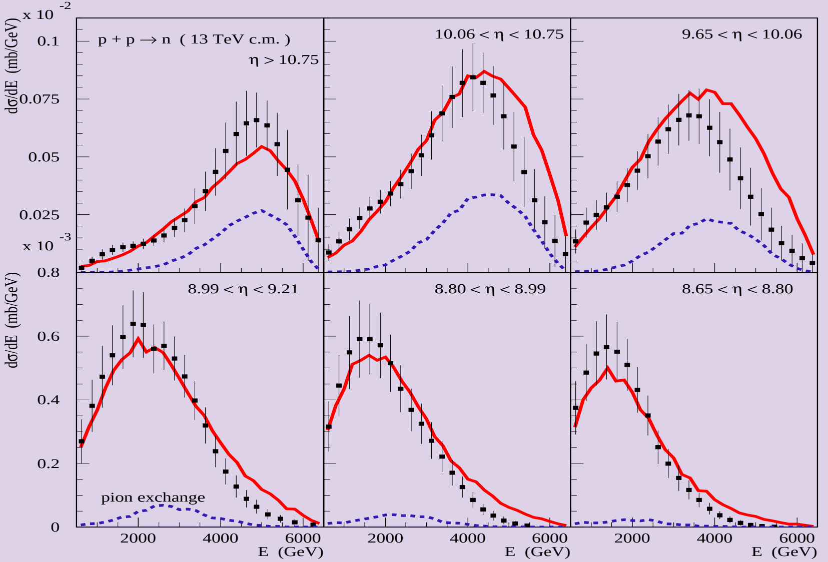
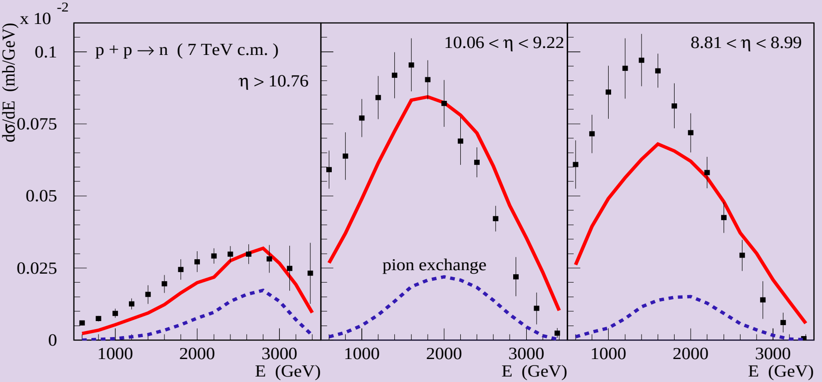
And moving over 6 energy decades to 13 TeV c.m.



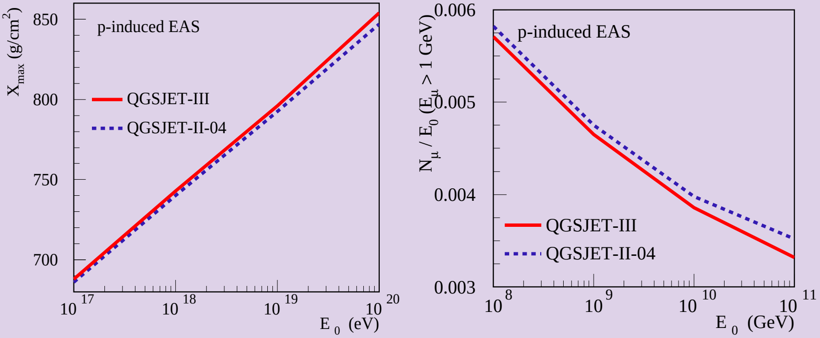
Technical improvement: π-exchange *[SO, Phys.At.Nucl. 44 (2021) 1017]*

But: larger forward *n*-yield seen by LHCf at 7 TeV than at 13 TeV



Results for extensive air showers

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



- up to ~ 5 g/cm^2 shift of $X_{\max}$ wrt QGSJET-II-04
- up to $\sim 5\%$ change of N_μ

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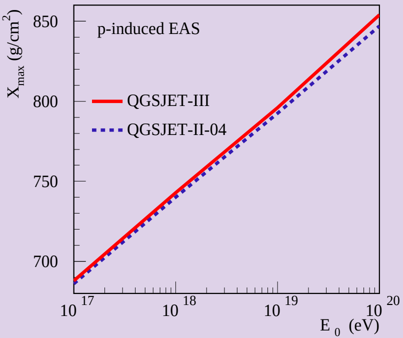

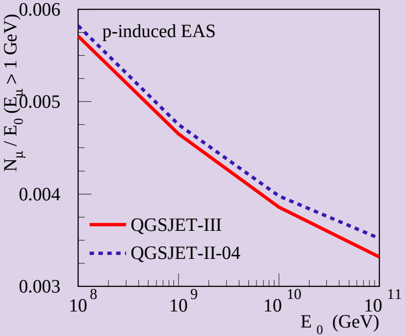

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What is the reason for the stability of the predictions?

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

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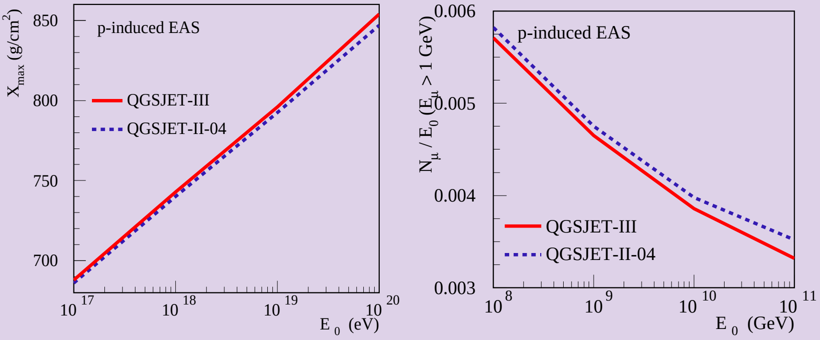

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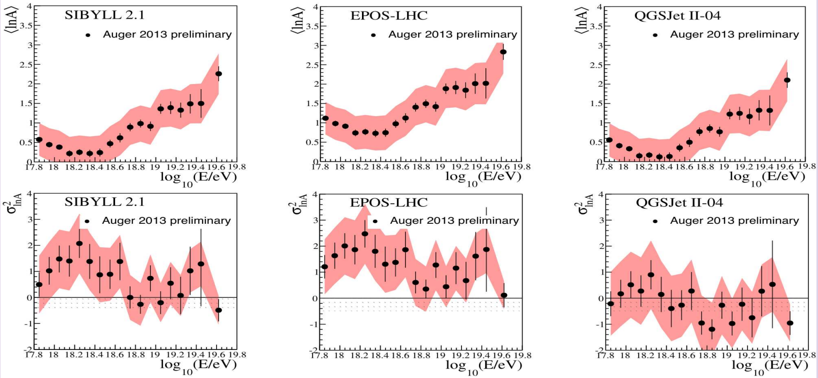
Regarding N_μ: studies in progress (talk of G. Sigl)

Model uncertainties for $X_{\max}$ calculations

What about the tension with PAO data on $X_{\max}$ and $\sigma(X_{\max})$?



- $\sigma(X_{\max})$: very robust theoretically *[SO, Adv.Space Res. 64 (2019) 2445]*
- how feasible to obtain a much deeper $X_{\max}$?

Model uncertainties for $X_{\max}$ calculations

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

- inelastic proton-air cross section ($\sigma^{\mathrm{inel}}_{p-\mathrm{air}}$)
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Inelastic cross section: well constrained by LHC data

- $<3\%$ difference for $\sigma^{\text{inel}}_{pp}$ between ATLAS & TOTEM (79.5 ± 1.80 & 77.41 ± 2.92 mb)
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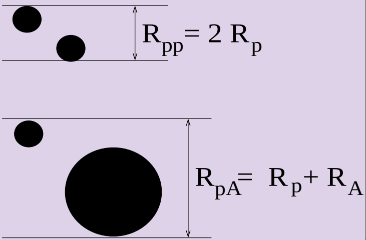

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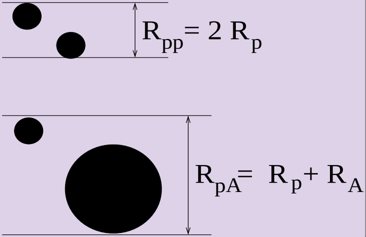

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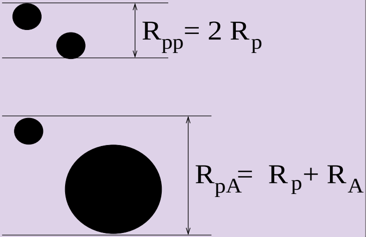

Diffraction uncertainties: $\Delta X_{\max} \lesssim 5$ g/cm^2 *[SO, PRD89 (2014) 074009]*

- now more precise: $\sigma_{pp}^{\rm SD}$ measured by TOTEM & ATLAS (using Roman Pots techniques)

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

- higher energy $\Rightarrow$ higher multiple scattering $\Rightarrow$ higher $K_{p-\text{air}}^{\text{inel}}$
- $\Rightarrow$ one needs softer spectra for secondary hadrons $(\pi, K \ldots)$
  - ideally: Feynman scaling for forward spectra

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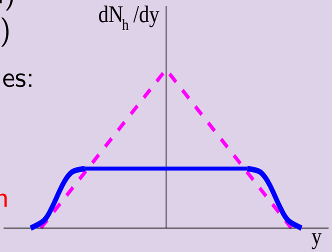
How to give less energy away to secondary hadrons?

- 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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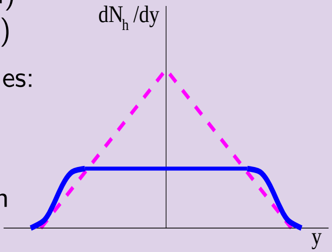
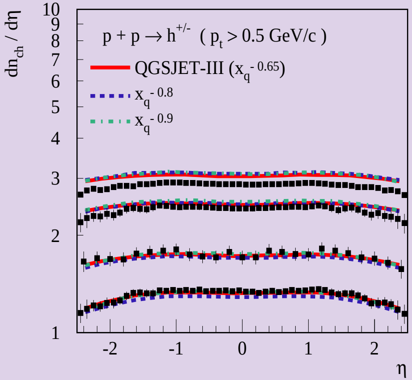


- NB: may not work for semihard scattering (minijet production)

Model uncertainties for $X_{\max}$ calculations

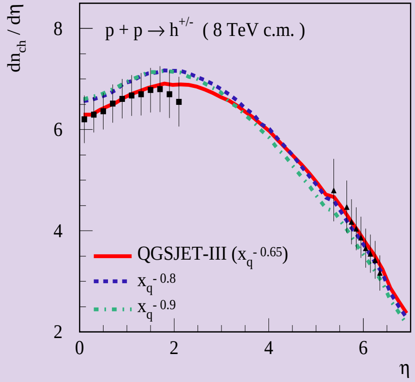
Vary the string end distributions, $x^{-\alpha_q}$: with $\alpha_q = 0.65, 0.8, 0.9$



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

Model uncertainties for $X_{\max}$ calculations

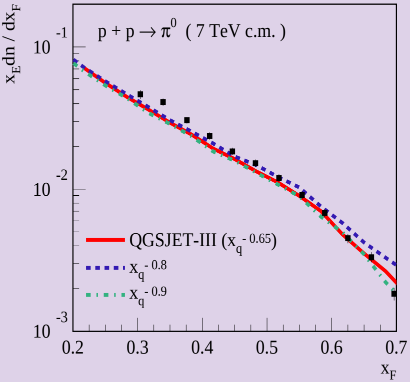
Check with more forward data from CMS & TOTEM



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

Model uncertainties for $X_{\max}$ calculations

Same conclusions, when comparing to LHCf data



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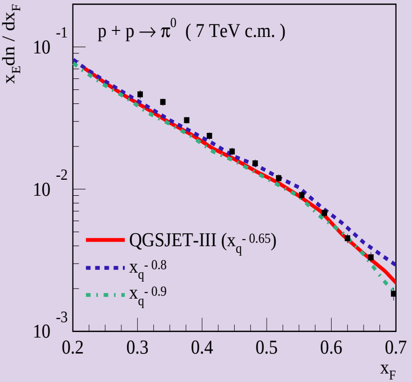
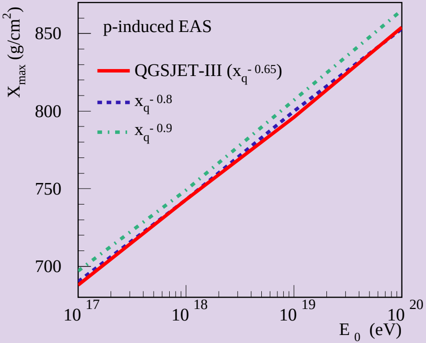


- NB: higher discrimination power expected from combined studies with central/forward detectors

  [SO, Bleicher, Pierog & Werner, PRD94 (2016) 114026]

Model uncertainties for $X_{\max}$ calculations

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



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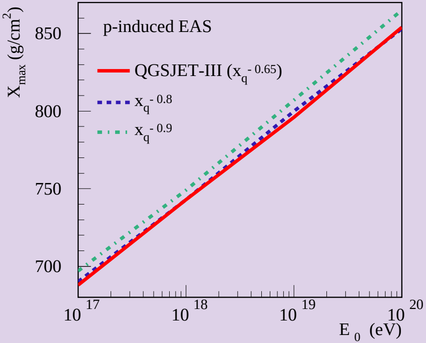

- up to 10 g/cm^2 shift of $X_{\max}$
- why a moderate effect on particle production & $X_{\max}$?
- 'warranted' scaling violation due to semihard scattering?

Hard scattering: importance of the parton cascade

- high energies $\Rightarrow$ 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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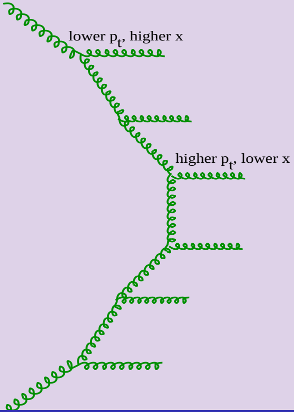

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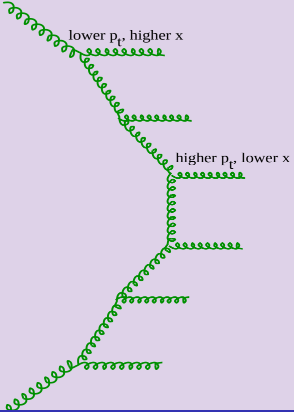

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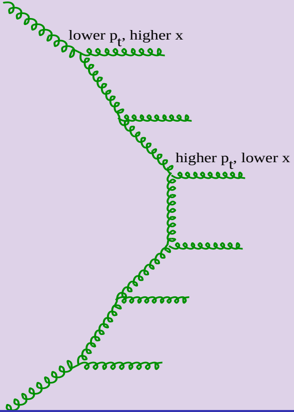

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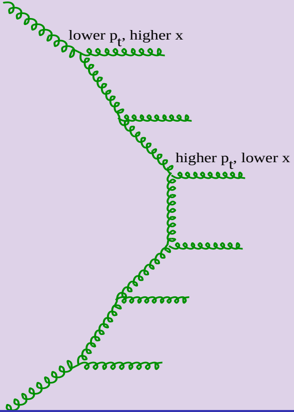
- no: *x*-distribution of those gluons is weighted with the hard scattering!



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

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

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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)

Outlook

1. 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
   - dynamical treatment: stronger effects at small b, higher energy, for heavier nuclei
2. Technical improvement: treatment of π-exchange process
   - energy-dependence: due to absorptive corrections (probability not to have additional inelastic rescattering)
   - the mechanism cross checked with LHCf data on $pp \to nX$
3. Rather small changes for EAS characteristics (wrt QGSJET-II)
   - up to ~ 5 g/cm^2 shift of $X_{\max}$ and up to $\sim 5\%$ change of N_μ
4. Typical model uncertainties for $X_{\max}$: at ~ 10 g/cm^2 level

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