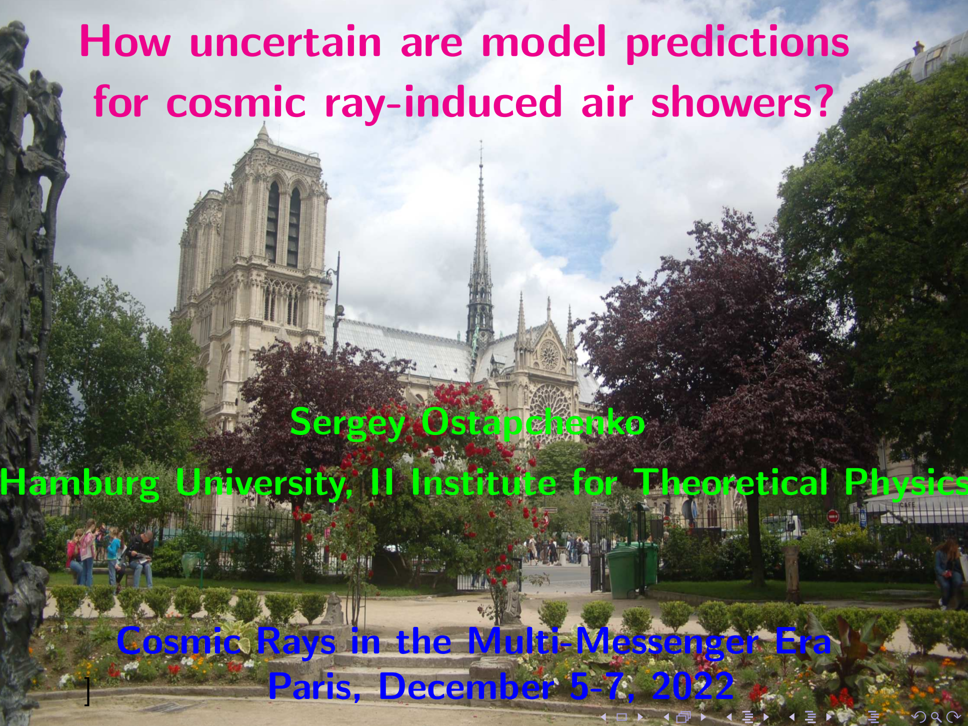


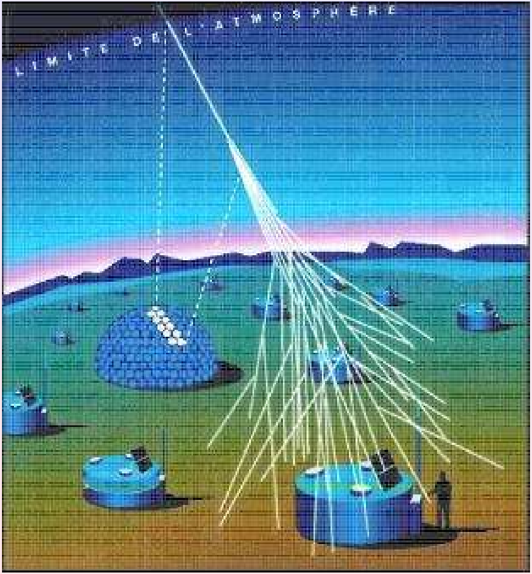
How uncertain are model predictions for cosmic ray-induced air showers?

Sergey Ostapchenko

Hamburg University, II Institute for Theoretical Physics

Cosmic Rays in the Multi-Messenger Era
Paris, December 5-7, 2022

Cosmic ray studies with Extensive Air Shower technique



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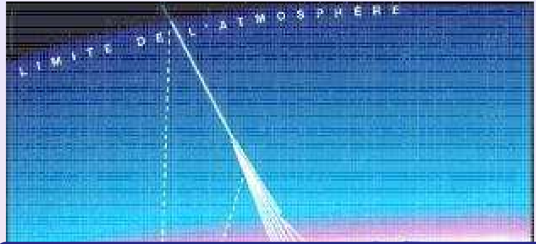

Indirect detection ⇒ depends on the accuracy of EAS modeling

- experimental analyses of CR composition: crucially rely on predictions of hadronic interaction models
    - e.g. 'tuning' such models with EAS data = diletant dream

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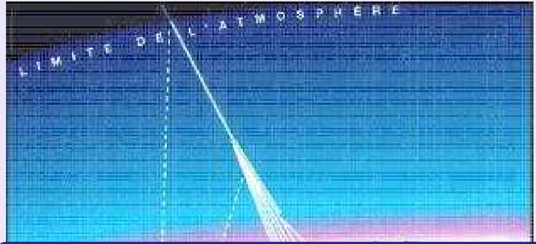

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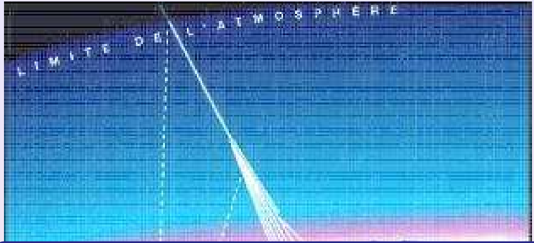

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    - can one quantify the range of uncertainty for their predictions?
    - uncertainties may be smaller/larger than the spread of model predictions (some/all models may be wrong)

QGSJET-III & its EAS results *[SO, Phys.At.Nucl. 84 (2021) 1017; arXiv: 2208.05889]*

- General purpose MC generators necessarily involve both perturbative ($p_{\rm t} > Q_0$) & nonperturbative physics
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- $\Rightarrow$ there should be a perturbative mechanism damping jet production in the small p_t limit

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All current MC generators: using leading twist QCD factorization

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

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

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[Qiu & Vitev, PRL 93 (2004) 262301; PLB 632 (2006) 507]

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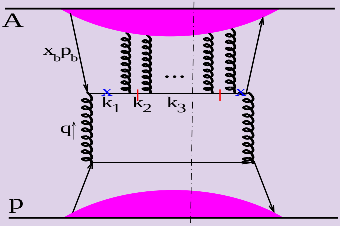

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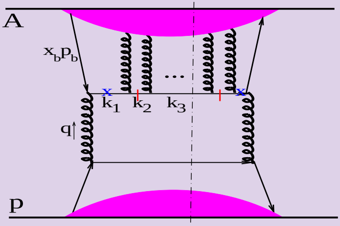

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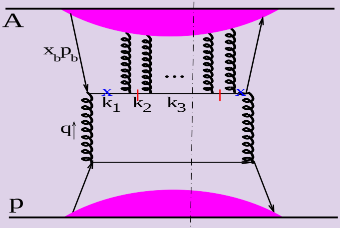

Implementation in QGSJET-III *[SO & Bleicher, Universe 5 (2019) 106]*

- strong damping of hard scattering in the small $p_{\rm t}$ limit
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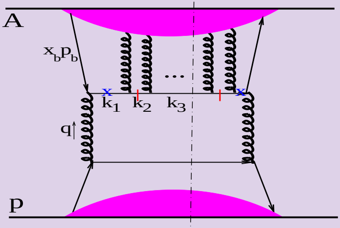

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Additionally - technical improvement: pion exchange process

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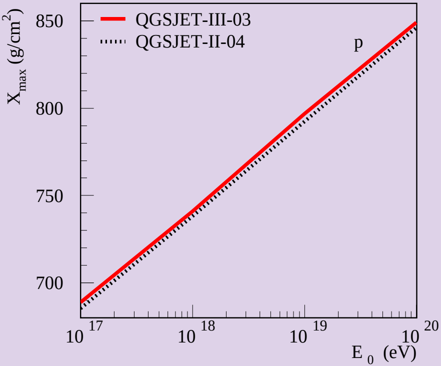
EAS predictions: rather similar for QGSJET-III & QGSJET-II



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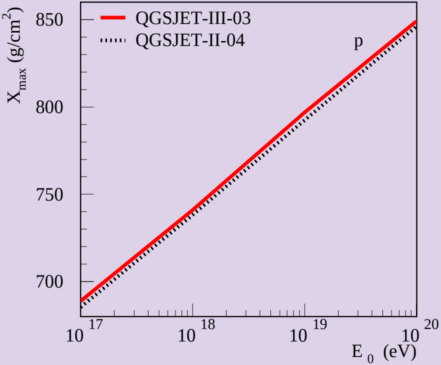

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- EAS predictions sufficiently constrained by accelerator data?

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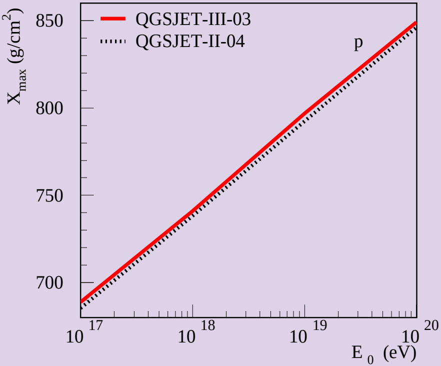

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What is the reason for the stability of EAS predictions?!

- EAS predictions sufficiently constrained by accelerator data?
- or a mere consequence of a particular model approach?
  - some important physics is missing in the model?

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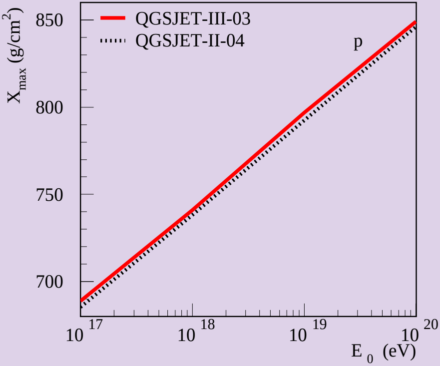

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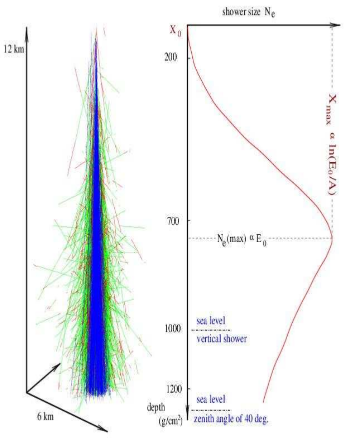
SIBYLL & EPOS-LHC: of little help *[SO, arXiv: 2208.05889; extra slides]*

- EAS predictions: biased by serious deficiences of those models

Main sources of model uncertainties for EAS predictions?

EAS profile: main impact - from the primary CR interaction

- $\sigma(X_{\max})$: smallest uncertainties
  - $\sigma_p(X_{\max})$: mostly from $\sigma^{\rm inel}_{p-{\rm air}}$ (constrained by data on $\sigma^{\rm tot/el}_{pp}$)
  - uncertainties due to diffractive interactions: < 3 g/cm^2 *[SO, PRD 89 (2014) 074009]*
  - $\sigma_A(X_{\max})$: from collision geometry & nuclear breakup *[SO, AdSR 64 (2019) 2445]*



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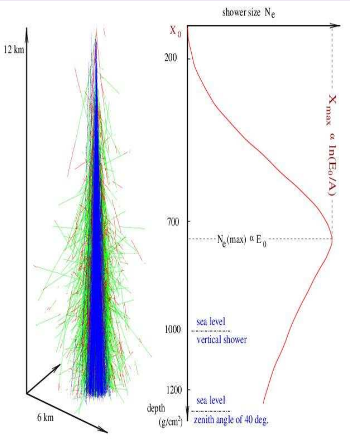

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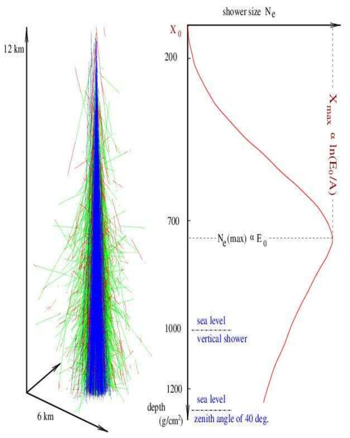

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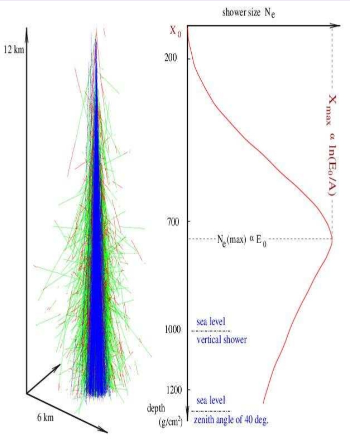

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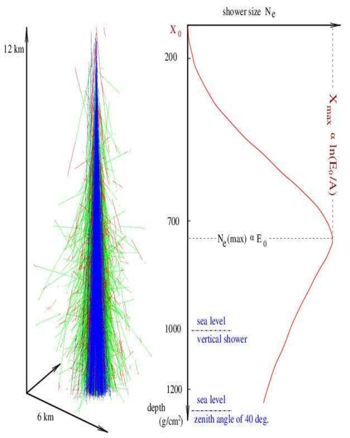

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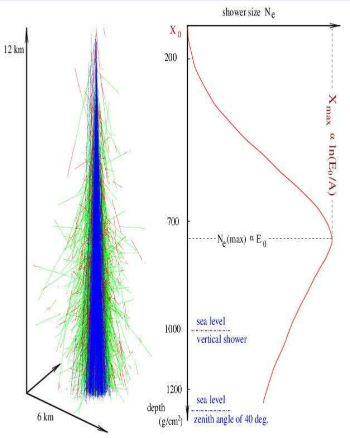

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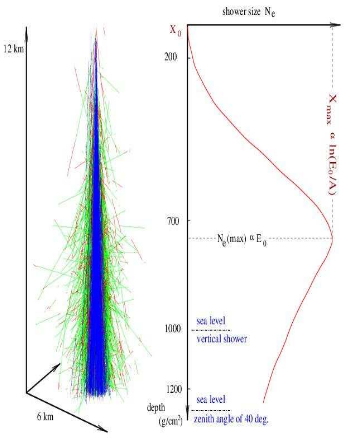

- $\pi-$air interactions: small impact on $\langle X_{\max}\rangle$

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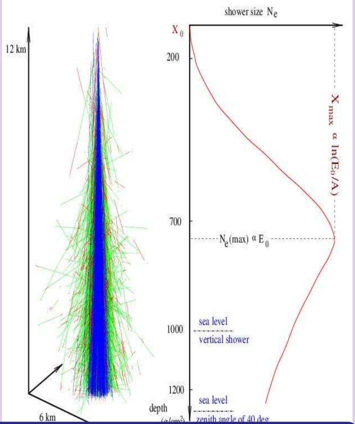
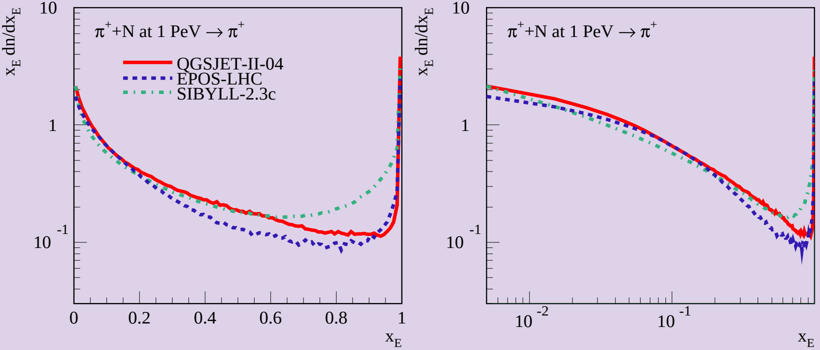


N_μ & $X^\mu_{\max}$: potentially highest uncertainties

- depend on the whole cascade history ⇒ on π-air interactions

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

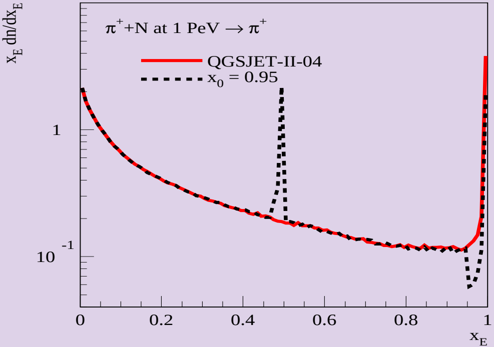
π^{+} spectrum for $\pi^{+} - {}^{14}N$ collisions at 1 PeV



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

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

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^0s remains unchanged!
- e.g. for x_0 close to 1: only diffraction affected

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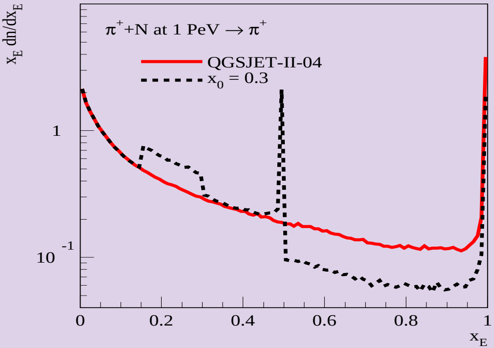

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  - NB: fraction of energy going into π^0s remains unchanged!
- e.g. for x_0 close to 1: only diffraction affected
- for $x_0 \to 0$: 50% higher multiplicity & much softer spectra

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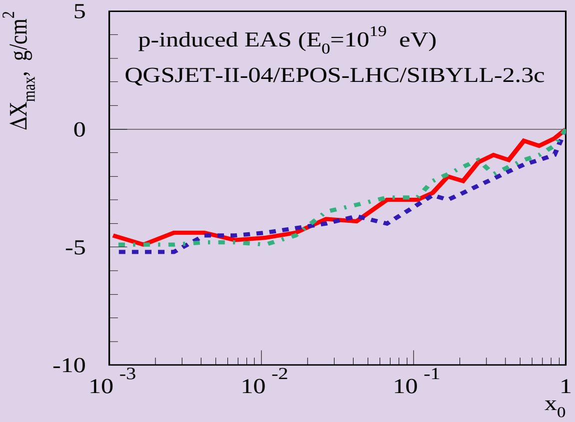
Impact on $X_{\max}$ ('splitting' pions with $x_E > x_0$)



- miserable dependence on pion diffraction ($\Delta X_{\max} \simeq 1$ g/cm^2)
- even for extreme changes ($x_0 \to 0$): $\Delta X_{\max} \lesssim 5$ g/cm^2
- $\Rightarrow$ $X_{\max}$ is strongly dominated by *p*-air interactions

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

$$N_p^\mu(E_0) \simeq \int dx\, \frac{dN^{\pi^\pm}_{p-{\rm air}}(E_0,x)}{dx}\, N^\mu_{\pi^\pm}(xE_0).$$

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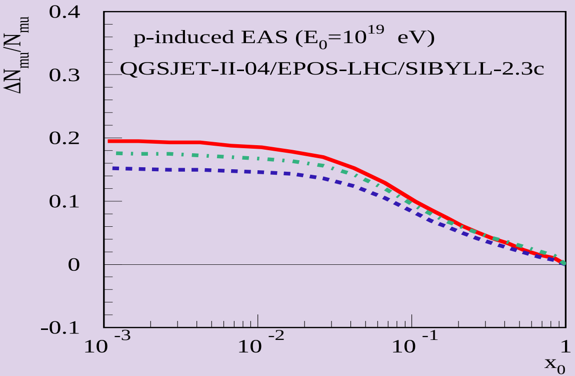
$$N^{\mu}_{p}(E_0) \propto E_0^{\alpha} \int_{x_{\min}}^{1} dx\, x^{\alpha-1-\Delta}\,(1-x)^{\beta}.$$

- 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 $X_{\max}$, $X^{\mu}_{\max}$ & N_{μ}

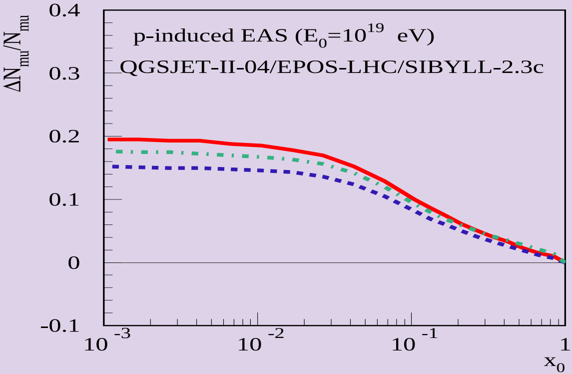
Cross check the impact on N_μ ('splitting' pions with $x_E > x_0$)



- extreme changes (50% higher multiplicity): $\Delta N_\mu / N_\mu \lesssim 20\%$

Interactions of pions: impact on $X_{\max}$, $X^{\mu}_{\max}$ & N_μ

Cross check the impact on N_μ ('splitting' pions with $x_E > x_0$)



- extreme changes (50% higher multiplicity): $\Delta N_\mu / N_\mu \lesssim 20\%$
- main change of N_μ: for $x_E \sim 0.1$

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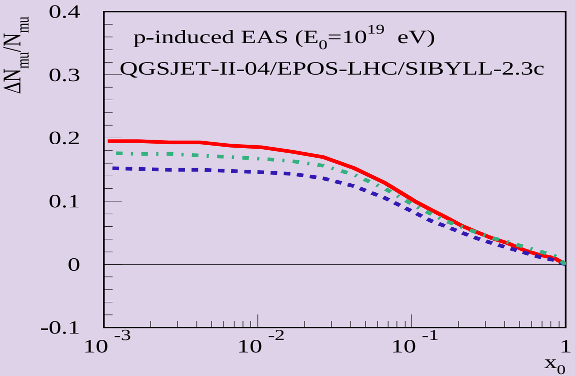

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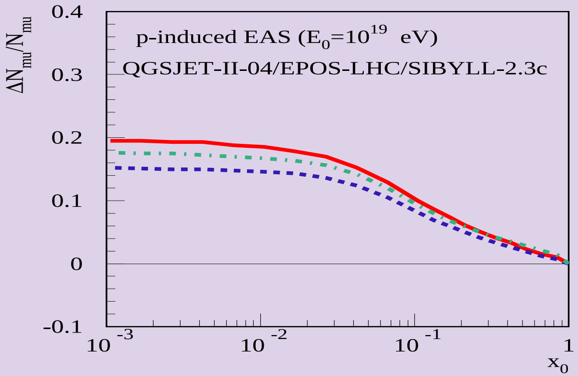

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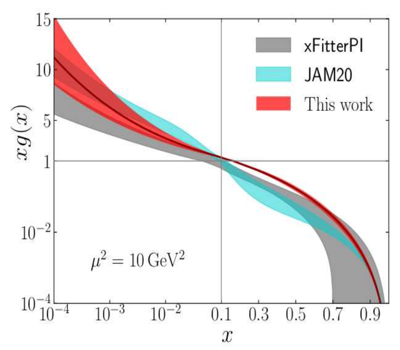
- main change of N_μ: for $x_E \sim 0.1$
    - pion production at $x_{\rm F} \sim 0.1$: well measured at low energies
    - energy evolution: driven by the rise of gluon density in pion (yet reasonably constrained for $x_{\rm F} \sim 0.1$)

Gluon density in the pion

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



[de Téramond et al., arXiv: 2107.01231]

- $q_\pi^{\mathrm{v}}(x, q^2)$ - well constrained by Drell-Yan process studies
    - but: uncertainties for $\langle x_g \rangle$ and $\langle x_{q_{\mathrm{sea}}} \rangle$
- $G_\pi(x, q^2)$ - constrained by direct photon & J/ψ production studies
    - smallest uncertainties at $x \sim 0.1$
    - factor of 2 uncertainties at $x \sim 0.01$

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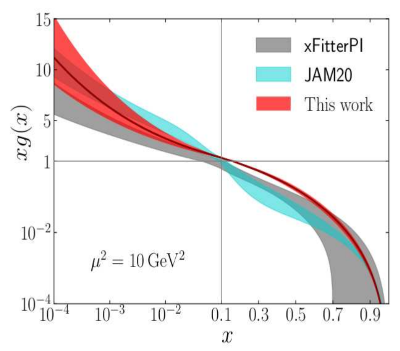

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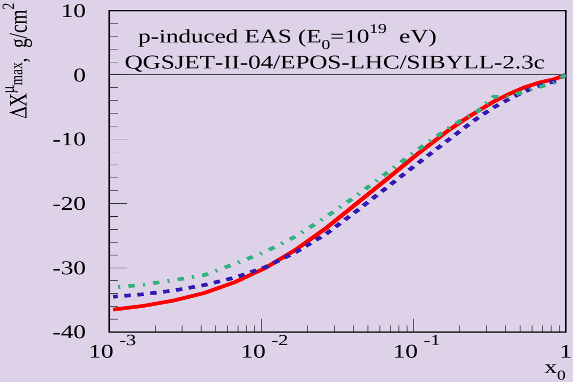

- pion diffraction is irrelevant
- main change for $0.01 < x_E < 0.1$
- why?

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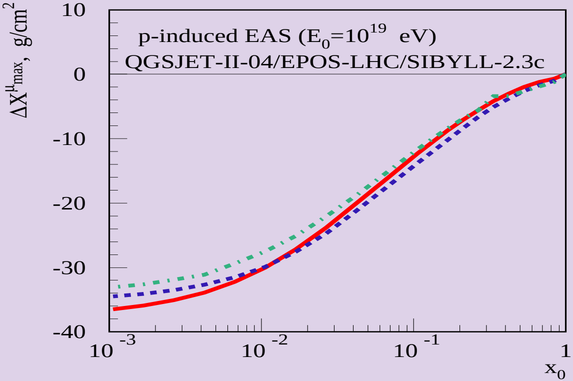

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- $\sigma^{\text{inel}}_{\pi-\text{air}}$ & $\sigma^{\text{diffr}}_{\pi-\text{air}}$ impact the number of 'generations' (cascade steps) till that point

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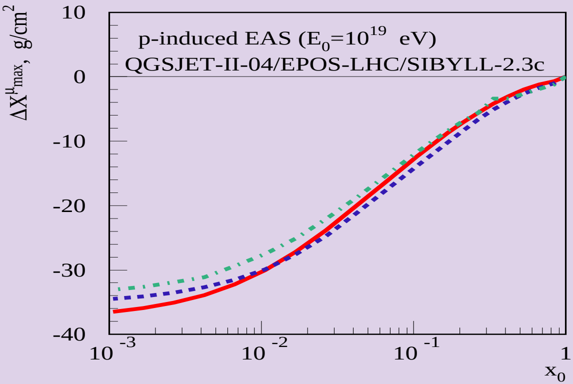

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- but: multiplicity controls the speed of pion energy decrease

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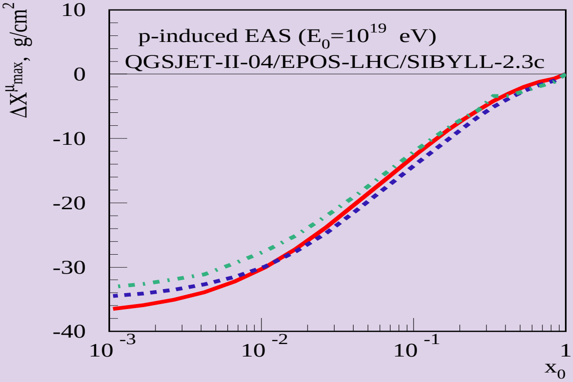

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- pion production at $0.01 < x_F < 0.1$: well measured at fixed target energies
- energy evolution: gluon density rise in pion
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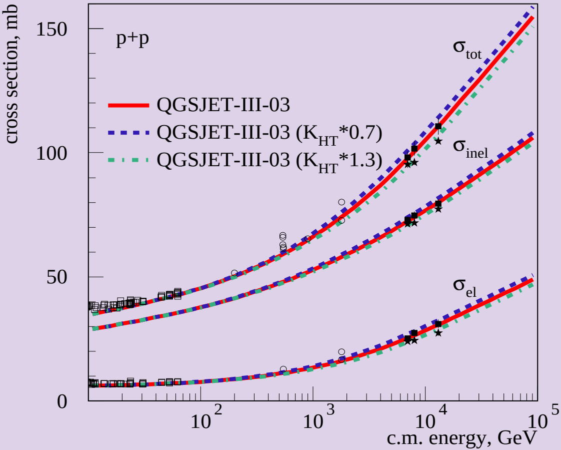
How constraining are LHC data?

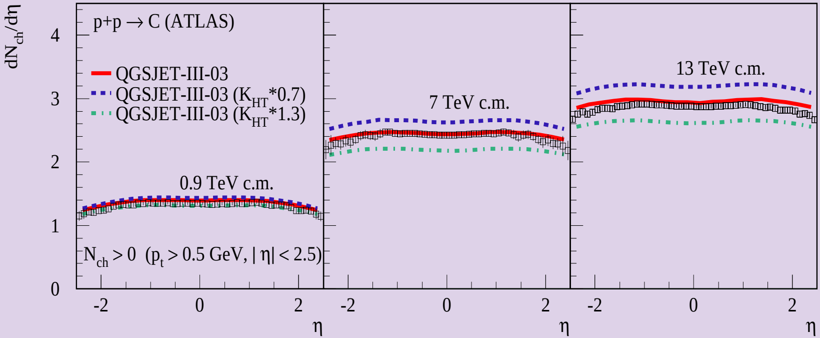
$\sigma_{pp}^{\mathrm{tot/el/inel}}(s)$: varying the strength of higher twist effects by ±30%



- $\sigma_{pp}^{\mathrm{tot/inel}}$: up to ±5% variation

How constraining are LHC data?

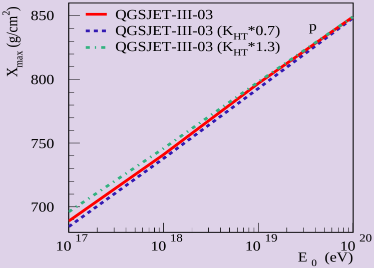
$dN^{ch}_{pp}/d\eta$ in QGSJET-III & for ±30% variation of K_{HT}



- $\pm 10\%$ variation at $\sqrt{s} = 13$ TeV
- smaller impact on π-air interactions (lower energies relevant)

How constraining are LHC data?

EAS predictions: rather similar for QGSJET-III & QGSJET-II



- variation of $X^p_{\max}$: ≤ 5 g/cm^2
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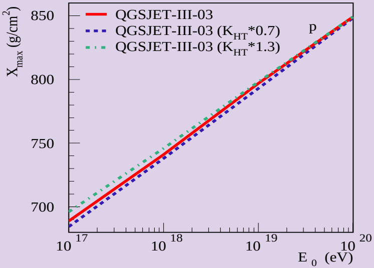

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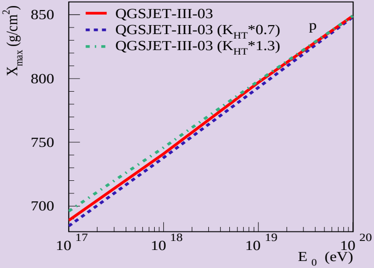

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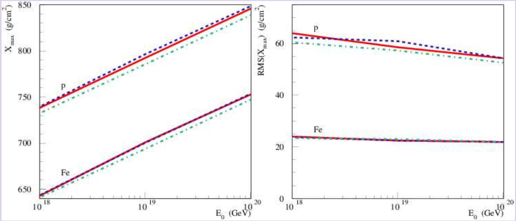
Larger uncertainties related to diffraction *[SO, PRD 89 (2014) 074009]*



- up to $+5/\text{-}10$ g/cm^2 for $X_{\max}^p$
- up to ± 3 g/cm^2 for $\sigma(X_{\max}^p)$

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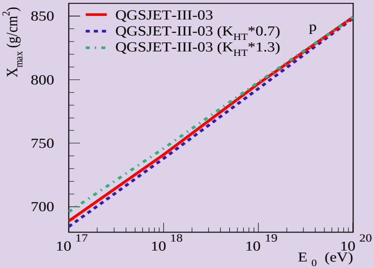
EAS predictions: rather similar for QGSJET-III & QGSJET-II



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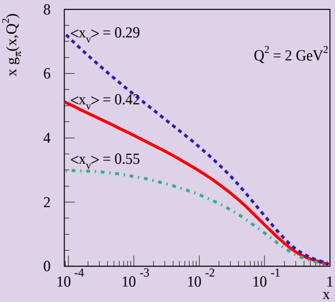
Another source of uncertainty: inelasticity for ND interactions

Gluon density in the pion: impact on EAS muon content

Let us try extreme changes: ±30% variation of $\langle x_{q_v} \rangle$



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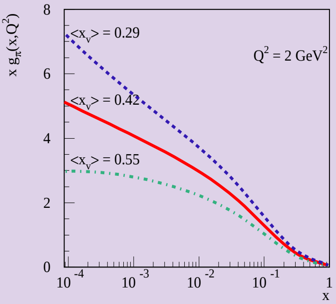

- $\Rightarrow$ large variation of the glue
- variation of N_μ: $\sim \pm 1\%$
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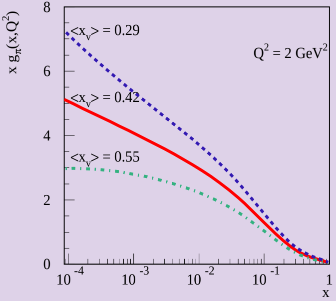

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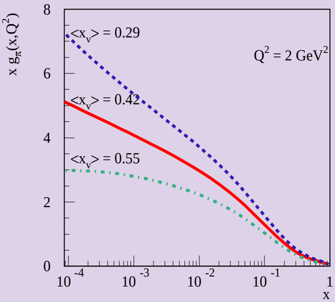

- ⇒ large variation of the glue
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Clearly, this study of model uncertainties is not comprehensive

- yet it demonstrates that there are good reasons for a stability of model predictions for EAS characteristics

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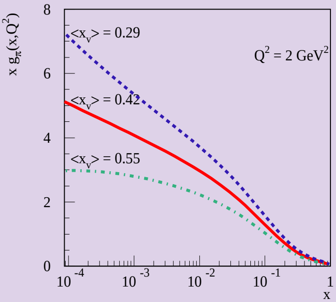

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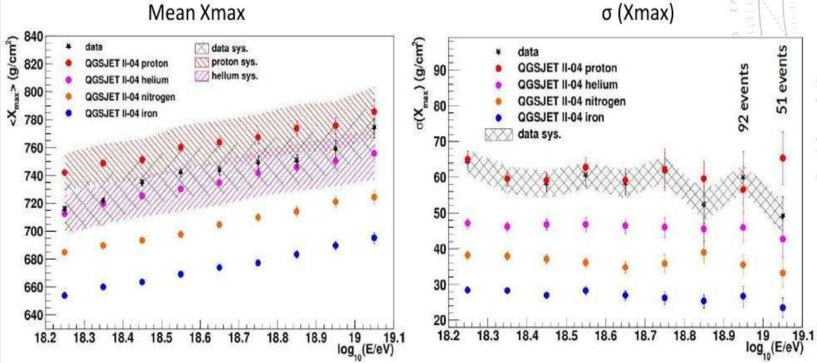
Clearly, this study of model uncertainties is not comprehensive

- yet it demonstrates that there are good reasons for a stability of model predictions for EAS characteristics
  - unless one employs approaches which are obviously wrong

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

TA data allow a consistent interpretation of $X_{\max}$ & $\sigma(X_{\max})$



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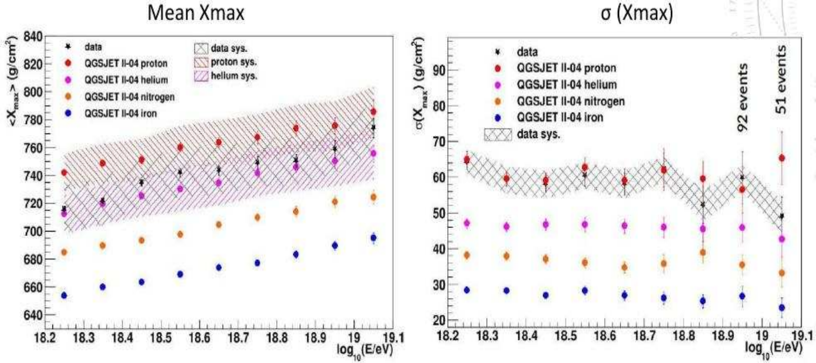
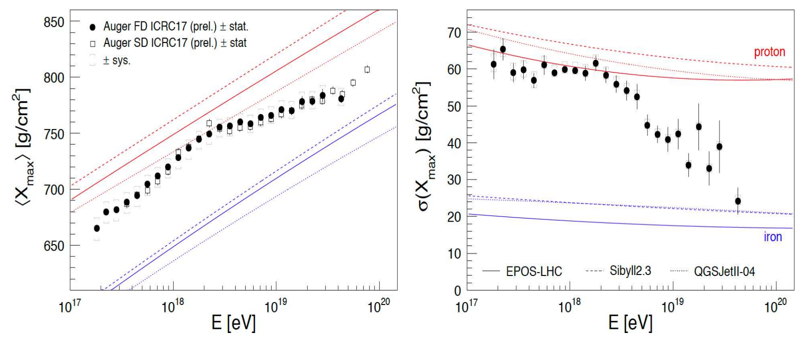


- $X_{\max}$ & $\sigma(X_{\max})$: consistent with pure protons / light mix (in the energy range characterized by sufficient statistics)
- main question: can one exclude pure proton composition?
    - NB: smaller model uncertainties implied by the current analysis

PAO analysis of UHECR composition & implications

[JCAP 04 (2017) 038; arXiv: 2211.02857]

X_{max}-data: interpreted with EPOS-LHC, despite its wrong $\sigma(X_{\mathrm{max}})$



- (artificially) small $\sigma(X_{\mathrm{max}})$: crucial for consistent interpretation

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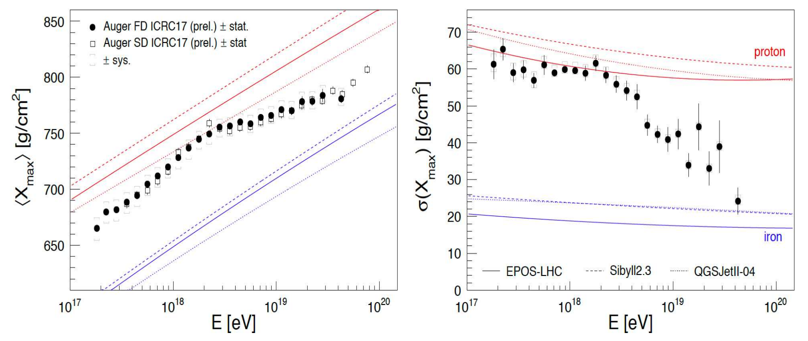
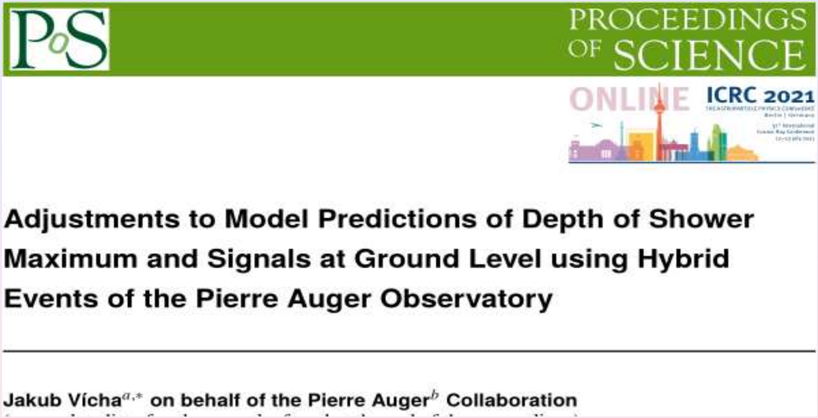


- (artificially) small $\sigma(X_{\max})$: crucial for consistent interpretation
- alternative: higher elongation rate (deeper $X_{\max}$)
    - by how much?!

PAO data: what kind of interaction physics is required?



PoS 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

- to be compatible with PAO data,
  $X_{\max}$ of QGSJET-II should be larger by $48 \pm 2^{+9}_{-12}$

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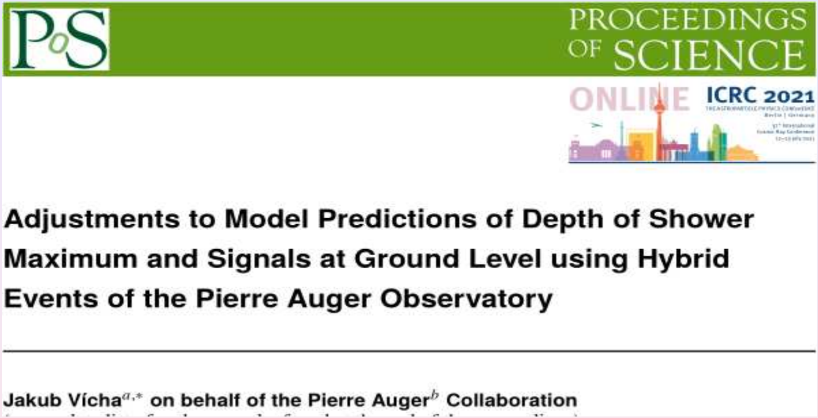
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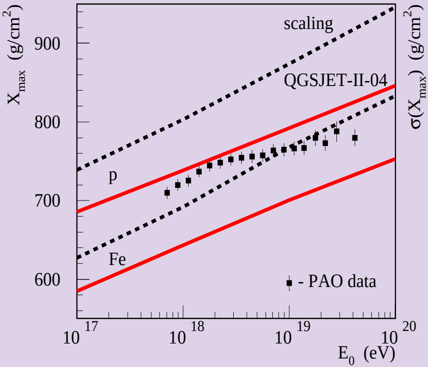
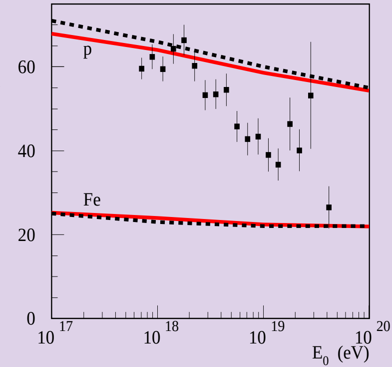
- to be compatible with PAO data,
  $X_{\max}$ of QGSJET-II should be larger by $48 \pm 2^{+9}_{-12}$
- is it feasible, having $\sigma^{\text{inel}}_{p-\text{air}}$ fixed?
  - what is the cost of this physics-wise?

PAO data: what kind of interaction physics is required?

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

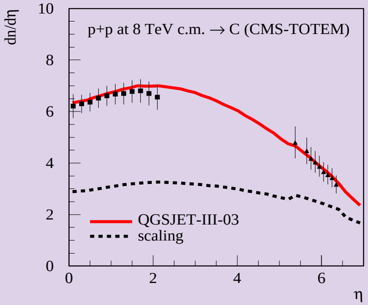




- $\sigma^{\mathrm{inel}}_{p-\mathrm{air}}$, $\sigma^{\mathrm{inel}}_{A-\mathrm{air}}$, $\sigma^{\mathrm{inel}}_{\pi-\mathrm{air}}$ - all kept unchanged
- nonlinear effects & hard scattering switched off (K-factor$=0$, $G_{\mathbb{PPP}}=0$, $K_{\mathrm{HT}}=0$)
- production spectra - frosen at 100 GeV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

Scaling model is dead since $>$ 50 years

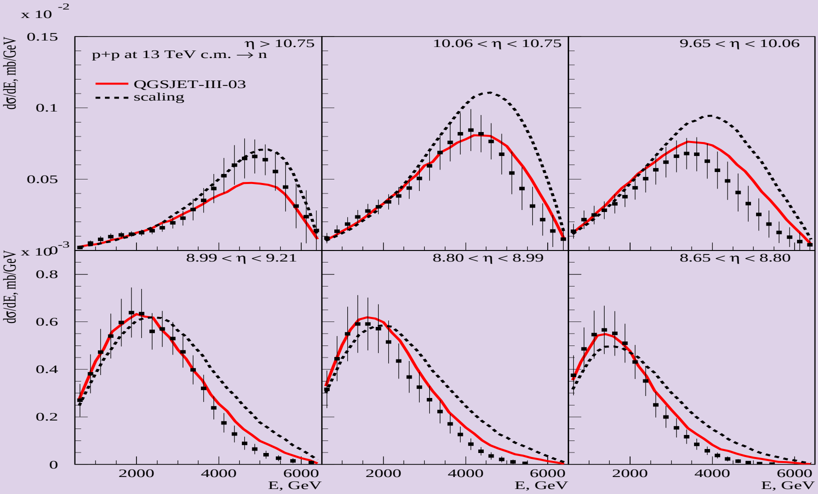
Since it misses the observed rise of the 'rapidity plato' $dN^{\rm ch}_{pp}/d\eta$



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

Scaling model is dead since > 50 years

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

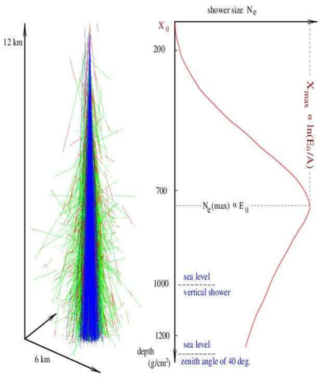


- scaling: energy loss of leading nucleons is underestimated

Most general warning for 'deep $X_{\max}$ dreamers'

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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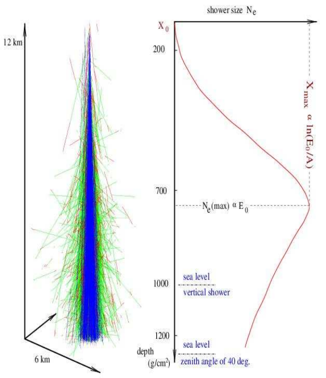
- ⇒ parallel up/down shift of the cascade profile (same shape)



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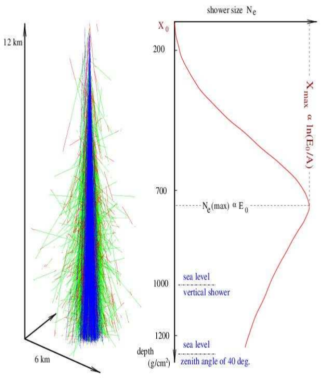
- $\Rightarrow$ same effect on $X_{\max}$ & $X^{\mu}_{\max}$



Most general warning for 'deep X_{max} dreamers'

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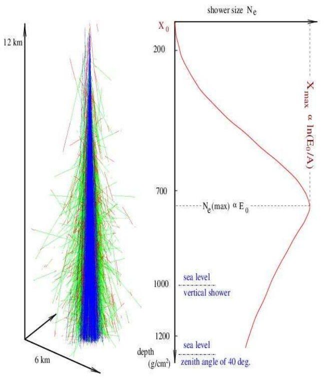
- any change of the primary interaction ($\sigma^{\mathrm{inel}}_{p-\mathrm{air}}$, $\sigma^{\mathrm{diffr}}_{p-\mathrm{air}}$, $K^{\mathrm{inel}}_{p-\mathrm{air}}$) impacts only the initial stage of EAS development

- $\Rightarrow$ parallel up/down shift of the cascade profile (same shape)
- $\Rightarrow$ same effect on X_{max} & X^{μ}_{max}
- the corresponding physics change impacts also π-air interactions (at all the steps of the cascade)
  - $\Rightarrow$ cumulative effect on X^{μ}_{max}



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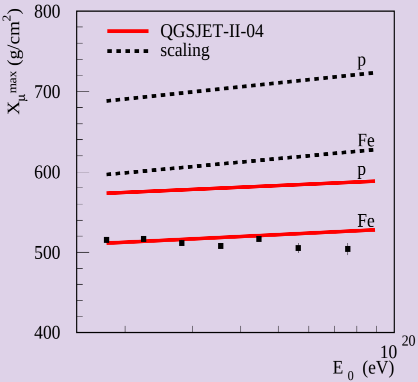
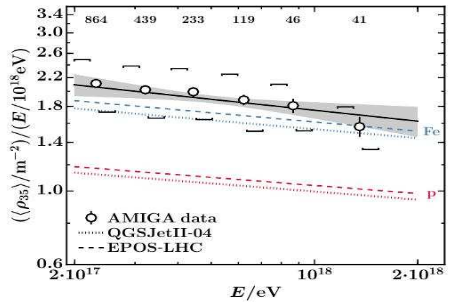


- e.g. using Feynman scaling: UHECRs are transuraniums

Perhaps one 'makes an elephant out of a fly'?

Measurement of muon density by the AMIGA detector of PAO

[A. Aab et al., Eur. Phys. J. C 80 (2020) 751]



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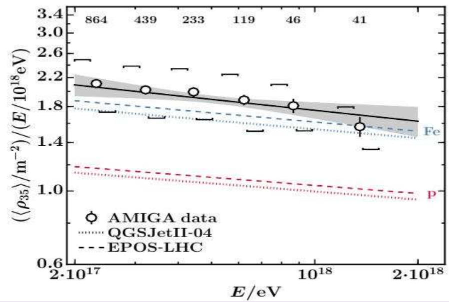
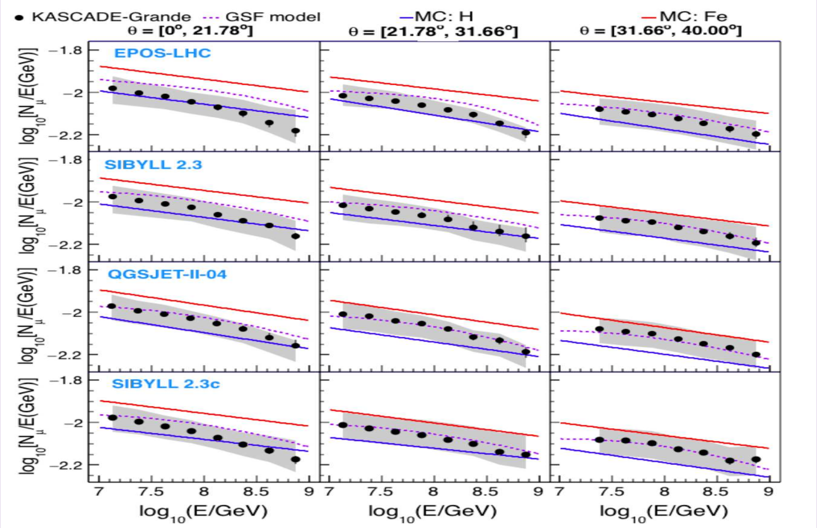


- energy-dependence: as predicted by the models
- but: normalization differs (by less than 3σ)
- is $< 3\sigma$ discrepancy sufficient to expect barn-level BSM physics at LHC energies?!

Perhaps one 'makes an elephant out of a fly'?

NB: no 'muon deficit' seen by Ice-Top & KASCADE-Grande



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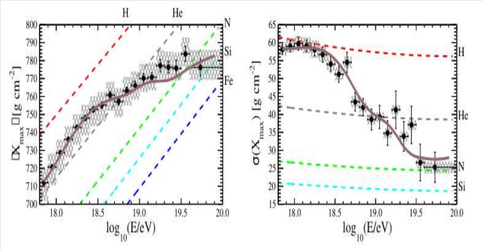
Decreasing $\sigma(X_{\max})$ (with small systematic errors) $\Rightarrow$ many effects



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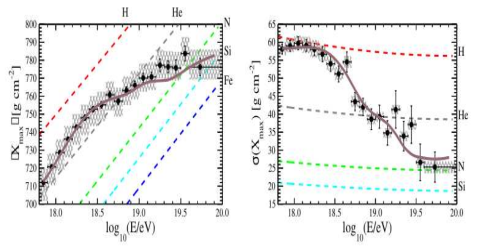

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- would they dissappear if systematic uncertainties were higher?

Summary

1. QGSJET-II/QGSJET-III: small differences for EAS properties
    - stability of $X_{\max}$ predictions:
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3. Perhaps, it is the right time to critically re-access systematic uncertainties of UHECR measurements?

Extra slides

Hard scattering: importance of the parton cascade

- high energies ⇒ high p_t parton production important
  - small $\alpha_\mathrm{s}(p_\mathrm{t}^2)$ - compensated by infrared and collinear logs (arising from parton cascading): $\ln(x_i/x_{i+1})$, $\ln(p^2_{\mathrm{t}_{i+1}}/p^2_{\mathrm{t}_i})$

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Why (mini)jet production is important for EAS predictions?

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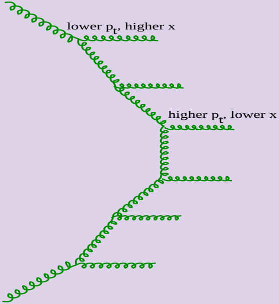

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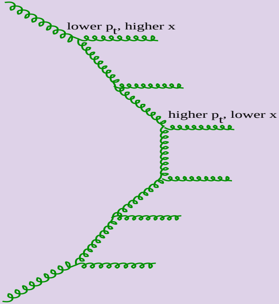
- but: hardest scattering preceeded by parton cascade (smaller p_{t} & higher x)
  - $\Rightarrow$ most important are first ('softest') partons in the cascade



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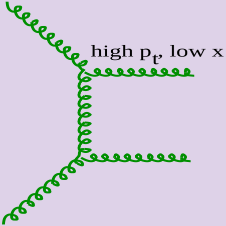
General pathology of the SIBYLL model

- parton cascade completely neglected
- minijet contribution $\equiv$ hardest gg-scattering (high $p_{\rm t}$ & small x)



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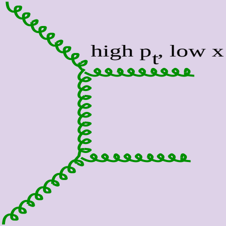

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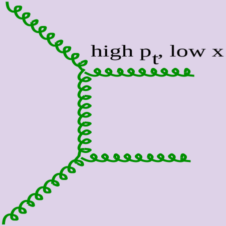

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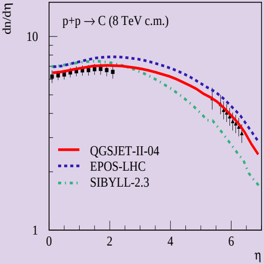
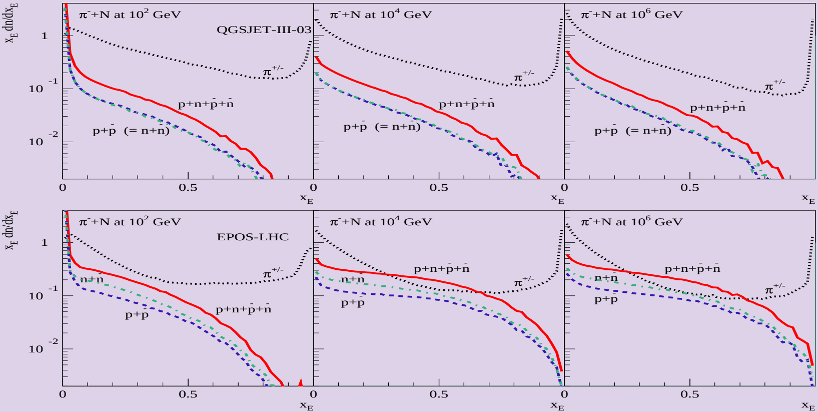
- at variance with LHC data on $dN_{pp}^{\rm ch}/d\eta$



Energy-dependence of (anti)nucleon production

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



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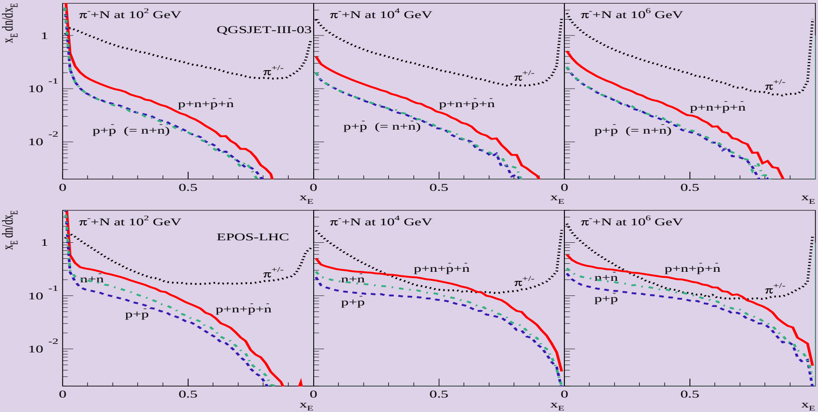
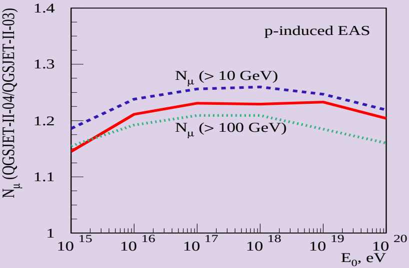


- artificial 'hardening' of the baryon yield with energy in EPOS: no viable theoretical mechanism
- violation of the isospin invariance - obviously wrong (yields of $p+\overline{p}$ & $n+\overline{n}$ should coincide)

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_μ (> 1 GeV) (relative to QGSJET-II-03)
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- nearly same N_μ excess up to $E_\mu \sim 100$ GeV

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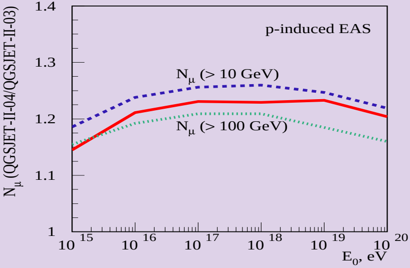

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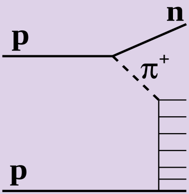
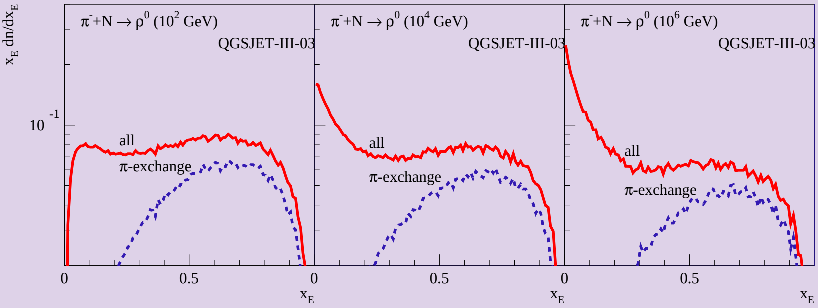
Check/tune the mechanism with forward neutron production in *pp*?

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



π-exchange process in pion-nucleus collisions

Energy-dependence of ρ^0 production in $\pi^- N$ collisions



- 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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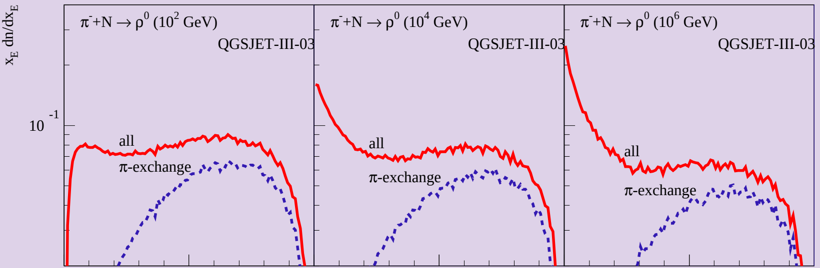
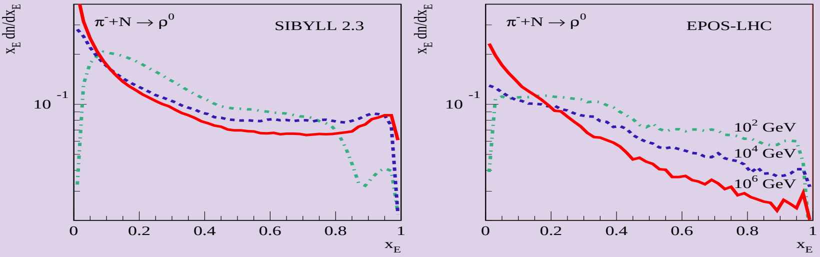


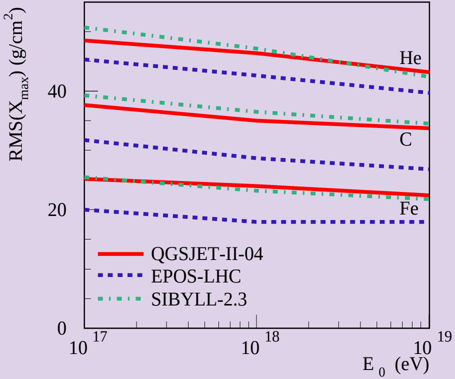
ρ^0 production in SIBYLL-2.3 & EPOS-LHC (10^2, 10^4 & 10^6 GeV)



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

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

But: small $\sigma(X_{\max})$ of EPOS for A-induced EAS?!



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Two extreme scenarios for nuclear break-up ⇒ factor 2 difference for $\sigma(X_{\max})$ *[Kalmykov & SO, Phys.At.Nucl. 56 (1993) 346]*

1. complete break up of nuclear spectator part (into separate nucleons) ⇒ smallest RMS($X_{\max}$)
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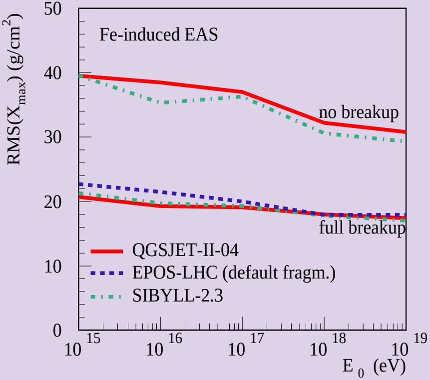

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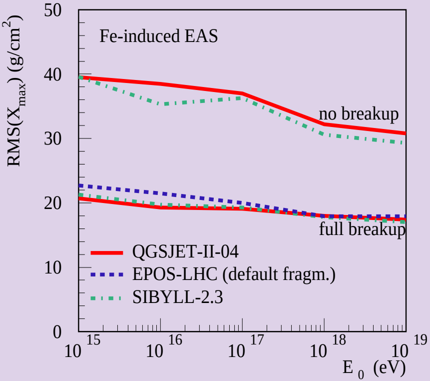
- EPOS results: close to the full break up option



Caused by incorrect matching between the interaction and nuclear fragmentation procedures in EPOS