CR composition & secondary production

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Sources of Galactic cosmic rays
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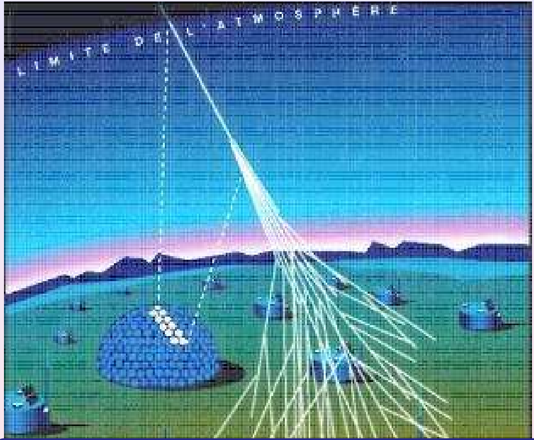
arXiv: 1608.07791, 1601.06567, 1402.508

Cosmic ray studies with Extensive Air Shower technique



ground-based observations

- primary CR energy $\Longleftrightarrow$ charged particle density at ground
- CR composition $\Longleftrightarrow$ muon density ρ_μ at ground

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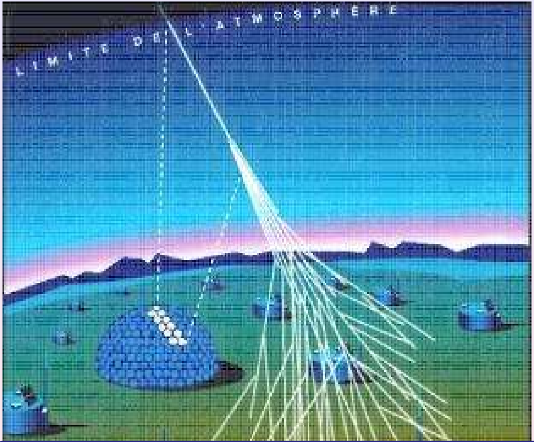
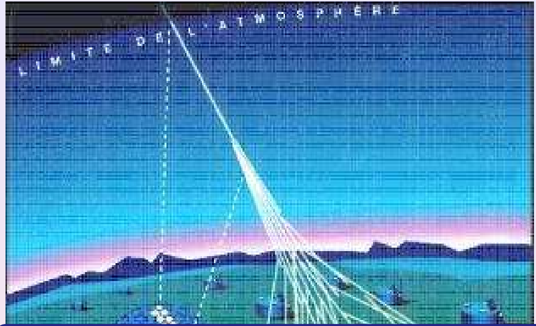


measurements of EAS fluorescence light

- primary CR energy $\Longleftrightarrow$ integrated light
- CR composition $\Longleftrightarrow$ shower maximum position $X_{\max}$

Cosmic ray studies with Extensive Air Shower technique



CR composition studies – most dependent on interaction models

- e.g. predictions for $X_{\max}$: on the properties of the primary particle interaction ($\sigma^{\text{inel}}_{p-\text{air}}$, forward particle spectra)
  - $\Rightarrow$ most relevant to LHC studies of pp collisions
- predictions for muon density: on secondary particle interactions (cascade multiplication); mostly on $N^{\text{ch}}_{\pi-\text{air}}$
  - $\Rightarrow$ small potential influence of 'new physics'

Astrophysical studies with high energy γ-rays, $\bar{p}$-s & ν-s

- e.g. inferring primary CR spectra from observed γ-ray fluxes
  - involve spectra of π^0 (also η) for pp, pA & AA collisions
- spectra of antiprotons:
  for constraining CR acceleration & propagation models
  - also background for indirect searches of dark matter
- production of ν-s in pp & Ap (AA) collisions:
  for calculations of astrophysical neutrino fluxes
  - also for estimating the atmospheric neutrino background

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  for calculations of astrophysical neutrino fluxes
    - also for estimating the atmospheric neutrino background
- I'll not discuss these here
  (see e.g. arXiv:1206.4705, 1405.3797, 1406.0035, 1502.04158)

Cosmic ray interaction models

1. QGSJET-II-04 *[SO, 2011]*
    - original ideas: QGS model *[Kaidalov & Ter-Martirosyan, 1982]* → QGSJET *[Kalmykov & SO, 1993, 1997]* → QGSJET-II *[SO, 2006]*
    - theoretically most advanced: e.g. microscopic treatment of nonlinear effects (Pomeron-Pomeron interaction diagrams)
    - ⇒ strong predictive power (minimal number of parameters)

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2. EPOS-LHC *[Pierog, Karpenko, Katzy, Yatsenko & Werner, 2015]*
    - VENUS *[Werner, 1993]* → NEXUS *[Drescher, Hladik, SO, Pierog & Werner, 2001]* → EPOS *[Werner, Liu & Pierog, 2006]*
    - more phenomenological (e.g. parametrized saturation effects)
        - ⇒ larger parameter freedom
    - additional theoretical mechanisms (e.g. energy-momentum sharing at the amplitude level, hydrodynamics for final states)
    - generally better description of existing data (e.g. p_t spectra)

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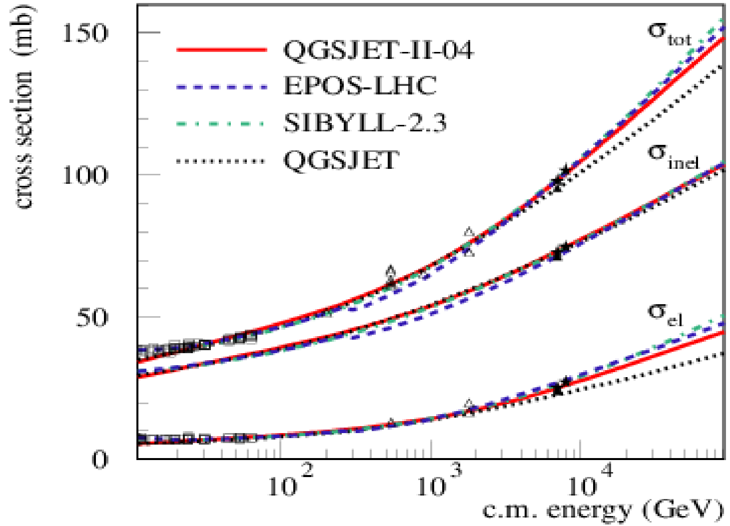
3. SIBYLL-2.3 *[Riehn, Engel, Fedynitch, Gaisser & Stanev, 2015]*
   - SIBYLL-1.7 *[Fletcher, Gaisser, Lipari & Stanev, 1994]*
     → SIBYLL-2.1 *[Ahn, Engel, Gaisser, Lipari & Stanev, 2009]*
   - relatively simple ('minijet' approach)
   - differs from QGSJET-II & EPOS in many important aspects
   - has similarities to models used at LHC (e.g. PYTHIA)

All the models: updated with Run 1 data of LHC

Very similar high energy extrapolations for σ_{pp} for all the models



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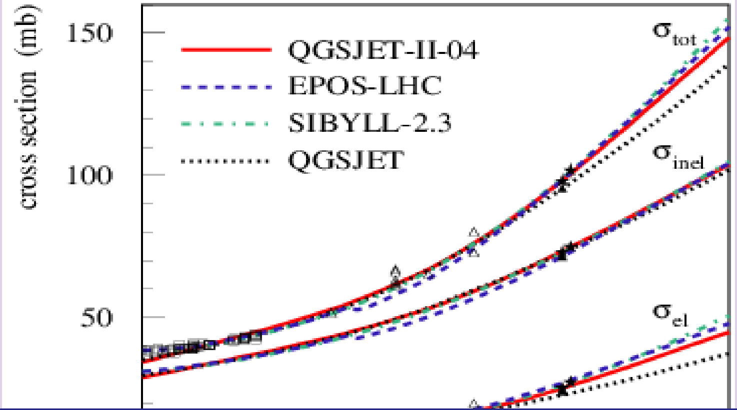
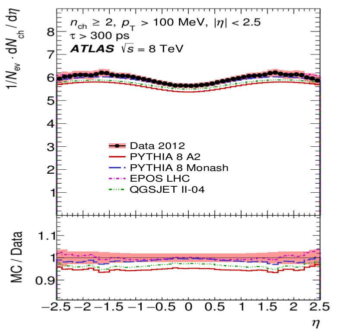


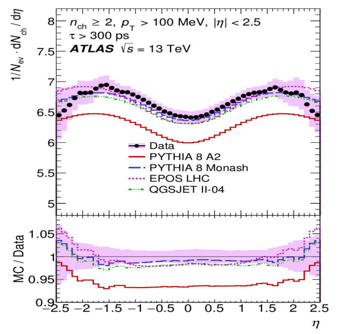
NB: old QGSJET model - outdated physics-wise ($>$ 20 years old)

- yet agrees with LHC data on $\sigma_{pp}^{tot/inel}$ & particle production
- $\Rightarrow$ used here to study 'potential' range of model uncertainties

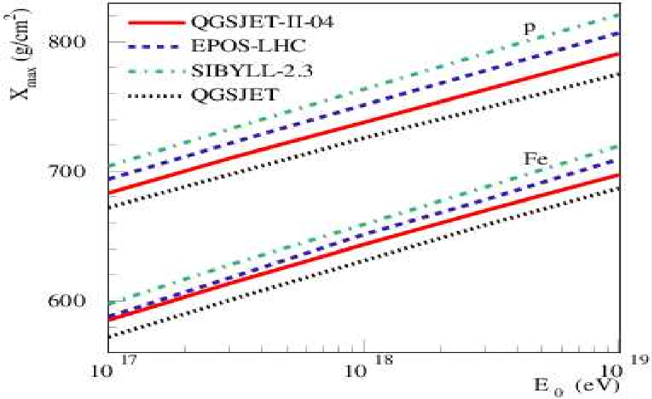
All the models: updated with Run 1 data of LHC

$dn_{pp}^{\mathrm{ch}}/d\eta$ of ATLAS ($\sqrt{s} = 8$ and 13 TeV): CR models o.k.



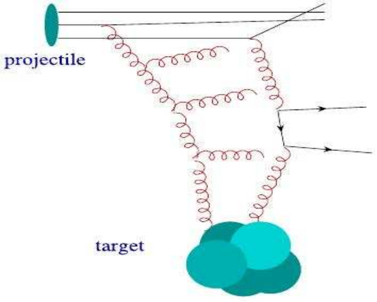


Model predictions for $X_{\max}$: yet large differences



Hadronic interactions: qualitative picture

- QCD-inspired: interaction mediated by parton cascades



- pQCD input:
  for inclusive high p_t spectra

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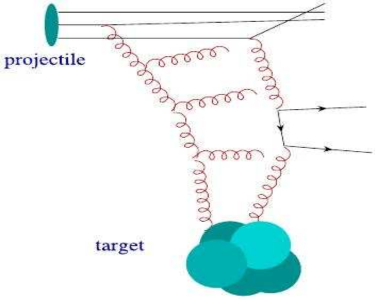


- pQCD input:
  for inclusive high p_t spectra

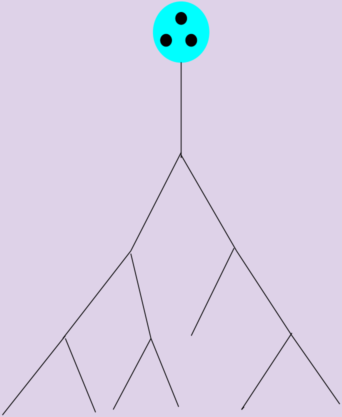
What is beyond and why the models are different?

- nonperturbative (low p_t) parton cascades
- multiple scattering
- nonlinear effects (interactions between parton cascades)
- constituent parton Fock states
  (initial conditions for parton cascades)

Hadronic interactions: nonperturbative Fock states

1. (Implicitely) always same nonperturbative Fock state (typical for models used at colliders, also SIBYLL model)

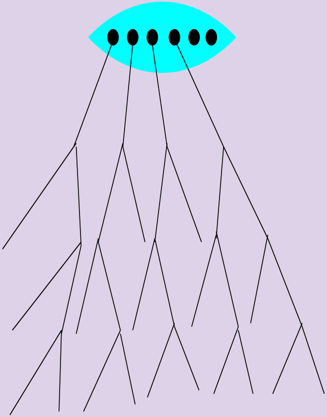
- multiple parton cascades originate from the same initial parton state
- multiple scattering has small impact on forward spectra
  - new branches emerge at small x $(G(x,q^2) \propto 1/x)$
- $\Rightarrow$ Feynman scaling & limiting fragm. for forward production
- higher $\sqrt{s} \Rightarrow$ more abundant central particle production
- forward & central production – decoupled from each other
  - (descreasing number of cascade branches for increasing x)



Hadronic interactions: nonperturbative Fock states

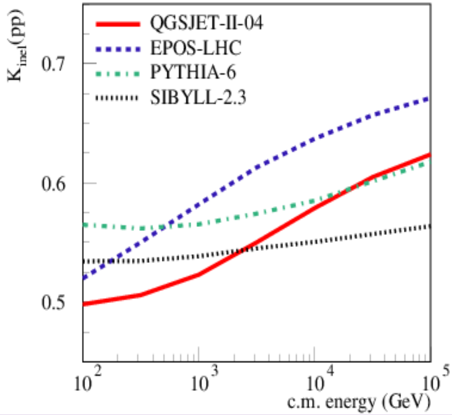
2. $p = \sum$ of multi-parton Fock states [EPOS & QGSJET(-II)]

- many cascades develop in parallel (already at nonperturbative stage)
- higher $\sqrt{s} \Rightarrow$ larger Fock states come into play: $|qqq\rangle \to |qqq\bar{q}q\rangle \to \ldots\ |qqq\bar{q}q \ldots \bar{q}q\rangle$
  - $\Rightarrow$ softer forward spectra (energy sharing between constituent partons)
- forward & central particle production - strongly correlated
  - e.g. more activity in central detectors $\Rightarrow$ larger Fock states $\Rightarrow$ softer forward spectra



Why of importance for EAS predictions (e.g. for $X_{\max}$)?

Main cause: energy-dependence of the nucleon 'inelasticity'



- SIBYLL & PYTHIA: weak $\sqrt{s}$–dependence of K_{pp}^{inel}
  - for increasing $\sqrt{s}$, only central production enhanced
- smaller K^{inel} $\Rightarrow$ stronger 'leading particle' effect
- $\Rightarrow$ slower shower development (larger $X_{\max}$)

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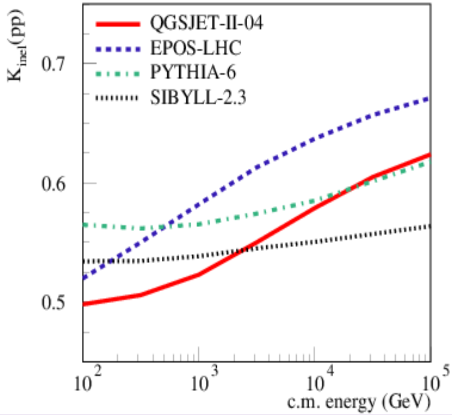

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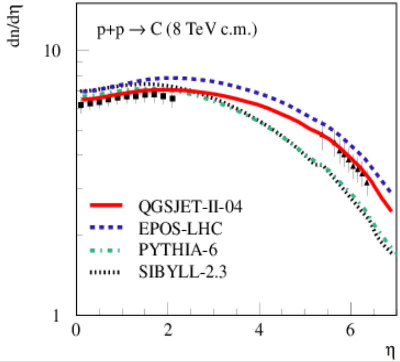
  - for increasing $\sqrt{s}$, only central production enhanced
- smaller K^{inel} ⇒ stronger 'leading particle' effect
- ⇒ slower shower development (larger $X_{\max}$)

- strong energy rise of K_{pp}^{inel} in EPOS & QGSJET-II: due to energy-momentum sharing in multiparton Fock states (less energy left for the proton 'remnants')

Why of importance for EAS predictions (e.g. for $X_{\max}$)?

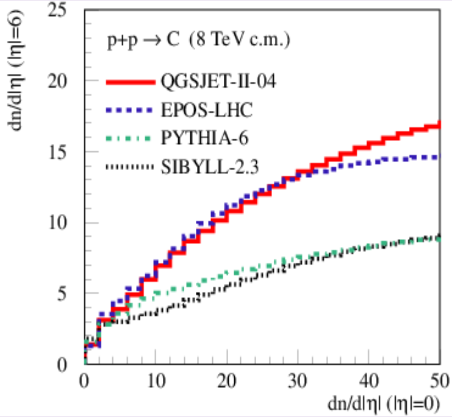
Test: combined CMS-TOTEM data on $dN_{\rm ch}/d\eta$

- flatter $dN_{\rm ch}/d\eta$ of EPOS & QGSJET-II agrees with data
- SIBYLL & PYTHIA – disfavored



Why of importance for EAS predictions (e.g. for $X_{\max}$)?

Crucial test: cross-correlation of $dN_{pp}^{\text{ch}}/d|\eta|$ in CMS & TOTEM



- strong correlation for QGSJET-II & EPOS (apart from the tails of the N^{ch} distributions)
- twice weaker correlation for SIBYLL & PYTHIA

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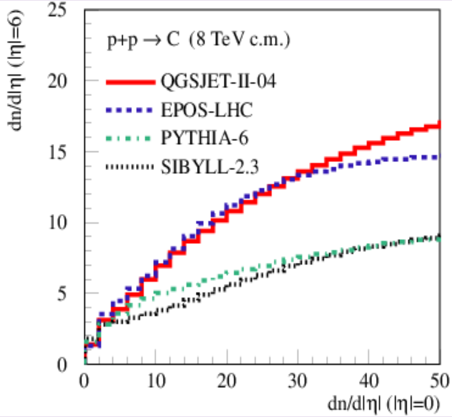
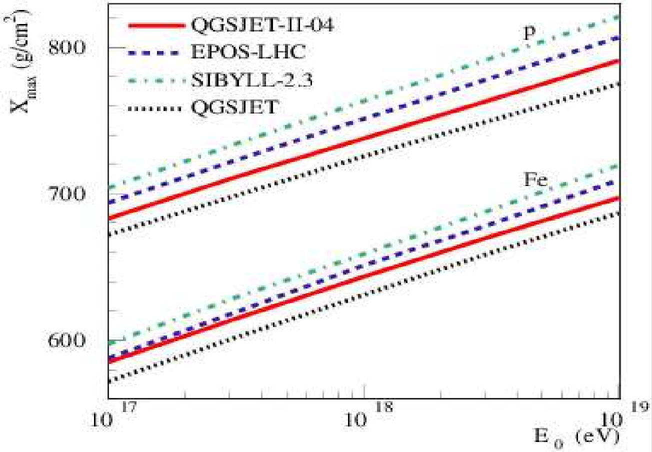


- strong correlation for QGSJET-II & EPOS (apart from the tails of the $N^{\rm ch}$ distributions)
- twice weaker correlation for SIBYLL & PYTHIA

- if strong correlation confirmed:
  final disproval of SIBYLL predictions for EAS

Relevance of the inelastic diffraction

Why different $X_{\max}$ predictions for the other three models?



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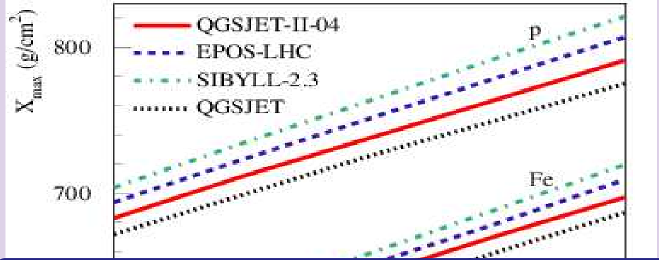


Model differences concerning the treatment of diffraction?

- predictions for $X_{\max}$ depend on $\sigma^{\rm inel}_{p-{\rm air}}$, $\sigma^{\rm diffr}_{p-{\rm air}}$, $K^{\rm inel}_{p-{\rm air}}$
  - $\sigma^{\rm tot/el}_{pp}$ can be reliably extrapolated thanks to LHC studies
  - $\sigma^{\rm diffr}_{pp}$ impacts recalculation from pp to pA (AA)
    - $\sigma^{\rm inel}_{p-{\rm air}}$ – due to inelastic screening
    - directly related to $\sigma^{\rm diffr}_{p-{\rm air}}$, hence, also to $K^{\rm inel}_{p-{\rm air}}$:
      due to small 'inelasticity' of diffractive collisions

Inelastic diffraction

Presently: tension between CMS & TOTEM concerning $\sigma_{pp}^{\rm SD}$

	TOTEM	CMS
M_X range, GeV	$7-350$	$12-394$
$\sigma_{pp}^{\rm SD}(\Delta M_X)$, mb	$\simeq 3.3$	4.3 ± 0.6
$\frac{d\sigma_{pp}^{\rm SD}}{dy_{\rm gap}}$, mb	0.42	0.62

- ⇒ may be regarded as the characteristic uncertainty for $\sigma_{pp}^{\rm SD}$
  - impact on $X_{\max}$?

Impact of uncertainties of $\sigma_{pp}^{\mathrm{SD}}$ on $X_{\max}$ predictions

Two alternative model versions (tunes): SD+ & SD-

- SD+: increased high mass diffraction (HMD)
  – to approach CMS results
  - slightly smaller LMD – to soften disagreement with TOTEM

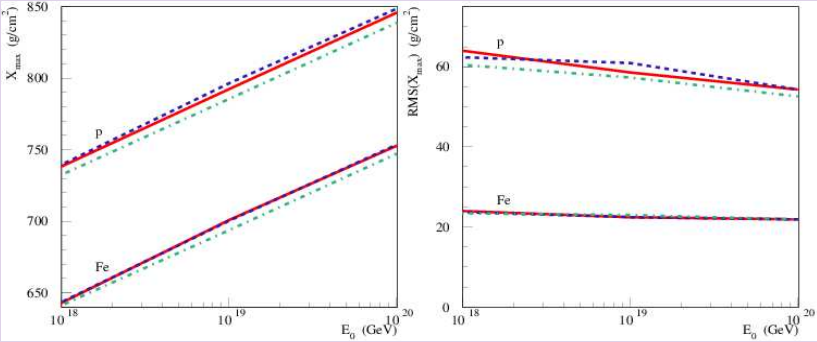
Impact of uncertainties of $\sigma_{pp}^{\mathrm{SD}}$ on $X_{\max}$ predictions

Two alternative model versions (tunes): SD+ & SD-

- SD+: increased high mass diffraction (HMD)
  – to approach CMS results
    - slightly smaller LMD – to soften disagreement with TOTEM
- SD-: smaller LMD (by 30%), same HMD
- similar $\sigma_{pp}^{\mathrm{tot/el}}$ & central particle production in both cases

Impact of uncertainties of $\sigma_{pp}^{\mathrm{SD}}$ on $X_{\max}$ predictions

Impact on $X_{\max}$ & RMS($X_{\max}$)

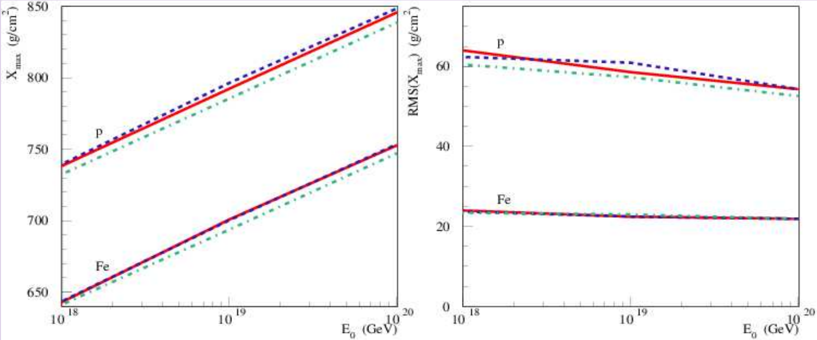


Option SD-: smaller low mass diffraction

- ⇒ smaller inelastic screening ⇒ larger $\sigma_{p-\mathrm{air}}^{\mathrm{inel}}$
- smaller diffraction for proton-air ⇒ larger $K_{p-\mathrm{air}}^{\mathrm{inel}}$
- ⇒ smaller $X_{\max}$ (all effects work in the same direction): $\Delta X_{\max} \simeq -10\,\mathrm{g/cm}^2$

Impact of uncertainties of $\sigma_{pp}^{\mathrm{SD}}$ on $X_{\max}$ predictions

Impact on $X_{\max}$ & RMS($X_{\max}$)

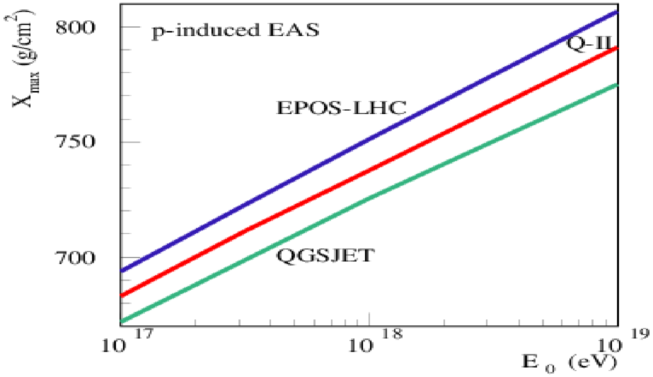


Option SD+: larger high mass diffraction

- opposite effects
- but: minor impact on $X_{\max}$ ($\Delta X_{\max} < 5\,\mathrm{g/cm^2}$)
- in both cases: minor impact on RMS($X_{\max}$): $< 3\,\mathrm{g/cm^2}$ (dominated by $\sigma_{p-\mathrm{air}}^{\mathrm{inel}}$)

Other sources of model uncertainties for $X_{\max}$

Model differences for $X_{\max}$ twice bigger (reach $20\,\mathrm{g/cm^2}$)

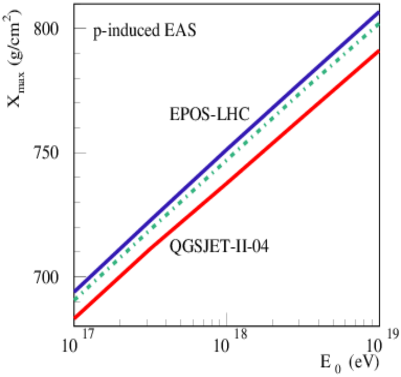


- previous analysis not general enough?
- or other interaction properties relevant?
- to answer - use “cocktail” model approach

Other sources of model uncertainties for $X_{\max}$

Let us compare $X_{\max}$ of EPOS-LHC & QGSJET-II-04

- and construct 'mixture models'
- use QGSJET-II for $\sigma^{\rm inel}_{p-\rm air}$ & leading nucleon spectrum (EPOS-LHC for the rest)
- $\Delta X_{\max} \leq 5$ g/cm^2 - in agreement with above



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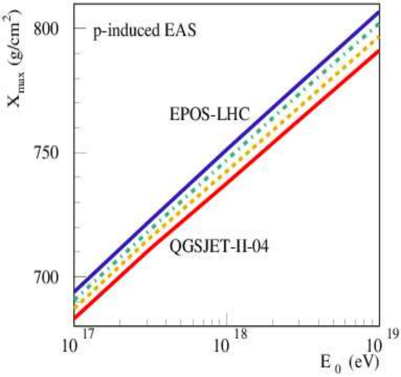
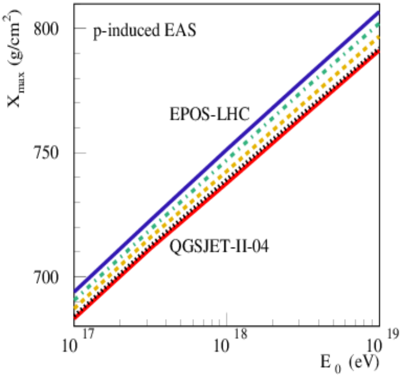
- QGSJET-II for $\sigma^{\rm inel}_{p-{\rm air}}$ & leading nucleon spectrum (EPOS-LHC for the rest)
- $\Delta X_{\max} \leq 5$ g/cm^2 - in agreement with above
- now QGSJET-II for the complete 1st interaction (EPOS-LHC for the rest)
- $\Delta X_{\max} \leq 5$ g/cm^2
- reason: harder pion spectra in $p-{\rm air}$ in EPOS-LHC



Other sources of model uncertainties for $X_{\max}$

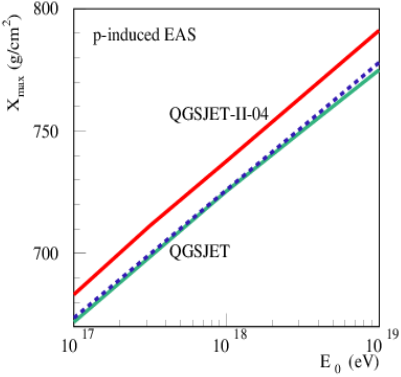
Let us compare $X_{\max}$ of EPOS-LHC & QGSJET-II-04

- QGSJET-II for $\sigma^{\text{inel}}_{p-\text{air}}$ & leading nucleon spectrum (EPOS-LHC for the rest)
- $\Delta X_{\max} \leq 5$ g/cm^2 - in agreement with above
- now QGSJET-II for the complete 1st interaction (EPOS-LHC for the rest)
- $\Delta X_{\max} \leq 5$ g/cm^2
- remaining difference: copious $\bar{p}p$- & $\bar{n}n$-pair production in π- & K-air in EPOS-LHC



Other sources of model uncertainties for $X_{\max}$

Now compare $X_{\max}$ of QGSJET & QGSJET-II-04



- use QGSJET-II for the complete 1st interaction (QGSJET for the rest)
- $\Delta X_{\max} \leq 3$ g/cm^2

Other sources of model uncertainties for $X_{\max}$

Now compare $X_{\max}$ of QGSJET & QGSJET-II-04

- use QGSJET-II for the complete 1st interaction (QGSJET for the rest)
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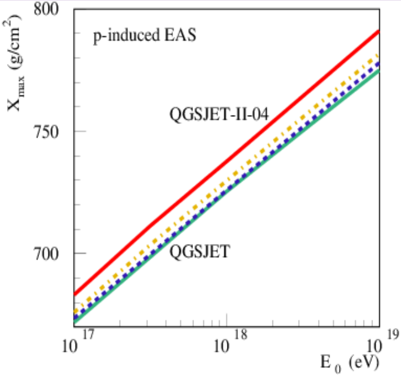
- next: QGSJET-II for the 1st interaction & for all $\sigma^{\rm inel}_{\pi-{\rm air}}$, $\sigma^{\rm inel}_{K-{\rm air}}$



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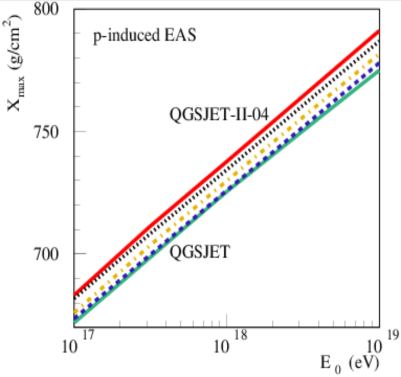
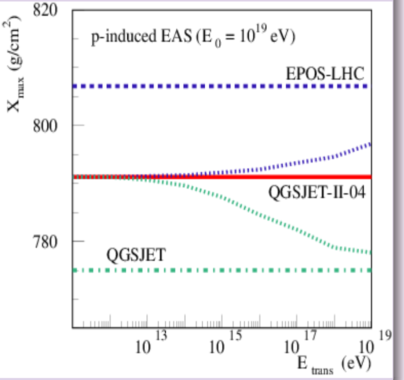
- next: QGSJET-II for the 1st interaction & for all $\sigma^{\mathrm{inel}}_{\pi-\mathrm{air}}$, $\sigma^{\mathrm{inel}}_{K-\mathrm{air}}$
- rest: mostly due to softer pion & kaon spectra in π-air in QGSJET



Other sources of model uncertainties for $X_{\max}$

Present $X_{\max}$ uncertainties: largely due to very high energy $\pi - \mathrm{air}$

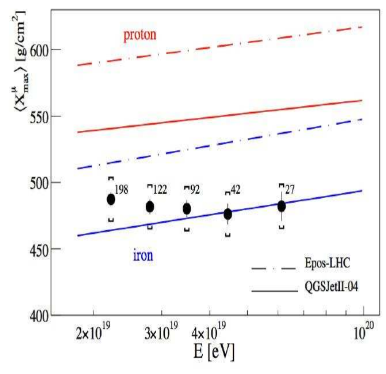
- $X_{\max}$ for 10^{19} eV proton EAS using 'cocktail': QGSJET-II for $E > E_{\mathrm{trans}}$ and EPOS-LHC or QGSJET for $E < E_{\mathrm{trans}}$
- main difference for $E \to E_0$ (before most of the energy goes into the e/m cascade)
- how to constrain pion-air collisions at VHE?!



Testing models with air shower data

PAO measurement of maximal muon production depth $X^{\mu}_{\max}$

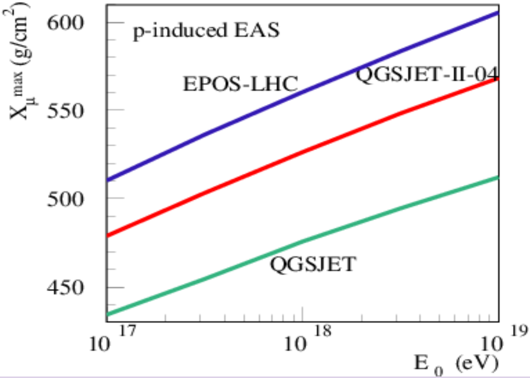
- models predict deeper $X^{\mu}_{\max}$ than observed
  - e.g. one needs primary iron for QGSJET-II-04
  - or primary gold for EPOS-LHC...



[from M. Roth, "Composition-2015" talk]

Testing models with air shower data

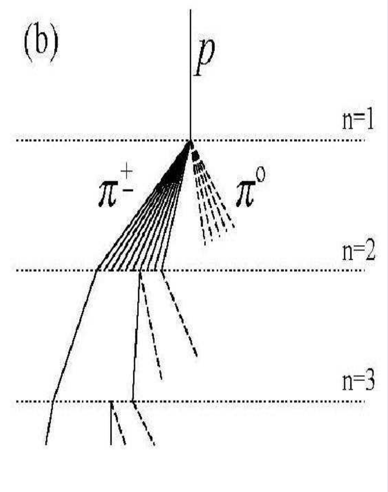
What is the physics behind the different predictions for $X^{\mu}_{\max}$?



Testing models with air shower data

1) Smallness of the $\pi-\mathrm{air}$ cross section?

- NB: muons originate from a multi-step hadron cascade
- smaller $\sigma^{\mathrm{inel}}_{\pi-\mathrm{air}}$ $\Rightarrow$ larger distances between the cascade steps
  - $\Rightarrow$ deeper $X^{\mu}_{\max}$
  - NB: larger diffraction in $\pi-\mathrm{air}$ $\Rightarrow$ similar effect *[credits to T. Pierog]*



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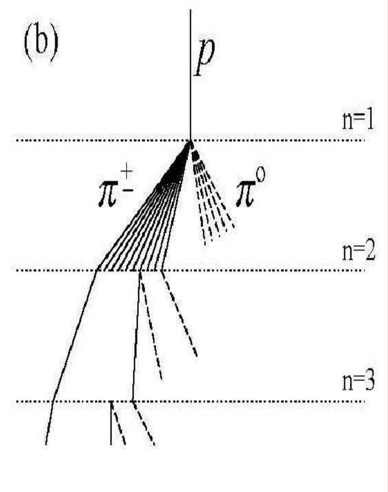
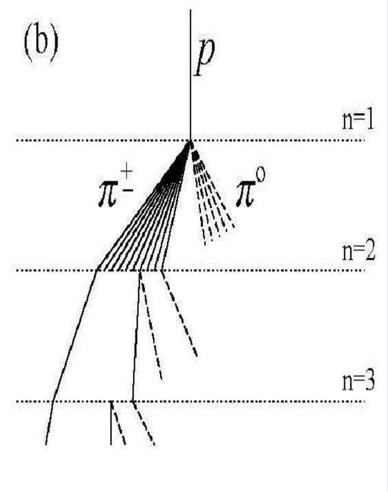


Testing models with air shower data

2) Hardness of pion spectra in $\pi - \mathrm{air}$?

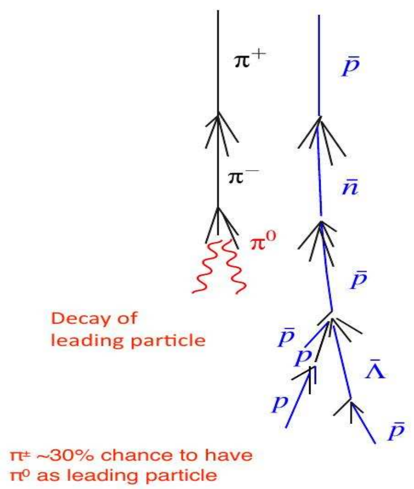


- pion decay probability: $p_{\mathrm{decay}} \propto E_\pi^{\mathrm{crit}}/E_\pi/X$
- $X_{\max}^{\mu}$: where $p_{\mathrm{decay}} \sim p_{\mathrm{inter}}$
- harder spectra in $\pi - \mathrm{air}$ $\Rightarrow$ deeper $X_{\max}^{\mu}$ (effectively one more cascade step)

Testing models with air shower data

3) Copious production of (anti-)nucleons?

- no decay for p & $\bar{p}$ (n & $\bar{n}$)
  $\Rightarrow$ few more cascade steps
- but: impact on $X_{\max}^{\mu}$ IFF $N_{p,\bar{p},n,\bar{n}}$ comparable to N_{π}! (the case of EPOS)

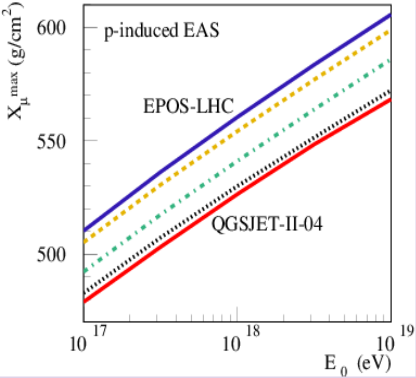


[from R. Engel, "Composition-2015" talk]

Testing models with air shower data

Difference of $X^{\mu}_{\max}$: EPOS-LHC / QGSJET-II-04, using “cocktail”

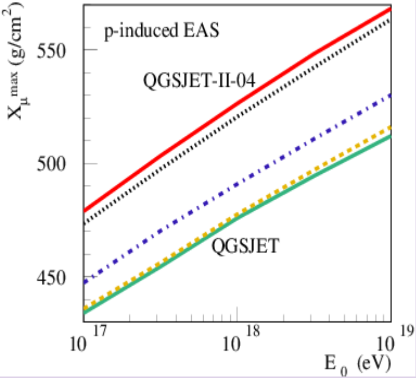
- QGSJET-II for 1st inter.; EPOS-LHC for the rest (minor effect)
- largest effect: copious $\bar{p}p$ & $\bar{n}n$ production in EPOS
- remaining difference: higher diffraction in π- & K-air in EPOS



Testing models with air shower data

Difference of $X^{\mu}_{\max}$: QGSJET / QGSJET-II-04, using "cocktail"

- QGSJET-II for 1st interaction, rest – QGSJET: minor effect
- QGSJET-II for 1st interaction & $\sigma^{\rm inel}_{\pi,K-{\rm air}}$
- main effect: softer $\pi^{\pm}$ & $K^{\pm}$ spectra in π-air in QGSJET



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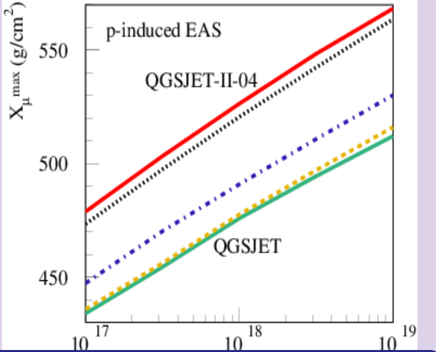

Model-dependence of $X^{\mu}_{\max}$: same features of π-air as for $X_{\max}$

- $X^{\mu}_{\max}$ – even more sensitive!
- ⇒ can be used to constrain model approaches
- e.g. PAO data disfavor copious $\bar{p}p$ & $\bar{n}n$ production and large diffraction of pions in EPOS-LHC

Summary: constraints on models

From LHC data along:

- SIBYLL – disfavored
- EPOS-LHC & QGSJET-II-04 – equally good

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- correcting those will push $X_{\max}$ higher in the atmosphere (closer to QGSJET-II-04)
- QGSJET-II-04? (to be discussed later)

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Compared to PAO, one goes few decades down in energy

- ⇒ smaller number of cascades steps
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- in addition: pion-air collisions better constrained by fixed target data (notably from NA61)

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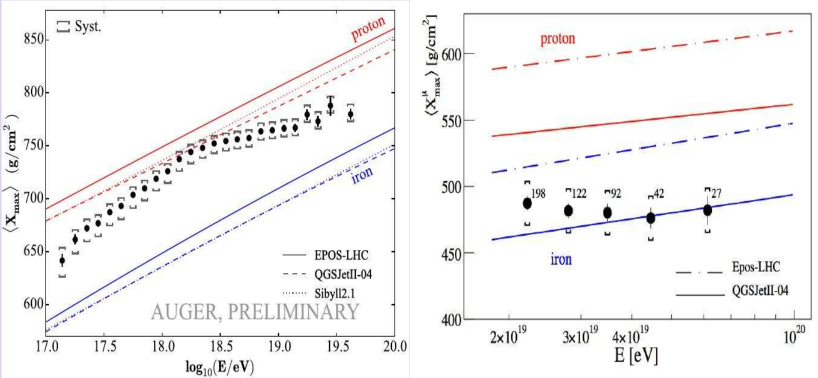
Interpreting simulteneously PAO data on $X_{\max}$ & $X^{\mu}_{\max}$?

This would require a faster development of the hadronic cascade



- because: impact on $X^{\mu}_{\max}$ - stronger than on $X_{\max}$
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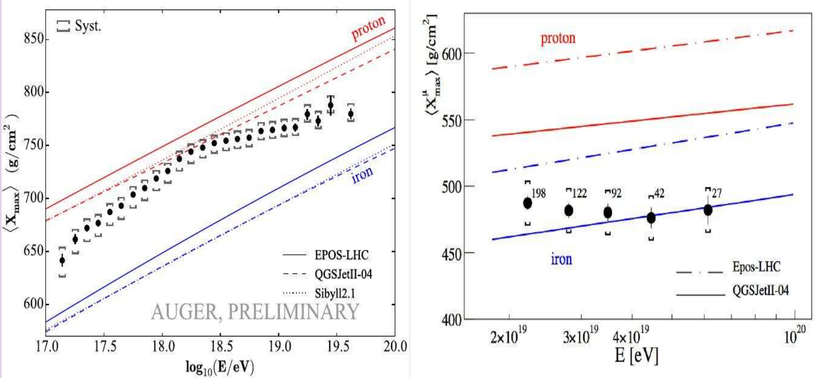

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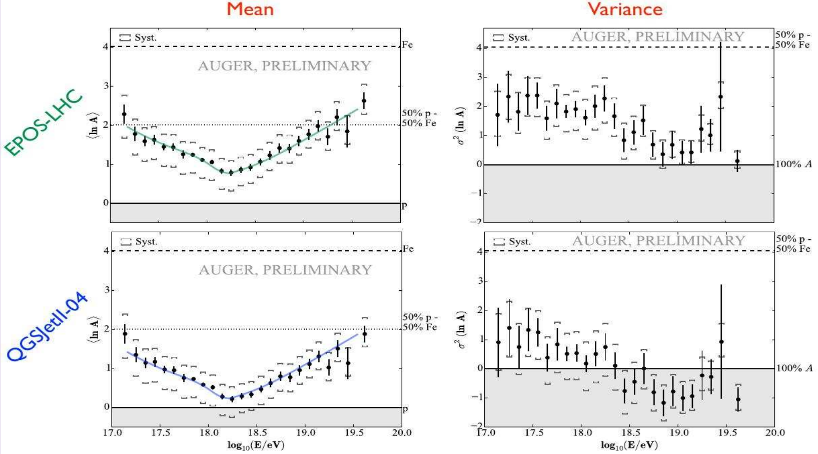
- technically: requires higher $\sigma^{\text{inel}}_{\pi-\text{air}}$ and/or softer $\pi^{\pm}$ spectra
  - ⇒ towards old QGSJET
- ⇒ this would push us towards a light composition?!

Conflict with RMS($X_{\max}$)?

PAO analysis favors models with deeper $X_{\max}$ & smaller RMS($X_{\max}$)



[from M. Roth, "Composition-2015" talk]

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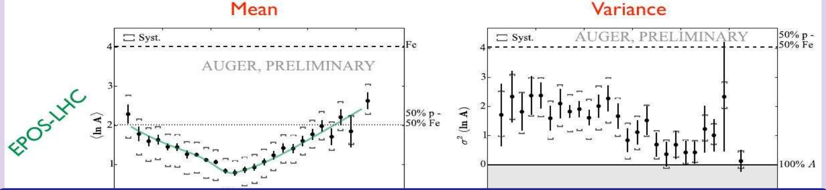
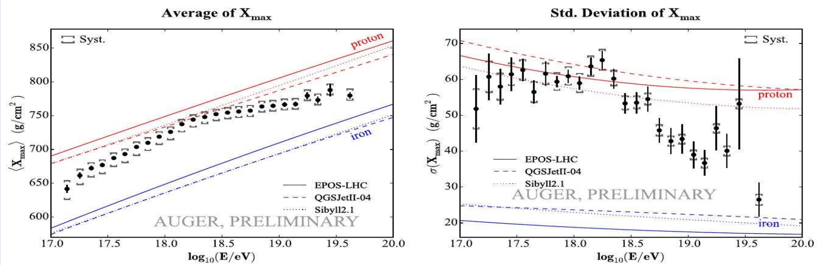


PAO data & model predictions for $X_{\max}$ & RMS($X_{\max}$)

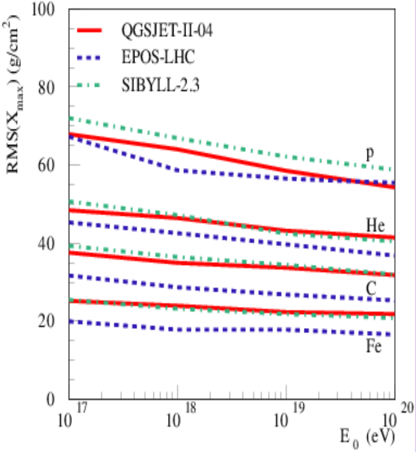


- for deeper $X_{\max}$ – see the discussion above
- what about the model differences for RMS($X_{\max}$)?

Conflict with RMS($X_{\max}$)?

NB: small model uncertainty for RMS($X_{\max}$) based on LHC data

- tuning to LHC data on $\sigma_{pp}^{\rm inel}$ ⇒ similar RMS($X_{\max}$) for protons

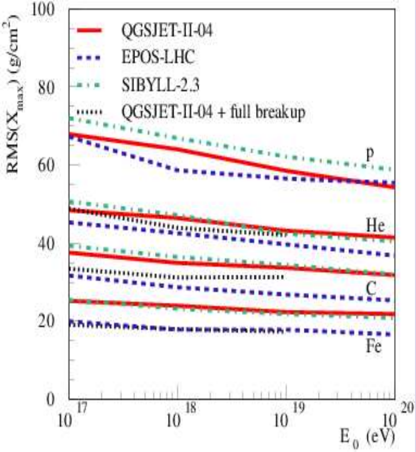


- differences for A-induced EAS: fragmentation of nuclear 'spectator' part

Conflict with RMS($X_{\max}$)?

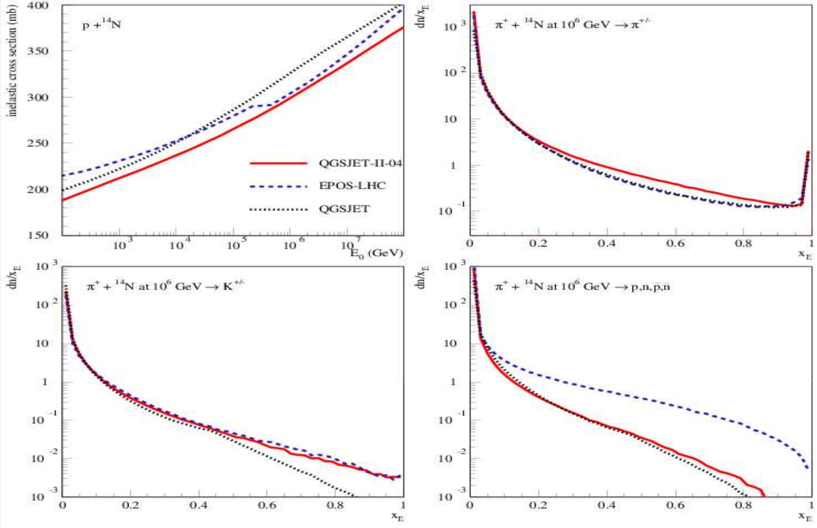
NB: small model uncertainty for RMS($X_{\max}$) based on LHC data

- tuning to LHC data on $\sigma_{pp}^{\rm inel}$ ⇒ similar RMS($X_{\max}$) for protons
- differences for A-induced EAS: fragmentation of nuclear 'spectator' part
- to explain EPOS results: QGSJET-II & full break up of nuclear spectator part (into separate nucleons)
  - NB: full break up – in variance with exp. data at fixed target energies
- ⇒ no real freedom here!



Extra slides

$\sigma_{\rm inel}$ & forward hadron spectra for pion-nytrogen collisions



Forward π^0 spectra at $\sqrt{s} = 7$ (solid) and 2.76 (dashed) TeV compared to LHCf data