High Energy Cosmic Ray Interactions and UHECR Composition Problem

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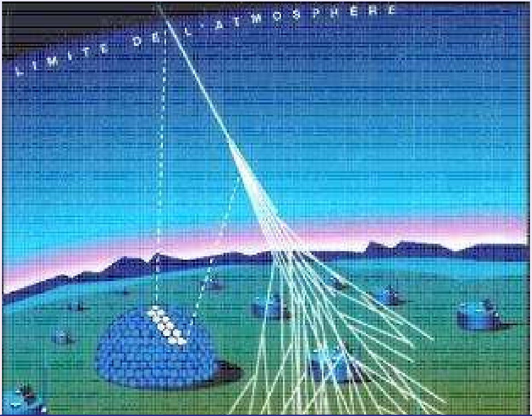
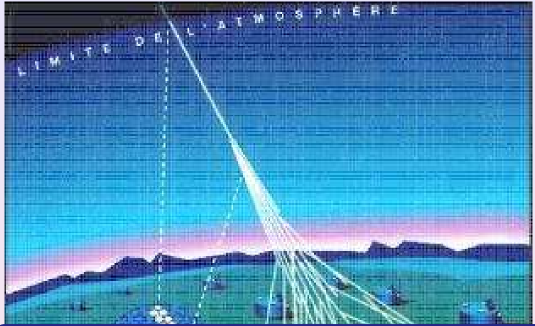
Cosmic ray studies with Extensive Air Shower technique



CR composition – inferred from air shower properties

- e.g., shower maximum position $X_{\max}$
- or muon density ρ_μ at ground
- problem: consistency between different measurements?!

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'

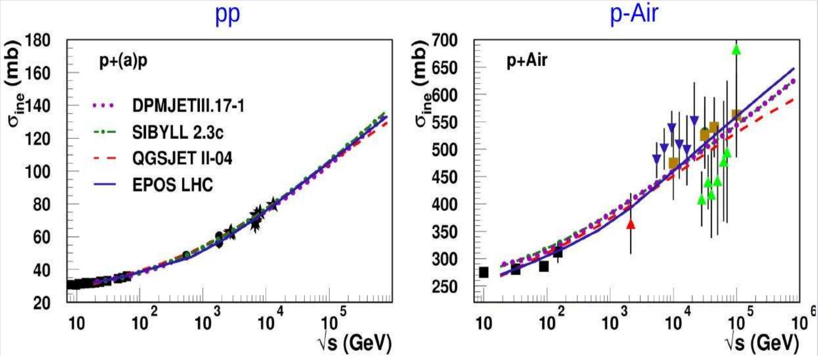
CR interaction models, LHC data, and EAS predictions

List of models available in the CORSIKA EAS simulation code
(from T. Pierog, ISVHECRI-2018)

- **Which model for CR ?** (alphabetical order)
  - **DPMJETIII.17-1** by S. Roesler, A. Fedynitch, R. Engel and J. Ranft
  - **EPOS (1.99/LHC)** (from VENUS/NEXUS before) by H.J. Drescher, F. Liu, T. Pierog and K.Werner.
  - **QGSJET** (01/II-03/II-04/III) by S. Ostapchenko (starting with N. Kalmykov)
  - **Sibyll (2.1/2.3c)** by E-J Ahn, R. Engel, R.S. Fletcher, T.K. Gaisser, P. Lipari, F. Riehn, T. Stanev

CR interaction models, LHC data, and EAS predictions

All the models: updated with data from LHC Run 1
(notably on $\sigma_{pp}^{\mathrm{tot/el}}$ by TOTEM & ATLAS ALFA)

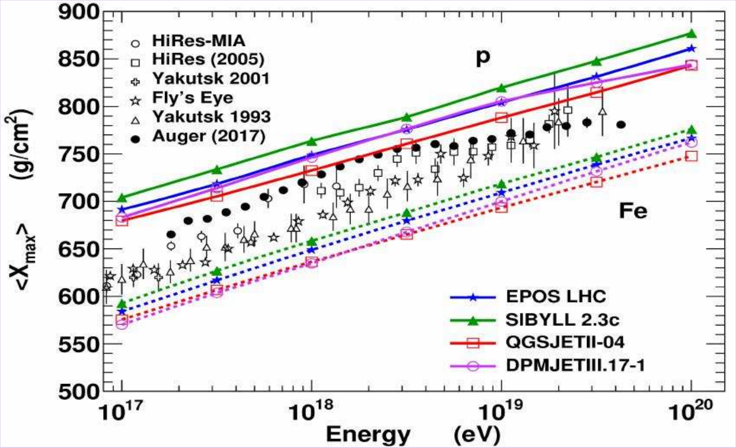


[T. Pierog, ISVHECRI-2018]

- $\Rightarrow$ very similar high energy extrapolations for $\sigma_{pp}^{\mathrm{inel}}$ & $\sigma_{p-\mathrm{air}}^{\mathrm{inel}}$
- $\Rightarrow$ strong constraint on $X_{\max}$ predictions
  ($< 10\%$ difference in $\sigma_{p-\mathrm{air}}^{\mathrm{inel}} \Rightarrow \lesssim 10$ g/cm^2 shift in $X_{\max}$)

CR interaction models, LHC data, and EAS predictions

Yet large (up to 40 g/cm^2) differences for $X_{\max}$ predictions



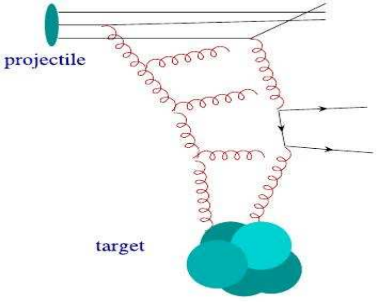
[T. Pierog, ISVHECRI-2018]

- largest differences between SIBYLL & QGSJET-II (to be addressed below)

Same qualitative picture for all the models

- QCD-inspired: interaction mediated by parton cascades

- multiple scattering (many cascades in parallel)
- real cascades $\Rightarrow$ particle production
- virtual cascades $\Rightarrow$ elastic rescattering (just momentum transfer)



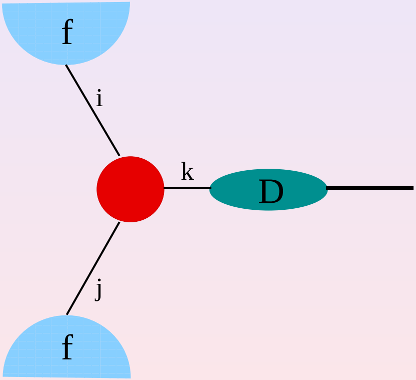
Universal interaction mechanism $\Rightarrow$ predictive power

- different hadrons (nuclei) $\Rightarrow$ different initial conditions (parton Fock states) but same mechanism
- energy-evolution of the observables (e.g. σ_{pp}^{tot}): due to a larger phase space for cascades to develop

Hadronic interactions: input from pQCD & problems

- pQCD: collinear factorization applies for inclusive spectra
  $\frac{d^3\sigma_{pp\to h}}{dp^3} = \sum_{i,j,k} f_{i/p} \otimes \sigma_{ij\to k} \otimes f_{j/p} \otimes D_{h/k}$

- pQCD predicts evolution of PDFs ($f_{i/p}$) & FFs ($D_{h/k}$)
- $\Rightarrow$ allows to treat high p_t hadron production



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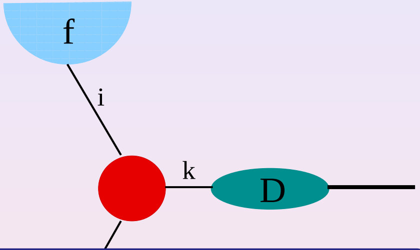


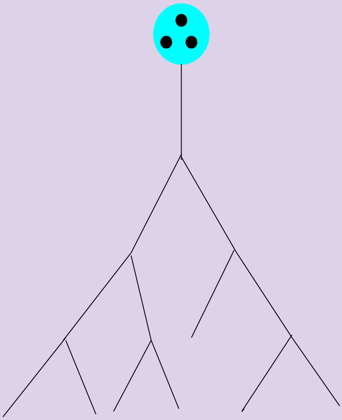
What is beyond and why the models are so different?

- nonperturbative (low p_t) parton evolution ('soft' rescatterings; very initial stage of 'semihard' cascades)
- multiple scattering aspect
- nonlinear effects (interactions between parton cascades)
- constituent parton Fock states & hadron 'remnants'

Nonperturbative parton Fock states: 2 approaches

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

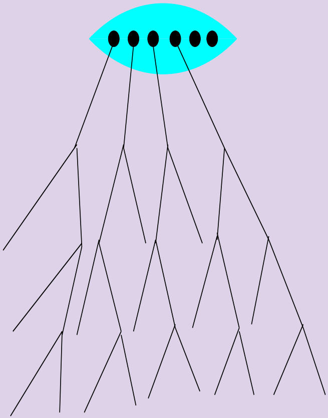
- multiple parton cascades originate from the same initial parton state
- multiple scattering has small impact on forward spectra
  - new branches emerge at small x $(G(x,q^2) \propto 1/x)$
- $\Rightarrow$ Feynman scaling for forward particle production
- higher $\sqrt{s} \Rightarrow$ more abundant central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



Nonperturbative parton Fock states: 2 approaches

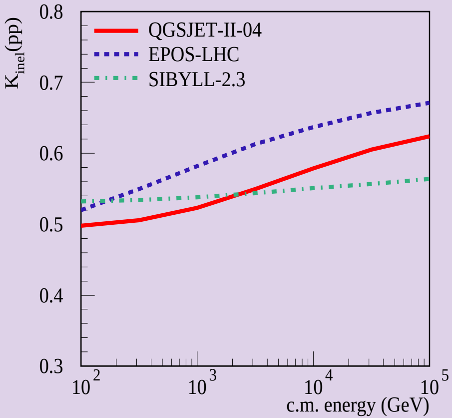
2. $p = \sum$ of multi-parton Fock states [EPOS & QGSJET(-II)]

- many cascades develop in parallel (already at nonperturbative stage)
- higher $\sqrt{s} \Rightarrow$ larger Fock states come into play: $|qqq\rangle \rightarrow |qqq\bar{q}q\rangle \rightarrow \ldots\ |qqq\bar{q}q\ldots\bar{q}q\rangle$
  - $\Rightarrow$ 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 air shower predictions?

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



- SIBYLL: $K_{pp}^{\rm inel}$ - weak energy dependence
  - for increasing $\sqrt{s}$, mostly central production enhanced
- smaller $K^{\rm inel}$ $\Rightarrow$ stronger 'leading particle' effect
- $\Rightarrow$ slower shower development (deeper $X_{\max}$)

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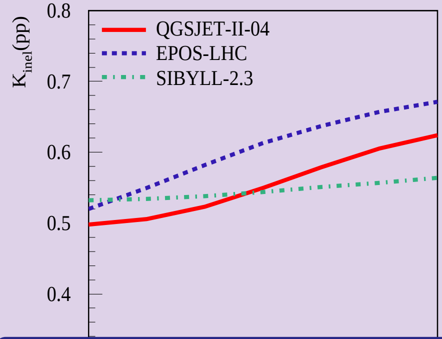

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- $\Rightarrow$ slower shower

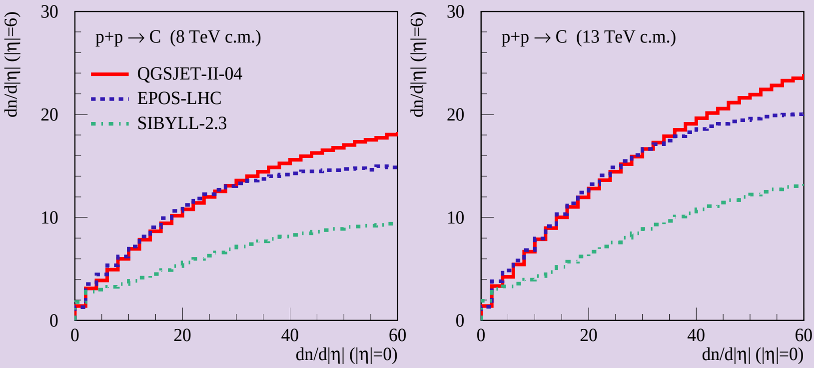
Strong energy-rise of K_{pp}^{inel} in EPOS & QGSJET-II

- due to energy sharing between larger numbers of constituent partons at higher energies
  - $\Rightarrow$ less energy left for proton 'remnants'
- $\Rightarrow$ quicker EAS development (smaller $X_{\max}$)

'Smoking gun' test: signal correlations in CMS & TOTEM

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

Cross-correlation of $dN_{pp}^{\rm ch}/d|\eta|$ at $\eta = 0$ ($p_t > 0.1$ GeV) and $\eta = 6$



- strong correlation for QGSJET-II-04 & EPOS-LHC (apart from the tails of the multiplicity distributions)
- twice weaker correlation for SIBYLL-2.3

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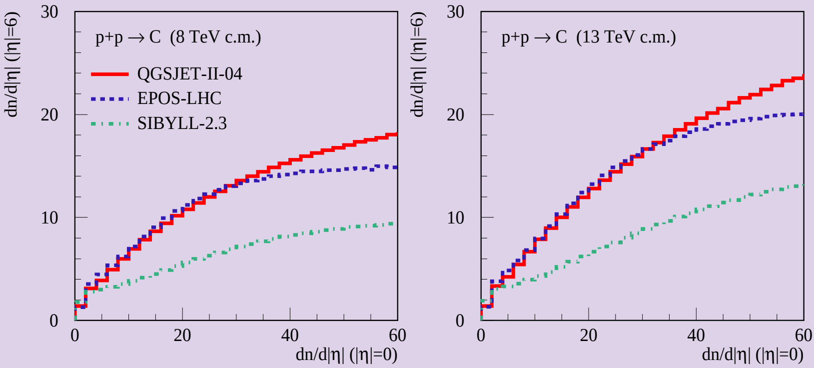


- strong correlation for QGSJET-II-04 & EPOS-LHC (apart from the tails of the multiplicity distributions)

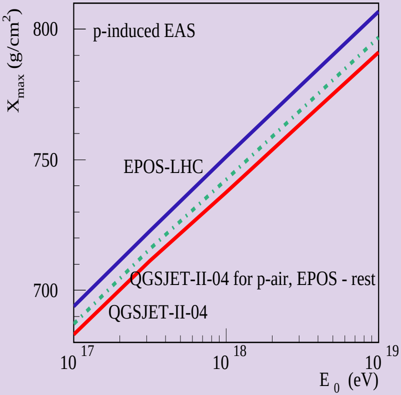
Similar studies possible with LHCf & ATLAS detectors

Other model uncertainties largely due to π-air interactions

[SO & Bleicher, PRD93 (2016) 051501]

E.g., compare X_{max} of EPOS-LHC & QGSJET-II-04

- and make a "cocktail": QGSJET-II for the 1st interaction & EPOS-LHC for the rest of the cascade



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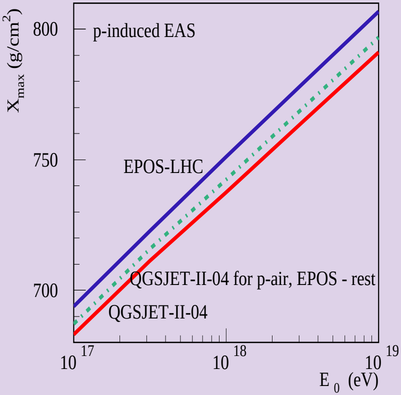
E.g., compare X_{max} of EPOS-LHC & QGSJET-II-04

- and make a "cocktail": QGSJET-II for the 1st interaction & EPOS-LHC for the rest of the cascade
- large part of EPOS & QGSJET-II X_{max}-difference: due to π-air collisions (difference between red & green lines)
- caused by a copious $\bar{p}p$- & $\bar{n}n$-pair production and higher pion diffraction rate in EPOS-LHC



How to solve the UHECR composition puzzle?

Present data on UHECR composition: no coherent interpretation

- because of deficiences of current CR interaction models?
- or the problem is with the data themselves?
- $\Rightarrow$ let us start with one benchmark observable

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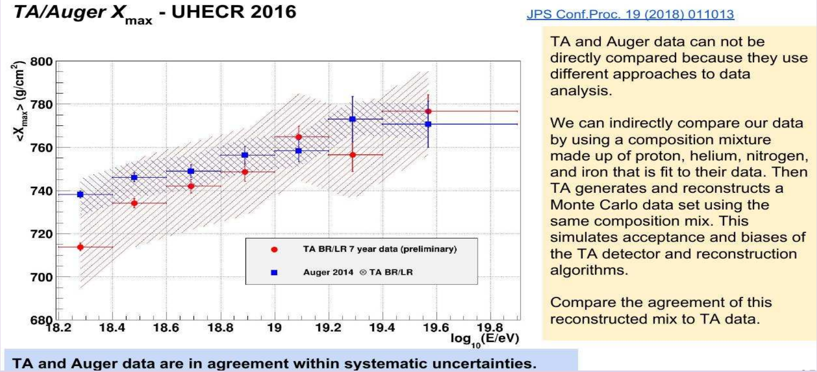
- ⇒ let us start with one benchmark observable

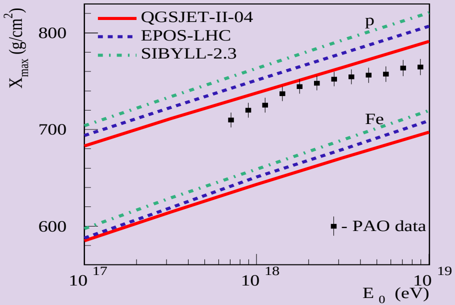
$\langle X_{\max} \rangle$ – good candidate: PAO & TA – consistent with each other



[W. Hanlon, ISVHECRI-2018]

How to solve the UHECR composition puzzle?

But: which model to use to interprete the data?



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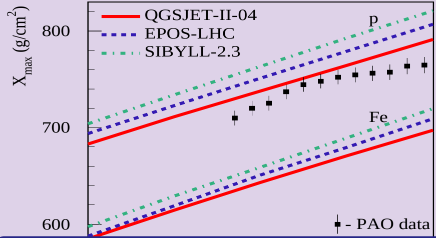
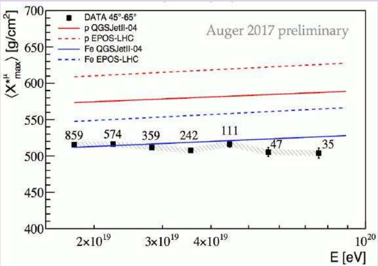


- or all the models are deficient?

PAO data on maximal muon production depth $X^{\mu}_{\max}$ may help

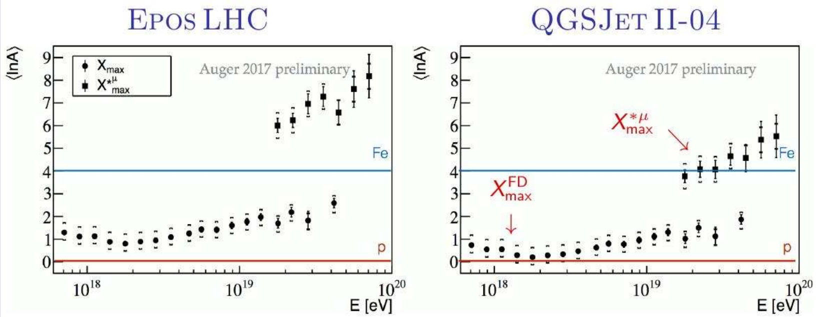


[R. Prado, ISVHECRI-2018]

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

How to solve the UHECR composition puzzle?

Change models to 'marry' $X_{\max}$ & $X^{\mu}_{\max}$ data composition-wise?



[R. Prado, ISVHECRI-2018]

- the two sets of data should overlap in terms of $\langle \ln A \rangle$
  - for $1 \leq A \leq 56$!

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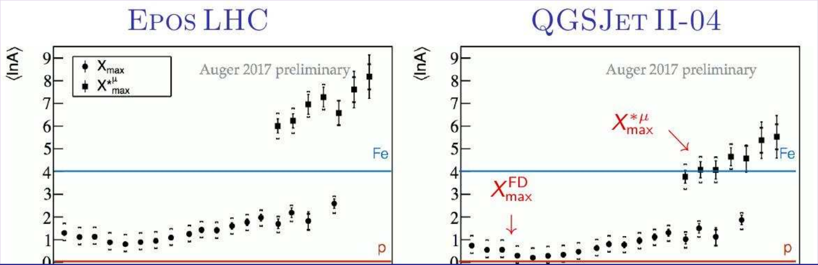

Acient Greek wisdom may help...

- change a model to modify $X_{\max}$ prediction:
  - $X^{\mu}_{\max}$ will move in the same direction!
- or vice versa

Modifying CR interaction models: which way to go?

- start with QGSJET-II and change the treatment of $p-\mathrm{air}$:
  - $\sigma^{\mathrm{inel}}_{p-\mathrm{air}}$ – little freedom in view of LHC data
  - treatment of diffractive collisions: $< 10\ \mathrm{g/cm^2}$ effect on $X_{\max}$ *[SO, PRD89 (2014) 074009]*
  - treatment of forward hadron production ($\Rightarrow$ impact on $K^{\mathrm{inel}}_{p-\mathrm{air}}$) – some freedom left (see the SIBYLL/QGSJET-II difference)

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  - $\Rightarrow$ (nearly) same effect on X_{max} and X^{μ}_{max}

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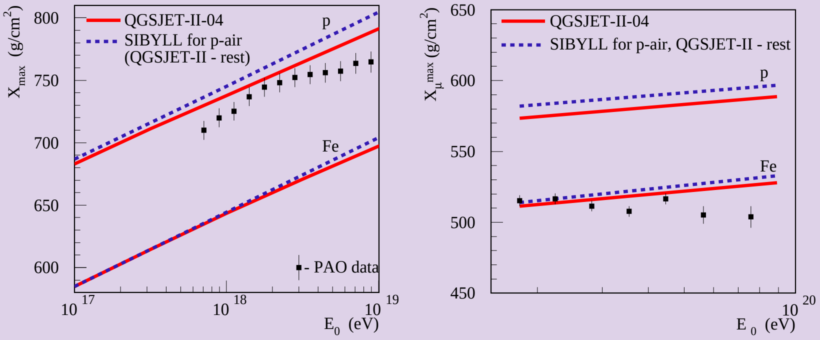
SIBYLL-2.3 for $p-$air ($\Rightarrow$ smaller $K^{\rm inel}_{p-\rm air}$); QGSJET-II for the rest

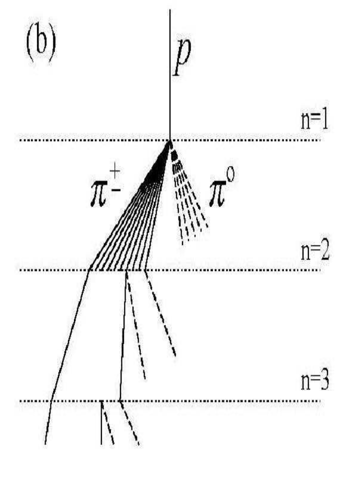


- $\Rightarrow$ larger $\langle \ln A \rangle$ from $X_{\max}$ but $\langle A \rangle > 56$, based on $X^{\mu}_{\max}$?!

Modifying CR interaction models: which way to go?

Changing the treatment of $\pi -$ air collisions ('Achilles & Tortoise')

- e.g., $\sigma^{\rm inel}_{\pi-{\rm air}}$, $\sigma^{\rm diffr}_{\pi-{\rm air}}$, $K^{\rm inel}_{\pi-{\rm air}}$
  - $\equiv$ making special assumptions concerning the pion structure



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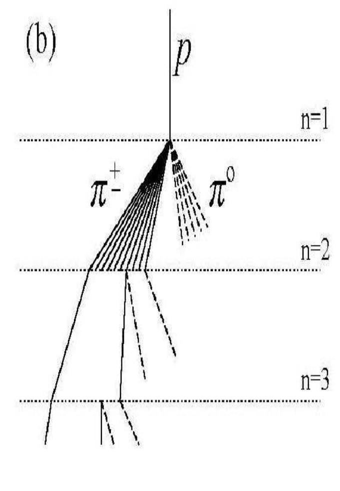

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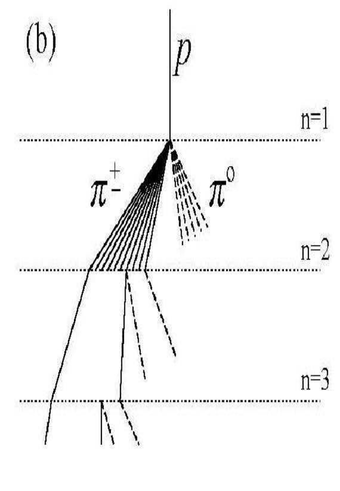
  - $\equiv$ making special assumptions concerning the pion structure
- affects every step in the multi-step hadron cascade
  - $\Rightarrow$ cumulative effect on $X^{\mu}_{\rm max}$
- but: only the first few steps in the cascade impact $X_{\rm max}$
  - after few steps, most of energy channelled into e/m cascades
  - $\Rightarrow$ much weaker effect on $X_{\rm max}$



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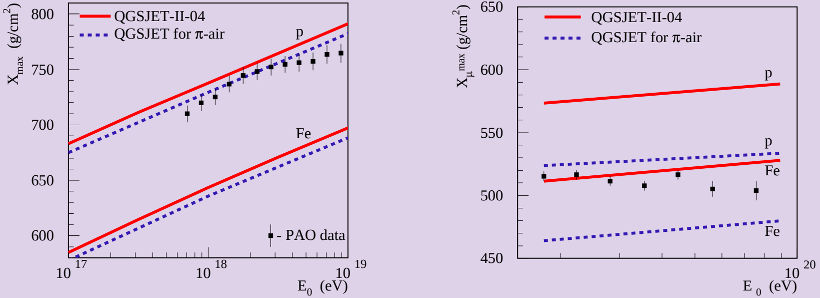
E.g., employing the old QGSJET model for $\pi-$air collisions

- $\Rightarrow$ higher $\sigma^{\rm inel}_{\pi-{\rm air}}$, larger $N^{\rm ch}_{\pi-{\rm air}}$ & $K^{\rm inel}_{\pi-{\rm air}}$



- $\Rightarrow$ (almost) pure proton composition for UHECRs

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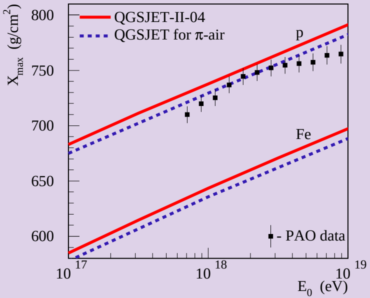

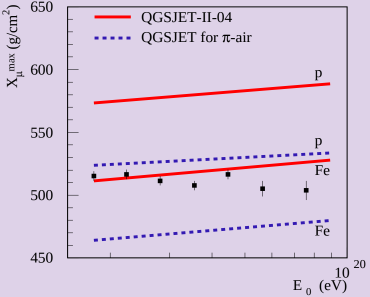

- $\Rightarrow$ (almost) pure proton composition for UHECRs

NB: rather an indication of the tendency, not a solution

- old QGSJET – outdated; known to overestimate particle production in $\pi-$air collisions

Summary on $X_{\max}$ & $X^{\mu}_{\max}$

Current situation

- data on $X_{\max}$ favor a light primary composition
- data on $X^{\mu}_{\max}$: close to model results for primary iron (at best)

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- parallel up/down shift of the cascade profile
  - $\Rightarrow$ same effect on $X_{\max}$ and $X^{\mu}_{\max}$
- $\Rightarrow$ no way to 'marry' $X_{\max}$ & $X^{\mu}_{\max}$ data composition-wise

Summary on X_{max} & X_{max}^{μ}

Current situation

- data on X_{max} favor a light primary composition
- data on X_{max}^{μ}: close to model results for primary iron (at best)

Changing the treatment of $\pi -$air interactions?

- strong effect on X_{max}^{μ} but minor shift of X_{max}
- $\Rightarrow$ self-consistent interpretation of the data on X_{max} & X_{max}^{μ}

Summary on $X_{\max}$ & $X^{\mu}_{\max}$

Current situation

- data on $X_{\max}$ favor a light primary composition
- data on $X^{\mu}_{\max}$: close to model results for primary iron (at best)

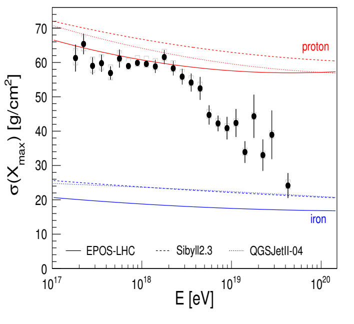
Changing the treatment of $\pi-$air interactions?

- strong effect on $X^{\mu}_{\max}$ but minor shift of $X_{\max}$
- $\Rightarrow$ self-consistent interpretation of the data on $X_{\max}$ & $X^{\mu}_{\max}$
- but: very light primary composition?!

Can model changes resolve the conflict with RMS(X_{max})?

Model predictions for RMS(X_{max}): no freedom for primary protons

- RMS(X_{max}): dominated by σ^{inel}_{p-air} (mean free pass)
  - now fixed by LHC data
- impact of diffraction: few g/cm^2 *[SO, PRD89 (2014) 074009]*
- fluctuations of K^{inel}_{p-air}: (Glauber) geometry of p-air collisions (N of 'wounded' nucleons)



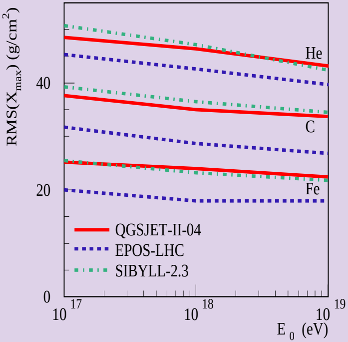
- ⇒ similar results for all the models

Can model changes resolve the conflict with RMS($X_{\max}$)?

Model predictions for RMS($X_{\max}$): no freedom for primary nuclei

- $\sigma^{\rm inel}_{A-{\rm air}}$ of weak impact (short mean free pass)
- universal (Glauber) collision geometry (fluctuations of the number of 'wounded' nucleons)
- but: sensitive to fragmentation of nuclear spectator part

  [Kalmykov & SO, Sov.J.Nucl.Phys. 50 (1989) 315; Phys.At.Nucl. 56 (1993) 346]



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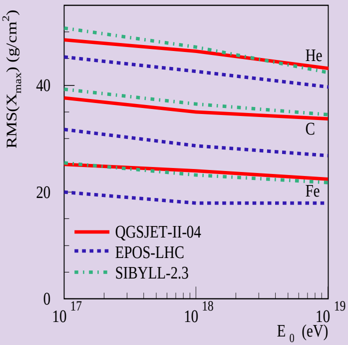
- universal (Glauber) collision geometry (fluctuations of the number of 'wounded' nucleons)
- but: sensitive to fragmentation of nuclear spectator part *[Kalmykov & SO, Sov.J.Nucl.Phys. 50 (1989) 315; Phys.At.Nucl. 56 (1993) 346]*

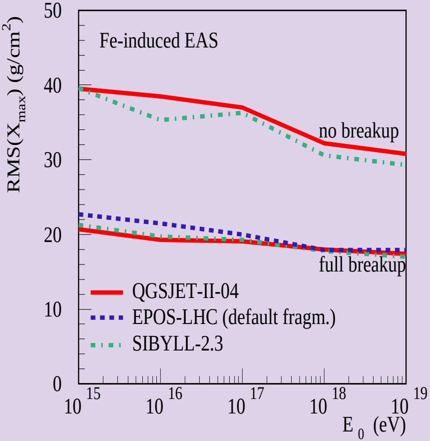


- experimental fact: relative fragment yields scale above few GeV/nucleon
- ⇒ calibration at low energies warranties HE predictions
- ⇒ no further freedom for RMS(X_{max}) (c.f. SIBYLL & QGSJET-II results)

Why smaller RMS(X_{max}) of EPOS-LHC? *[SO, arXiv:1612.09461]*

Cross check with SIBYLL & QGSJET-II: two extreme scenarios

1. complete break up of nuclear spectator part (into separate nucleons)
   $\Rightarrow$ smallest RMS(X_{max})
2. no break up (single secondary fragment)
   $\Rightarrow$ largest RMS(X_{max})



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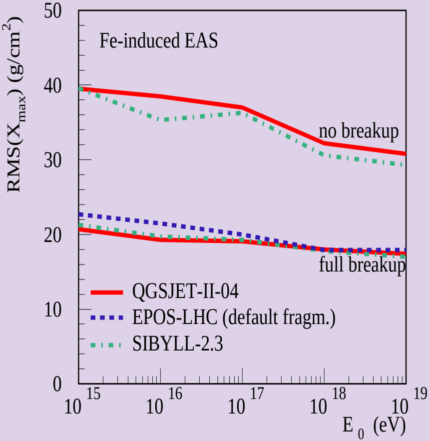

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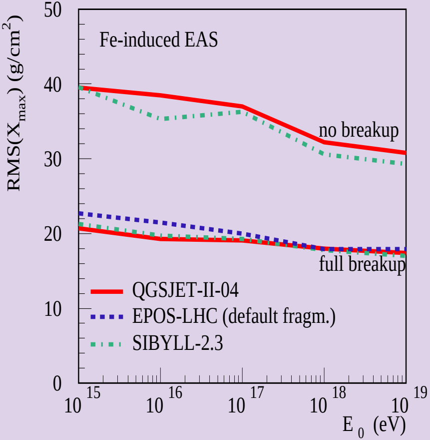
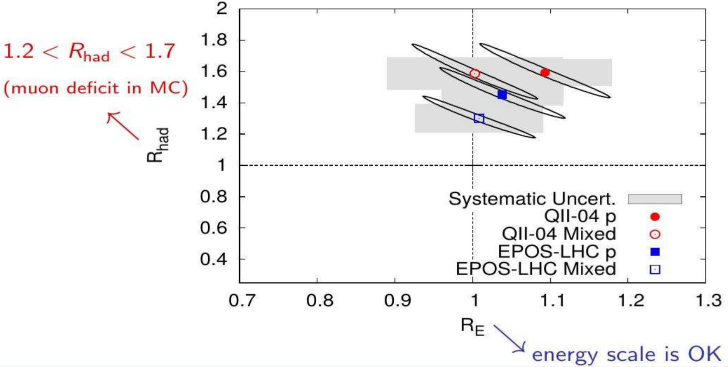


Likely reason: incorrect matching between the interaction and nuclear fragmentation procedures in EPOS (double count of knock-out nucleons)

Muon excess in air showers *[more details in extra slides]*

- indications on $20 - 70\%$ muon deficit in EAS simulations
  - $R_E \rightarrow$ energy scale
  - $R_{had} \rightarrow$ hadronic component



[R. Prado, ISVHECRI-2018]

Muon excess in air showers *[more details in extra slides]*

Can be explained by a change of the primary interaction?

- large N_μ-enhancement $\Leftrightarrow$ order of magnitude rise of N^{ch} (proton should look like a gold nucleus)
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- large N_μ-enhancement $\Leftrightarrow$ order of magnitude rise of N^{ch} (proton should look like a gold nucleus)
  - $\Rightarrow$ requires new physics
- but: with a huge (barn level) cross section
- can be discriminated experimentally: will cause factor of 10 enhancement of muon density fluctuations at ground

Muon excess in air showers *[more details in extra slides]*

Conventional physics: change of pion-air interactions?

- N_μ results from a multi-step hadron cascade
- simple Geitler model: $N_\mu(E_0) \simeq N_\mu(E_{\rm ref})\,(E_0/E_{\rm ref})^{\alpha_\mu}$
- assume a new model which predicts a faster energy rise: $\alpha_\mu \to \tilde{\alpha}_\mu$ (higher $N^{\rm ch}$ in π-air, smaller charge exchange, etc.)

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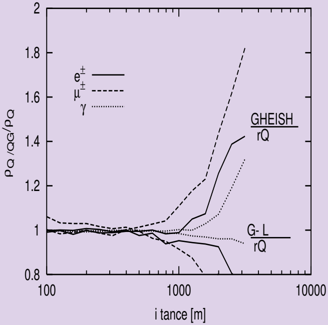
- assume a new model which predicts a faster energy rise: $\alpha_\mu \to \tilde{\alpha}_\mu$ (higher $N^{\rm ch}$ in π-air, smaller charge exchange, etc.)
- $\Rightarrow$ a substantial N_μ-enhancement at lower energies too
  - e.g., for $E_{\rm ref} = 10^{15}$ eV, R_μ enhancement at $E_0 = 10^{19}$ eV corresponds to $\sqrt{R_\mu}$ enhancement at 10^{17} eV

Muon excess in air showers *[more details in extra slides]*

Other options: change of LDF shape at large distances?

- current measurements of muon excess: mostly at large distances
- muon LDF at large R_{core}: sensitive to p_{t}-tails of low energy (~ 100 GeV) interactions at large heights
  - $\Rightarrow$ cross check of low energy models/use of alternative models
  - e.g., EPOS-LHC performs well compared to NA61 data



[Drescher et al., Asropart.Phys. 21 (2004) 87]

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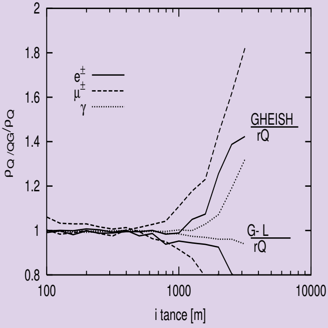


[Drescher et al., Asropart.Phys. 21 (2004) 87]

- another question: validity of the EGS4 treatment at large R_{core}, e.g., of the treatment of Landau scattering?

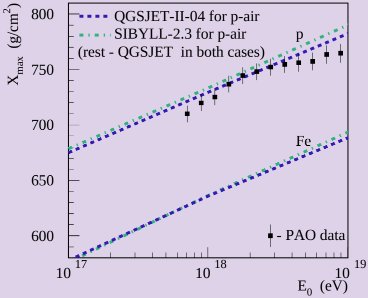
Summary

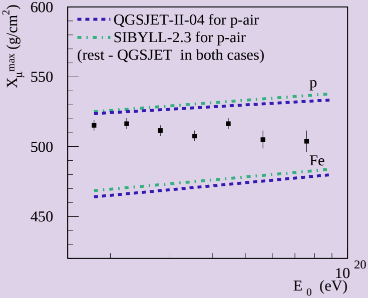
1. LHC studies of pp collisions constrained interaction models
    - most important for CR physics: $\sigma_{pp}^{\rm tot/el}$ by TOTEM & ATLAS
    - yet important differences between model predictions
2. Differences for predicted $K_{p-\rm air}^{\rm inel}$ ($\Rightarrow X_{\max}$):
   model assumptions for constituent parton Fock states
    - discrimination: correlations of forward & central production
3. Other uncertainties: mostly related to π-air interactions
4. Coherent interpretation of present data on $X_{\max}$ & $X_{\max}^{\mu}$
   $\Rightarrow$ very light composition of UHECRs
5. But: no freedom in the models to 'marry' a small RMS($X_{\max}$) to a light UHECR composition
6. Muon excess in air showers remains a puzzle
    - potential solutions with HE interactions – not too appealing
    - another possibility: change of muon LDF shape at large $R_{\rm core}$

Extra slides

Changing the treatment of both $p-$air & $\pi-$air collisions in opposite directions?

E.g., using SIBYLL-2.3 for $p-$air and QGSJET for $\pi-$air

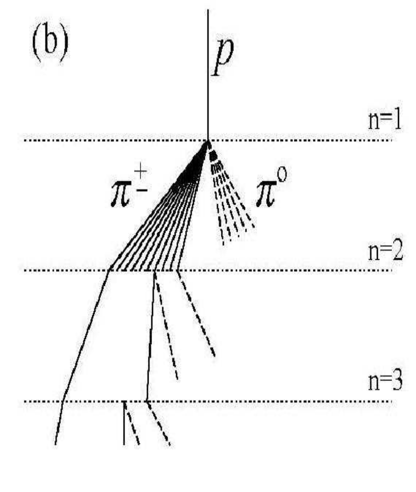




- still a very light UHECR composition
  - LHC data don't allow big changes for $p-$air
- NB: unnatural option – changes in models typically affect interactions of protons & pions similarly (e.g., rise of $N_{\rm ch}$)

Muon excess in air showers: potential options

- NB: N_μ results from a multi-step hadron cascade
  - $\lesssim 1$ cascade step per energy decade
- which $\pi -$ air interactions most important?
- $N_\mu \propto E_0^{\alpha_\mu} = \prod_{i=1}^{\mathrm{int}(\lg E_0)} 10^{\alpha_\mu}$
- each order of magnitude: factor $10^{\alpha_\mu} \simeq 8$ ($\alpha_\mu \simeq 0.9$)
- $\Rightarrow$ higher N_μ requires to change $\pi -$ air interactions over a wide energy range



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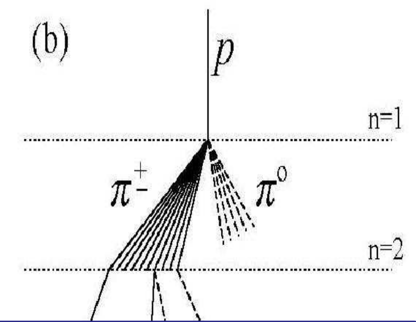


Producing muon excess by a change of the primary interaction?

- if we double N^{ch} for the 1st interaction?
  - $< 10\%$ increase for N_μ! *[SO, Czech.J.Phys. 56 (2006) A149]*
- to get, say, a factor 2 enhancement: N_{ch} should rise by an order of magnitude

Muon excess in air showers: potential options

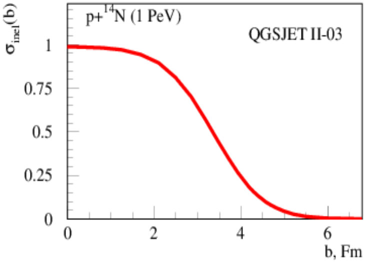
Producing muon excess by new physics?

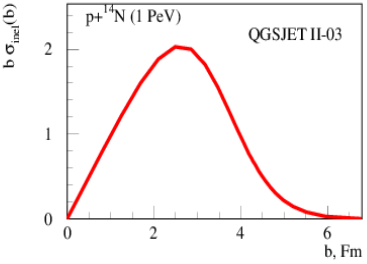
- proton-air cross section at ultrahigh energies: $\sigma_{p-\mathrm{air}}^{\mathrm{inel}} \sim 1/2$ b
- to be detected by air shower techniques:
  new physics should impact the bulk of interactions
- $\Rightarrow$ to emerge with barn-level cross section
  - presently at LHC: nothing at fb level (10^{-15} b)

Muon excess in air showers: potential options

NB: signals of new physics may be discriminated by PAO

p-air: interaction profile & distribution of the impact parameter b:





- $\Rightarrow$ interactions dominated by peripheral (large b) collisions
- at large b: low parton density
  - $\Rightarrow$ not suitable for new physics to emerge

Muon excess in air showers: potential options

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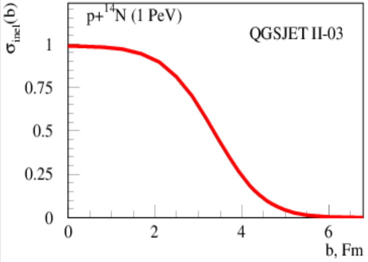

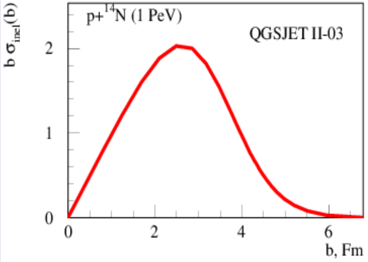

Assume new physics to emerge in 10% of most central collisions

- and result in EAS with a factor of 10 higher muon density...
  - $\Rightarrow$ 90% muon excess ($\langle\rho_\mu\rangle = 0.1 * 10\rho_\mu^{(0)} + 0.9 * \rho_\mu^{(0)} = 1.9\rho_\mu^{(0)}$)
- $\Rightarrow$ large fluctuations of muon density: $\sigma_{\rho_\mu}/\rho_\mu \simeq 100\%$
- $\Rightarrow$ can be easily discriminated in PAO data (for usual EAS: $\sigma_{\rho_\mu}/\rho_\mu \simeq 10 \div 15\%$)