Hadronic & Shower models: Summary

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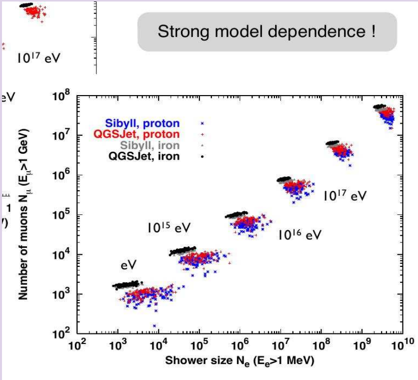
HAP Workshop on CR Composition

KIT, September 21-23, 2015

Time of big changes ('Perestrojka') for shower simulations

Old times: clear differences between models

- each model had a 'label'
- differences could be traced down to physics mechanisms

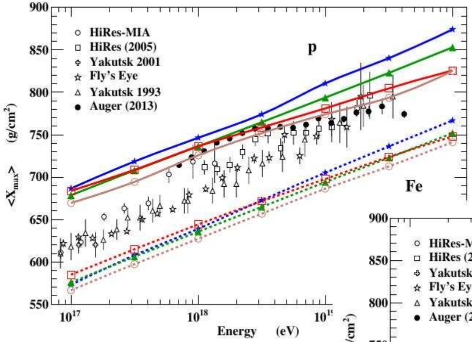


[from R. Engel]

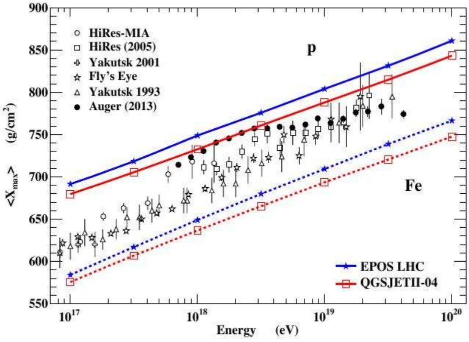
Time of big changes ('Perestrojka') for shower simulations

Start of LHC triggered model updates

pre-LHC models



post-LHC models

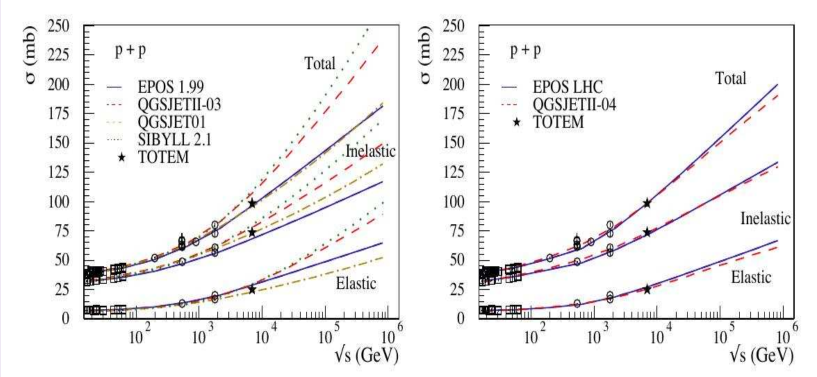


New models favour interpretation as heavier composition than before

(Pierog 2013, 2014)

Time of big changes ('Perestrojka') for shower simulations

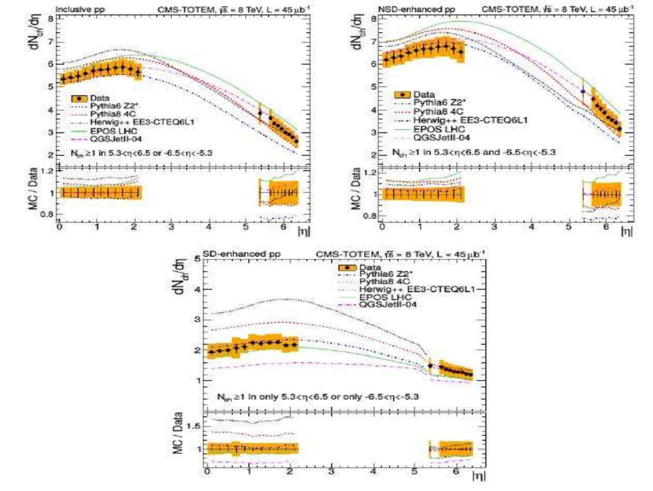
Mostly thanks to TOTEM measurement of $\sigma_{pp}^{\mathrm{tot/inel}}$



[from R. Engel]

Time of big changes ('Perestrojka') for shower simulations

But also lots of other very valuable data



[from R. Ulrich]

Time of big changes ('Perestrojka') for shower simulations

Additionally: serious updates not related to LHC data

Not directly related to LHC data:

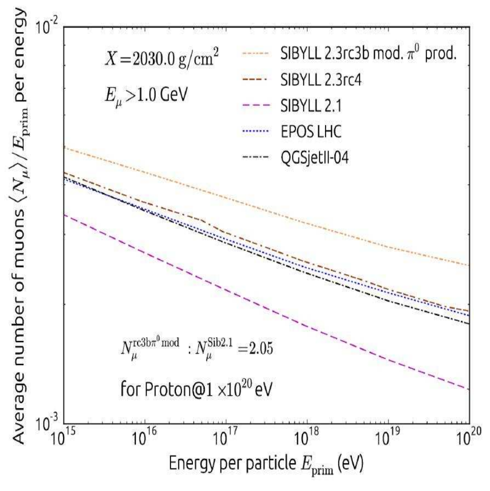
1 Baryon-Antibaryon pair production *(Pierog, Werner)*

- Baryon number conservation
- Low-energy particles: large angle to shower axis
- Transverse momentum of baryons higher
- Enhancement of mainly **low-energy** muons

(Grieder ICRC 1973; Pierog, Werner PRL 101, 2008)

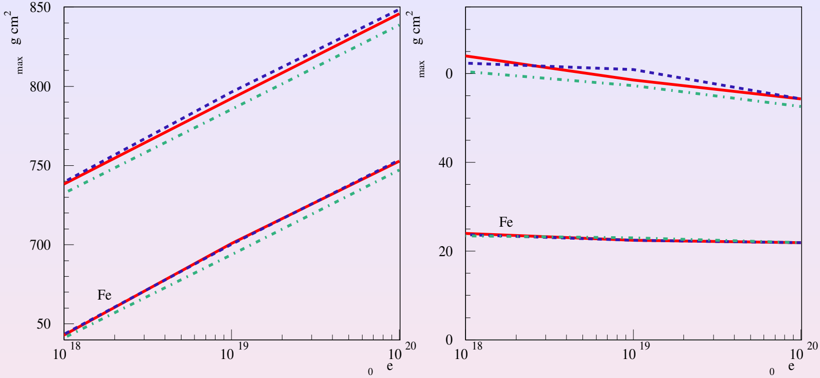
2 Leading particle effect for pions *(Drescher 2007, Ostapchenko)*

- Leading particle for a π could be ρ^0 and not π^0
- Decay of ρ^0 almost 100% into two charged pions



[from R. Engel & F. Riehn]

How uncertain are present model predictions?



Option SD-: smaller low mass diffraction

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

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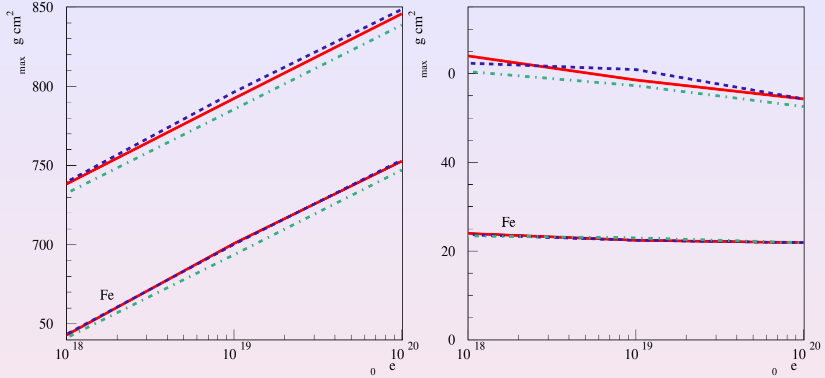

Option SD+: larger high mass diffraction

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

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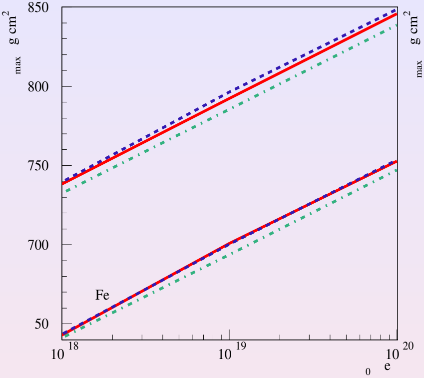
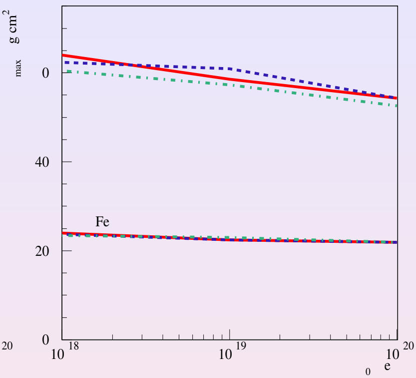
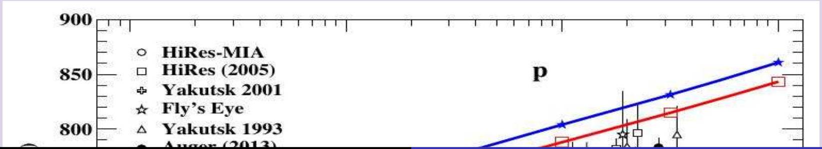


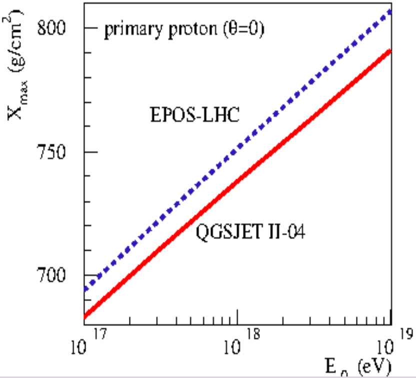


Why larger $X_{\max}$ differences with other models (e.g. EPOS-LHC)?



Is everything allowed now?

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



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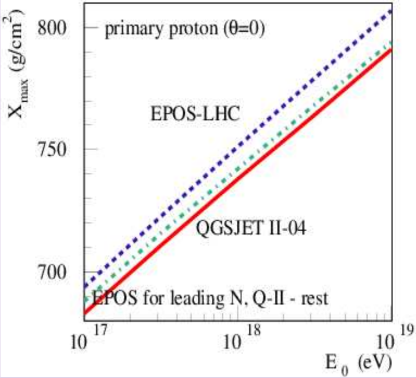
Let us compare $X_{\max}$ of EPOS-LHC & QGSJET-II-04

- and construct 'mixture models'
- use EPOS spectrum for leading nucleon in 1st interaction and QGSJET-II for the rest
- $\Delta X_{\max} \simeq 5\ \mathrm{g/cm^2}$ - in agreement with above



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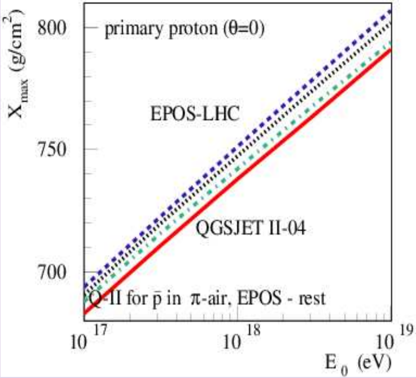
- now from the other side: QGSJET-II spectra for $p, \bar{p}, n, \bar{n}$ production in $\pi - \text{air}$, $K - \text{air}$ and EPOS for all the rest
- $\Delta X_{\max} \simeq 4$ g/cm^2



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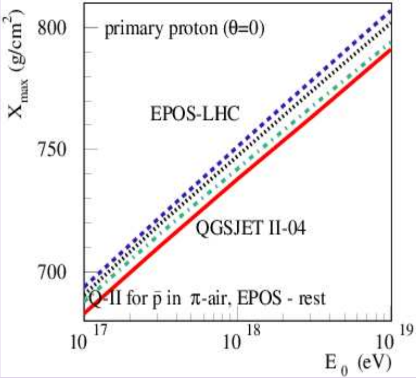
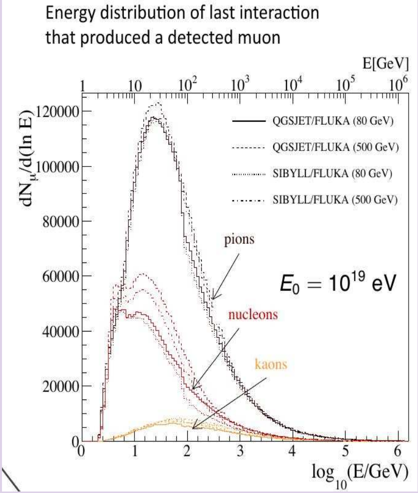
- $\Delta X_{\max} \simeq 4$ g/cm^2
- remaining difference: partly due to harder pion spectra in $p - \mathrm{air}$



Pion-air interactions relevant for N_μ

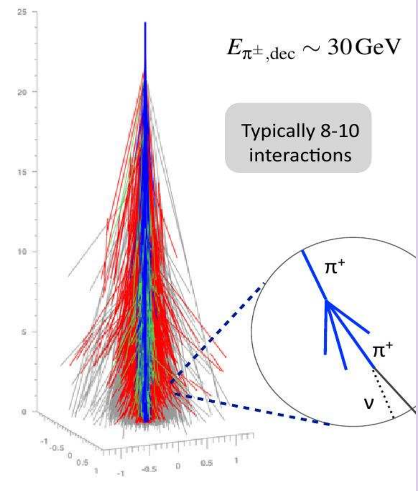
- muon 'parent' pions: from low energy interactions



[from R. Engel]

Pion-air interactions relevant for N_μ

- muon 'parent' pions: from low energy interactions
- preceeded by a multi-step hadron cascade
    - ~ 1 cascade step per energy decade
- which $\pi -$air interactions most important?



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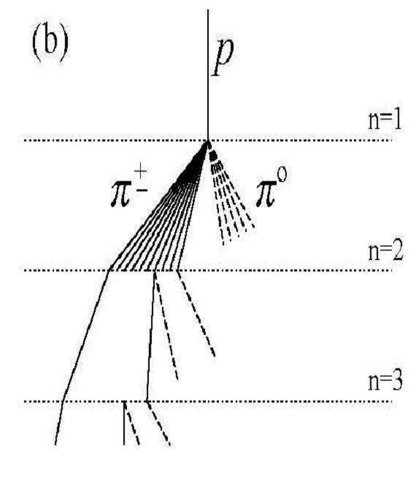
Pion-air interactions relevant for N_μ

- multi-step hadron cascade
  - ~ 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 $10^{\alpha_\mu} \simeq 8$ for N_μ ($\alpha_\mu \simeq 0.9$)

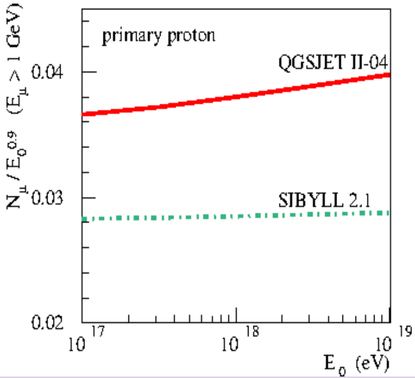


[from J. Matthews]

Pion-air interactions relevant for N_μ

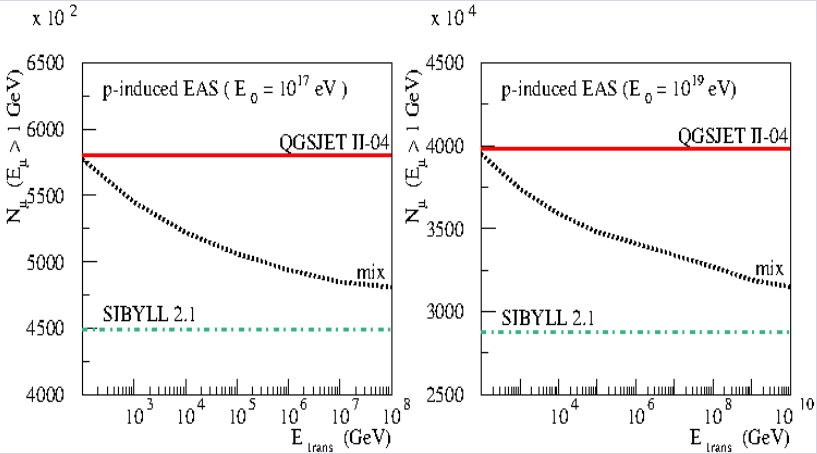
E.g. let us study the difference in N_μ for SIBYLL & QGSJET-II

- and use a 'mixed' model: SIBYLL($E < E_{\text{trans}}$) + QGSJET-II($E > E_{\text{trans}}$)
- NB: GHEISHA used for $E < 80$ GeV



Pion-air interactions relevant for N_μ

Half the difference comes from $\pi -$ air interactions above 1 TeV!



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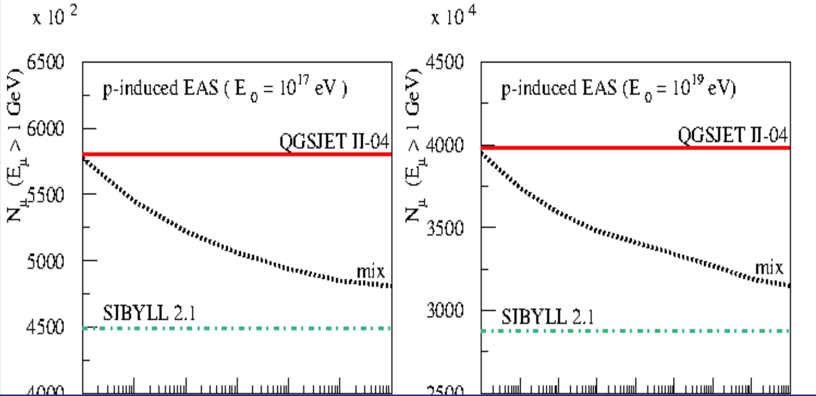

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- but: relevant physics is there for $E < 1$ TeV (e.g. ρ^0 production)
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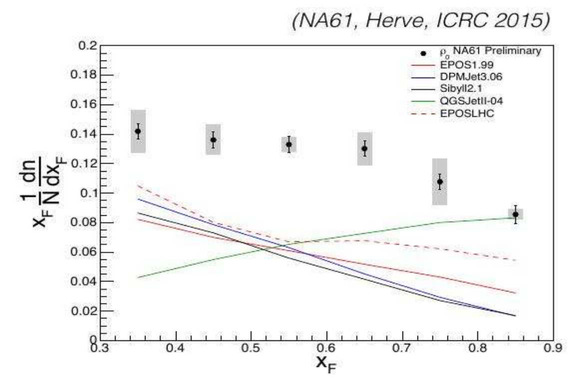
New data from NA61 very useful



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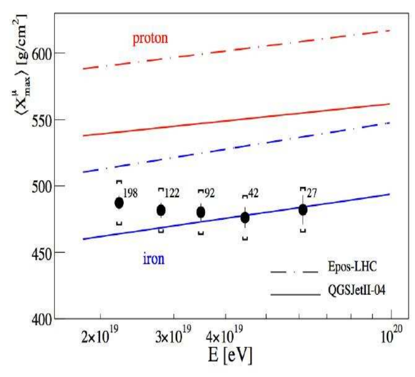
"Saving sinking people is the business of the sinking people"

[Russian national wisdom]

Testing models with air shower data

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

- challenging measurement
- interesting results
- what is the physics behind the model differences?

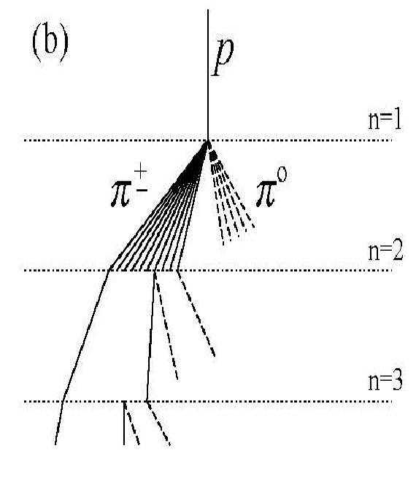


[from M. Roth]

Testing models with air shower data

1) 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 $p_{\mathrm{decay}} > p_{\mathrm{inter}}$



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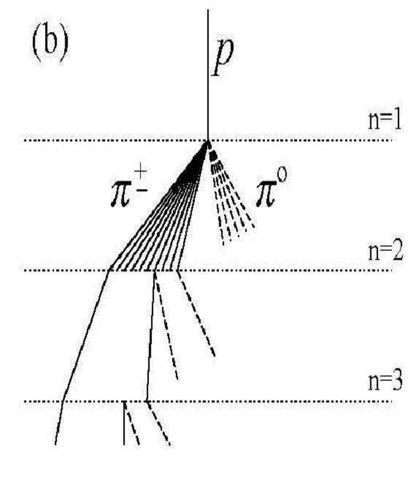
- X_{max}^{μ}: where $p_{\mathrm{decay}} > p_{\mathrm{inter}}$
- harder spectra in $\pi-\mathrm{air}$ $\Rightarrow$ deeper X_{max}^{μ} (effectively one more cascade step)

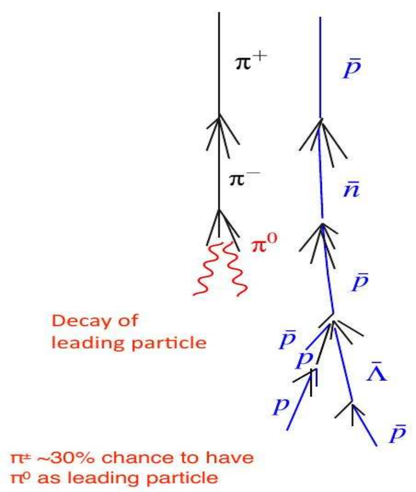


[from J. Matthews]

Testing models with air shower data

2) Copious production of (anti-)nucleons

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



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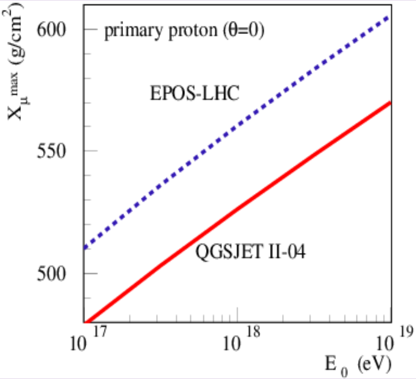

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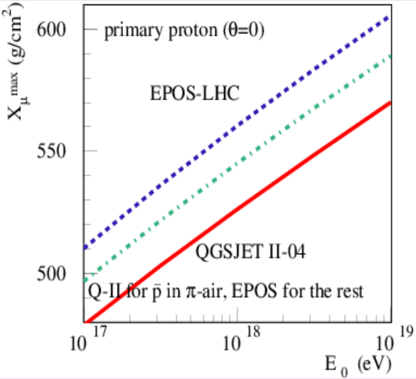

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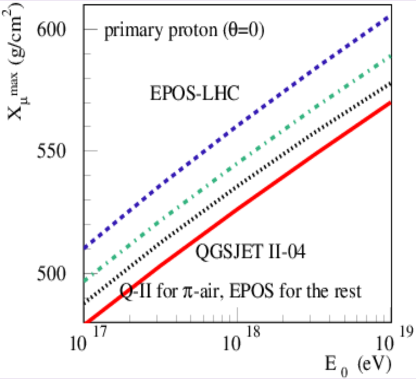
- now QGSJET-II for all $\pi - \mathrm{air}$, $K - \mathrm{air}$ interact. and EPOS for all the rest
- the two effects explain major part of the difference for $X^{\mu}_{\max}$



How robust are predictions for N_μ?

- let us assume that muon predictions are o.k. up to energy E_A
- how difficult to get enhancement at energy E_B $(E_B < 100 E_A)$?
  - this should be achieved within 2 orders of magnitude in energy

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  - $\Rightarrow$ there is less than 2 cascade steps between 10^{17} and 10^{19}
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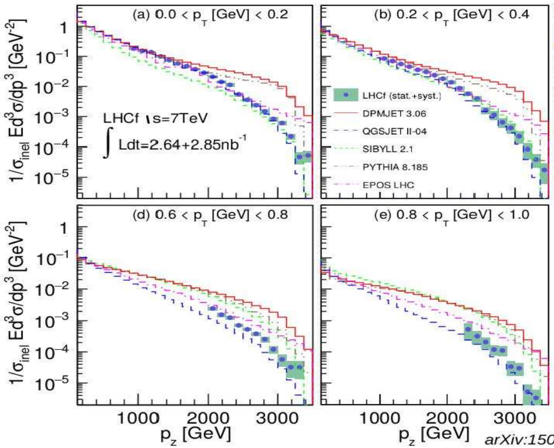
- if we double $N_{\rm ch}$ for the 1st interaction?
  - $< 10\%$ increase for N_μ!
- to get, say, a factor 2 enhancement:
  $N_{\rm ch}$ should rise by an order of magnitude

Back to LHC data: they are and will be of great help

Especially true for measurements in the forward direction, like LHCf

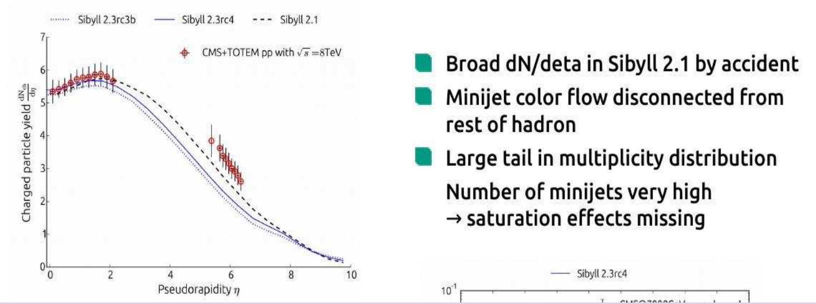


- Good agreement of QGSJET II-04
- EPOS-LHC harder at $P_z > 2$ TeV
- DPMJET and Pythia OK at $P_T < 0.2$ GeV and $P_z < 1.6$ TeV, harder at $P_z > 1.6$ TeV
- SIBYLL similar to DPMJET and PYTHIA increasing P_T, low yield at $P_T < 0.2$ GeV

arXiv:1507:08764v1 Submitted to PRD

Back to LHC data: they are and will be of great help

Most remarkable: LHC data constrain physics mechanisms in models



[from F. Riehn]

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Welcome to the Time of Big Changes in Sims!