Constraining hadronic interaction models with LHC & cosmic ray data

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QCD at Cosmic Energies - VII

Chalkida, Greece, May 16 - 20, 2016

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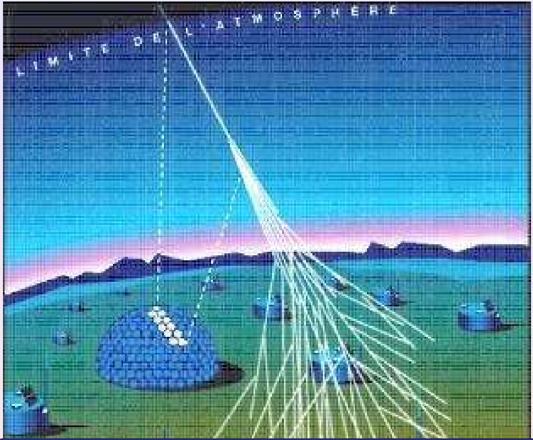
arXiv: 1601.06567, 1402.5084

Outline of the talk

1. Motivation: model uncertainties for air shower predictions
2. Input from LHC data & remaining model differences for $X_{\max}$
3. Two basic approaches for constituent parton Fock states
   - differences in model results
   - how to test at LHC
4. Relevance of the inelastic diffraction
5. Other uncertainties & model tests with UHECR data
6. Outlook

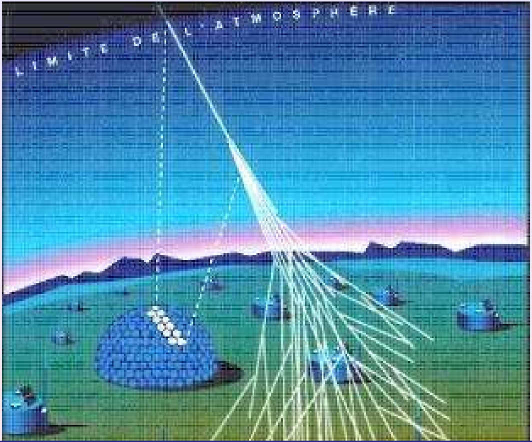
Cosmic ray studies with Extensive Air Shower technique



ground-based observations (= thick target experiments)

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

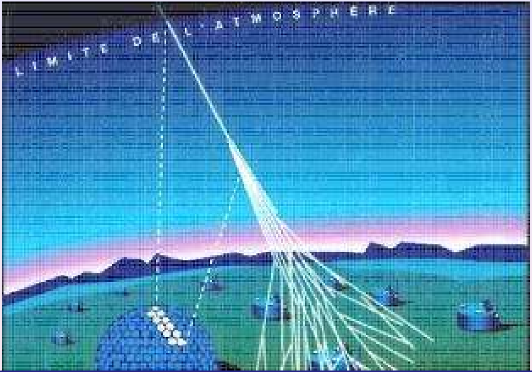
Cosmic ray studies with Extensive Air Shower technique



measurements of EAS fluorescence light

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

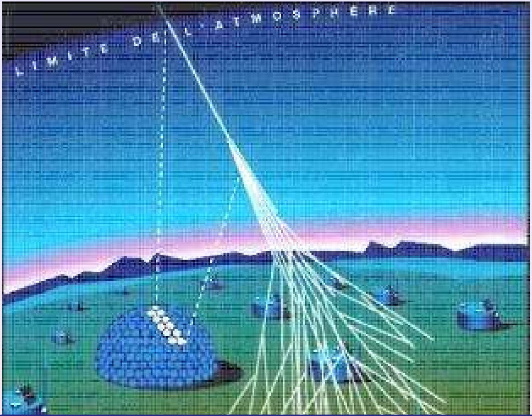
Cosmic ray studies with Extensive Air Shower technique



CR composition studies – most dependent on interaction models

- e.g. predictions for X_{max}: on the properties of the primary particle interaction (σ^{inel}_{p-air}, forward particle spectra)
- predictions for muon density: on secondary particle interactions (cascade multiplication); mostly on $N^{ch}_{\pi-air}$

Cosmic ray studies with Extensive Air Shower technique

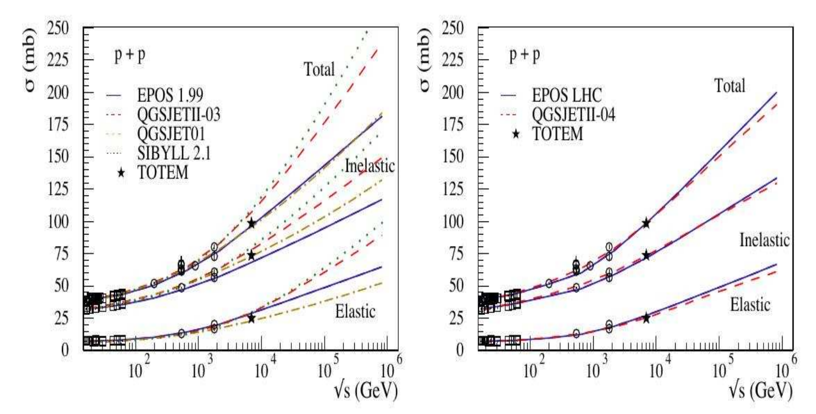


this talk: mostly devoted to model predictions for $X_{\max}$

- relation of the differences for predicted $X_{\max}$ to the treatments of proton-proton & pion-proton collisions
- how to constrain by LHC & CR measurements

Most of the models: updated with Run 1 data of LHC

Most important for CR applications: results of TOTEM for $\sigma_{pp}^{tot/inel}$

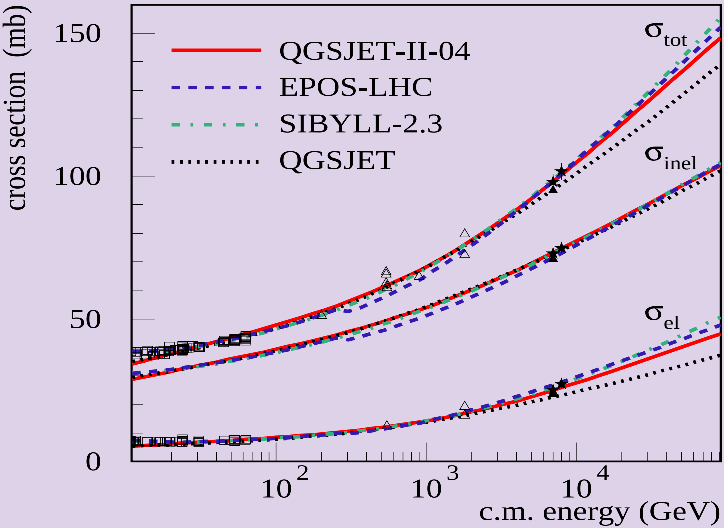


[from R. Engel]

- important: results of ATLAS ALFA - consistent with TOTEM

Most of the models: updated with Run 1 data of LHC

Now: very similar high energy extrapolations for all the models



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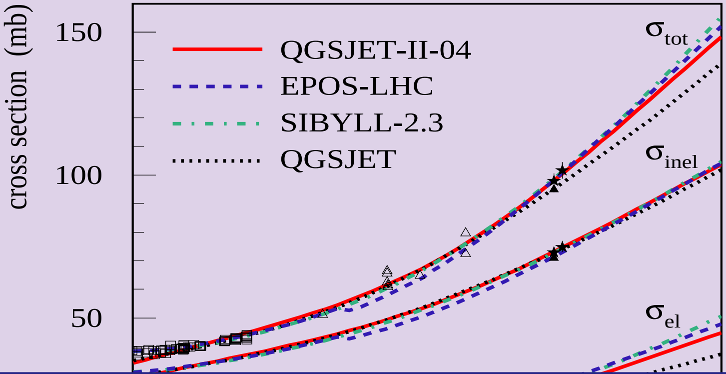
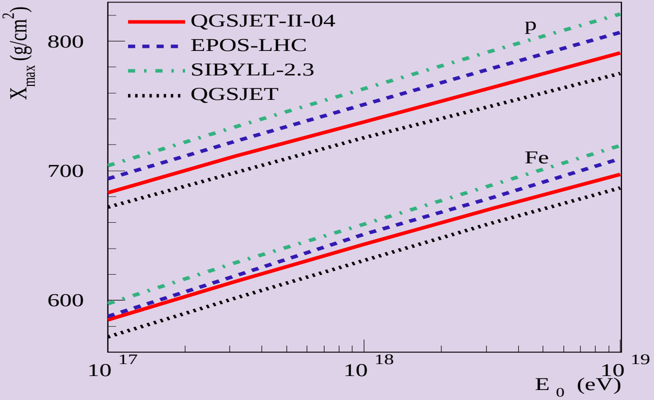


NB: old QGSJET model - outdated physics-wise (> 20 years old)

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

Most of the models: updated with Run 1 data of LHC

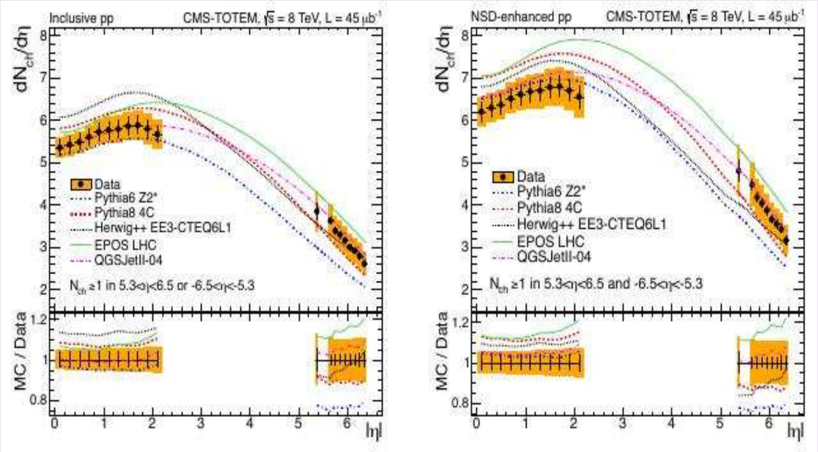
Yet large model differences for the predicted X_{max}?!



- important: spread of X_{max} predictions for p-induced EAS - comparable to p-Fe difference!
  - inelastic diffraction or/and 'inelasticity' for p-air?
  - or something else?

Most of the models: updated with Run 1 data of LHC

Hint (SIBYLL case): combined CMS-TOTEM analysis of $dN_{ch}/d\eta$



- only EPOS-LHC & QGSJET-II-04 describe the spectral shape

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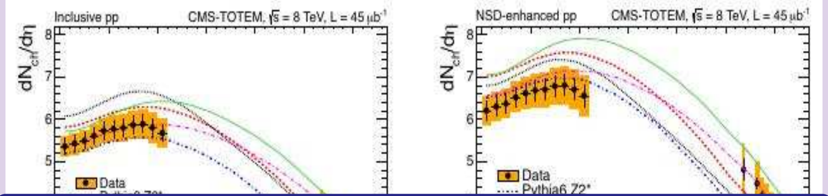
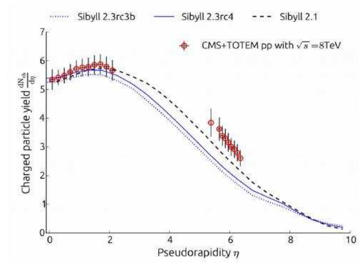


The problem with other models appeared to be generic!



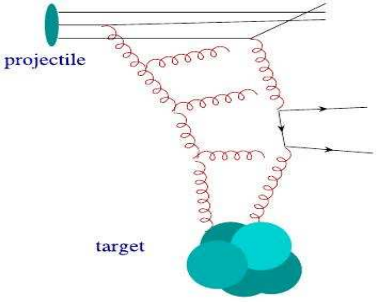
- Broad dN/deta in Sibyll 2.1 by accident
- Minijet color flow disconnected from rest of hadron
- Large tail in multiplicity distribution

  Number of minijets very high
  → saturation effects missing

[F. Riehn, talk at "Composition-2015"]

Hadronic interactions: qualitative picture

- 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)



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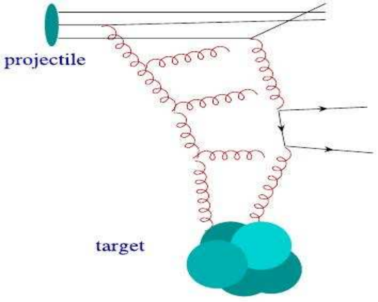


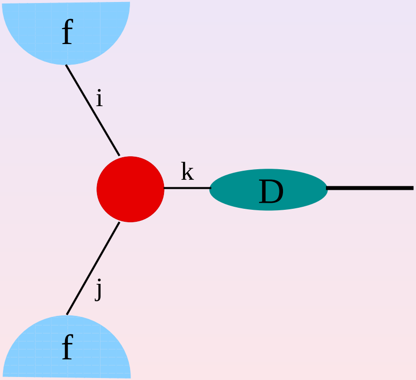
Universal interaction mechanism

- different hadrons (nuclei) ⇒ 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
  $\frac{d^3\sigma_{pp\to h}}{dp^3} = \sum_{i,j,k} f_{i/p} \otimes \sigma_{ij\to k} \otimes f_{j/p} \otimes D_{h/k}$

- separates short- & long-distance dynamics
- pQCD predicts evolution of PDFs ($f_{i/p}$) & FFs ($D_{h/k}$)
- $\Rightarrow$ allows to simulate perturbative (high p_t) part of parton cascades (initial & final state emission)



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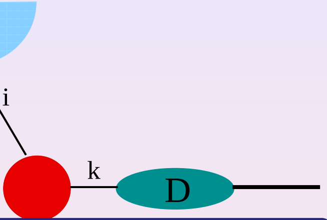

- separates short- & long-distance dynamics
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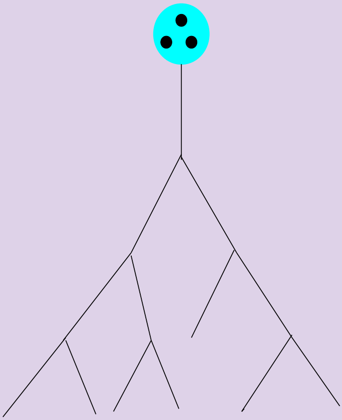
What is beyond?

- 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' *(e.g. the talk of Mark)*

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)



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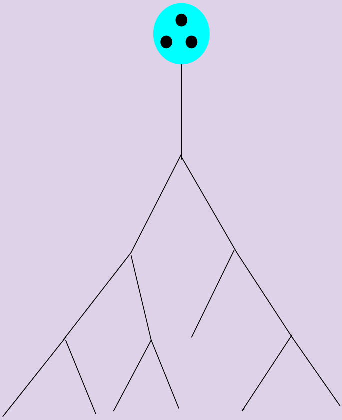
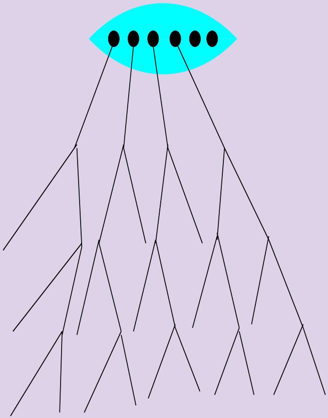


Hadronic interactions: nonperturbative Fock states

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



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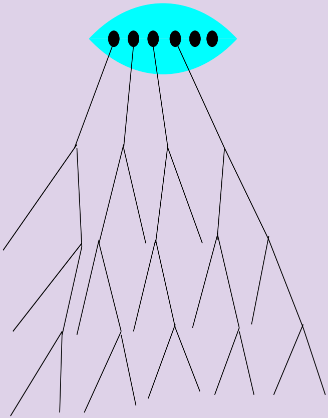

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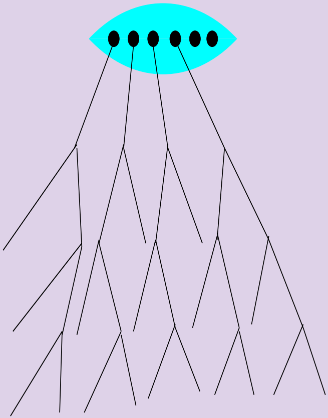

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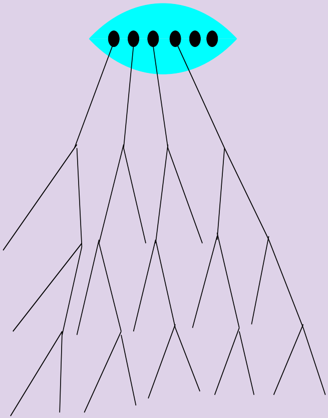
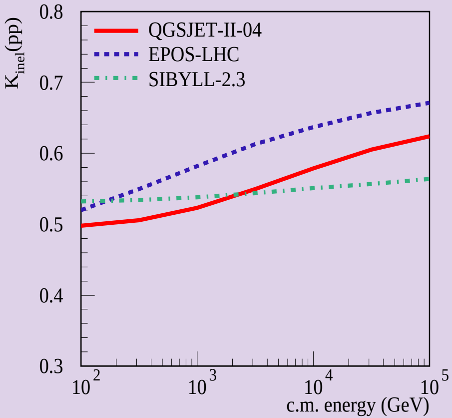


Why of importance for air showers?

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



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

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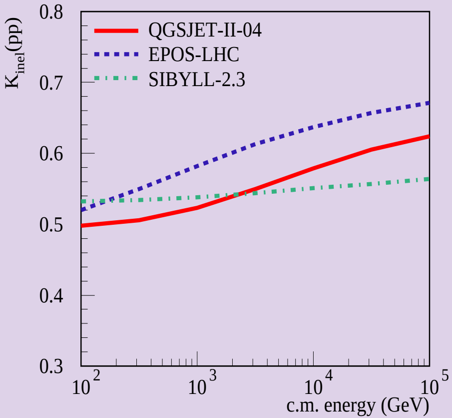

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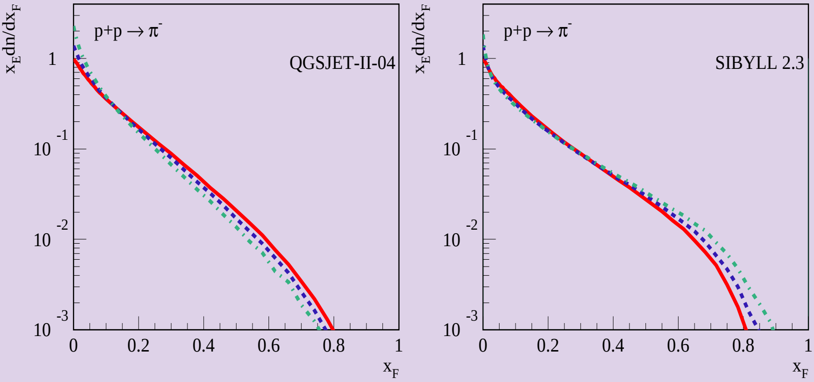
Why of importance for air showers?

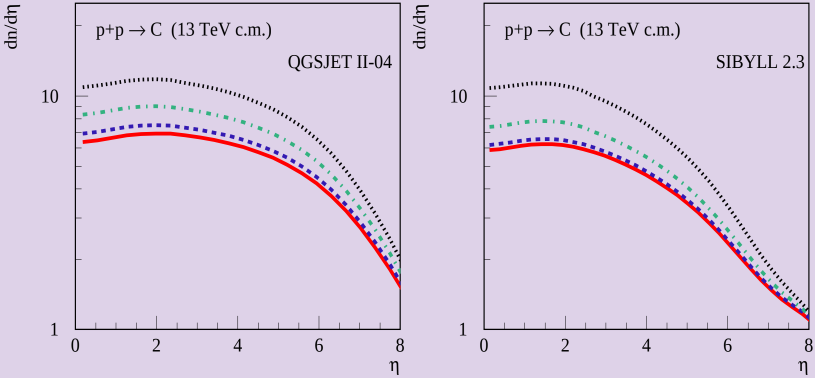
$\sqrt{s}$-dependence of forward meson spectra ($\sqrt{s} = 10^2 - 10^4$ GeV)



- at very high energies, forward mesons contribute to the leading hadron effect (proton looses most of its energy in *p*-air)
- softening of forward spectra in QGSJET-II: due to energy sharing between constituent partons

Tests at LHC: correlations of central & forward production

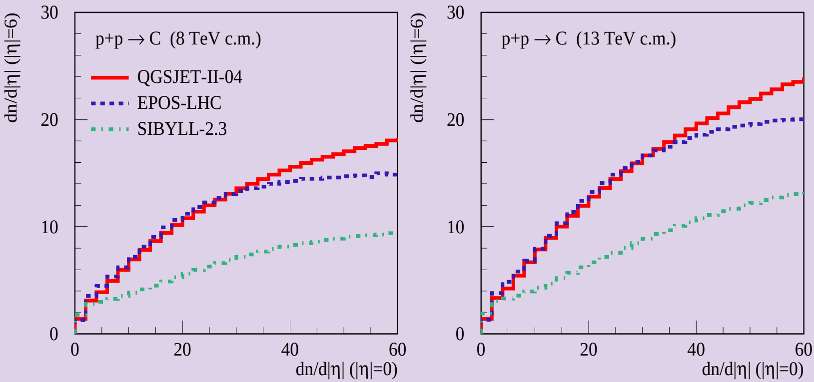
E.g. study $dN^{\rm ch}_{pp}/d\eta$ by triggering different activity in CMS
(here ≥ 1, 5, 10, 20 charged hadrons of $p_{\rm t} > 0.1$ GeV & $|\eta| < 2.5$)



- QGSJET-II-04: production enhanced over the whole η-range
- SIBYLL-2.3: much weaker enhancement in the forward region

Tests at LHC: correlations of central & forward production

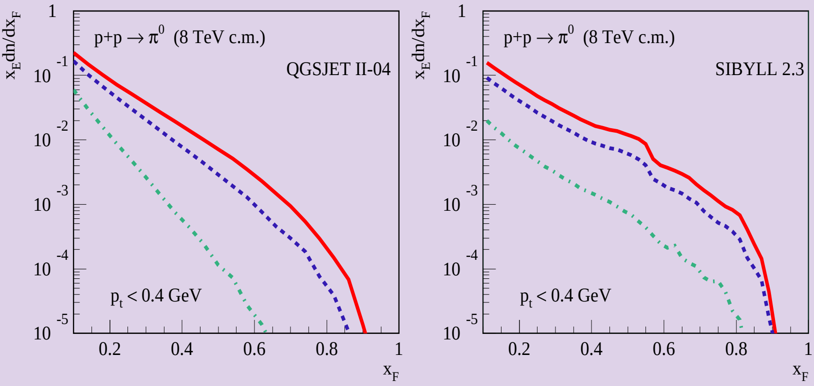
Cross-correlation of $dN^{ch}_{pp}/d|\eta|$ in CMS ($|\eta| < 1$, $p_t > 0.1$ GeV) and TOTEM ($5.5 < |\eta| < 6.5$, $p_t > 0$)



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

Tests at LHC: correlations of central & forward production

Alternatively, forward π^0 spectra in LHCf for different ATLAS triggers (≥ 1, 6, 20 charged hadrons of $p_t > 0.5$ GeV & $|\eta| < 2.5$)



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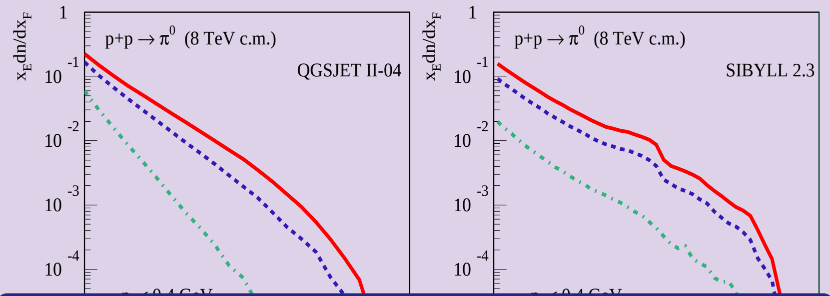


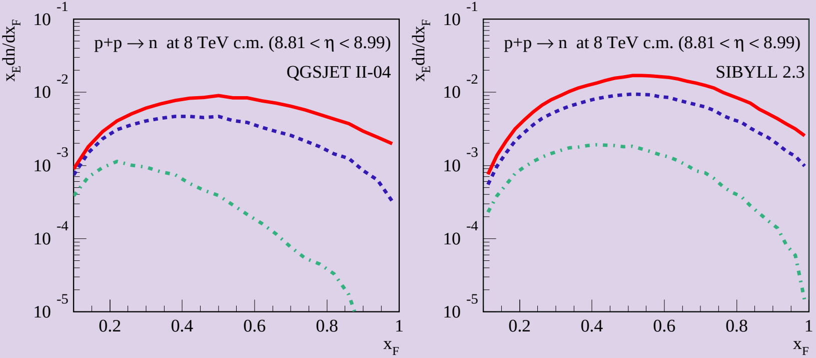
Compare QGSJET-II-04 (left) to SIBYLL 2.3 (right)

- enhanced multiple scattering $\Rightarrow$ softer pion spectra
- $\Rightarrow$ violation of limiting fragmentation (energy sharing between constituent partons)

- nearly same spectral shape for all the triggers
- $\Rightarrow$ perfect limiting fragmentation (central production decoupled)

Tests at LHC: correlations of central & forward production

Neutron spectra in LHCf ($8.99 < \eta < 9.22$) for same triggers



- remarkably universal spectral shape in SIBYLL-2.3 (decoupling of central production)
  - closely related to the small 'inelasticity' of the model
- strong suppression of forward neutrons in QGSJET-II-04
  - higher central activity $\Rightarrow$ more constituent partons involved $\Rightarrow$ less energy left for the proton 'remnant'

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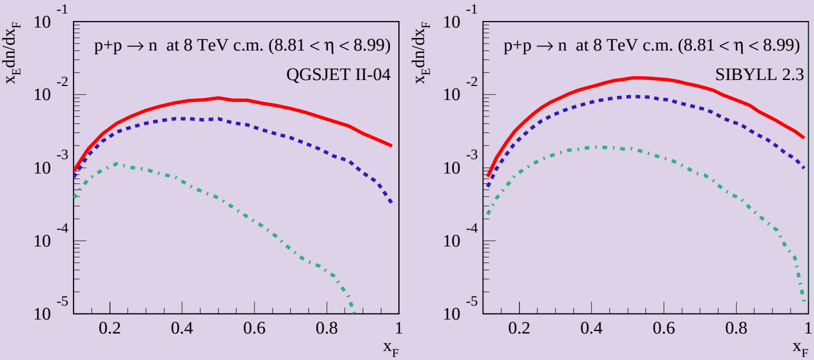

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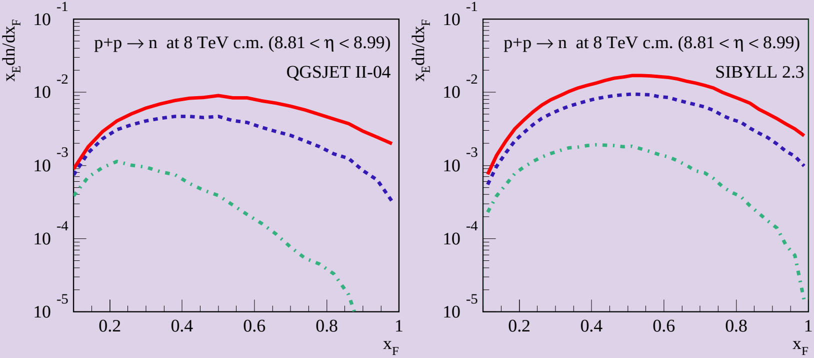
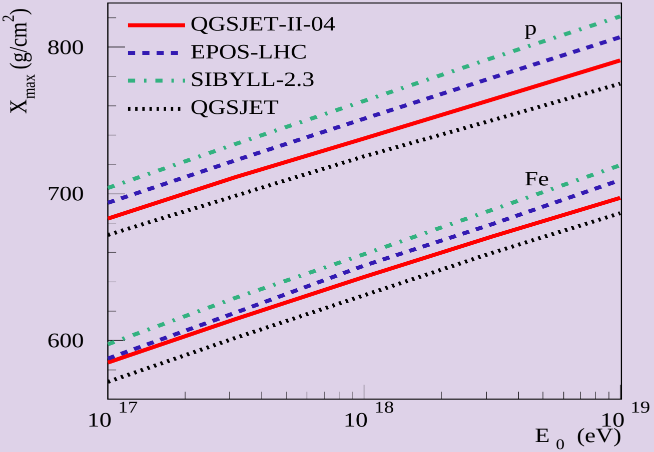


NB: in addition/instead, production of forward neutrons may be strongly suppressed by the 'diquark splitting' mechanism

- e.g. CGC treatment by Drescher, Dumitru & Strikman (2005)
- may be discriminated based on p_t-dependence
  - e.g. stronger suppression in higher η bins in LHCf

Relevance of the inelastic diffraction

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



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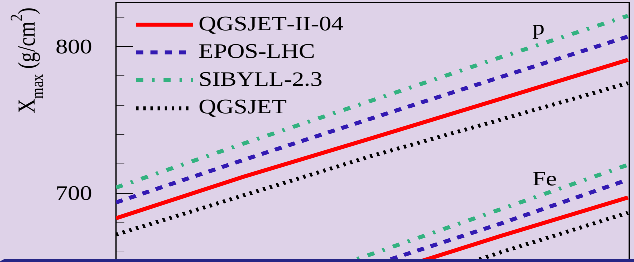

Model differences concerning the treatment of diffraction?

- 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 (especially for target SD)

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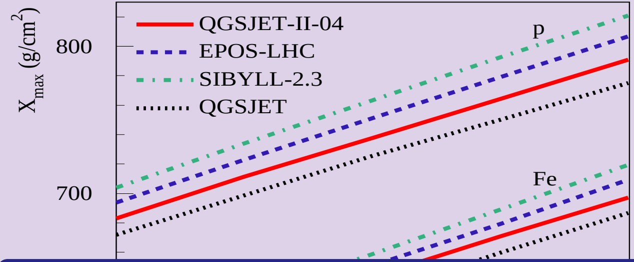

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Impact of uncertainties of σ_{pp}^{SD} on $X_{\max}$ predictions

Presently: tension between CMS & TOTEM concerning σ_{pp}^{SD}

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

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

Impact of uncertainties of $\sigma_{pp}^{\rm SD}$ 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

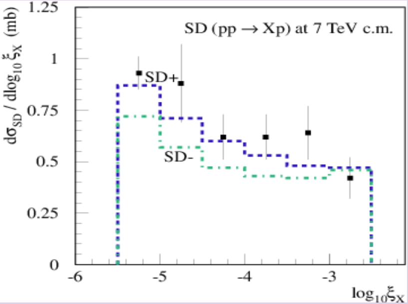
Two alternative model versions (tunes): SD+ & SD-

- 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 σ_{pp}^{SD} on $X_{\max}$ predictions

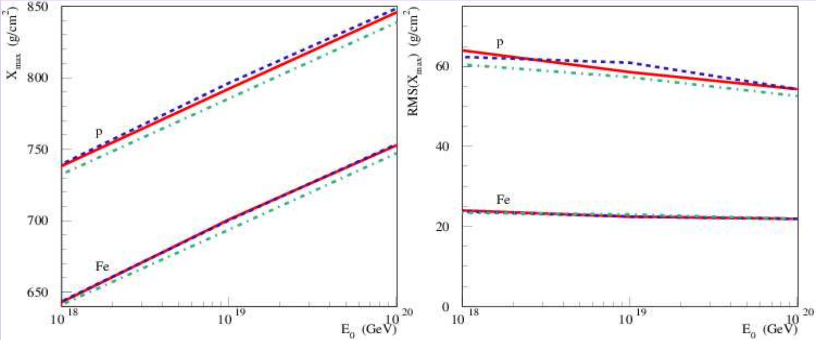
Single diffraction: SD- agrees with TOTEM, SD+ o.k. with CMS

M_X range, GeV	< 3.4	$3.4 - 1100$	$3.4 - 7$	$7 - 350$	$350 - 1100$
TOTEM	2.62 ± 2.17	6.5 ± 1.3	$\simeq 1.8$	$\simeq 3.3$	$\simeq 1.4$
option SD+	3.2	8.2	1.8	4.7	1.7
option SD-	2.6	7.2	1.6	3.9	1.7



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

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

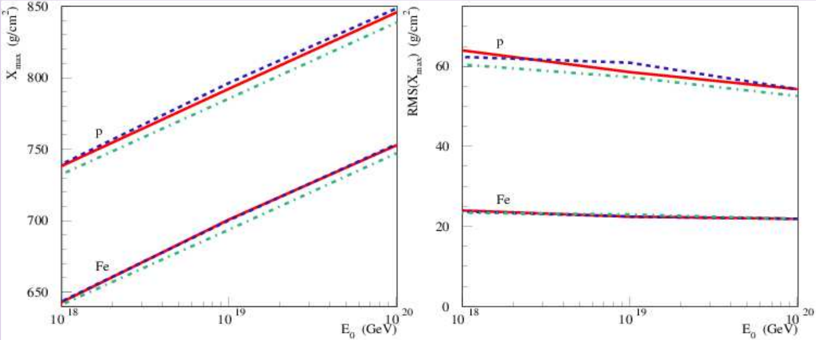


Option SD-: smaller low mass diffraction

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

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

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

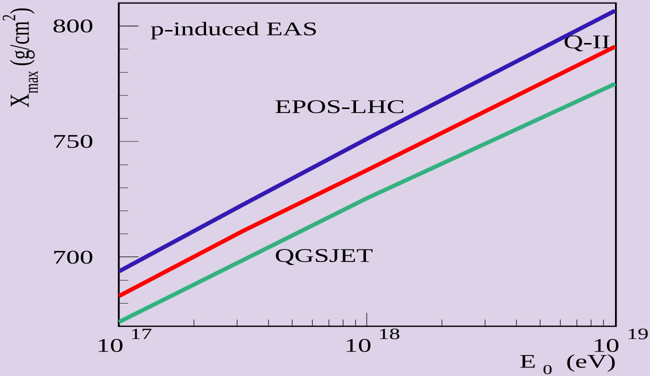


Option SD+: larger high mass diffraction

- 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 $20\,\mathrm{g/cm^2}$)

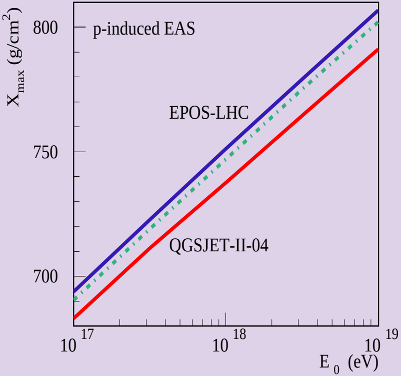


- previous analysis not general enough?
- or other interaction properties relevant?
- to answer - use "cocktail" model approach

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

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

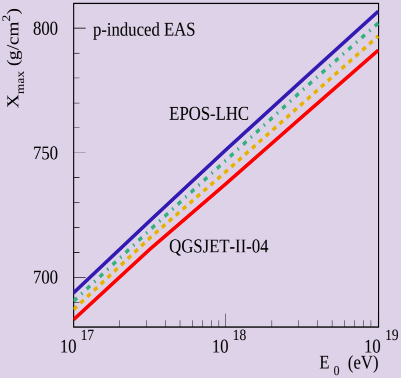
- and construct 'mixture models'
- use QGSJET-II for $\sigma^{\rm inel}_{p-\rm air}$ & leading nucleon spectrum (EPOS-LHC for the rest)
- $\Delta X_{\max} \leq 5$ g/cm^2 - in agreement with above



Other sources of model uncertainties for X_{max}

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

- QGSJET-II for σ^{inel}_{p-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 $p-$air in EPOS-LHC



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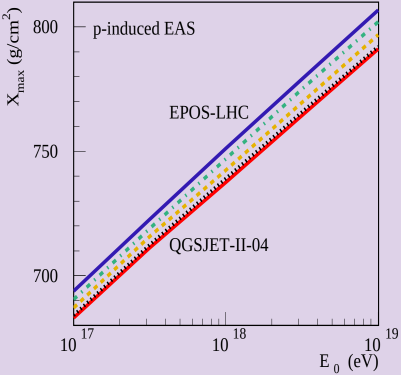
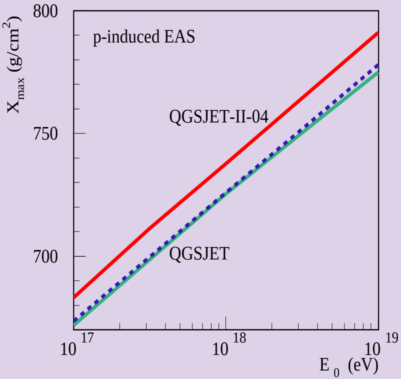
- now QGSJET-II for the complete 1st interaction (EPOS-LHC for the rest)
- $\Delta X_{\max} \leq 5$ g/cm^2
- remaining difference: copious $\bar{p}p$- & $\bar{n}n$-pair production in π- & K-air in EPOS-LHC



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

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

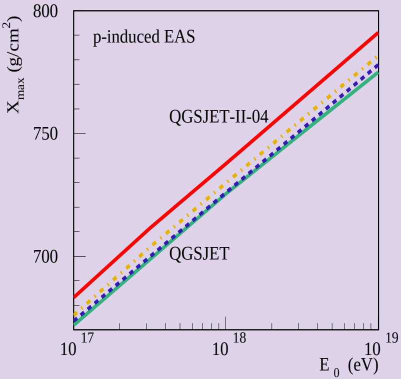
- use QGSJET-II for the complete 1st interaction (QGSJET for the rest)
- $\Delta X_{\max} \leq 3$ g/cm^2



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)
- $\Delta X_{\max} \leq 3\ \mathrm{g/cm^2}$
- 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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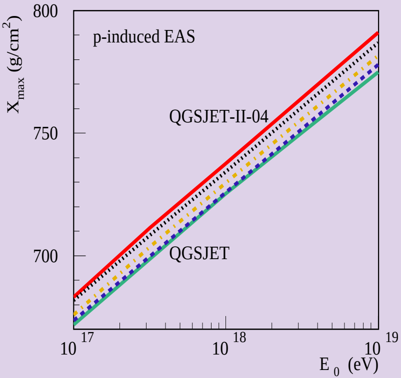
Now compare $X_{\max}$ of QGSJET & QGSJET-II-04

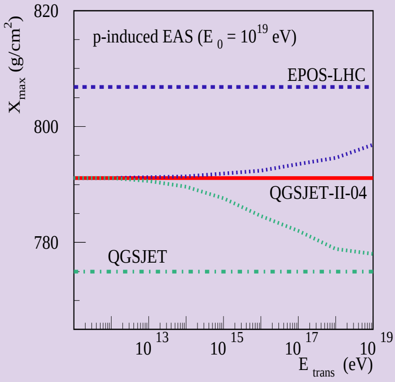
- use QGSJET-II for the complete 1st interaction (QGSJET for the rest)
- $\Delta X_{\max} \leq 3$ g/cm^2
- next: QGSJET-II for the 1st interaction & for all $\sigma^{\rm inel}_{\pi-{\rm air}}$, $\sigma^{\rm inel}_{K-{\rm air}}$
- rest: mostly due to softer pion & kaon spectra in π-air in QGSJET



Other sources of model uncertainties for X_{max}

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

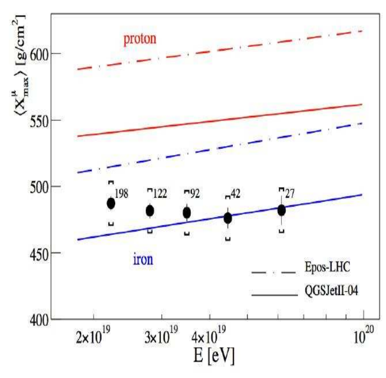
- X_{max} for 10^{19} eV proton EAS using 'cocktail': QGSJET-II for $E > E_{trans}$ and EPOS-LHC or QGSJET for $E < E_{trans}$
- main difference for $E \to E_0$ (before most of the energy goes into the e/m cascade)
- how to constrain pion-air collisions at VHE?!



Testing models with air shower data

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

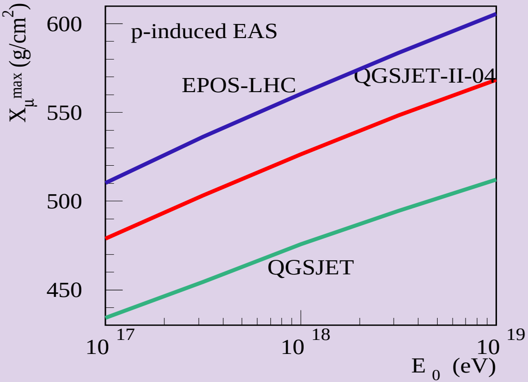
- models predict deeper $X^{\mu}_{\max}$ than observed
  - e.g. one needs primary iron for QGSJET-II-04
  - or primary gold for EPOS-LHC...



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

Testing models with air shower data

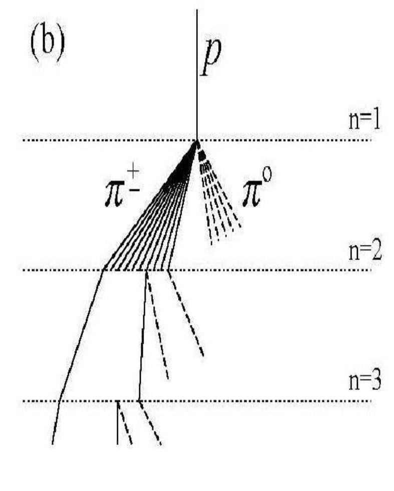
What is the physics behind the different predictions for $X^{\mu}_{\max}$?



Testing models with air shower data

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

- NB: muons originate from a multi-step hadron cascade
- smaller $\sigma^{\text{inel}}_{\pi-\text{air}} \Rightarrow$ longer distances between the cascade steps
  - $\Rightarrow$ deeper $X^{\mu}_{\max}$



[from J. Matthews]

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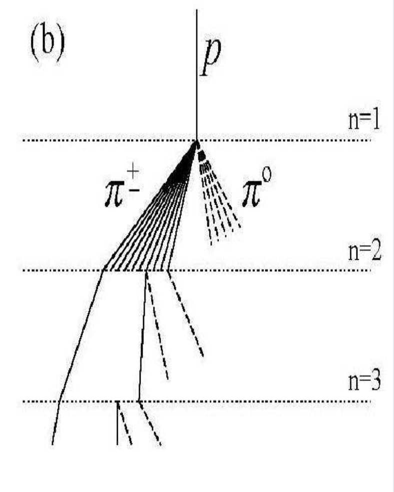
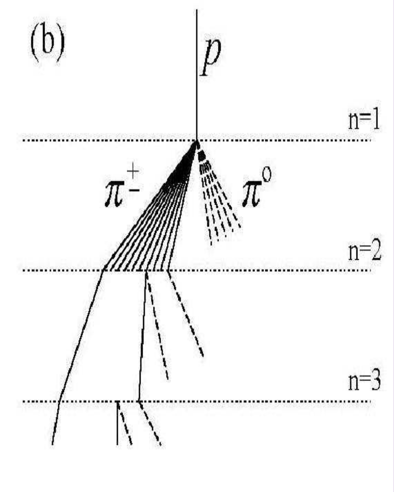


[from J. Matthews]

Testing models with air shower data

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

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



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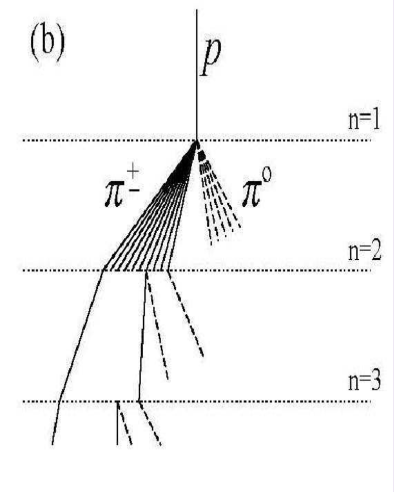
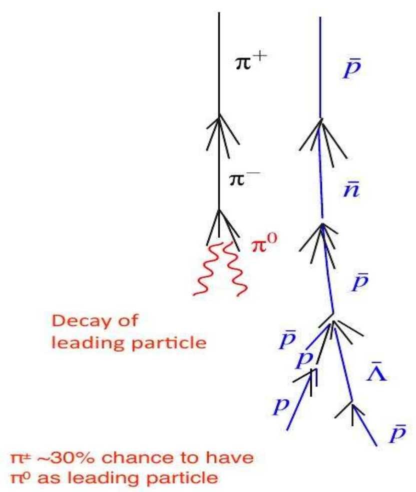


[from J. Matthews]

Testing models with air shower data

3) Copious production of (anti-)nucleons?

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



[from R. Engel]

Testing models with air shower data

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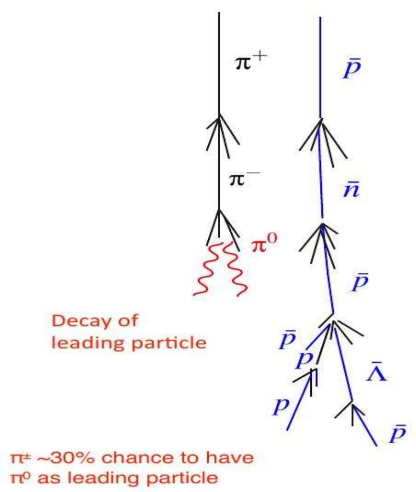
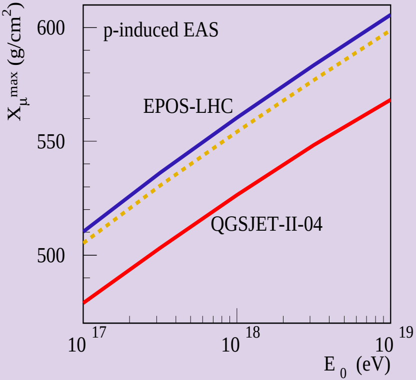


[from R. Engel]

Testing models with air shower data

Difference of X^{μ}_{max}: EPOS-LHC / QGSJET-II-04, using "cocktail"

- use QGSJET-II for 1st interaction and EPOS-LHC for the rest
- small effect: X^{μ}_{max} difference – due to pion-air collisions



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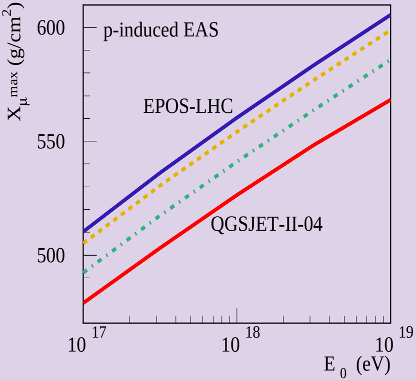
- largest effect: copious $\bar{p}p$ & $\bar{n}n$ production in π-air



Testing models with air shower data

Difference of $X_{\max}^{\mu}$: EPOS-LHC / QGSJET-II-04, using "cocktail"

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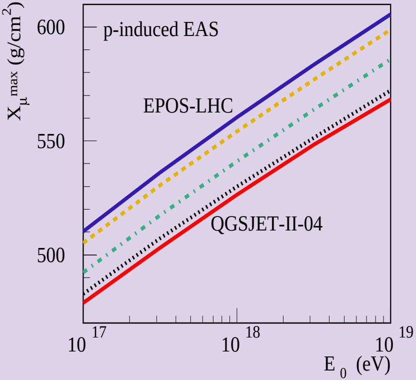
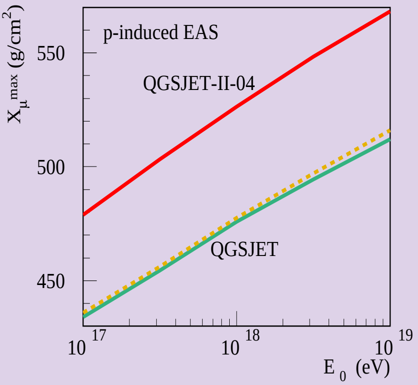


Testing models with air shower data

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

- QGSJET-II for 1st interaction, rest – QGSJET: minor effect



Testing models with air shower data

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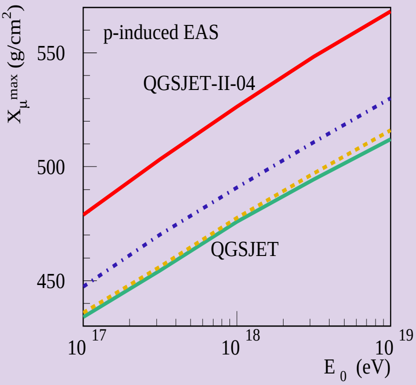
- QGSJET-II for 1st interaction, rest – QGSJET: minor effect
- QGSJET-II for 1st interaction & $\sigma^{\rm inel}_{\pi,K-\rm air}$



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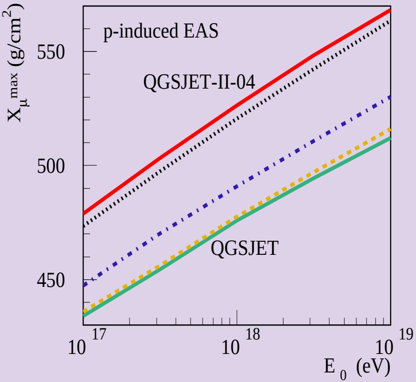

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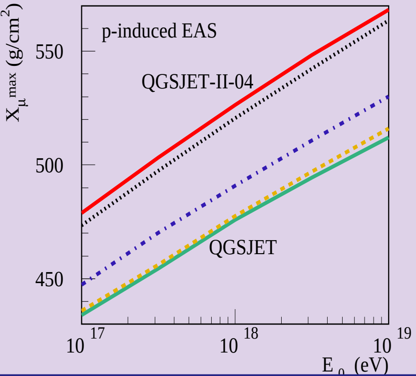
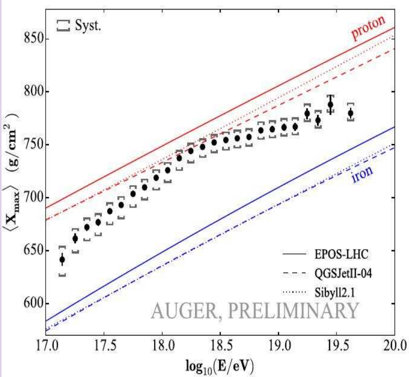


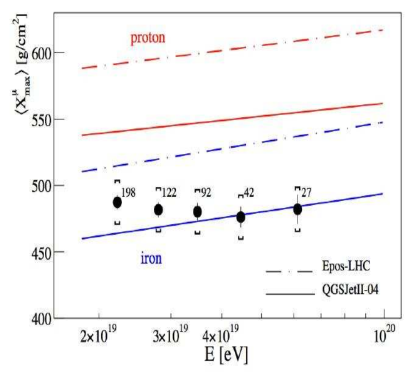
Model-dependence of $X^{\mu}_{\max}$: same features of π-air as for $X_{\max}$

- $X^{\mu}_{\max}$ – even more sensitive!
- $\Rightarrow$ can be used to constrain model approaches
- e.g. copious $\bar{p}p$ & $\bar{n}n$ production disfavored by Auger data

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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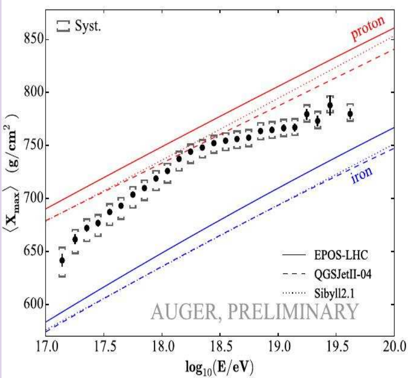
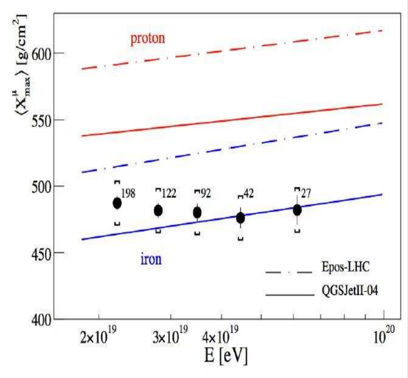
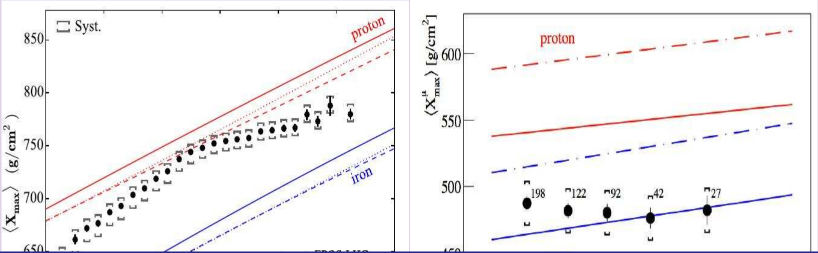




- because: impact on $X^{\mu}_{\max}$ - stronger than on $X_{\max}$
- this would lead us to almost pure proton composition?!

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

This would require a faster development of the hadronic cascade



Is it feasible model-wise?

- one has to approach the results of the old QGSJET
- higher pion-air cross section - unlikely
- $\Rightarrow$ the only way: softer pion spectra in π-air
- may be obtained in CGC-like approach
  (e.g. as in Drescher, Dumitru & Strikman 2005)
- but: stronger effect expected for *pp* ('diquark breakup')
  - $\Rightarrow$ can be tested at LHC (notably by LHCf & ATLAS)

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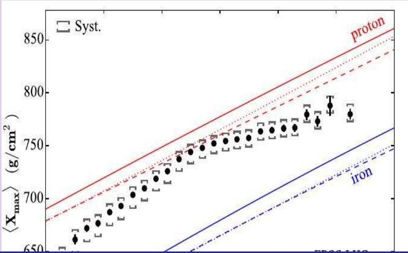

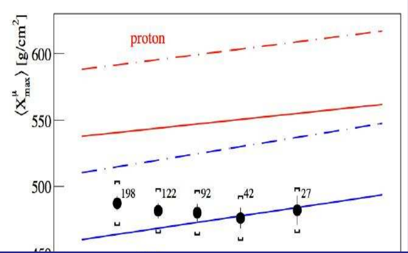

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Outlook

1. Most important LHC input for UHECR physics: $\sigma_{pp}^{\mathrm{tot/el}}$
2. Of considerable importance: to resolve the diffraction issue
3. Next crucial point: to constrain model approaches for constituent parton Fock states
    - will impact ALL the present models
    - requires combined studies with forward & central detectors
4. Present uncertainties for X_{max}: largely related to VHE pion-air interactions
5. May be constrained by X_{max}^{μ} measurements in CR experiments

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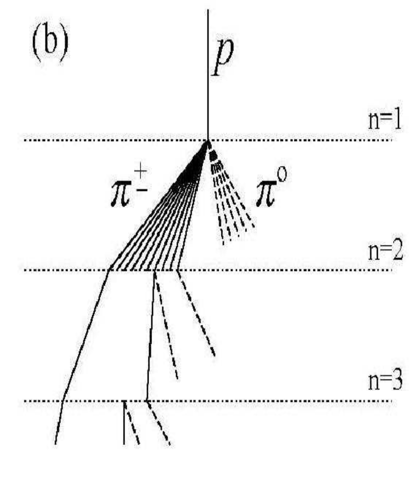
Comments on the 'muon excess': see extra slides

Extra slides

How robust are predictions for EAS muon content?

- NB: N_μ results from a multi-step hadron cascade
  - ~ 1 cascade step per energy decade
- assume: muon predictions are o.k. up to energy E_A
- how difficult to get enhancement at energy E_B ($E_B < 100 E_A$)?
  - i.e. within 2 orders of magnitude in energy
- secondary pions: mostly with $x_{\rm F} < 0.1$
  - $\Rightarrow$ just 1 cascade step between E_A & E_B



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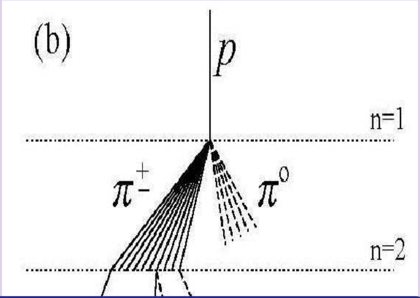

$\Rightarrow$ Muon excess has to be produced by primary CR interactions

- 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

Prospects for seeing new physics in CR air showers?

- proton-air cross section at UH 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