LHC results & hadronic interaction models

Sergey Ostapchenko
Frankfurt Institute for Advanced Studies

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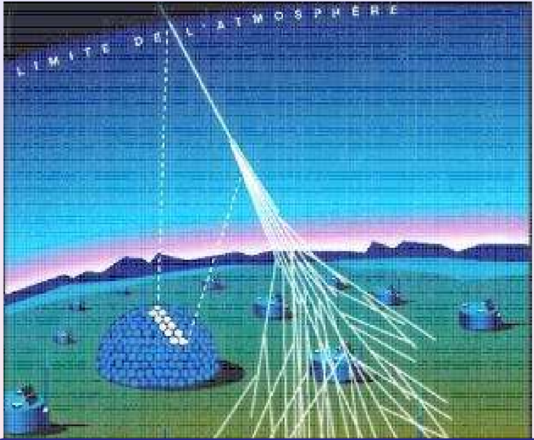
Cosmic ray studies with Extensive Air Shower technique



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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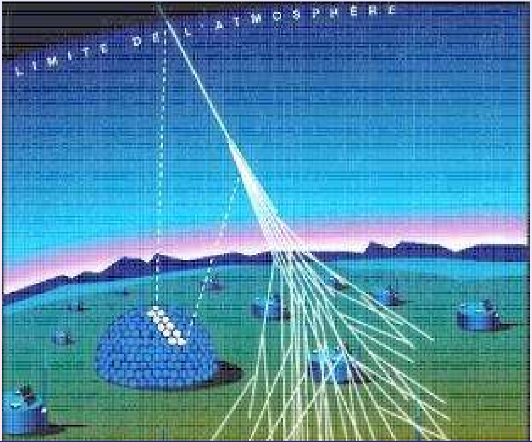
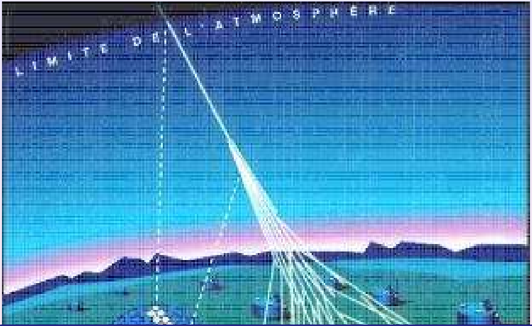


measurements of EAS fluorescence light

- 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'

Cosmic ray interaction models

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

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2. EPOS-LHC *[Pierog, Karpenko, Katzy, Yatsenko & Werner, 2015]*
   - VENUS *[Werner, 1993]* $\rightarrow$ NEXUS *[Drescher, Hladik, SO, Pierog & Werner, 2001]* $\rightarrow$ EPOS *[Werner, Liu & Pierog, 2006]*
   - more phenomenological (e.g. parametrized saturation effects)
     - $\Rightarrow$ 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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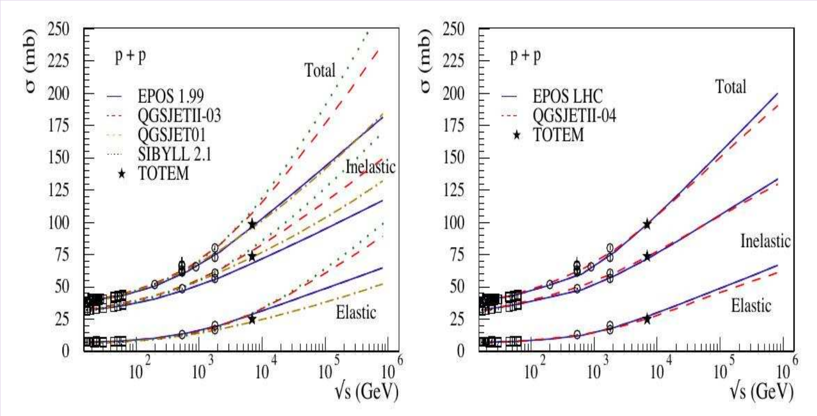
3. SIBYLL-2.3 *[Riehn, Engel, Fedynitch, Gaisser & Stanev, 2015]*
   - SIBYLL-1.7 *[Fletcher, Gaisser, Lipari & Stanev, 1994]*
     $\rightarrow$ SIBYLL-2.1 *[Ahn, Engel, Gaisser, Lipari & Stanev, 2009]*
   - relatively simple ('minijet' approach)
   - differs from QGSJET-II & EPOS in many important aspects
   - has similarities to models used at LHC (e.g. PYTHIA)

All the models: updated with Run 1 data of LHC

Most important: data of TOTEM & ATLAS ALFA for $\sigma_{pp}^{tot/el}$



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

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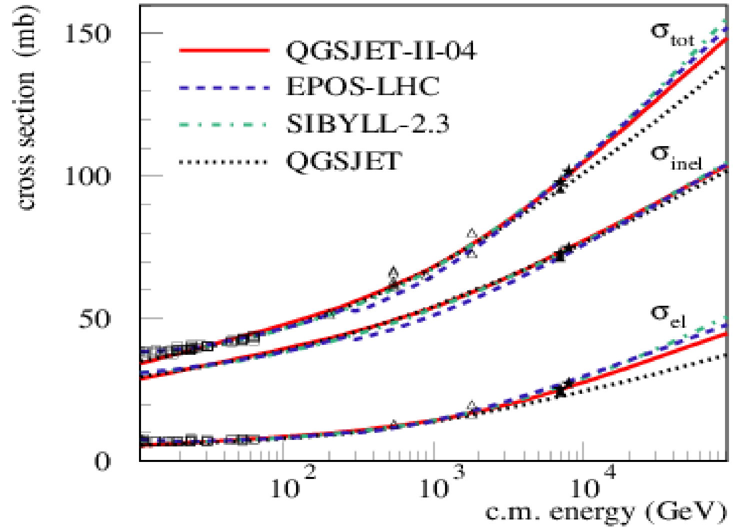
Now: very similar high energy extrapolations for all the models



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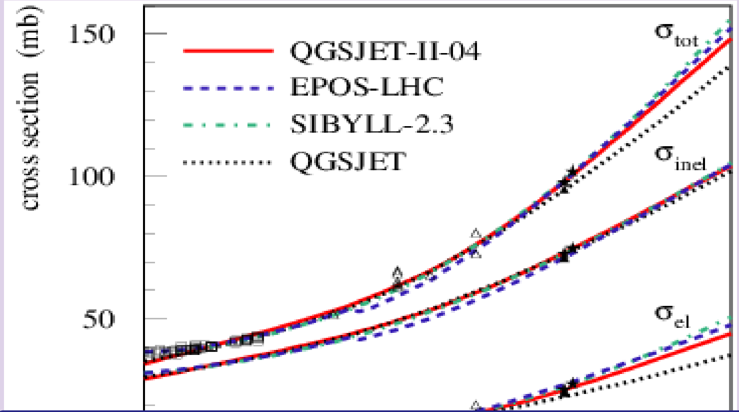
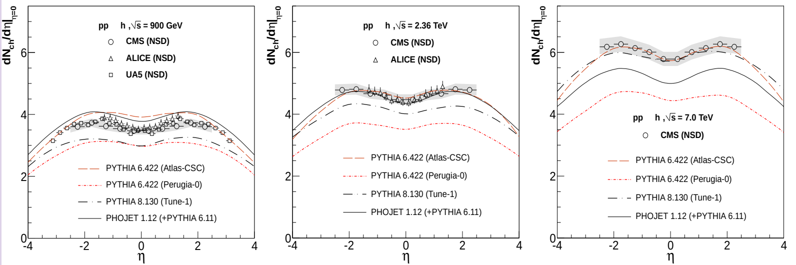


NB: old QGSJET model - outdated physics-wise (> 20 years old)

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

Central production: no surprise for CR interaction models

$dn^{ch}_{pp}/d\eta$ ($\sqrt{s} = 7$ TeV): underestimated by models used at colliders



[plots from d'Enterria et al., Astrop. Phys. 35 (2011) 98]

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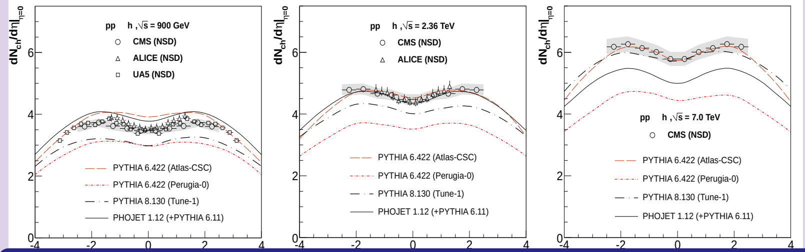
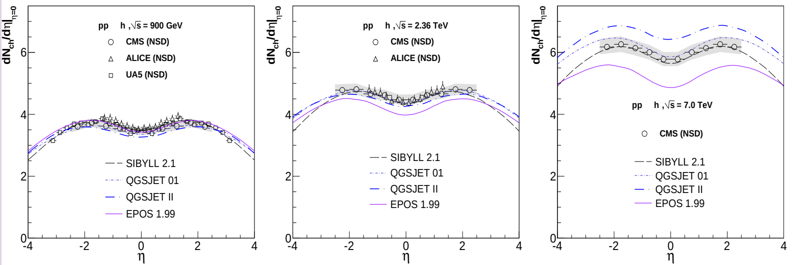


Data well bracketed by predictions of CR interaction models



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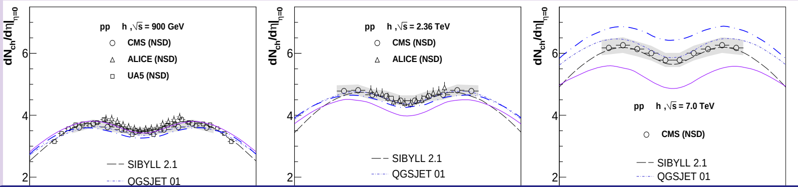
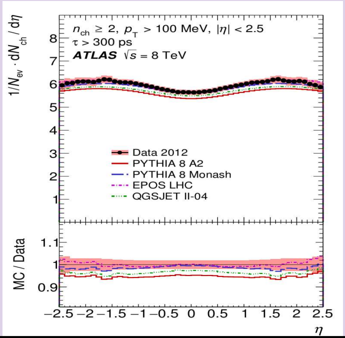
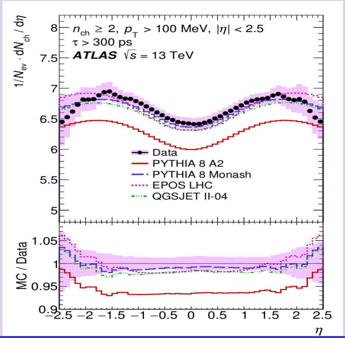
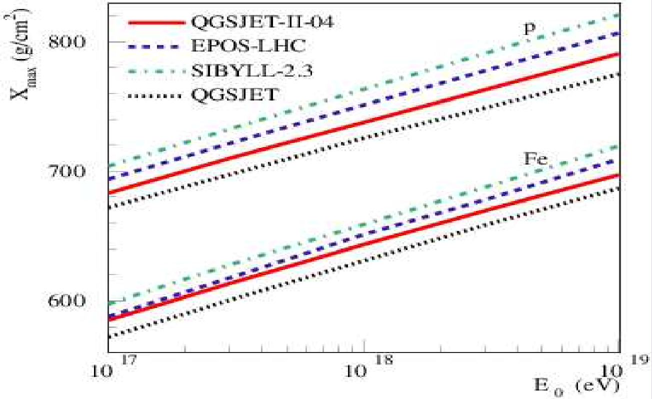


$dn_{pp}^{ch}/d\eta$ of ATLAS ($\sqrt{s} = 8$ and 13 TeV): retuned models o.k.





Model predictions for X_{max}: yet large differences



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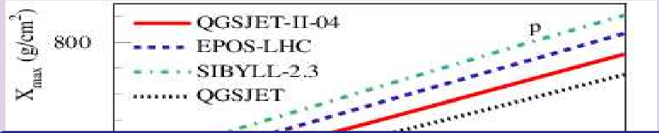
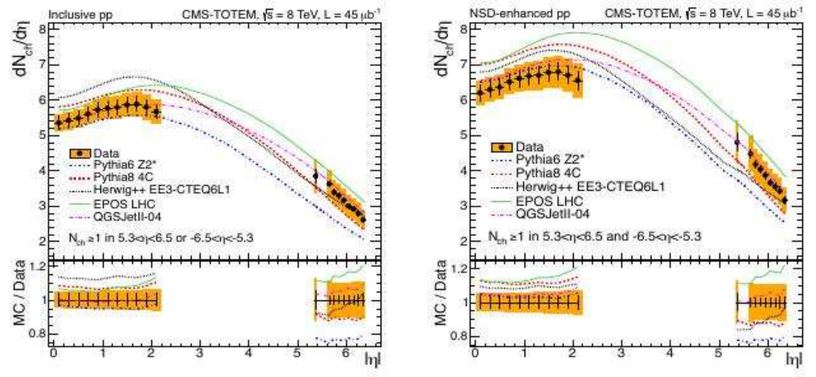
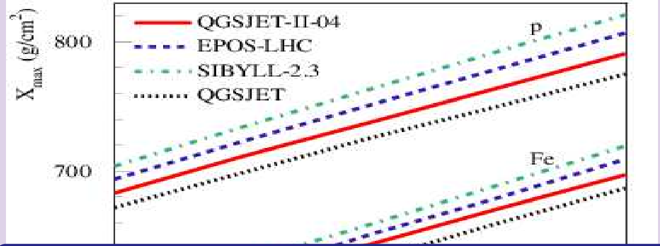


1st hint: combined CMS-TOTEM analysis of $dN_{\mathrm{ch}}/d\eta$

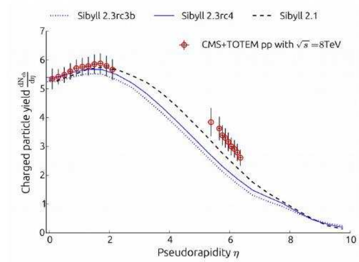


- only EPOS-LHC & QGSJET-II-04 describe the spectral shape

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

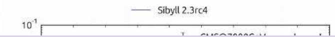


Same problem emerges for the SIBYLL model



- 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

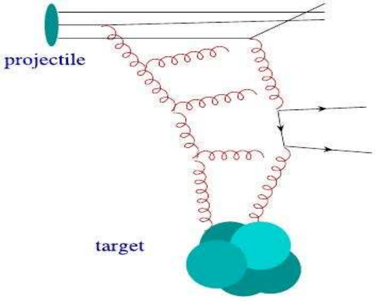


[F. Riehn, talk at "Composition-2015"]

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)



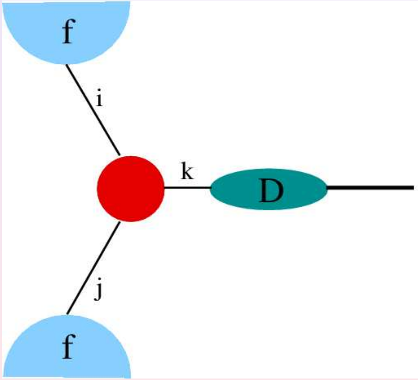
Universal interaction mechanism

- different hadrons (nuclei) $\Rightarrow$ different initial conditions (parton Fock states) but same mechanism
- energy-evolution of the observables (e.g. $\sigma_{pp}^{\mathrm{tot}}$): 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)



Hadronic interactions: input from pQCD & problems

- pQCD: collinear factorization applies for inclusive spectra

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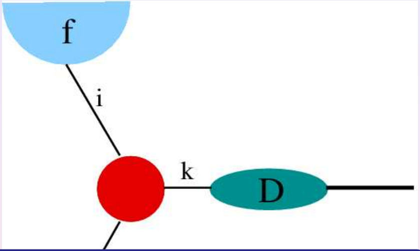


- separates short- & long-distance dynamics
- pQCD predicts evolution of PDFs ($f_{i/p}$) & FFs ($D_{h/k}$)
- $\Rightarrow$ allows to simulate

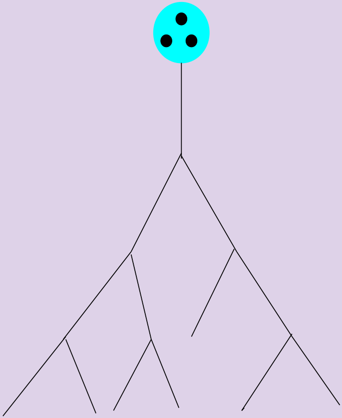
What is beyond and why the models are so different?

- 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'

Hadronic interactions: nonperturbative Fock states

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

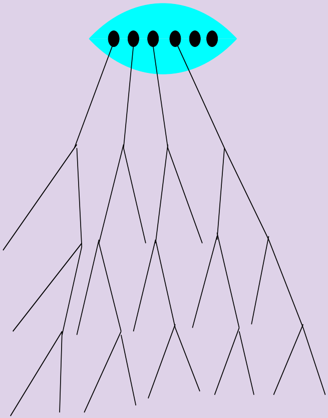
- multiple parton cascades originate from the same initial parton state
- multiple scattering has small impact on forward spectra
  - new branches emerge at small x ($G(x,q^2) \propto 1/x$)
- $\Rightarrow$ Feynman scaling & limiting fragm. for forward production
- higher $\sqrt{s} \Rightarrow$ more abundant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



Hadronic interactions: nonperturbative Fock states

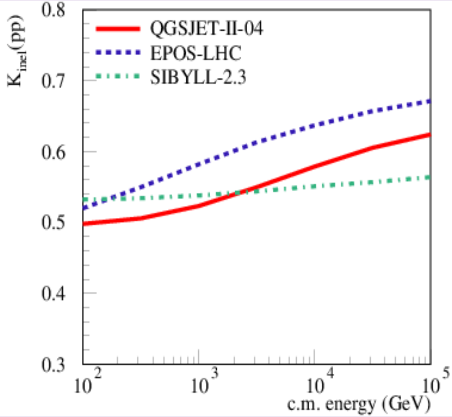
2. $p = \sum$ of multi-parton Fock states [EPOS & QGSJET(-II)]

- 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 air shower predictions?

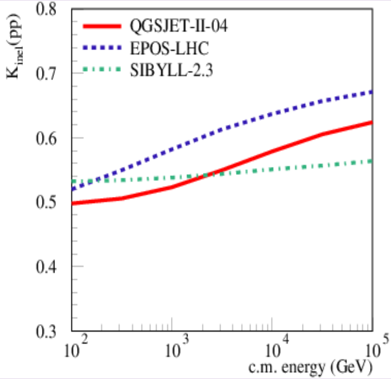
Main cause: energy-dependence of the nucleon 'inelasticity'

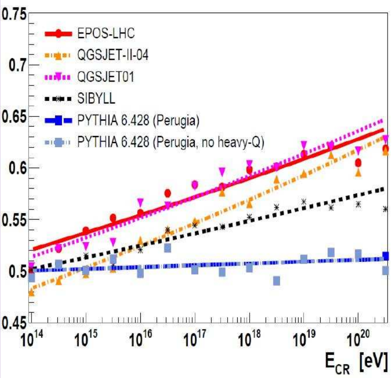


- SIBYLL: K_{pp}^{inel} - weak energy dependence
  - for increasing $\sqrt{s}$, mostly central production enhanced
- smaller K^{inel} $\Rightarrow$ stronger 'leading particle' effect
- $\Rightarrow$ slower shower development (larger X_{max})

Why of importance for air shower predictions?

'Inelasticity' in PYTHIA-6 - similar (almost s-independent)

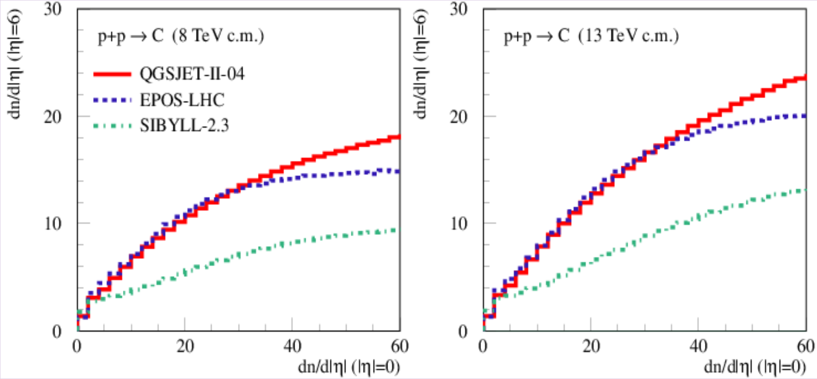




[from Sun Guanhao's talk at "Cosmic QCD-2016"]

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

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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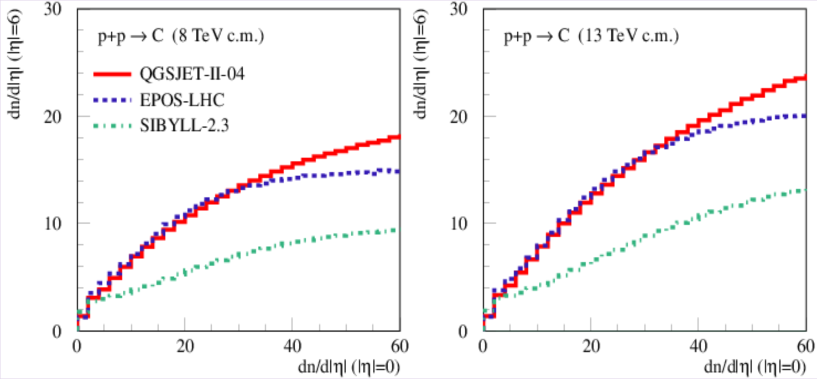
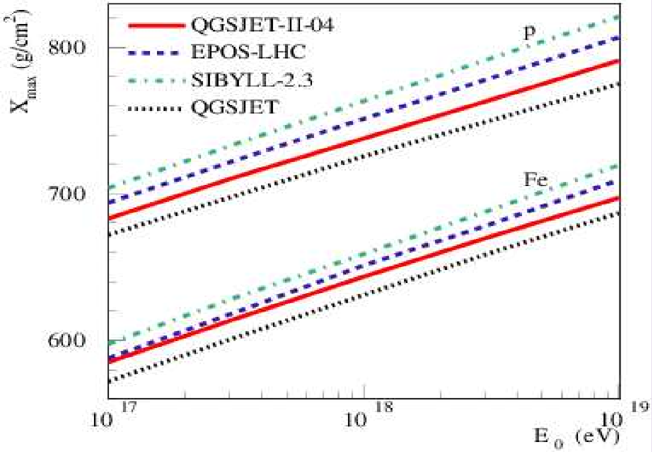


- strong correlation for QGSJET-II-04 & EPOS-LHC (apart from the tails of the multiplicity distributions)

Alternatively: discrimination by LHCf & ATLAS (see extra slides)

Relevance of the inelastic diffraction

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



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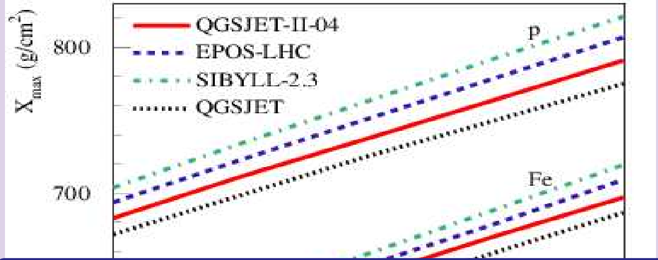
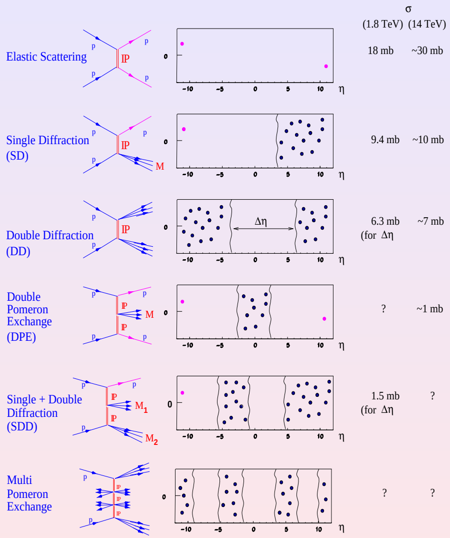


Model differences concerning the treatment of diffraction?

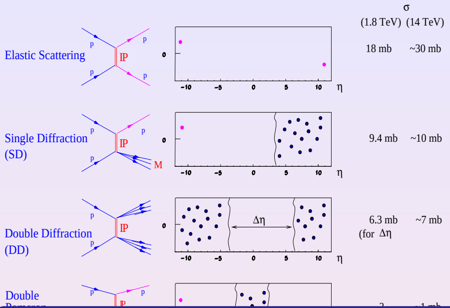
- predictions for X_{max} depend on σ^{inel}_{p-air}, σ^{diffr}_{p-air}, K^{inel}_{p-air}
  - $\sigma^{tot/el}_{pp}$ can be reliably extrapolated thanks to LHC studies
  - σ^{diffr}_{pp} impacts recalculation from pp to pA (AA)
    - σ^{inel}_{p-air} – due to inelastic screening
    - directly related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

Inelastic diffraction



- Experimentally: formation of LRG not covered by secondaries
- classification as low/high mass diffraction: matter of convention
- theoretically: different mechanisms for low and high mass diffraction (e.g. in QGSJET-II)

Inelastic diffraction



- Experimentally: formation of LRG not covered by secondaries
- classification as low/high mass diffraction:

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
$\frac{d\sigma_{pp}^{SD}}{dy_{gap}}$, 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 $X_{\rm max}$ 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 σ_{pp}^{SD} on X_{max} predictions

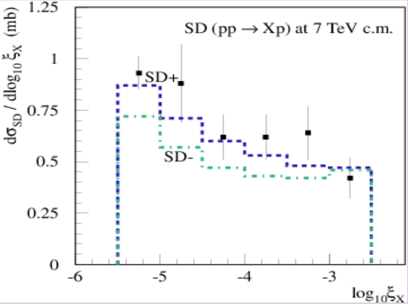
Two alternative model versions (tunes): SD+ & SD-

- 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 $\sigma_{pp}^{tot/el}$ & central particle production in both cases

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

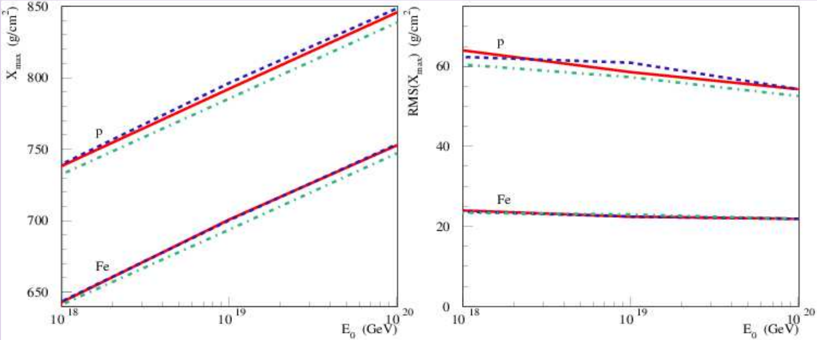
Single diffraction: SD- agrees with TOTEM, SD+ o.k. with CMS

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

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

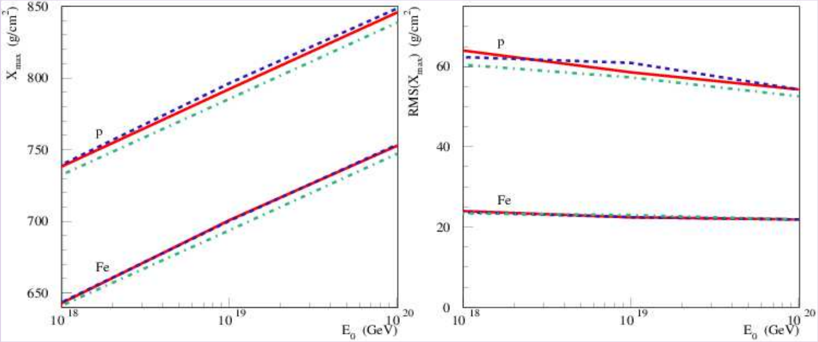


Option SD-: smaller low mass diffraction

- $\Rightarrow$ 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 $\sigma_{pp}^{\mathrm{SD}}$ on $X_{\max}$ predictions

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

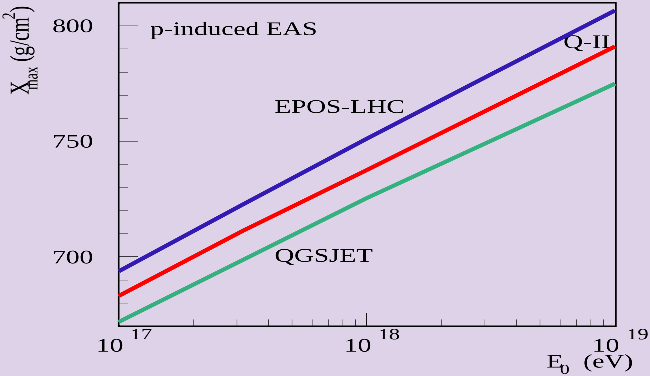


Option SD+: larger high mass diffraction

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

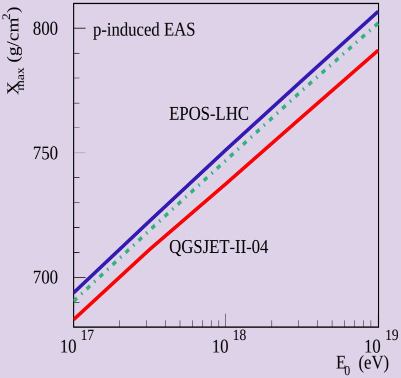


- previous analysis not general enough?
- or other interaction properties relevant?
- to answer - use "cocktail" model approach

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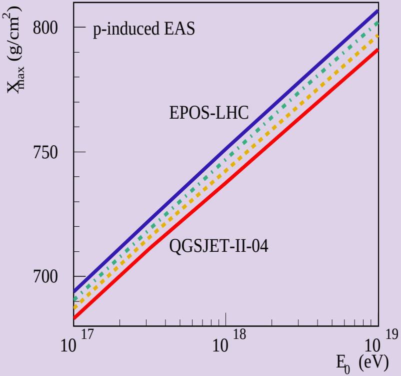
- $\Delta X_{\max} \leq 5$ g/cm^2 - in agreement with above
- now QGSJET-II for the complete 1st interaction (EPOS-LHC for the rest)
- $\Delta X_{\max} \leq 5$ g/cm^2
- reason: harder pion spectra in $p-$air in EPOS-LHC



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- now QGSJET-II for the complete 1st interaction (EPOS-LHC for the rest)
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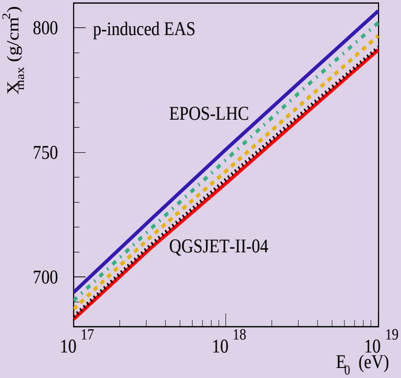
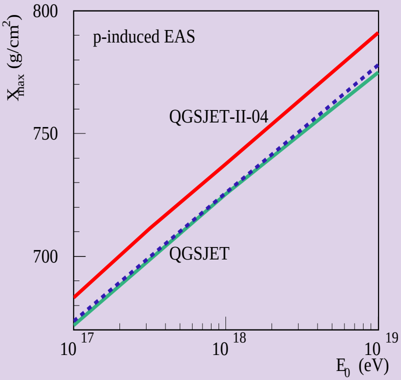
- remaining difference: copious $\bar{p}p$- & $\bar{n}n$-pair production in π- & K-air in EPOS-LHC



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



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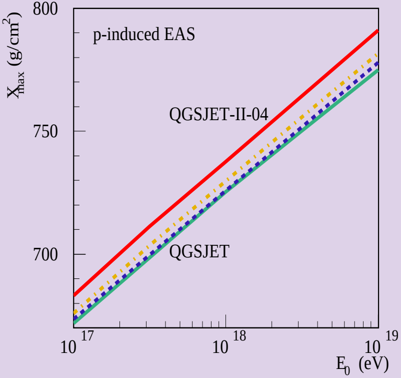
Now compare $X_{\max}$ of QGSJET & QGSJET-II-04

- 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 $\sigma^{\rm inel}_{\pi-{\rm air}}$, $\sigma^{\rm inel}_{K-{\rm air}}$



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

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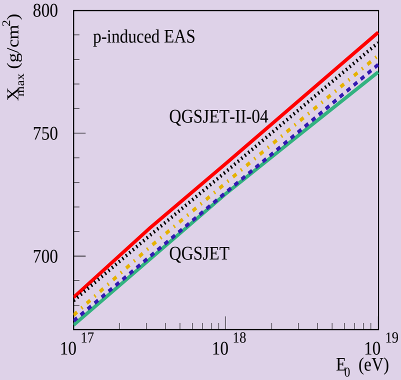
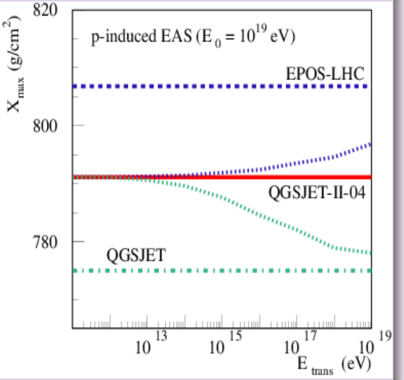
- use QGSJET-II for the complete 1st interaction (QGSJET for the rest)
- $\Delta X_{\max} \leq 3$ g/cm^2
- next: QGSJET-II for the 1st interaction & for all $\sigma^{\rm inel}_{\pi-{\rm air}}$, $\sigma^{\rm inel}_{K-{\rm air}}$
- rest: mostly due to softer pion & kaon spectra in π-air in QGSJET



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

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

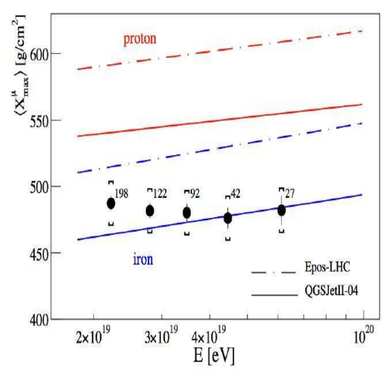
- $X_{\max}$ for 10^{19} eV proton EAS using 'cocktail': QGSJET-II for $E > E_{\text{trans}}$ and EPOS-LHC or QGSJET for $E < E_{\text{trans}}$
- main difference for $E \to E_0$ (before most of the energy goes into the e/m cascade)
- how to constrain pion-air collisions at VHE?!



Testing models with air shower data

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

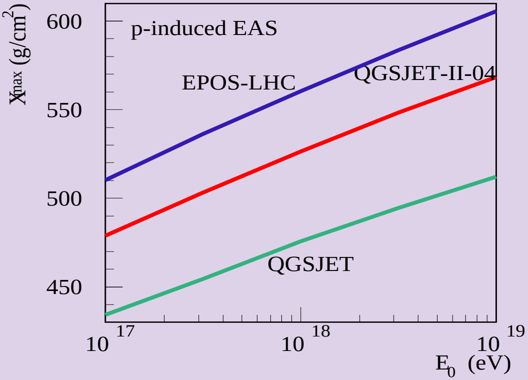
- models predict deeper $X^{\mu}_{\max}$ than observed
  - e.g. one needs primary iron for QGSJET-II-04
  - or primary gold for EPOS-LHC...



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

Testing models with air shower data

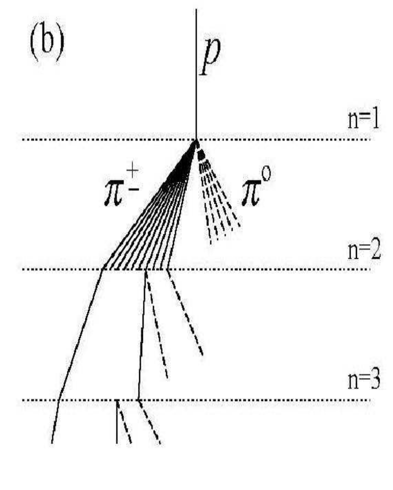
What is the physics behind the different predictions for X^{μ}_{max}?



Testing models with air shower data

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

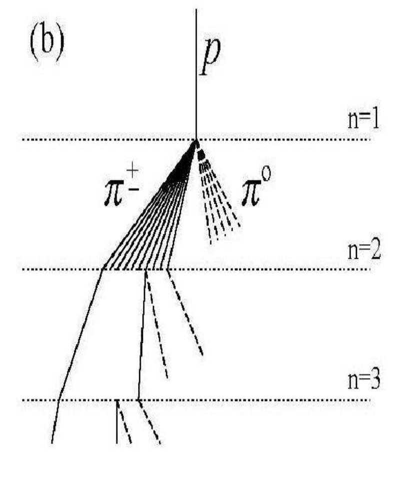
- NB: muons originate from a multi-step hadron cascade
- smaller $\sigma^{\text{inel}}_{\pi-\text{air}}$ $\Rightarrow$ larger distances between the cascade steps
  - $\Rightarrow$ deeper $X^{\mu}_{\max}$
  - NB: larger diffraction in $\pi - \text{air}$ $\Rightarrow$ similar effect *[credits to T. Pierog]*



Testing models with air shower data

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

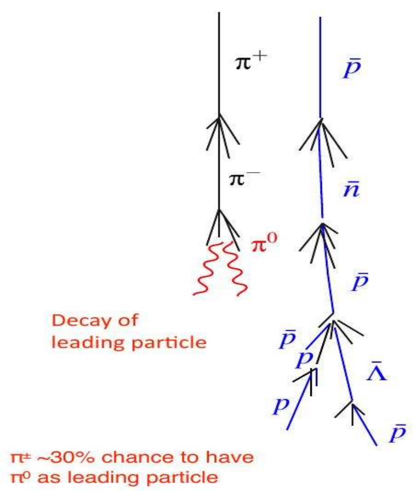
- pion decay probability: $p_{\text{decay}} \propto E_\pi^{\text{crit}} / E_\pi / X$
- X^μ_{max}: where $p_{\text{decay}} \sim p_{\text{inter}}$
- harder spectra in $\pi - \text{air}$ $\Rightarrow$ deeper X^μ_{max} (effectively one more cascade step)



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 $X^{\mu}_{\max}$ IFF $N_{p,\bar{p},n,\bar{n}}$ comparable to N_{π}! (the case of EPOS)

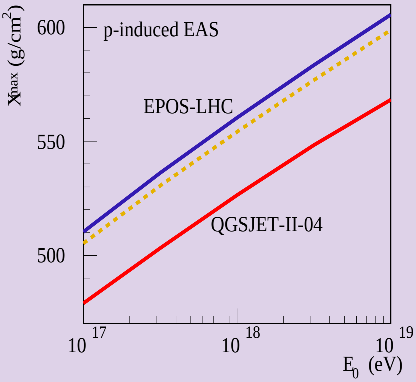


[from R. Engel, "Composition-2015" talk]

Testing models with air shower data

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

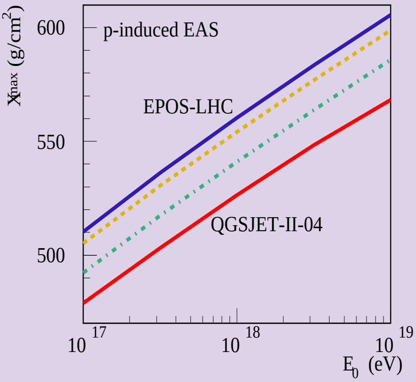
- use QGSJET-II for 1st interaction and EPOS-LHC for the rest
- small effect: $X^{\mu}_{\max}$ difference – due to pion-air collisions



Testing models with air shower data

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

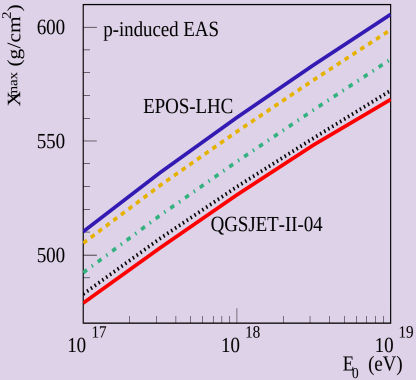
- use QGSJET-II for 1st interaction and EPOS-LHC for the rest
- small effect: X_{max}^{μ} difference – due to pion-air collisions
- now QGSJET-II also for $\bar{p}p$ & $\bar{n}n$ production in π-air – largest effect



Testing models with air shower data

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

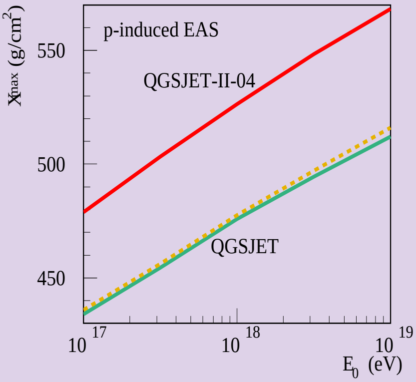
- use QGSJET-II for 1st interaction and EPOS-LHC for the rest
- small effect: $X^{\mu}_{\max}$ difference – due to pion-air collisions
- largest effect: copious $\bar{p}p$ & $\bar{n}n$ production in EPOS
- remaining difference: $\pi^{\pm}$ & $K^{\pm}$ spectral shapes & diffraction in π- & K-air



Testing models with air shower data

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

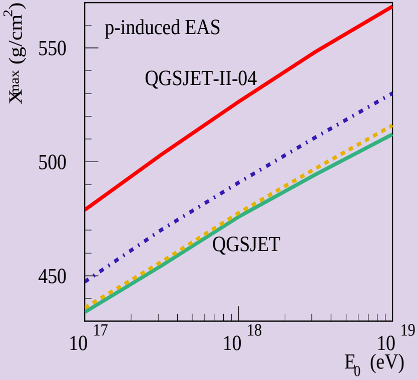
- QGSJET-II for 1st interaction, rest – QGSJET: minor effect



Testing models with air shower data

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

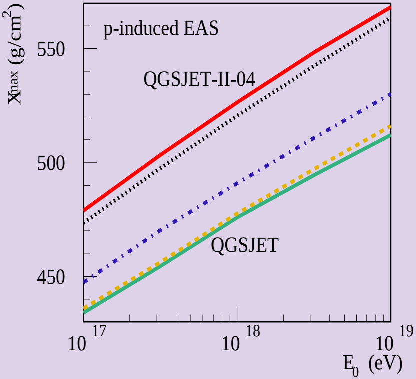
- QGSJET-II for 1st interaction, rest – QGSJET: minor effect
- QGSJET-II for 1st interaction & $\sigma^{inel}_{\pi,K-air}$



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 & $\sigma^{\mathrm{inel}}_{\pi,K-\mathrm{air}}$
- main effect: softer $\pi^{\pm}$ & $K^{\pm}$ spectra in π-air in QGSJET



Testing models with air shower data

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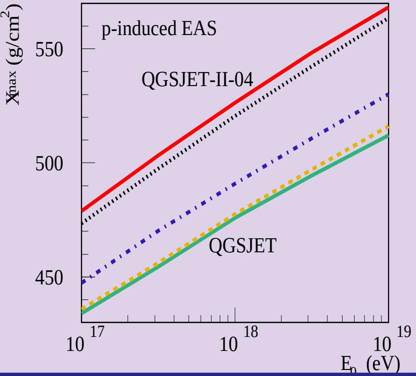
- main effect: softer $\pi^{\pm}$ & $K^{\pm}$ spectra in π-air in QGSJET

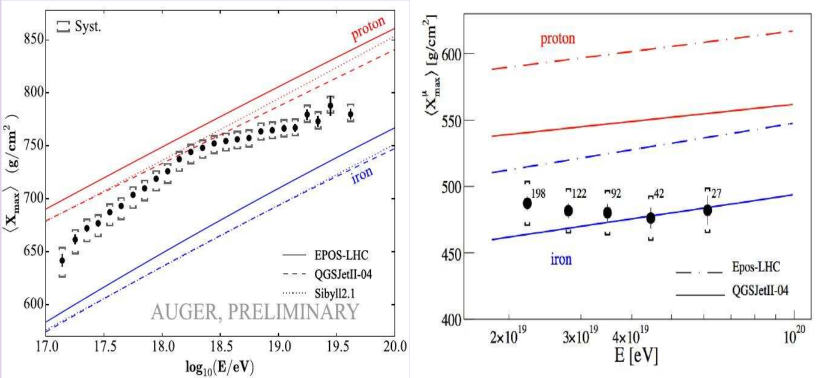


Model-dependence of $X^{\mu}_{\max}$: same features of π-air as for $X_{\max}$

- $X^{\mu}_{\max}$ – 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 $X_{\max}$ & $X_{\max}^{\mu}$?

This would require a faster development of the hadronic cascade



- because: impact on $X_{\max}^{\mu}$ - stronger than on $X_{\max}$
- technically: requires higher $\sigma_{\pi-\text{air}}^{\text{inel}}$ and/or softer $\pi^{\pm}$ spectra
  - $\Rightarrow$ towards old QGSJET

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

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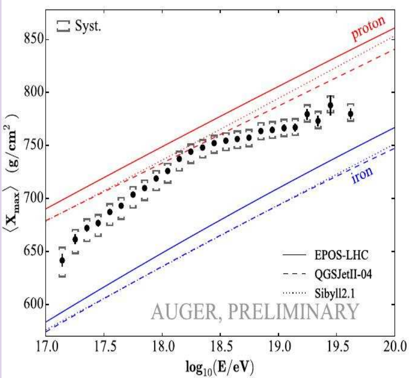
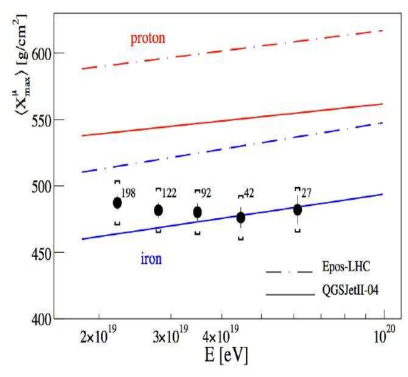
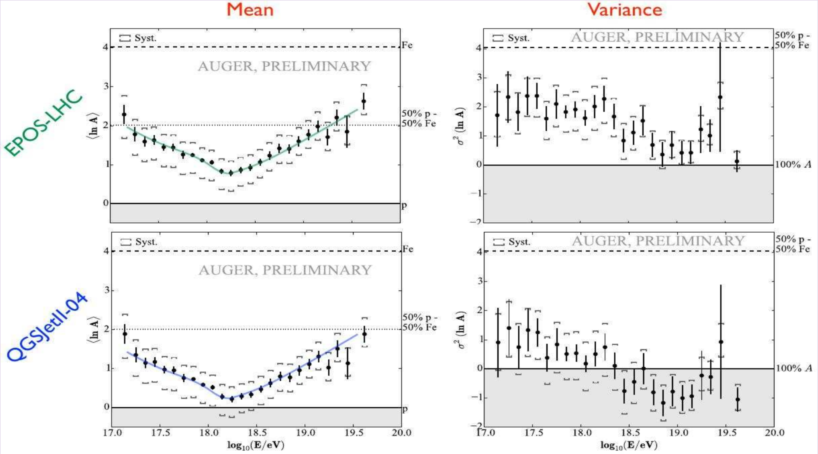




- because: impact on $X^{\mu}_{\max}$ - stronger than on $X_{\max}$
- technically: requires higher $\sigma^{\rm inel}_{\pi-{\rm air}}$ and/or softer $\pi^{\pm}$ spectra
  - $\Rightarrow$ towards old QGSJET
- $\Rightarrow$ this would push us towards a light composition!

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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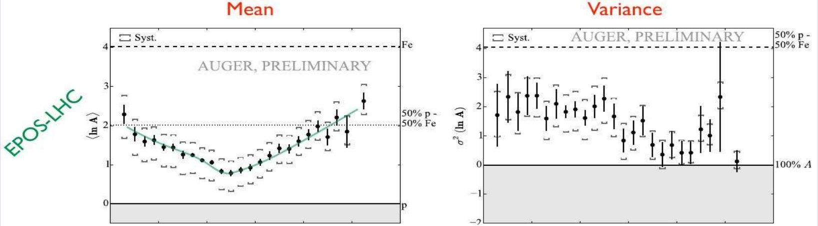
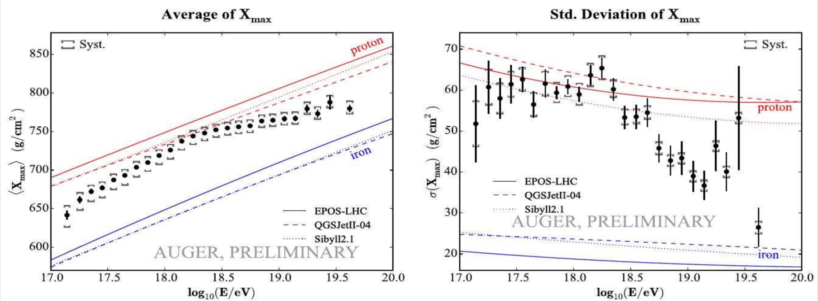


PAO data & model predictions for X_{max} & RMS(X_{max})



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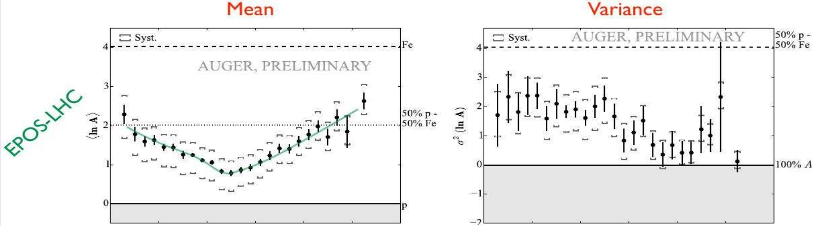
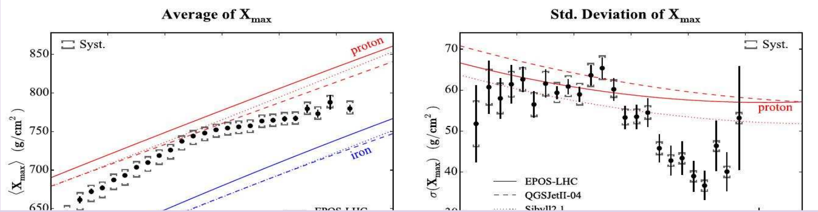


PAO data & model predictions for $X_{\max}$ & RMS($X_{\max}$)

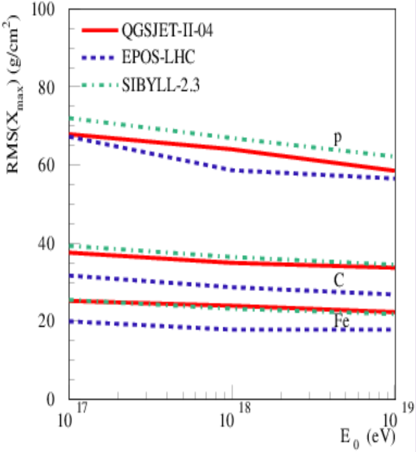


- for deeper $X_{\max}$ – see the discussion above
- what about the model differences for RMS($X_{\max}$)?

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

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

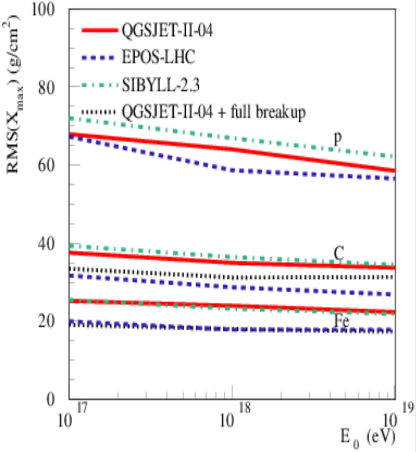
- models tuned to LHC data on $\sigma_{pp}^{\text{inel}}$ $\Rightarrow$ similar RMS($X_{\max}$) for protons
- differences for primary nuclei: due to the fragmentation of the 'spectator' part



Conflict with RMS(X_{max})?

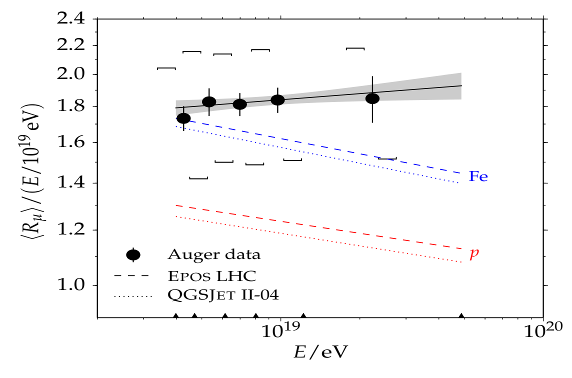
NB: small model uncertainty for RMS(X_{max}) based on LHC data

- models tuned to LHC data on σ_{pp}^{inel} $\Rightarrow$ similar RMS(X_{max}) for protons
- differences for nucleus-induced EAS: due to the fragmentation of the 'spectator' part
- to explain EPOS results: QGSJET-II & full break up of the spectator part (into separate nucleons)
  - NB: full break up – in variance with exp. data



Few comments on the 'muon excess' in air showers

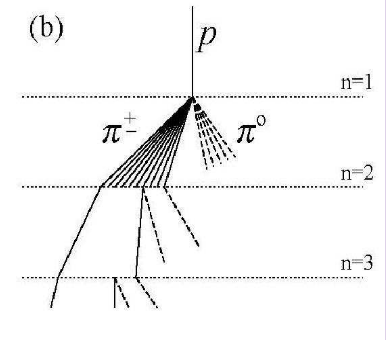
PAO observed higher EAS muon content than predicted by models



- excess by a large factor $(1.5 \div 2)$

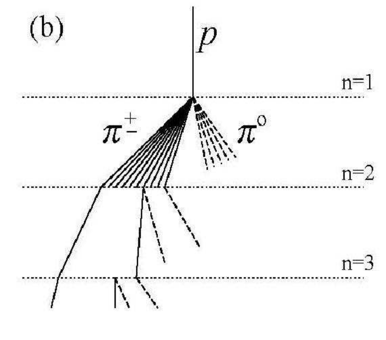
Few comments on the 'muon excess' in air showers

- NB: N_μ results from a multi-step hadron cascade
  - ~ 1 cascade step per energy decade



Few comments on the 'muon excess' in air showers

- NB: N_μ results from a multi-step hadron cascade
  - ~ 1 cascade step per energy decade
- let N_μ be o.k. up to energy E_A
- strong N_μ enhancement at energy E_B $(E_B < 100 E_A)$?
  - i.e. within 2 orders of magnitude in energy



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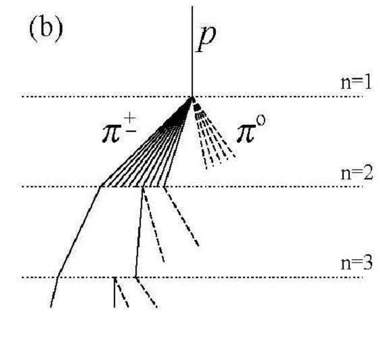
- let N_μ be o.k. up to energy E_A
- strong N_μ enhancement at energy E_B ($E_B < 100 E_A$)?
  - i.e. within 2 orders of magnitude in energy
- secondary pions: mostly with $x_F < 0.1$
  - $\Rightarrow$ at most 1 cascade step between E_A & E_B!



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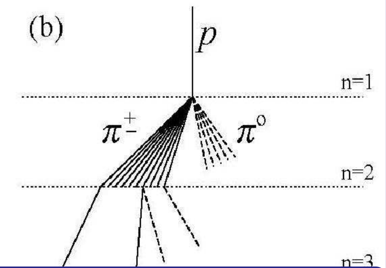
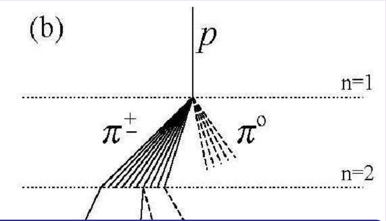


Can muon excess be produced by 1-2 cascade steps?

- if we double N^{ch} for the 1st interaction?
  - $< 10\%$ increase for N_μ! *[SO, talk at C2CR-2005]*
- to get, say, a factor 2 enhancement: N_{ch} should rise by an order of magnitude

Few comments on the 'muon excess' in air showers

- NB: N_μ results from a multi-step hadron cascade
  - ~ 1 cascade step per energy decade
- let N_μ be o.k. up to energy E_A
- strong N_μ enhancement at energy E_B $(E_B < 100 E_A)$?
  - i.e. within 2 orders of magnitude in energy
- secondary pions:



Perhaps 'new physics' does it?

- proton-air cross section at UH energies: $\sigma^{\rm inel}_{p-{\rm air}} \sim 1/2$ 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)

Few comments on the 'muon excess' in air showers

- NB: N_μ results from a multi-step hadron cascade
  - ~ 1 cascade step per energy decade
- let N_μ be o.k. up to energy E_A
- strong N_μ enhancement at energy E_B ($E_B < 100 E_A$)?
  - i.e. within 2 orders of magnitude in energy
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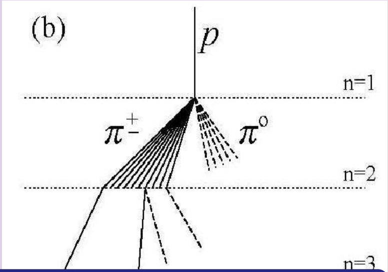


Can muon excess be produced by 1-2 cascade steps?

- if we double N^{ch} for the 1st interaction?
  - $< 10\%$ increase for N_μ! *[SO, talk at C2CR-2005]*

If the muon excess is real it should be seen already at 10^{17} eV!

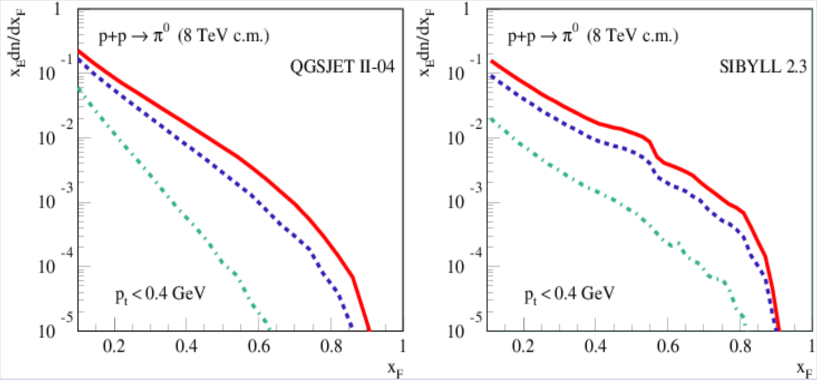
Summary

1. LHC studies of pp collisions constrained interaction models
   - most important for CR physics: $\sigma_{pp}^{\mathrm{tot/el}}$ by TOTEM & ATLAS
   - of importance: to resolve the diffraction issue
2. Differences for predicted $K_{p-\mathrm{air}}^{\mathrm{inel}}$ ($\Rightarrow X_{\max}$):
   model assumptions for constituent parton Fock states
   - can be discriminated by combined measurements with forward & central detectors
   - e.g. studies of CMS-TOTEM correlation may refute SIBYLL
3. Present uncertainties for EAS predictions:
   largely due to the treatment of pion-air interactions
   - can be constrained by $X_{\max}^{\mu}$ measurements in CR experiments
4. Present PAO data on $X_{\max}^{\mu}$: push towards a light composition
   - but: conflict with PAO results on RMS($X_{\max}$)

Extra slides

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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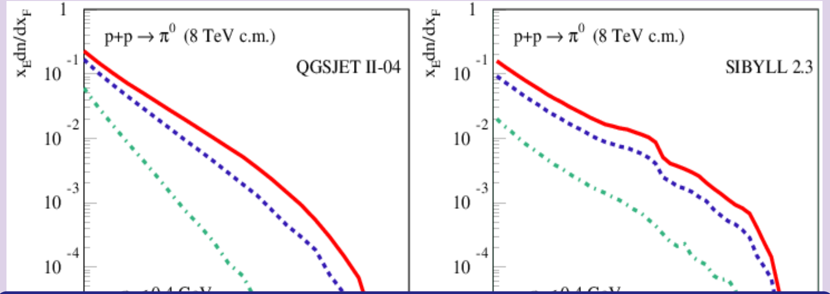


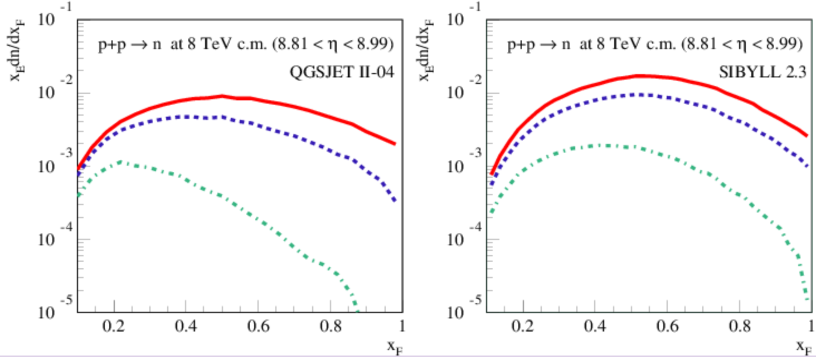
Compare QGSJET-II-04 (left) to SIBYLL 2.3 (right)

- 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 ⇒ more constituent partons involved ⇒ less energy left for the proton 'remnant'

σ_{inel} & forward hadron spectra for pion-nytrogen collisions