Monte Carlo generators for CR interactions

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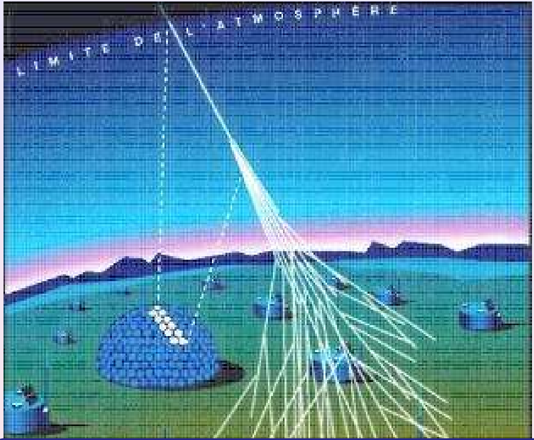
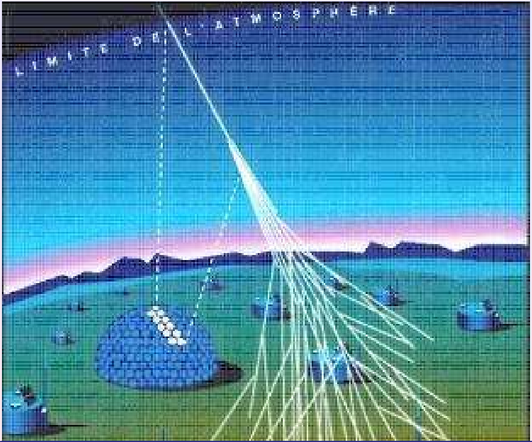
Cosmic ray studies with Extensive Air Shower technique



ground-based observations

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

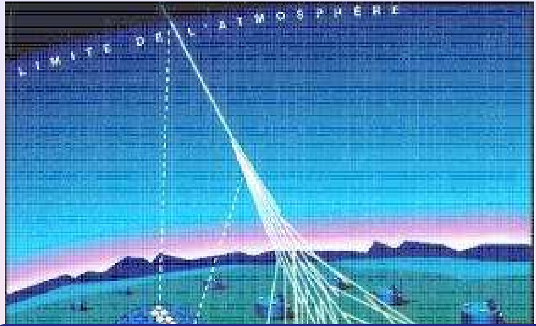
Cosmic ray studies with Extensive Air Shower technique



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

Cosmic ray interaction models

1. QGSJET-II-04 *[SO, PRD83 (2011) 014018]*
   - based on the Reggeon Field Theory (RFT) approach
   - nonlinear effects: Pomeron-Pomeron interactions

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2. EPOS-LHC *[Pierog, Karpenko, Katzy, Yatsenko & Werner, PRC92 (2015) 034906]*
    - also RFT-based but involves phenomenological solutions (e.g. parametrized saturation effects)
    - 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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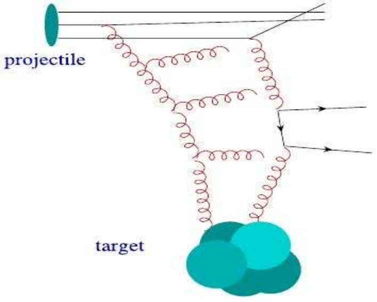
3. SIBYLL-2.3 *[Riehn, Engel, Fedynitch, Gaisser & Stanev, arXiv:1510.00568]*
   - similar to most of the generators used at the LHC (based on the 'minijet' approach)
   - includes multiple soft interactions ⇒ some similarity to RFT-based models

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)



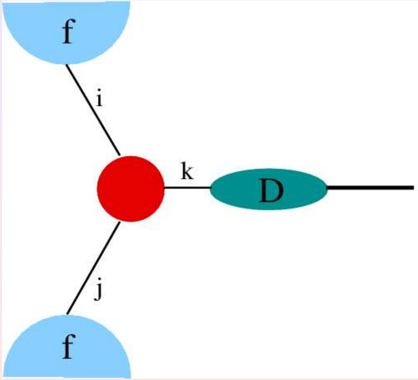
Universal interaction mechanism

- 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)



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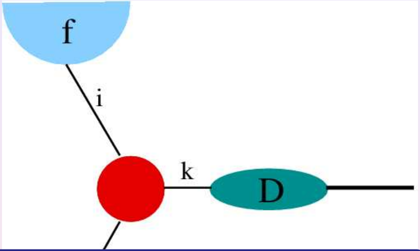

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- pQCD predicts evolution of PDFs ($f_{i/p}$) & FFs ($D_{h/k}$)
- $\Rightarrow$ allows to simulate

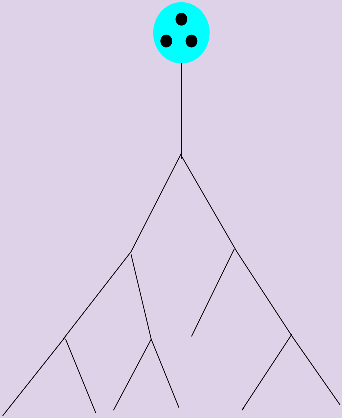
What is beyond and why the models are so different?

- 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)

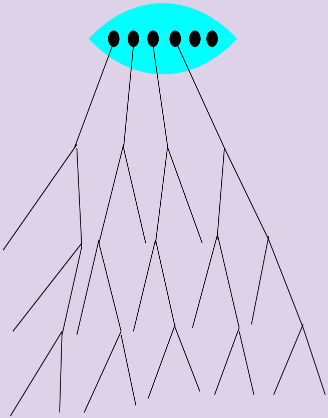
- multiple parton cascades originate from the same initial parton state
- multiple scattering has small impact on forward spectra
  - new branches emerge at small x ($G(x,q^2) \propto 1/x$)
- $\Rightarrow$ Feynman scaling & limiting fragm. for forward production
- higher $\sqrt{s} \Rightarrow$ more abundant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



Hadronic interactions: nonperturbative Fock states

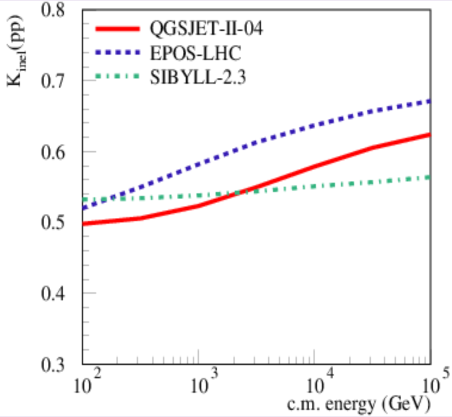
2. $p = \sum$ of multi-parton Fock states [EPOS & QGSJET(-II)]

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



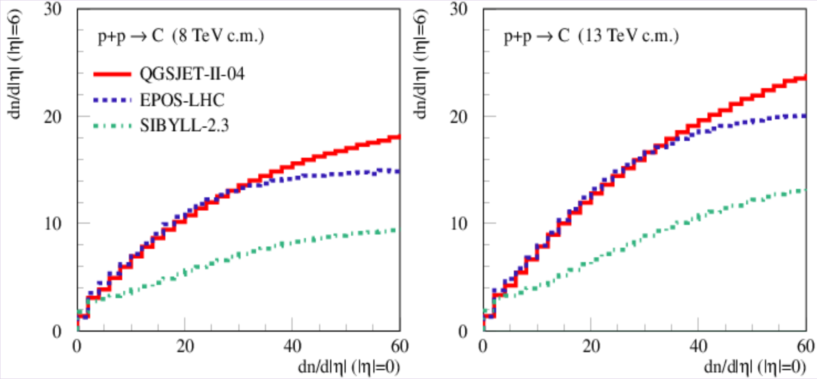
Why of importance for air shower predictions?

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



- SIBYLL: K_{pp}^{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})

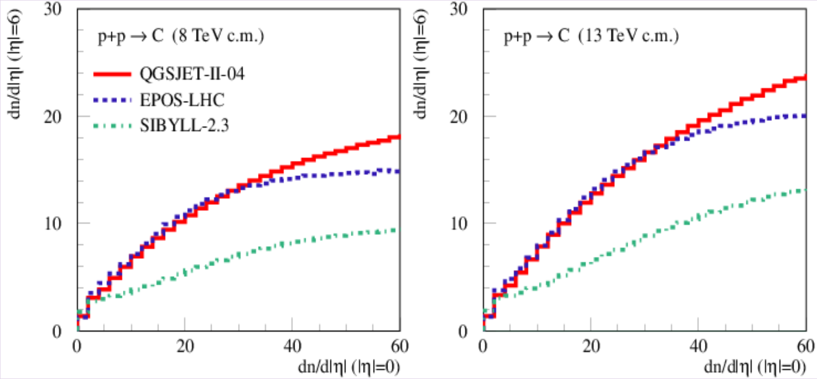
Cross-correlation of $dN_{pp}^{\rm ch}/d|\eta|$ at $\eta = 0$ ($p_t > 0.1$ GeV) and $\eta = 6$



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

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

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



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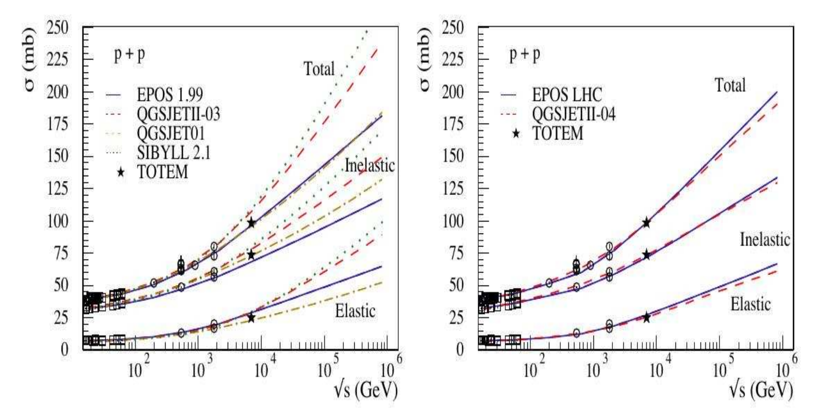
Alternatively: discrimination by LHCf & ATLAS (see extra slides)

All the models: updated with Run 1 data of LHC

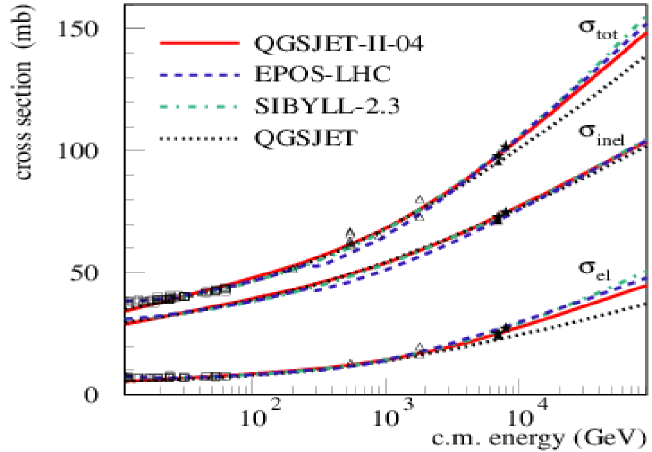
Most important: data of TOTEM & ATLAS ALFA for $\sigma_{pp}^{tot/el}$



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

All the models: updated with Run 1 data of LHC

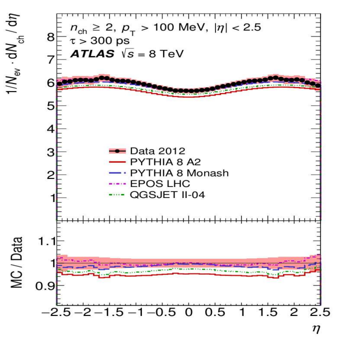
Now: very similar high energy extrapolations for all the models

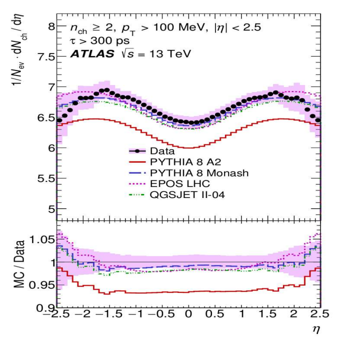


- NB: σ^{inel}_{p-air} defines where the cascade starts

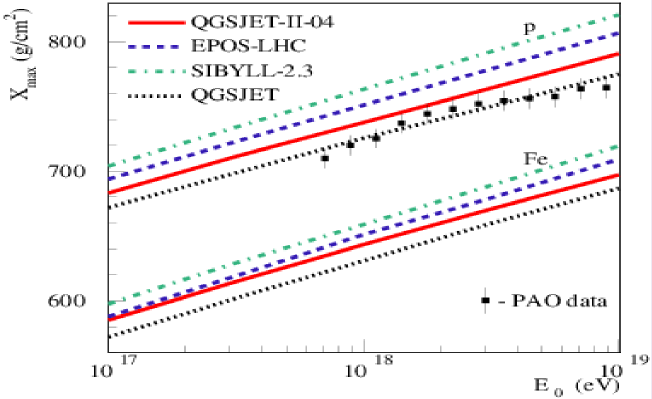
All the models: updated with Run 1 data of LHC

Also for central production: $dn^{ch}_{pp}/d\eta$ vrs. ATLAS ($\sqrt{s} = 8, 13$ TeV)





Model predictions for EAS, e.g. $X_{\max}$: yet large differences



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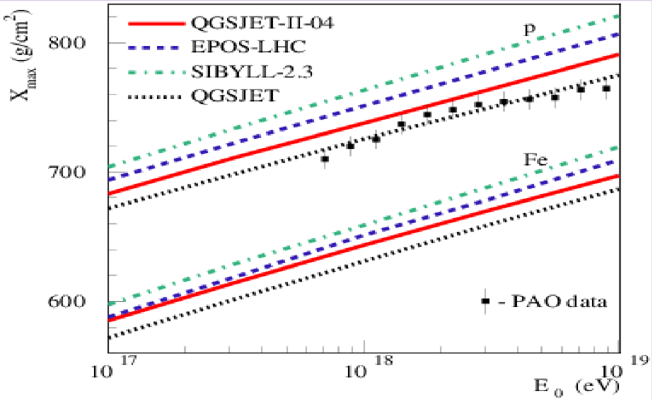
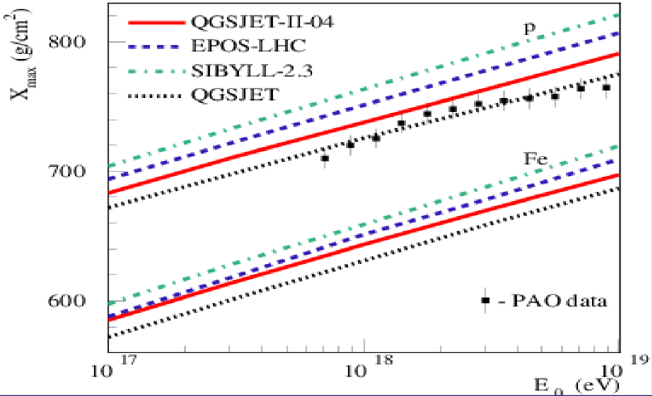


Deepest $X_{\max}$ of SIBYLL-2.3 – mainly due to the smallest $K^{\text{inel}}_{p-\text{air}}$

- direct consequence of the assumptions on parton Fock states
  - can be discriminated at LHC (central-forward correlations)

Model predictions for EAS, e.g. $X_{\max}$: yet large differences



For other models: treatment of proton diffraction?

- $\sigma_{pp}^{\rm diffr}$ impacts recalculation from pp to pA (AA)
  - $\sigma_{p-{\rm air}}^{\rm inel}$ – due to inelastic screening
  - directly related to $\sigma_{p-{\rm air}}^{\rm diffr}$, hence, also to $K_{p-{\rm air}}^{\rm inel}$ – due to small 'inelasticity' of diffractive collisions (especially for target SD)

Impact of diffraction uncertainties on $X_{\max}$ predictions

[SO, PRD 89, 074009 (2014)]

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

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

- $\Rightarrow$ may be regarded as the characteristic uncertainty for $\sigma_{pp}^{\rm SD}$

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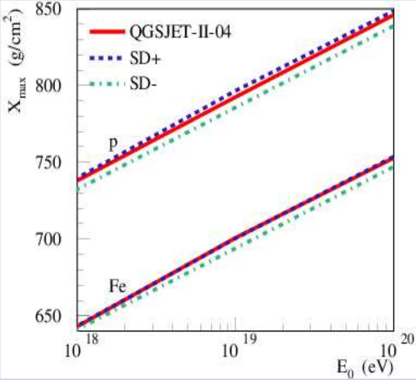
Two alternative model versions (tunes): SD+ & SD-

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

Impact of diffraction uncertainties on $X_{\max}$ predictions

Characteristic differences: $\Delta X_{\max} \simeq 10\,\mathrm{g/cm^2}$



- option SD-:
  - smaller inelastic screening $\Rightarrow$ larger $\sigma^{\rm inel}_{p-\rm air}$
  - smaller diffraction for p-air $\Rightarrow$ larger $K^{\rm inel}_{p-\rm air}$
  - $\Rightarrow$ smaller $X_{\max}$ (all effects in the same direction)
- option SD+: opposite effects

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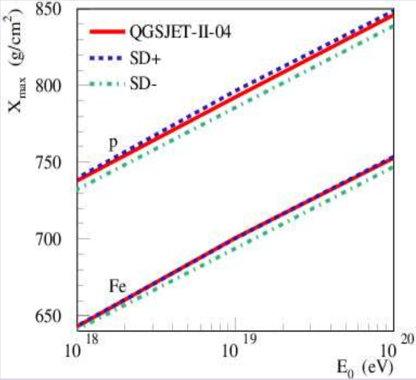

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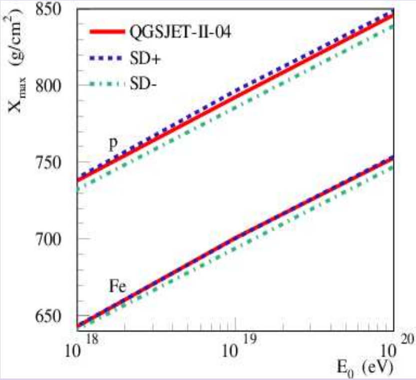

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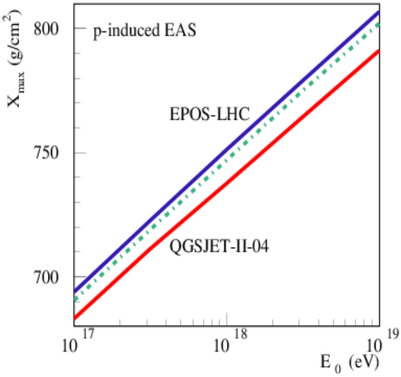
Model differences for $X_{\max}$ twice bigger (reach $20\,\mathrm{g/cm^2}$)

- other interaction properties relevant?
- may be checked using the "cocktail" approach:
  using different models for certain interactions in air showers

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 $X_{\max}$

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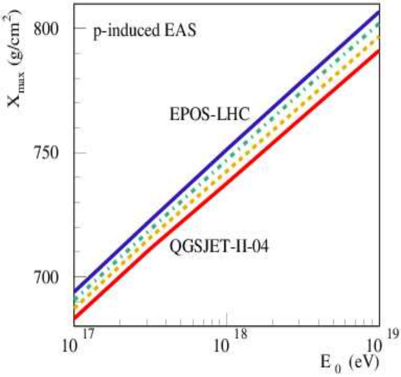
- QGSJET-II for $\sigma_{p-\mathrm{air}}^{\mathrm{inel}}$ & leading nucleon spectrum
- $\Delta X_{\max} \leq 5$ g/cm^2 - in agreement with above
- now QGSJET-II for the complete 1st interaction (EPOS-LHC for the rest)
- $\Delta X_{\max} \leq 5$ g/cm^2
- reason: harder pion spectra in $p-$air in EPOS-LHC



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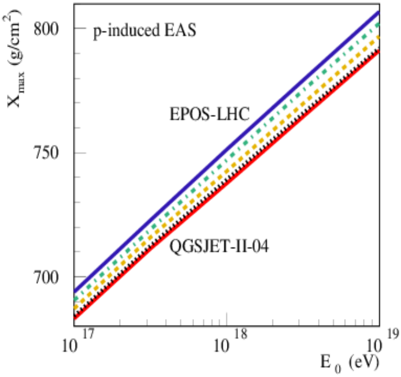
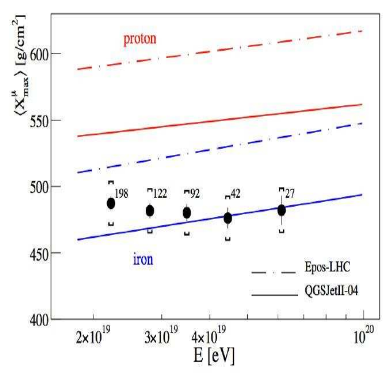
- $\Delta X_{\max} \leq 5$ g/cm^2 - in agreement with above
- now QGSJET-II for the complete 1st interaction
- $\Delta X_{\max} \leq 5$ g/cm^2
- remaining difference: copious $\bar{p}p$- & $\bar{n}n$-pair production and higher diffraction for π-air collisions in EPOS-LHC



Constraining pion interactions by cosmic ray 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...

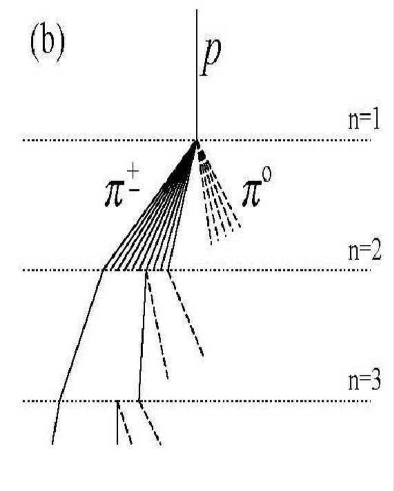


[from M. Roth, "Composition-2015" talk]

Constraining pion interactions by cosmic ray data

X^{μ}_{max}: effects of inelastic & diffractive $\pi - \mathrm{air}$ cross sections

- NB: muons originate from a multi-step hadron cascade
- smaller $\sigma^{inel}_{\pi-\mathrm{air}}$ $\Rightarrow$ larger distances between the cascade steps
  - $\Rightarrow$ deeper X^{μ}_{max}
- larger diffraction in $\pi - \mathrm{air}$ $\Rightarrow$ similar effect



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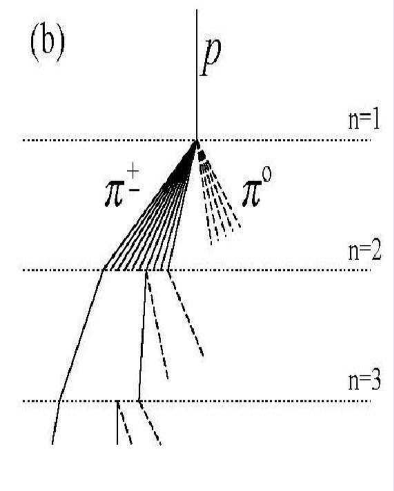
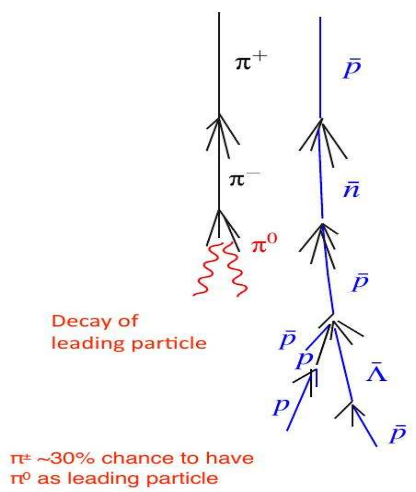


Constraining pion interactions by cosmic ray data

$X^{\mu}_{\max}$: relation to (anti-)baryon production



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

- 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)

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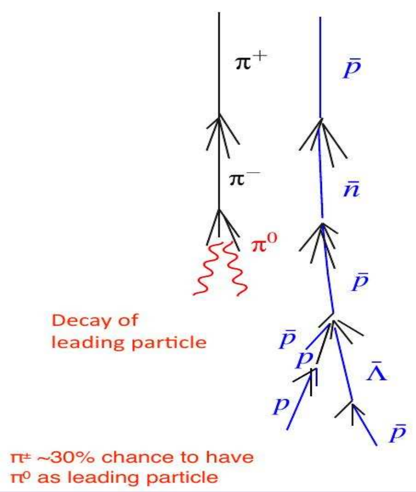

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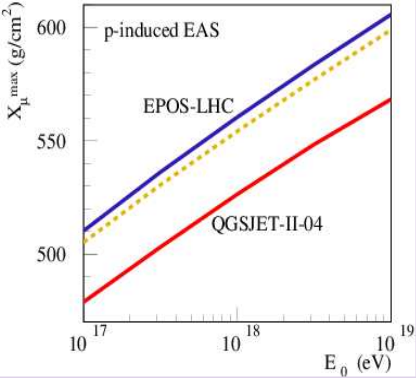
Constraining pion interactions by cosmic ray data

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



Constraining pion interactions by cosmic ray data

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

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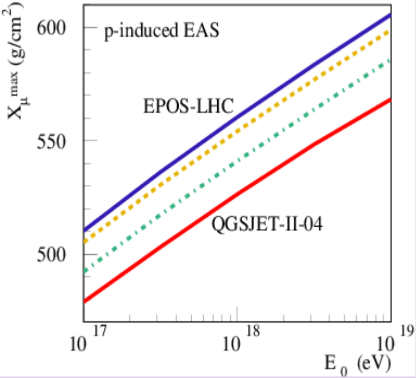
- small effect: $X_{\max}^{\mu}$ difference – due to pion-air collisions
- now QGSJET-II also for $\bar{p}p$ & $\bar{n}n$ production in π-air – largest effect



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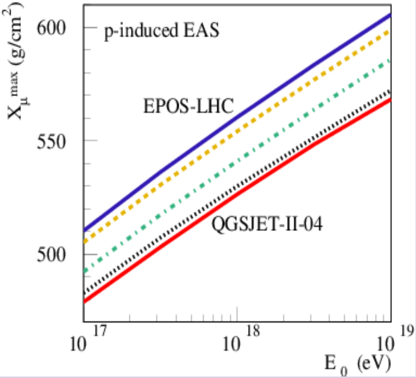
- largest effect: copious $\bar{p}p$ & $\bar{n}n$ production in EPOS
- remaining difference: $\pi^{\pm}$ & $K^{\pm}$ spectral shapes & diffraction in π- & K-air



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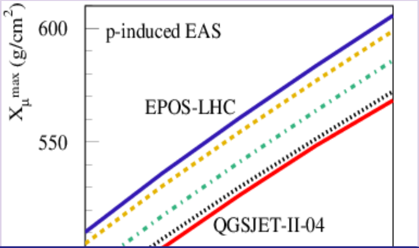
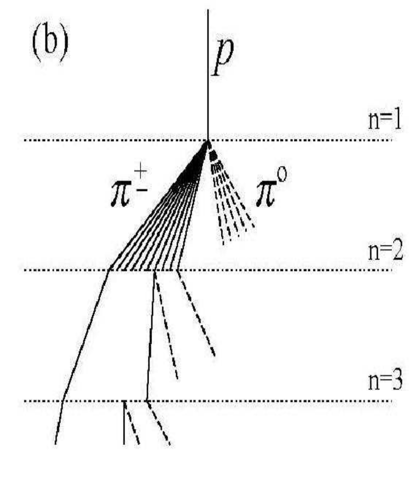


Model-dependence of $X^{\mu}_{\max}$: same features of π-air as for $X_{\max}$

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

Muon component of air showers & PAO muon excess

- NB: N_μ results from a multi-step hadron cascade
  - ~ 1 cascade step per energy decade
- $N_\mu \propto E_0^{\alpha_\mu} = \prod_{i=1}^{\mathrm{int}(\lg E_0)} 10^{\alpha_\mu}$
- each order of magnitude: factor $10^{\alpha_\mu} \simeq 8$ ($\alpha_\mu \simeq 0.9$)



Muon component of air showers & PAO muon excess

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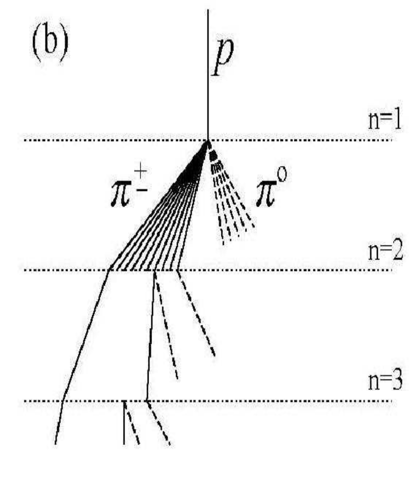

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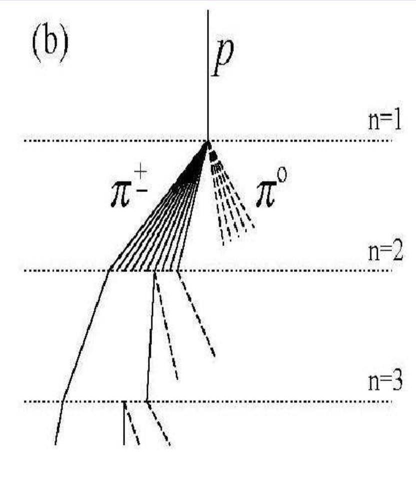


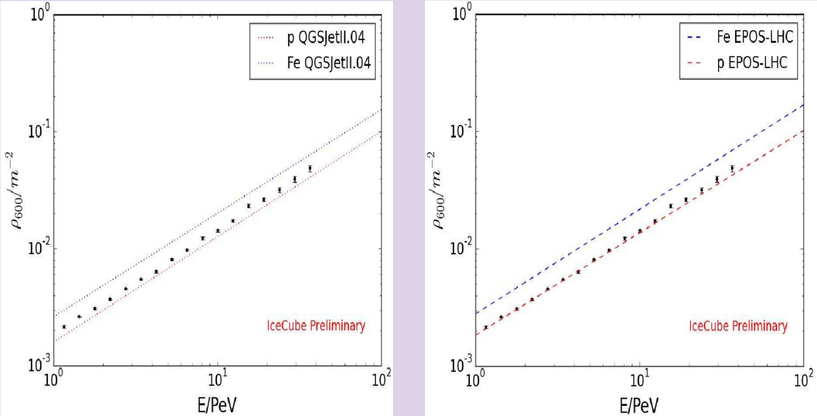
$\Rightarrow$ muon excess will emerge also at lower energies

Muon component of air showers & PAO muon excess

⇒ muon excess will emerge also at lower energies

Problem: muon excess not seen up to 10^{17} eV

E.g., IceCube data on ρ_μ – consistent with primary protons/helium



Muon component of air showers & PAO muon excess

Muon excess produced by 1-2 cascade steps between 10^{17} & 10^{19}?

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

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- proton-air cross section at UH energies: $\sigma^{\rm inel}_{p-{\rm air}} \sim 1/2$ b
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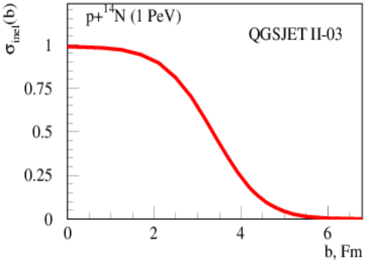
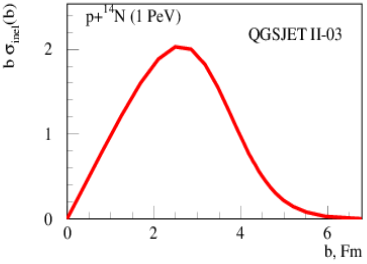
- to be detected by air shower techniques:
  new physics should impact the bulk of interactions
- $\Rightarrow$ to emerge with barn-level cross section
  - presently at LHC: nothing at fb level

Muon component of air showers & PAO muon excess

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 component of air showers & PAO muon excess

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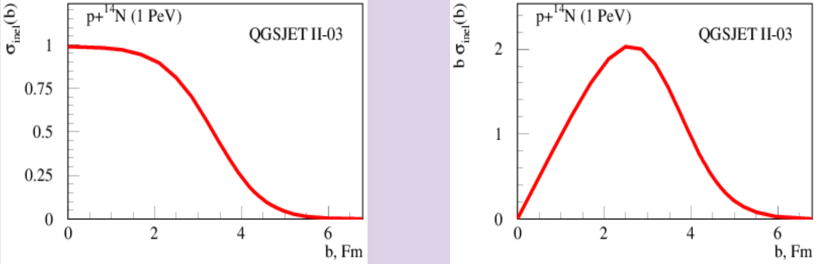


Assume new physics to emerge in 10% of most central collisions

- 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: $\sigma_{\rho_\mu}/\rho_\mu \simeq 10 \div 15\%$)

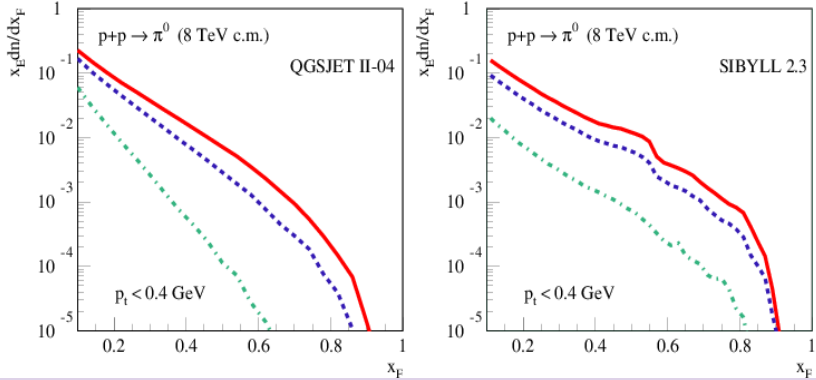
Summary

1. LHC studies of pp collisions constrained interaction models
   - most important for CR physics: $\sigma_{pp}^{\rm tot/el}$ by TOTEM & ATLAS
   - of importance: to resolve the diffraction issue
2. Differences for predicted $K_{p-\rm air}^{\rm inel}$ ($\Rightarrow X_{\rm max}$):
   model assumptions for constituent parton Fock states
   - can be discriminated by combined measurements with central & forward-looking detectors at the LHC
3. Present uncertainties for EAS predictions:
   largely due to the treatment of pion-air interactions
   - can be constrained by $X_{\rm max}^{\mu}$ measurements in CR experiments
4. Present PAO data on $X_{\rm max}^{\mu}$:
   disfavor model features which lead to deep $X_{\rm max}$
5. PAO muon excess implies a higher N_μ at lower energies
   - more exotic options may be discriminated by studying fluctuations of muon density at ground

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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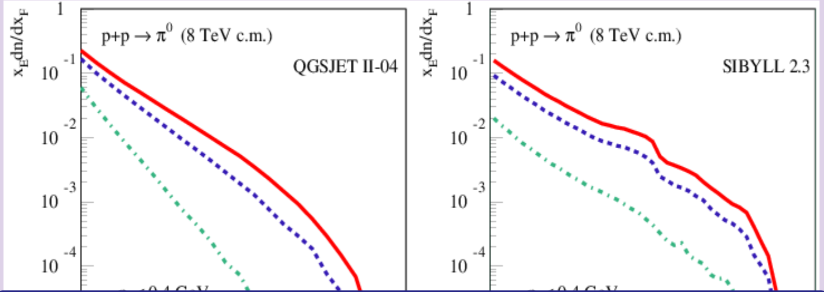


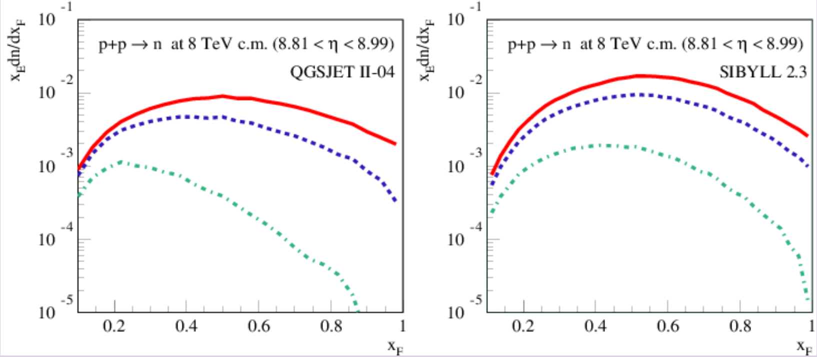
Compare QGSJET-II-04 (left) to SIBYLL 2.3 (right)

- 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