Cosmic Ray Interaction Models: Overview

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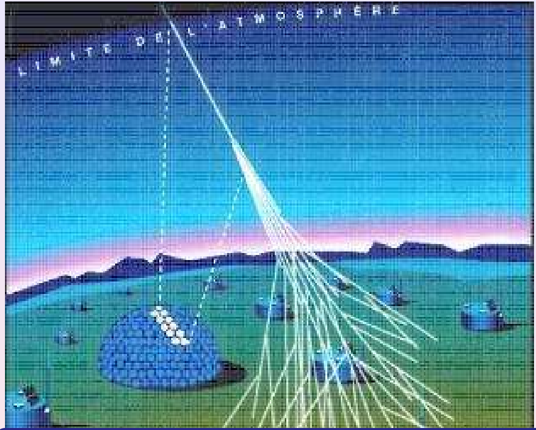
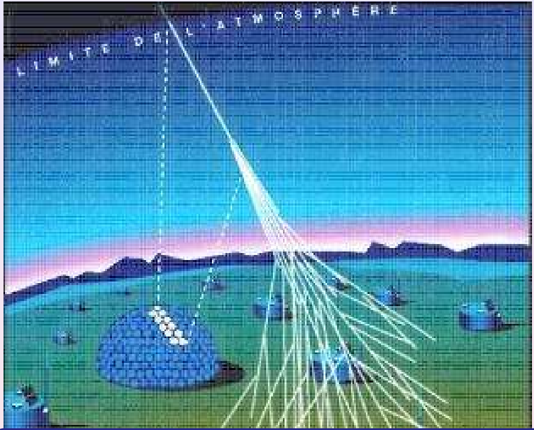
Cosmic ray studies with extensive air shower techniques



ground-based observations (= thick target experiments)

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

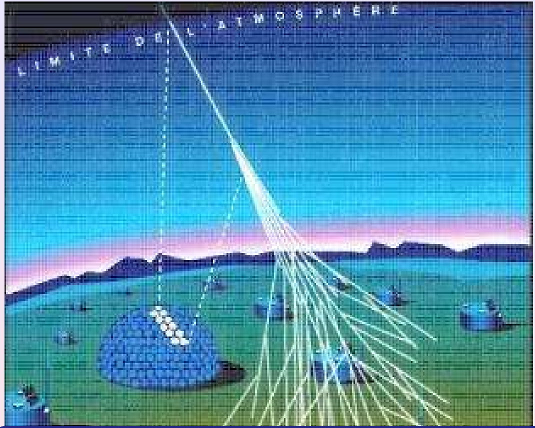
Cosmic ray studies with extensive air shower techniques



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 techniques



CR composition studies – most dependent on interaction models

- e.g. predictions for $X_{\max}$ depend on $\sigma^{\rm inel}_{p-\rm air}$, $\sigma^{\rm diffr}_{p-\rm air}$, ...
- predictions for muon density – on the multiplicity $N^{\rm ch}_{\pi-\rm air}$, ...

Cosmic ray interaction models

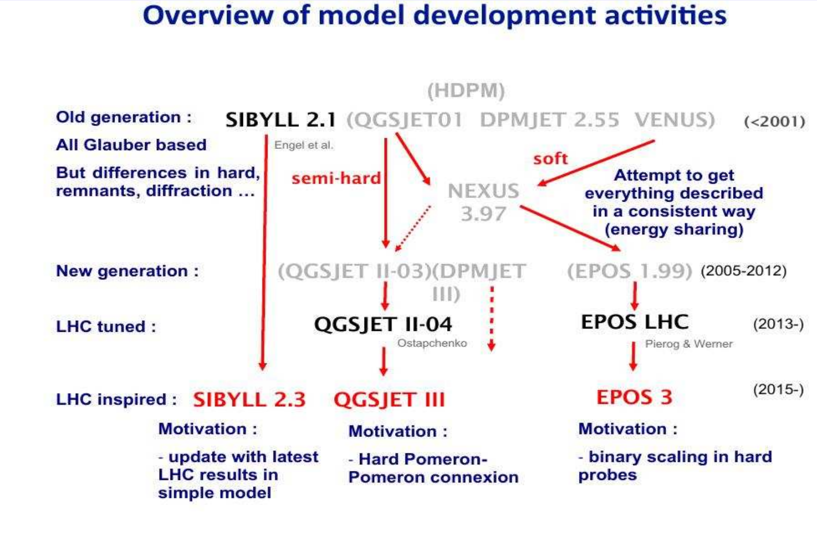
Requirements to models

- predictions for cross sections
- treatment of most general p-air & π-air (K-air) collisions
- of special importance: forward particle production

Most popular models

- EPOS *[Werner, Liu & Pierog, PRC74 (2006) 044902]*
- QGSJET-II *[SO, PRD83 (2011) 014018]*
- SIBYLL *[Ahn, Engel, Gaisser, Lipari & Stanev, PRD80 (2009) 094003]*

Cosmic ray interaction models

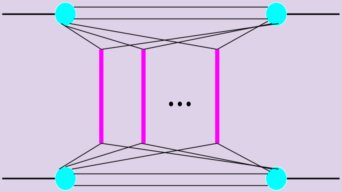


(slide from Tanguy Pierog, ISVHECRI 2014)

Cosmic ray interaction models

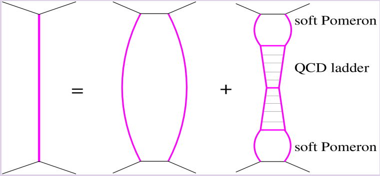
EPOS & QGSJET-II - based on Reggeon Field Theory: Pomerons = 'elementary' cascades

- e.g. elastic amplitude
- requires Pomeron amplitude & Pomeron-hadron vertices



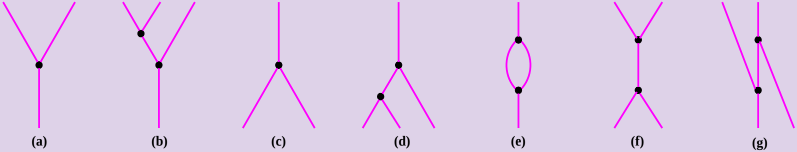
Hard processes included using the 'semihard Pomeron' approach

- soft Pomerons to describe soft (parts of) cascades $(p_t^2 < Q_0^2)$
  - $\Rightarrow$ transverse expansion governed by the Pomeron slope
- DGLAP for hard cascades
- taken together: 'general Pomeron'



Cosmic ray interaction models

QGSJET-II: full resummation for Pomeron-Pomeron interactions (scattering of partons off the proj./target hadrons & off each other)

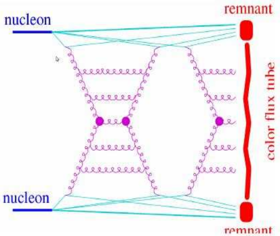


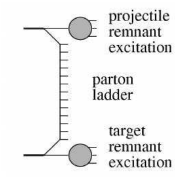
thick lines = Pomerons = 'elementary' parton cascades

- partial cross sections for various final states (including diffractive): from unitarity cuts of elastic diagrams
  - $\Rightarrow$ no additional free parameters (e.g. for diffraction)
- s-channel unitarity satisfied: $\sum_{\rm graphs,cuts} \bar{\chi}^{\rm cut} = 2 \sum_{\rm graphs} \chi^{\rm uncut}$
- positive-definite cross sections for all final states $\Rightarrow$ MC generation
- no additional free parameters for hA & AA collisions

EPOS: impact on energy sharing & collective effects

The EPOS Model





EPOS is a parton model, with many binary parton-parton interactions, each one creating a parton ladder.

- Energy-sharing : for cross section calculation AND particle production
- Parton Multiple scattering
- Outshell remnants
- Screening and shadowing via unitarization and splitting
- Collective effects for dense systems

EPOS can be used for minimum bias hadronic interaction generation (h-p to A-B) from 100 GeV (lab) to 1000 TeV (cms) : used for air shower !

[from T. Pierog]

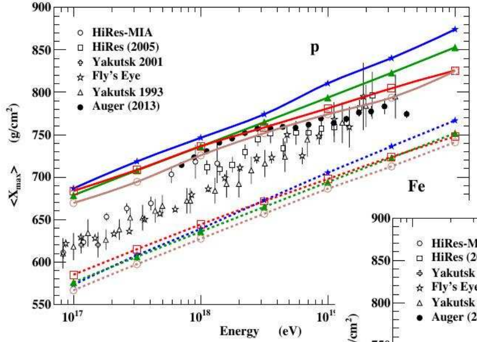
Cosmic ray interaction models

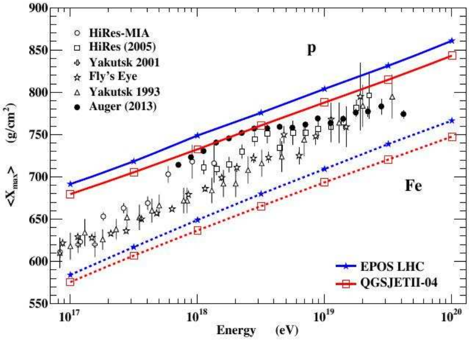
SIBYLL: based on the minijet approach

- pretty similar to many models used at colliders
- energy dependence - driven by (mini-)jet production
- standard eikonalization of inclusive jet cross section
  - e.g. $n_{pp}^{\rm jet}(s,b) = \sigma_{pp}^{\rm jet}(s,p_t^{\rm cut})\,A(b)$ - average number of jet pairs for given b; $A(b)$ - parton overlap function
- multiple scattering:
  mostly impacts particle production at central rapidities

LHC data: impact on CR interaction models

Start of LHC triggered model updates



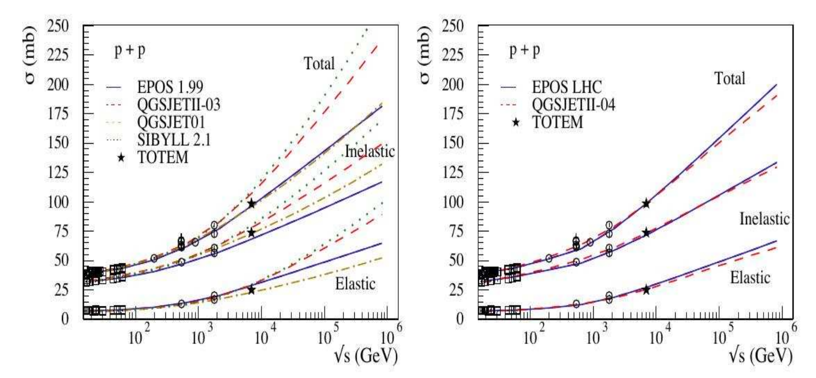


New models favour interpretation as heavier composition than before

(Pierog 2013, 2014)

LHC data: impact on CR interaction models

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

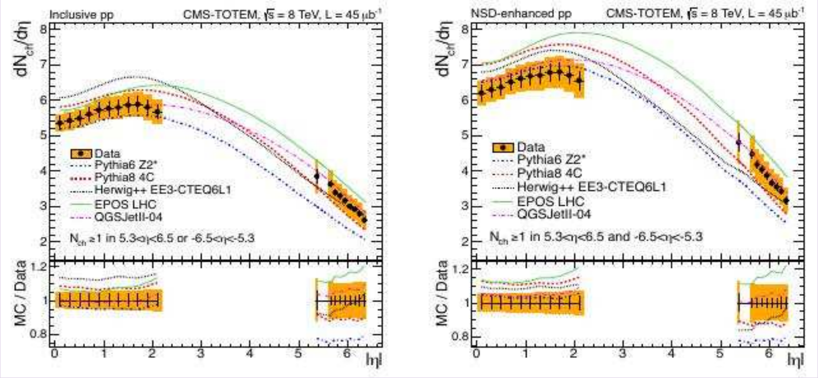


[from R. Engel]

- important: results of ATLAS ALFA - consistent with TOTEM

LHC data: impact on CR interaction models

Combined CMS-TOTEM analysis of $dN_{\rm ch}/d\eta$



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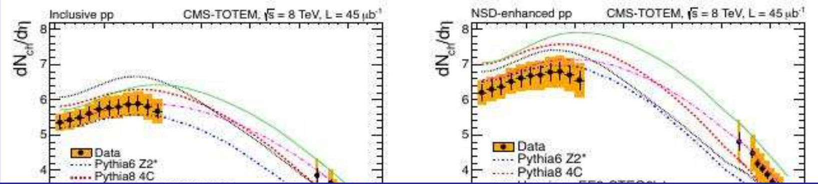
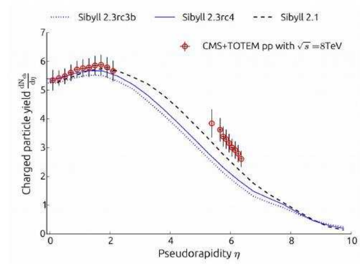
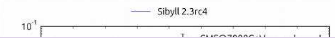


Remarkable: LHC data constrain forward production mechanisms



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

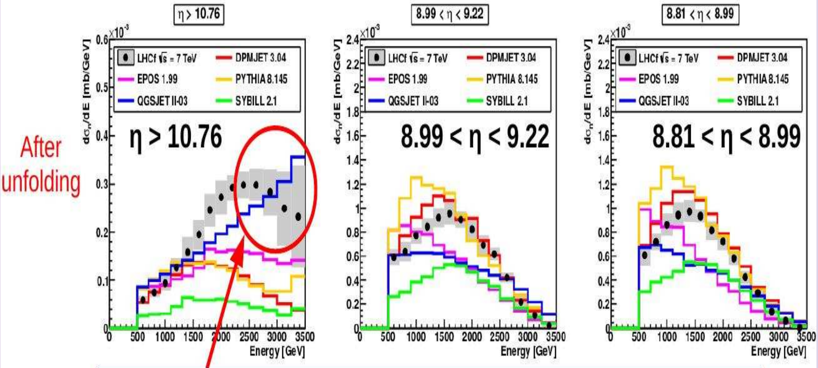
  Number of minijets very high
  → saturation effects missing



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

Forward production: neutrons

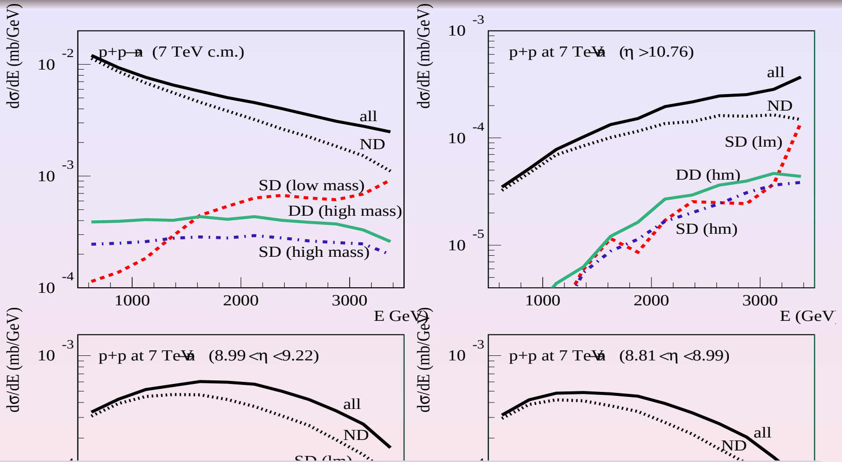
LHCf data at 7 TeV c.m. *[talk of A. Tiberio at HSZD-2015]*



- Large amount of high energy neutrons for η > 10.76 (only predicted by QGSJET)
  → small inelasticity in the very forward region

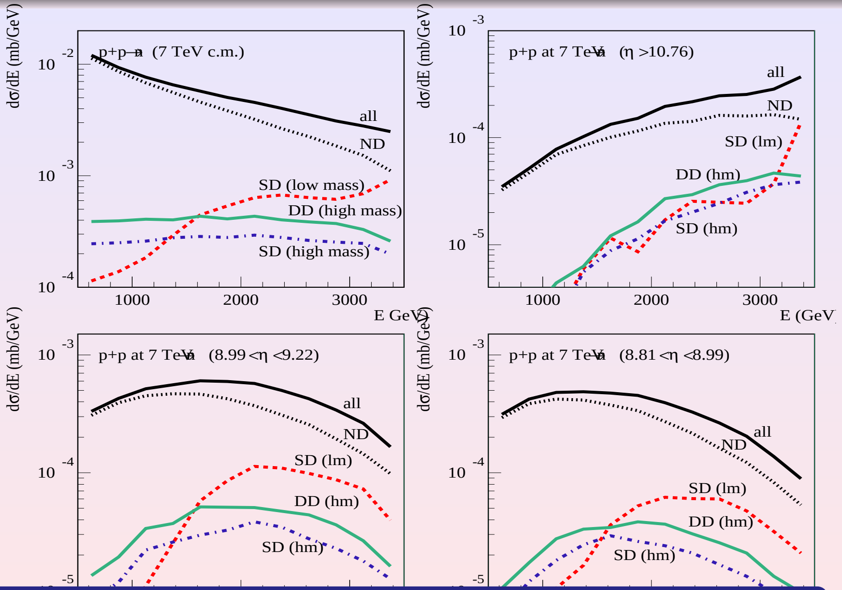
How to understand the results?

Forward neutron spectra in LHCF: different contributions



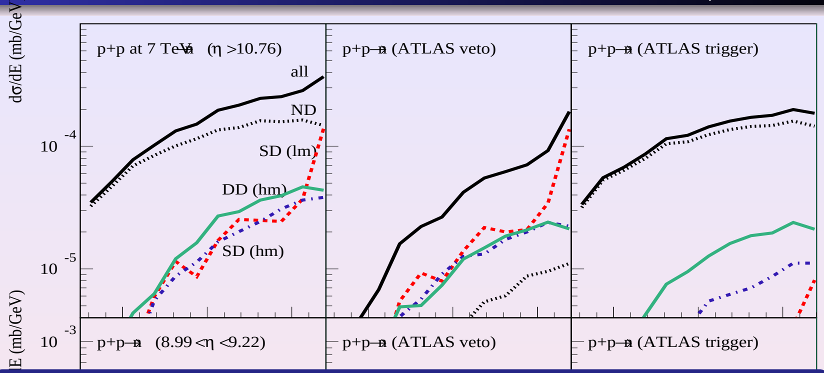
- low mass projectile diffr.: up to 50% contribution at $x_F \to 1$
- main contribution: nondiffractive collisions
  - for large x_F - dominated by pion exchange mechanism ($\mathbb{RRP}$-contribution) *[Kopeliovich et al., PRD91 (2015) 054030]*

Forward neutron spectra in LHCF: different contributions



how to separate different contributions experimentally?

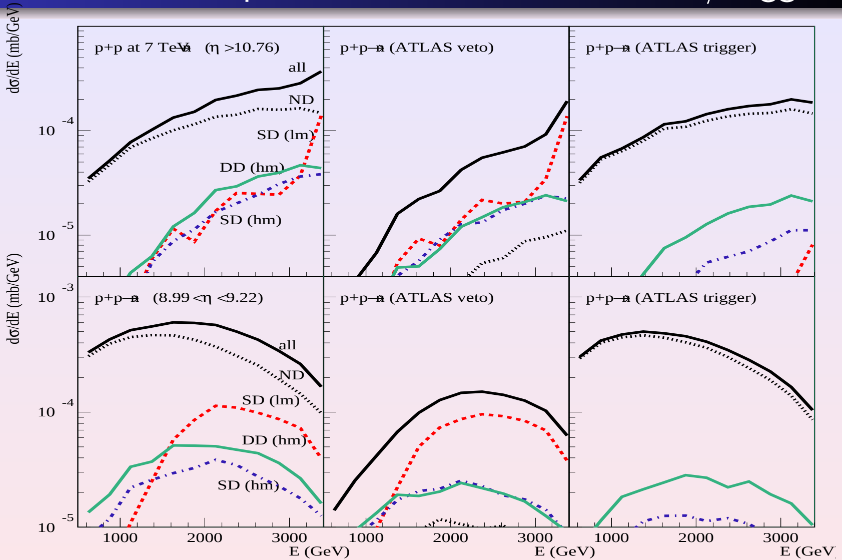
Forward neutron spectra: LHCF + ATLAS veto/trigger



ATLAS to veto/trigger charged particles ($p_t > 0.5$ GeV, $|\eta| < 2.5$)

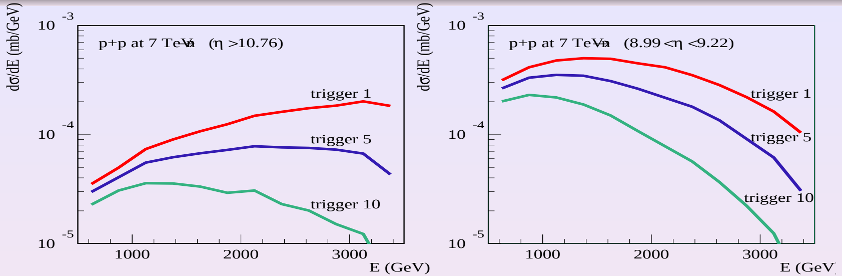
- veto removes ND almost completely!
  - $\Rightarrow$ allows a clean detection of low mass diffraction (impossible with other LHC detectors)
- triggering activity in ATLAS removes most of diffraction
  - $\Rightarrow$ neutron spectra measurement in ND events

Forward neutron spectra: LHCF + ATLAS veto/trigger



Combination of the 3 measurements ⇒ separation of the different components!

'Centrality' dependence in pp: test of pp to p-air transition

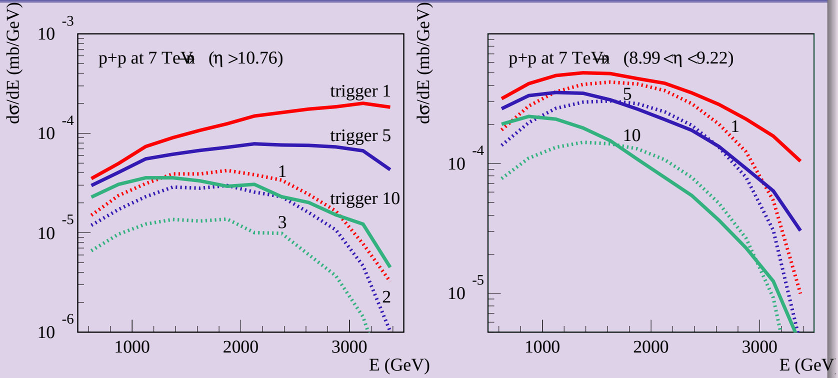


Require at least 1, 5, 10 charged particles in ATLAS ($p_t > 0.5$ GeV)

- enhanced multiple scattering
- ⇒ strong suppression of forward neutron production
  - pion exchange goes away
  - higher energy loss by the 'remnant' state
- important test for CR applications:
  measure of the 'inelasticity' in ND collisions
- NB: ND $p-$air collision - like more 'central' pp interaction

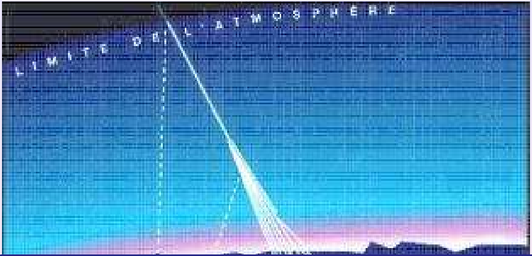
'Centrality' dependence in *pp*: test of *pp* to *p*-air transition

Compare QGSJET-II-04 (solid lines) to SIBYLL 2.1 (dotted)



- order of magnitude differences
- nearly same spectral shape in SIBYLL for all the triggers!
  (forward spectra decoupled from central production)
- ⇒ important discriminator between models

Model predictions for shower maximum: uncertainties



$X_{\max}$ – best suited for CR composition studies

- 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 (notably by TOTEM, ATLAS ALFA)
  - $\sigma^{\rm diffr}_{pp}$ impacts recalculation from pp to pA (AA)
    - $\sigma^{\rm inel}_{p-{\rm air}}$ – due to inelastic screening (correlated with $\sigma^{\rm diffr}_{pp}$)
    - $K^{\rm inel}_{p-{\rm air}}$ – due to small 'inelasticity' of diffractive collisions

Impact of uncertainties of $\sigma_{pp}^{\rm SD}$ on $X_{\max}$ *[SO, PRD89 (2014)]*

- Presently: serious tension between CMS & TOTEM concerning diffraction rate in pp

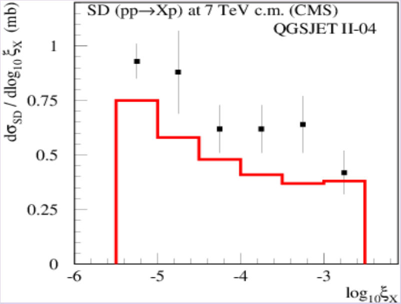
	TOTEM	CMS
M_X range, GeV	$7-350$	$12-394$
$\sigma_{pp}^{\rm SD}(\Delta M_X)$, mb	$\simeq 3.3$	4.3 ± 0.6
$\frac{d\sigma_{pp}^{\rm SD}}{dy_{\rm gap}}$, mb	0.42	0.62

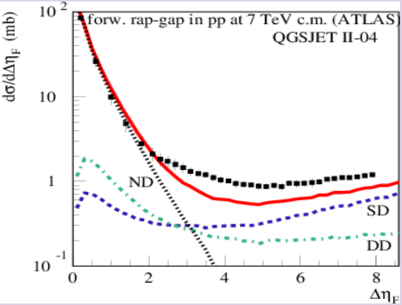
Impact of uncertainties of σ_{pp}^{SD} on $X_{\max}$ [SO, PRD89 (2014)]

E.g. σ_{pp}^{SD} of QGSJET-II agrees with TOTEM (M_X-shape and rate)

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	$\simeq 1.8$	$\simeq 3.3$	$\simeq 1.4$
QGSJET-II-04	3.9	7.2	1.9	3.9	1.5

Predicted M_X-shape agrees with SD (CMS) & rap-gaps (ATLAS)





- but: rates of SD & rap-gaps - $30 - 40\%$ below CMS & ATLAS

Impact of uncertainties of σ_{pp}^{SD} on $X_{\max}$ *[SO, PRD89 (2014)]*

- Presently: serious tension between CMS & TOTEM concerning diffraction rate in pp

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

- $\Rightarrow$ may be regarded as a characteristic uncertainty for σ_{pp}^{SD}
  - impact on $X_{\max}$ & RMS($X_{\max}$)?

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

- SD+: increased high mass diffraction (HMD) (larger $r_{3\mathbb{P}}$) – 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

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

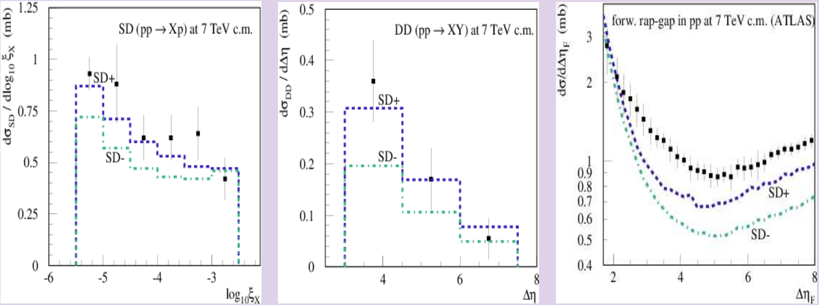
M_X range, GeV	< 3.4	$3.4-1100$	$3.4-7$	$7-350$	$350-1100$
TOTEM	2.62 ± 2.17	6.5 ± 1.3	$\simeq 1.8$	$\simeq 3.3$	$\simeq 1.4$
option SD+	3.2	8.2	1.8	4.7	1.7
option SD-	2.6	7.2	1.6	3.9	1.7

CMS ($M_X = 12-394$ GeV)	option SD+	option SD-
4.3 ± 0.6	3.7	3.1

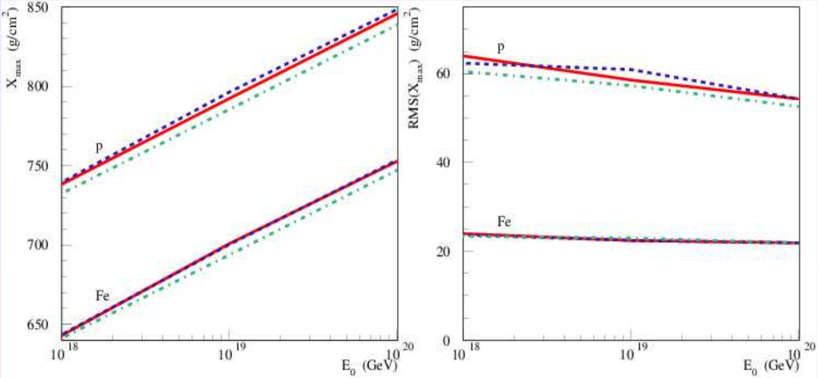
Two alternative model versions (tunes): SD+ & SD-

- SD+: increased high mass diffraction (HMD) (larger $r_{3\mathbb{P}}$) – 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

Comparison with differential SD & DD (CMS) & rap-gap (ATLAS)



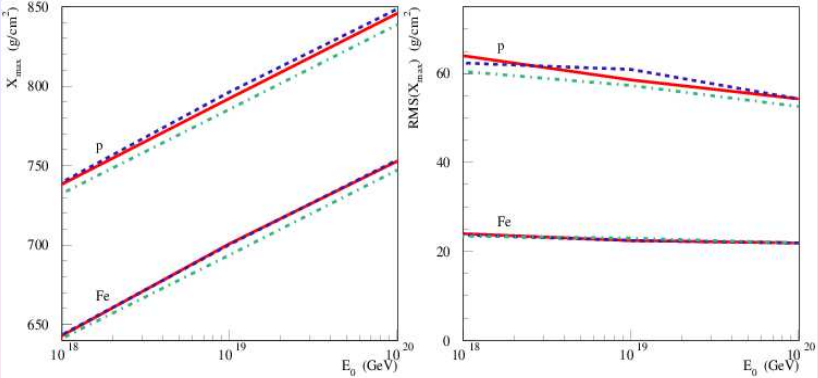
Impact on $X_{\max}$ & RMS($X_{\max}$)



Option SD-: smaller low mass diffraction

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

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

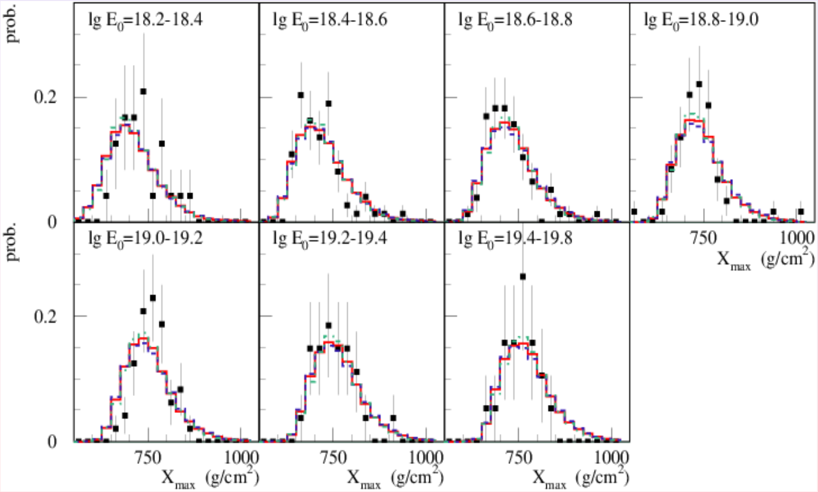


Option SD+: larger high mass diffraction

- 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}): $< 3\,\mathrm{g/cm^2}$

Potential impact on CR composition studies

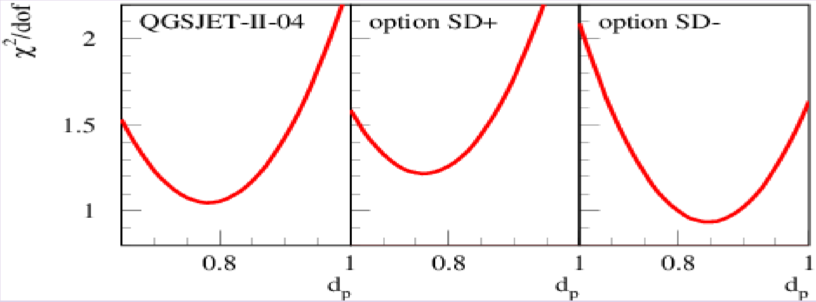
- Fit of Telescope Array data by p+Fe CR composition:
  - good fit quality for all the 3 interaction models
  - but: for different CR compositions



Potential impact on CR composition studies

- Fit of Telescope Array data by p+Fe CR composition:
  - good fit quality for all the 3 interaction models
  - but: for different CR compositions

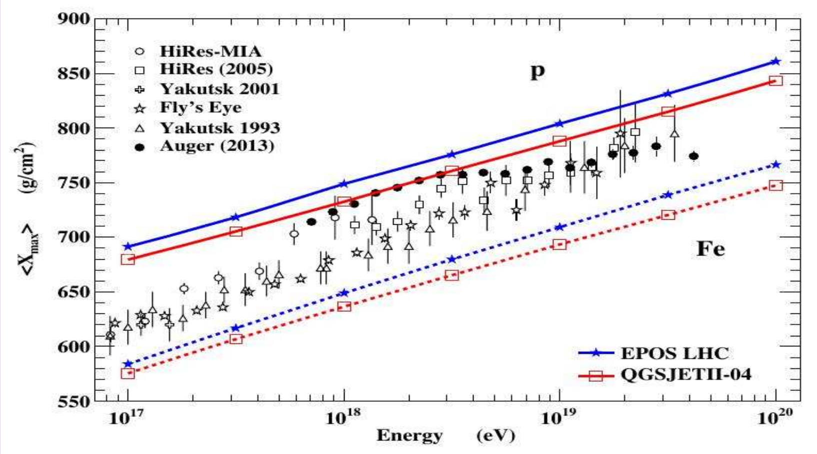
Fit quality for different proton abundances d_p ($d_{\rm Fe} = 1 - d_p$)



- option SD+: pure proton composition excluded
- option SD-: almost pure proton composition is o.k. (scenario favored by some astrophysical models)

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

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

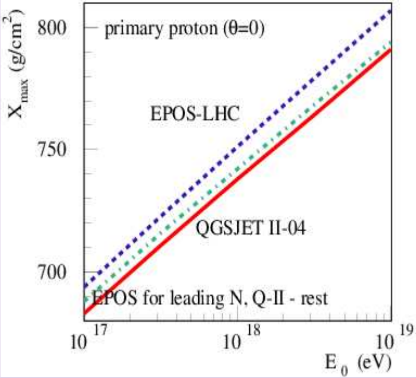


[plot from T. Pierog]

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

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

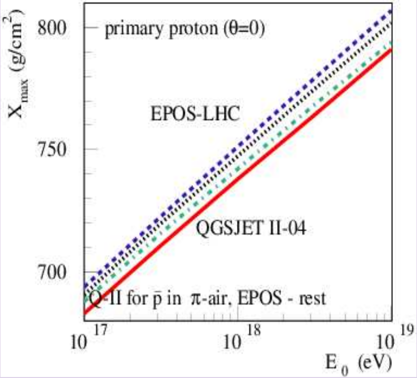
- and construct 'mixture models'
- use EPOS spectrum for leading nucleon in 1st interaction and QGSJET-II for the rest
- $\Delta X_{\max} \simeq 5$ g/cm^2 - in agreement with above



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

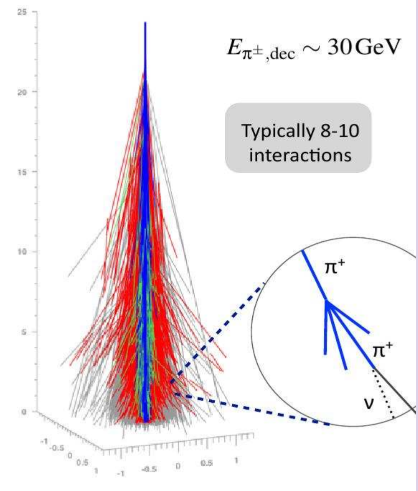
Let us compare $X_{\max}$ of EPOS-LHC & QGSJET-II-04

- EPOS for leading nucleon, QGSJET-II - rest
- $\Delta X_{\max} \simeq 5$ g/cm^2 - in agreement with above
- now from the other side: QGSJET-II spectra for $p, \bar{p}, n, \bar{n}$ production in $\pi - \text{air}$, $K - \text{air}$ and EPOS for all the rest
- $\Delta X_{\max} \simeq 4$ g/cm^2
- remaining difference: partly due to harder pion spectra in $p - \text{air}$



EAS muon content N_μ: model predictions & uncertainties

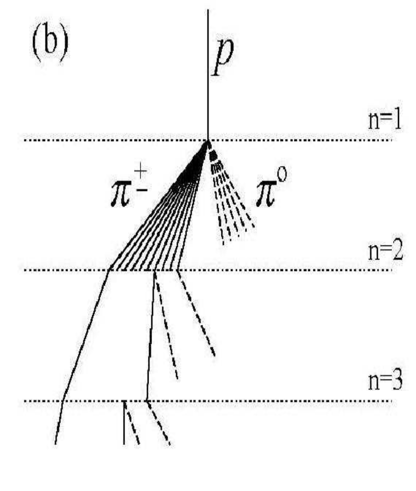
- shower N_μ: results from multi-step hadron cascade
  - ~ 1 cascade step per energy decade
- which $\pi-$air interactions most important?



[from R. Engel]

EAS muon content N_μ: model predictions & uncertainties

- multi-step hadron cascade
  - ~ 1 cascade step per energy decade
- which $\pi - \mathrm{air}$ interactions most important?
- $N_\mu \propto E_0^{\alpha_\mu} = \prod_{i=1}^{\mathrm{int}(\lg E_0)} 10^{\alpha_\mu}$
- each order of magnitude: factor $10^{\alpha_\mu} \simeq 8$ for N_μ ($\alpha_\mu \simeq 0.9$)

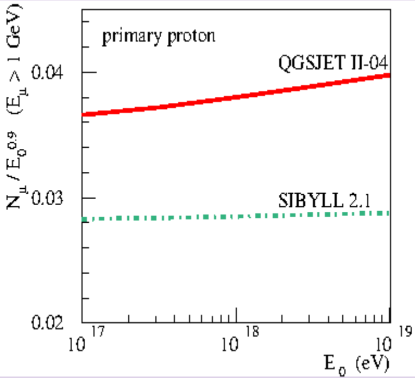


[from J. Matthews]

EAS muon content N_μ: model predictions & uncertainties

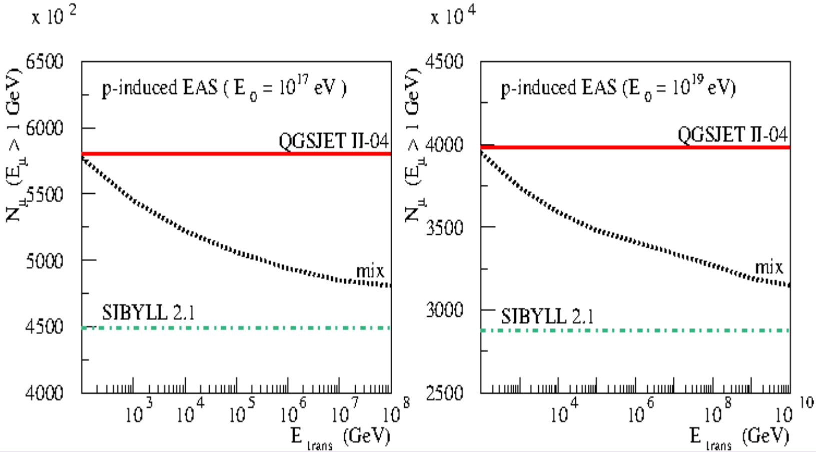
E.g. let us study the difference in N_μ for SIBYLL & QGSJET-II

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



EAS muon content N_μ: model predictions & uncertainties

The difference - mostly due to $\pi -$ air interactions above 1 TeV!



Present model differences both for N_μ & $X_{\max}$: largely due to the treatment of $\pi -$air interactions

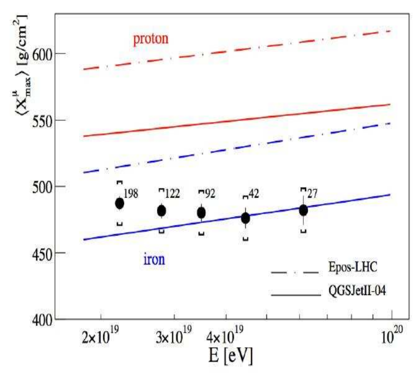
How to constrain?

- new πp (πA) experiments at high energies (LHC in fixed target mode?)
- use fixed target πp & πA data to test the models (relevant physics already there)
- constrain physics meachanisms in models using pp & pA data from LHC
- model self-consistency checks with air shower data

Testing models with air shower data

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

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

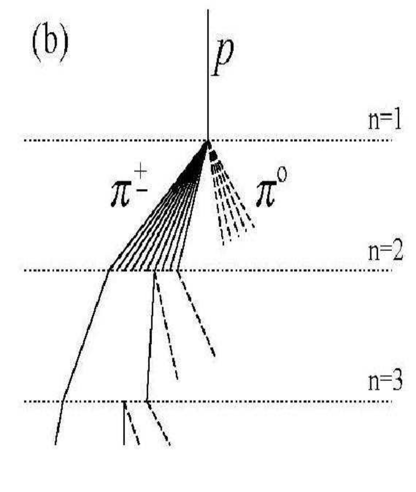


[from M. Roth]

Testing models with air shower data

1) Hardness of pion spectra in $\pi - \mathrm{air}$

- pion decay probability: $p_{\mathrm{decay}} \propto E_\pi^{\mathrm{crit}} / E_\pi / X$
- X_{max}^{μ}: where $p_{\mathrm{decay}} > p_{\mathrm{inter}}$

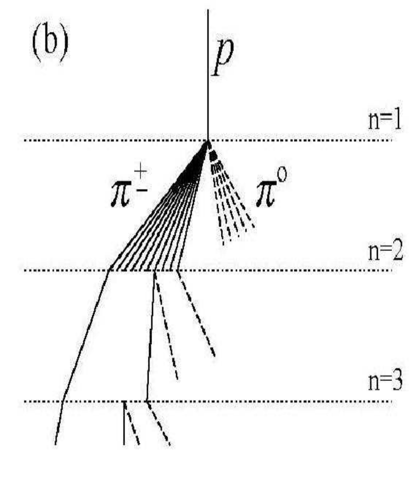


[from J. Matthews]

Testing models with air shower data

1) Hardness of pion spectra in $\pi - \mathrm{air}$

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

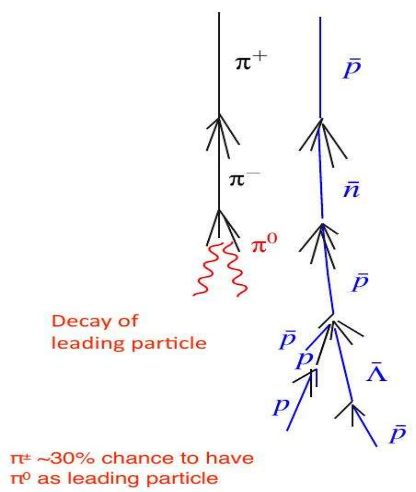


[from J. Matthews]

Testing models with air shower data

2) Copious production of (anti-)nucleons

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

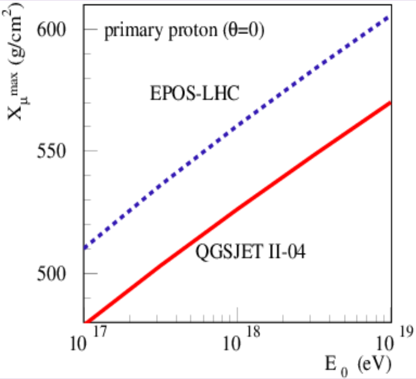


[from R. Engel]

Testing models with air shower data

Let us compare $X^{\mu}_{\max}$ of EPOS-LHC & QGSJET-II-04

- and construct 'mixture models'



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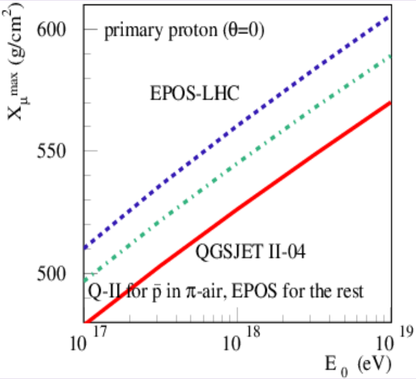
Let us compare $X^{\mu}_{\max}$ of EPOS-LHC & QGSJET-II-04

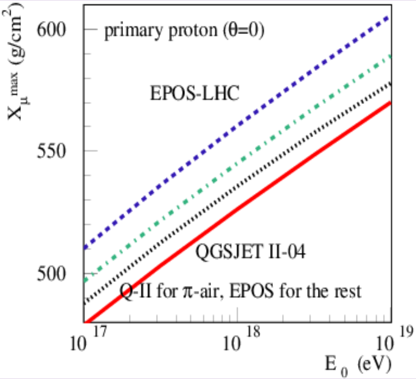
- and construct 'mixture models'
- use QGSJET-II spectra for $p, \bar{p}, n, \bar{n}$ production in $\pi - \text{air}$, $K - \text{air}$ and EPOS for all the rest



Testing models with air shower data

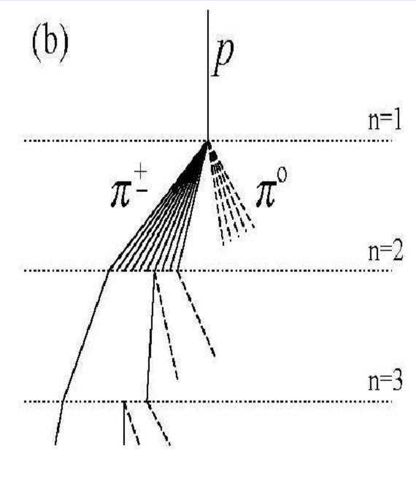
Let us compare $X_{\max}^{\mu}$ of EPOS-LHC & QGSJET-II-04

- and construct 'mixture models'
- use QGSJET-II spectra for $p, \bar{p}, n, \bar{n}$ production in $\pi-$air, $K-$air and EPOS for all the rest
- now QGSJET-II for all $\pi-$air, $K-$air interact. and EPOS for all the rest
- the two effects explain major part of the difference for $X_{\max}^{\mu}$



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 $x_F < 0.1$
  - $\Rightarrow$ just 1 cascade step between E_A & E_B



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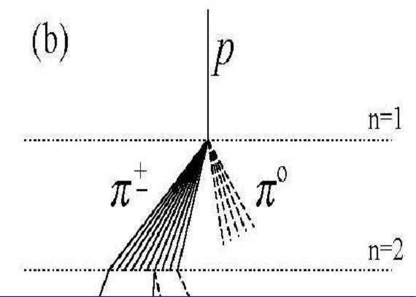


⇒ Muon excess has to be produced by primary CR interactions

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

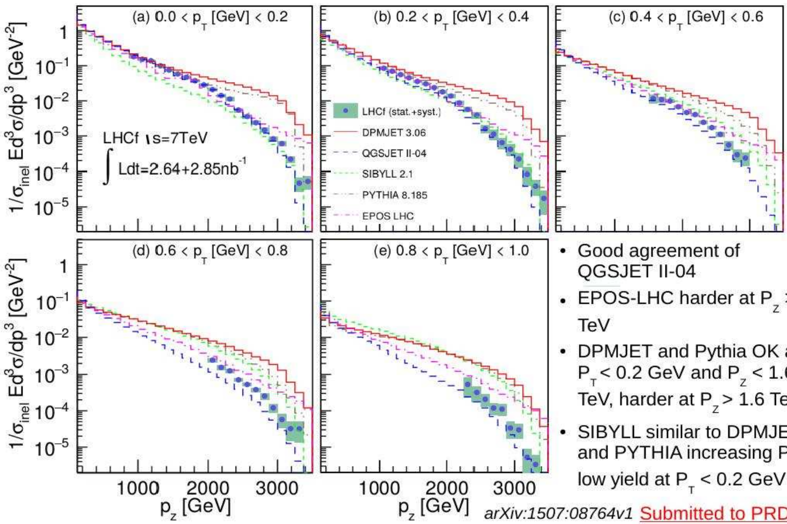
Prospects for seeing new physics in CR air showers?

- 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

Extra slides

Forward production: π^0

LHCf data at 7 TeV c.m. *[talk of A. Tiberio at HSZD-2015]*



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

arXiv:1507:08764v1 Submitted to PRD

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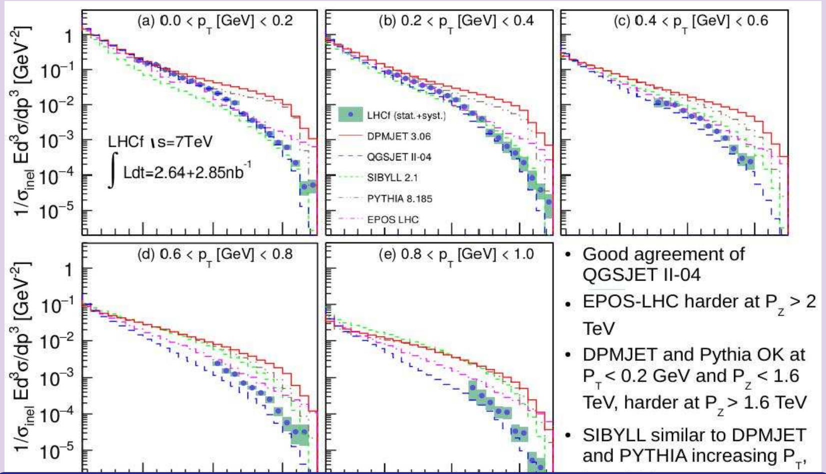
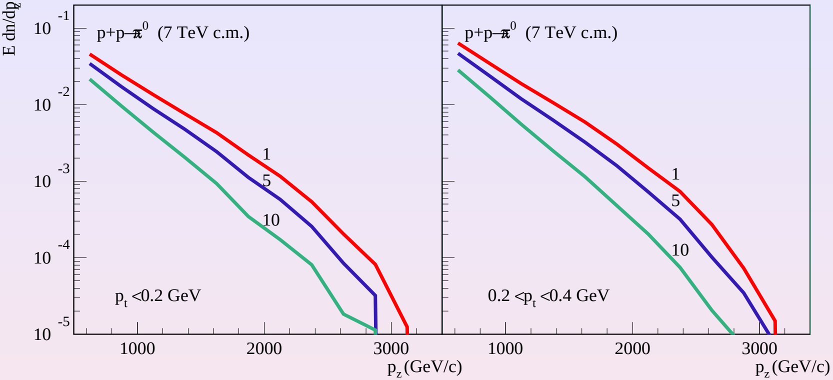


How the spectra should evolve from pp to p-air?

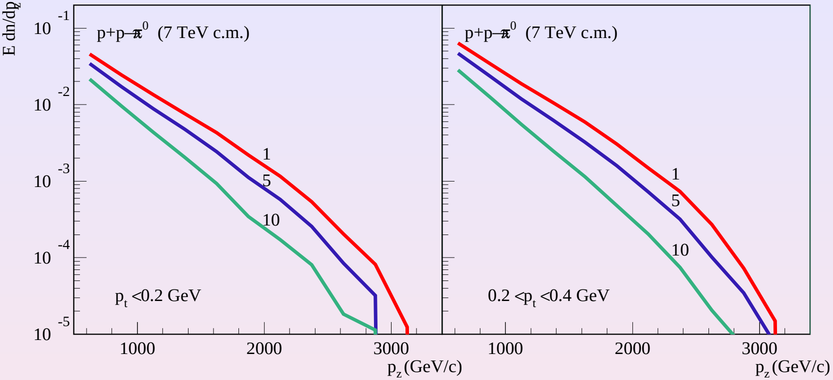
- NB: forward spectra of $\pi^{\pm}$ - of importance for $X^{\mu}_{\max}$!

'Centrality' dependence as a test for pp to p-air transition



- increasing 'centrality' of pp collisions by ATLAS triggers:
  - $\Rightarrow$ enhanced multiple scattering
  - $\Rightarrow$ softer pion spectra
  - clear violation of the limiting fragmentation
- NB: same mechanism for violation of the Feynman scaling (increase of multiple scattering with energy)

'Centrality' dependence as a test for *pp* to *p*-air transition



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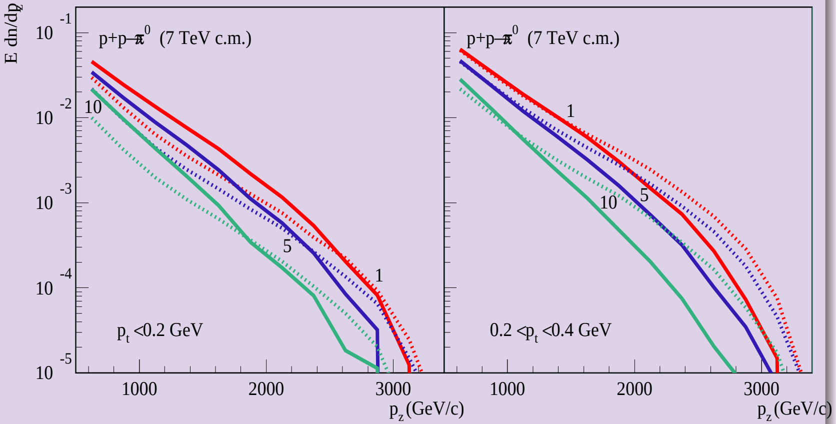
Compare QGSJET-II-04 (solid lines) to SIBYLL 2.1 (dotted)



- almost perfect limiting fragmentation in SIBYLL
- related: nearly perfect Feynman scaling in that model
- NB: TOTEM & CMS may test this with charged hadrons

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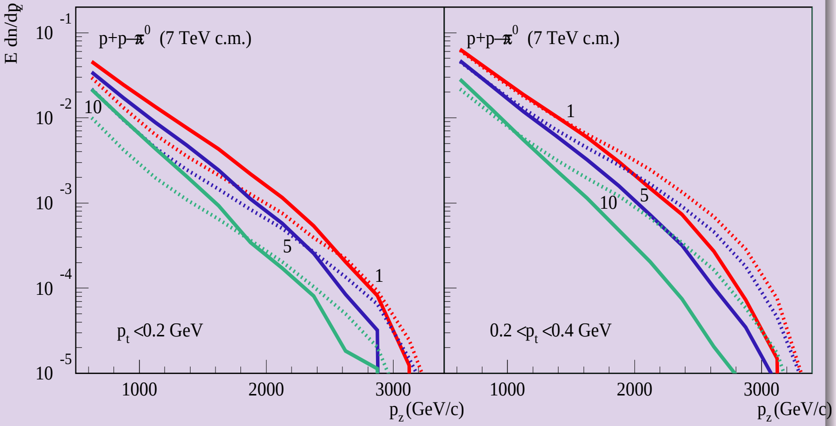

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