High energy interactions of CRs: a view on the UHECR composition

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Kozma Prutkov (19th century)

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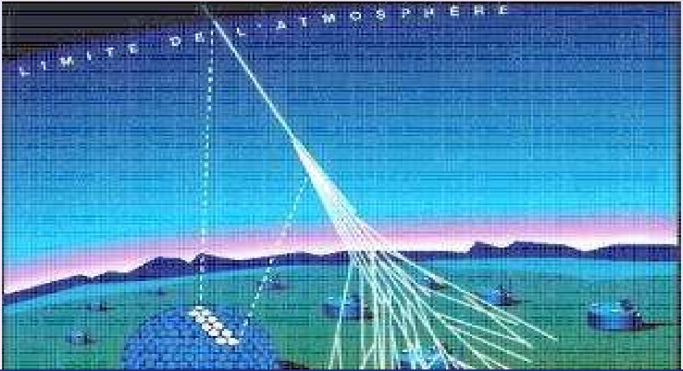
- The most of what follows has been discussed previously
- One can't prove that a phenomenological model is correct
- Therefore, I'll concentrate on things which are either obviously wrong or likely wrong...

High energy CR studies: extensive air shower techniques



CR composition studies – most dependent on interaction models

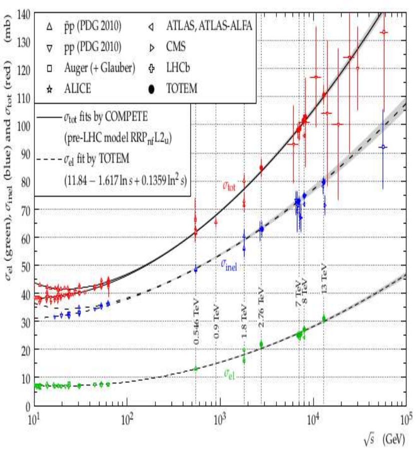
- e.g. predictions for $X_{\max}$: on the properties of the primary particle interaction ($\sigma^{\text{inel}}_{p-\text{air}}$, forward particle spectra)
  - $\Rightarrow$ most relevant to LHC studies of pp collisions
- predictions for muon density: on secondary particle interactions (cascade multiplication); mostly on $N^{\text{ch}}_{\pi-\text{air}}$
  - $\Rightarrow$ small potential influence of ‘new physics’

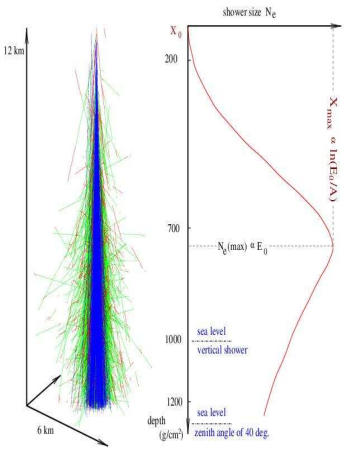
Cosmic ray interaction models

1. QGSJET-II-04 *[SO, 2011]*
   - theoretically most advanced: e.g. microscopic treatment of nonlinear effects (Pomeron-Pomeron interaction diagrams)
   - $\Rightarrow$ strong predictive power (minimal number of parameters)
2. EPOS-LHC *[Pierog, Karpenko, Katzy, Yatsenko & Werner, 2015]*
   - 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)
3. SIBYLL-2.3 *[Riehn, Engel, Fedynitch, Gaisser & Stanev, 2015]*
   - relatively simple ('minijet' approach)
   - differs from QGSJET-II & EPOS in many important aspects
   - has similarities to models used at LHC (e.g. PYTHIA)

Of highest importance: measurements of $\sigma_{pp}^{tot/el}$ at LHC

- allow one to calculate $\sigma_{p/A-\mathrm{air}}^{\mathrm{inel}}$ (Glauber-Gribov approach)
- $\sigma_{p/A-\mathrm{air}}^{\mathrm{inel}} \Rightarrow$ position of 1st interaction of the primary particle
  - $\Rightarrow$ impacts all EAS observables, notably, $X_{\max}$





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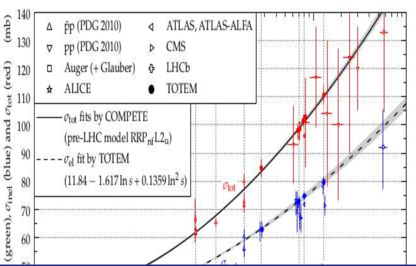

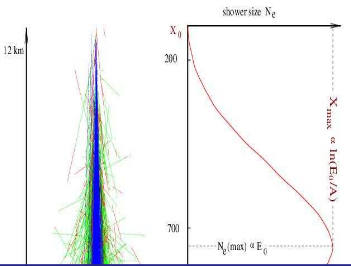

In principle, calculating $\sigma_{p/A-\mathrm{air}}^{\mathrm{inel}}$ involves other inputs

- e.g. depends on the transverse profile of the proton
- it is also correlated with the treatment of diffraction ('inelastic screening' effect)
- yet the decisive effect comes from $\sigma_{pp}^{\mathrm{inel}}$

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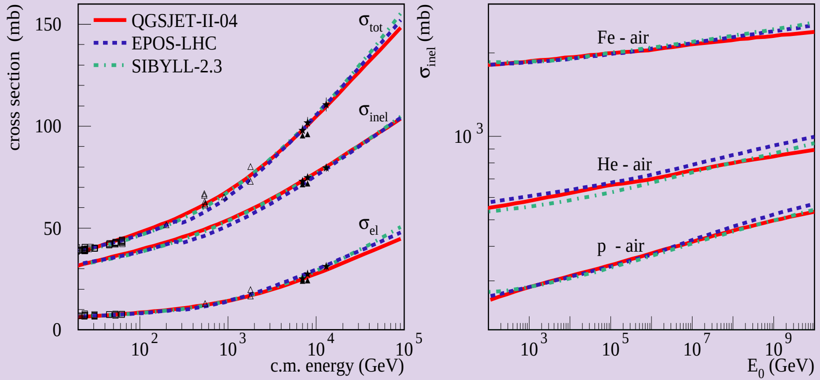
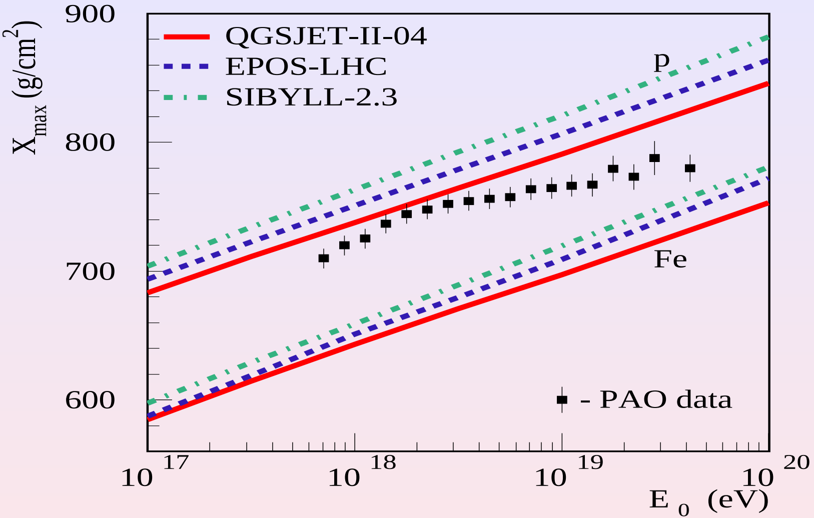
Model calibration to LHC data $\Rightarrow$ similar results for $\sigma_{p/A-\mathrm{air}}^{\mathrm{inel}}$

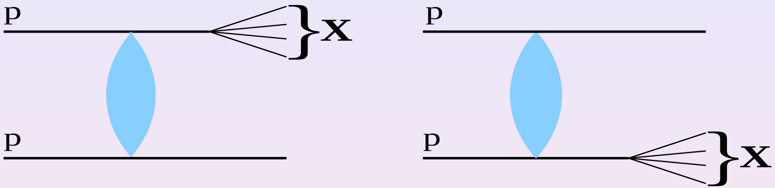


Model predictions for $X_{\max}$: huge differences



Predicted $X_{\max}$ depends also on the rate of inelastic diffraction & the 'inelasticity' $K^{\rm inel}_{p-{\rm air}}$; also on the treatment of $\pi-$air collisions

Inelastic diffraction: LHC results & QGSJET-II-04



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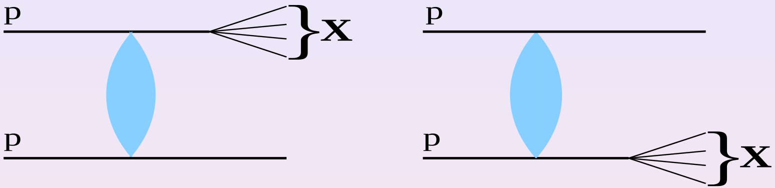

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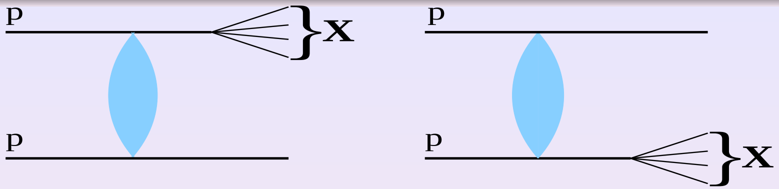

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So far: tension between CMS & TOTEM concerning $\sigma_{pp}^{\rm SD}$

	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

- CMS measured $\simeq 50\%$ higher diffraction rate than TOTEM!

Inelastic diffraction: LHC results & QGSJET-II-04

QGSJET-II-04 vrs. TOTEM: agreement of M_X-shape and SD-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

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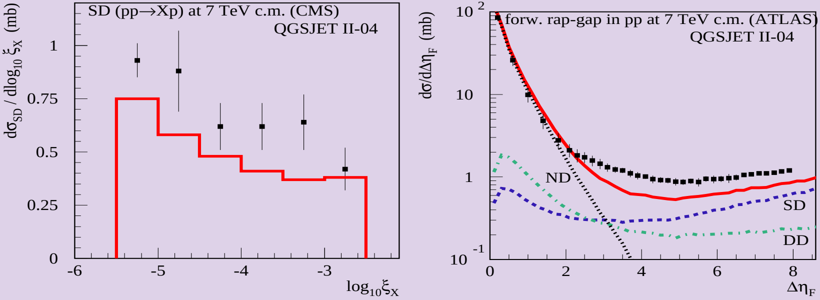
Predicted M_X-shape agrees with SD (CMS) & rap-gaps (ATLAS)



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

Impact of uncertainties of $\sigma_{pp}^{\mathrm{SD}}$ *[SO, PRD 89 (2014) 074009]*

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

- SD+: higher diffraction rate – to approach CMS results
- SD-: smaller low mass diffraction (by 30%) – to fit TOTEM
- similar $\sigma_{pp}^{\mathrm{tot/el}}$ & central particle production in both cases

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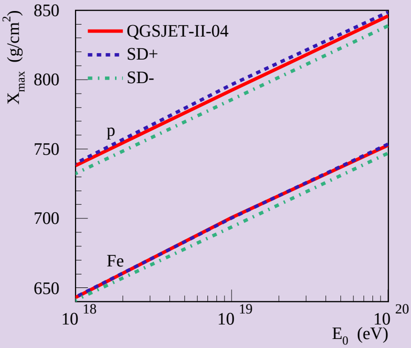
Impact of uncertainties of $\sigma_{pp}^{\mathrm{diffr}}$ on X_{max}



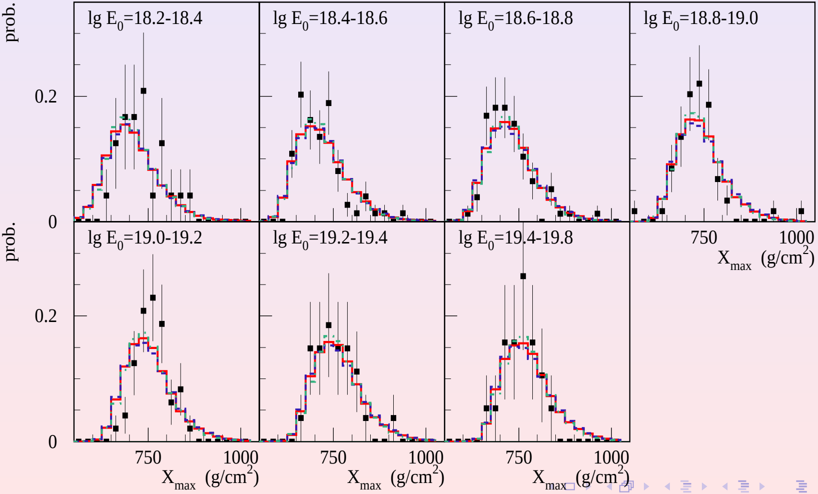
smaller diffraction rate:

- smaller inelastic screening $\Rightarrow$ larger $\sigma_{p-\mathrm{air}}^{\mathrm{inel}}$
- smaller diffraction for p-air $\Rightarrow$ larger $K_{p-\mathrm{air}}^{\mathrm{inel}}$, $N_{p-\mathrm{air}}^{\mathrm{ch}}$
- $\Rightarrow$ smaller X_{max} (all effects work in the same direction)

higher diffraction $\Rightarrow$ opposite

Impact on CR composition: interpretation of TA data

- fit TA data by p+Fe CR composition: SD+ & SD- tunes
  - good fit quality for both tunes (and for original QGSJET-II-04)
  - however: for different CR compositions



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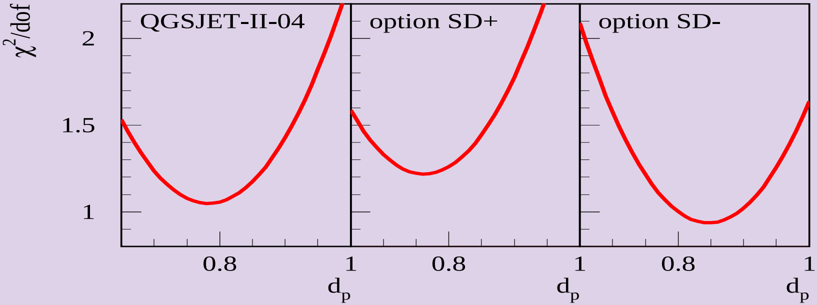
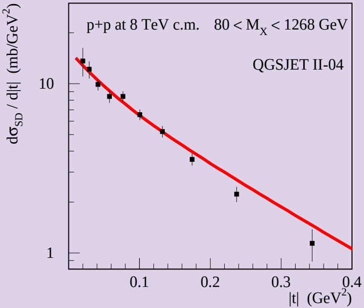
Fit quality for different proton abundances d_p ($d_{\rm Fe} = 1 - d_p$)



- option SD-: UHECRs are mostly protons (NB: 'dip' model)
- option SD+: pure proton composition excluded

Inelastic diffraction: moment of truth

ATLAS measurement (Roman Pots) of $d\sigma_{pp}^{SD}/dt$ vrs. QGSJET-II-04



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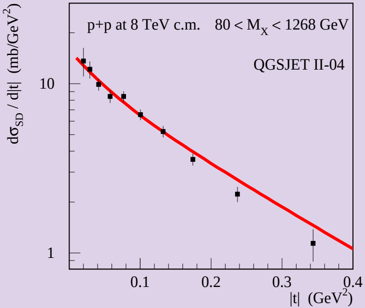

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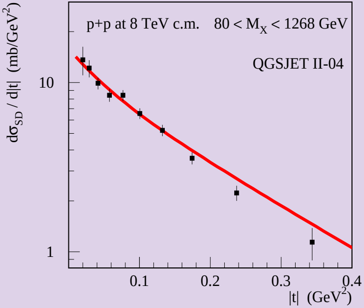

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Other models overestimate high mass (large M_X) diffraction

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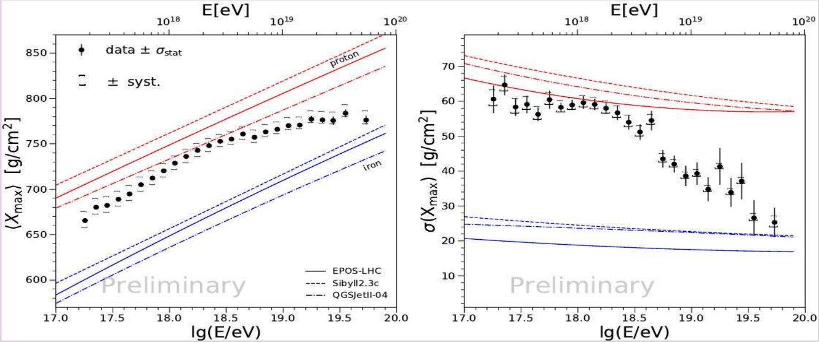
TOTEM	2.62 ± 2.17	6.5 ± 1.3	$\simeq 1.8$	$\simeq 3.3$	$\simeq 1.4$
EPOS-LHC	4.0	7.1	1.0	3.9	2.2
SIBYLL 2.3	1.6	11.8	1.1	6.7	4.0

Interpretation of PAO data on $X_{\max}$ & its fluctuations

PAO data on $X_{\max}$ & $\sigma(X_{\max})$: a self-consistent interpretation?



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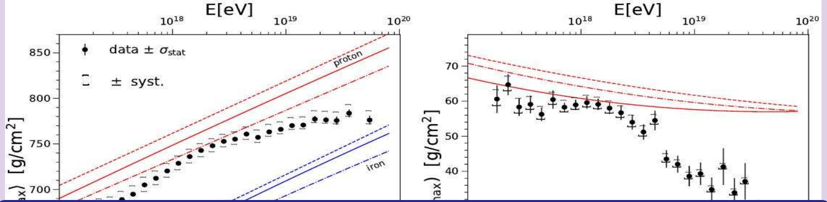
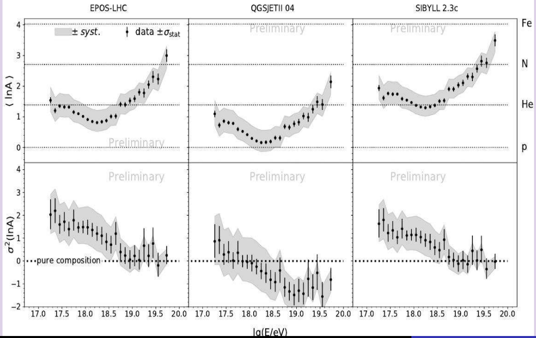


Not the case for QGSJET-II-04: $X_{\max}$-distributions too wide



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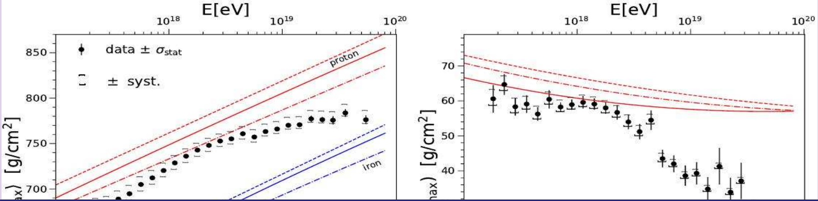

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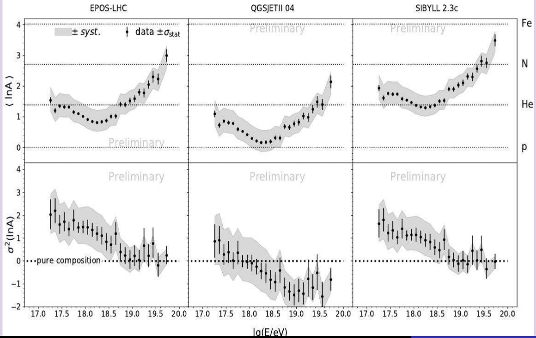

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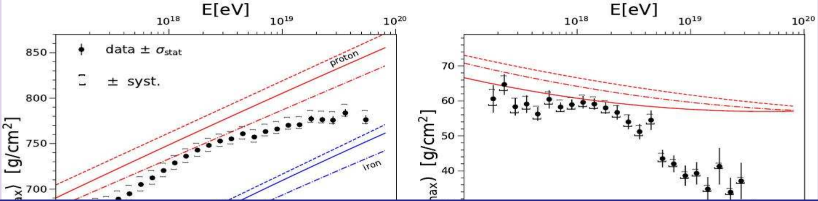

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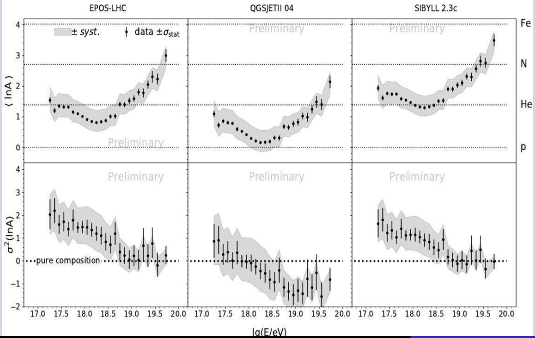
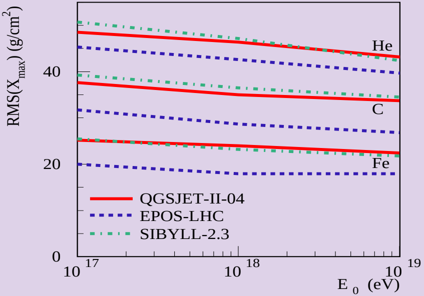


- inconsistency of QGSJET-II-04...
- or a problem with PAO data?
- why other models agree better?

Nuclear fragmentation & $\sigma(X_{\max})$ *[SO, arXiv:1612.09461]*

EPOS-LHC: much smaller $\sigma(X_{\max})$ for primary nuclei



- = main reason for the better agreement with PAO data
- why $\sigma(X_{\max})|_C$ in EPOS is almost as small as $\sigma(X_{\max})|_{Fe}$ in QGSJET-II & SIBYLL?

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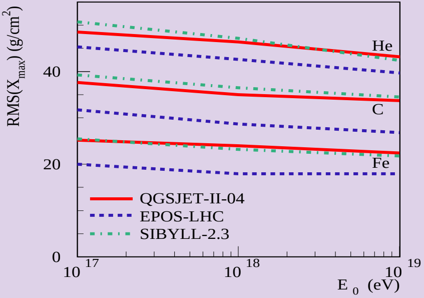

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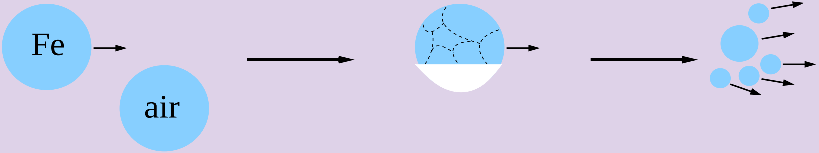
$\sigma(X_{\max})$: depends on the fragmentation of nuclear spectator part

[Kalmykov & SO, Sov.J.Nucl.Phys. 50 (1989) 315; Phys.At.Nucl. 56 (1993) 346]

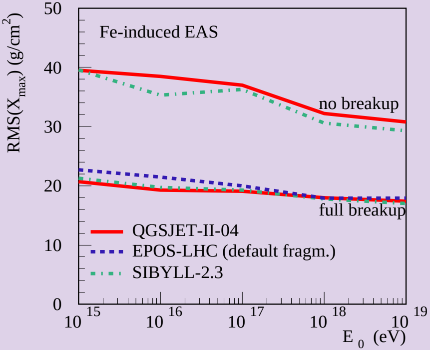


- e.g. factor 2 difference between two extreme options

Nuclear fragmentation & $\sigma(X_{max})$

Cross check with SIBYLL & QGSJET-II: two extreme scenarios

1. complete break up of nuclear spectator part (into separate nucleons) $\Rightarrow$ smallest $\mathrm{RMS}(X_{max})$
2. no break up (single secondary fragment) $\Rightarrow$ largest $\mathrm{RMS}(X_{max})$



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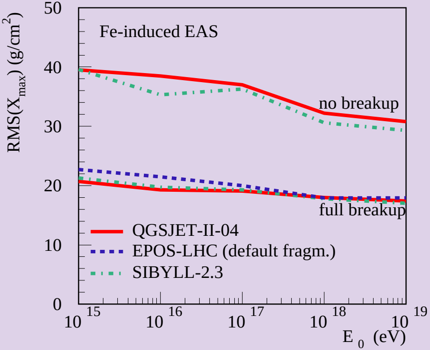

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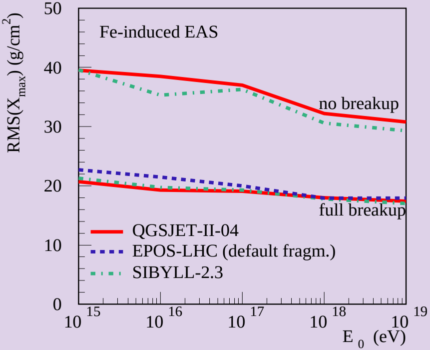

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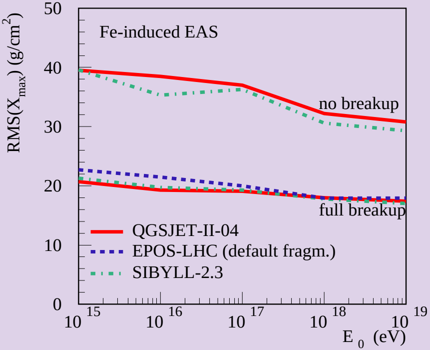

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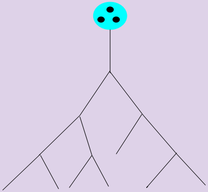
- $\Rightarrow$ consistent interpretation of PAO data on X_{max} & $\sigma(X_{max})$ requires large predicted X_{max} (like in SIBYLL 2.3)

Treatment of multiple scattering & energy dependence of the inelasticity *[SO et al., PRD 94 (2016) 114026]*

SIBYLL (also PYTHIA & other models used at colliders): multiple scattering mostly affects central (low x) production

- multiple scattering has small impact on forward spectra
  - new sub-cascades emerge at small x ($G(x,q^2) \propto 1/x$)
- $\Rightarrow$ Feynman scaling for forward production



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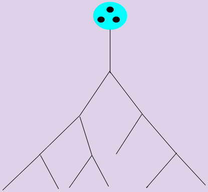

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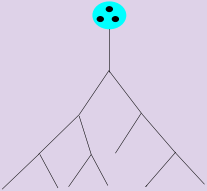
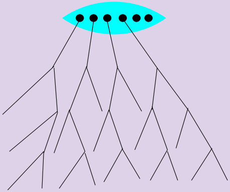


EPOS & QGSJET(-II): multiple scattering starts already at large x

- $\Rightarrow$ softer forward spectra (energy sharing between constituent partons)



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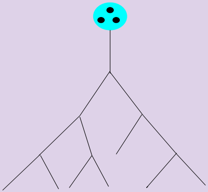

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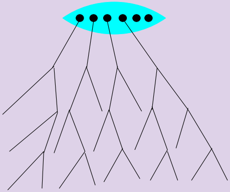
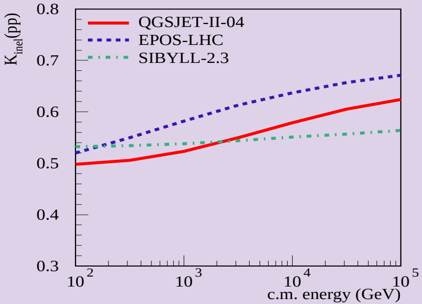
- $\Rightarrow$ softer forward spectra (energy sharing between constituent partons)
- forward & central particle production: strongly correlated
  - e.g. more activity in central detectors $\Rightarrow$ softer forward spectra



Treatment of multiple scattering & s-dependence of $K^{\rm inel}_{p-{\rm air}}$

Of importance for cosmic ray studies: $\sqrt{s}$-dependence of $K^{\rm inel}_{pp}$



- SIBYLL 2.3: weak energy dependence of $K^{\rm inel}_{pp}$ (for increasing $\sqrt{s}$, mostly rise of central production)

Treatment of multiple scattering & s-dependence of $K^{\text{inel}}_{p-\text{air}}$

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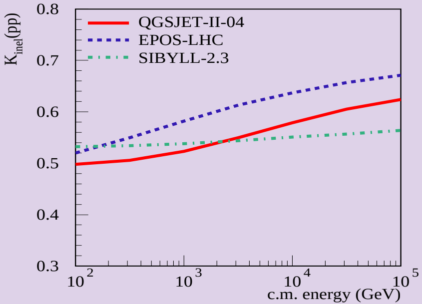

- SIBYLL 2.3: weak energy dependence of K^{inel}_{pp} (for increasing $\sqrt{s}$, mostly rise of central production)
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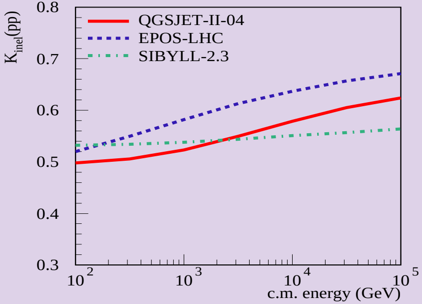

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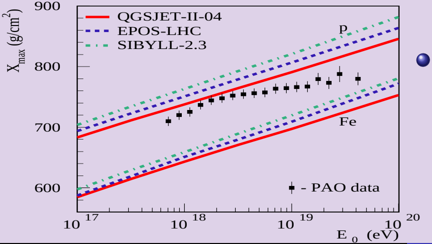
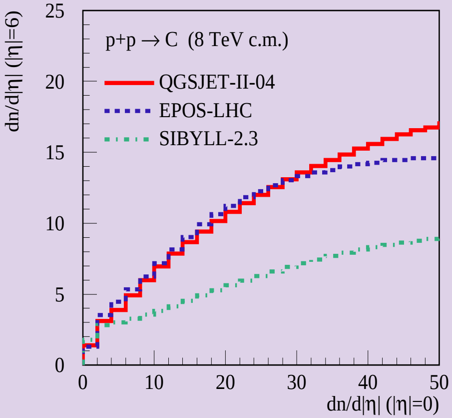


- SIBYLL 2.3:
  slower energy rise of $K^{\rm inel}_{p-{\rm air}}$
  - $\Rightarrow$ larger elongation rate
  - $\Rightarrow$ deeper $X_{\rm max}$ at the highest energies

Treatment of multiple scattering & s-dependence of $K^{\mathrm{inel}}_{p-\mathrm{air}}$

Crucial test: cross-correlation of $dN^{\mathrm{ch}}_{pp}/d|\eta|$ at $\eta = 0$ and $\eta = 6$

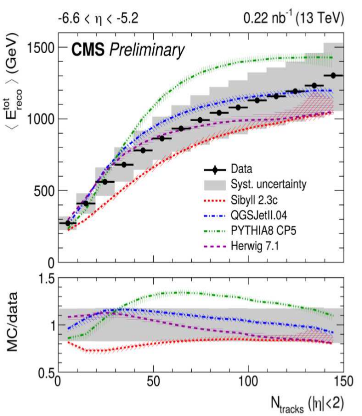


- QGSJET-II & EPOS: strong correlation (apart from the tails of the N^{ch} distributions)
- SIBYLL 2.3: twice weaker correlation

Treatment of multiple scattering & s-dependence of $K^{\text{inel}}_{p-\text{air}}$

Now measured: correlation of forward energy (in CASTOR) with central activity (N of charged particle tracks) in CMS

- NB: forward energy is a worse observable than N_{ch}:
  sensitive to 'softening' of forward spectra in QGSJET-II-04



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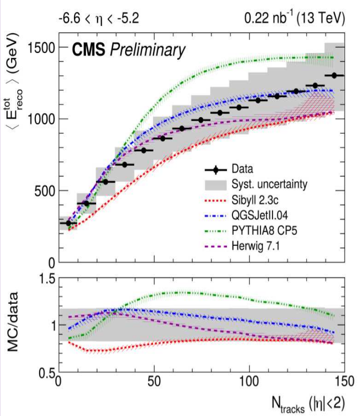

- ⇒ only first 3 bins relevant (binning too crude)
- NB: 1st bin may be biased by experimental event selection
  - ⇒ no decisive discrimination

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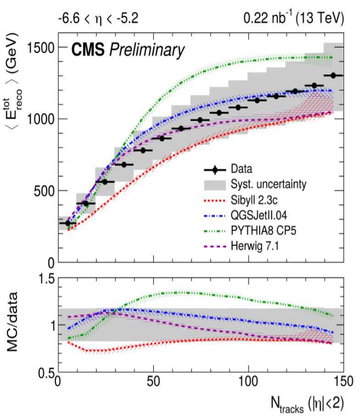

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Treatment of multiple scattering & s-dependence of $K_{p-\text{air}}^{\text{inel}}$

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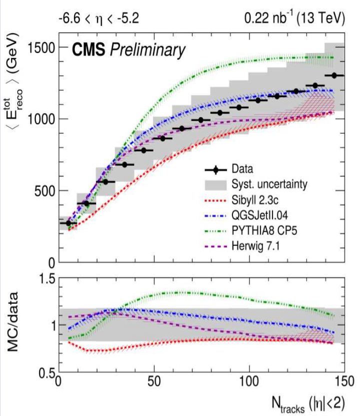

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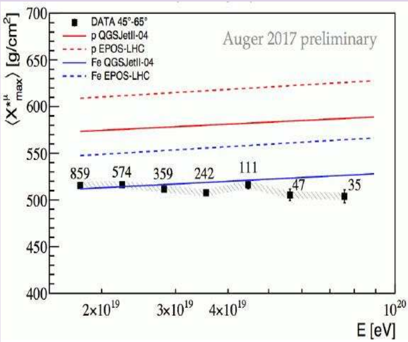
- QGSJET-II-04: correlation may be too strong compared to data?
  - $X_{\max}$ underestimated?

UHECR composition: inference from PAO data

PAO data on 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

[R. Prado, ISVHECRI-2018]

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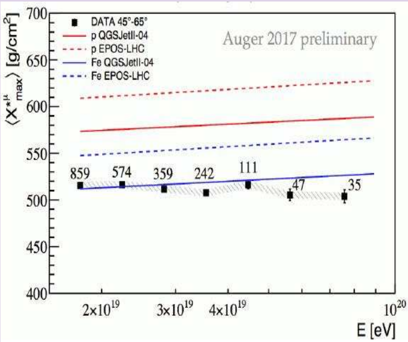
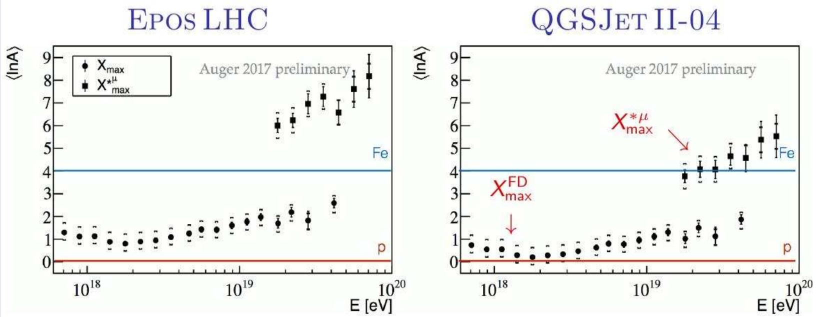


[R. Prado, ISVHECRI-2018]

- models predict deeper $X^{\mu}_{\max}$ than observed
  - e.g. one needs primary iron for QGSJET-II-04
  - or primary gold for EPOS-LHC (& SIBYLL 2.3)

UHECR composition: inference from PAO data

Change models to 'marry' $X_{\max}$ & $X^{\mu}_{\max}$ data composition-wise?



[R. Prado, ISVHECRI-2018]

- the two sets of data should overlap in terms of $\langle \ln A \rangle$
  - for $1 \leq A \leq 56$!

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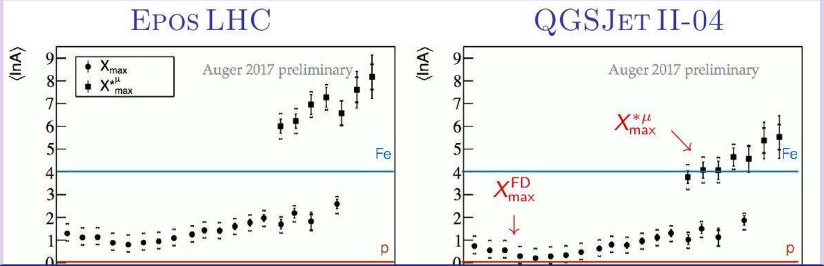

We are back to Zeno's paradox...

- change a model to modify $X_{\max}$ prediction:
  - $X^{\mu}_{\max}$ will move in the same direction!
- or vice versa

Modifying CR interaction models: which way to go?

- changing the treatment of $p-$air collisions?
  - $\sigma^{\rm inel}_{p-{\rm air}}$ – little freedom in view of LHC data
  - same for the rate of diffractive collisions
  - treatment of forward hadron production ($\Rightarrow$ impact on $K^{\rm inel}_{p-{\rm air}}$) – some freedom left (see the SIBYLL/QGSJET-II difference)
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  - $\Rightarrow$ (nearly) same effect on $X_{\rm max}$ and $X^{\mu}_{\rm max}$

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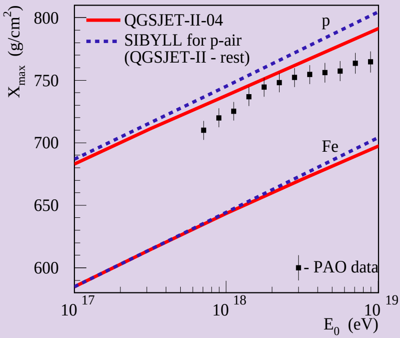
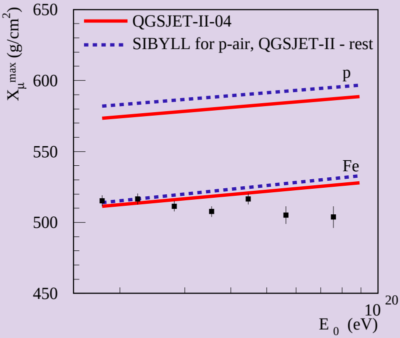
SIBYLL-2.3 for $p-$air ($\Rightarrow$ smaller $K^{\rm inel}_{p-{\rm air}}$); QGSJET-II for the rest



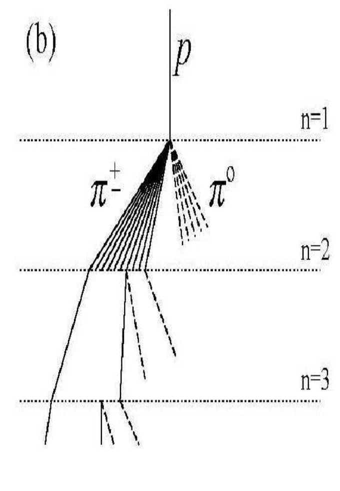


- $\Rightarrow$ larger $\langle \ln A \rangle$ from $X_{\max}$ but $\langle A \rangle > 56$, based on $X^{\mu}_{\max}$?!

Modifying CR interaction models: which way to go?

Changing the treatment of $\pi-$air collisions ('Achilles & Tortoise')

- e.g., $\sigma^{\rm inel}_{\pi-{\rm air}}$, $\sigma^{\rm diffr}_{\pi-{\rm air}}$, $K^{\rm inel}_{\pi-{\rm air}}$
  - $\equiv$ making special assumptions concerning the pion structure



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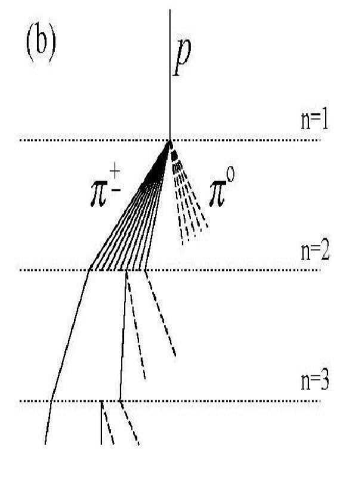

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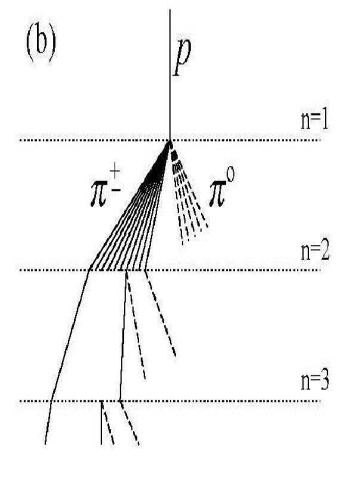
  - $\equiv$ making special assumptions concerning the pion structure
- affects every step in the multi-step hadron cascade
  - $\Rightarrow$ cumulative effect on $X^{\mu}_{\max}$
- but: only the first few steps in the cascade impact $X_{\max}$
  - after few steps, most of energy channelled into e/m cascades
  - $\Rightarrow$ much weaker effect on $X_{\max}$



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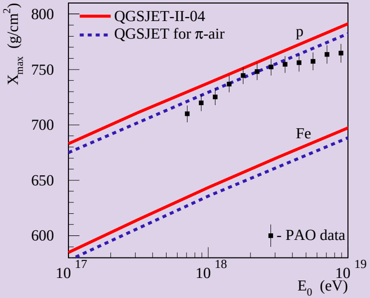
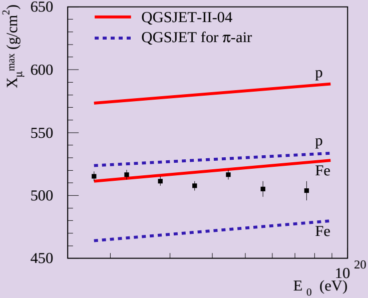
E.g., employing the old QGSJET model for $\pi - $air collisions

- $\Rightarrow$ higher $\sigma^{\rm inel}_{\pi-{\rm air}}$, larger $N^{\rm ch}_{\pi-{\rm air}}$ & $K^{\rm inel}_{\pi-{\rm air}}$





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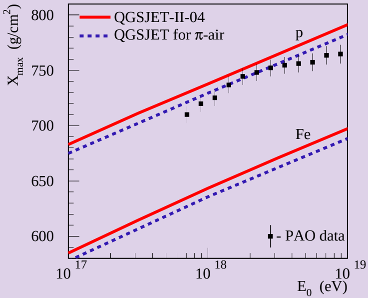

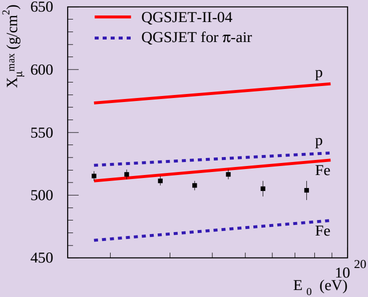

- $\Rightarrow$ (almost) pure proton composition for UHECRs

NB: rather an indication of the tendency, not a solution

- old QGSJET – outdated; known to overestimate particle production in $\pi-$air collisions at low energies

Summary on $X_{\max}$ & $X^{\mu}_{\max}$

Current situation

- data on $X_{\max}$ favor a light UHECR composition (for QGSJET-II)
- data on $X^{\mu}_{\max}$: close to model results for primary iron (at best)

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- but: very light primary composition?!

Outlook

1. Interpretation of TA data on $X_{\max}$-distributions, using QGSJET-II-04 (adjusted to LHC results on diffraction):
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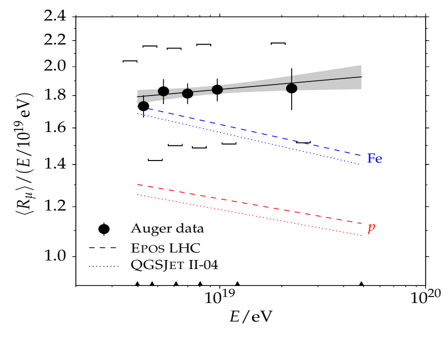
comments on the PAO 'muon excess': backup slides

Extra slides

Few comments on the PAO 'muon excess'

PAO observed higher EAS muon content than predicted by models



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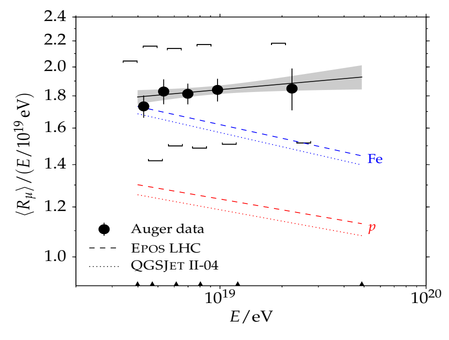


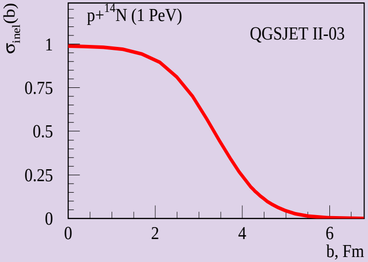
- excess by a large factor: $(1.5 \div 2)$

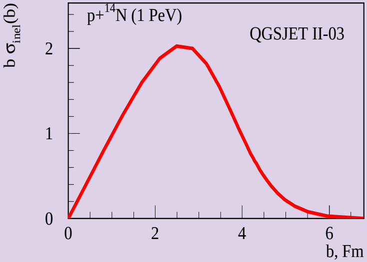
Can muon excess be produced by 1-2 cascade steps?

- e.g. 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

Potential 'new physics' can be discriminated by fluctuations of muon density *[SO, arXiv:1612.09461]*

p-air: interaction profile & distribution of the impact parameter b





- $\Rightarrow$ interactions dominated by peripheral ($b \gtrsim 2$ fm) collisions

Potential 'new physics' can be discriminated by fluctuations of muon density *[SO, arXiv:1612.09461]*

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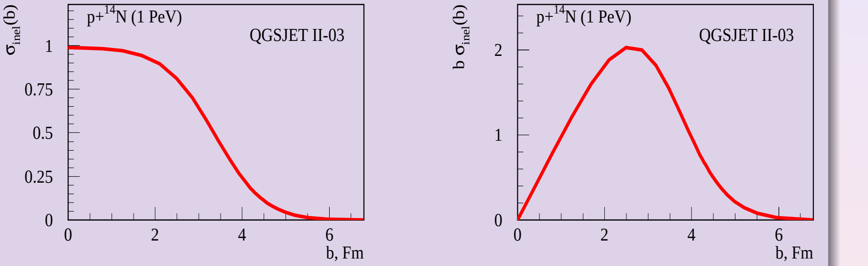

- ⇒ interactions dominated by peripheral ($b \gtrsim 2$ fm) collisions
- at large *b*: low parton density
  - ⇒ not suitable for new physics to emerge

Potential 'new physics' can be discriminated by fluctuations of muon density *[SO, arXiv:1612.09461]*

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 ($\langle \rho_\mu \rangle = 0.1 * 10\rho_\mu^{(0)} + 0.9 * \rho_\mu^{(0)} = 1.9\rho_\mu^{(0)}$)

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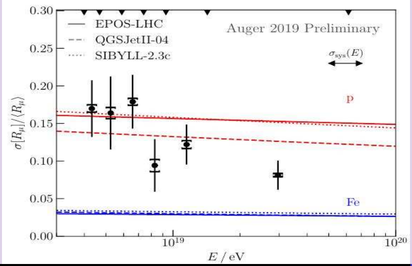
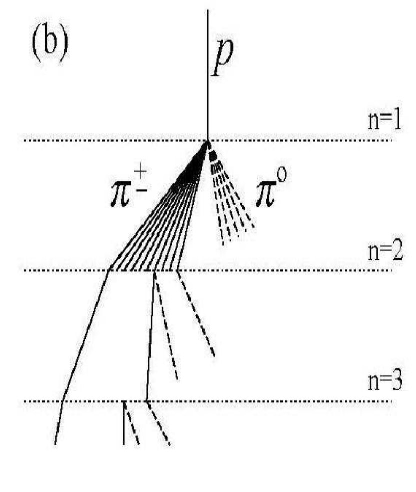
$\sigma_{\rho_\mu}/\rho_\mu$ – now obtained by PAO (ICRC-2019)



- $\Rightarrow$ no room for further speculations

Muon component of EAS: conventional physics

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



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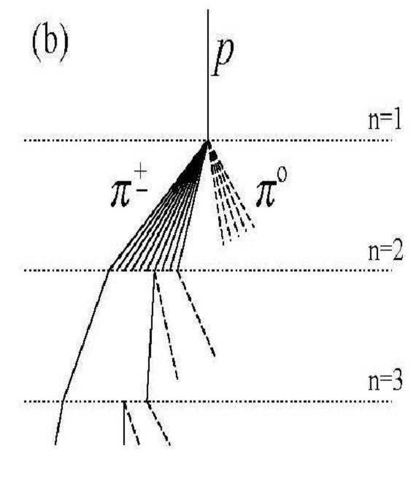
- each order of magnitude: factor $10^{\alpha_\mu} \simeq 8$ $(\alpha_\mu \simeq 0.9)$



Muon component of EAS: conventional physics

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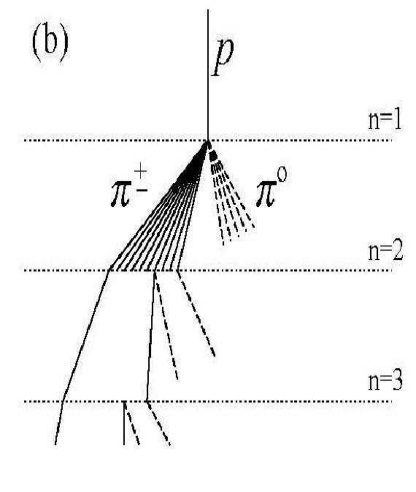

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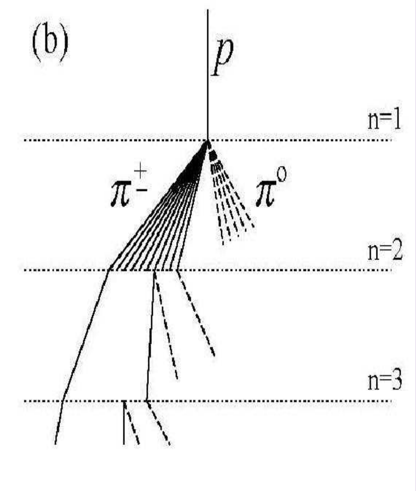

If 'muon excess' is real: $\alpha_\mu \rightarrow \tilde{\alpha}_\mu > 1$ between 10^{17} & 10^{19} eV

Muon component of EAS: conventional physics

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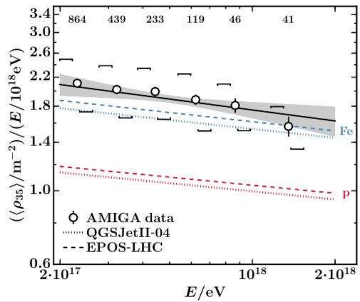
ρ_μ – now measured by the AMIGA detector of PAO (ICRC-2019)



- $\alpha_\mu = 0.89 \pm 0.04(\text{stat}) \pm 0.04$ (sys)