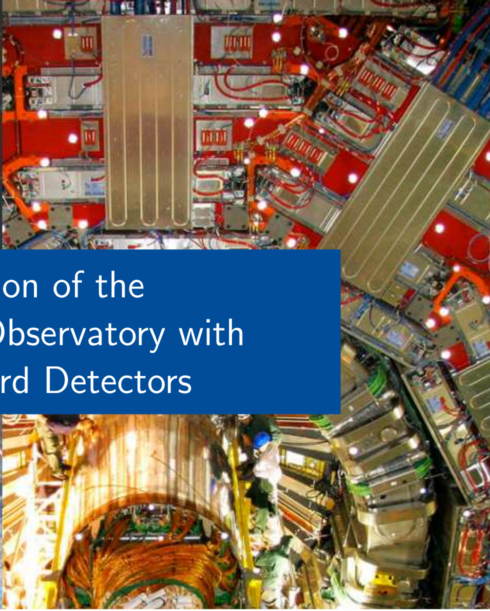


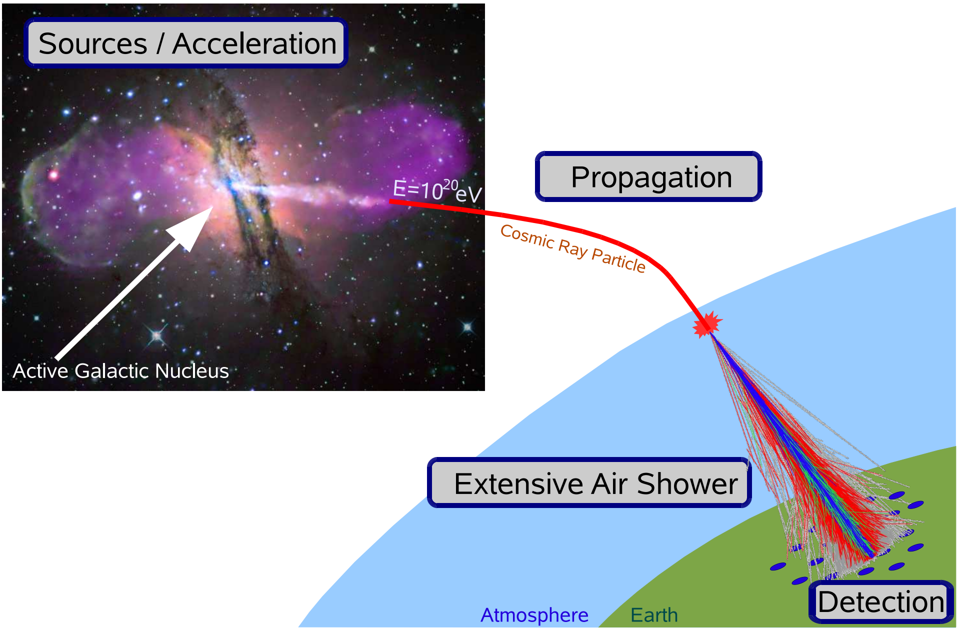
Calibration of the Pierre Auger Observatory with LHC Forward Detectors

Ralf Ulrich

Karlsruhe Institute of Technology

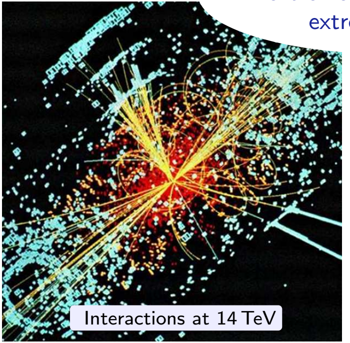
DESY Seminar 18./19. Januar 2011

Cosmic Rays and Extensive Air Showers

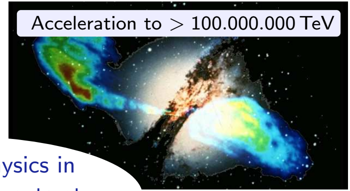


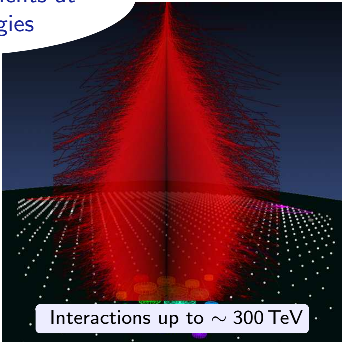
Particle Accelerators: Man-Made versus Cosmic Rays

Large Hadron Collider (LHC)



Ultra-High Energy Cosmic Rays



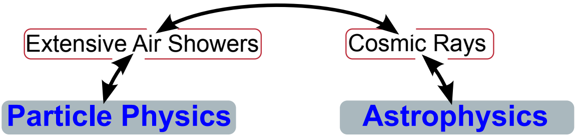


Fundamental physics in extreme environments at extreme energies

Overview

Our understanding of hadronic interactions at cosmic ray energies is incomplete

- The interpretation of air shower data is very model dependent
- Hadronic interaction features are not well constraint at cosmic ray energies
- Calibrate air shower simulations at LHC energy
- Determine properties of hadronic interactions at ultra-high energies from cosmic ray data



Overview of Cosmic Ray Data

Characterization of Current Situation

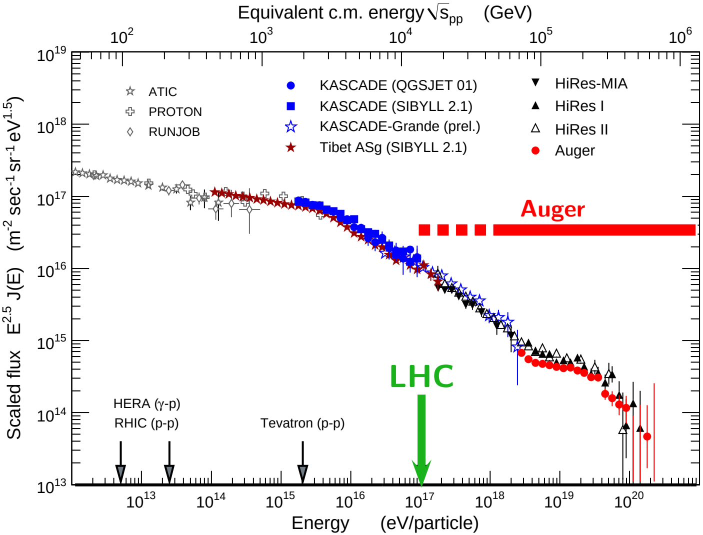
Large amounts of high quality cosmic ray data

Auger, HiRes, AGASA, TA, Future: Auger-North, JEM-EUSO

BUT

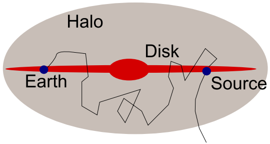
Lack of reliable hadronic interaction models, which are needed for a detailed interpretation

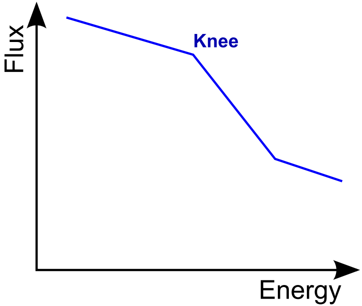
Energy Flux



Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)
10^2
10^3
10^4
10^5
10^6
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
Scaled flux $E^{2.5}$ J(E) (m^{-2} sec^{-1} sr^{-1} $eV^{1.5}$)
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande (prel.)
Tibet ASg (SIBYLL 2.1)
HiRes-MIA
HiRes I
HiRes II
Auger
Auger
LHC
HERA (γ-p)
RHIC (p-p)
Tevatron (p-p)
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
Energy (eV/particle)

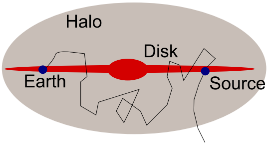
Physics of the Knee

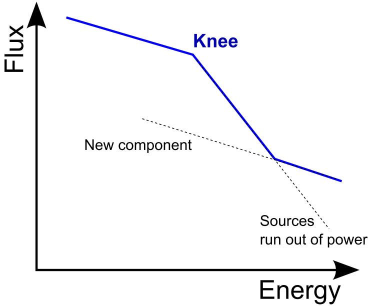




- Astrophysical scenarios: $E_{\mathrm{knee}} \propto Z$
- Particle physics: $E_{\mathrm{knee}} \propto A$
  $\Rightarrow >20\,\%$ of missing energy at LHC ...

Physics of the Knee





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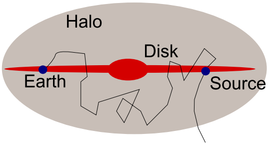

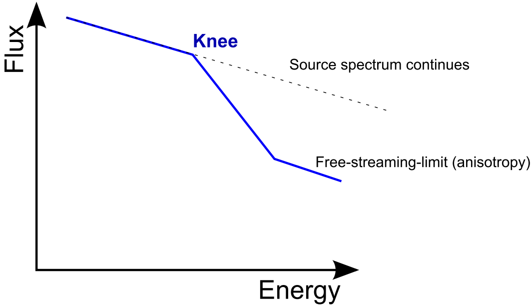

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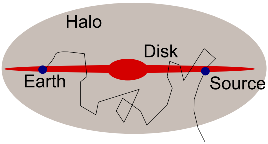

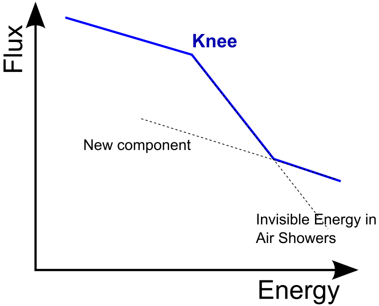

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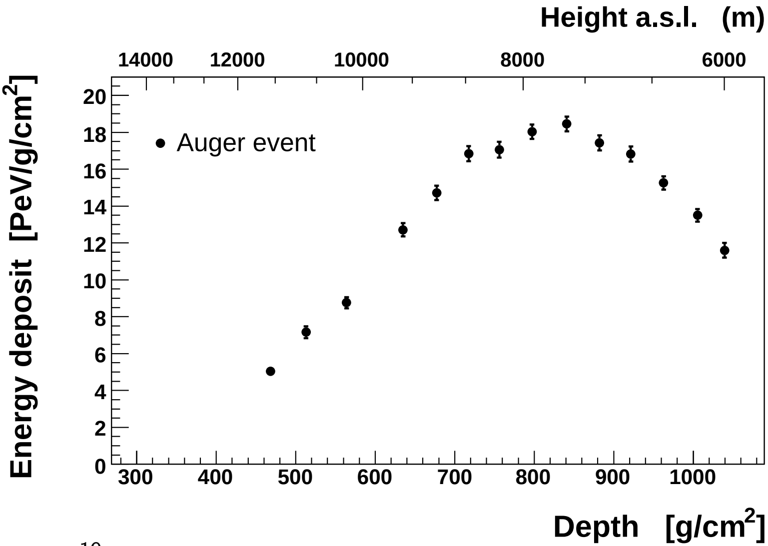
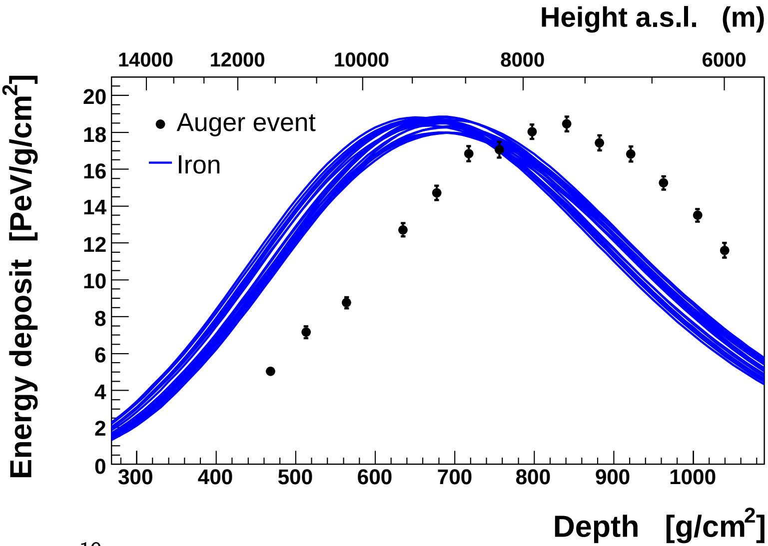
Longitudinal Profiles



$E \sim 10^{19}\,\mathrm{eV}$

Longitudinal Profiles



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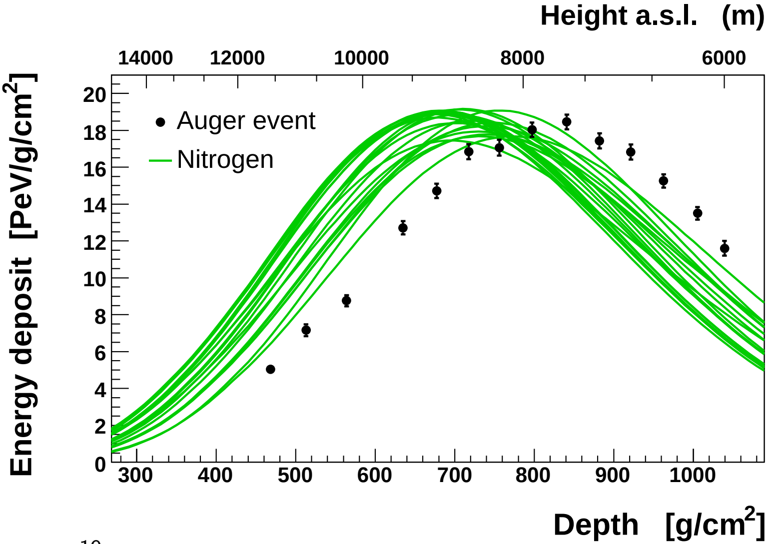

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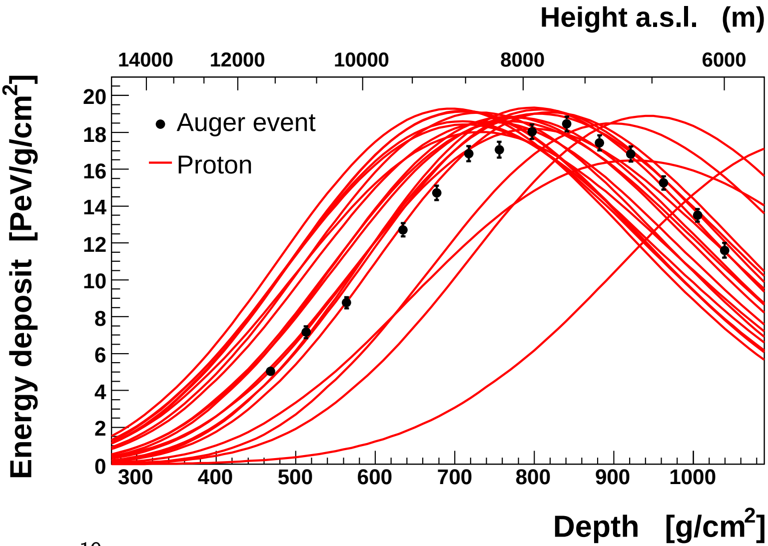
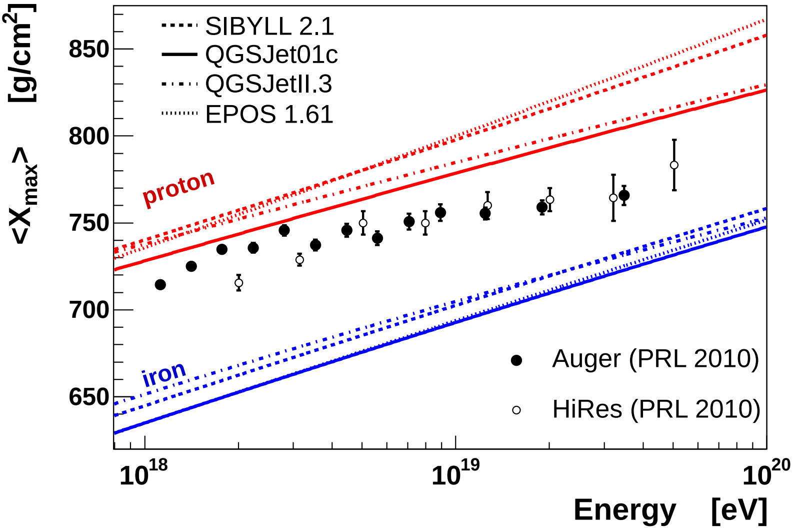
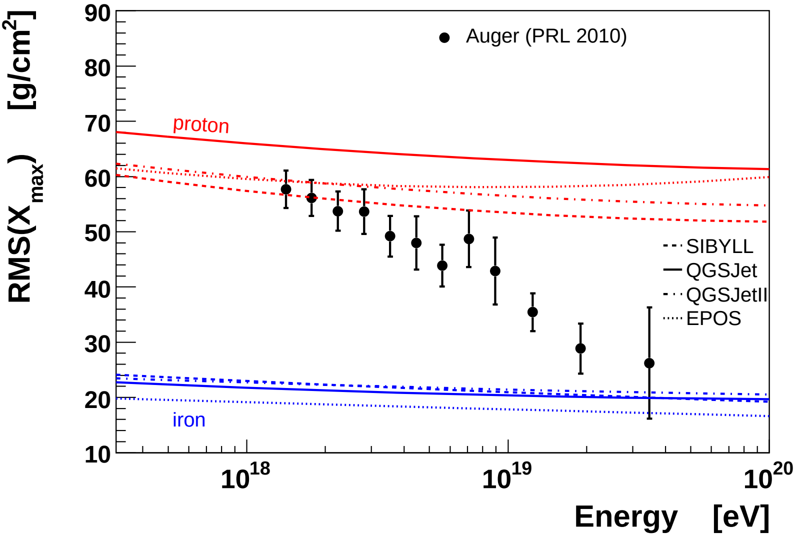


$E \sim 10^{19}\,\mathrm{eV}$

Average $X_{\max}$



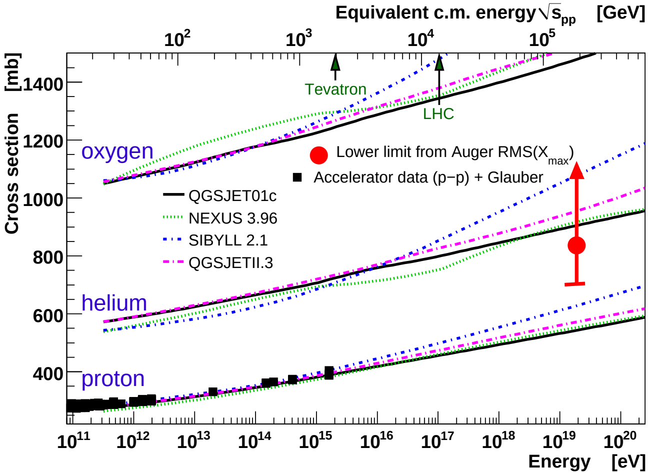
Fluctuations of $X_{\max}$



$\Rightarrow$ Strong trend to reduced fluctuations at high energy

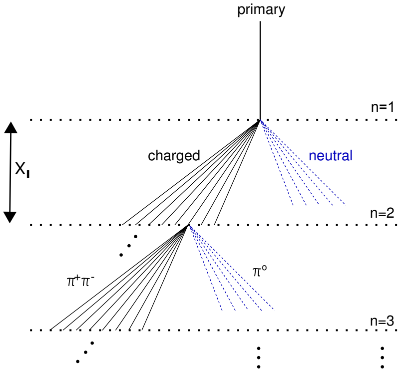
Limit: no fluctuation in the air shower after first interaction

$$\sigma_{\mathrm{cr-air}} = \frac{\langle m \rangle}{RMS(X_1)} > \frac{\langle m \rangle}{RMS(X_{\mathrm{max}})}$$



Extensive Air Showers and Hadronic Interactions

Extended Heitler Model



Shower maximum

$$X_{\max} \approx \lambda_{\mathrm{I}} + X_0 \ln \frac{E_0}{N_{\mathrm{mult}}\, E_{\mathrm{crit}}^{\mathrm{e.m.}}}$$

Muon number at observation level

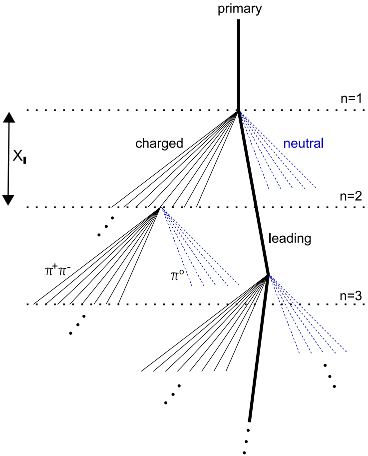
$$N_\mu = N_{\pi^\pm} = \left(\frac{E_0}{E_{\mathrm{crit}}^{\mathrm{I}}}\right)^\beta$$

where

$$\beta = \ln\left(\tfrac{2}{3}\, N_{\mathrm{mult}}\right) / \ln\left(N_{\mathrm{mult}}\right) \approx 0.9$$

(J. Matthews, APP 22 (2005) 387)

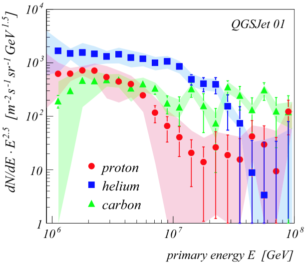
Beyond the Heitler Model ...

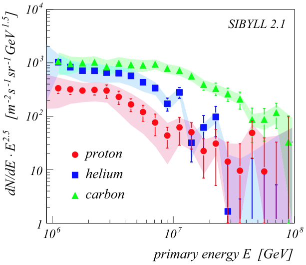


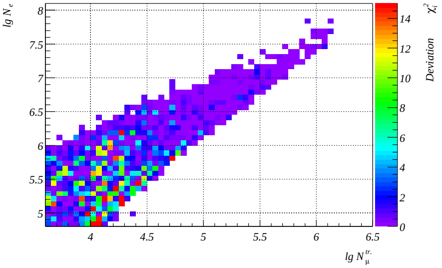
- Cross Section: λ
- Multiplicity: n_{mult}
- Elasticity: $k_{\mathrm{ela}} = E_{\mathrm{max}}/E_{\mathrm{tot}}$
- Charge ratio: $c = n_{\pi^0}/(n_{\pi^0} + n_{\pi^-} + n_{\pi^+})$
- Nuclear primary: A

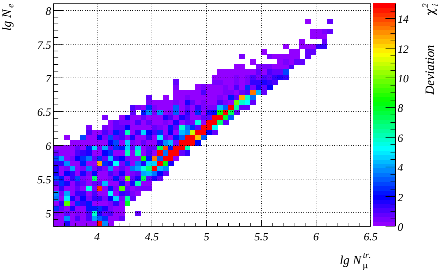
Analysis of Cosmic Ray Data

KASCADE - Electron/Muon-Frequencies



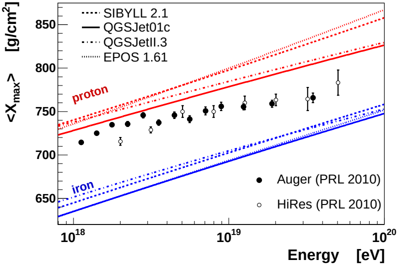


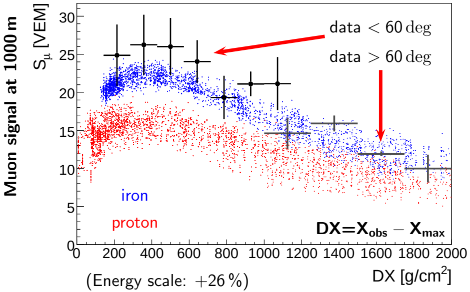




(KASCADE, APP:24 1 (2005), astro-ph/0505413)

Pierre Auger Observatory: $X_{\max}$ vs. Muons



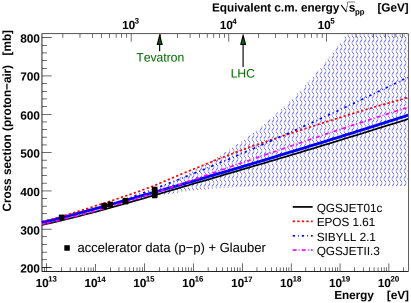


(Auger/HiRes $X_{\max}$: PRL 2010,
Muons: e.g. ICRC 2007, arXiv:0706.1921 [astro-ph])

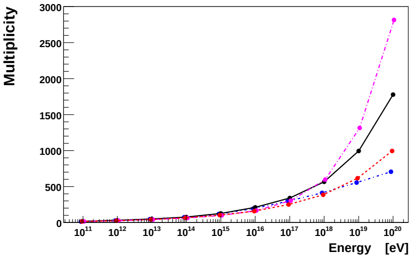
Cosmic Ray Analysis/Modeling Uncertainties

Modeling Uncertainties

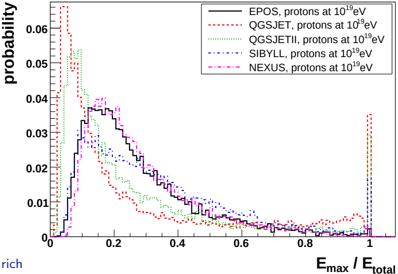
Cross Section



Multiplicity



Elasticity



Estimate Importance On Air Shower Interpretation

Modify specific features of hadronic interactions during air shower Monte-Carlo simulation:

- Assume logarithmically growing deviation from original model prediction above 10^{15} eV.
- Below 10^{15} eV the original model is used.
- The parameter f_{19} denotes the nominal deviation at 10^{19} eV.

$$\boxed{\alpha^{\text{modified}}(\mathbf{E}) = \alpha^{\text{HE-model}}(\mathbf{E}) \cdot \left(1 + (\mathbf{f}_{19} - 1) \cdot \frac{\log_{10}(\mathbf{E}/1\,\mathbf{PeV})}{\log_{10}(10\,\mathbf{EeV}/1\,\mathbf{PeV})}\right)}$$

Where α can be:

- Cross Section: $\sigma_{\text{had}}^{\text{prod}}$
- Multiplicity: n_{mult}
- Elasticity: $k_{\text{ela}} = E_{\text{leading}}/E_{\max}$
- Pion-Charge Ratio: $c = n_{\pi^0}/(n_{\pi^0} + n_{\pi^+} + n_{\pi^-})$

(R. Ulrich et al., submitted to PRD, arXiv 1010.4310 [hep-ph])

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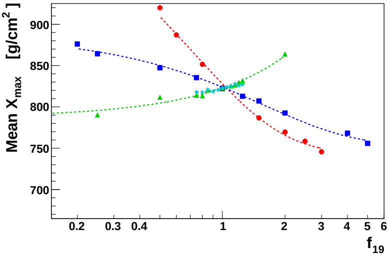
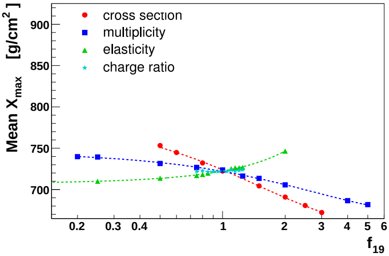
(R. Ulrich et al., submitted to PRD, arXiv 1010.4310 [hep-ph])

Results for $\langle X_{\max} \rangle$

Proton **Iron**

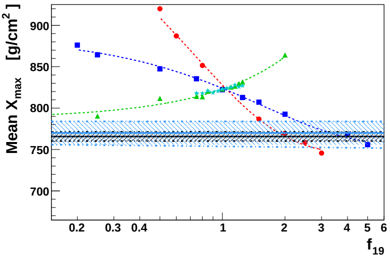




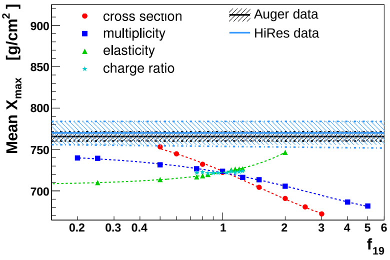
- $\langle X_{\max} \rangle$ can be shifted significantly
- Data are suggesting
  - Intermediate mass, mixed composition, or:
  - Large cross section for a proton dominated composition
  - Small cross section for a iron dominated composition

Results for $\langle X_{\max} \rangle$

Proton



Iron



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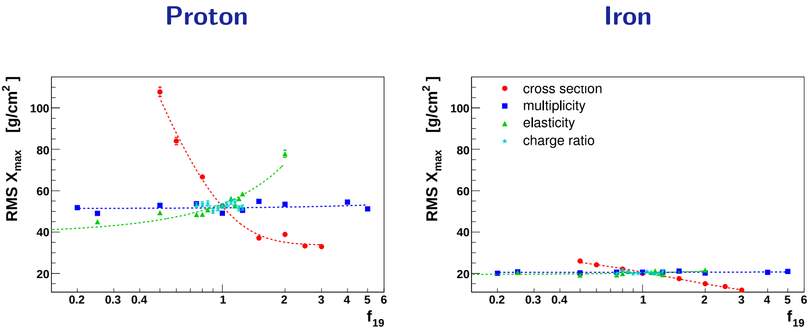
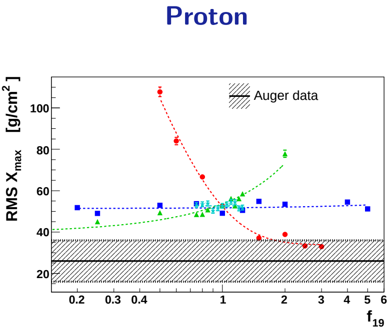
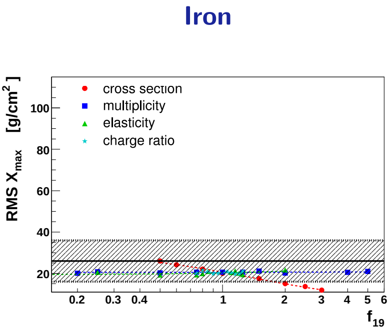
Results for RMS($X_{\max}$)



- RMS($X_{\max}$) mostly impacted by cross section, and elasticity
- Iron induced showers very robust
- Auger data only marginally compatible with protons in a high cross section scenario

Results for RMS($X_{\max}$)





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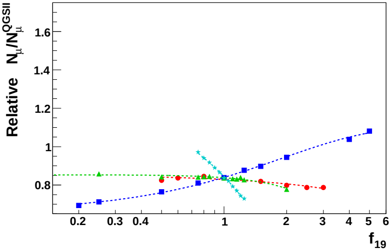
Results for Muon Numbers

Proton



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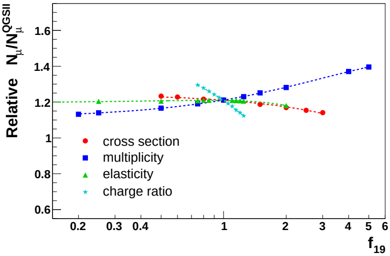

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- Even for iron primaries: multiplicity must be high and pion-charge-ratio small

Results for Muon Numbers

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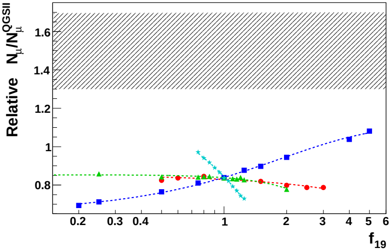
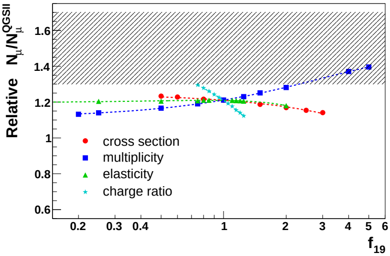


Iron



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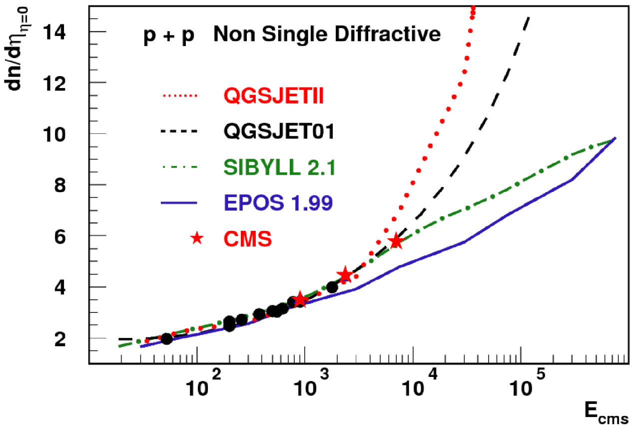
Caution: Definition of Muon number is not identical, e.g.:
Auger measures at 1000 m, Simulations give total muon number

LHC Data

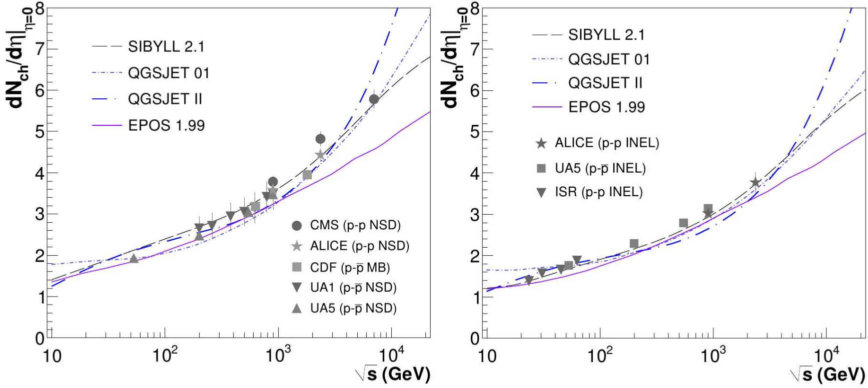
as a benchmark for existing models

Rise of Secondary Multiplicity



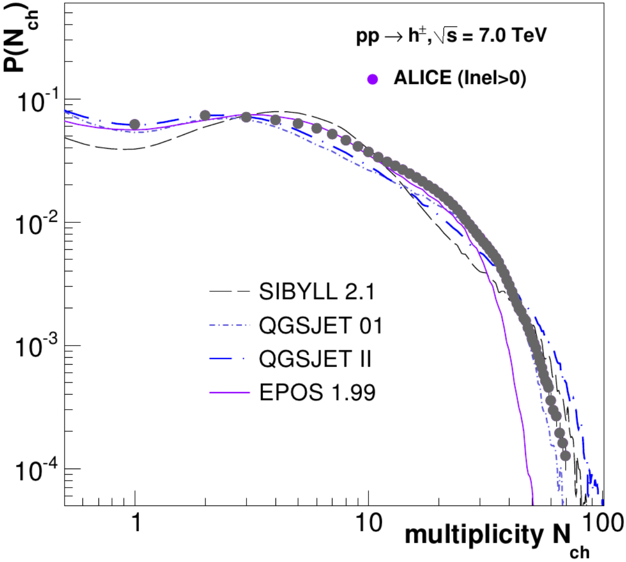
(T. Pierog)

Rise of Secondary Multiplicity



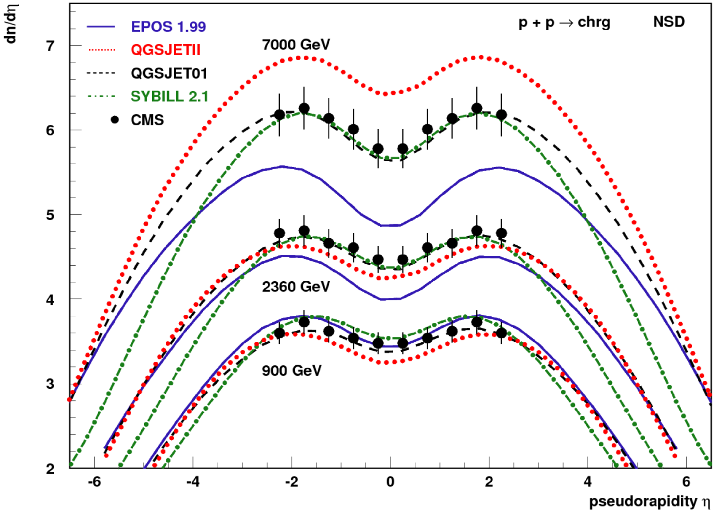
(D. d'Enterria et al., to be published)

Multiplicity Distribution



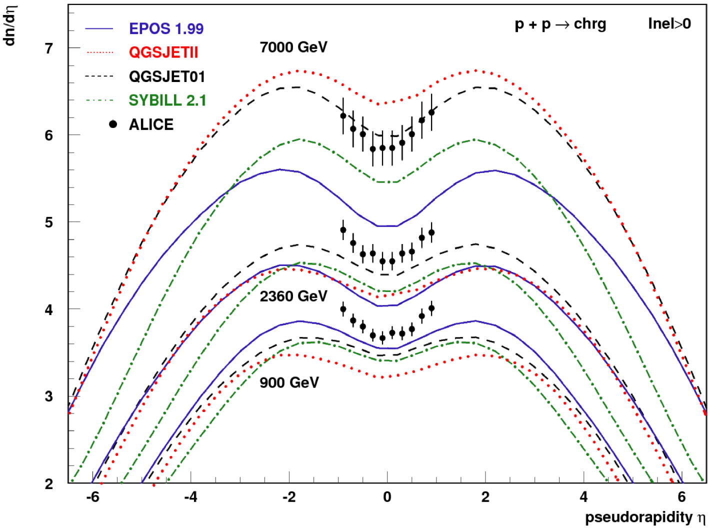
(D. d'Enterria et al., to be published)

Pseudorapidity Distribution, NSD



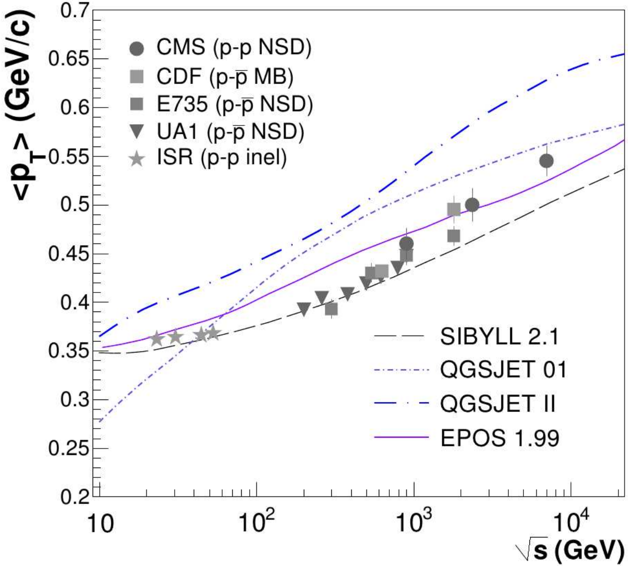
(T. Pierog)

Pseudorapidity Distribution, INEL



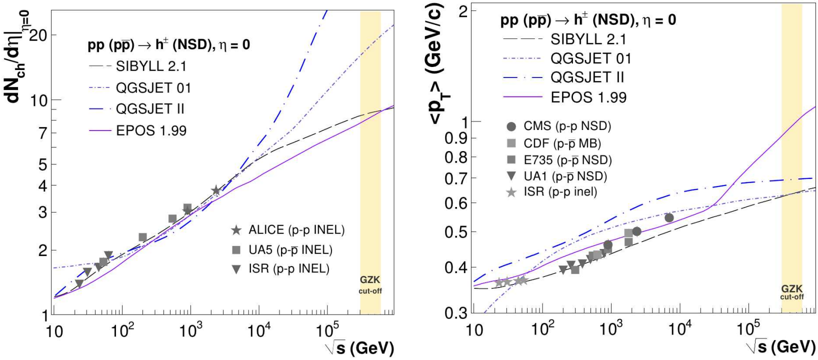
(T. Pierog)

Average Transverse Momentum



(D. d'Enterria et al., to be published)

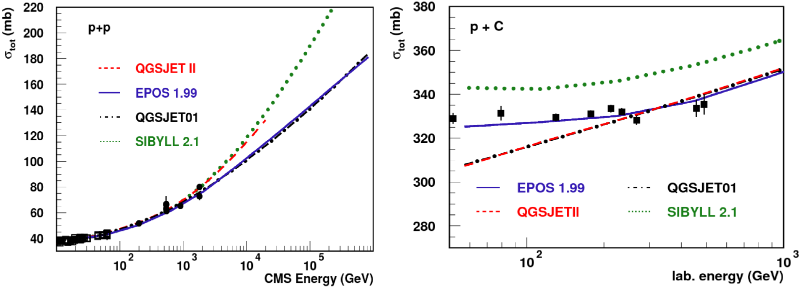
Extrapolation to GZK Energies



(D. d'Enterria et al., to be published)

⇒ Data at 14 TeV are mandatory

Interactions with Nuclei/Air



(T. Pierog)

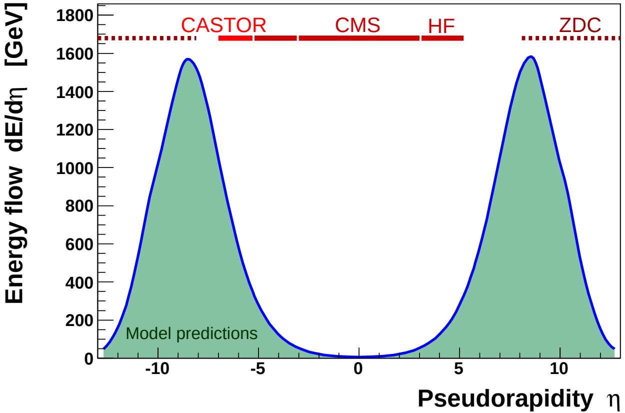
Air Showers: p-Air, A-Air, π-Air, ...

$\Rightarrow$ not just p-p, but nuclei and nuclei combinations

Forward Detectors

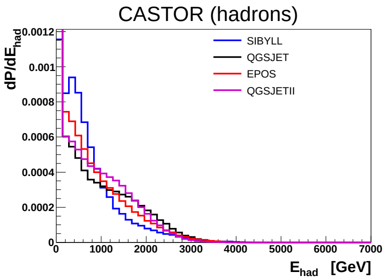
(TOTEM, ZDC, CASTOR)

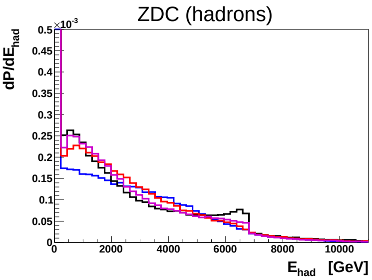
Forward Detectors

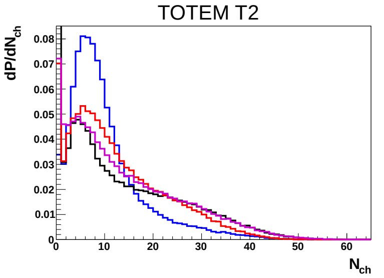


⇒ Crucial for air showers is particle production in **forward direction**!

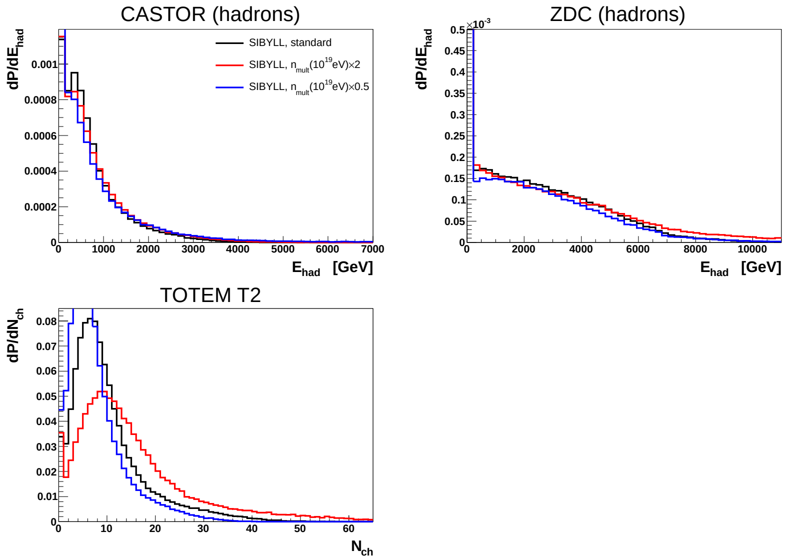
Predicted Particle Production in Forward Direction





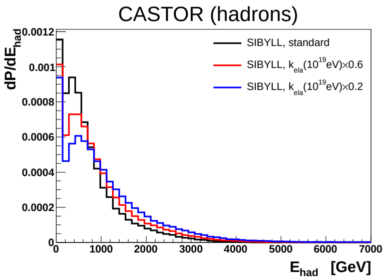


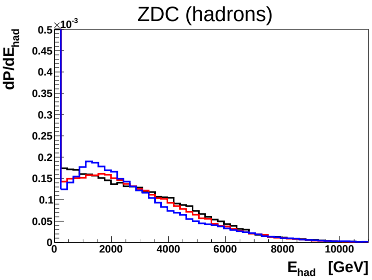
Impact of Modified Multiplicity

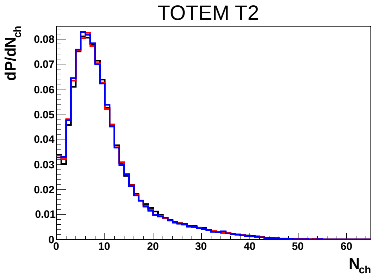


(cf. Ulrich et al., submitted, arXiv:1010.4310v1 [hep-ph])

Impact of Modified Elasticity





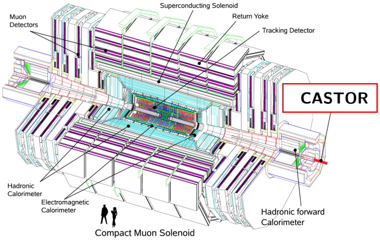


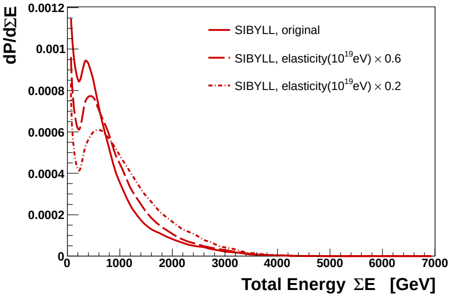
(cf. Ulrich et al., submitted, arXiv:1010.4310v1 [hep-ph])

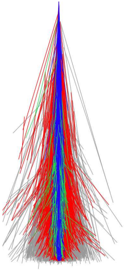
Potential Impact of LHC on Interpretation of EAS Data

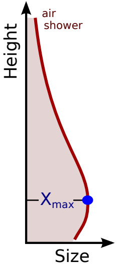
At the example of a precise measurement of the elasticity and CASTOR

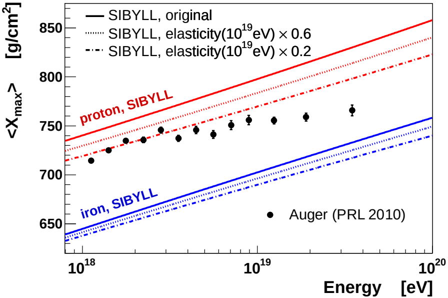
Relevance of CASTOR for Cosmic Ray Interpretation



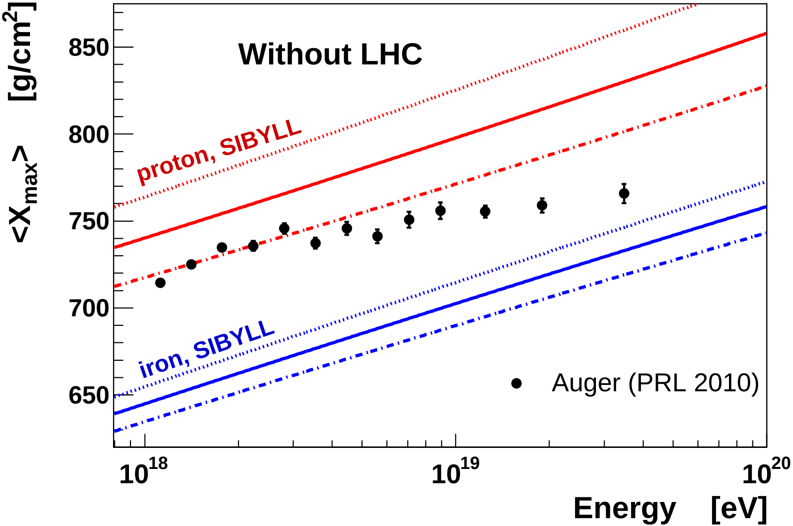






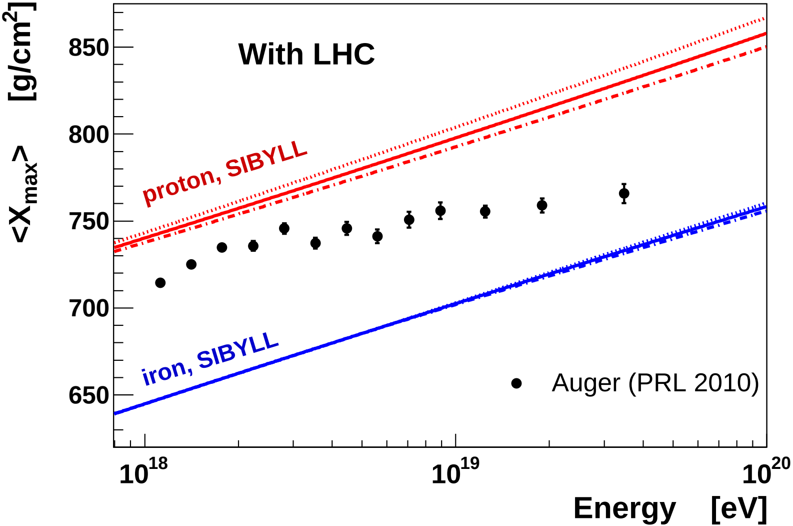


Impact of Elasticity / Leading Particles



- Precise measurement of elasticity at $300\,\mathrm{GeV}$
- Extrapolation uncertainty grows by $10\,\%$ per decade in energy

Impact of Elasticity / Leading Particles



- Precise measurement of elasticity at 14 TeV
- Extrapolation uncertainty grows by 10 % per decade in energy

Summary

- High energy models need tuning to data as close to the phase space relevant in air showers as possible
- Interaction characteristics has impact on air shower observables on the same order of magnitude as as primary mass composition
  - $\Rightarrow$ Almost impossible to "measure" mass composition from air shower observables in the moment
- If cosmic ray mass composition is constrained
  $\Rightarrow$ Air shower data sensitive to interaction physics up to $\sim 300\,\mathrm{TeV}$

So far:

- LHC data is well bracketed by cosmic ray models
- Cosmic ray community needs the data at 14 TeV and high η

Outlook

Helmholtz Young Investigator Group at KIT:
CMS forward physics / Pierre Auger Observatory