particle physics measurements at the highest energies with the Pierre Auger Observatory

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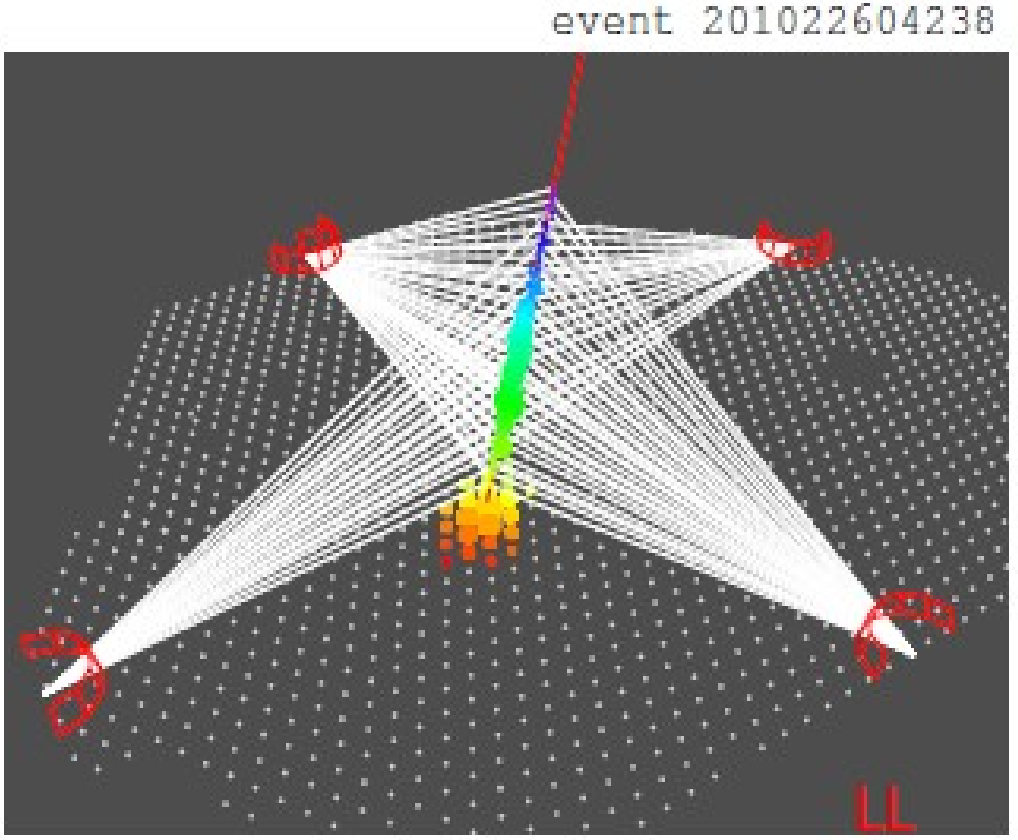
for the Pierre Auger Collaboration

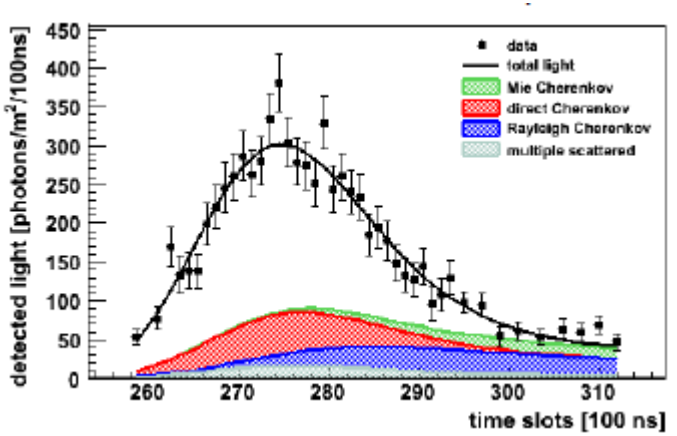
PIERRE AUGER OBSERVATORY

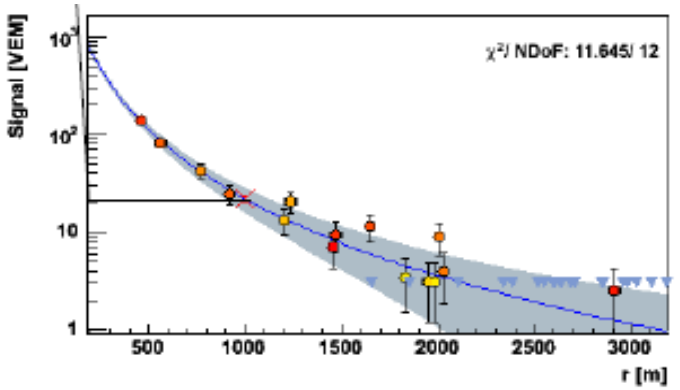
EPS-HEP Stockholm, July 2013

The Pierre Auger Observatory

- **precision Fluorescence Detector 4x180°x30° telescopes**
  images development of electrogmanetic shower component
- **high statistics Surface Detector 3000 km² ground array**
  samples electromagnetic and muonic shower at ground level



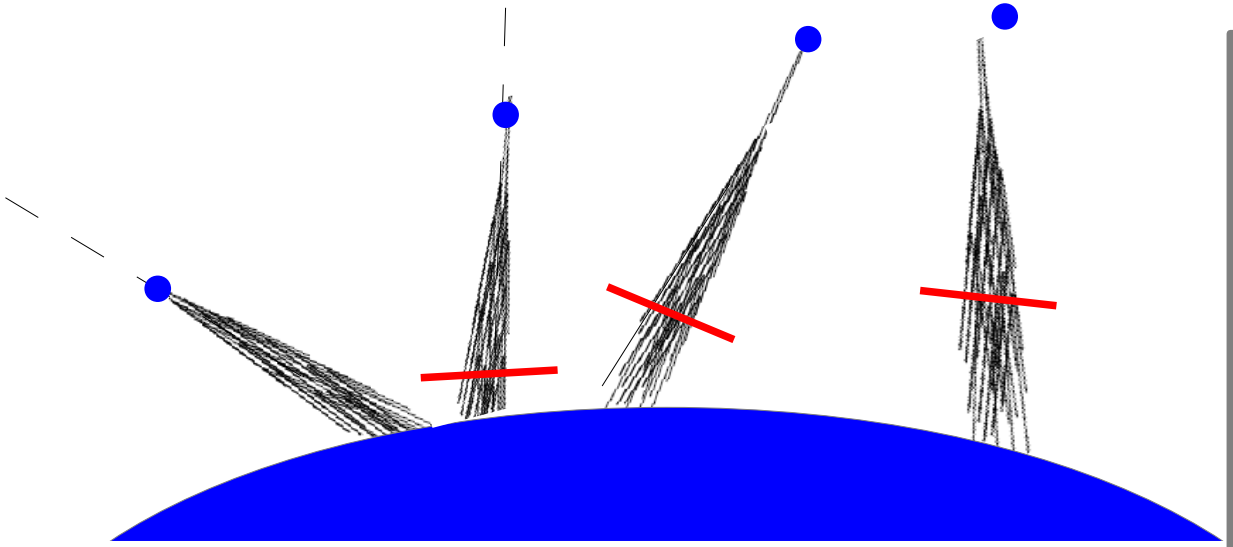




New FD energy scale: +15% / +10%; (22% --> 14% uncertainty)

Exploring the highest energy beams

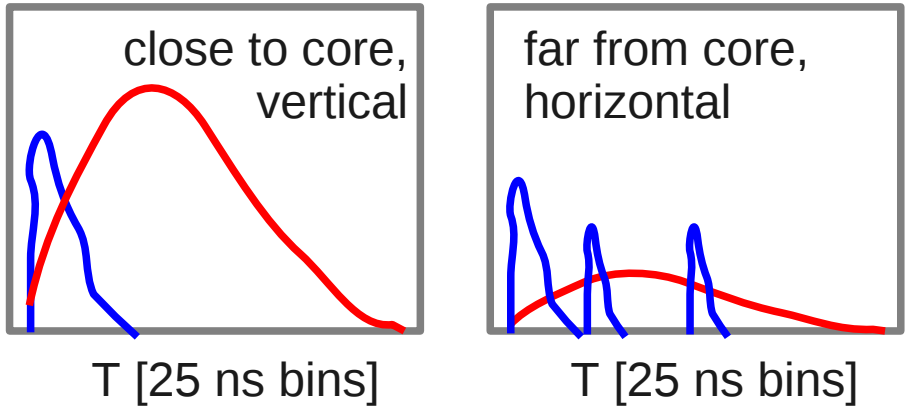
Neutrinos? Photons? Nuclei (p – Fe)?



Main variables relate to

depth of shower maximum: Xmax = X1 + DX

particle content at ground: Signal = μ + e/γ



Outline:

Limits of ν/γ

Xmax –> Cross-Section
–> Nuclear Mass

Muons –> Multiplicity
–> new Xmax

Hadronic Interactions

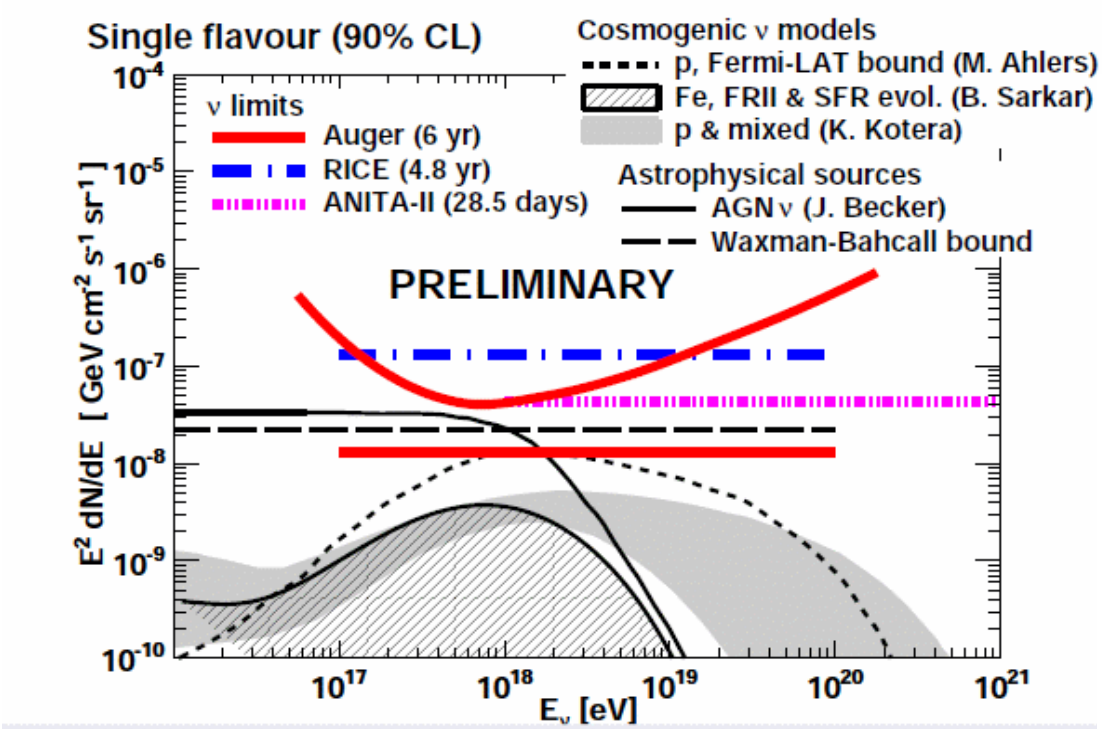
Limits on neutrino and photon fluxes

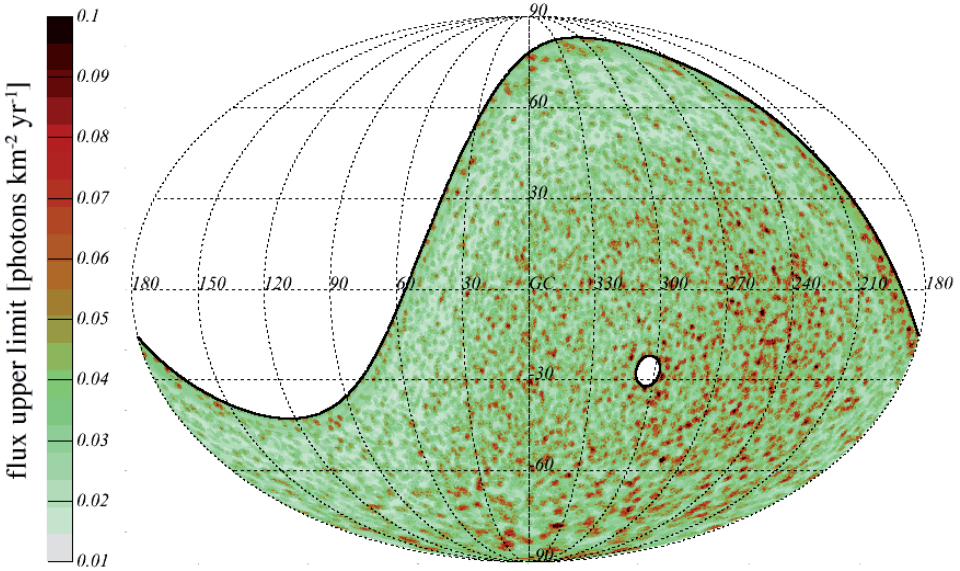
constraining production models, GZK predictions not reached yet

60° to 95° neutrino showers:

0 candidates (vs 0.2-0.6 from GZK;
2.2 IceCube PeV extrapolation with E^{-2})

Deep electromagnetic γ showers:
multivariate selection from nuclei
New directional limits < 0.1 γ/km²/yr



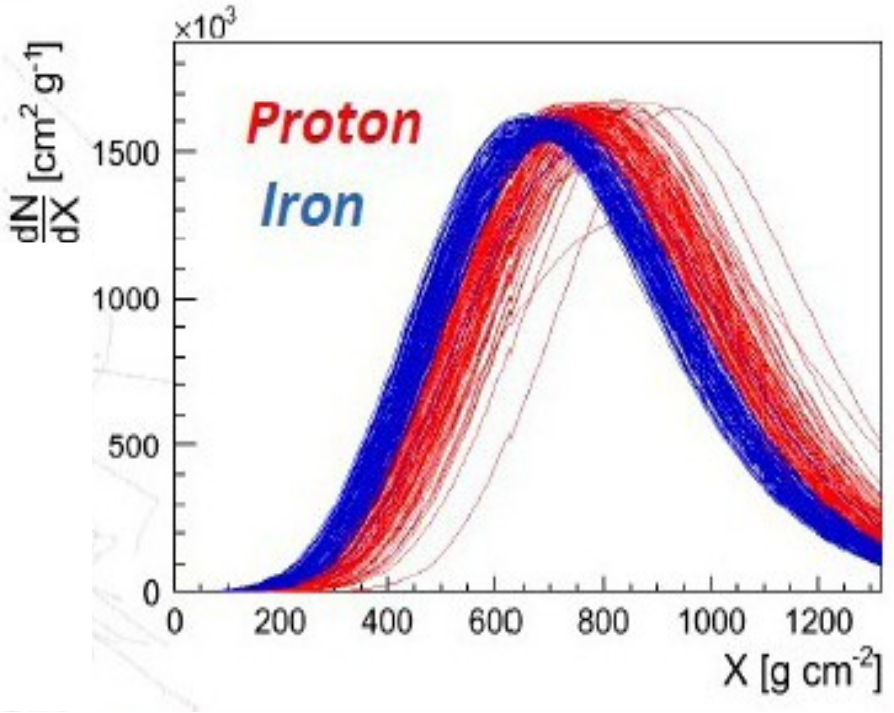


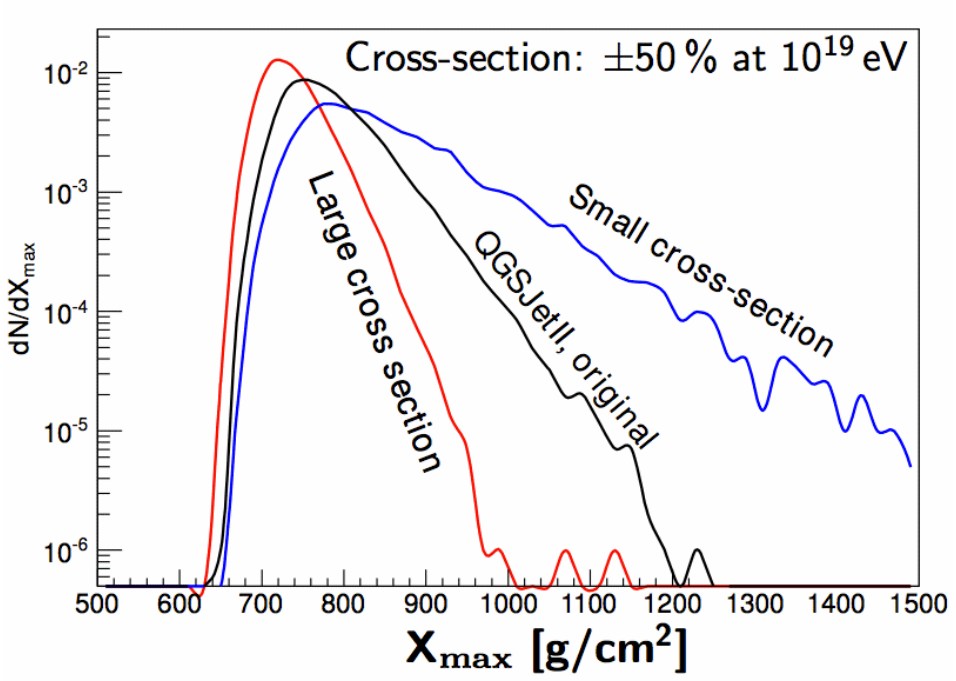
also low energy galactic neutrons are constrained using directions

Exploring the nuclei beam with Xmax = X1 + DX

Depends on cross-section and multiplicity of first interactions

Shower maximum of light nuclei is deeper and fluctuates more





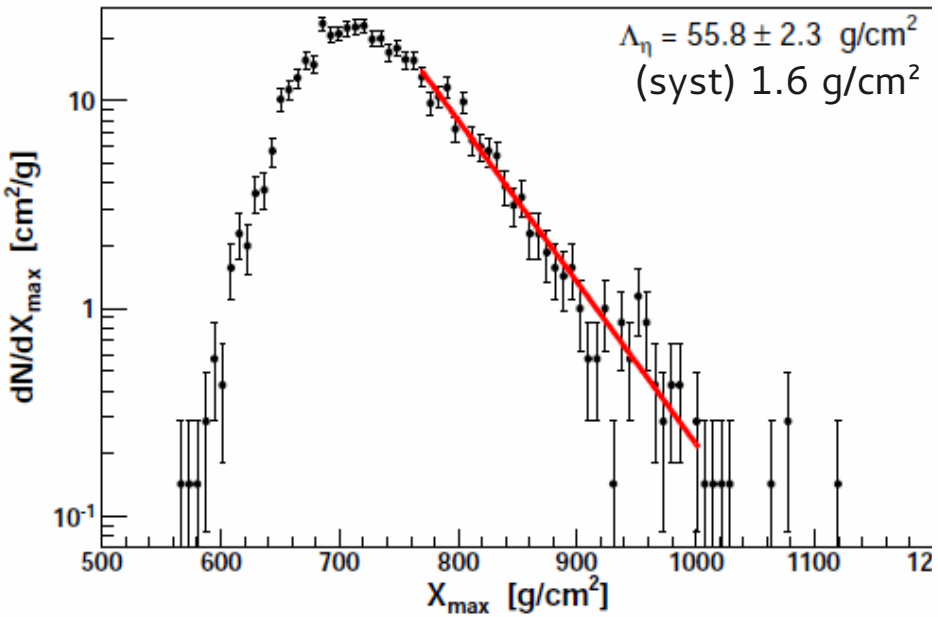
Can select proton sample in Xmax tail to measure cross-section

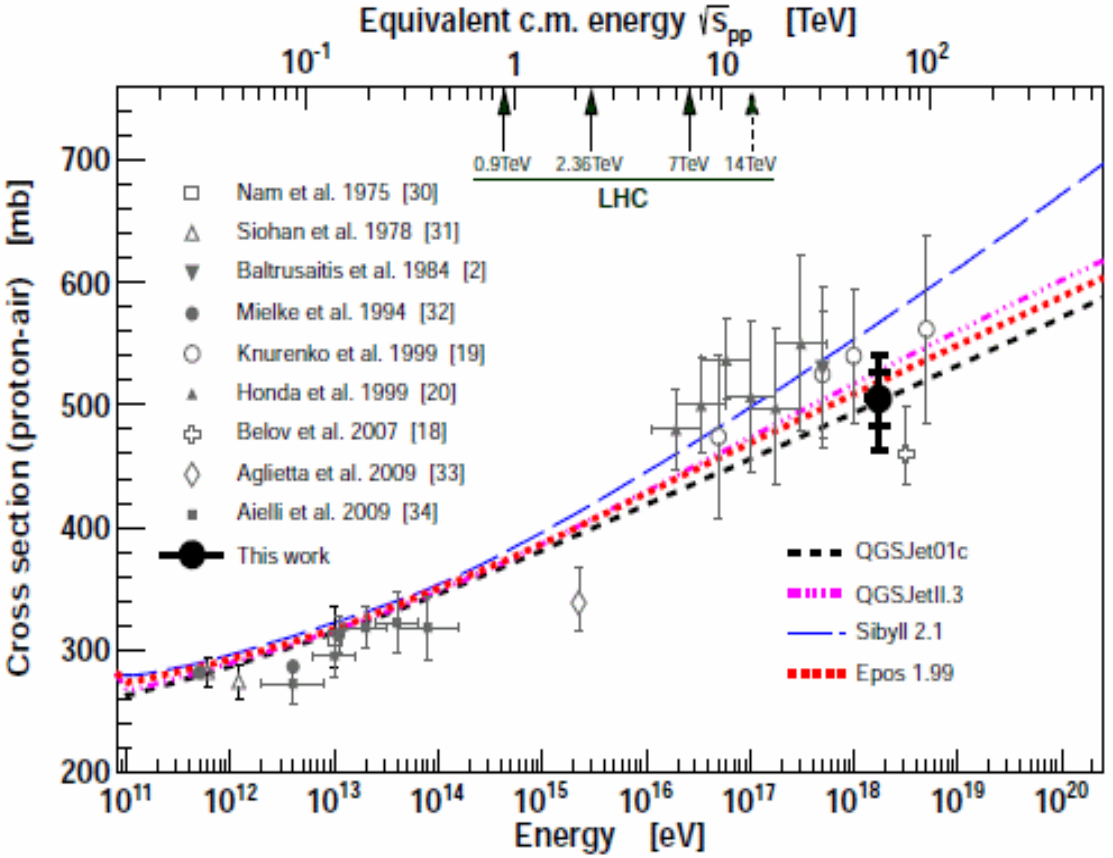
Unbiased selection:

using only geometries in which all the tail can be observed

p–air cross–section @ 1–3 EeV (laboratory frame)

3082 events out of 11628 allow unbiased observation of tail;
783 are in the exponential fitting range





cross-section: 505 +/- 22 (stat) +/- 18 (syst) mb

from changes in hadronic interaction models: (-8, + 19) mb

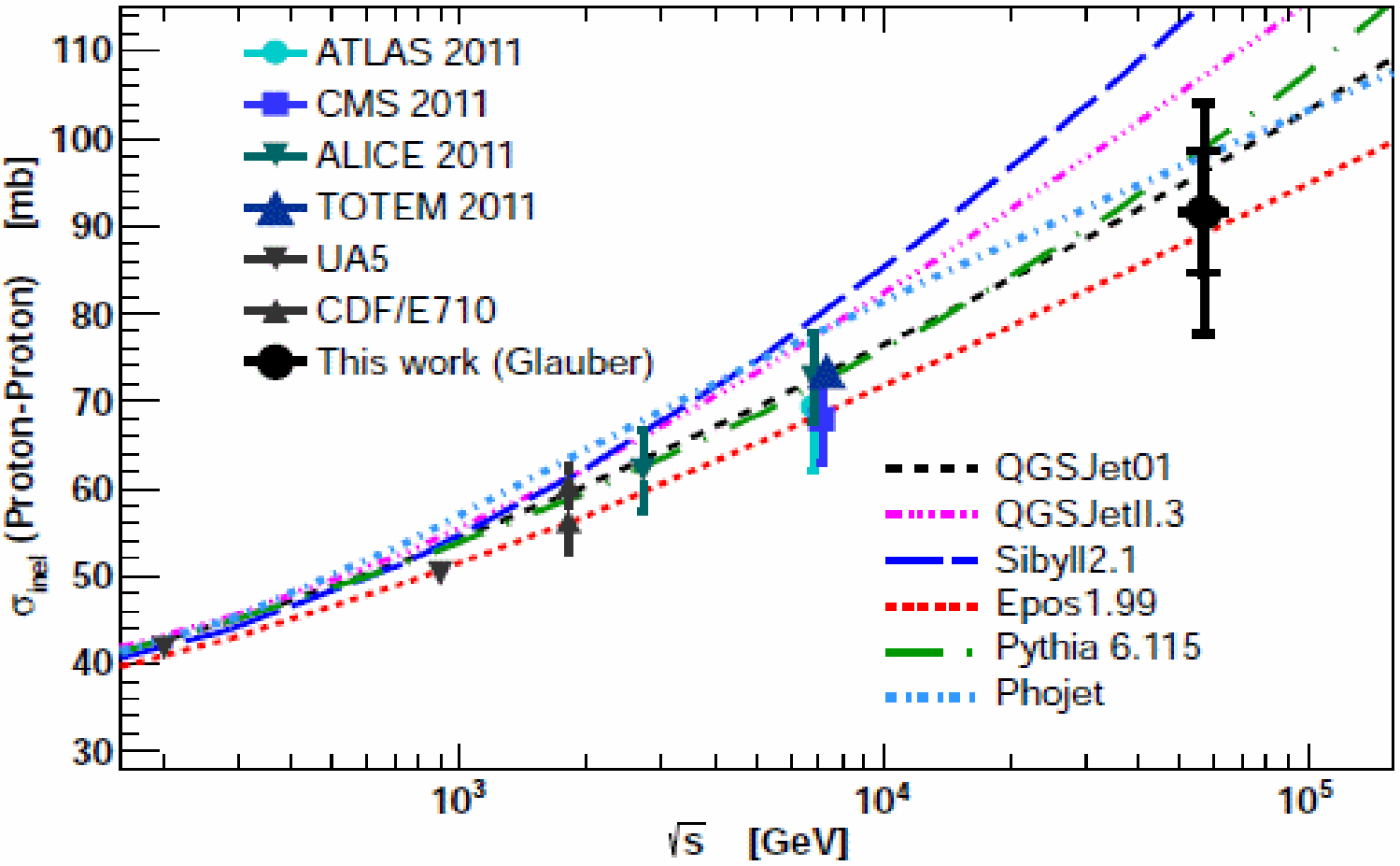
from unkown beam contamination [25% He, <0.5% γ]: (-30, +10) mb

proton cross-section @ 57 ±6 TeV (centre-of-mass)

proton-proton cross-section obtained with Glauber model

σ_{sp}	Inel	Total
(mb)	92	133
Stat	+7	+13
Syst	-11,+9	-20,+17
Air-p	+7	+16

PRL109 (2012) 062002

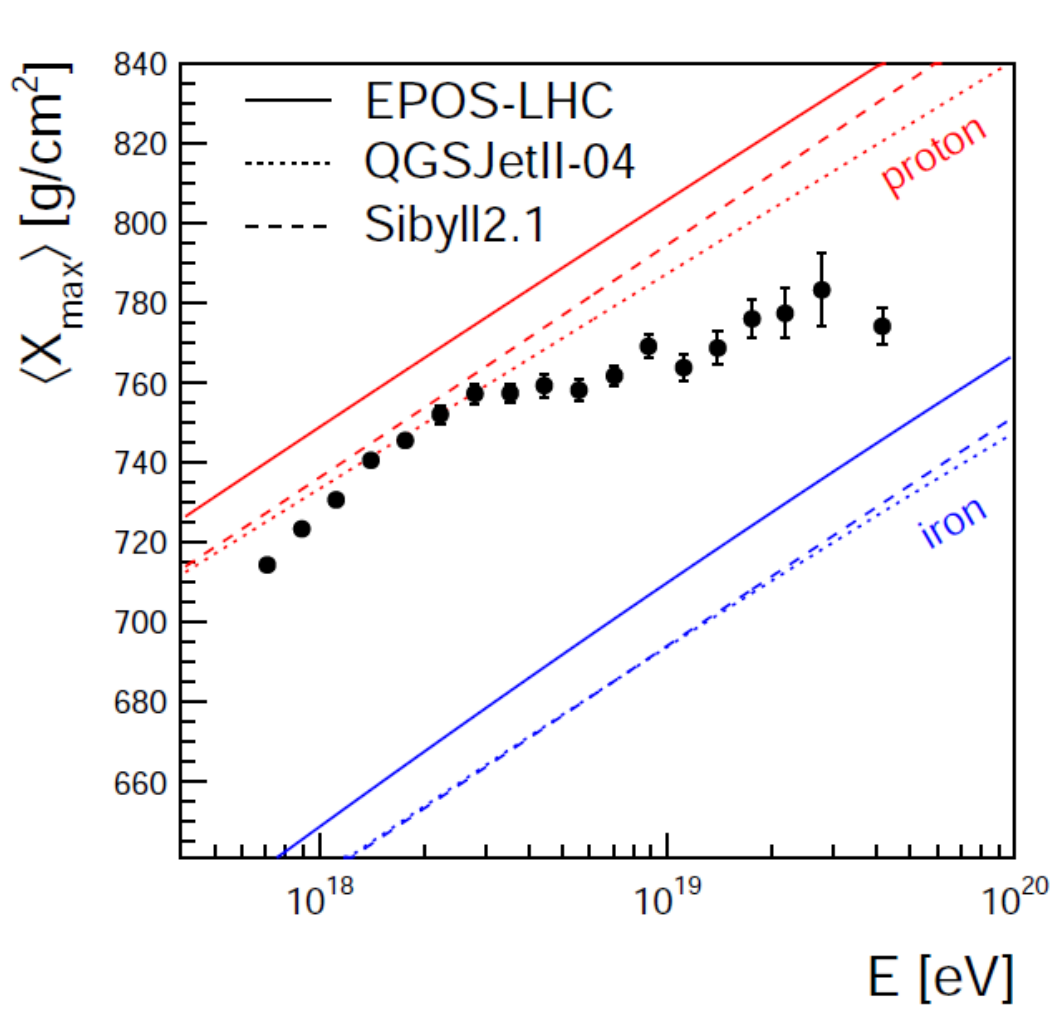


Uncertainties from the modelling of the elasticity slope, difractive ratios, and nuclear density profile, constrained with models

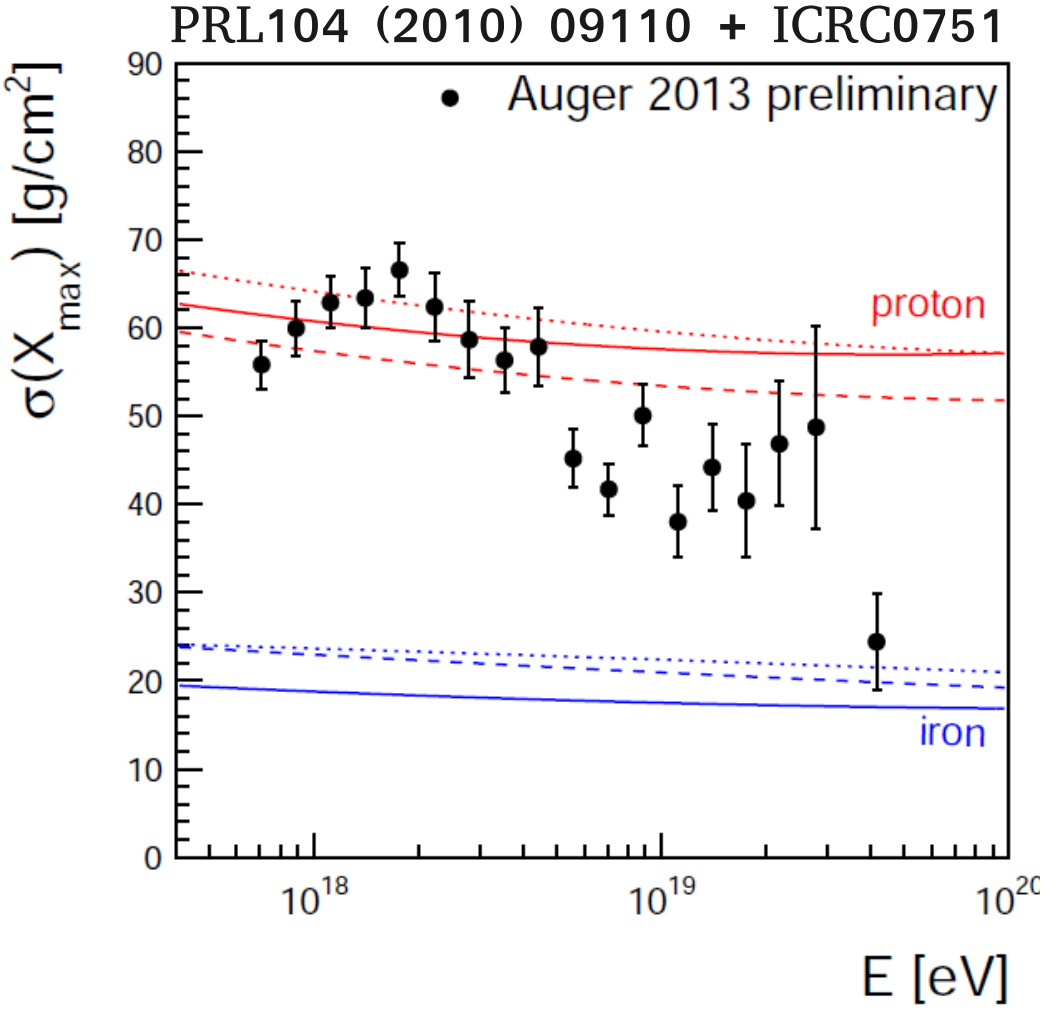
in good agreement with extrapolation of also later LHC results

Towards measurements at higher energies

Xmax unbiased selection in all the possible range



PRL104 (2010) 09110 + ICRC0751



Protons at lower energies... may be not so at higher energies...

Interpretation depends on hadronic interaction modelling

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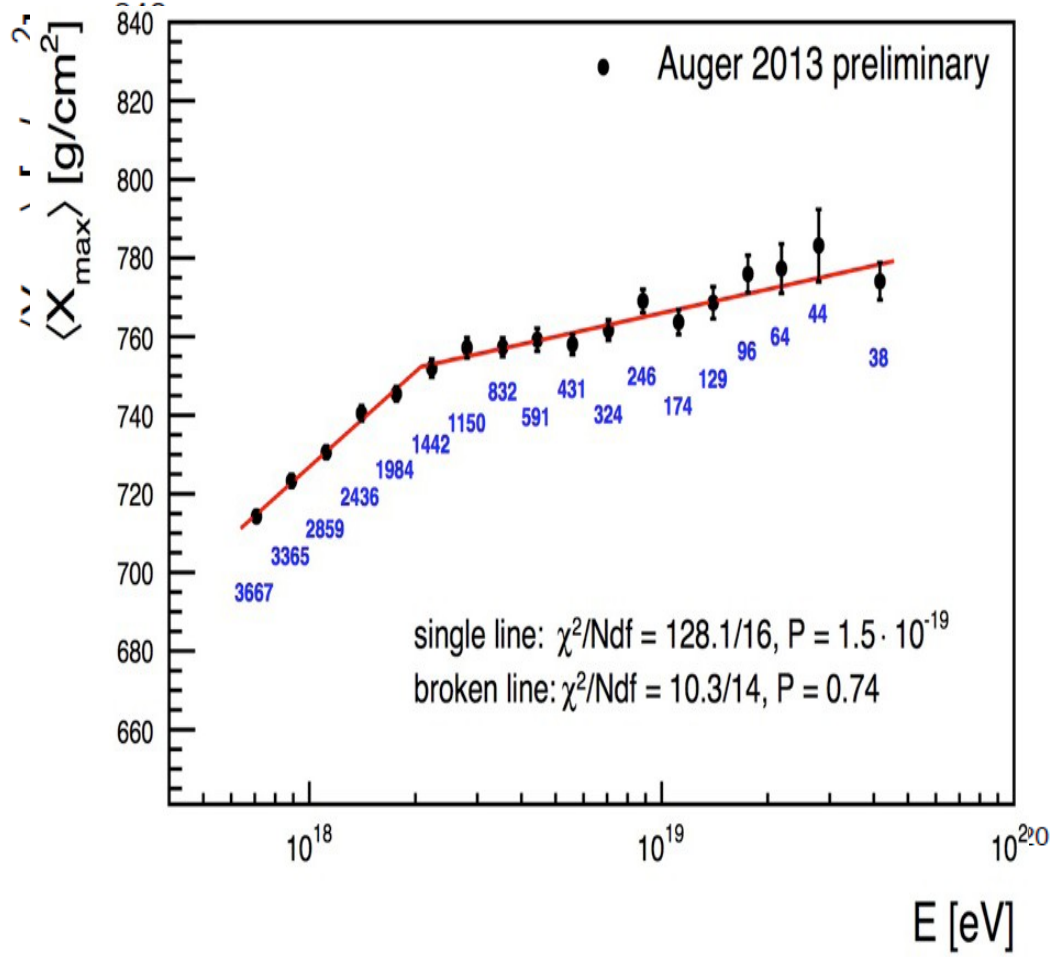

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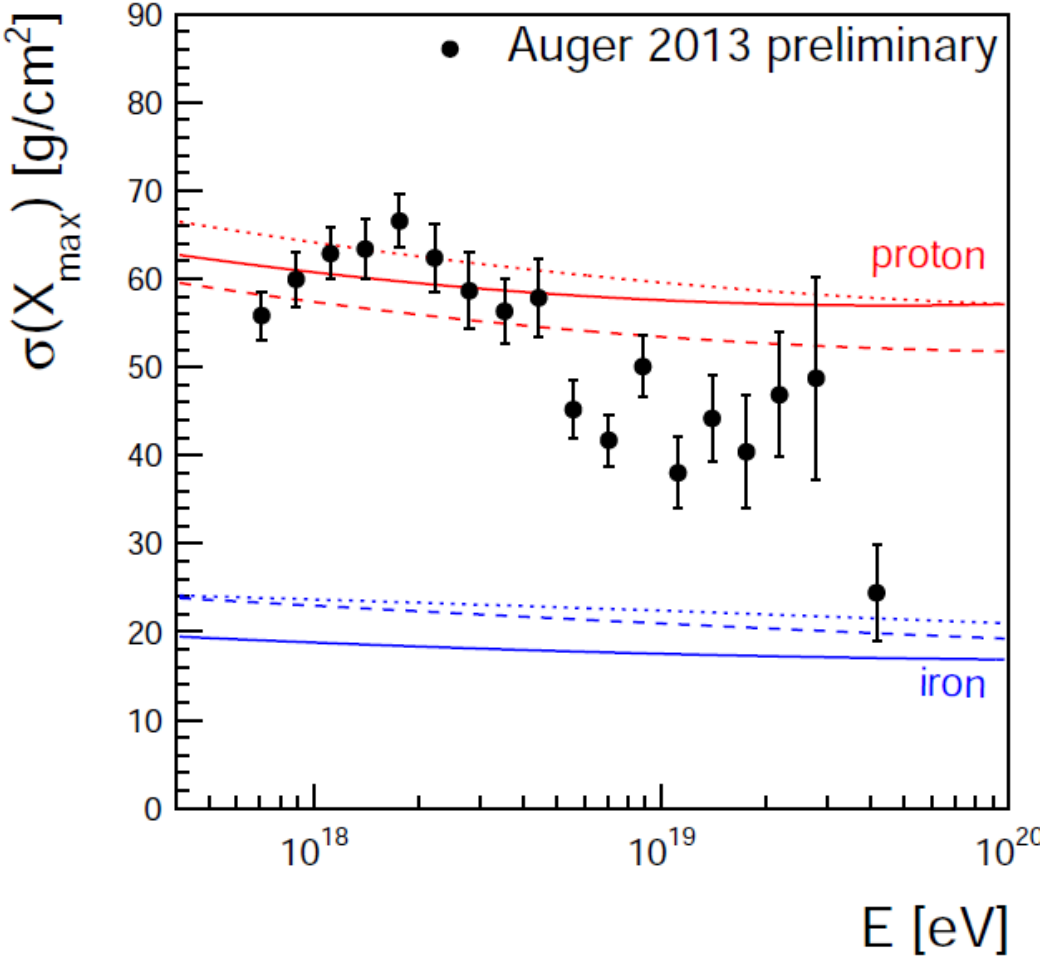

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Interpretation depends on hadronic interaction modeling

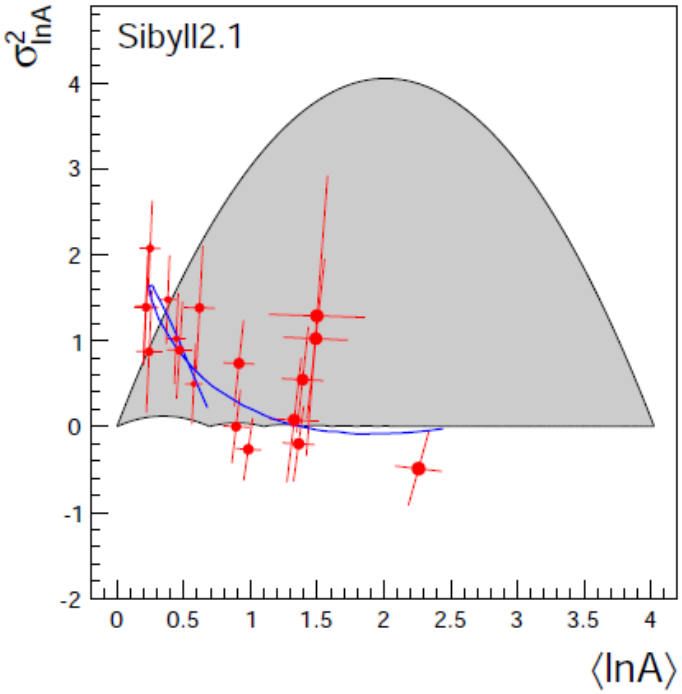
Nuclear mass composition and hadronic models

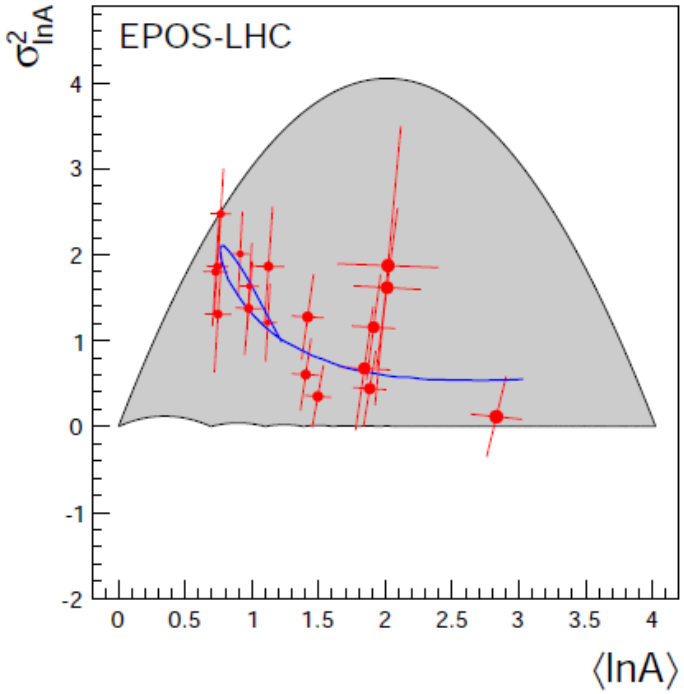
Xmax distribution depends on the lnA distribution in the beam

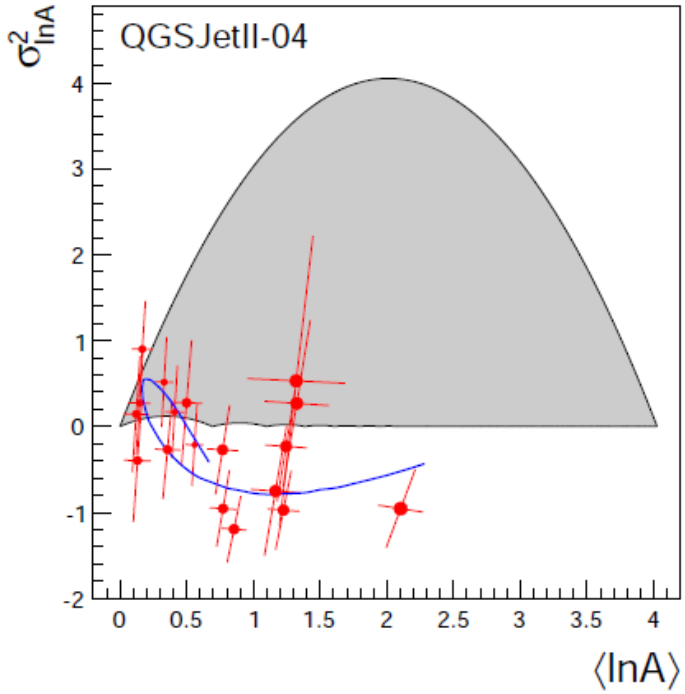
$\langle X_{max} \rangle = \langle X_{max} \rangle_p - f(E) \langle \ln A \rangle$;

$\sigma^2(X_{max}) = \langle \sigma^2 \rangle + f^2(E) (\langle \ln A^2 \rangle - \langle \ln A \rangle^2)$

JCAP 1302 (2013) 026 + ICRC0690







Mass increases with decreasing dispersion => hard spectrum source?

but some tension with models tunned to accelerator (LHC) data

and extrapolated in both energy and rapidity for cosmic ray physics

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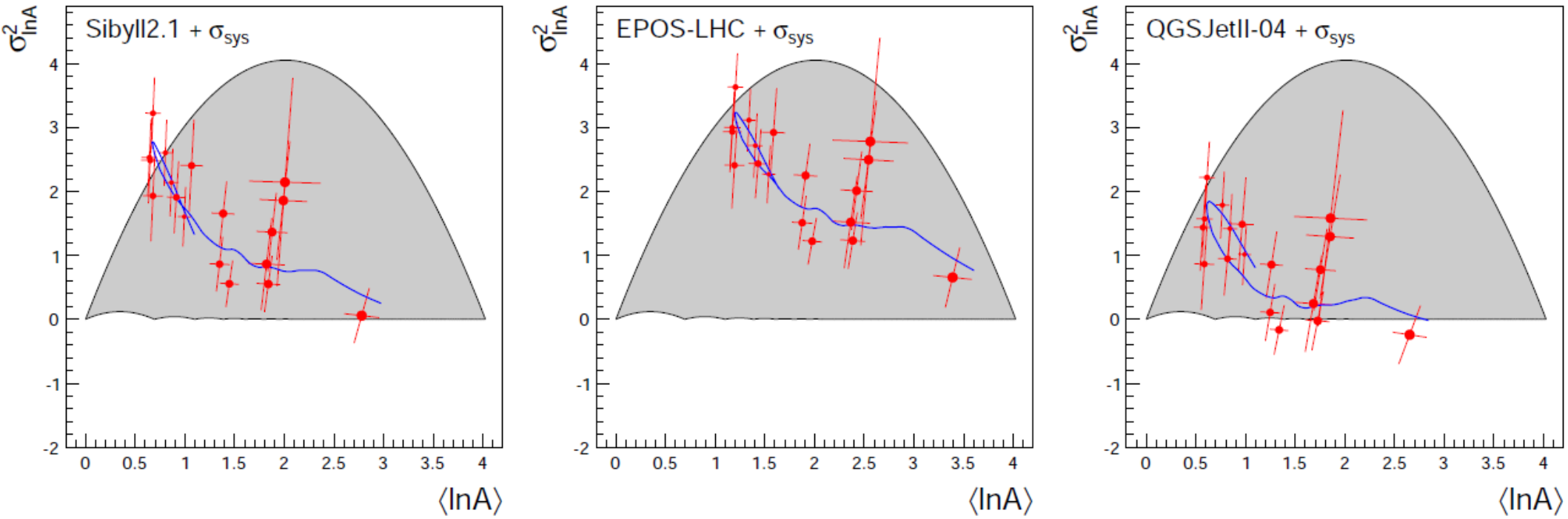
Shifted by systematic uncertainty



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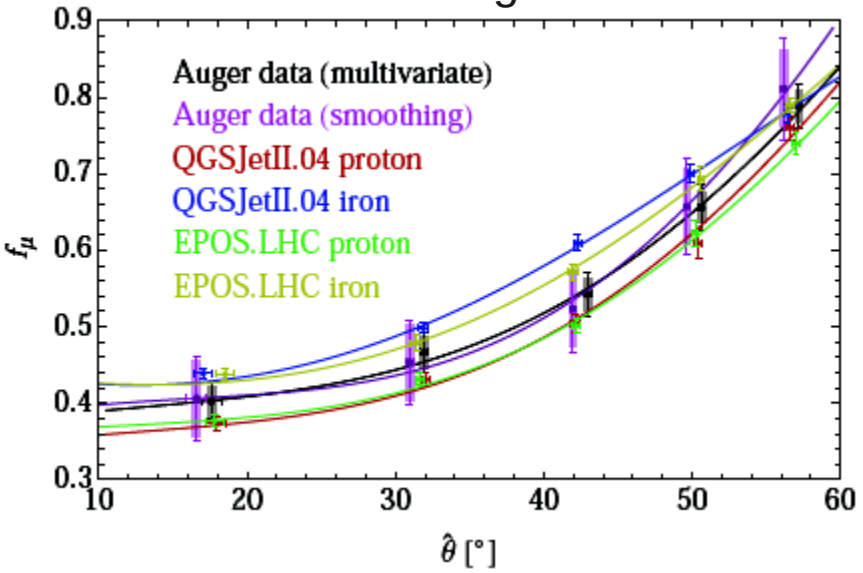
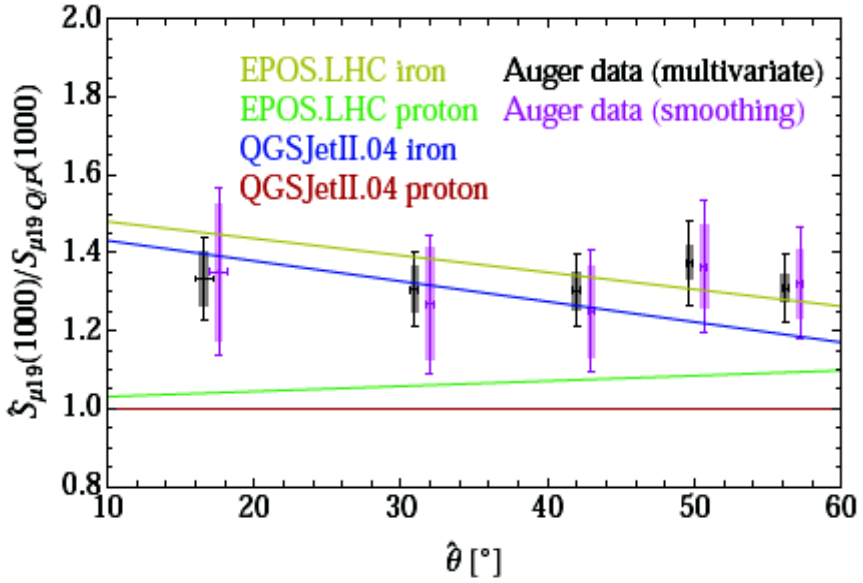
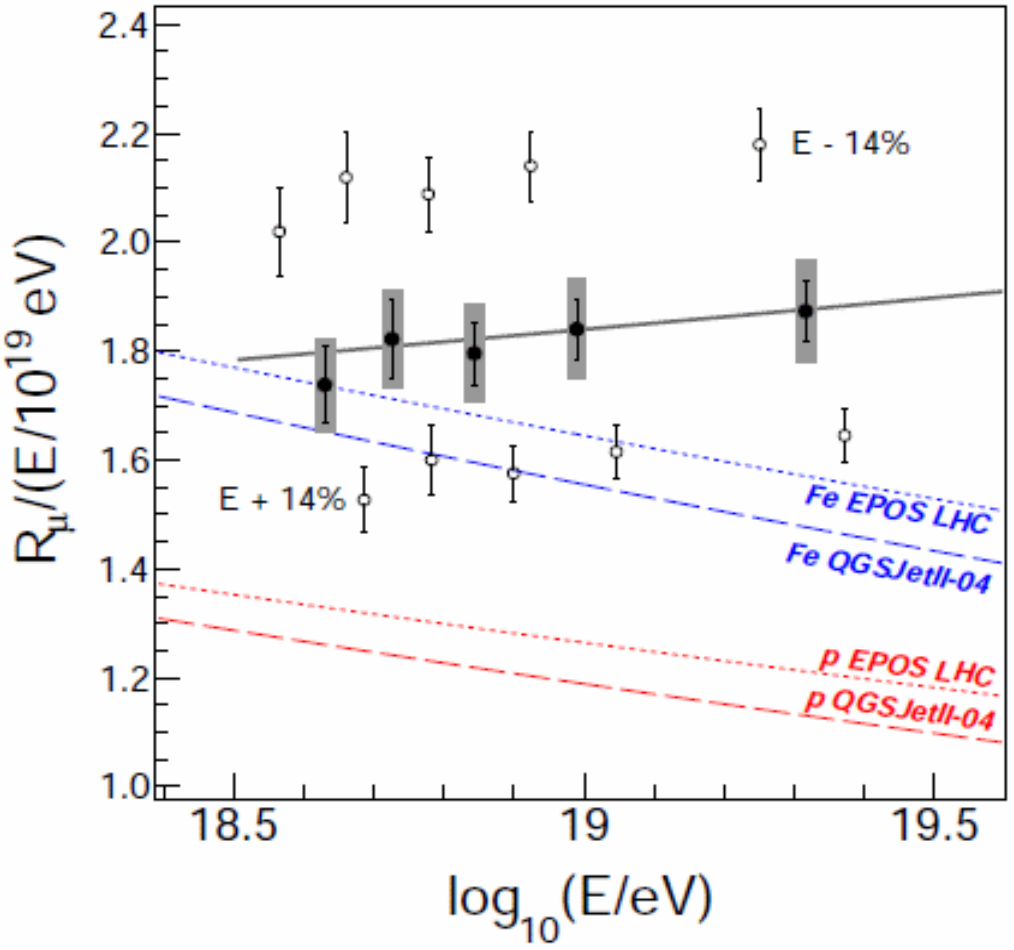
SD analysis: muon numbers in ground signals

Dependence on zenith angle (at 10 EeV) and total energy (at 62°)

fraction of muon signal at 1000 m







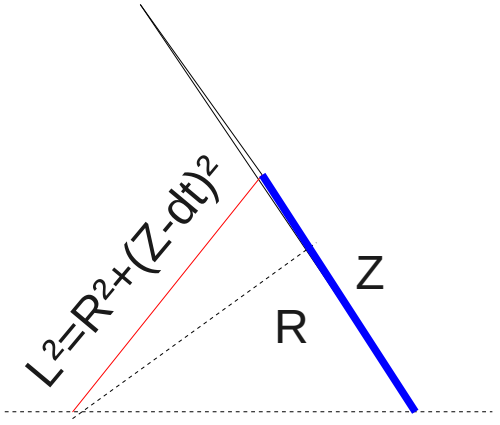
three consistent analyses

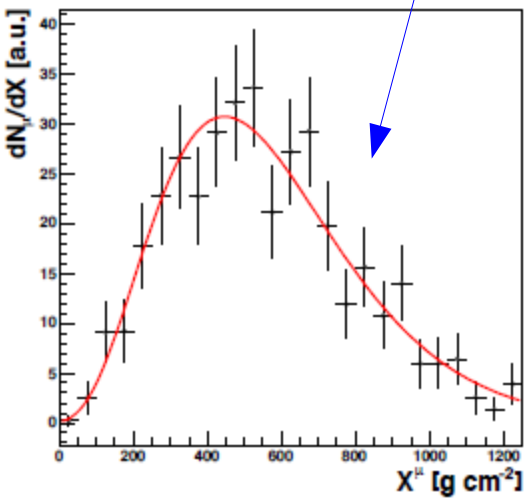
but only Fe at 10 EeV is disfavoured

slope vs. constant lnA @1.7 σ

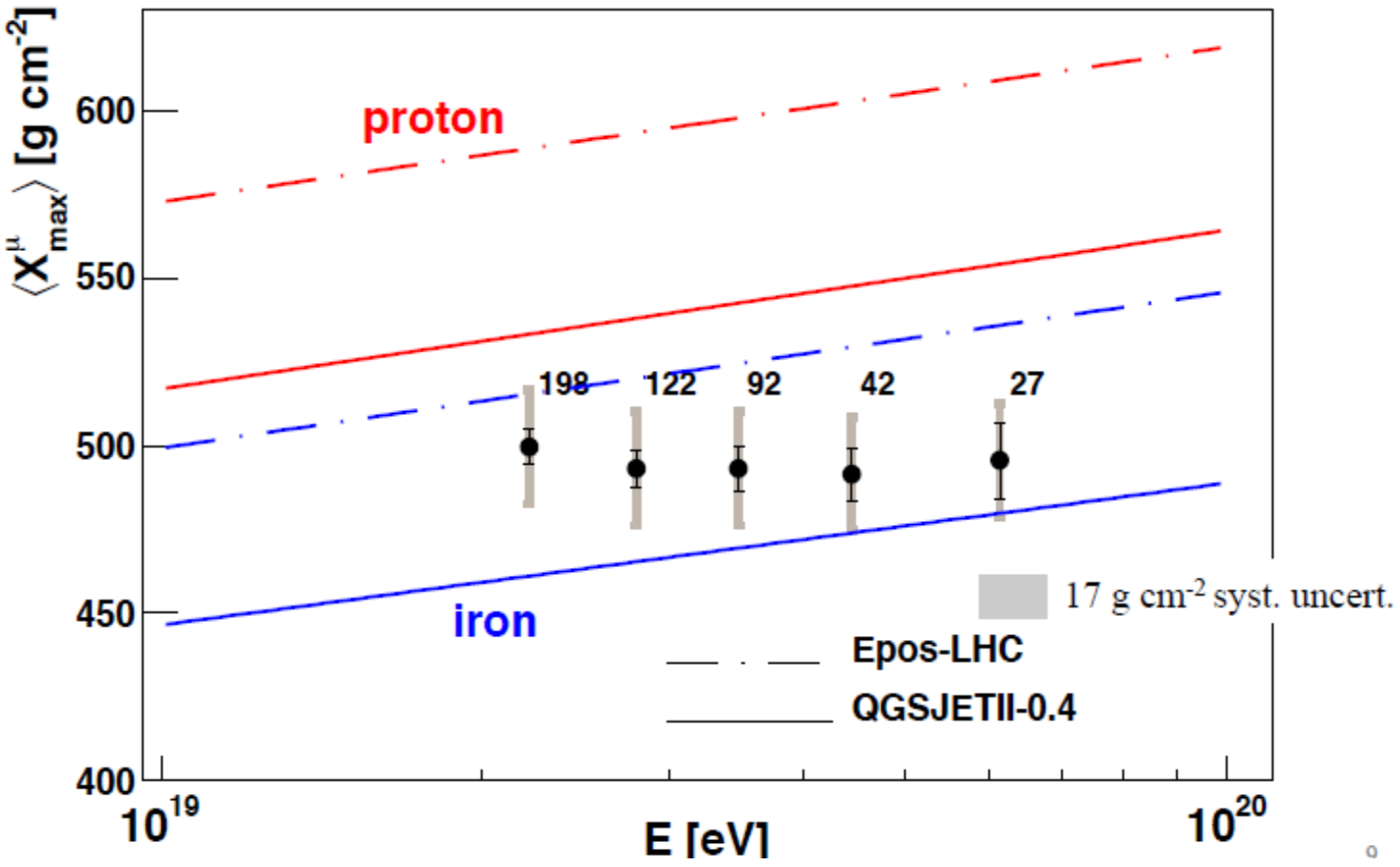
Increasing the "Xmax" data sample with SD muons

$\langle X^{\mu}_{max} \rangle$ from arrival times in inclined showers, far from the core





ICRC0694

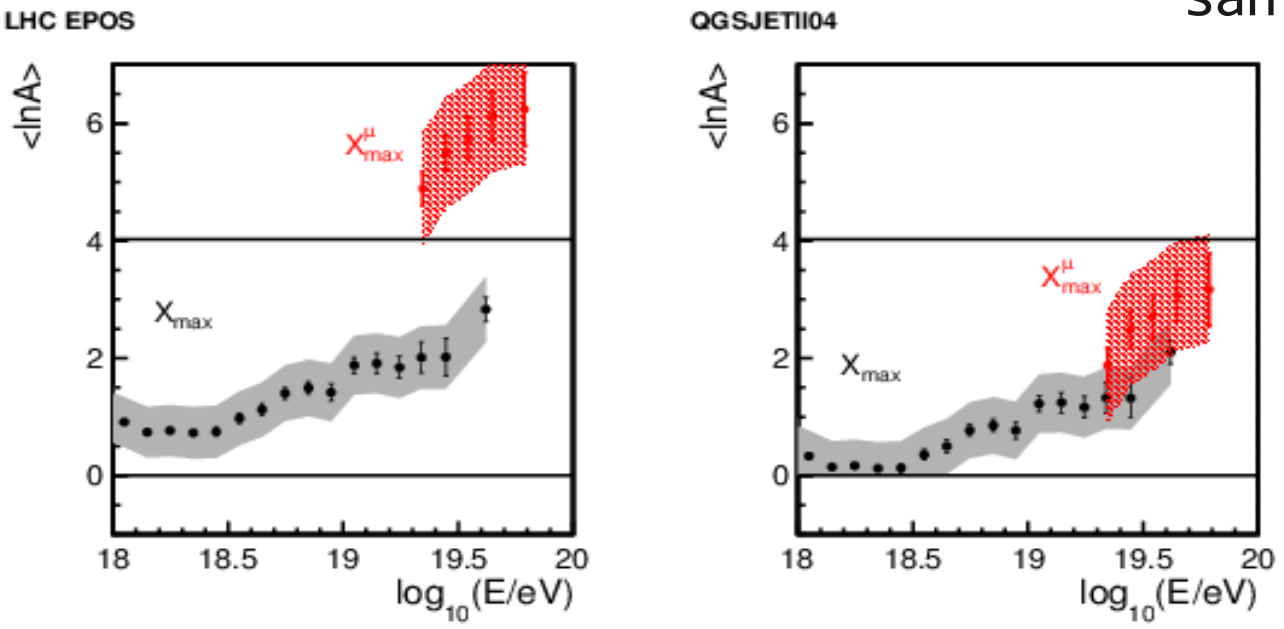


Results generally consistent with $\langle X_{max} \rangle = \langle X^{\mu}_{max} \rangle + \Delta$

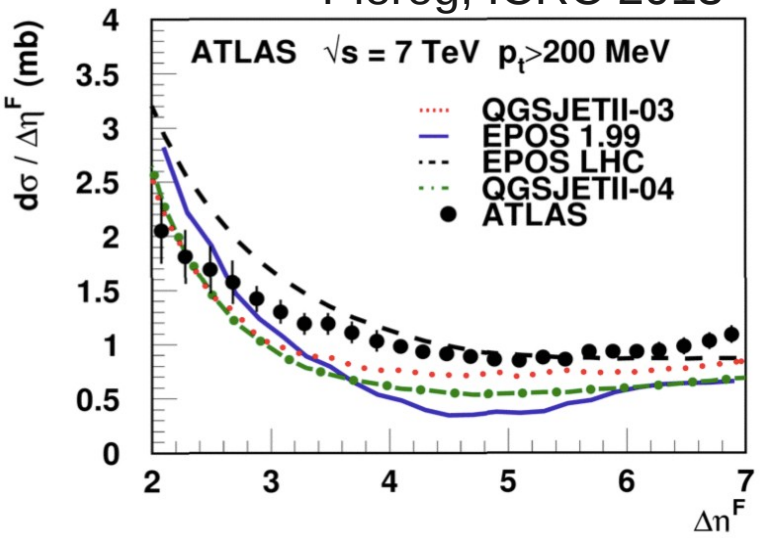
same cross-section (<X1>), different development (<DX>)

Towards a consistent picture of showers

both <X_{max}> and <X^{μ}_{max}> should follow from the same <lnA>, with same <X1>, different <DX>



Pierog, ICRC 2013



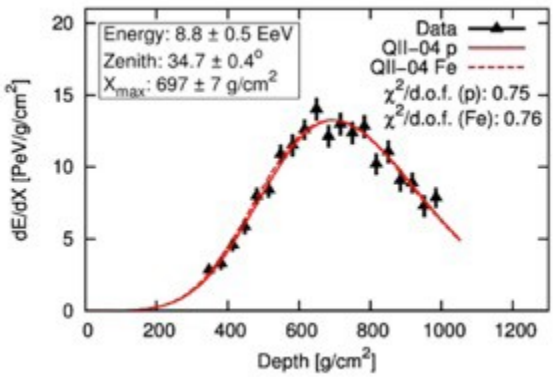
interpretation sensitive also to
particle physics variables of shower development
multiplicity, inelasticity, baryon ratio and rapidity gap distributions

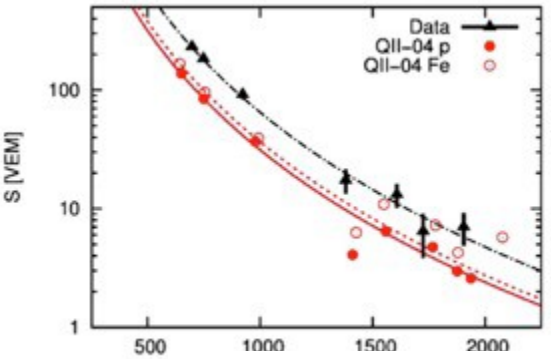
High energy cosmic rays can be used to improve hadronic models

Summary

- No neutral particle signals yet
  - constrain exotic production and galactic models
  - cosmogenic production in reach soon
- Protons at EeV scale (pp @ 60 TeV)
  - cross-section consistent with LHC extrapolation
  - good calibration point for following analyses
- Heavier nuclei at higher energies ?
  - can be difficult for astrophysical source models
  - hadronic interaction models are also not perfect
- Hadronic interactions tested with more observables
  - models will be improved by the Auger data
  - direct measurements and consistency checks

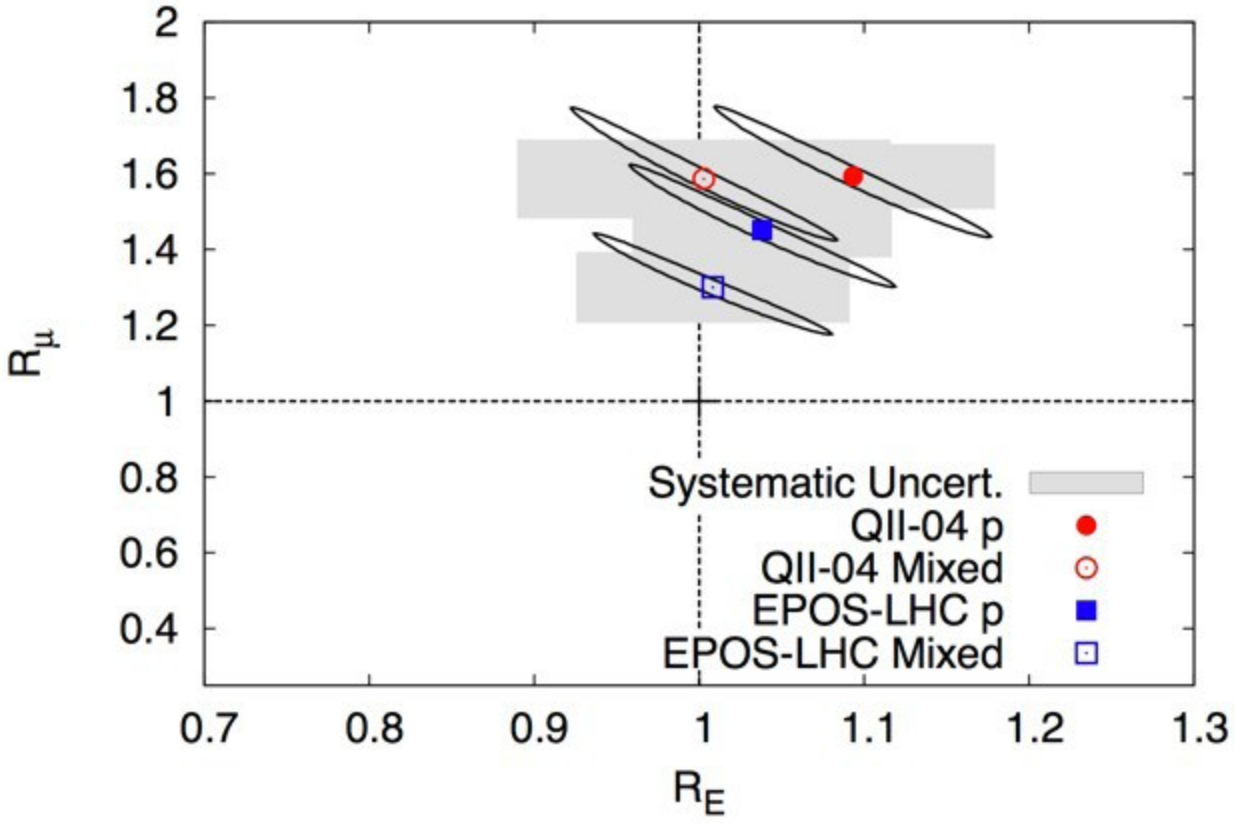
Hadronic interaction models and FD/SD consistency



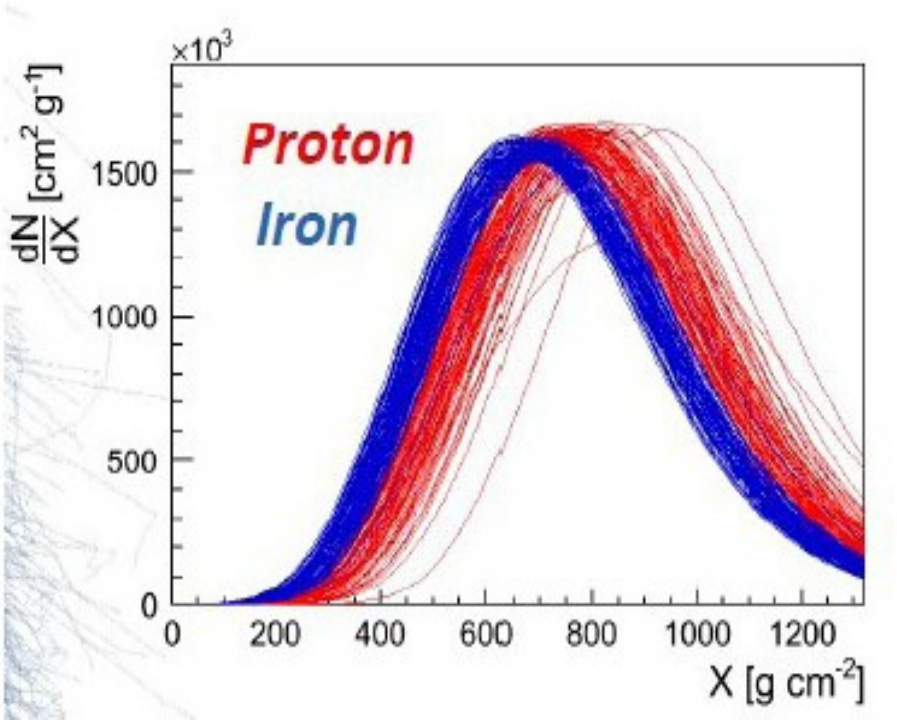


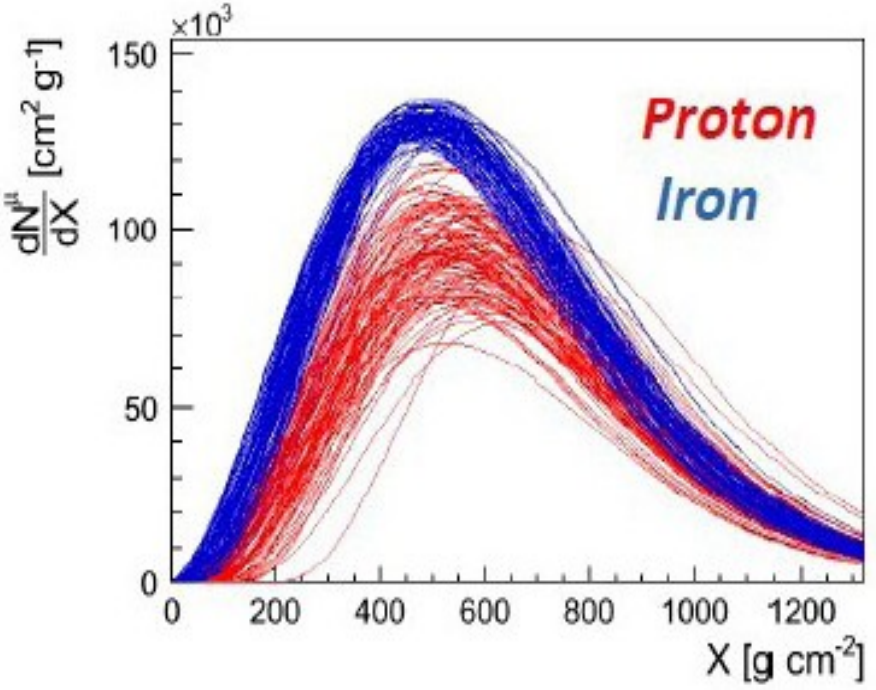
Simultaneous
fit of
longitudinal FD profile
and
lateral SD profile

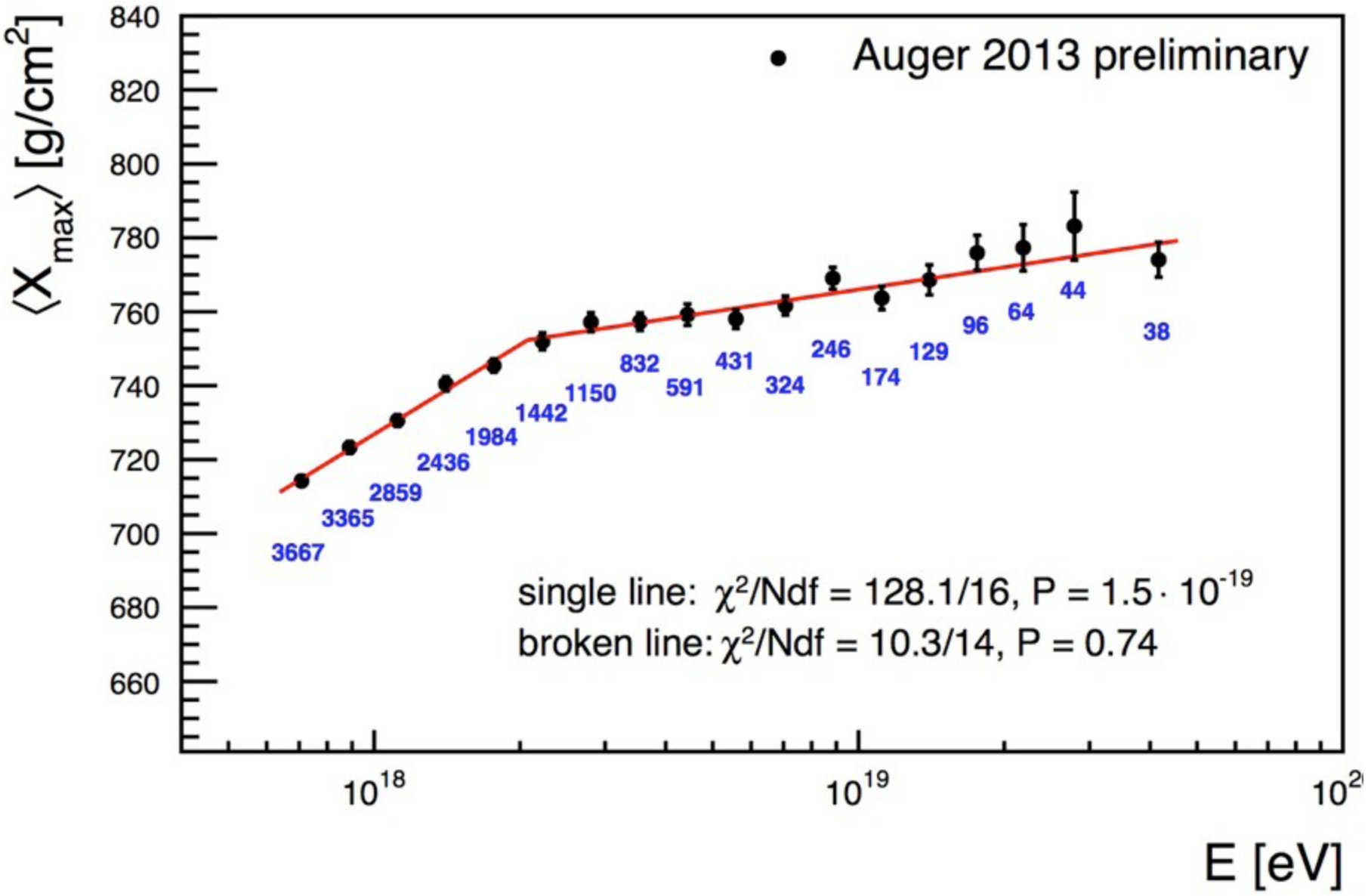
need rescalings to get
coherent results



Electromagnetic and Muonic longitudinal profiles






Auger 2013 preliminary
$\langle X_{max} \rangle$ [g/cm^2]
840
820
800
780
760
740
720
700
680
660
3667
3365
2859
2436
1984
1442
1150
832
591
431
324
246
174
129
96
64
44
38
single line: χ^2/Ndf = 128.1/16, P = 1.5 · 10^{-19}
broken line: χ^2/Ndf = 10.3/14, P = 0.74
10^{18}
10^{19}
E [eV]

Changes in elongation rate with new energy scale