Hadronic interactions at ultra high energies

tests with the Pierre Auger Observatory

LIP

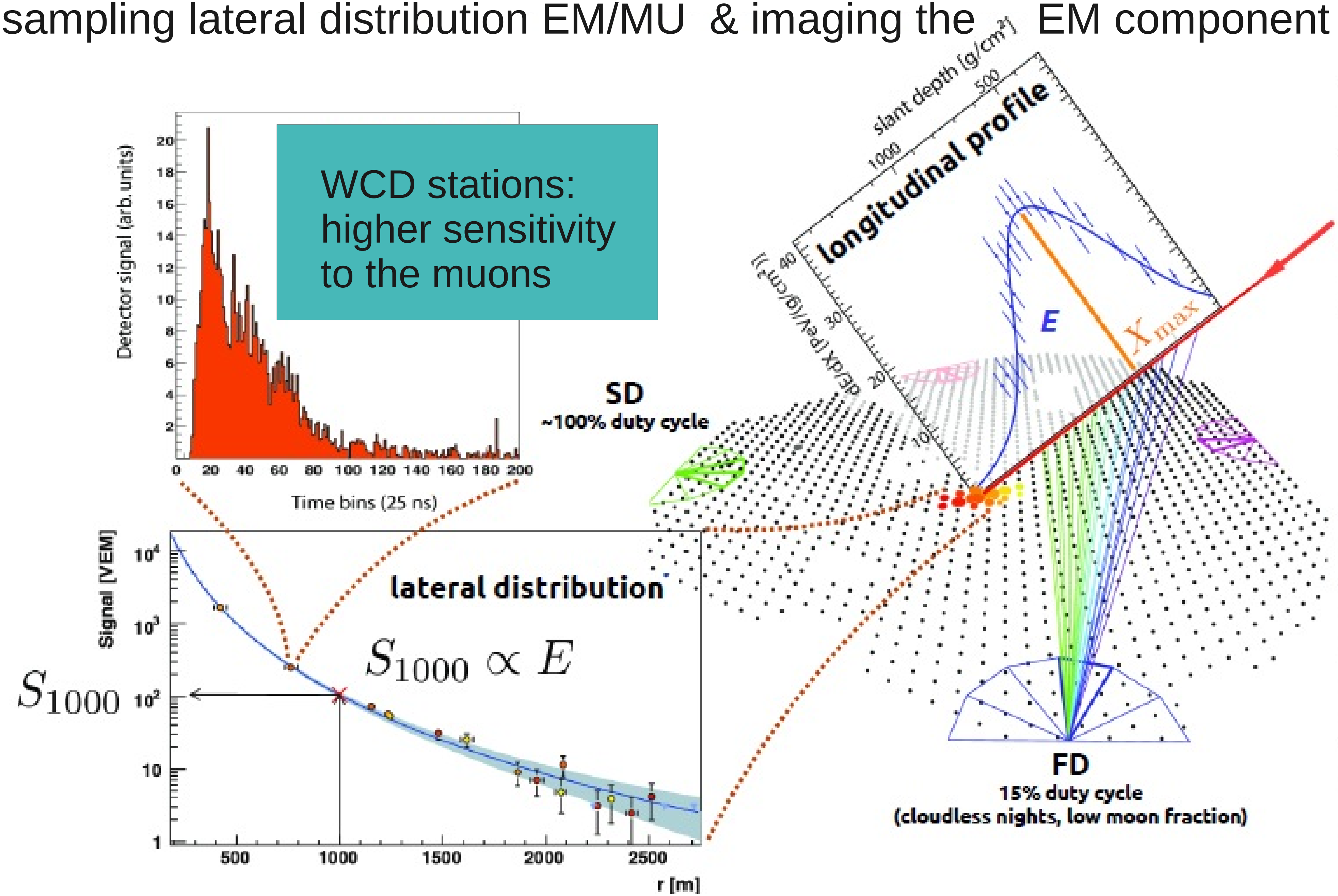
Sofia Andringa (LIP) for the Pierre Auger Collaboration

PIERRE AUGER OBSERVATORY

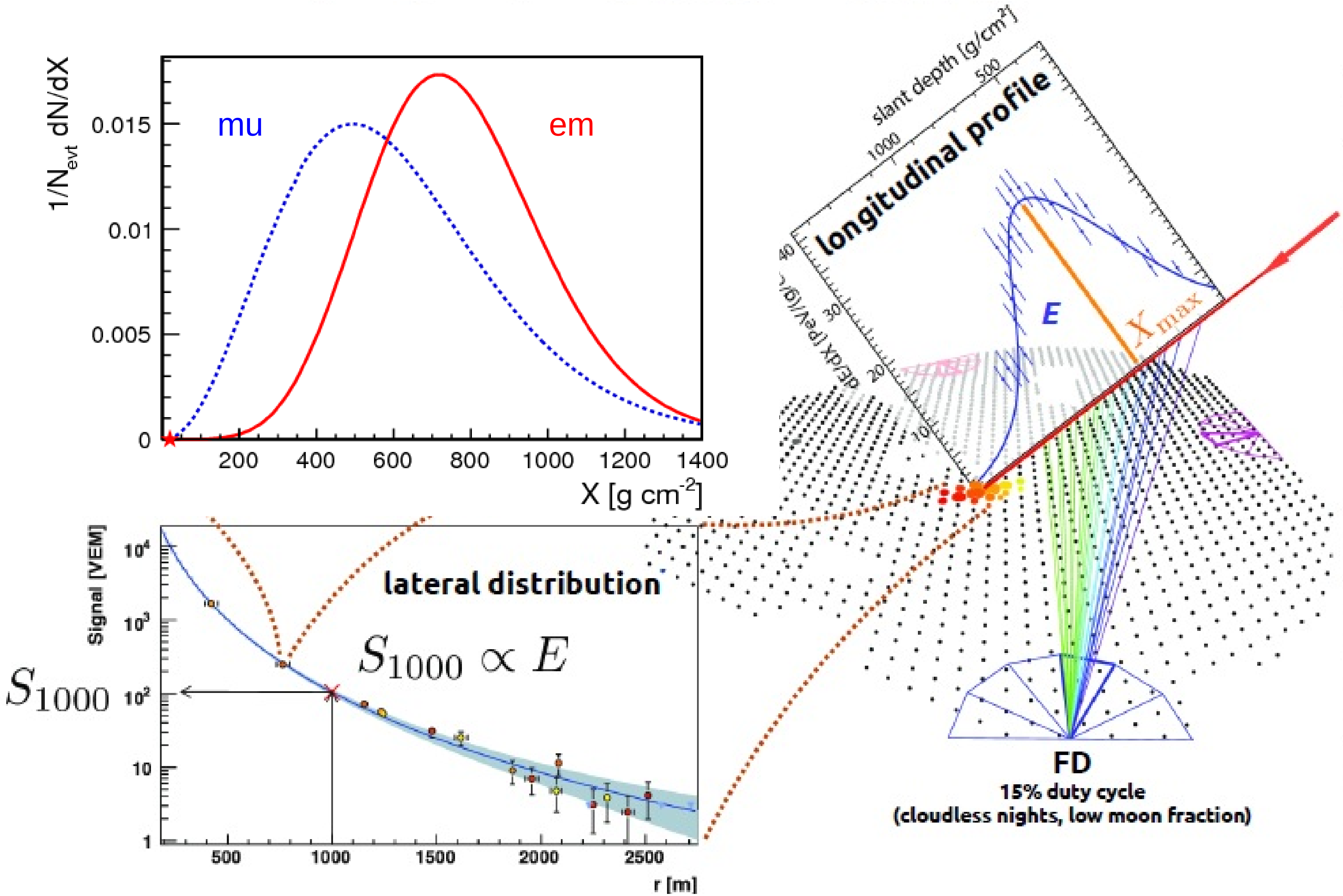
EDS Blois 2017, Prague, June 2017
The 17th conference on Elastic and Diffractive scattering

the Pierre Auger Observatory

1600 SD stations w/ 1500 m (and 750 m) spacing + 27 FD telescopes
sampling lateral distribution EM/MU & imaging the EM component



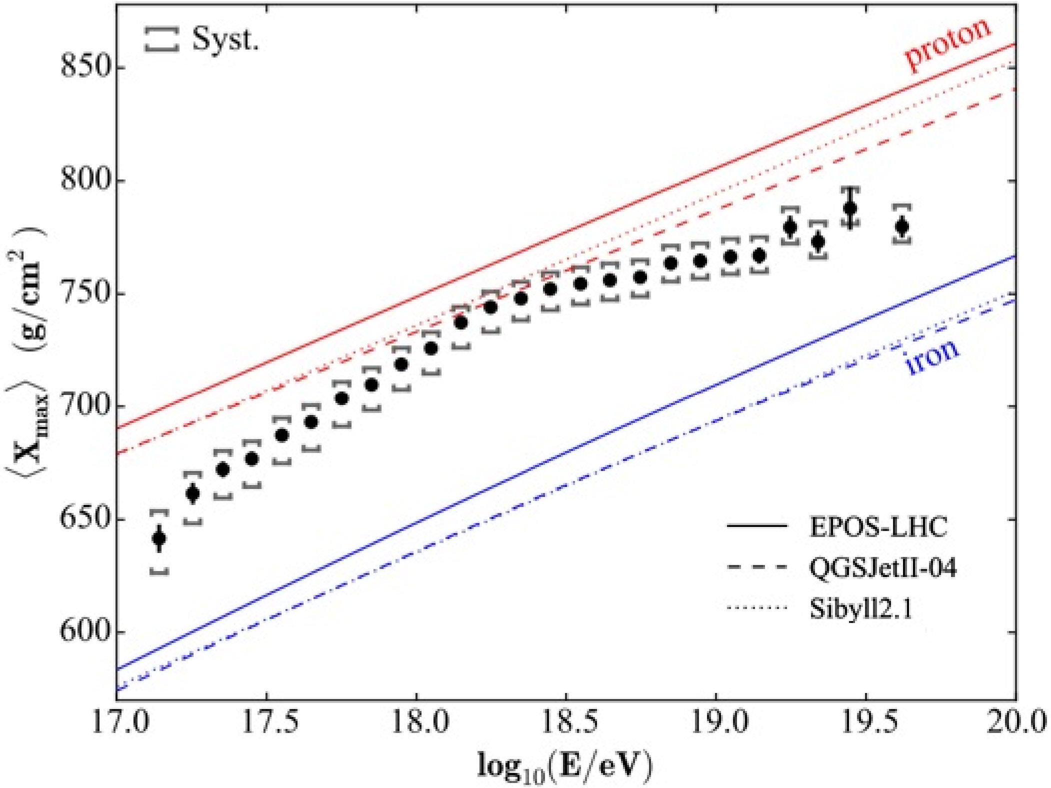
the Pierre Auger Observatory

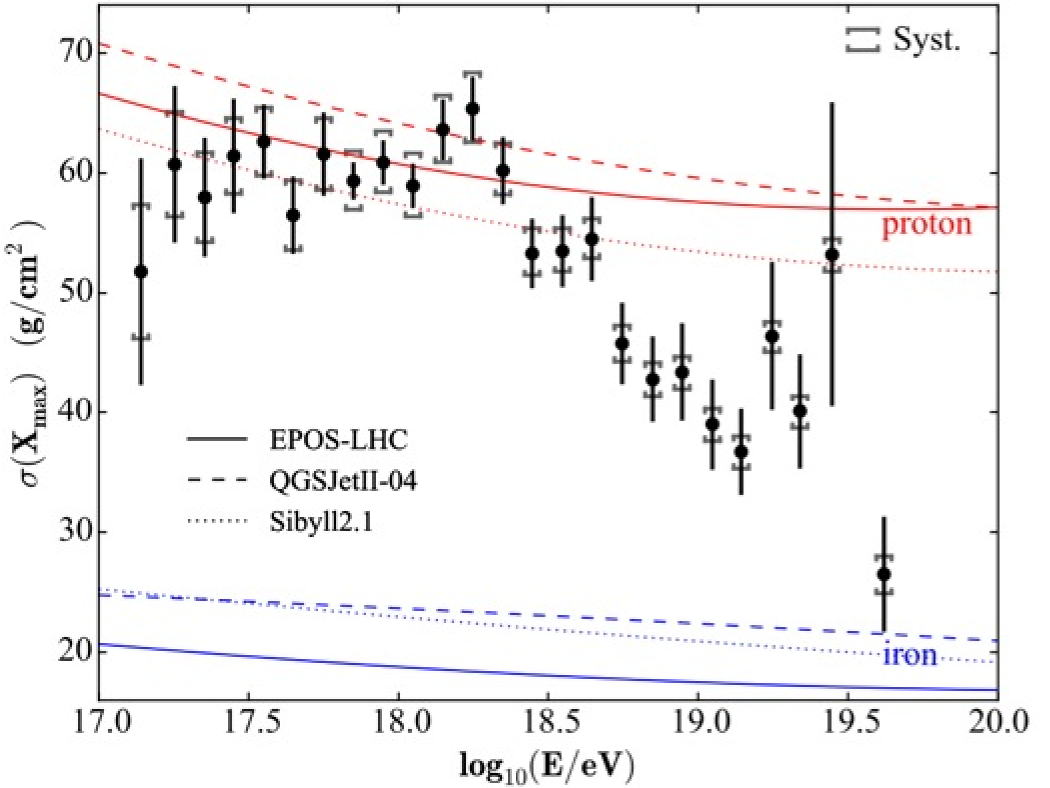


electromagnetic shower: Xmax

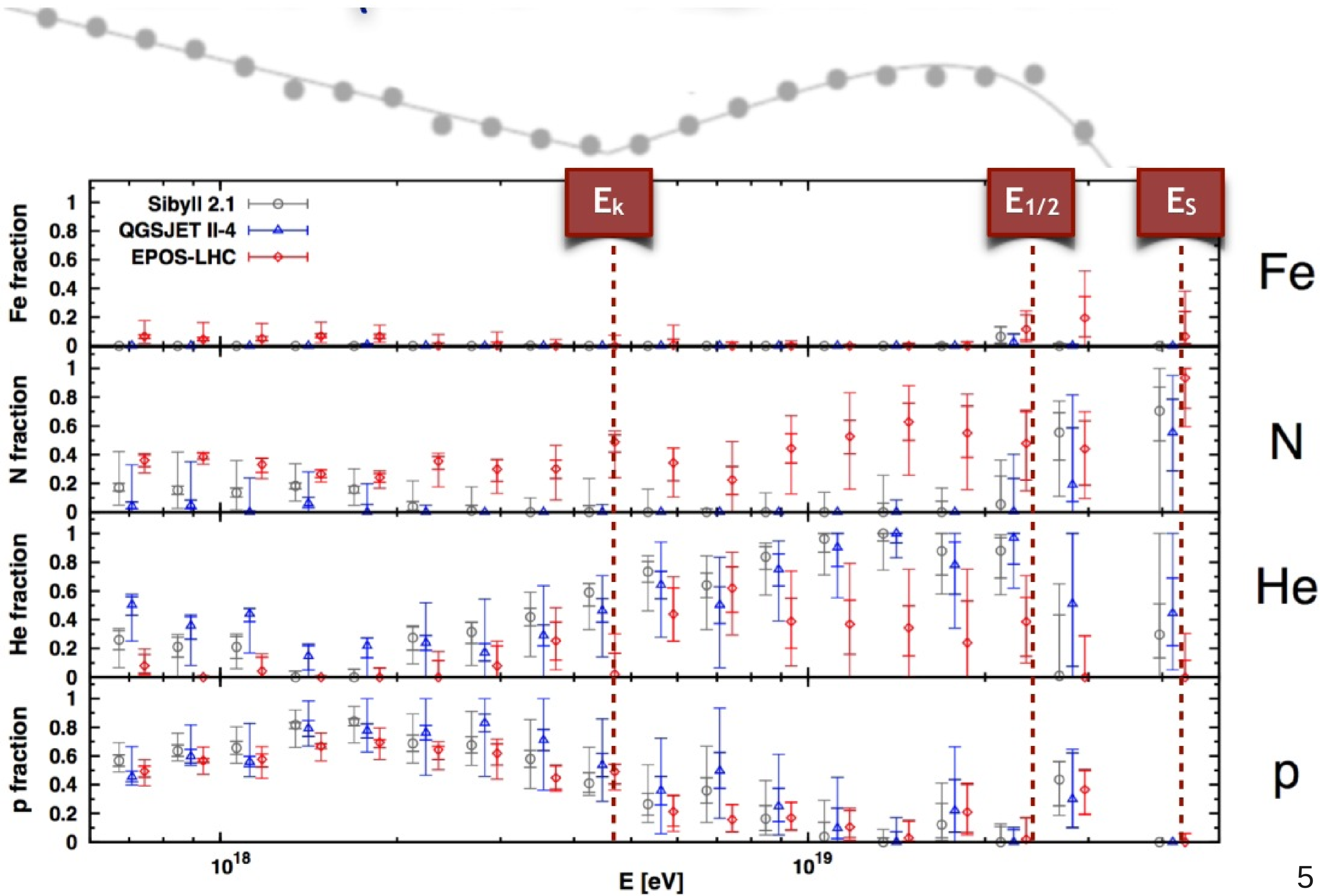
Anti-bias selection for composition: <Xmax>, σ (Xmax) from <lnA>, σ(lnA)

Model differences much smaller after LHC data was explored
Auger approaching same energy, from a different phase space





composition evolution with spectra



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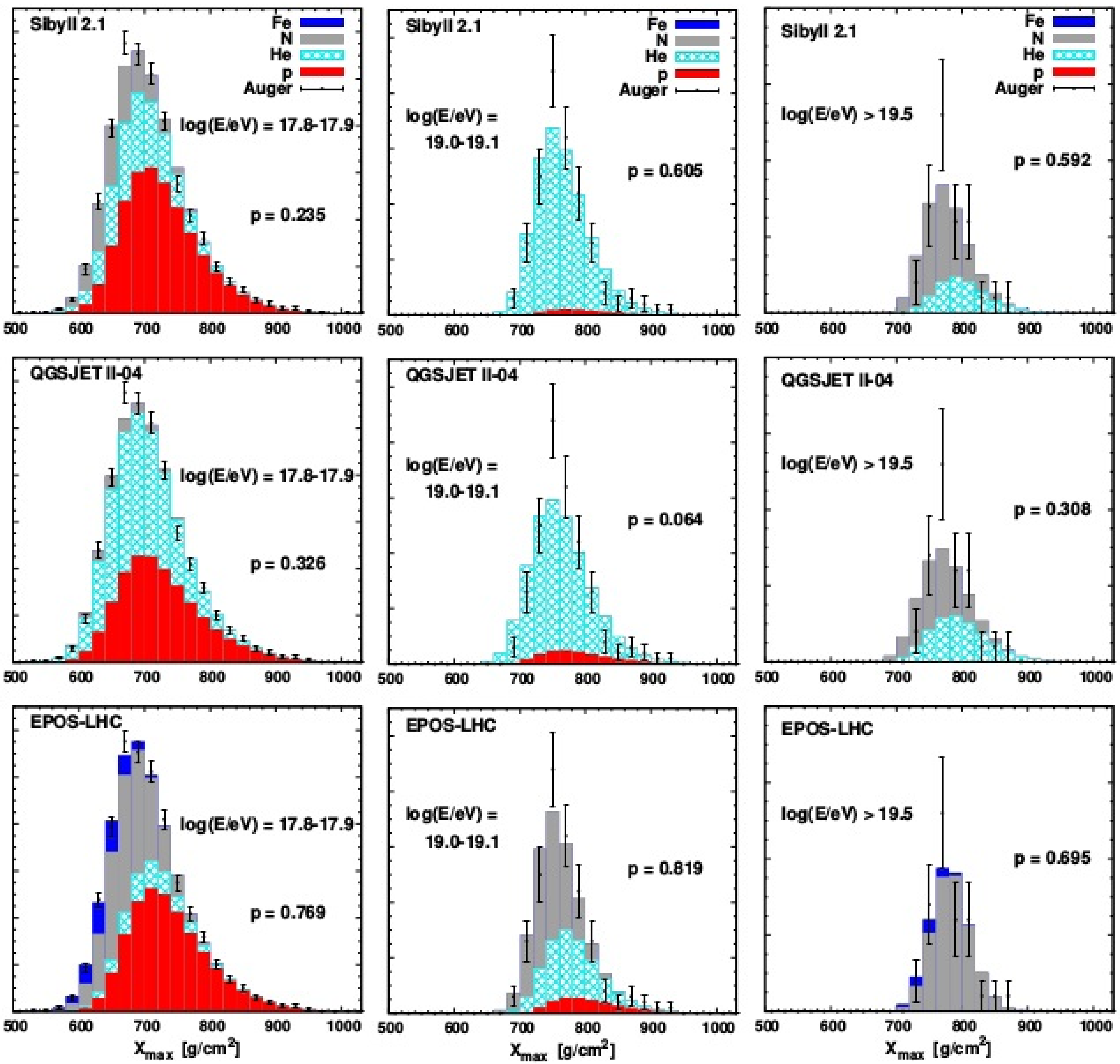


different primary templates at the highest energies

3 models + composition (using 4 mass groups)

Main trends are common: [from heavy to light, and] from light to intermediate

$$<X_{max}> = <X_{max}>_p + f <\ln A>$$

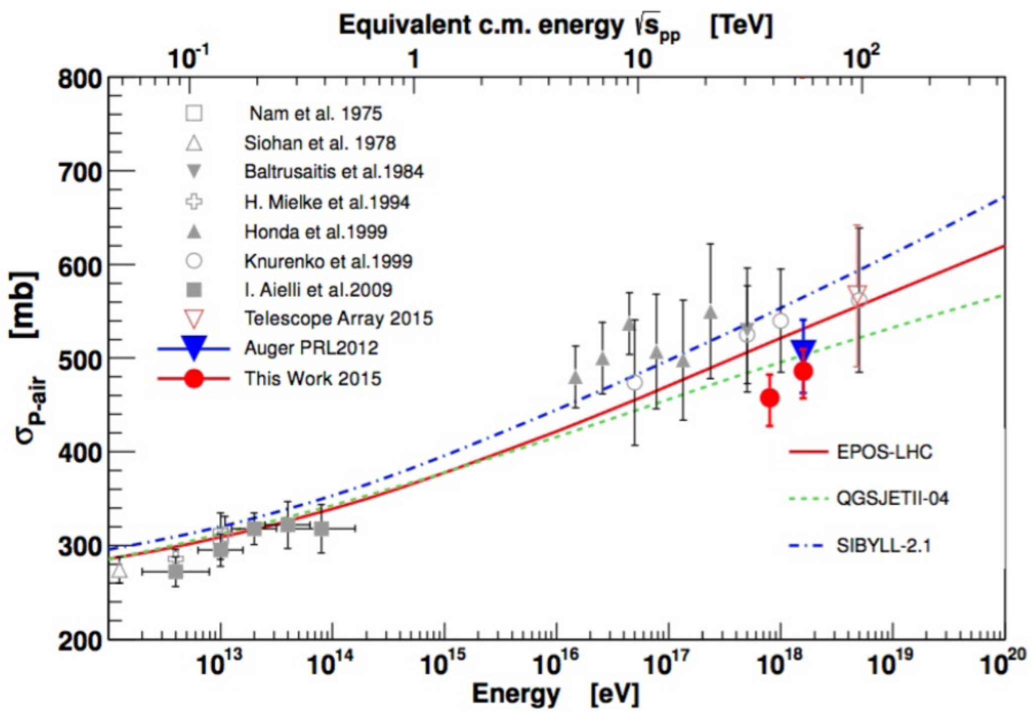
$$\sigma^2(X_{max}) = <\sigma^2_{sh}> + f\ \sigma^2_{\ln A}$$

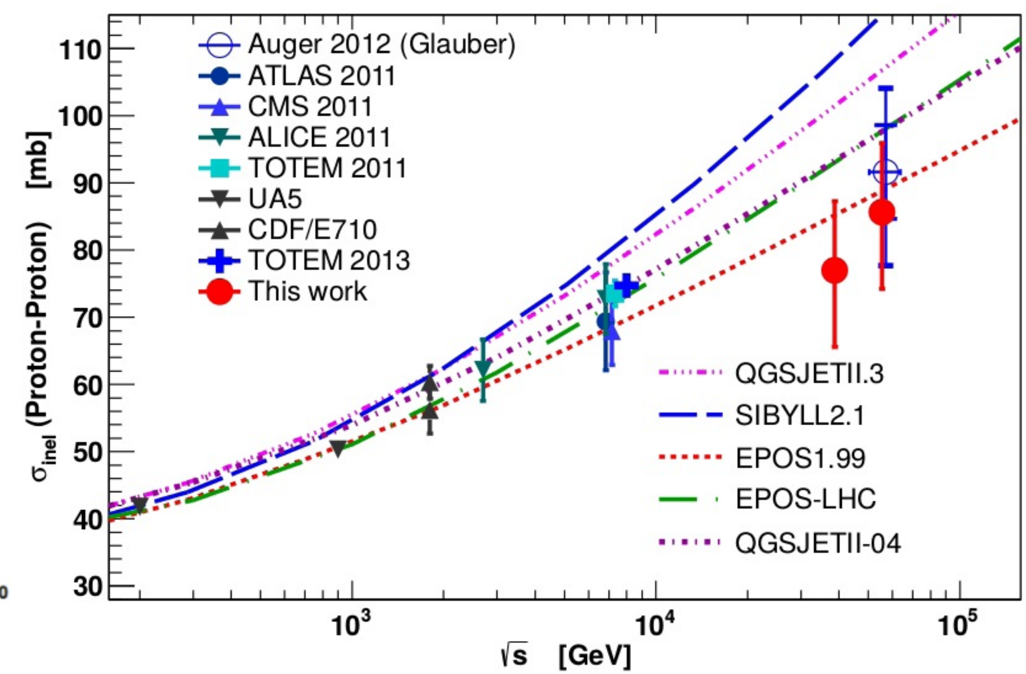
width from shower-to-shower fluctuations or **lnA** evolution?

high energy proton showers: X1

Xmax_em = X1 (A, E) + Δ_em (A, E, γ showering)

lowest cross-section in exponential tail of Xmax





energy range limited due to He, N

$$\frac{dp}{dX_1} = \frac{1}{\lambda_{p-Air}} e^{-X_1/\lambda_{p-Air}}$$

$$\sqrt{s} = 38.7 \pm 2.5\ TeV$$

$$76.95 \pm 5.4(stat)^{+5.2}_{-7.2}(sys) \pm 7.0(Glauber)mb$$

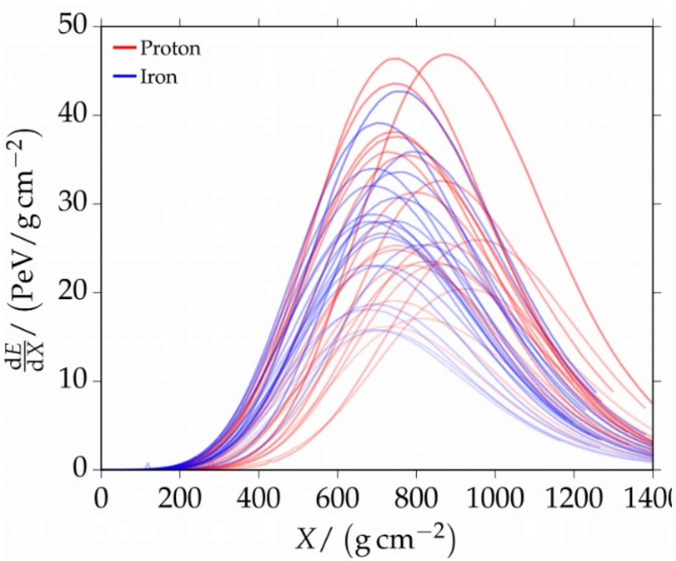
$$\sqrt{s} = 55.5 \pm 3.6\ TeV$$

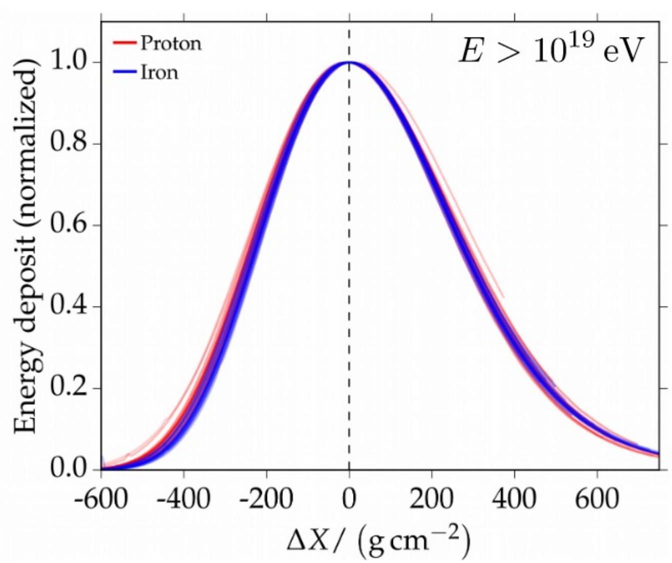
$$85.62 \pm 5.0(stat)^{+5.5}_{-7.4}(sys) \pm 7.1(Glauber)mb$$

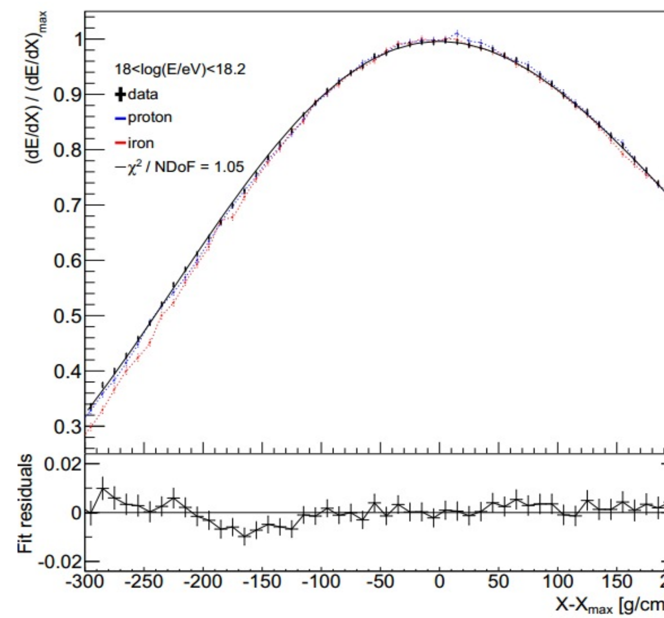
electromagnetic showers: Δ

Xmax_em = X1 (A, E) + Δ_em (A, E, γ showering)

more information in shower profile shape





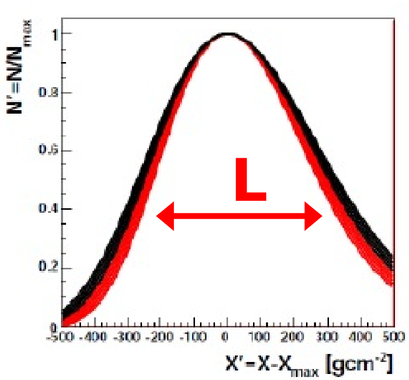


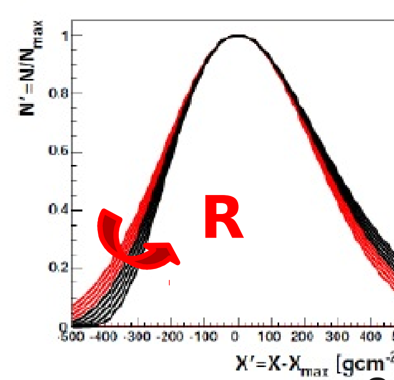
Average shower around maximum is Gaisser-Hillas with 1% accuracy

$$N' = \left(1 + R\frac{X'}{L}\right)^{R^{-2}} \exp\left(-\frac{X'}{RL}\right)$$

$$E \propto \sqrt{2\pi} \cdot N_{\max} \cdot L$$

with correction from R below 1%

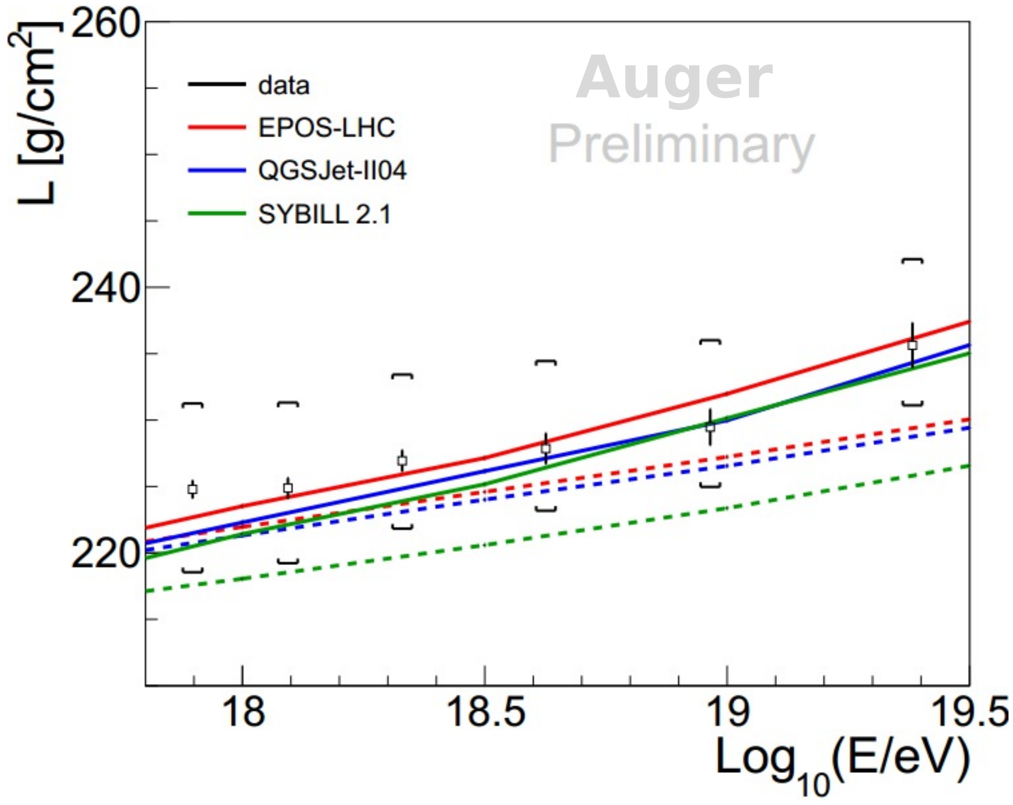


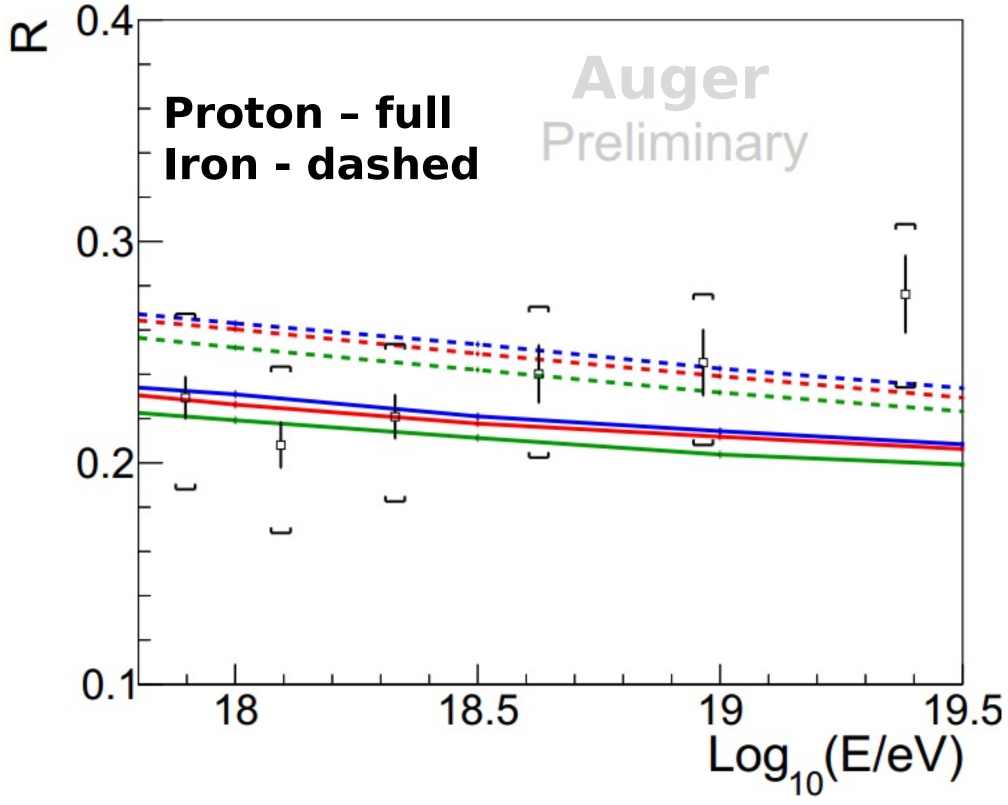


electromagnetic showers: Δ

Xmax_em = X1 (A, E) + Δ_em (A, E, γ showering)

more information on shower profile shape



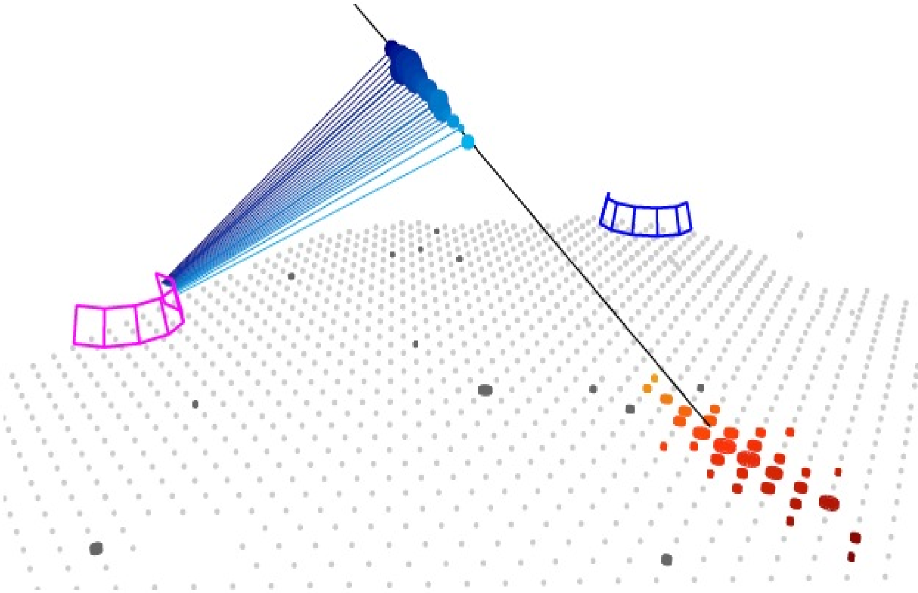


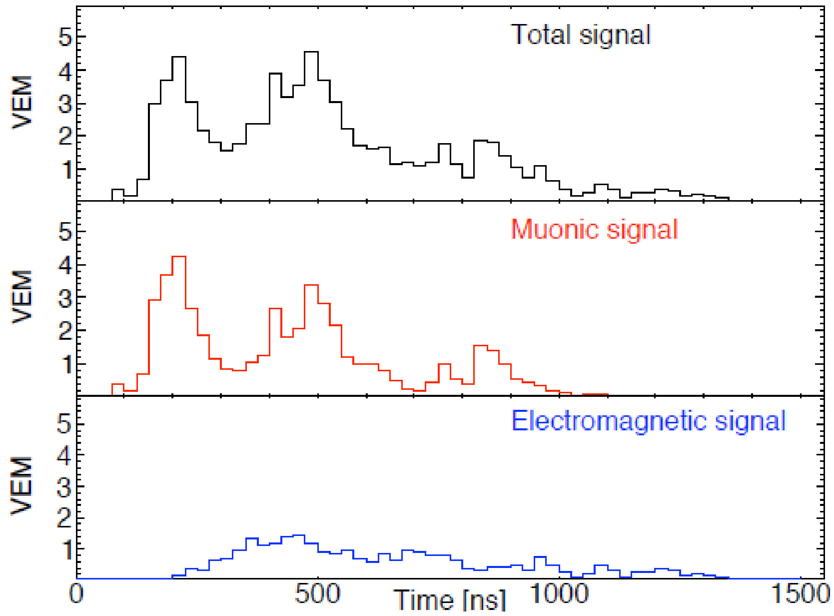
Average Gaisser-Hillas shape consistent with model predictions

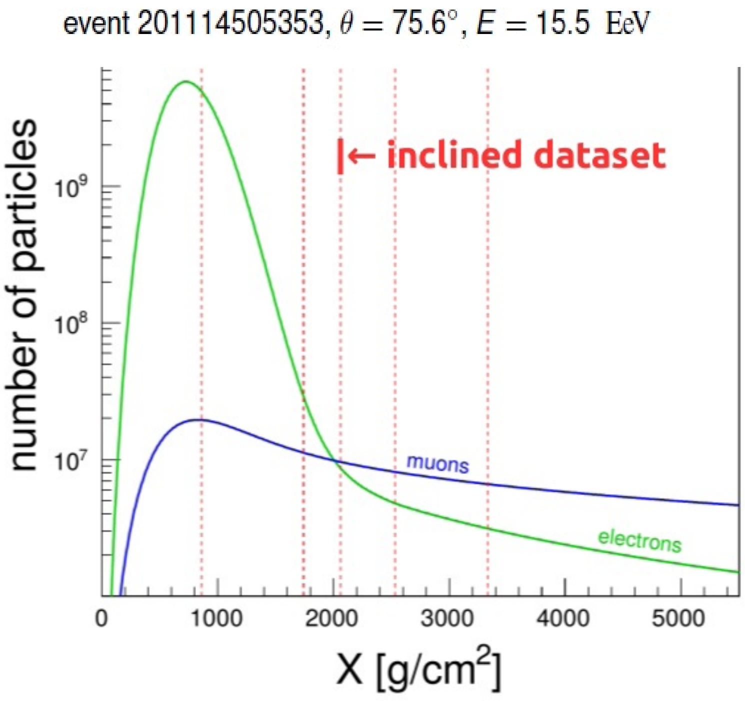
L, main factor for calorimetric energy, follows expected energy evolution

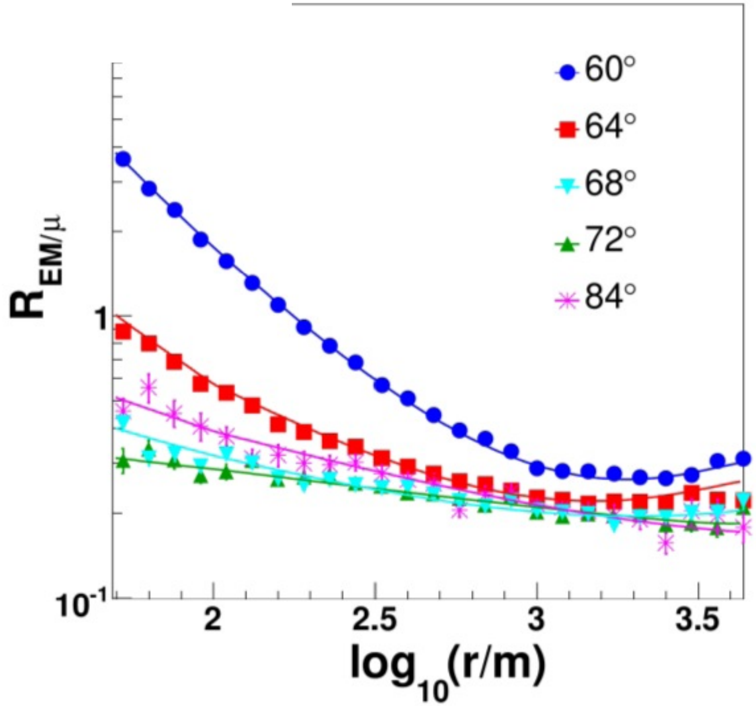
R, more sensitive to shower start, indicates a more complex energy evolution

from FD(em) to SD(&mu)

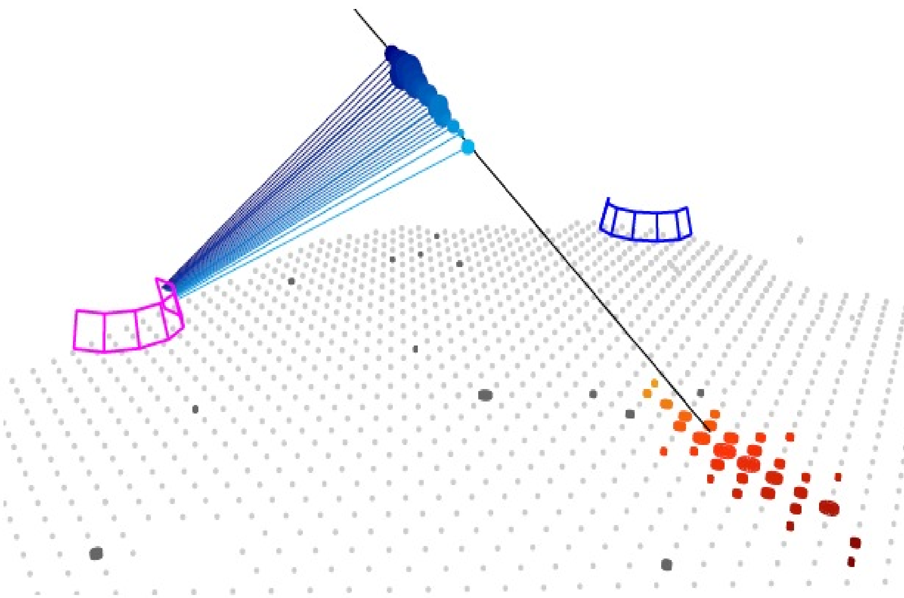




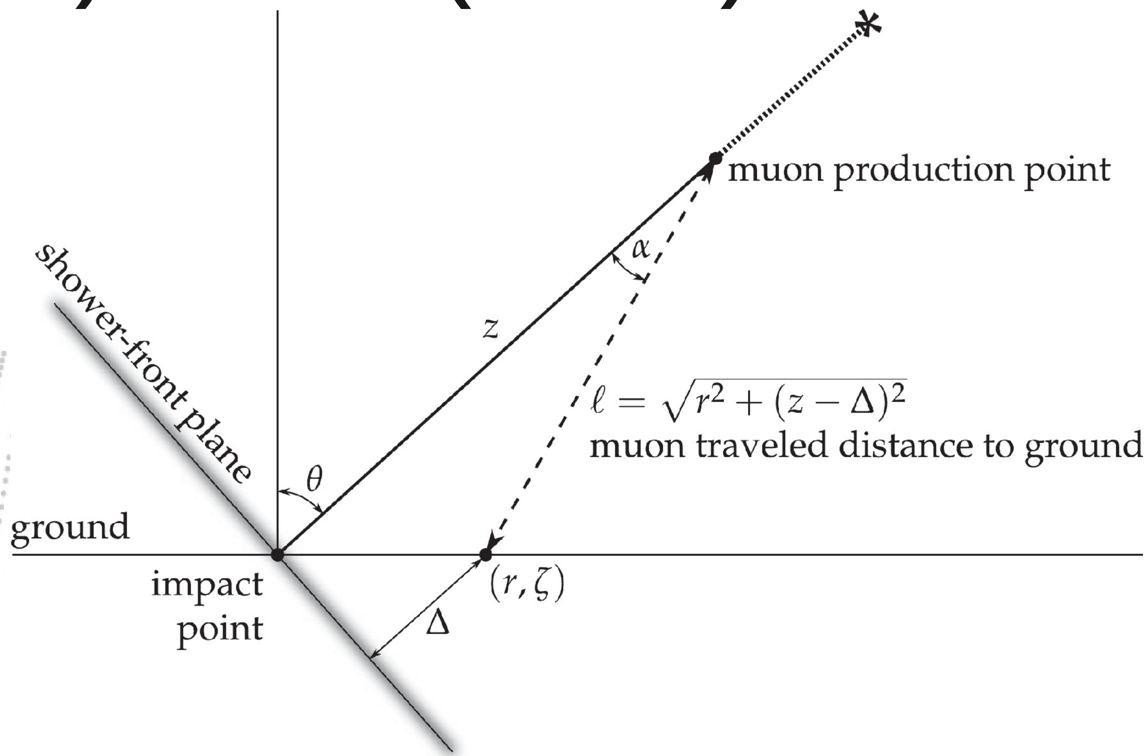




from FD(em) to SD(&mu)



event 201114505353, $\theta = 75.6°$, $E = 15.5$ EeV

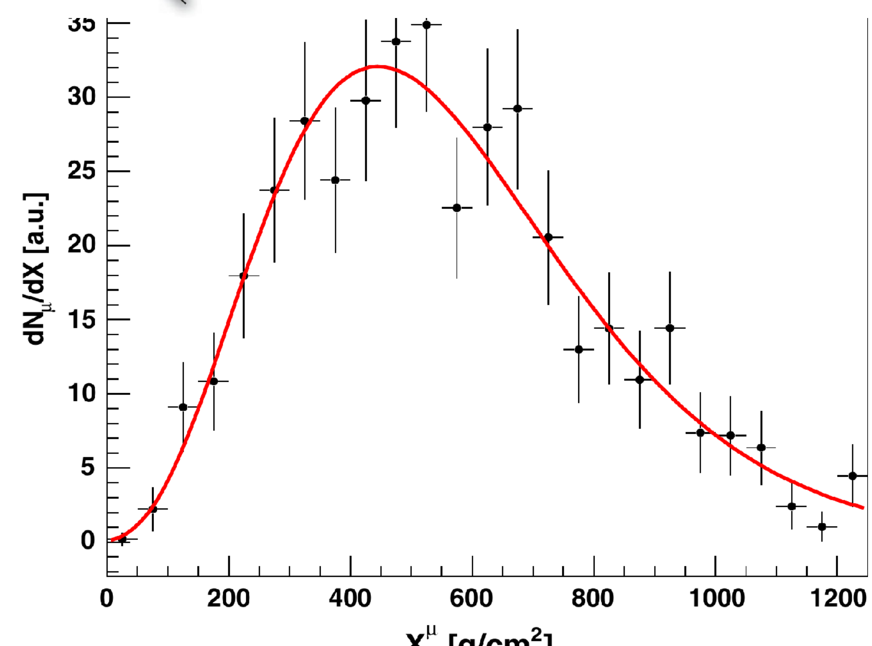


t [ns] → z [m] → X [g cm^{-2}]

$$z \simeq \frac{1}{2}\left(\frac{r^2}{c(t - \langle t_\epsilon \rangle)} - c(t - \langle t_\epsilon \rangle\right) + \Delta - \langle z_\pi \rangle$$

MPD $$X^\mu = \int_z^\infty \rho(z')dz'$$

MPD is also a Gaisser-Hillas but w/ different parameters (higher L and R)

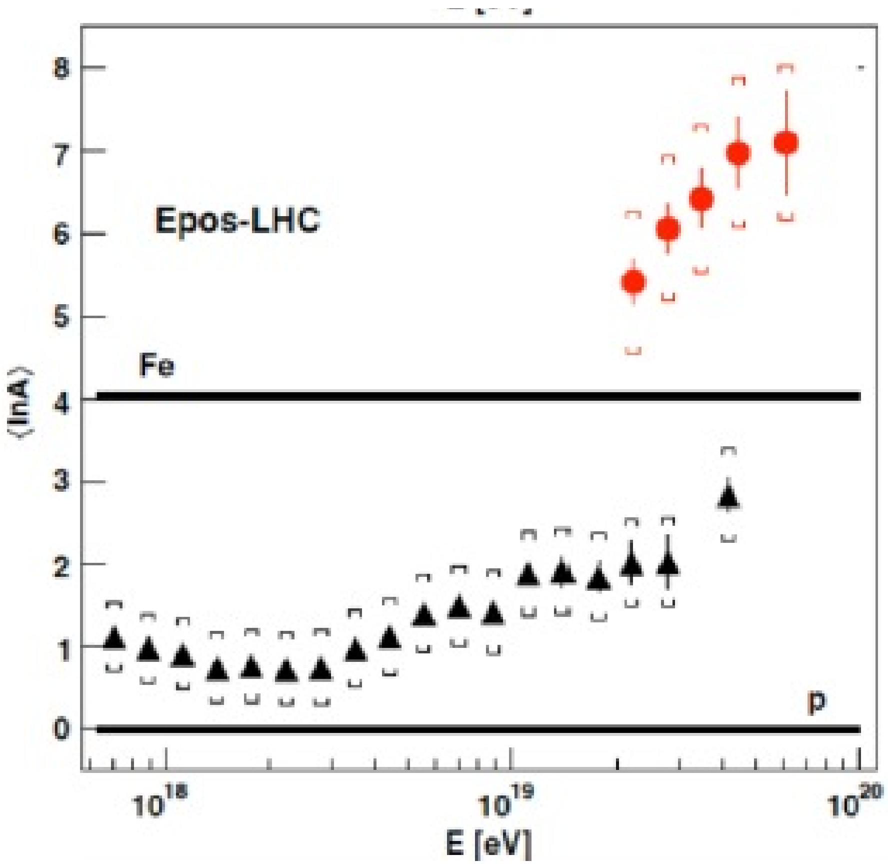


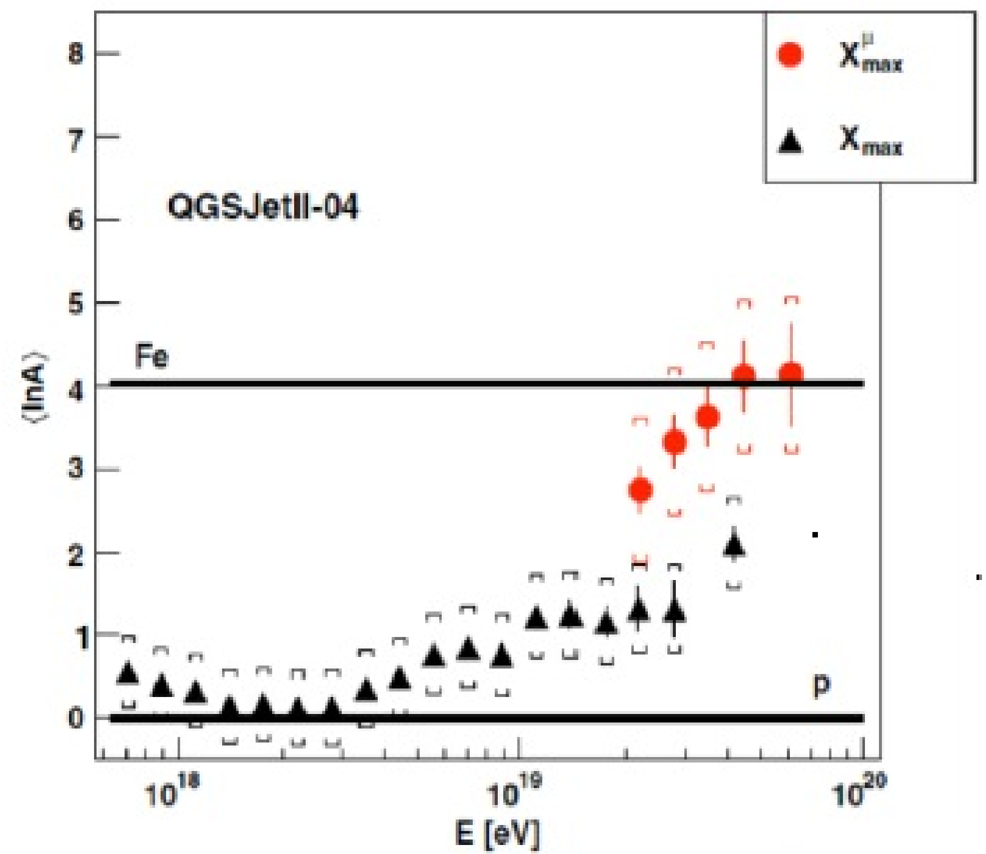
Xmax em / mu showers in FD / SD

Xmax_em = X1 (A, E) + Δ_em (A, E, γ showering)   in FD

Xmax_mu = X1 (A, E) + Δ_mu (A, E, μ production)   in SD

common!   differences from γ/μ parents





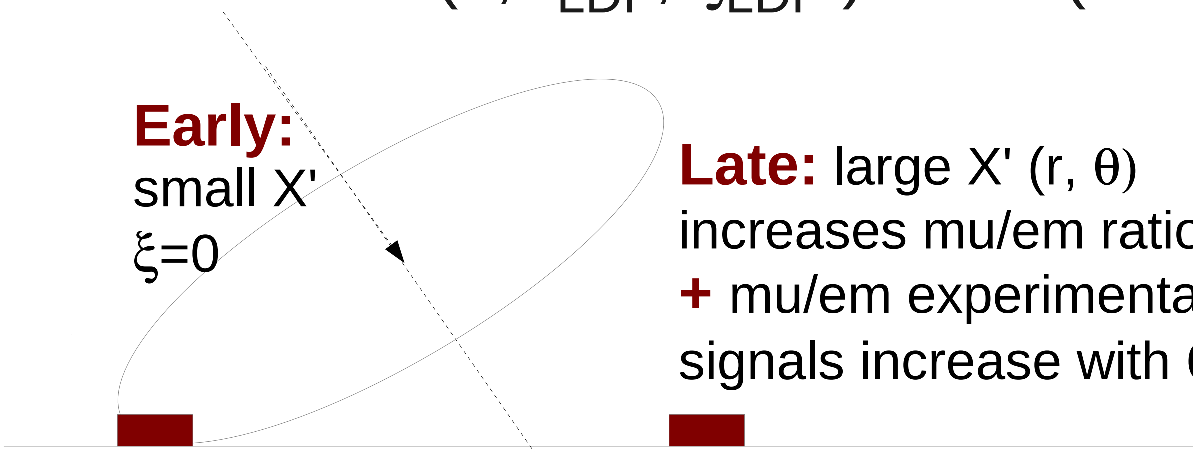
muon production Xmax at smaller depths than expected in models
probably not first but later interactions; also muon energy spectra?

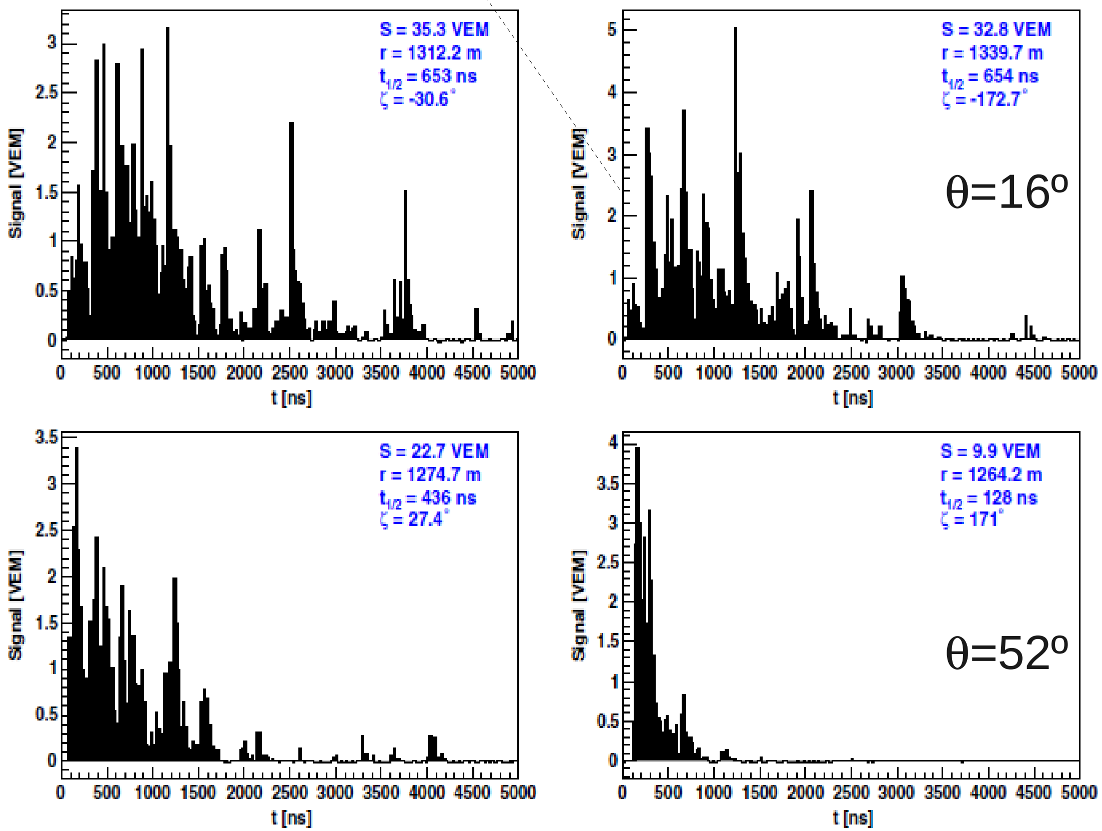
mu / em ratios in SD: X' and r dist.

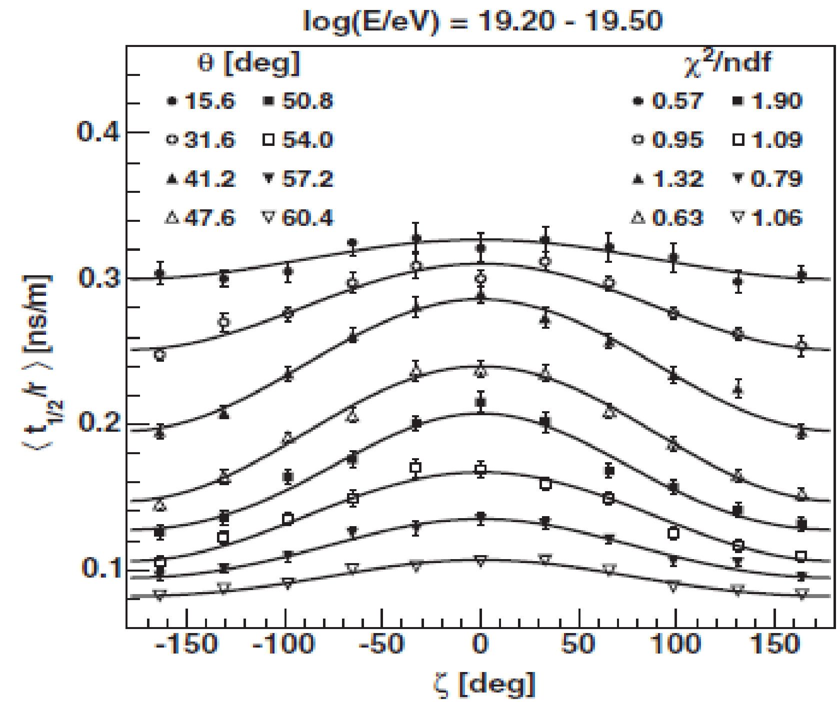
SD rise-time (θ, r_{LDF}, ξ_{LDF}) => X' (mu/em)

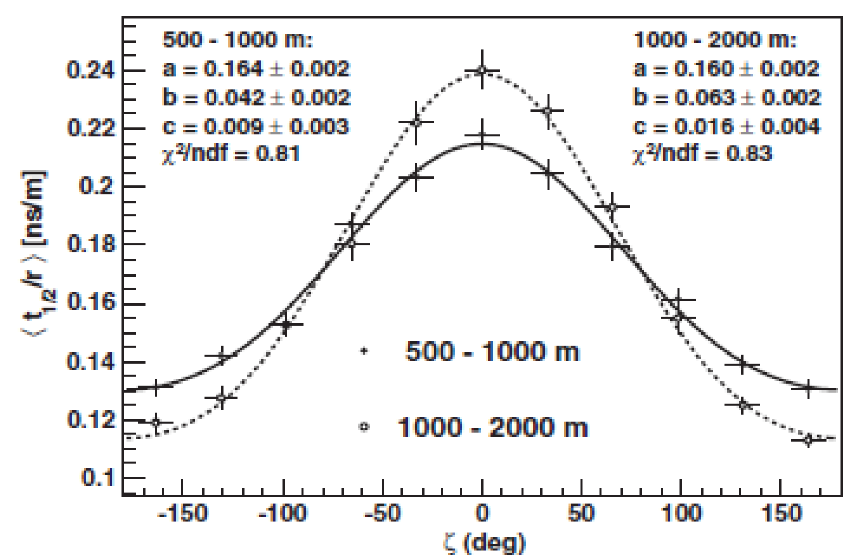
Early: small X' ξ=0

Late: large X' (r, θ) increases mu/em ratio + mu/em experimental signals increase with θ

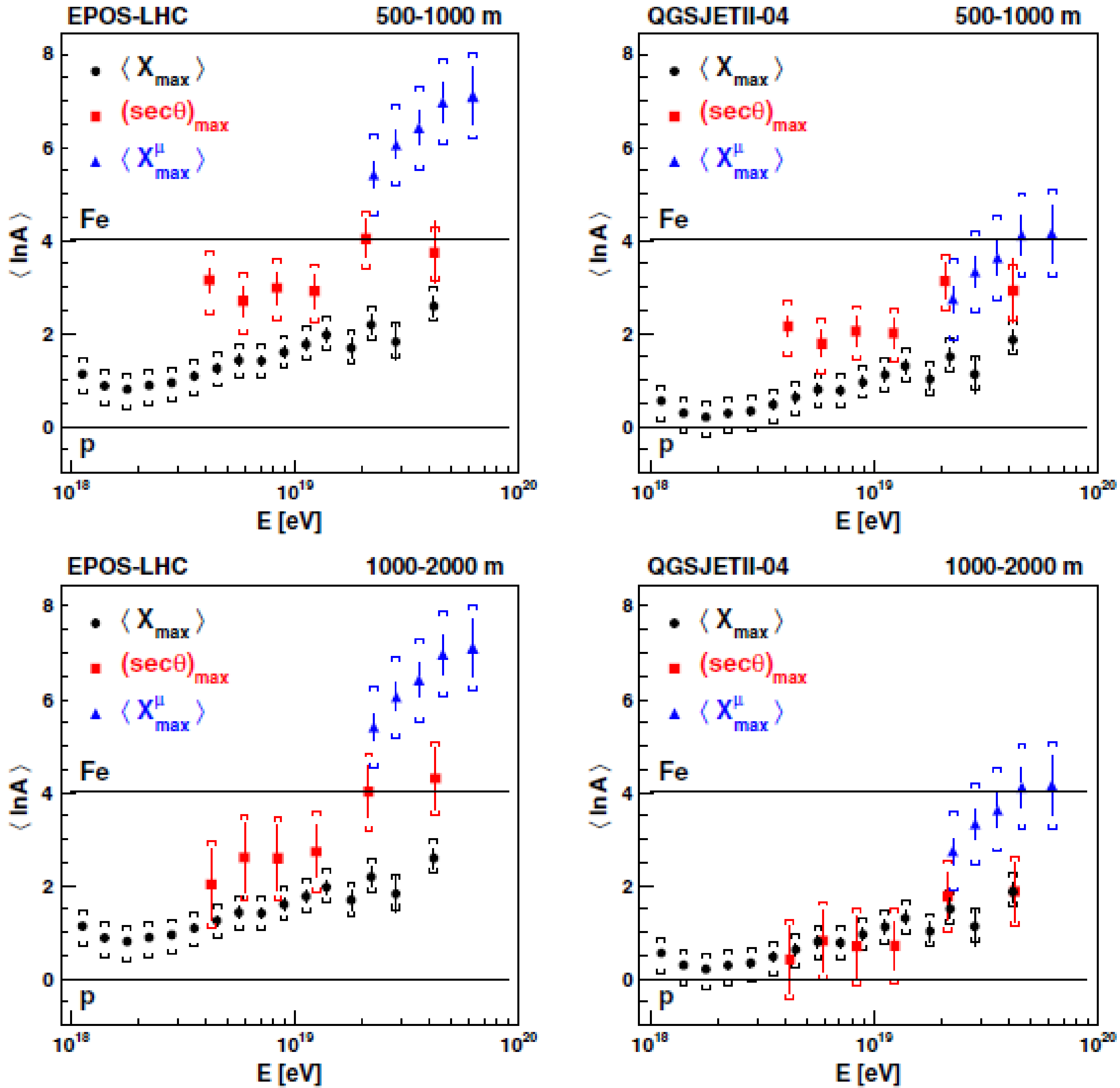








mu / em ratios in SD: X' and r dist.



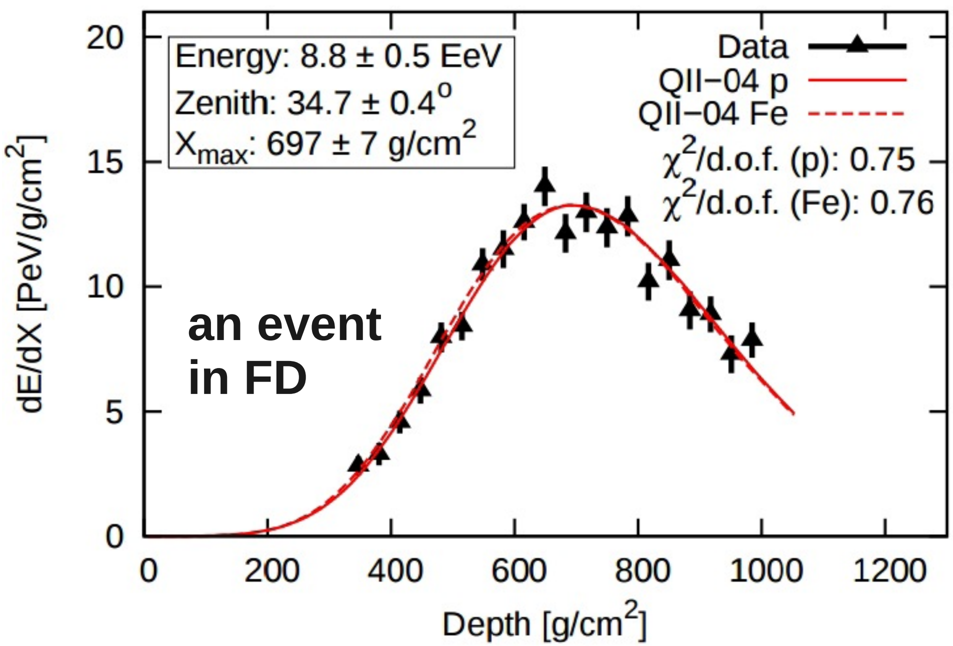
low radius, with larger electromagnetic ratio, inconsistent with Xmax

high radius, with more sensitivity to muons, larger differences btw the two models

QGSJetII-04: inconsistency in em/mu lateral distribution

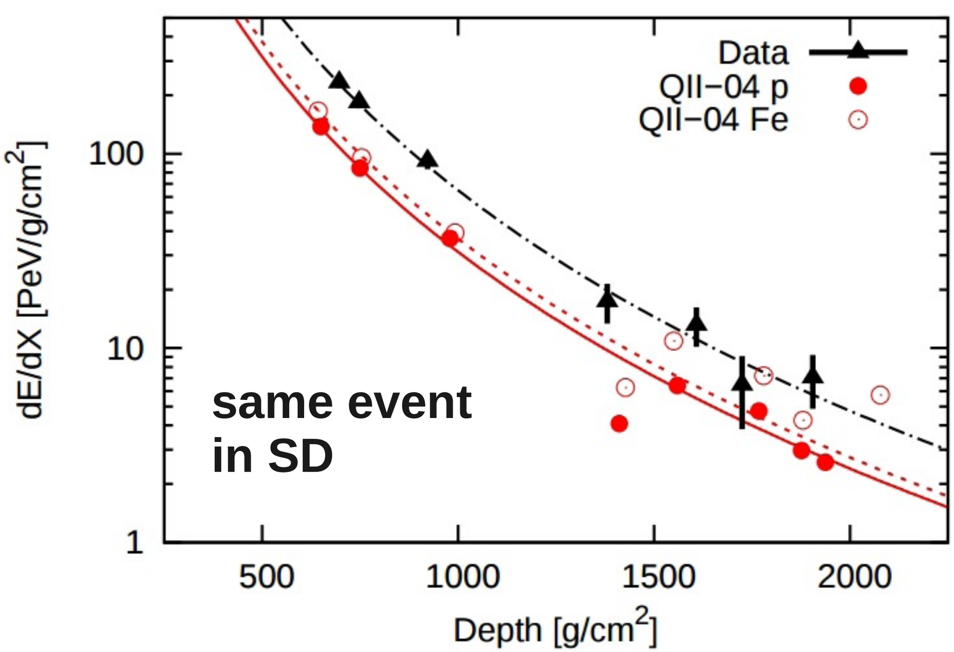
EPOS-LHC: Inconsistency in em/mu longitudinal distribution

matching SD to FD (lateral to long.)

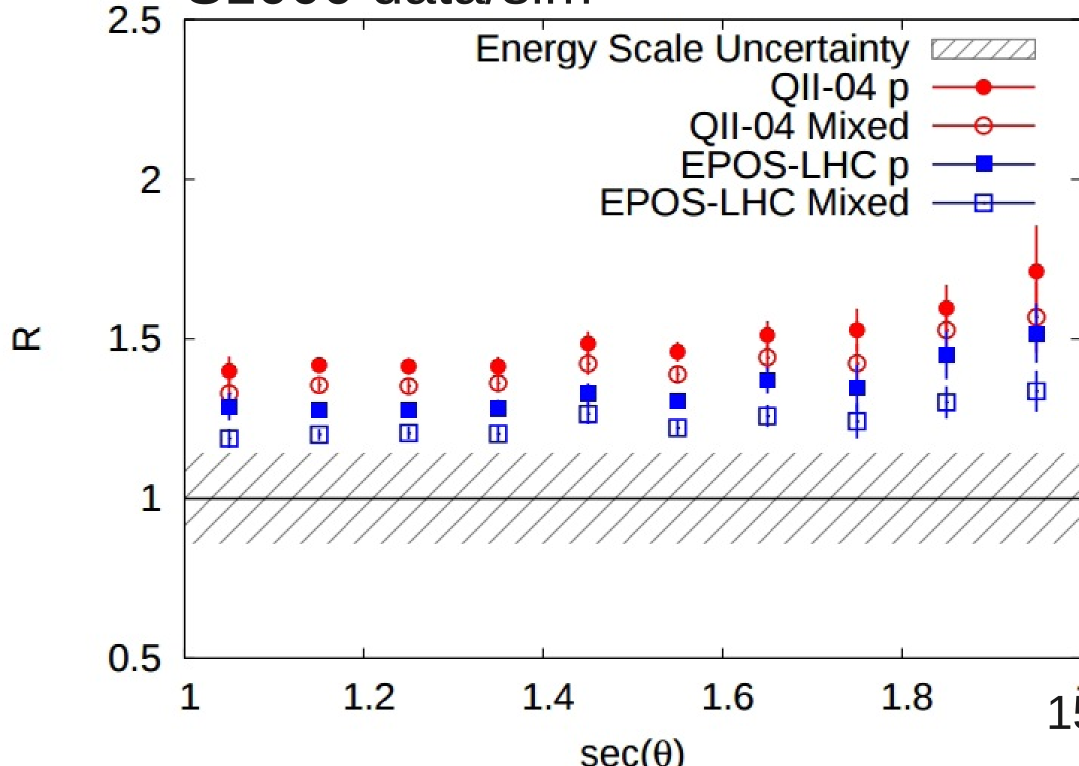


lateral + longitudinal shapes fitted event-by-event with MC templates (different models and primaries)

All ground signal needs re-scaling



S1000 data/sim



matching SD to FD

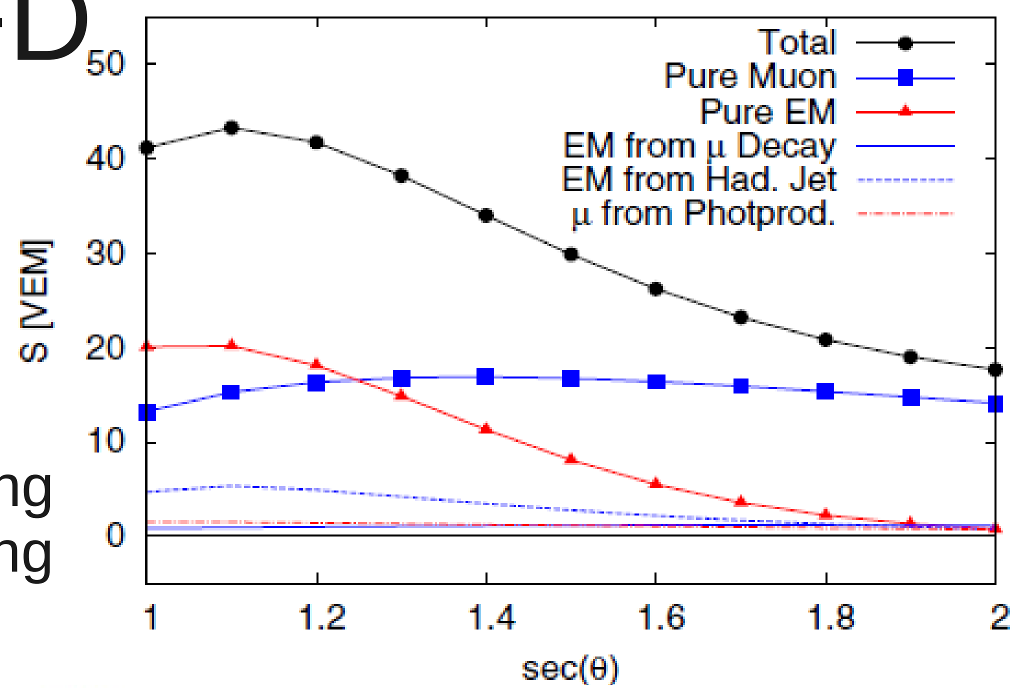
$S_{resc}\,(R_{em}, R_{had}) =$

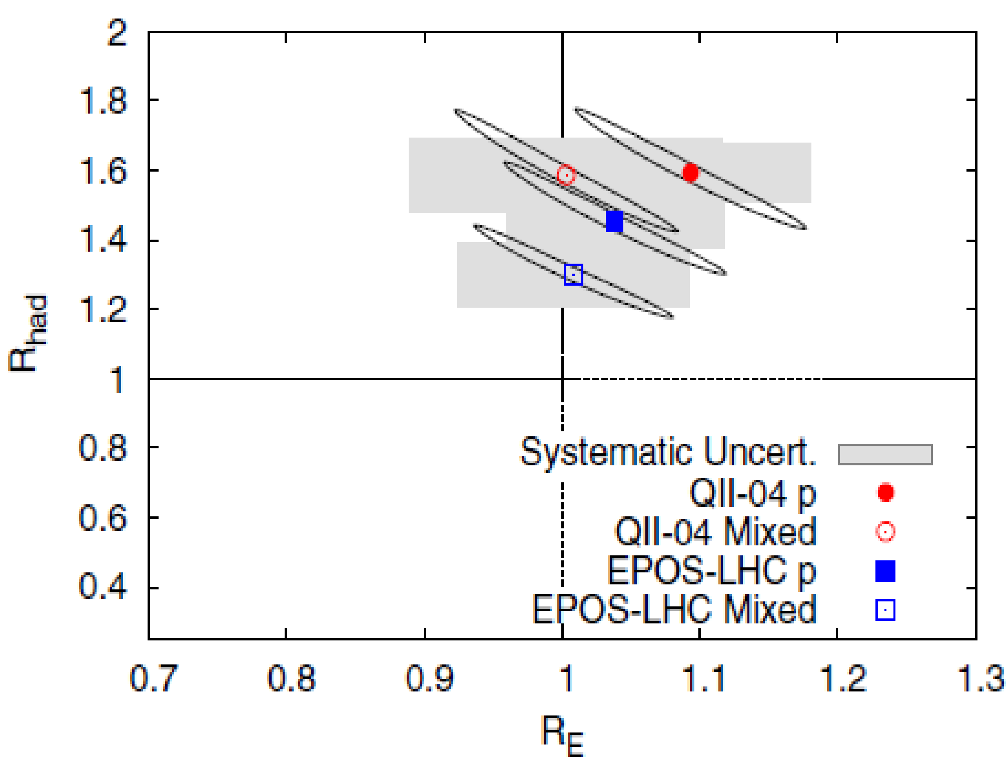
$R_{em}\, S_{em} + R^{\alpha}_{em}\, R_{had}\, S_{had}$

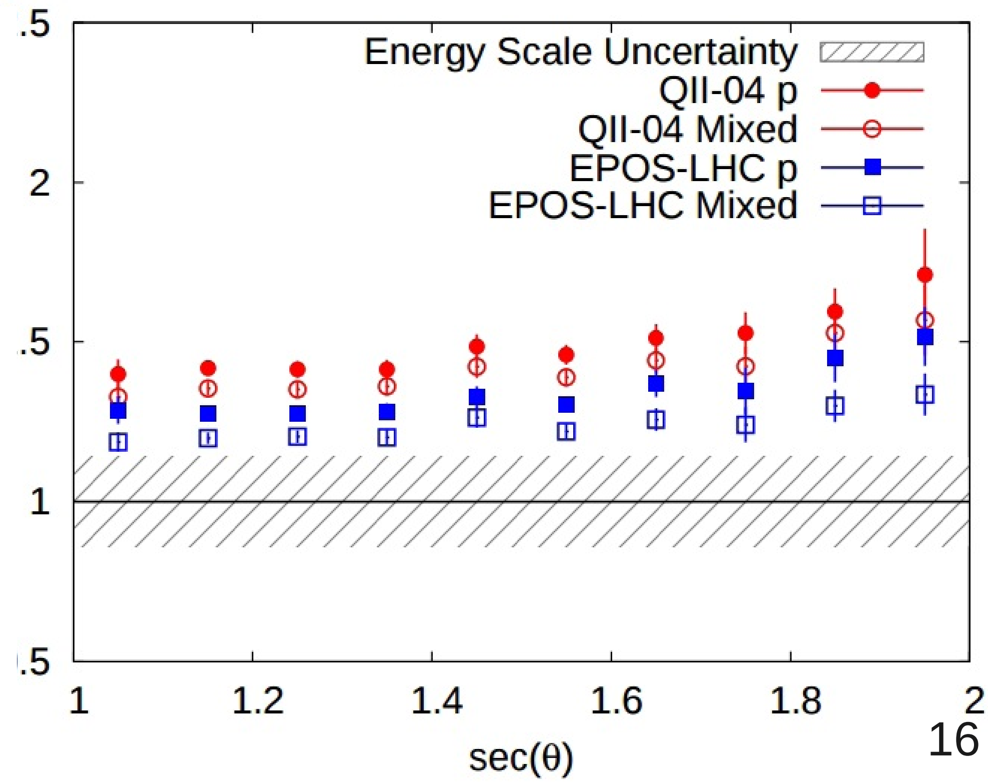
$\alpha = 0.9$ for all models/primaries

No need for electromagnetic scaling
Need for 30%-60% hadronic scaling

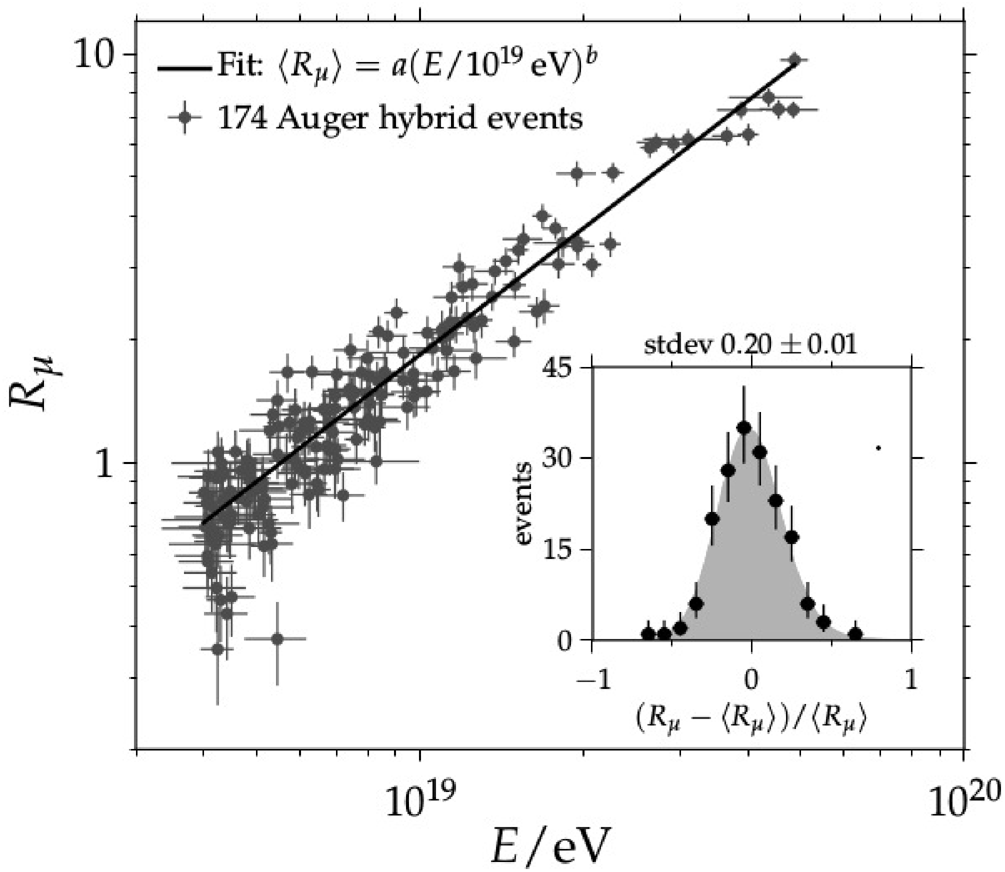
S1000 in QGSJetII-04 proton @10 EeV

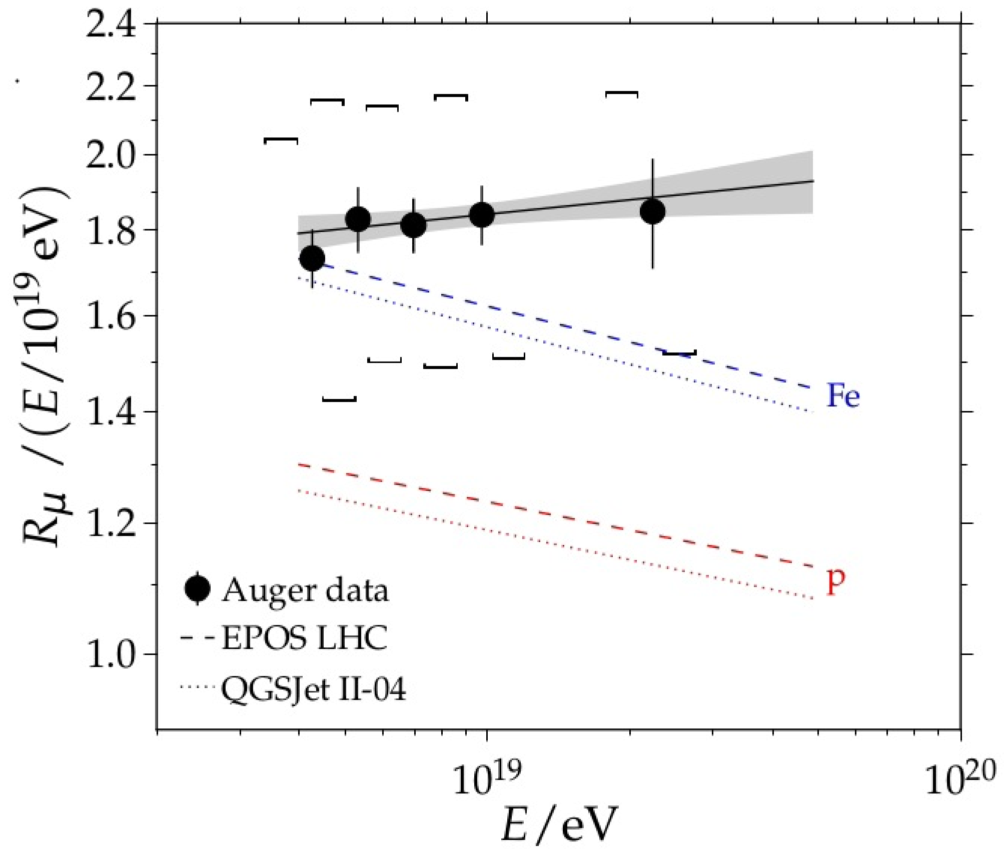






muon deficit in inclined showers

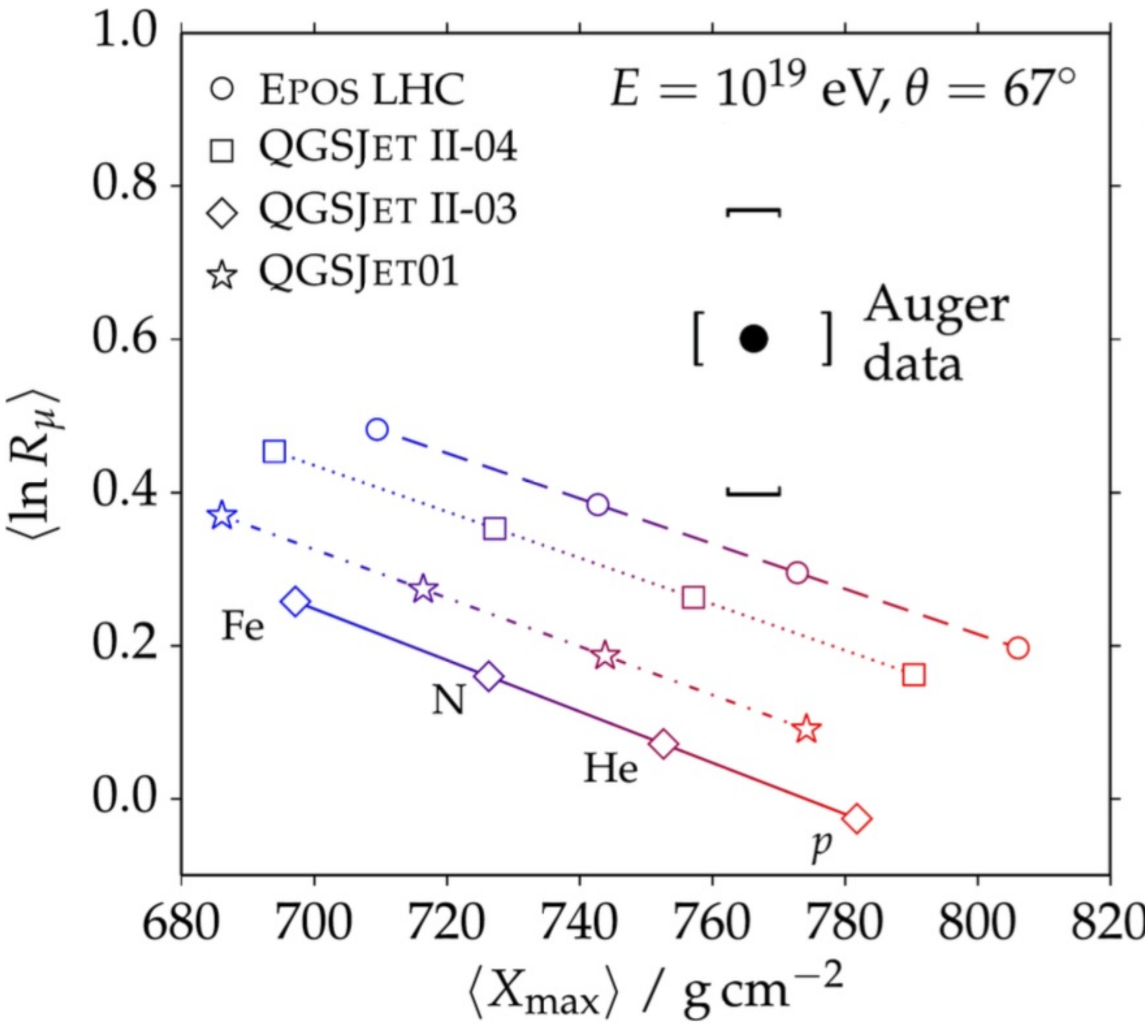




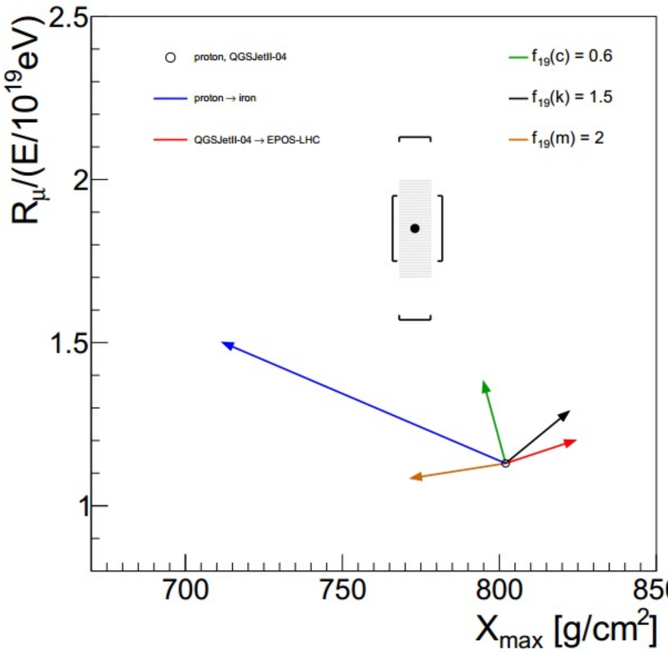
Number of muons is energy estimator for inclined showers seen in SD, calibrated with FD, cross-checked in CIC energy spectrum
(deficit of muons in models change the FD invisible energy estimate, data-driven correction backed by Matthews-Heitler model)

Muon deficit in models seems to grow with energy

"summary" mu / em plot @ 10 EeV



model & composition not enough



charge ratio, elasticity, multiplicity

Auger FD has full description of the electromagnetic shower component
Auger SD find puzzles in "muonic", ie hadronic, shower component

None of the hadronic interaction models consistently describes our data

towards Auger PRIME

Combination of accelerator & cosmic ray measurements needed

Auger will increase data at lower energies and on energy evolution

Auger upgrade will increase information for larger hybrid data sets

Primary cosmic **R**ay **I**dentification through **M**uons and **E**lectrons

Increasing FD duty-cycle
Getting closer to shower core with SD

2 detector technologies (+ radio):
=> more direct em / mu separation

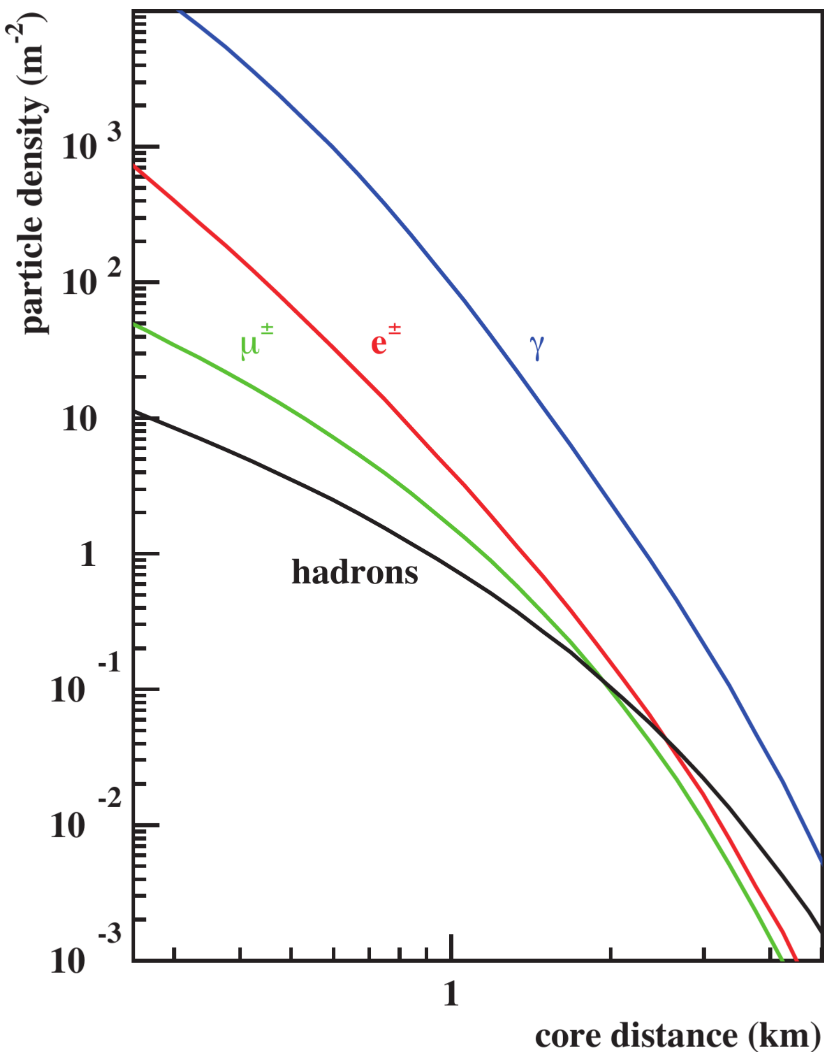
Extending analysis at LHC-like energies

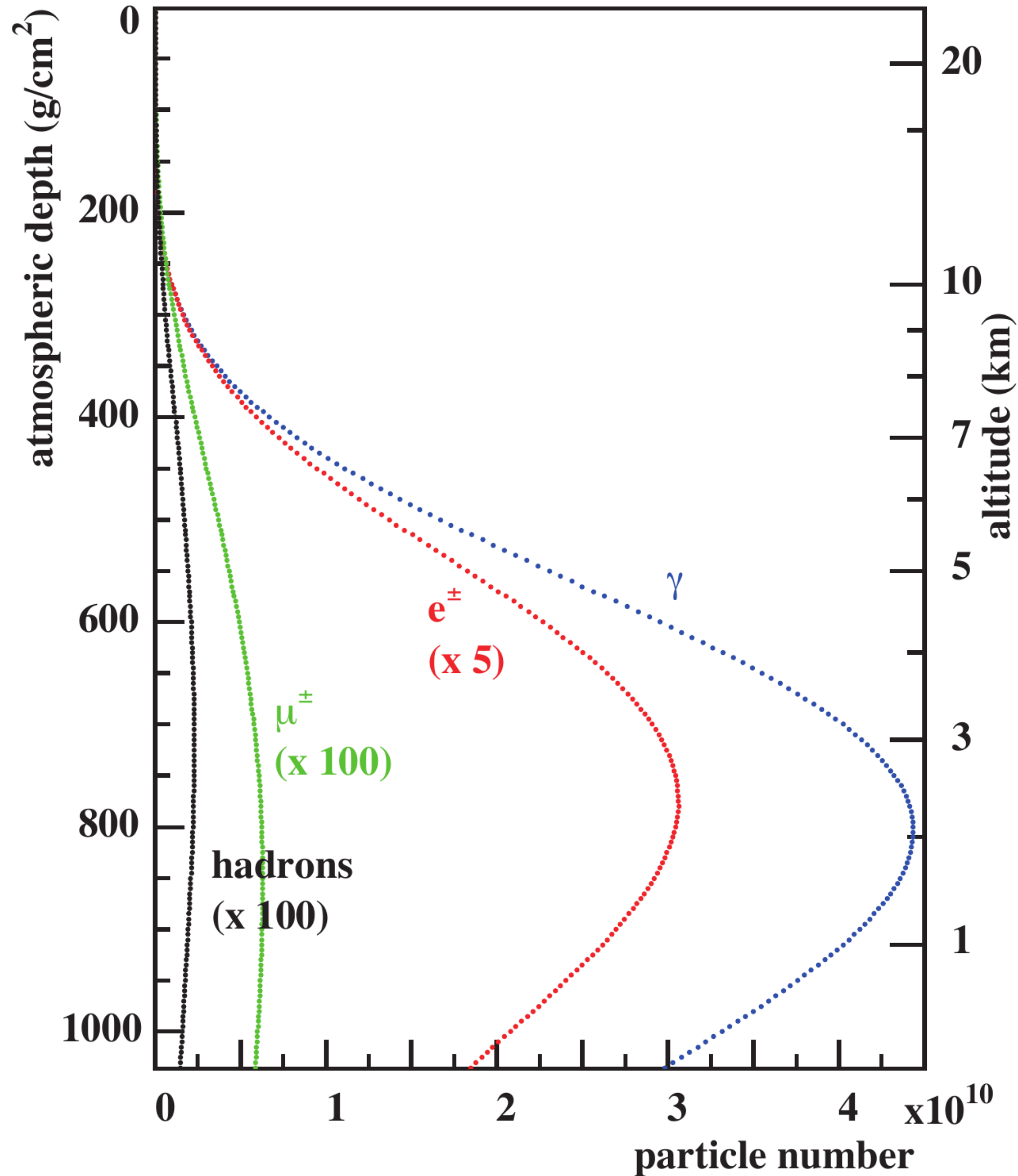
AMIGA 2.25 m deep

Exploring muons with different thresholds

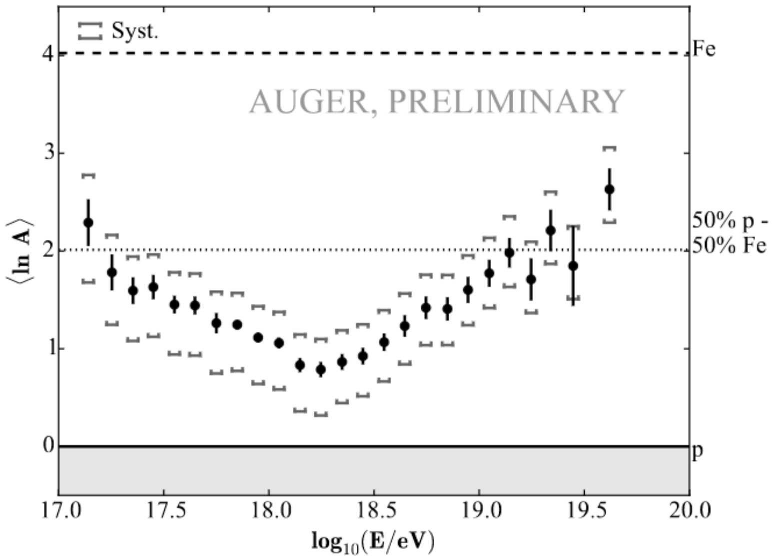
1600 SD stations + 27 FD telescopes;
sampling lateral distribution EM/MU & imaging the EM component

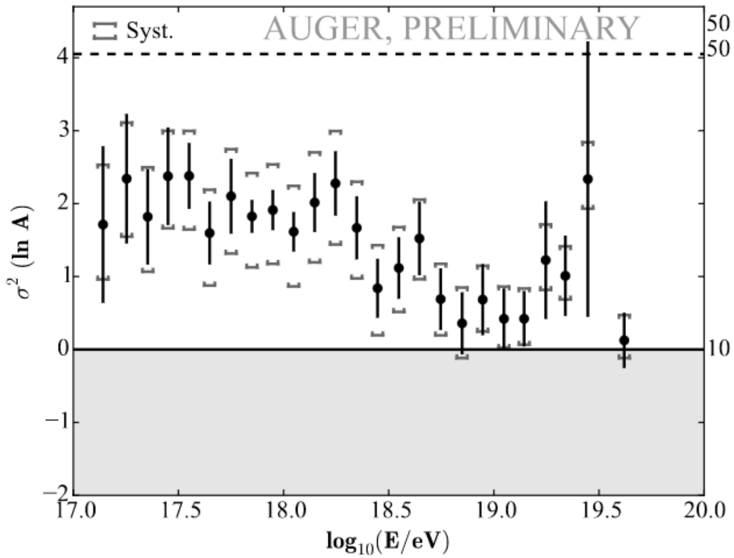
Engel, ARNPS 61(2011) 467



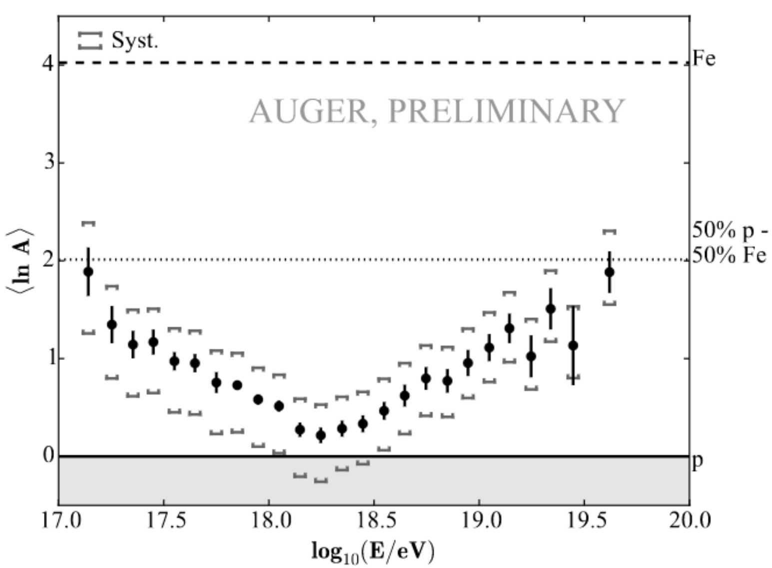


em showers measured in FD: lnA

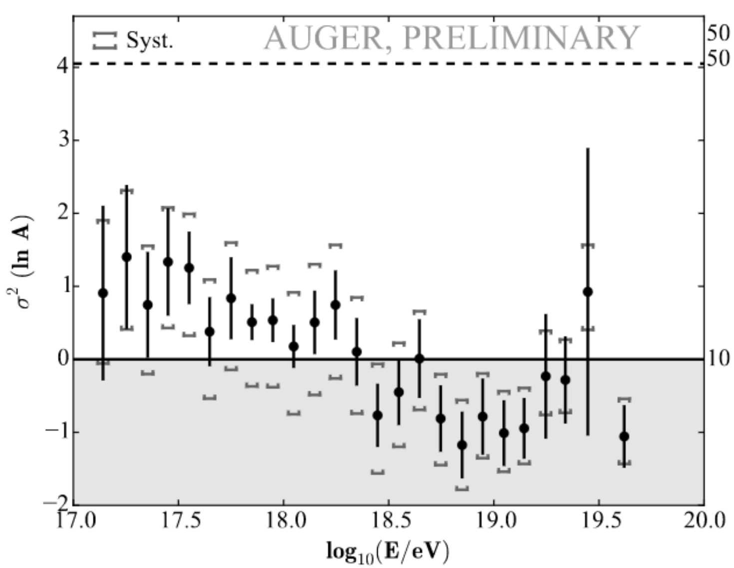




QGSJetII-04 (Mean of ln A)



QGSJetII-04 (Variance of ln A)



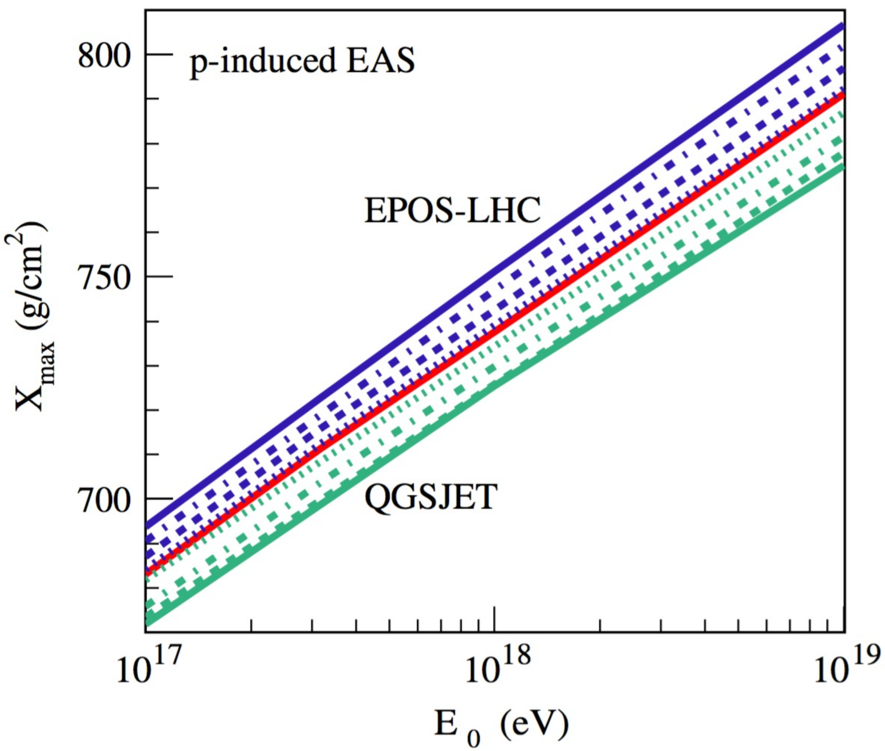
$\langle X_{max}\rangle = \langle X_{max}\rangle_p + \mathbf{f} \langle \ln A\rangle$ $\sigma^2(X_{max}) = \langle\sigma^2_{sh}\rangle + \mathbf{f}\, \sigma^2_{\ln A}$

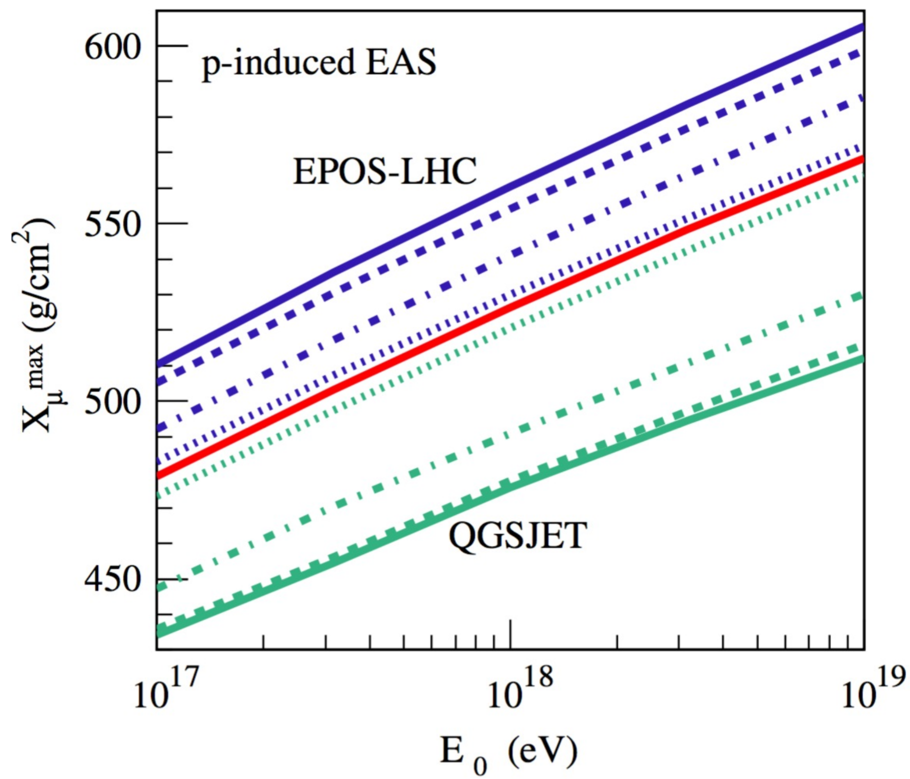
em / mu showers in FD / SD: Δ / Δ

Xmax_em = X1 (A, E) + Δ_em (A, E, γ showering)   in FD

Xmax_mu = X1 (A, E) + Δ_mu (A, E, μ production)   in SD

common   differences in secondaries

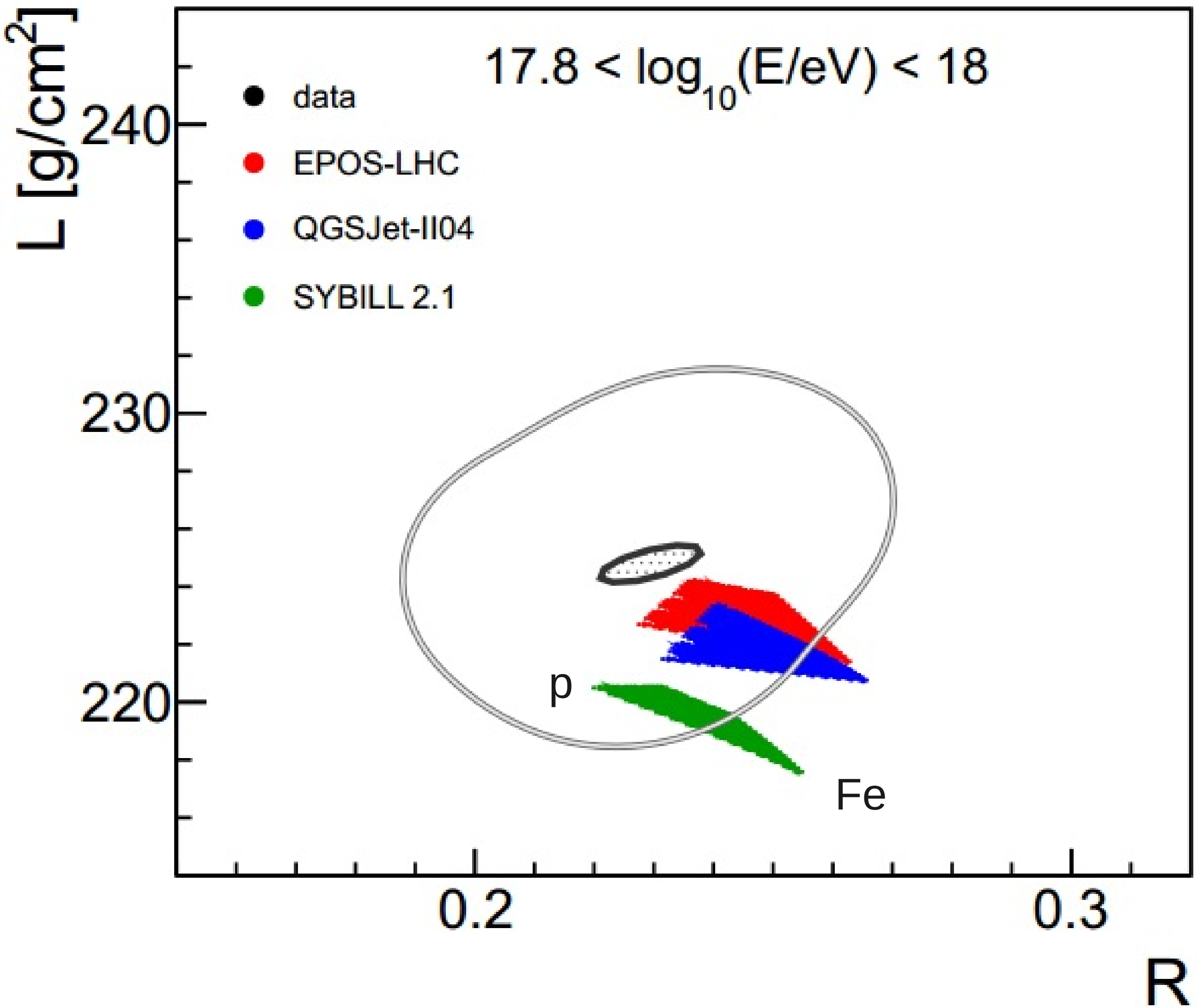




[@S.Ostapchenko, M.Bleicher, PRD93 (2016) 051501]

em showers measured in FD: Δ

Xmax_em = X1 (A, E) + Δ_em (A, E, γ showering)
more information on shower profile shape



Profile shape insensitive to 1st interaction cross-section

Probing secondary spectra: elasticity, multiplicity and charges at high energy

Preliminary:
still large uncertainties
but global model testing

em showers measured in FD: Δ

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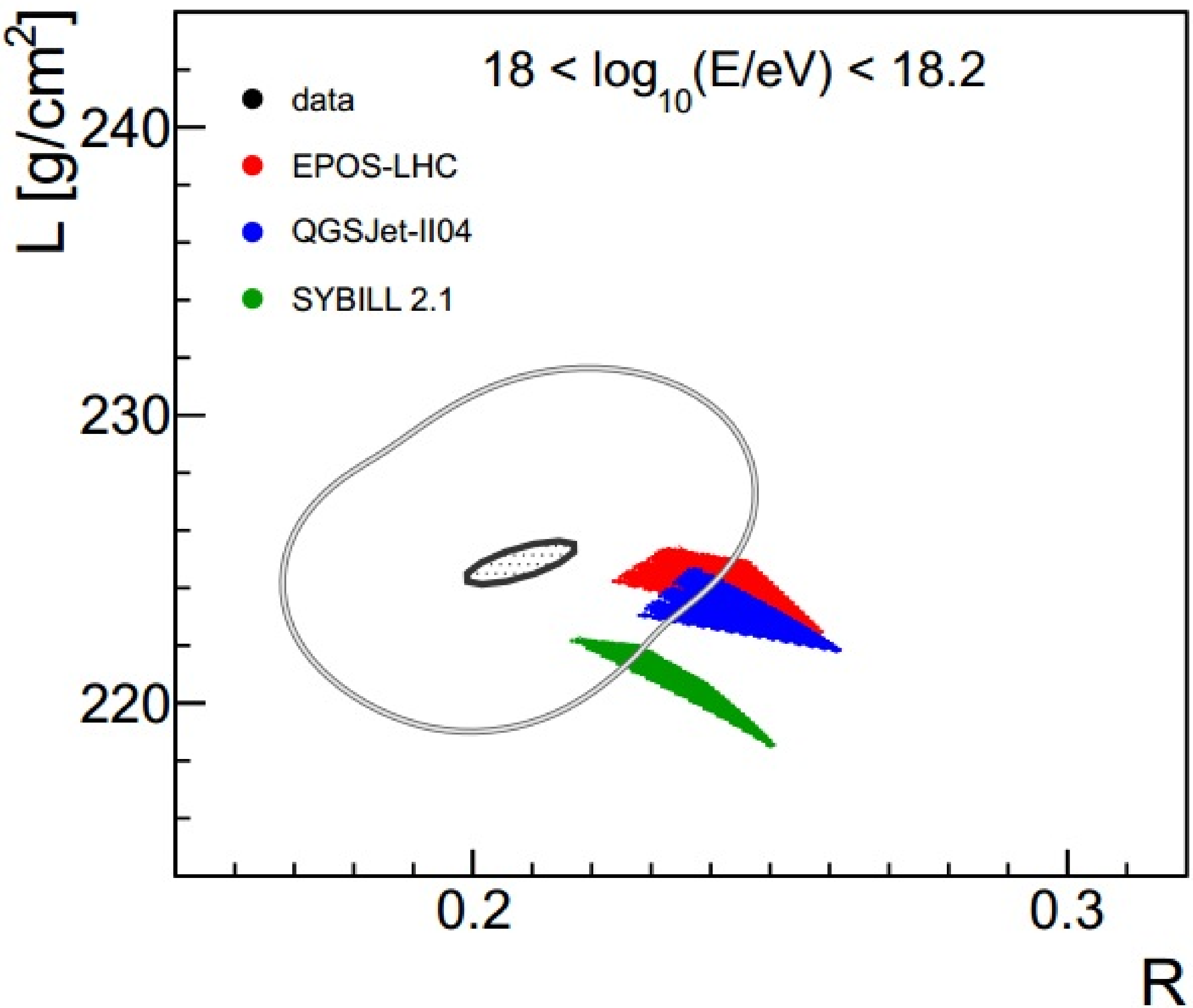
more information on shower profile shape



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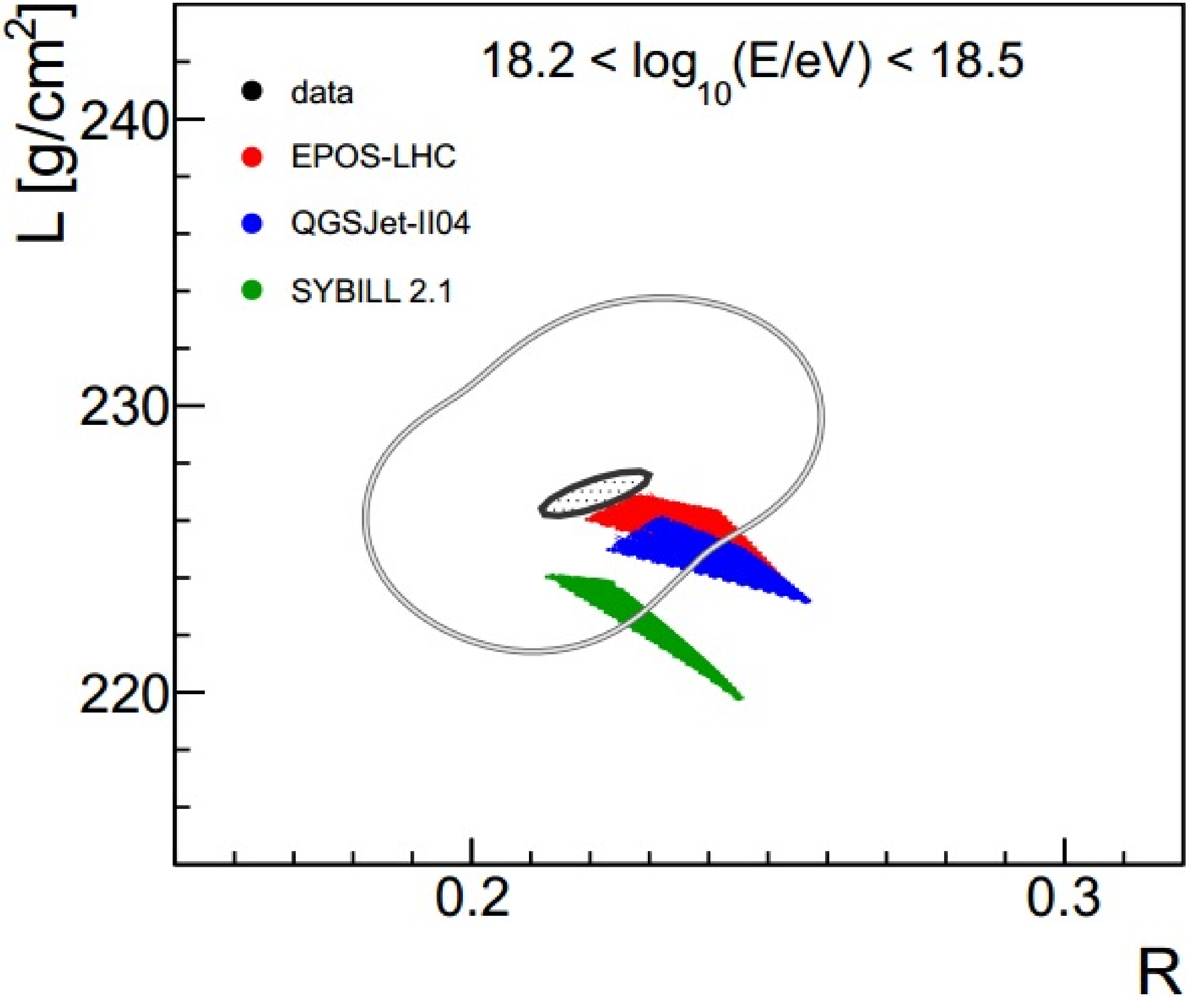

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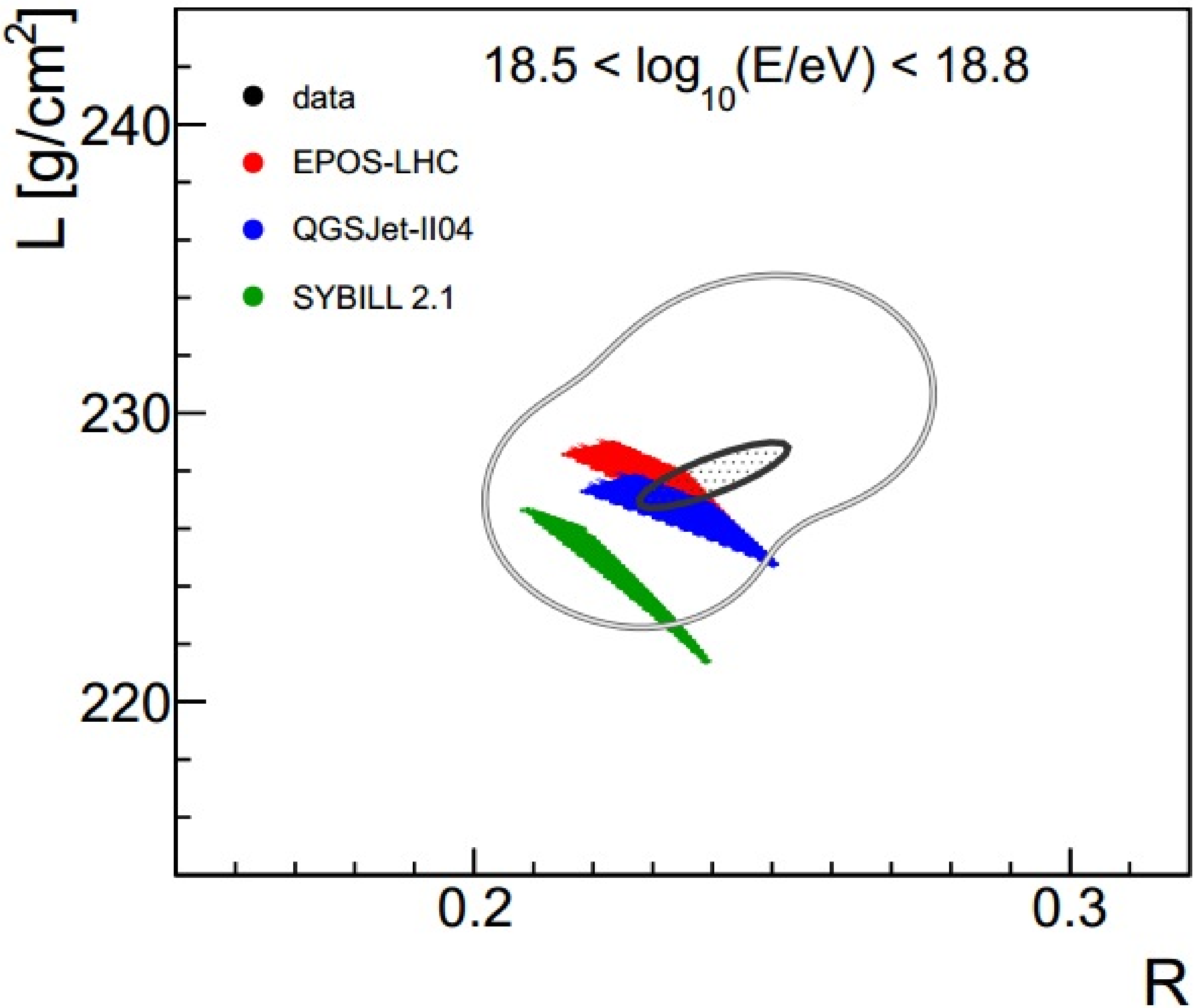

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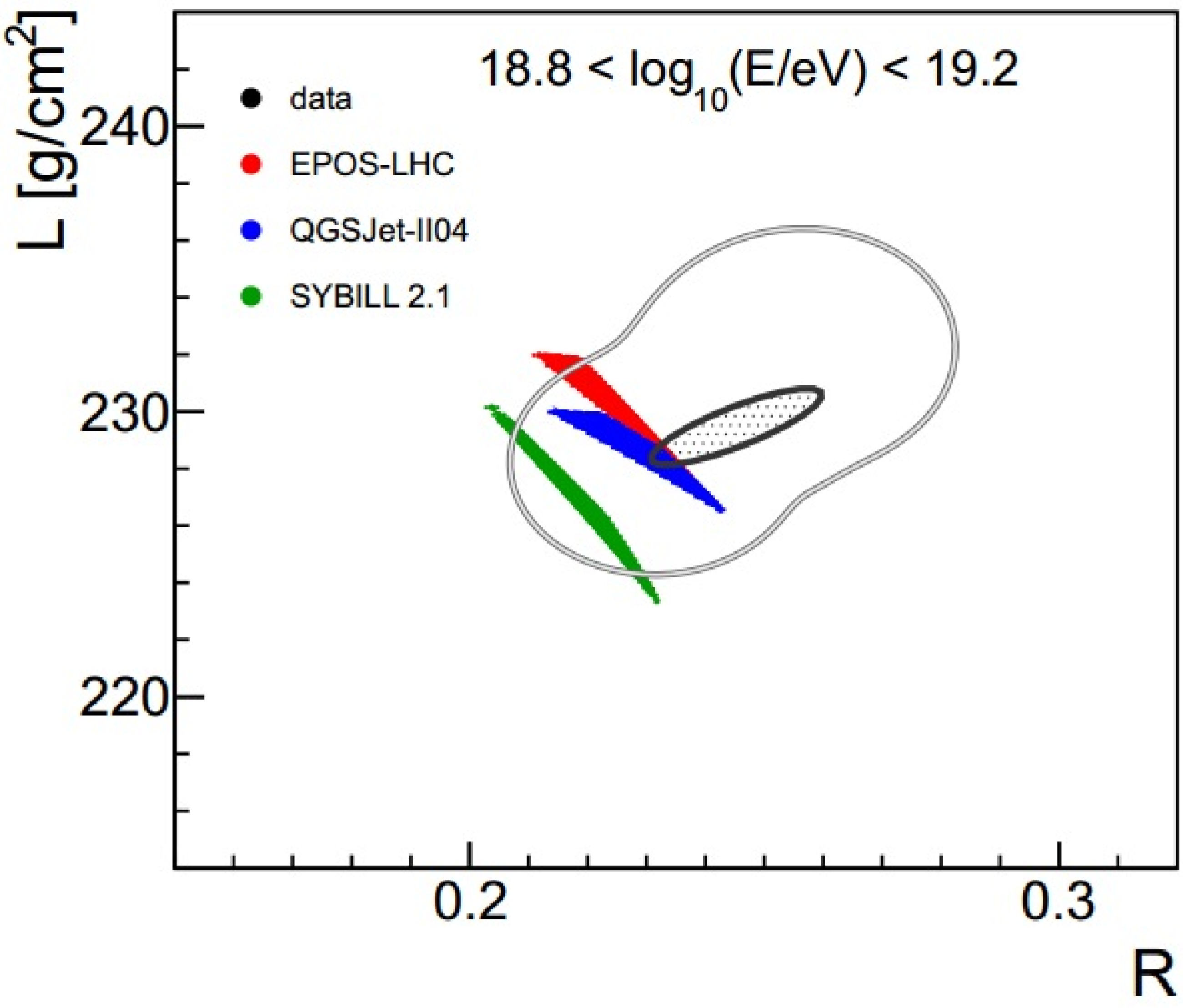

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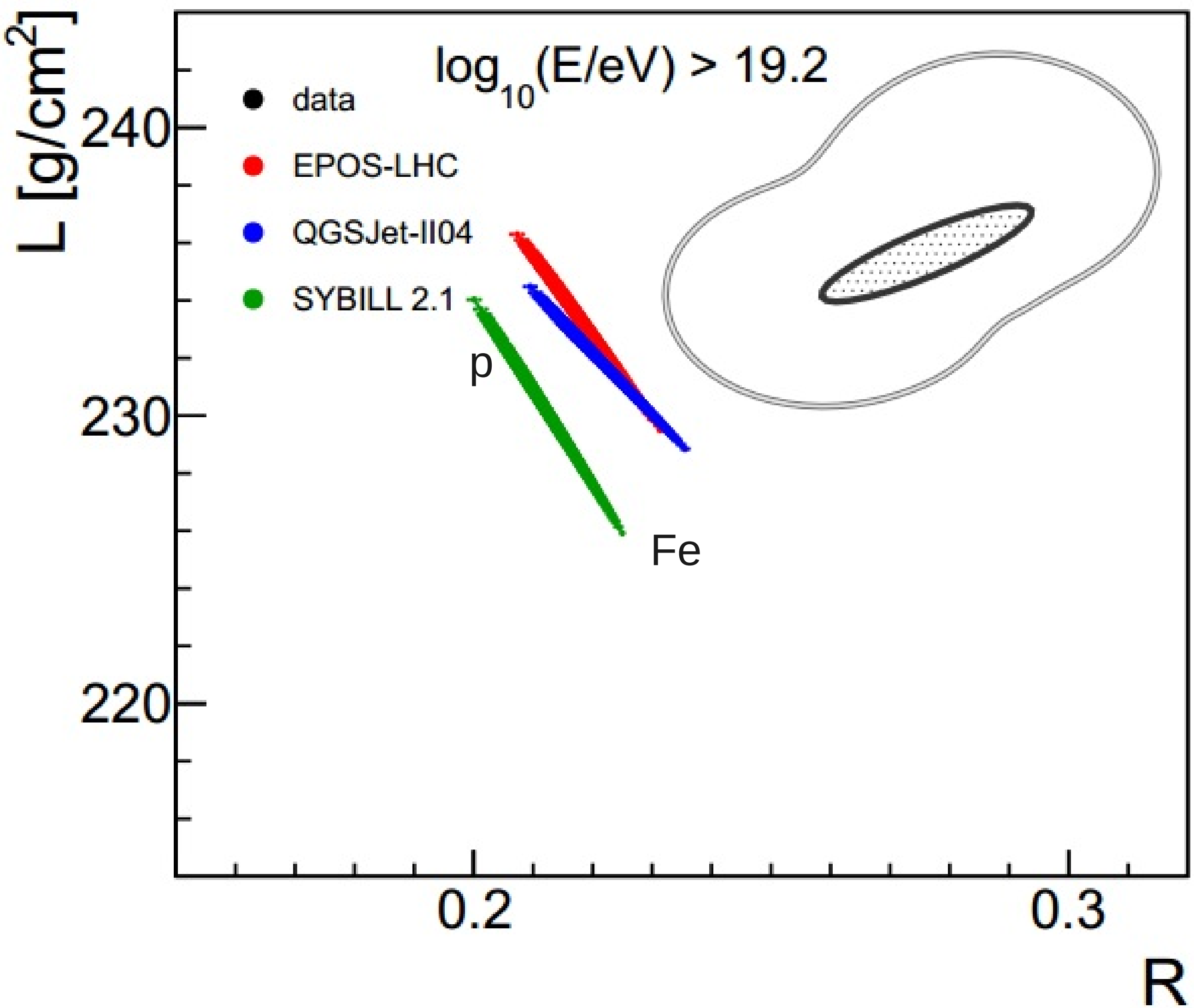

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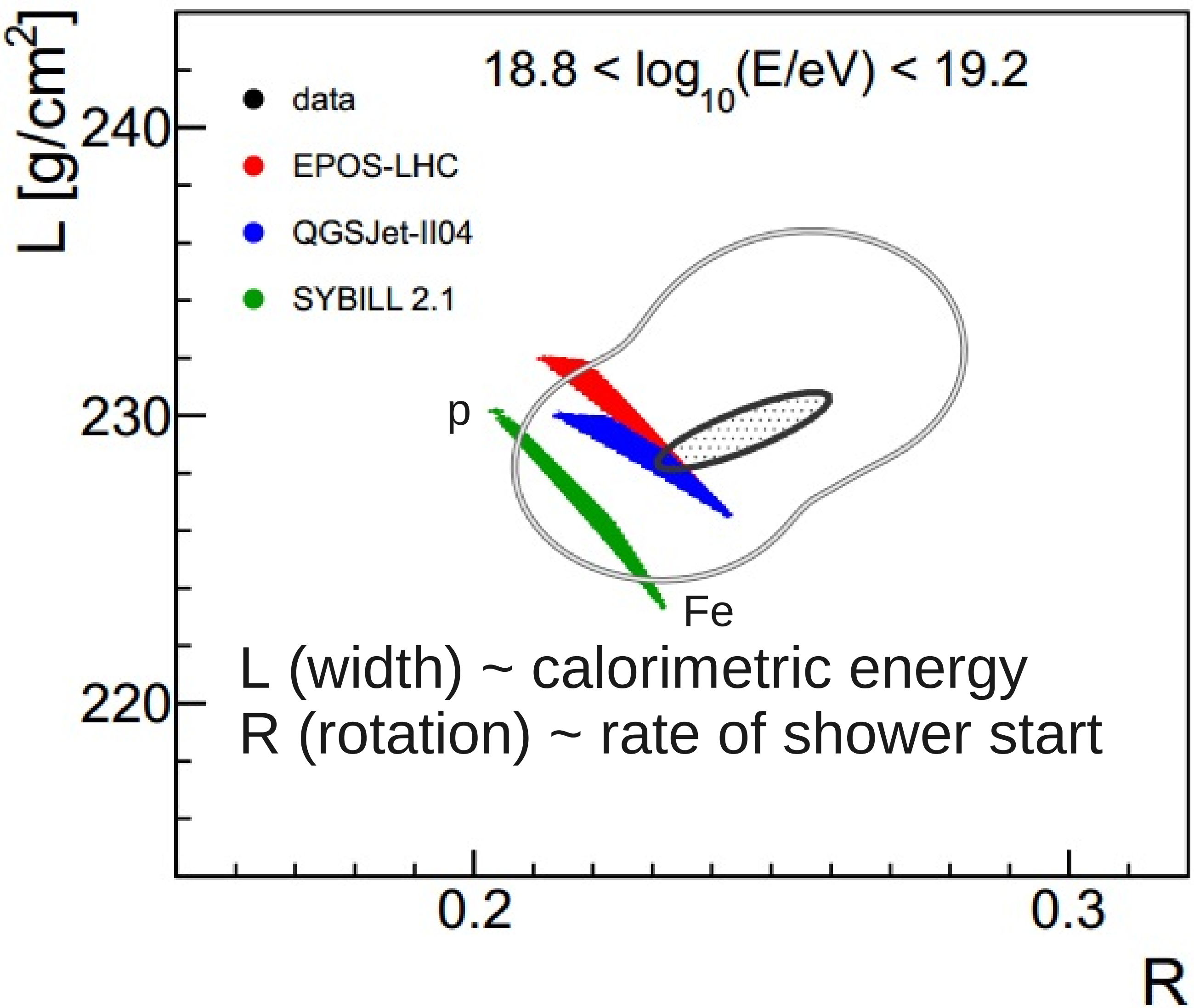

L (width) ~ calorimetric energy
R (rotation) ~ rate of shower start

Profile shape insensitive to 1^{st} interaction cross-section

Probing secondary spectra: elasticity, multiplicity and charges at high energy

Preliminary:
still large uncertainties
but global model testing

linear in lnA at the highest energies?
(more linear in Sybill 2.1)