Hadronic Interactions in Air Showers

Working Group Summary

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Where We Left Off…

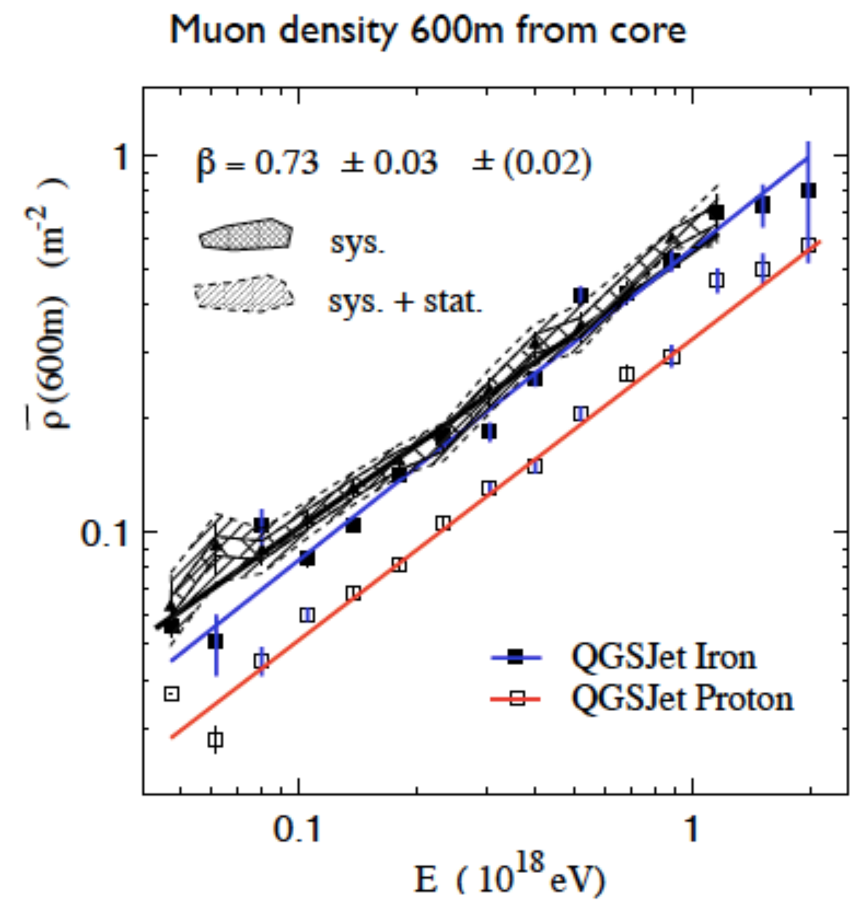
- Overall agreement in description of air shower features (θ, ϕ, r, s).
  The devil is in the details…

- Discrepancies in detector signal and muon densities,
  (TA SD-FD, Auger muons)

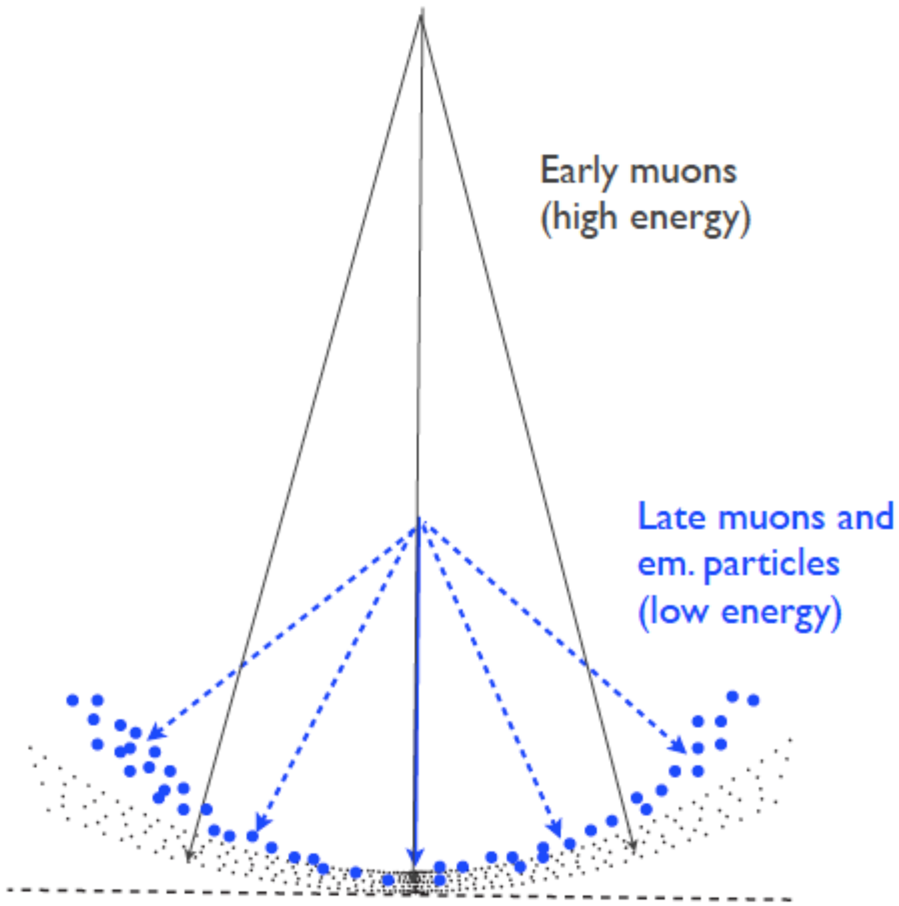
- Increased baryon production in EPOS 1.99.

- At what energy does the “*muon problem*” appear?

- Shower front curvature should be measured.

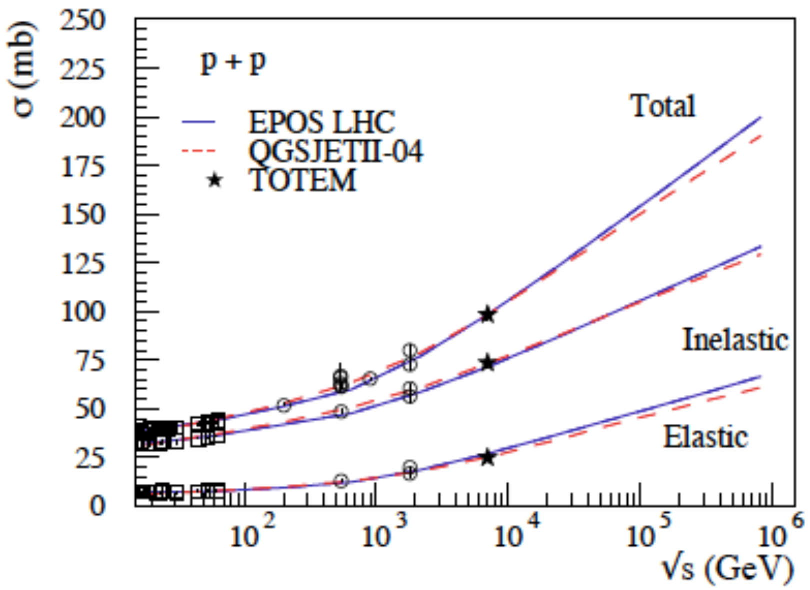


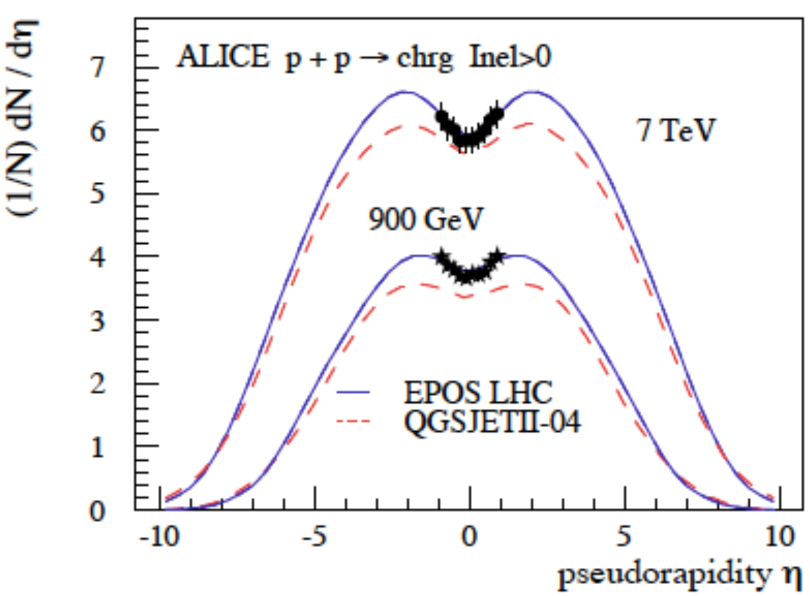
(HiRes Fly's Eye and MIA Collabs., Phys. Rev. Lett. 84, 2000)



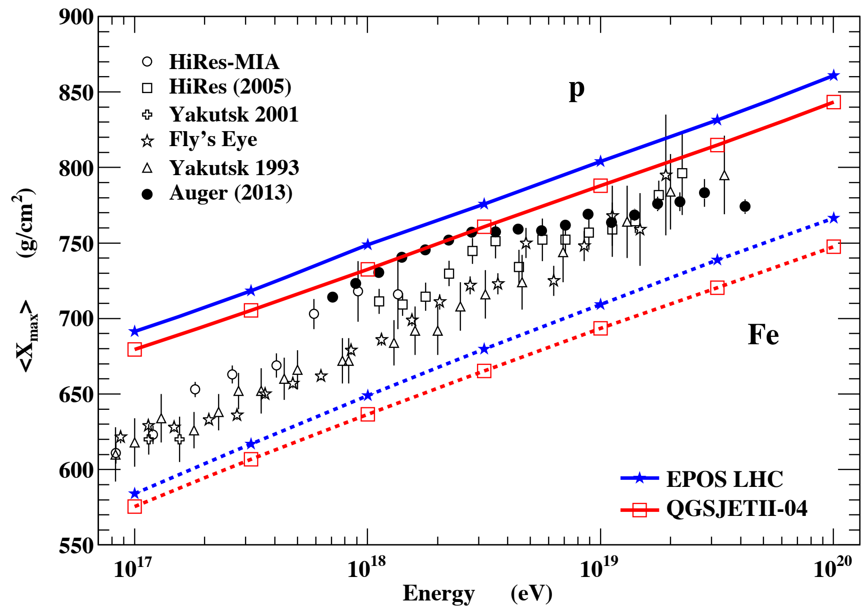
Hadronic Models tuned to LHC

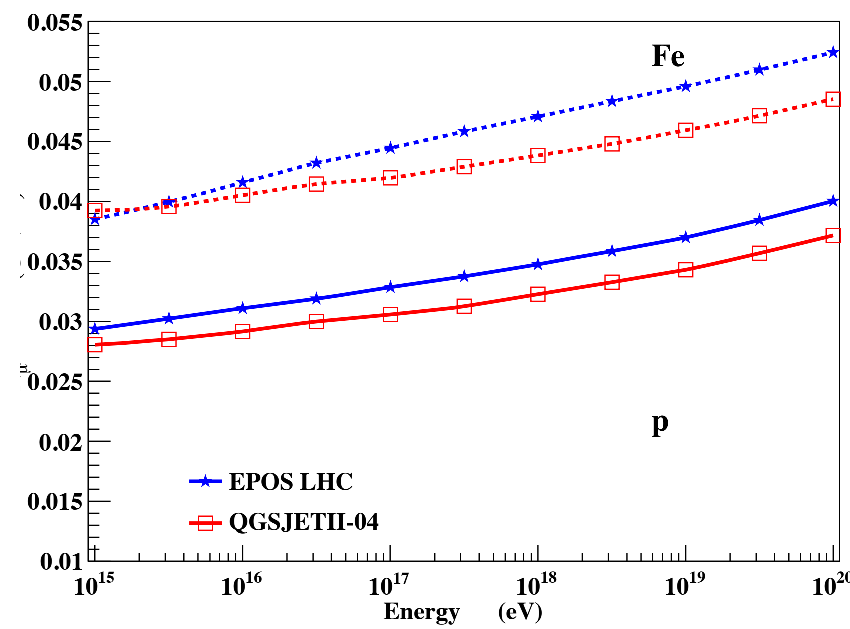
(see talks by R.Ulrich, R. Engel, N. Sakurai)





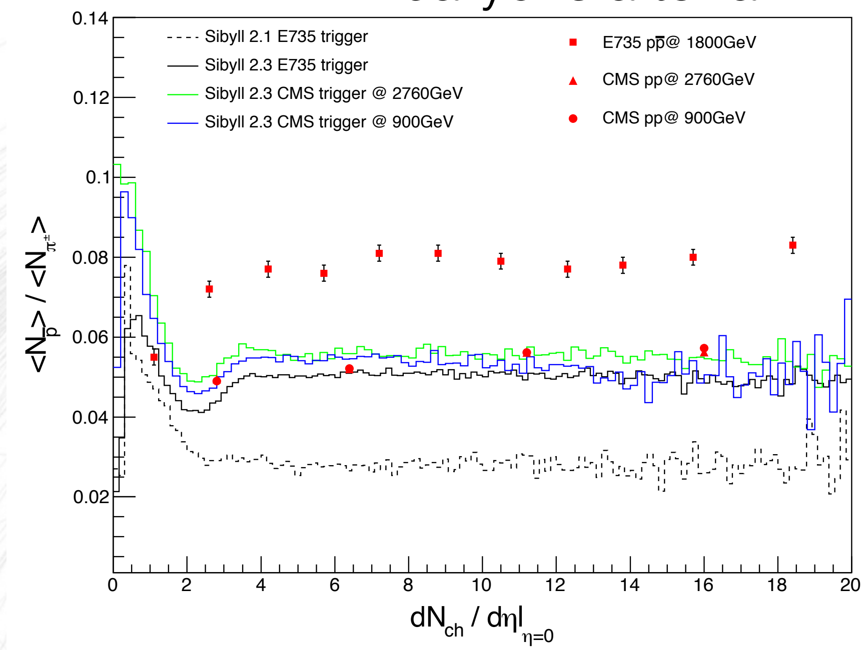
cross-sections
pseudo-rapidity distributions





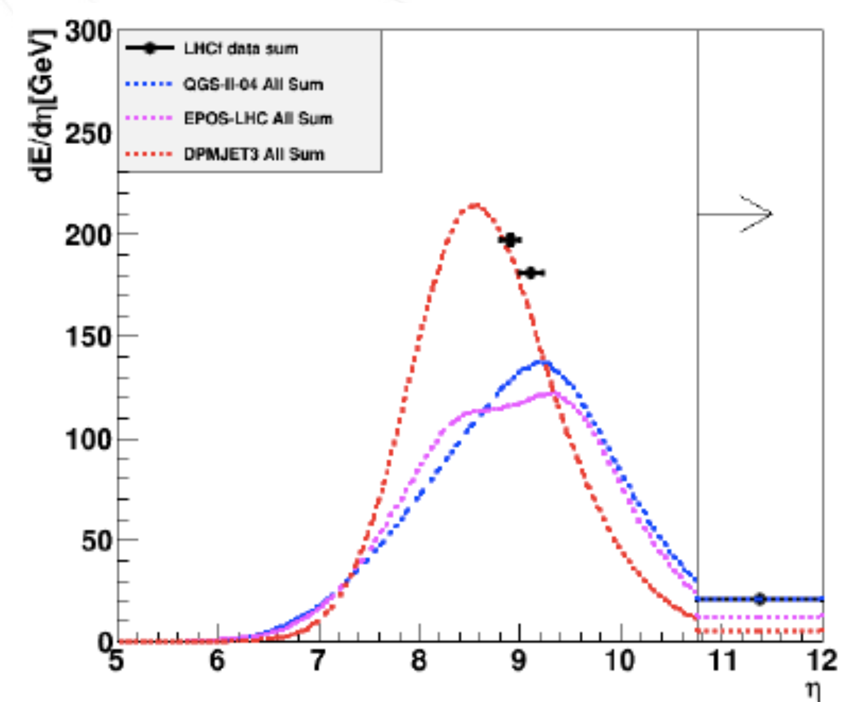
Xmax and muon number
more consistent between models

EPOS 1.99 had too many baryons after all



ρ mesons also increase muon number!

but maybe neutrons are underestimated?



Different Experiments/Observables

- TA
  - FD-SD signal scale in hybrid events
  - Shower front curvature
- Auger
  - FD-SD signal from hybrid events (especially inclined, θ>60°)
  - Xmax and its fluctuations
  - Muon production depth (MPD)
- IceCube
  - Muon number from lateral signal distribution, muons in the ice.
- Yakutsk
  - Direct muon measurements
- Akeno/AGASA
  - Multiple techniques, muon detectors, scintillators and, notably, lead-burgers.

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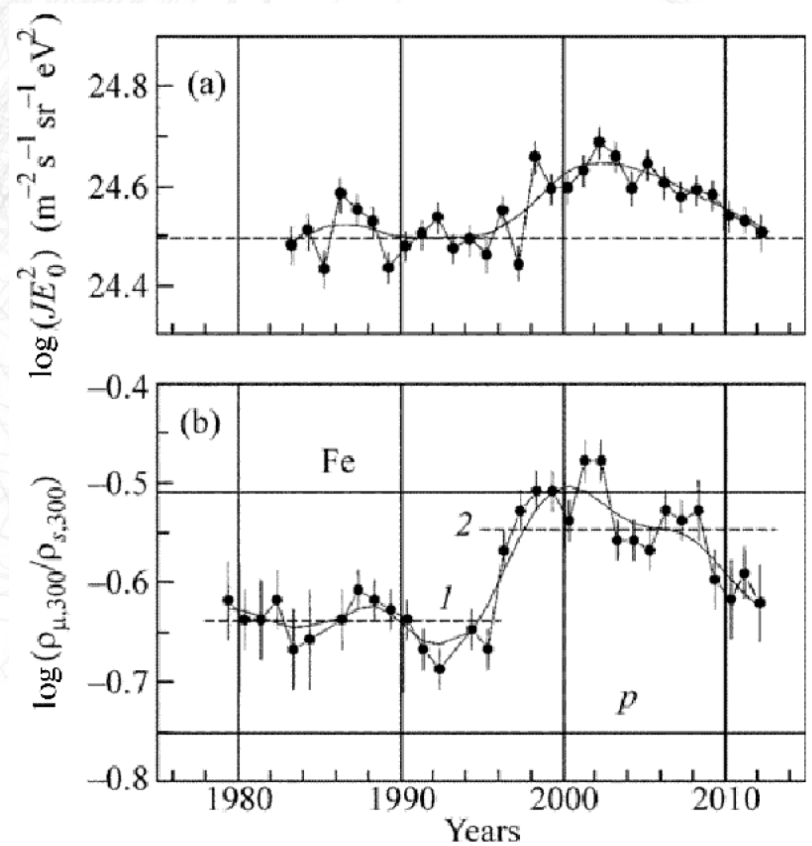
- Energy re-calibrated
- Muon data after 1996 needs to be re-evaluated



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lots of data there,
a comparison to new models
would be a good idea!

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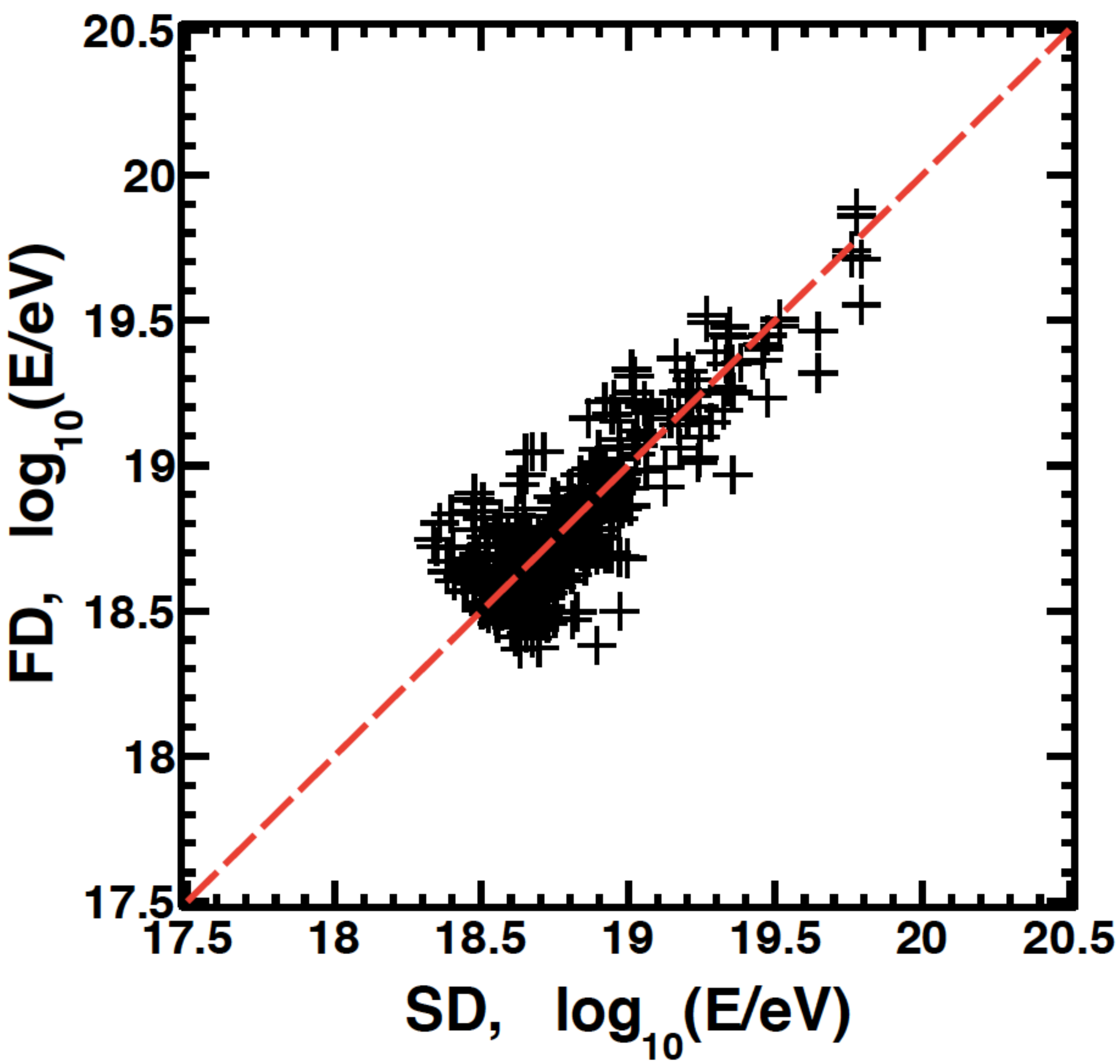
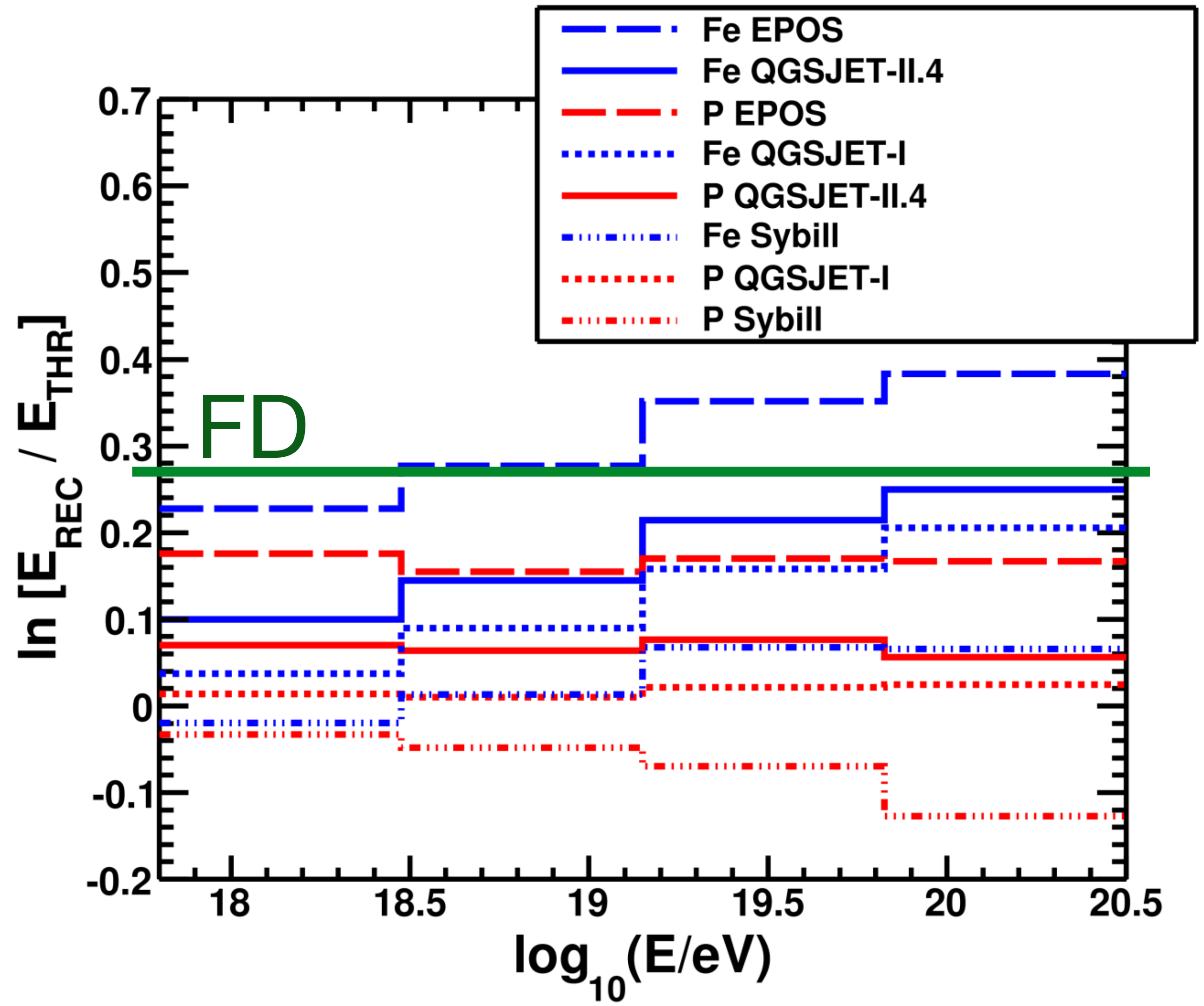
Do they agree?

TA

SD-FD Energy Scale



$E_{SD}/1.27$

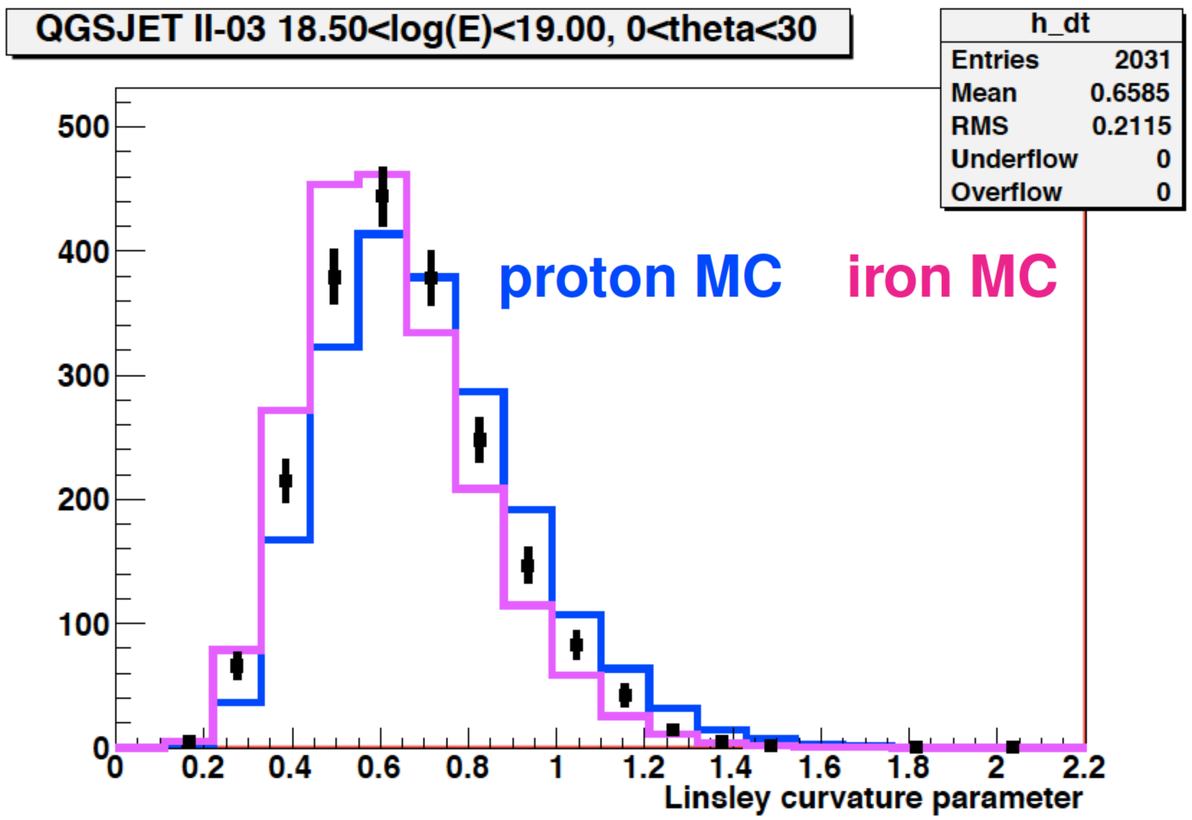


Reconstructed energy needs to be rescaled to agree with expectation from simulations

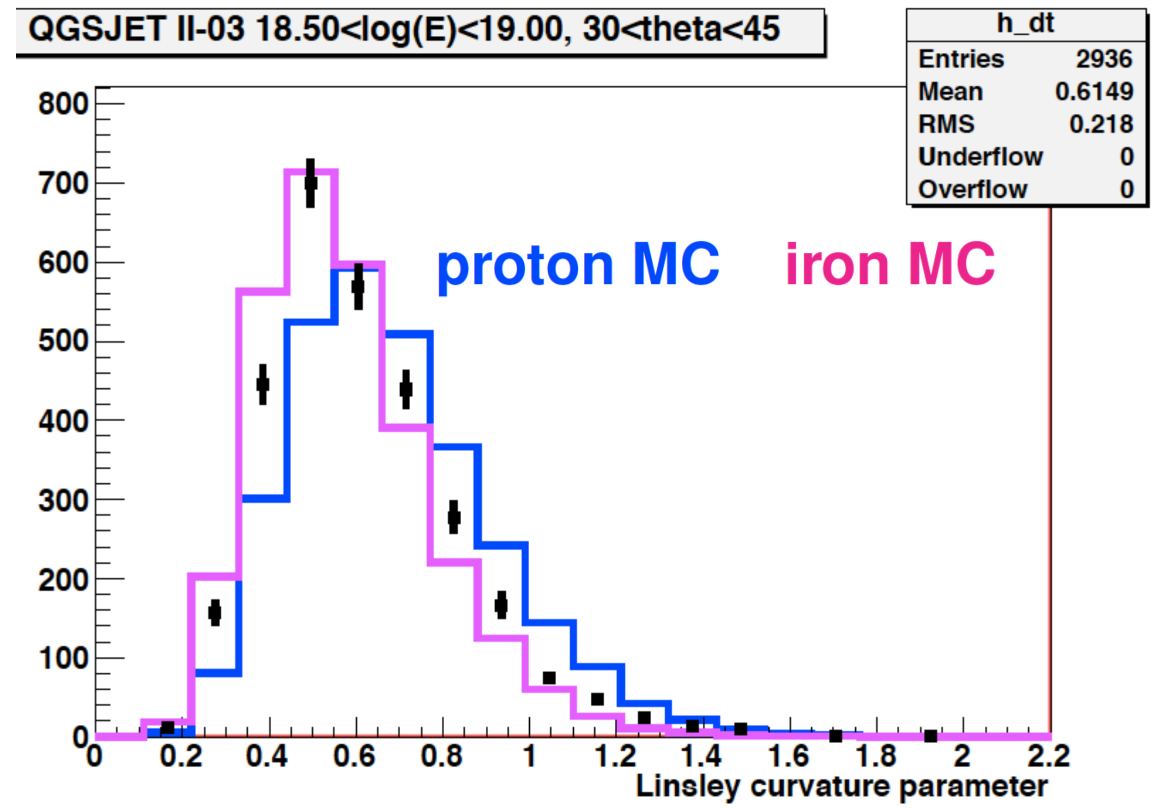
FD: -27%
QGSJet II.04: -5%
EPOS: -20%
Sibyll: +5-1-%

TA: Shower Front Curvature

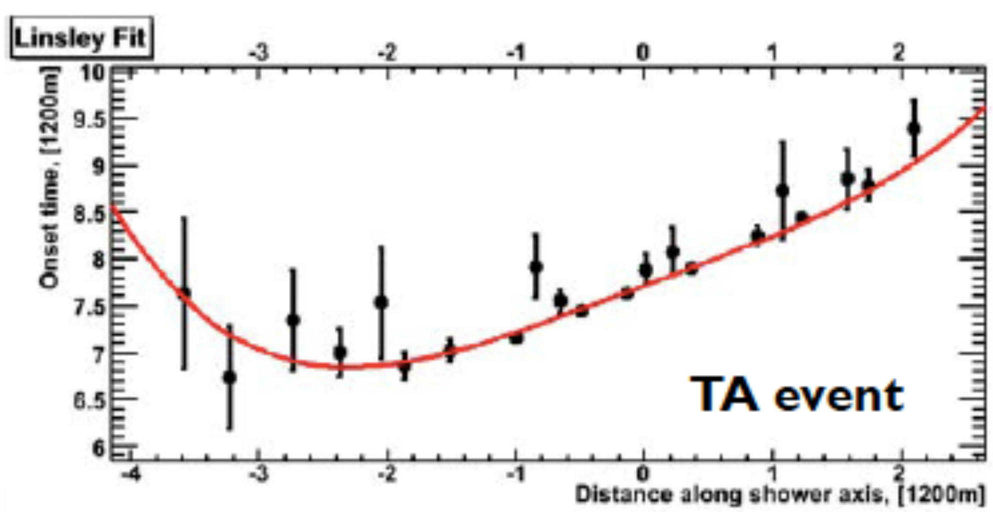
(QGSJet II-03)



KS distance: **0.098** **0.088**



KS distance: **0.14** **0.076**



$$S(r) = S_{800} \times LDF(r)\,,$$

$$t_0(r) = t_0 + t_{plane} + a \times 0.67\,(1 + r/R_L)^{1.5} LDF^{-0.5}(r)$$

TA, Phys.Rev. D88 (2013) 11, 112005, arXiv:1304.5614

Dataset:

- 5 years: 2008-05-11 – 2013-05-04
- θ < 45
- 7 or more detectors triggered
- E > 1018 eV
- 10733 events after cuts

Monte-Carlo set:

- QGSJET II-03
- full simulation including de-thinning and detector calibration

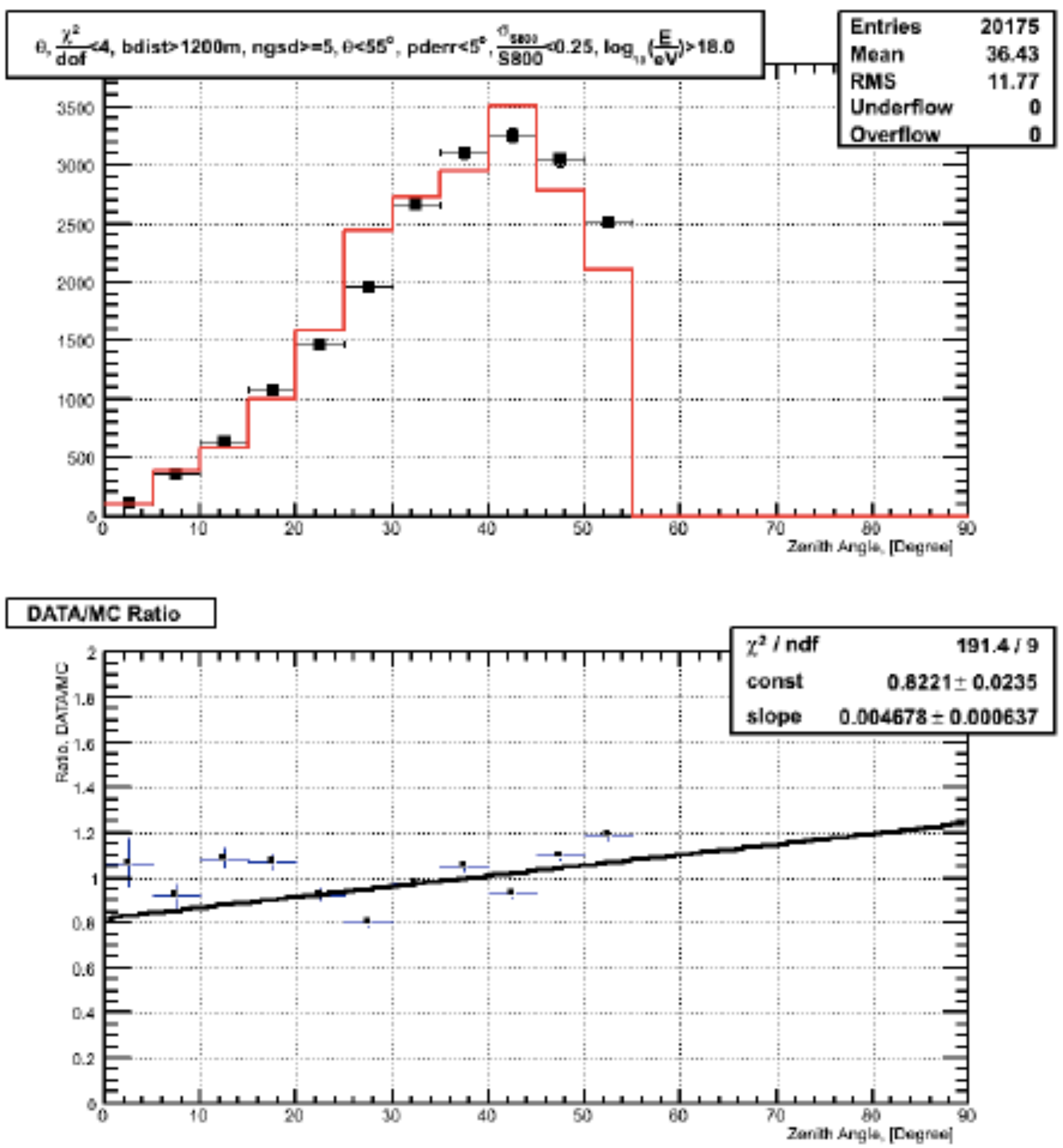
Showing only one energy bin here

TA: ZenithAngle

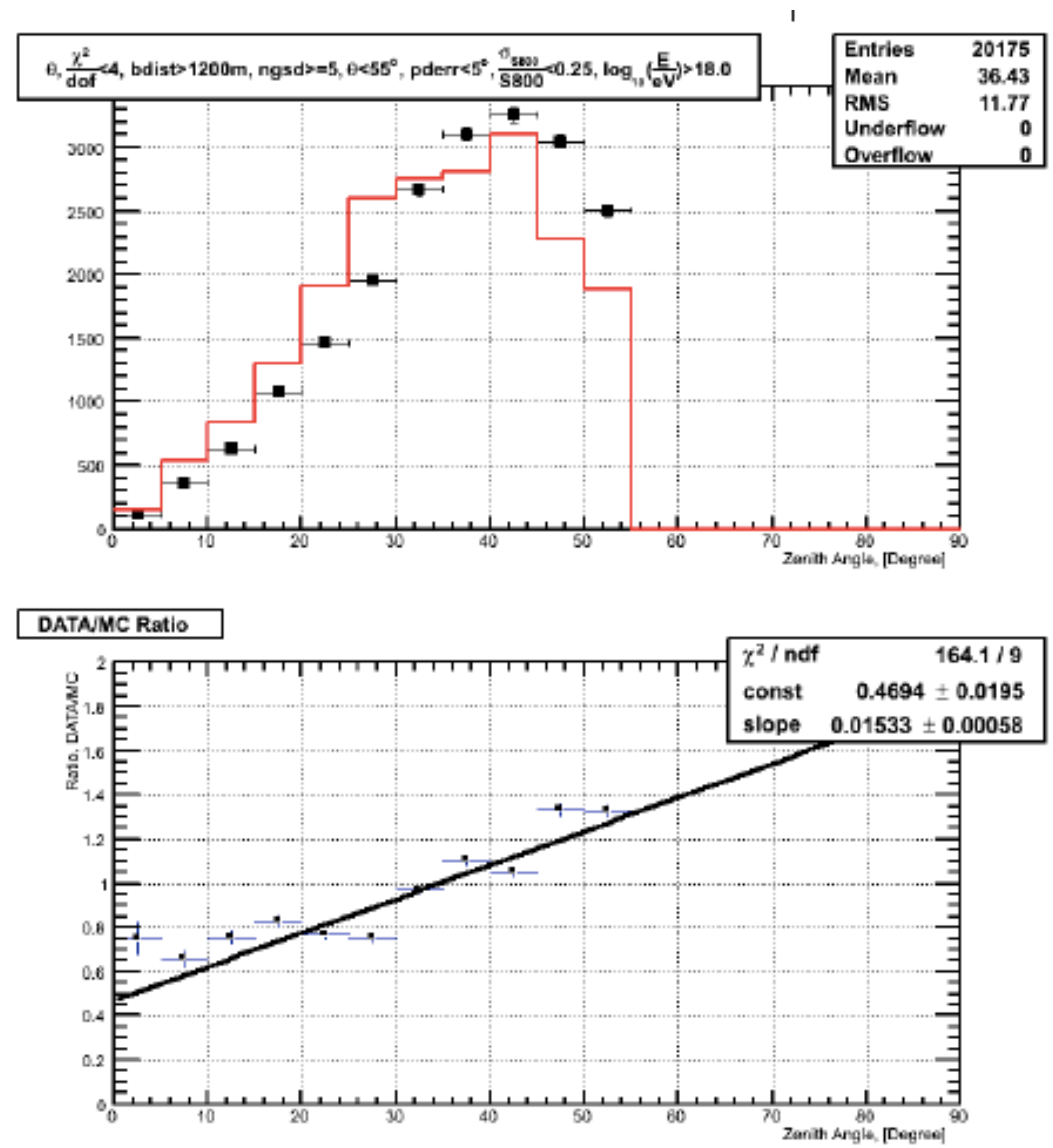
(QGSJet II-04)

$\theta < 55°$

Proton



Iron



Proton fits better than iron

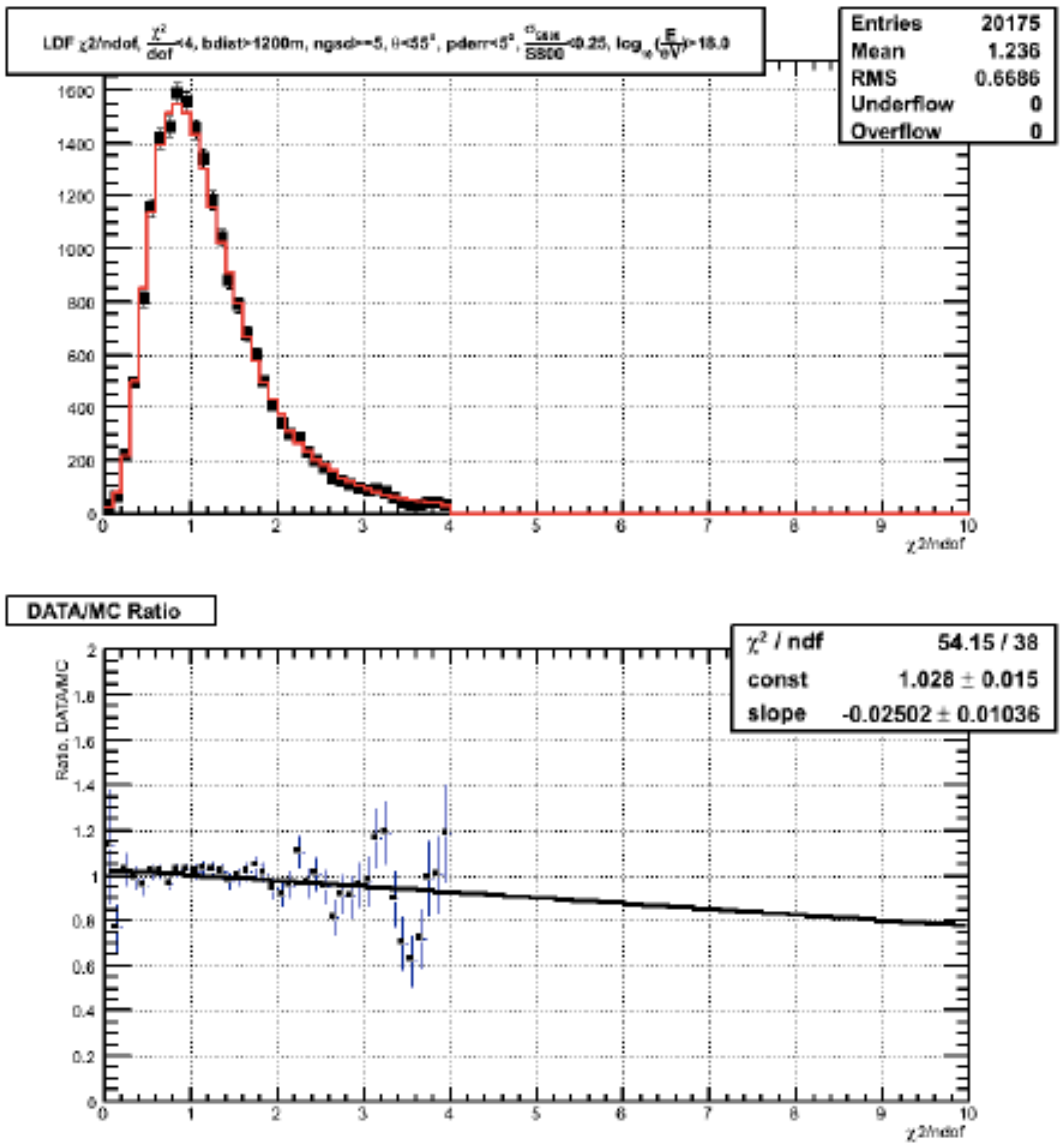
B. Stokes et al. ICRC 2013-0353

TA: Lateral Profile χ^2

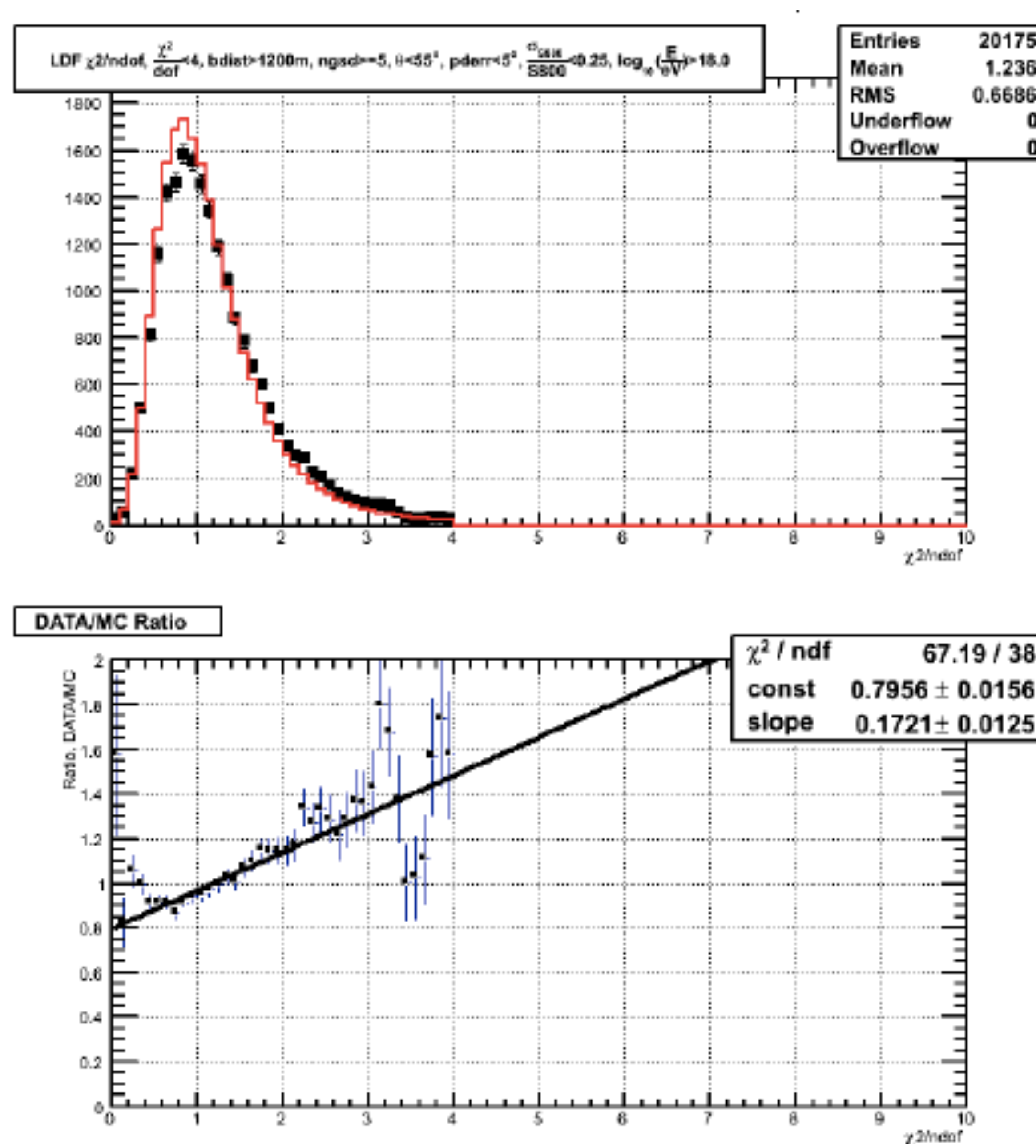
(QGSJet II-04)

$\theta < 55°$

Proton



Iron



Proton fits better than iron

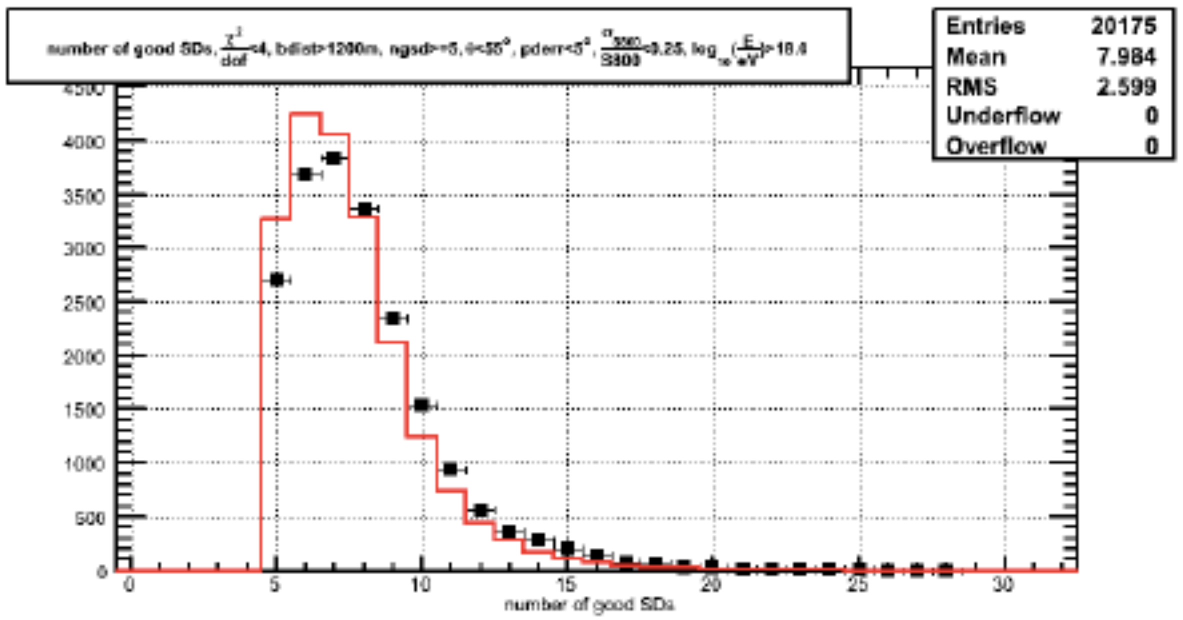
B. Stokes et al. ICRC 2013-0353

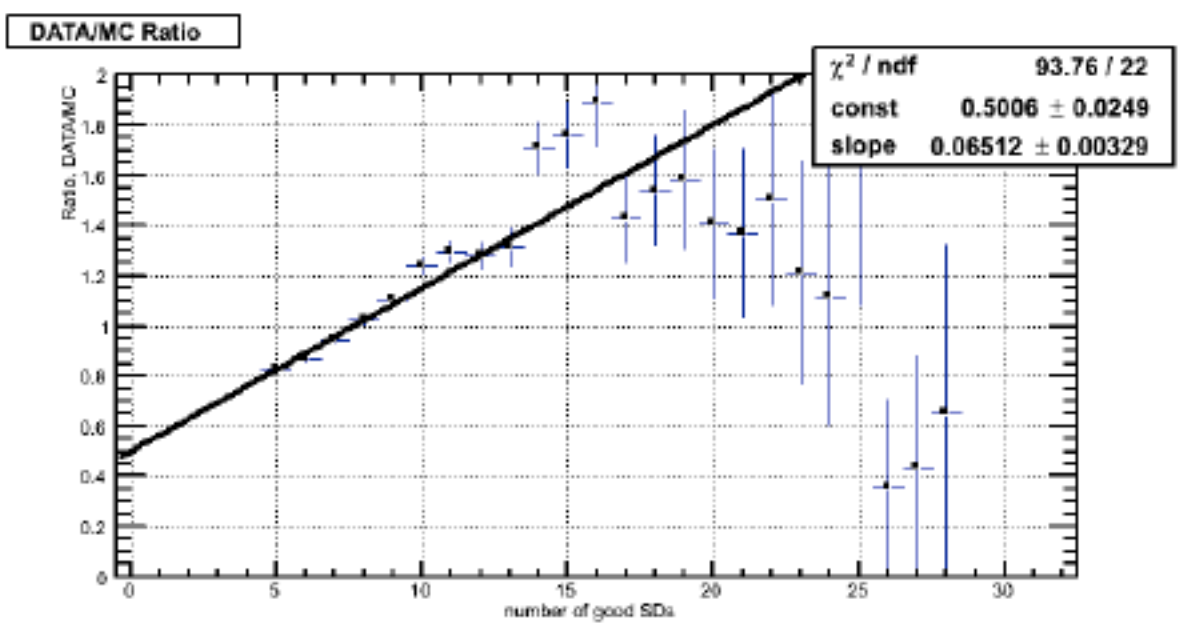
TA: Counters per Event

(QGSJet II-04)

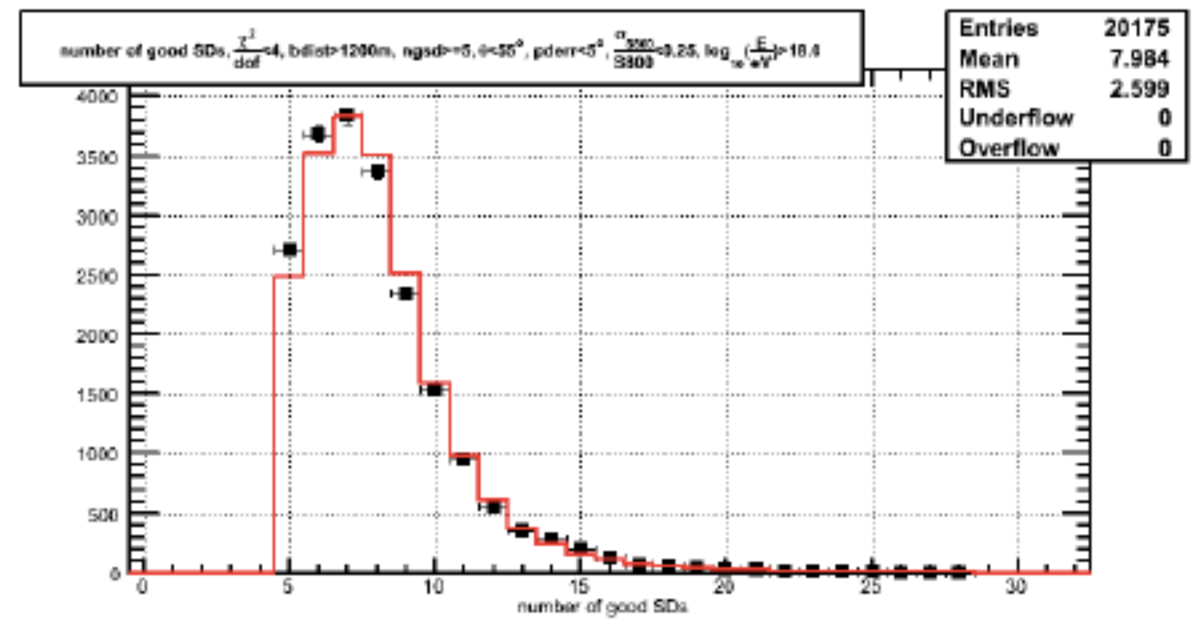
$\theta < 55°$

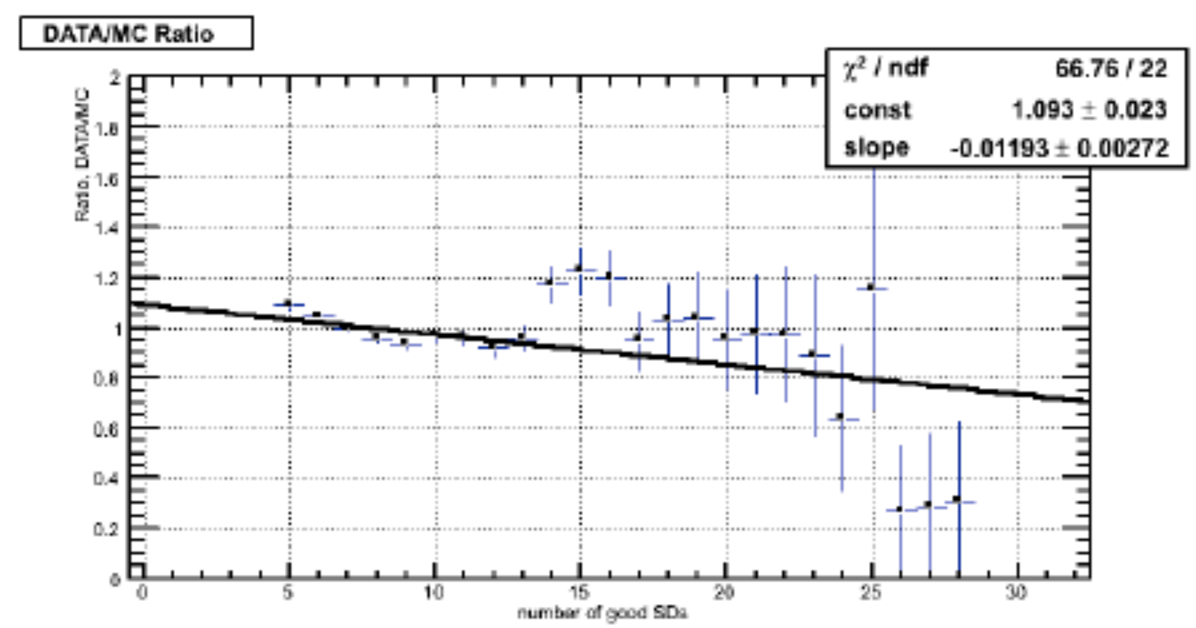
Proton





Iron





Iron fits better than proton

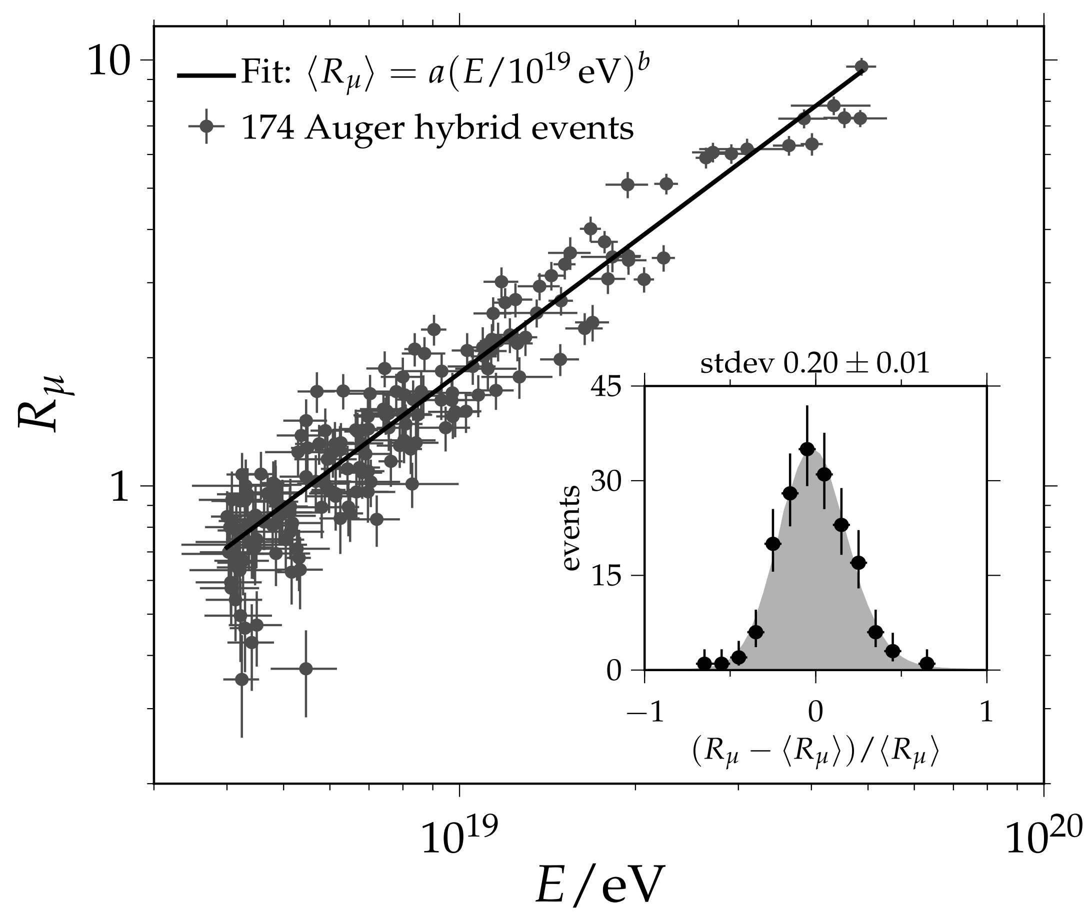
B. Stokes et al. ICRC 2013-0353

Telescope Array

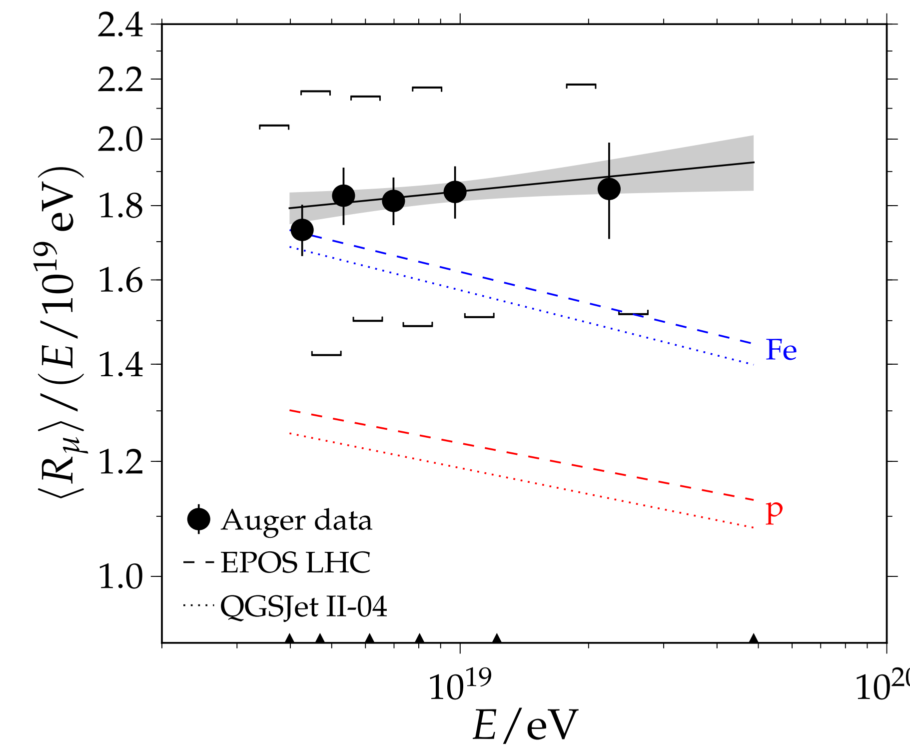
- TA observes SD/FD energy difference which is model dependent:
  E_{SD}/E_{FD} = 1.27 for QGSJET II-03 protons.
  (it is noted that most of the signal is not from muons)
- Curvature distribution seems closer to iron for higher zenith angles (vertical and inclined are not consistent).
  - *the curvature distribution is not described by either proton or iron. It is bracketed by them. Further studies with different models and composition assumptions would be interesting.*
  - A muon excess when compared QGSJET II-03 *could* cause this. Could it also be produced by mixed composition?
- Other interesting parameters (similar across different models):
  - Zenith angle distribution. Better fit by proton.
  - lateral profile χ^2. Better fit by proton.
  - number of counters per event. Better fit by iron.

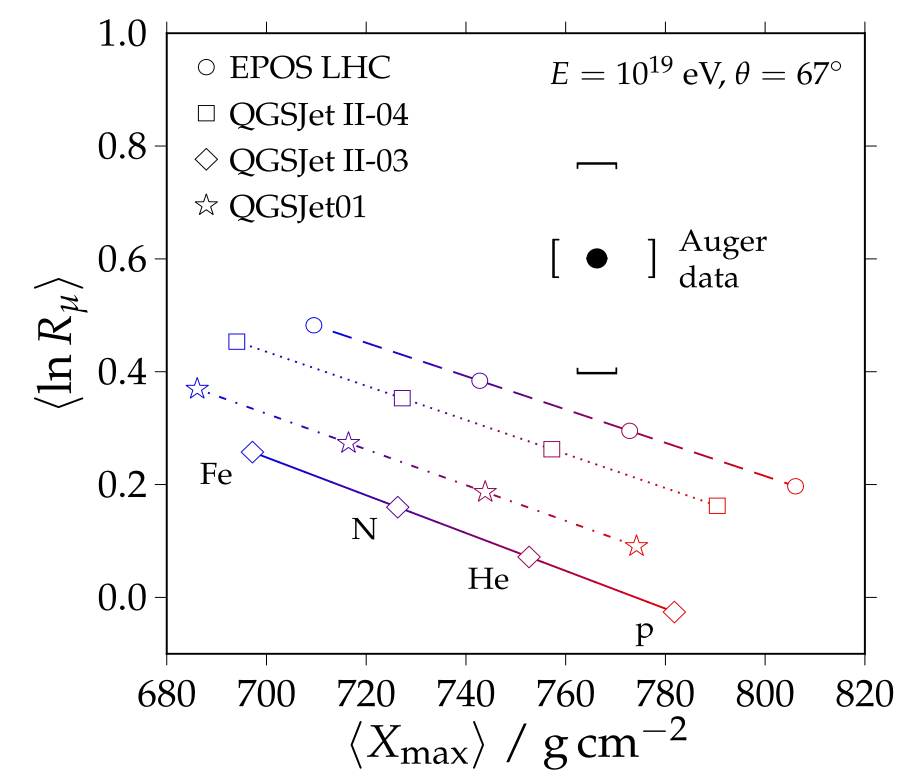
Pierre Auger θ >60

Energy calibration relative to muon map of proton showers at 10^{19} eV (QGSJet II.03)



R_μ 35% above EPOS-LHC

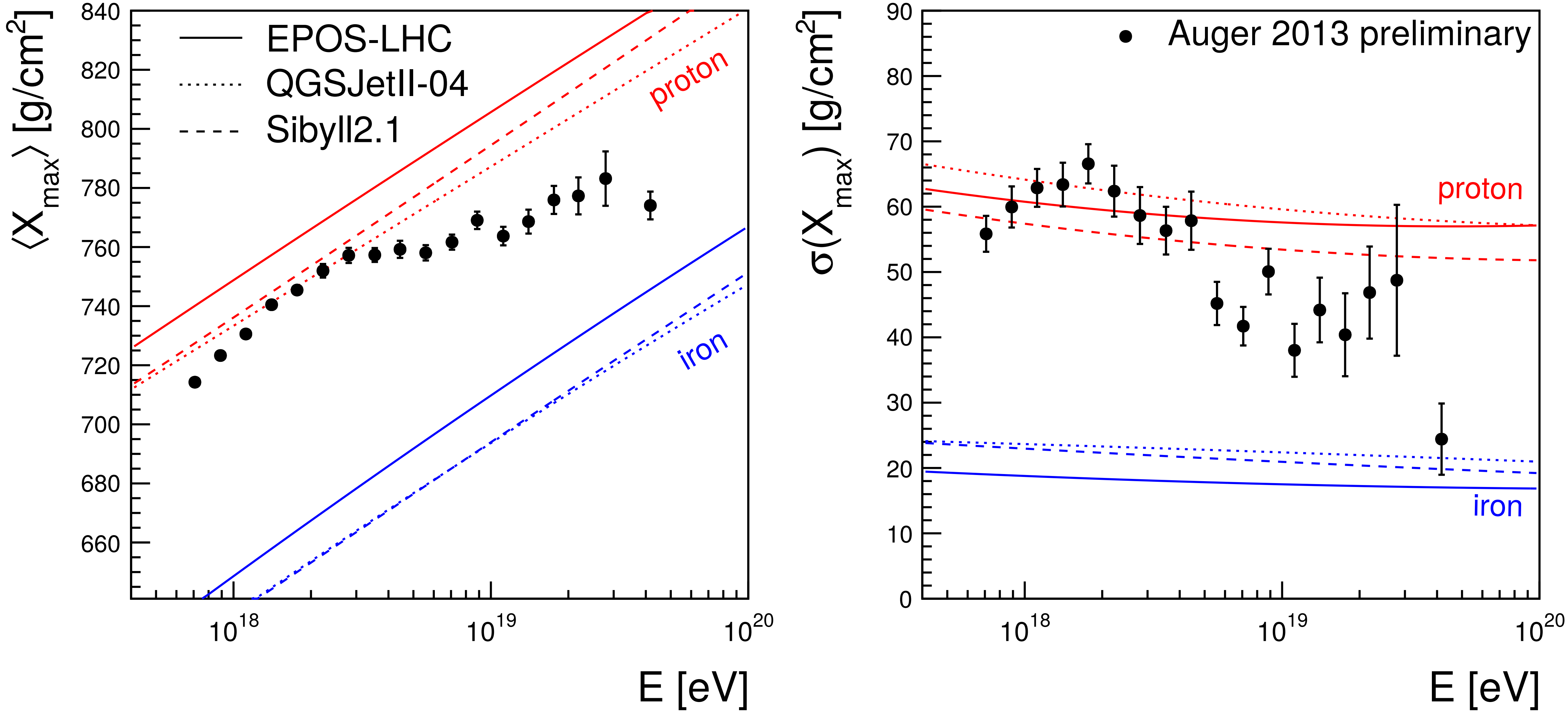




(FD-SD difference also in vertical hybrid events)

Pierre Auger

X_{max}



Pierre Auger

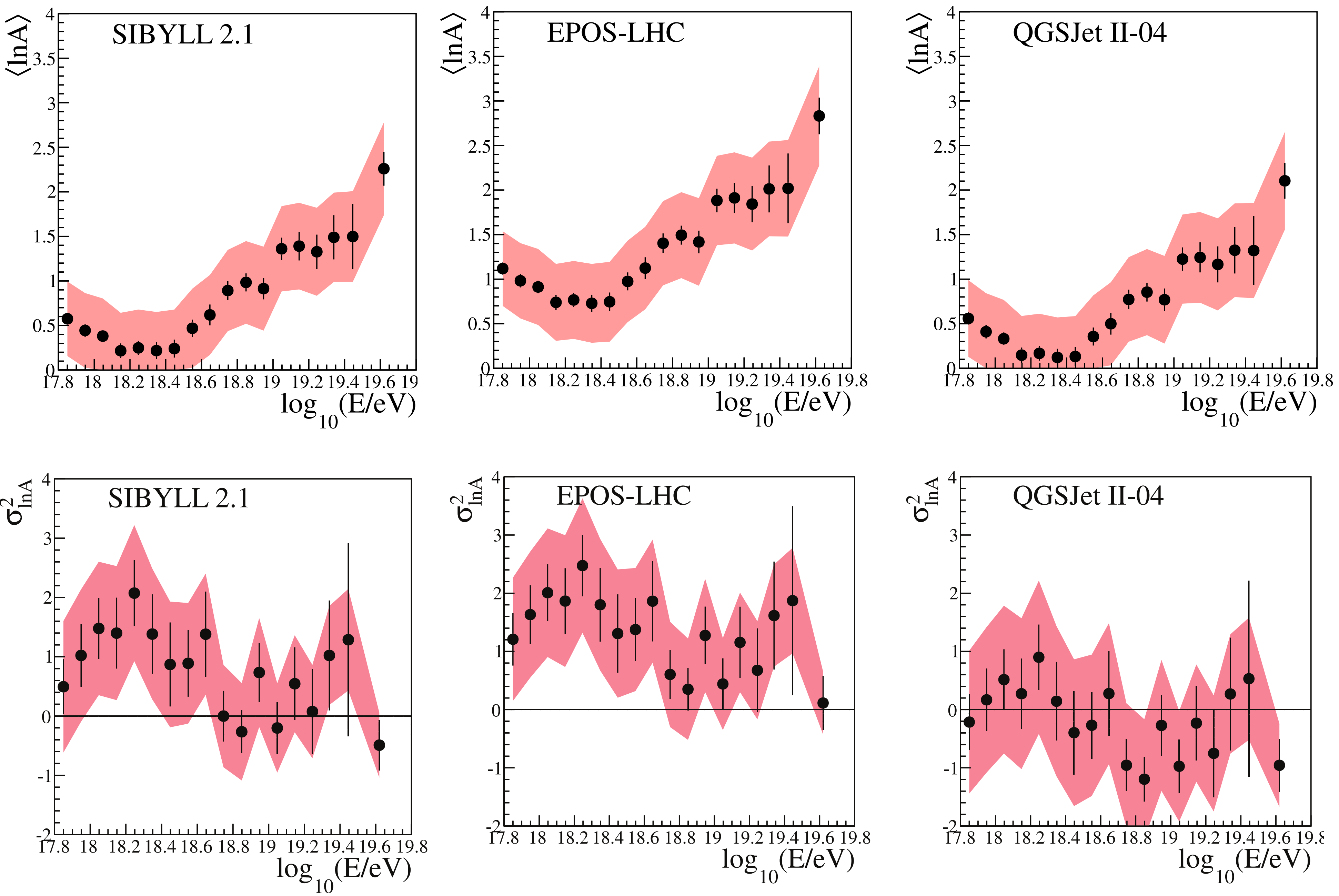
X_{max}

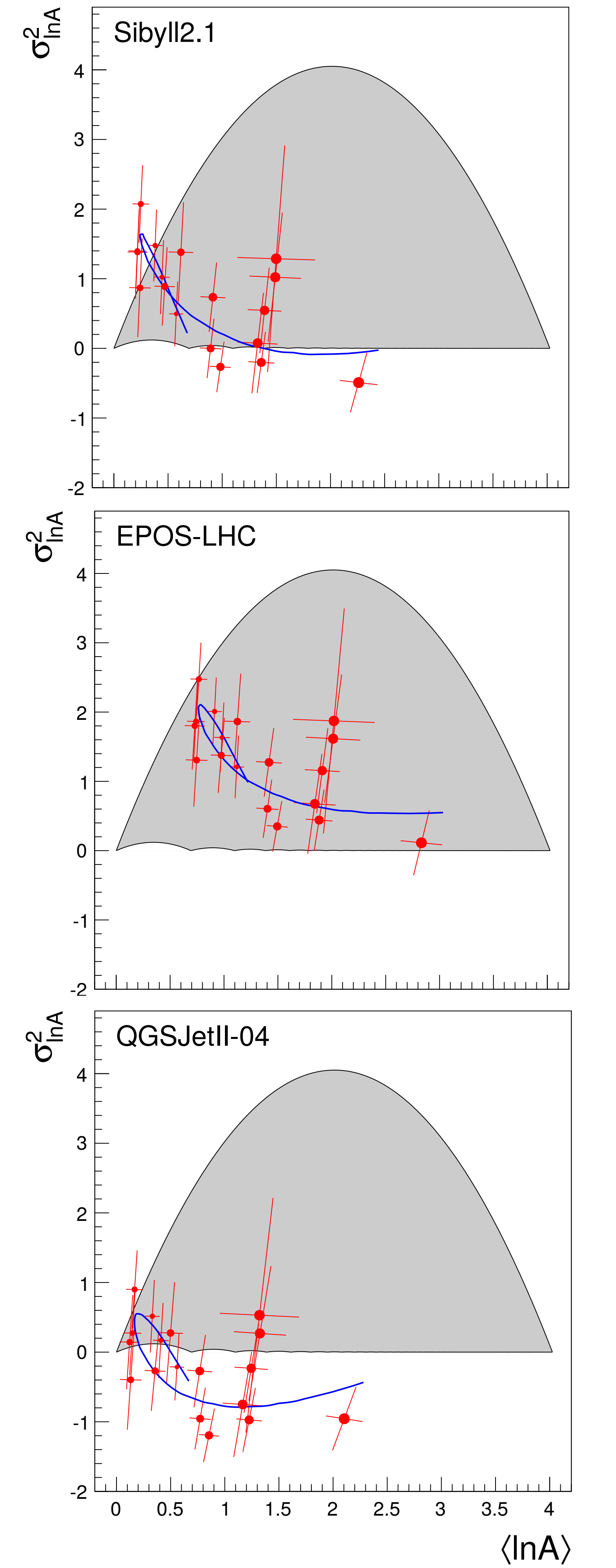
JCAP 02 (2013) 026

$\sigma^2(X_{max}) \approx \sigma^2_{sh} + \sigma^2_{\ln A}\,(D_{10}/\ln(10))^2$ $\qquad X_{max} \approx X^p_{max} - \ln A\; D_{10}/\ln(10)$

σ_{sh} — shower-to-shower X_{max} fluctuations for a fixed mass;

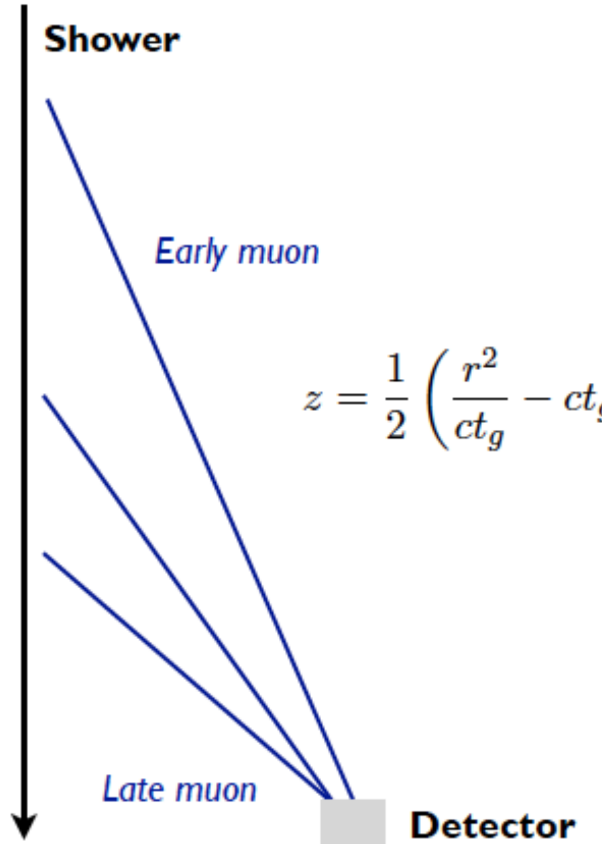
$\sigma^2_{\ln A}$: zero for pure compositions; ≈ 4 for 50% p – 50% Fe



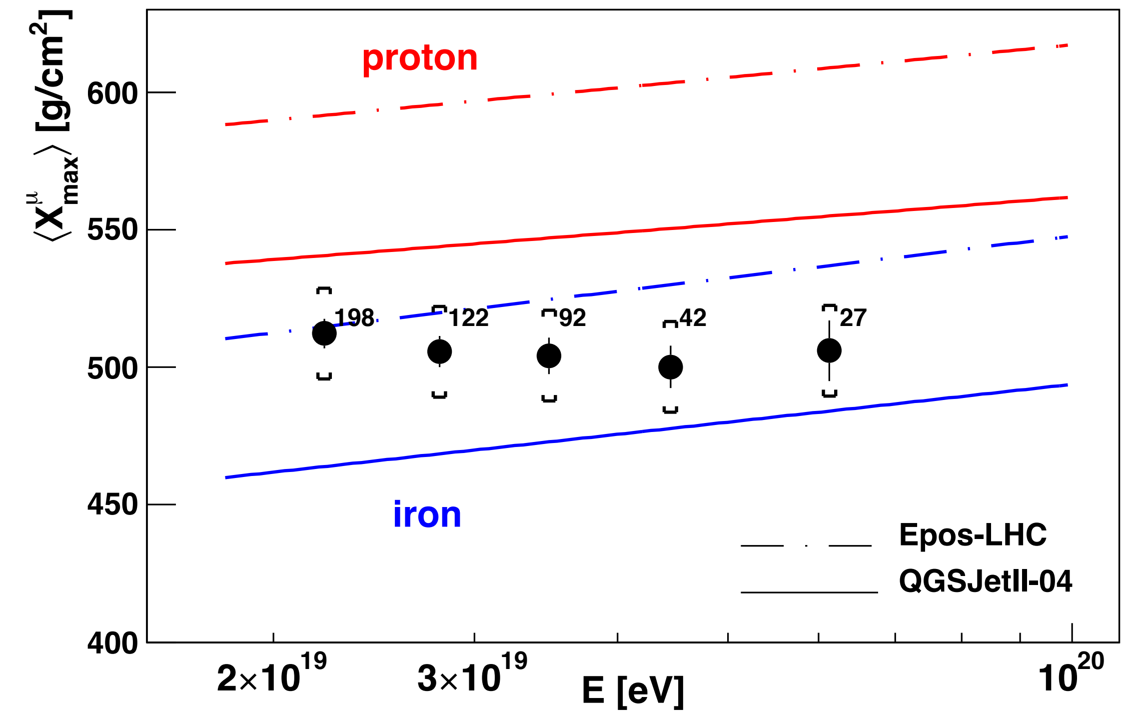


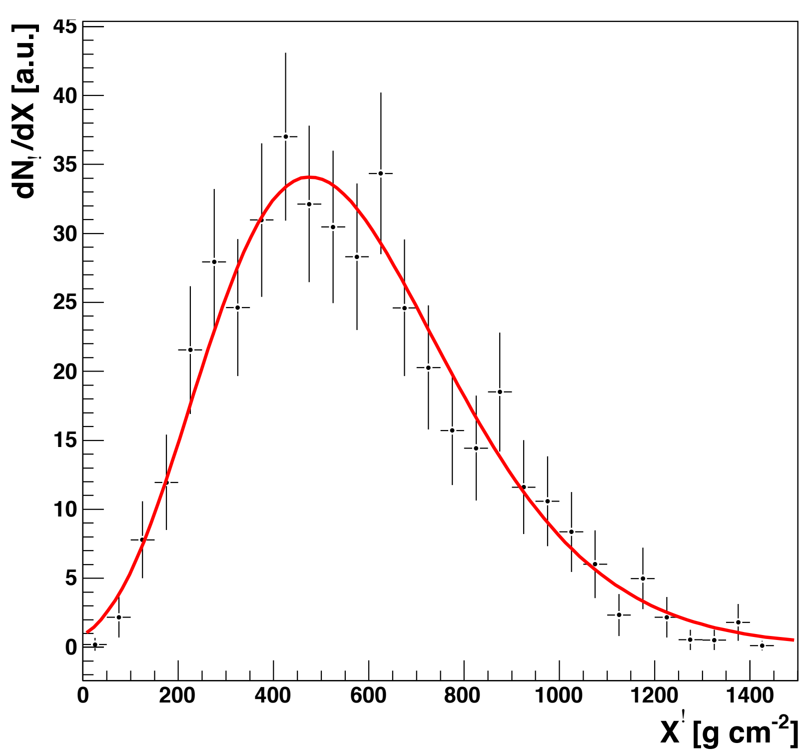
Pierre Auger

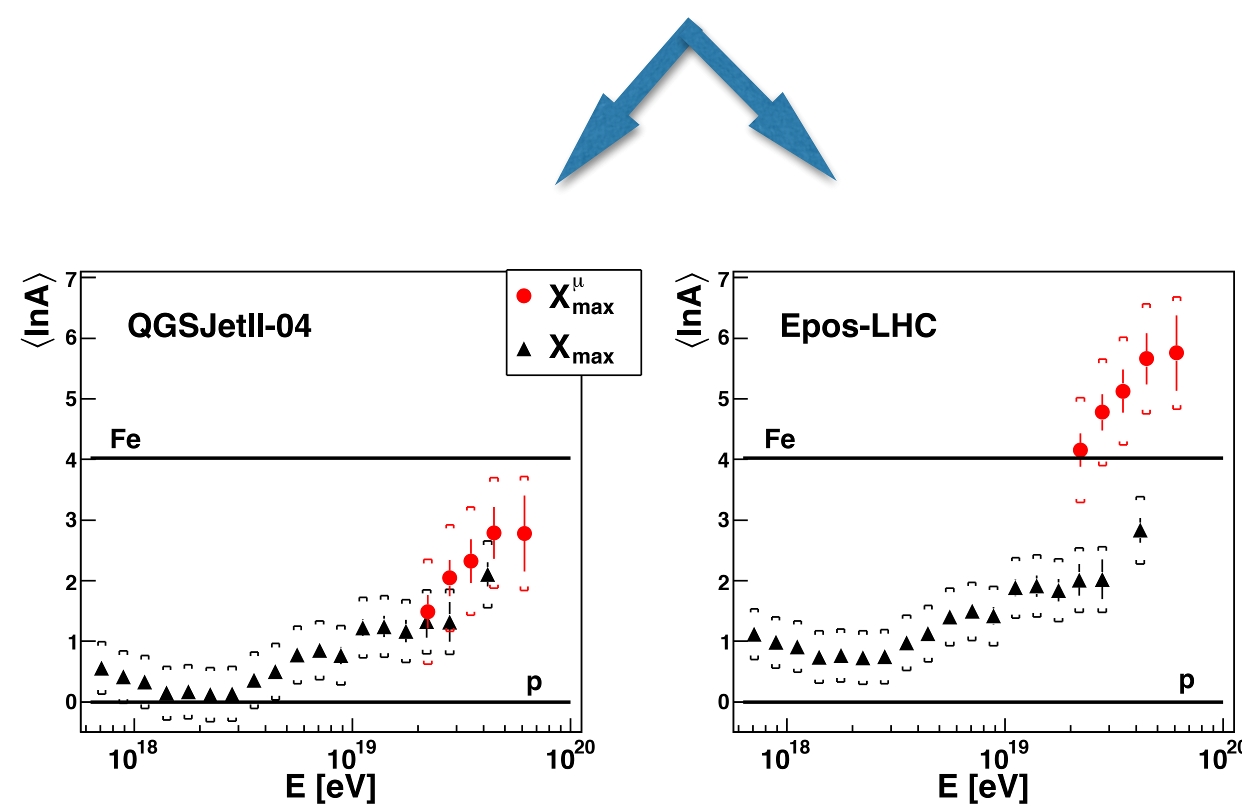
X^{μ}_{max}



$$z = \frac{1}{2}\left(\frac{r^2}{ct_g} - ct_g\right) + \Delta$$

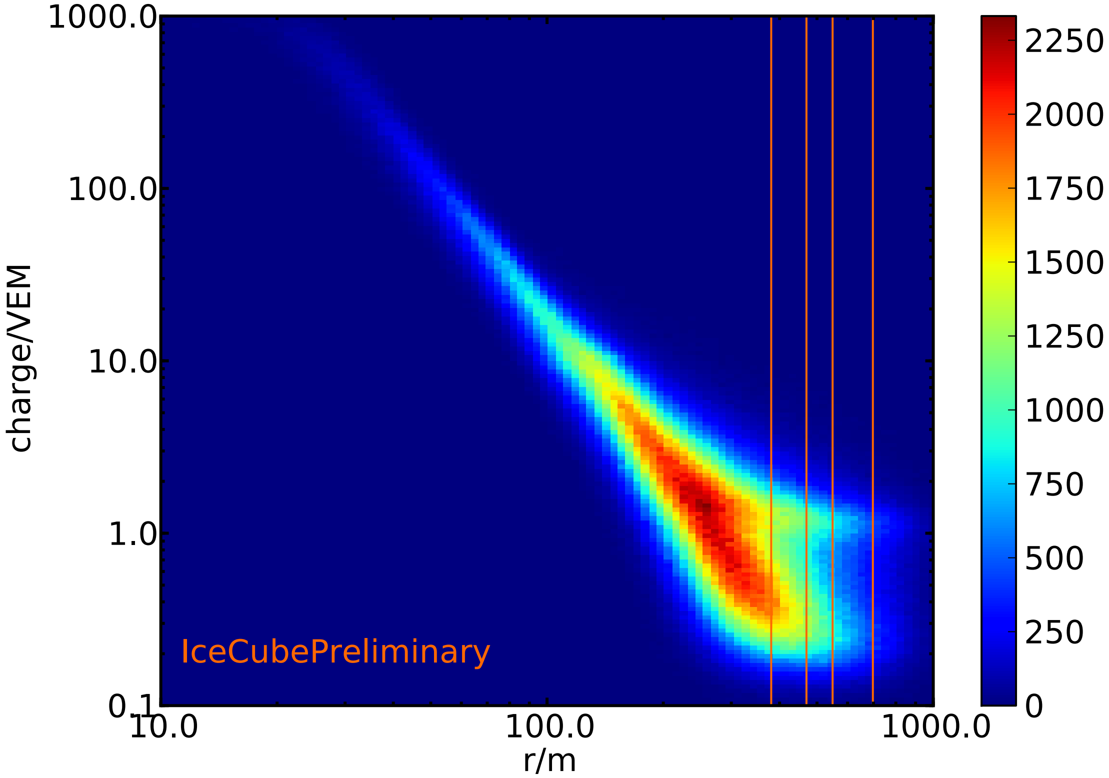


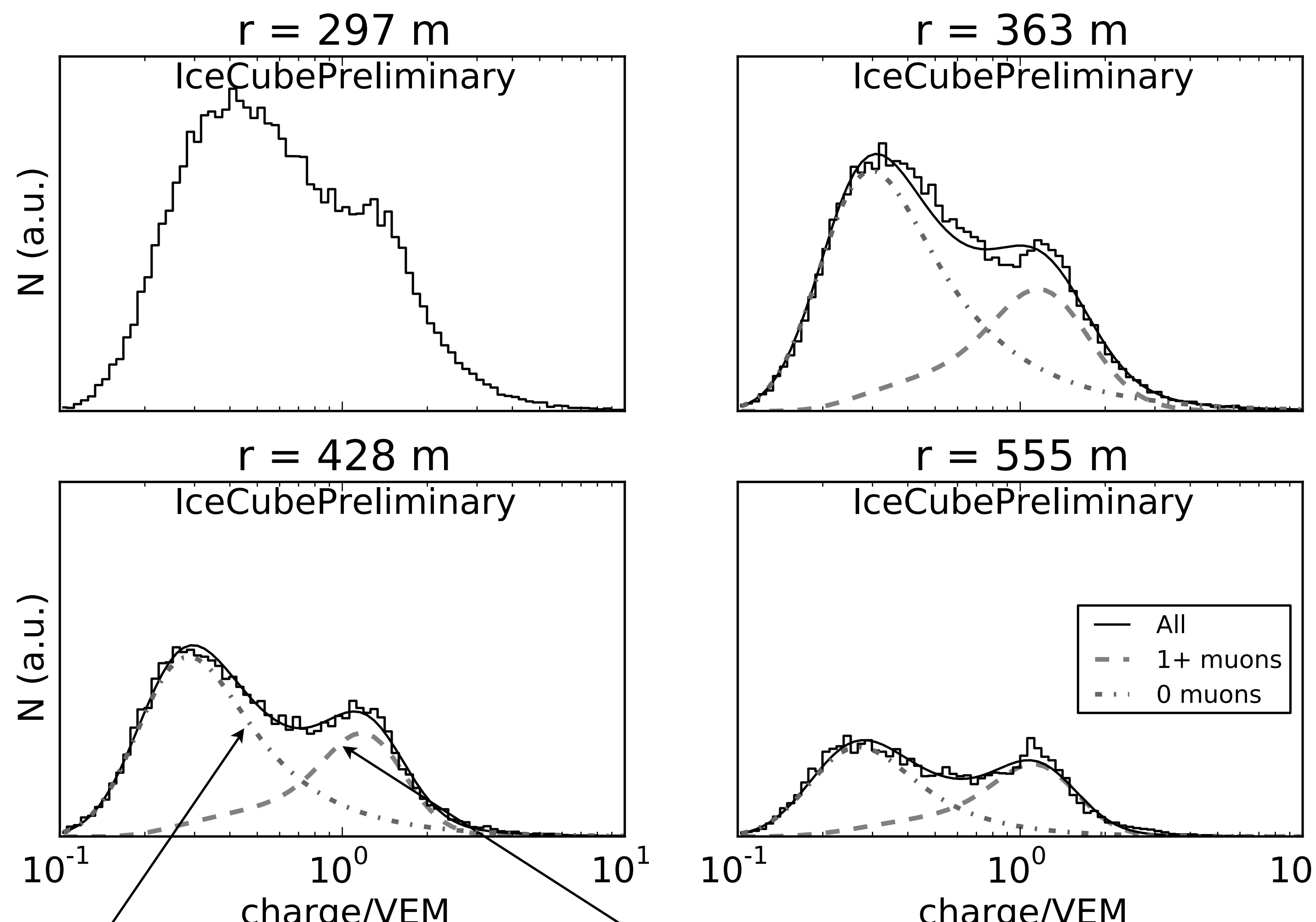




IceCube

(Muons at large lateral distances in IceTop)





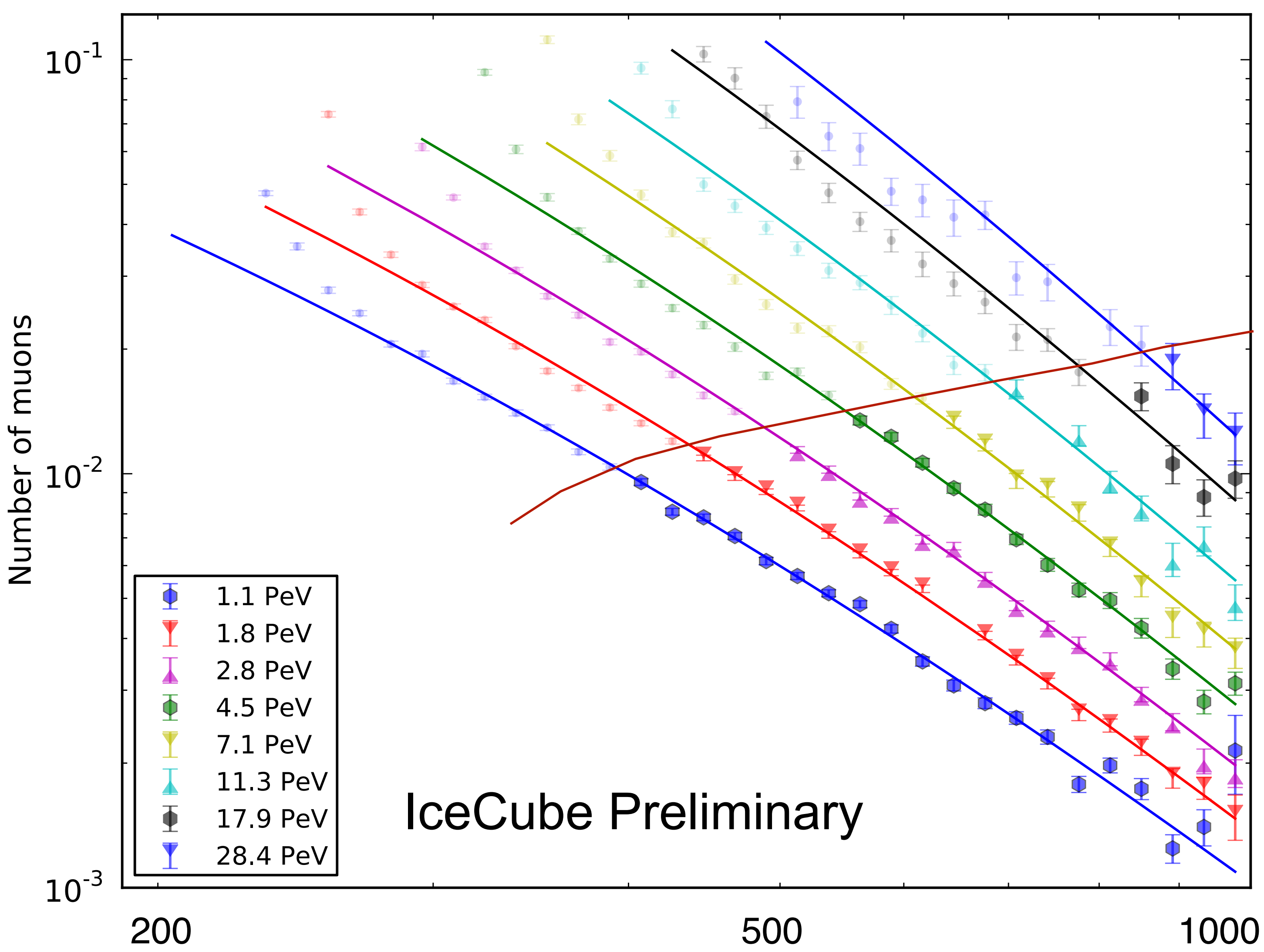
$$p_{\mu\, hit} = \frac{N_{\mu \geq 1}}{N_{tanks}}$$
$$= 1 - e^{-\langle N_\mu \rangle}$$

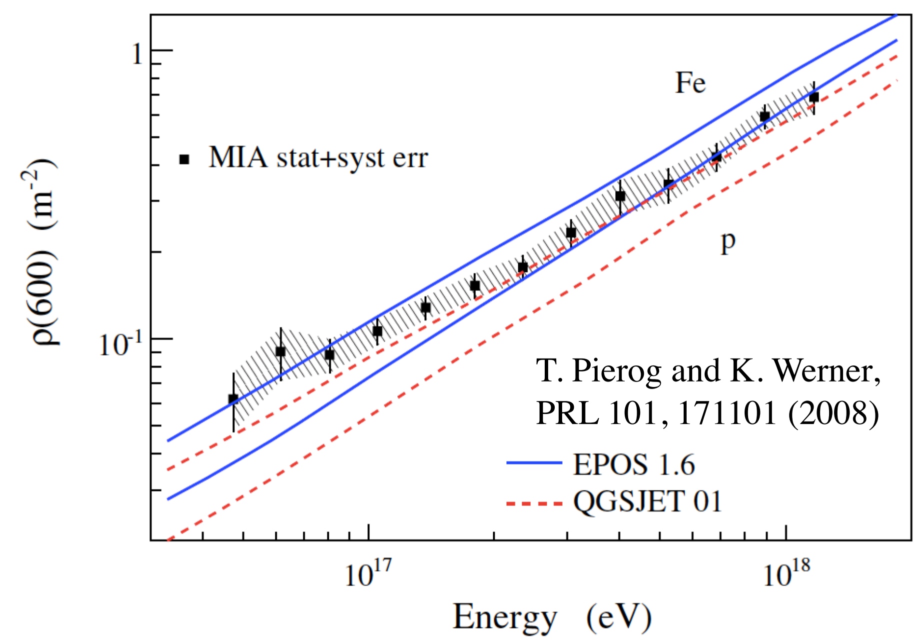
Signal distribution for tanks detecting no muon (Tail of the EM distribution)

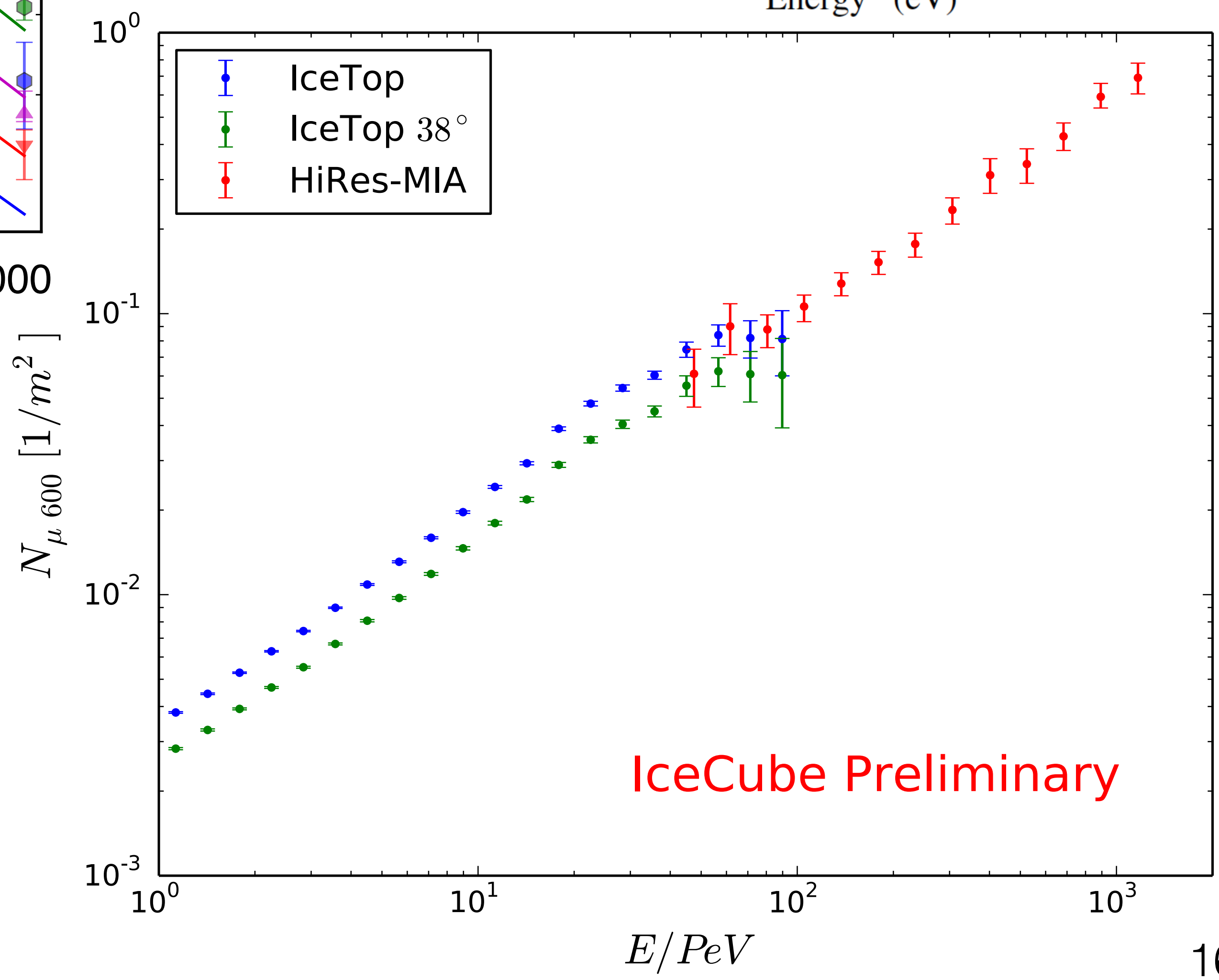
Signal distribution for tanks detecting at least one muon

IceTop Muon LDF

Example LDF, vertical events







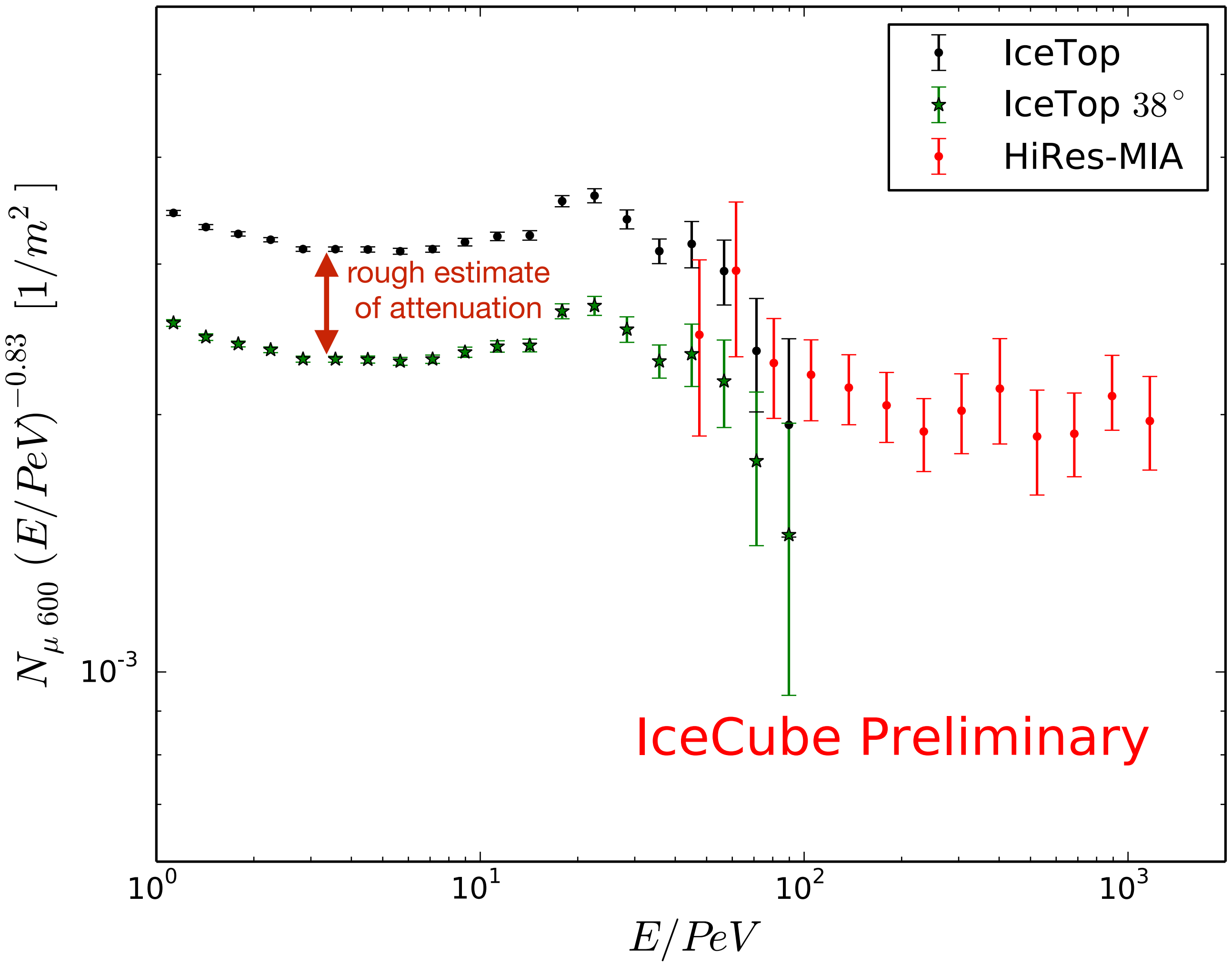
Laterally separated muons in deep ice also interesting although not considered for this meeting.

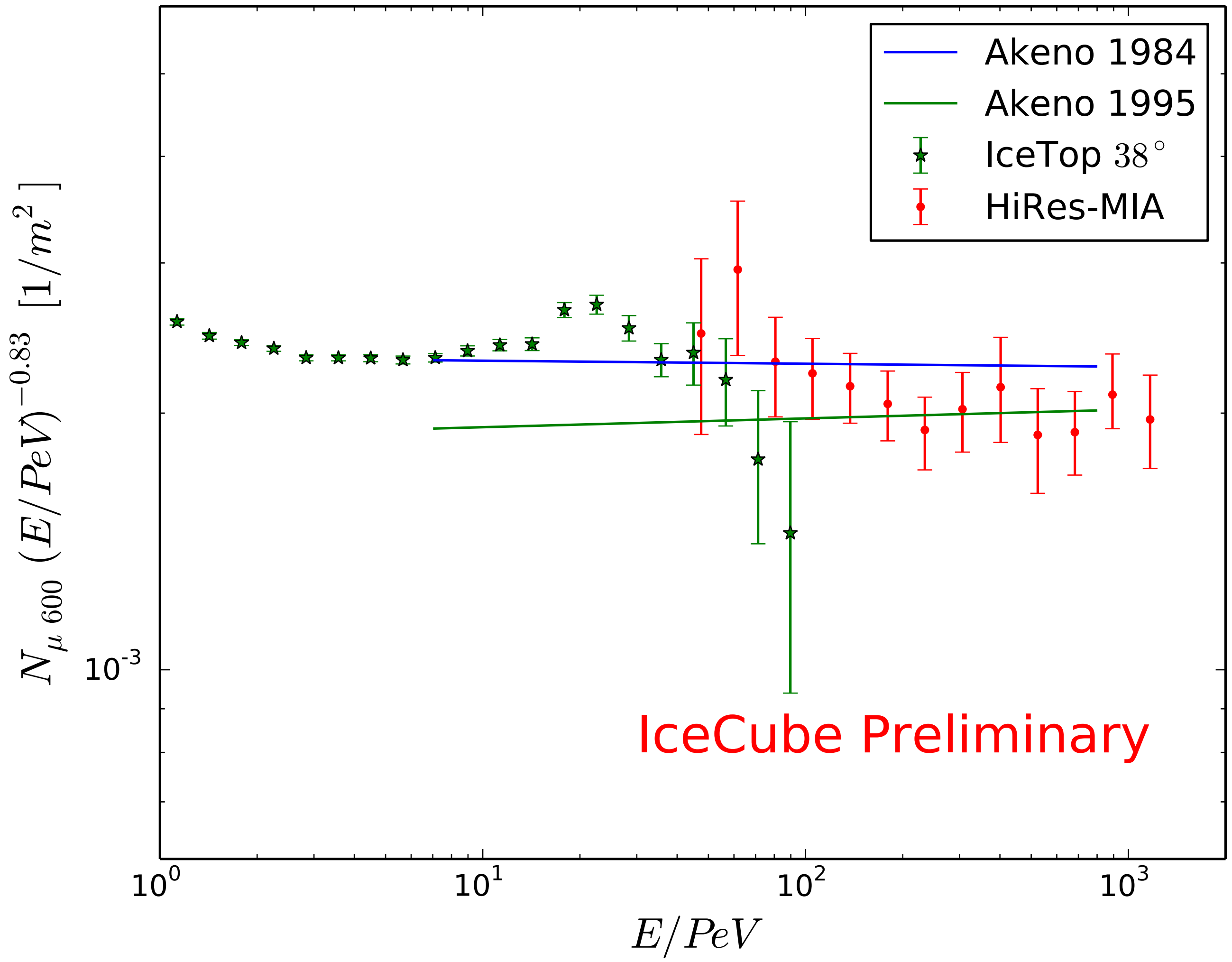
Phys. Rev. D 87 (2013) 012005
http://journals.aps.org/prd/abstract/10.1103/PhysRevD.87.012005

High energy muon bundles in the ice also not considered in this meeting.

Muons at 600 m from Shower Axis

(IceTop is very preliminary!)





NOTE: The slope in Akeno/AGASA does not change between $10^{14.5}$ and 10^{19} eV

Akeno 1984 $E_0 = 1.17 \times 10^{17} \left(\frac{N_\mu}{10^6}\right)^{1.21}$ eV $\rho_{\mu\,\mathrm{akeno}}(600) = 2.32 \times 10^{-3}(E_0/PeV)^{1./1.21}$

(J. Phys. G: Nucl. Phys. 10 (1984) 1295-1310.)

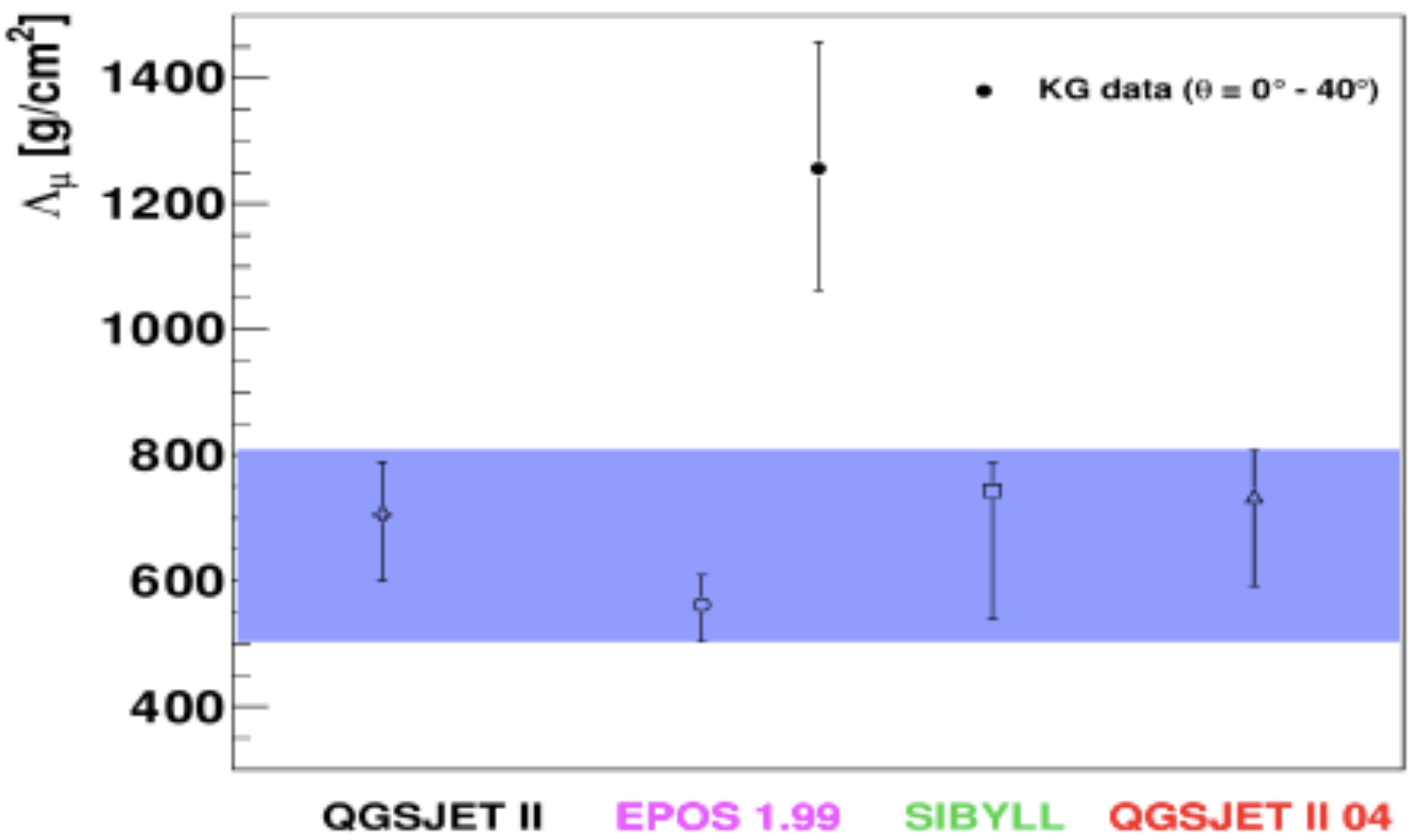
Akeno 1995 $E_0 = 2.16 \times 10^{18} \left(\frac{N_\mu}{10^7}\right)^{1.19}$ eV $\rho_{\mu\,\mathrm{akeno}}(600) = 1.88 \times 10^{-3}(E_0/PeV)^{1./1.19}$

(N Hayashida et al 1995 J. Phys. G: Nucl. Part. Phys. 21)

KASCADE-Grande

Not presented in the working group but in S. Schoo.

Attenuation not well described by hadronic models.
Something that could be cross-checked by others.

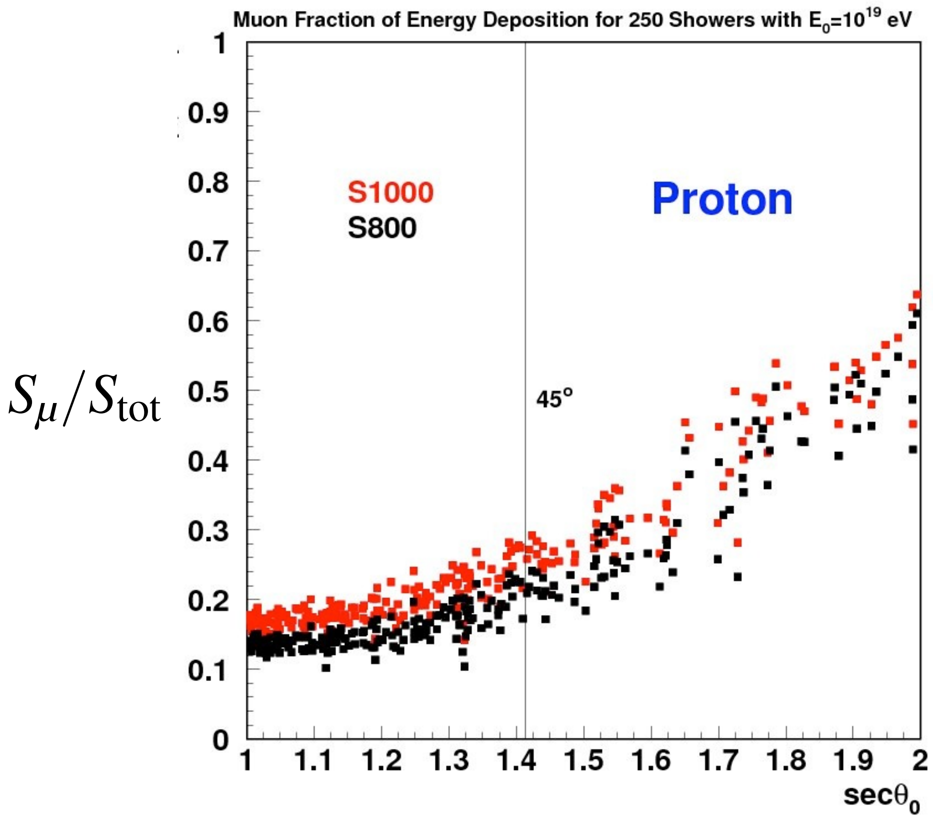


Is the TA FD-SD Difference the same as Auger's "Muon" Deficit?

From Sakurai-san:

TA-SD is the thin (1.2cm) scintillator.
→ **Most of the signal is due to EM component.**

Muon surplus reported by Auger is one of the candidate of the source of this difference.
I consider the lateral distribution of EM component is also the candidate.



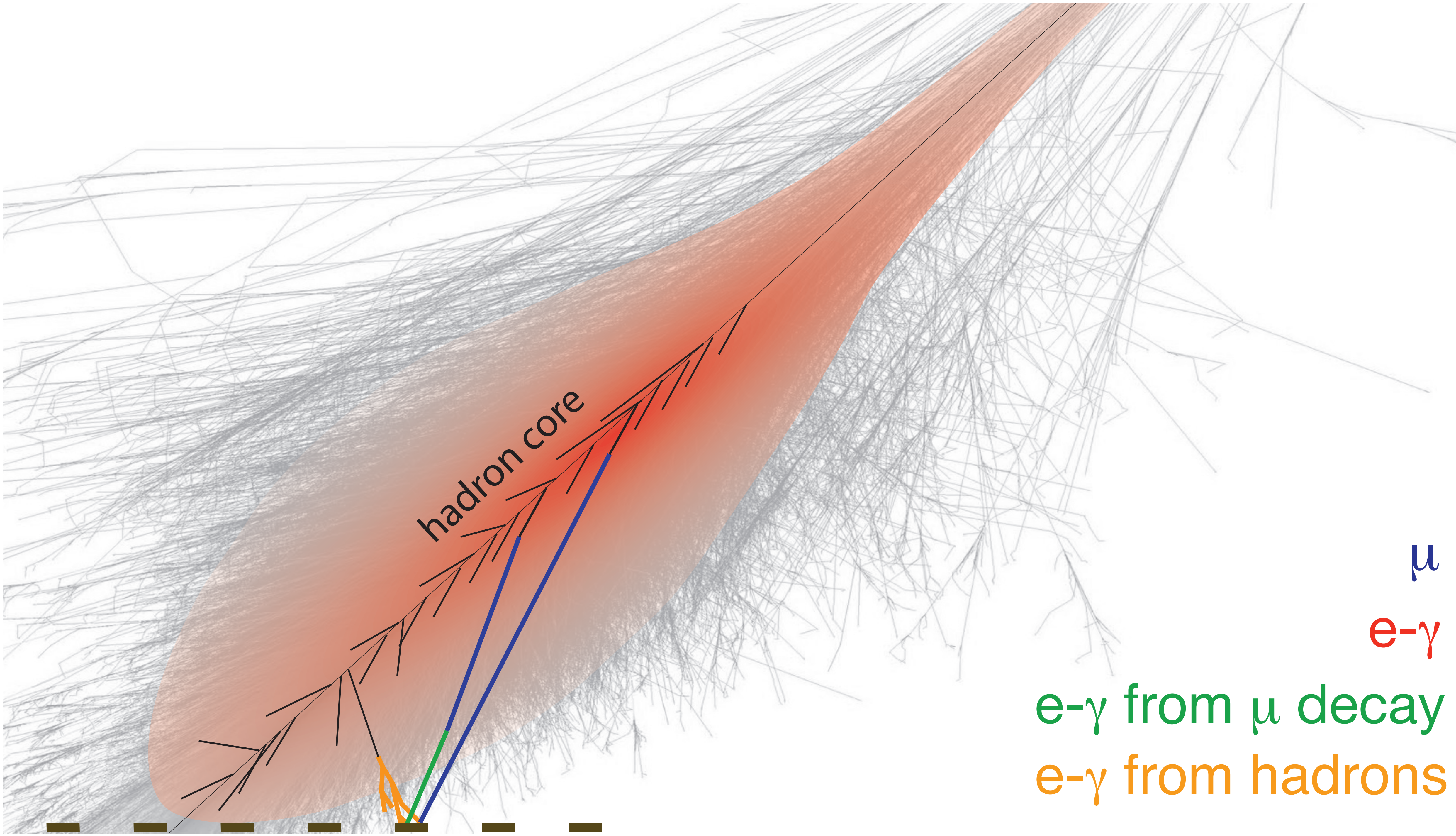
Muon signal fraction in TA ~ 12%

I agree!

But still… are TA and Auger seeing the same effect?
How can we tell?

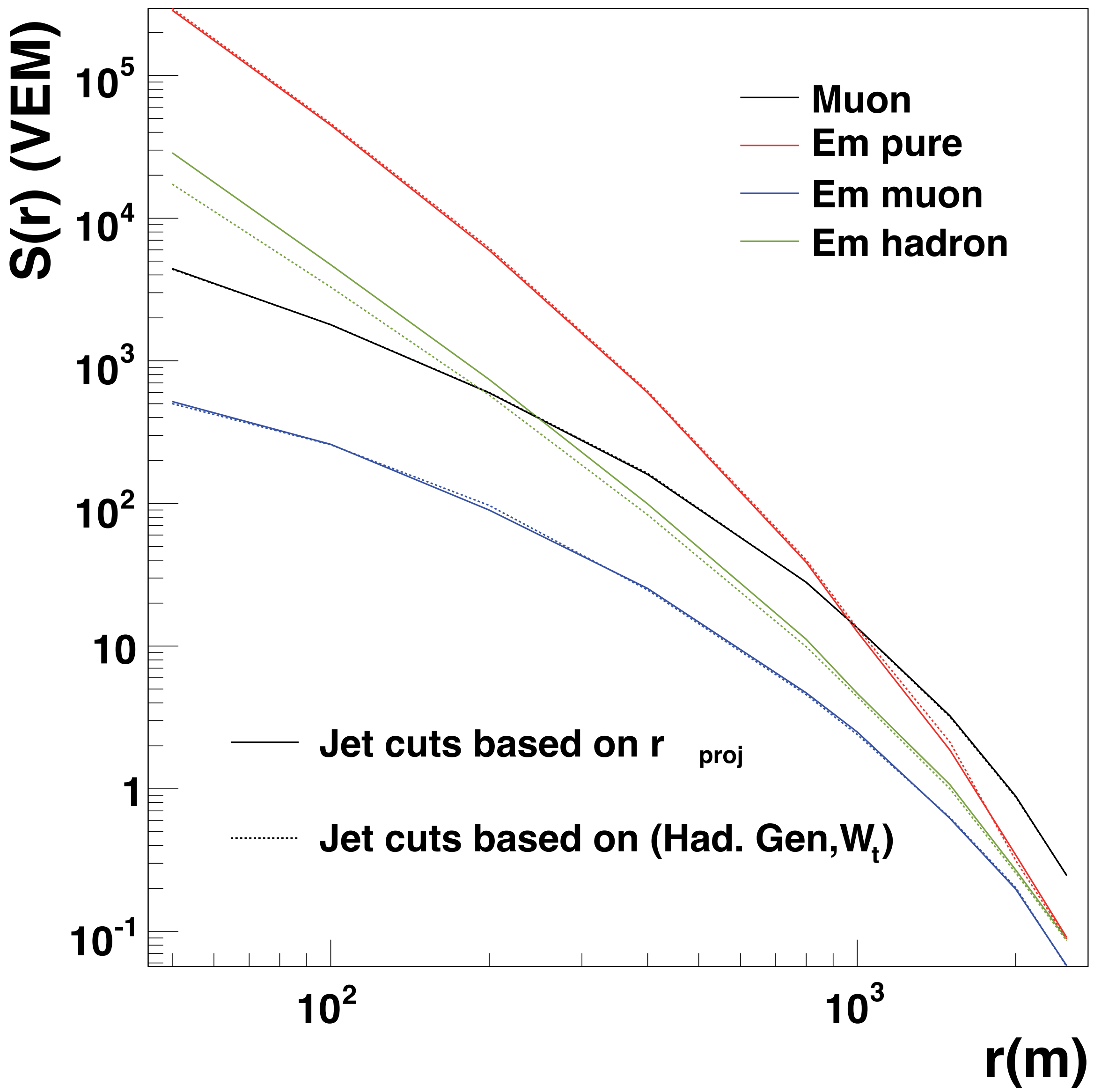
Shower “Universality” I

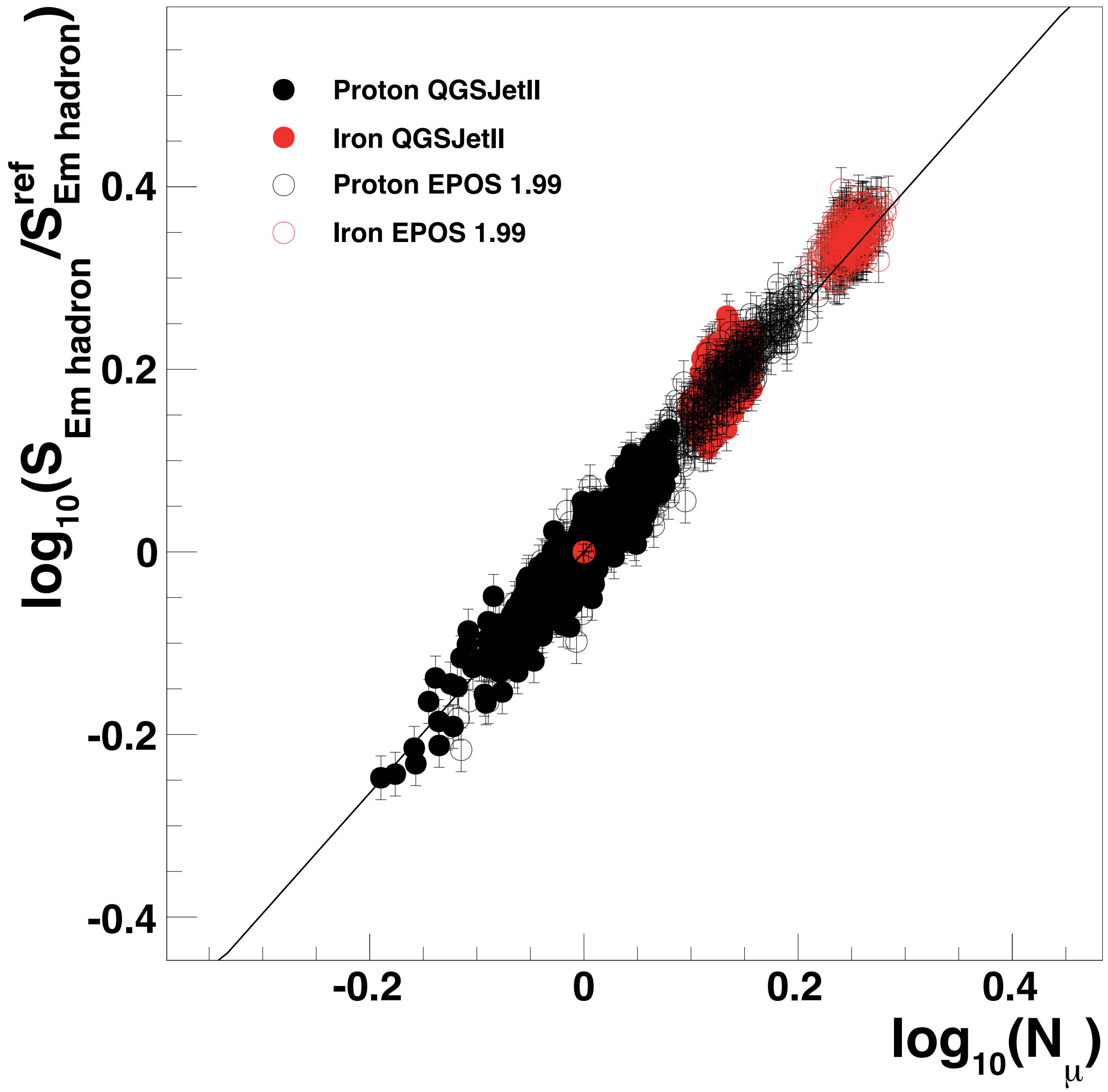
Air showers can be seen as the sum of **four** components
(independently of hadronic model and composition)



Extensive Air Shower Universality of Ground Particle Distributions
Ave et al., ICRC 2011 Beijing, #1025

Shower "Universality" II





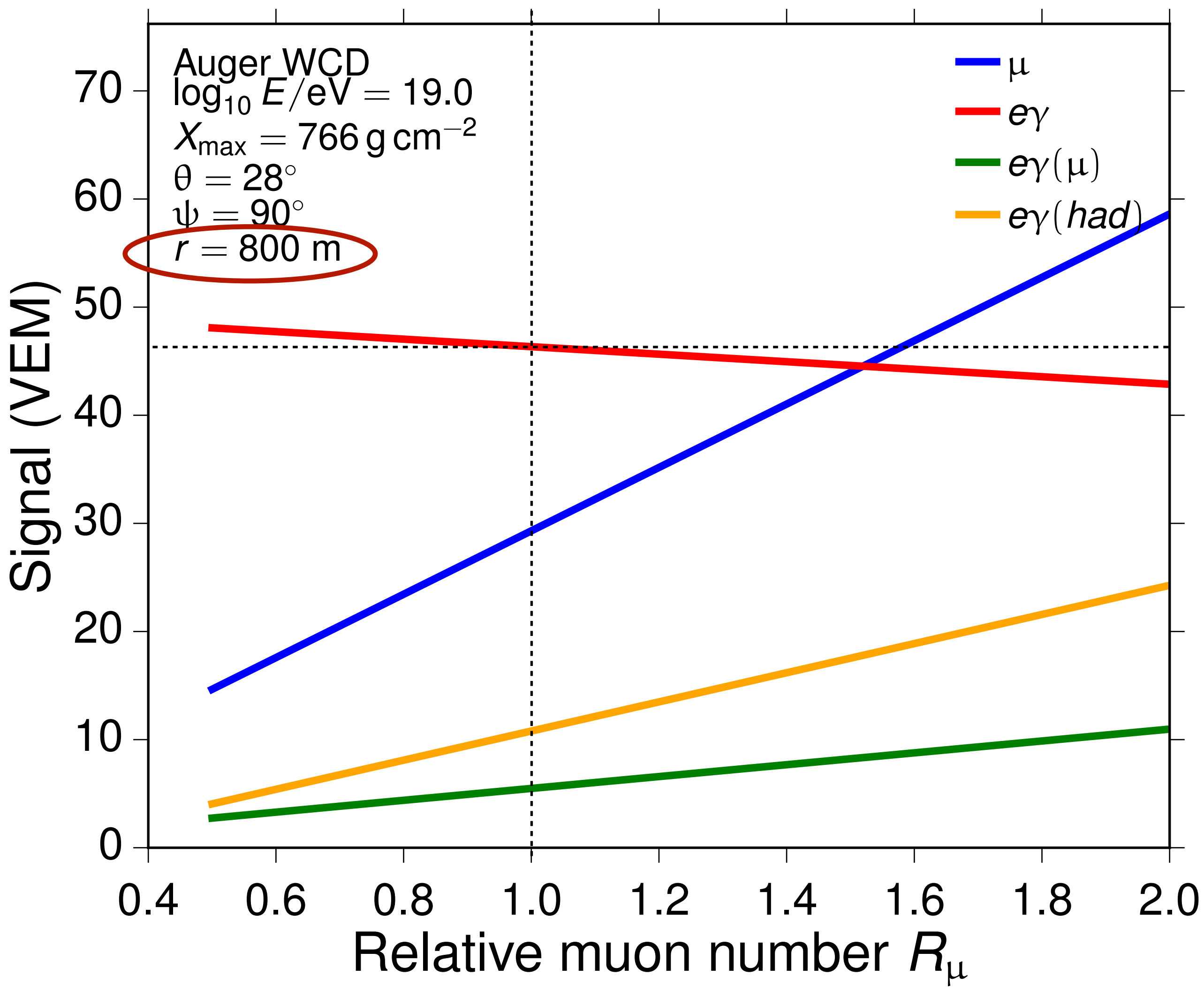
An increase in muon number comes accompanied by:

- an increase in the e-γ component
  (e-γ from hadrons + e-γ from muons)
- a decrease in calorimetric energy
  (e-γ)

Careful then with what we mean by muon excess/deficit

Signal Scaling from Universality I

Signal dependence on muon scale in Pierre Auger WCDs
(plot from A. Schulz, KIT)



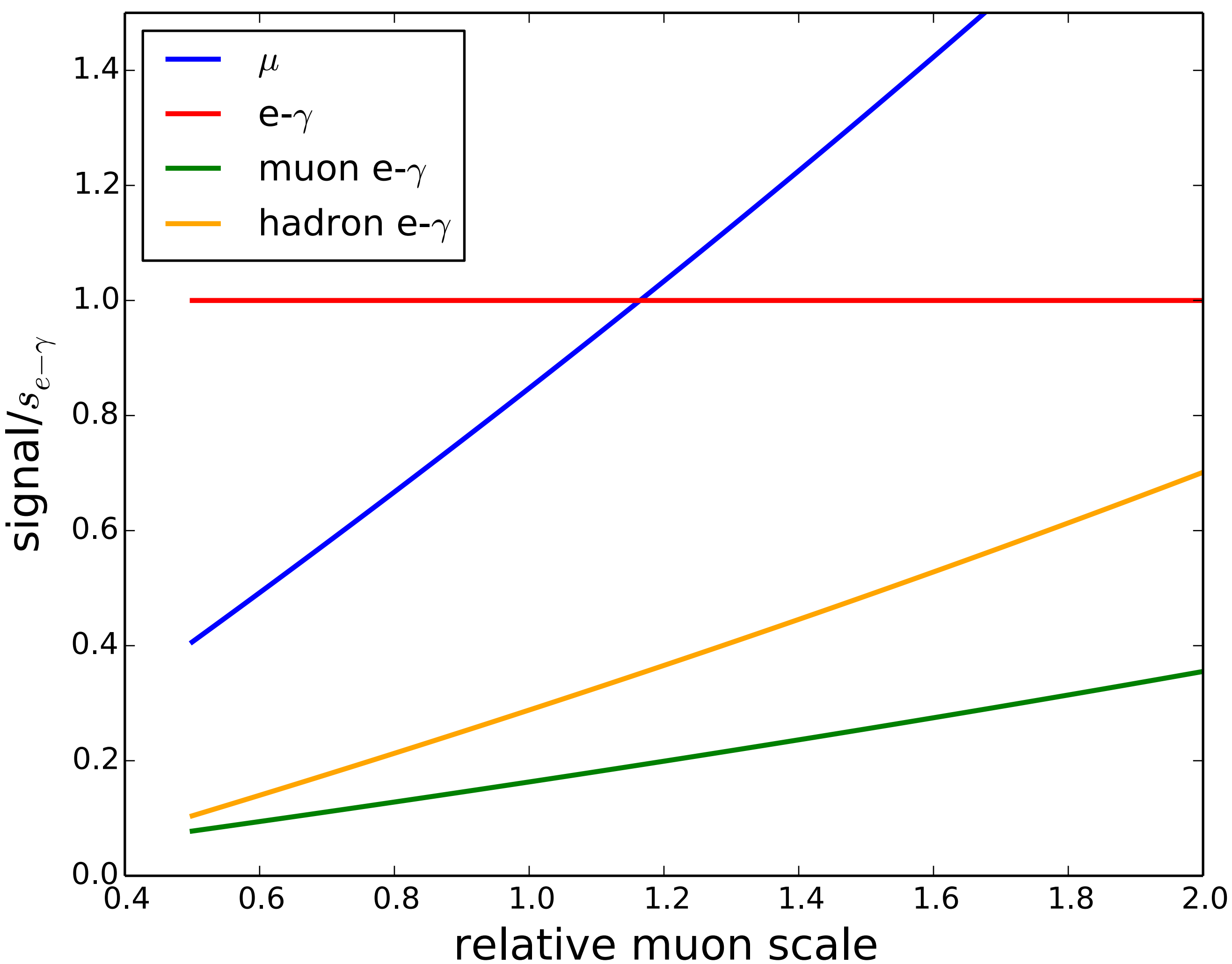
R_μ = 1.5 → $\delta s_{e\gamma}$ ~ -3.8%

- Let's consider how signals scale with muon number.
  Please humor me for a while.
- Take Auger signal from universality:
  (representative X_{max}, zenith angle and polar angle)
  - Scale the muon signal so the signal fraction from muons is 12% (to agree with TA).
  - Normalize signals by the e-γ signal ($S_{e\text{-}\gamma} \propto E_{cal}$)
- Scale energies to compare showers with the same calorimetric energy.

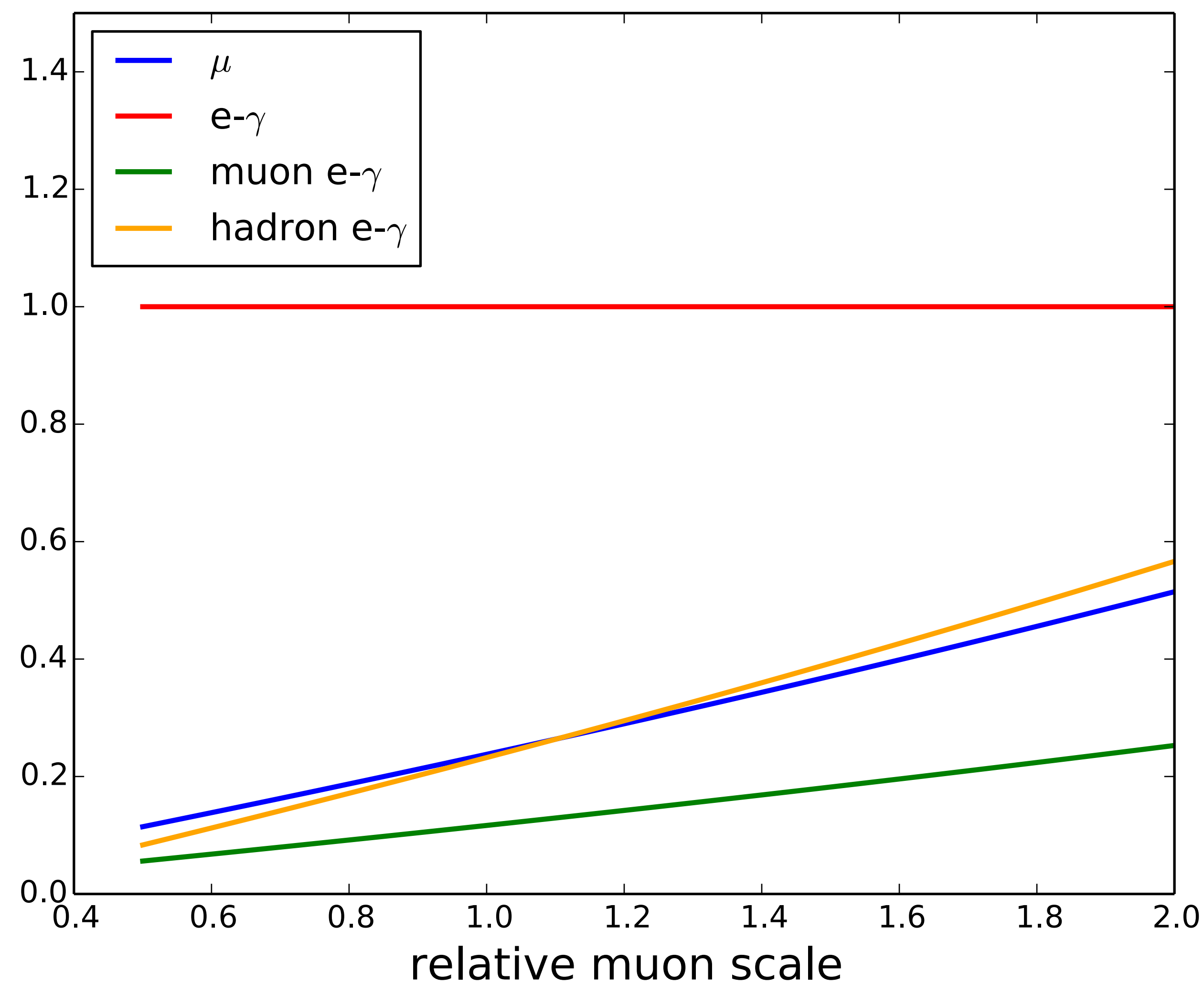
I know… the devil is in the details

Signal Scaling from Universality II

Pierre Auger (1000 m)



Telescope Array (800 m)



In TA, a muon scale of 1.5 means a signal increase of ~20.4%:
(7.5% from muons, 9.2% from hadron e-γ, 3.7% from muon halo)

Note that "muon scale" is not just a scaling of the muon signal in this case.

Is the TA FD-SD Difference the same as Auger's "Muon Deficit"?

I say they could be consistent. Not a confirmation but in the realm of possibility.

- If Auger uses TA's missing energy, δE ~ -6%, and fluorescence yield δE ~ +12%
- After this, TA and Auger spectra would disagree by about 7%
- TA's FD-SD difference is 27% relative to QGSJet II.03 proton.
- Auger's muon scale relative to QGSJet II.03 proton is R_μ~1.82

Assuming:

- EM signal from hadrons scales with the number of muons as in previous figure,
- Usual EM signal scales with calorimetric energy,
- we can scale the muons' relative contribution from Auger WCD response so the relative muon contribution is 12% of the total… as it should be for TA.

With R_μ of 1.5, we expect a change of 20.4% in signal in typical TA-SD events.

This goes along with a 3.8% decrease in FD energy, for a total of ~ 24%.

This is before we consider any light yield or composition systematics.

Clearly a simple view. Details will change the numbers,

but not by an order of magnitude… Someone from TA would have to look into it.

In this simple picture, what would we need if we want to be consistent with Auger's R_μ?

	1	**1.3**	**1.5**	**1.8**
μ	0	4.5%	7.5%	12%
E–γ from μ	0	2.2%	3.7%	6.0%
E–γ from h	0	5.5%	9.2%	14.6%
E–	0	-2.3%	-3.8%	-6%
Apparent difference	**0**	**14.5%**	**24.1%**	**38.6%**

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δE_{SD} ~ 32.6%

→ increase "missing" energy by 6%

Shift FD (calorimetric) energy down by ~12% ← 38.6% - 27% = 11.6%

Where we Stand

Signal Differences (easier to interpret as more/less muons)

- Auger muons. EPOS-LHC, QGSJet II.04.
- Telescope Array FD-SD difference and Auger muon problem…
  Are they the same thing? Universality arguments for consistency
  (using TA's FD-SD, could we repeat with Auger?)
- Can we stop calling it "muon" excess/deficit then?
  Call it "low-energy hadron enhancement", if you will. Think about it.

Time Structure

- TA curvature data promising, but hints are difficult to quantitatively estimate any muon excess/deficit.
  Perhaps EPOS-LHC will show more drastic behavior here?
  (like Auger's MPD)
- Muon Production Depth from Auger. EPOS-LHC.
- No curvature data from Auger?

Where we Stand

Longitudinal Development

- X_{max} Fluctuations from Auger. QGSJet II.04 (only marginally)

Muons

- Yakutsk and IceCube can add some in the future.
  (as well as Auger + TA extensions)
- Some recommendations for comparing muon data. When producing muon numbers, do it
  - at reference depths (~800 g/cm^2?)
  - at a set of reference radii (600 m? 1000 m?)
  - total number of muons?
  - relative to a model?

Modeling

- General understanding: not much room for tweaking and increasing the number of muons.