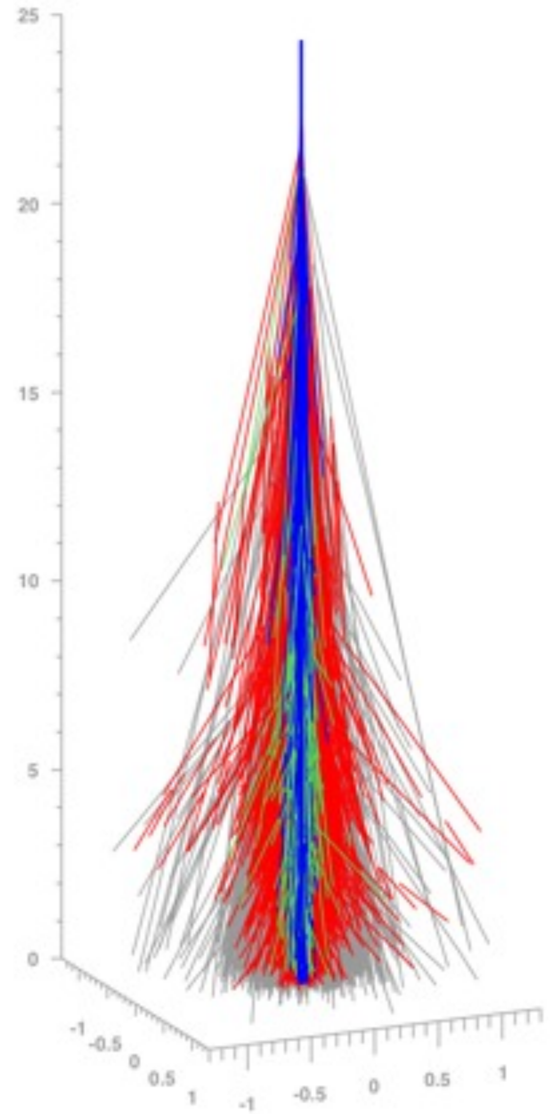
Air Showers and Hadronic Interactions (3/3)



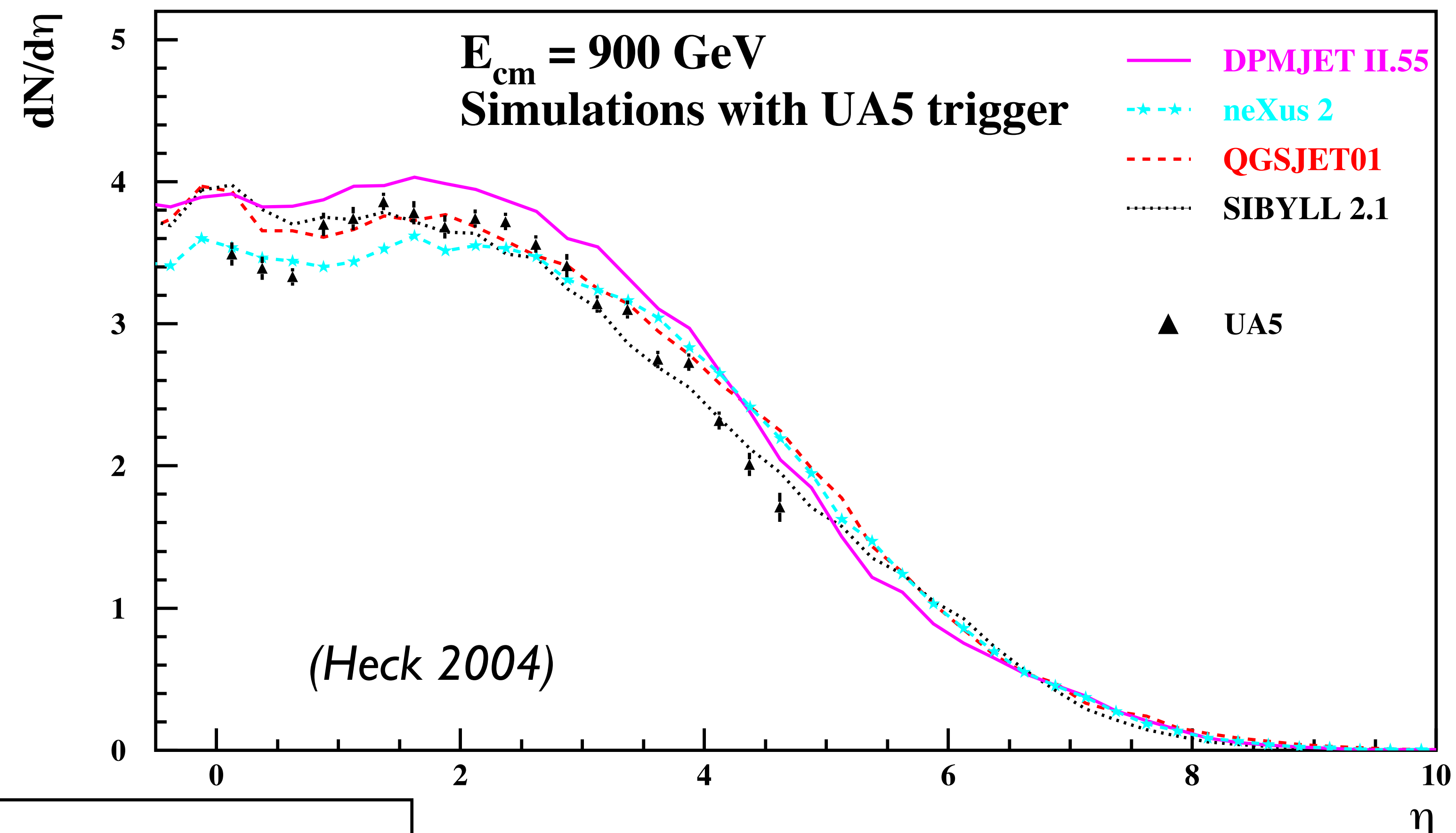
Ralph Engel

Karlsruhe Institute of Technology (KIT)

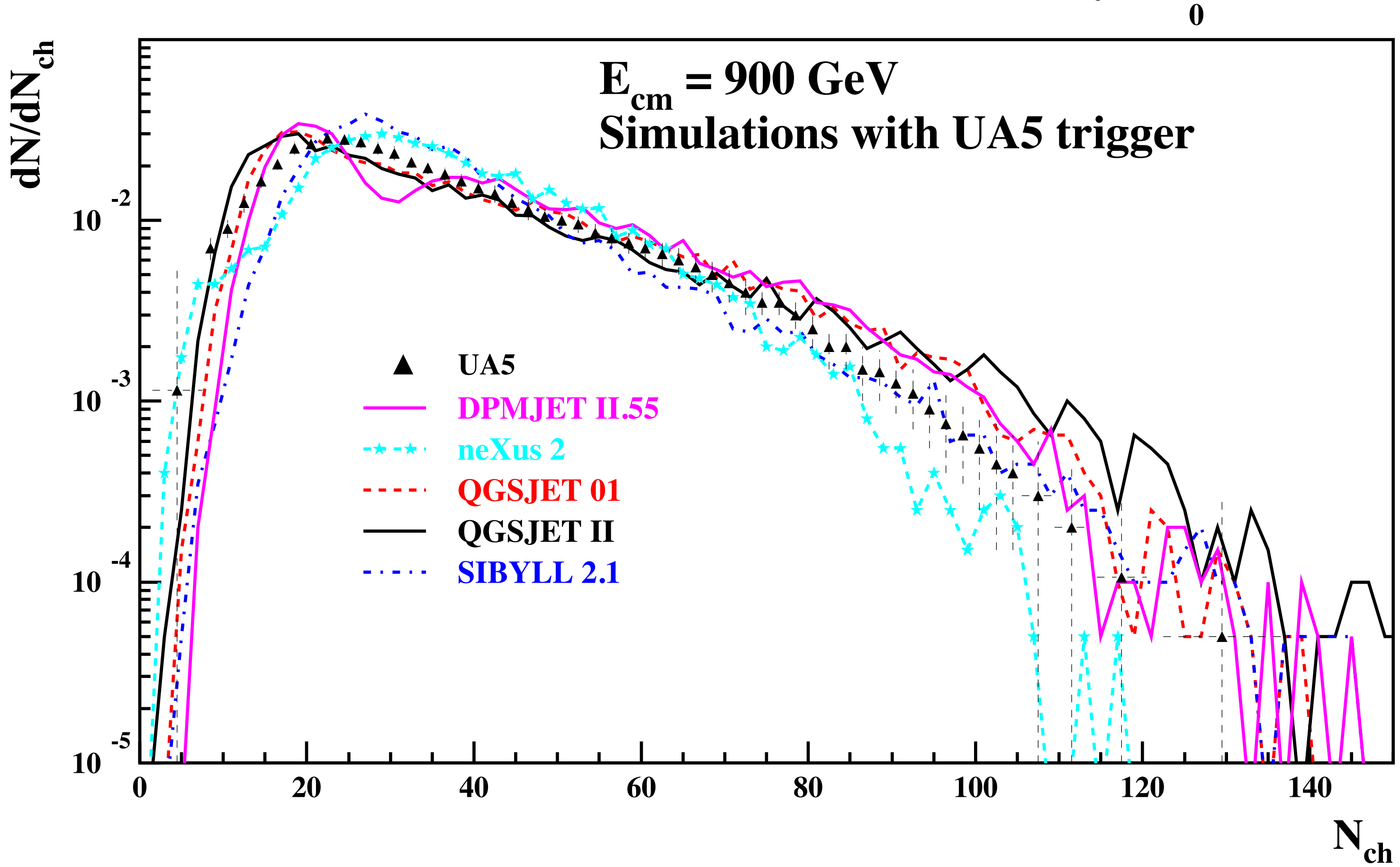
Karlsruhe Institute of Technology

Collider distributions: reasonable agreement

Many updated comparisons of models and data available, see talk by Tanguy Pierog

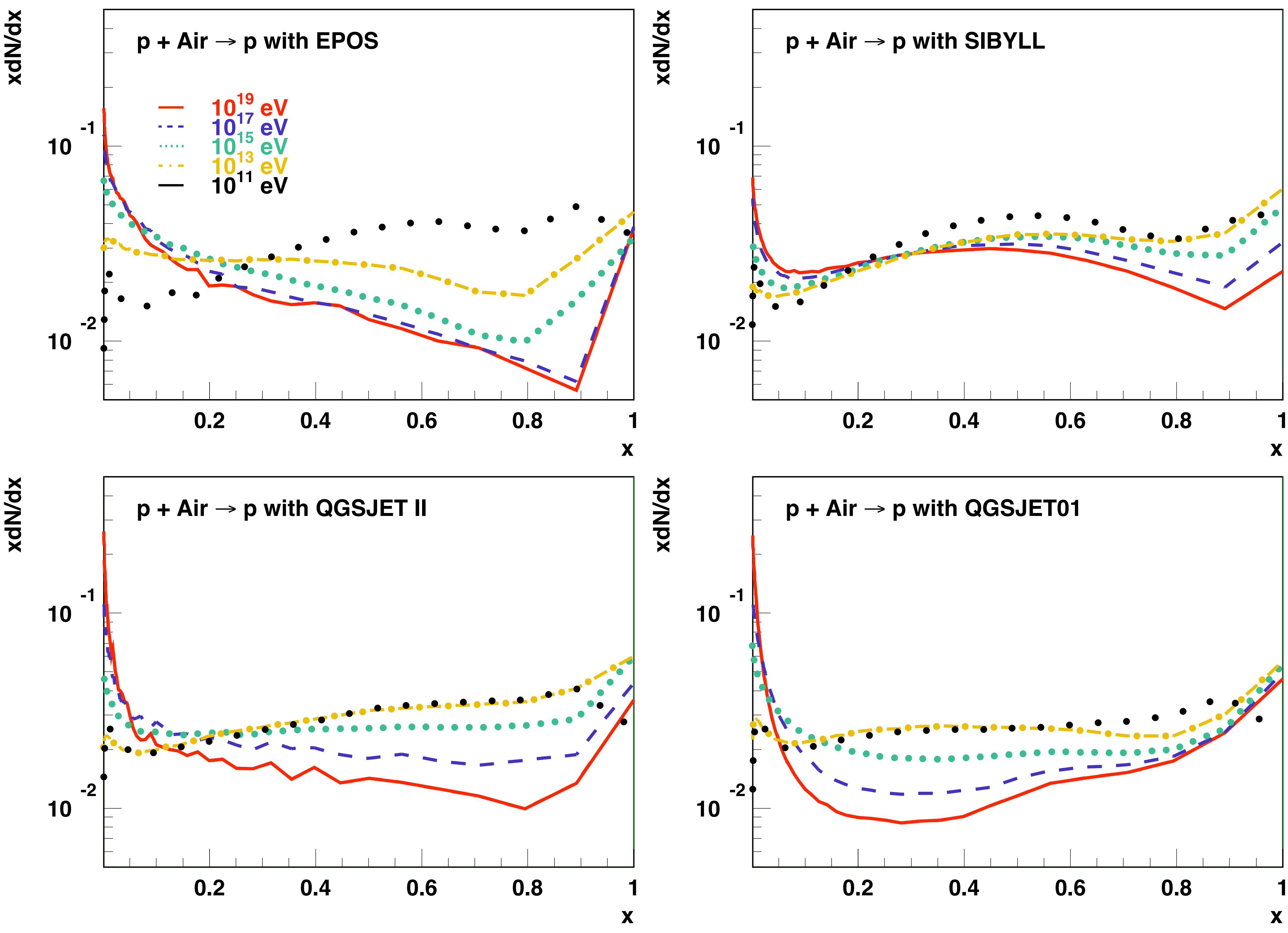


(Heck 2004)

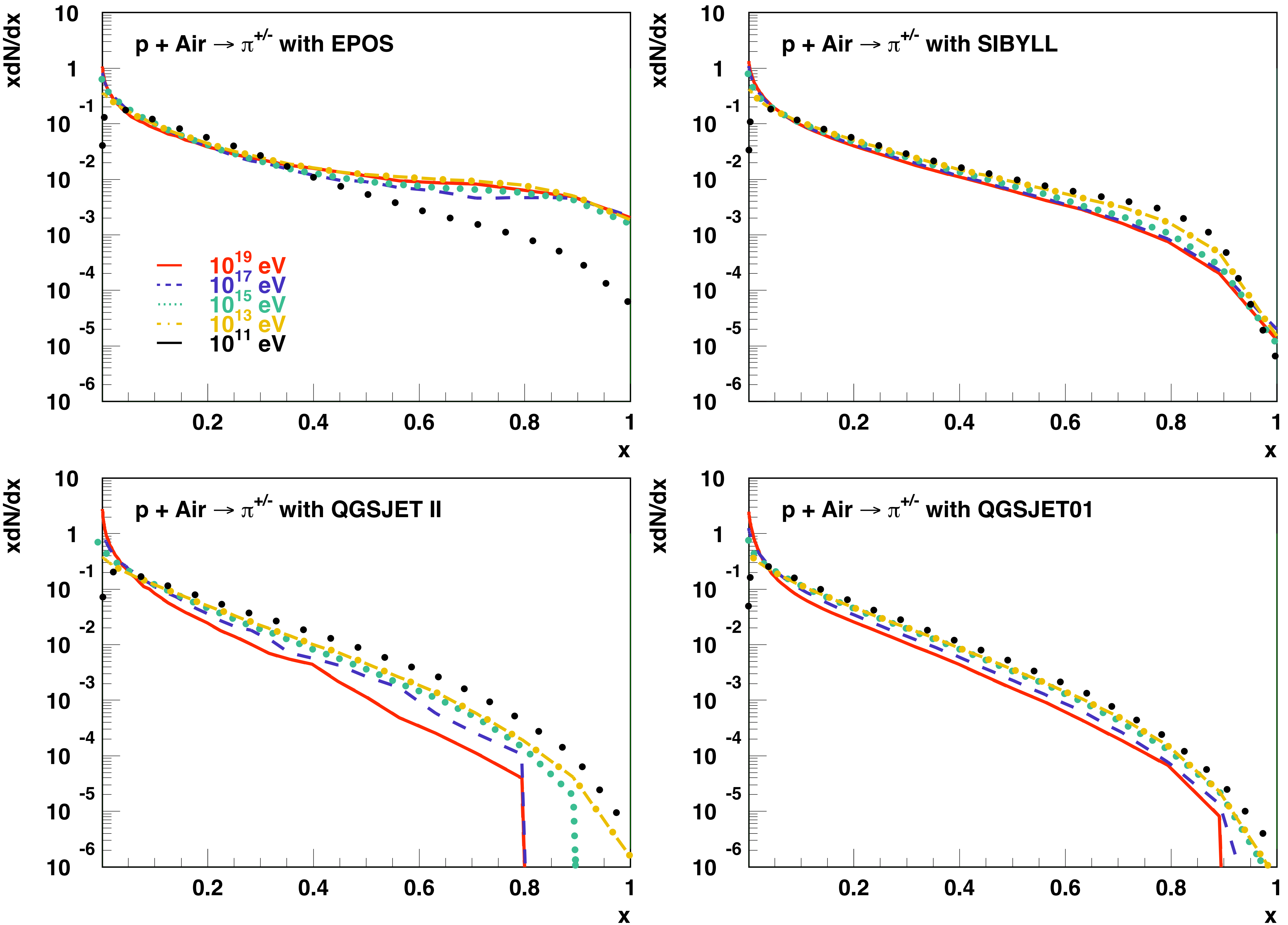


(Heck 2005)

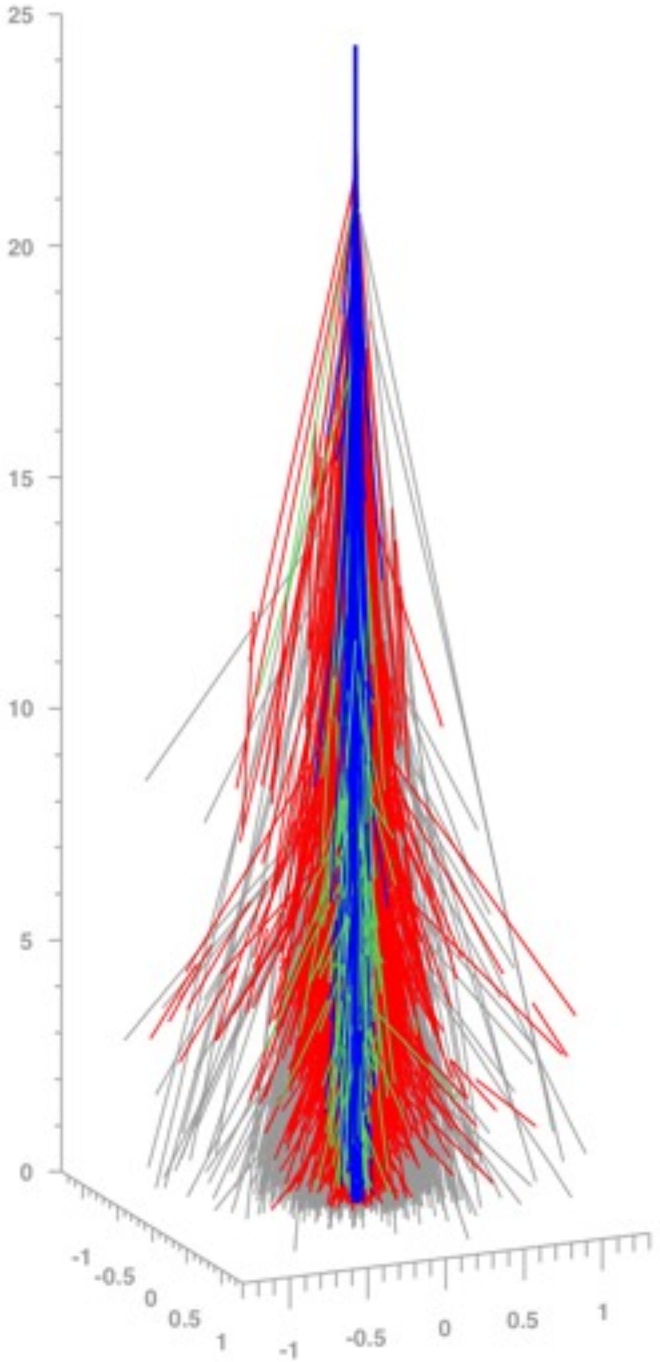
Scaling: model predictions (i)



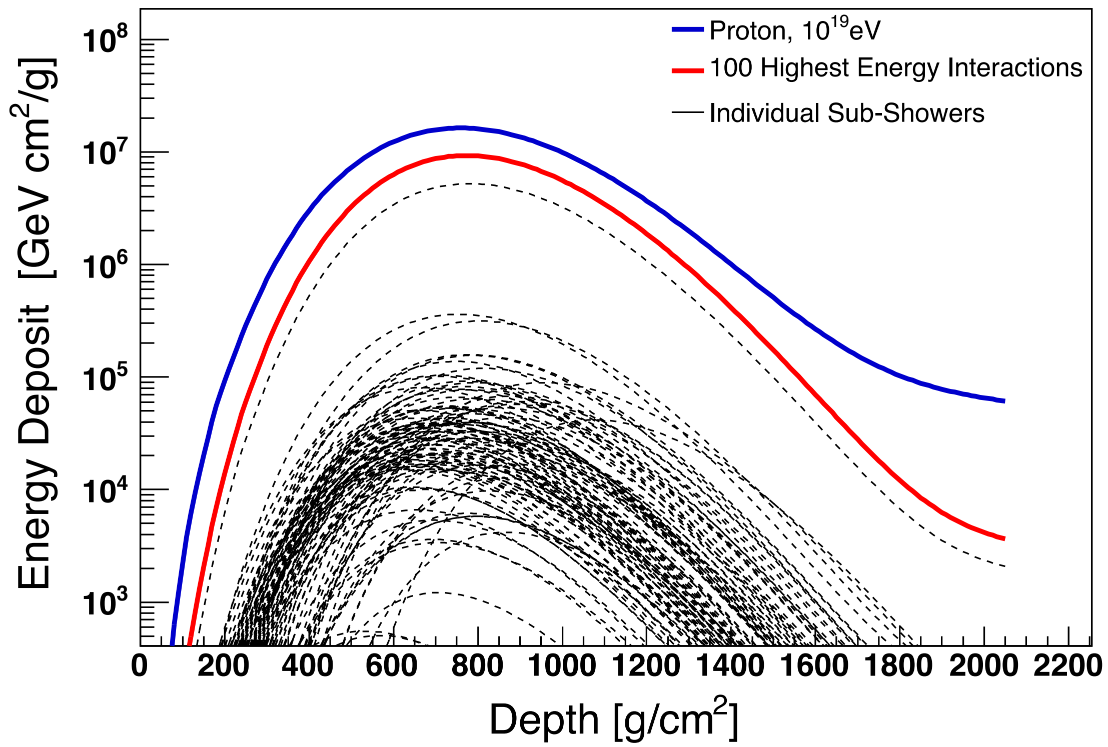
Scaling: model predictions (ii)



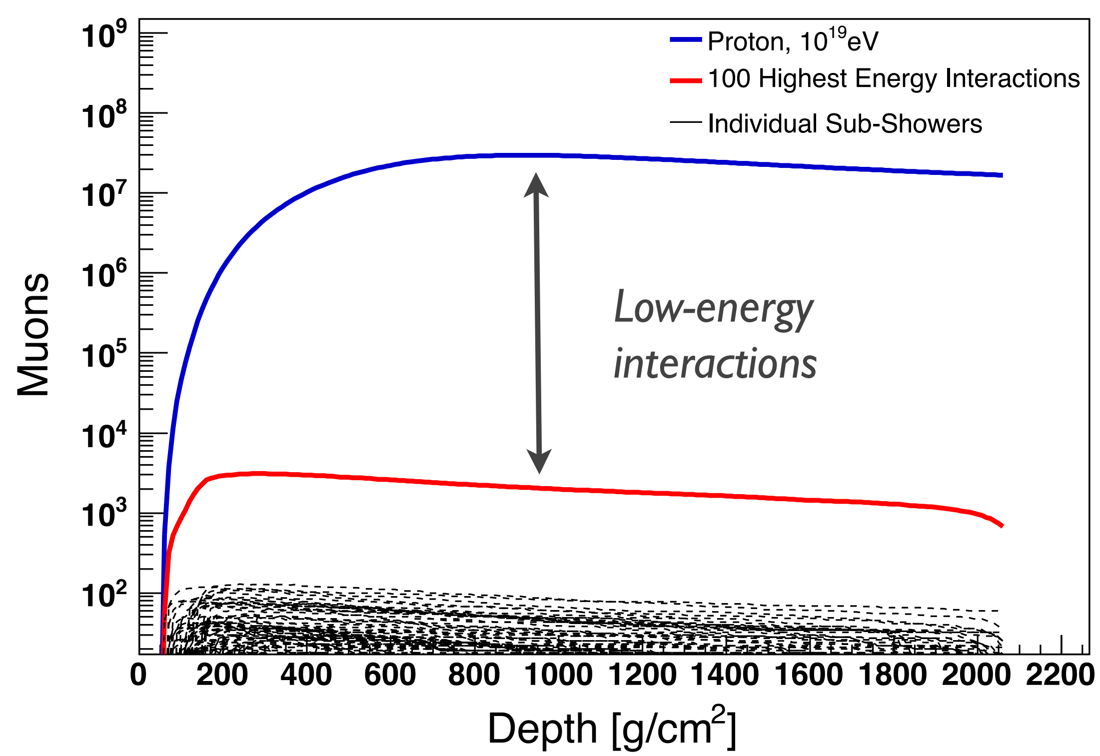
Importance of hadronic interactions



Electrons



Muons



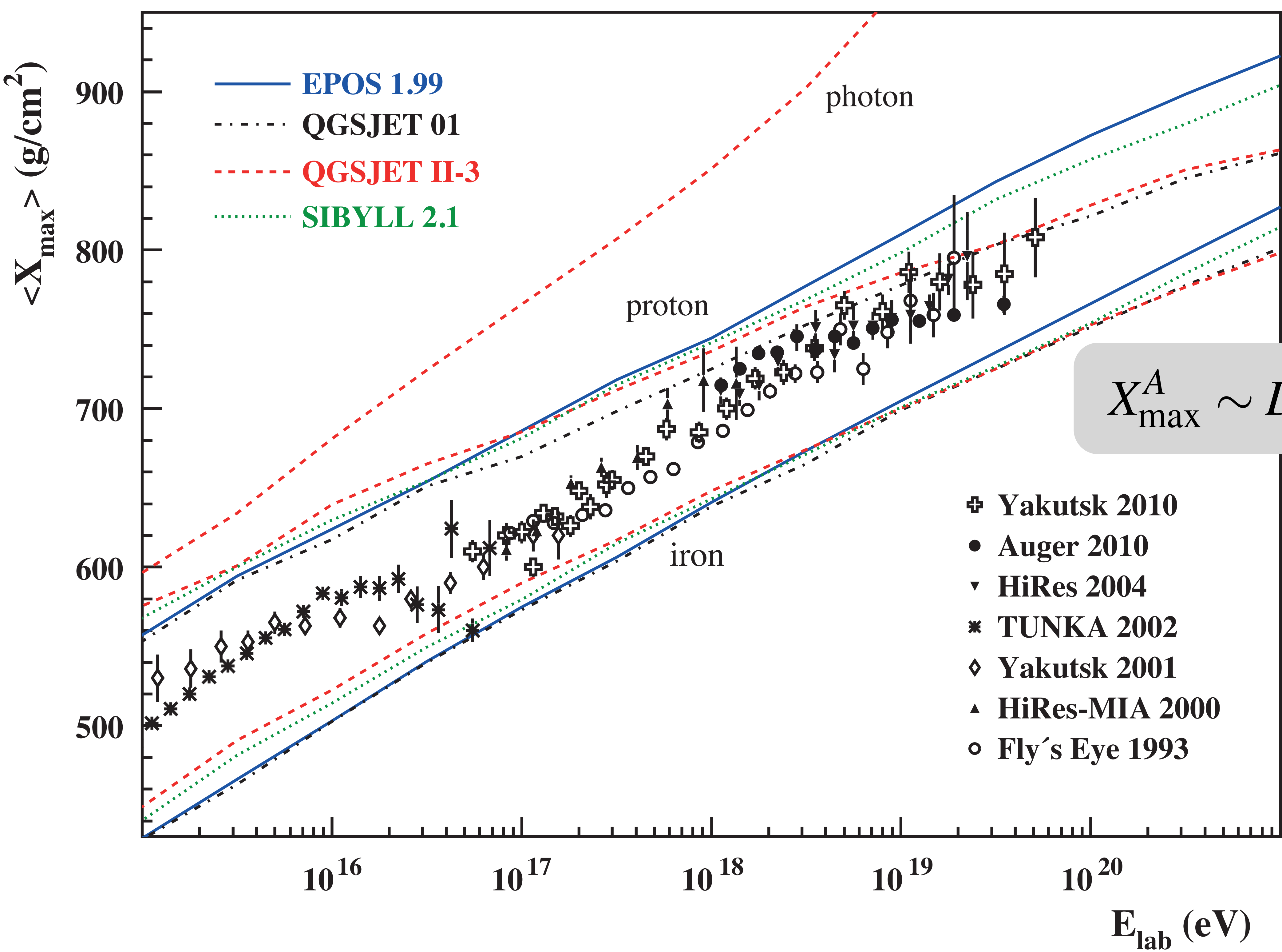
Shower particles produced in 100 interactions of highest energy

Electrons/photons: high-energy interactions

Muons/hadrons: low-energy interactions

(Ralf Ulrich, 2012)

Mean depth of shower maximum



$$X^A_{\rm max} \sim D_e \ln(E_0/AE_c)$$

(RE, Pierog, Heck, ARNPS 2011)

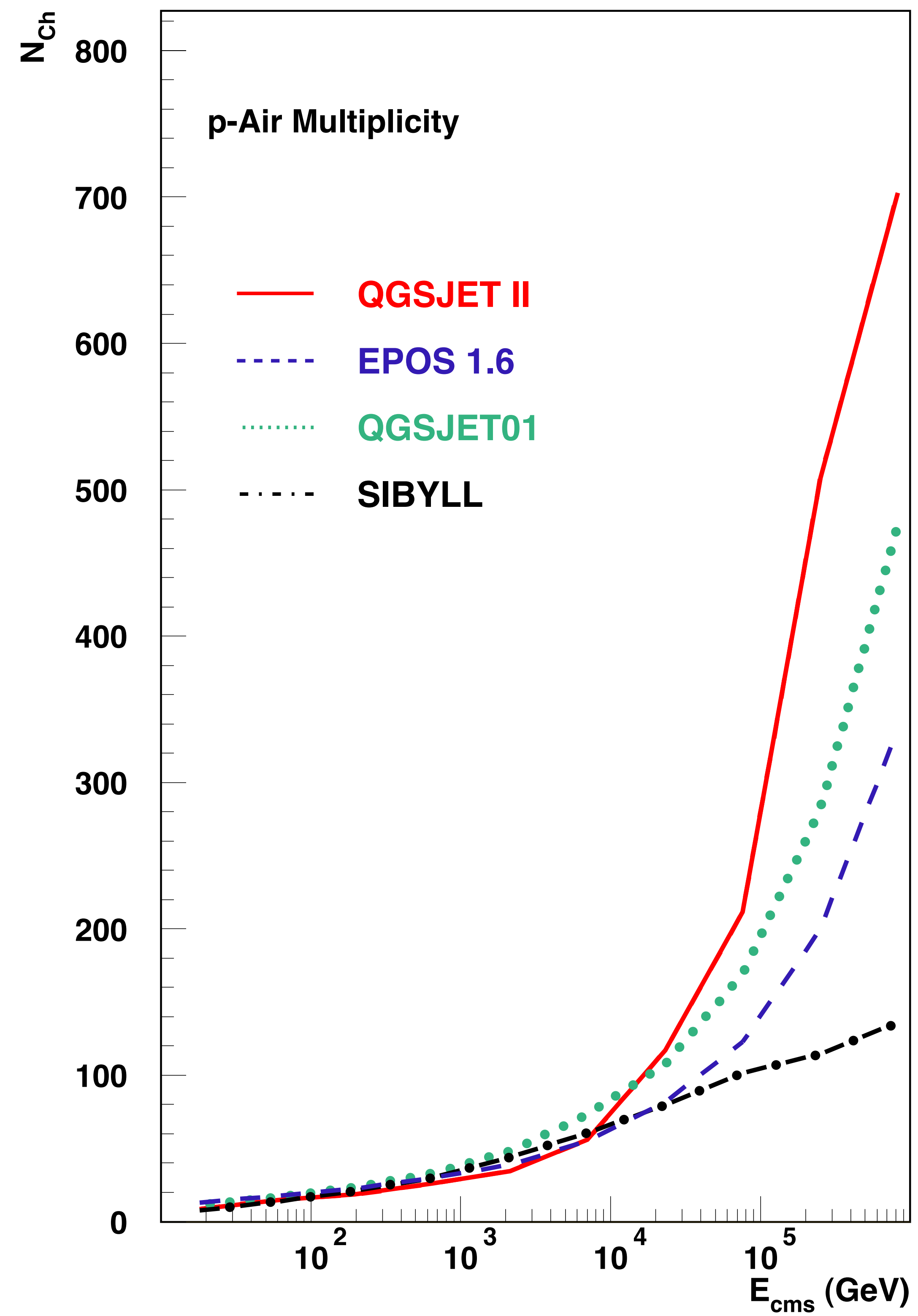
Elongation rates and model features

Elongation rate theorem

$$D_{10}^{\mathrm{had}} = \ln 10 \, X_0 (1 - B_n - B_\lambda)$$

(Linsley, Watson PRL46, 1981)

factor ~ 87 g/cm^2



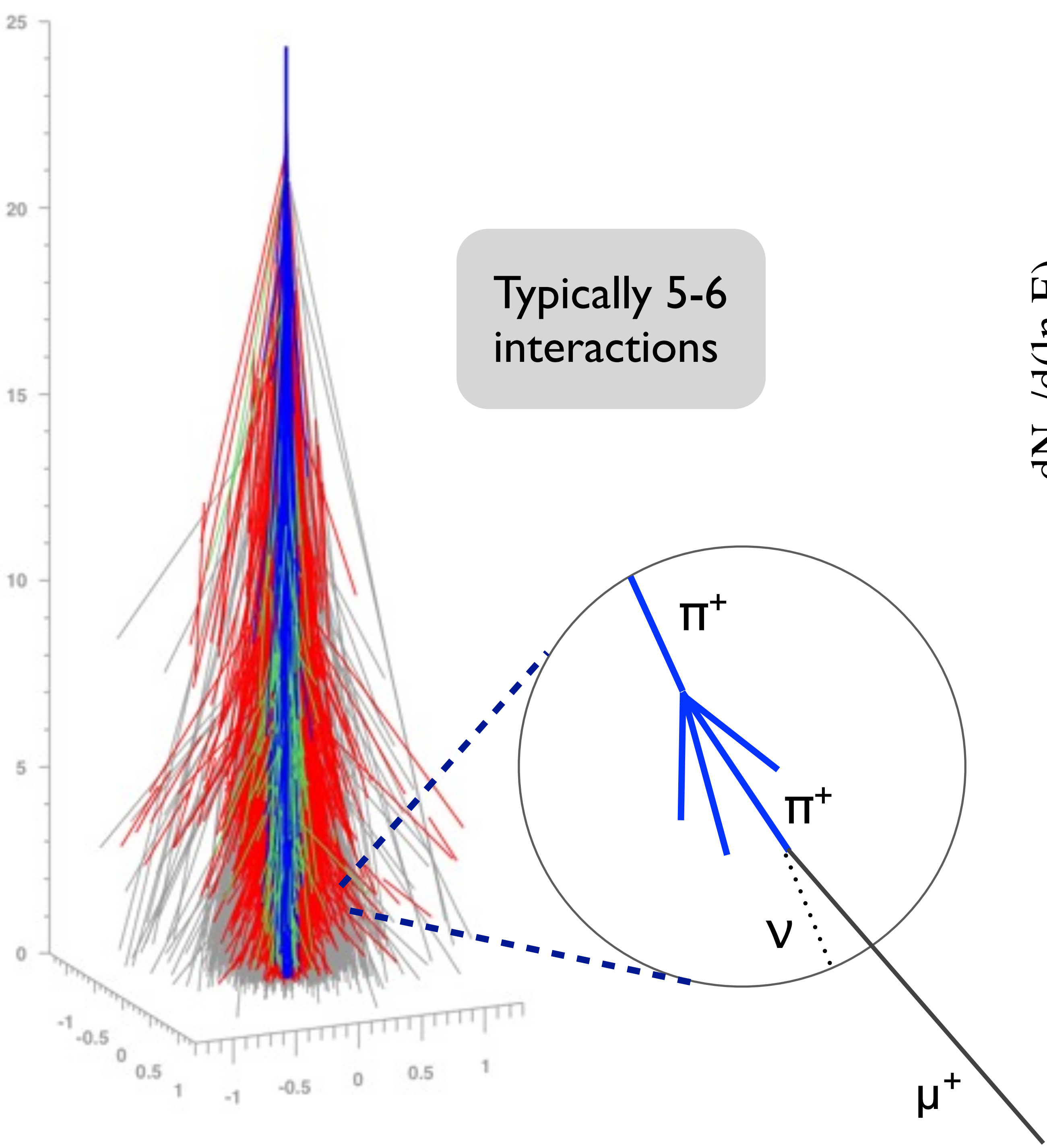
$$B_n = \frac{d \ln n_{\mathrm{tot}}}{d \ln E}$$

Large if multiplicity of high energy particles rises very fast, **zero in case of scaling**

$$B_\lambda = -\frac{1}{X_0} \frac{d\lambda_{\mathrm{int}}}{d \ln E}$$

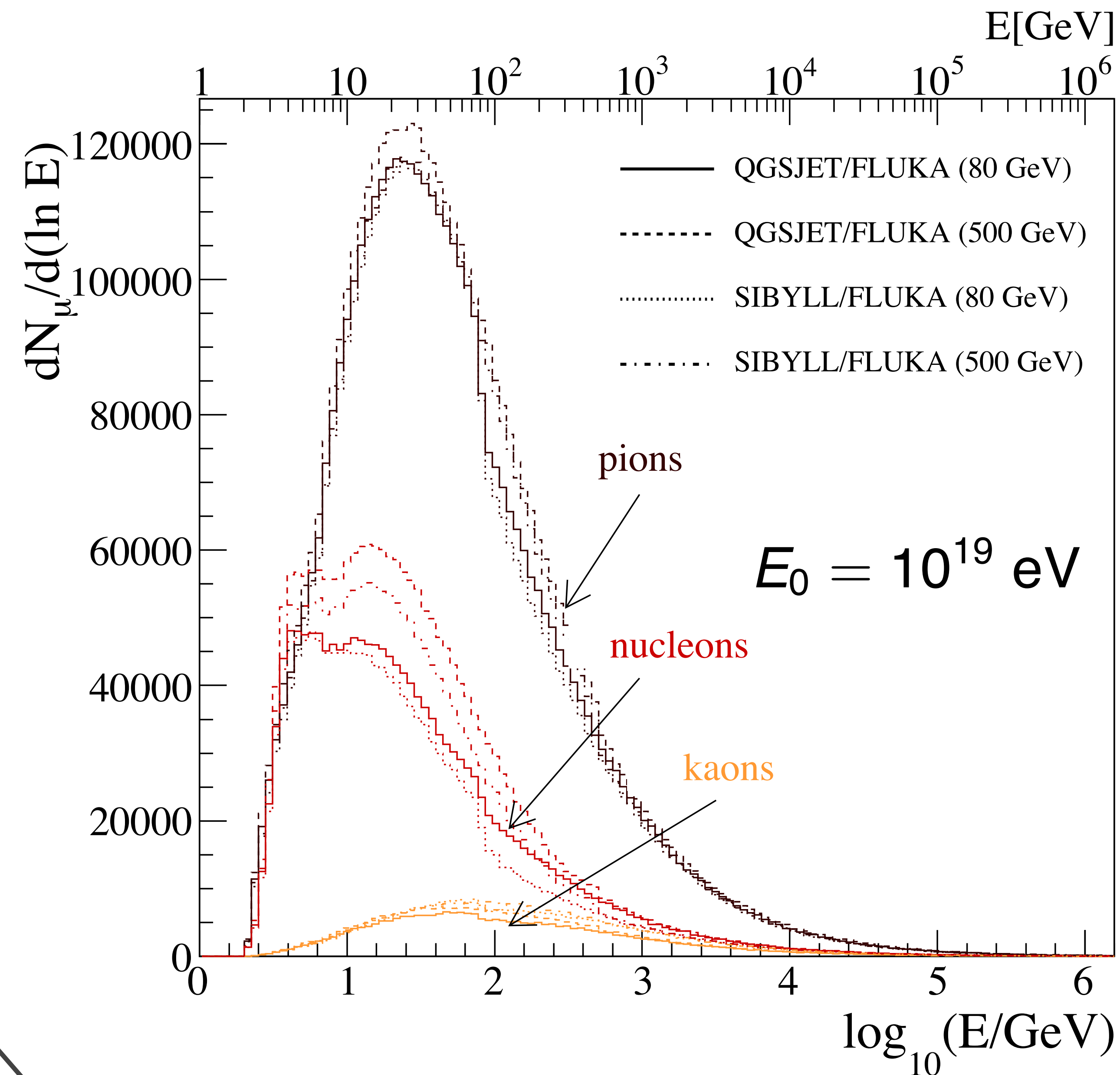
Large if cross section rises rapidly with energy

Muon production at large lateral distance



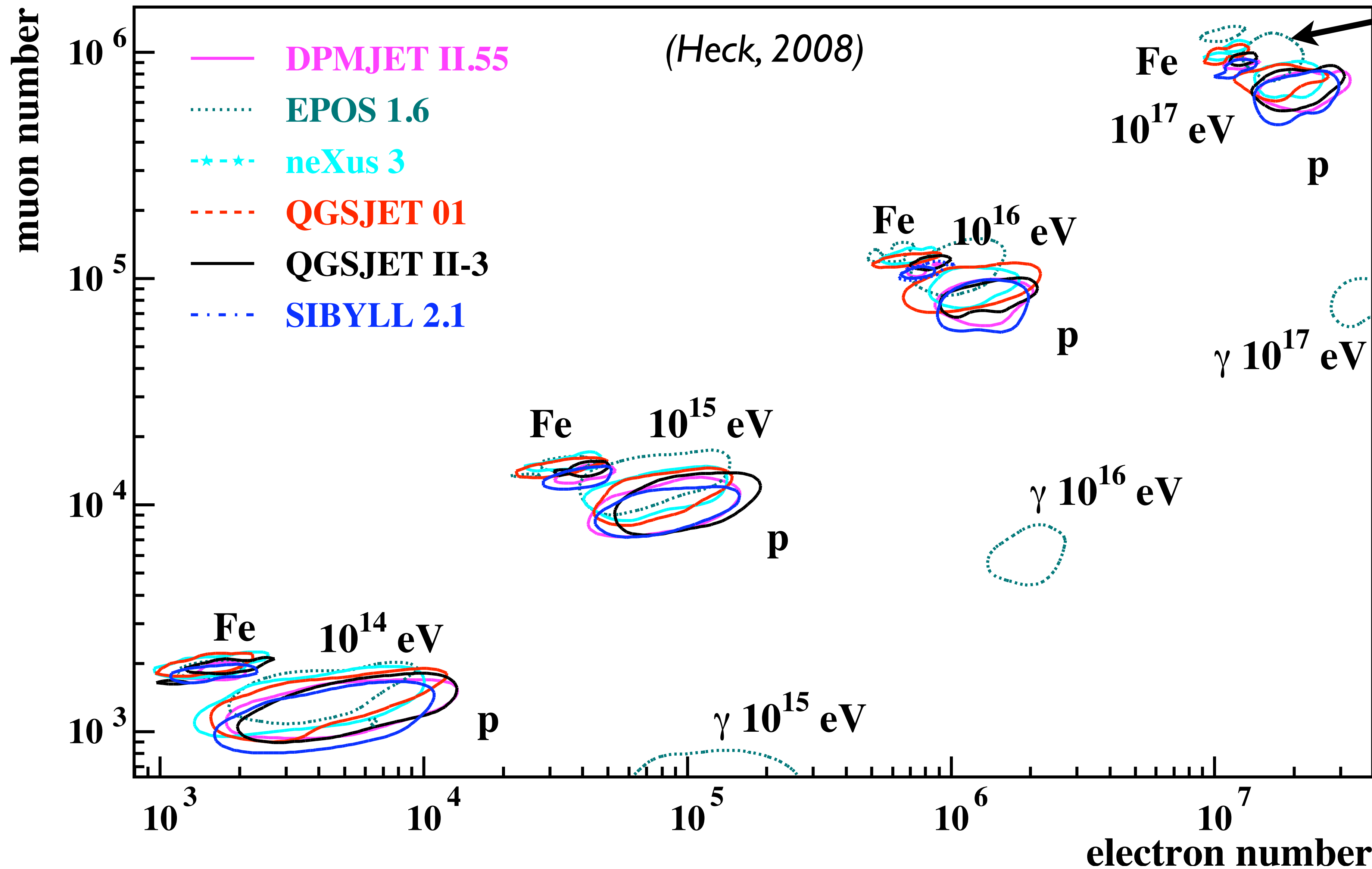
Muon observed at 1000 m from core

Energy distribution of last interaction that produced a detected muon



(Maris et al. ICRC 2009)

Electron and muon numbers of showers at ground



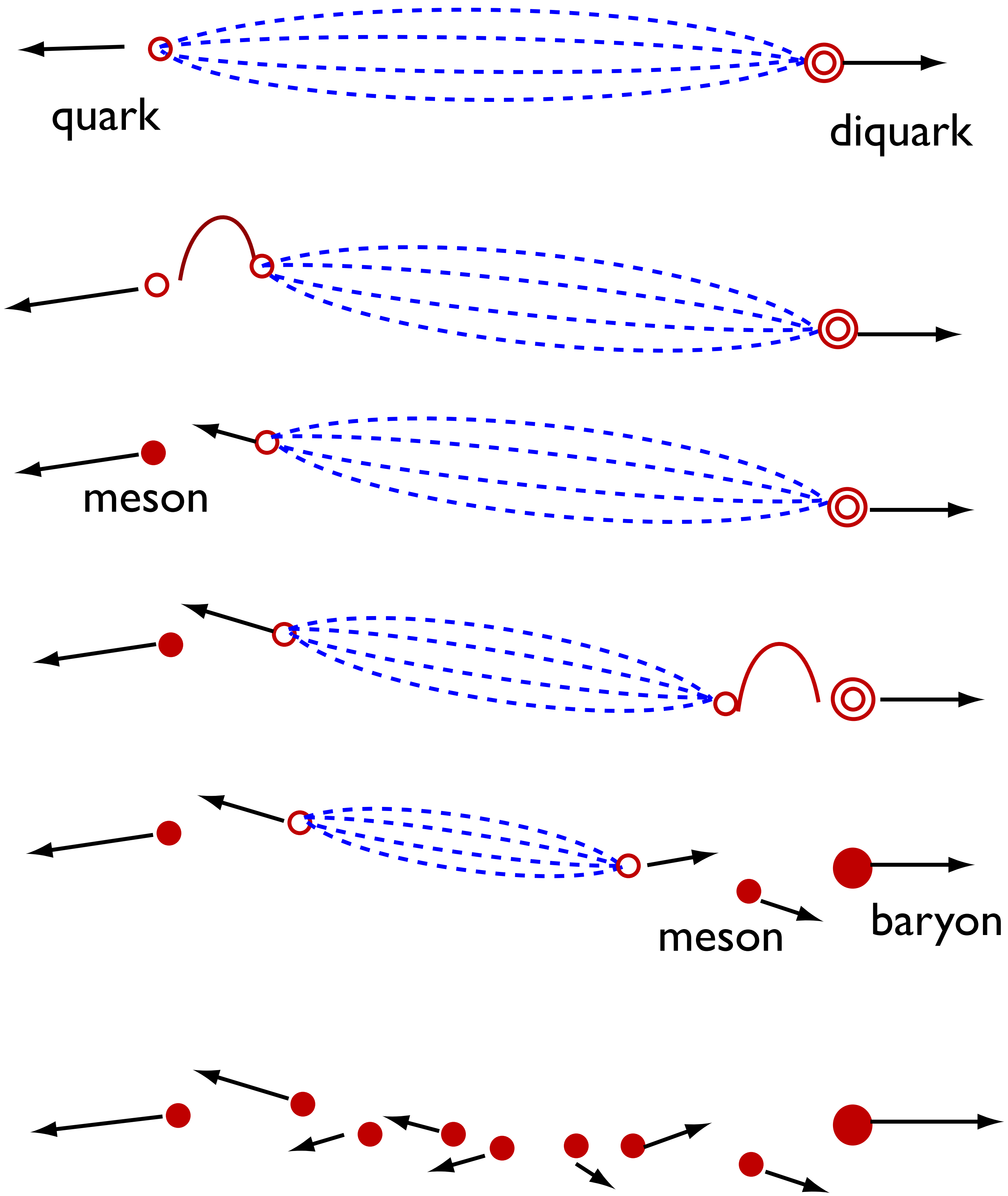
EPOS: largest muon number

vertical showers, sea level detector

$$N_\mu^{(FE)} \approx 1.4\, N_\mu^{(p)}$$

Dominating uncertainty of composition and energy measurements due to hadronic interaction models

Modification of ratio of neutral to charged pions

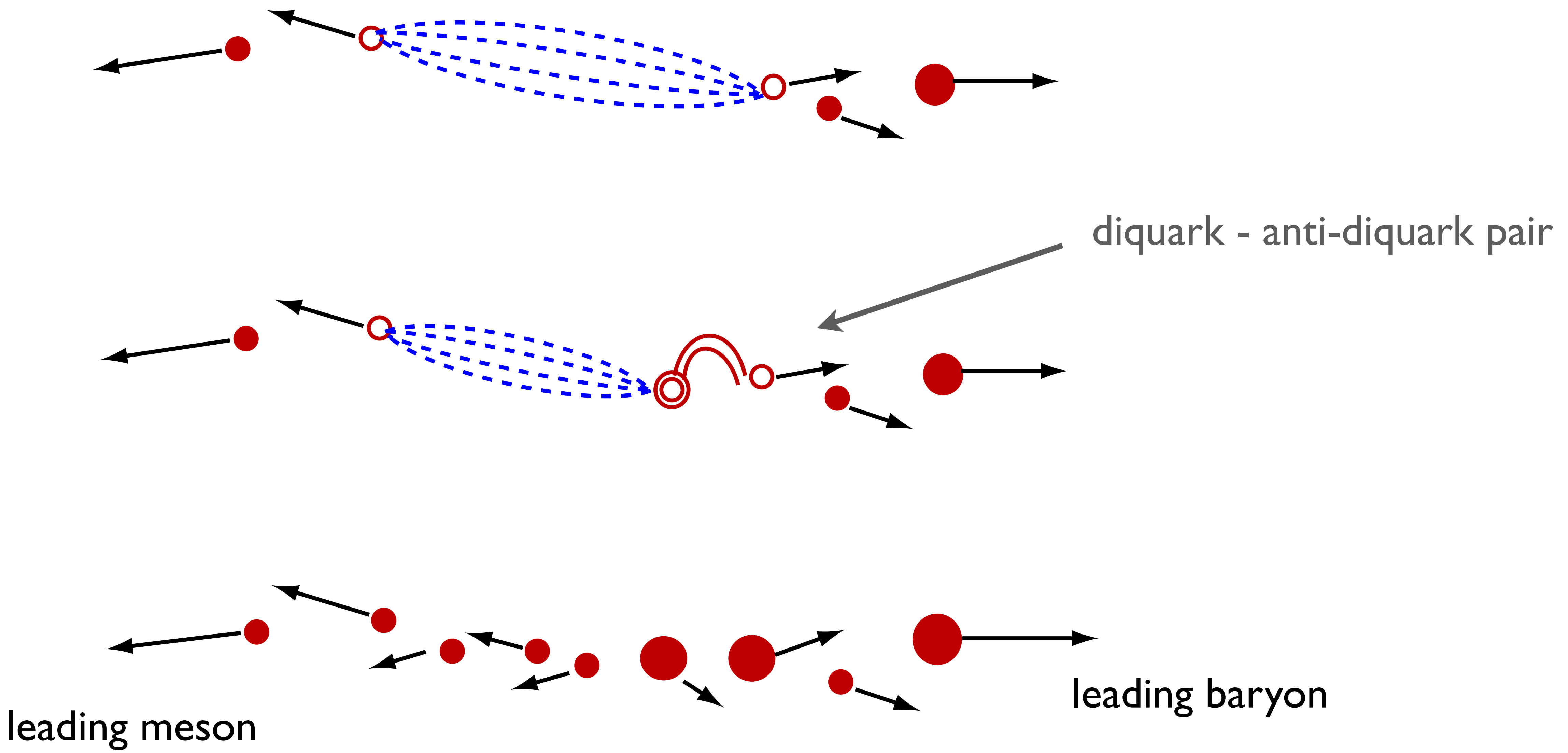


$$N_\mu = \left(\frac{E_0}{E_{\rm dec}}\right)^\alpha$$

$$\alpha = \frac{\ln(n_{\rm ch})}{\ln(n_{\rm tot})}$$

Particle ratios:
quark counting and SU(3) symmetry !

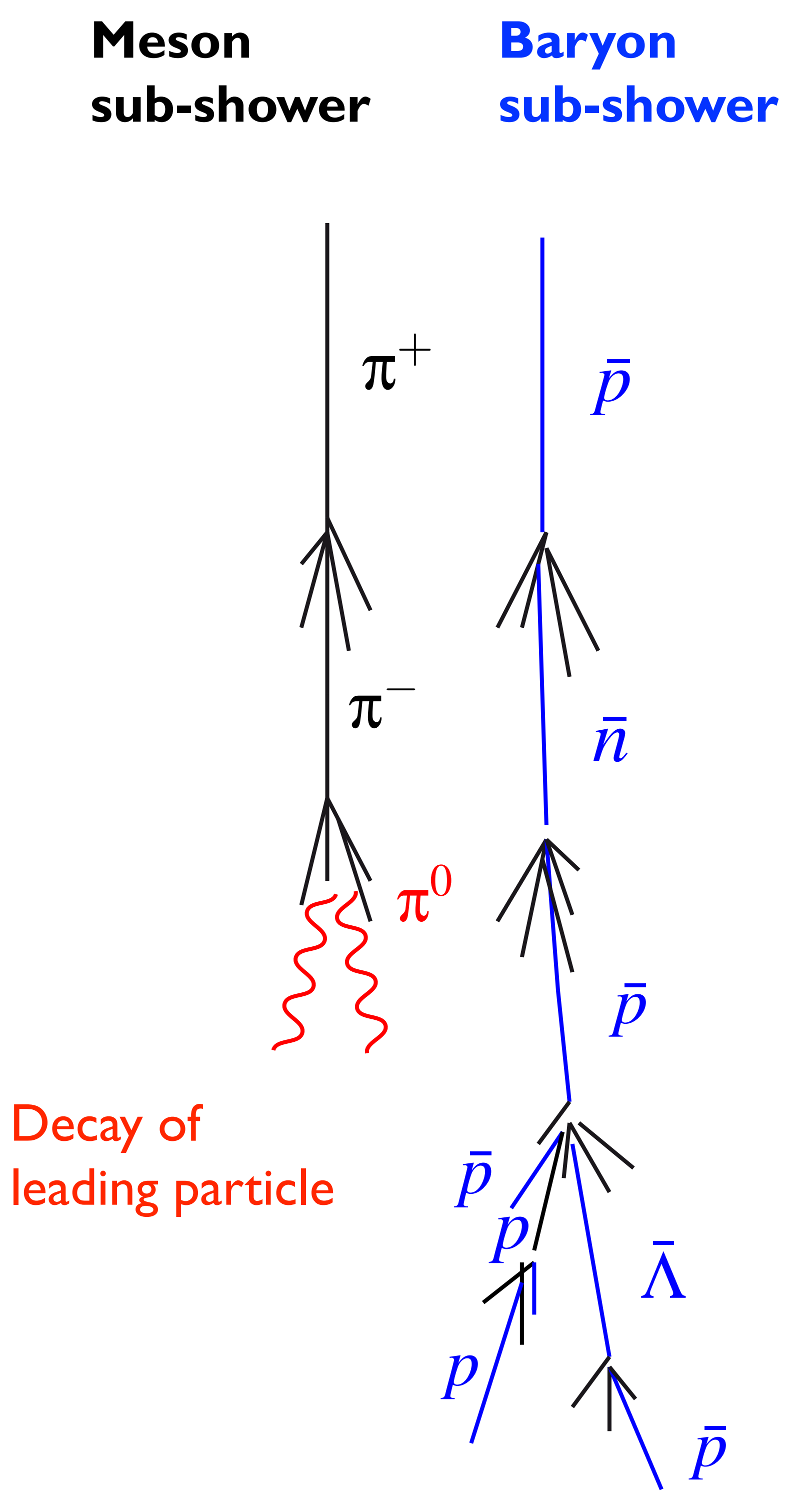
String fragmentation: baryon pairs



Baryon number conservation !

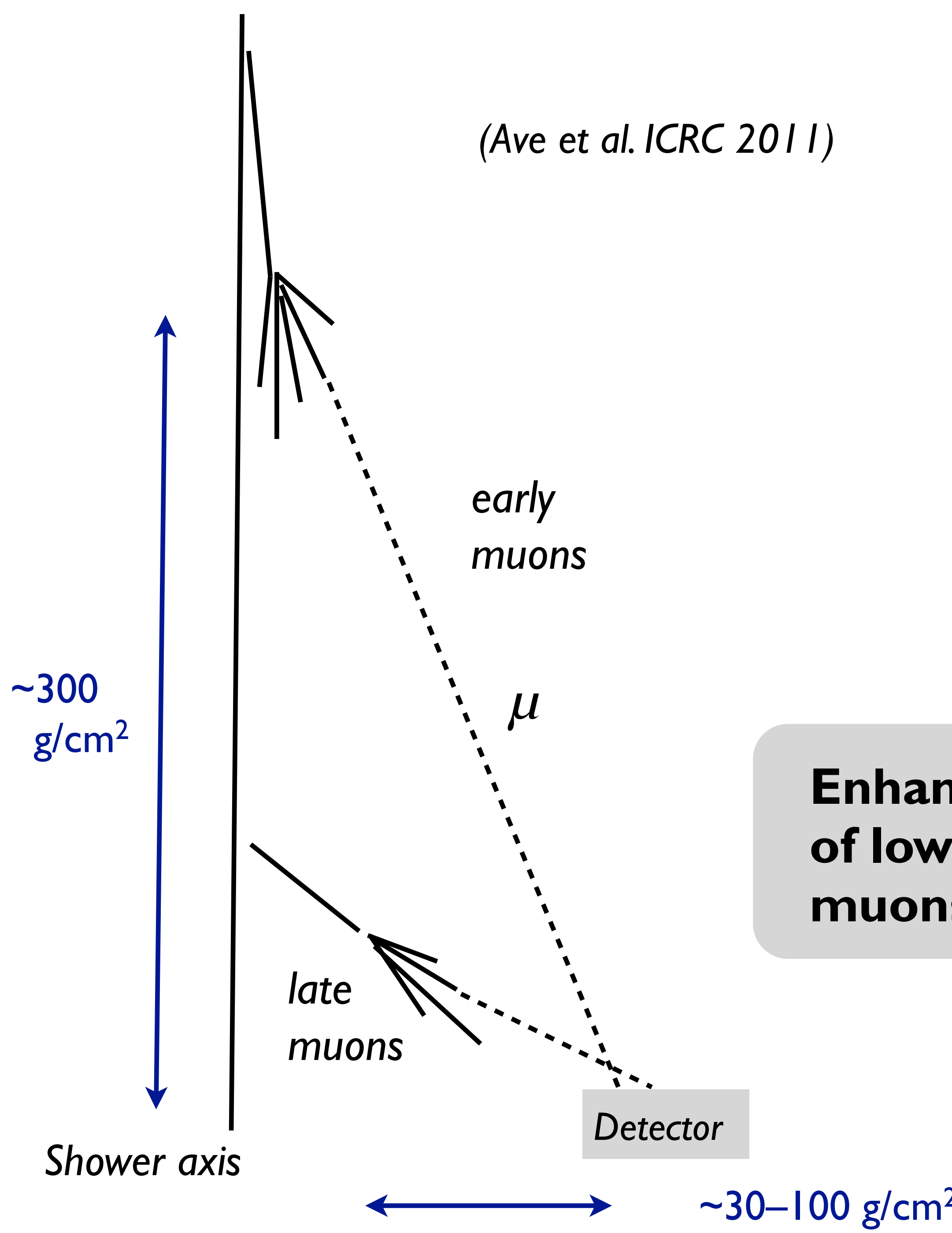
(Grieder, ICRC 1971)

Baryon pairs: enhancement of low-energy muons



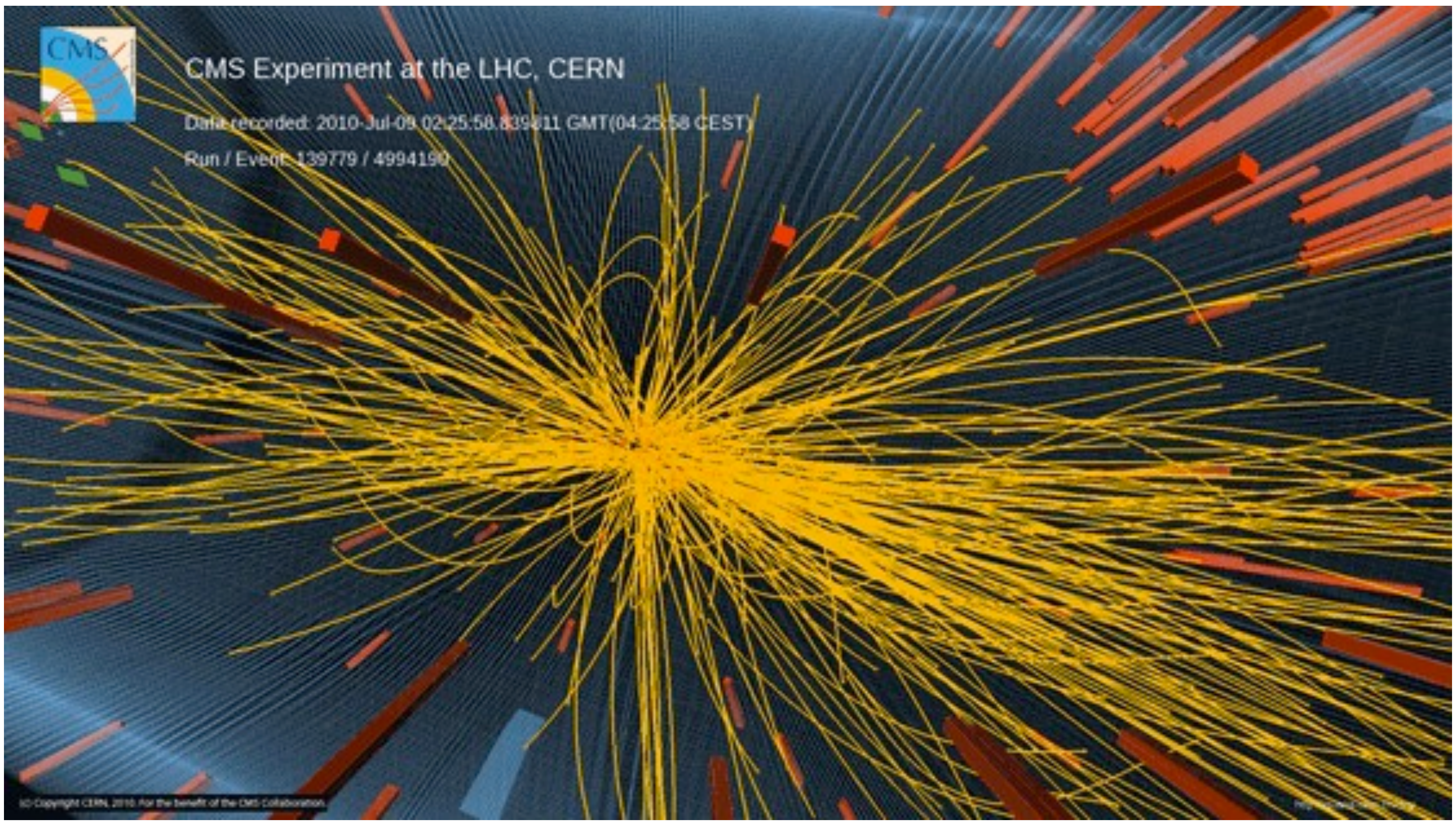
EPOS 1.6 and 1.9

(Pierog, Werner PRL 101, 2008)



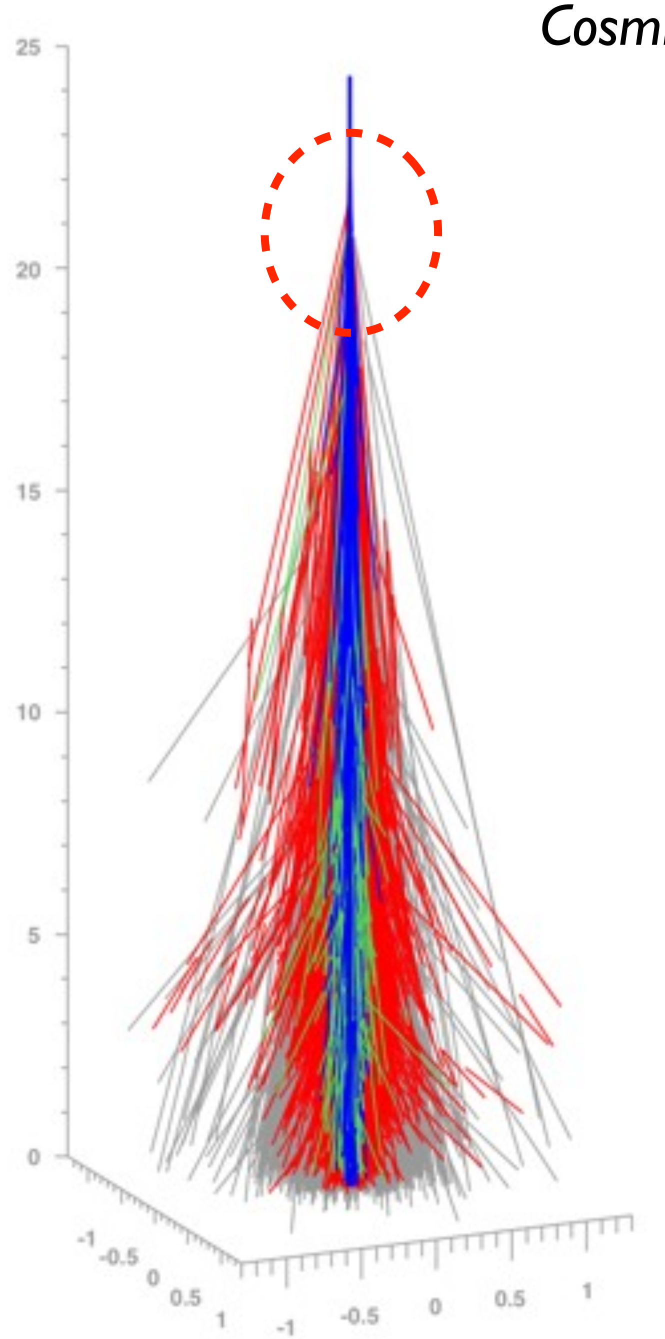
Enhancement of low-energy muons !

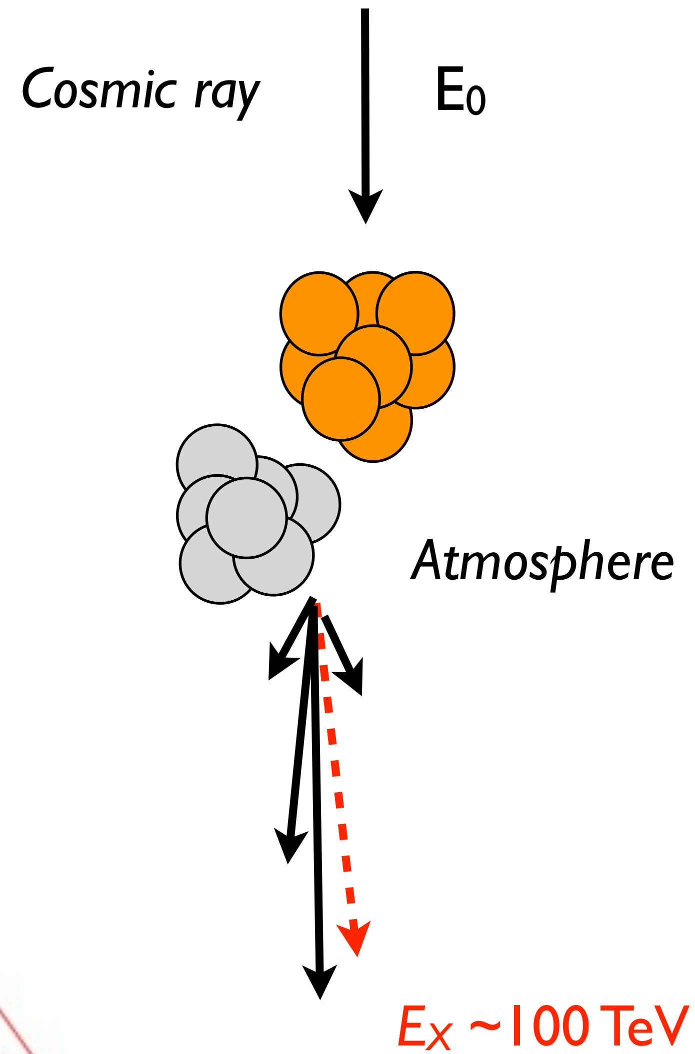
LHC data and model predictions



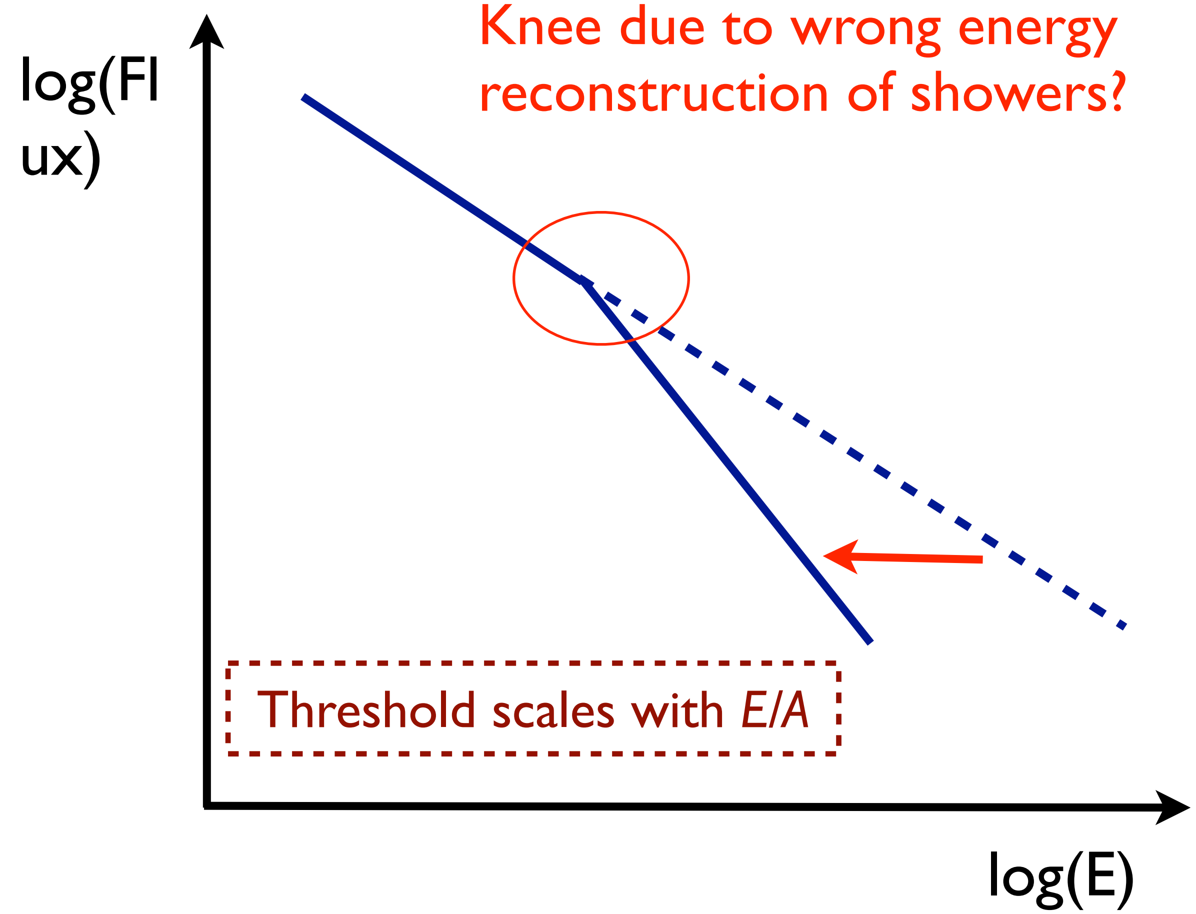
Proton-proton event at 7 TeV c.m. energy

Exotic models for the knee



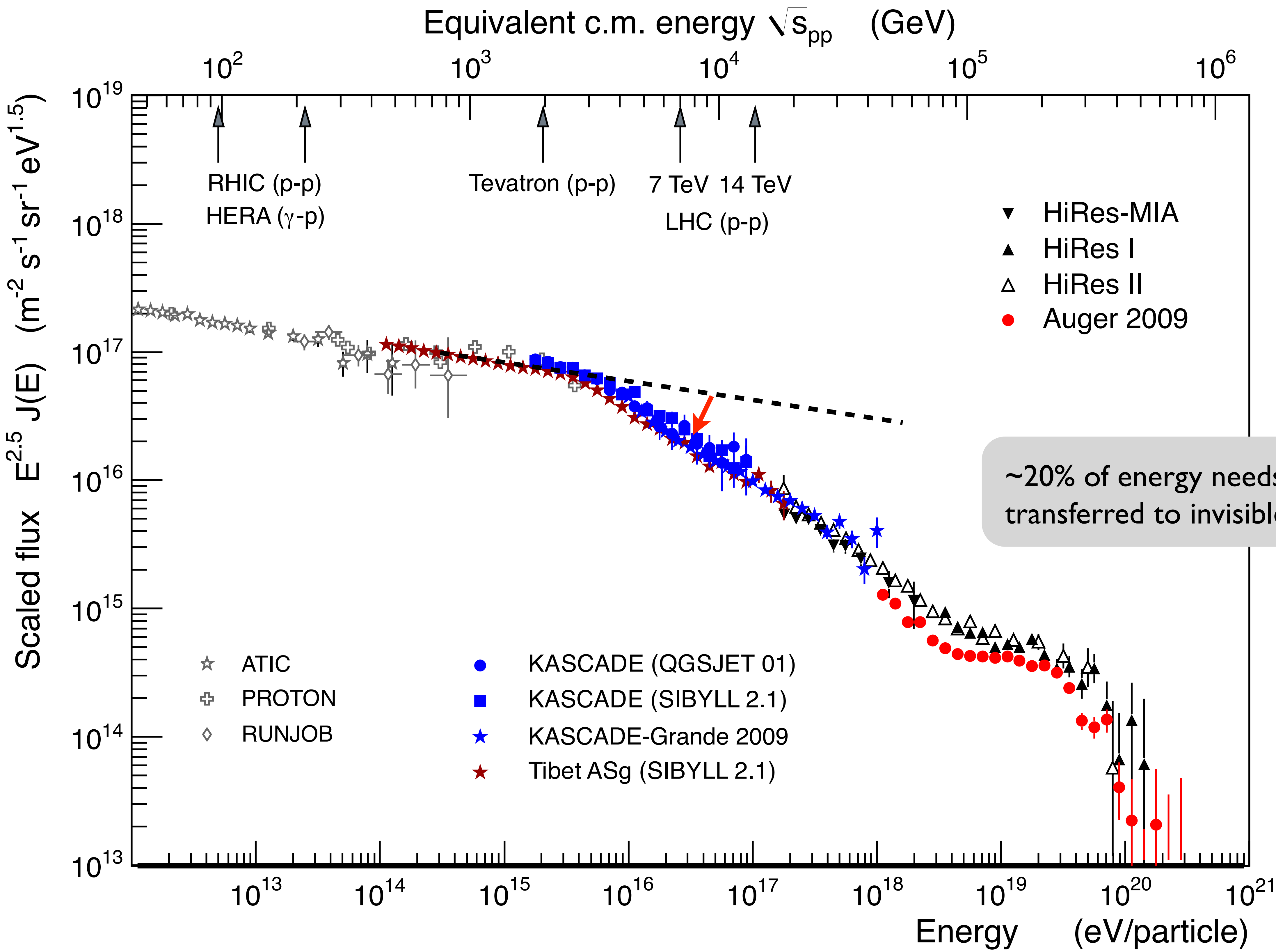


Petrukhin, NPB 151 (2006) 57
Barcelo at al. JACP 06 (2009) 027
Dixit et al. EPJC 68 (2010) 573
Petrukhin NPB 212 (2011) 235



New physics: scaling with nucleon-nucleon cms energy

LHC data probe the region beyond the knee



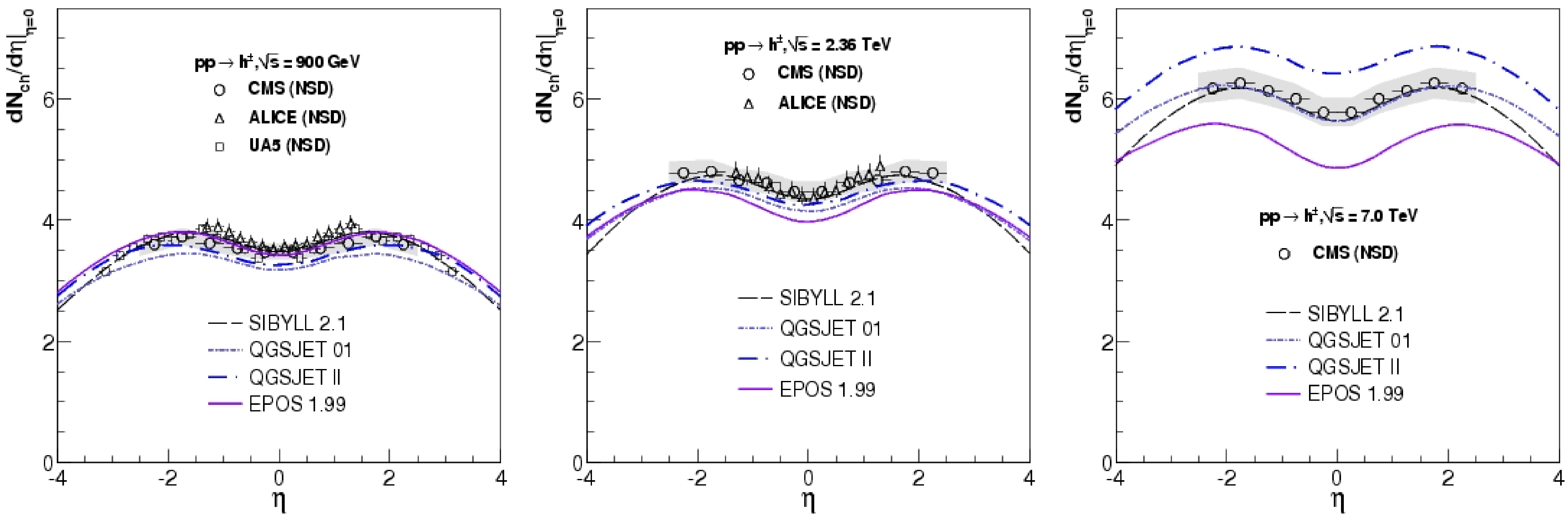
~20% of energy needs to be transferred to invisible channel

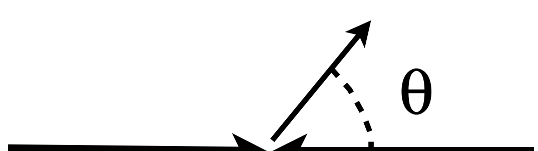
LHC data probe the region beyond the knee

Protons: $E_{lab} = 3 \times 10^{16}$ eV

Pseudorapidity distribution of charged particles

0.9 TeV 2.36 TeV 7.0 TeV





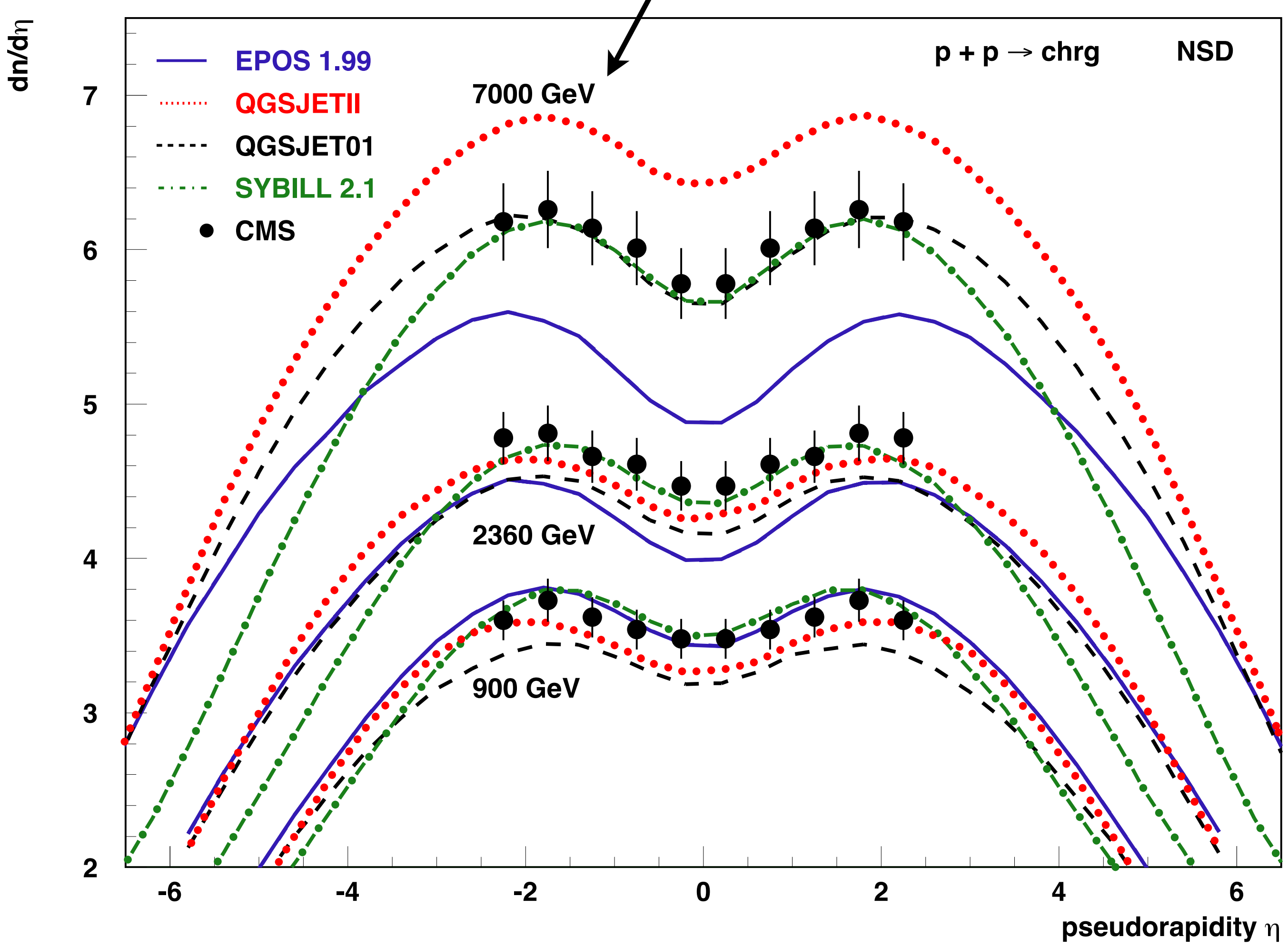
$$\eta = -\ln \tan \frac{\theta}{2}$$

LHC: Exotic scenarios for knee very unlikely, model predictions bracket LHC data on secondary particle multiplicity

(D'Enterria at al. Astropart Phys 35, 2011)

Charged particle distribution in pseudorapidity

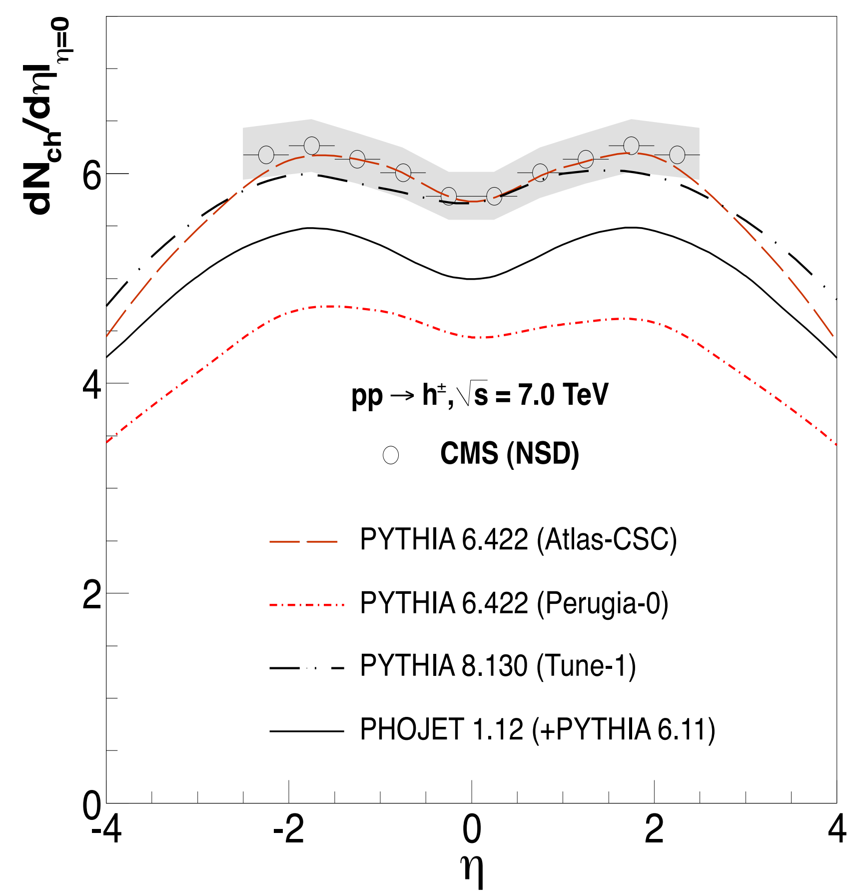
Protons: $E_{lab} = 3 \times 10^{16}$ eV



(data from all LHC experiments, CMS shown as example)

Detailed LHC comparison

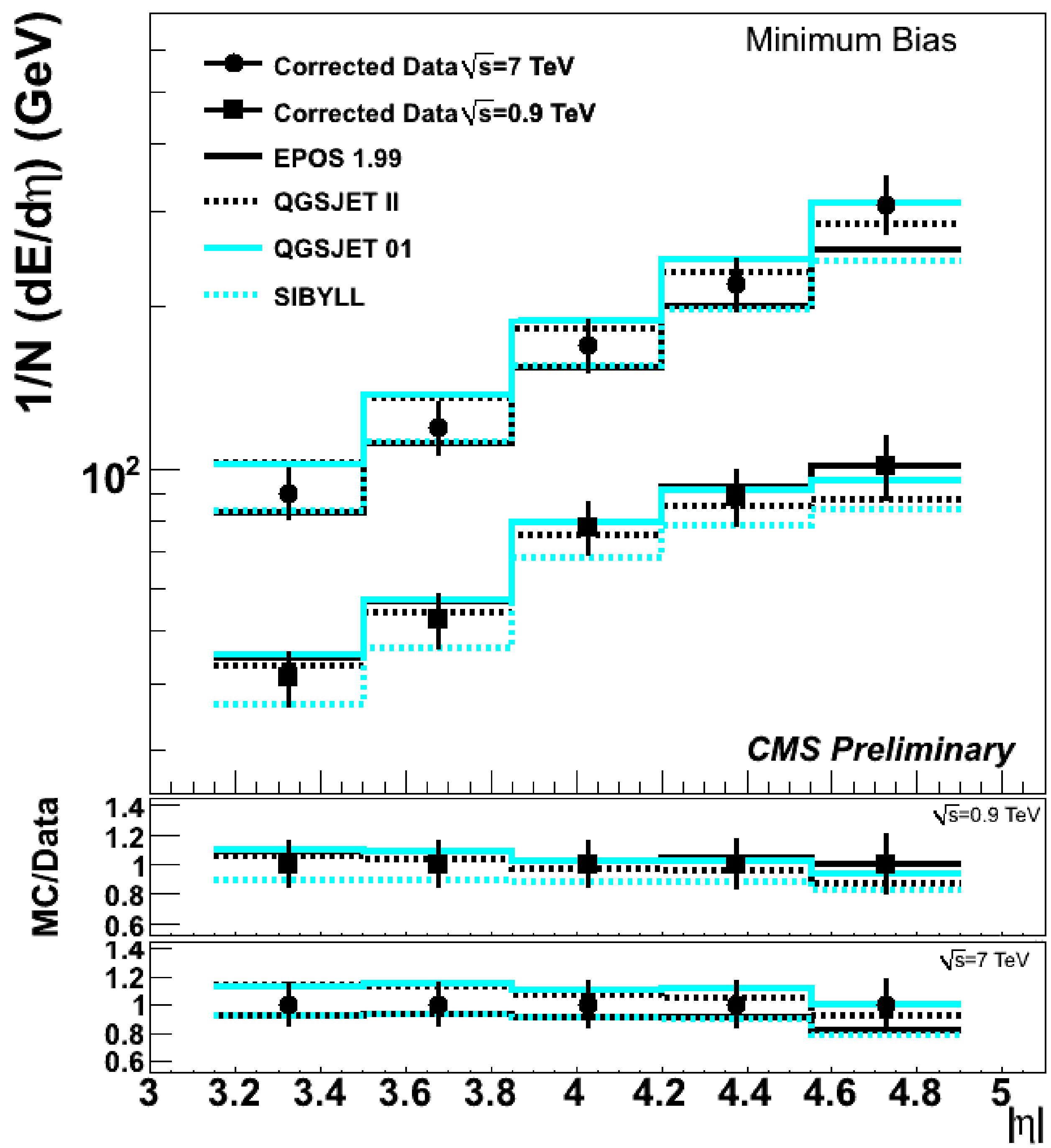
(D'Enterria et al., Astropart. Phys. 35, 2011)



Models for air showers typically better in agreement with LHC data

LHC: total energy deposited by secondary particles

CMS data: forward energy flow measured in calorimeter



Cosmic ray interaction models

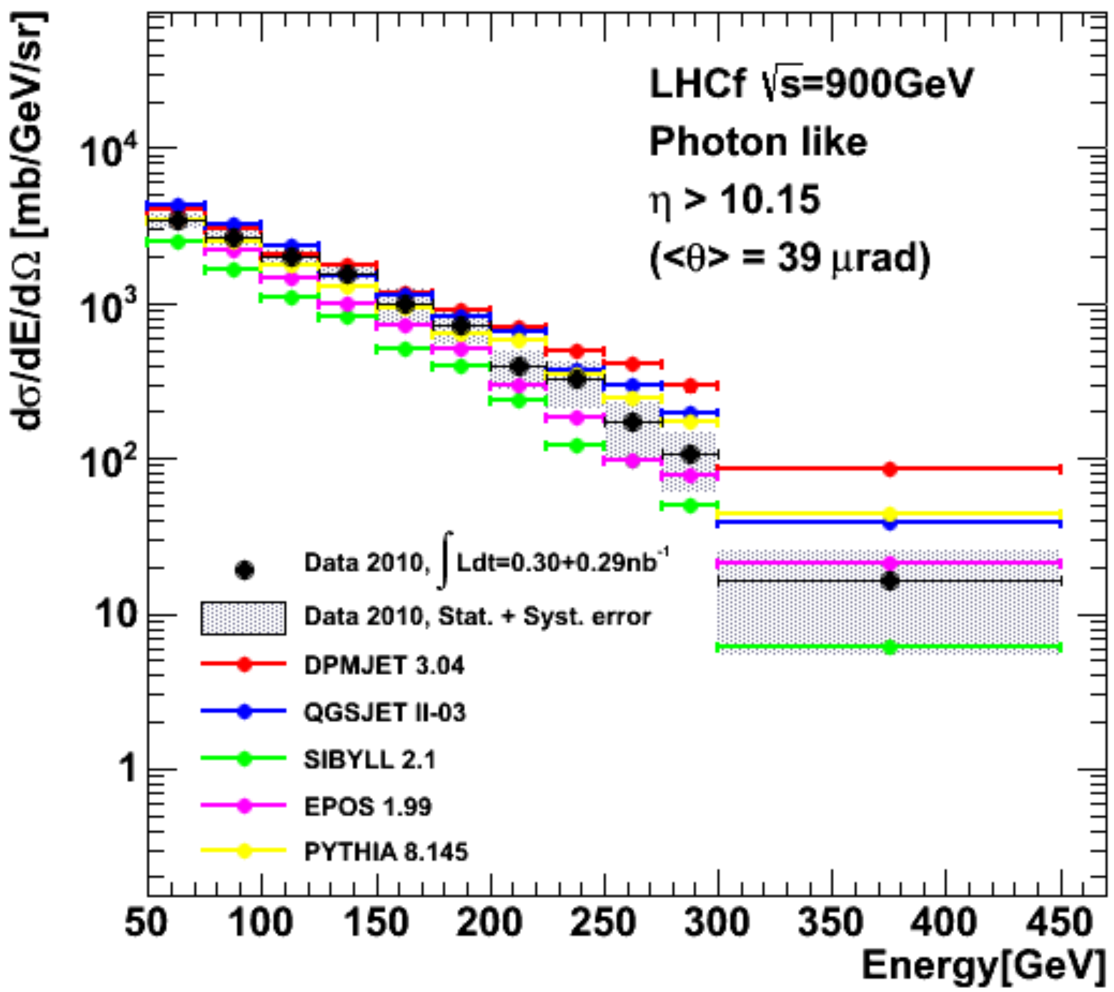
7 TeV

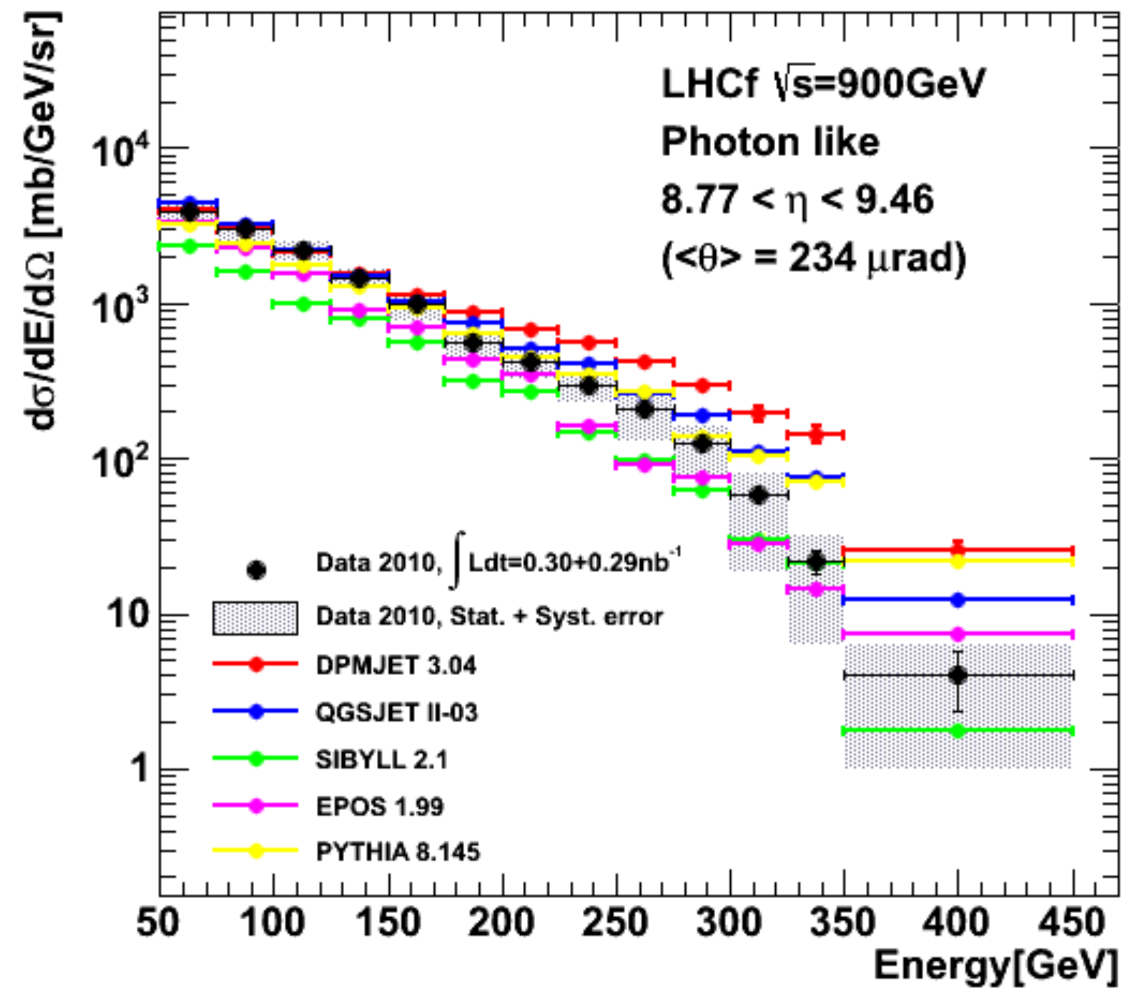
0.9 TeV

Exotic scenarios for knee very unlikely, model predictions bracket LHC data on secondary particle distributions

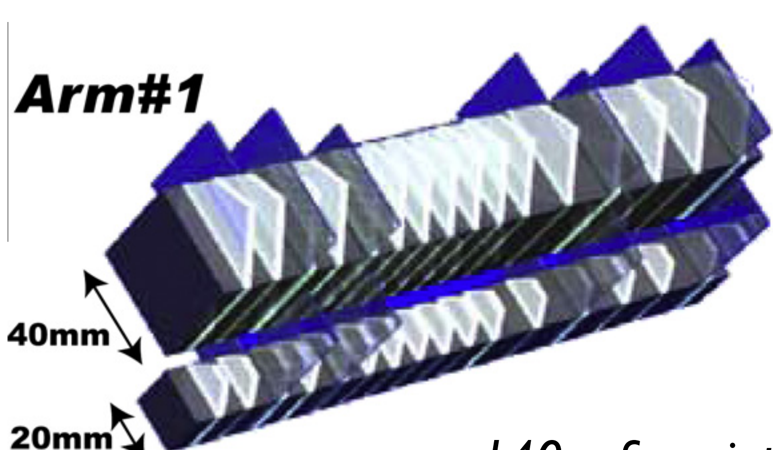
(CMS Collab., EPS 2001)

LHCf: forward photon production





(Mitsuka, this meeting)



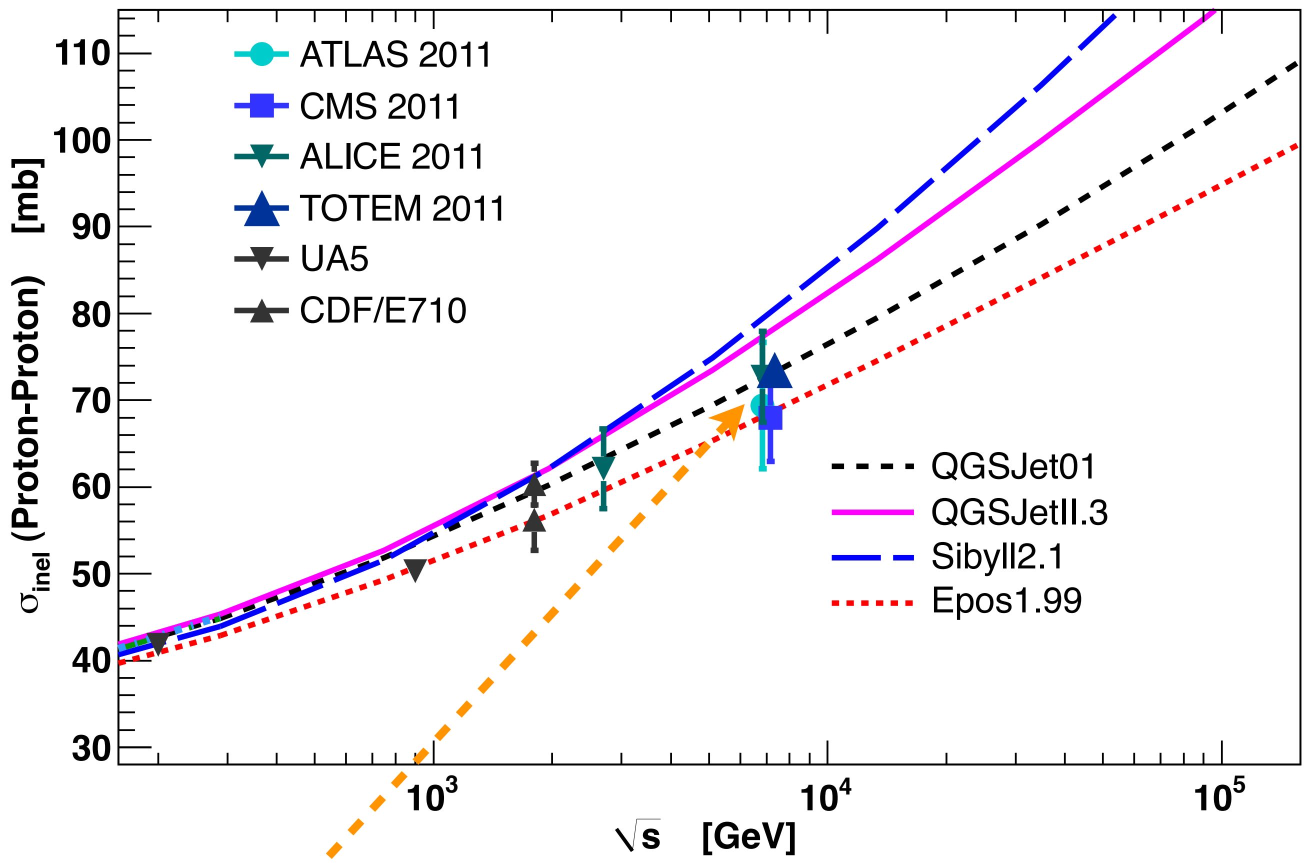
$$pp \to \gamma X$$

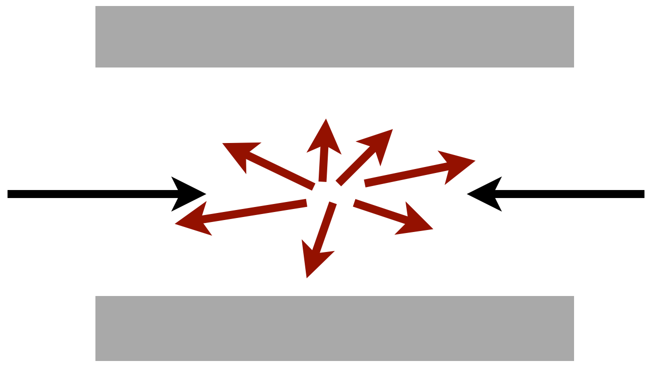
Model predictions bracket LHC data

140m from interaction point

Cross section measurements at LHC

Inelastic proton-proton cross section





$$\frac{\Delta p}{p} = \xi > 5 \times 10^{-6}$$

$$\sigma_{ATLAS} = 60.3 \pm 0.05 \pm 0.5 \pm 2.1\text{mb}$$

$$\boxed{\sigma_{TOTEM} = 73.6 \pm 0.6 + 1.8 - 1.3\text{mb}}$$

N_{trk} Pt (MeV)	3 200	4 200	3 250	4 250	σ_{tot}
CMS	59.7	58.6	58.9	57.3	
Q-II-03	65.2	64.6	63.0	62.0	77.5
SYBILL-2.1	71.5	71.0	70.2	69.3	79.6

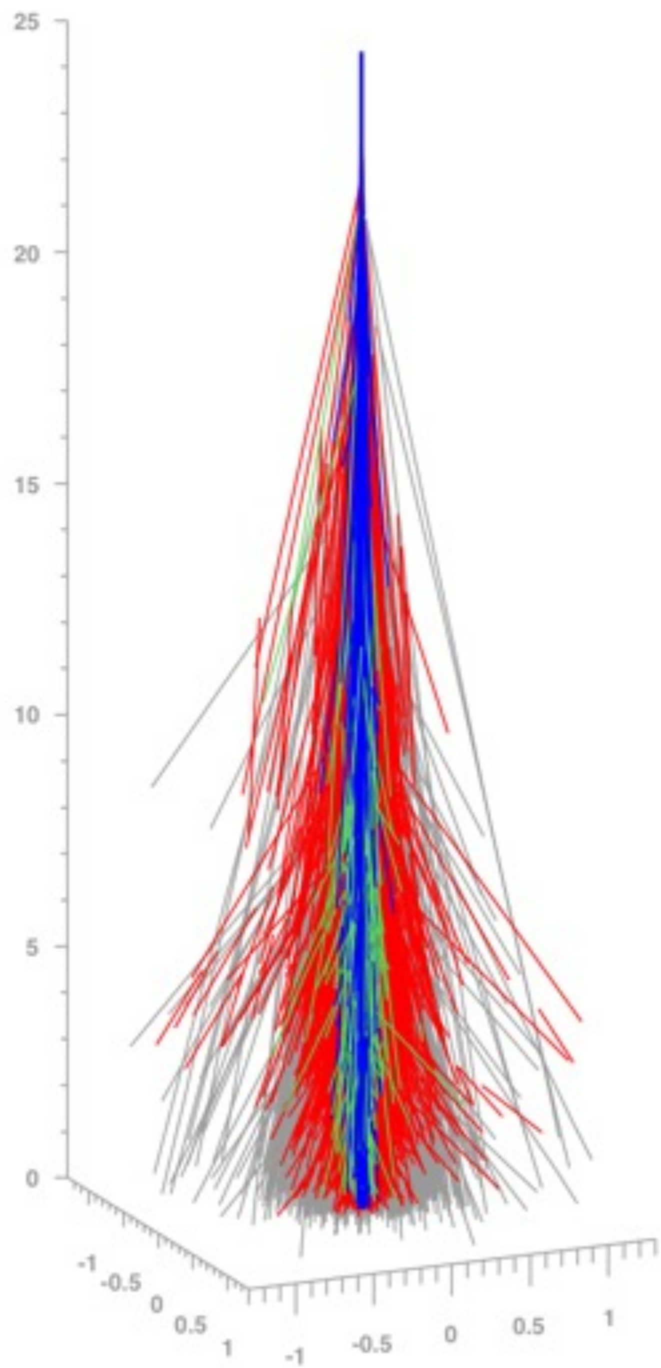
(CMS, DIS Workshop, Brookhaven)

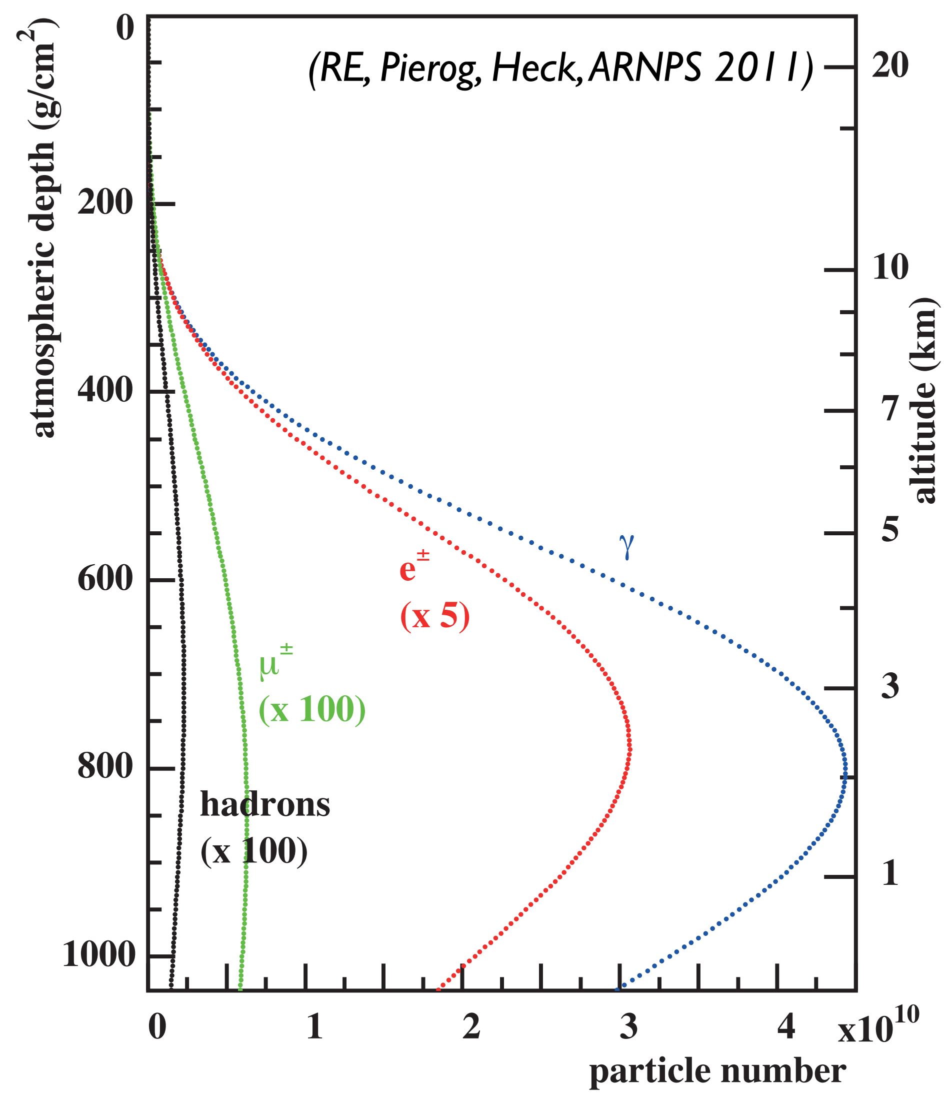
No big surprise given Tevatron measurements, but re-tuning of model cross sections needed

$$\sigma_{ALICE} = 72.7 \pm 1.1 \pm 5.1\text{mb}$$

Do simulated showers describe observations ?

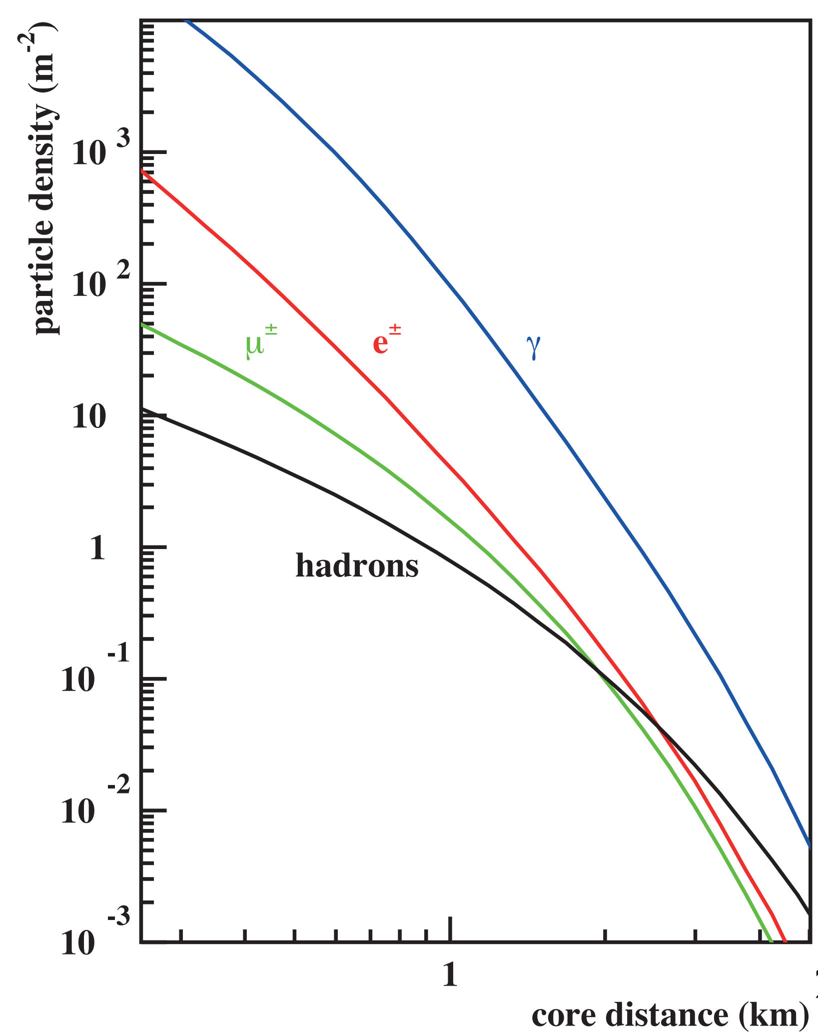
Measured components of air showers





Longitudinal profile:

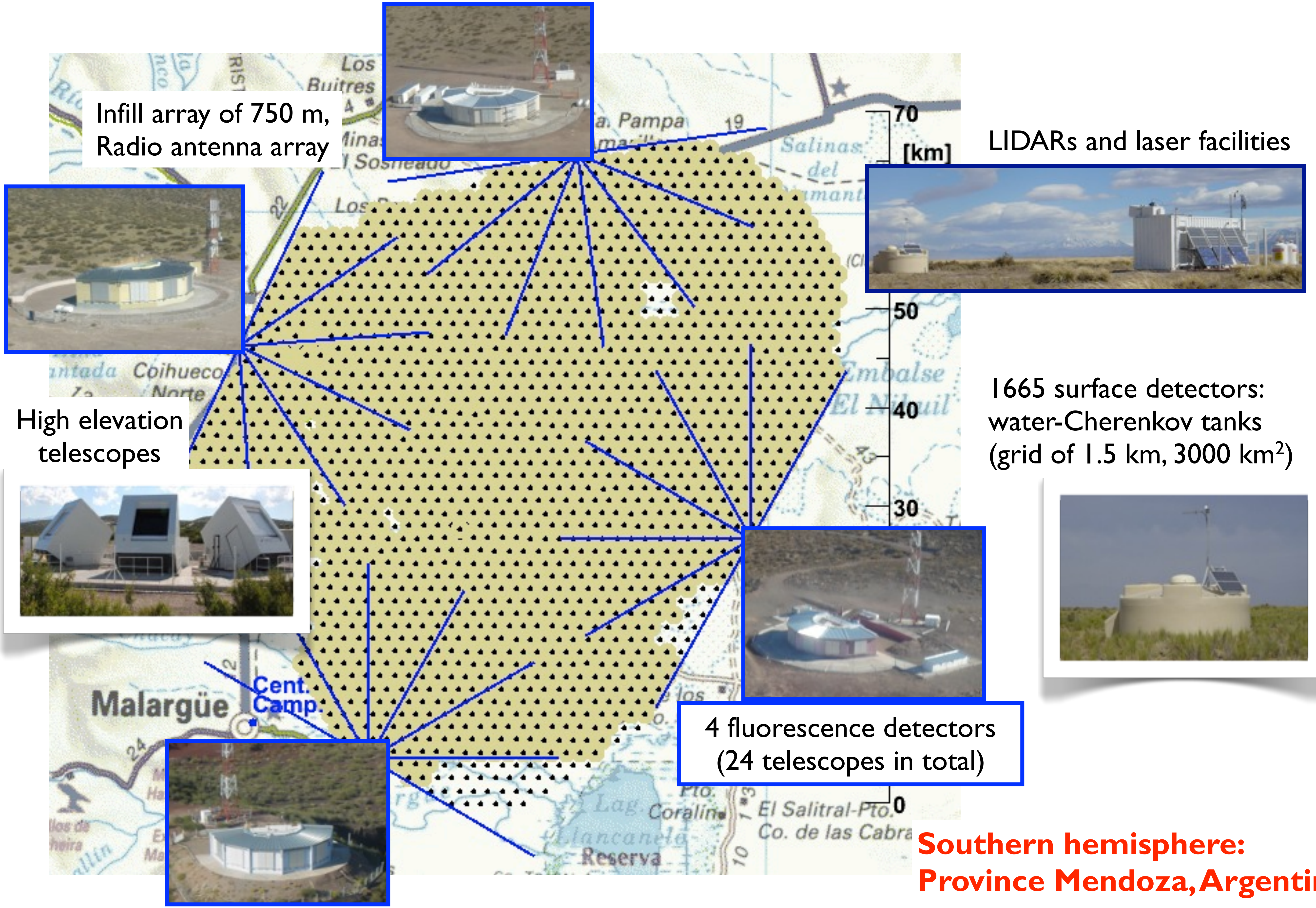
Cherenkov light
Fluorescence light
(bulk of particles measured)



Lateral profiles:

particle detectors at ground
(very small fraction of particles sampled)

The Pierre Auger Observatory



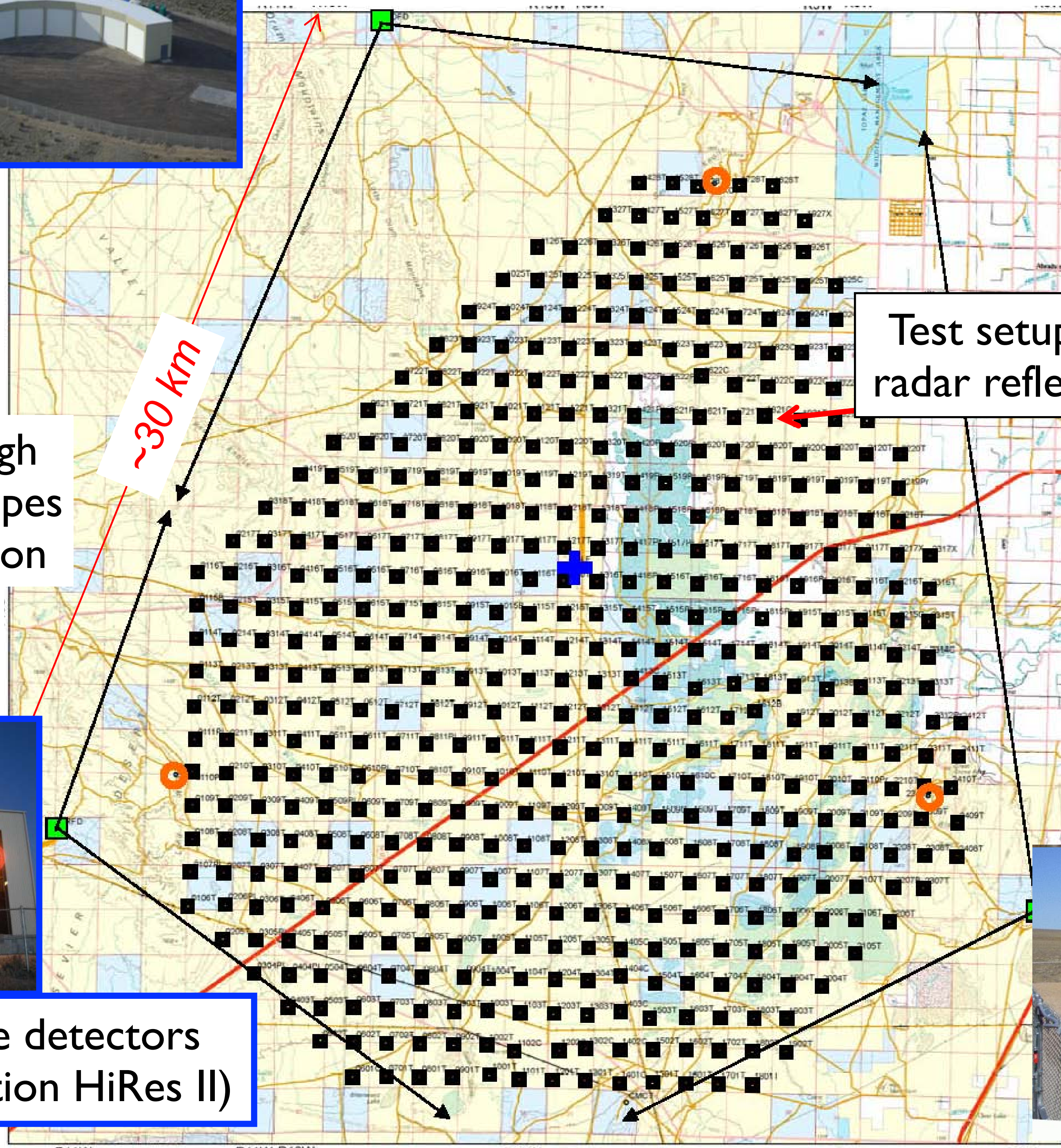
Southern hemisphere:
Province Mendoza, Argentin

Telescope Array (TA)

Middle Drum: based on HiRes II

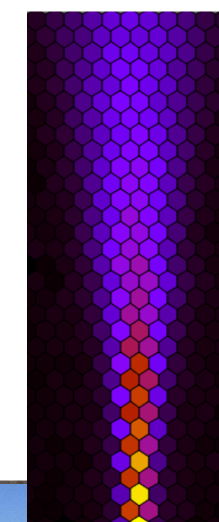
507 surface detectors:
double-layer scintillators
(grid of 1.2 km, 680 km^2)

LIDAR
Laser facility



Test setup for
radar reflection

Infill array and high
elevation telescopes
under construction

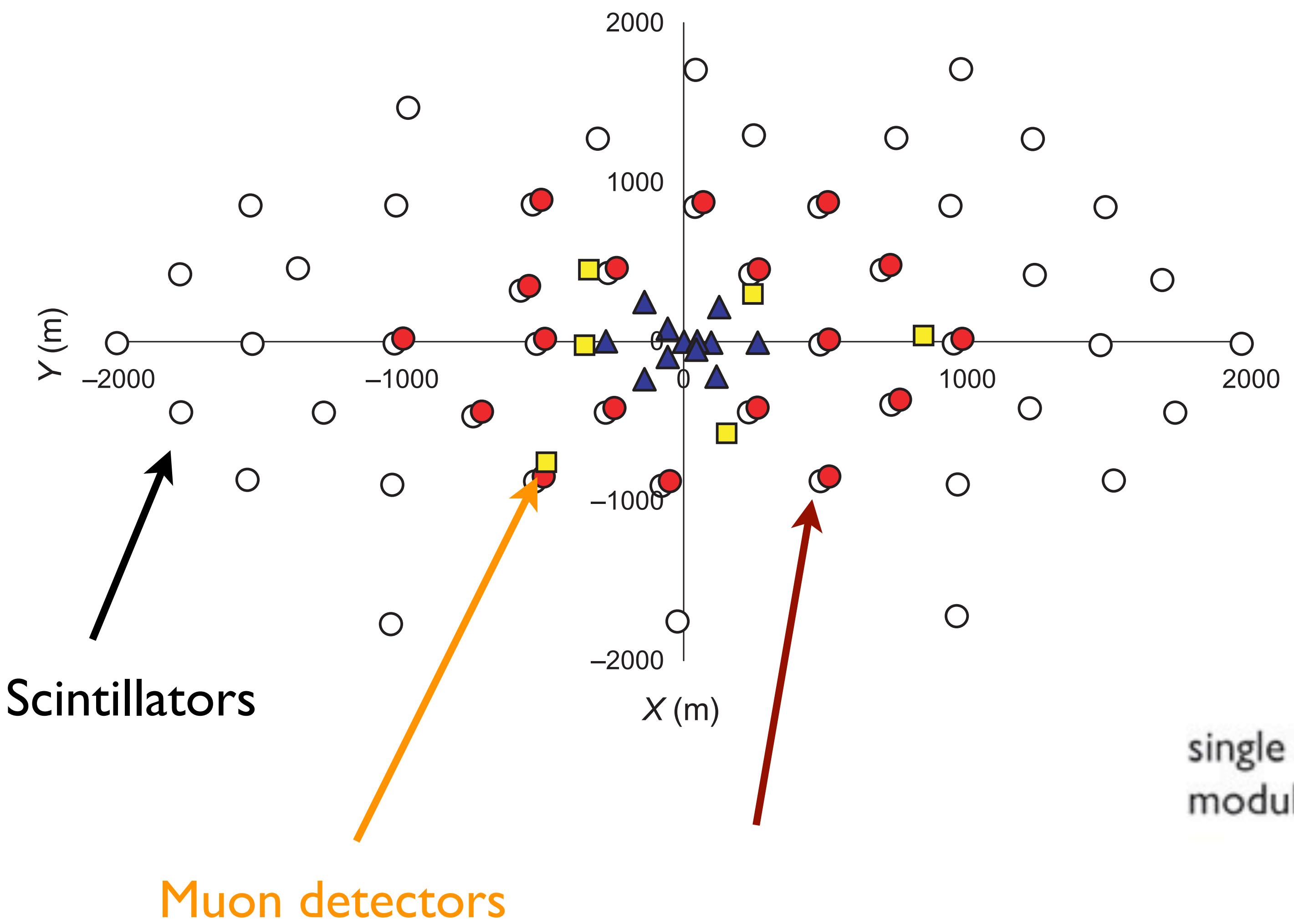


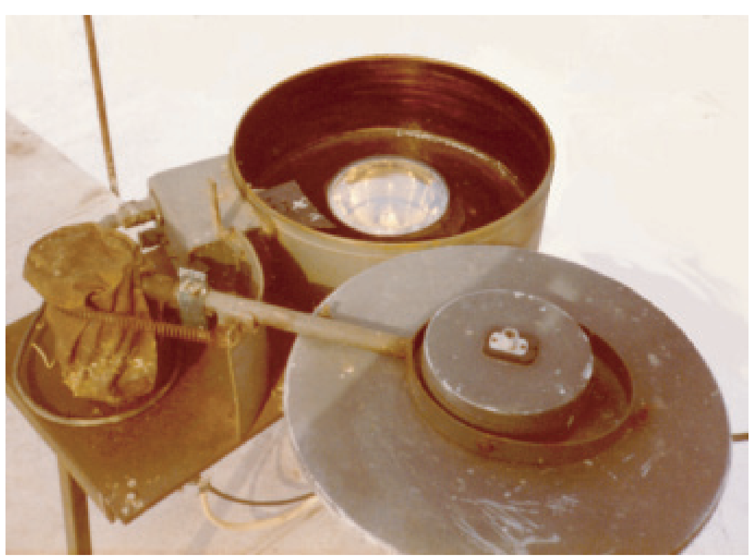
Electron light source
(ELS): ~40 MeV

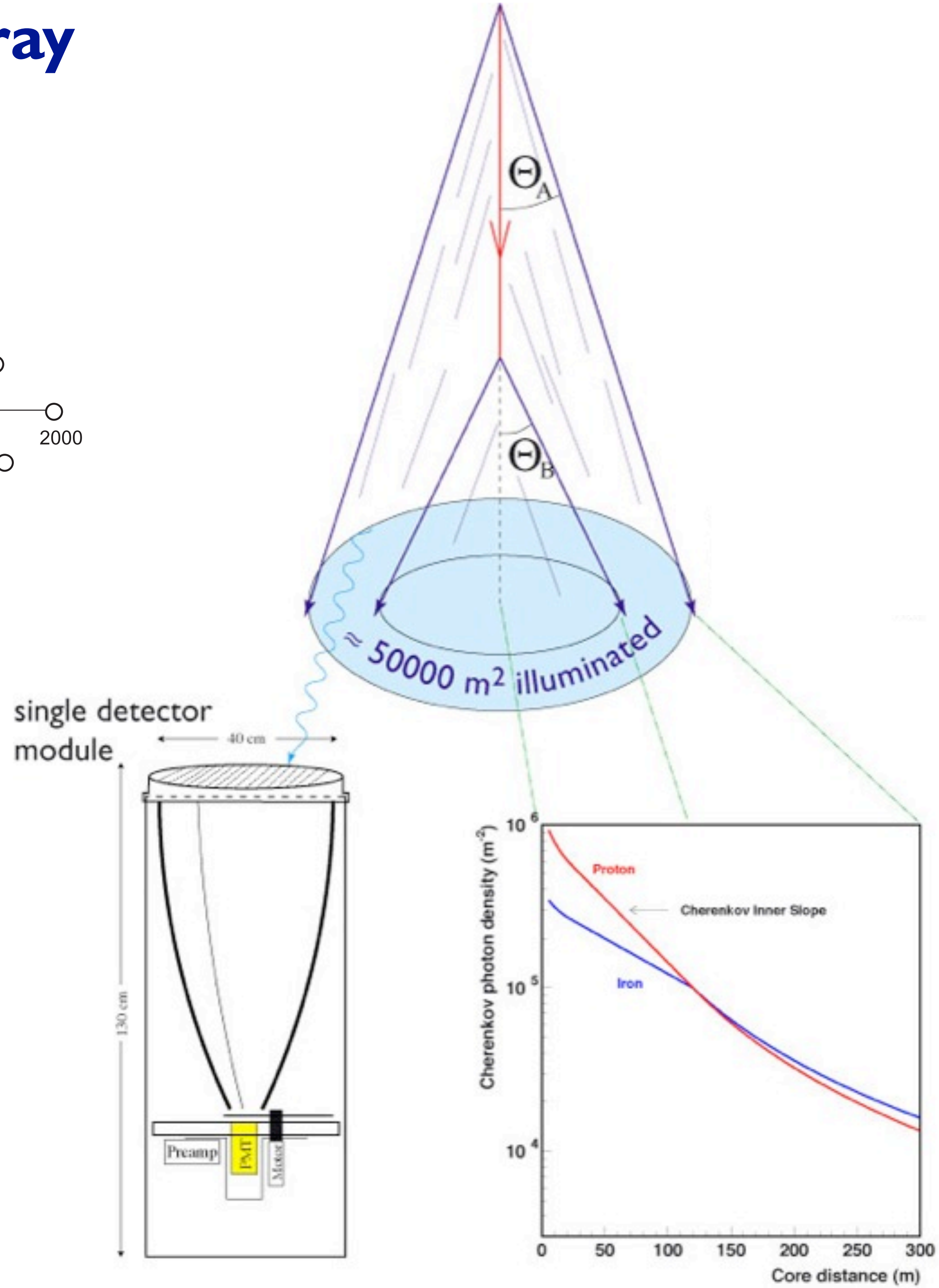
3 fluorescence detectors
(2 new, one station HiRes II)

Northern hemisphere: Utah, USA

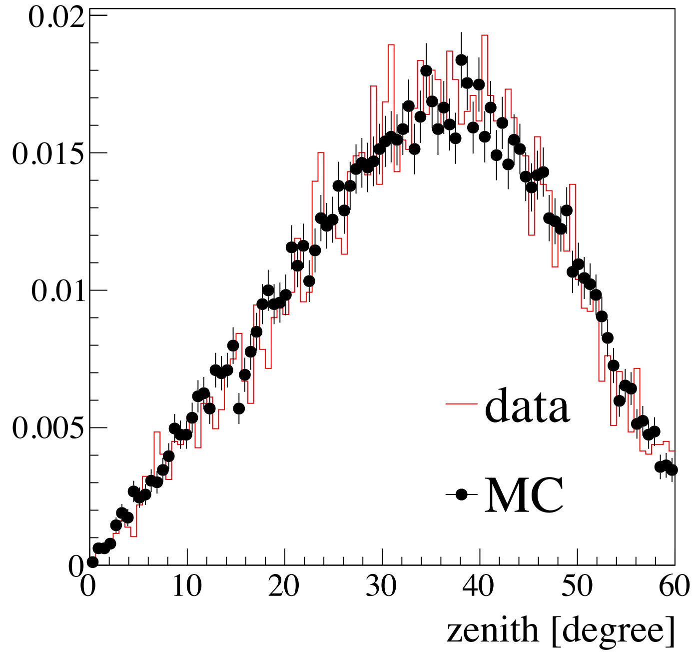
Yakutsk air shower array



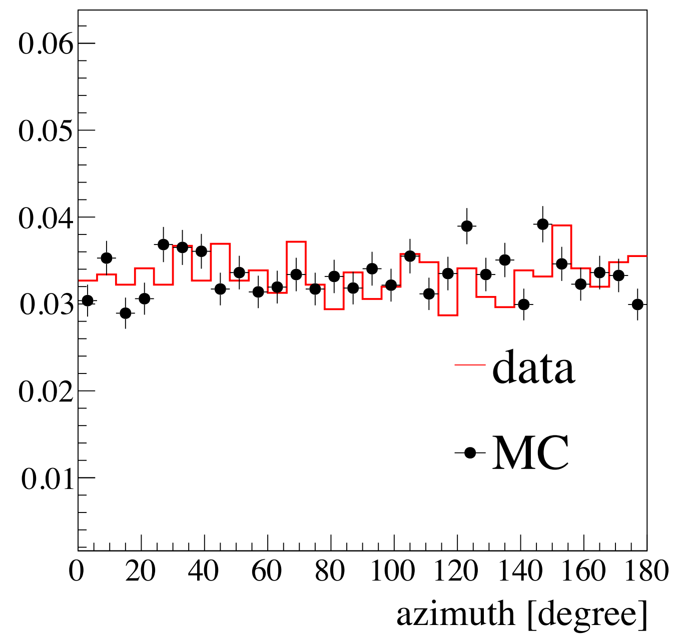




Auger event simulation for surface array

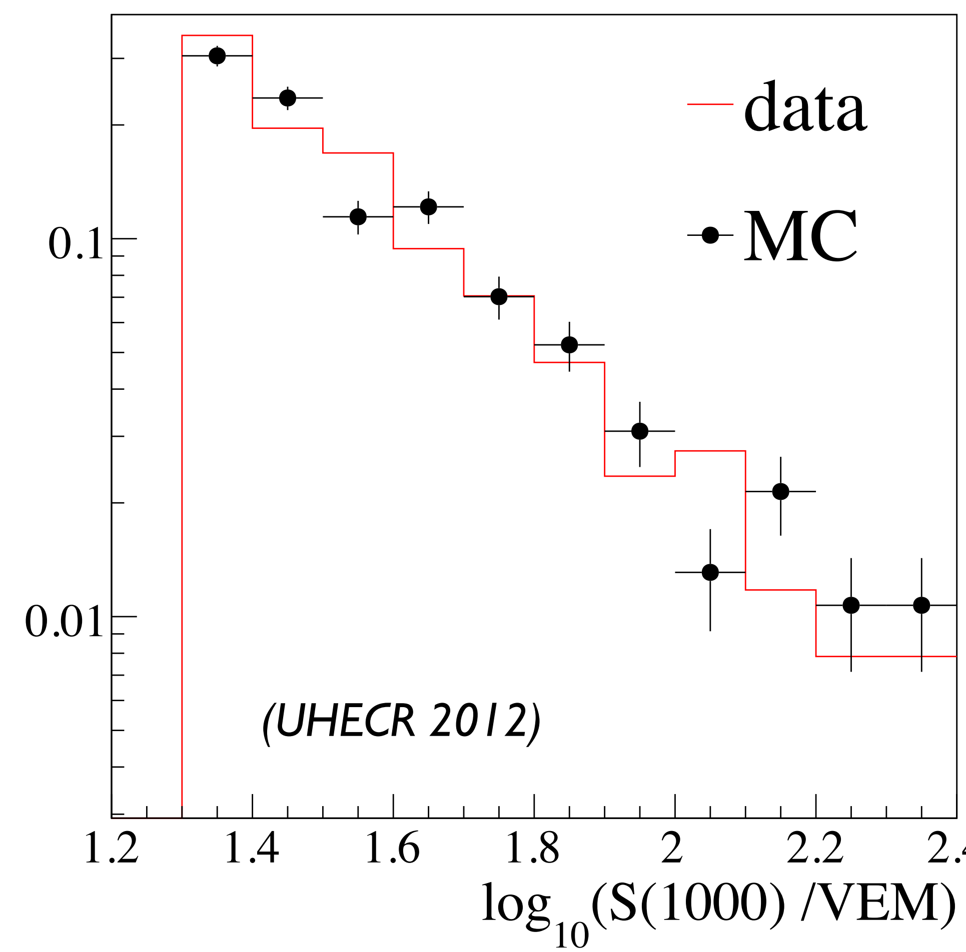


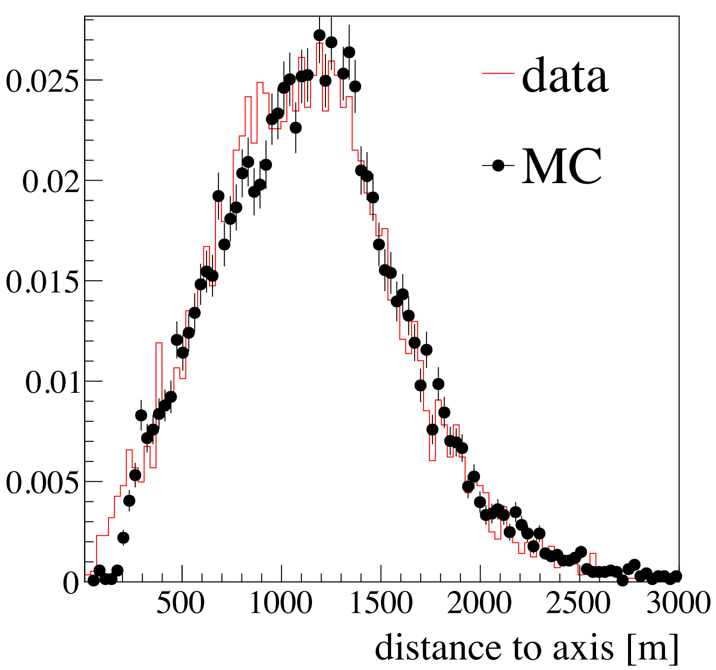
Zenith angle



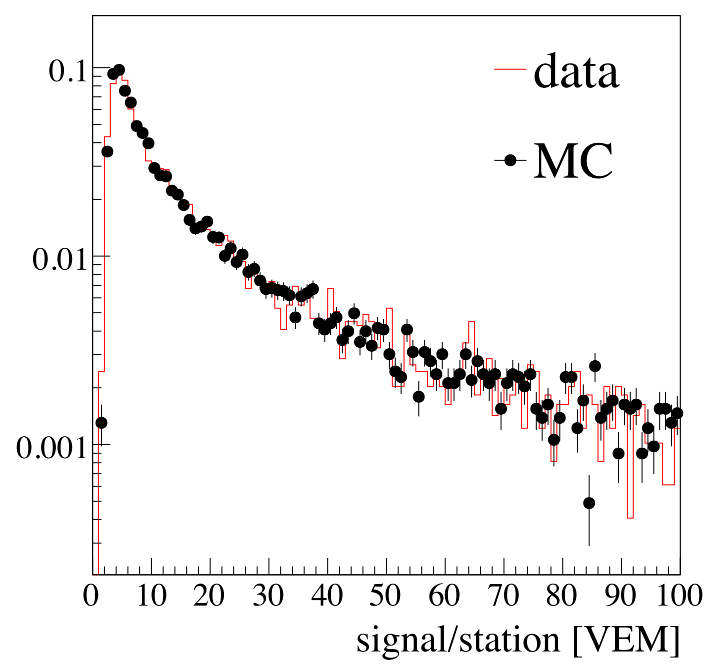
Azimuth angle

CORSIKA + full detector simulation (50% p + 50% Fe)





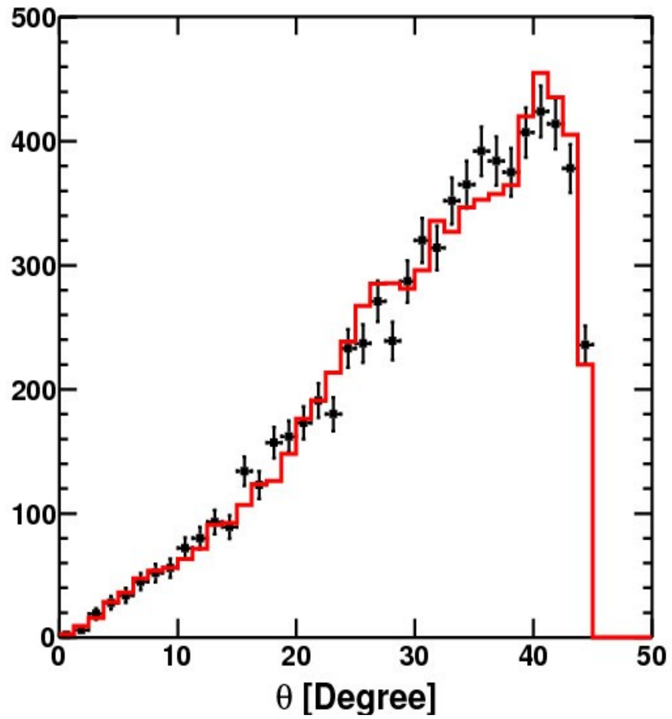
Distance of triggered stations



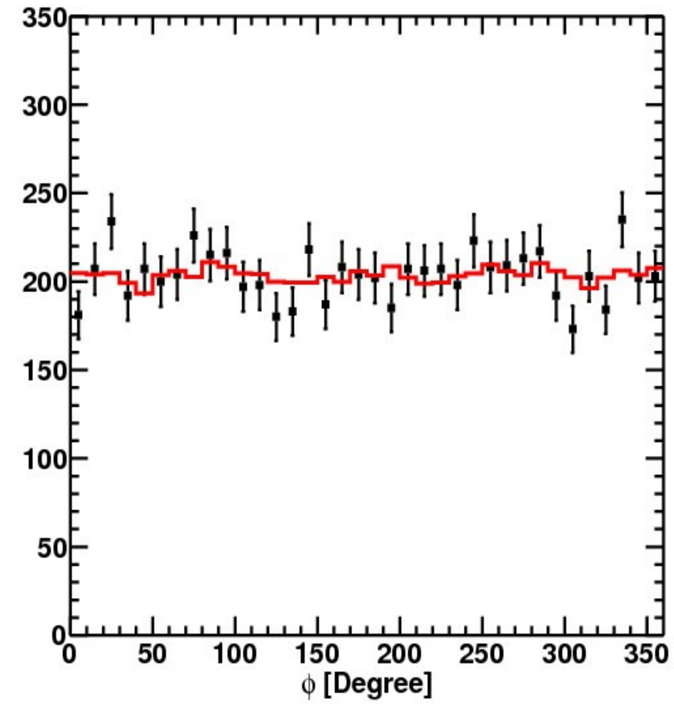
Signal per station

Very good agreement

TA event simulation for surface array

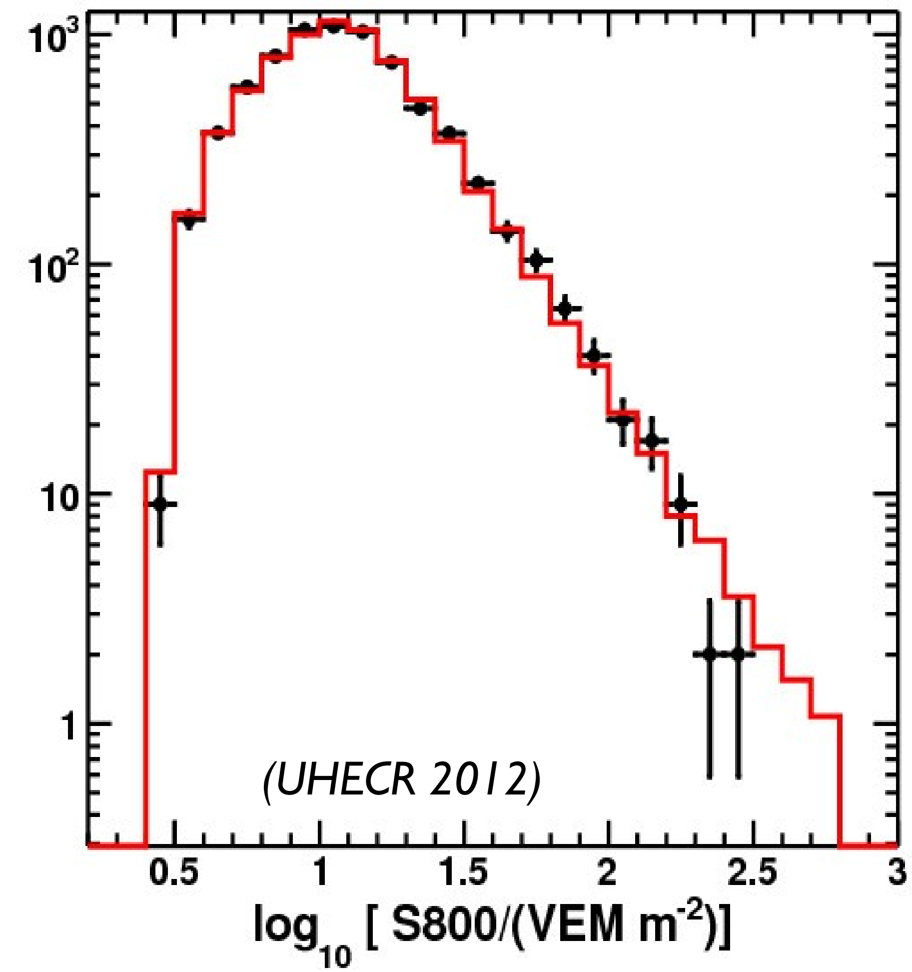


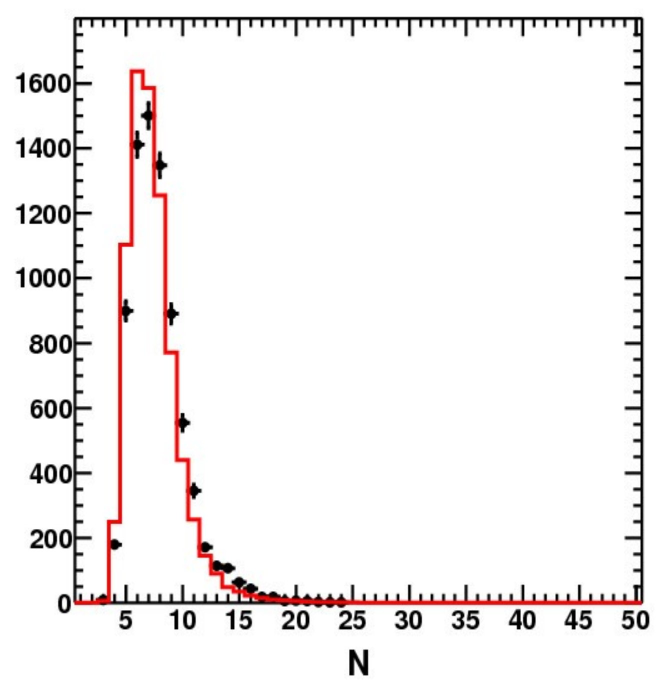
Zenith Angle



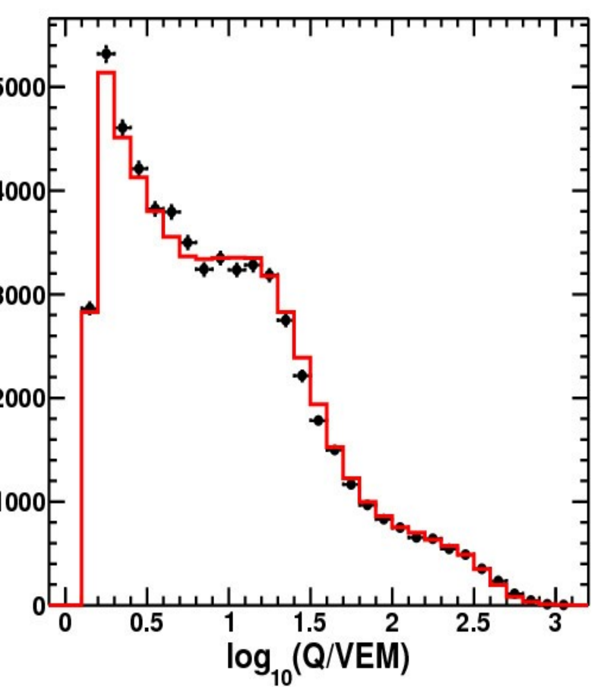
Azimuth Angle

CORSIKA + full detector simulation (proton primaries)





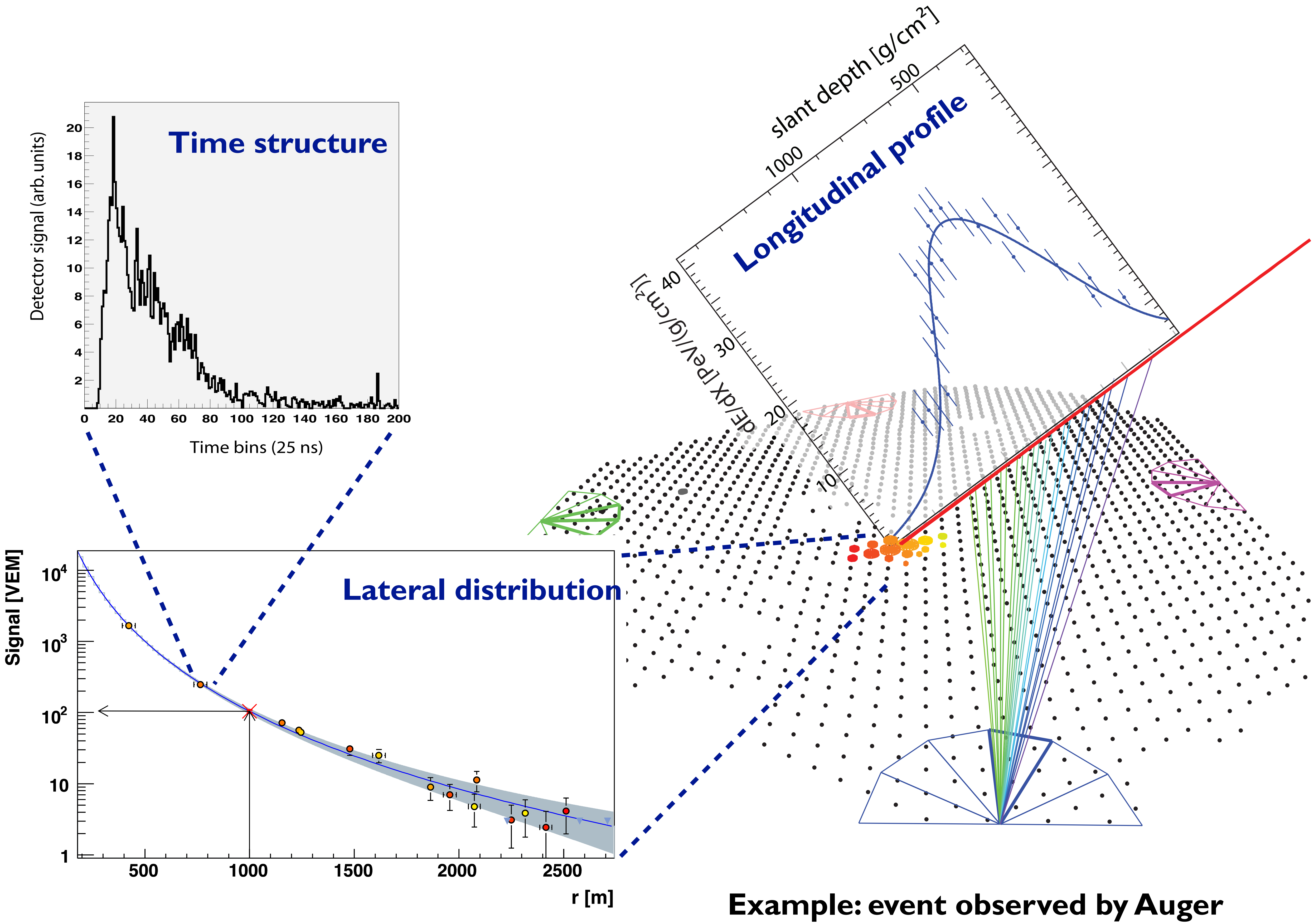
Number of Good Counters/Event



Charge/Counter/Event

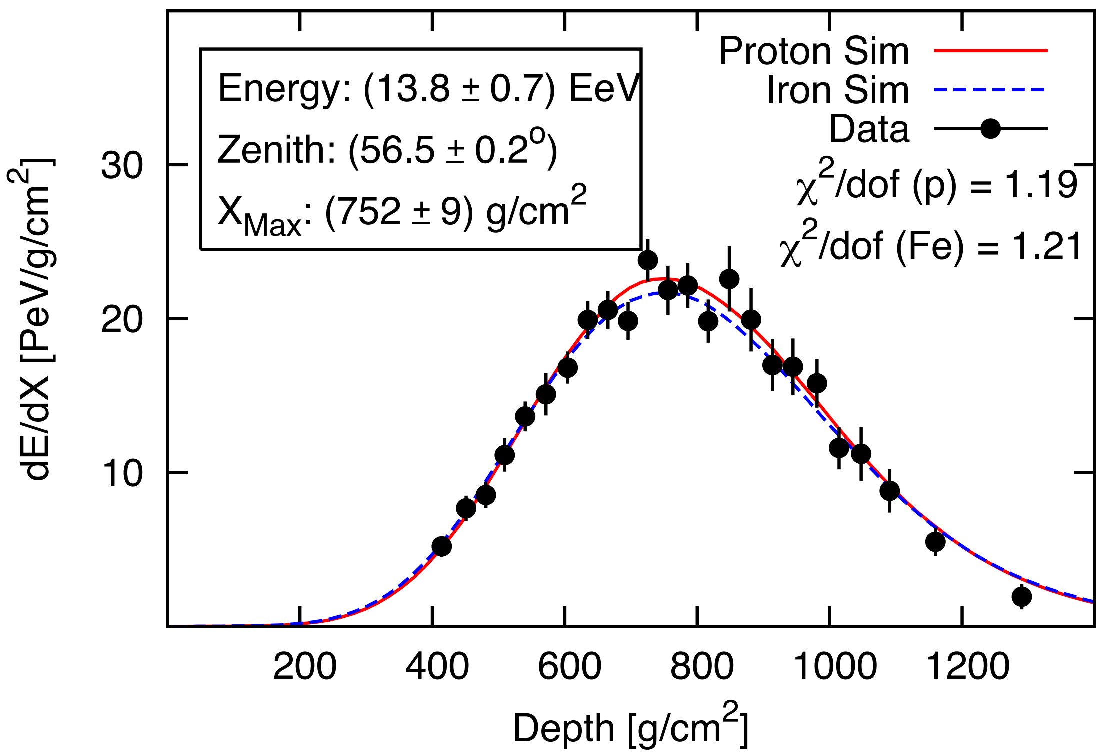
Very good agreement

Several shower observables



Example: event observed by Auger

Discrepancy: shower profile and muons at ground

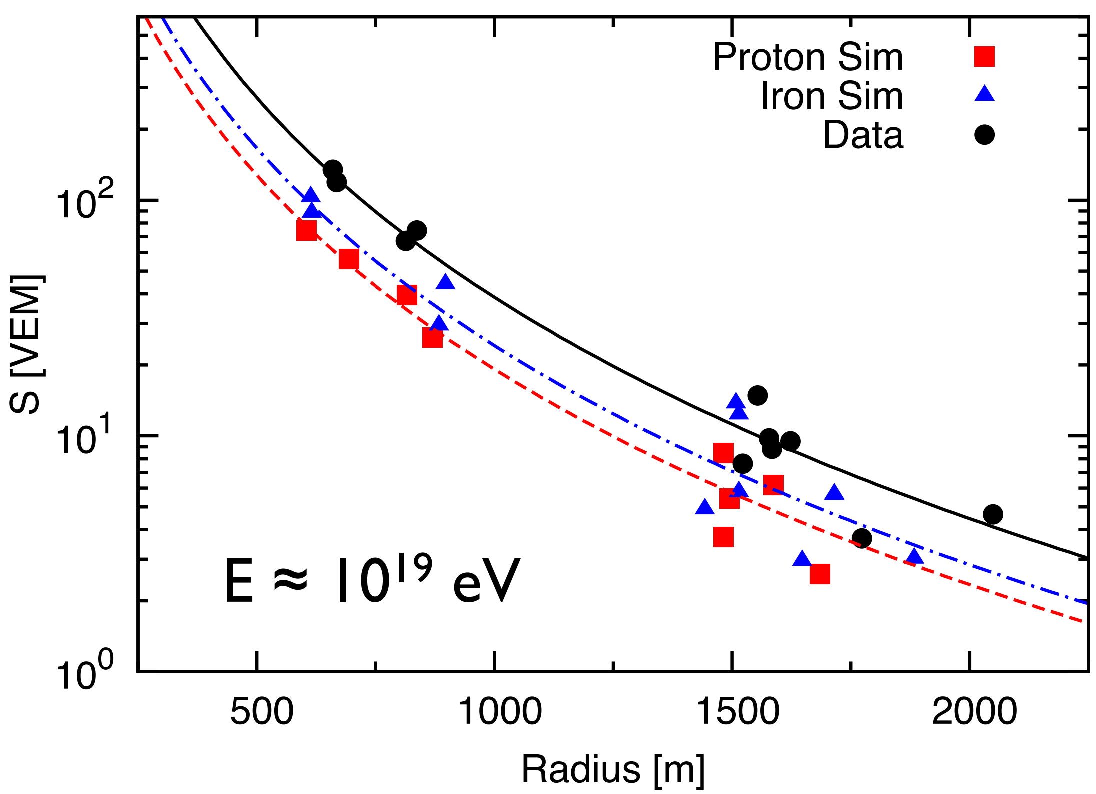


Phenomenological model ansatz

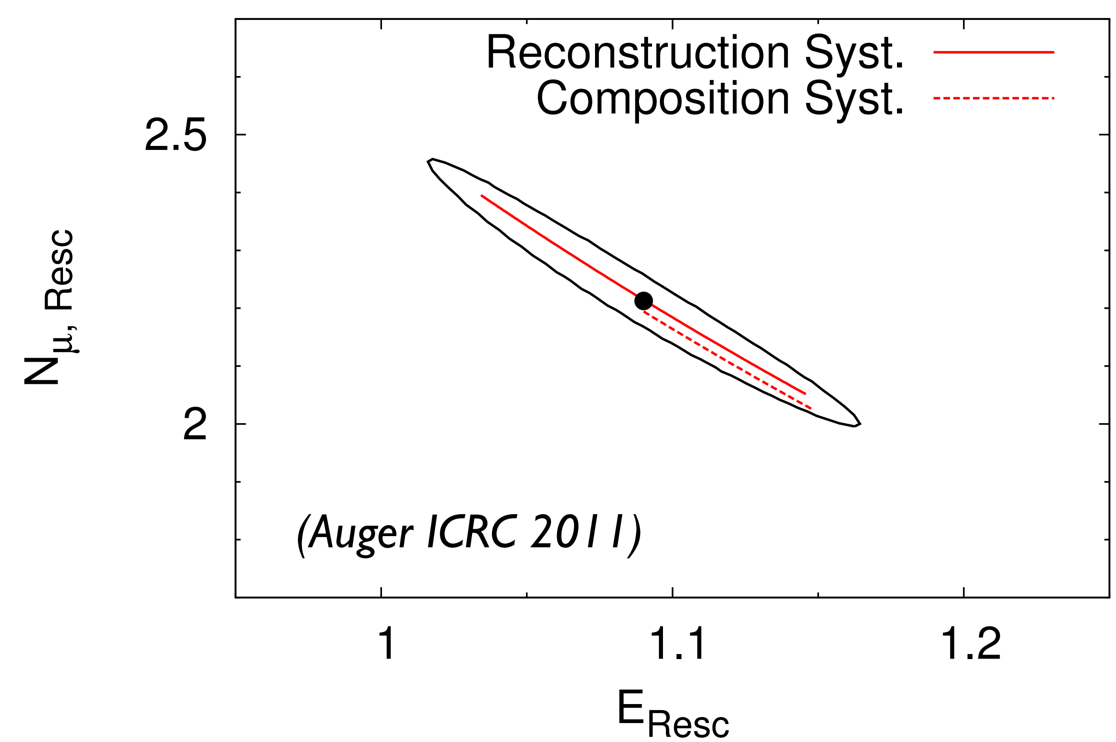
Energy scaling: em. particles and muons

Muon scaling: hadronically produced muons and muon interaction/decay products

Full detector simulation after re-scaling



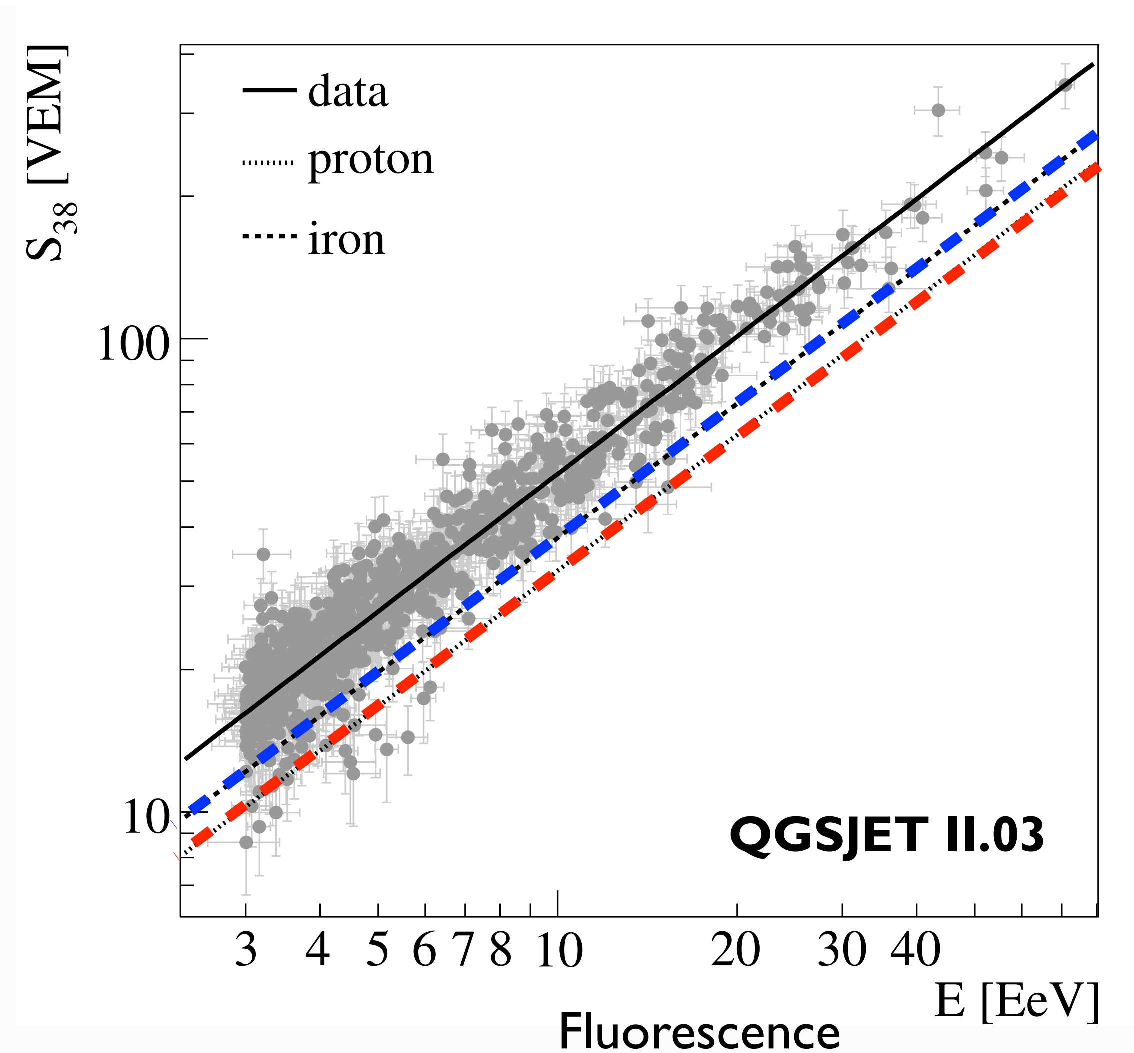
QGSJET II.03 (proton reference)



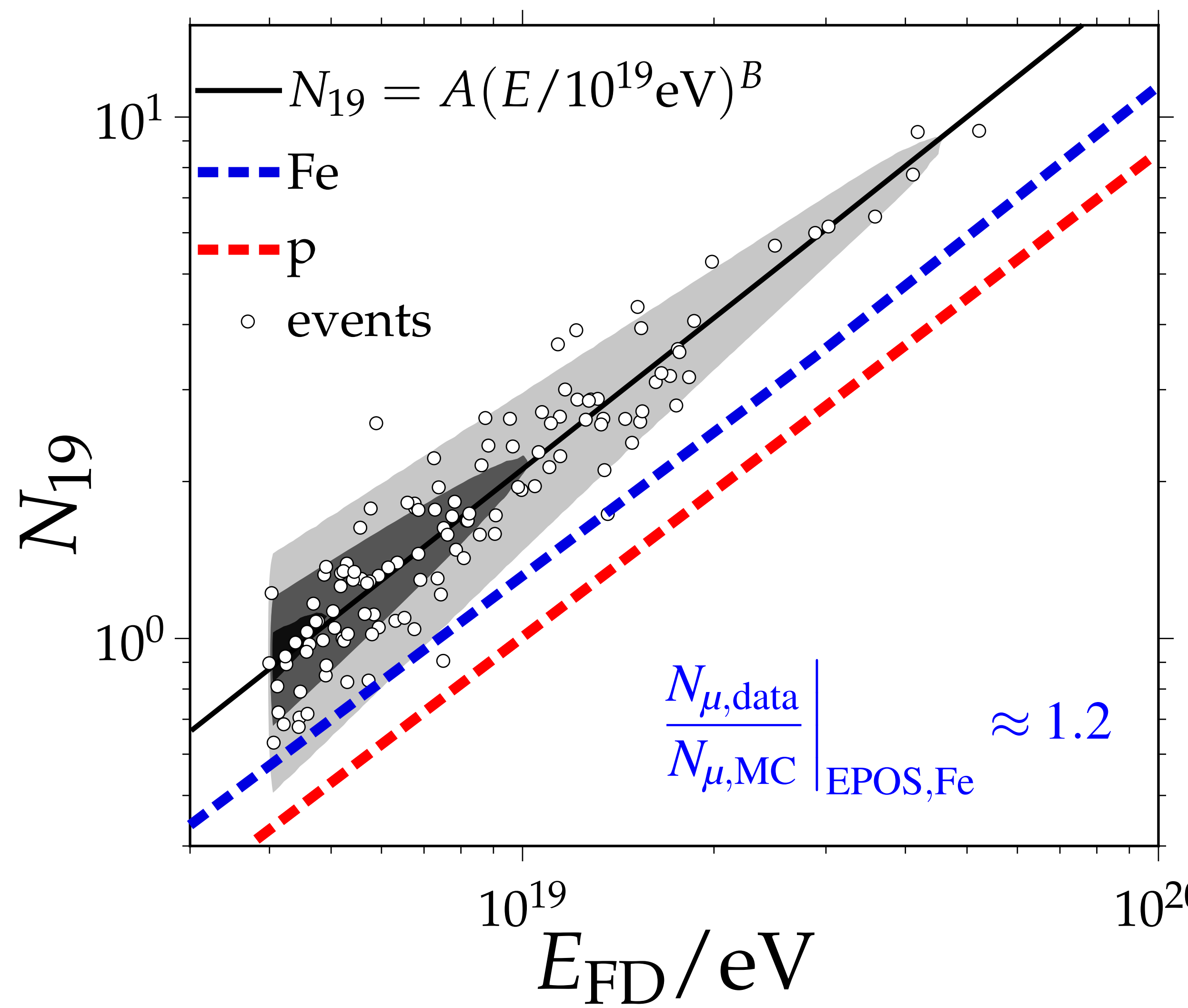
(Cazon, this meeting)

Auger: comparison of surface detector signals

Showers up to 60° zenith angle



Inclined showers (muon dominated)



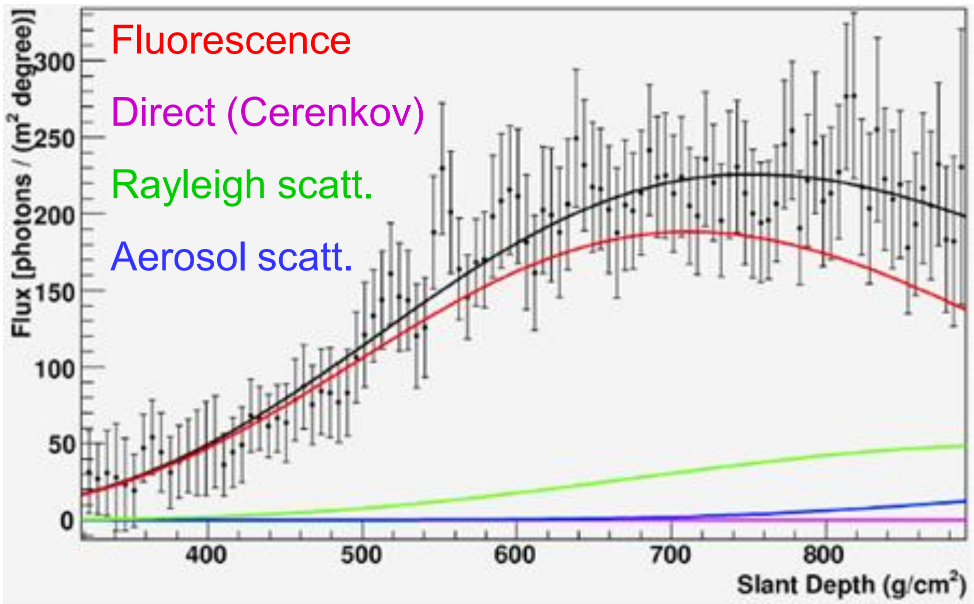
Discrepancy due mainly to muons

$$\left.\frac{N_{\mu,\mathrm{data}}}{N_{\mu,\mathrm{MC}}}\right|_{\mathrm{QGS,p}} = 2.13 \pm 0.04(\mathrm{stat}) \pm 0.11(\mathrm{sys})$$

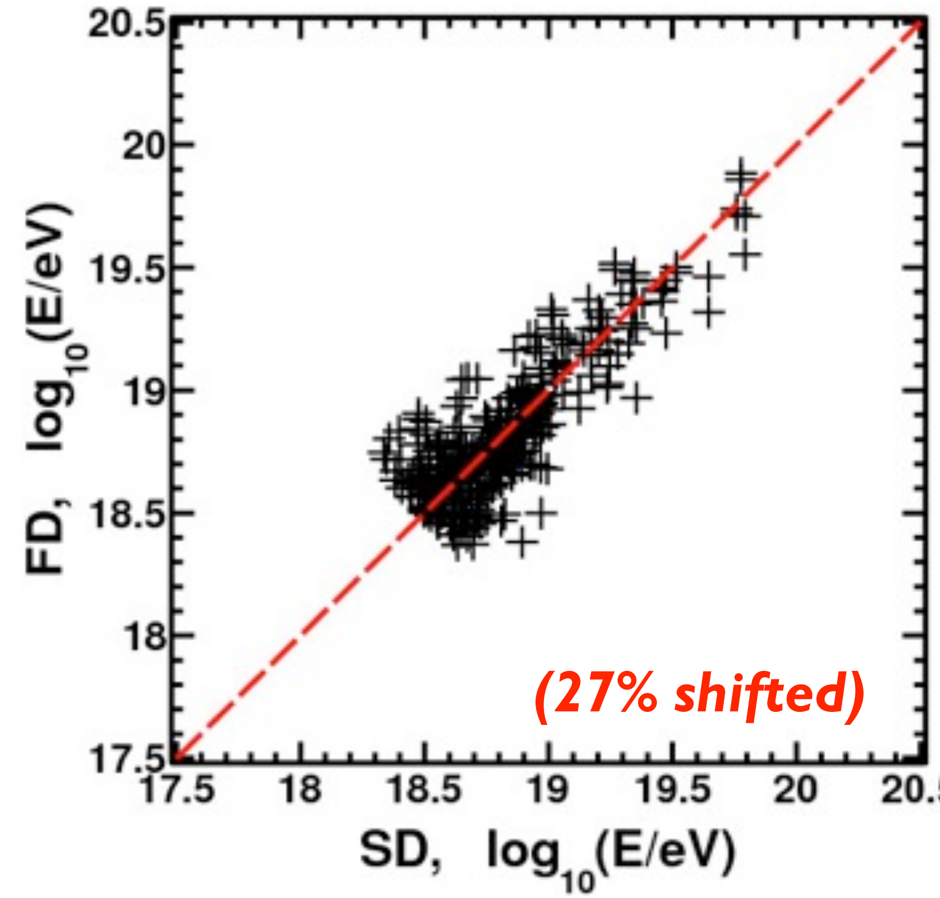
(Independent confirmation with several other observables)

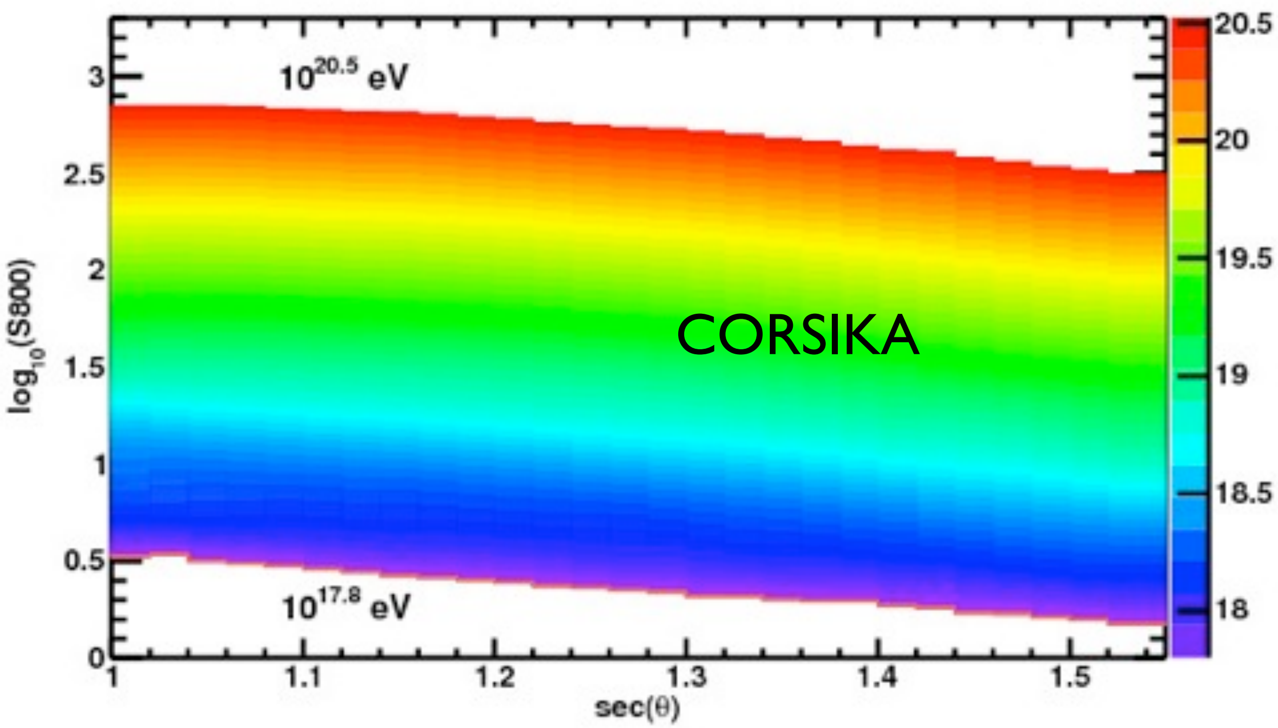
(HadInt Working Group, UHECR 2012)

TA: comparison of surface detector signals



Energy derived from fluorescence light profile

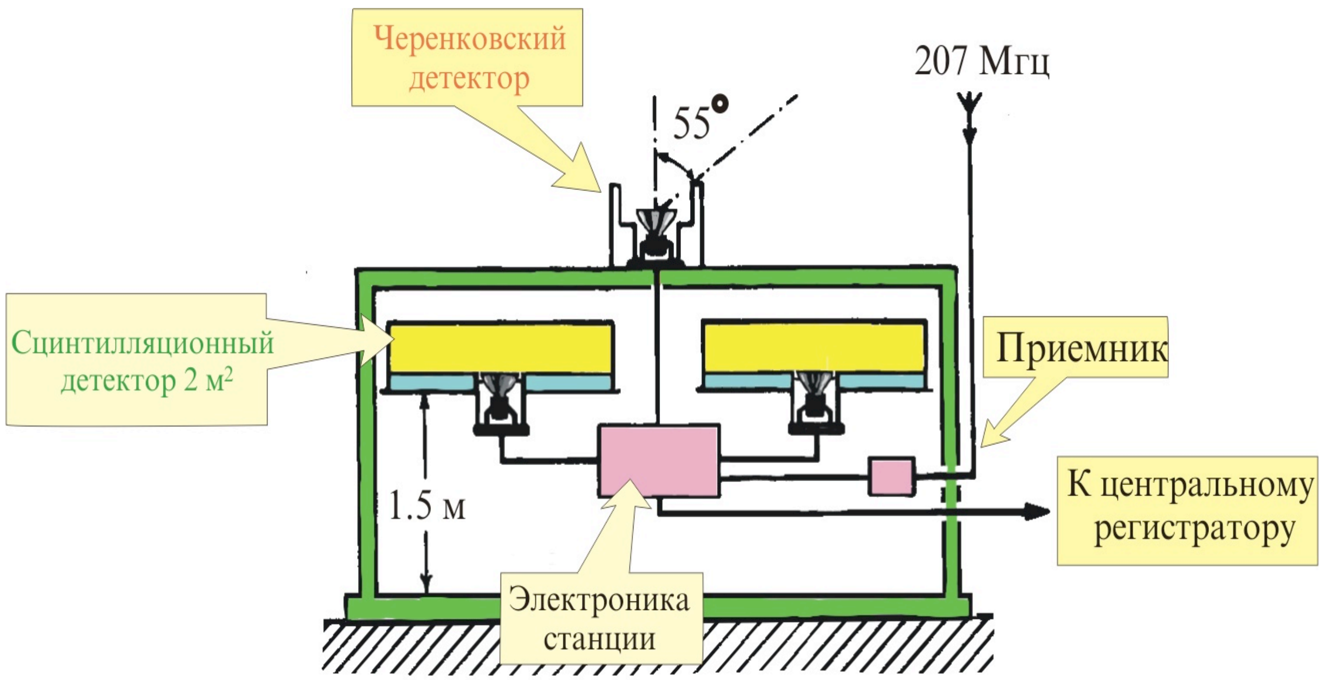


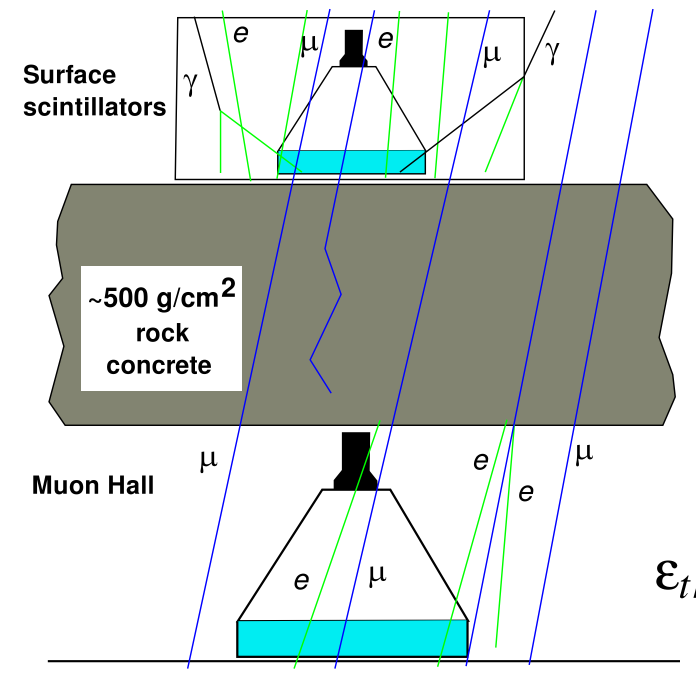


Simulated SD signal at 800m used to determine SD energy

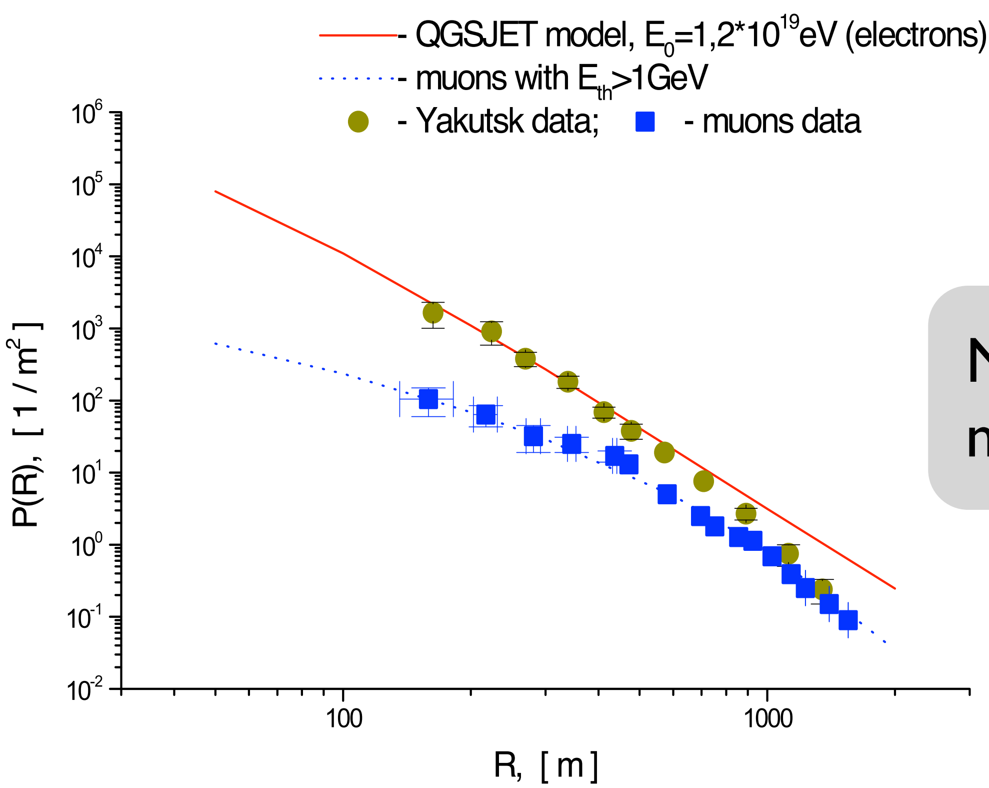
SD energies 27% higher than FD energies (QGSJET II, protons)

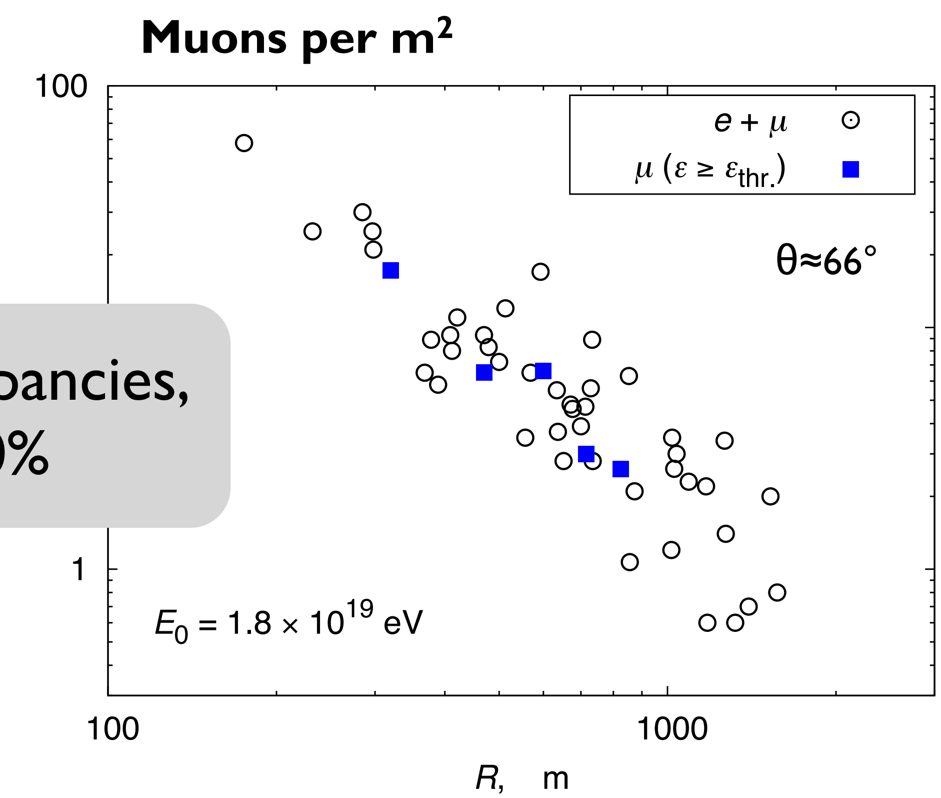
Yakutsk: direct measurement of muons





$\varepsilon_{thr} = 1\text{GeV}$

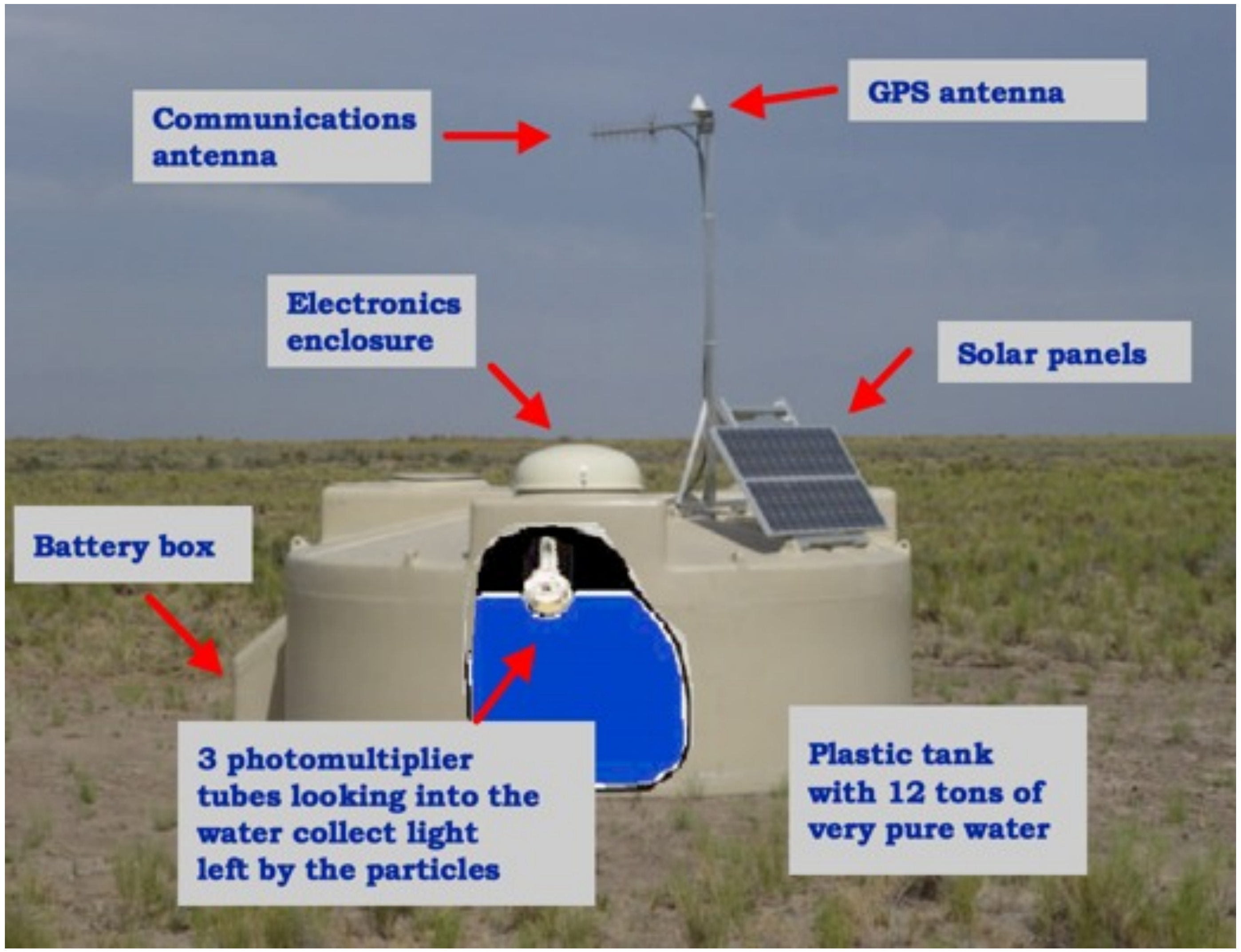




No significant discrepancies, muon deficit ~ 10-20%

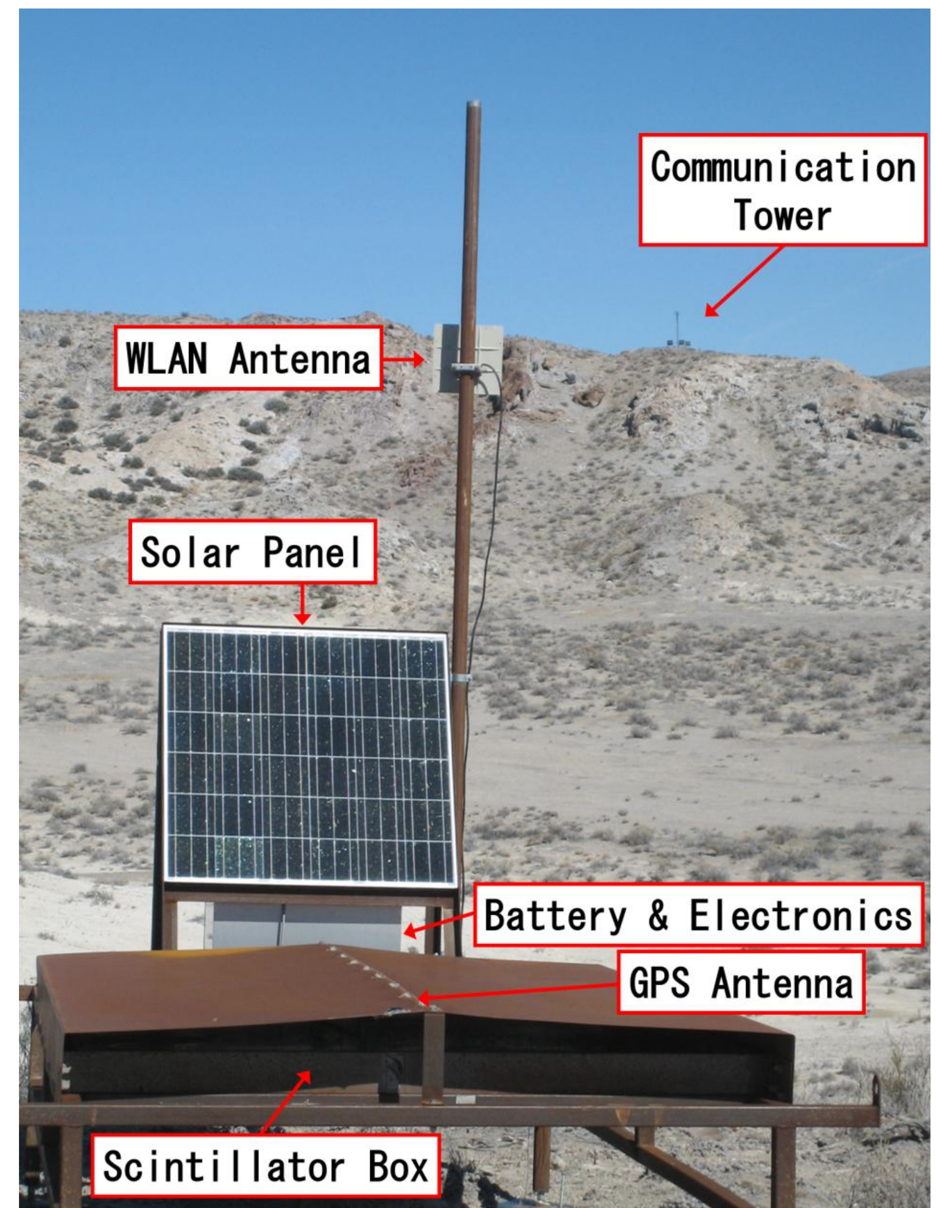
(Yakutsk Collab., UHECR 2012)

Comparison of surface detectors



Auger: thick water-Cherenkov detectors
(large part of signal due to muons, large acceptance to inclined showers)

Telescope Array: thin scintillators
(main part of signal due to em. particles, low sensitivity to muons)

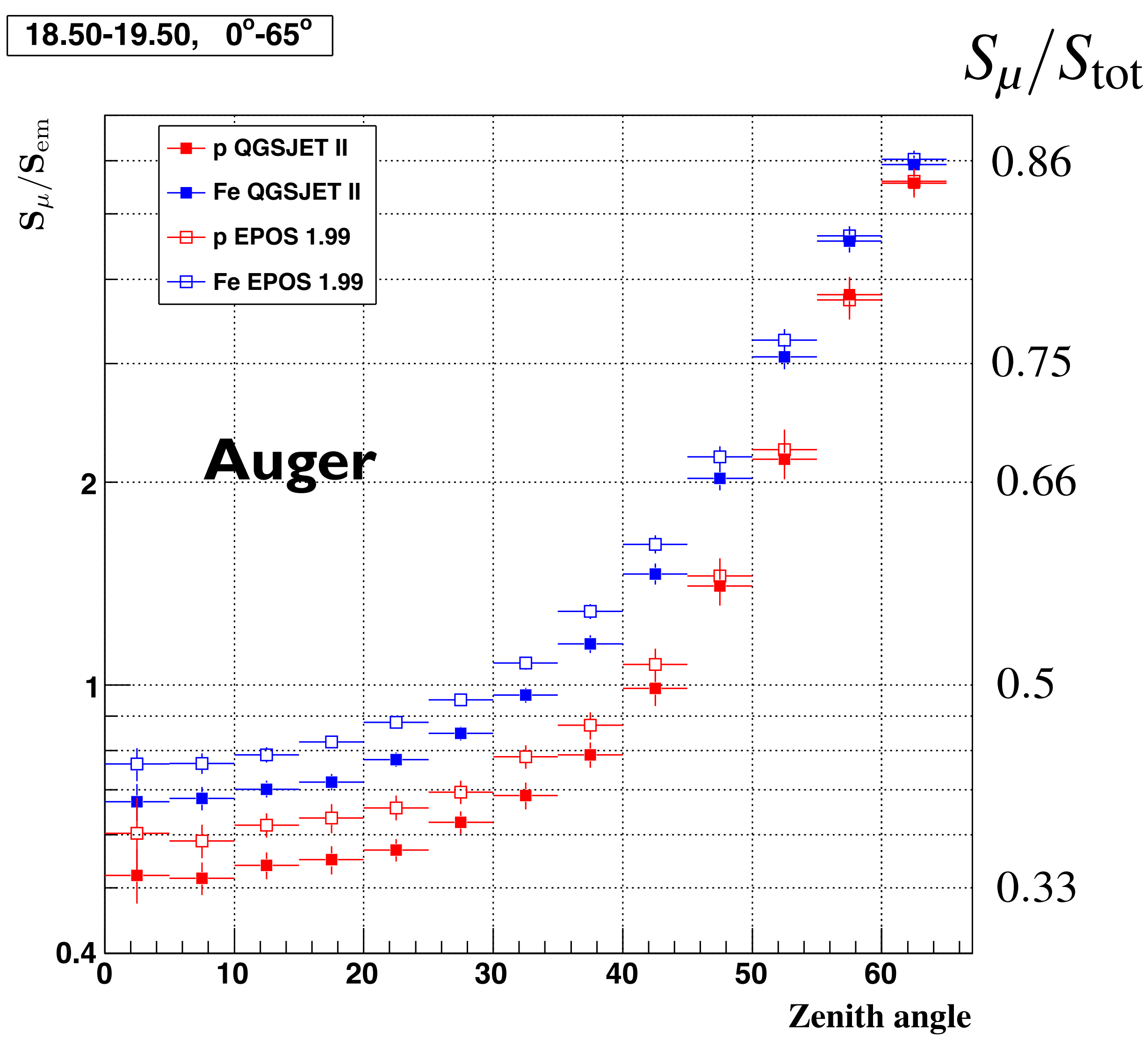


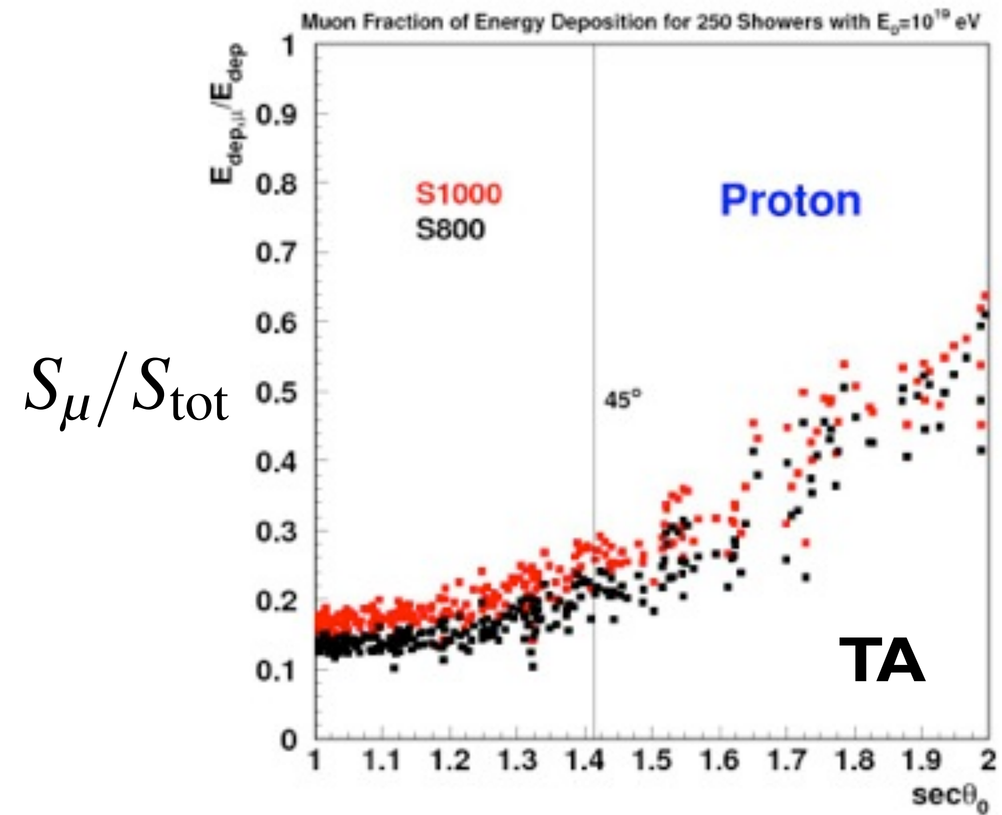
Complementary surface detector arrays

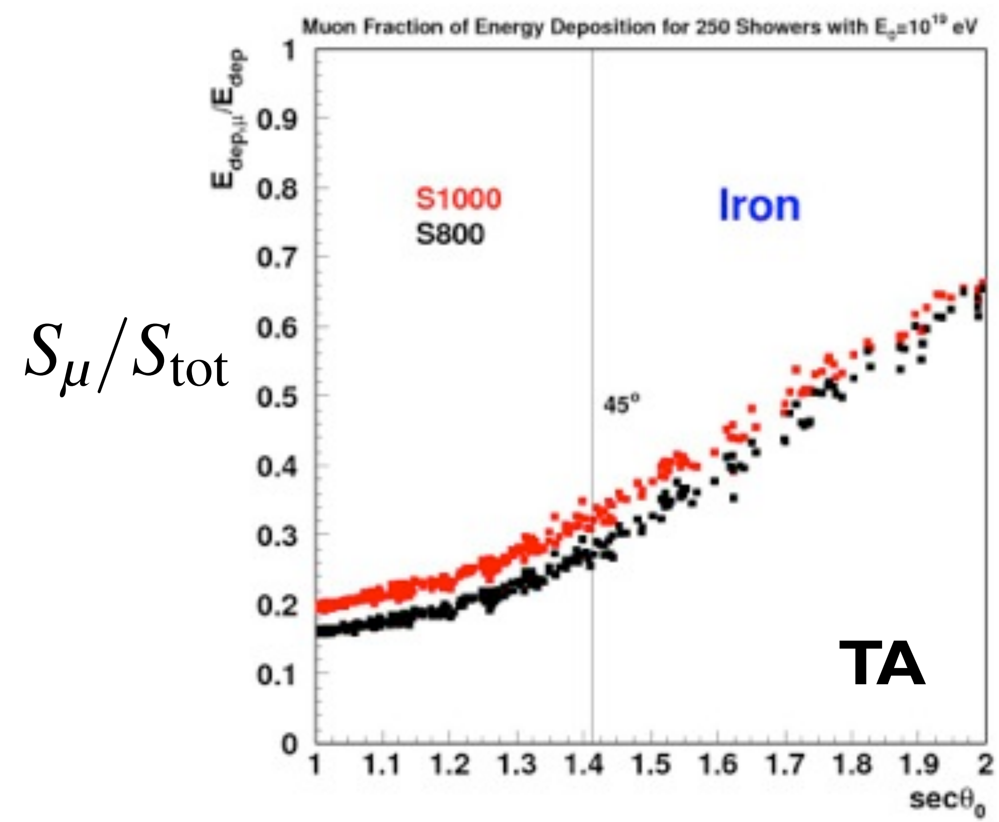
Accounting for different sensitivity to muons

Muon component

- Auger: 30–80% of detector signal
- TA: 15–20% of detector signal

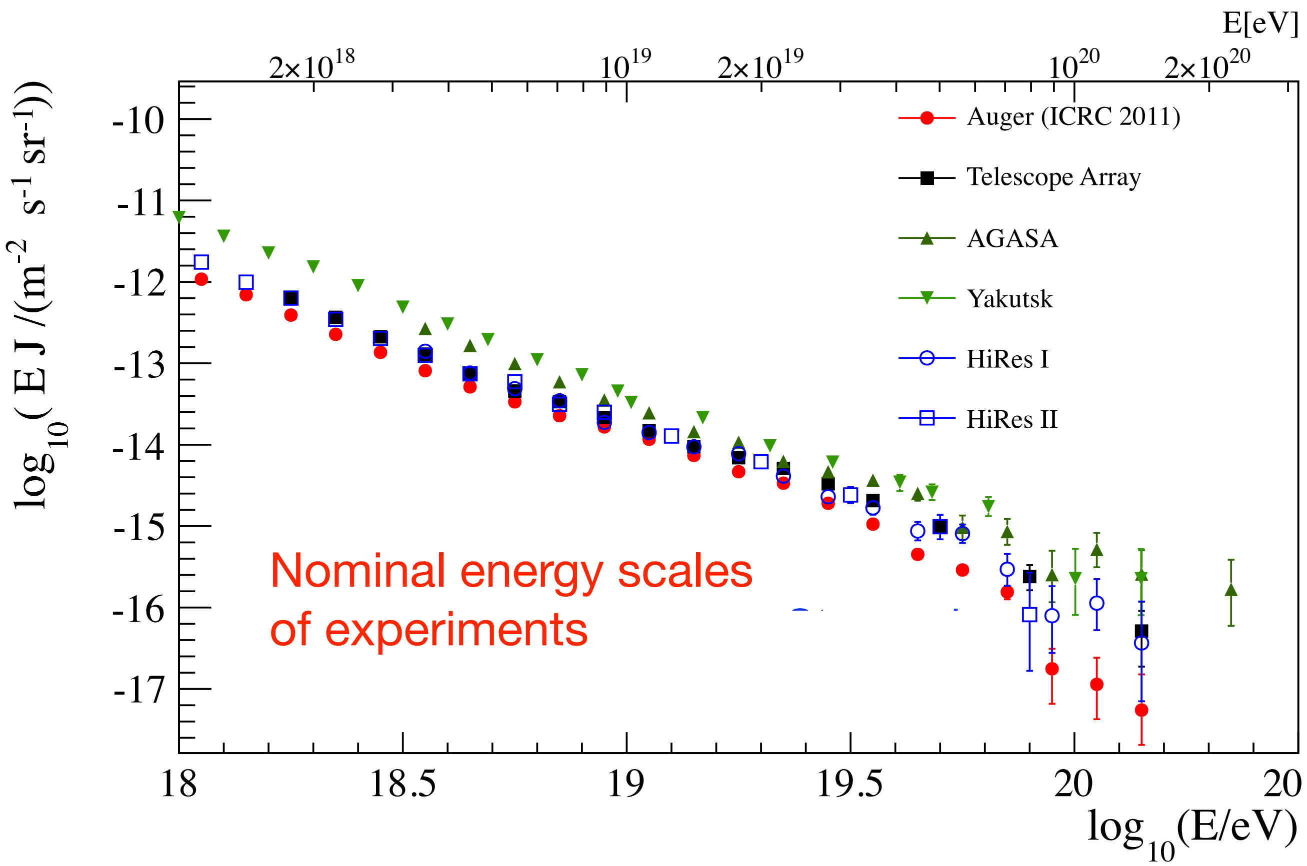


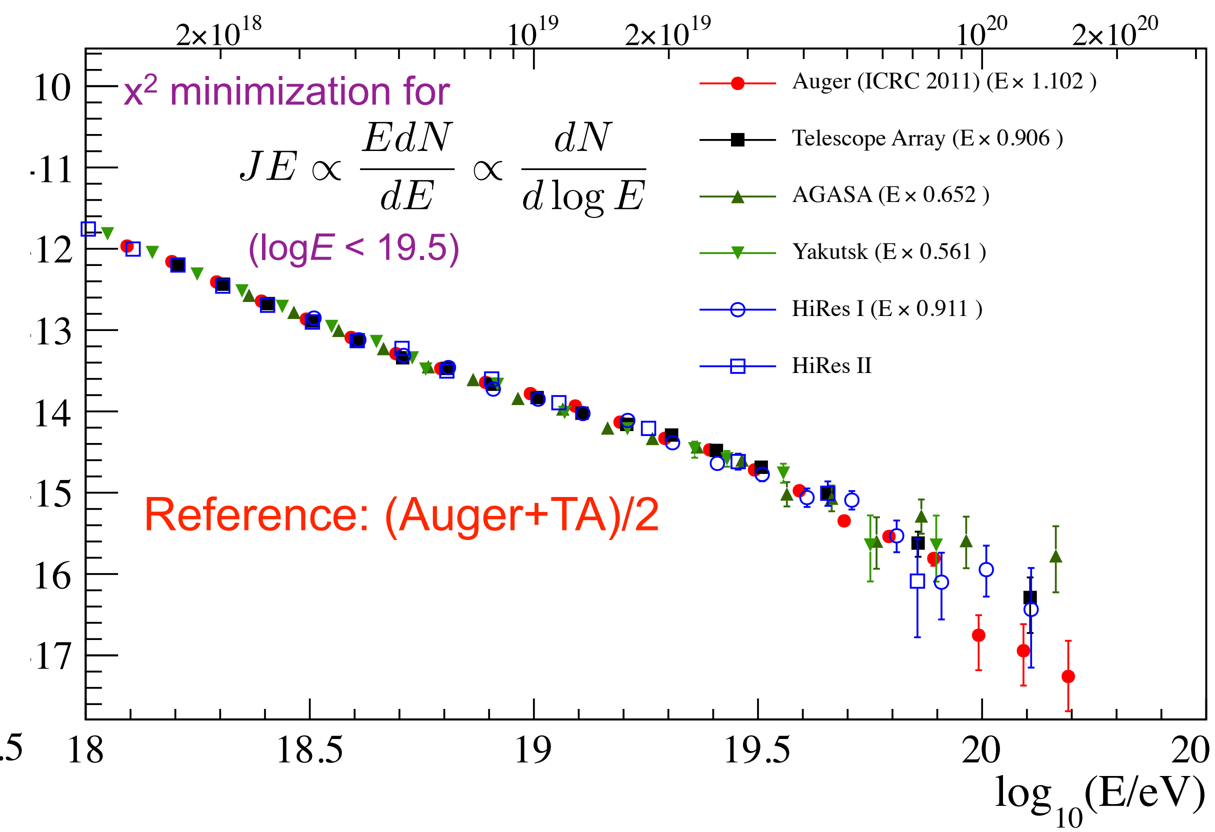




(HadInt Working Group, UHECR 2012)

Accounting for different energy scales





(UHECR 2012, Spectrum working group)

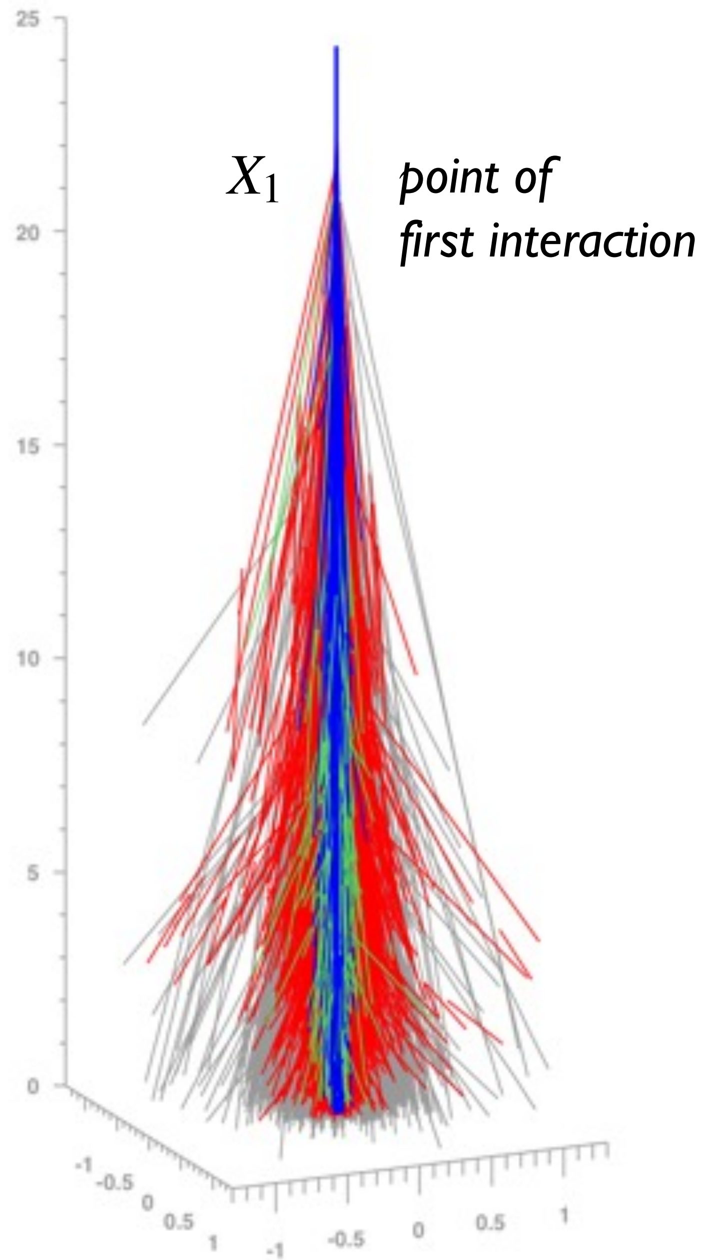
	f_Auger	f_TA	f_Yakutsk
Auger	–	0.82	0.50
TA	1.21	–	0.62
Yakutsk	1.97	1.62	–

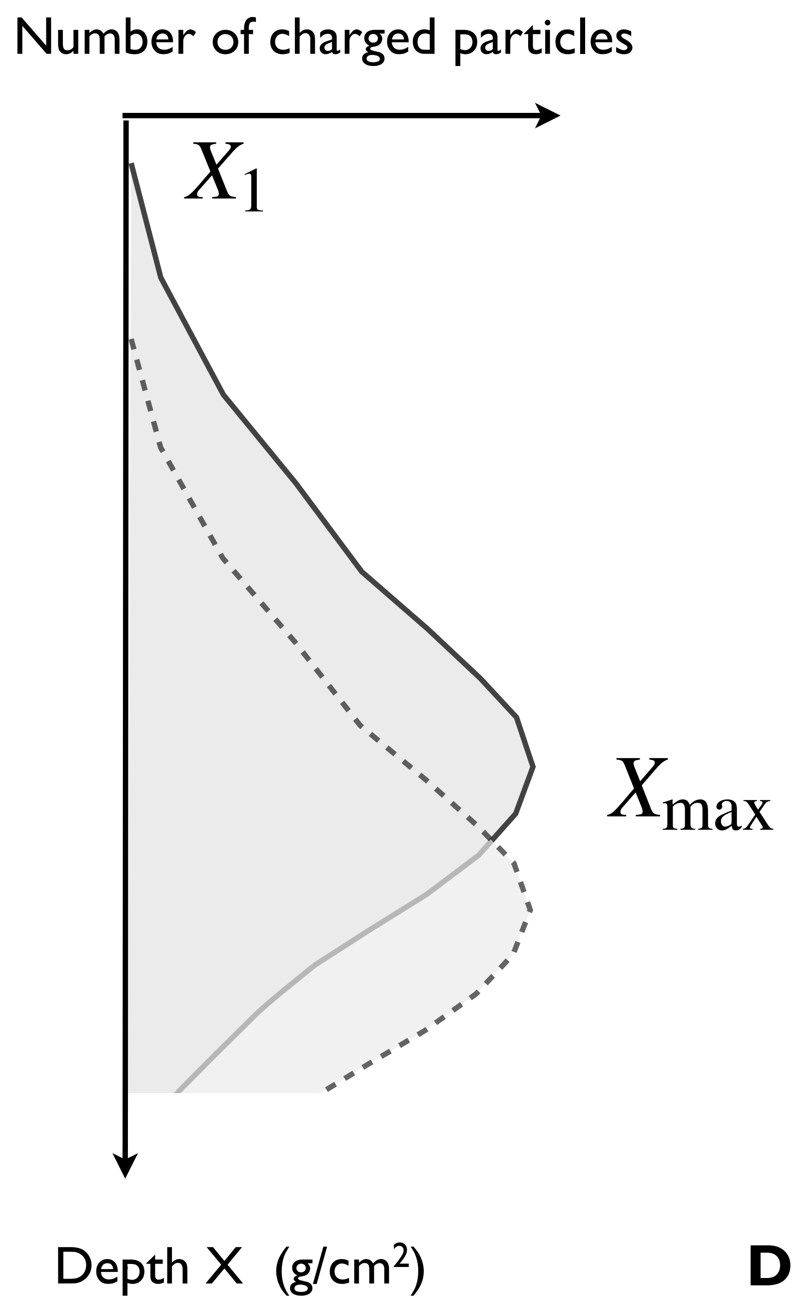
(UHECR 2012, Hadronic interaction working group)

Results of all experiments compatible with significant deficit of muon number in simulation

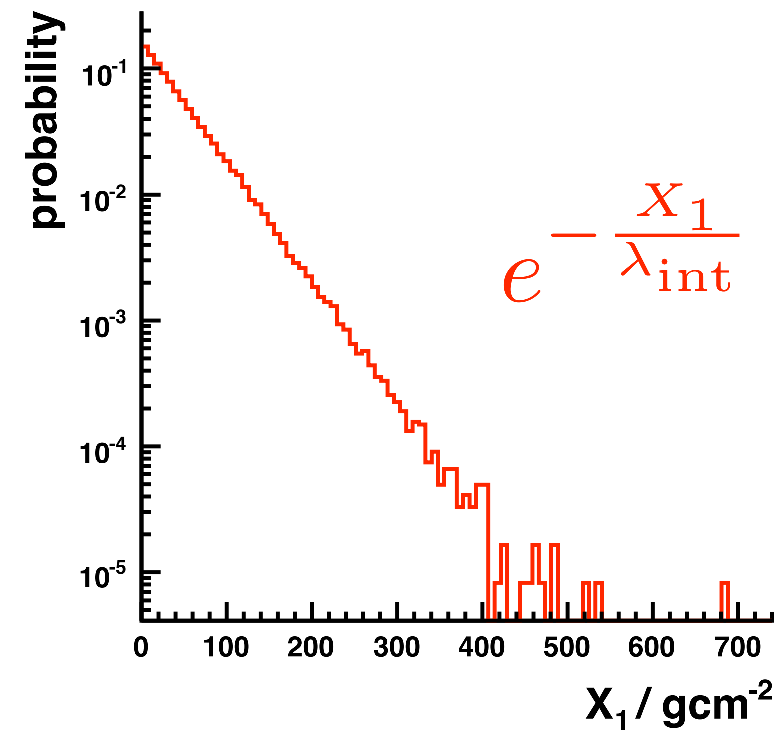
Learning about hadronic physics from air showers

Cross section measurement with air showers





Depth of first interaction



$$\sigma_{\text{prod}} = \frac{\langle m_{\text{air}} \rangle}{\lambda_{\text{int}}}$$

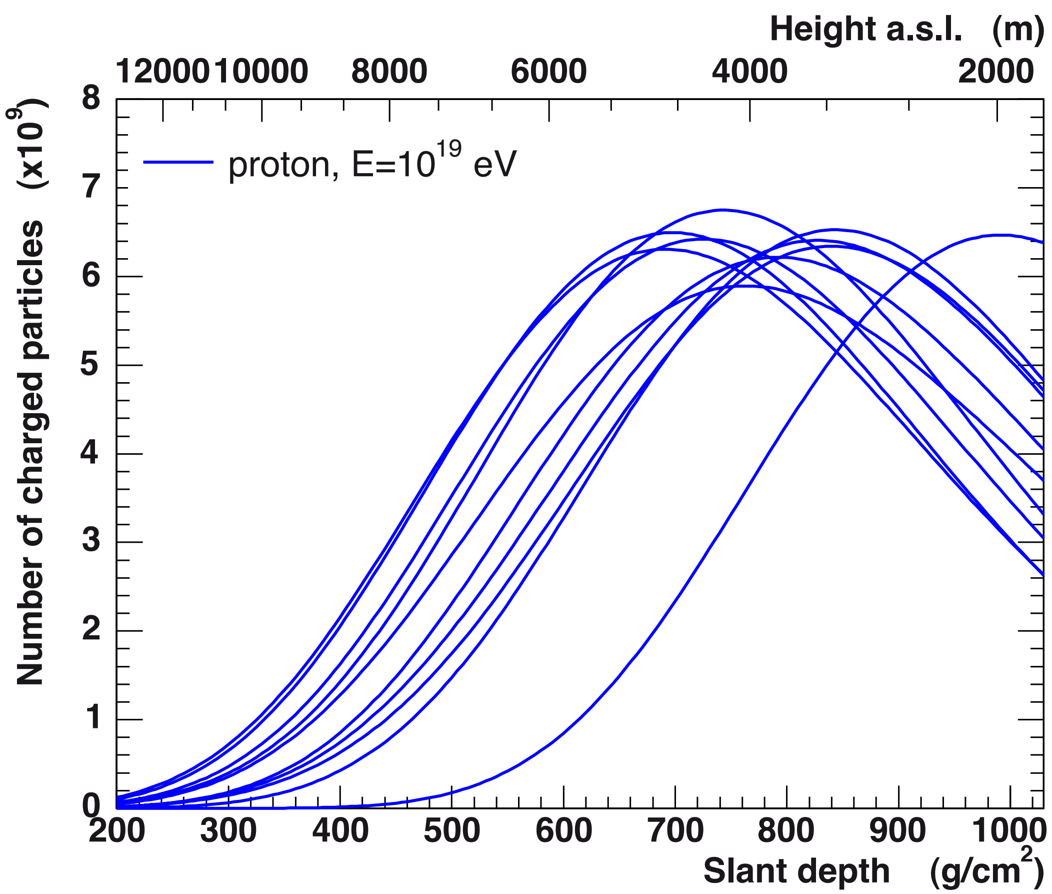
Difficulties

- mass composition (protons?)
- X_1 cannot be measured directly

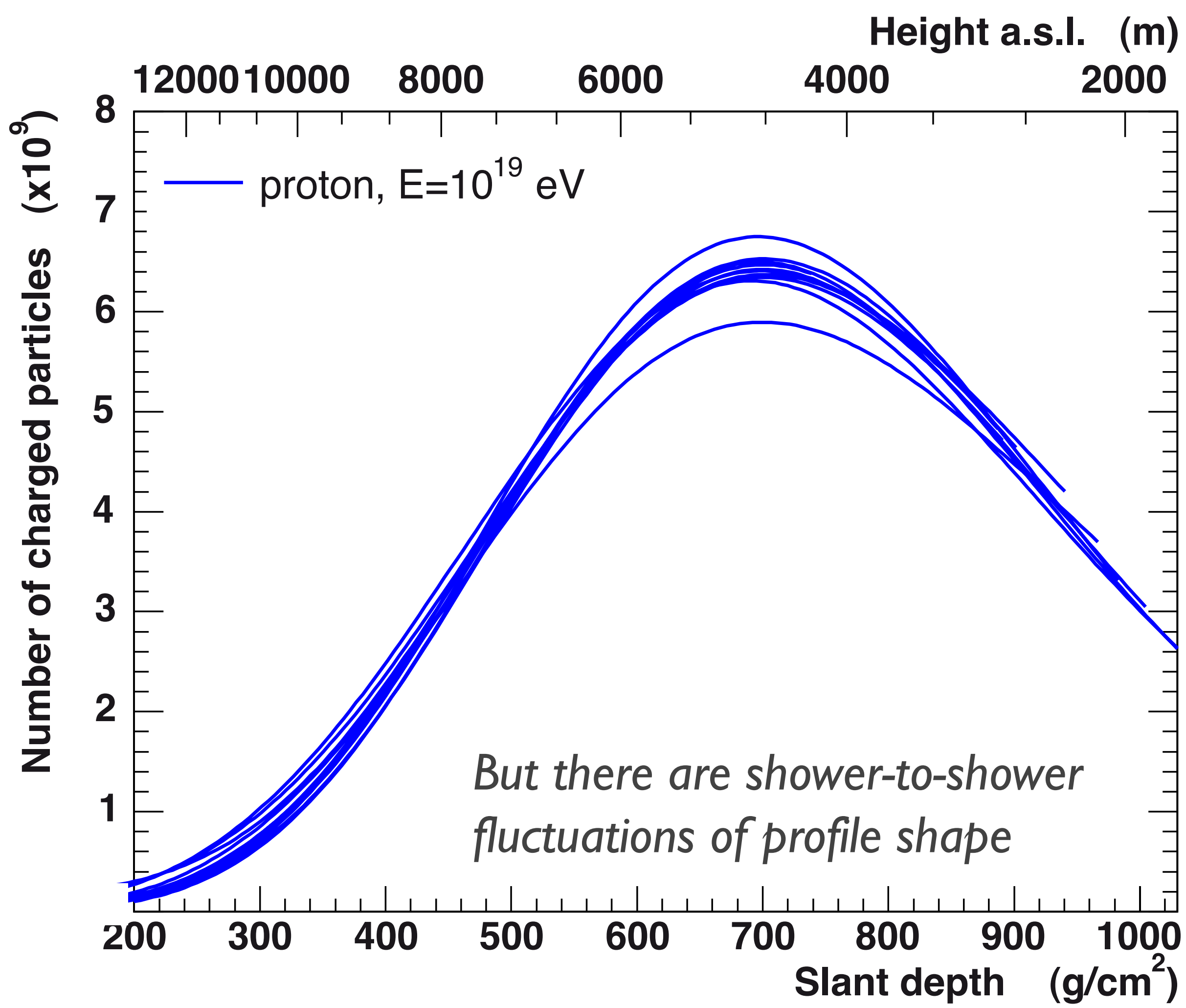
(R. Ulrich et al. NJP 11, 2009, and talk at this meeting)

Universality features of high-energy showers (i)

Simulated shower profiles



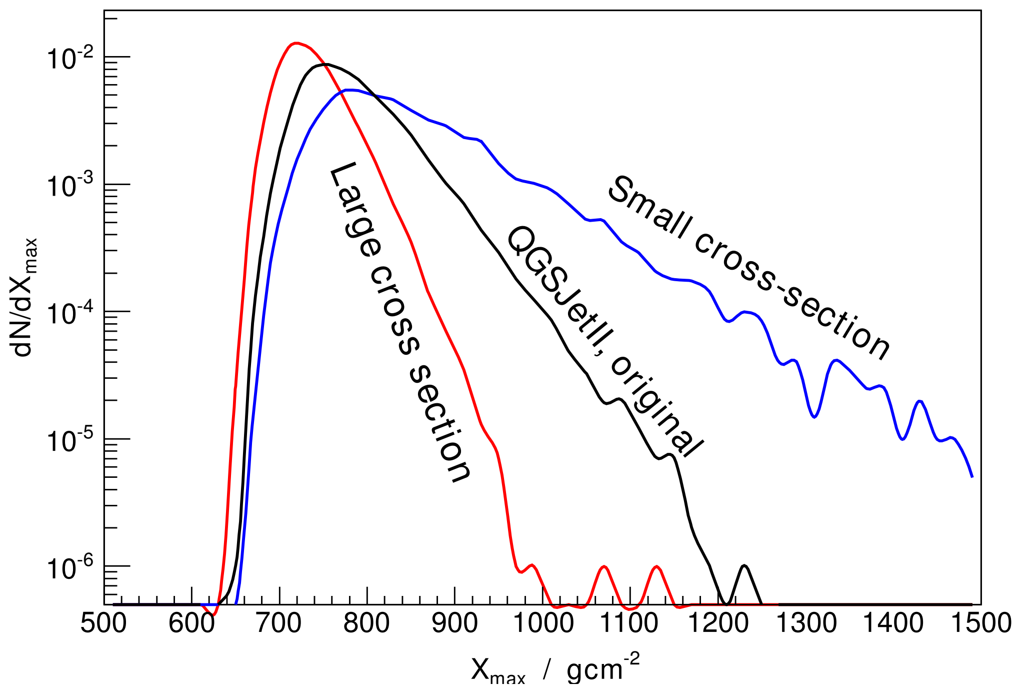
Profiles shifted in depth



Depth of X_I and X_{max} strongly correlated, use X_{max} for analysis

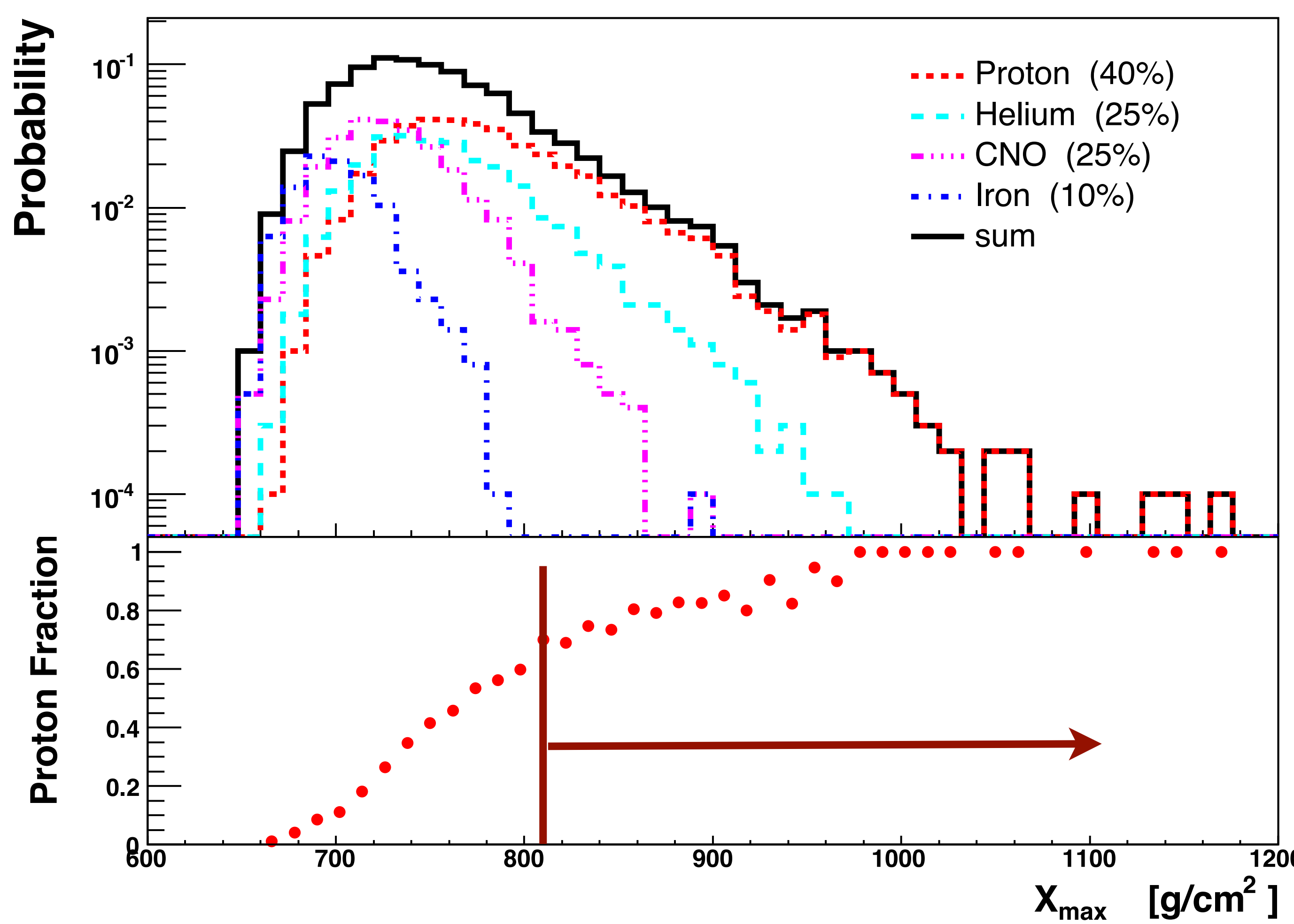
Selection of protons: select very deep showers

Cross section measurement: composition



Simulation for proton showers with different cross sections: very good sensitivity of tail of distribution

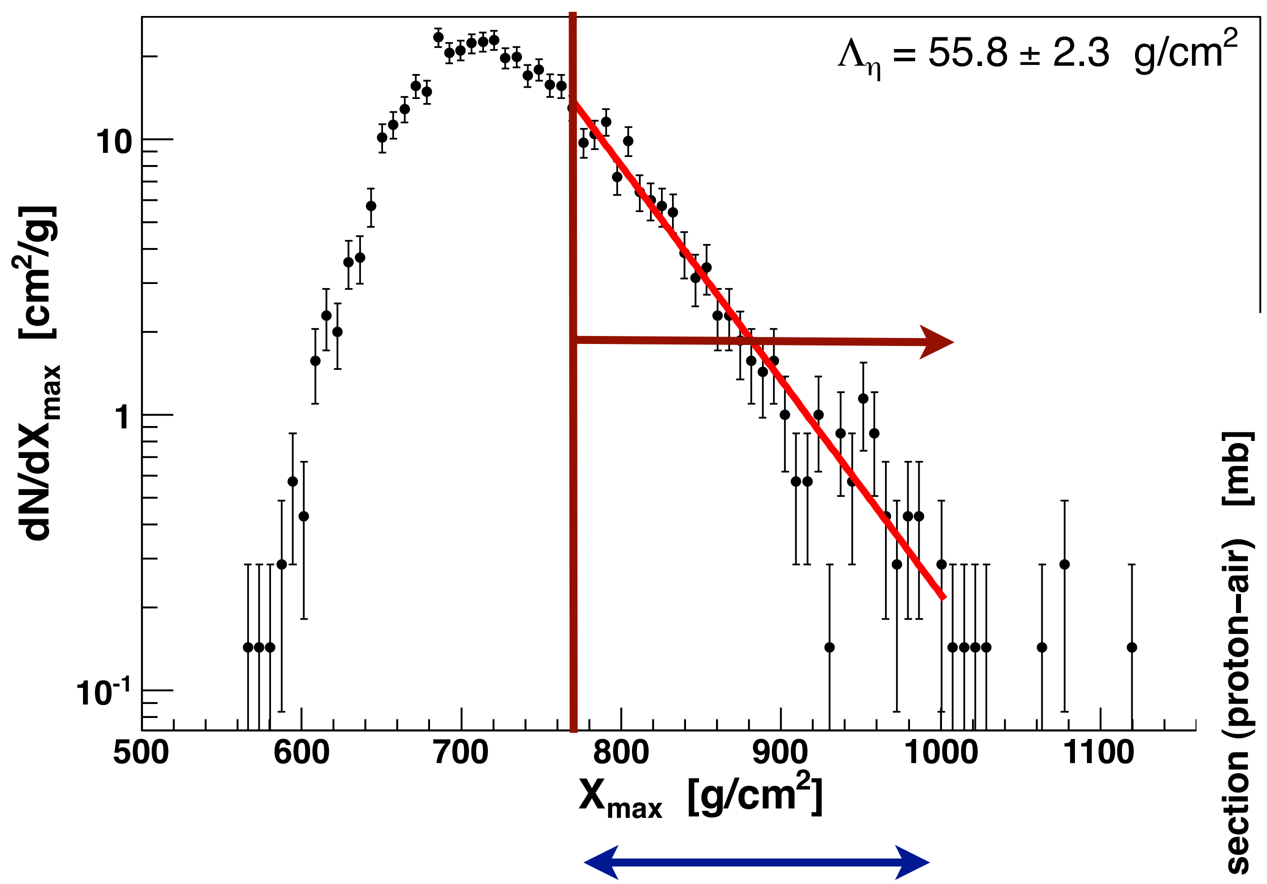
(Pierre Auger Collab. 1107.4804)



Example of distribution of X_{max} for mixed composition

Only deep showers are used in analysis to enhance proton fraction in data sample

Cross section measurement: self-consistency

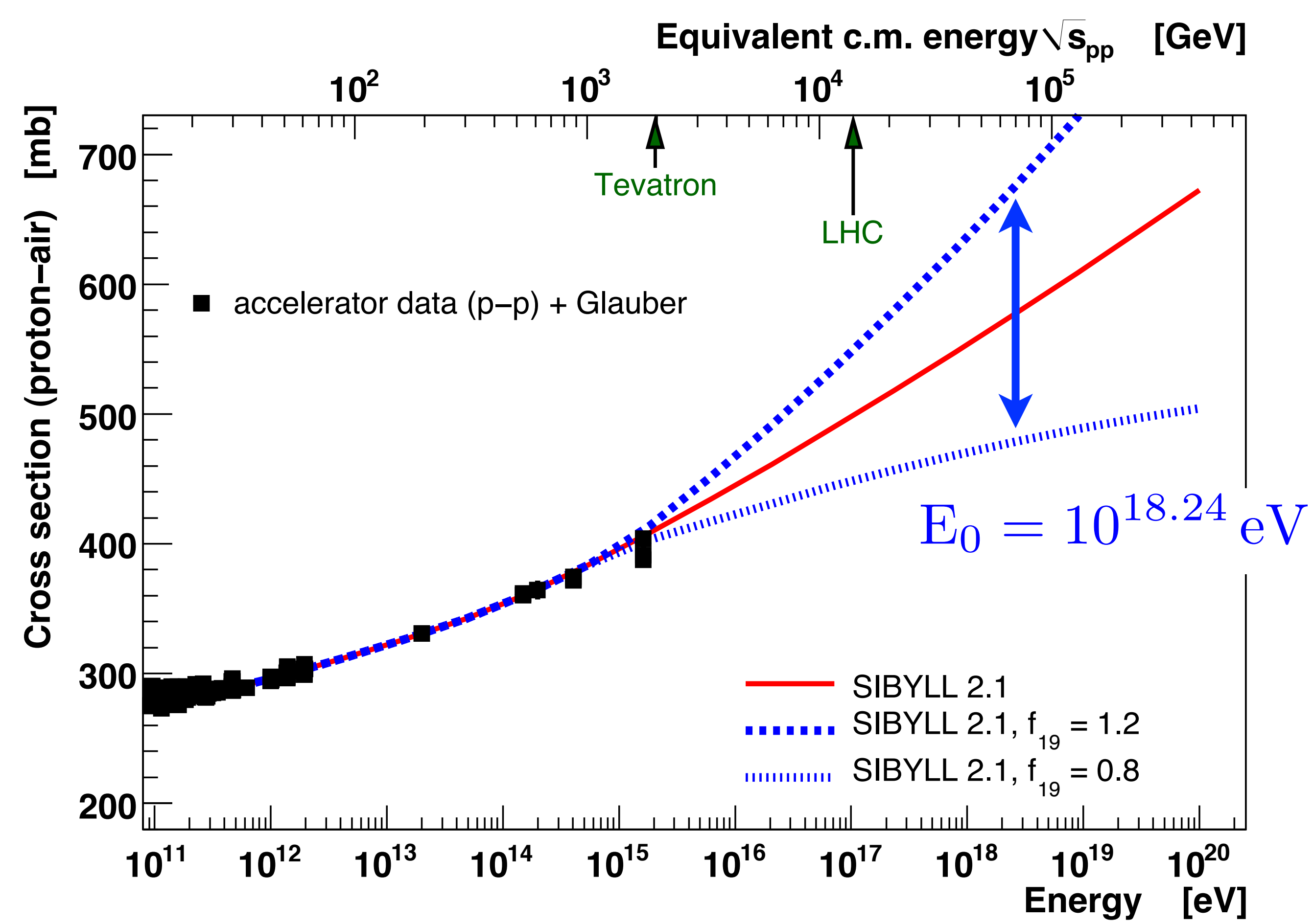


Depth range of analysis

Cross section accepted if simulated slope fits measured slope of X_{max} distribution

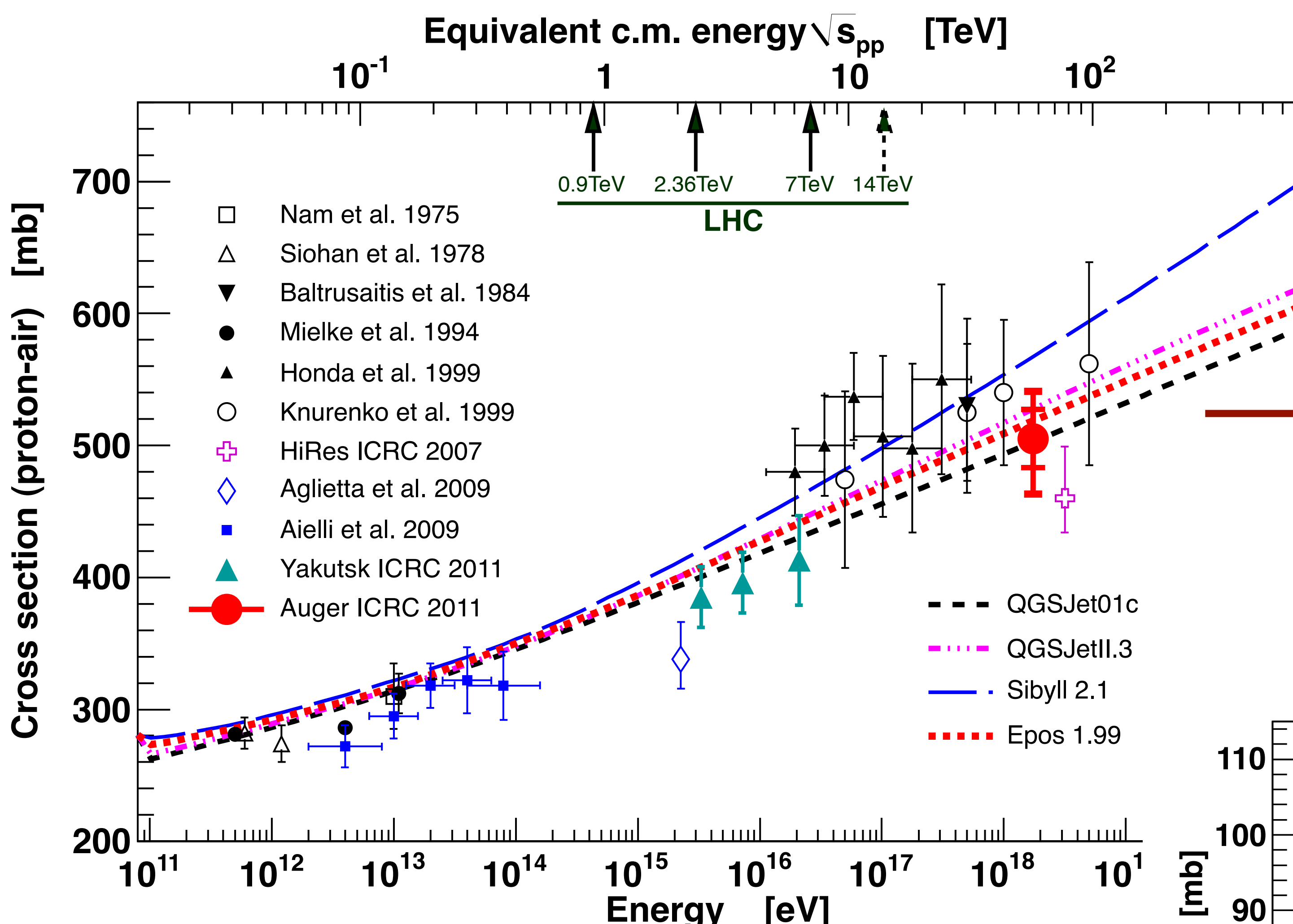
$$\sigma_{p\text{-air}} = \left(505\ \pm 22_{\rm stat}\ \left({}^{+26}_{-34}\right)_{\rm sys}\right)\ \mathrm{mb}$$

(Auger Collab. 1107.4804)



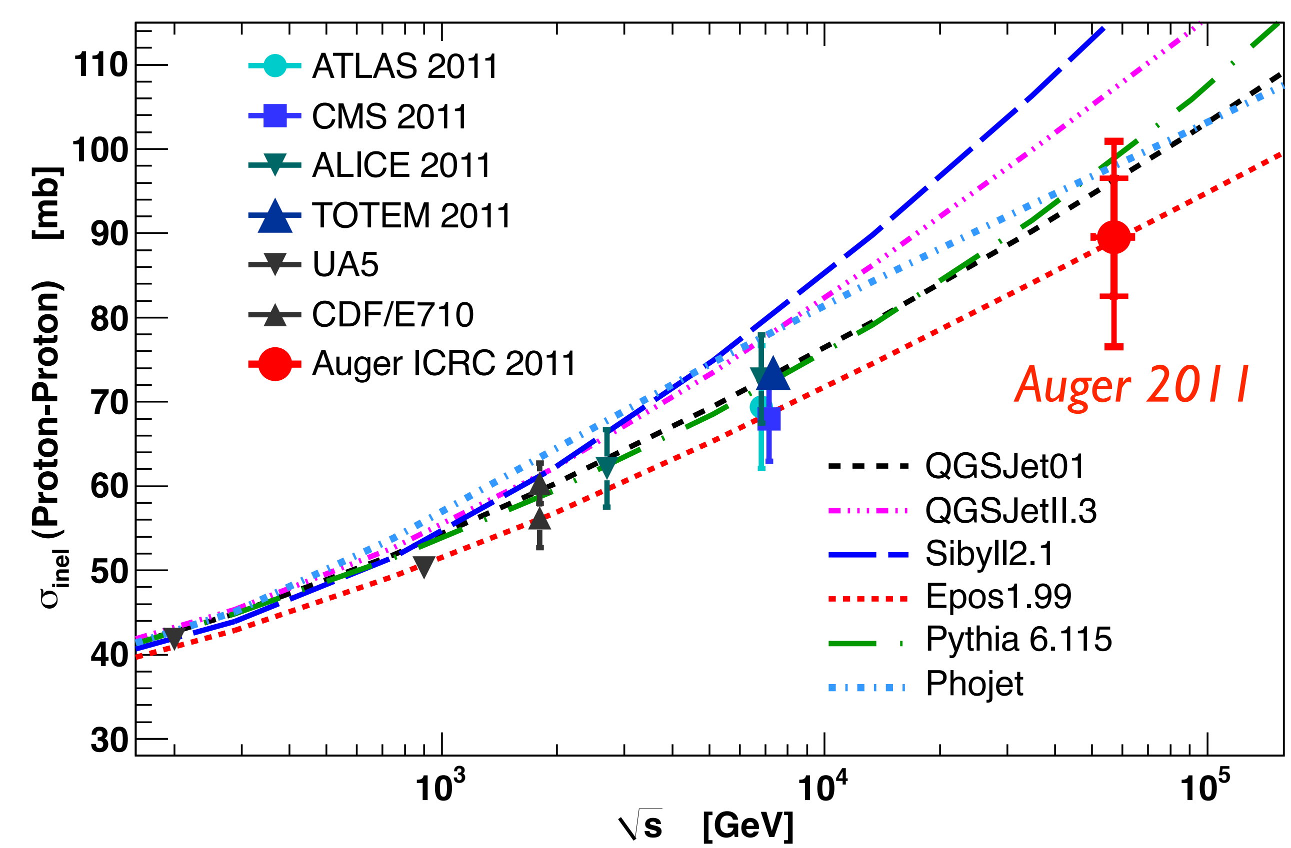
Simulation of data sample with different cross sections, interpolation to measured low-energy values

High-energy frontier: proton-air cross section



Conversion from p-air to p-p cross section always model-dependent

Glauber model



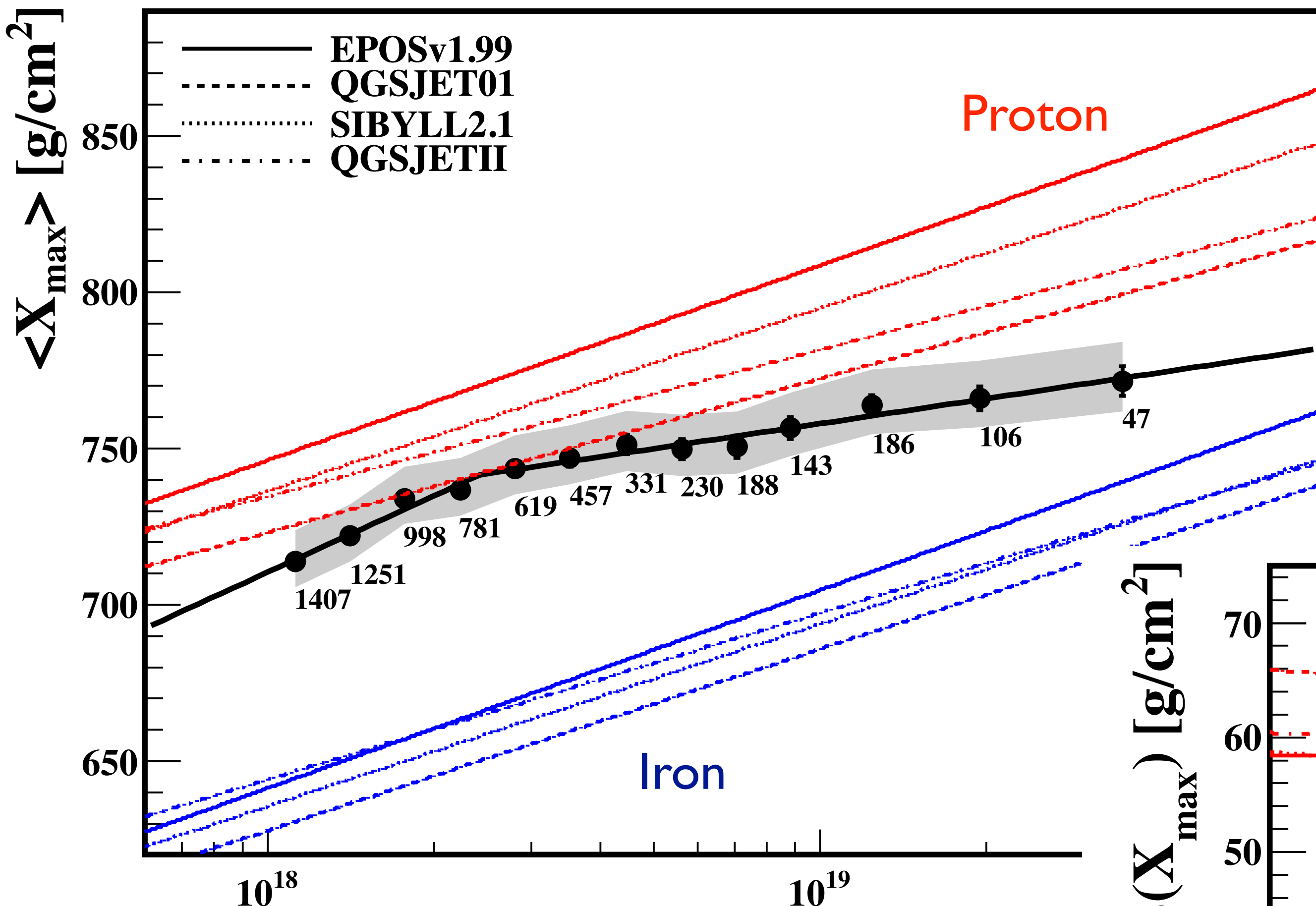
Cross section independent of LHC data, very good agreement with extrapolated data

(Pierre Auger Collab. 1107.4804, Phys. Rev. Lett. 2012)

Backup slides

Auger Observatory: Composition data

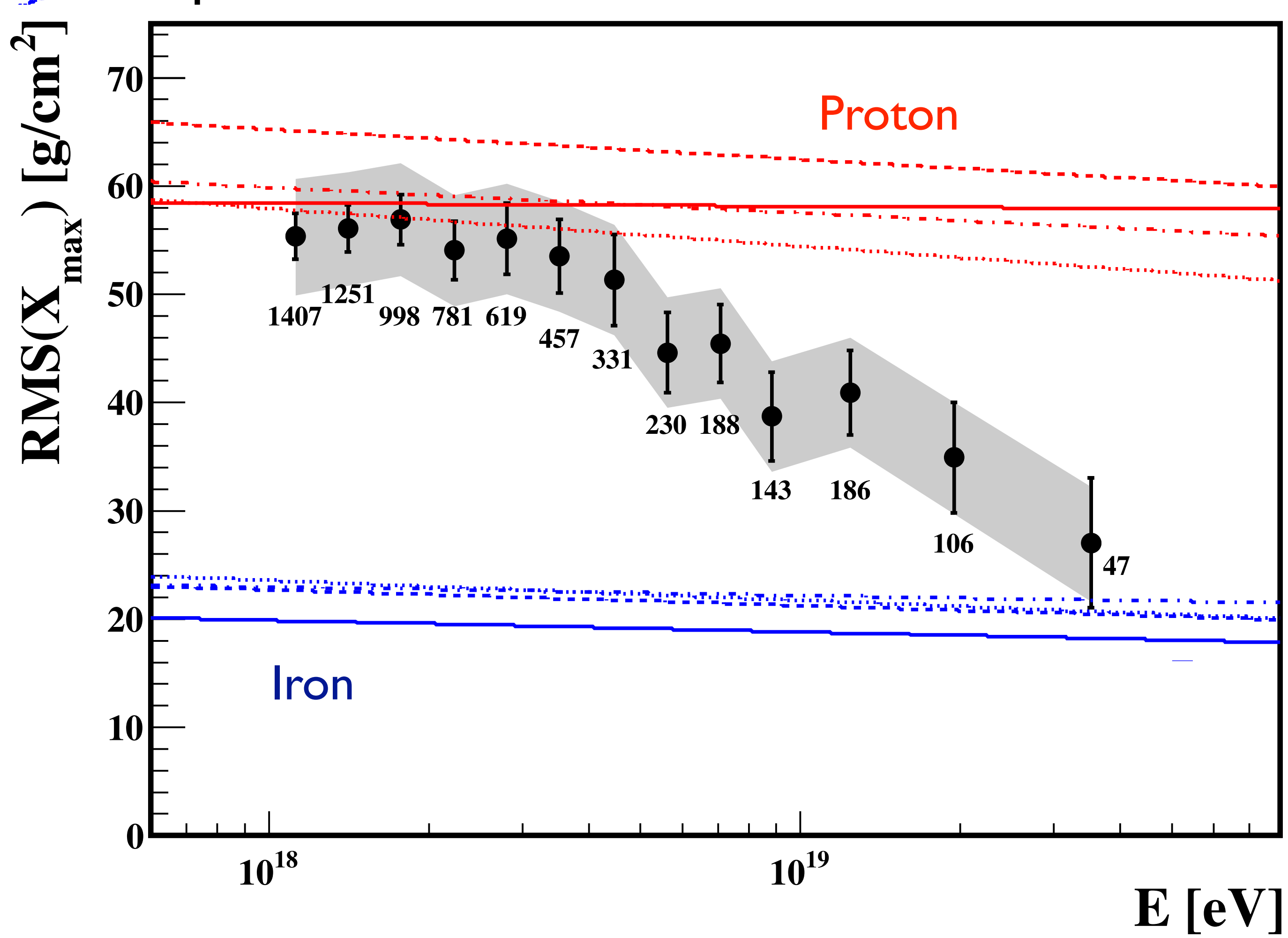
Mean depth of shower maximum



Change of cosmic ray composition from mixed or light to heavy ?

(Auger Collab. PRL 104, 2010, updated: Facal, ICRC 2011)

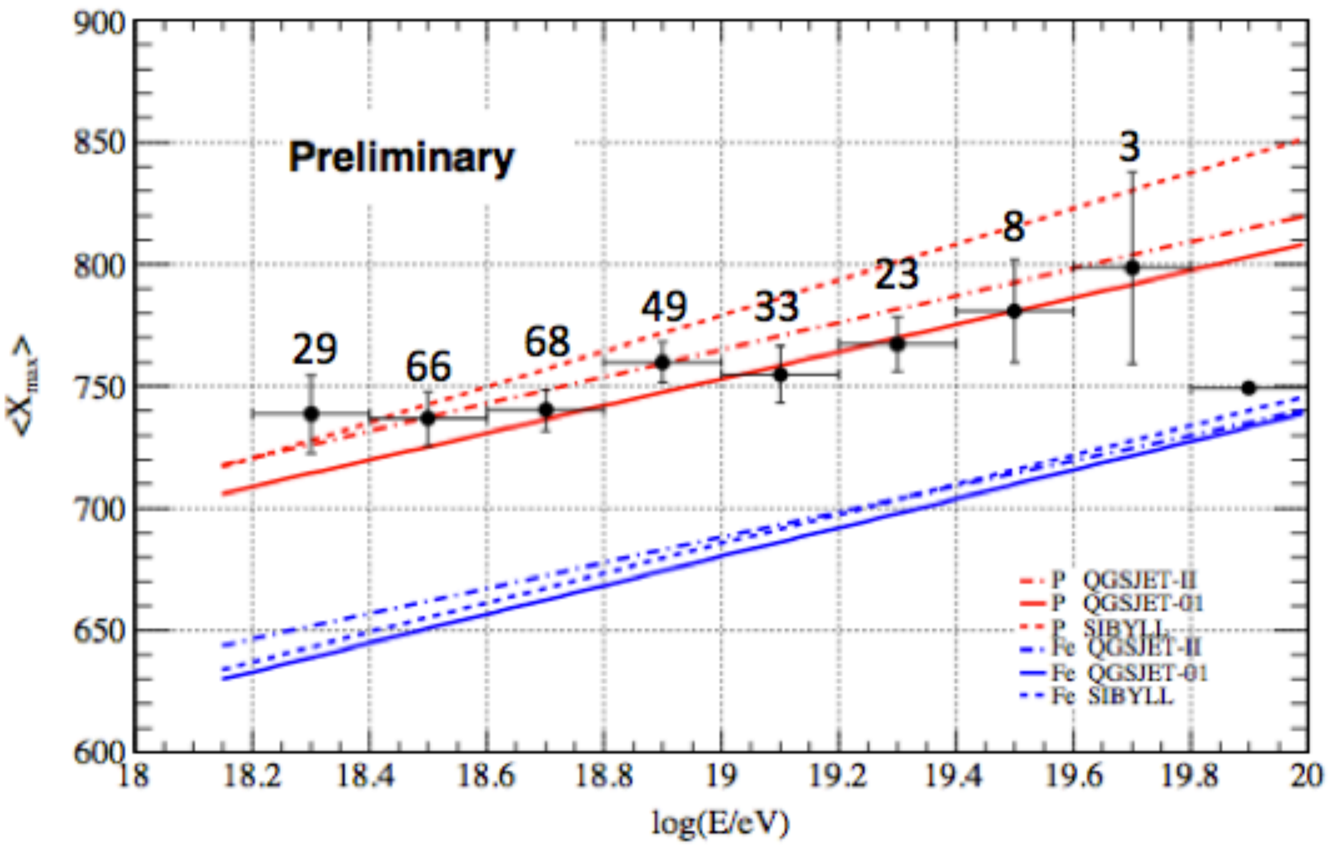
Fluctuations of depth of shower maximum



Sys. uncertainty: 13 g/cm^2 (mean)
6 g/cm^2 (RMS)

Independent confirmation from other composition indicators

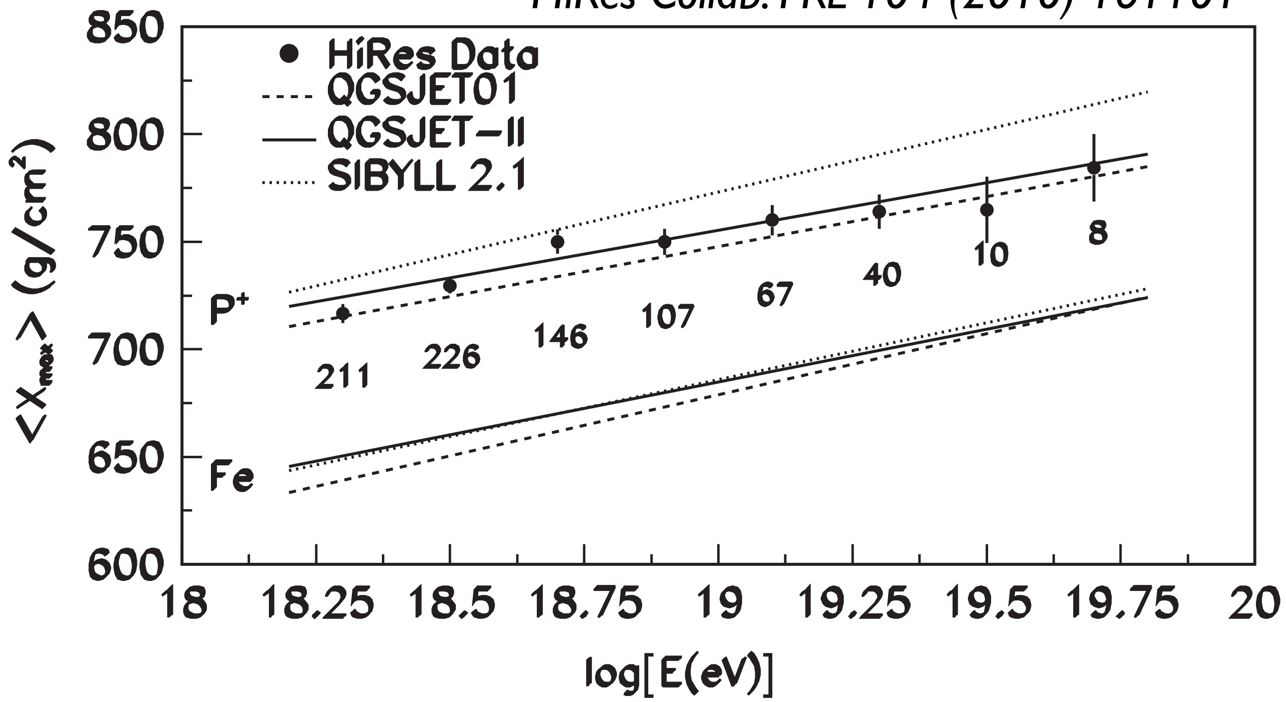
Telescope Array: Composition measurement



TA data compatible with light composition (independent analysis)

(Tameda, TA Collab., ICRC 2011)

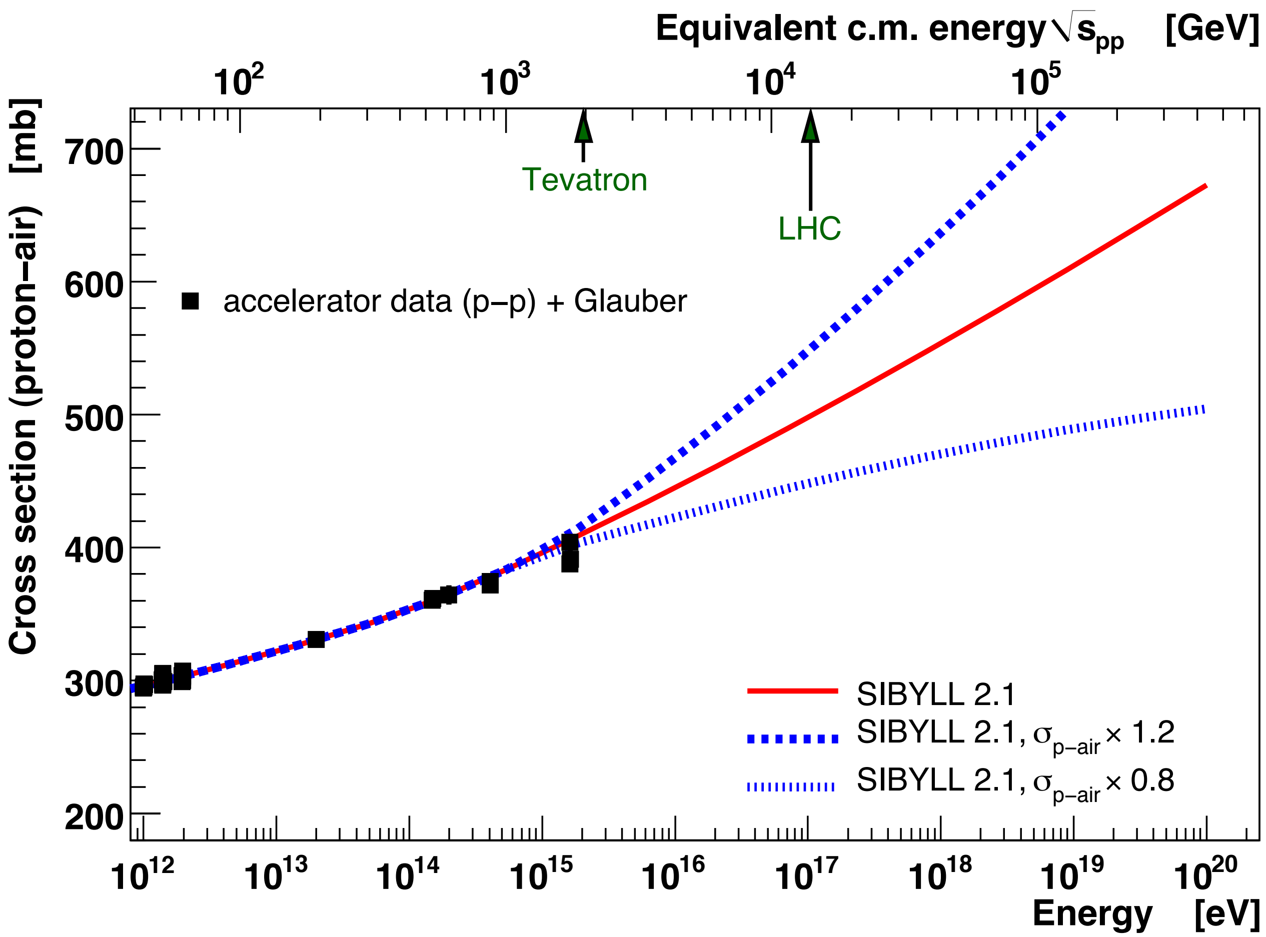
HiRes Collab. PRL 104 (2010) 161101



Note: no direct comparison of data possible:

- Auger: fiducial volume cuts to avoid shower selection bias
- TA: selection bias included in MC simulations, not explicitly corrected for to increase statistics
- Data still compatible within sys. uncertainties

Modification of characteristics of interactions ?



Logarithmic interpolation starting at 10^{15} eV

$$f(E) = 1 + (f_{19} - 1)\frac{\ln(E/10^{15}\,\mathrm{eV})}{\ln(10^{19}\,\mathrm{eV}/10^{15}\,\mathrm{eV})}$$

Modification factor at 10^{19} eV

Modification of

- cross sections (p-air, π-air, K-air)
- secondary particle multiplicity
- elasticity (leading particle)

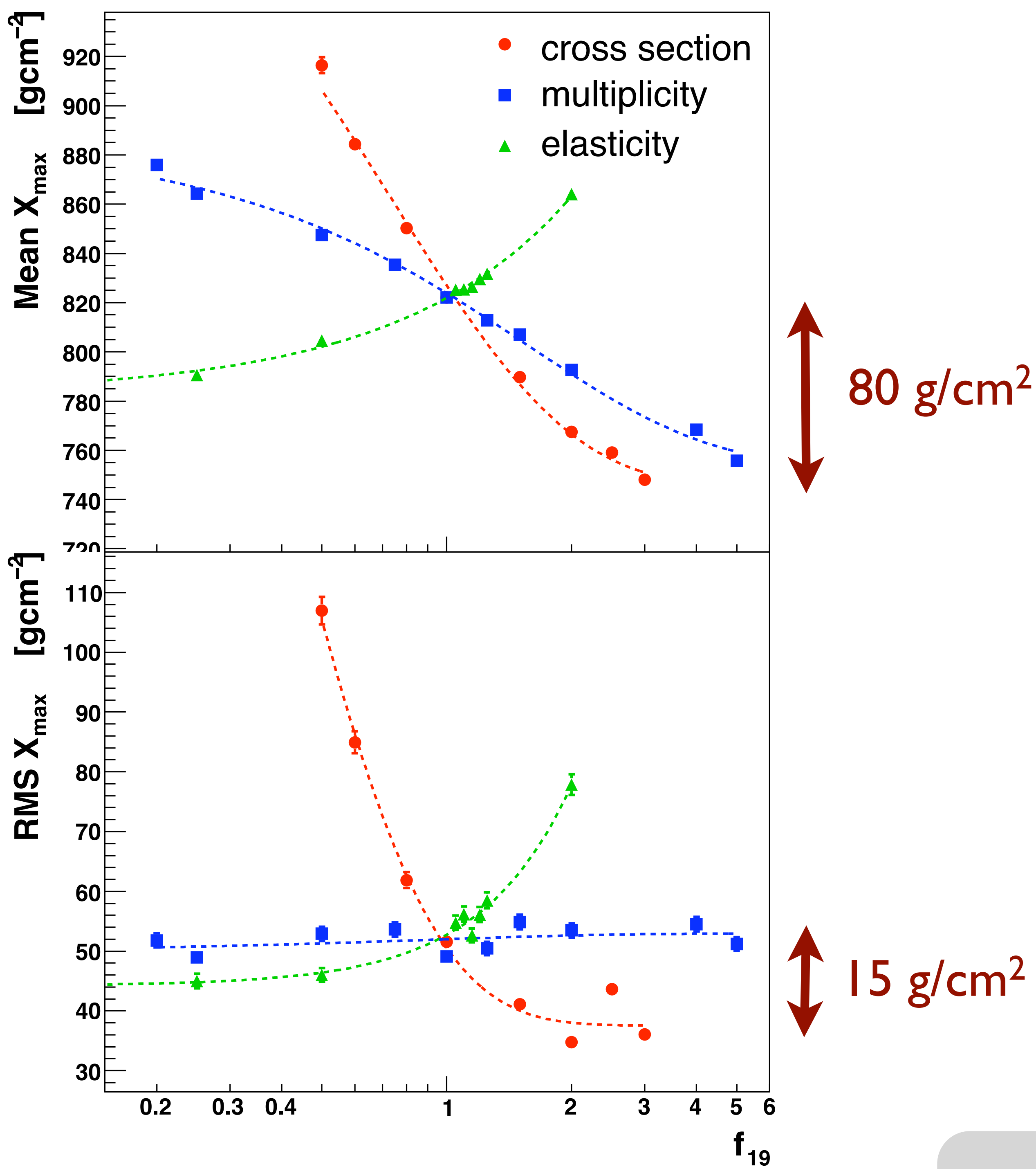
Implementation

- rescaling after event generation
- separate treatment of leading particle
- conservation of energy and charge
- modified version of CONEX
- available for different interaction models
- shown here for SIBYLL

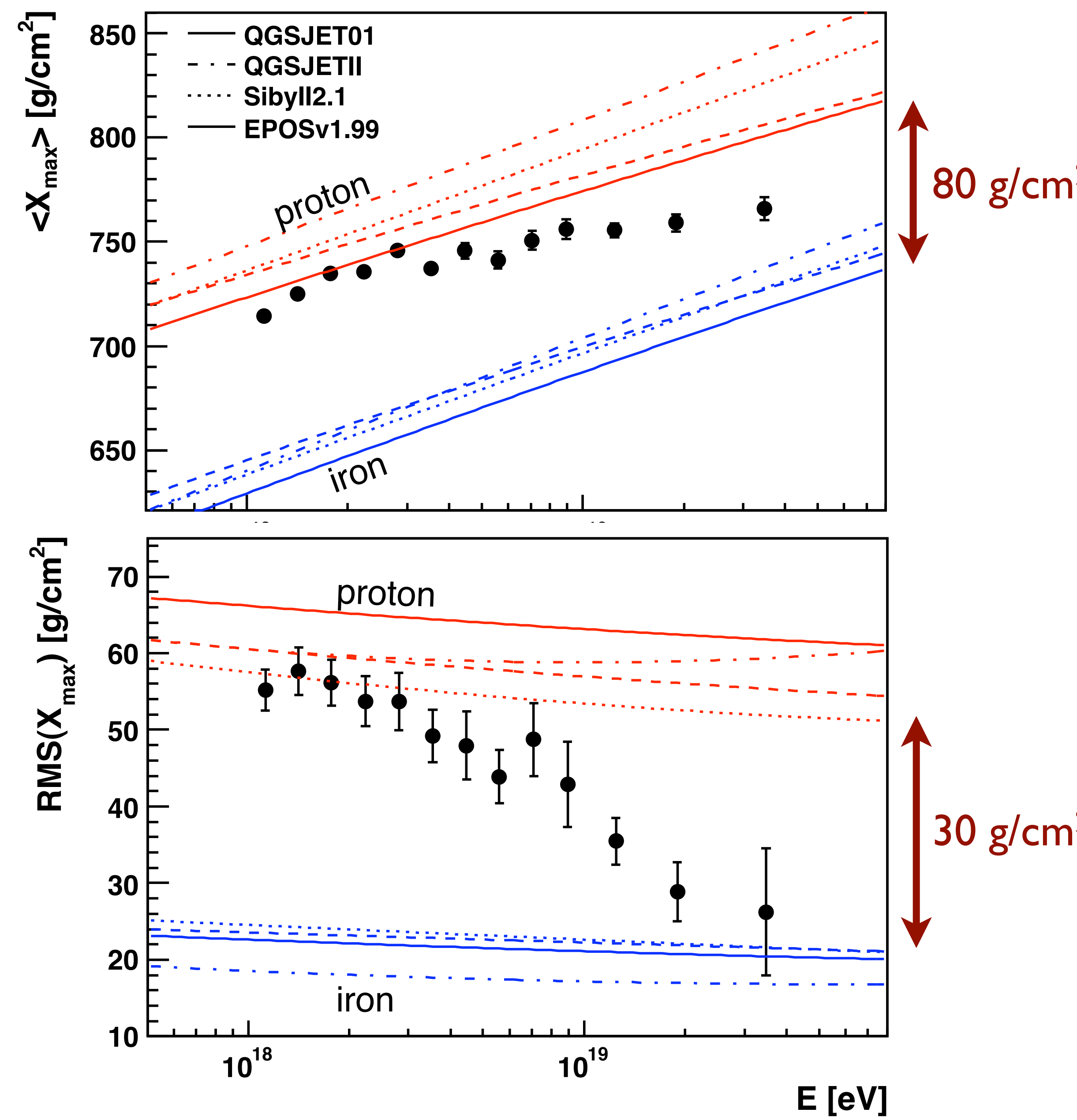
(R. Ulrich et al. PRD83 (2011) 054026)

Results for proton showers: X_{max}

(R. Ulrich et al. PRD83 (2011) 054026)



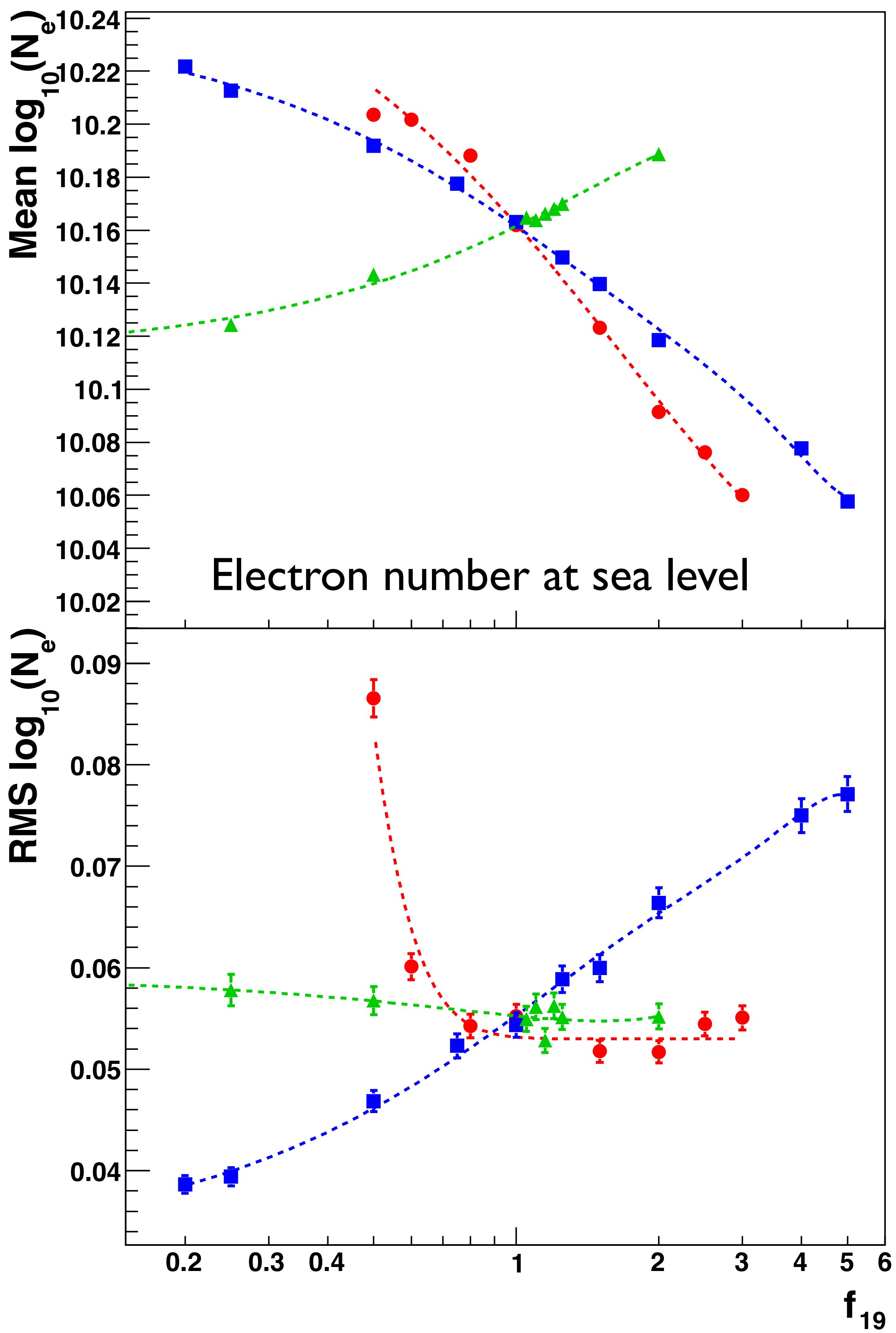
Auger data 2009



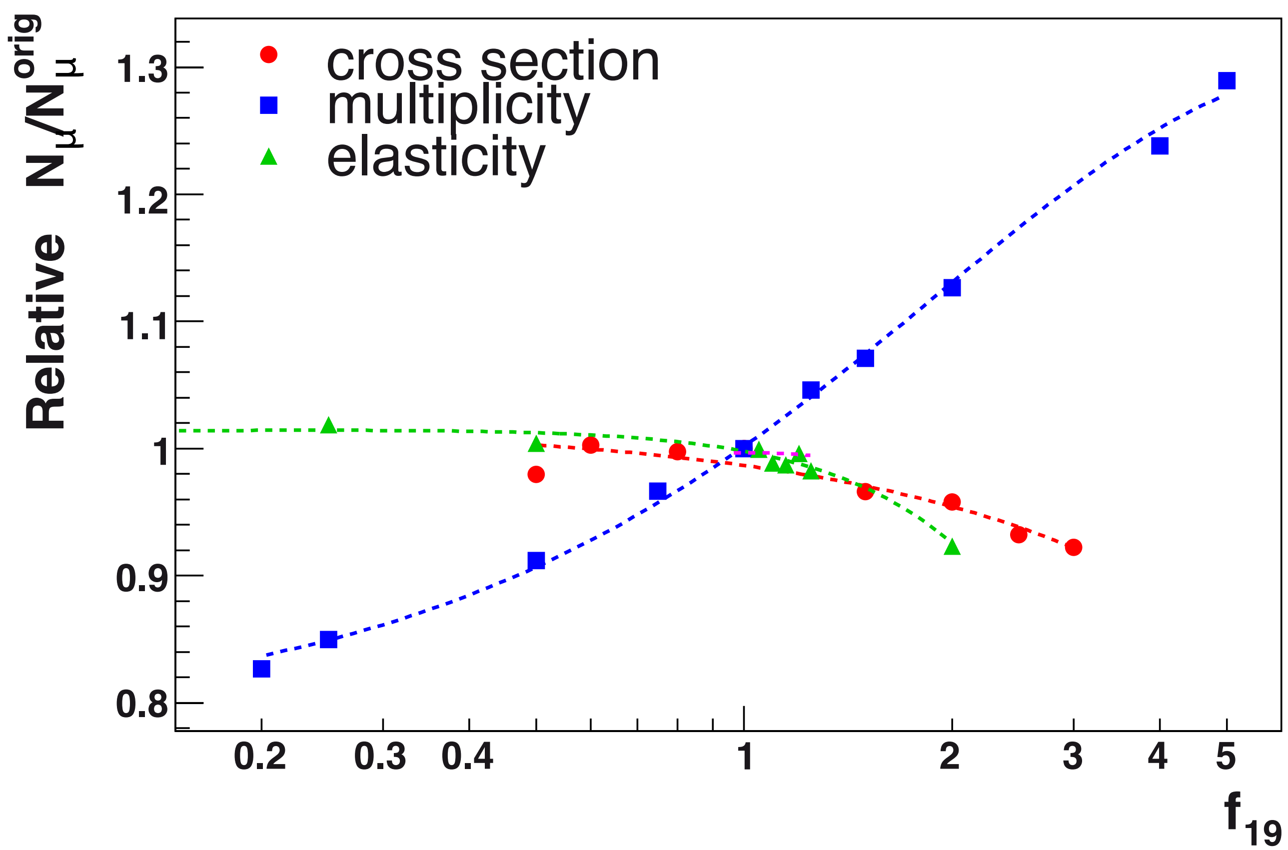
$E = 10^{19.5}$ eV ($E_{cm} \approx 250$ TeV)

- Variables influence differently mean and RMS
- Cross section most important

Results for proton showers: Ne, Nμ



$E = 10^{19.5}$ eV   ($E_{cm} \approx 250$ TeV)



Prediction for ratio of muon numbers for iron/proton showers ~1.4

- Electron number correlated with Xmax
- Muon number depends mainly on multiplicity

(*R. Ulrich et al. PRD83 (2011) 054026*)

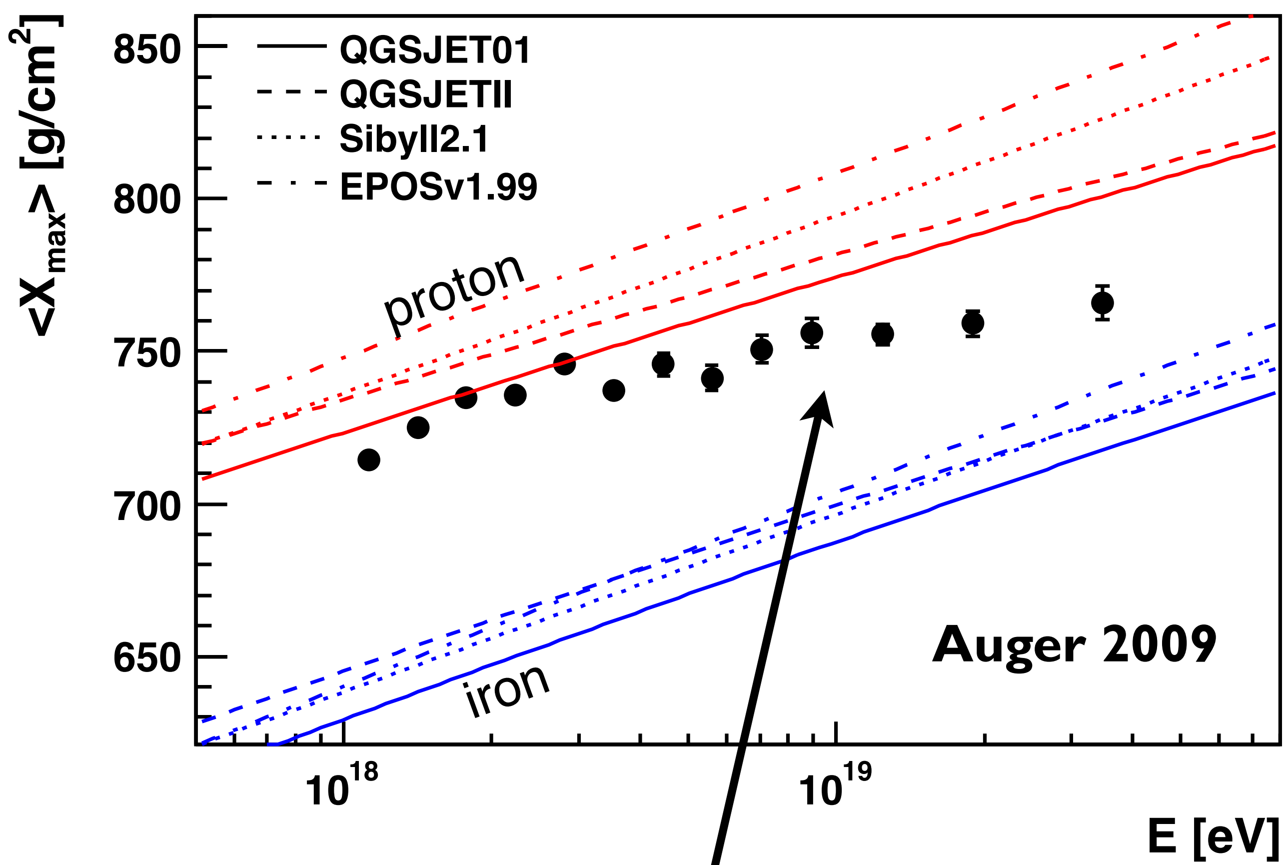
Change of interaction physics?

Elongation rate theorem

$$D_{10}^{\mathrm{had}} = \ln 10 \, X_0 (1 - B_n - B_\lambda)$$

(Linsley, Watson PRL46, 1981)

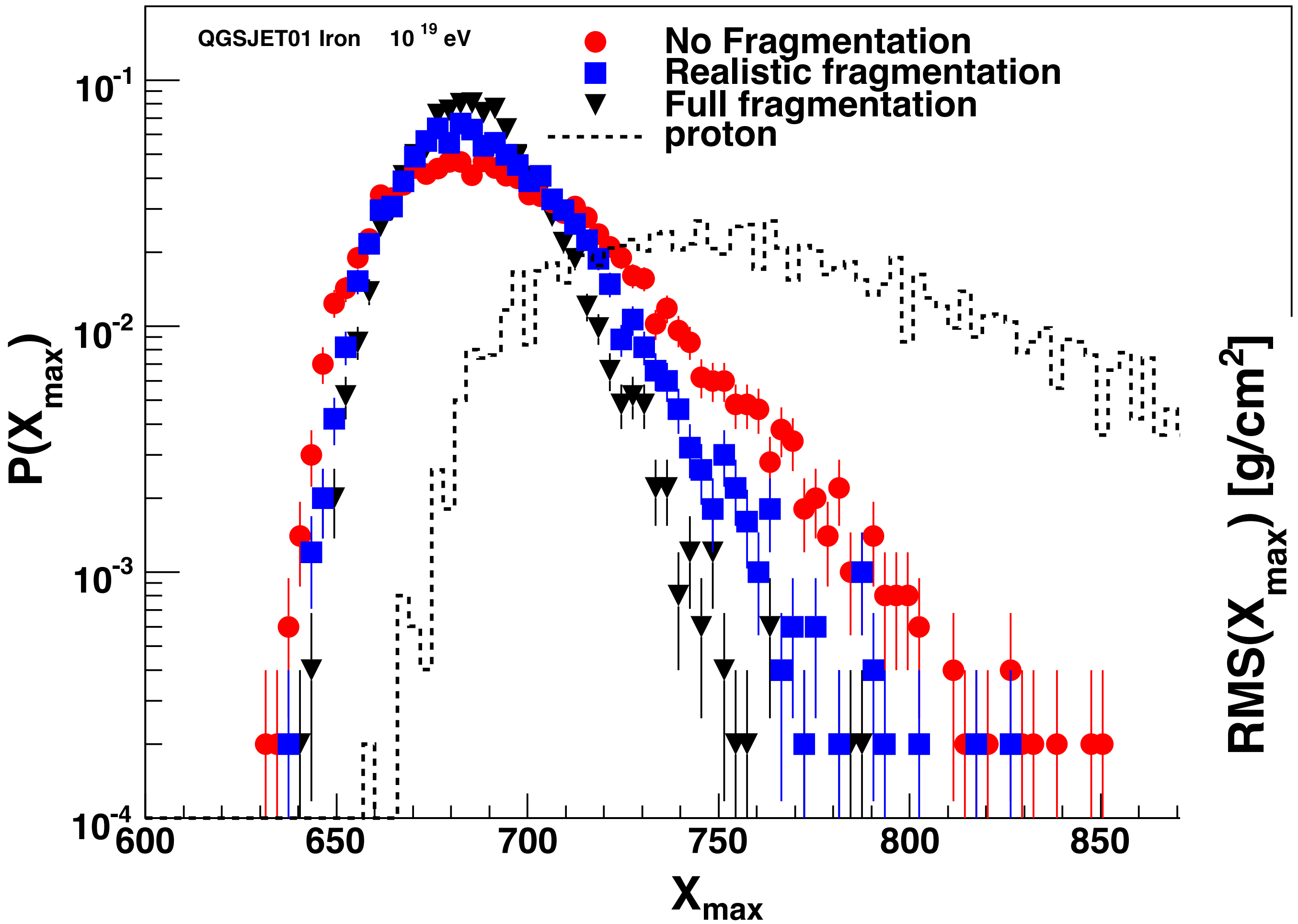
factor ~ 87 g/cm^2



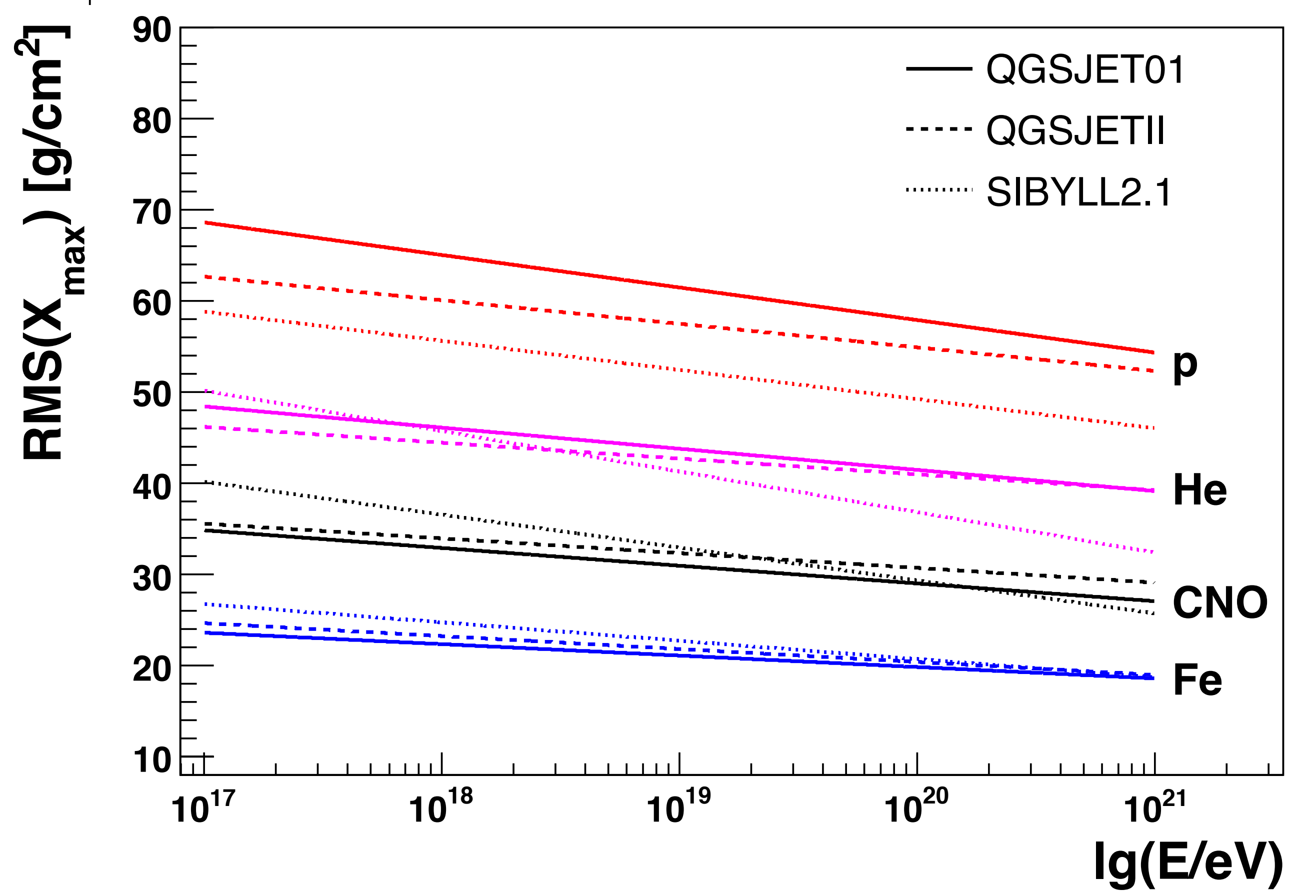
$$D_{10}^{\mathrm{had}} = 24 \pm 3 \ \mathrm{g/cm^2}$$

Model by Farrar & Allen, UHECR 2012
- Restoration of chiral symmetry
- Strong enhancement of baryon production

Importance of correlations for fluctuations

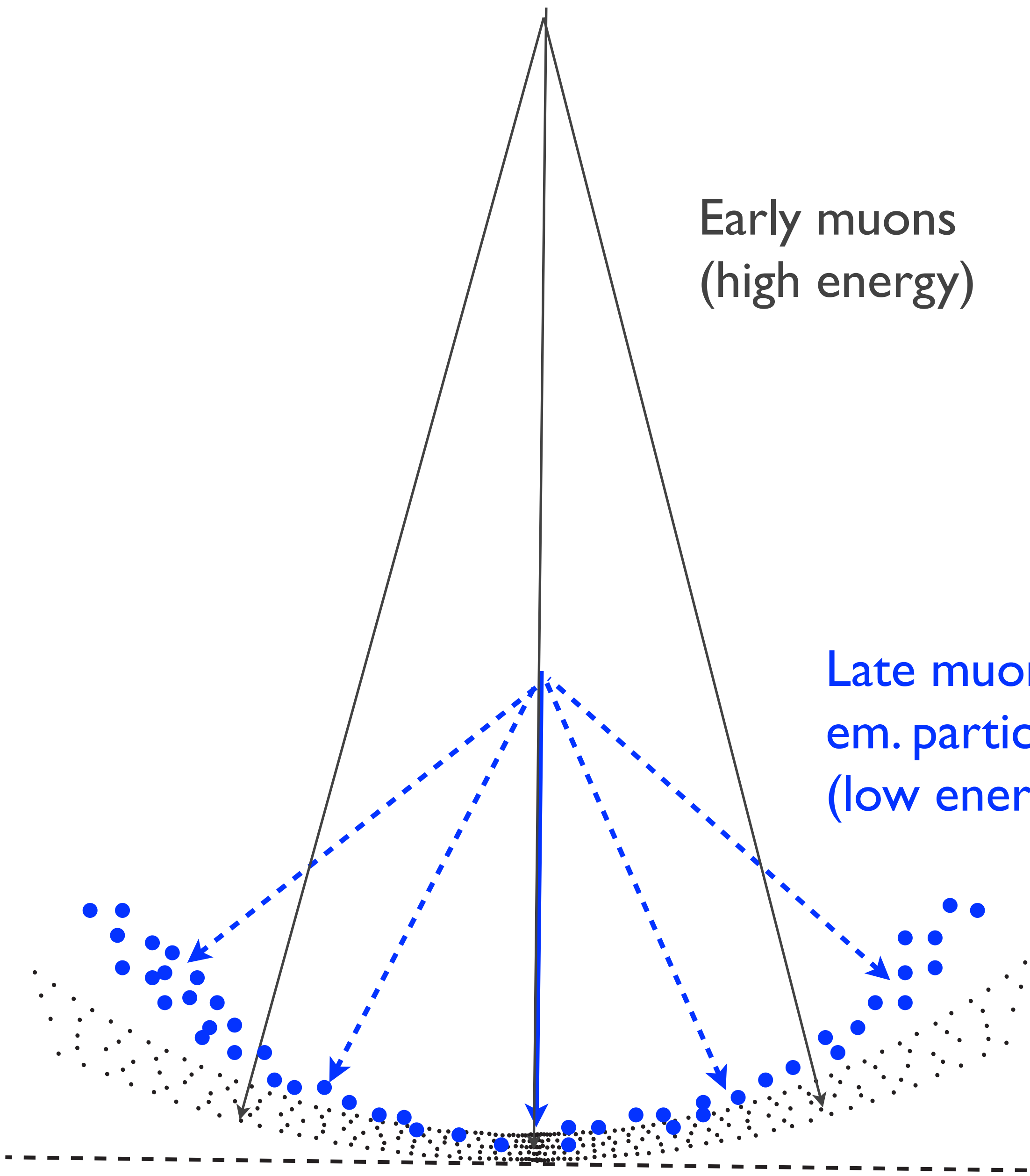


RMS(Xmax) = 29 g/cm^2
21 g/cm^2
16 g/cm^2



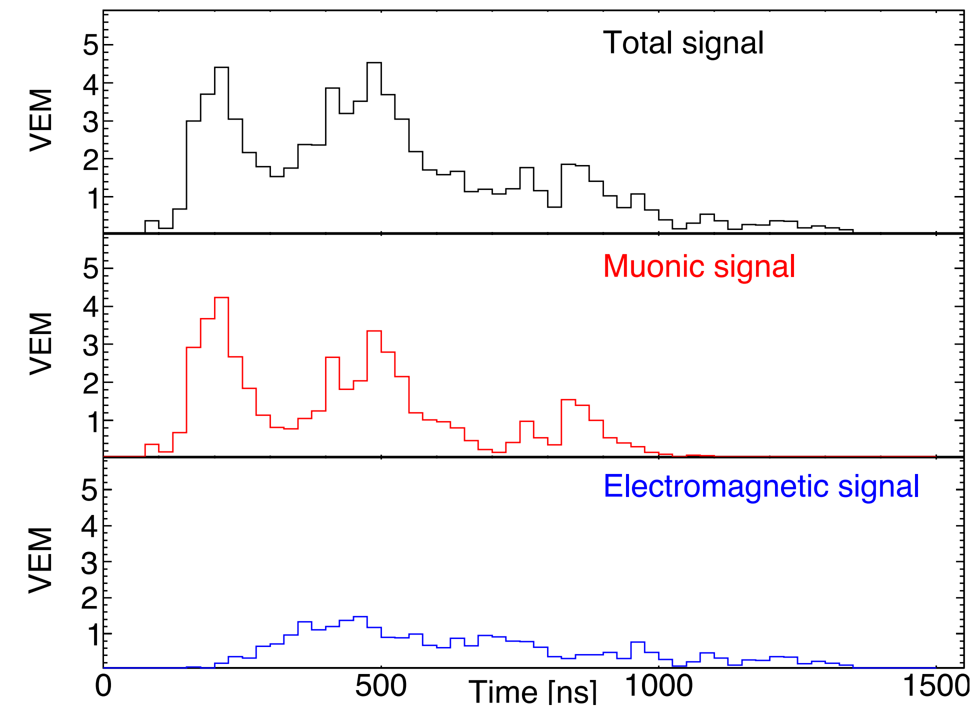
Nuclear fragmentation is important for quantitative predictions

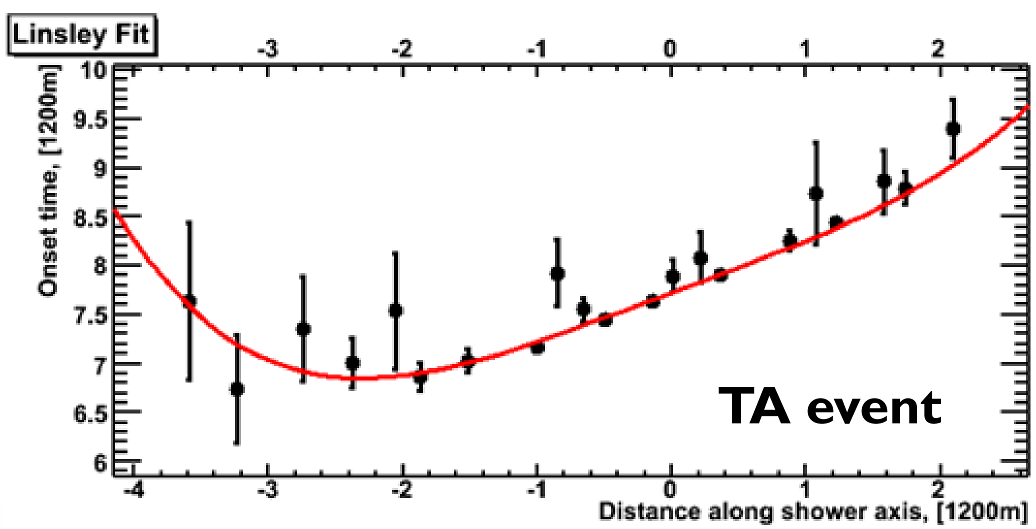
Early muons: importance of shower front curvature



Curvature of shower front
sensitive to early muons

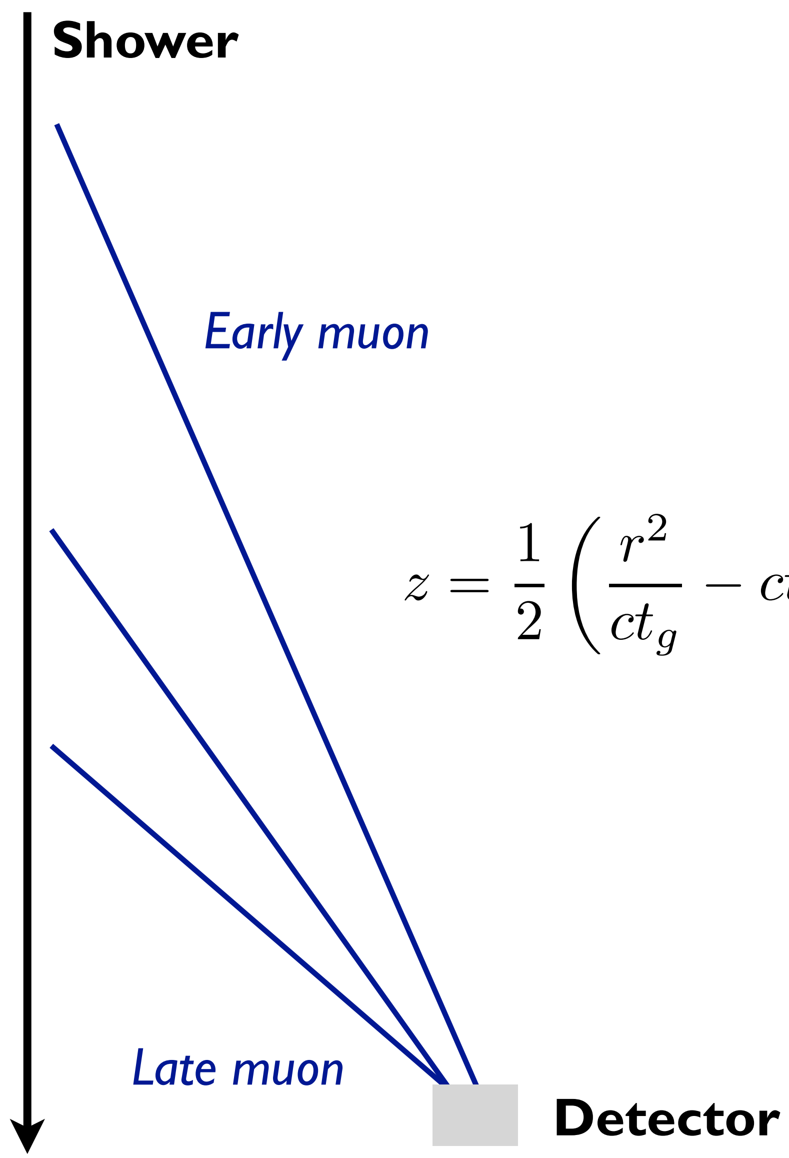
proton shower E = 10^{19} eV, θ = 45°



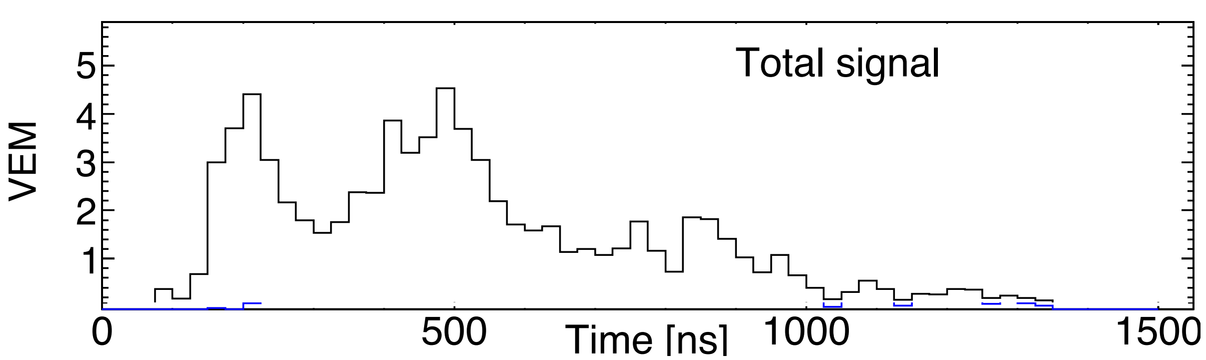


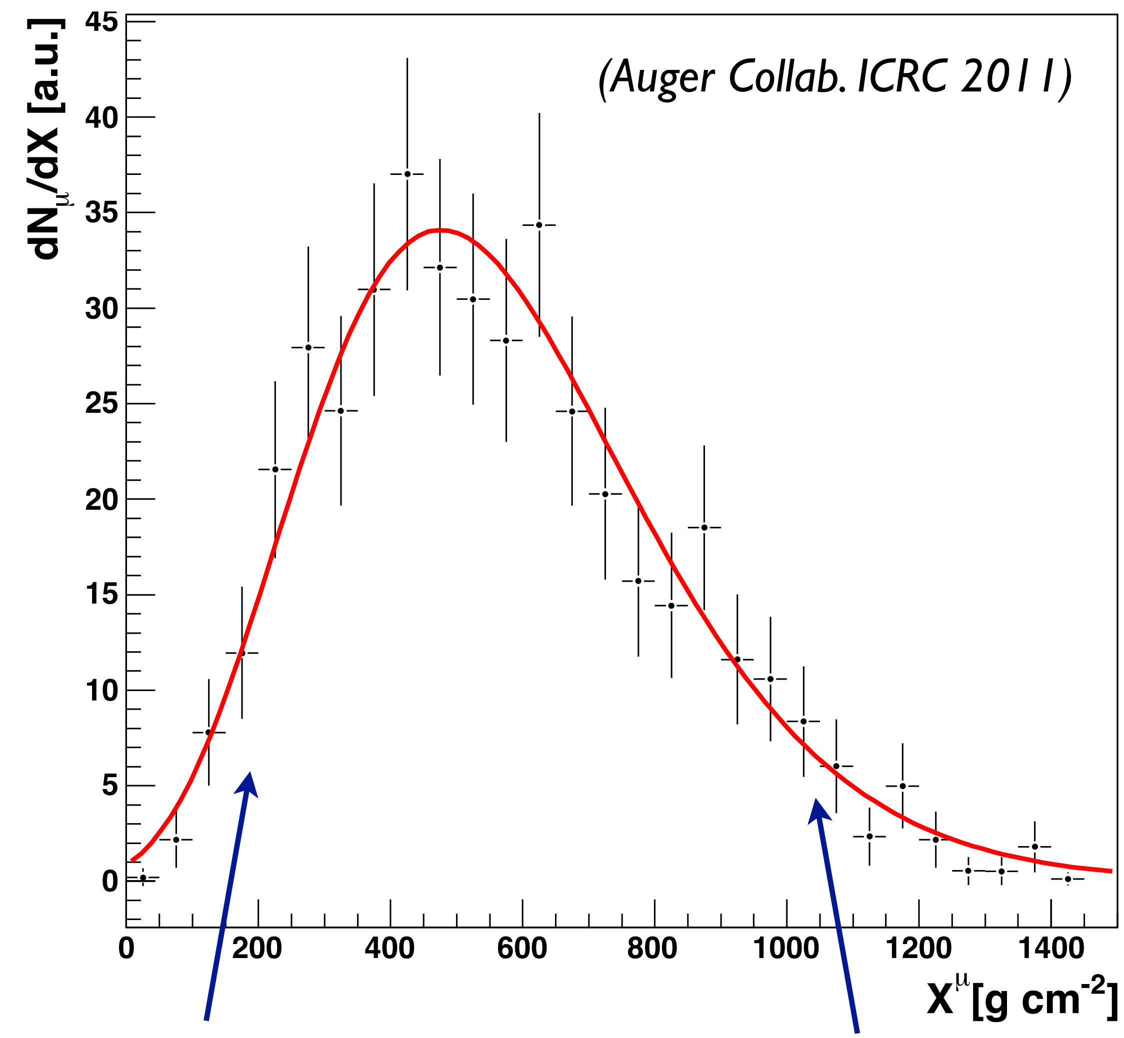
Curvature should be measured

Outlook: muon production depth



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





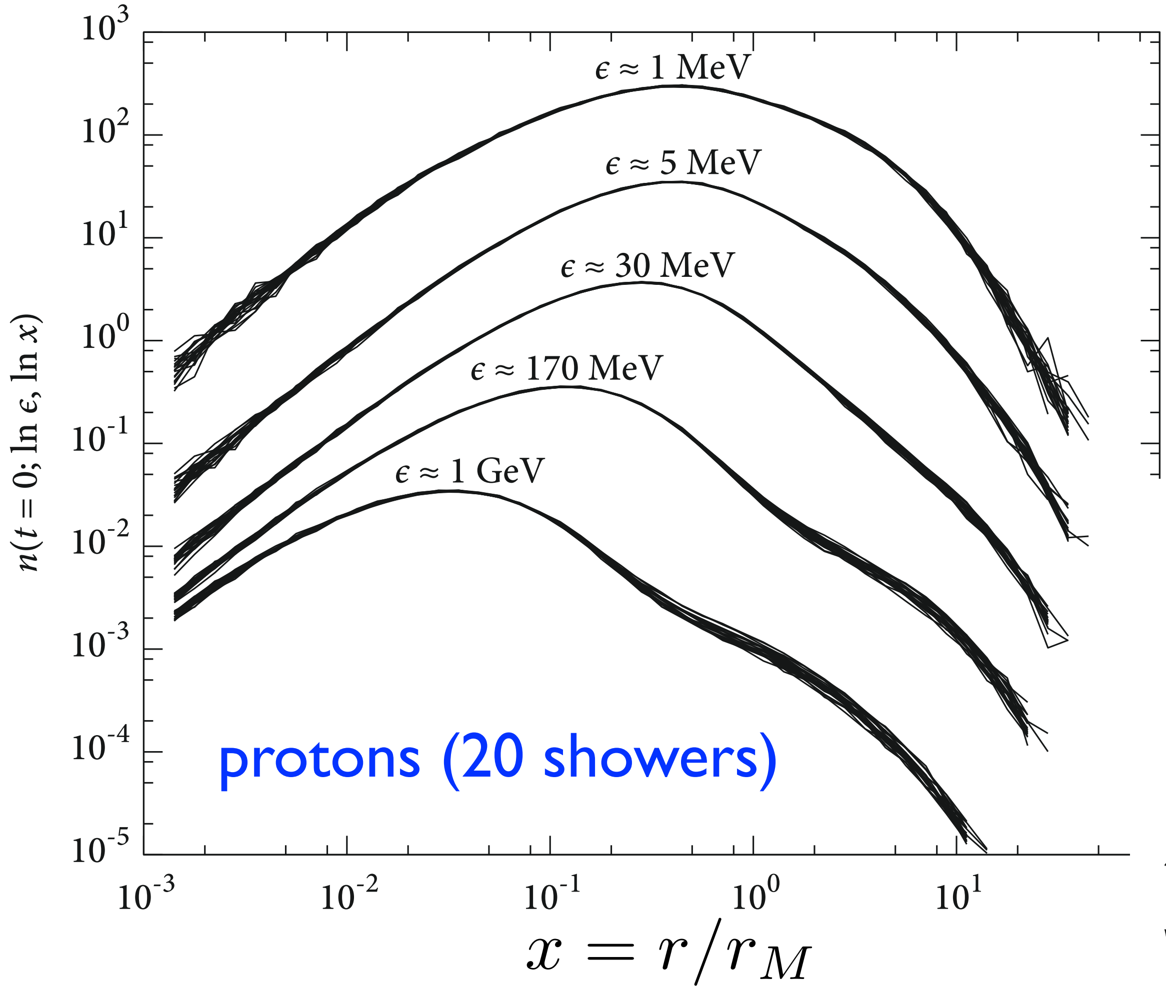
Muons from high-energy interactions

Muons from low-energy interactions

Auger Observatory: upgrade of surface detector array planned

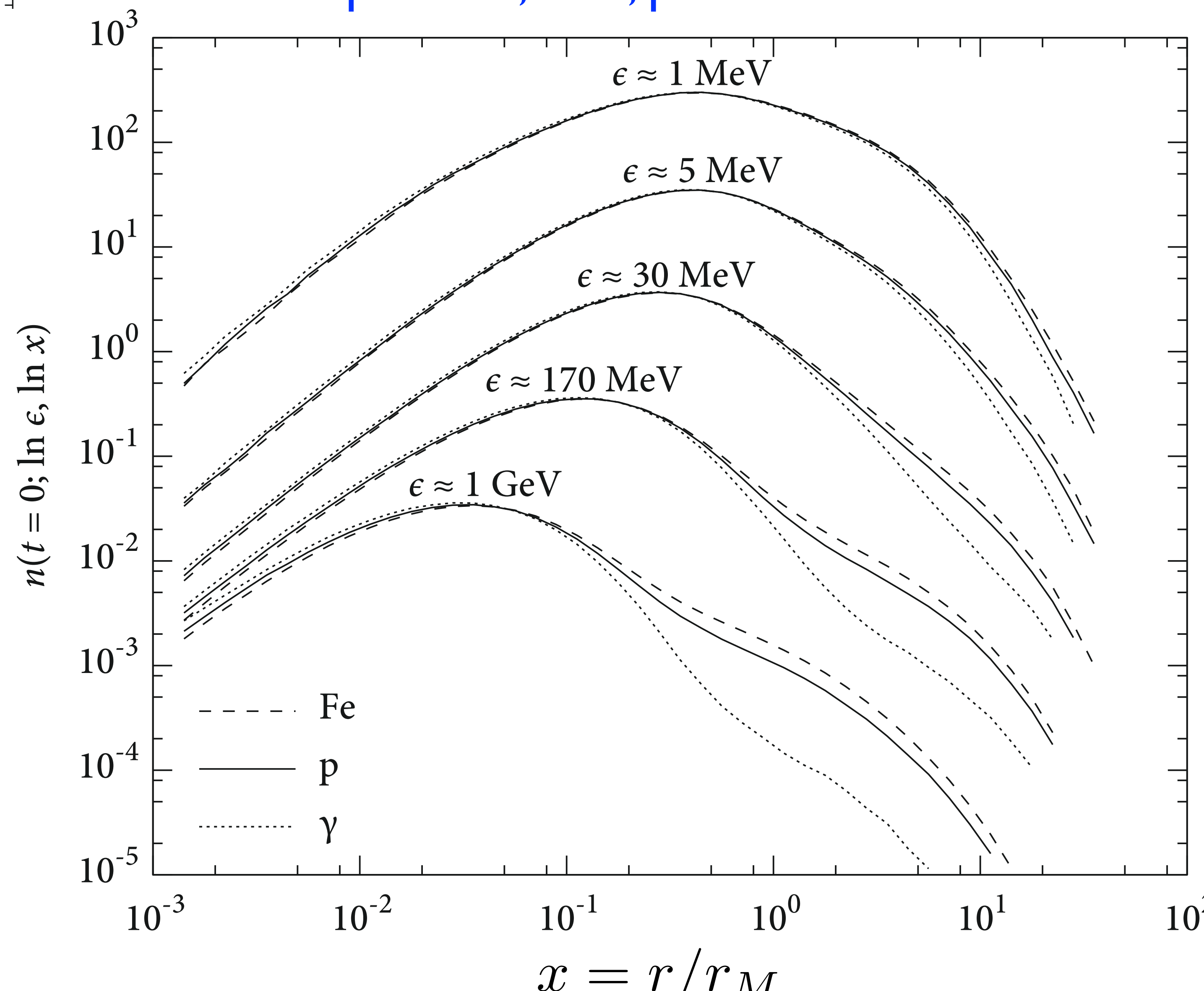
(Cazon et al. Astropart. Phys. 23, 2005 & 1201.5294)

Universality features of high-energy showers (ii)



Lateral distribution for fixed shower age

protons, iron, photons



$$\left.\frac{dN_{e^\pm}}{d\ln x}\right|_{s=1}$$

(S. Lafebre et al., Astropart. Phys. 31, 2009)