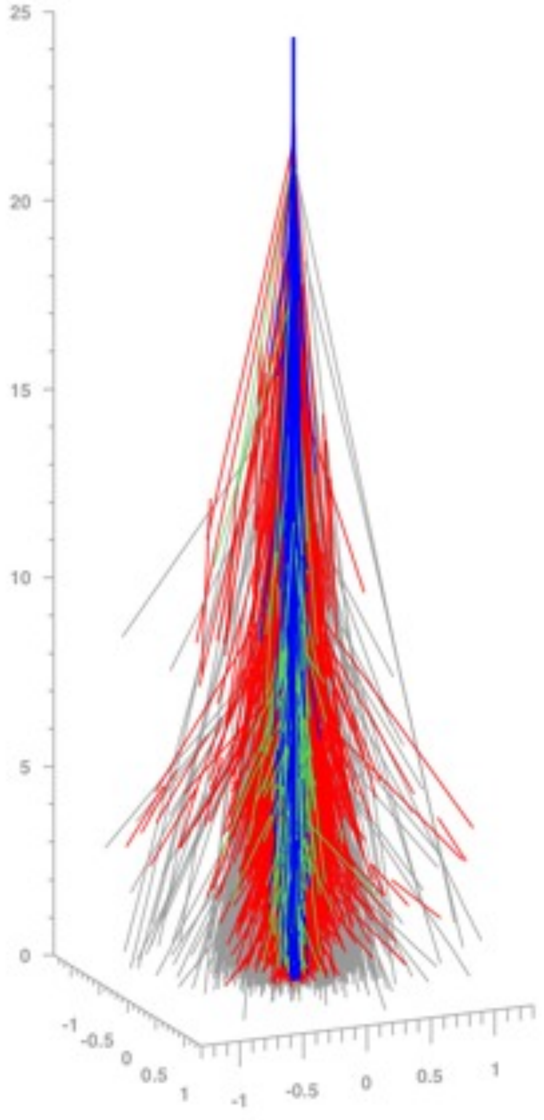
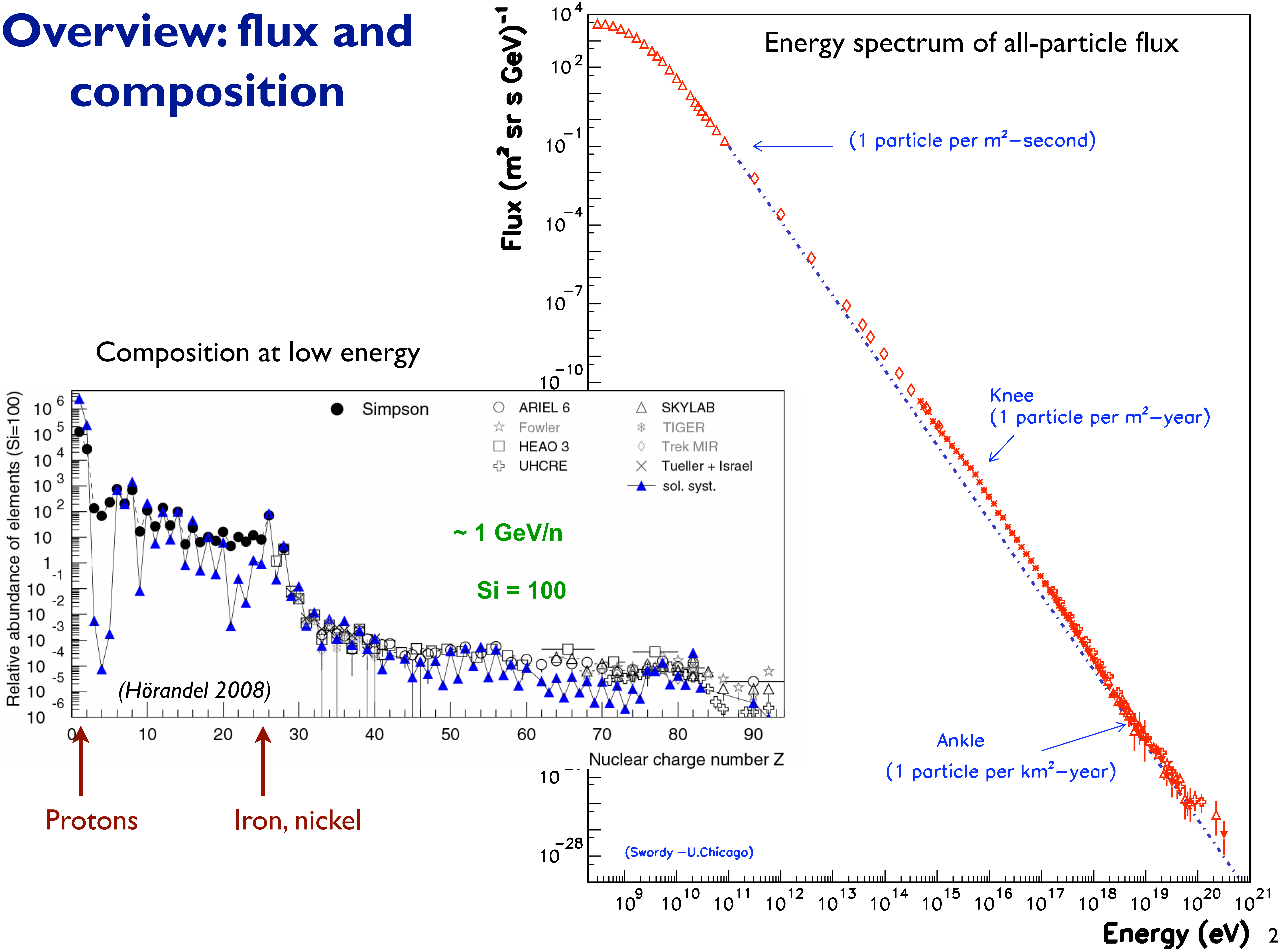
Ultra High Energy Cosmic Rays and Air Shower Physics



Ralph Engel

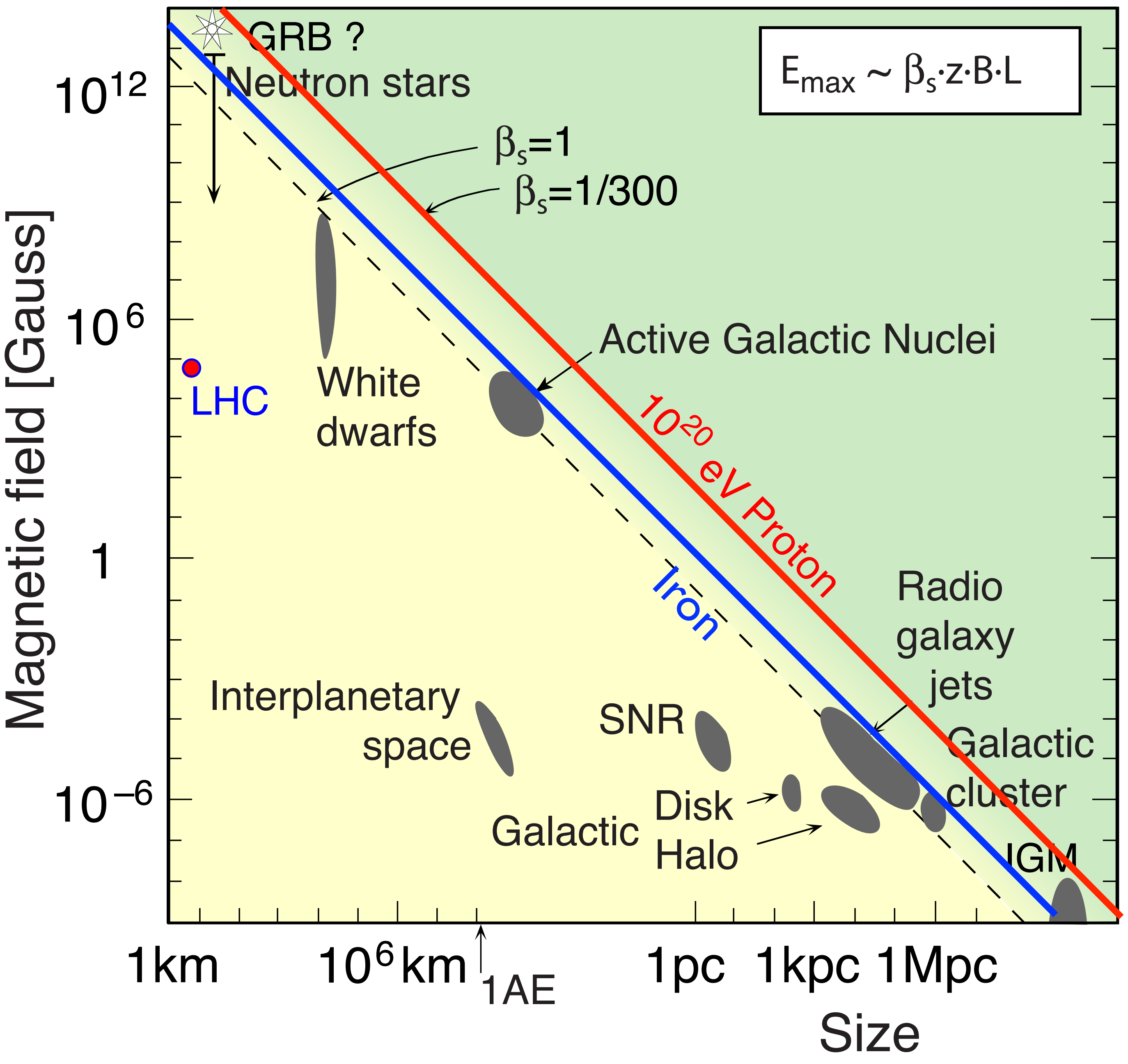
Karlsruhe Institute of Technology (KIT)

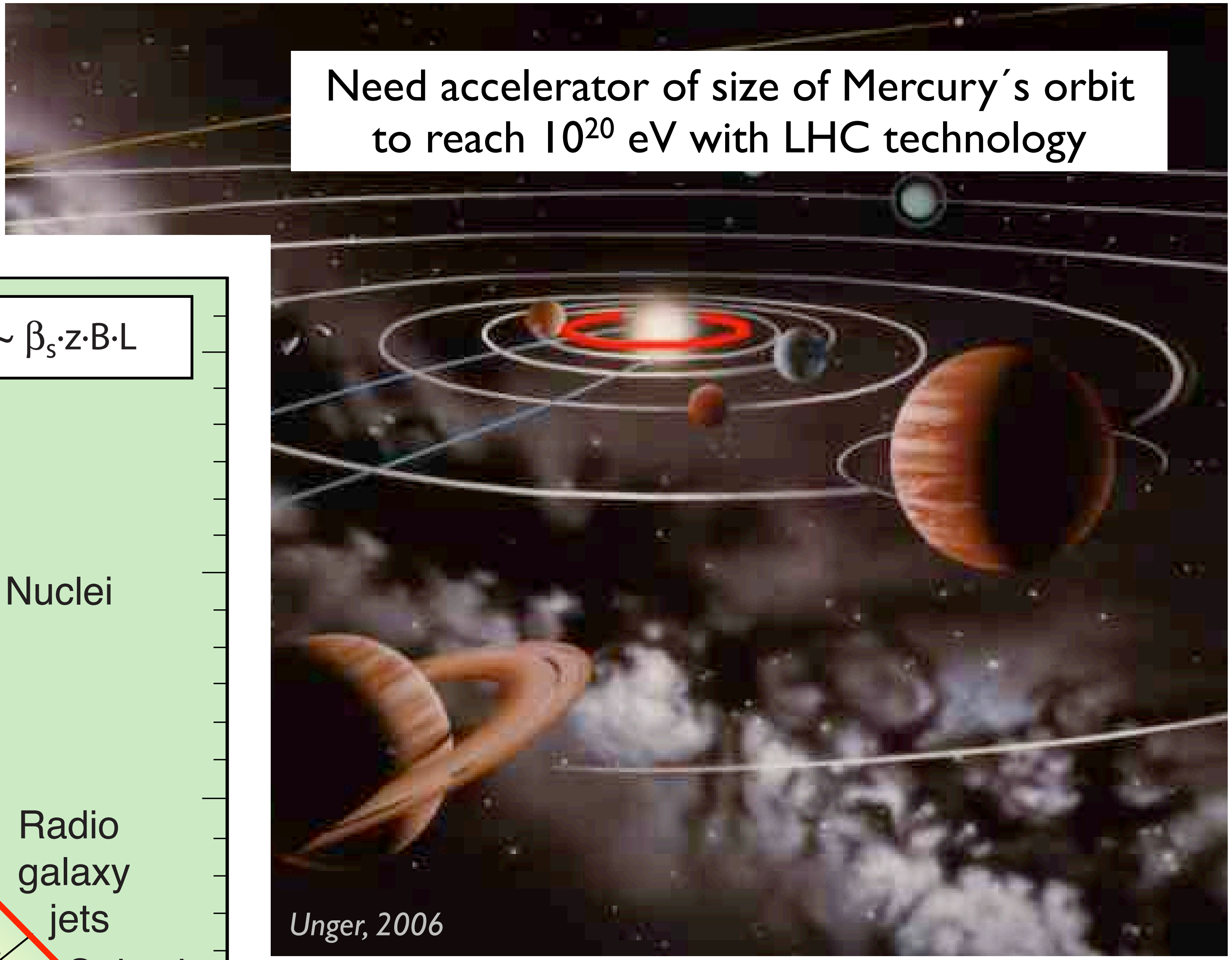
Overview: flux and composition



Problem 1: Sources of 10^{20} eV particles

Hillas plot (1984)





Need accelerator of size of Mercury´s orbit to reach 10^{20} eV with LHC technology

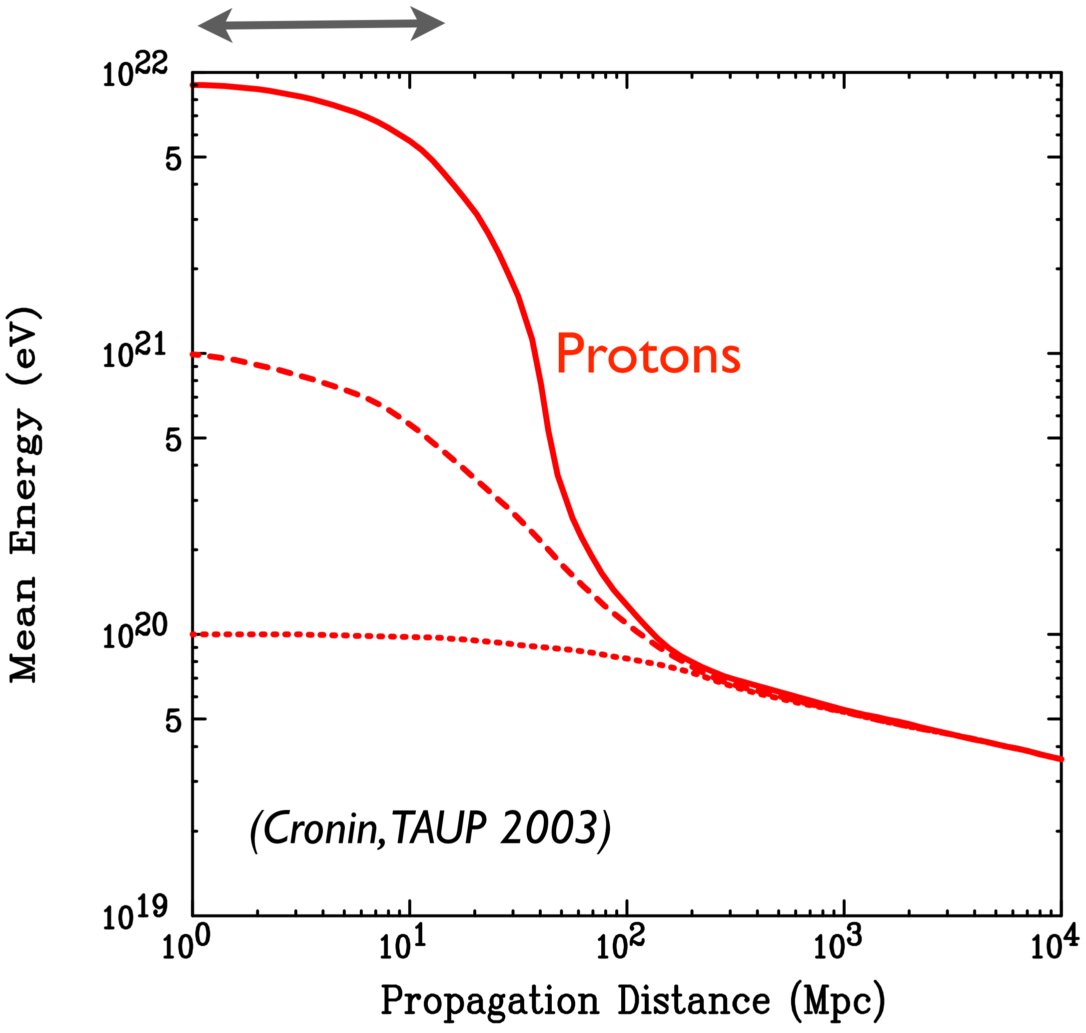
Unger, 2006

Realistic constraints more severe

- small acceleration efficiency
- synchrotron & adiabatic losses
- interactions in source region

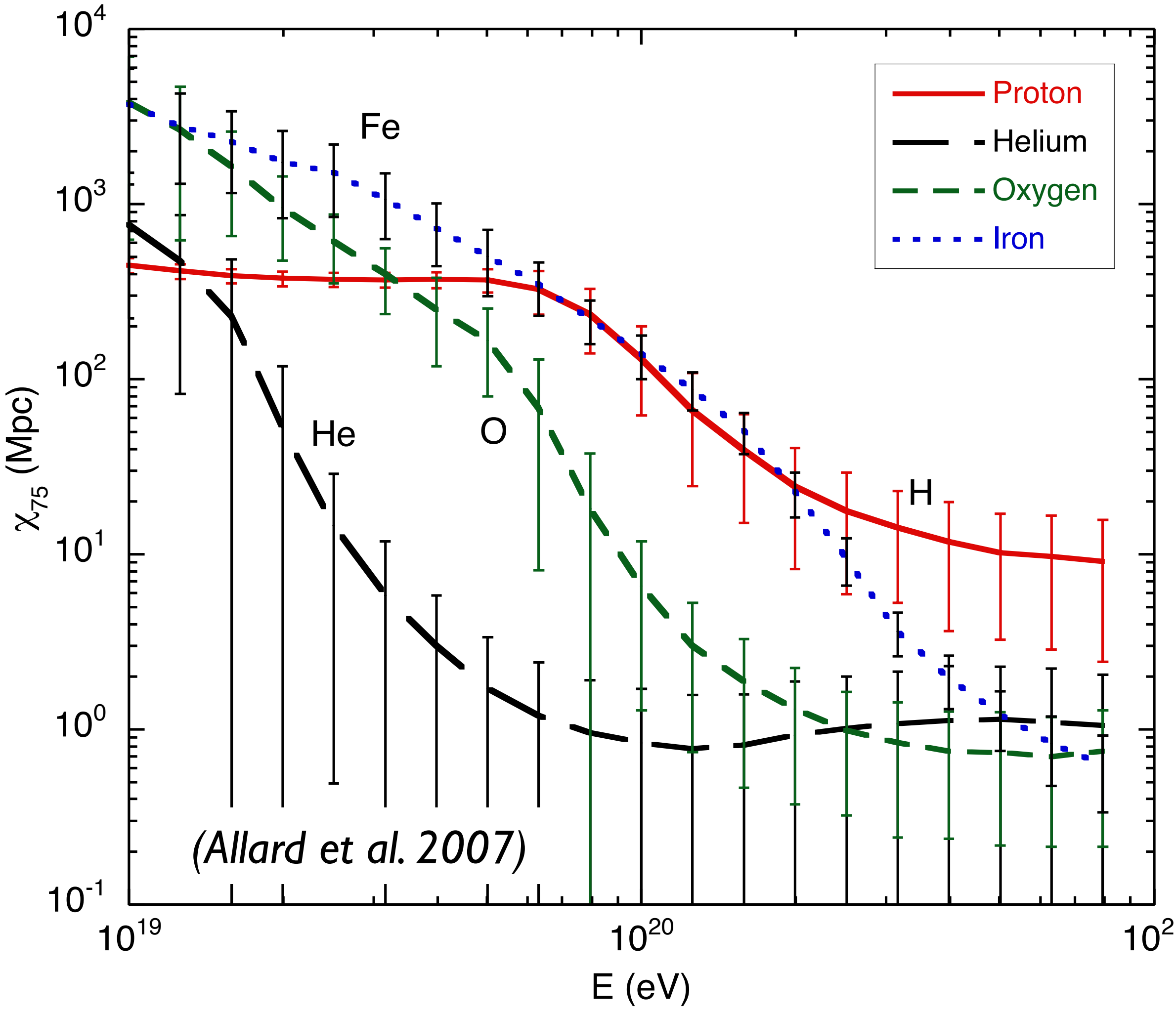
Problem 2: Flux suppression due to GZK effect

Energy loss length



(Cronin, TAUP 2003)

Energy loss length



(Allard et al. 2007)

Greisen-Zatsepin-Kuzmin effect (1966)

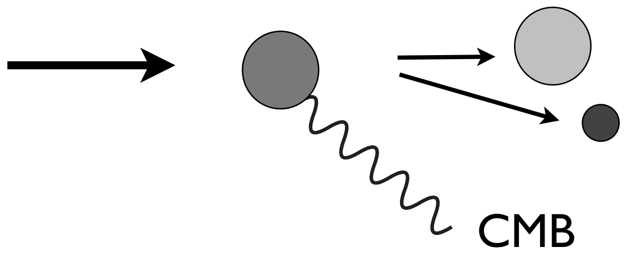
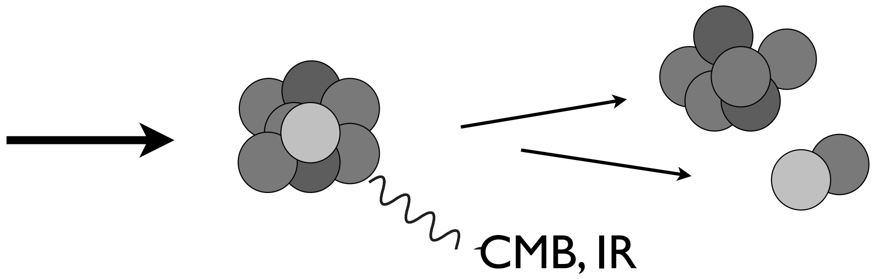
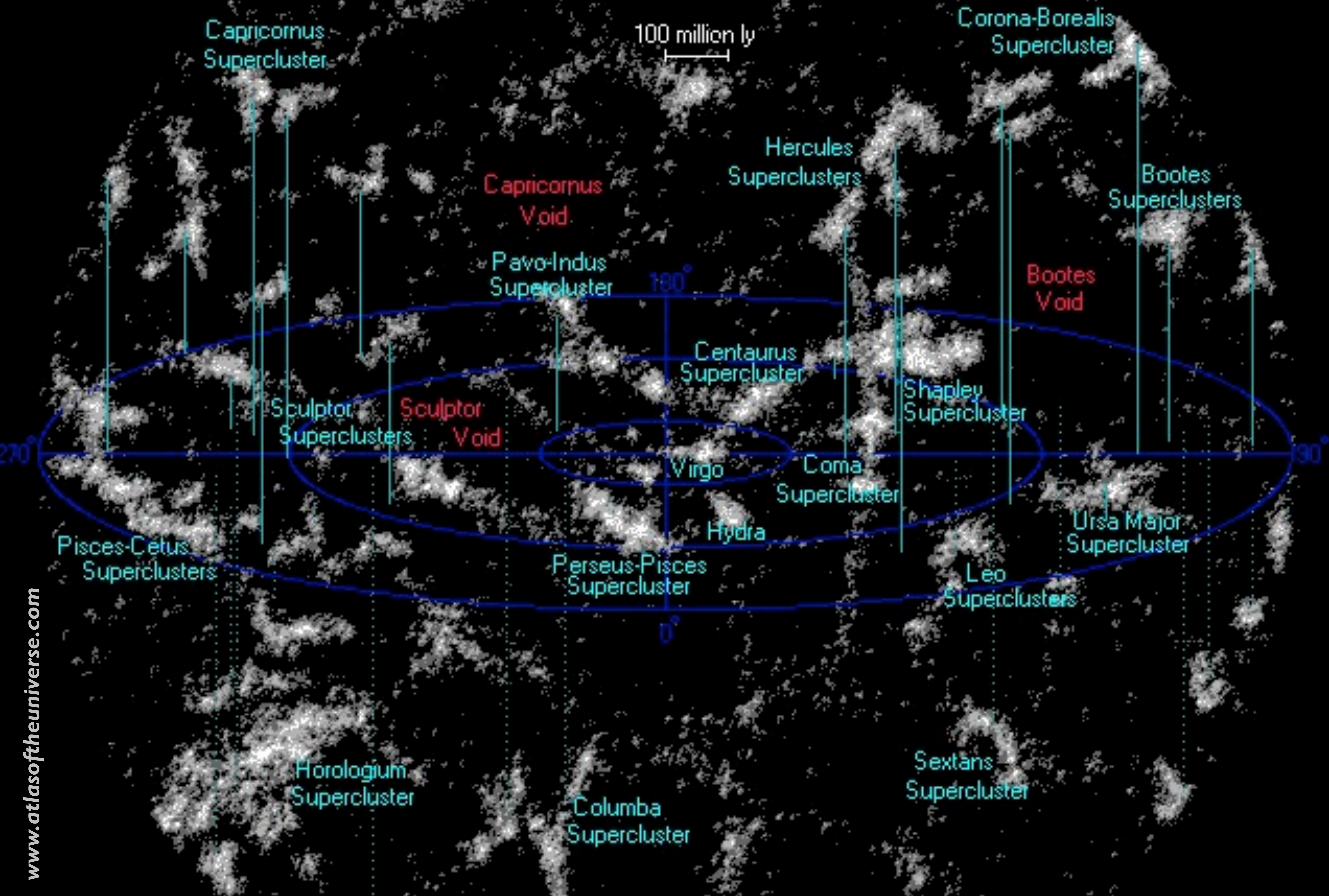


Photo-pion production

Photo-dissociation (giant dipole resonance)

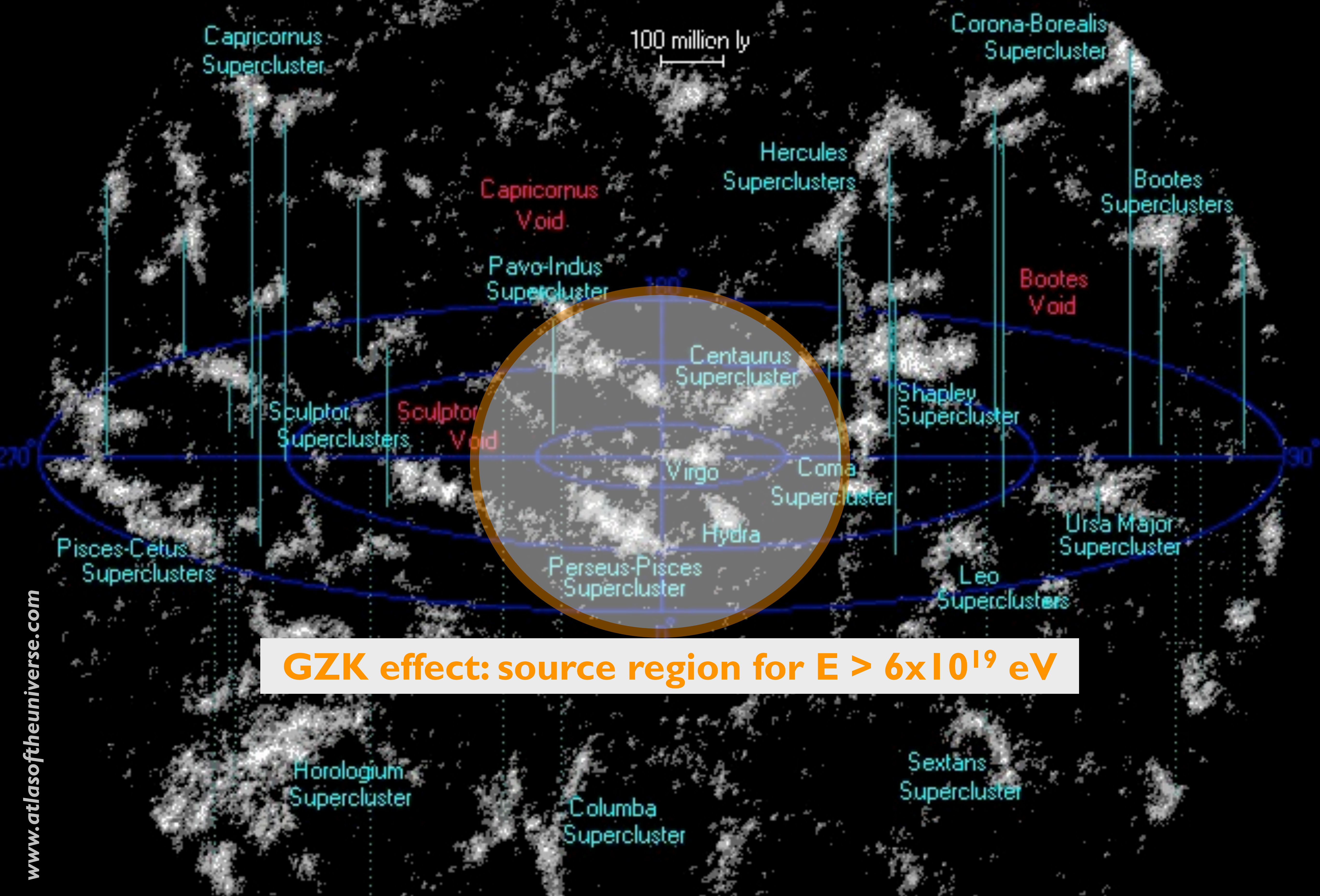


Problem 3: Arrival direction distribution



www.atlasoftheuniverse.com

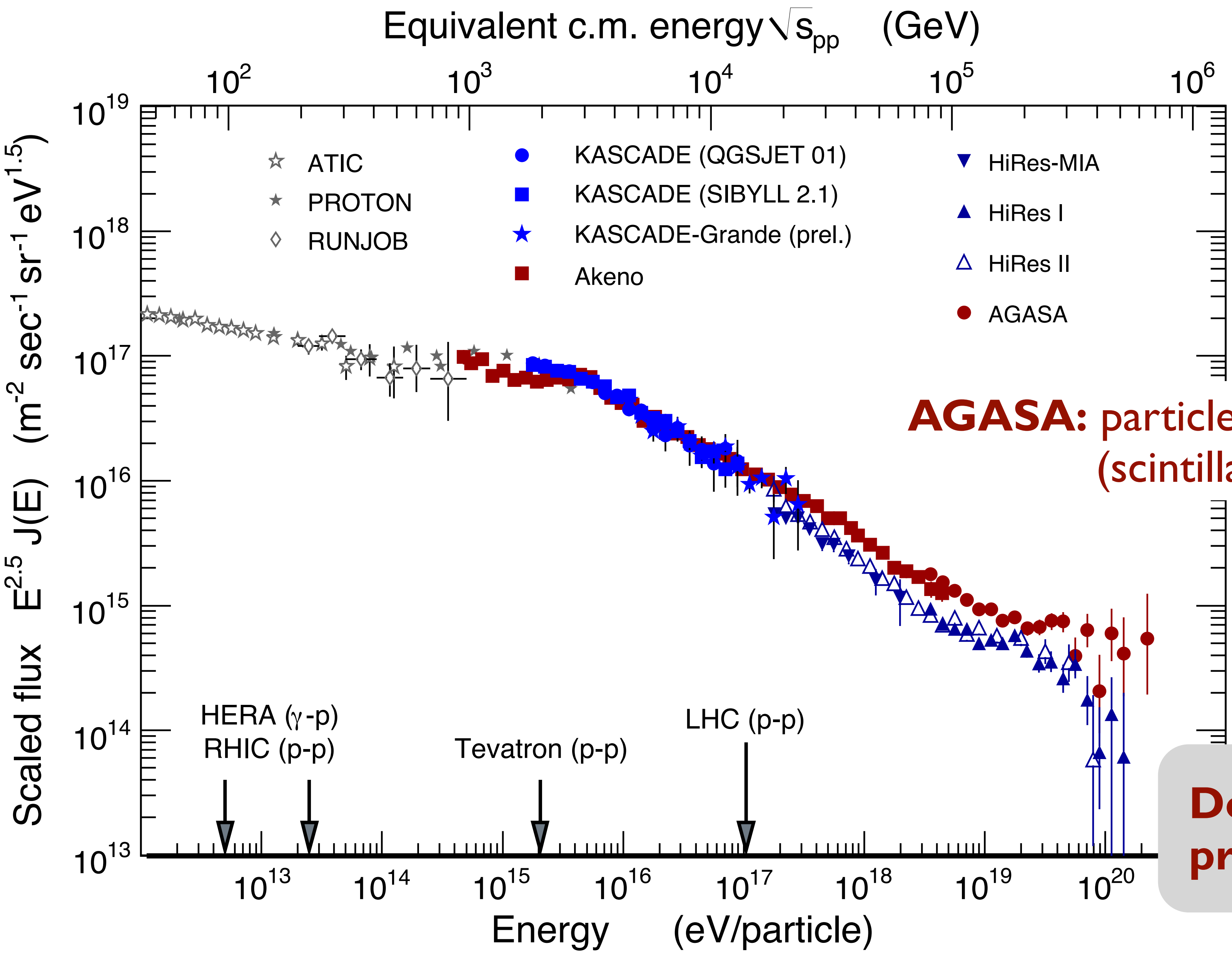
GZK effect: anisotropy expected for light elements



GZK effect: source region for E > 6×10^{19} eV

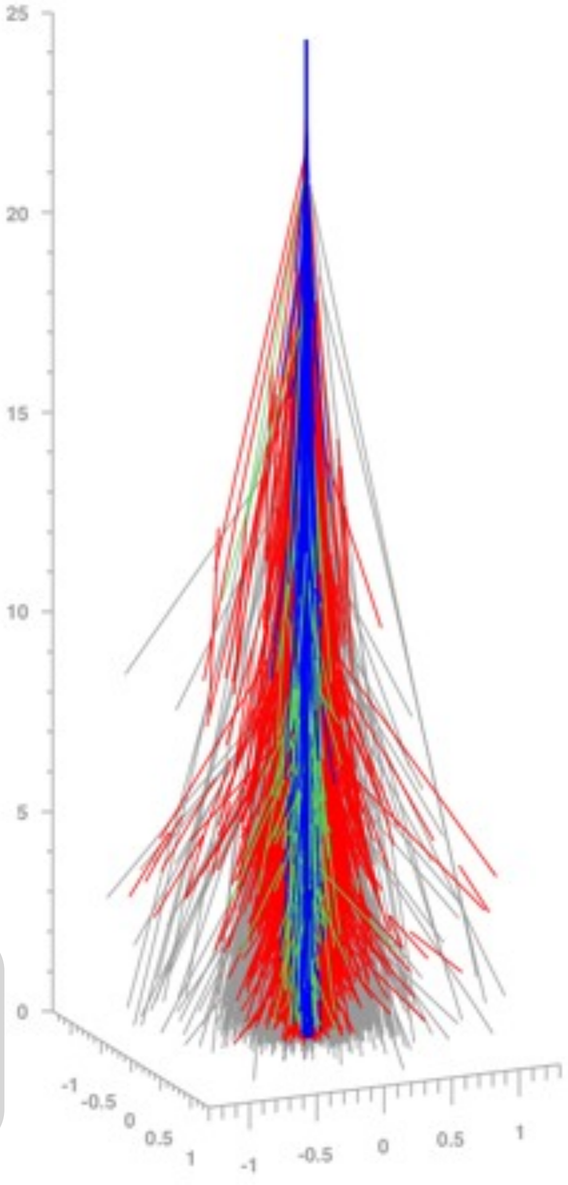
www.atlasoftheuniverse.com

Status of some years ago



AGASA: particles at ground
(scintillator array)

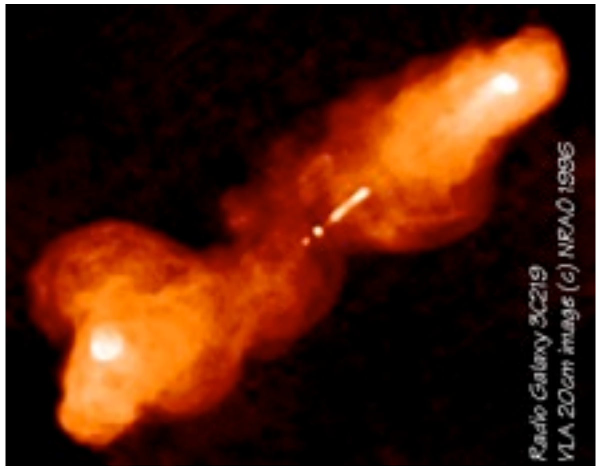
Does GZK suppression exist ?



HiRes Fly´s Eye: longitudinal shower profile
(fluorescence telescopes)

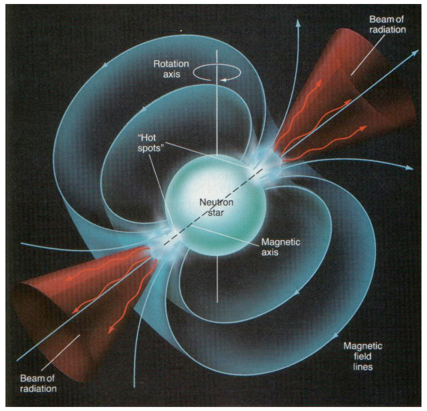
- **Flux data contradictory**
- **Composition: protons ?**
- **Apparent isotropy**

Exotic source and propagation scenarios ?



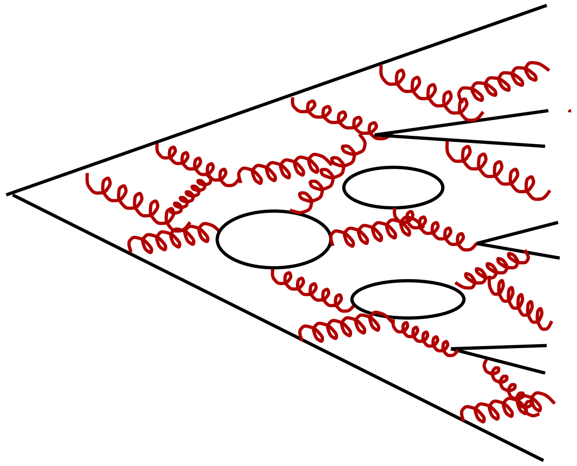
Active Galactic Nuclei (AGN):
Black Hole of $\sim 10^9$ solar masses

Magnetars:
magnetic field
up to $\sim 10^{15}$ G



	Process	Distribution	Injection flux
AGNs, GRBs, ... (☆)	Diffuse shock acceleration	Cosmological	p ... Fe
Young pulsars (☆☆)	EM acceleration	Galaxy & halo	mainly Fe
X particles (☆☆☆)	Decay & particle cascade	(a) Halo (SHDM) (b) Cosmological	ν, γ-rays and p
Z-bursts (☆☆☆☆)	Z^0 decay & particle cascade	Cosmological & clusters	ν, γ-rays and p

Super-heavy particles,
topological defects:
$M_X \sim 10^{23}$ - 10^{24} eV

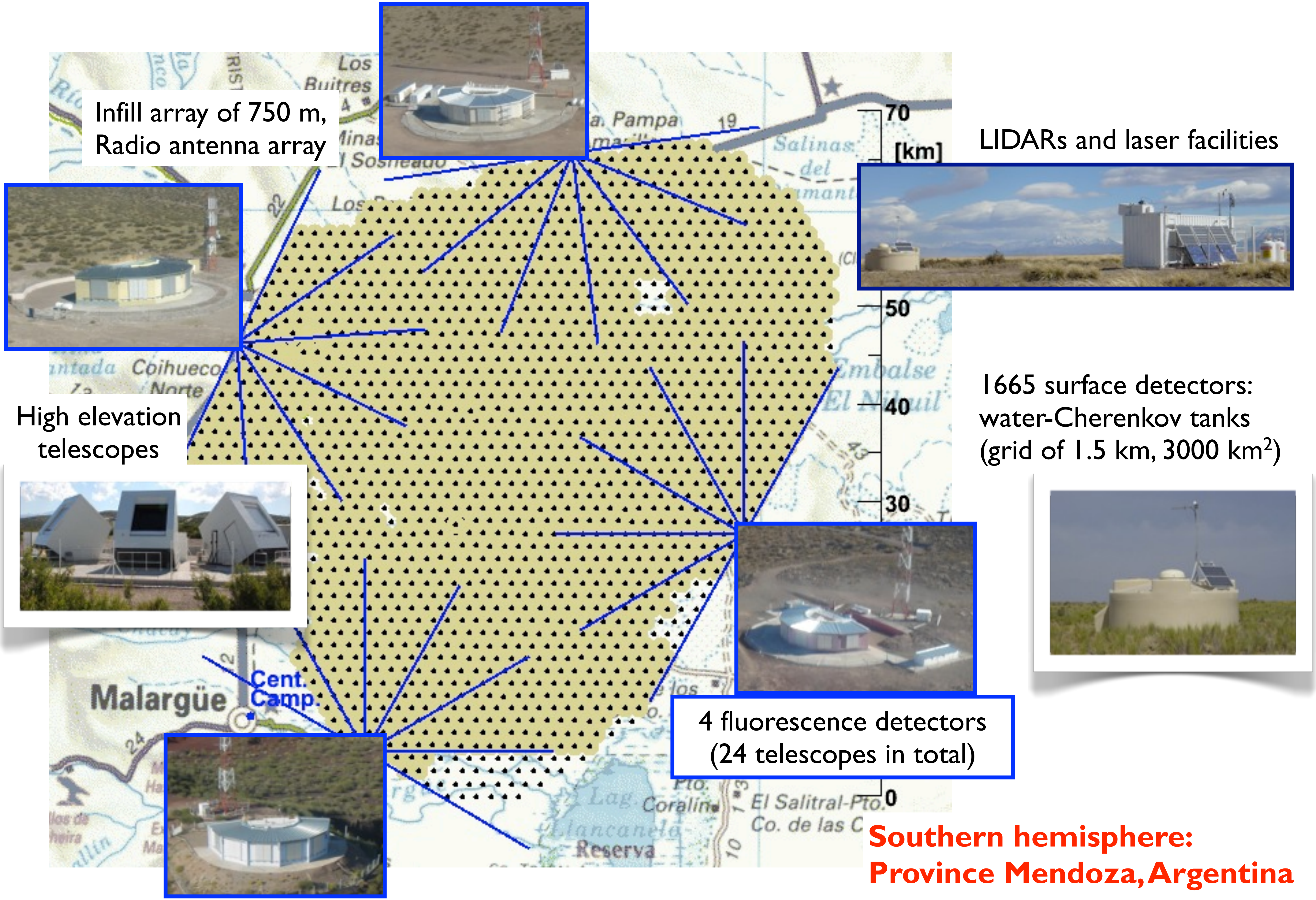


large fluxes of
photons and
neutrinos

(RE, Nijmegen Summer School, 2006)

New generation of cosmic ray detectors

The Pierre Auger Observatory



Infill array of 750 m,
Radio antenna array

LIDARs and laser facilities

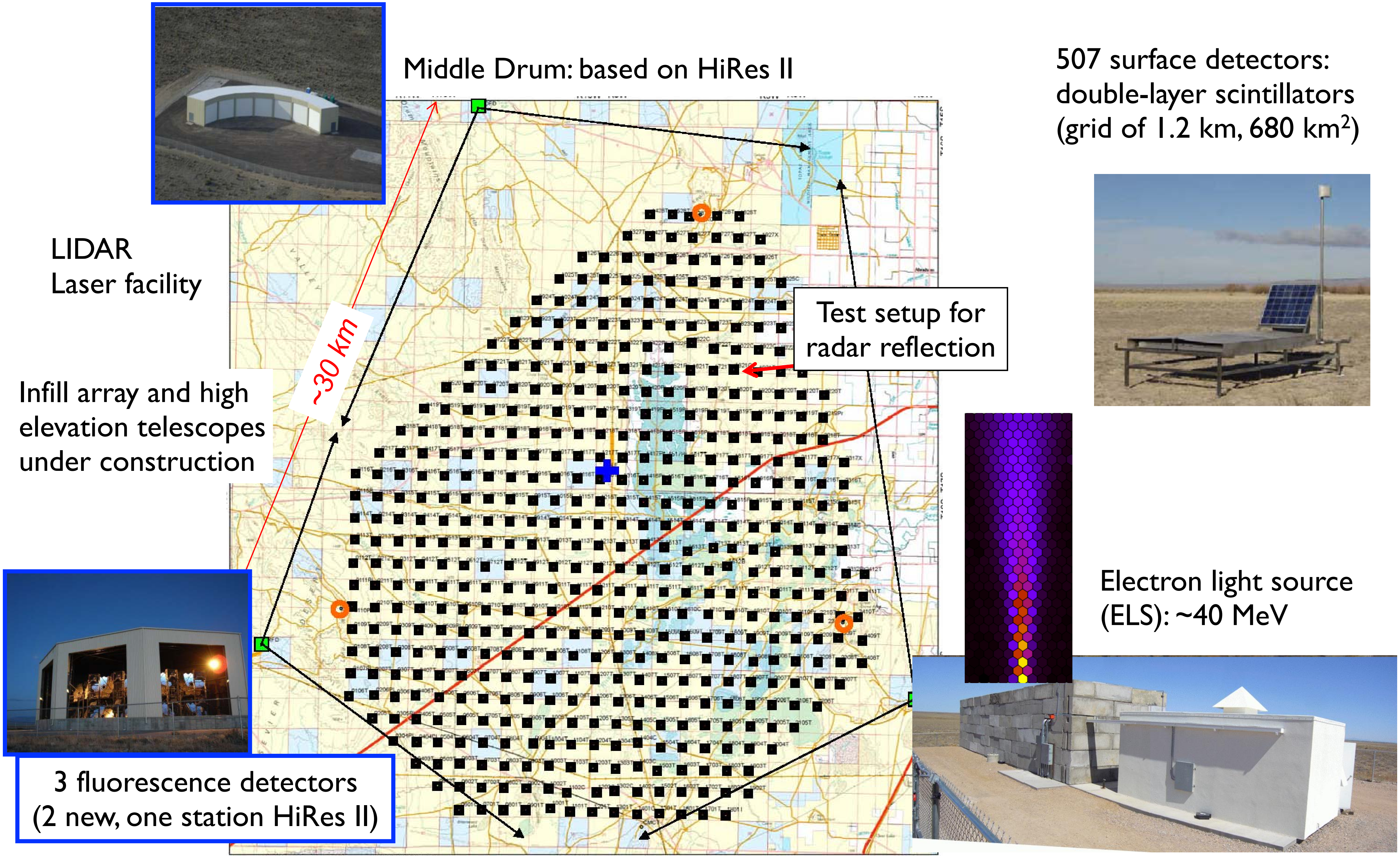
1665 surface detectors:
water-Cherenkov tanks
(grid of 1.5 km, 3000 km^2)

High elevation
telescopes

4 fluorescence detectors
(24 telescopes in total)

Southern hemisphere:
Province Mendoza, Argentina

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

Infill array and high
elevation telescopes
under construction

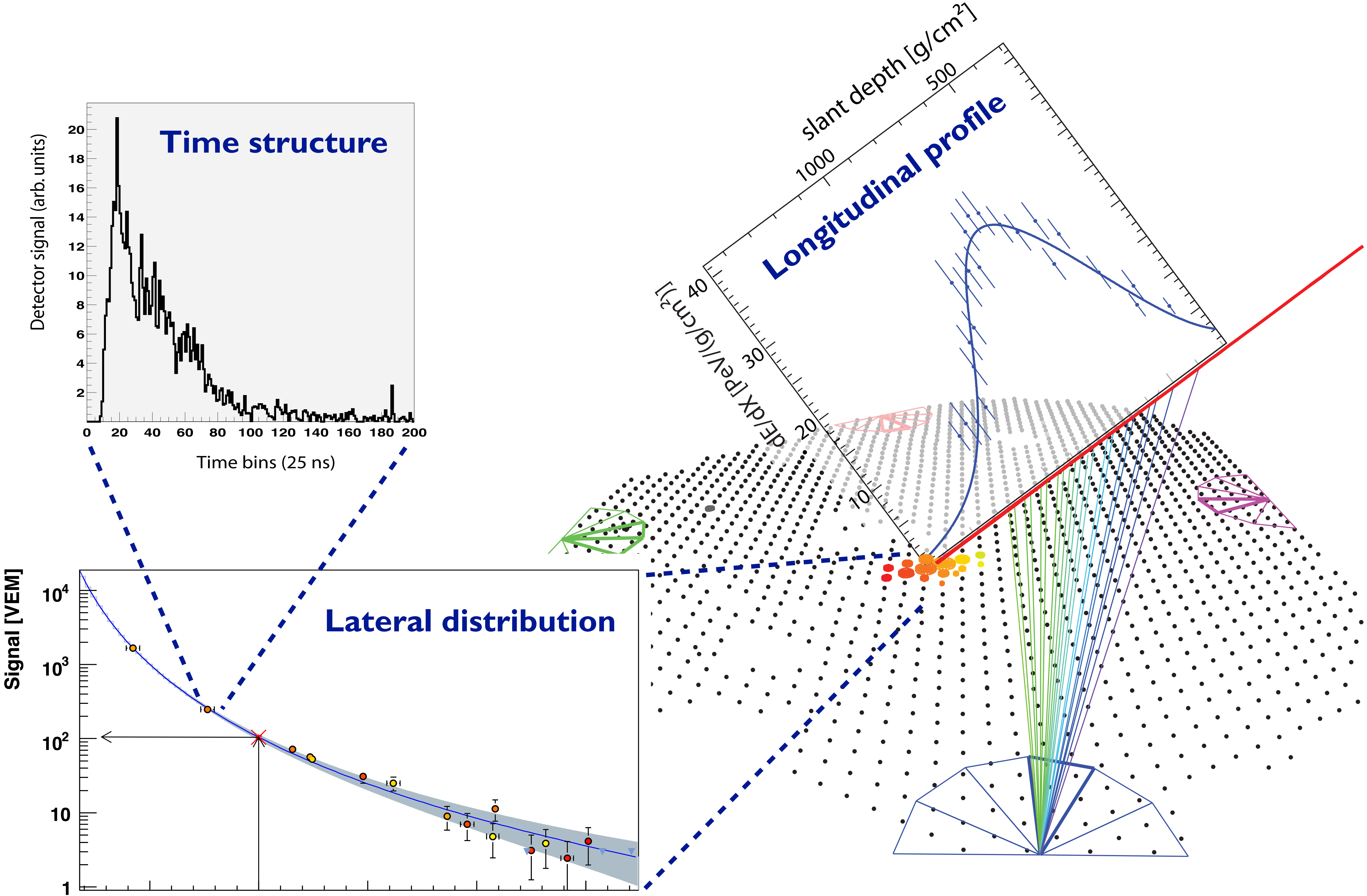
Test setup for
radar reflection

Electron light source
(ELS): ~40 MeV

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

Northern hemisphere: Utah, USA

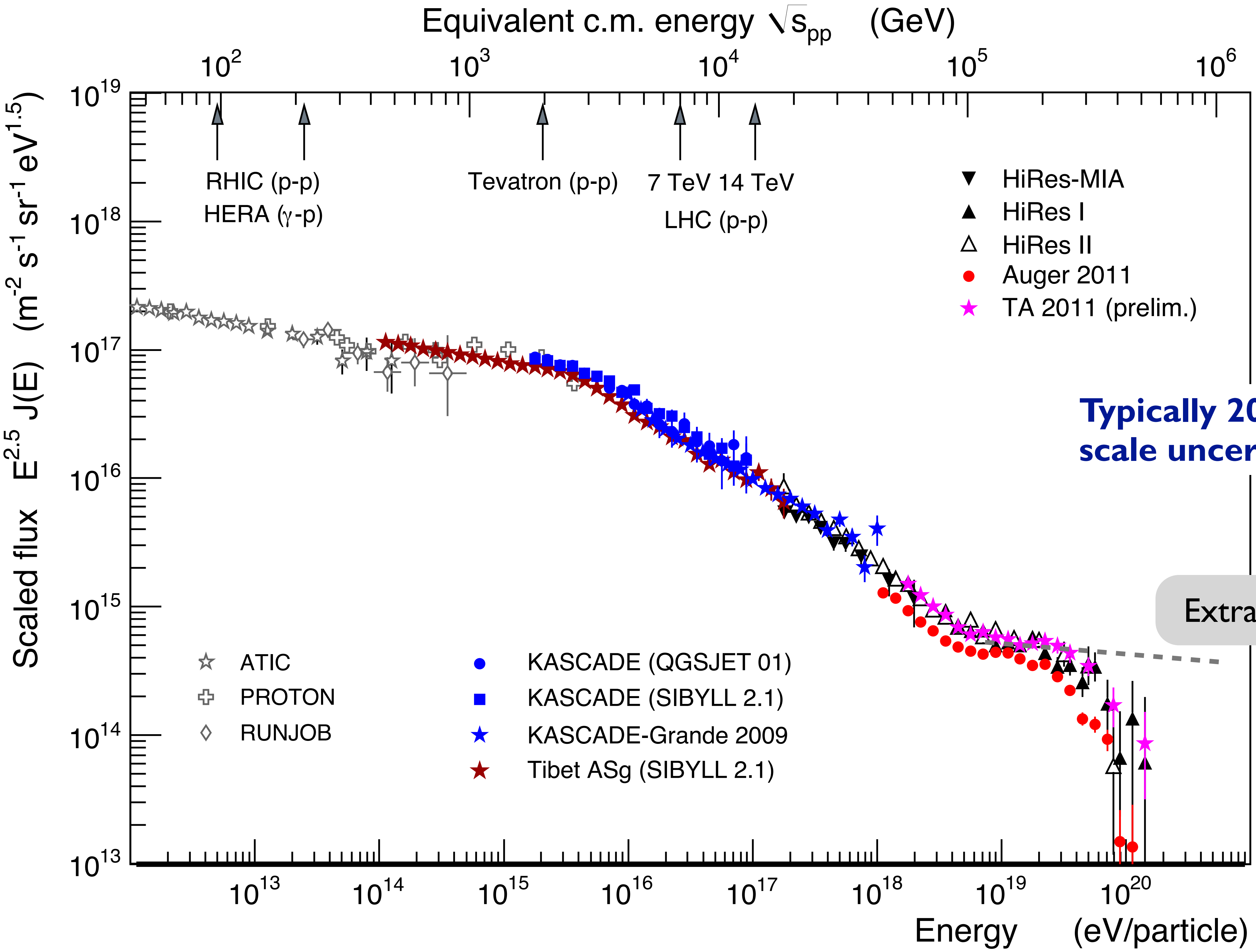
Several shower observables



Example: event observed by Auger

New results on ultra-high energy cosmic rays

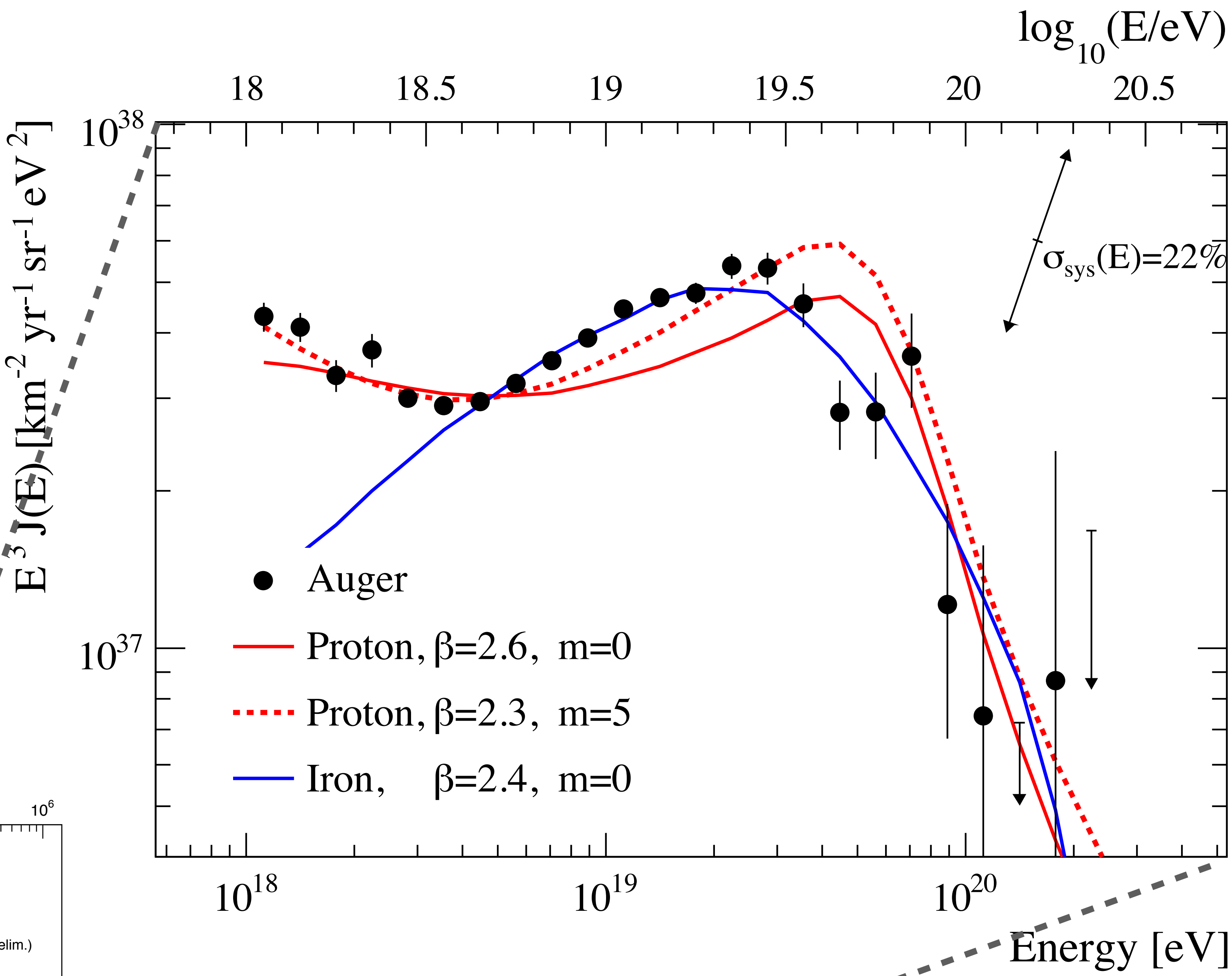
Unambiguous detection of flux suppression



Typically 20% energy scale uncertainty

Extrapolated flux

Flux suppression compatible with GZK effect ?

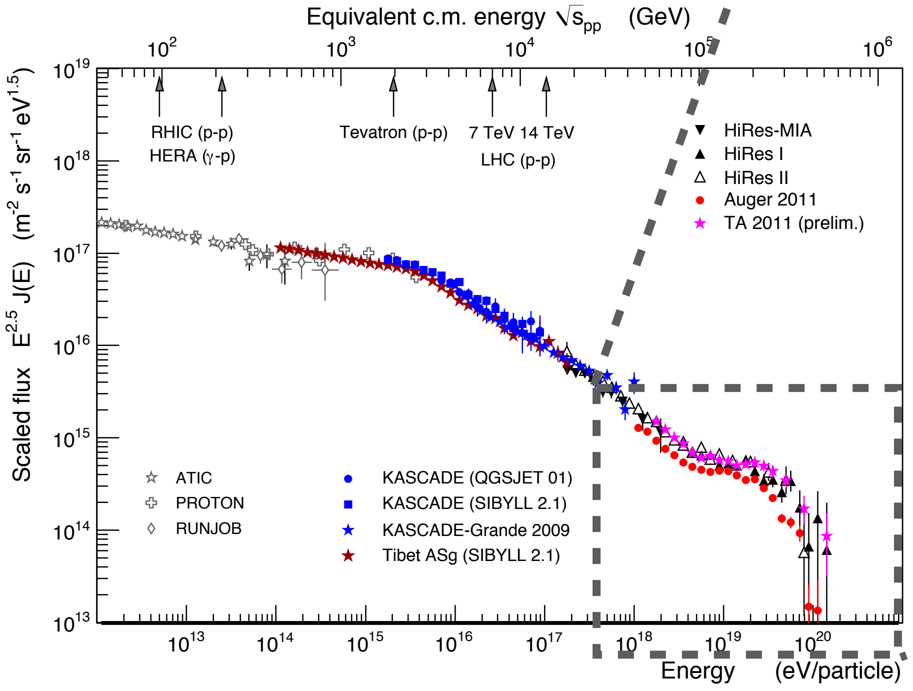


Proton dominated flux

Ankle: e^+e^- pair production

Suppression: delta resonance

(Dip model of Berezinsky et al.)



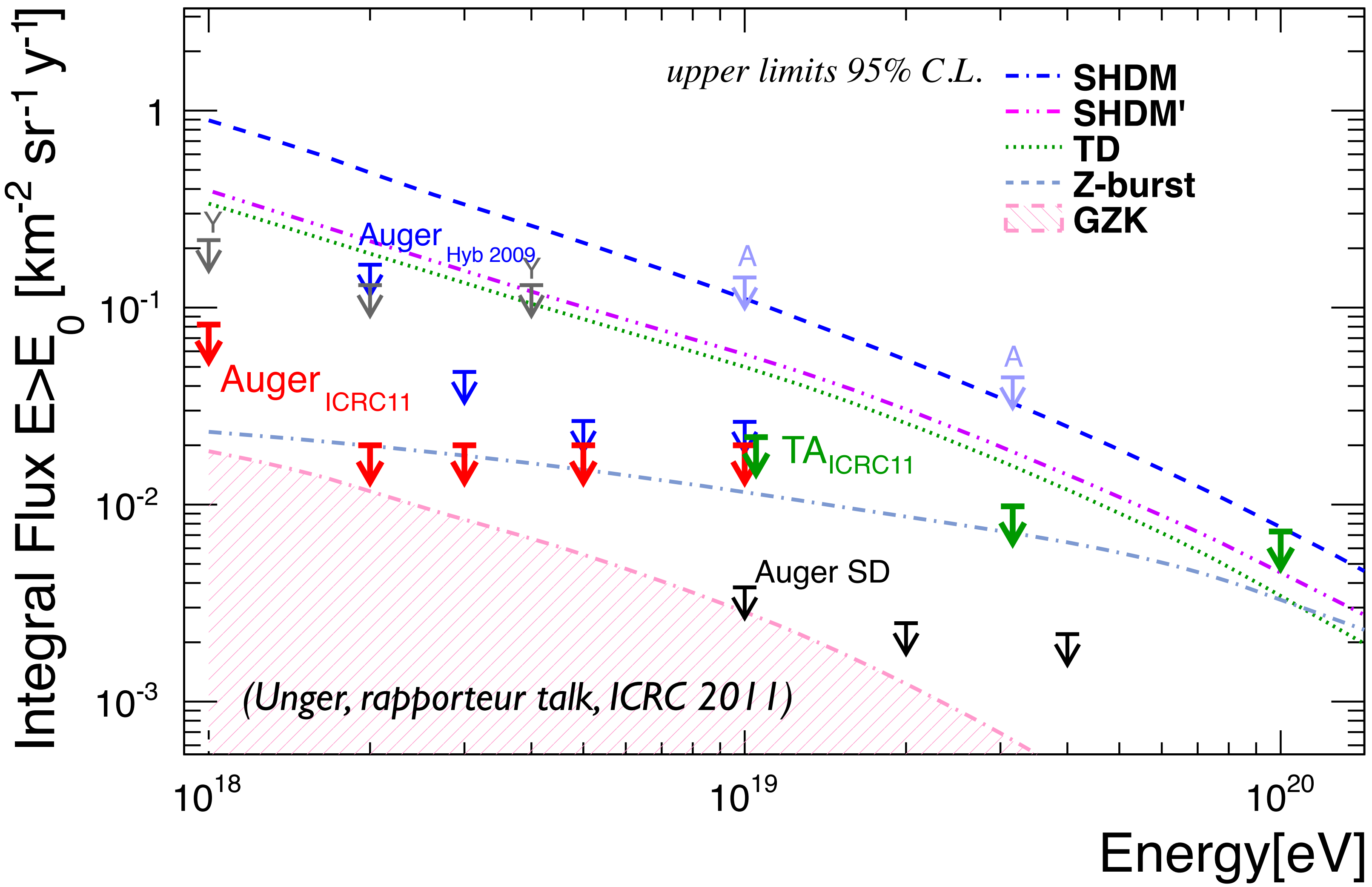
Iron dominated flux

Ankle: transition to galactic sources

Suppression: giant dipole resonance

Limits on exotic source scenarios

Searches for photon- and neutrino-induced showers: integral limits



Super-heavy dark matter
Topological defects

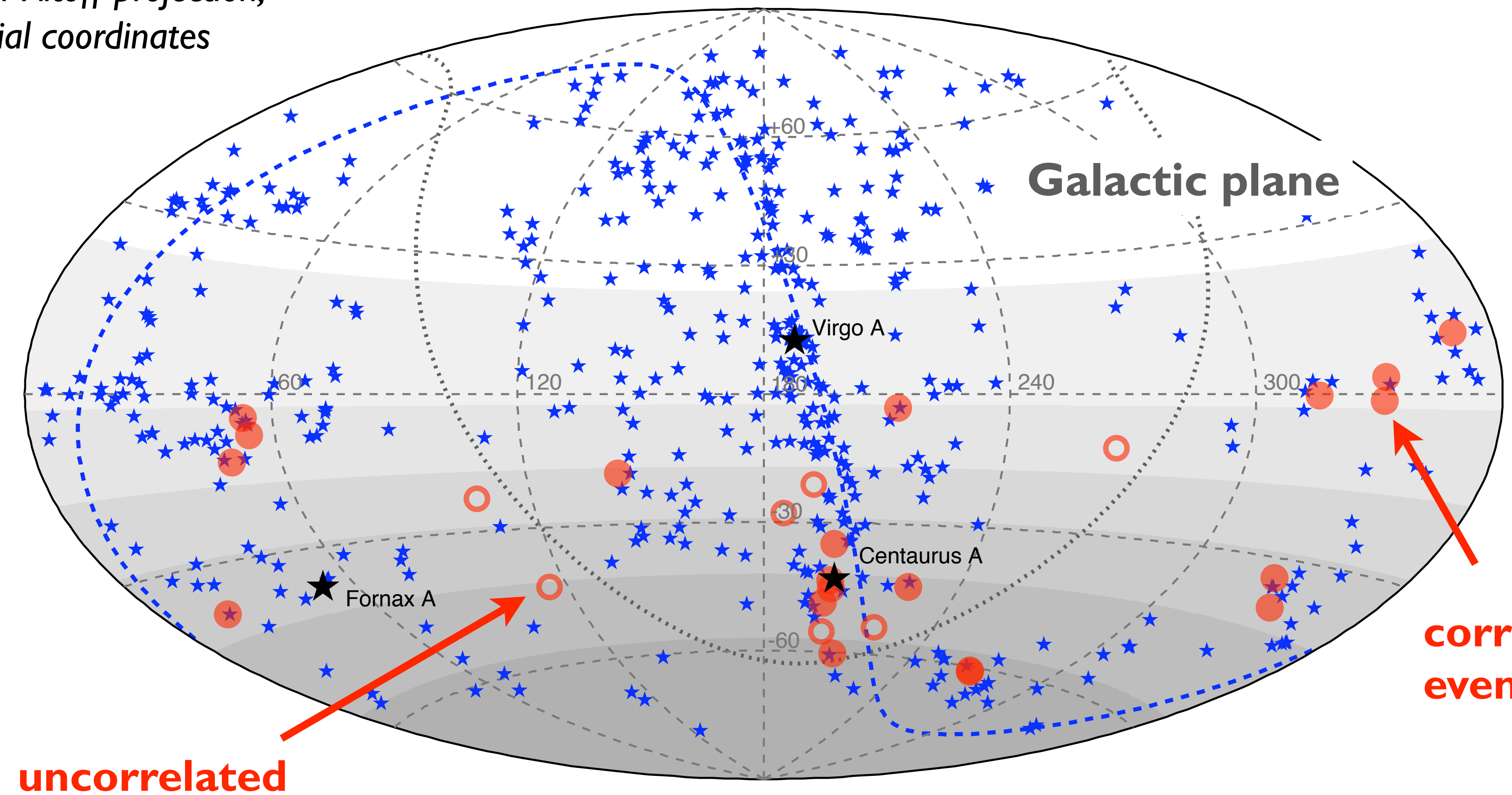
Photon showers penetrate deeper in the atmosphere, contain almost no muons

Most exotic source scenarios excluded or strongly disfavoured, similar results for ultra-high energy neutrino searches

Anisotropy of arrival direction distribution

Auger Collab. 2007

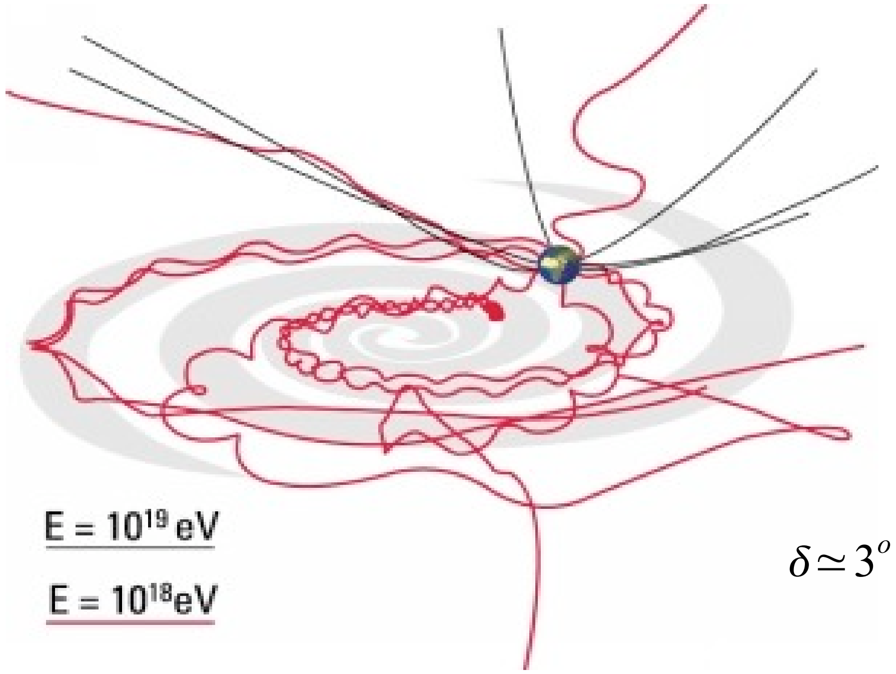
Hammer-Aitoff projection,
Equatorial coordinates



Less than 1% chance probability

uncorrelated events (7)

correlated events (20)



Active Galactic Nuclei: sources or tracer of sources

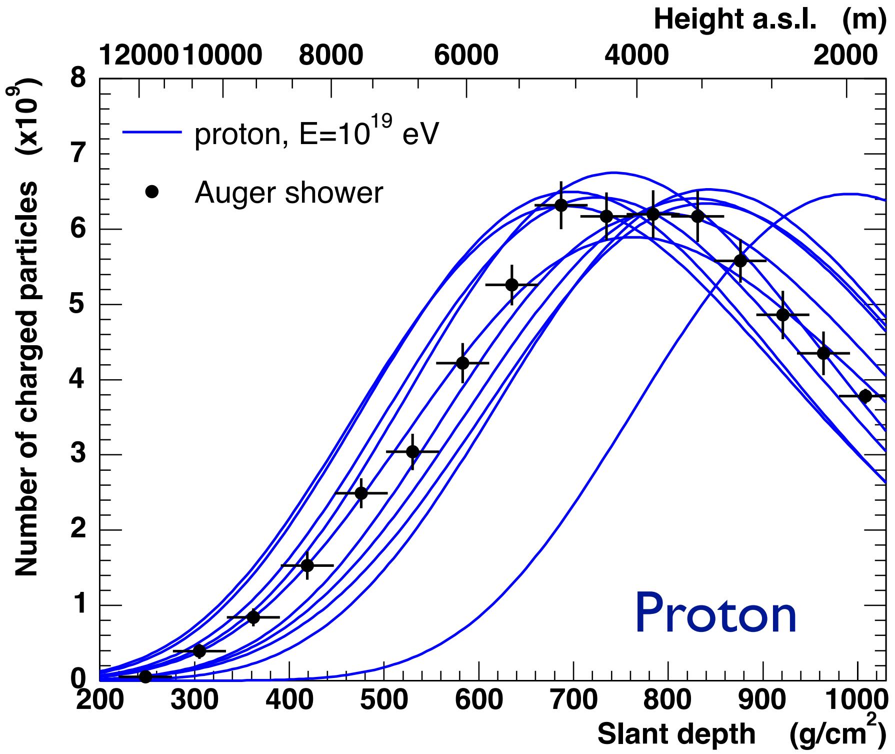
Small magnetic deflection: protons or light nuclei

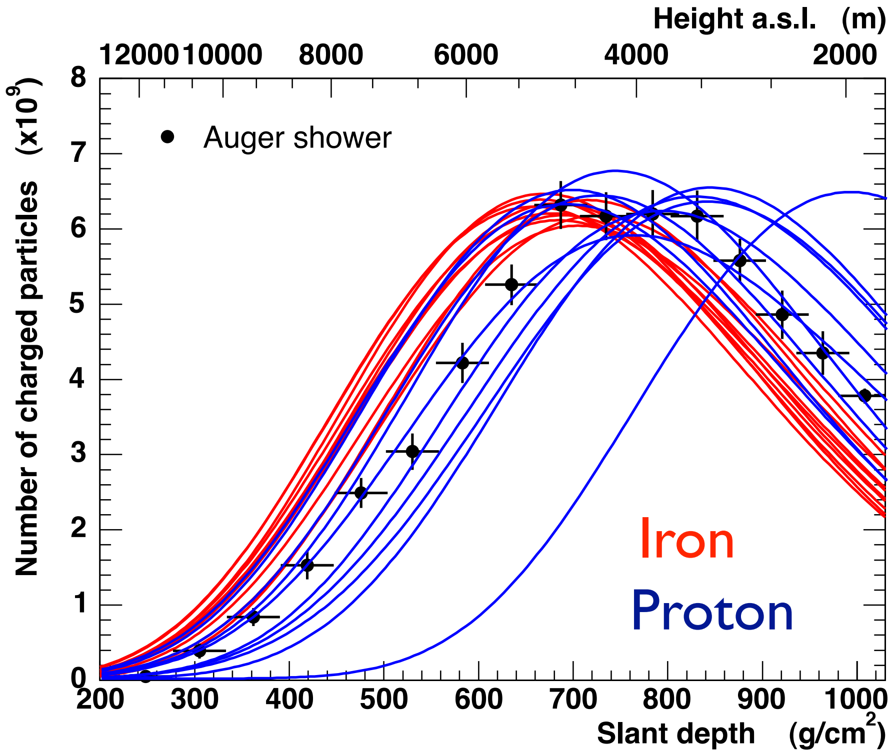
$$\delta \simeq 3^o \frac{B}{3\,\mu G} \frac{L}{kpc} \frac{6\times 10^{19} eV}{E/Z}$$

70% of particles with E > 5.5 10^{19} eV correlated with AGNs (D < 75 Mpc) within 3.1°, 21% expected

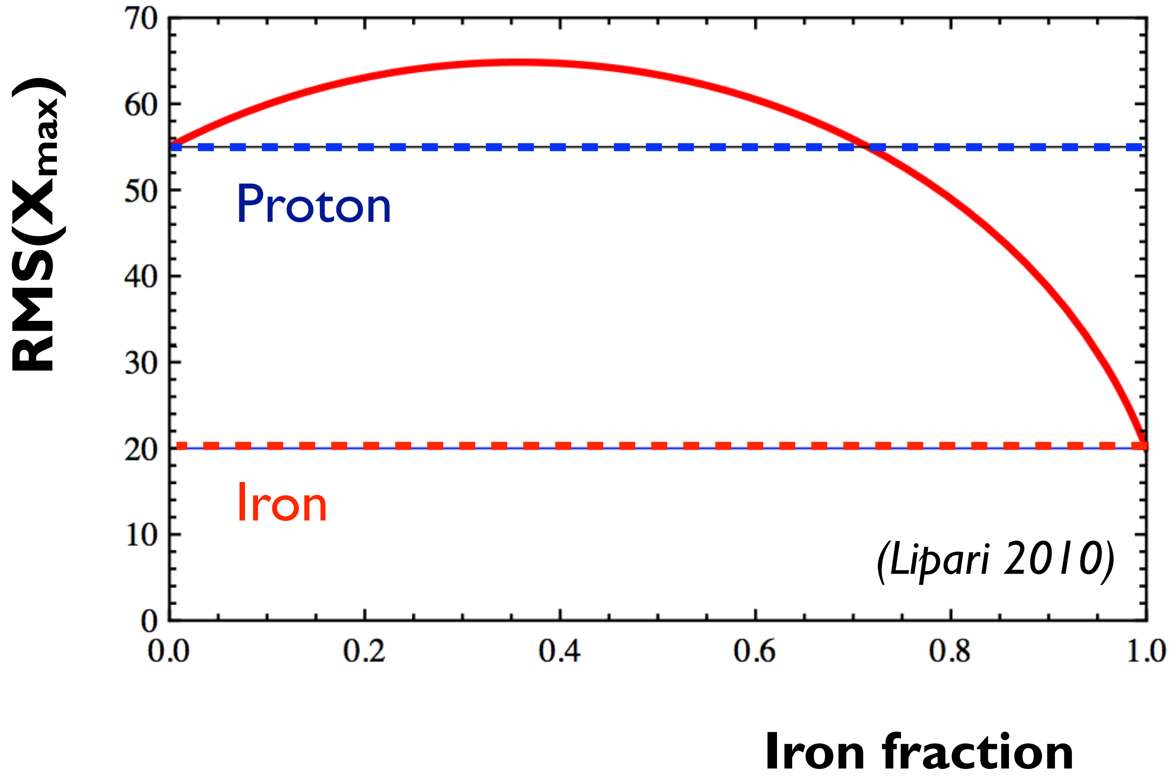
What about direct composition measurements ?

Auger data on shower profiles





Fluctuations of depth of shower maximum



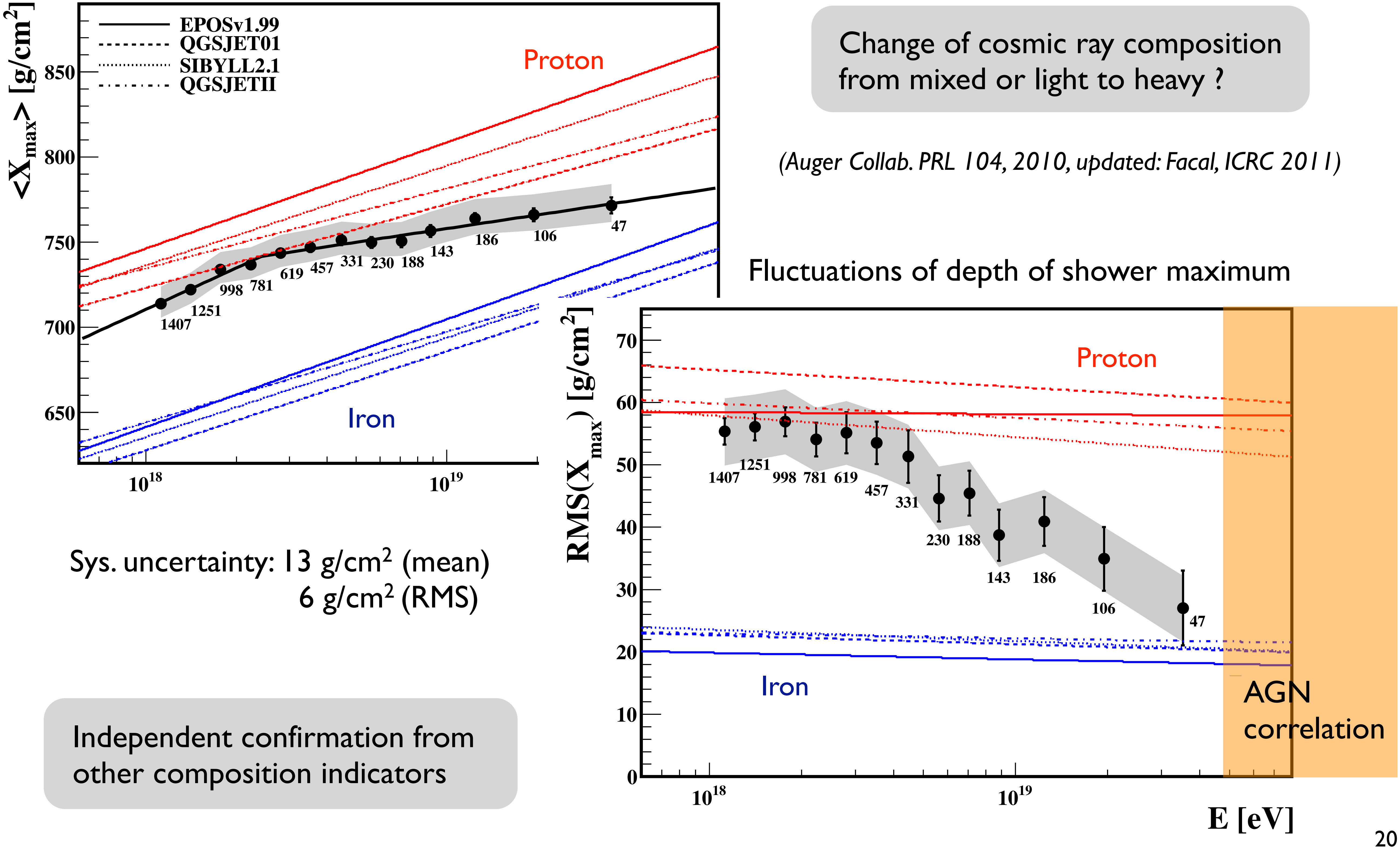
Mean depth of shower profiles and shower-to-shower fluctuations as measure of composition

Example: event measured by Auger Collab.

Auger Observatory: composition data

Mean depth of shower maximum

Fluctuations of depth of shower maximum



AGN correlation

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

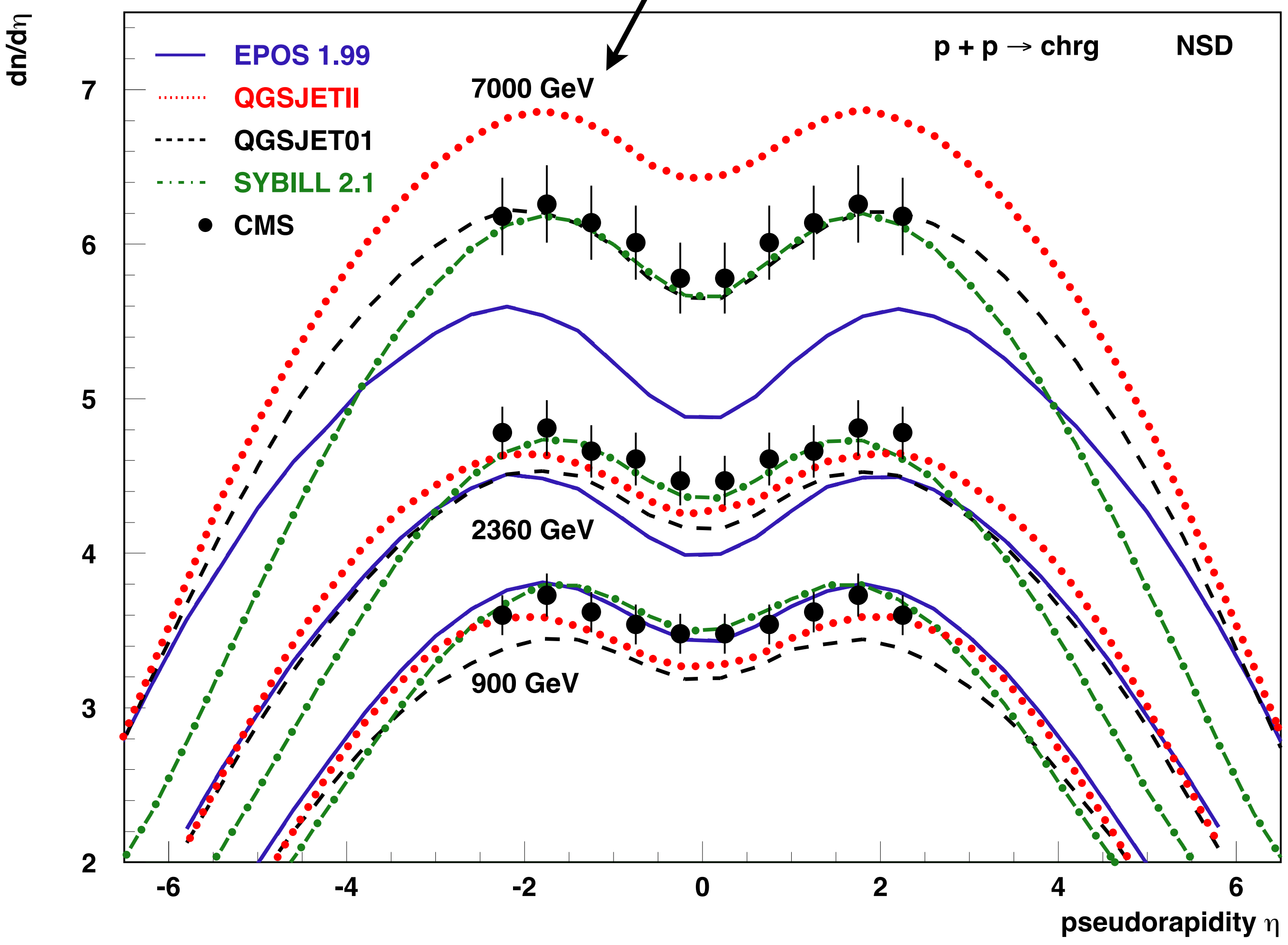
(Auger Collab. PRL 104, 2010, updated: Facal, ICRC 2011)

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

Independent confirmation from other composition indicators

Hadronic interaction models and first LHC data

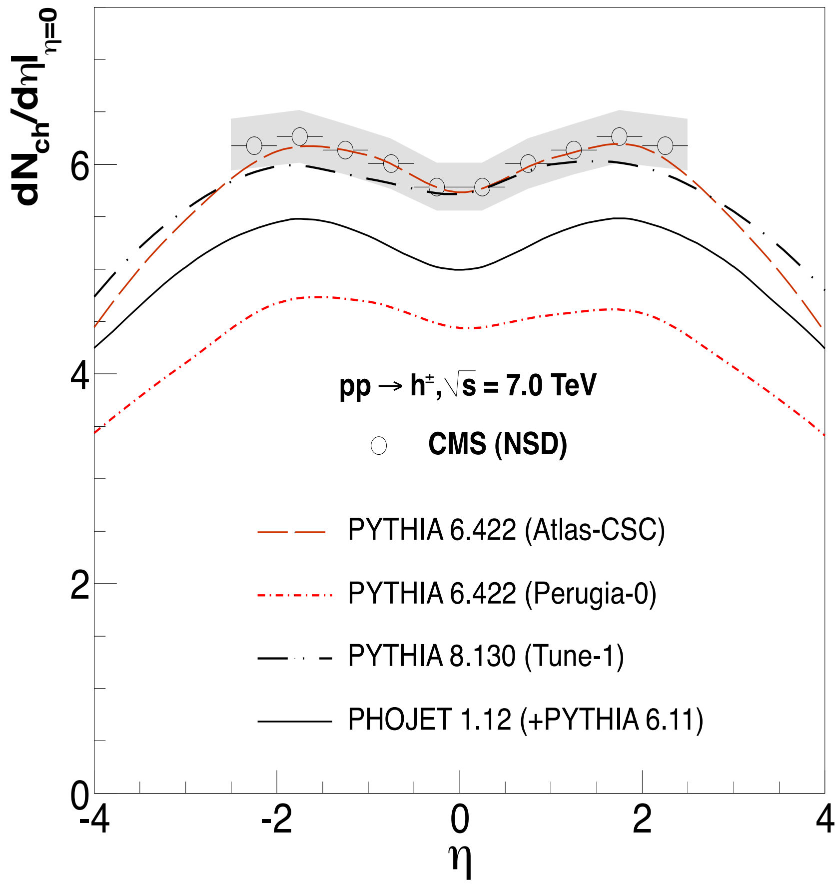
Protons: $E_{lab} = 3 \times 10^{16}$ eV



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

Detailed LHC comparison

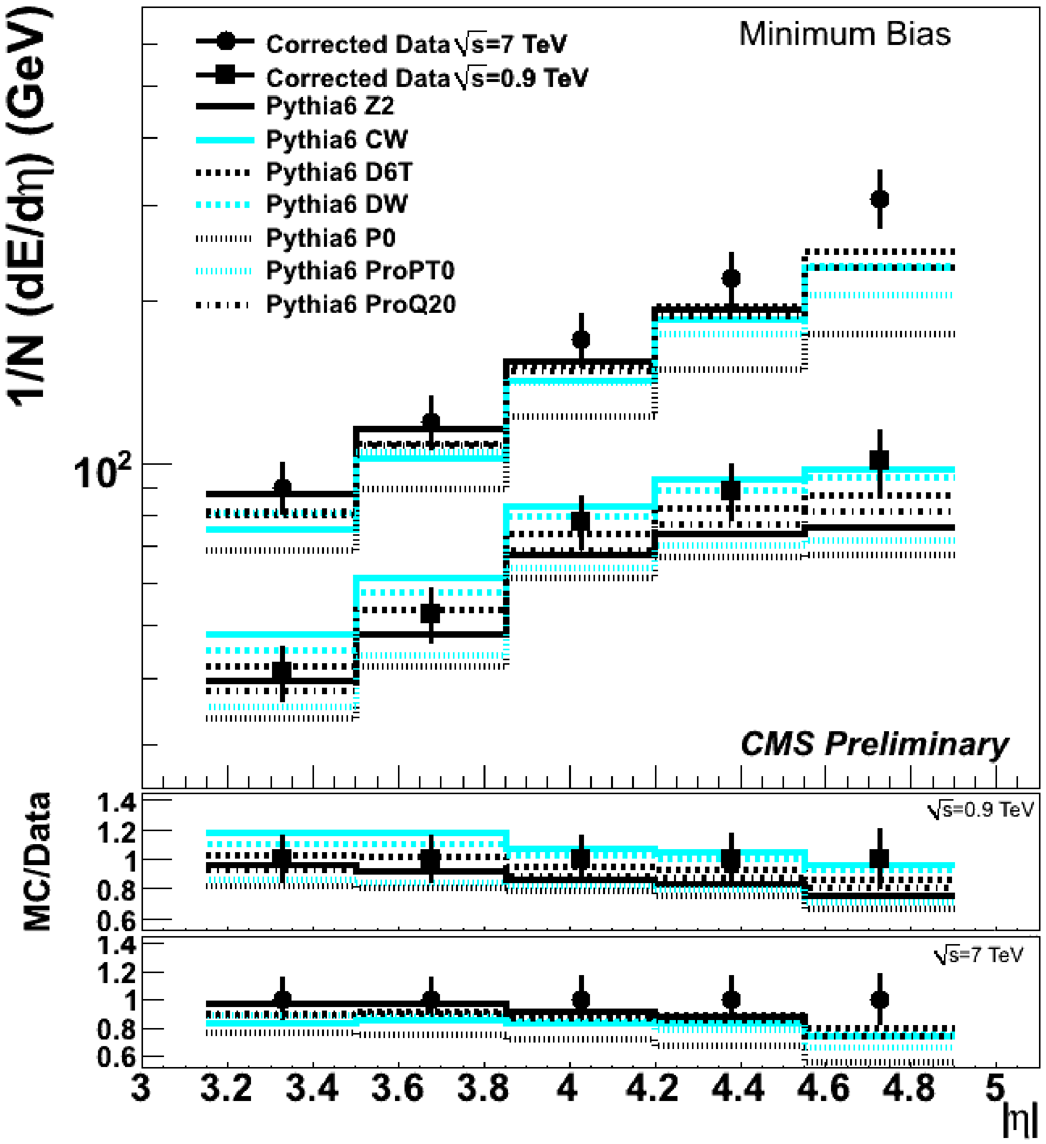
(D'Enterria et al., Astropart. Phys. 35, 2011)



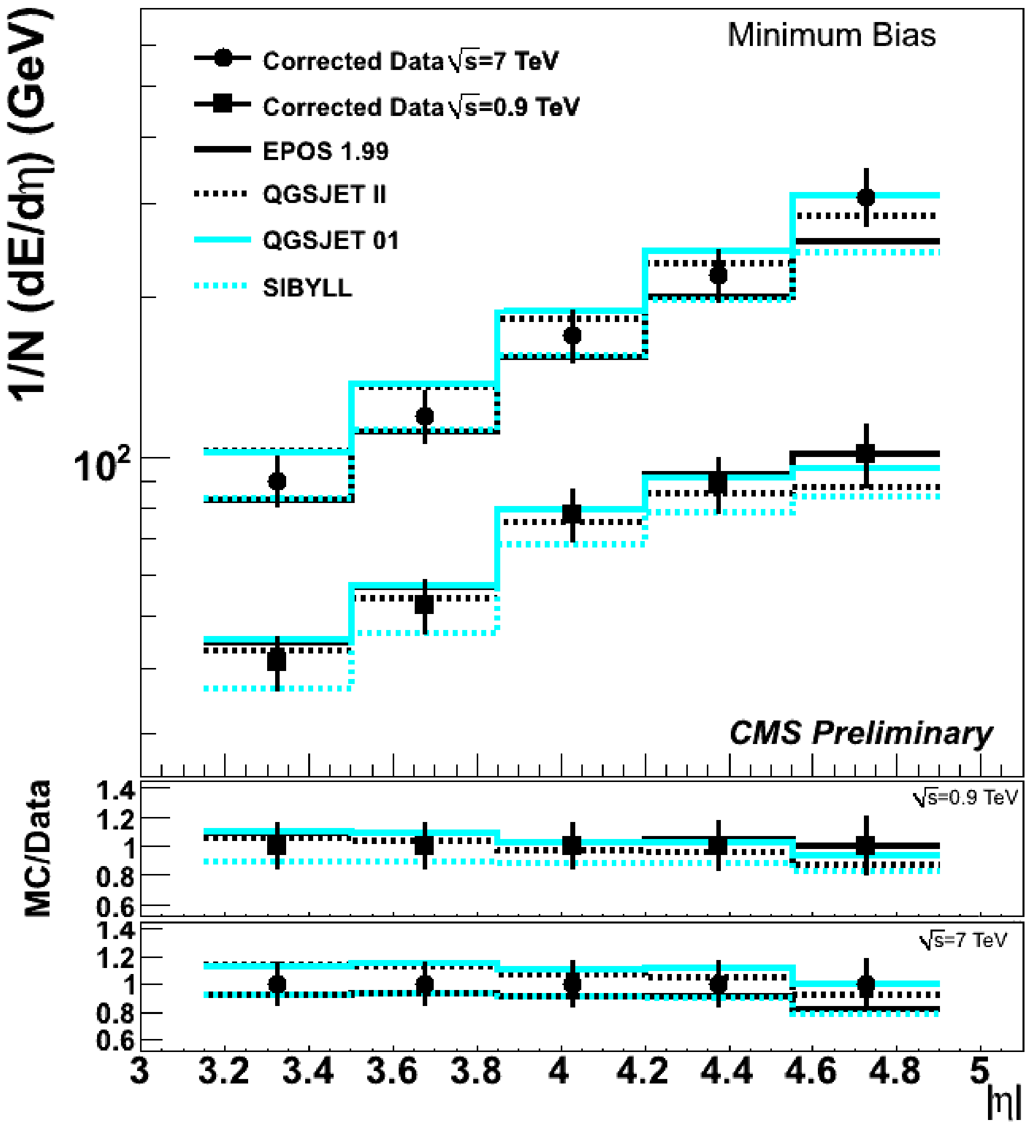
Models for air showers typically even better in agreement with LHC data

Energy flow in forward calorimeter

PYTHIA as typical HEP model



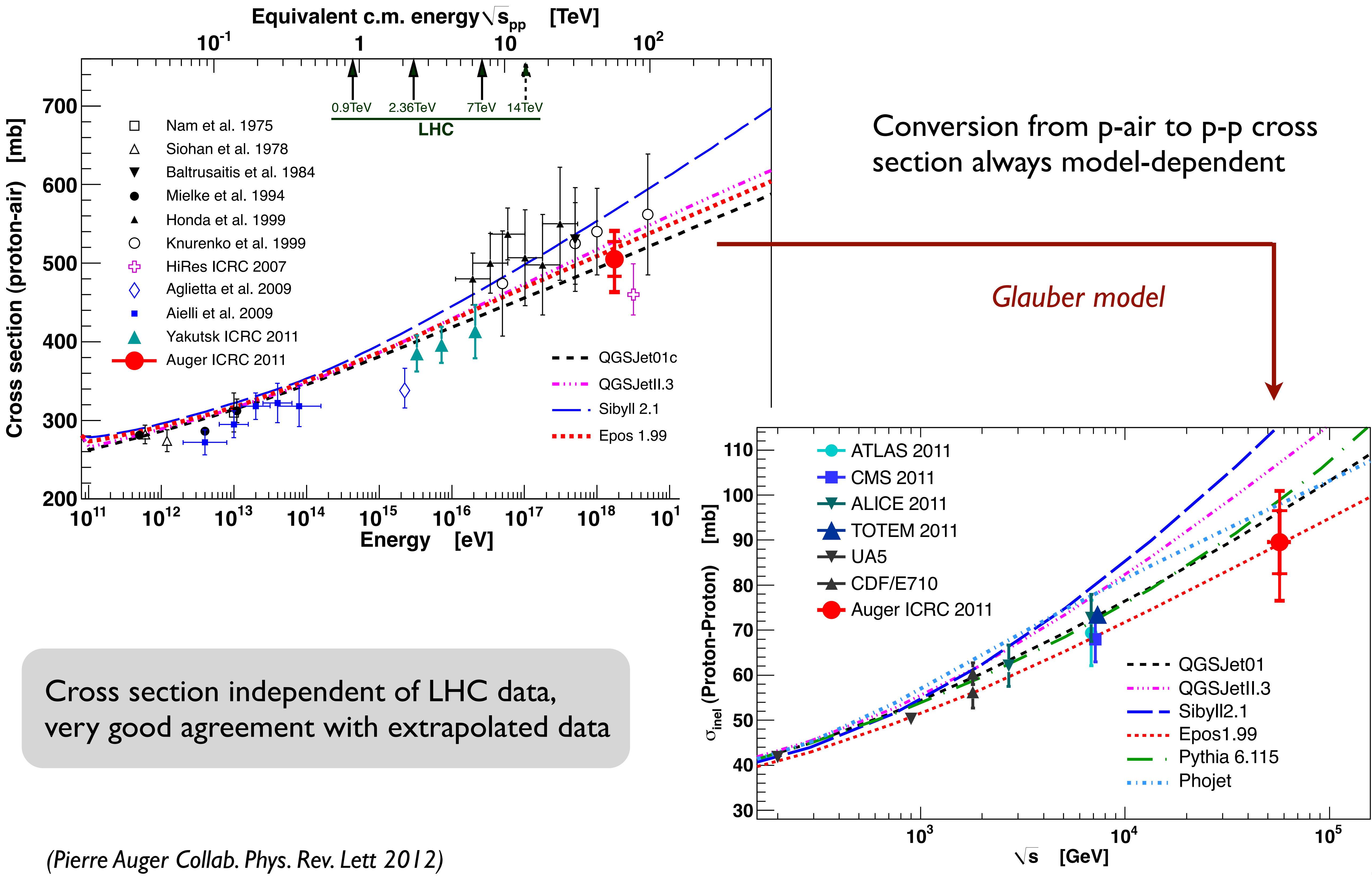
Cosmic ray interaction models



(CMS Collab., EPS 2011)

Cosmic ray models used directly by LHC collaborations

Cross section in good agreement with proton hypothesis



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

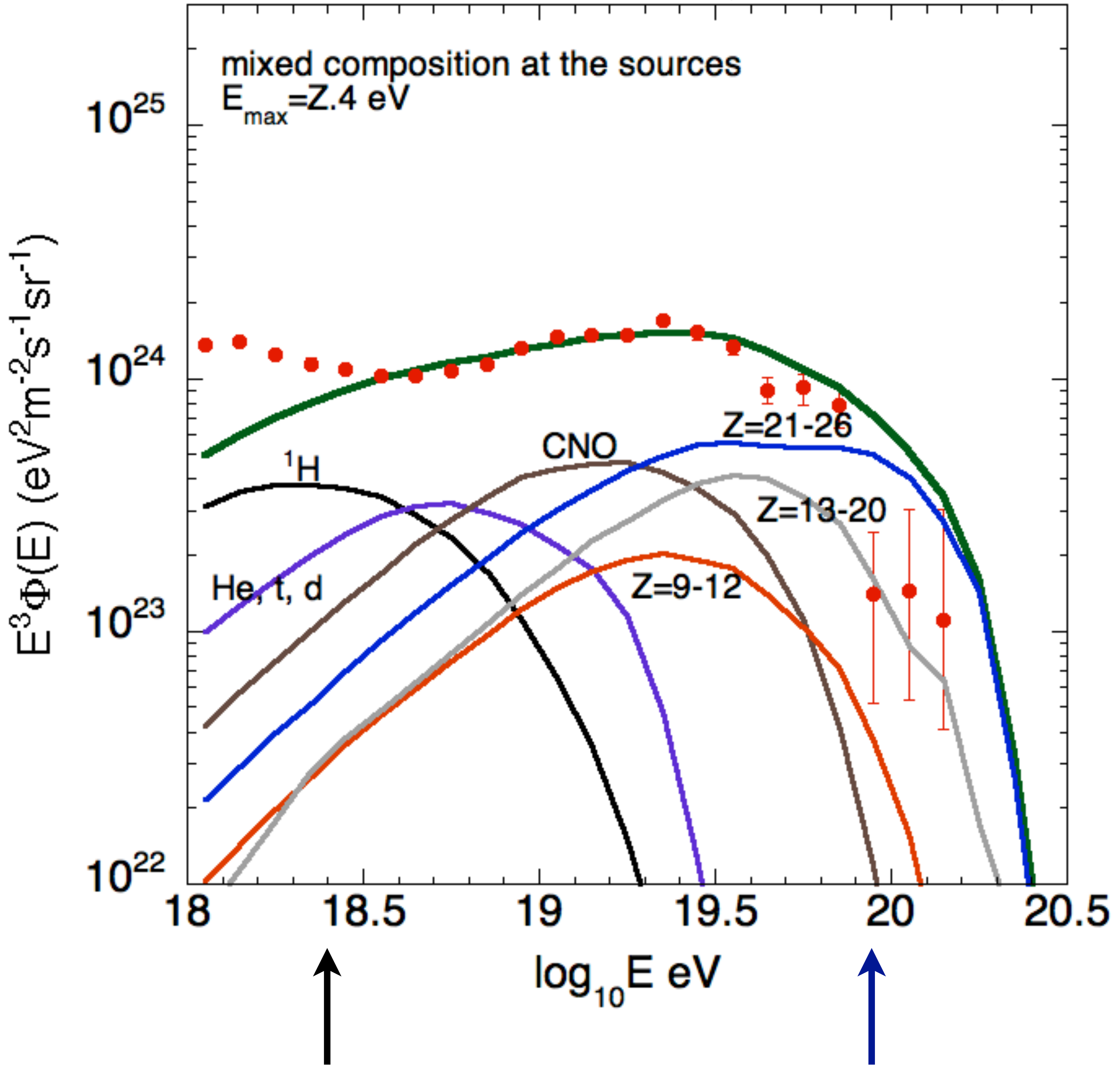
Cross section independent of LHC data, very good agreement with extrapolated data

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

Upper end of source energy spectrum seen ?

Particle flux

(Allard, 1111.3290)



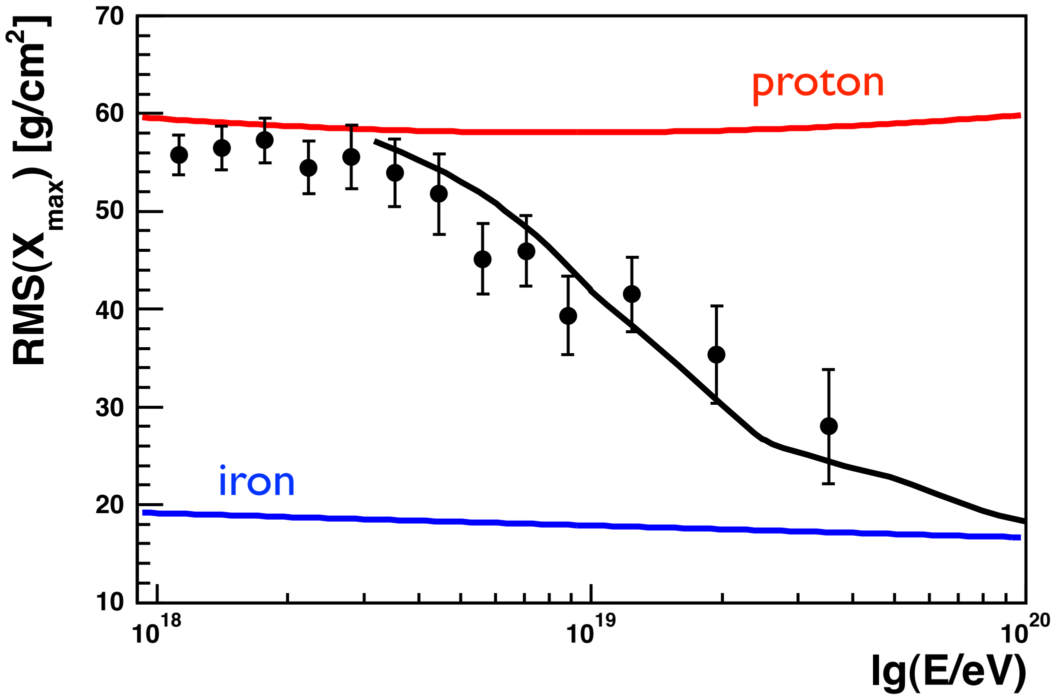
Protons $E_{max,p} = 10^{18.4}$ eV

Iron $E_{max, Fe} = 26\ E_{max,p}$
$= 10^{20}$ eV

Natural transition to heavier composition at high energy !

Fluctuations of X_{max}

(Unger 2012)



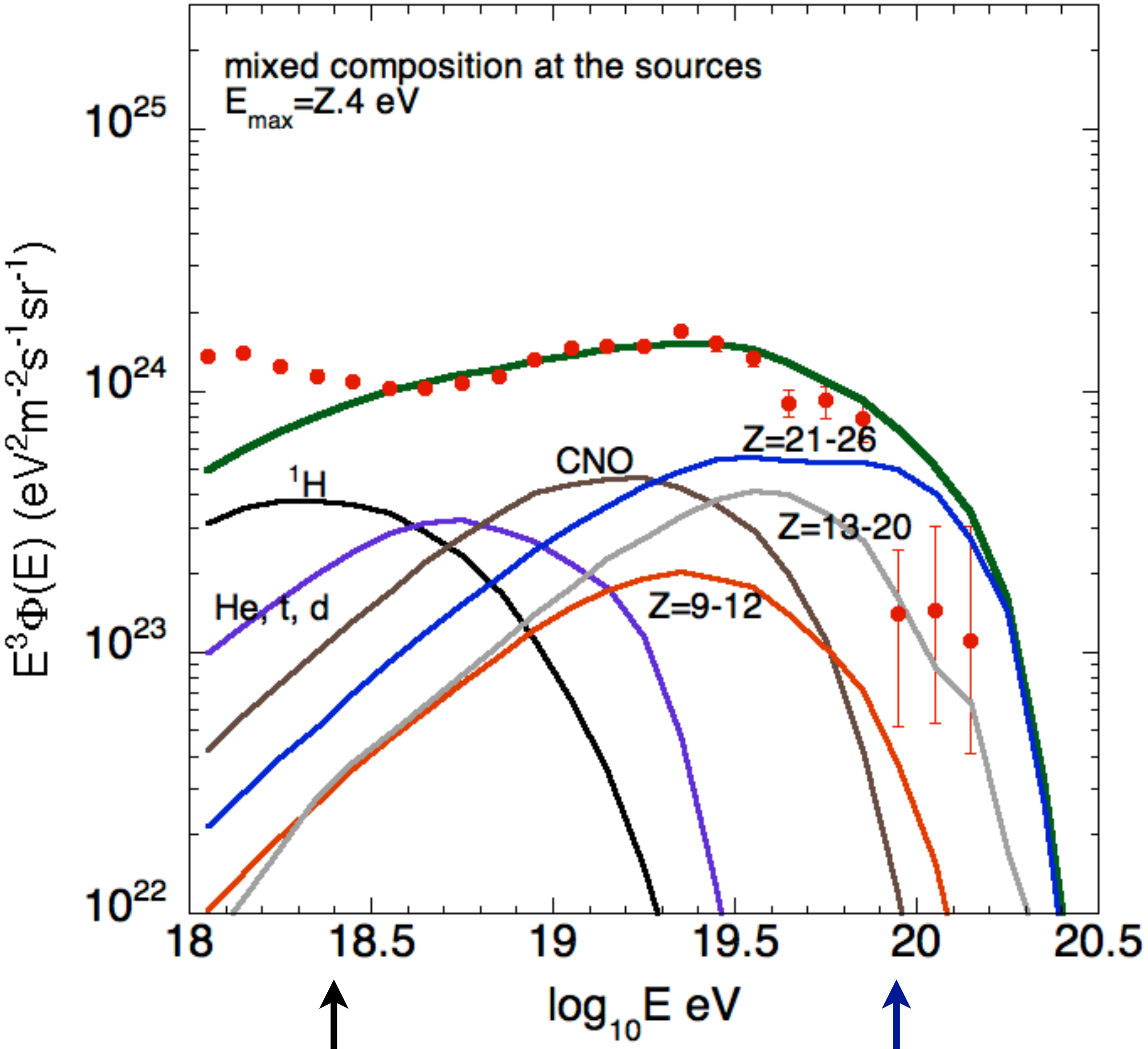
Different interpretation:
Suppression not due mainly to GZK energy-loss effect

(see also Calvez et al. 2010, Aloisio et al. 2011)

Upper end of source energy spectrum seen ?

Particle flux

(Allard, 1111.3290)



Protons $E_{max,p} = 10^{18.4}$ eV

Iron $E_{max,Fe} = 26\ E_{max,p}$
$= 10^{20}$ eV

- Charge-dependent maximum injection energy
- Galactic composition
- Hard source injection spectrum

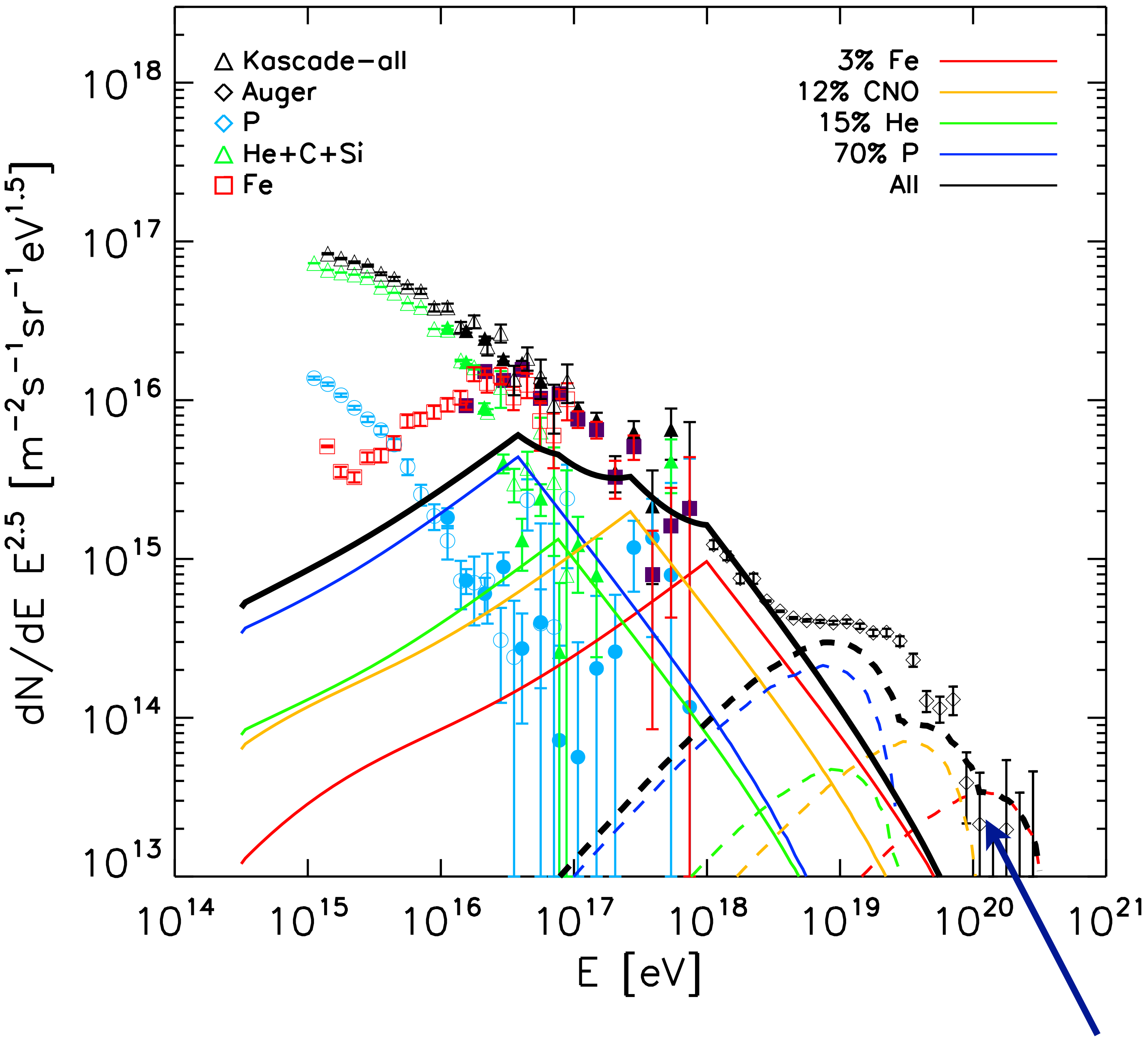
$$\frac{dN}{dE} \sim E^{-(1.0...1.8)}$$

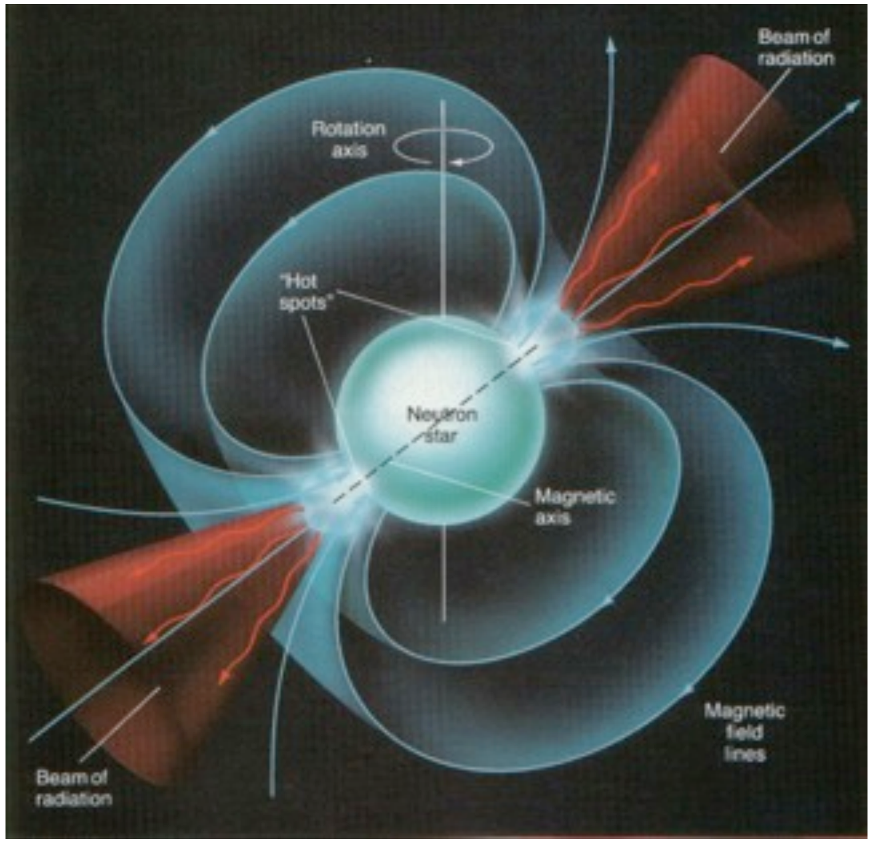
Astrophysics: very exotic result!

(see also Calvez et al. 2010, Aloisio et al. 2011)

Example: magnetar model

(Aron 2003, Olinto, Kotera et al., 2012, Fang et al. 2013)





$$\frac{\mathrm{d}N_{\mathrm{inj}}}{\mathrm{d}E} \sim E^{-1}\left(1+\frac{E}{E_g}\right)^{-1}$$

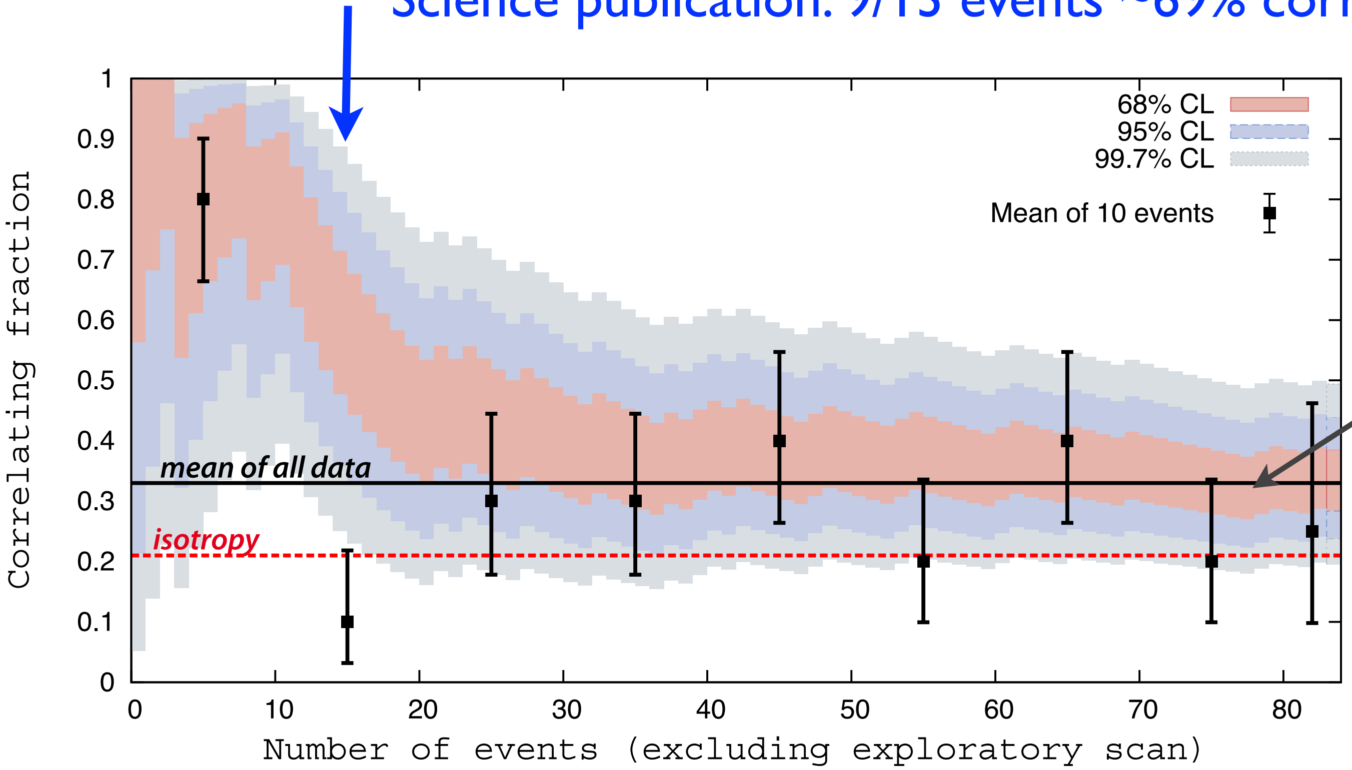
Low-energy part:
many galactic magnetars

High-energy part:
extragalactic (extreme) magnetar

And what about the protons from the AGN correlation?

Auger Observatory (2011)

Science publication: 9/13 events ~69% correlated, expectation for isotropy 21%



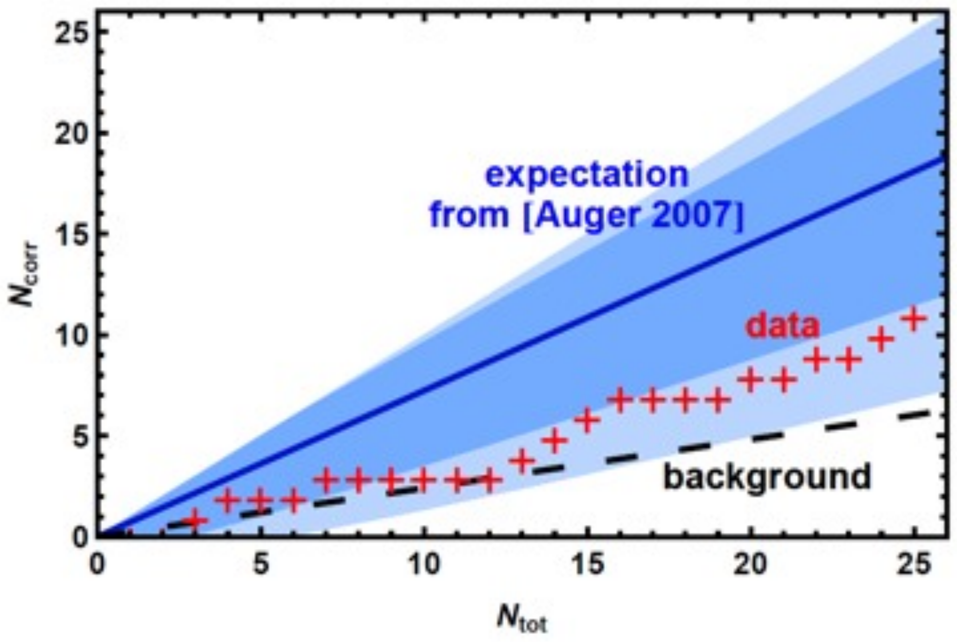
Differential estimate
every 10 events

June 2011: 28 out of 84 correlated
estimate now 33 ± 5% (P = 0.006)

Auger data

- compatible with ~10% protons
- anisotropy could come from ~10% protons

Telescope Array (2012)



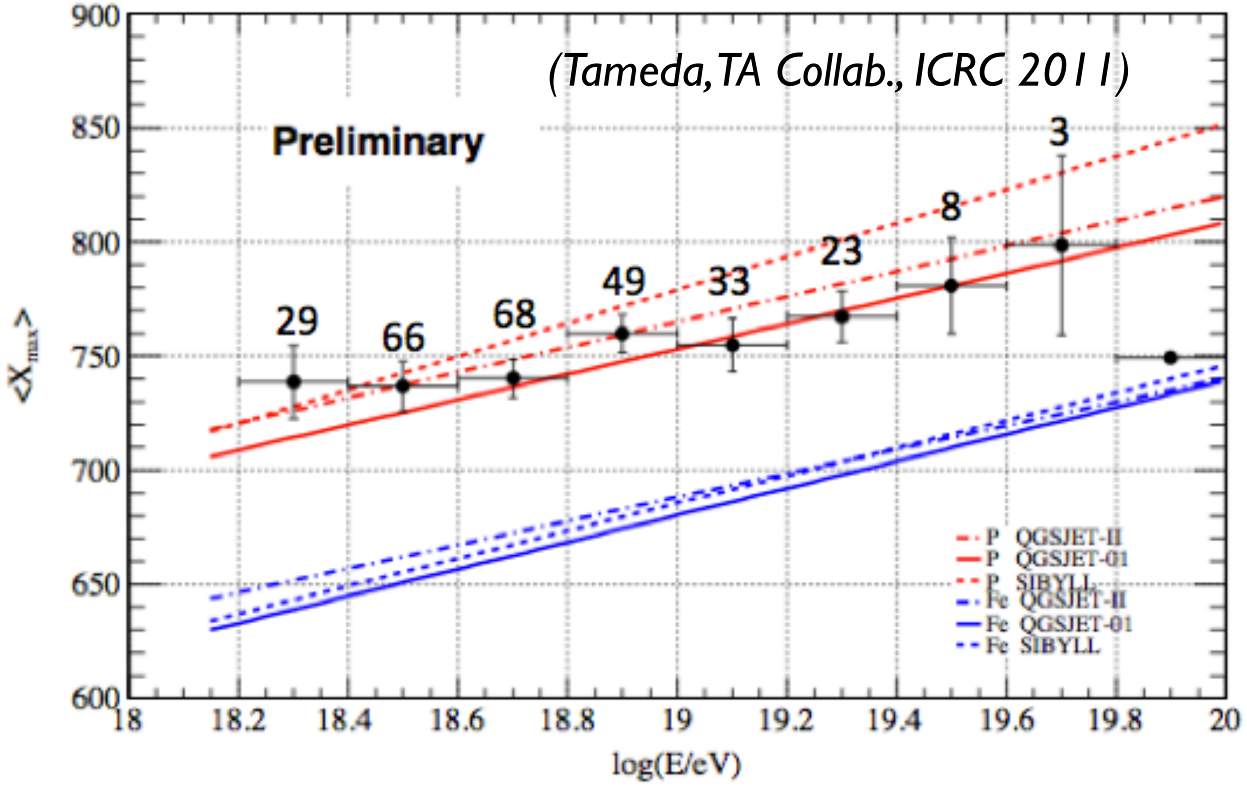
73%

44%

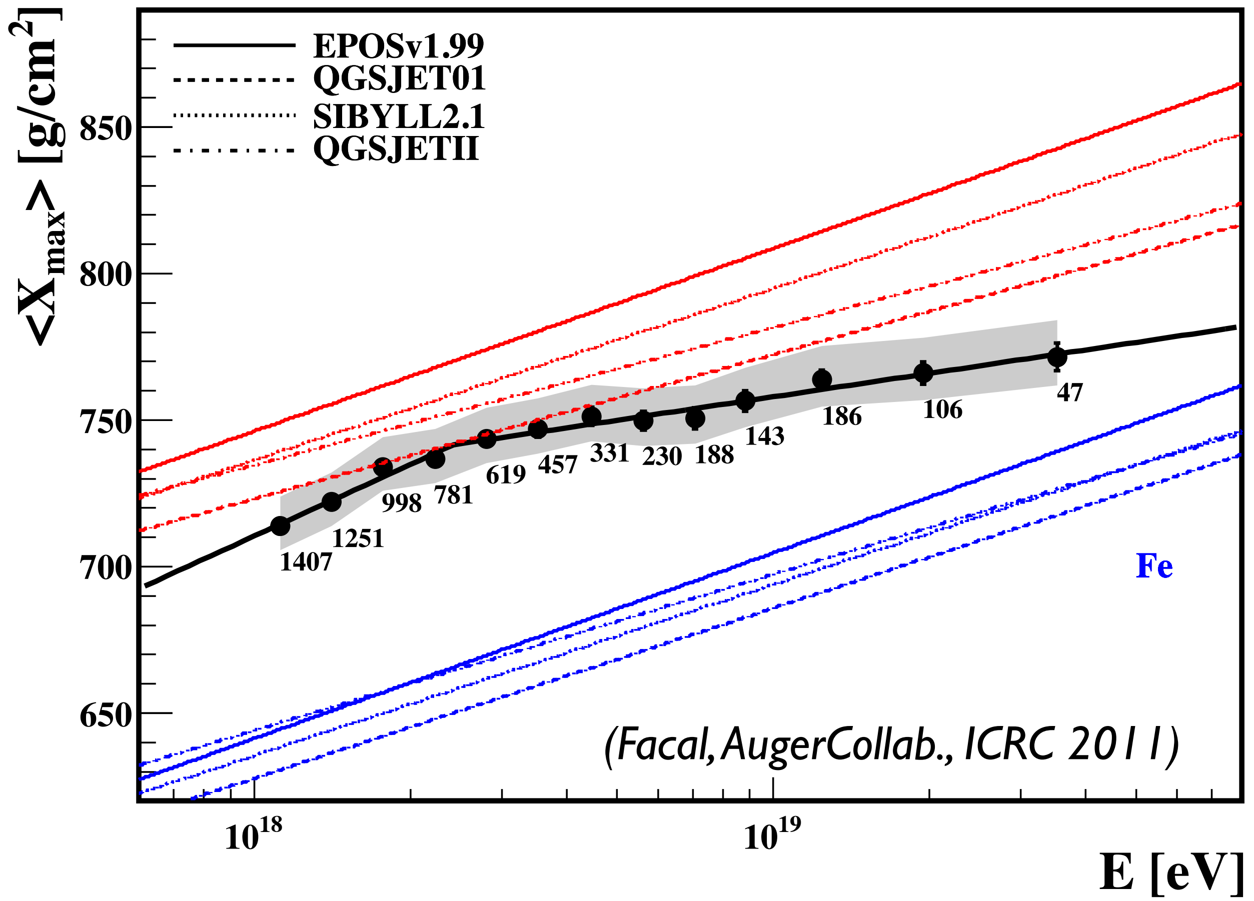
25%

Expectation comes from Auger 69% (=9/13)
which is converted to northern sky 73%.
The background chance probability is 25%

Northern hemisphere: composition light ?



TA data compatible with light composition (independent analysis)



International Symposium on Future Directions in UHECR Physics

UHECR 2012

CERN, Geneva
Febr.13-16, 2012
web site & contact:
http://2012.uhecr.org
conf@uhecr.org

Scope:
- Discuss the highlights and challenges of UHECR observations
- Prepare for a next generation ground based giant detector
- Evaluate the complementarity of ground and space based observations
- Identify technological challenges and related R&D works

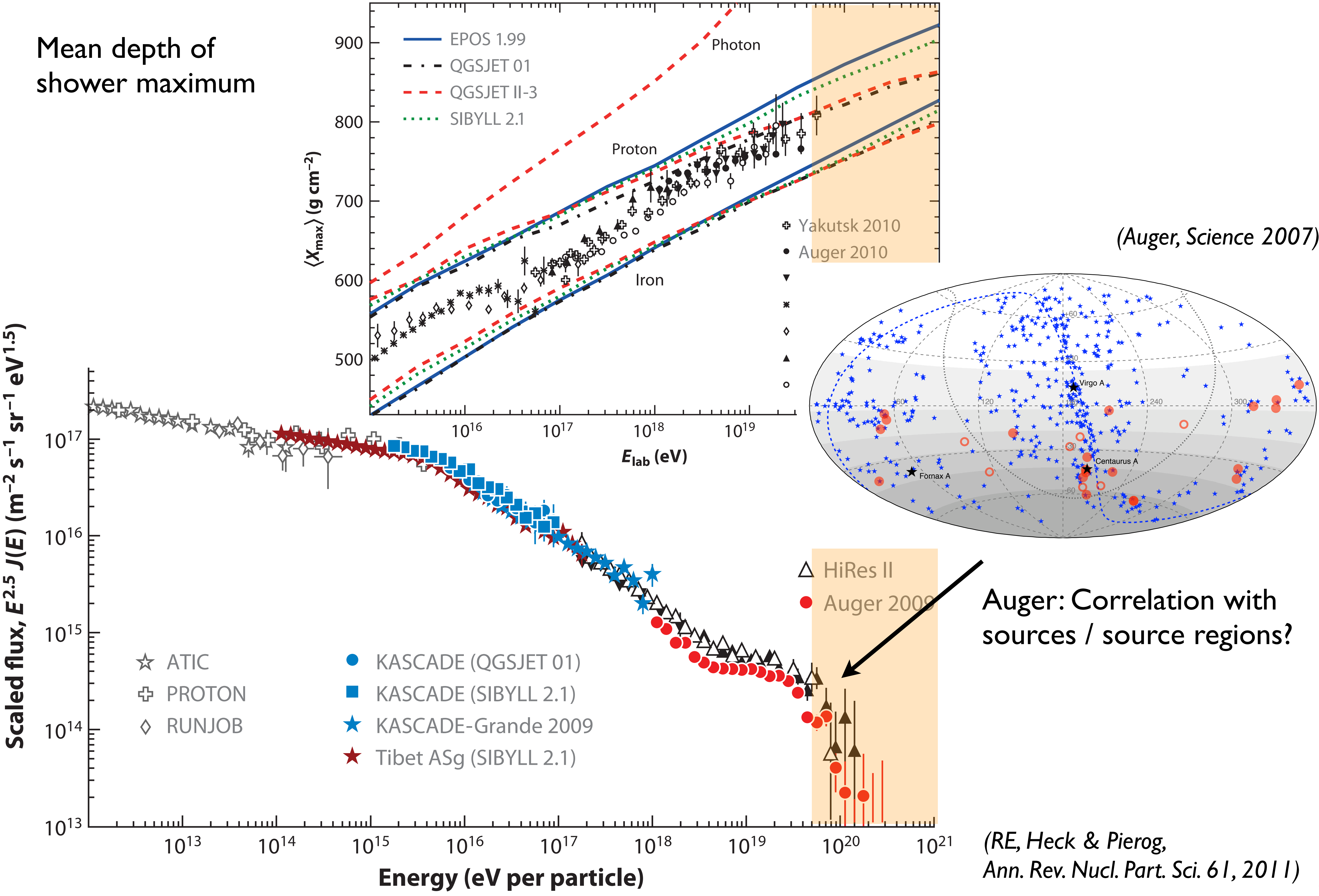
International Advisory Committee

Local Organization Committee

Supported by

Origin of flux suppression by measuring composition

Mean depth of shower maximum

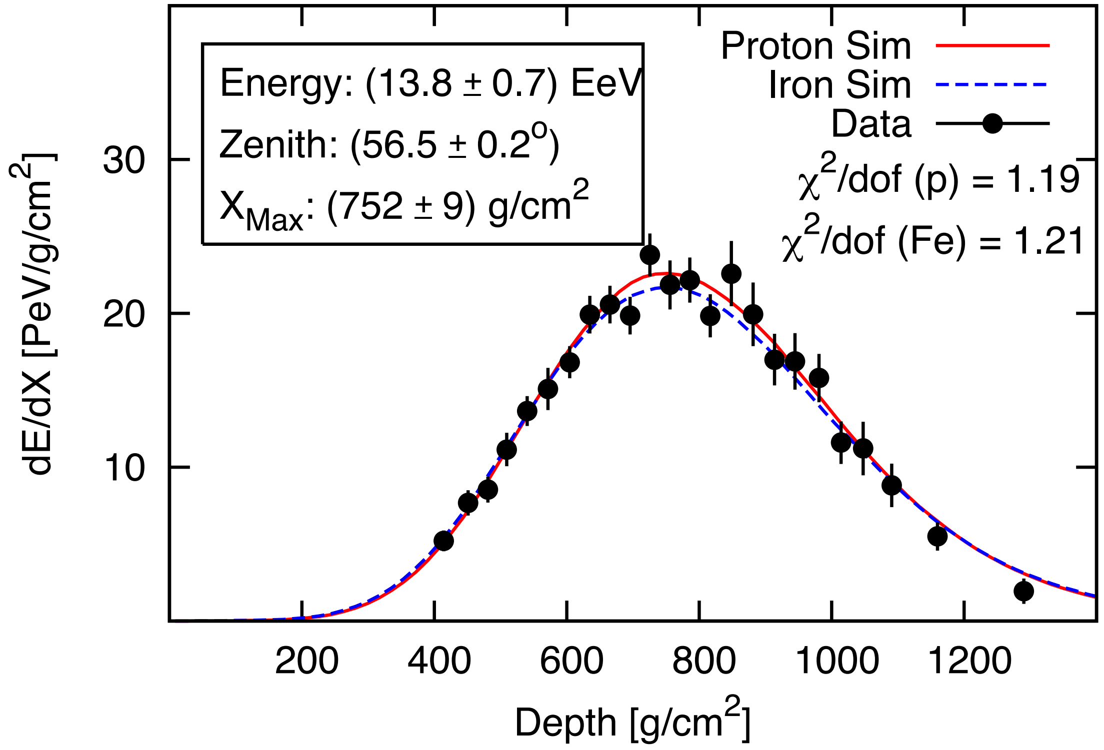


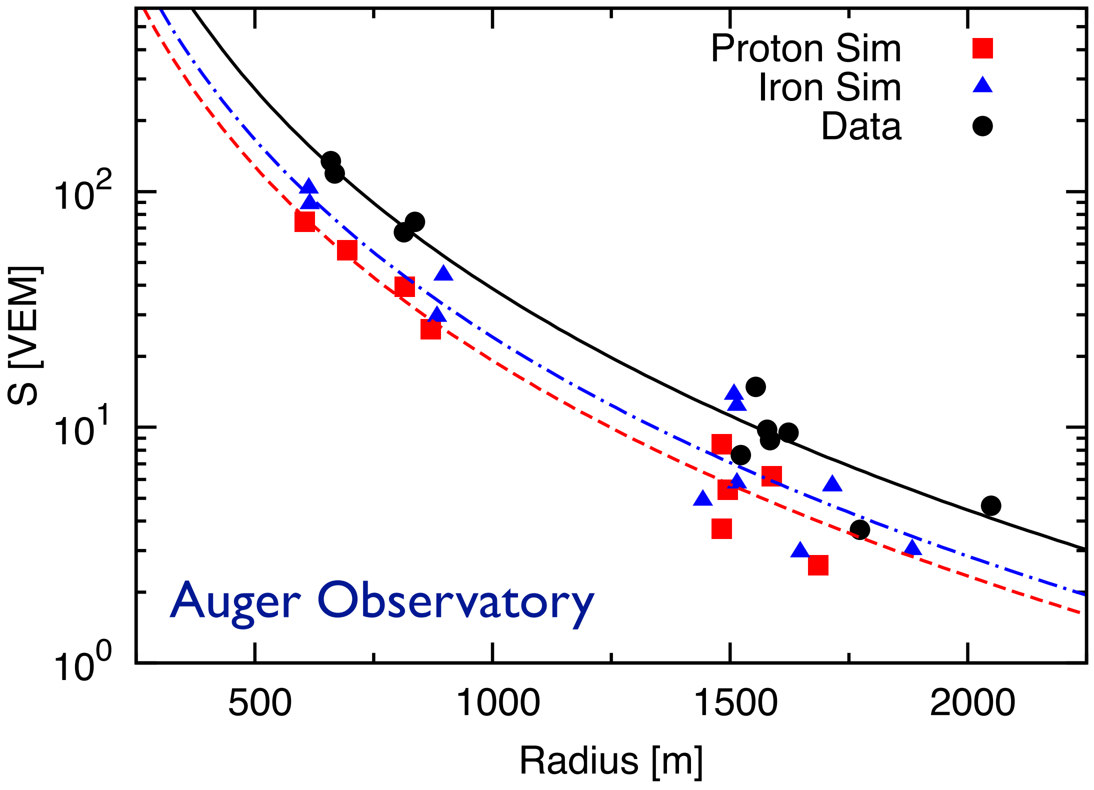
(Auger, Science 2007)

Auger: Correlation with sources / source regions?

(RE, Heck & Pierog, Ann. Rev. Nucl. Part. Sci. 61, 2011)

Discrepancy between data and simulated showers





Procedure

- High-quality showers E ~10^{19} eV
- Proton or iron primaries
- surface detector simulation for best longitudinal profiles

Results

- Signal deficit found for **both** proton and iron like showers
- Showers with same X_{max} show only 10-15% variation
- Discrepancy much larger than 22% energy calibration uncertainty

Monte Carlo simulations cannot be used for energy calibration (reason for AGASA excess?)

(Pierre Auger Collab. 1107.4804)

Outlook

Telescope Array:

Extension of existing array by factor ~10 (comparable to Auger array)

Auger Observatory: upgrade of detector array to be operated until 2023

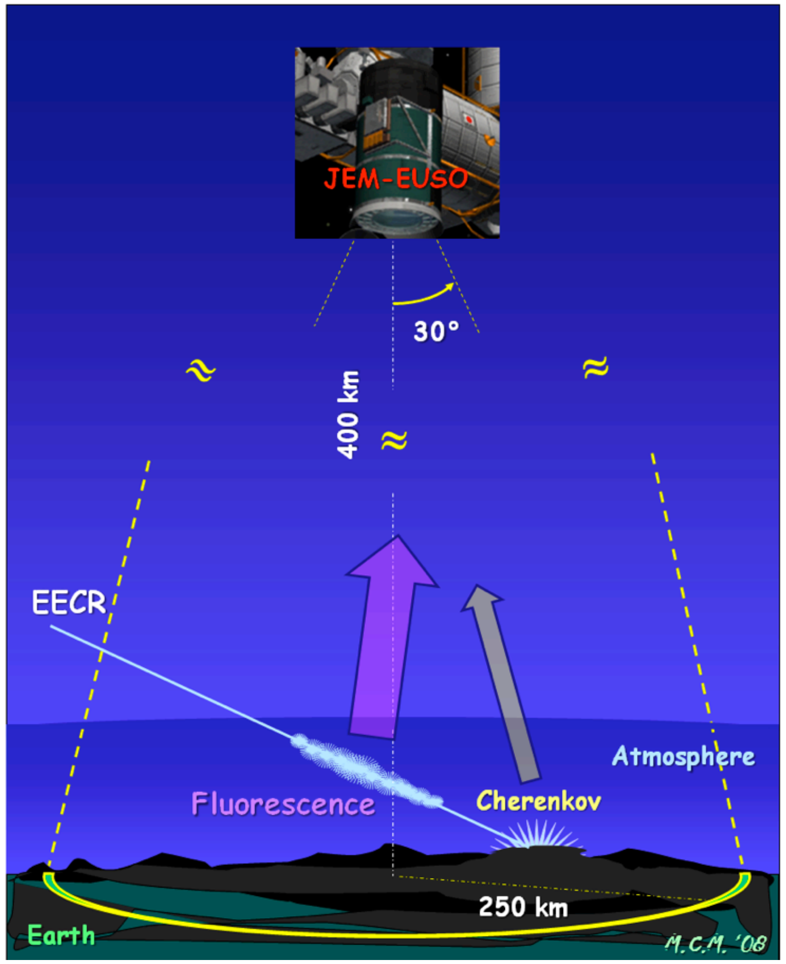
Measurement composition up to highest energies

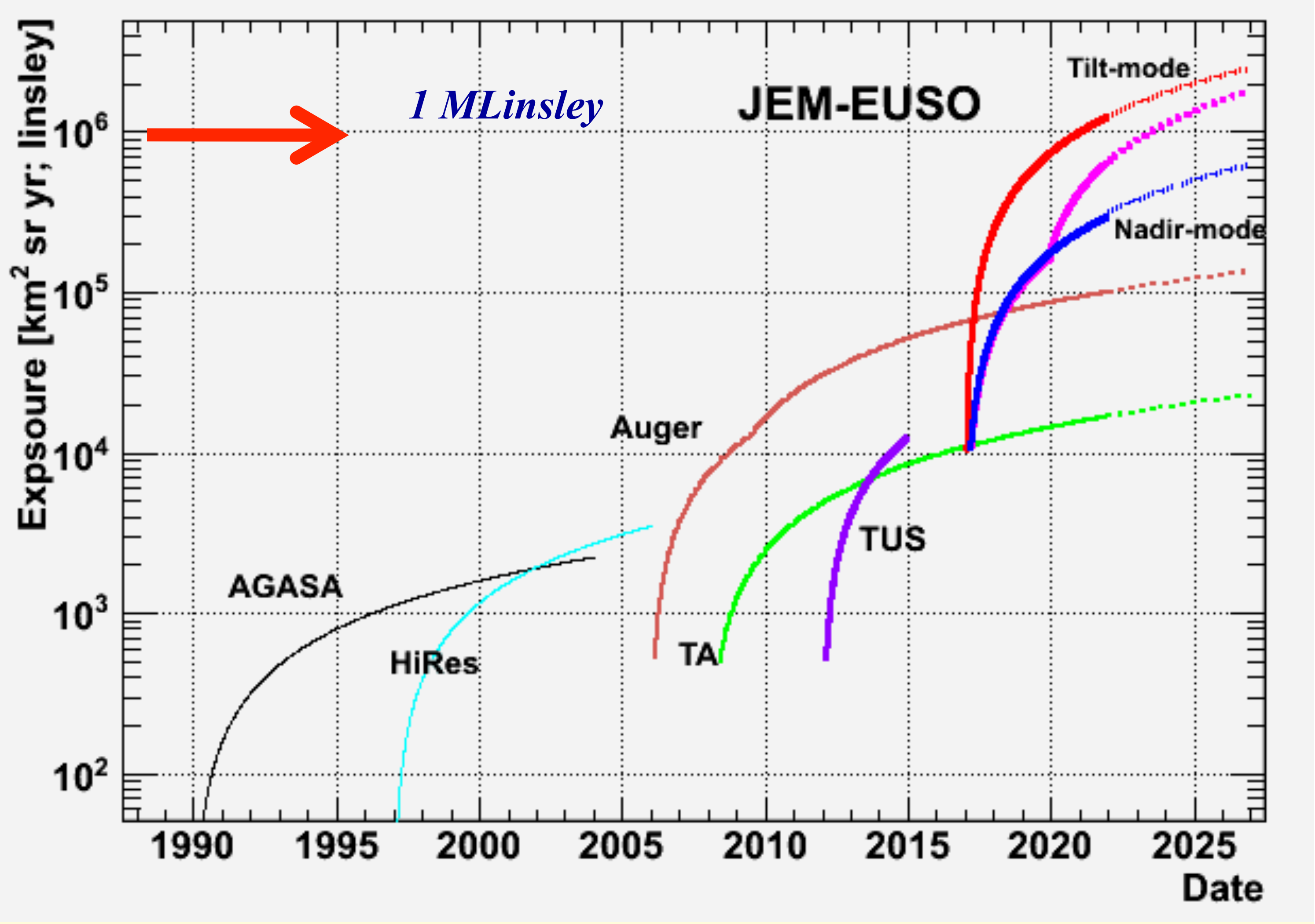
Study of hadronic interactions in air showers, muon counting

Detectors with larger aperture:

Observation from space (JEM-EUSO, 2017 - xx, limited composition sensitivity)

Next generation ground array

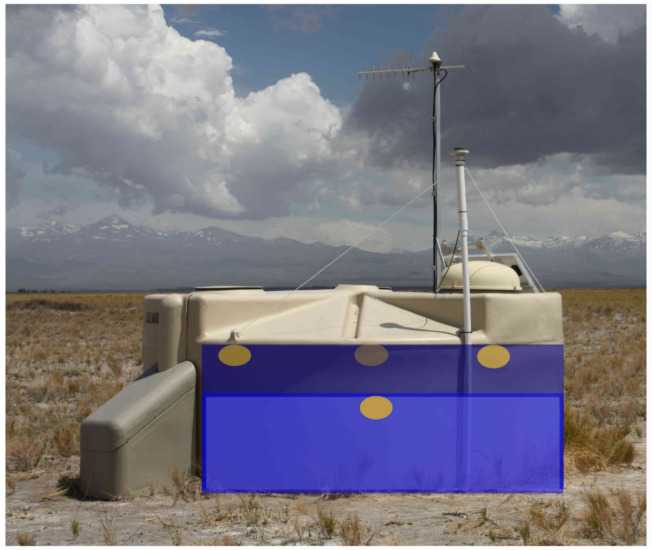


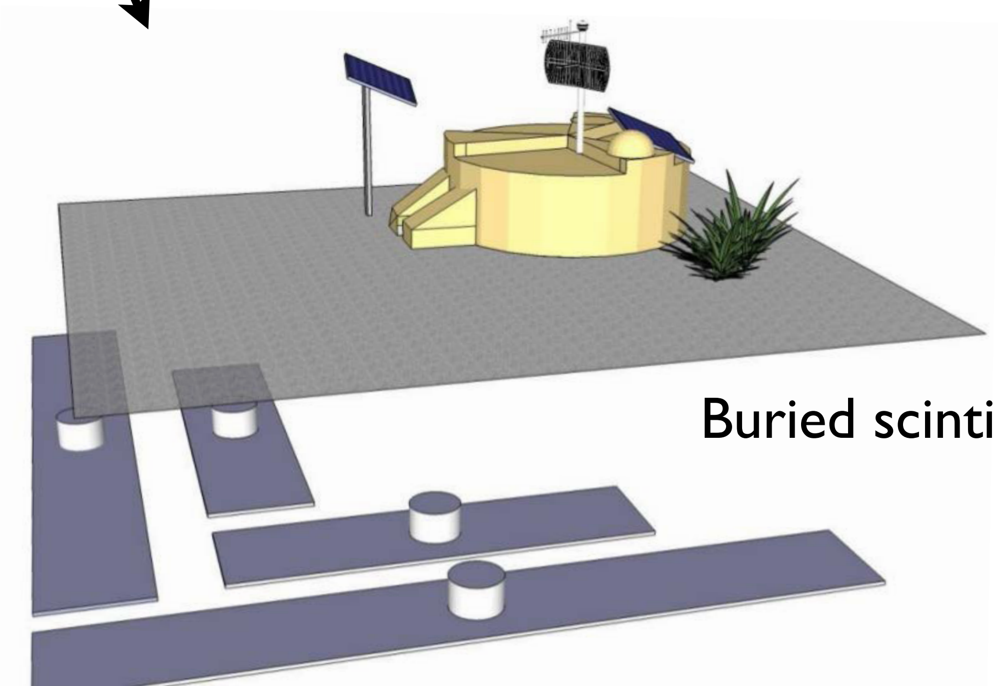


Measurement of muonic and em. shower components

Surface detector station of Auger array

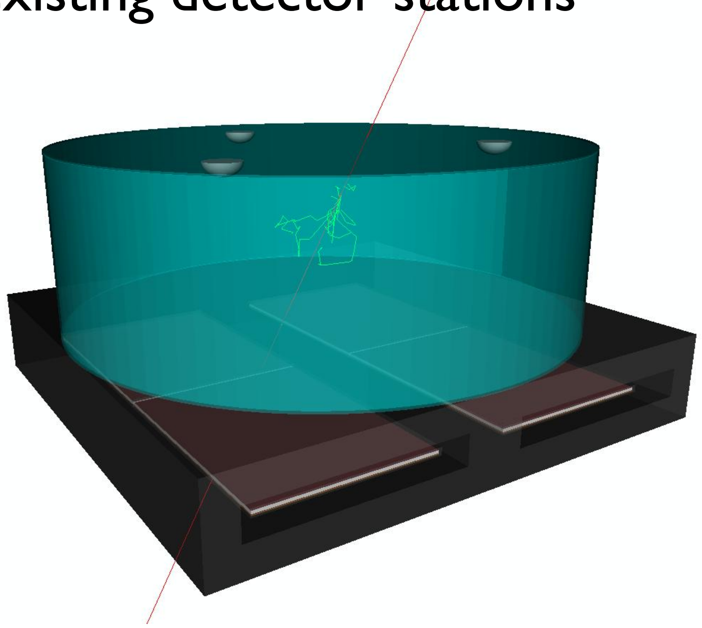
Semented detectors
(upper layer acts as absorber)



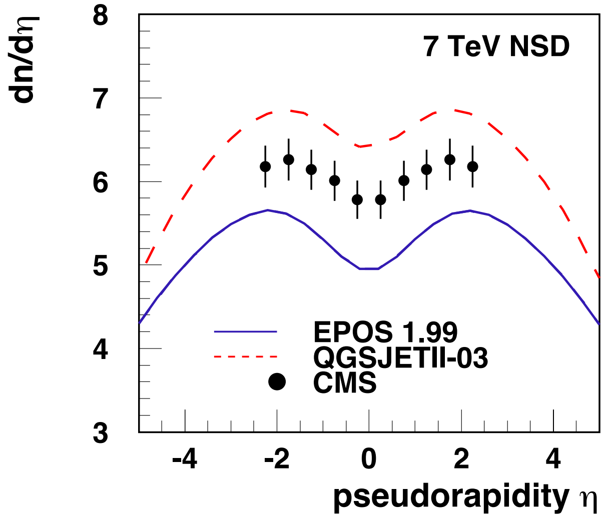


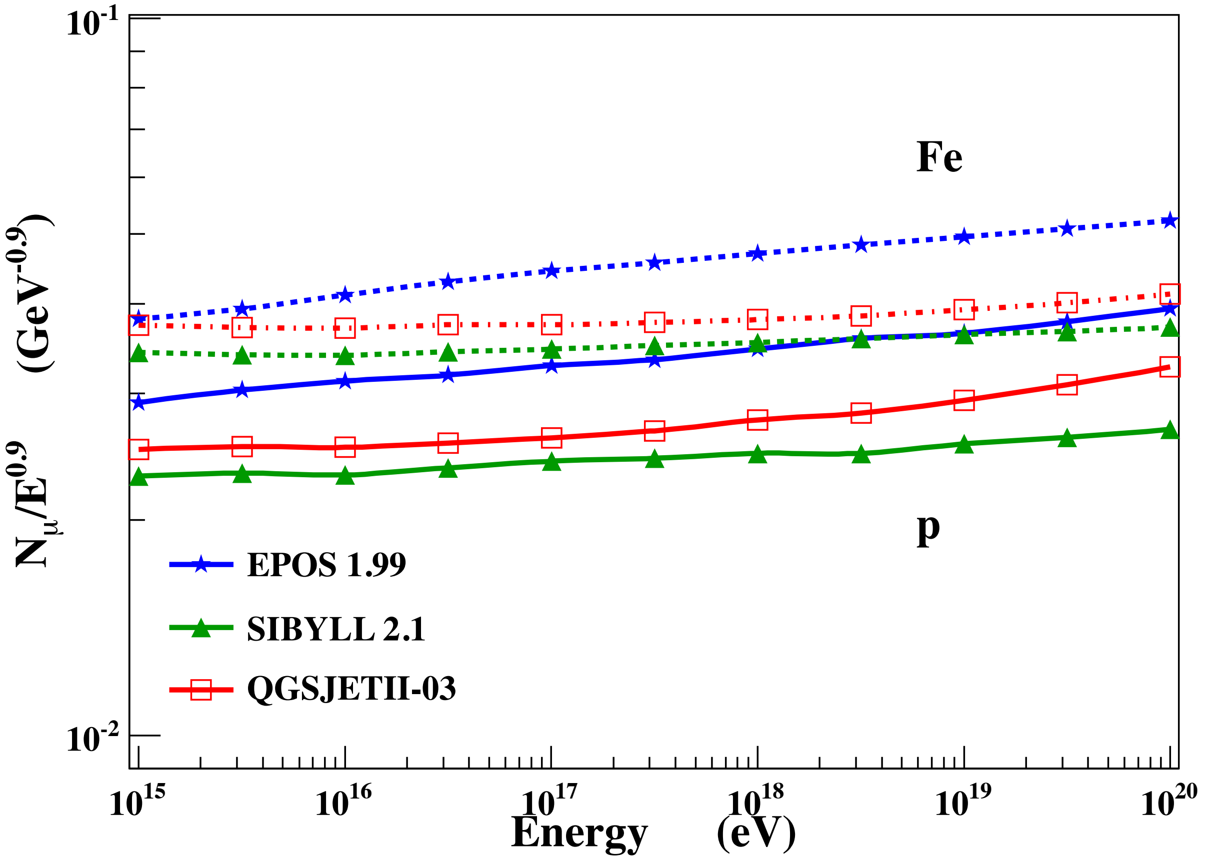
Buried scintillators

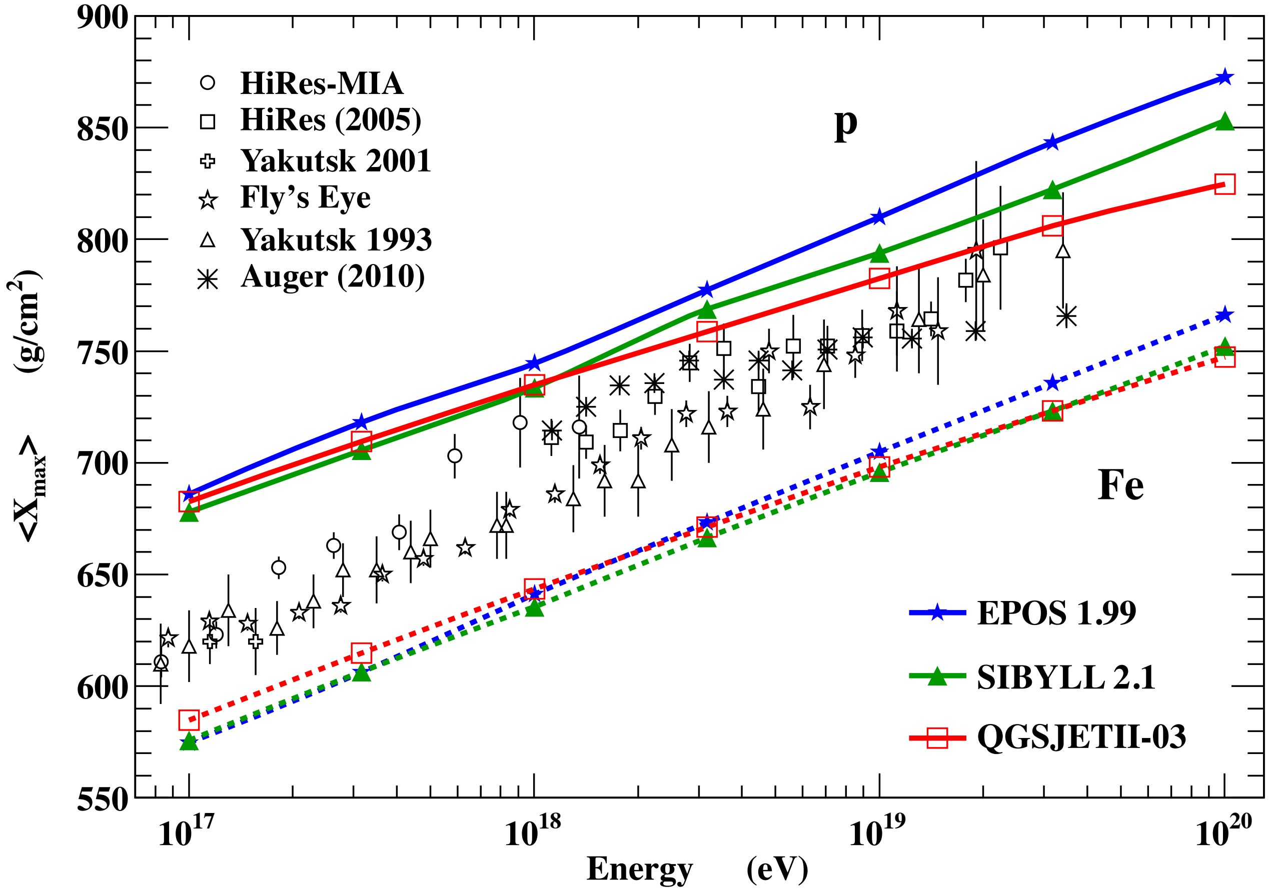
Place RPC detectors below
existing detector stations



Using new LHC data to improve interaction models (i)

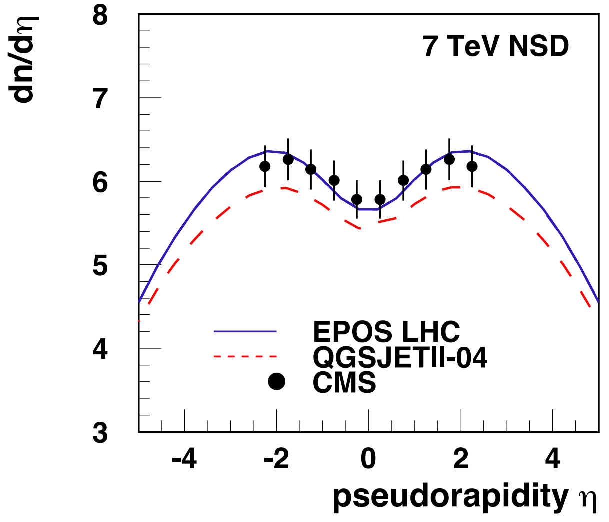


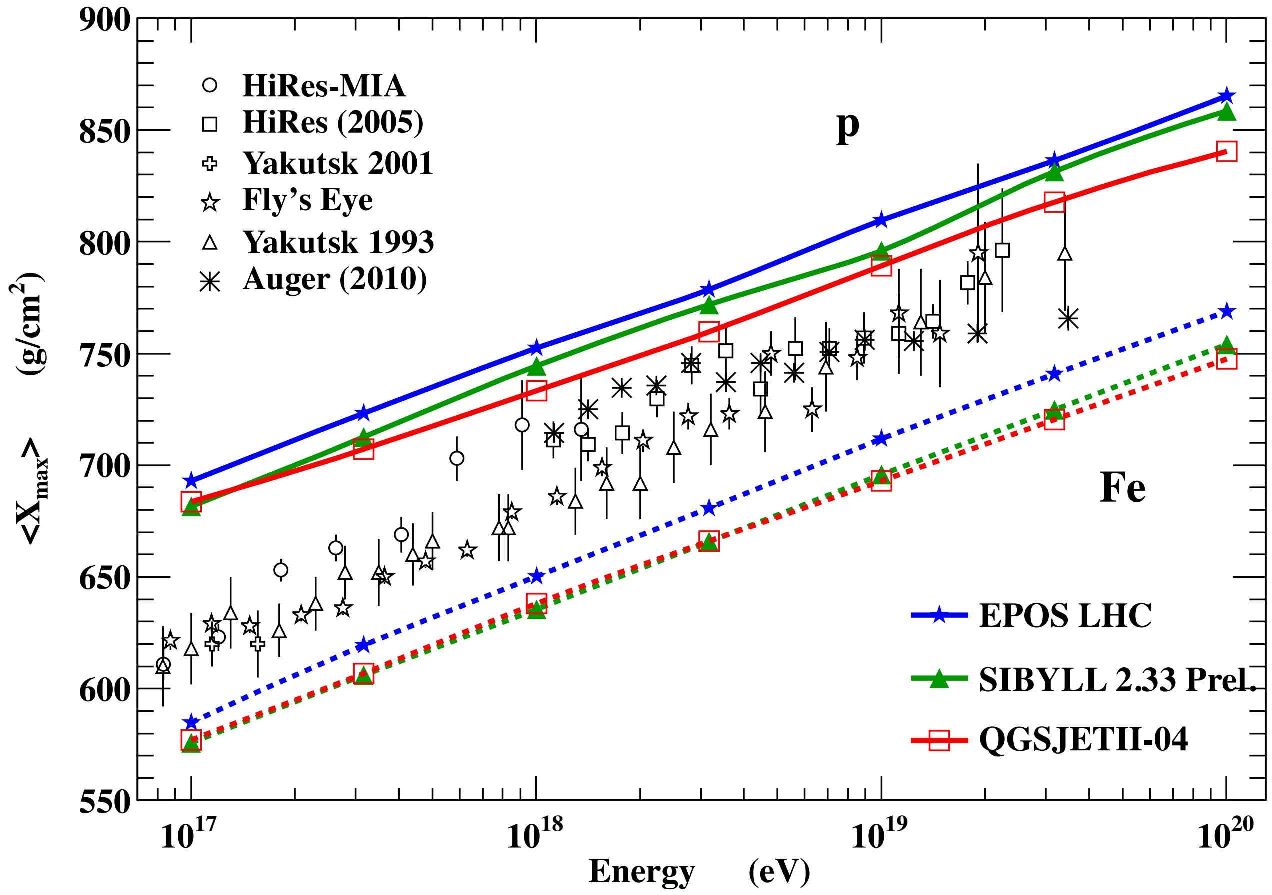


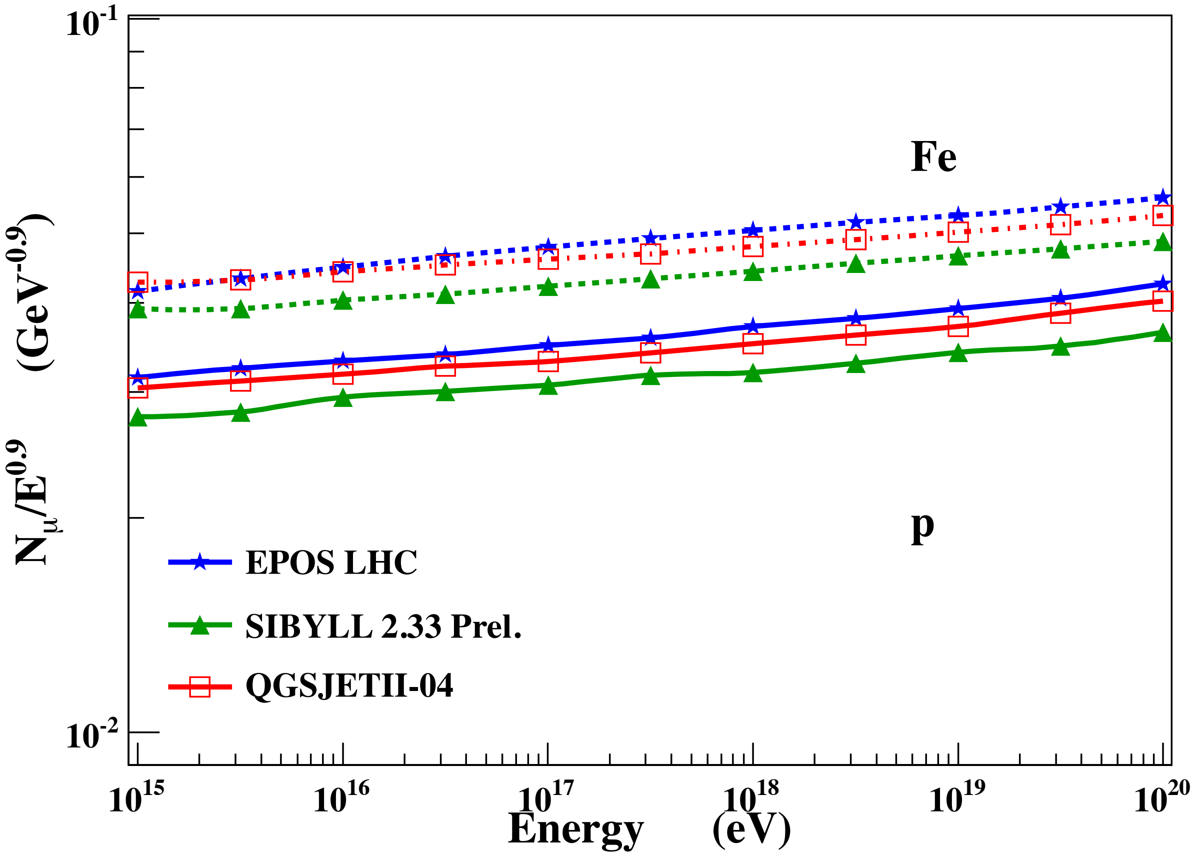


Model predictions before LHC

Using new LHC data to improve interaction models (ii)





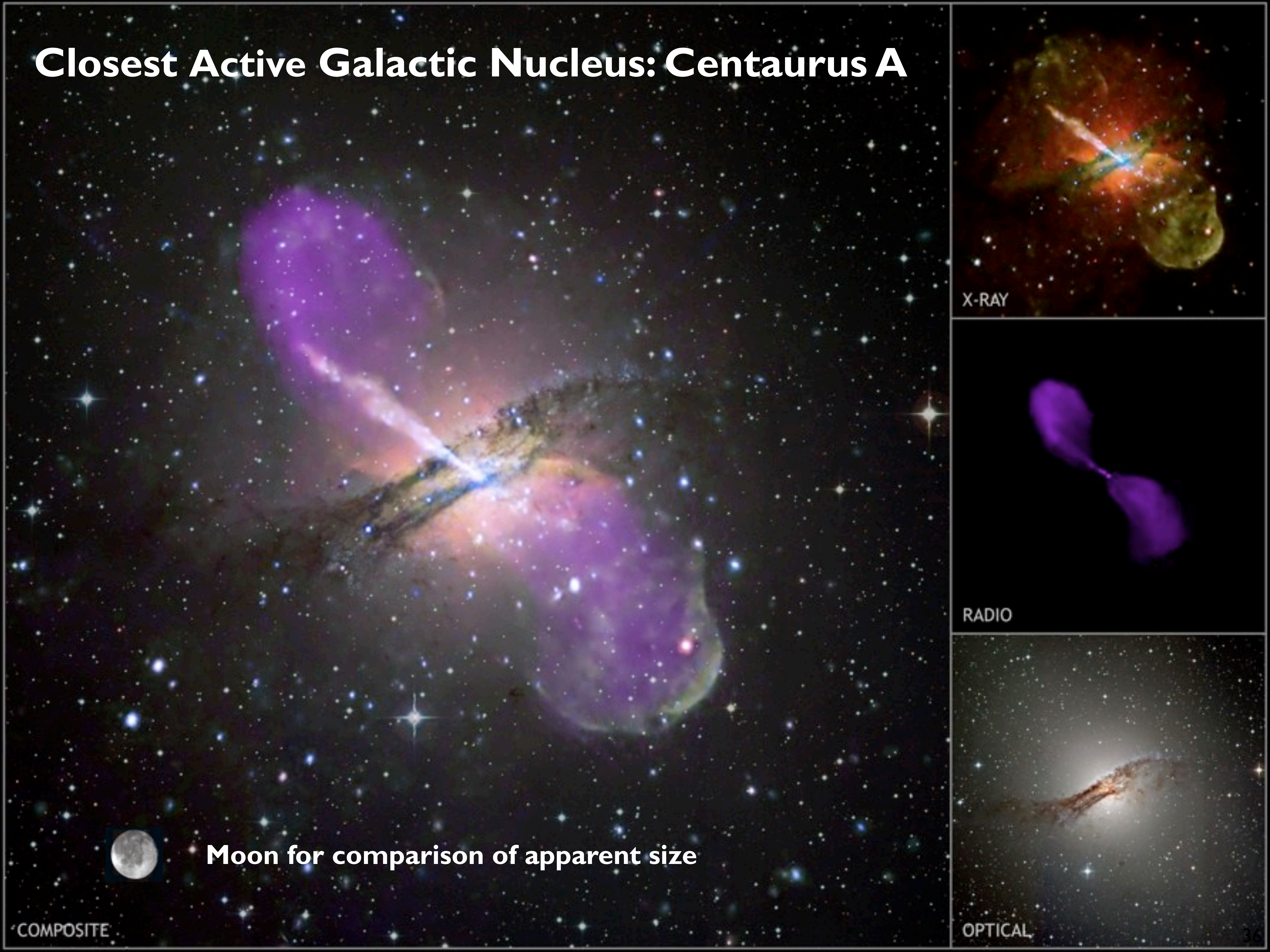


Model predictions after LHC (work in progress)

- *X*max predictions increase & converge at SIBYLL
- *N*μ predictions converge at high value of EPOS

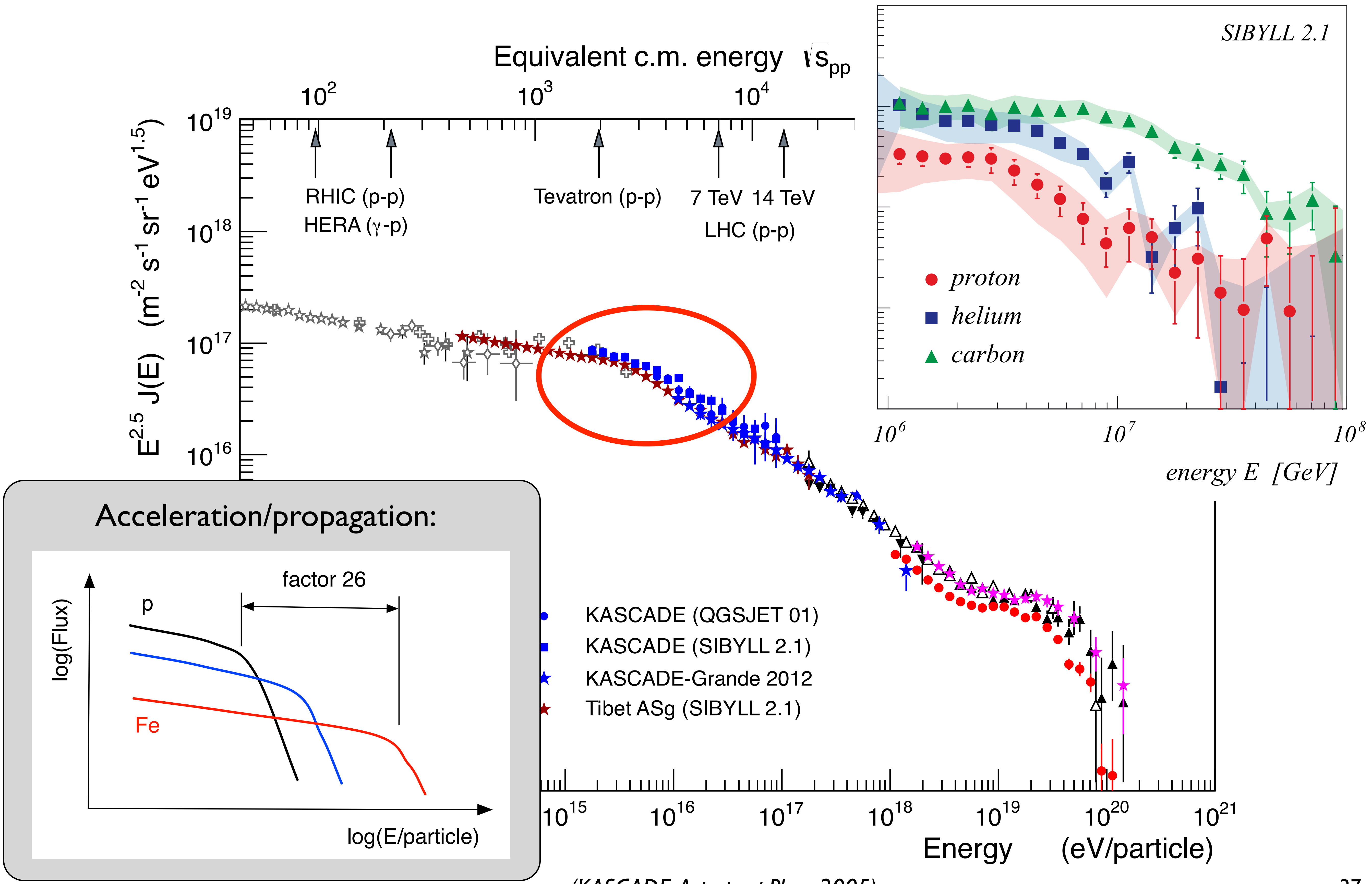
Backup slides

Closest Active Galactic Nucleus: Centaurus A



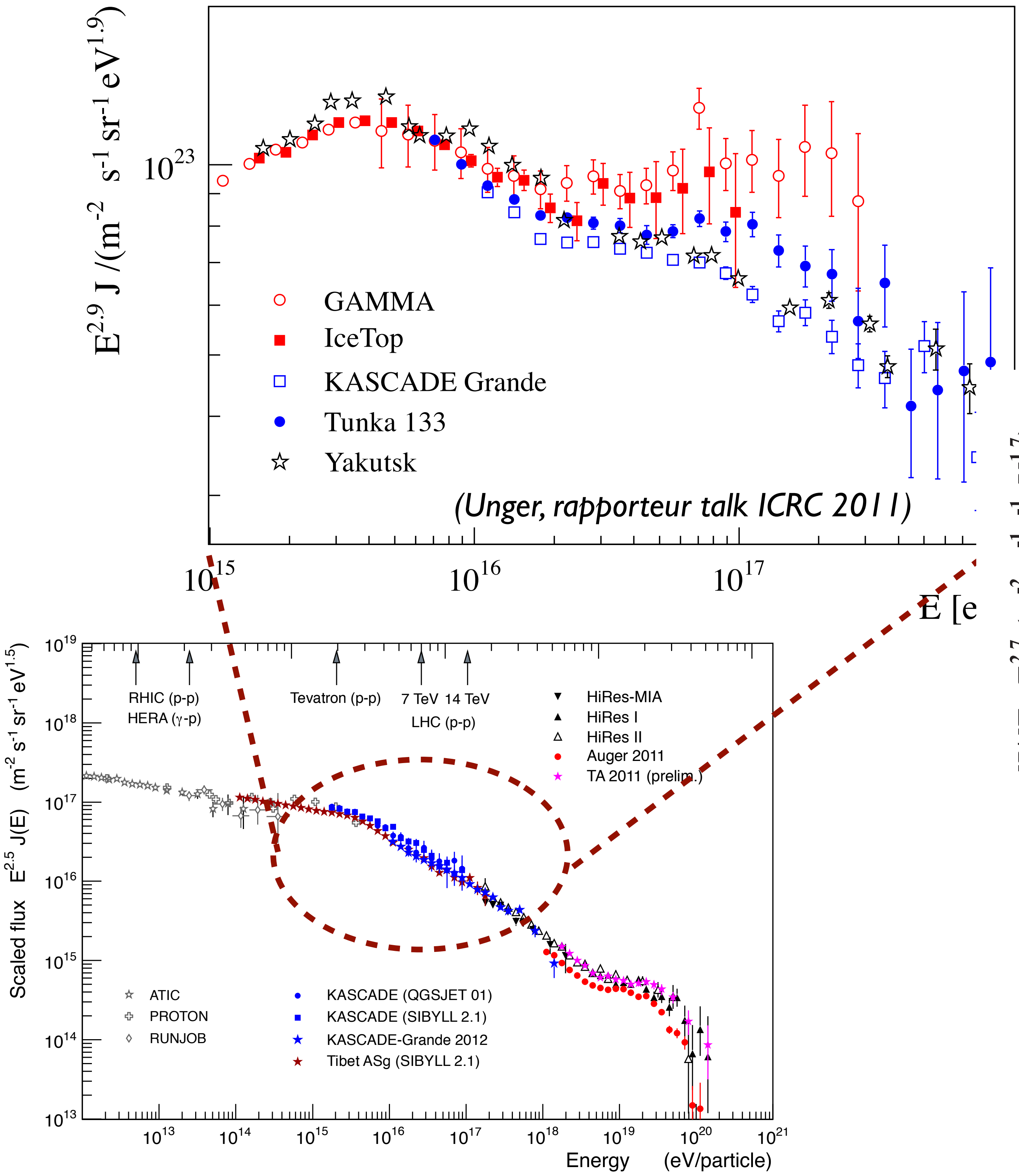
Moon for comparison of apparent size

Origin and physics of the knee



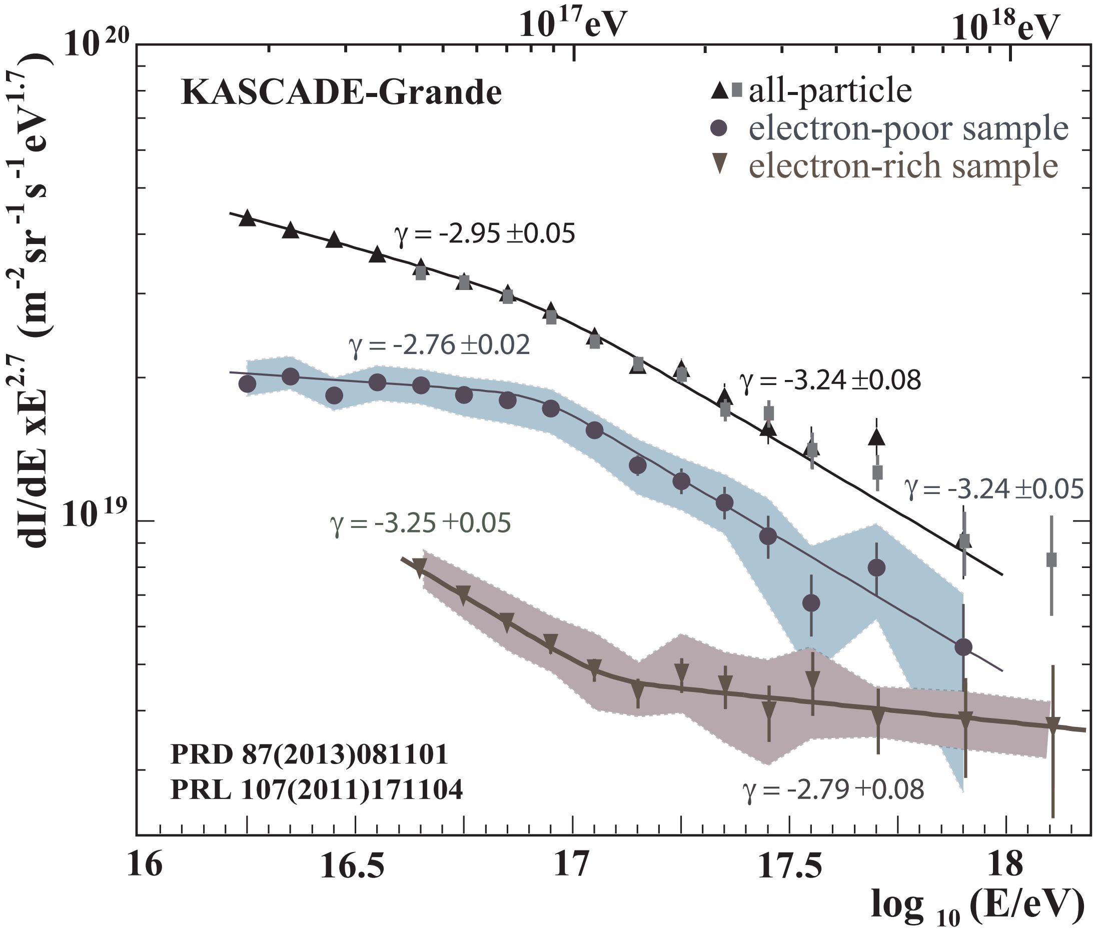
(KASCADE, Astropart.Phys. 2005)

New structures found above knee



(Unger, rapporteur talk ICRC 2011)

(Apel et al., Astropart. Phys. 36 (2012) 183)



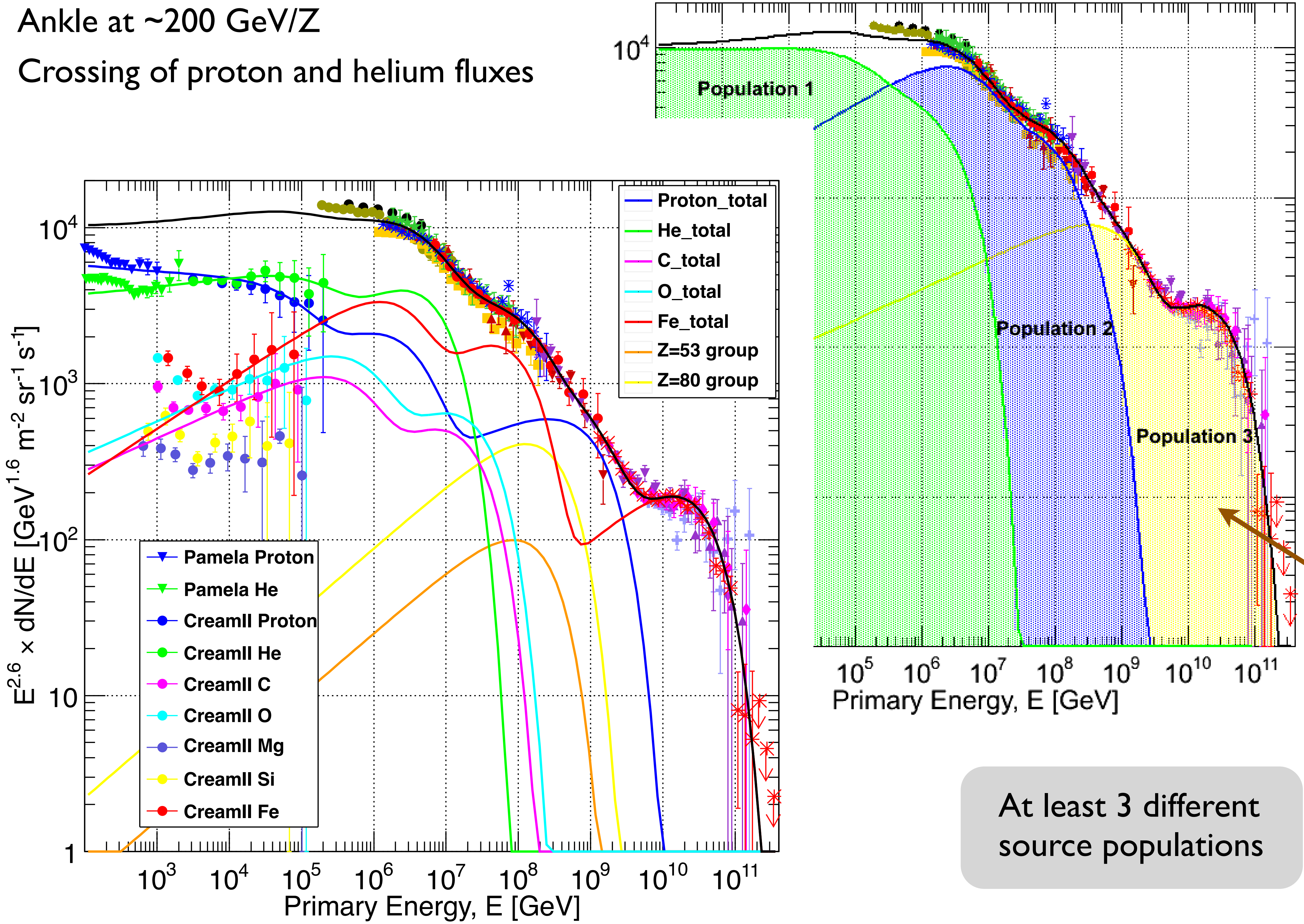
(Apel et al., Phys.Rev.Lett. 107 (2011) 171104,
Phys.Rev. D87 (2013) 081101)

Example of one possible interpretation

(Gaisser, Stanev, Tilav 1303.3565)

Ankle at ~200 GeV/Z

Crossing of proton and helium fluxes

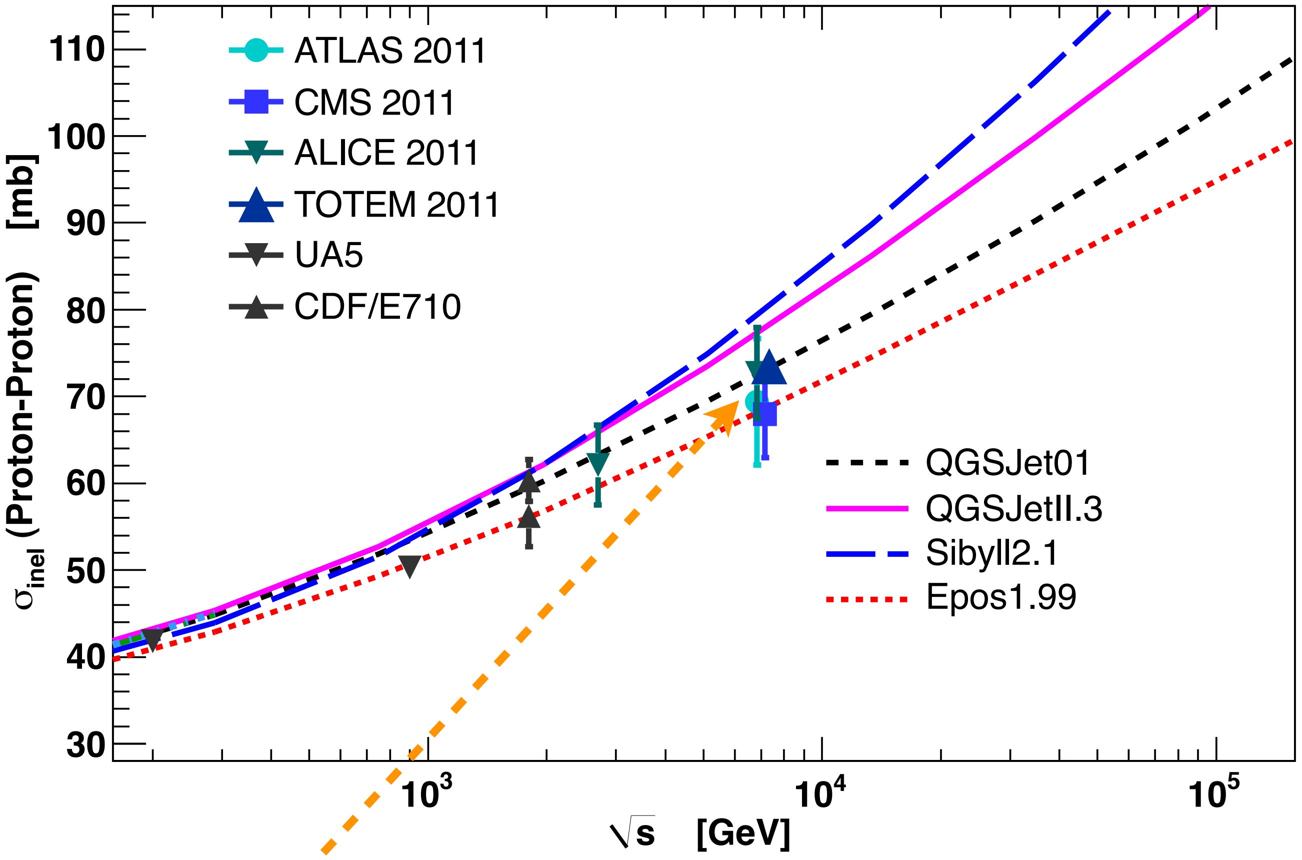


Extragalactic sources

At least 3 different source populations

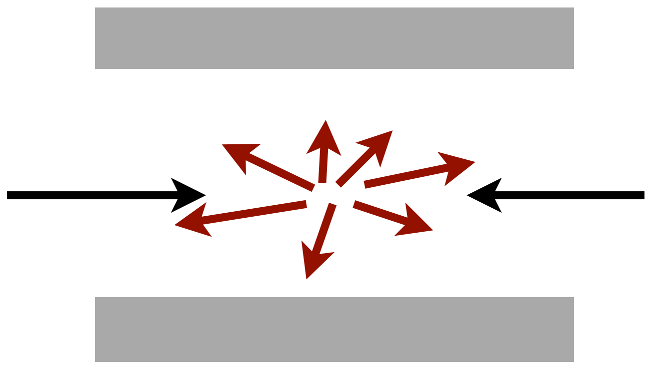
Cross section measurements at LHC

Inelastic proton-proton cross section



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

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



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

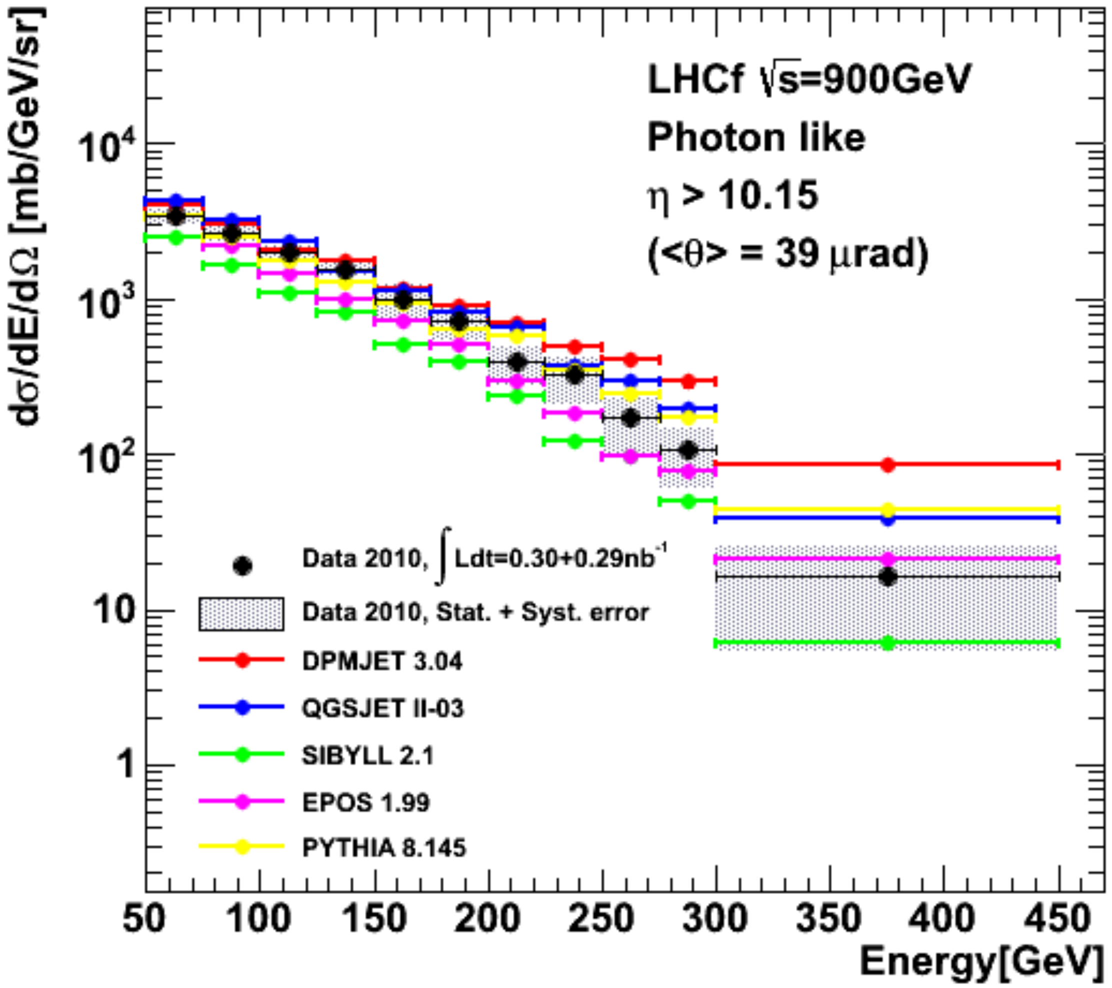
$$\sigma_{\mathrm{ATLAS}} = 60.3 \pm 0.05 \pm 0.5 \pm 2.1\mathrm{mb}$$

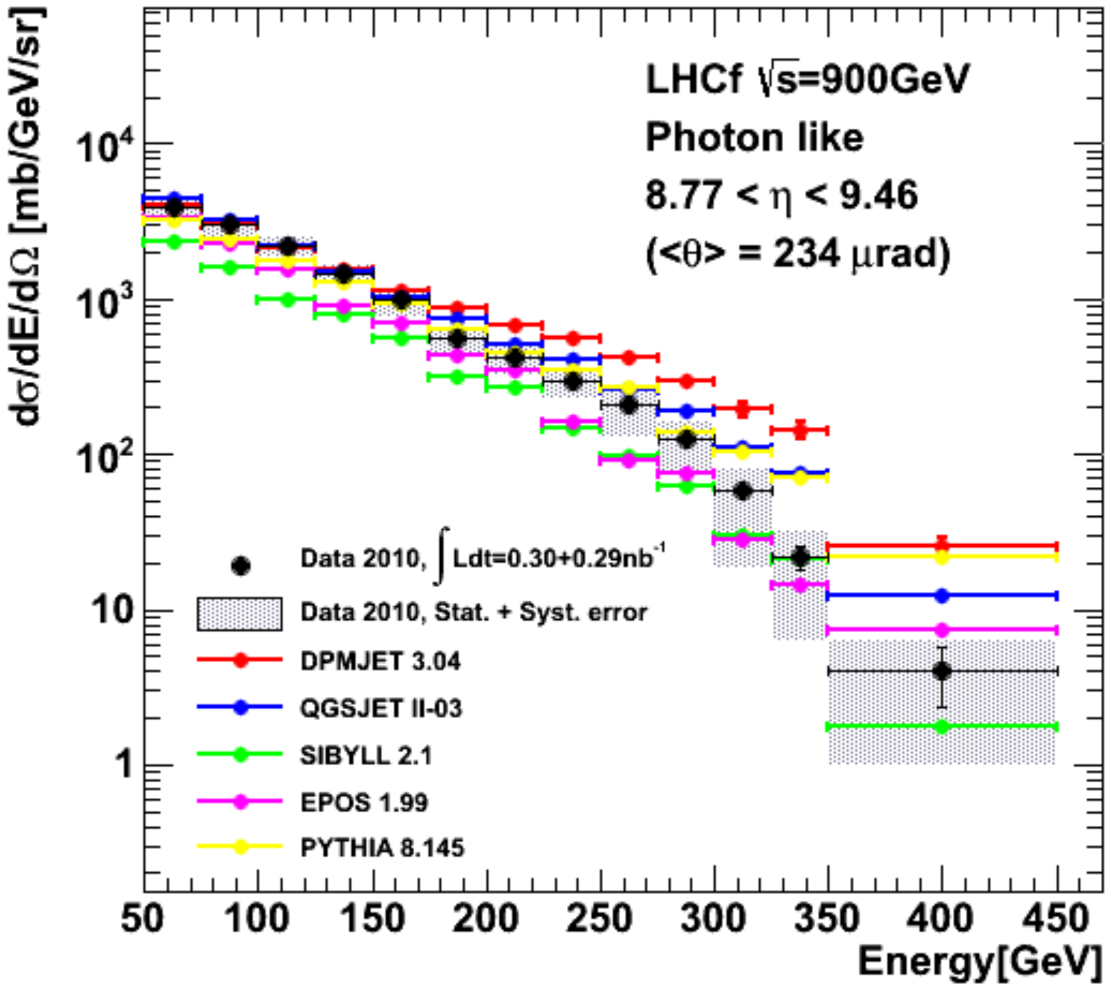
N_{trk} Pt (MeV)	3 200	4 200	3 250	4 250	σ_{tot}
CMS	**59.7**	**58.6**	**58.9**	**57.3**	
Q-II-03	65.2	64.6	63.0	62.0	77.5
SYBILL-2.1	71.5	71.0	70.2	69.3	79.6

(CMS, DIS Workshop, Brookhaven)

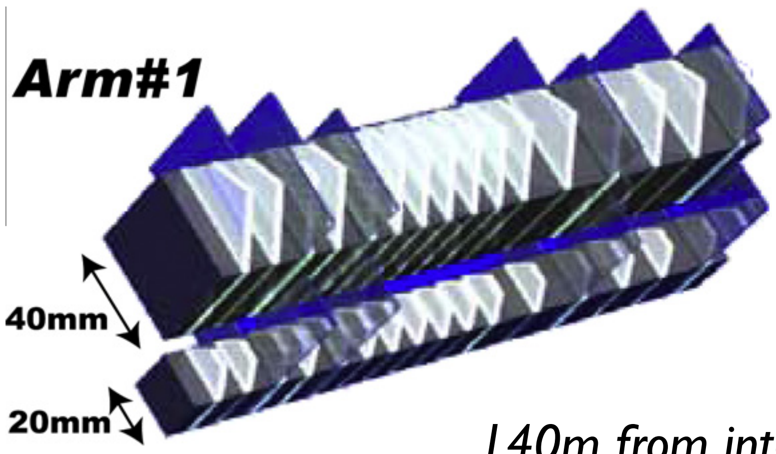
$$\sigma_{\mathrm{ALICE}} = 72.7 \pm 1.1 \pm 5.1\mathrm{mb}$$

LHCf: forward photon production





(Mitsuka, this meeting)

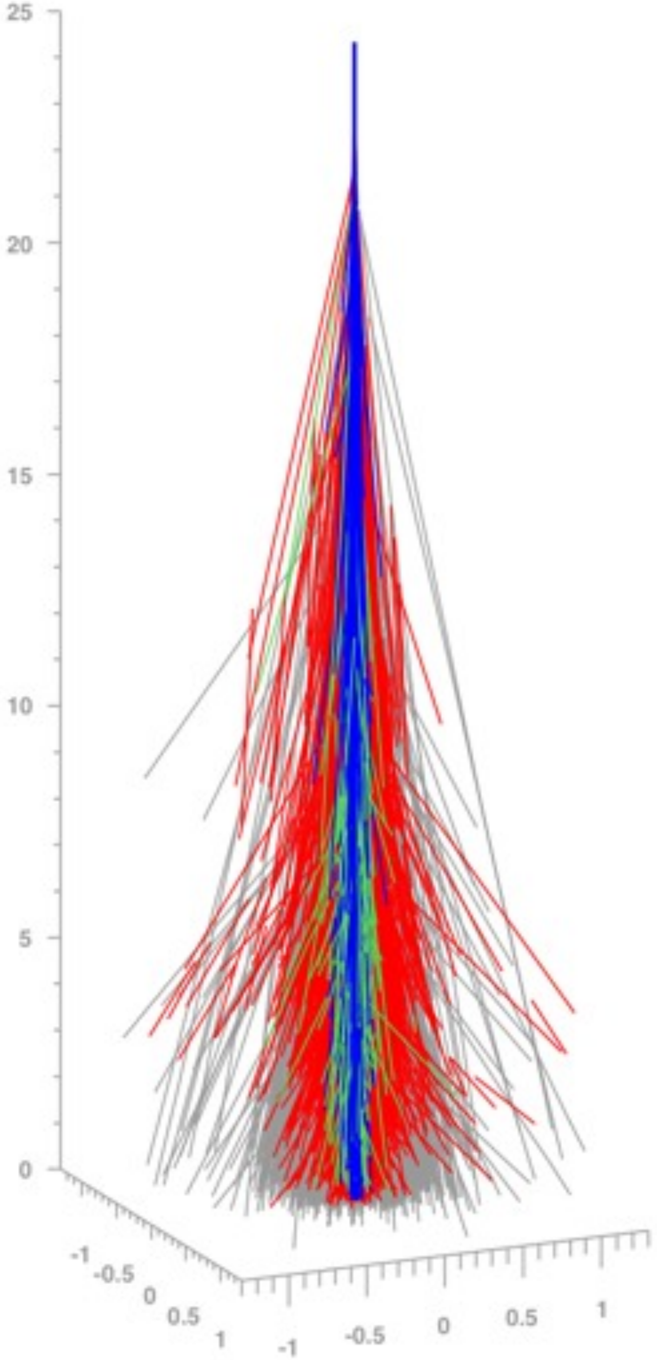


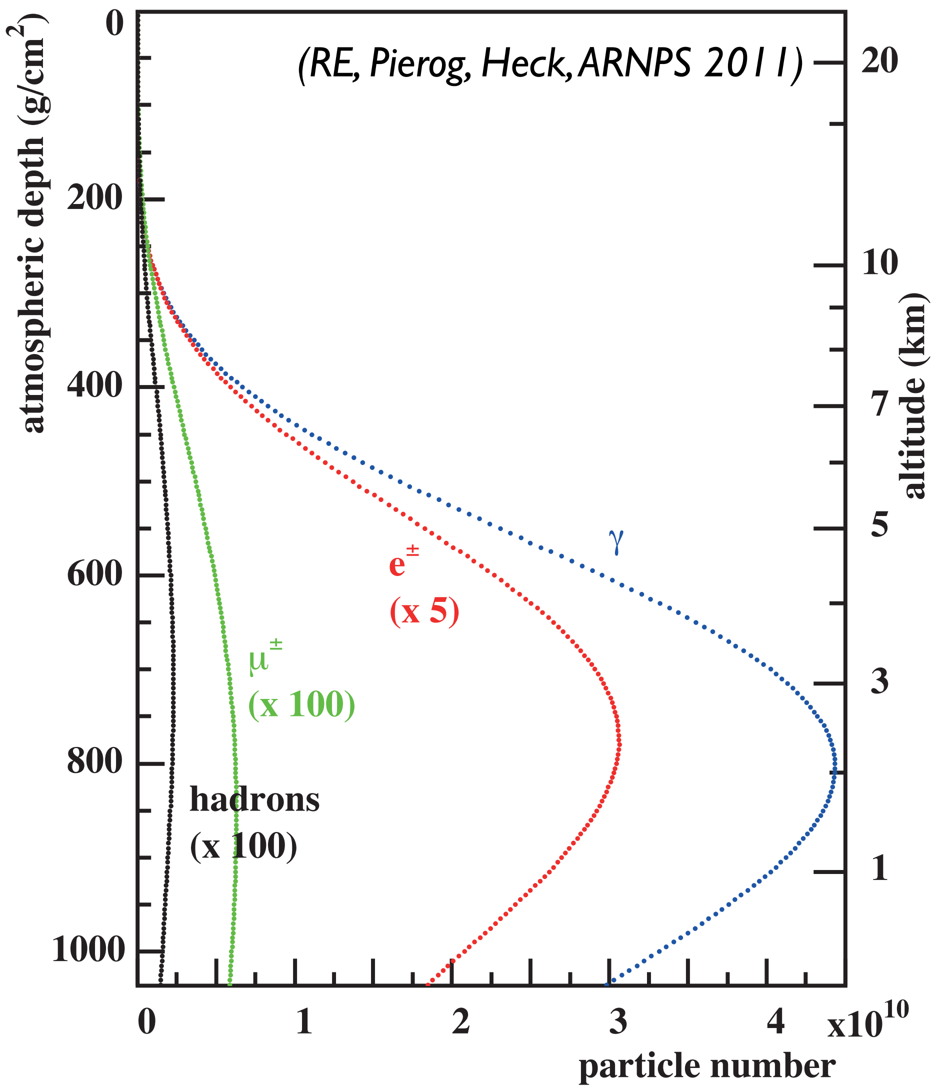
140m from interaction point

$$pp \to \gamma X$$

Model predictions bracket LHC data

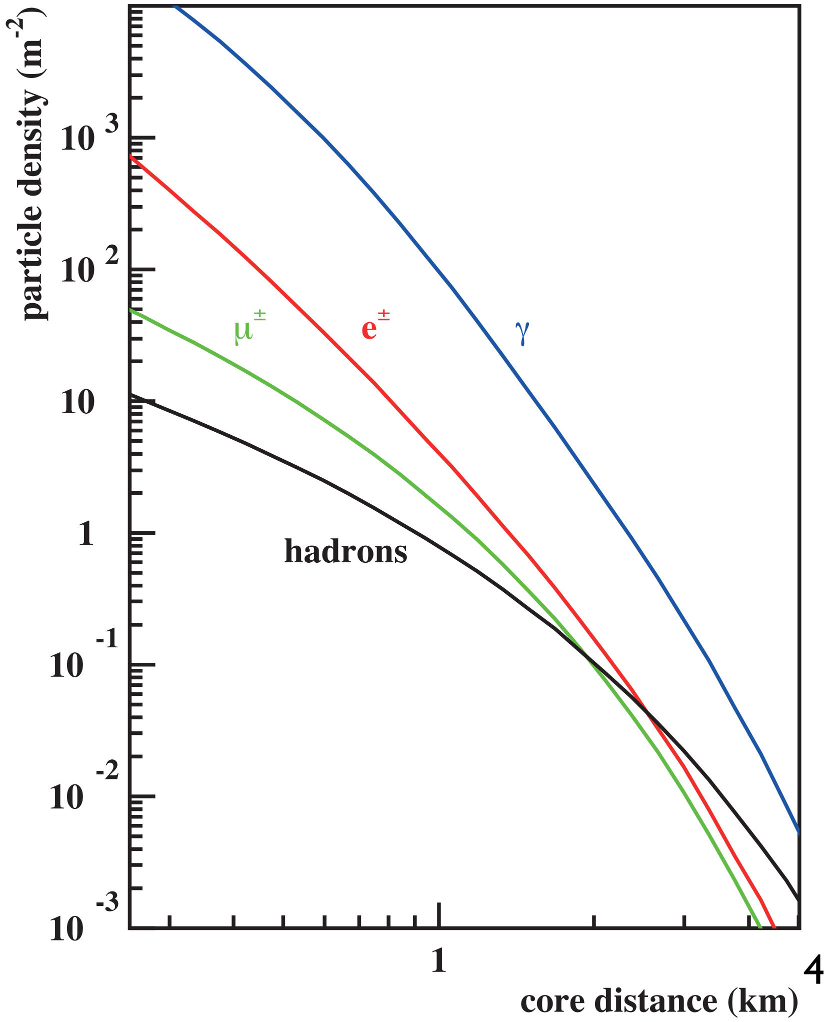
Measured components of air showers





Longitudinal profile:

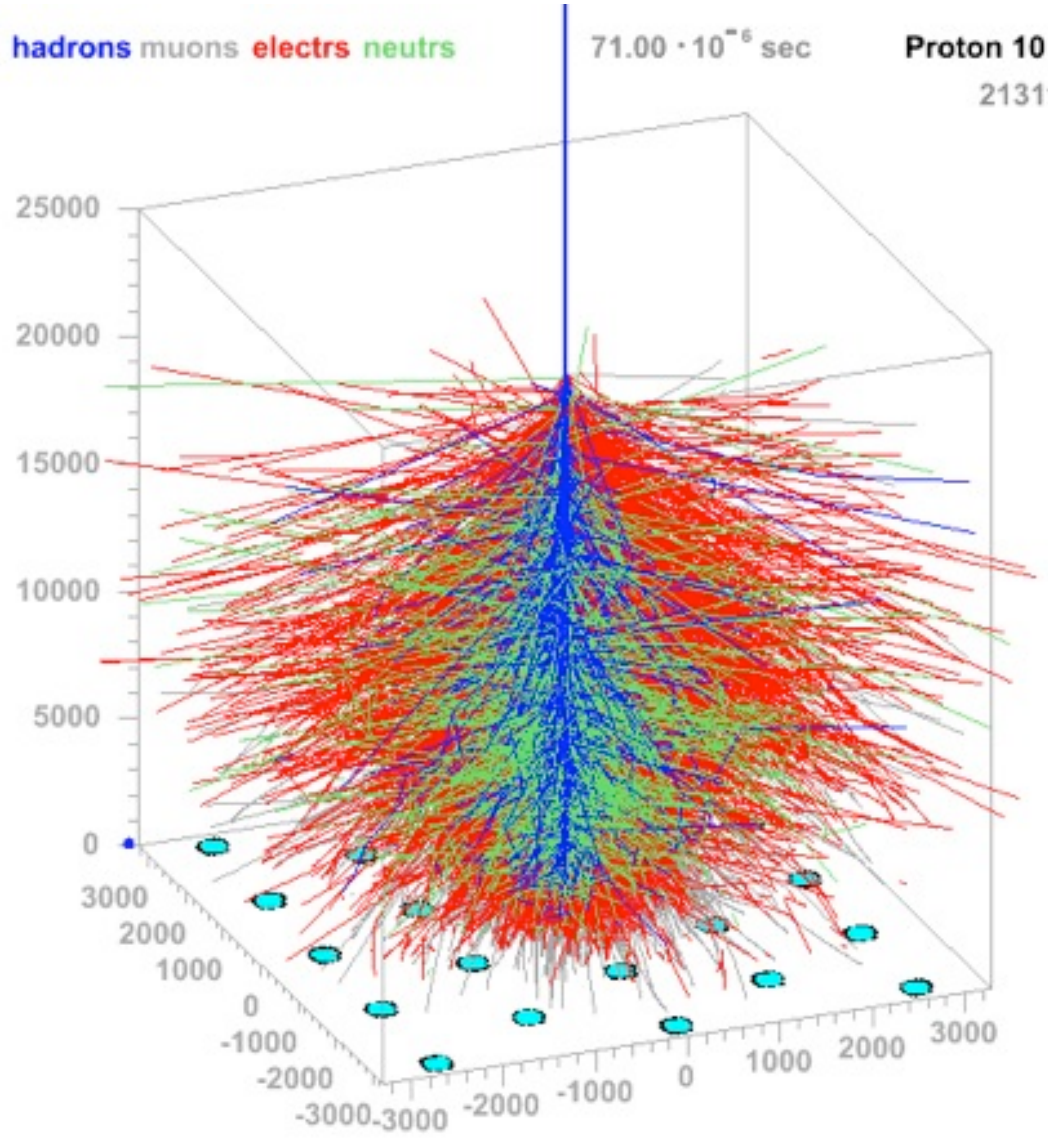
Cherenkov light
Fluorescence light
(bulk of particles measured)



Lateral profiles:

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

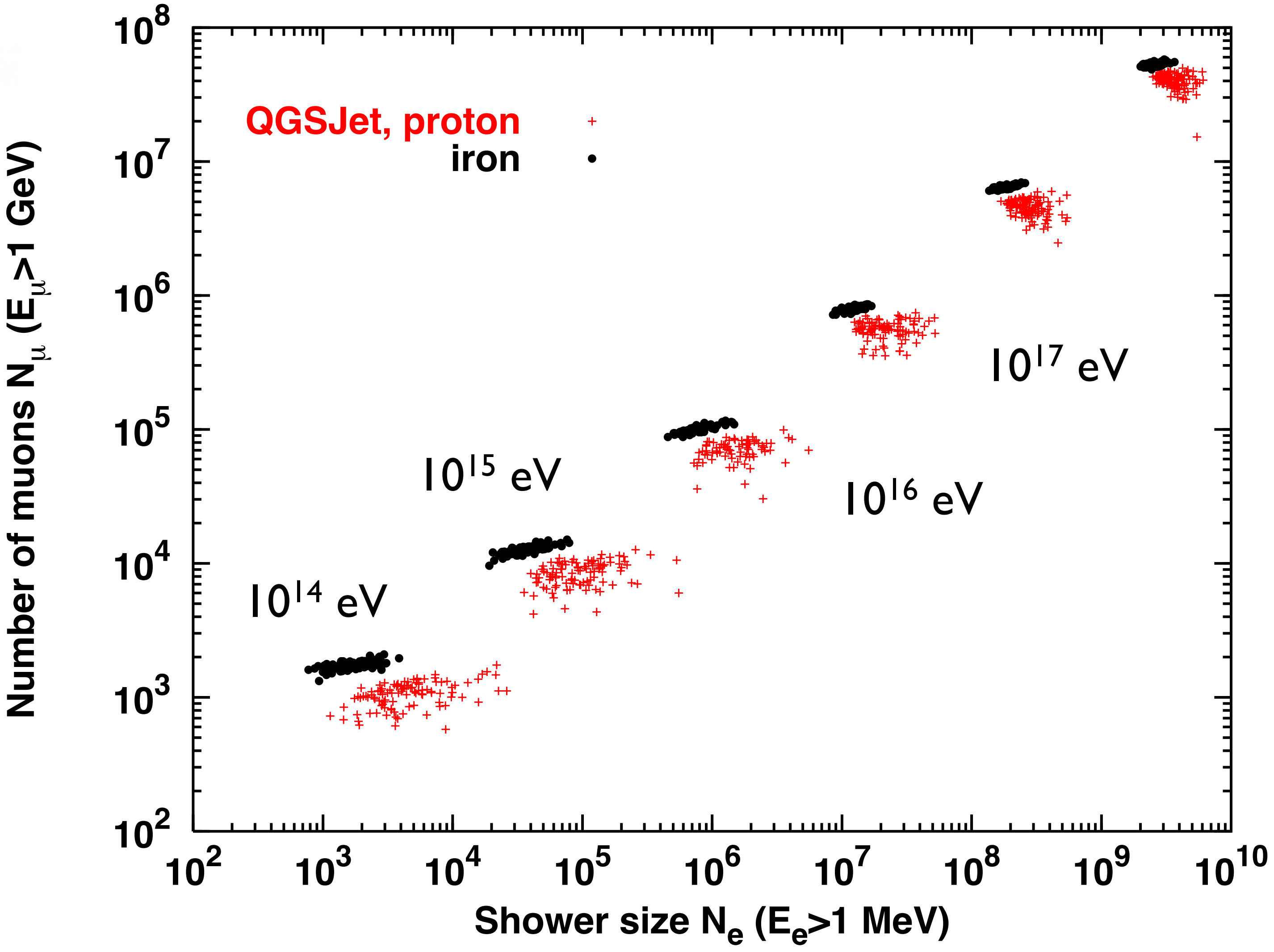
Air shower ground arrays



J.Oehlschlaeger,R.Engel,FZKarlsruhe

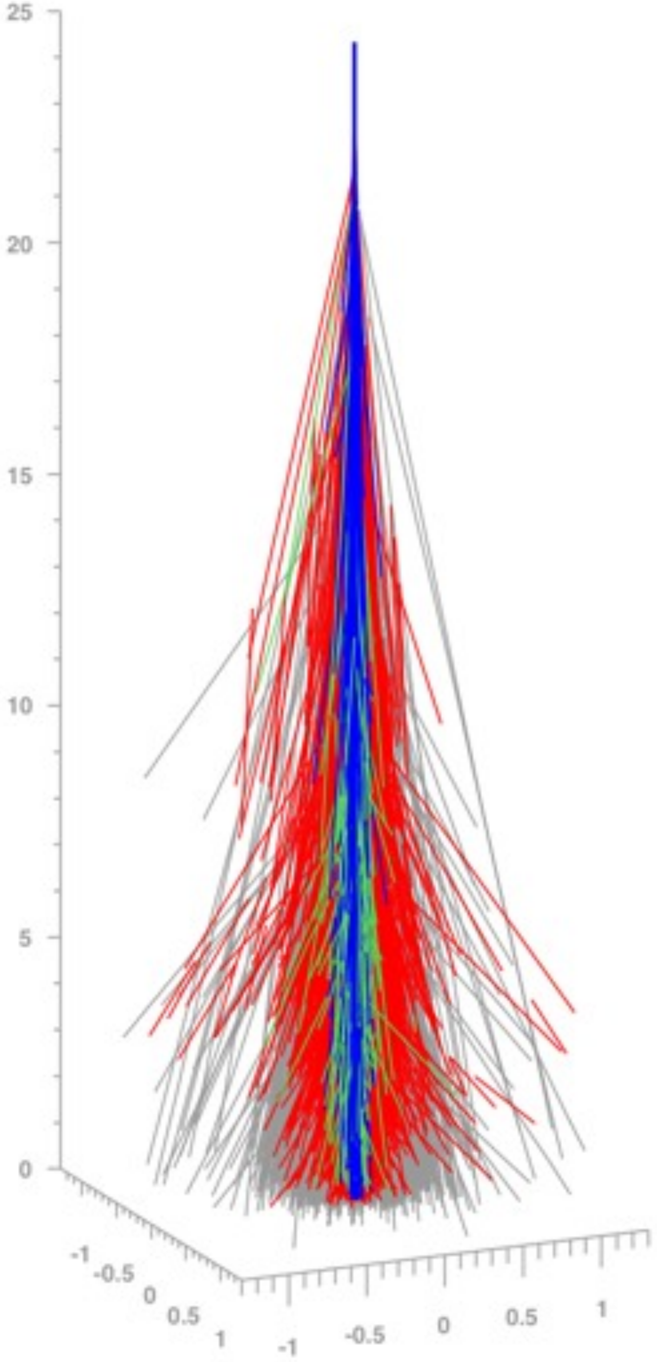
Example:
KASCADE-Grande (Karlsruhe)

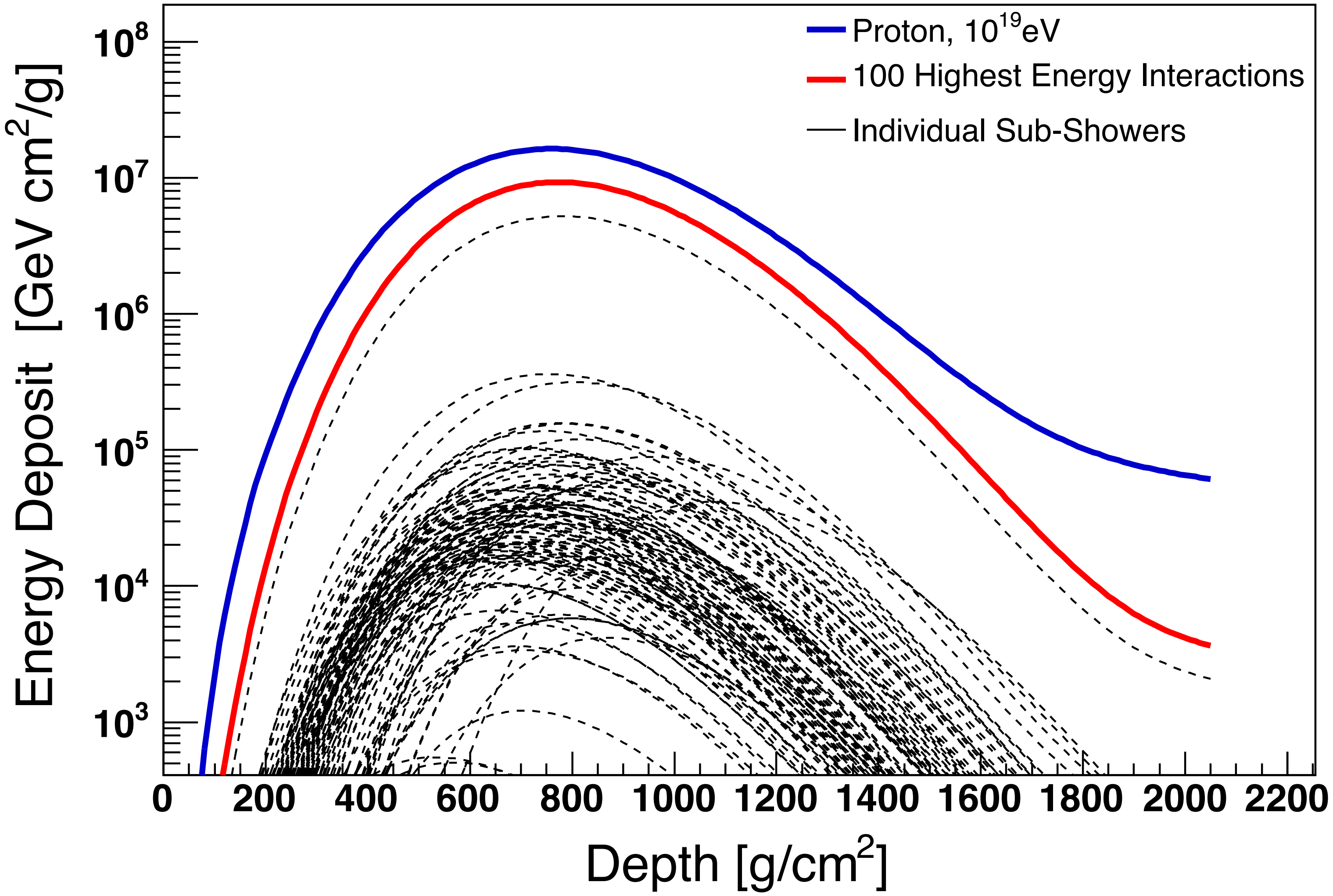
Combined energy-composition analysis



How to improve reliability of Xmax predictions ?

Shower particles produced in 100 interactions of highest energy

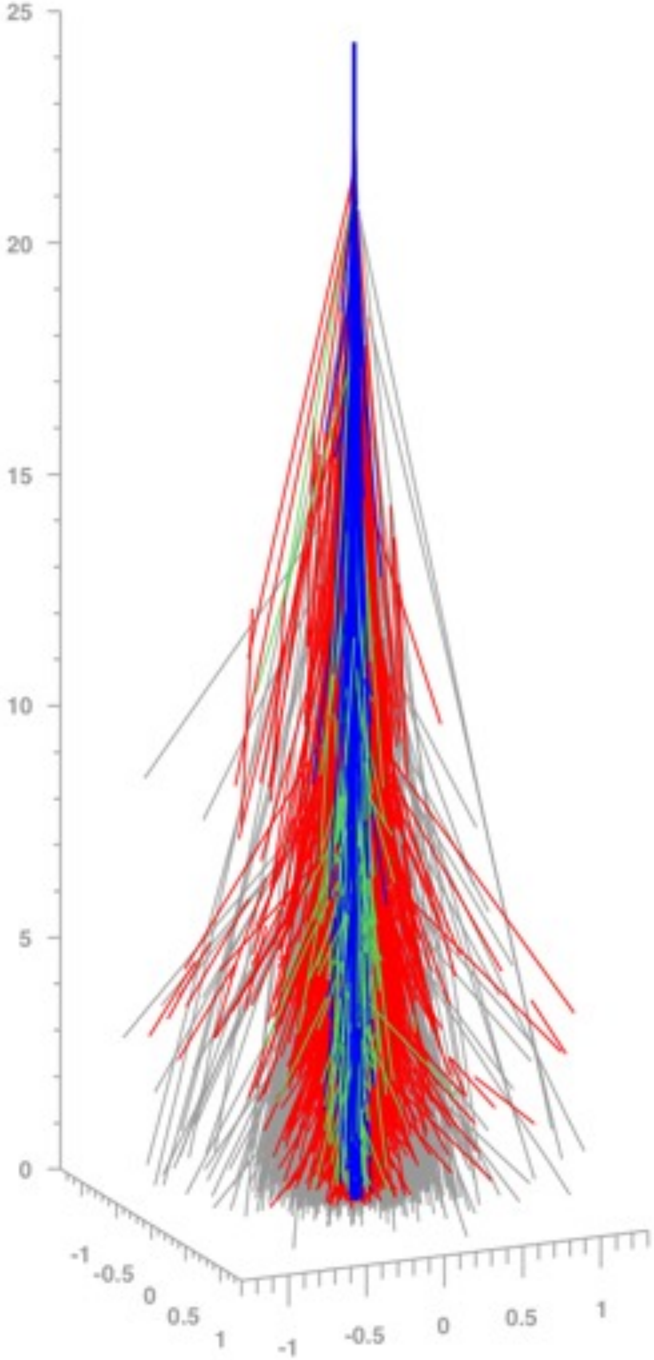



Depth of shower maximum

(Ralf Ulrich, 2012)

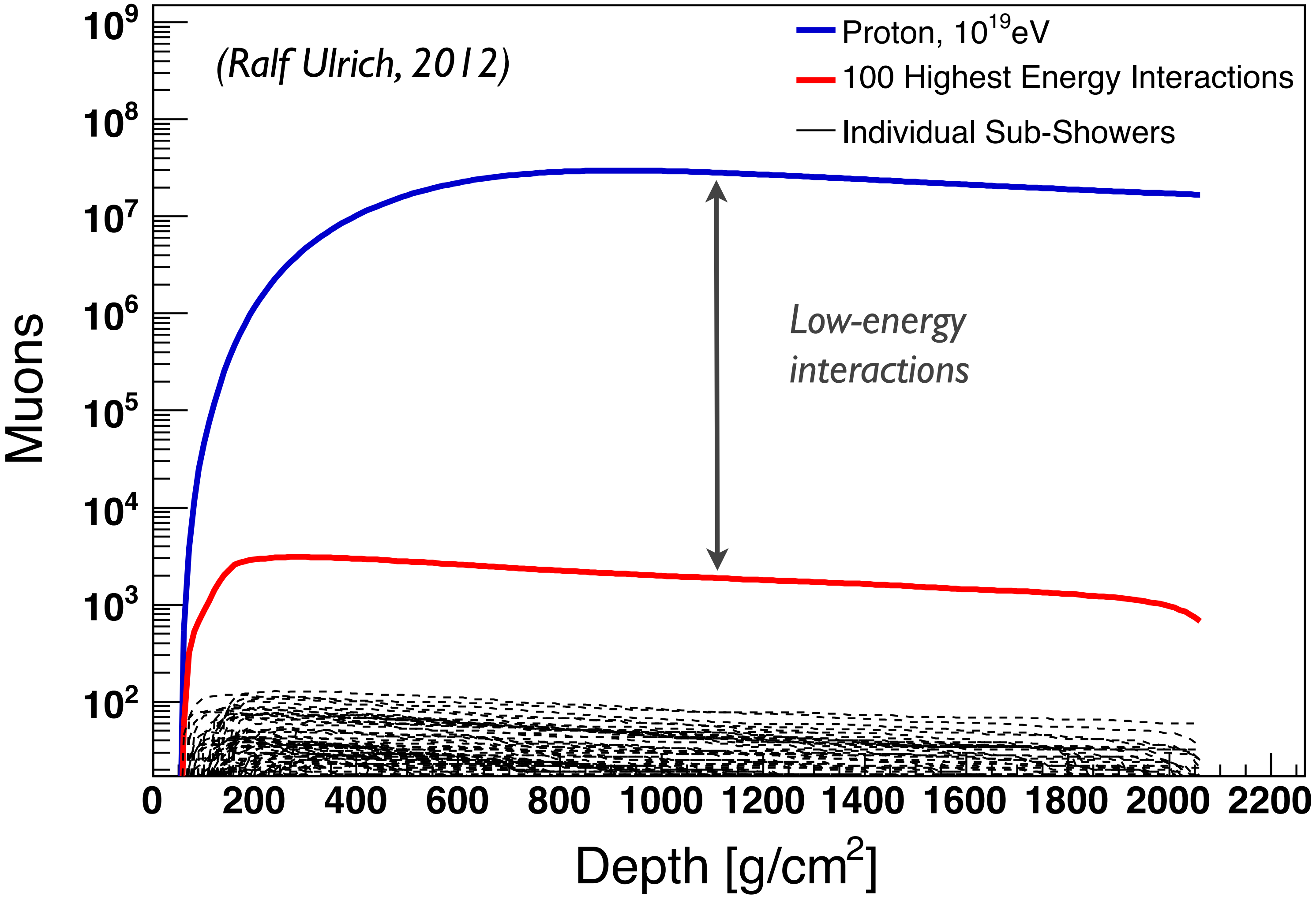
Electrons/photons:
high-energy interactions

How to improve predictions for muons ?



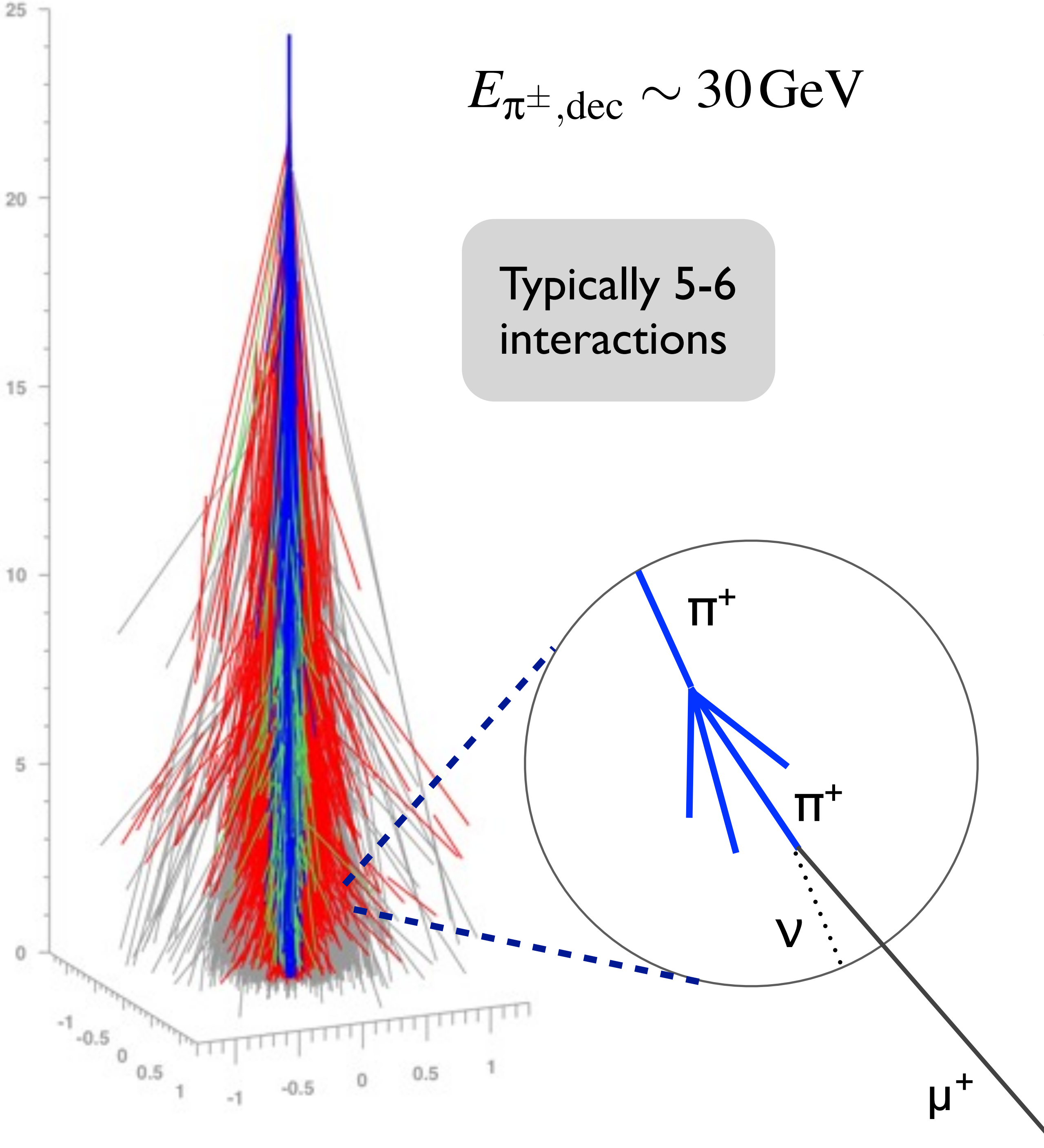
Shower particles produced in 100 interactions of highest energy

Muons



Muons/hadrons: high- and low-energy interactions

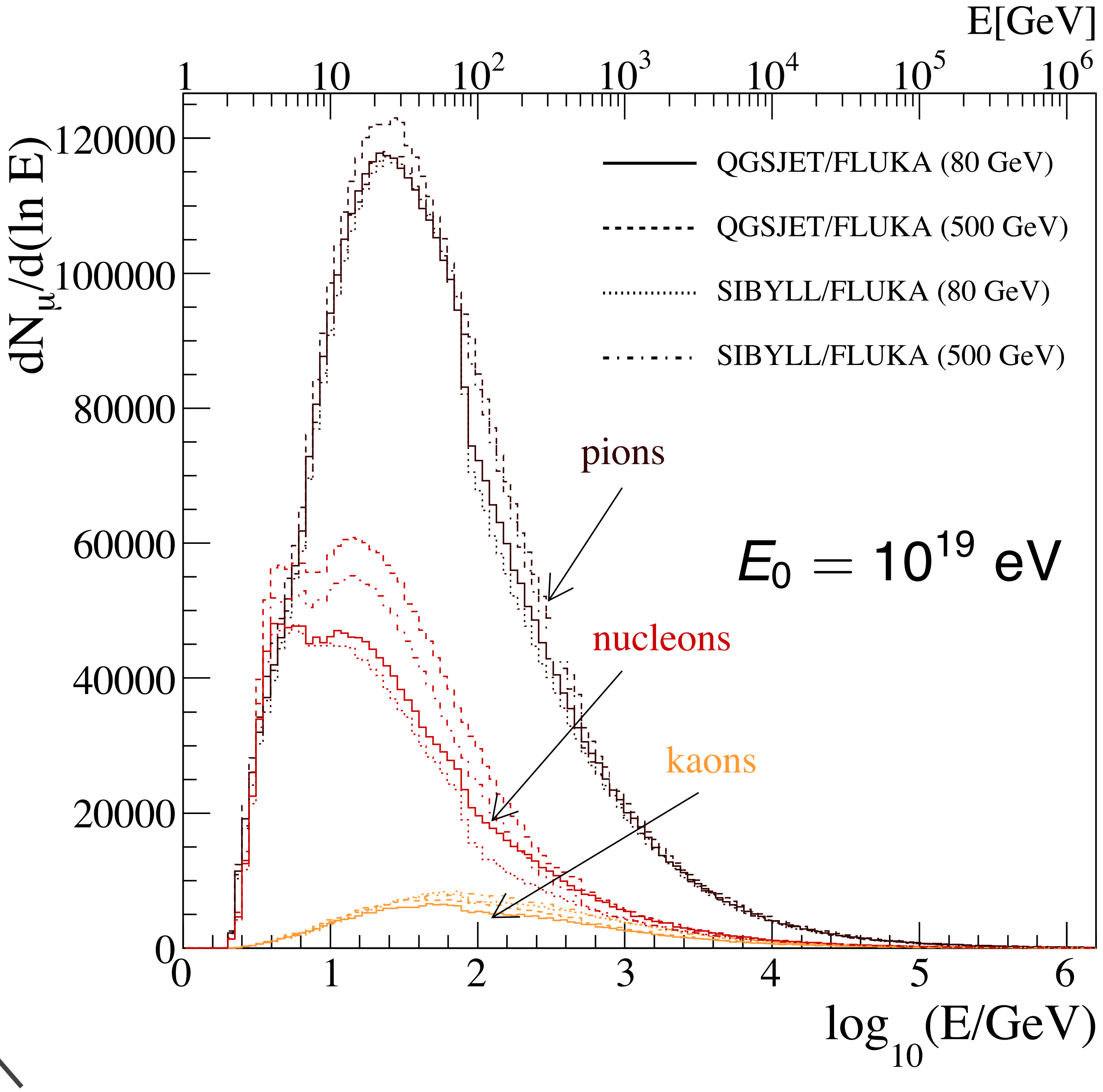
Muon production at large lateral distance



$E_{\pi^\pm,\mathrm{dec}} \sim 30\,\mathrm{GeV}$

Typically 5-6 interactions

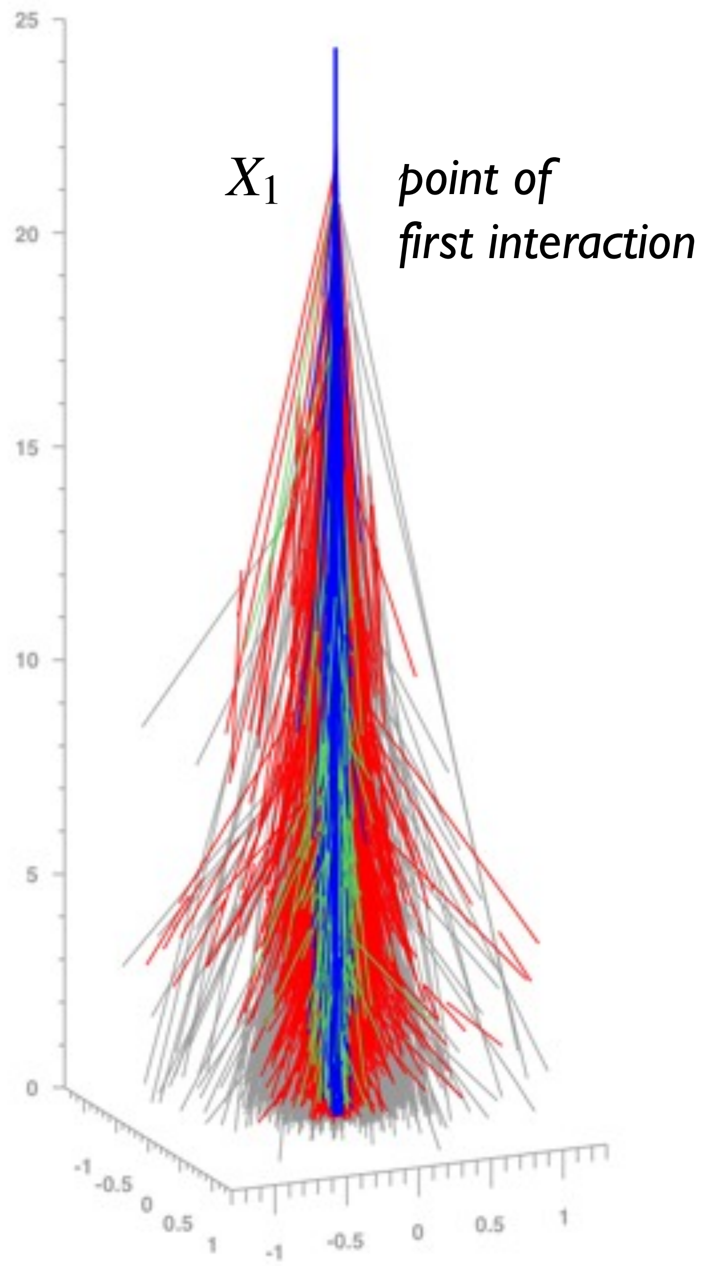
Energy distribution of last interaction that produced a detected muon

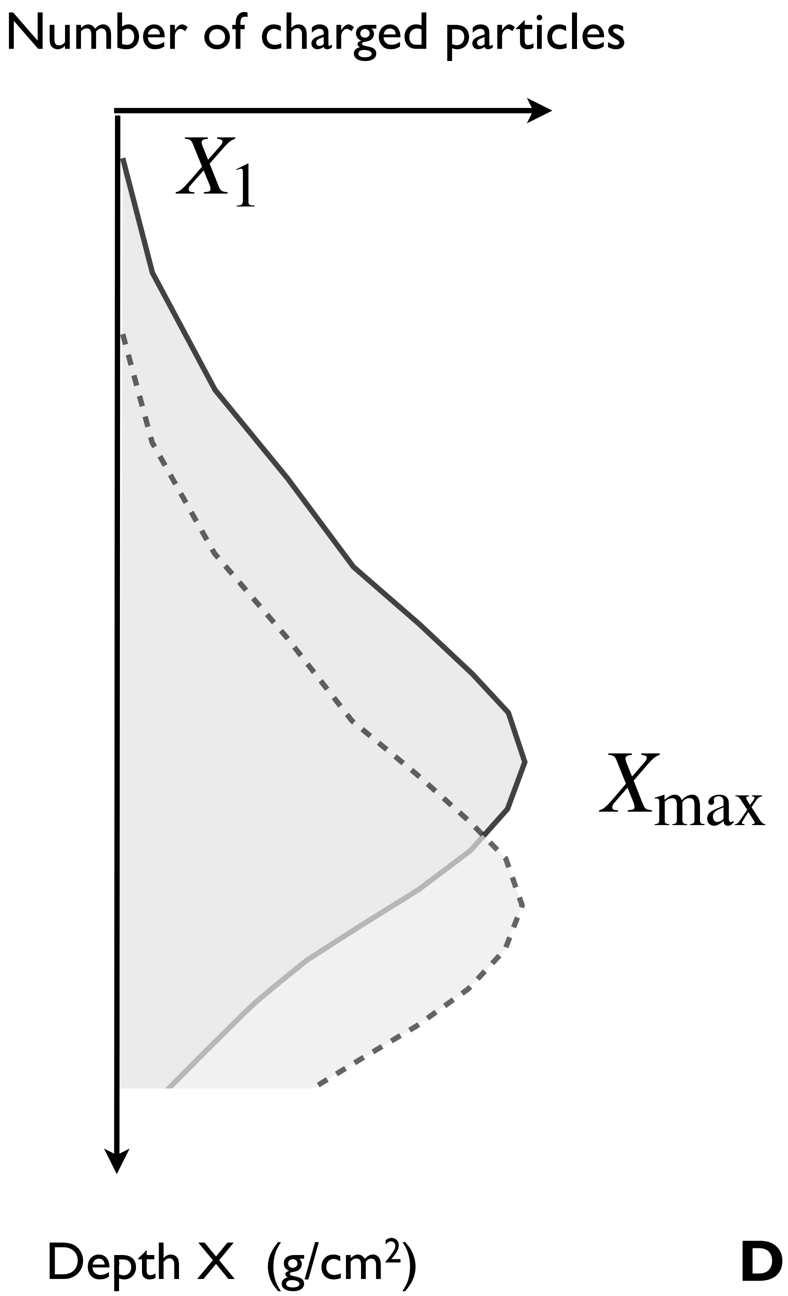


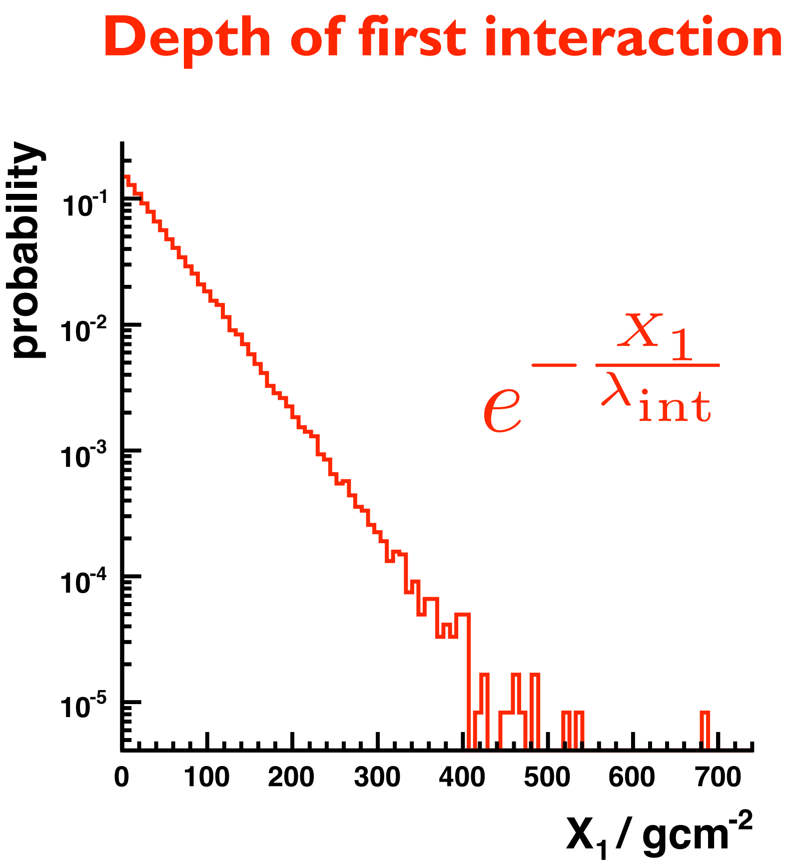
Muon observed at 1000 m from core

(Maris et al. ICRC 2009)

Cross section measurement with air showers







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

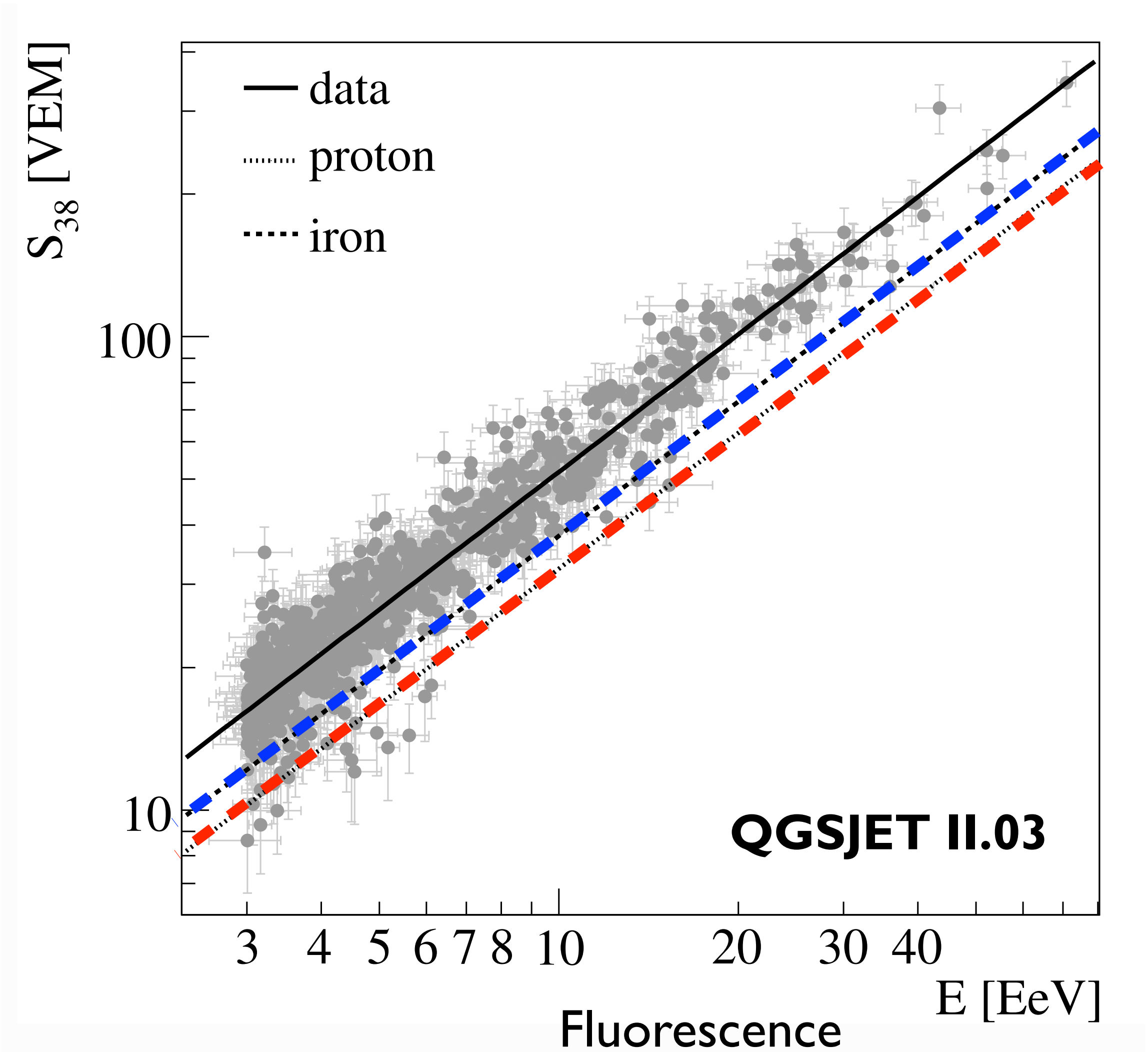
Difficulties

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

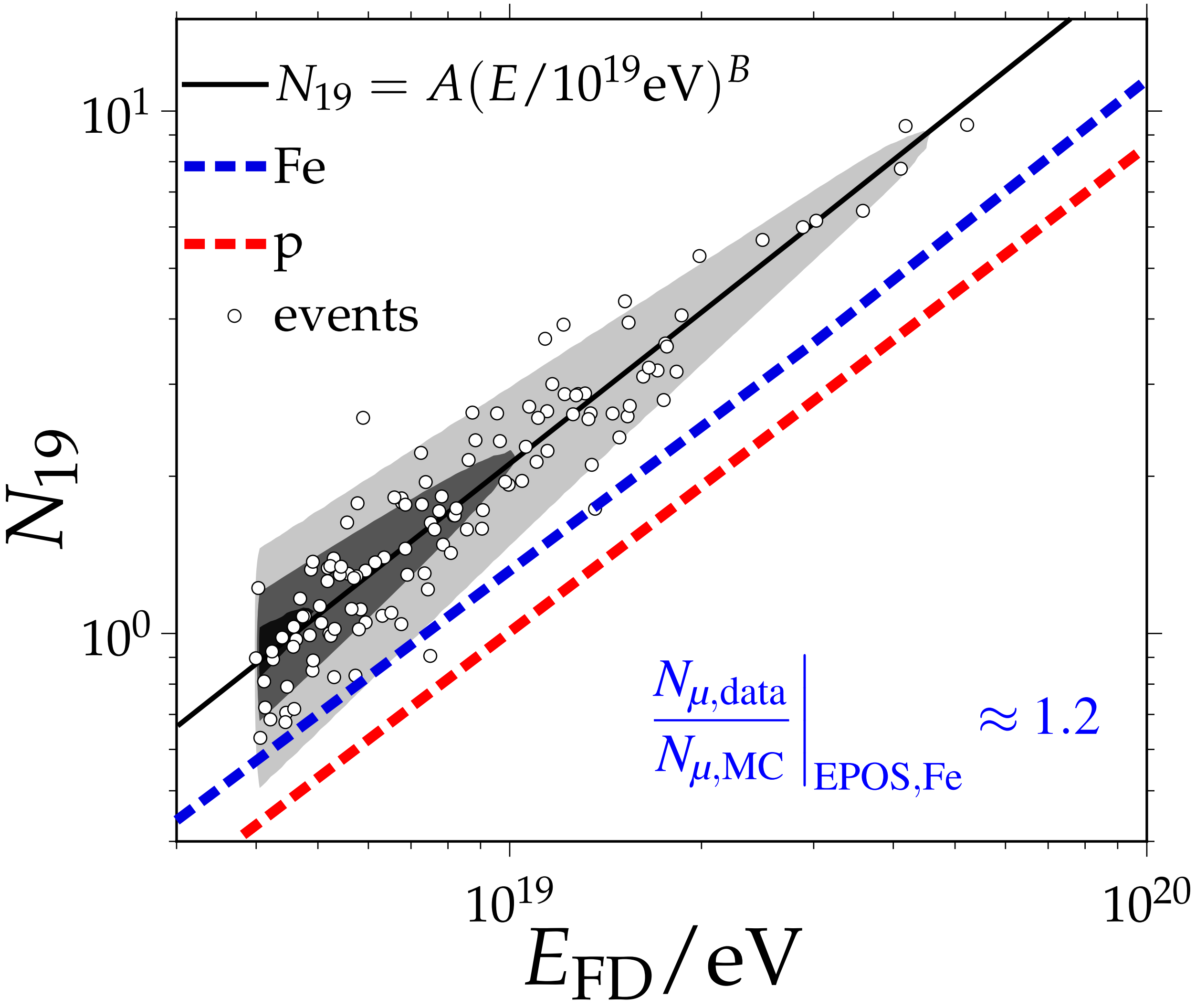
(R. Ulrich et al. NJP 11, 2009, and talk at this meeting)

Auger: comparison of surface detector signals

Showers up to 60° zenith angle



Inclined showers (muon dominated)



Discrepancy due mainly to muons

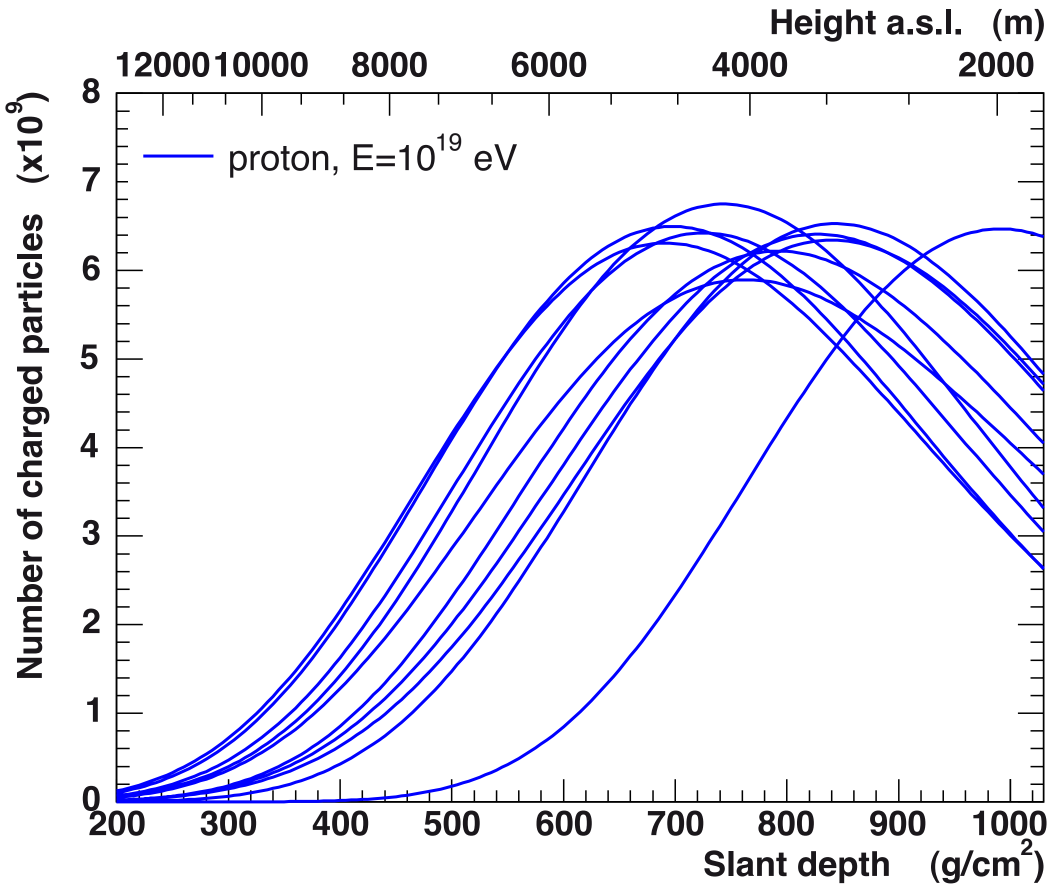
$$\left.\frac{N_{\mu,\mathrm{data}}}{N_{\mu,\mathrm{MC}}}\right|_{\mathrm{QGS,p}} = 2.13 \pm 0.04(\mathrm{stat}) \pm 0.11(\mathrm{sys})$$

(Independent confirmation with several other observables)

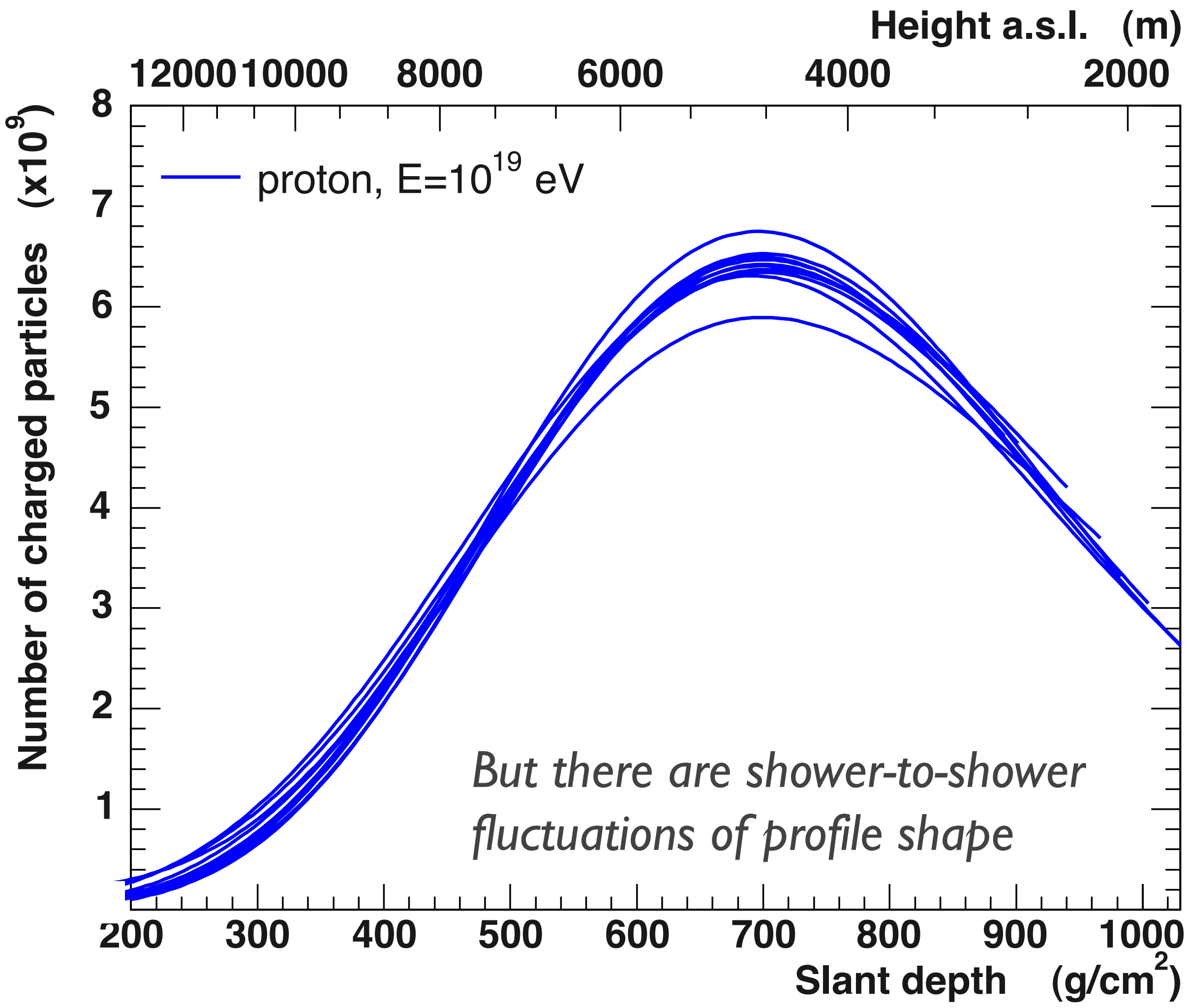
(HadInt Working Group, UHECR 2012)

Universality features of high-energy showers (i)

Simulated shower profiles



Profiles shifted in depth

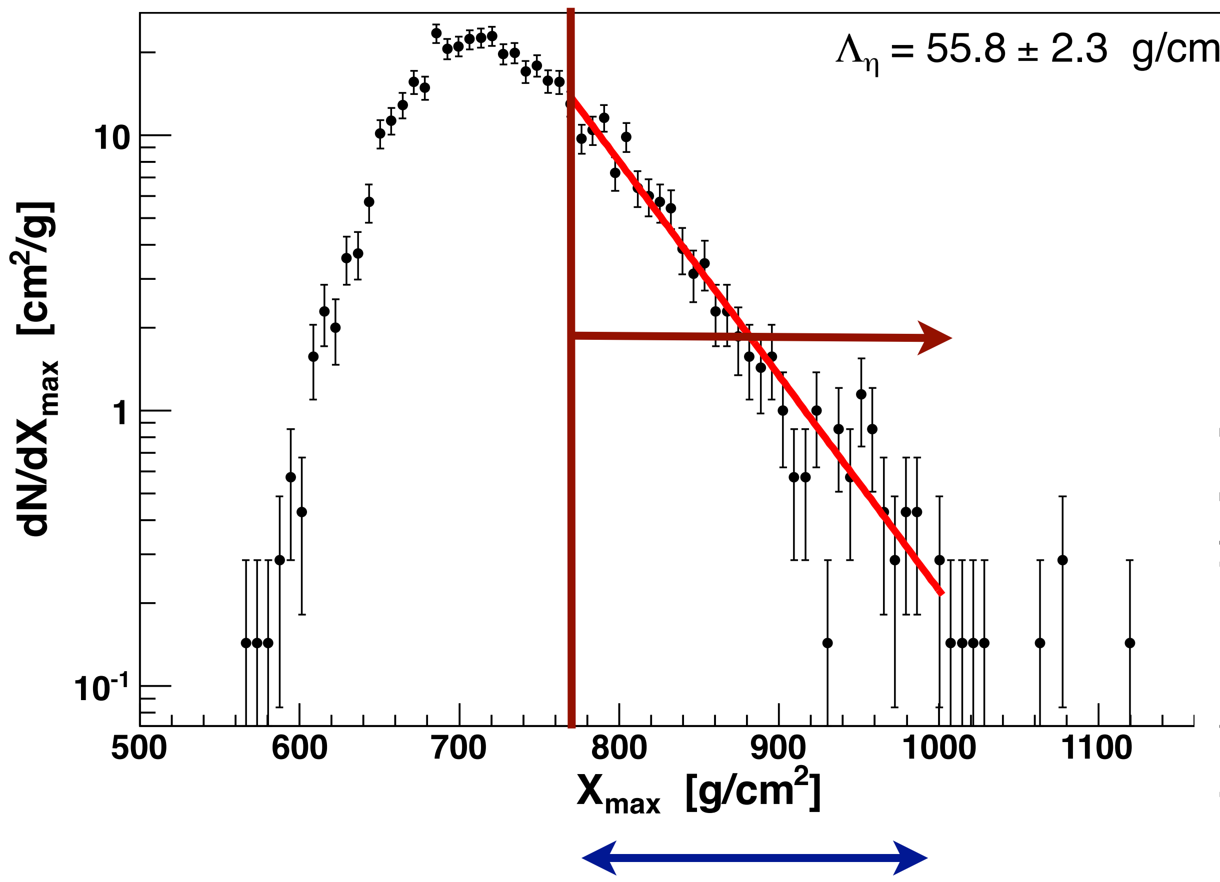


But there are shower-to-shower fluctuations of profile shape

Depth of X_1 and X_{max} strongly correlated, use X_{max} for analysis

Selection of protons: select very deep showers

Cross section measurement: self-consistency

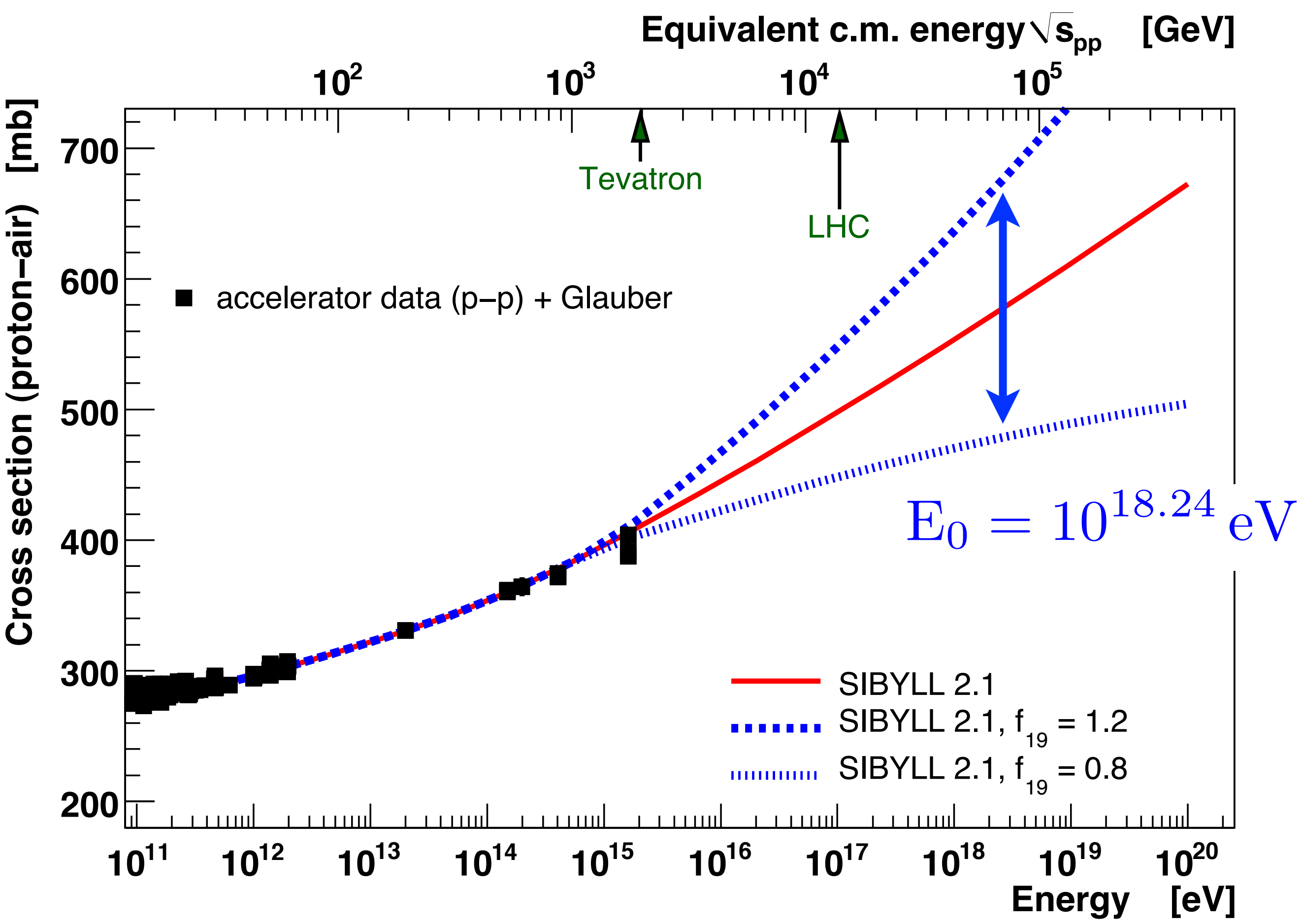


Depth range of analysis

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

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

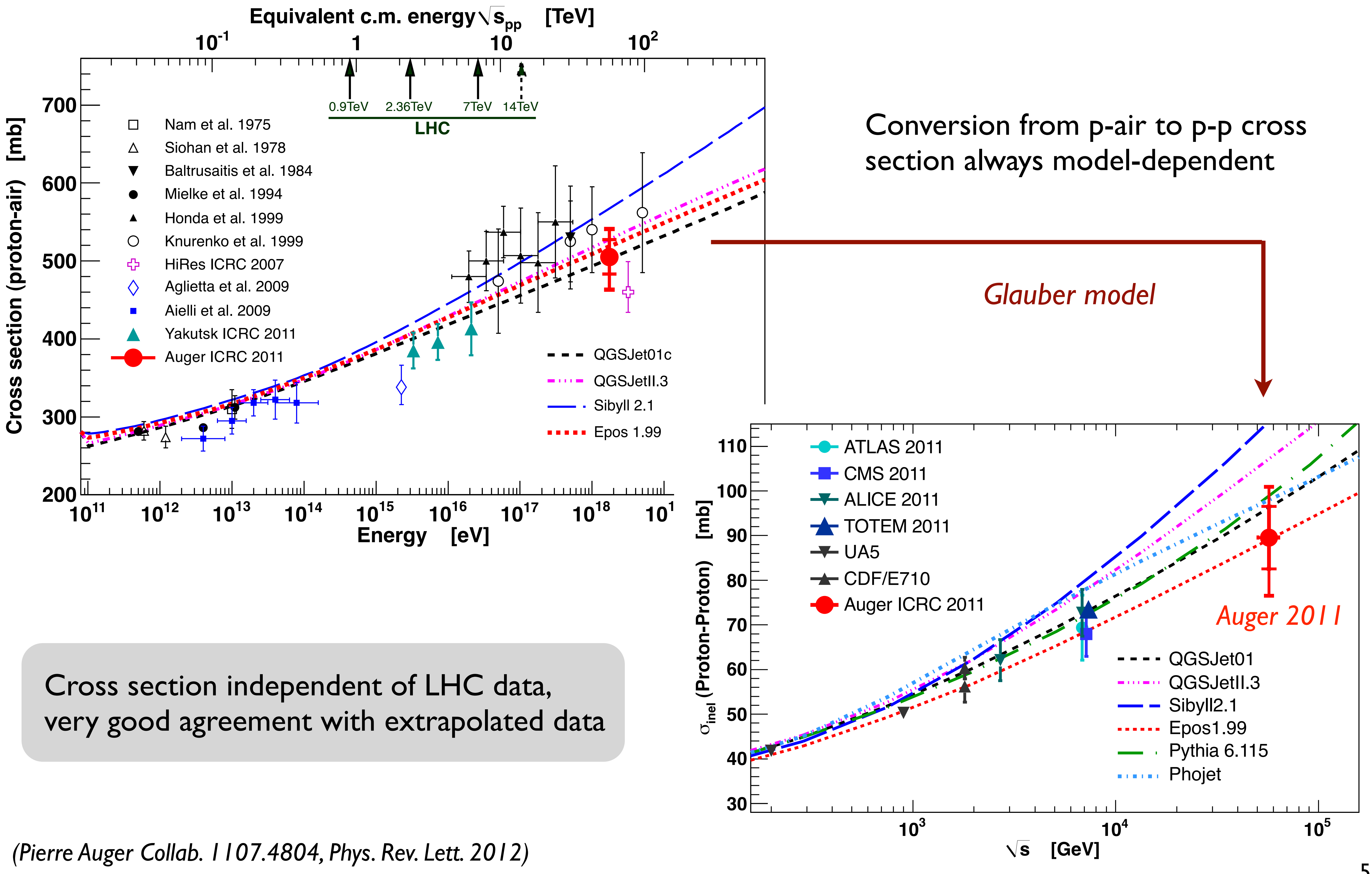
(Auger Collab. 1107.4804)



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

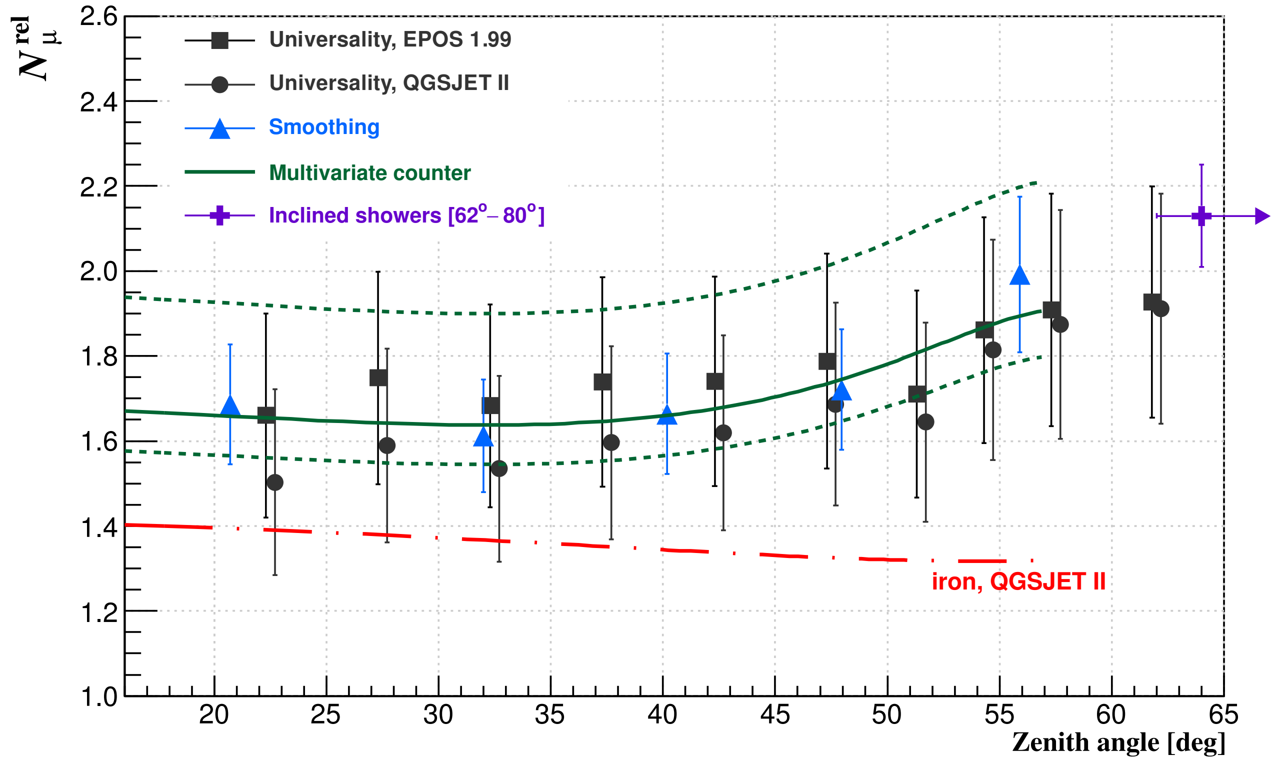
Auger 2011

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

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

Auger results of related measurements

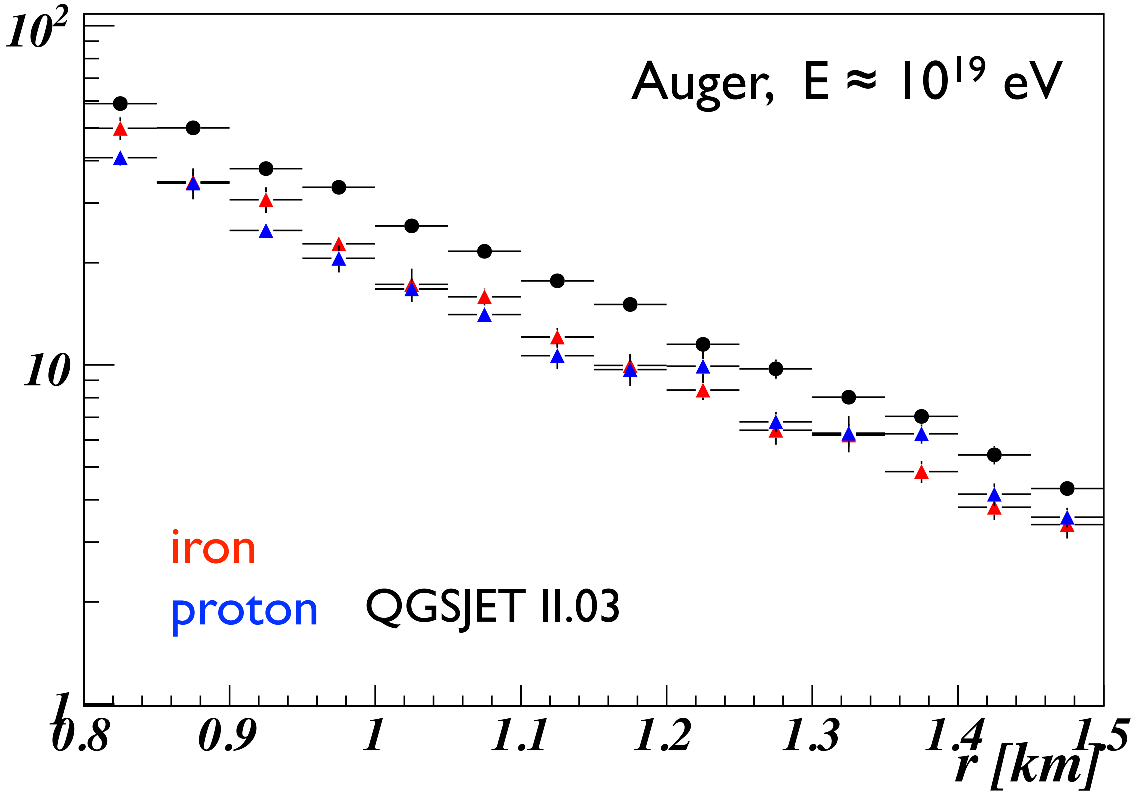
Different methods: **muon contribution**



(Yushkov, Auger UHECR 2012)

Energy uncertainty of 22% not included

Em. component (smoothing method)



(Auger ICRC 2009)

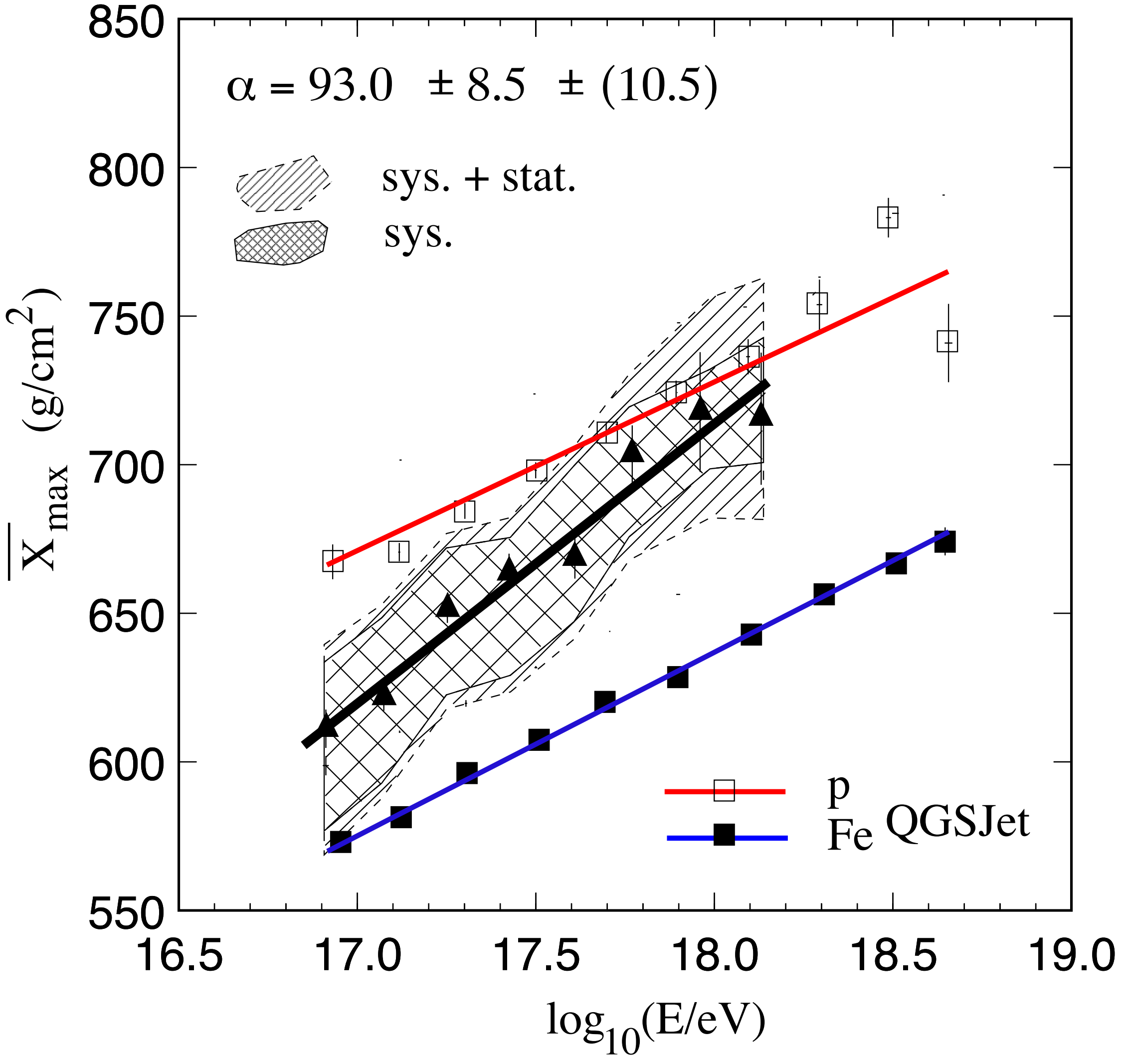
Electromagnetic component:

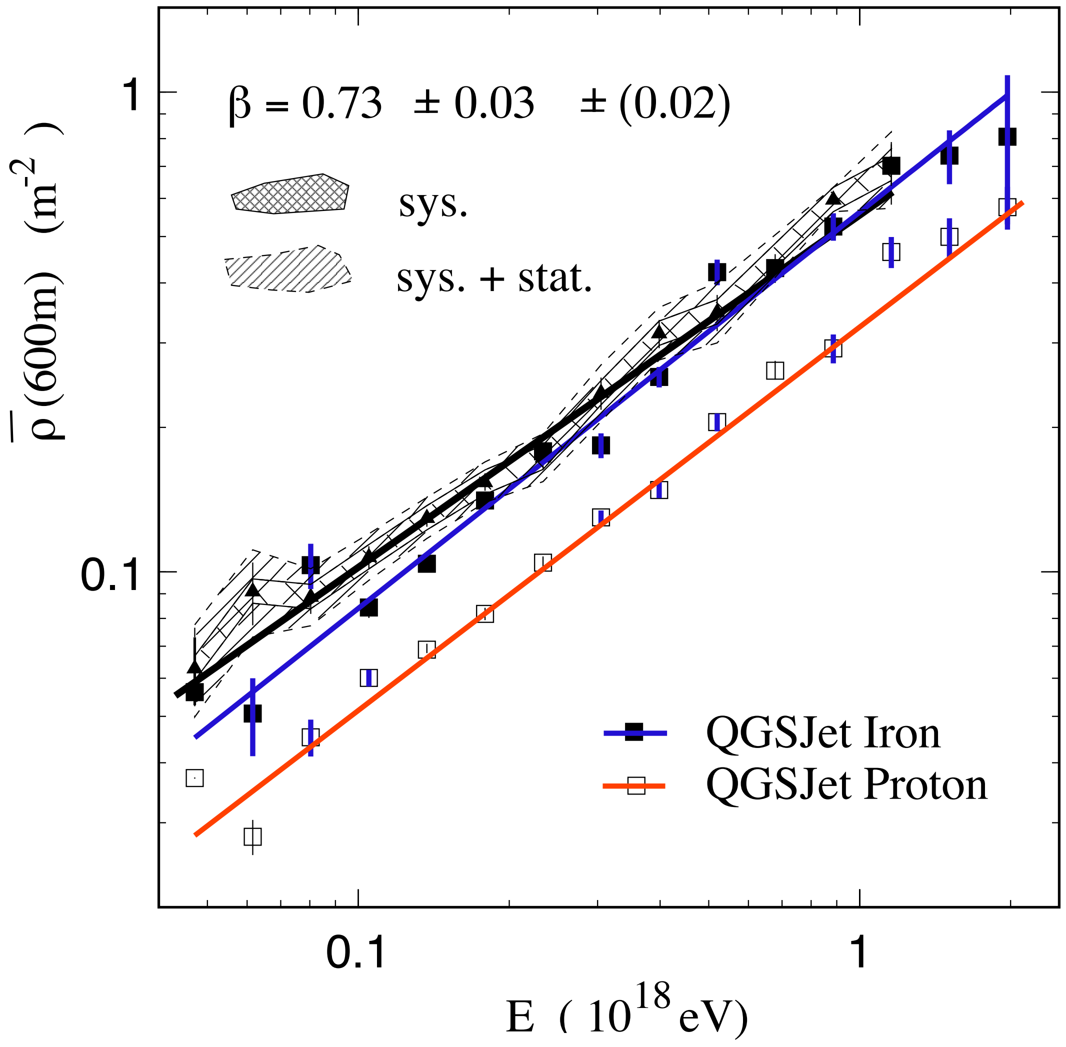
25-30% more particles than QGSJET II.03?

Same problem found also at lower energy

HiRes prototype + MIA

Muon density 600m from core

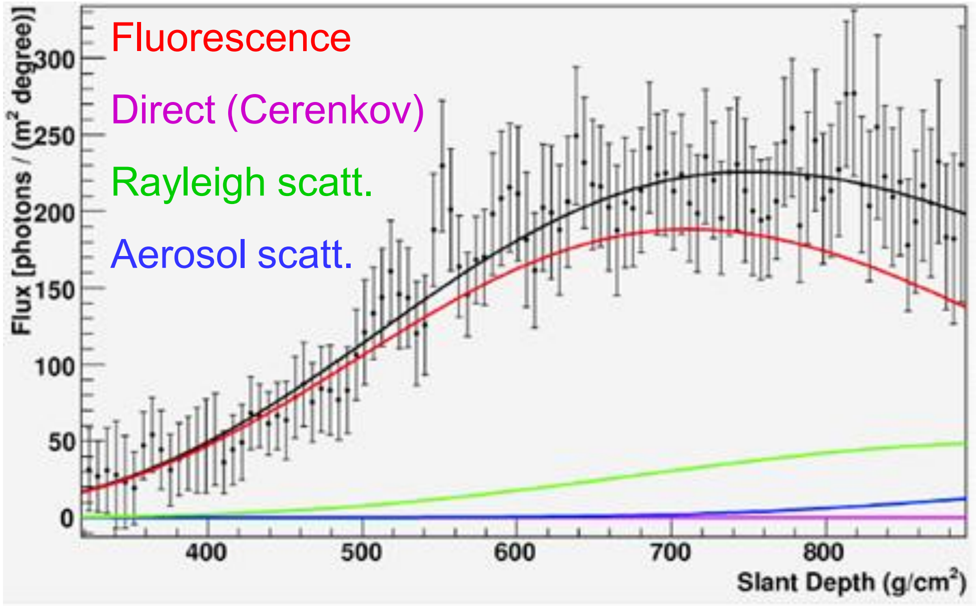




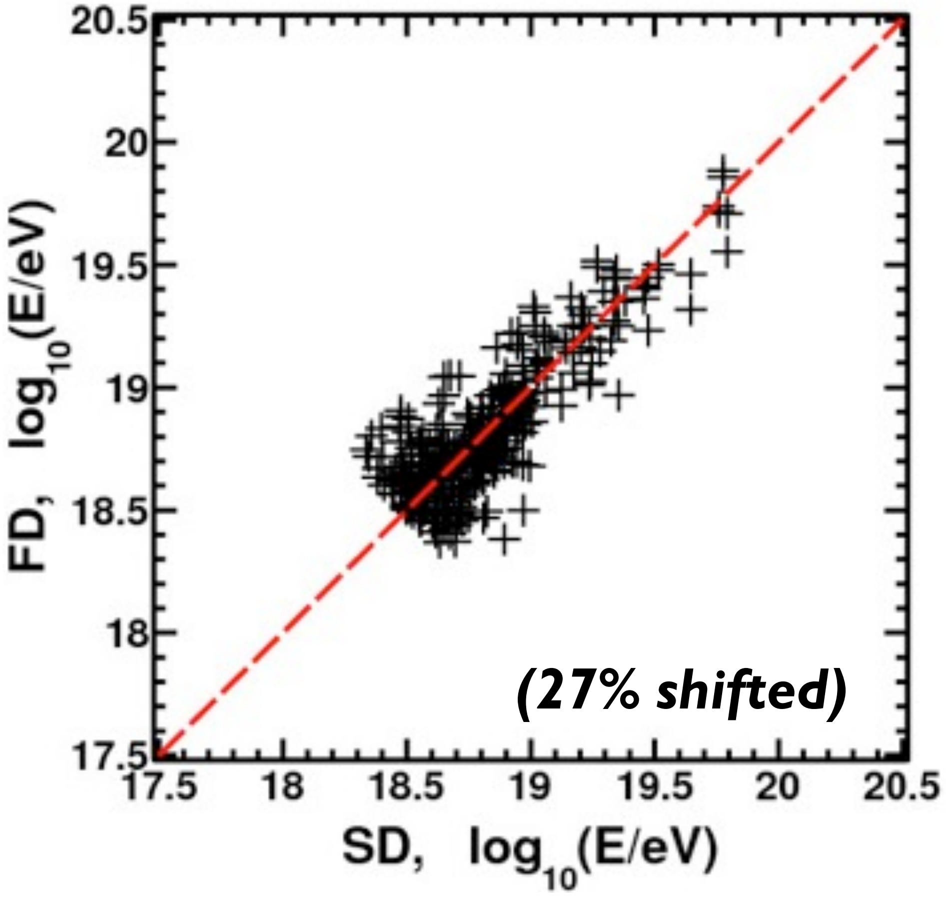
(HiRes Fly's Eye and MIA Collabs., Phys. Rev. Lett. 84, 2000)

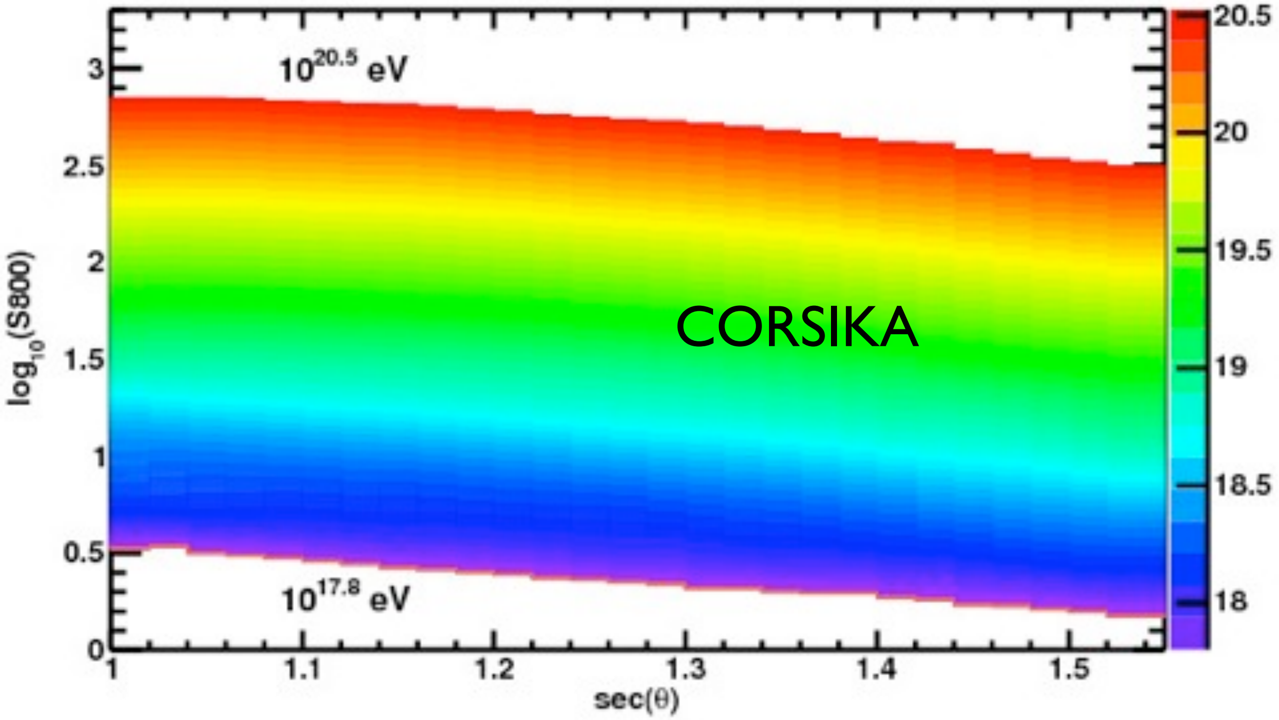
At what energy does the muon problem appear ?

TA: comparison of energy scales



Energy derived from fluorescence light profile

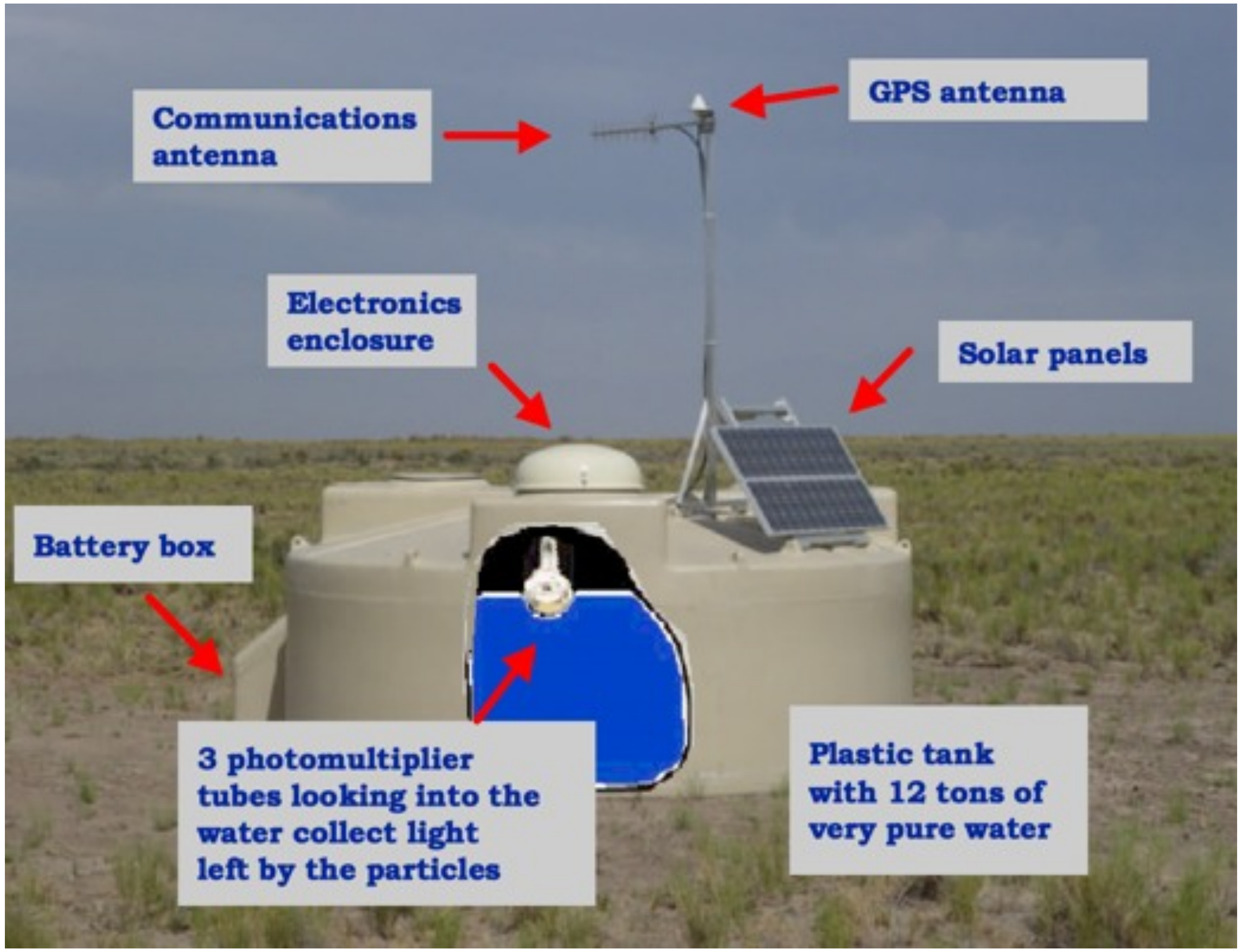




Simulated SD signal at 800m used to determine SD energy

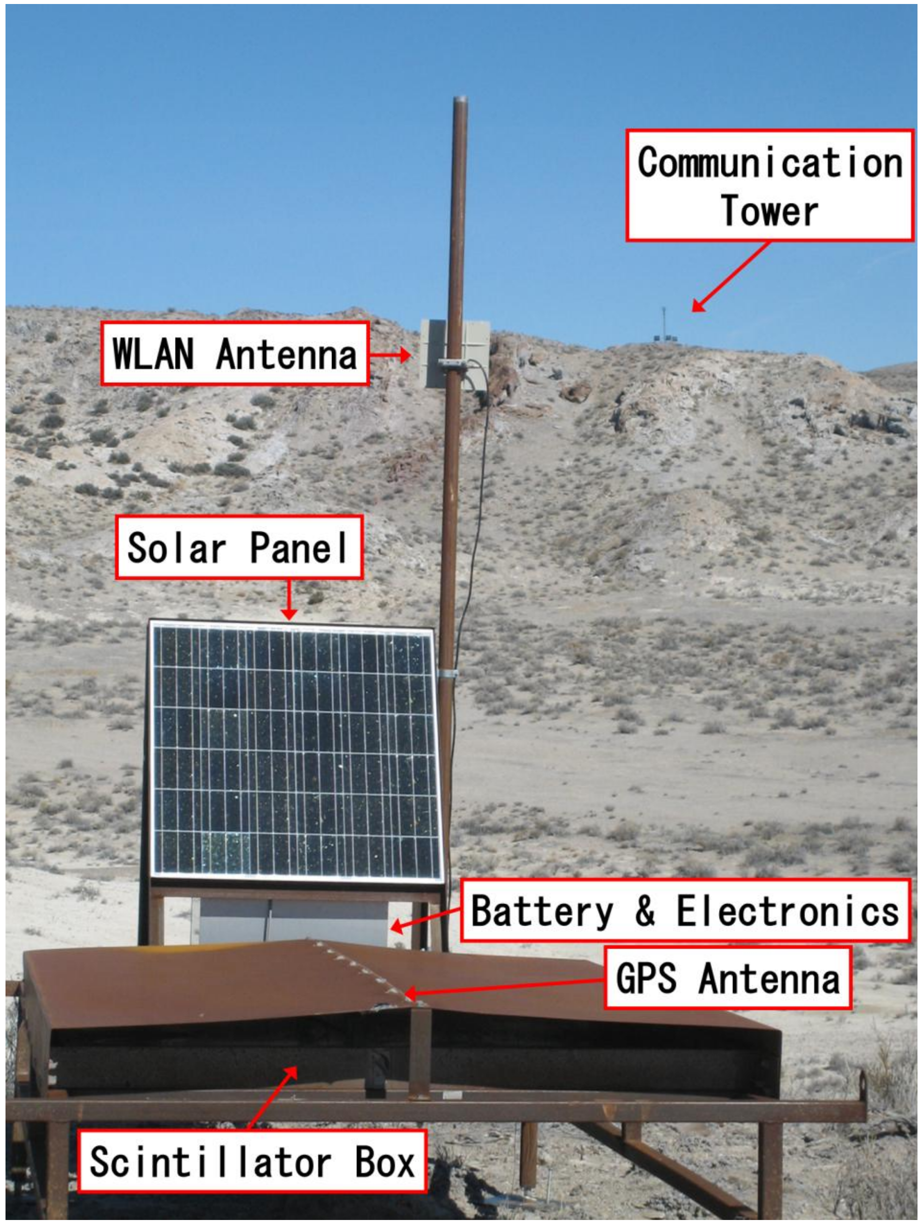
SD energies 27% higher than FD energies (QGSJET II, protons)

Comparison of surface detectors



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

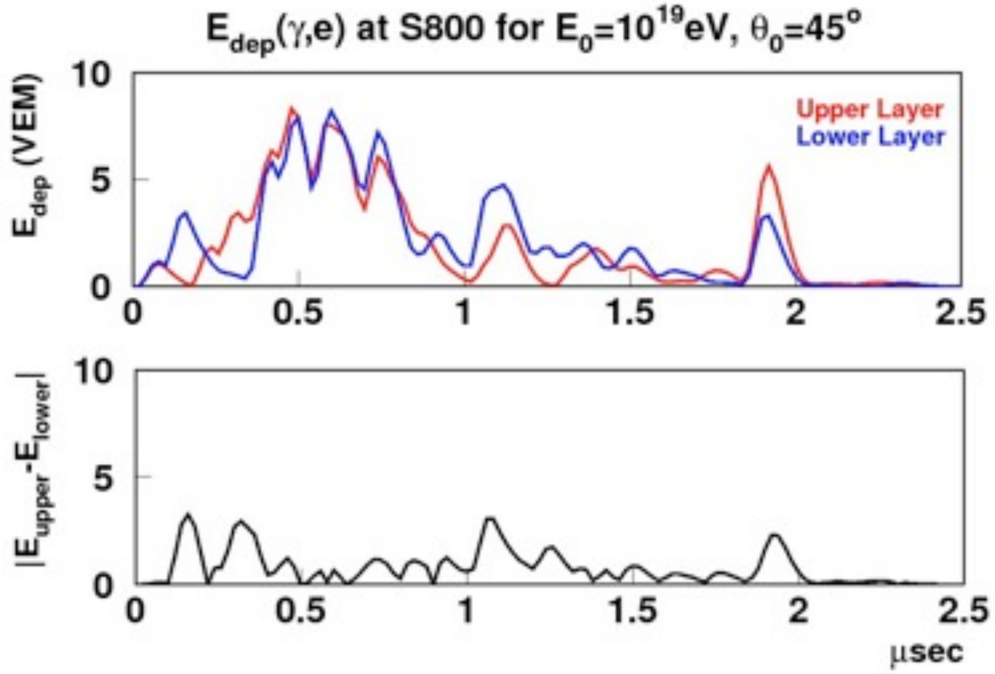
Telescope Array: thin scintillators
(main part of signal due to em. particles,
low sensitivity to muons)



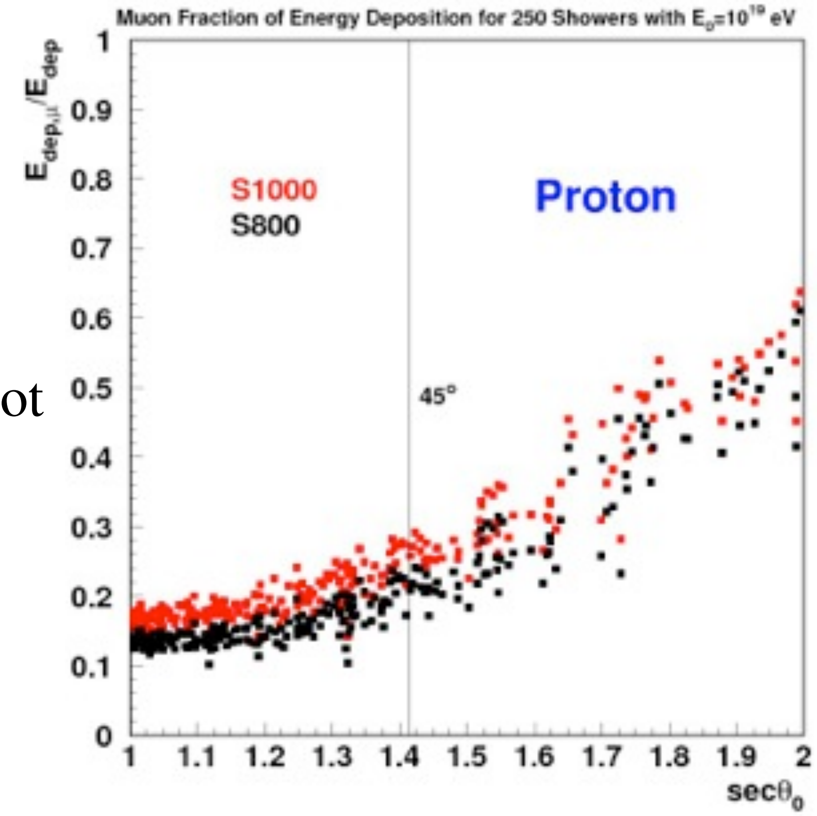
Complementary surface detector arrays

TA: detector signal and muonic component

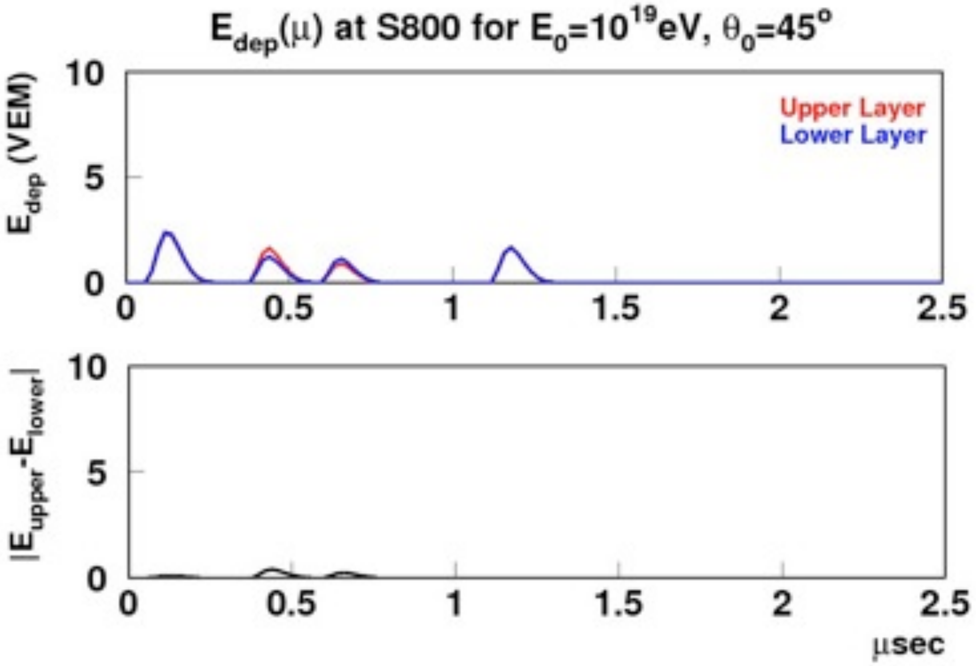
Em. particles



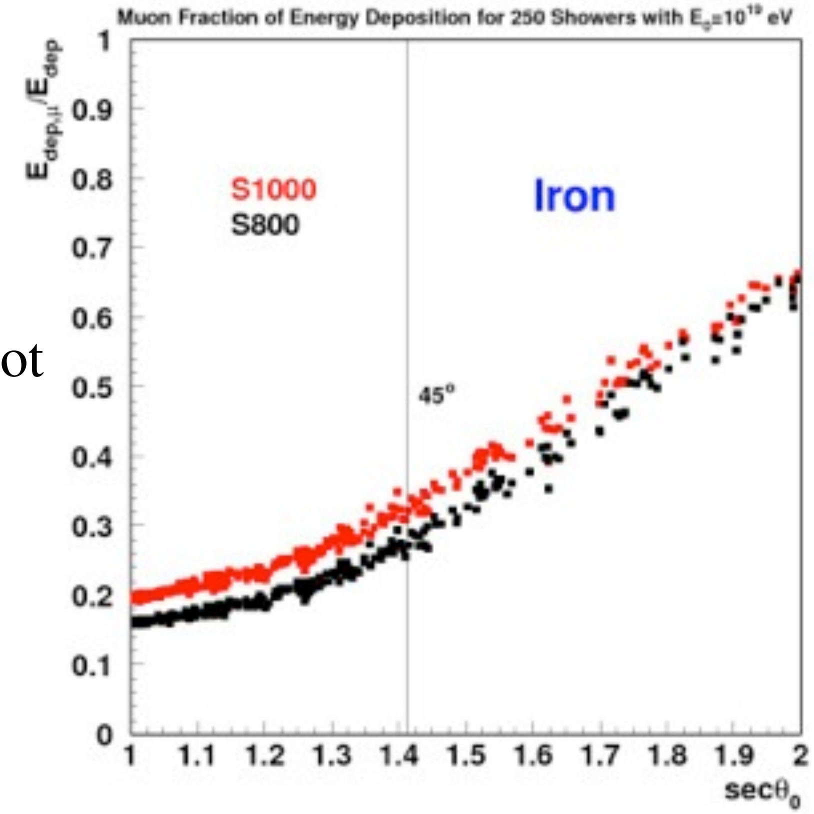
S_μ/S_{tot}



Muons

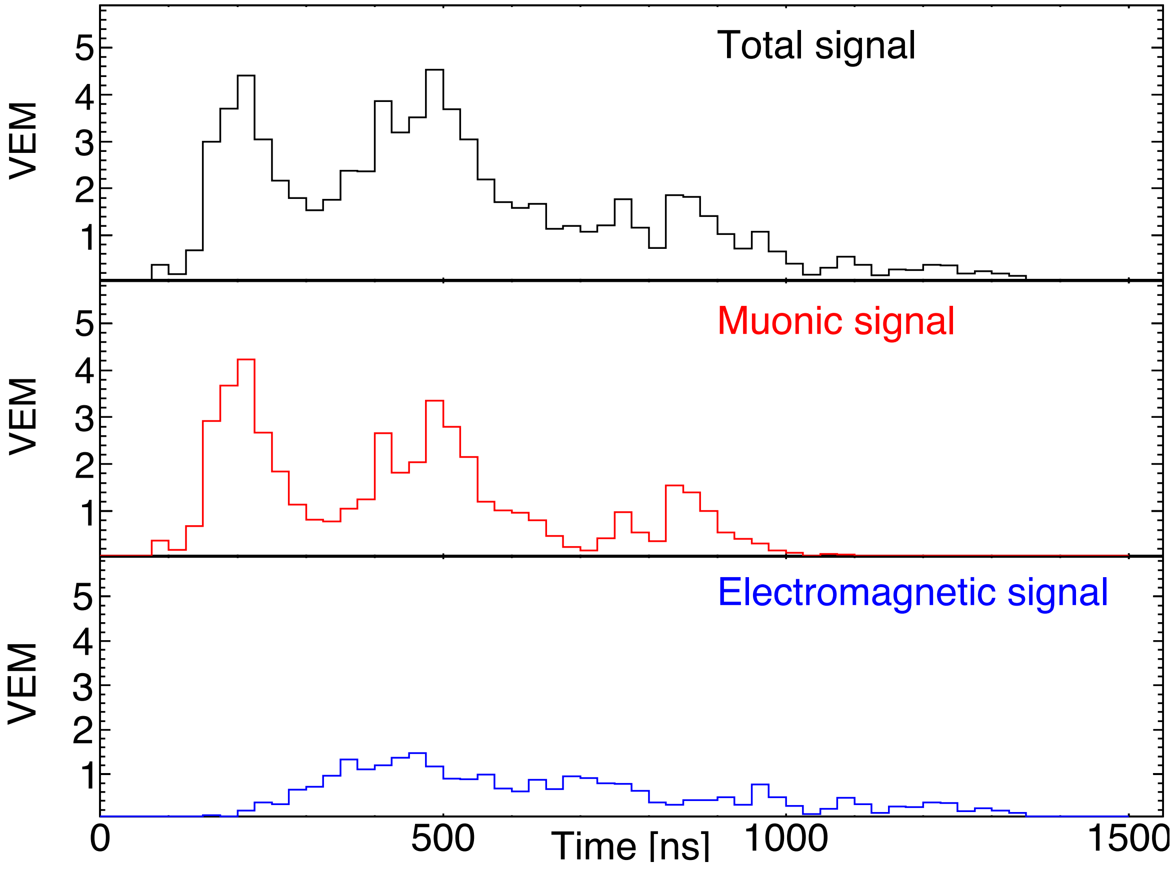


S_μ/S_{tot}



Auger: detector signal and muonic component

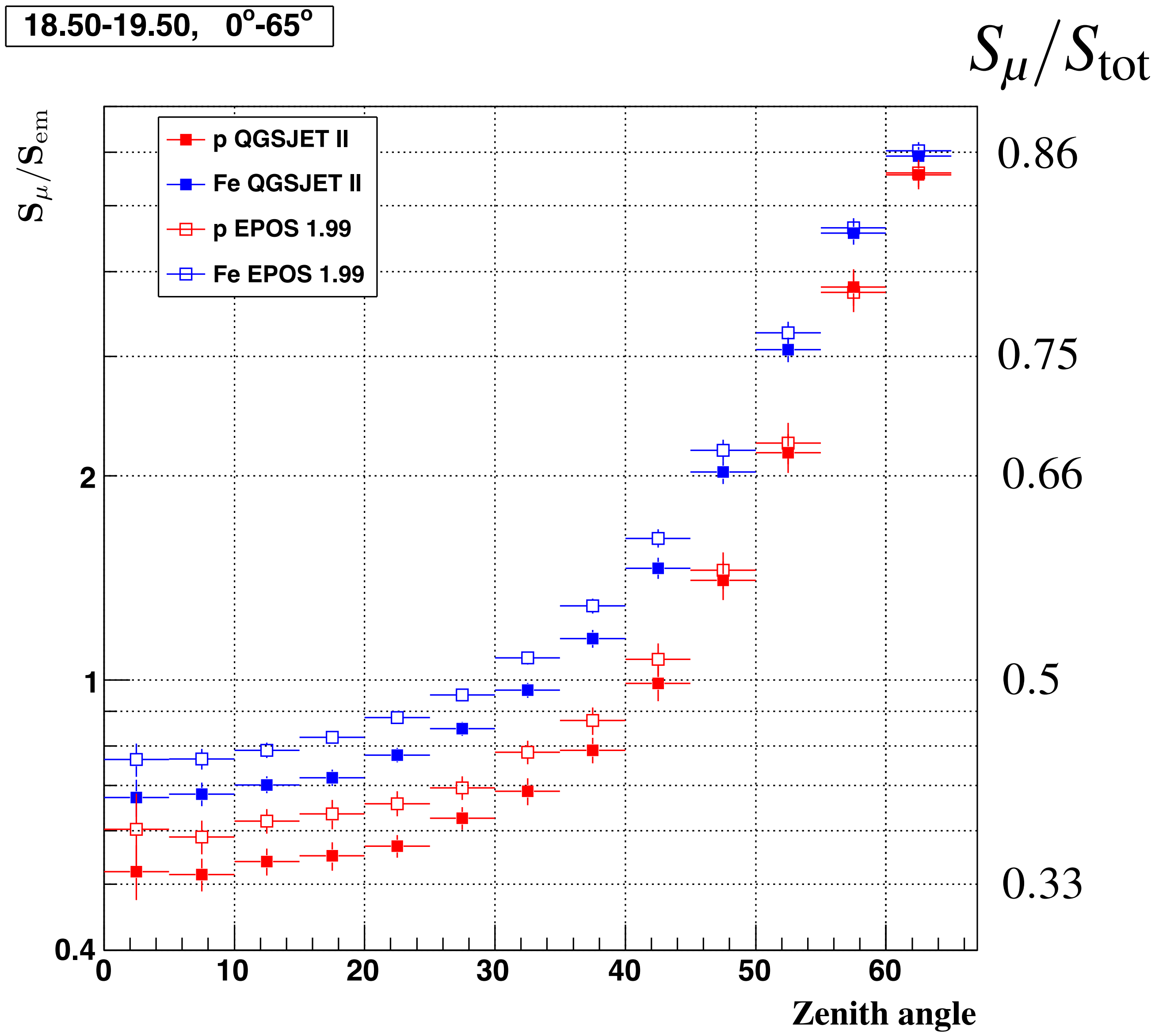
Simulated proton shower E = 10^{19} eV, θ = 45°,



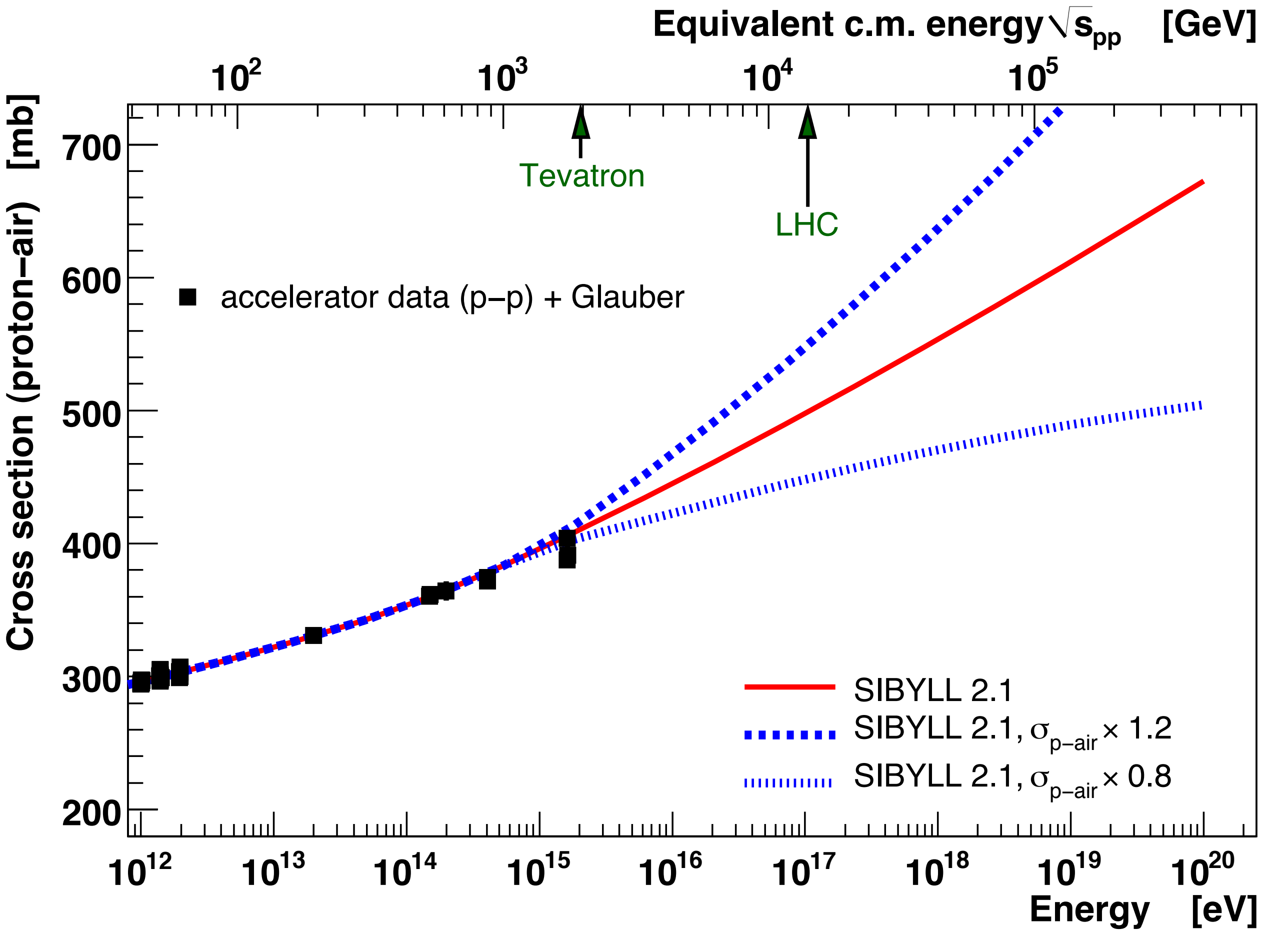
Cherenkov tank is thick:
shower continues to evolve
in detector, smooth em. signal

Muon component

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



Modification of characteristics of interactions ?



Modification of

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

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

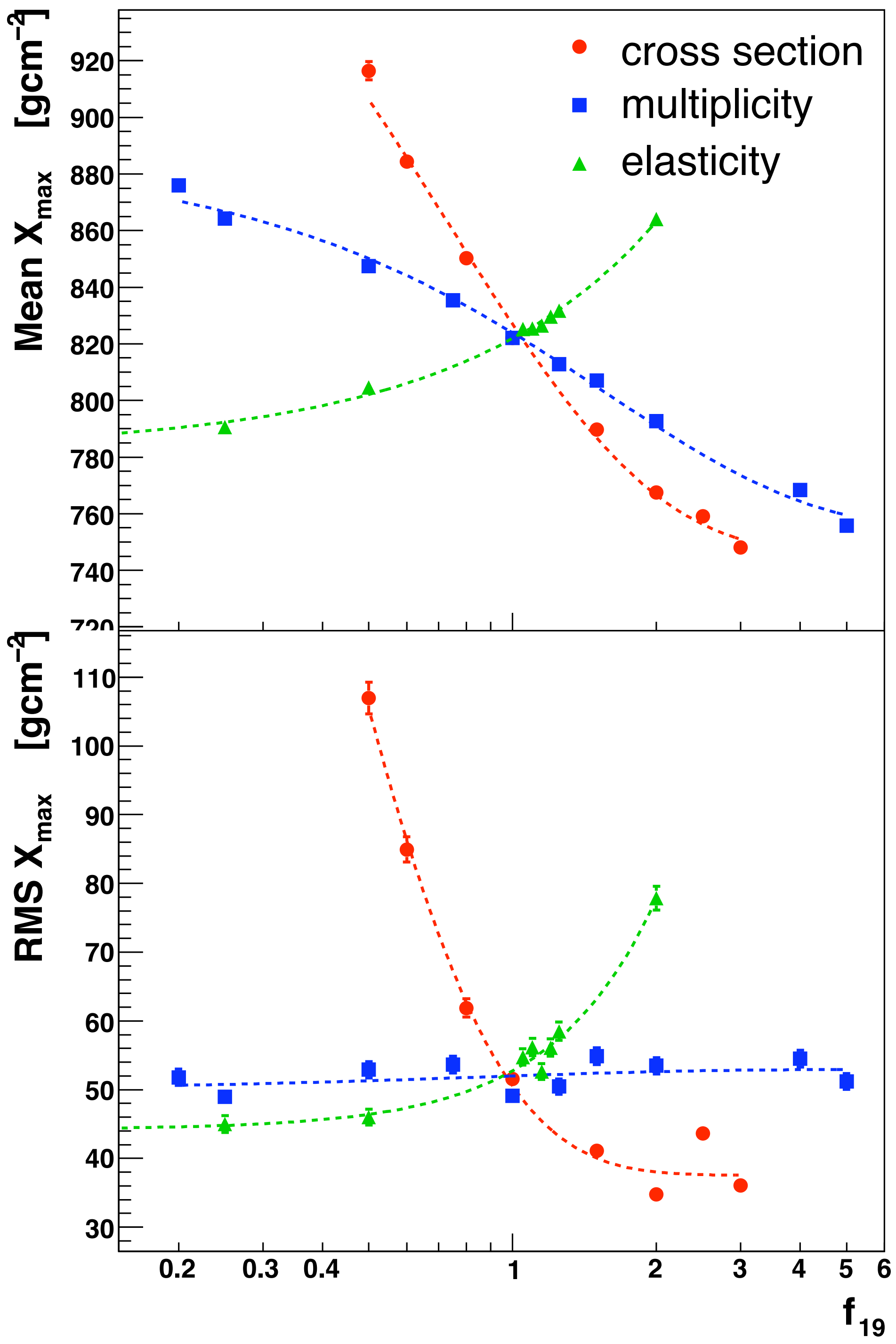
Implementation

- 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}

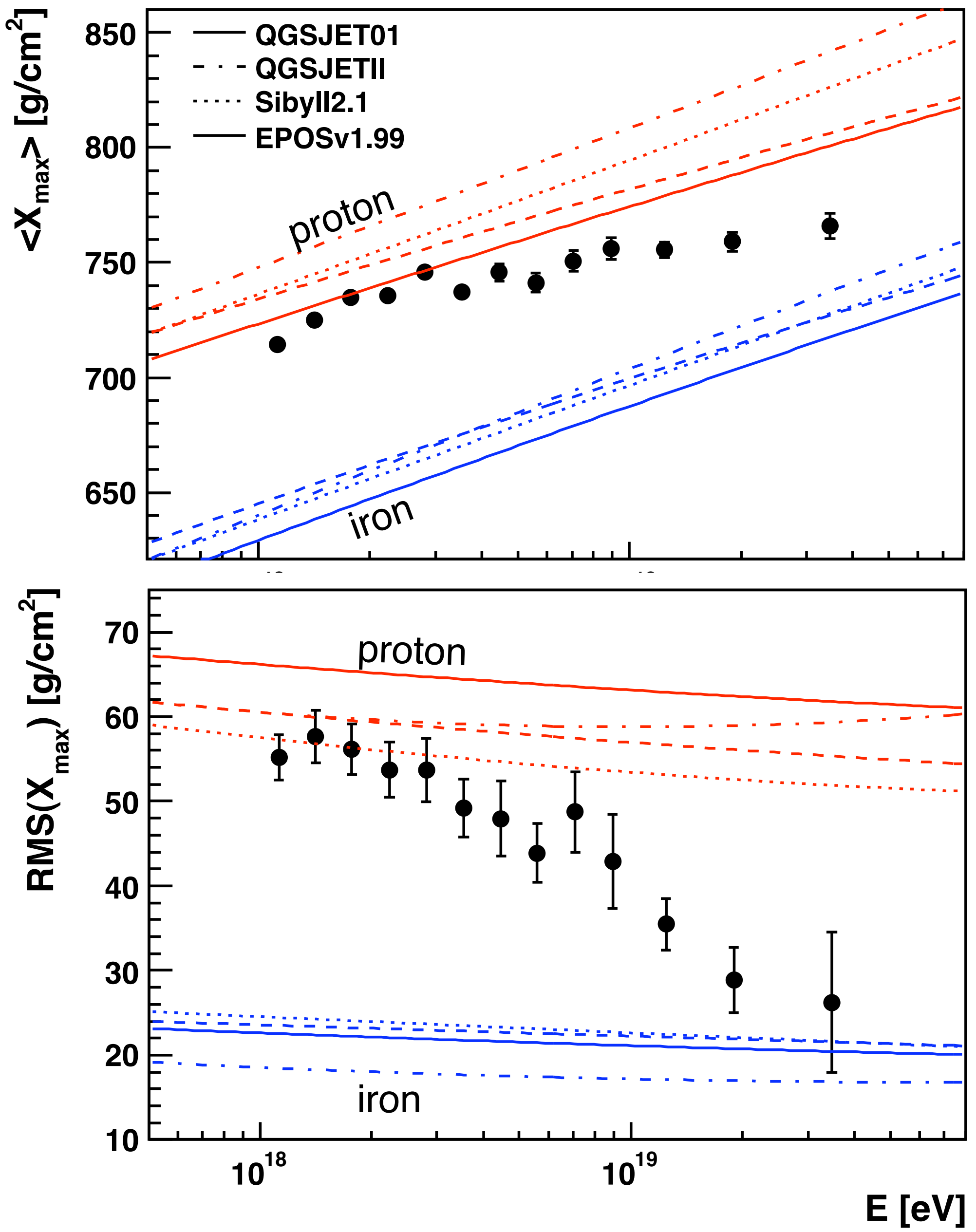
(R. Ulrich et al. PRD83 (2011) 054026)



80 g/cm^2

15 g/cm^2

Auger data 2009



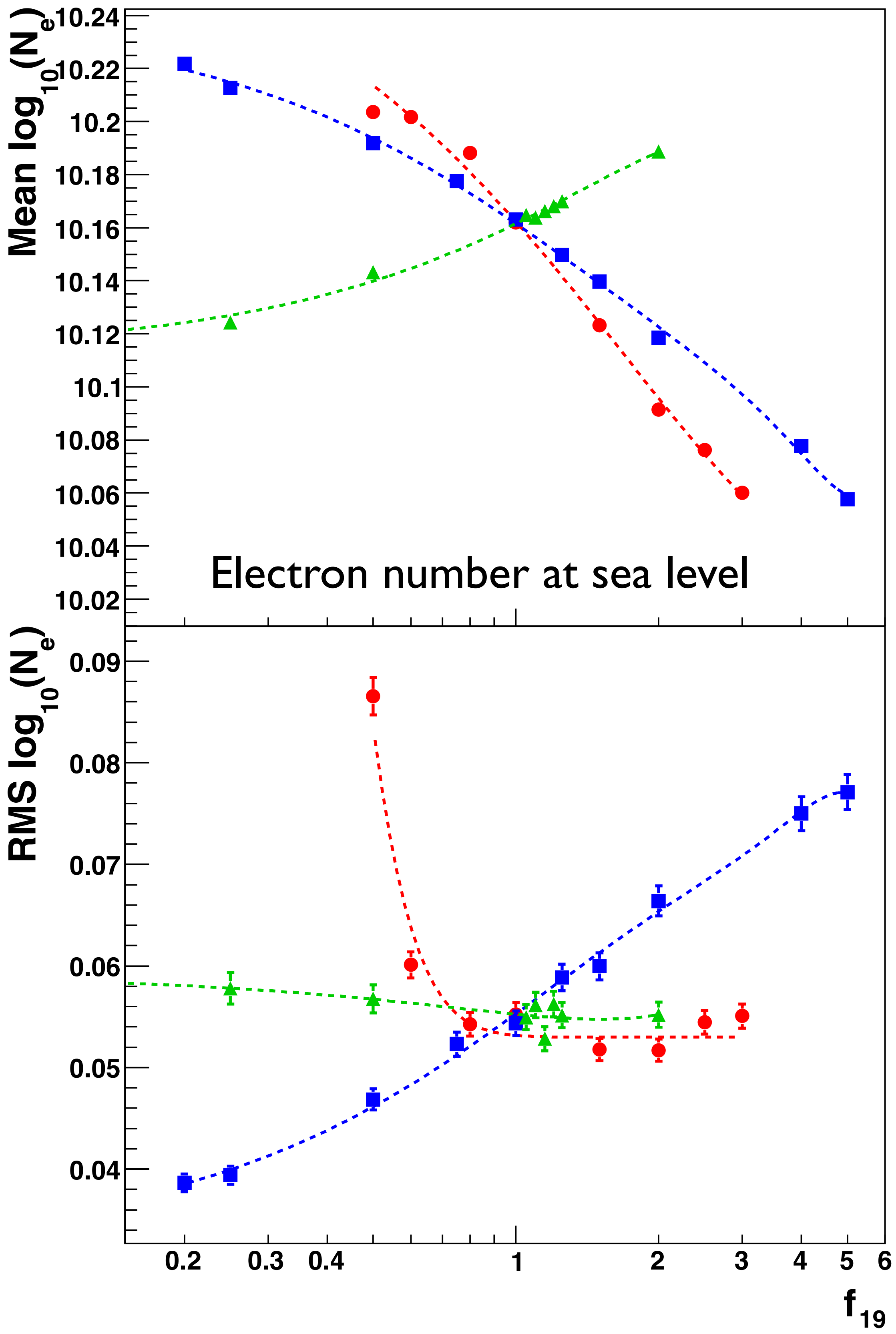
80 g/cm^2

30 g/cm^2

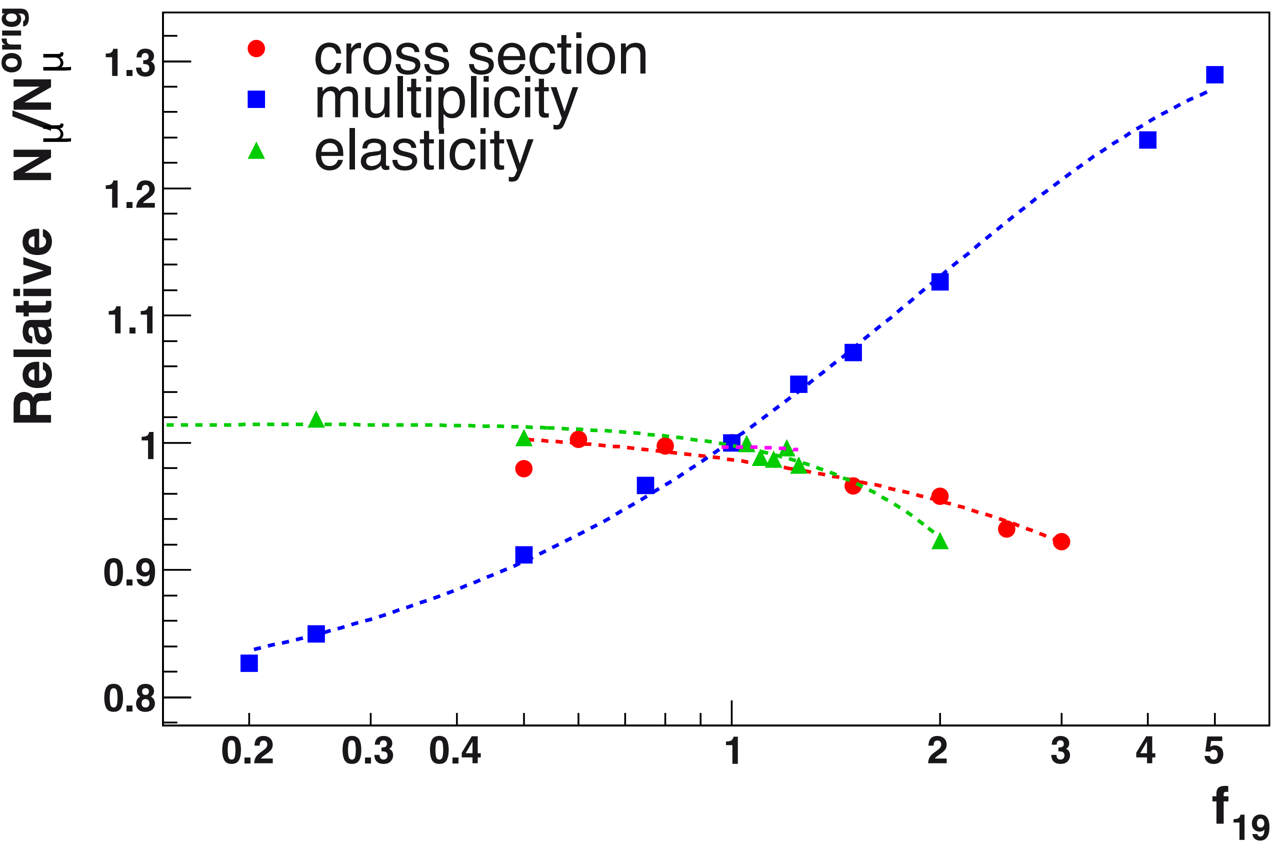
E = $10^{19.5}$ eV (E_{cm} ≈ 250 TeV)

- 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)

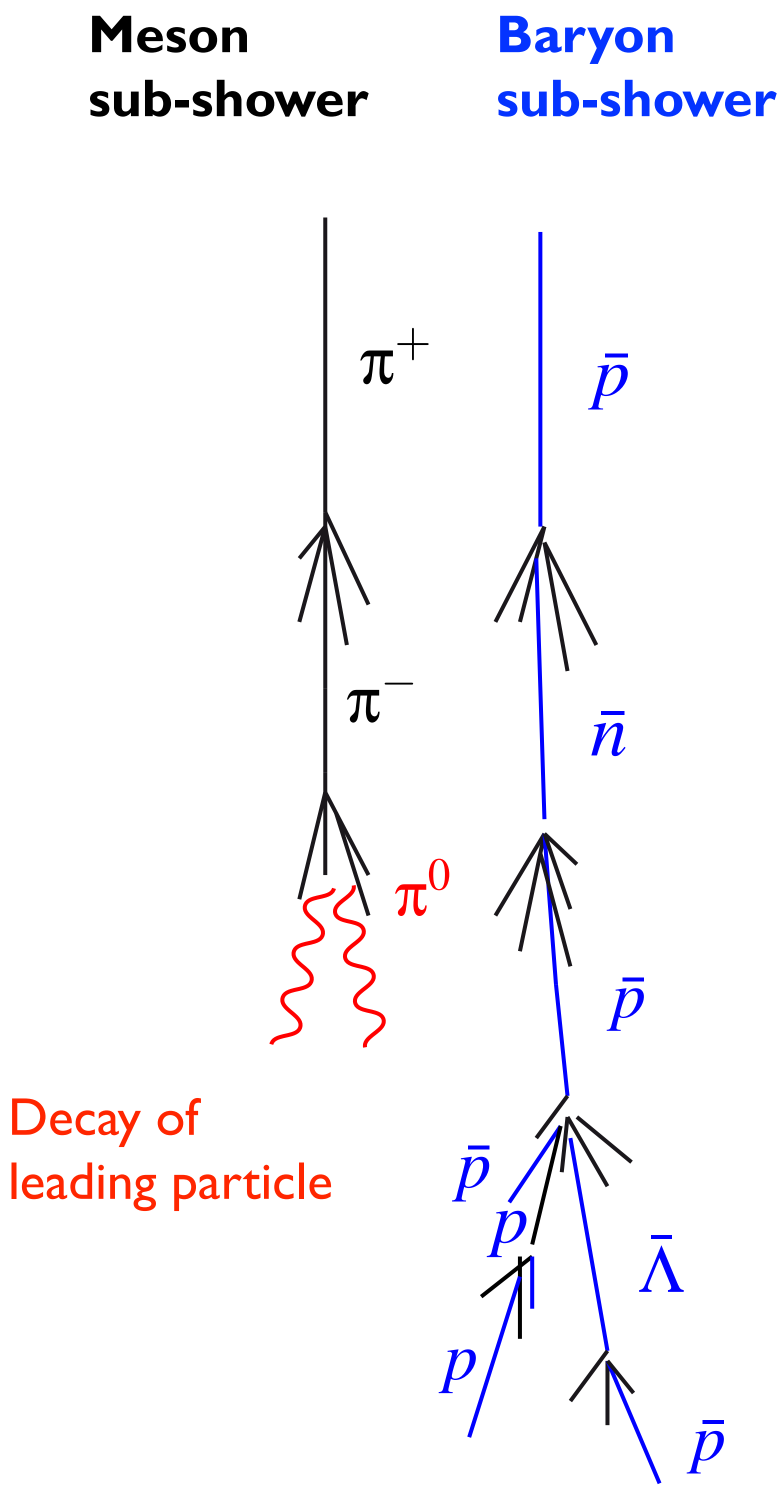


Prediction for ratio of muon numbers for iron/proton showers ~1.4

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

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

Enhancement of muon number in air showers



Meson sub-shower

Baryon sub-shower

Decay of leading particle

1 Baryon-Antibaryon pair production *(Pierog, Werner)*

- Baryon number conservation
- Low-energy particles: large angle to shower axis
- Transverse momentum of baryons higher
- **Enhancement of mainly low-energy muons**

2 Leading particle effect for pions *(Drescher, Ostapchenko)*

- Leading particle for a π could be ρ^0 and not π^0
- Decay of ρ^0 almost 100% into two charged pions

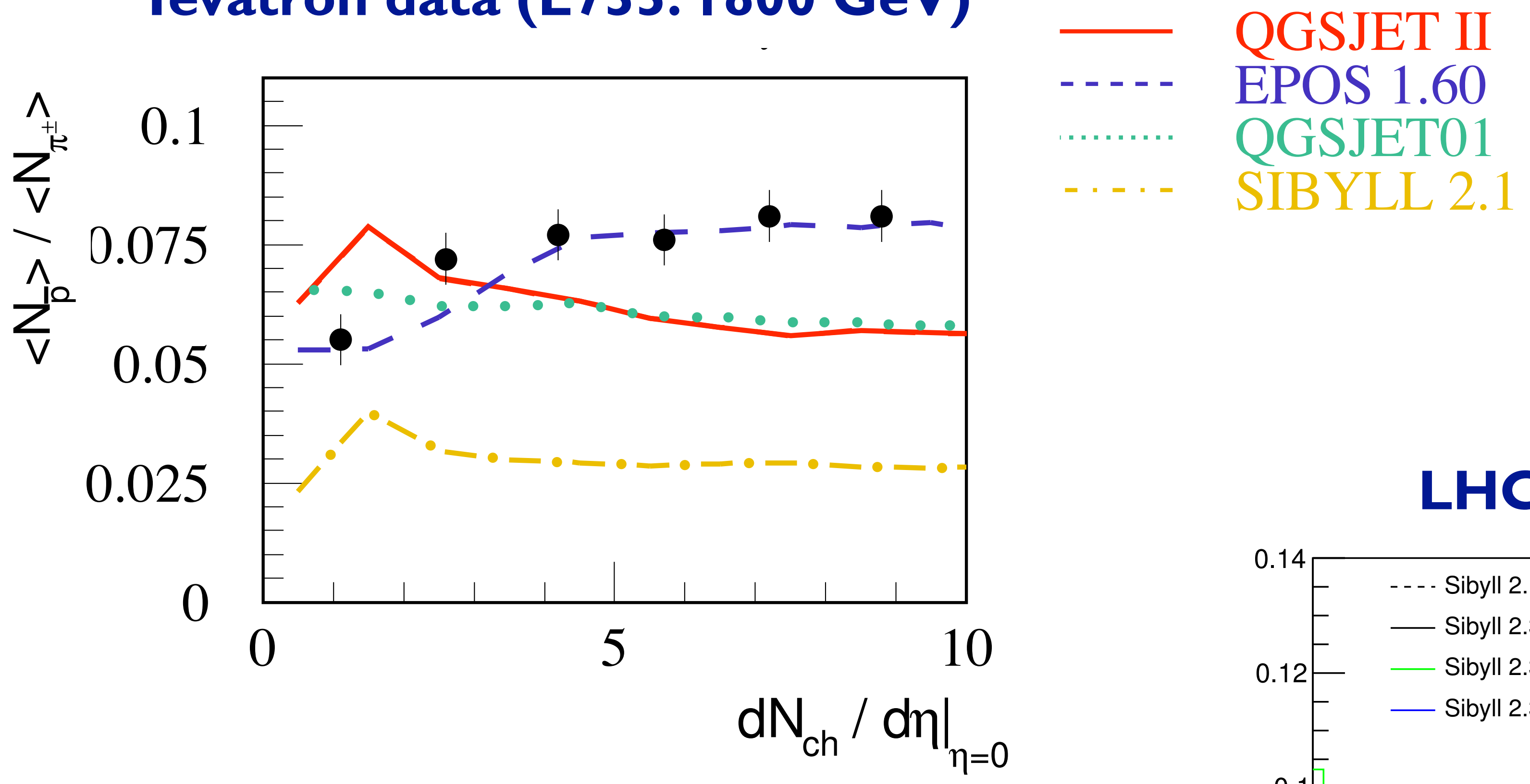
3 Chiral symmetry restoration *(Farrar, Allen)*

- **Proton primaries, applies above energy threshold**
- Pion production suppressed relative to baryons
- Large inelasticity of the events
- Faster increase of total cross section (reduction of fluctuations)

(Pierog, Werner PRL 101, 2008)

LHC data: Baryon production lower than assumed

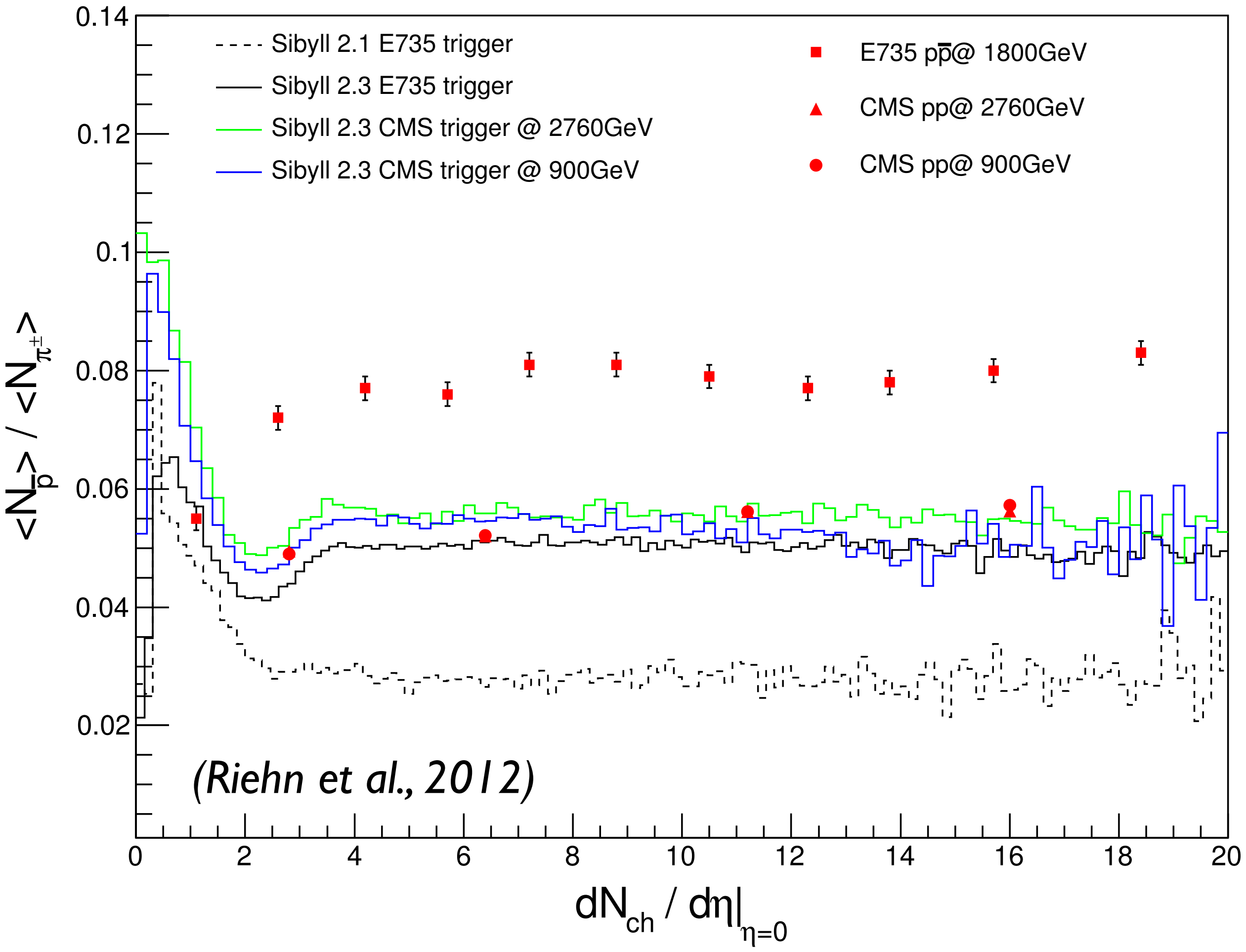
Tevatron data (E735: 1800 GeV)



(Pierog, Werner Phys. Rev. Lett. 101, 2008)

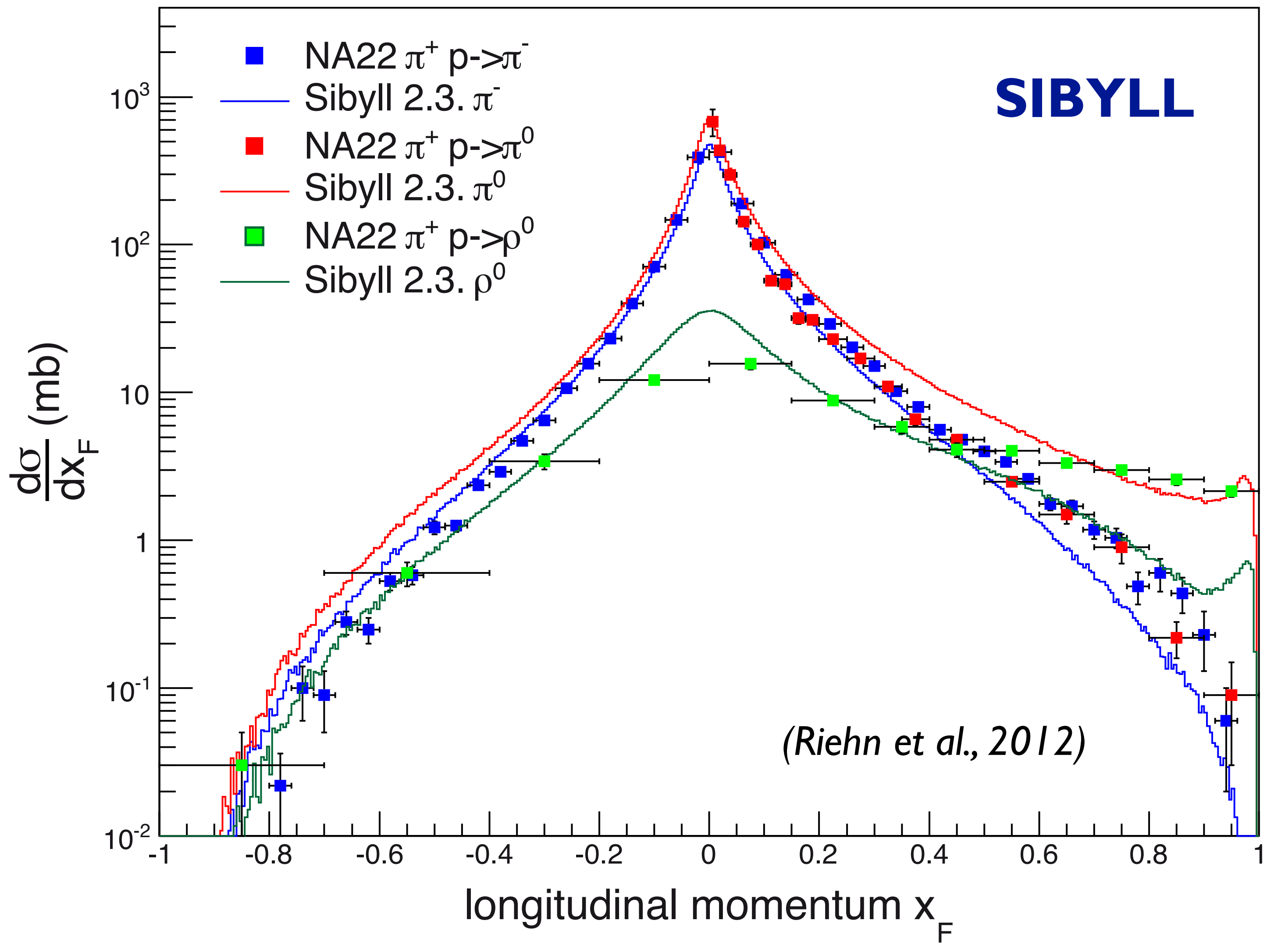
Baryon production rate not as high as expected from Tevatron data

LHC data (CMS: 900 and 2760 GeV)



(Riehn et al., 2012)

Leading particle for π-air interactions



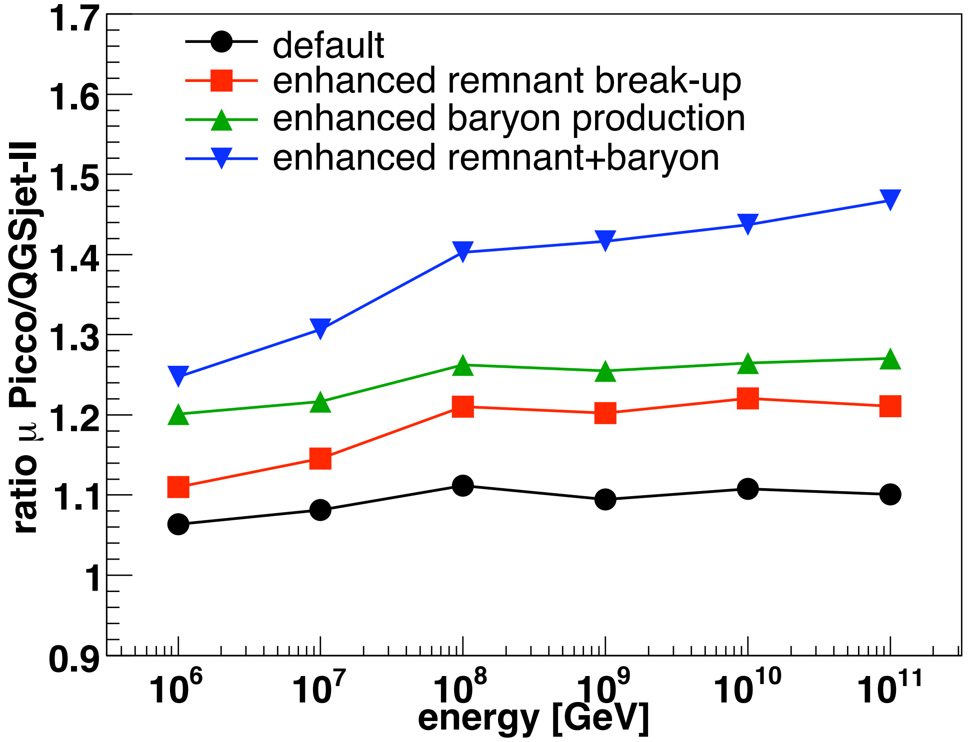
(Riehn et al., 2012)

Fixed-target data: NA22
at 250 GeV (22 GeV c.m.s.)

$$\rho^0 \longrightarrow \pi^+ \pi^-$$

$$\pi^0 \longrightarrow \gamma\gamma$$

More work needed to clarify situation (energy dependence?)



(Drescher Phys. Rev. D77, 2008)