Air Shower Physics

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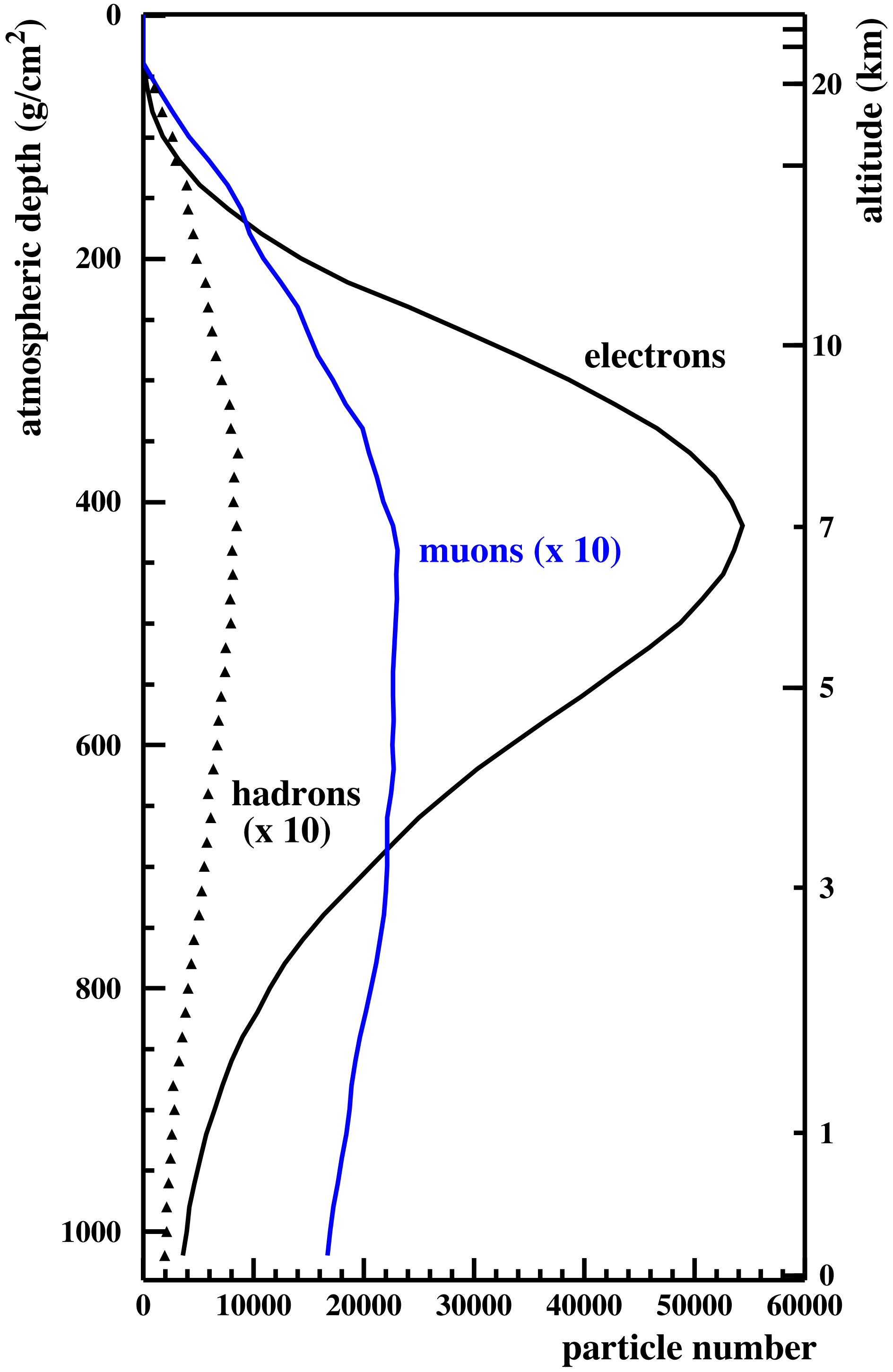
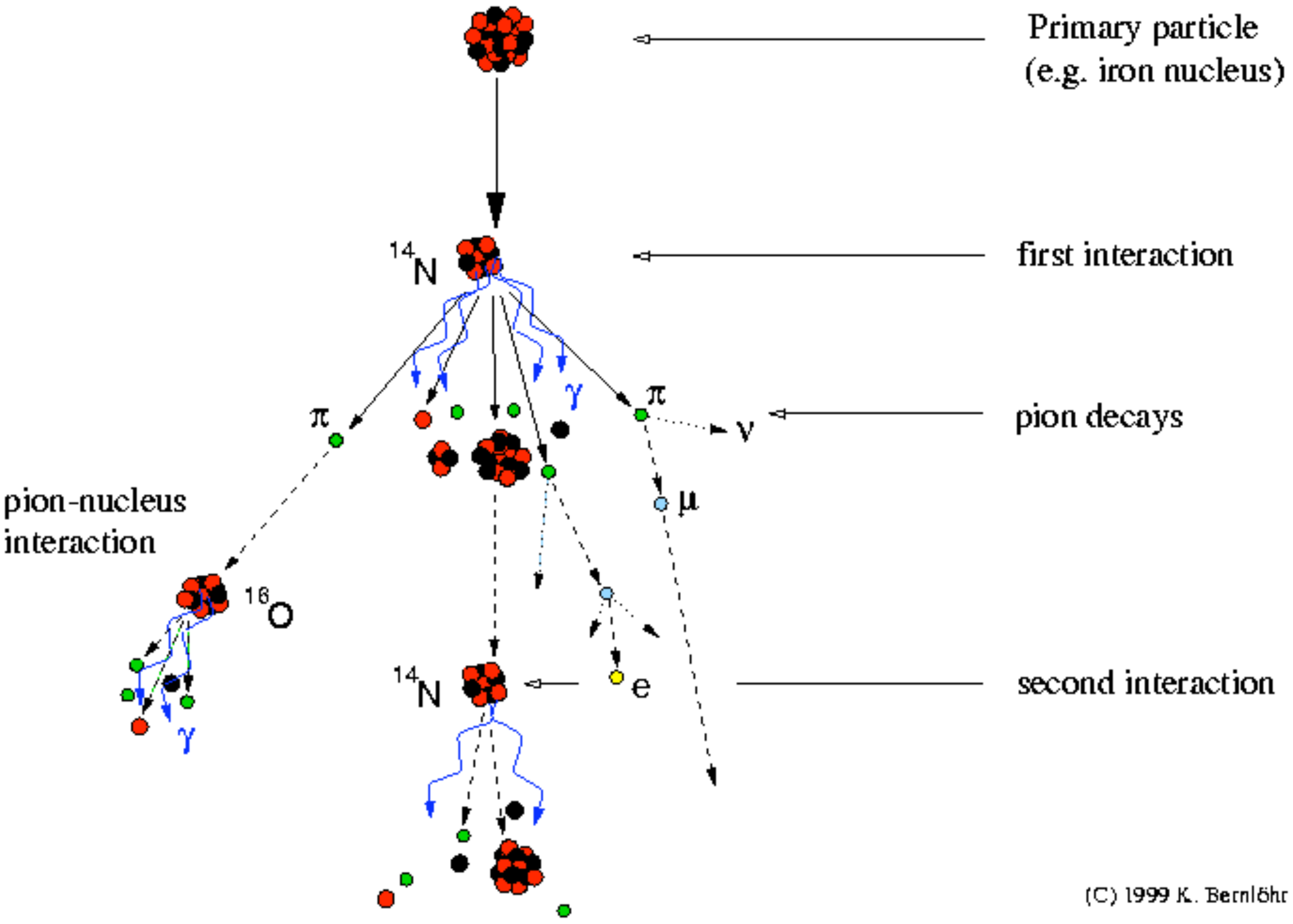
Extensive air showers

$$\int \rho_{\mathrm{air}}\, \mathrm{d}l = X$$

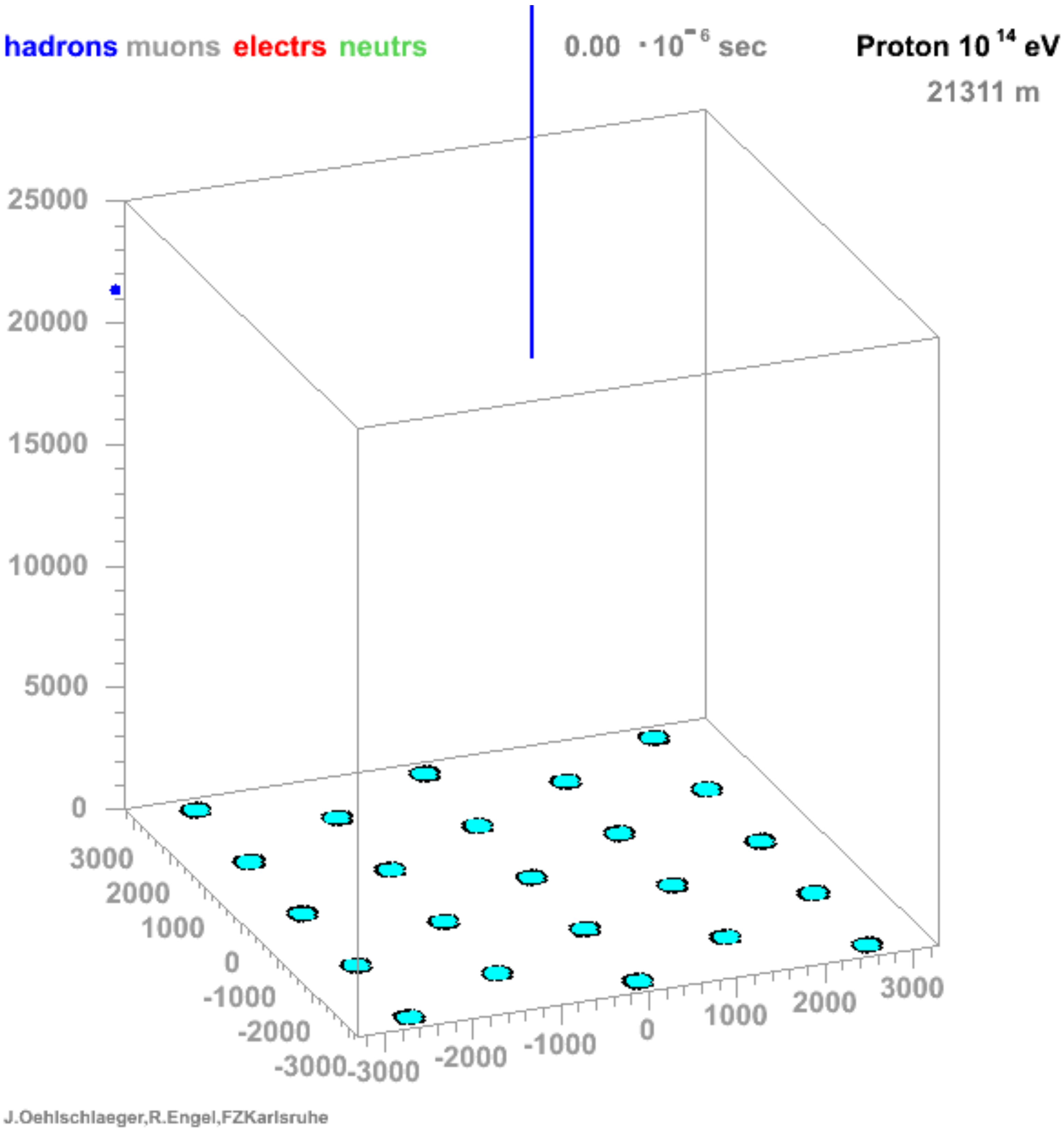




Decay of neutral pions feeds em. shower component

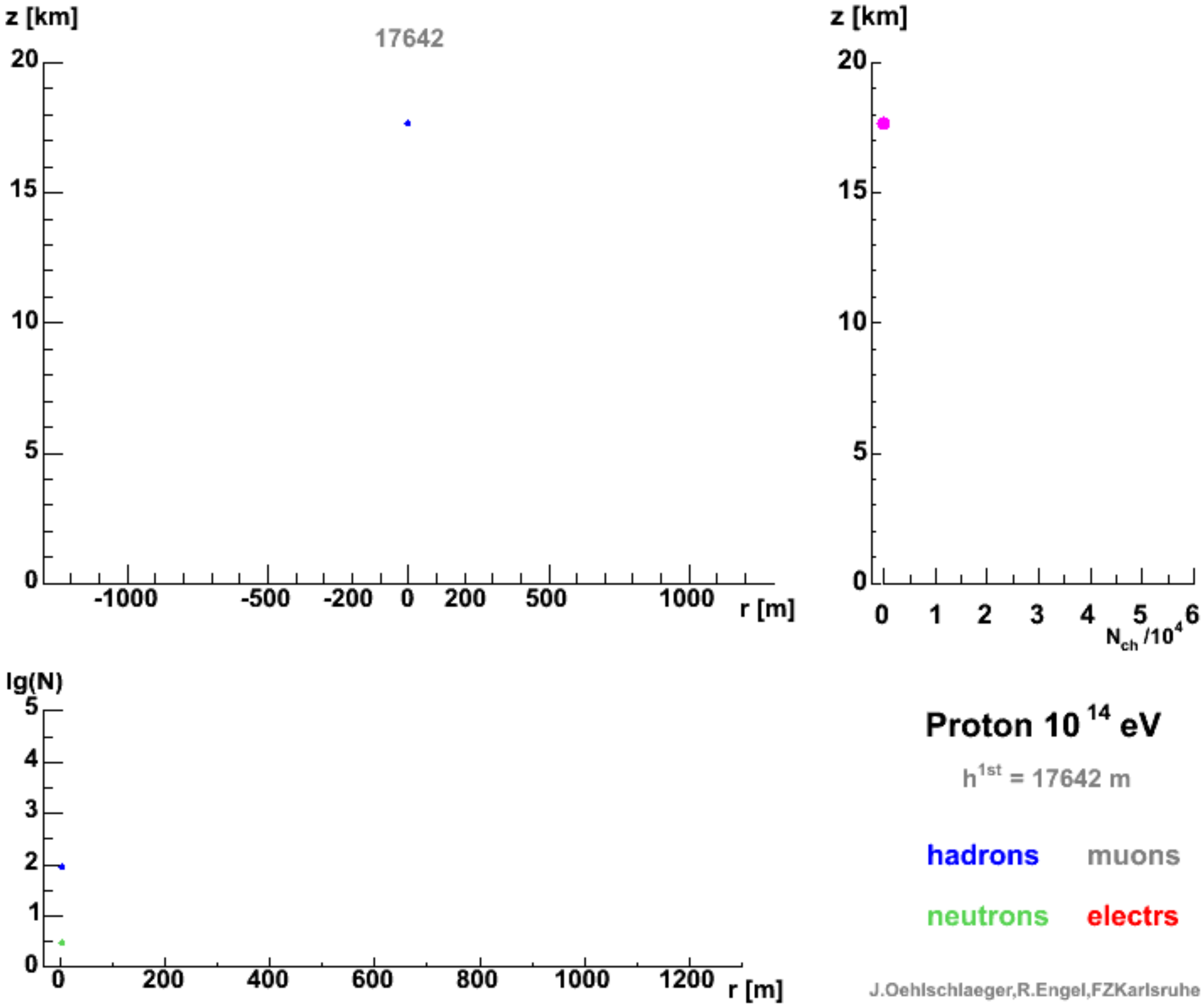
Decay of charged pions (~30 GeV) feeds muonic component

Simulation of shower development (i)

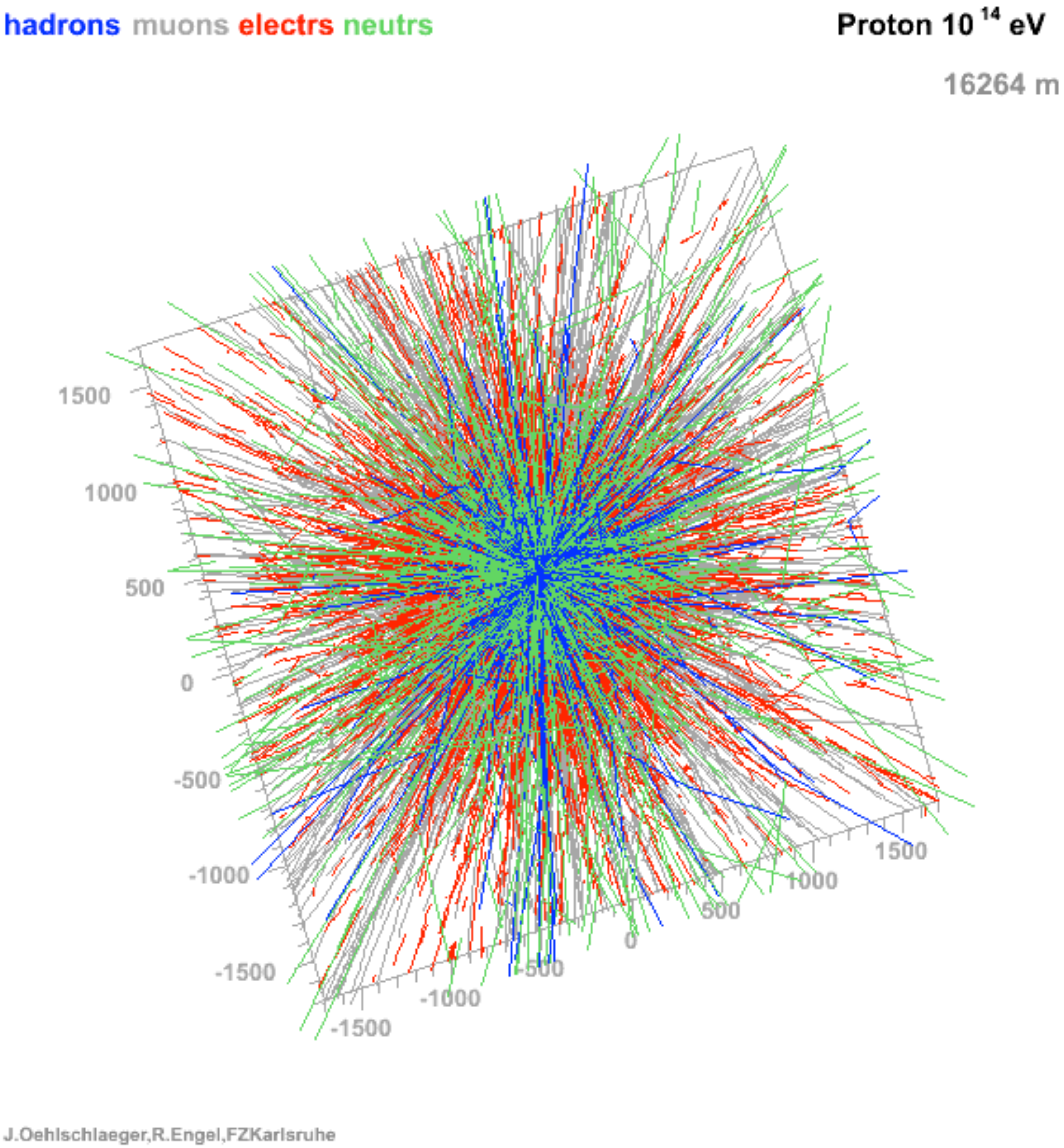


Proton shower of low energy (knee region)

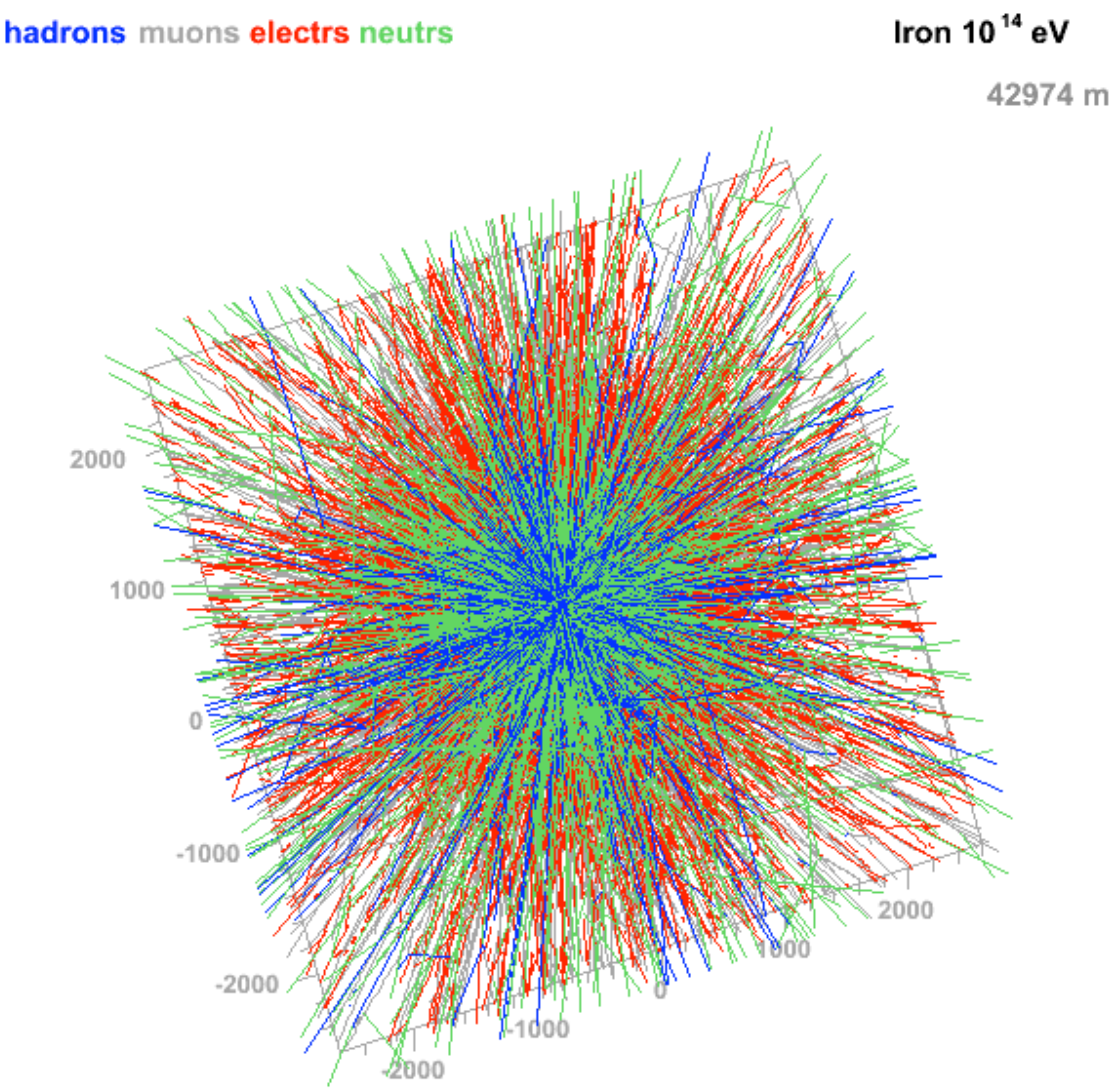
Simulation of shower development (ii)



Simulation of air shower tracks (i)



Simulation of air shower tracks (ii)



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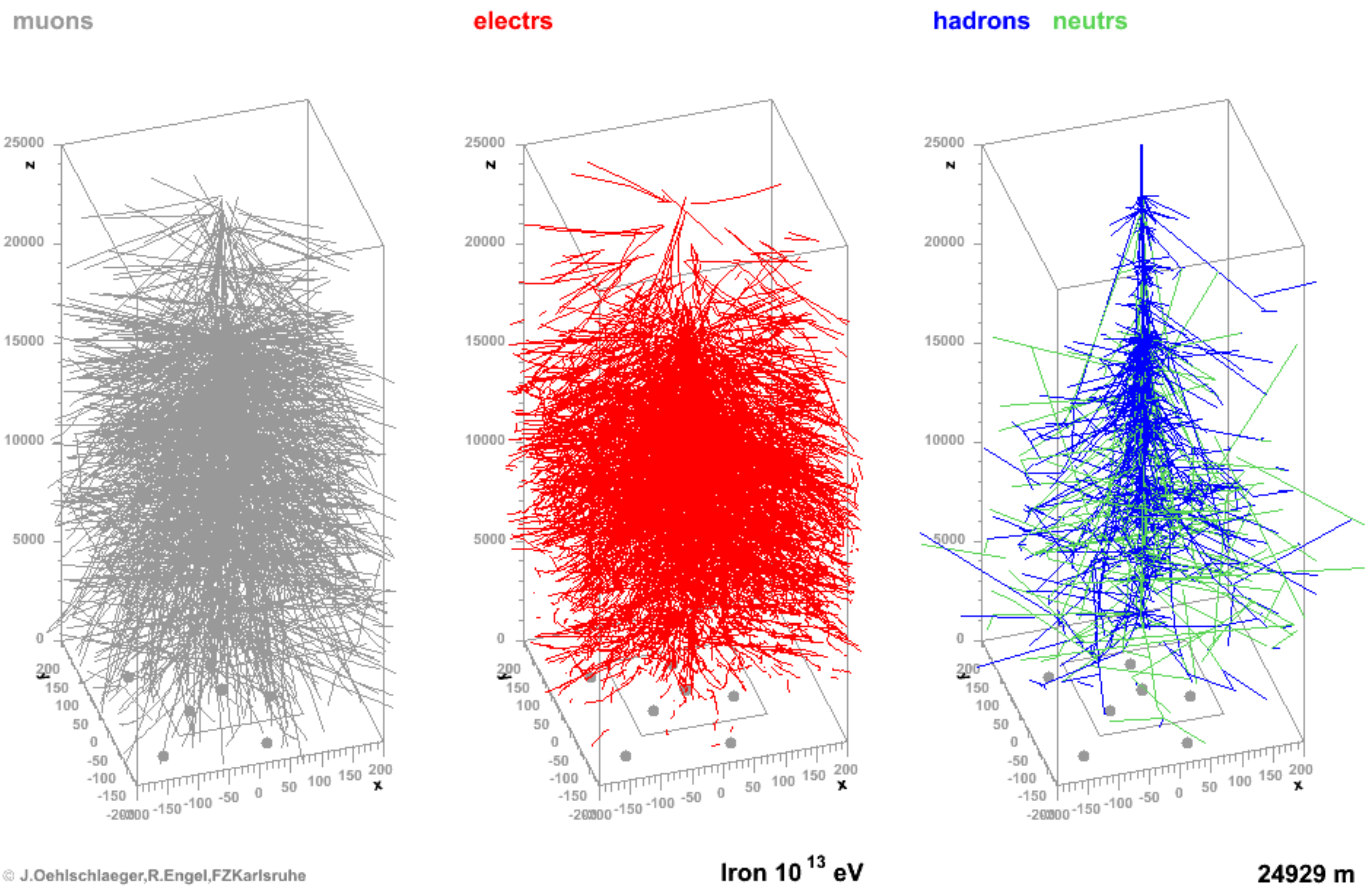
Particles of an iron shower



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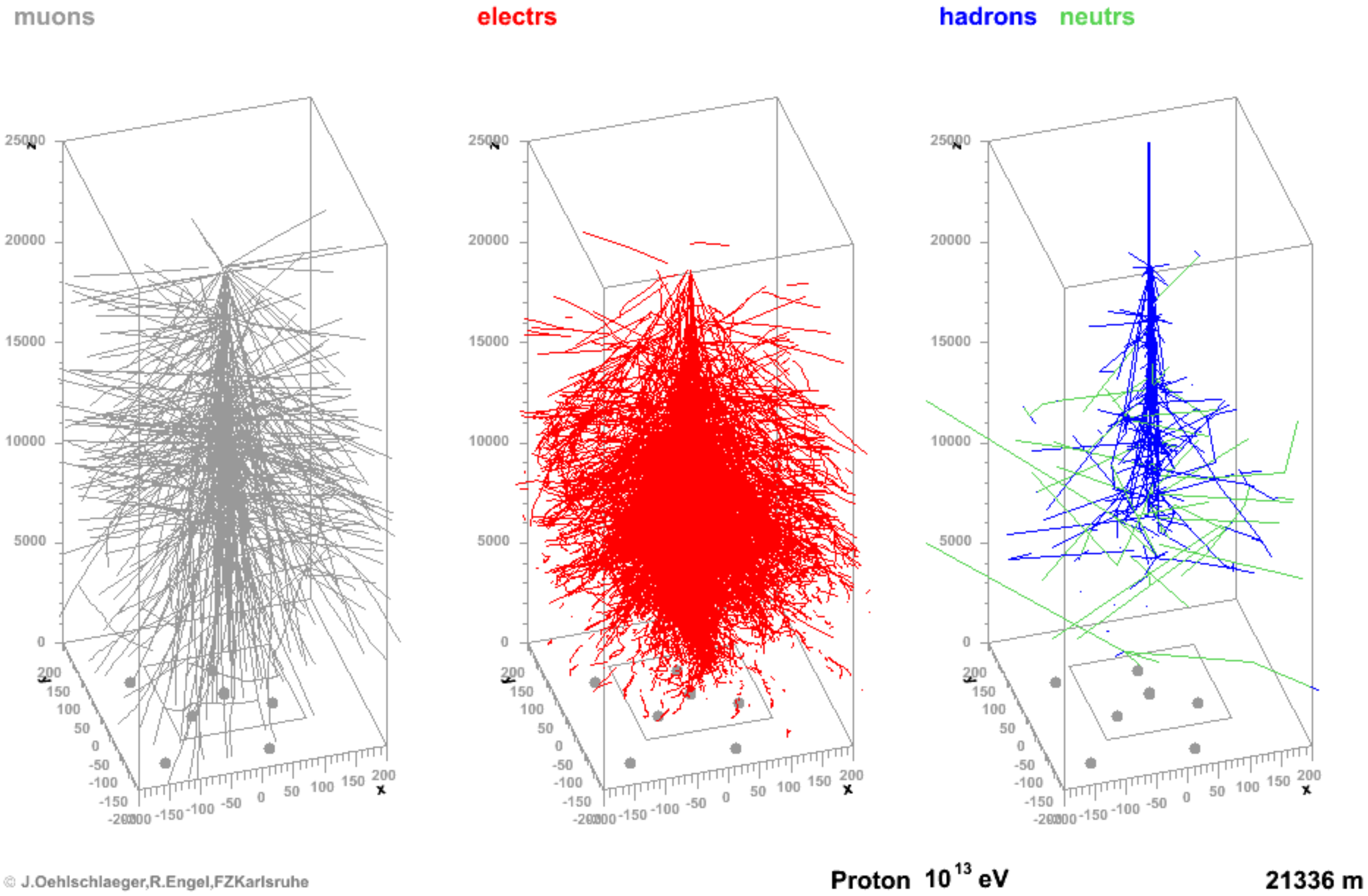
Particles of an proton shower



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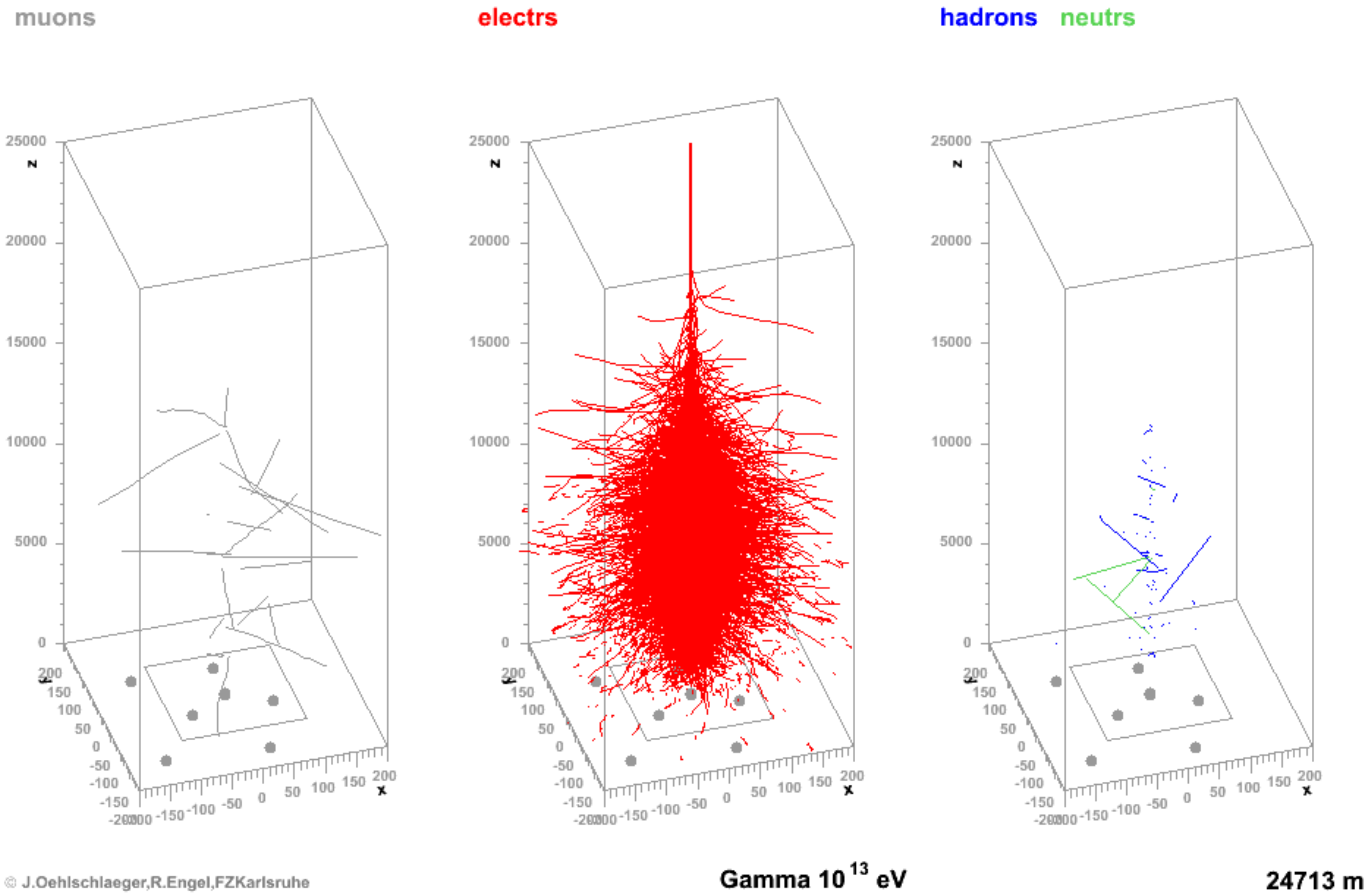
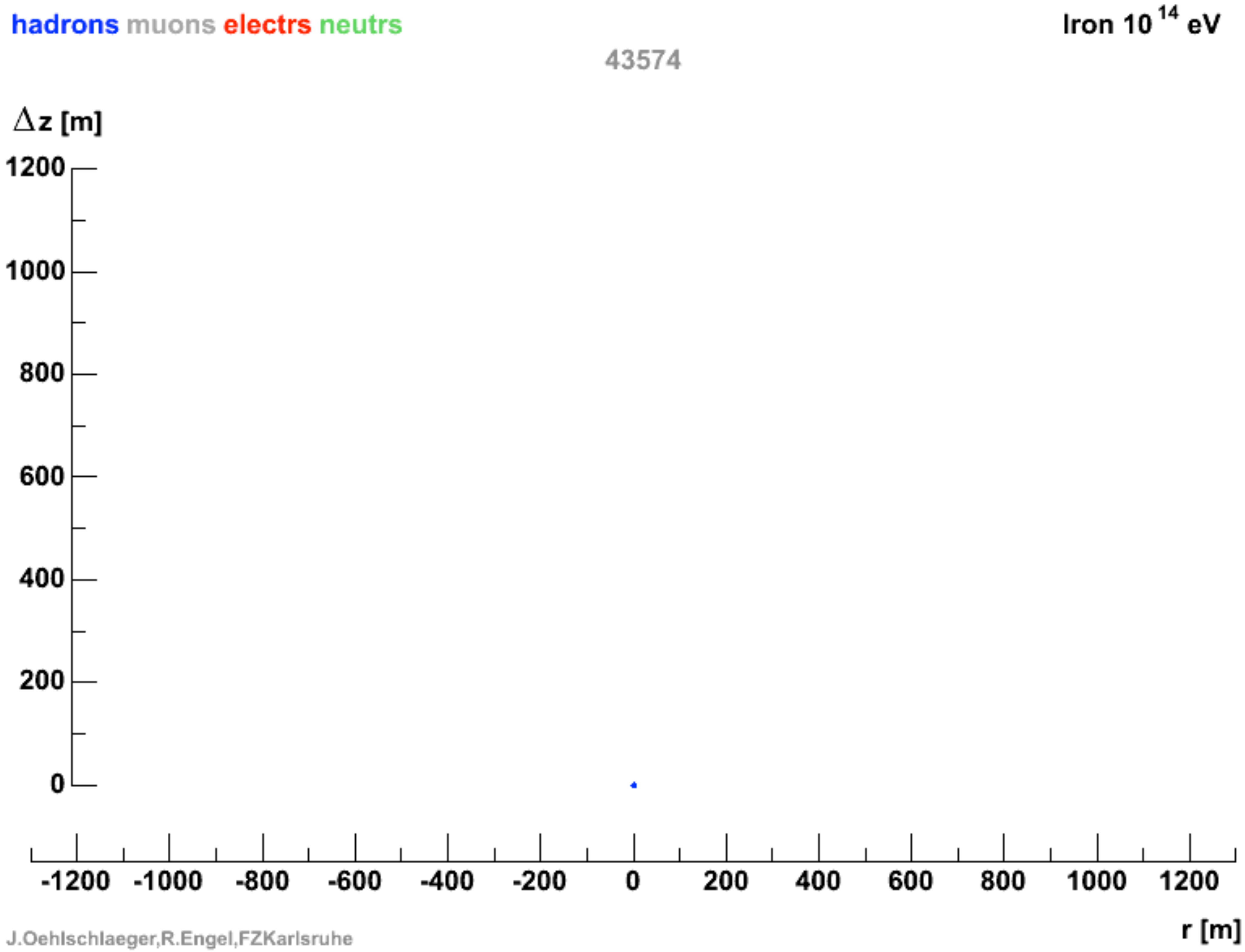
Particles of a gamma-ray shower



Time structure in shower front



Atmosphere and interaction length

Altitude (km)	Vertical depth (g/cm^2)	Local density (10^{-3} g/cm^3)	Molière unit (m)	Electron Cherenkov threshold (MeV)	Cherenkov angle (°)
40	3	3.8×10^{-3}	2.4×10^4	386	0.076
30	11.8	1.8×10^{-2}	5.1×10^3	176	0.17
20	55.8	8.8×10^{-2}	1.0×10^3	80	0.36
15	123	0.19	478	54	0.54
10	269	0.42	223	37	0.79
5	550	0.74	126	28	1.05
3	715	0.91	102	25	1.17
1.5	862	1.06	88	23	1.26
0.5	974	1.17	79	22	1.33
0	1,032	1.23	76	21	1.36

US standard atmosphere

Atmospheric depth

$$\int \rho_{\mathrm{air}}\, \mathrm{d}l = X$$

Interaction length

$$\lambda_{\mathrm{int}} = \frac{\langle m_{\mathrm{air}} \rangle}{\sigma_{\mathrm{int}}} = \frac{24160\,\mathrm{mb\ g/cm^2}}{\sigma_{\mathrm{int}}}$$

$$\frac{\mathrm{d}\Phi}{\mathrm{d}X} = -\frac{\sigma_{\mathrm{int}}}{\langle m_{\mathrm{air}} \rangle}\,\Phi = -\frac{1}{\lambda_{\mathrm{int}}}\,\Phi$$

Typical values

$$\lambda_\pi \approx \lambda_K \approx 120\,\mathrm{g/cm^2}$$

$$\lambda_p \approx 90\,\mathrm{g/cm^2}$$

$$\lambda_{Fe} \approx 5\,\mathrm{g/cm^2}$$

Competing processes of interaction and decay

Interaction length

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

$$\lambda_\pi \approx \lambda_K \approx 120\,{\rm g/cm^2}$$

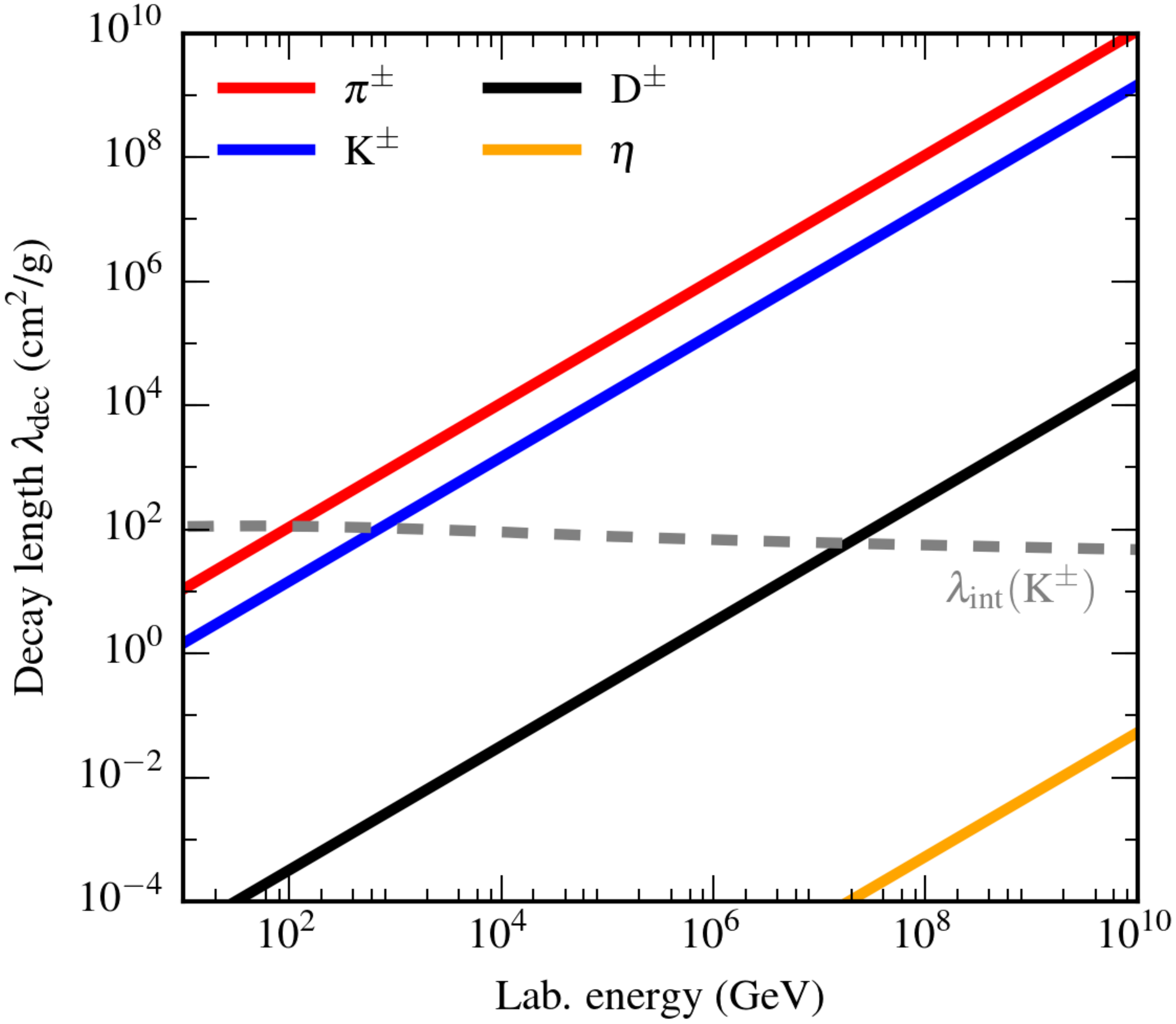
Decay length

$$l_{\rm dec} = \beta c \tau \Gamma \approx c\tau \frac{E}{m}$$

$$\lambda_{\rm dec} = \rho\, l_{\rm dec} \approx c\tau\rho\, \frac{E}{m}$$

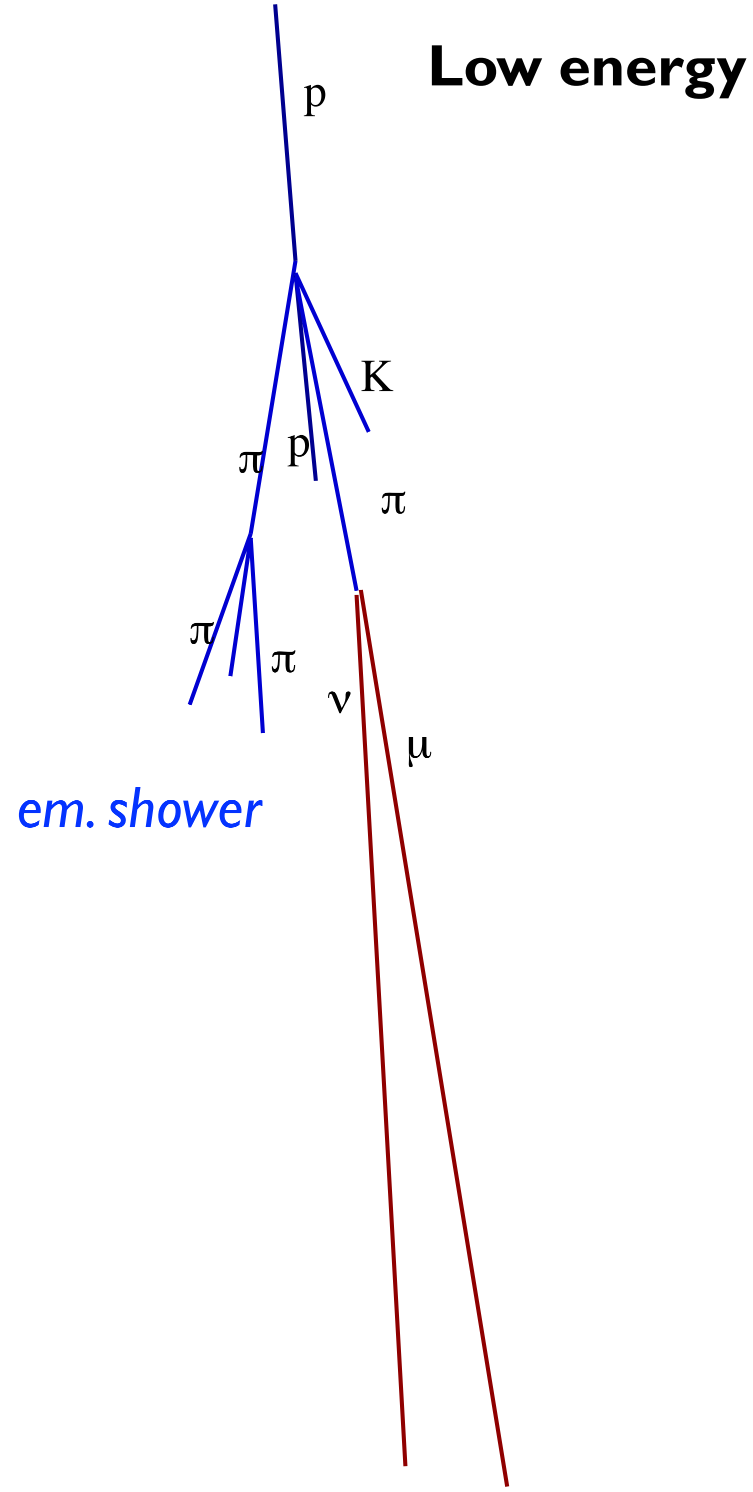
air density

(Fedynitch 2017)



Altitude of 8 km

Hadronic cascades

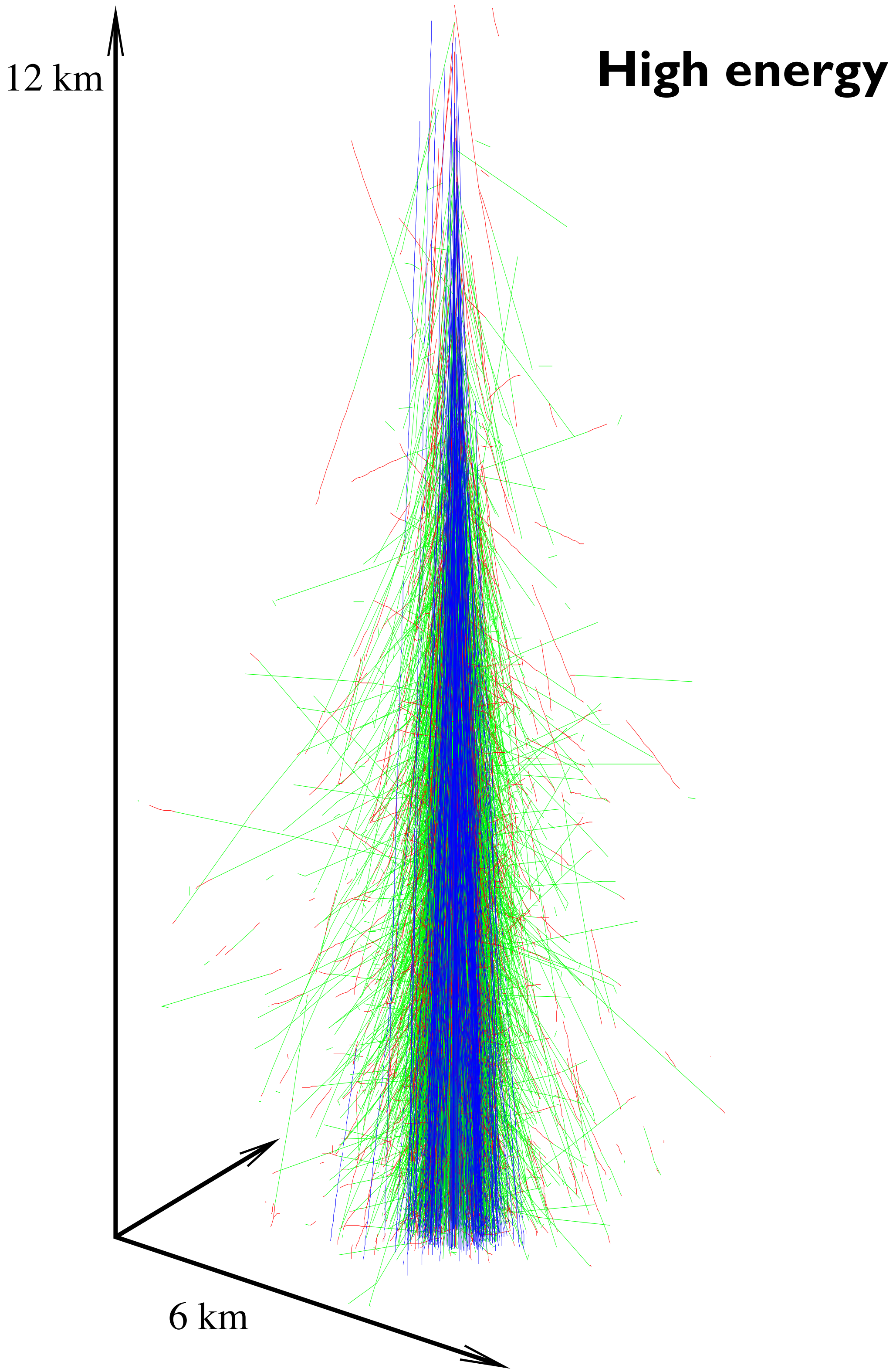


Typical energies above which particles interact

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

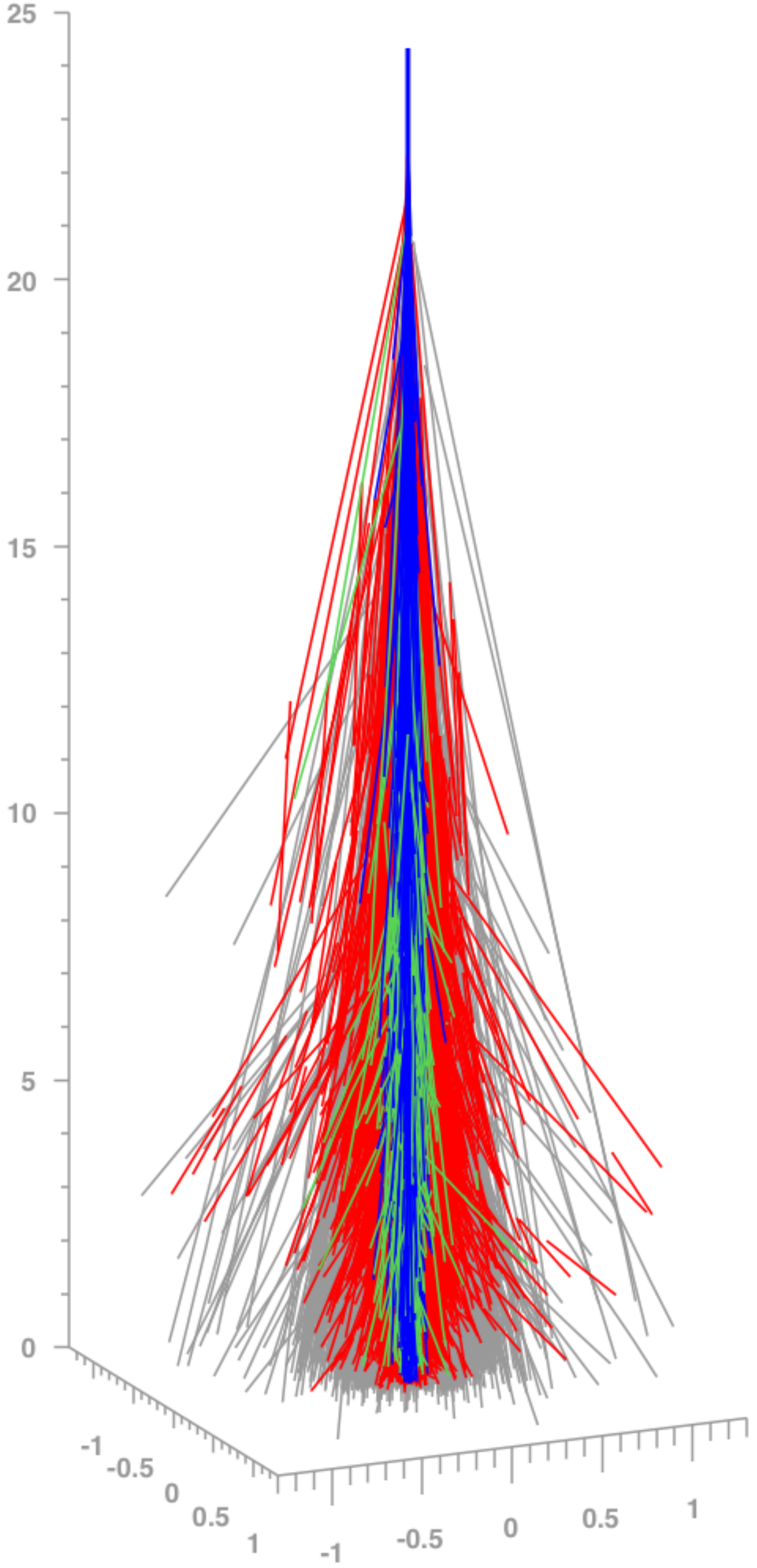
$$E_K \sim 200\,\mathrm{GeV}$$

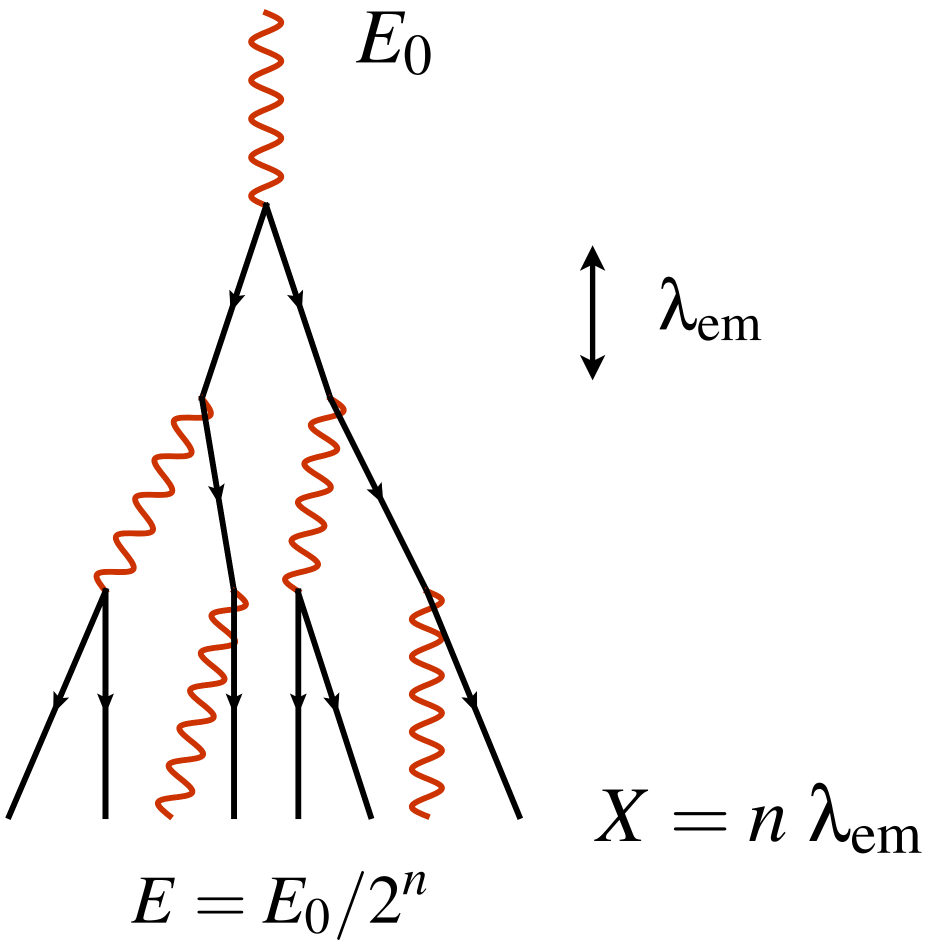
$$E_{\pi^0} \sim 10^{19}\,\mathrm{eV}$$



Electromagnetic showers

Heitler model





Shower maximum: $E = E_c$

$$N_{\max} = E_0/E_c$$

$$X_{\max} \sim \lambda_{\text{em}} \ln(E_0/E_c)$$

Cascade equations

Energy loss of electron: $$\frac{\mathrm{d}E}{\mathrm{d}X} = -\alpha - \frac{E}{X_0}$$

Critical energy: $E_c = \alpha\, X_0 \sim 85\,\mathrm{MeV}$

Radiation length: $X_0 \sim 36\,\mathrm{g/cm^2}$

Cascade equations

$$\frac{\mathrm{d}\Phi_e(E)}{\mathrm{d}X} = -\frac{\sigma_e}{\langle m_{\mathrm{air}}\rangle}\Phi_e(E) + \int_E^\infty \frac{\sigma_e}{\langle m_{\mathrm{air}}\rangle}\Phi_e(\tilde{E})P_{e\to e}(\tilde{E},E)\mathrm{d}\tilde{E}$$

$$+\int_E^\infty \frac{\sigma_\gamma}{\langle m_{\mathrm{air}}\rangle}\Phi_\gamma(\tilde{E})P_{\gamma\to e}(\tilde{E},E)\mathrm{d}\tilde{E} \; + \; \alpha\frac{\partial\Phi_e(E)}{\partial E}$$

$$X_{\mathrm{max}} \approx X_0 \ln\left(\frac{E_0}{E_c}\right) \qquad N_{\mathrm{max}} \approx \frac{0.31}{\sqrt{\ln(E_0/E_c) - 0.33}}\frac{E_0}{E_c}$$

(Rossi & Greisen, Rev. Mod. Phys. 13 (1940) 240)

Shower age and Greisen formula

Longitudinal profile

$$N_e(X) \approx \frac{0.31}{[\ln E_0/E_c]^{1/2}} \exp\left\{ \frac{X}{X_0} \left(1 - \frac{3}{2} \ln s \right) \right\}$$

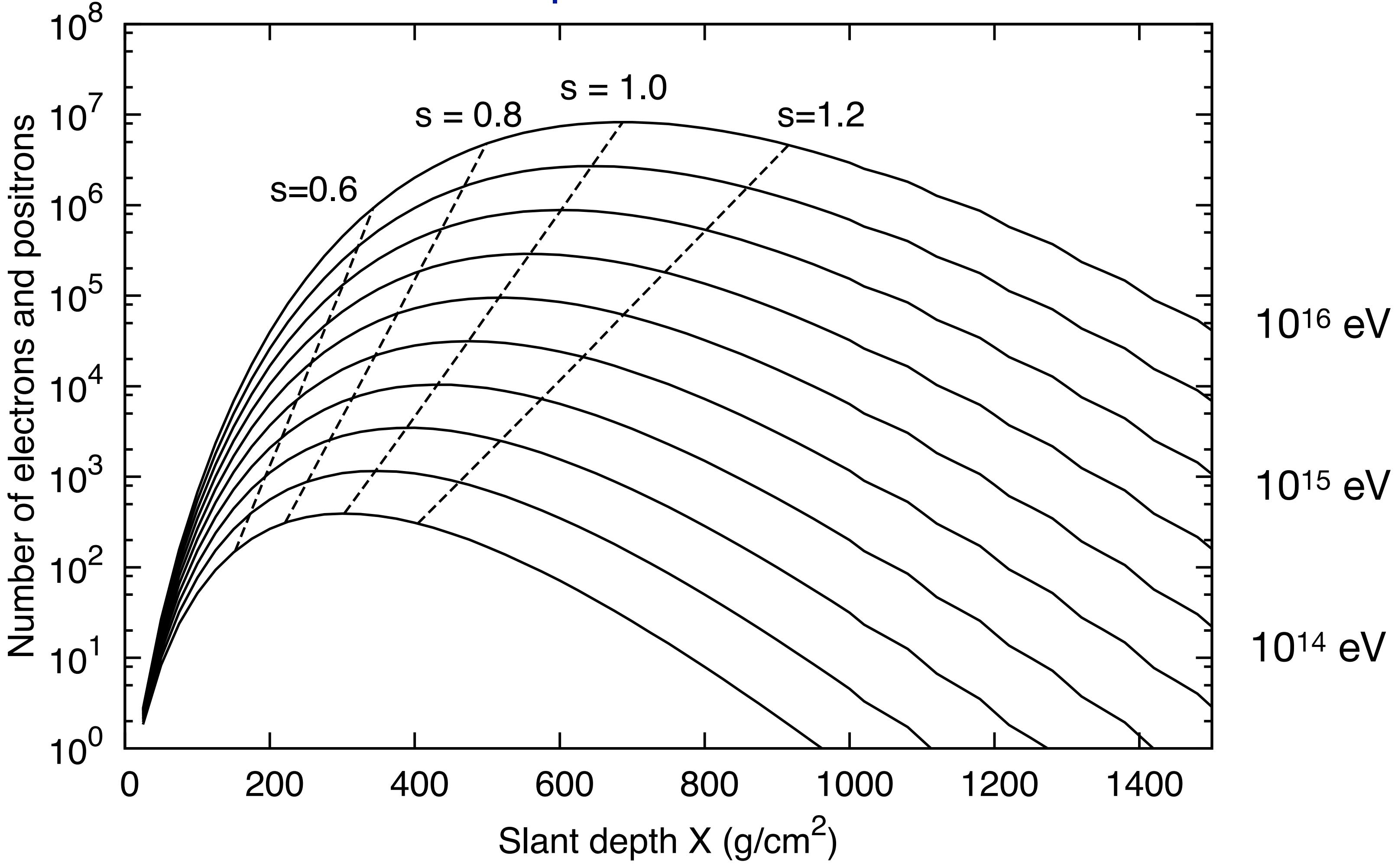
(Greisen 1956, see also Lipari PRD 2009)

Shower age

$$s = \frac{3X}{X + 2X_{\max}}$$

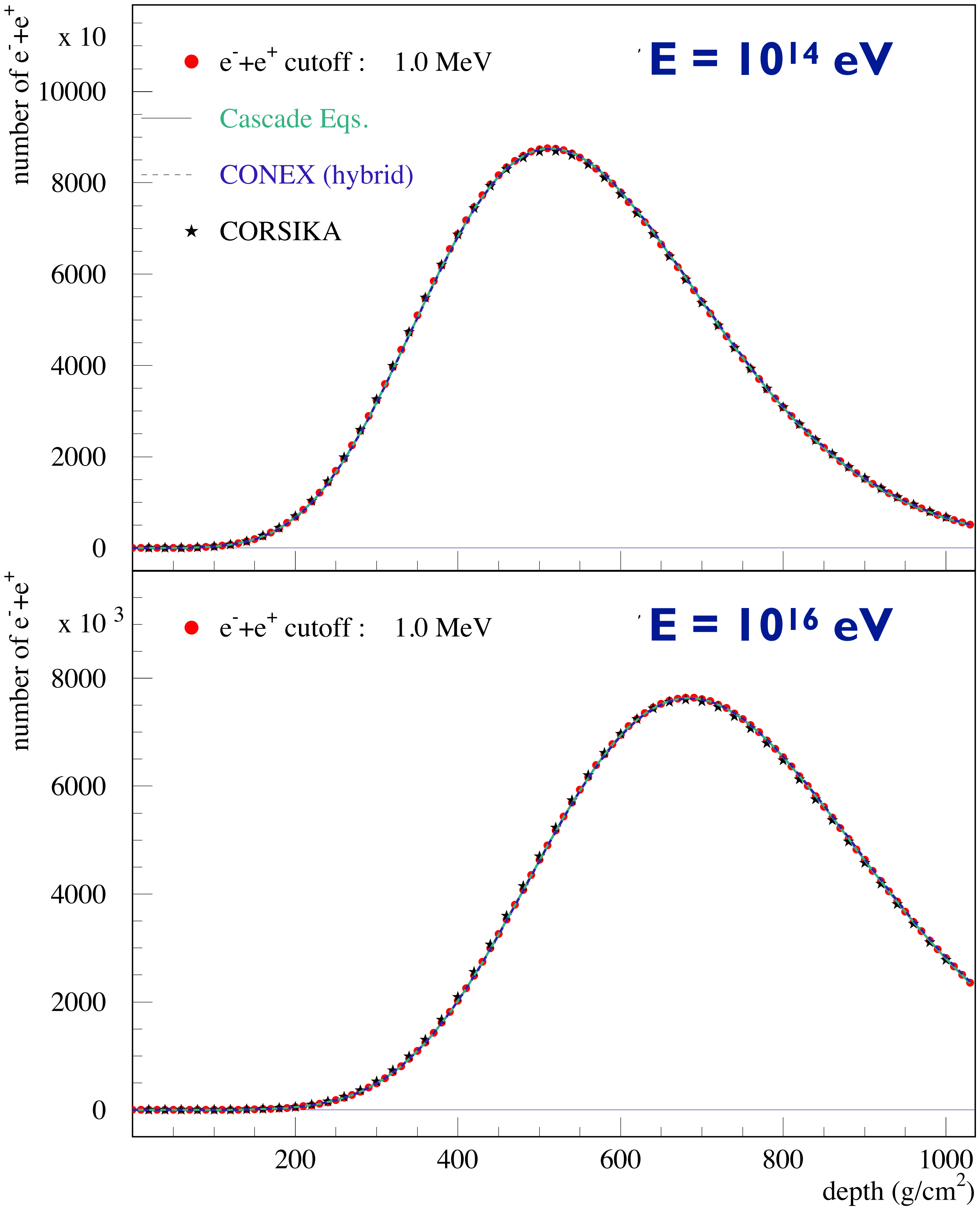
Energy spectrum particles

$$\frac{\mathrm{d}N_e}{\mathrm{d}E} \sim \frac{1}{E^{1+s}}$$



Electrons in photon-initiated shower

Mean longitudinal shower profile



Calculation with cascade Eqs.

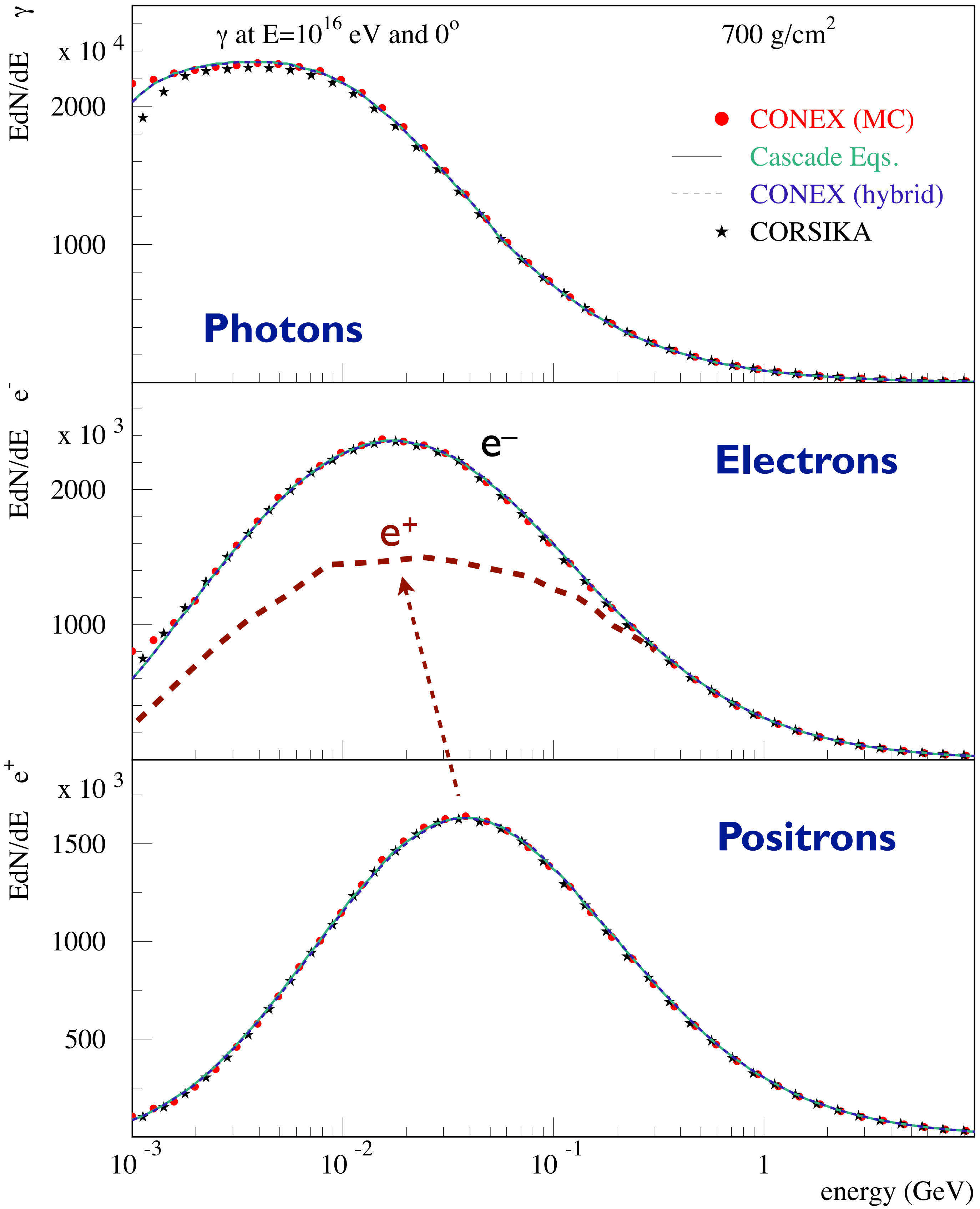
Photons
- Pair production
- Compton scattering

Electrons
- Bremsstrahlung
- Moller scattering

Positrons
- Bremsstrahlung
- Bhabha scattering

(Bergmann et al., Astropart.Phys. 26 (2007) 420)

Energy spectra of secondary particles



Number of photons divergent

- Typical energy of electrons and positrons $E_c \sim 80$ MeV
- Electron excess of 20 - 30%
- Pair production symmetric
- Excess of electrons in target

(Bergmann et al., Astropart.Phys. 26 (2007) 420)

Lateral distribution of shower particles

$$\frac{\mathrm{d}N}{\mathrm{d}\Omega} = \frac{1}{64\pi} \frac{1}{\ln(191Z^{-1/3})} \left(\frac{E_s}{E}\right)^2 \frac{1}{\sin^4 \theta/2}$$

$$E_s \approx 21\,\mathrm{MeV}$$

Expectation value

$$\int \theta^2 \frac{\mathrm{d}N}{\mathrm{d}\Omega} \mathrm{d}\Omega$$

$$\langle\theta^2\rangle \sim \left(\frac{E_s}{E}\right)^2$$

Displacement of particle

$$r \sim \left(\frac{E_s}{E}\right) \frac{X_0}{\rho_{\mathrm{air}}}$$

$$r_1 = \left(\frac{E_s}{E_c}\right) \frac{X_0}{\rho_{\mathrm{air}}}$$

$$\frac{\mathrm{d}N_e}{\mathrm{d}E} \sim \frac{E_c}{E^{1+s}}$$

Moliere unit
(78 m at sea level)

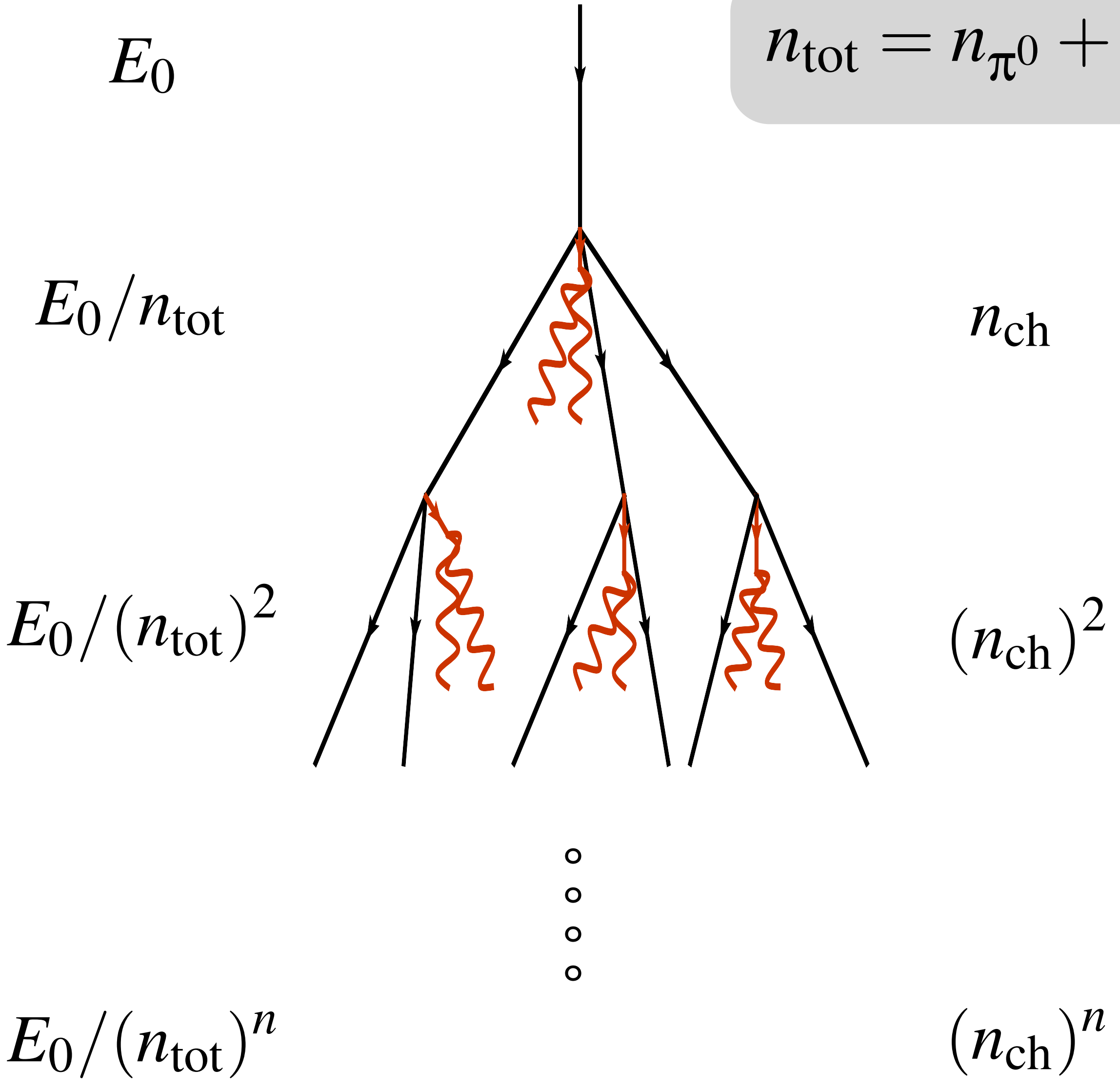
$$\frac{\mathrm{d}N_e}{r\,\mathrm{d}r} \sim \left(\frac{r}{r_1}\right)^{s-2} \left(1 + \frac{r}{r_1}\right)^{s-4.5}$$

Nishimura-Kamata-Greisen lateral distribution function

Hadronic showers

Muon production in hadronic showers

$$n_{\text{tot}} = n_{\pi^0} + n_{\text{ch}}$$



Primary particle proton

π⁰ decay immediately

π± initiate new cascades

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

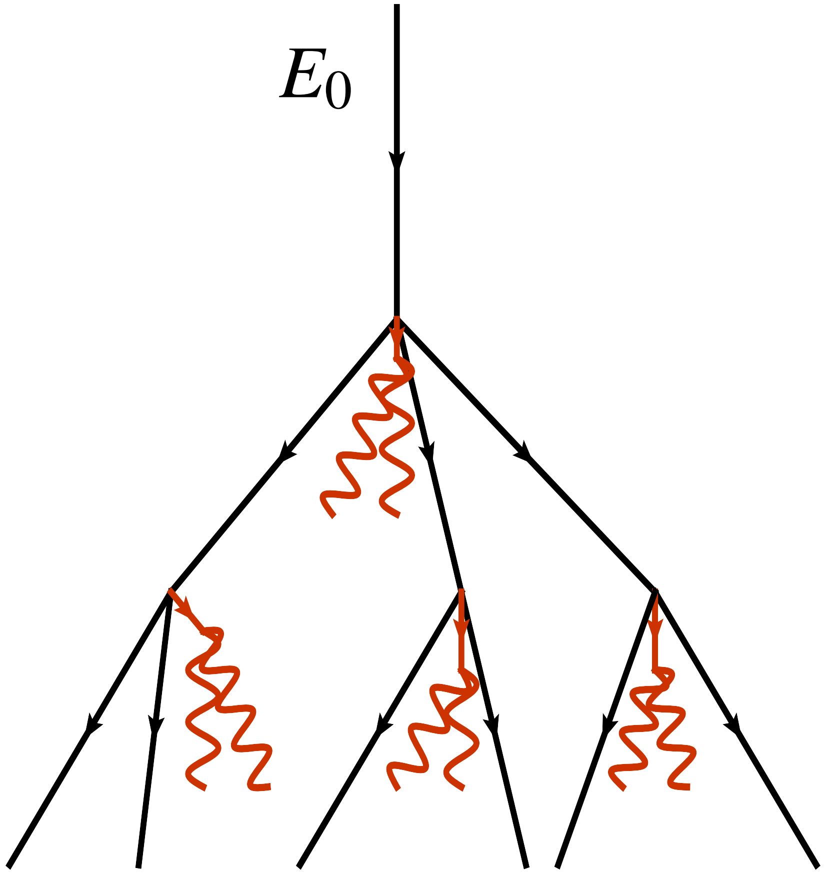
$$\alpha = \frac{\ln n_{\text{ch}}}{\ln n_{\text{tot}}} \approx 0.82\ldots0.95$$

Assumptions:

- cascade stops at $E_{\text{part}} = E_{\text{dec}}$
- each hadron produces one muon

(Matthews, Astropart.Phys. 22, 2005)

Electromagnetic energy and energy transfer



Hadronic energy

$$\frac{2}{3}E_0$$

$$\frac{2}{3}\left(\frac{2}{3}E_0\right)$$

∘
∘
∘
∘

$$\boxed{E_{\text{had}} = \left(\frac{2}{3}\right)^n E_0}$$

Electromagnetic energy

$$\frac{1}{3}E_0$$

$$\frac{1}{3}E_0 + \frac{1}{3}\left(\frac{2}{3}E_0\right)$$

∘
∘
∘
∘

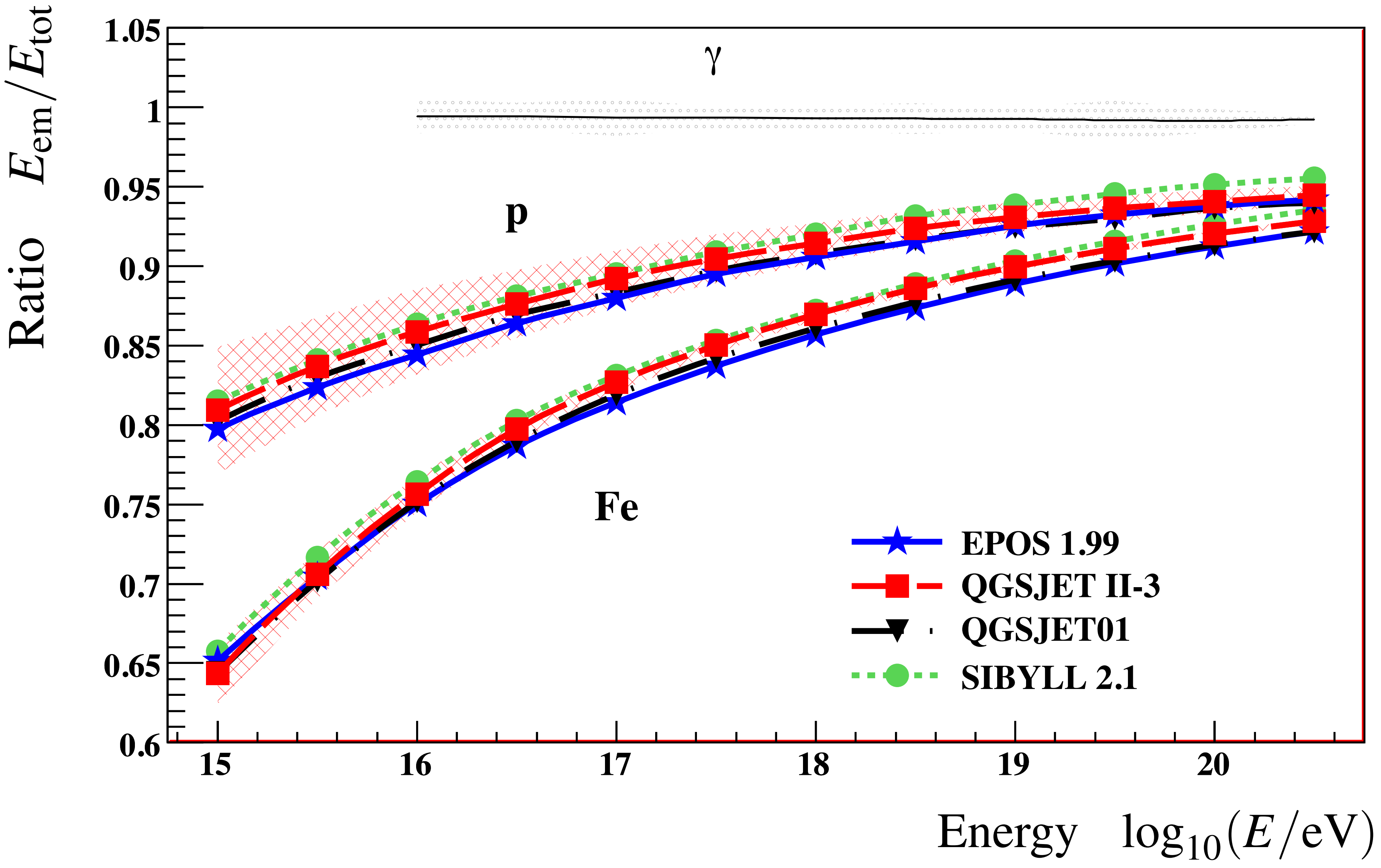
$$\boxed{E_{\text{em}} = \left[1 - \left(\frac{2}{3}\right)^n\right] E_0}$$

After n generations ...

$$\boxed{\begin{aligned} n = 5,\quad & E_{\text{had}} \sim 12\% \\ n = 6,\quad & E_{\text{had}} \sim 8\% \end{aligned}}$$

Energy transferred to electromagnetic component

(RE, Pierog, Heck, ARNPS 2011)



Ratio of em. to total shower energy

Detailed Monte Carlo simulation with CONEX

Model dependence of correction to obtain total energy small

Superposition model

Proton-induced shower

$$N_{\max} = E_0/E_c$$

$$X_{\max} \sim \lambda_{\text{eff}} \ln(E_0)$$

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

$$\alpha \approx 0.9$$

Assumption: nucleus of mass *A* and energy E_0 corresponds to *A* nucleons (protons) of energy $E_n = E_0/A$

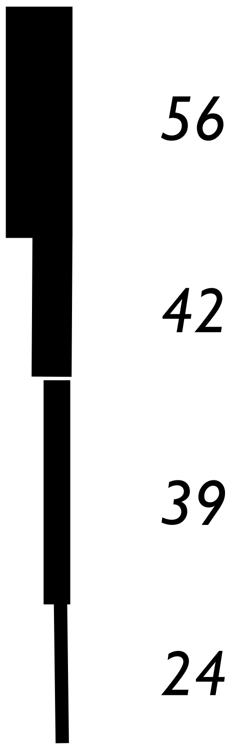
$$N_{\max}^A = A\left(\frac{E_0}{AE_c}\right) = N_{\max}$$

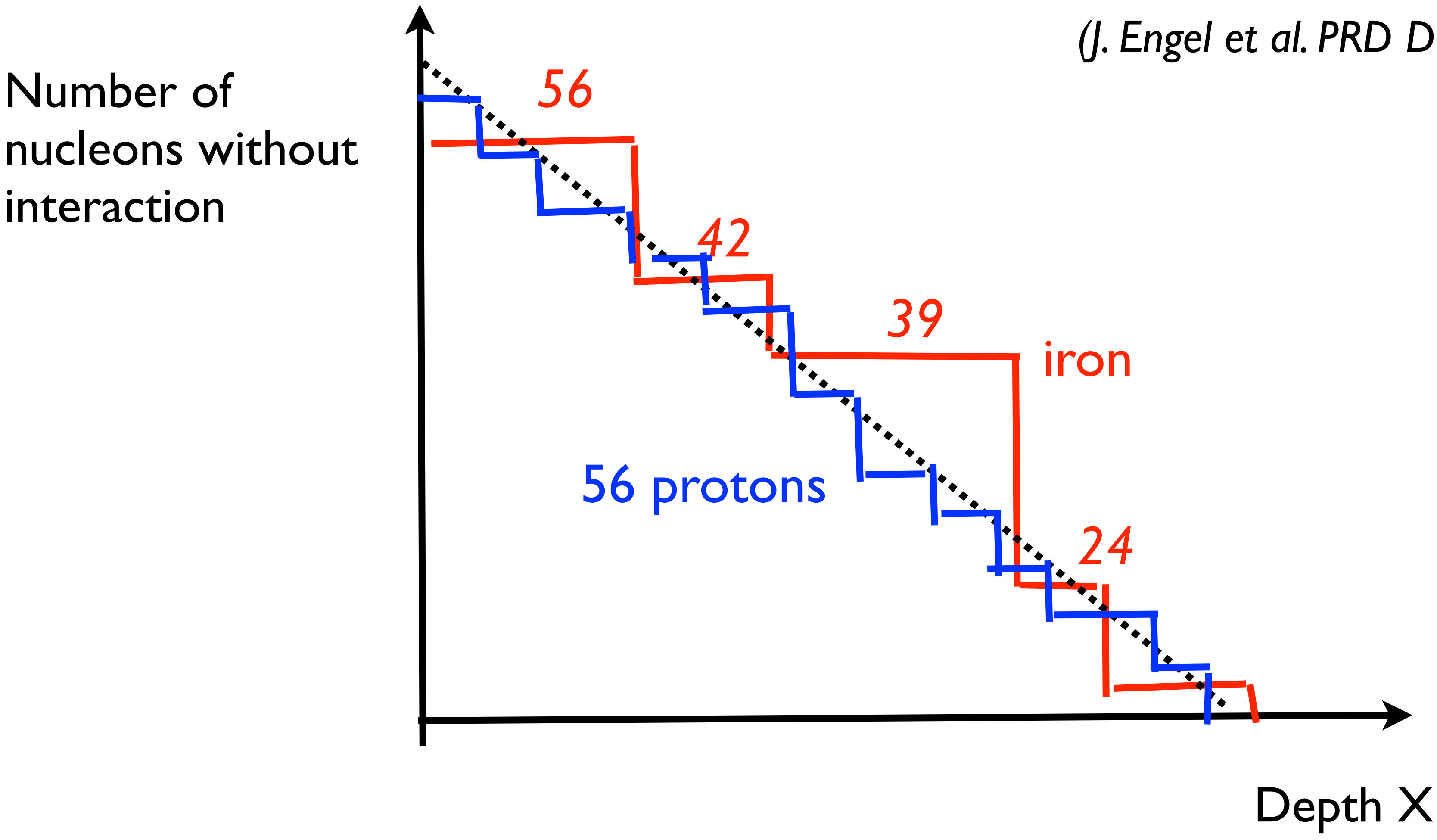
$$X_{\max}^A \sim \lambda_{\text{eff}} \ln(E_0/A)$$

$$N_\mu^A = A\left(\frac{E_0}{AE_{\text{dec}}}\right)^\alpha = A^{1-\alpha} N_\mu$$

Superposition model: correct prediction of mean Xmax

iron nucleus





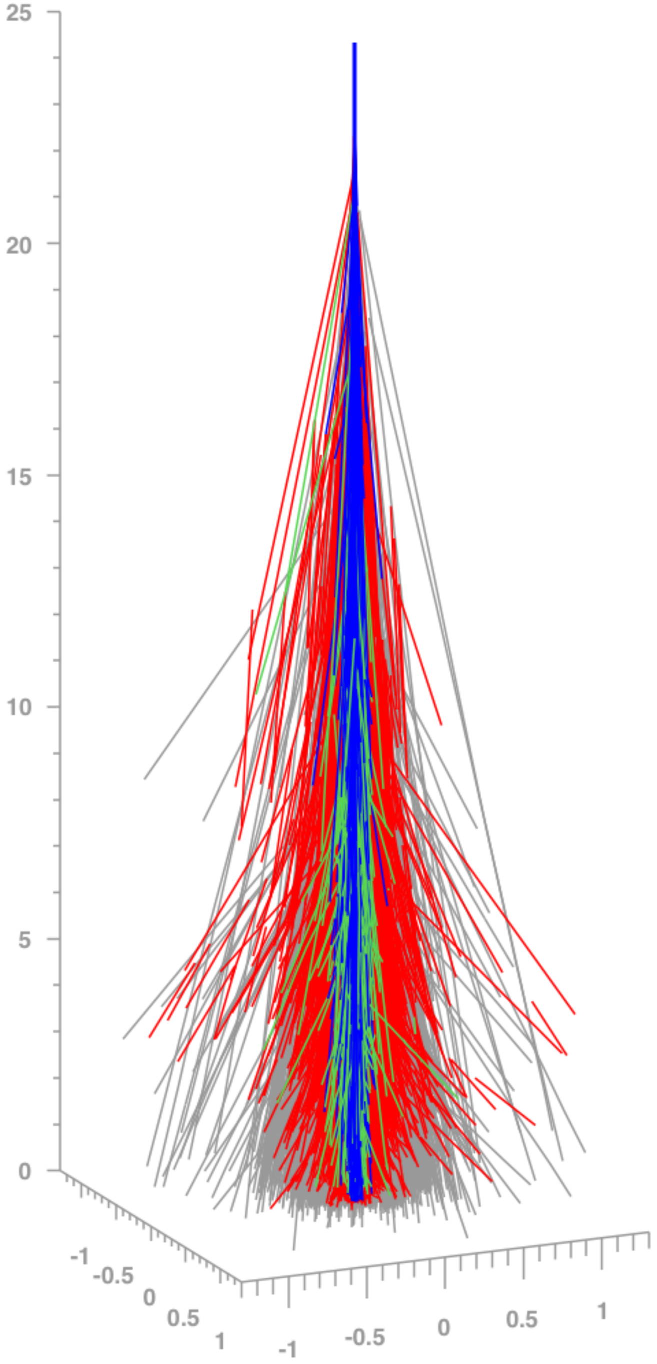
(J. Engel et al. PRD D46, 1992)

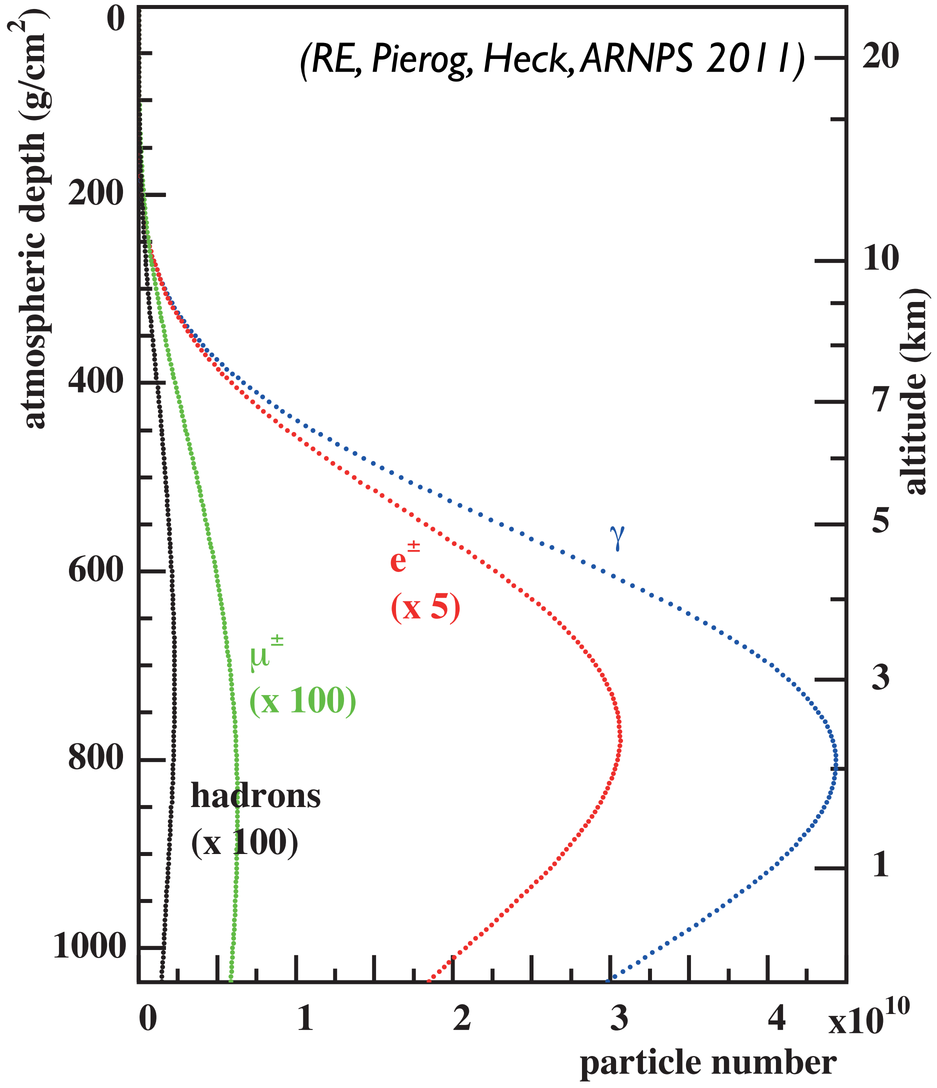
Glauber approximation (unitarity)

$$n_{\mathrm{part}} = \frac{\sigma_{\mathrm{Fe-air}}}{\sigma_{\mathrm{p-air}}}$$

Superposition and semi-superposition models applicable to inclusive (averaged) observables

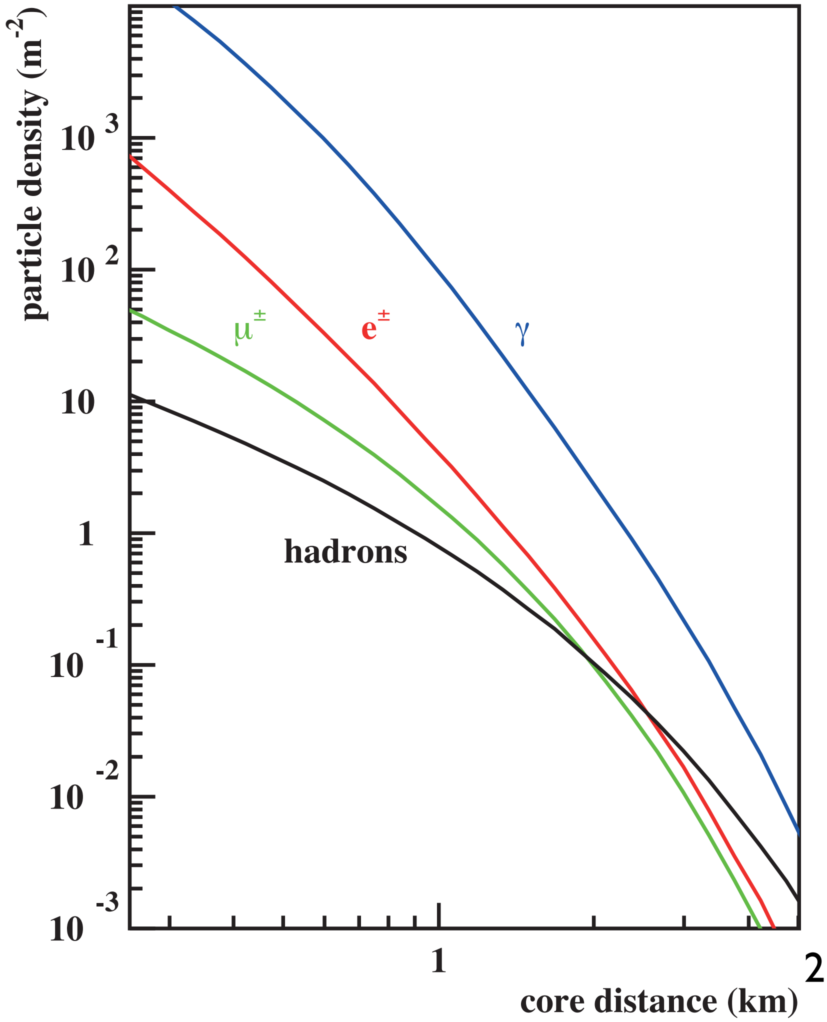
Measured components of air showers




(RE, Pierog, Heck, ARNPS 2011)

Longitudinal profile:

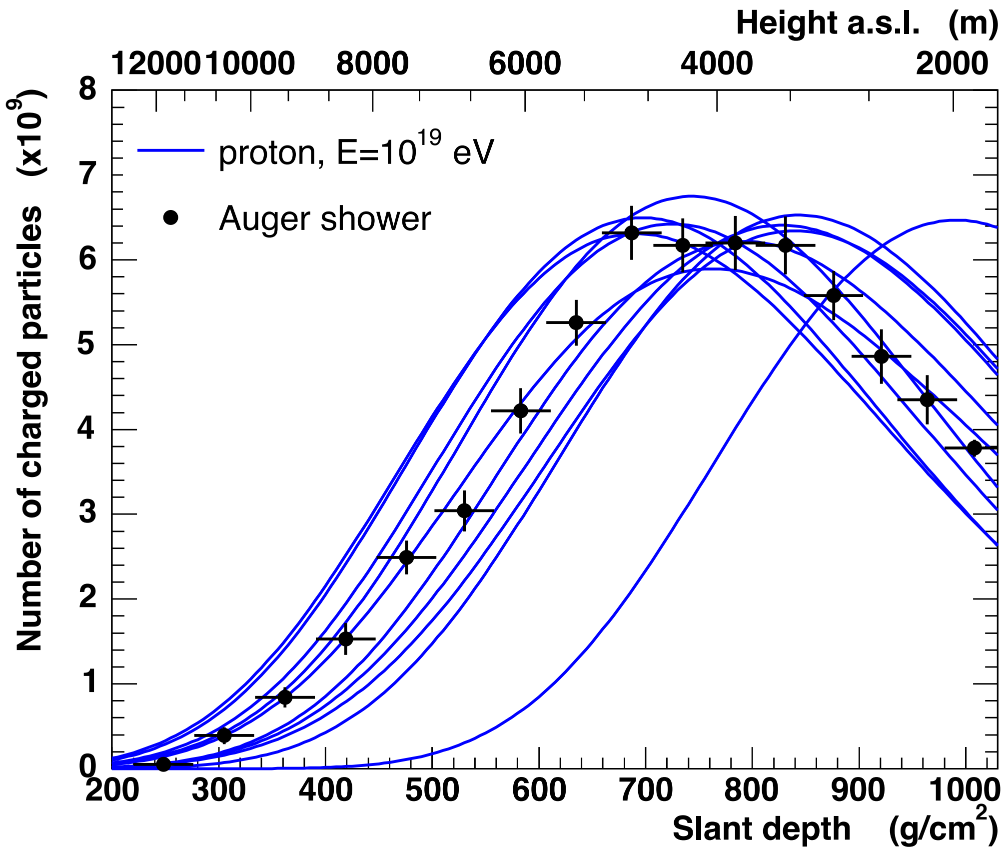
Cherenkov light
Fluorescence light
(bulk of particles measured)

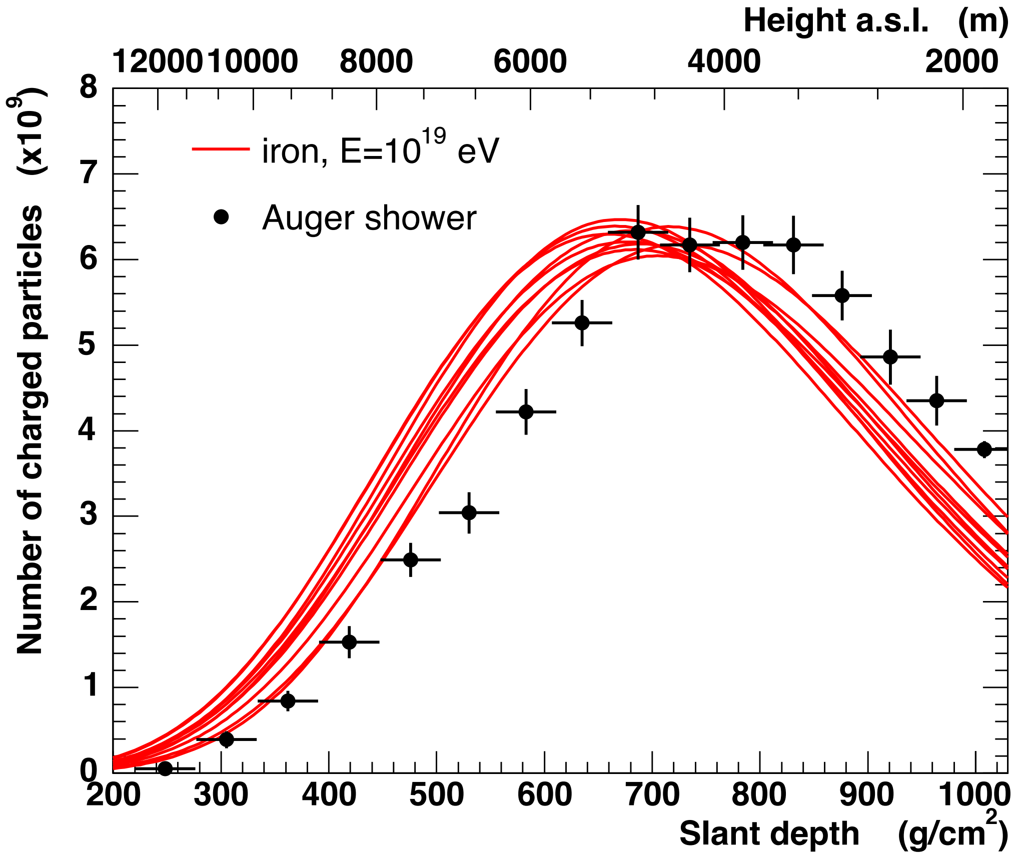


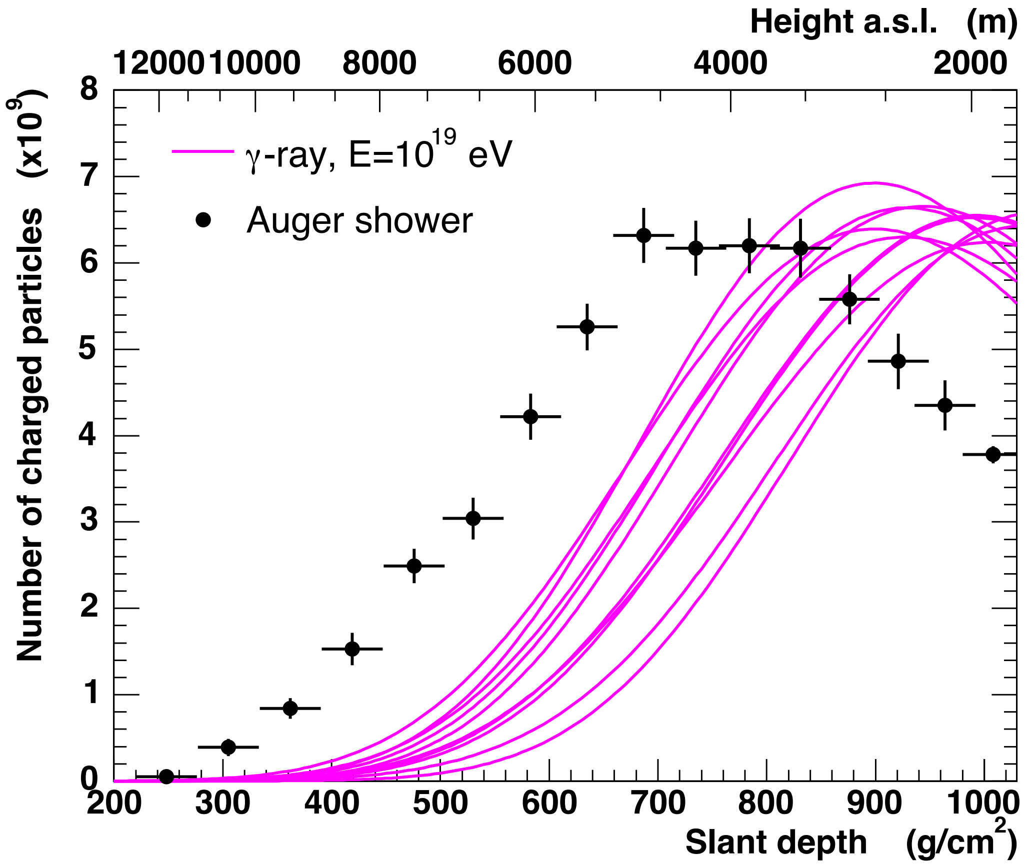
Lateral profiles:

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

Longitudinal shower profile







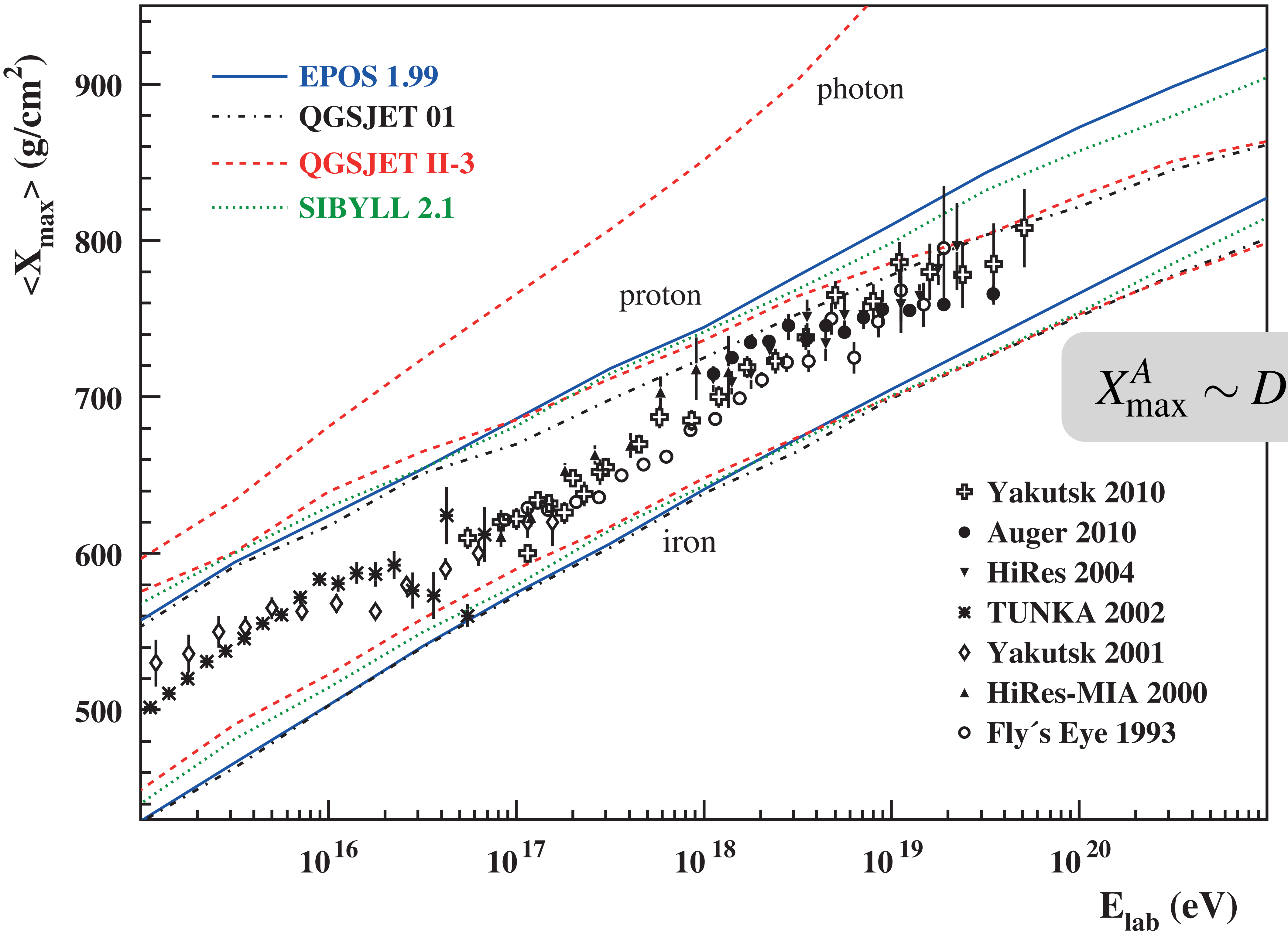
$$N_{\max} = E_0/E_c$$

$$X_{\max} \sim D_{\mathrm{e}} \ln(E_0/E_c)$$

Superposition model:

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

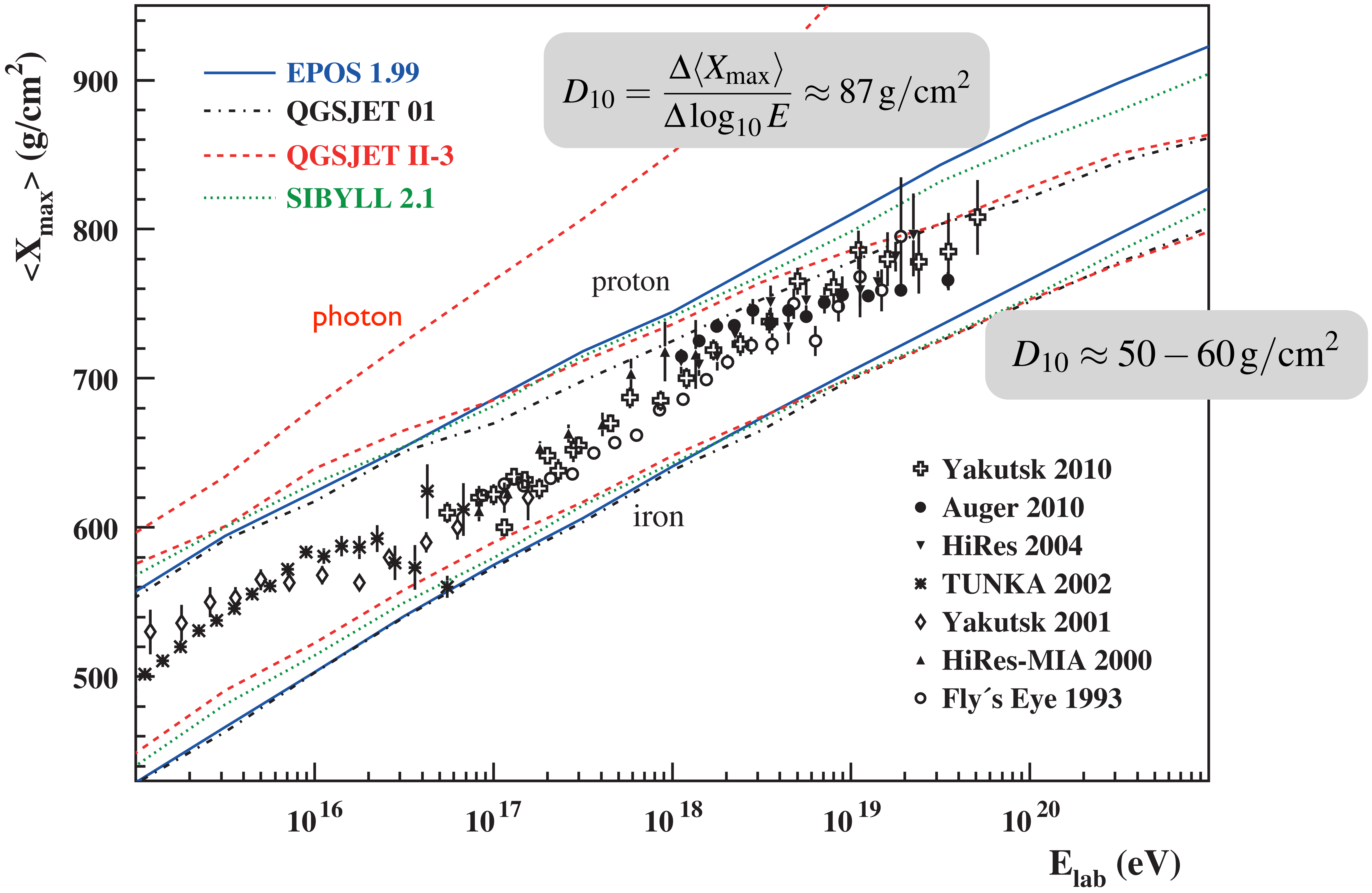
Mean depth of shower maximum



$$X_{\max}^{A} \sim D_e \ln(E_0/AE_c)$$

(RE, Pierog, Heck, ARNPS 2011)

Different slopes for em. and hadronic showers

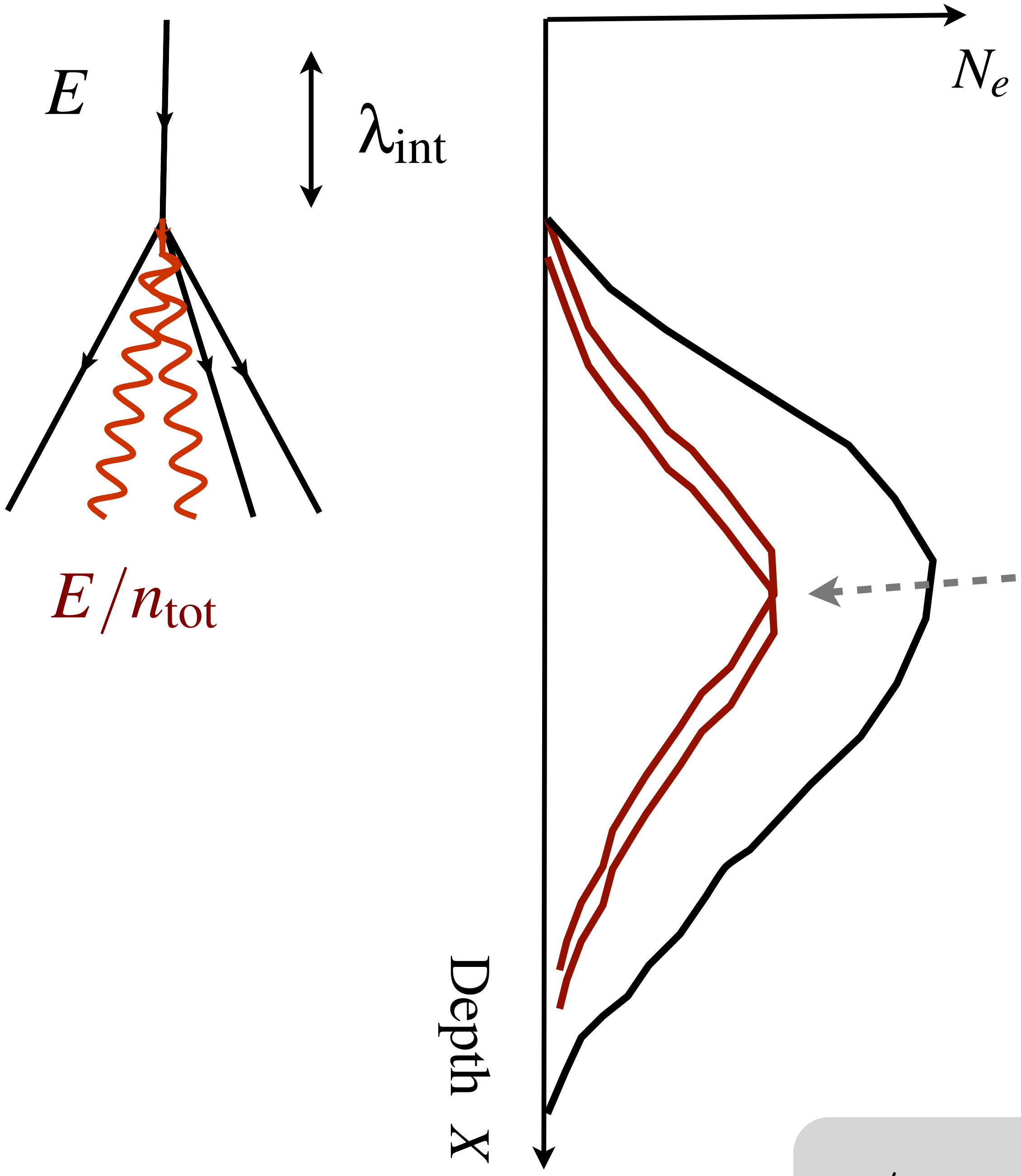


$$D_{10} = \frac{\Delta\langle X_{\max}\rangle}{\Delta \log_{10} E} \approx 87\,\mathrm{g/cm^2}$$

$$D_{10} \approx 50 - 60\,\mathrm{g/cm^2}$$

(RE, Pierog, Heck, ARNPS 2011)

Derivation of elongation rate theorem



$$\langle X_{\rm max}(E)\rangle = \langle X_{\rm max}^{\rm em}(E/n_{\rm tot})\rangle + \lambda_{\rm int}$$

$$\langle X_{\rm max}^{\rm em}\rangle \sim X_0 \ln(E/n_{\rm tot})$$

$$\langle X_{\rm max}(E)\rangle = X_0 \, \log(E/n_{\rm tot}) + c + \lambda_{\rm int}$$

taking derivative $\log E$

$$\frac{{\rm d}\langle X_{\rm max}(E)\rangle}{{\rm d}\log E} = X_0 - X_0 \frac{{\rm d}\,\log n_{\rm tot}}{{\rm d}\log E} + \frac{{\rm d}\,\lambda_{\rm int}}{{\rm d}\log E}$$

Elongation rate of em. shower

Elongation rate theorem

X_0 = 36 g/cm^2

$$\boxed{D_e^{\mathrm{had}} = X_0(1 - B_n - B_\lambda)}$$

(Linsley, Watson PRL46, 1981)

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

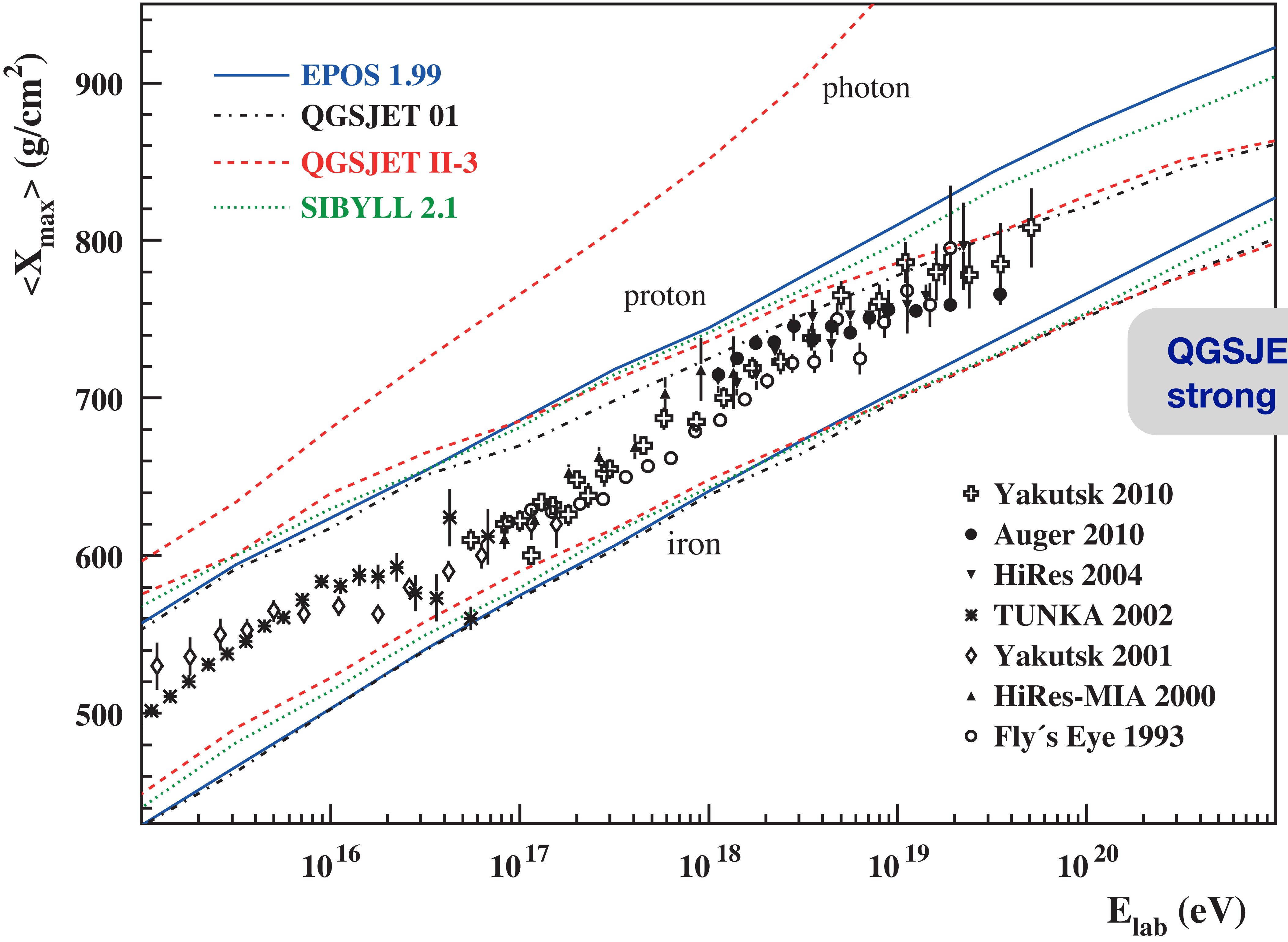
Large if multiplicity of high energy particles rises very fast, **zero in case of scaling**

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

Large if cross section rises rapidly with energy

Note: $D_{10} = \log(10) D_e$

Mean depth of shower maximum



QGSJET predicts very strong scaling violations

(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)

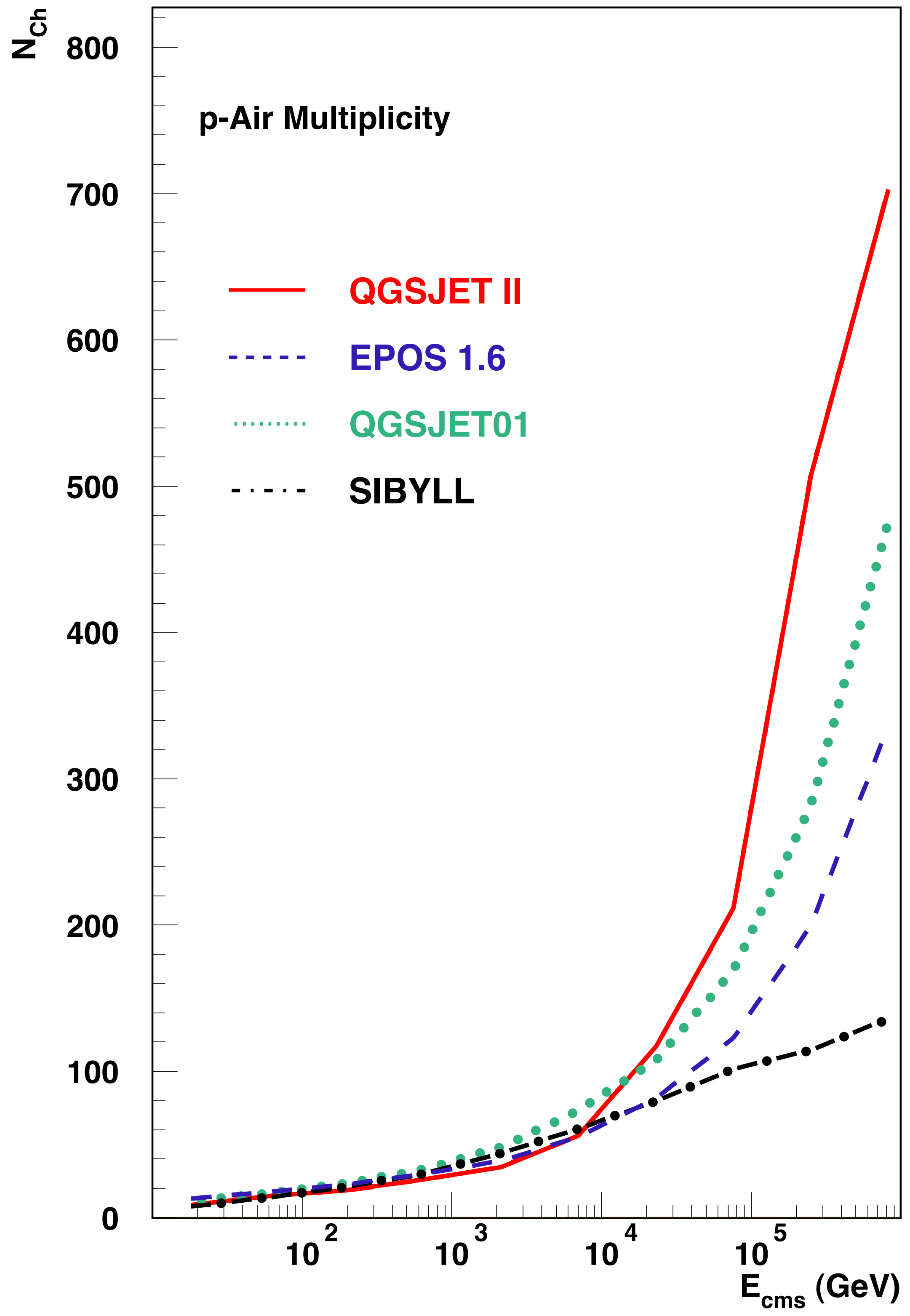
factor ~ 87 g/cm²

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

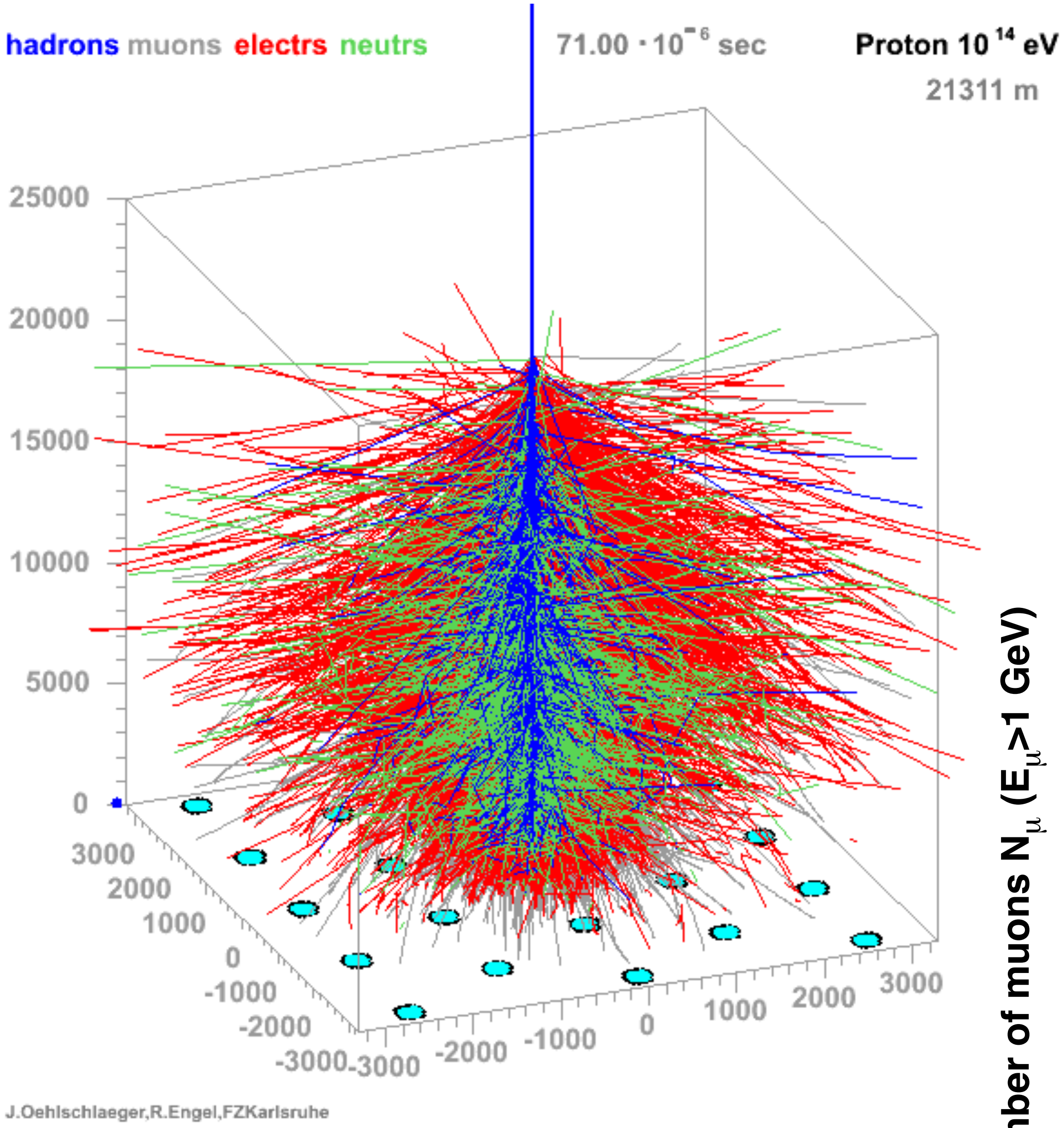
Large if multiplicity of high energy particles rises very fast, **zero in case of scaling**

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

Large if cross section rises rapidly with energy



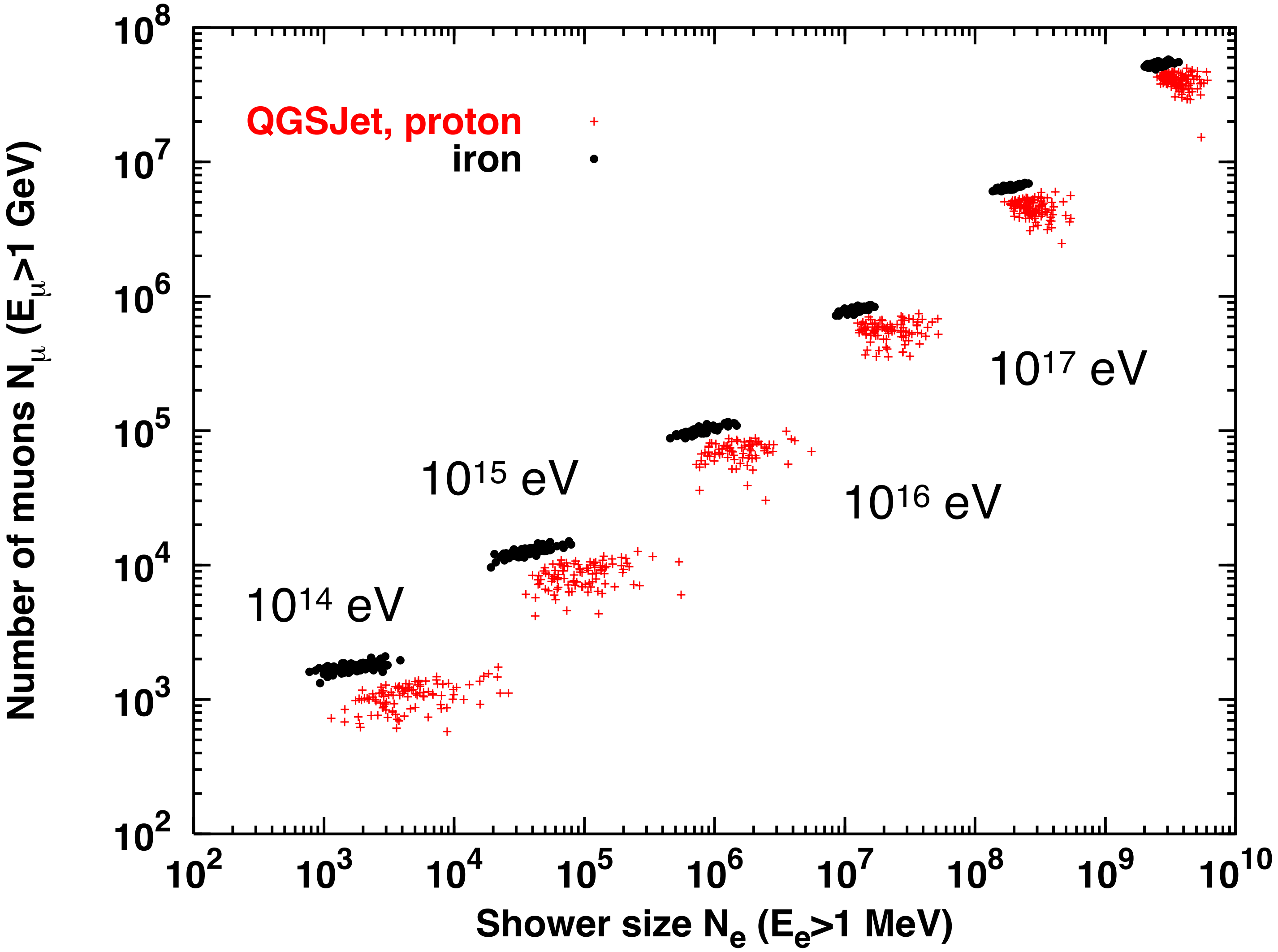
Air shower ground arrays: N_e and N_μ



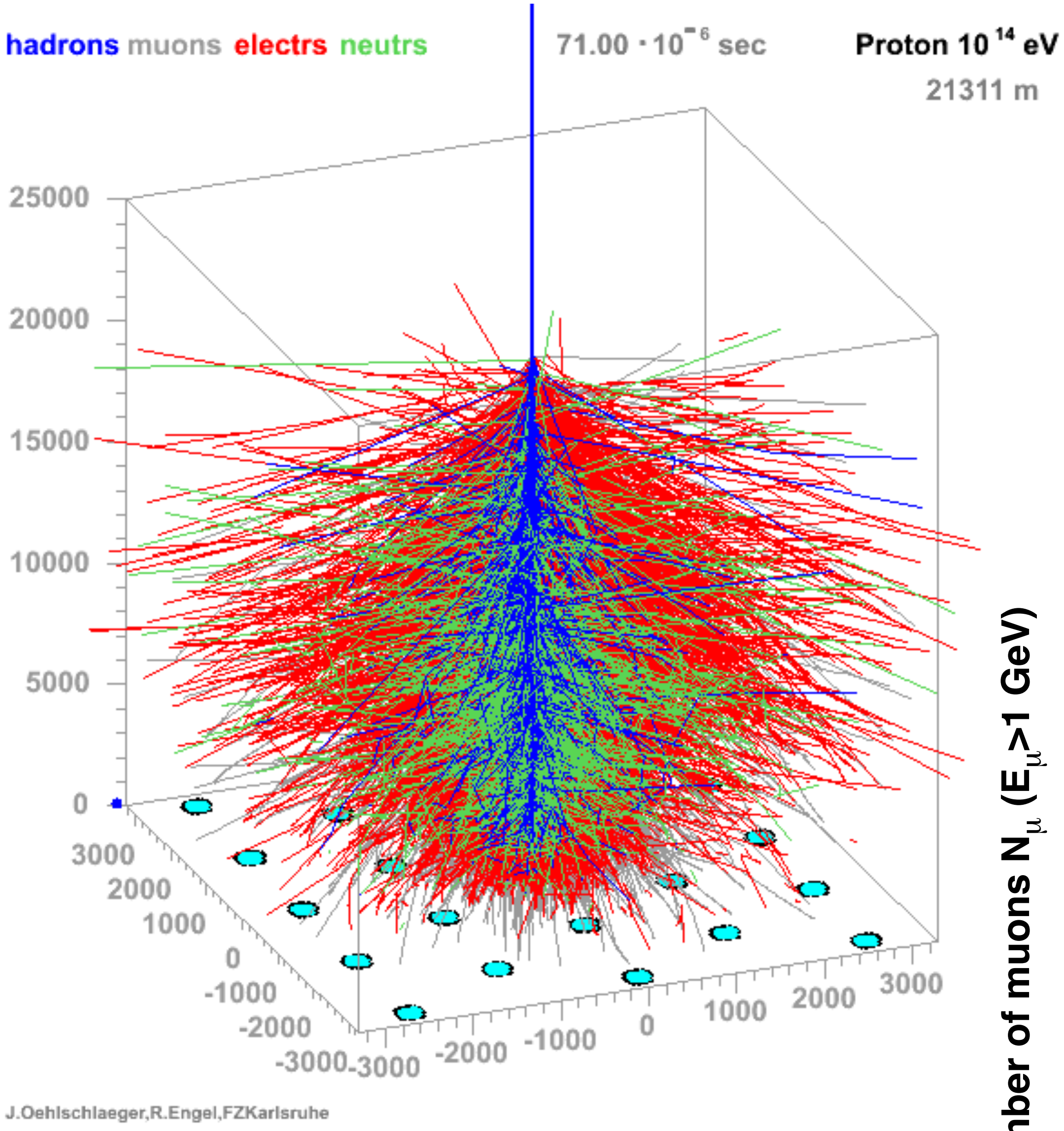
KASCADE and KASCADE-Grande

Energy conservation

$$\ln E = a \cdot \ln N_e + b \cdot \ln N_\mu$$



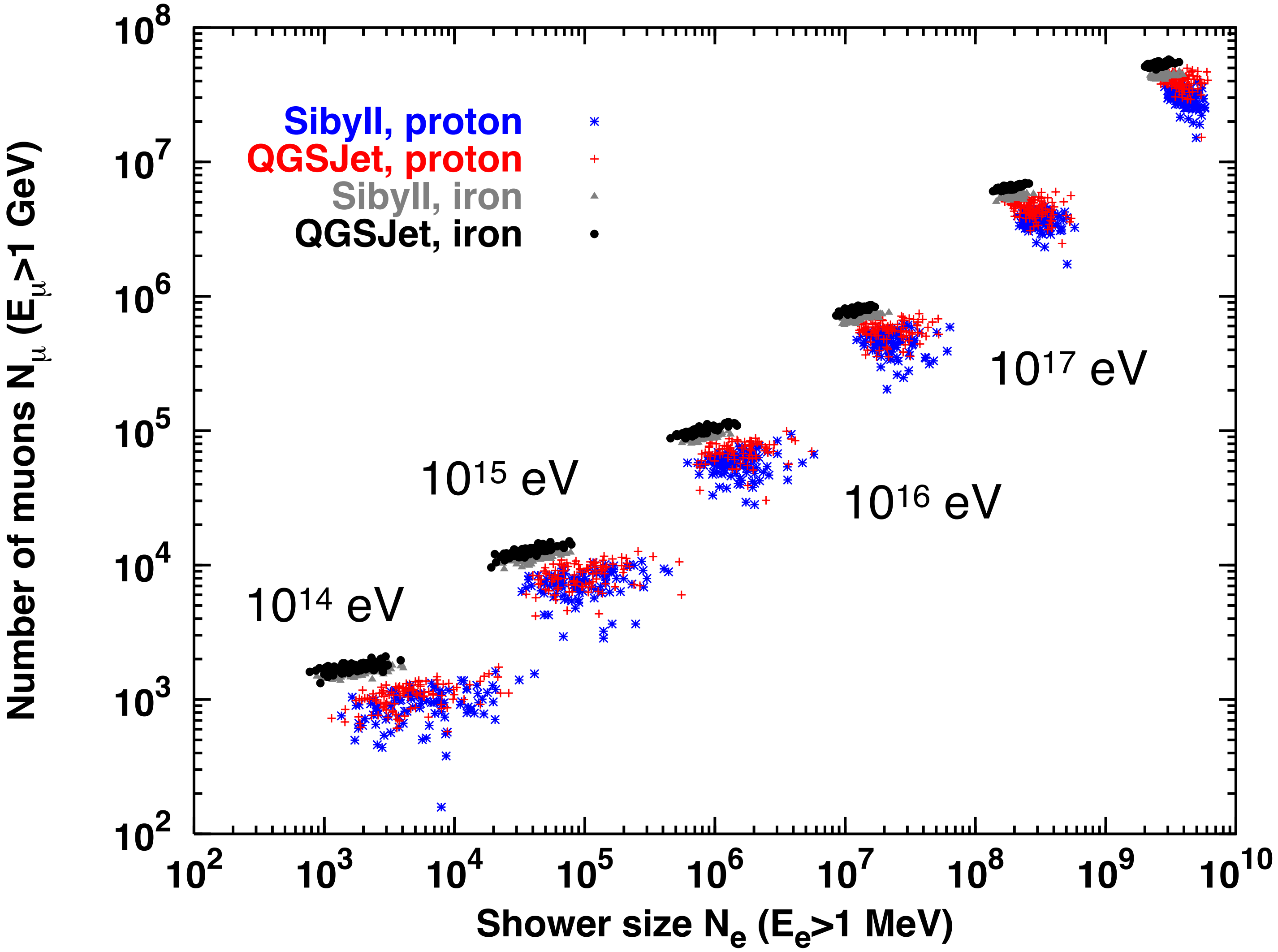
Air shower ground arrays: N_e and N_μ



KASCADE and KASCADE-Grande

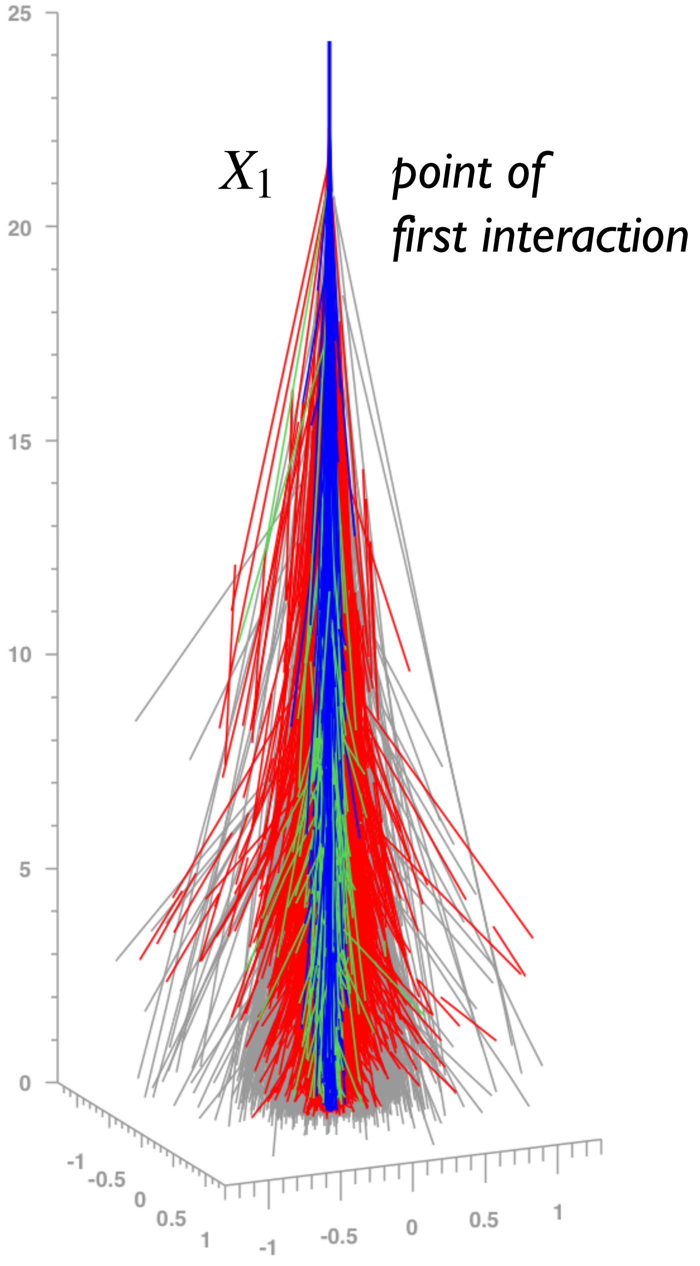
Energy conservation

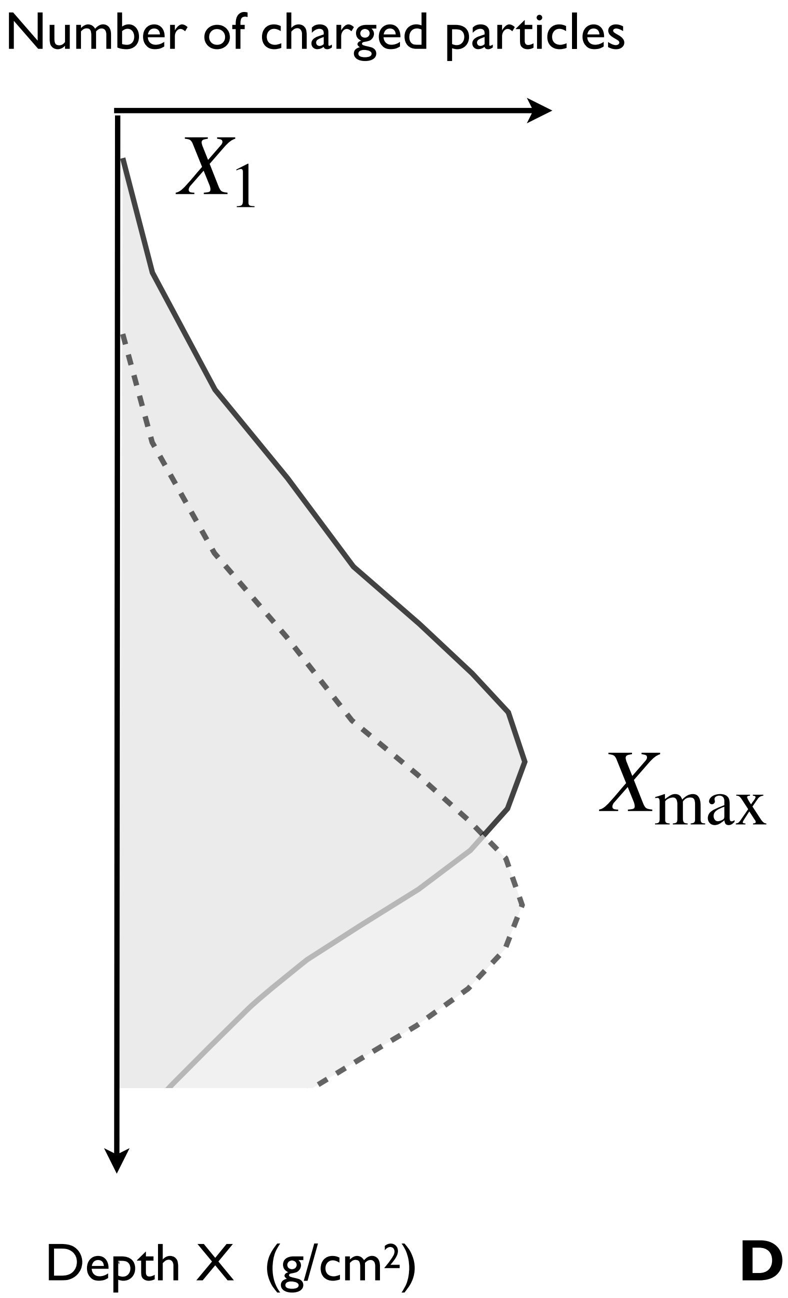
$$\ln E = a \cdot \ln N_e \; + \; b \cdot \ln N_\mu$$



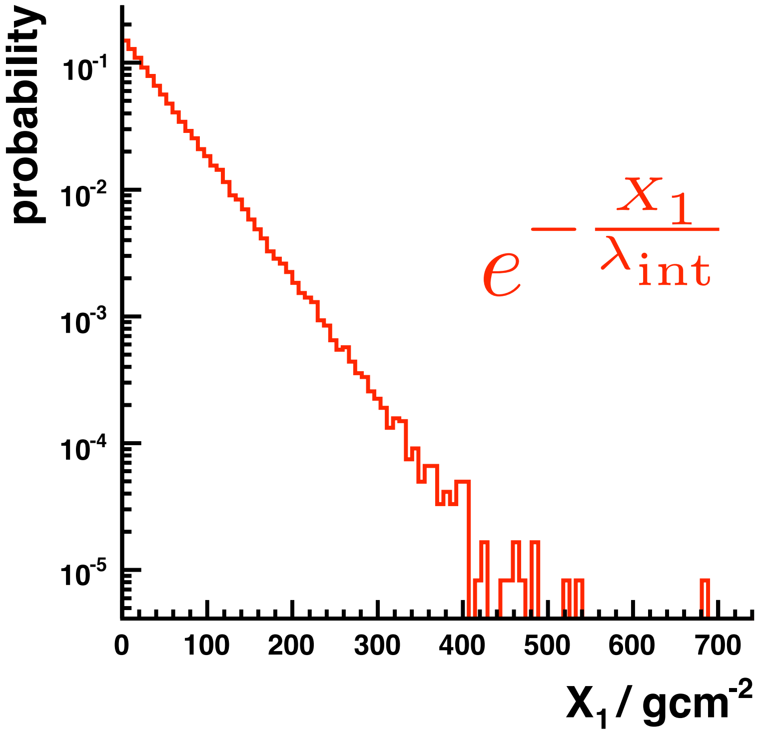
Measurement of hadronic cross section

Cross section measurement with air showers





Depth of first interaction



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

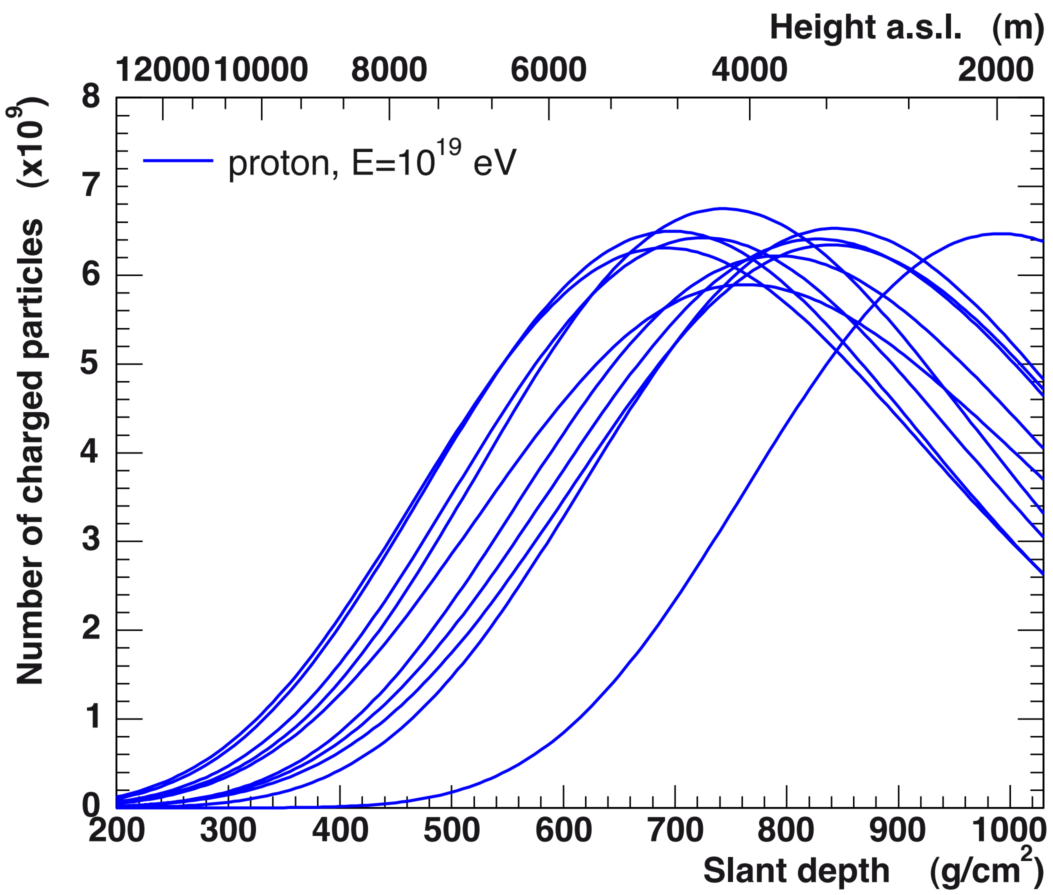
Difficulties

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

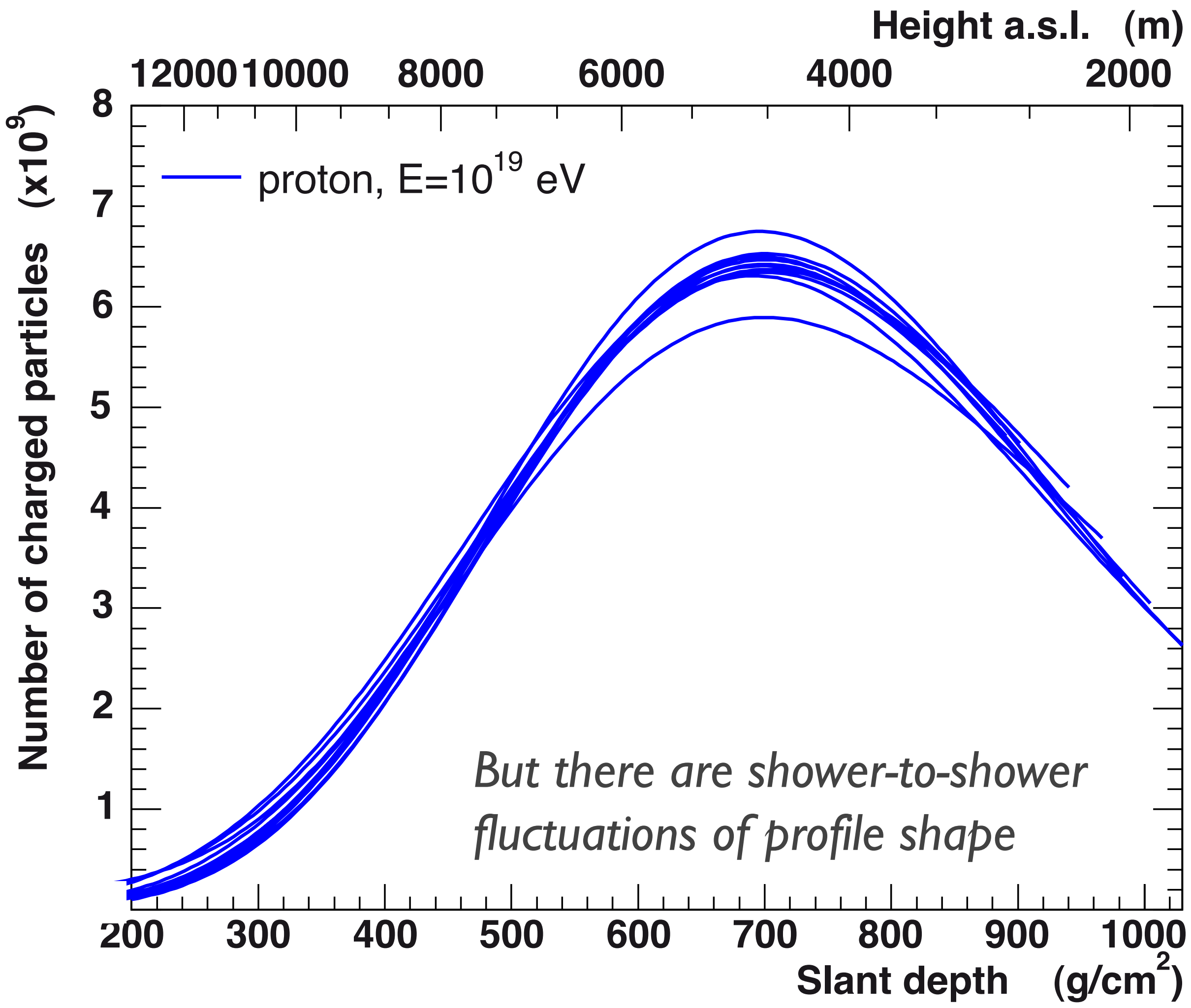
(R. Ulrich et al. NJP 11, 2009, and talk at this meeting)

Universality features of high-energy showers (i)

Simulated shower profiles



Profiles shifted in depth

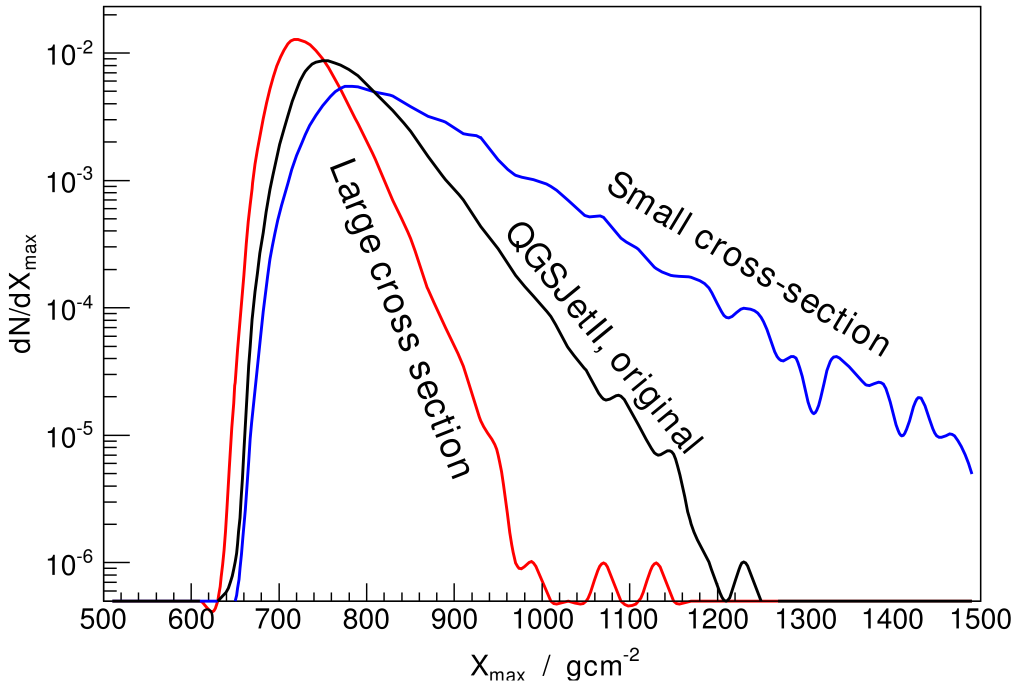


But there are shower-to-shower fluctuations of profile shape

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

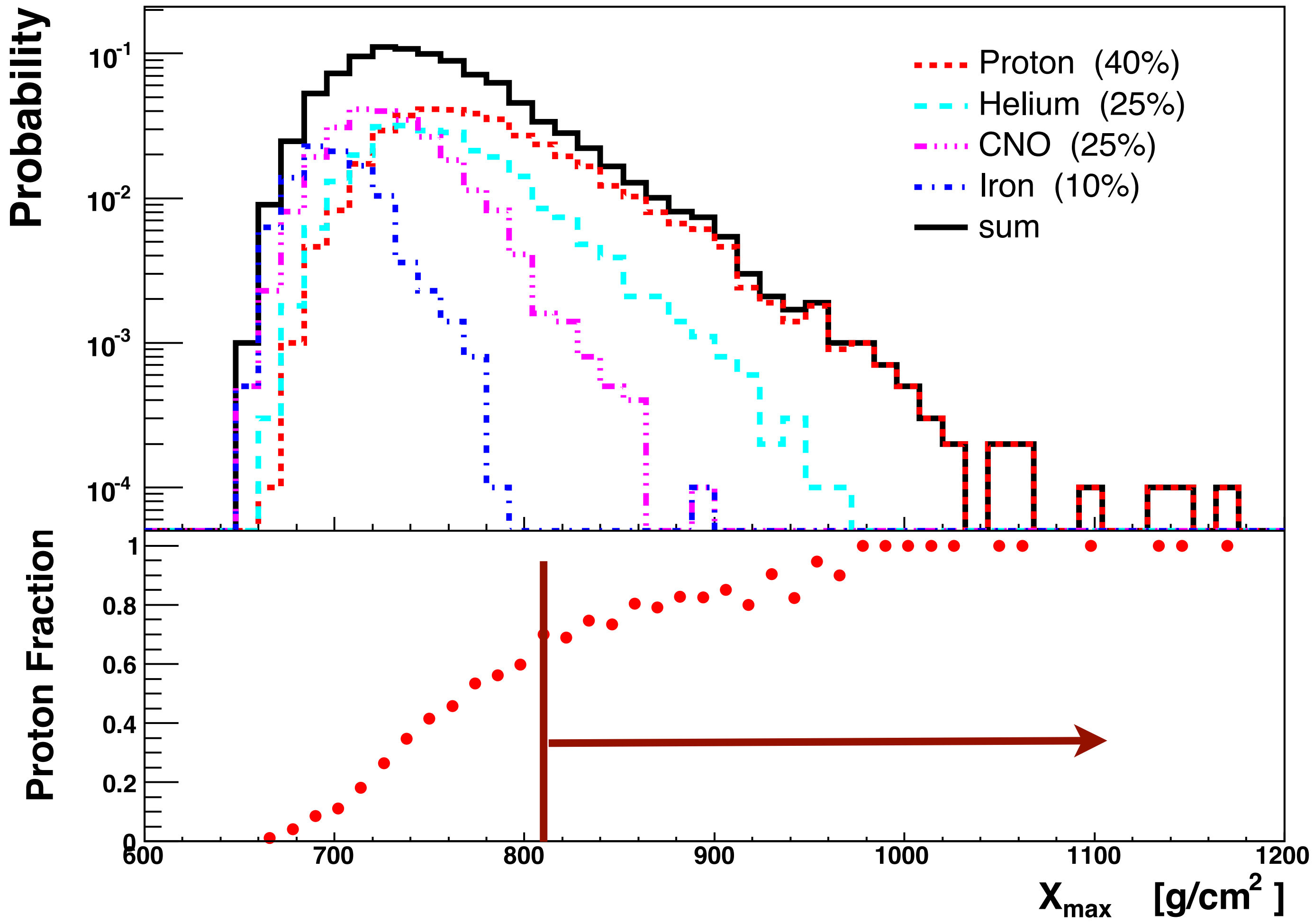
Selection of protons: select very deep showers

Cross section measurement: composition



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

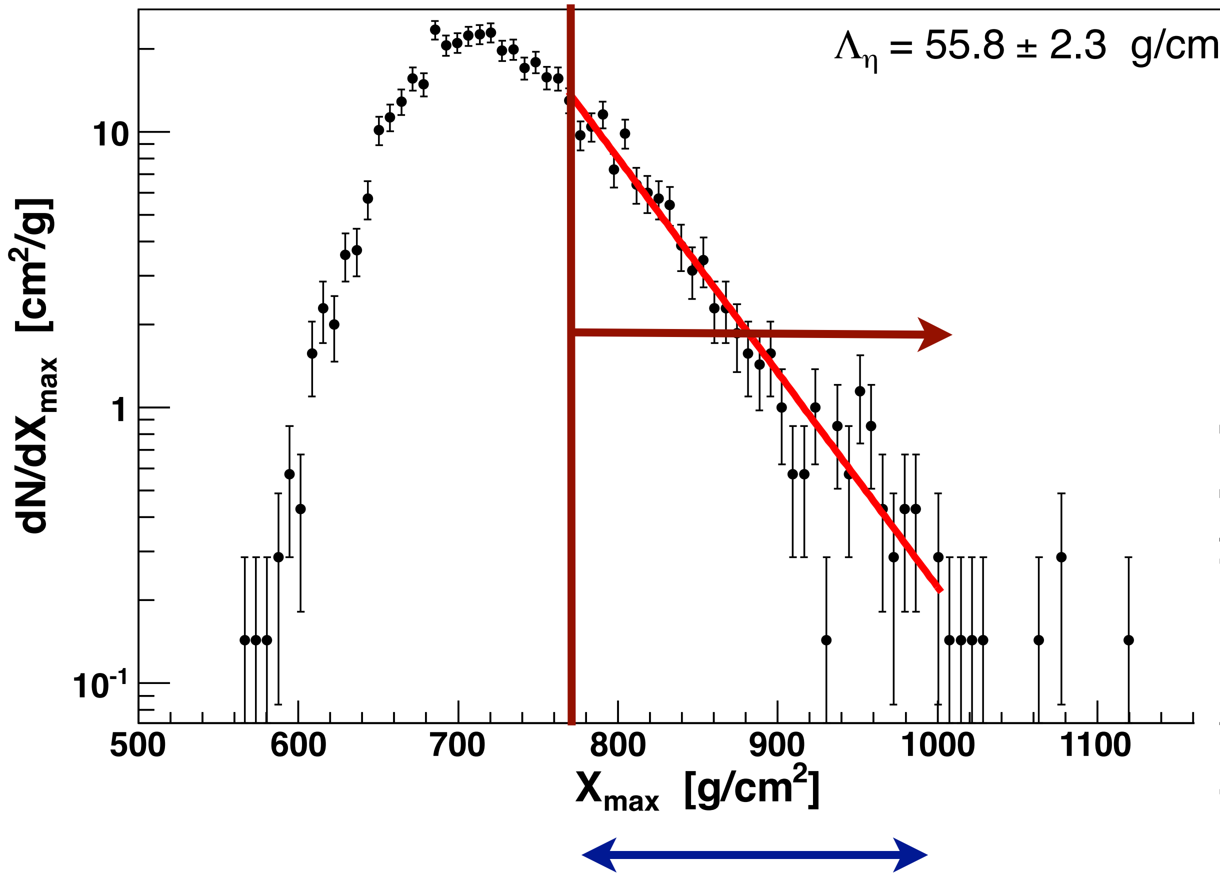
(Pierre Auger Collab. 1107.4804)



Example of distribution of X_{max} for mixed composition

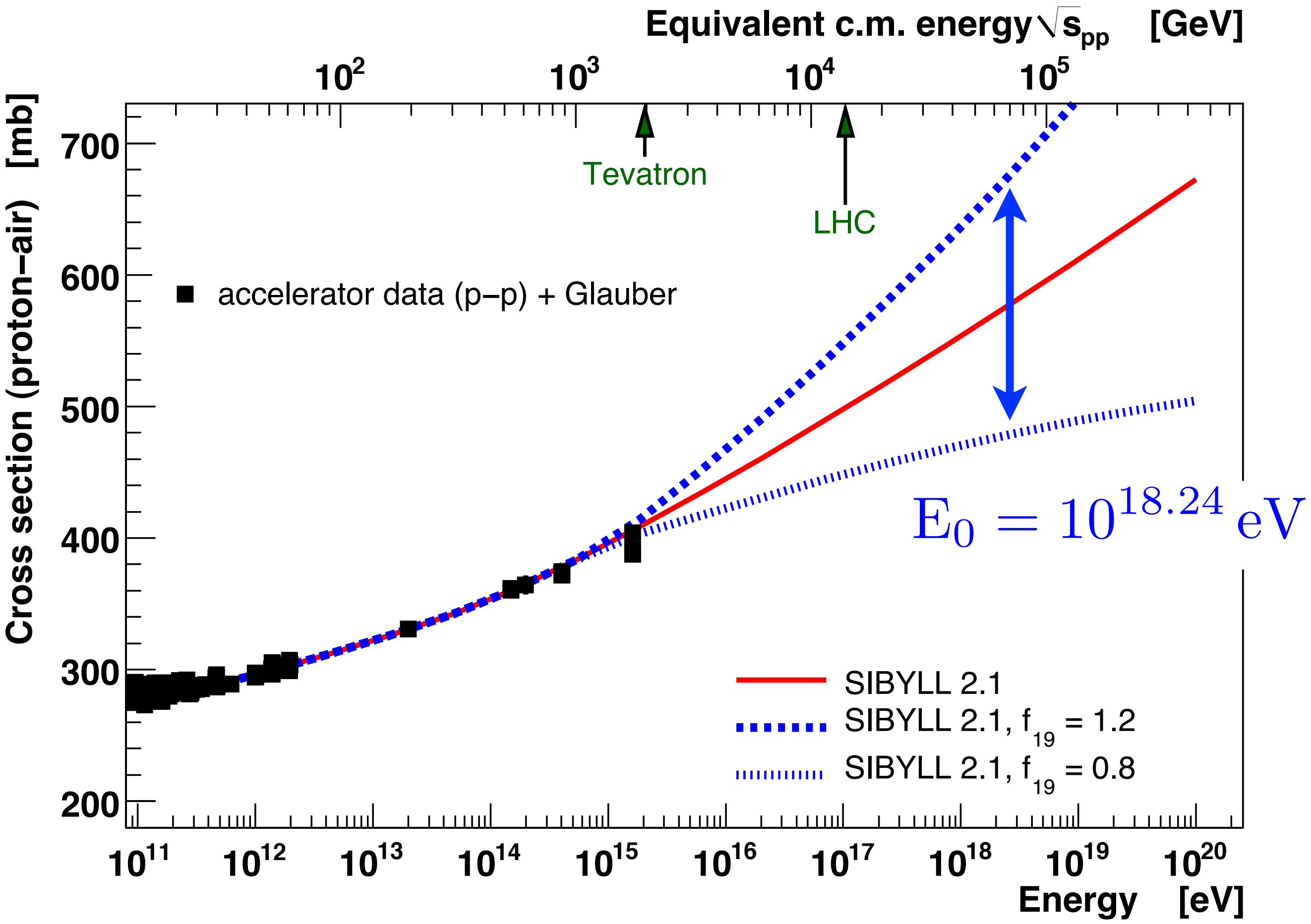
Only deep showers are used in analysis to enhance proton fraction in data sample

Cross section measurement: self-consistency



Depth range of analysis

(Auger Collab. 1107.4804)

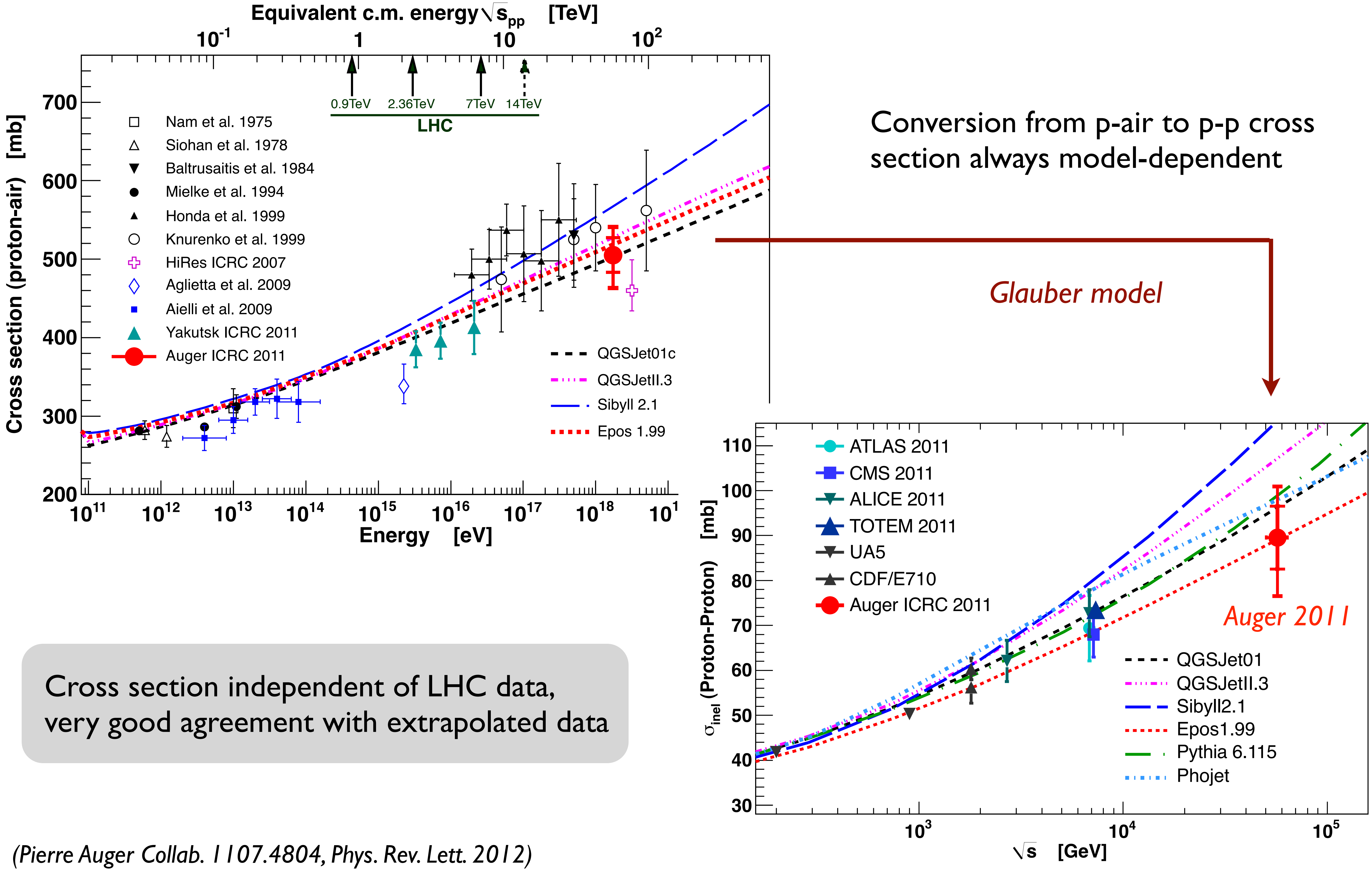


Cross section accepted if simulated slope fits measured slope of X_{max} distribution

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

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

High-energy frontier: proton-air cross section



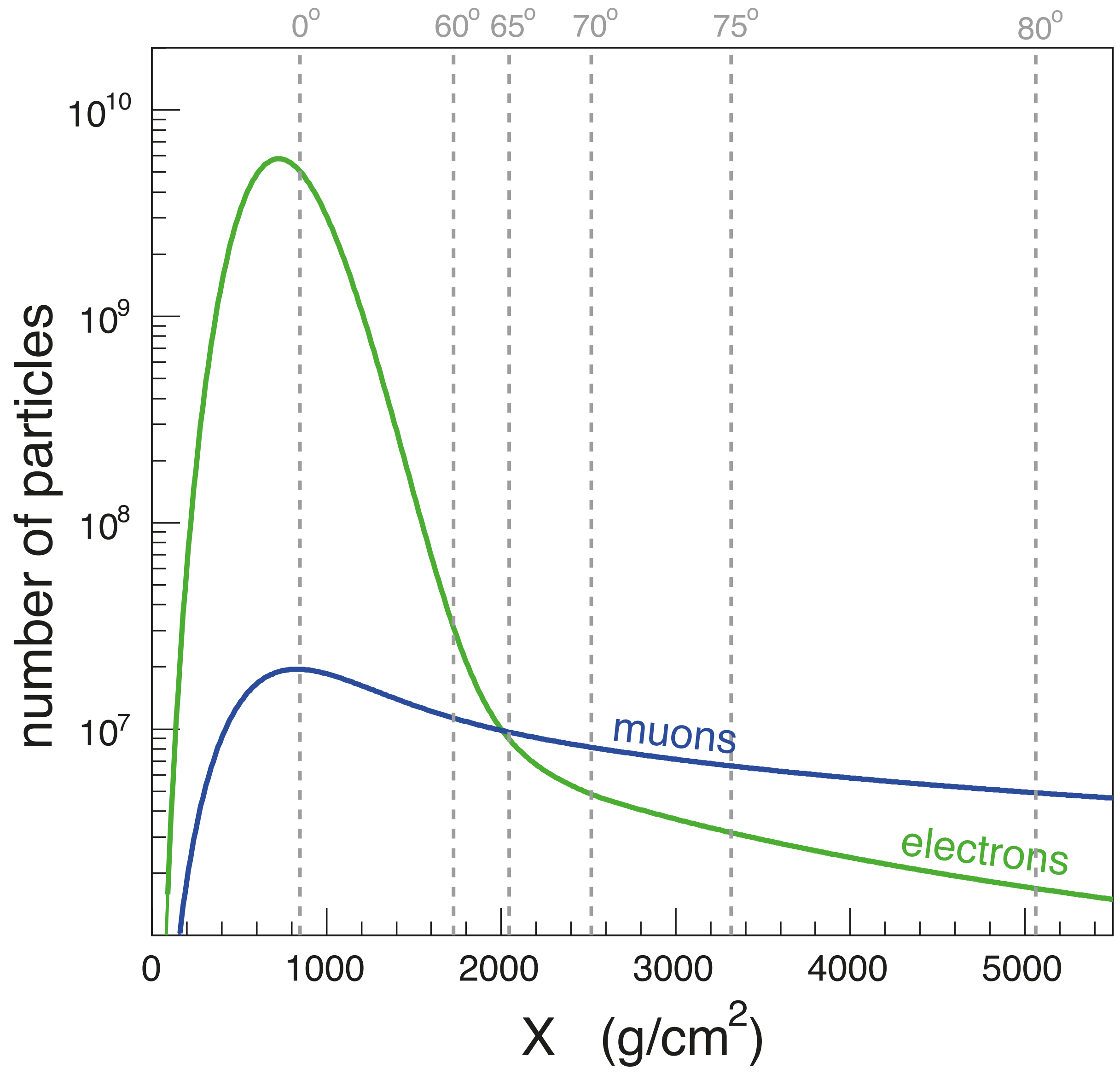
Conversion from p-air to p-p cross section always model-dependent

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

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

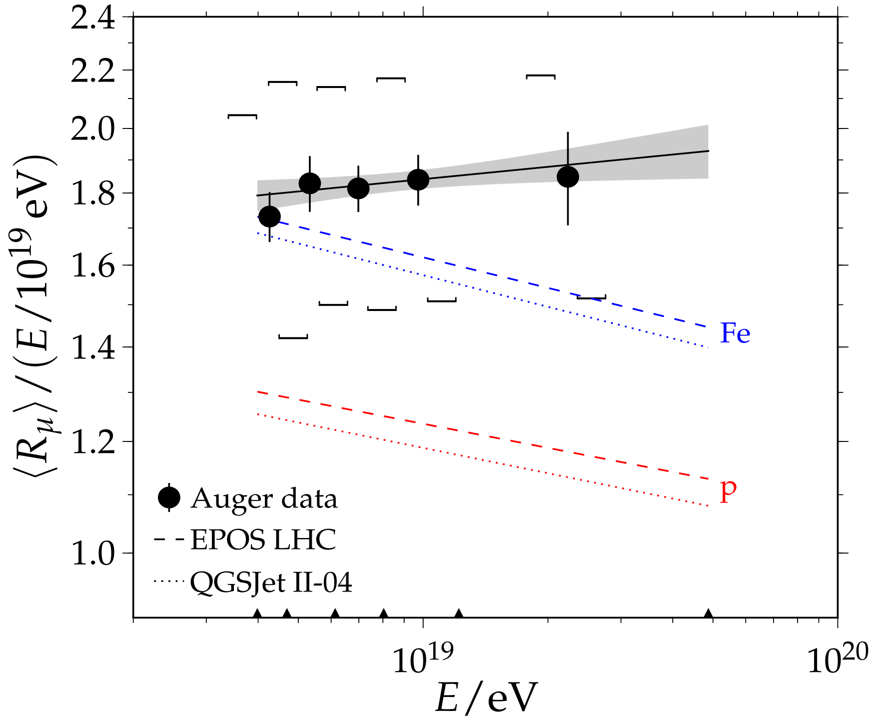
The muon problem

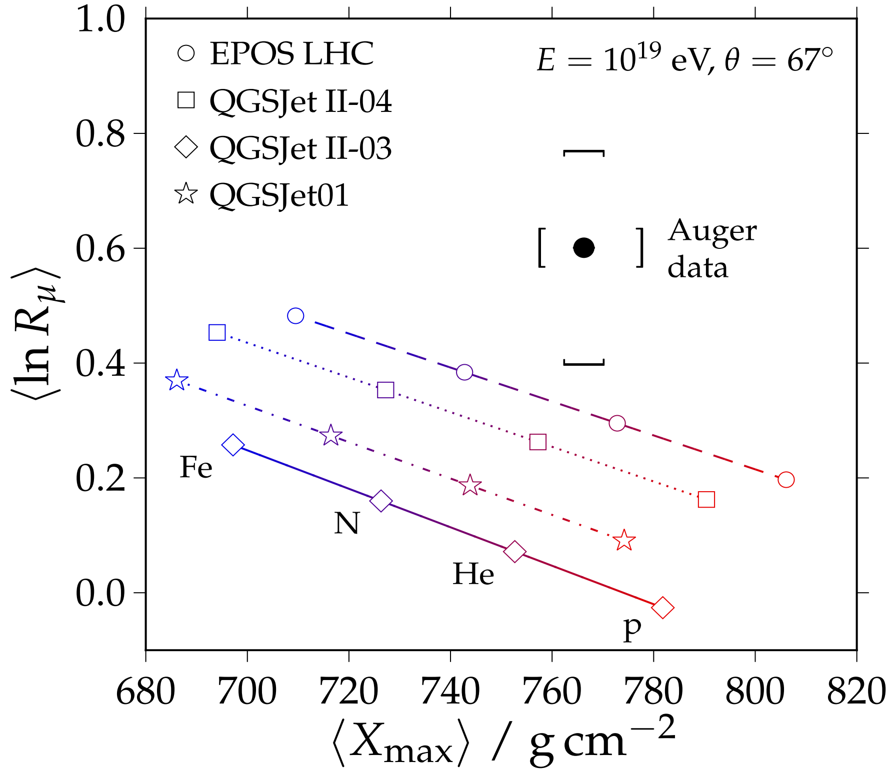
Muon number in inclined showers



(Auger, PRD91, 2015)

Number of muons in showers with θ>60°





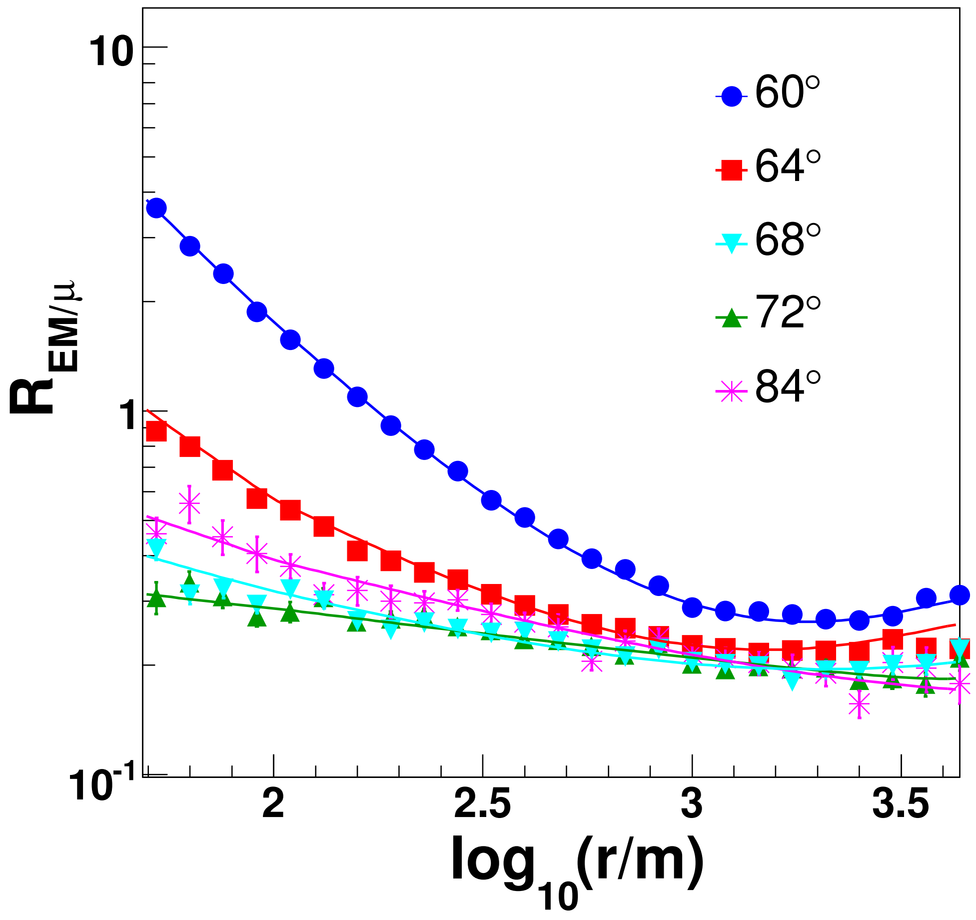
Several measurements: indications for muon discrepancy

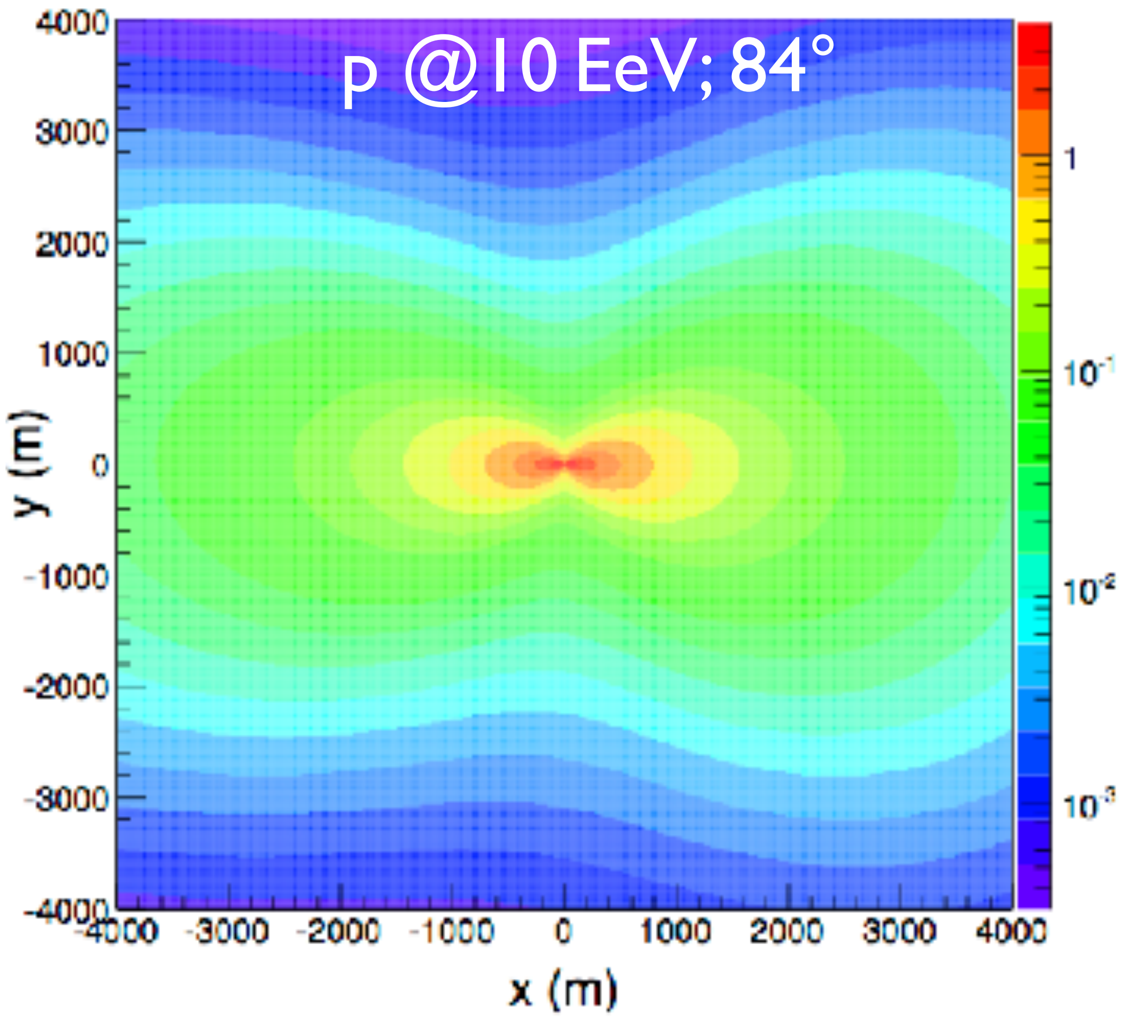
Hybrid events: N_{19} used for muon counting

- Muonic component dominates
  - (≈ 20% residual e.m. component)
- Energy estimator N_{19}:

$$N_{19} = \rho_\mu / \rho_{\mu,\,19}(x, y, \theta, \phi)$$

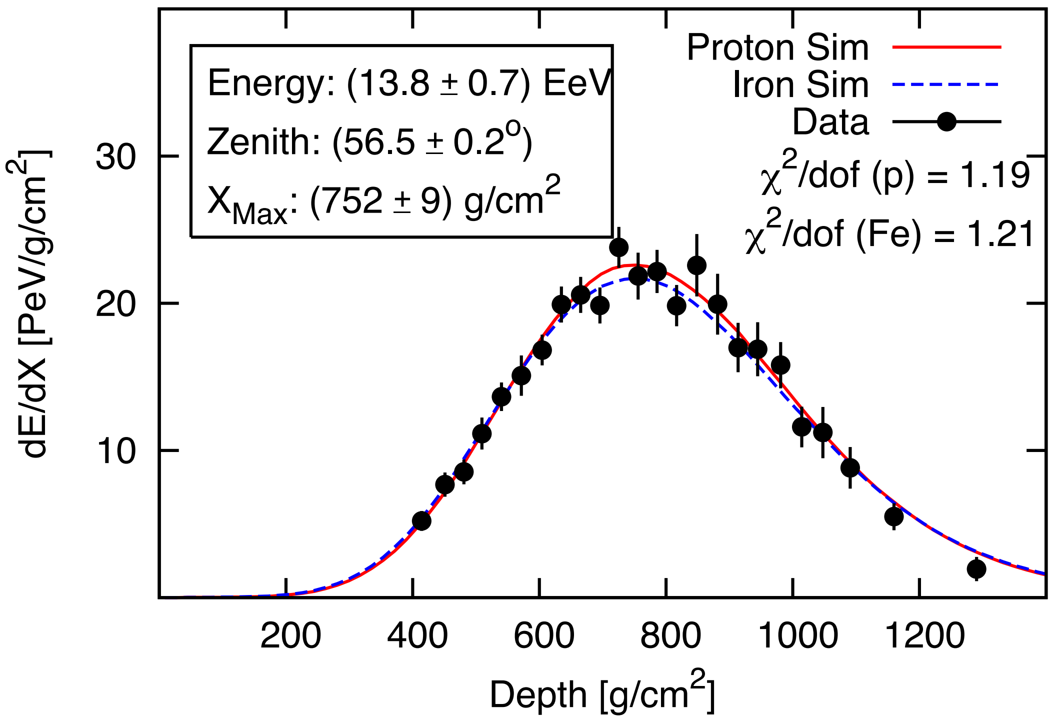
- zenith angle independent

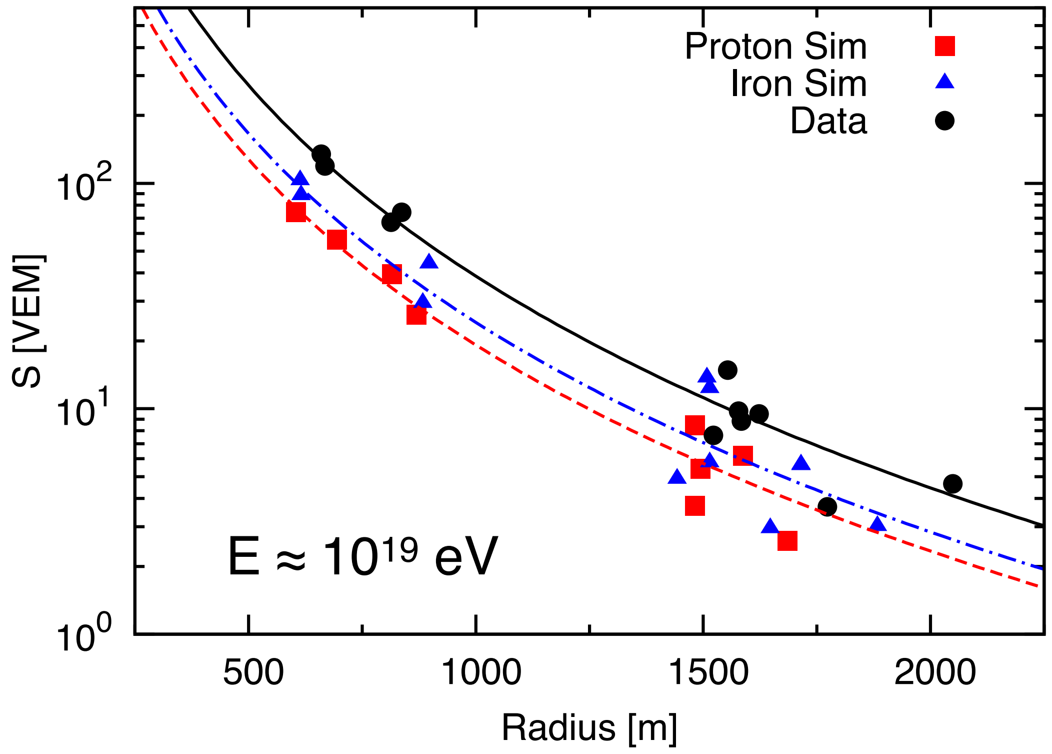




Simulated muon maps (magnetic deflection)

Ultimative test: simulation of individual events





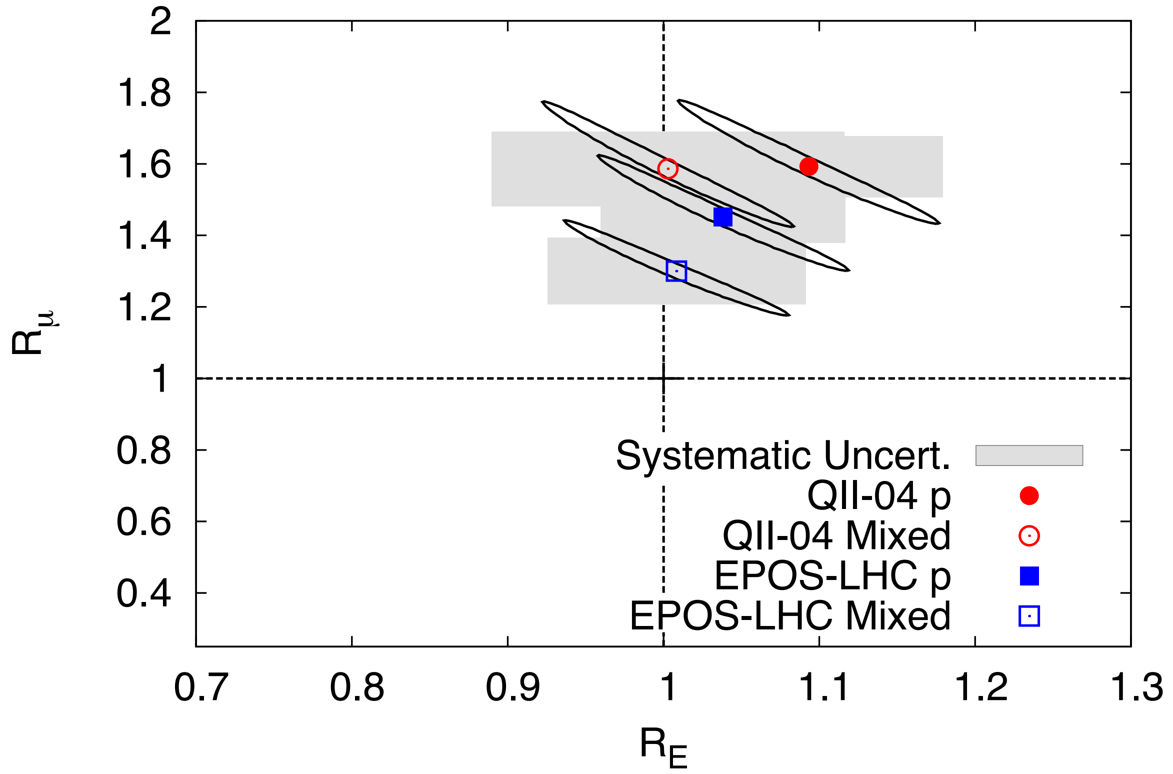
(Auger, PRL 117, 2016)

Phenomenological model ansatz

Energy scaling: em. particles and muons

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

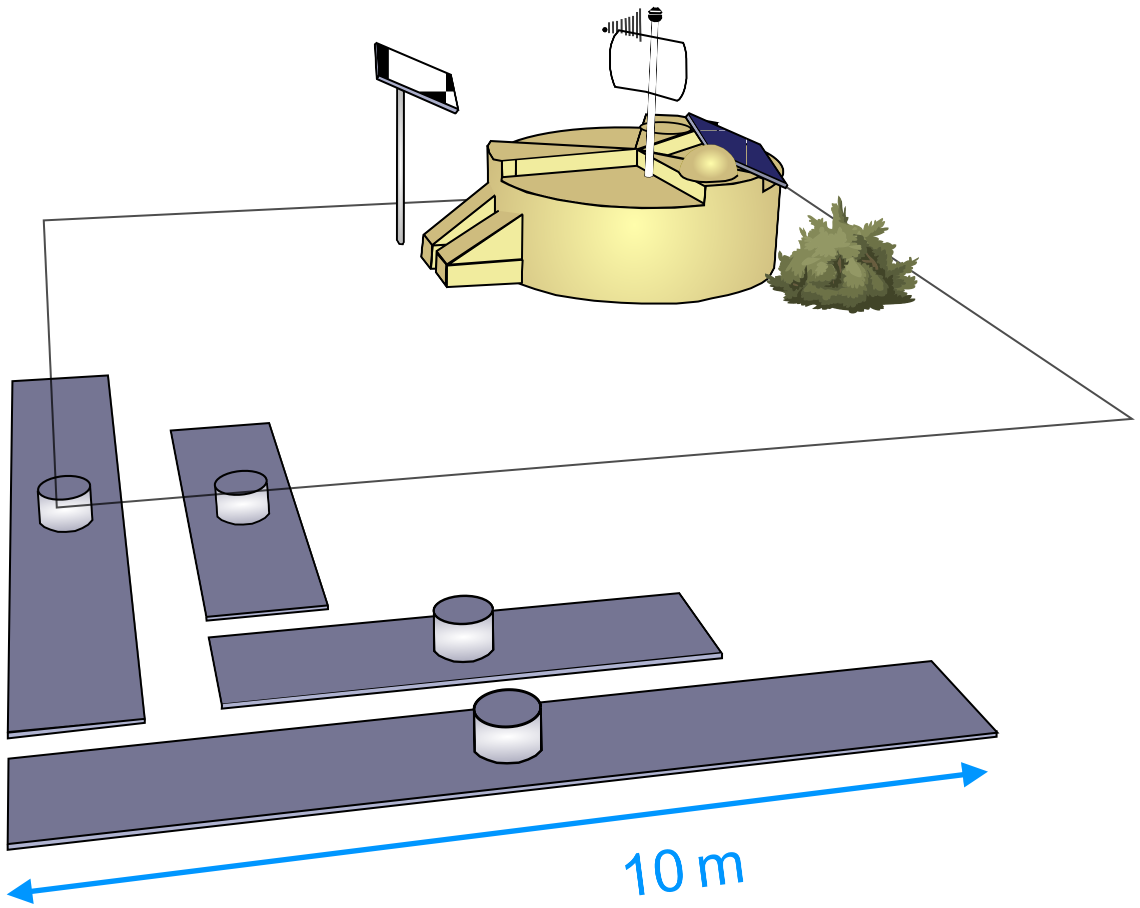
Full detector simulation after re-scaling



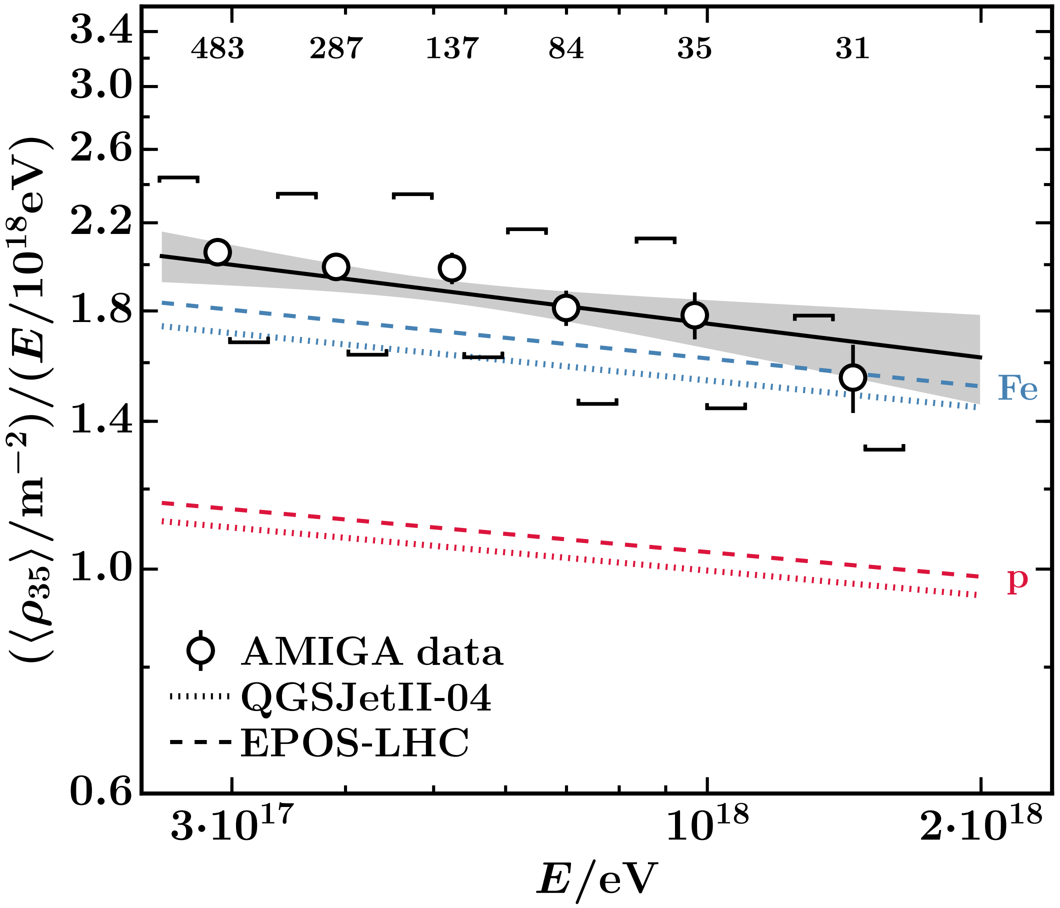
None of the models gives a really good description ?

AugerPrime – buried muon detectors (AMIGA)

- 61 positions
- 30 m² each
- 750 m spacing
- 2.5 m of soil



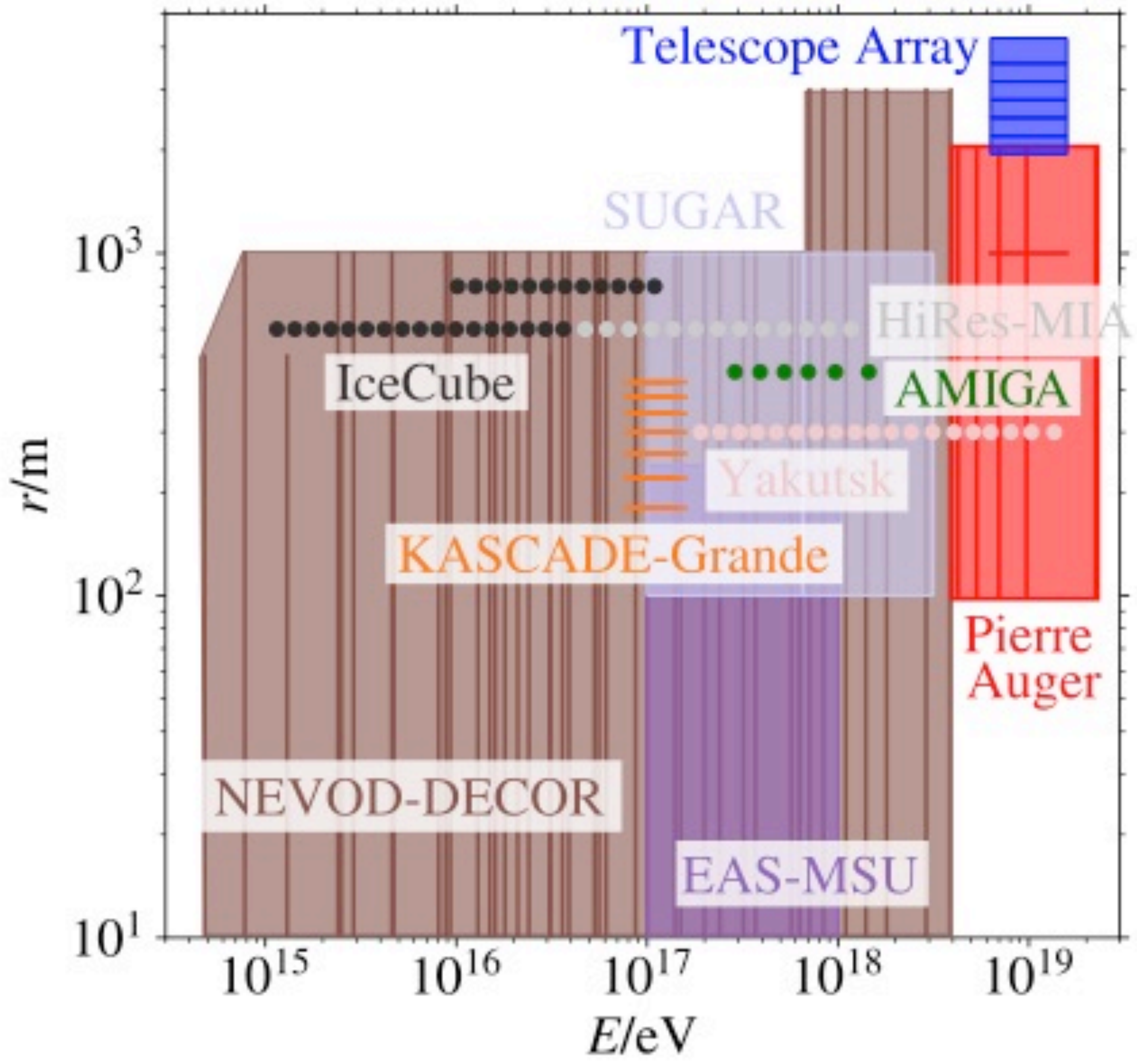
Muon density



Auger, UHECR 2018, Paris

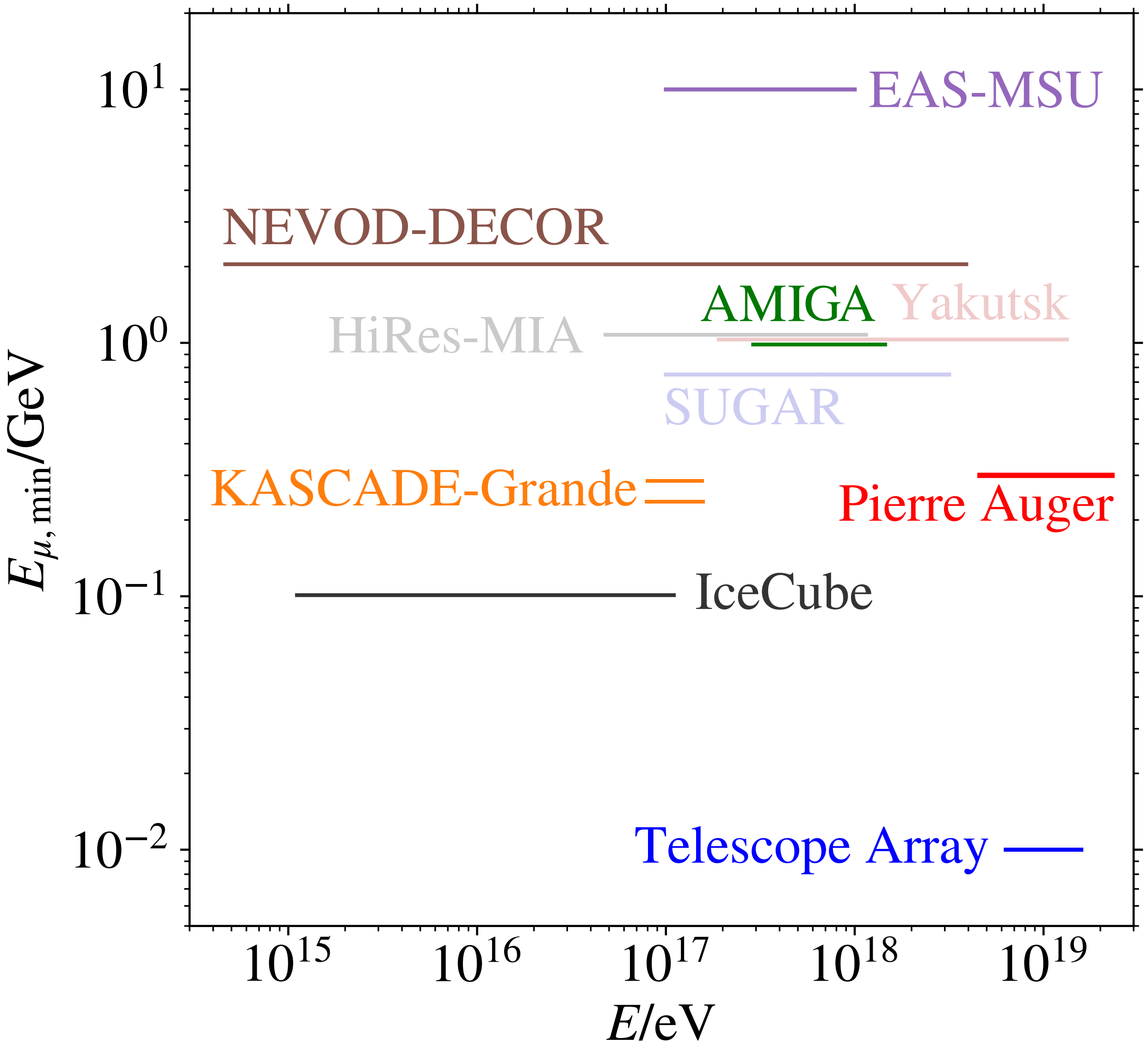
Analysis of world data set on muons (i)

Muon lateral distance



k

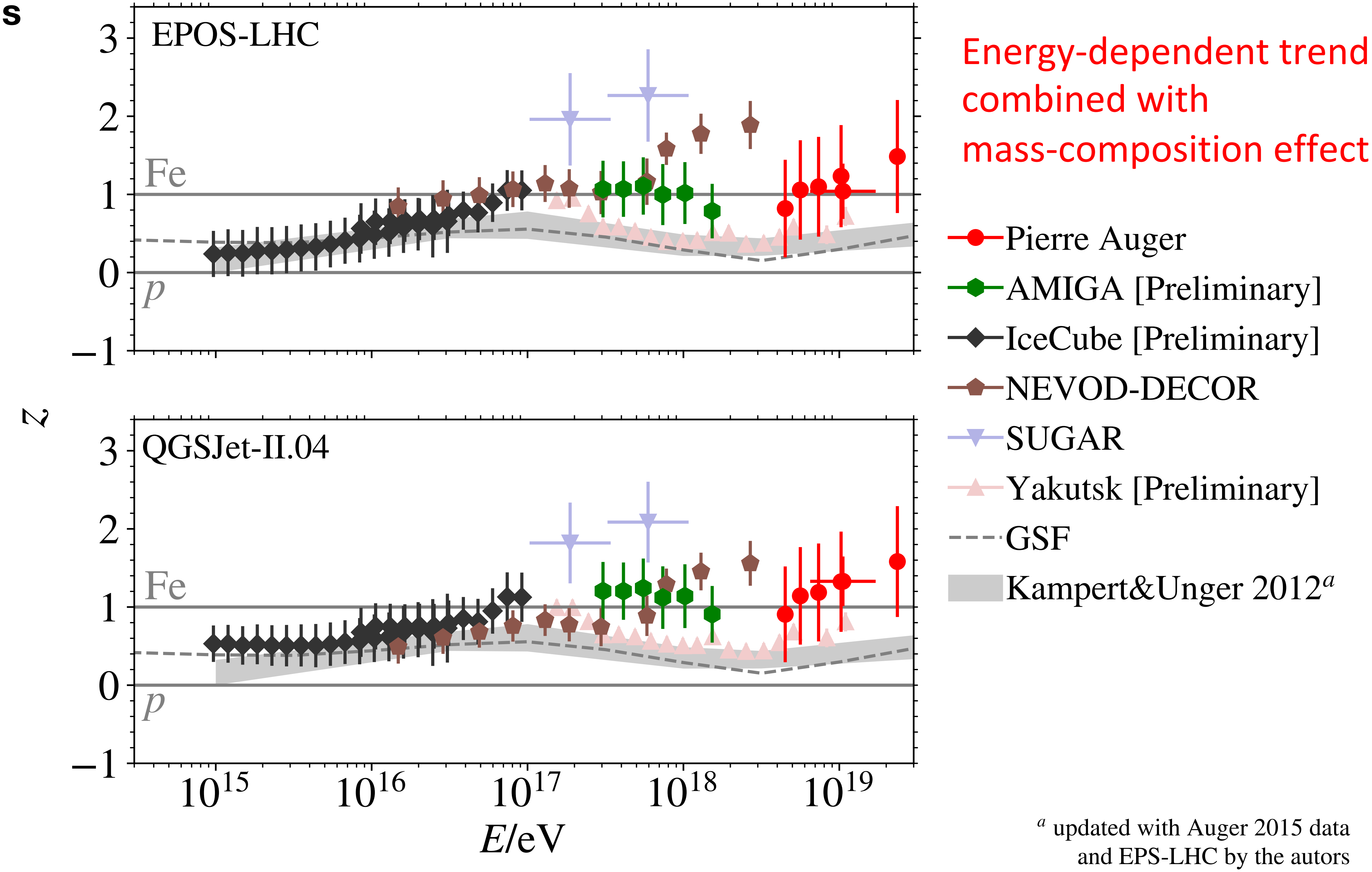
Muon energy threshold



Dembinski et al., Working group, UHECR 2018, Paris

Analysis of world data set on muons (ii)

Scaled number of muons

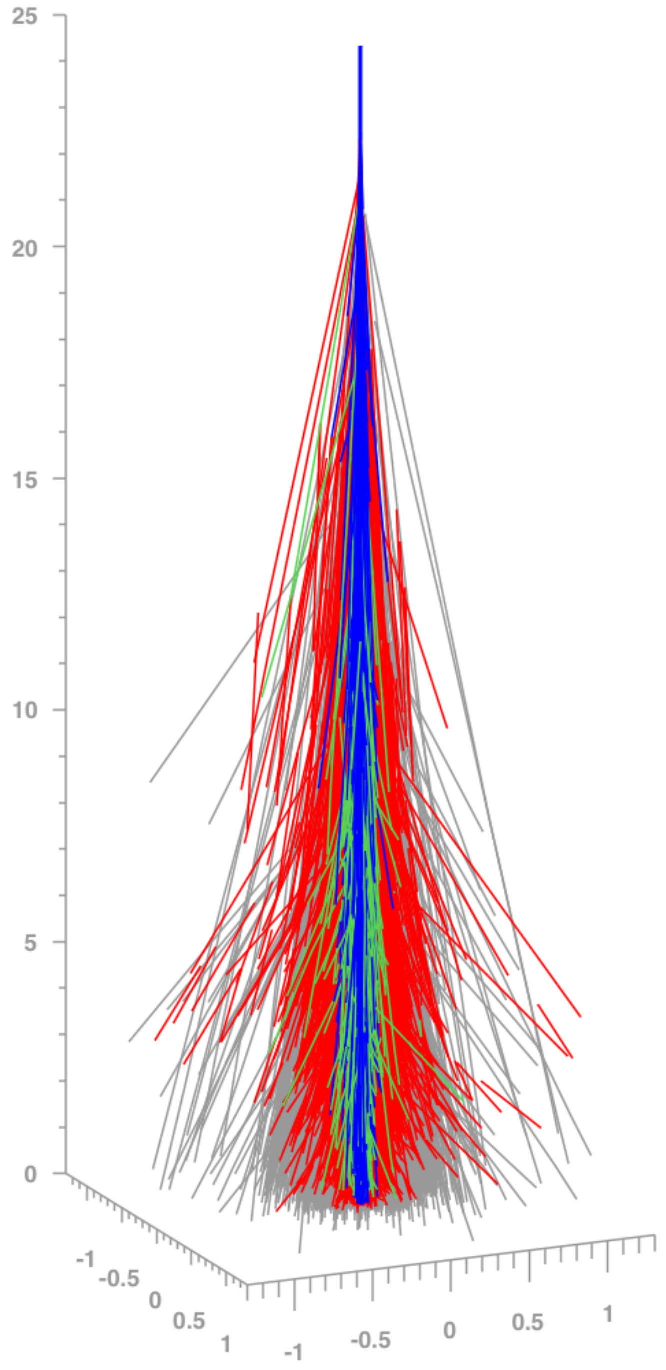


^{a} updated with Auger 2015 data and EPS-LHC by the autors

Energy-dependent trend combined with mass-composition effect

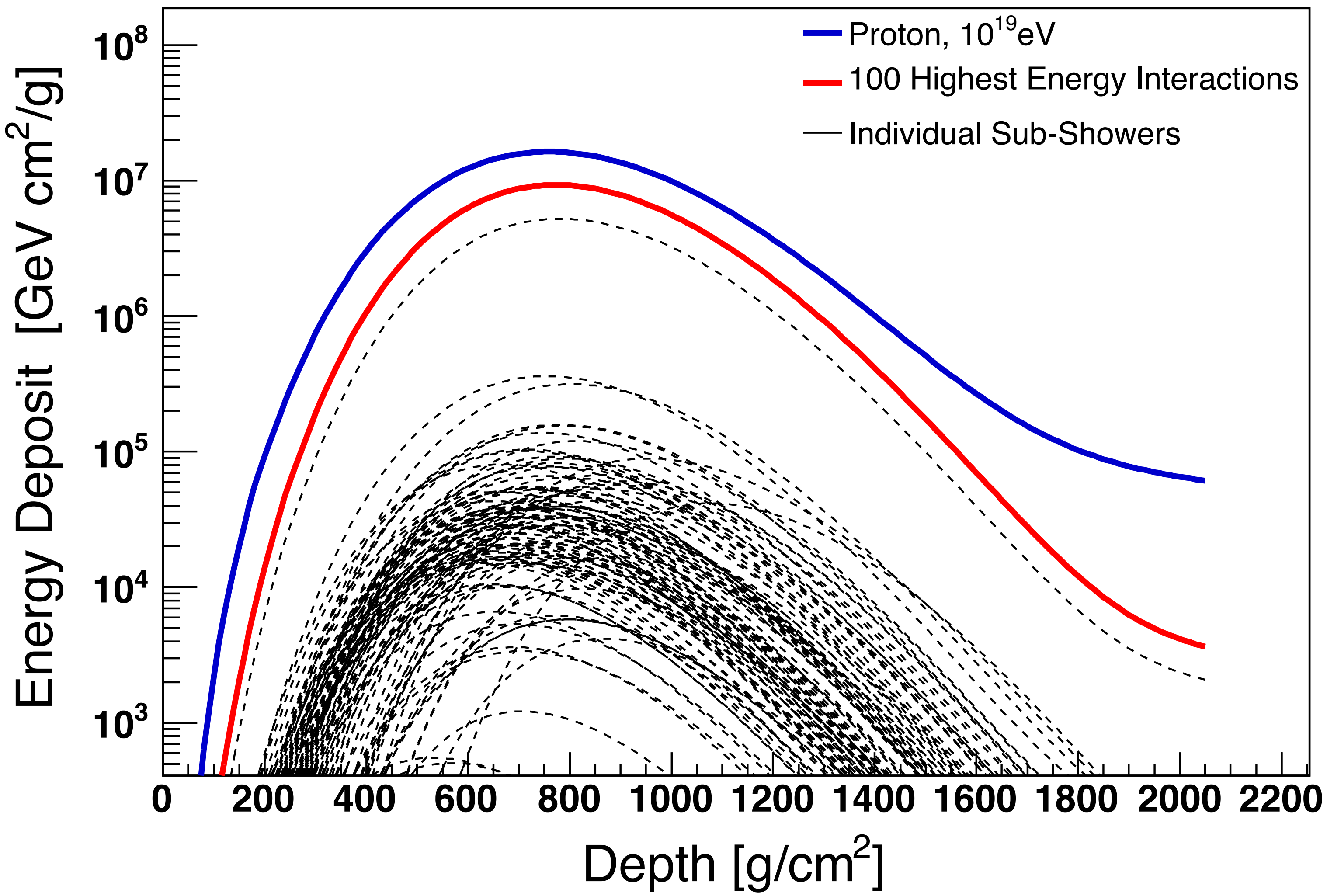
Dembinski et al., Working group, UHECR 2018, Paris

High-energy interactions determine shower maximum



Shower particles produced in 100 interactions of highest energy

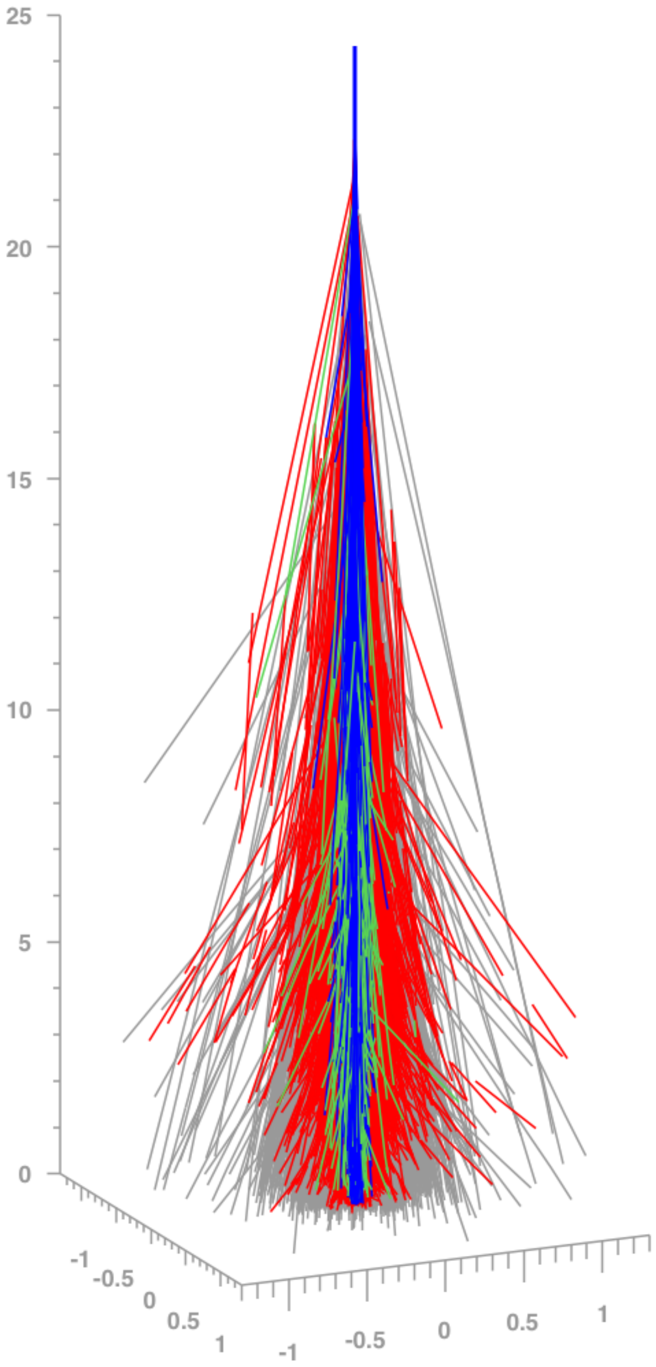
Depth of shower maximum



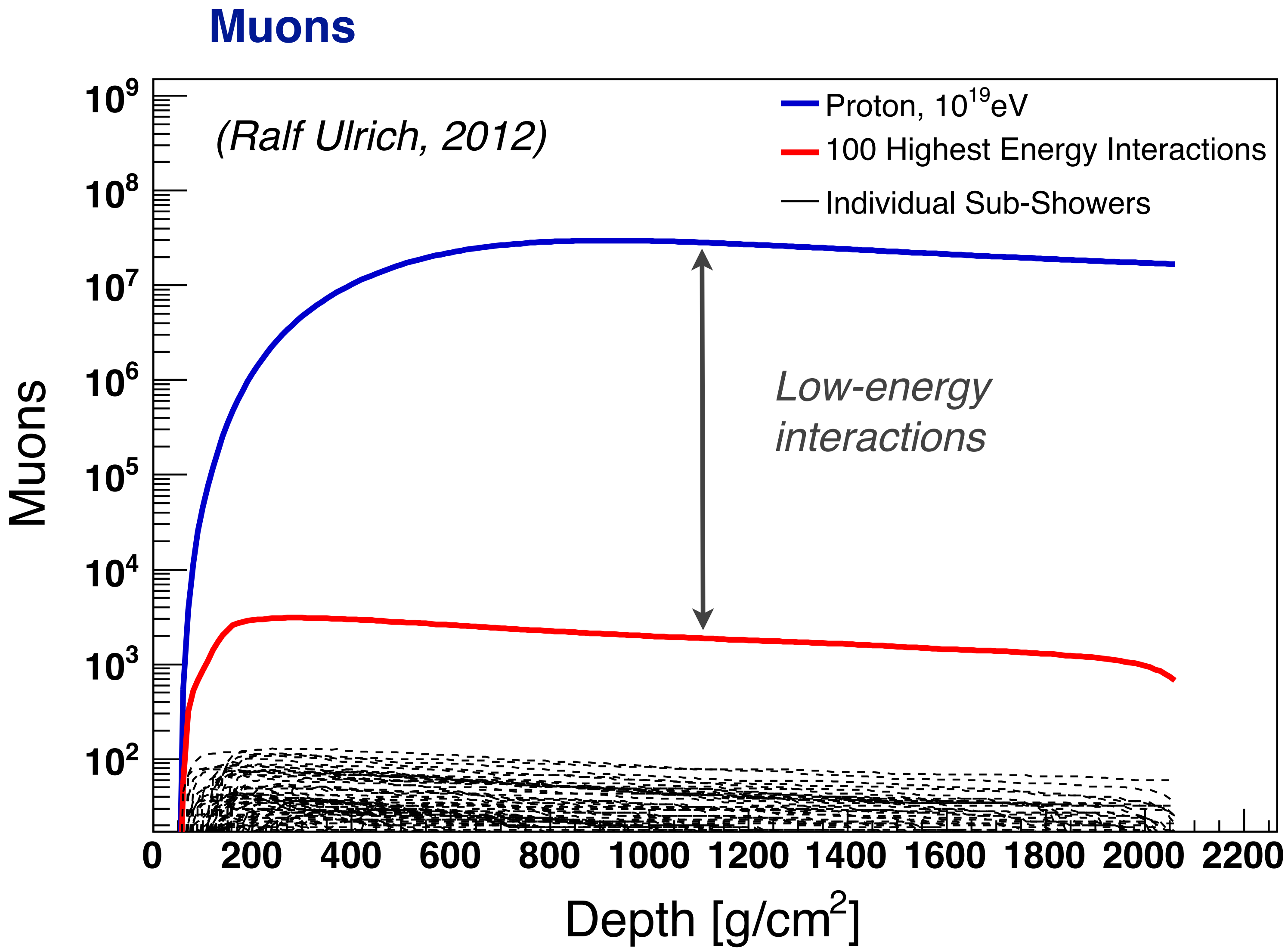
(Ralf Ulrich, 2012)

Electrons/photons: high-energy interactions

Interactions of all energies of relevance to muons



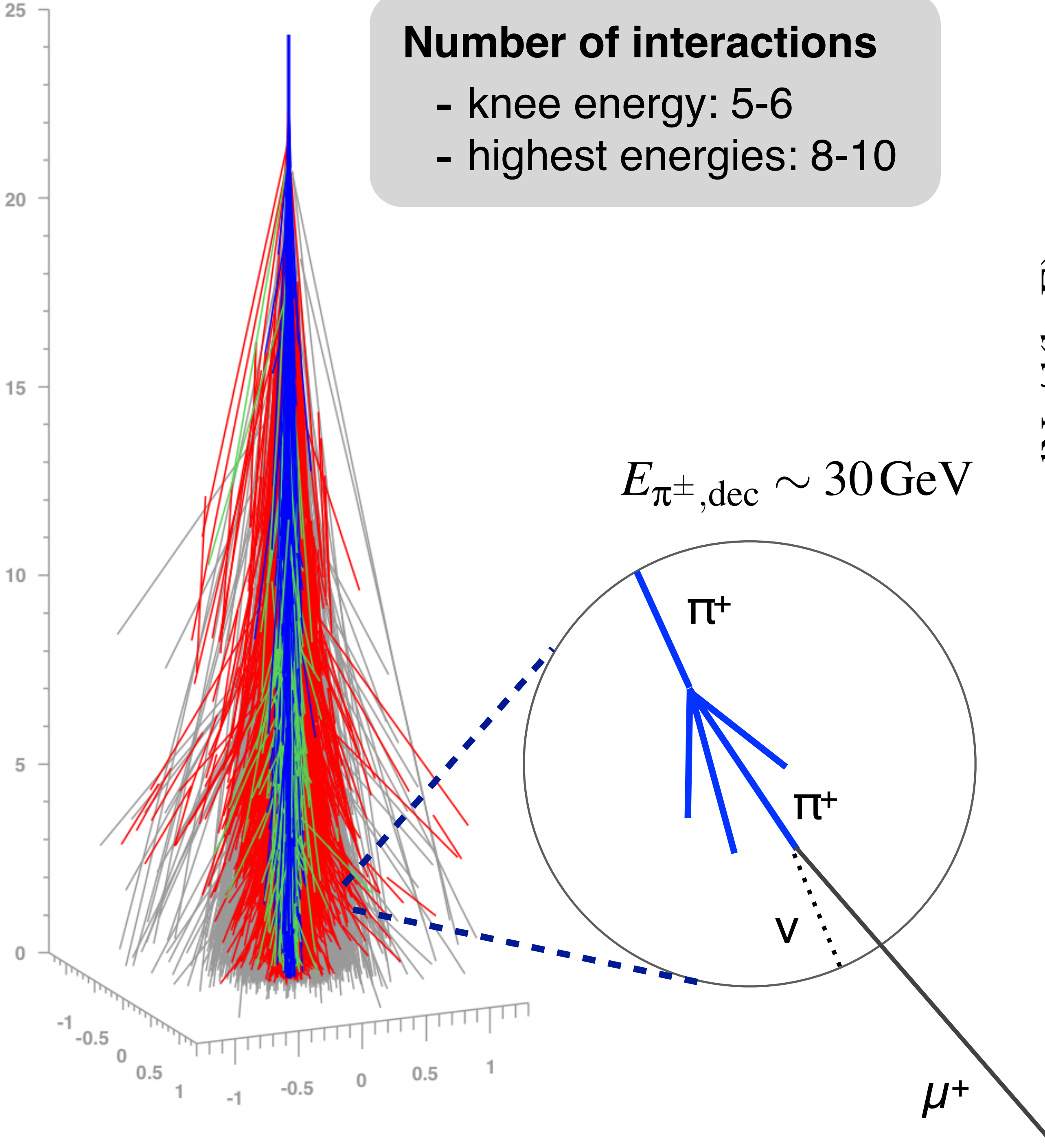
Shower particles produced in 100 interactions of highest energy



Muons/hadrons: high- and low-energy interactions

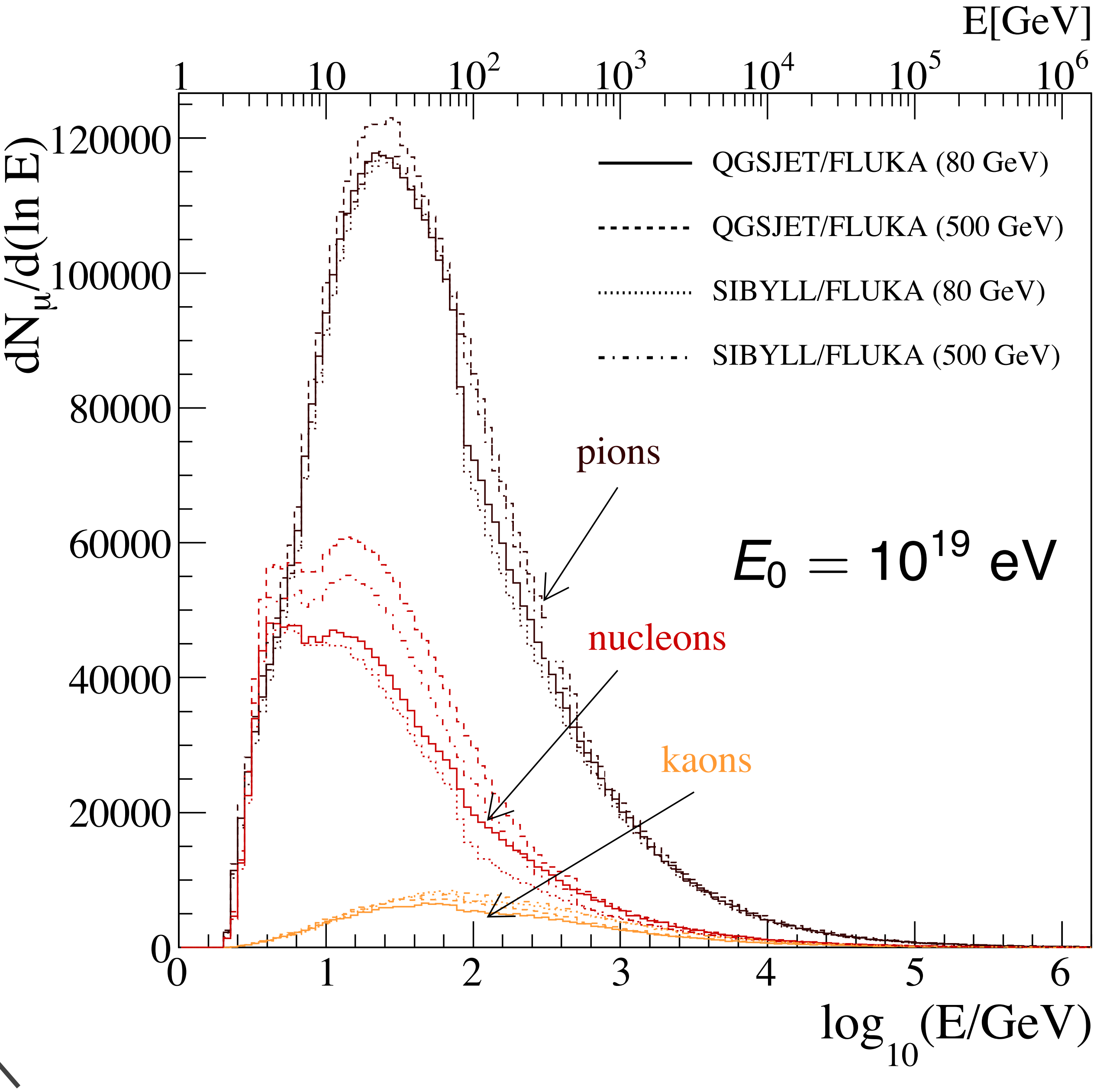
Muon production at large lateral distance

Number of interactions
- knee energy: 5-6
- highest energies: 8-10



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

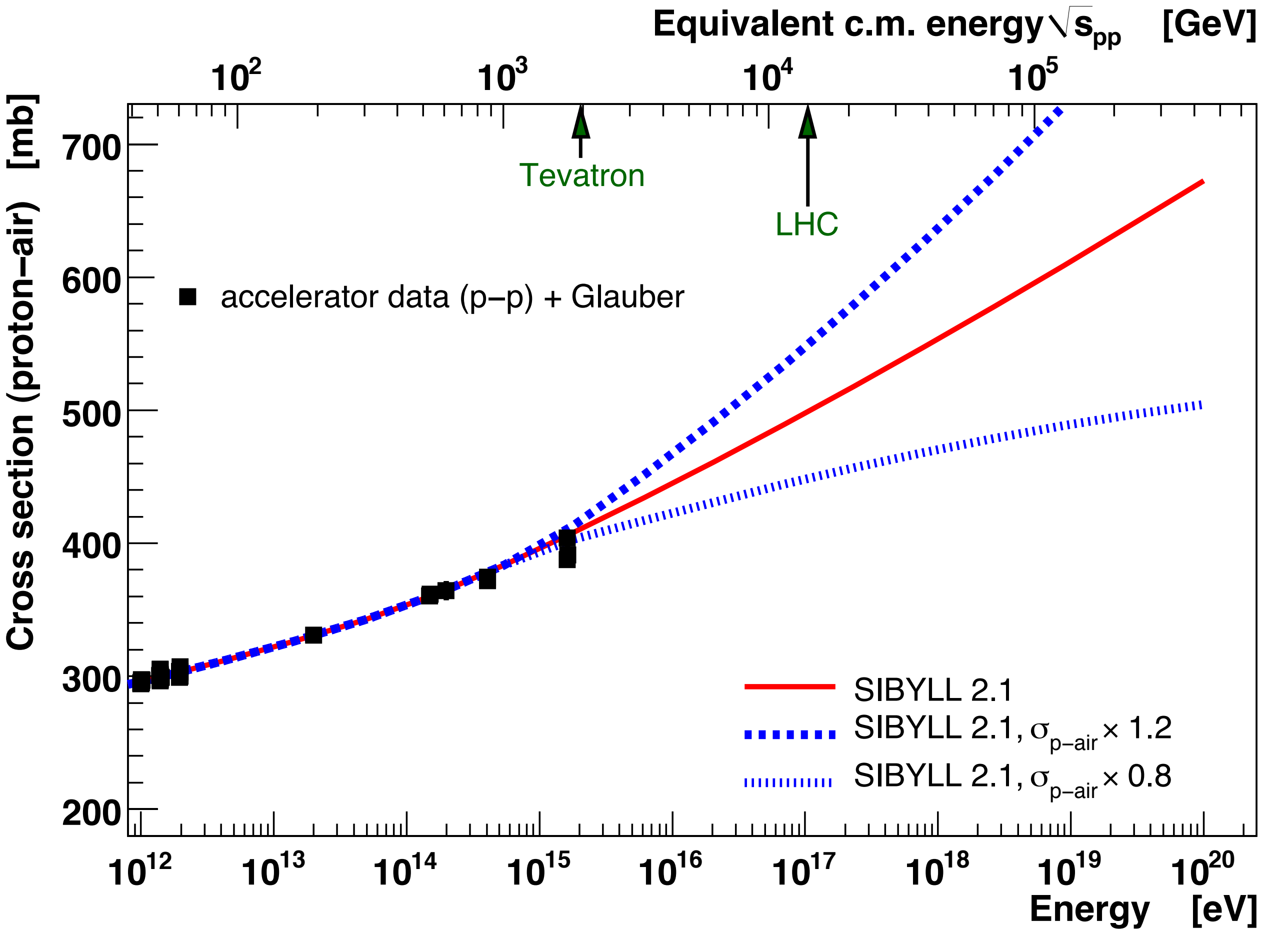
Energy distribution of last interaction
that produced a detected muon



Muon observed at 1000 m from core

(Maris et al. ICRC 2009)

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

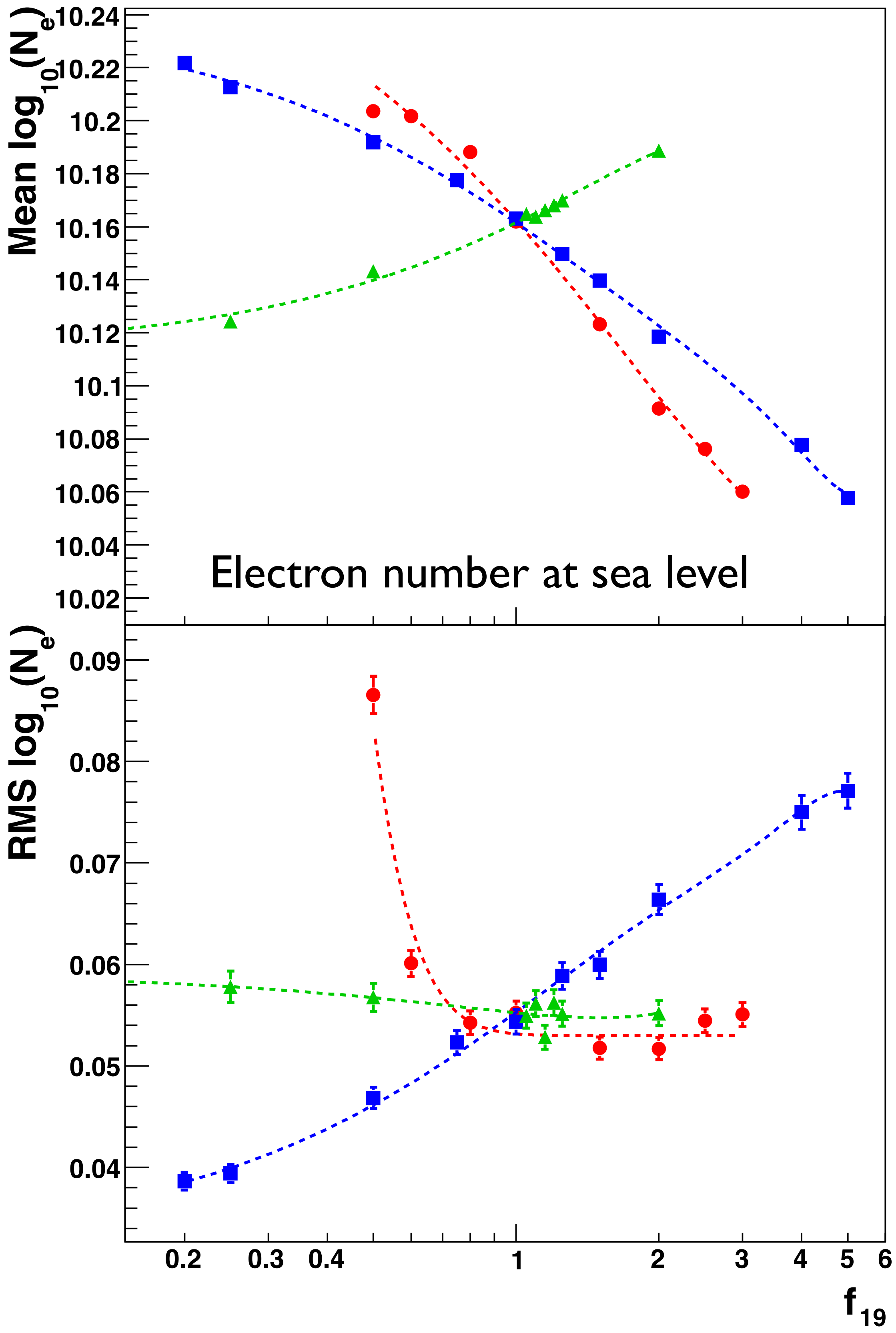
- cross sections (p-air, π-air, K-air)
- secondary particle multiplicity
- elasticity (leading particle)

Implementation

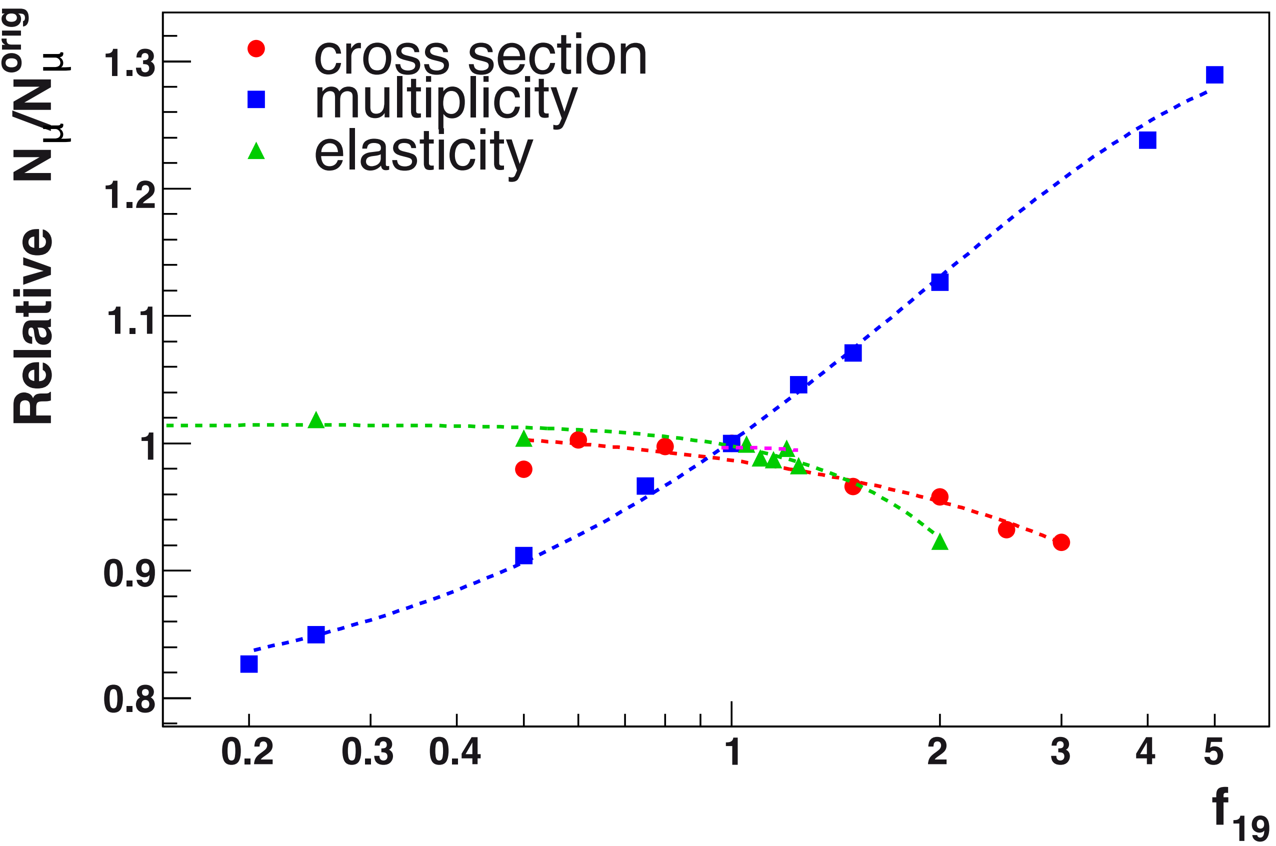
- rescaling after event generation
- separate treatment of leading particle
- conservation of energy and charge
- modified version of CONEX
- available for different interaction models
- shown here for SIBYLL

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

Results for proton showers: Ne, Nμ



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



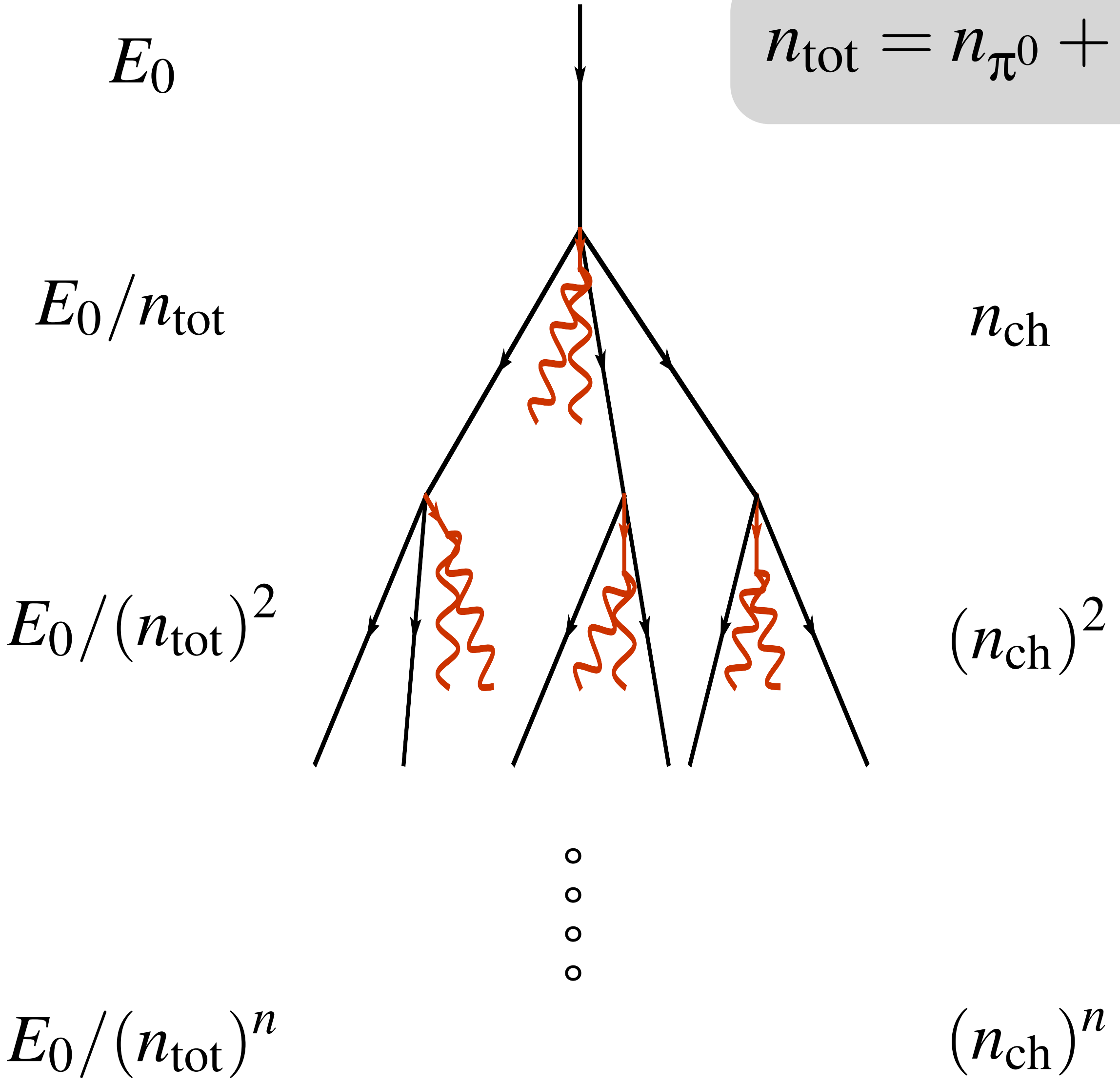
Prediction for ratio of muon numbers for iron/proton showers ~1.4

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

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

Muon production in hadronic showers

$$n_{\text{tot}} = n_{\pi^0} + n_{\text{ch}}$$



Primary particle proton

π^0 decay immediately

$\pi^\pm$ initiate new cascades

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

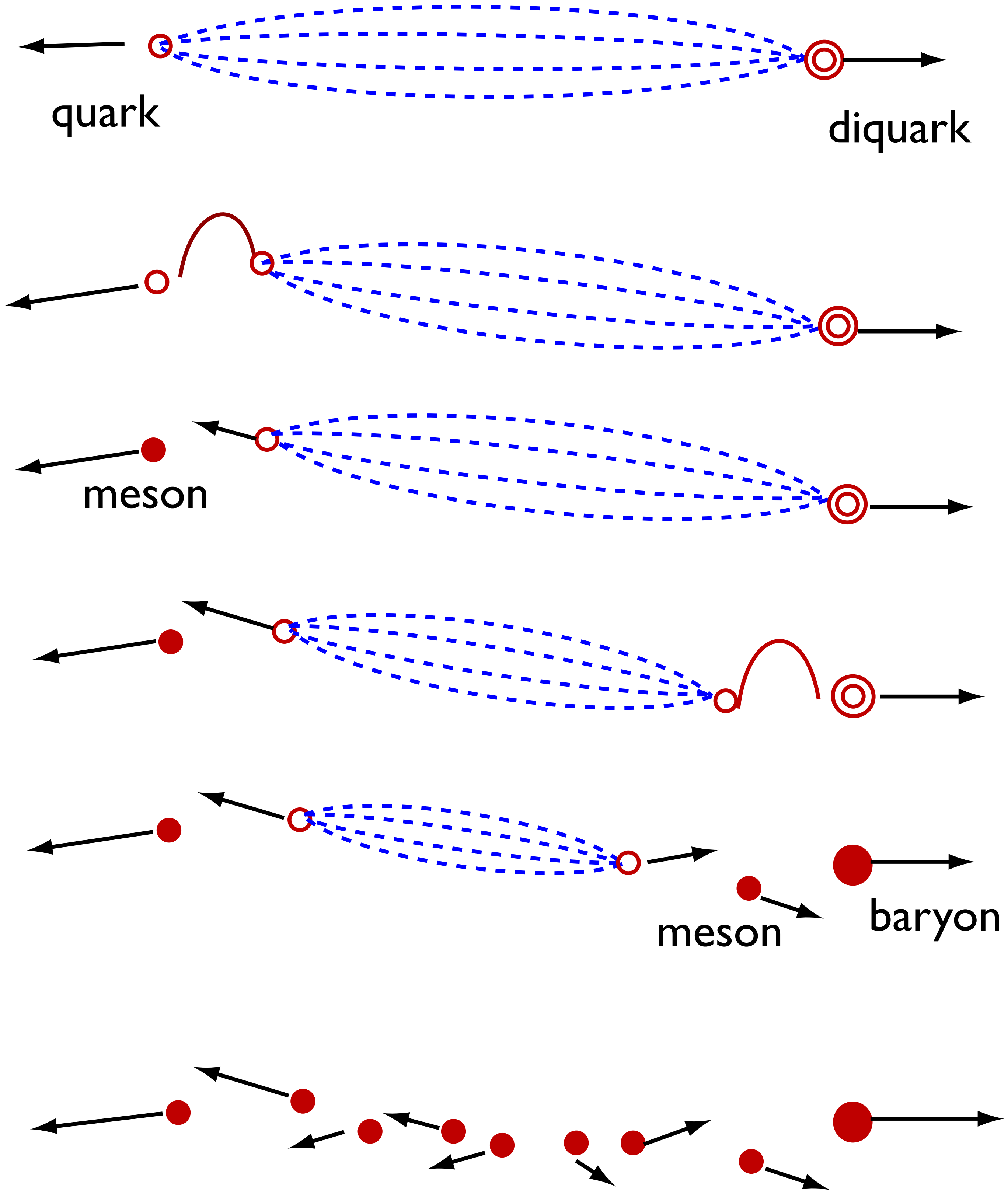
$$\alpha = \frac{\ln n_{\text{ch}}}{\ln n_{\text{tot}}} \approx 0.82 \ldots 0.95$$

Assumptions:

- cascade stops at $E_{\text{part}} = E_{\text{dec}}$
- each hadron produces one muon

(Matthews, Astropart.Phys. 22, 2005)

Modification of ratio of neutral to charged pions

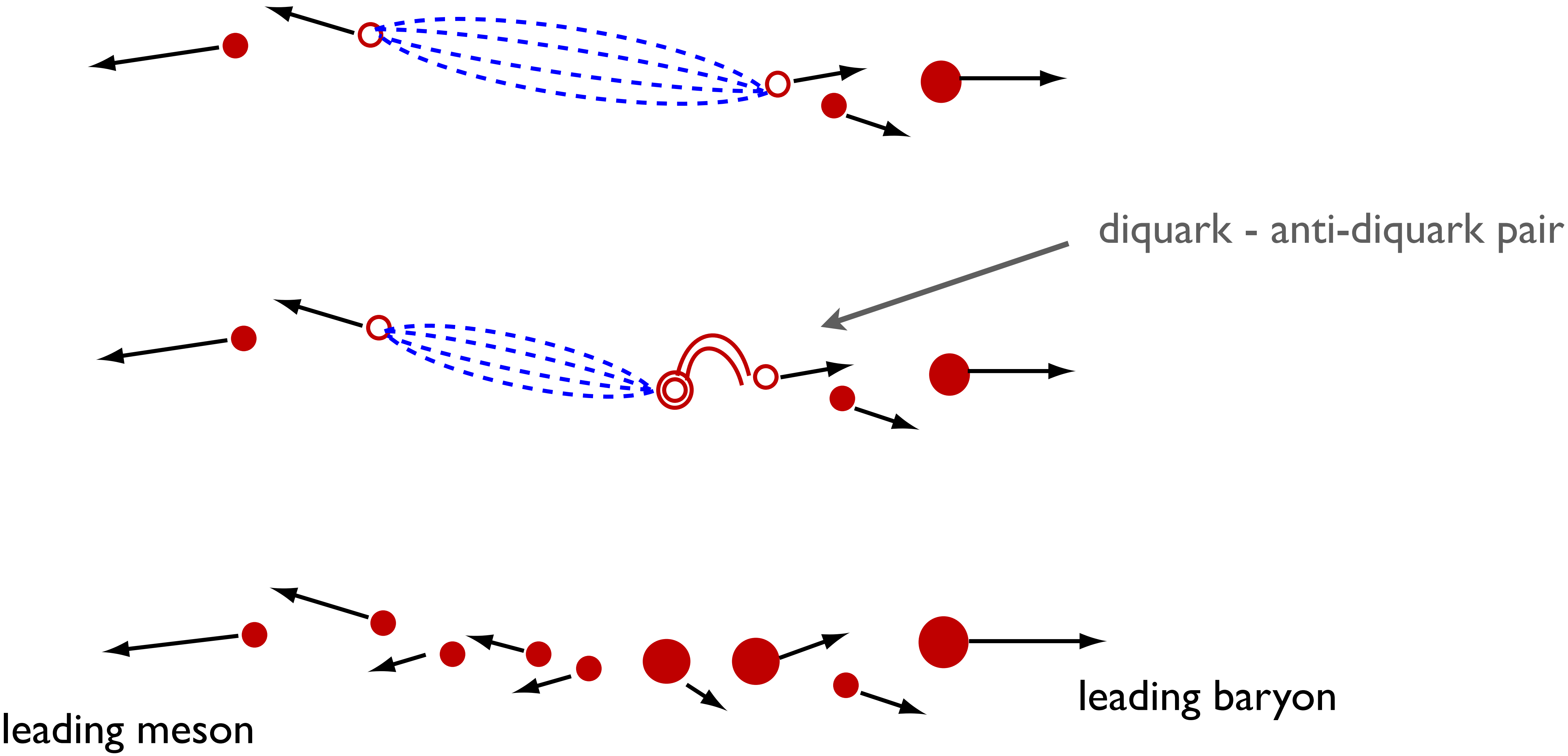


$$N_\mu = \left(\frac{E_0}{E_\text{dec}}\right)^\alpha$$

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

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

String fragmentation: baryon pairs



diquark - anti-diquark pair

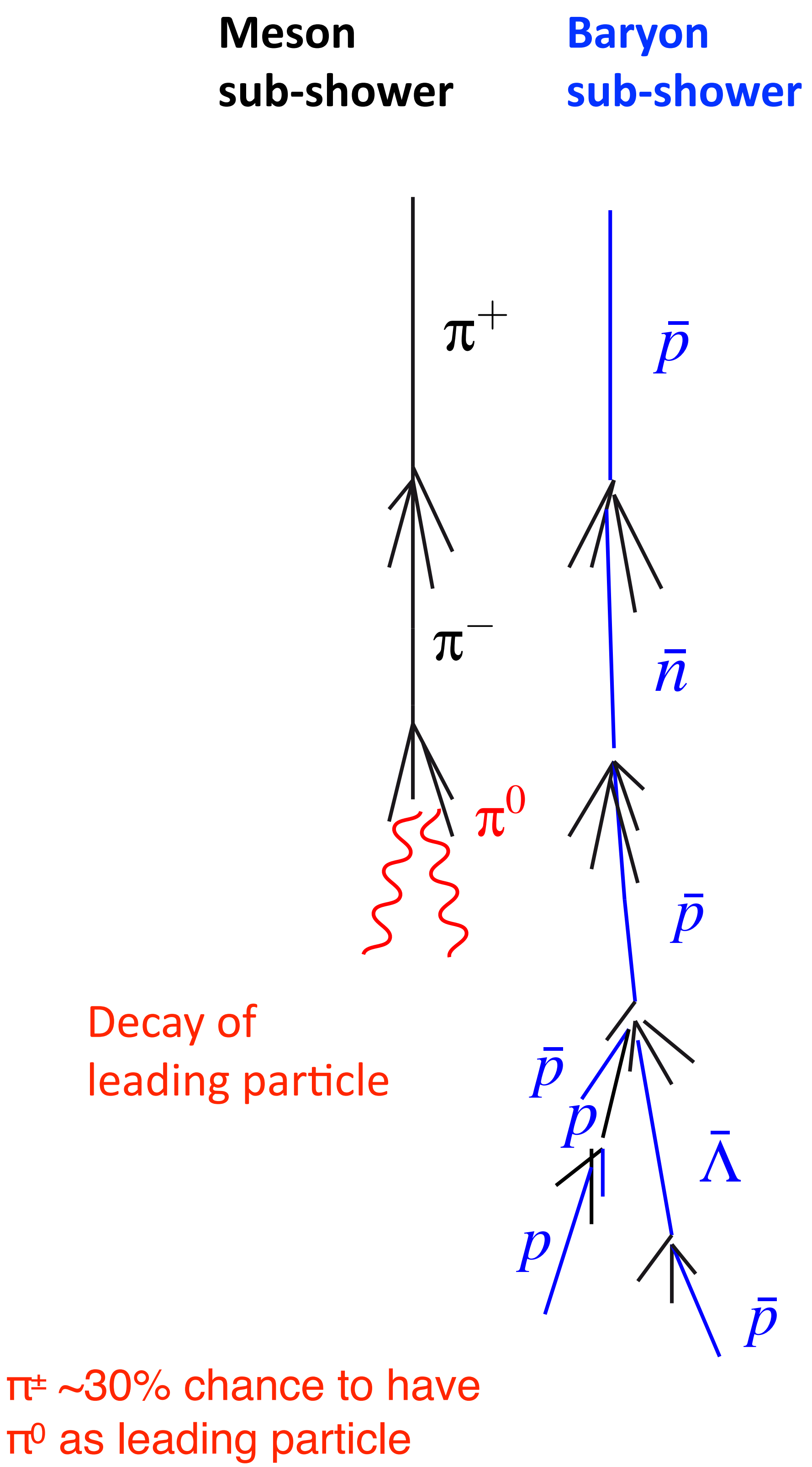
leading meson

leading baryon

Baryon number conservation !

(Grieder, ICRC 1971)

Muon production and hadronic energy flow



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

(Grieder ICRC 1973; Pierog, Werner PRL 101, 2008)

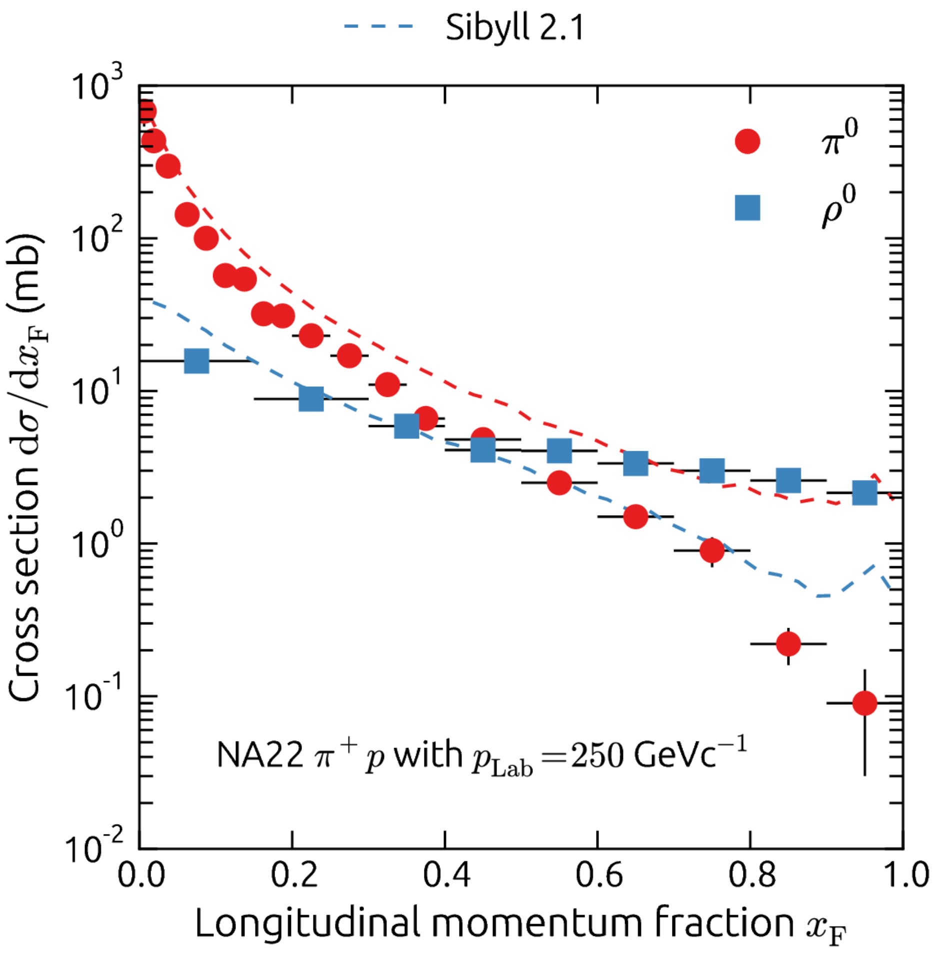
2 Leading particle effect for pions *(Drescher 2007, Ostapchenko 2014)*

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

3 New hadronic physics at high energy *(Farrar, Allen 2012)*

- Inhibition of π^0 decay (Lorentz invariance violation etc.)
- Chiral symmetry restauration

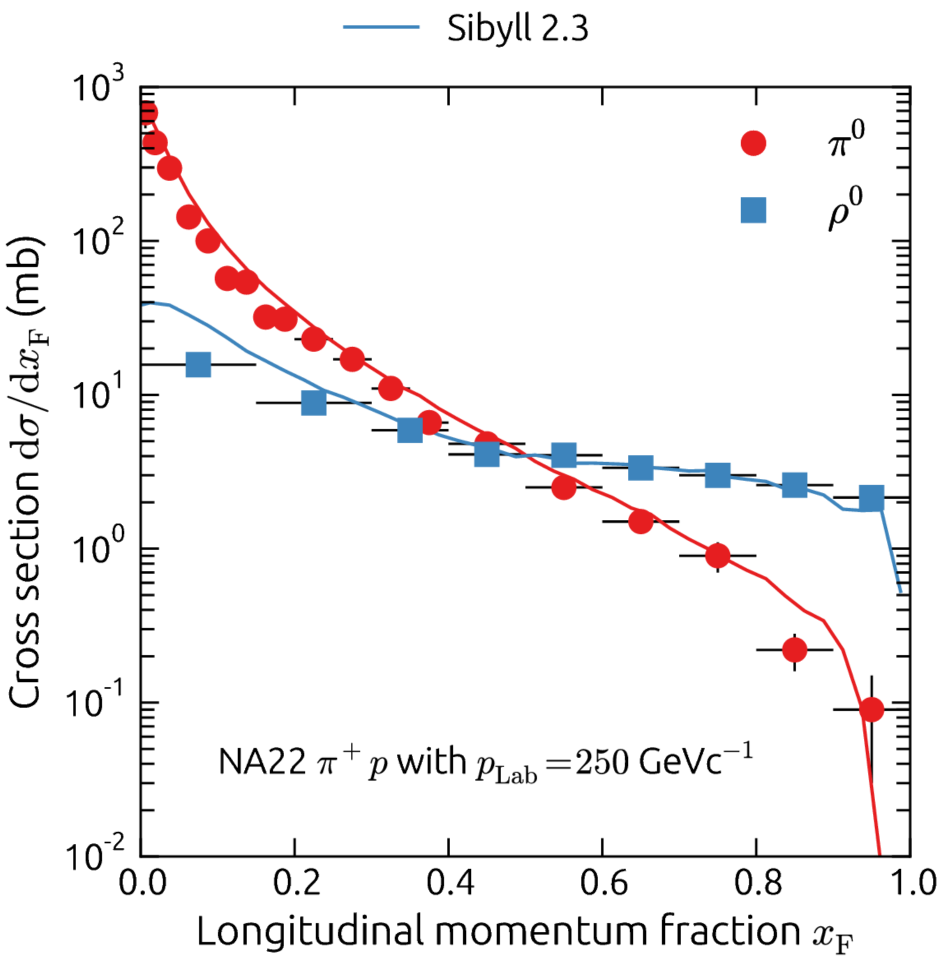
Rho production in π-p interactions (Sibyll 2.1 → Sibyll 2.3)



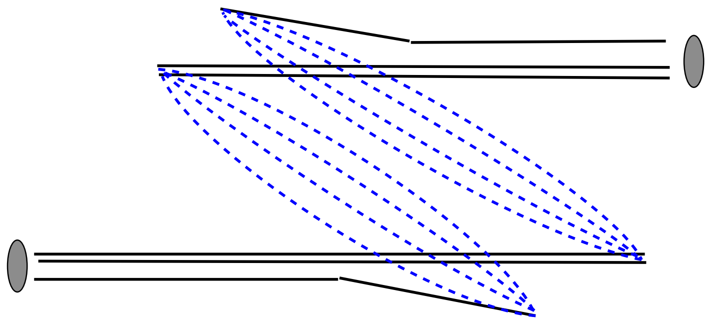
$$\pi^+ p \rightarrow \pi^0 \rightarrow 2\gamma$$

$$\pi^+ p \rightarrow \rho^0 \rightarrow \pi^+ \pi^-$$

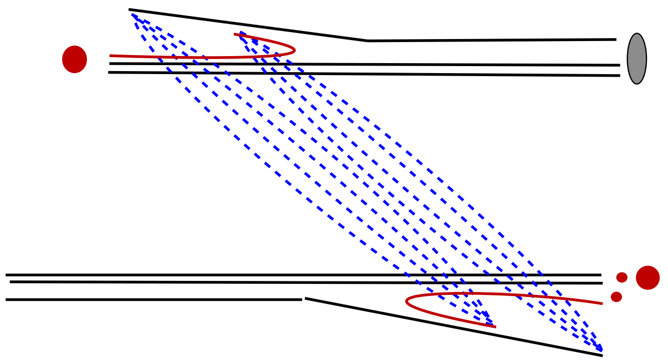
$$E_{\mathrm{lab}} = 250\,\mathrm{GeV}$$



$$x_F = p_\parallel / p_{\max}$$



$$R_{\rho^0}/R_{\pi^0} = 0.3$$

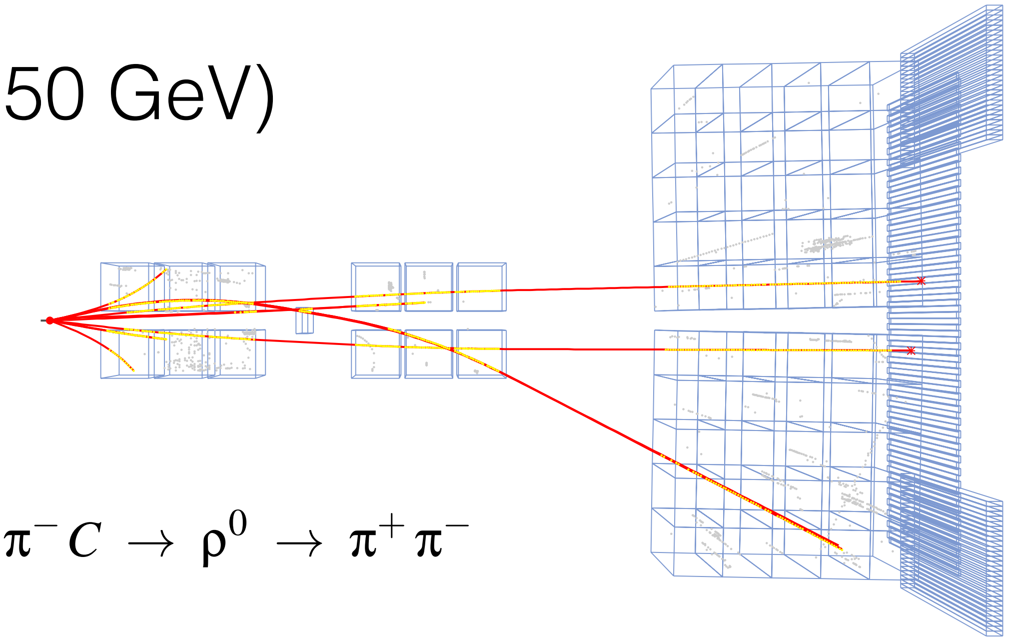


$$R_{\rho^0}/R_{\pi^0} = f(x_F)$$

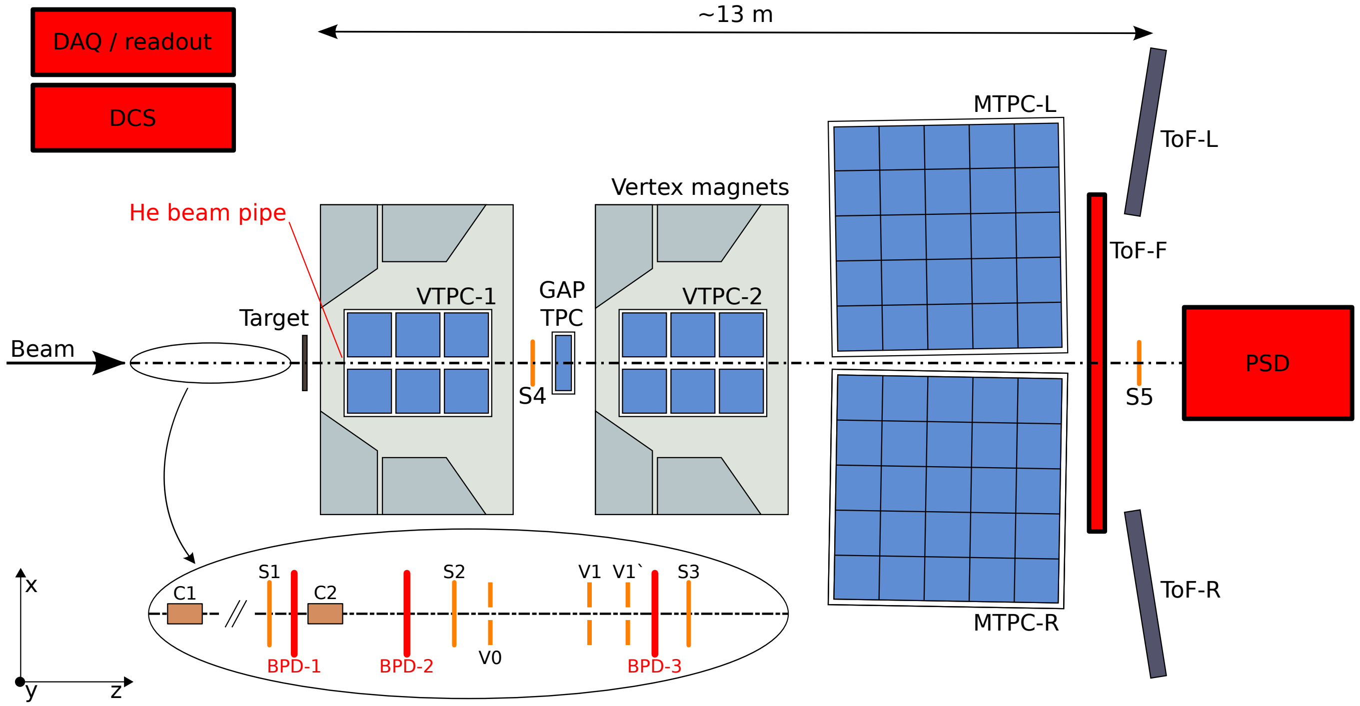
(Riehn et al., ICRC 2015)

NA61 experiment at CERN SPS

Dedicated cosmic ray runs (π-C at 158 and 350 GeV)

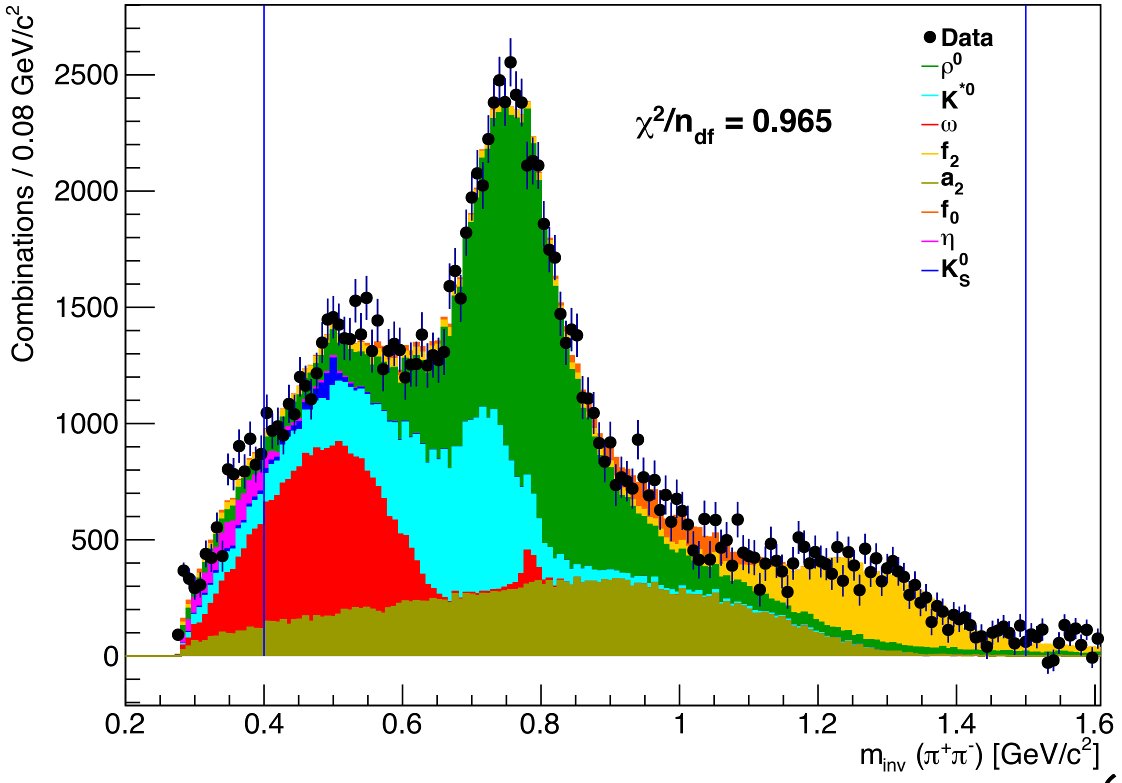


$\pi^- C \rightarrow \rho^0 \rightarrow \pi^+ \pi^-$



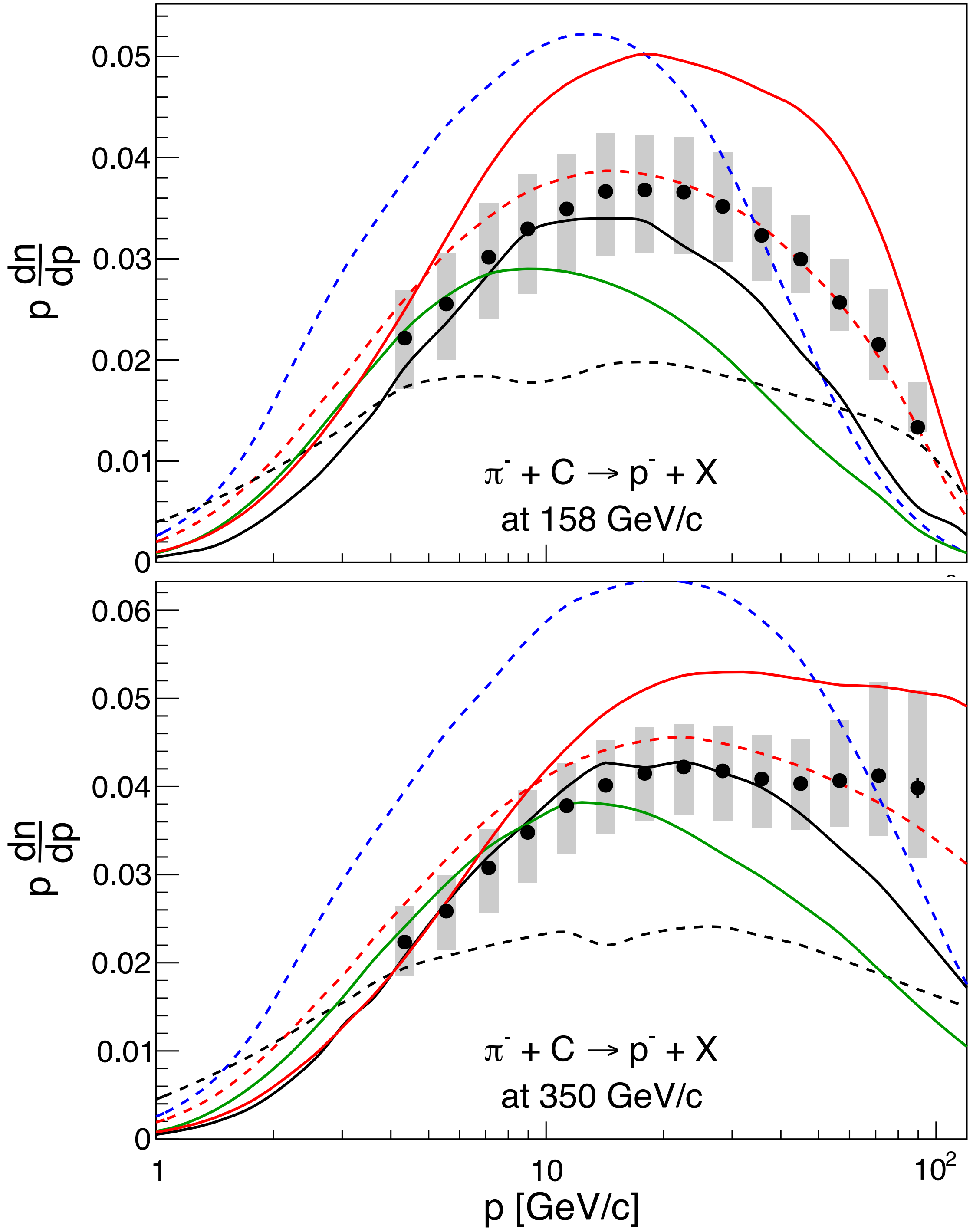
(former NA49 detector, extended)

Invariant mass of two charged tracks

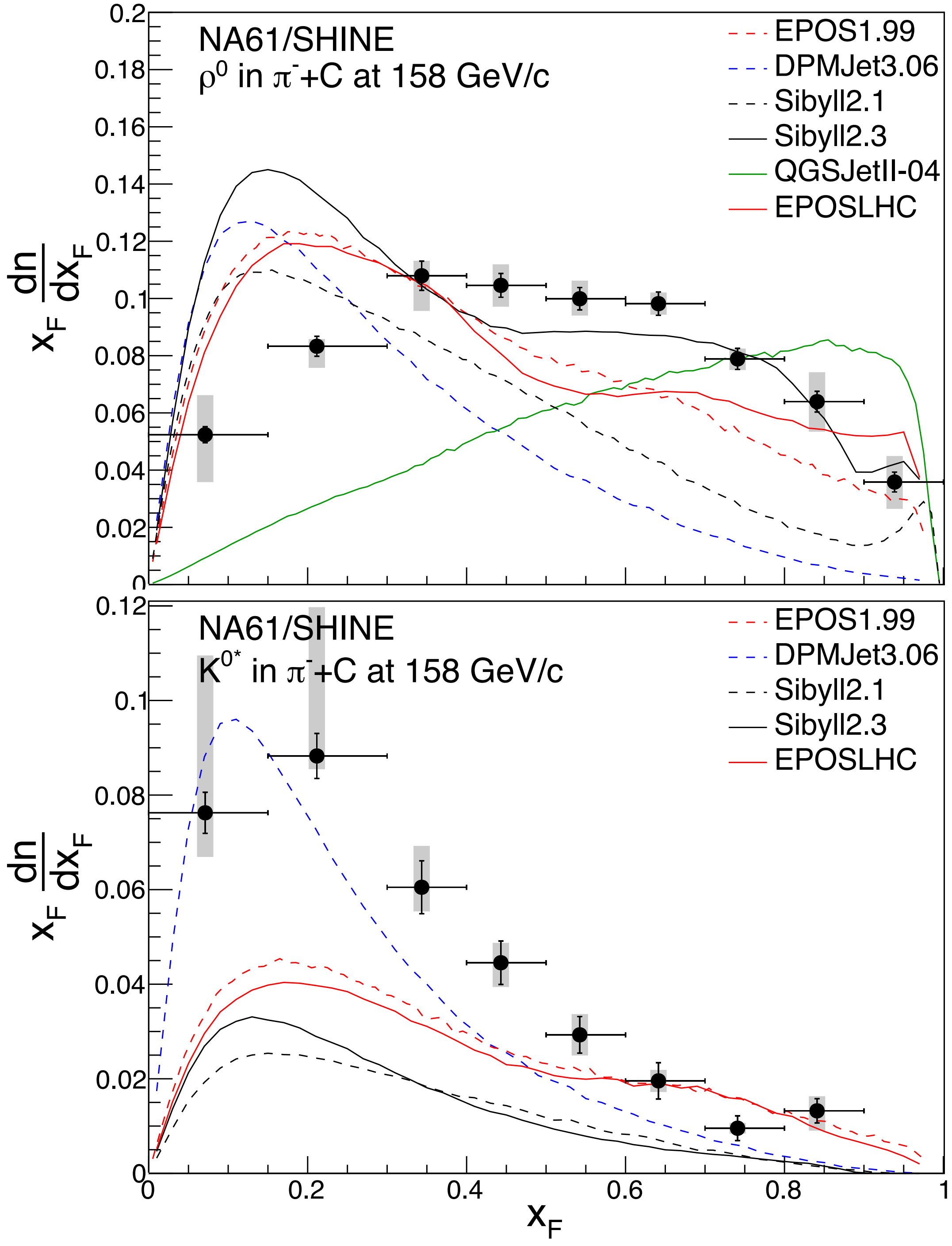


Some NA61 results

antiproton production

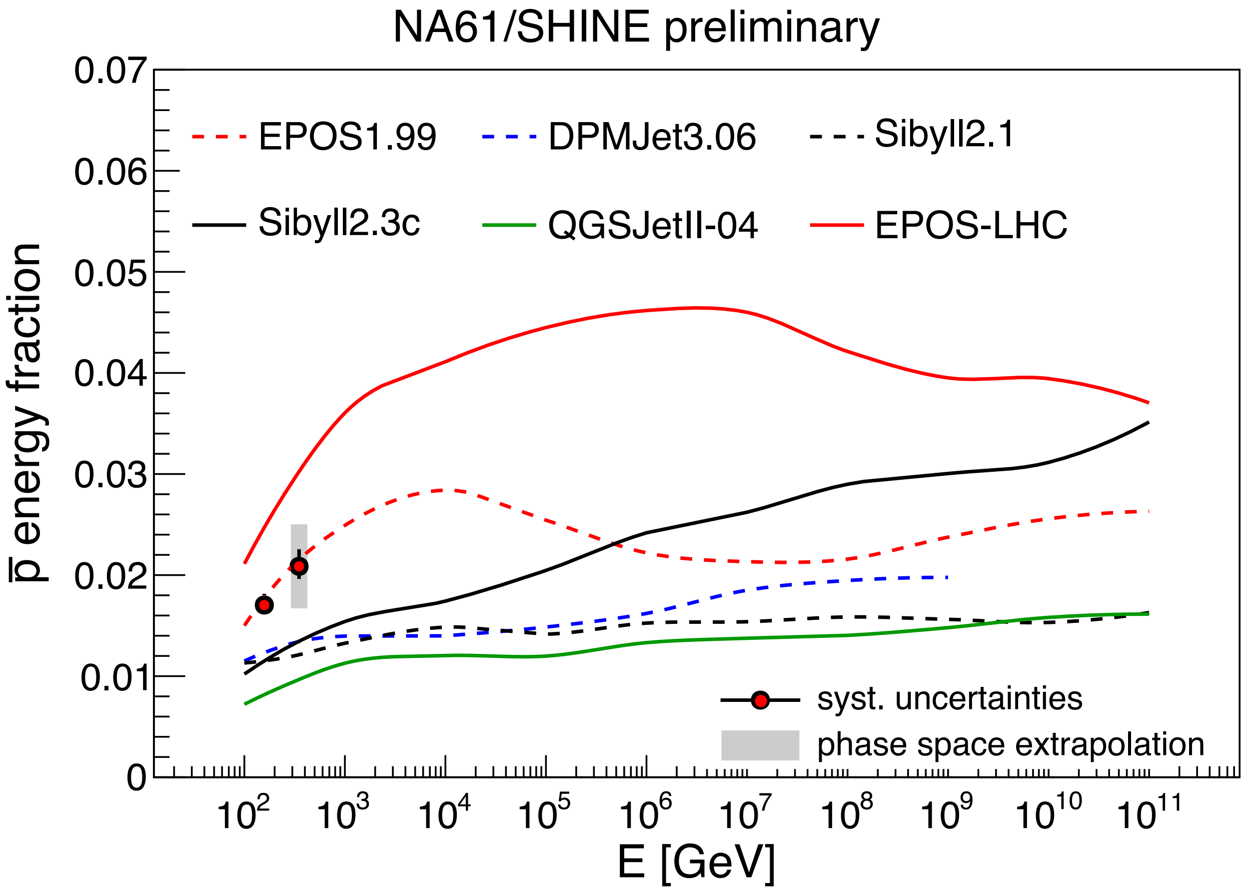


rho-0 production

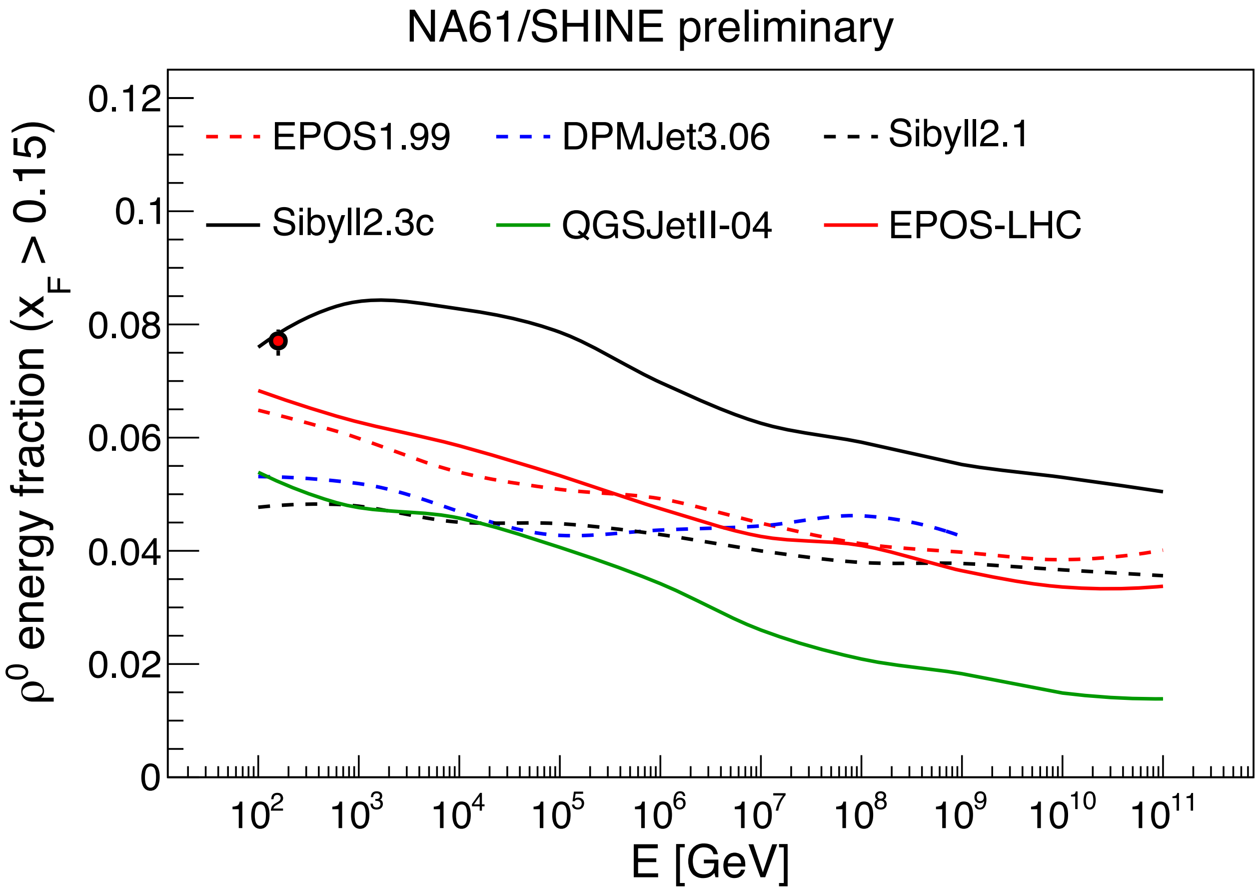


(Prado ICRC 2017, EPJ 2016)

NA61 results and extrapolation to high energy



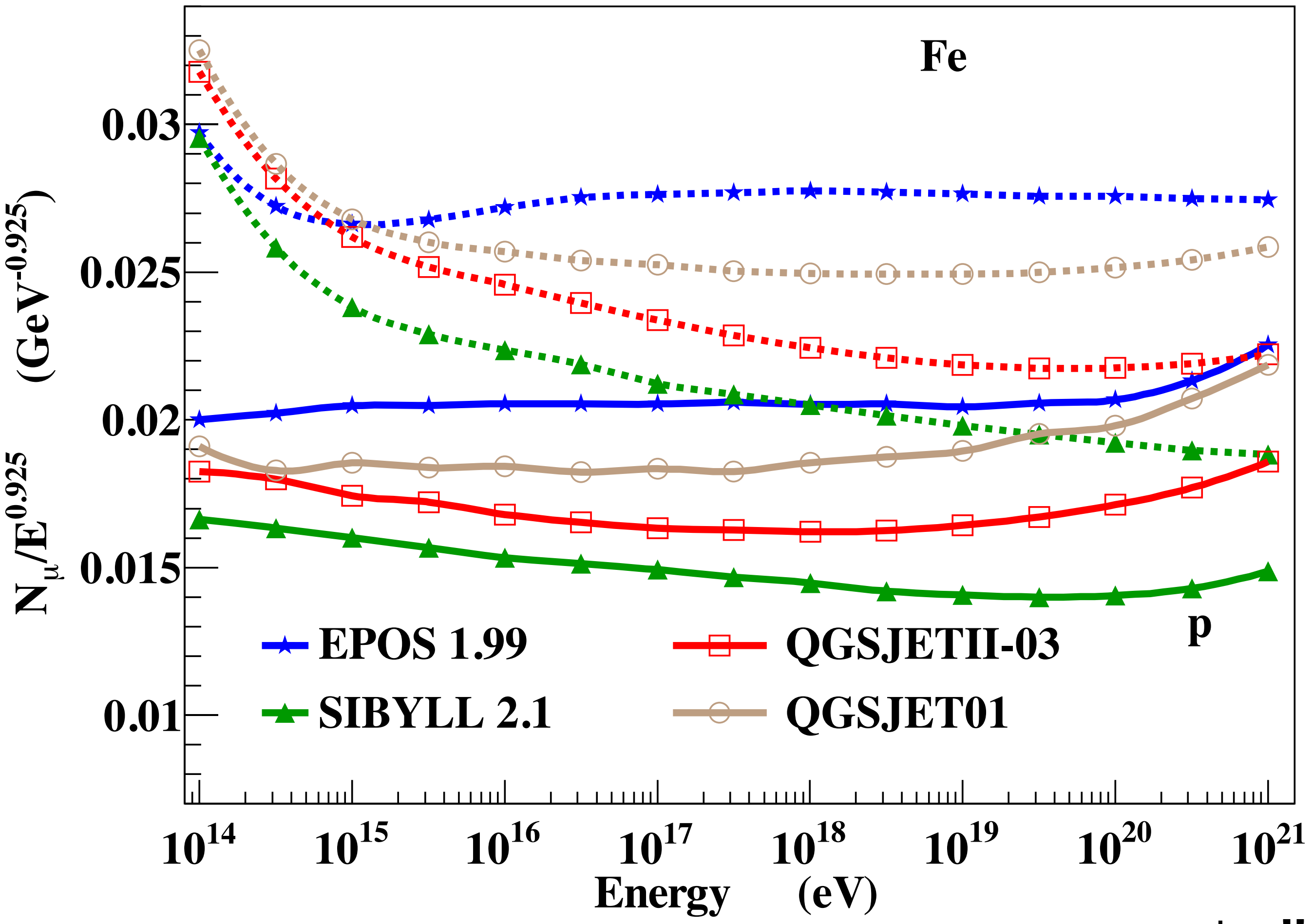
p̄ energy fraction in π^-+C



ρ^0 energy fraction in π^-+C

(Prado, NA61, ICRC 2017)

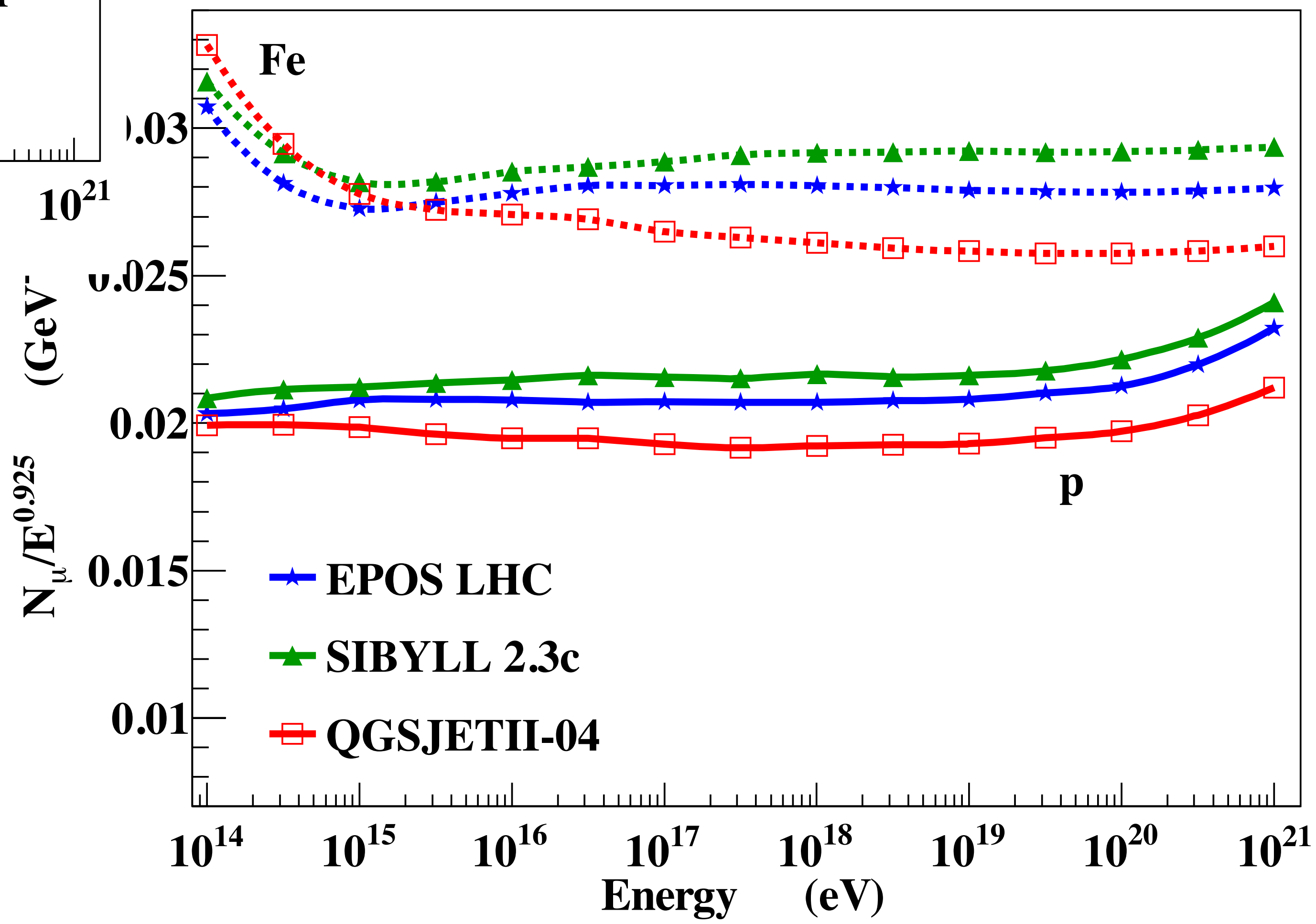
Predictions for muon number at ground (updated)



pre-LHC models

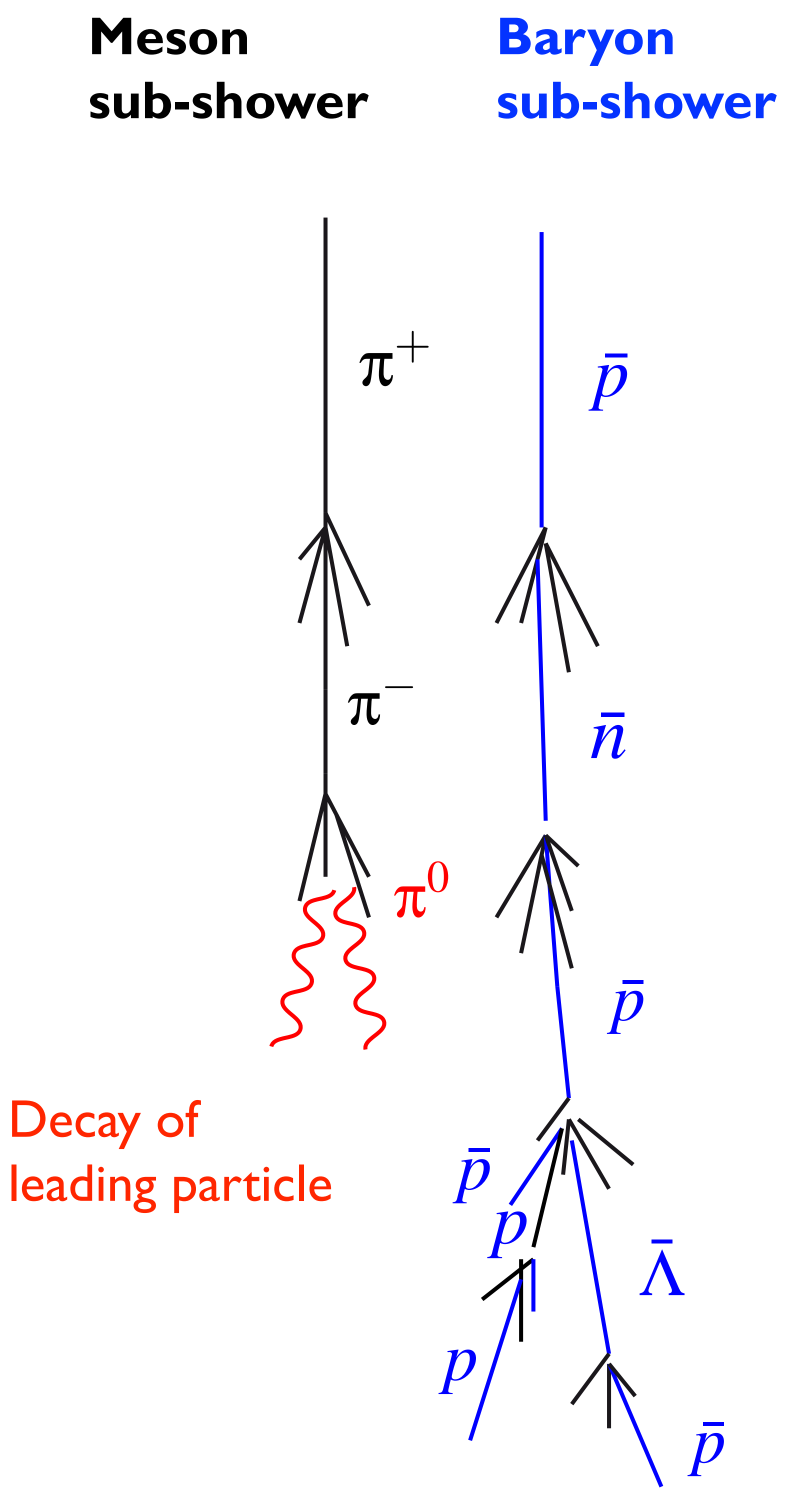
(Pierog 2017)

post-LHC models



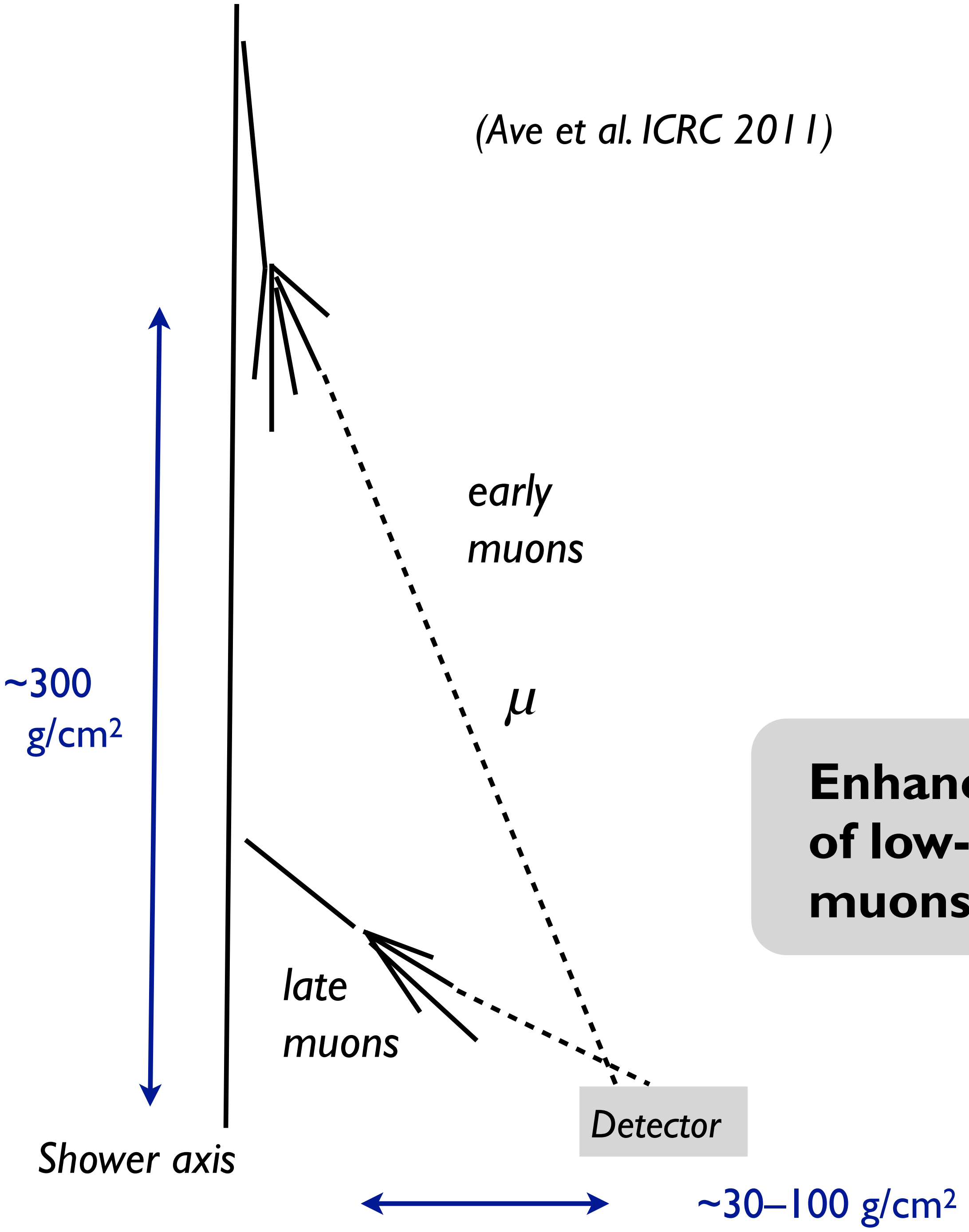
New models favour interpretation as lighter composition than before

Baryon pairs: enhancement of low-energy muons



EPOS

(Pierog, Werner PRL 101, 2008)

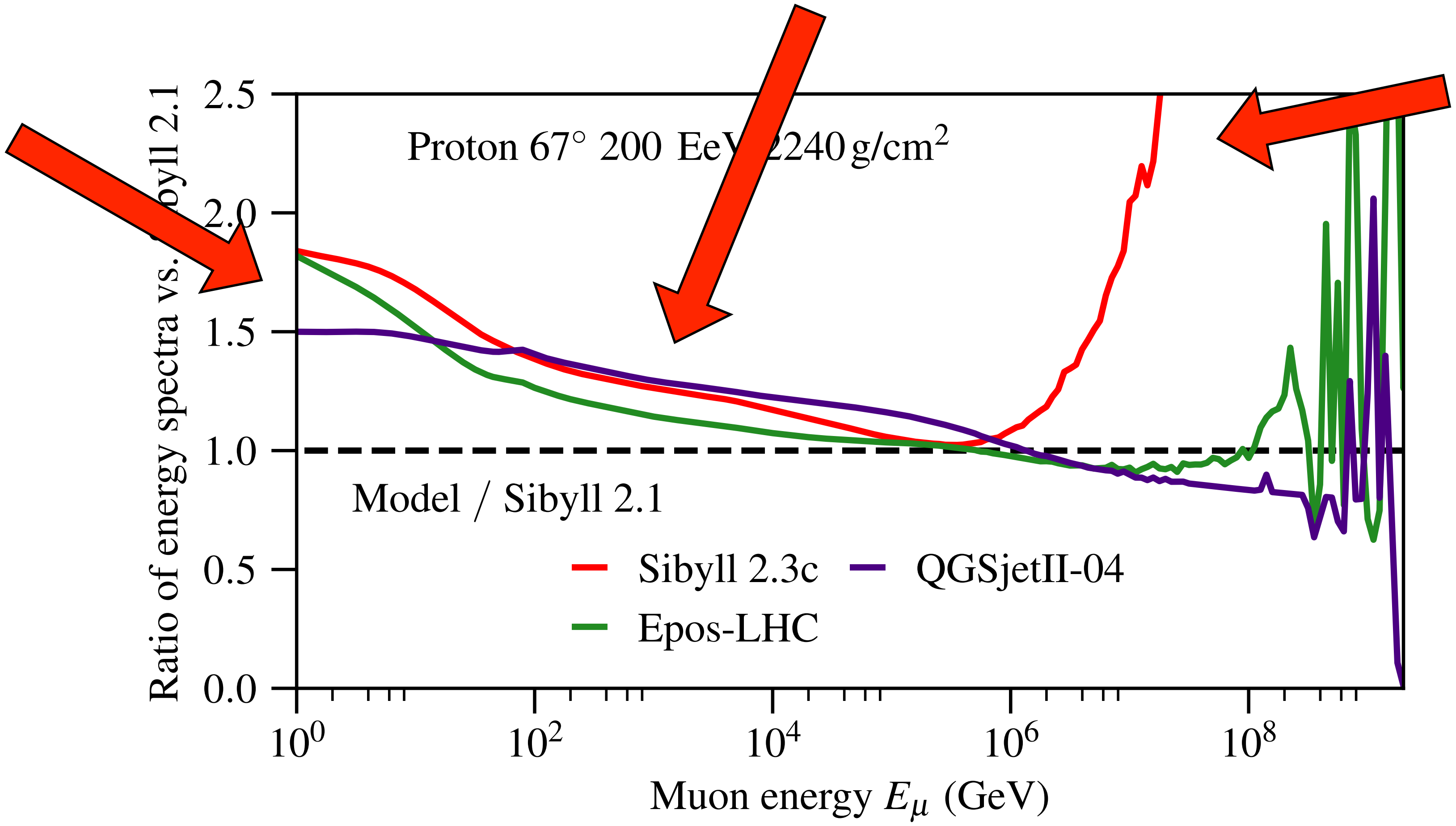


(Ave et al. ICRC 2011)

Enhancement of low-energy muons !

Relative energy spectrum of muons in EAS

Muon energy spectra relative to that of Sibyll 2.1



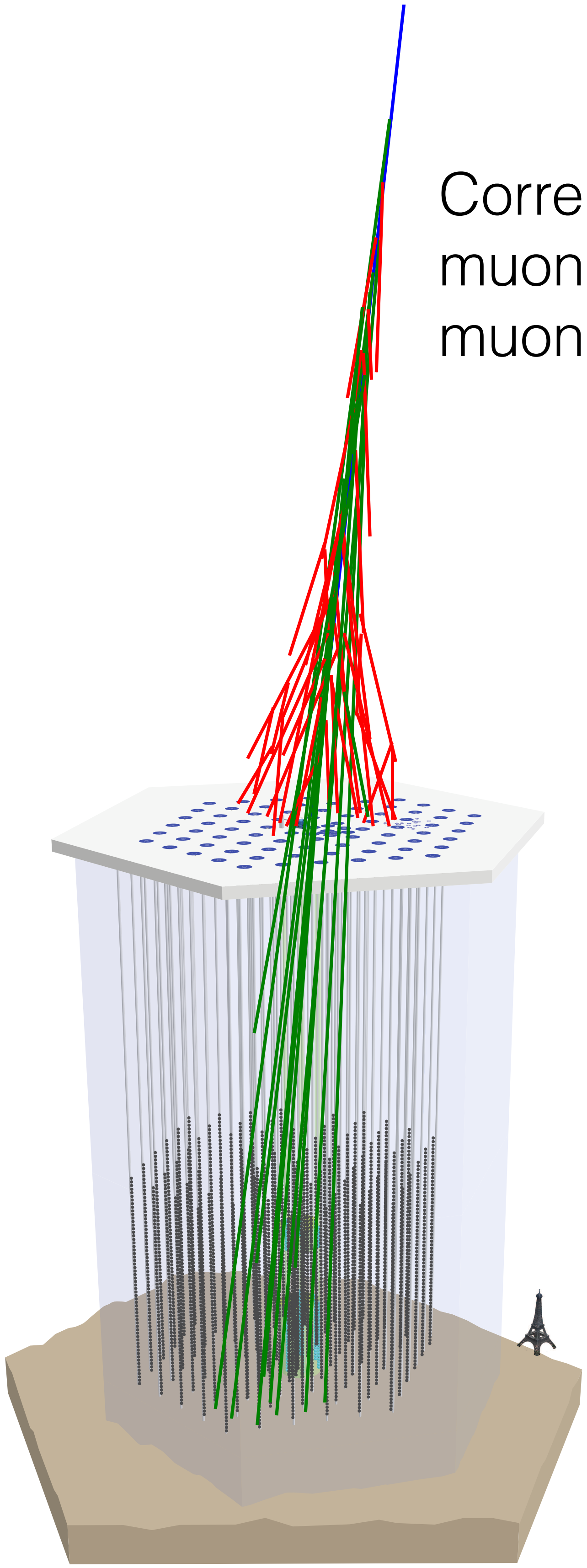
Low-energy enhancement due to baryon pair production

Rho-0 production

Charm particles (only Sibyll 2.3, and Sibyll 2.3c)

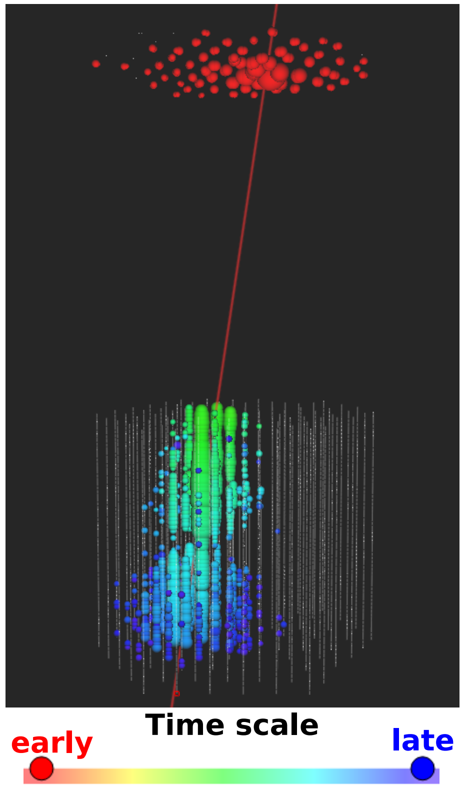
Discrimination by IceCube (surface array and in-ice muon data)?

IceCube: discrimination of enhancement scenarios?

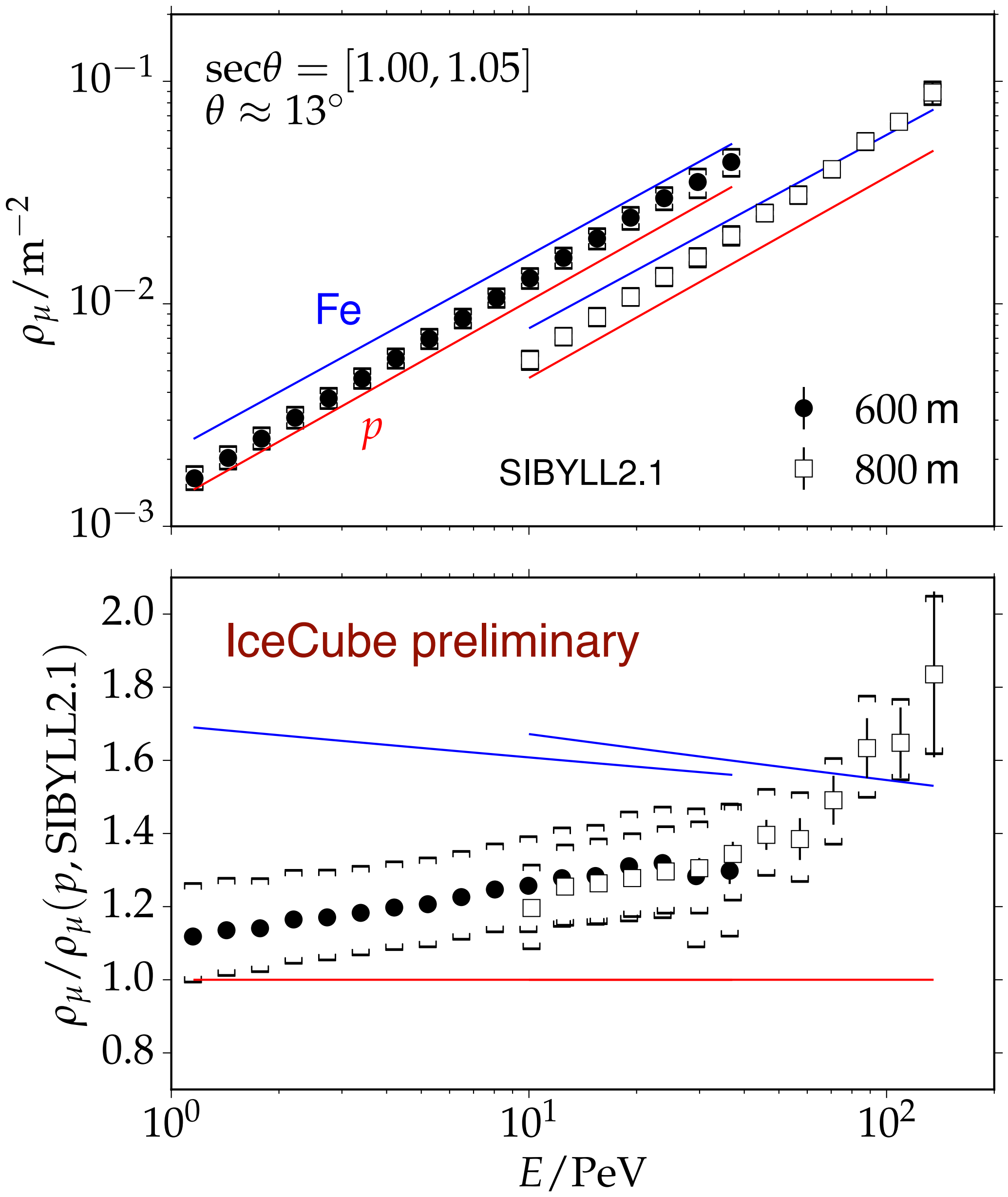


Correlation of low energy muons (surface) and in-ice muon bundles

IceTop: E$_\mu$ ~1 GeV

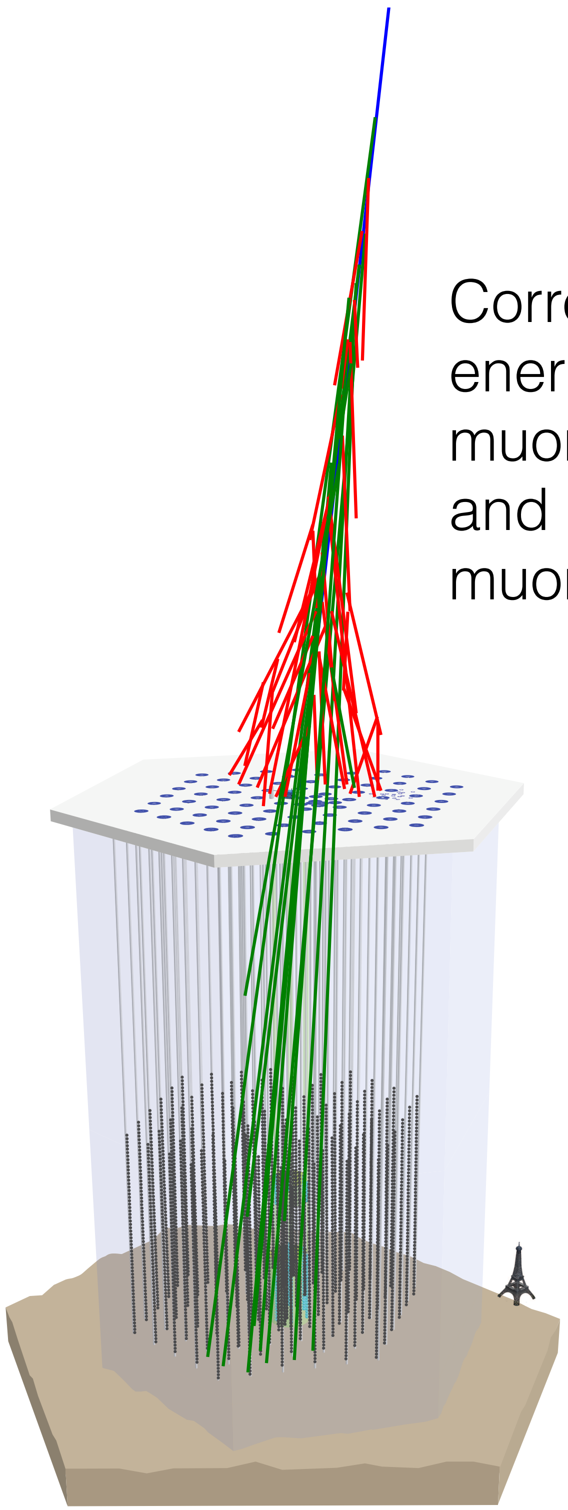


(IceCube, Gonzalez & Dembinski et al. 2016)

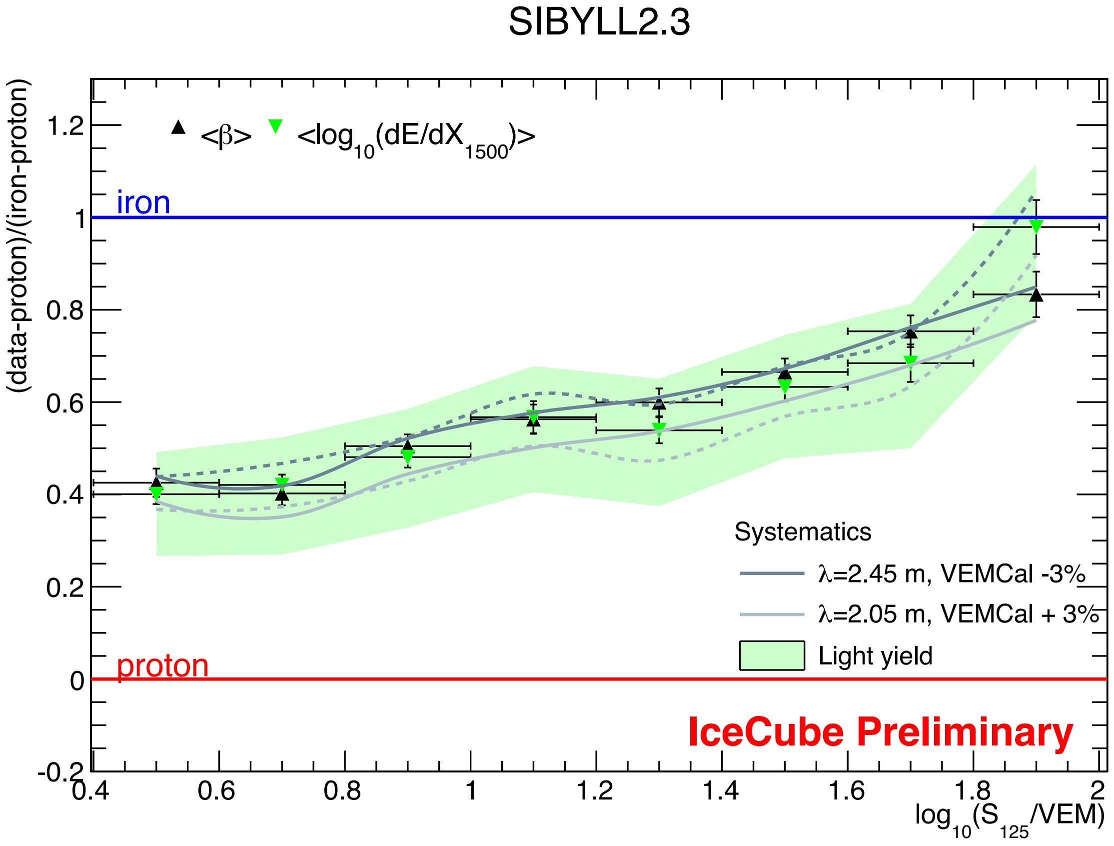


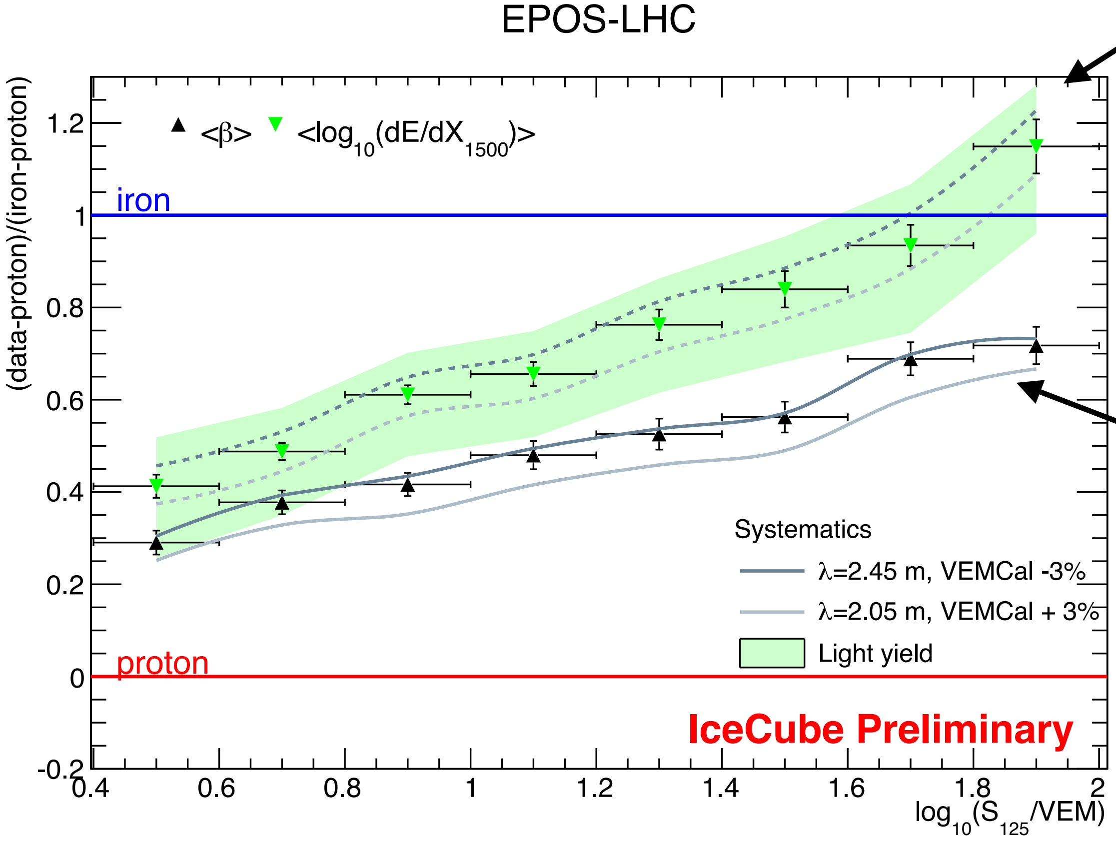
IceCube: E$_\mu$ >300 GeV

IceCube: discrimination of enhancement scenarios?



Correlation of low
energy
muons (surface)
and in-ice
muon bundles



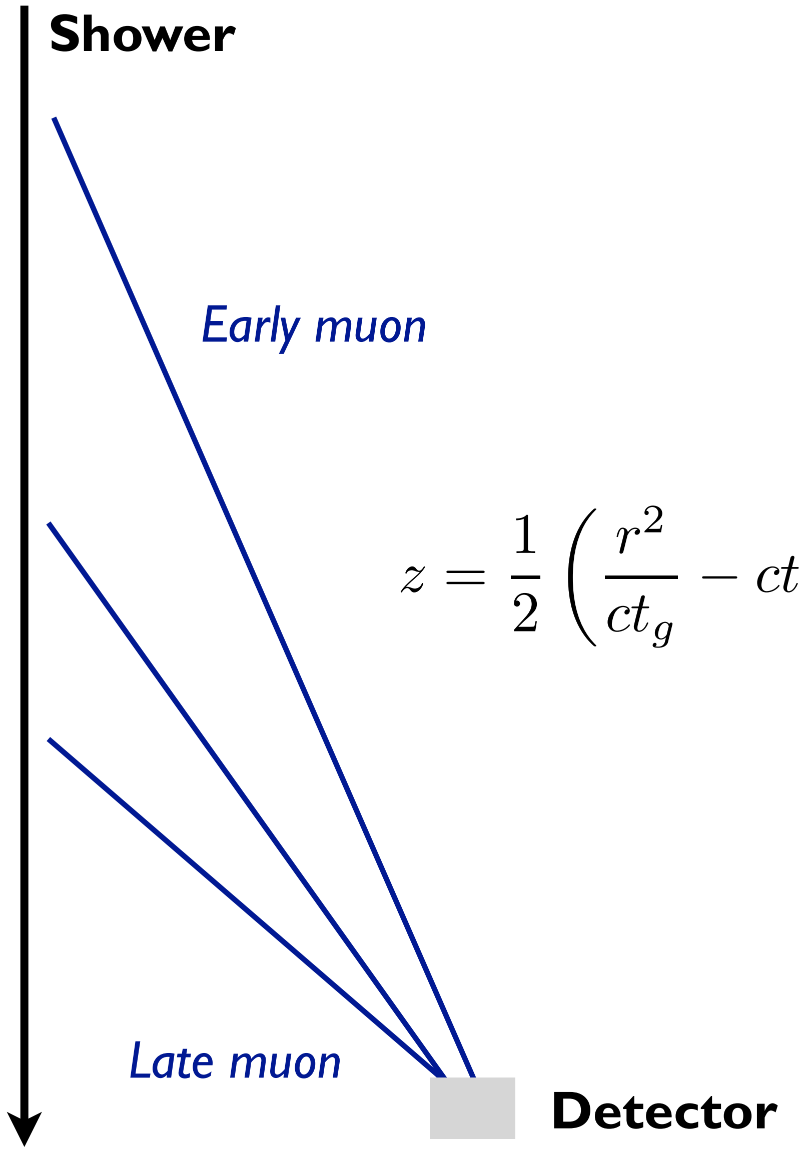


In-ice muons
(~300 GeV)

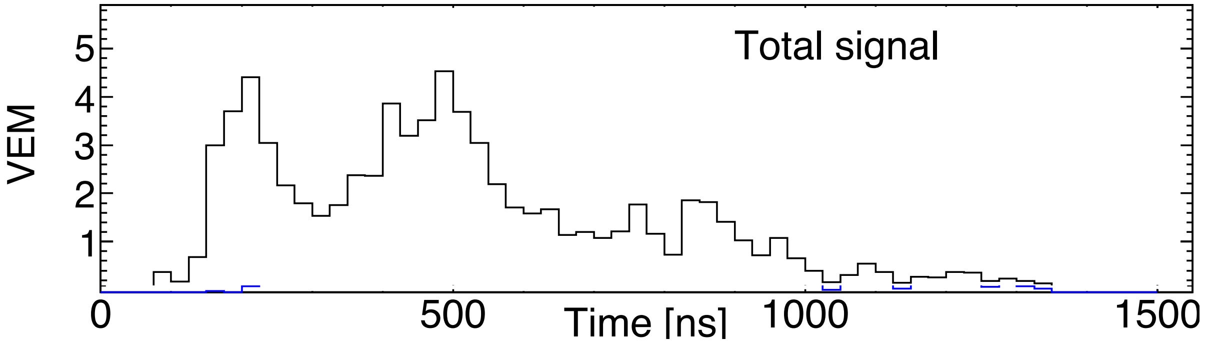
Surface
muons
(~1 GeV)

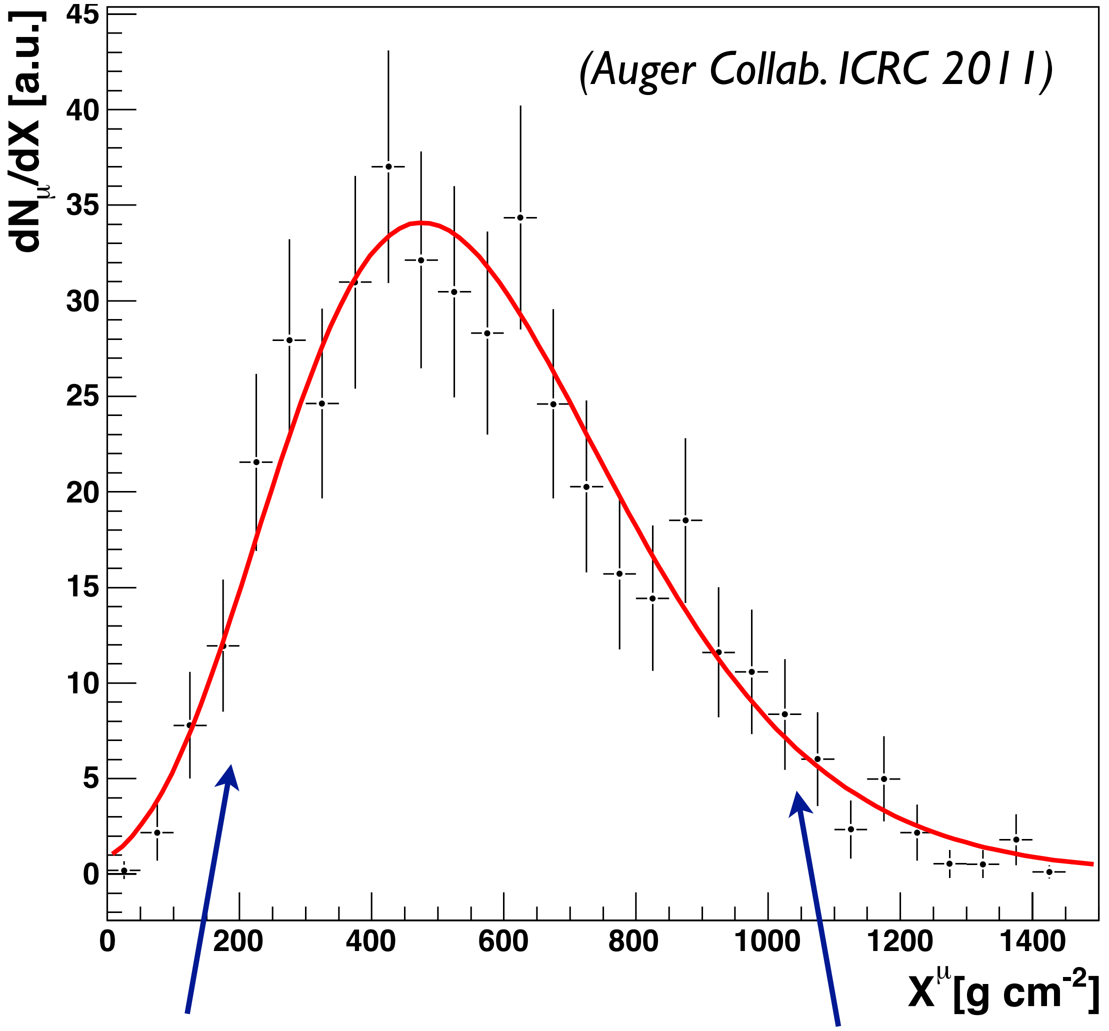
*(de Ridder, Gaisser,
IceCube, ICRC 2017)*

Outlook: muon production depth



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



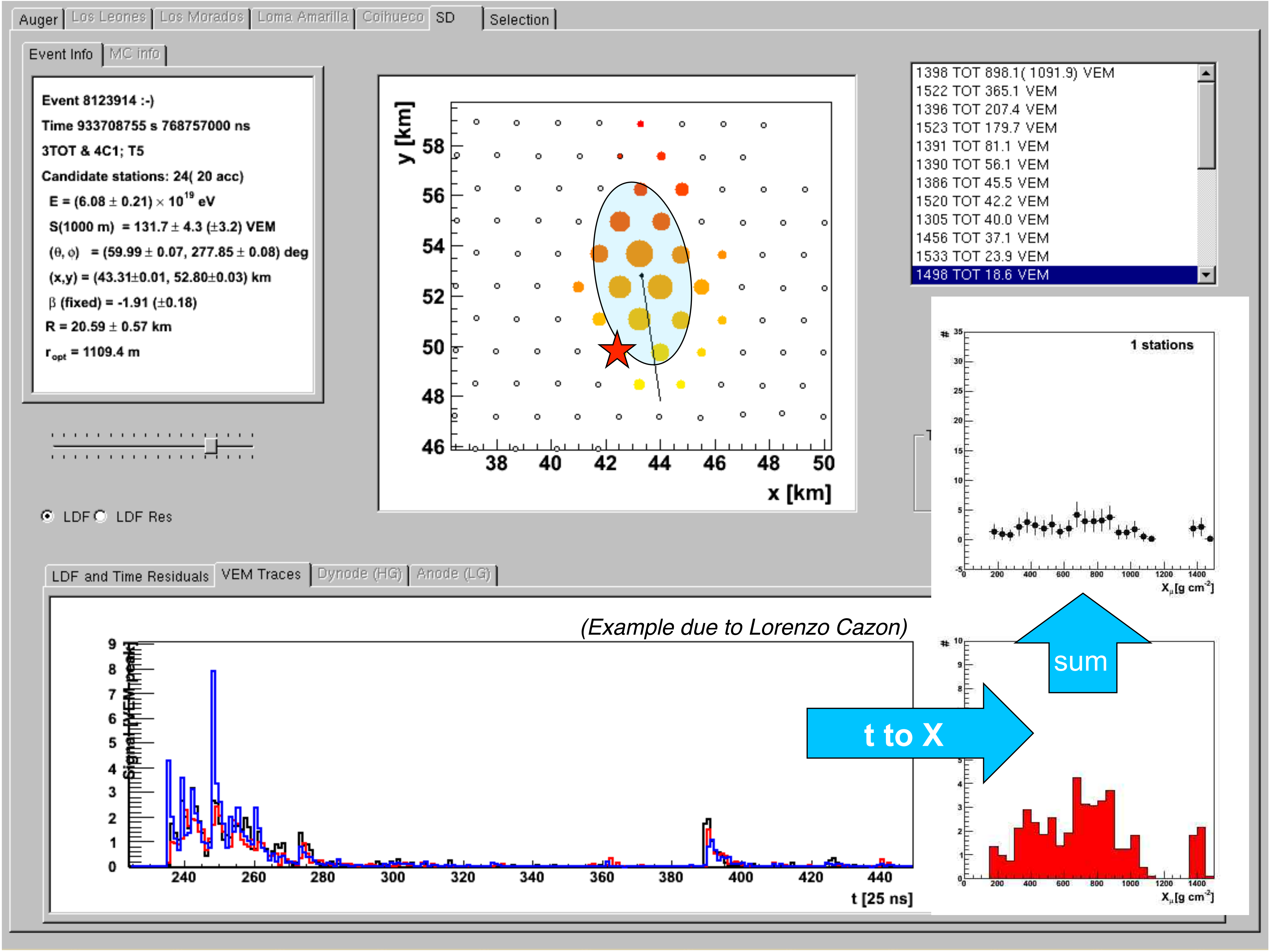


Muons from high-energy interactions

Muons from low-energy interactions

Auger Observatory: upgrade of surface detector array planned

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



Event 8123914 :-)
Time 933708755 s 768757000 ns
3TOT & 4C1; T5
Candidate stations: 24(20 acc)
E = (6.08 ± 0.21) × 10^{19} eV
S(1000 m) = 131.7 ± 4.3 (±3.2) VEM
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(x,y) = (43.31±0.01, 52.80±0.03) km
β (fixed) = -1.91 (±0.18)
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1520 TOT 42.2 VEM
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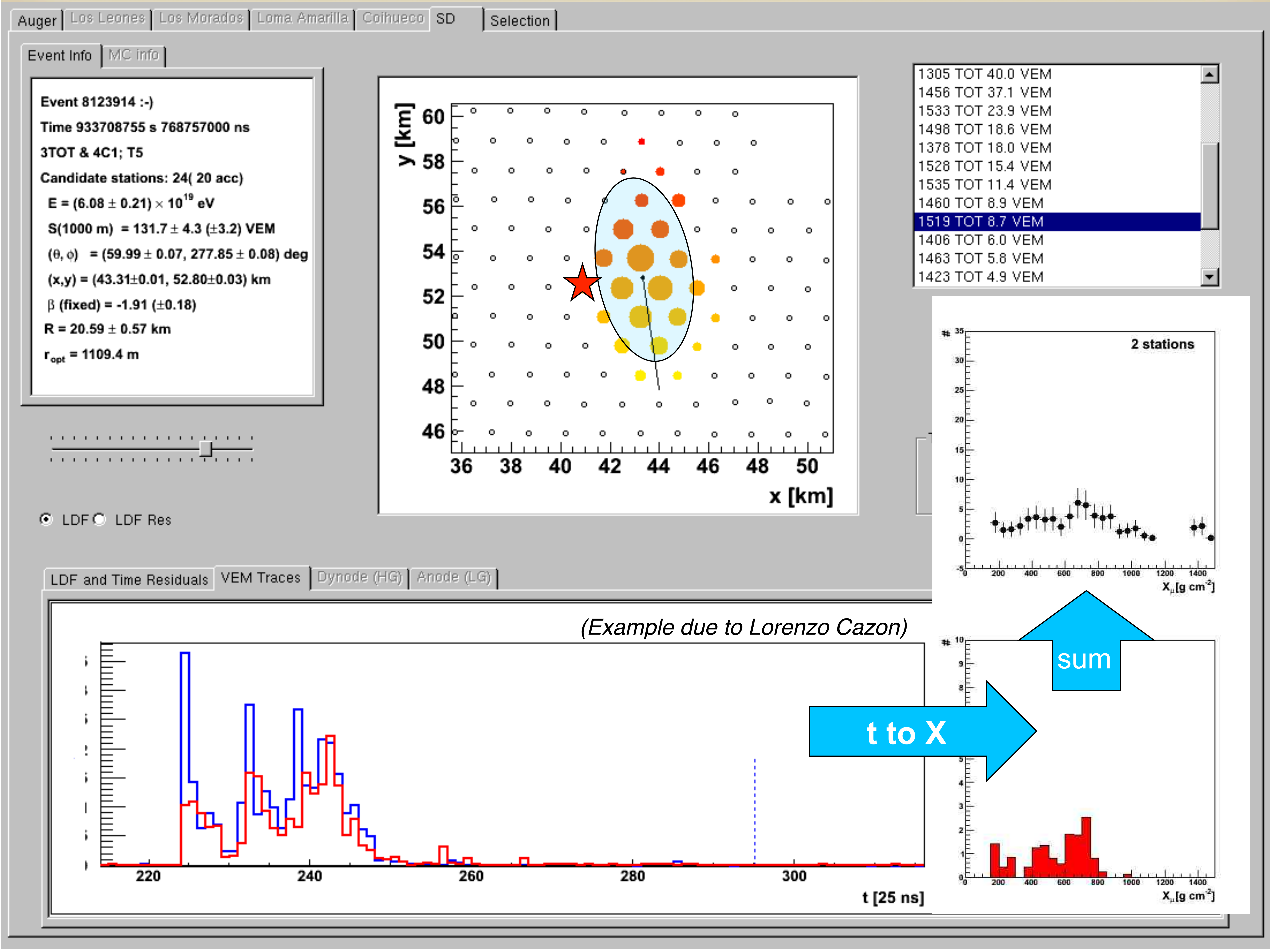
1456 TOT 37.1 VEM
1533 TOT 23.9 VEM
1498 TOT 18.6 VEM

(Example due to Lorenzo Cazon)



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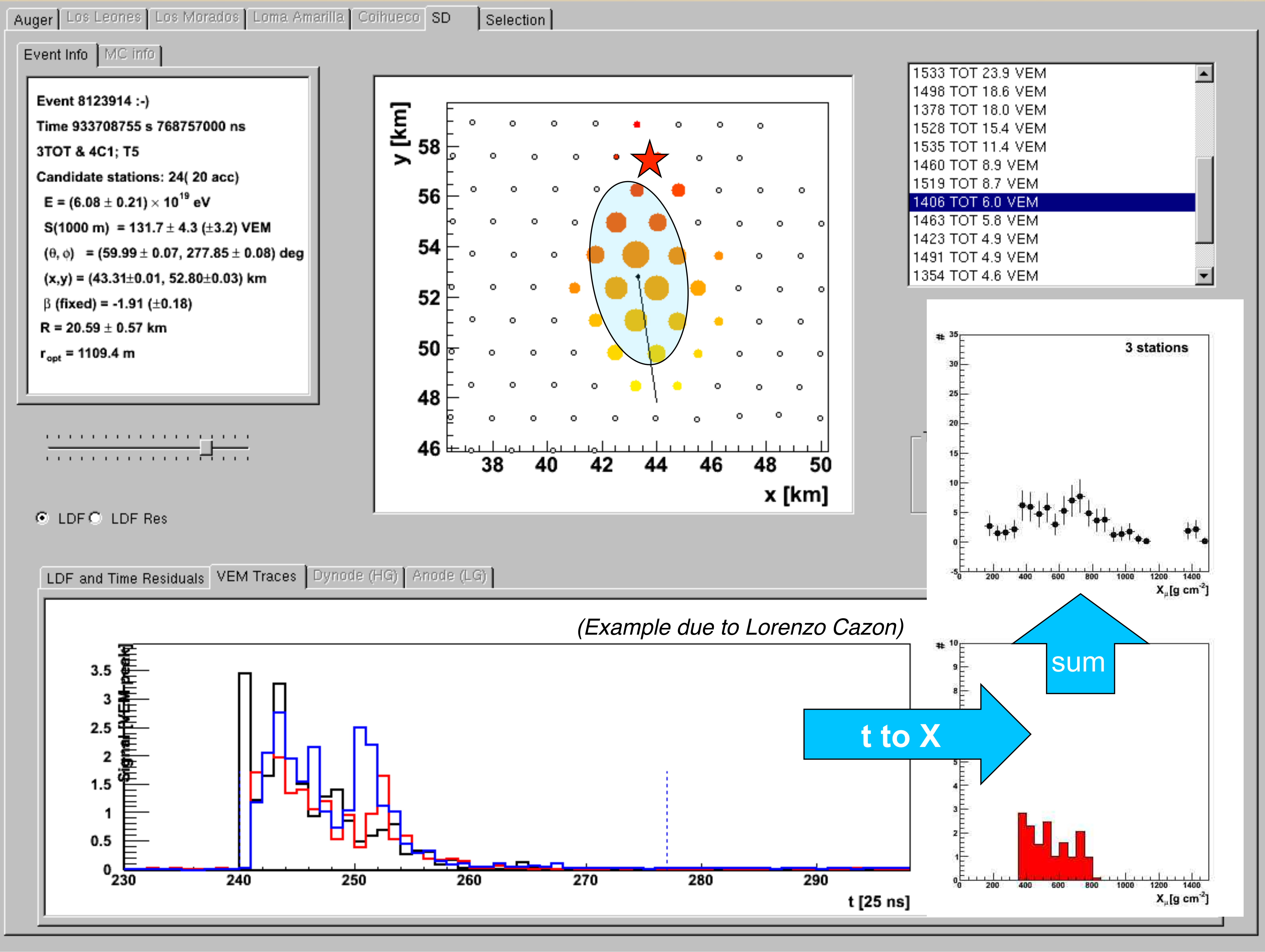
1406 TOT 6.0 VEM
1463 TOT 5.8 VEM
1423 TOT 4.9 VEM
```

● LDF ○ LDF Res

(Example due to Lorenzo Cazon)



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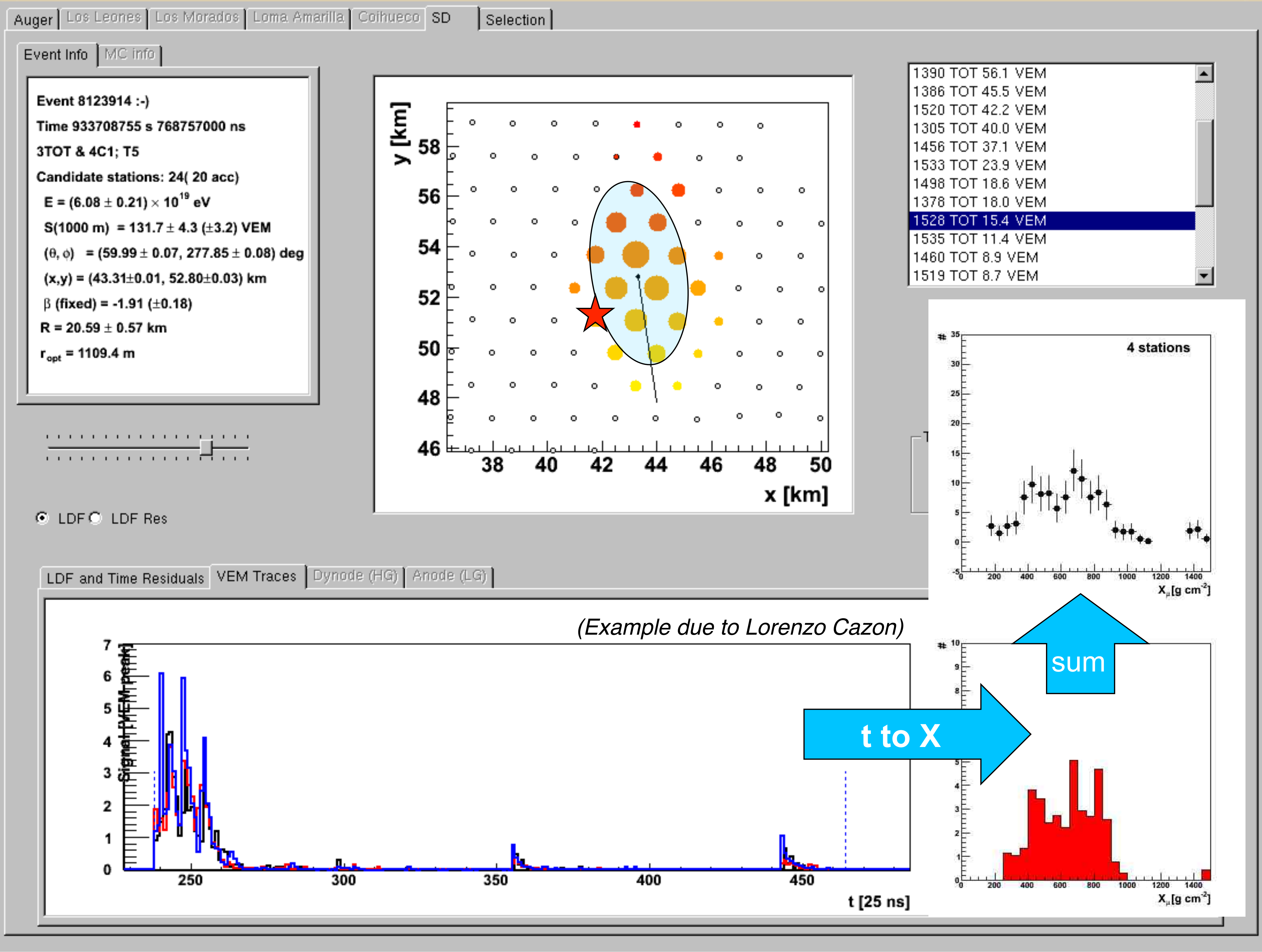

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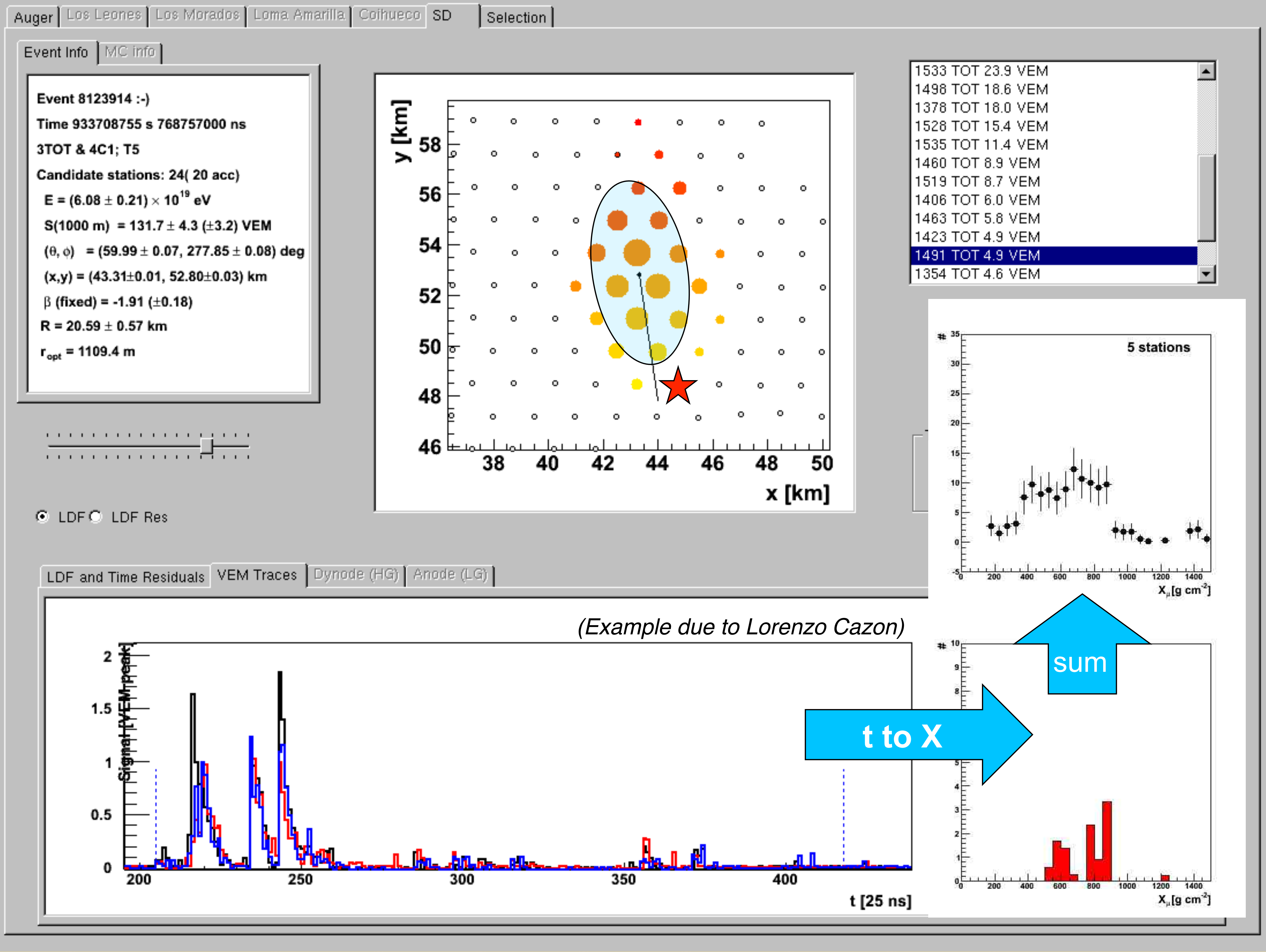
(Example due to Lorenzo Cazon)

t to X

sum



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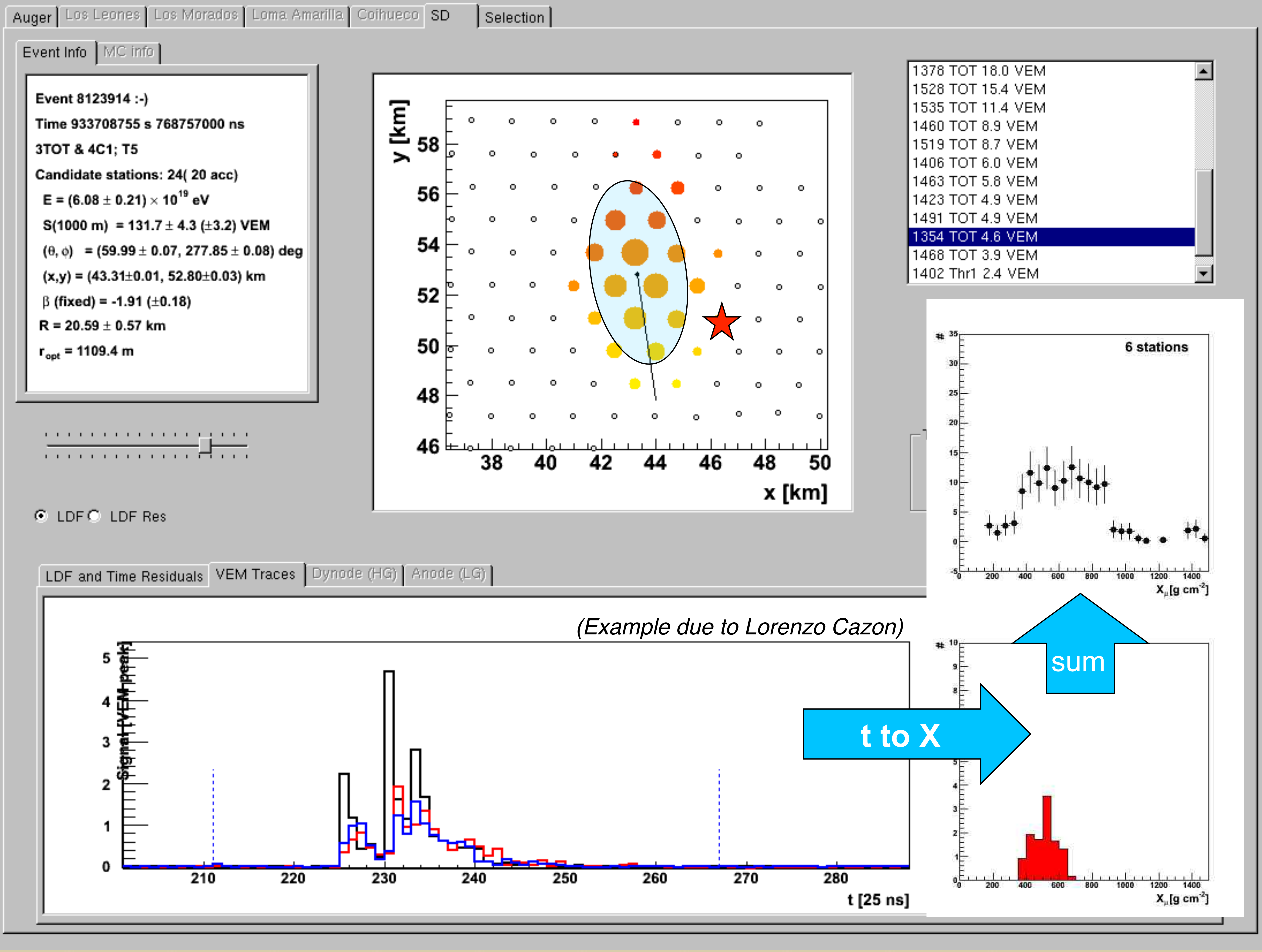

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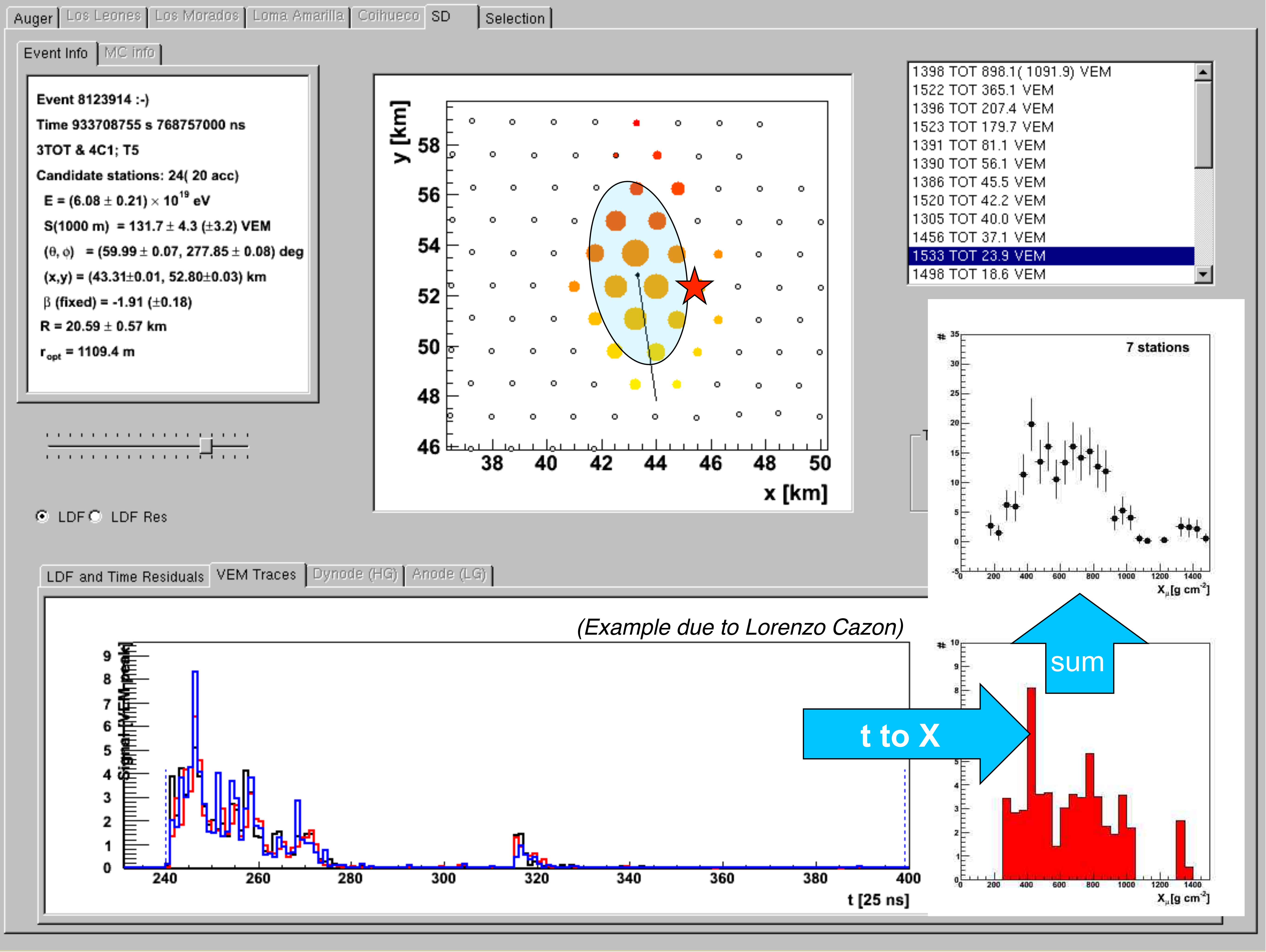

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● LDF ○ LDF Res

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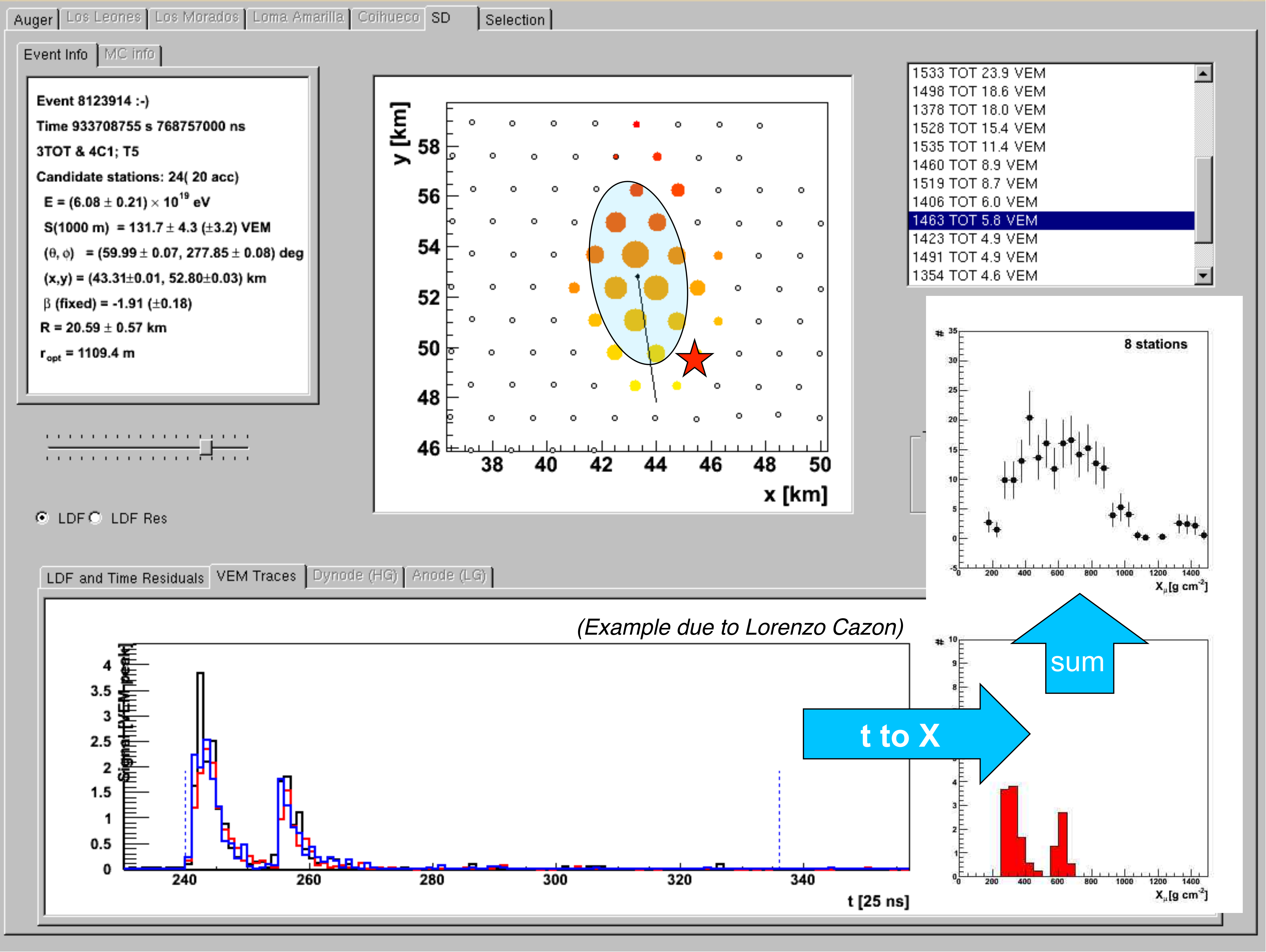

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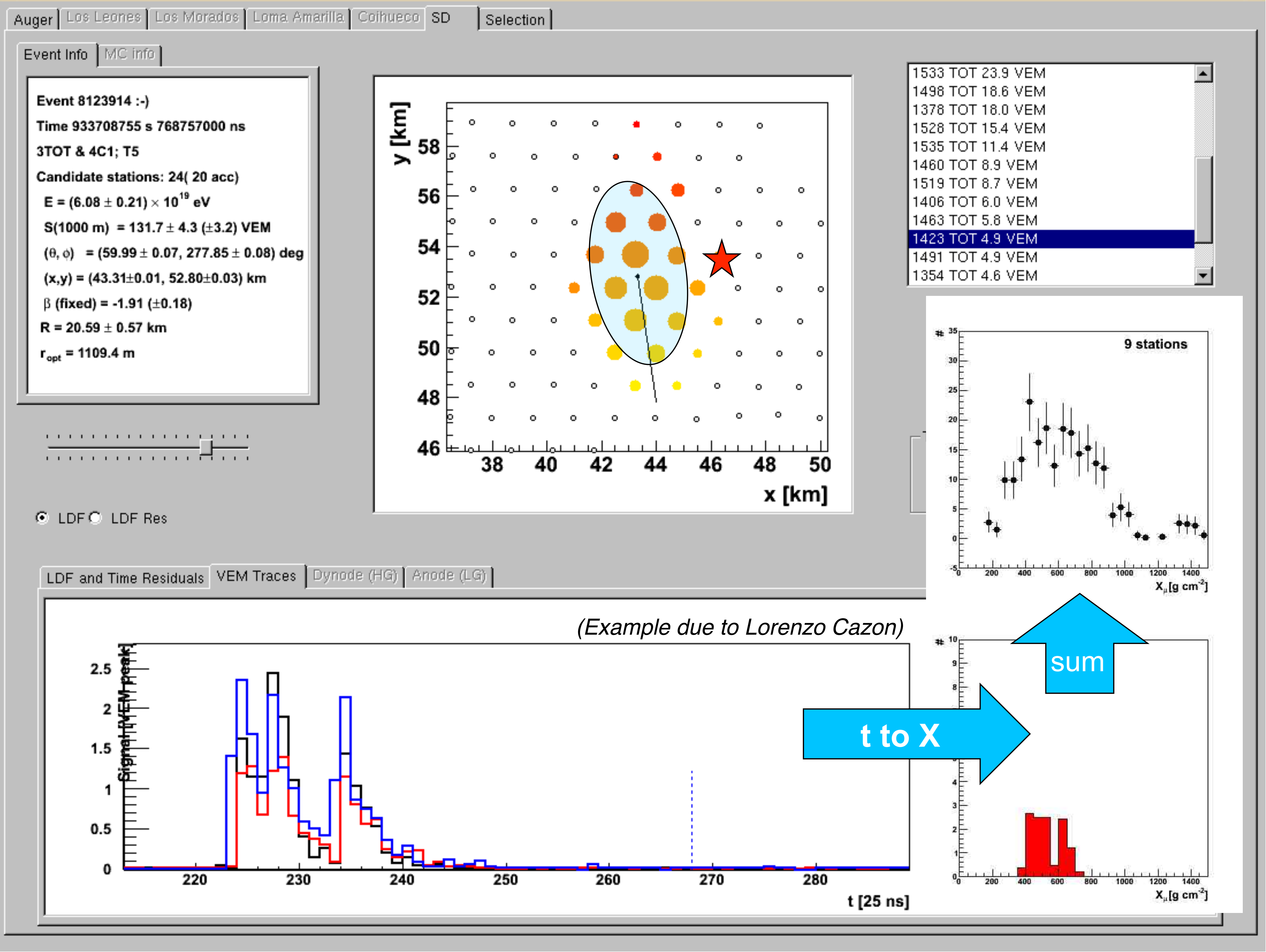

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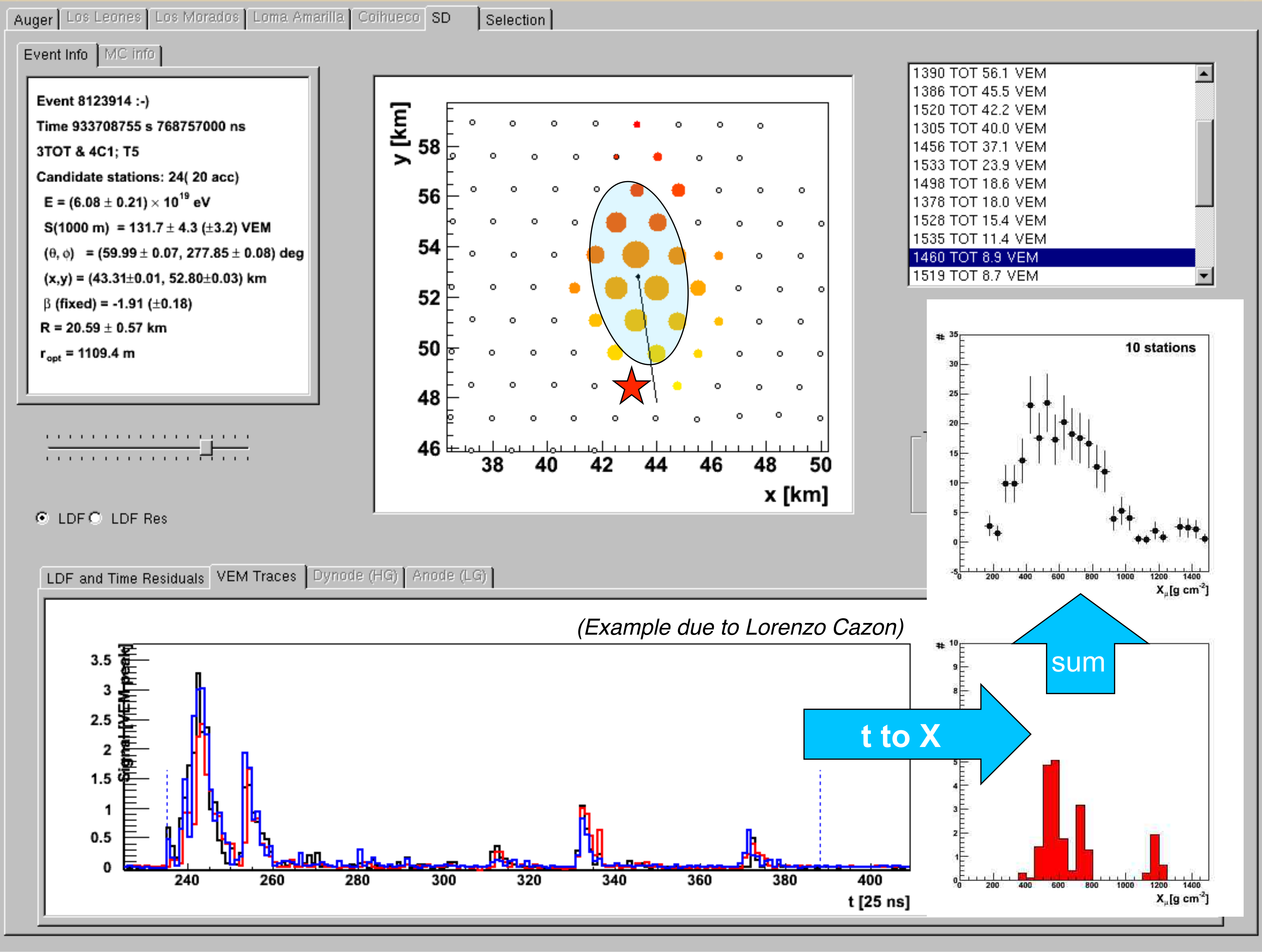

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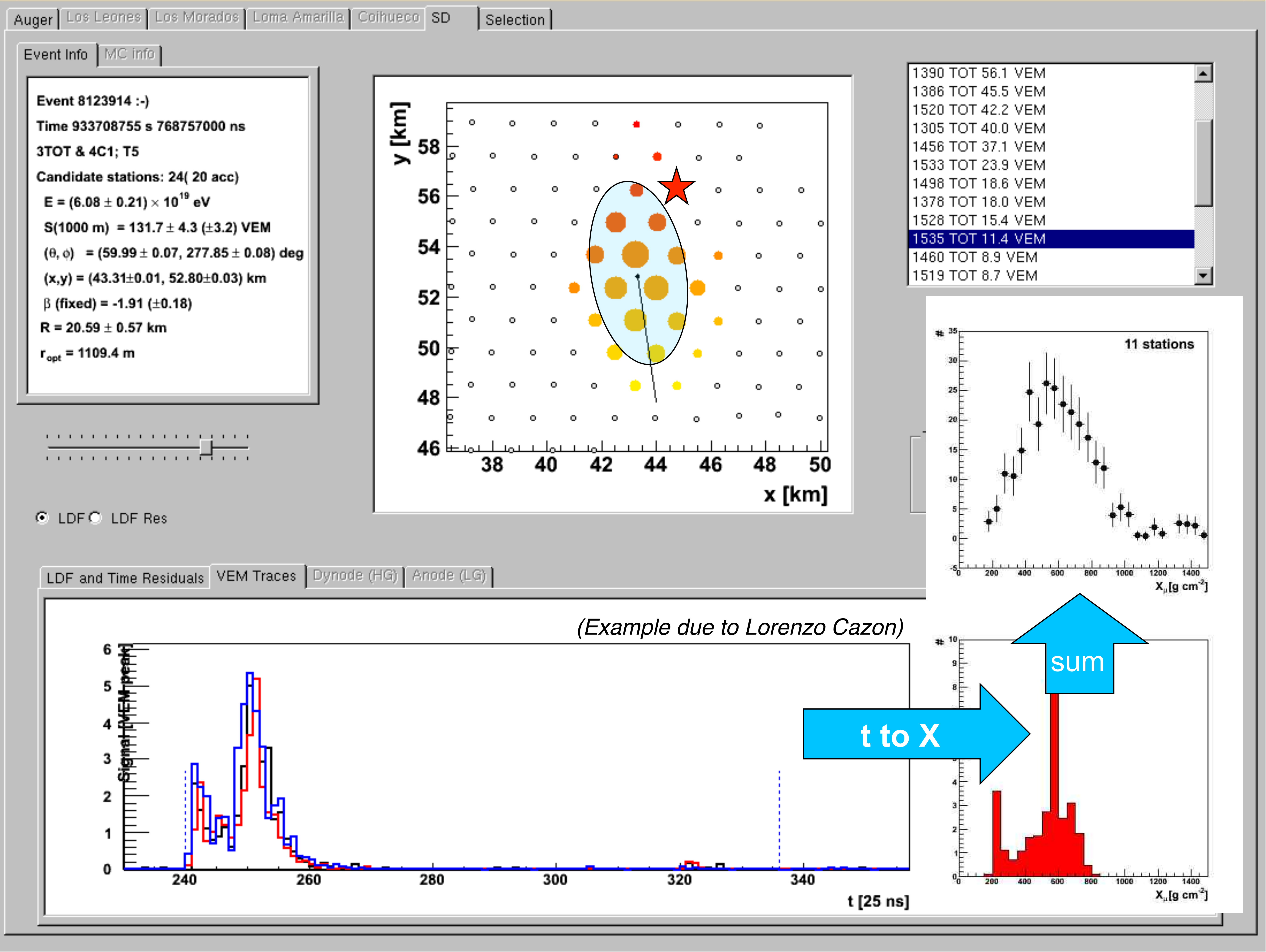

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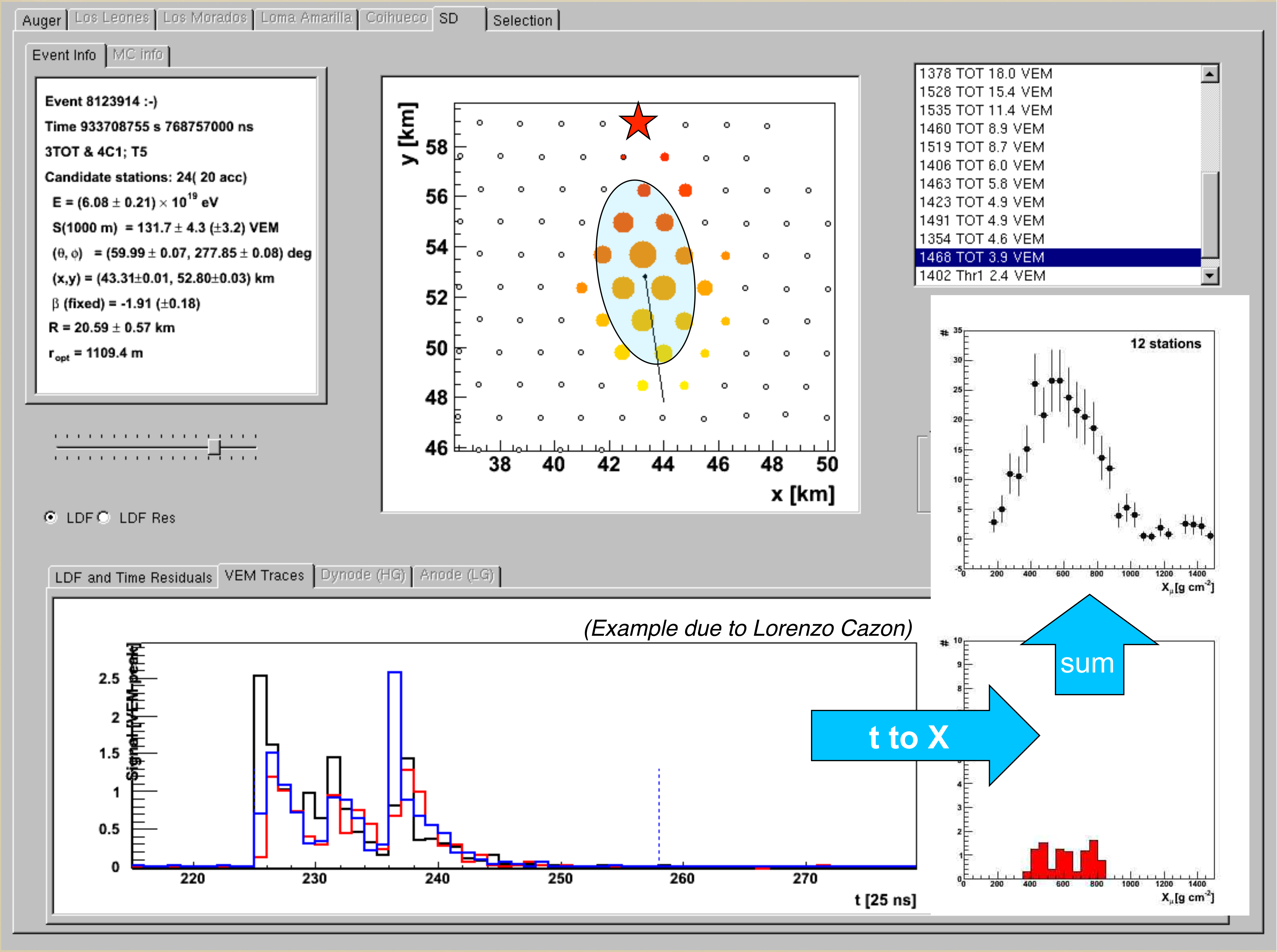

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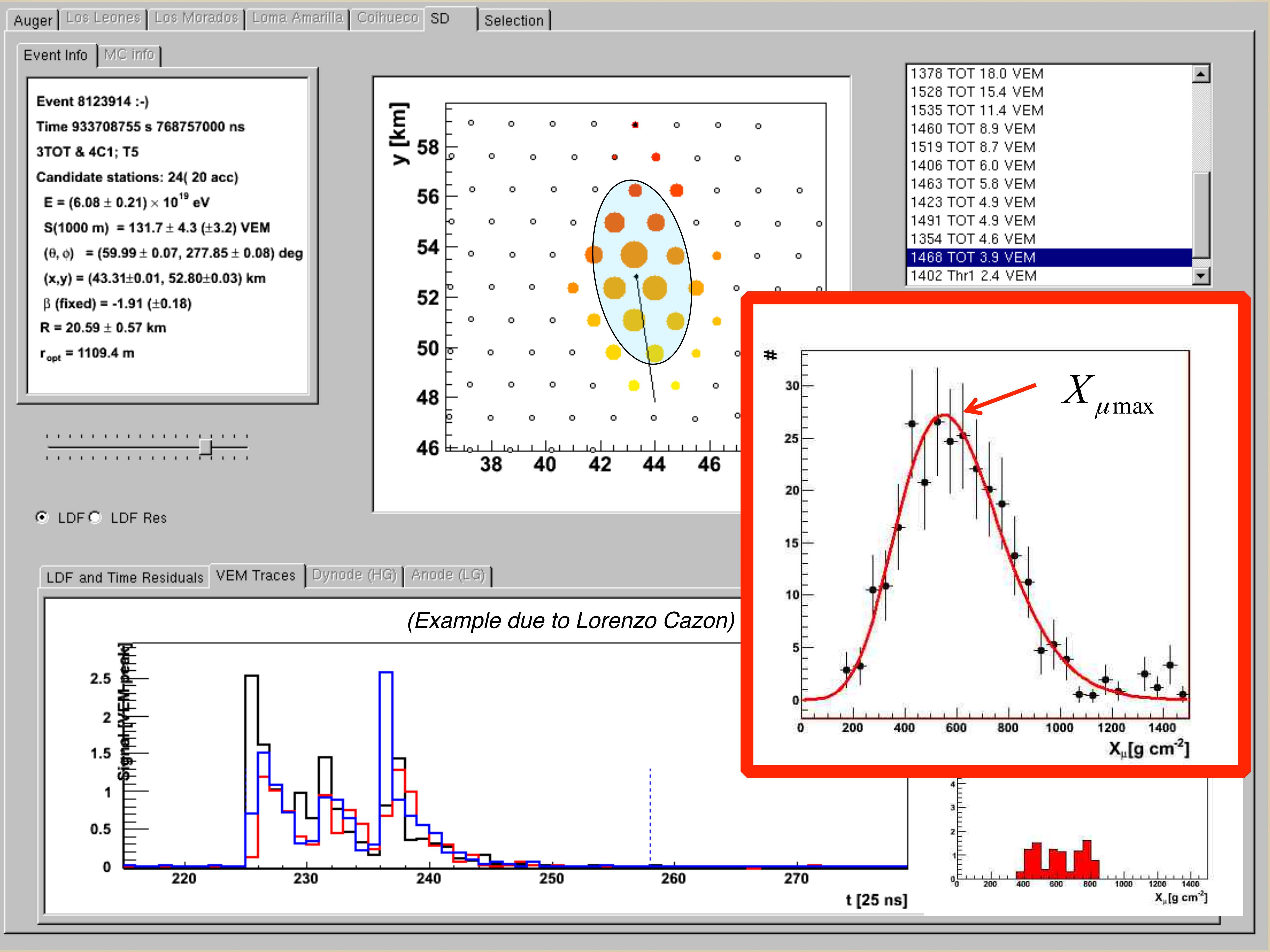

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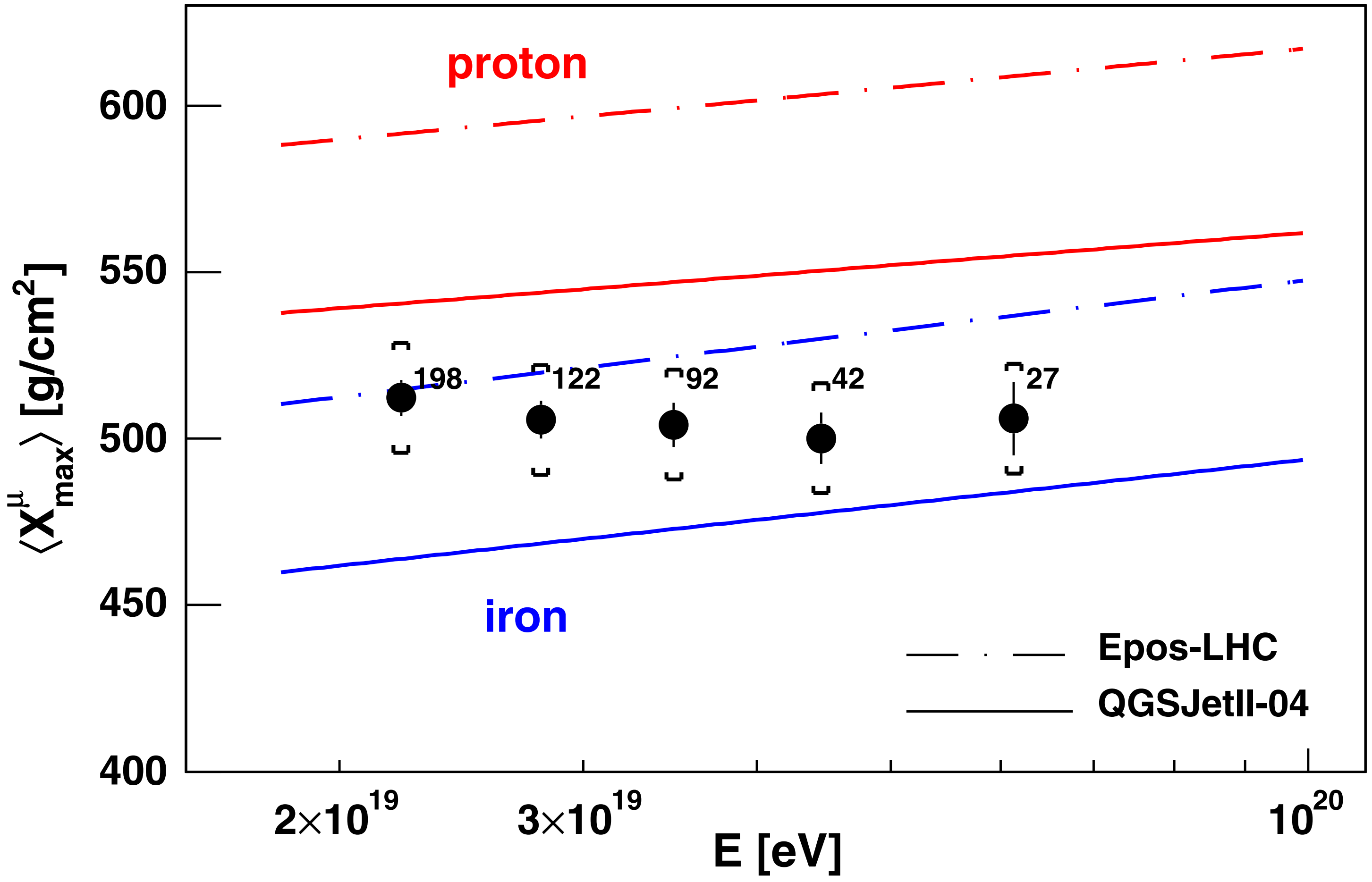
(Example due to Lorenzo Cazon)

Depth of maximum muon production



EPOS prediction: muons are produced too deep in atmosphere

QGSJET predictions consistent with Auger data

(Auger, PRD 90, 2014)

Summary

Different air shower observables are sensitive to hadronic interactions of different energies

- em. particles and X_{max}: first few high-energy interactions
- muons and $X\mu_{max}$: wide range of interaction energies

Model building relies heavily on measurements at accelerators

LHC tuning and further developments have led to an convergence of the predictions

- X_{max} data: interpreted as heavier in mass than before
- N_{μ} data: interpreted as lighter in mass than before
- selfconsistency improved

Overall good description of most shower features reached

Shortcomings clearly revealed in dedicated air shower measurements

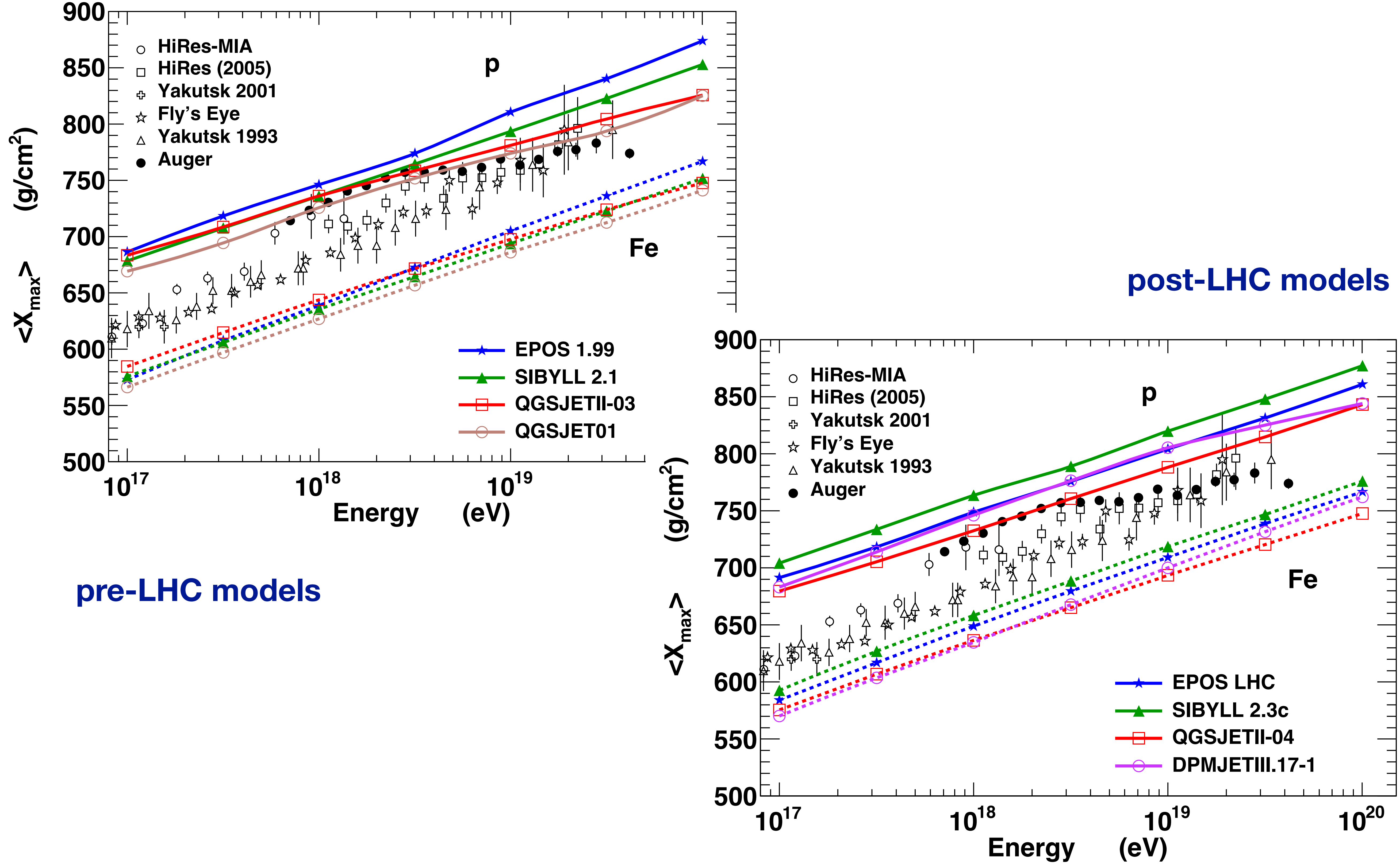
- correlation of two independent measurements
- none of the LHC-tuned models much better in data description than others

LHC measurements of p-O and further air shower studies important for progress

Models should be used with care, cross-checks always needed

Backup slides

Change of model predictions thanks to LHC data

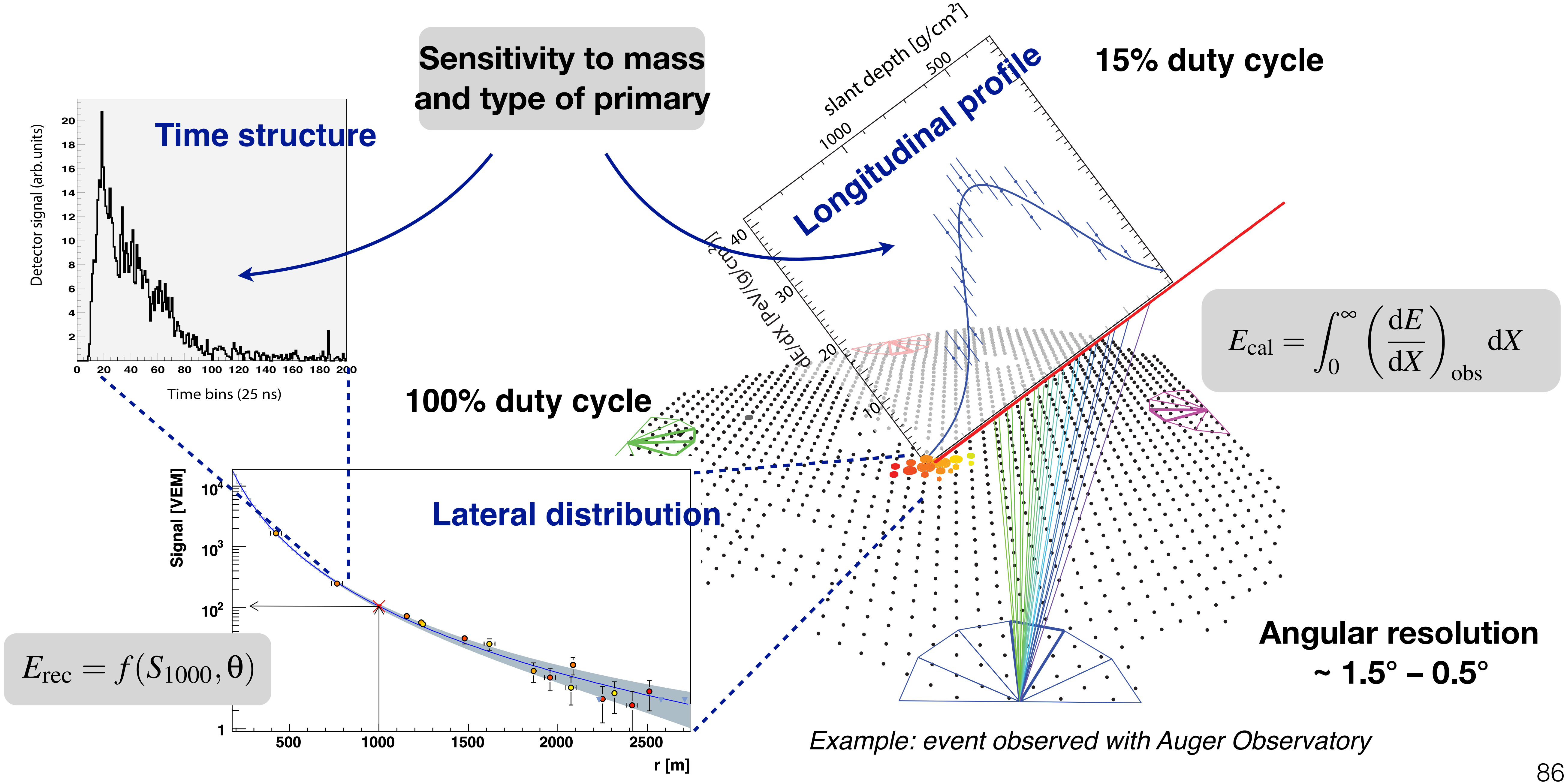


pre-LHC models

post-LHC models

(Pierog, ICRC 2017)

UHECRs: How to detect them



Sensitivity to mass and type of primary

Time structure

Longitudinal profile

15% duty cycle

$$E_{\mathrm{cal}} = \int_0^\infty \left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_{\mathrm{obs}} \mathrm{d}X$$

100% duty cycle

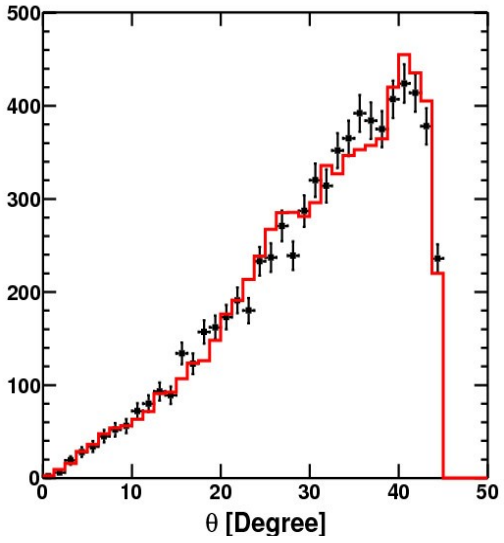
Lateral distribution

$$E_{\mathrm{rec}} = f(S_{1000}, \theta)$$

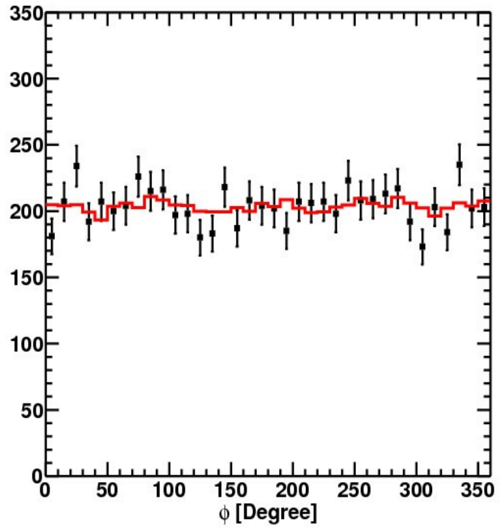
Angular resolution
~ 1.5° – 0.5°

Example: event observed with Auger Observatory

TA event simulation for surface array

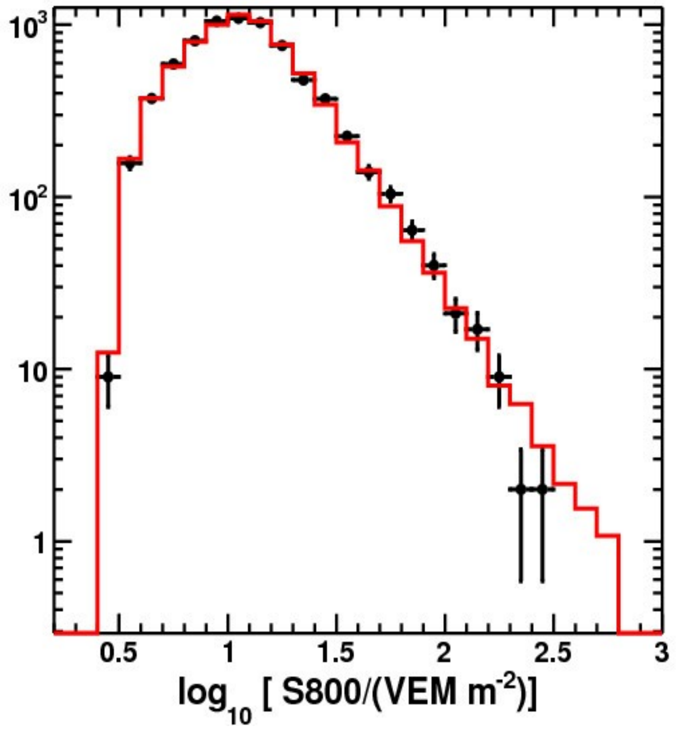


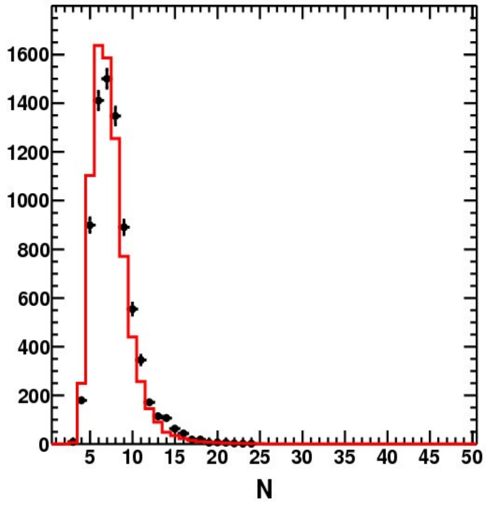
Zenith Angle



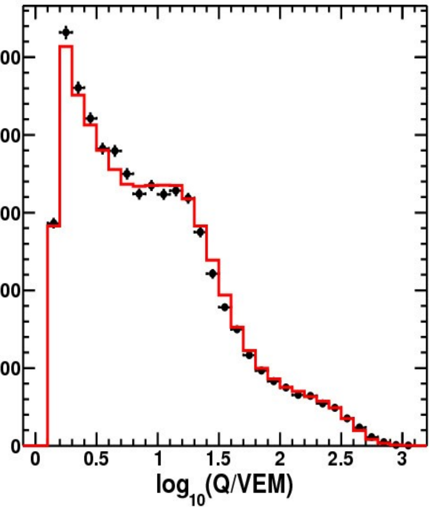
Azimuth Angle

CORSIKA + full detector simulation (proton primaries)





Number of Good Counters/Event

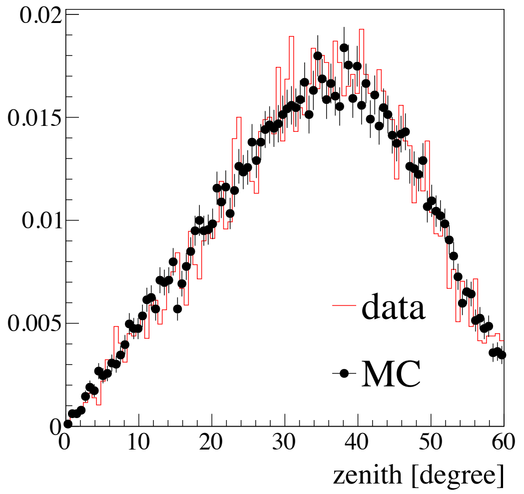


Charge/Counter/Event

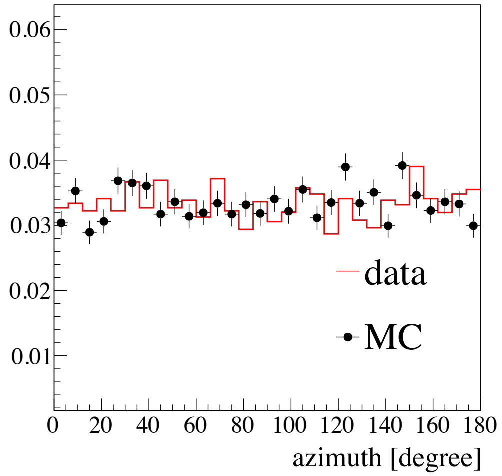
(UHECR 2012)

Very good agreement

Auger event simulation for surface array

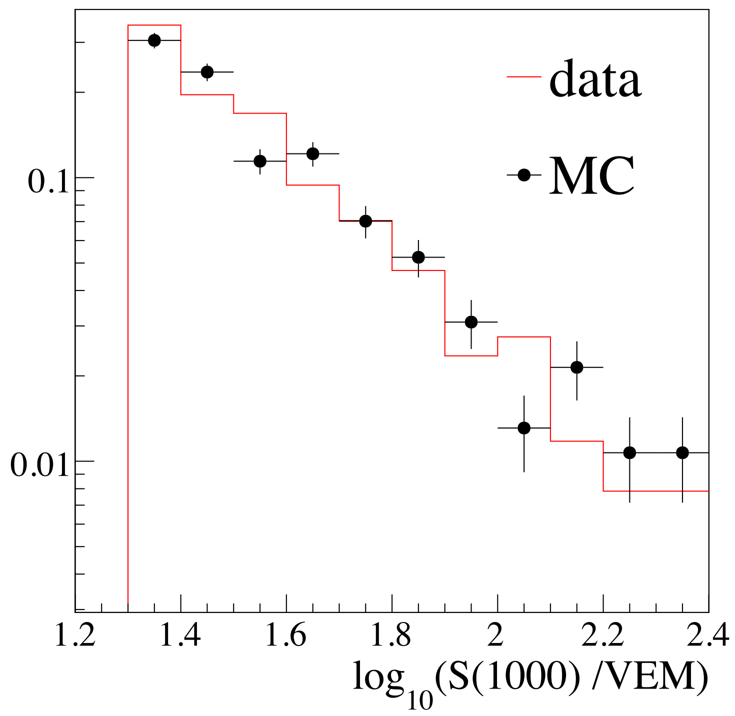


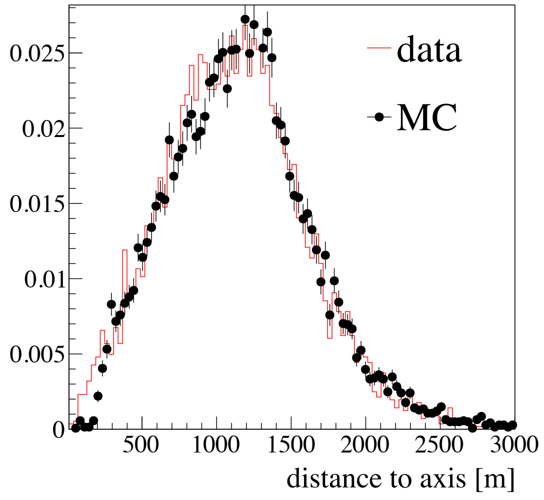
Zenith angle



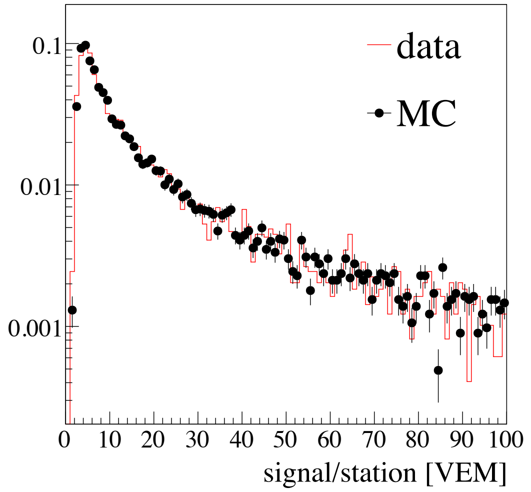
Azimuth angle

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





Distance of triggered stations

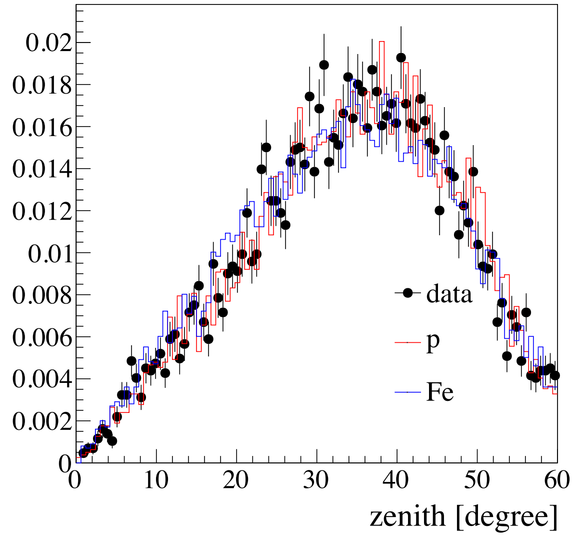


Signal per station

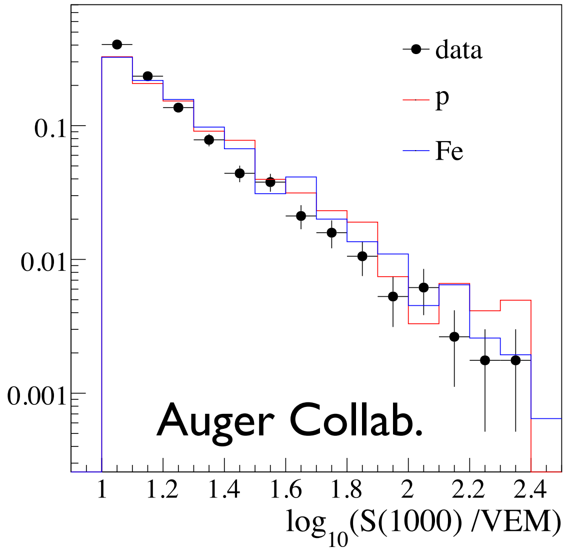
(UHECR 2012)

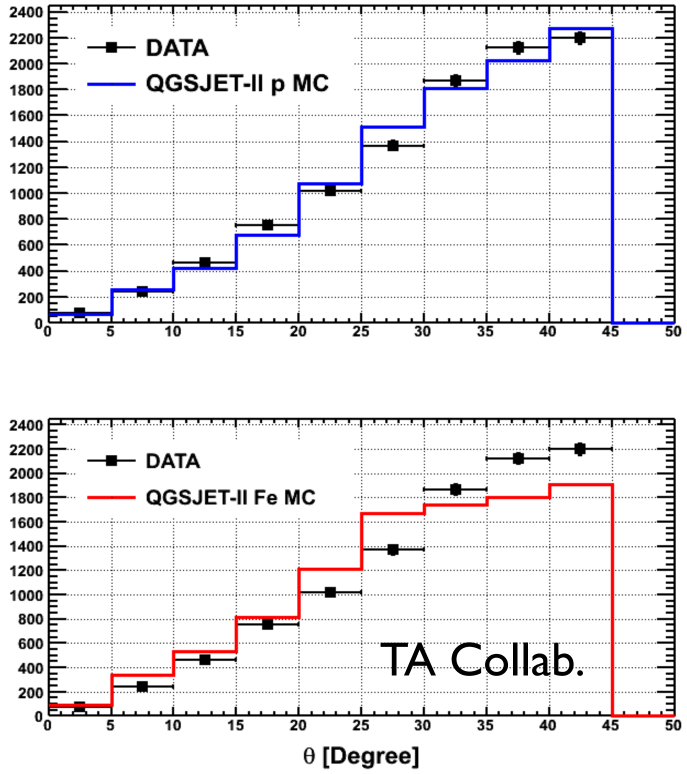
Very good agreement

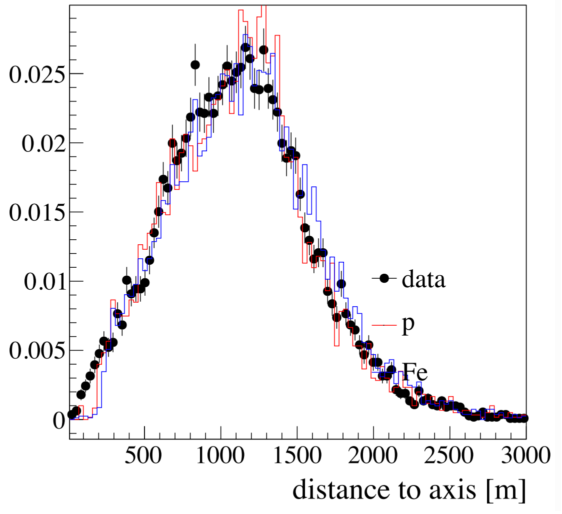
Composition and model sensitivity ?



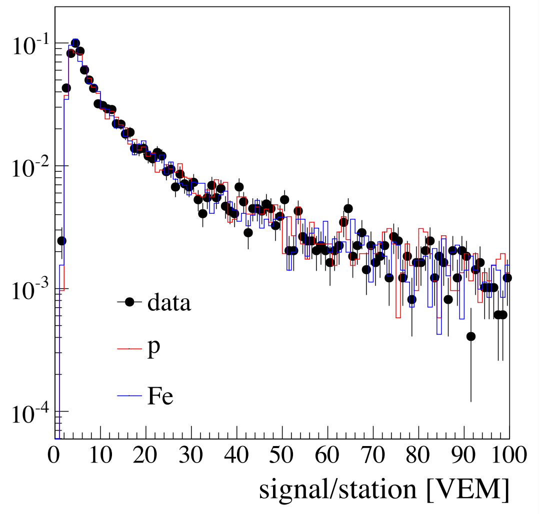
Zenith angle







Distance of triggered stations

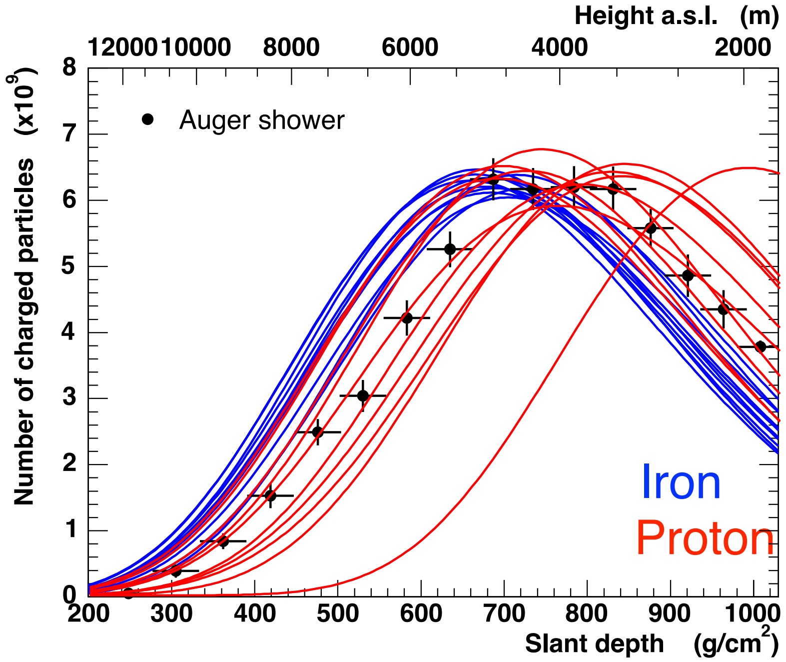


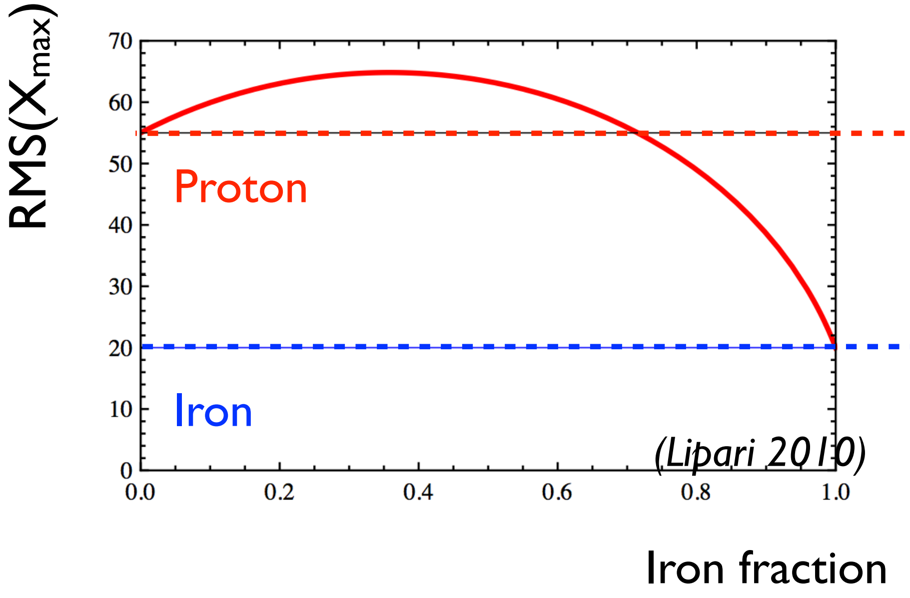
Signal per station

(UHECR 2012)

Most observables not very sensitive
to details of shower simulation

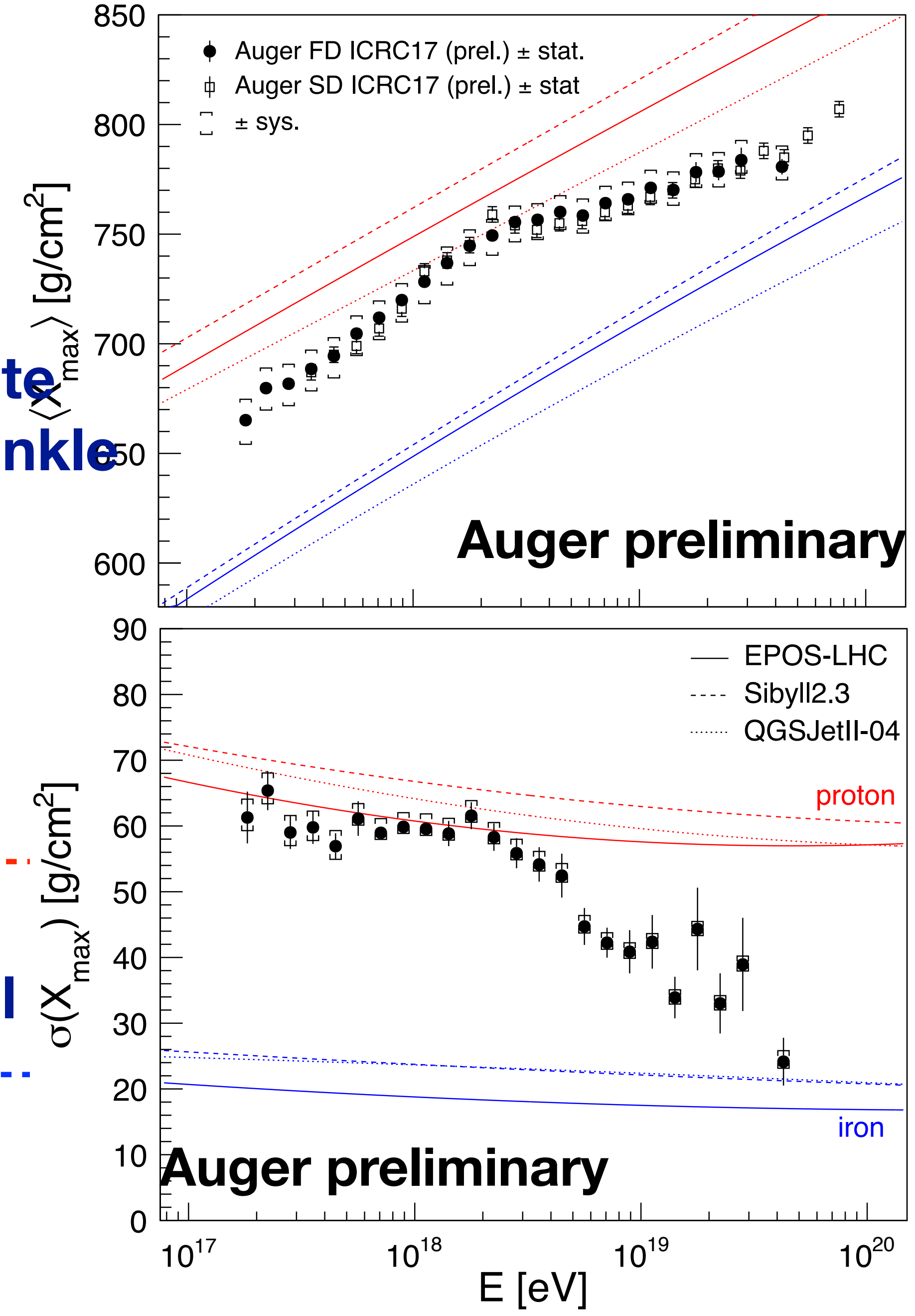
Depth of shower maximum (Auger results)



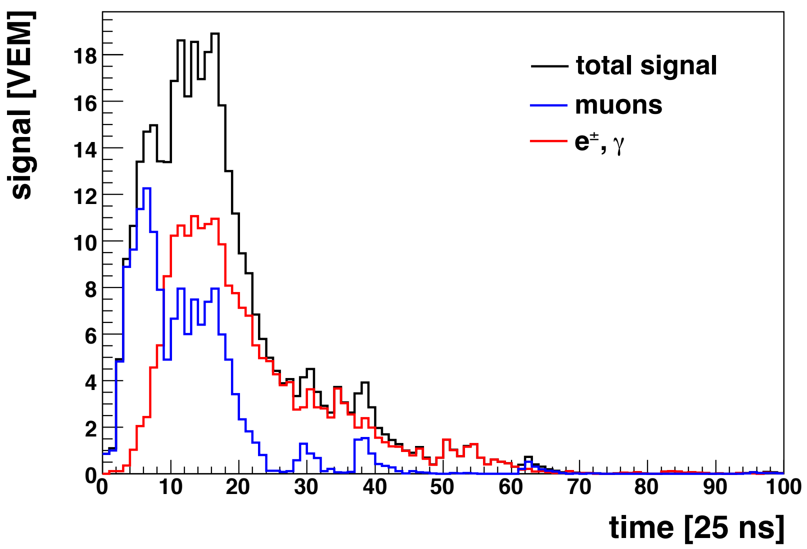


Break in elongation rate just below energy of ankle

Shower-by-shower fluctuations very small

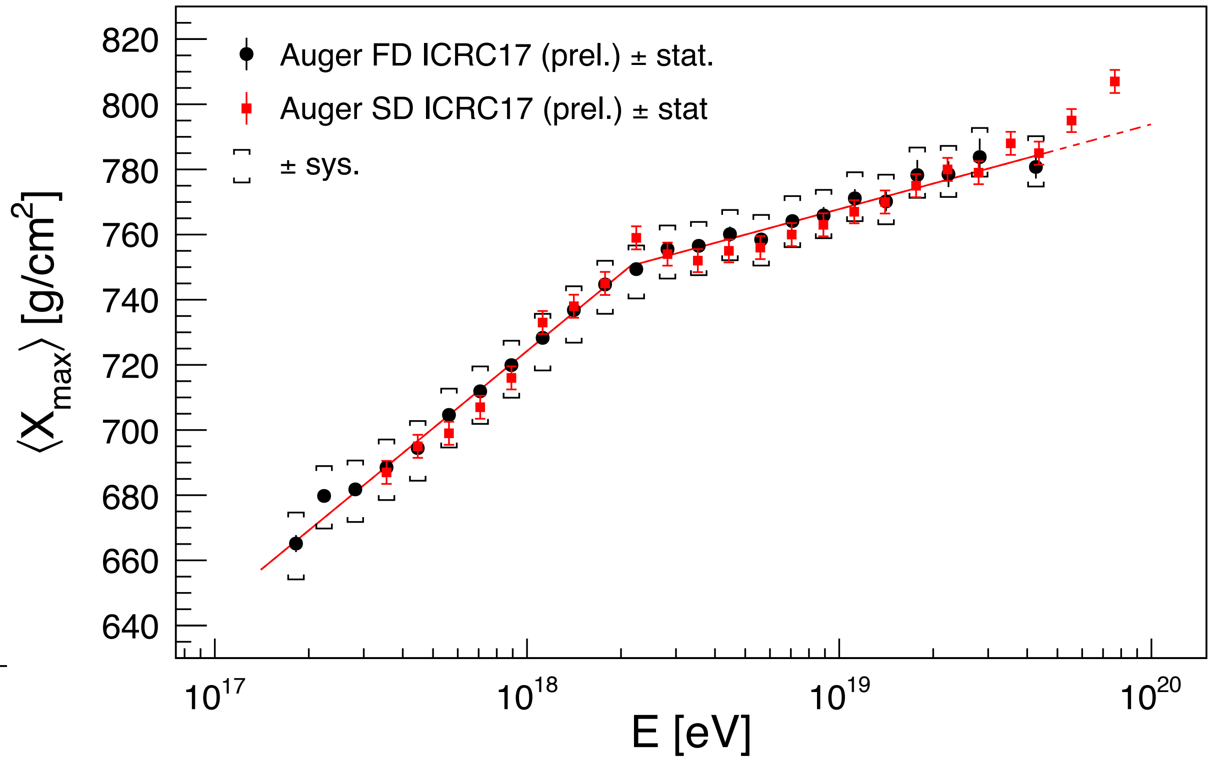


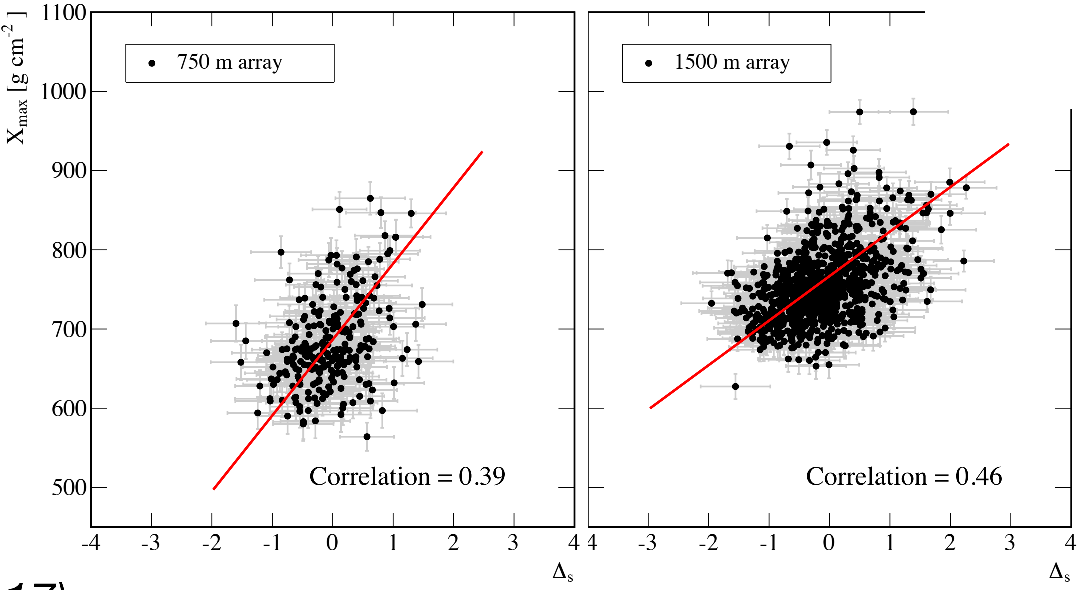
Composition estimate using rise time of signal



Rise time of signal

$$t_{1/2} = t_{50\%} - t_{10\%}$$





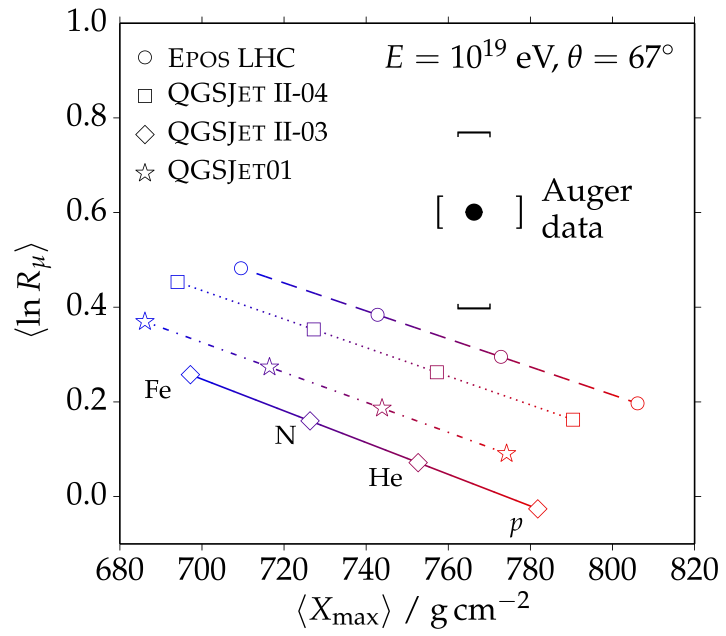
Result not directly depending on models

- Calibrated on Xmax data of fluorescence detectors
- Calibration function assumed to be valid also at higher energy

(Sanchez-Lucas ICRC 2017)

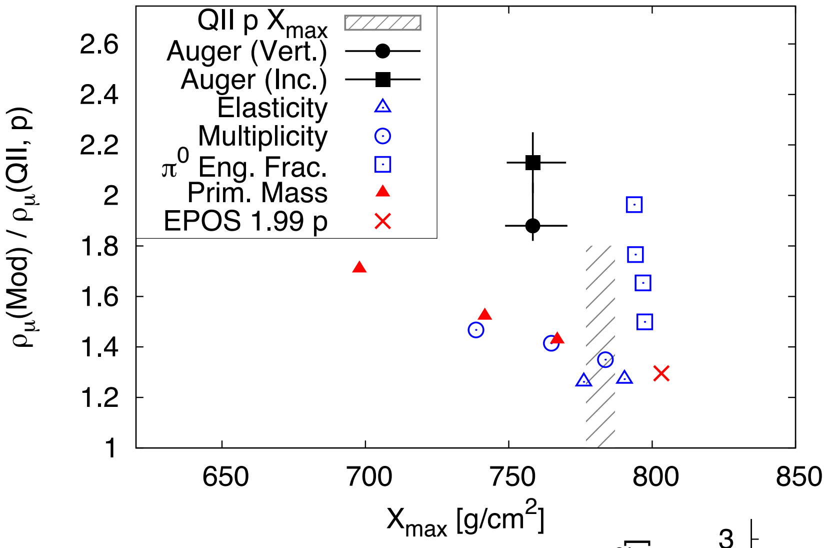
Particle physics with the upgraded Auger Observatory

Results on muon number of showers still not understood, important effect missing in models?



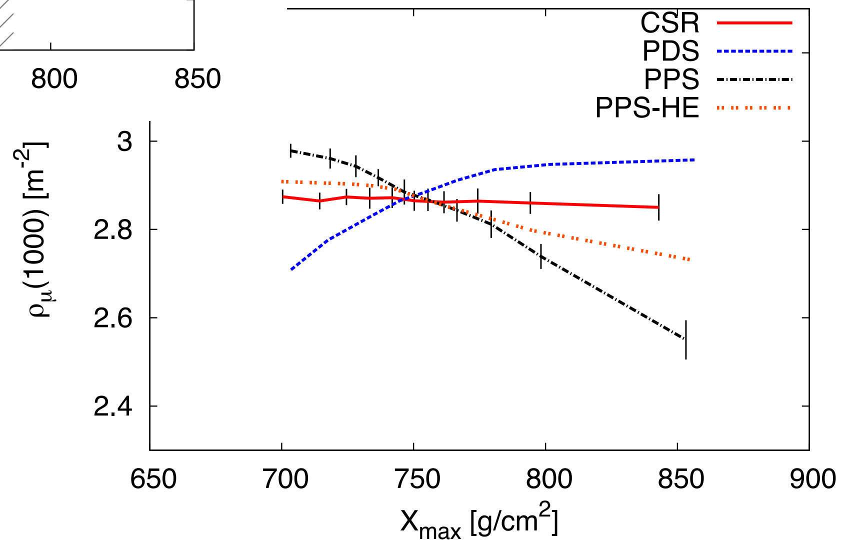
(Auger Collab. Phys. Rev. D91, 2015 & ICRC 2015)

Example of power of upgraded detectors



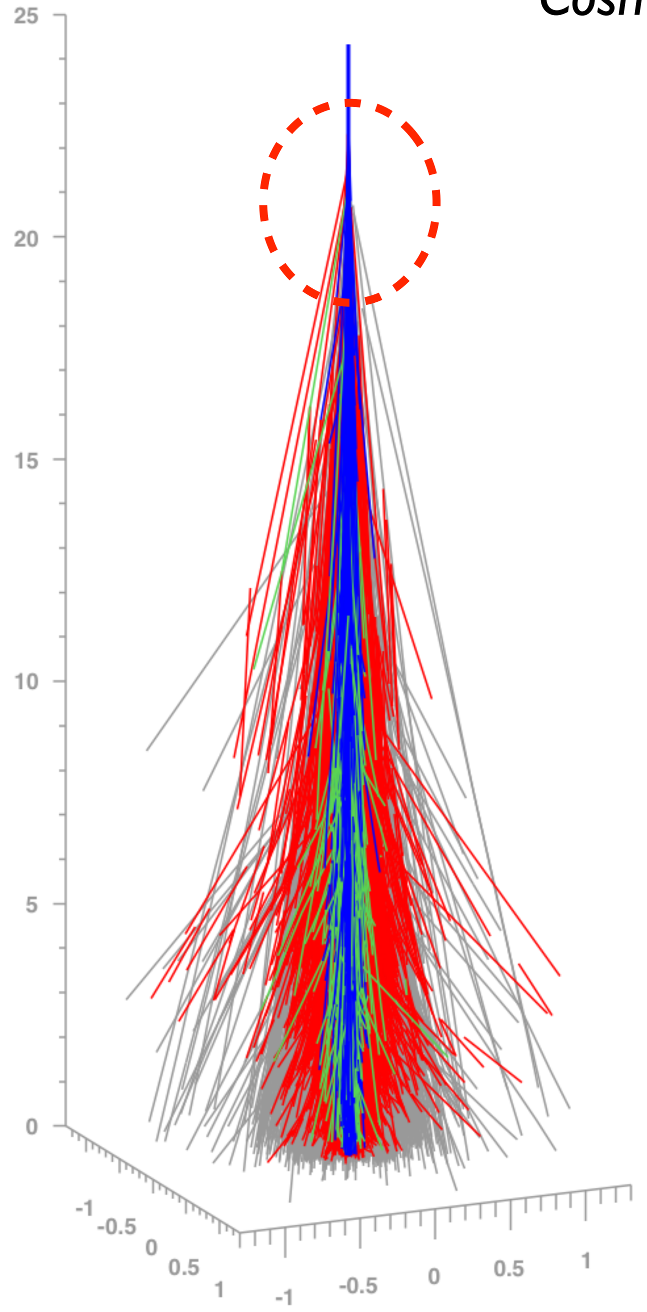
Correlations between X_{max} and muon density

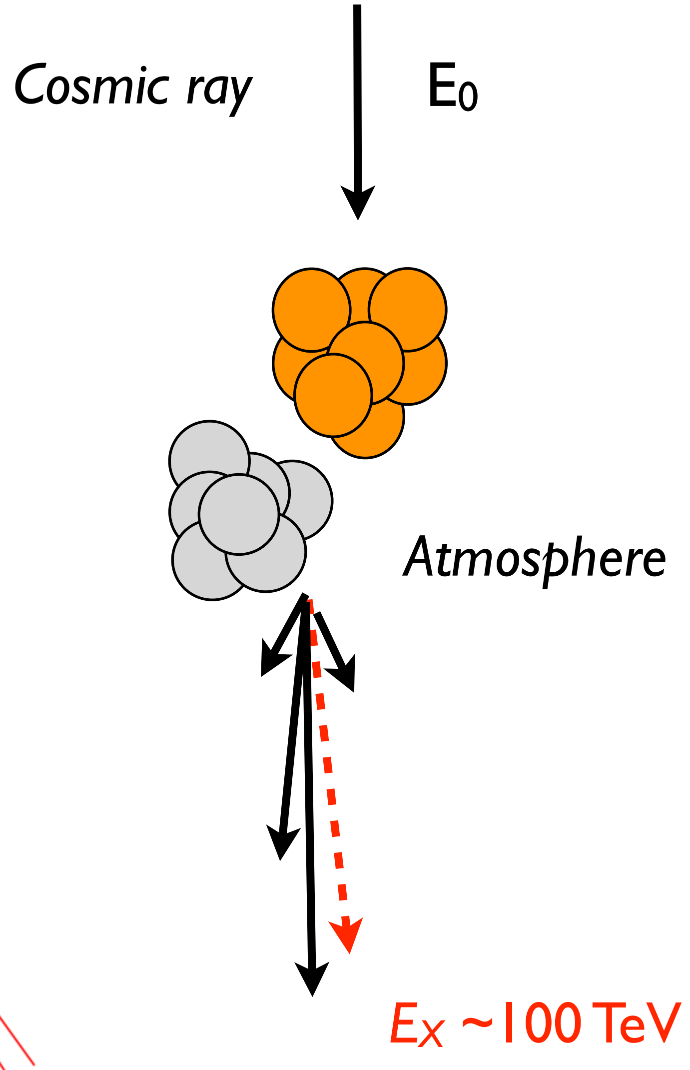
(Allen & Farrar, 1307.7131)

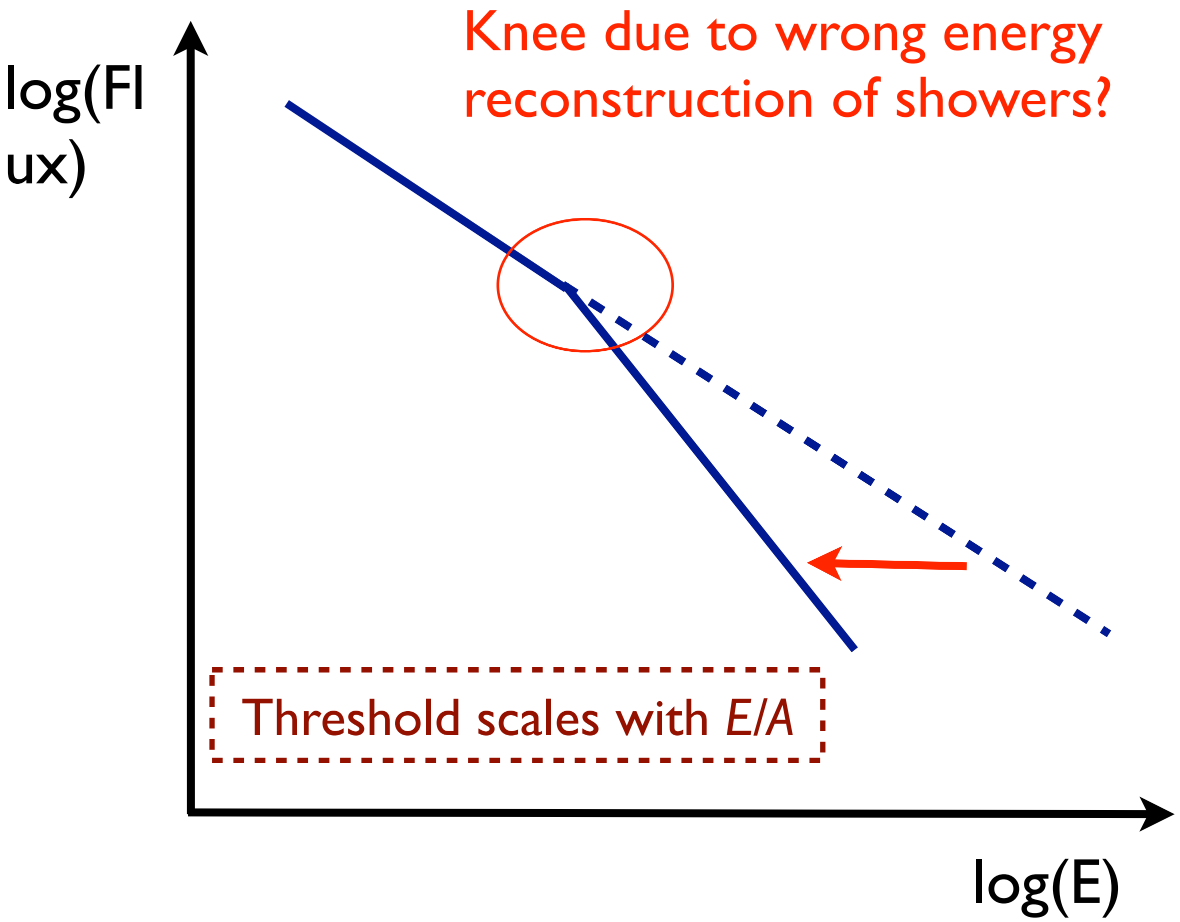


Exotic models for the knee

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

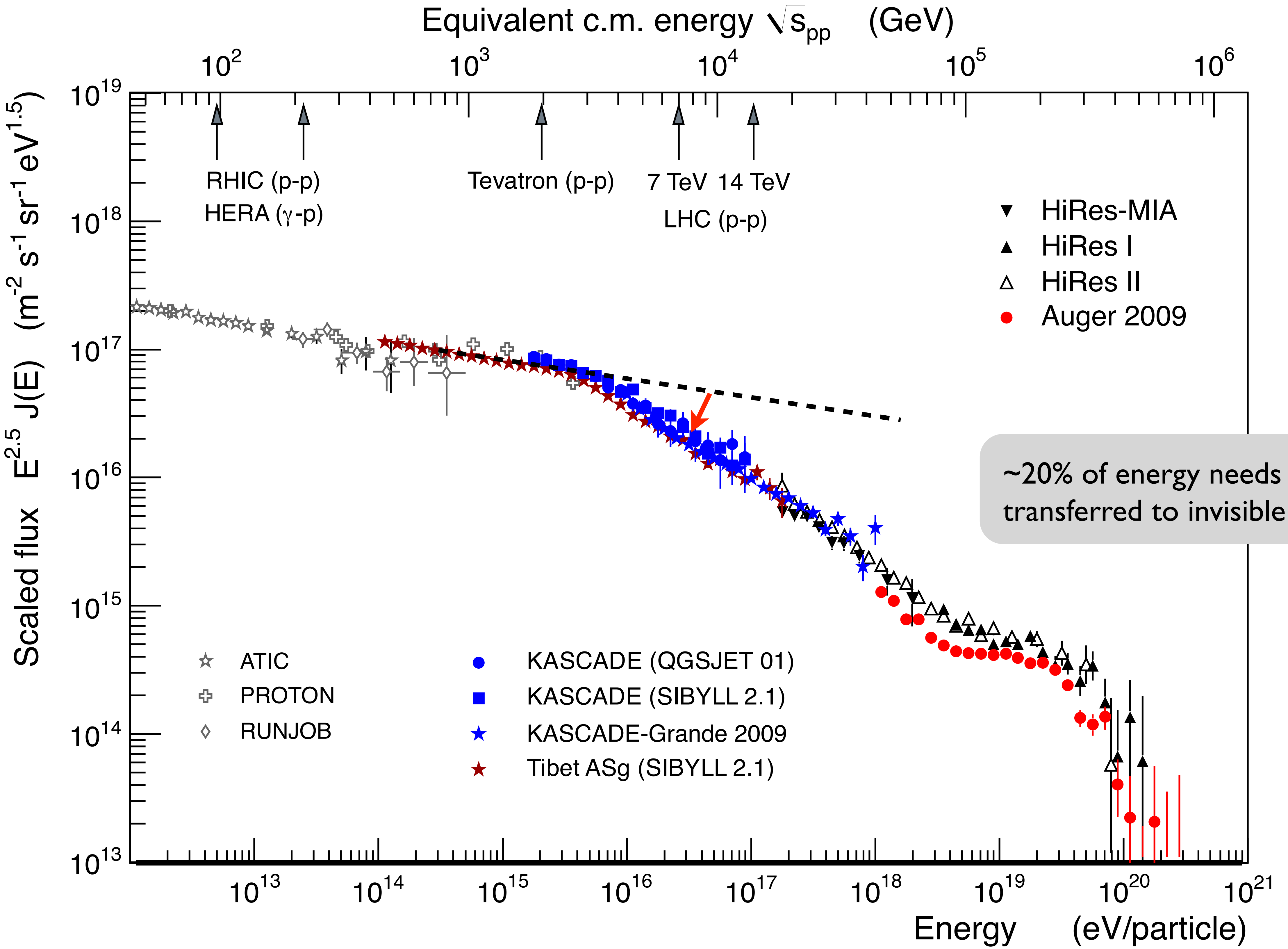






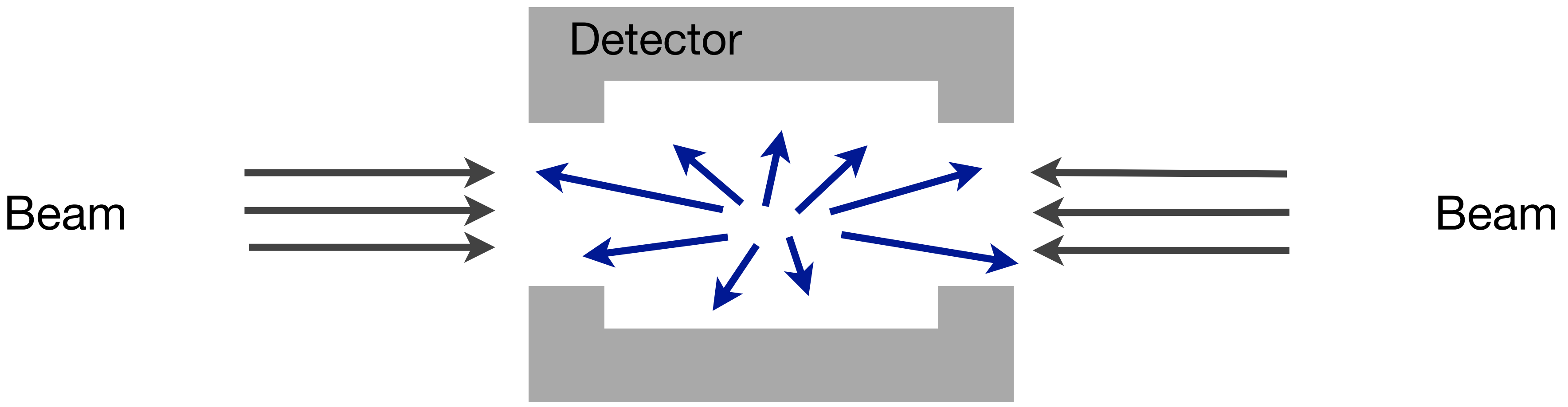
New physics: scaling with nucleon-nucleon cms energy

LHC data probe the region beyond the knee

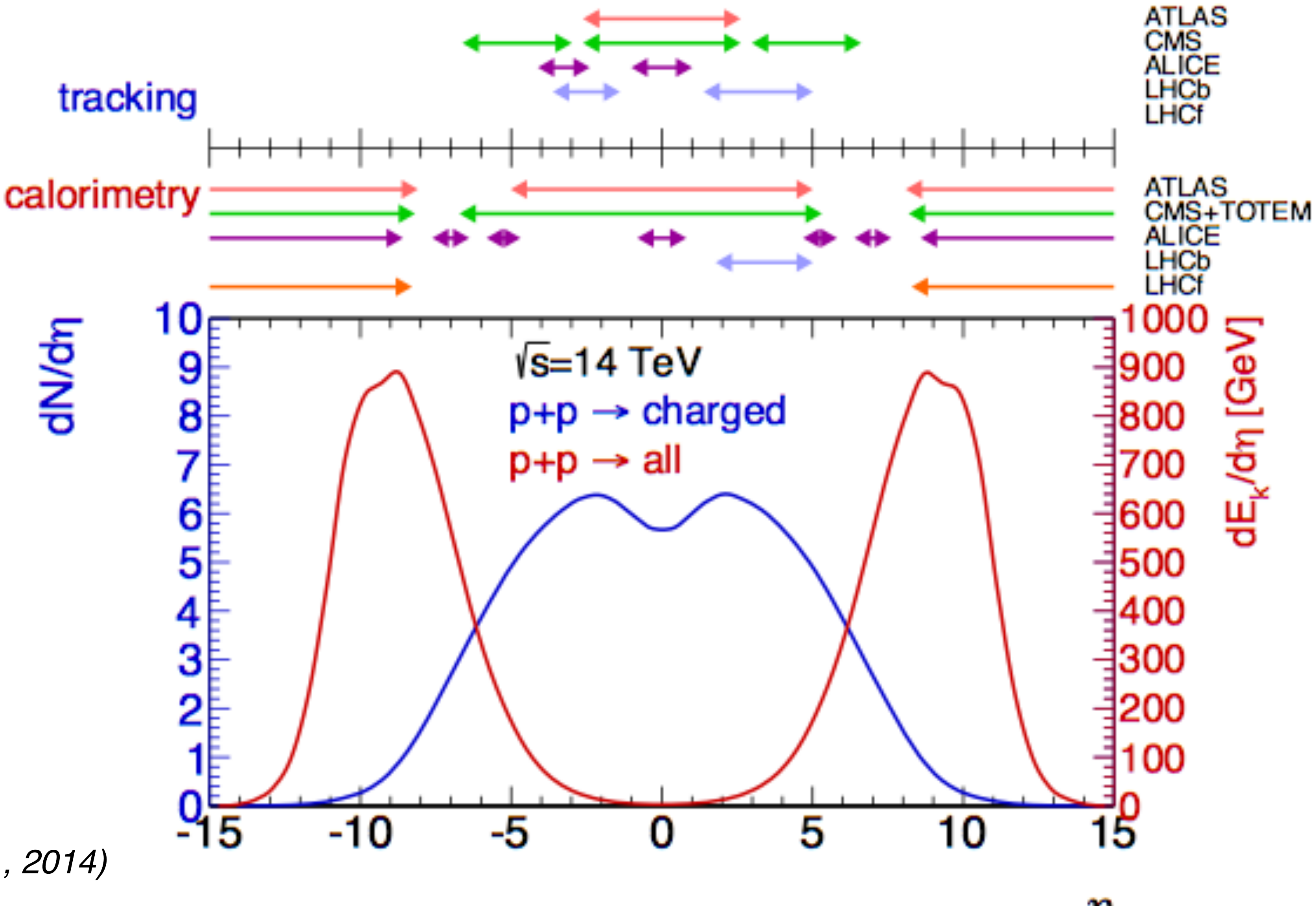


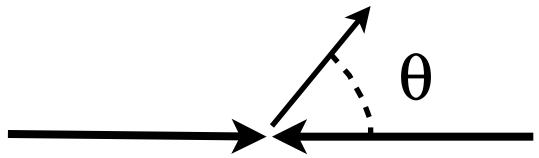
~20% of energy needs to be transferred to invisible channel

Problem of limited phase space coverage



Collider setup



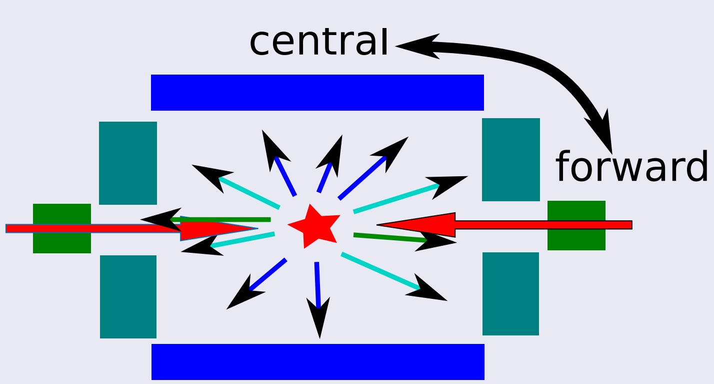


$$\eta = -\ln \tan \frac{\theta}{2}$$

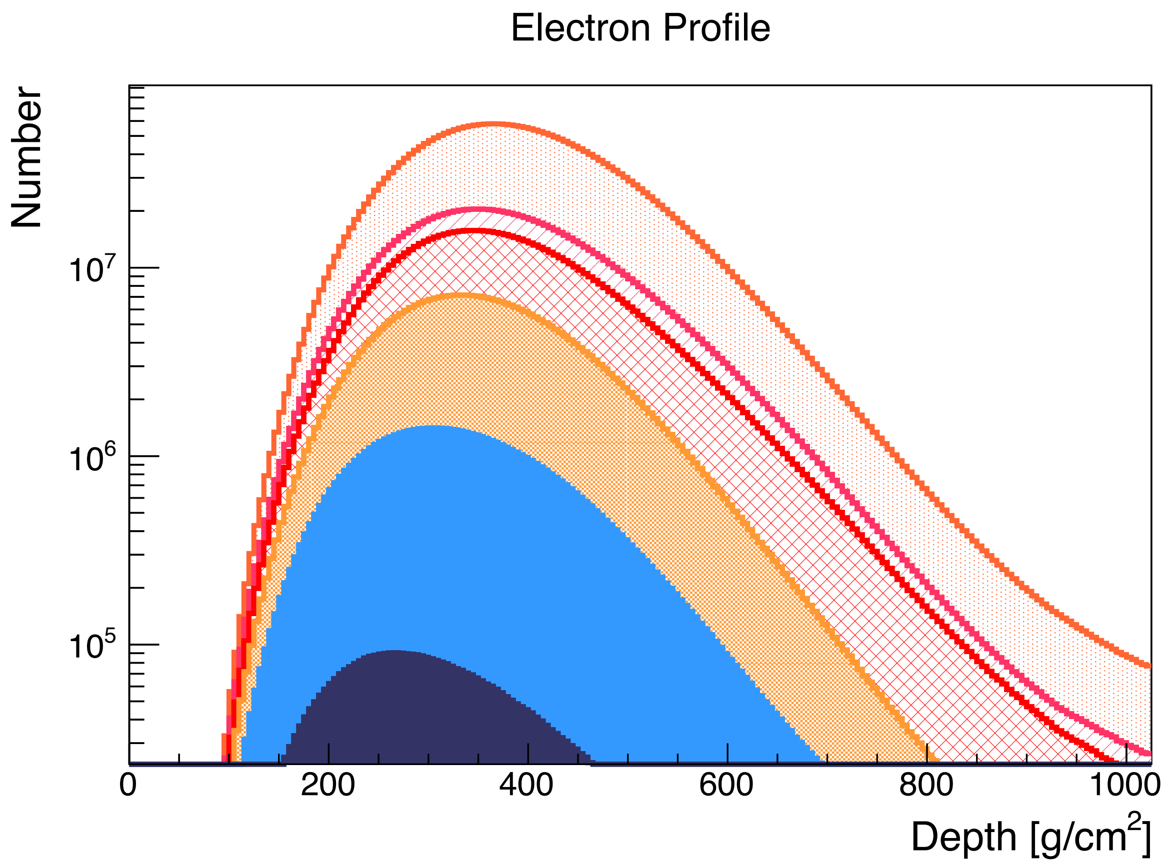
Air showers: Particles of highest energy most important

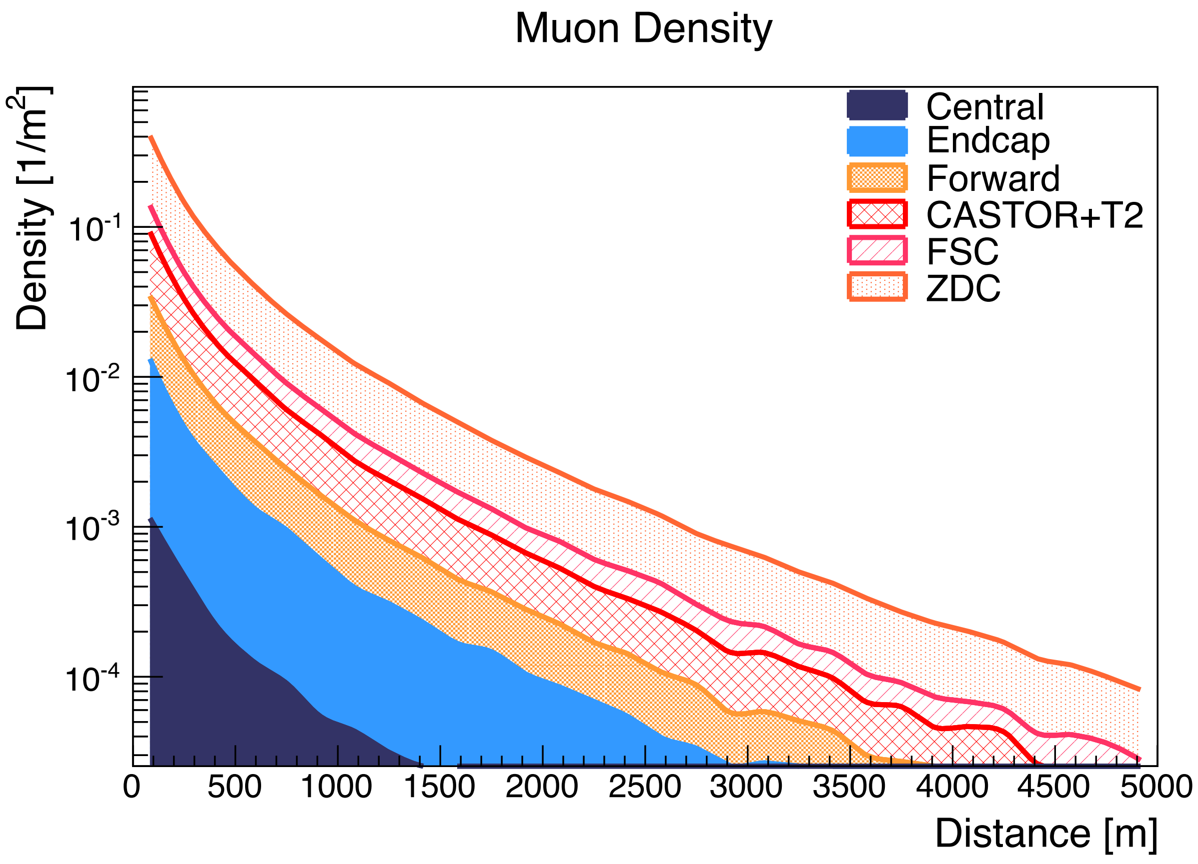
(Salek et al., 2014)

Example: generic LHC detector coverage



- Central ($|\eta| < 1$)
- Endcap ($1 < |\eta| < 3.5$)
- Forward ($3 < |\eta| < 5$), HF
- CASTOR+T2 ($5 < |\eta| < 6.6$)
- FSC ($6.6 < |\eta| < 8$)
- ZDC ($|\eta| > 8$), LHCf

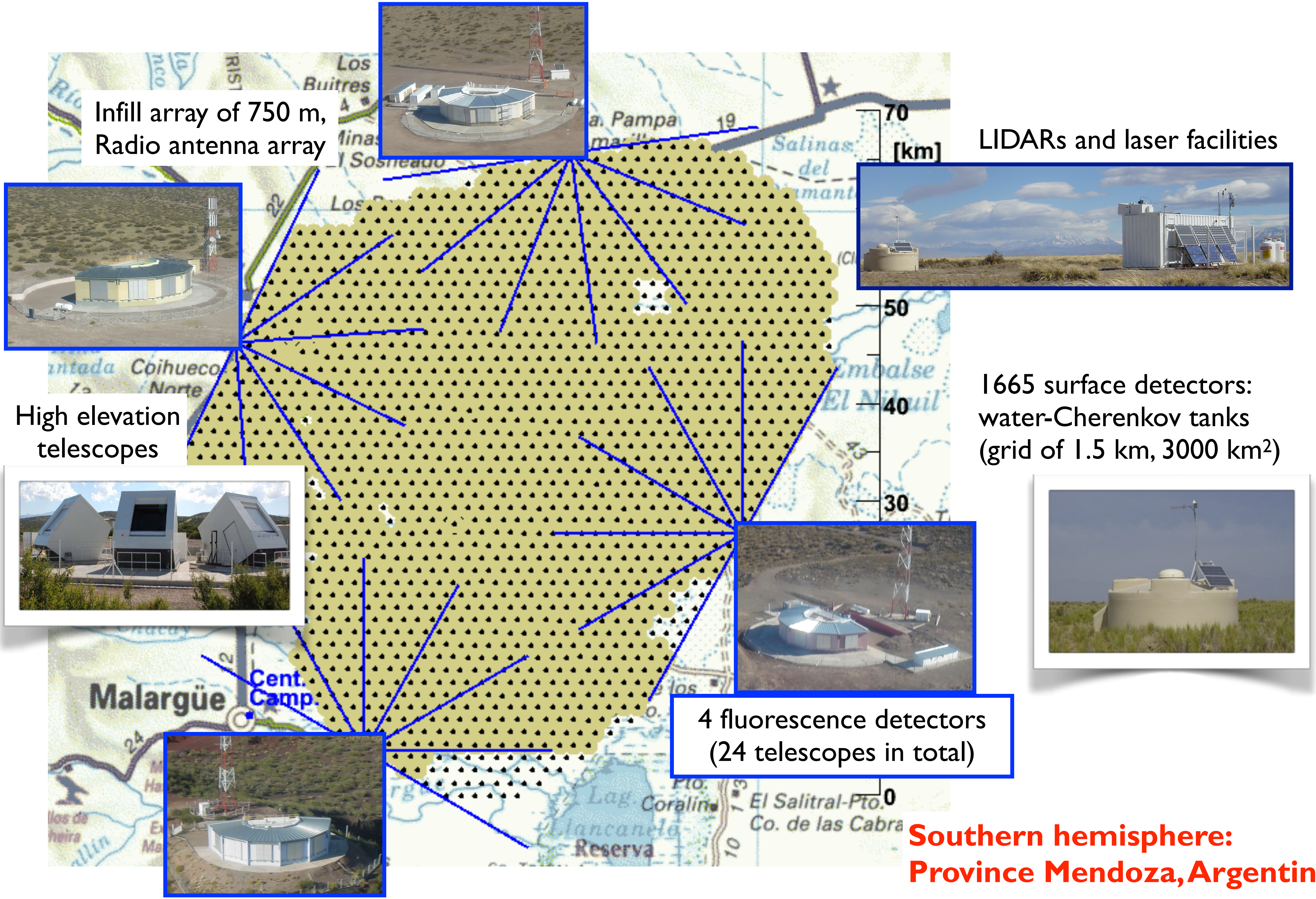




More than 50% of all measured secondaries from particles of $\eta > 8$

(Ulrich, DPG meeting 2014)

The Pierre Auger Observatory



Infill array of 750 m, Radio antenna array

LIDARs and laser facilities

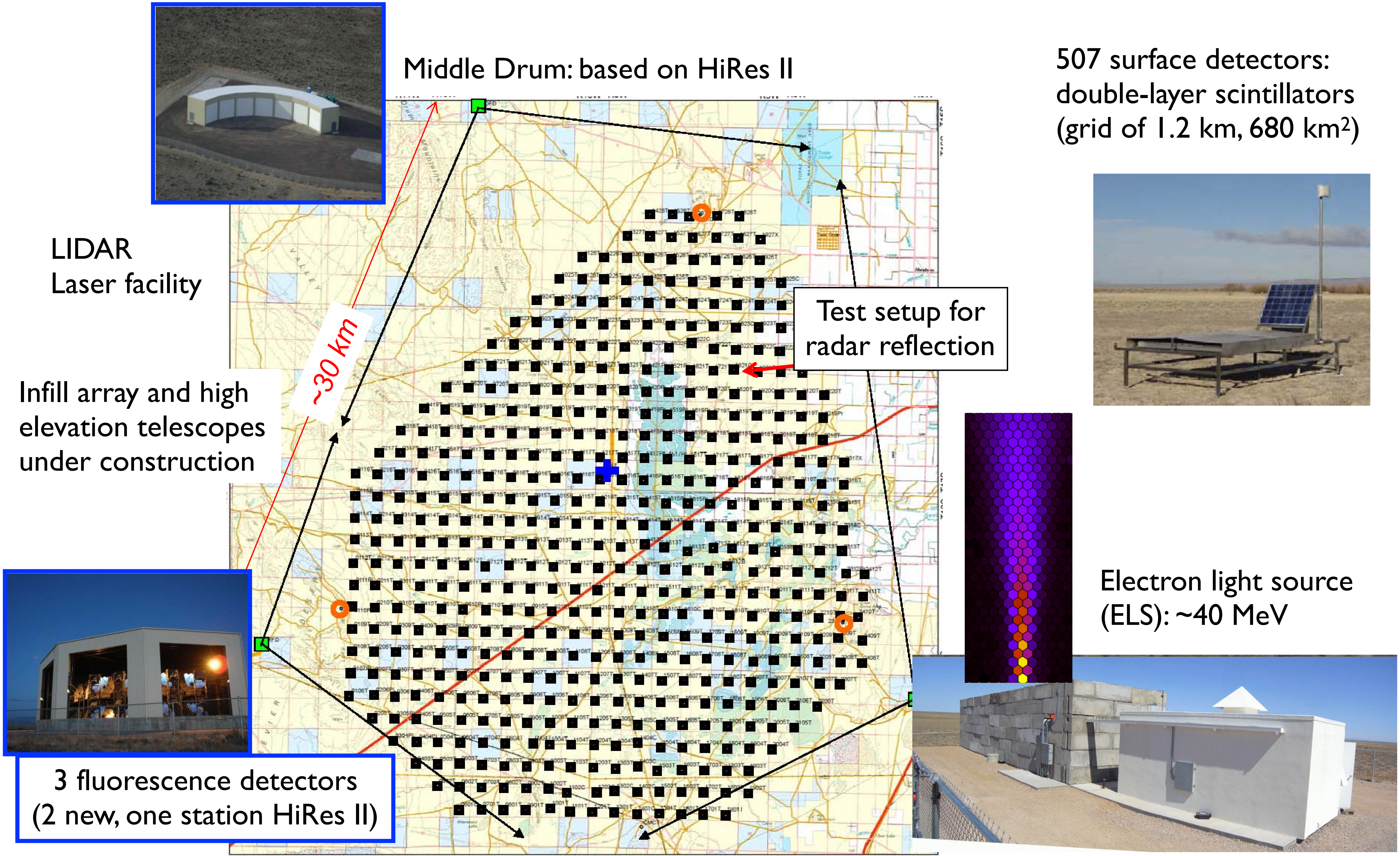
High elevation telescopes

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

4 fluorescence detectors (24 telescopes in total)

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

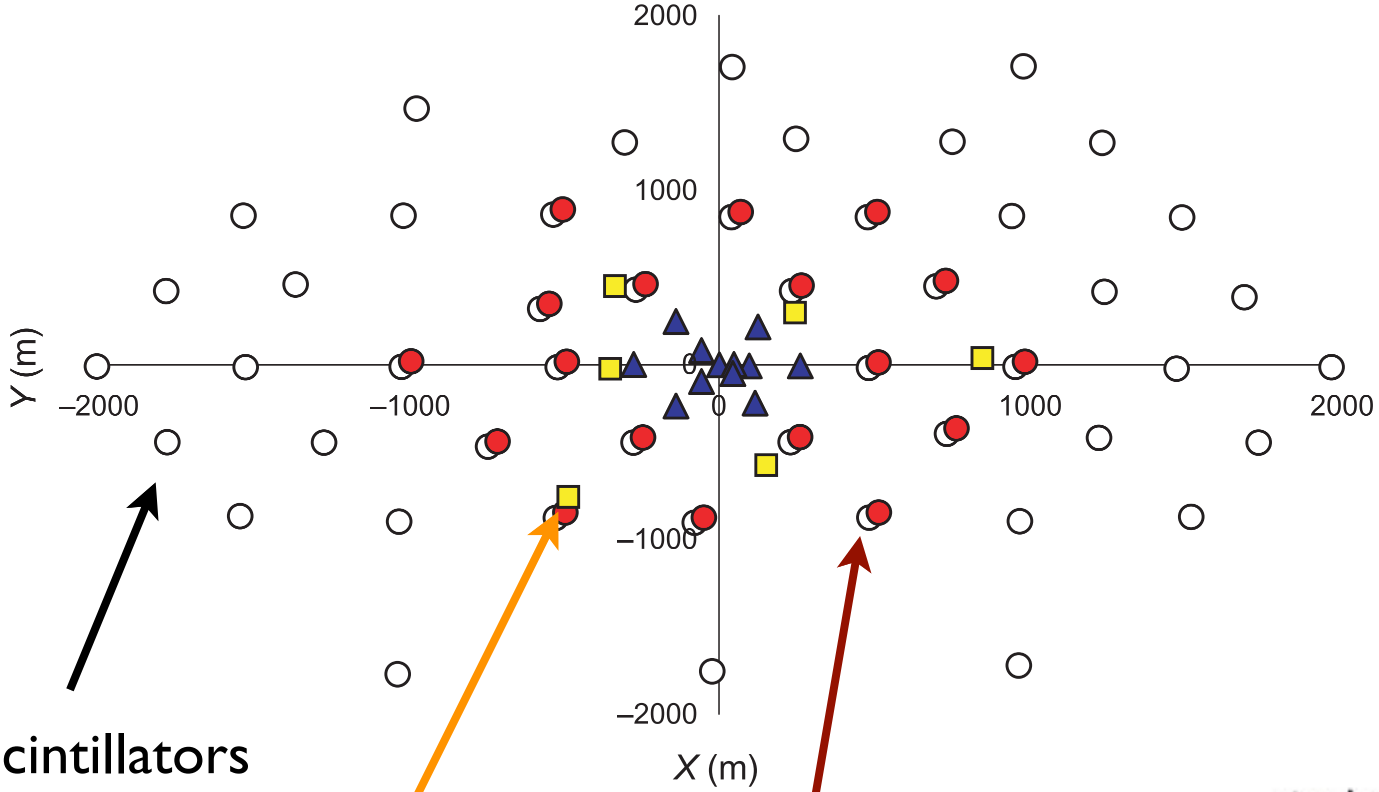
Infill array and high
elevation telescopes
under construction

Electron light source
(ELS): ~40 MeV

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

Northern hemisphere: Utah, USA

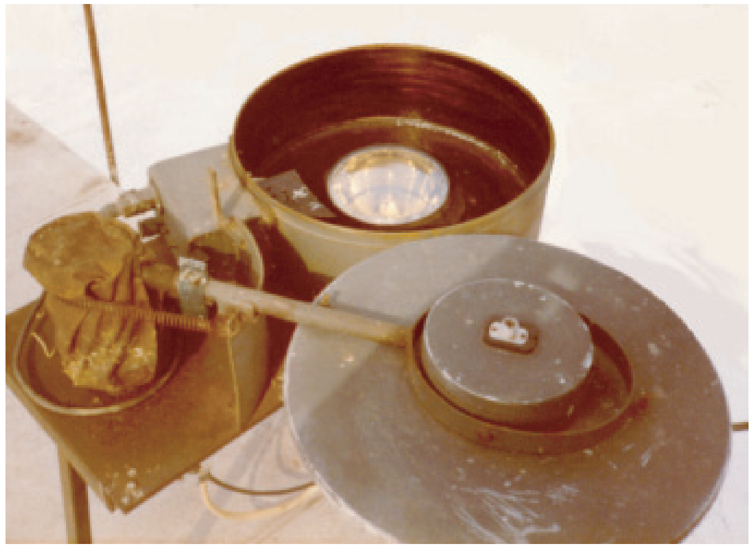
Yakutsk air shower array

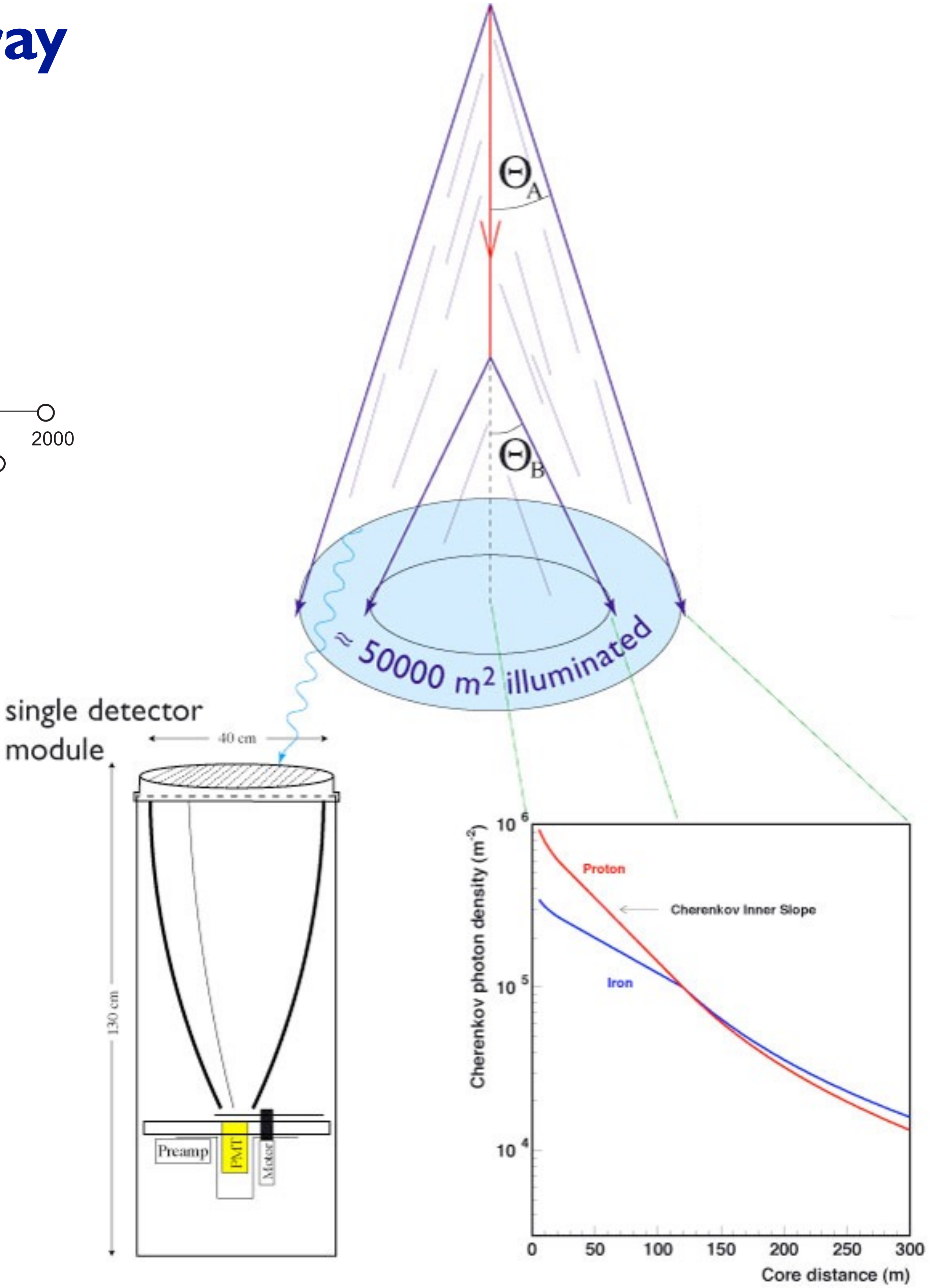


Scintillators

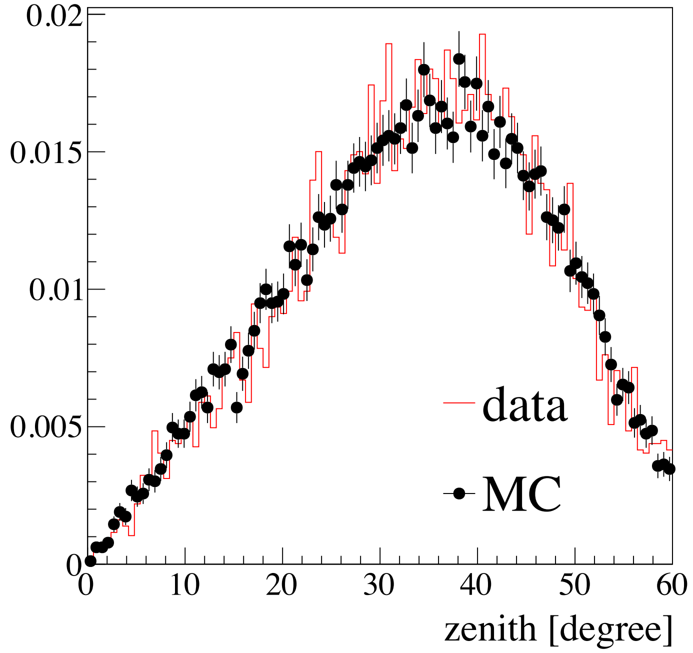
Muon detectors

Air Cherenkov detectors

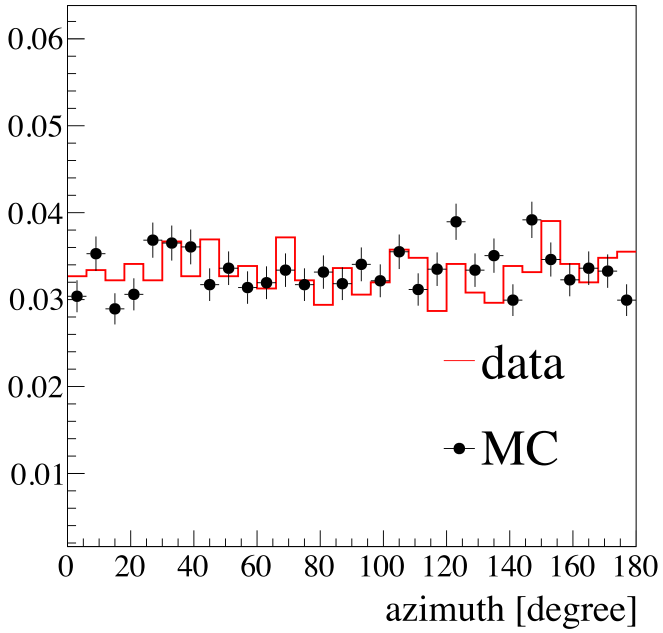




Auger event simulation for surface array

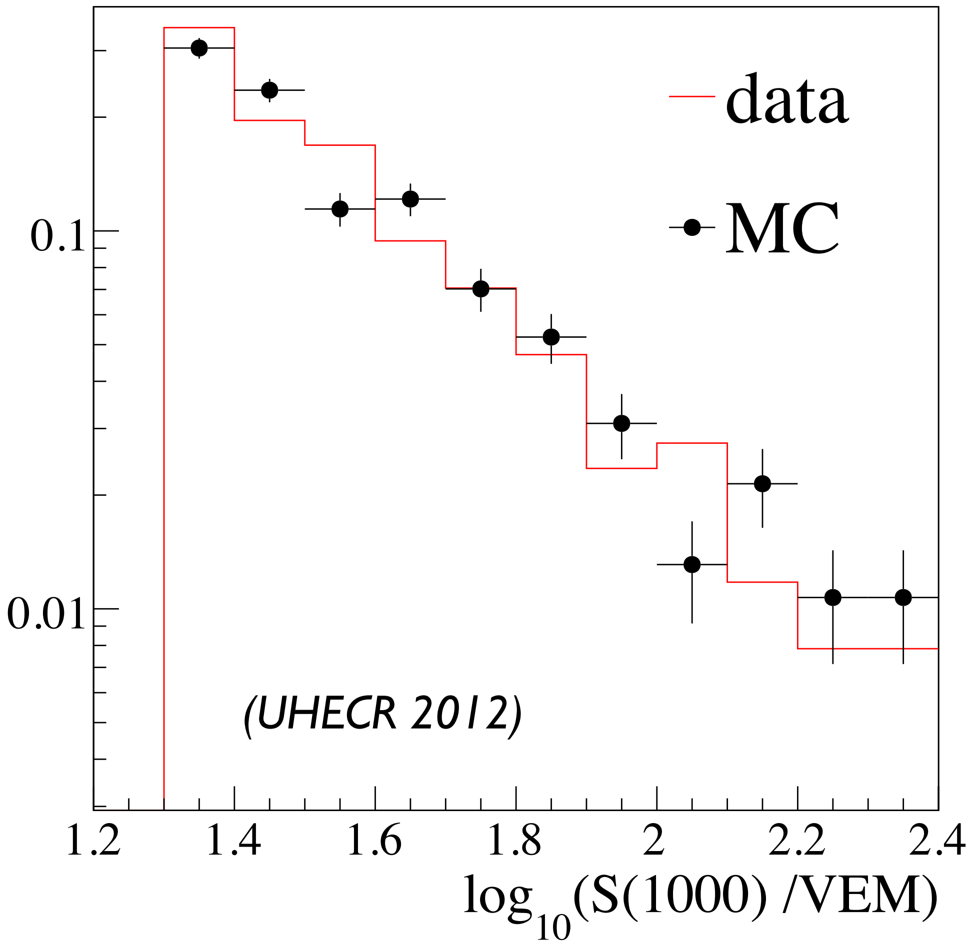


Zenith angle

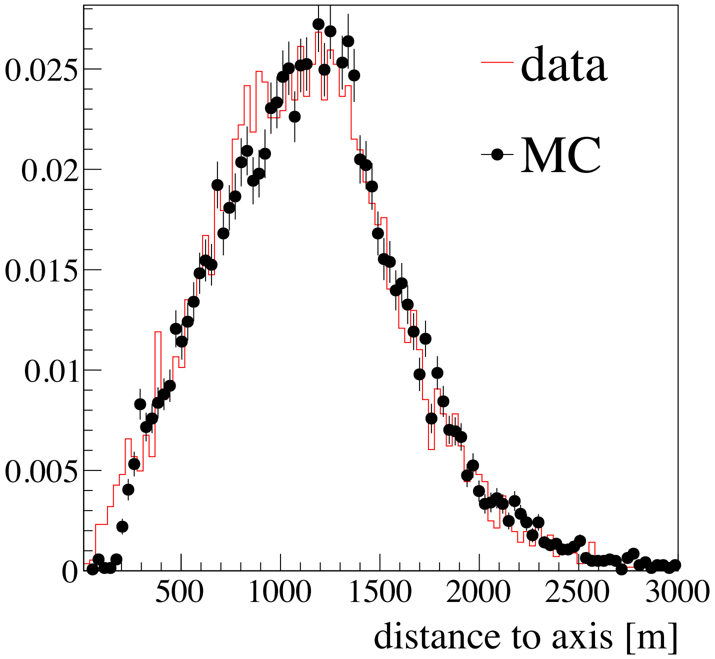


Azimuth angle

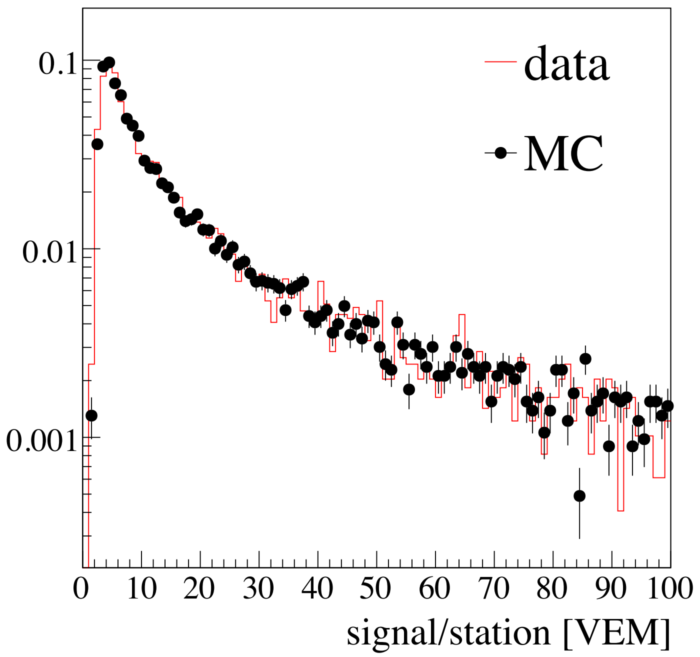
CORSIKA + full detector simulation (50% p + 50% Fe)



(UHECR 2012)



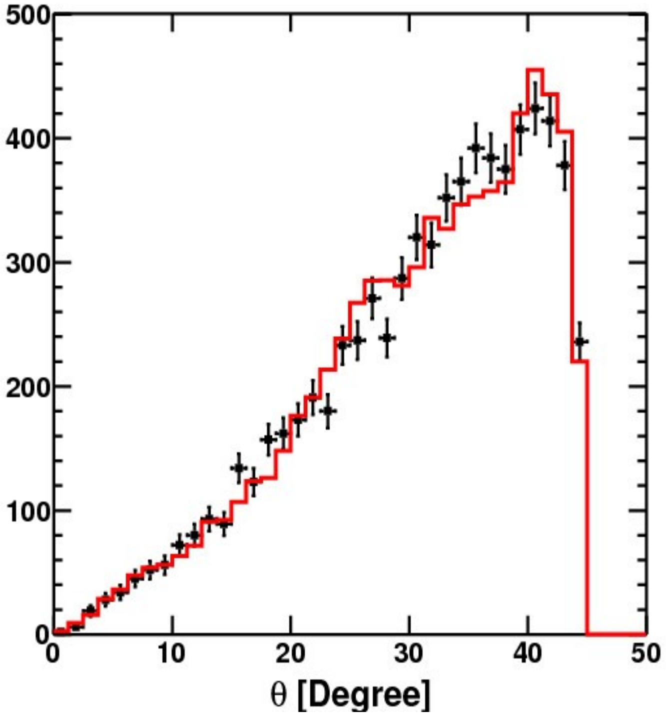
Distance of triggered stations



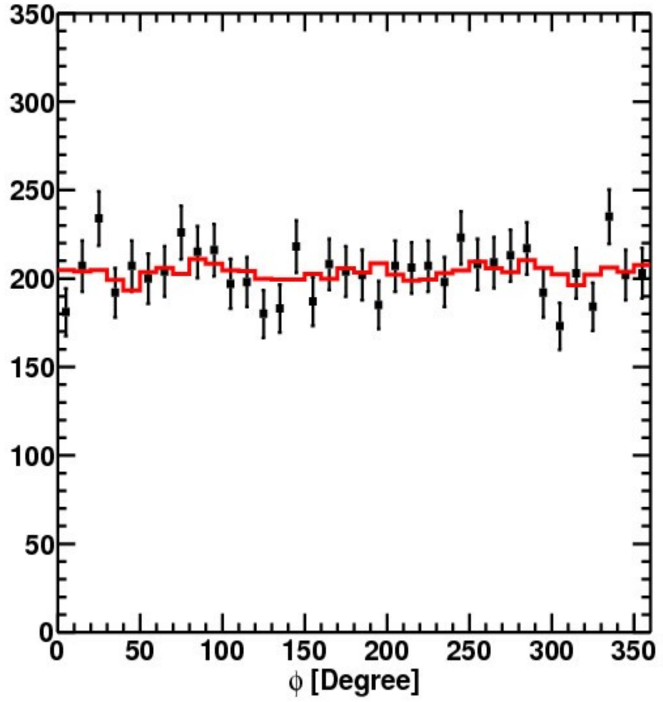
Signal per station

Very good agreement

TA event simulation for surface array

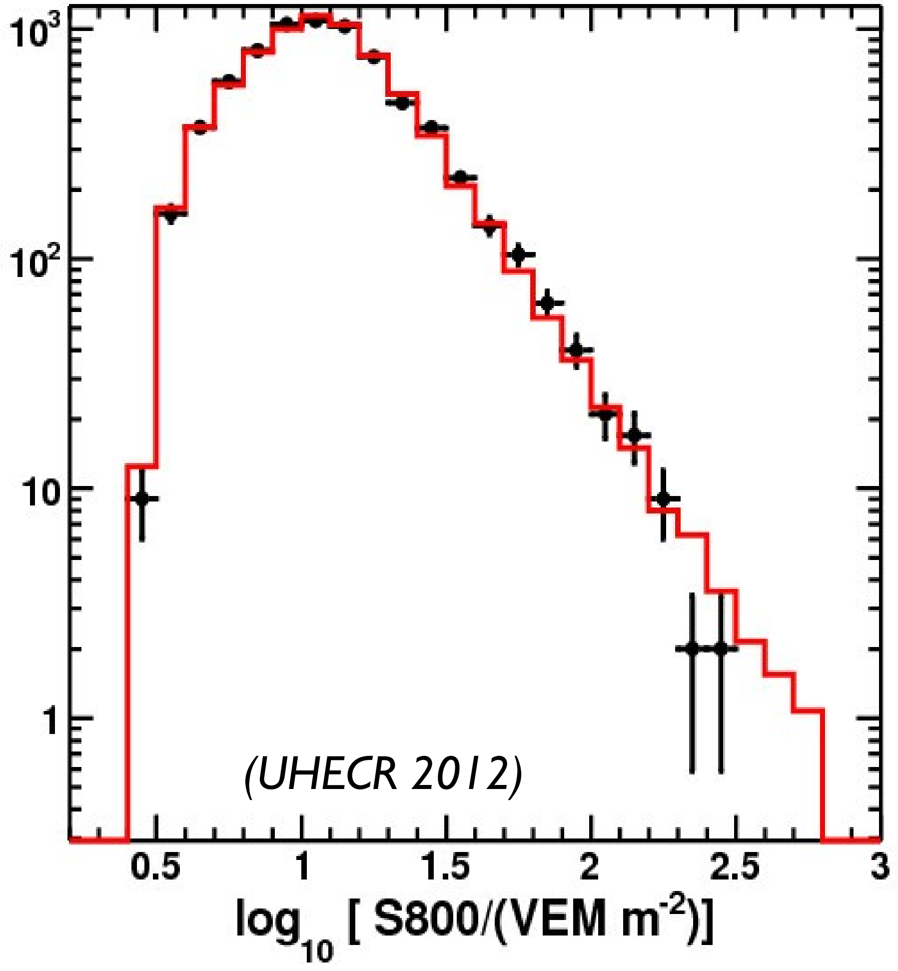


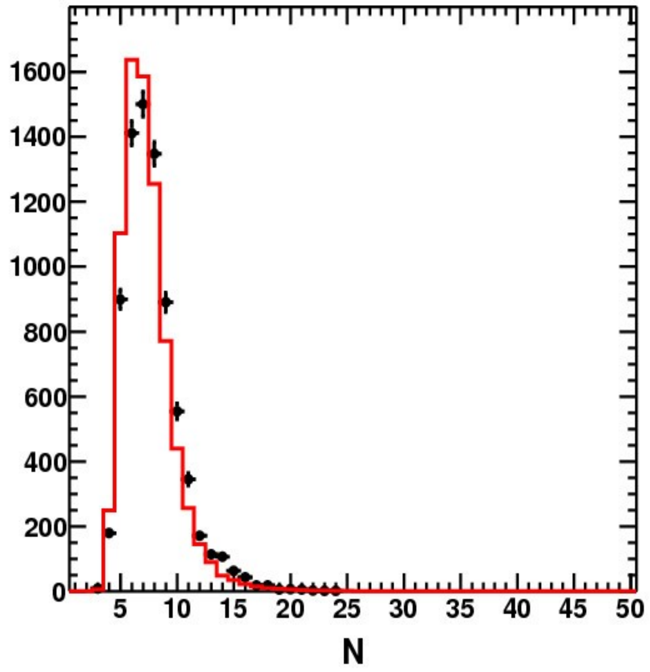
Zenith Angle



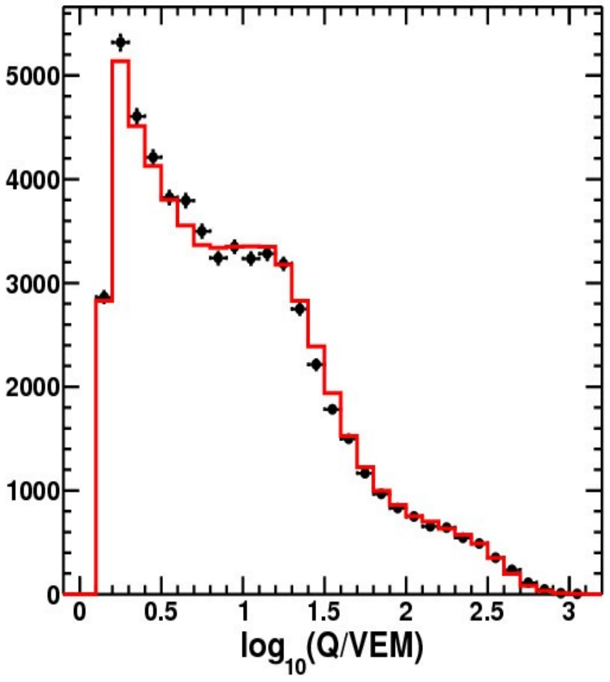
Azimuth Angle

CORSIKA + full detector simulation (proton primaries)





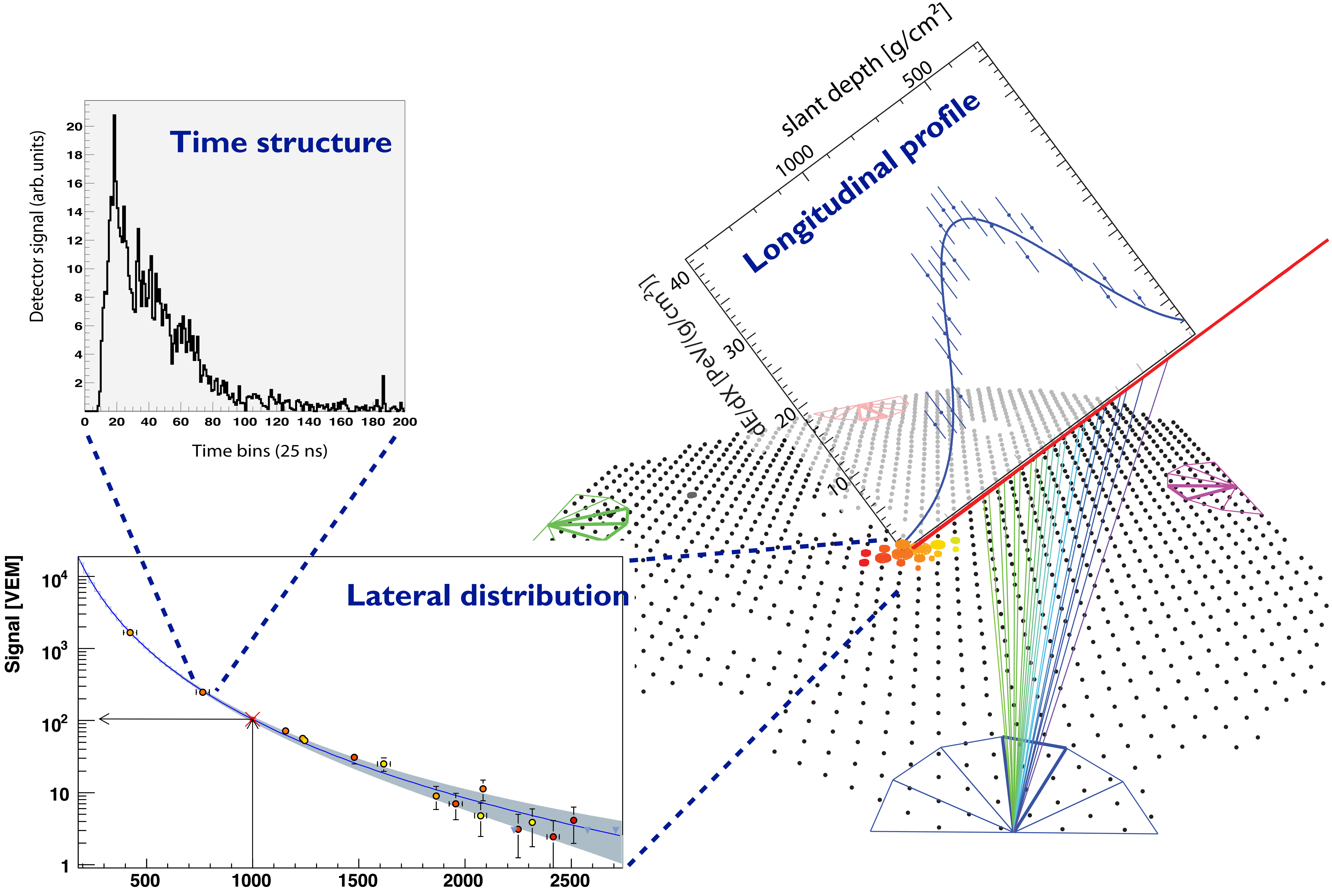
Number of Good Counters/Event



Charge/Counter/Event

Very good agreement

Several shower observables

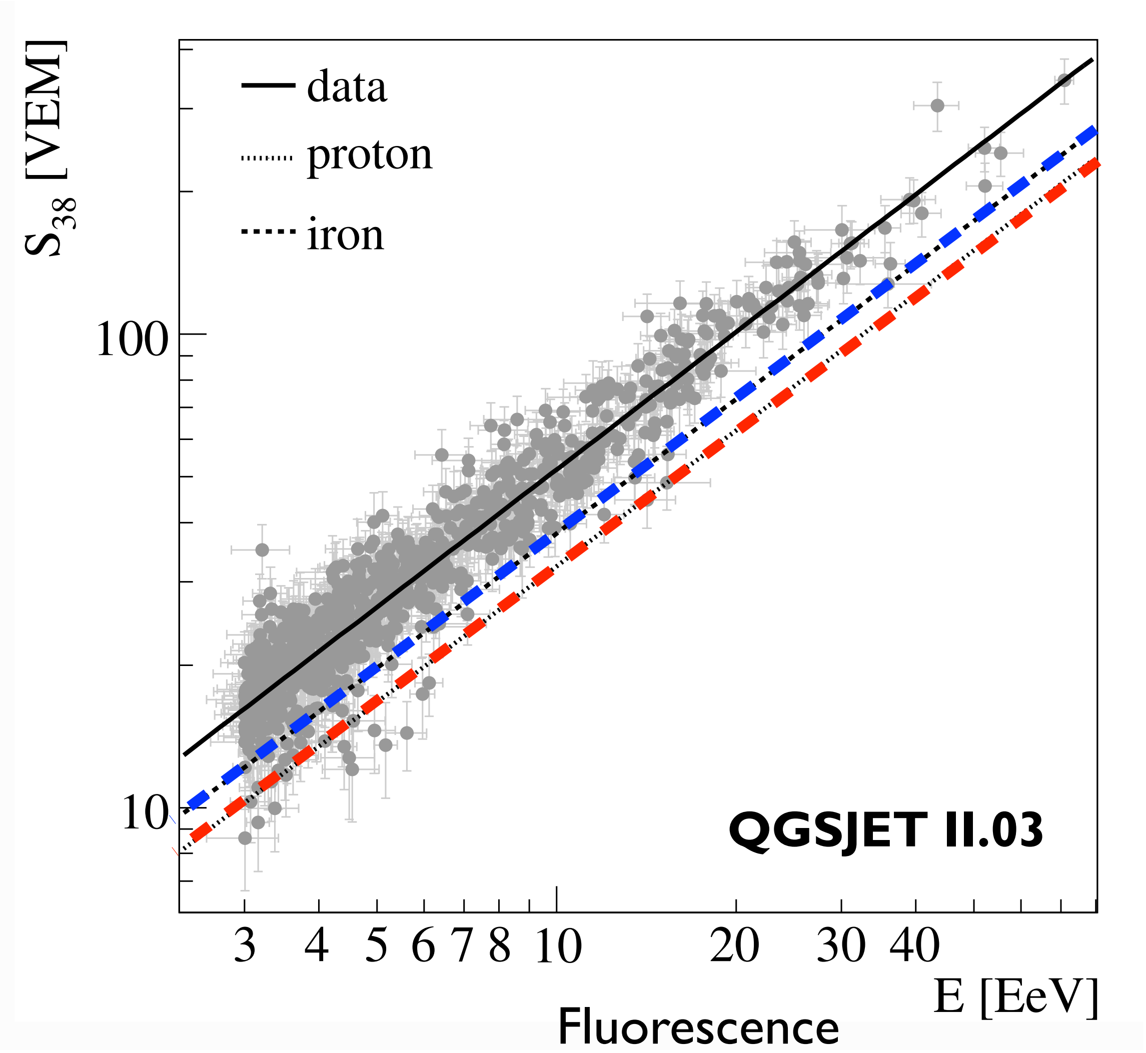


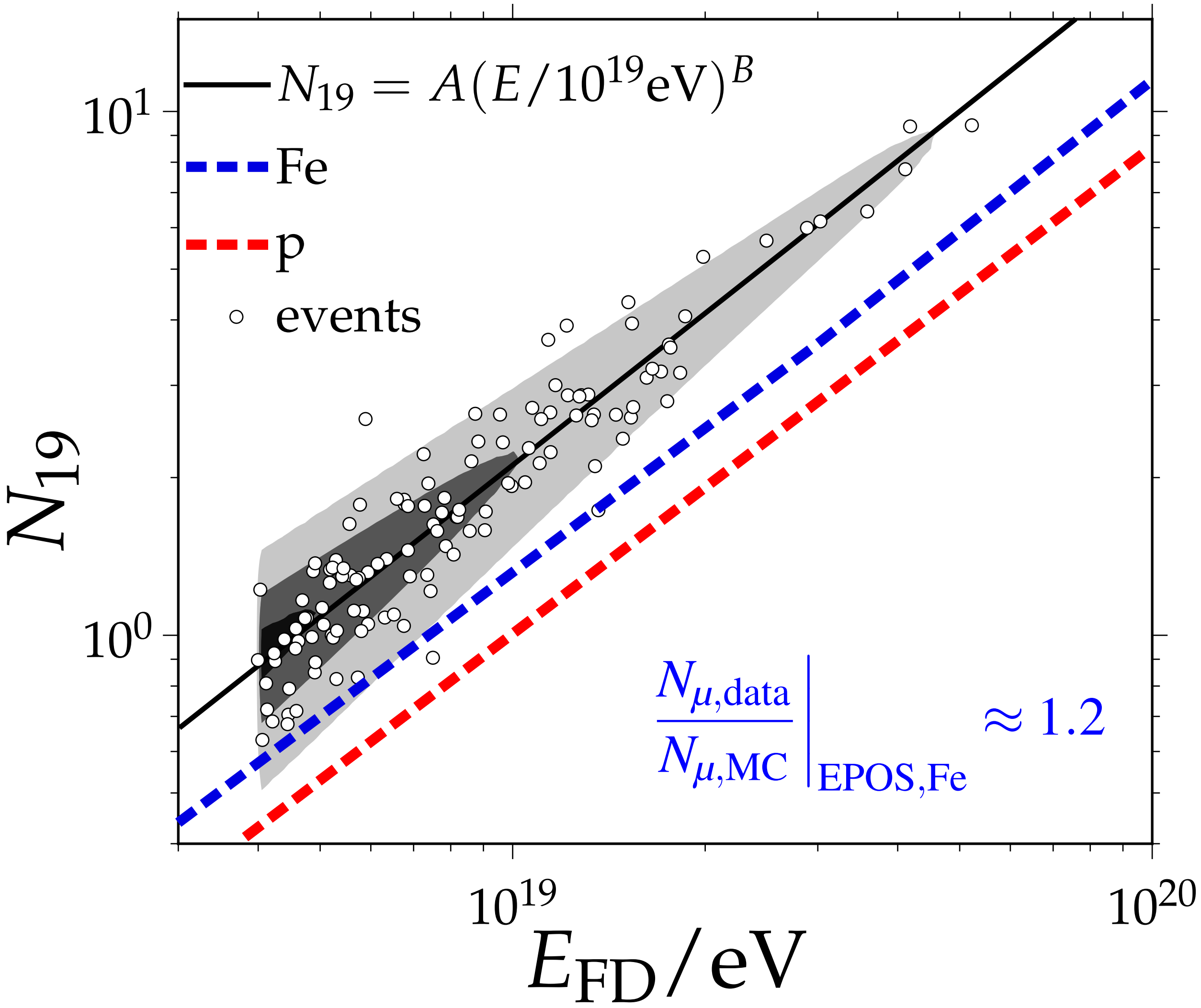
Example: event observed by Auger

Auger: comparison of surface detector signals

Showers up to 60° zenith angle

Inclined showers (muon dominated)





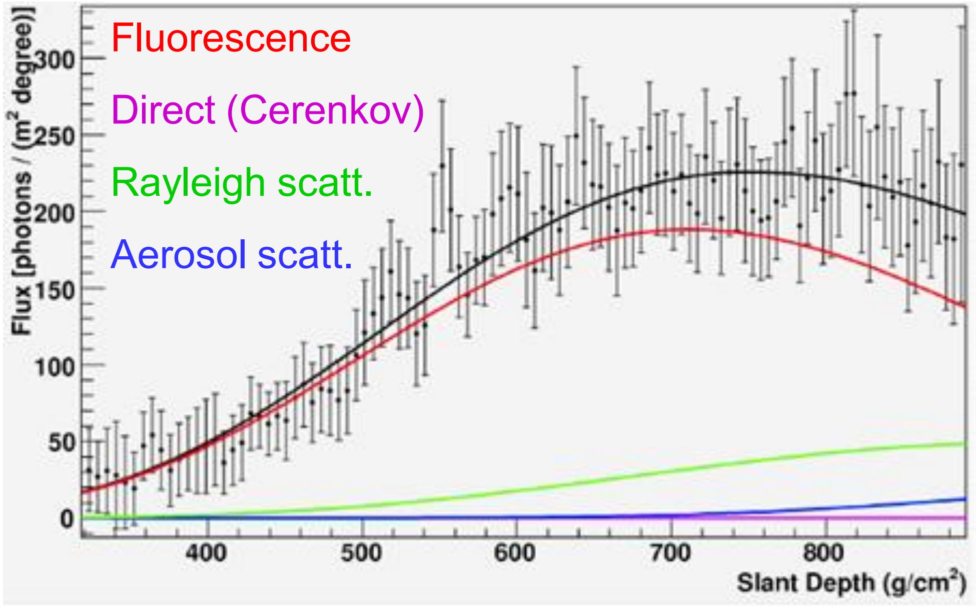
Discrepancy due mainly to muons

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

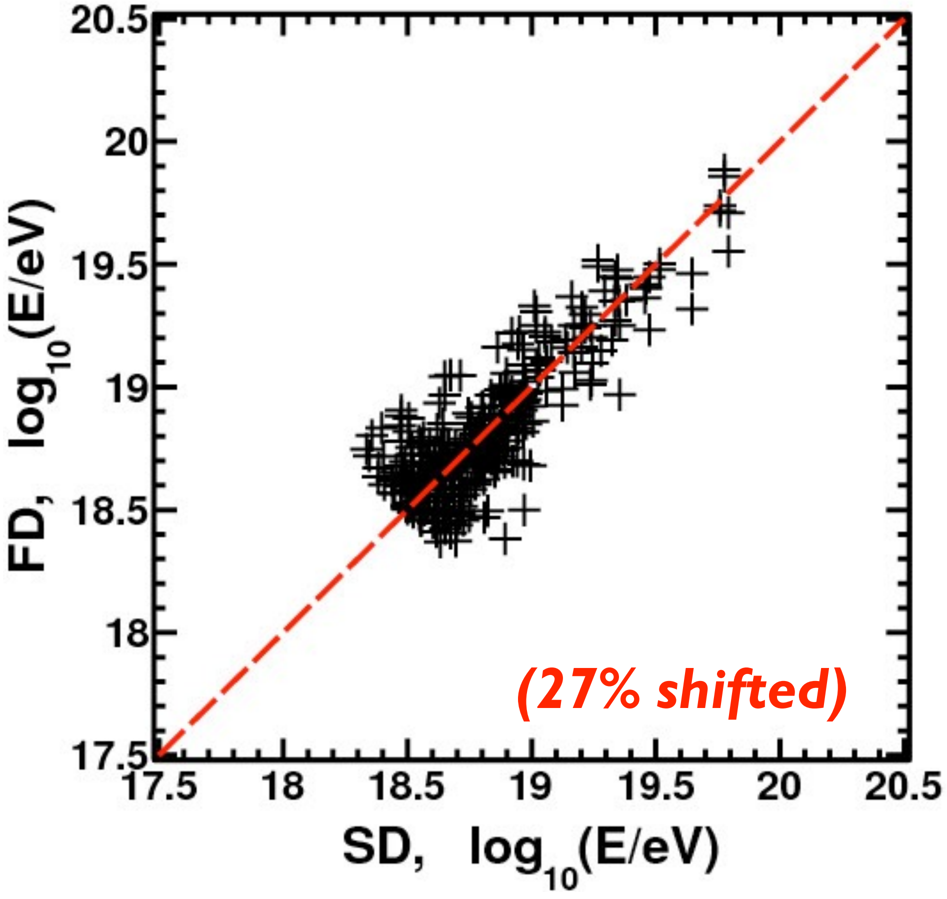
(Independent confirmation with several other observables)

(HadInt Working Group, UHECR 2012)

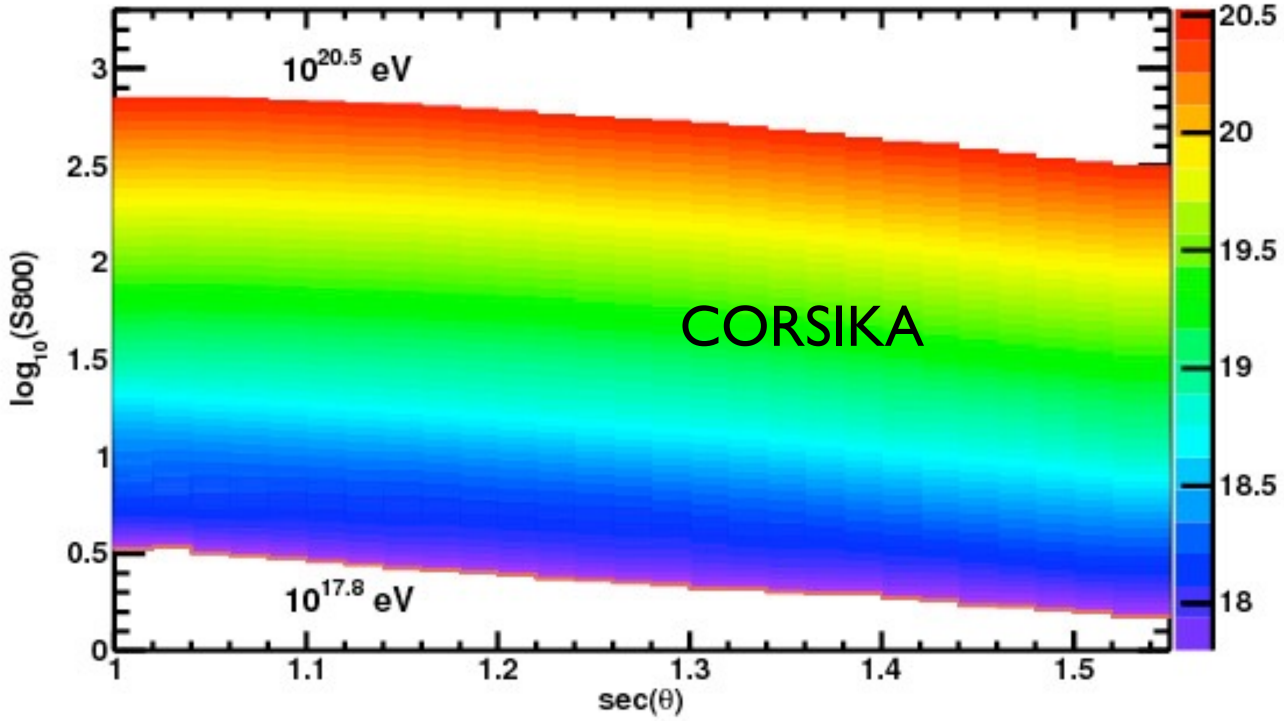
TA: comparison of surface detector signals



Energy derived from fluorescence light profile



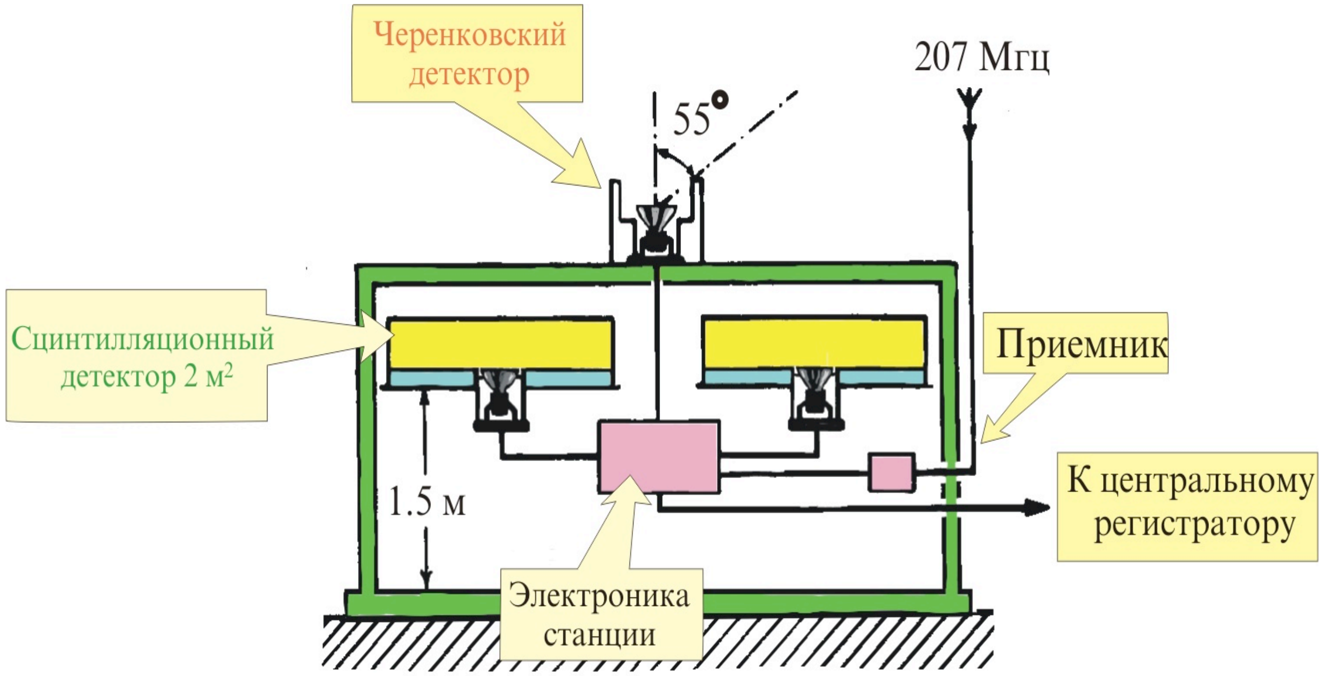
(27% shifted)

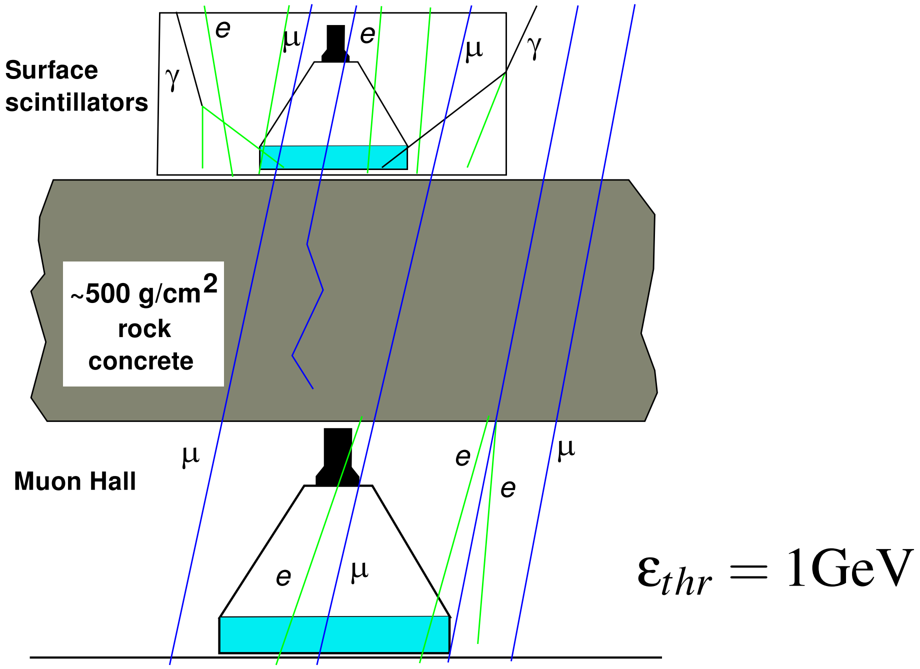


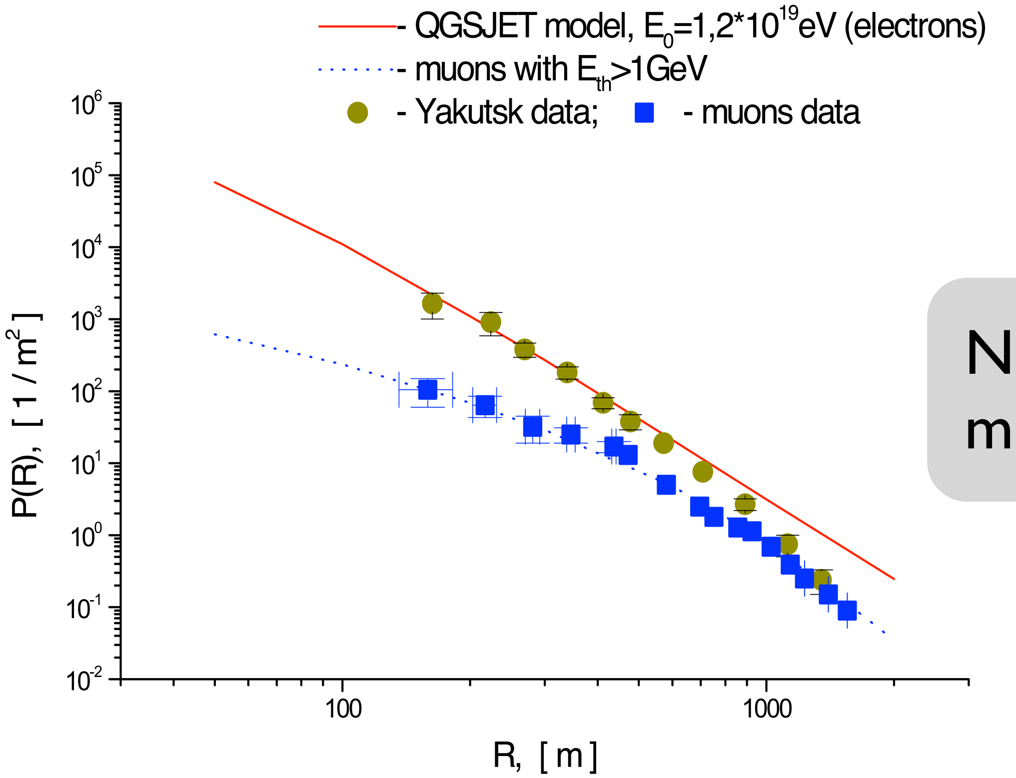
Simulated SD signal at 800m used to determine SD energy

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

Yakutsk: direct measurement of muons

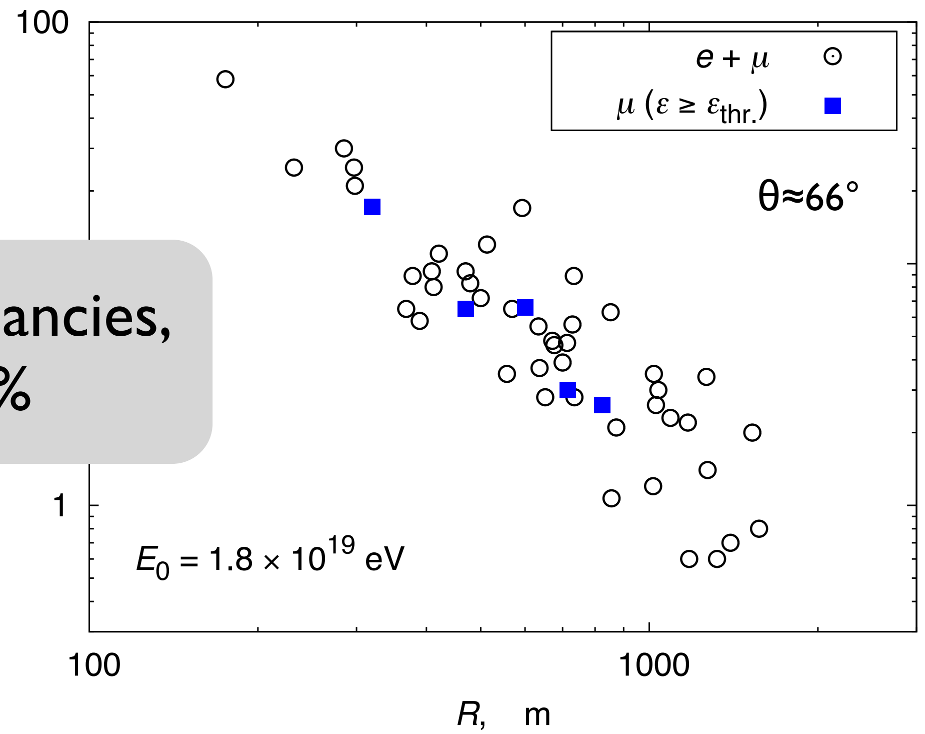






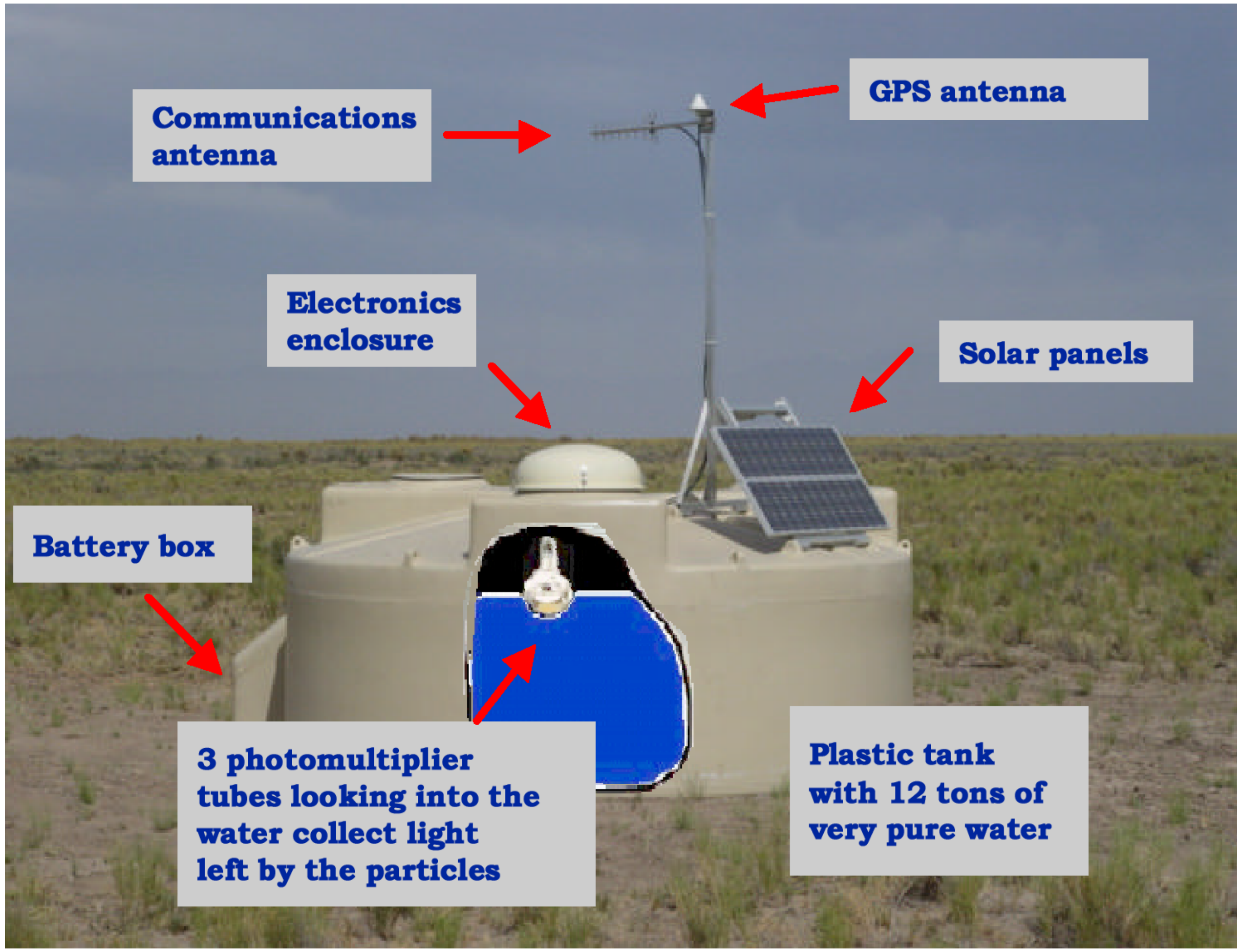
No significant discrepancies, muon deficit ~ 10-20%

Muons per m²



(Yakutsk Collab., UHECR 2012)

Comparison of surface detectors



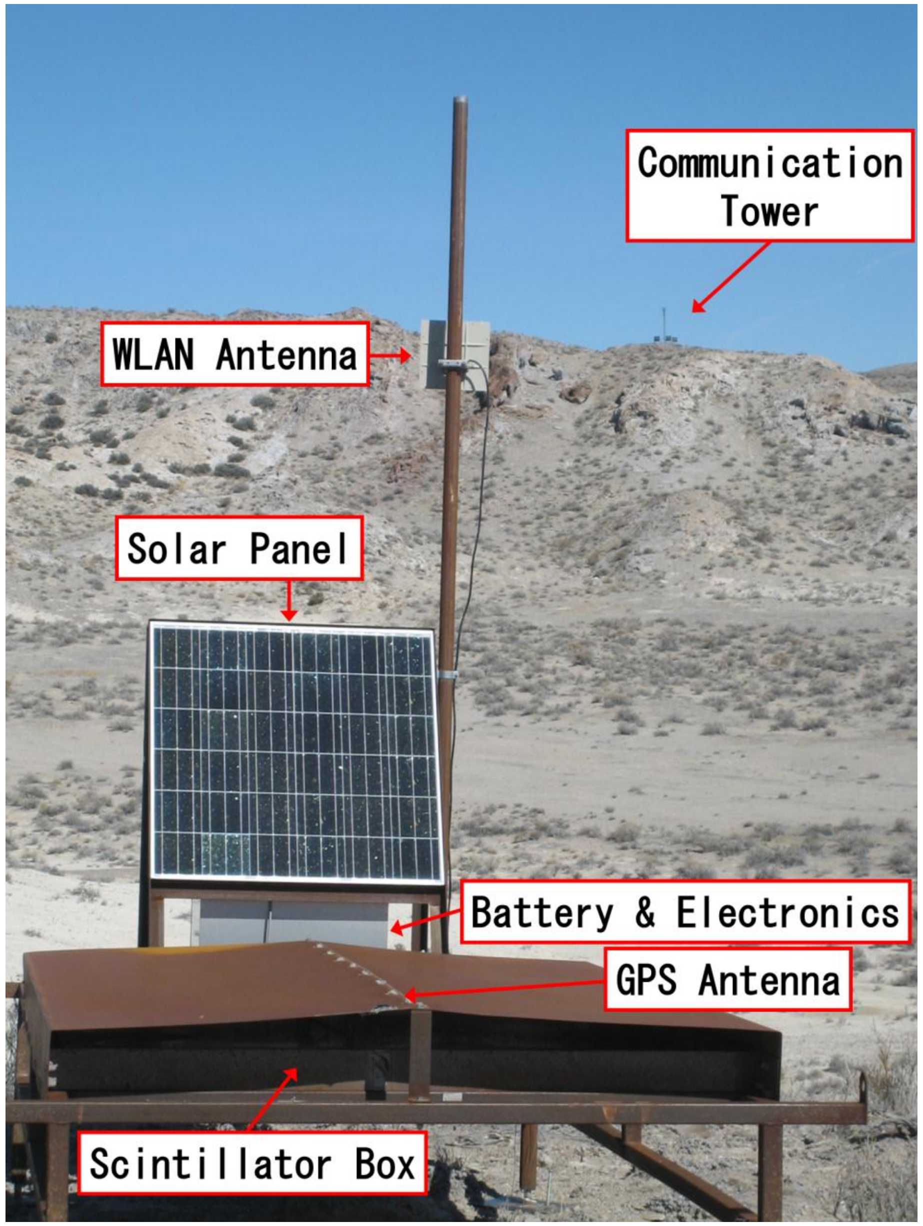
Auger: thick water-Cherenkov detectors

(large part of signal due to muons,
large acceptance to inclined showers)

Complementary surface detector arrays

Telescope Array: thin scintillators

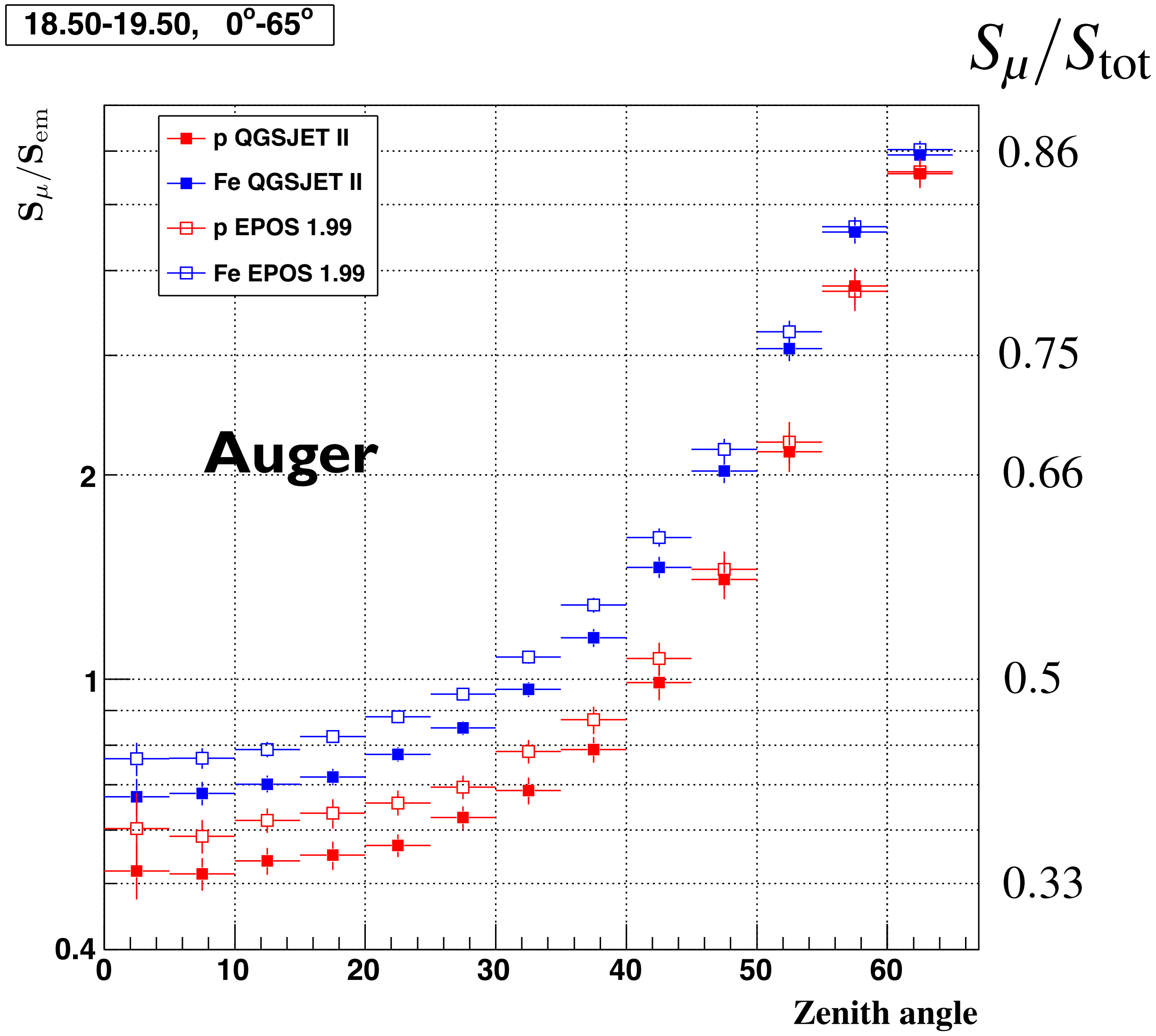
(main part of signal due to em. particles,
low sensitivity to muons)

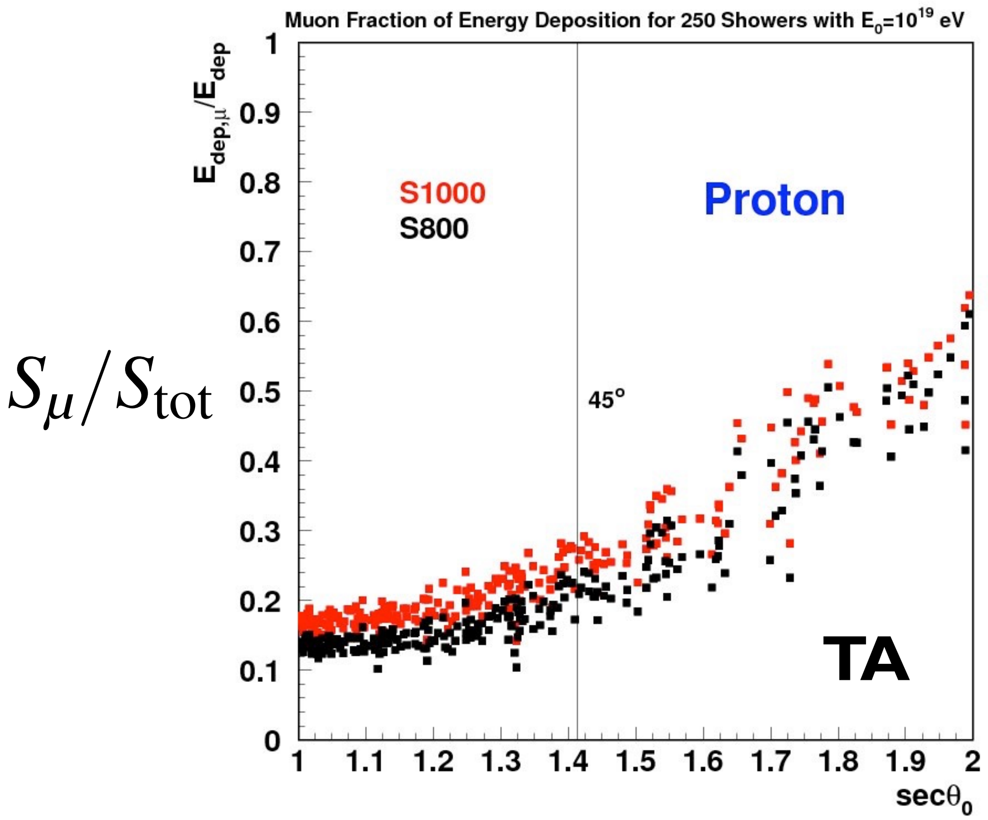


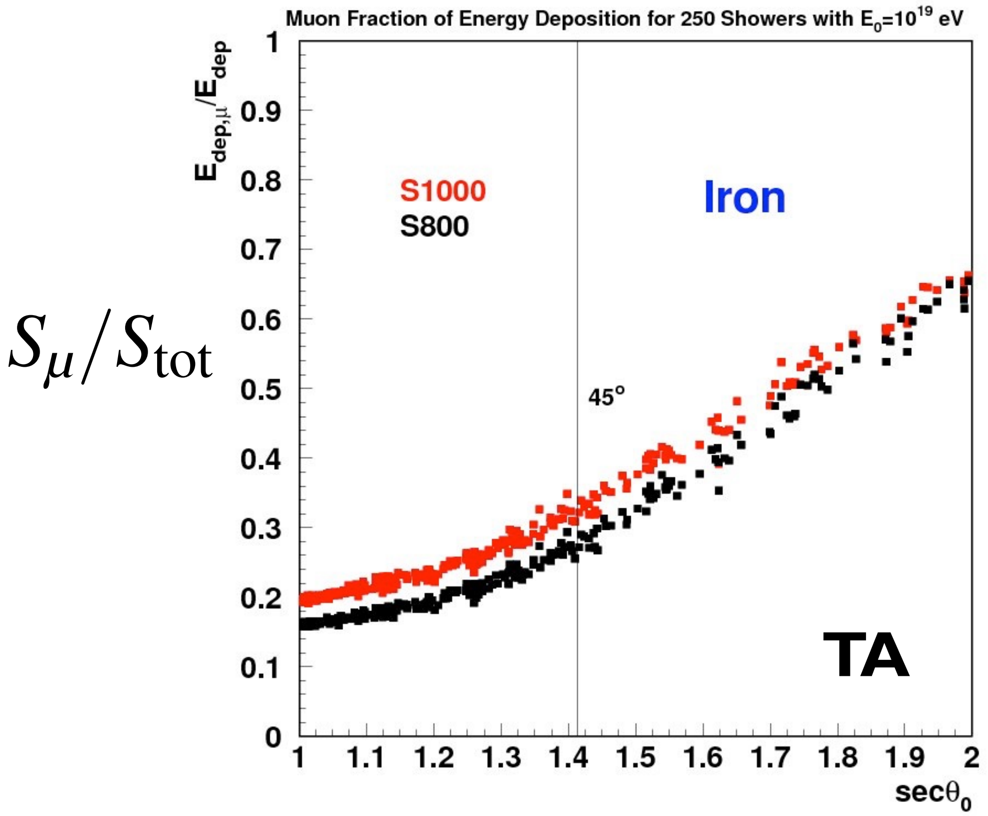
Accounting for different sensitivity to muons

Muon component

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



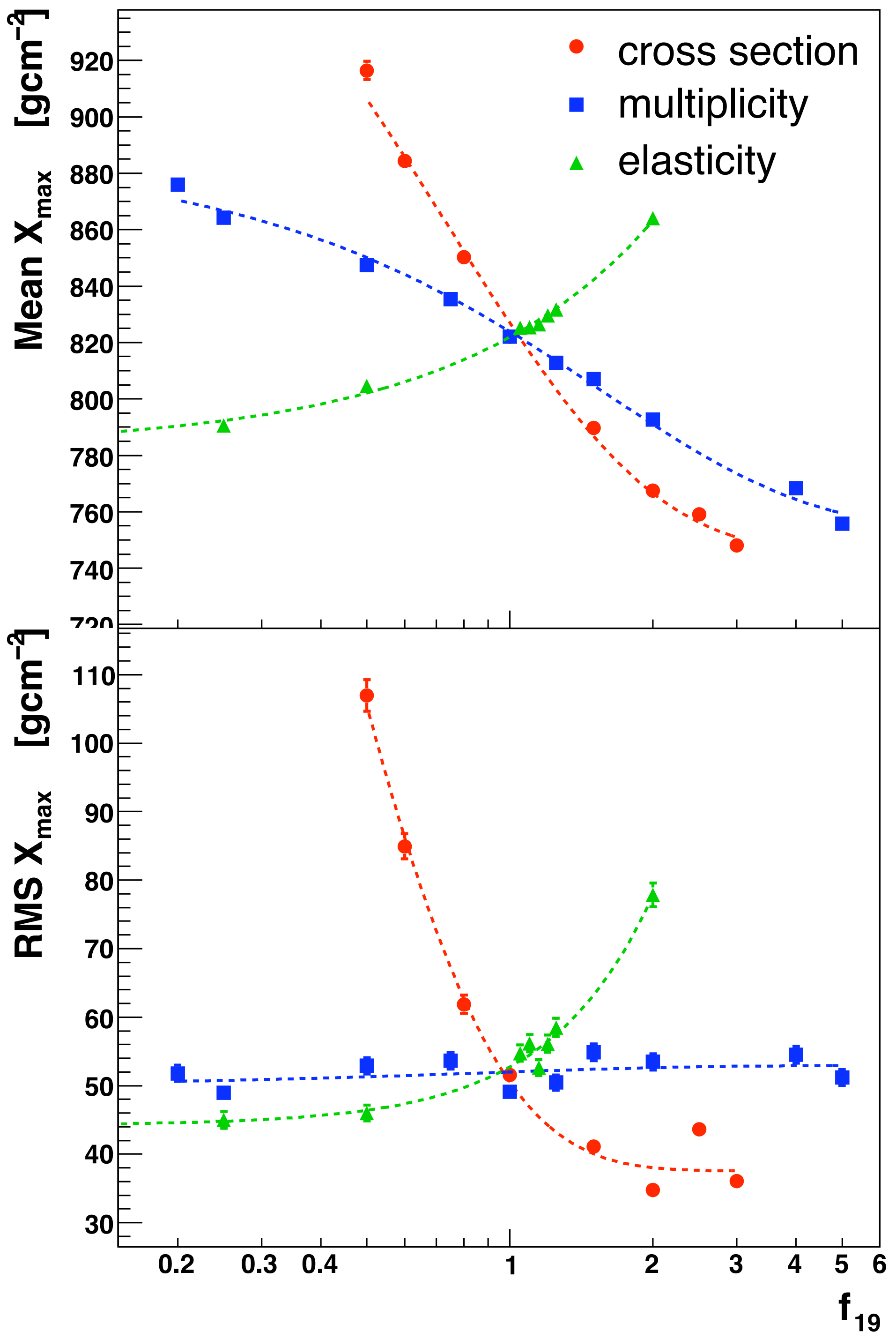




(HadInt Working Group, UHECR 2012)

Results for proton showers: X_{max}

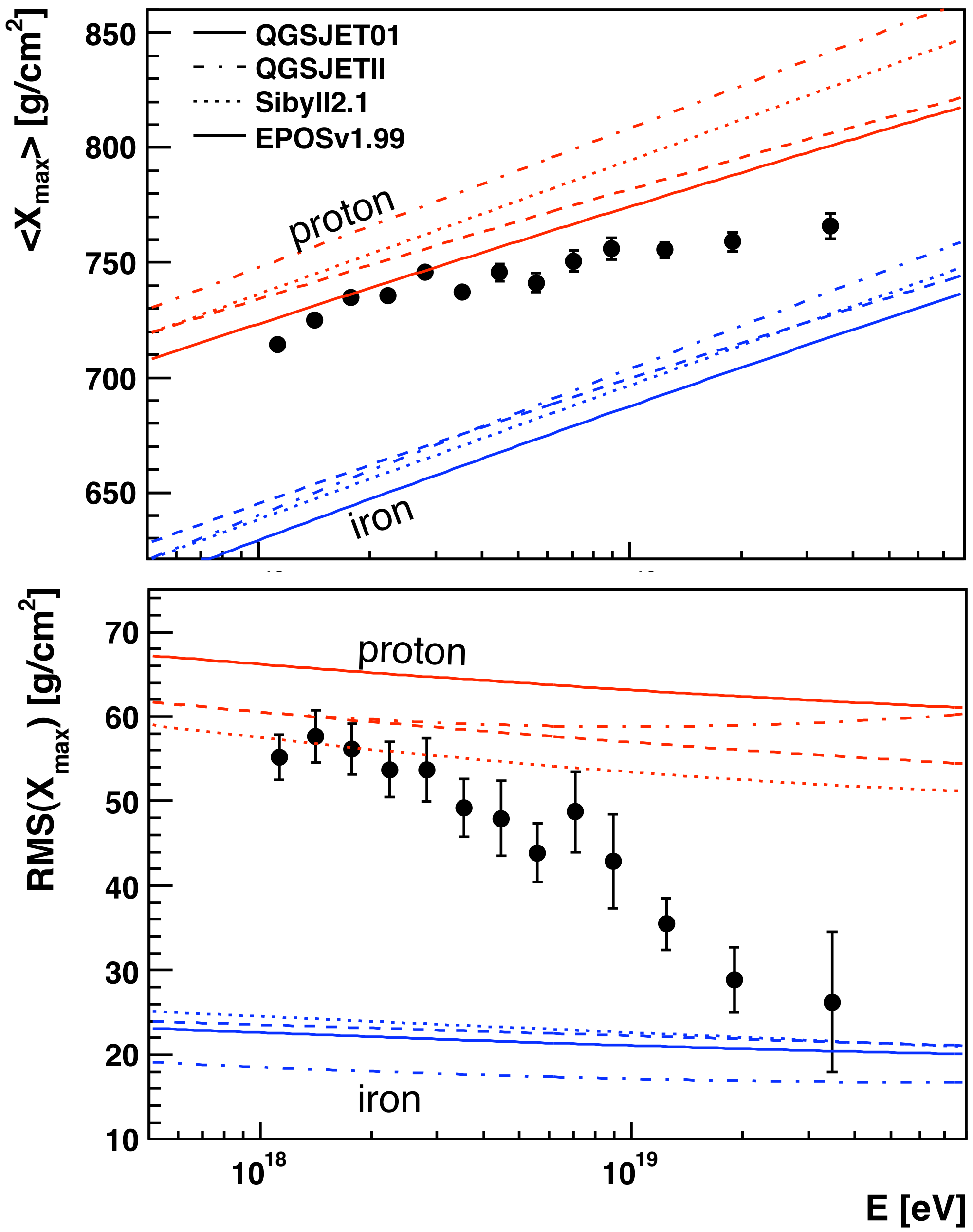
(R. Ulrich et al. PRD83 (2011) 054026)



80 g/cm²

15 g/cm²

Auger data 2009



80 g/cm²

30 g/cm²

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

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

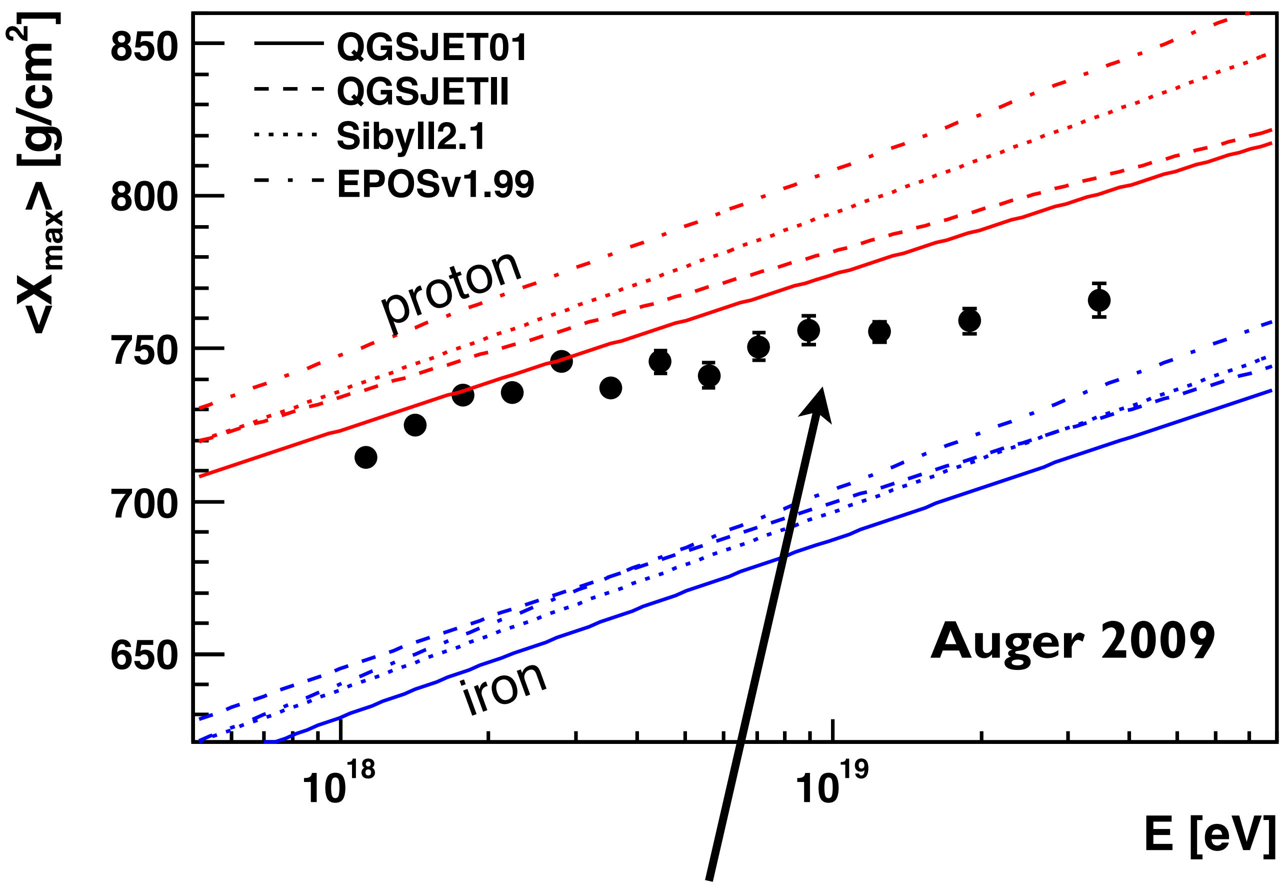
Change of interaction physics?

Elongation rate theorem

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

(Linsley, Watson PRL46, 1981)

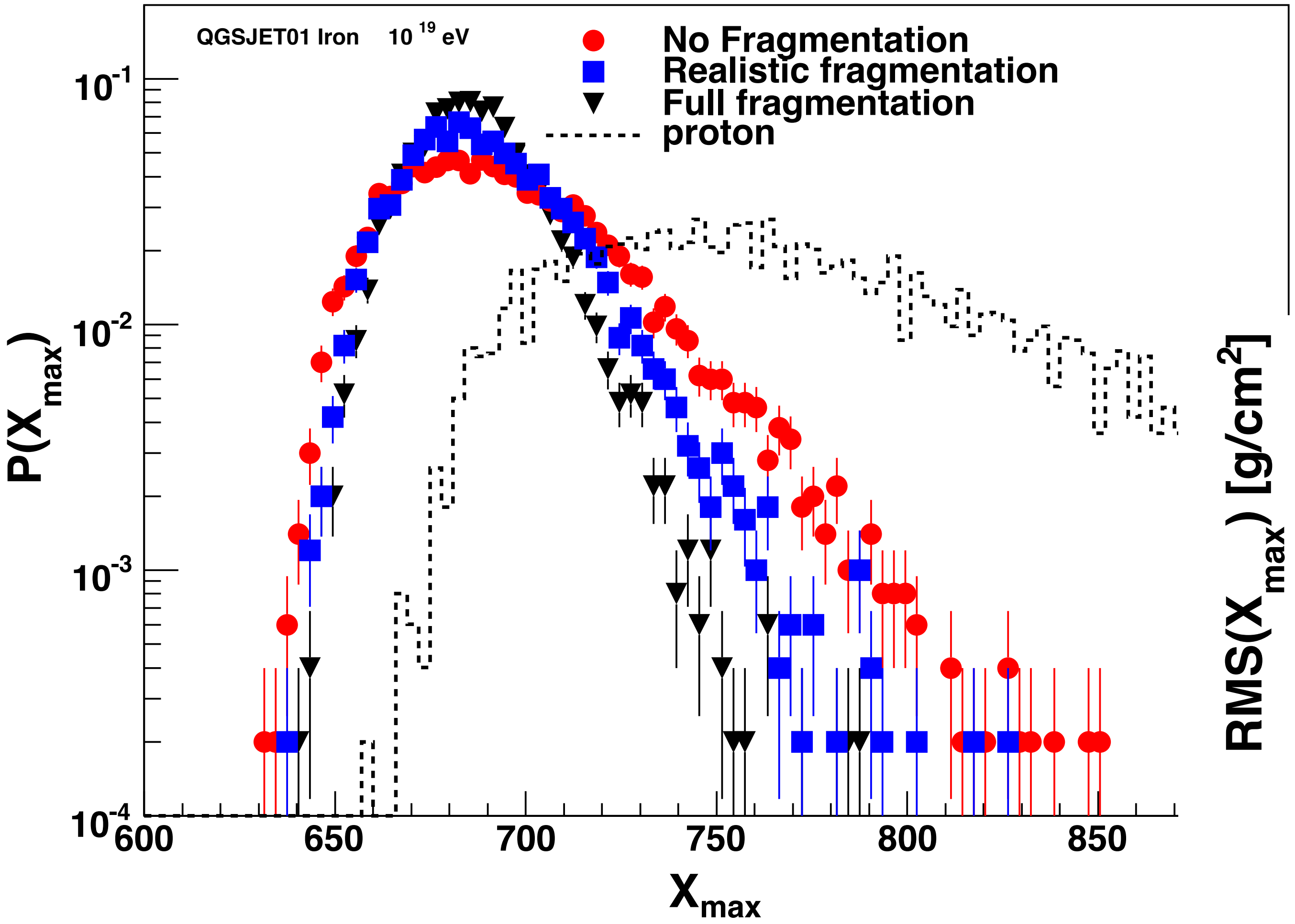
factor ~ 87 g/cm²

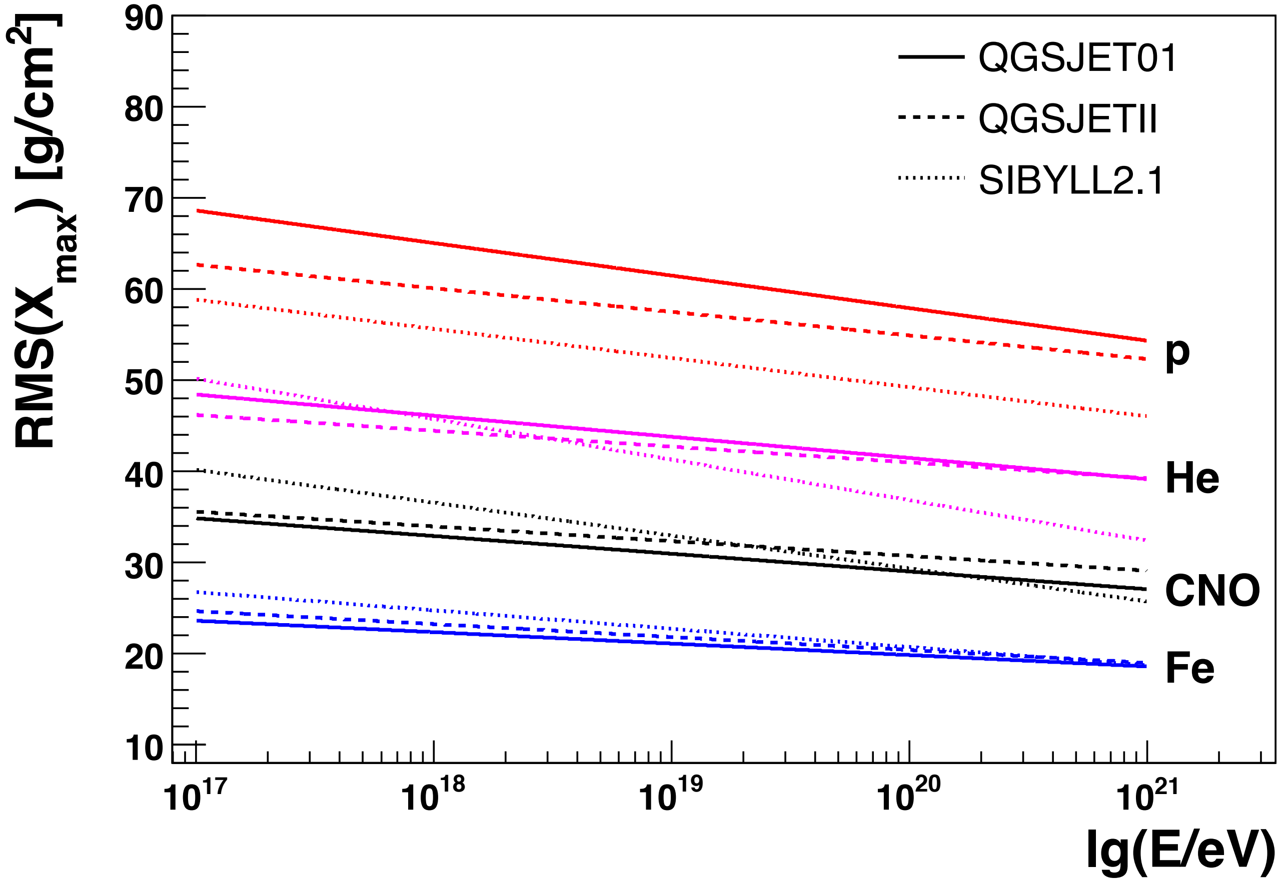


$$D_{10}^{\mathrm{had}} = 24 \pm 3 \ \mathrm{g/cm^2}$$

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

Importance of correlations for fluctuations





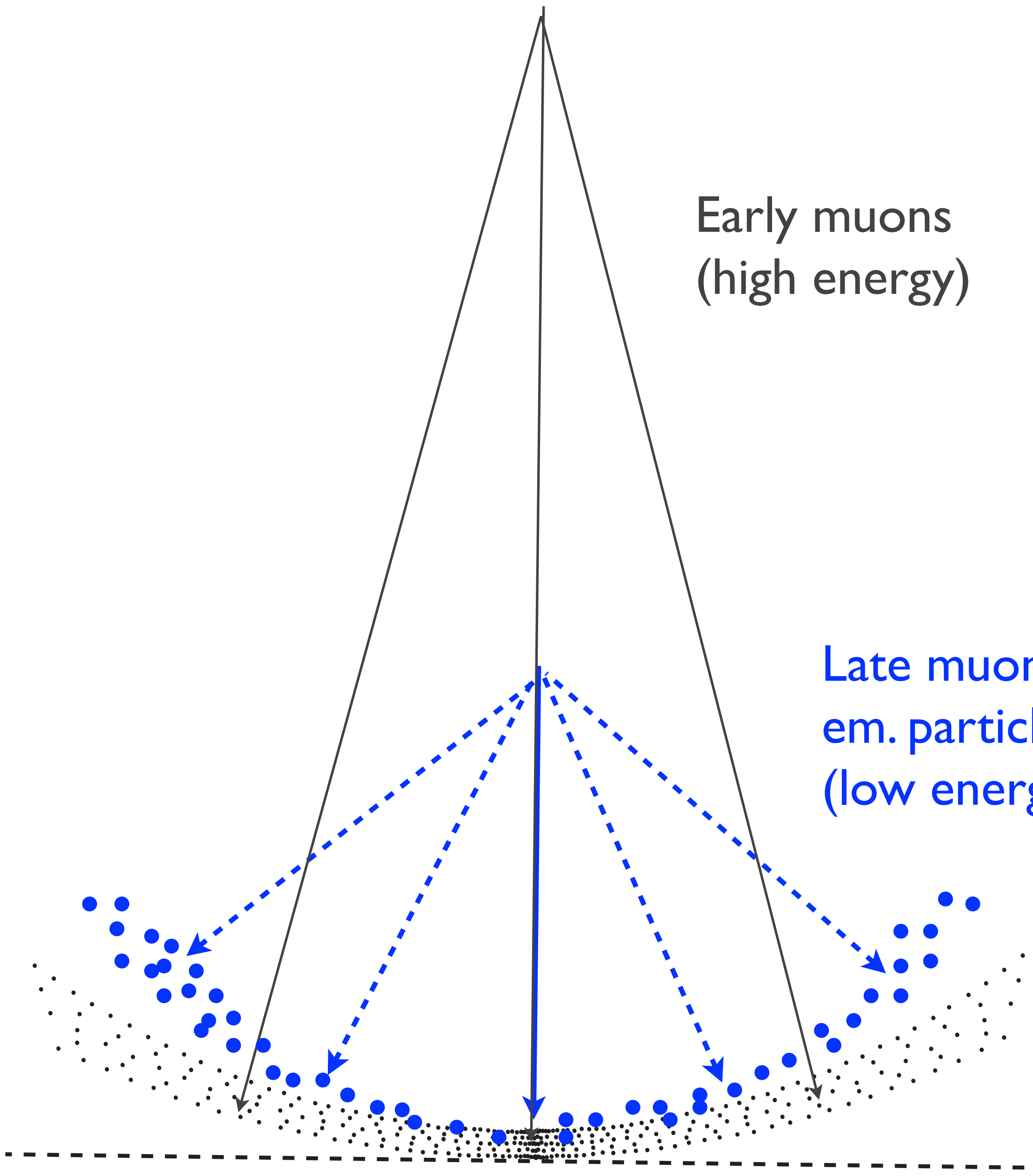
RMS(Xmax) = 29 g/cm²

21 g/cm²

16 g/cm²

Nuclear fragmentation is important for quantitative predictions

Early muons: importance of shower front curvature

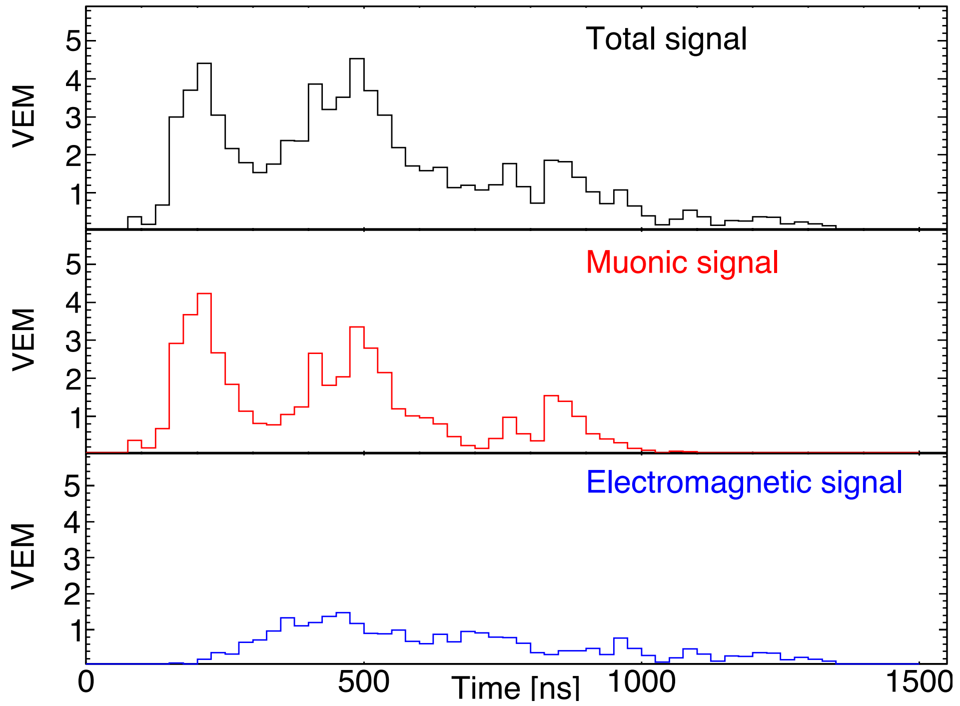


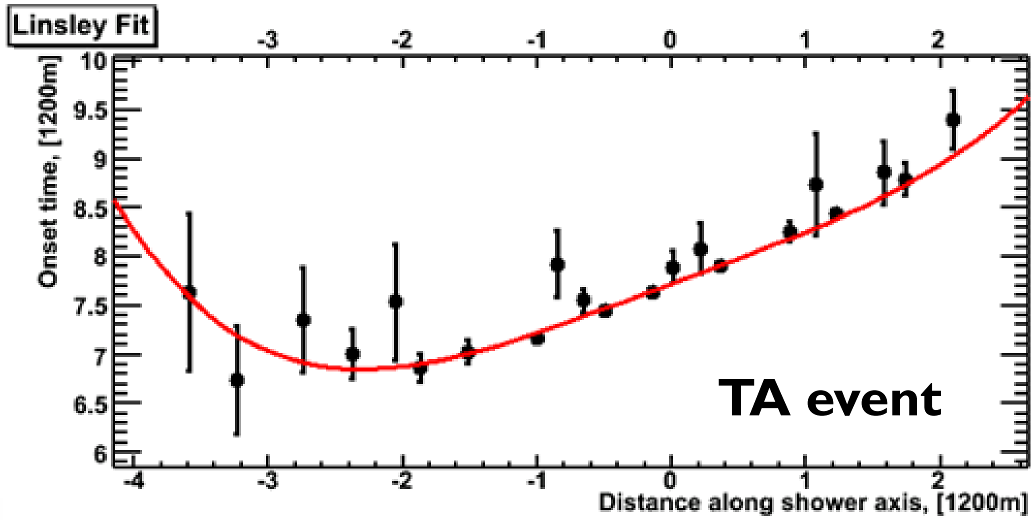
Early muons
(high energy)

Late muons and
em. particles
(low energy)

Curvature of shower front
sensitive to early muons

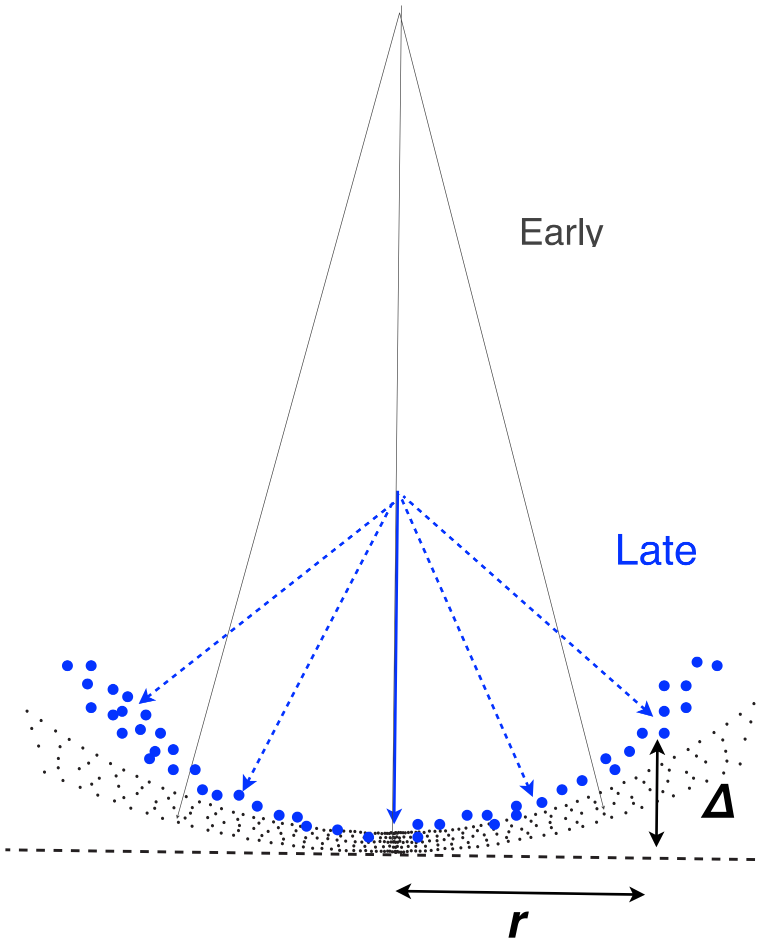
proton shower E = 10^{19} eV, θ = 45°





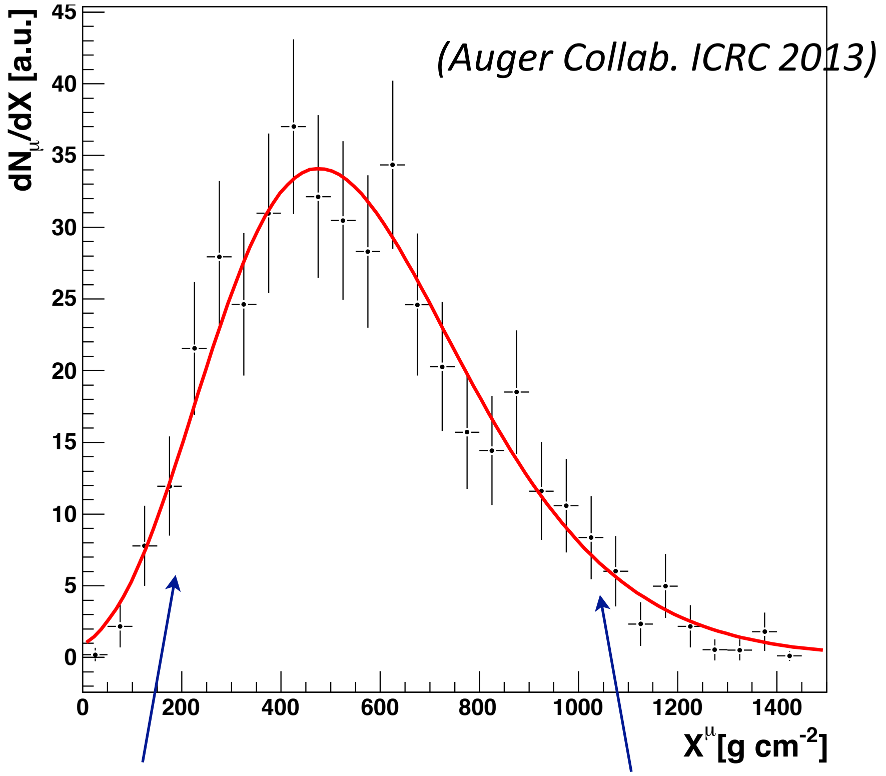
Curvature should be measured

Distribution of muon production depth (MPD)



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

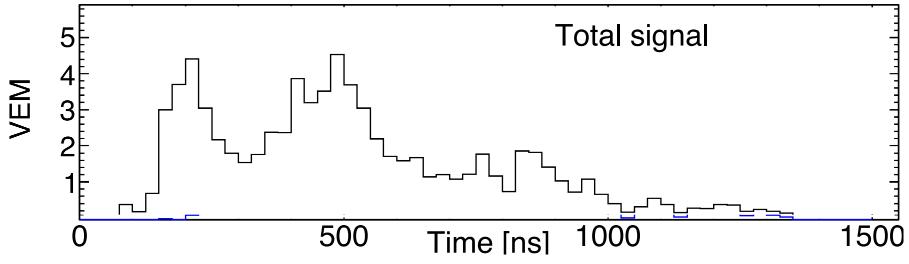
(Cazon et al. Astropart. Phys. 23, 2005)



(Auger Collab. ICRC 2013)

Muons from early interactions

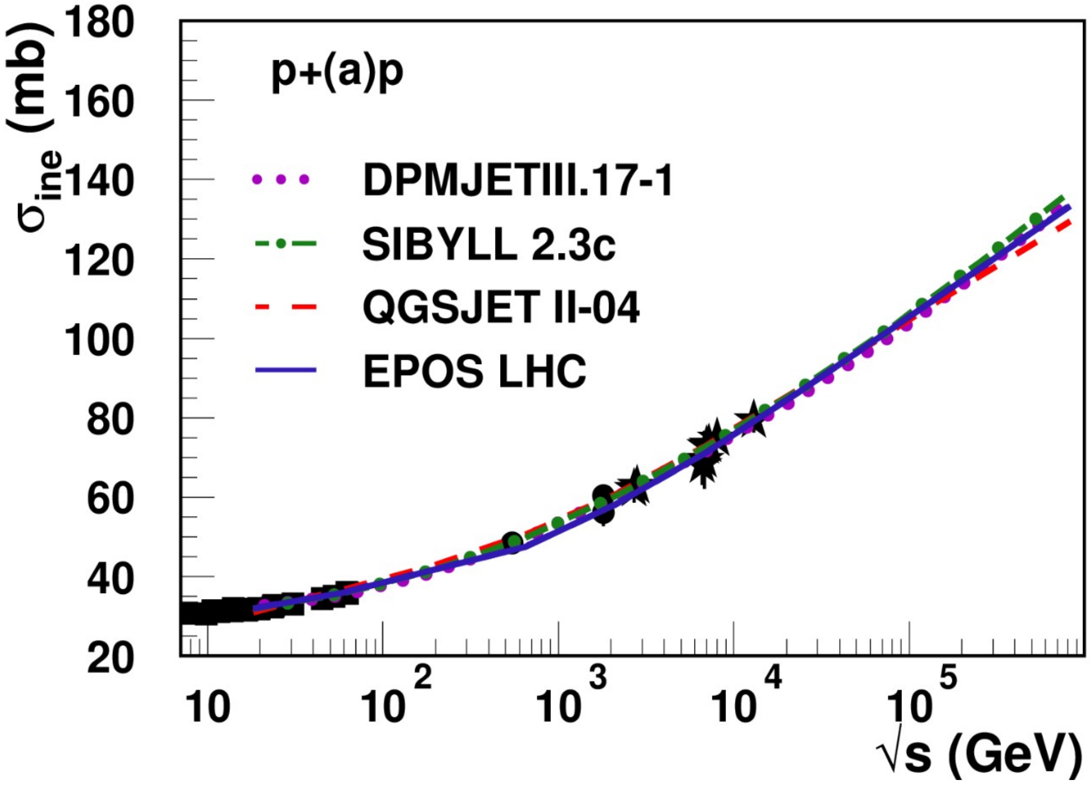
Muons from late interactions



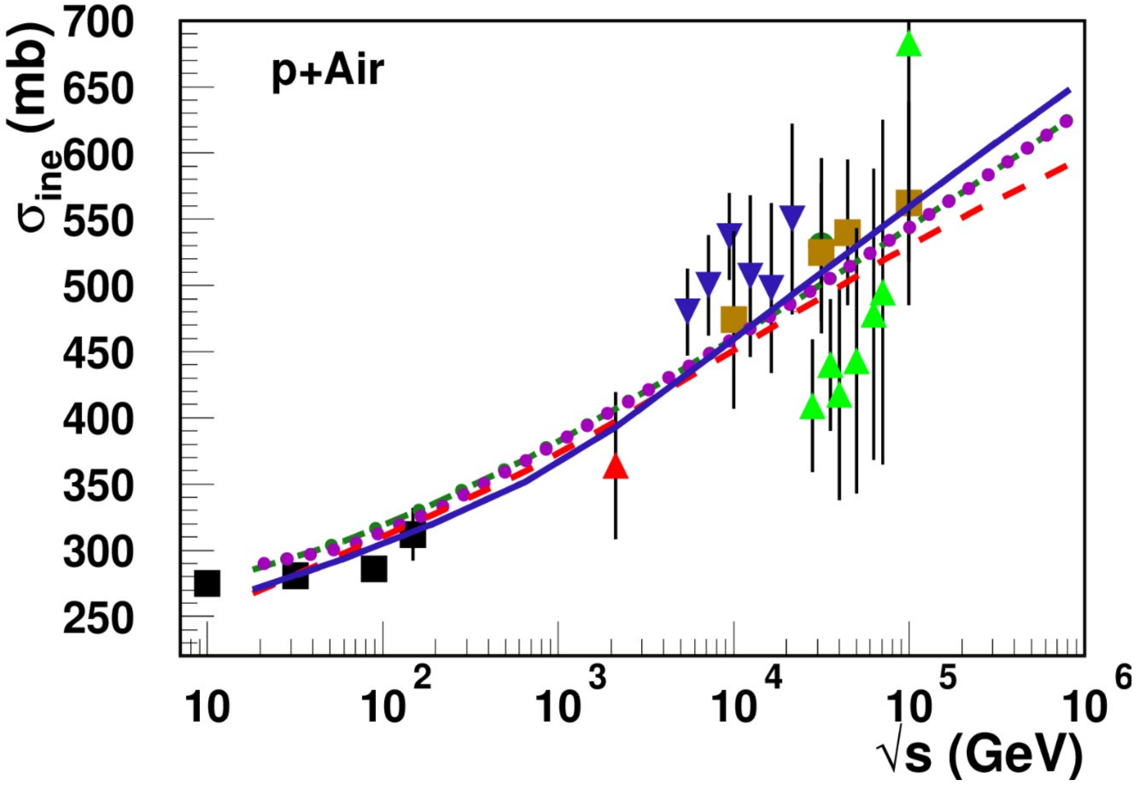
Backup slides

Performance plots of recent model versions

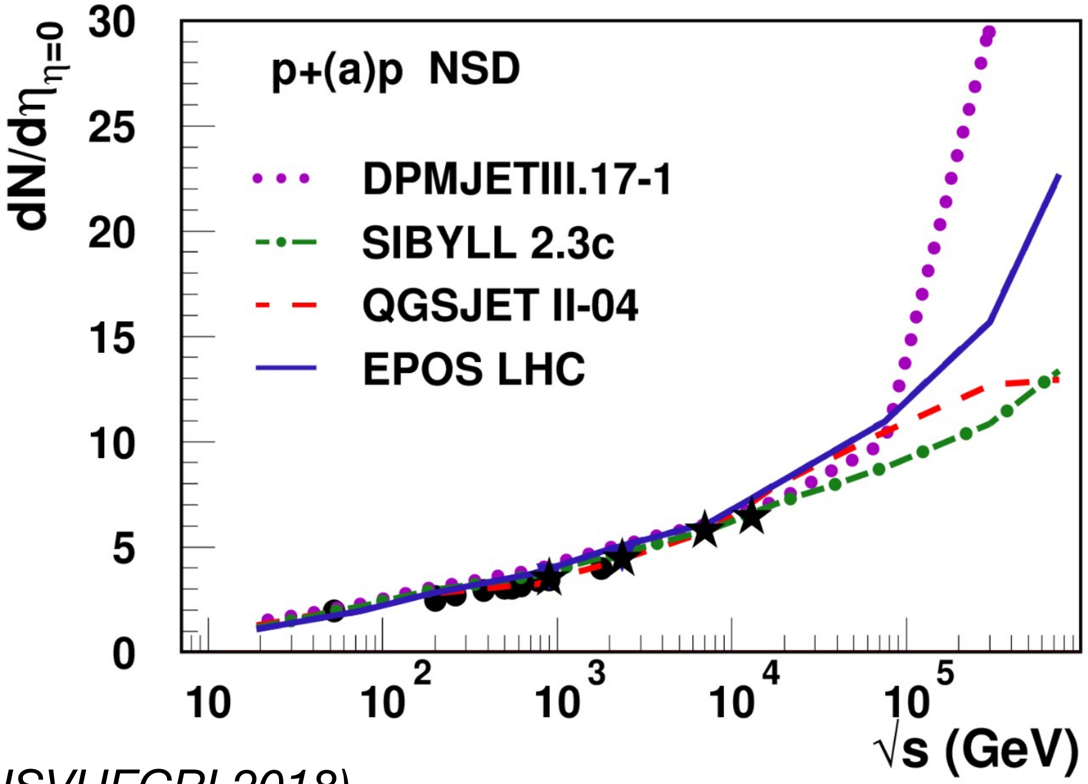
pp



p-Air



pp



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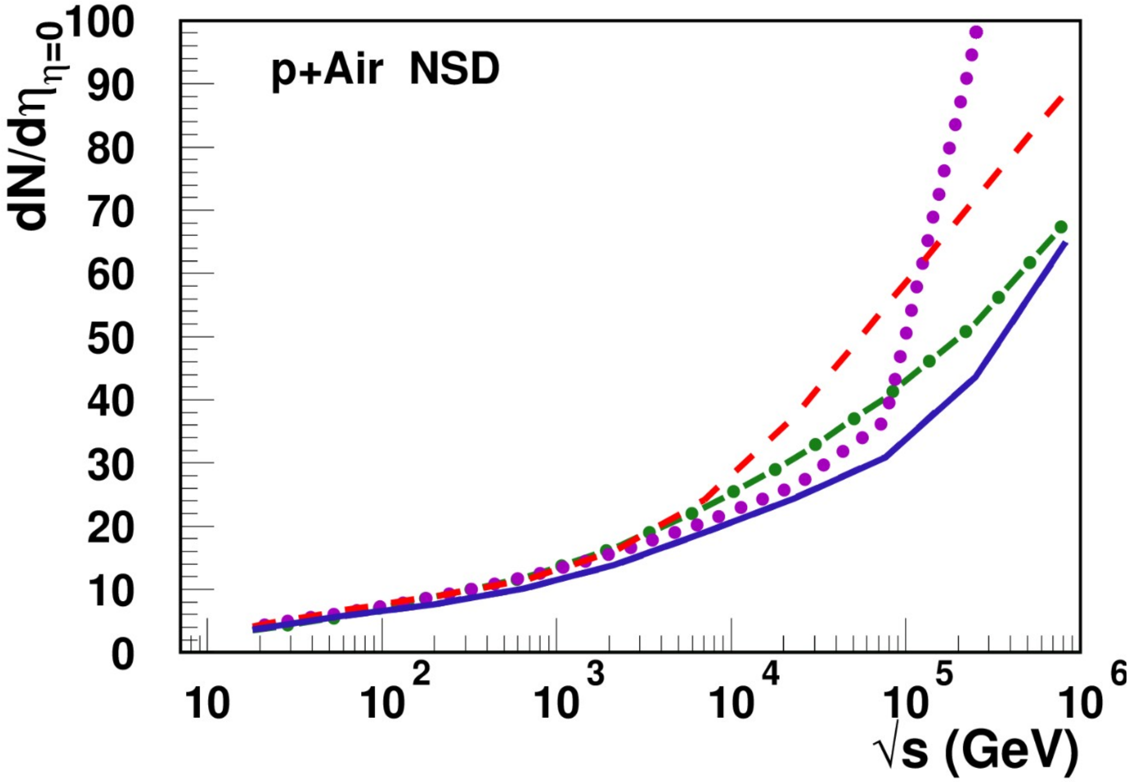
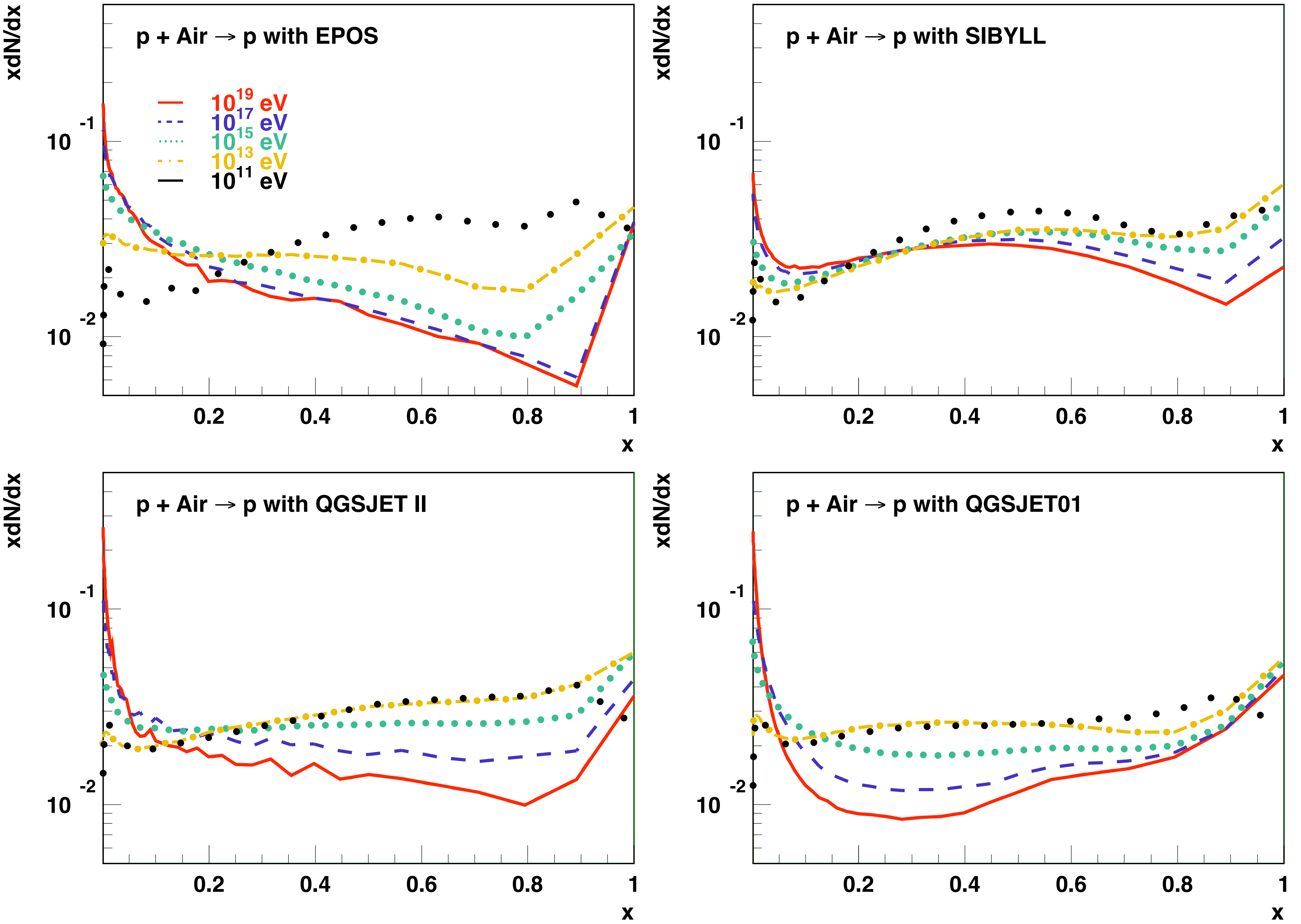
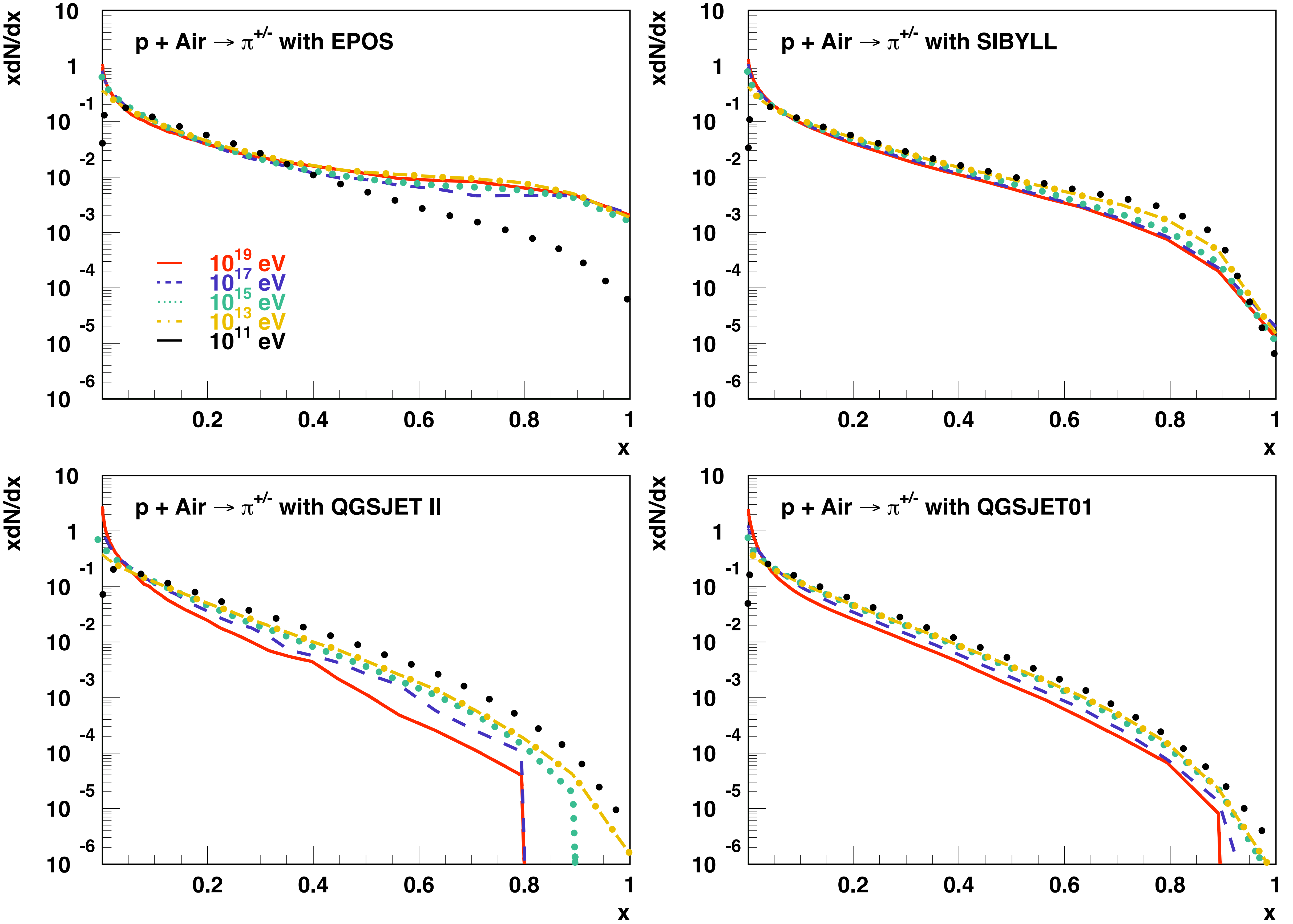


(Pierog ISVHECRI 2018)

Scaling: model predictions (i)



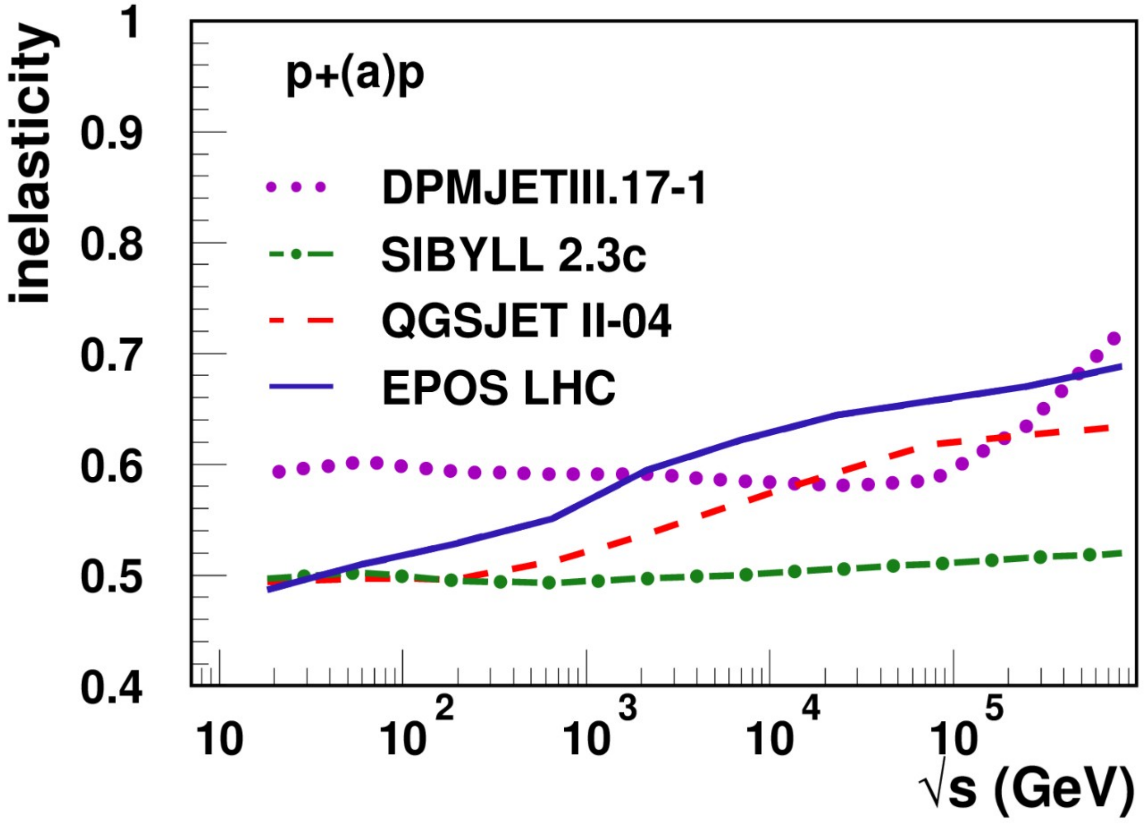
Scaling: model predictions (ii)



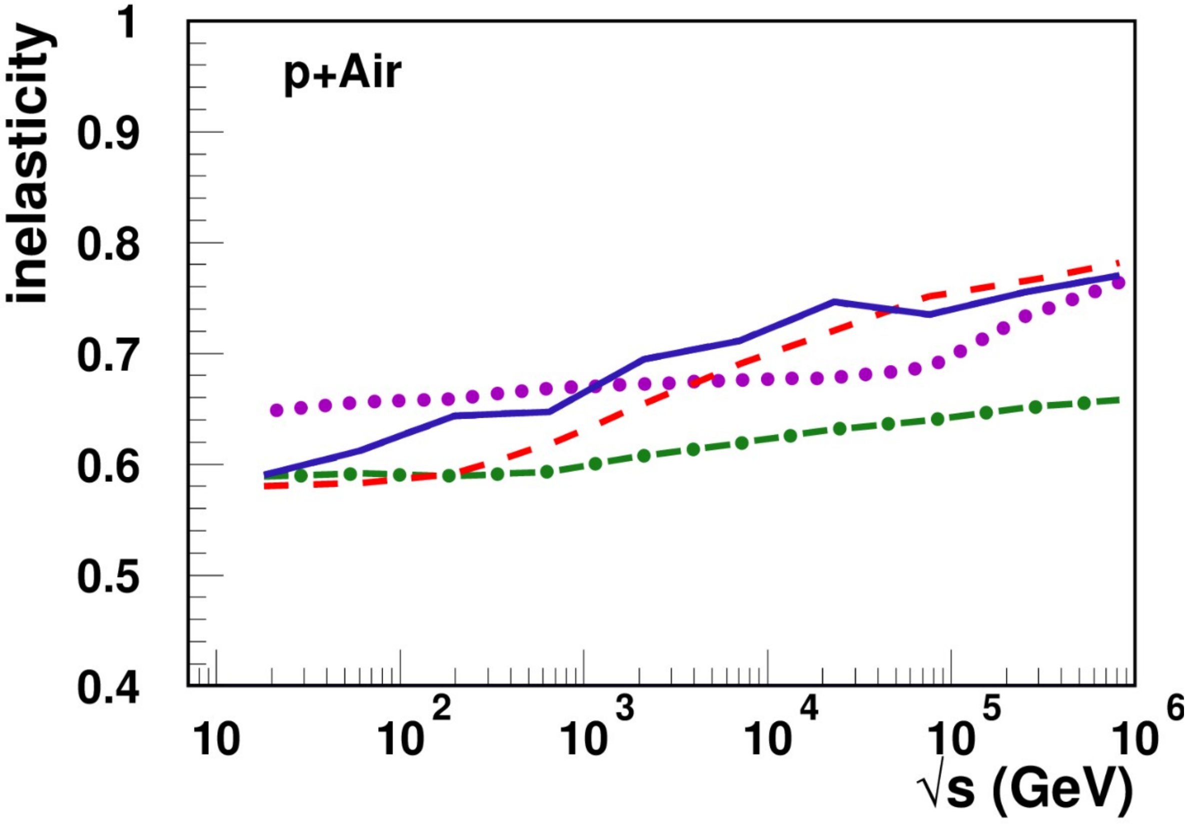
Scaling: model predictions (iii)

Inelasticity: fraction of beam particle energy that is transferred to secondary particles except the leading one

pp



p-Air



(Pierog ISVHECRI 2018)

Elasticity = 1 - Inelasticity

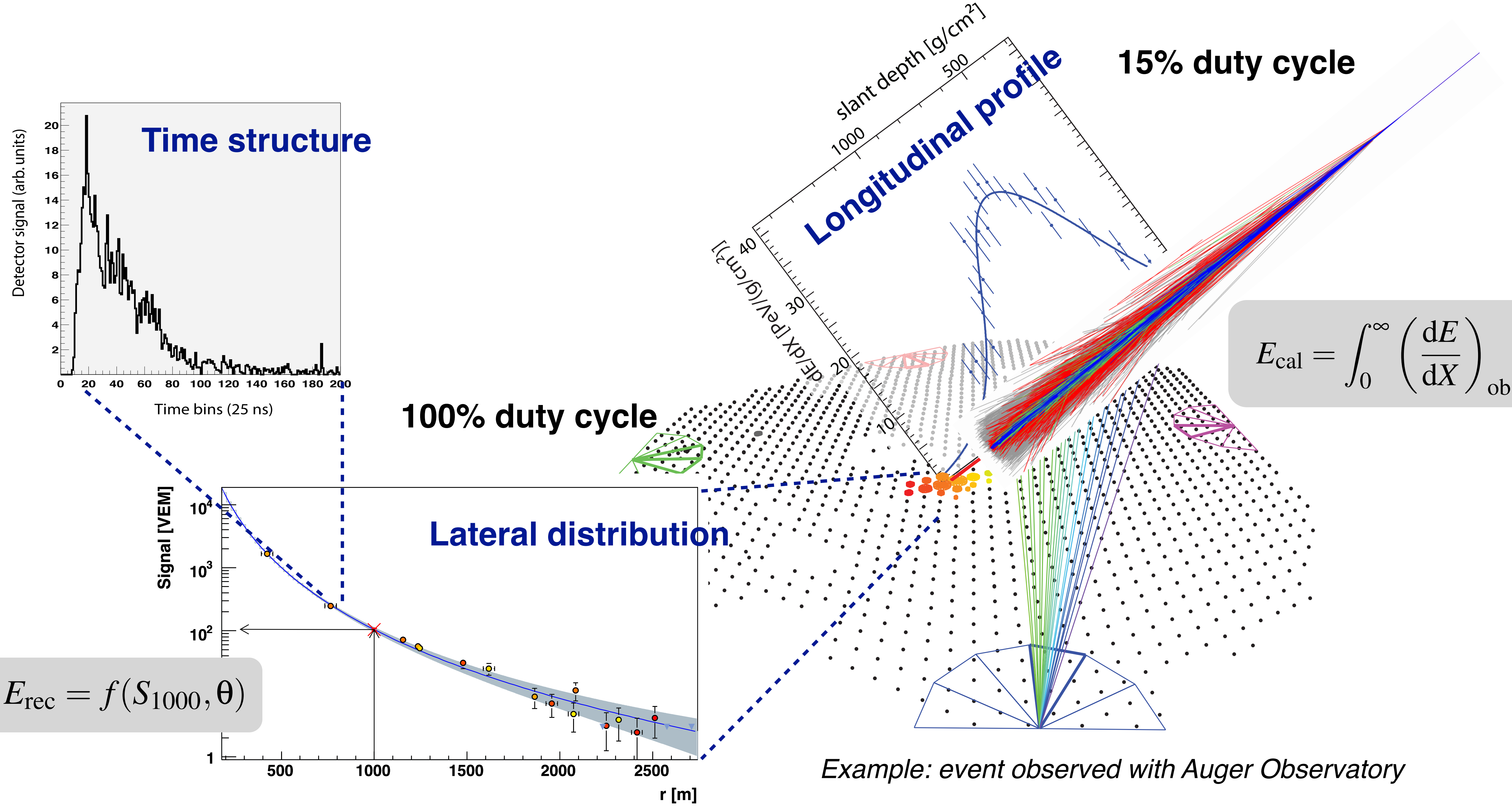
Particle	Constituent quarks	Mass (MeV)	Mean life ($c\tau$)	Decay channels	branching ratio (%)
p	uud	938.3	∞	–	–
n	udd	939.6	$2.64 \times 10^8\,\mathrm{km}$	$p\ e^-\ \overline{\nu}_e$	100
$N^+(1444)$	uud	1440	$\approx 300\,\mathrm{MeV}$	$p\ \pi^0$	
				$n\ \pi^+$	
				$p\ \pi^+\ \pi^-$	
				$n\ \pi^+\ \pi^0$	
				$p\ \gamma$	$0.35 - 0.48$
$\Delta^+(1230)$	uud	1232	$117\,\mathrm{MeV}$	$p\ \pi^0$	66.7
				$n\ \pi^+$	33.3
Λ^0	uds	1115.7	$7.89\,\mathrm{cm}$	$p\ \pi^-$	63.9
				$n\ \pi^+$	35.8
				$p\ e^-\ \overline{\nu}_e$	8.3×10^{-2}
				$p\ \mu^-\ \overline{\nu}_\mu$	16.3×10^{-2}
Σ^+	uus	1189.4	$2.40\,\mathrm{cm}$	$p\ \pi^0$	51.6
				$n\ \pi^+$	48.3
Ξ^-	dss	1321.7	$4.91\,\mathrm{cm}$	$\Lambda\ \pi^-$	99.9
Ω^-	sss	1672.5	$2.46\,\mathrm{cm}$	$\Lambda\ K^-$	67.8
				$\Xi^0\ \pi^-$	23.6
				$\Xi^-\ \pi^0$	8.6
Λ_c^+	udc	2286	$59.9\,\mu\mathrm{m}$	$\Lambda/p/n\ \ldots$	73
				$\Lambda\ e^+\ \nu_e$	2.1
				$\Lambda\ \mu^+\ \nu_\mu$	2.0

Particle	Constituent quarks	Mass (MeV)	Mean life ($c\tau$)	Decay channels	branching ratio (%)
π^+	$u\bar{d}$	139.6	7.80 m	$\mu^+ \ \nu_\mu$	99.99
				$\mu^+ \ \nu_\mu \ \gamma$	2.0×10^{-2}
				$e^+ \ \nu_e$	1.2×10^{-2}
π^0	$\frac{1}{\sqrt{2}}\left(d\bar{d} - u\bar{u}\right)$	135.0	25.5 nm	$\gamma \ \gamma$	98.8
				$e^+ \ e^- \ \gamma$	1.17
K^+	$u\bar{s}$	493.7	3.71 m	$\mu^+ \ \nu_\mu$	63.6
				$\pi^+ \ \pi^0$	20.7
				$\pi^+ \ \pi^- \ \pi^+$	5.59
				$\pi^0 \ e^+ \ \nu_e$	5.07
				$\pi^0 \ \mu^+ \ \nu_\mu$	3.35
				$\pi^+ \ \pi^0 \ \pi^0$	1.76
K^0	$d\bar{s}$	497.6	–	–	–
K^0_L	$\frac{1}{\sqrt{2}}\left(d\bar{s} - s\bar{d}\right)$	497.6	15.34 m	$\pi^\pm \ e^\mp \ \nu_e$	40.5
				$\pi^\pm \ \mu^\mp \ \nu_\mu$	27.0
				$\pi^0 \ \pi^0 \ \pi^0$	19.5
				$\pi^+ \ \pi^- \ \pi^0$	12.5
				$\pi^+ \ \pi^-$	0.19
K^0_S	$\frac{1}{\sqrt{2}}\left(d\bar{s} + s\bar{d}\right)$	497.6	2.68 cm	$\pi^+ \ \pi^-$	69.2
				$\pi^0 \ \pi^0$	30.7
				$\pi^+ \ \pi^- \ \gamma$	0.18

Some useful relations (units)

- Speed of light: $c = 2.9979 \times 10^{10}\,\mathrm{cm\,s^{-1}}$
- Gravitational constant: $G = 6.6738 \times 10^{-8}\,\mathrm{cm^3\,g^{-1}\,s^{-2}}$
- Planck constant: $h = 6.626 \times 10^{-27}\,\mathrm{erg\,s} = 4.136 \times 10^{-15}\,\mathrm{eV\,s}$, $\hbar = h/(2\pi) = 1.0546 \times 10^{-27}\,\mathrm{erg\,s}$
- Boltzmann constant: $k_B = 8.6173 \times 10^{-5}\,\mathrm{eV\,K^{-1}} = 1.3806 \times 10^{-16}\,\mathrm{erg\,K^{-1}}$
- Avogadro constant: $N_A = 6.0221 \times 10^{23}$. By definition, N_A atoms of carbon ^{12}C have a mass of 12 g. Therefore, the mean mass of a nucleon can be written as $m_N = (m_p + m_n)/2 \approx (1/N_A)\,\mathrm{g} = 1.6605 \times 10^{-24}\,\mathrm{g}$.
- Energy units: $1\,\mathrm{erg} = 10^{-7}\,\mathrm{J}$, $1\,\mathrm{eV} = 1.6022 \times 10^{-12}\,\mathrm{erg}$, $1\,\mathrm{cm^{-1}} = 0.000123986\,\mathrm{eV}$, $1\,\mathrm{fm} = 5.06773\,\mathrm{GeV^{-1}}$
- A photon of $E_\gamma = 1\,\mathrm{keV}$ has a frequency of $\nu = 2.4 \times 10^{17}\,\mathrm{Hz}$. This statement is based on $E_\gamma = h\nu$. Direct conversion of units using $\hbar = h/(2\pi) = 6.582 \times 10^{-22}\,\mathrm{MeV\,s}$ would give a result that differs by 2π.
- Distances: $1\,\mathrm{pc} = 3.0857 \times 10^{18}\,\mathrm{cm}$, $1\,\mathrm{AU} = 1.496 \times 10^{13}\,\mathrm{cm}$
- Cross sections: $1\,\mathrm{mb} = 10^{-27}\,\mathrm{cm^2}$, $(1\,\mathrm{fm})^2 = 10\,\mathrm{mb}$, $(1\,\mathrm{GeV})^{-2} = 0.389365\,\mathrm{mb}$
- Thomson cross section: $\sigma_\mathrm{T} = 8\pi r_e^2/3 = 665.25\,\mathrm{mb} = 6.652 \times 10^{-25}\,\mathrm{cm^2}$, where r_e is the classical electron radius $r_e = e^2/(m_e c^2) = 2.818 \times 10^{-13}\,\mathrm{cm}$
- Solar mass and luminosity: $M_\odot = 1.9885 \times 10^{33}\,\mathrm{g}$, $L_\odot = 3.828 \times 10^{33}\,\mathrm{erg\,s^{-1}}$
- Flux density used in radio astronomy (Jansky): $1\,\mathrm{Jy} = 10^{-26}\mathrm{W\,m^{-2}\,Hz^{-1}} = 10^{-23}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,Hz^{-1}}$
- Magnetic field strength: $1\,\mathrm{G} = 10^{-4}\,\mathrm{T}$

UHECRs: How to detect them



Time structure

Longitudinal profile

15% duty cycle

100% duty cycle

Lateral distribution

$$E_{\text{cal}} = \int_0^{\infty} \left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_{\text{obs}} \mathrm{d}X$$

$$E_{\text{rec}} = f(S_{1000}, \theta)$$

Example: event observed with Auger Observatory