Physics of High-Energy Showers

Lecture 2

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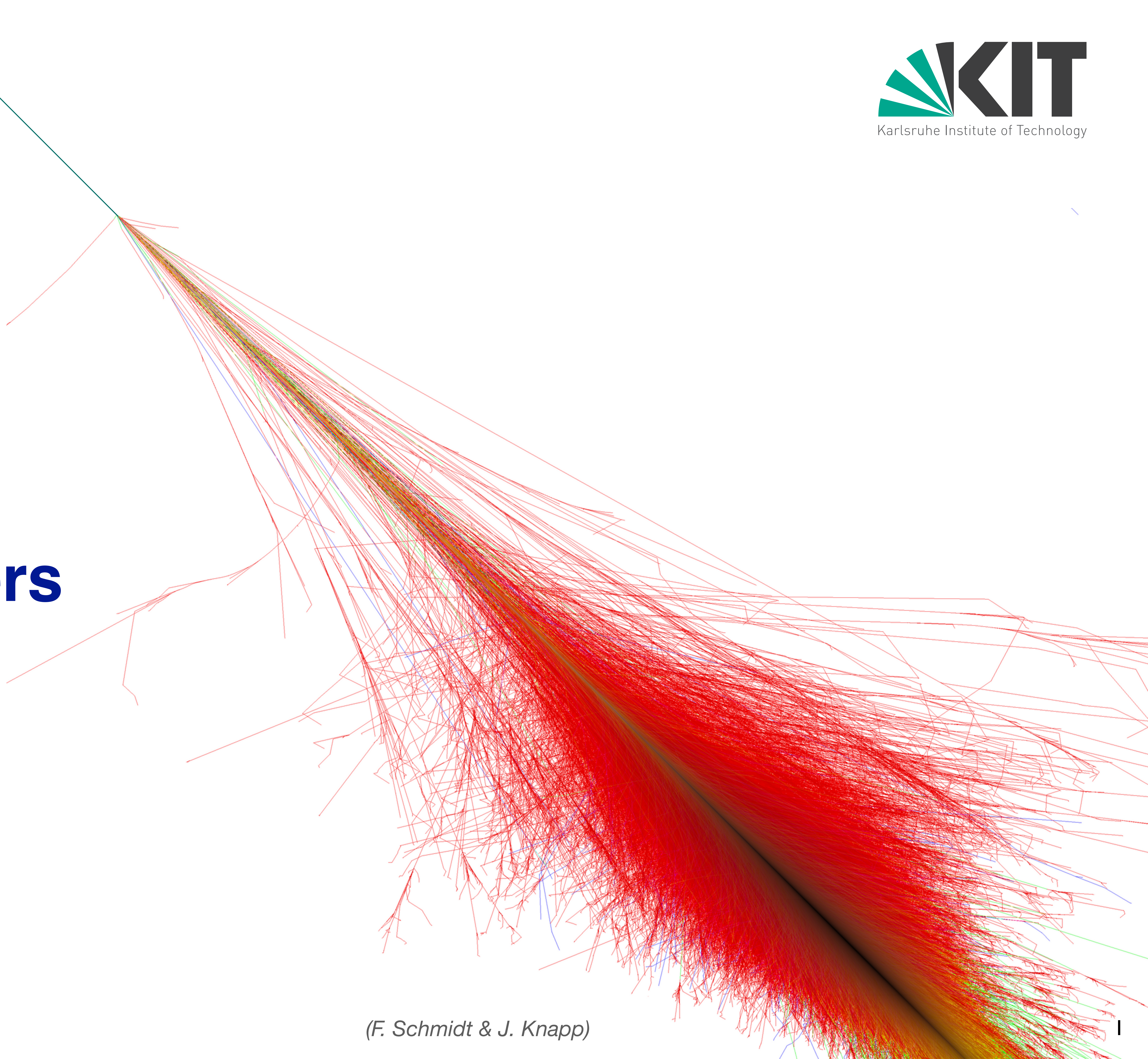
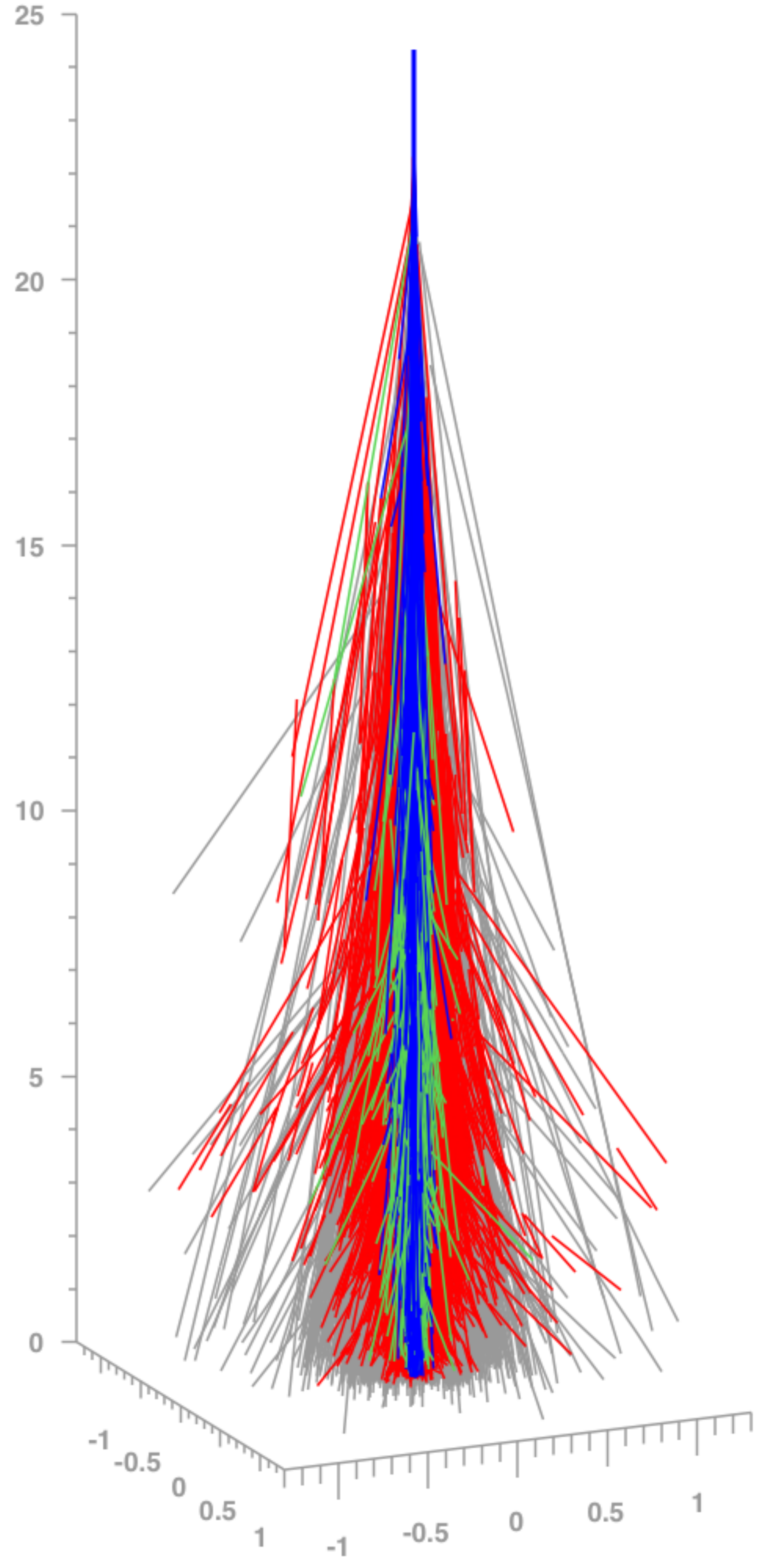
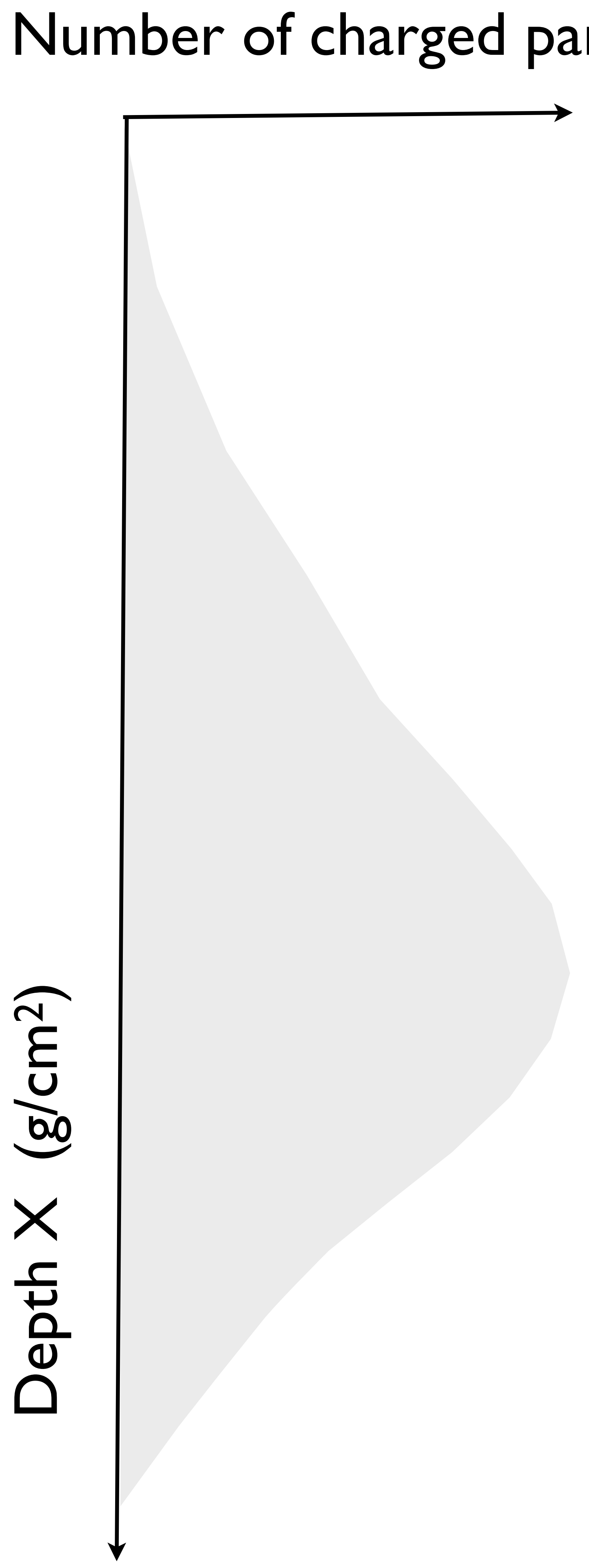


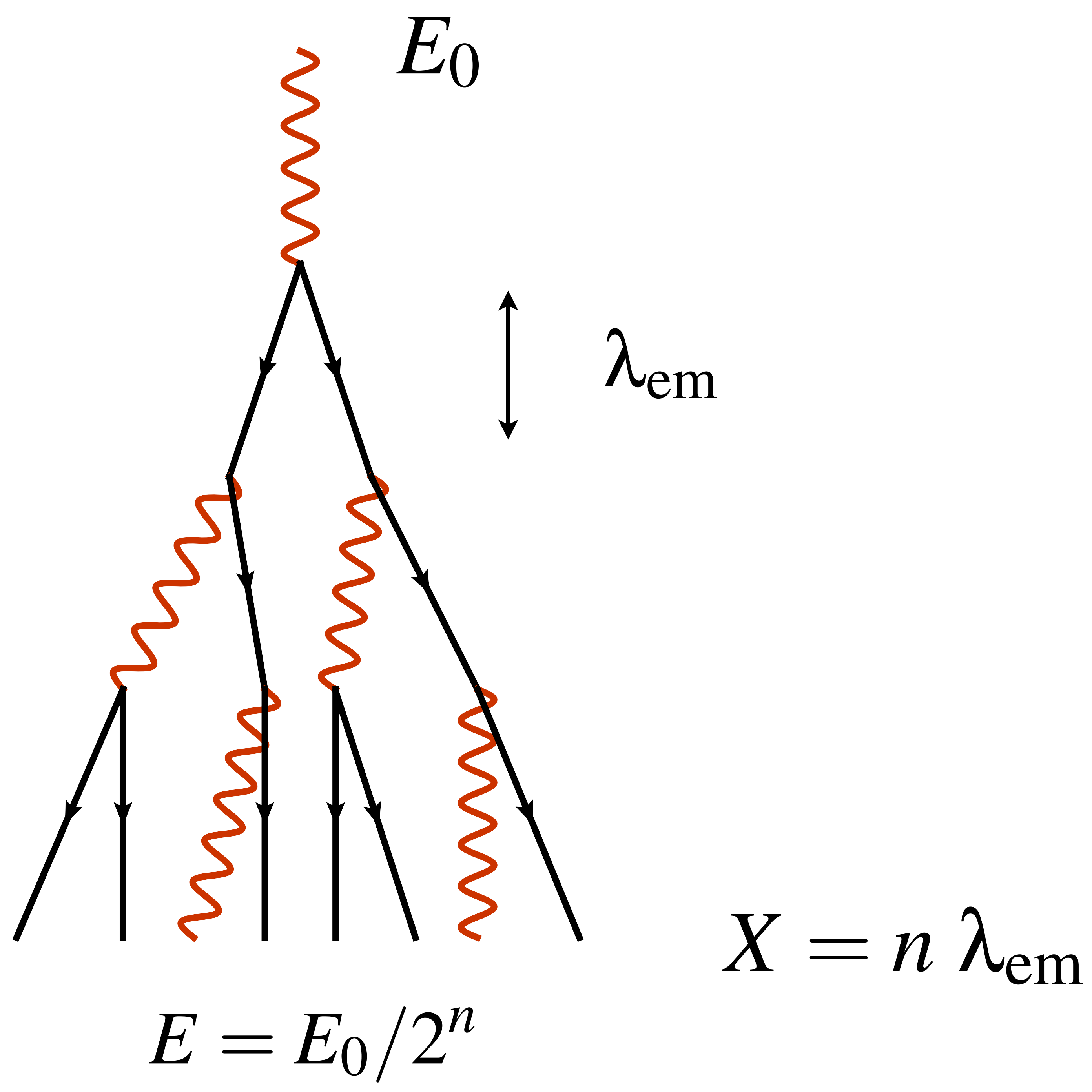
(F. Schmidt & J. Knapp)

1. Recap of last lecture

Qualitative approach: Heitler model







Shower maximum: $E = E_c$

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

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

Electromagnetic shower theory

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

$$\boxed{\lambda_{\mathrm{pair}} = \frac{\langle m_{\mathrm{air}} \rangle}{\sigma_{\mathrm{pair,tot}}} = \frac{9}{7} X_0}$$

Longitudinal profile (Greisen formula)

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

Shower age

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

Energy spectrum particles

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

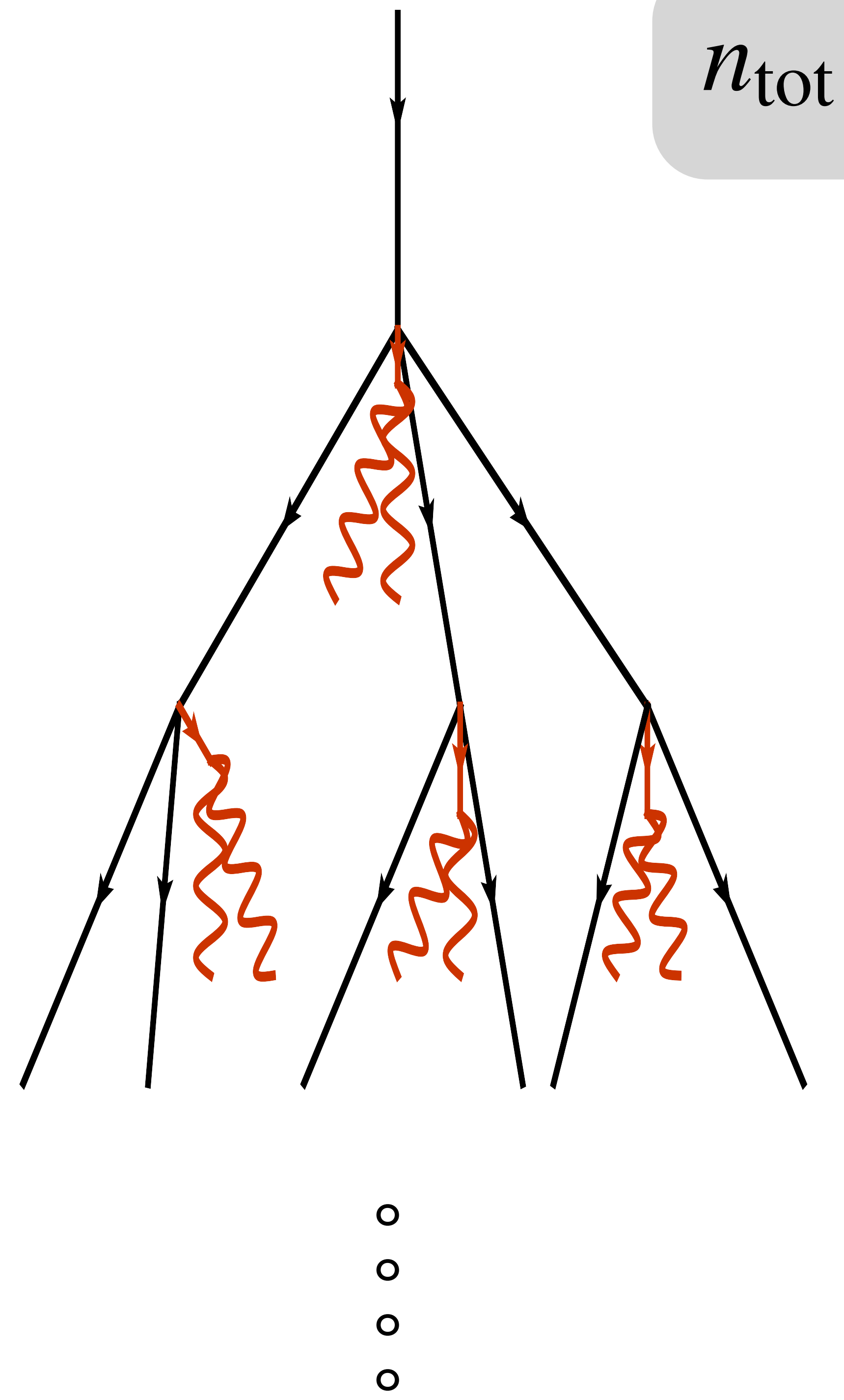
$$X_{\mathrm{max}} \approx X_0 \ln\left(\frac{E_0}{E_c}\right) \qquad N_{\mathrm{max}} \approx \frac{0.31}{\sqrt{\ln(E_0/E_c) - 0.33}} \frac{E_0}{E_c}$$

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

Qualitative approach: Heitler-Matthews model

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

Energy		Particles
E_0		
E_0/n_{tot}		n_{ch}
$E_0/(n_{\mathrm{tot}})^2$		$(n_{\mathrm{ch}})^2$
$E_0/(n_{\mathrm{tot}})^n$		$(n_{\mathrm{ch}})^n$



Primary particle proton

π^0 decay immediately

$\pi^\pm$ initiate new cascades

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

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

Assumptions:

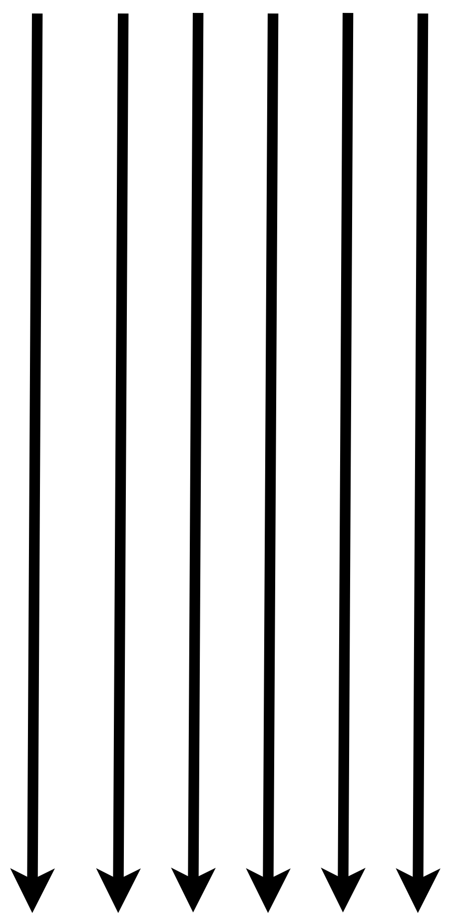
- cascade stops at $E_{\mathrm{part}} = E_{\mathrm{dec}}$
- each hadron produces one muon

(Matthews, Astropart.Phys. 22, 2005)

Superposition model

Nucleus

$$E_i = E_0/A$$



Target

Proton-induced shower

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

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

$$N_\mu = \left(\frac{E_0}{E_{\text{dec}}}\right)^\alpha \qquad \alpha \approx 0.9$$

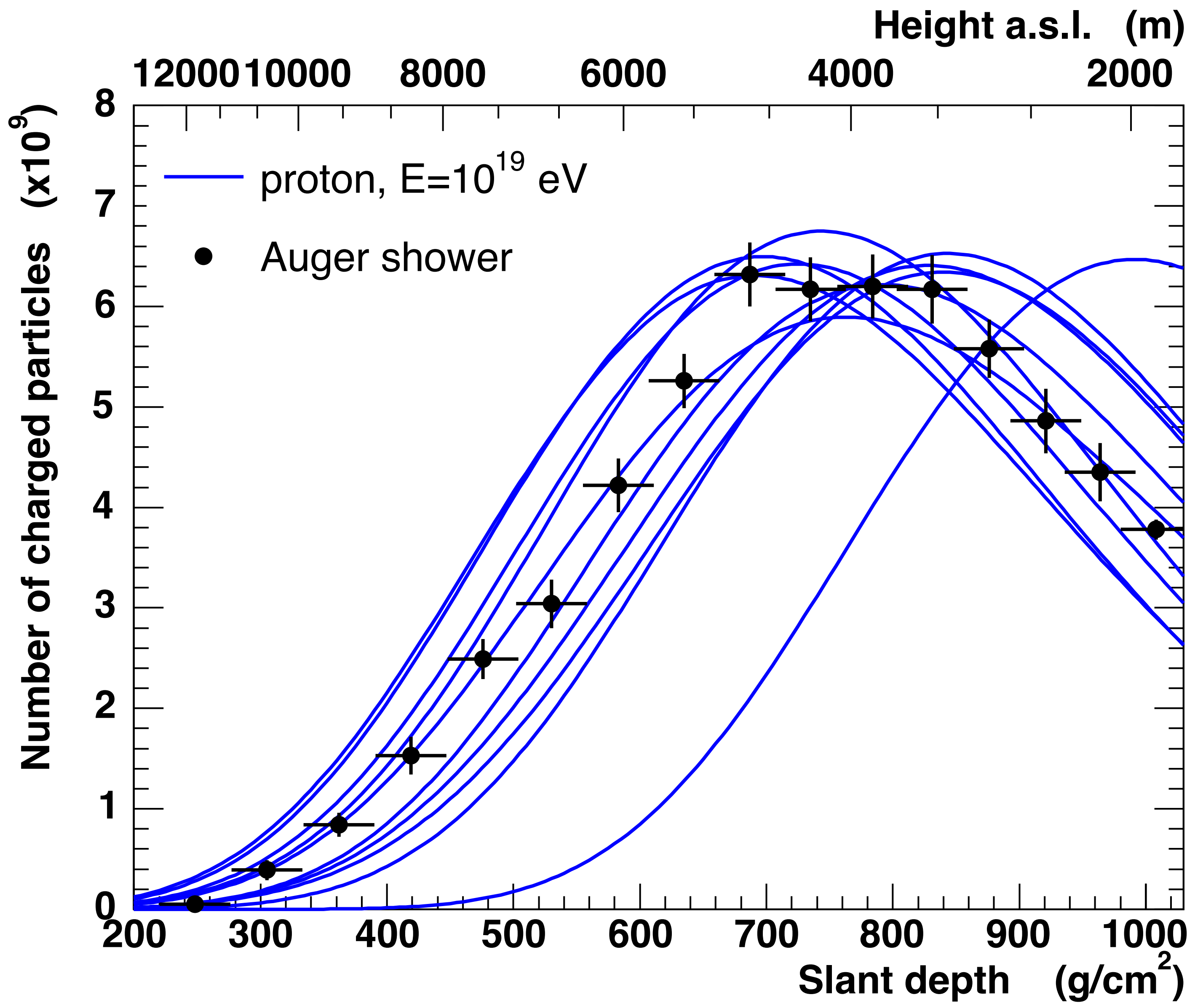
Assumption: nucleus of mass *A* and energy E_0 corresponds to *A* nucleons (protons) of energy $E_n = E_0/A$

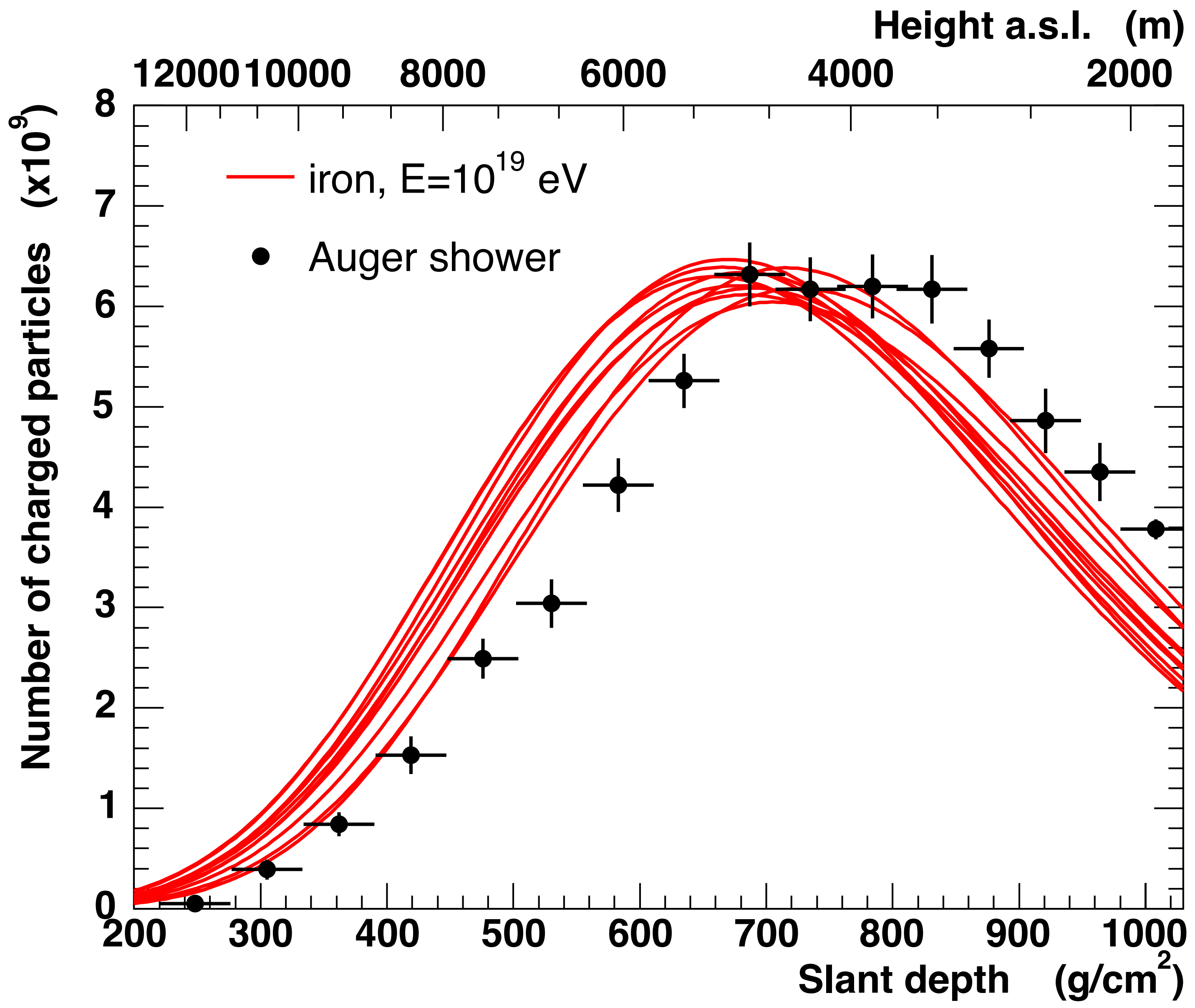
$$N_{\max}^A \sim A\left(\frac{E_0}{AE_c}\right) = N_{\max}$$

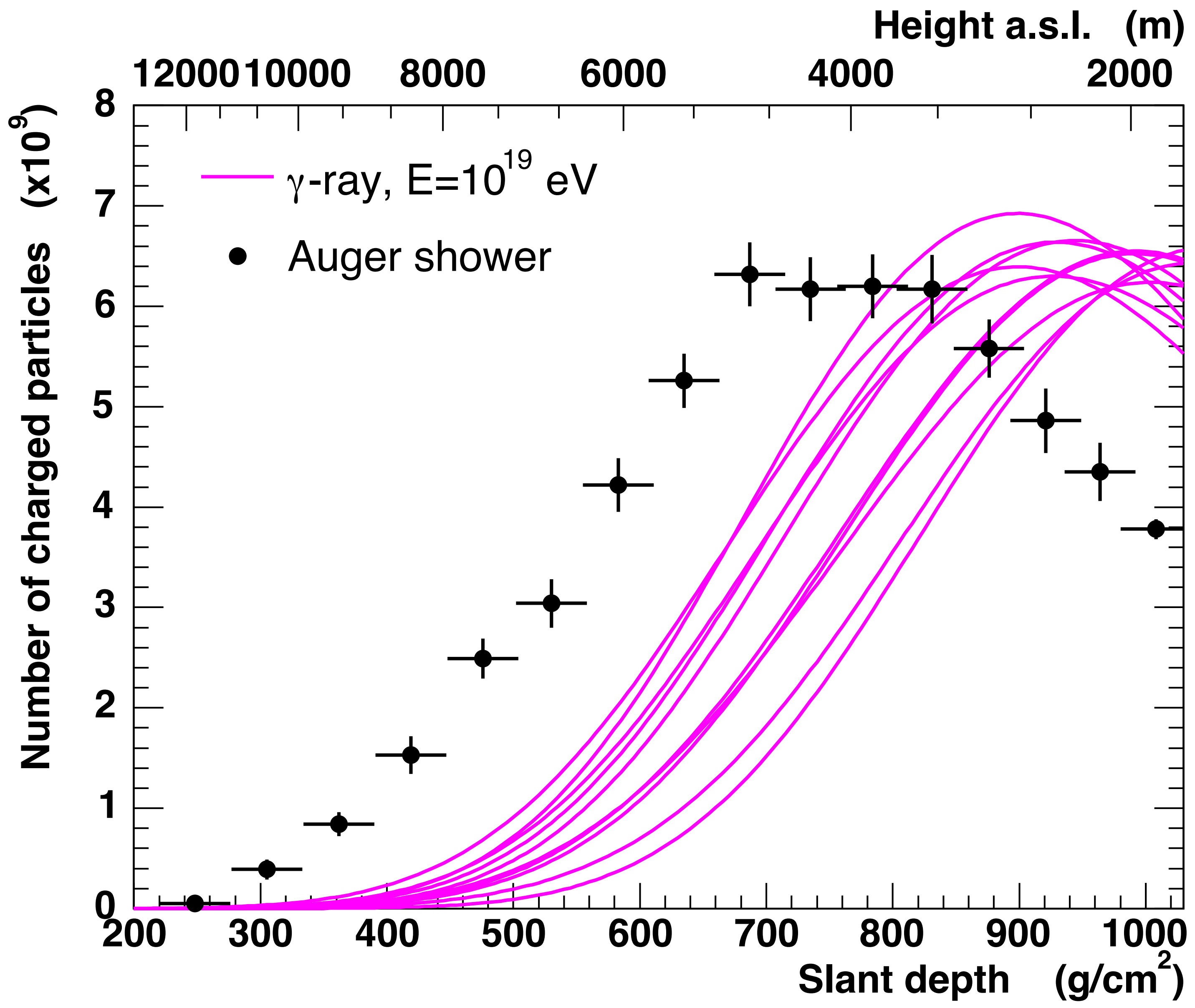
$$X_{\max}^A \sim \lambda_{\text{eff}} \ln(E_0/A)$$

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

Longitudinal shower profiles: simulations and data







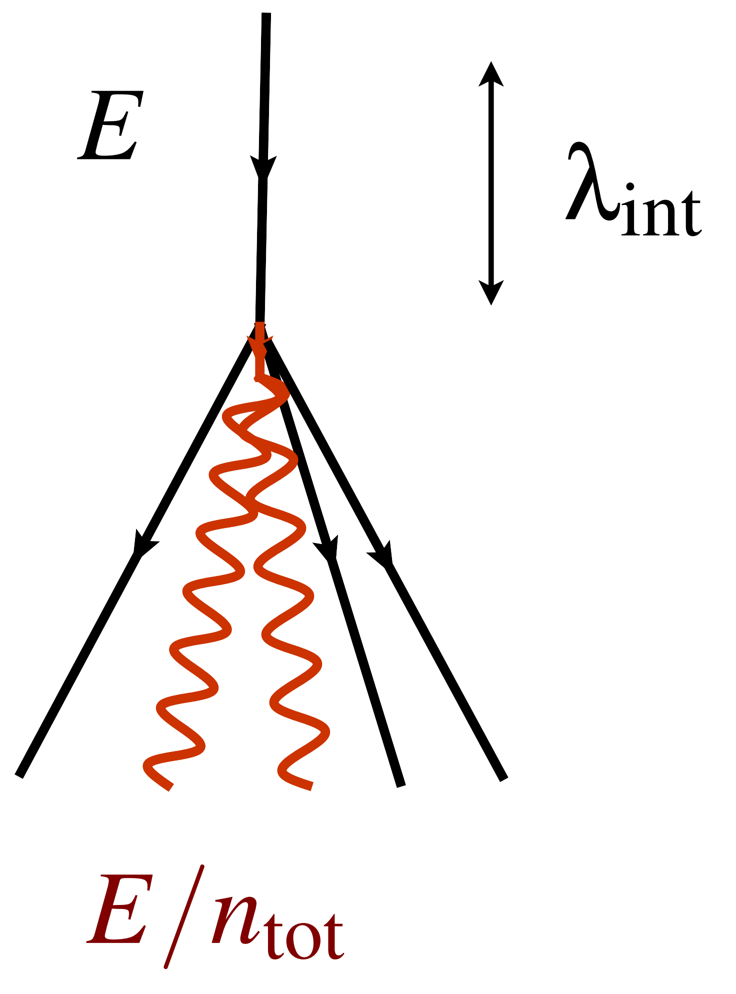
$$N_{\max} = E_0/E_c$$

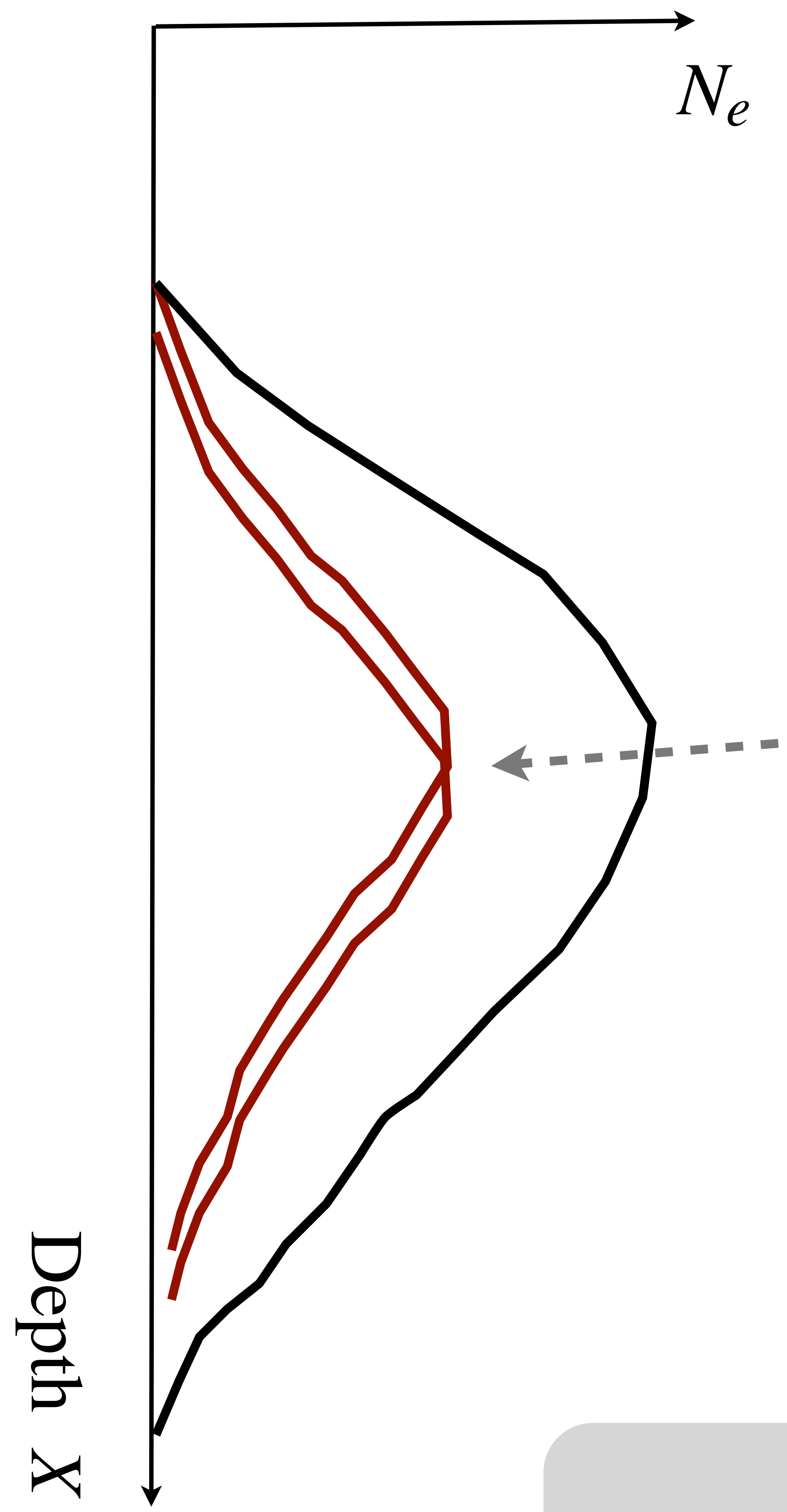
$$X_{\max} \sim D_{\mathrm{e}} \ln(E_0/E_c)$$

Superposition model:

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

Derivation of elongation rate theorem





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

em. cascade theory

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

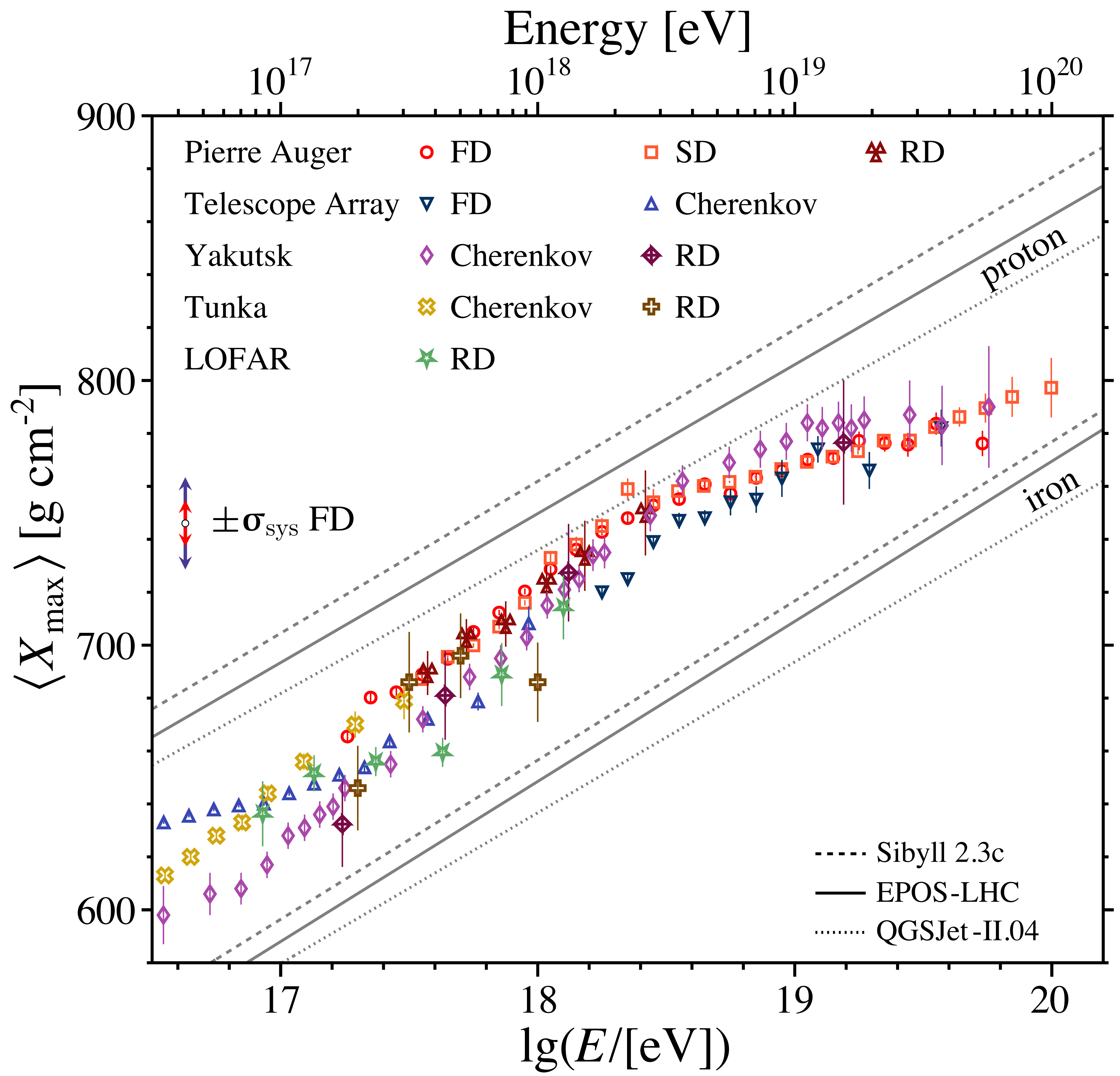
$$\langle X_{\max}(E)\rangle \;=\; X_0\; \ln(E/n_{\rm tot}) + c \;+\; \lambda_{\rm int}$$

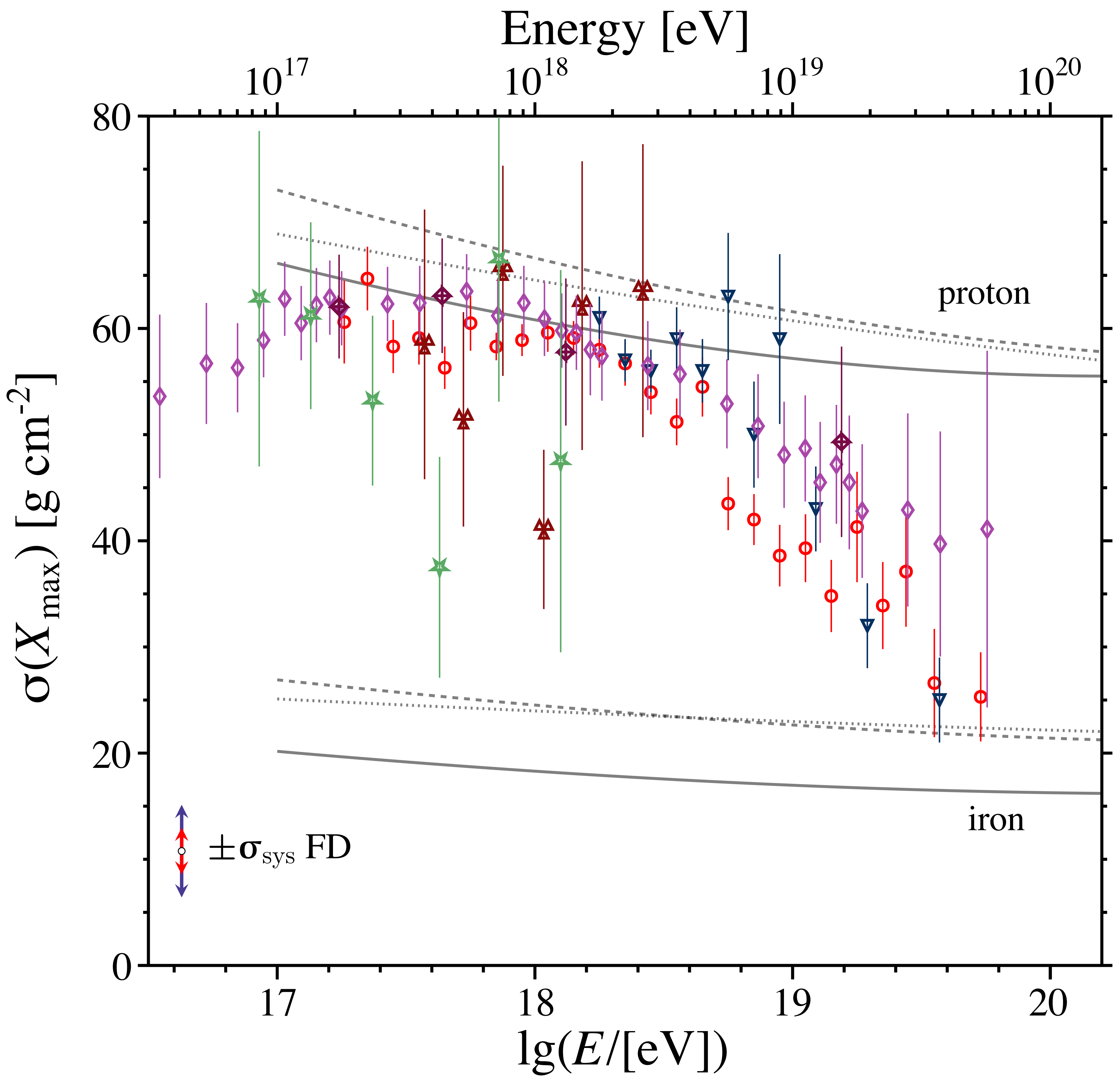
taking derivative $\log E$

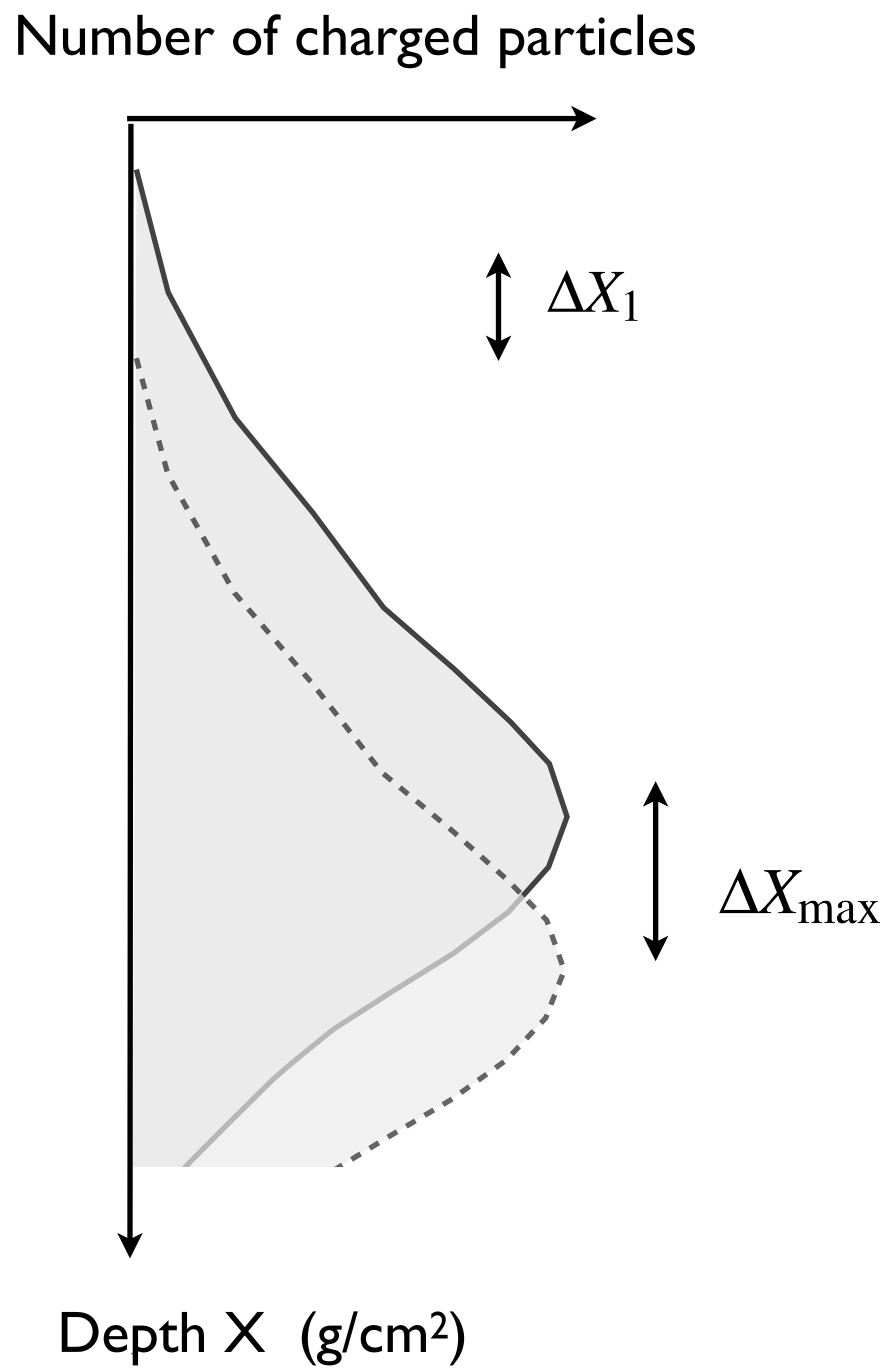
$$D_e = \frac{\mathrm{d}\langle X_{\max}(E)\rangle}{\mathrm{d}\ln E} \;\leq\; X_0 \;-\; X_0 \frac{\mathrm{d}\ln n_{\rm tot}}{\mathrm{d}\ln E} \;+\; \frac{\mathrm{d}\lambda_{\rm int}}{\mathrm{d}\ln E}$$

Elongation rate of em. shower

Mass composition results – world data







$$\frac{dP}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

$$\boxed{\begin{array}{l}\sigma_{X_1,p} \sim 45 - 55\,\mathrm{g/cm^2} \\ \sigma_{X_1,Fe} \sim 10\,\mathrm{g/cm^2}\end{array}}$$

$(E \sim 10^{18}\,\mathrm{eV})$

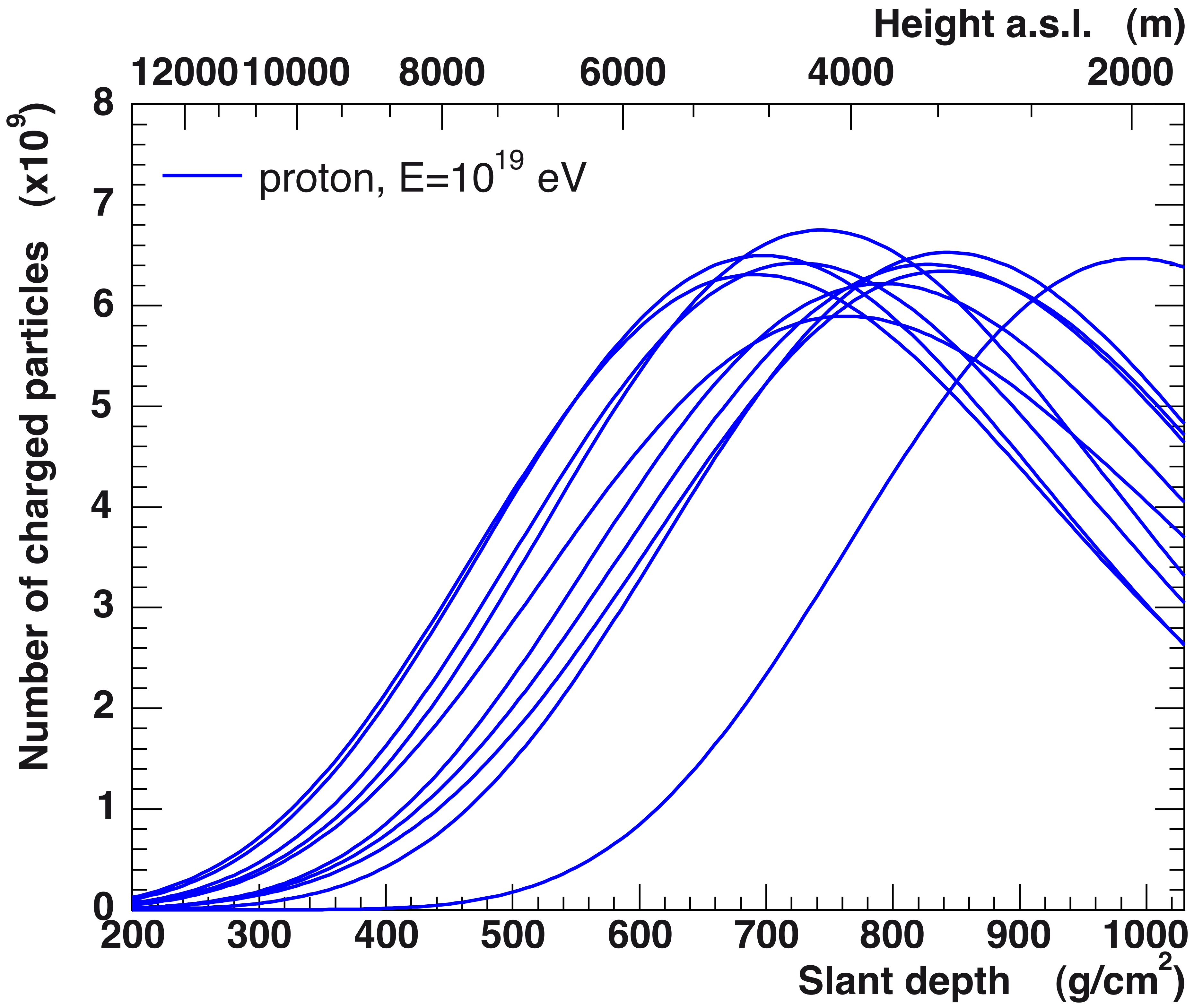
Important: LHC-tuned interaction models used for interpretation

(Snowmass report UHECR composition, 2022)

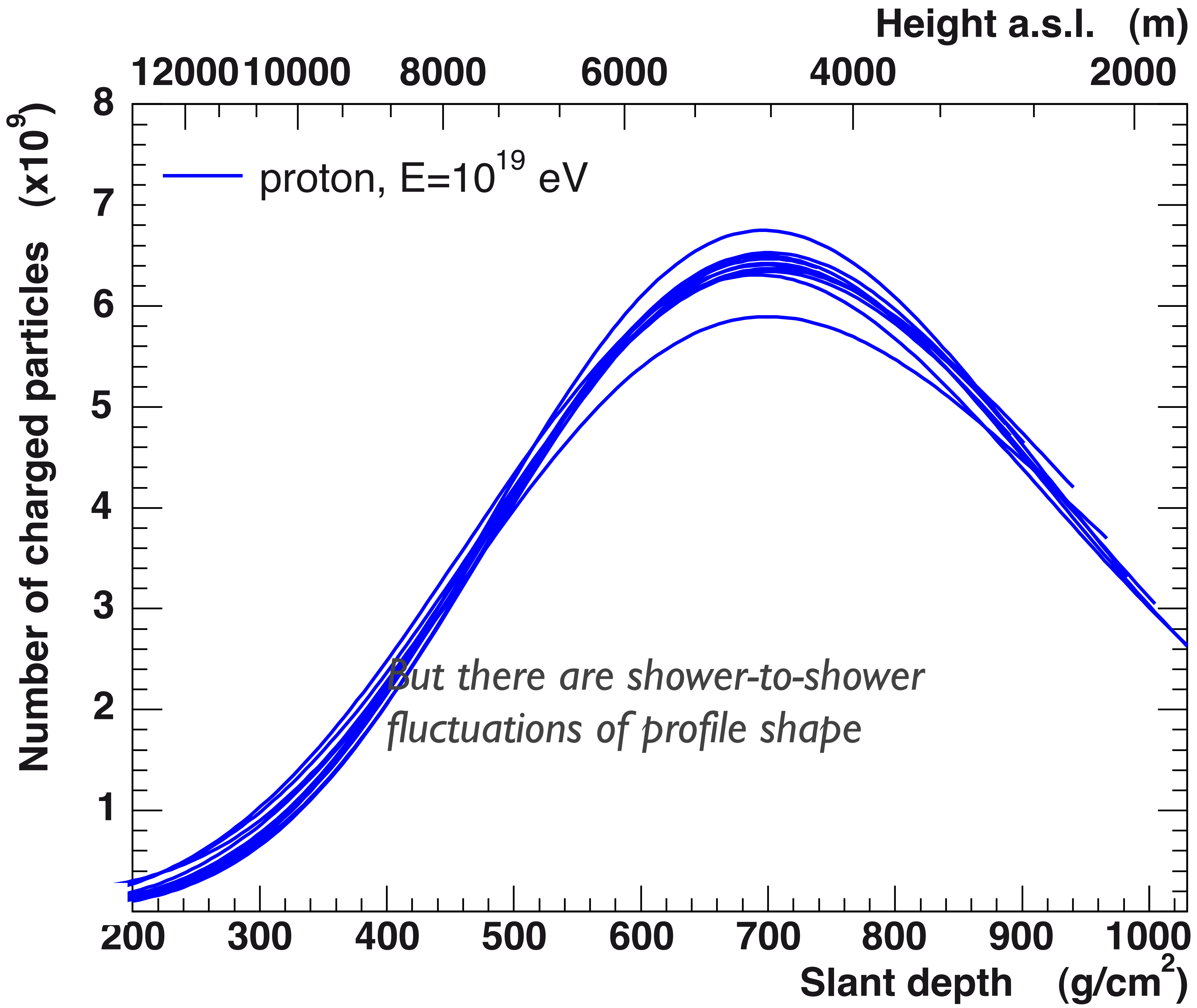
(Phys. Rev. D96 (2017), 122003)

Universality features of high-energy shower profiles

Simulated shower profiles

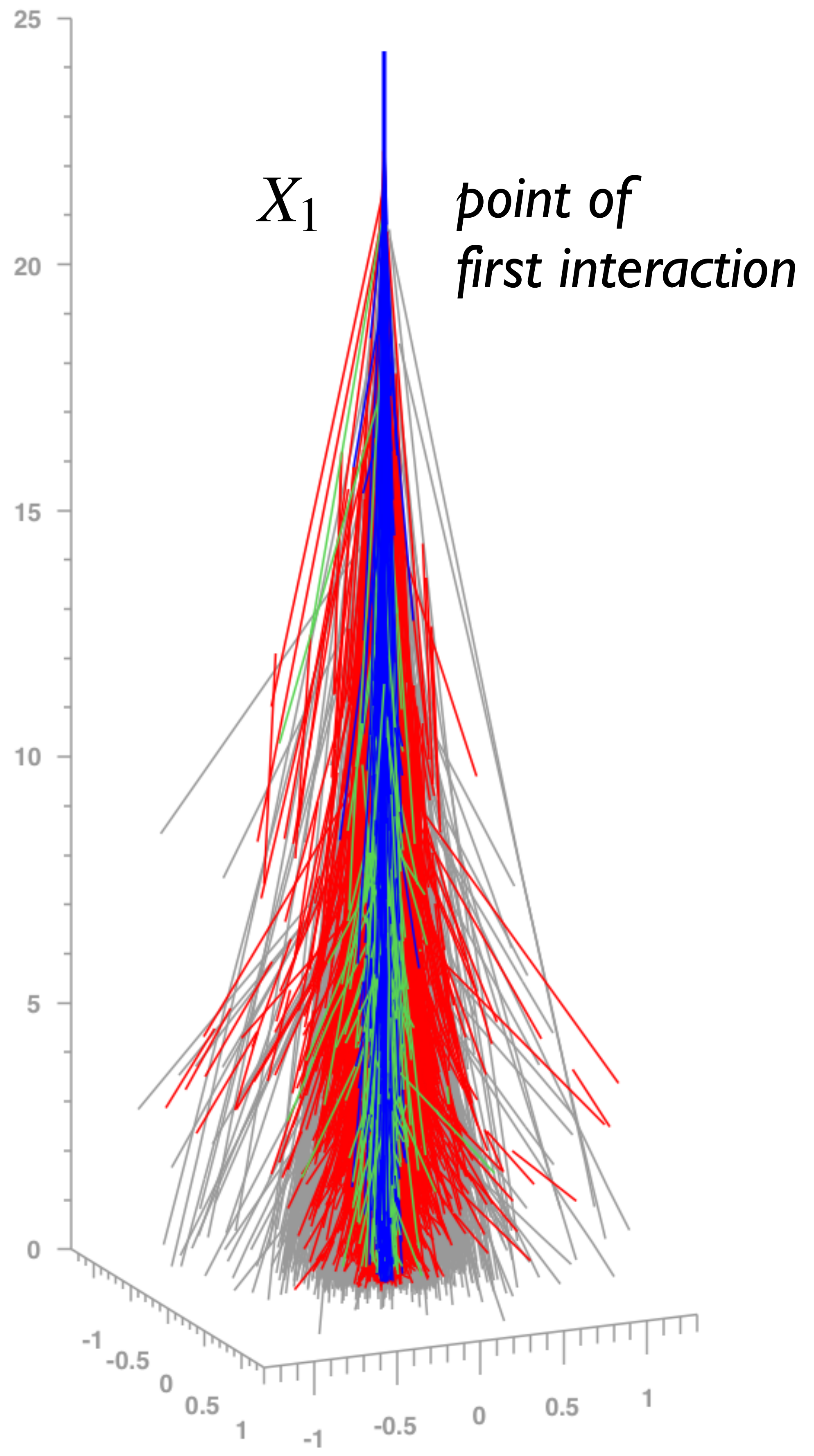


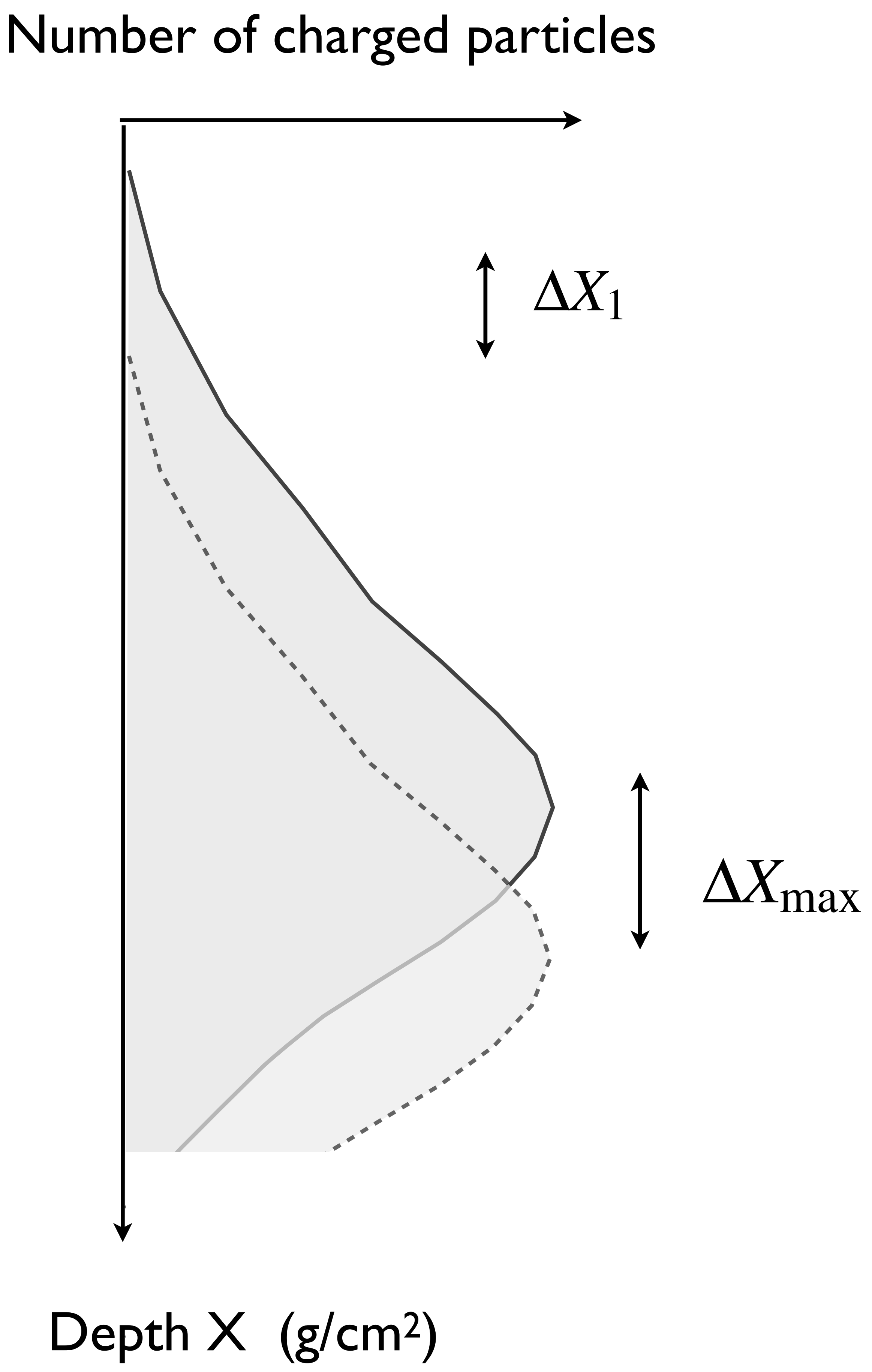
Profiles shifted in depth



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

Measurement of proton-air cross section



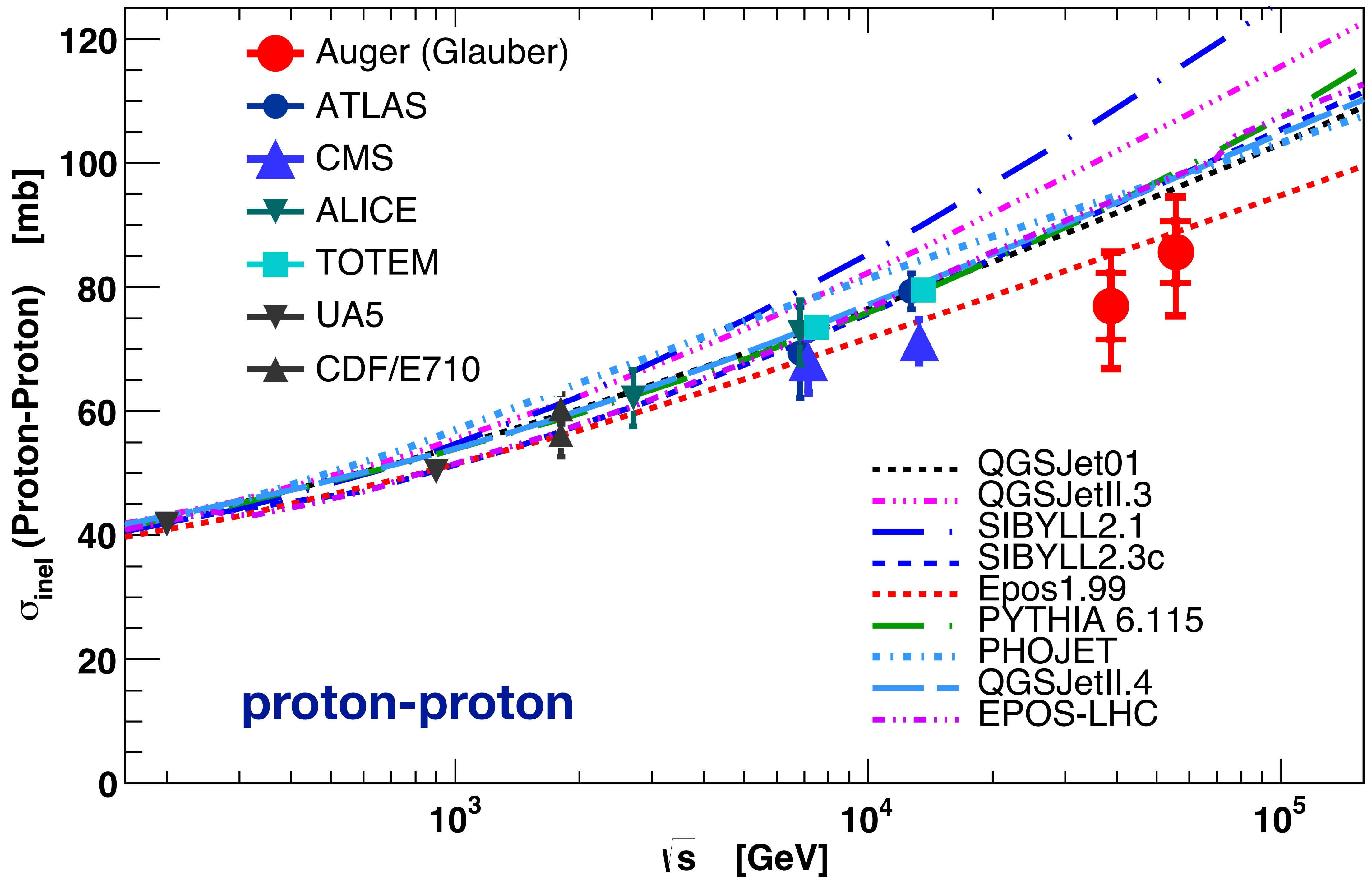


$$\frac{dP}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

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

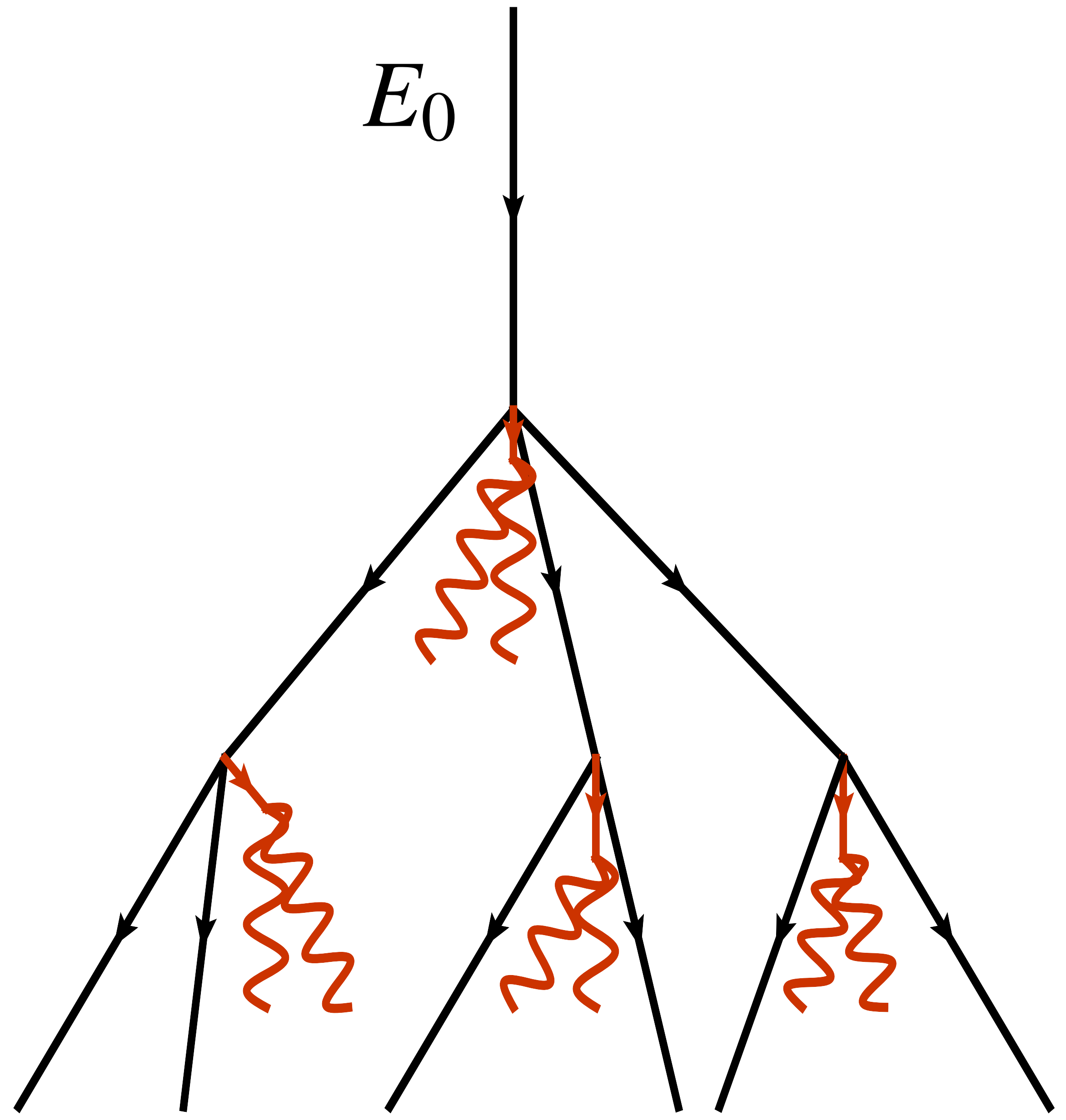
Difficulties

- mass composition
- fluctuations in shower development (model needed for correction)



(Auger PRL 109, 2012; Telescope Array PRD 92, 2015)

Electromagnetic energy and energy transfer



Hadronic energy

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

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

$$\vdots$$

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

After n generations …

$$n = 5,\ \ E_{had} \sim 12\%$$
$$n = 6,\ \ E_{had} \sim 8\%$$

Electromagnetic energy

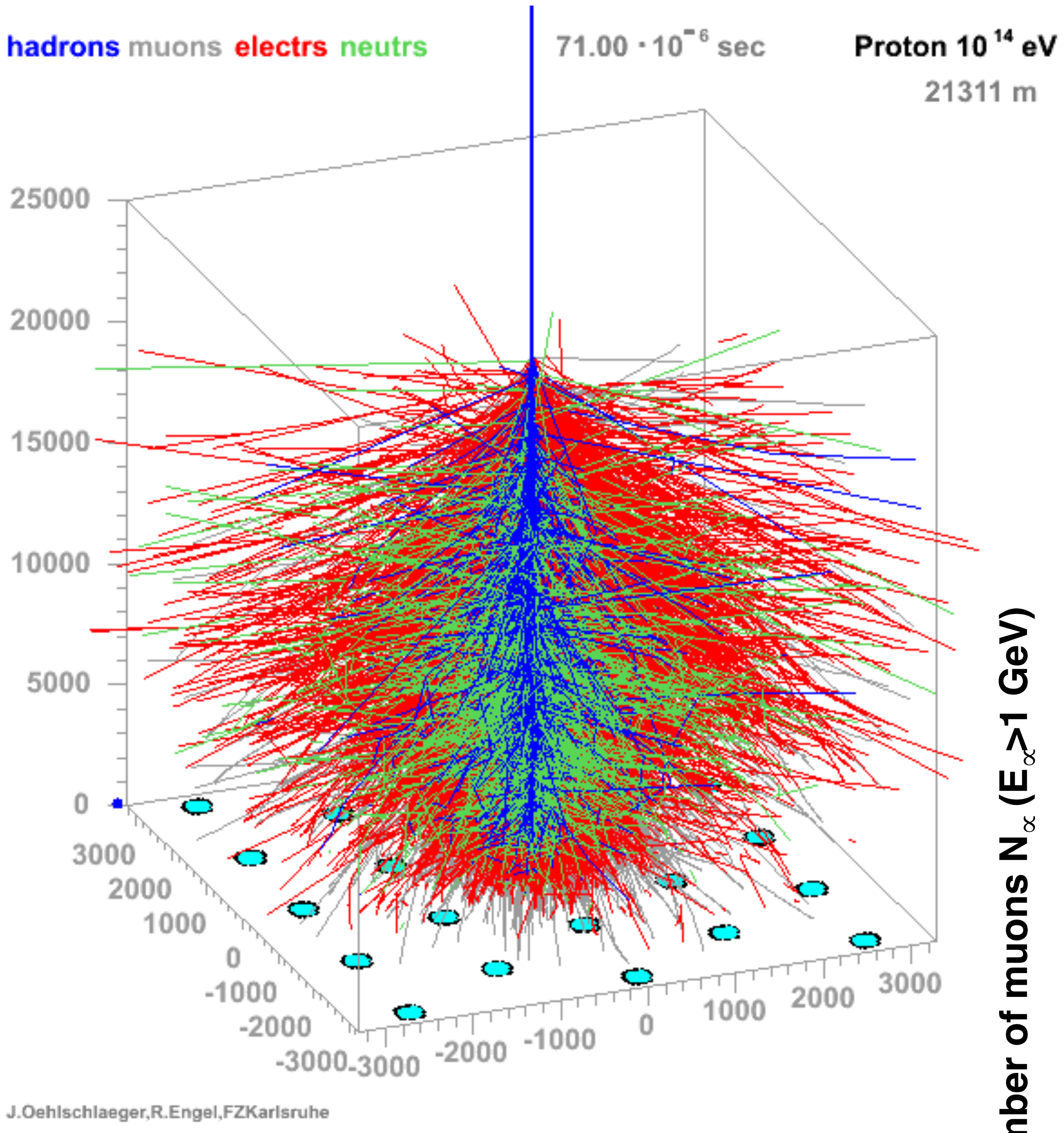
$$\frac{1}{3}E_0$$

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

$$\vdots$$

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

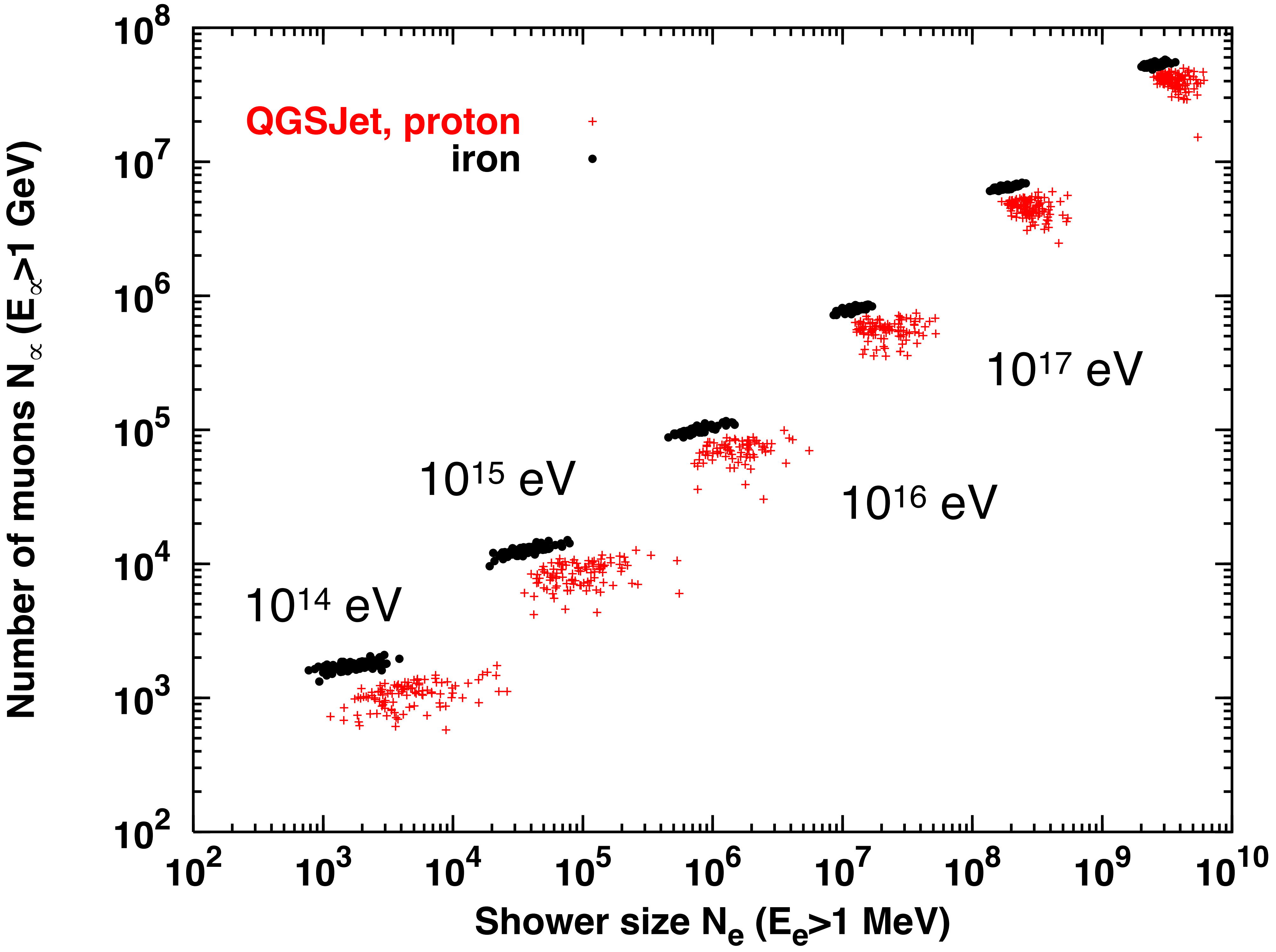
Air shower ground arrays: N_e and N_μ



KASCADE and KASCADE-Grande

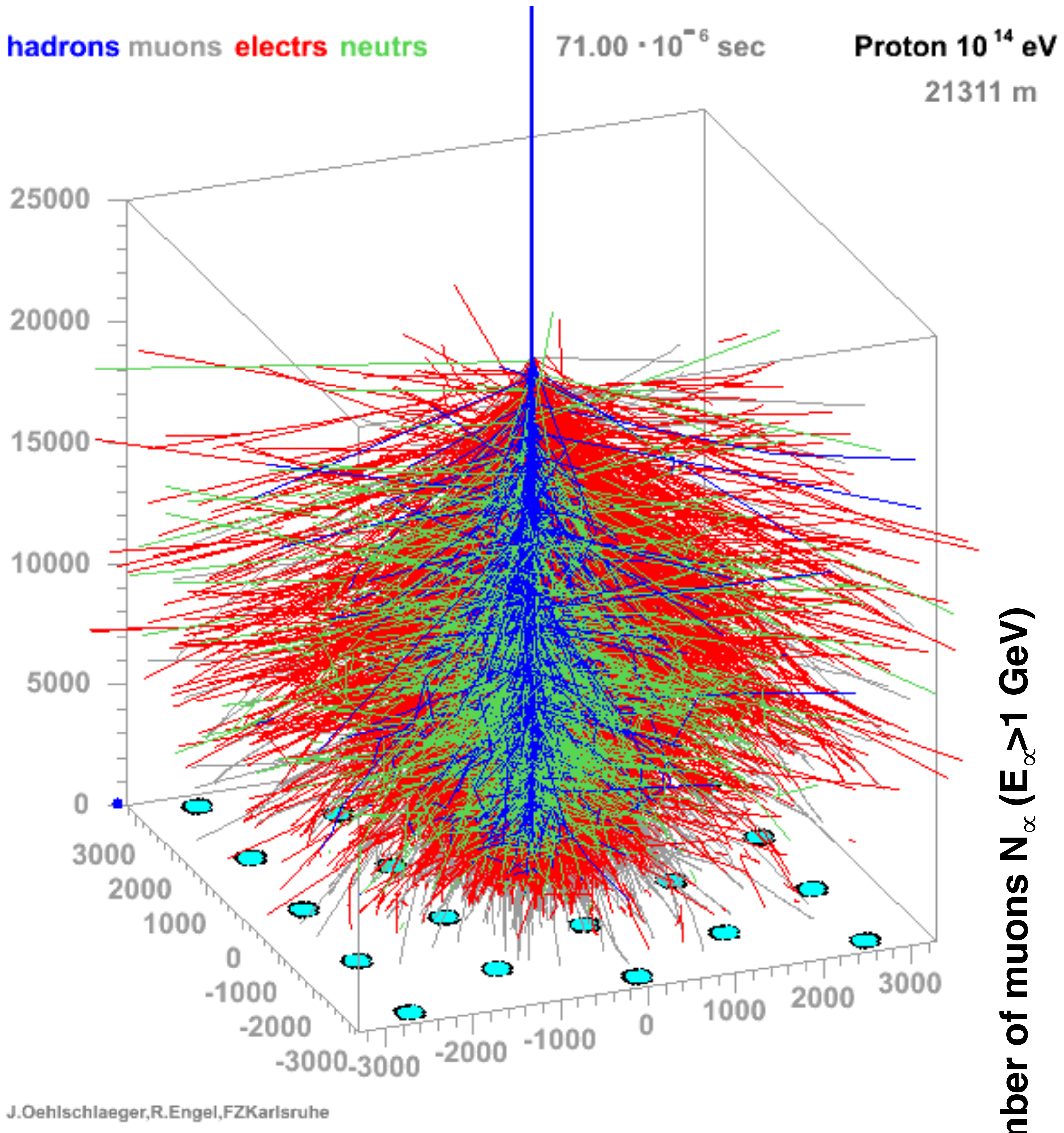
Energy conservation

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



Air shower ground arrays

Air shower ground arrays: N_e and N_μ



KASCADE and KASCADE-Grande

Energy conservation

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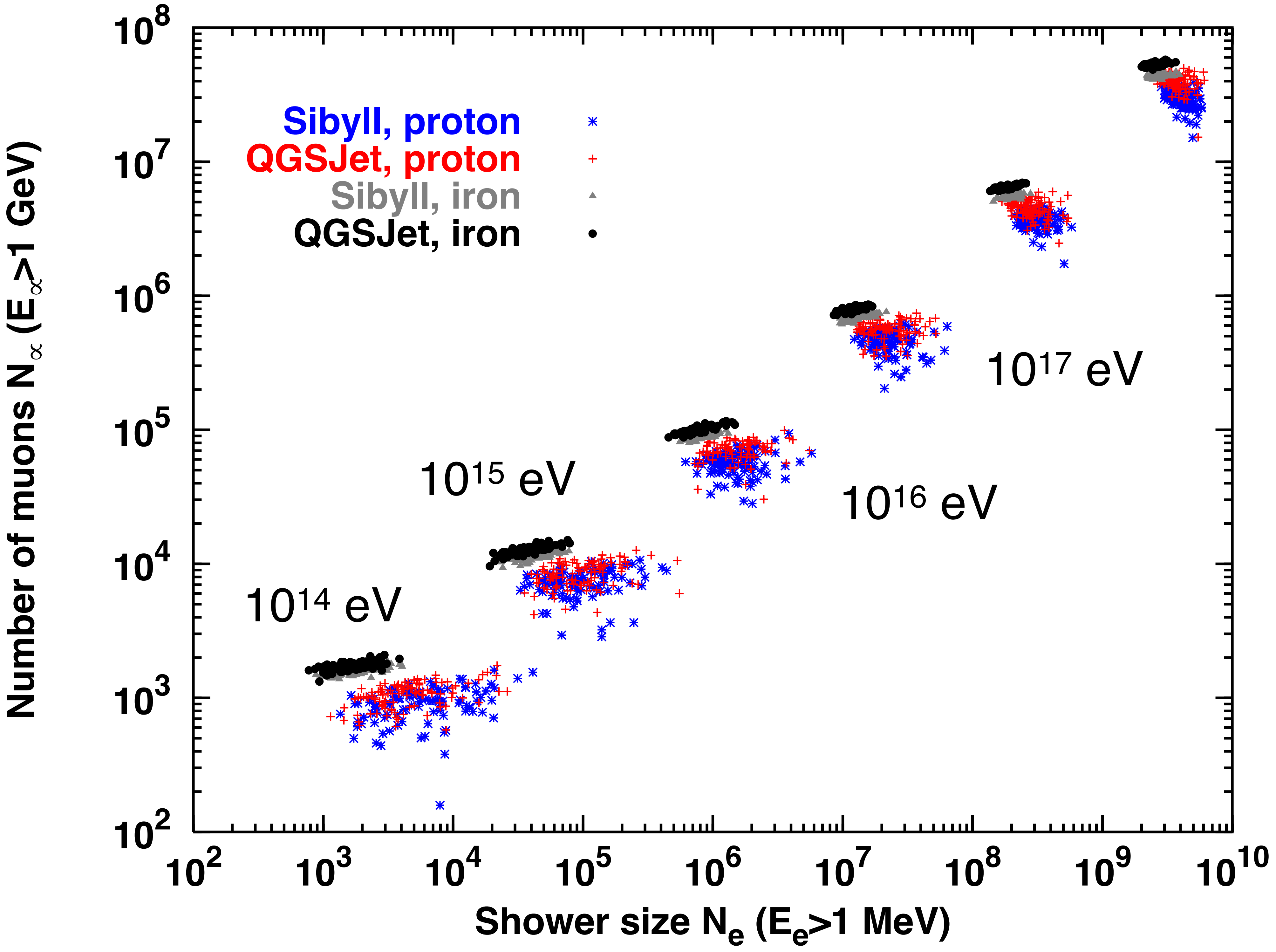
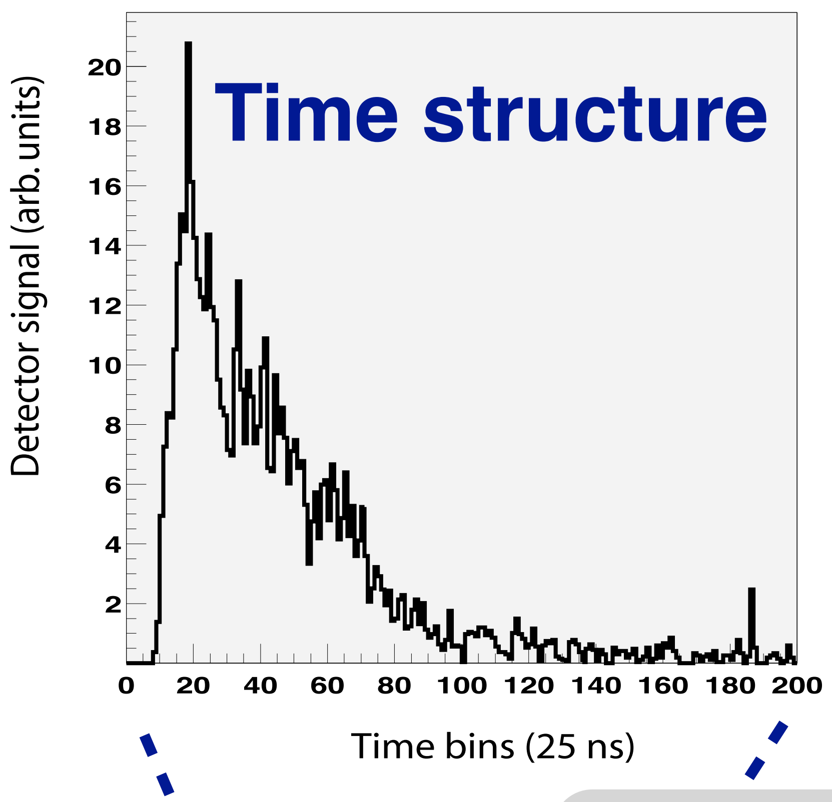
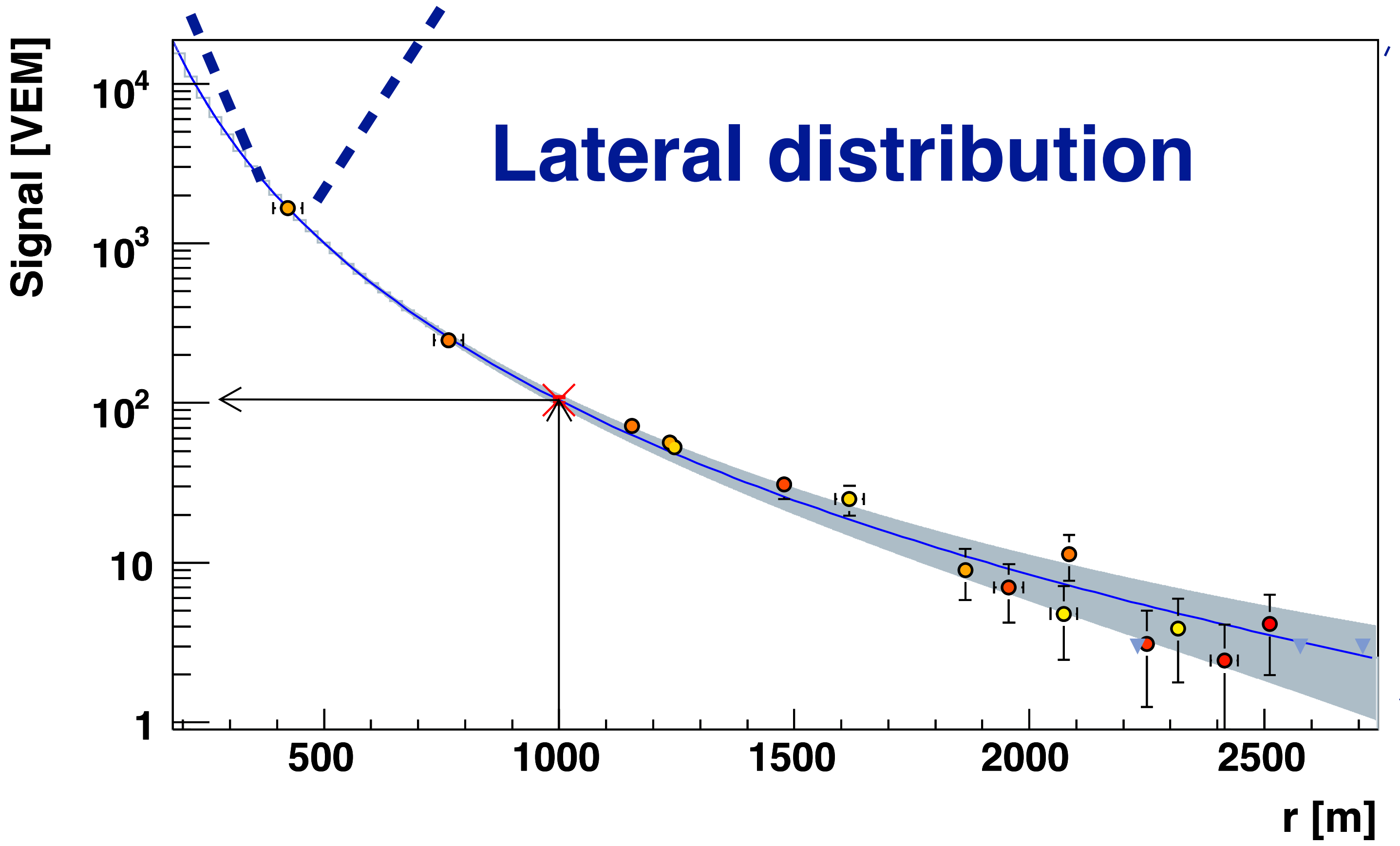


2. Overall description of air shower data

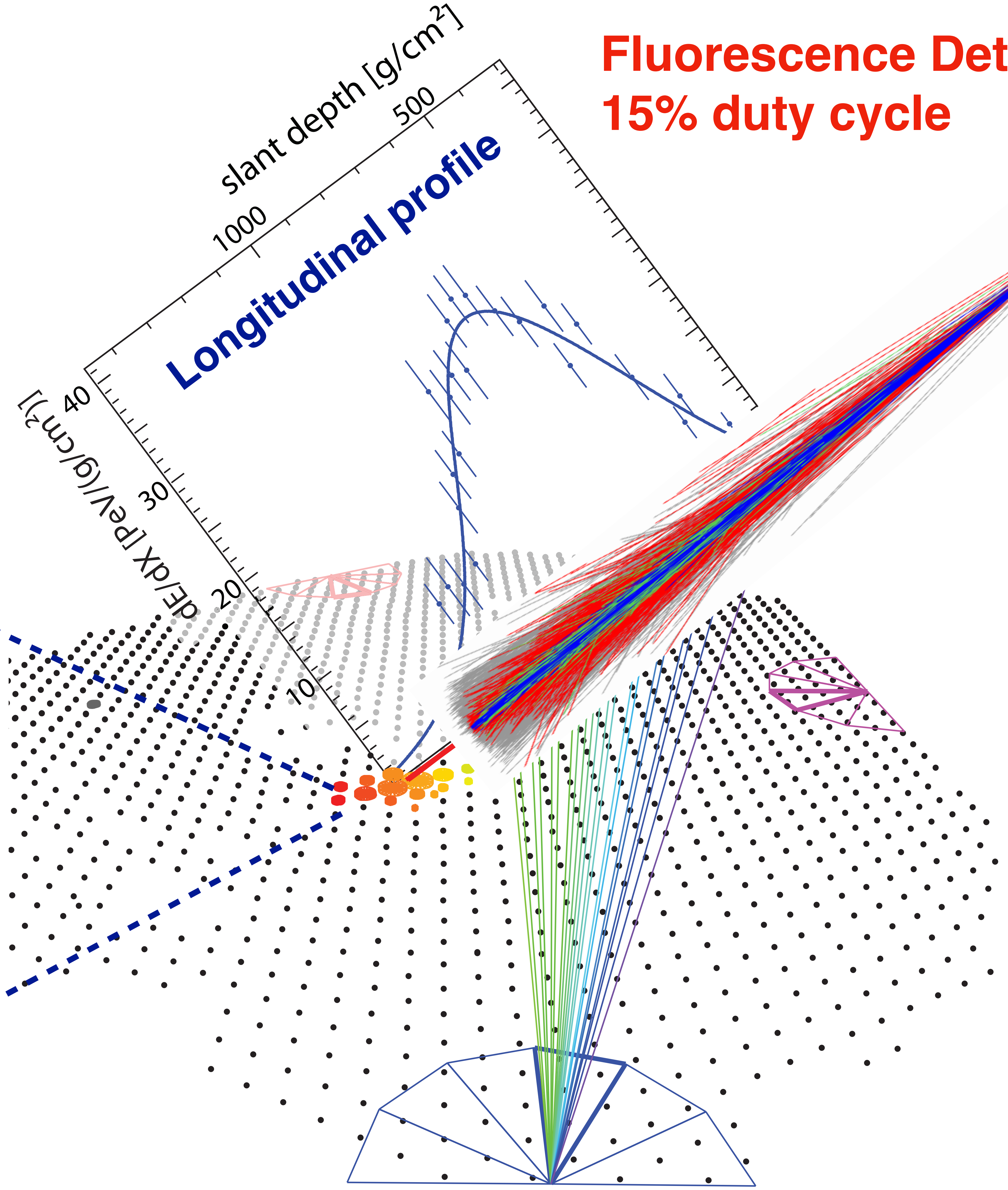
Air shower observables (Auger hybrid observation)



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



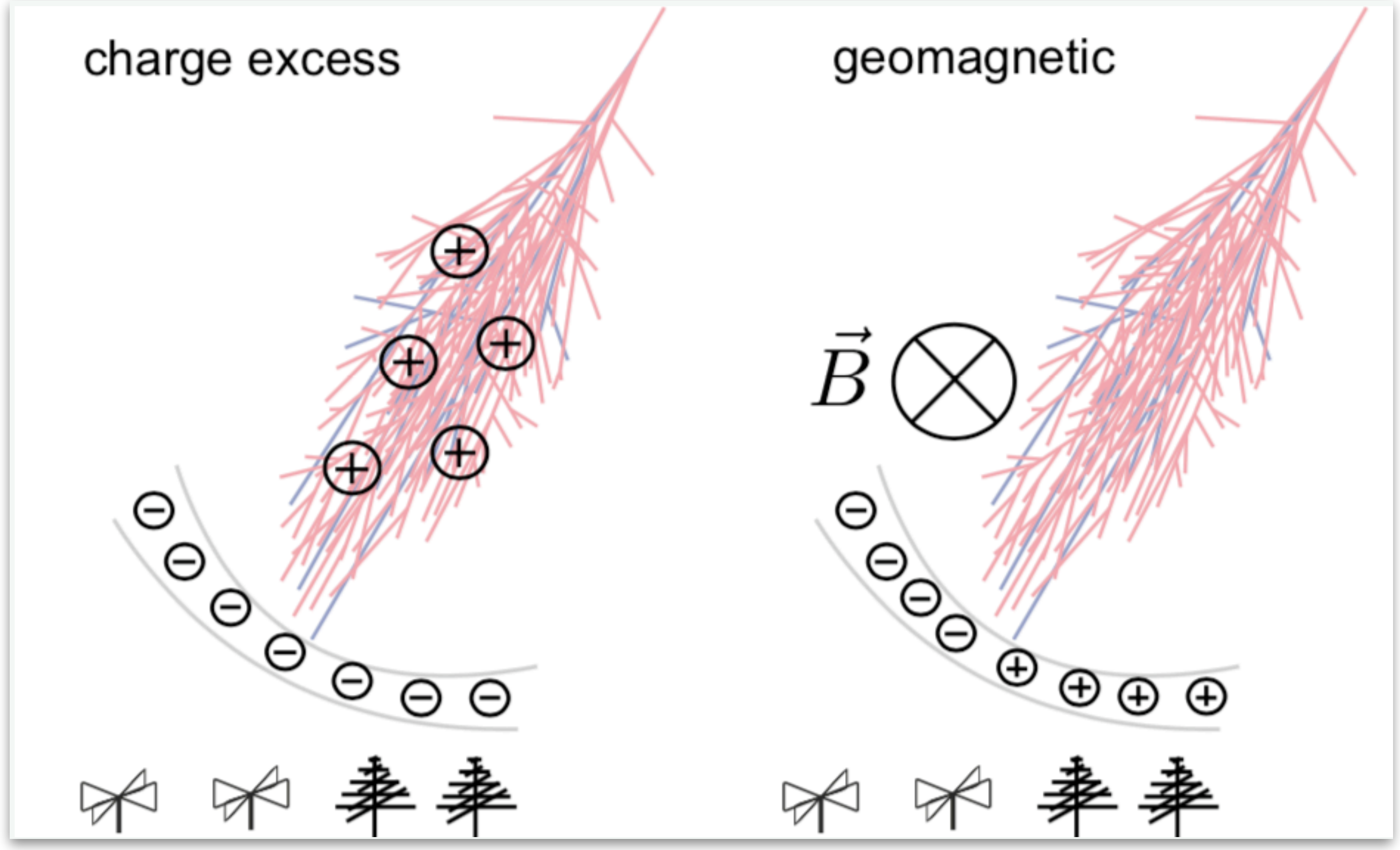
Surface Detector (SD)
100% duty cycle



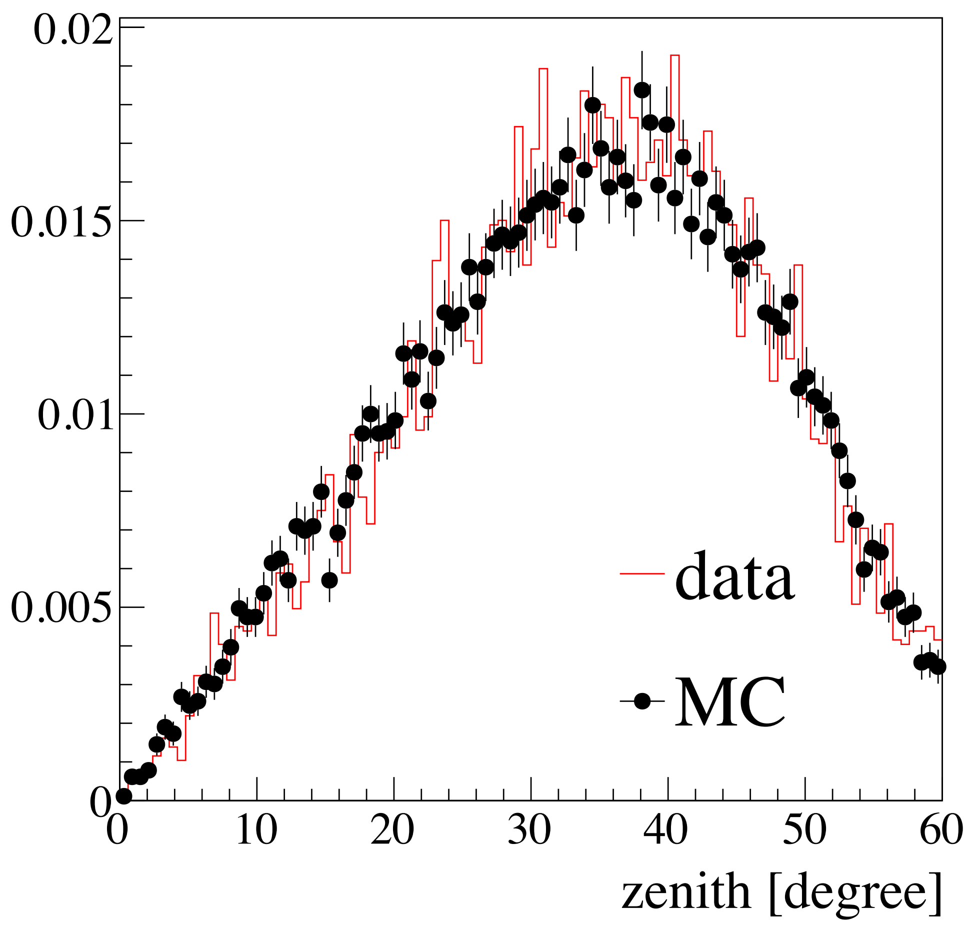
Fluorescence Detector (FD):
15% duty cycle

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

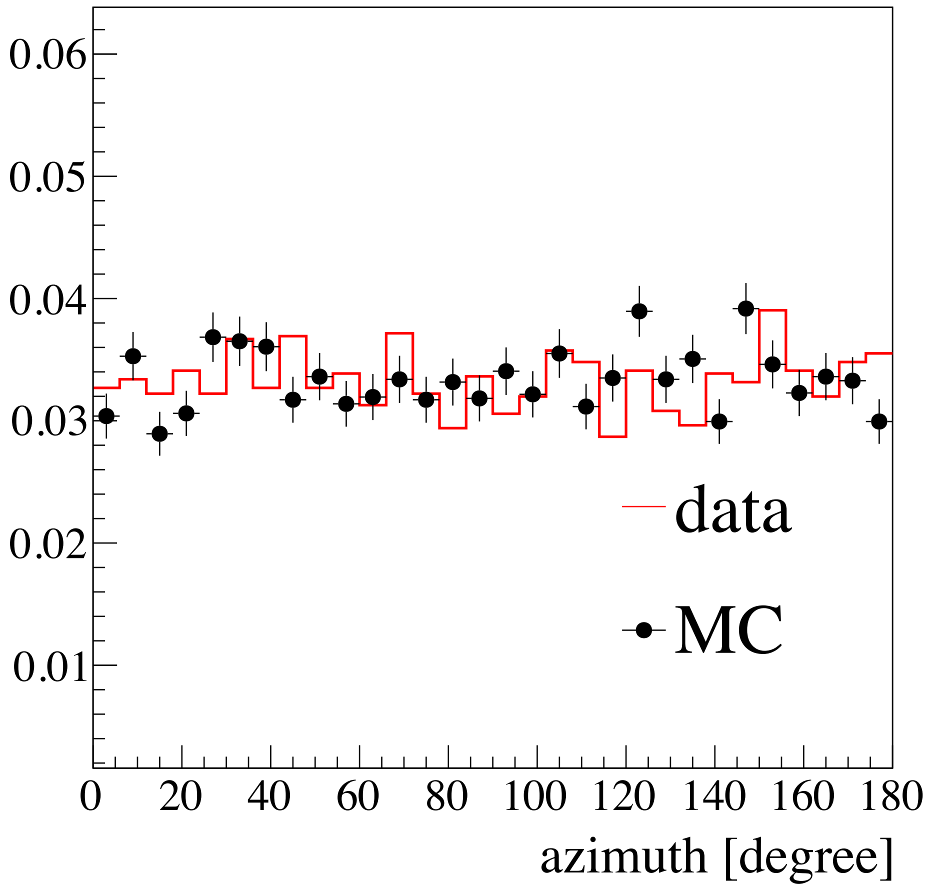
Radio Detector (RD):
100% duty cycle



Auger event simulation for surface array

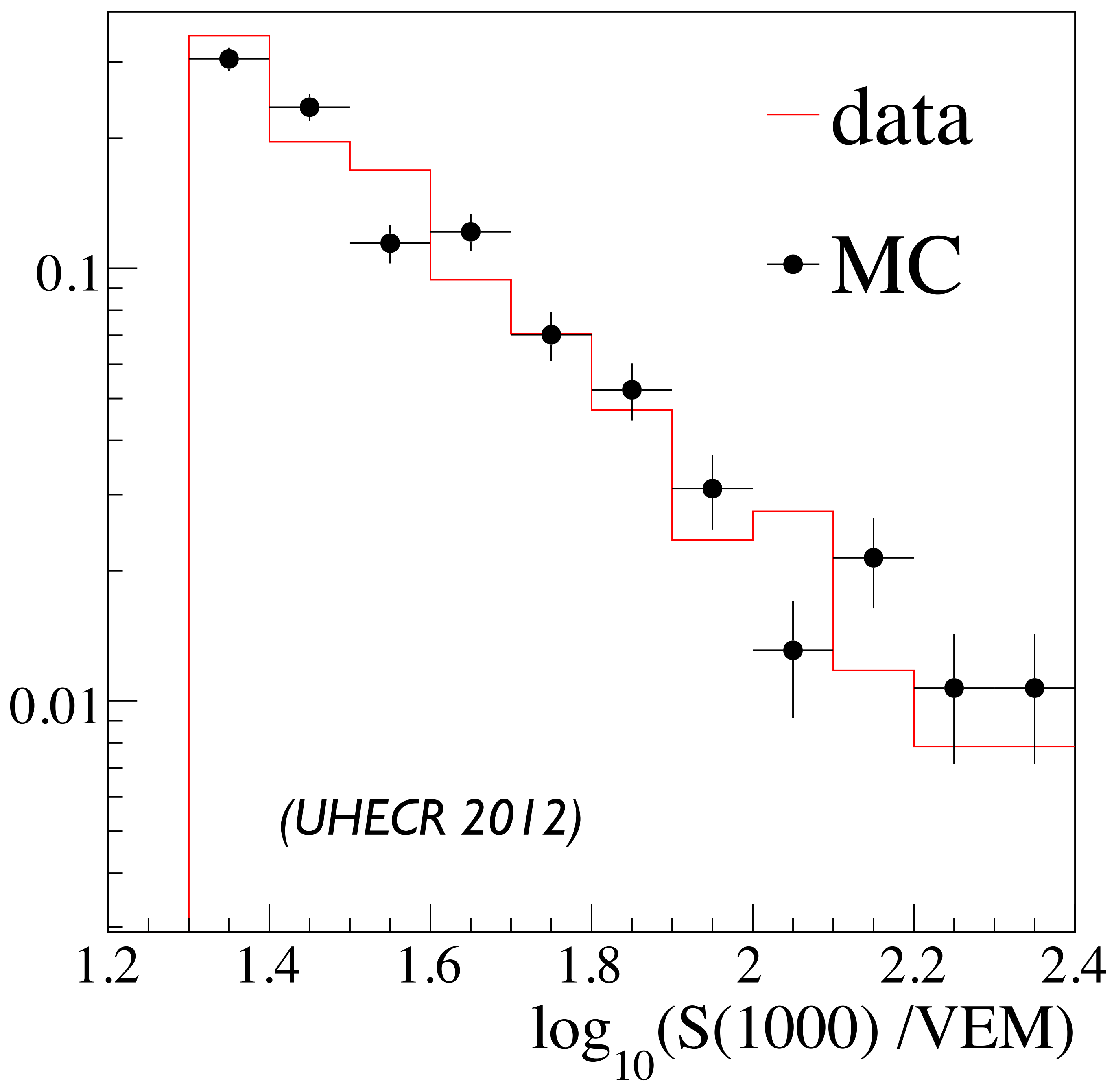


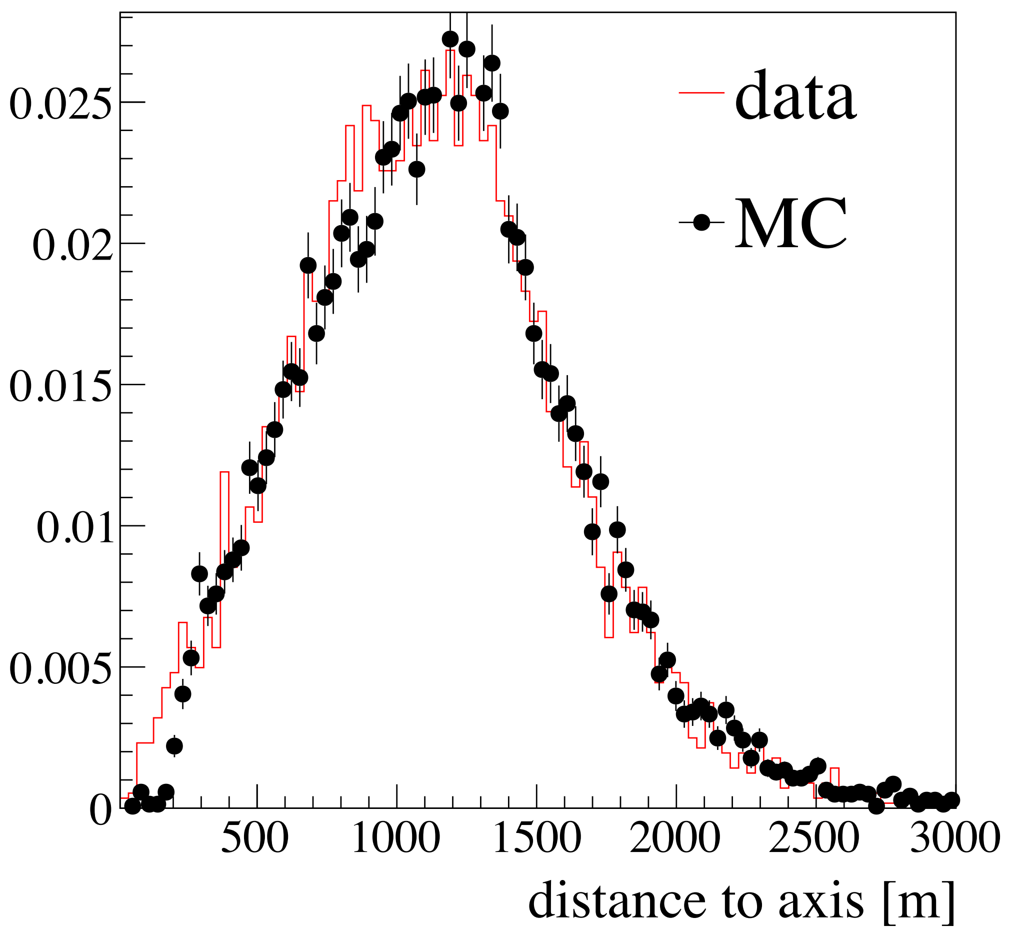
Zenith angle



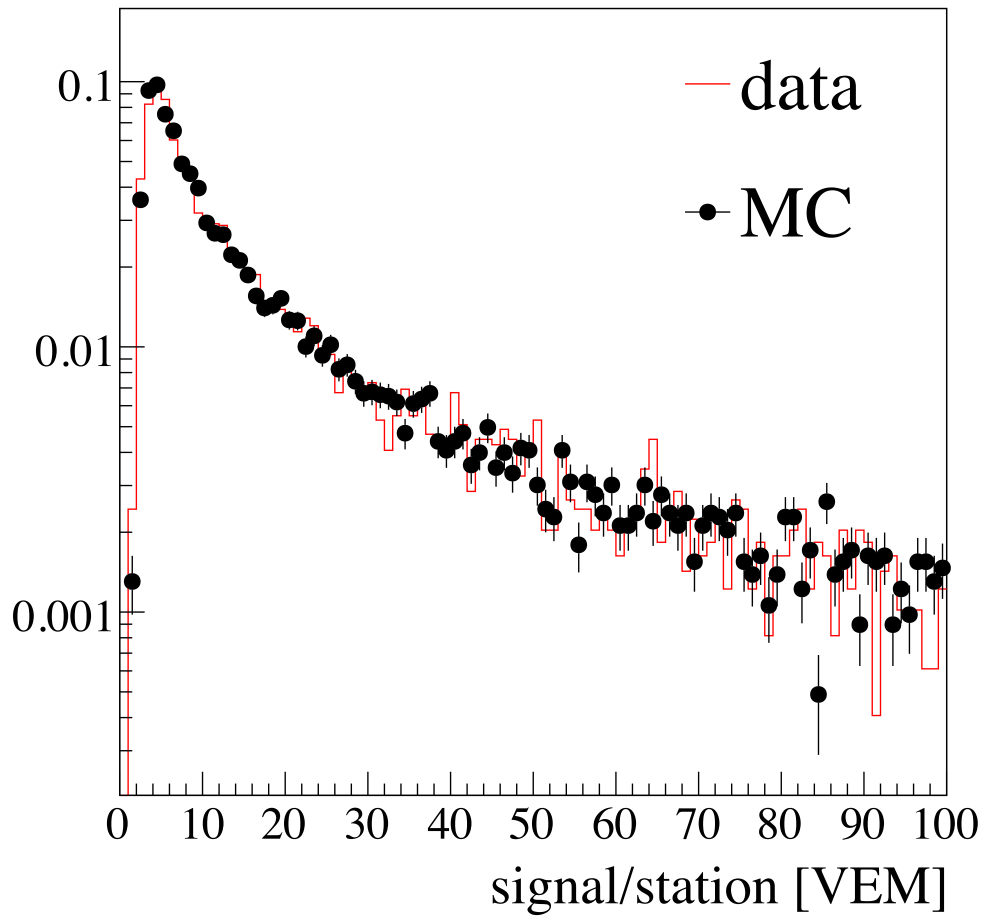
Azimuth angle

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





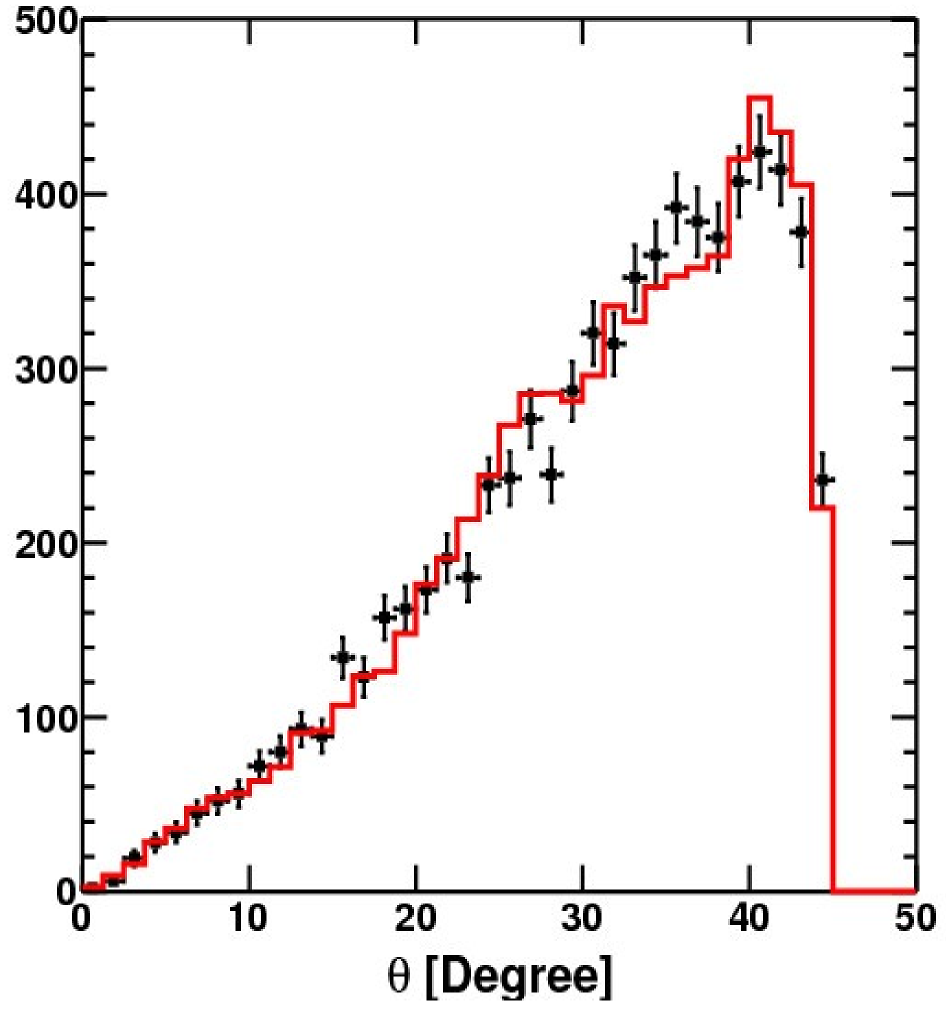
Distance of triggered stations



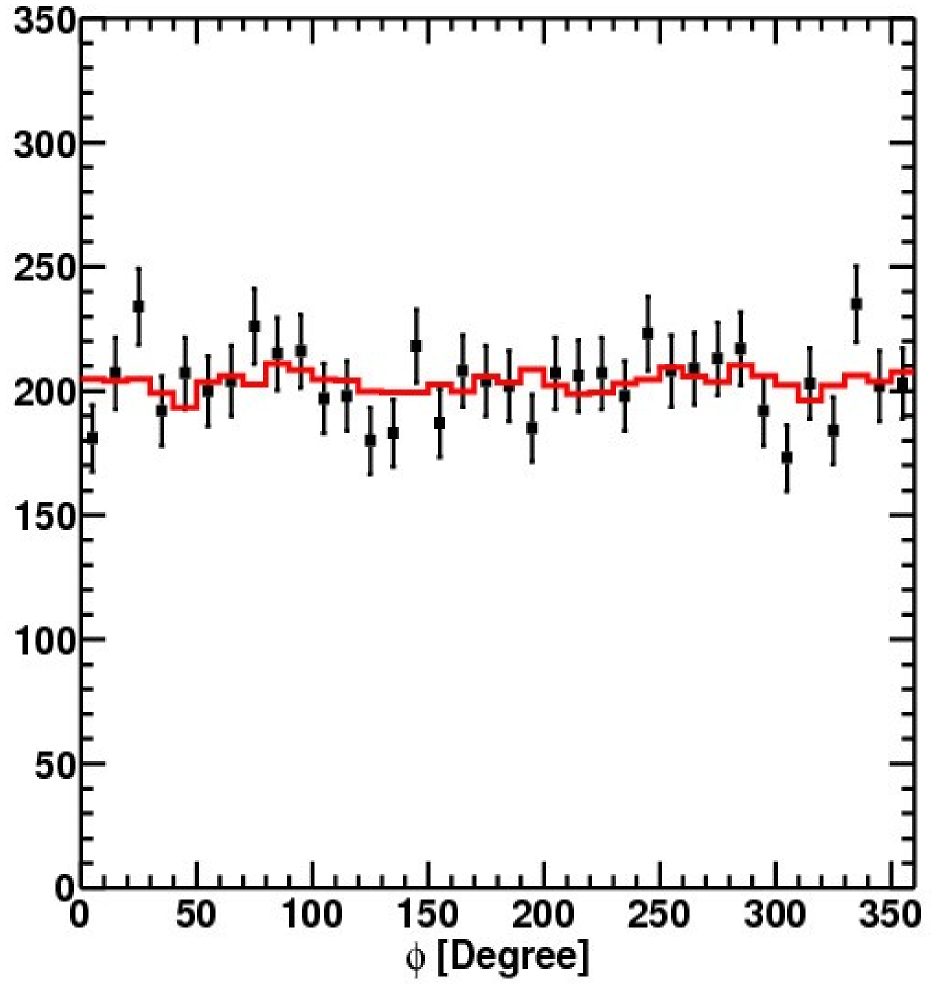
Signal per station

Very good agreement

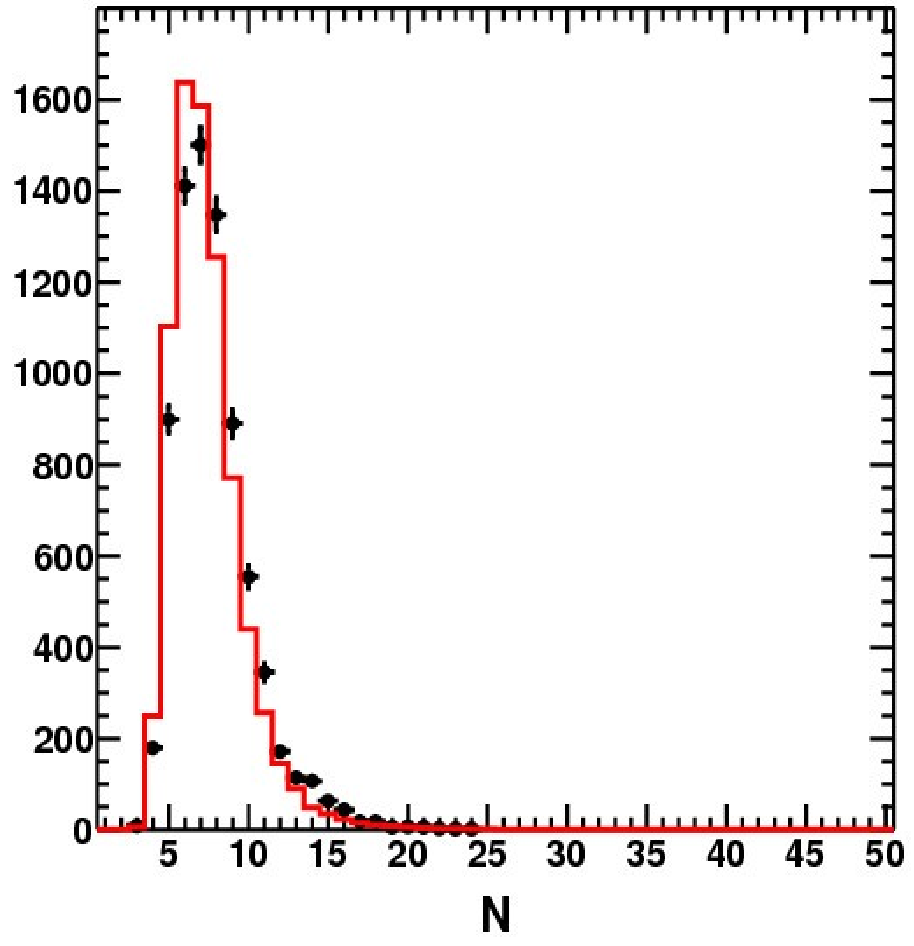
Telescope Array event simulation for surface array



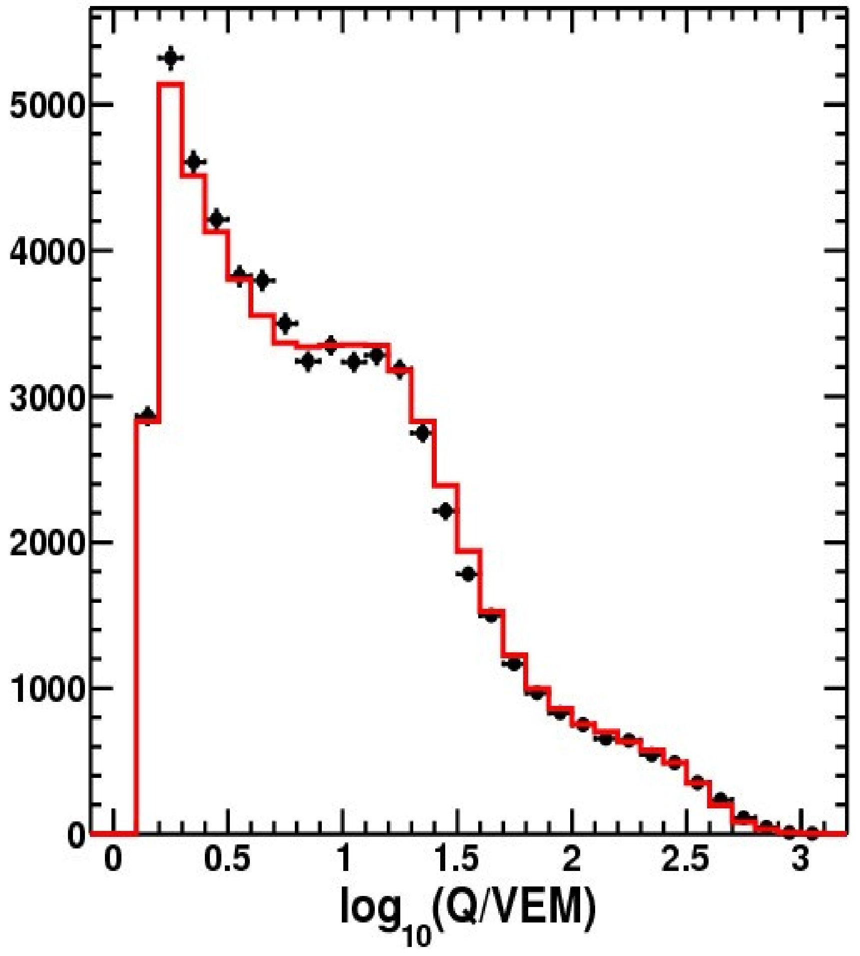
Zenith Angle



Azimuth Angle

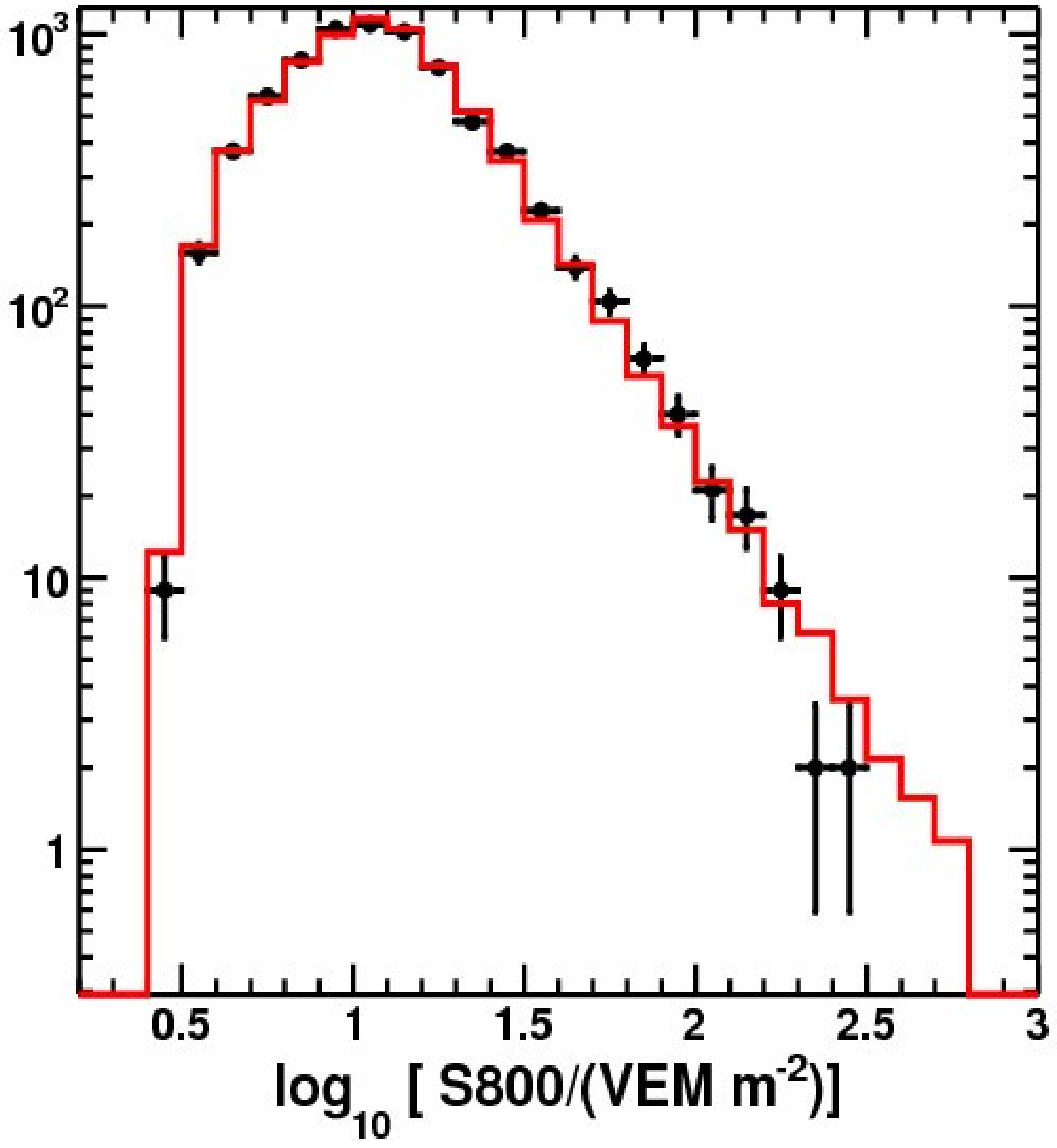


Number of Good Counters/Event



Charge/Counter/Event

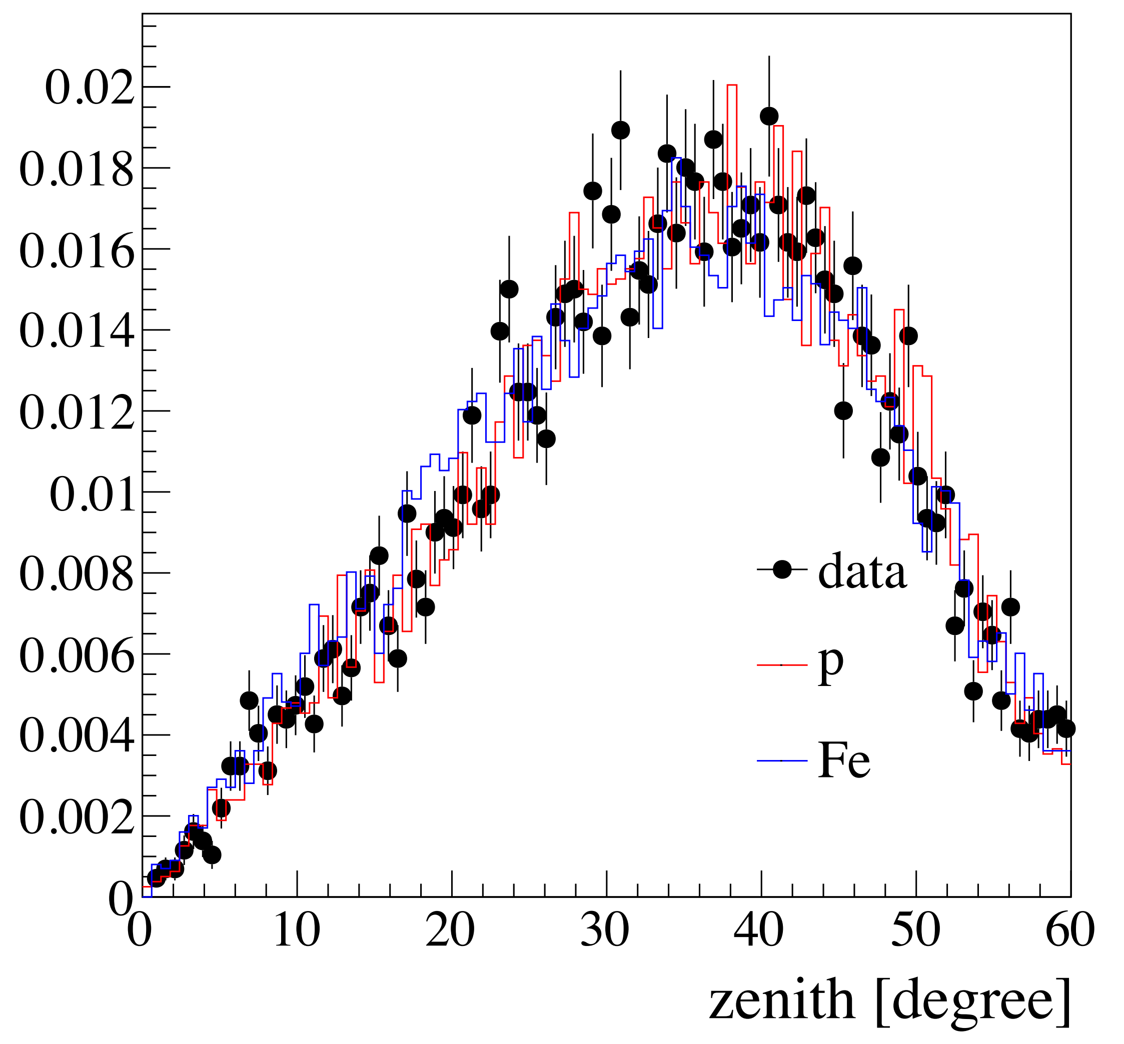
CORSIKA + full detector simulation
(proton primaries)



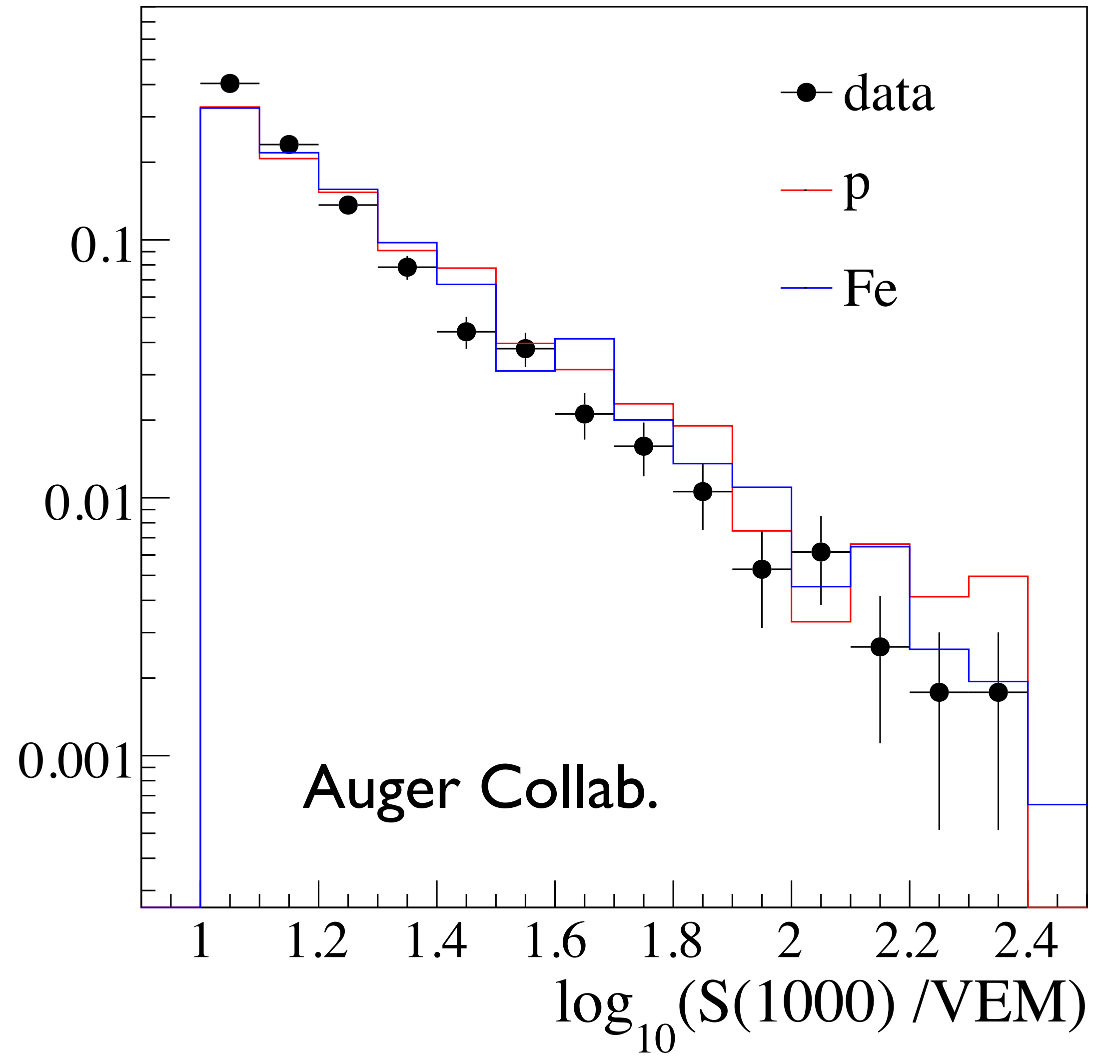
(UHECR 2012)

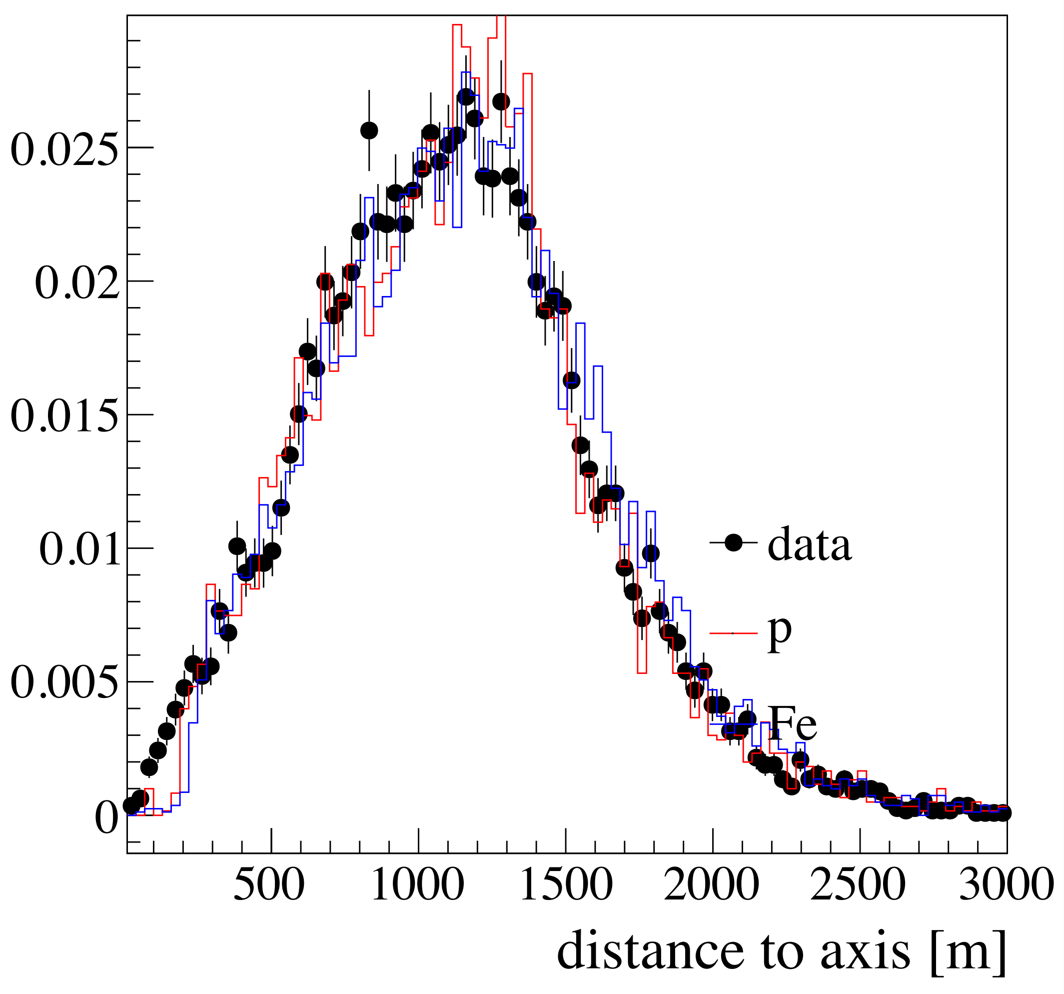
Very good agreement

Composition sensitivity of data description?

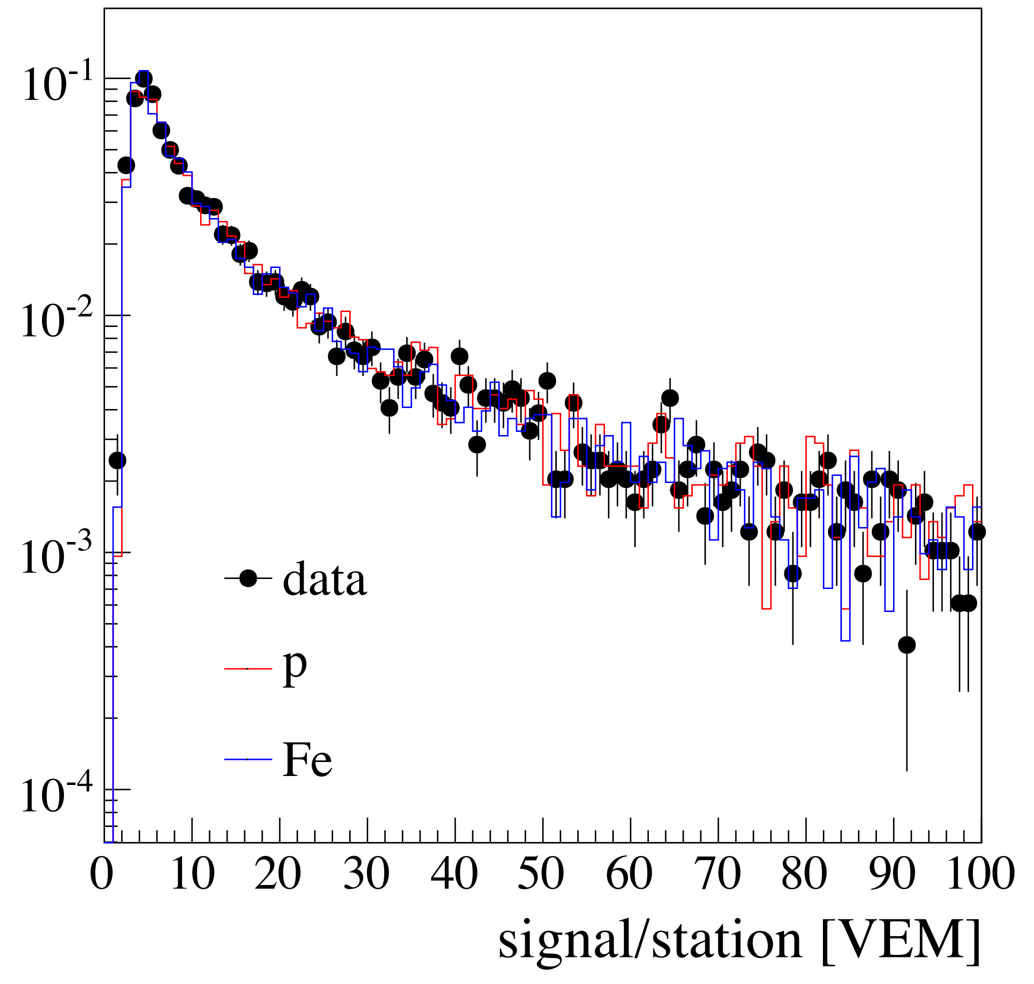


Zenith angle

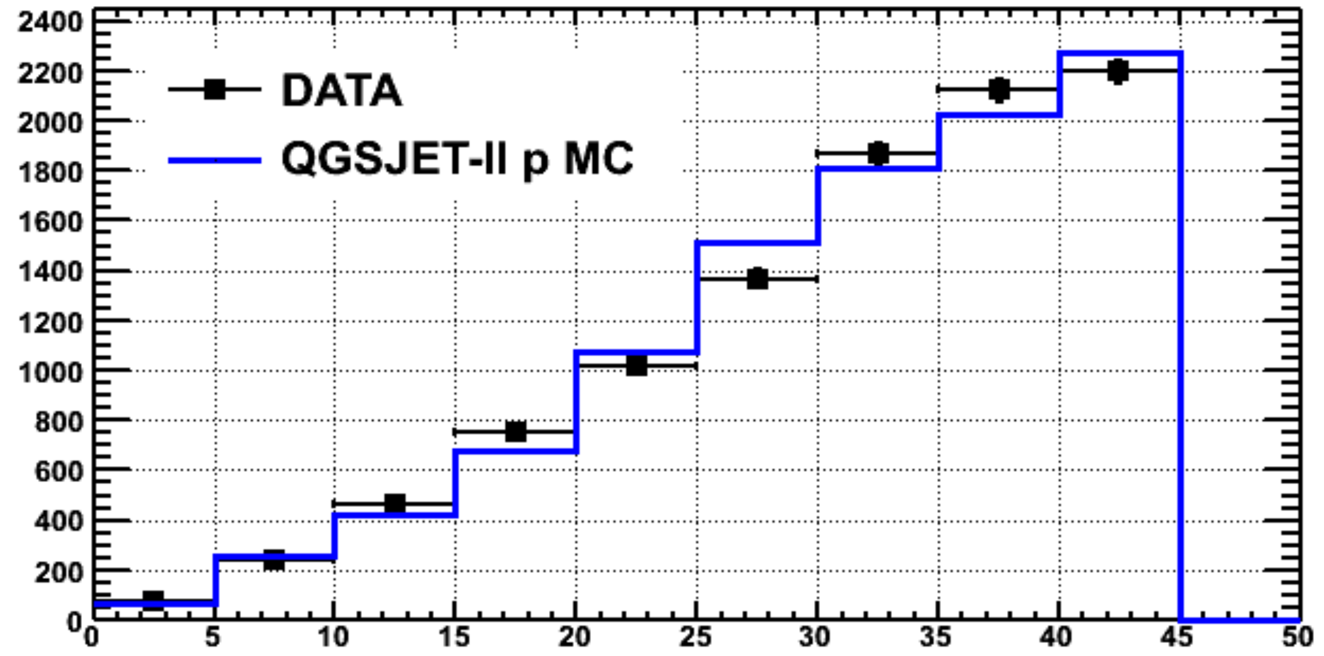


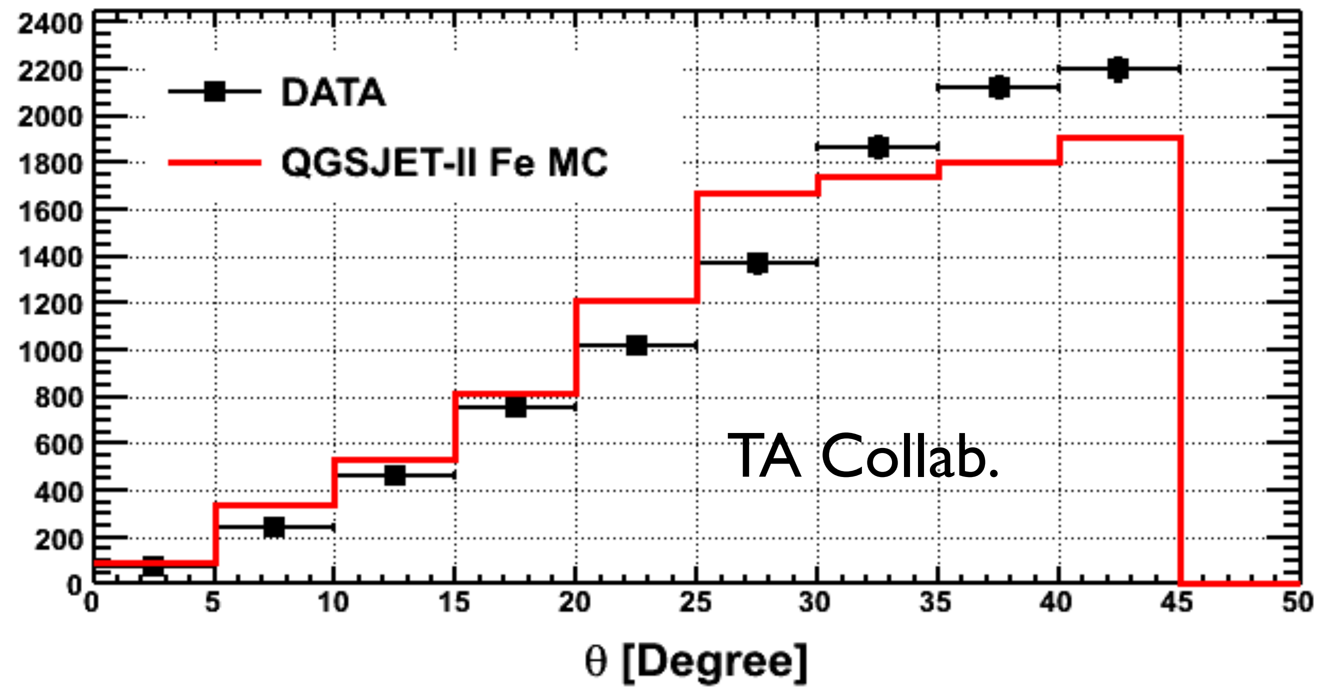


Distance of triggered stations



Signal per station



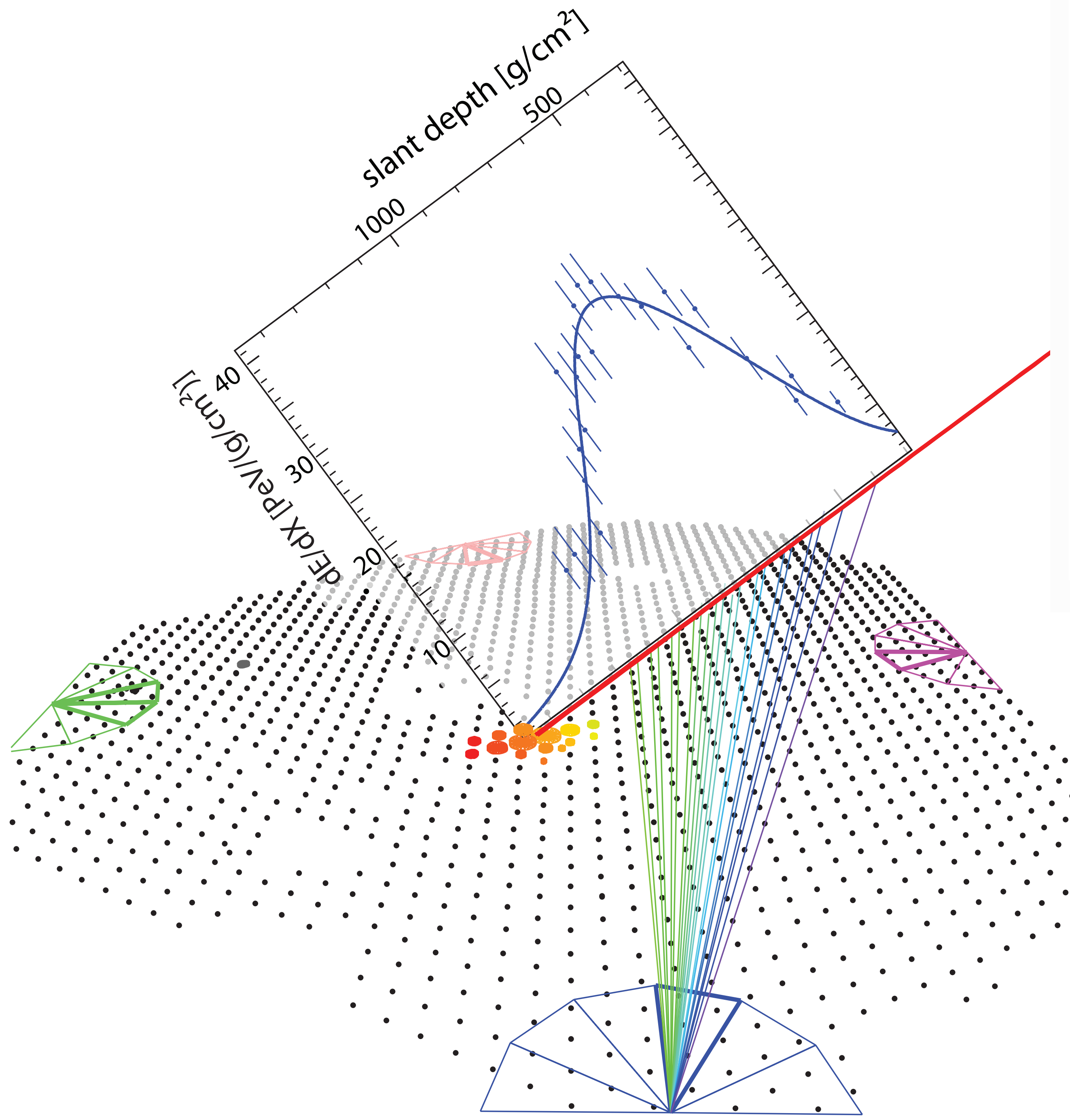


Most observables not very sensitive to details of shower simulation

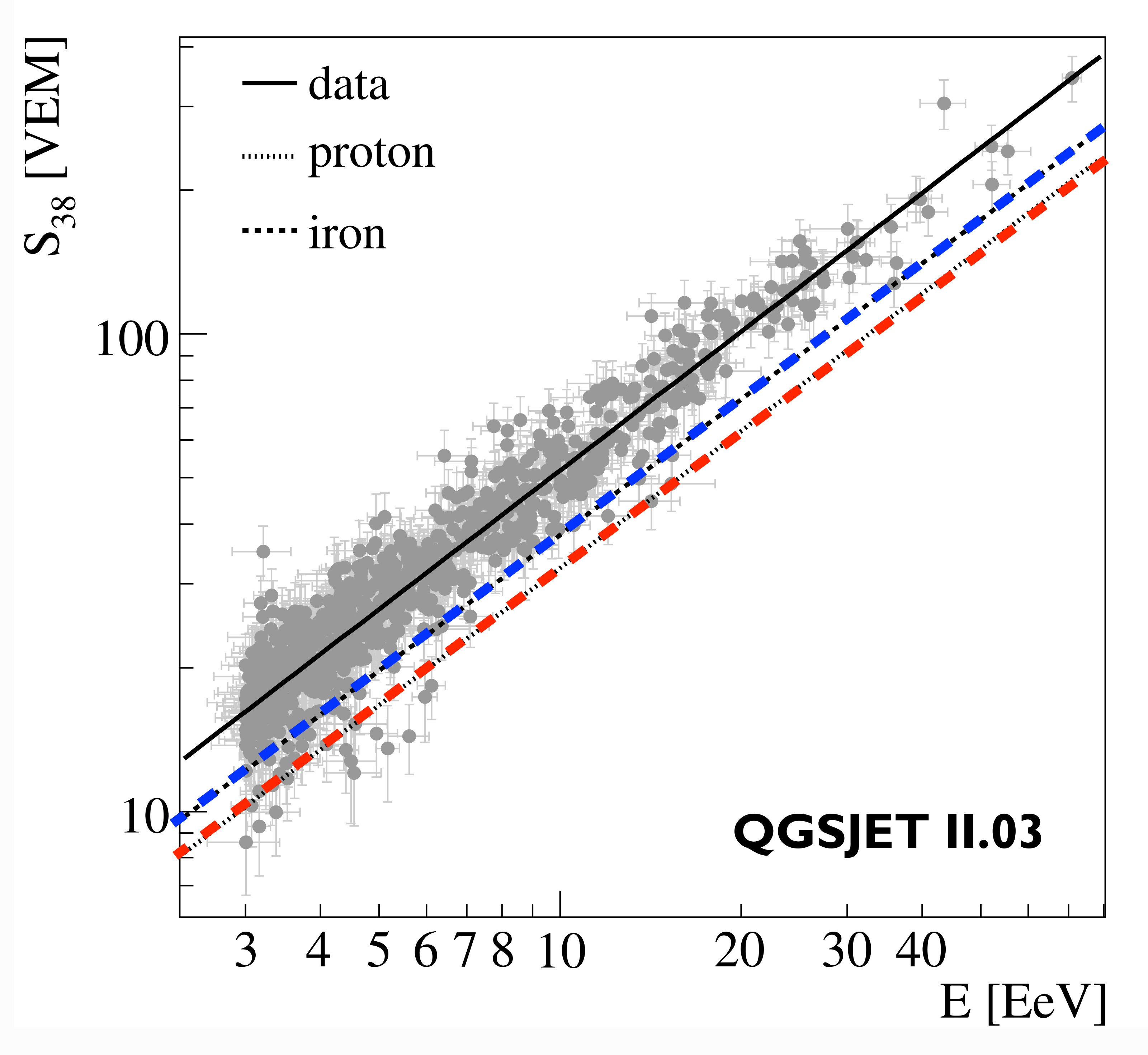
(UHECR 2012)

Auger Observatory: comparison of surface detector signals

Subset of date with
full hybrid observation

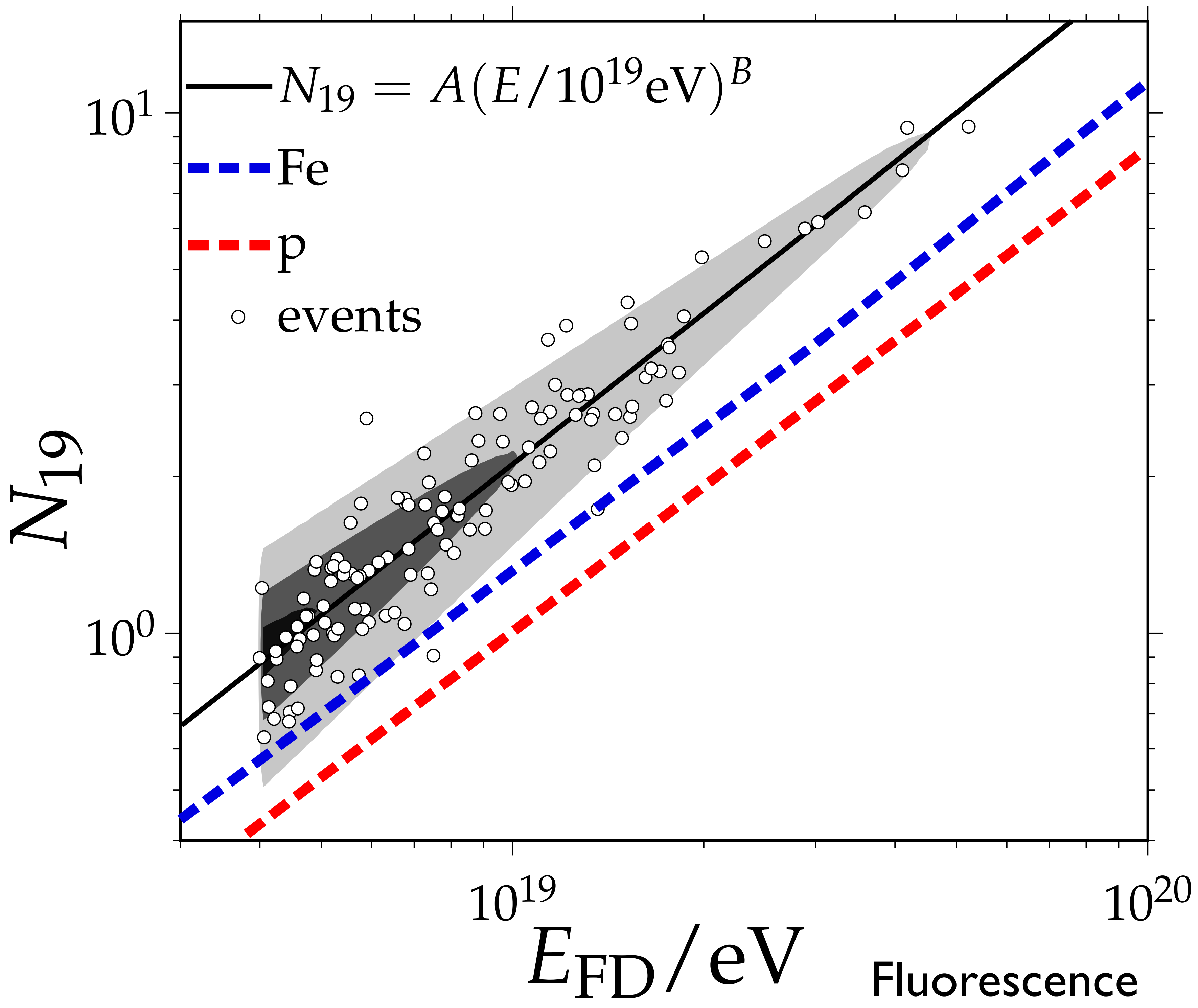


Showers up to 60° zenith angle



Fluorescence

Inclined showers (muon dominated)

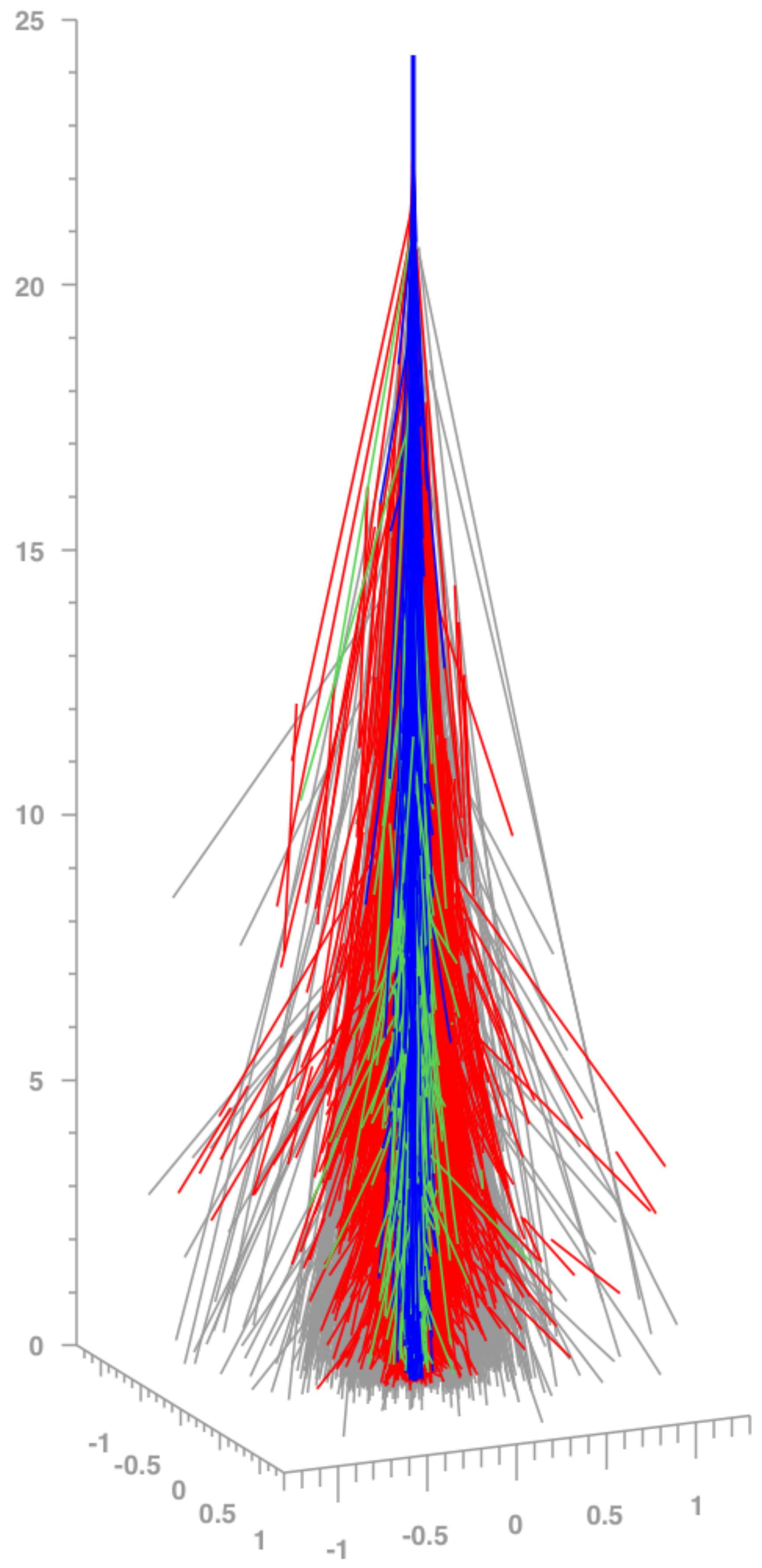


Fluorescence

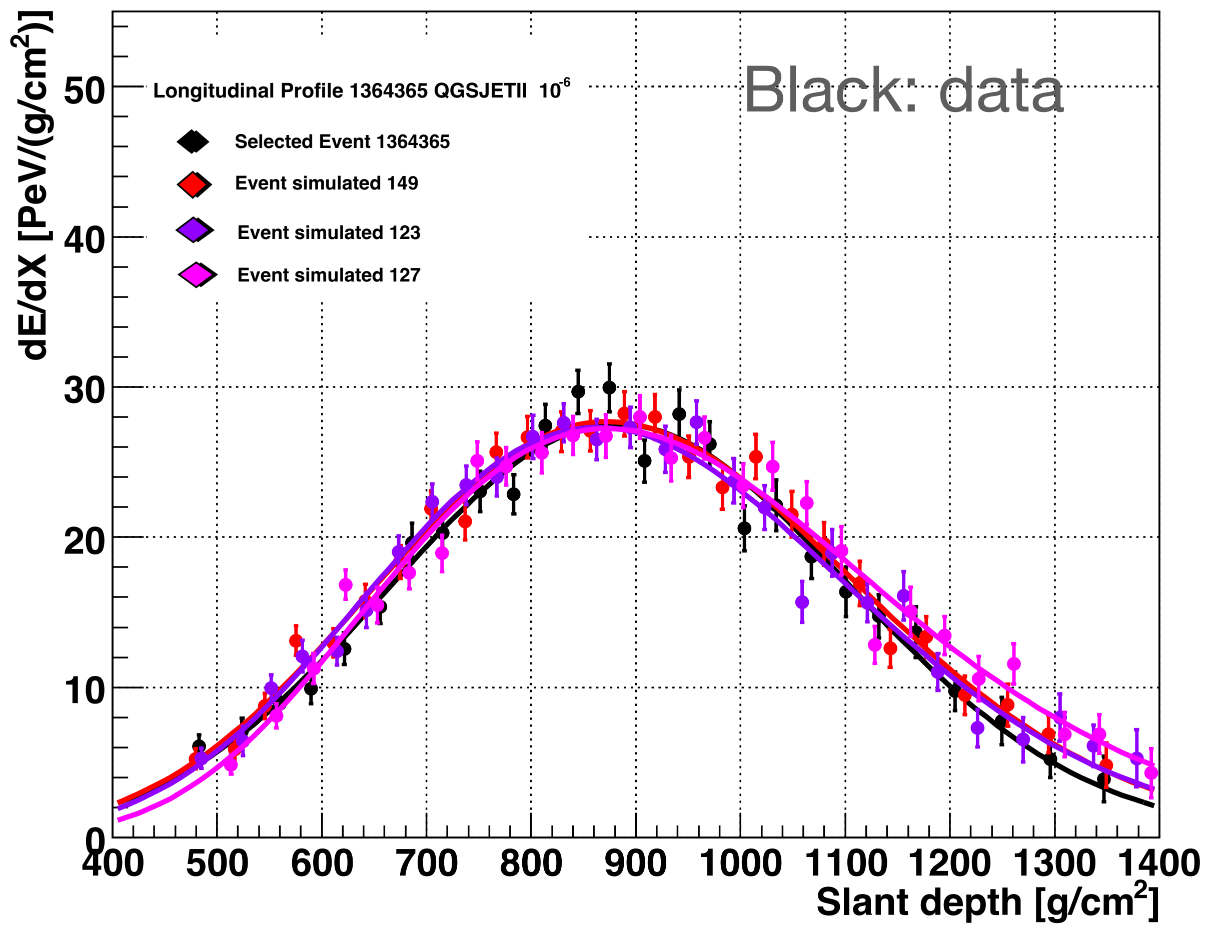
(HadInt Working Group, UHECR 2012)

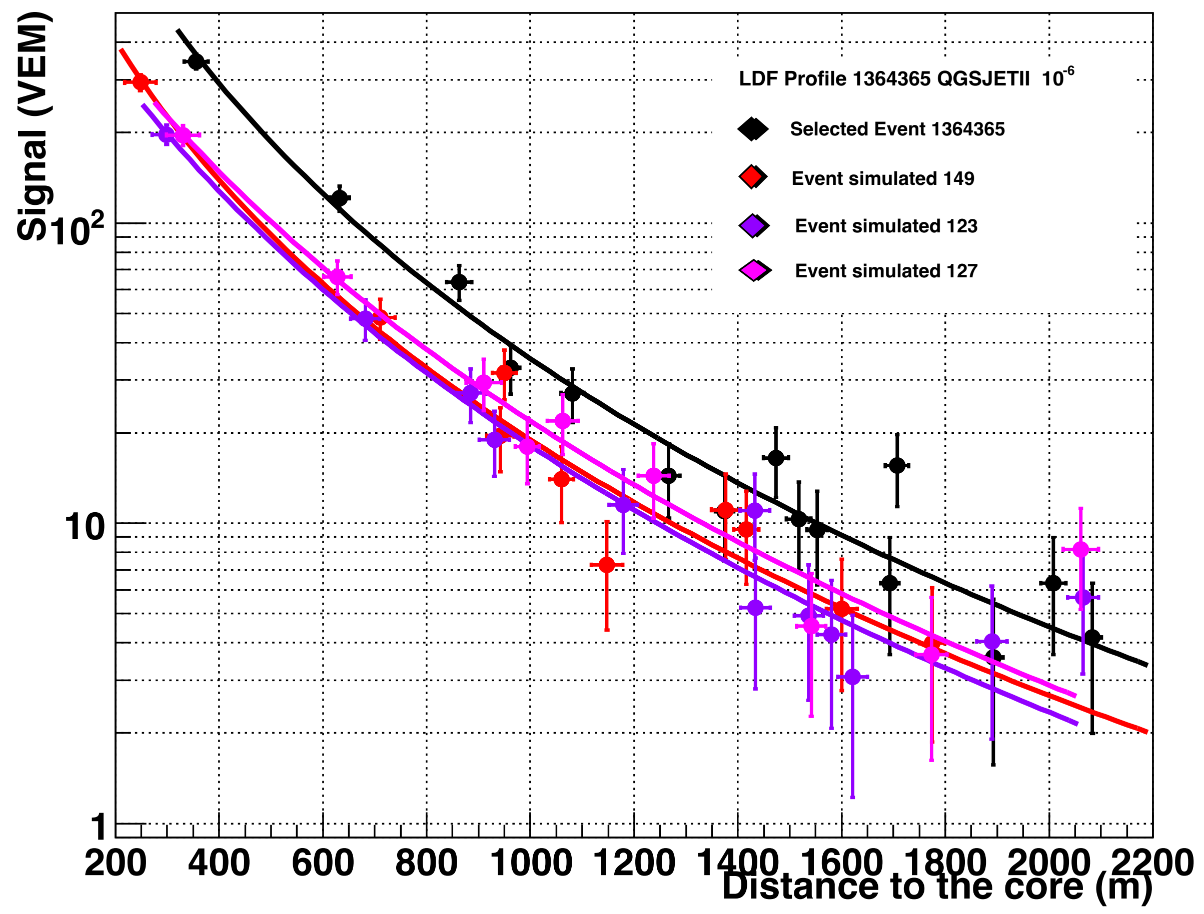
3. The muon puzzle

Comparison of longitudinal and lateral shower profiles (i)

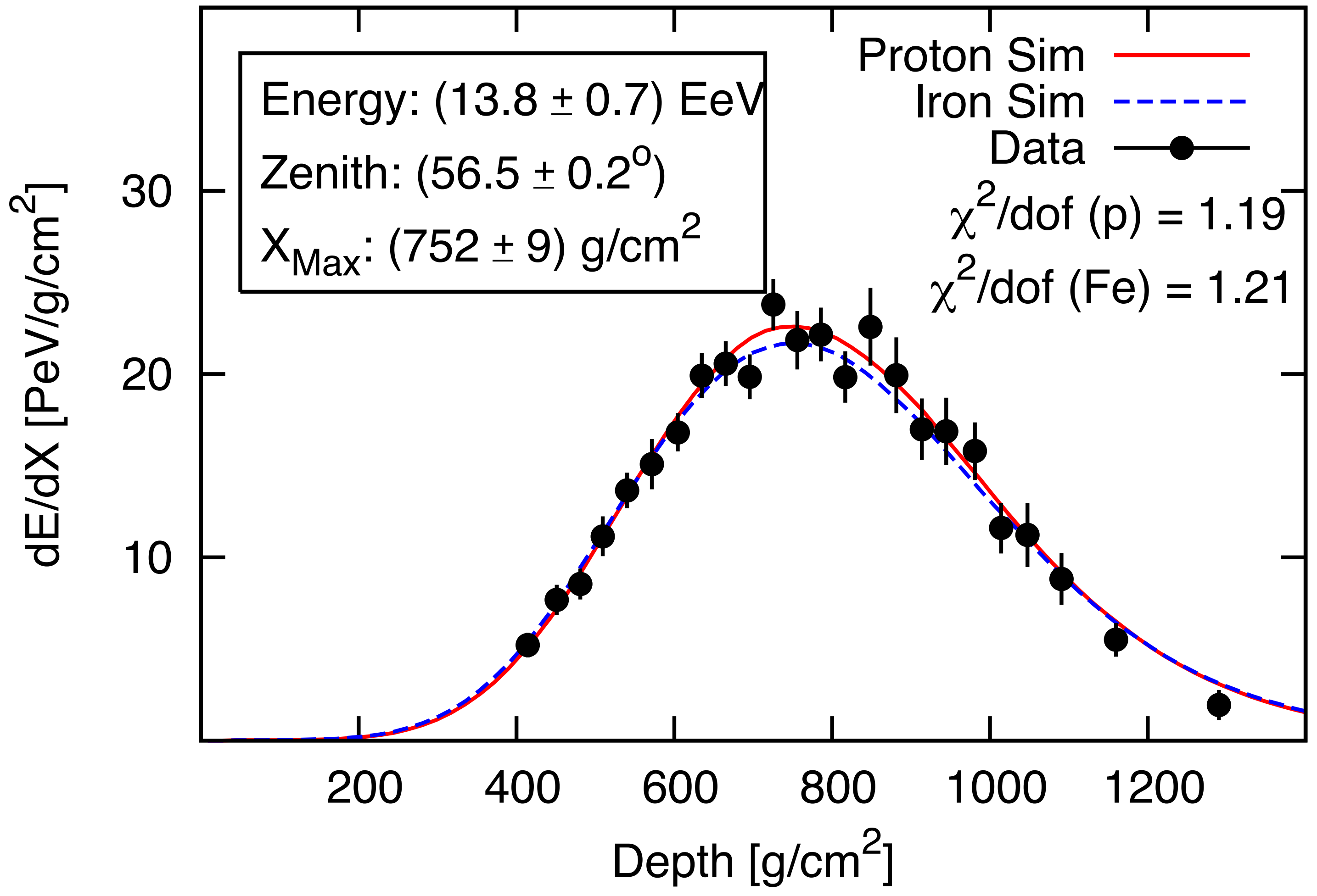


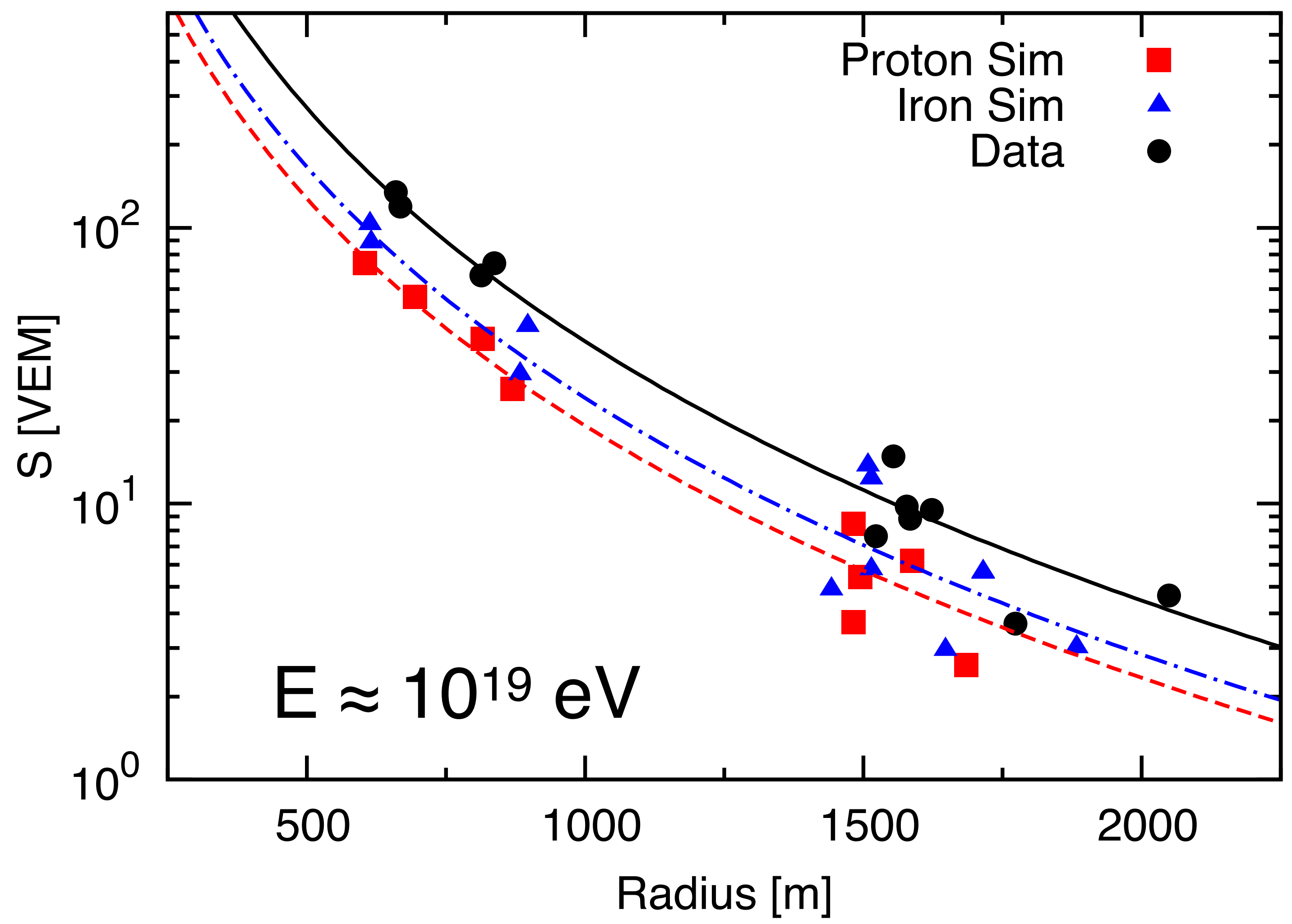
Several simulated showers





Different primary masses

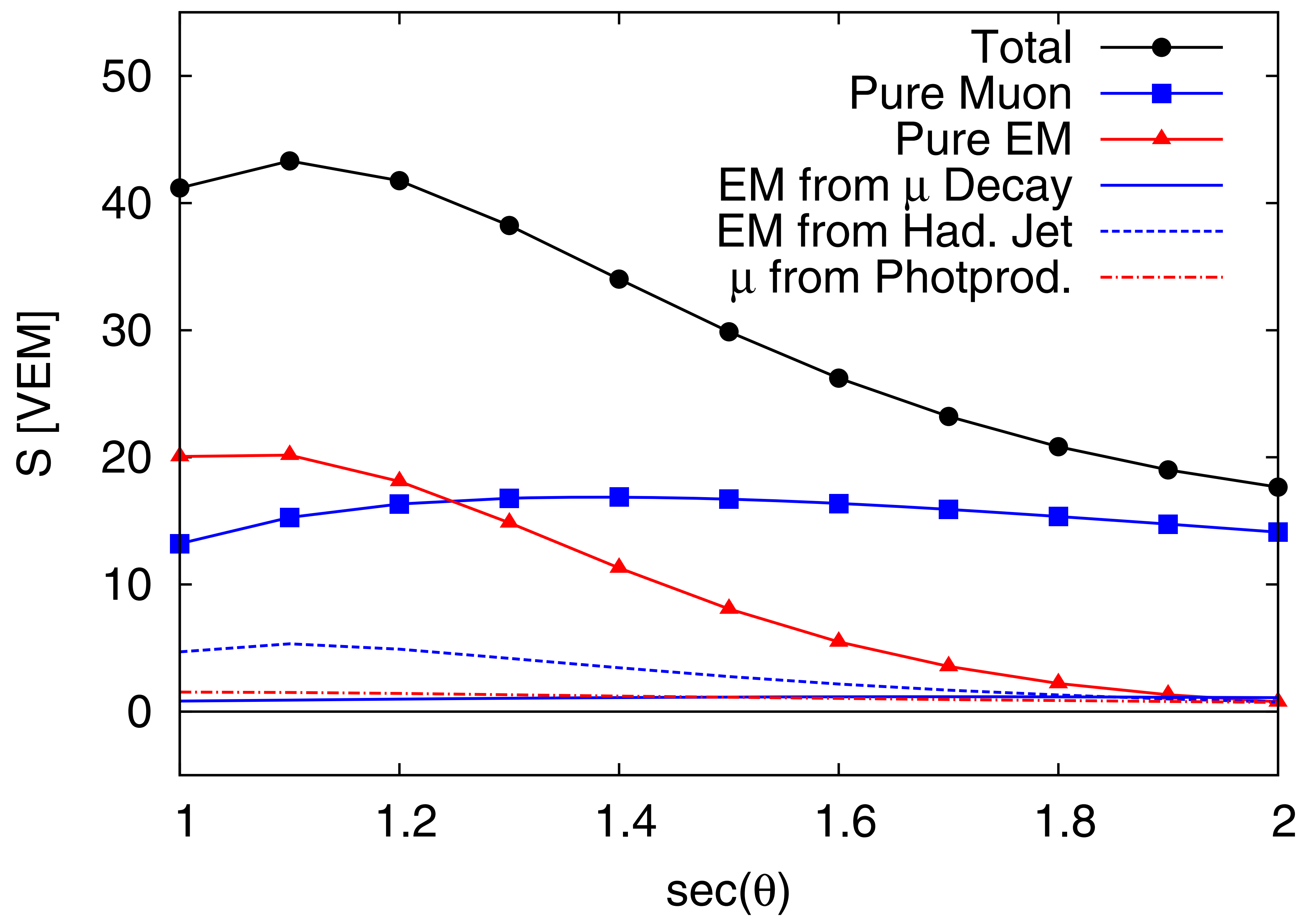




(Auger, ICRC 2013, Phys. Rev. Lett. 2016)

Comparison of longitudinal and lateral profiles (ii)

Shower signal at 1000 m from core



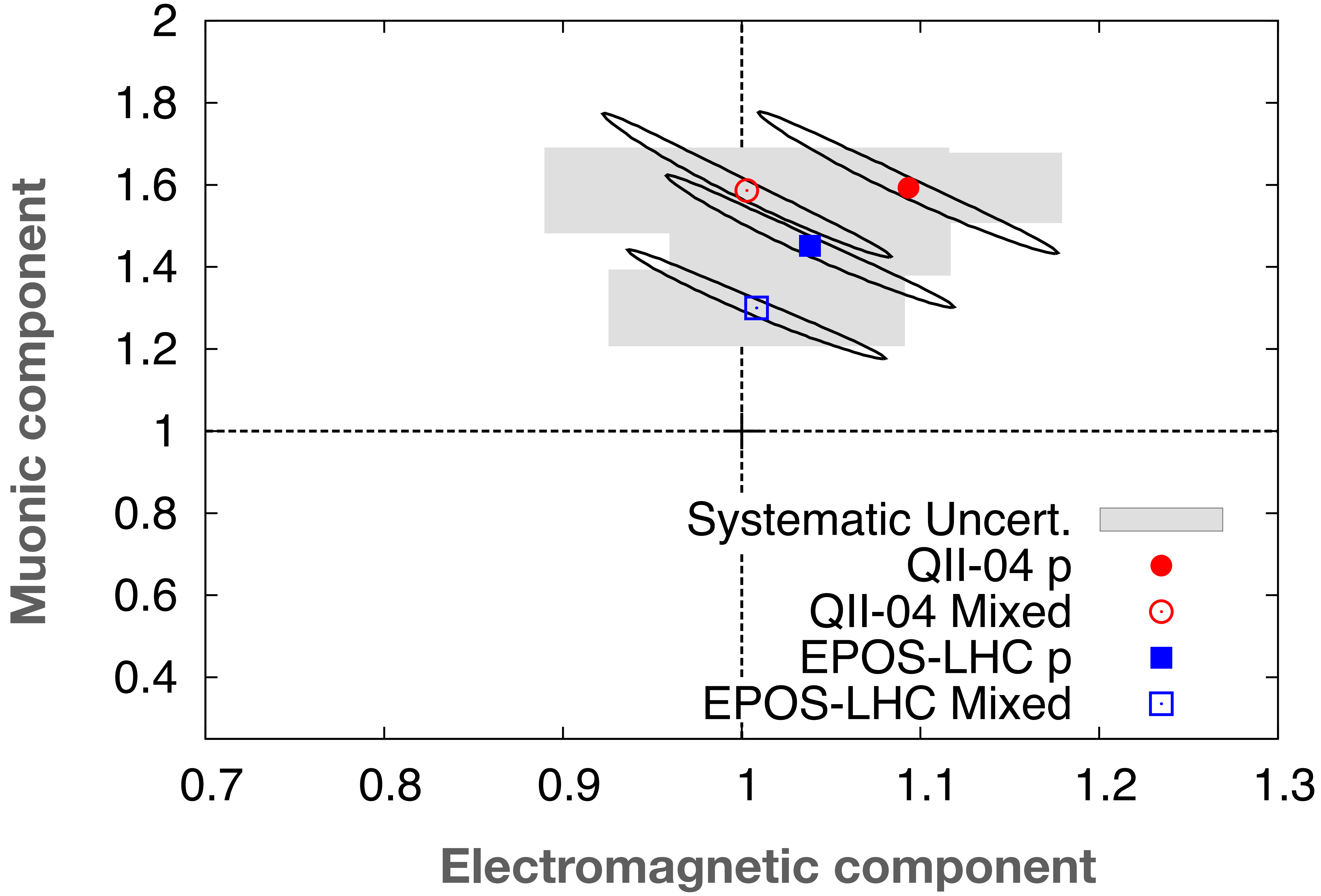
Energy scaling: em. particles and muons

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

Full detector simulation after re-scaling

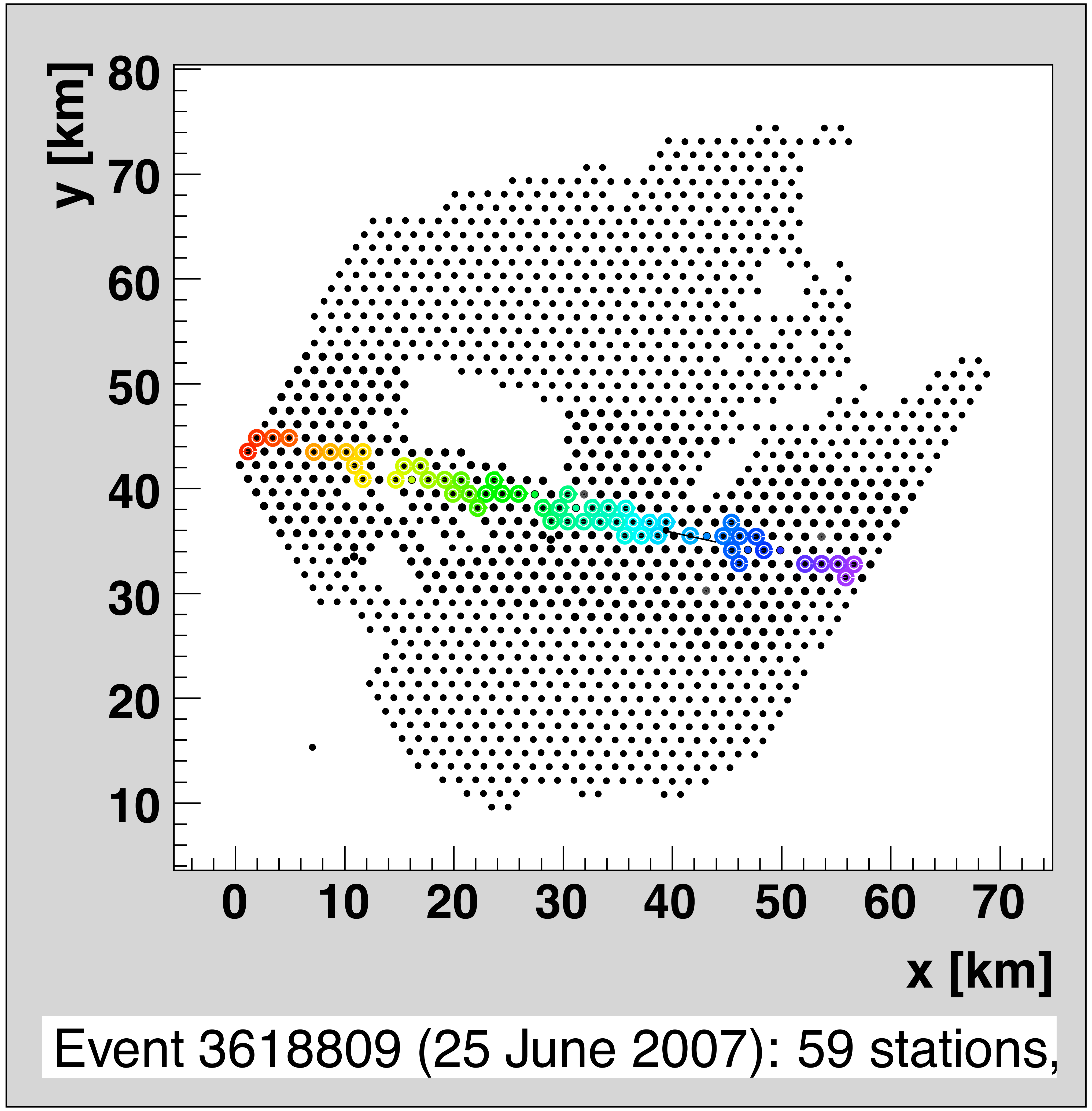
Phenomenological model ansatz

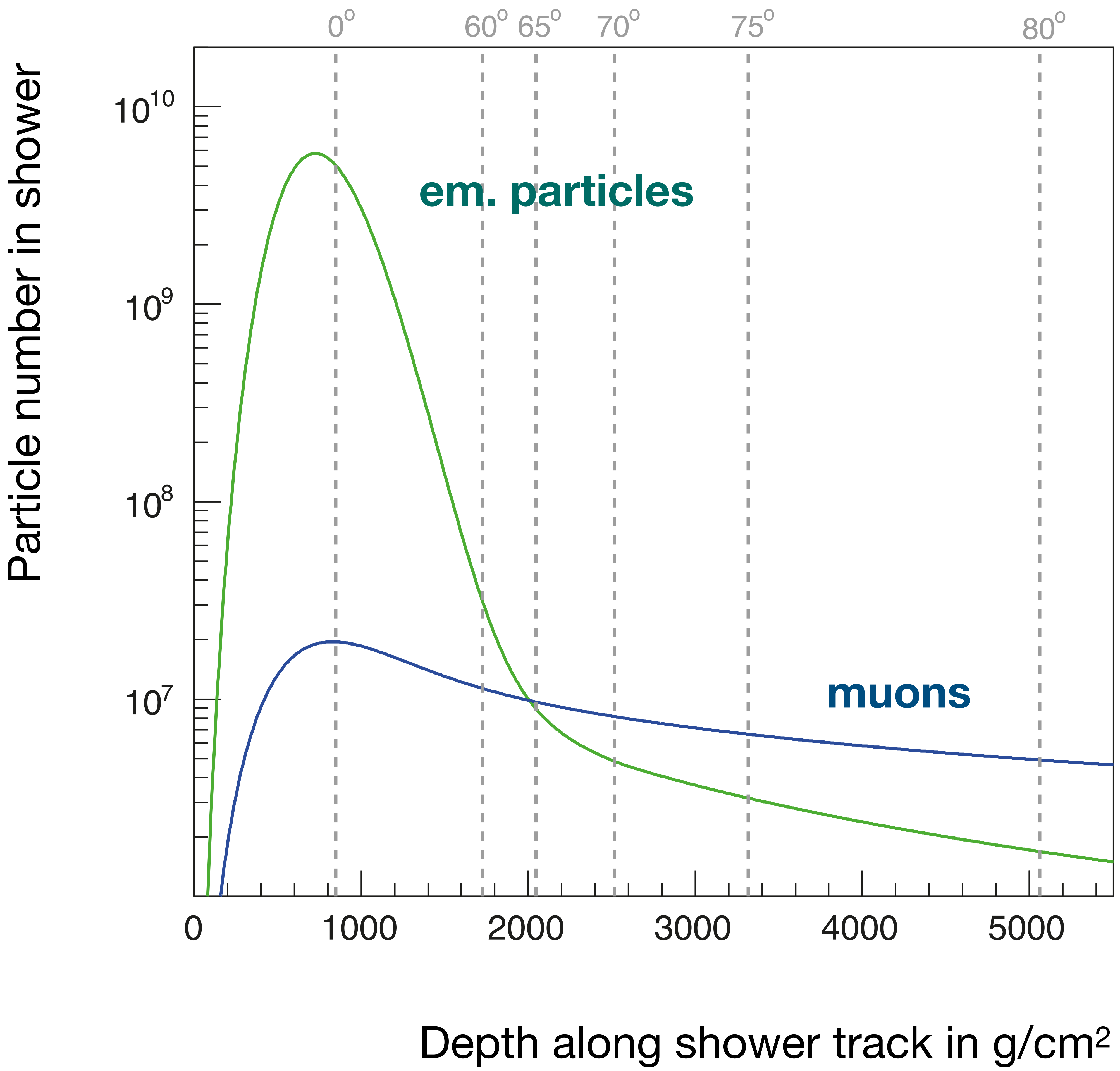
Needed rescaling factors for correcting average signal at ground



(Auger, ICRC 2013, Phys. Rev. Lett. 2016)

Inclined showers (θ > 60°), em. component absorbed



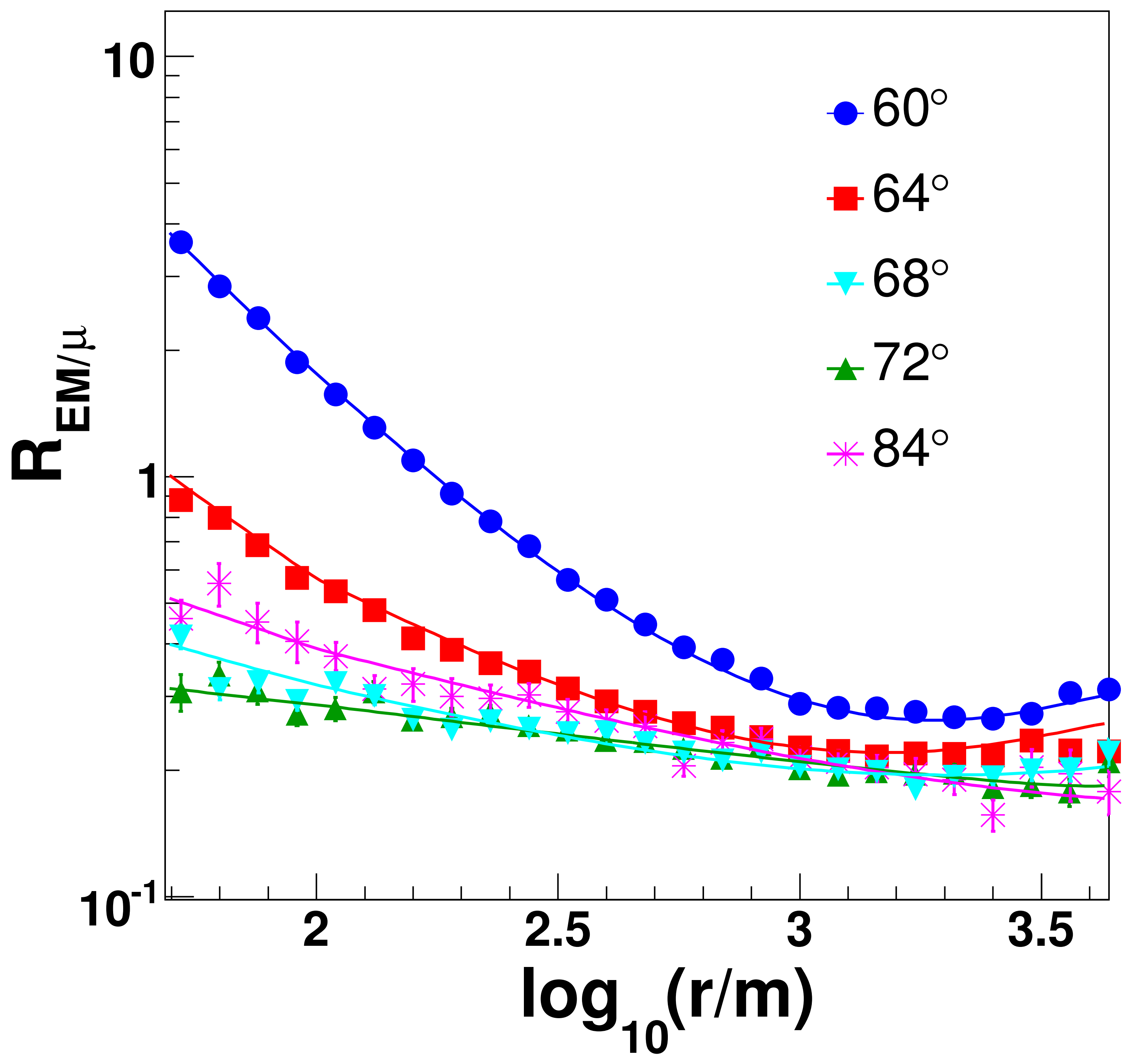


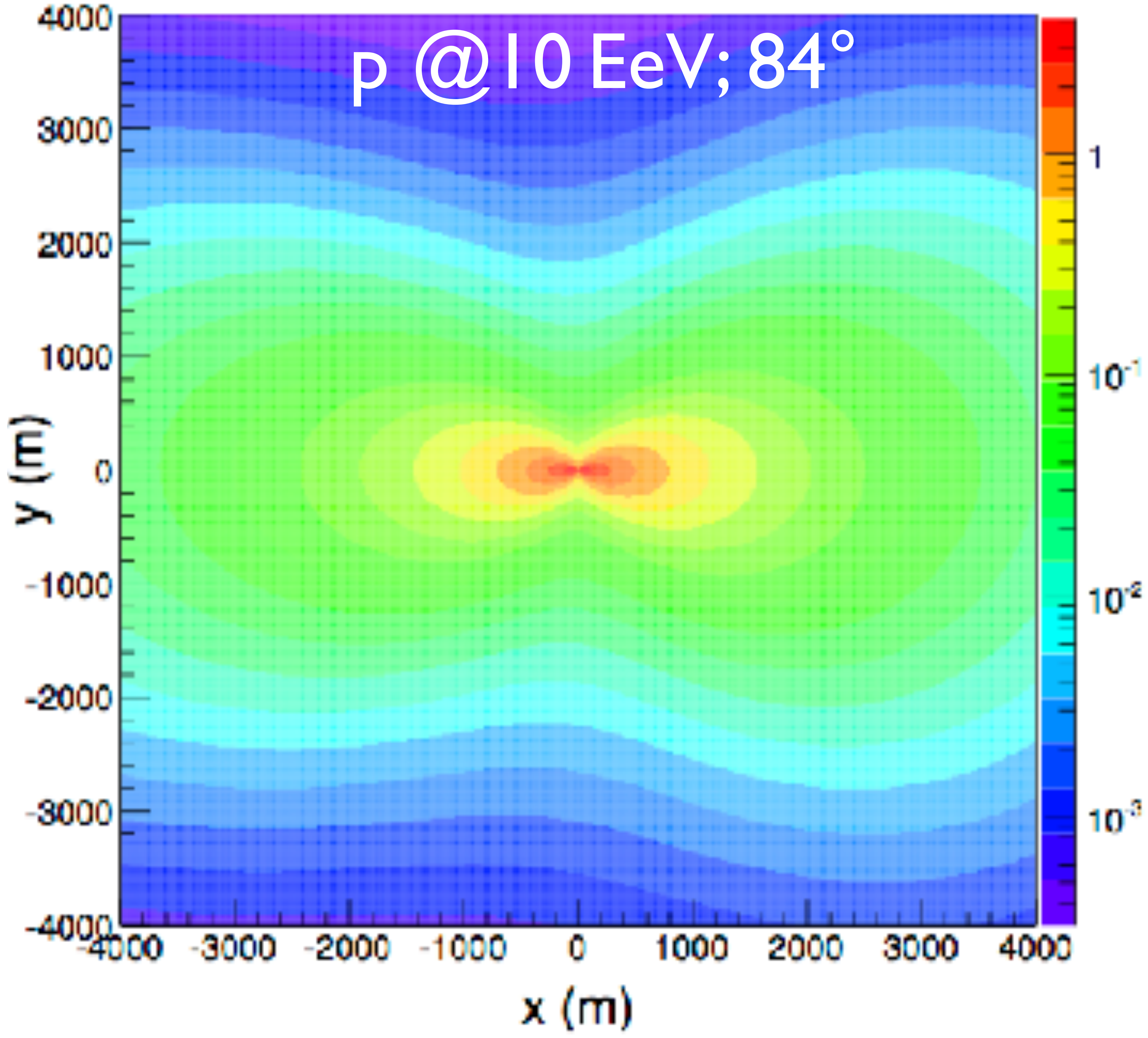
Hybrid events: N_{19} used for muon counting

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

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

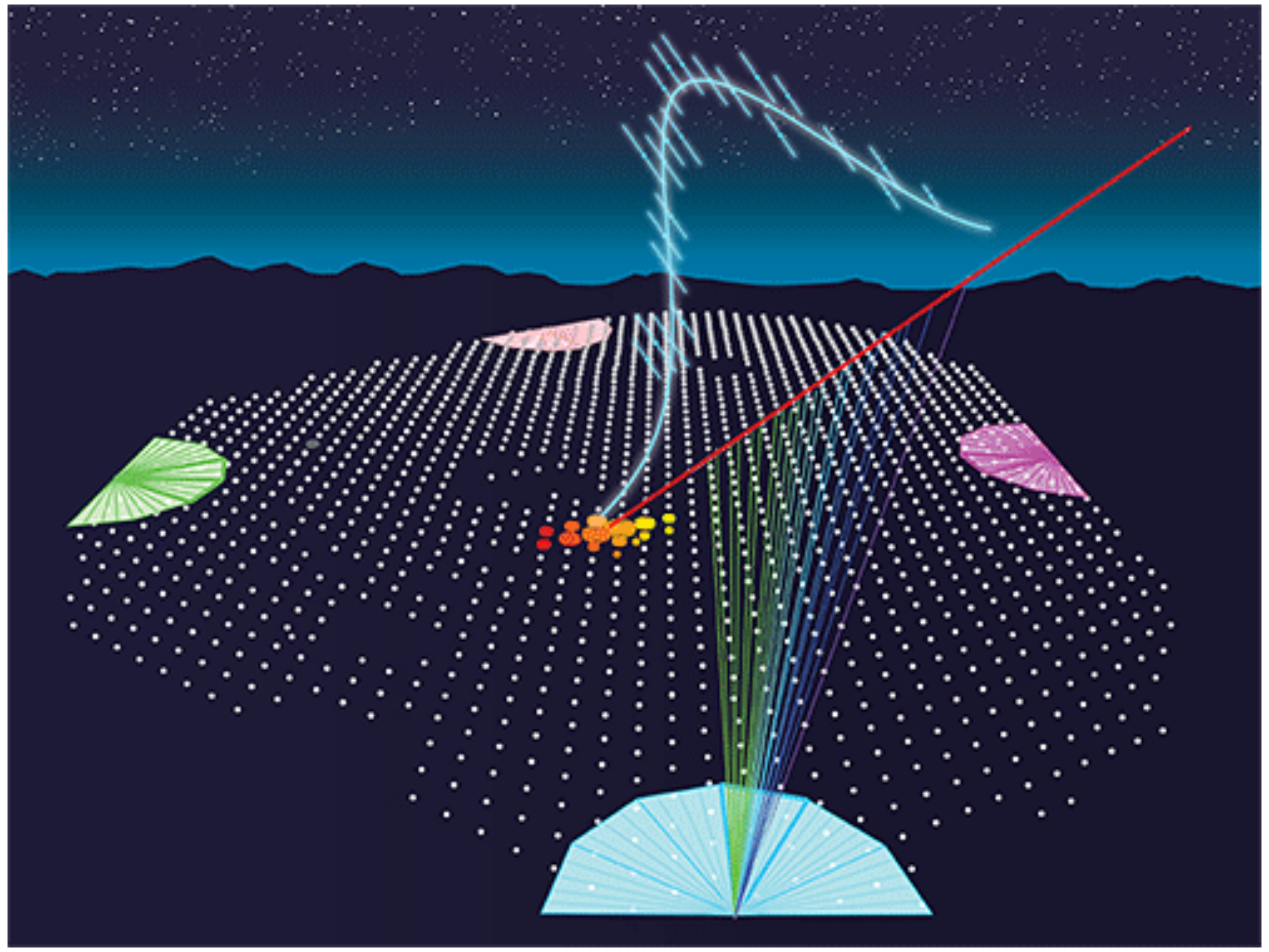
- zenith angle independent

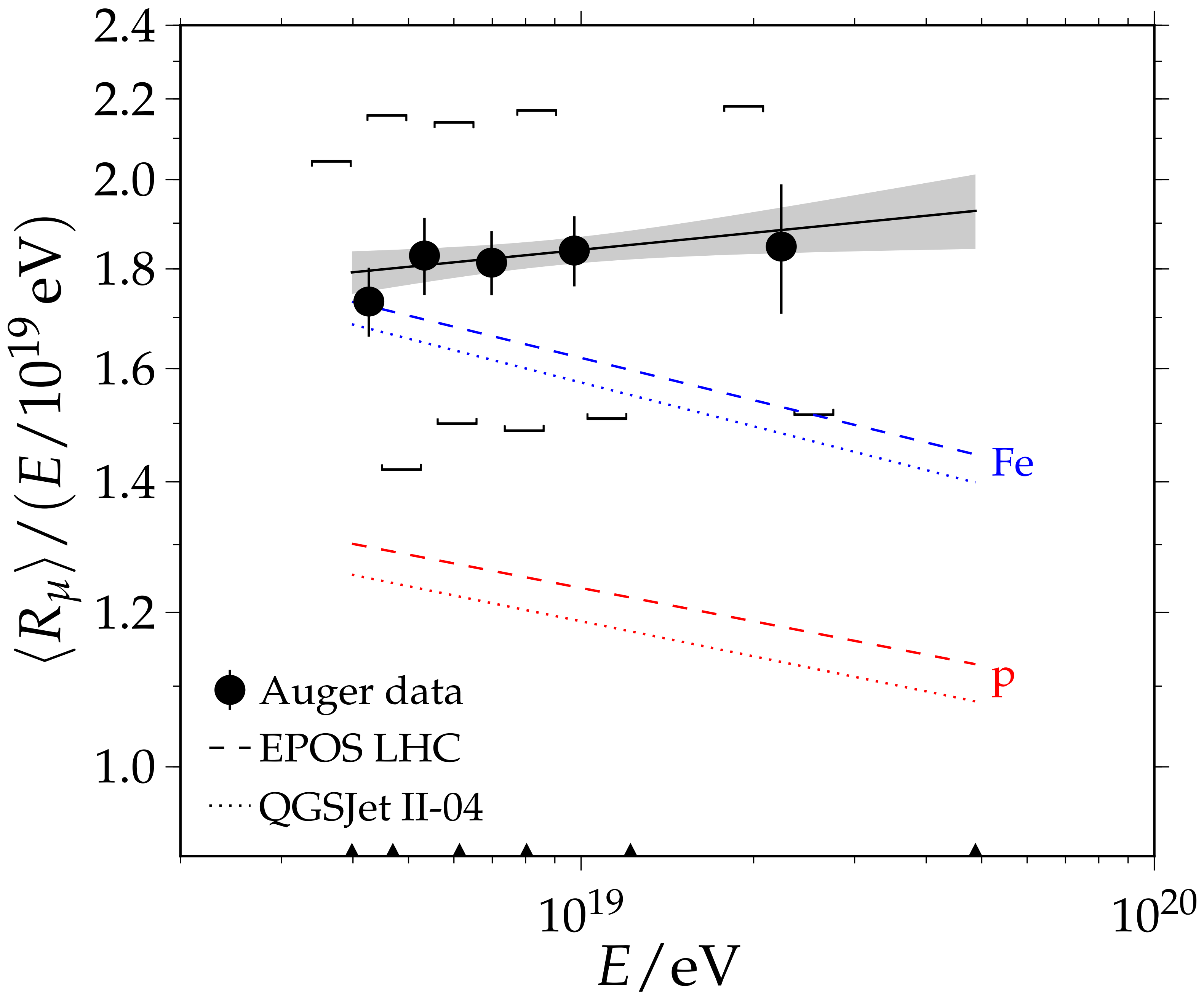




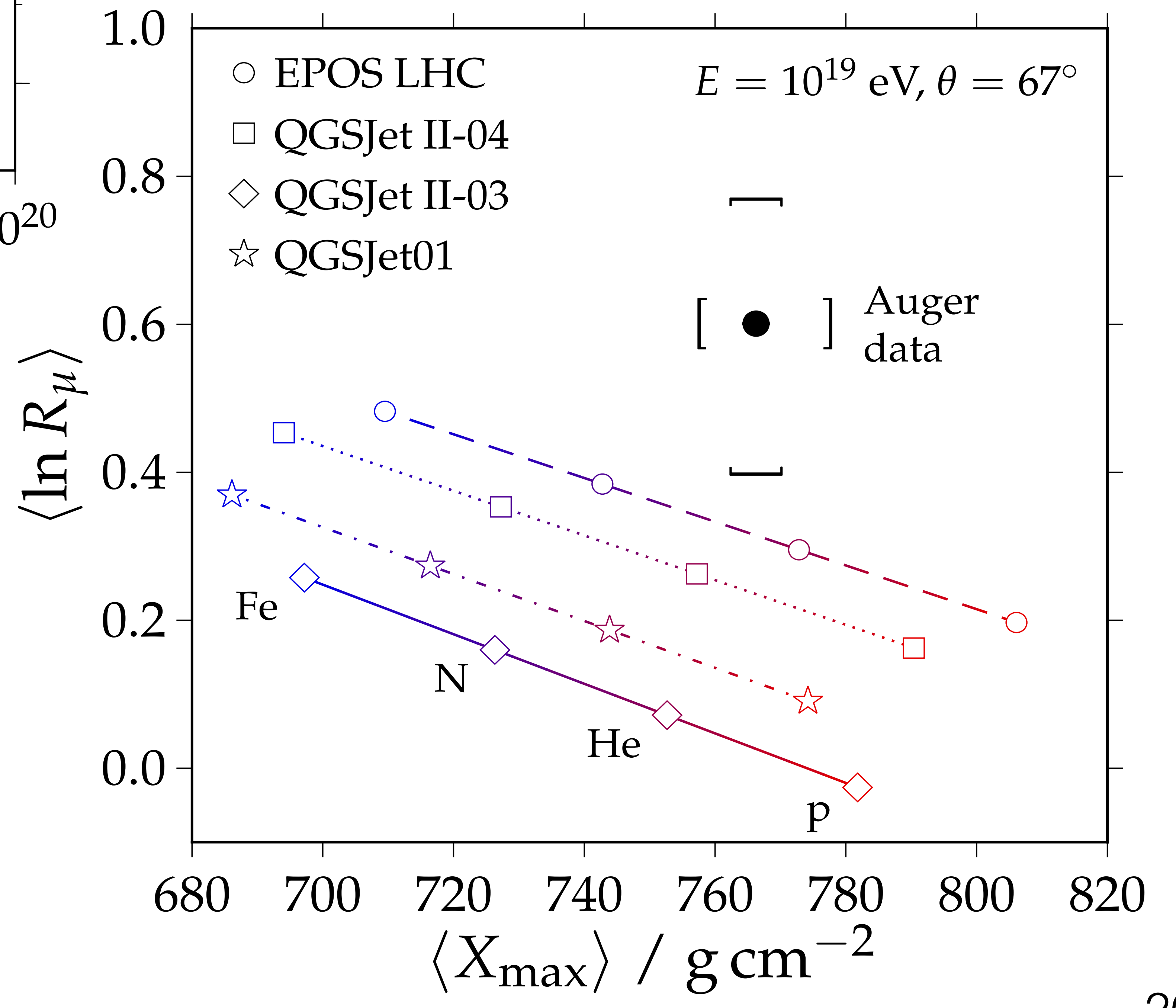
Simulated muon maps (magnetic deflection)

Muon number in inclined showers (nearly background-free)





Relative number of muons in showers with θ>60°

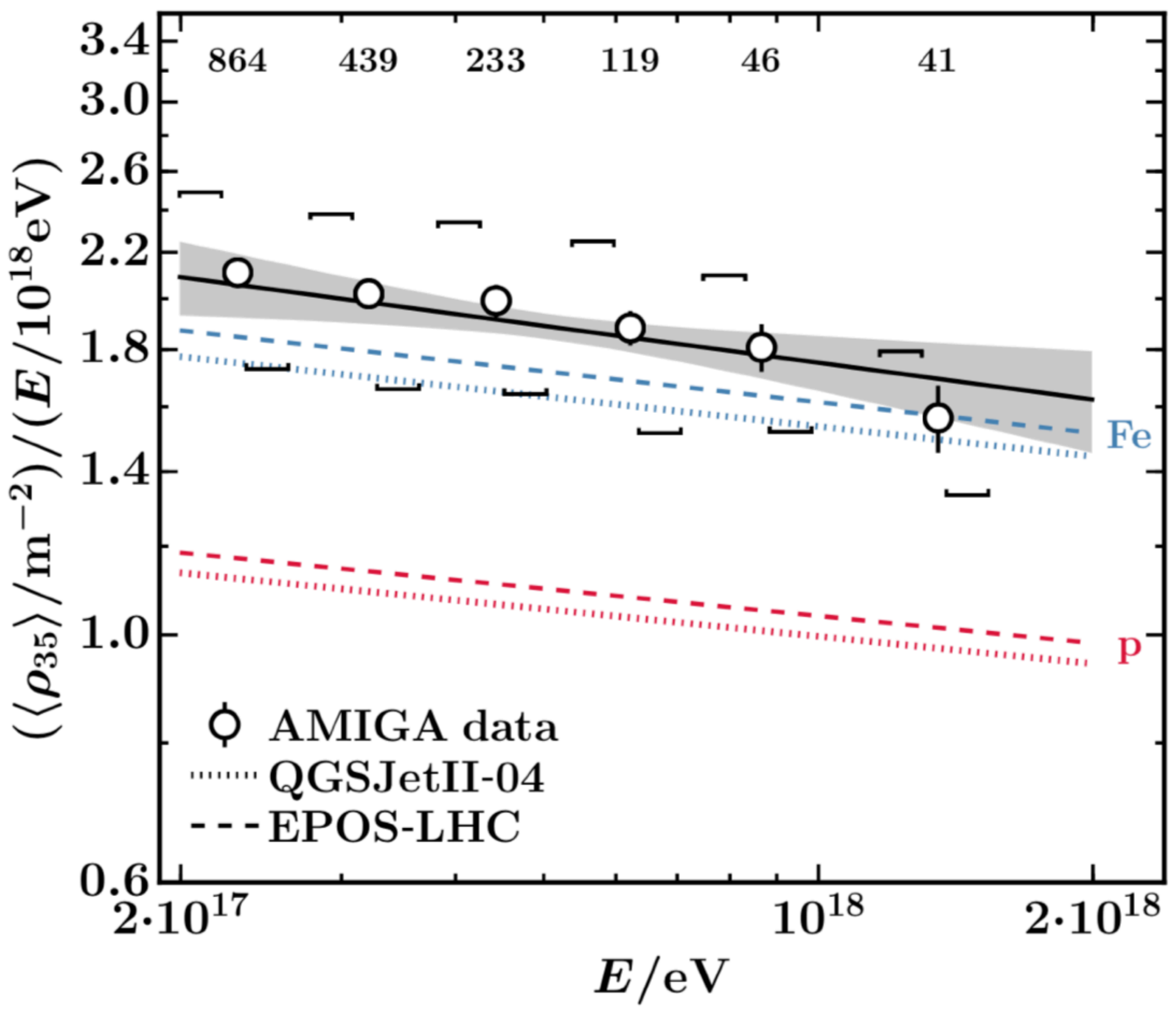


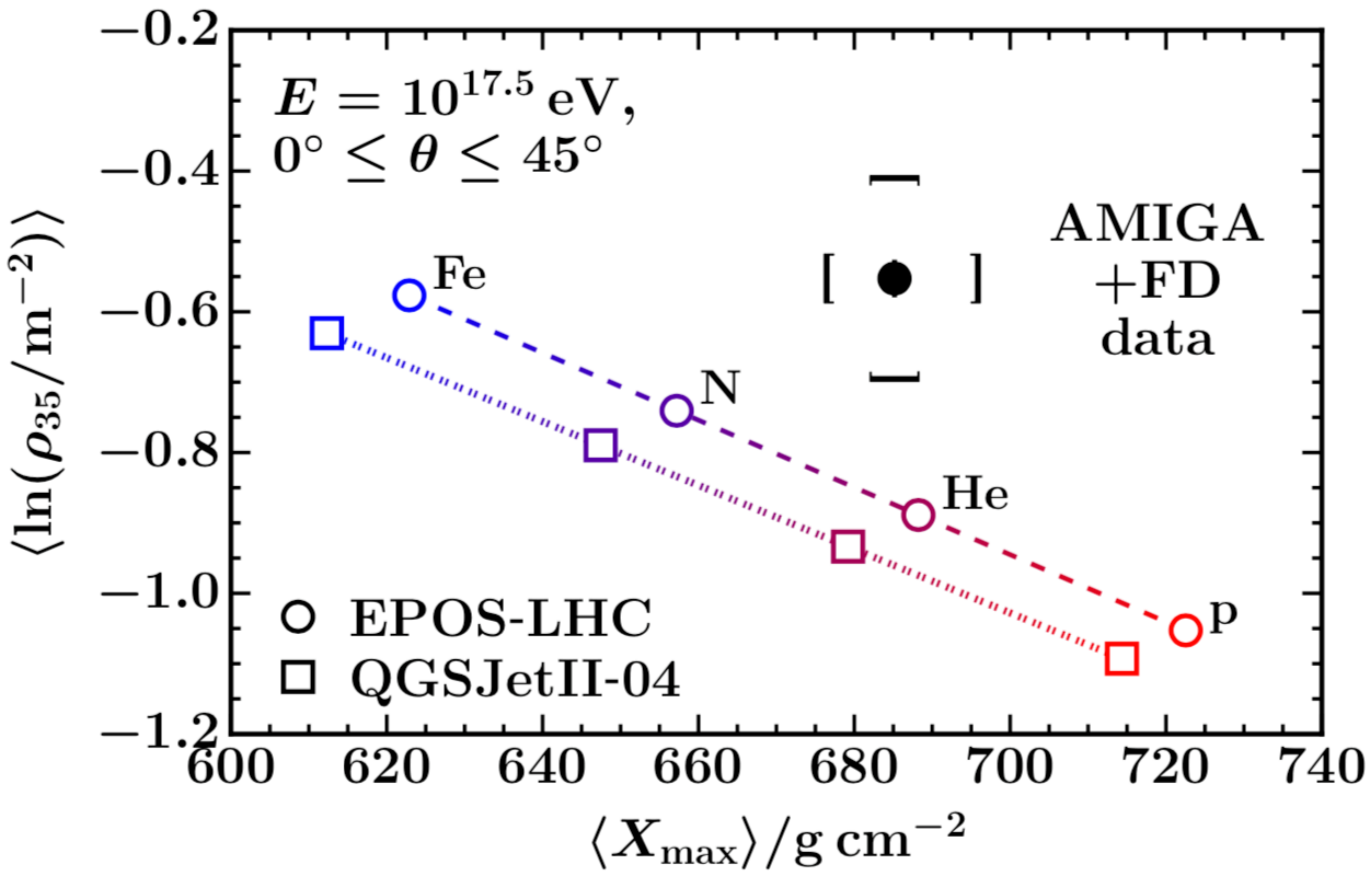
Muon discrepancy confirmed

(Auger, Phys. Rev. Lett. 117 (2016) 192001, Phys. Rev. D91 (2015) 032003)

Direct measurement of muons at lower energy

Underground muon detectors
(2.3 m soil for shielding)





In range 3×10^{17} eV to 2×10^{18} eV simulations don't reproduce muon densities

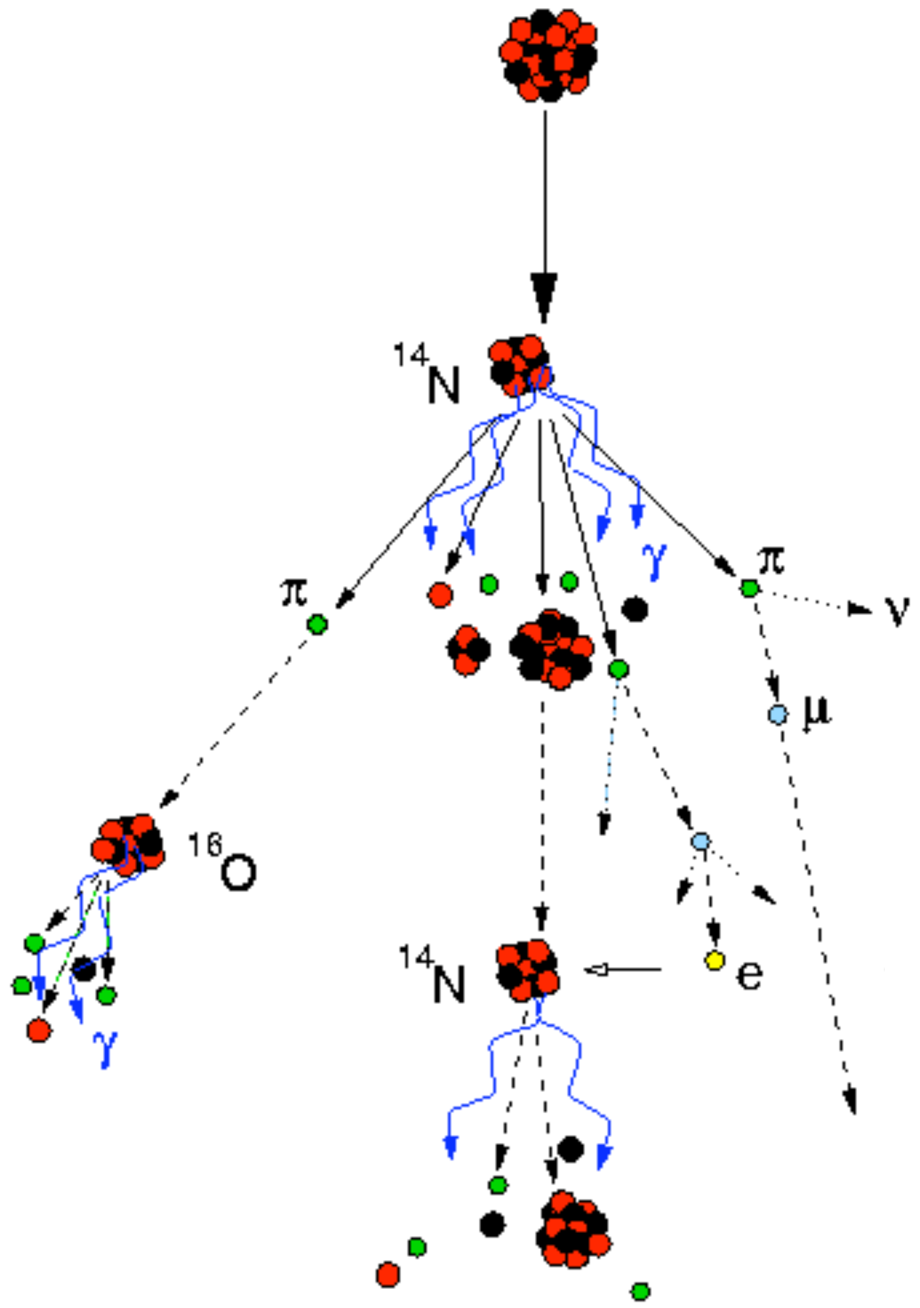
40% (50%) increase in $\langle N_\mu \rangle$ at 10^{18} eV needed for EPOS-LHC (QGSJetII-04)

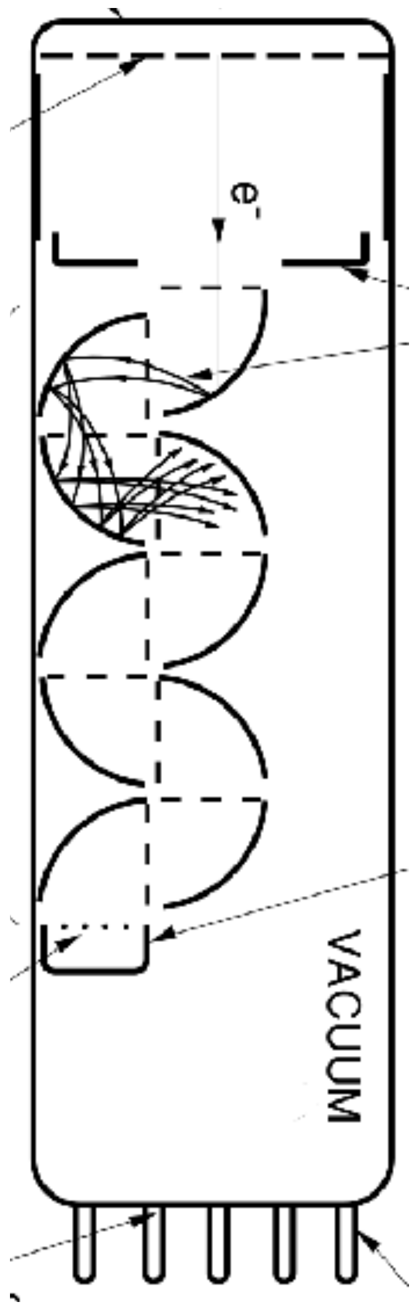
Note: this is in energy range of LHC

(Auger, Eur. Phys. J. C80 (2020) 751)

Muon number fluctuations in inclined showers (θ > 60°)

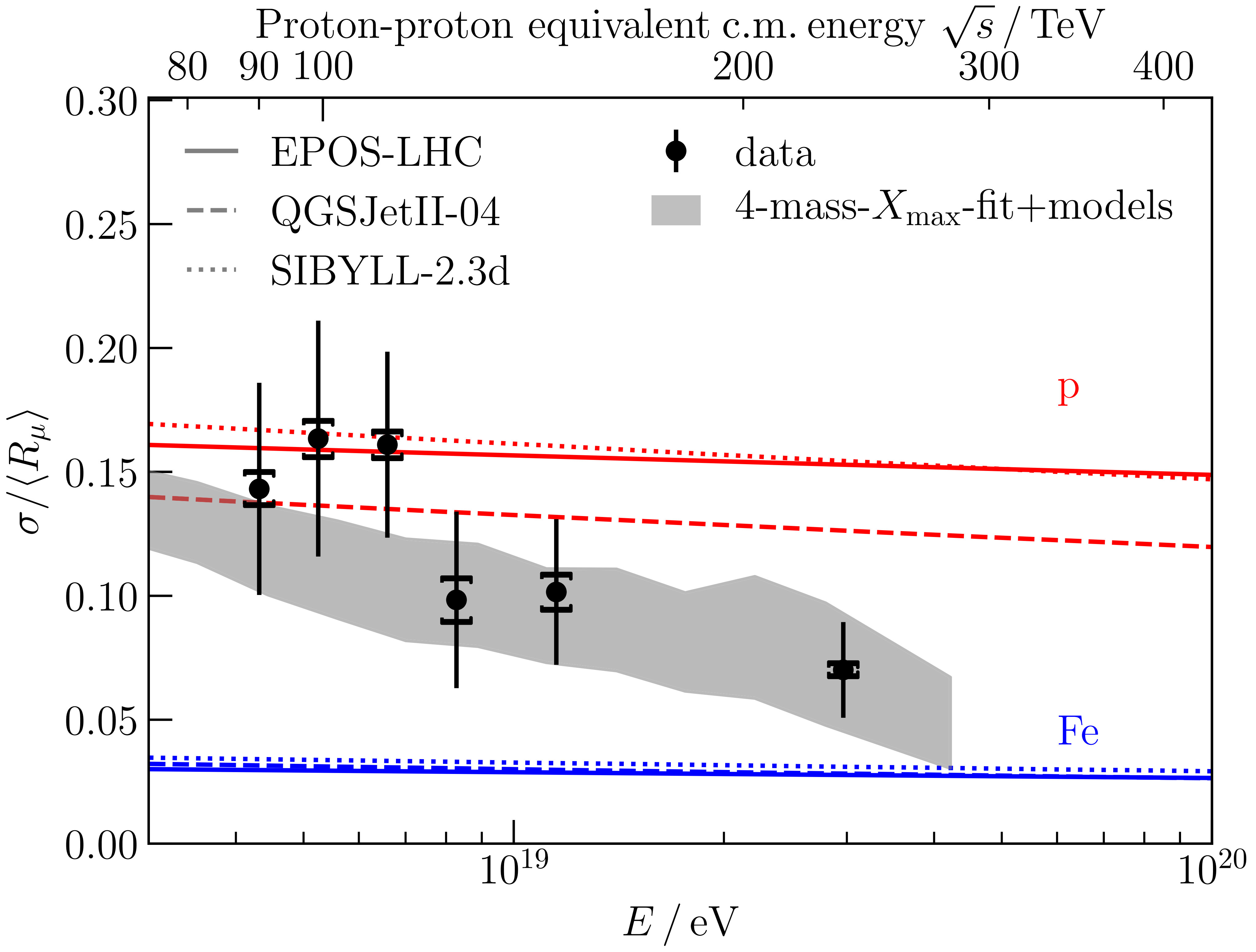
Hybrid events and inclined showers





PMT analogy of air shower

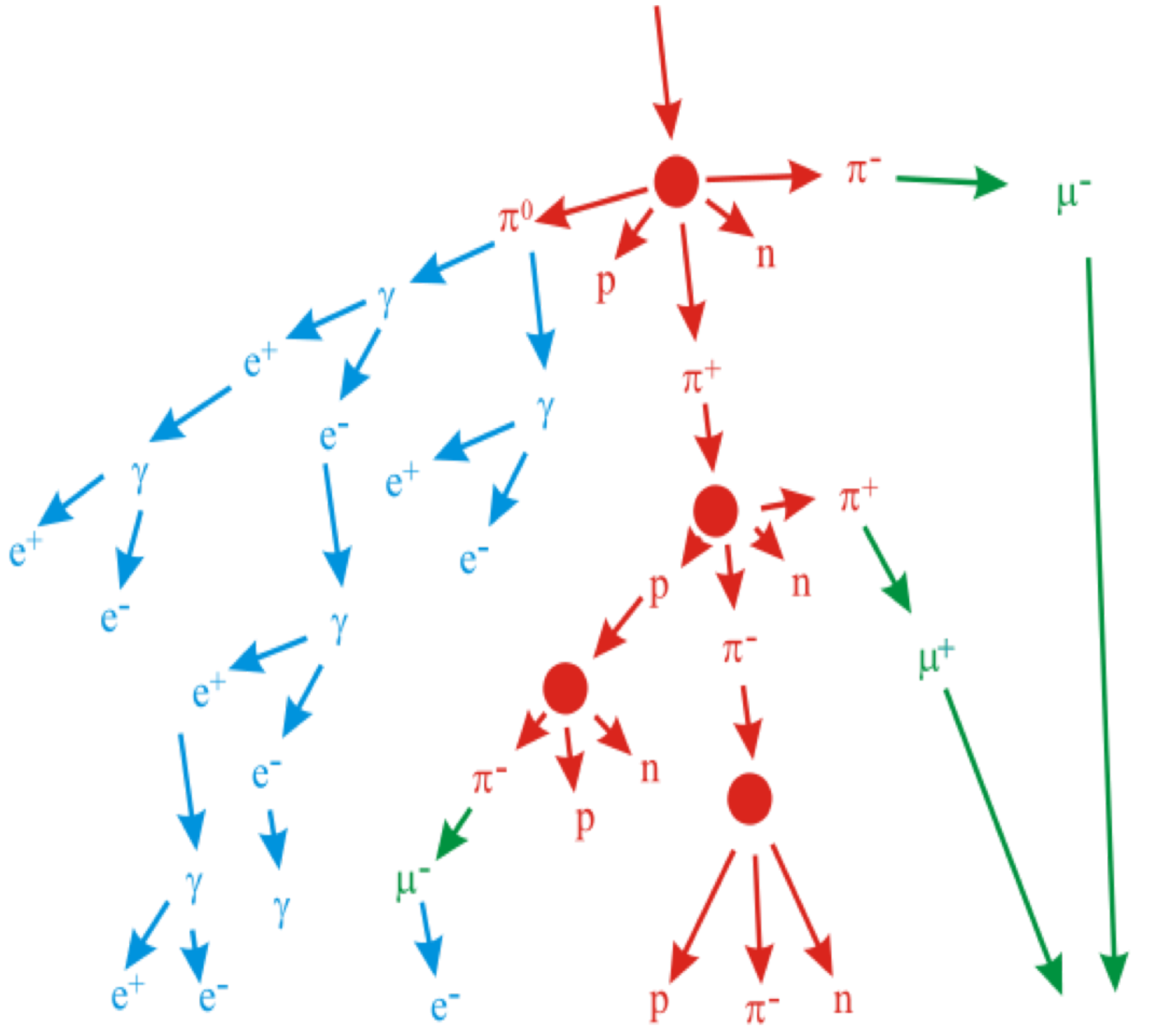
Muon fluctuations driven by first interactions

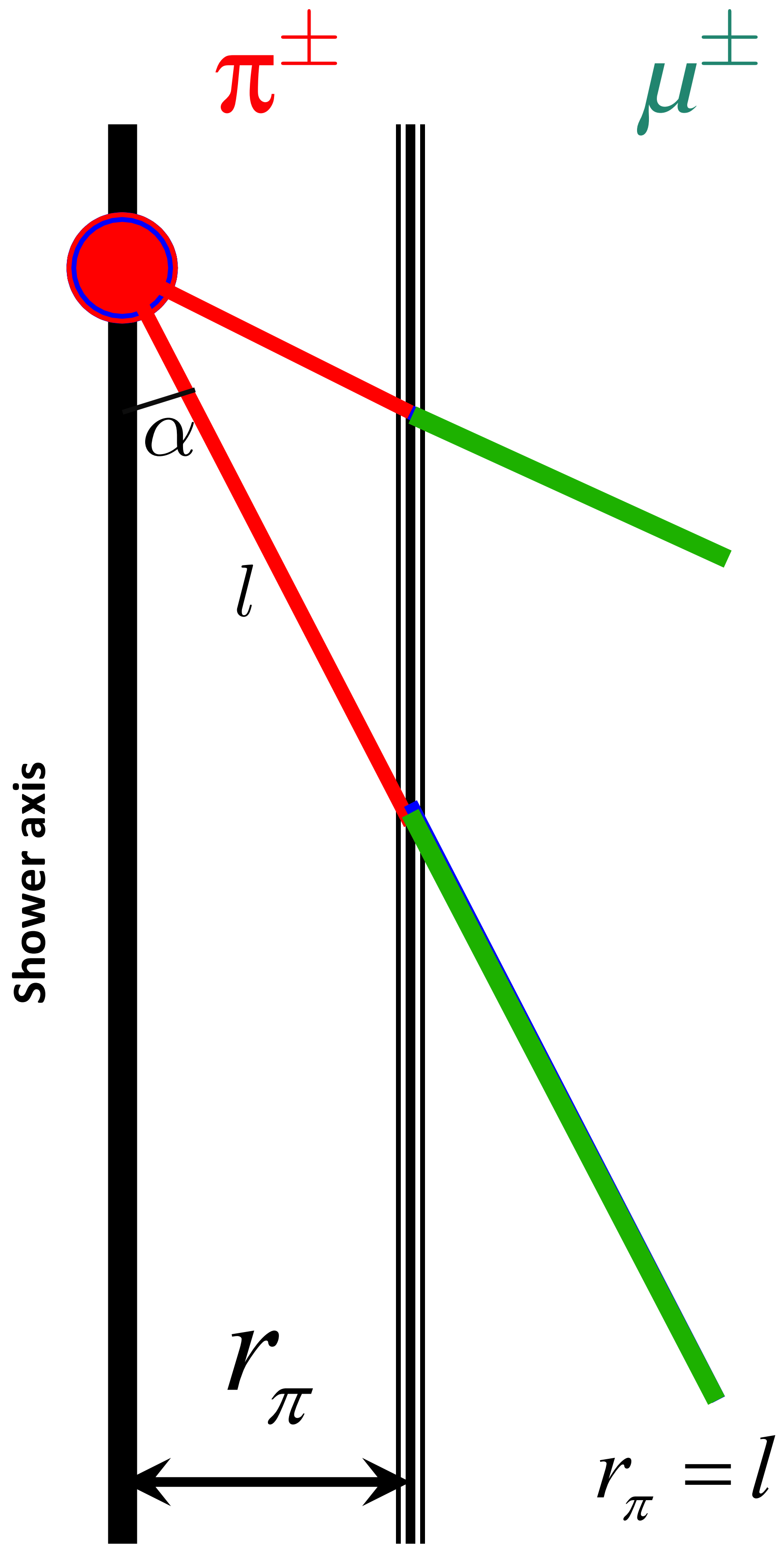


Size of fluctuations as expected

(Phys. Rev. Lett. 126 (2021) 152002)

Physics of muon production and number fluctuations





Lorenzo Cazon et al.
Astropart. Phys. 36 (2012) 211
Phys. Lett. B784 (2018) 68

$$\sin\alpha = \frac{cp_t}{E}$$

$$l = \frac{E}{m_\pi c^2} c\tau_\pi$$

$$r_\pi = l\sin\alpha = \frac{\tau_\pi p_t}{m_\pi}$$

Lateral distance

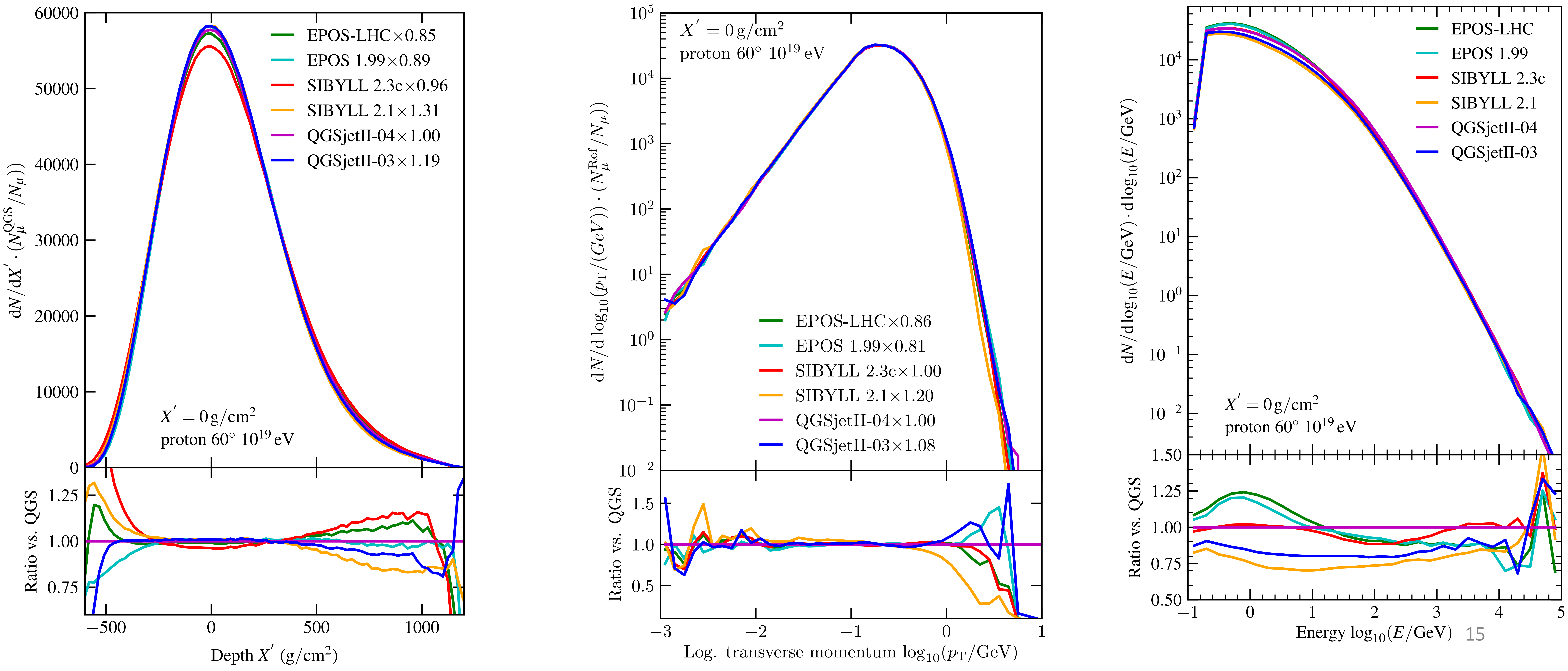
59% of all muons

$$r_\pi < 22\,\mathrm{m}$$

$$\left(\frac{\sigma(N_\mu)}{N_\mu}\right)^2 \simeq \left(\frac{\sigma(\alpha_1)}{\alpha_1}\right)^2 + \left(\frac{\sigma(\alpha_2)}{\alpha_2}\right)^2 + \ldots + \left(\frac{\sigma(\alpha_c)}{\alpha_c}\right)^2$$

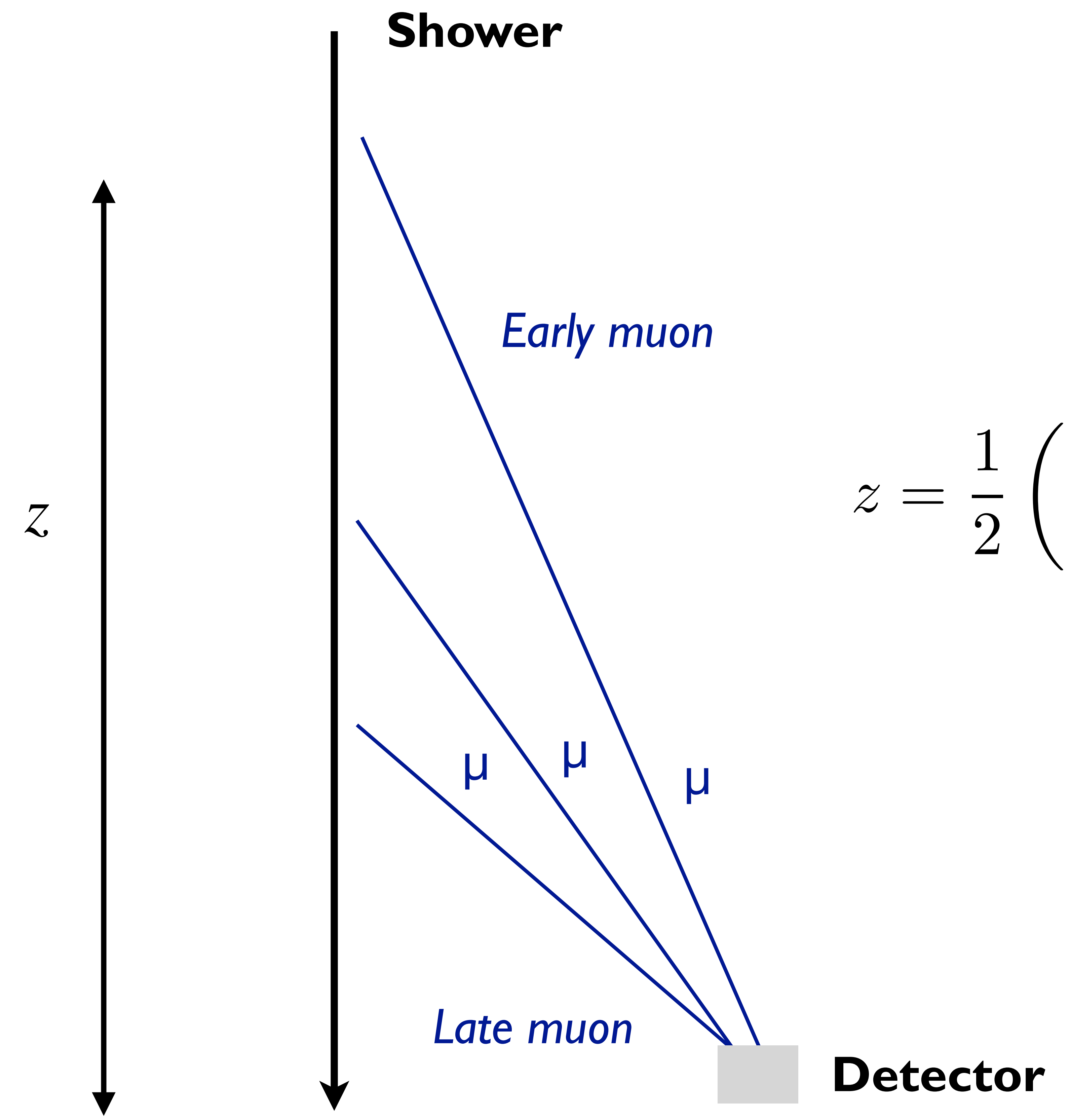
70% of fluctuations from first interaction

Universality features of muon production

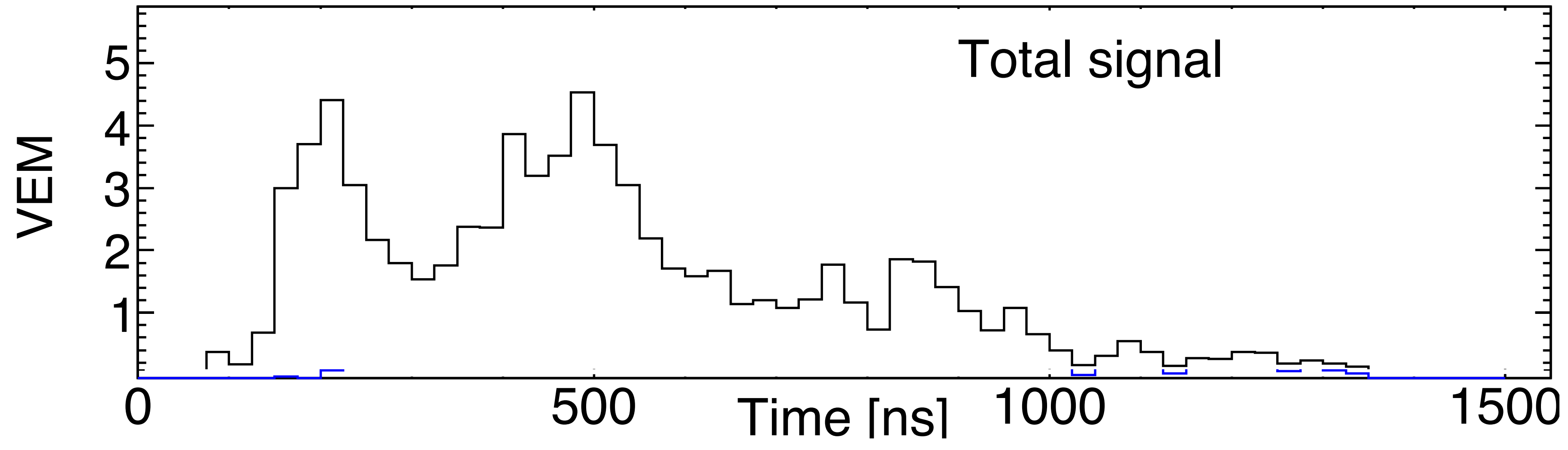


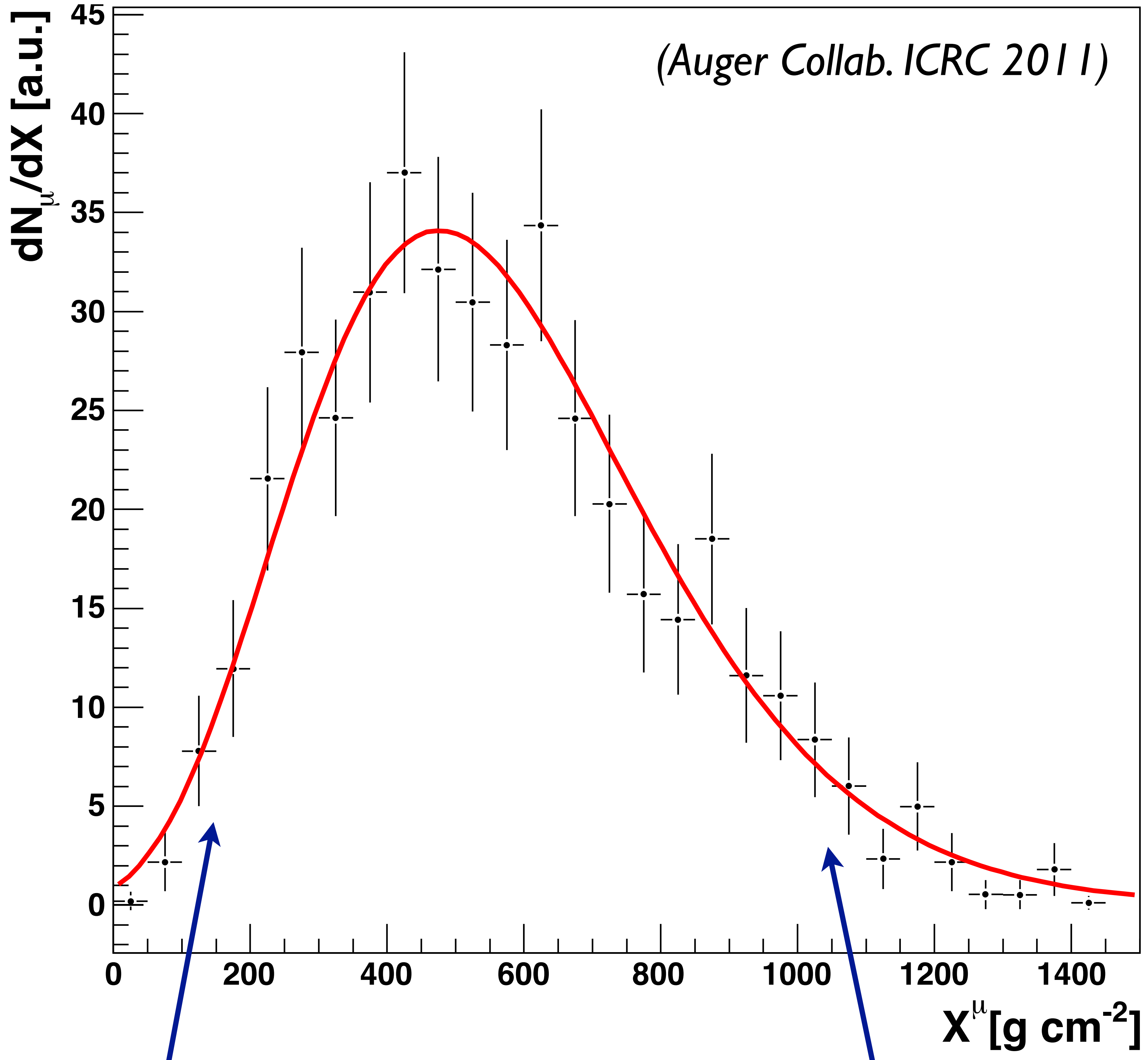
(Cazon, Epiphany Conference 2022)

Muon production depth



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



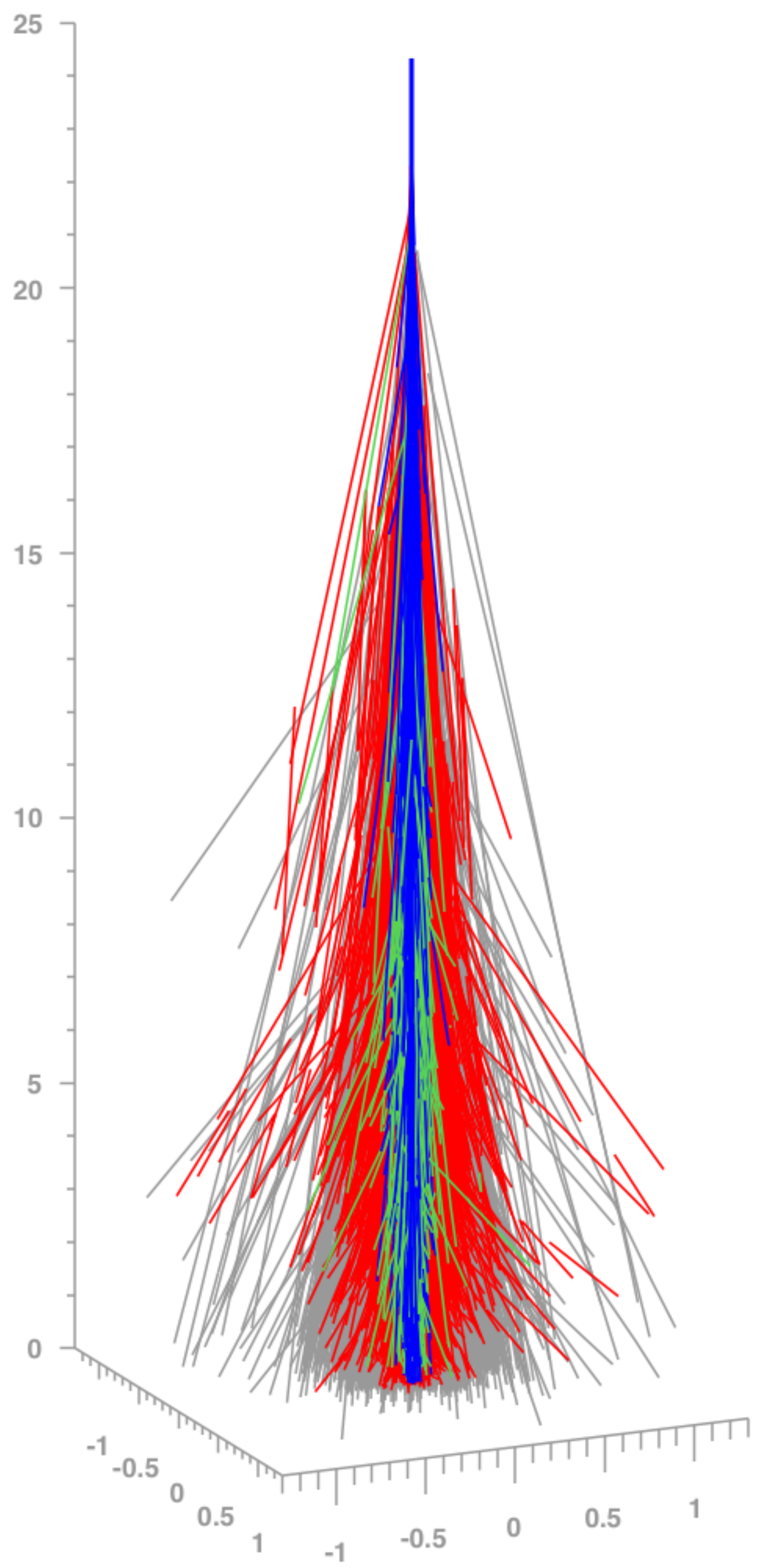


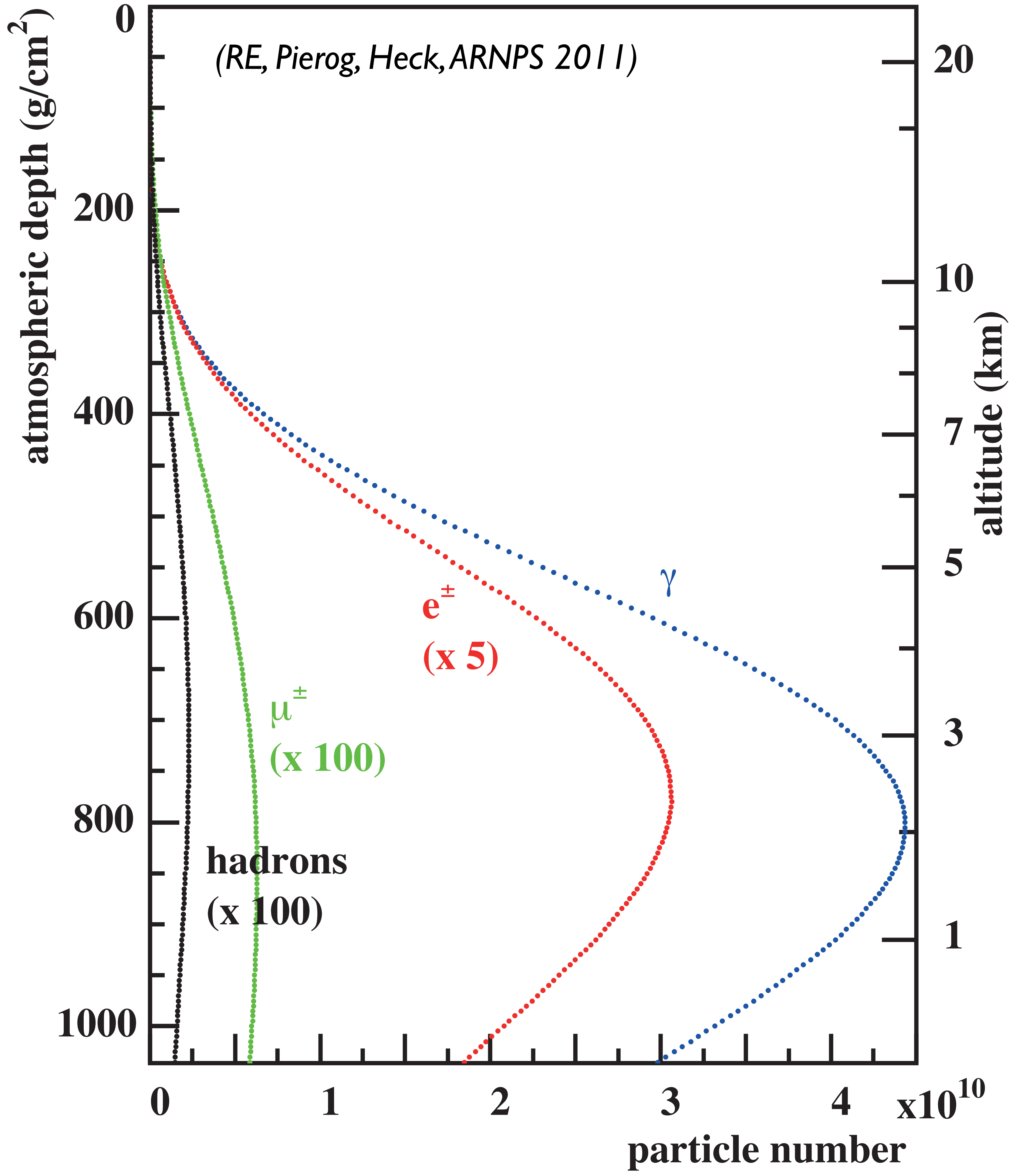
Muons from high-energy interactions

Muons from low-energy interactions

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

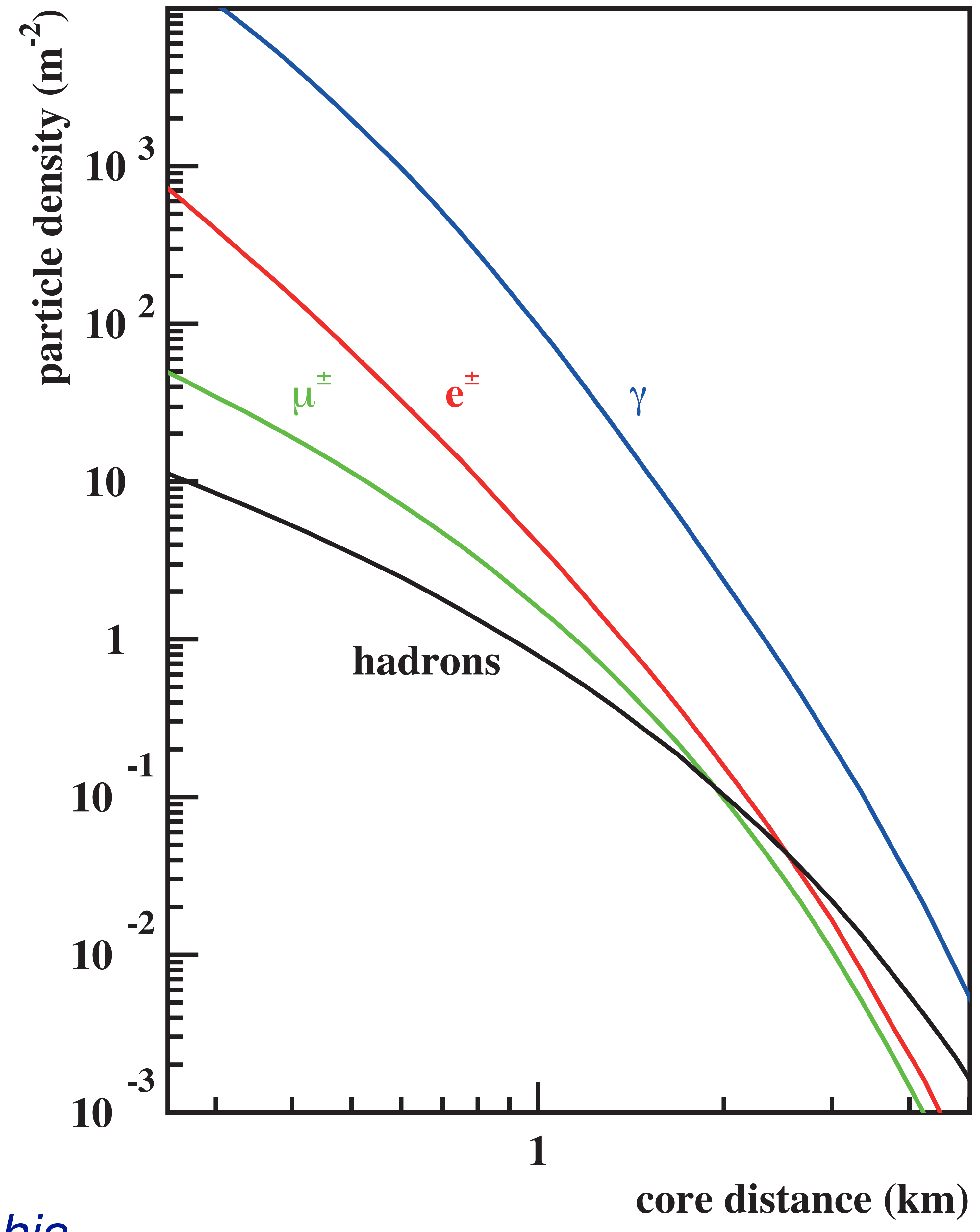
Expectation from simulations



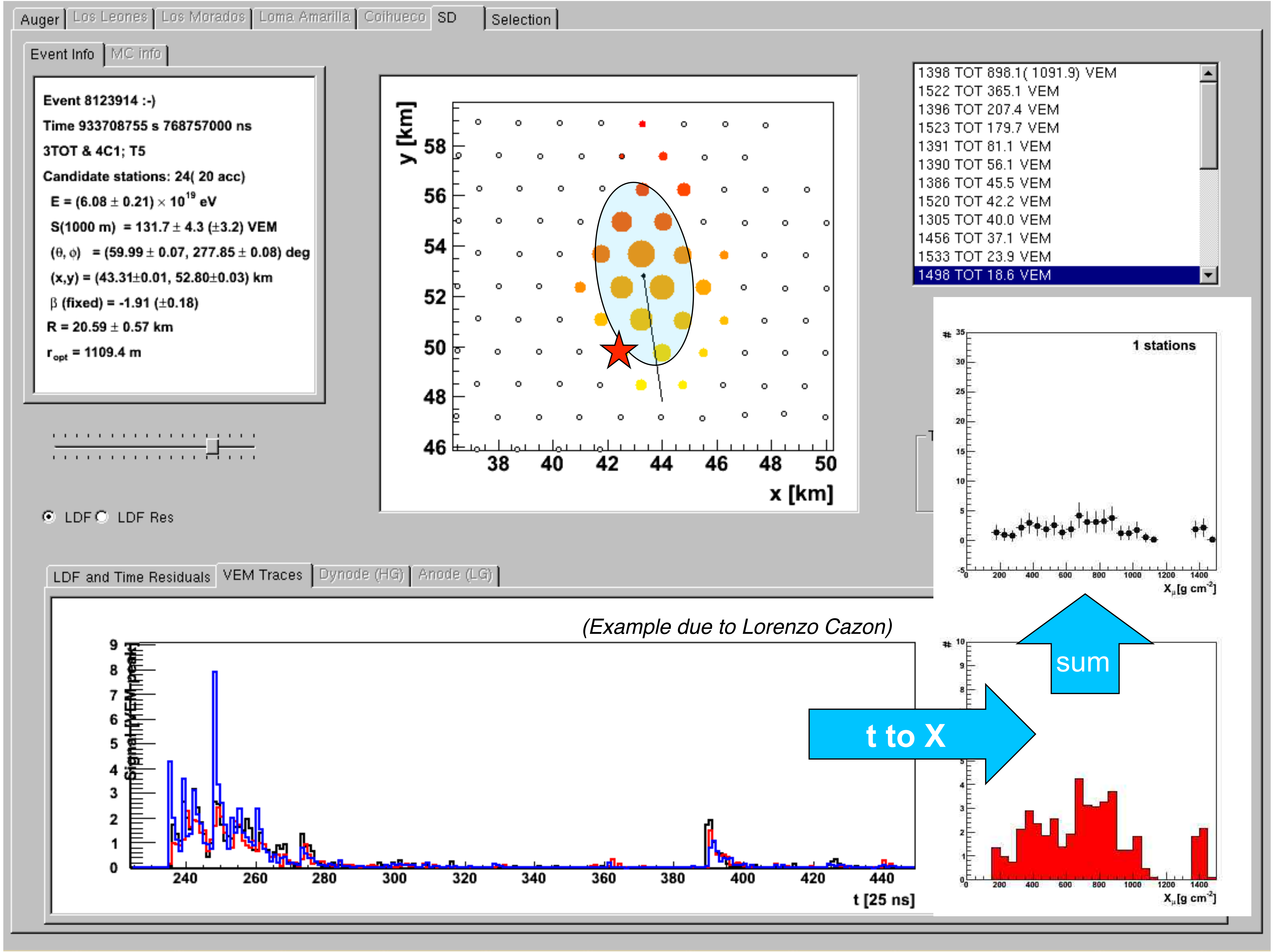


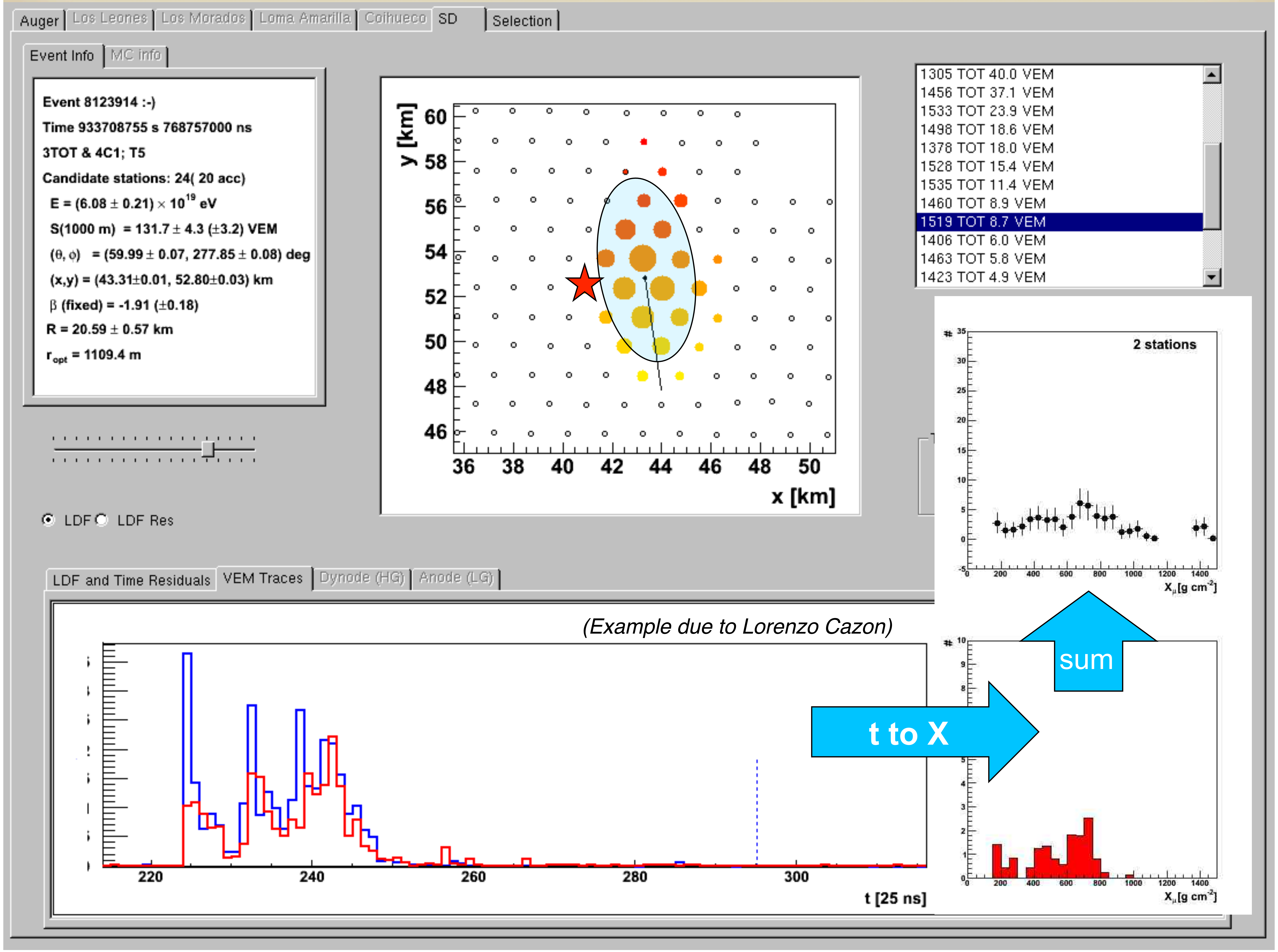
Longitudinal profile:
Cherenkov light
Fluorescence light
(bulk of particles measured)

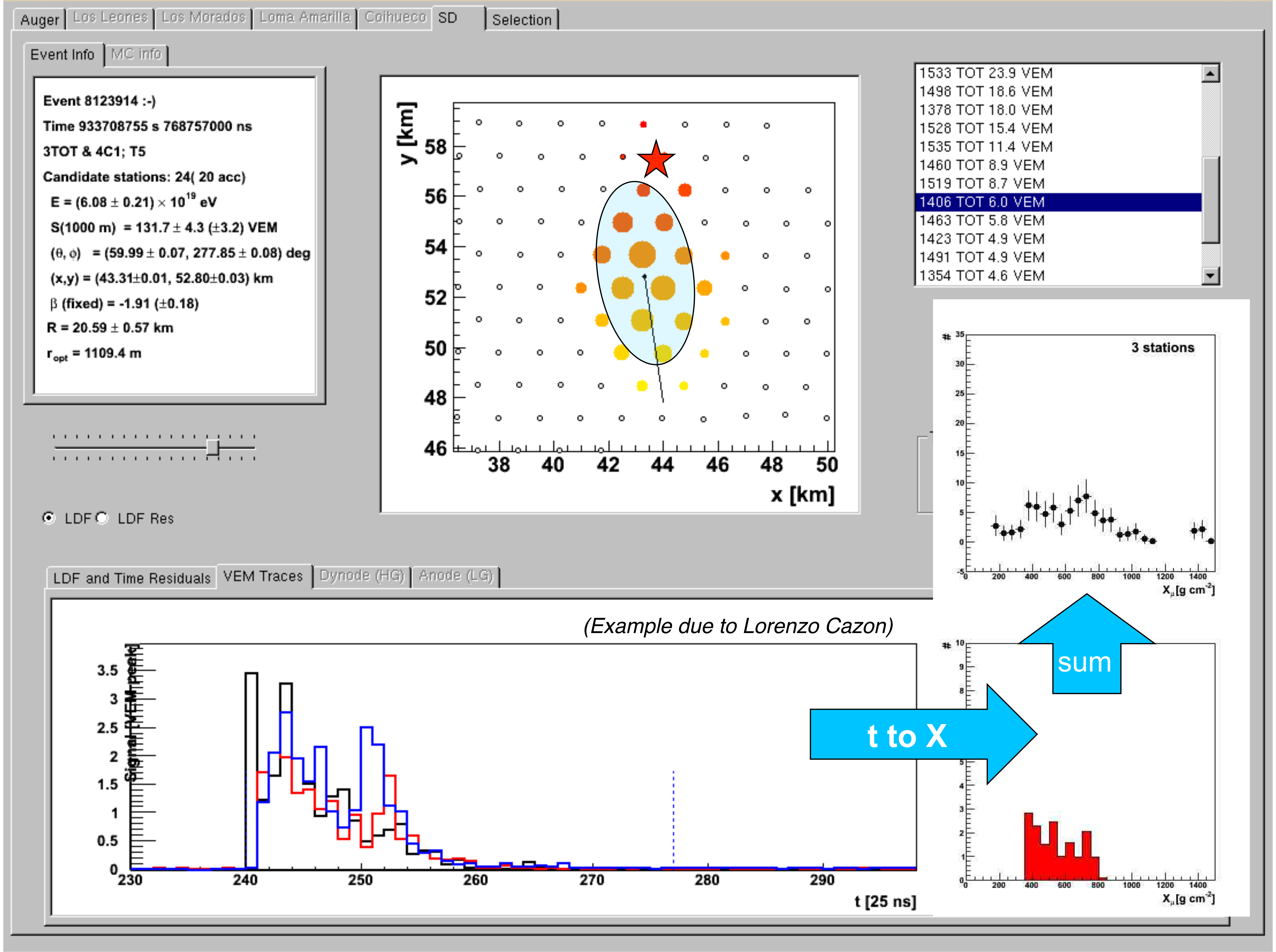
Lateral profiles:
particle detectors at ground
(very small fraction of particles sampled)



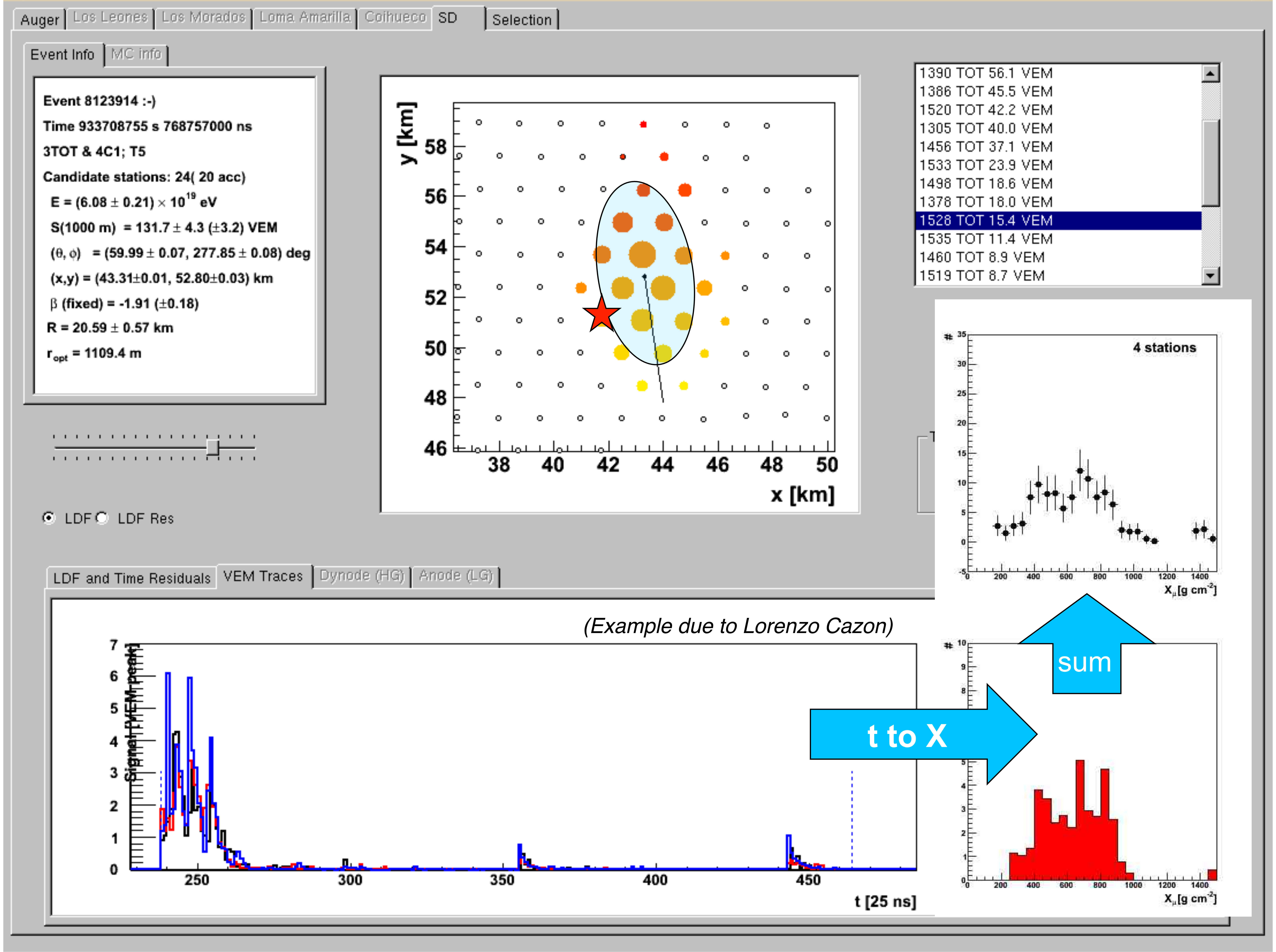
See talk by Piera Ghia


Auger
Los Leones
Los Morados
Loma Amarilla
Coihueco
SD
Selection
Event Info
MC info
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
(θ, φ) = (59.99 ± 0.07, 277.85 ± 0.08) deg
(x,y) = (43.31±0.01, 52.80±0.03) km
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
y [km]
x [km]
1398 TOT 898.1(1091.9) VEM
1522 TOT 365.1 VEM
1396 TOT 207.4 VEM
1523 TOT 179.7 VEM
1391 TOT 81.1 VEM
1390 TOT 56.1 VEM
1386 TOT 45.5 VEM
1520 TOT 42.2 VEM
1305 TOT 40.0 VEM
1456 TOT 37.1 VEM
1533 TOT 23.9 VEM
1498 TOT 18.6 VEM
LDF
LDF Res
LDF and Time Residuals
VEM Traces
Dynode (HG)
Anode (LG)
(Example due to Lorenzo Cazon)
Signal [VEM peak]
t [25 ns]
1 stations
X_μ [g cm^-2]
t to X
sum

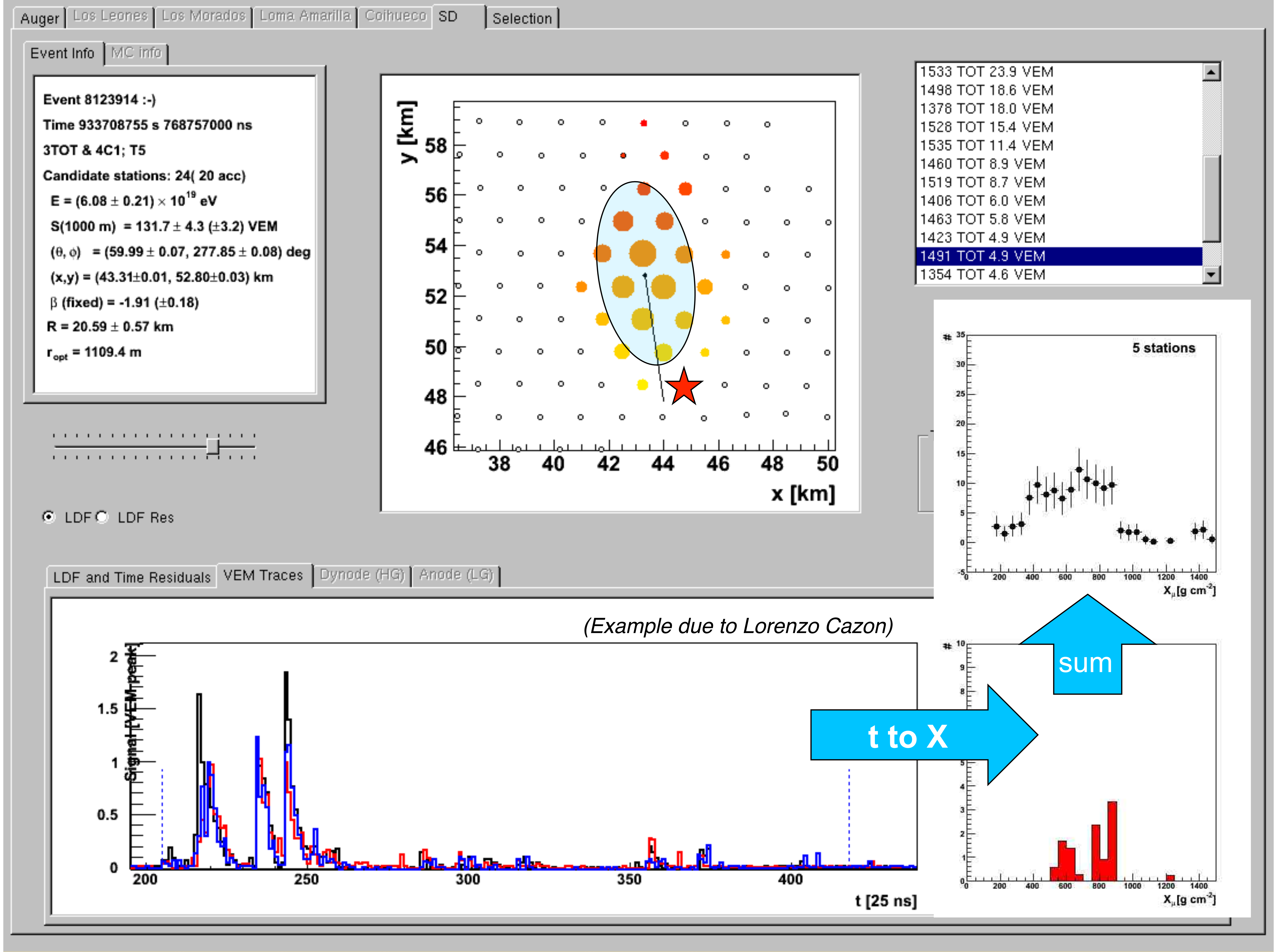

Auger
Los Leones
Los Morados
Loma Amarilla
Coihueco
SD
Selection
Event Info
MC info
Event 8123914 :-)
Time 933708755 s 768757000 ns
3TOT & 4C1; T5
Candidate stations: 24(20 acc)
E = (6.08 ± 0.21) × 10^19 eV
S(1000 m) = 131.7 ± 4.3 (±3.2) VEM
(θ, φ) = (59.99 ± 0.07, 277.85 ± 0.08) deg
(x,y) = (43.31±0.01, 52.80±0.03) km
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
y [km]
x [km]
1305 TOT 40.0 VEM
1456 TOT 37.1 VEM
1533 TOT 23.9 VEM
1498 TOT 18.6 VEM
1378 TOT 18.0 VEM
1528 TOT 15.4 VEM
1535 TOT 11.4 VEM
1460 TOT 8.9 VEM
1519 TOT 8.7 VEM
1406 TOT 6.0 VEM
1463 TOT 5.8 VEM
1423 TOT 4.9 VEM
LDF
LDF Res
LDF and Time Residuals
VEM Traces
Dynode (HG)
Anode (LG)
(Example due to Lorenzo Cazon)
t [25 ns]
2 stations
X_μ [g cm^-2]
sum
t to X



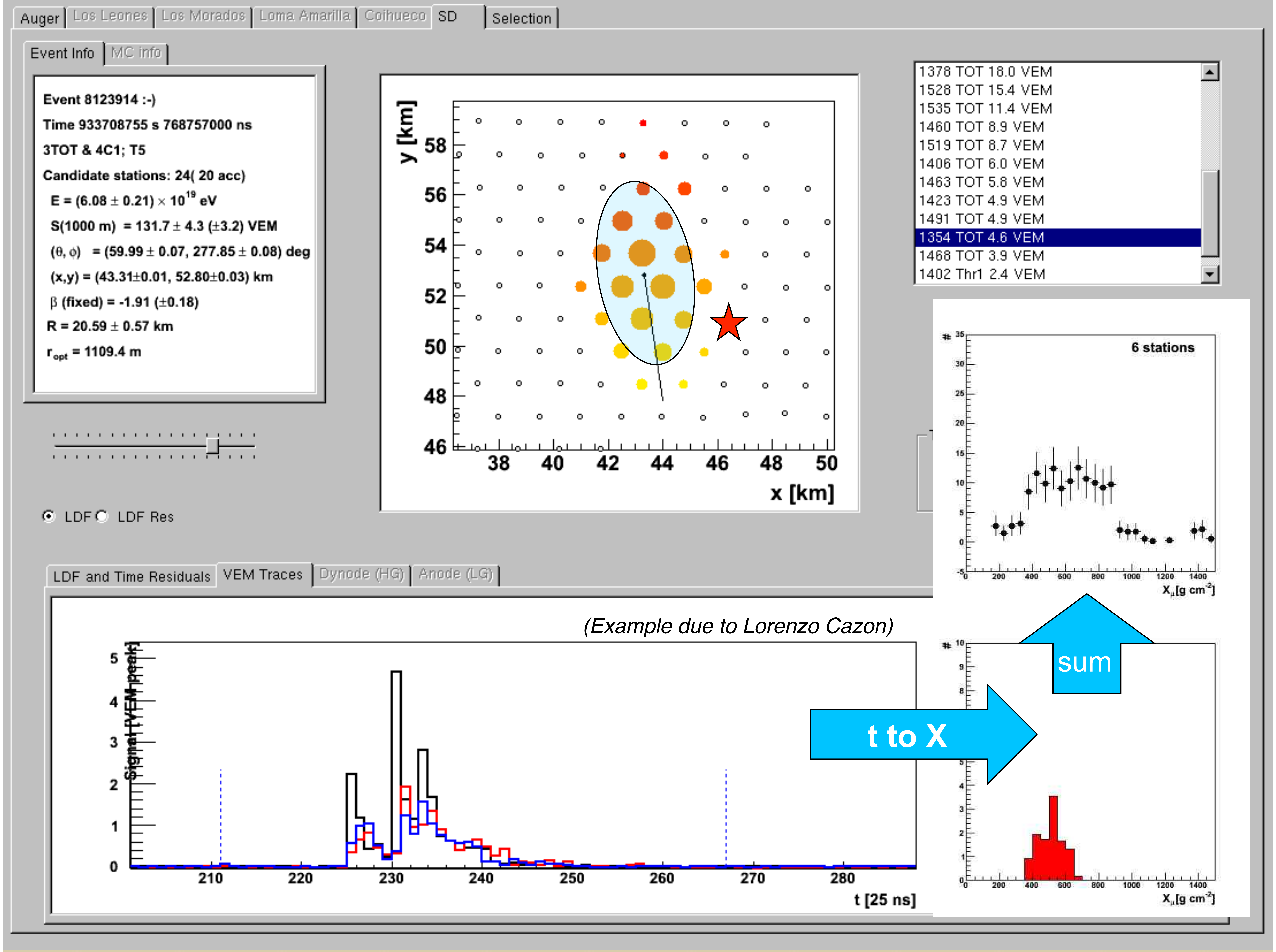
Auger
Los Leones
Los Morados
Loma Amarilla
Coihueco
SD
Selection
Event Info
MC info
Event 8123914 :-)
Time 933708755 s 768757000 ns
3TOT & 4C1; T5
Candidate stations: 24(20 acc)
E = (6.08 ± 0.21) × 10^19 eV
S(1000 m) = 131.7 ± 4.3 (±3.2) VEM
(θ, φ) = (59.99 ± 0.07, 277.85 ± 0.08) deg
(x,y) = (43.31±0.01, 52.80±0.03) km
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
y [km]
x [km]
1533 TOT 23.9 VEM
1498 TOT 18.6 VEM
1378 TOT 18.0 VEM
1528 TOT 15.4 VEM
1535 TOT 11.4 VEM
1460 TOT 8.9 VEM
1519 TOT 8.7 VEM
1406 TOT 6.0 VEM
1463 TOT 5.8 VEM
1423 TOT 4.9 VEM
1491 TOT 4.9 VEM
1354 TOT 4.6 VEM
LDF
LDF Res
LDF and Time Residuals
VEM Traces
Dynode (HG)
Anode (LG)
(Example due to Lorenzo Cazon)
Signal [VEM peak]
t [25 ns]
3 stations
X_μ [g cm^-2]
sum
t to X



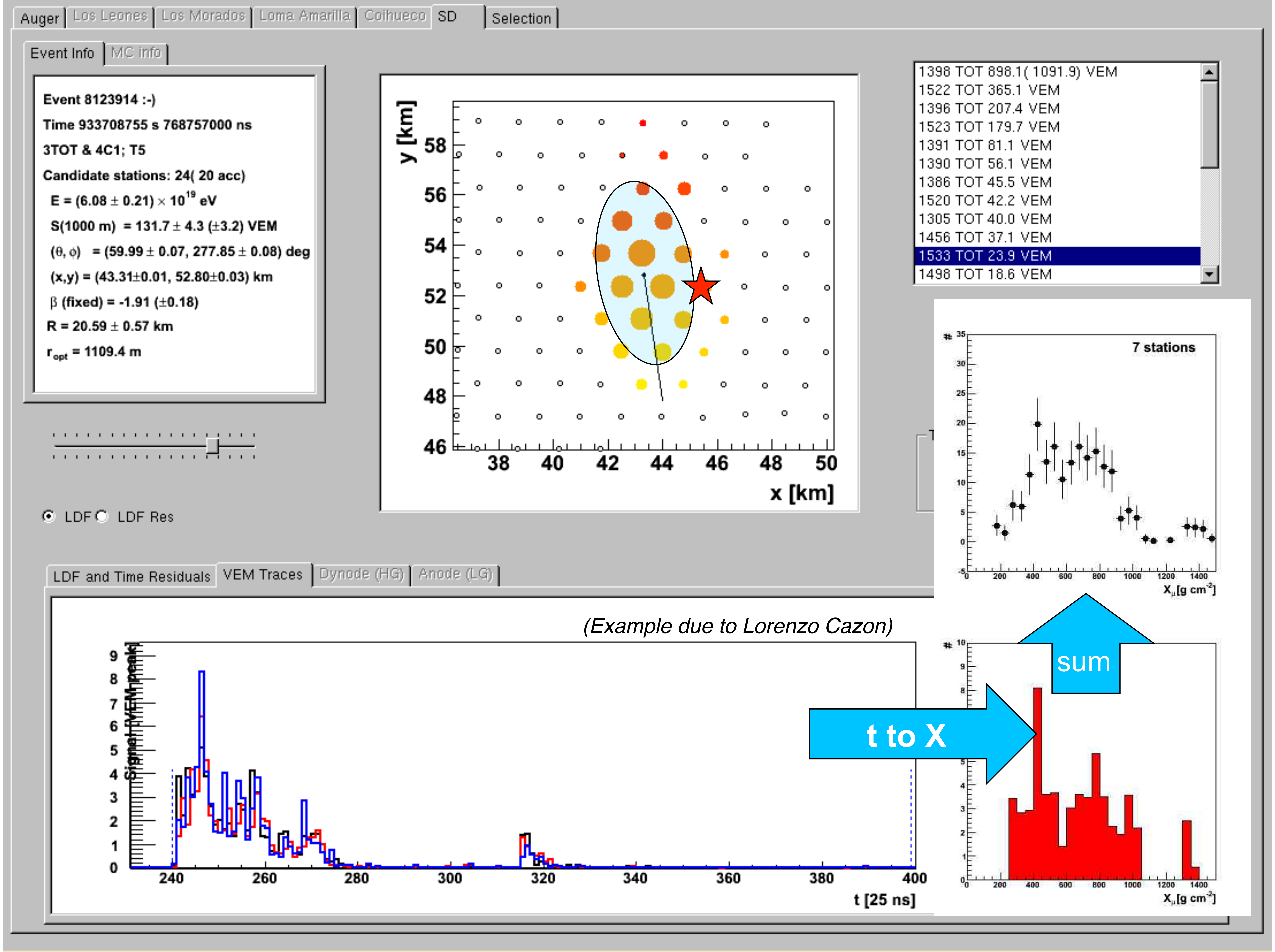
Auger
Los Leones
Los Morados
Loma Amarilla
Coihueco
SD
Selection
Event Info
MC info
Event 8123914 :-)
Time 933708755 s 768757000 ns
3TOT & 4C1; T5
Candidate stations: 24(20 acc)
E = (6.08 ± 0.21) × 10^19 eV
S(1000 m) = 131.7 ± 4.3 (±3.2) VEM
(θ, φ) = (59.99 ± 0.07, 277.85 ± 0.08) deg
(x,y) = (43.31±0.01, 52.80±0.03) km
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
y [km]
x [km]
1390 TOT 56.1 VEM
1386 TOT 45.5 VEM
1520 TOT 42.2 VEM
1305 TOT 40.0 VEM
1456 TOT 37.1 VEM
1533 TOT 23.9 VEM
1498 TOT 18.6 VEM
1378 TOT 18.0 VEM
1528 TOT 15.4 VEM
1535 TOT 11.4 VEM
1460 TOT 8.9 VEM
1519 TOT 8.7 VEM
LDF
LDF Res
LDF and Time Residuals
VEM Traces
Dynode (HG)
Anode (LG)
(Example due to Lorenzo Cazon)
Signal [VEM peak]
t [25 ns]
4 stations
X_μ [g cm^-2]
sum
t to X



Auger
Los Leones
Los Morados
Loma Amarilla
Coihueco
SD
Selection
Event Info
MC info
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
(θ, φ) = (59.99 ± 0.07, 277.85 ± 0.08) deg
(x,y) = (43.31±0.01, 52.80±0.03) km
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
y [km]
x [km]
1533 TOT 23.9 VEM
1498 TOT 18.6 VEM
1378 TOT 18.0 VEM
1528 TOT 15.4 VEM
1535 TOT 11.4 VEM
1460 TOT 8.9 VEM
1519 TOT 8.7 VEM
1406 TOT 6.0 VEM
1463 TOT 5.8 VEM
1423 TOT 4.9 VEM
1491 TOT 4.9 VEM
1354 TOT 4.6 VEM
LDF
LDF Res
5 stations
X_μ [g cm^-2]
LDF and Time Residuals
VEM Traces
Dynode (HG)
Anode (LG)
(Example due to Lorenzo Cazon)
Signal [VEM peak]
t [25 ns]
t to X
sum



Auger
Los Leones
Los Morados
Loma Amarilla
Coihueco
SD
Selection
Event Info
MC info
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
(θ, φ) = (59.99 ± 0.07, 277.85 ± 0.08) deg
(x,y) = (43.31±0.01, 52.80±0.03) km
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
y [km]
x [km]
1378 TOT 18.0 VEM
1528 TOT 15.4 VEM
1535 TOT 11.4 VEM
1460 TOT 8.9 VEM
1519 TOT 8.7 VEM
1406 TOT 6.0 VEM
1463 TOT 5.8 VEM
1423 TOT 4.9 VEM
1491 TOT 4.9 VEM
1354 TOT 4.6 VEM
1468 TOT 3.9 VEM
1402 Thr1 2.4 VEM
LDF
LDF Res
LDF and Time Residuals
VEM Traces
Dynode (HG)
Anode (LG)
(Example due to Lorenzo Cazon)
Signal [VEM peak]
t [25 ns]
6 stations
X_μ [g cm^-2]
sum
t to X



Auger
Los Leones
Los Morados
Loma Amarilla
Coihueco
SD
Selection
Event Info
MC info
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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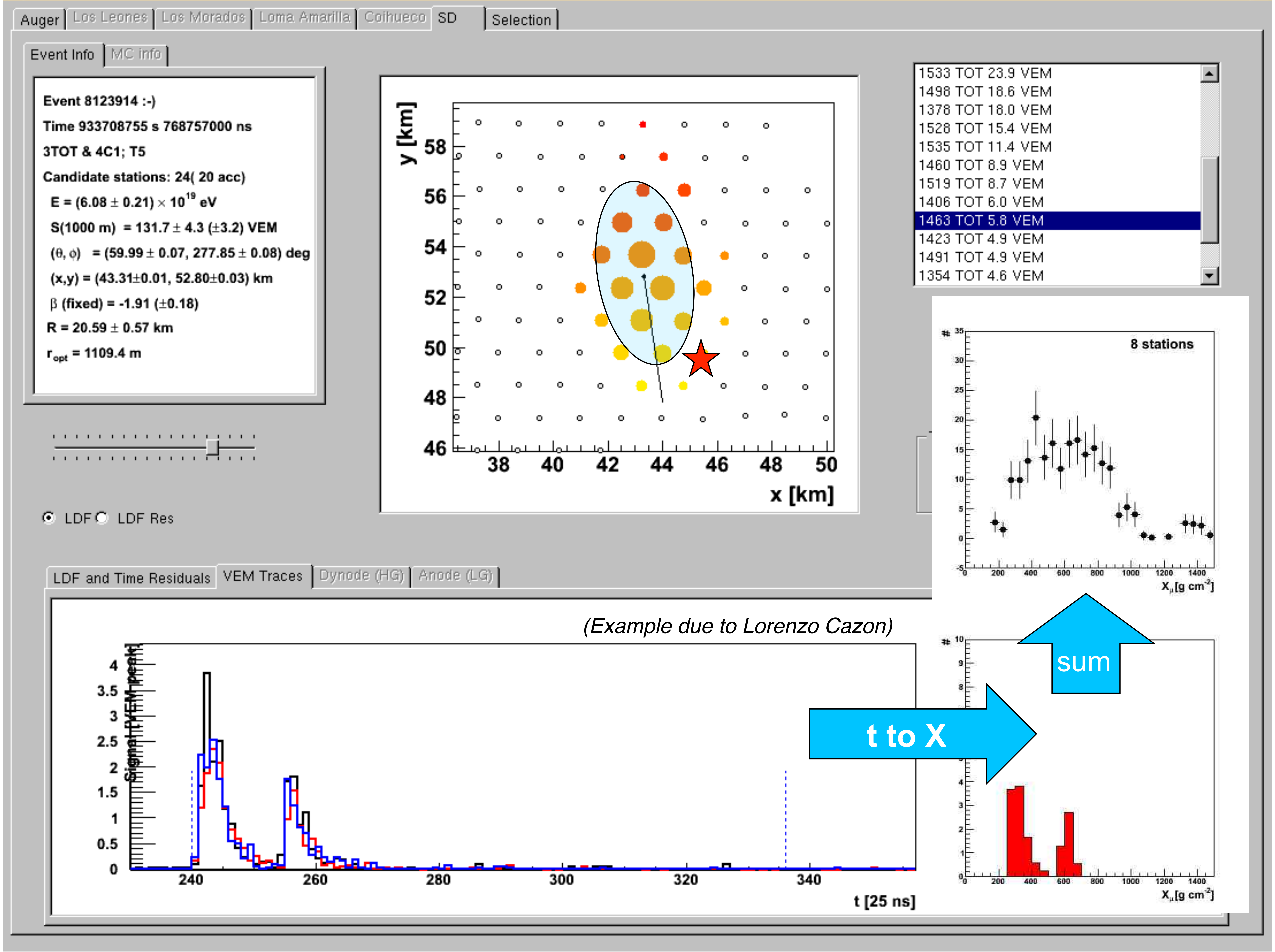
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
y [km]
x [km]
1398 TOT 898.1(1091.9) VEM
1522 TOT 365.1 VEM
1396 TOT 207.4 VEM
1523 TOT 179.7 VEM
1391 TOT 81.1 VEM
1390 TOT 56.1 VEM
1386 TOT 45.5 VEM
1520 TOT 42.2 VEM
1305 TOT 40.0 VEM
1456 TOT 37.1 VEM
1533 TOT 23.9 VEM
1498 TOT 18.6 VEM
LDF
LDF Res
LDF and Time Residuals
VEM Traces
Dynode (HG)
Anode (LG)
(Example due to Lorenzo Cazon)
Signal [VEM peak]
t [25 ns]
7 stations
X_μ [g cm^-2]
sum
t to X


Auger
Los Leones
Los Morados
Loma Amarilla
Coihueco
SD
Selection
Event Info
MC info
Event 8123914 :-)
Time 933708755 s 768757000 ns
3TOT & 4C1; T5
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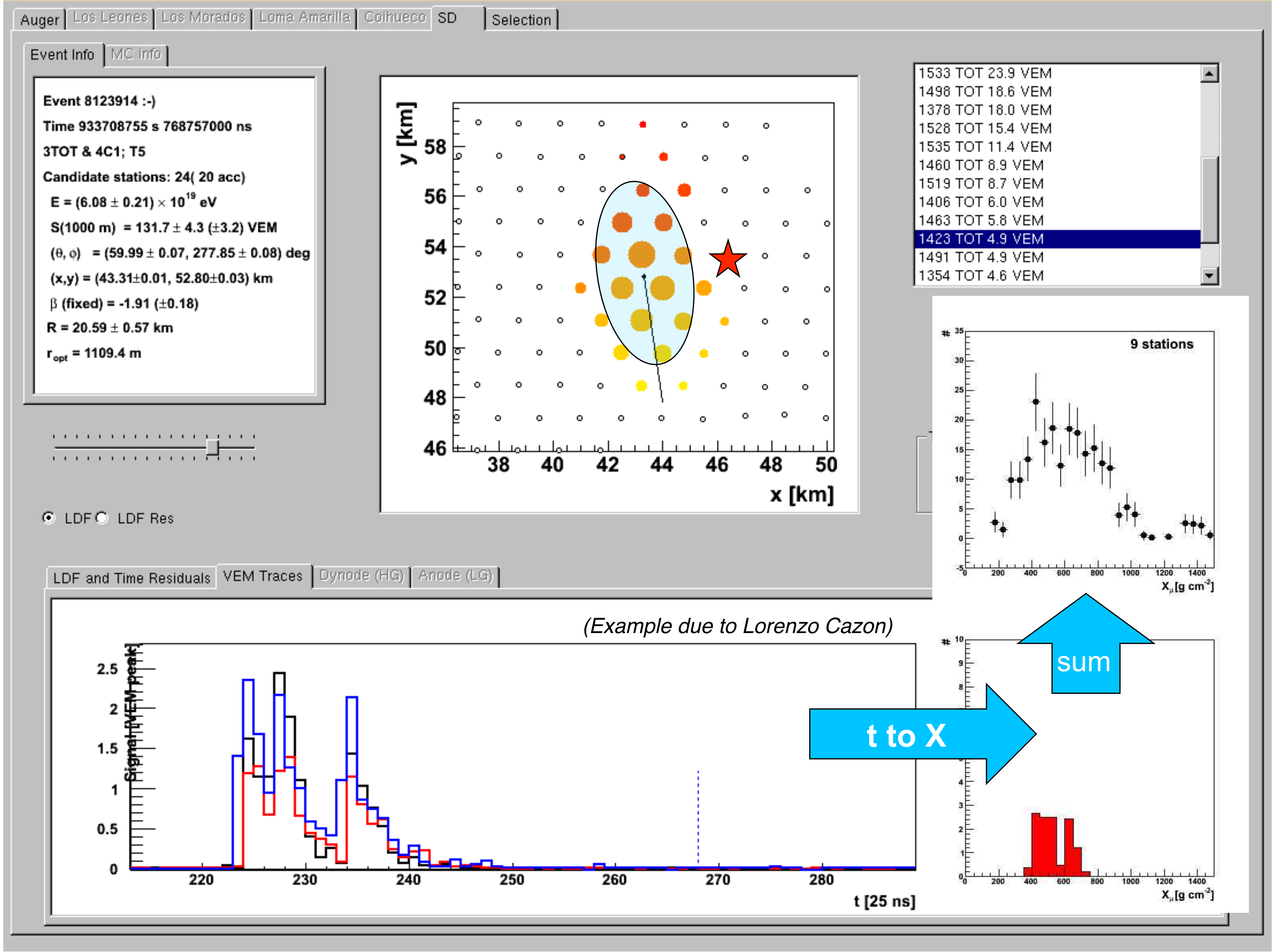
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
y [km]
x [km]
1533 TOT 23.9 VEM
1498 TOT 18.6 VEM
1378 TOT 18.0 VEM
1528 TOT 15.4 VEM
1535 TOT 11.4 VEM
1460 TOT 8.9 VEM
1519 TOT 8.7 VEM
1406 TOT 6.0 VEM
1463 TOT 5.8 VEM
1423 TOT 4.9 VEM
1491 TOT 4.9 VEM
1354 TOT 4.6 VEM
LDF
LDF Res
LDF and Time Residuals
VEM Traces
Dynode (HG)
Anode (LG)
(Example due to Lorenzo Cazon)
Signal [VEM peak]
t [25 ns]
8 stations
X_μ [g cm^-2]
sum
t to X



Auger
Los Leones
Los Morados
Loma Amarilla
Coihueco
SD
Selection
Event Info
MC info
Event 8123914 :-)
Time 933708755 s 768757000 ns
3TOT & 4C1; T5
Candidate stations: 24(20 acc)
E = (6.08 ± 0.21) × 10^19 eV
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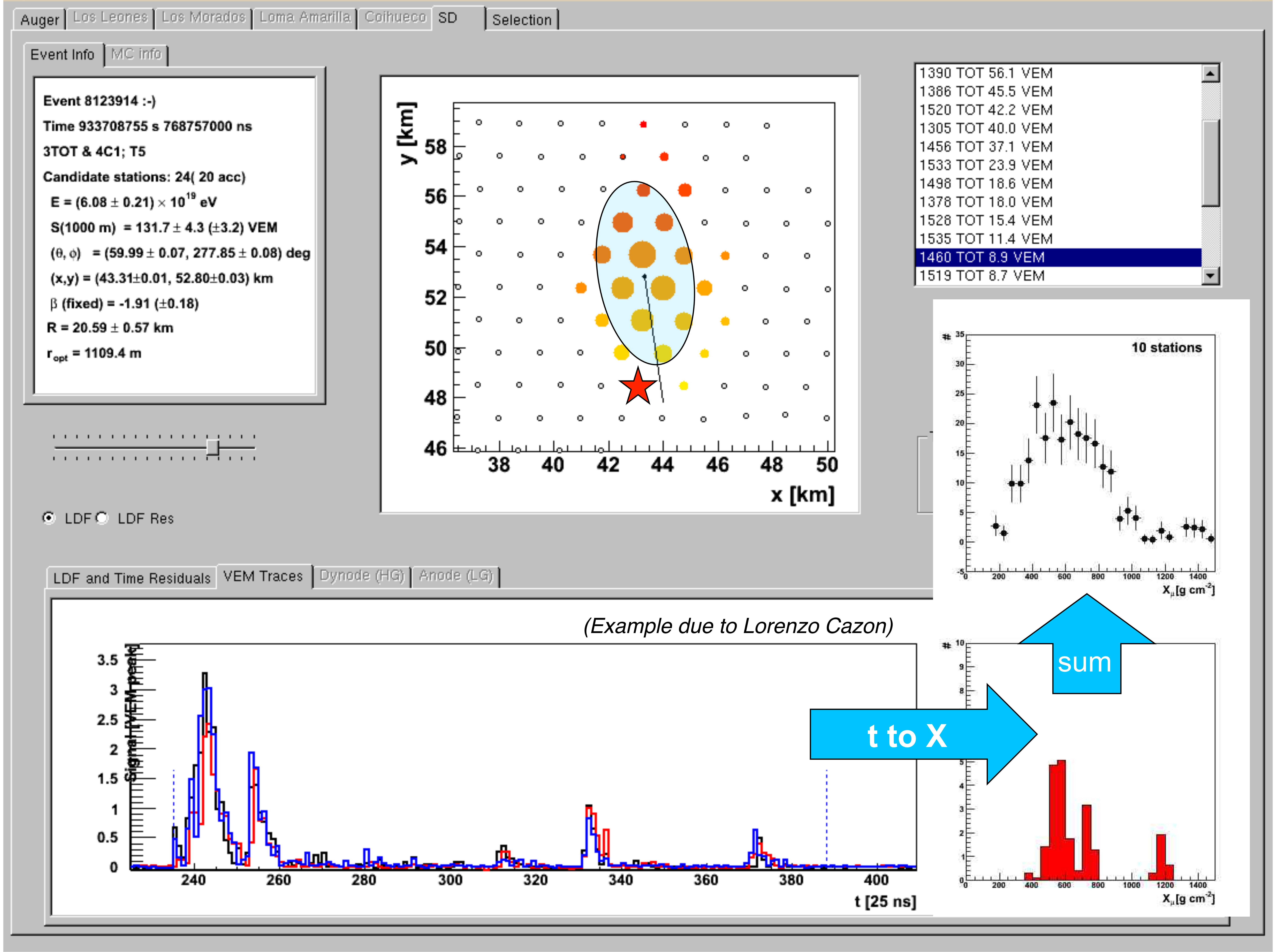
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
LDF
LDF Res
y [km]
x [km]
1533 TOT 23.9 VEM
1498 TOT 18.6 VEM
1378 TOT 18.0 VEM
1528 TOT 15.4 VEM
1535 TOT 11.4 VEM
1460 TOT 8.9 VEM
1519 TOT 8.7 VEM
1406 TOT 6.0 VEM
1463 TOT 5.8 VEM
1423 TOT 4.9 VEM
1491 TOT 4.9 VEM
1354 TOT 4.6 VEM
9 stations
X_μ [g cm^-2]
LDF and Time Residuals
VEM Traces
Dynode (HG)
Anode (LG)
(Example due to Lorenzo Cazon)
Signal [VEM peak]
t [25 ns]
sum
t to X


Auger
Los Leones
Los Morados
Loma Amarilla
Coihueco
SD
Selection
Event Info
MC info
Event 8123914 :-)
Time 933708755 s 768757000 ns
3TOT & 4C1; T5
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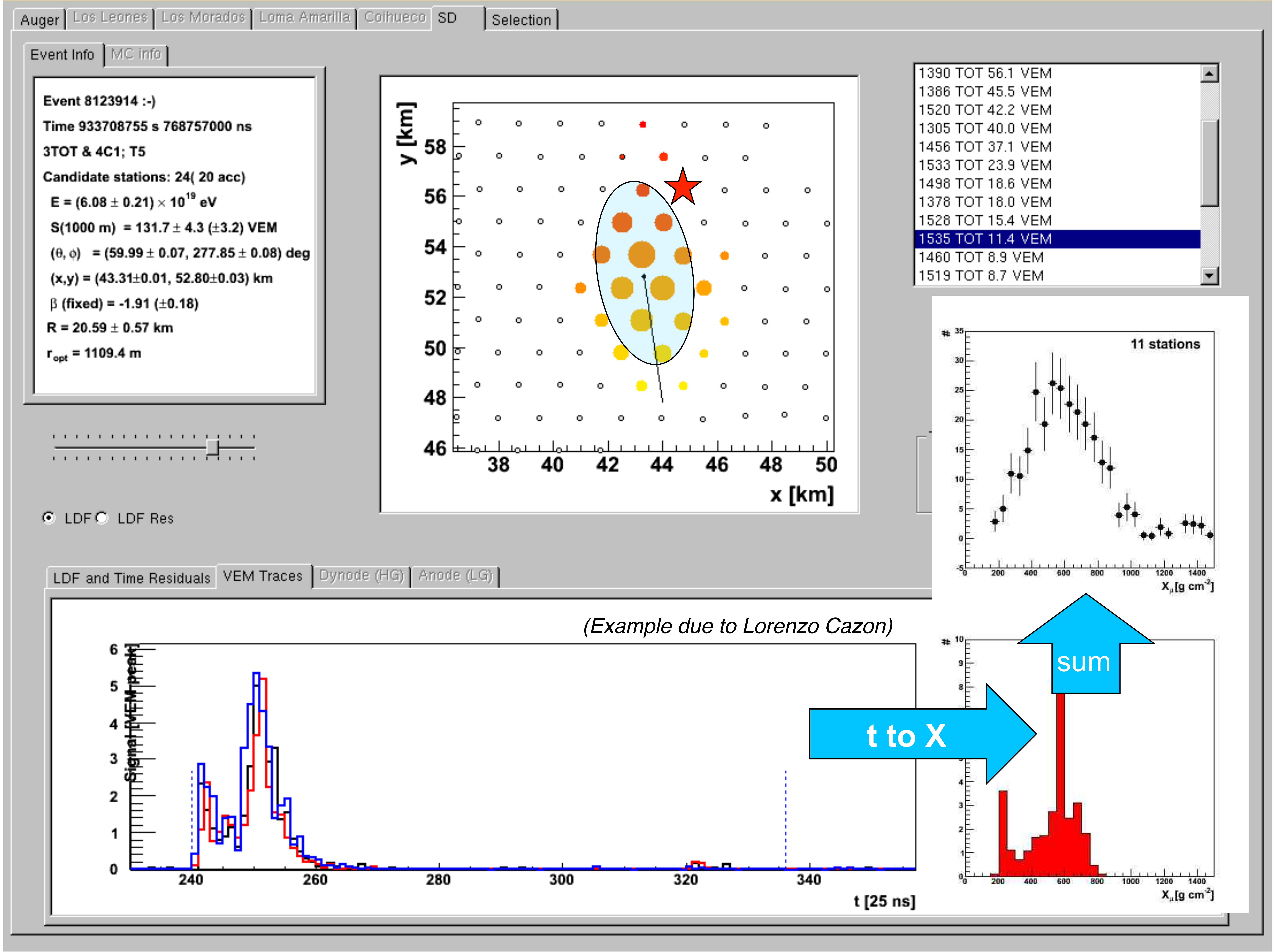
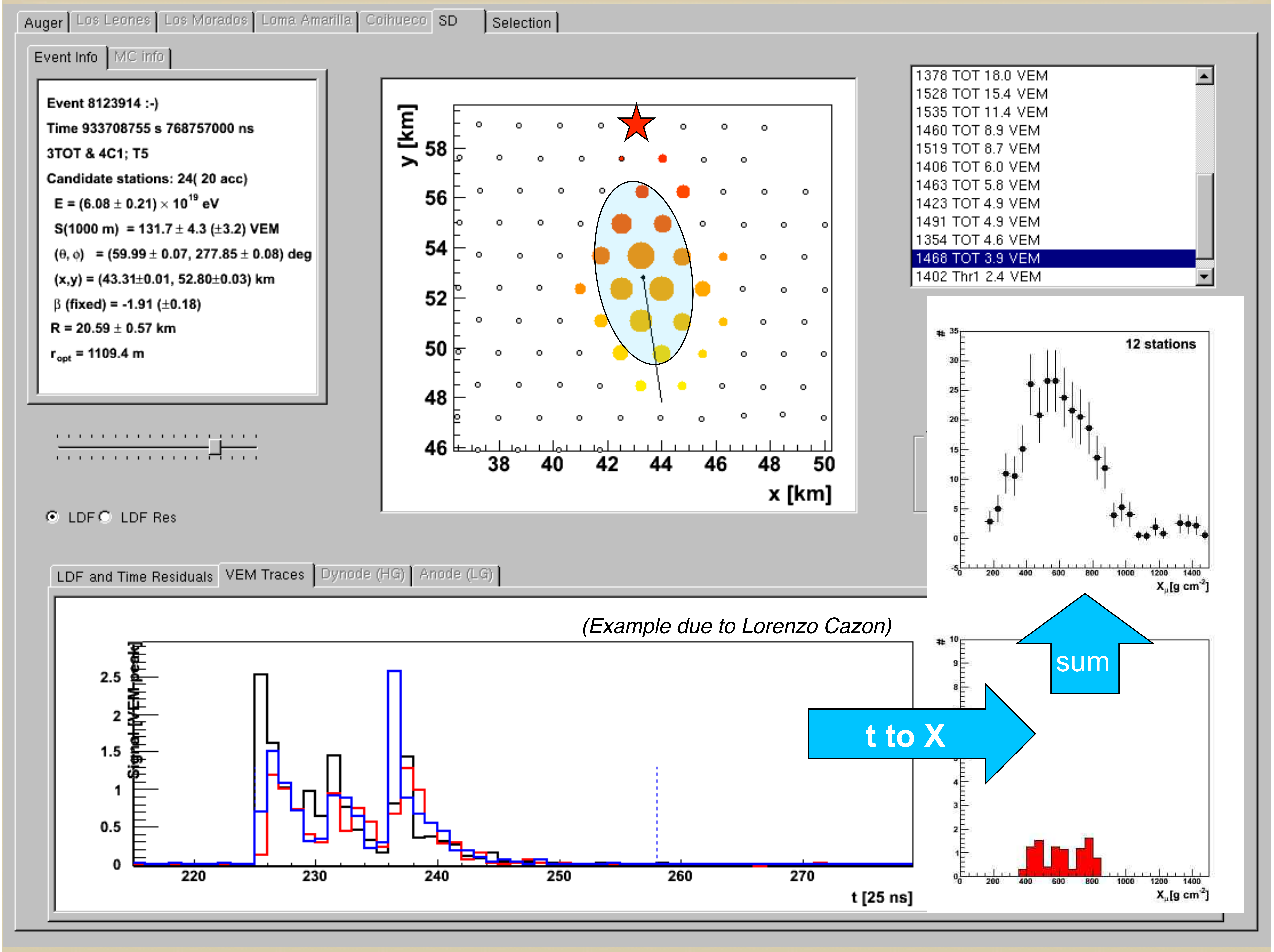
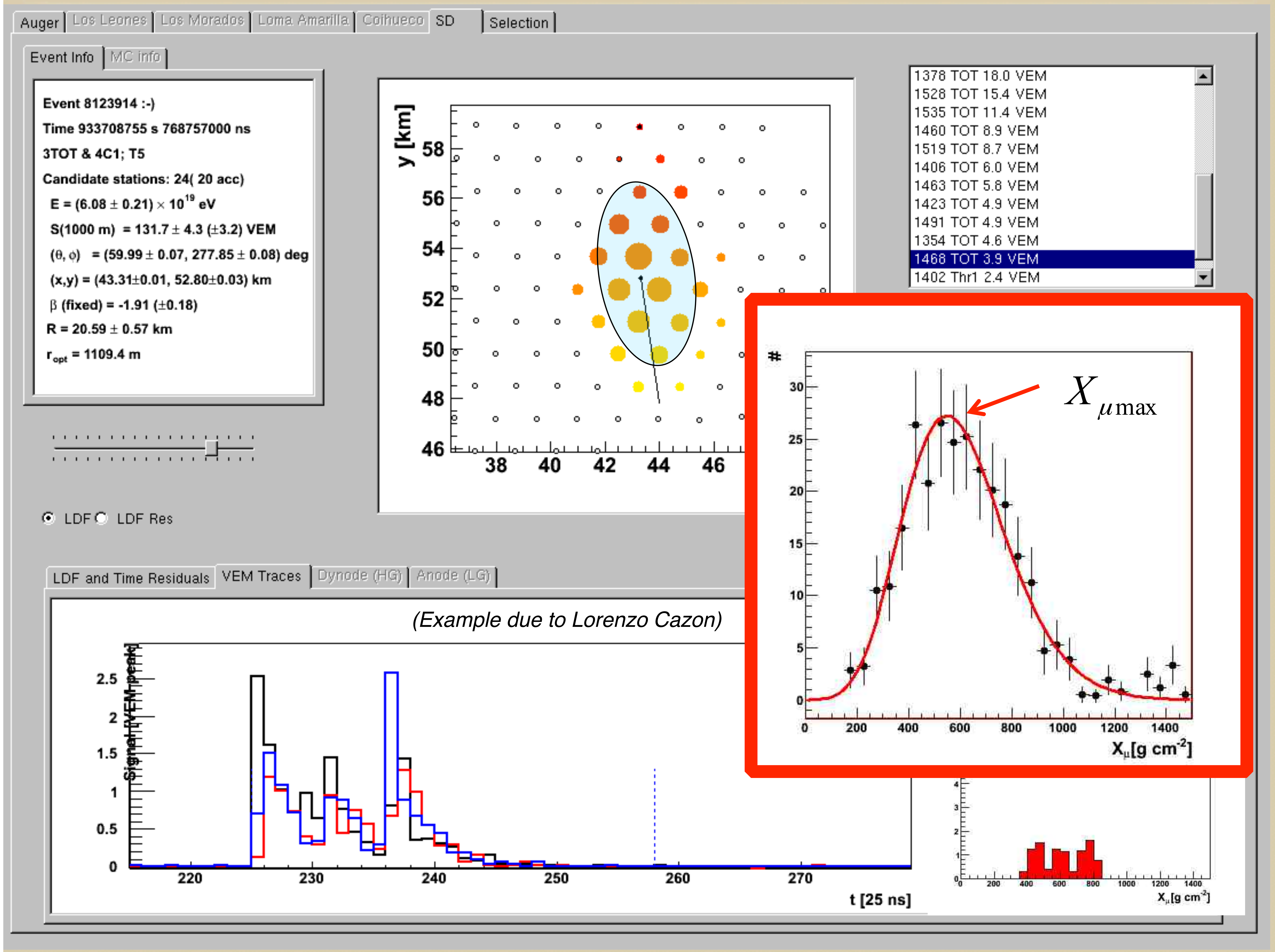
S(1000 m) = 131.7 ± 4.3 (±3.2) VEM
(θ, φ) = (59.99 ± 0.07, 277.85 ± 0.08) deg
(x,y) = (43.31±0.01, 52.80±0.03) km
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
y [km]
x [km]
1390 TOT 56.1 VEM
1386 TOT 45.5 VEM
1520 TOT 42.2 VEM
1305 TOT 40.0 VEM
1456 TOT 37.1 VEM
1533 TOT 23.9 VEM
1498 TOT 18.6 VEM
1378 TOT 18.0 VEM
1528 TOT 15.4 VEM
1535 TOT 11.4 VEM
1460 TOT 8.9 VEM
1519 TOT 8.7 VEM
10 stations
X_μ [g cm^-2]
LDF
LDF Res
LDF and Time Residuals
VEM Traces
Dynode (HG)
Anode (LG)
(Example due to Lorenzo Cazon)
Signal [VEM peak]
t [25 ns]
t to X
sum


Auger
Los Leones
Los Morados
Loma Amarilla
Coihueco
SD
Selection
Event Info
MC info
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
(θ, φ) = (59.99 ± 0.07, 277.85 ± 0.08) deg
(x,y) = (43.31±0.01, 52.80±0.03) km
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
y [km]
x [km]
1390 TOT 56.1 VEM
1386 TOT 45.5 VEM
1520 TOT 42.2 VEM
1305 TOT 40.0 VEM
1456 TOT 37.1 VEM
1533 TOT 23.9 VEM
1498 TOT 18.6 VEM
1378 TOT 18.0 VEM
1528 TOT 15.4 VEM
1535 TOT 11.4 VEM
1460 TOT 8.9 VEM
1519 TOT 8.7 VEM
LDF
LDF Res
LDF and Time Residuals
VEM Traces
Dynode (HG)
Anode (LG)
(Example due to Lorenzo Cazon)
Signal [VEM peak]
t [25 ns]
11 stations
X_μ [g cm^-2]
sum
t to X

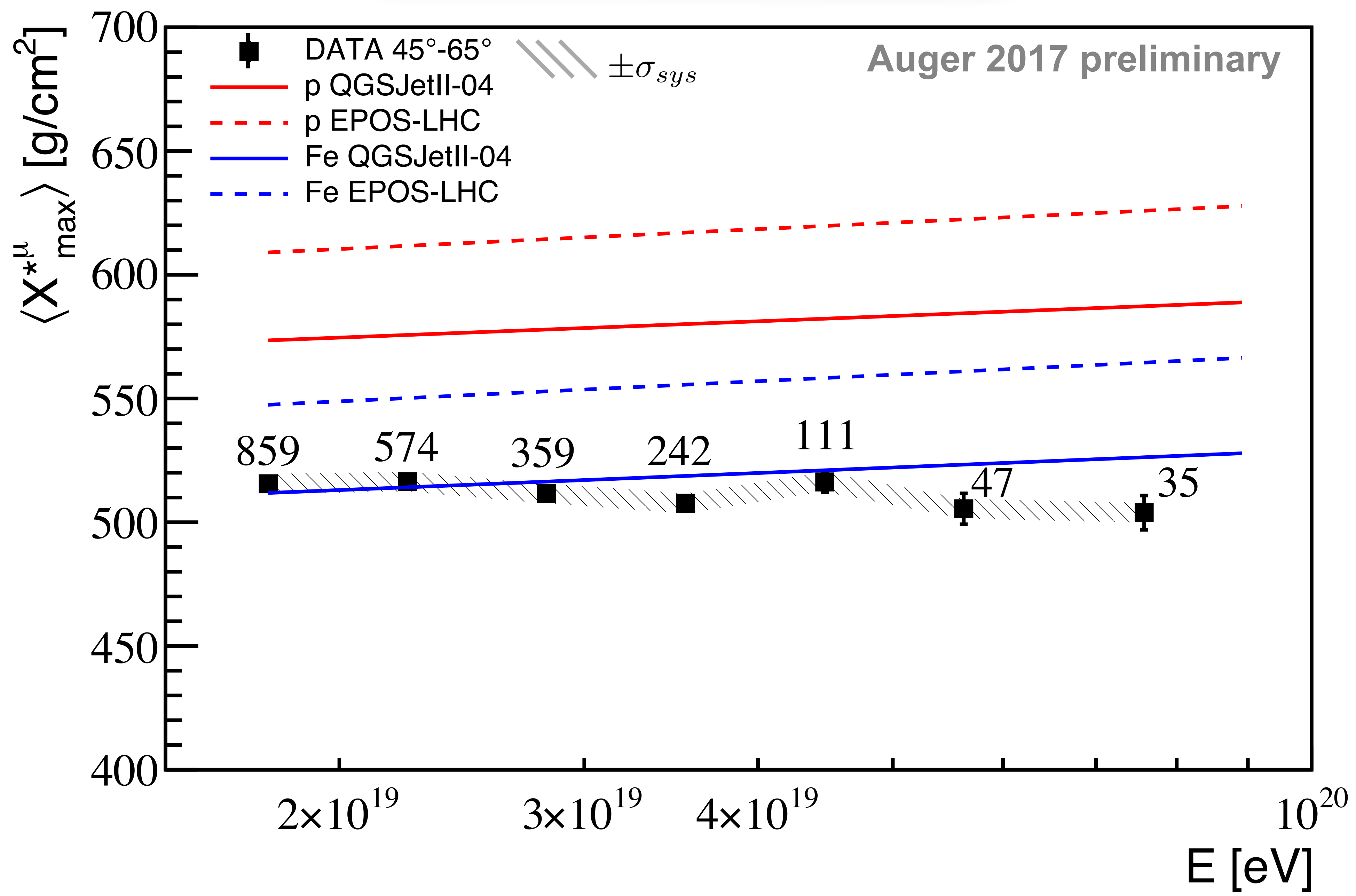


Auger
Los Leones
Los Morados
Loma Amarilla
Coihueco
SD
Selection
Event Info
MC info
Event 8123914 :-)
Time 933708755 s 768757000 ns
3TOT & 4C1; T5
Candidate stations: 24(20 acc)
E = (6.08 ± 0.21) × 10^19 eV
S(1000 m) = 131.7 ± 4.3 (±3.2) VEM
(θ, φ) = (59.99 ± 0.07, 277.85 ± 0.08) deg
(x,y) = (43.31±0.01, 52.80±0.03) km
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
y [km]
x [km]
1378 TOT 18.0 VEM
1528 TOT 15.4 VEM
1535 TOT 11.4 VEM
1460 TOT 8.9 VEM
1519 TOT 8.7 VEM
1406 TOT 6.0 VEM
1463 TOT 5.8 VEM
1423 TOT 4.9 VEM
1491 TOT 4.9 VEM
1354 TOT 4.6 VEM
1468 TOT 3.9 VEM
1402 Thr1 2.4 VEM
LDF
LDF Res
LDF and Time Residuals
VEM Traces
Dynode (HG)
Anode (LG)
(Example due to Lorenzo Cazon)
Signal [VEM peak]
t [25 ns]
12 stations
X_μ [g cm^-2]
sum
t to X

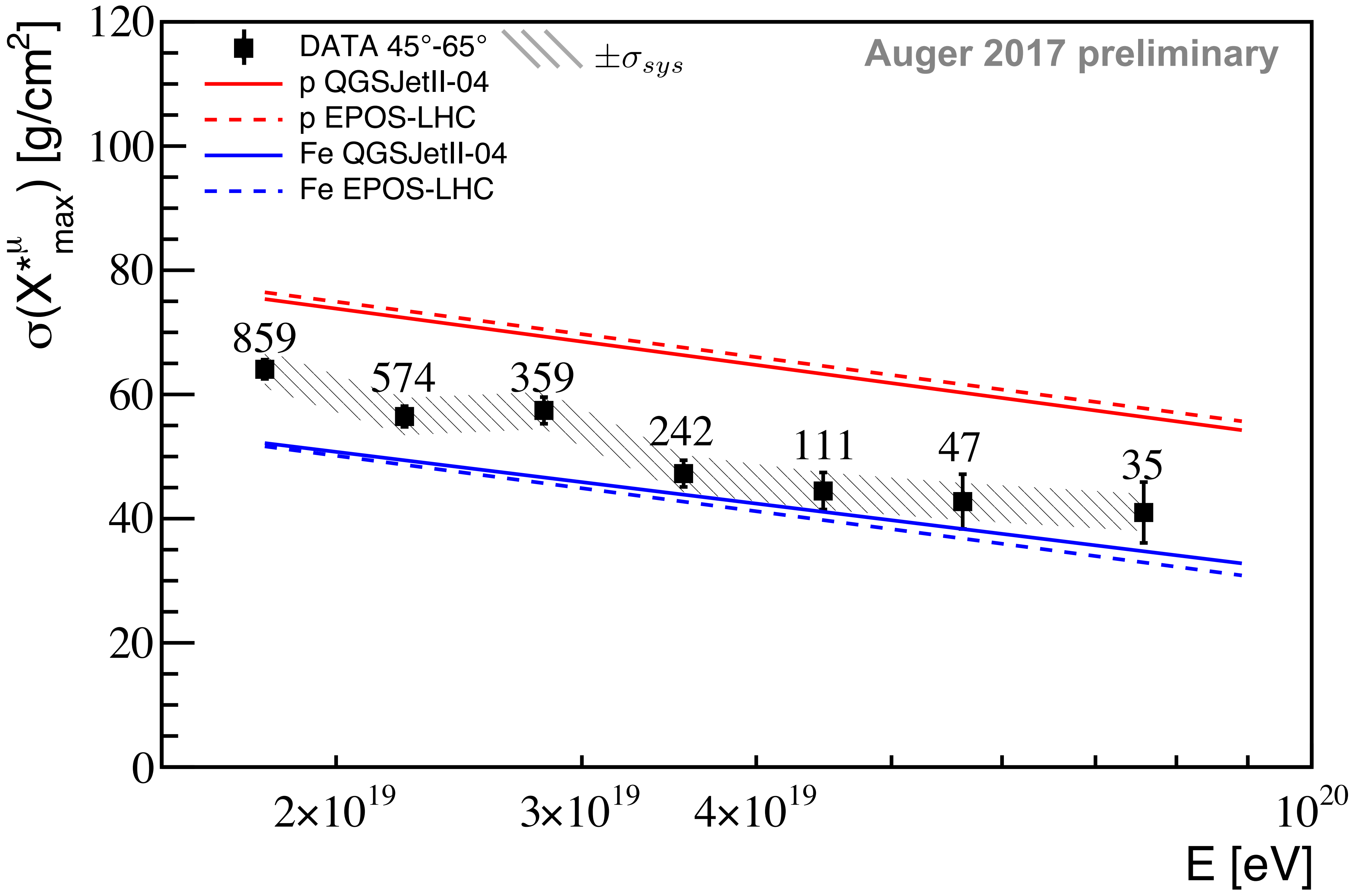

Auger | Los Leones | Los Morados | Loma Amarilla | Coihueco | SD | Selection
Event Info | MC info
Event 8123914 :-)
Time 933708755 s 768757000 ns
3TOT & 4C1; T5
Candidate stations: 24(20 acc)
E = (6.08 ± 0.21) × 10^19 eV
S(1000 m) = 131.7 ± 4.3 (±3.2) VEM
(θ, φ) = (59.99 ± 0.07, 277.85 ± 0.08) deg
(x,y) = (43.31±0.01, 52.80±0.03) km
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
y [km]
1378 TOT 18.0 VEM
1528 TOT 15.4 VEM
1535 TOT 11.4 VEM
1460 TOT 8.9 VEM
1519 TOT 8.7 VEM
1406 TOT 6.0 VEM
1463 TOT 5.8 VEM
1423 TOT 4.9 VEM
1491 TOT 4.9 VEM
1354 TOT 4.6 VEM
1468 TOT 3.9 VEM
1402 Thr1 2.4 VEM
LDF LDF Res
LDF and Time Residuals | VEM Traces | Dynode (HG) | Anode (LG)
(Example due to Lorenzo Cazon)
Signal [VEM peak]
t [25 ns]
$X_{\mu\max}$
#
X_μ[g cm^{-2}]

Depth of maximum for muon production

Mean values



Shower-by-shower fluctuations



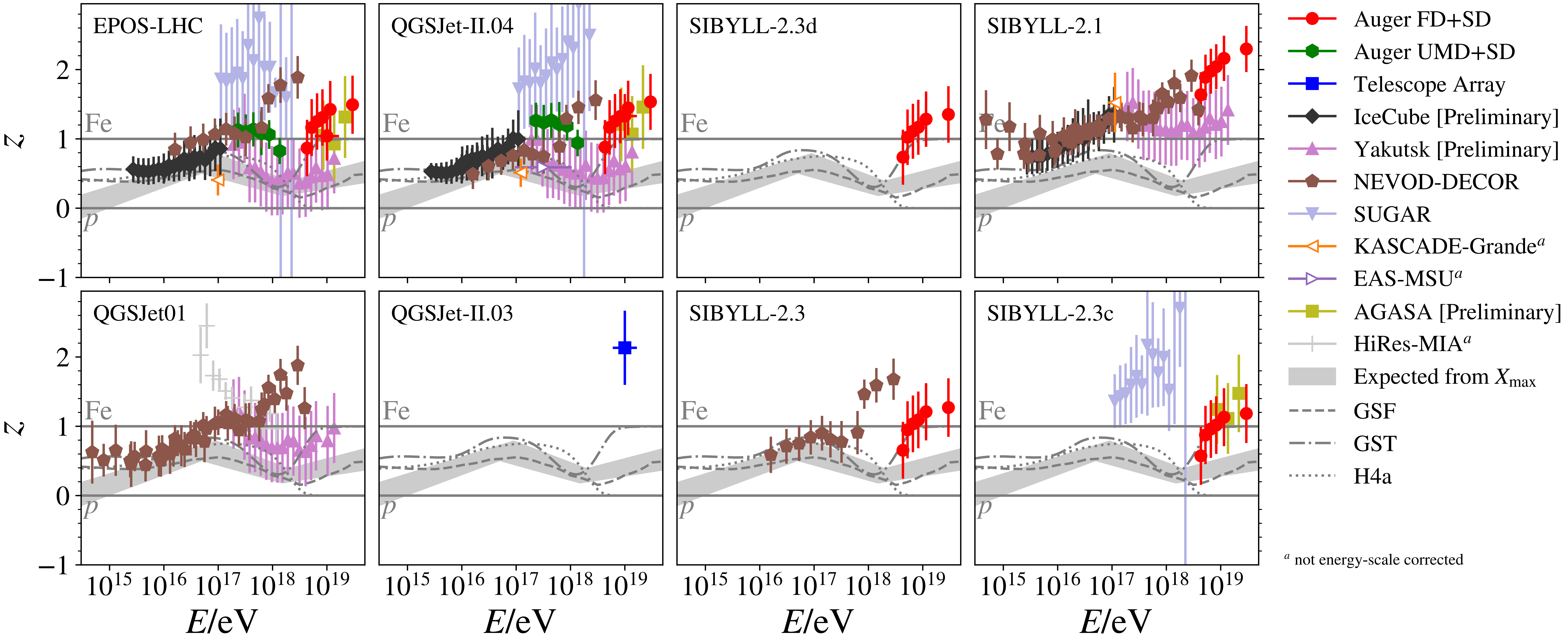
Similar situation for muon production depth

E>15 EeV
θ=45°-65
r>1200 m

(Auger, PRD 90, 2014) *(Mallamaci, Auger, ICRC 2017)*

WHISP: Compilation of muon-sensitive measurments

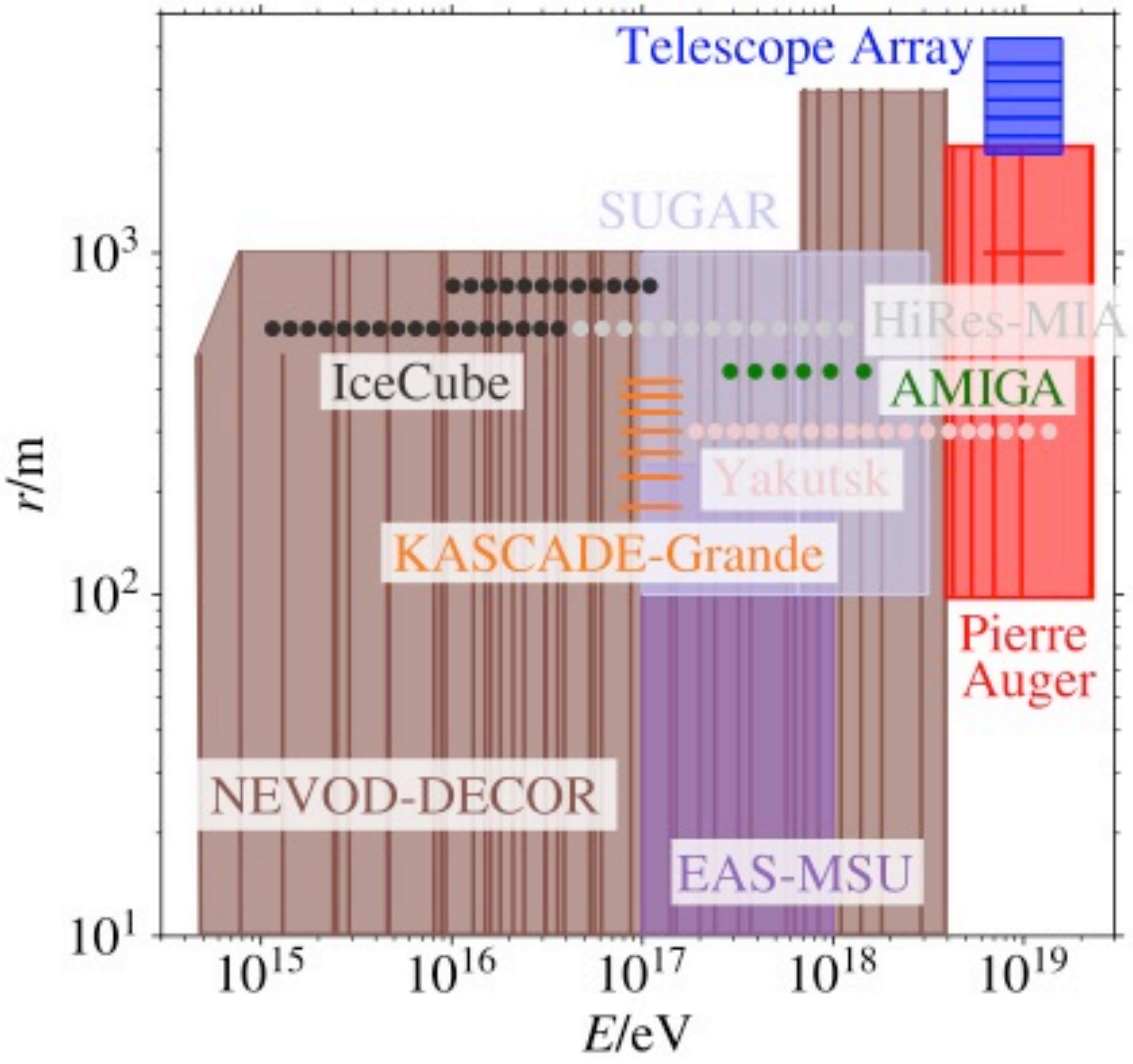
Scaling variable z: relative number of muons with proton predictions as reference



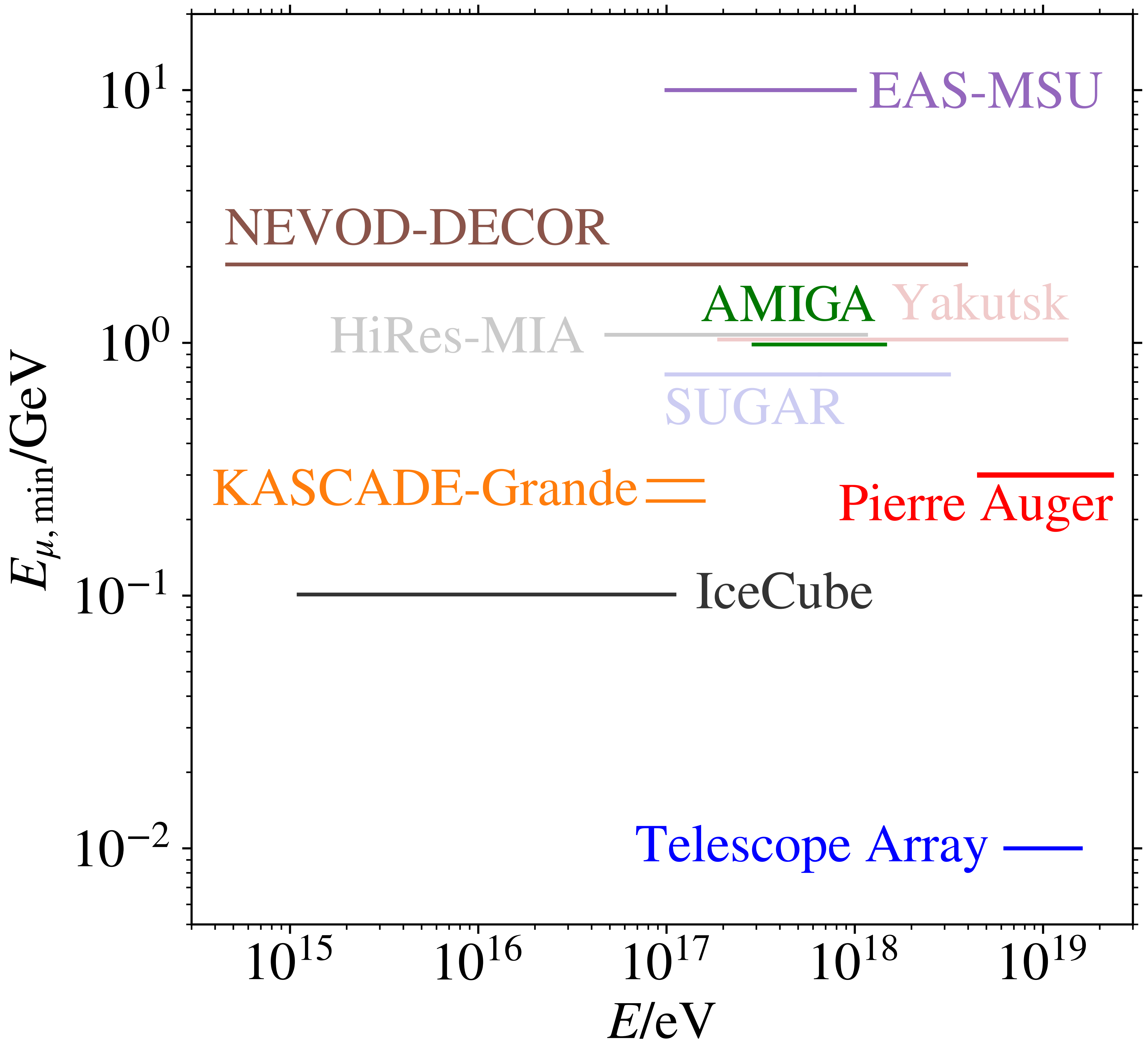
(WHISP working group, ICRC 2021, and review in Astrophysics and Space Science (2022) 367:27)

Analysis of world data set on muons (i)

Muon lateral distance



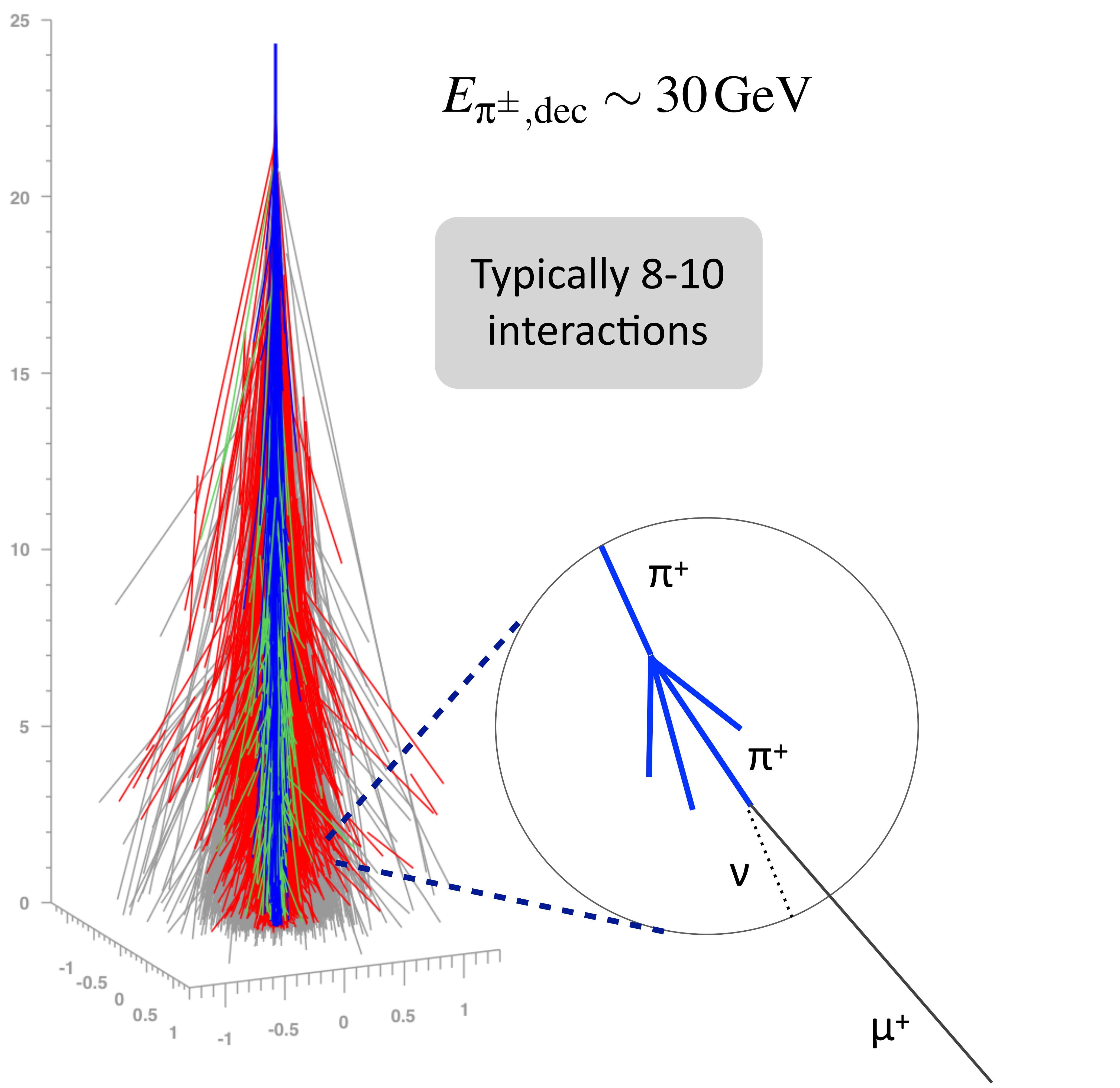
Muon energy thresholds



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

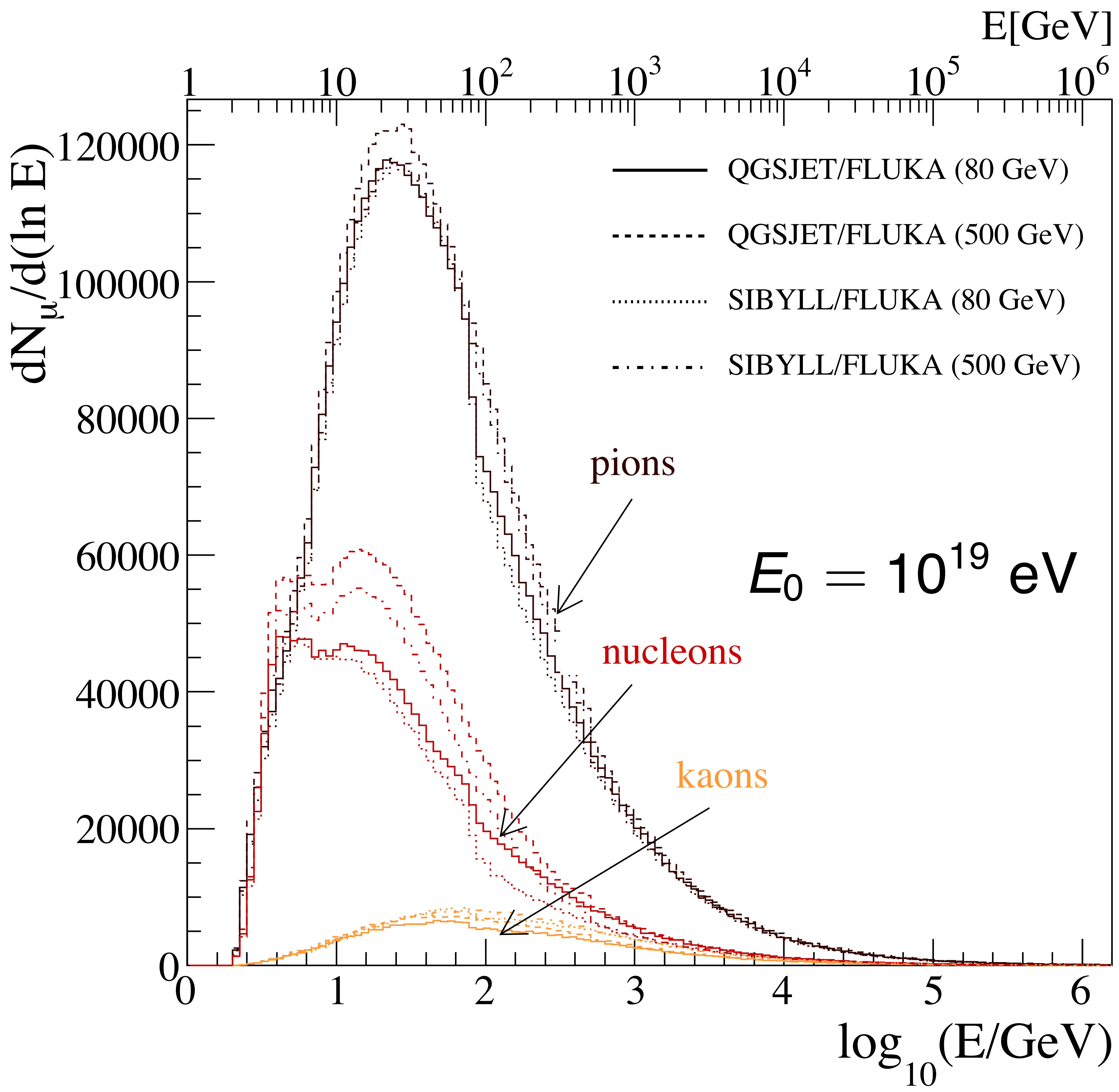
4. Closer look at muon production in showers

Muon production at large lateral distance



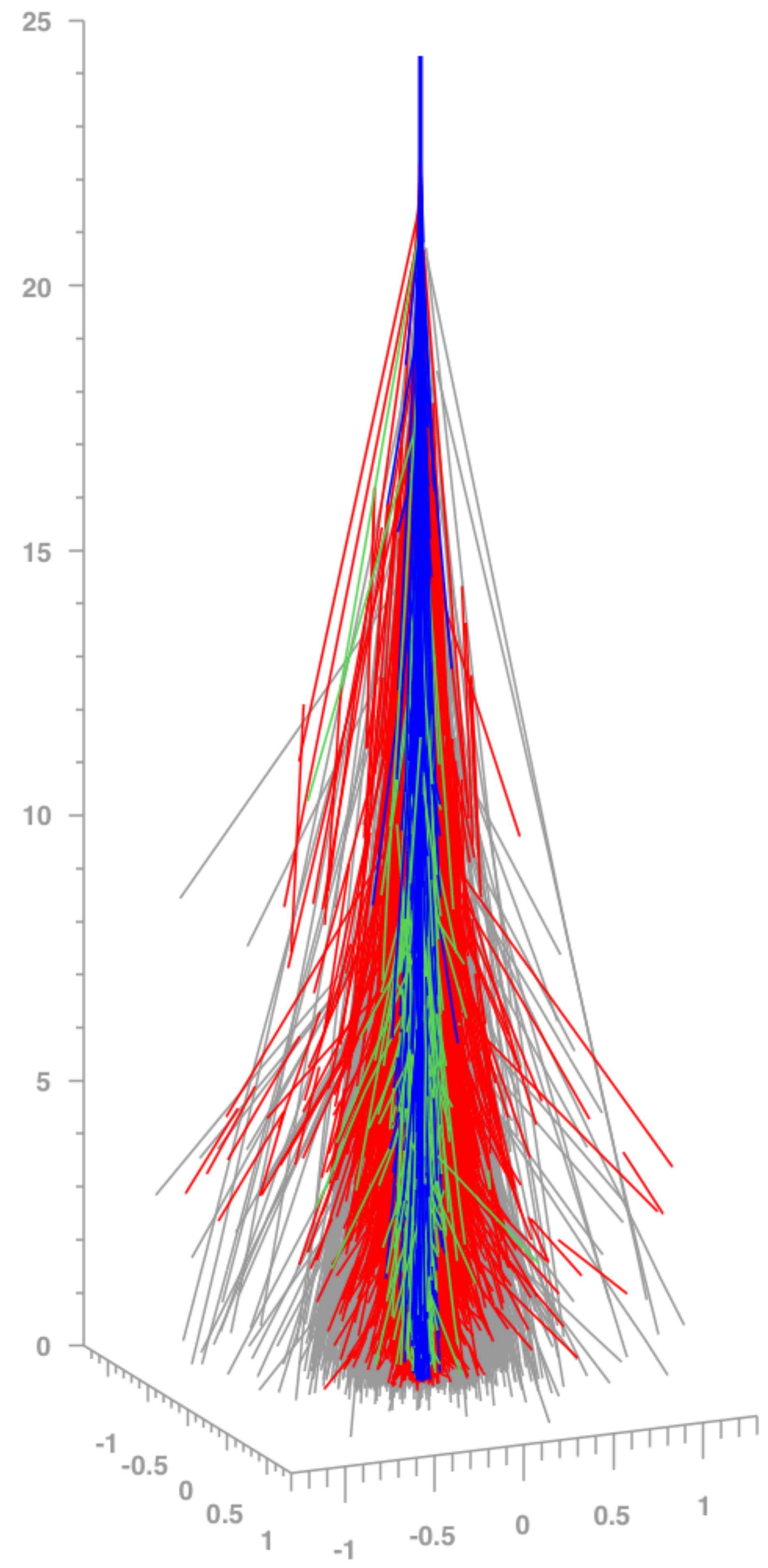
Muon observed at 1000 m from core

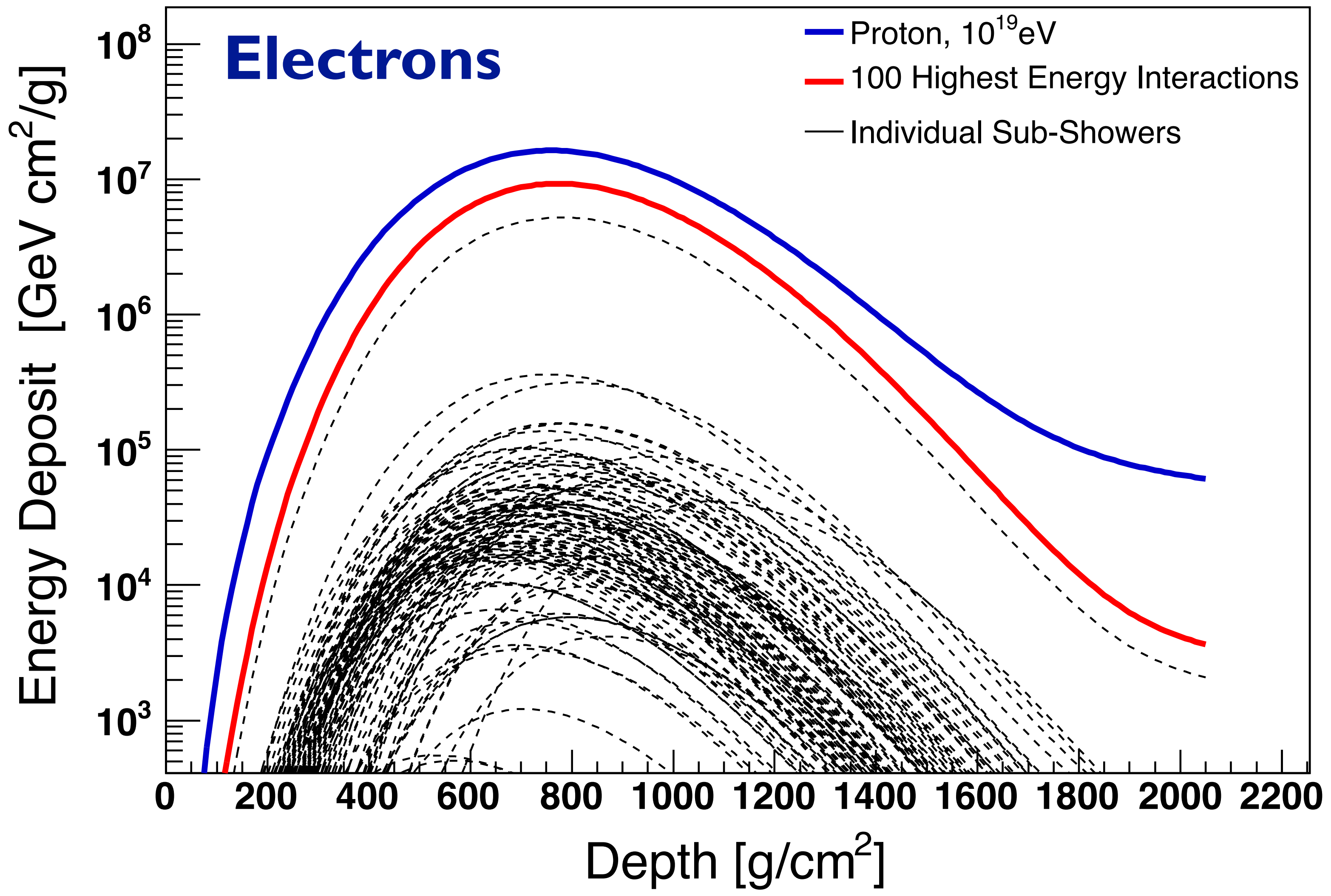
Energy distribution of **last interaction** that produced a detected muon

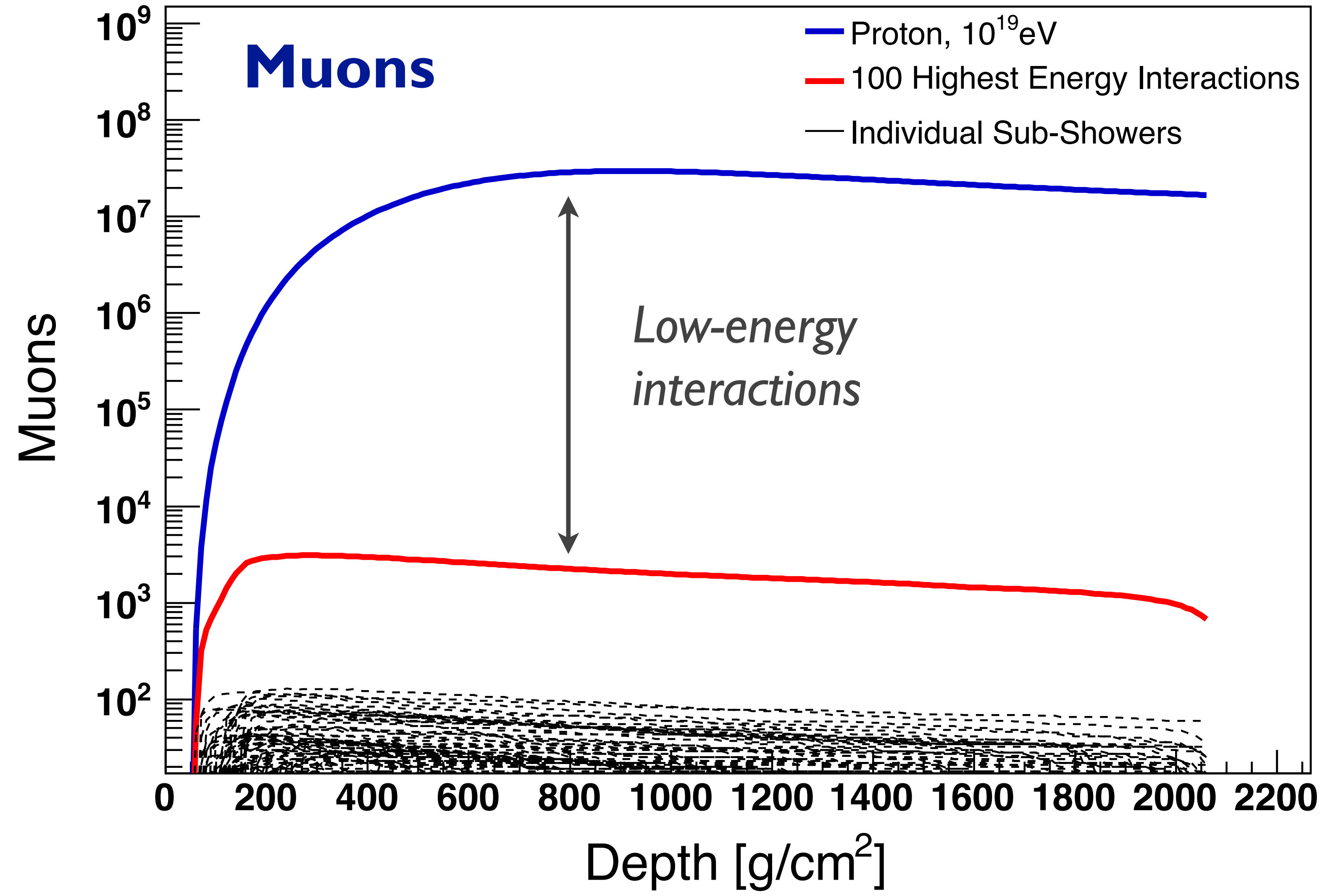


(Maris et al. ICRC 2009)

Importance of hadronic interactions at different energies







Shower particles produced in 100 interactions of highest energy

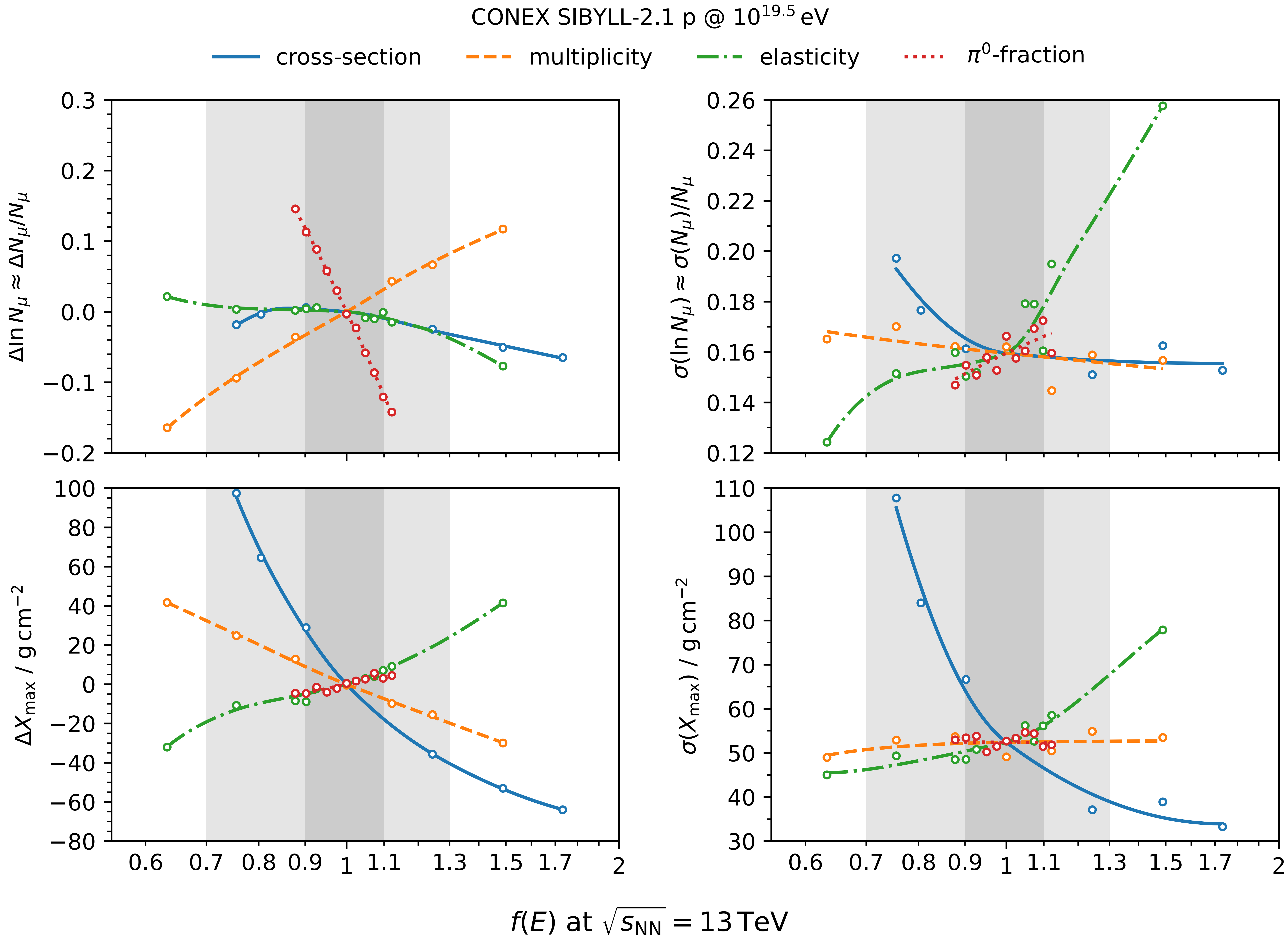
Electrons/photons:
high-energy interactions

Muons/hadrons:
low-energy interactions

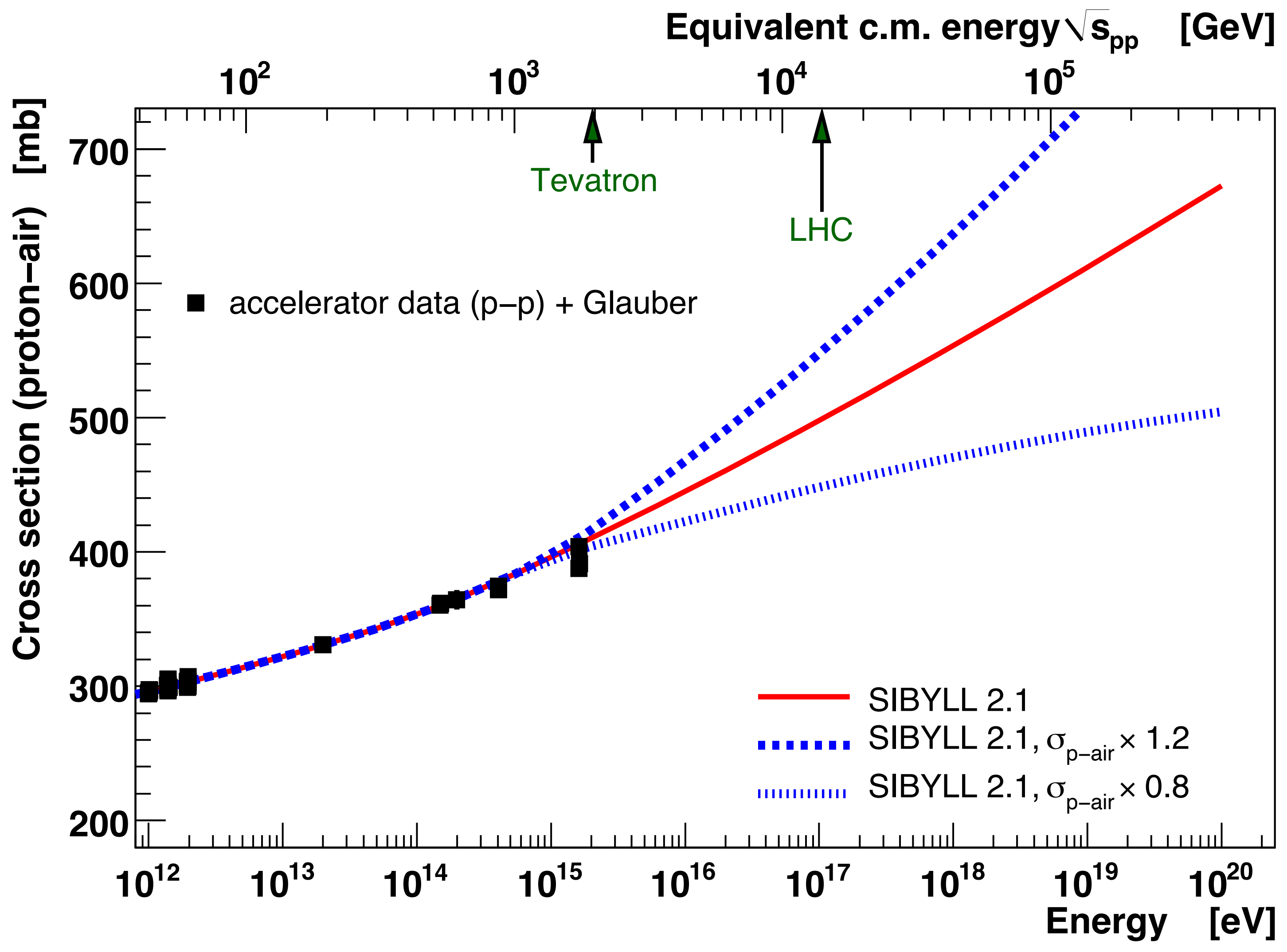
Muons: 8 – 12 generations, majority of muons produced in ~30 GeV interactions

(Ulrich APS 2010)

Systematic study of relation to interaction properties

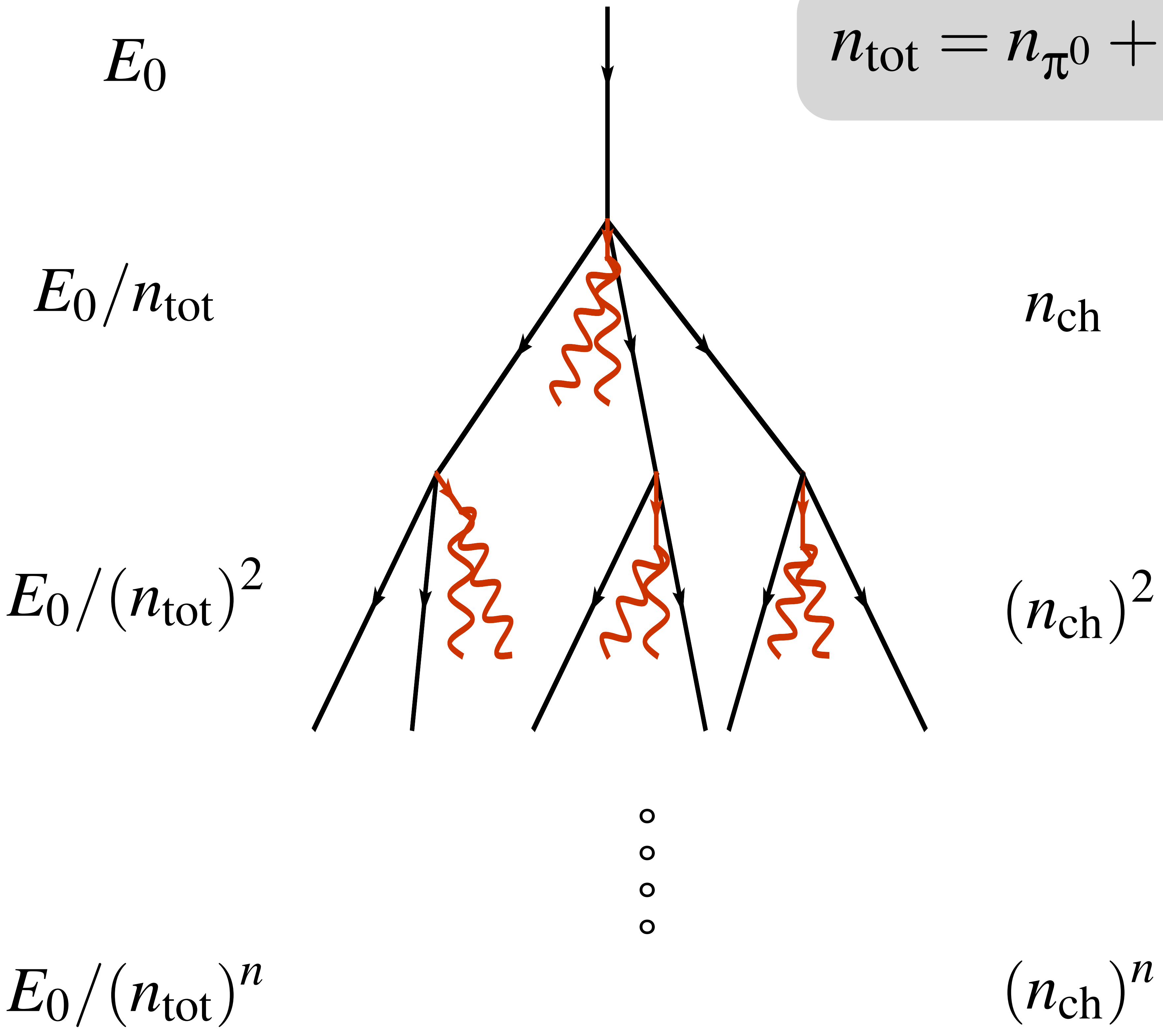


(Dembinski, ICRC 2021)



(Ulrich et al. Phys. Rev. D 83 (2011) 054026)

Muon production in hadronic showers



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

Primary particle proton

π^0 decay immediately

$\pi^{\pm}$ initiate new cascades

Pion decay energy ~30 GeV, Typically 8-12 generations

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

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

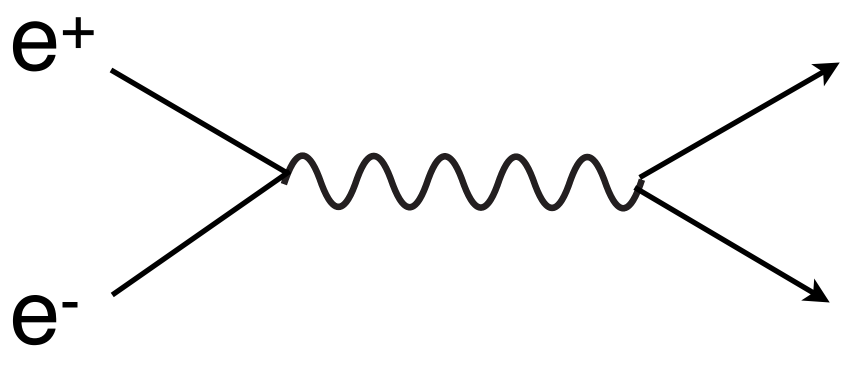
Assumptions:

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

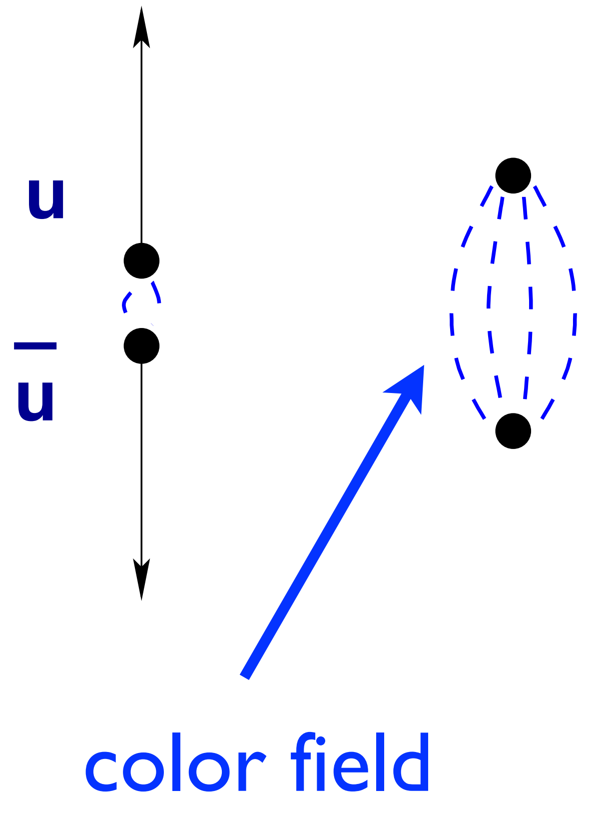
(Matthews, Astropart.Phys. 22, 2005)

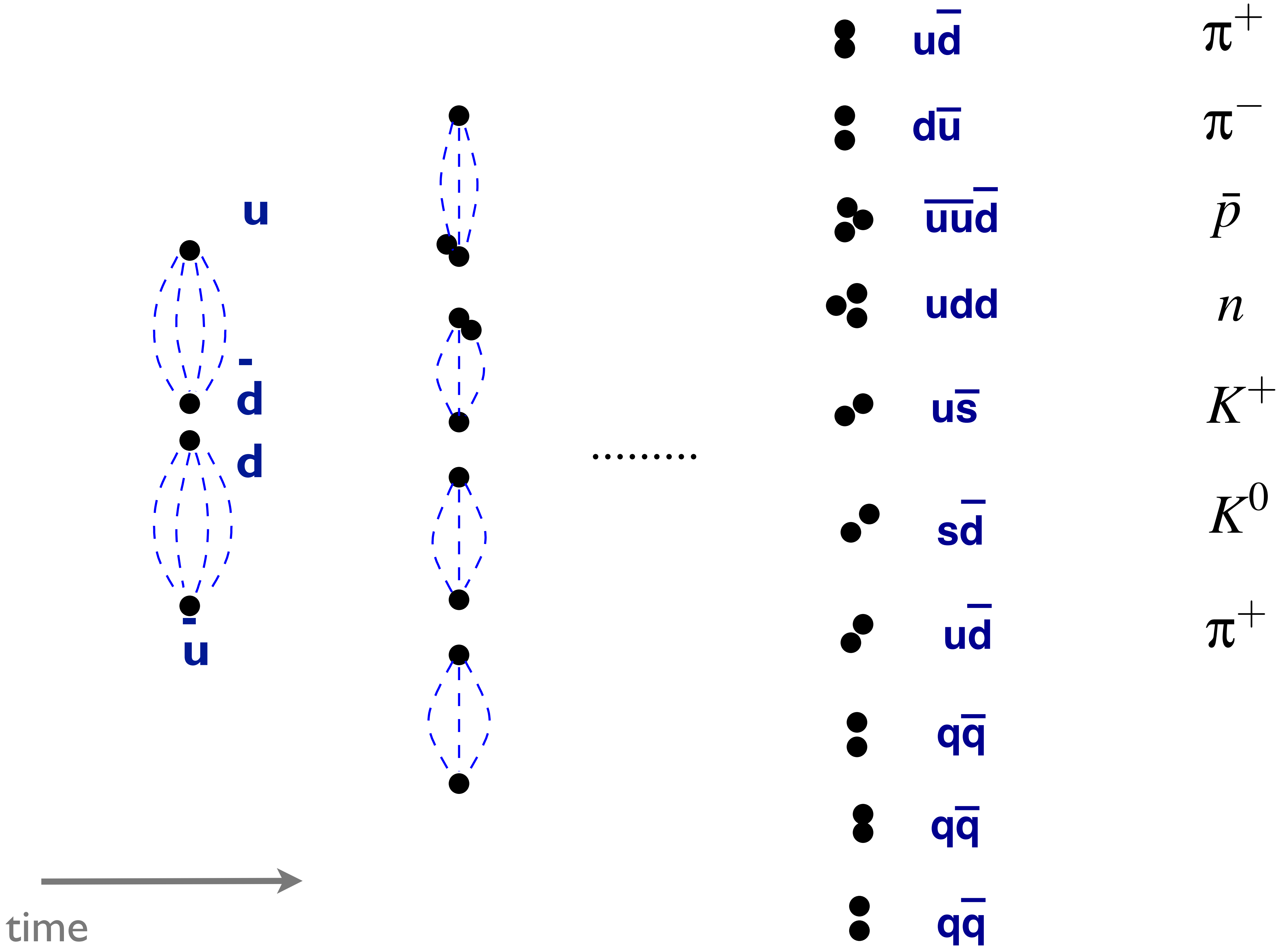
Comparison to e^+e^- annihilation into quarks

e+e- annihilation at high energy



Quarks together are
color-neutral system





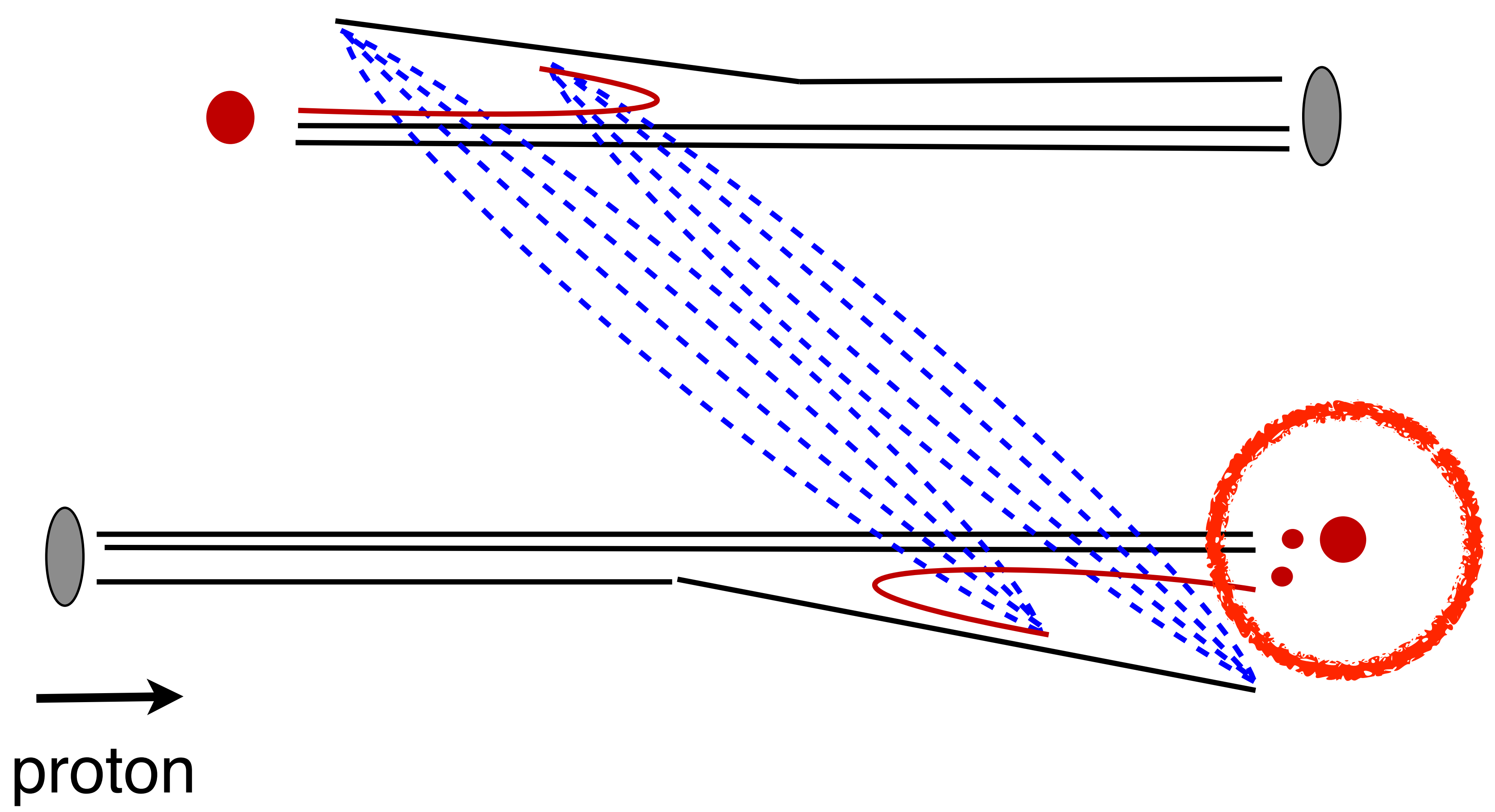
String fragmentation

Composition
u:d:s ~ 1:1:0.3

Confinement in QCD

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \lambda\, r$$

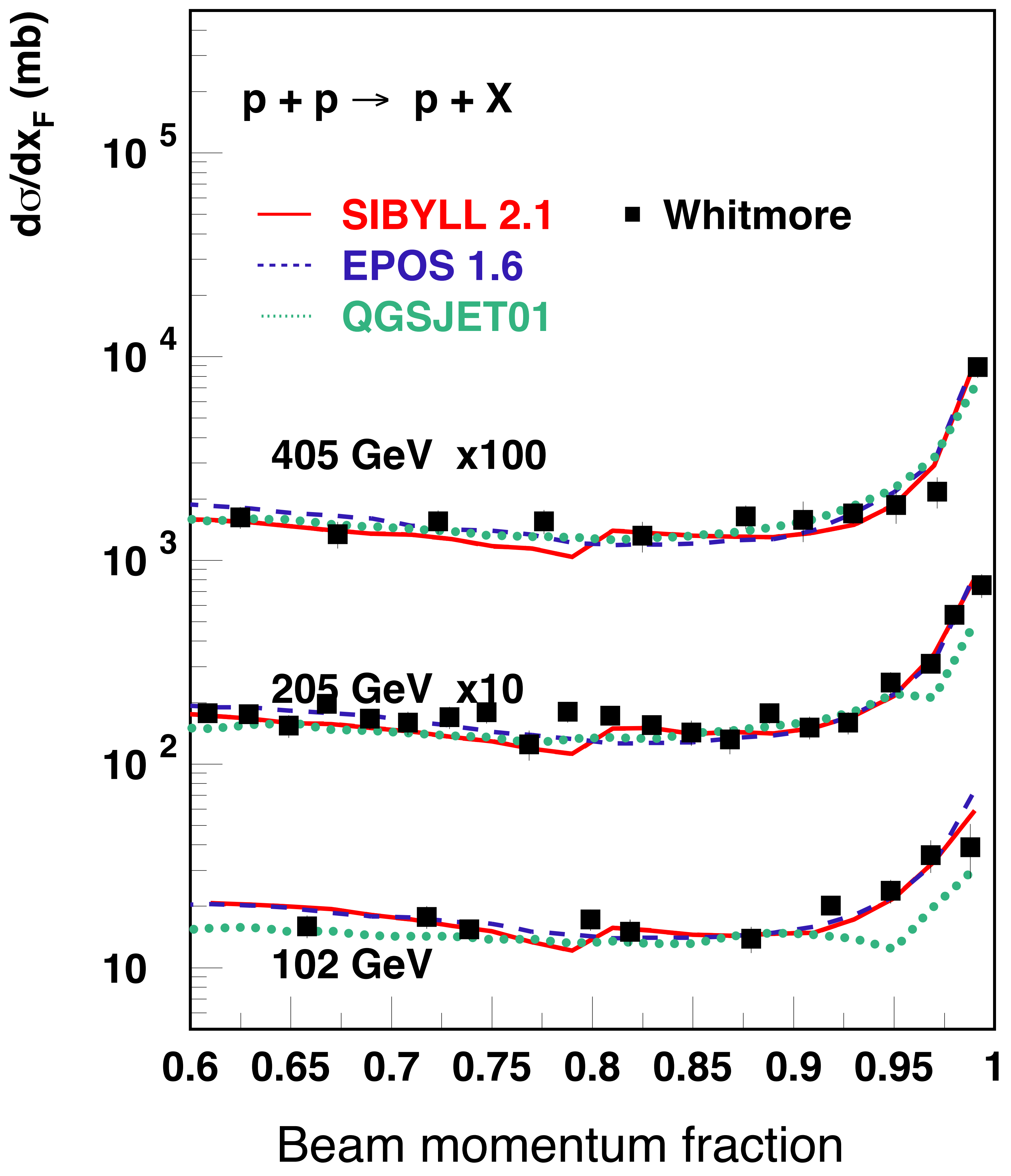
Particle production in hadronic interactions (i)



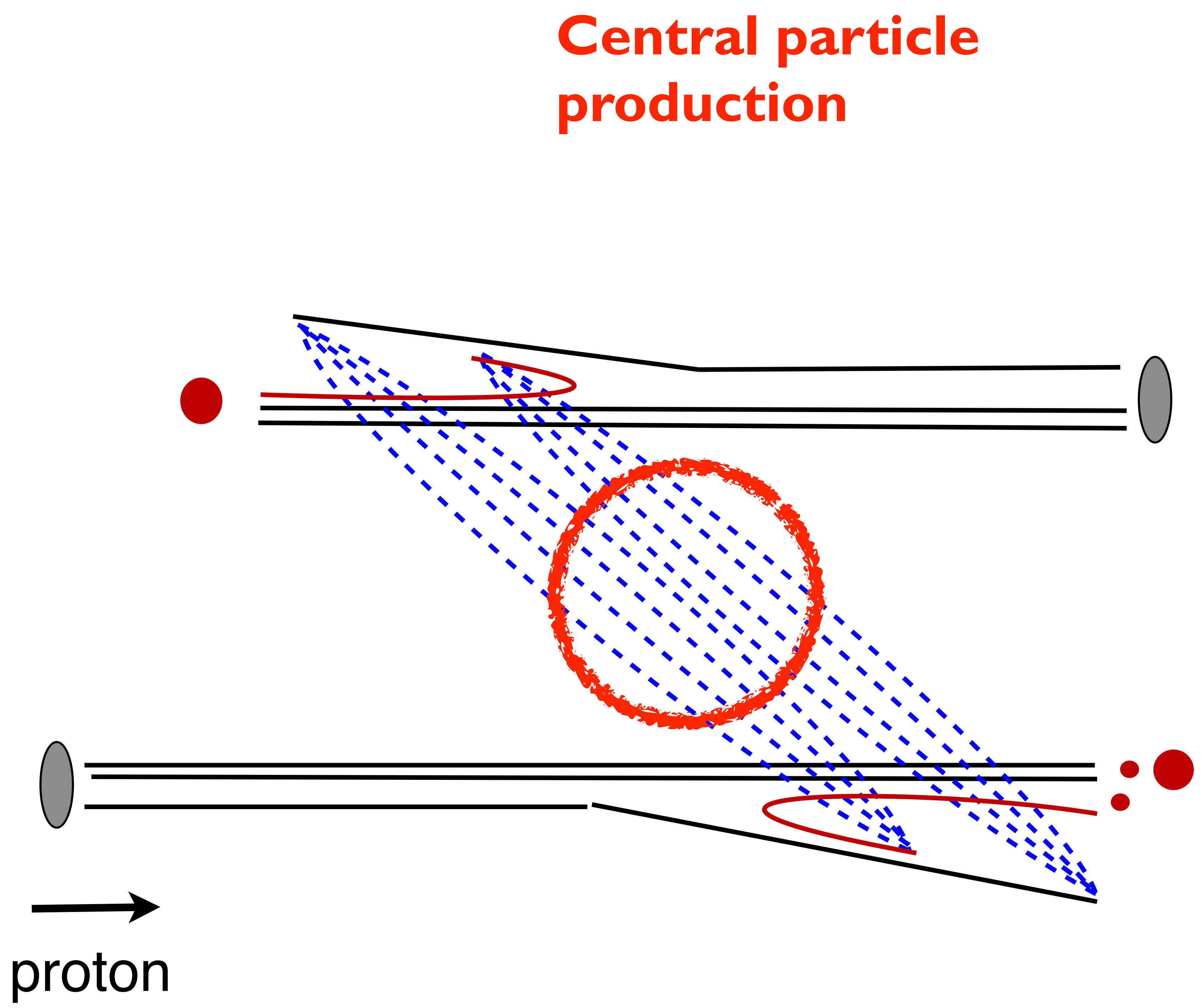
Fluctuations: generation of sea quark anti-quark pair and leading/excited hadron

Leading particle effect:

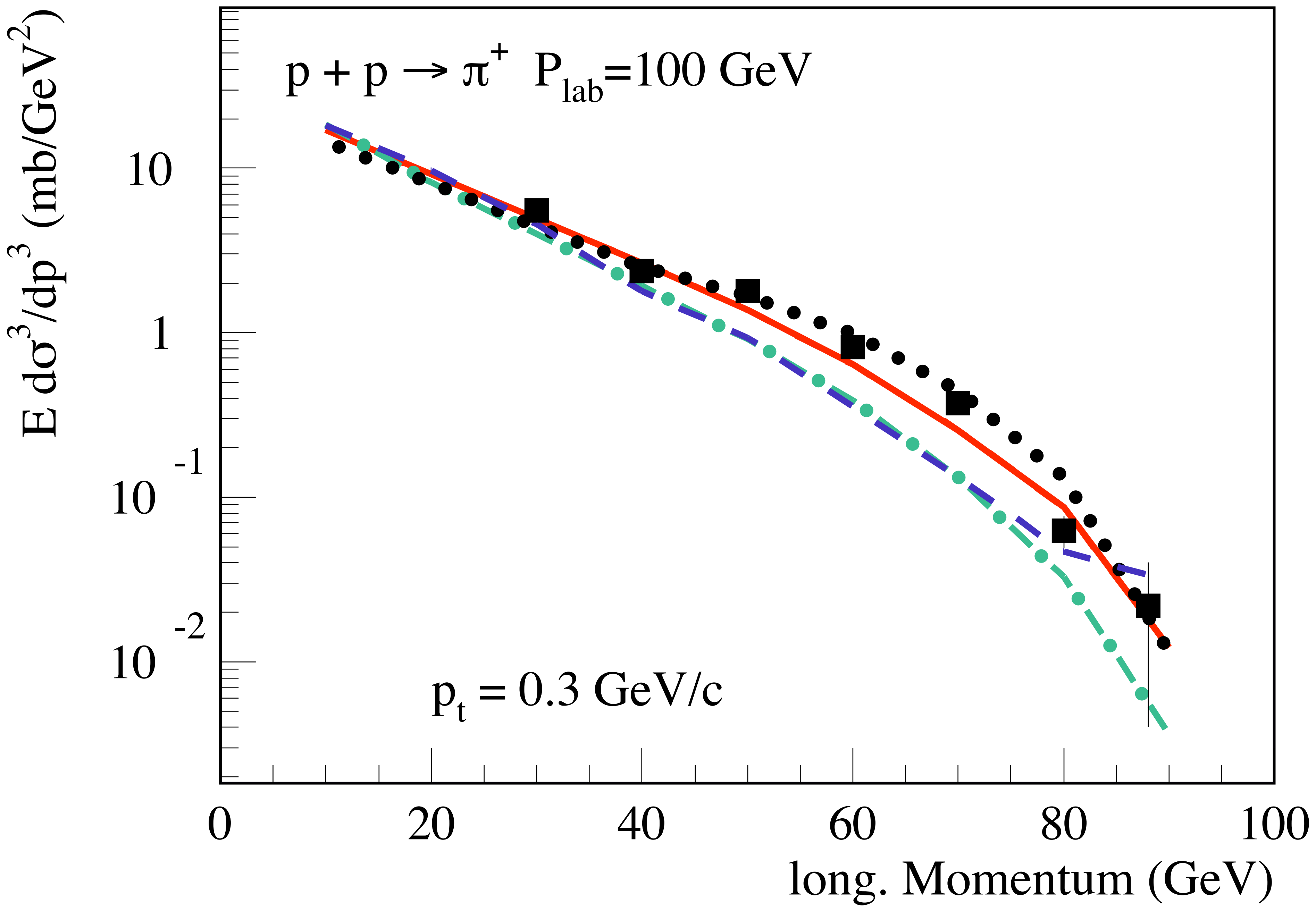
approx. 40–50% of energy of primary particle given to leading particle

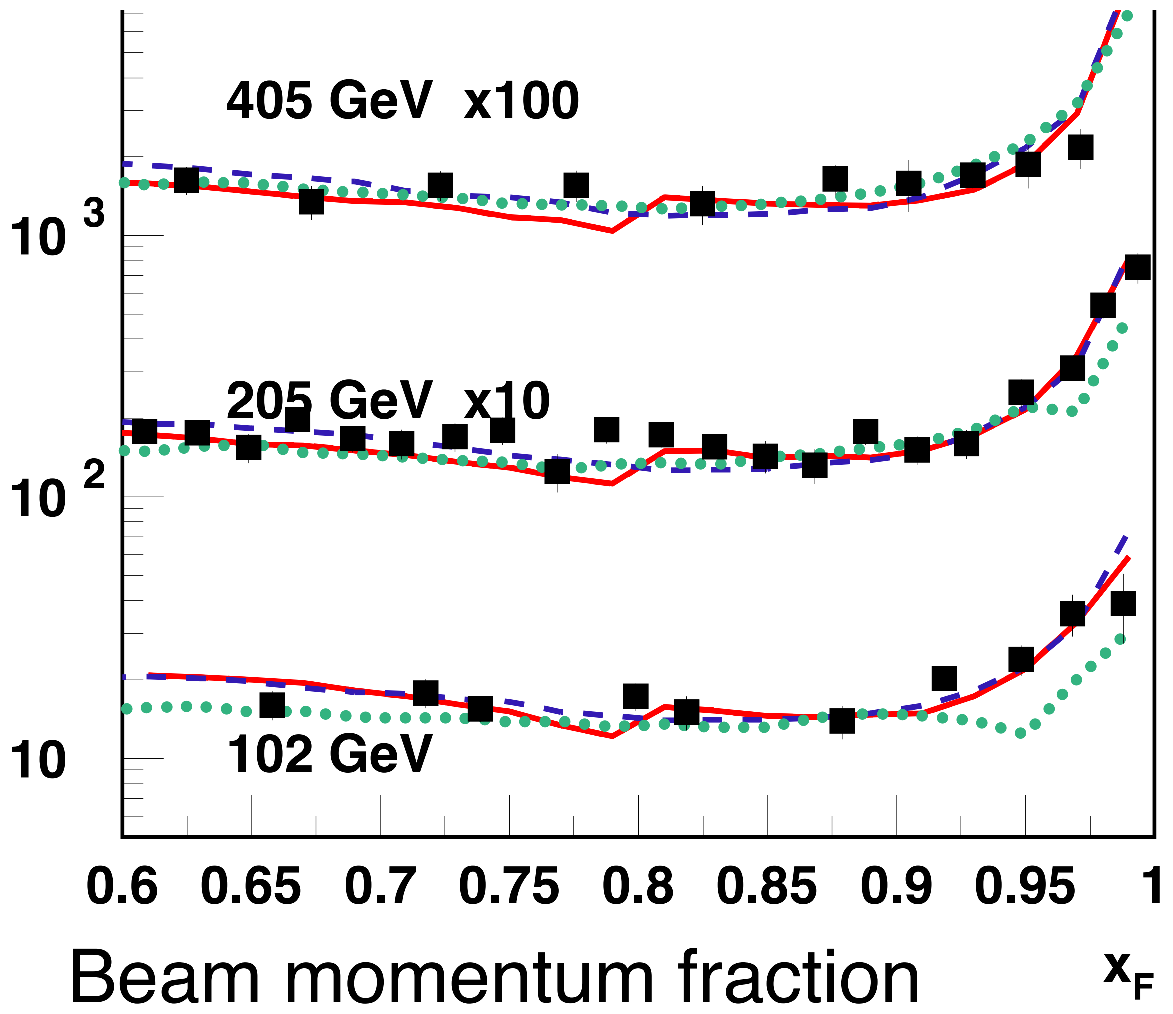


Particle production in hadronic interactions (ii)

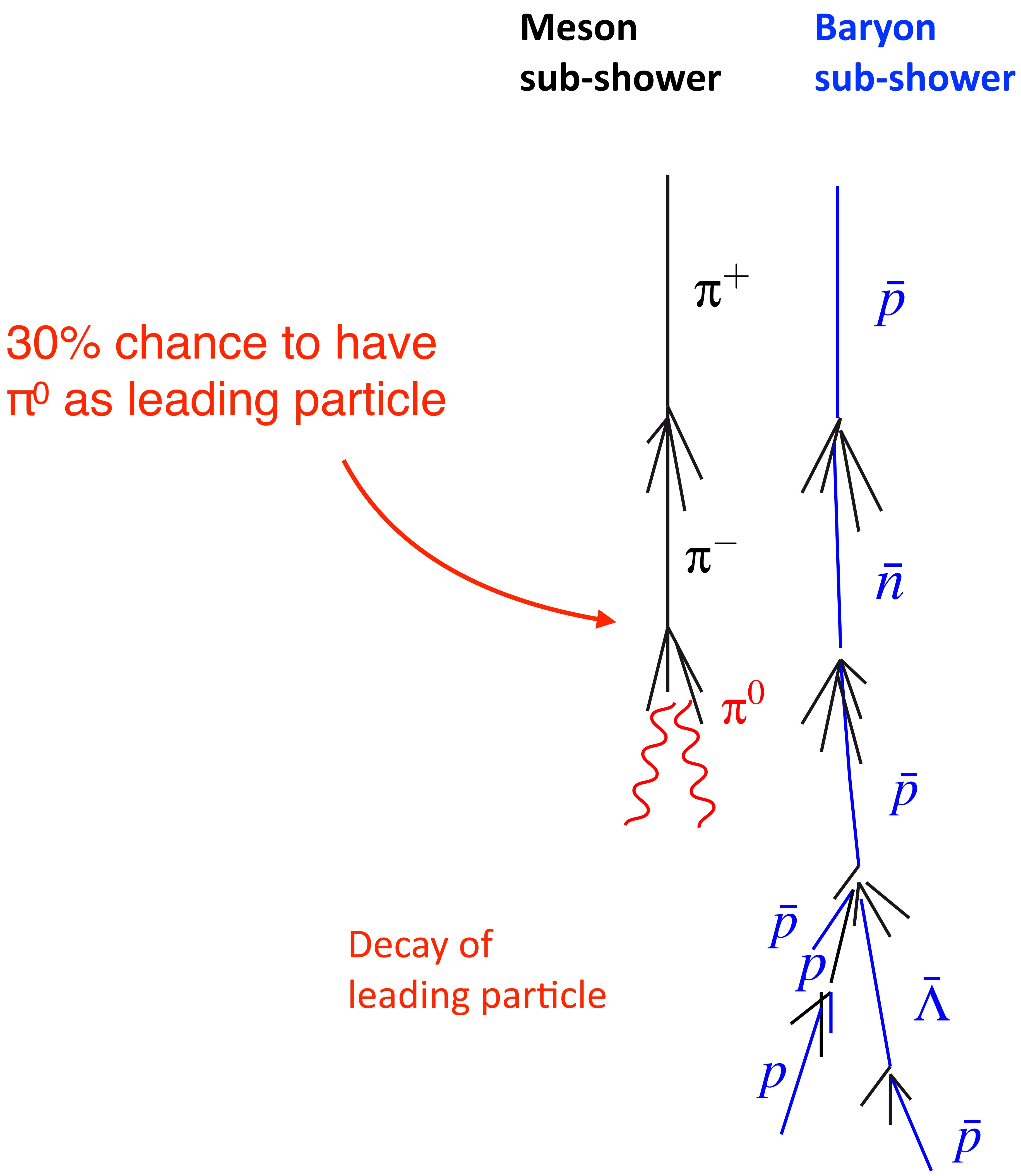


Fluctuations: generation of sea quark anti-quark pair and leading/excited hadron





Muon production depends on hadronic energy fraction



1 Baryon-Antibaryon pair production *(Pierog, Werner 2008)*

- 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 2016)*

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

Core-Corona model (Pierog et al.)

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

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

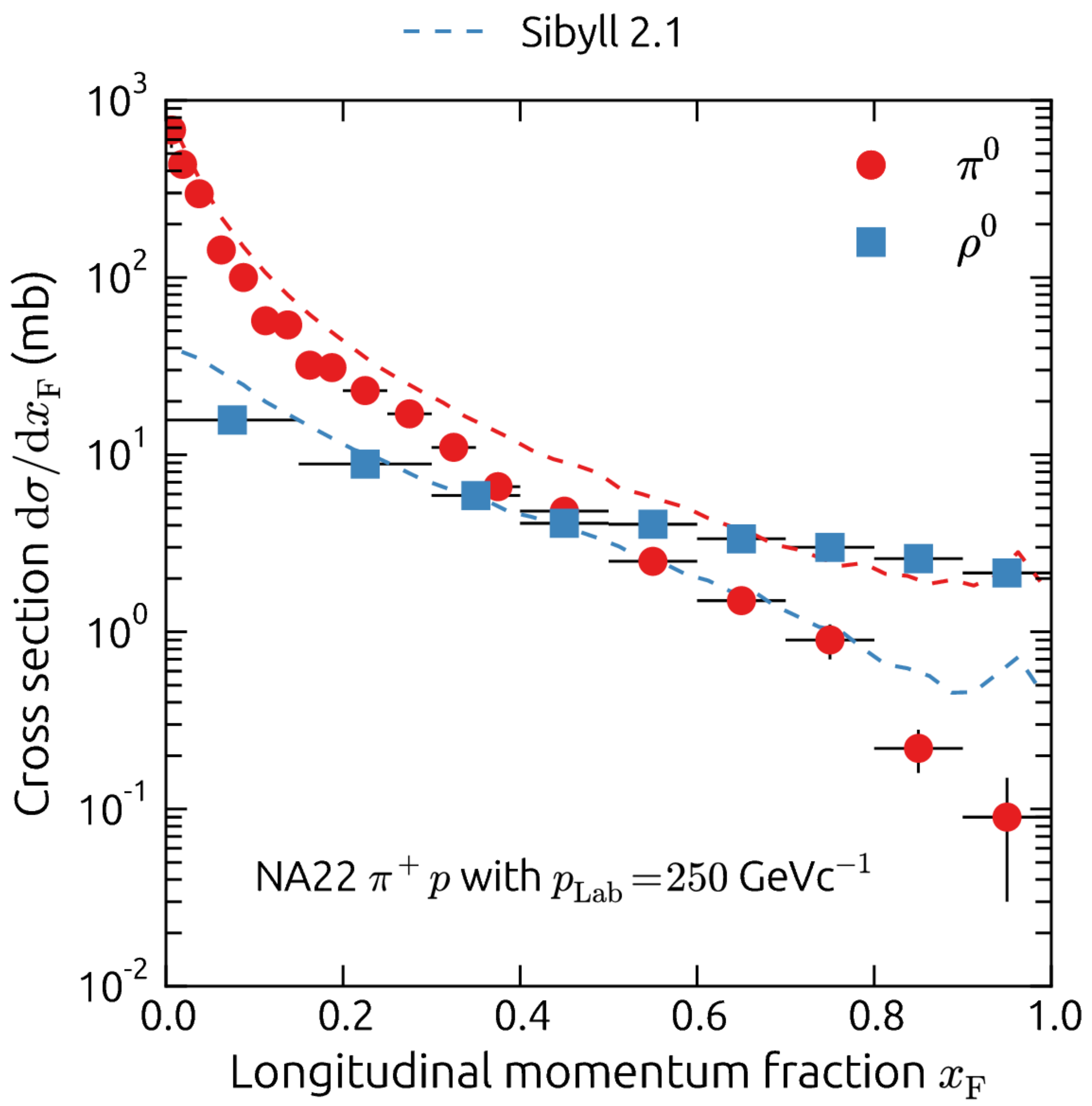
Rho production in π-p interactions (Sibyll 2.1 → Sibyll 2.3)

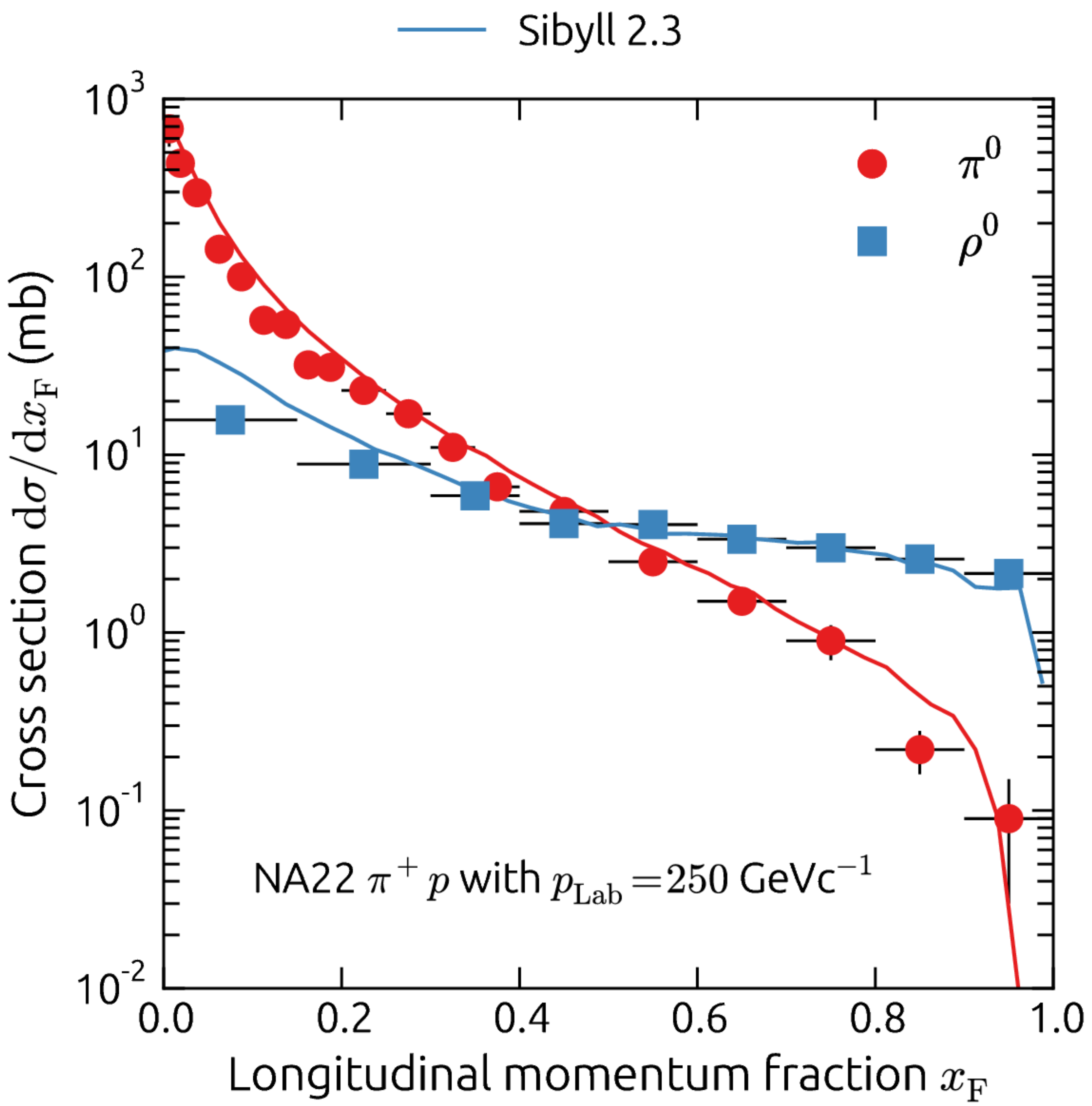
Leading particle production

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

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

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



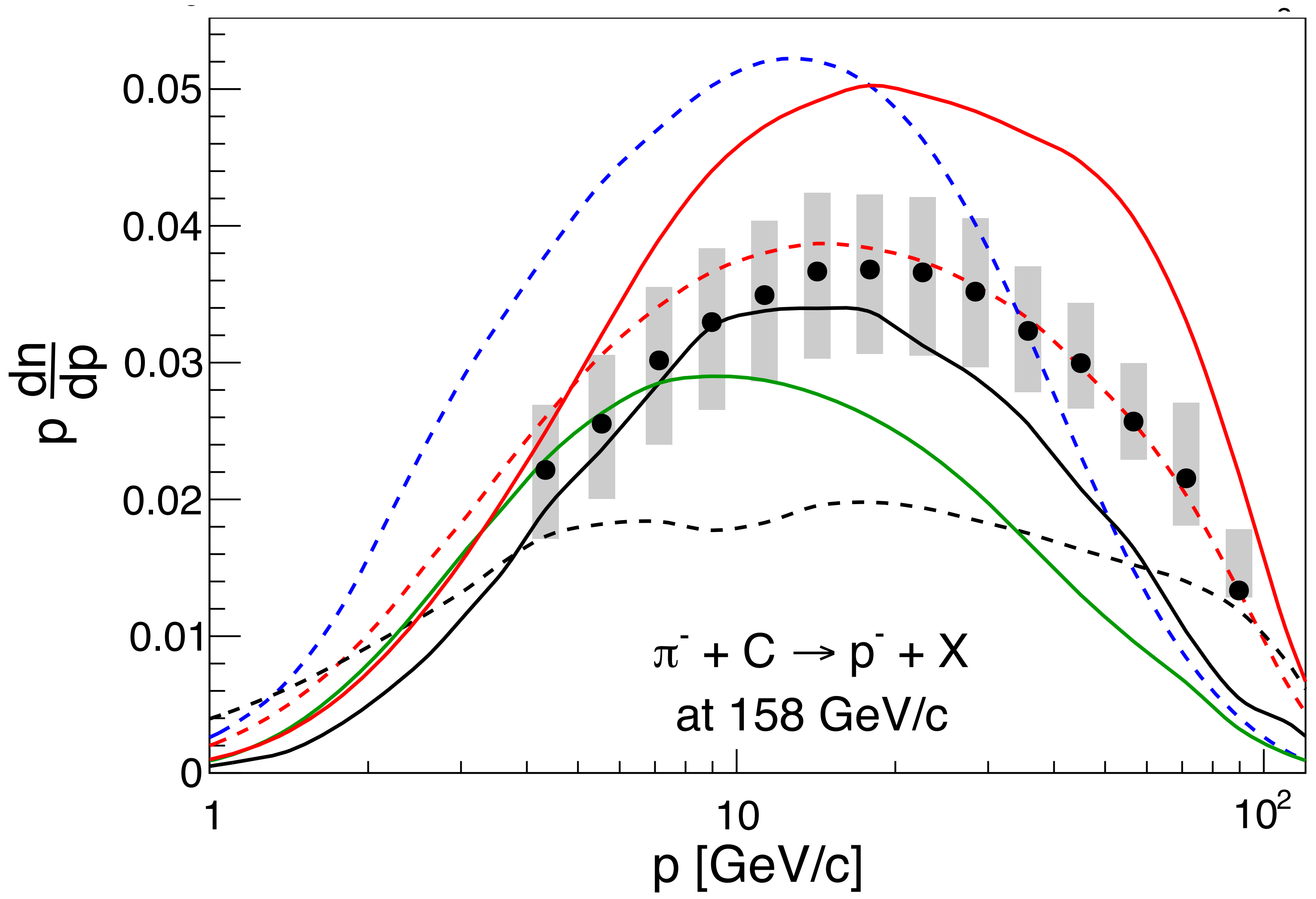


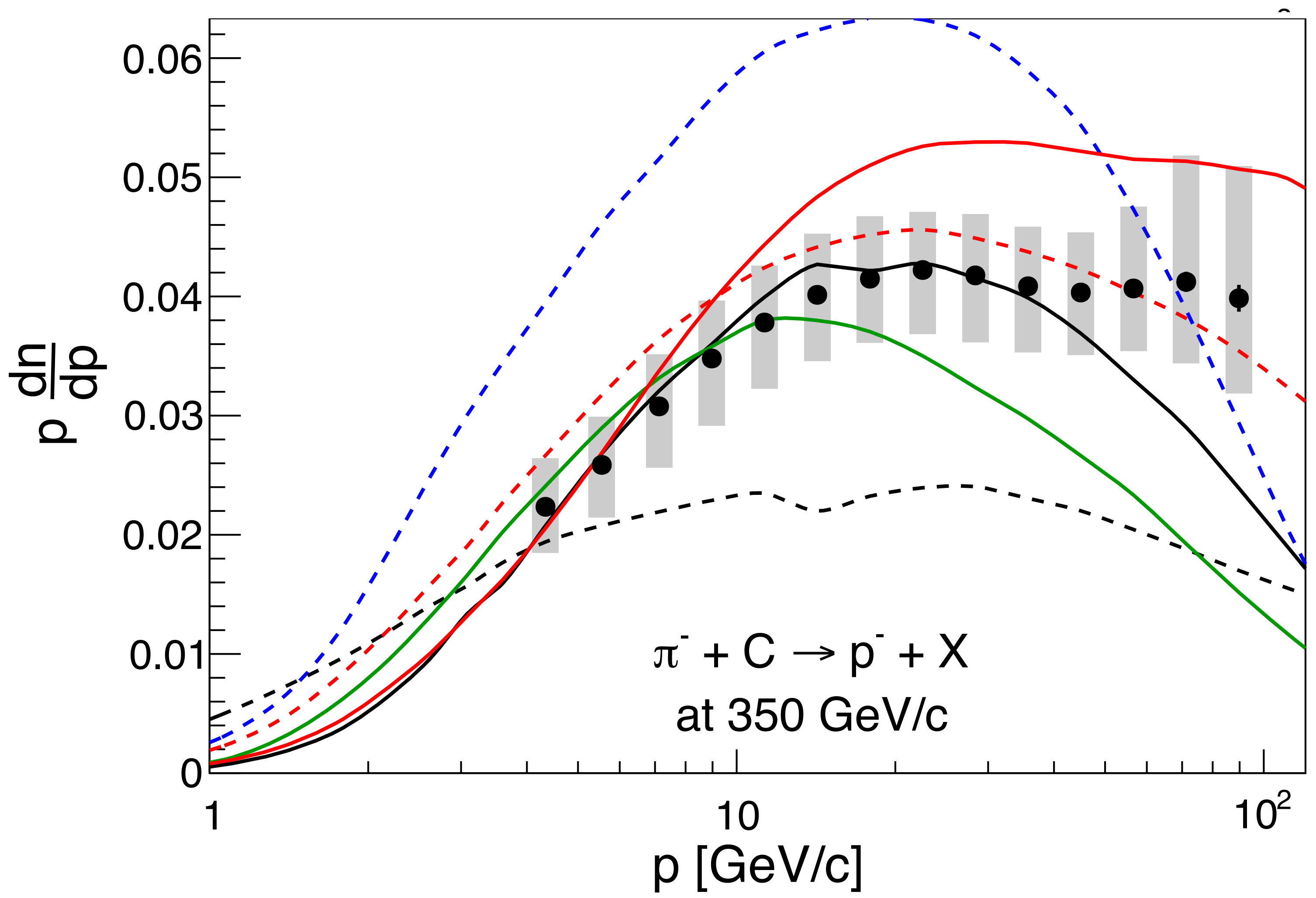
$$x_F = p_{\parallel} / p_{\max}$$

(Riehn et al., ICRC 2015)

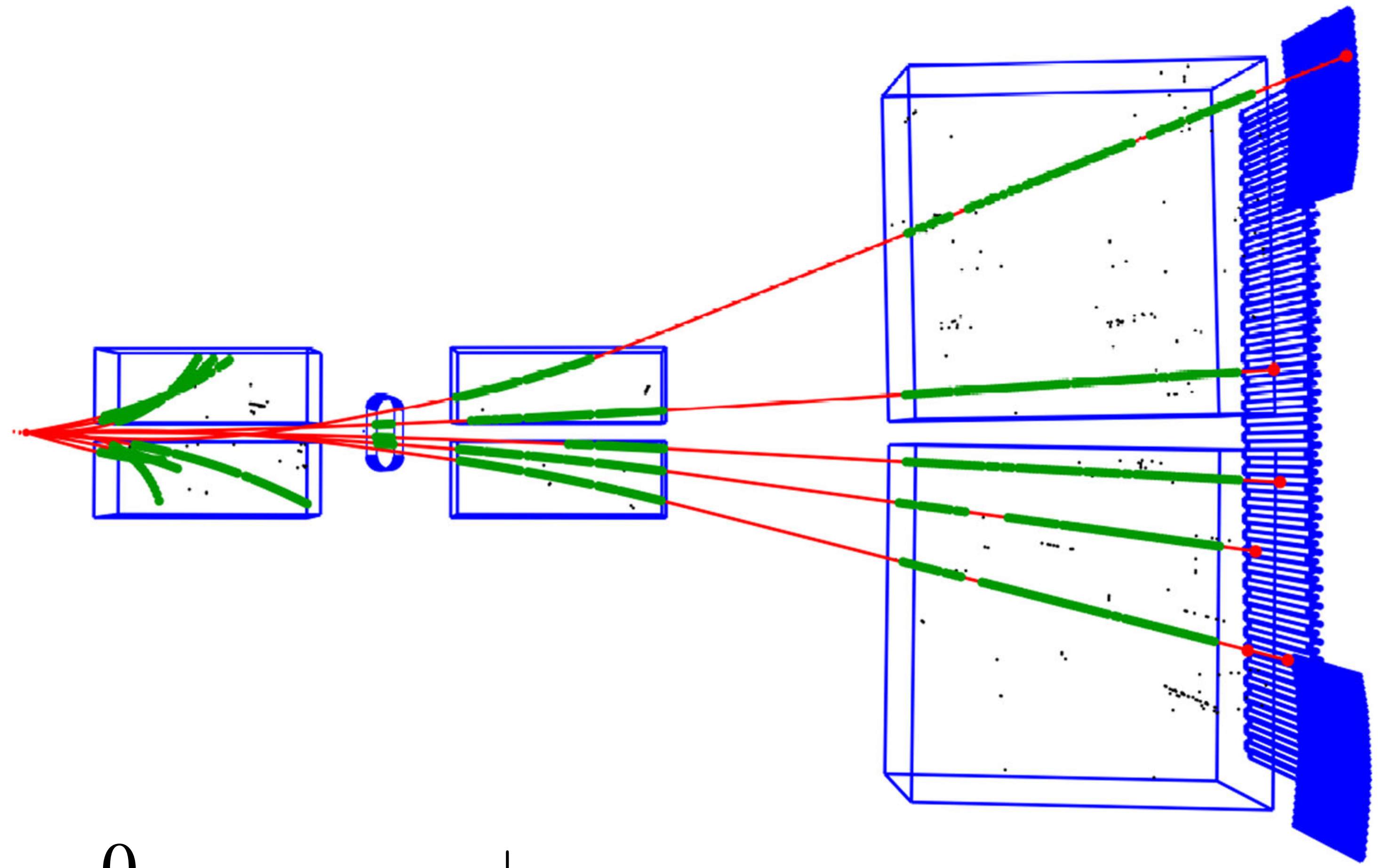
NA61 experiment at CERN SPS

$\pi^- C \to \bar{p}\, X$

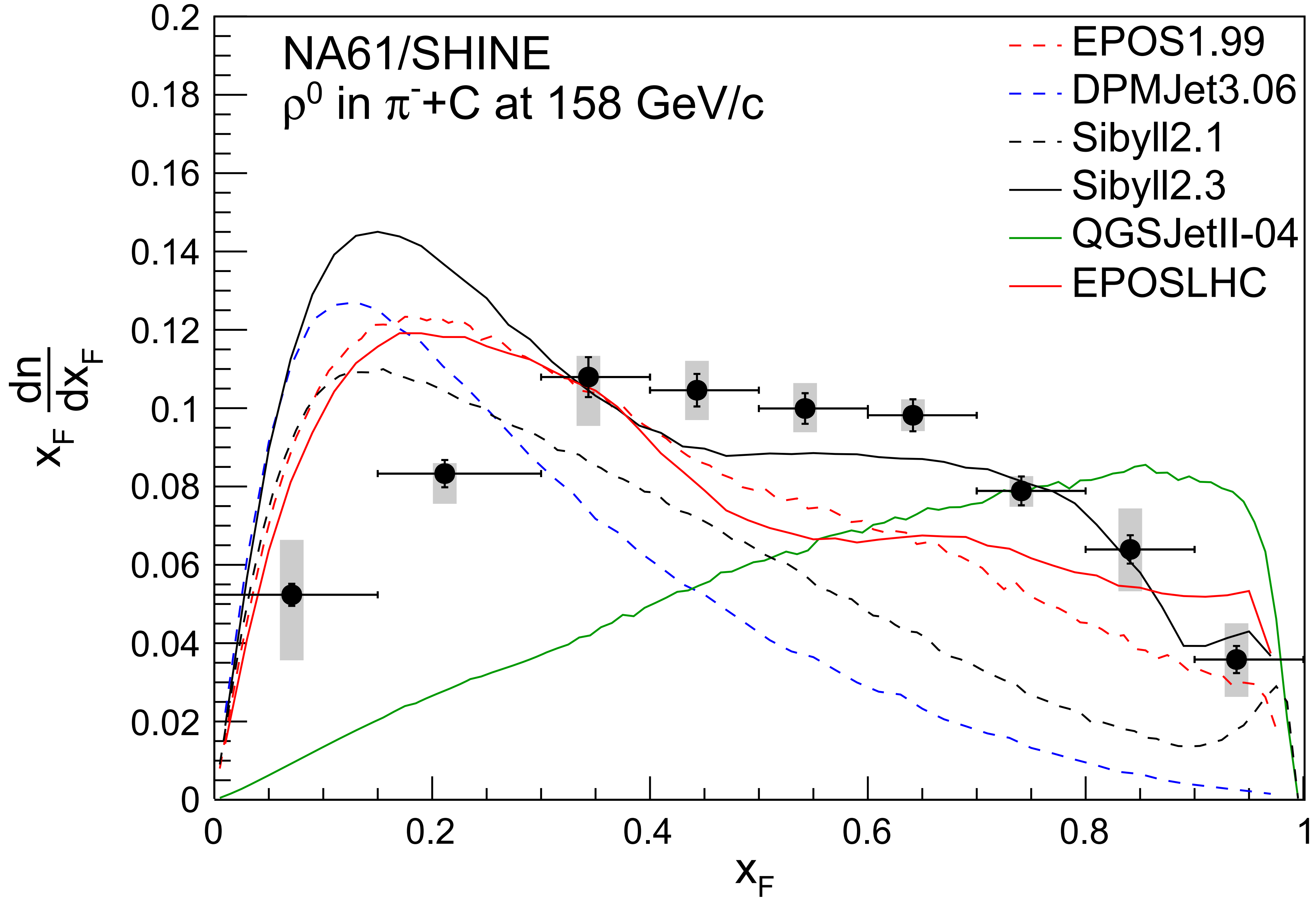




Dedicated cosmic ray runs
(π-C at 158 and 350 GeV)

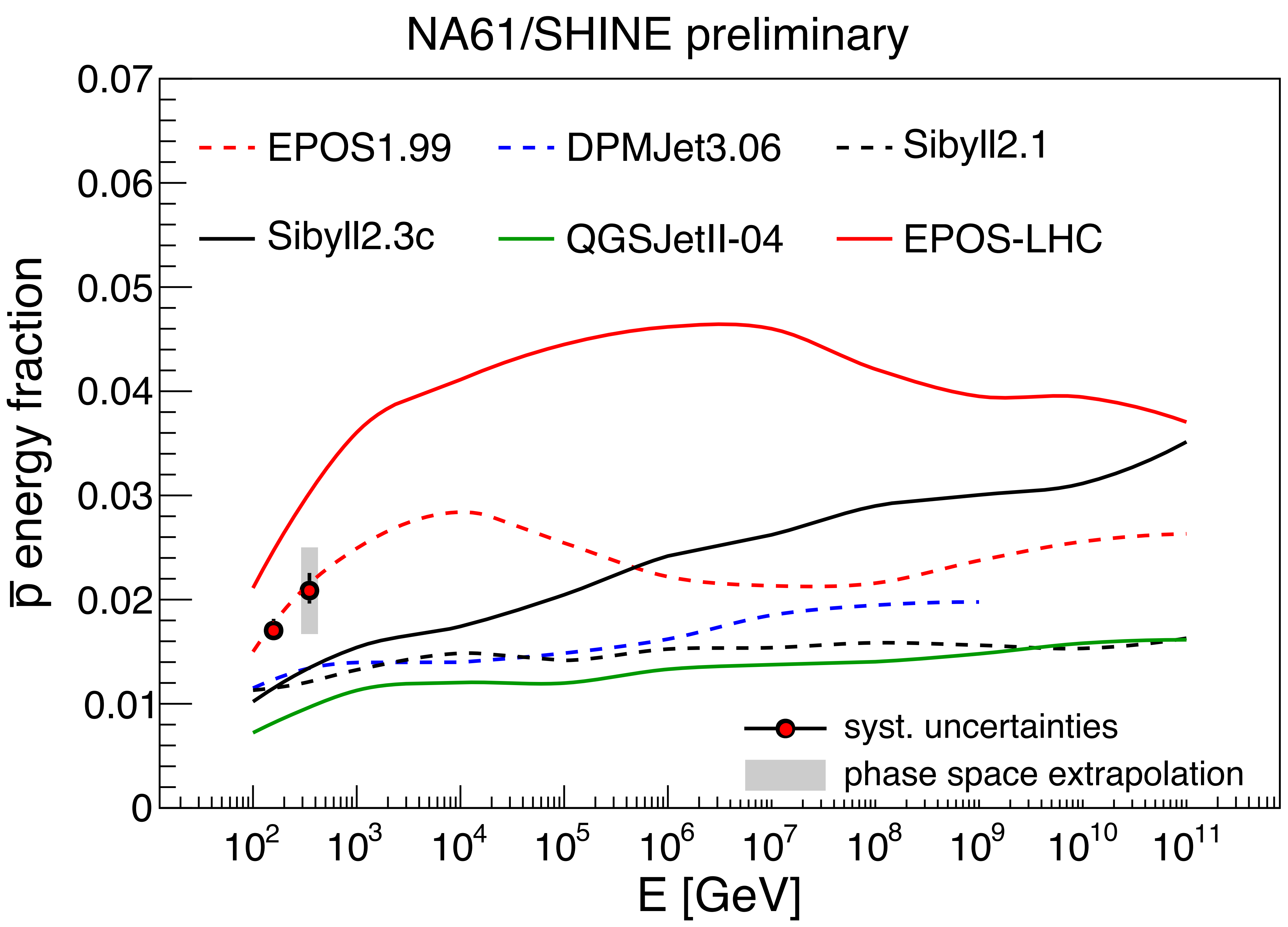


$\pi^- C \to \rho^0\, X \to \pi^+\pi^-\, X$

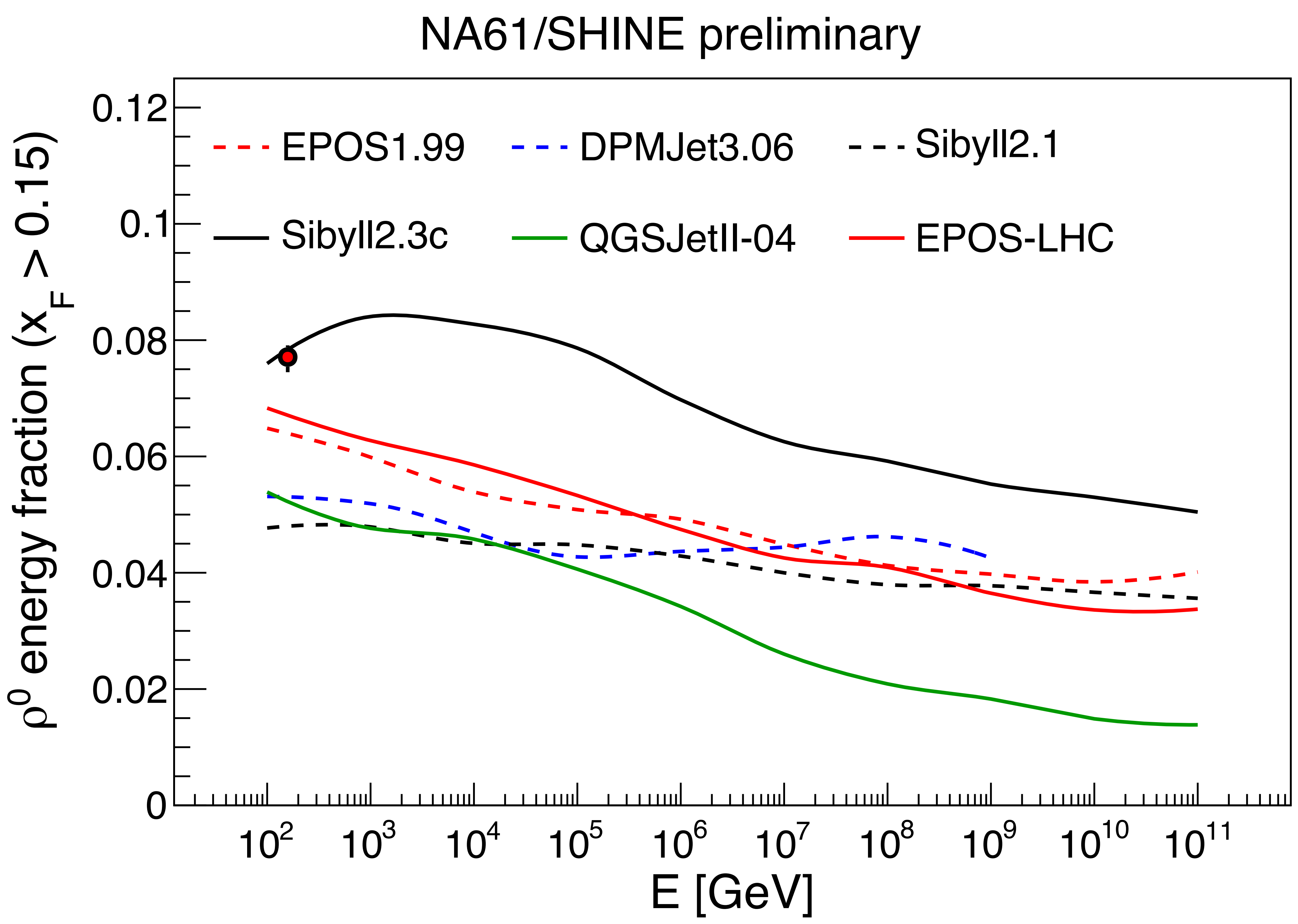


(NA61, EPJ 77, 2017)

NA61 results and extrapolation to high energy



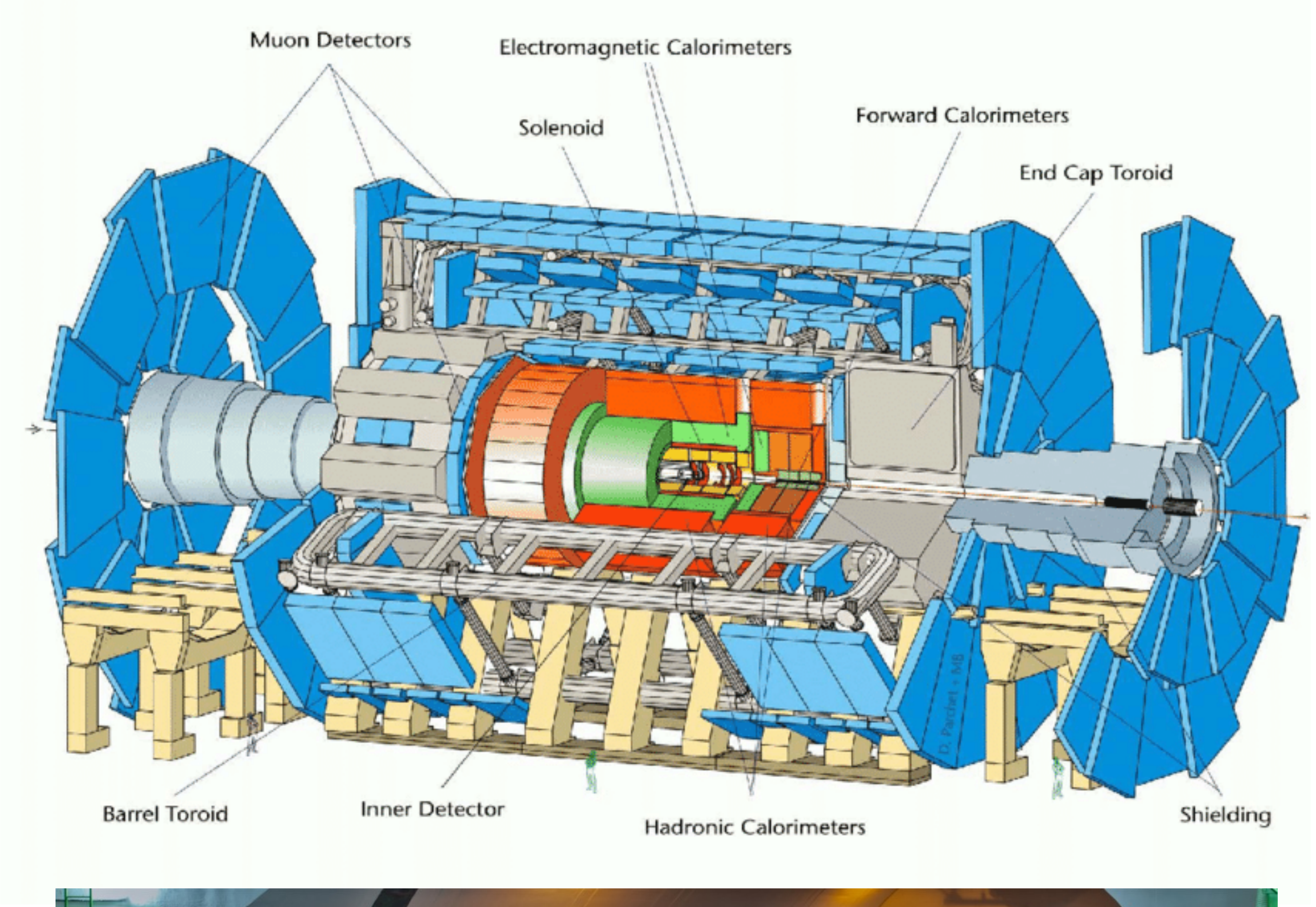
$\bar{p}$ energy fraction in π^-+C



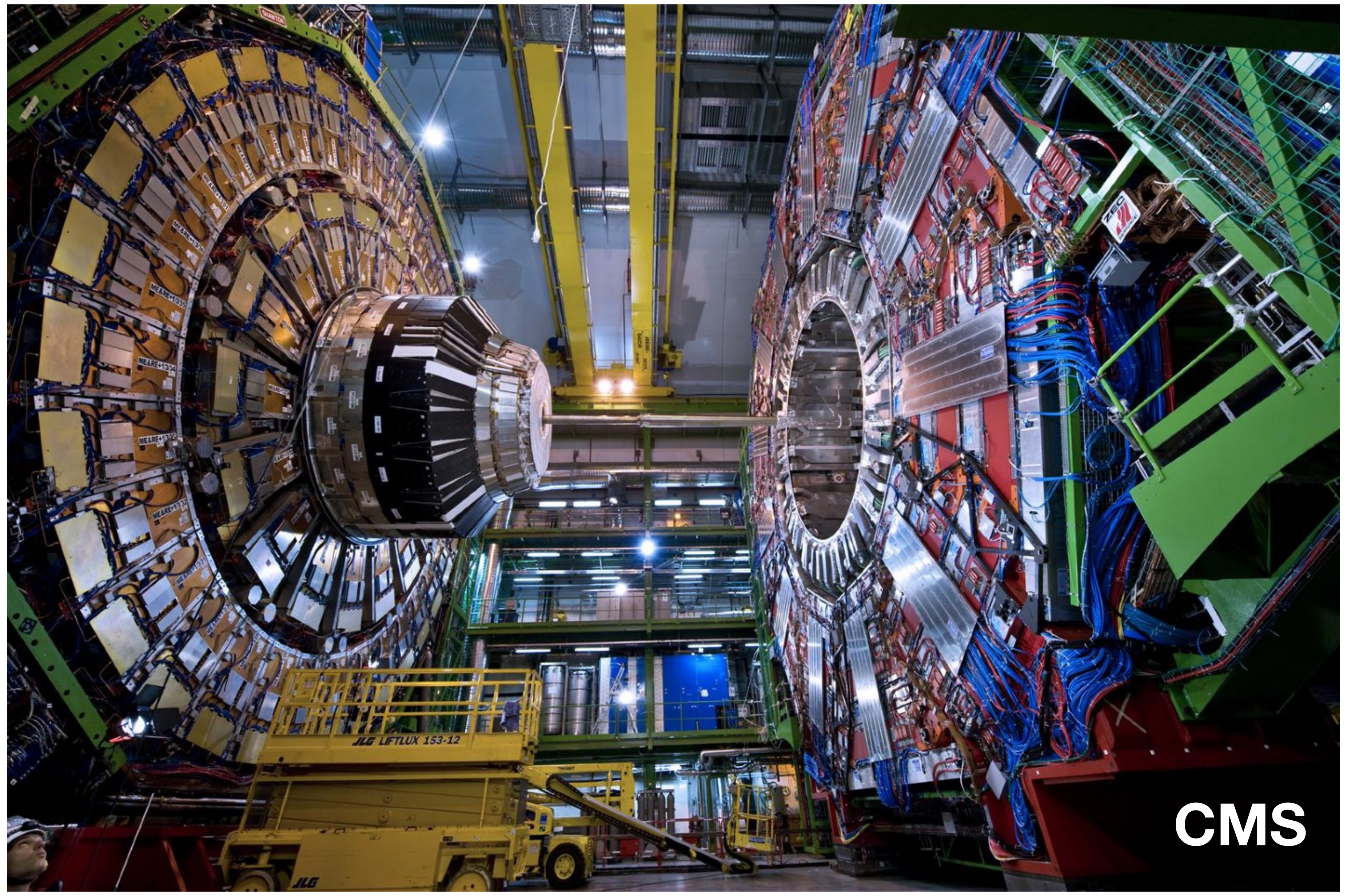
ρ^0 energy fraction in π^-+C

(Prado, NA61, ICRC 2017)

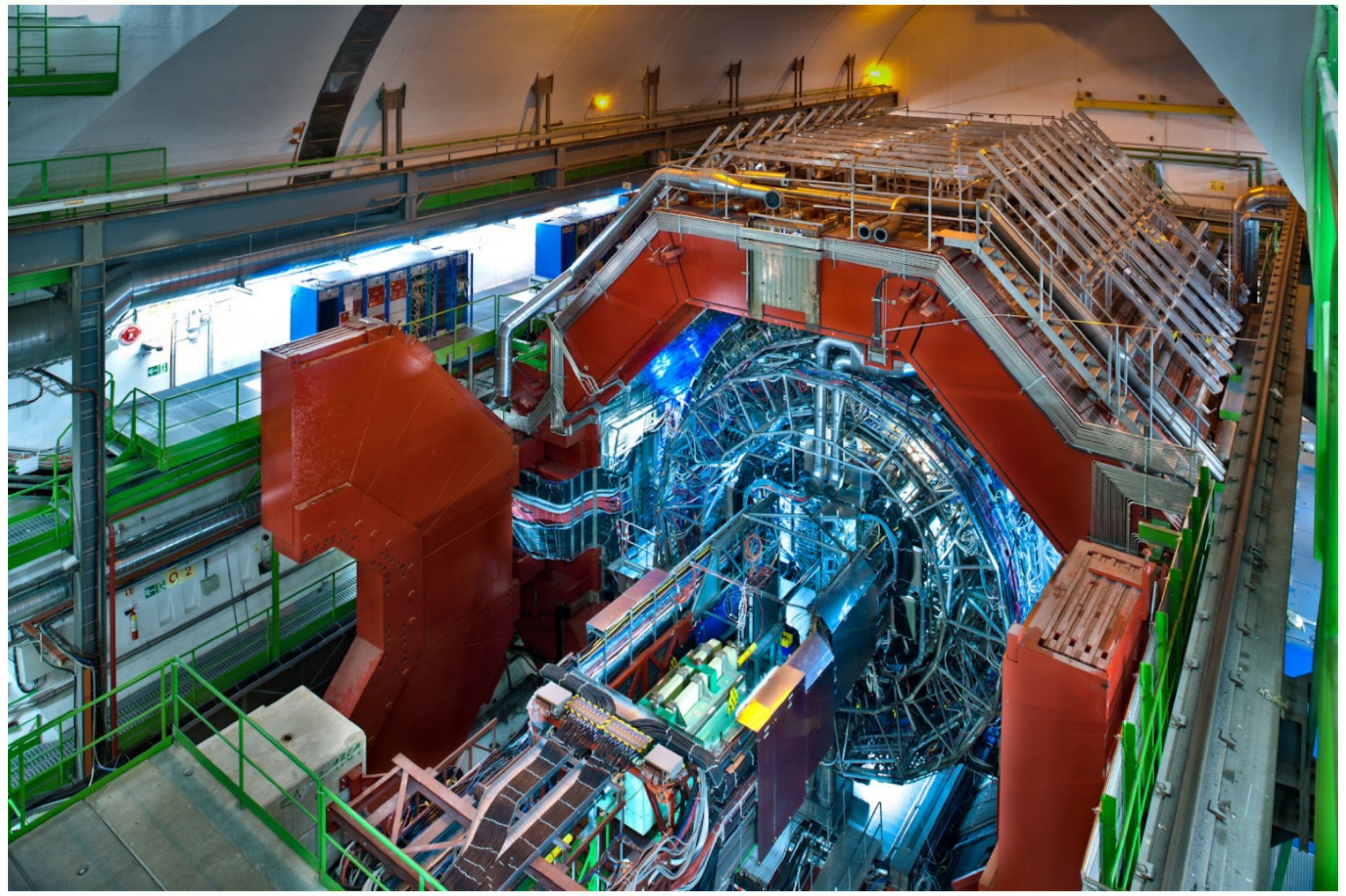
LHC and its experiments ($E_{equiv} \sim 10^{17}$ eV)



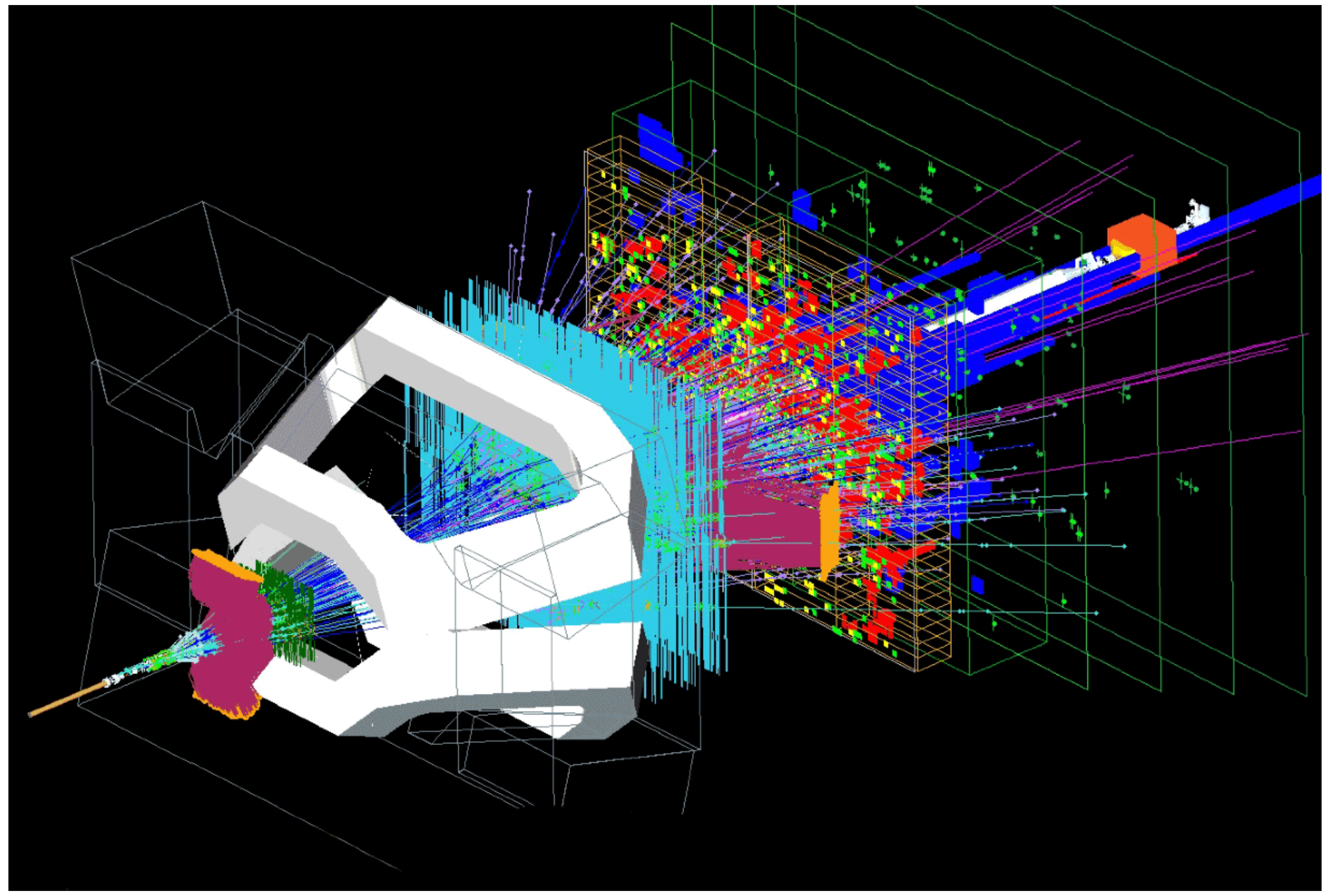
ATLAS



CMS

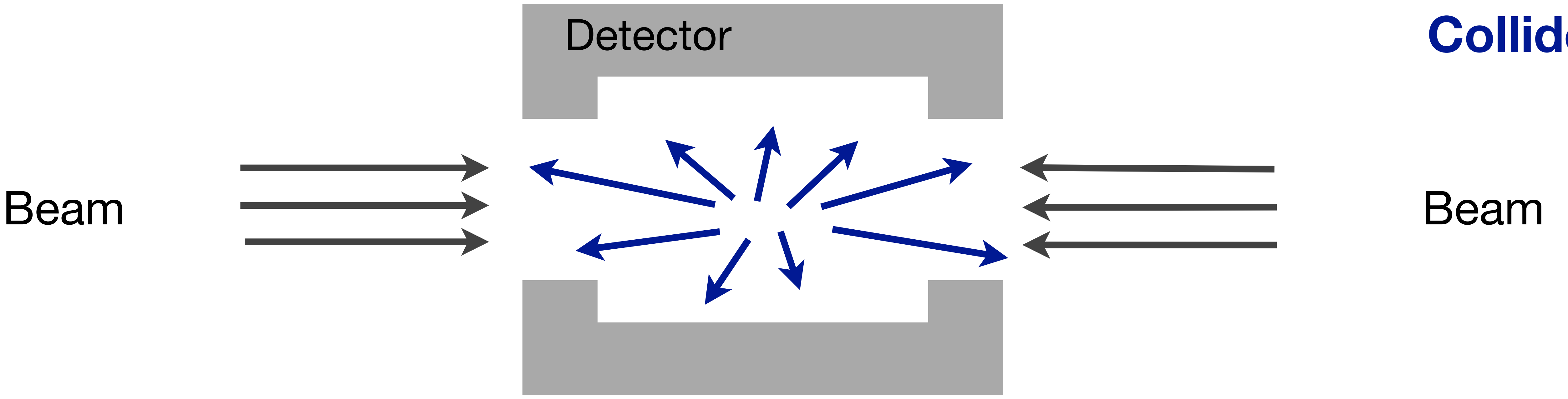


ALICE

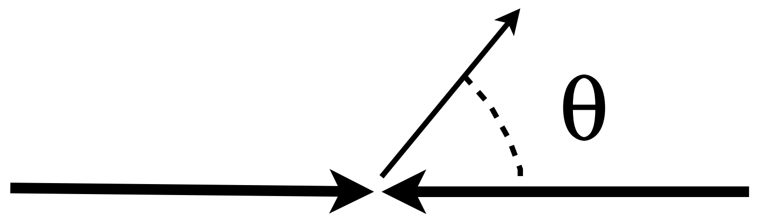


LHCb

Problem of limited phase space coverage



Collider setup

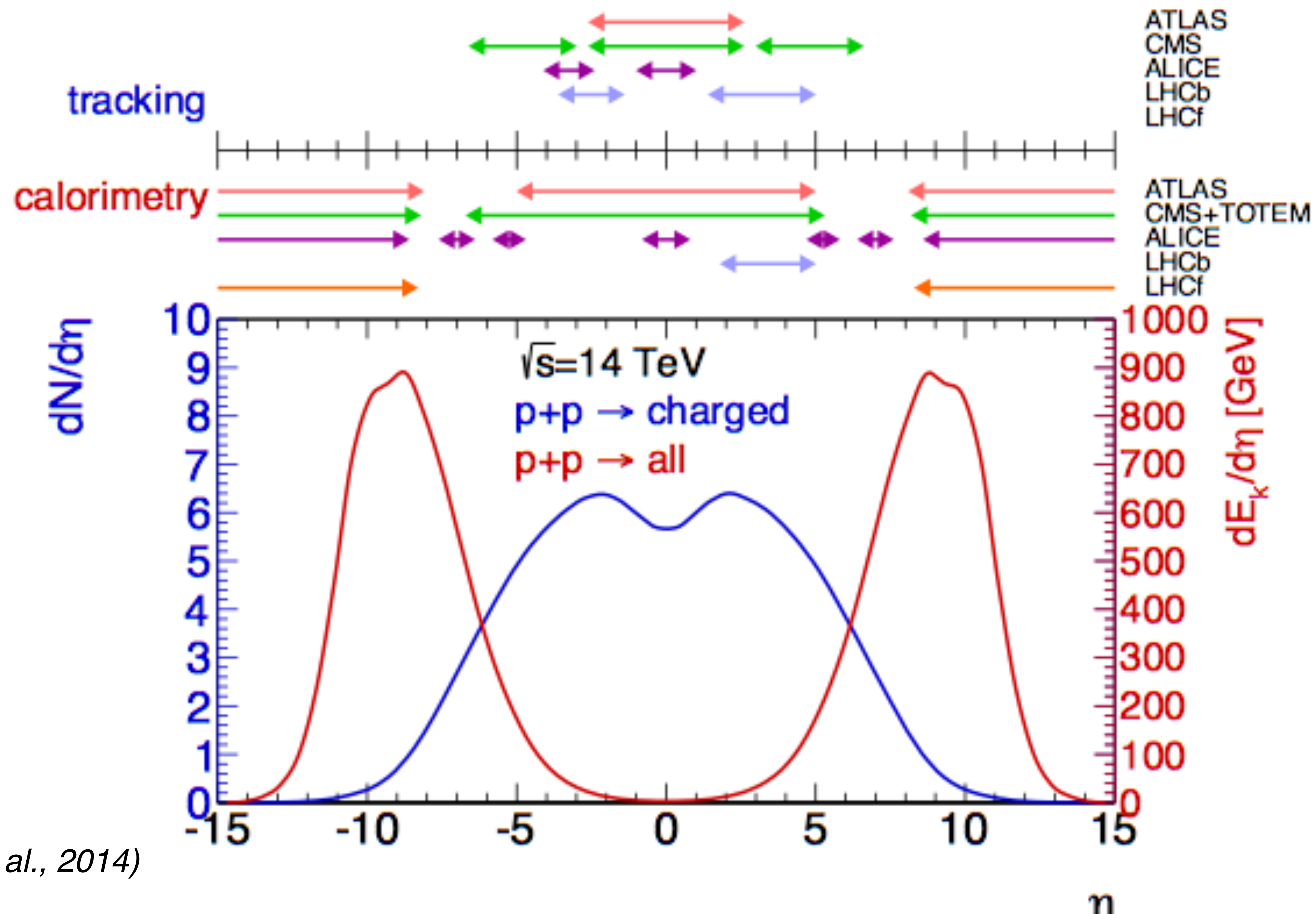


$$\eta = -\ln \tan \frac{\theta}{2}$$

Pseudorapidity

η	deg.	mrad.
3	5.7	97
5	0.77	10
8	0.04	0.7
10	0,005	0,009

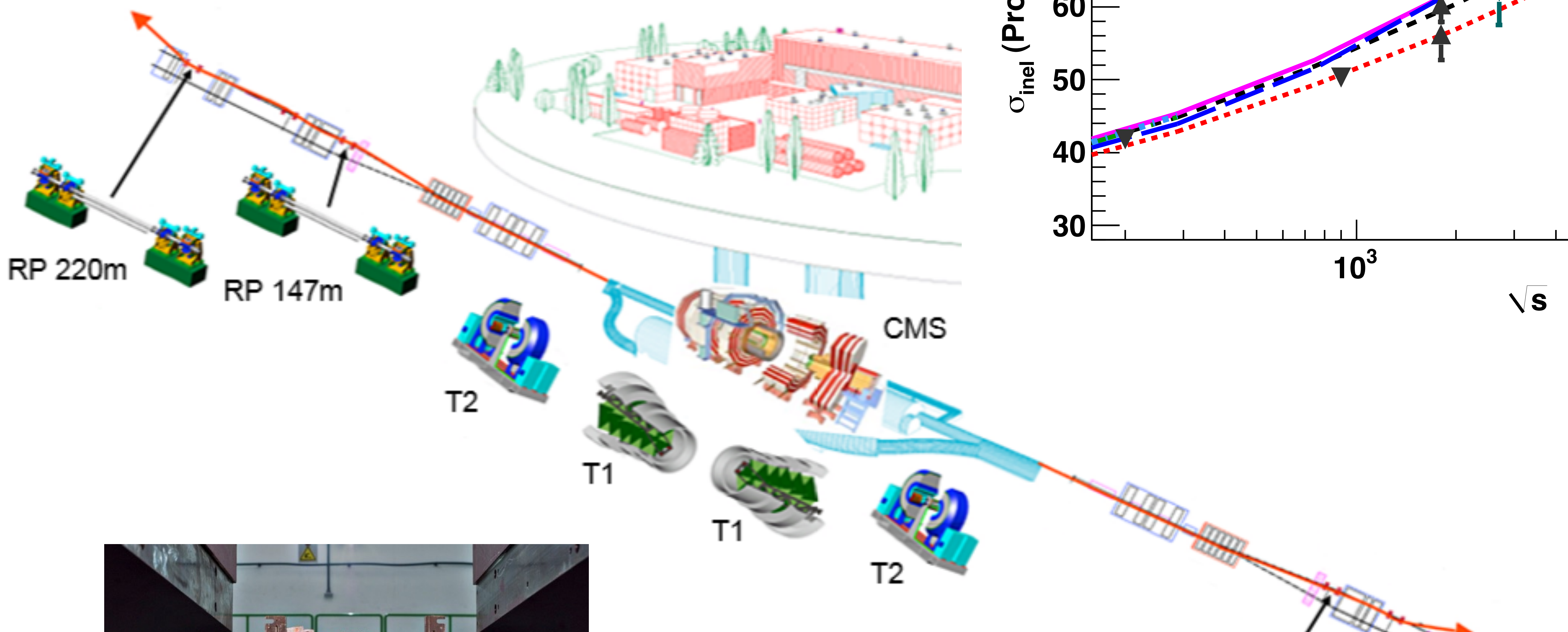
Air showers: Particles of highest energy most important

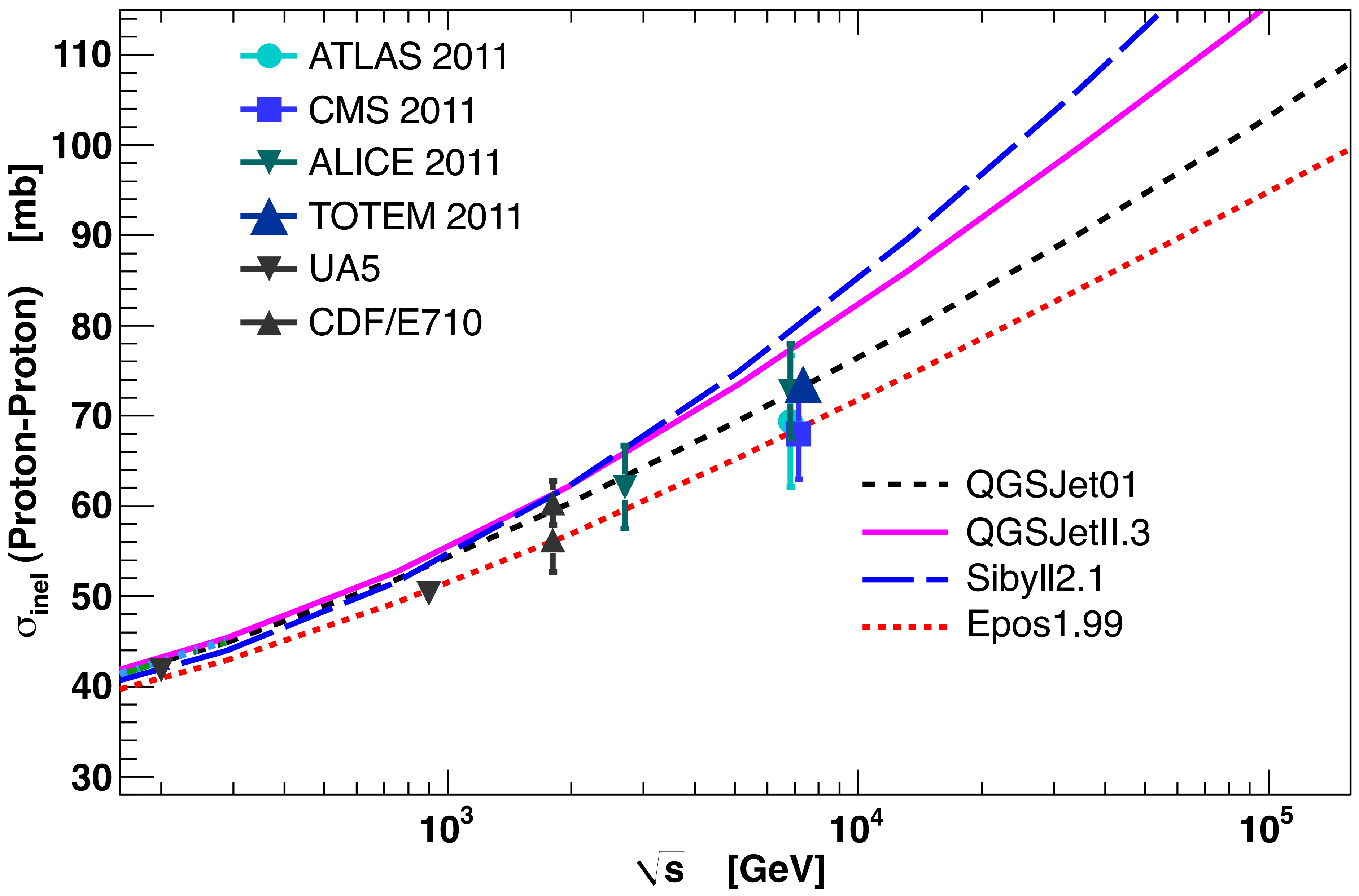


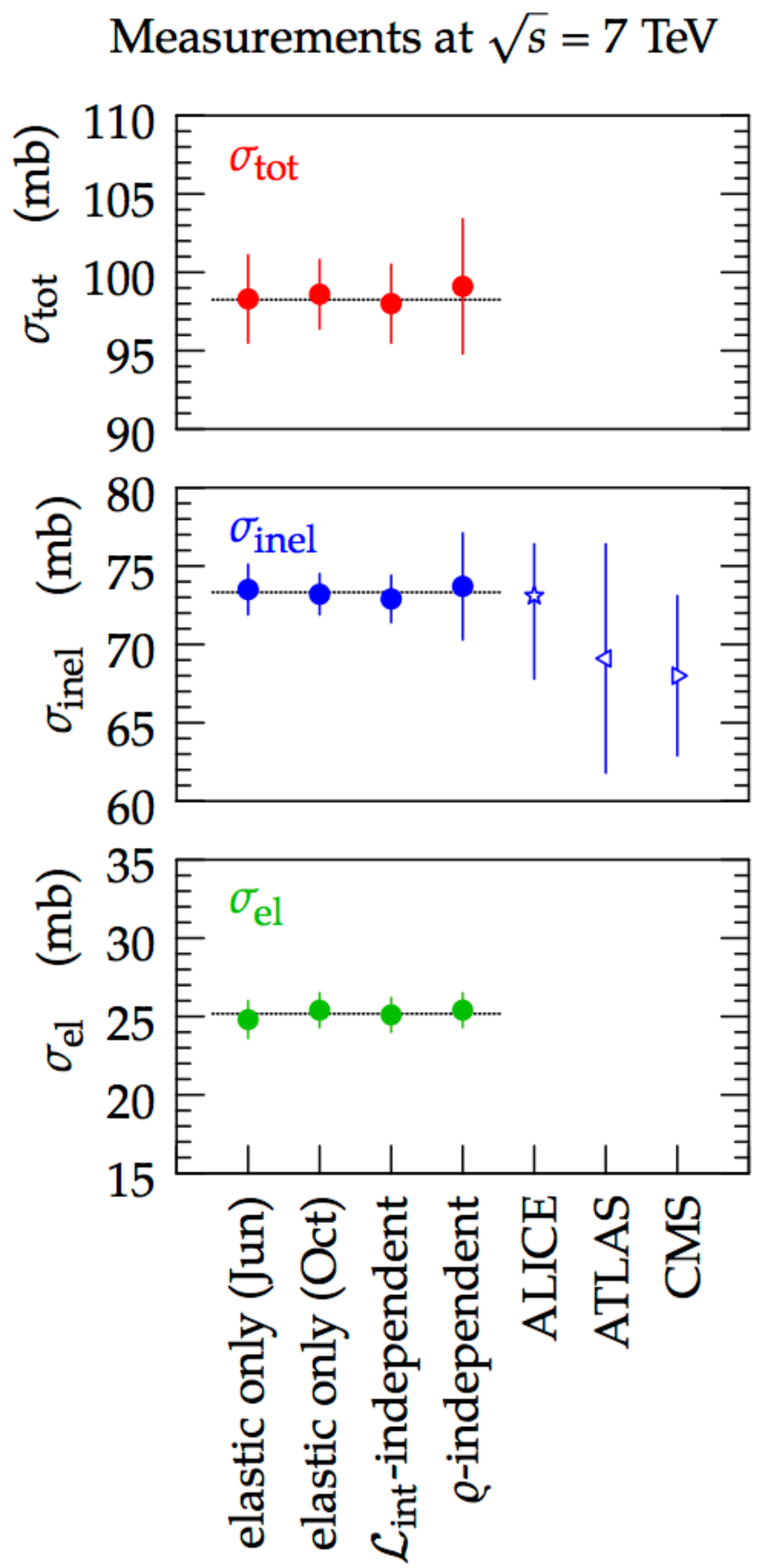
(Salek et al., 2014)

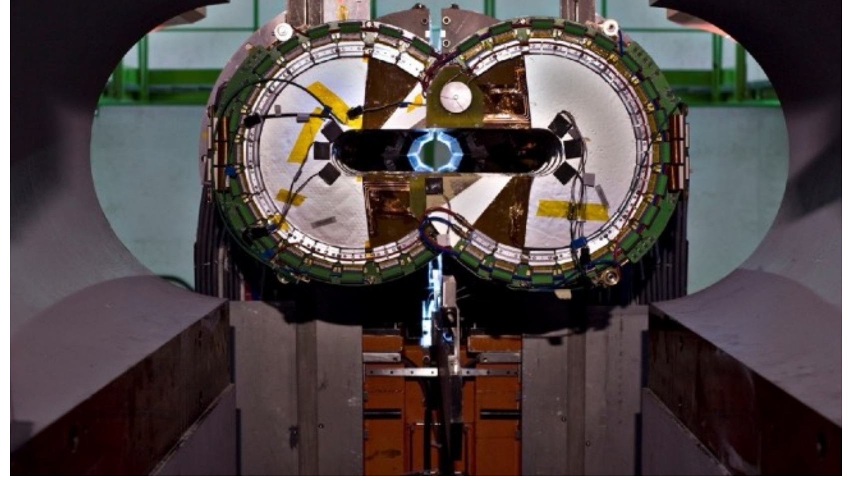
No particle identification in forward direction

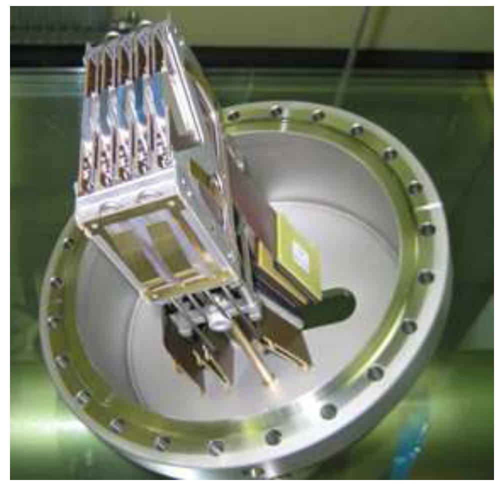
Cross section measurements at LHC

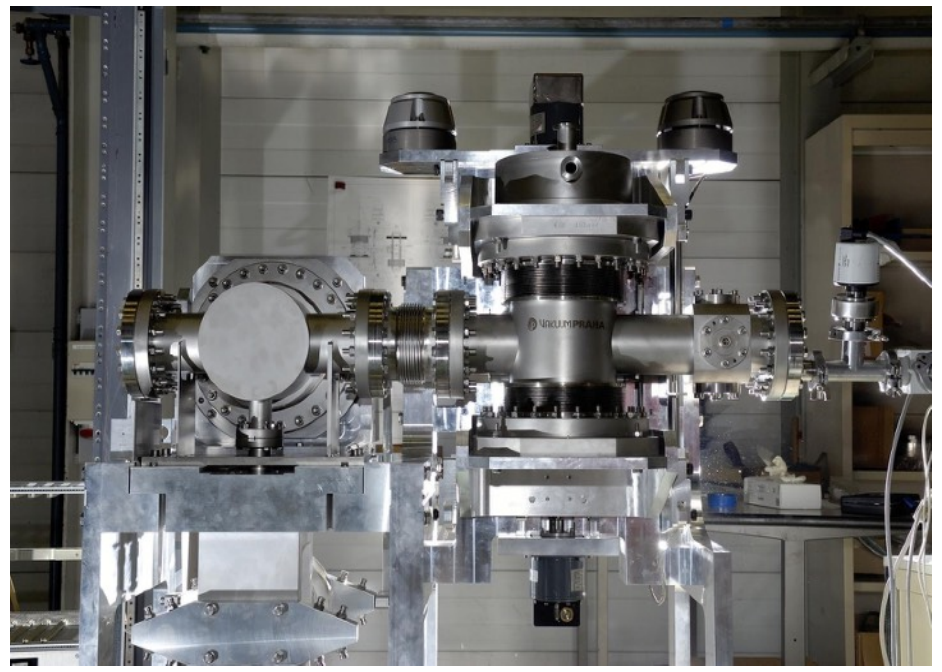




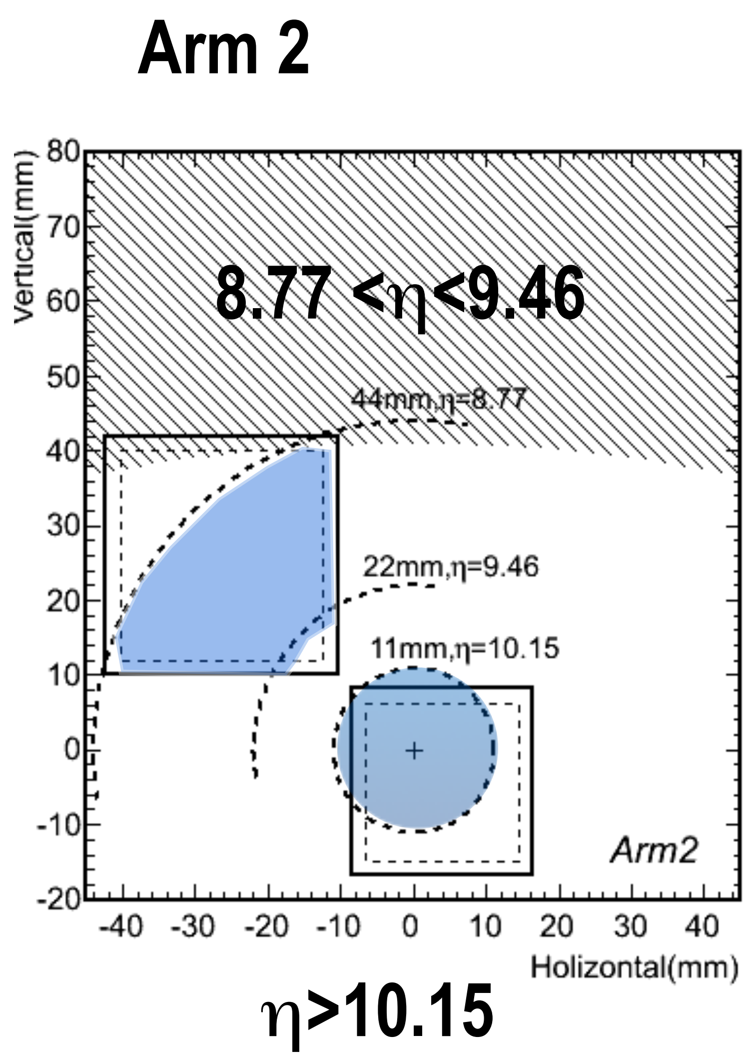


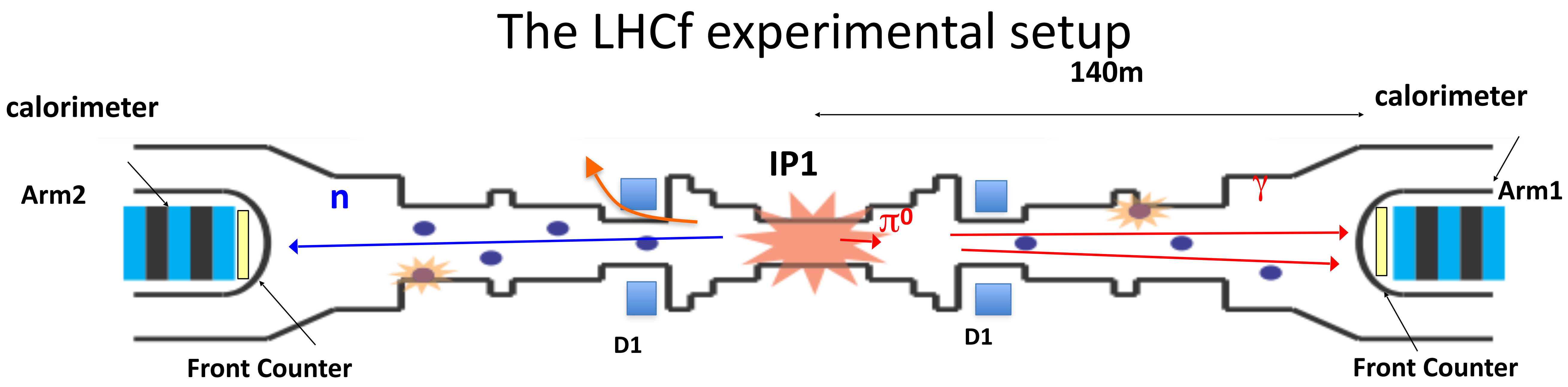


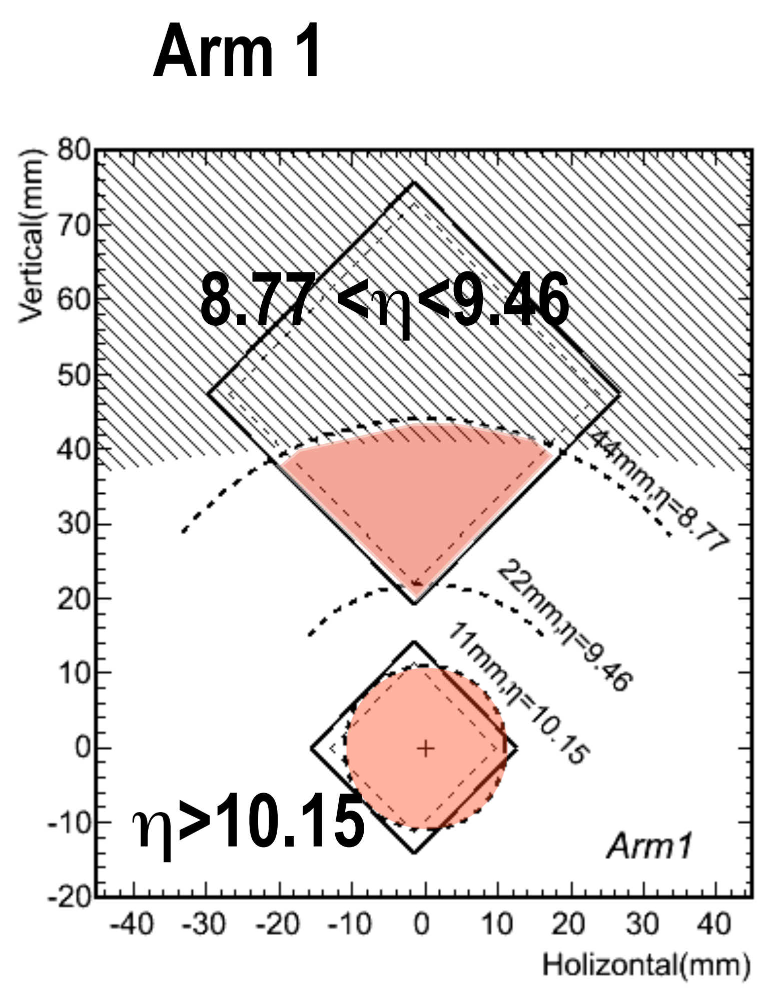




LHCf: very forward photon production at 7 TeV

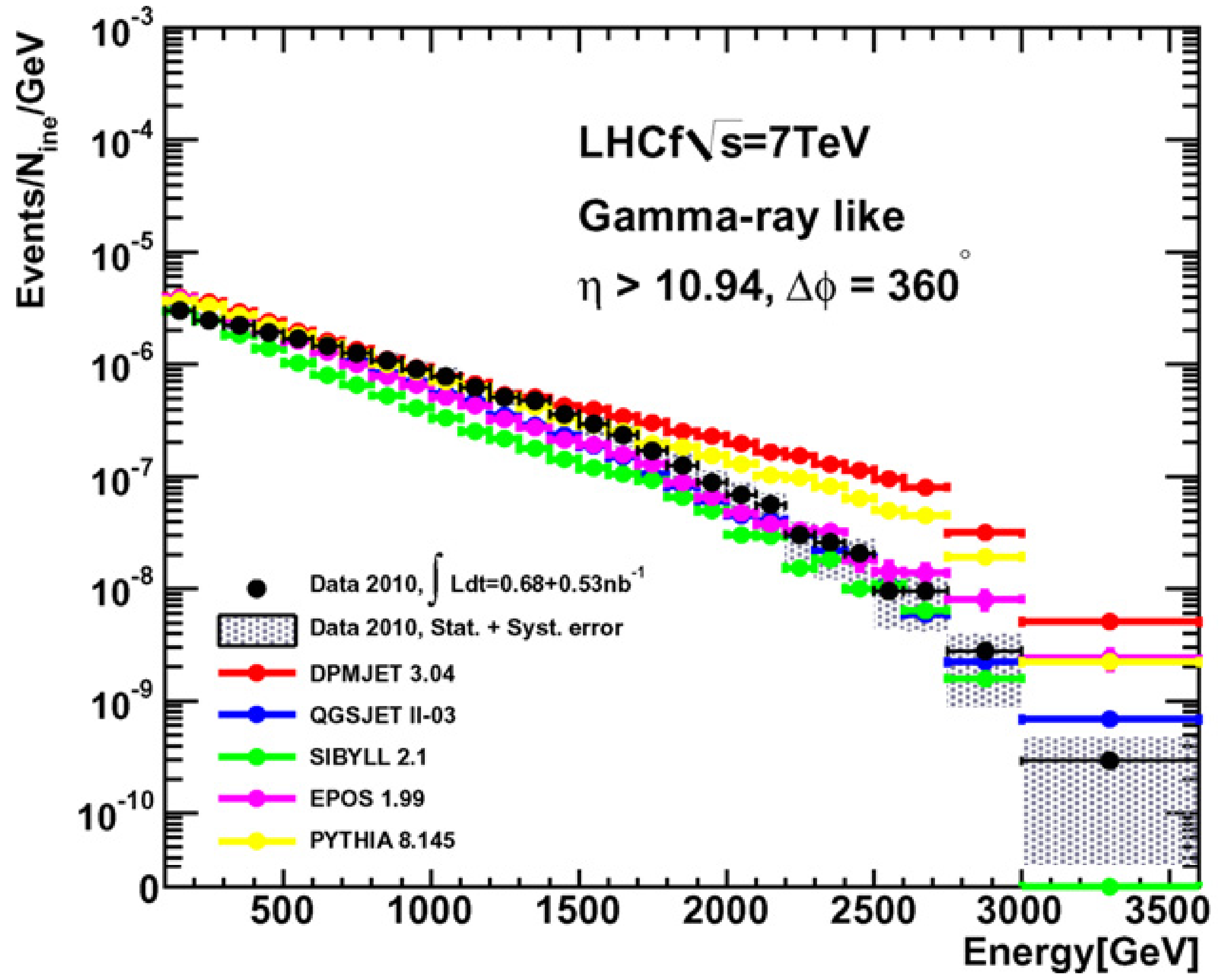


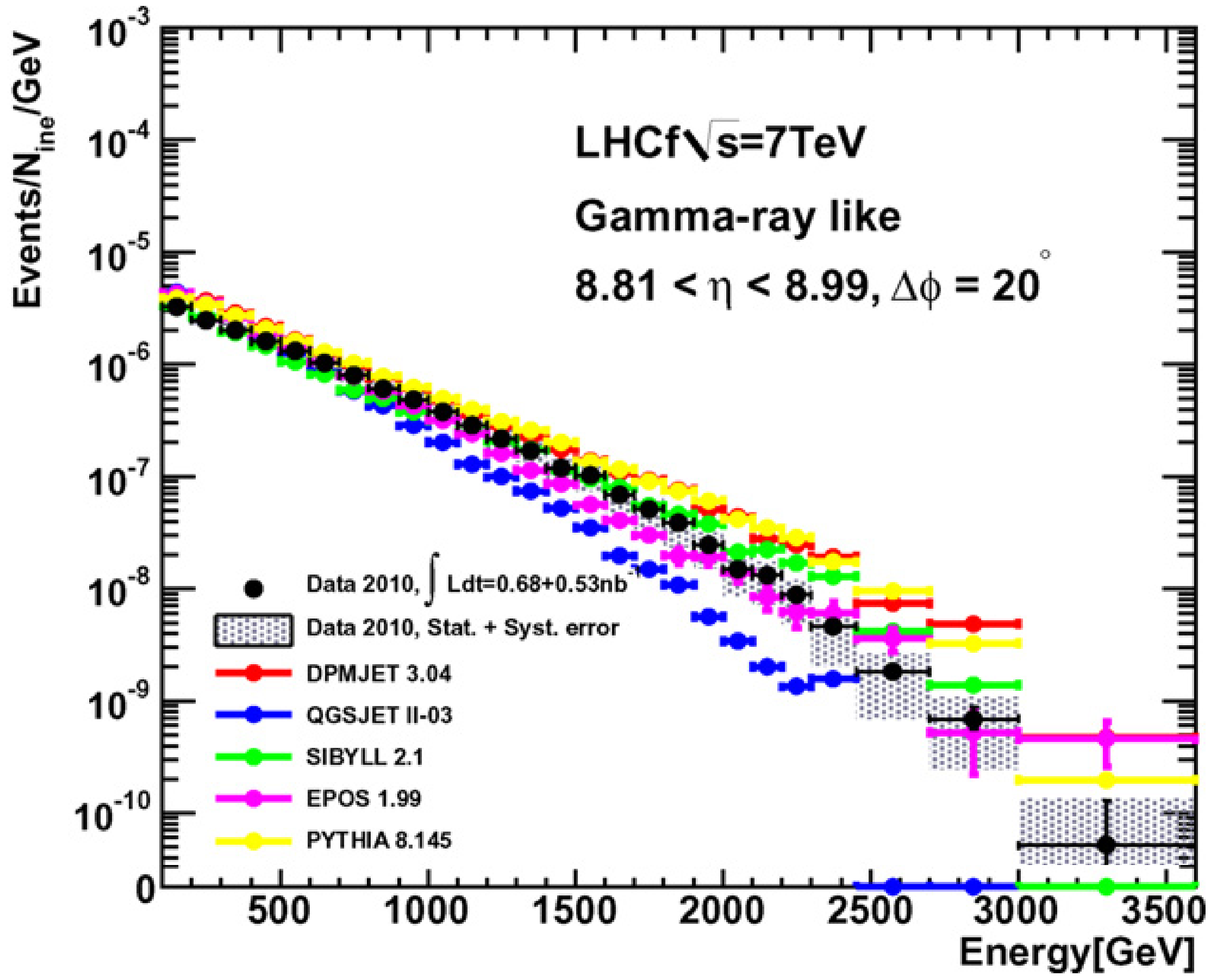


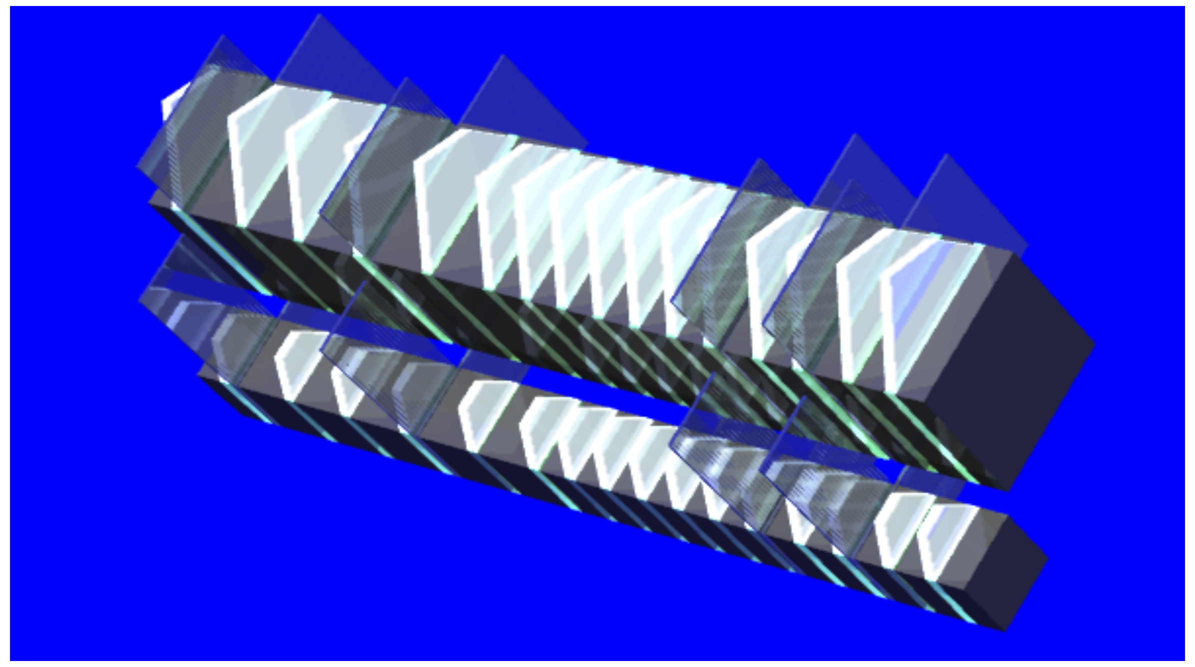


$$pp \to \gamma X$$

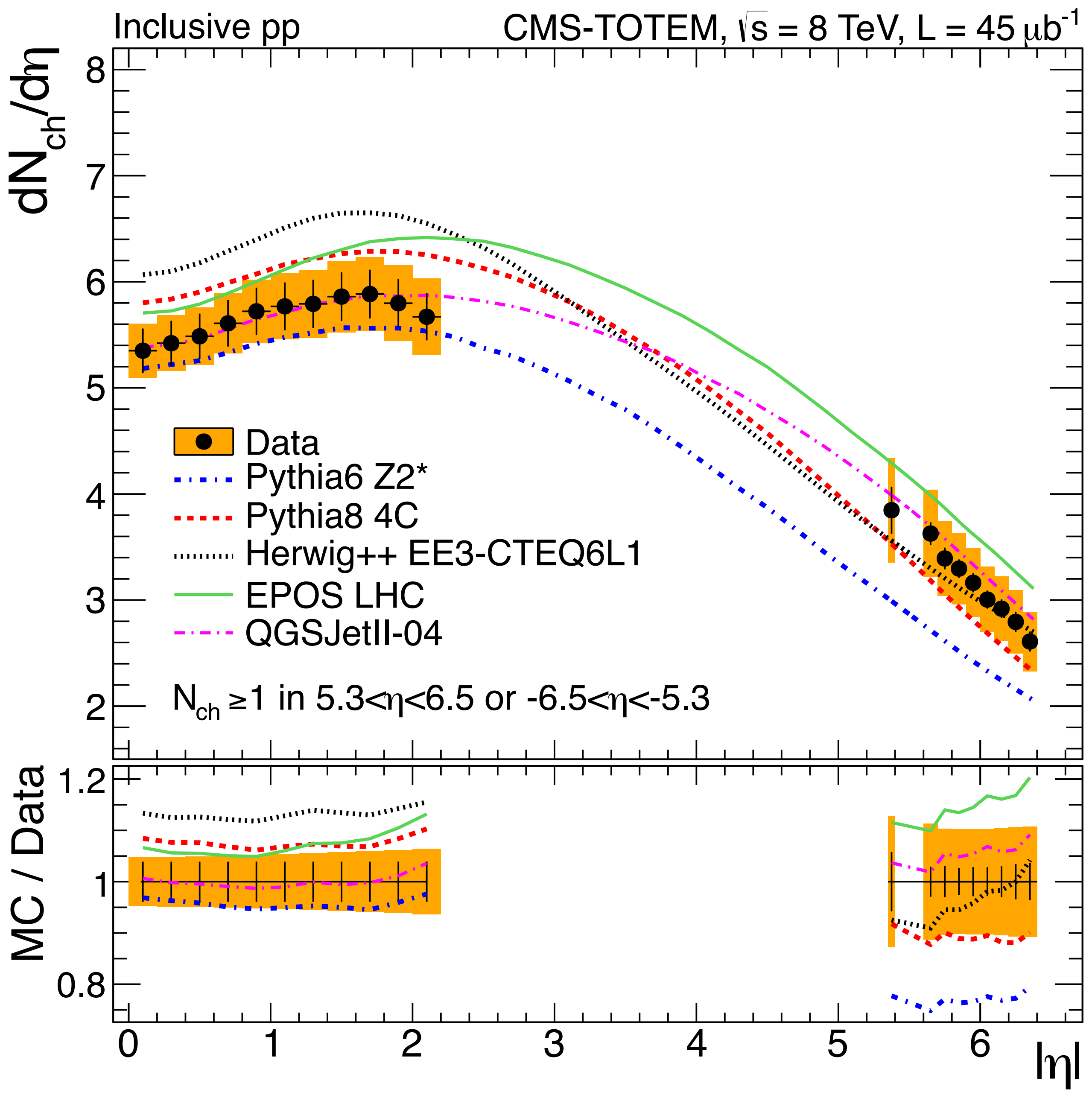
(LHCf Collab., Phys. Lett. B 703, 2011)

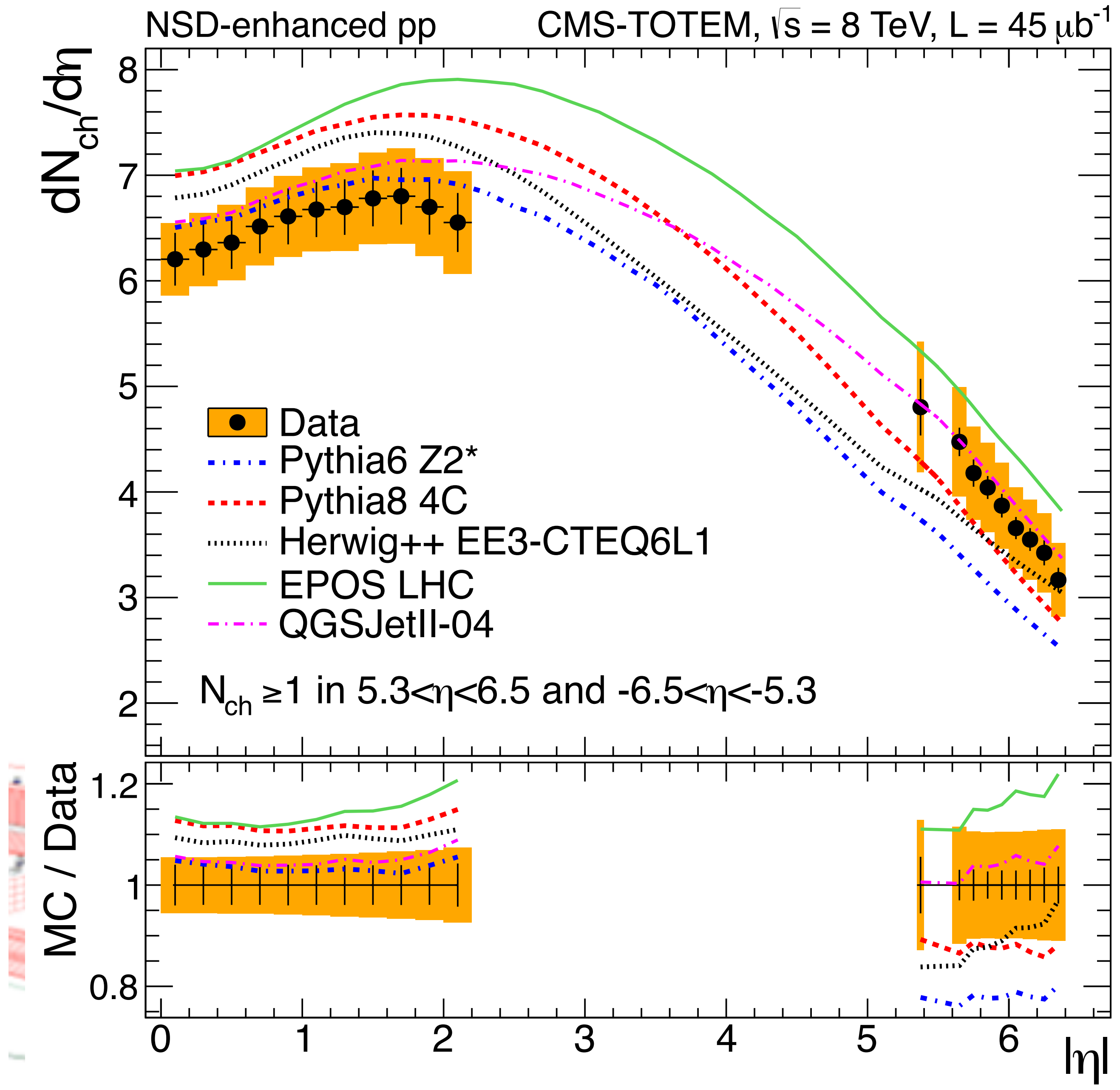


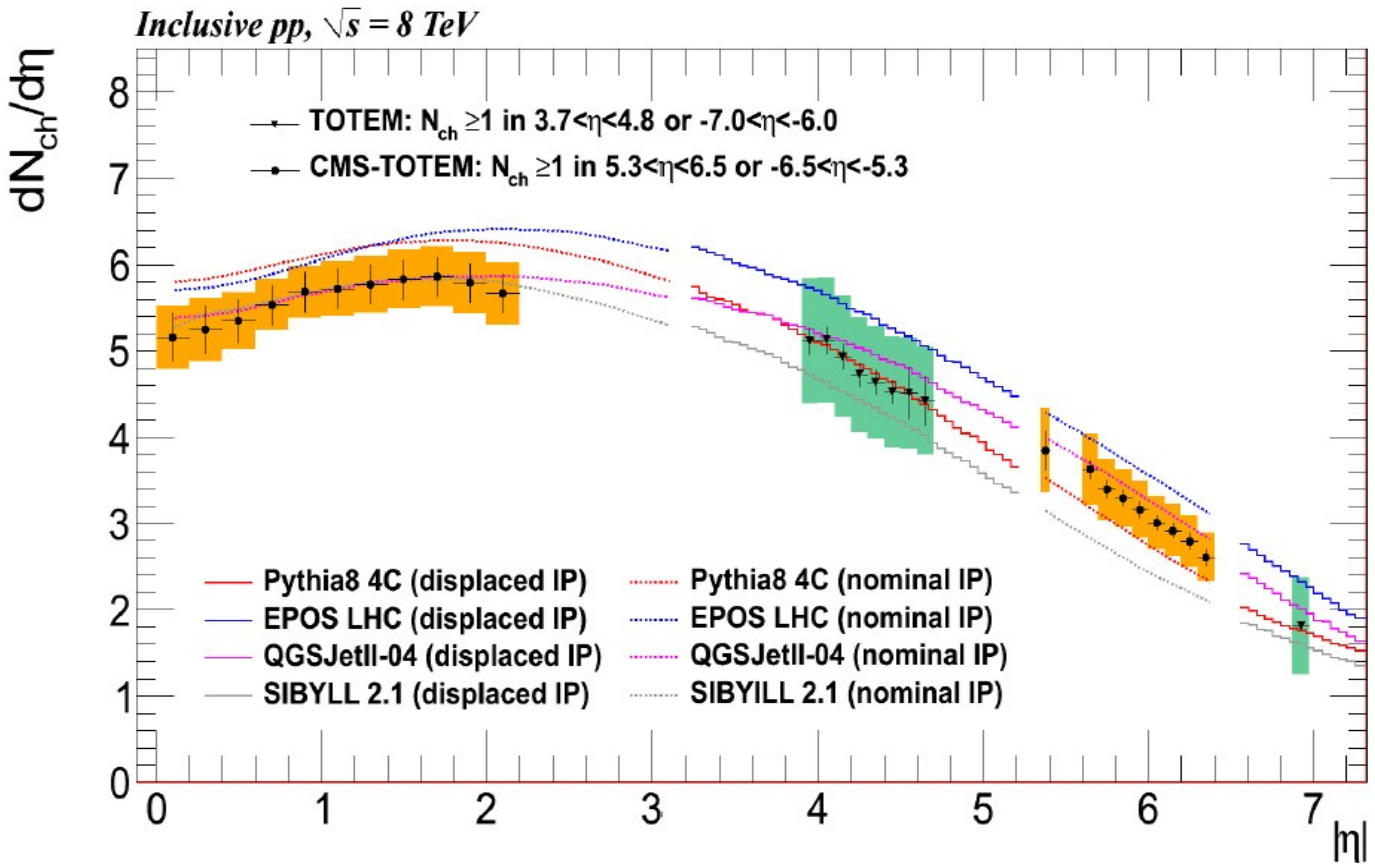


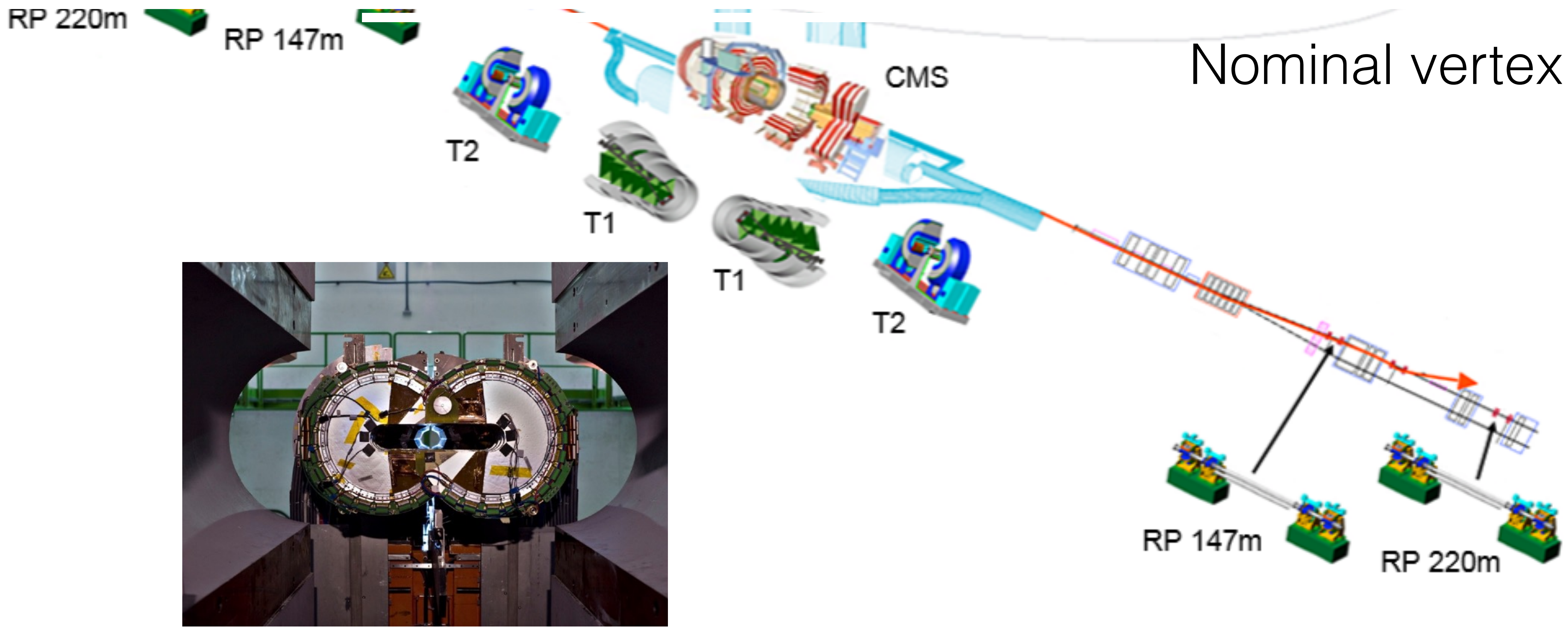


Combined CMS and TOTEM measurements



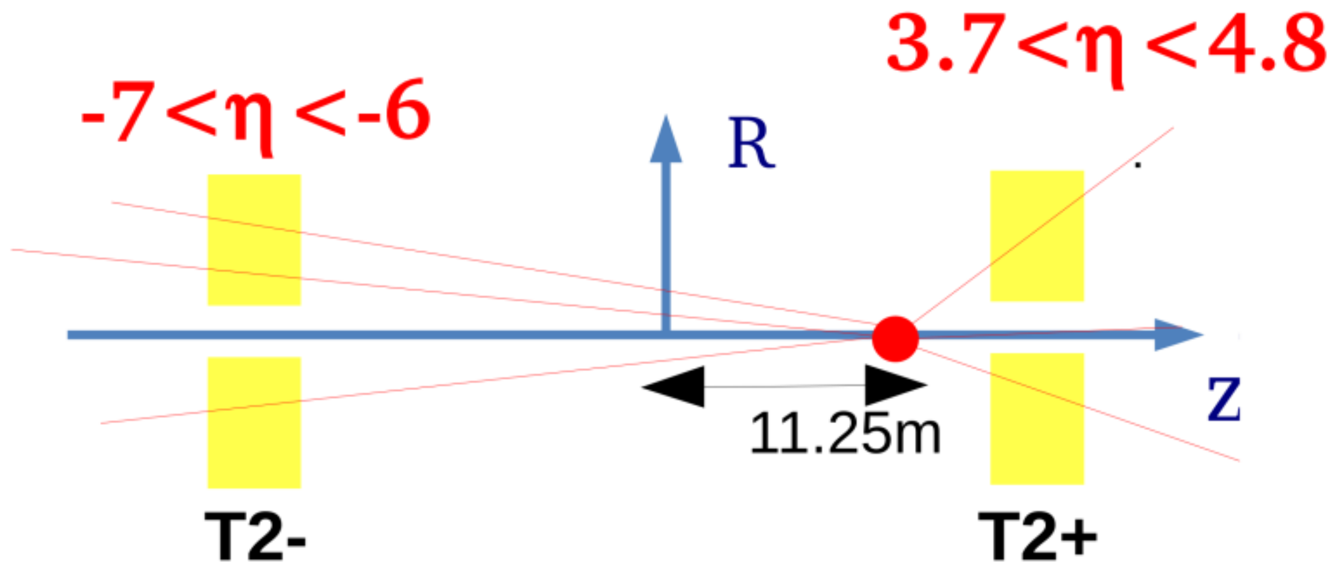




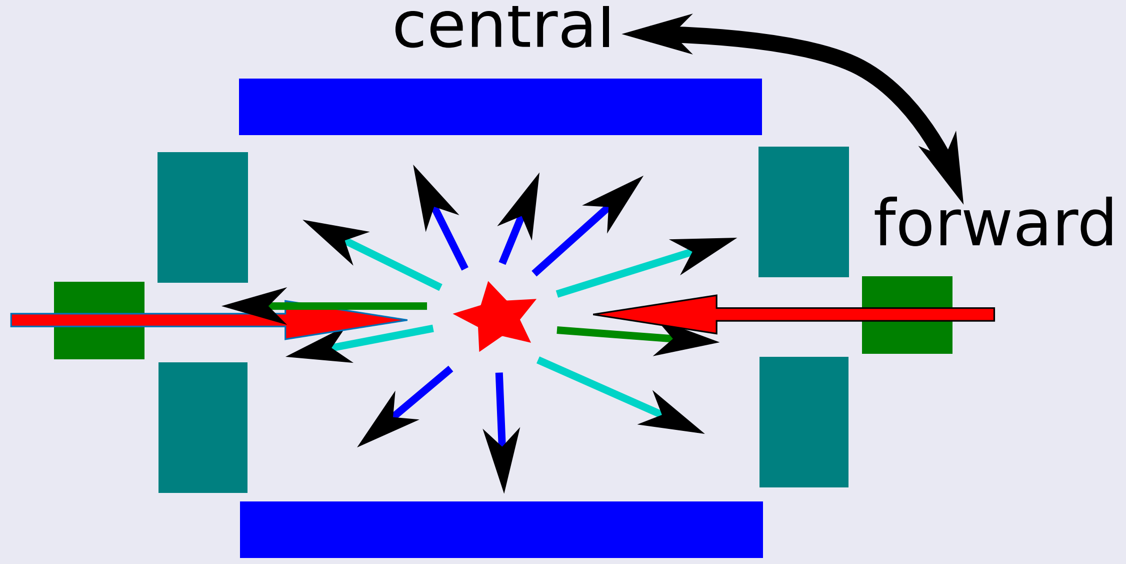


Nominal vertex

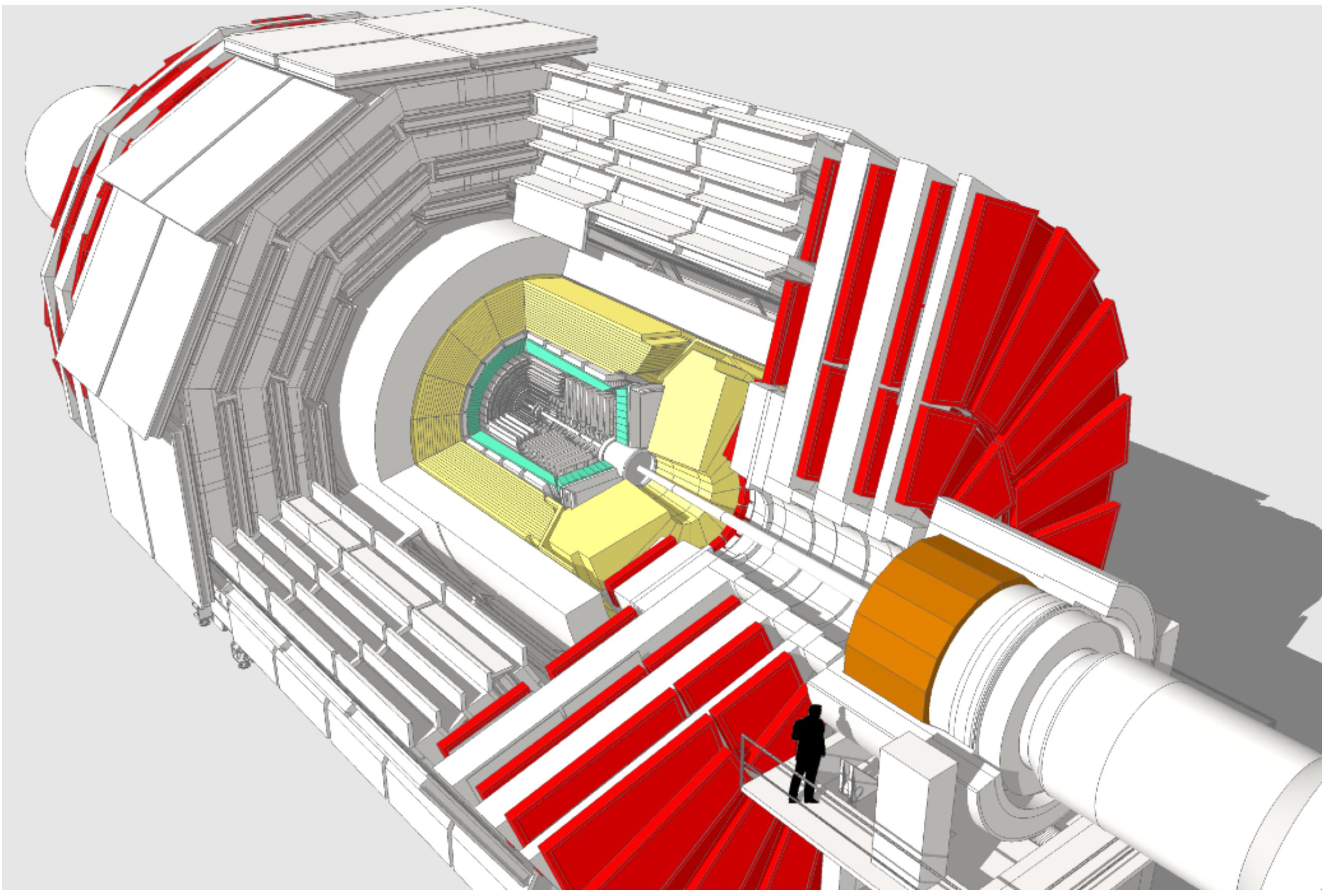
Shifted vertex



Challenge of limited phase space coverage

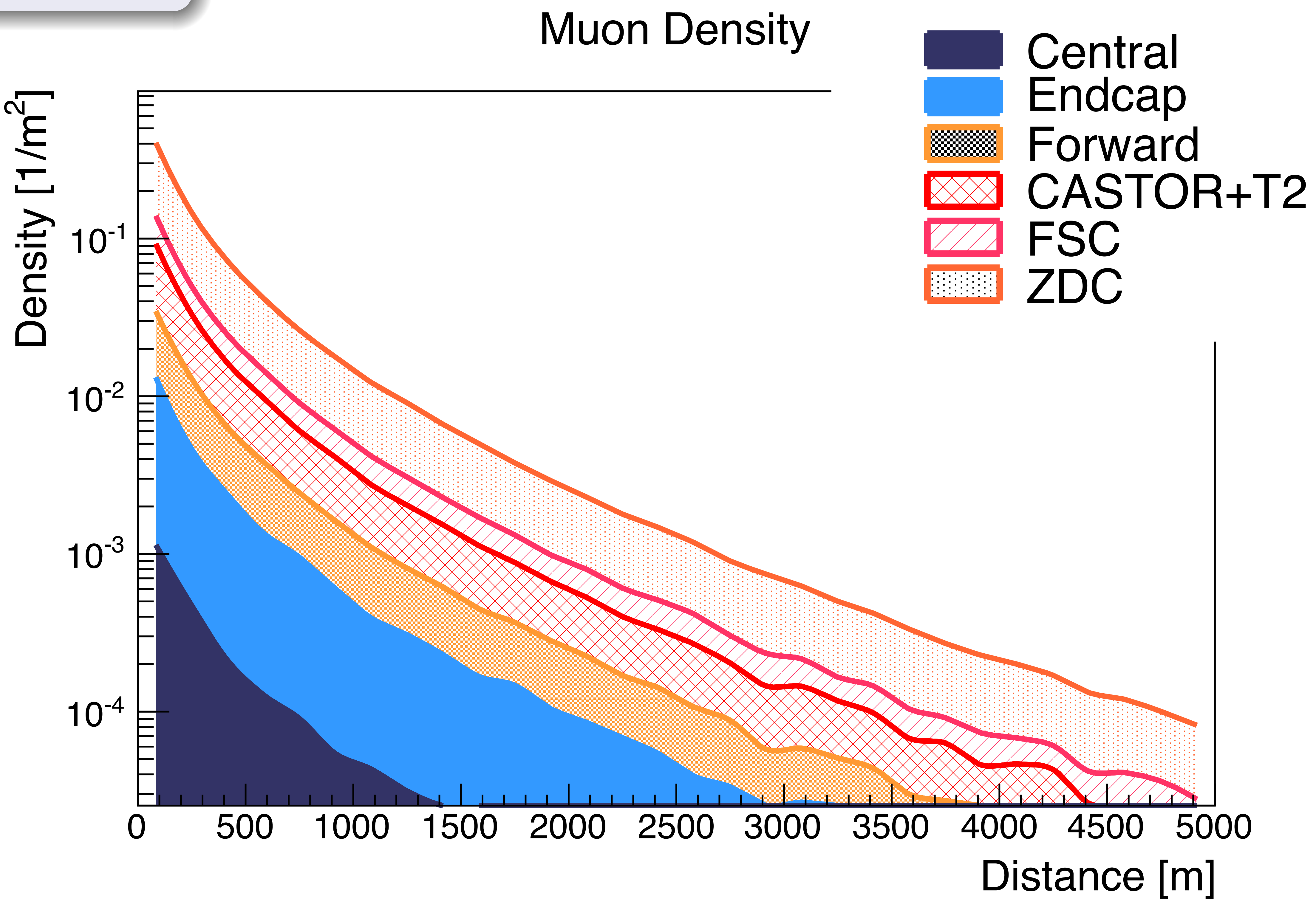


- Central ($|\eta| < 1$)
- Endcap ($1 < |\eta| < 3.5$)
- Forward ($3 < |\eta| < 5$), HF
- CASTOR+T2 ($5 < |\eta| < 6.6$)
- FSC ($6.6 < |\eta| < 8$)
- ZDC ($|\eta| > 8$), LHCf



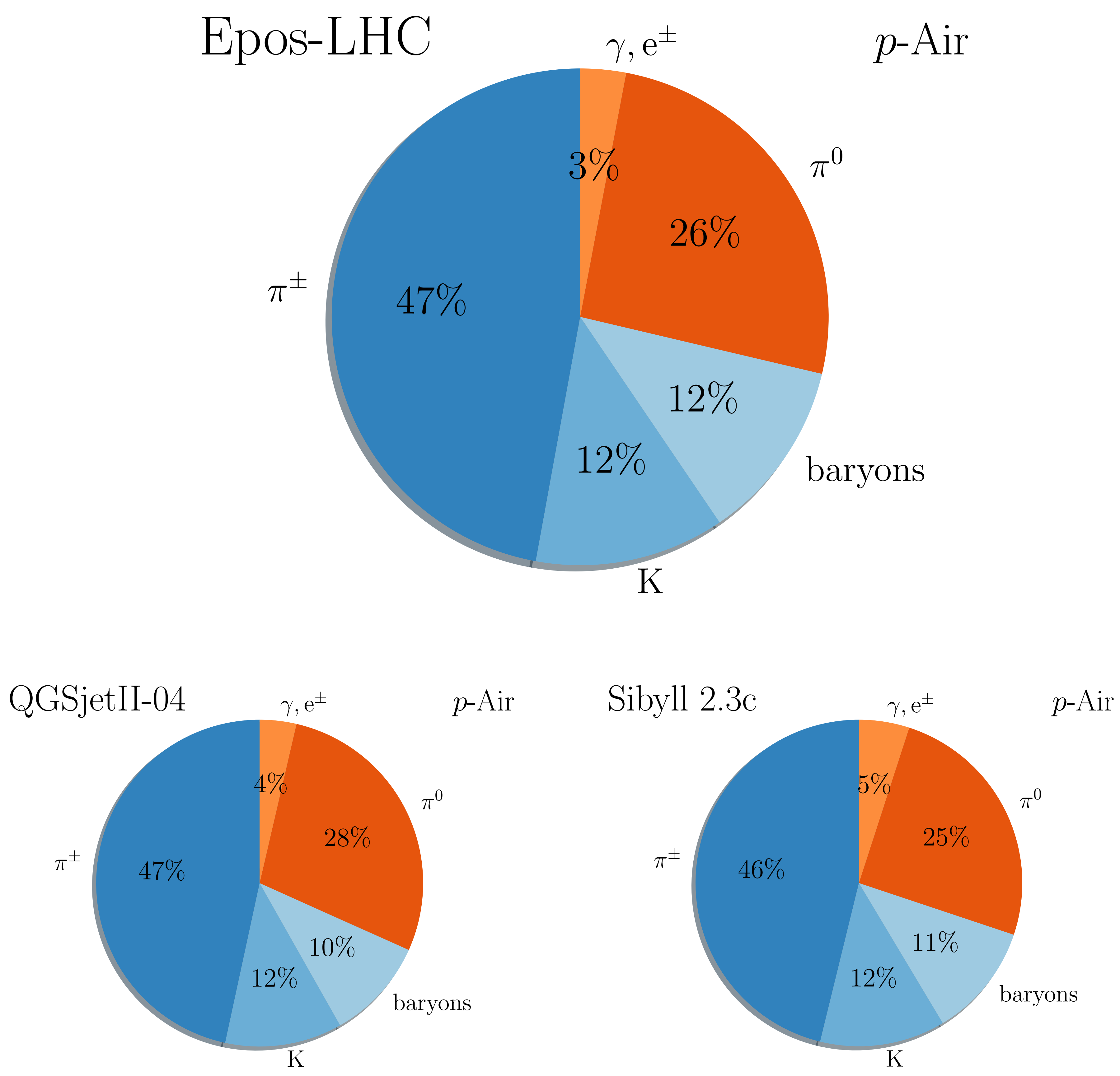
(data from all LHC experiments, CMS shown as example)

(Ulrich, DPG 2014)

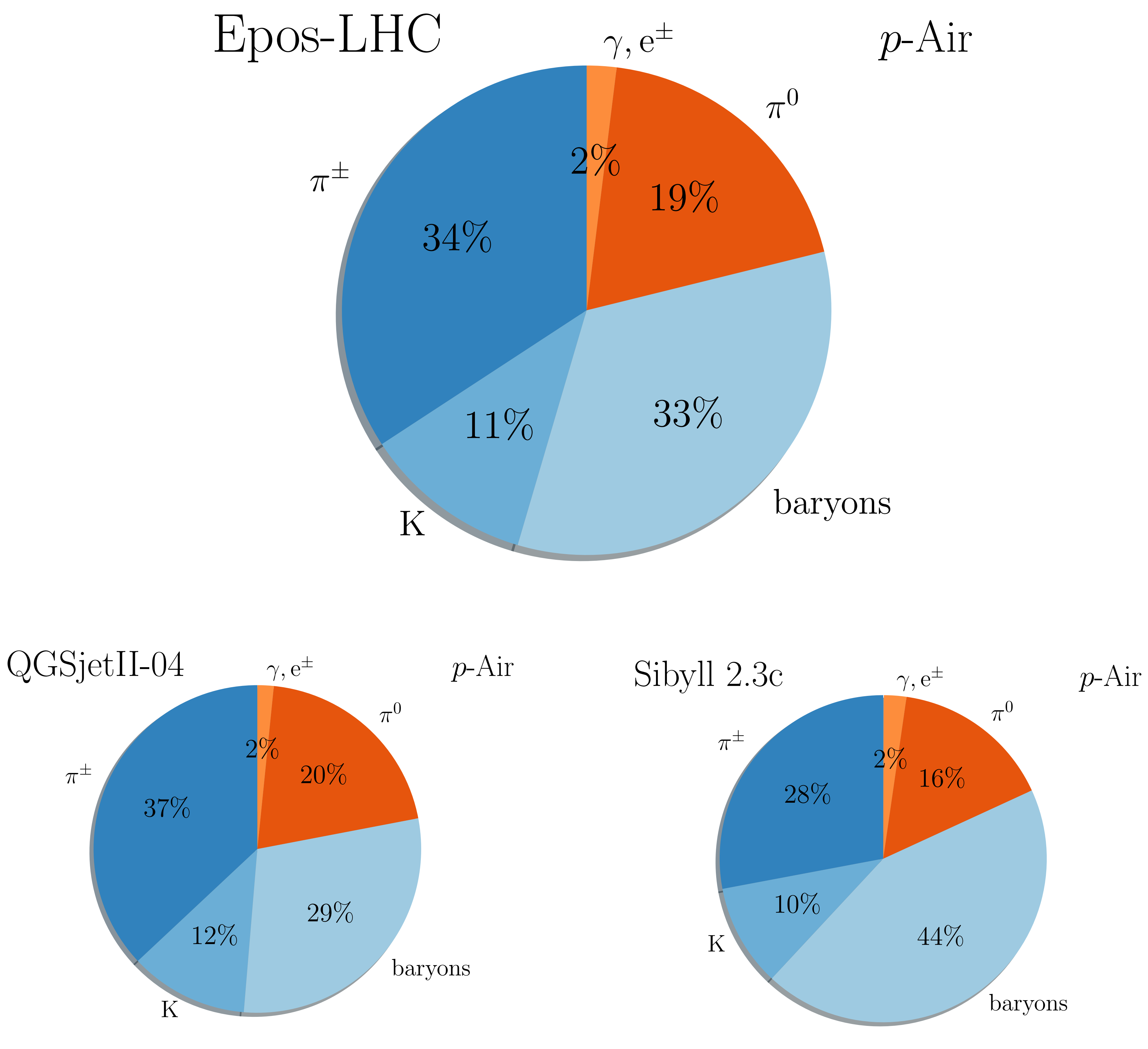


Model predictions for secondary particles: p-air

Particle multiplicity (10^{19} eV)



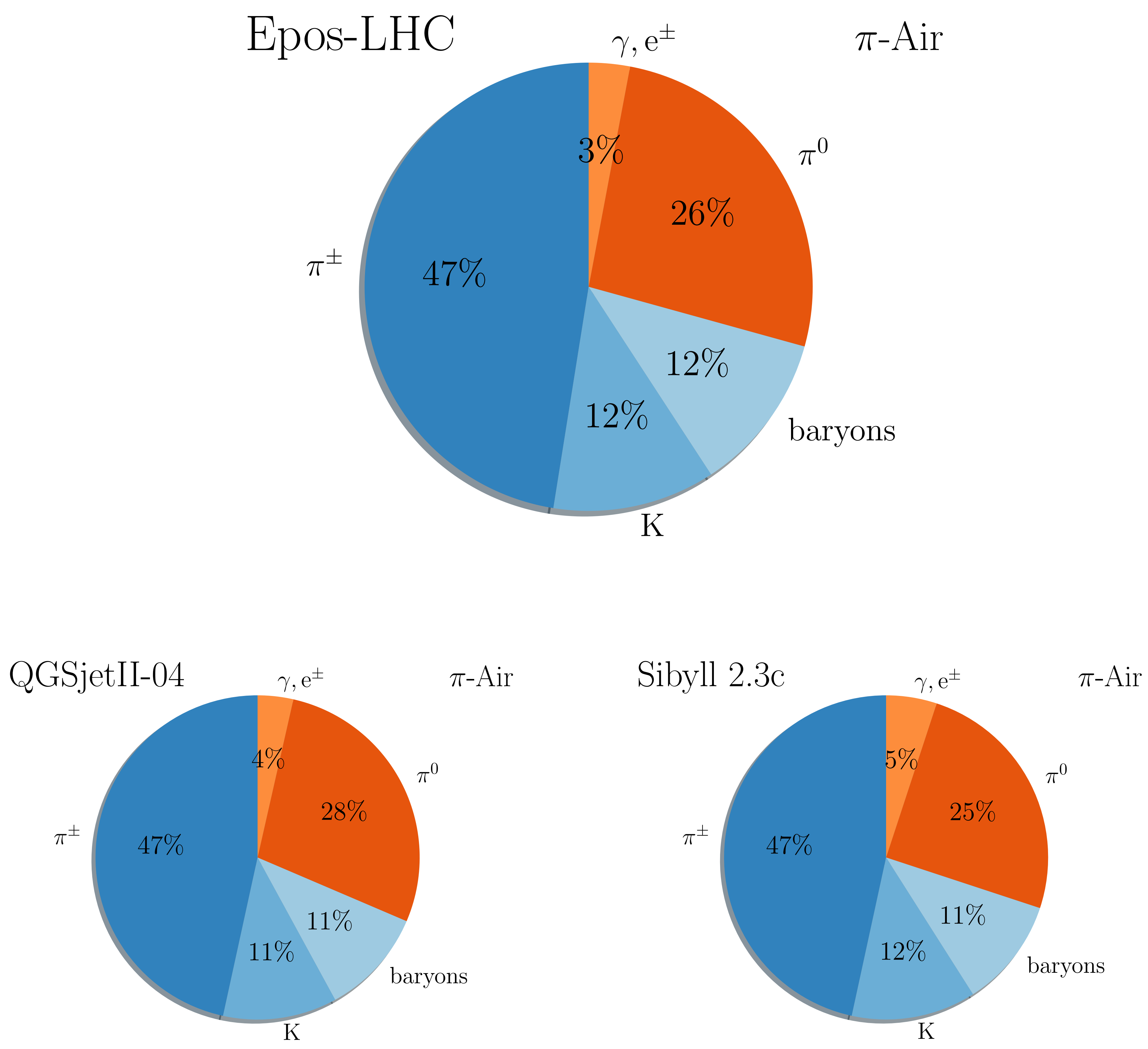
Particle energy fraction (10^{19} eV)



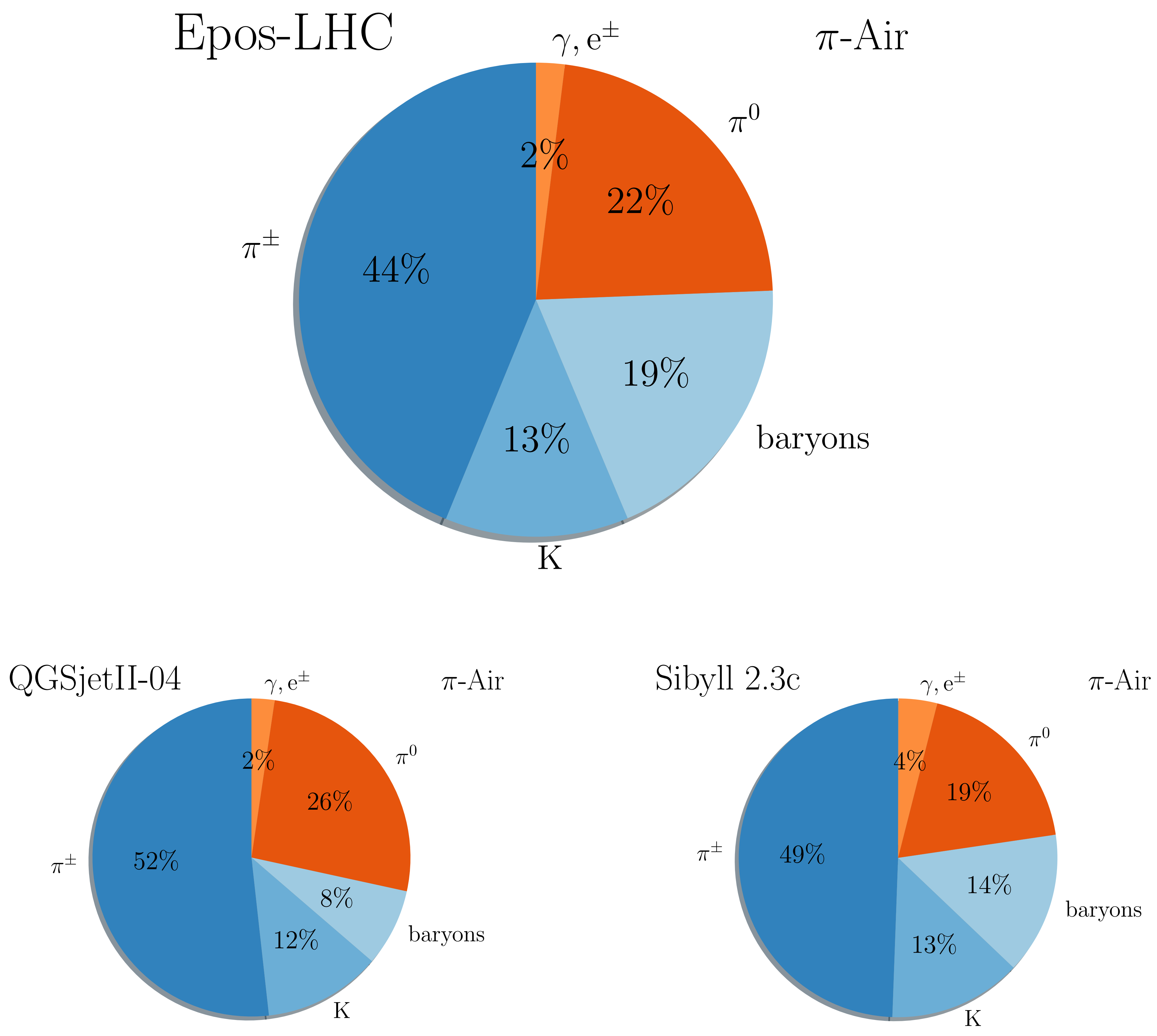
(Felix Riehn, 2022)

Model predictions for secondary particles: π-air

Particle multiplicity (10^{19} eV)

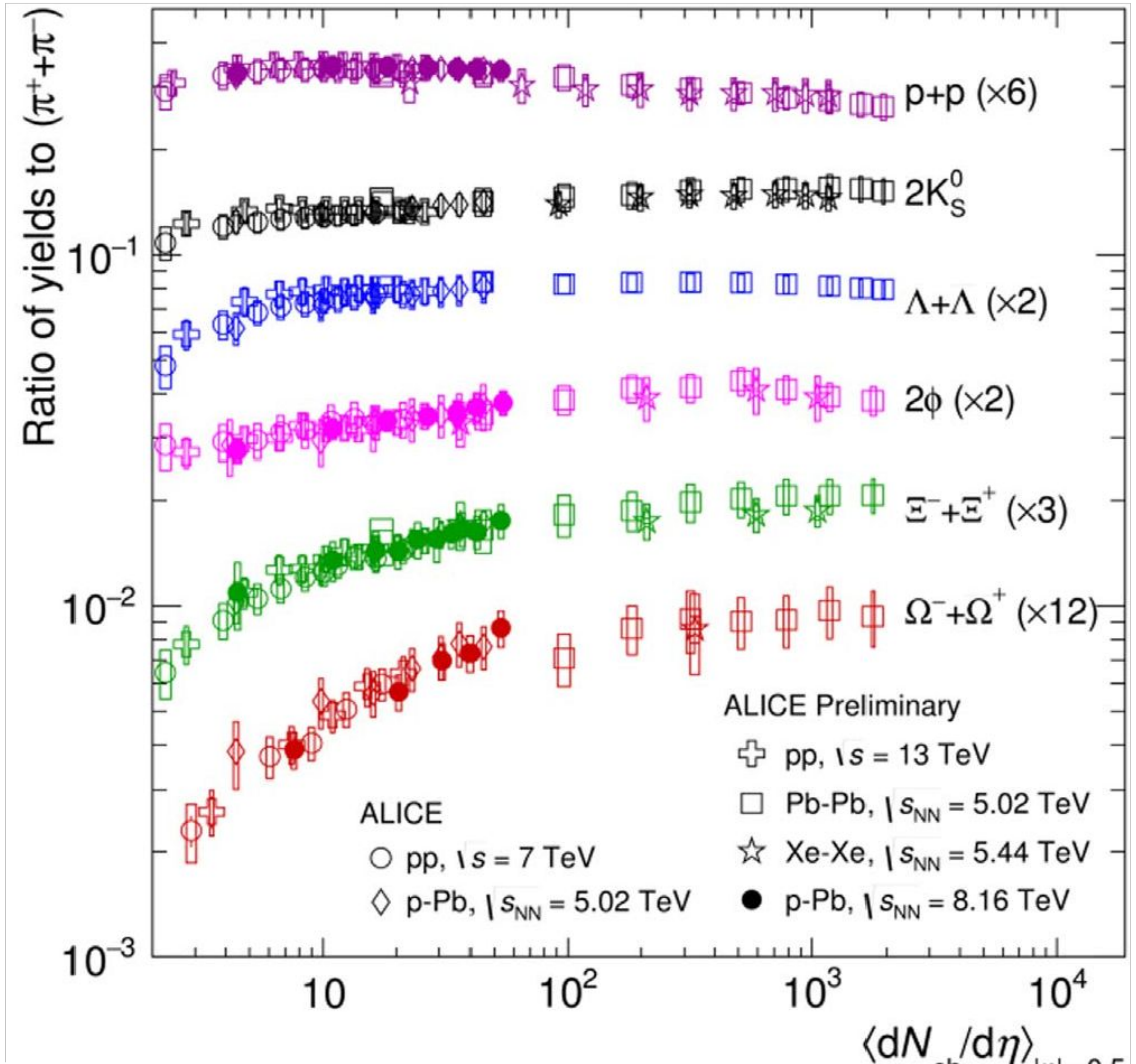


Particle energy fraction (10^{19} eV)



(Felix Riehn, 2022)

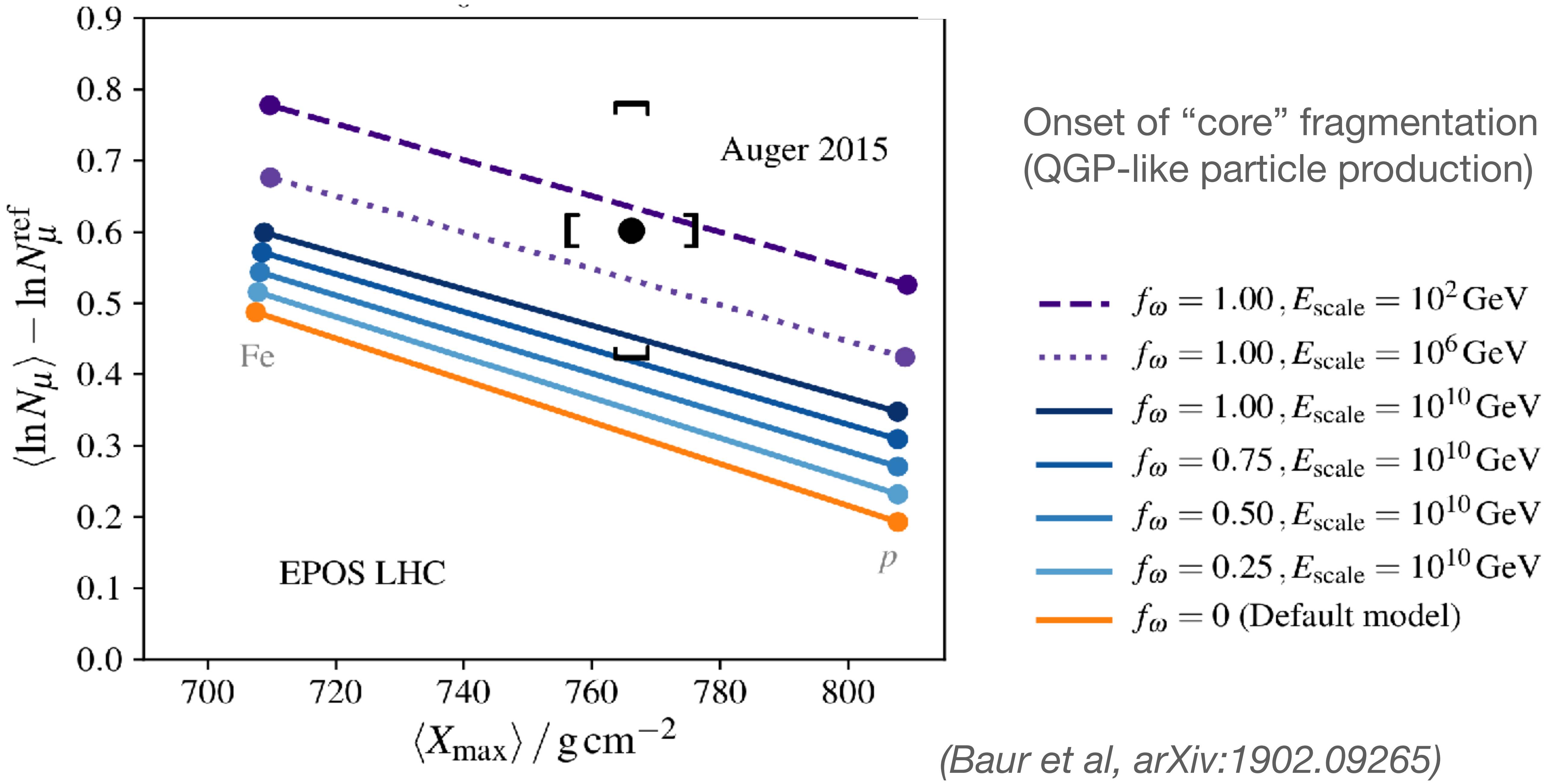
Universal particle scaling and core-corona model in EPOS



M. Vasileiou for ALICE, Phys. Scr. 95 (2020) 064007

ALICE: observation of **universal scaling of enhancement of heavy particles** with particle multiplicity or density *(Nature Phys. 13 (217) 535)*

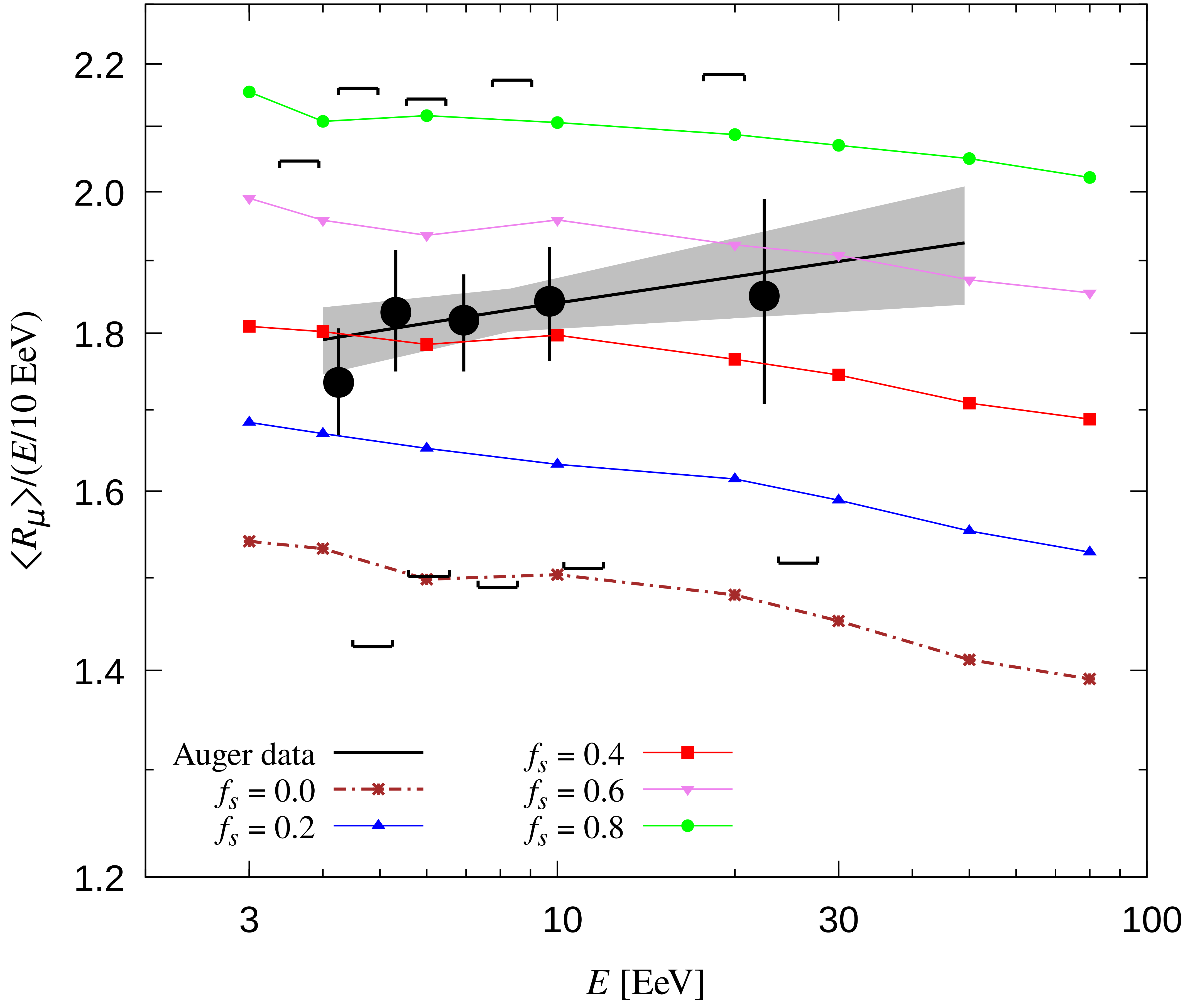
Does the same/similar scaling apply also in forward direction?



Onset of “core” fragmentation (QGP-like particle production)

(Baur et al, arXiv:1902.09265)

Phenomenological kaon enhancement model



(Anchordoqui et al. arXiv:2202.03095)

Probability f_s to change particles

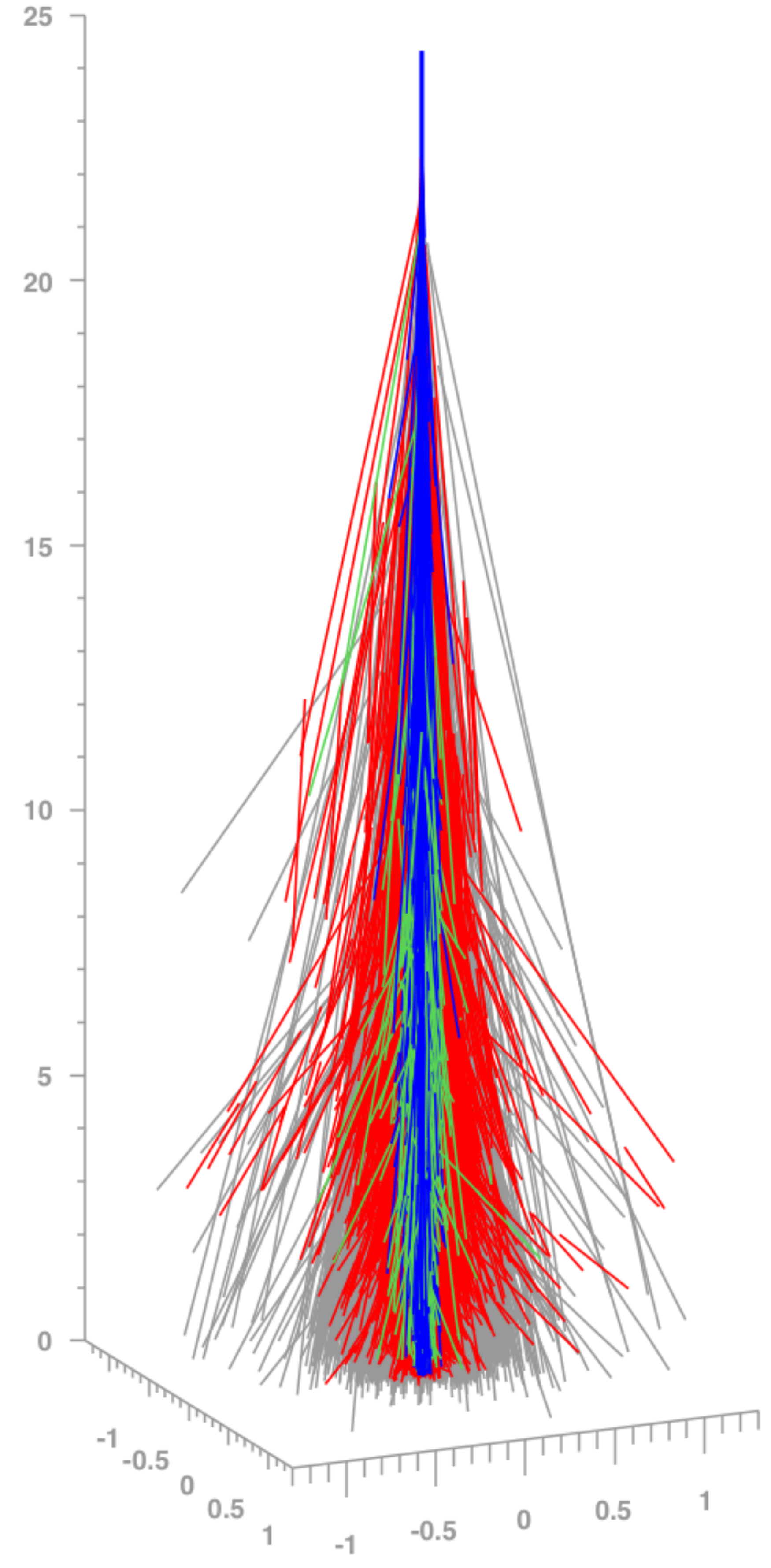
$$\pi^0 \longrightarrow K_S^0 / K_L^0$$

$$\pi^\pm \longrightarrow K^\pm$$

TABLE II: Global counters for the refined model with $f_s = 0.7$, in the case of 10^{19} eV proton showers inclined 67°.

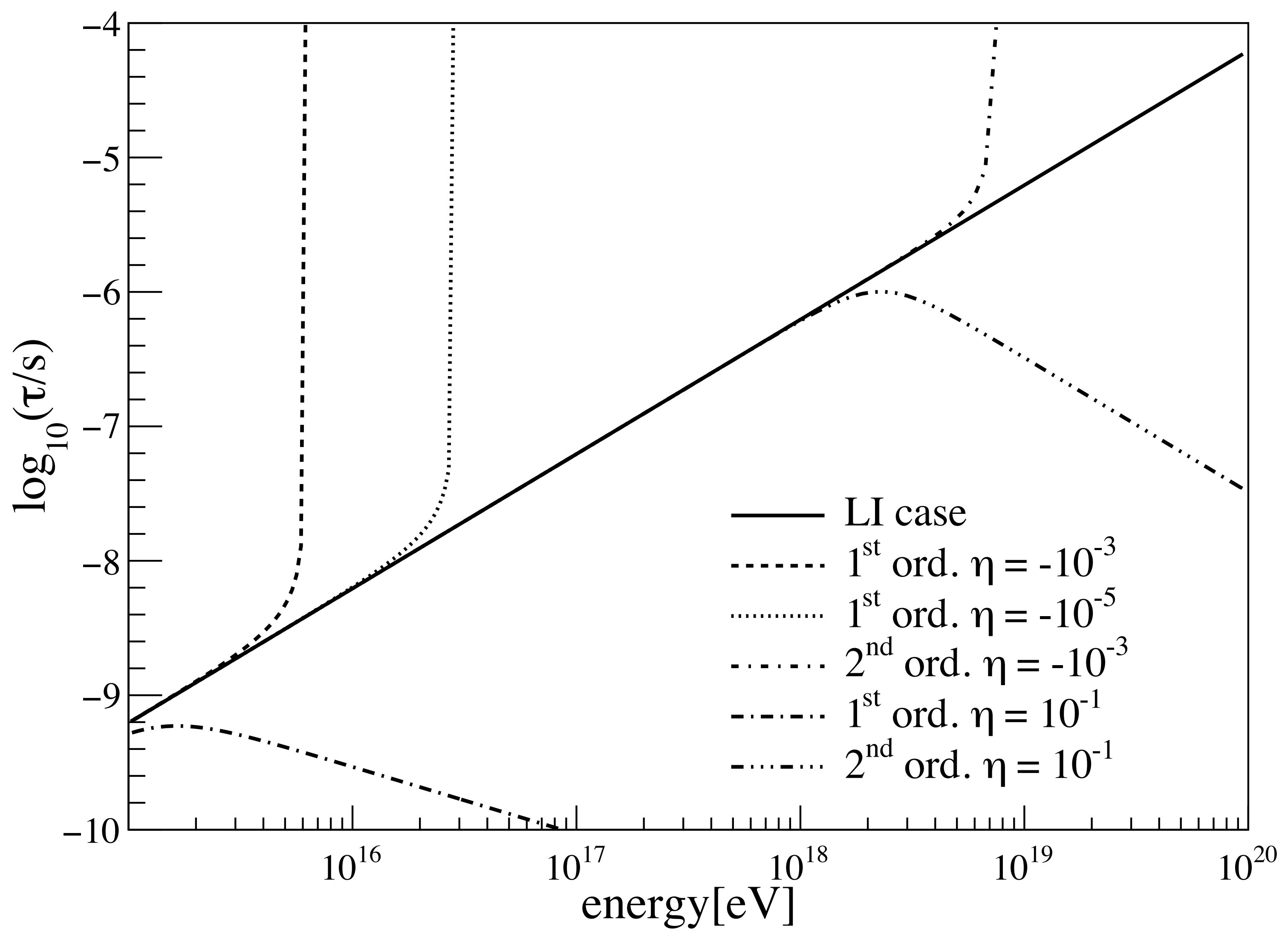
Total hadronic collisions per shower	264,600	100.00 %
Collisions with $E_{\text{proj}} < E_{\text{pmin}}$	262,070	99.04 %
Collisions with $E_{\text{proj}} > E_{\text{pmin}}$	2,530	0.96 %
Total number of secs. produced	6,806,244	100.00 %
Secs. from colls. with $E_{\text{proj}} < E_{\text{pmin}}$	6,544,194	96.15 %
Secs. from colls. with $E_{\text{proj}} > E_{\text{pmin}}$	262,050	3.85 %
Total number of pions scanned	134,060	1.97 %
Pions considered for swapping:		
Central ($\lvert\eta_{\text{CM}}\rvert < 4$)	99,790	1.47 %
Peripheral ($\lvert\eta_{\text{CM}}\rvert > 4$)	34,270	0.50 %
Total (central + peripheral)	134,060	1.97 %
Pions actually swapped	23,988	0.35 %

Lorentz invariance violation (LIV) and muon production



(Auger, ICRC 2021)

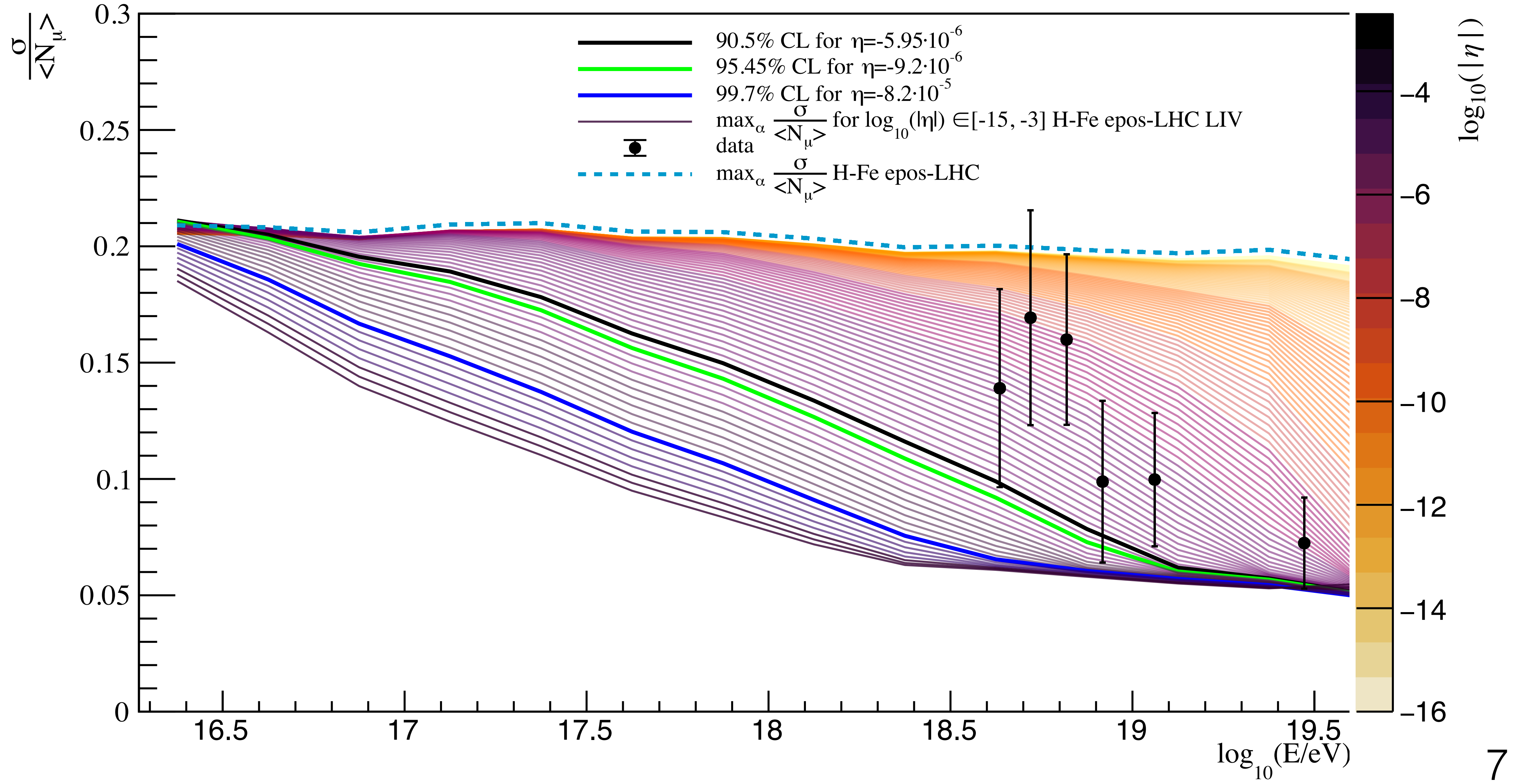
Lorentz-dilated lifetime of neutral pions



$$E^2 - p^2 = m^2 + \eta^{(n)} \frac{p^{n+2}}{M_{\rm Pl}^n}$$

$$\gamma_{\rm LIV} = E/m_{\rm LIV}$$

$$m_{\rm LIV}^2 = m^2 + \eta^{(n)} \frac{p^{n+2}}{M_{\rm Pl}^n}$$

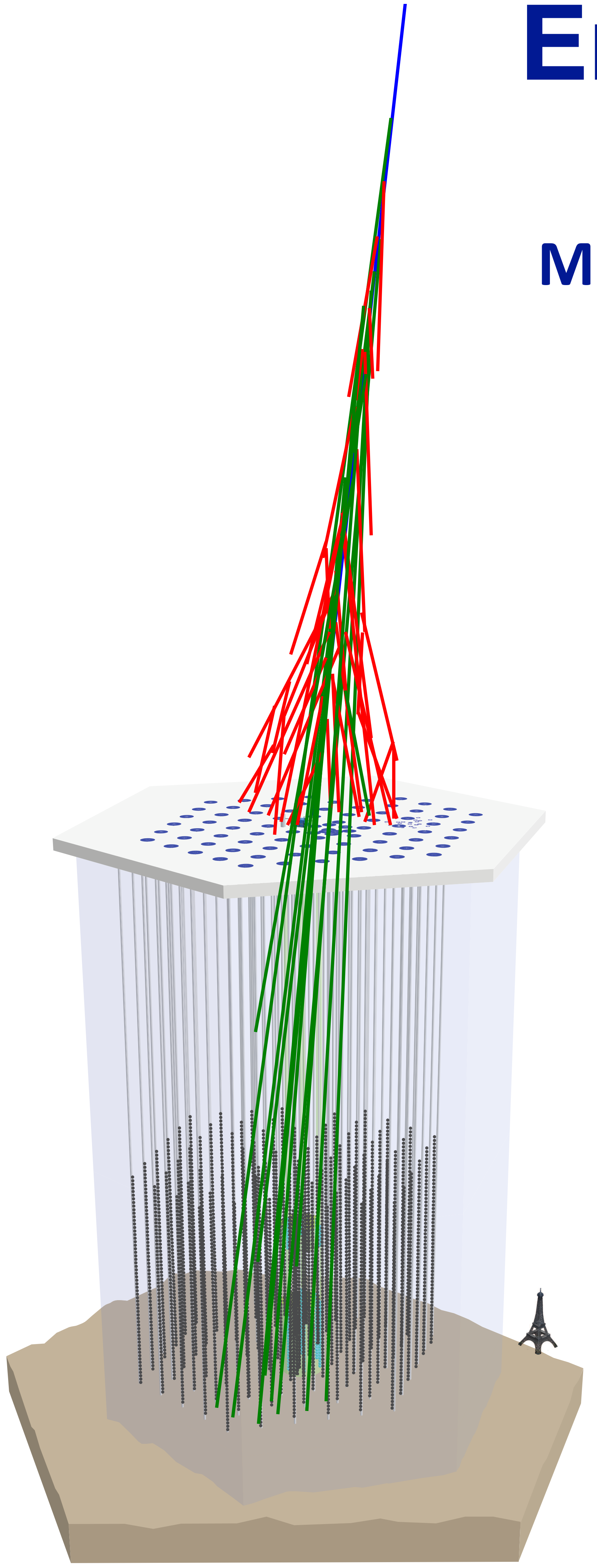


Comparison of model simulations with data on muon number fluctuations

Muon enhancement, limits on LIV

Energy spectrum of muons in air showers

Muon energy spectrum in EAS relative to that of Sibyll 2.1

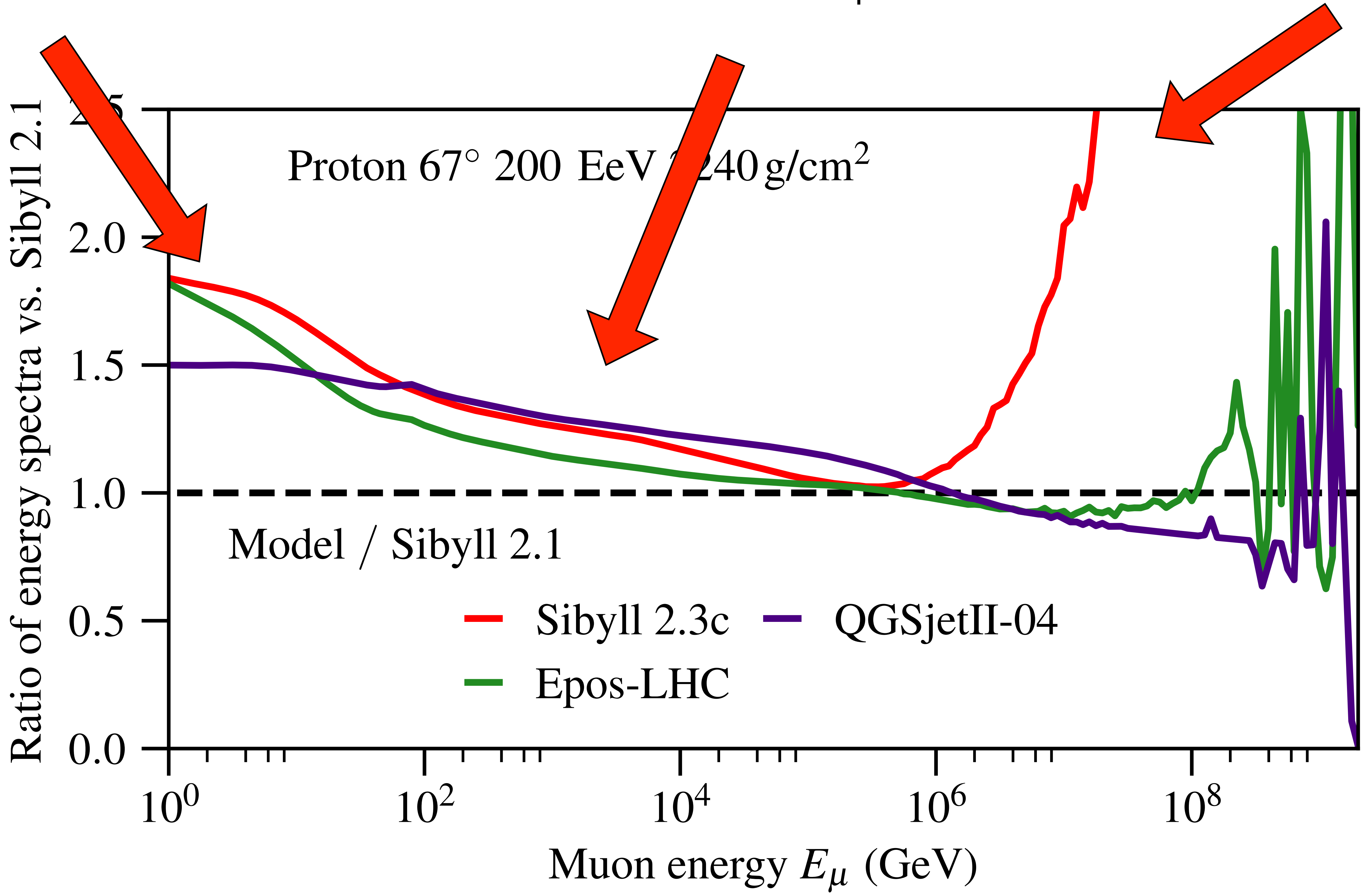


Correlation of low energy muons (surface ~ 1GeV) and in-ice (~500 GeV) muon bundles

Low-energy enhancement due to baryon pair production

Rho-0 production

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



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

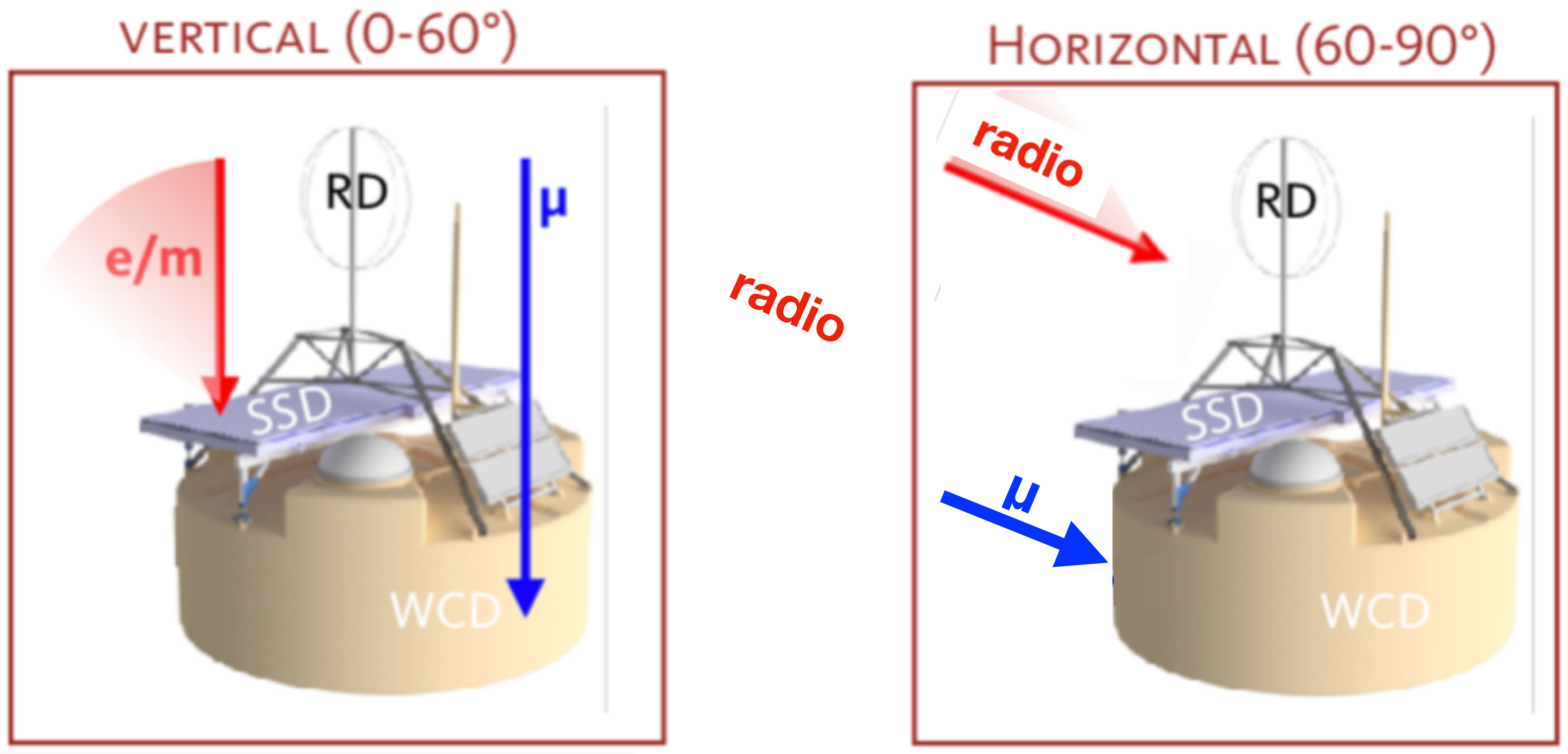
Backup slides

Upgrade of the Observatory – AugerPrime

Physics motivation

- Composition measurement up to 10^{20} eV
- Composition selected anisotropy
- Particle physics with air showers
- Much better understanding of **new and old** data

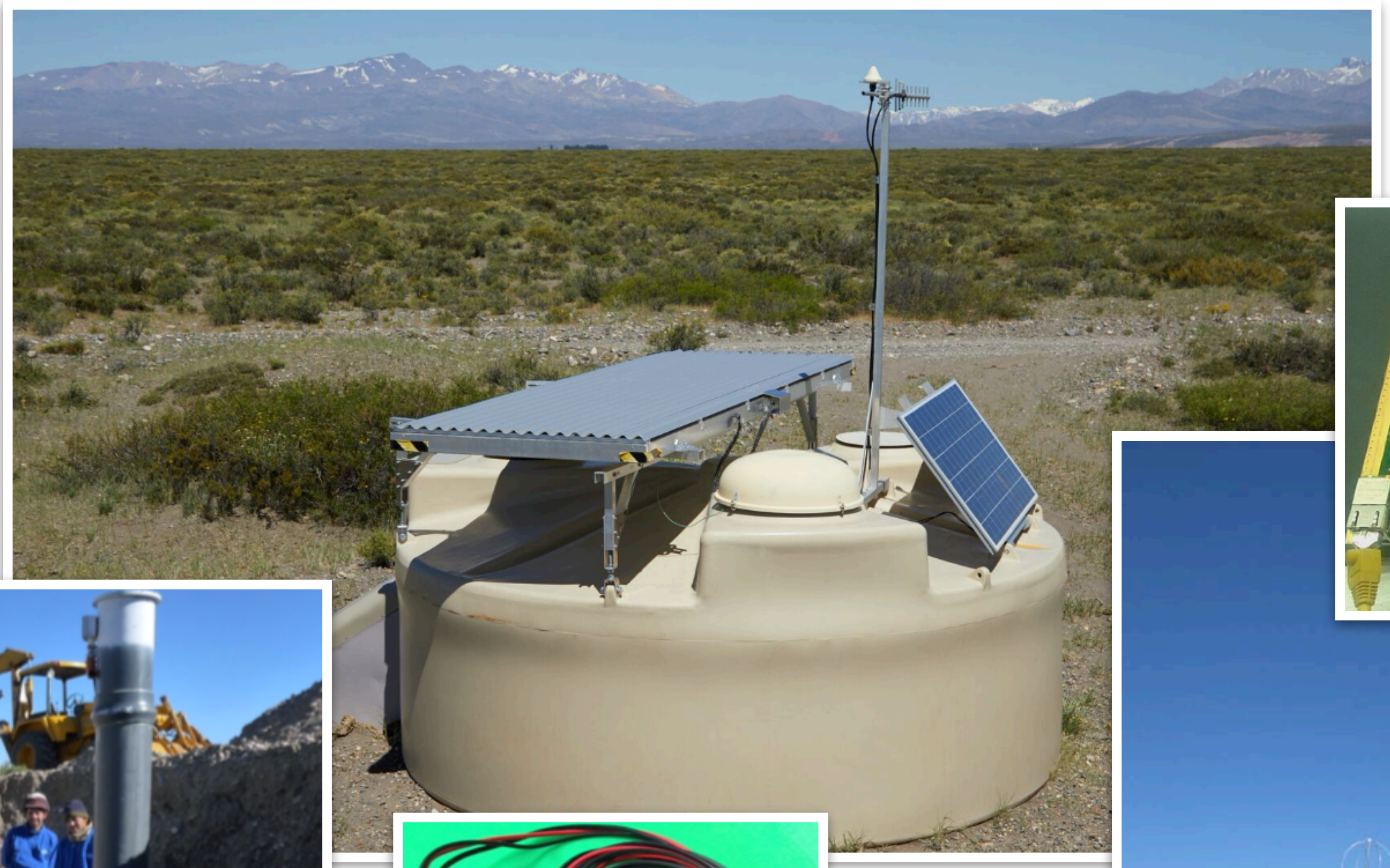
Composition sensitivity with 100% duty cycle

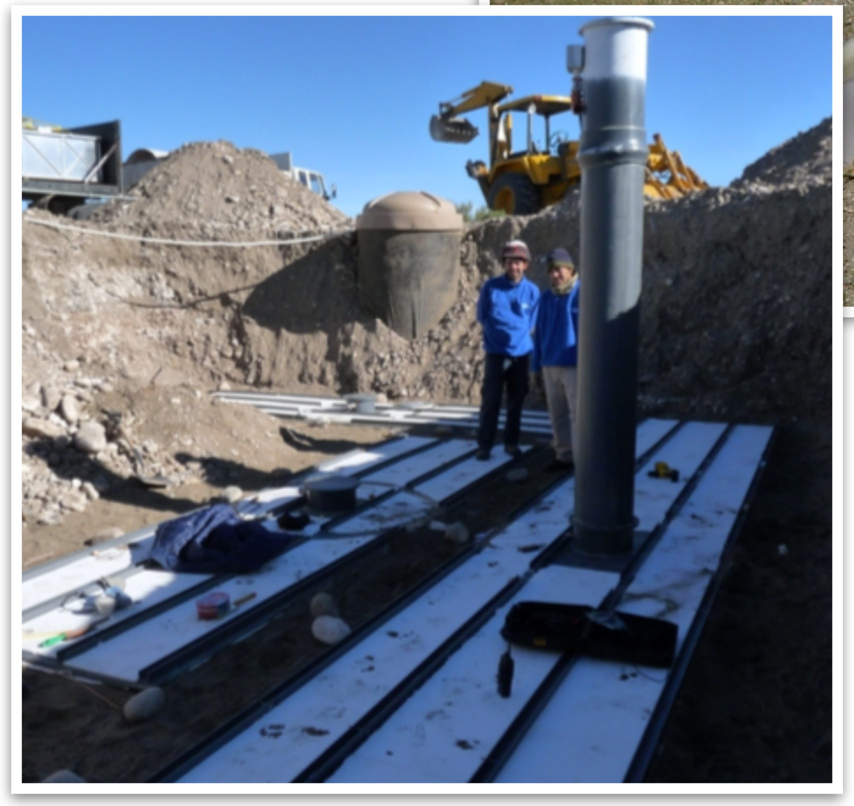


(AugerPrime design report 1604.03637)

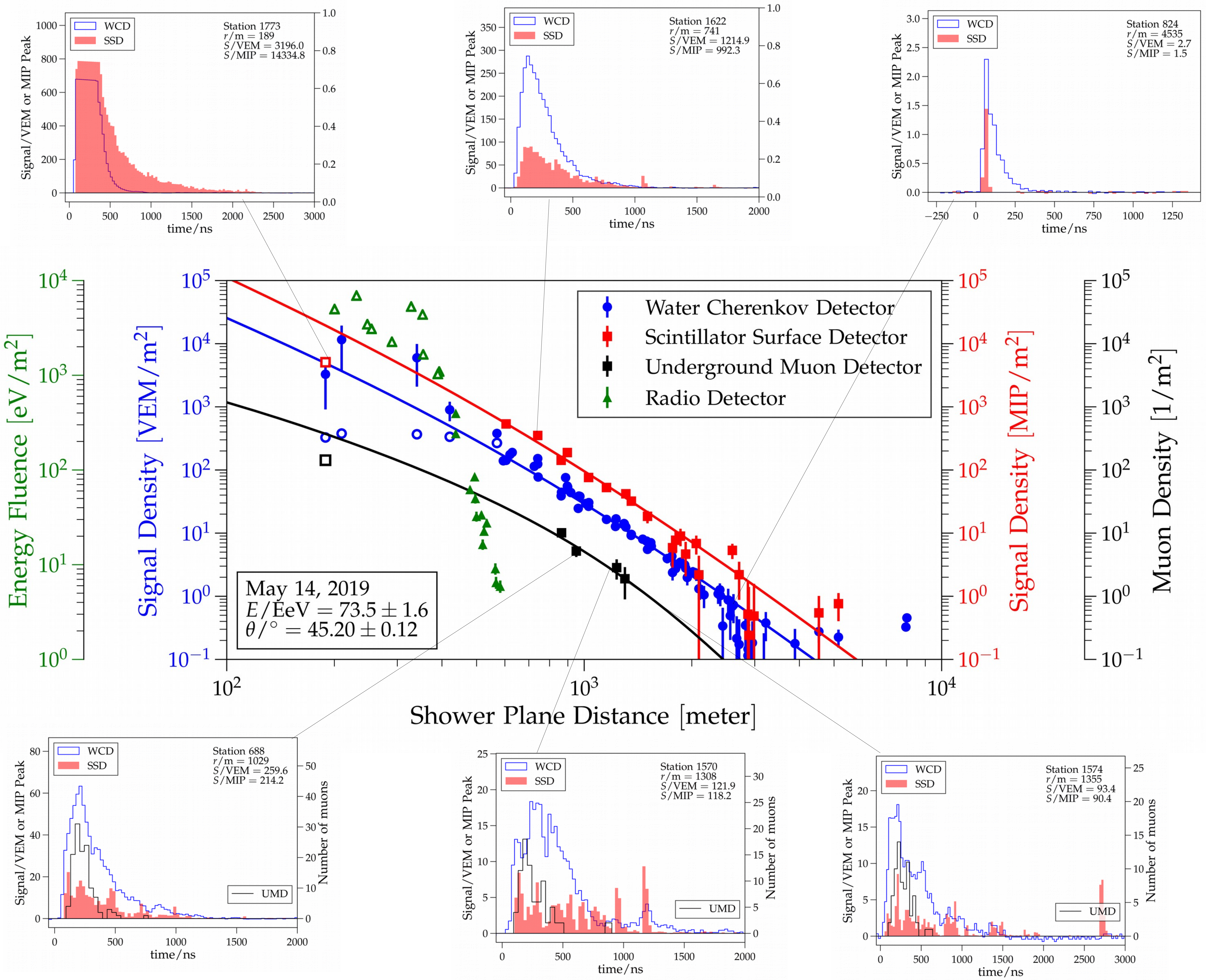
Components of AugerPrime

- 3.8 m^2 scintillator panels (SSD)
- New electronics (40 MHz -> 120 MHz)
- Small PMT (dynamic range WCD)
- Radio antennas for inclined showers
- Underground muon counters (750 m array, 433 m array)
- Enhanced duty cycle of fluorescence tel.

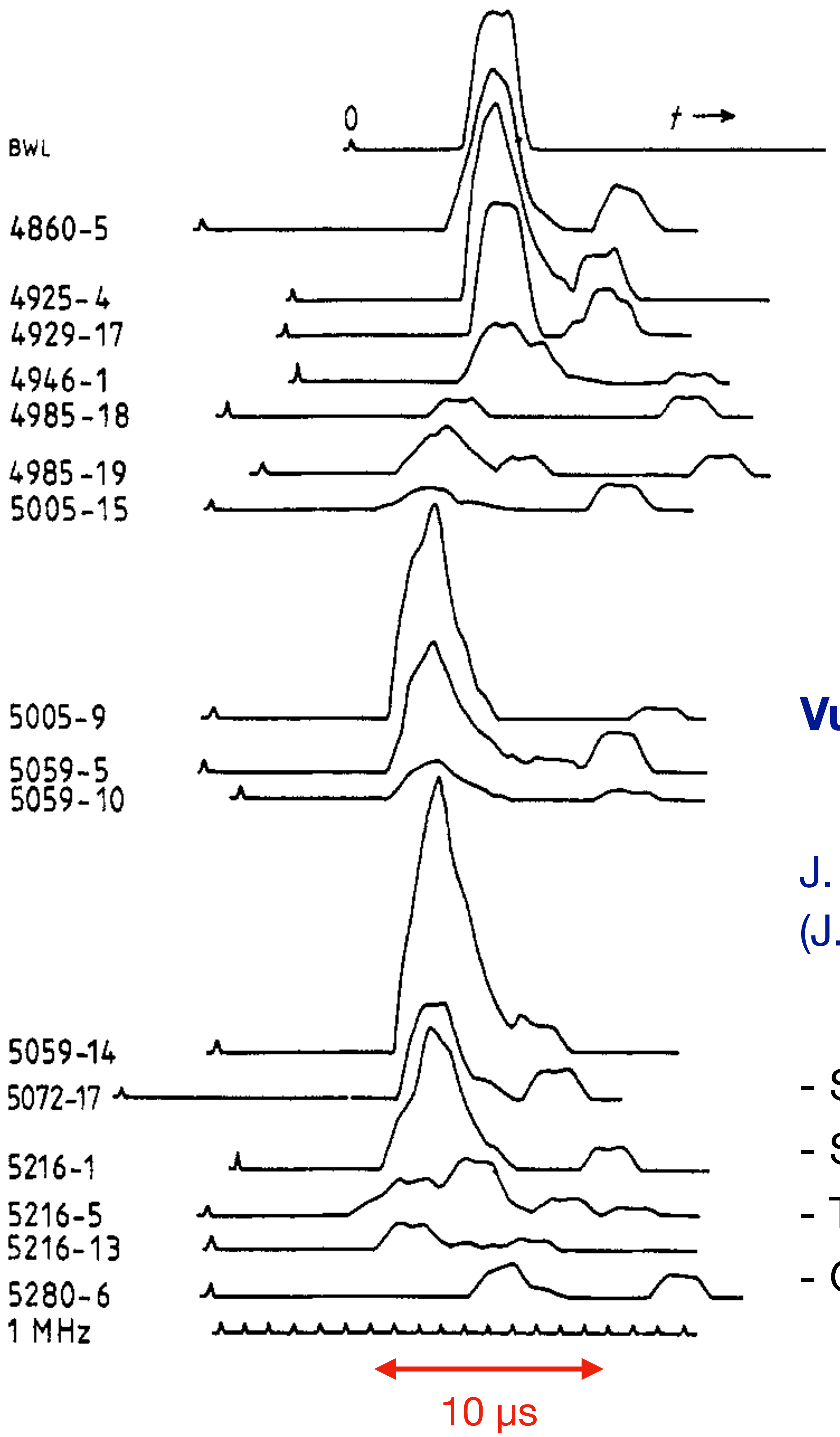




AugerPrime: New quality of data – multi-hybrid measurements



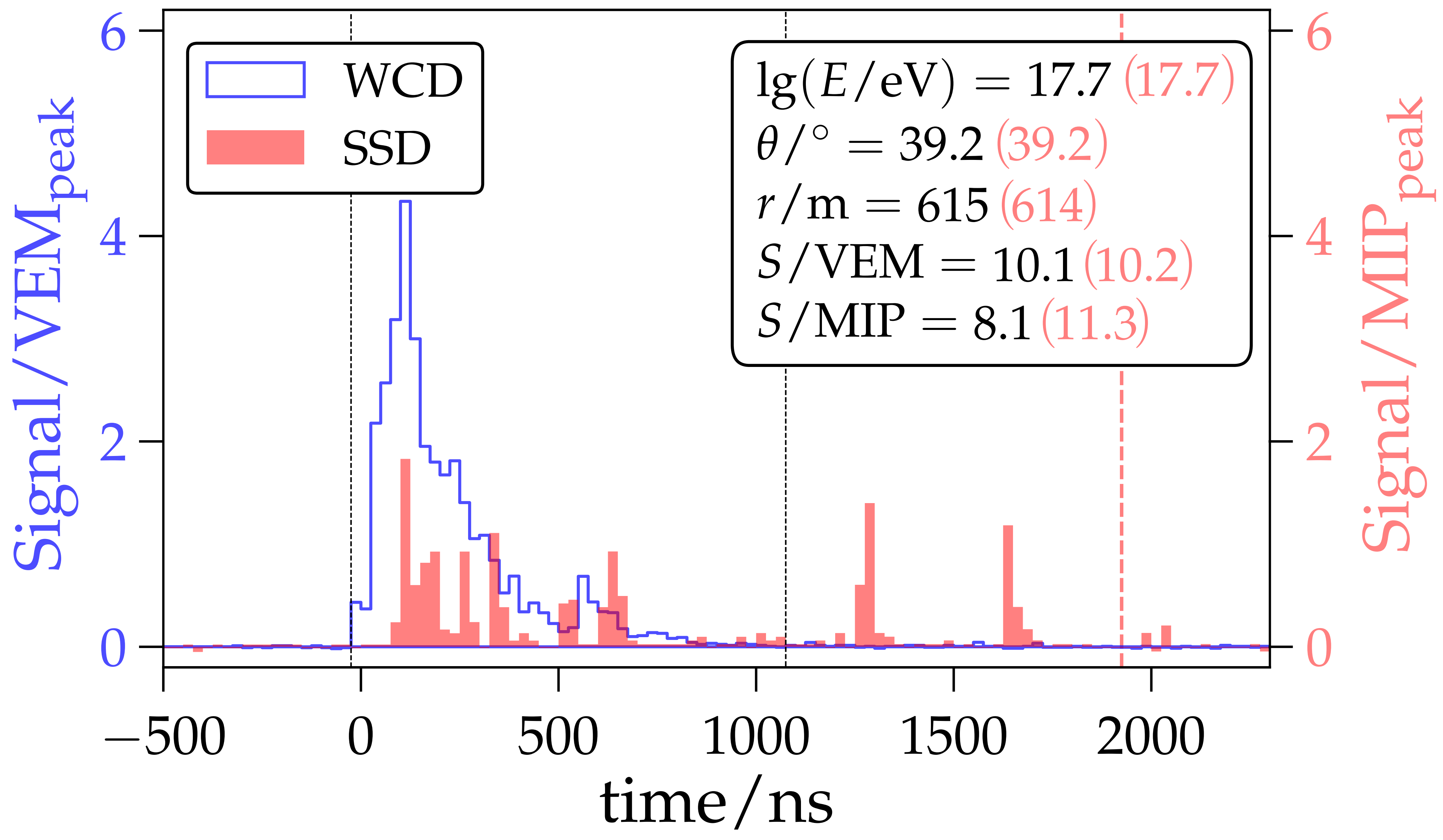
Sub-luminal neutrons in air showers



Vulcano Ranch (1962-63)

J. Linsley
(J. Phys. G: Nucl. Phys. 10 (1984) L191)

- Sub-luminal pulses with a delay of at least 3μs
- Sometimes several pulses observed
- Typically 1 km from core, high-energy showers
- Greisen: **neutrons** as sub-luminal particles

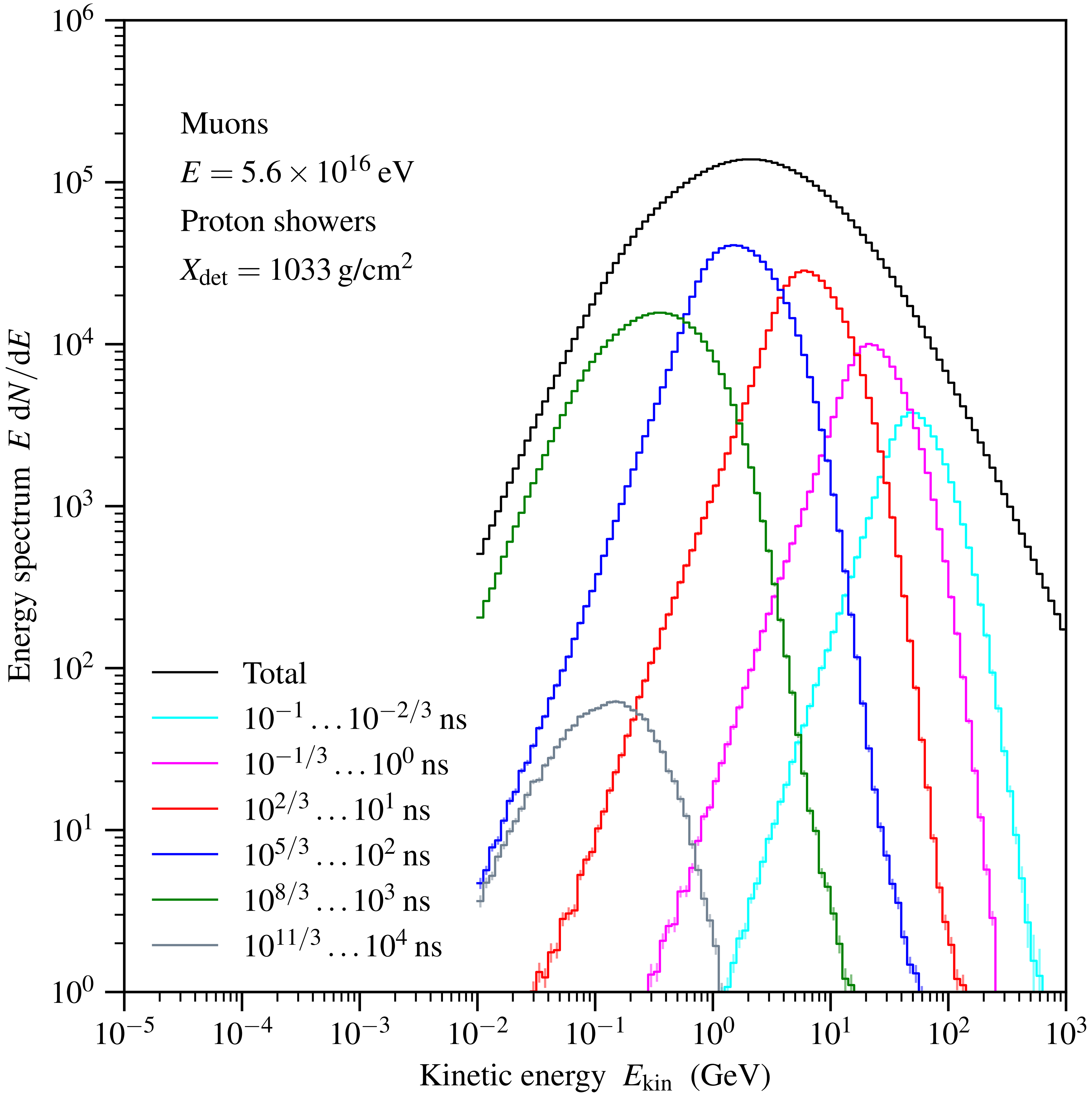


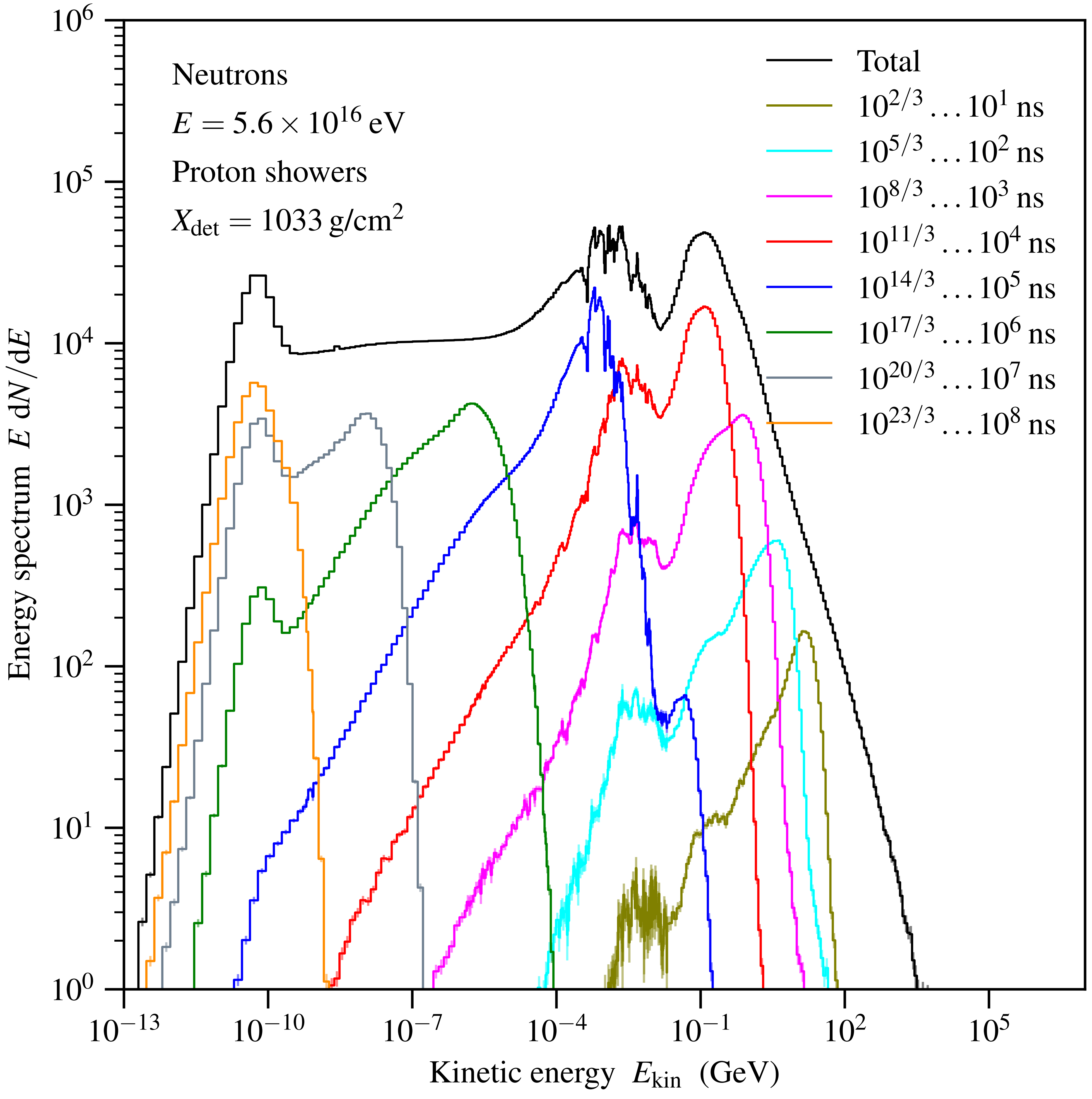
AugerPrime (2020-21)

D. Schmidt, Pierre Auger Collaboration
(this conference)

- Late signals seen in scintillators (SSD)
- Late pulses have no coincident signal in water-Cherenkov detectors (WCD)
- Similar height distribution of late pulses?

Air shower results: time delay distribution



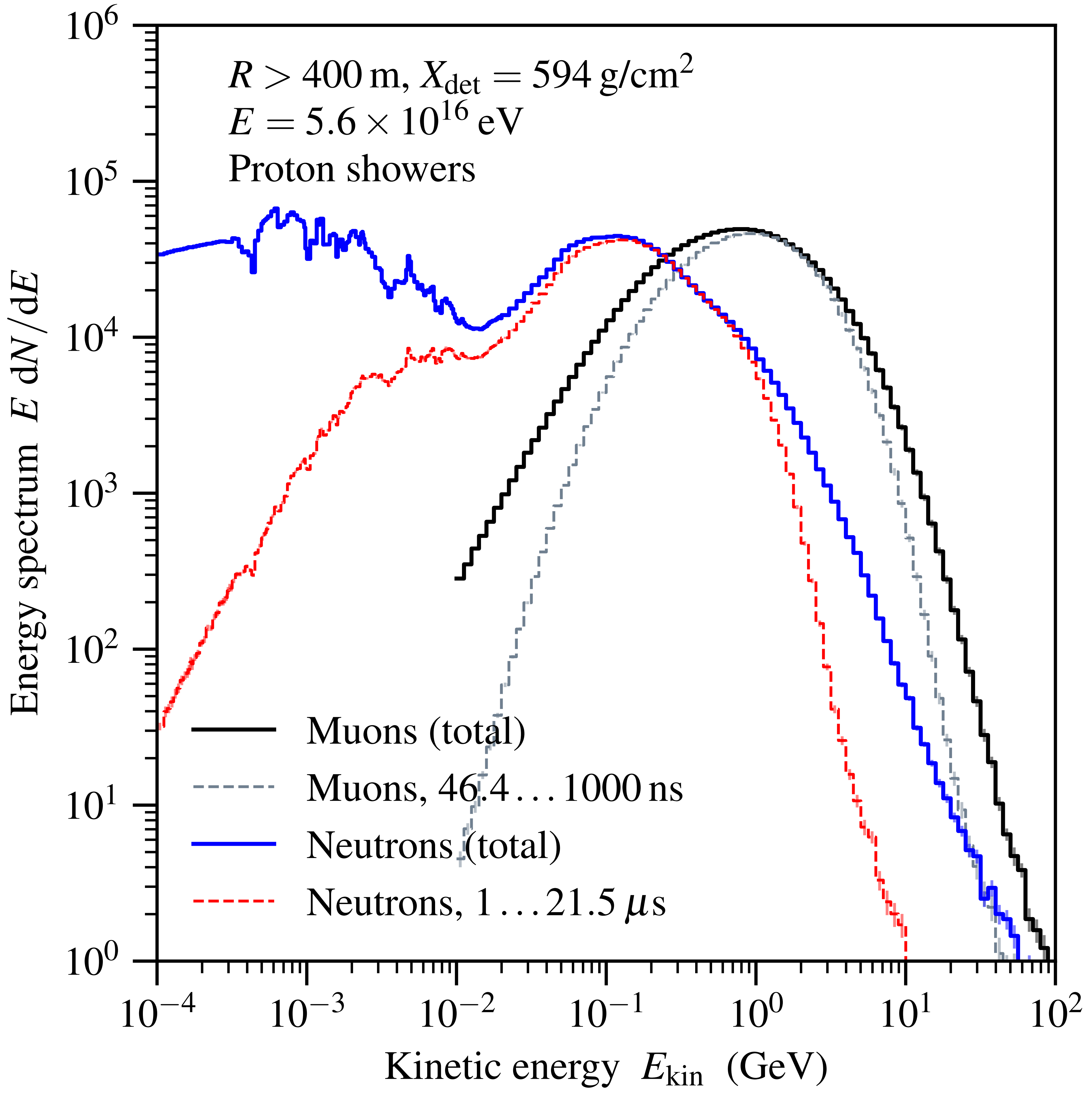


Muons: time delay of bulk of particles: 1 - 500 ns

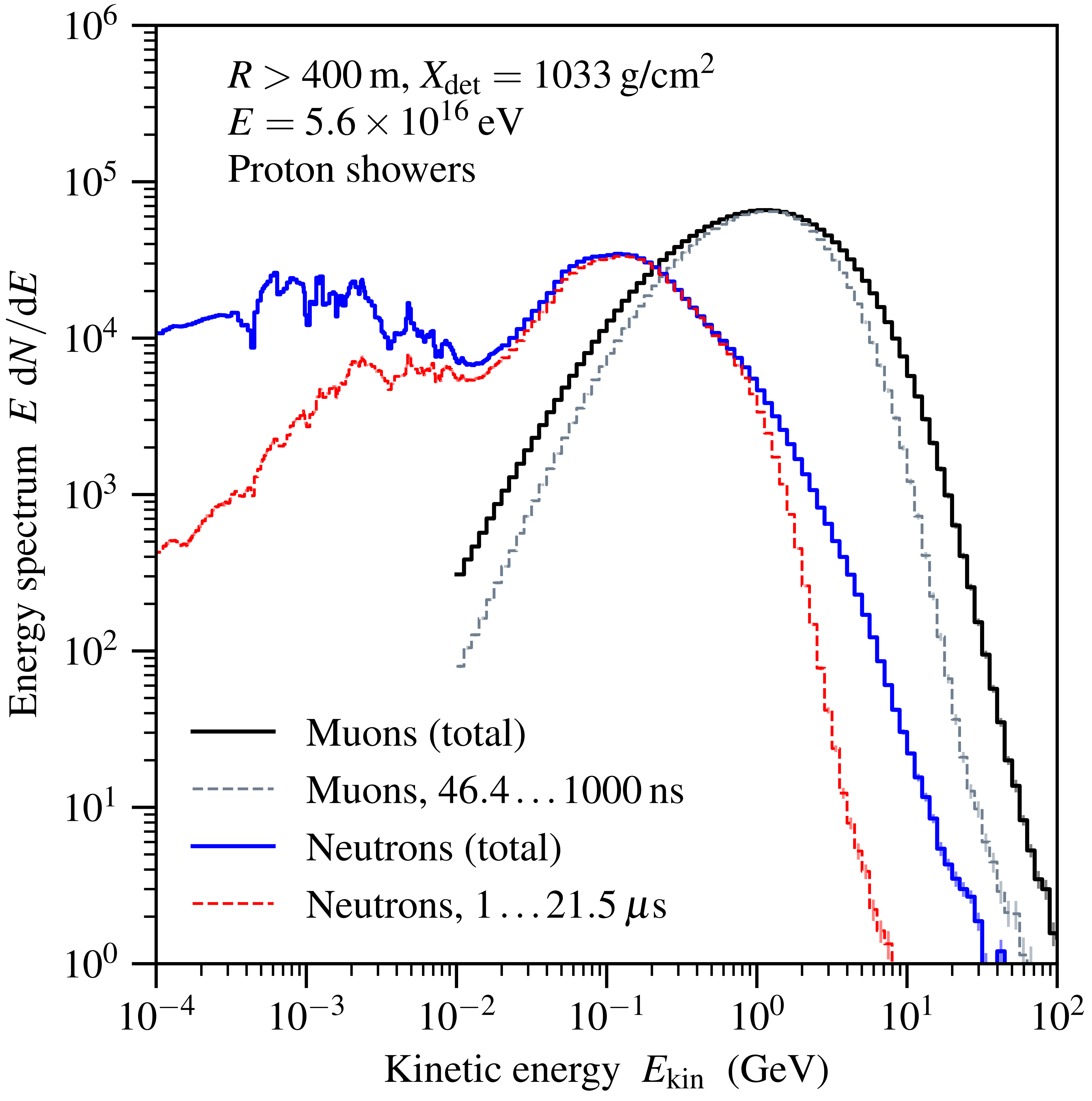
Neutrons: time delay of high-energy particles: 1 - 20 μs, slow (thermal) neutrons up to 100 ms

(RE & Ferrari et al. ICRC 2021)

Air shower results: muons vs. neutrons at large distance



Close to shower maximum: neutrons as abundant as muons



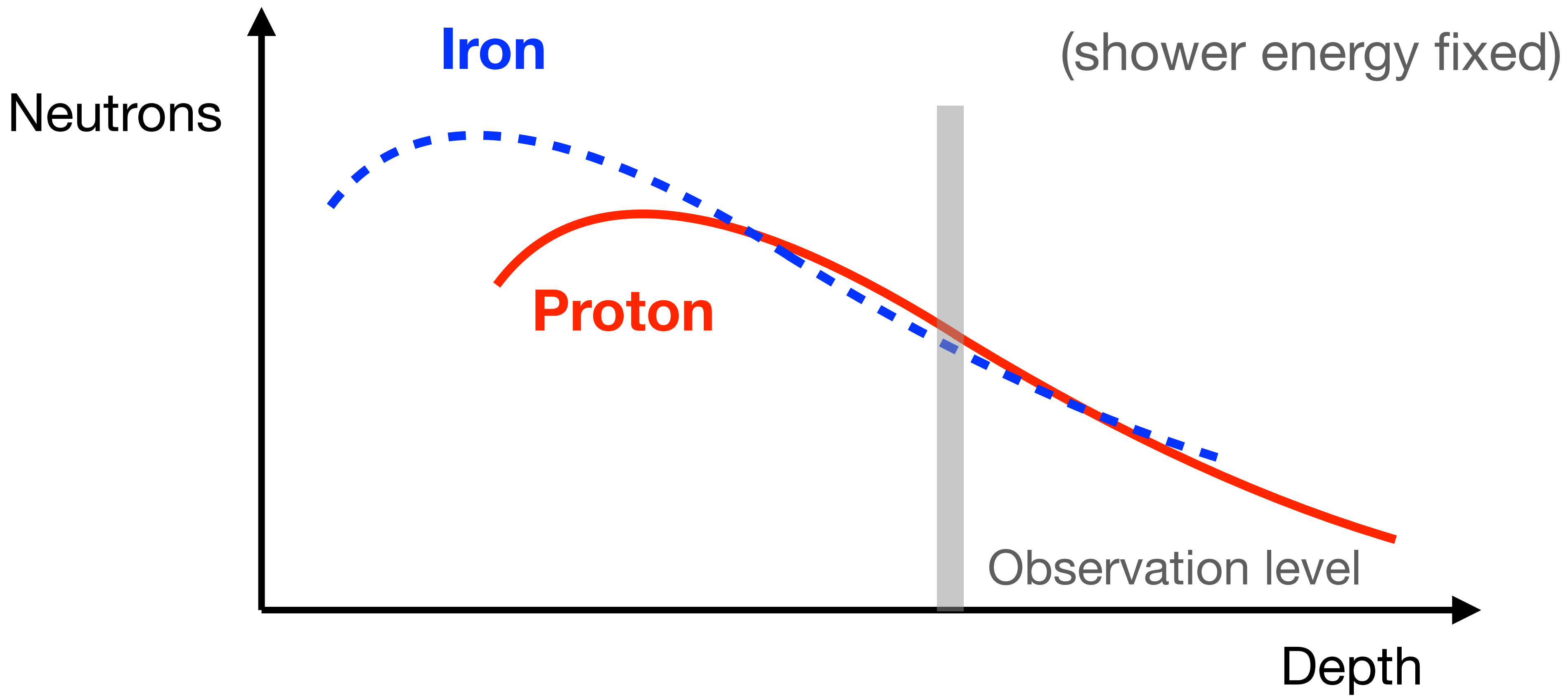
Past shower maximum: neutrons much less abundant than muons

(RE & Ferrari et al. ICRC 2021)

Do we learn anything from sub-luminal neutrons?

Neutrons

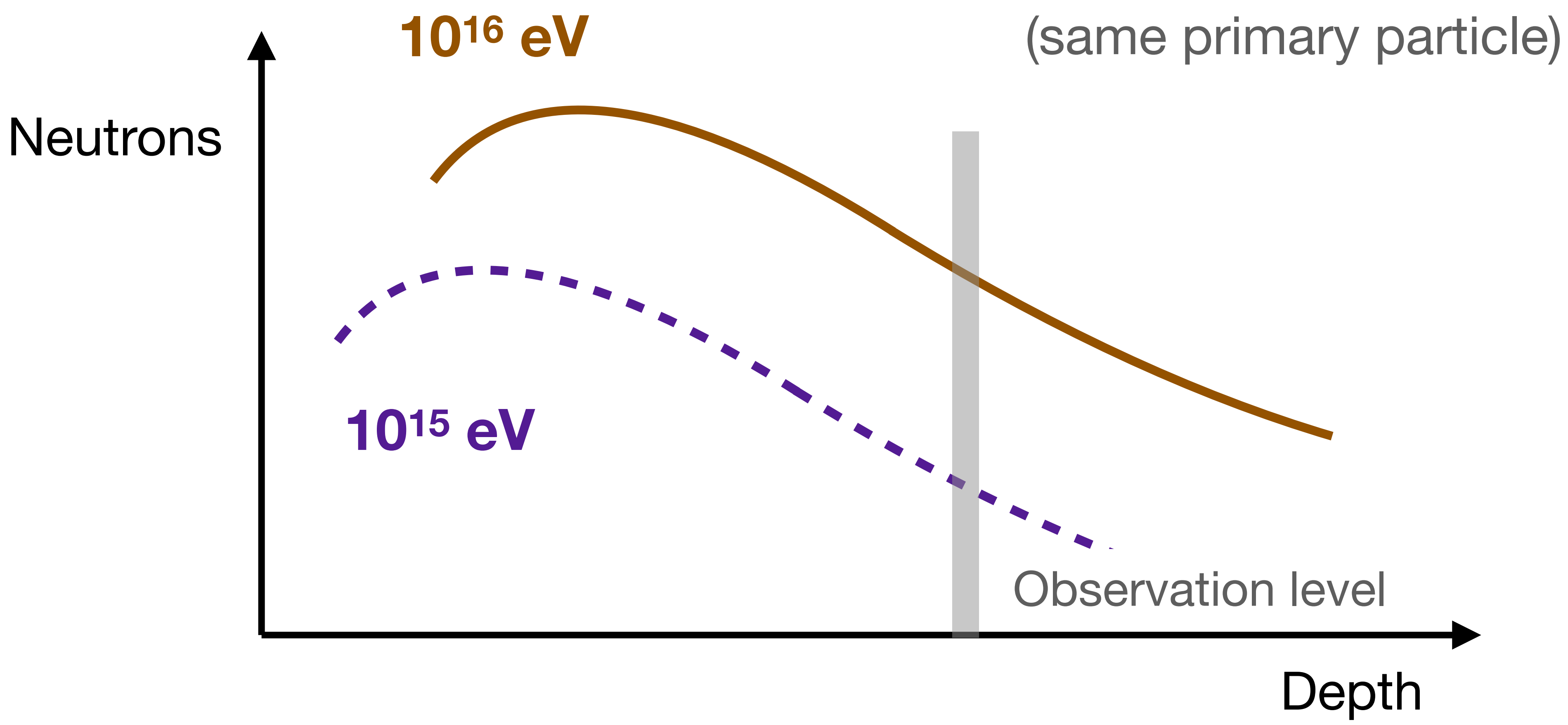
- Interesting sub-luminal particles
- Feature-rich and very wide energy spectrum
- Notoriously difficult to detect
- Very difficult to simulate accurately (environment)
- Expected to produce late pulses in scintillators



Reduced composition sensitivity?

Scaling observations

- Energy scaling of production similar to muons
- Primary dependence of production like muons
- Attenuation (neutron removal) length 80 … 200 g/cm^2
- Very wide lateral distribution, wider than muons
- Typical delay in arrival time ~ 1 … 20 μs (E_{kin} > 20 MeV)
- Thermal neutrons up to ~ 100 ms



Scaling faster than ~ $E^{0.9}$

(RE & Ferrari et al. ICRC 2021)