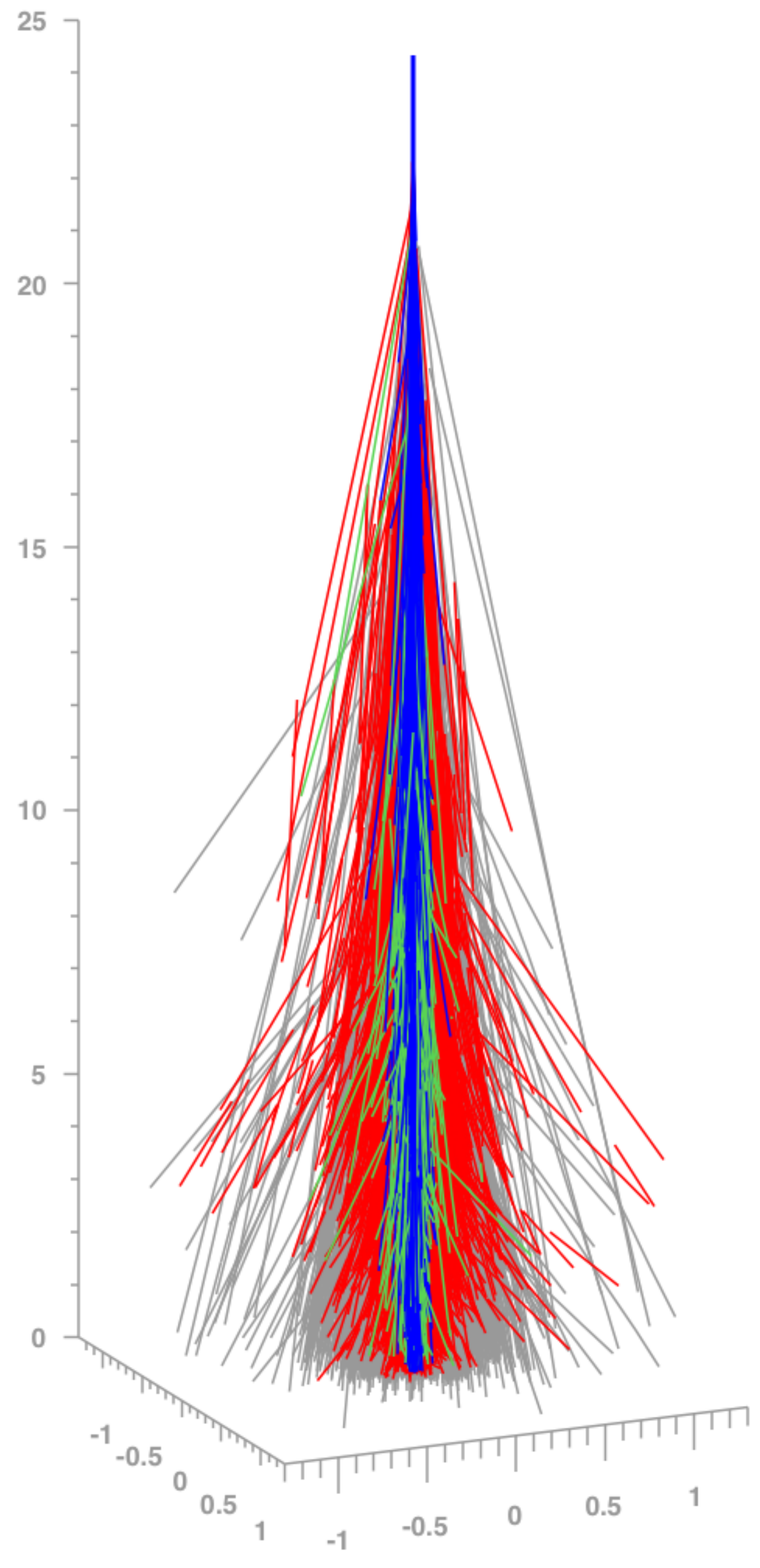
# Ultra-High-Energy Cosmic Rays and Hadronic Interactions

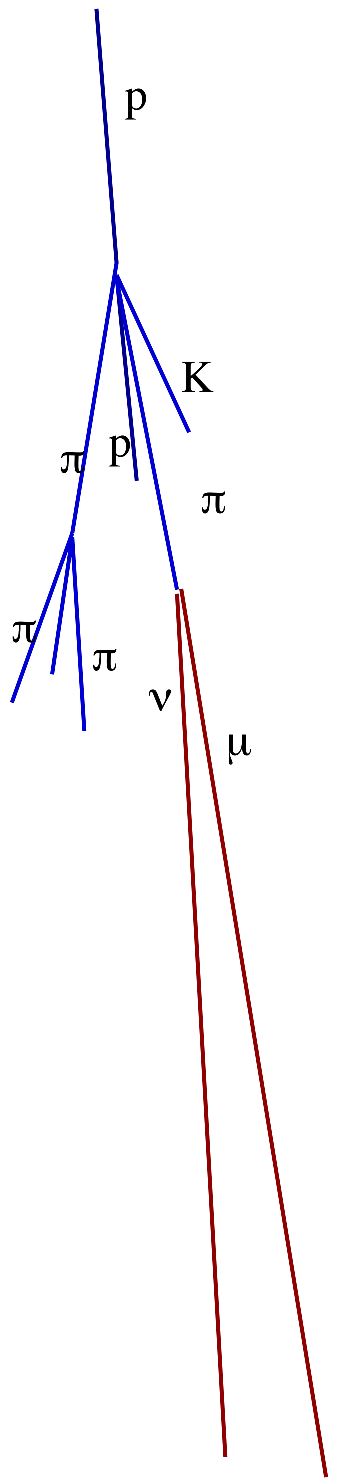
## Part 2: Particle Physics Aspects

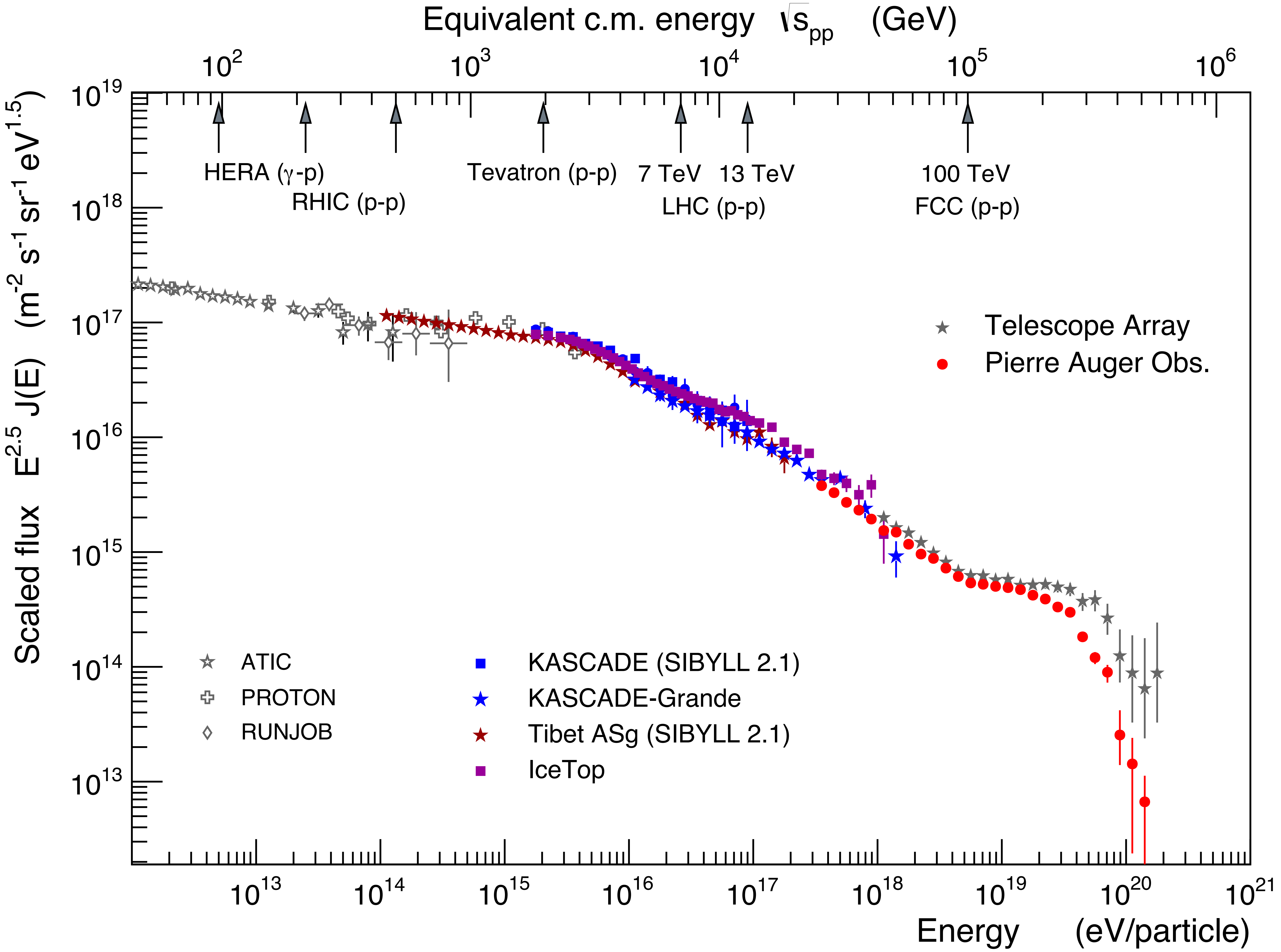


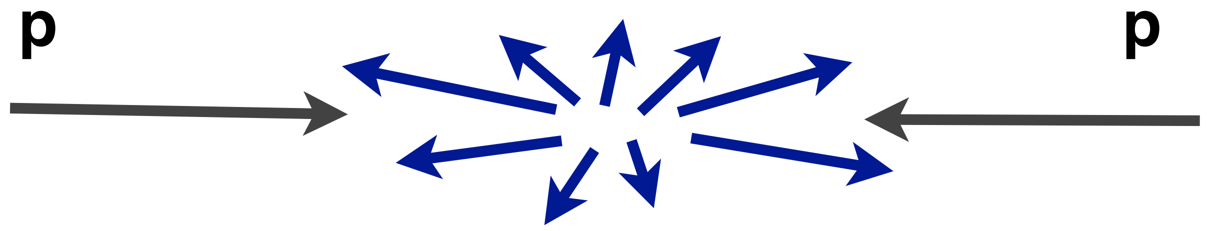

Ralph Engel *(Karlsruhe Institute of Technology)*

Karlsruhe Institute of Technology

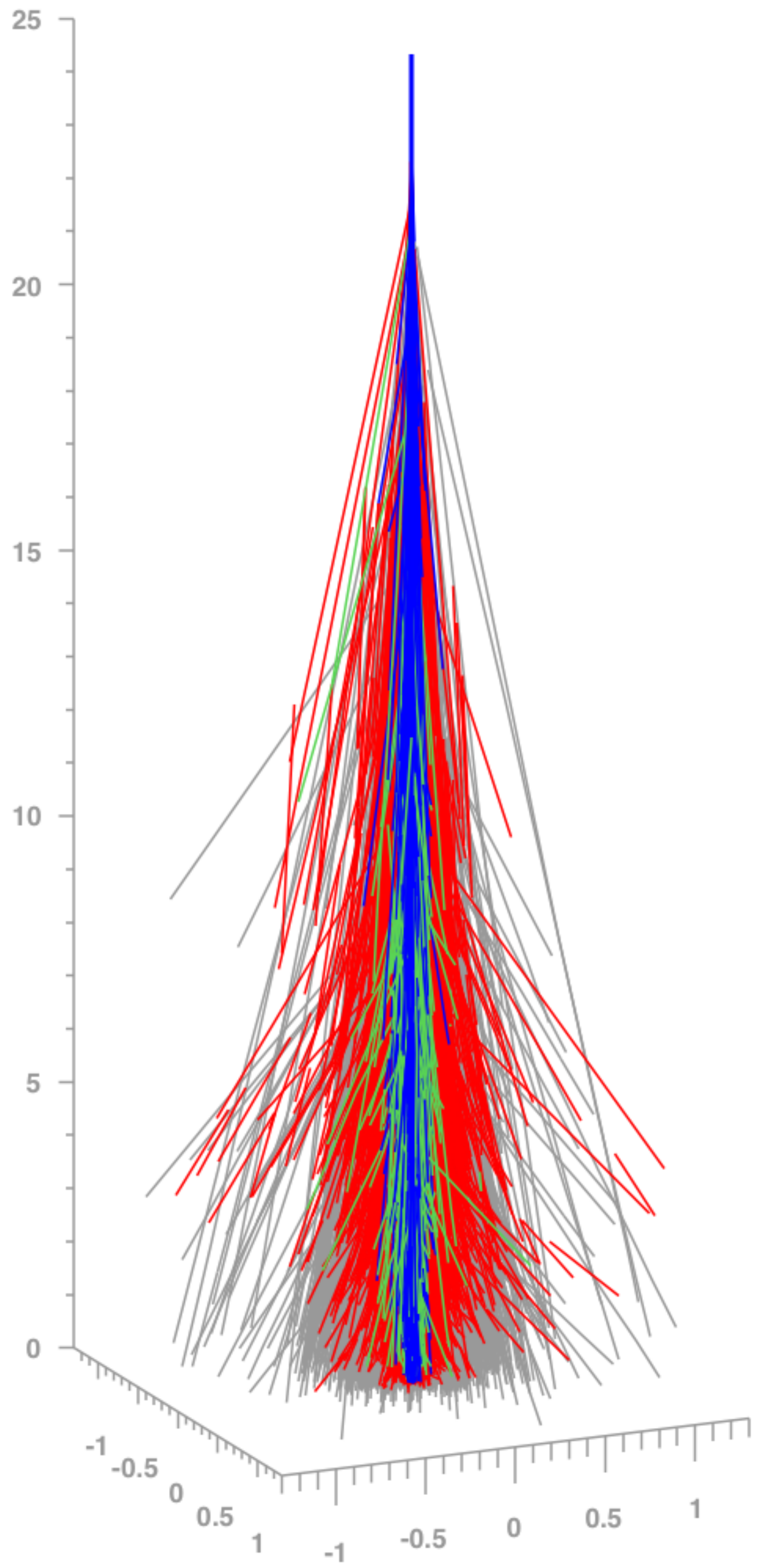
# Cosmic ray flux and interaction energies



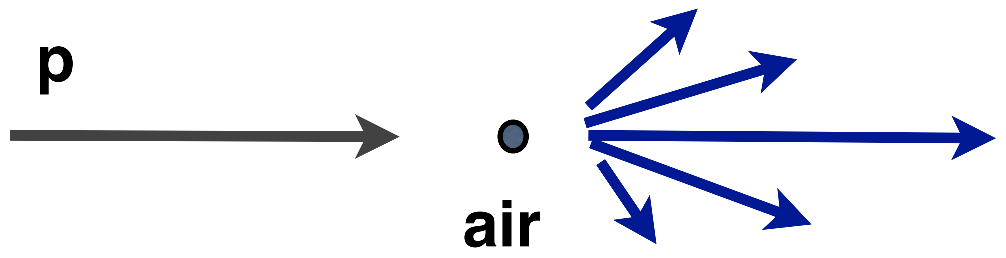



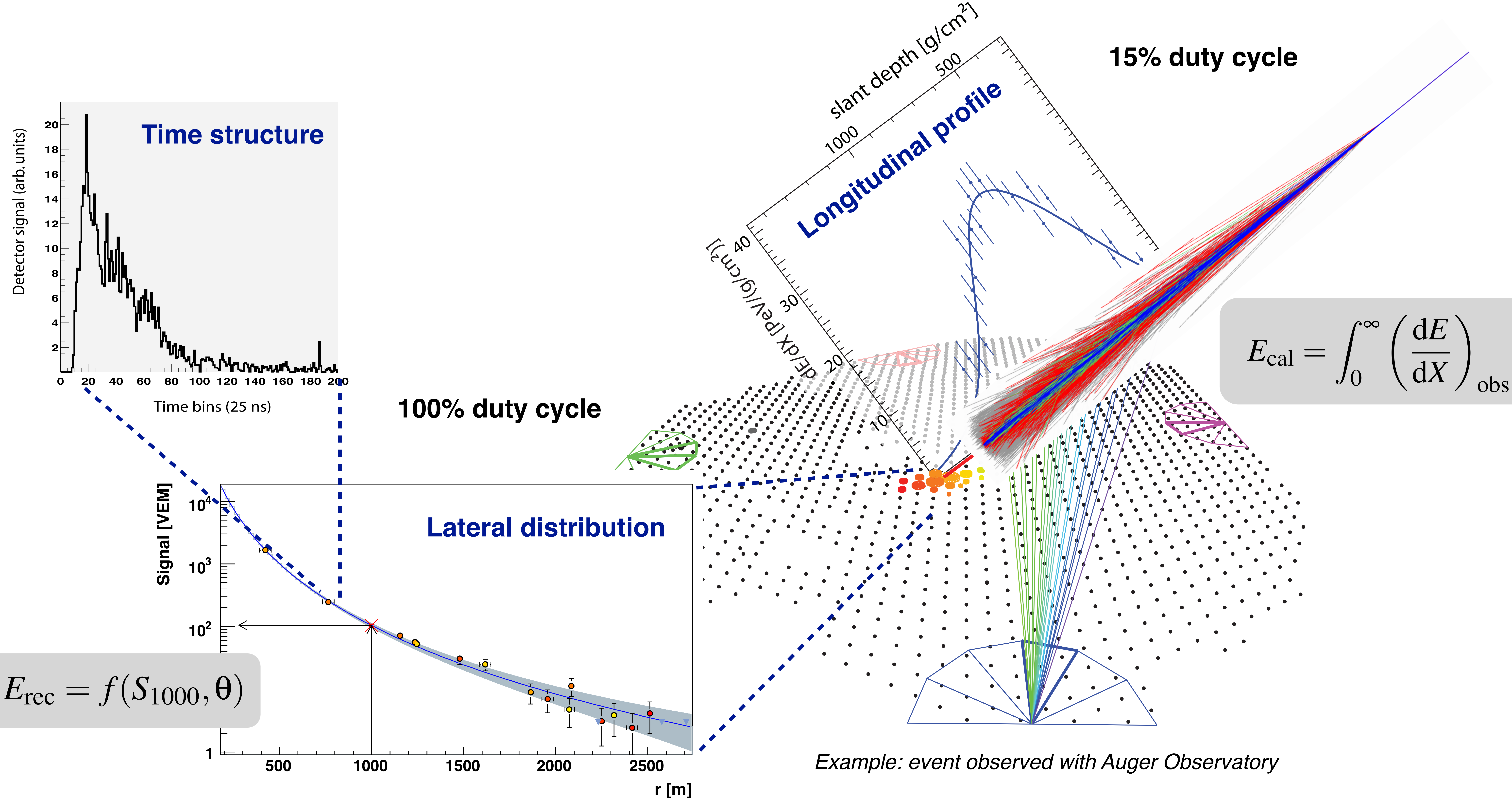

Center-of-mass energy




Laboratory energy



# Air shower detection at ultra-high energy

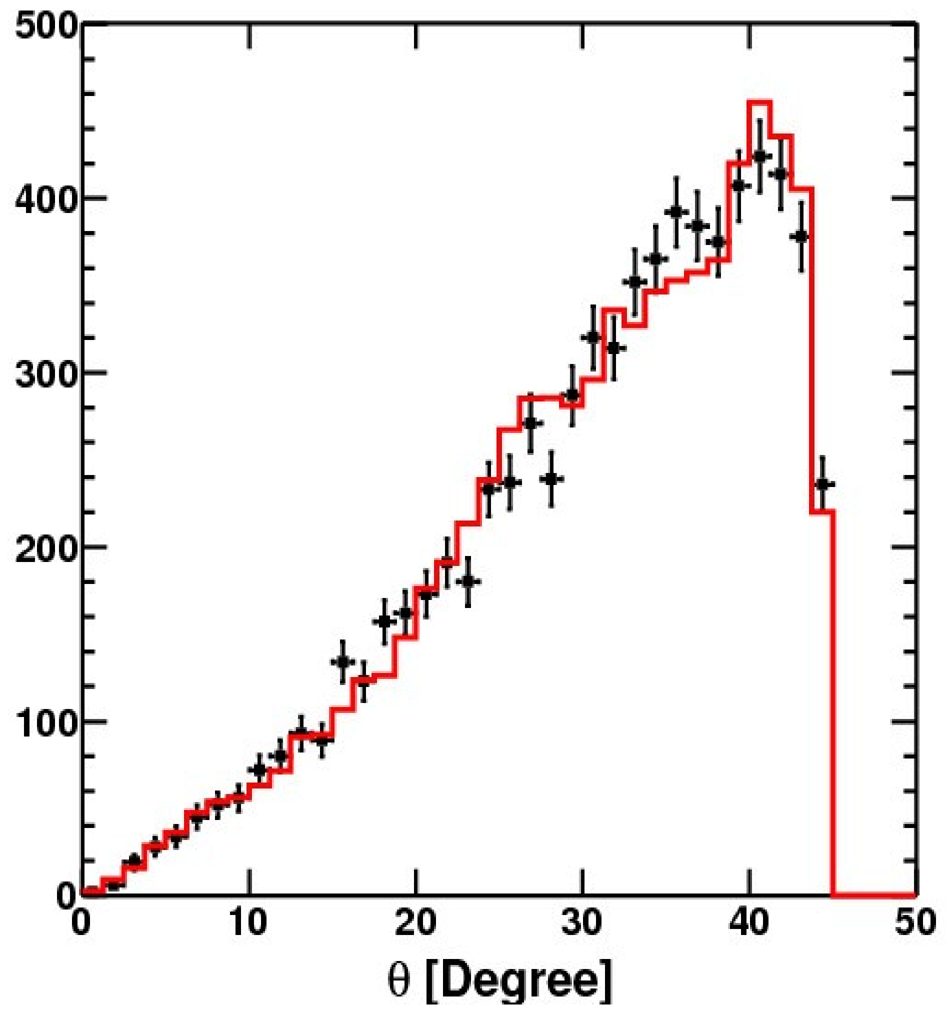



$$E_{\mathrm{rec}} = f(S_{1000}, \theta)$$

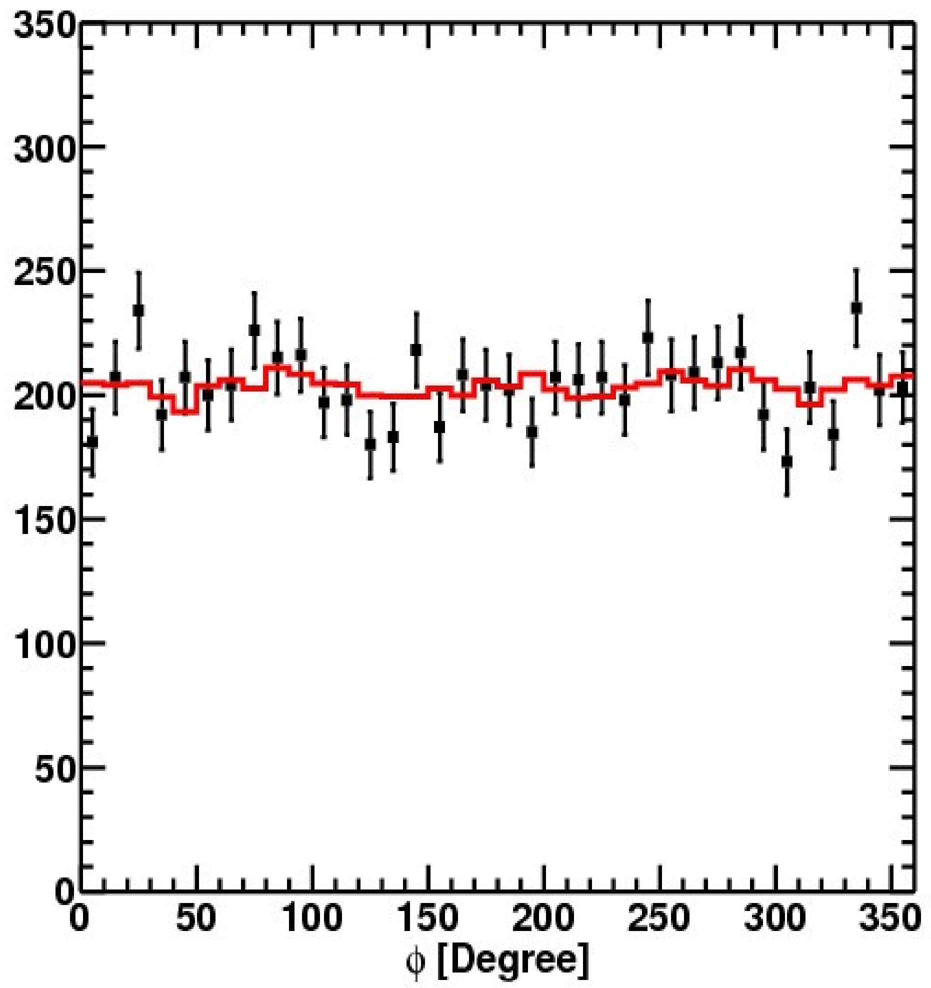
$$E_{\mathrm{cal}} = \int_0^\infty \left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_{\mathrm{obs}} \mathrm{d}X$$

*Example: event observed with Auger Observatory*

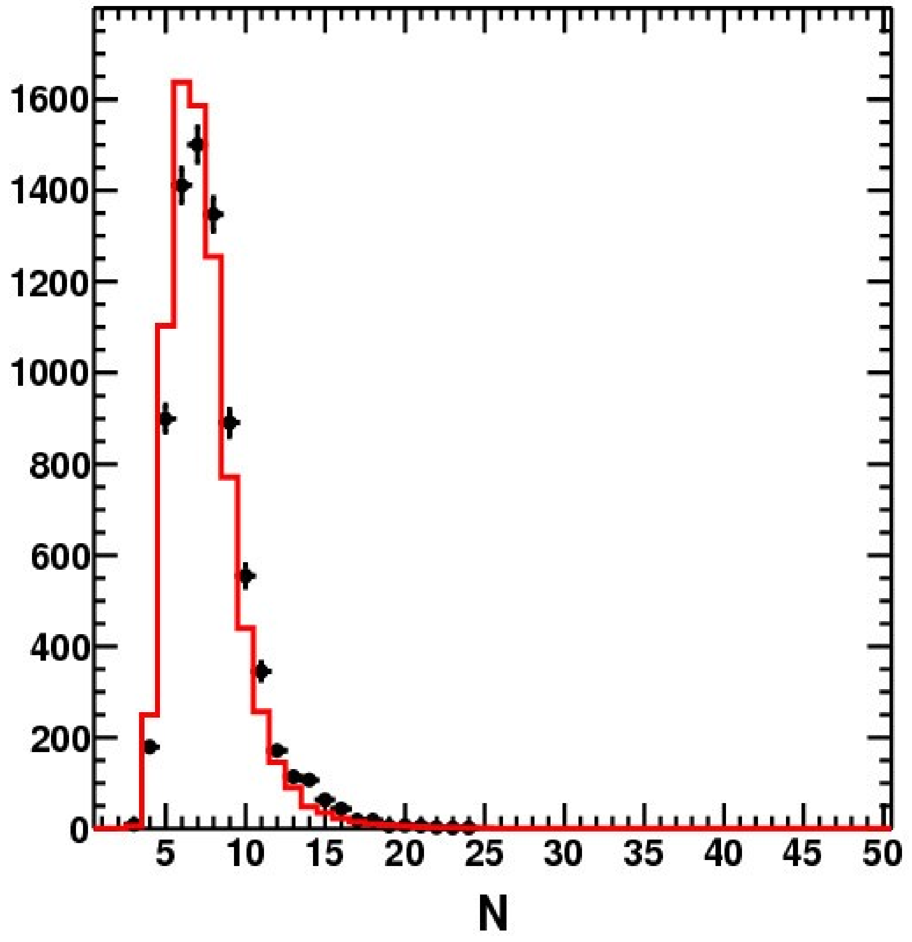
# TA event simulation for surface array



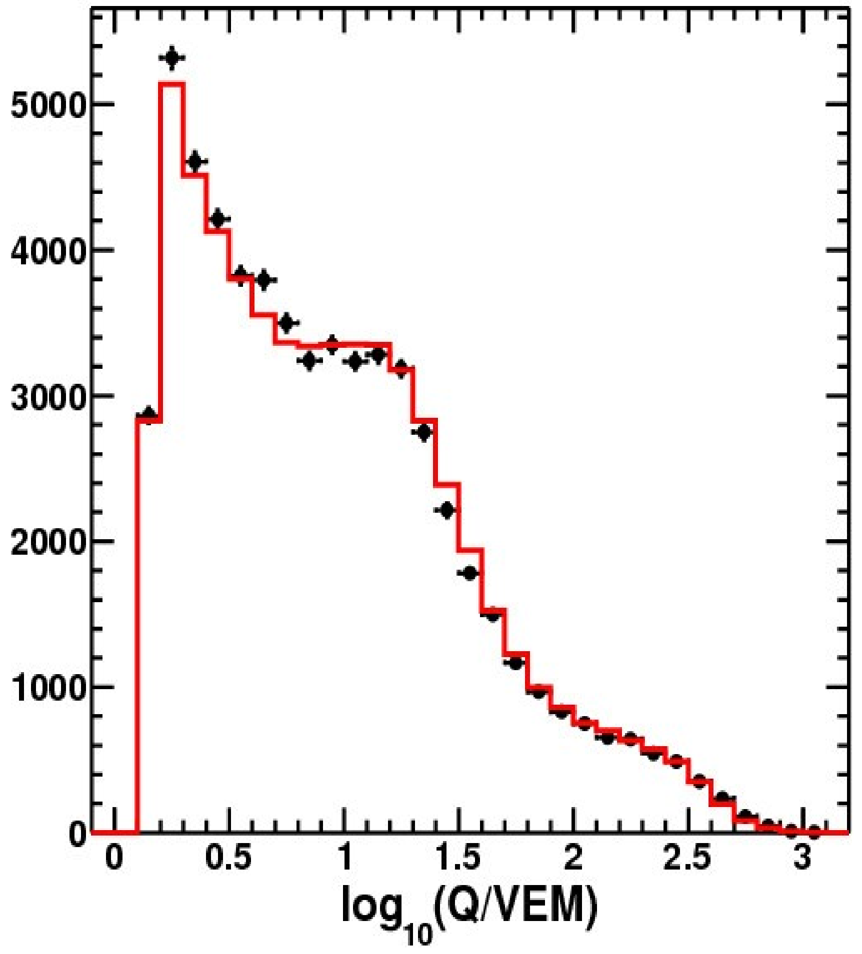

**Zenith Angle**




**Azimuth Angle**

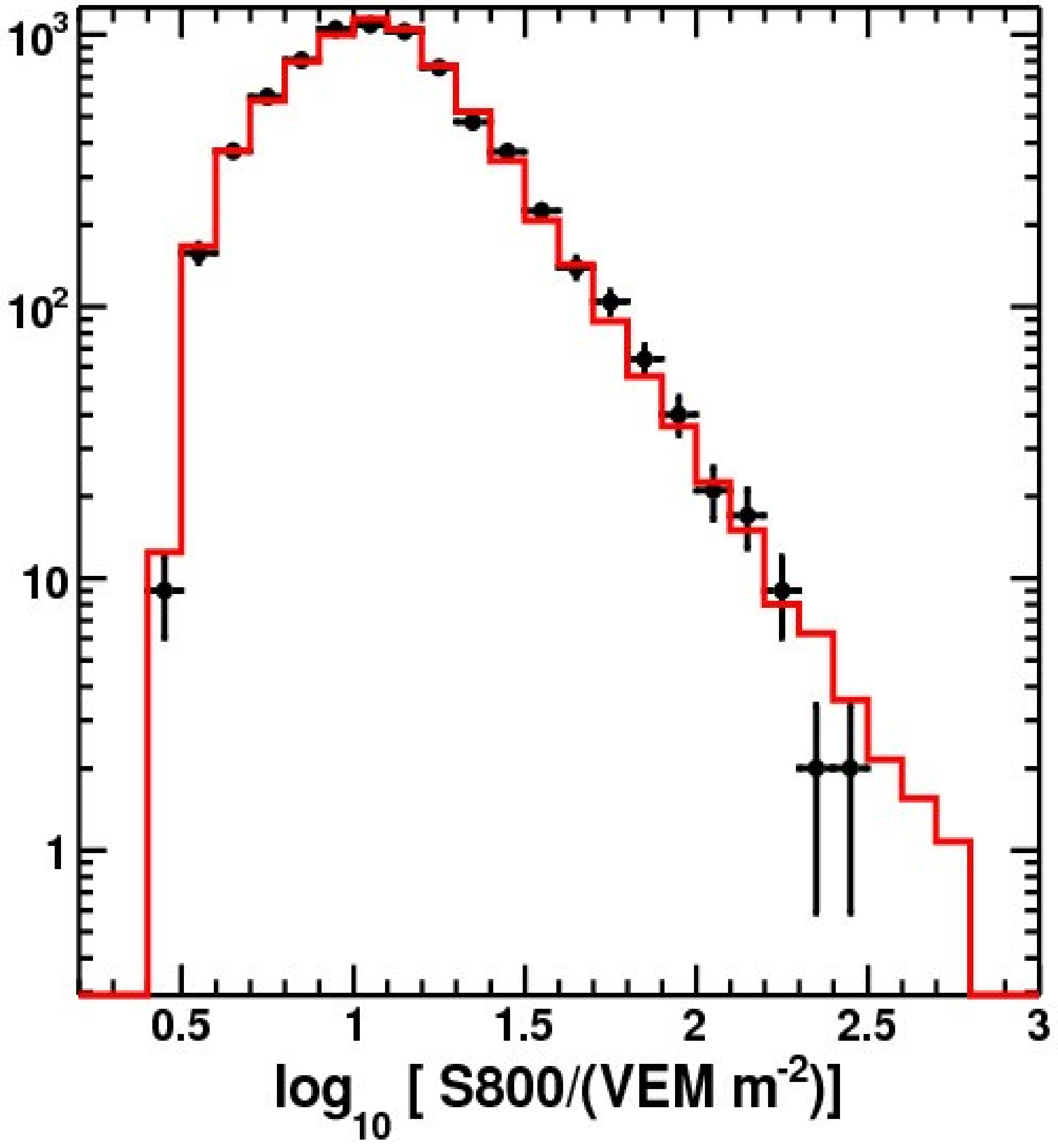



**Number of Good Counters/Event**




**Charge/Counter/Event**

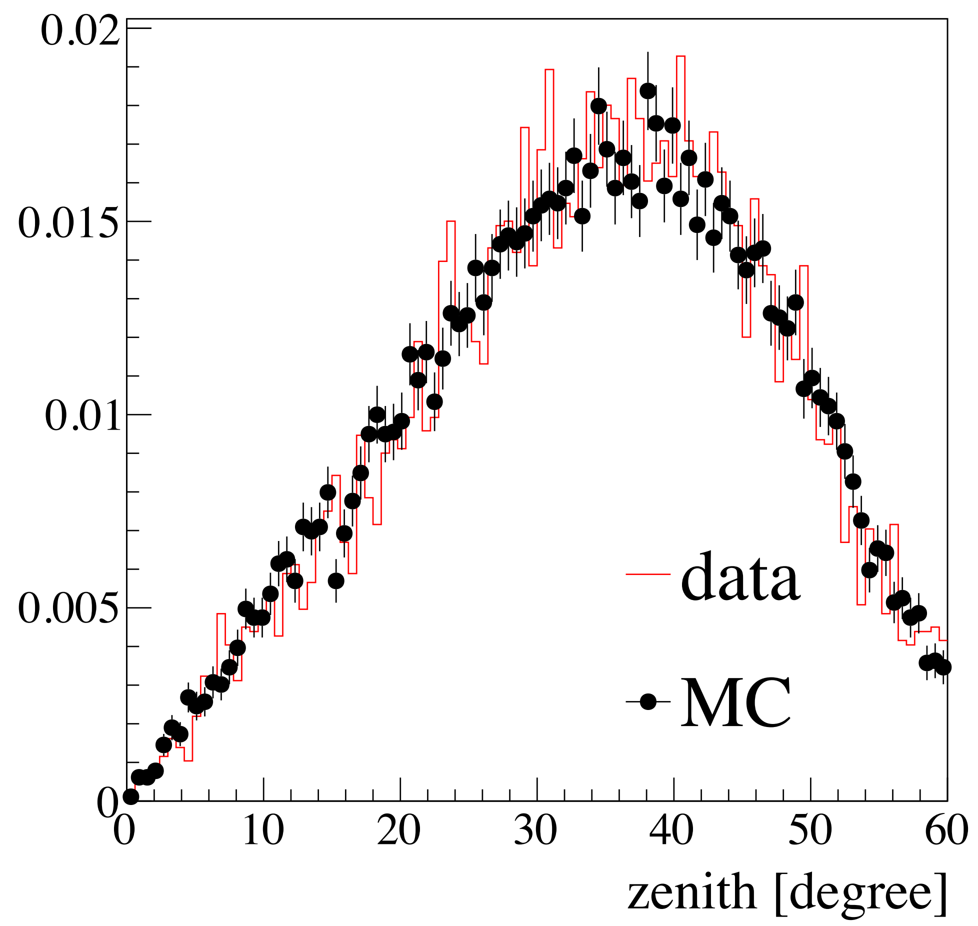
CORSIKA + full detector simulation
(proton primaries)



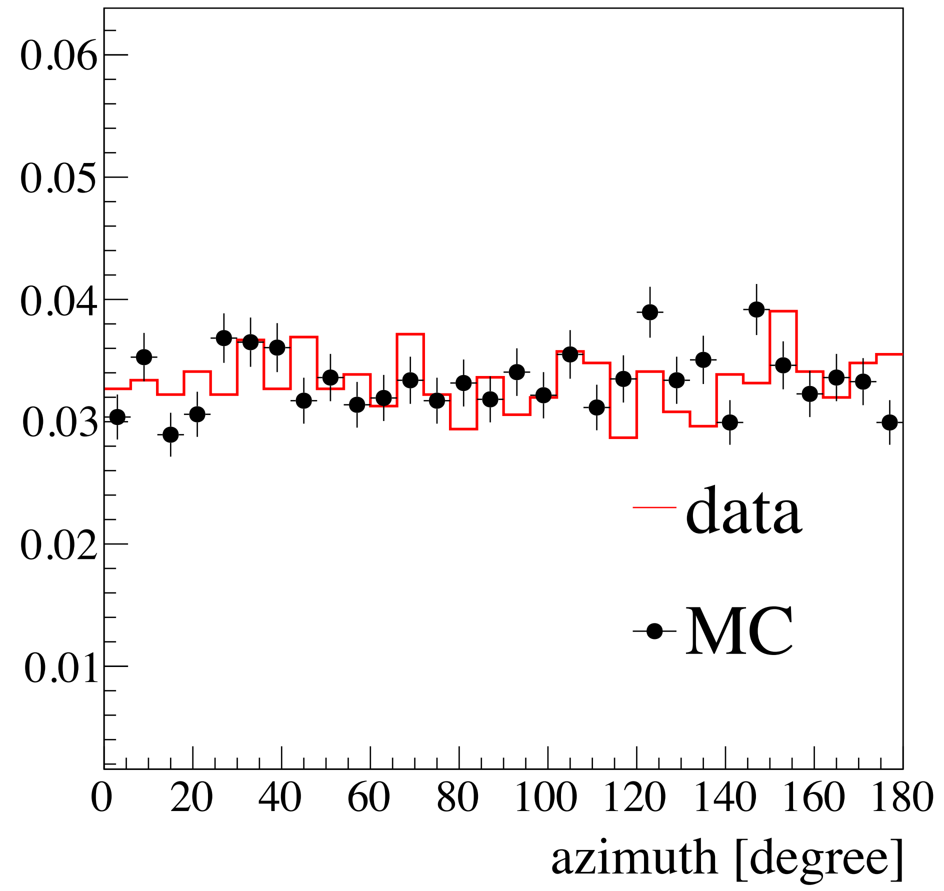

*(UHECR 2012)*

Very good agreement

# Auger event simulation for surface array

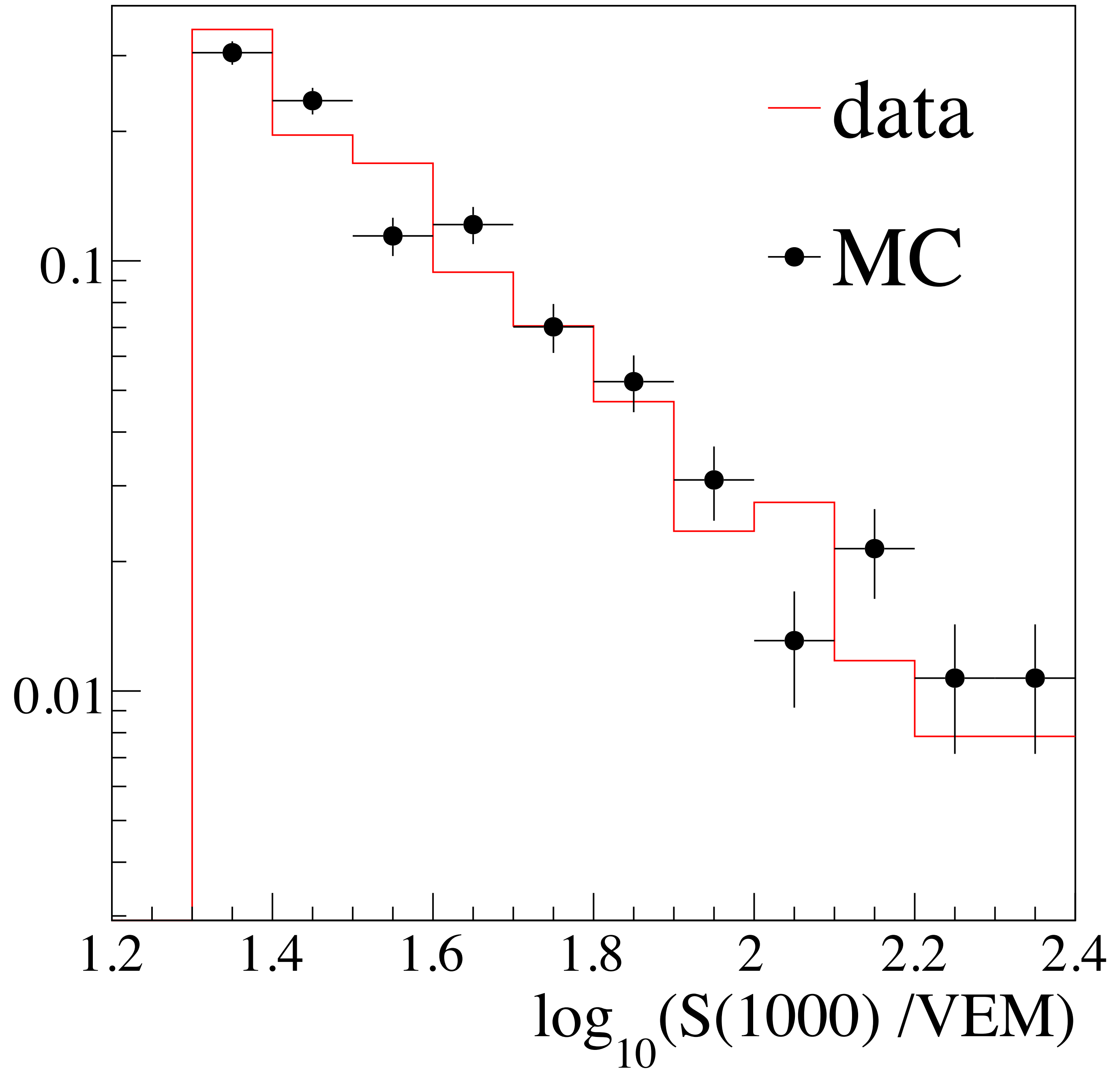


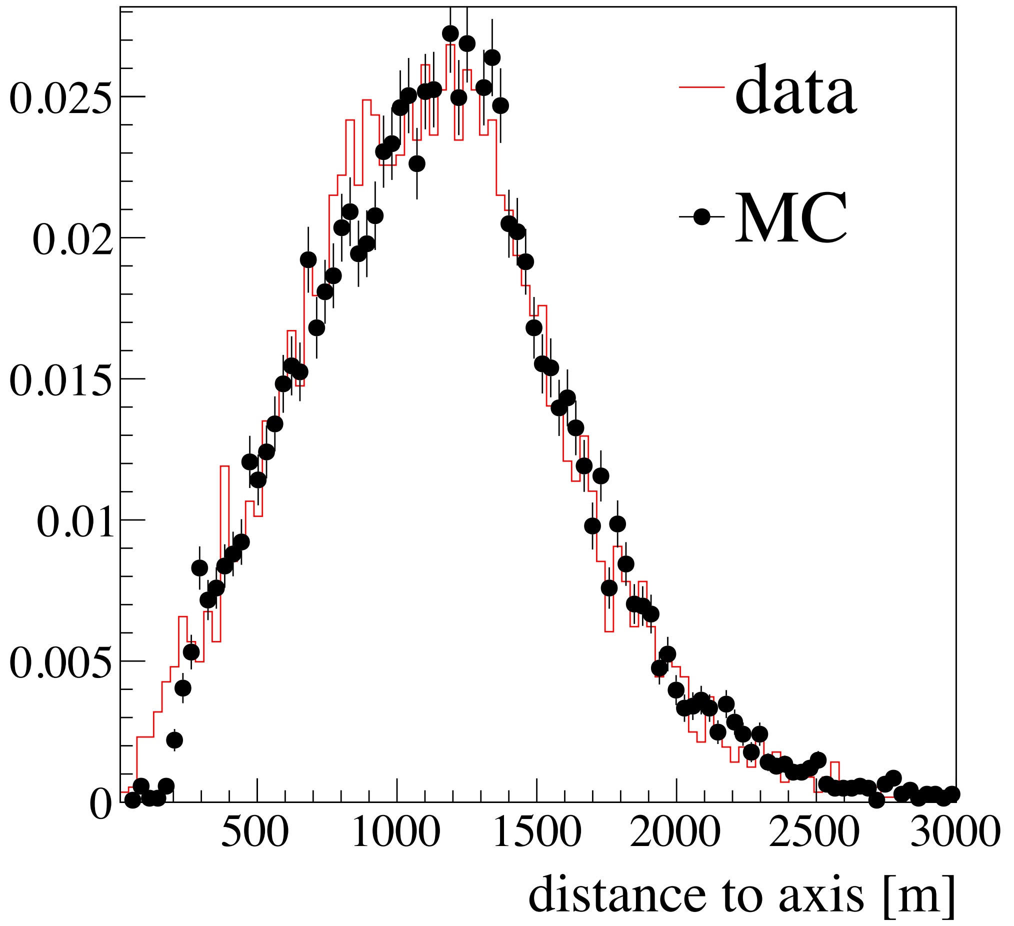

Zenith angle



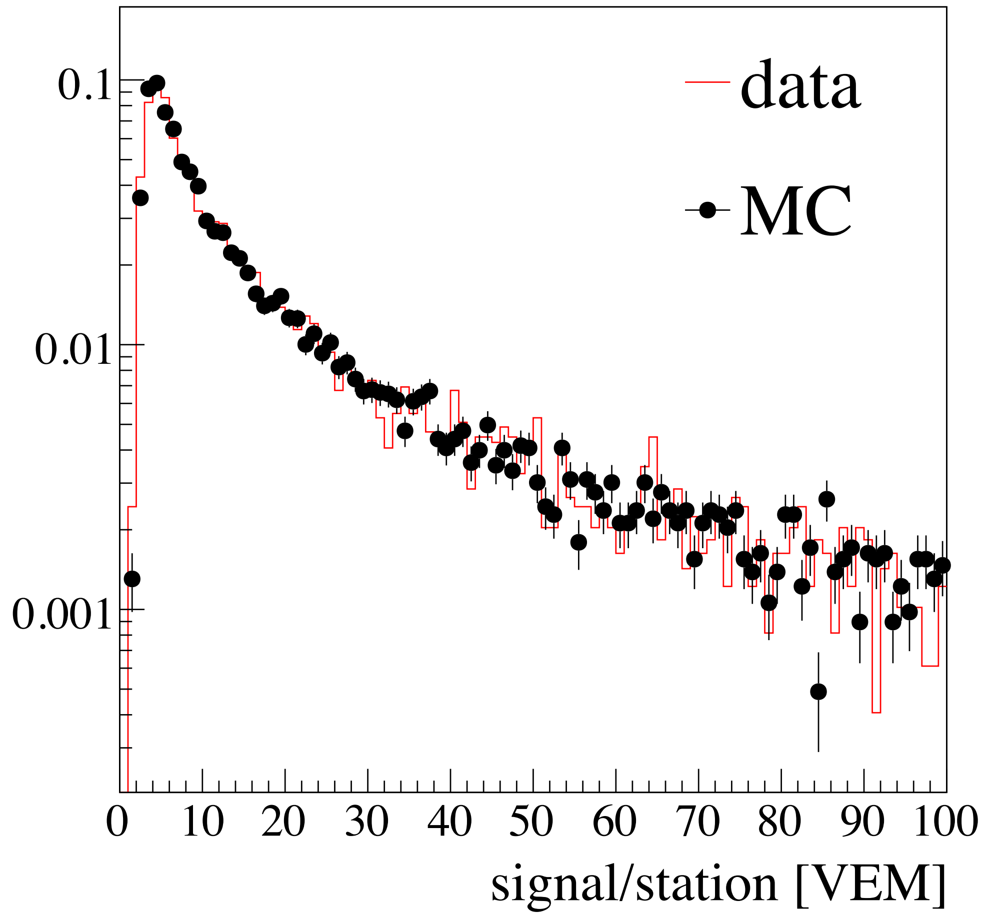

Azimuth angle

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




Distance of triggered stations

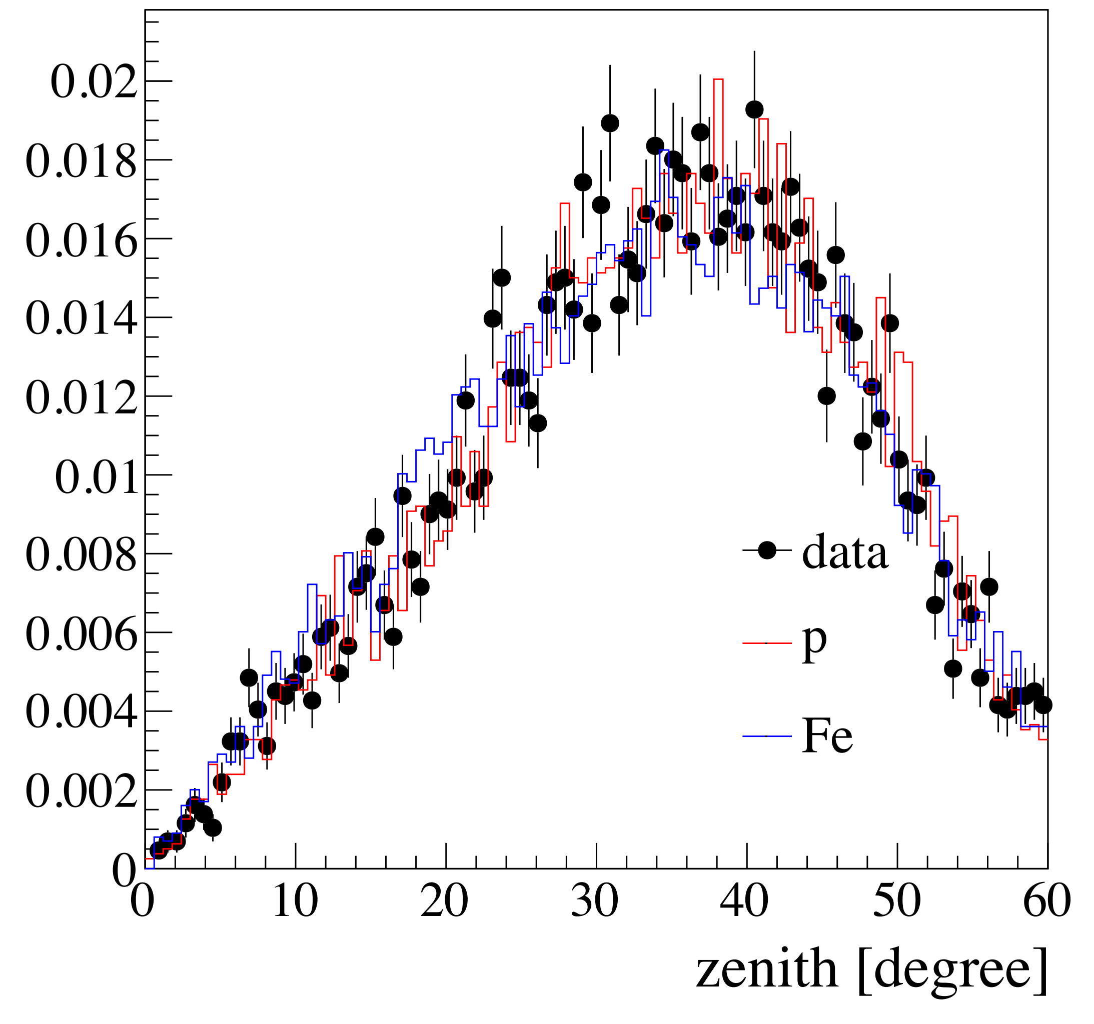



Signal per station

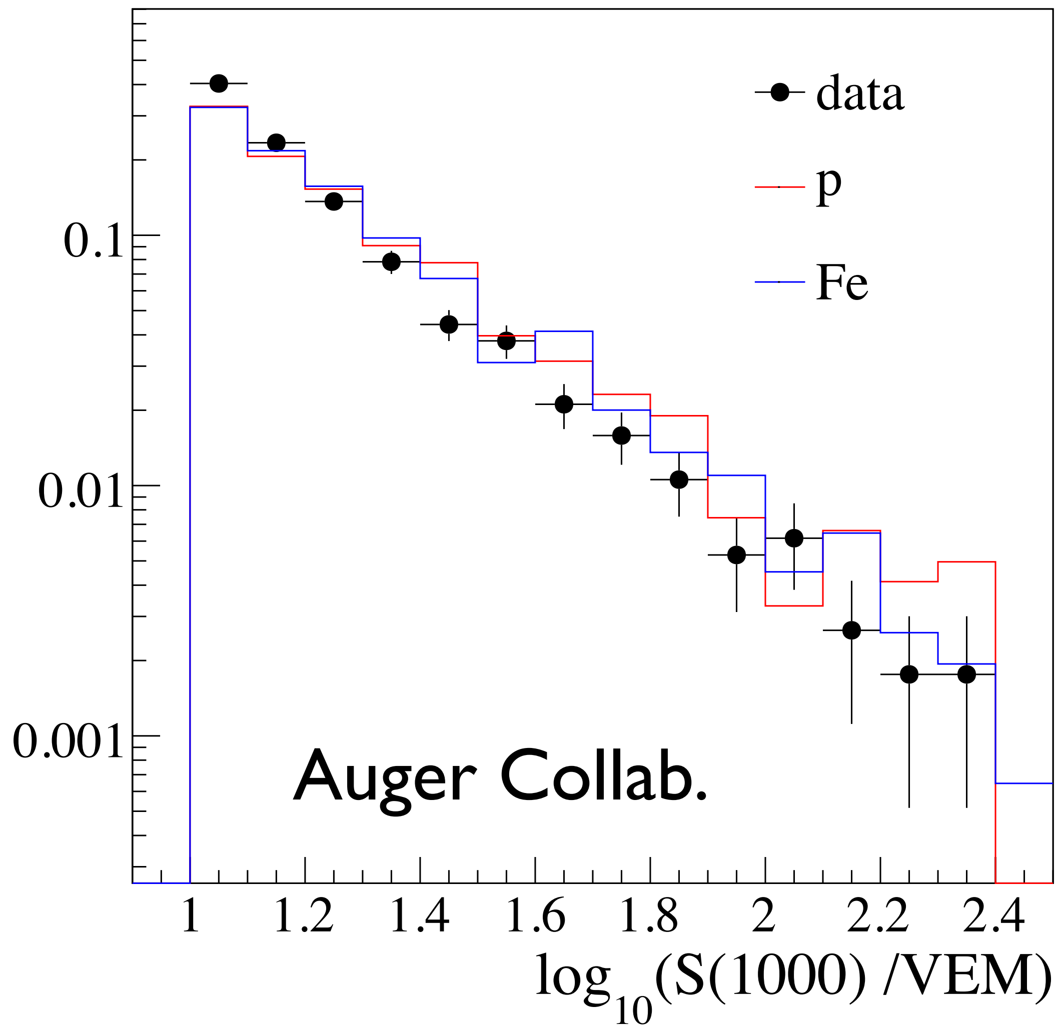
*(UHECR 2012)*

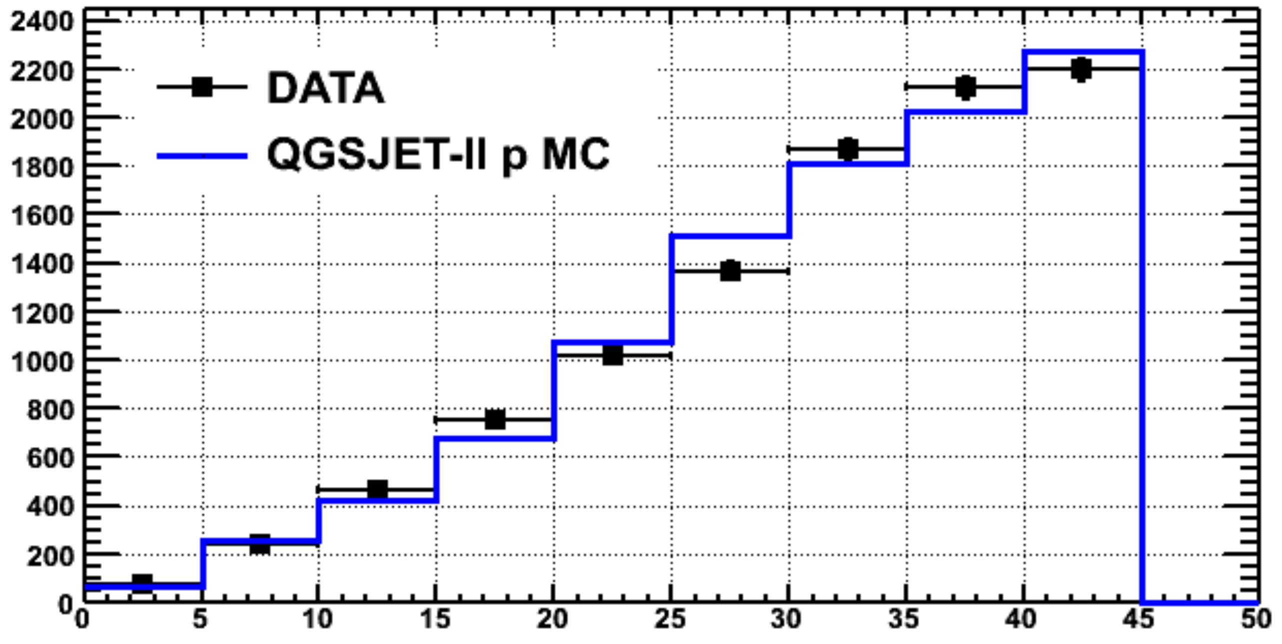
Very good agreement

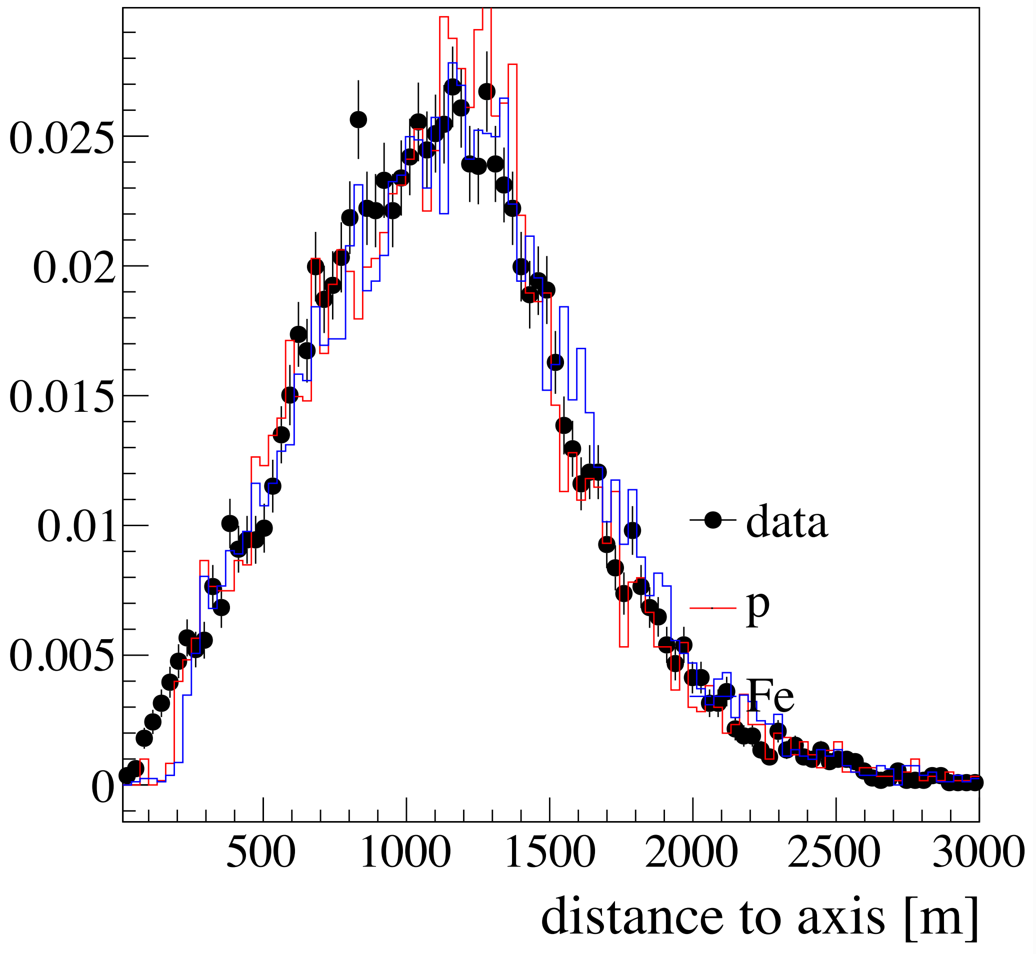
# Composition and model sensitivity ?



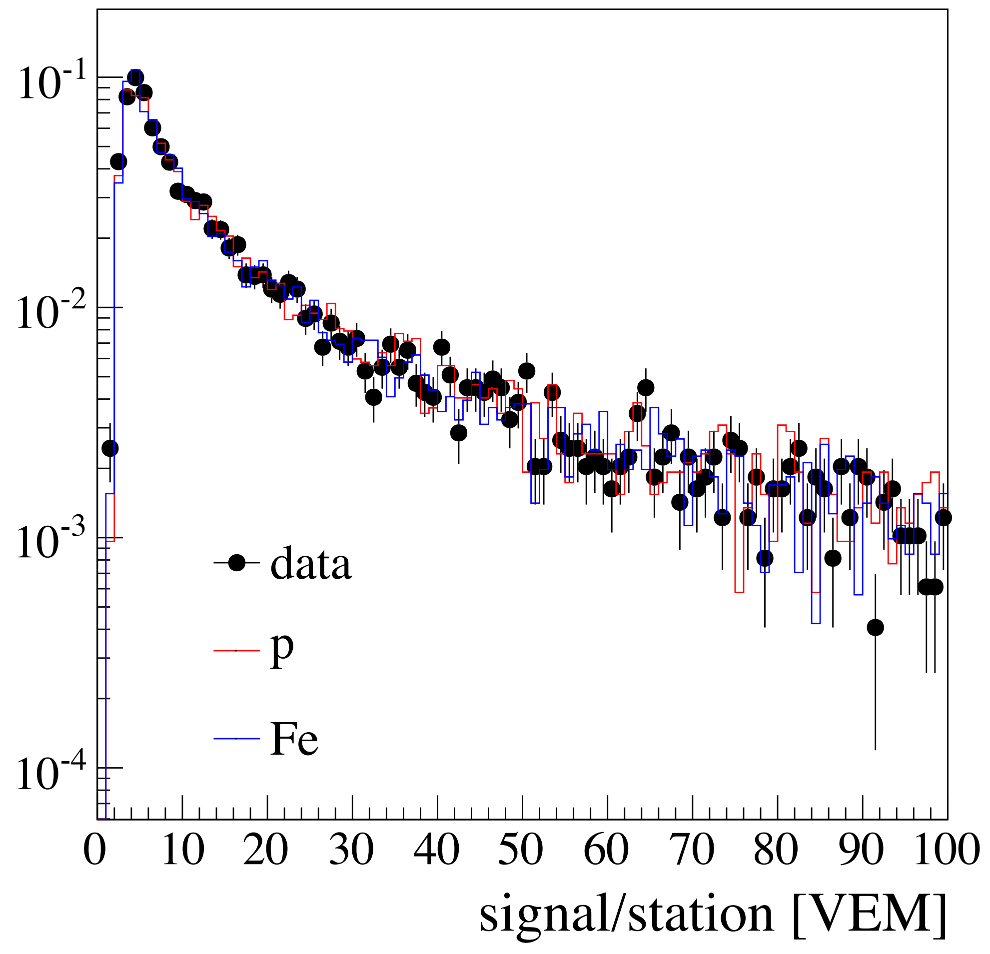

Zenith angle



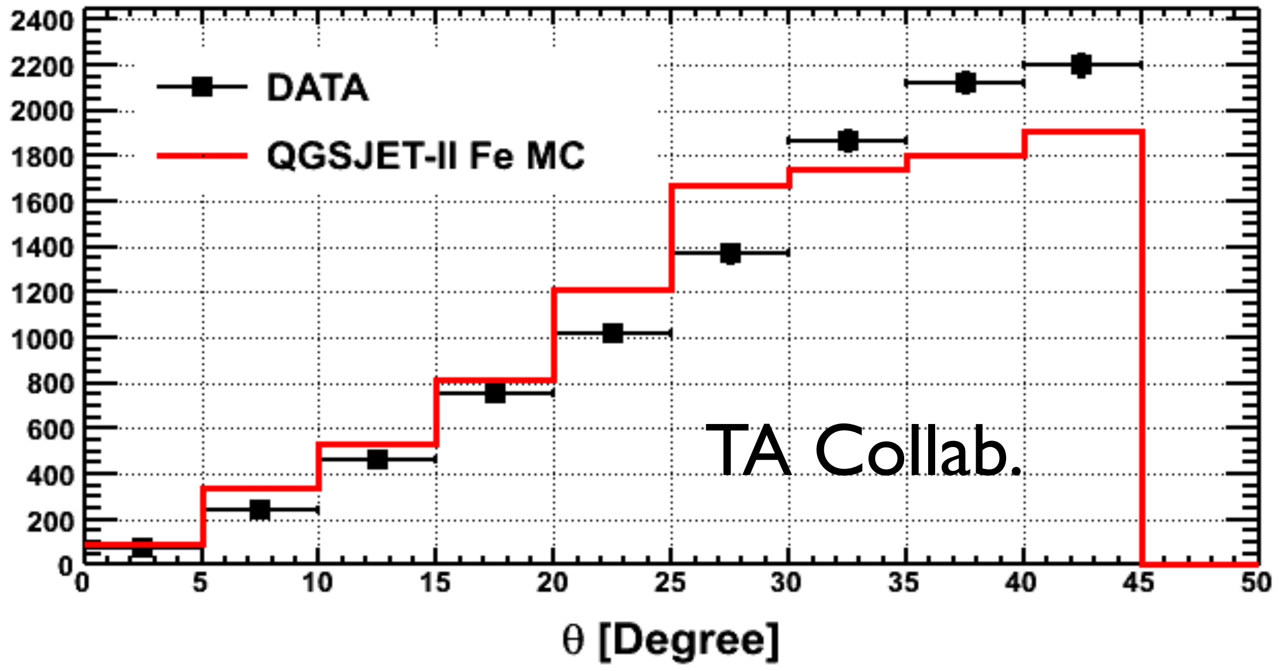




Distance of triggered stations




Signal per station



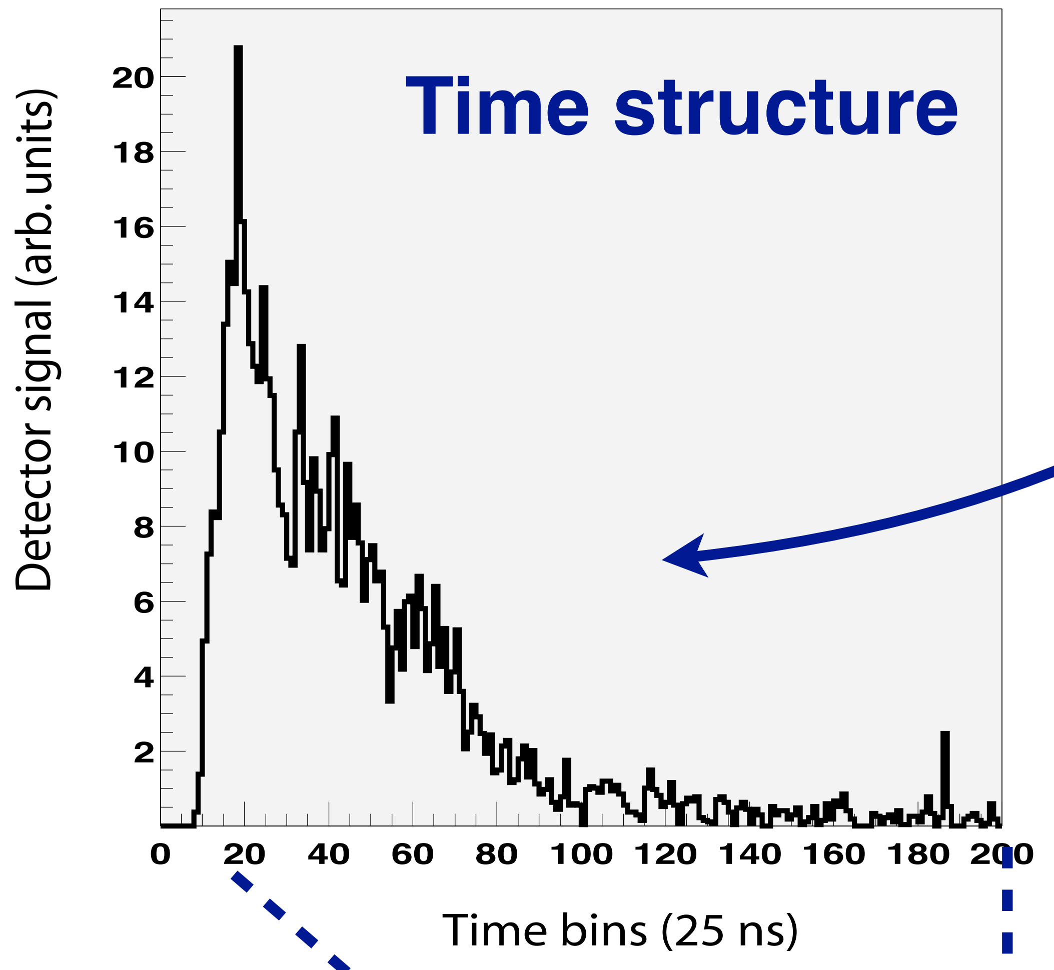

*(UHECR 2012)*

Most observables not very sensitive to details of shower simulation

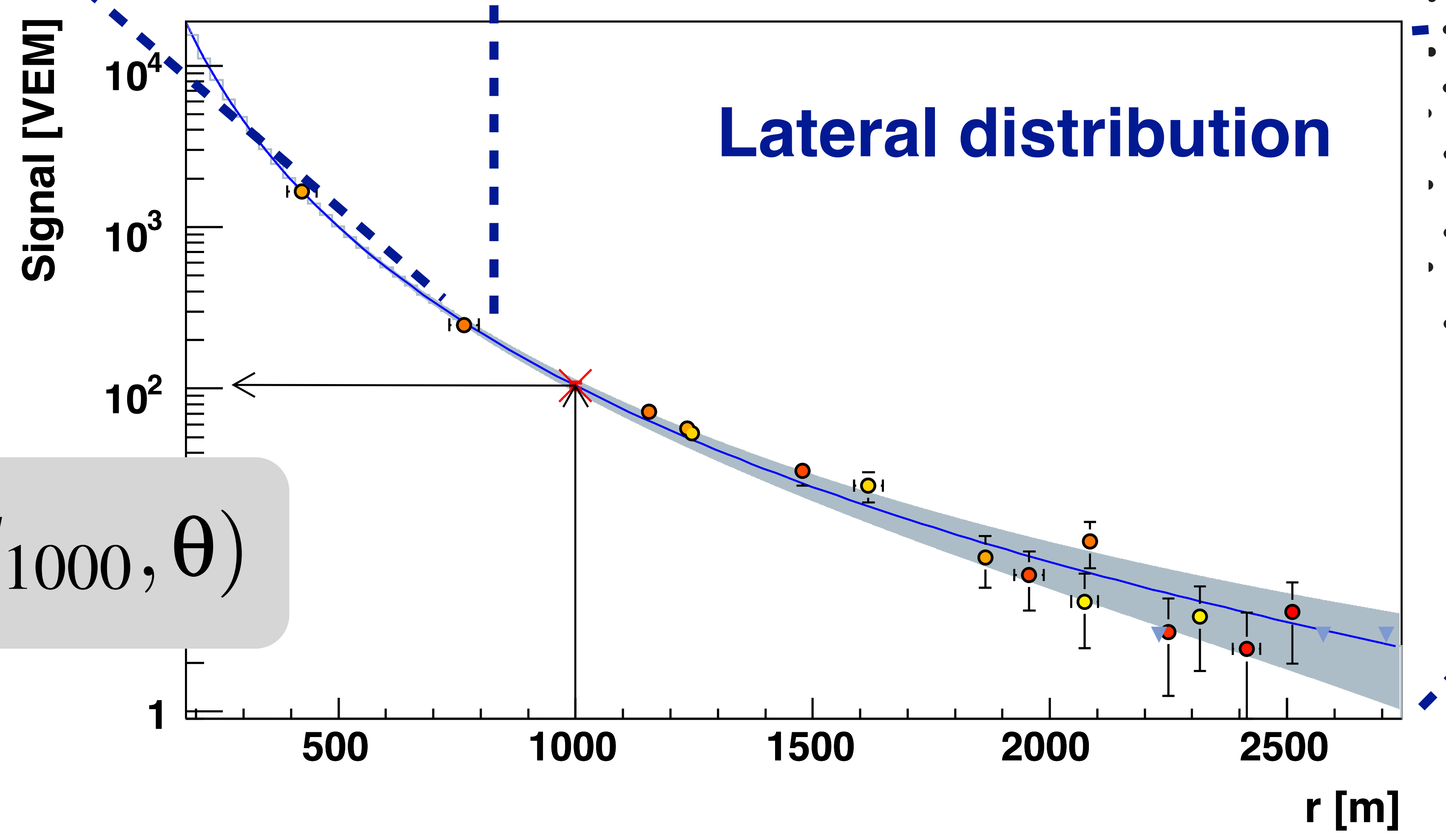
# Closer look at air showers and the inferred primary composition

# Air shower detection – composition-sensitive observables

**Sensitivity to mass and type of primary**

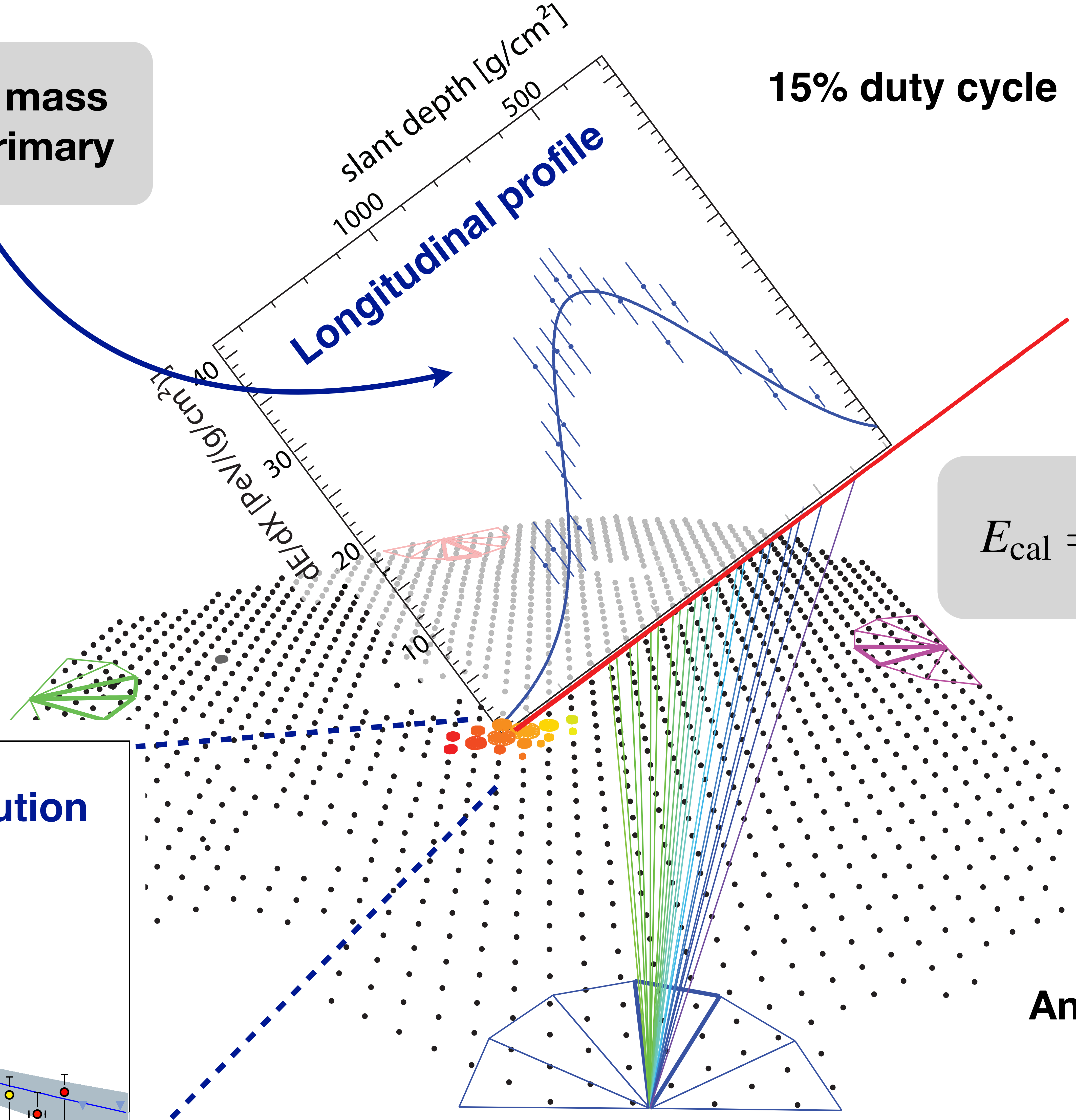



**100% duty cycle**




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

**15% duty cycle**

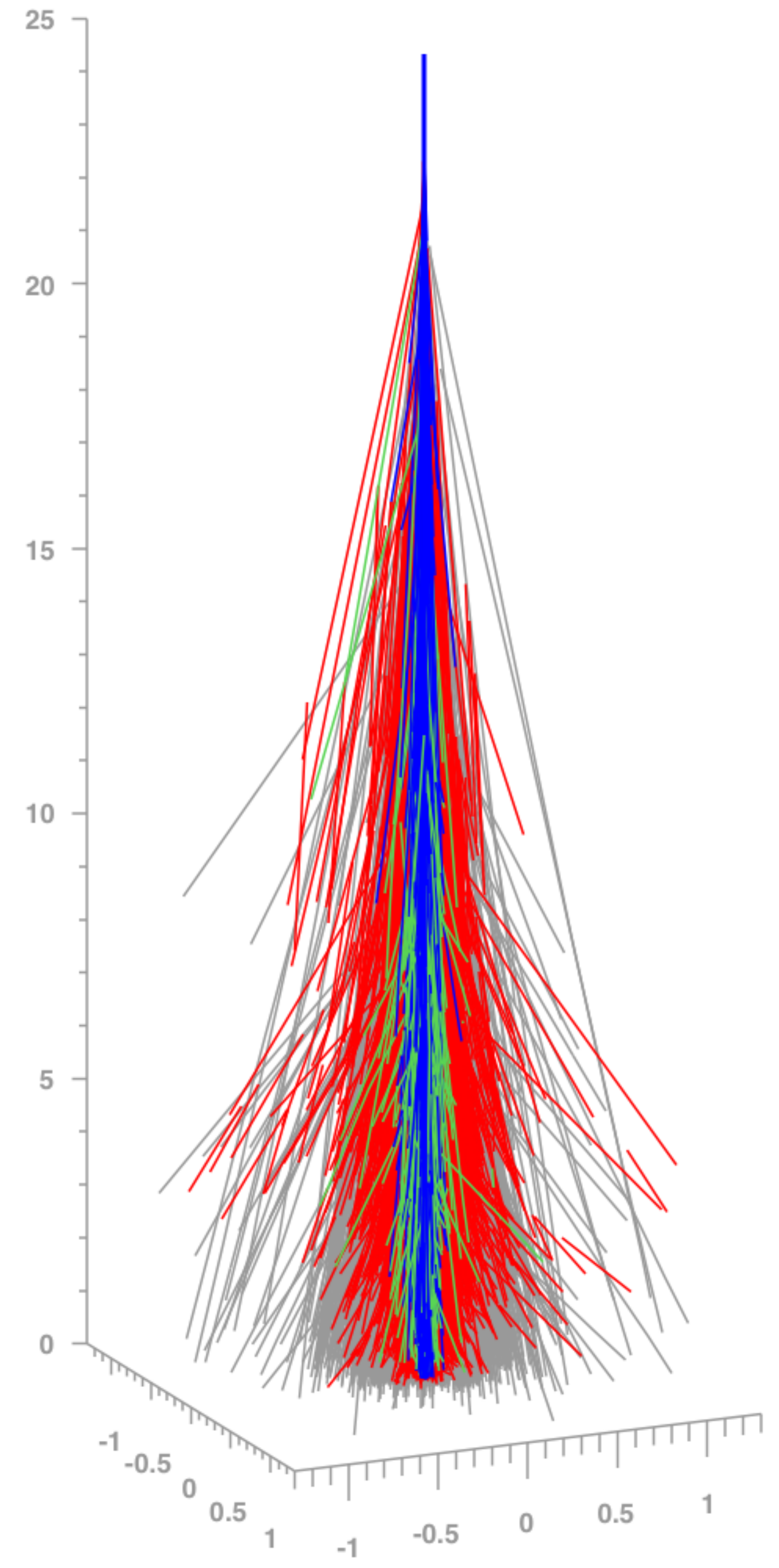


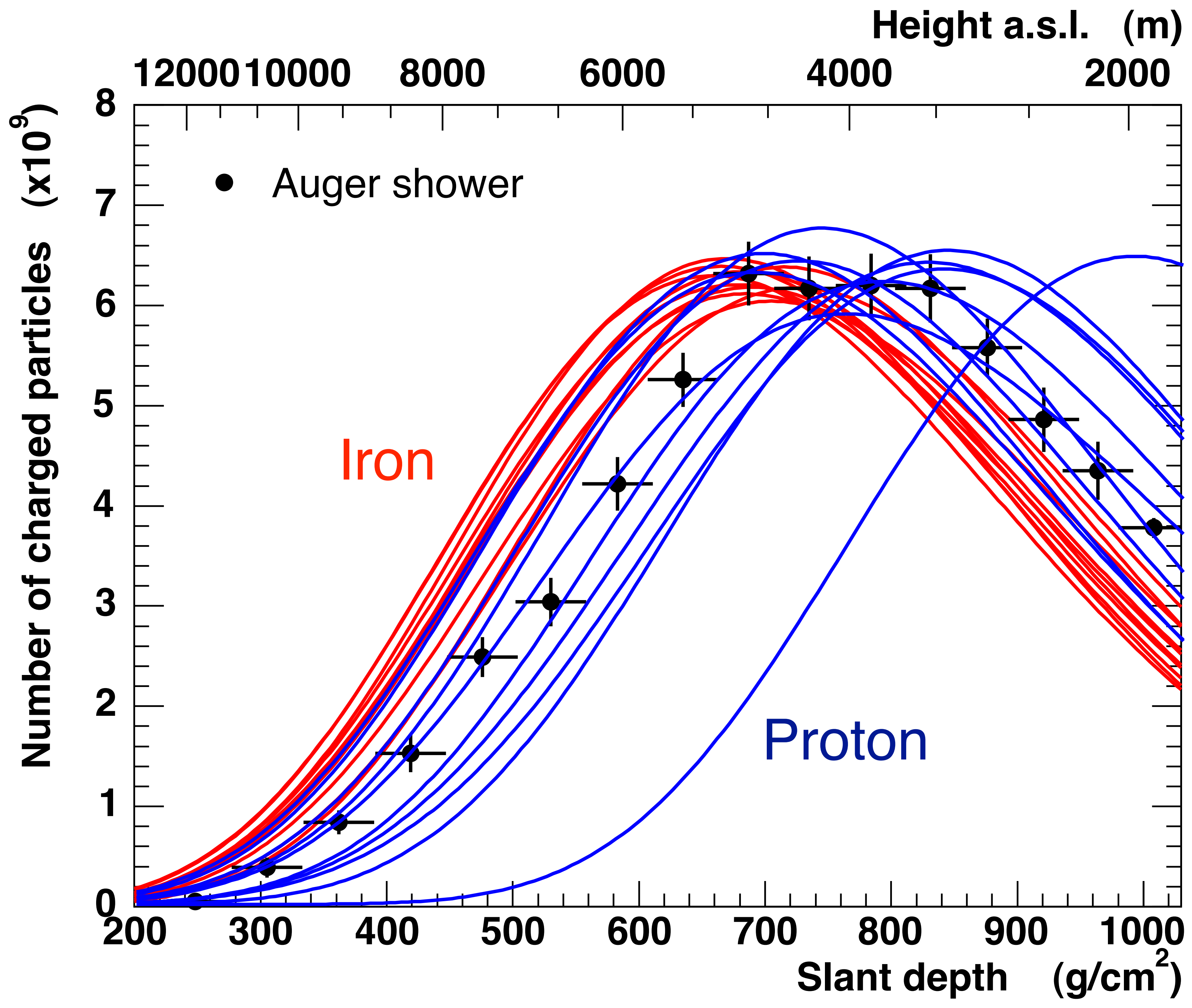

$$E_{\mathrm{cal}} = \int_0^\infty \left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_{\mathrm{obs}} \mathrm{d}X$$

**Angular resolution ~ 1.5° – 0.5°**

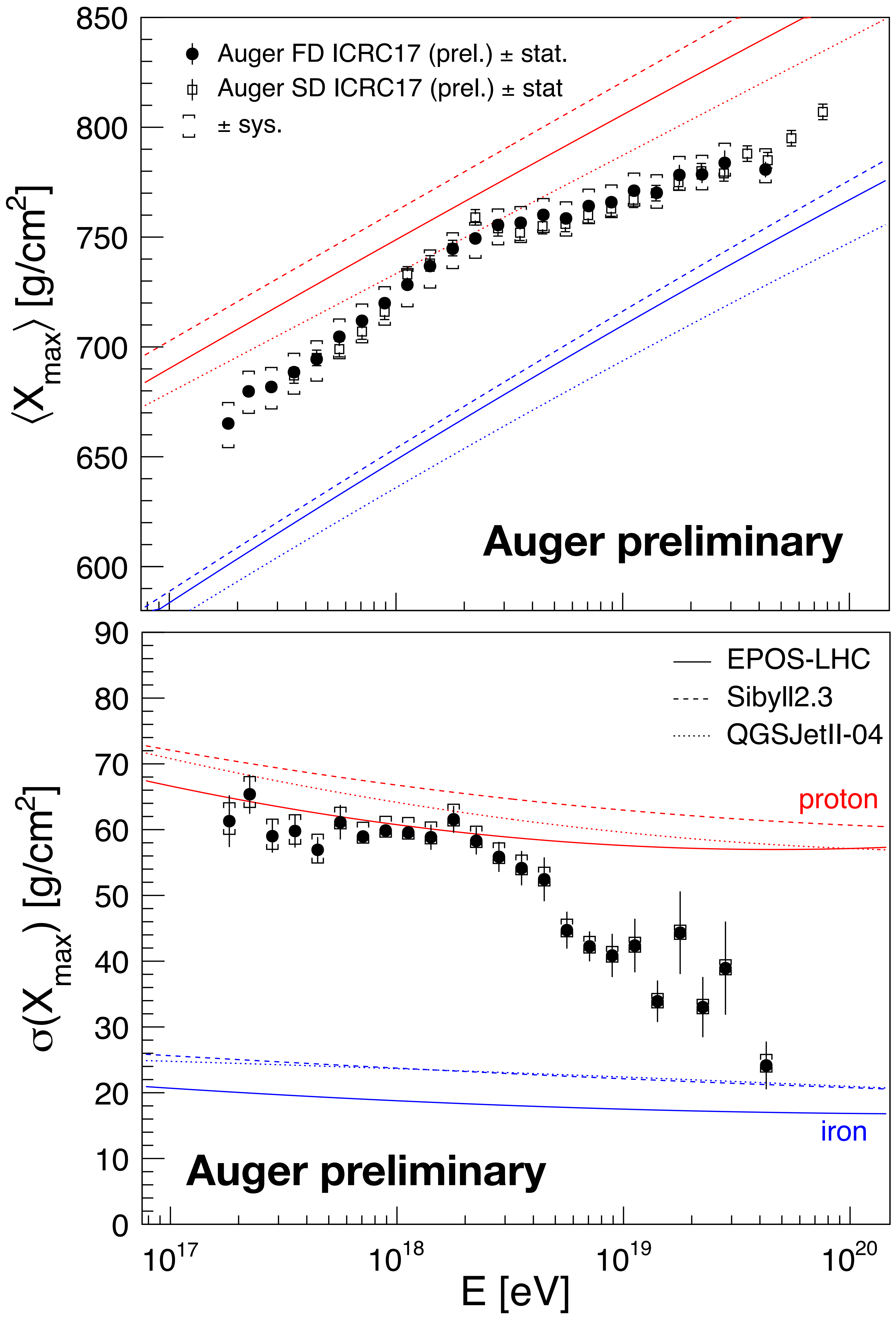
*Example: event observed with Auger Observatory*

# Composition from longitudinal shower profile



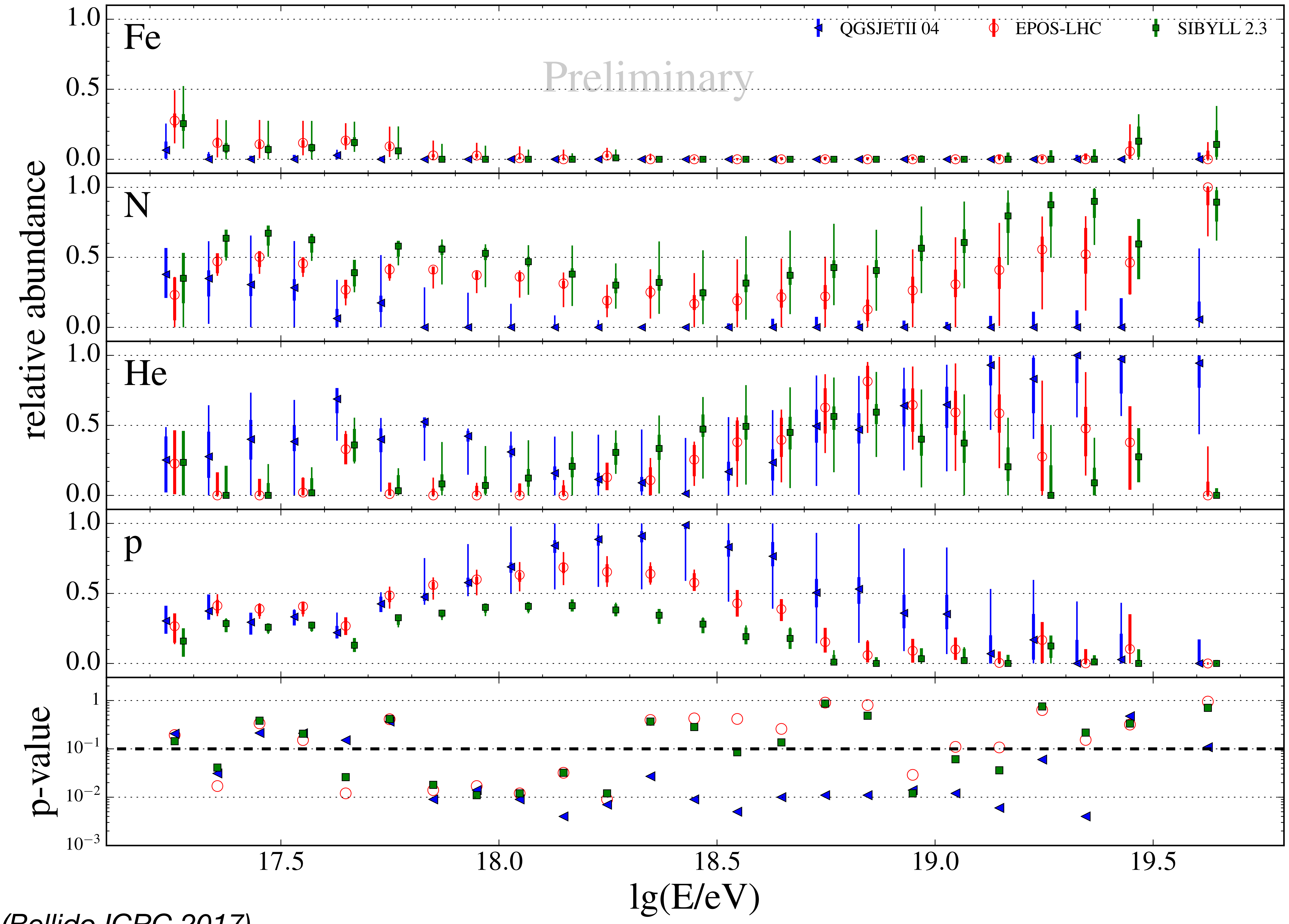


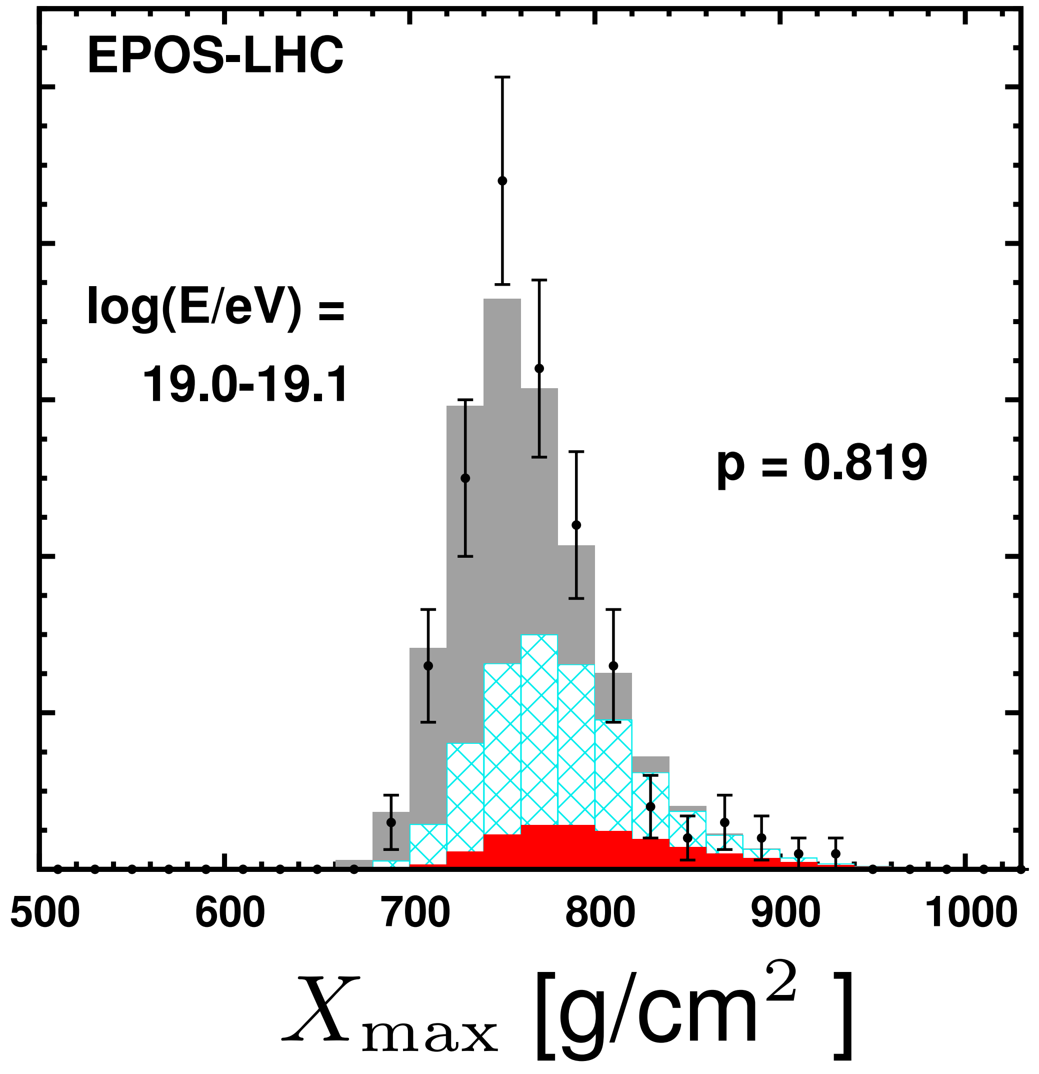

*Example: event measured by Auger Collab.*




*(Auger ICRC2017)*

# Mass composition at top of the atmosphere




p He N Fe

LHC-tuned interaction models

Fit quality not always good

No iron needed for interpretation

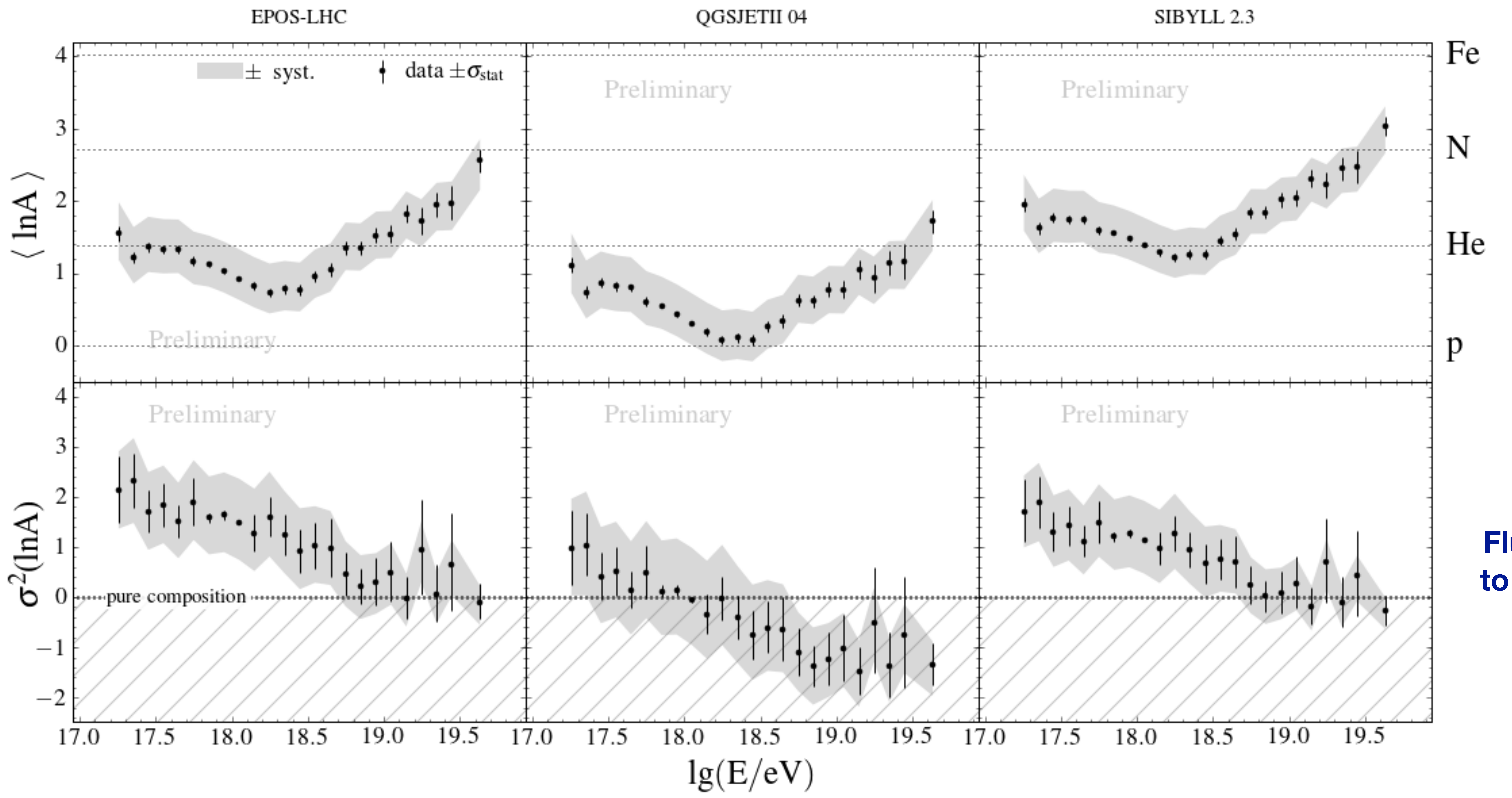
Large proton fraction below ankle

No obvious scaling with rigidity

Data cover only range up to $10^{19.5}$ eV

*(Bellido ICRC 2017)*

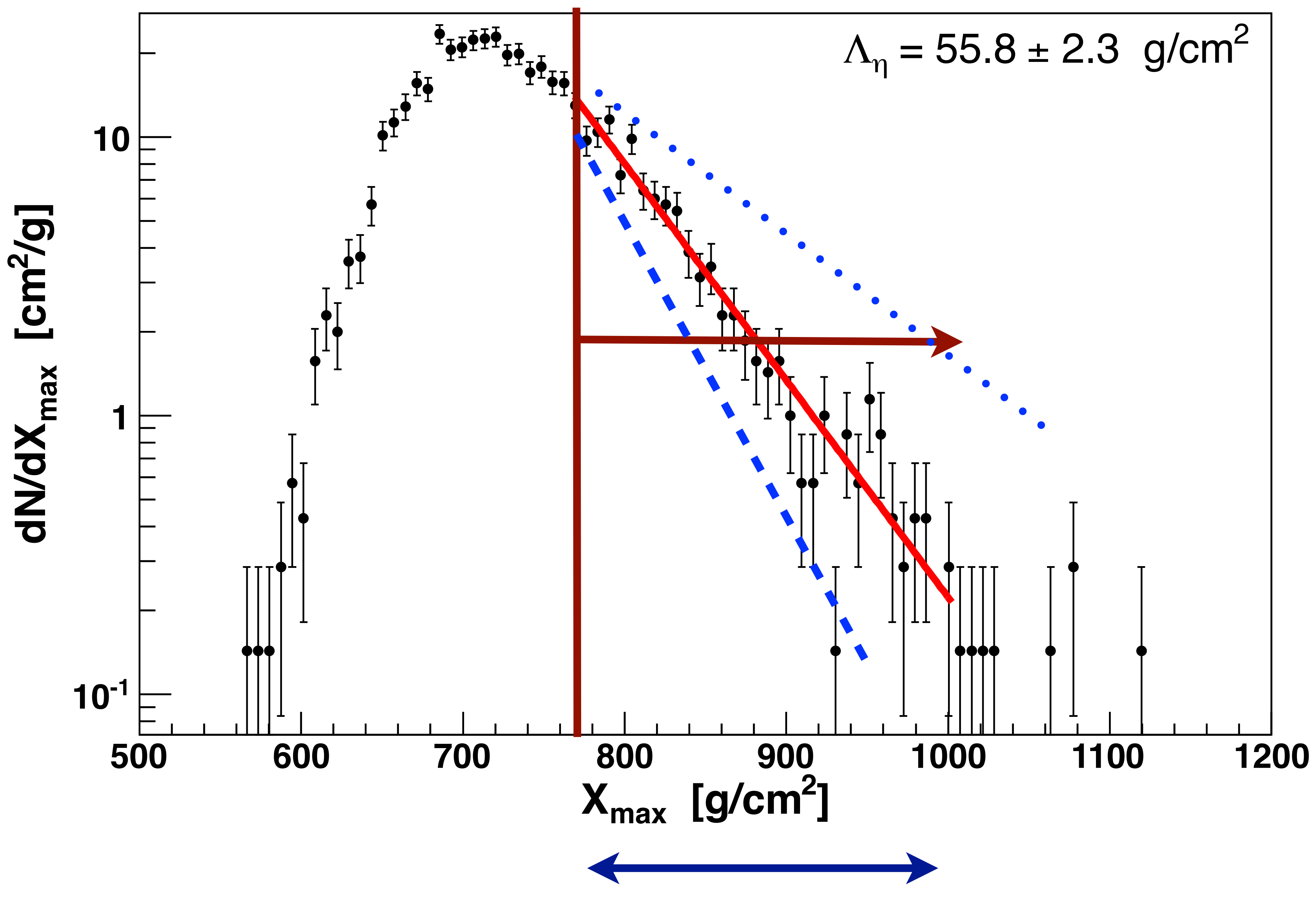
# Consistency of mean Xmax and shower-by-shower fluctuations




**Fluctuations due only to mix of composition**

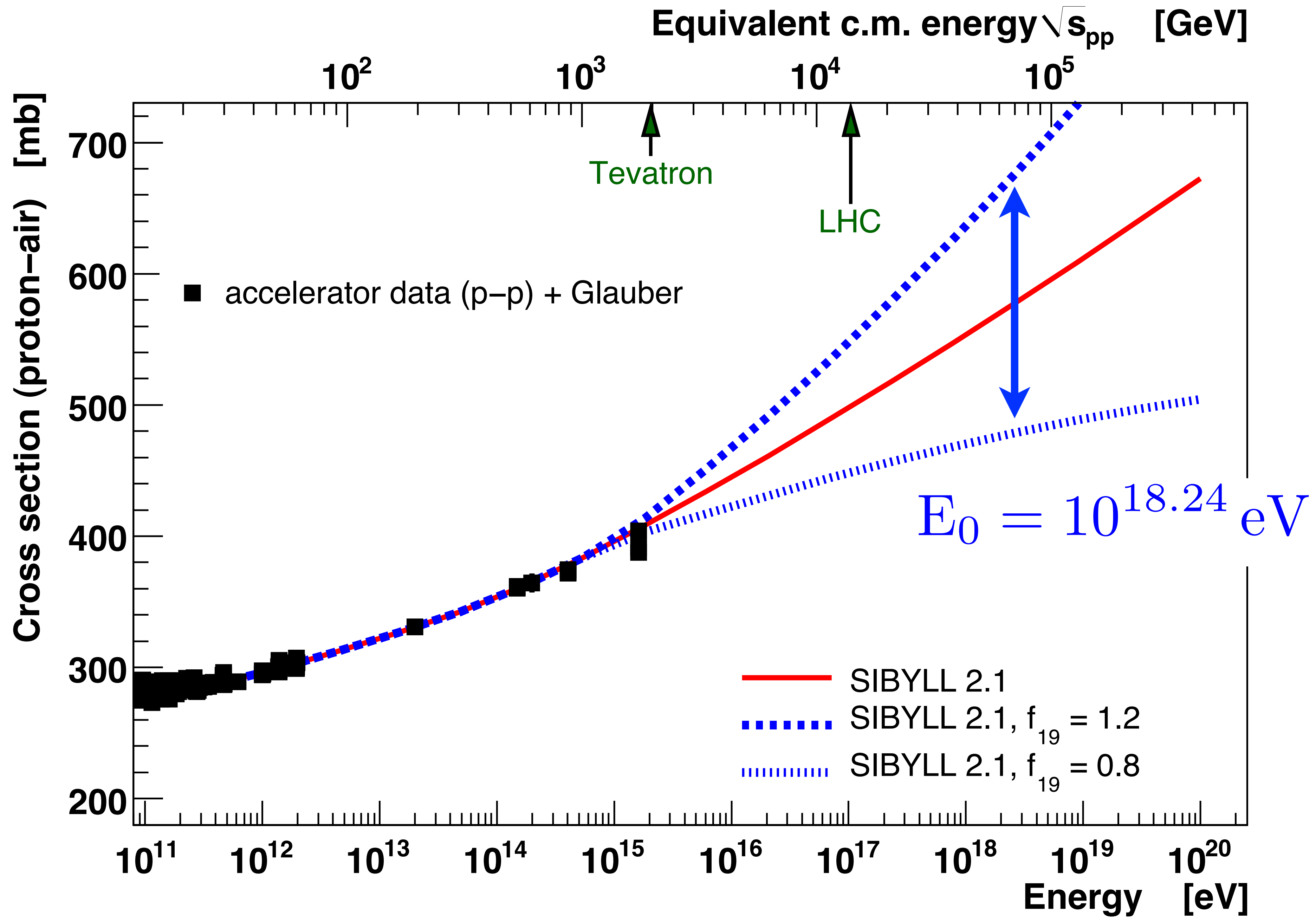
*(Bellido, ICRC 2017)*

# Cross section measurement: self-consistency




Depth range of analysis

(Auger Collab. PRL 2012)

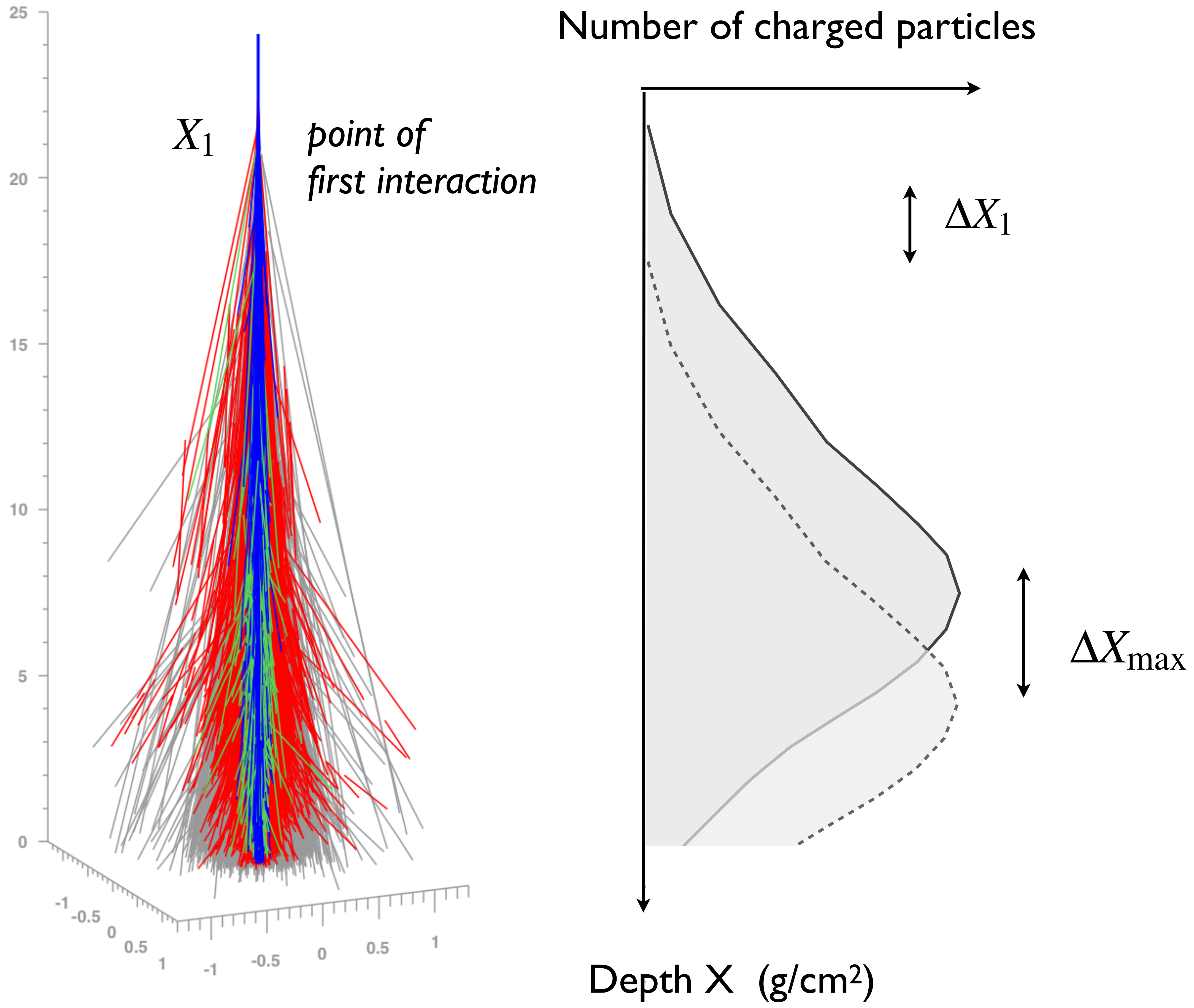



Cross section accepted if simulated slope fits measured slope of $X_{max}$ distribution

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

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

# Measurement of proton-air cross section

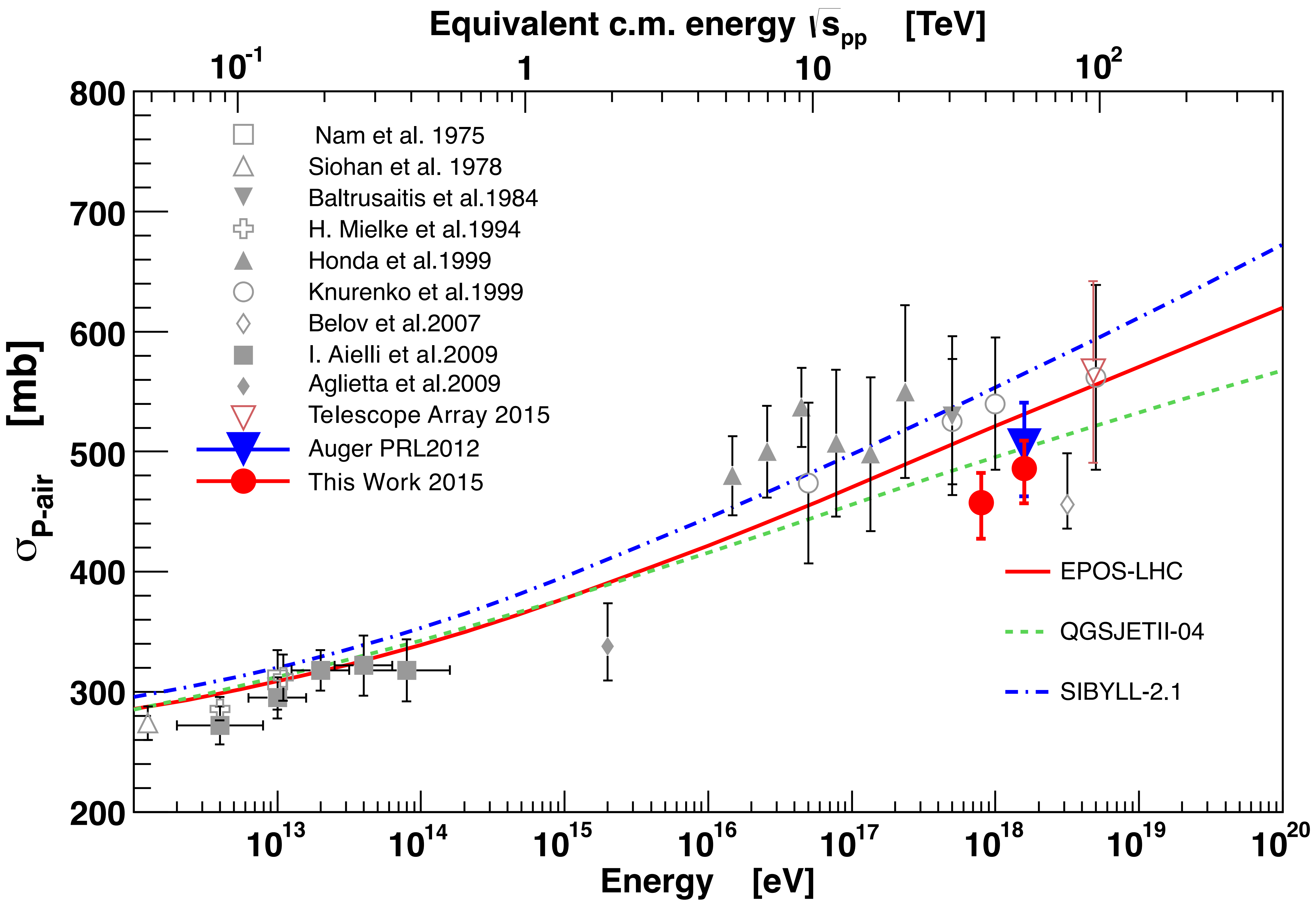



$$\frac{dP}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

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

Difficulties

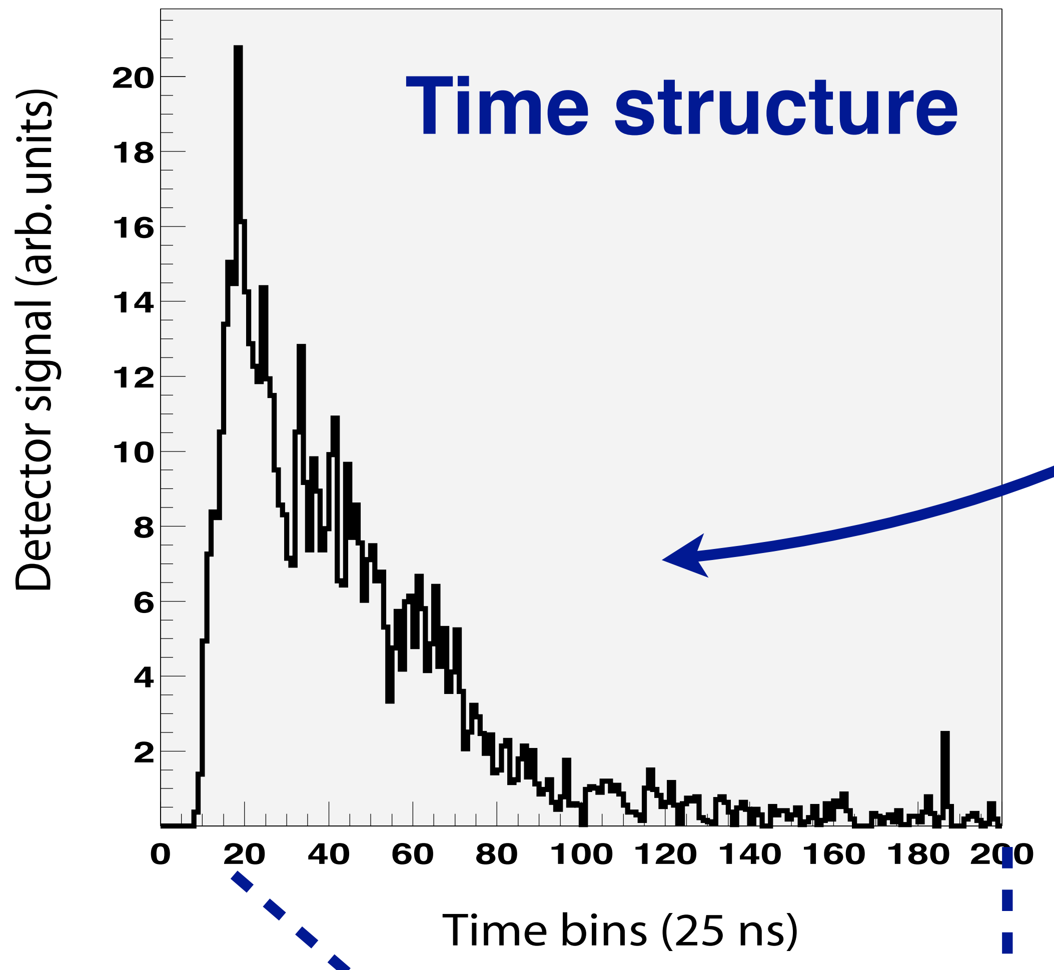
- mass composition
- fluctuations in shower development (model needed for correction)



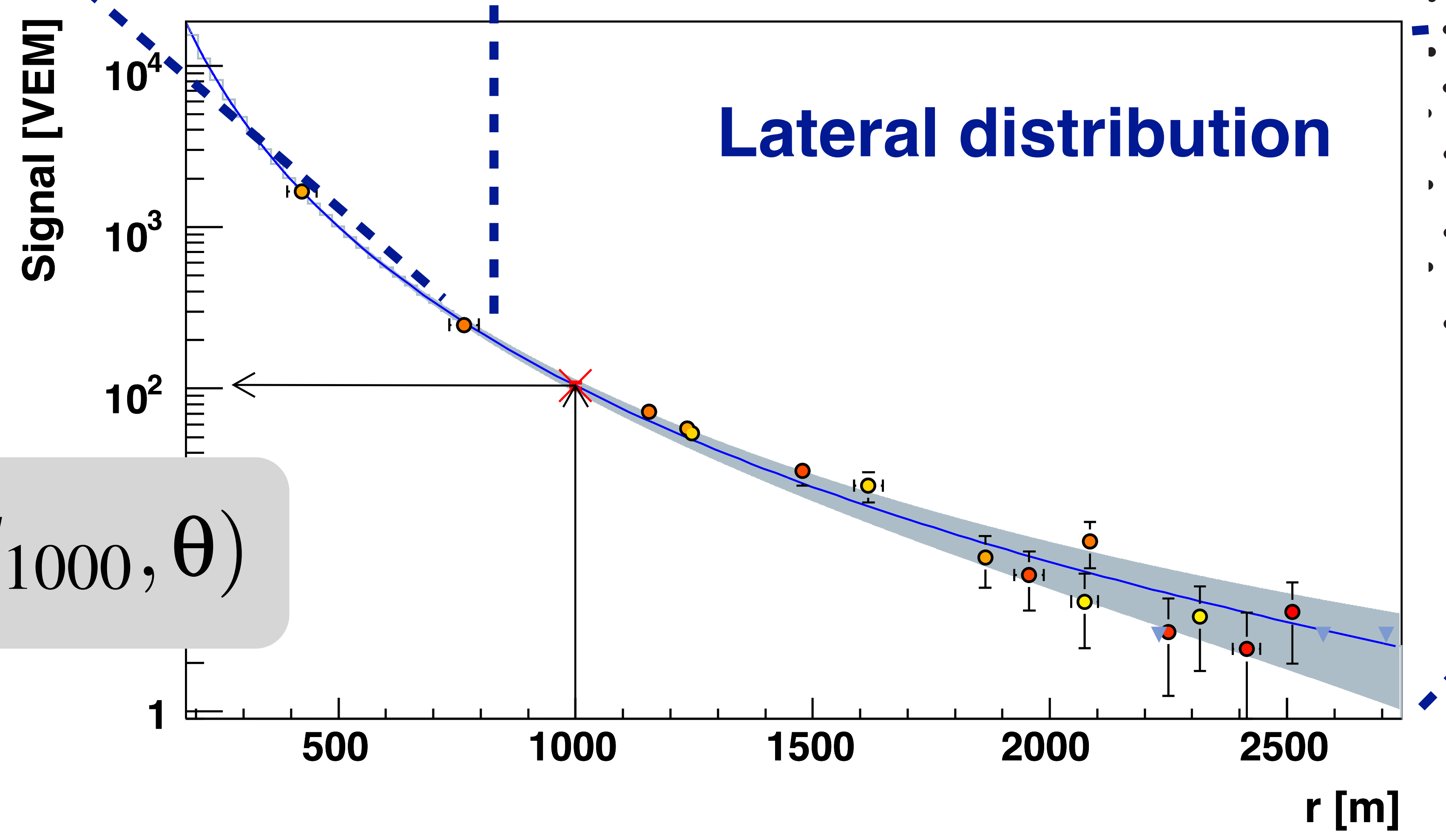

(Auger PRL 109, 2012; Telescope Array 1505.01860)

# Air shower detection – composition-sensitive observables

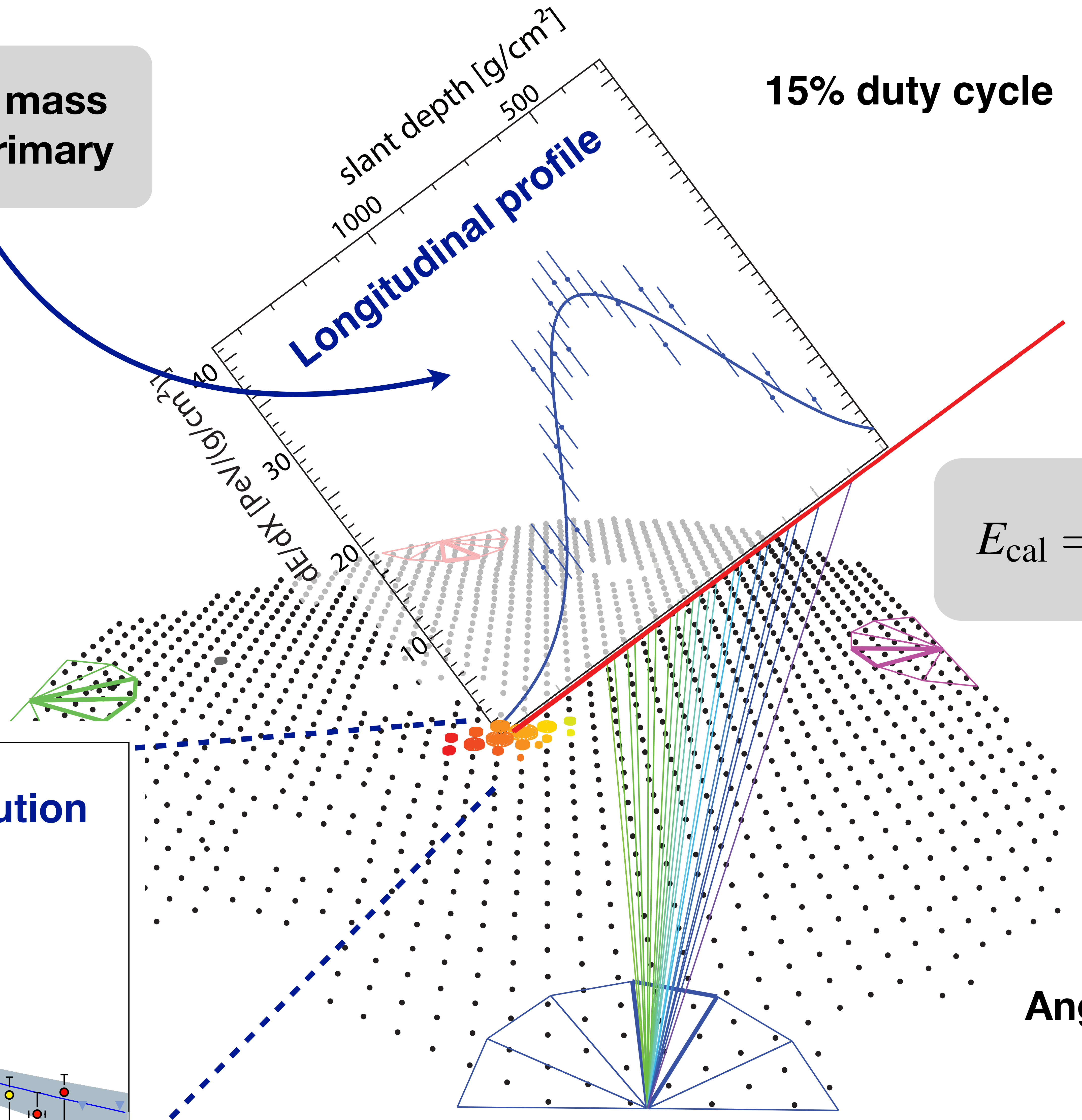
**Sensitivity to mass and type of primary**




**100% duty cycle**




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



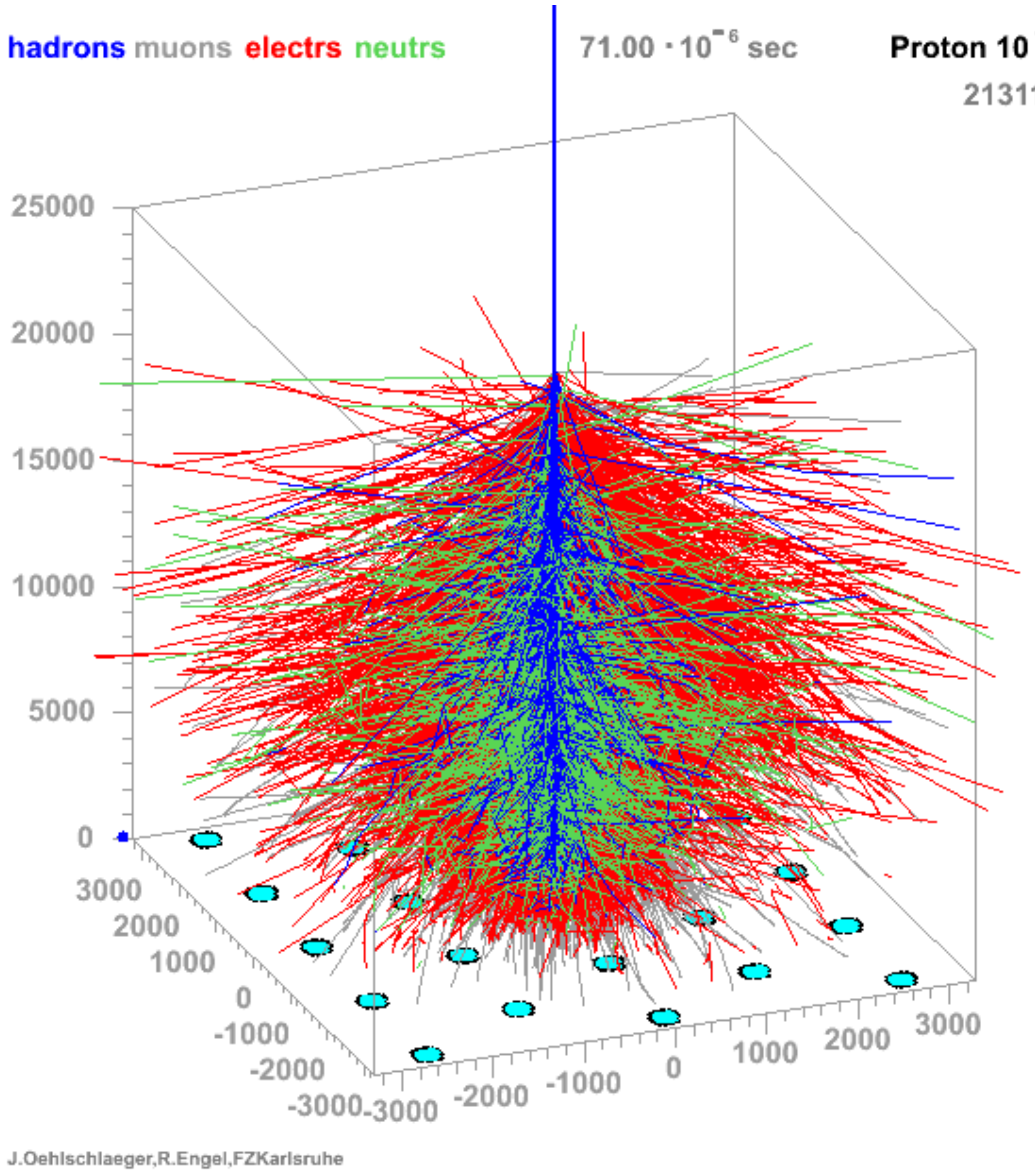

**15% duty cycle**

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

**Angular resolution ~ 1.5° – 0.5°**

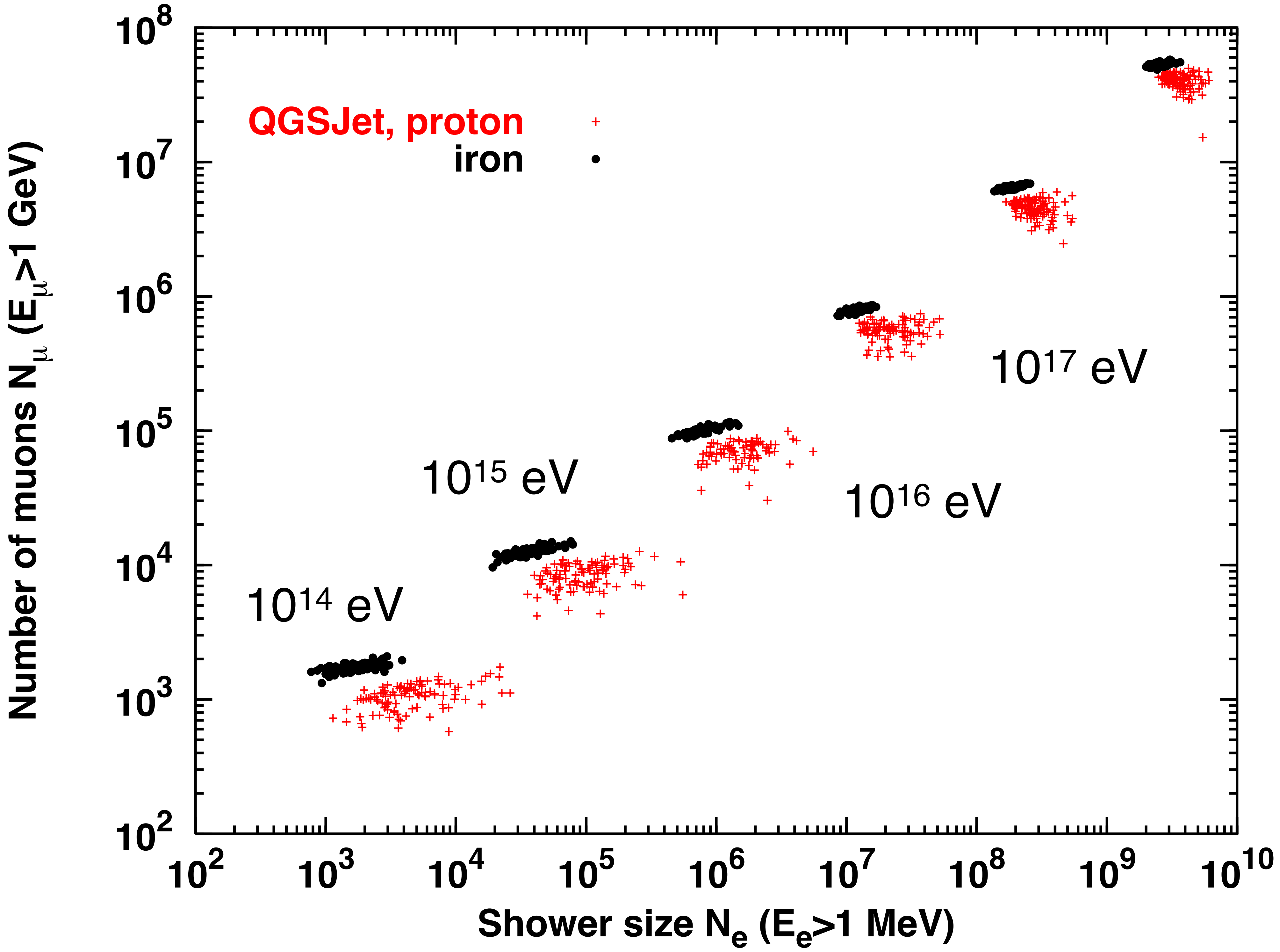
*Example: event observed with Auger Observatory*

# Classic way of composition measurement with air shower arrays

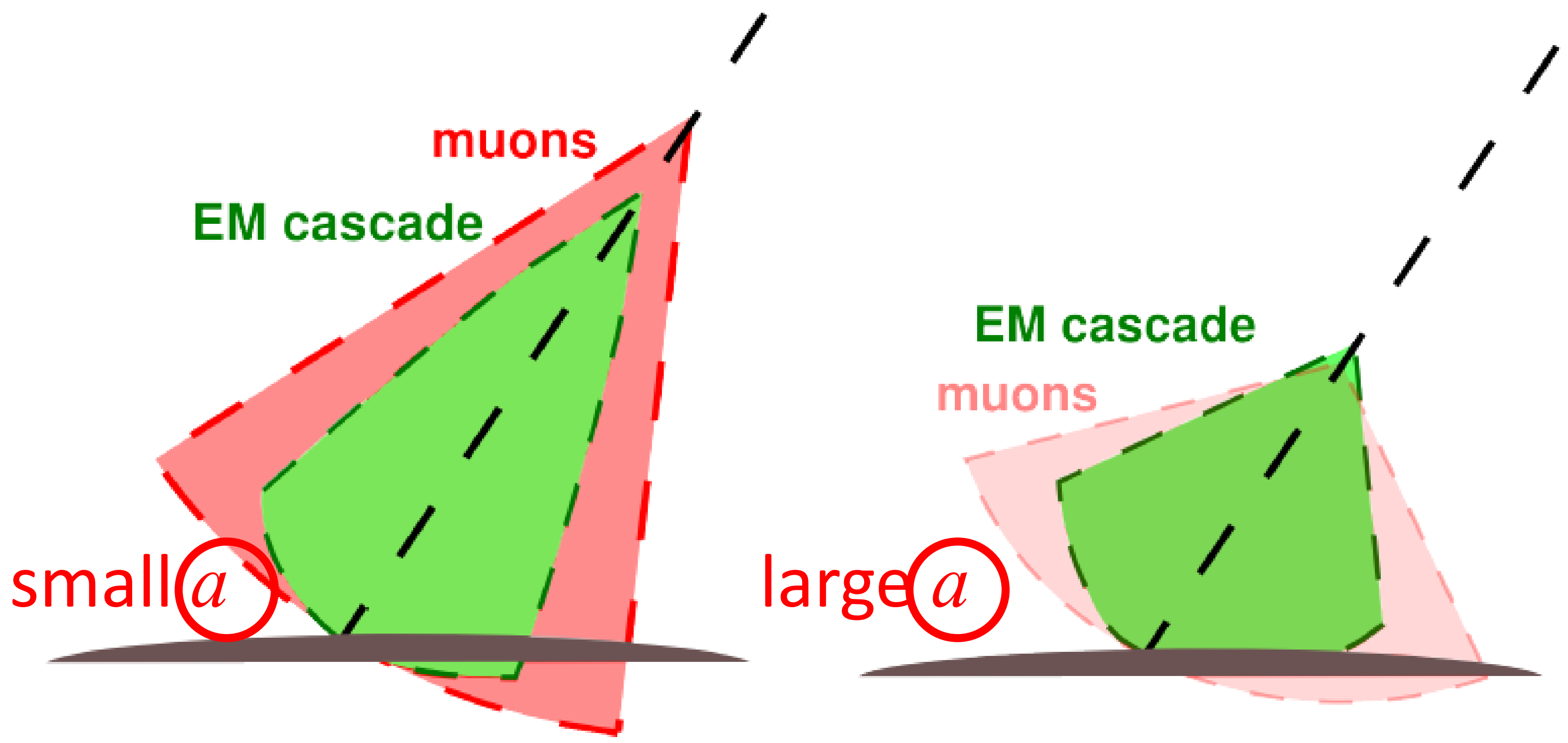



Low-energy shower shown ($10^{14}$ eV)

Combined energy-composition analysis

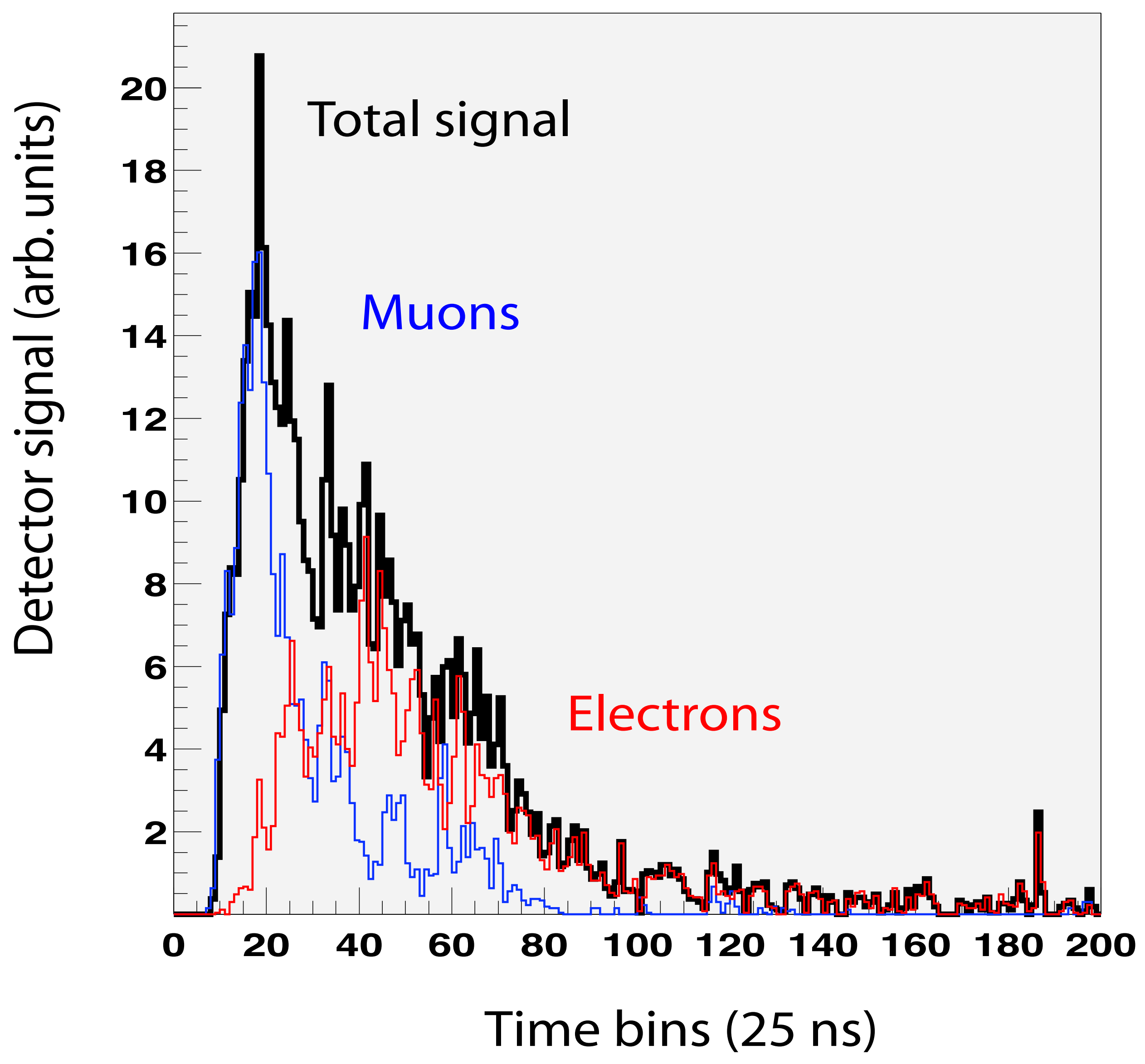


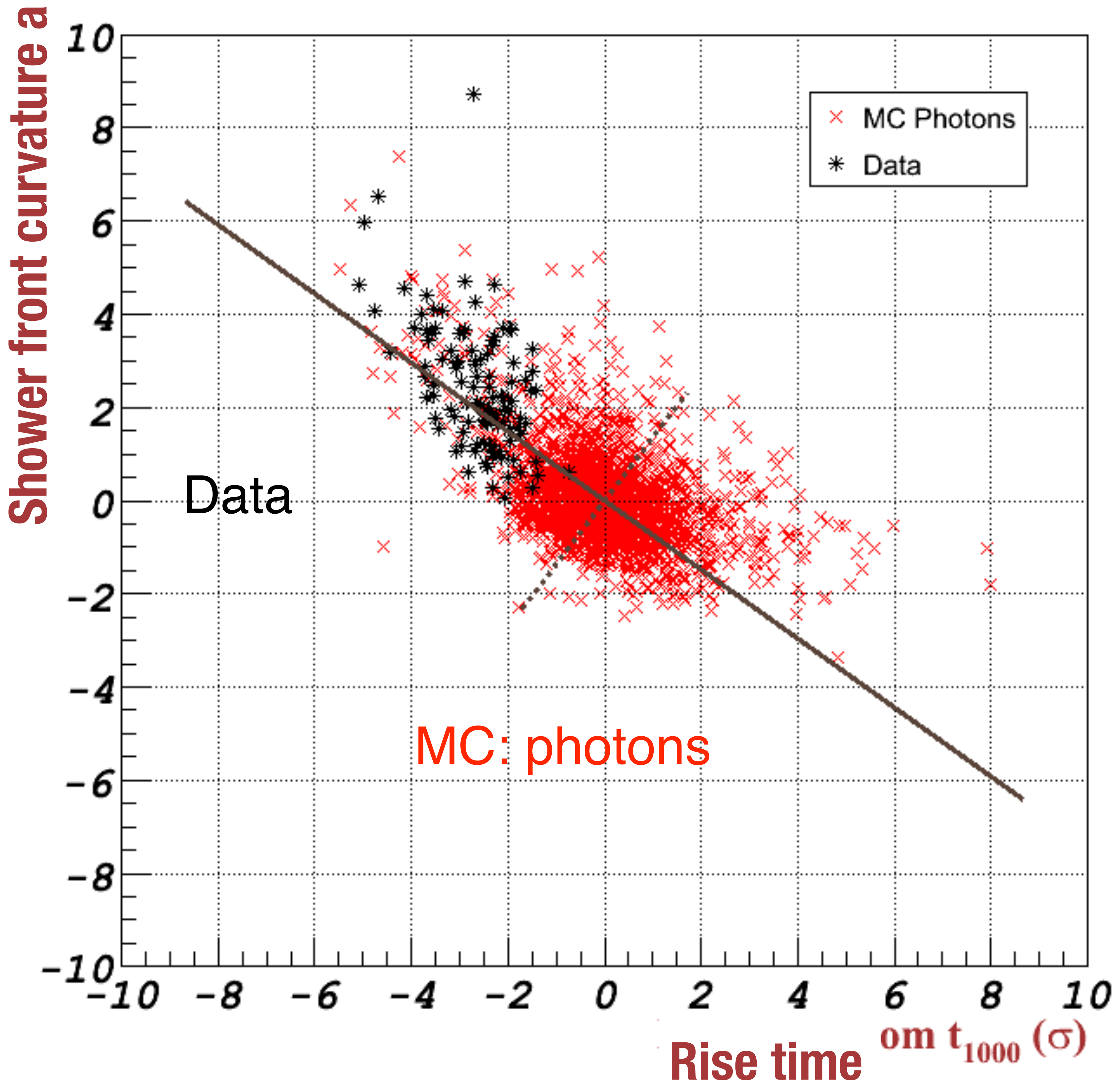
# Photon-induced shower sensitivity



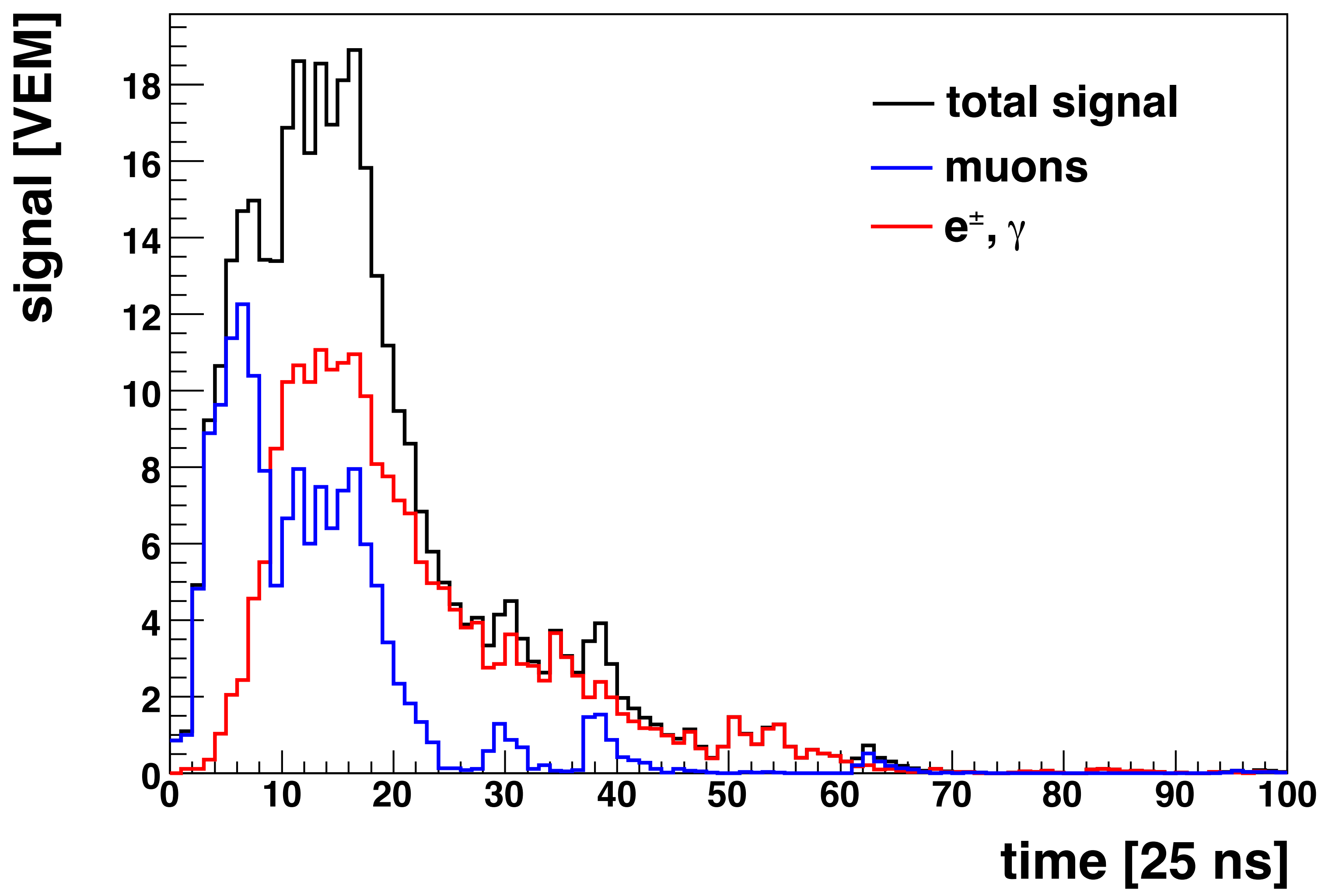

- Photons interact deeper in atmosphere
- Number of muons 1/7 to 1/5 of hadrons

*Signal rise time*



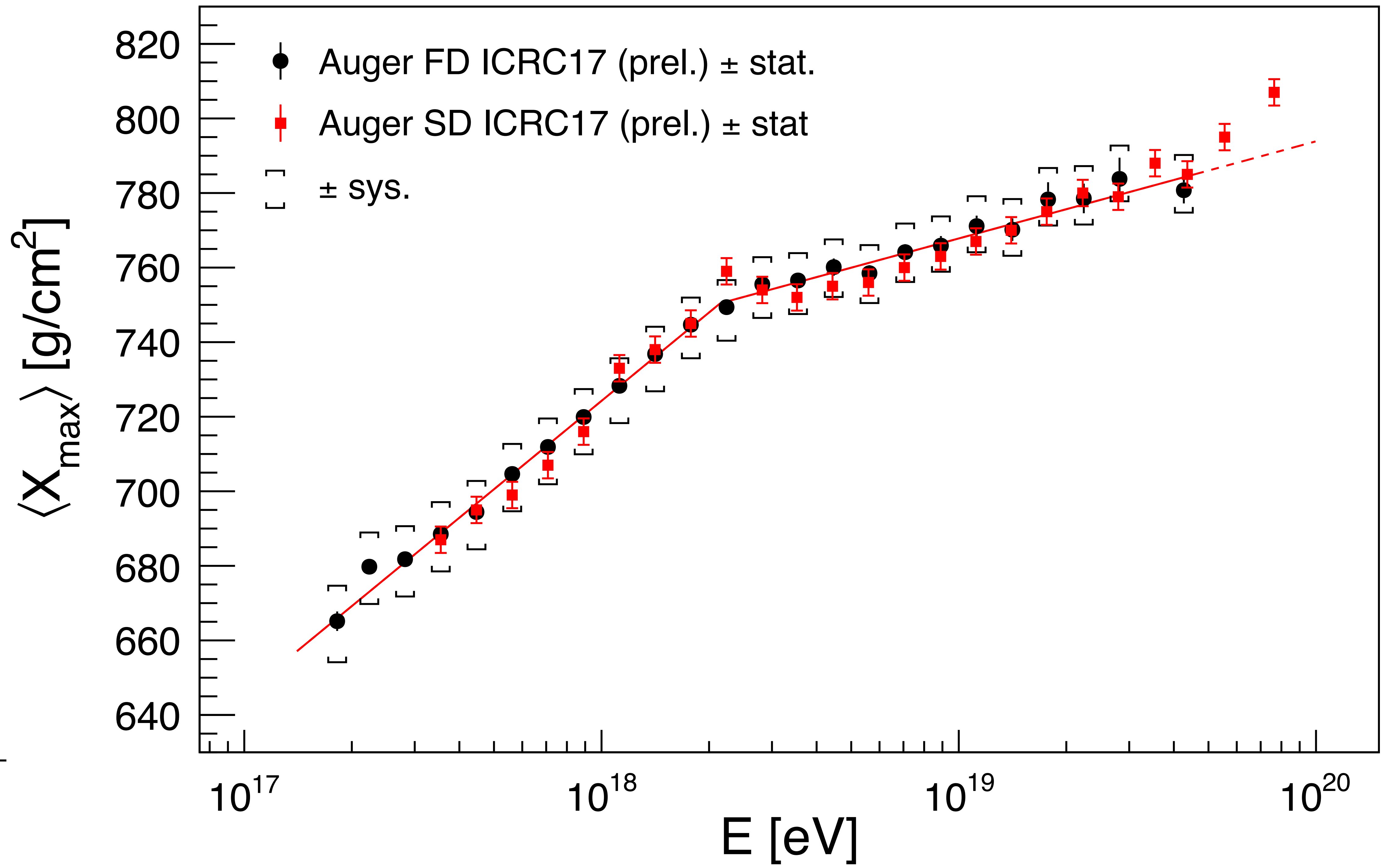



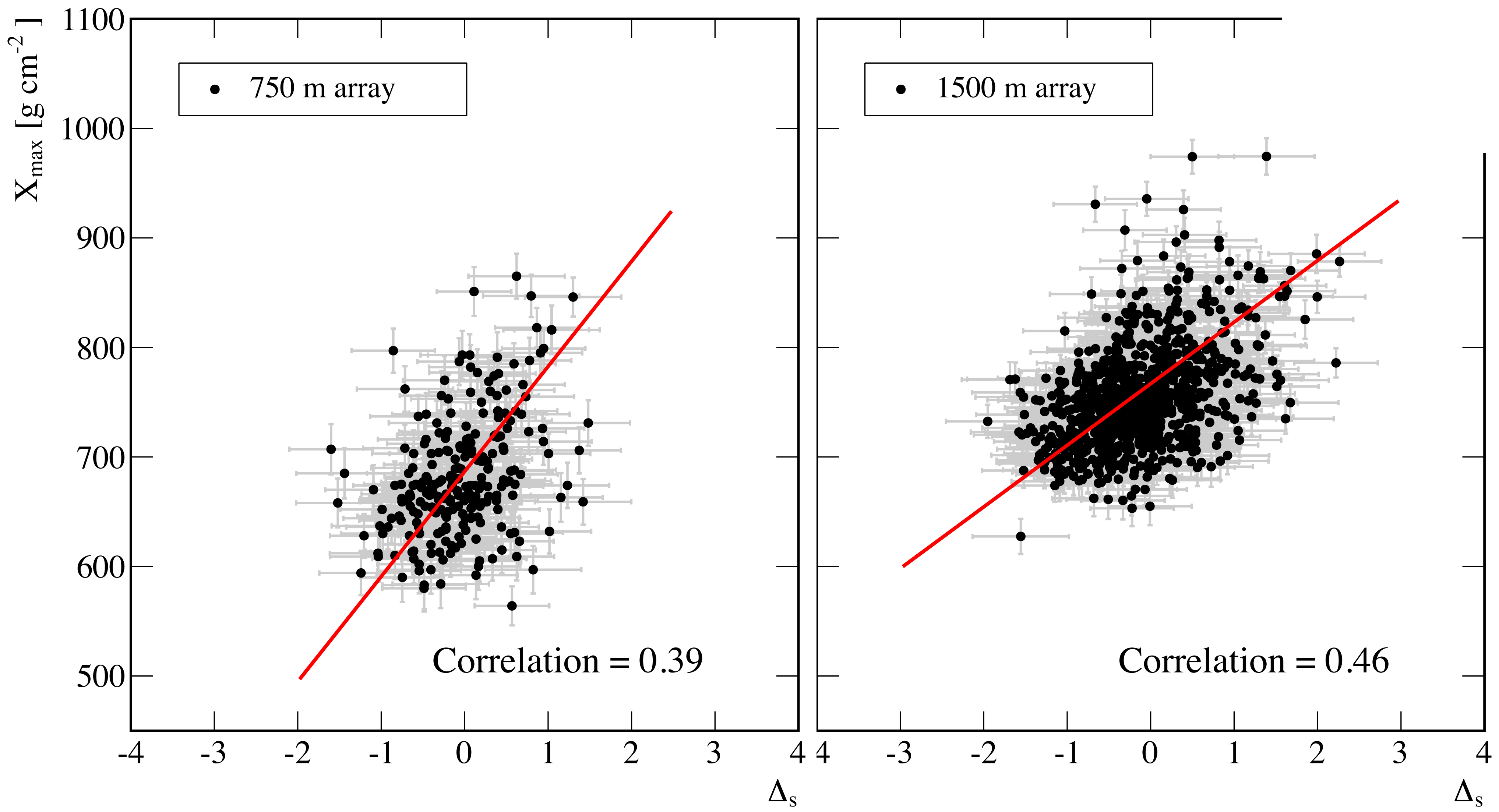
# Composition estimate using rise time of signal (i)




Rise time of signal

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



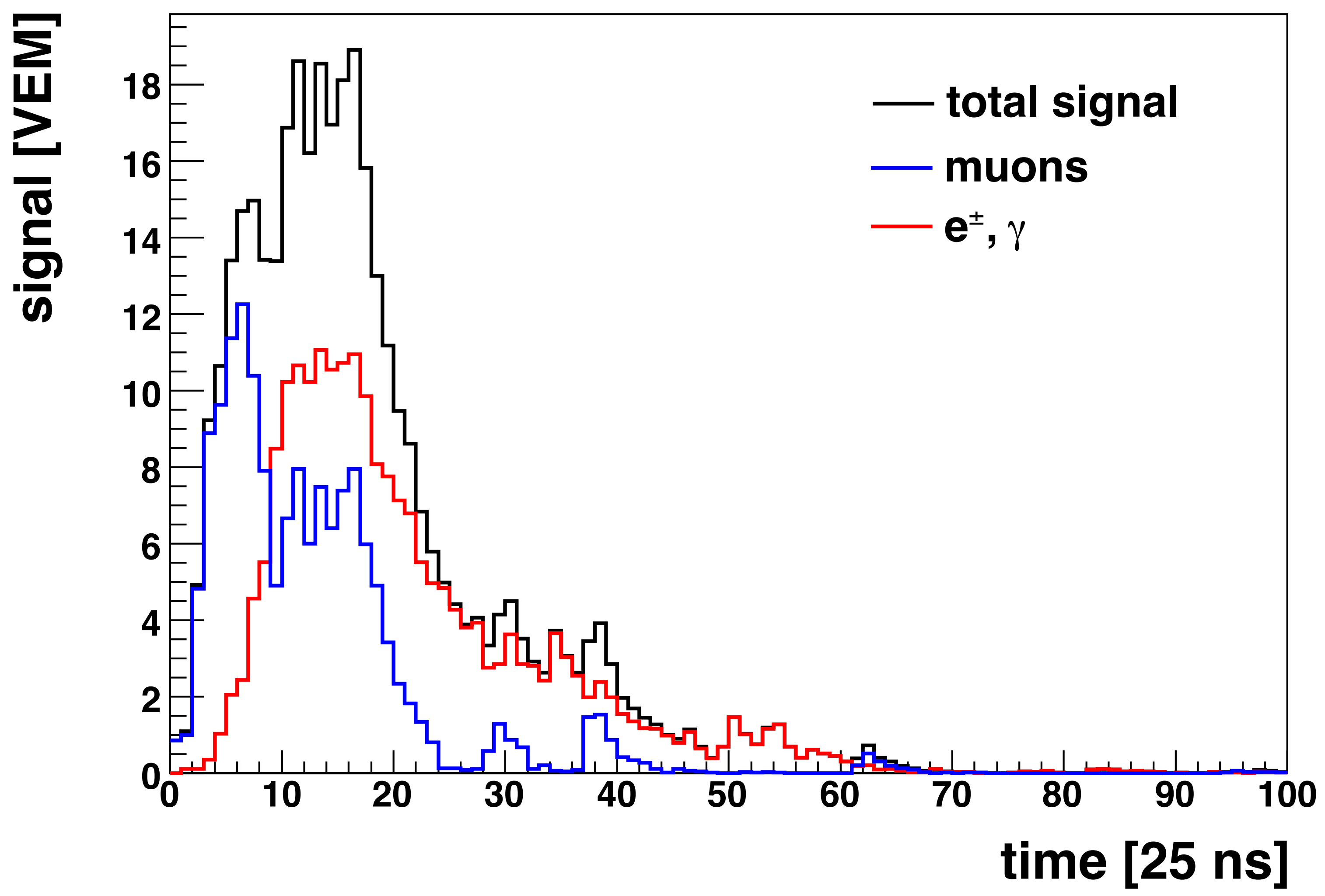




Result not directly depending on models

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

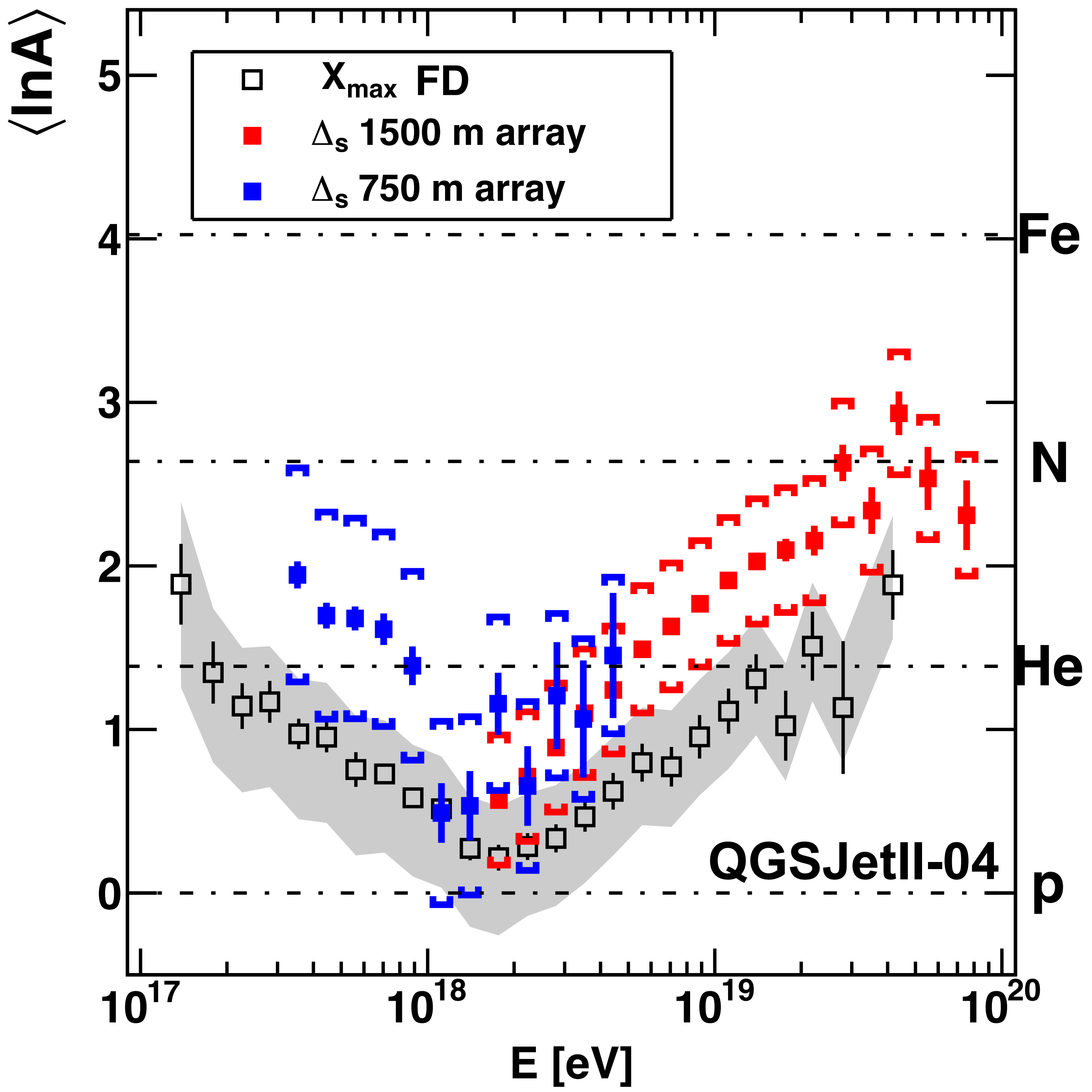
*(Sanchez-Lucas ICRC 2017)*

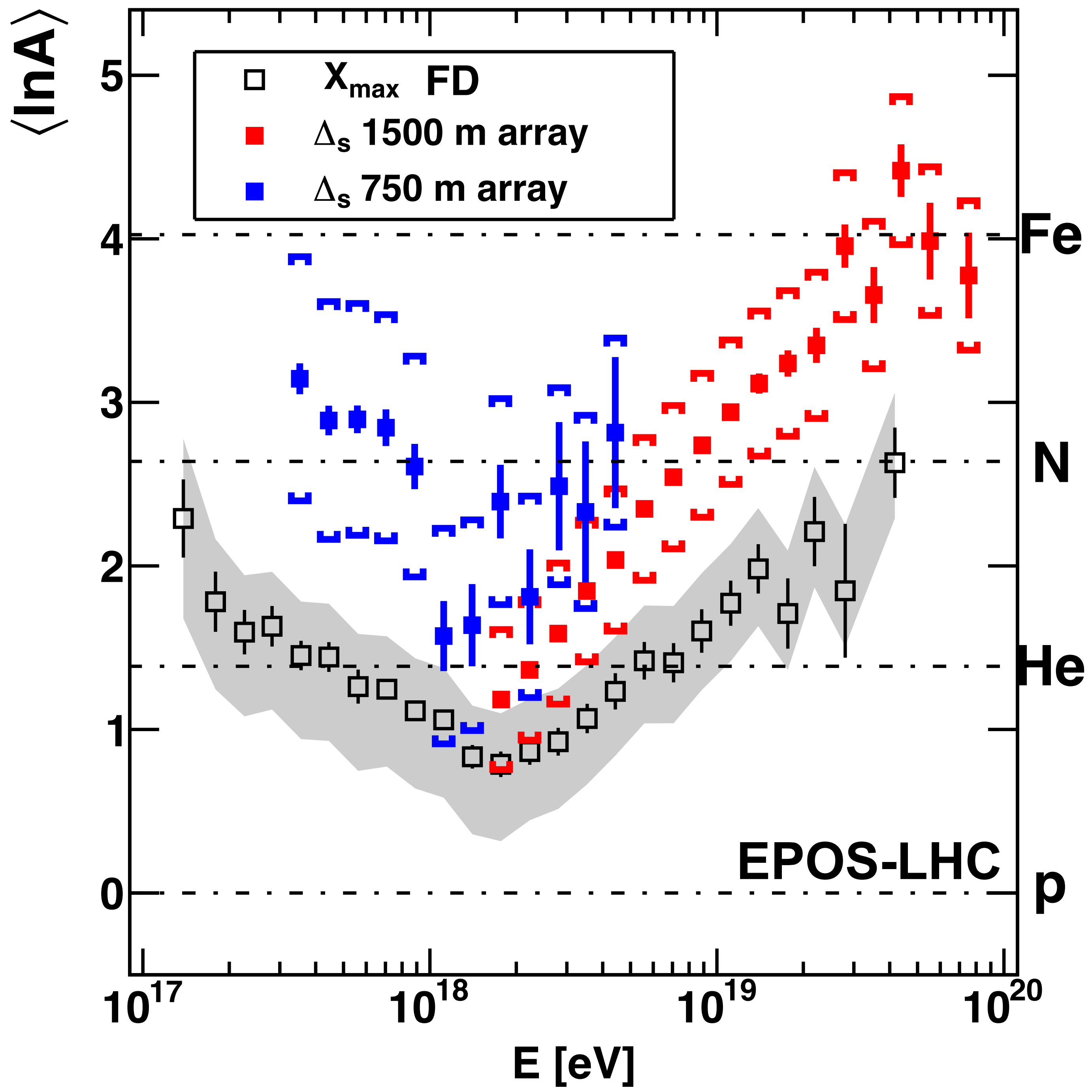
# Composition estimate using rise time of signal (ii)




Rise time of signal

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



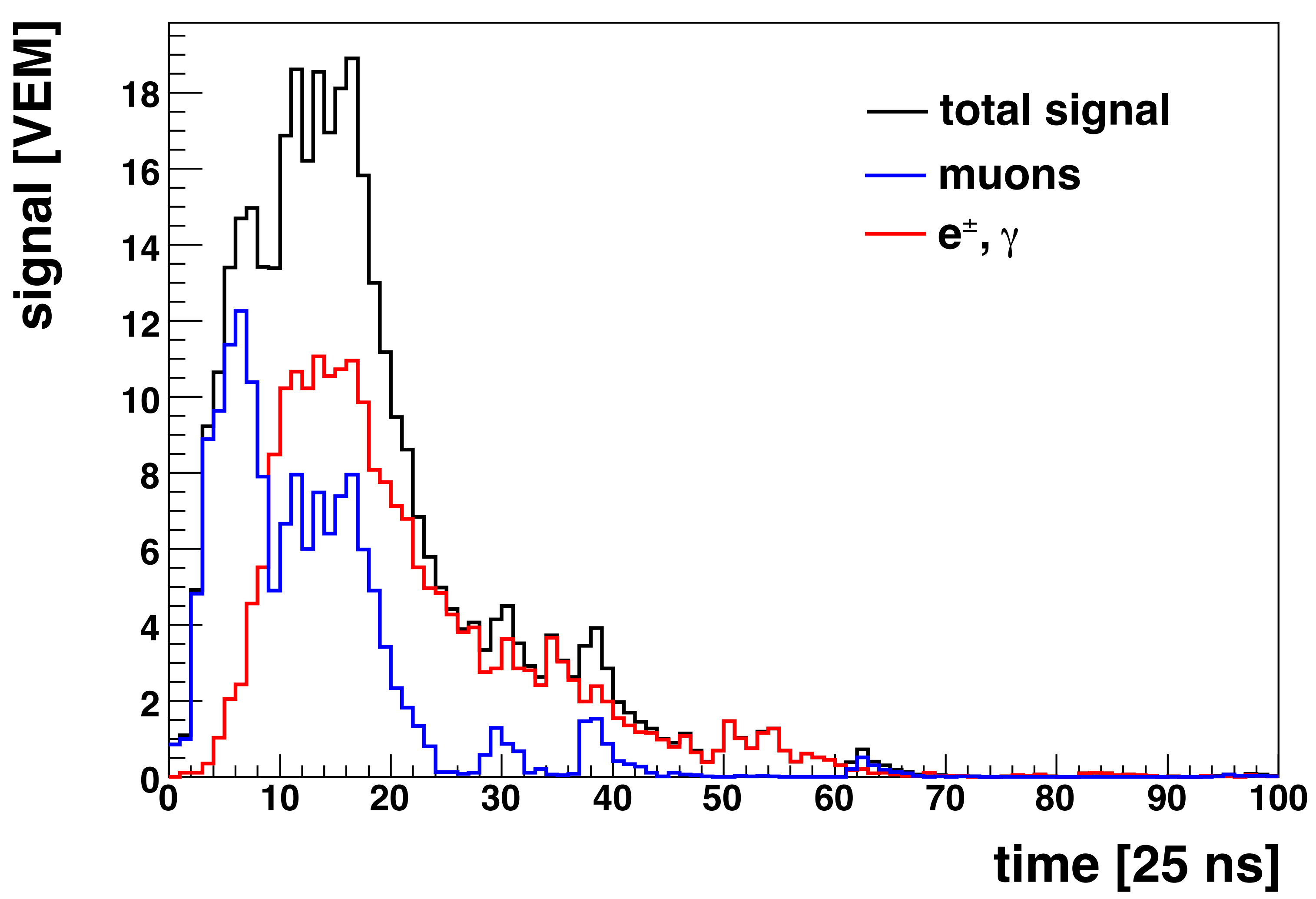




Interpretation with models

- No consistent picture with longitudinal profile (direct Xmax measurement)
- Same trends in changes of composition

*(Sanchez-Lucas ICRC 2017)*

# Composition estimate using rise time of signal (iii)

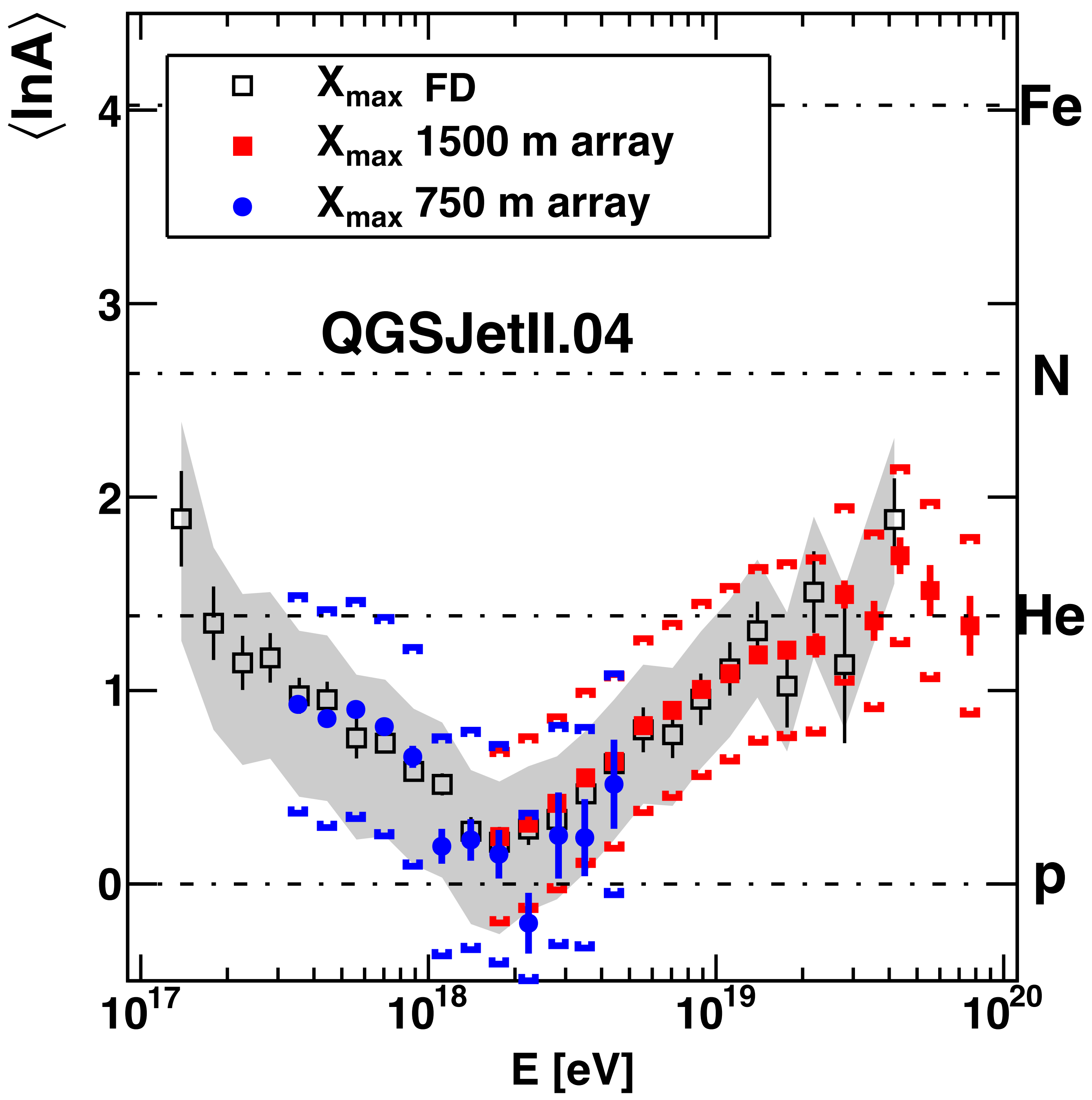


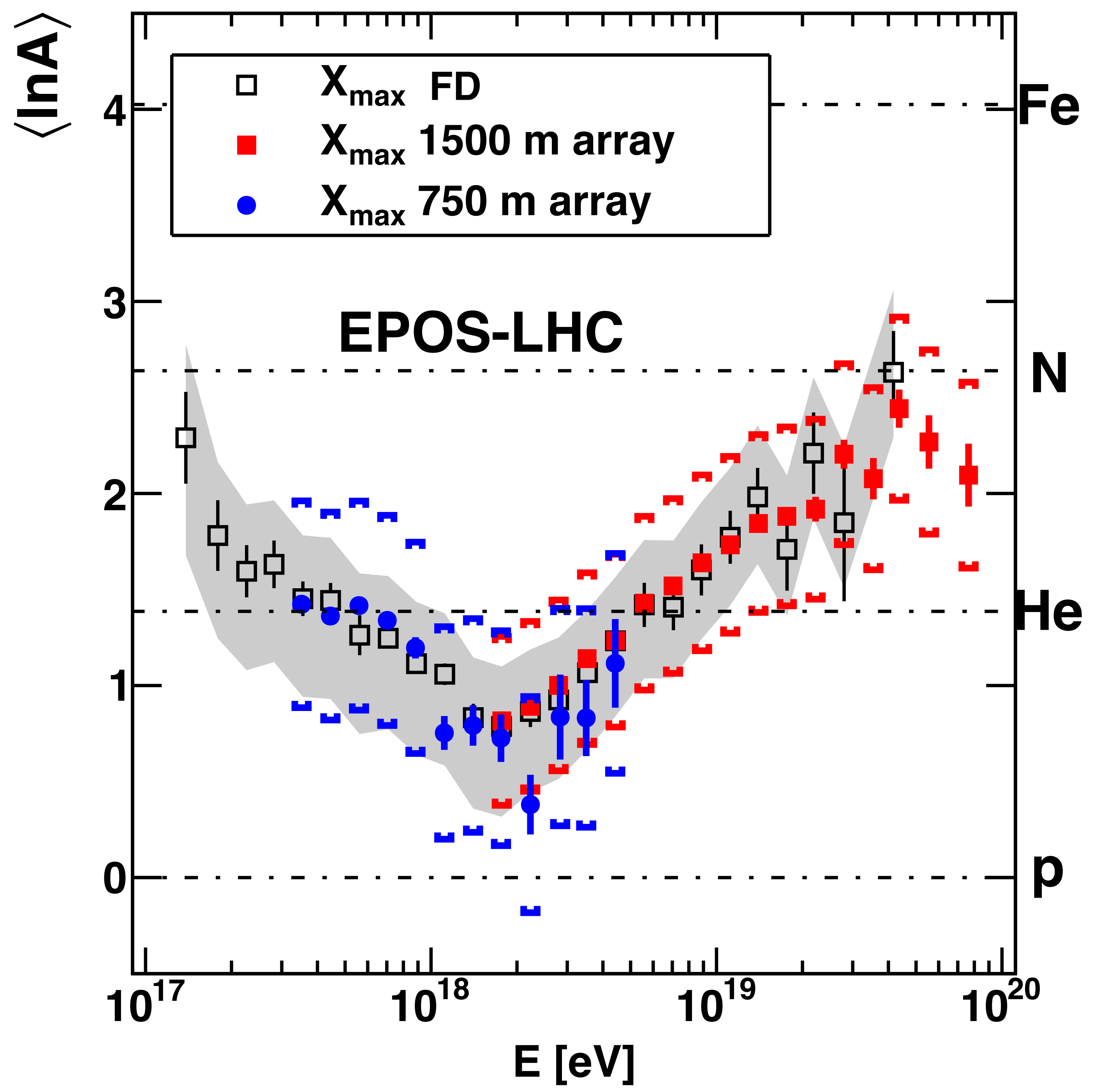

Rise time of signal

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

After calibration with fluorescence profiles

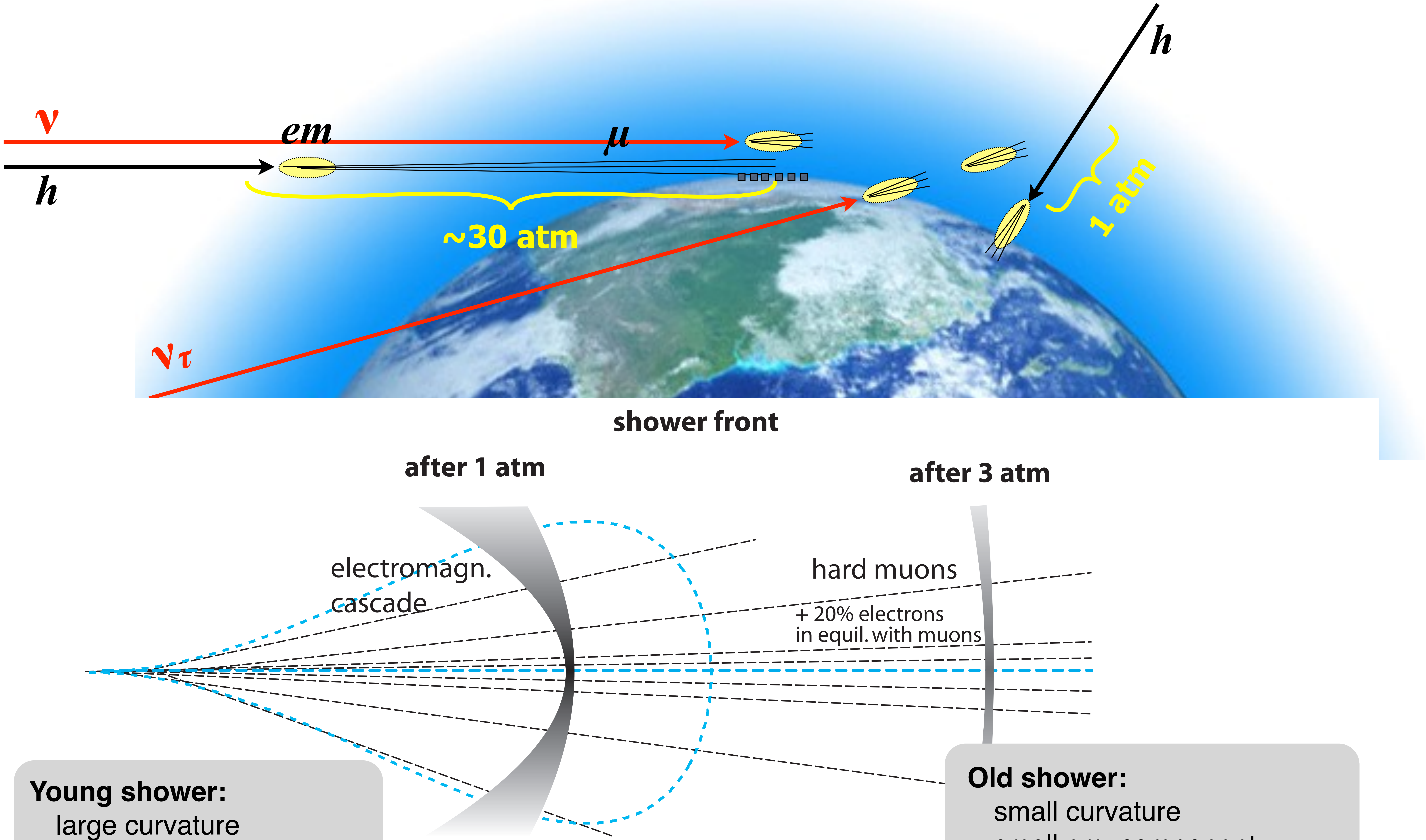
- Consistent picture with longitudinal profile (direct Xmax measurement)
- Extension to higher energy
- Only mean Xmax can be determined




(Sanchez-Lucas ICRC 2017)

# Physics of highly inclined showers

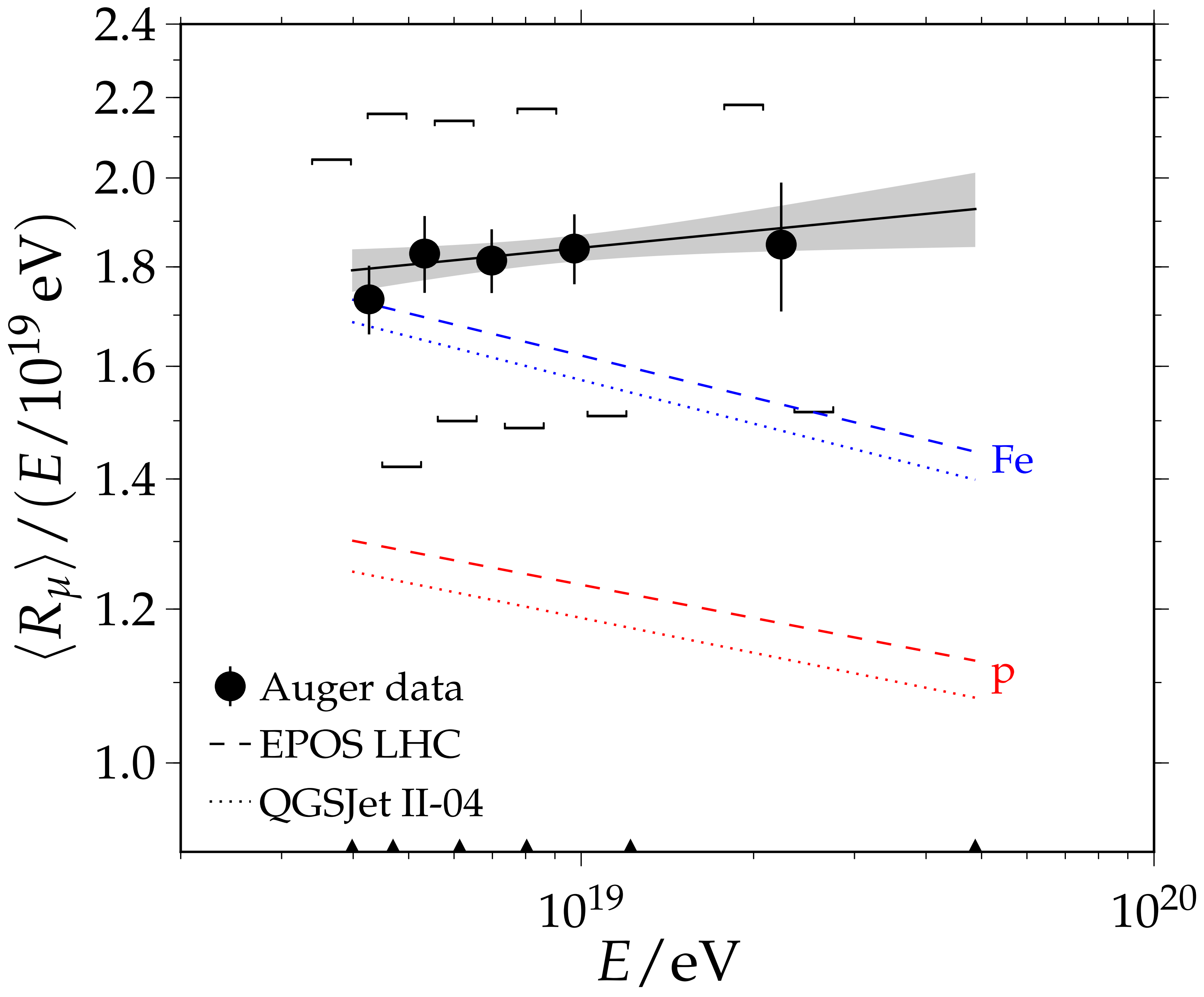



**Young shower:**
large curvature
large em. component
extended time structure

**Old shower:**
small curvature
small em. component
compressed time structure

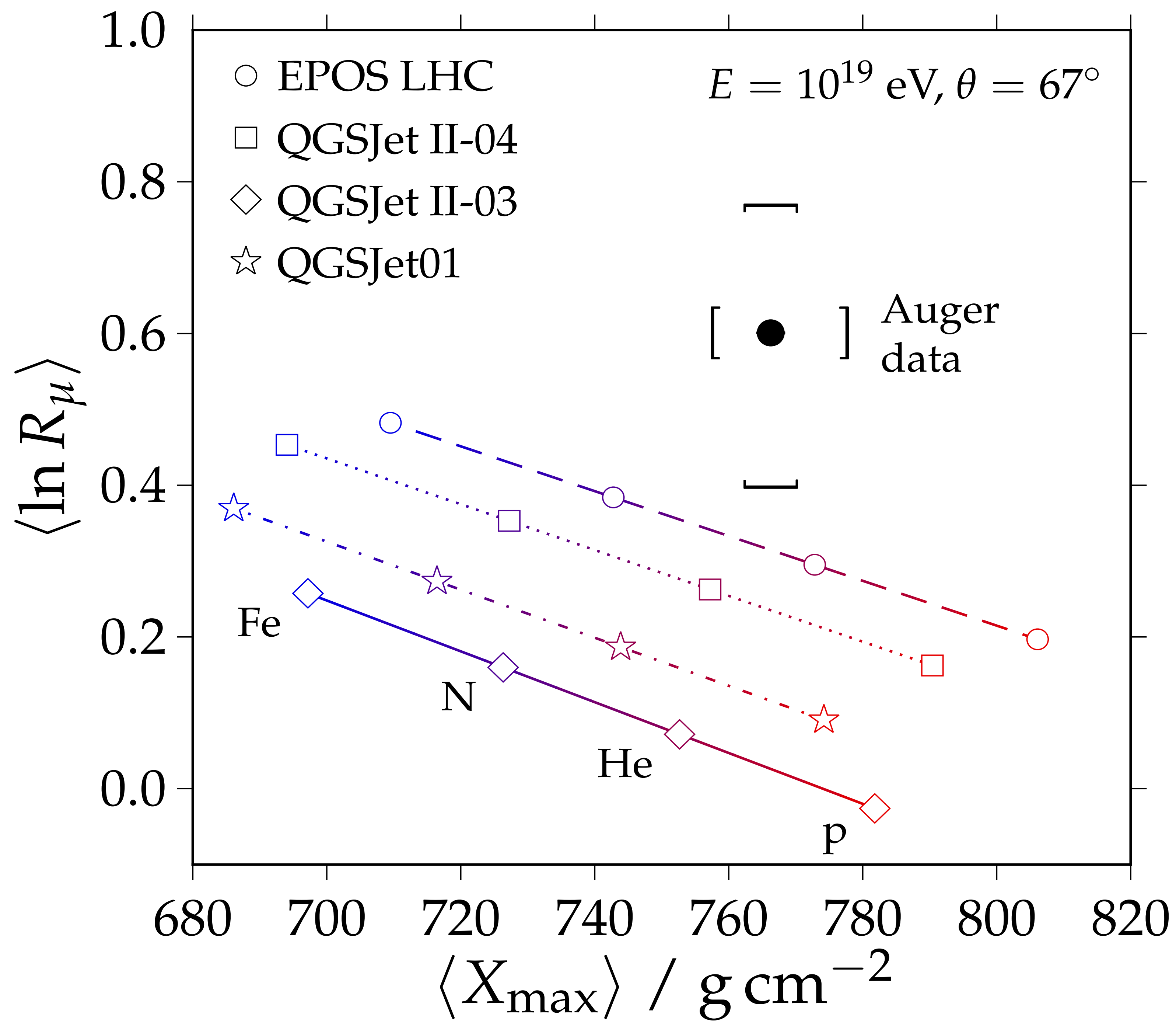
# Muon number in inclined showers

Number of muons in showers with θ>60°



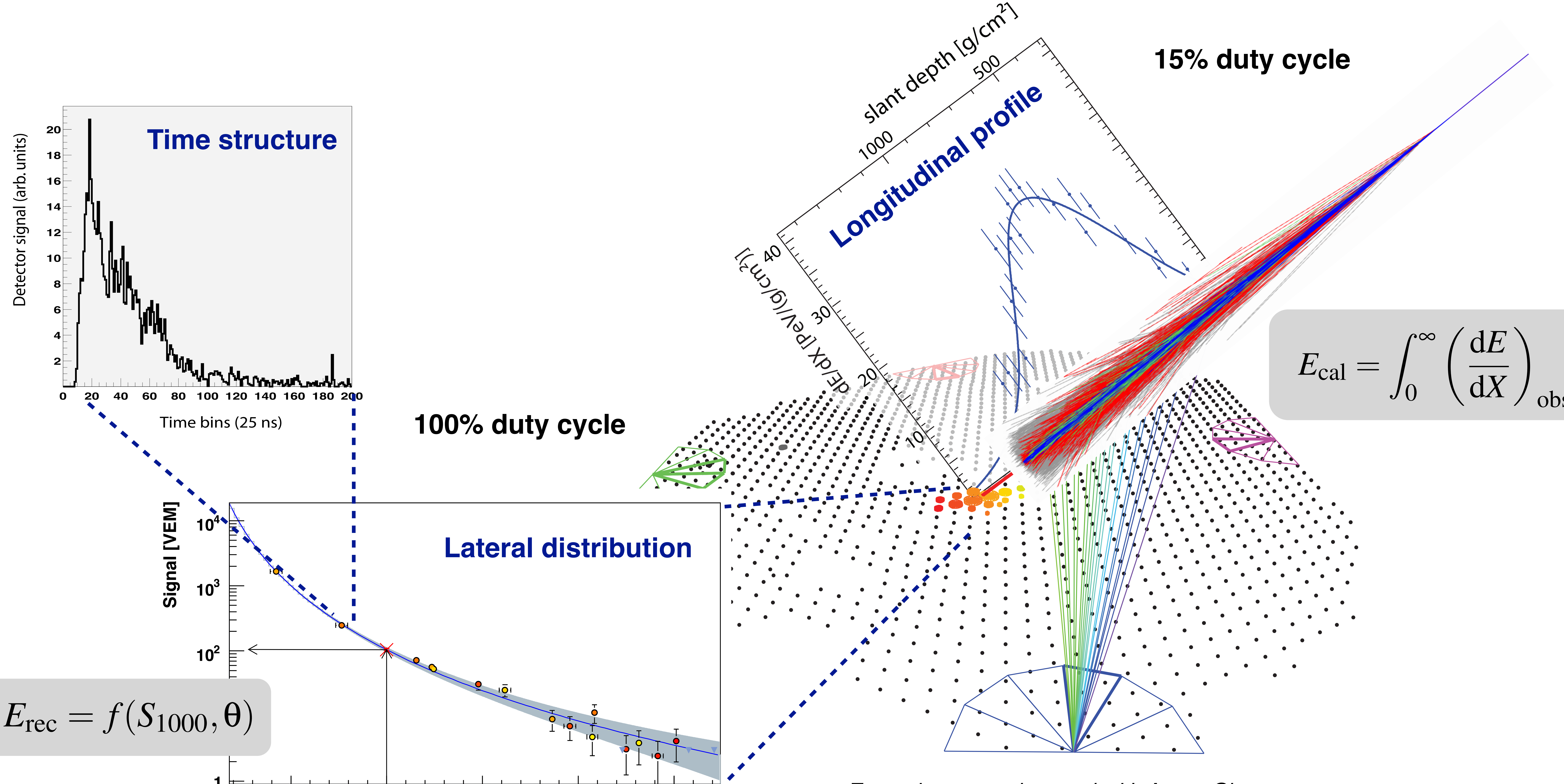

(Auger, PRD91, 2015)

Combination of information on mean depth of shower maximum and muon number at ground




Several measurements: indications for muon discrepancy

# Consistency check: longitudinal profile vs. ground signal

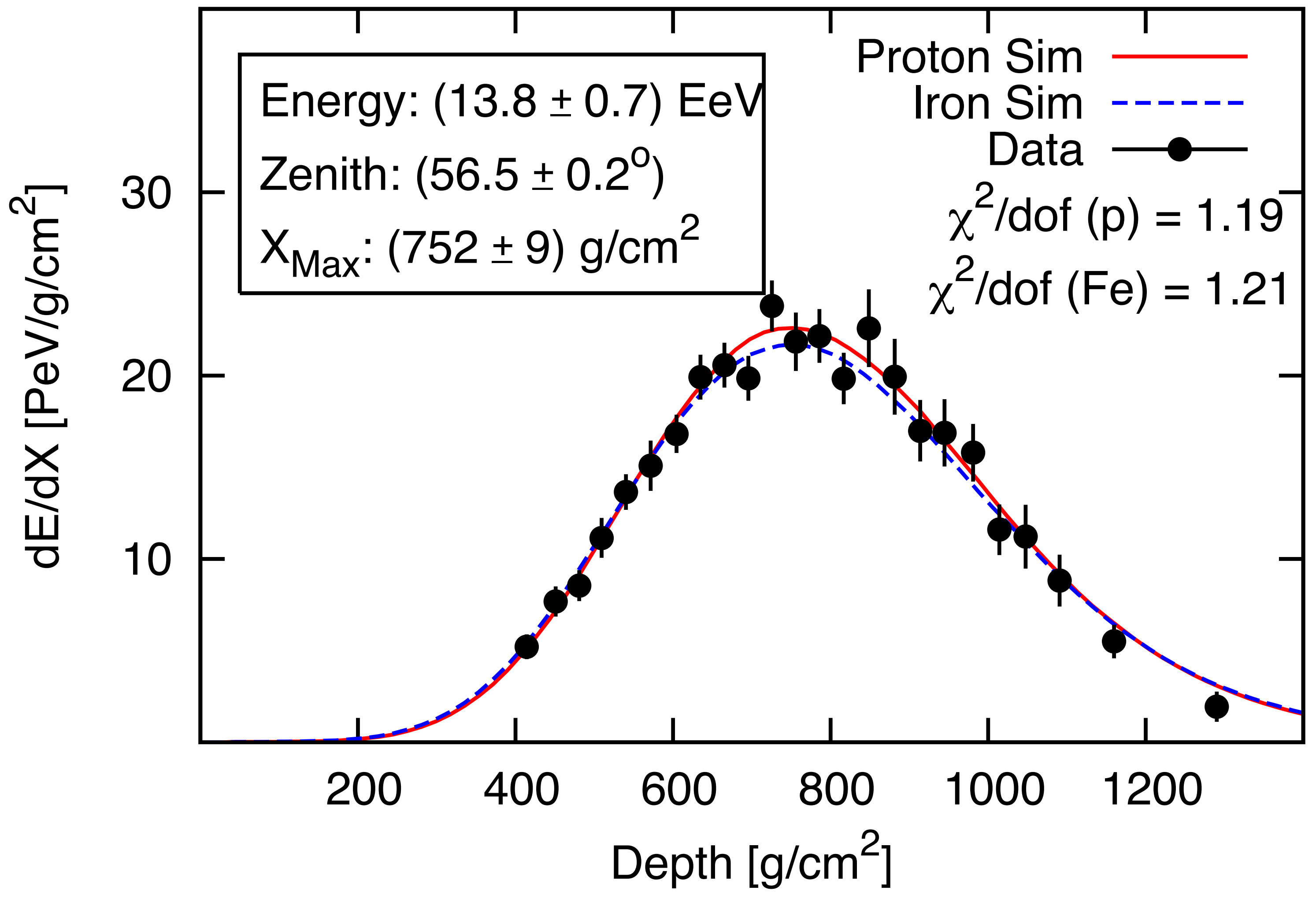


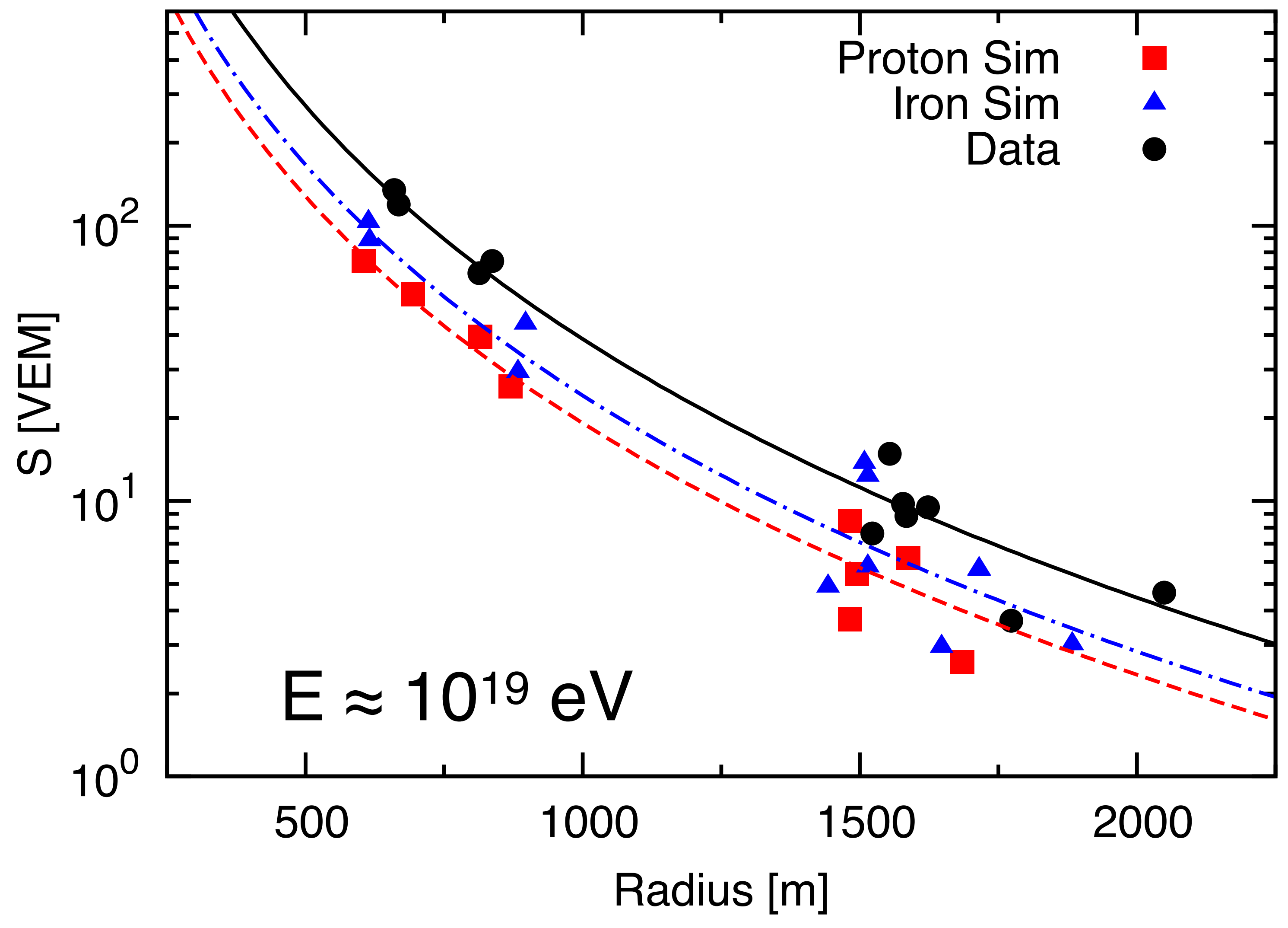

$$E_{\mathrm{rec}} = f(S_{1000}, \theta)$$

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

*Example: event observed with Auger Observatory*

# Ultimative test: simulation of individual events



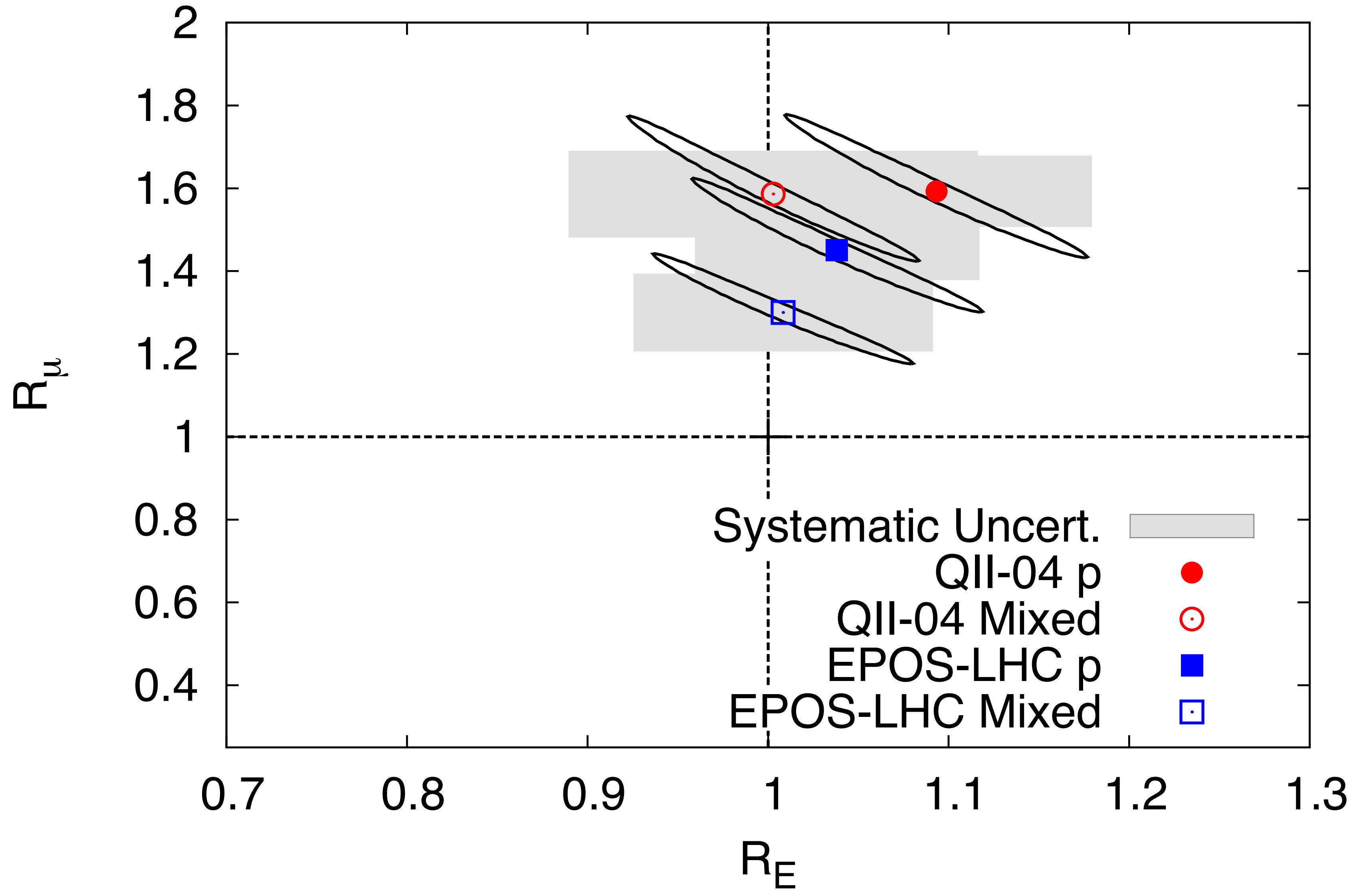




**Phenomenological model ansatz**

**Energy scaling:** em. particles and muons

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

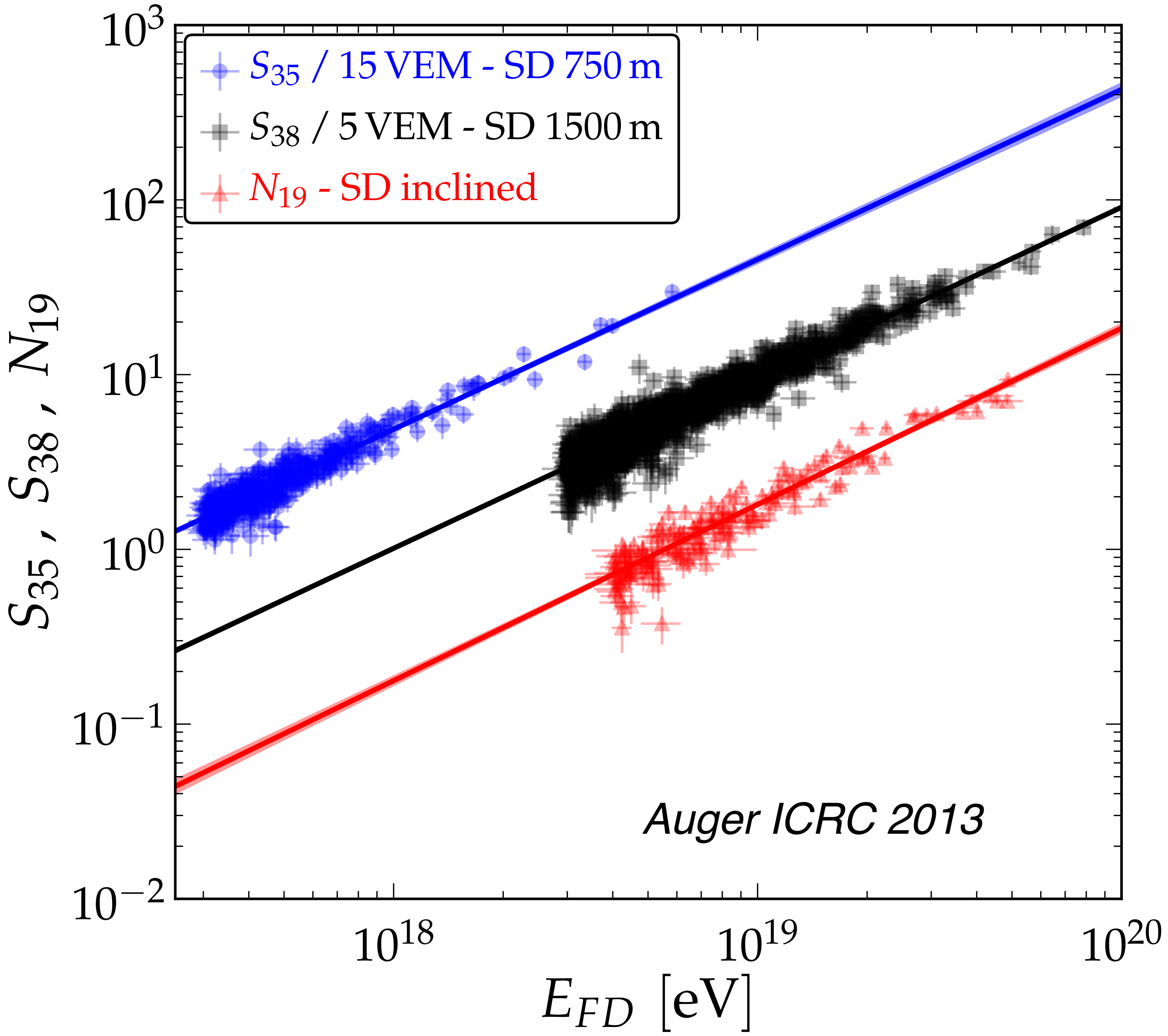
**Full detector simulation after re-scaling**

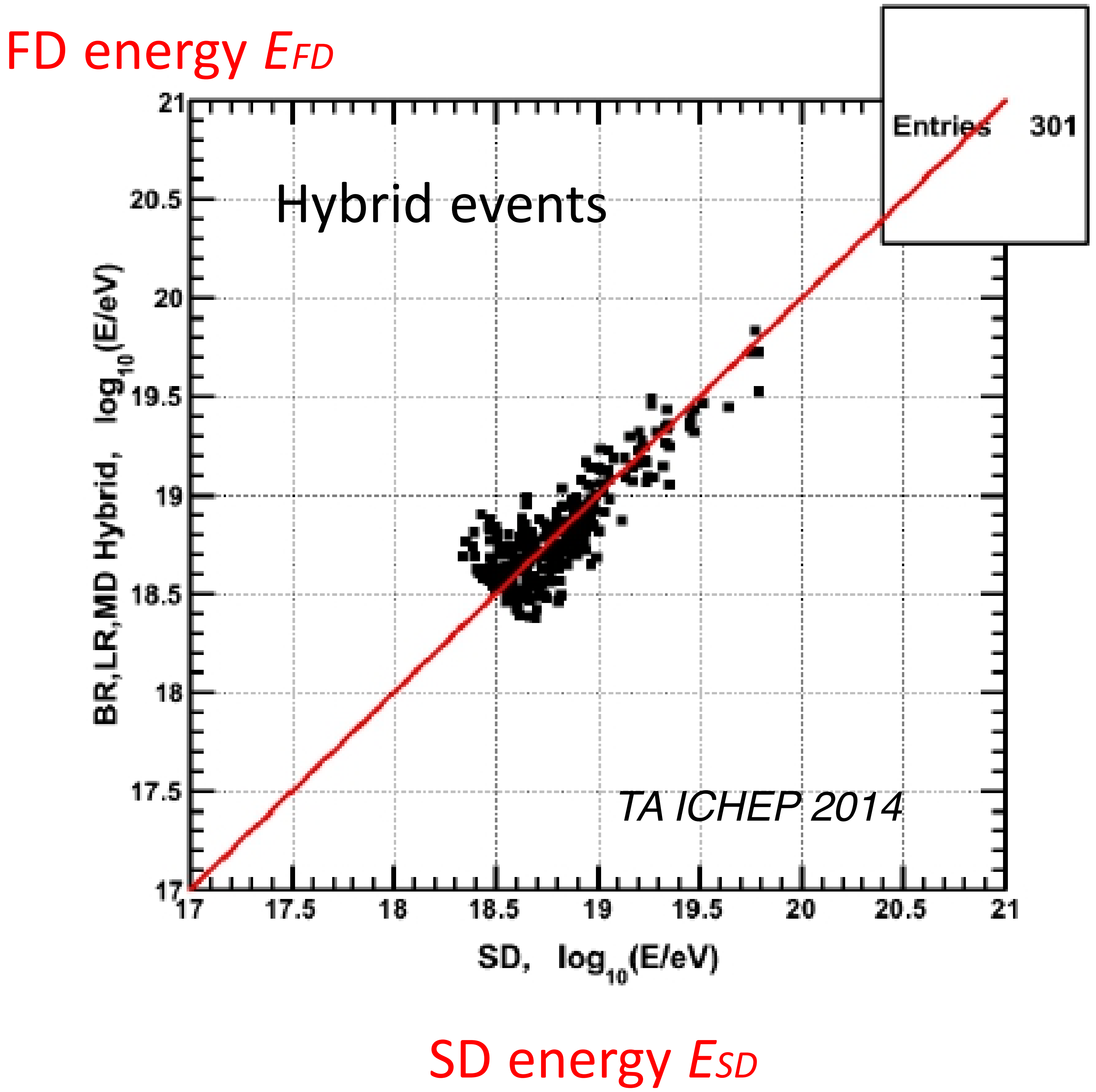



None of the models gives a really good description ?

*(Auger, ICRC 2013)*

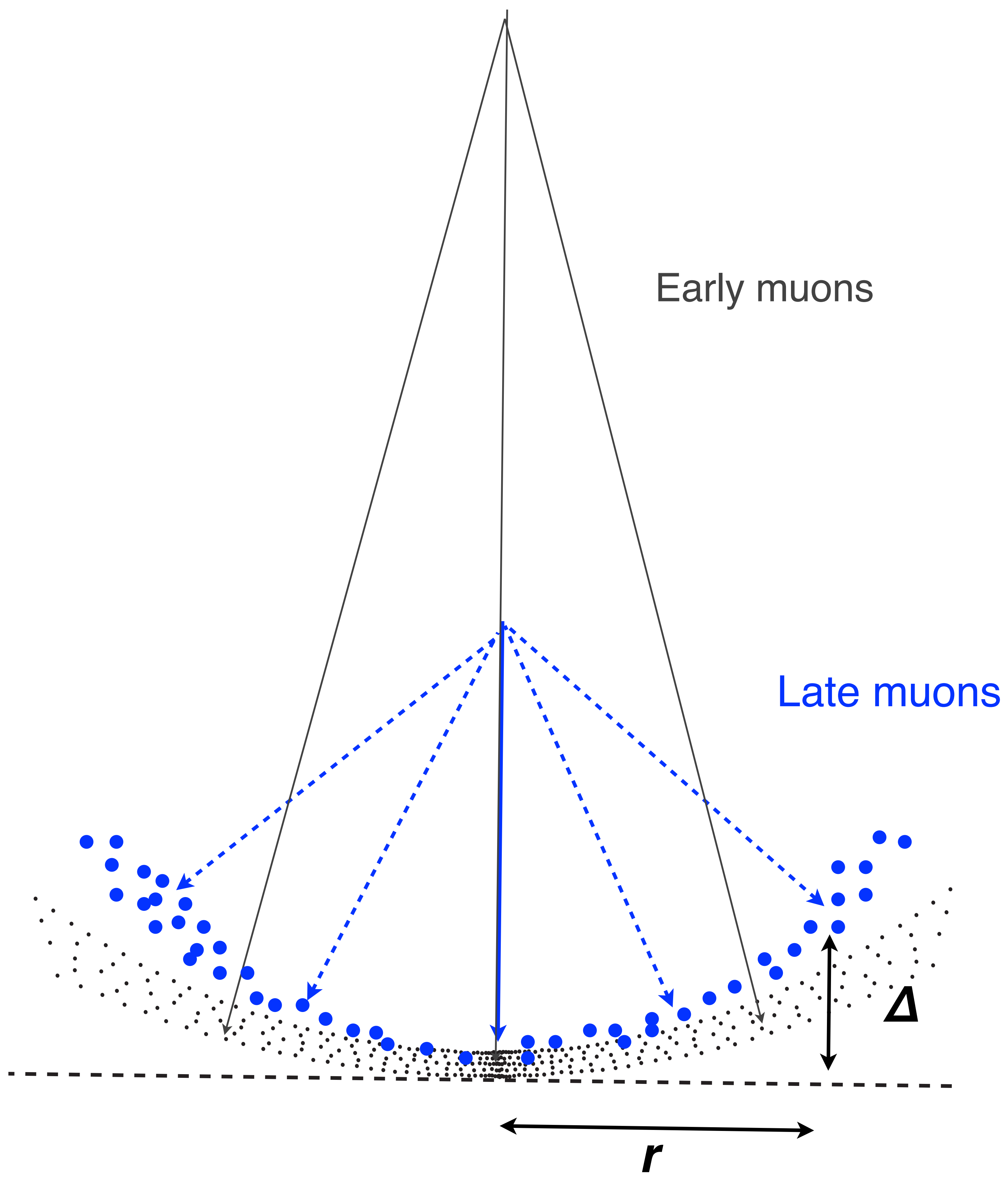
# Difference in fluorescence and simulated array signal



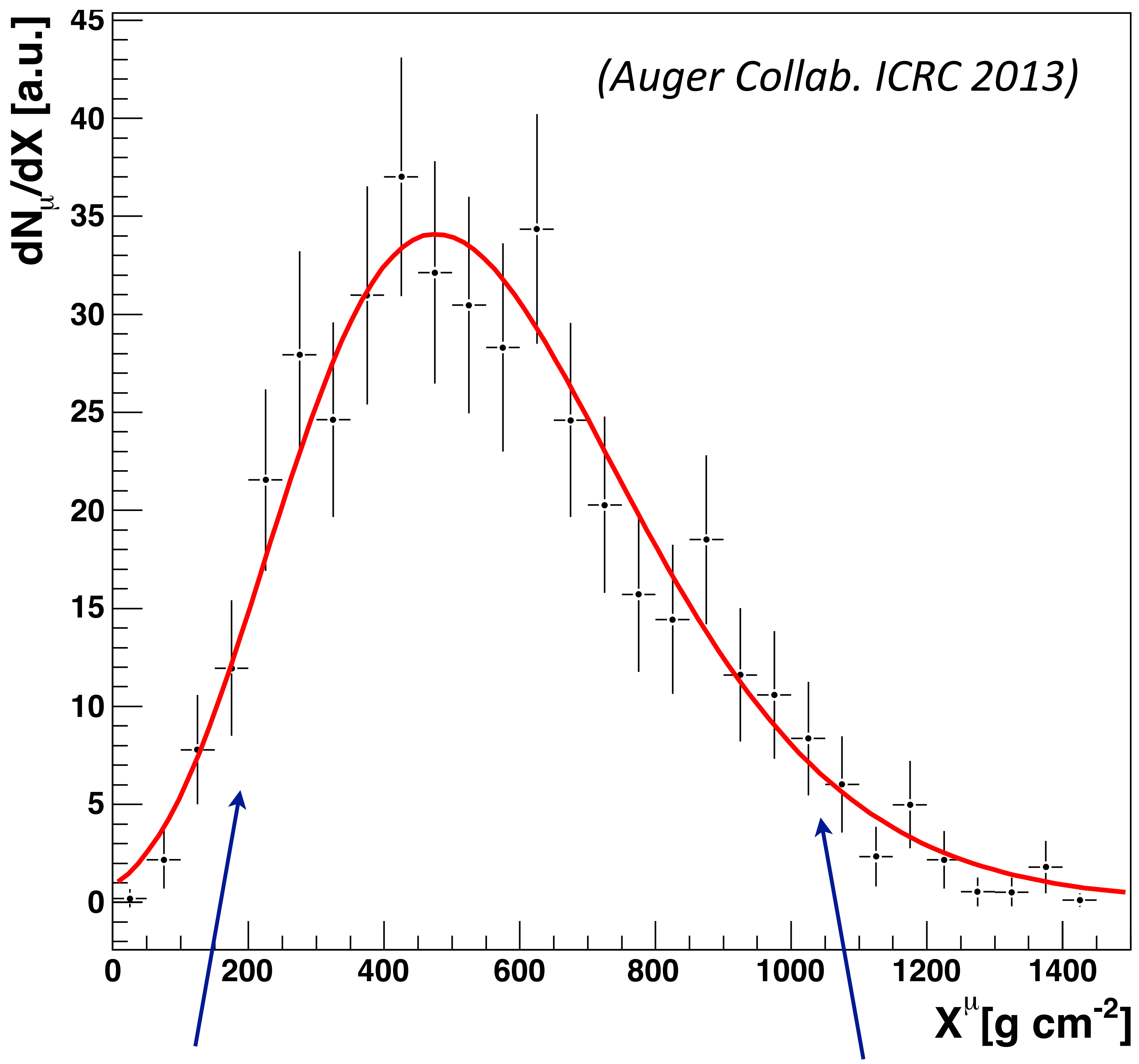

Auger: rescaling of 24% needed relative to 50/50 mix of p and Fe
TA: rescaling of 27% needed relative to protons (QGSJET II.03)

# Distribution of muon production depth (MPD)



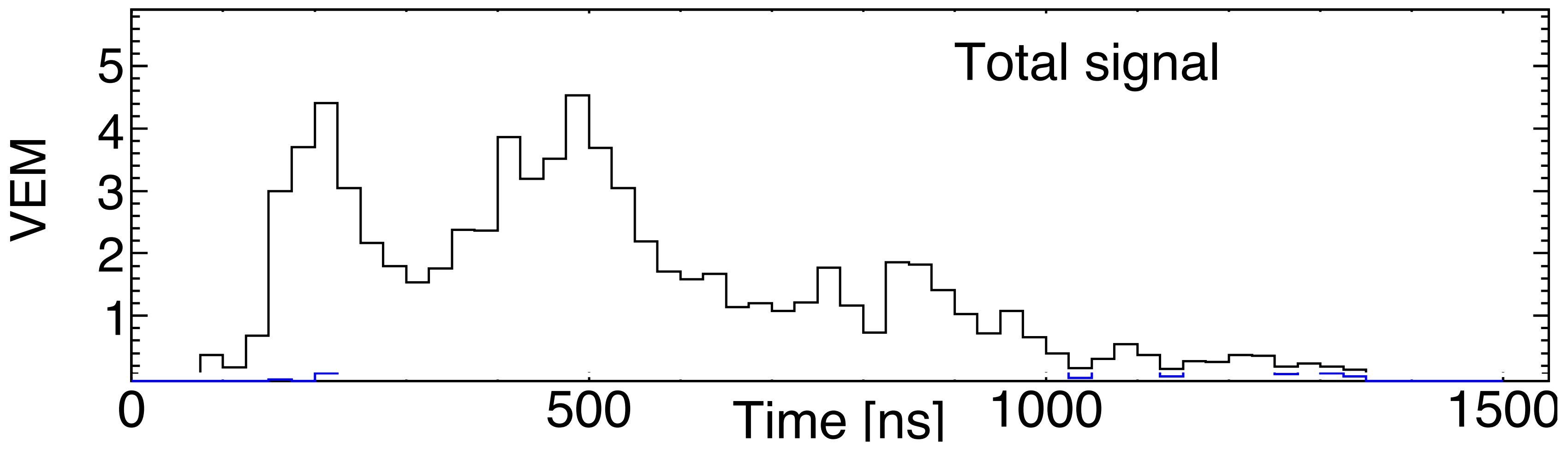

$$z \simeq \frac{1}{2}\left(\frac{r^2}{c(t-\langle t_\varepsilon\rangle)} - c(t-\langle t_\varepsilon\rangle)\right) + \Delta - \langle z_\pi\rangle$$

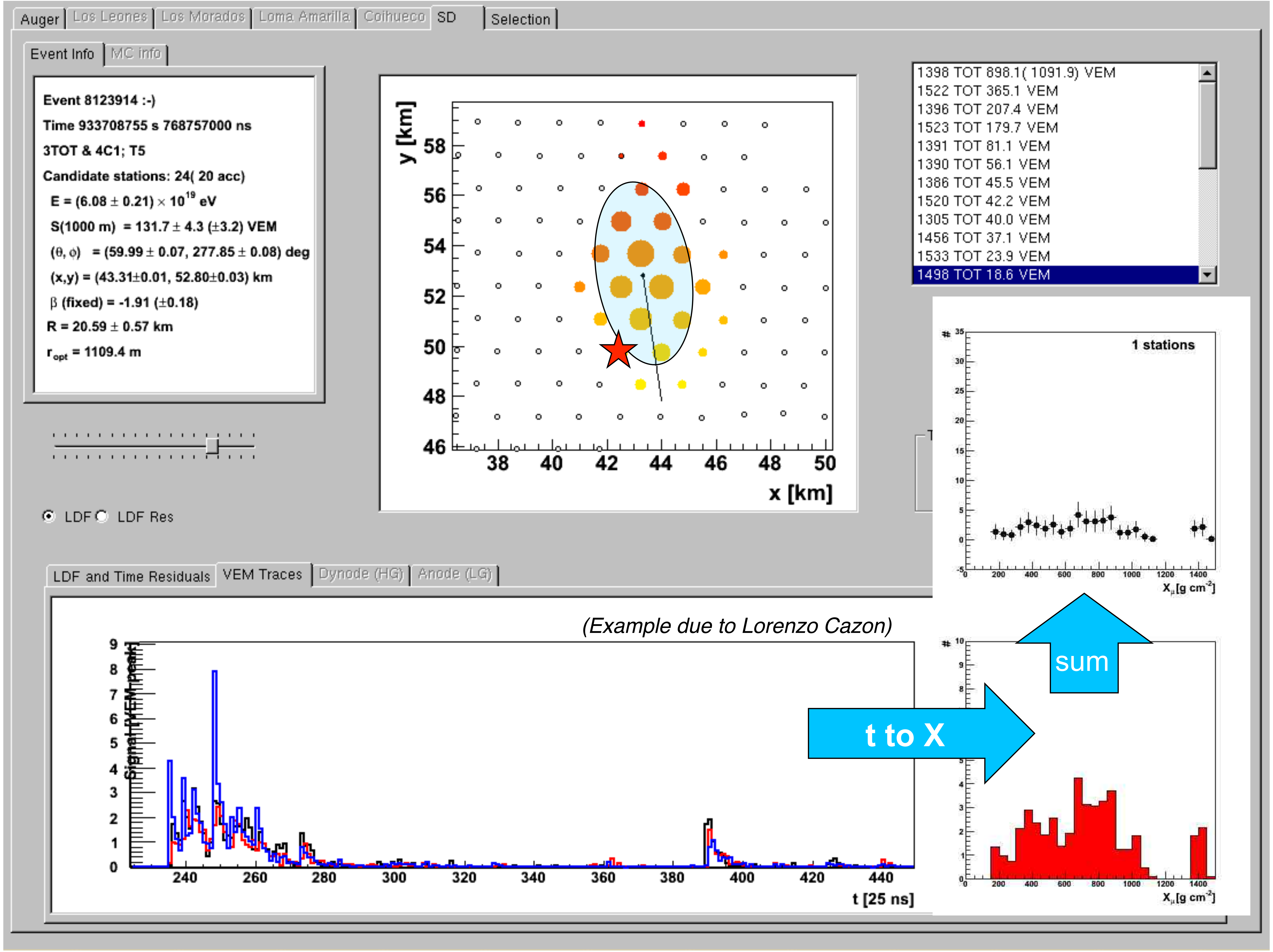
*(Cazon et al. Astropart. Phys. 23, 2005)*



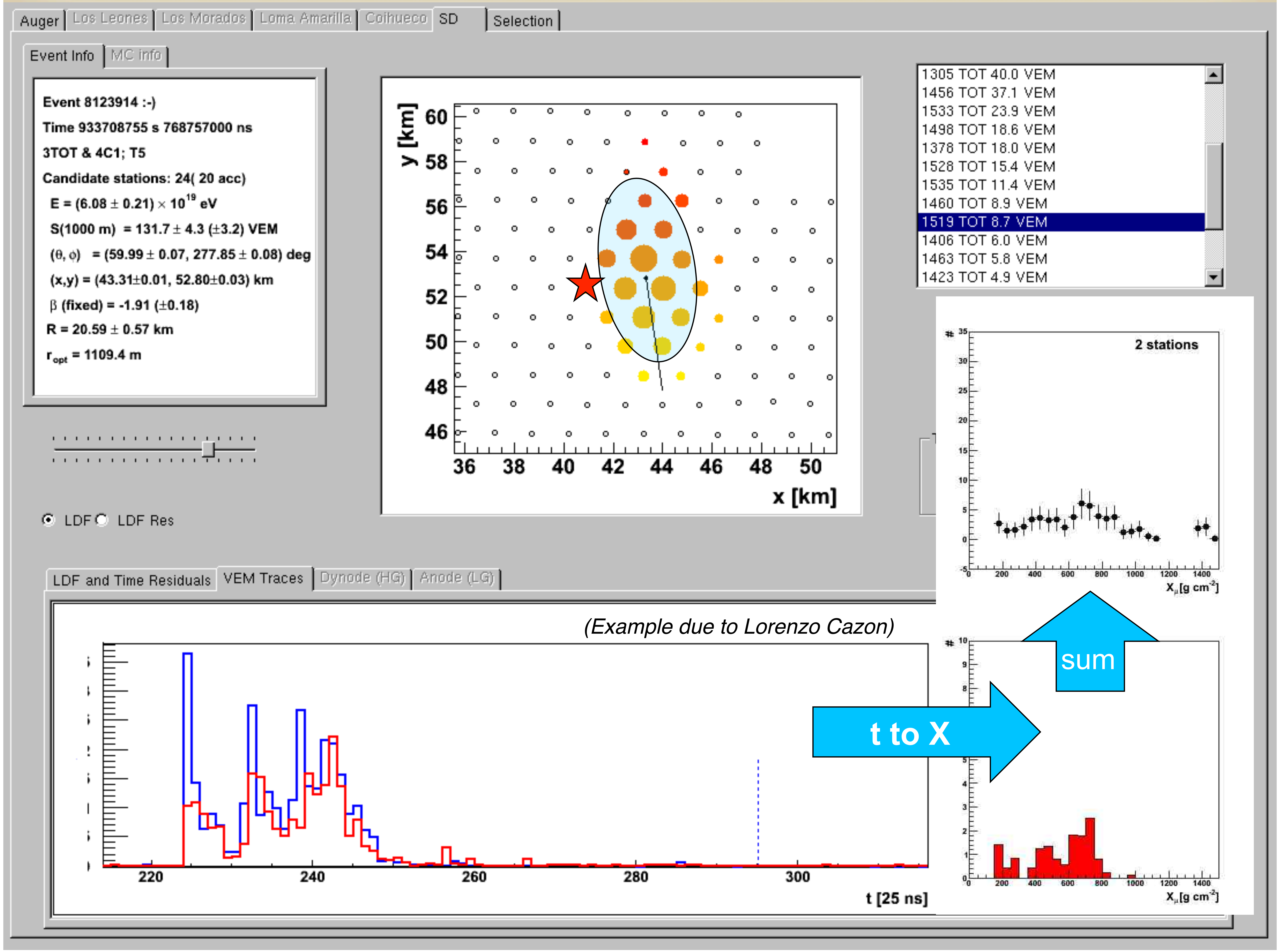

Muons from early interactions

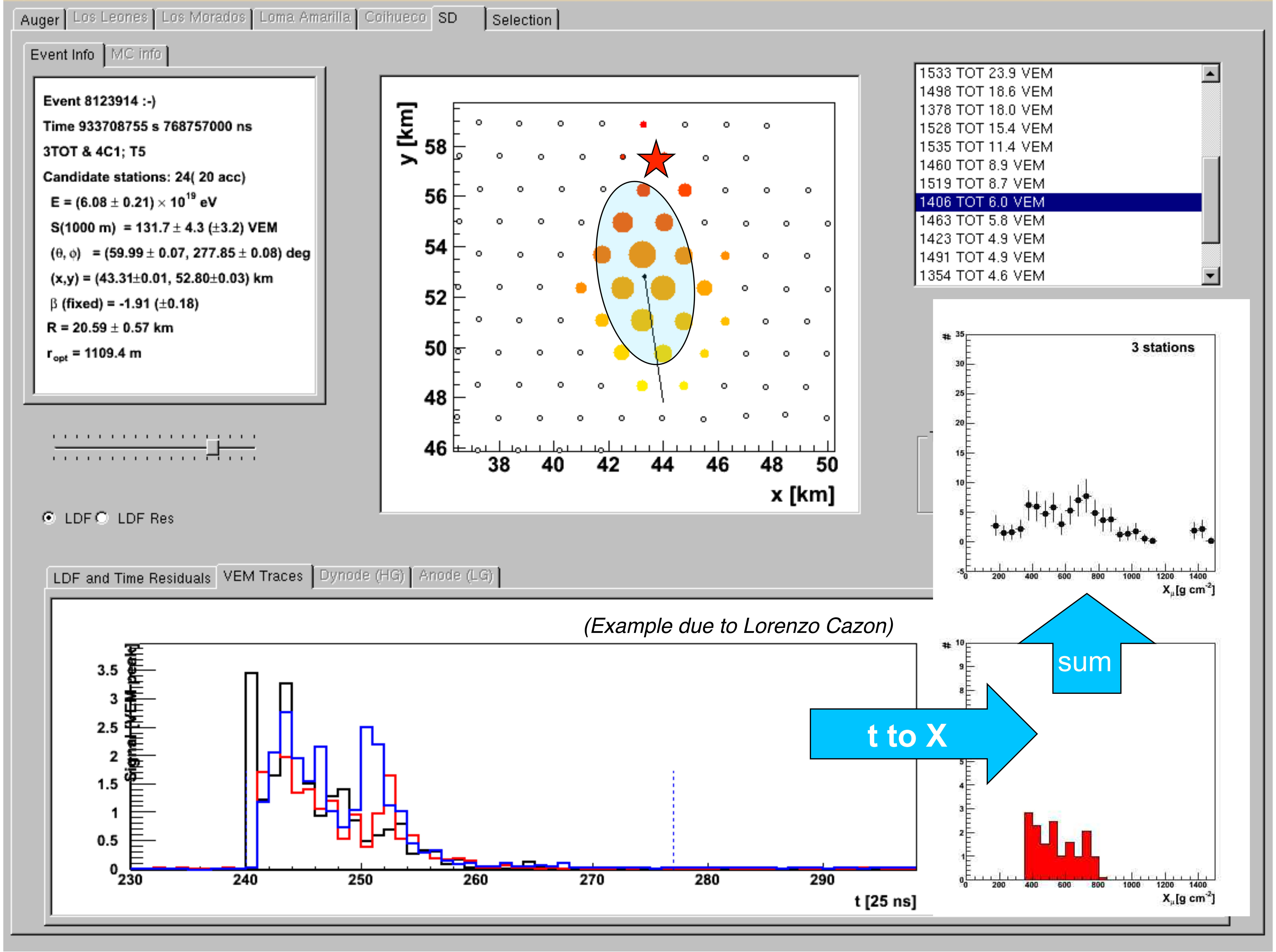
Muons from late interactions



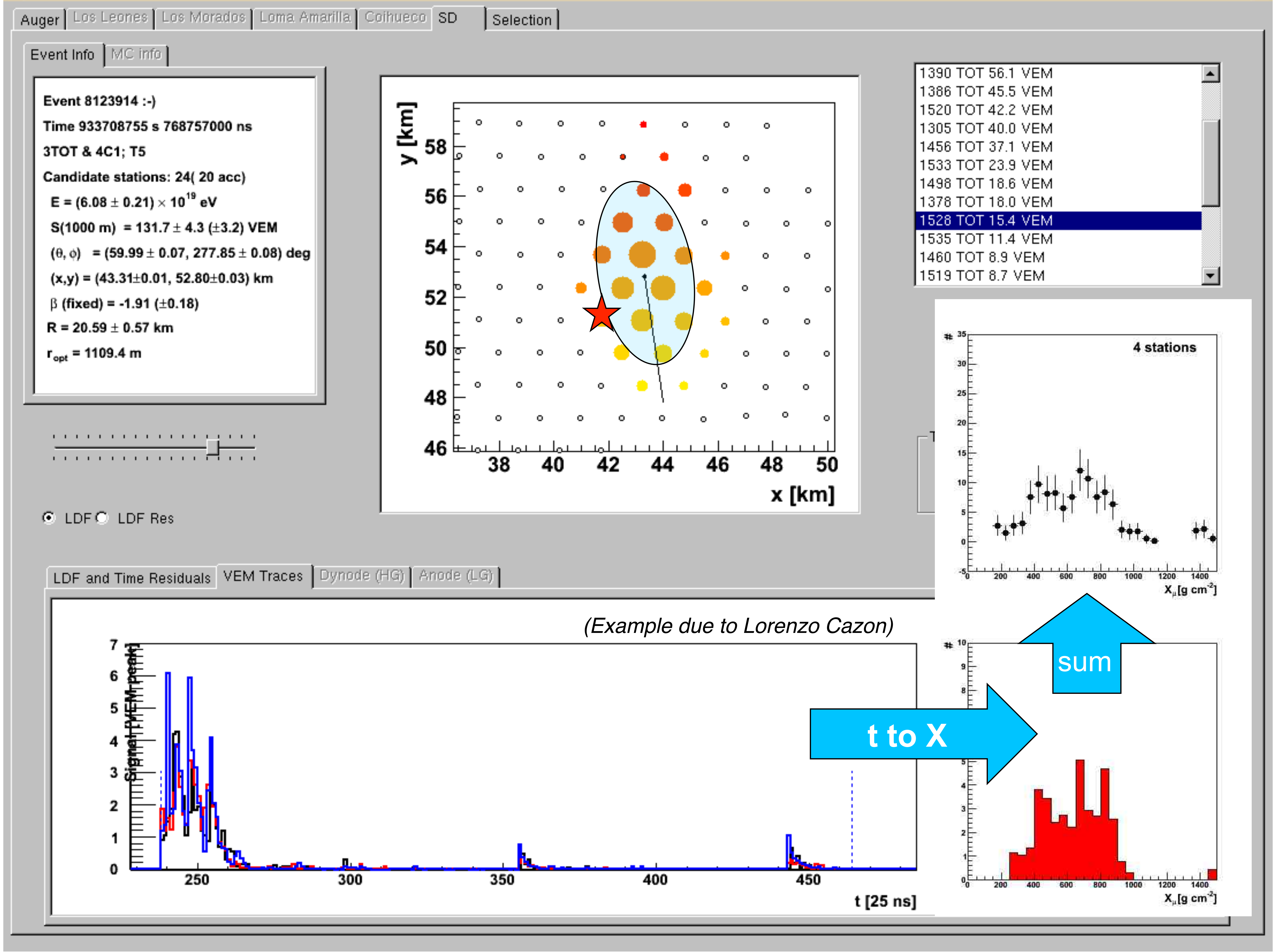


Auger
Los Leones
Los Morados
Loma Amarilla
Coihueco
SD
Selection
Event Info
MC info
Event 8123914 :-)
Time 933708755 s 768757000 ns
3TOT & 4C1; T5
Candidate stations: 24( 20 acc)
E = (6.08 ± 0.21) × 10^19 eV
S(1000 m) = 131.7 ± 4.3 (±3.2) VEM
(θ, φ) = (59.99 ± 0.07, 277.85 ± 0.08) deg
(x,y) = (43.31±0.01, 52.80±0.03) km
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
LDF
LDF Res
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
1 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

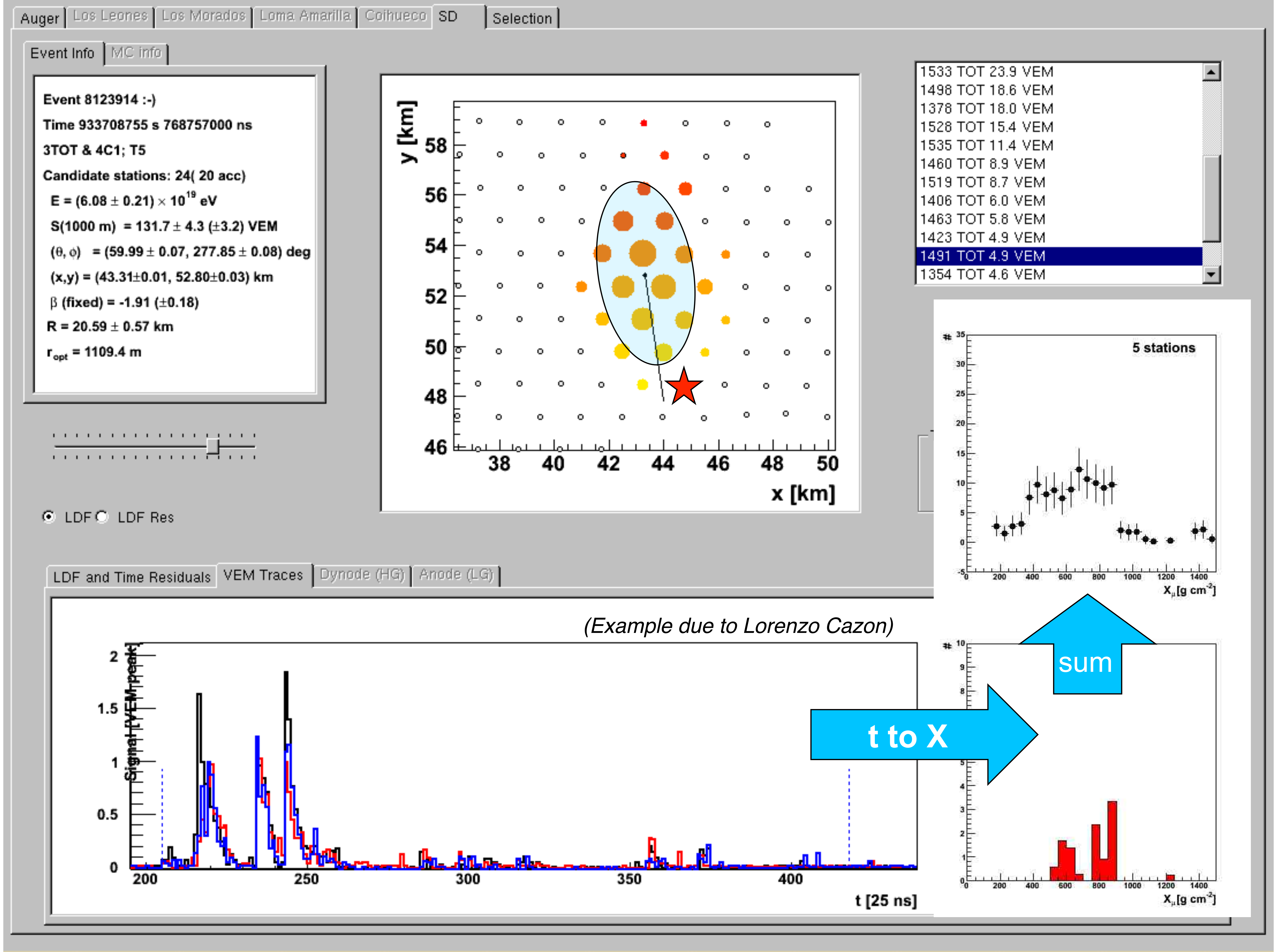

Auger
Los Leones
Los Morados
Loma Amarilla
Coihueco
SD
Selection
Event Info
MC info
Event 8123914 :-)
Time 933708755 s 768757000 ns
3TOT & 4C1; T5
Candidate stations: 24( 20 acc)
E = (6.08 ± 0.21) × 10^19 eV
S(1000 m) = 131.7 ± 4.3 (±3.2) VEM
(θ, φ) = (59.99 ± 0.07, 277.85 ± 0.08) deg
(x,y) = (43.31±0.01, 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]
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

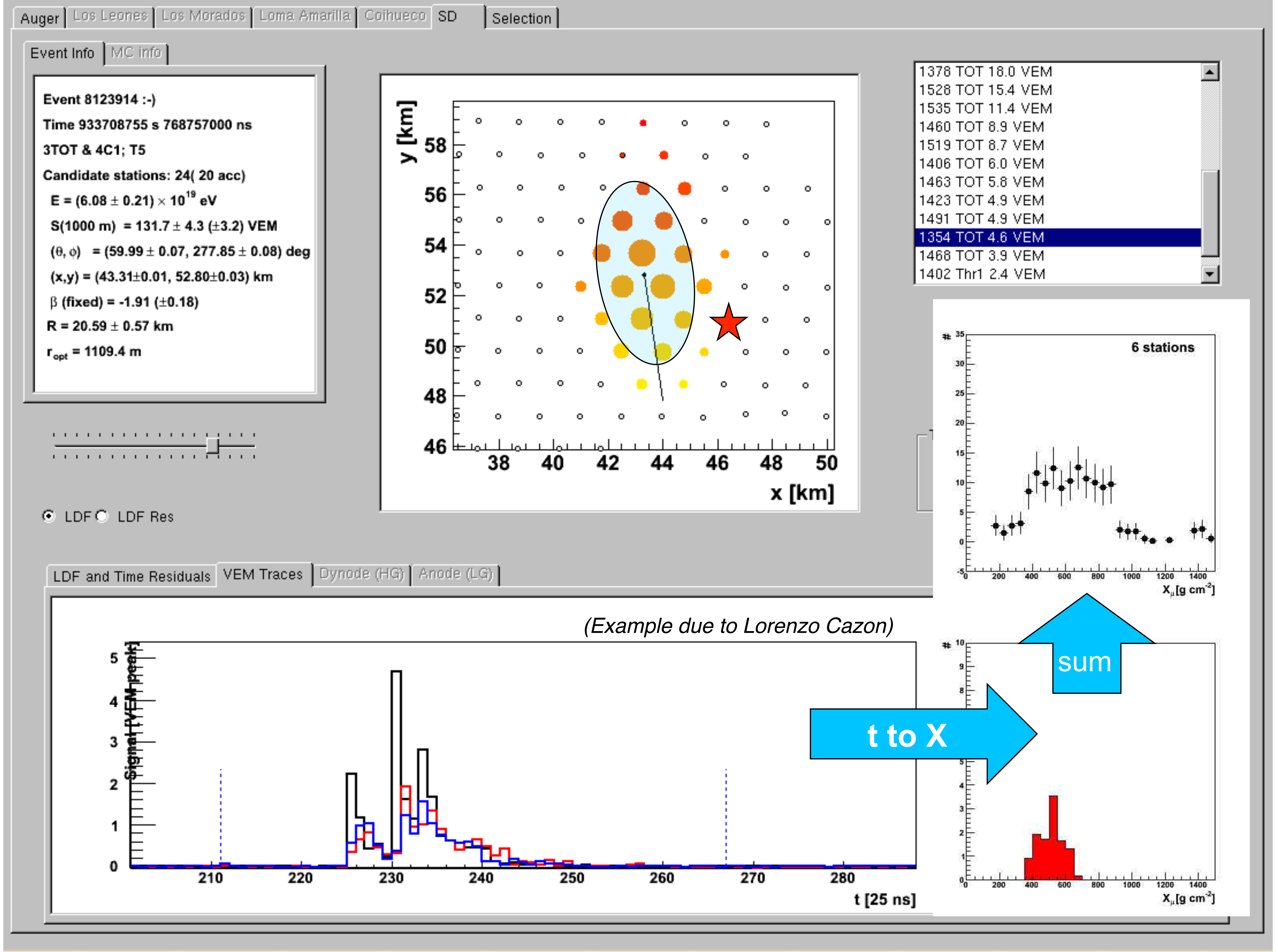


Auger
Los Leones
Los Morados
Loma Amarilla
Coihueco
SD
Selection
Event Info
MC info
Event 8123914 :-)
Time 933708755 s 768757000 ns
3TOT & 4C1; T5
Candidate stations: 24( 20 acc)
E = (6.08 ± 0.21) × 10^19 eV
S(1000 m) = 131.7 ± 4.3 (±3.2) VEM
(θ, φ) = (59.99 ± 0.07, 277.85 ± 0.08) deg
(x,y) = (43.31±0.01, 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
3 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]
sum
t to X
X_μ [g cm^-2]

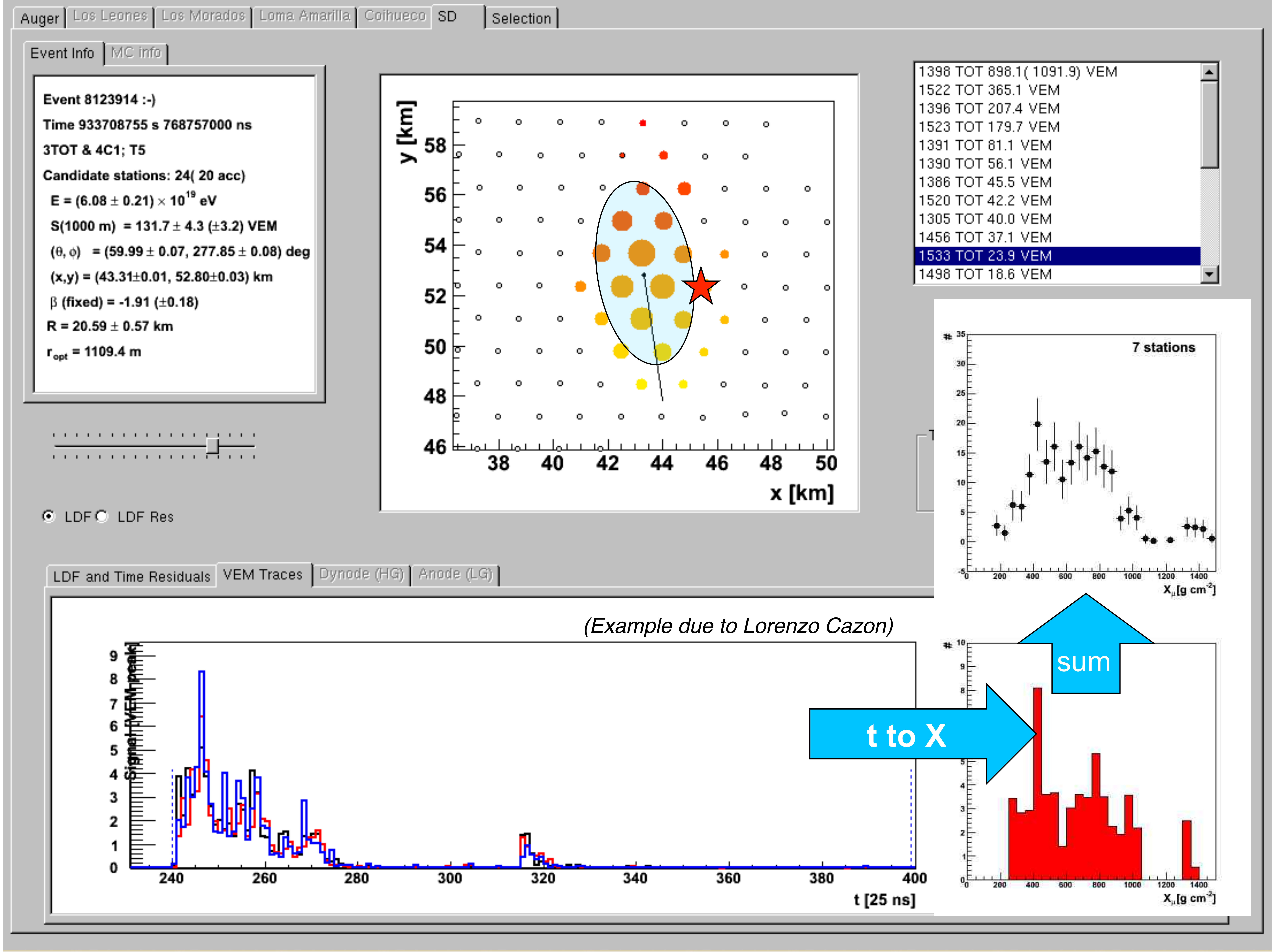


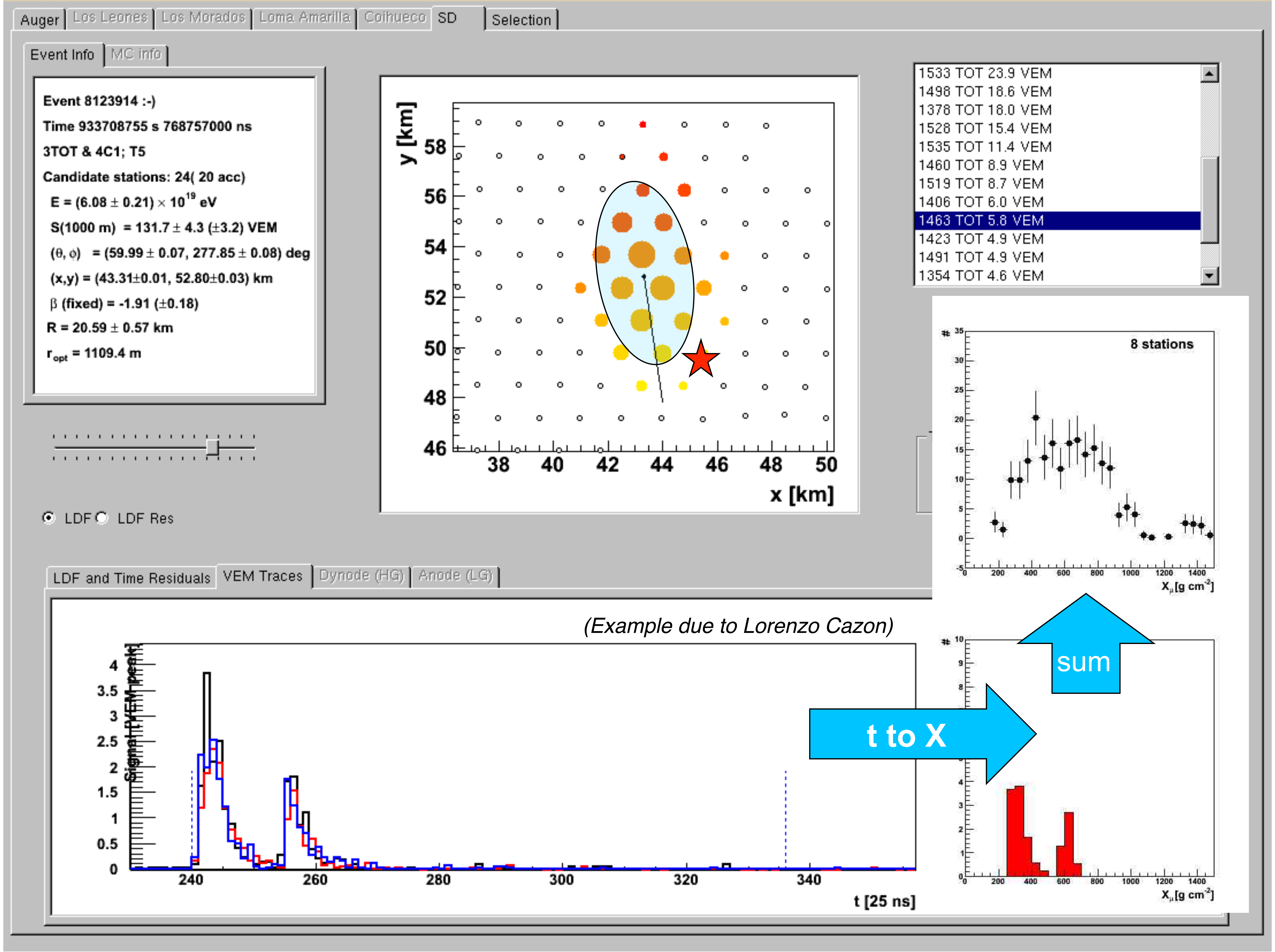
Auger
Los Leones
Los Morados
Loma Amarilla
Coihueco
SD
Selection
Event Info
MC info
Event 8123914 :-)
Time 933708755 s 768757000 ns
3TOT & 4C1; T5
Candidate stations: 24( 20 acc)
E = (6.08 ± 0.21) × 10^19 eV
S(1000 m) = 131.7 ± 4.3 (±3.2) VEM
(θ, φ) = (59.99 ± 0.07, 277.85 ± 0.08) deg
(x,y) = (43.31±0.01, 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
X_μ [g cm^-2]


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]
5 stations
X_μ [g cm^-2]
sum
t to X

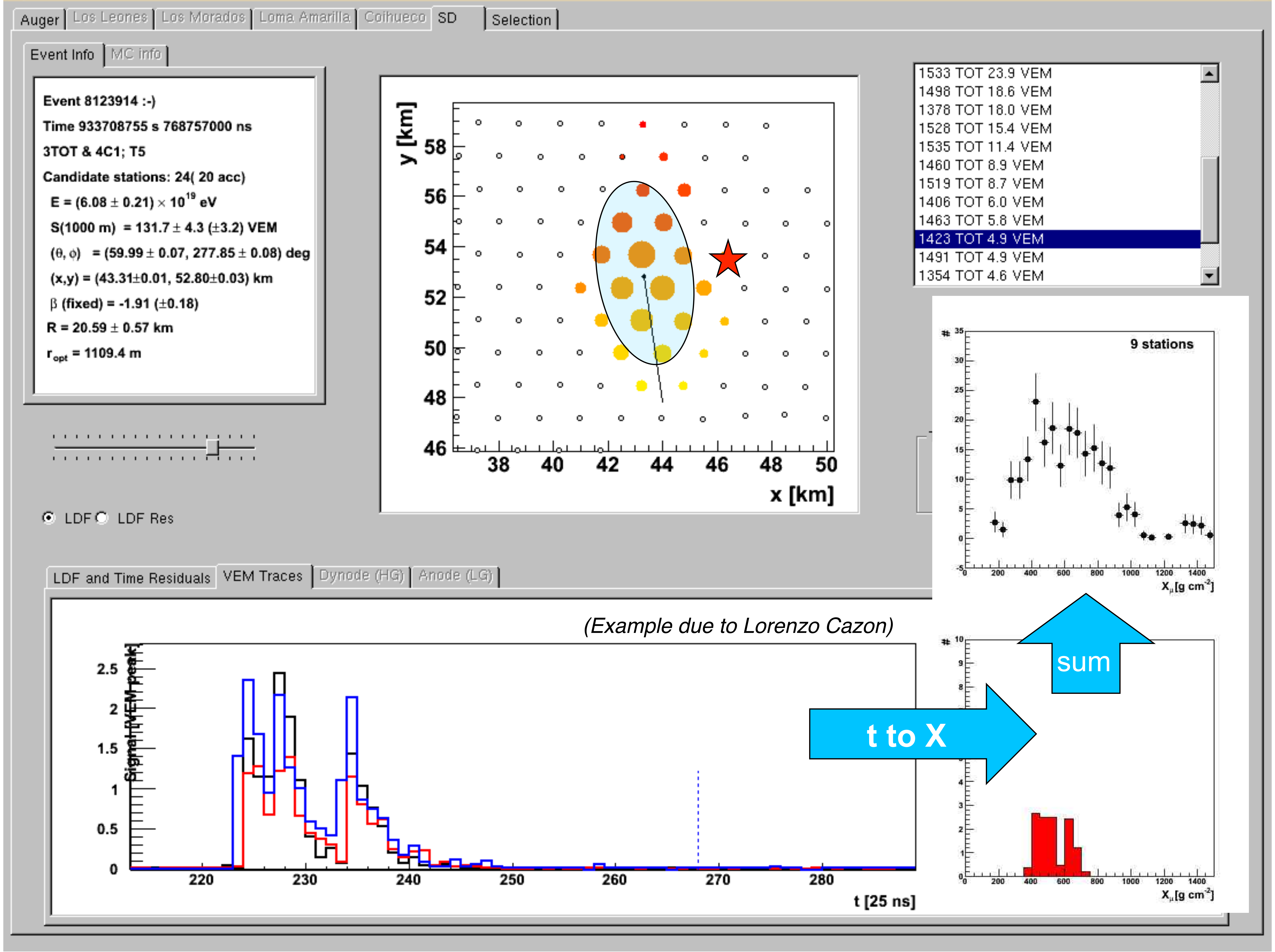


Auger
Los Leones
Los Morados
Loma Amarilla
Coihueco
SD
Selection
Event Info
MC info
Event 8123914 :-)
Time 933708755 s 768757000 ns
3TOT & 4C1; T5
Candidate stations: 24( 20 acc)
E = (6.08 ± 0.21) × 10^19 eV
S(1000 m) = 131.7 ± 4.3 (±3.2) VEM
(θ, φ) = (59.99 ± 0.07, 277.85 ± 0.08) deg
(x,y) = (43.31±0.01, 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]
6 stations
X_μ [g cm^-2]
sum
t to X
X_μ [g cm^-2]

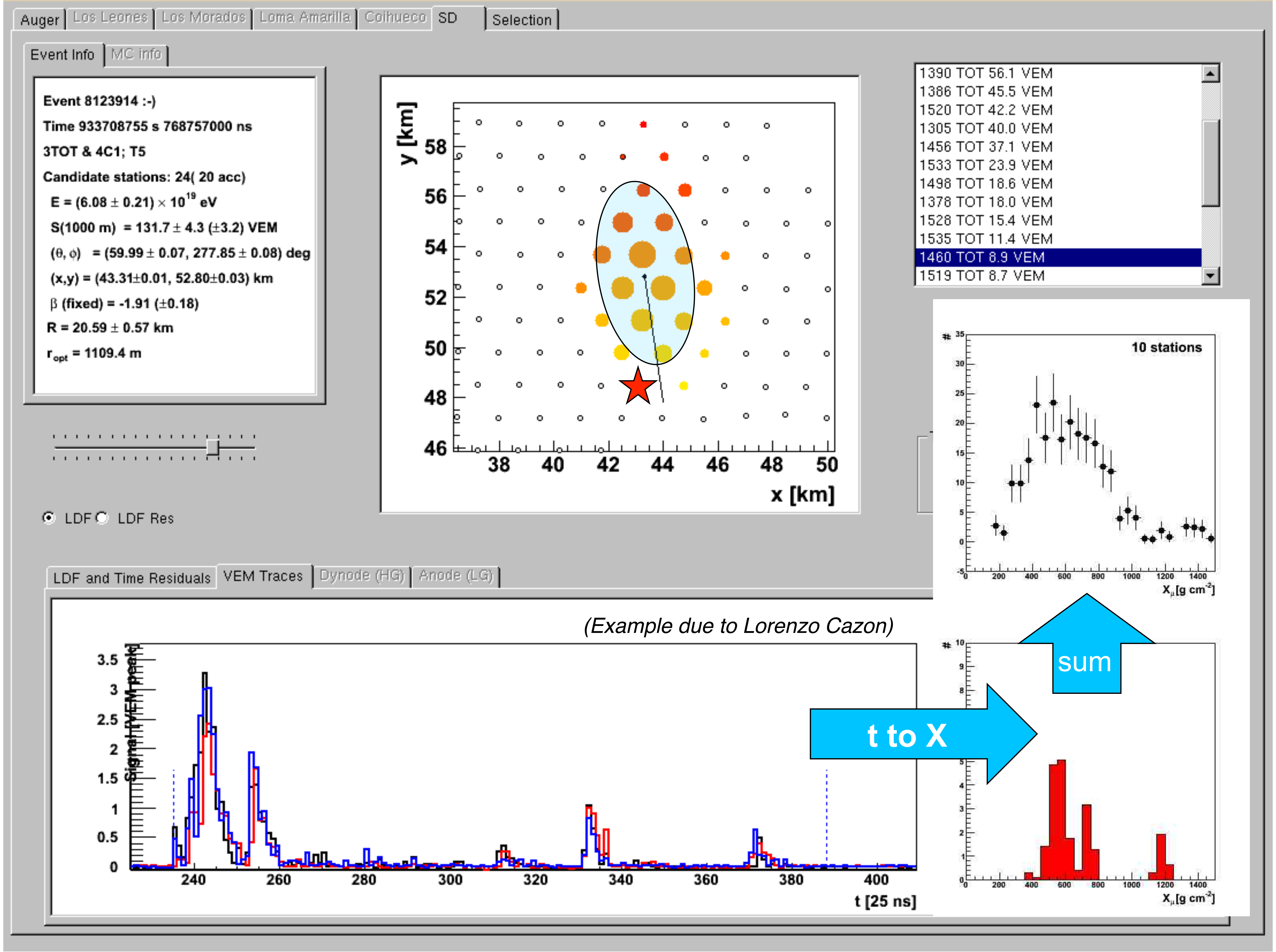

Auger
Los Leones
Los Morados
Loma Amarilla
Coihueco
SD
Selection
Event Info
MC info
Event 8123914 :-)
Time 933708755 s 768757000 ns
3TOT & 4C1; T5
Candidate stations: 24( 20 acc)
E = (6.08 ± 0.21) × 10^19 eV
S(1000 m) = 131.7 ± 4.3 (±3.2) VEM
(θ, φ) = (59.99 ± 0.07, 277.85 ± 0.08) deg
(x,y) = (43.31±0.01, 52.80±0.03) km
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
LDF
LDF Res
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
7 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
X_μ [g cm^-2]



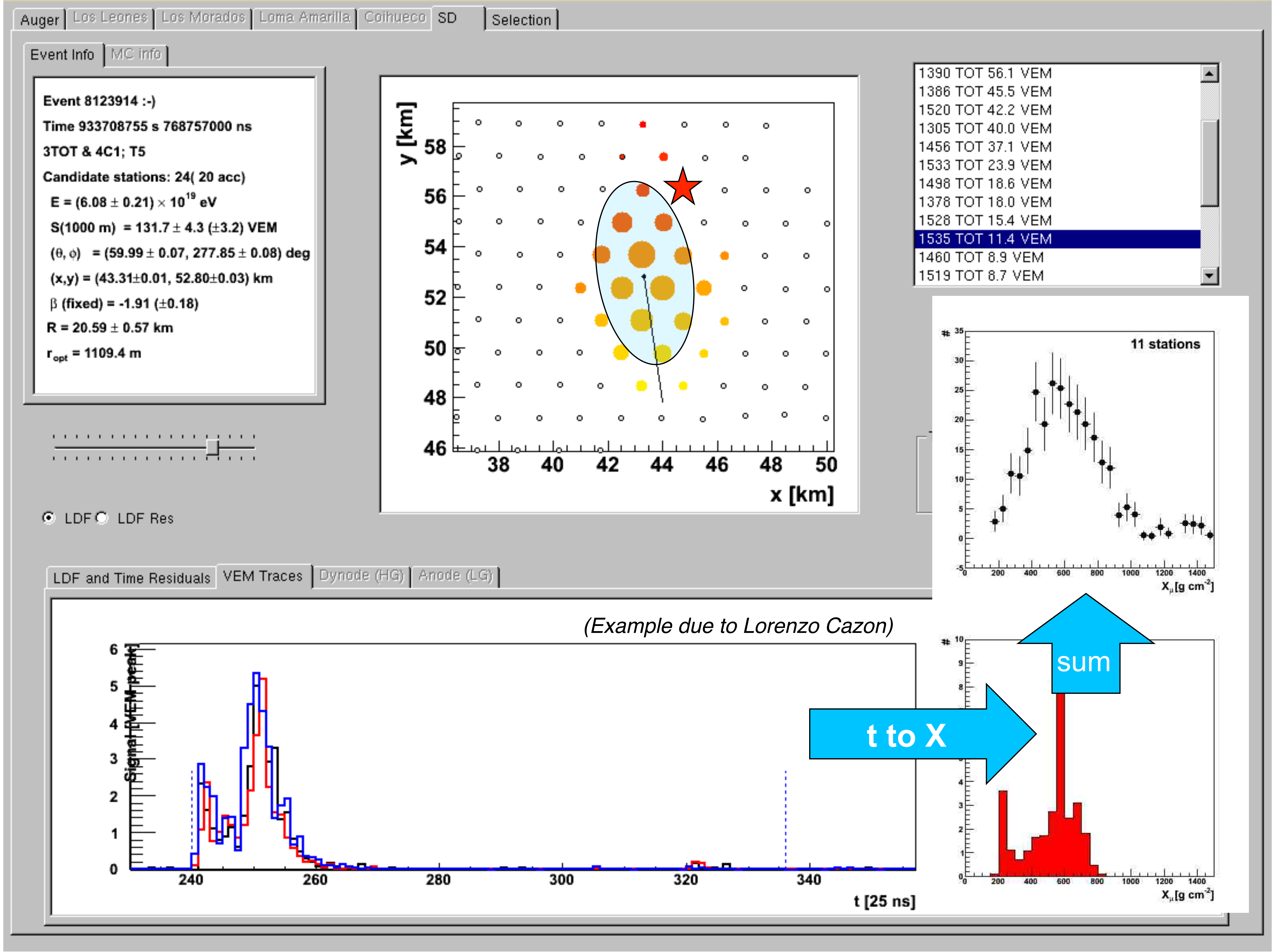
Auger
Los Leones
Los Morados
Loma Amarilla
Coihueco
SD
Selection
Event Info
MC info
Event 8123914 :-)
Time 933708755 s 768757000 ns
3TOT & 4C1; T5
Candidate stations: 24( 20 acc)
E = (6.08 ± 0.21) × 10^19 eV
S(1000 m) = 131.7 ± 4.3 (±3.2) VEM
(θ, φ) = (59.99 ± 0.07, 277.85 ± 0.08) deg
(x,y) = (43.31±0.01, 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]
8 stations
X_μ [g cm^-2]
sum
t to X
X_μ [g cm^-2]



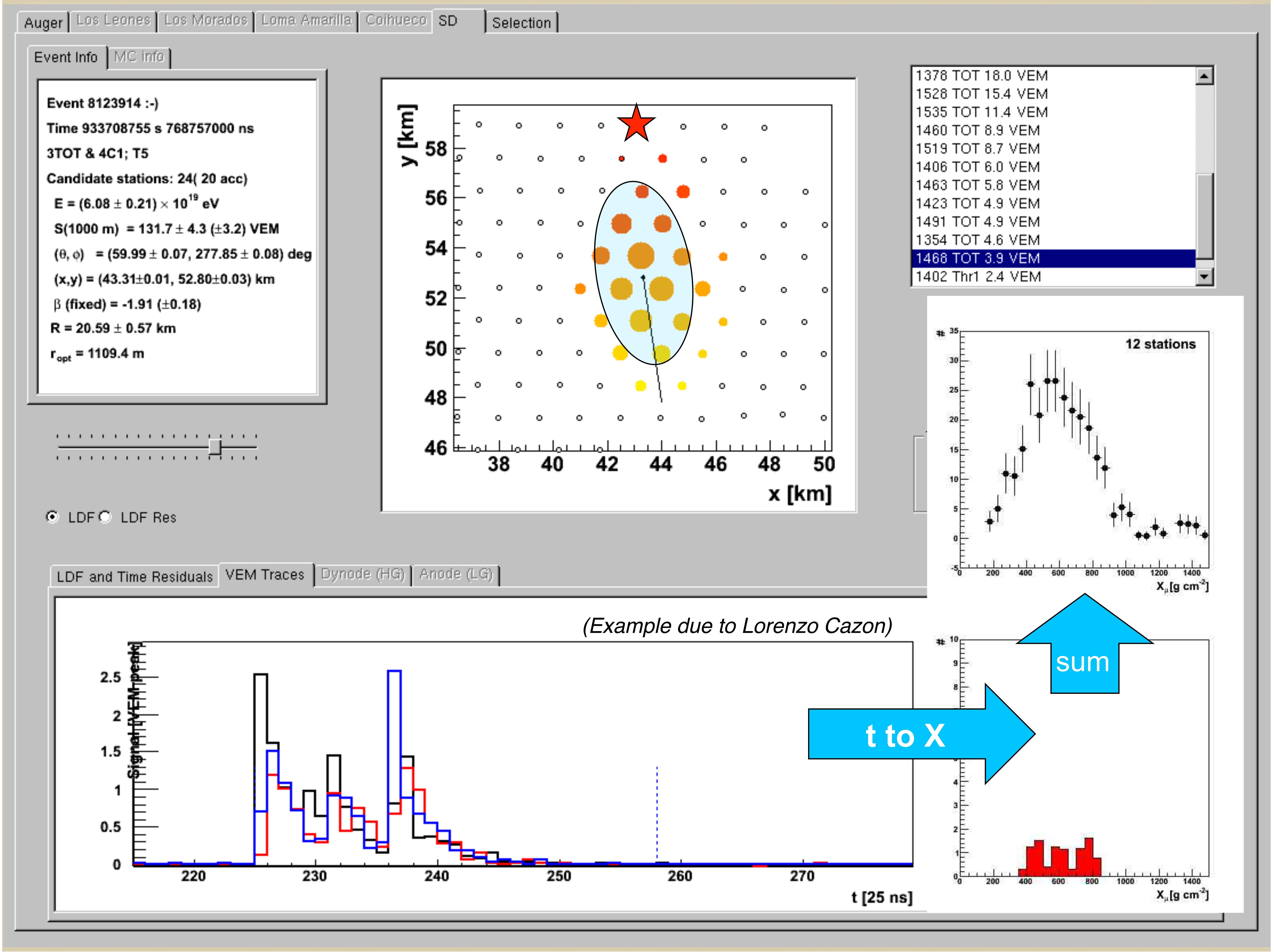
Auger
Los Leones
Los Morados
Loma Amarilla
Coihueco
SD
Selection
Event Info
MC info
Event 8123914 :-)
Time 933708755 s 768757000 ns
3TOT & 4C1; T5
Candidate stations: 24( 20 acc)
E = (6.08 ± 0.21) × 10^19 eV
S(1000 m) = 131.7 ± 4.3 (±3.2) VEM
(θ, φ) = (59.99 ± 0.07, 277.85 ± 0.08) deg
(x,y) = (43.31±0.01, 52.80±0.03) km
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
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



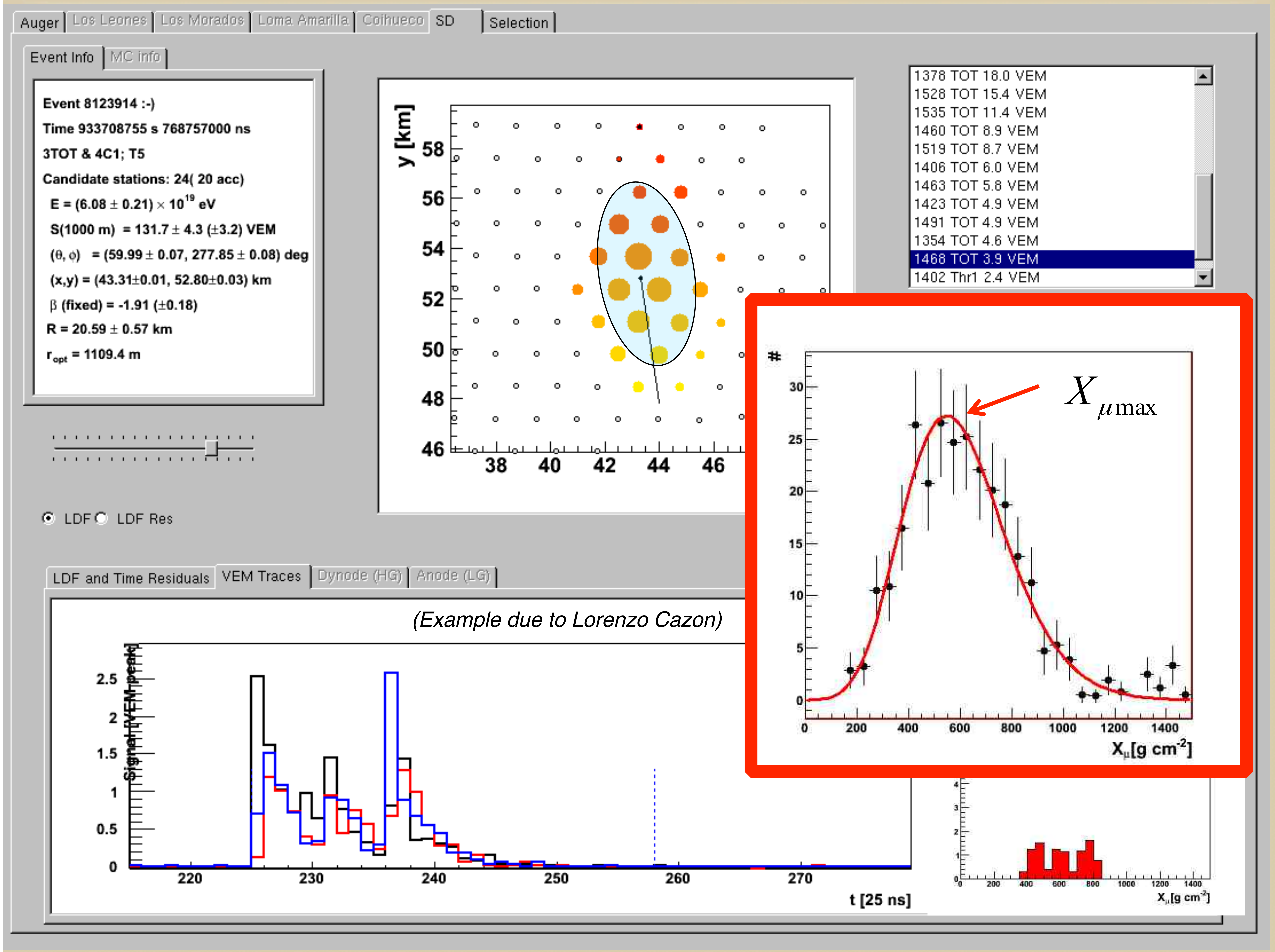
Auger
Los Leones
Los Morados
Loma Amarilla
Coihueco
SD
Selection
Event Info
MC info
Event 8123914 :-)
Time 933708755 s 768757000 ns
3TOT & 4C1; T5
Candidate stations: 24( 20 acc)
E = (6.08 ± 0.21) × 10^19 eV
S(1000 m) = 131.7 ± 4.3 (±3.2) VEM
(θ, φ) = (59.99 ± 0.07, 277.85 ± 0.08) deg
(x,y) = (43.31±0.01, 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]
10 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
11 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

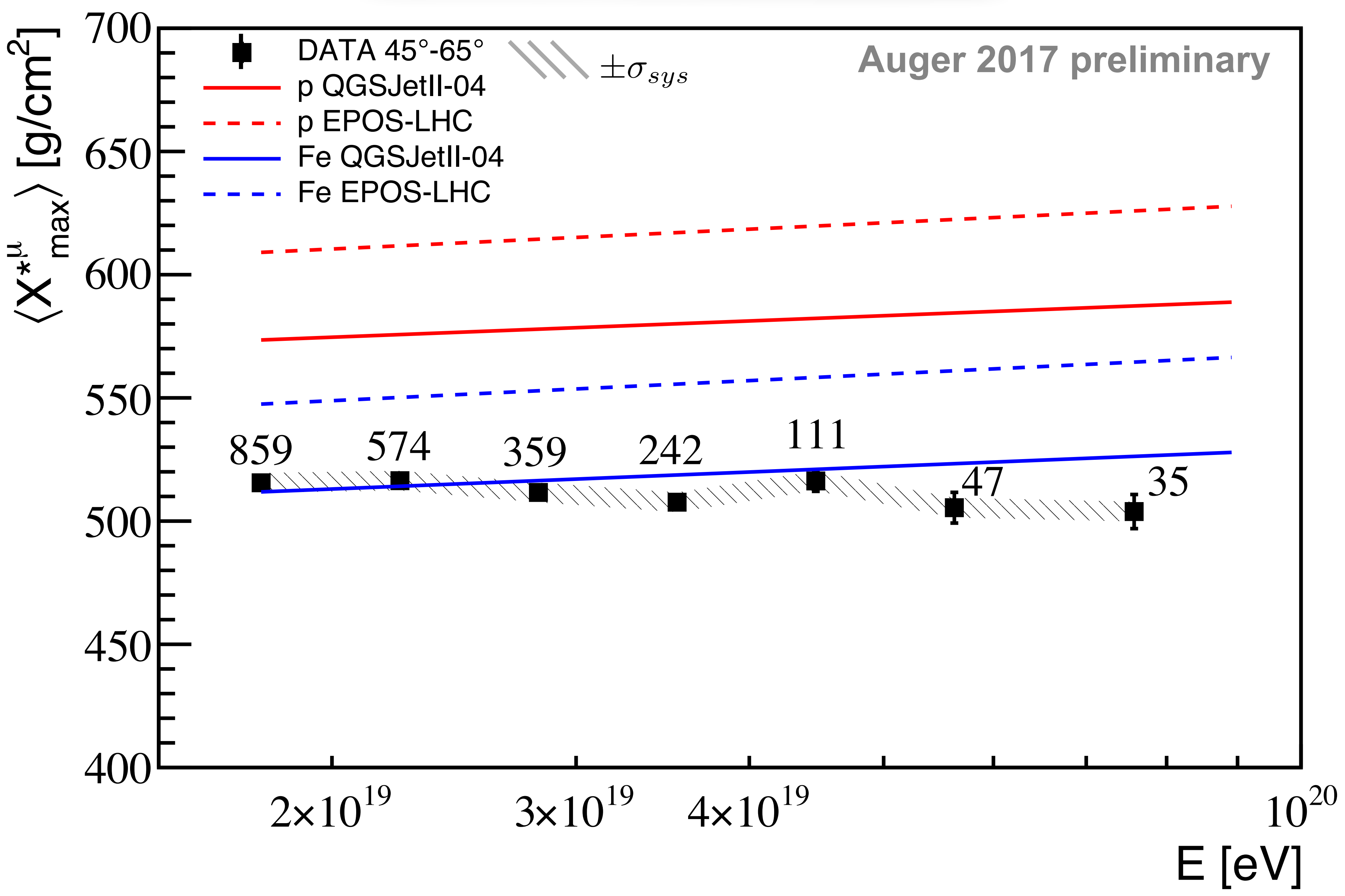


Auger
Los Leones
Los Morados
Loma Amarilla
Coihueco
SD
Selection
Event Info
MC info
Event 8123914 :-)
Time 933708755 s 768757000 ns
3TOT & 4C1; T5
Candidate stations: 24( 20 acc)
E = (6.08 ± 0.21) × 10^19 eV
S(1000 m) = 131.7 ± 4.3 (±3.2) VEM
(θ, φ) = (59.99 ± 0.07, 277.85 ± 0.08) deg
(x,y) = (43.31±0.01,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

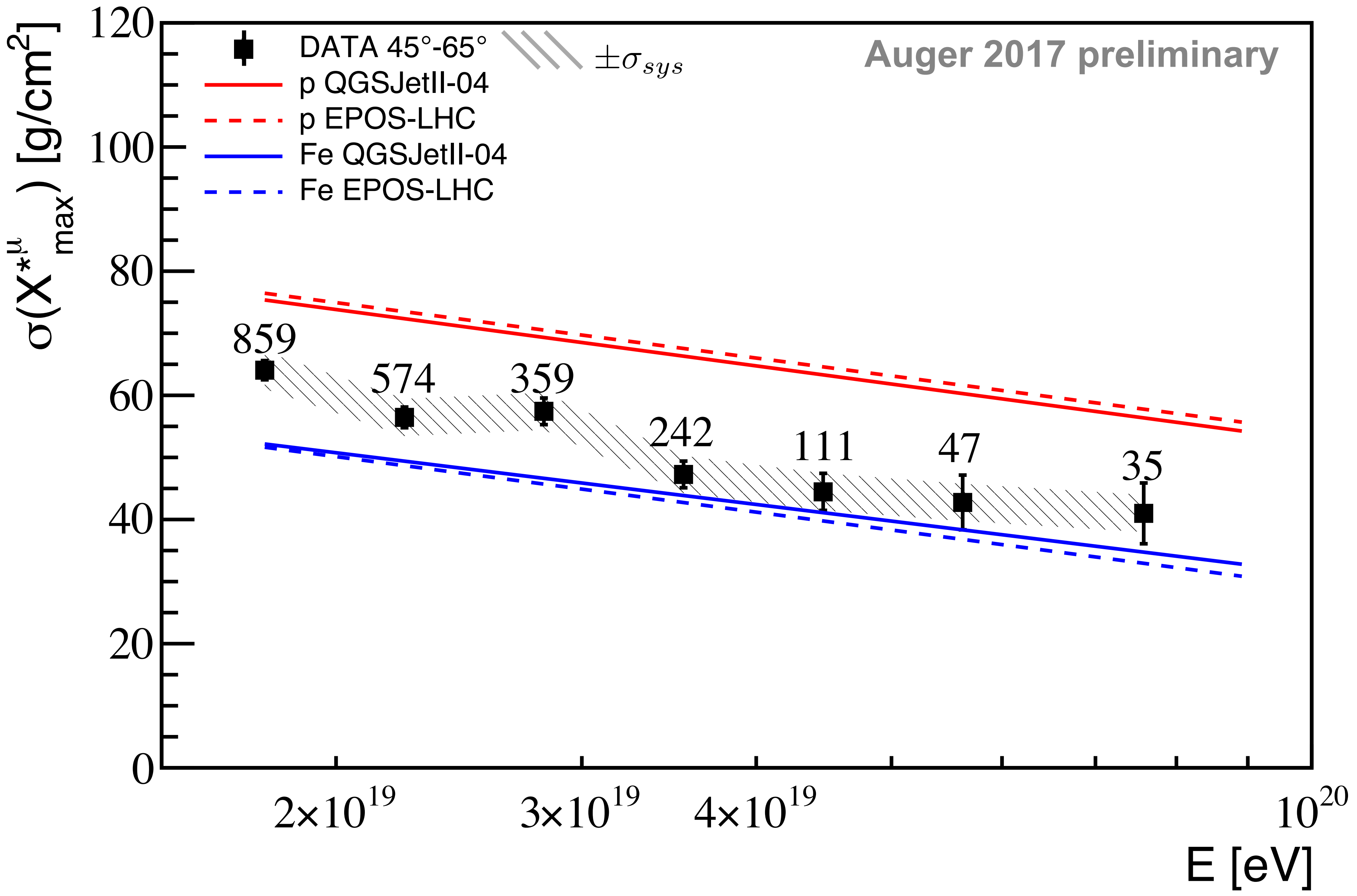

Auger
Los Leones
Los Morados
Loma Amarilla
Coihueco
SD
Selection
Event Info
MC info
Event 8123914 :-)
Time 933708755 s 768757000 ns
3TOT & 4C1; T5
Candidate stations: 24( 20 acc)
E = (6.08 ± 0.21) × 10^19 eV
S(1000 m) = 131.7 ± 4.3 (±3.2) VEM
(θ, φ) = (59.99 ± 0.07, 277.85 ± 0.08) deg
(x,y) = (43.31±0.01, 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]
#
$X_{\mu \max}$
$X_\mu$ [g cm$^{-2}$]

# Depth of maximum for muon production

Mean values




Shower-by-shower fluctuations




Model predictions of EPOS-LHC outside of expected range of composition

E>15 EeV
θ=45°-65
r>1200 m

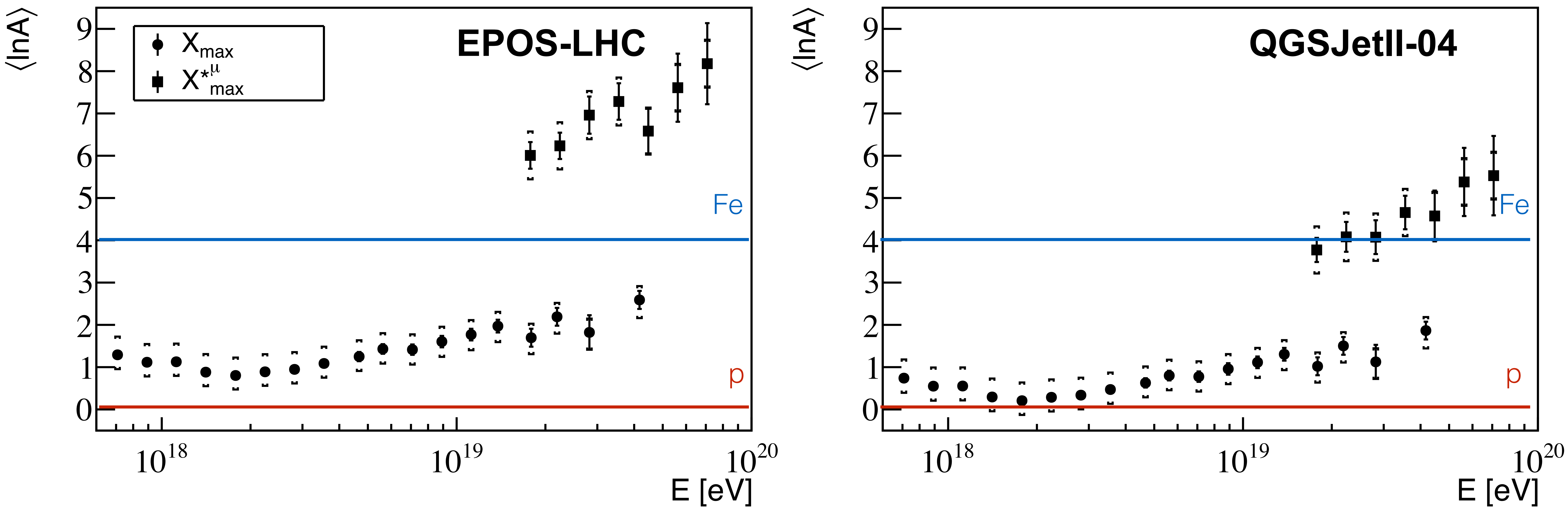
*(Mallamaci, ICRC 2017)*

# Comparison with results from electromagnetic profile

$$\langle lnA \rangle = ln56 \frac{\langle X^{*\mu}_{max} \rangle_p - \langle X^{*\mu}_{max} \rangle_{data}}{\langle X^{*\mu}_{max} \rangle_p - \langle X^{*\mu}_{max} \rangle_{Fe}}$$

$X_{max}$ from *A. Aab et al. (Pierre Auger Coll.), Phys.Rev. D90 (2014) 122005*

E>15 EeV
θ=45°-65
r>1200 m




No consistent composition found for different estimators, which one is more reliable?

*(Mallamaci, ICRC 2017)*

## How can LHC and accelerator experiments contribute ?

# Air showers: electromagnetic and hadronic components

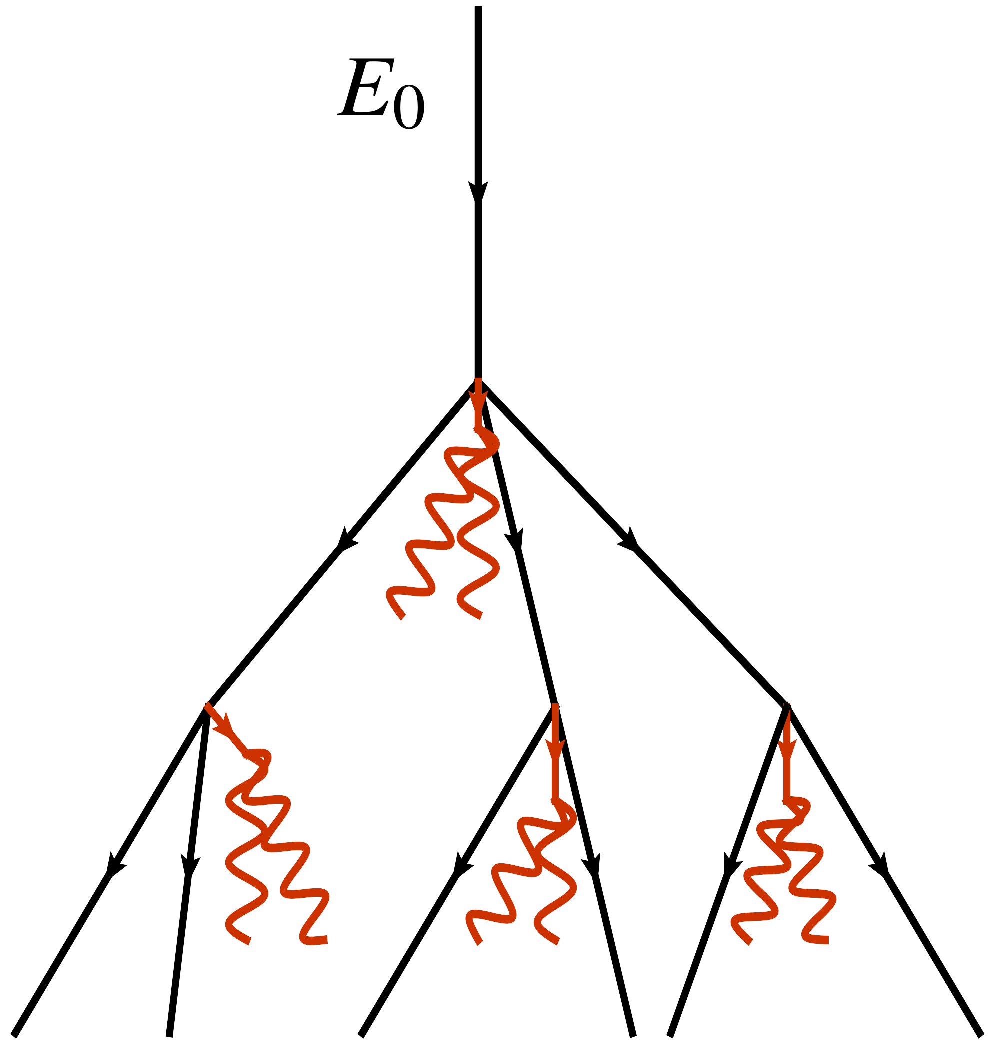
Hadronic energy

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

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

o
o
o

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




*After n generations ...*

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

Electromagnetic energy

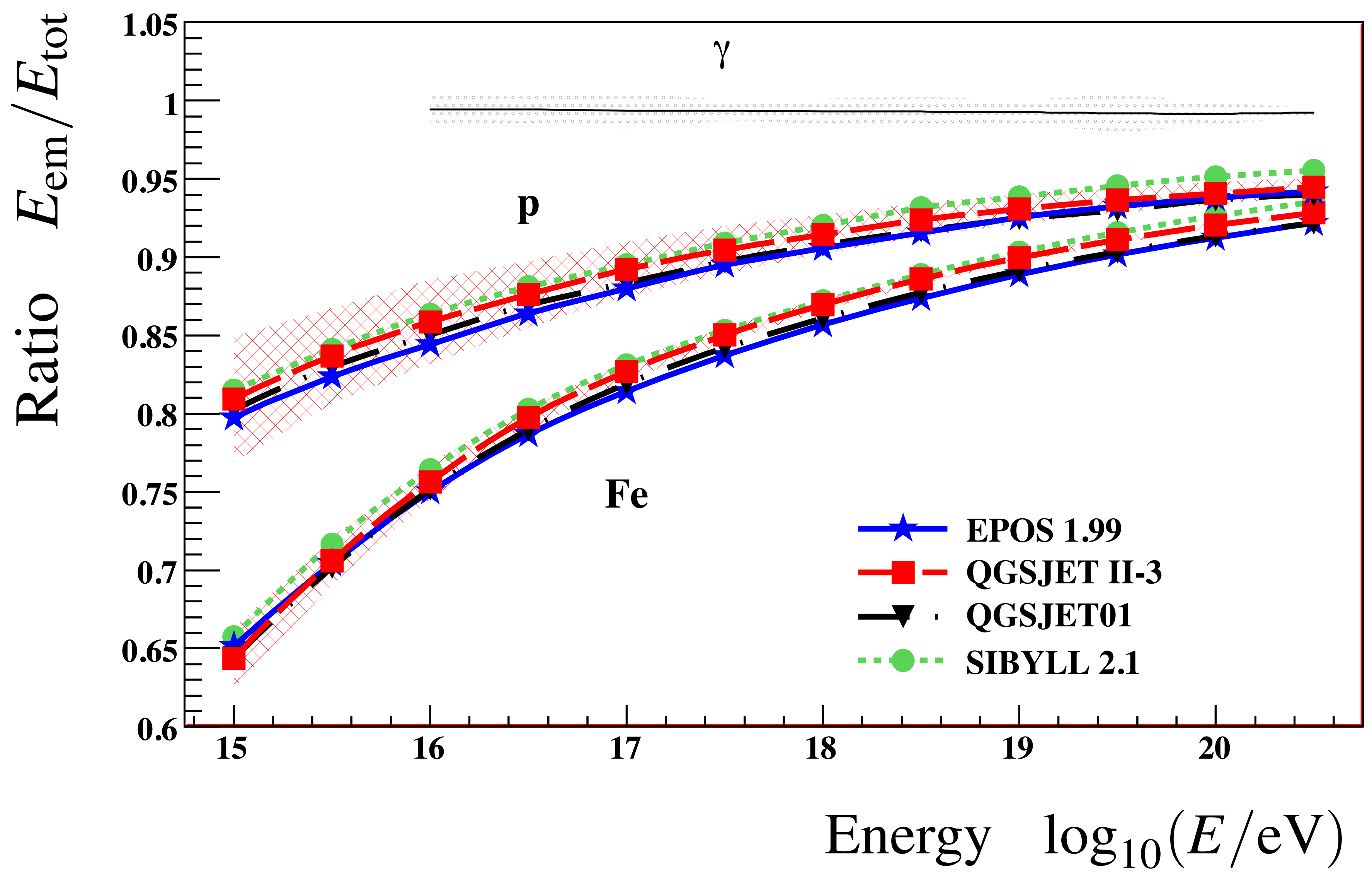
$$\frac{1}{3}E_0$$

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

o
o
o

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

*(RE, Pierog, Heck, ARNPS 2011)*

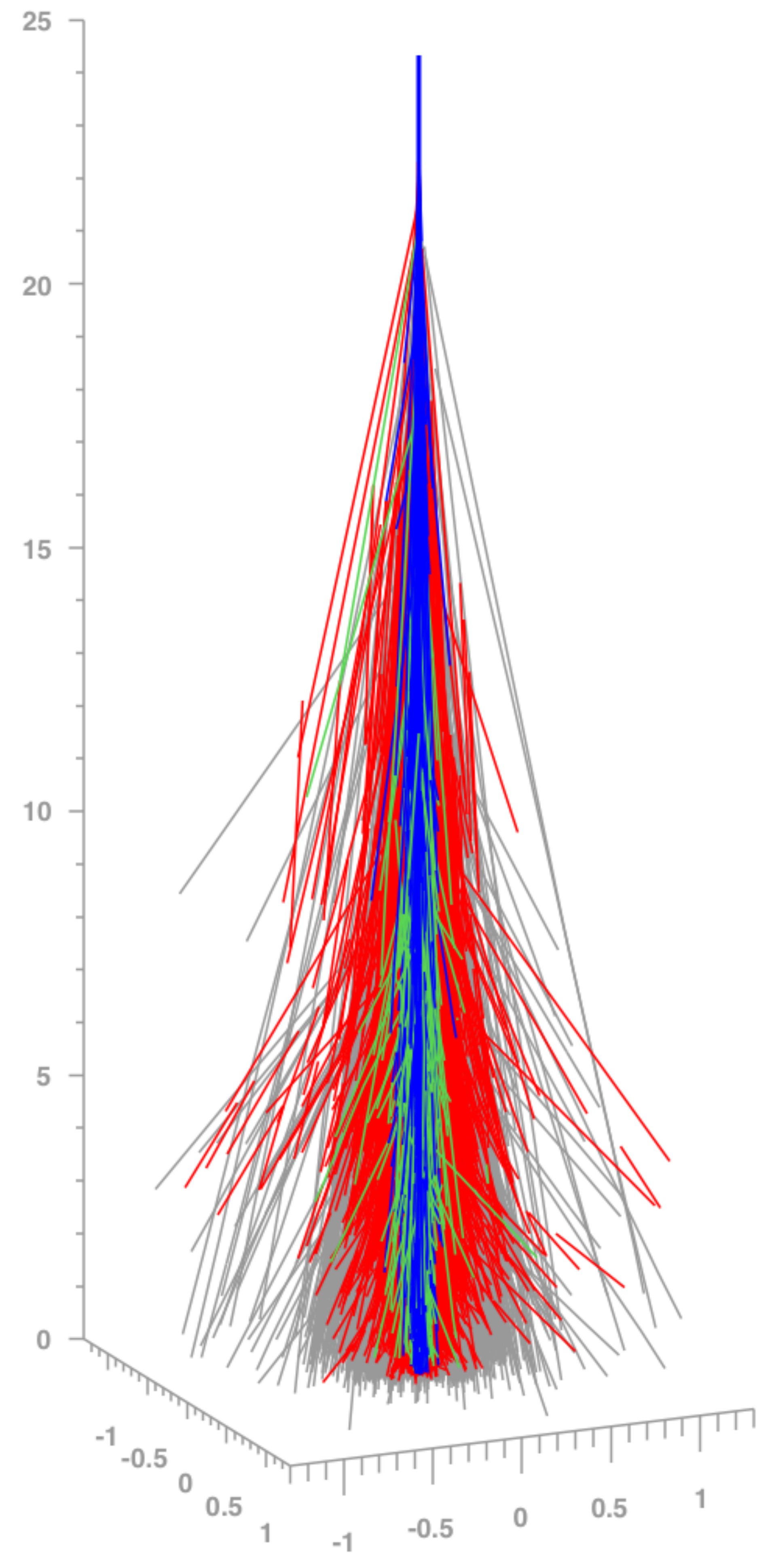



Very efficient transfer of hadronic energy to em. component

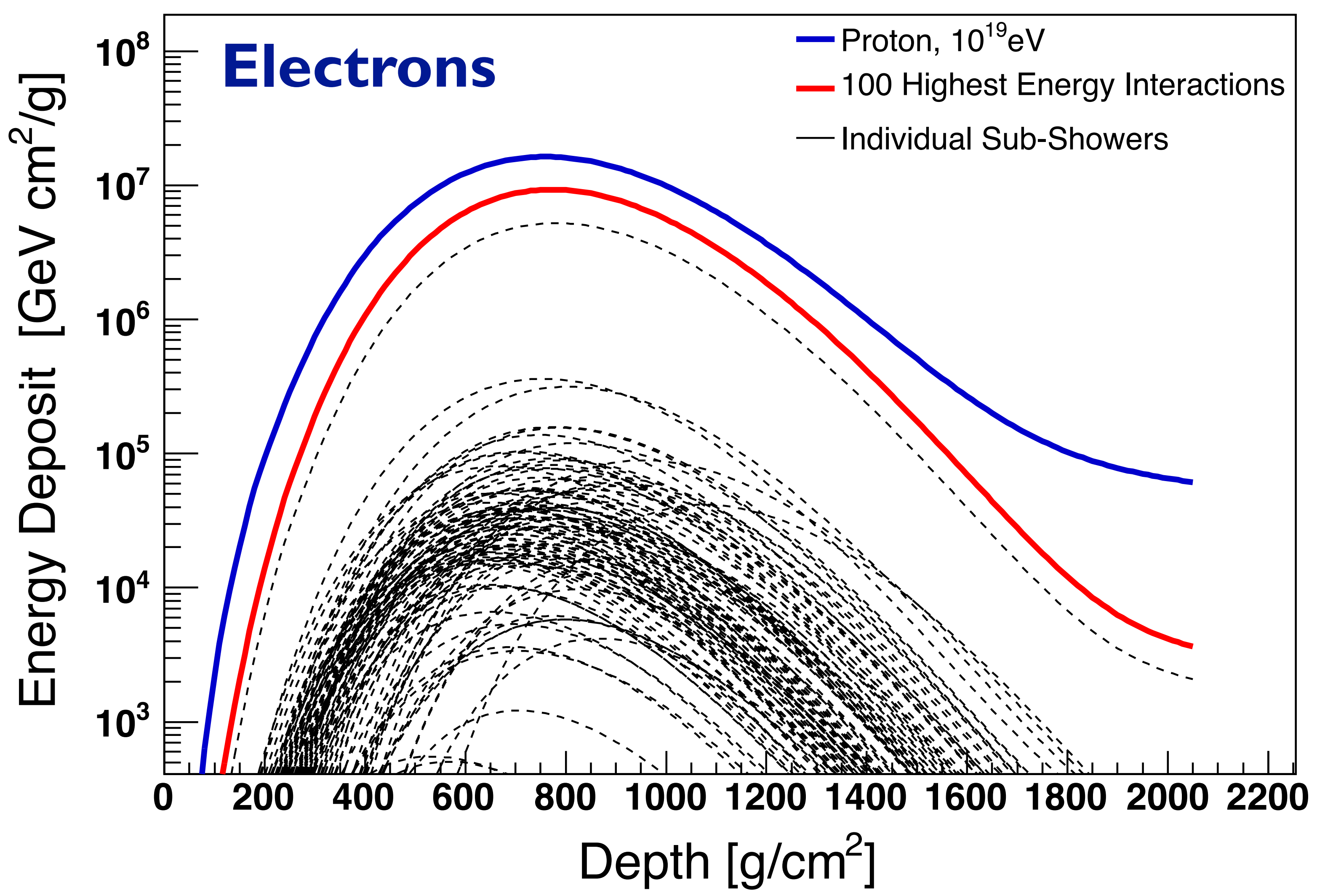
High-energy interactions most important

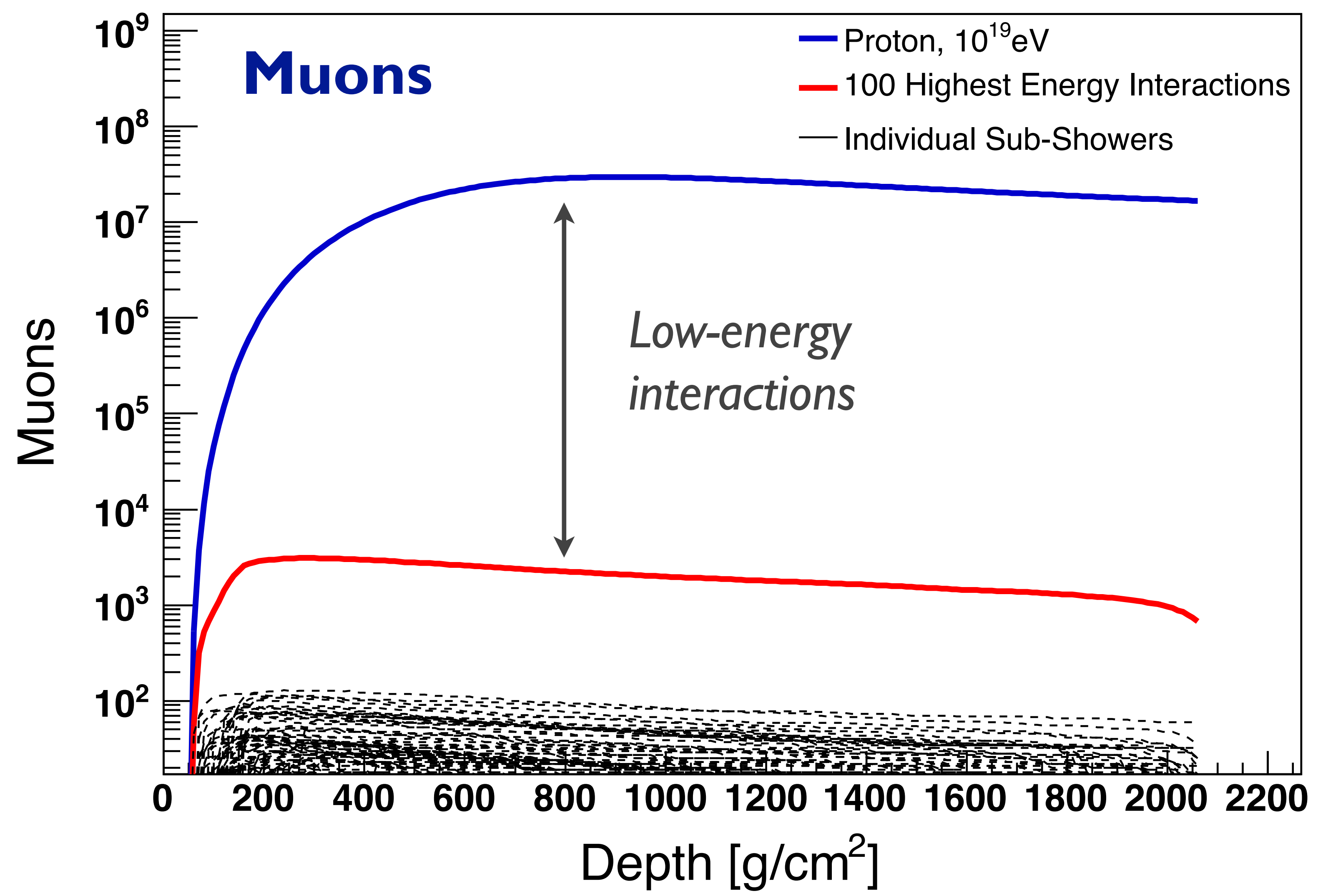
*(Matthews, APP22, 2005)*

# Importance of hadronic interactions at different energies




(Ulrich APS 2010)




Shower particles produced in 100 interactions of highest energy

Electrons/photons: high-energy interactions

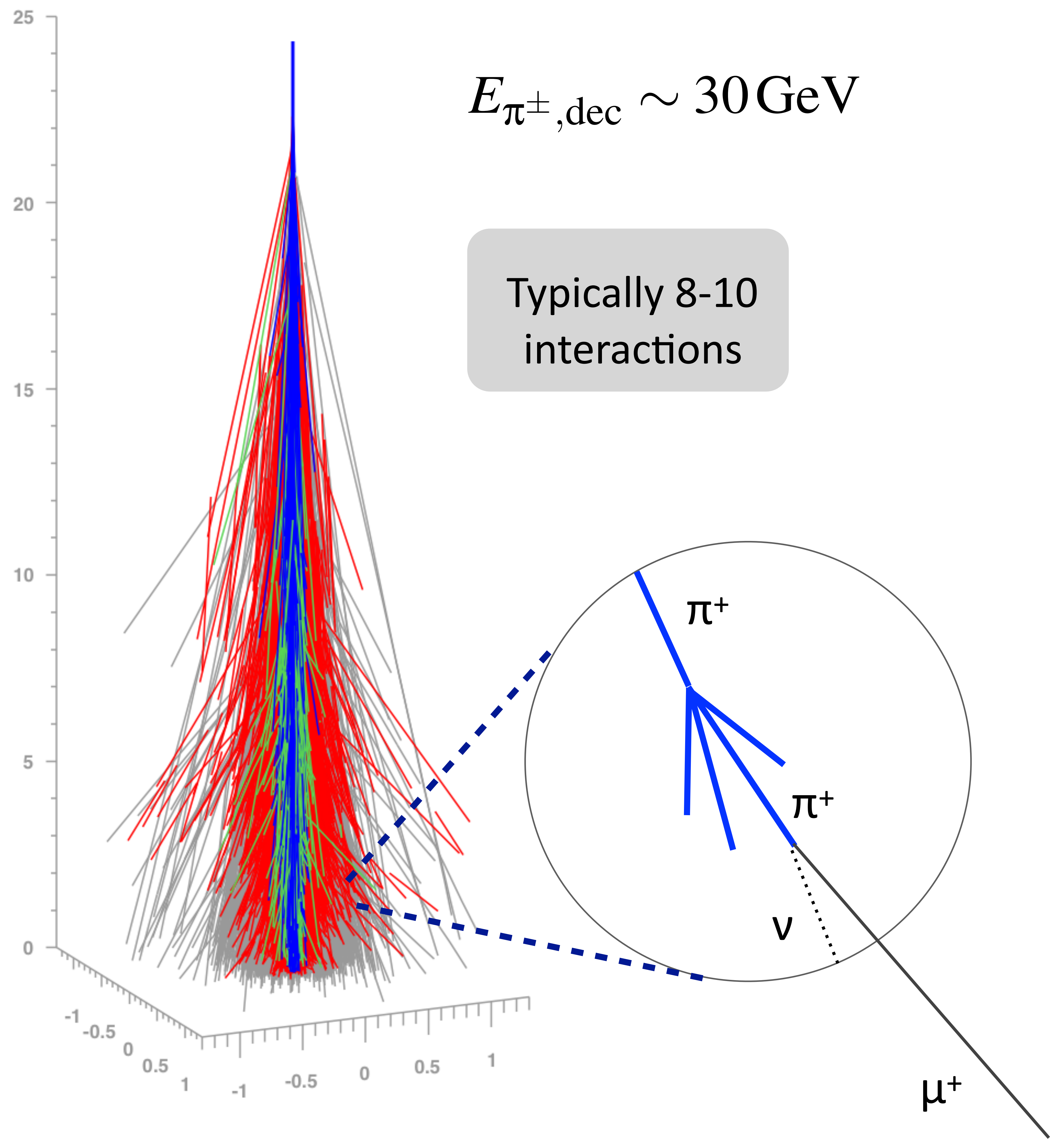
Muons/hadrons: low-energy interactions

Muons: majority produced in ~30 GeV interactions

# Muon production at large lateral distance

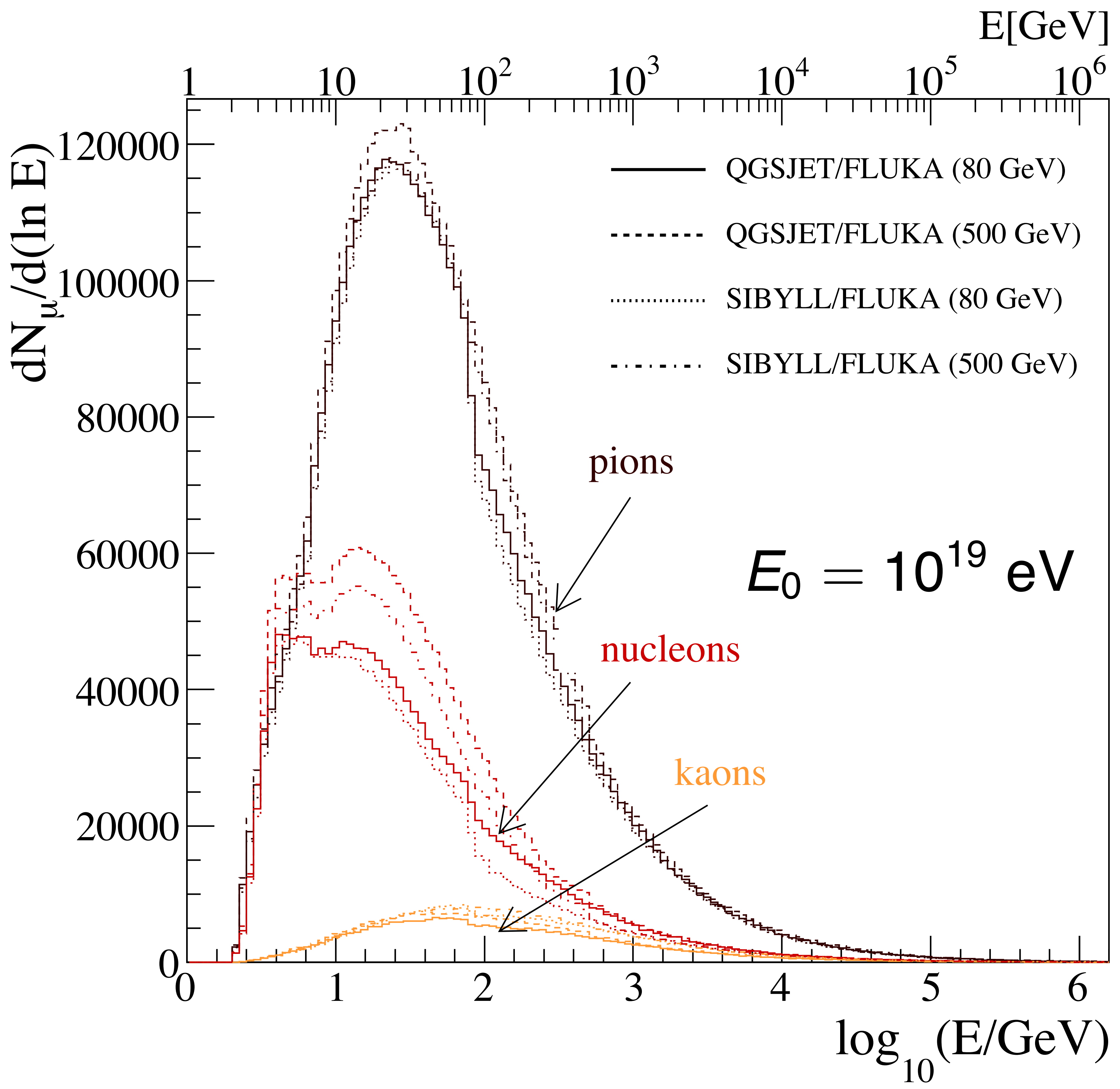
$E_{\pi^\pm,\mathrm{dec}} \sim 30\,\mathrm{GeV}$

Typically 8-10 interactions



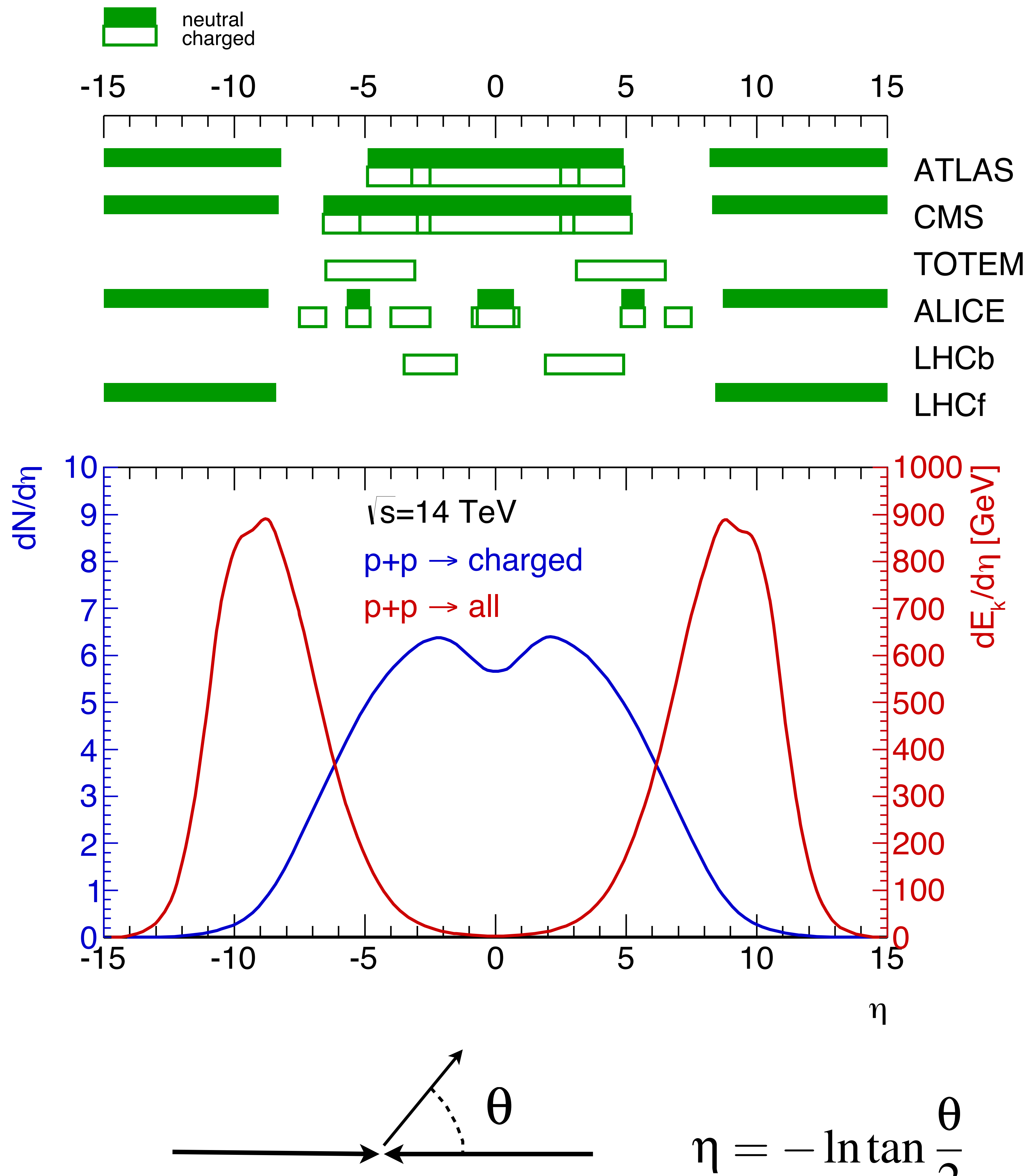

**Muon observed at 1000 m from core**

Energy distribution of last interaction that produced a detected muon



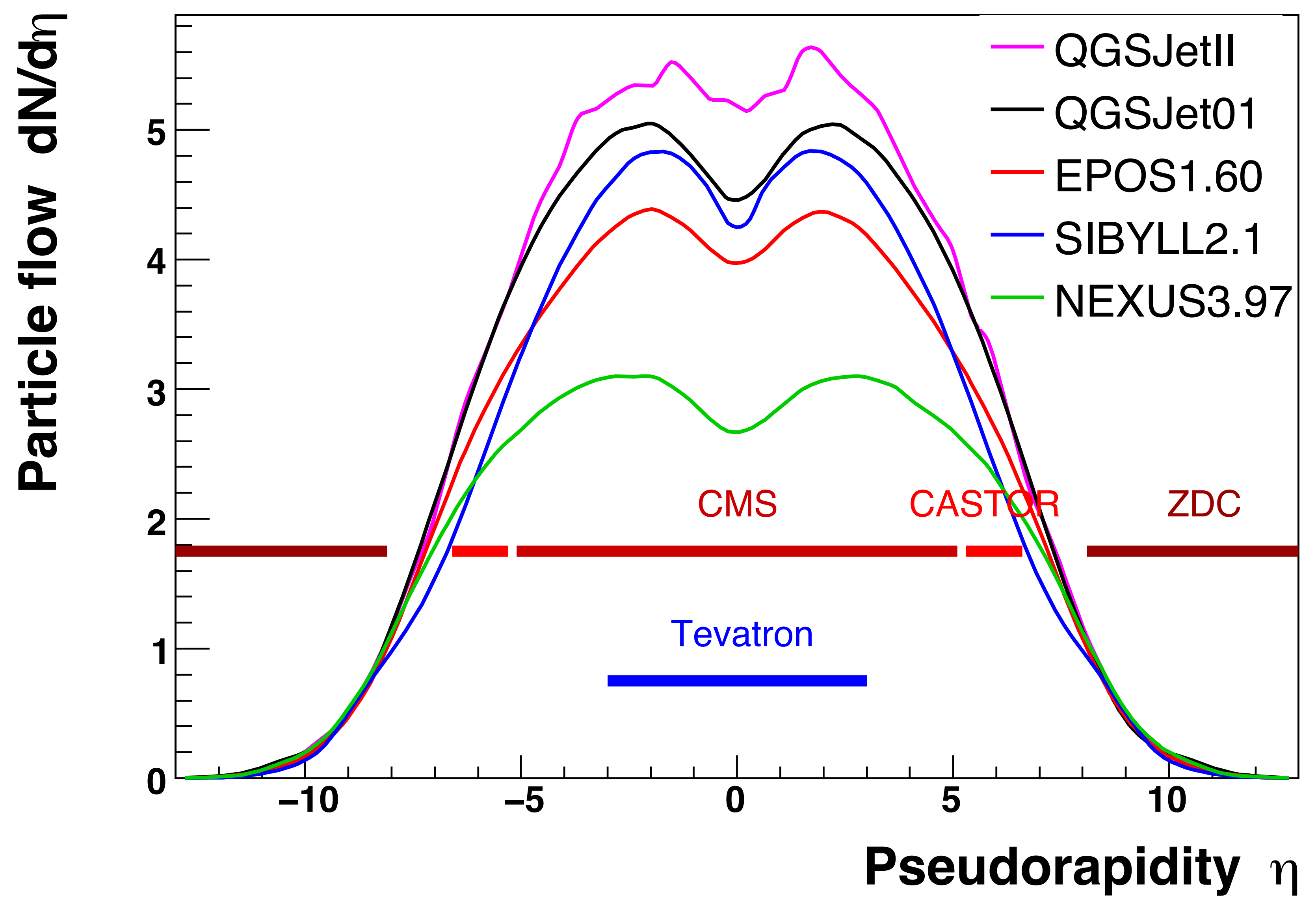

*(Maris et al. ICRC 2009)*

# Challenge of limited phase space coverage

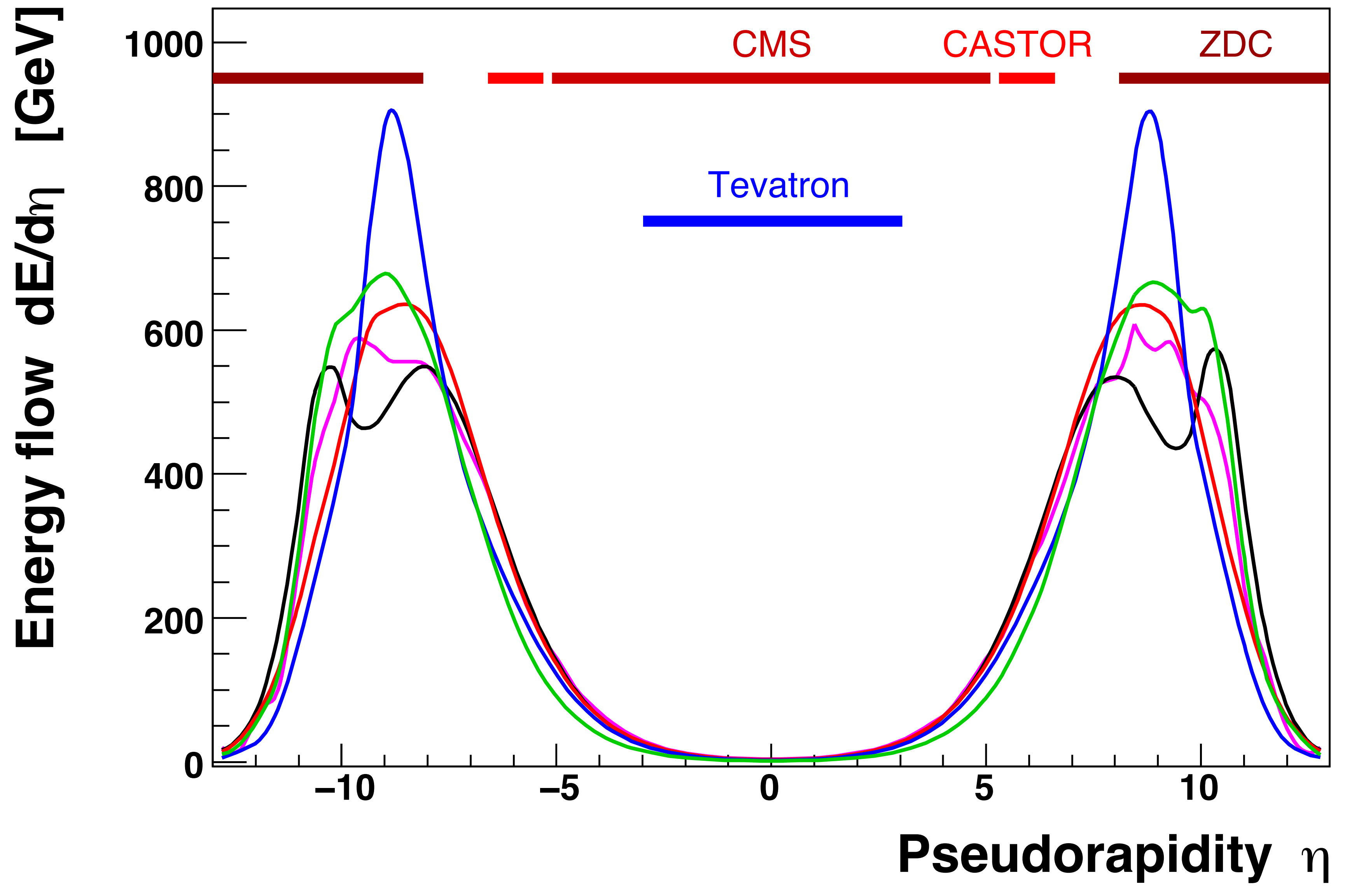



$$\eta = -\ln\tan\frac{\theta}{2}$$

Particle flow

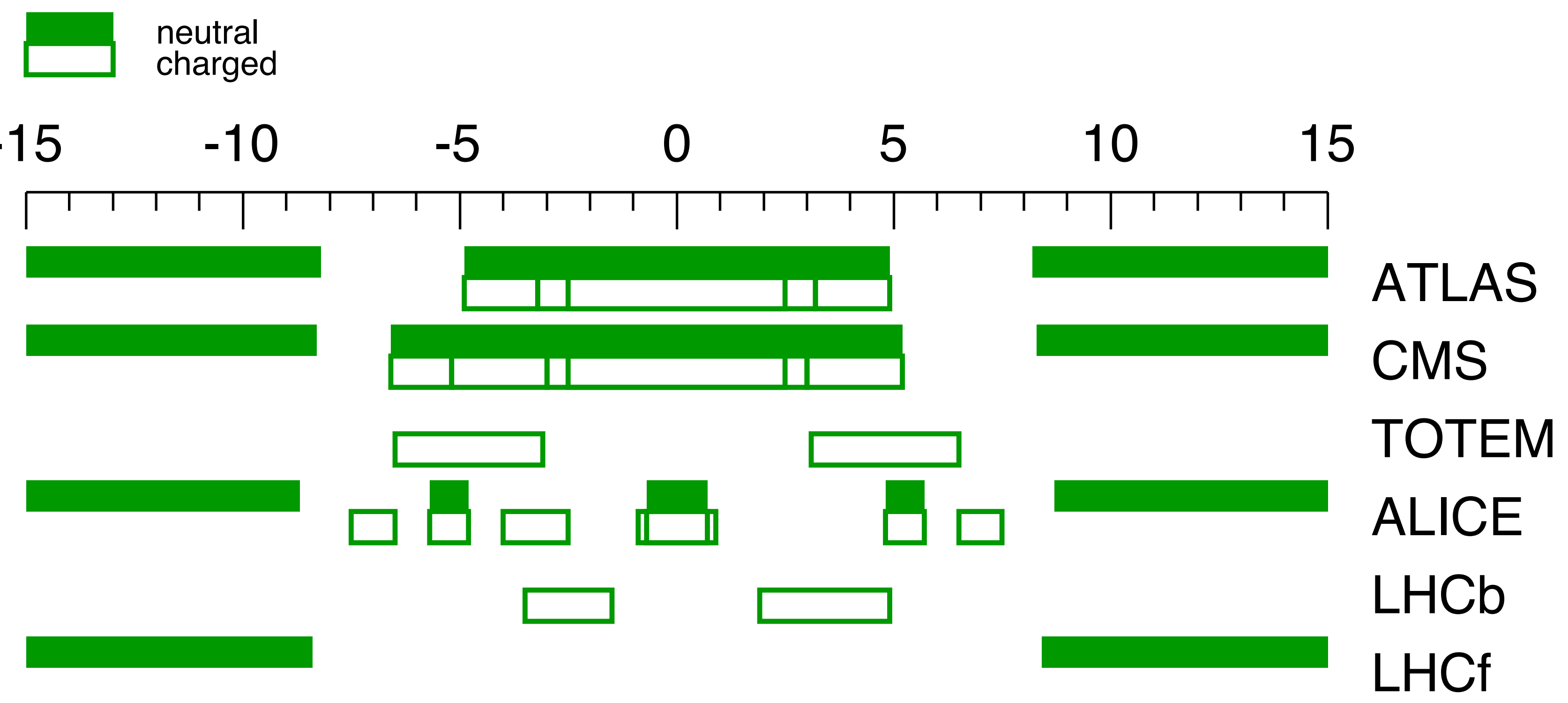


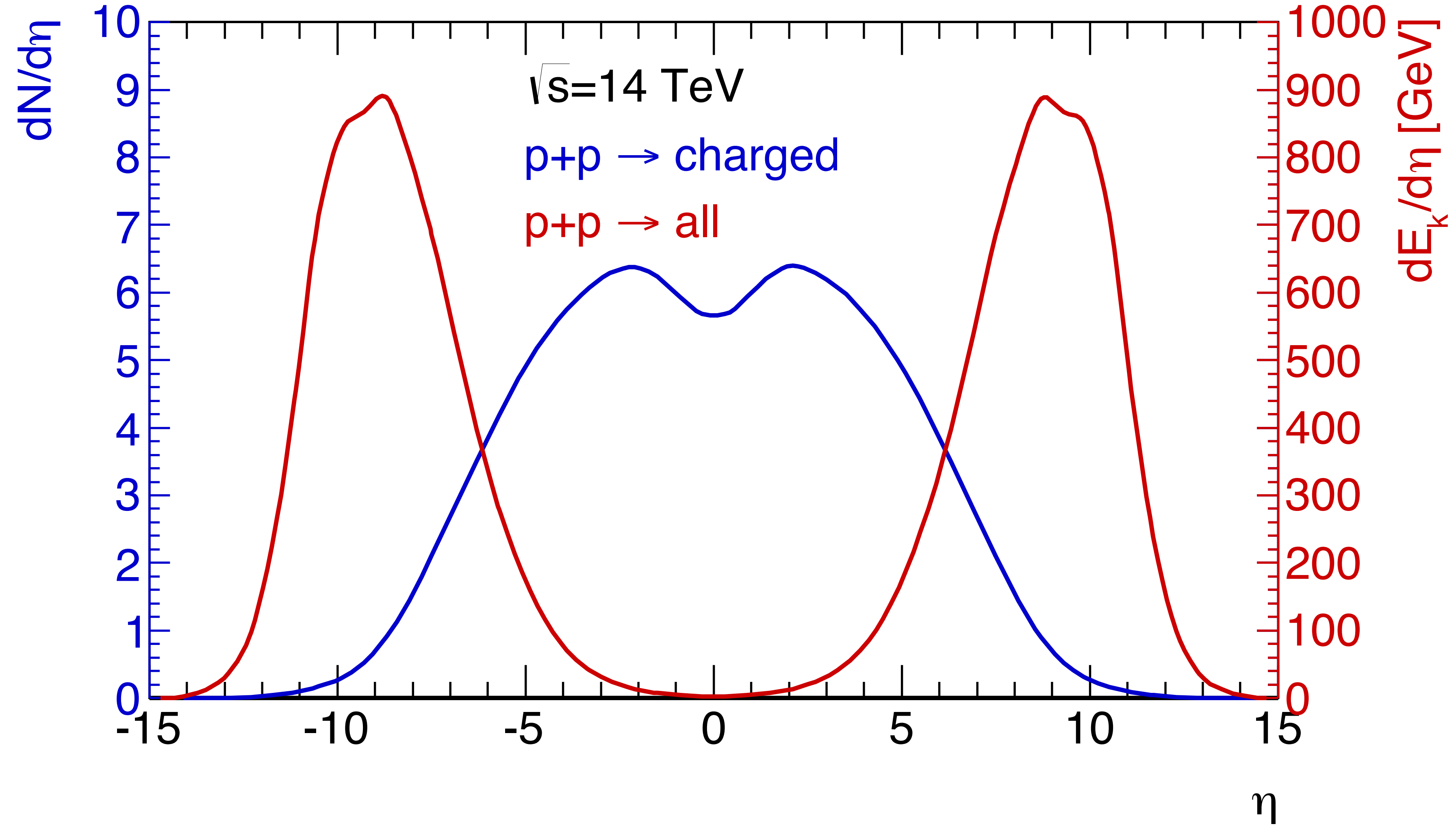

Energy flow

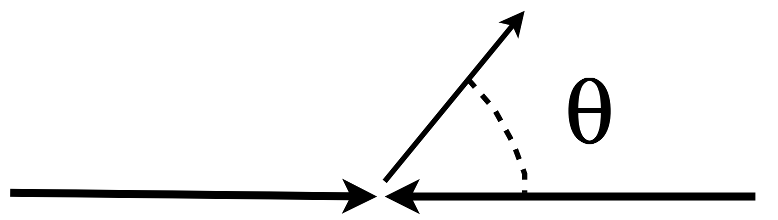



(Salek et al., 2014)

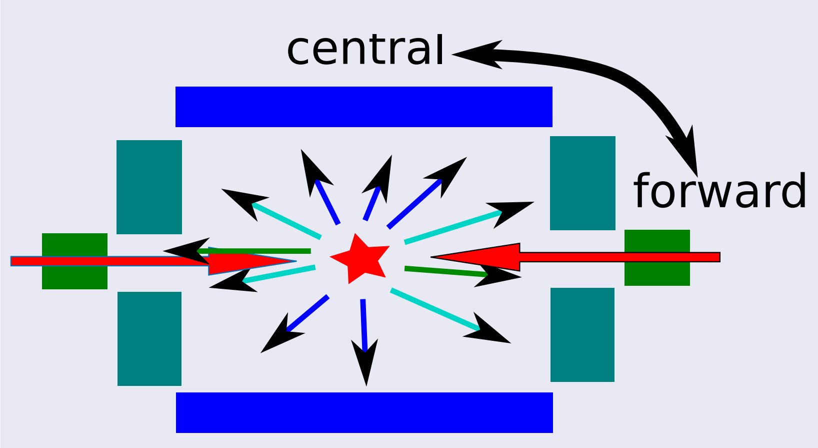
# Challenge of limited phase space coverage



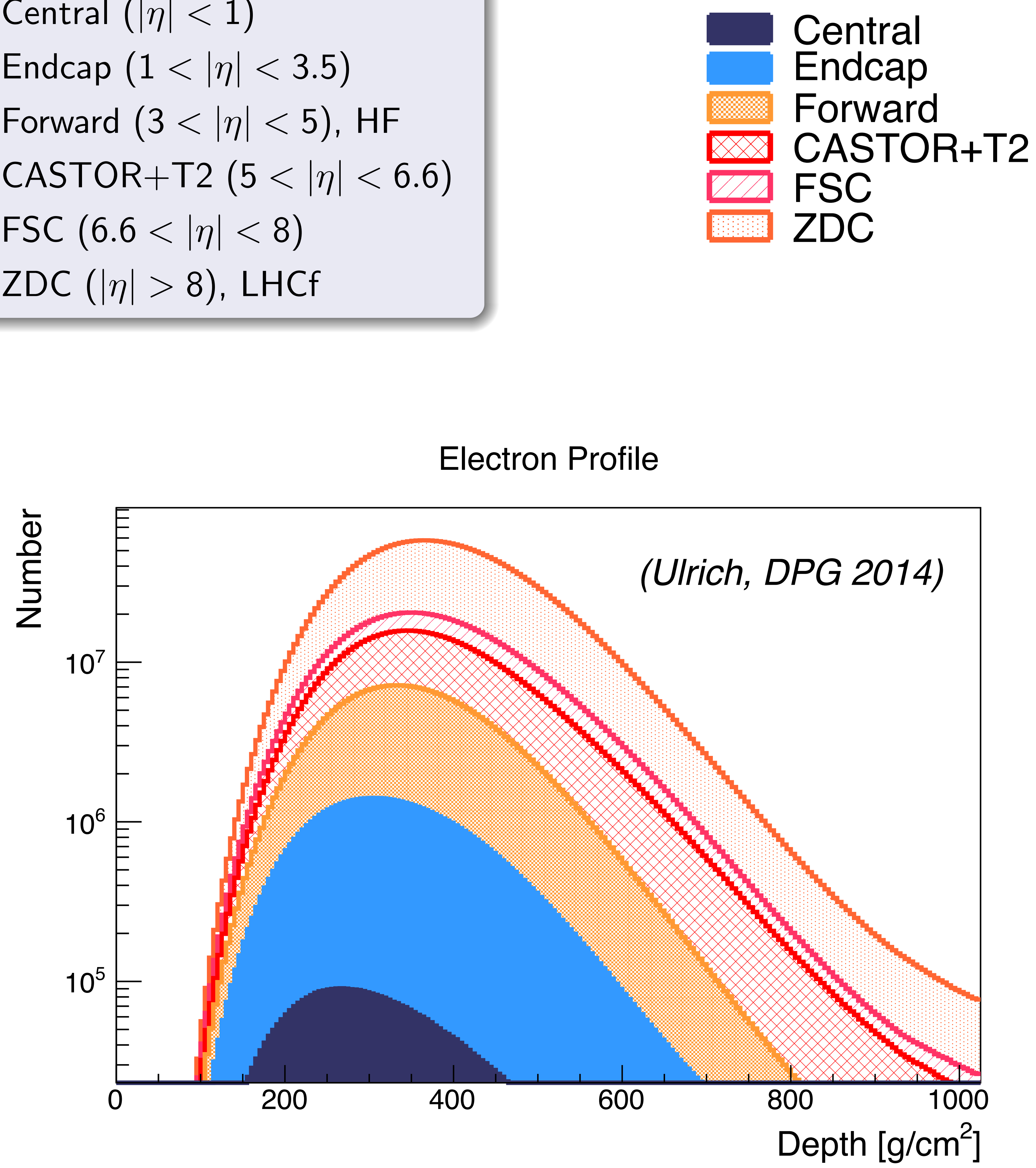




$$\eta = -\ln\tan\frac{\theta}{2}$$




- 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

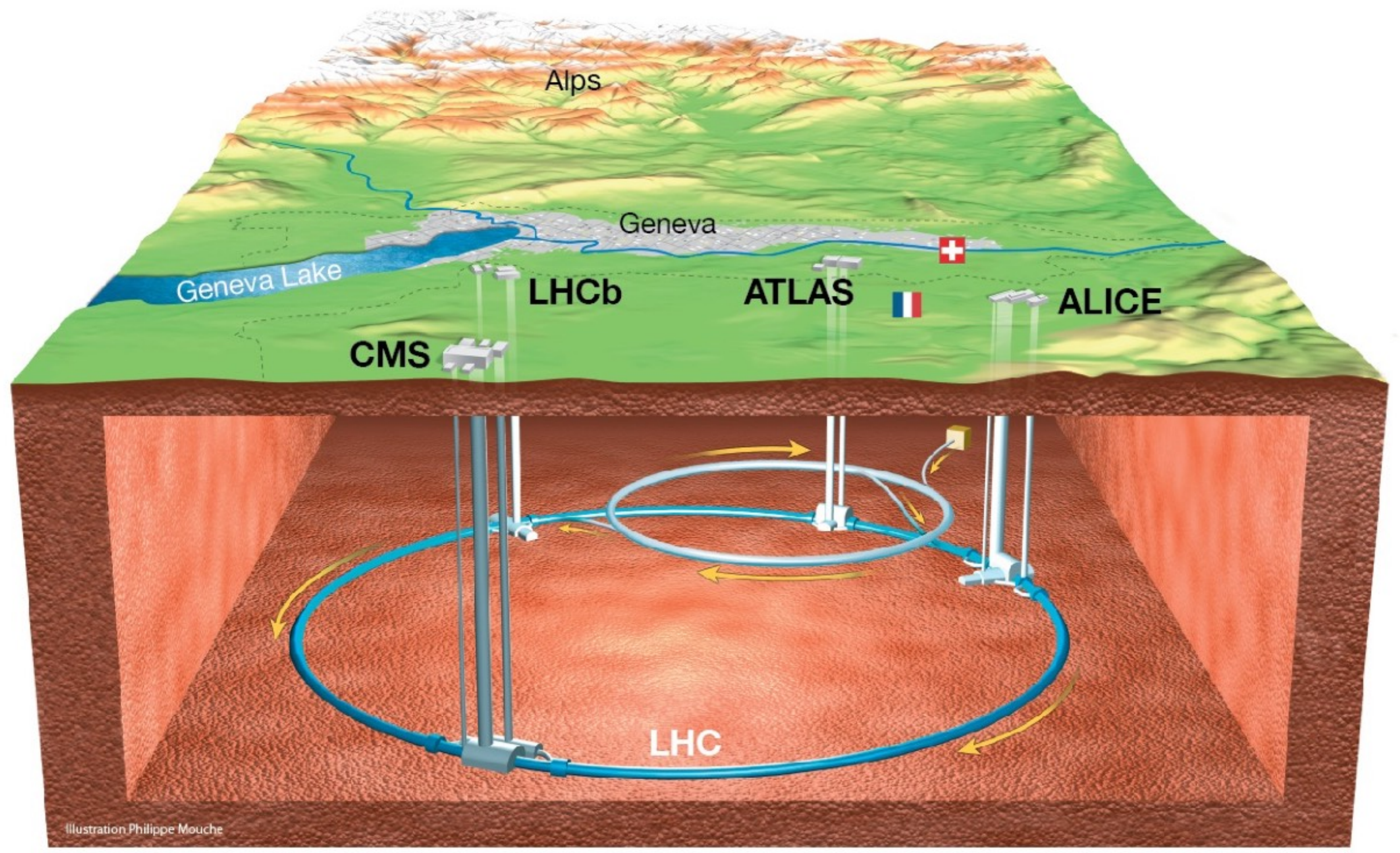
| η | deg. | mrad. |
|---|---|---|
| 3 | 5.7 | 97 |
| 5 | 0.77 | 10 |
| 8 | 0.04 | 0.7 |
| 10 | 0,005 | 0,009 |

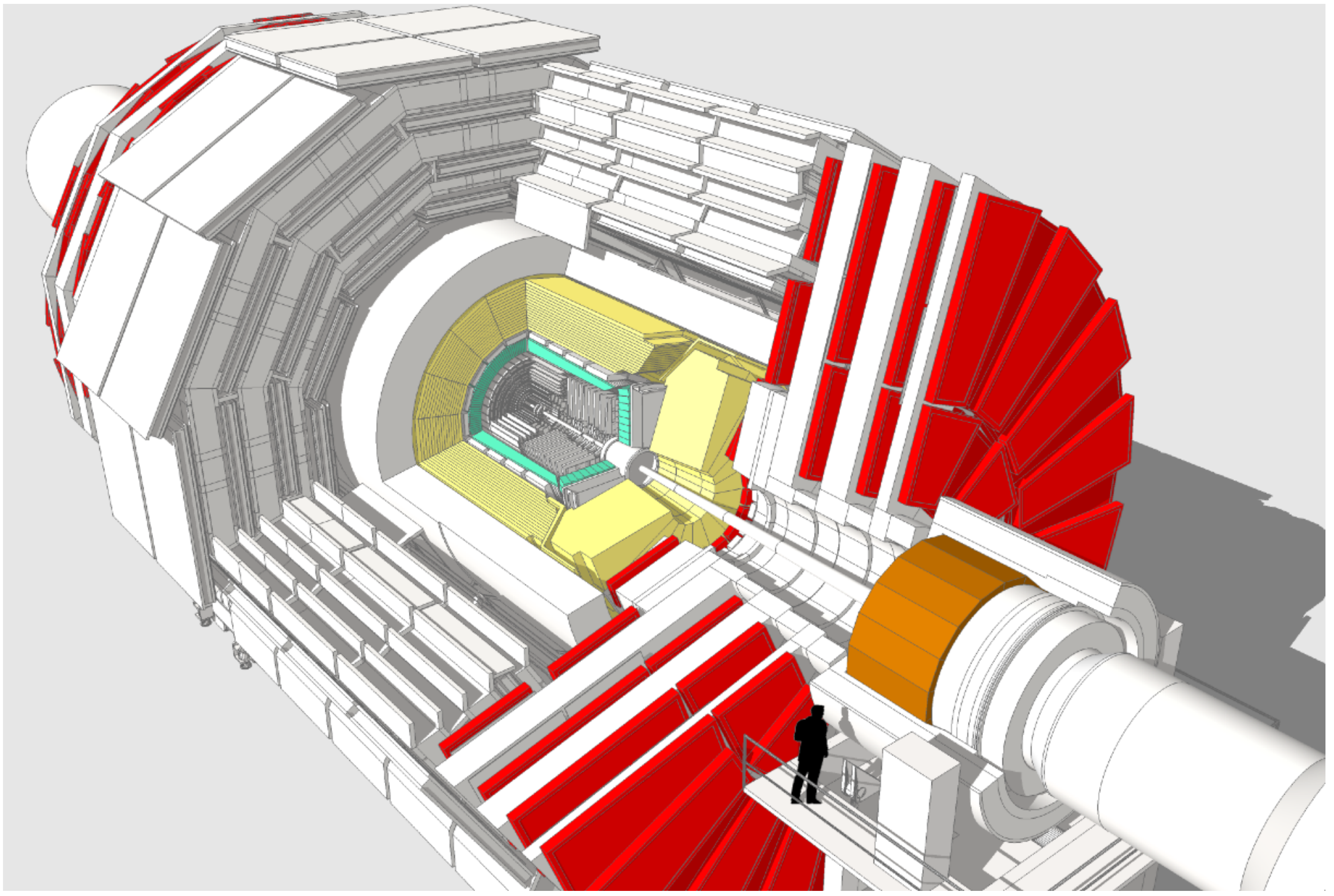



More than 50% of shower from η > 8

(Salek et al., 2014)

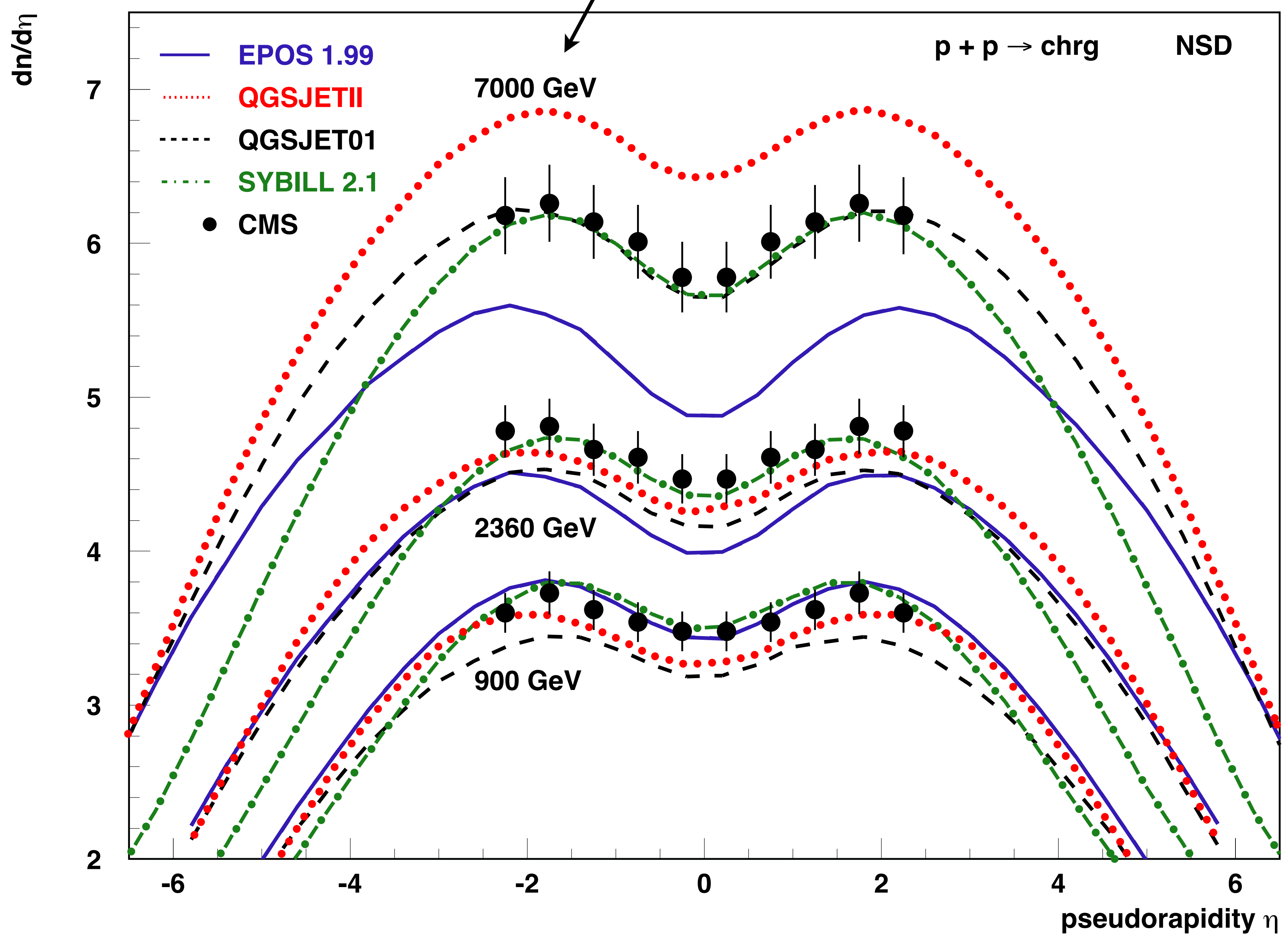
# Charged particle distribution in pseudorapidity



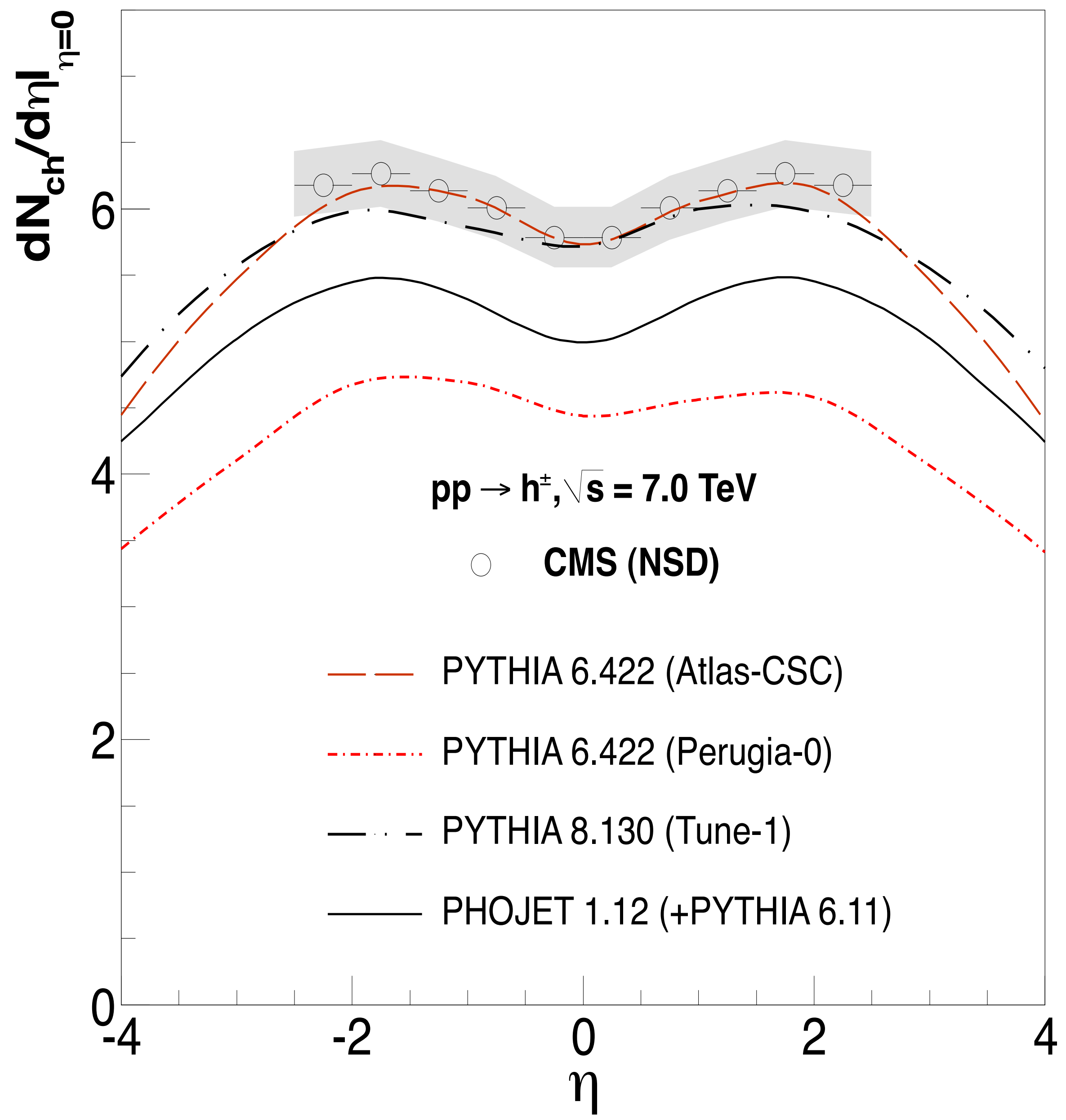
(data from all LHC experiments, CMS shown as example)

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




**Detailed LHC comparison**

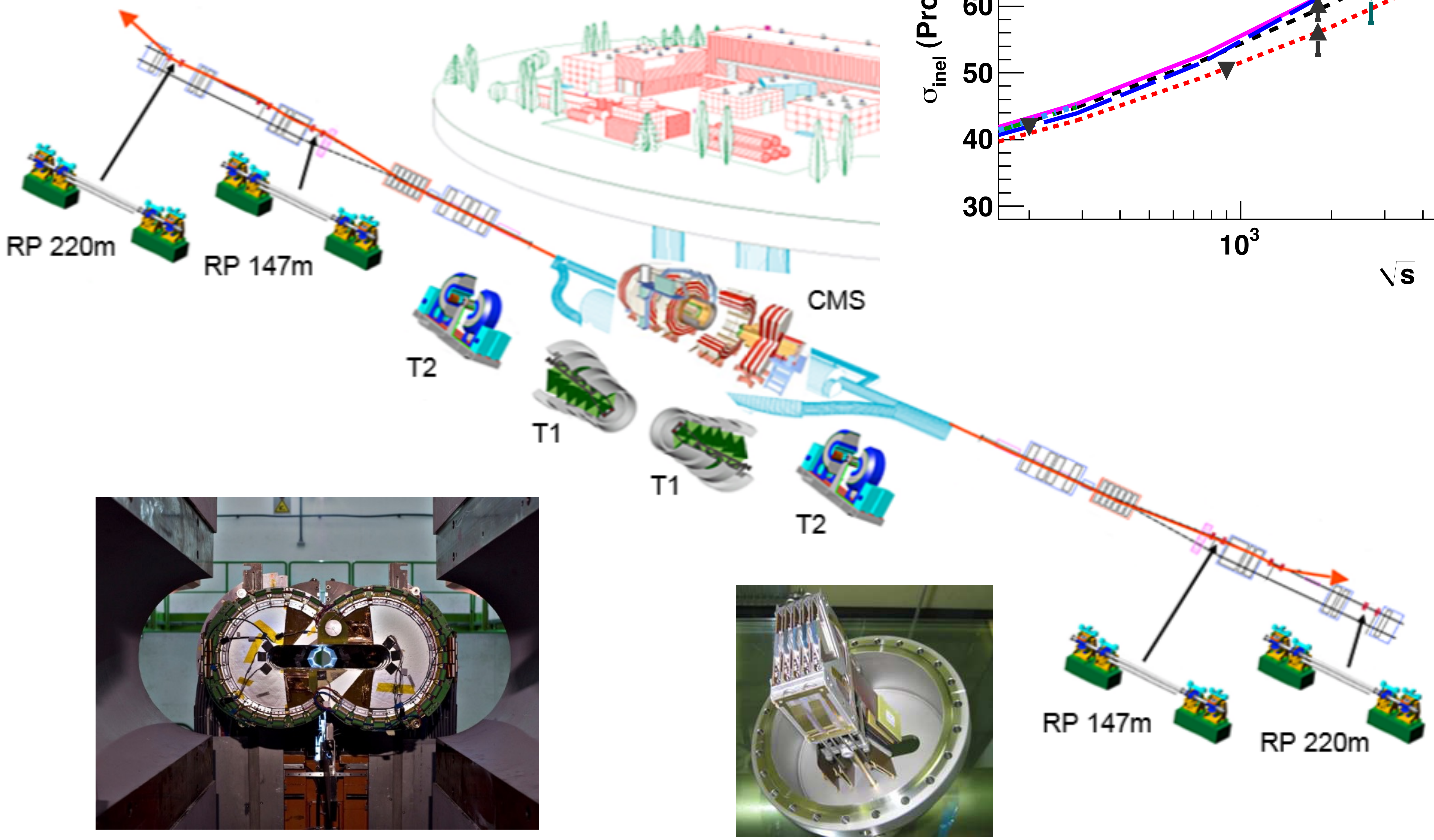
*(D'Enterria et al., APP 35, 2011)*

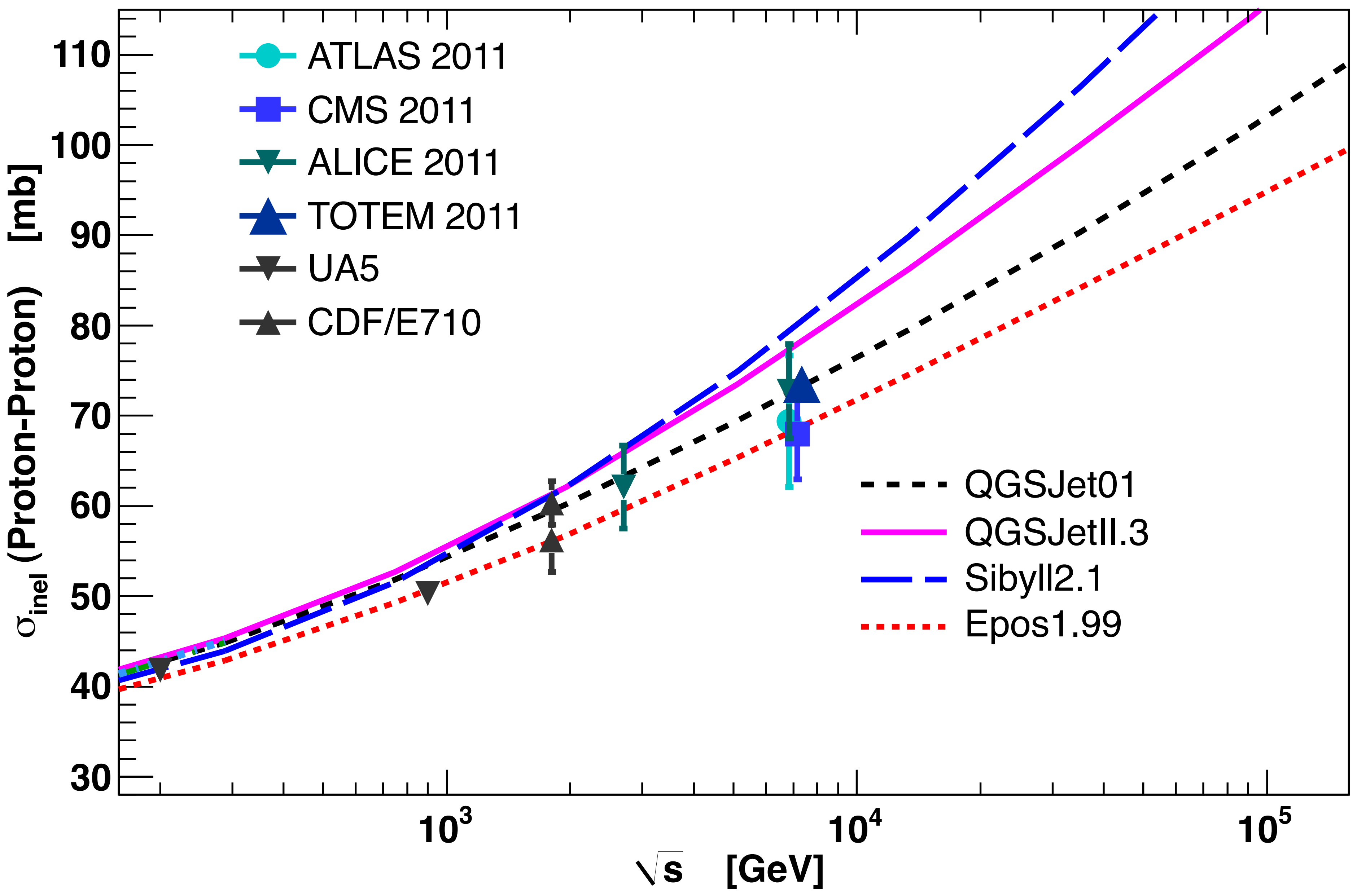


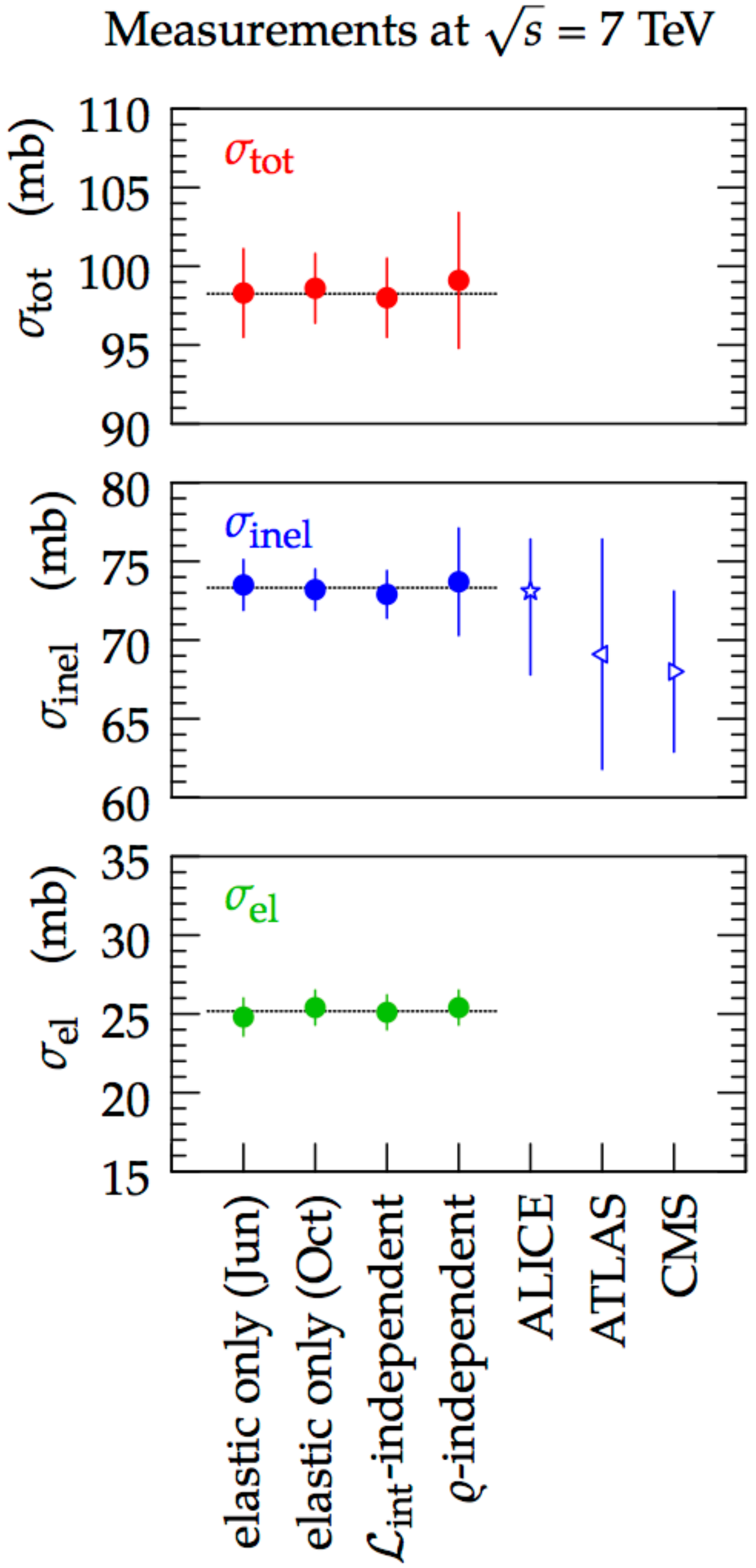

Models for air showers typically better in agreement with LHC data

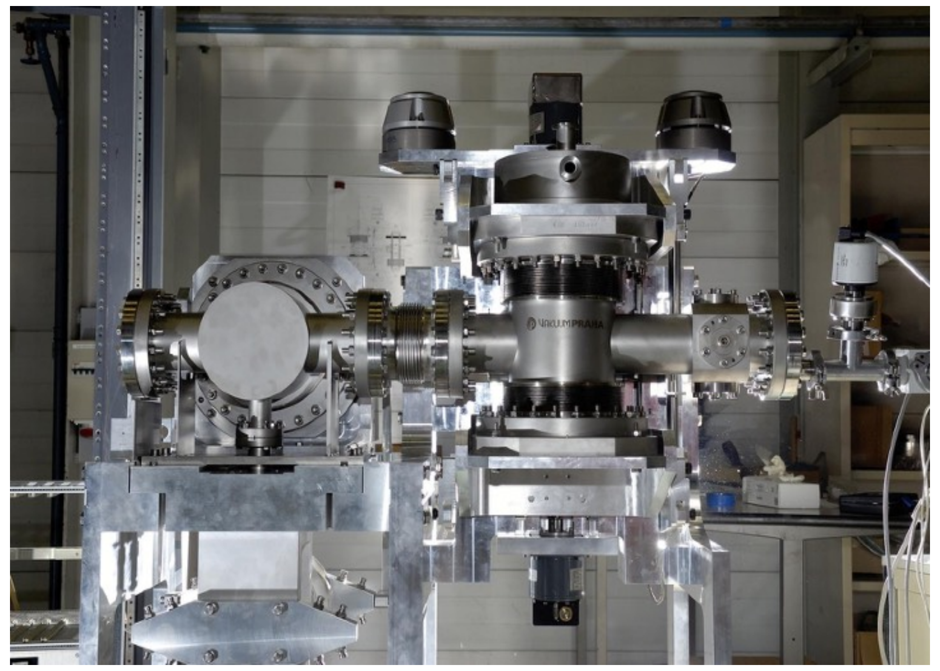
# Cross section measurements at LHC

*(Cafagna, ICRC 2015)*



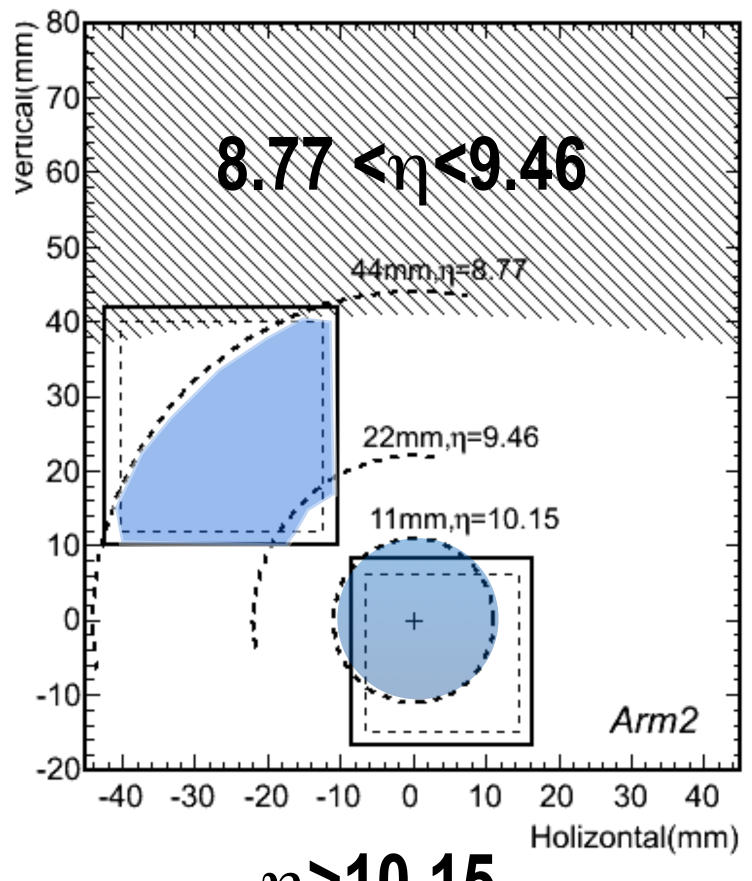



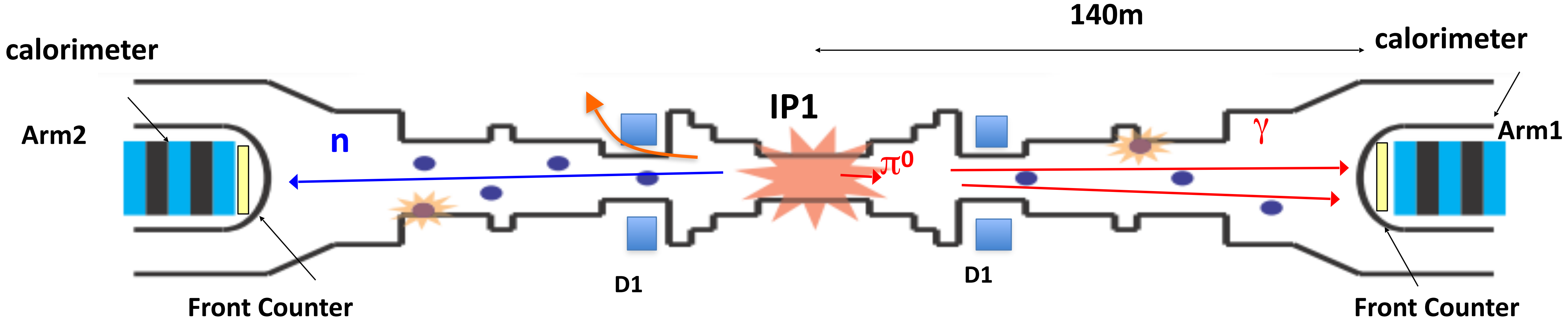
# LHCf: very forward photon production at 7 TeV

Arm 2

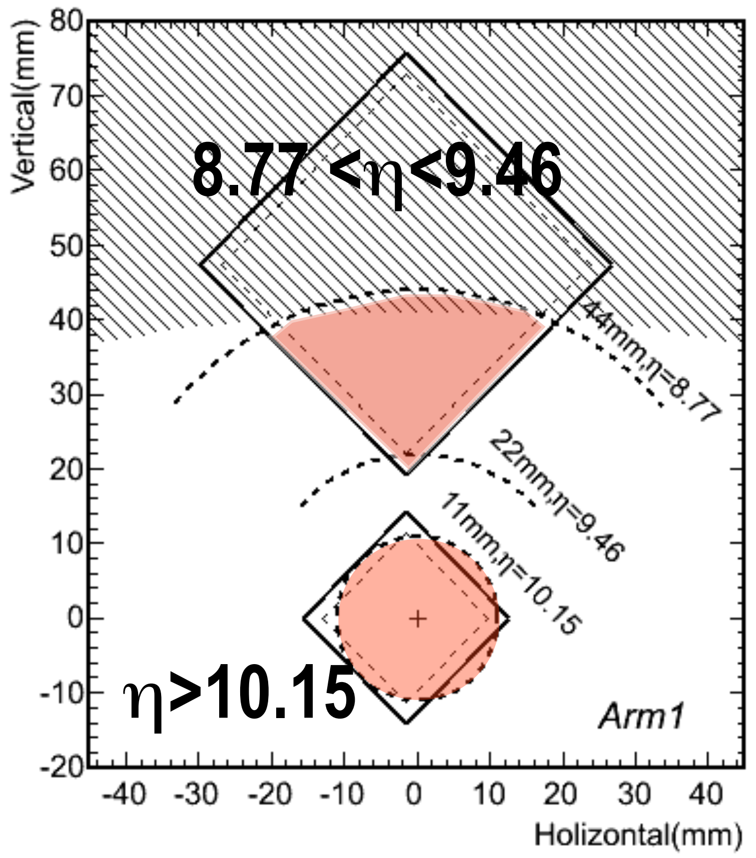



η>10.15

The LHCf experimental setup

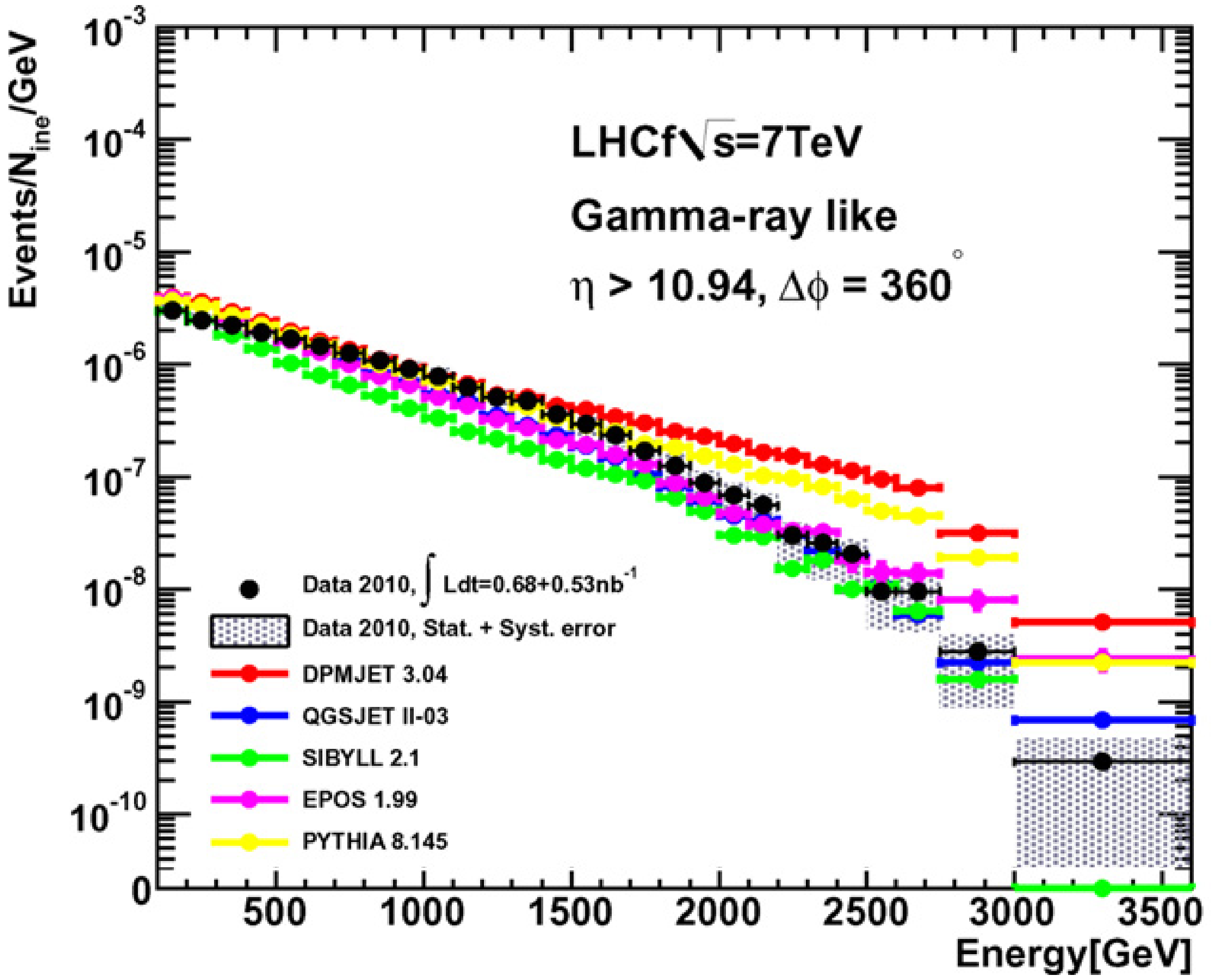


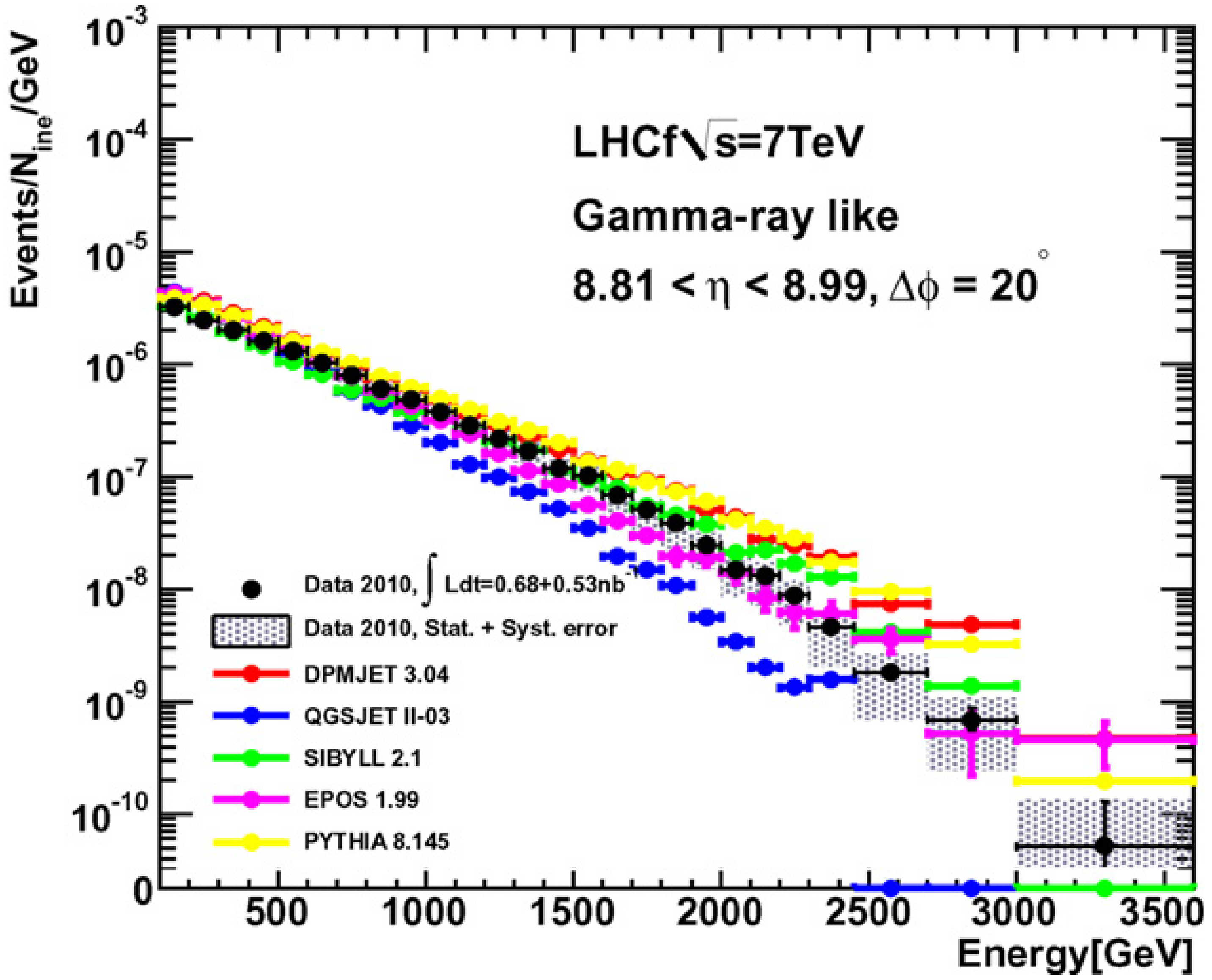

Arm 1

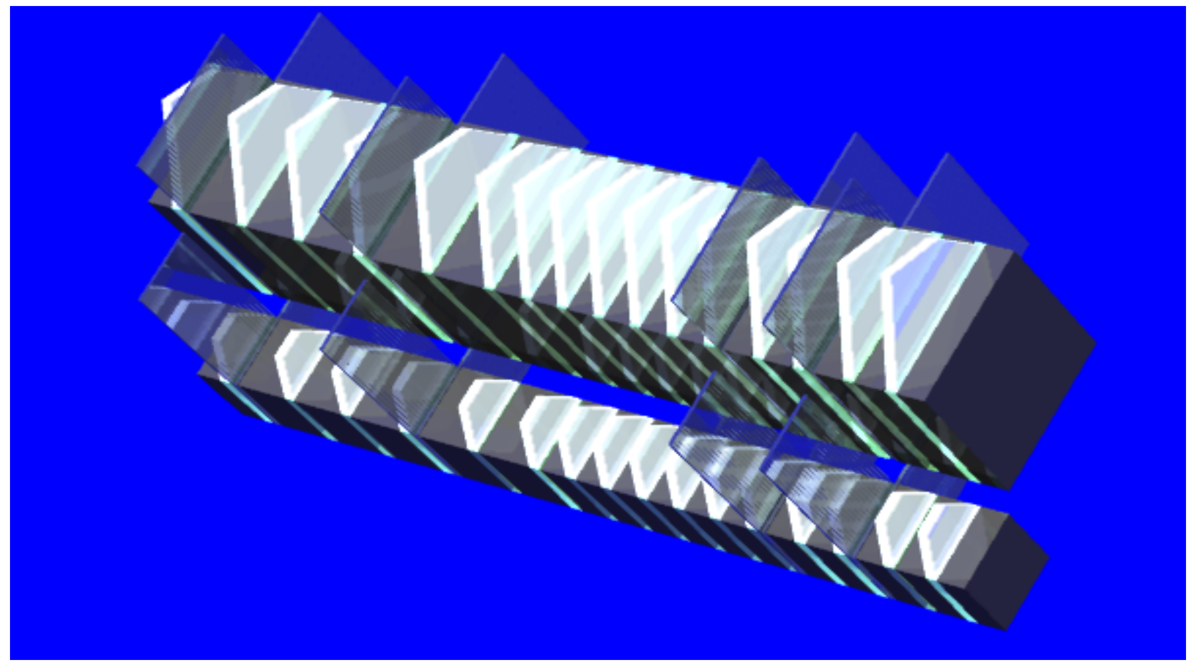



$$pp \to \gamma X$$

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

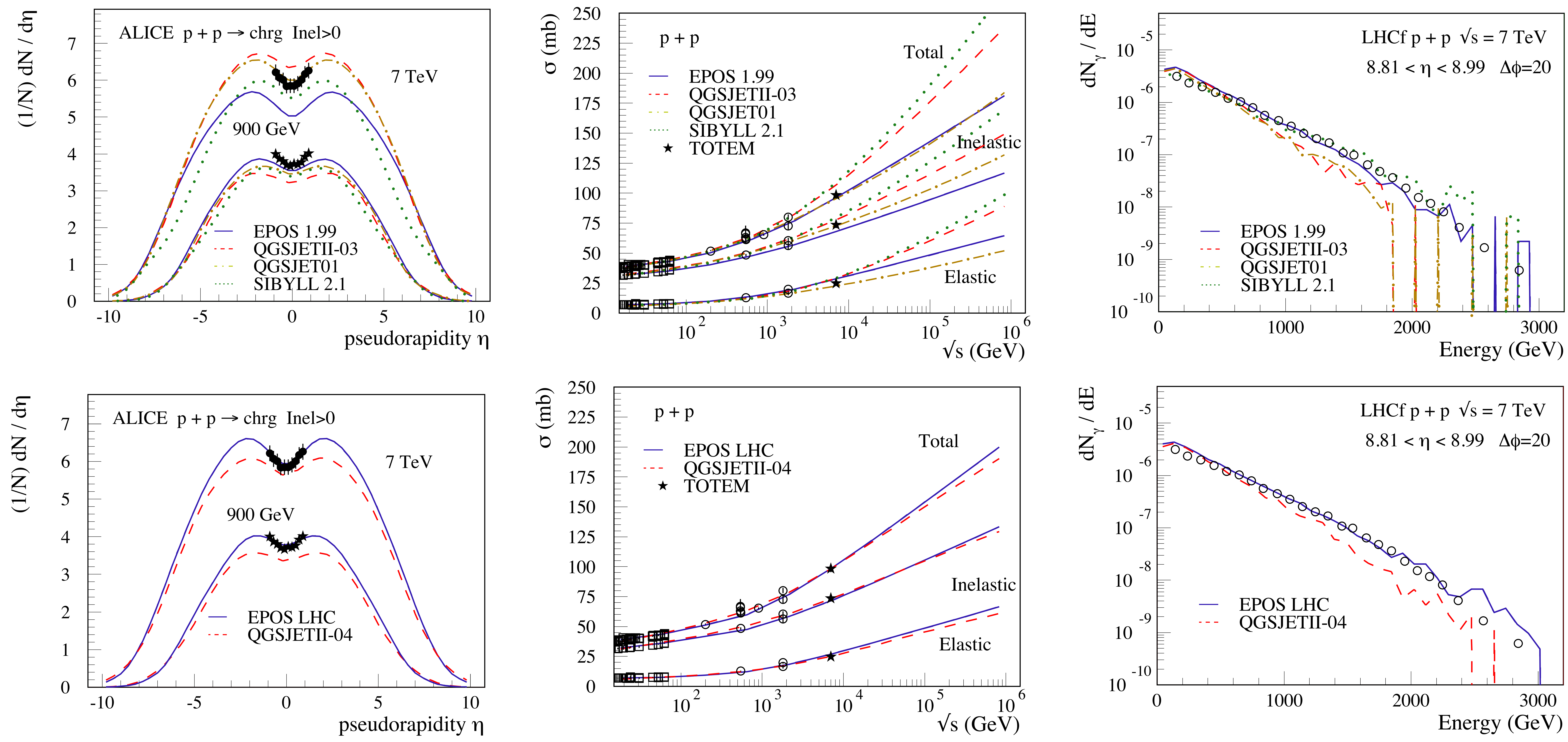


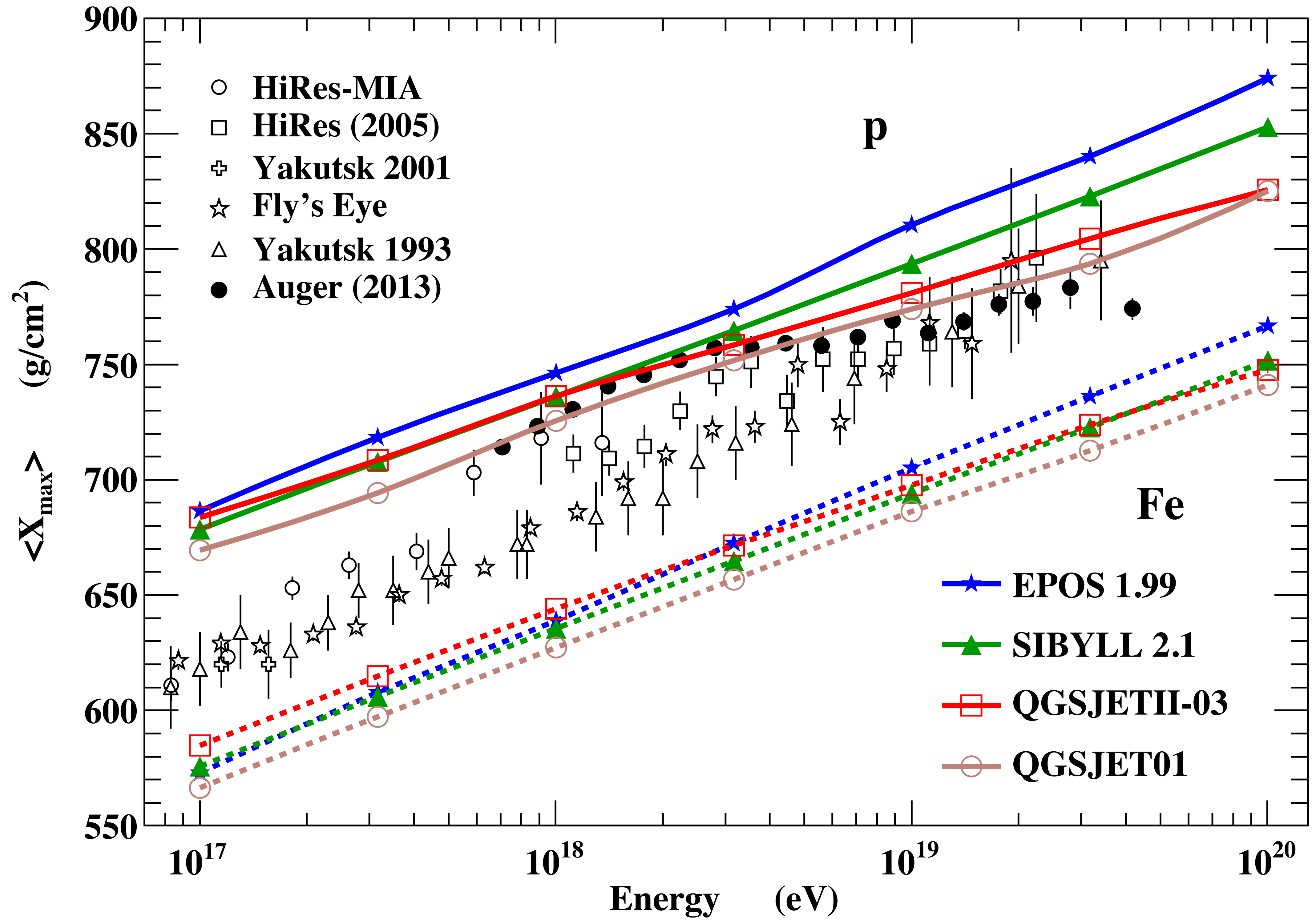
*(Itow, ICRC 2015)*

# Examples of tuning interaction models to LHC data



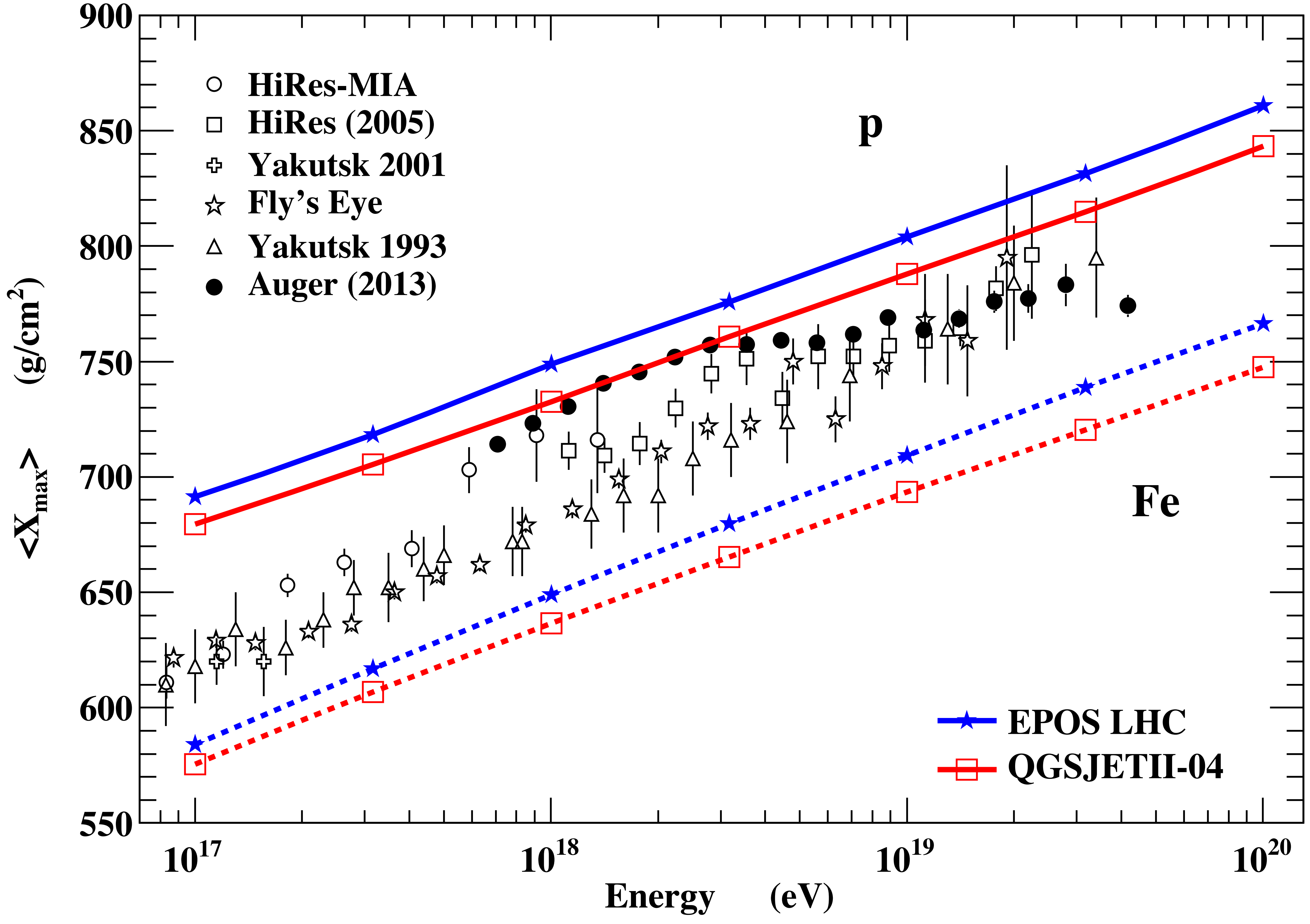

*(Pierog 2013, 2014)*

# Predictions for depth of shower maximum




pre-LHC models

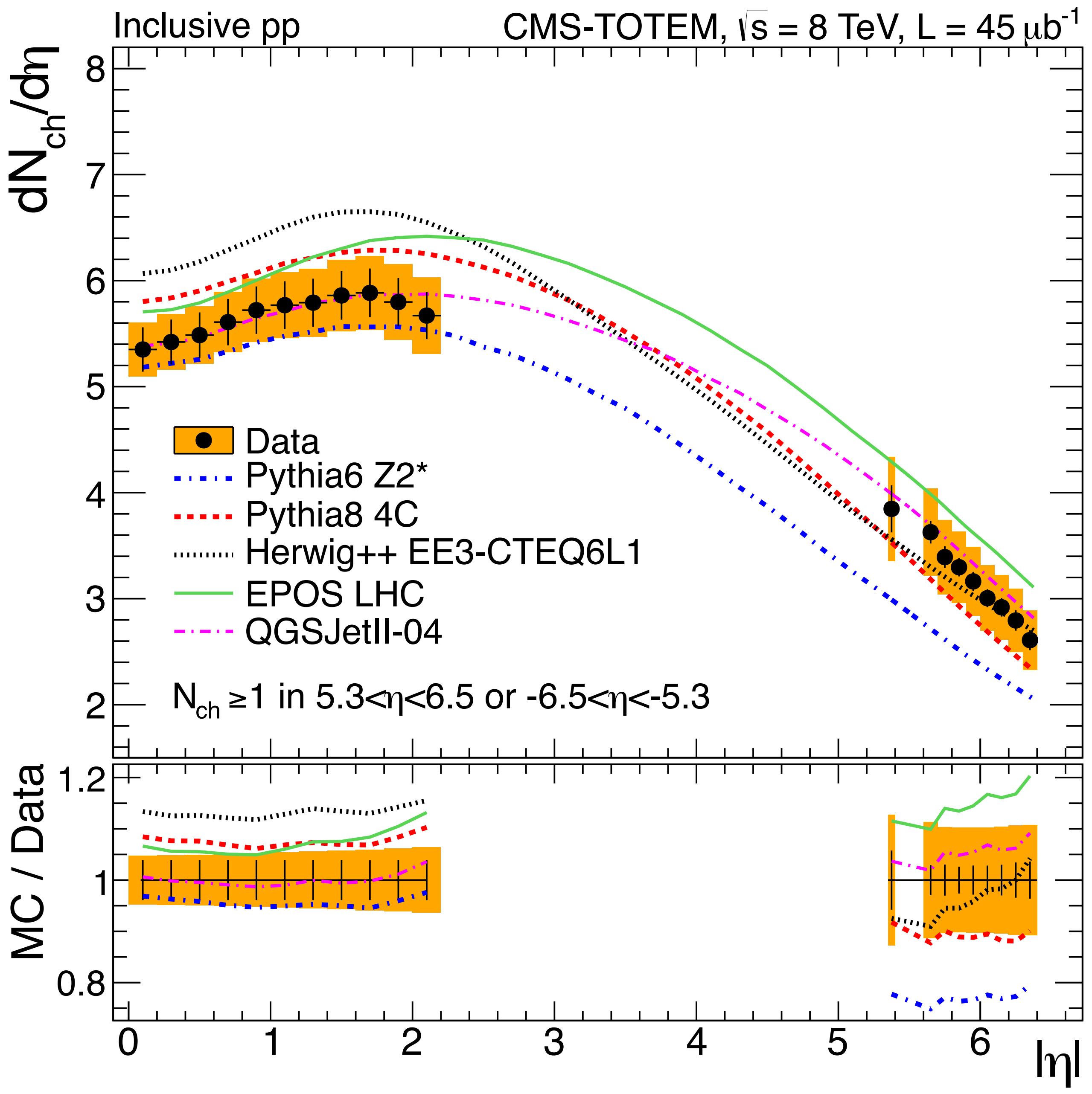
post-LHC models

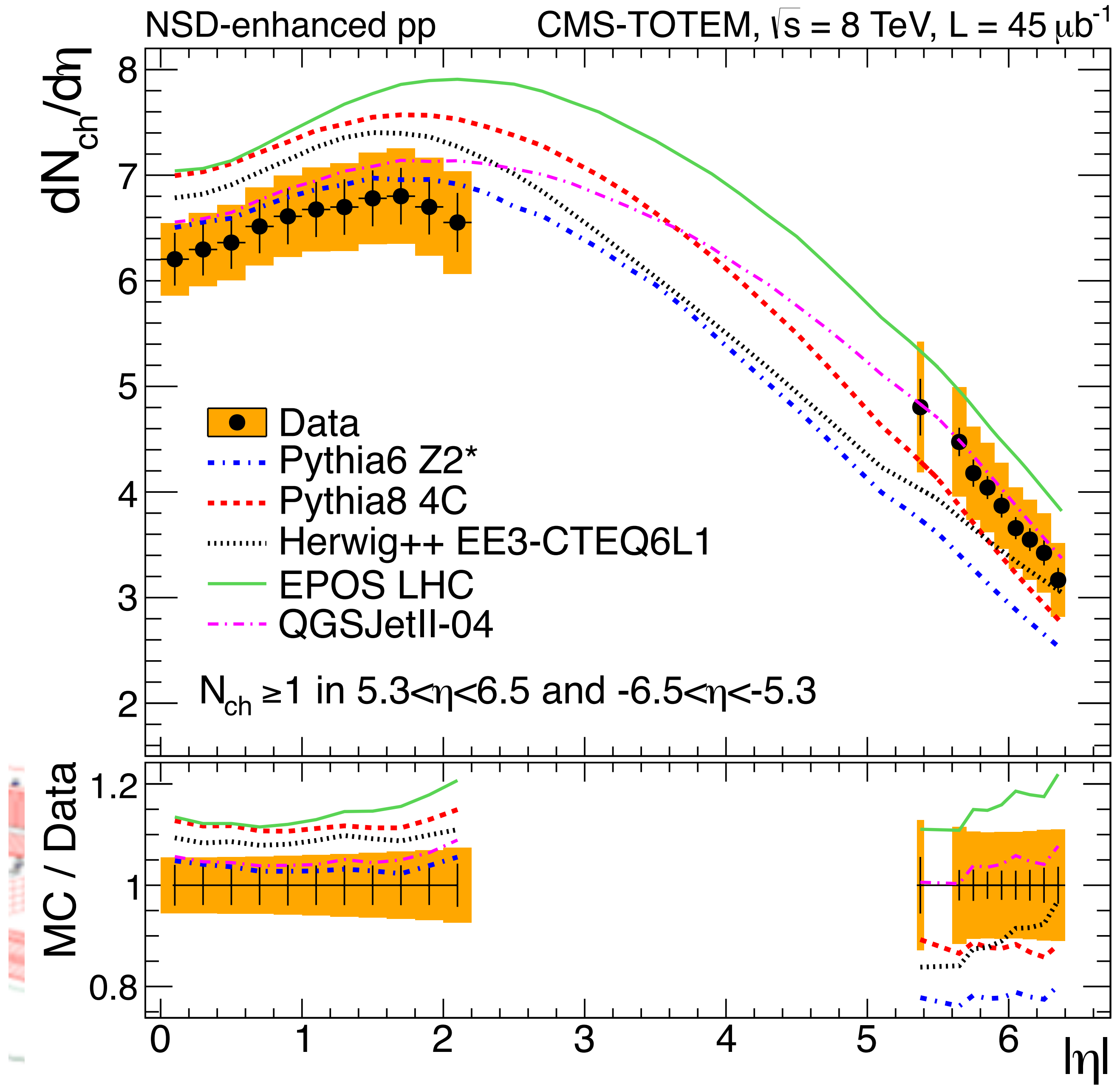



New models favour interpretation as heavier composition than before

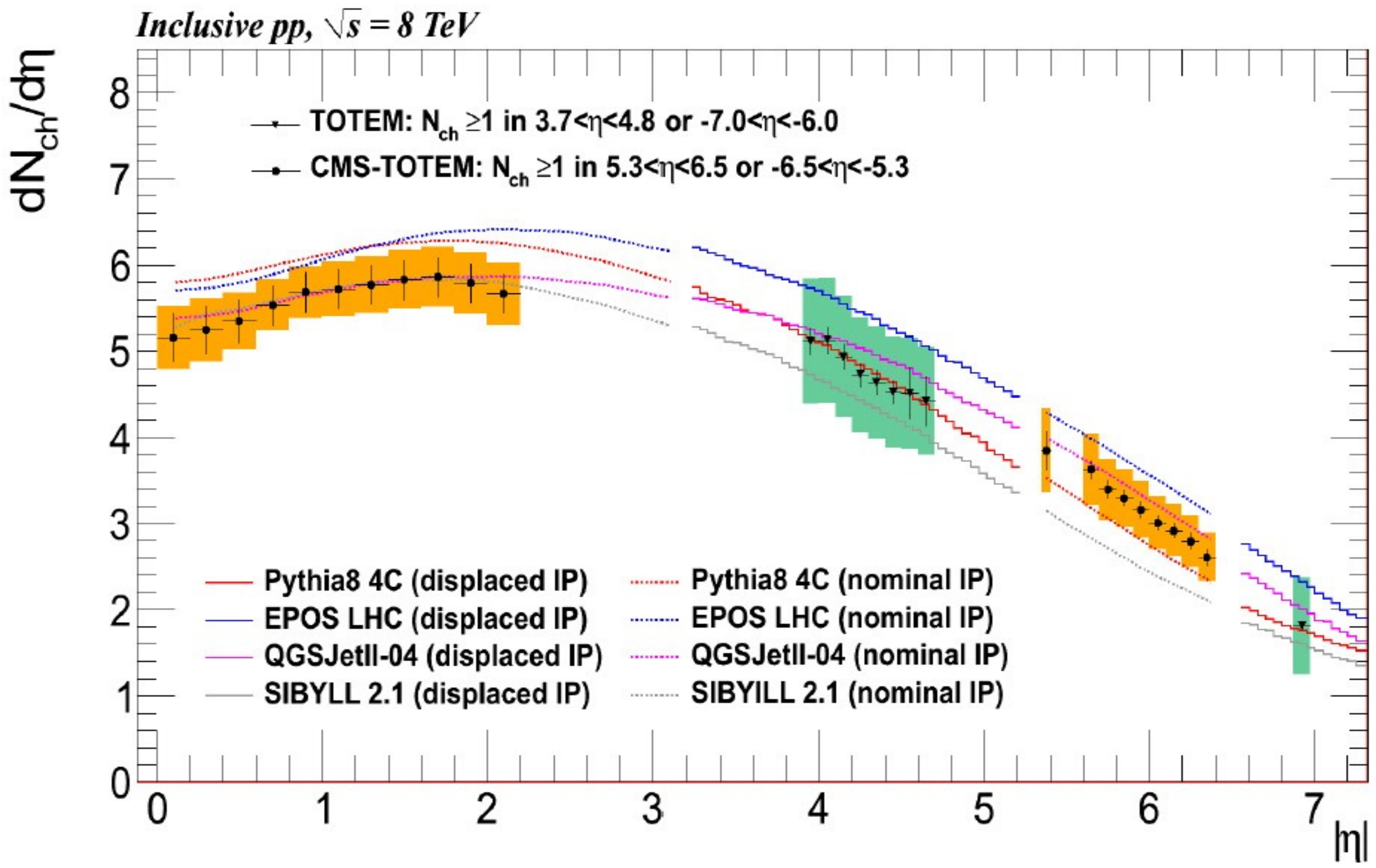
*(Pierog 2013, 2014)*

# Combined CMS and TOTEM measurements

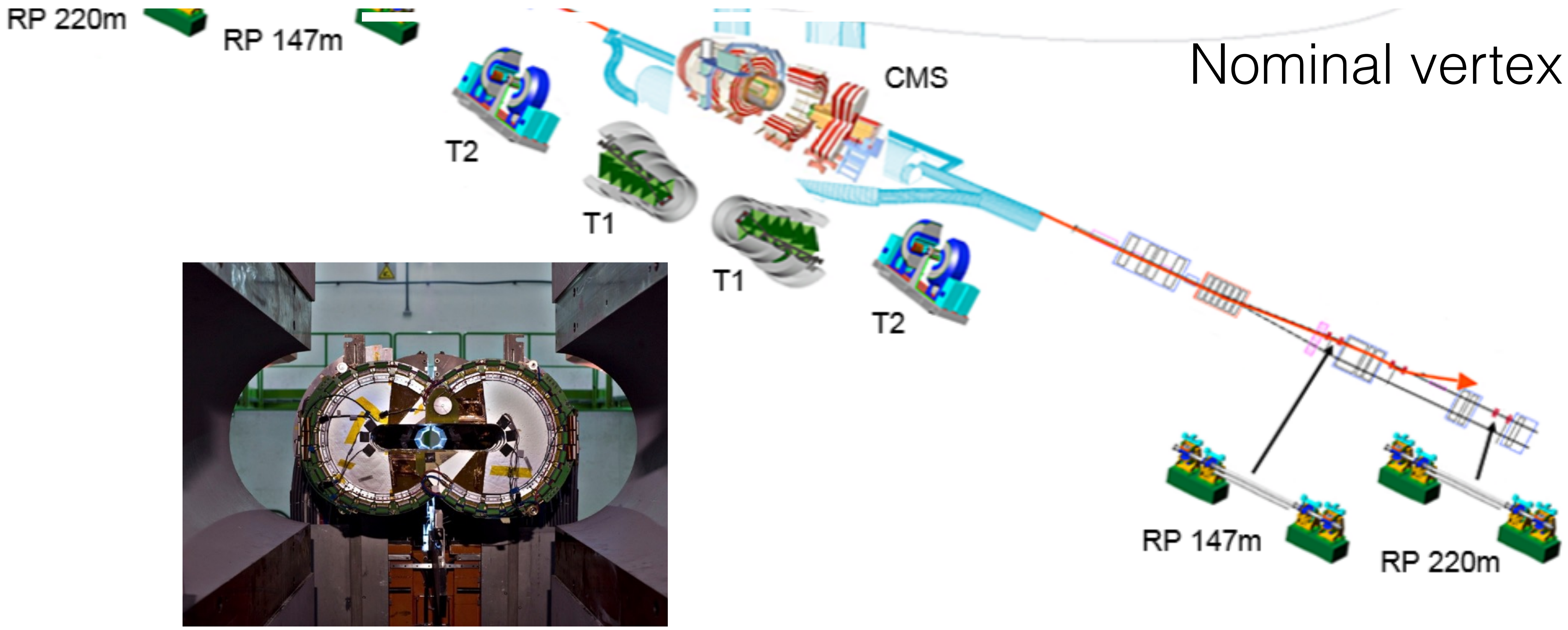


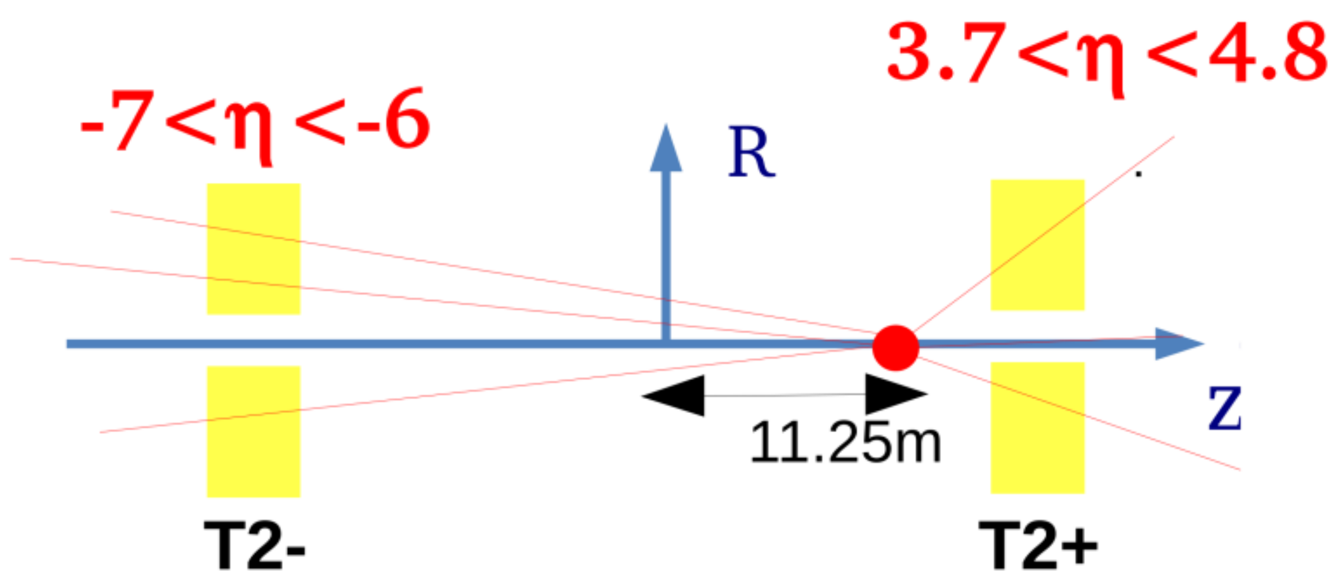




Nominal vertex

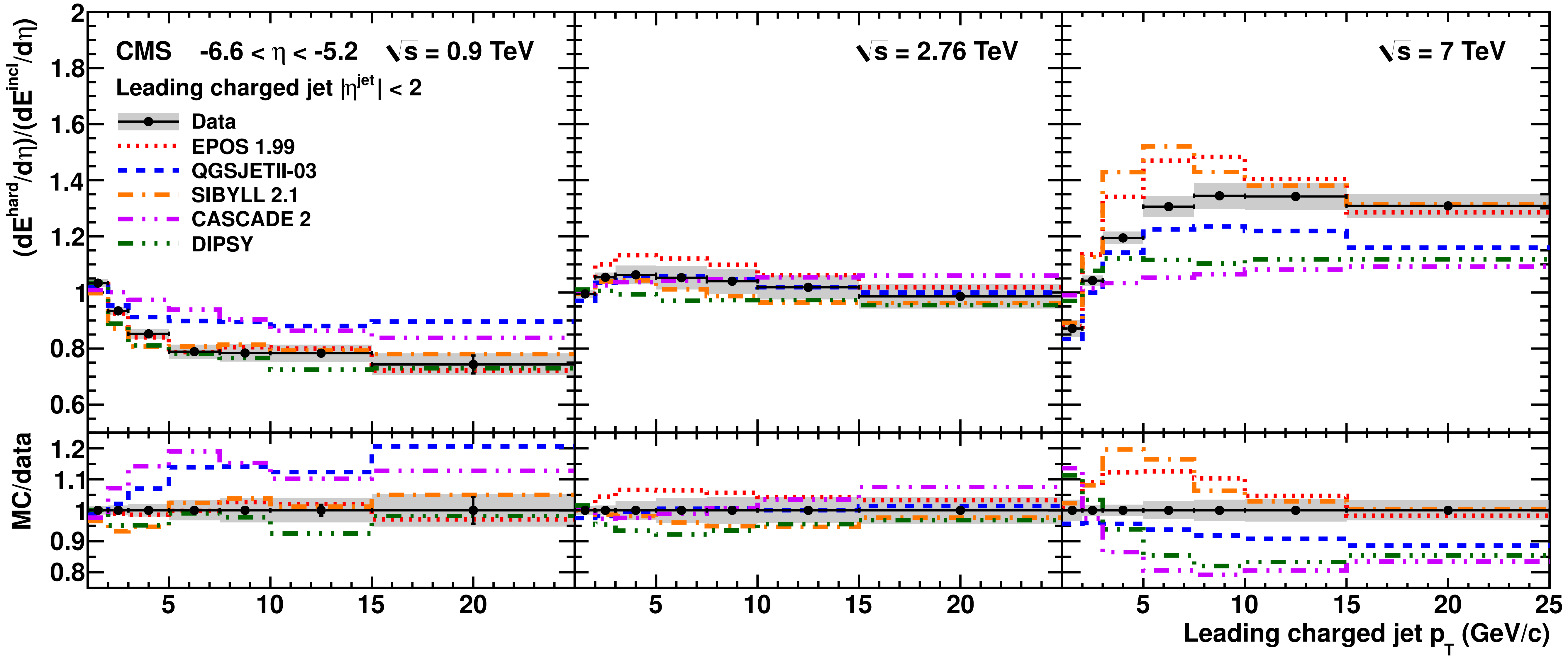



Shifted vertex



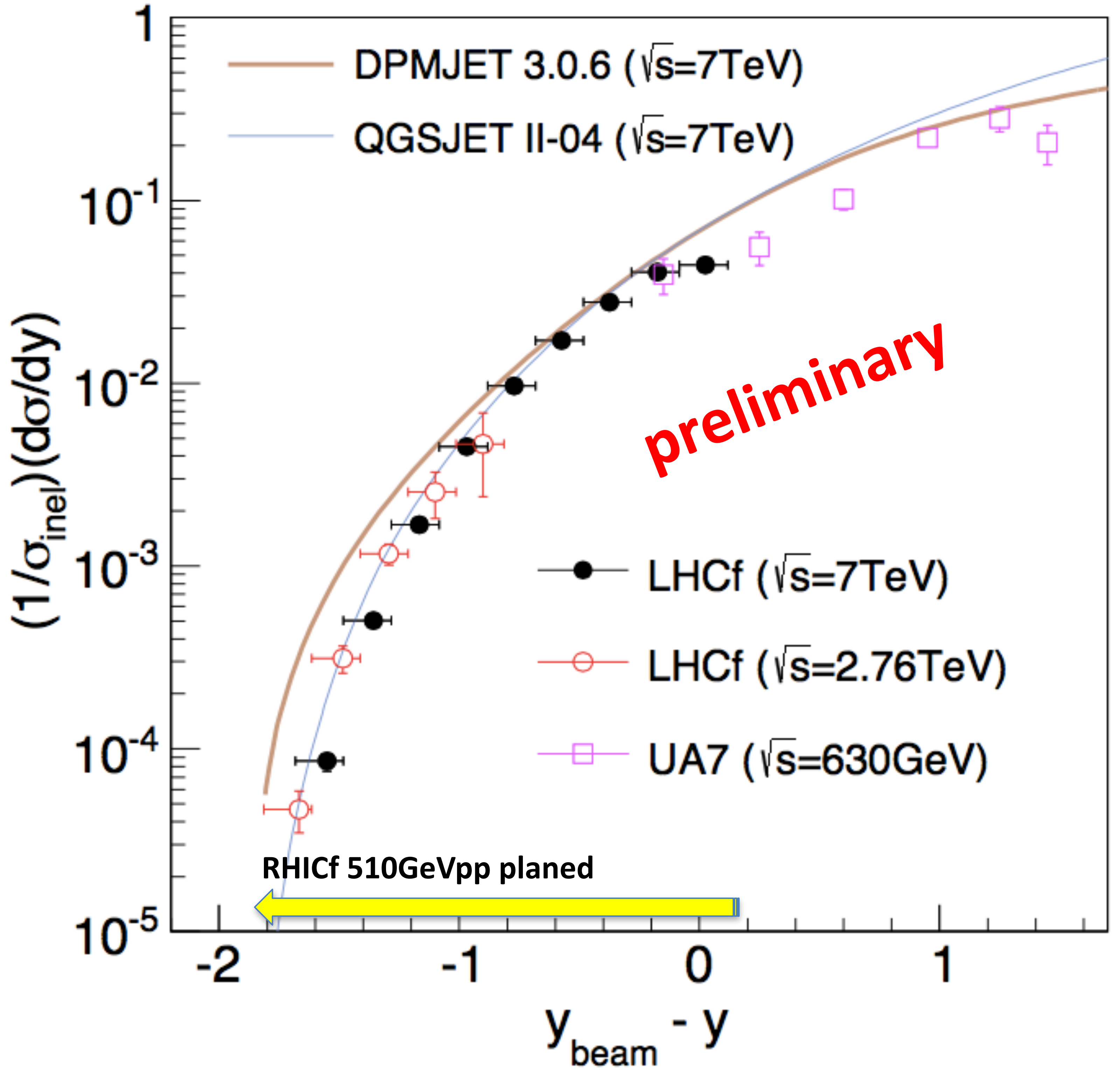



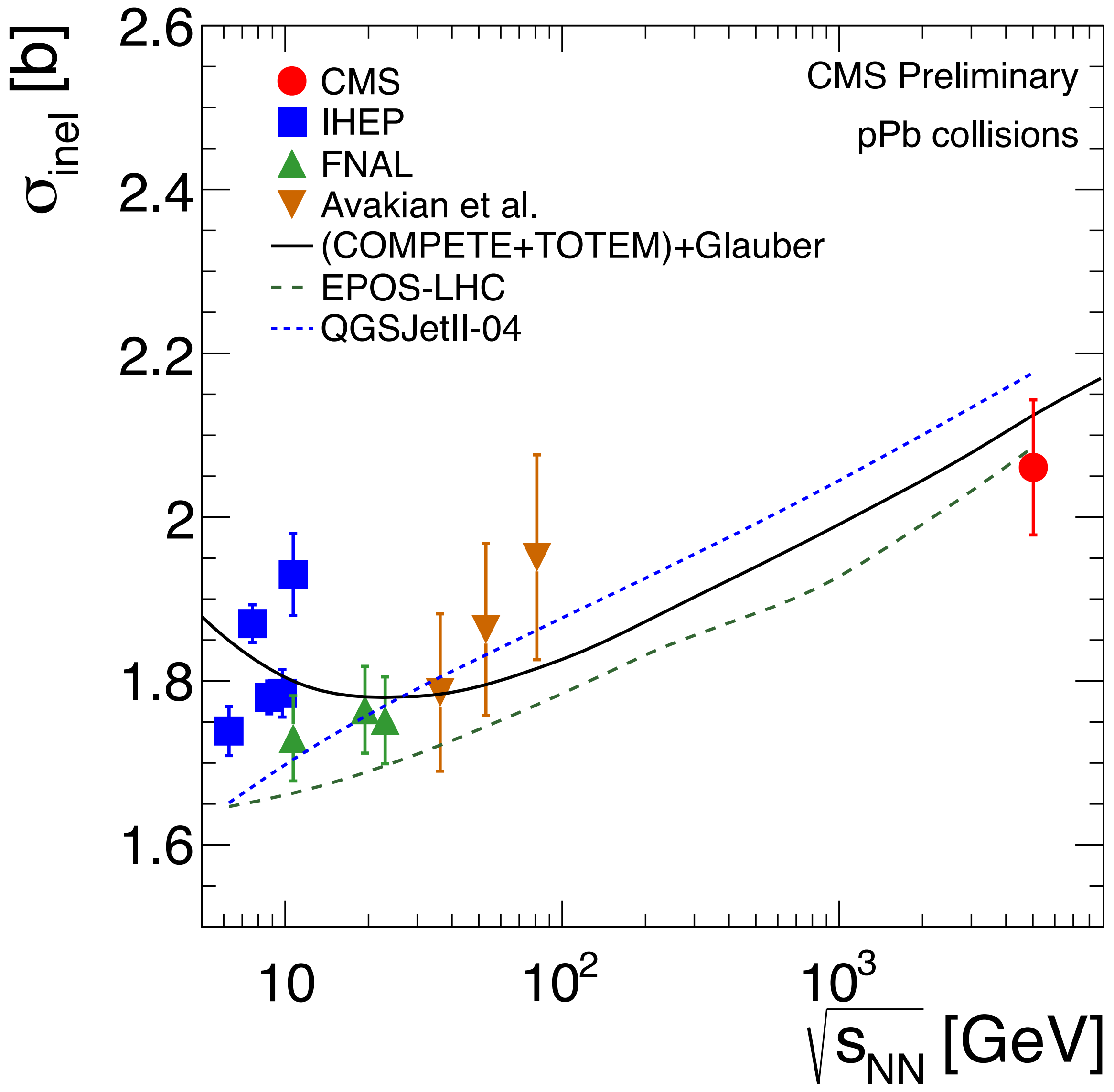
# Multitude of new LHC measurements




*(CMS, JHEP04, 2013)*

*(LHCf, ICRC 2015)*



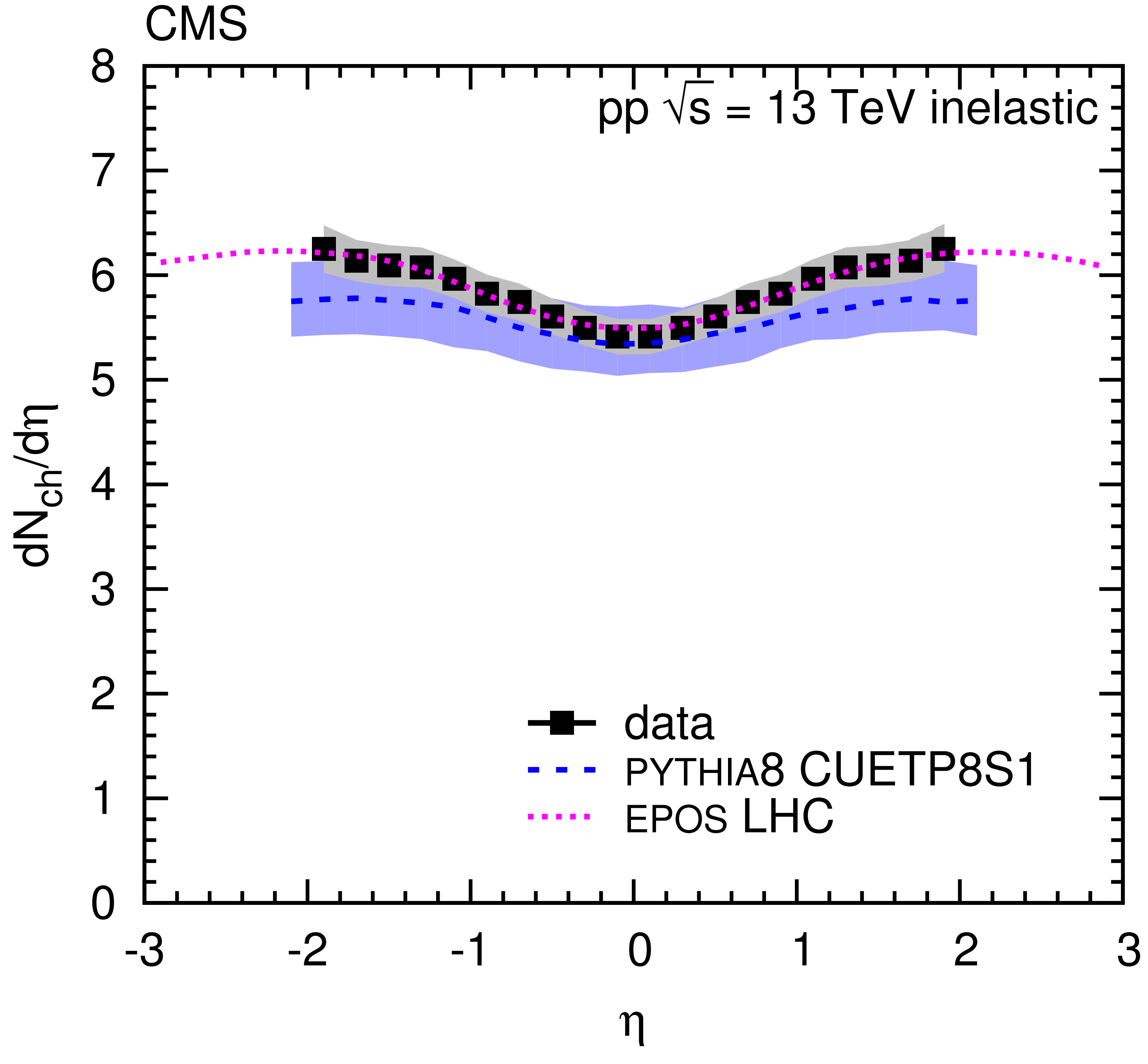




*(CMS, Baus ICRC 2015)*

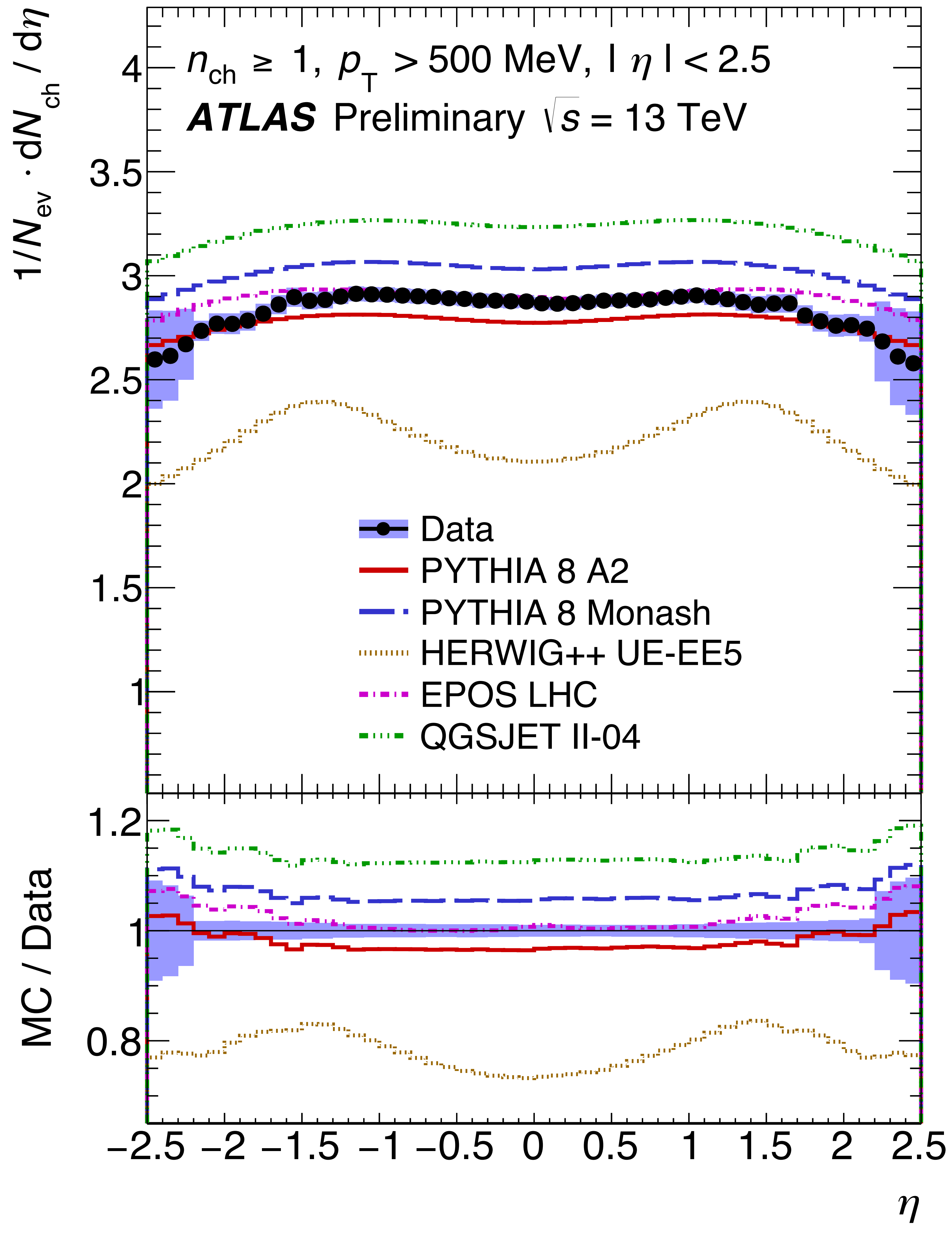
Increasing number of articles with direct comparison with cosmic ray models

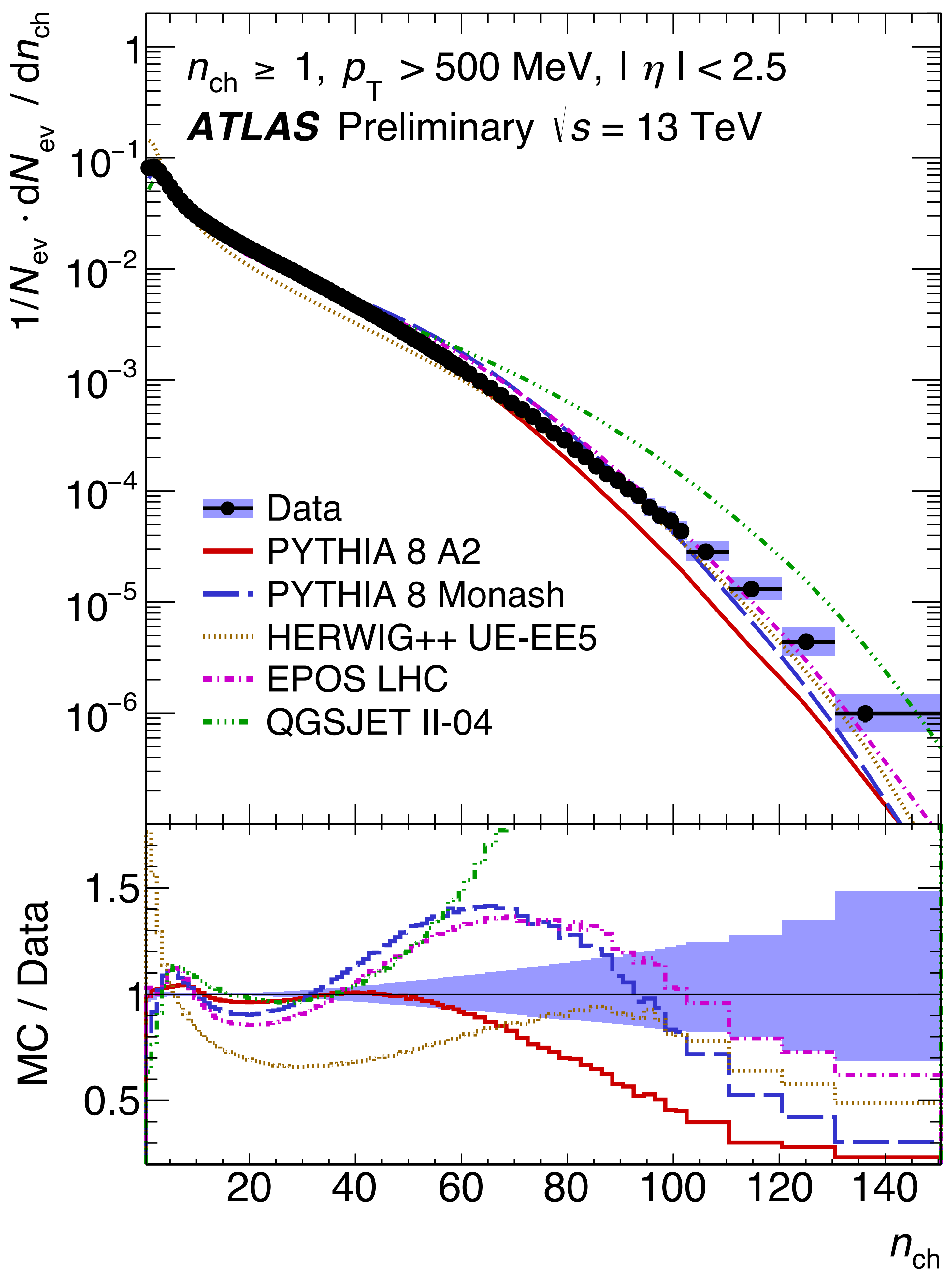
# First LHC data at 13 TeV c.m. energy

(CMS, 1507.05915)



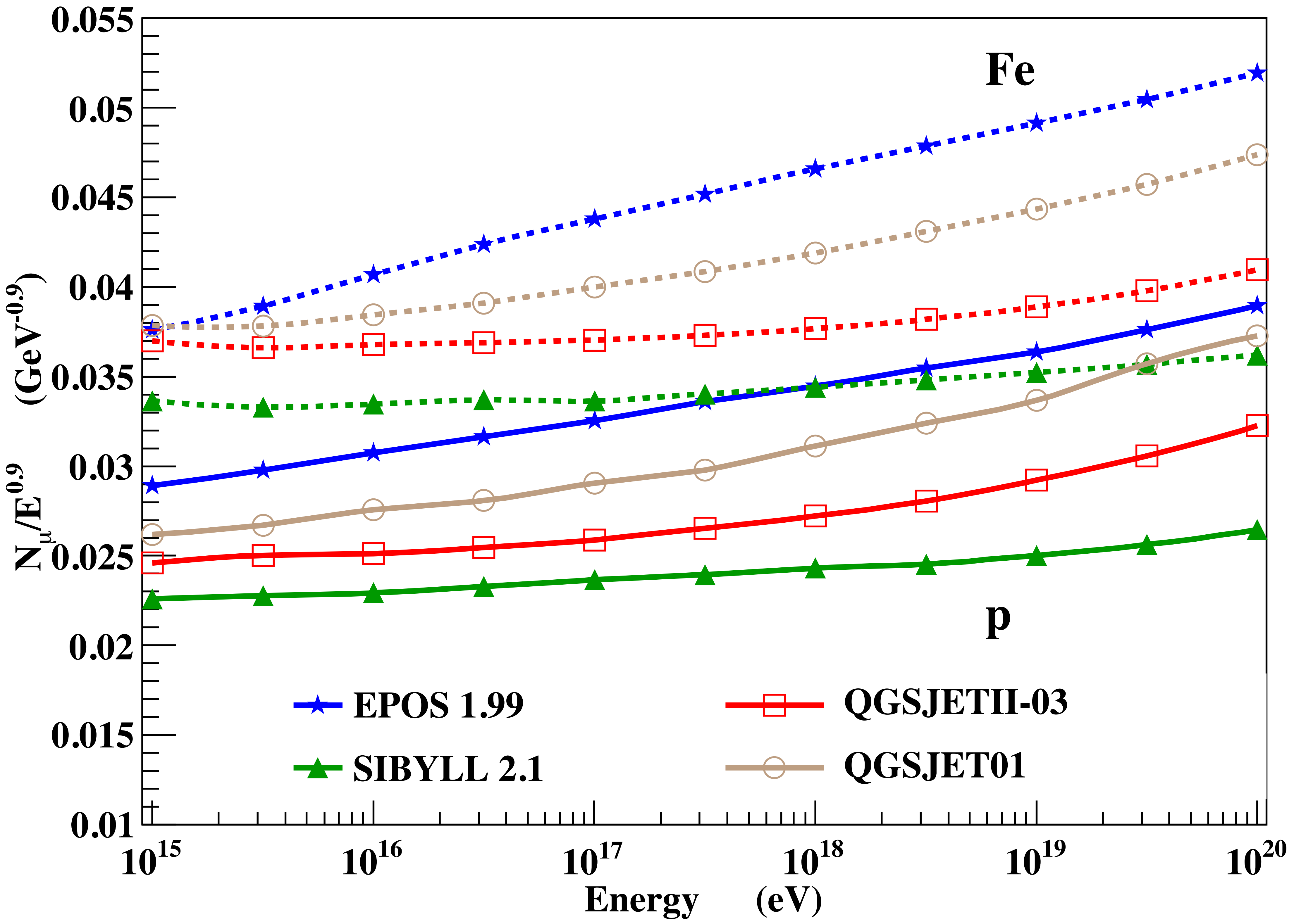

Good agreement with data !



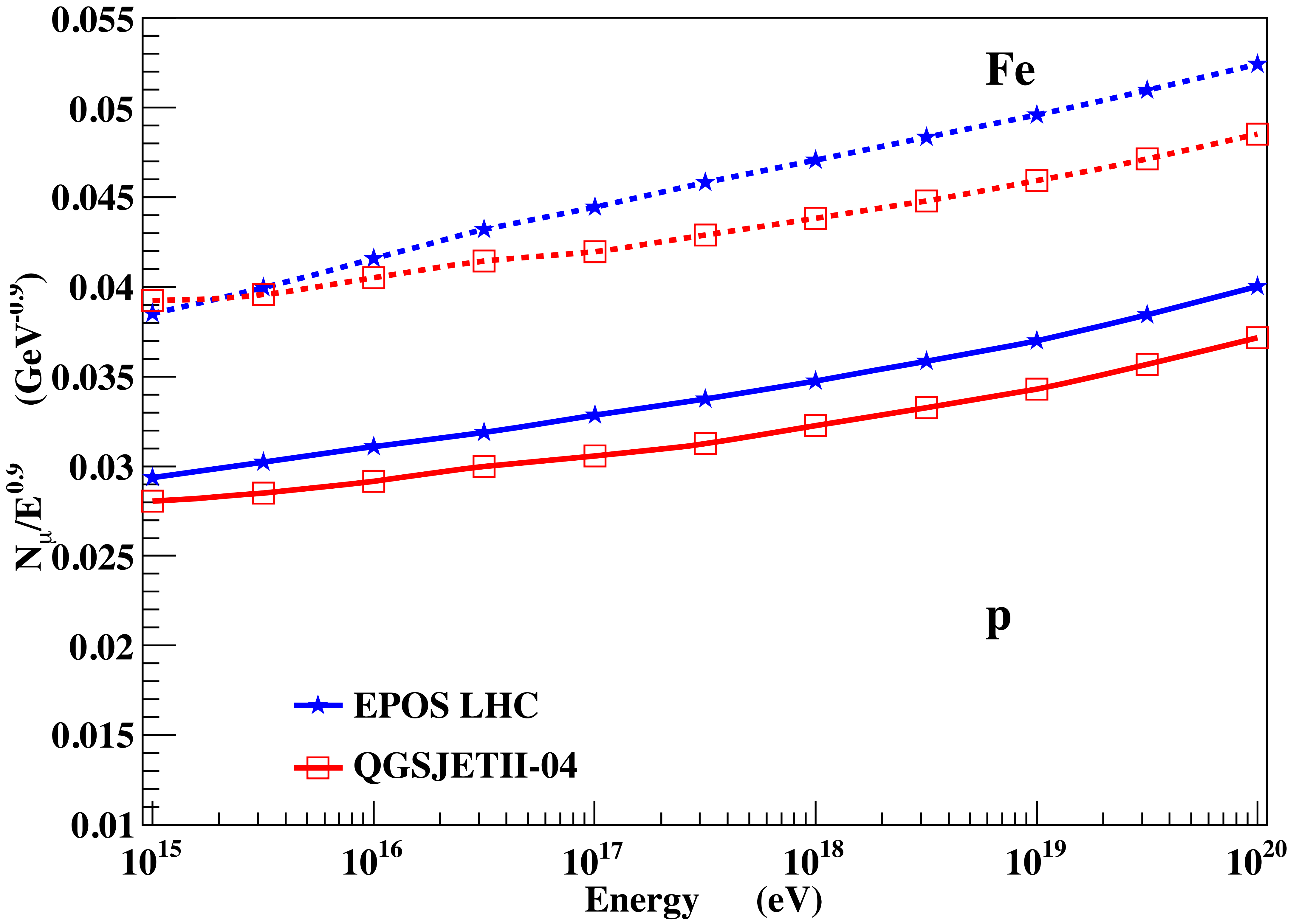

(ATLAS, EPS Geneva 2015)

# Predictions for muon number at ground




pre-LHC models

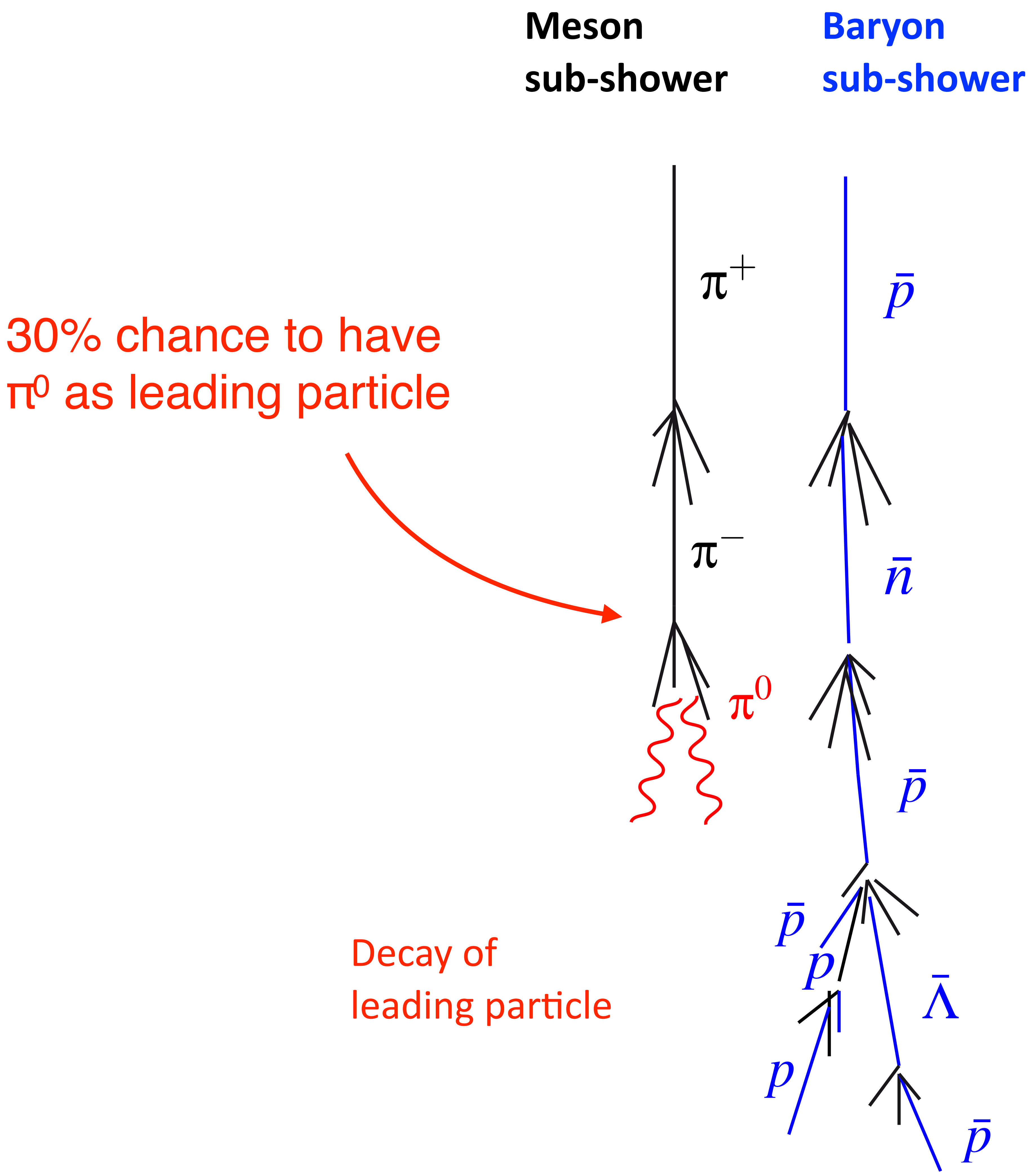
post-LHC models




New models favour interpretation as lighter composition than before

*(Pierog 2013, 2014)*

# Change of energy transferred to electromagnetic component




**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)*

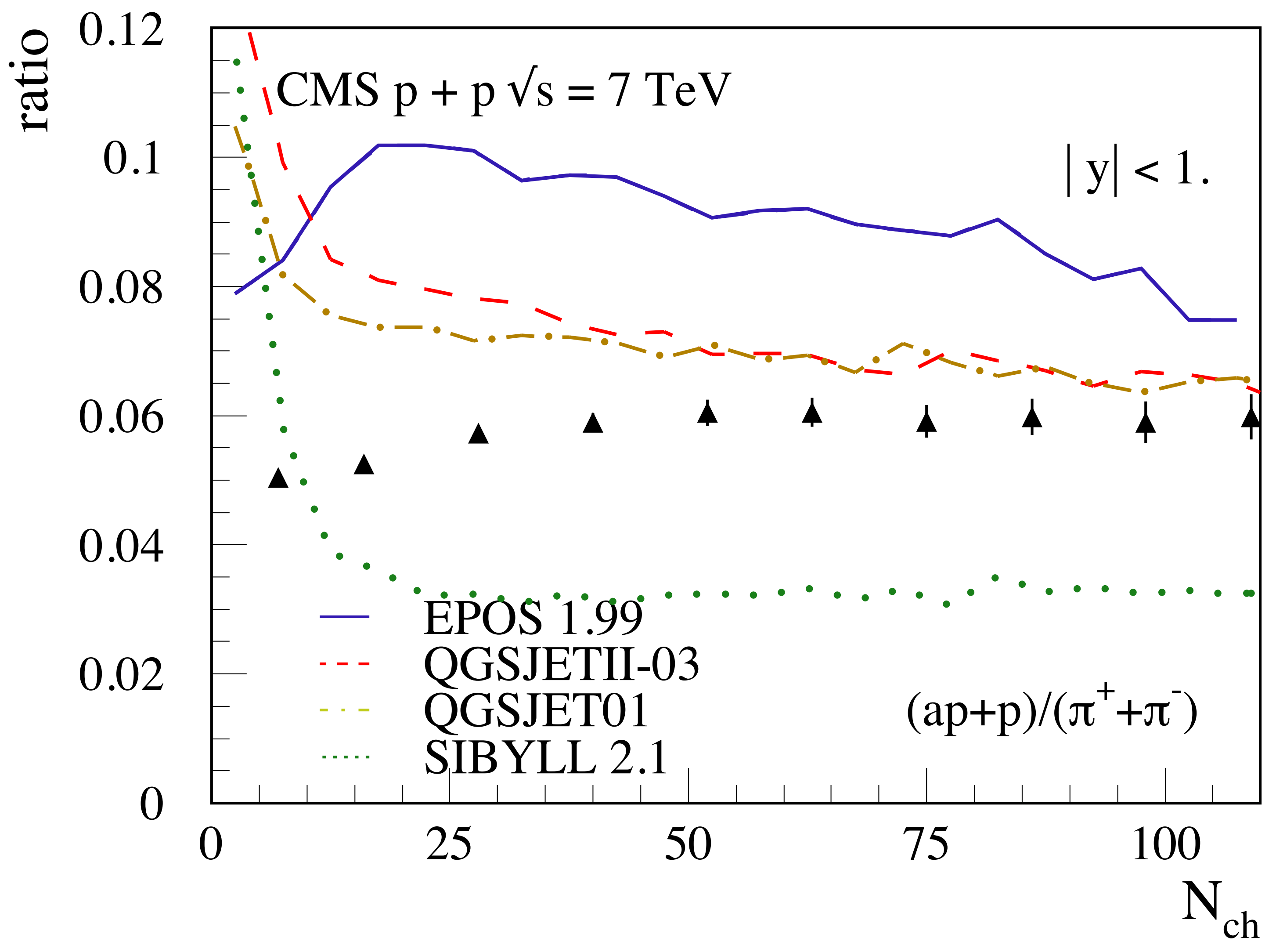
**2 Leading particle effect for pions** *(Drescher 2007, Ostapchenko )*

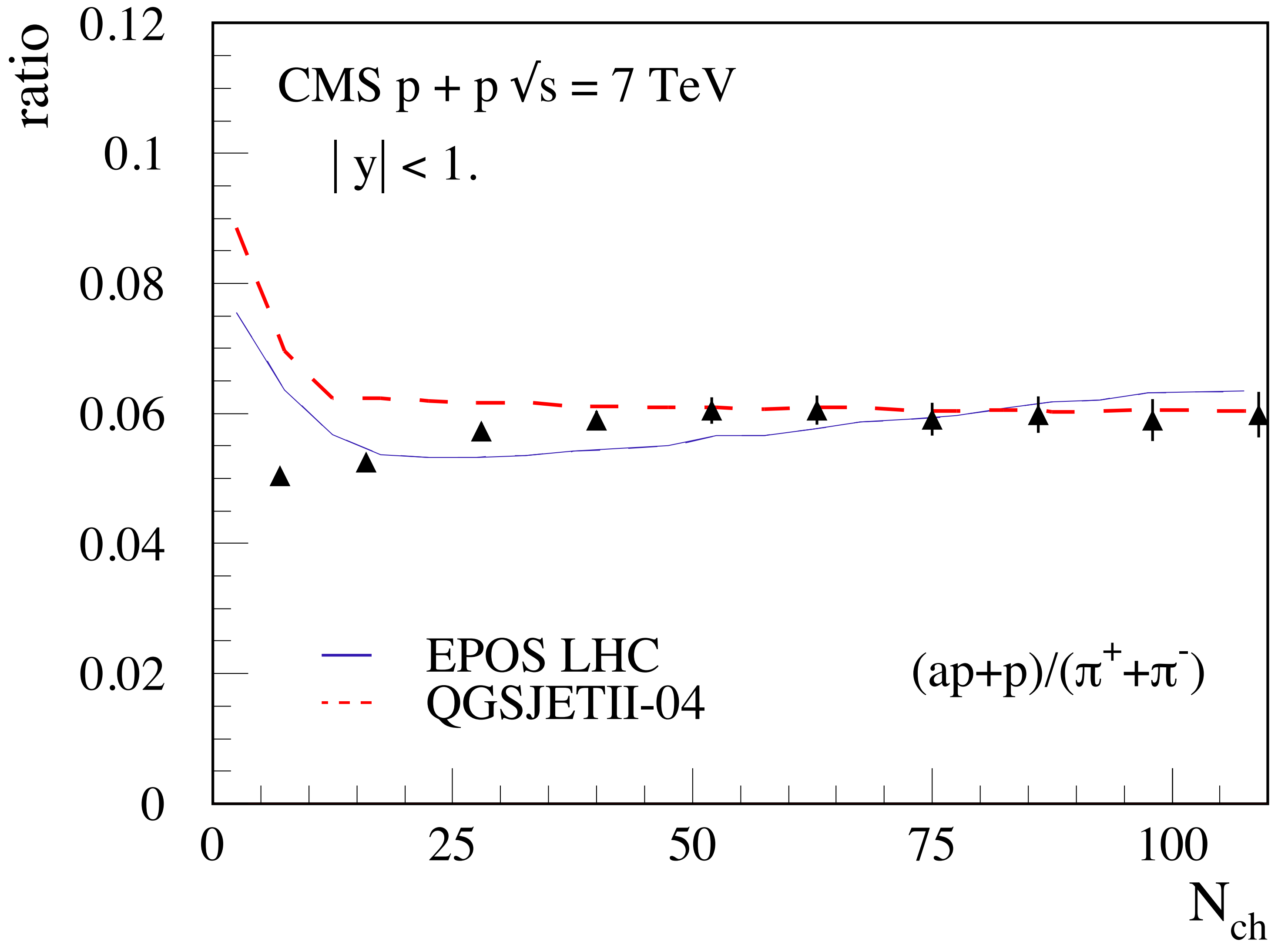
- Leading particle for a $\pi$ could be $\rho^0$ and not $\pi^0$
- Decay of $\rho^0$ to 100% into two charged pions

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

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

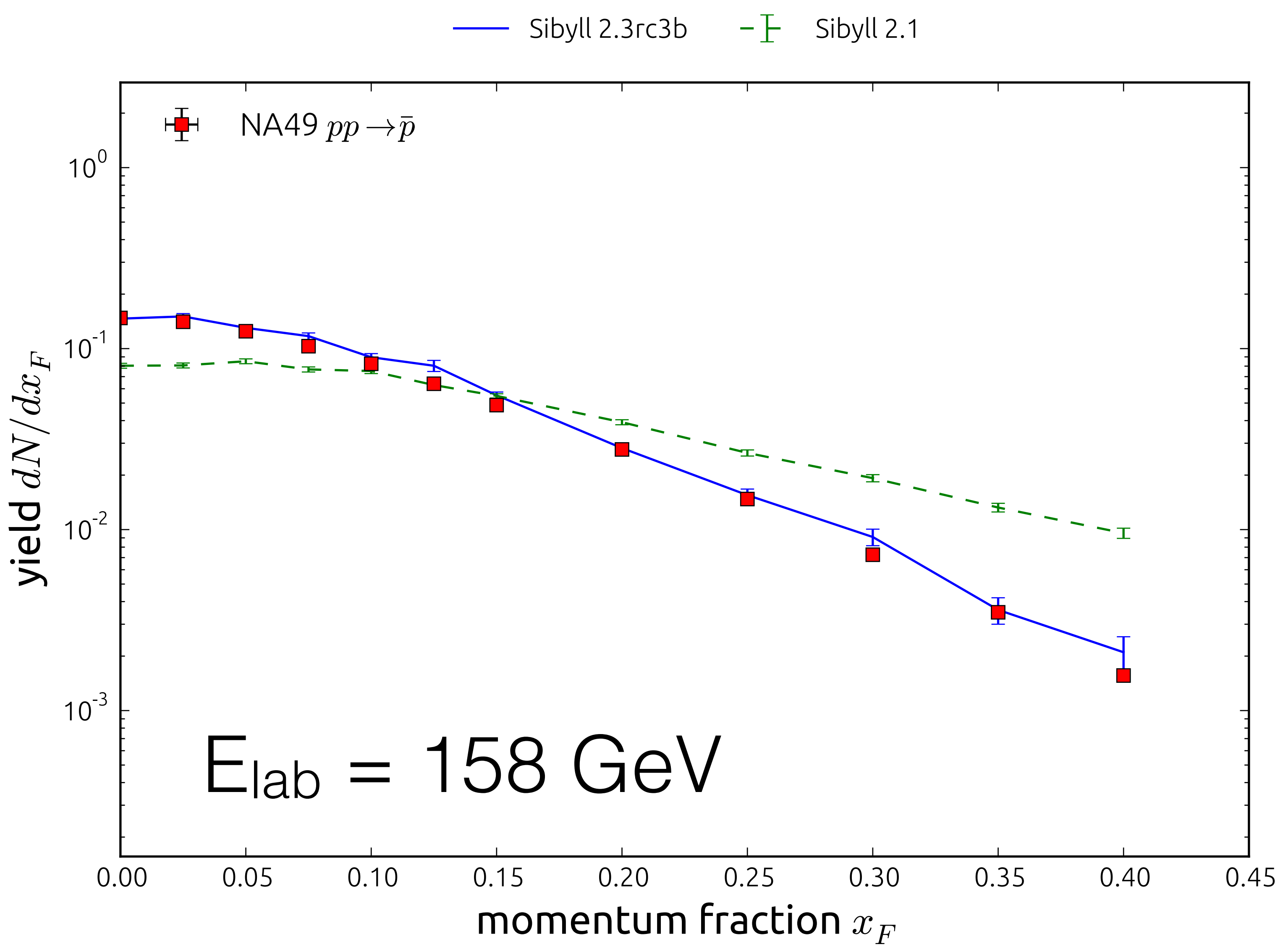
# Tuning of baryon-antibaryon production

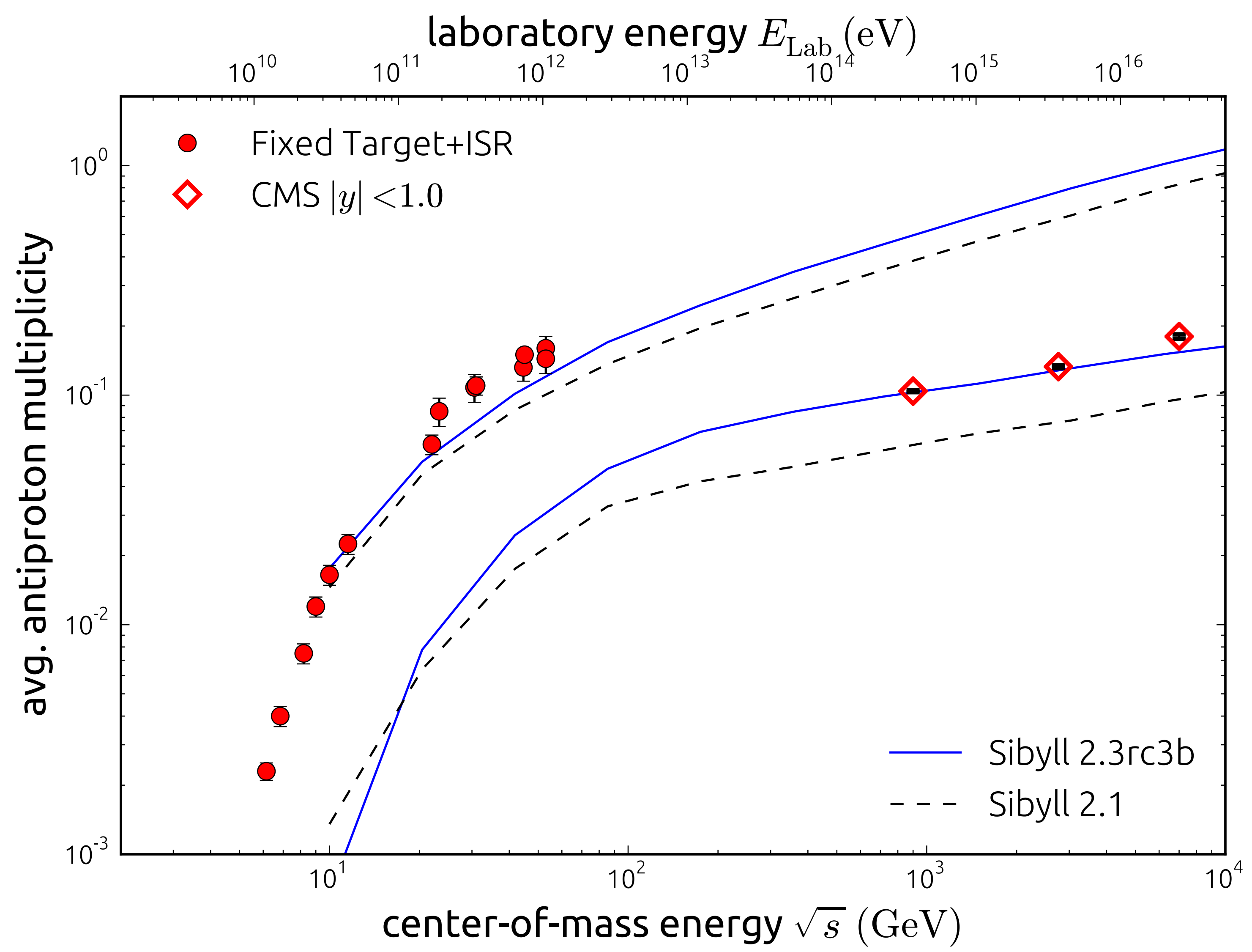



(Pierog 2013)

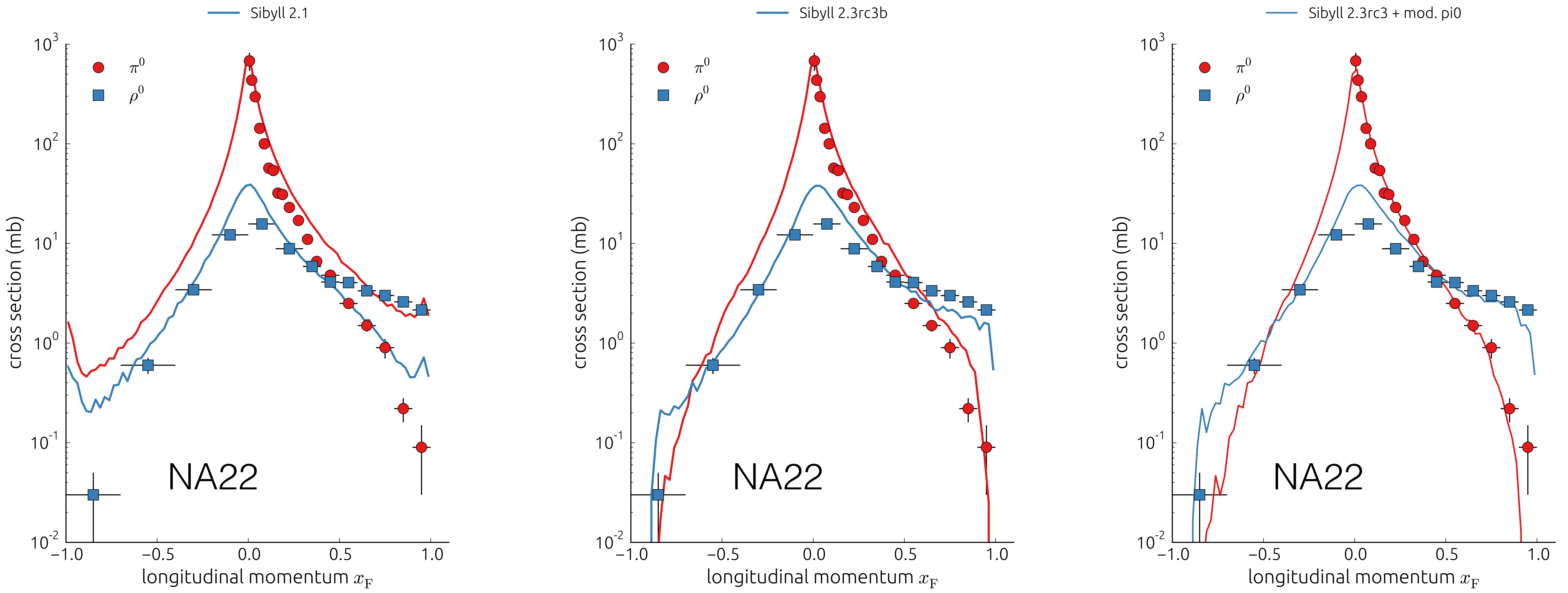
Sibyll 2.3 (release candidate)




(Riehn 2015)

# How important is forward $\pi^0$ and $\rho^0$ production ?




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

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

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

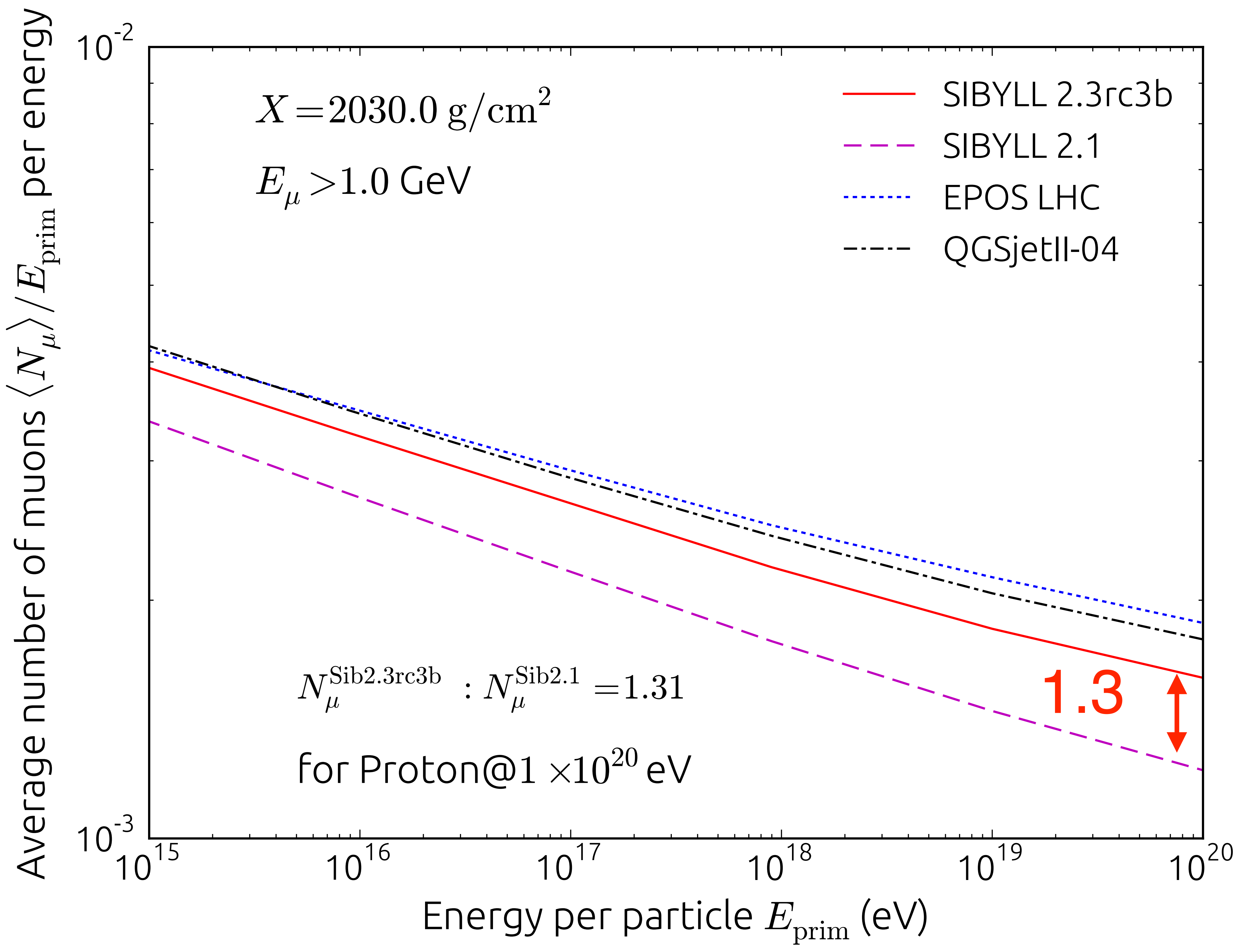
$$E_{lab} = 250\,\mathrm{GeV}$$

Sibyll 2.3
(release candidate)

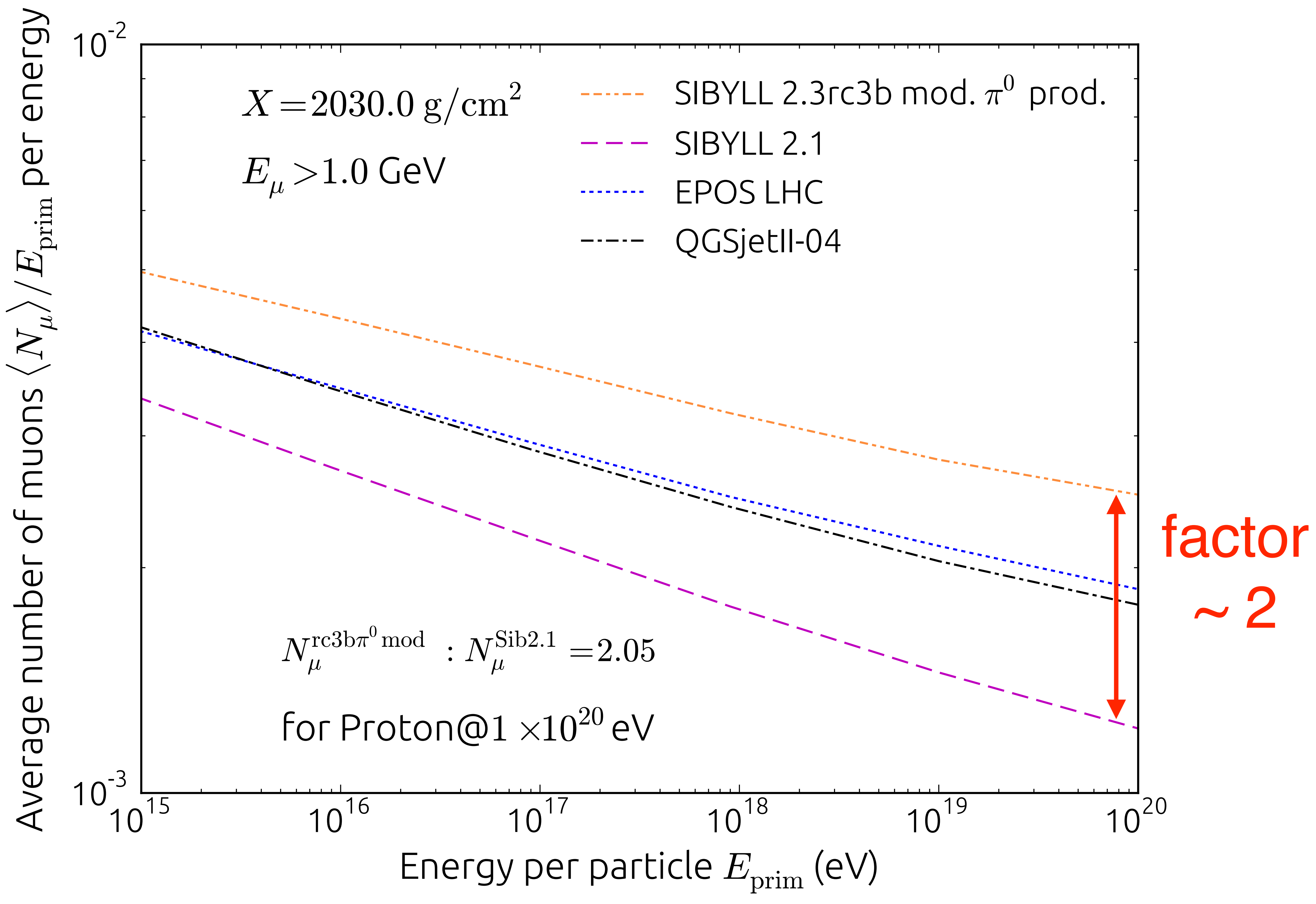
Sibyll 2.3
(mod. $\pi^0$)

*(Riehn 2015)*

# How important is forward π⁰ and ρ⁰ production ?




Sibyll 2.3 (release candidate)

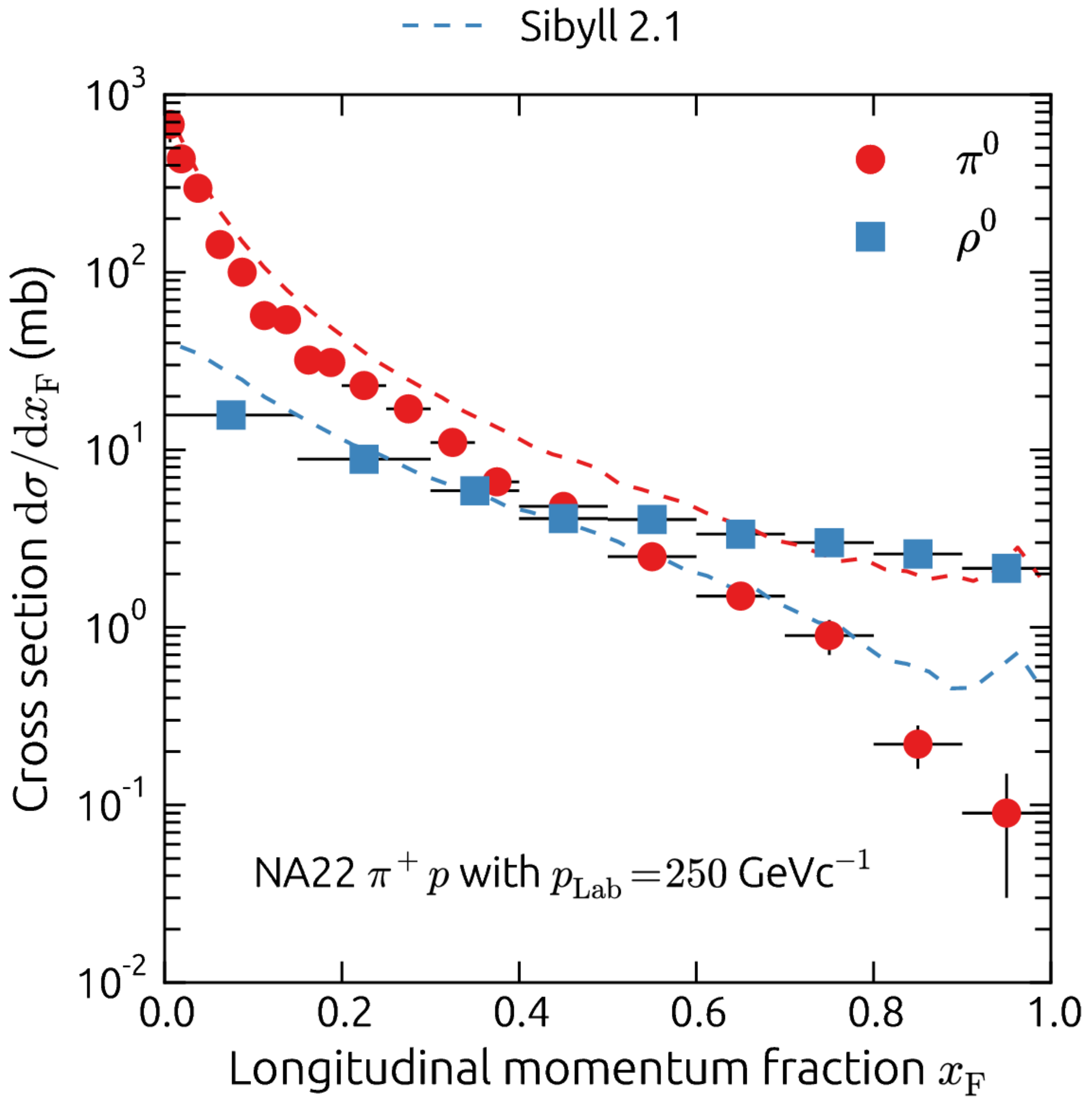



Sibyll 2.3 (mod. $\pi^0$)

*Note: change in Xmax due to enhanced $\rho^0$ production very small (negligible)*

*(Riehn 2015)*

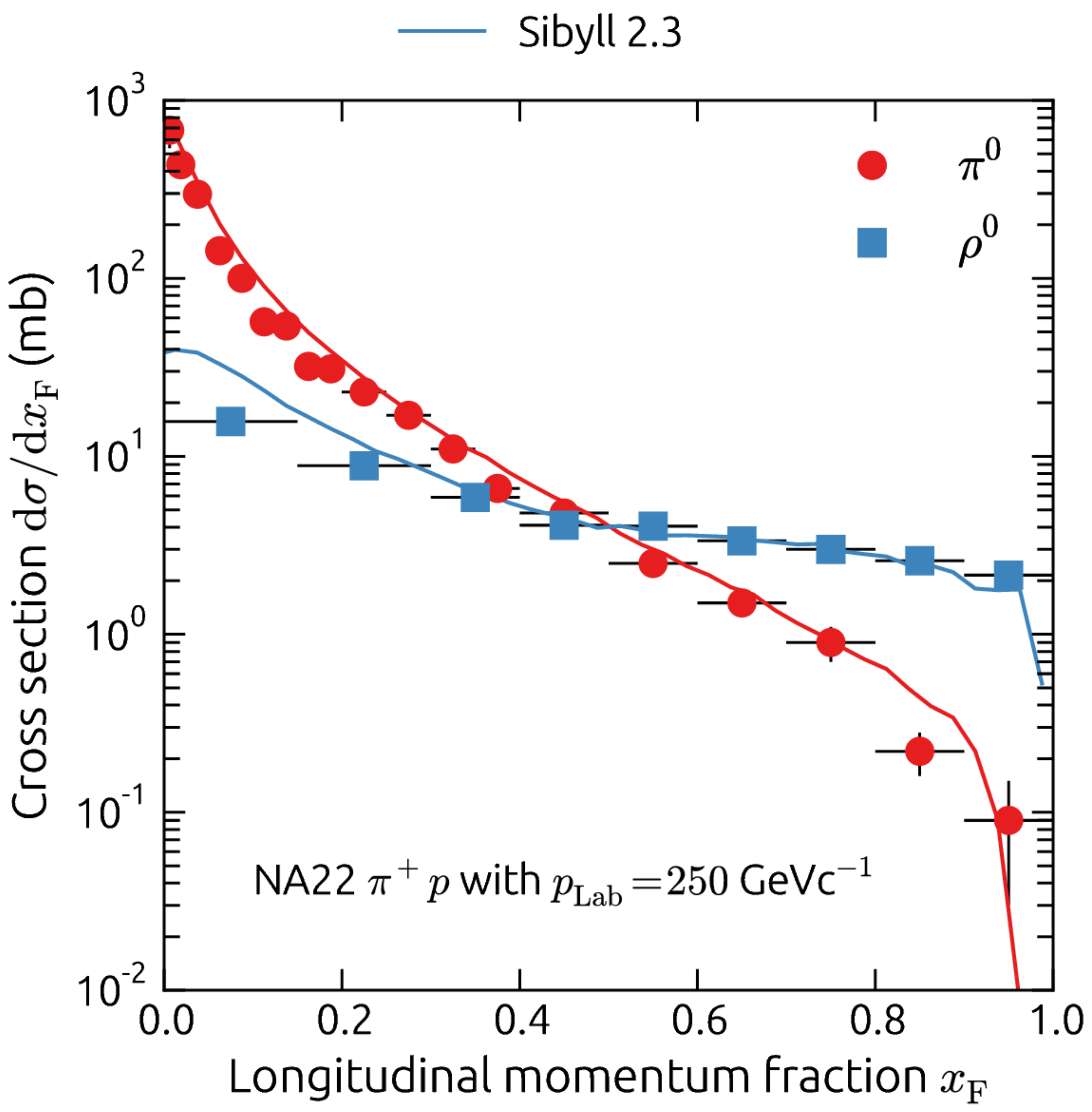
# Rho production in π-p interactions (Sibyll 2.1 → Sibyll 2.3)



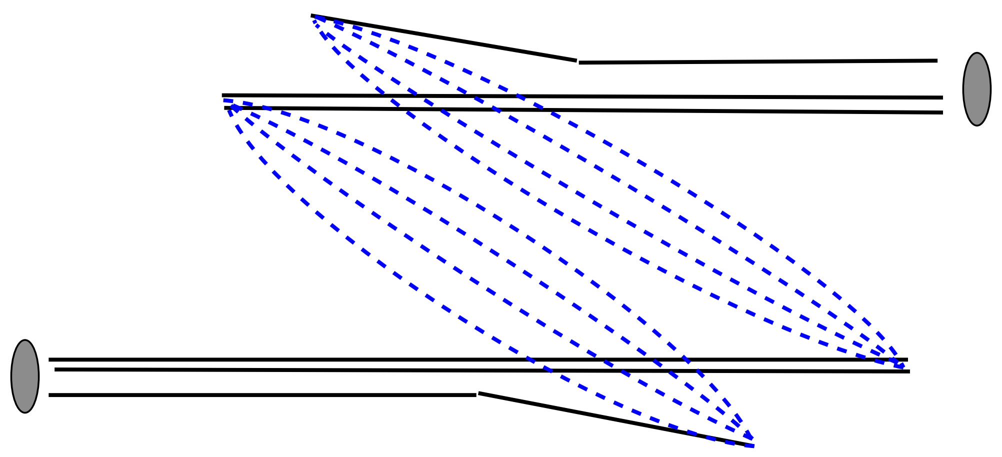

$$\pi^+ p \rightarrow \pi^0 \rightarrow 2\gamma$$

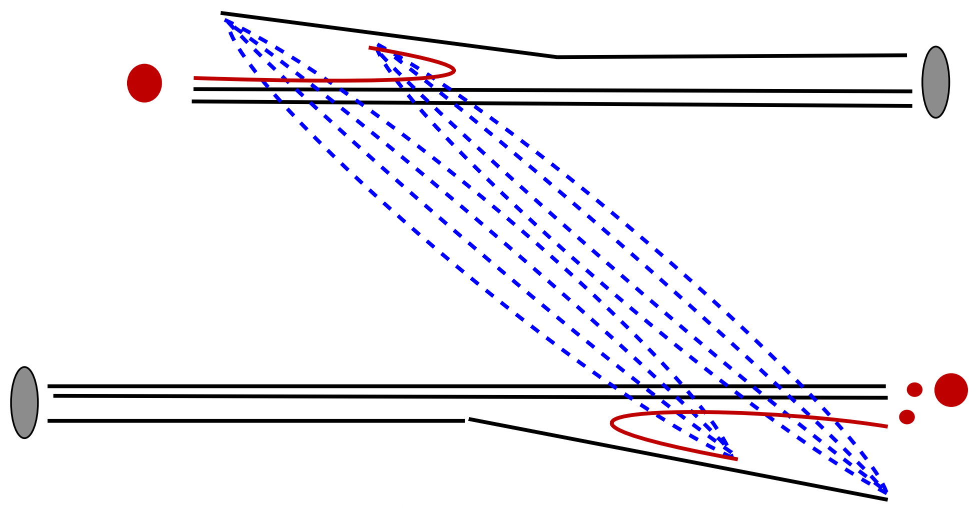
$$\pi^+ p \rightarrow \rho^0 \rightarrow \pi^+ \pi^-$$

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




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





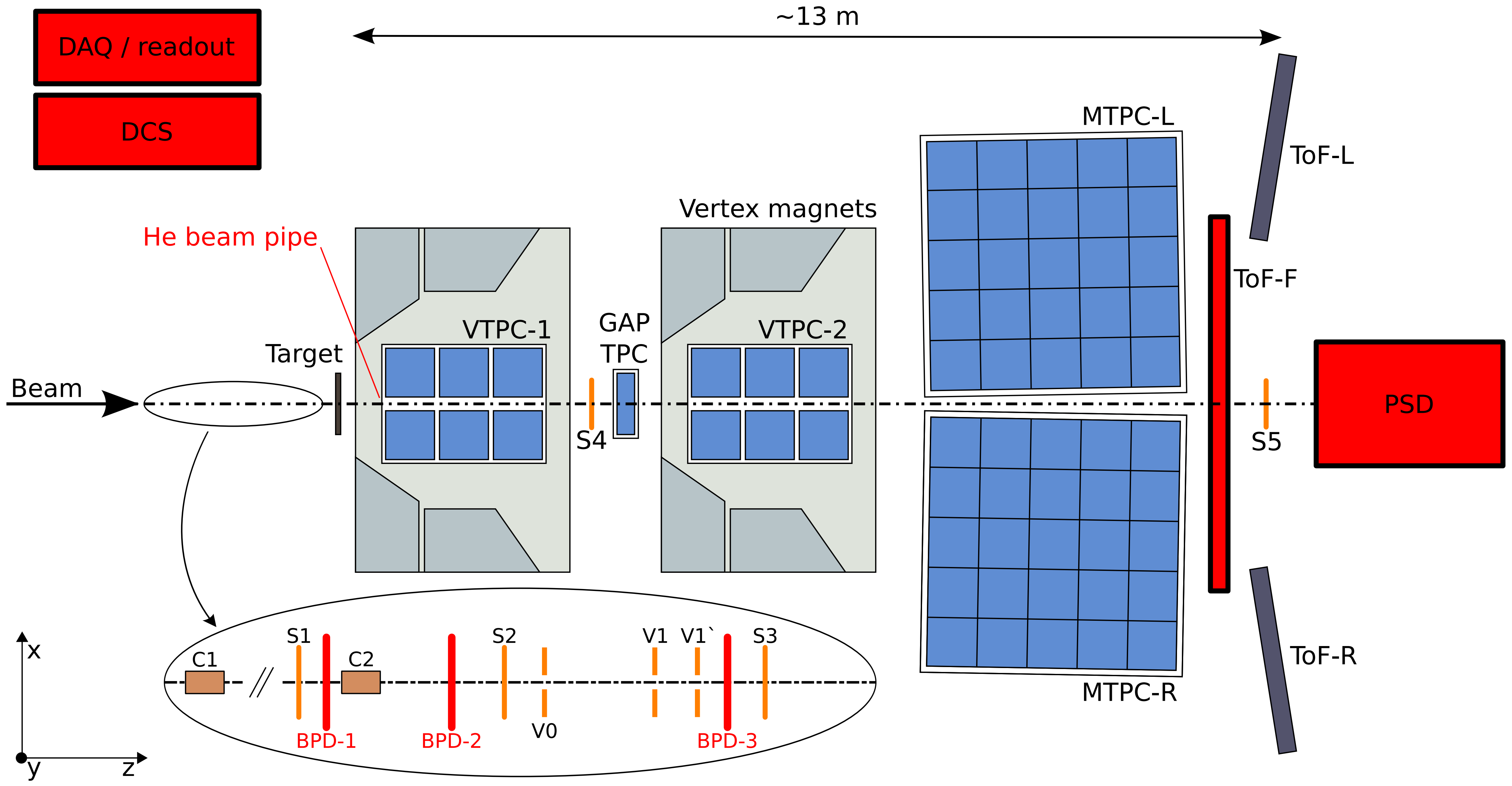
$$R_{\rho^0}/R_{\pi^0} = 0.3$$

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

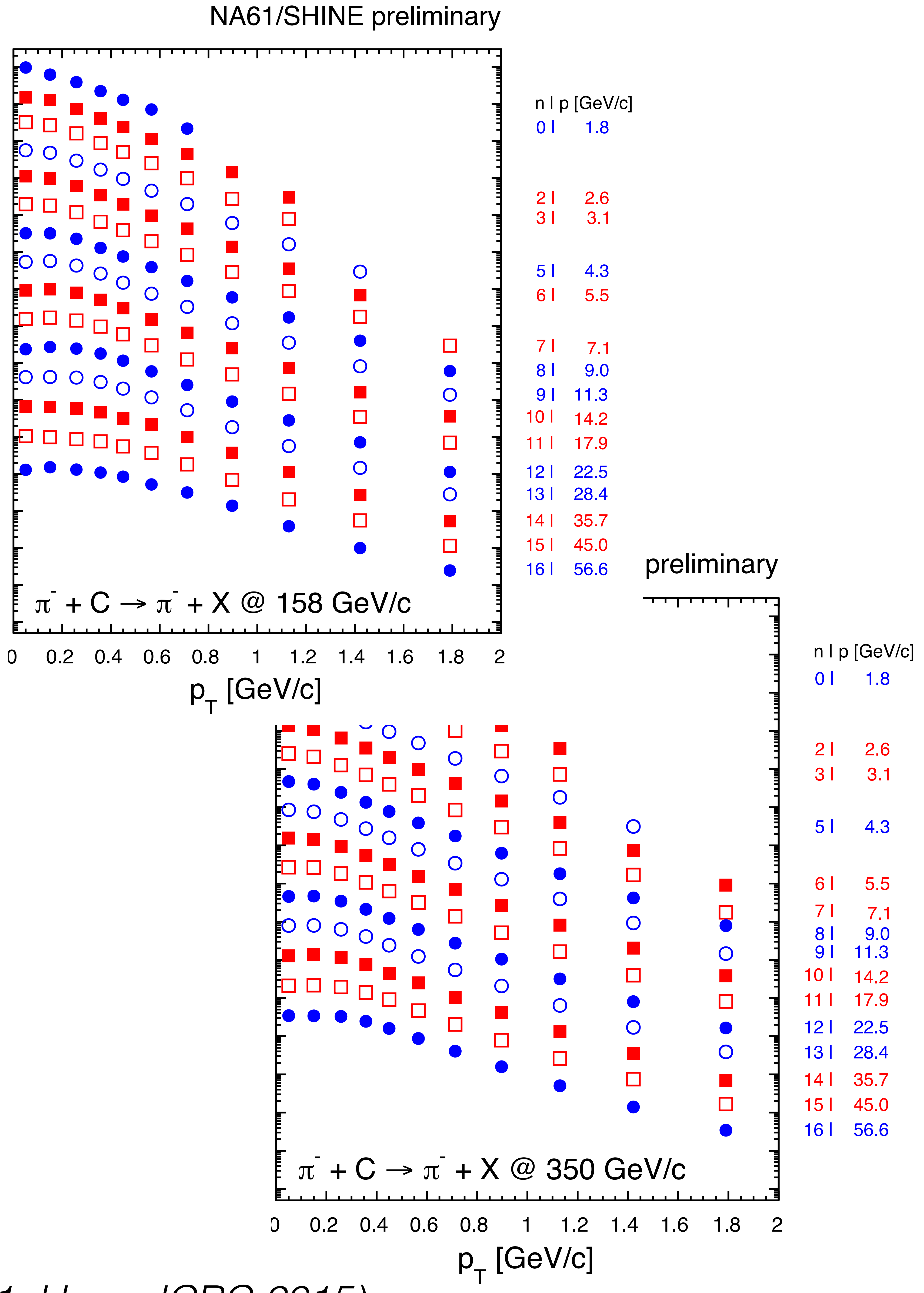
*(Riehn et al., ICRC 2015)*

# NA61 experiment at CERN SPS

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



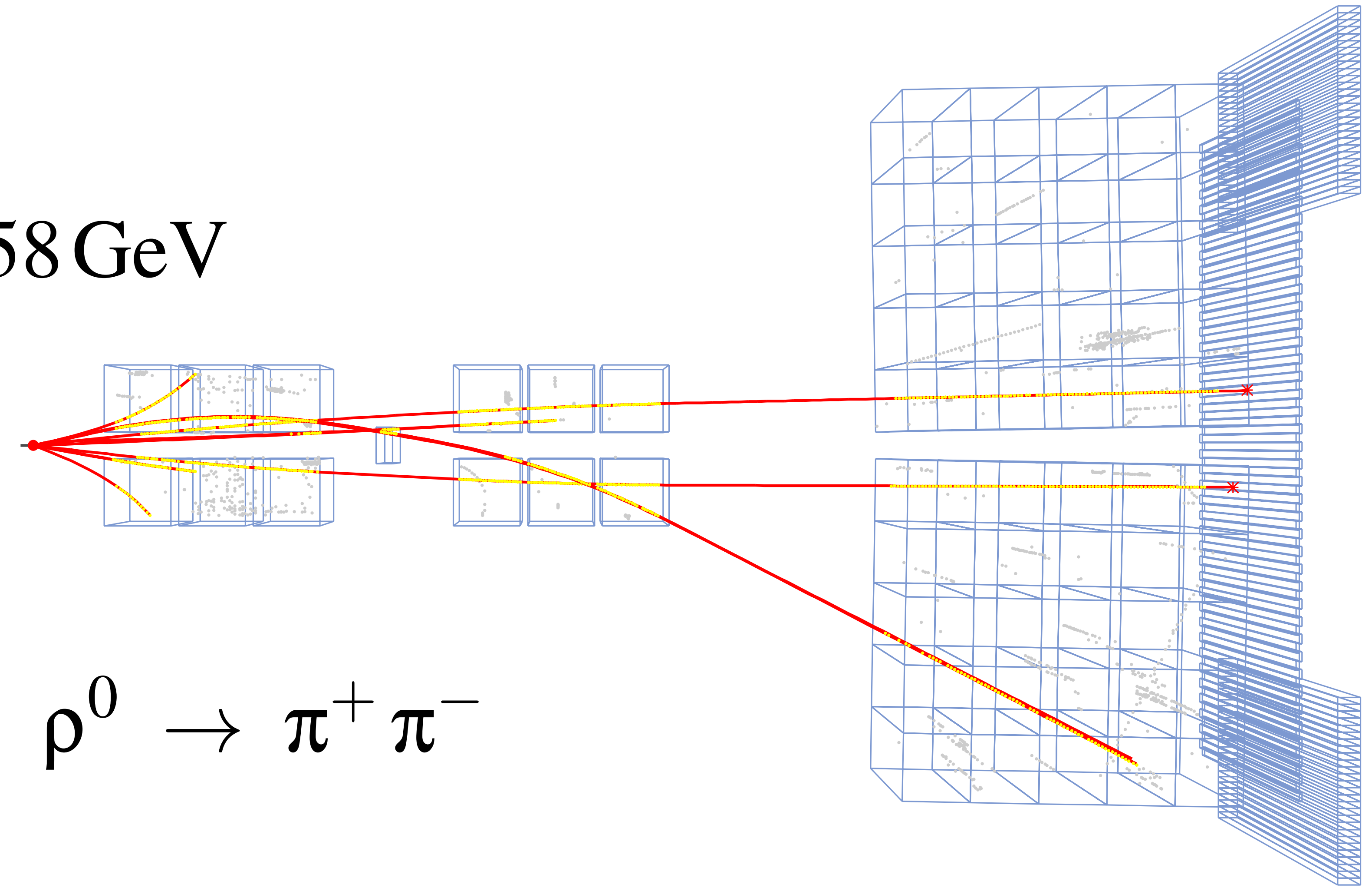

(former NA49 detector, extended)




(NA61, Herve ICRC 2015)

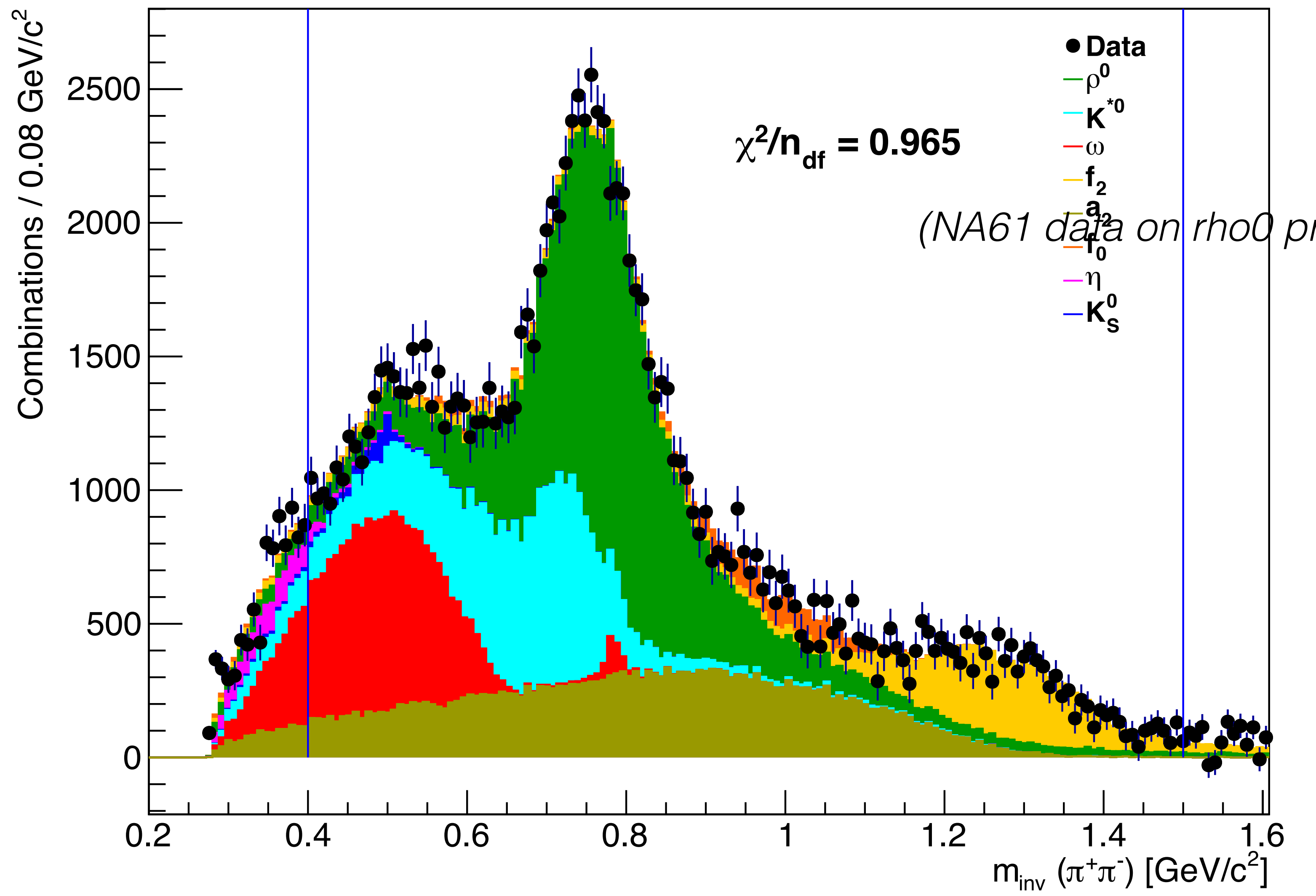
# New results from NA61: ρ⁰ production

$E_{\text{lab}} = 158\,\text{GeV}$

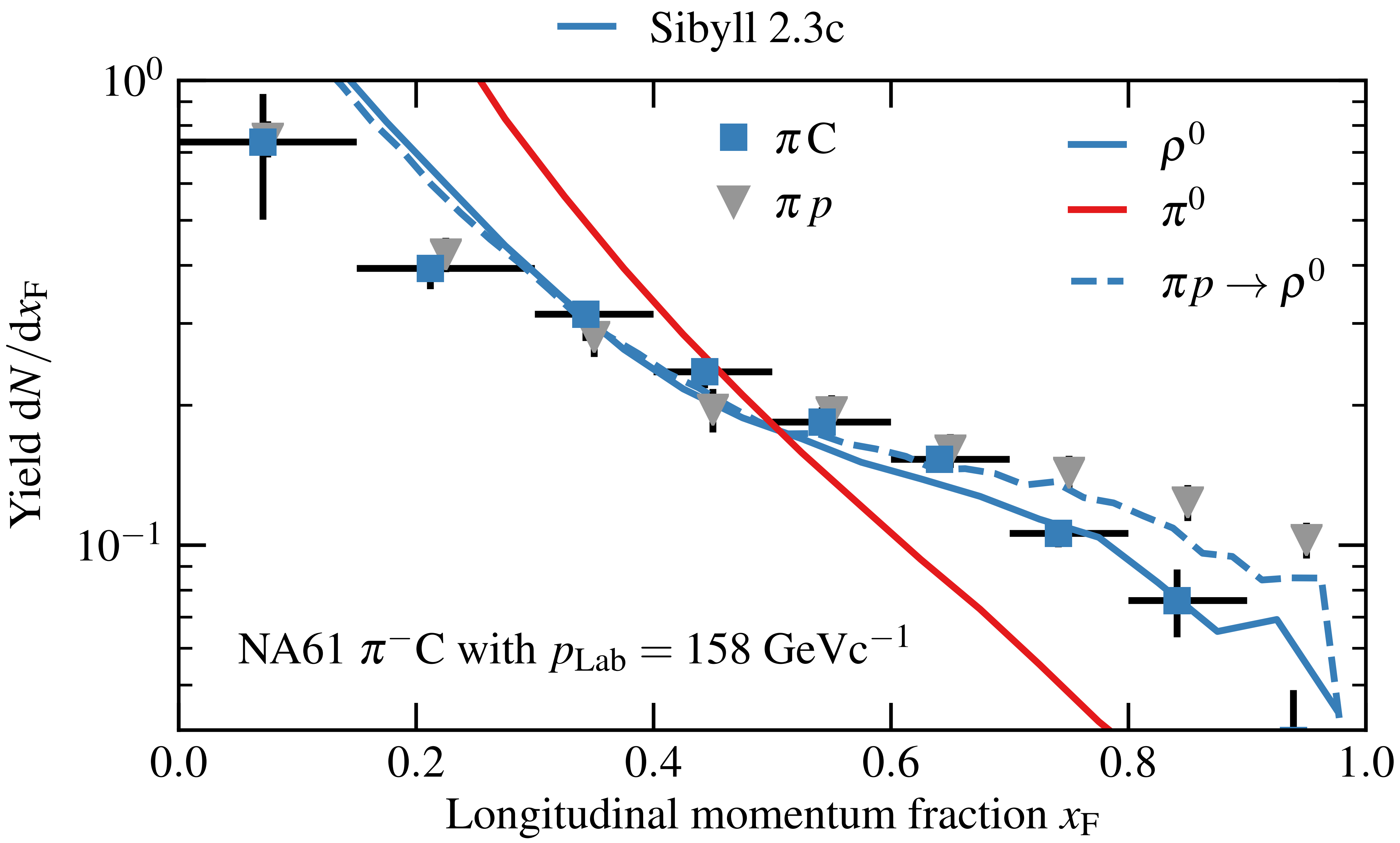


$\pi^- C \rightarrow \rho^0 \rightarrow \pi^+\pi^-$

Invariant mass of two charged tracks

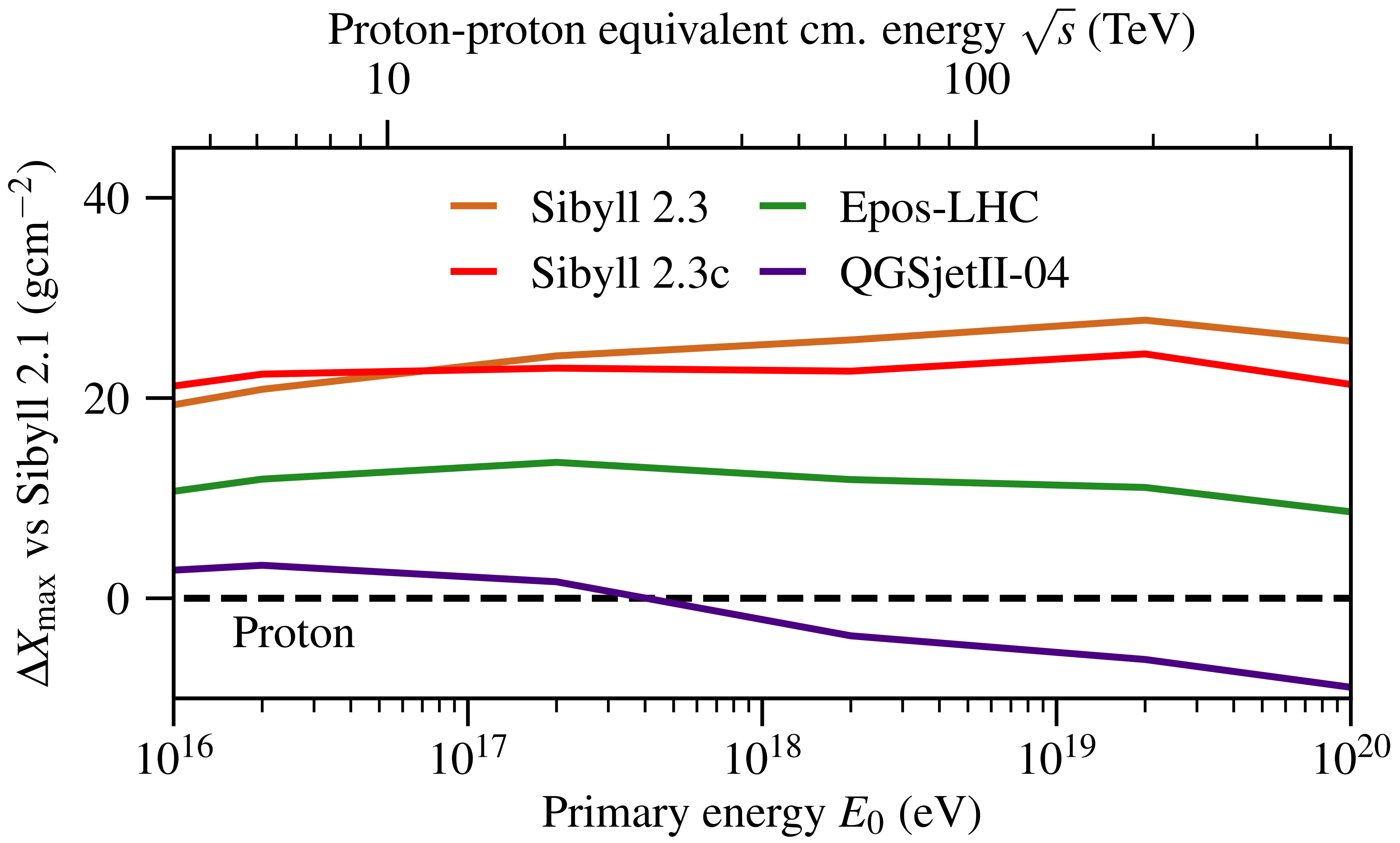



*(NA61 data on rho0 production, previous talk)*



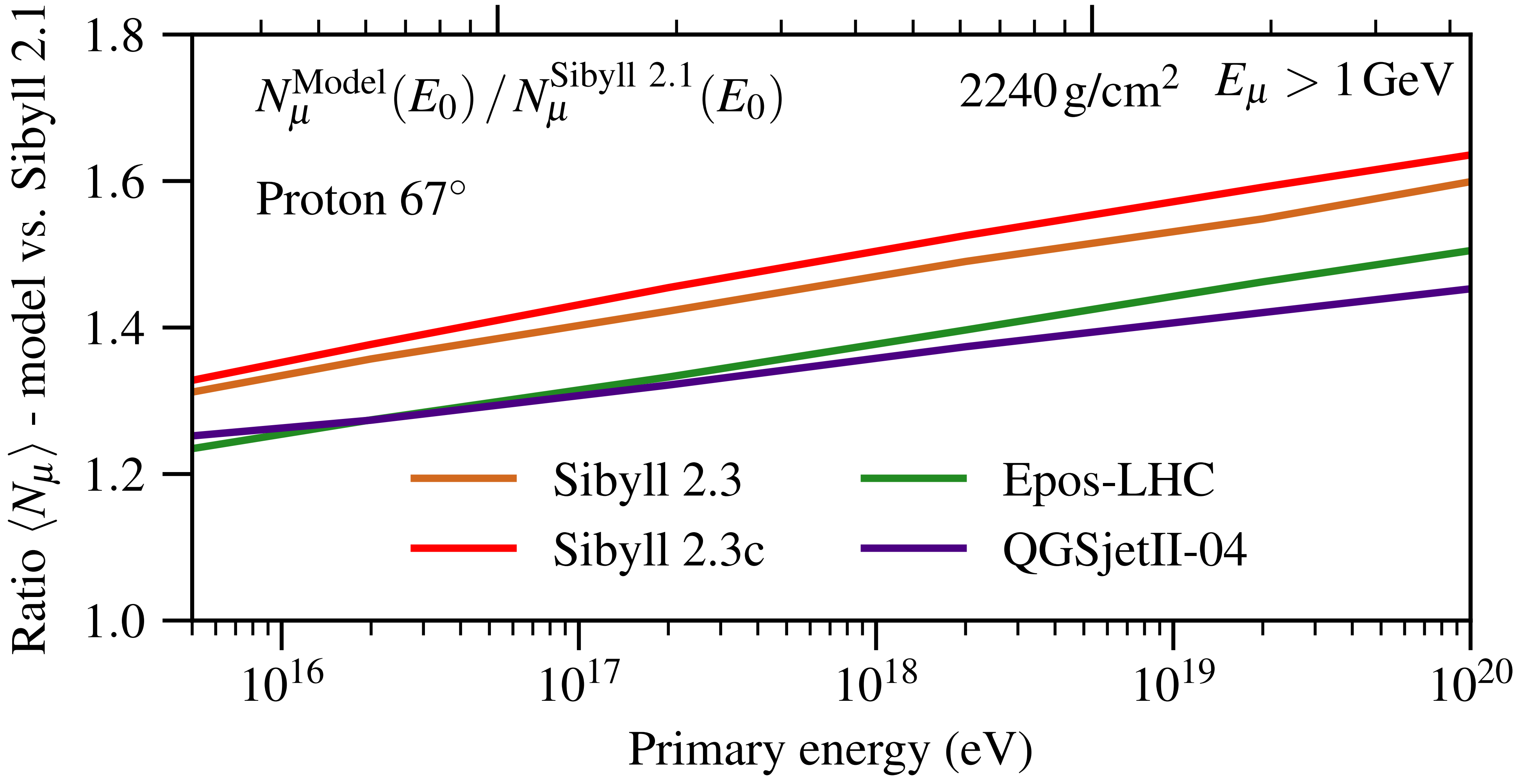

*(NA61, Herve, ICRC 2015)*

# Status of predictions for air showers




Reduction of inelastic cross section (LHC data)

Increase of diffraction dissociation on nuclei (two-channel Good-Walker model)

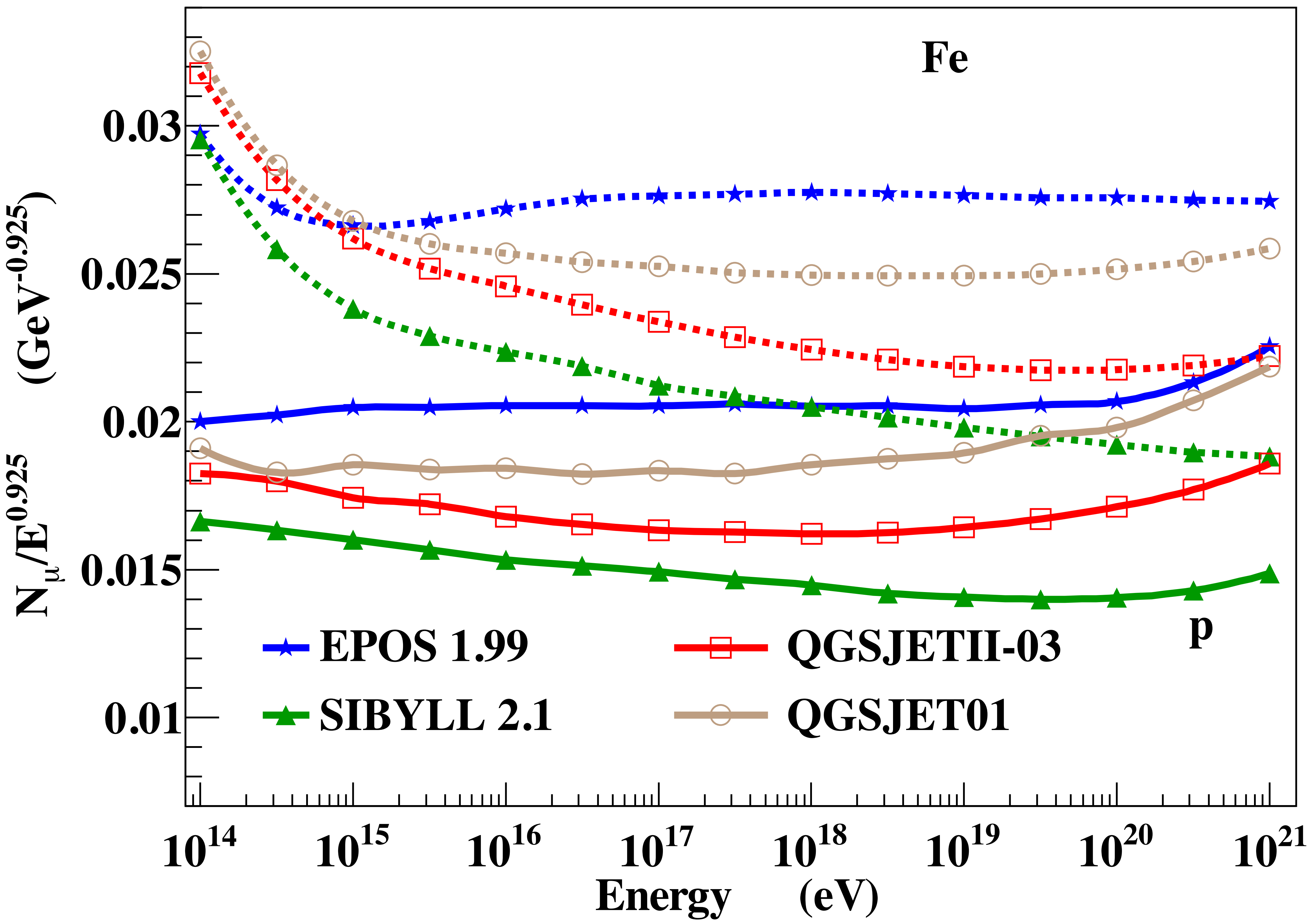



Introduction of forward rho0 production

Increase of baryon-antibaryon pair production

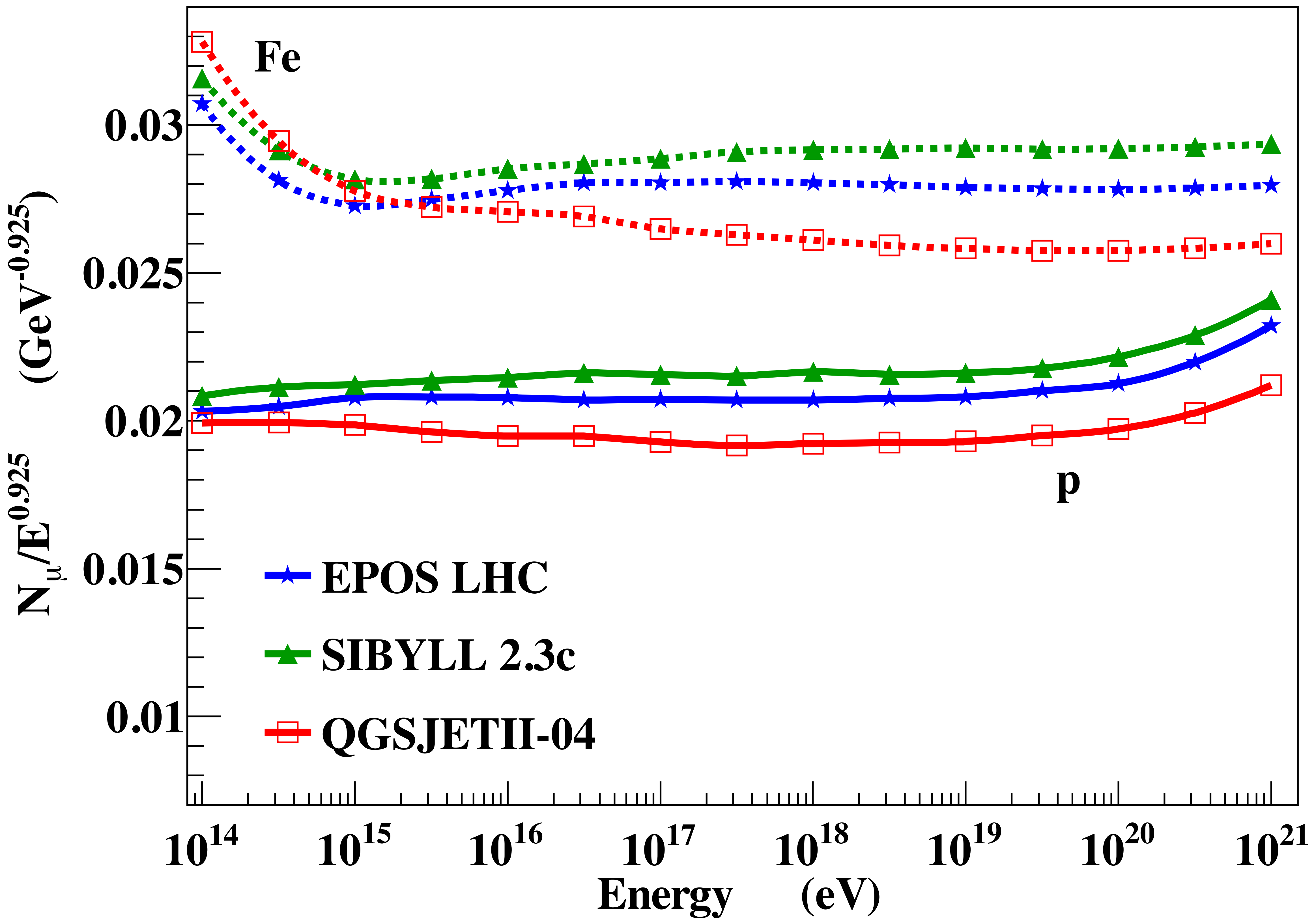
*(See talk by Anatoli Fedynitch on results on atmospheric leptons)*

# Predictions for muon number at ground (updated)




pre-LHC models

post-LHC models

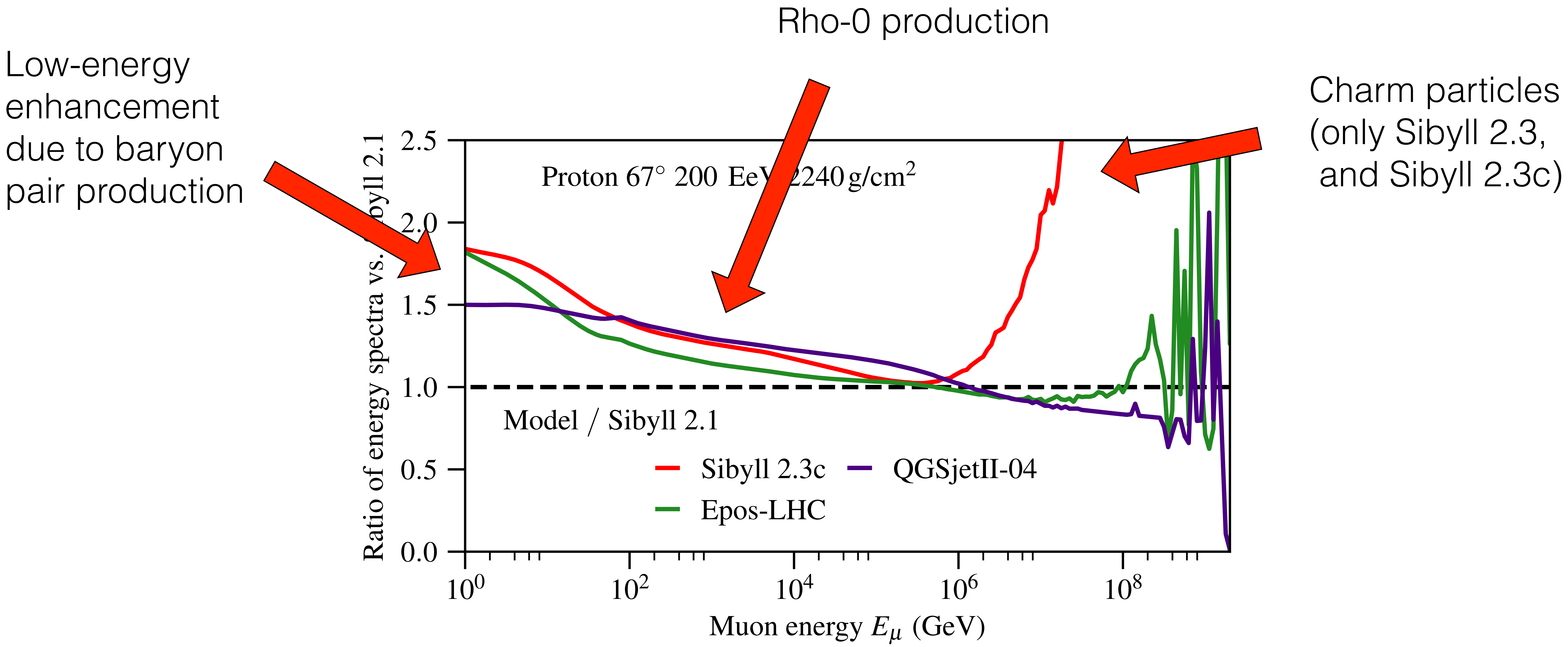



New models favour interpretation as lighter composition than before

*(Pierog 2017)*

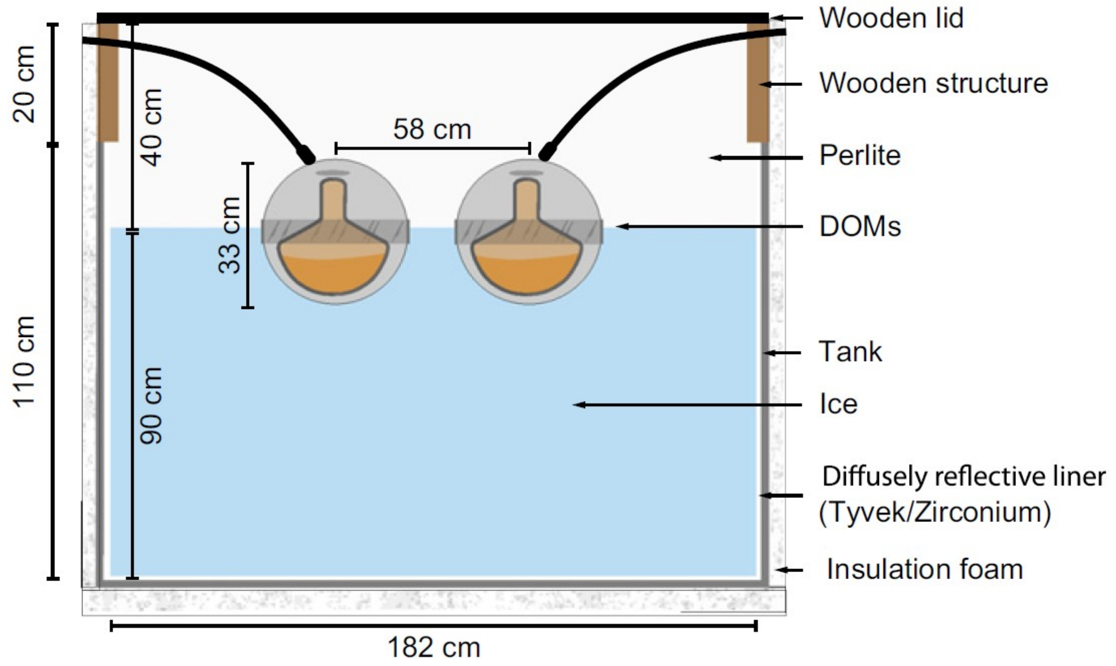
# Energy spectrum of muons in EAS

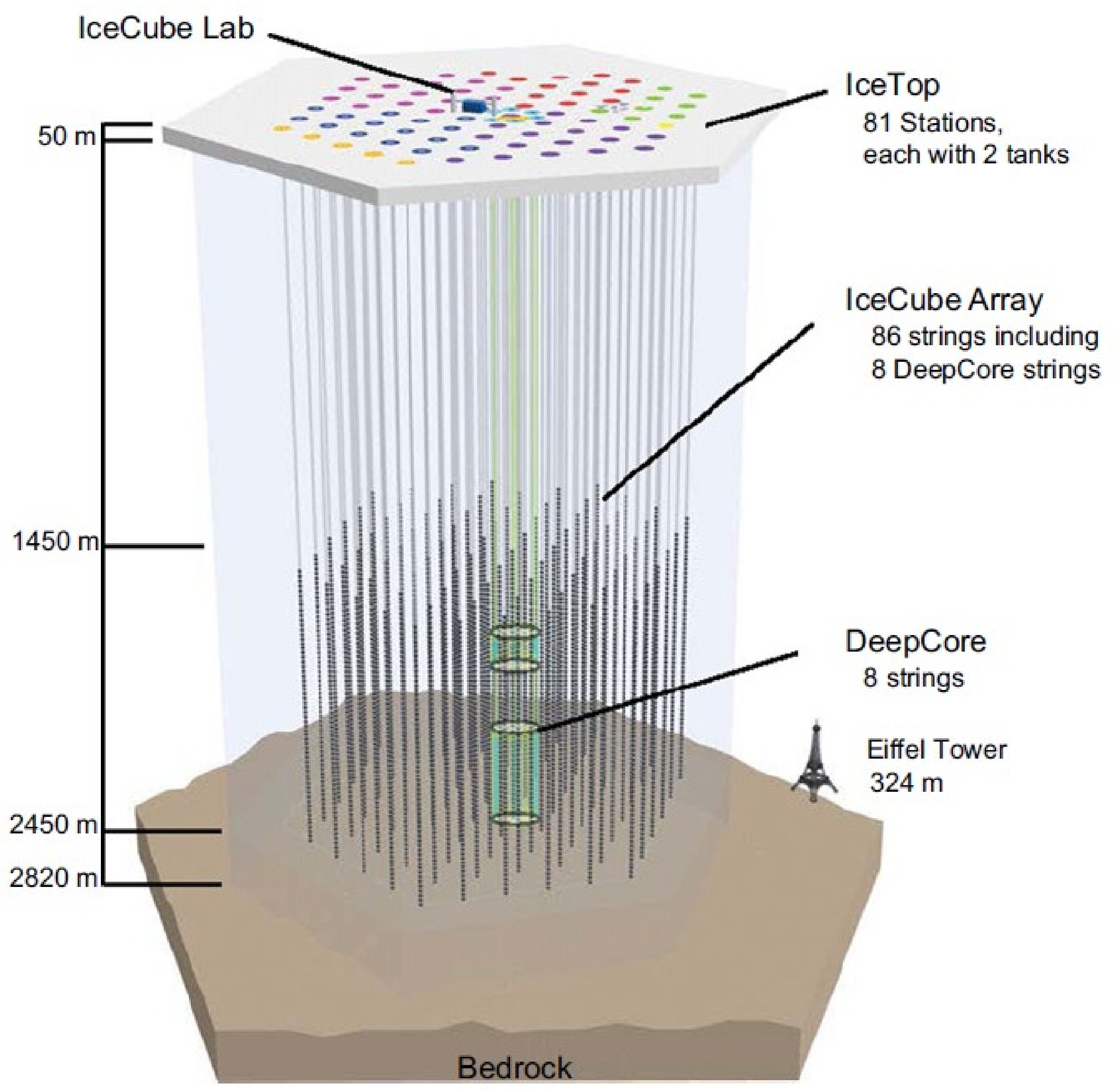
**Muon energy spectra relative to Sibyll 2.1**

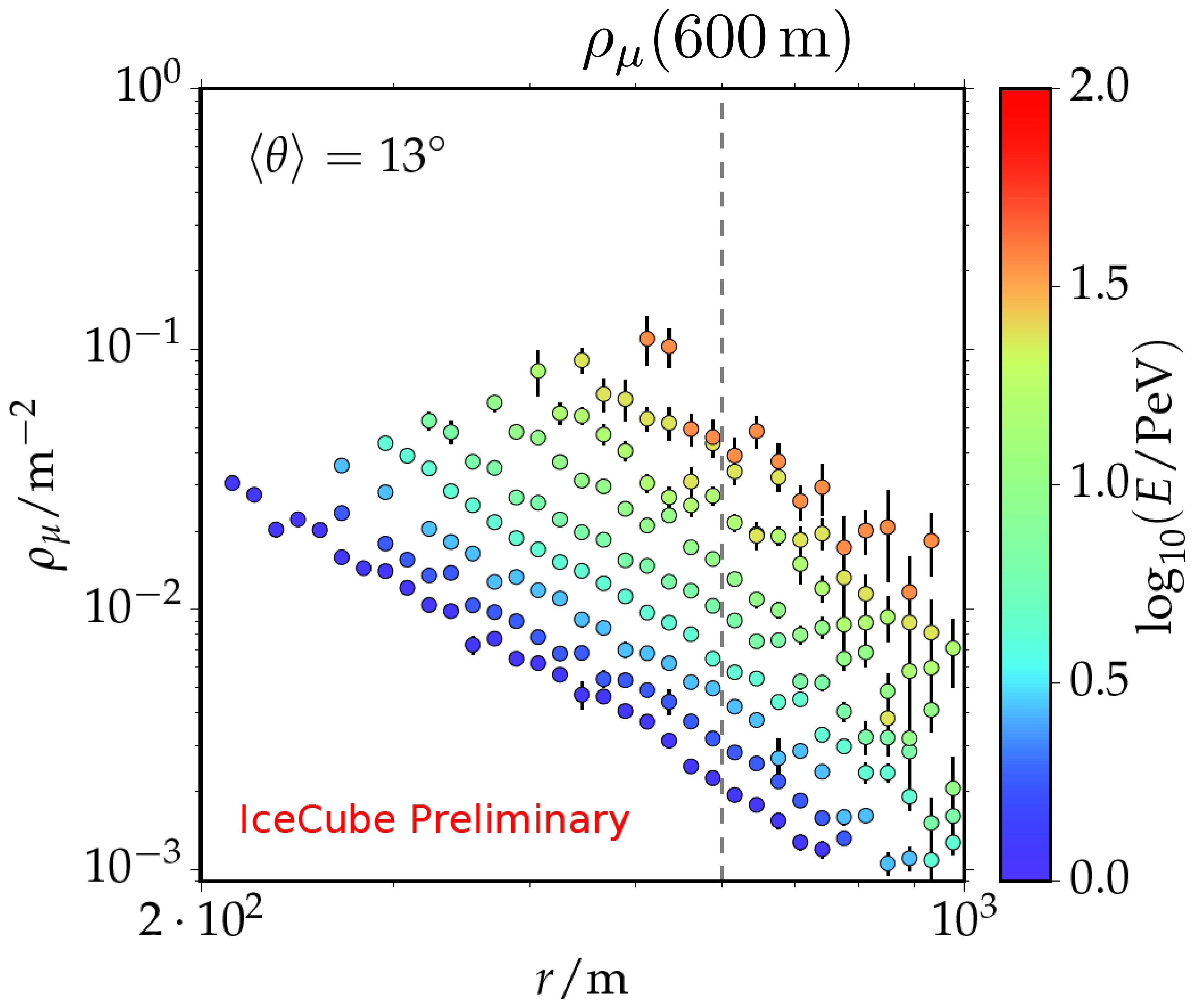



Discrimination by IceCube (surface array and in-ice muon data)?

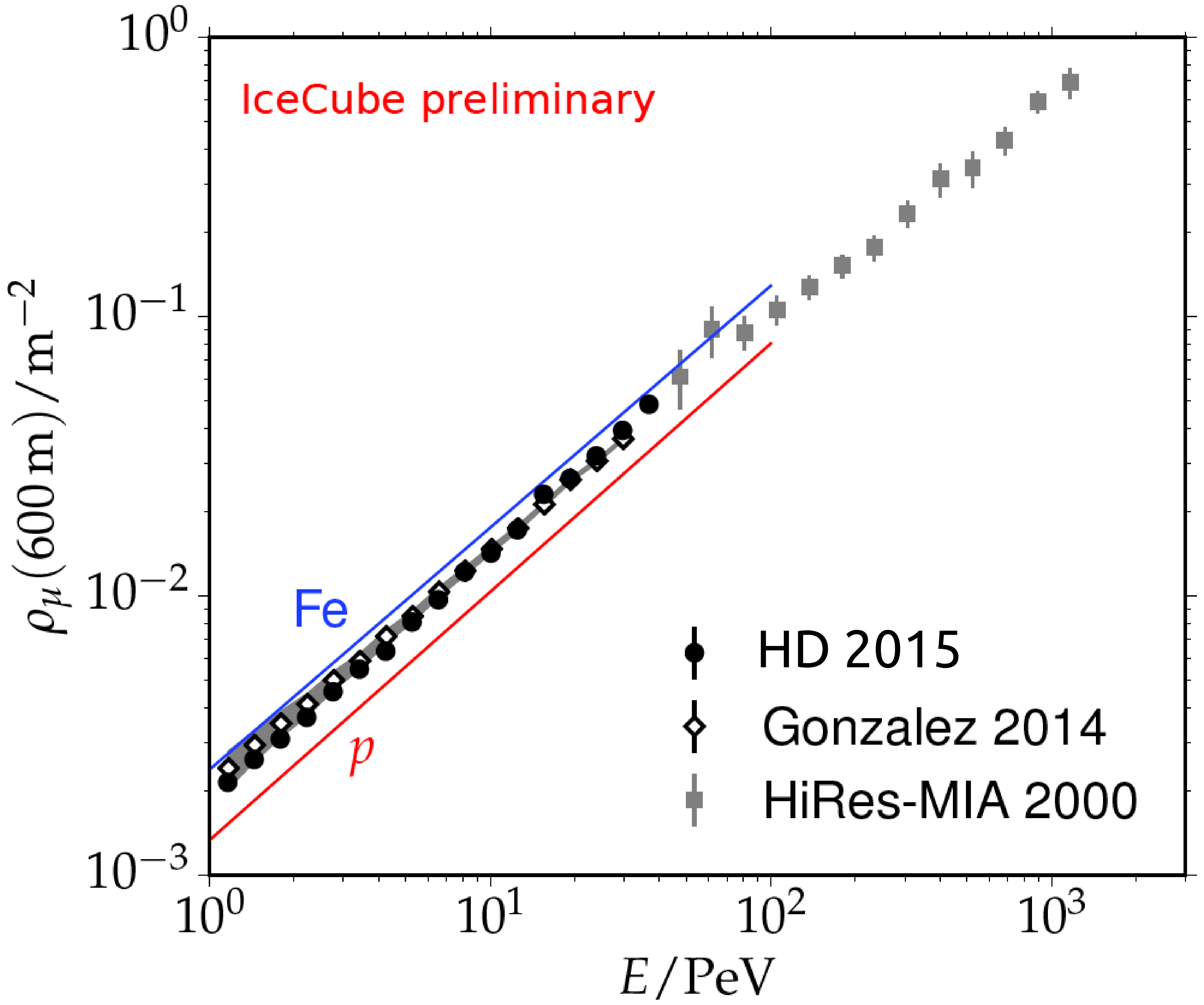
# Compatible with data at lower energy – IceTop ?



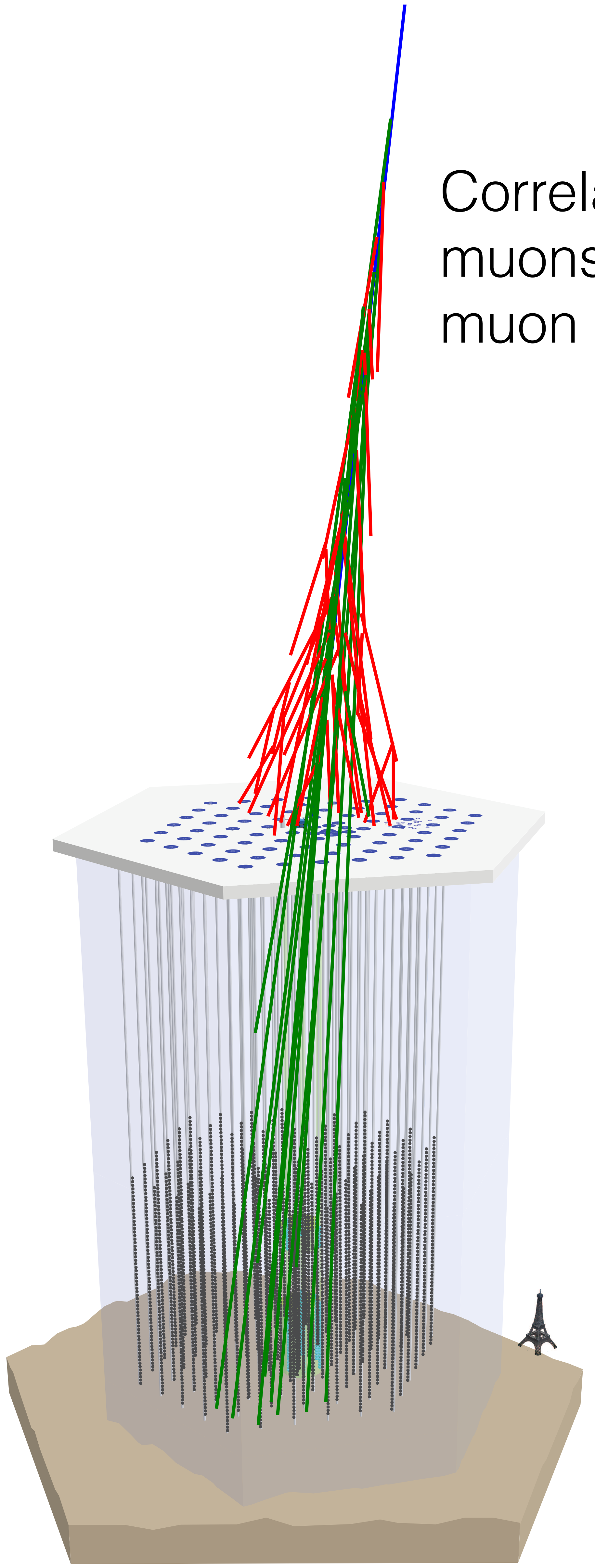

(IceCube, Dembinski & Gonzalez ICRC 2015)




Sibyll 2.1 predictions for p and Fe bracket data

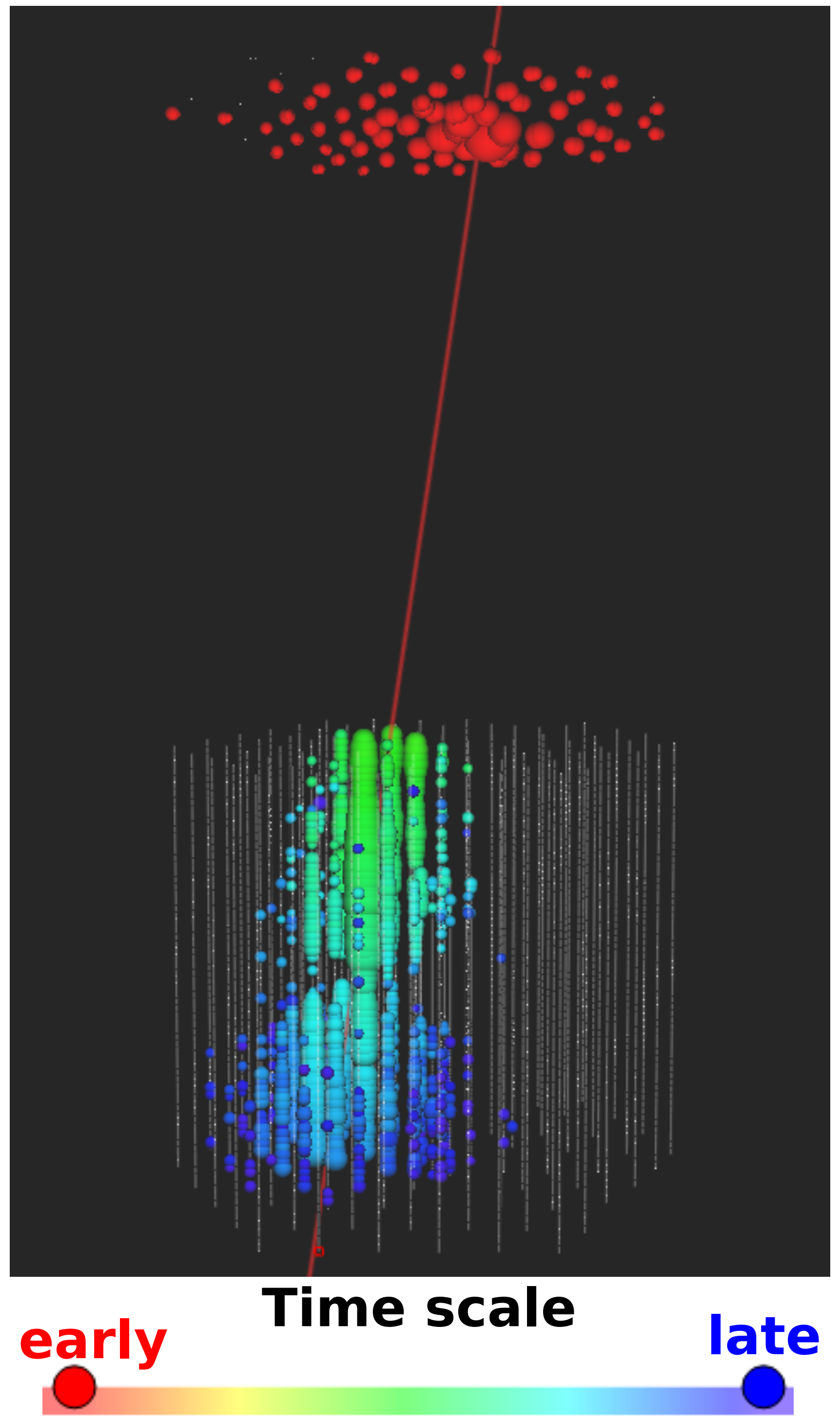
Consistency with lower energy showers essential for confirmation

# IceCube: discrimination of enhancement scenarios?

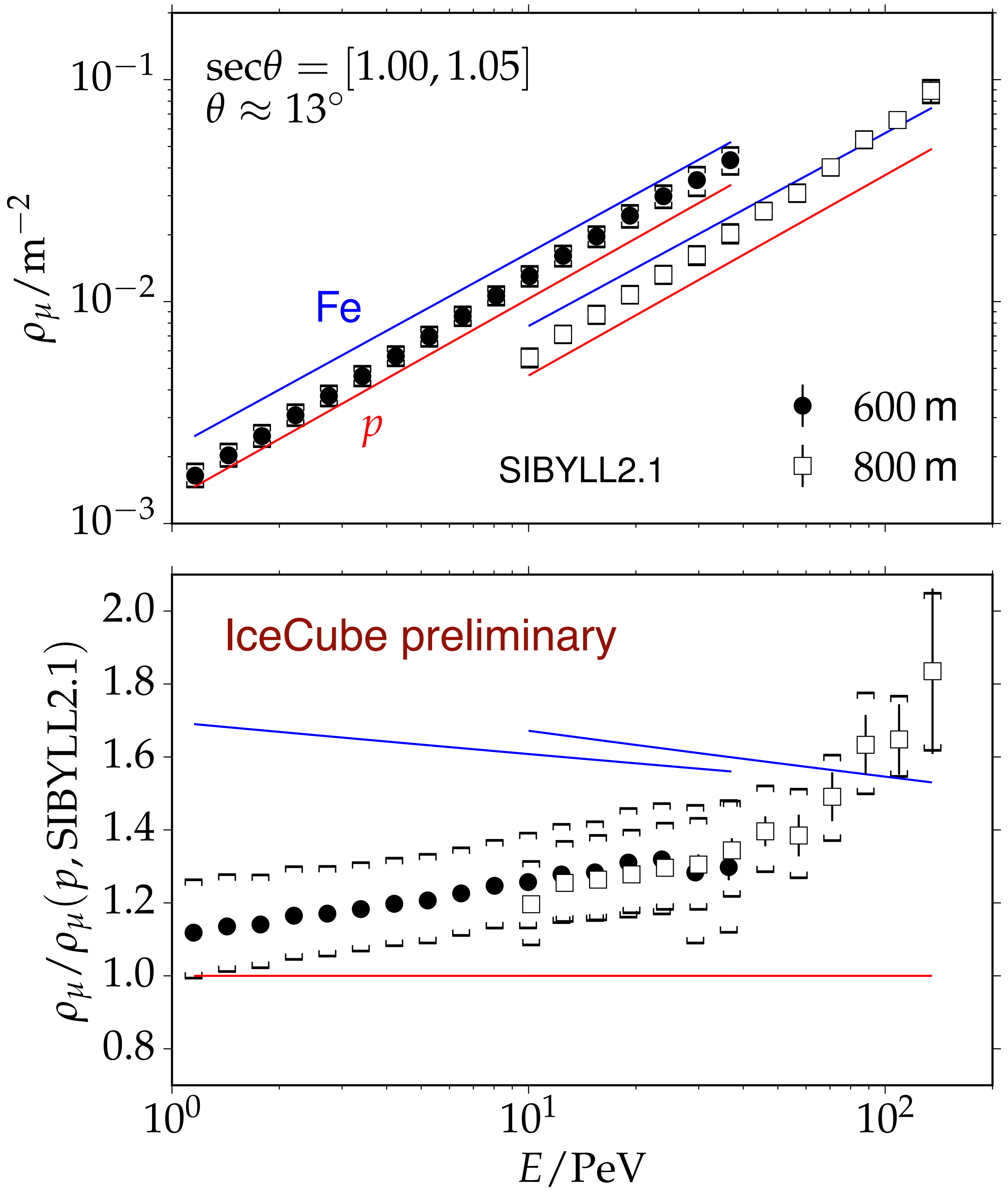


Correlation of low energy muons (surface) and in-ice muon bundles

IceTop: $E_{\mu}$ ~1 GeV

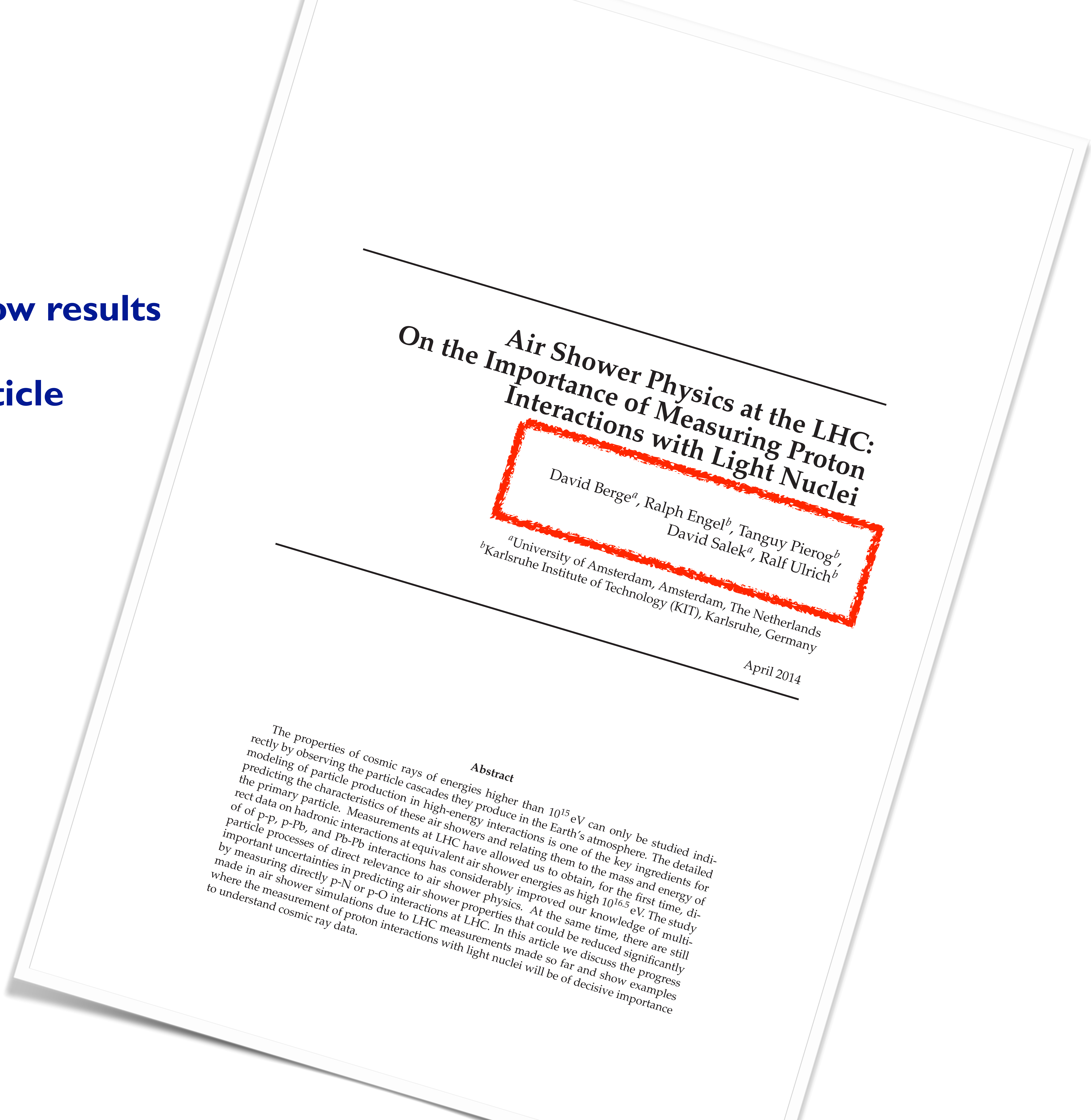



(IceCube, Gonzalez & Dembinski et al. 2016)




IceCube: $E_{\mu}$ >300 GeV

The following slides show results of ongoing study, to be published as journal article



Air Shower Physics at the LHC:
On the Importance of Measuring Proton Interactions with Light Nuclei

David Berge[a], Ralph Engel[b], Tanguy Pierog[b], David Salek[a], Ralf Ulrich[b]

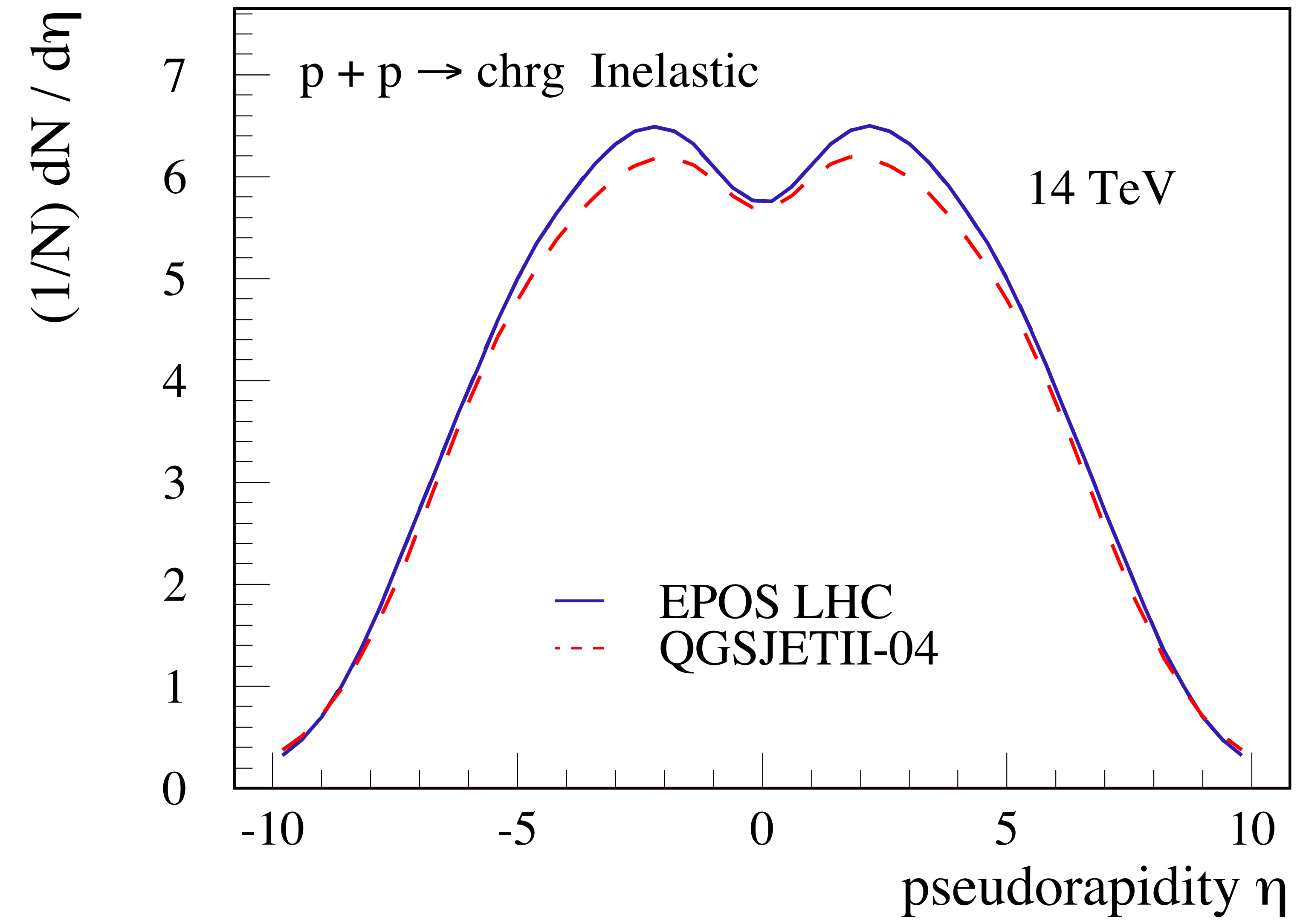
[a]University of Amsterdam, Amsterdam, The Netherlands
[b]Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

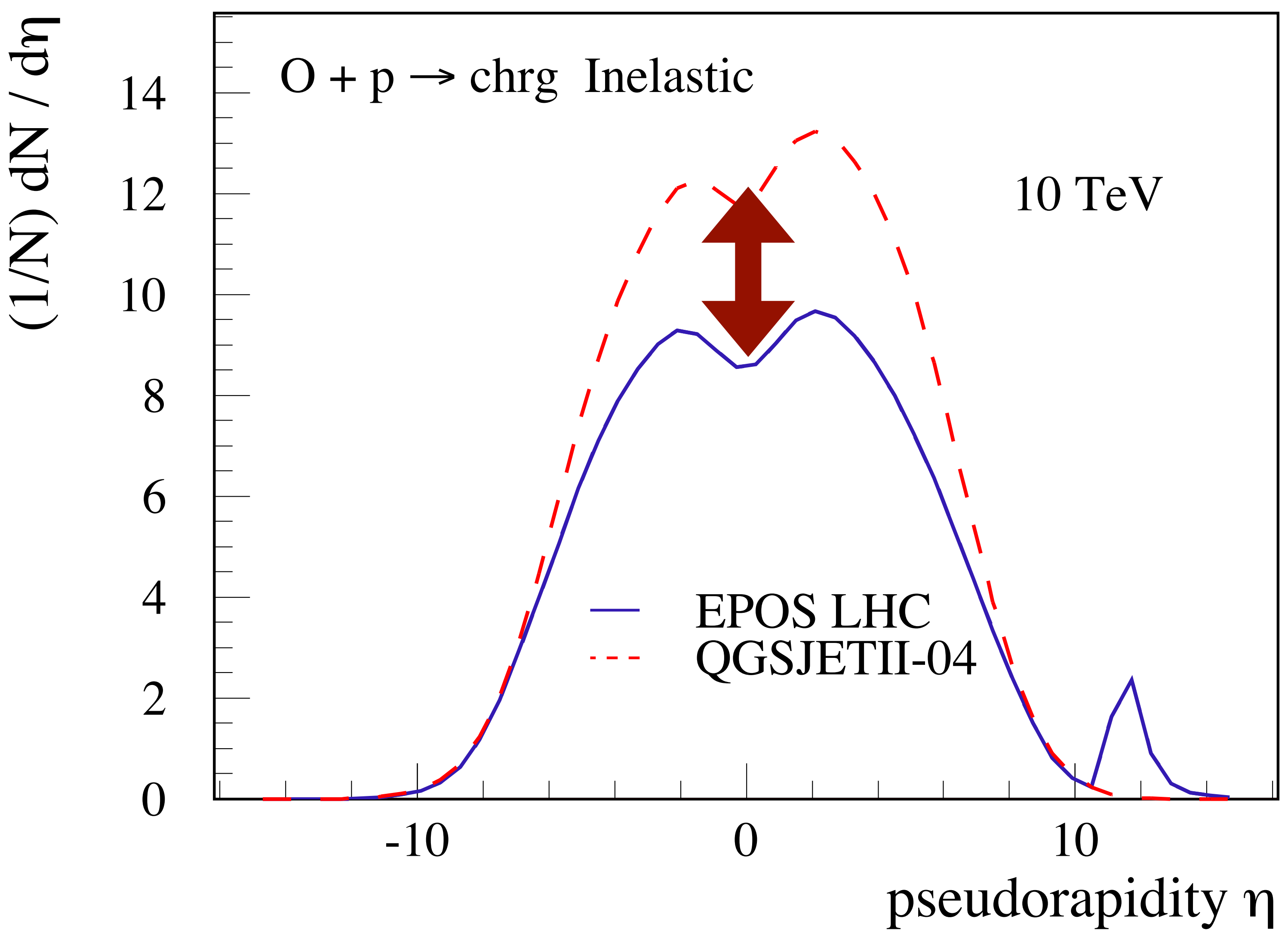
April 2014

**Abstract**

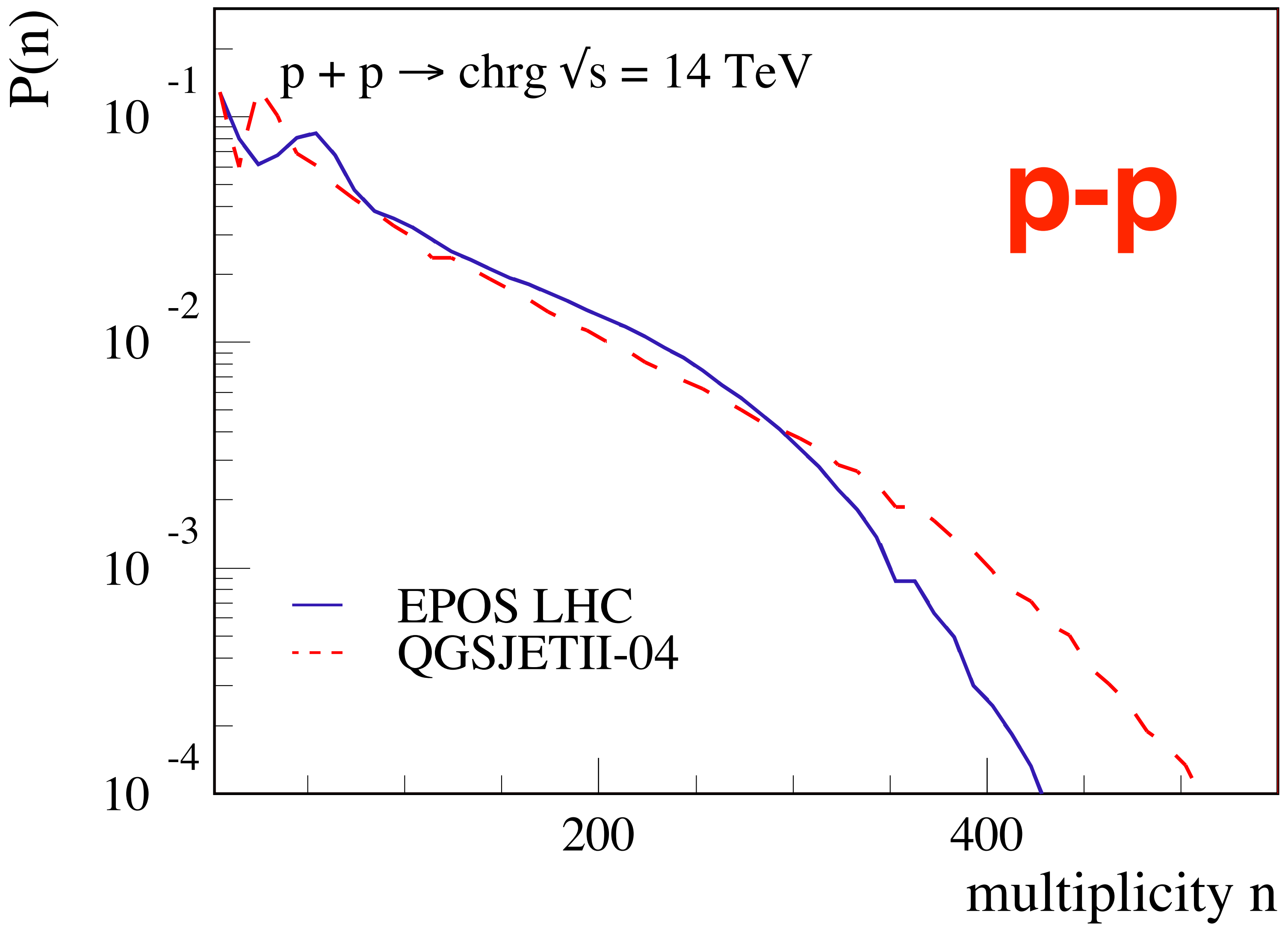
The properties of cosmic rays of energies higher than $10^{15}$ eV can only be studied indirectly by observing the particle cascades they produce in the Earth's atmosphere. The detailed modeling of particle production in high-energy interactions is one of the key ingredients for predicting the characteristics of these air showers and relating them to the mass and energy of the primary particle. Measurements at LHC have allowed us to obtain, for the first time, direct data on hadronic interactions at equivalent air shower energies as high $10^{16.5}$ eV. The study of p-p, p-Pb, and Pb-Pb interactions has considerably improved our knowledge of multi-particle processes of direct relevance to air shower physics. At the same time, there are still important uncertainties in predicting air shower properties that could be reduced significantly by measuring directly p-N or p-O interactions at LHC. In this article we discuss the progress made in air shower simulations due to LHC measurements made so far and show examples where the measurement of proton interactions with light nuclei will be of decisive importance to understand cosmic ray data.

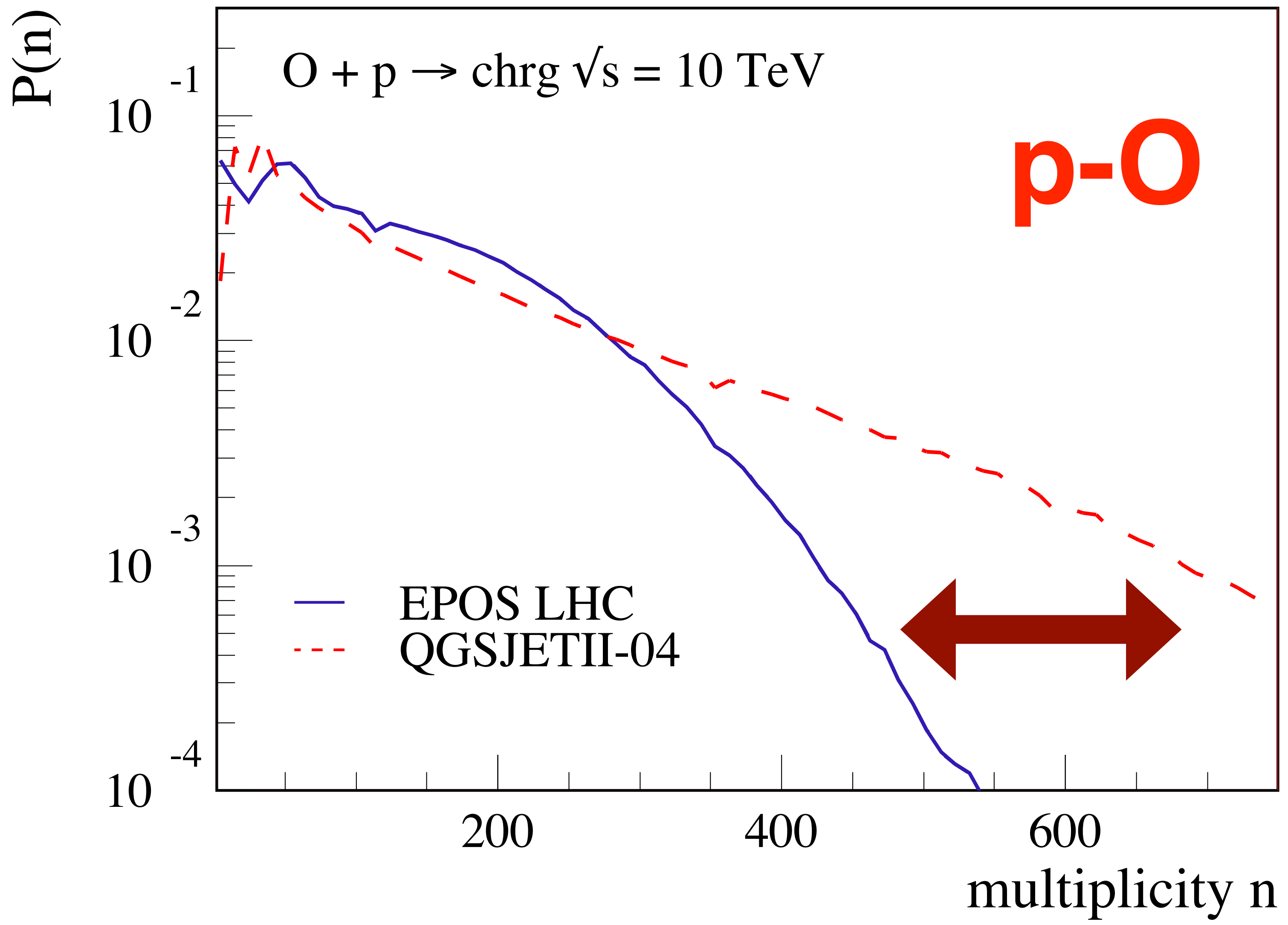
# Outlook: further improvement due to p-O collisions at LHC



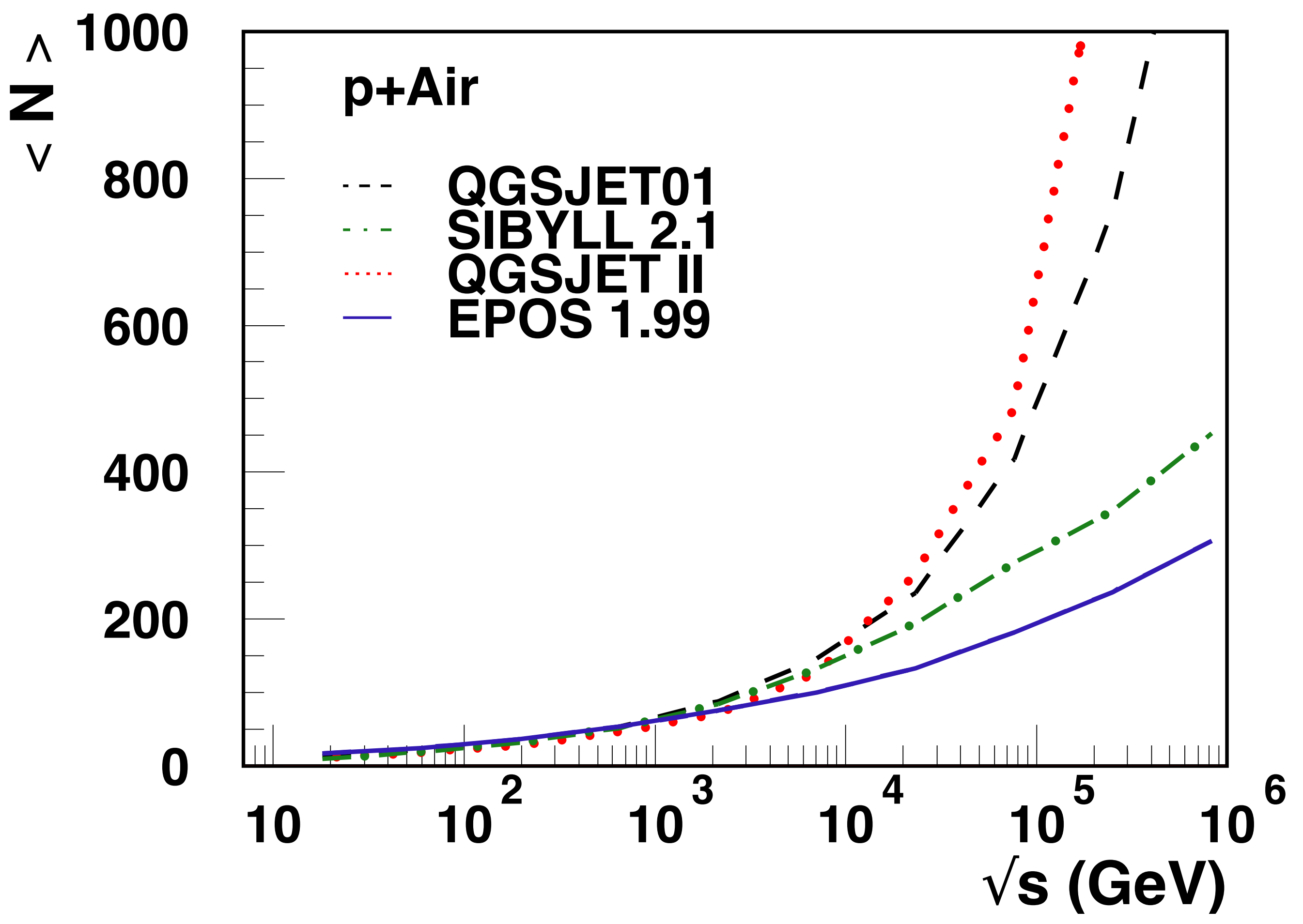

Currently predicted uncertainty in most optimistic case

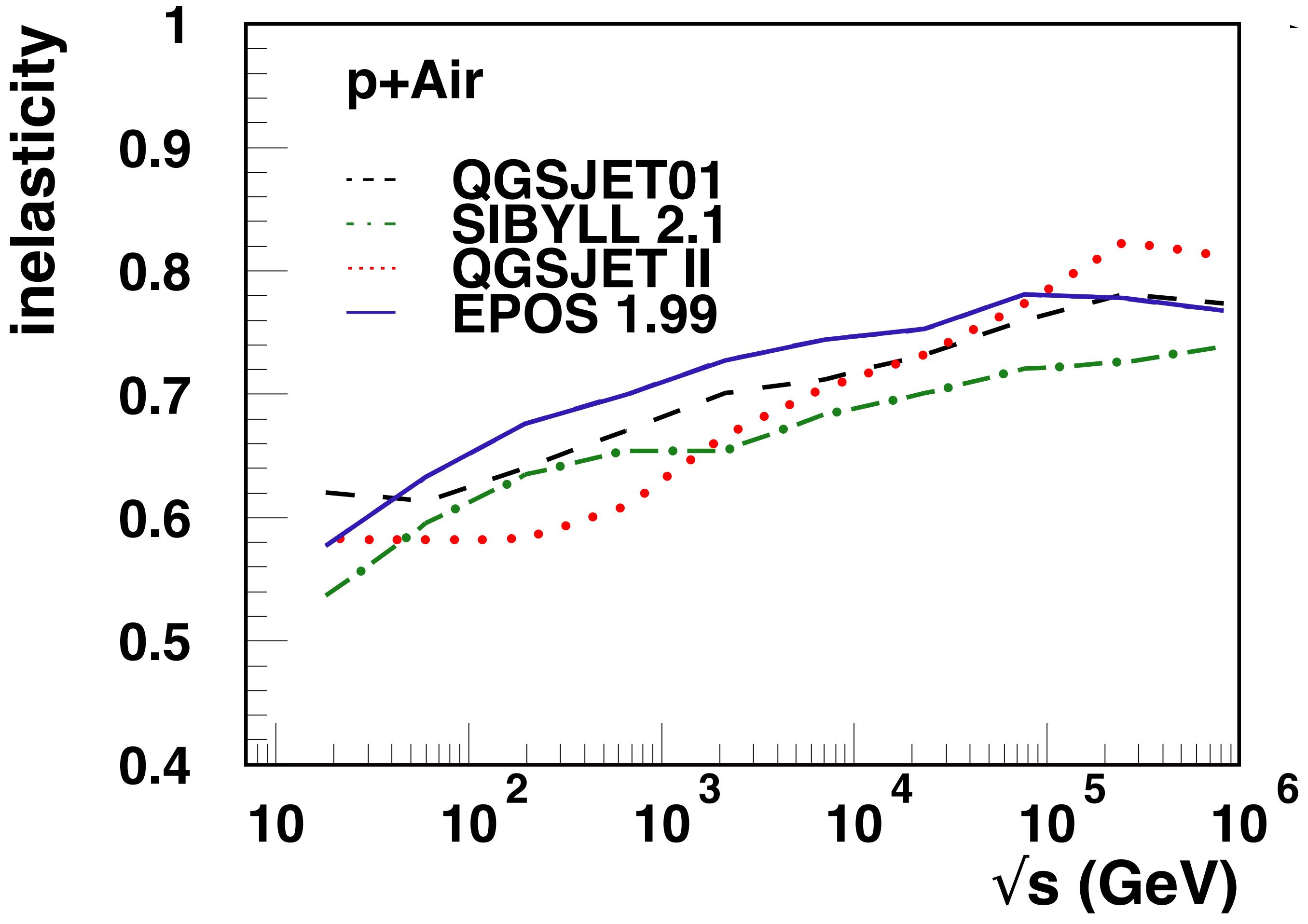


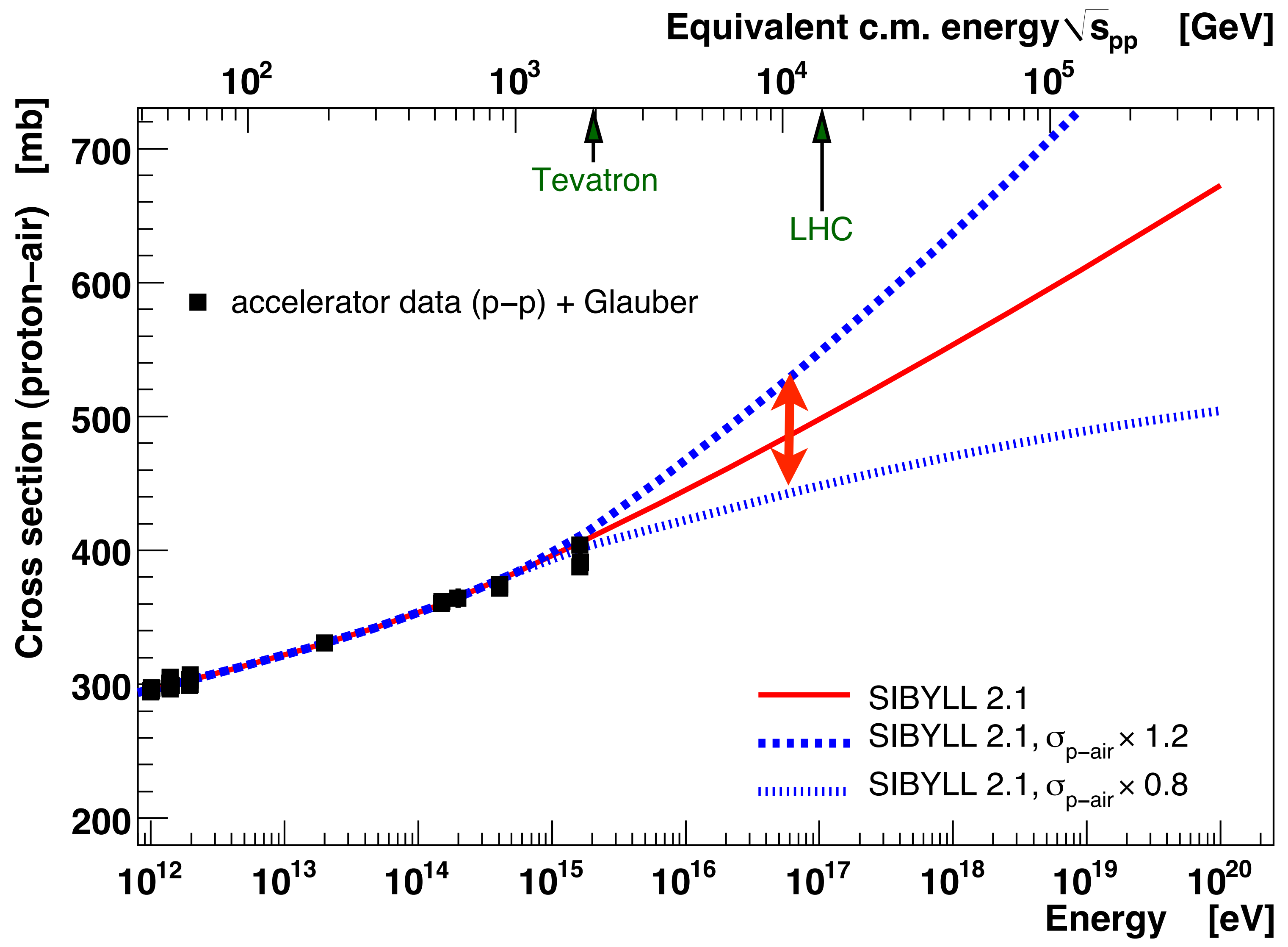




p-O technically feasible (O used as ion for Pb)

# Construction of phenomenological model




- LHC: p-O interactions with 10 TeV c.m.s. energy per nucleon
- Rescaling of specific features under study
- Extrapolation from 2 TeV c.m.s. energy linear in log(s)

*(similar to Ulrich et al., Phys. Rev. D83, 2011)*

# Impact on predicted depth of shower maximum

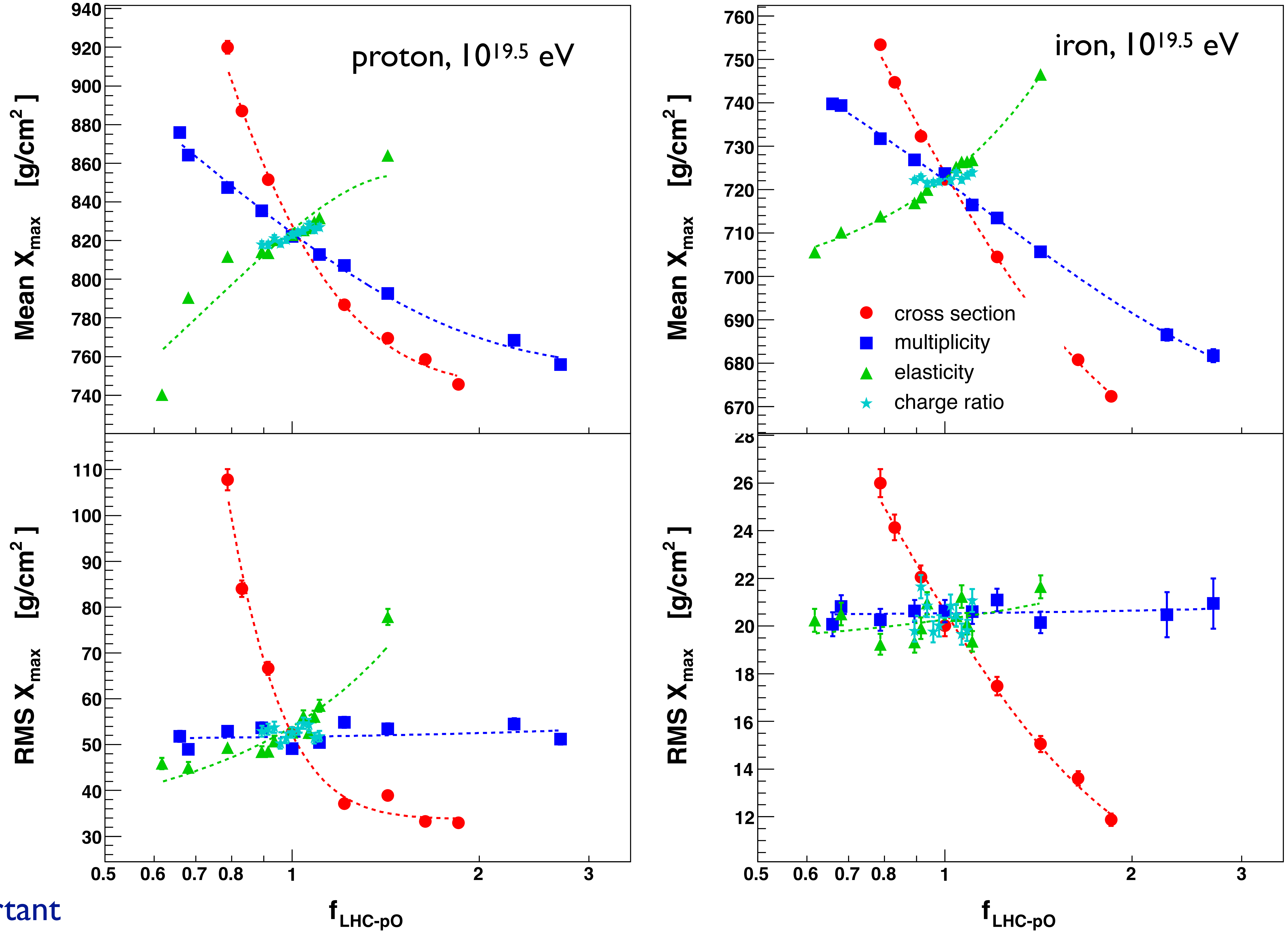
Fe

Si

CNO

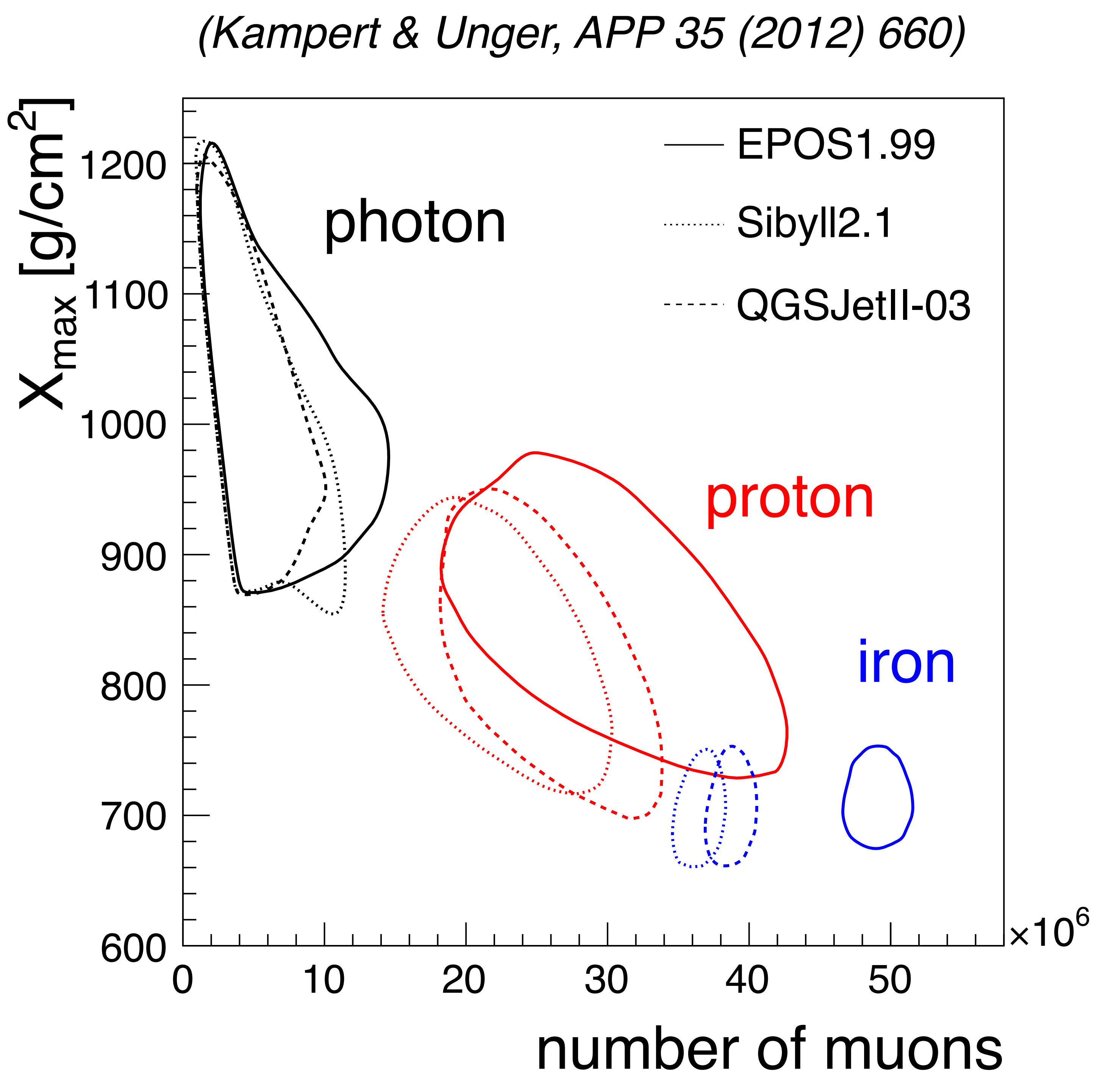
He

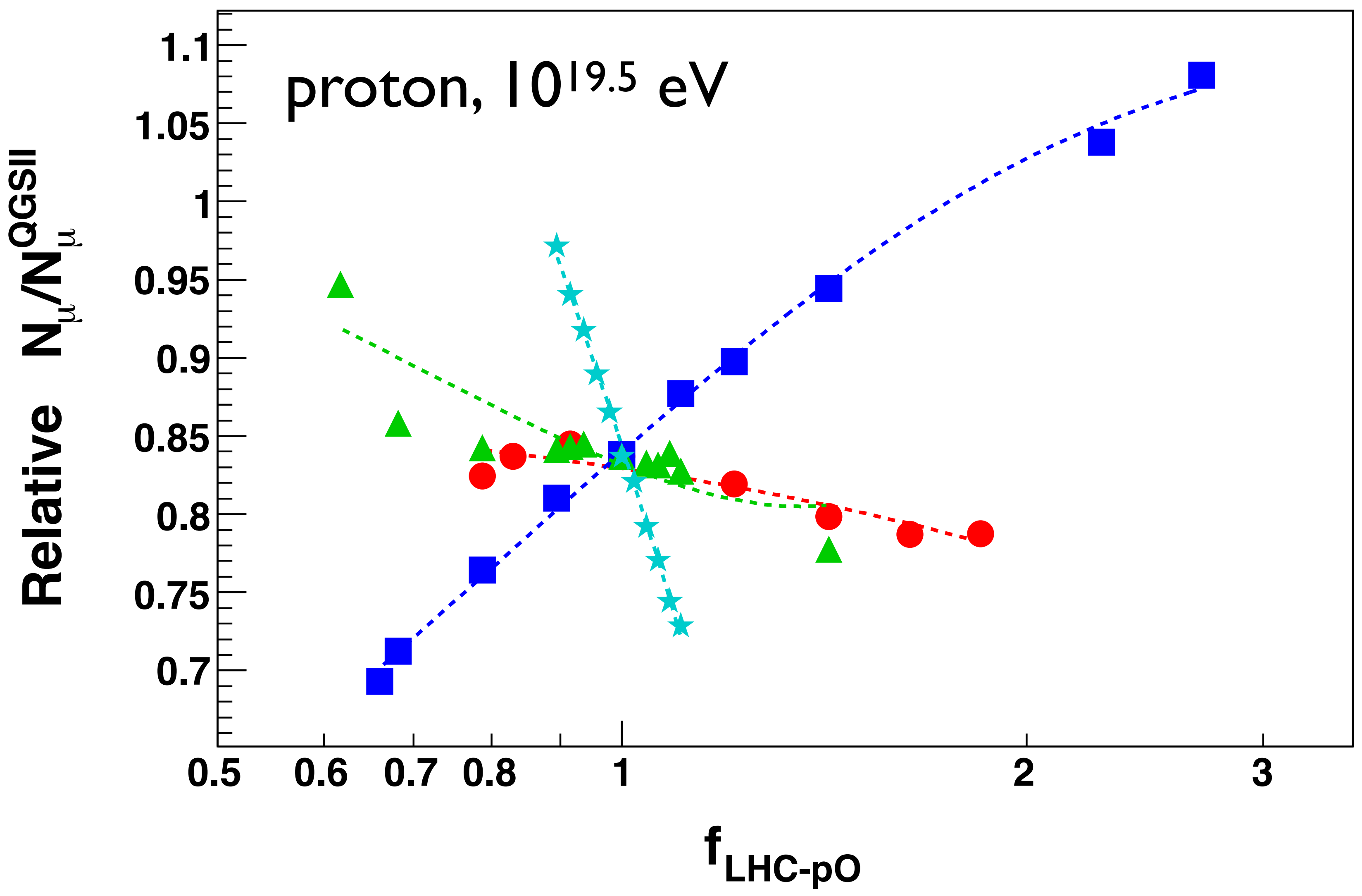
P

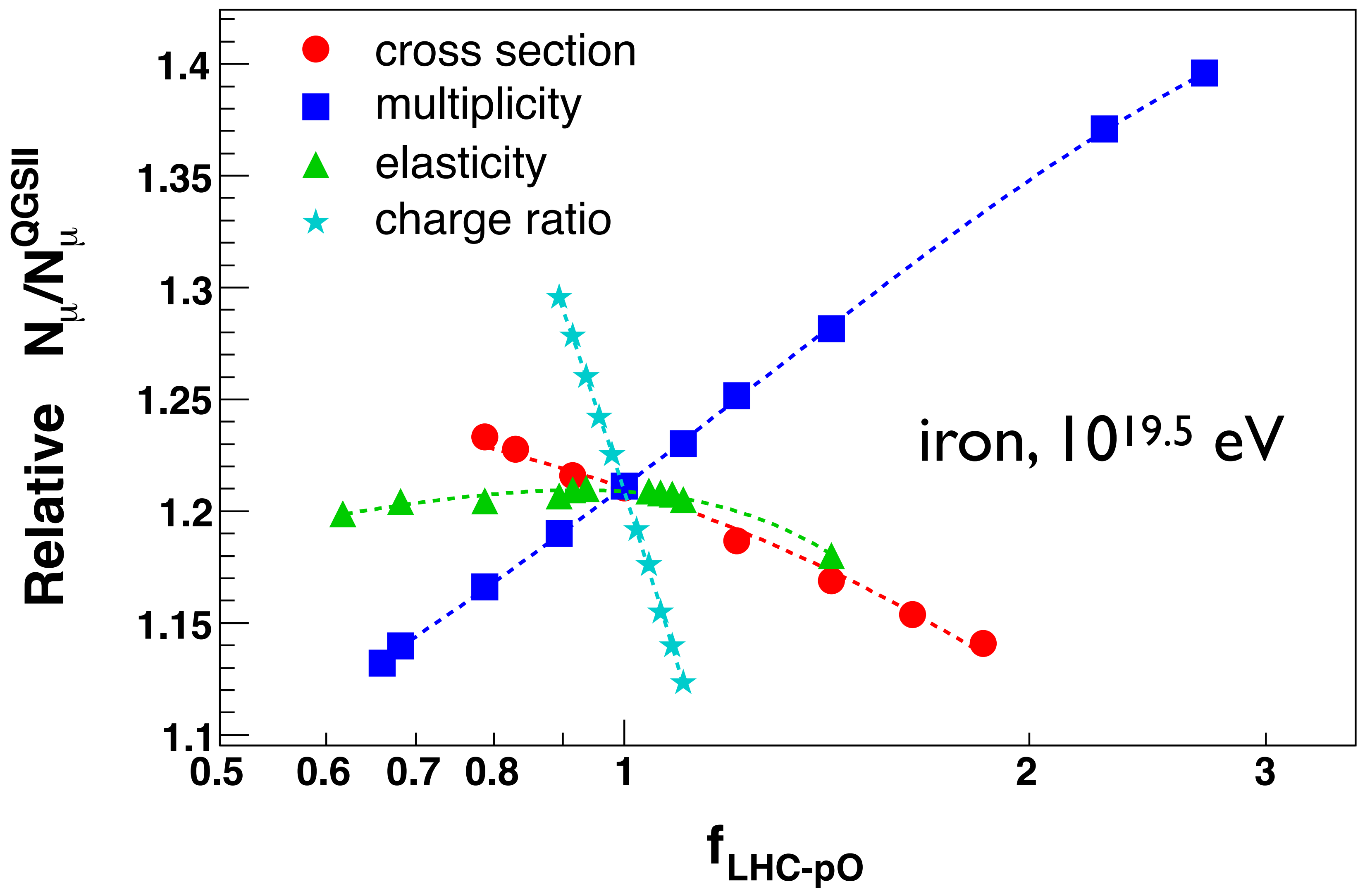



Changes of
25 g/cm² important

# Impact on predicted muon number at ground



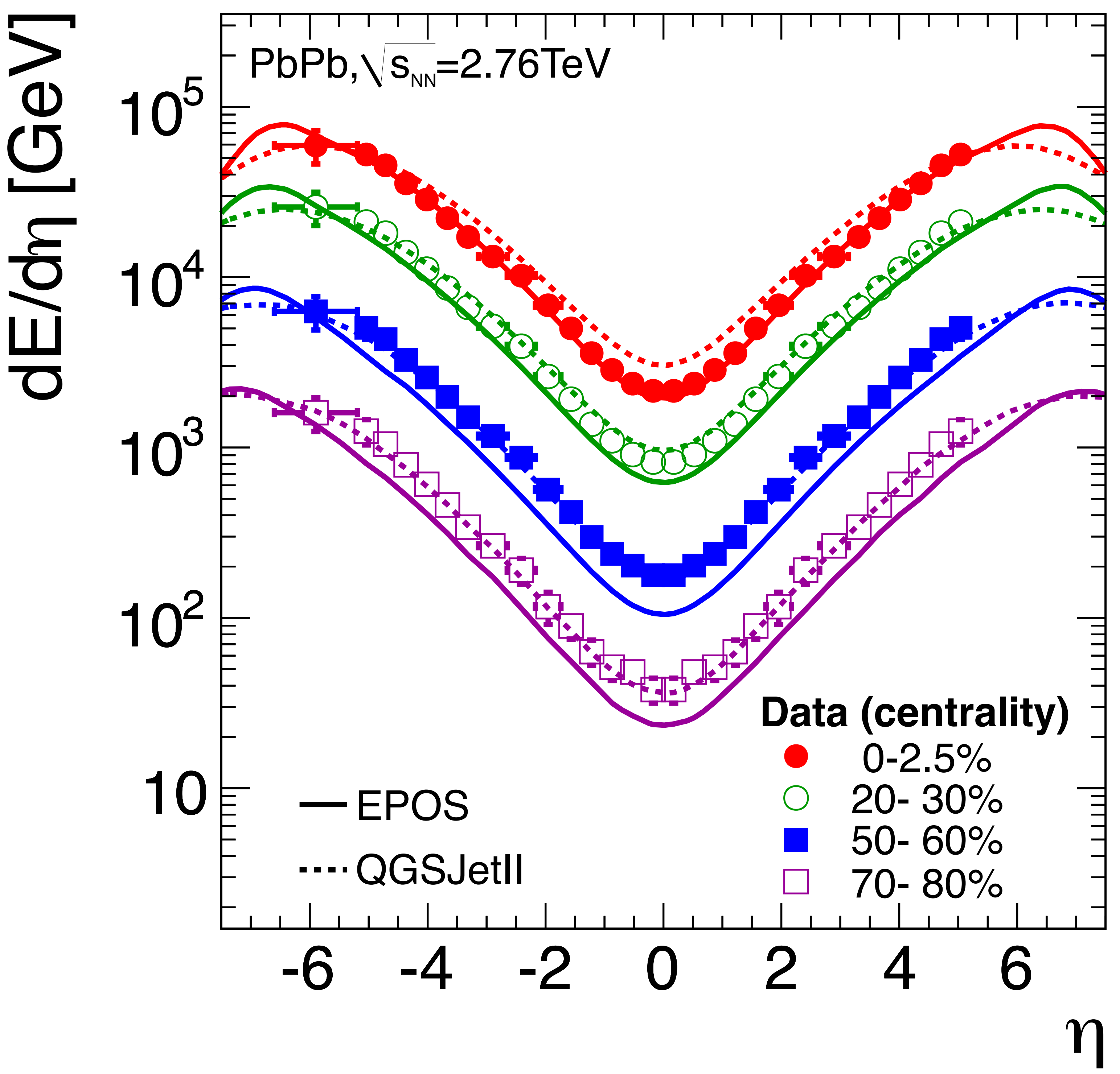



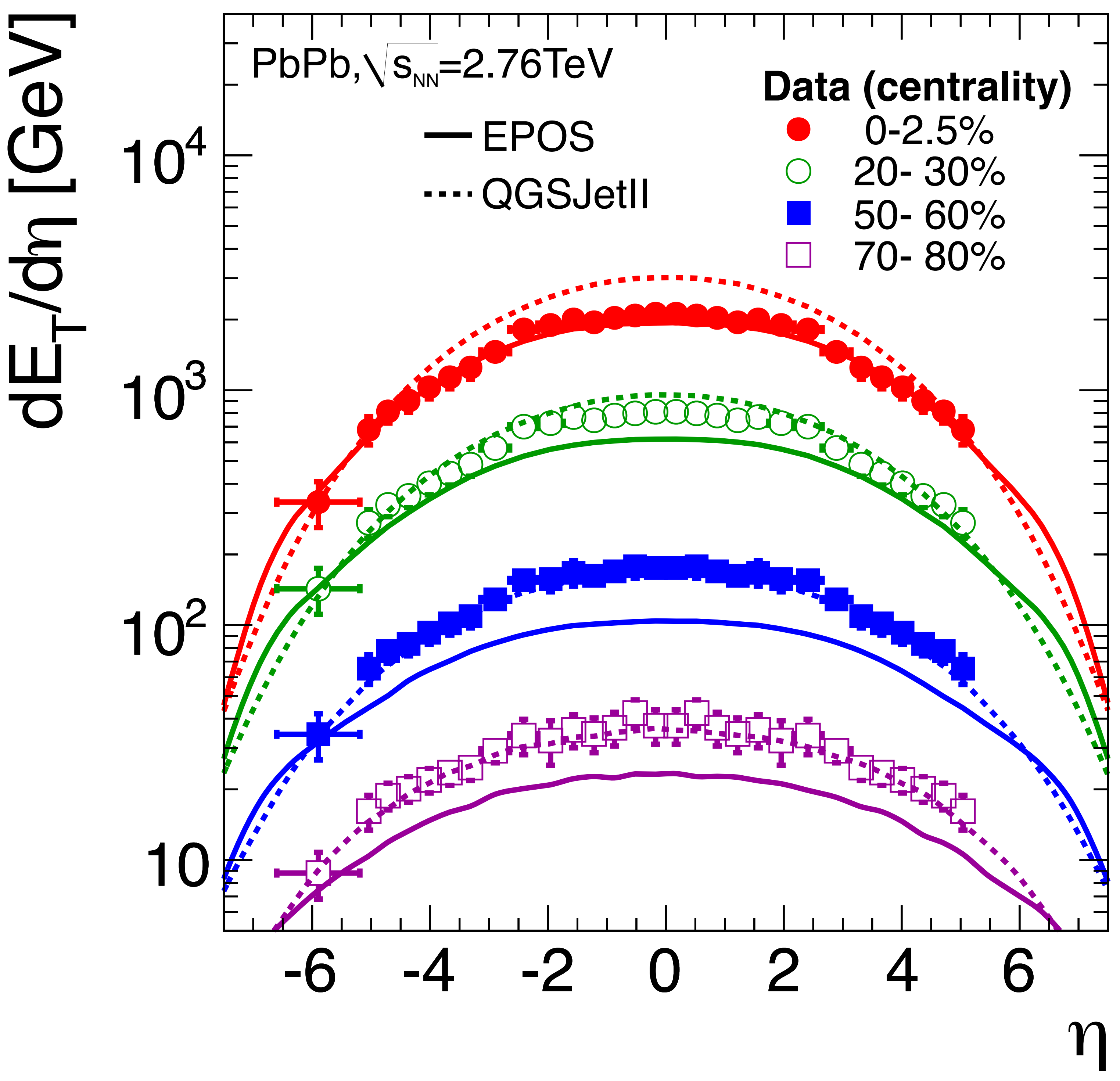



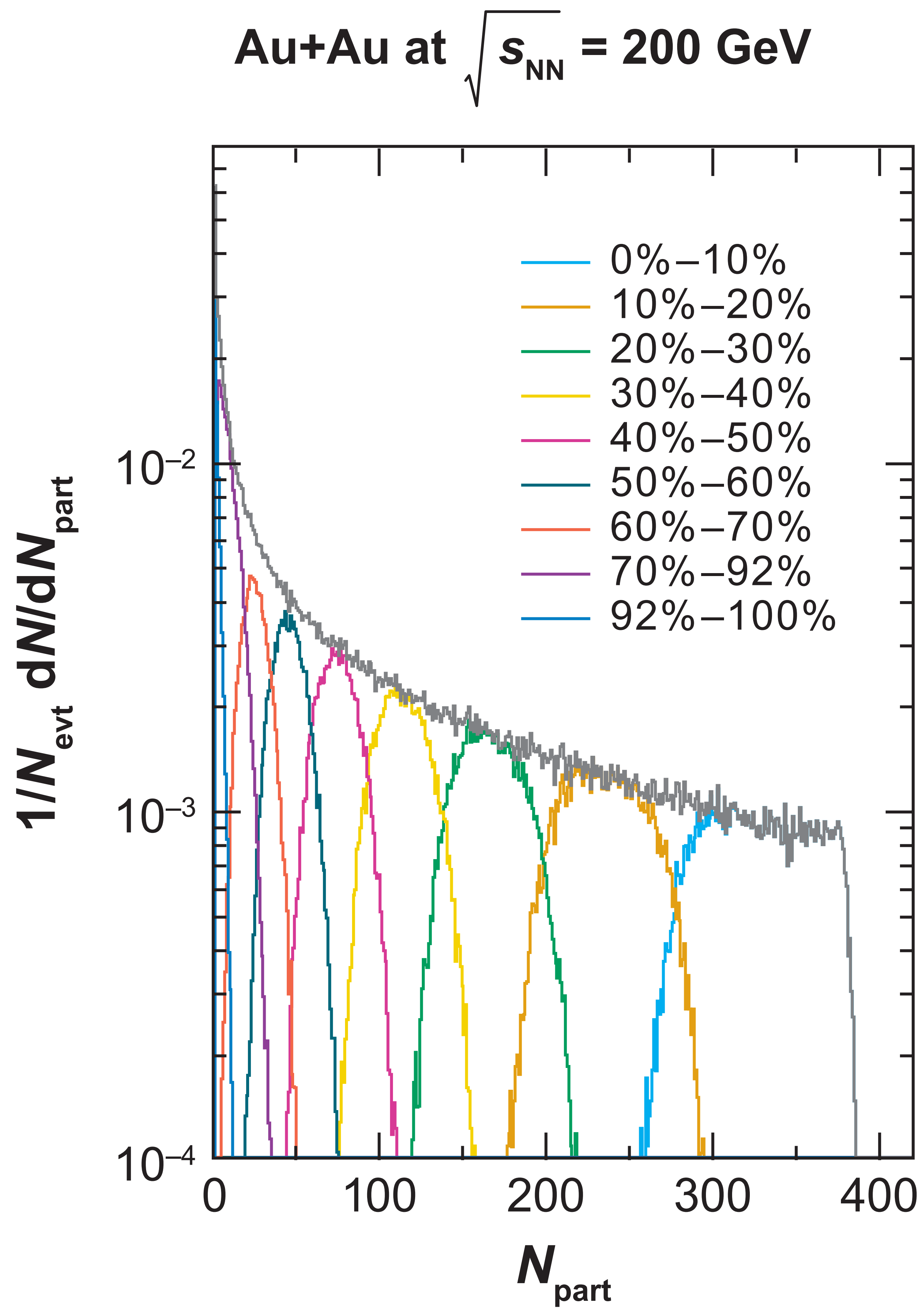

Changes of 10% important

# What can we learn from the Pb-Pb data ?

**Example: lead-lead collisions (CMS results)**

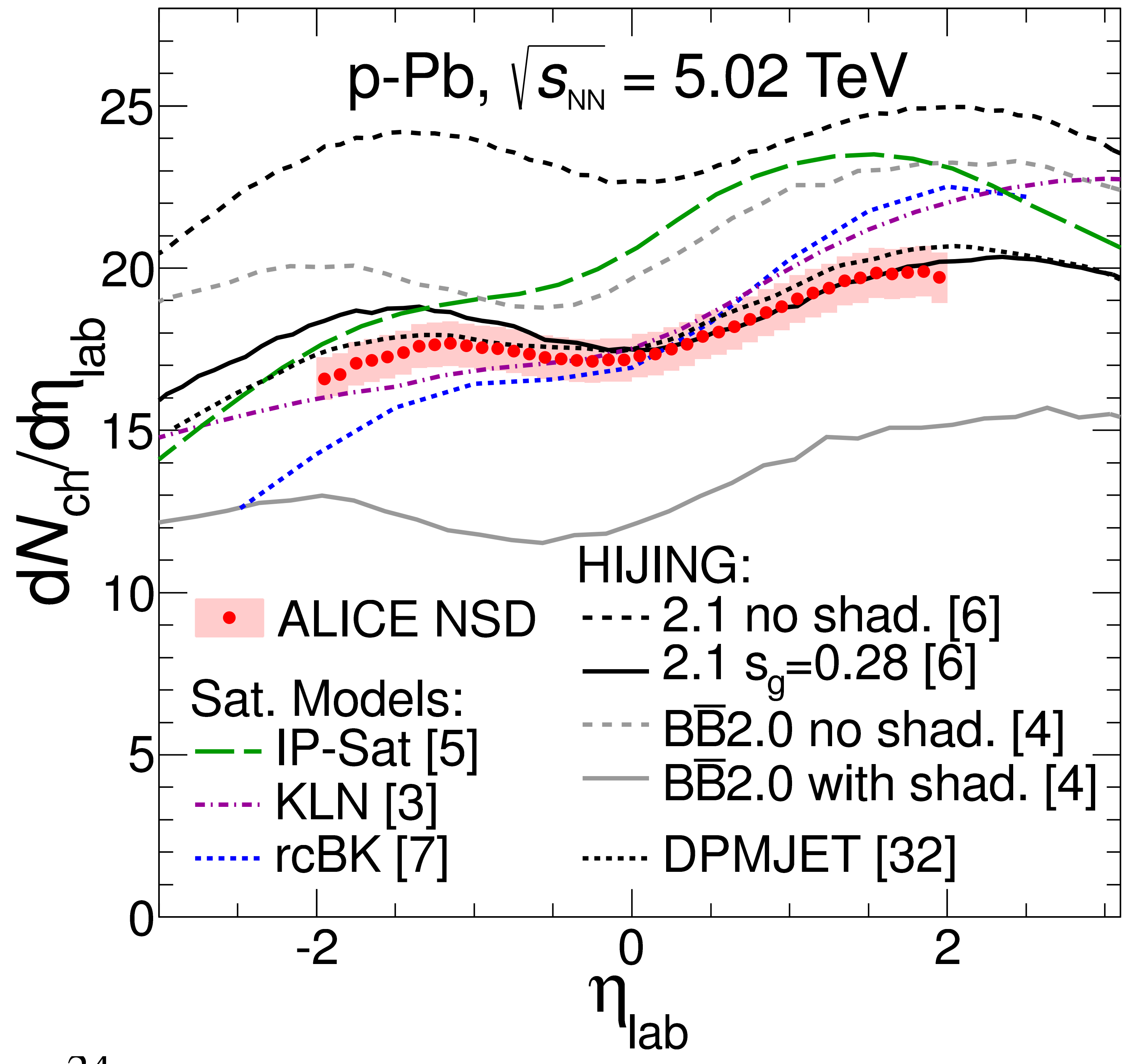


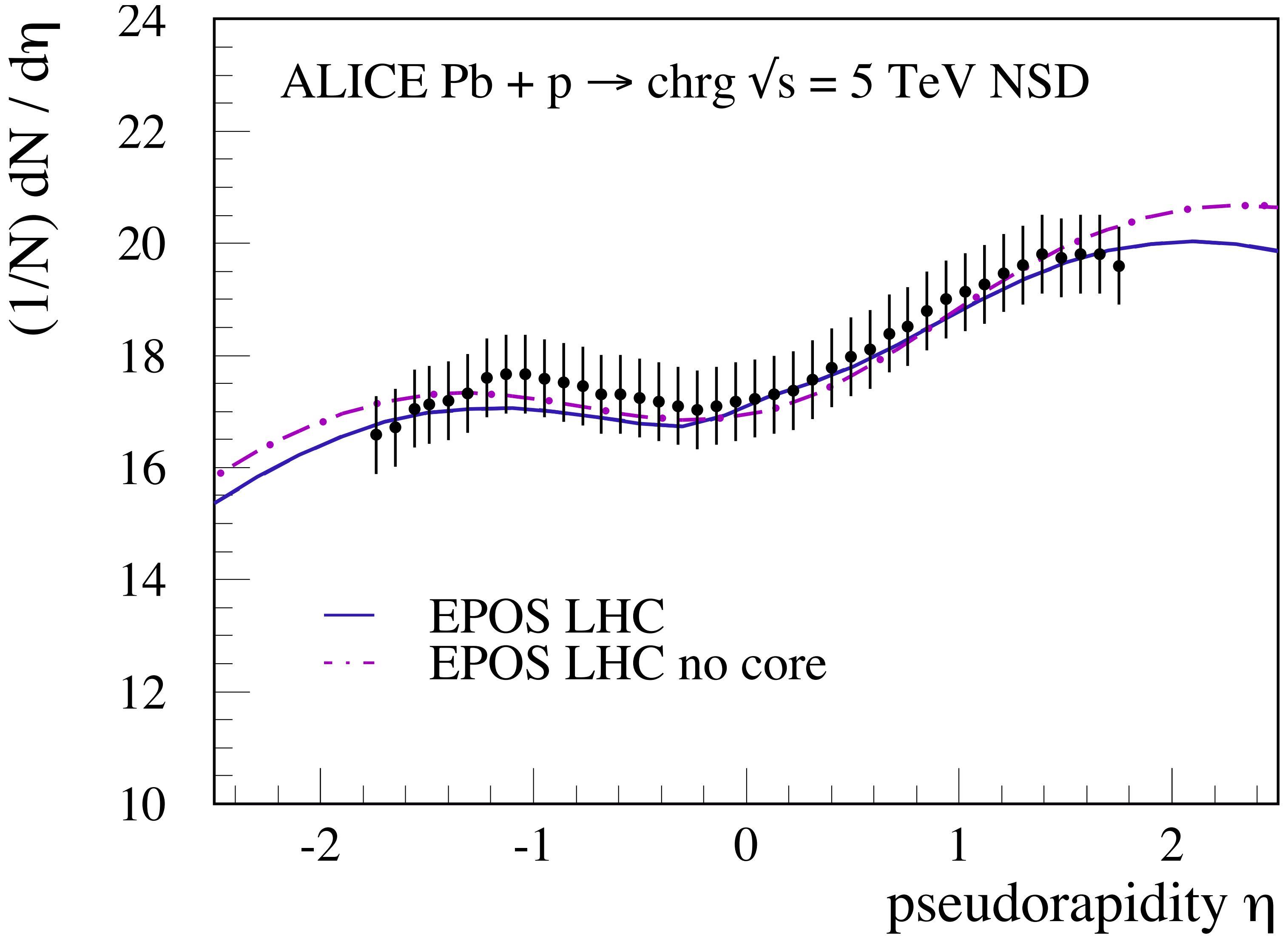



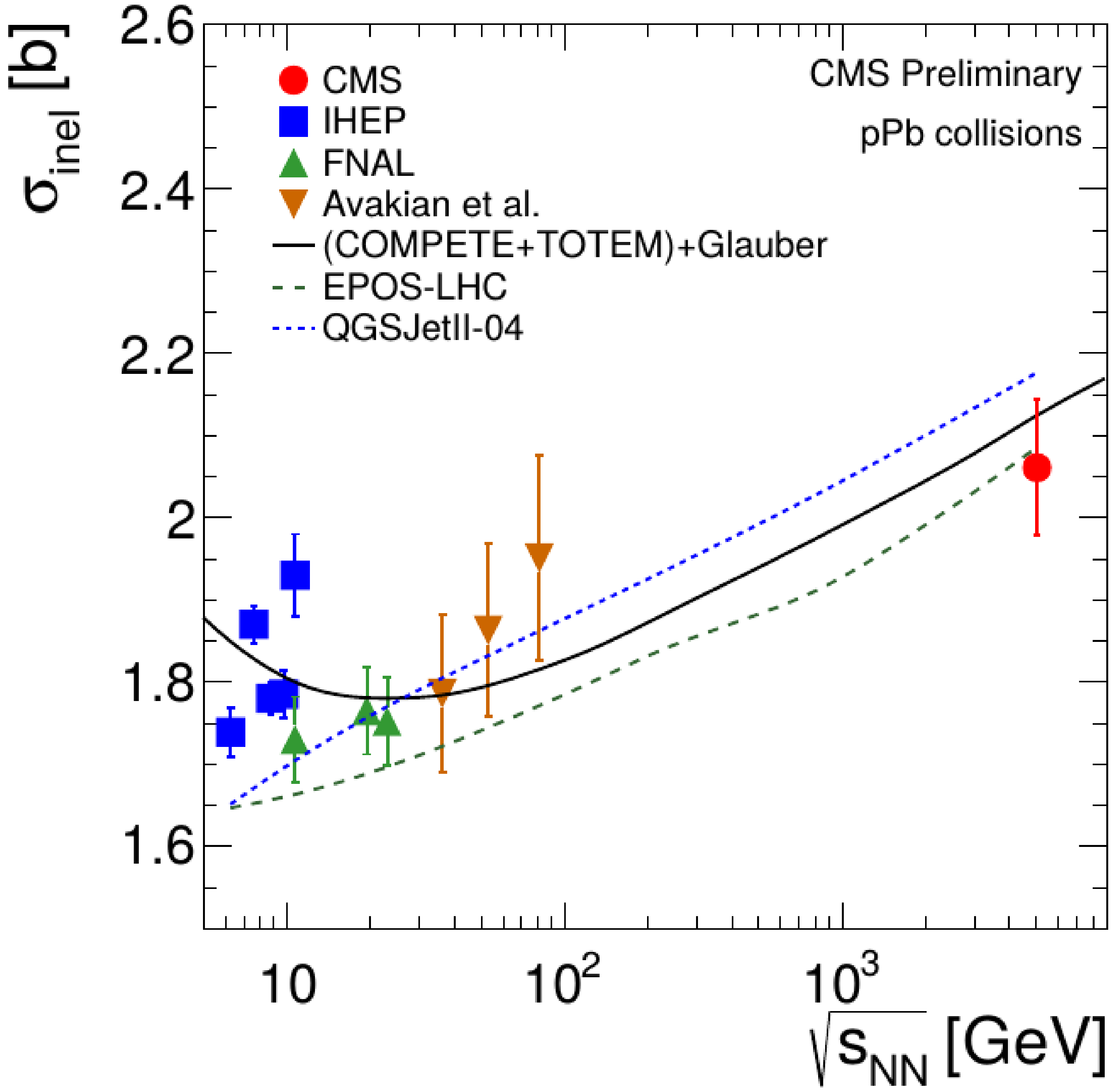




- Mixed results: EPOS better for central collisions, QGSJET better for peripheral ones ?
- Not all models can be run for heavy ions, no hydrodynamics implemented (except EPOS)
- Importance of high-density effects much higher in Pb-Pb than air showers

# And what about p-Pb data ?




**Problem:** no theory or recipe for transition from high-density physics to peripheral collisions

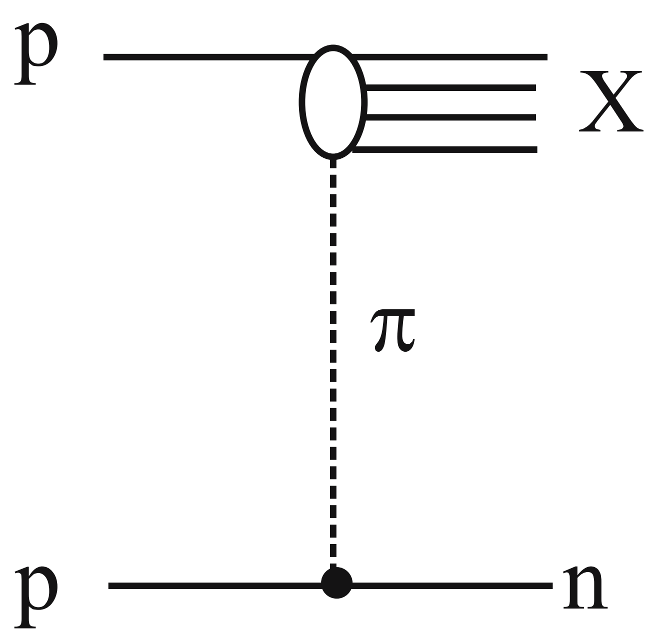
# Need for measuring p-O collisions at LHC

**So far models only tuned for p-p interactions (and partially p-Pb, Pb-Pb)**

- Models with similar p-p predictions differ significantly for p-O
- Example: difference in multiplicity prediction of models corresponds to difference between p and He of cosmic ray particles ($\Delta X_{max} \sim 20\ g/cm^2$)
- Forward particle production in p-O essentially unknown
- Peripheral collisions in p-O much more important than in p-Pb
- Model predictions give only **lower limit to real uncertainty** due to similar assumptions,
  need data to estimate real uncertainty

# Outlook: how to obtain data at higher energy ?

Measurement of pion exchange at LHC



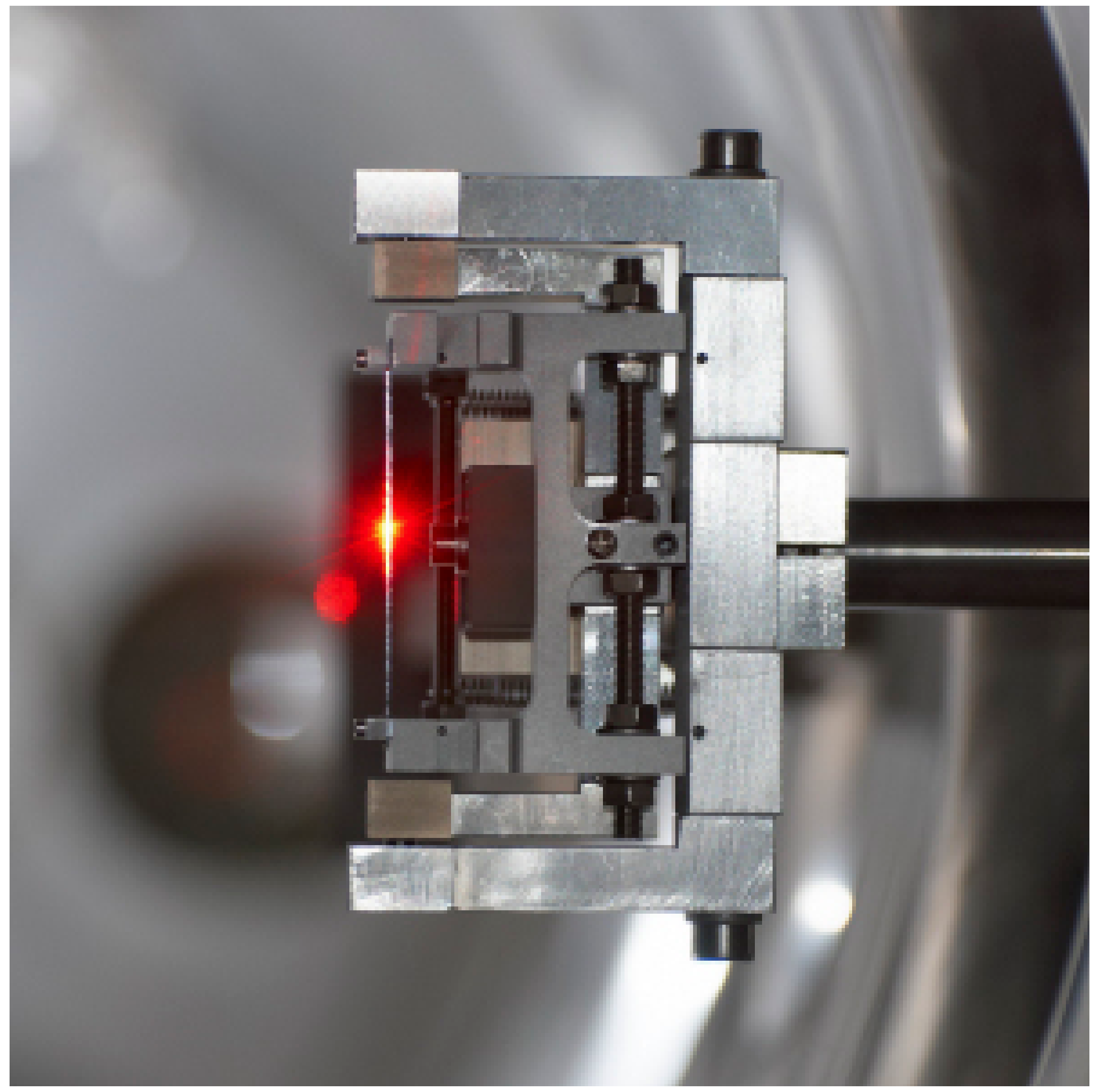

Pion fragmentation
region in ATLAS

Leading neutron in LHCf

Physics discussed in detail for HERA (H1 and ZEUS)
(see, for example, Khoze et al. Eur. Phys. J. C48 (2006), 797
Kopeliovich & Potashnikova et al.)

$$\frac{\mathrm{d}\sigma(\gamma p \to Xn)}{\mathrm{d}x_{\mathrm{L}}\,\mathrm{d}t} = S^2 \frac{G^2_{\pi^+ pn}}{16\pi^2} \frac{(-t)}{(t-m_\pi^2)^2} F^2(t) \times (1-x_{\mathrm{L}})^{1-2\alpha_\pi(t)} \sigma^{\mathrm{tot}}_{\gamma\pi}(M^2)$$

Fixed-target experiment at LHC

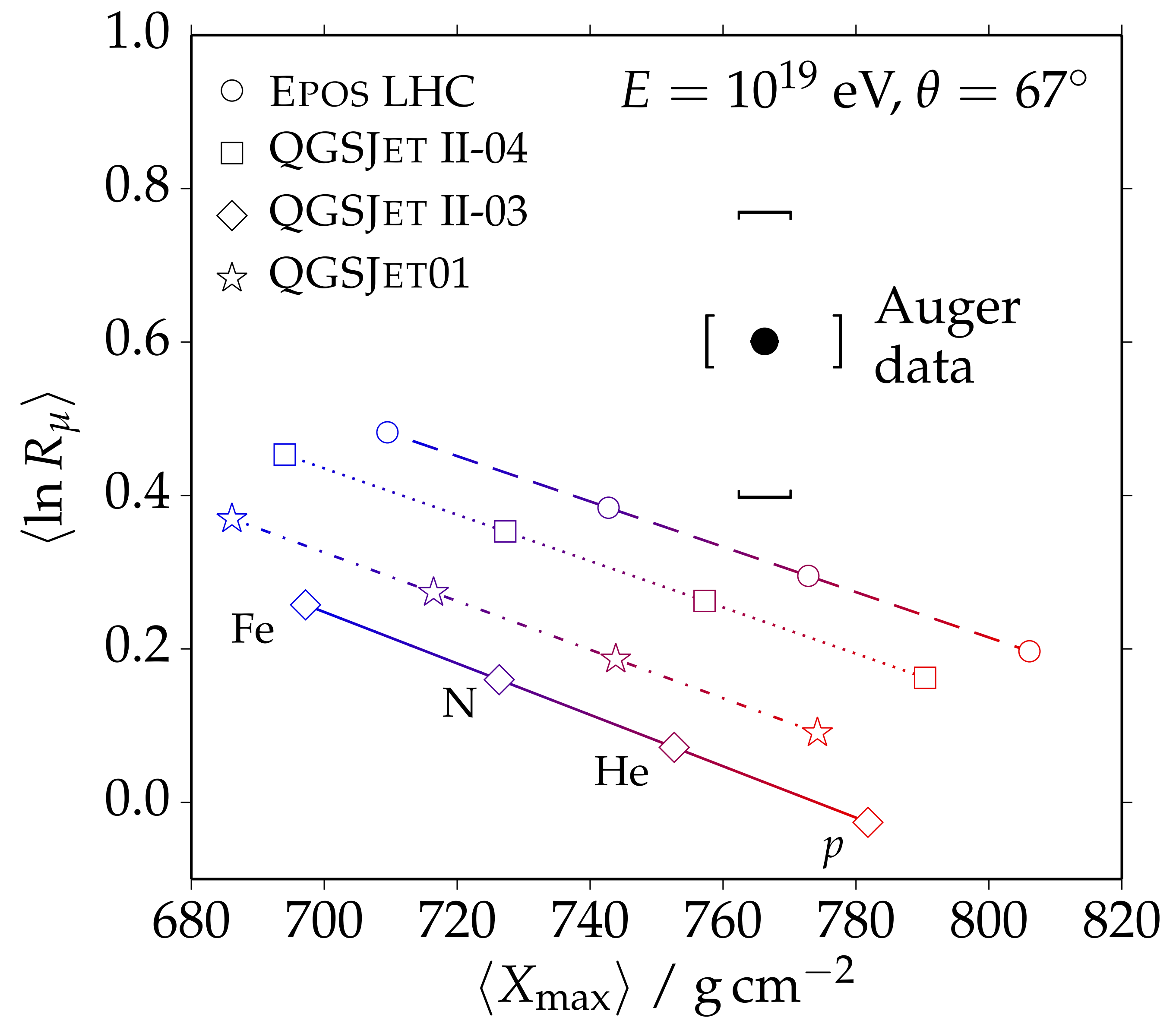


Deflection of protons
of beam halo by crystal

*(Ulrich ICRC 2015)*

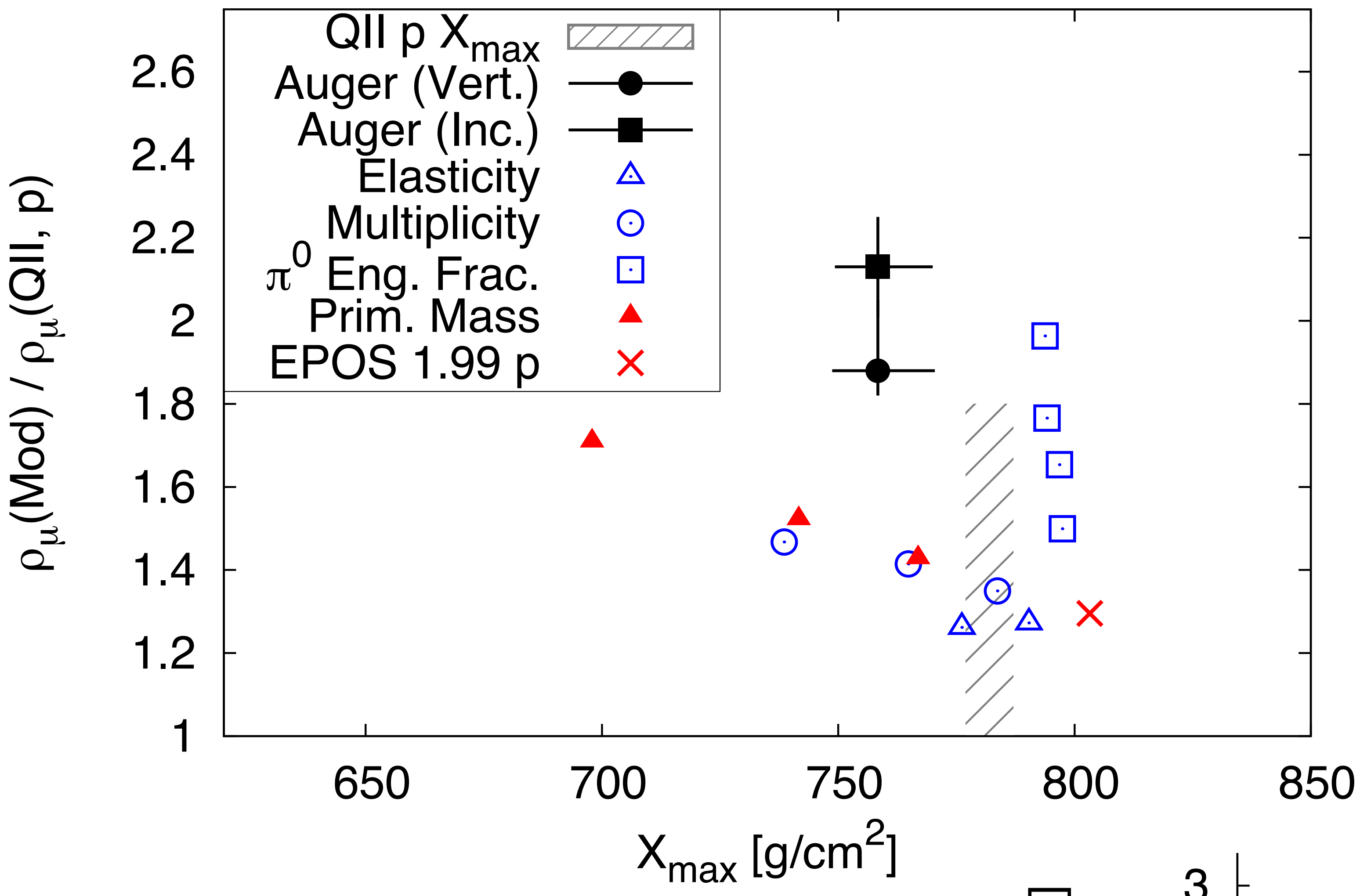
# Particle physics with the upgraded Auger Observatory

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



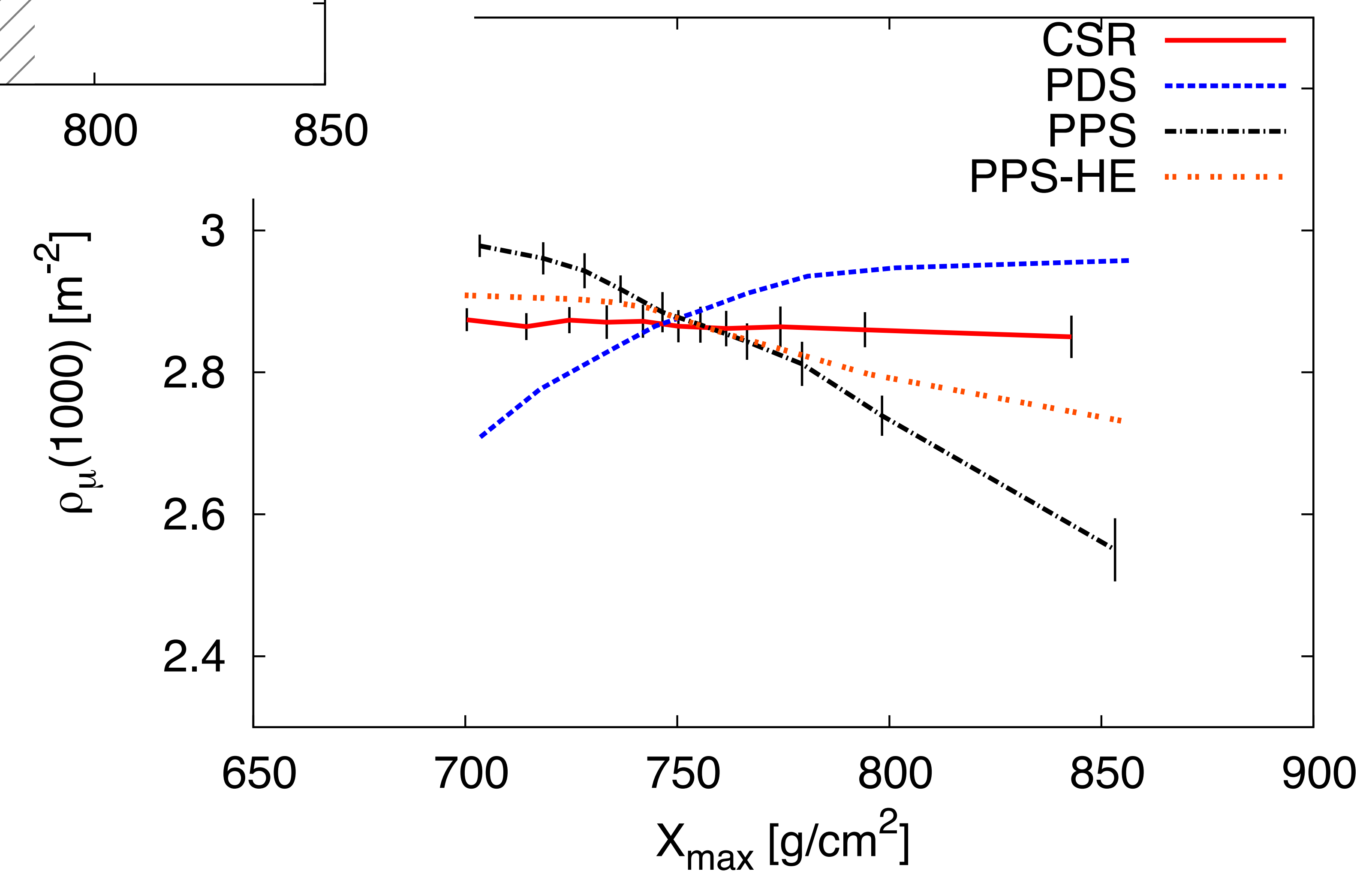

(Auger Collab. Phys. Rev. D91, 2015 & ICRC 2015)

Example of power of upgraded detectors



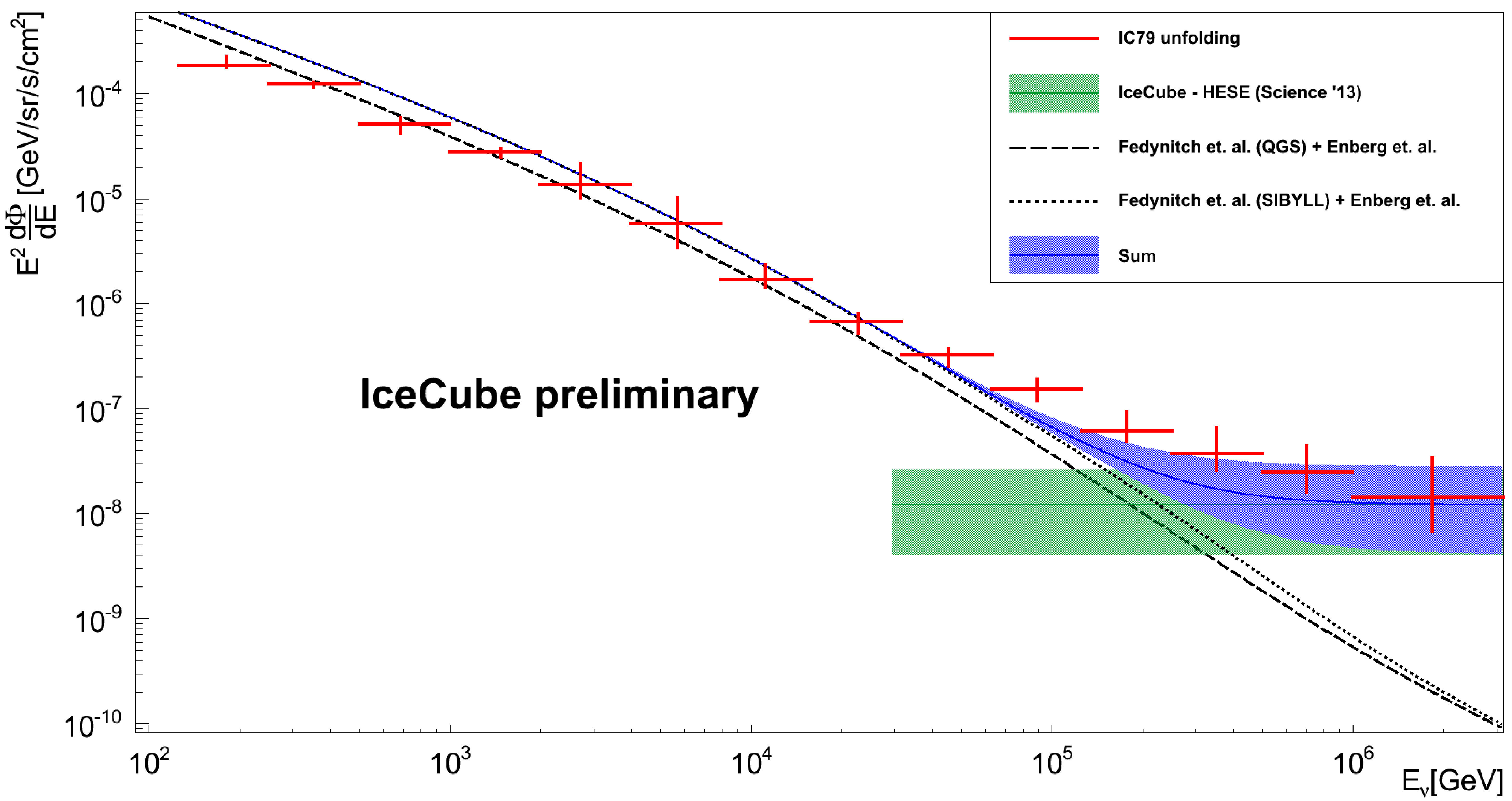

Correlations between $X_{max}$ and muon density

(Allen & Farrar, 1307.7131)

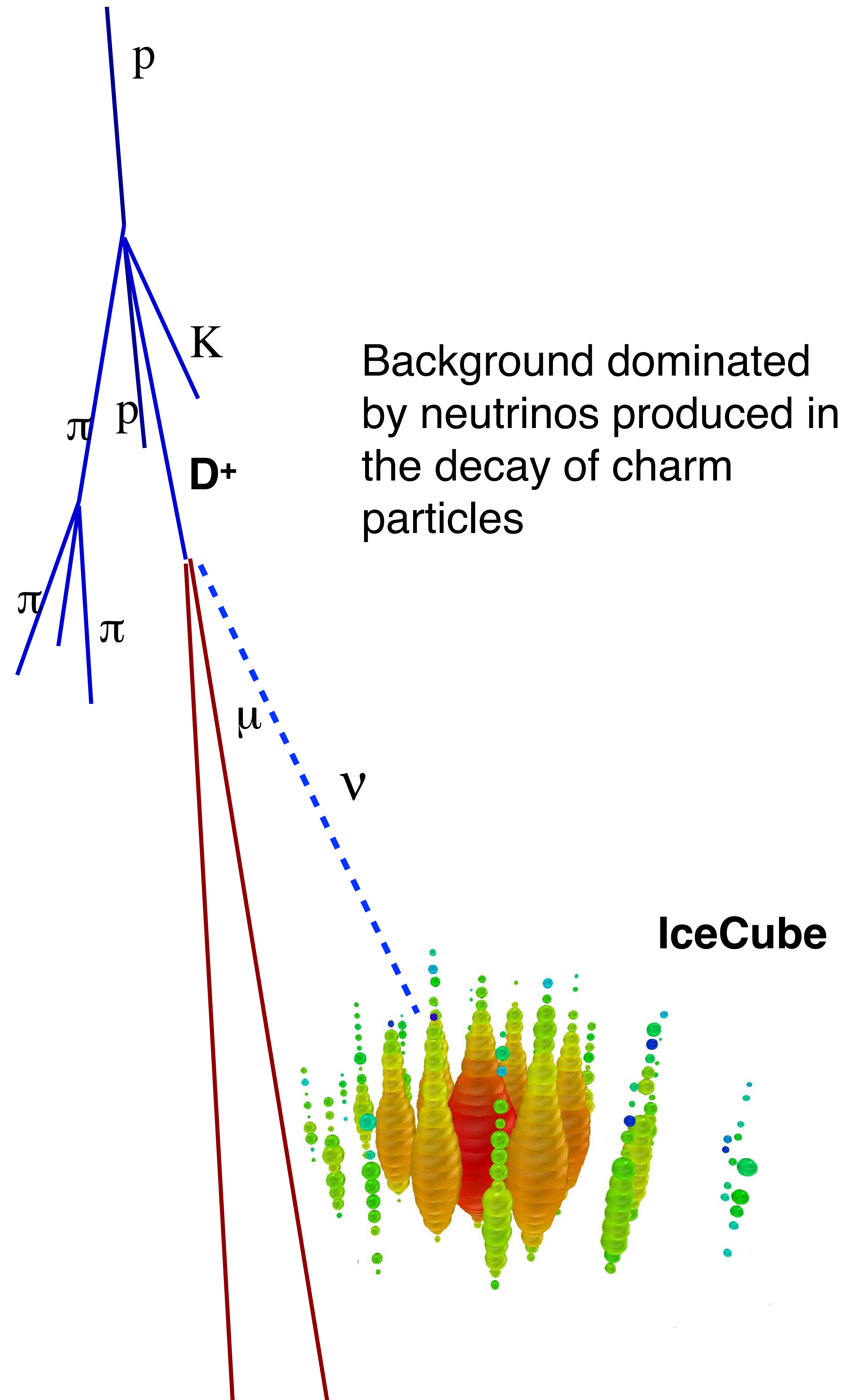


# Atmospheric neutrinos

# Atmospheric neutrinos as background to astrophysical signal




IceCube Analysis, ν−**induced muons**, TU Dortmund (Florian Scheriau, Martin Schmitz, Tim Ruhe, Wolfgang Rhode++), see their presentation @ Neutrino 2014



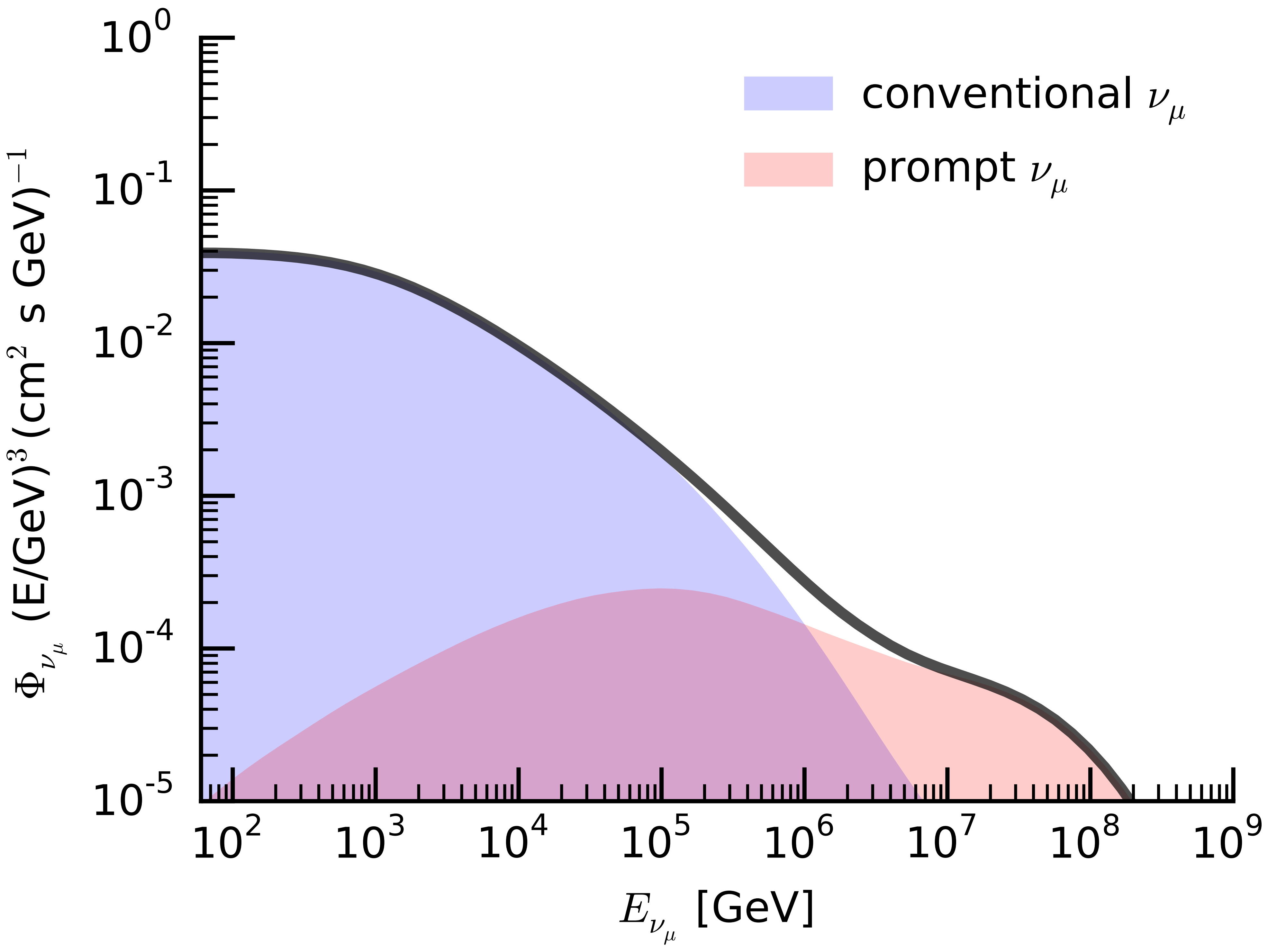

Background dominated by neutrinos produced in the decay of charm particles

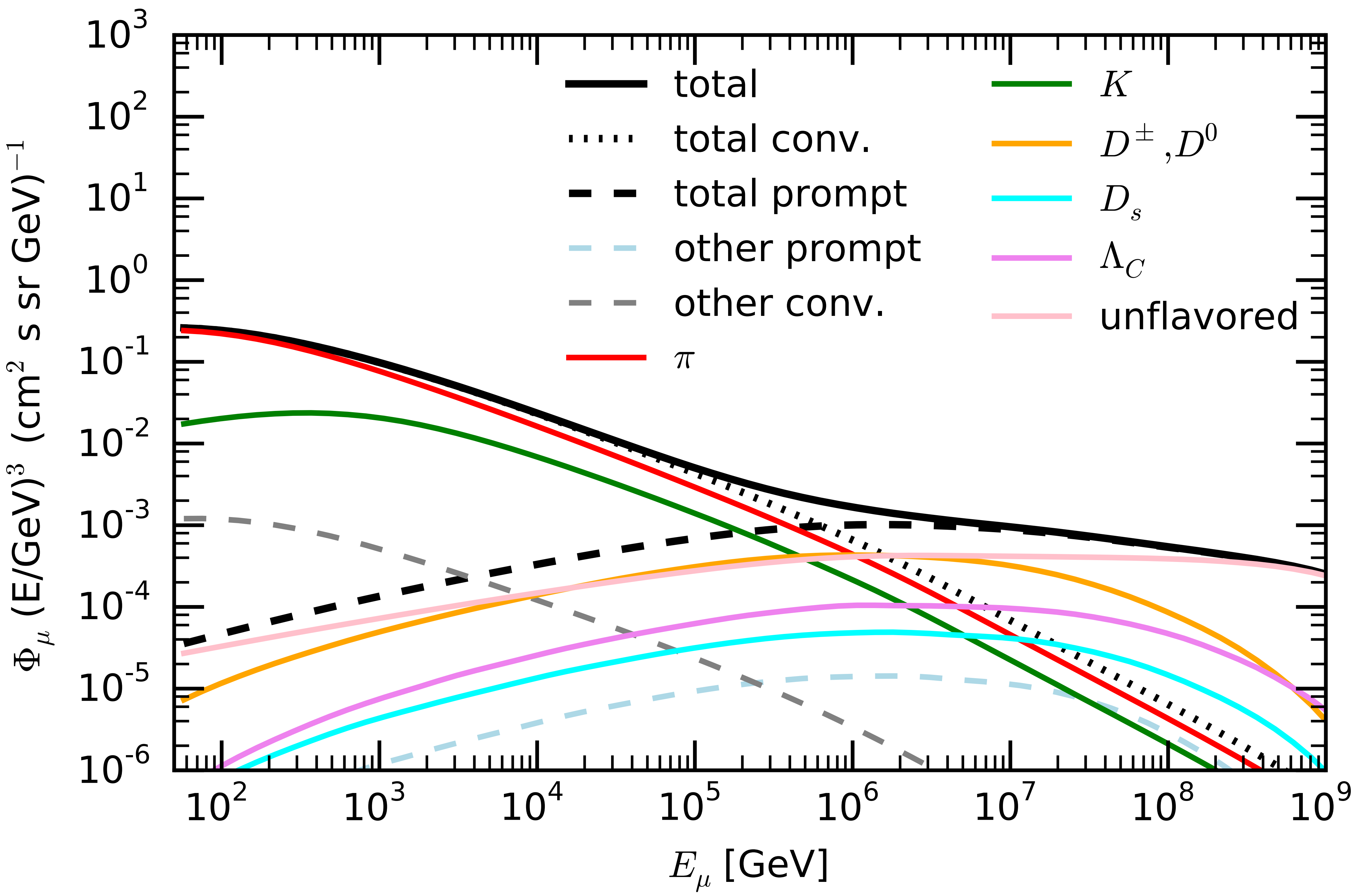
# Atmospheric neutrinos: conventional & prompt components

$$\frac{dN_p}{dE_p} = A \times E_p^{-\gamma} = \Phi_p(E_p)$$

$$\frac{dN_\nu}{dE_\nu} \sim \Phi_p(E_\nu) \int_0^1 x^{\gamma-1} \frac{dN_{p\to\pi^\pm}}{dx} dx$$

$$(x = E_{\pi^\pm}/E_p)$$

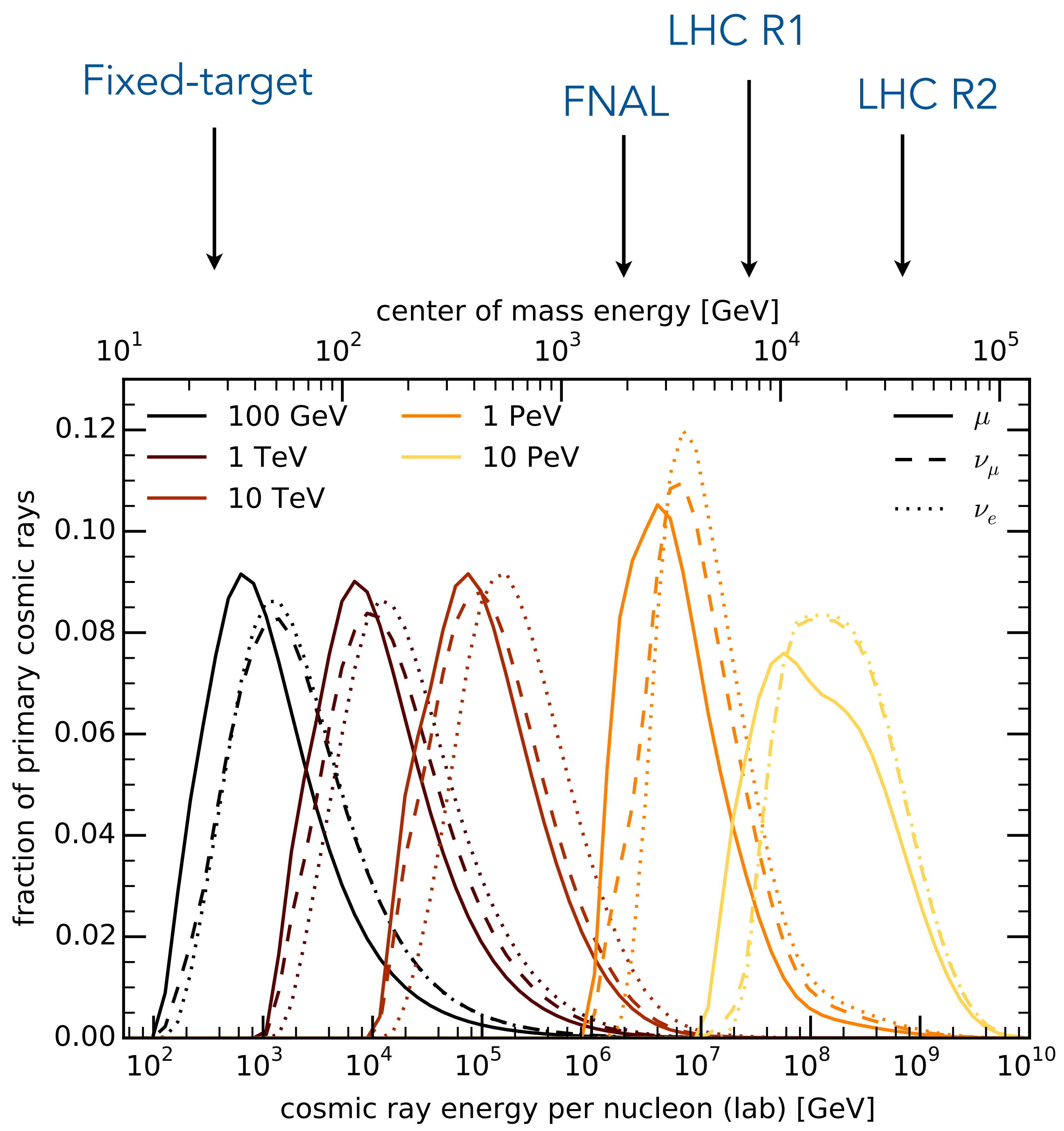


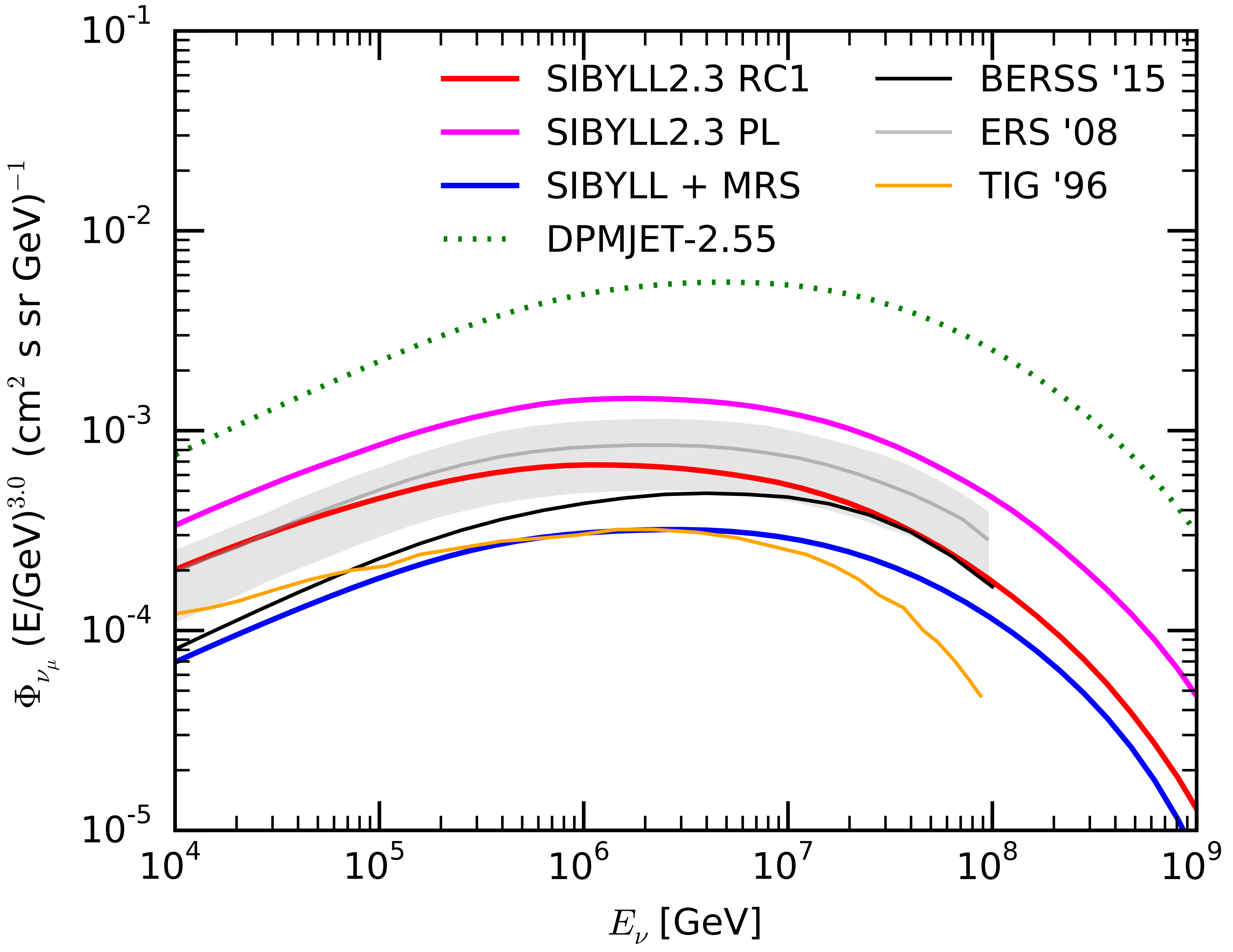


*(Fedynitch 2015)*

# Energies of importance for lepton fluxes




(Fedynitch 2015)




A measurement of absolute normalization contains information

non-perturbative effects

intrinsic charm

inclusive charm cross-section

partonic saturation

*BERSS: A. Bhattacharya, R. Enberg, M.H. Reno, I. Sarcevic and A. Stasto, arXiv:1502.01076*

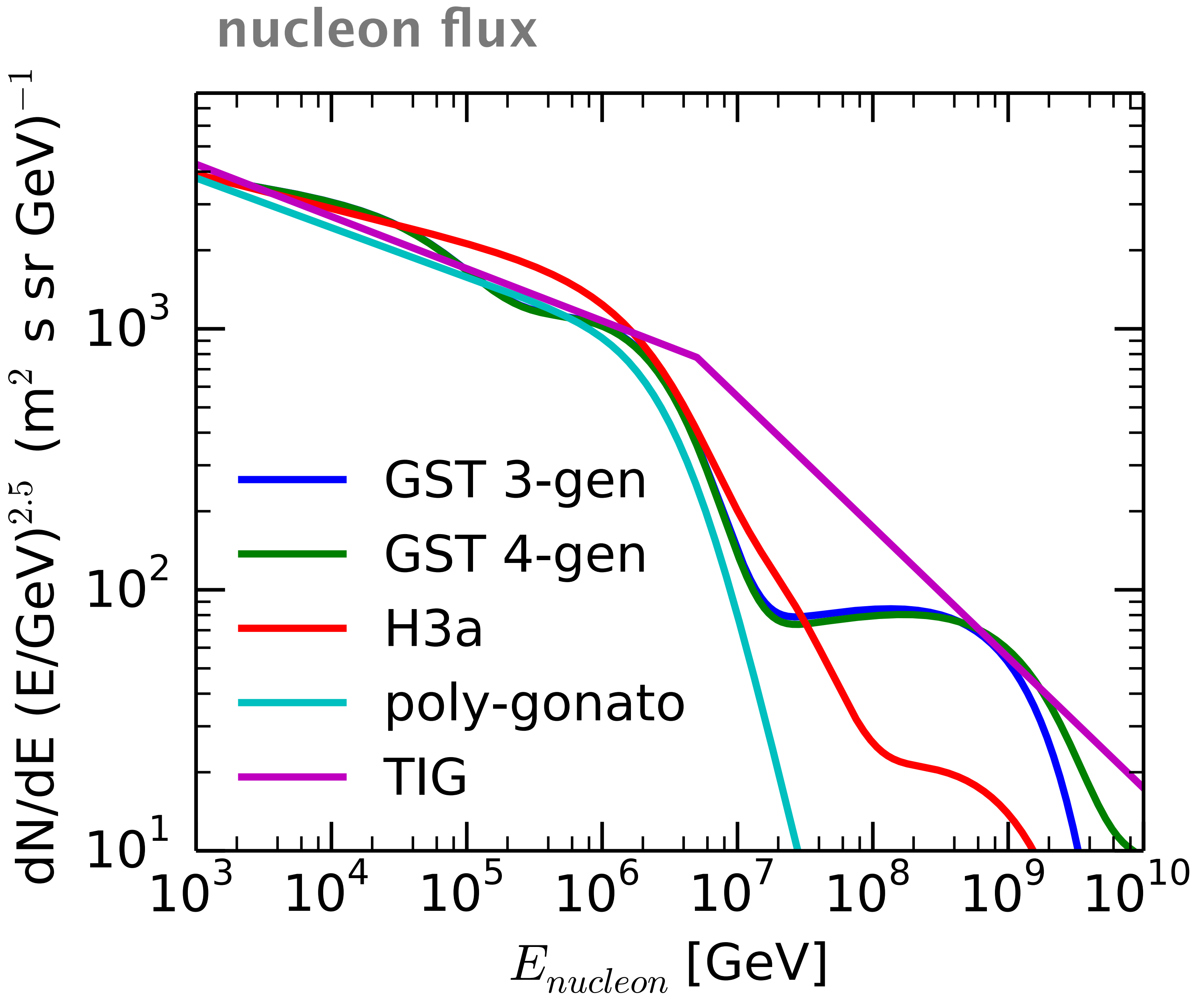
*ERS: R. Enberg, M. H. Reno, and I. Sarcevic, Phys. Rev. D 78, 43005 (2008).*

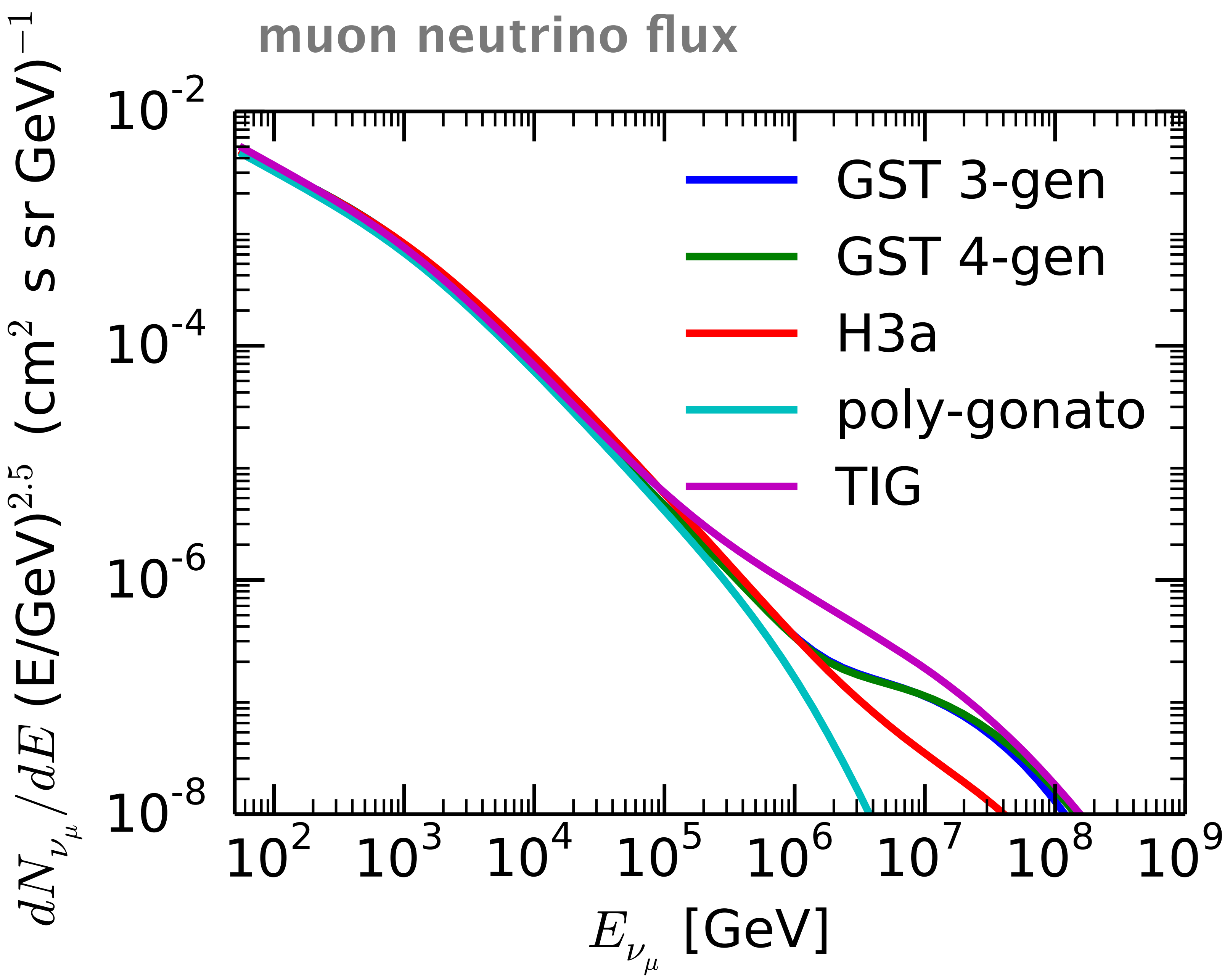
*MRS: A. D. Martin, M. G. Ryskin, and A. M. Stasto, Acta Physica Polonica B* ***34****, 3273 (2003).*

*SIBYLL: arXiv:1503.00544 and arXiv:1502.06353*

*TIG: M. Thunman, G. Ingelman, and P. Gondolo, Astroparticle Physics 5, 309 (1996).*

# Additional complication: dependence on primary flux




Inclusive nucleon flux important for lepton flux

*TIG - M. Thunman, G. Ingelman, and P. Gondolo, Astroparticle Physics 5, 309 (1996).*

*poly-gonato - [1] J. R. Hörandel, Astroparticle Physics 19, 2 (2003)*

*GST - T. K. Gaisser, T. Stanev, and S. Tilav, arXiv:1303.3565, (2013).*

*H3a - T. K. Gaisser, Astroparticle Physics 35, 801 (2012).*

*(Fedynitch 2015)*

# Summary

- Composition interpretation essential for understanding astrophysics
- LHC data of central importance for more reliable composition interpretation
- Very good collaboration between members of CR community and LHC/HEP
- Feedback from air shower observations, CR int. models very successful at LHC
- Cosmic ray data at $10^{19.5}$ eV most likely not protons (except exotic physics)
- Pion interactions as major uncertainty for muon discrepancy identified

  *Need measurement of energy dependence of $\rho^0$ production*

  *Consistent description at lower energy, transition to direct measurements*
- Forward charm production (theory and experiment) of increasing interest
- Primary flux composition also directly linked to inclusive lepton fluxes