Extensive Air Showers and Hadronic Interactions

Ralph Engel, for the Pierre Auger Collaboration

Karlsruhe Institute of Technology (KIT)

PIERRE AUGER OBSERVATORY

(photograph by S. Saffi)

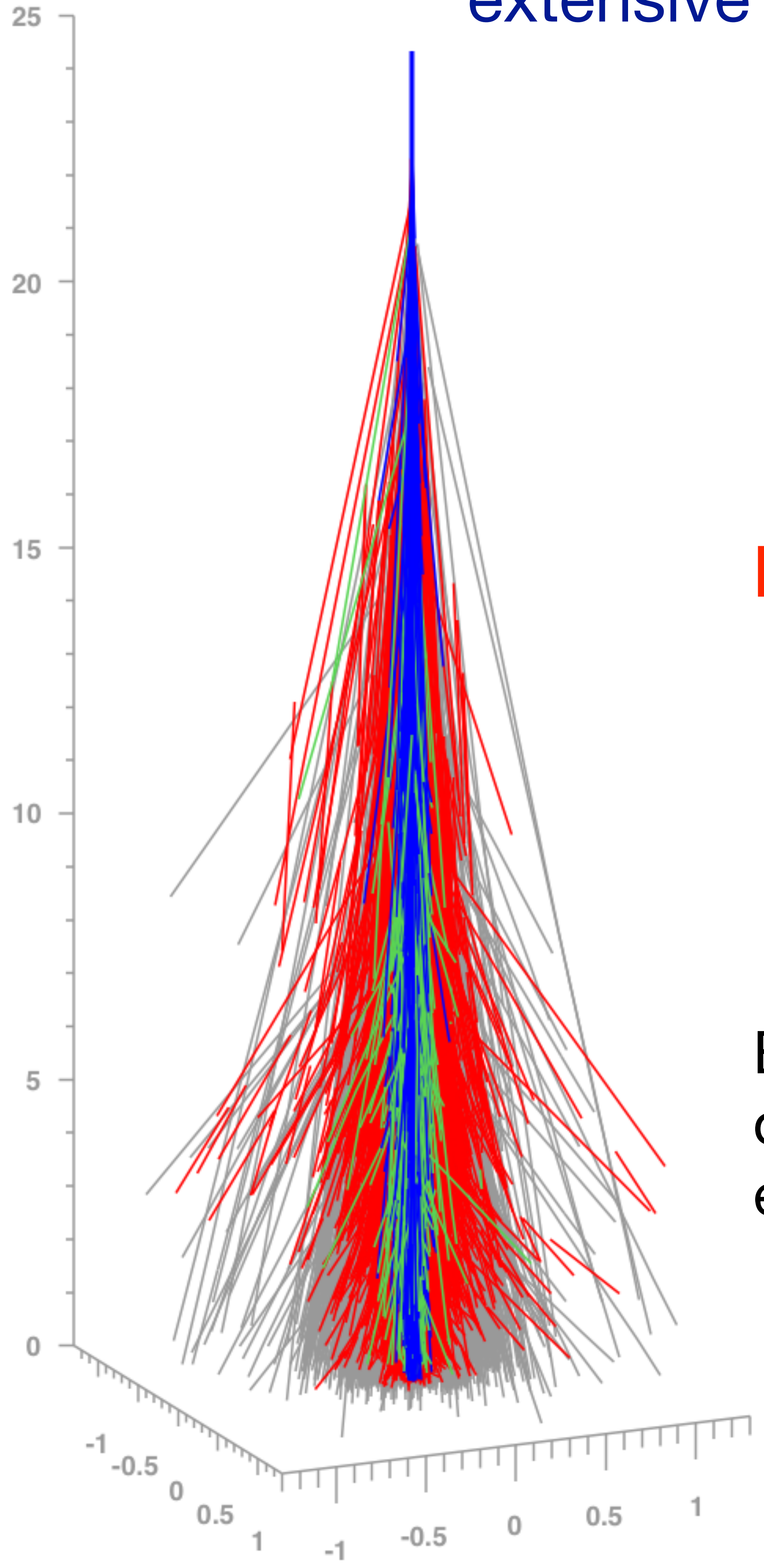
The first cosmic particle of ultra-high energy

VOLUME 10, NUMBER 4 PHYSICAL REVIEW LETTERS 15 FEBRUARY 1963

EVIDENCE FOR A PRIMARY COSMIC-RAY PARTICLE WITH ENERGY 10^{20} eV†

John Linsley
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 10 January 1963)

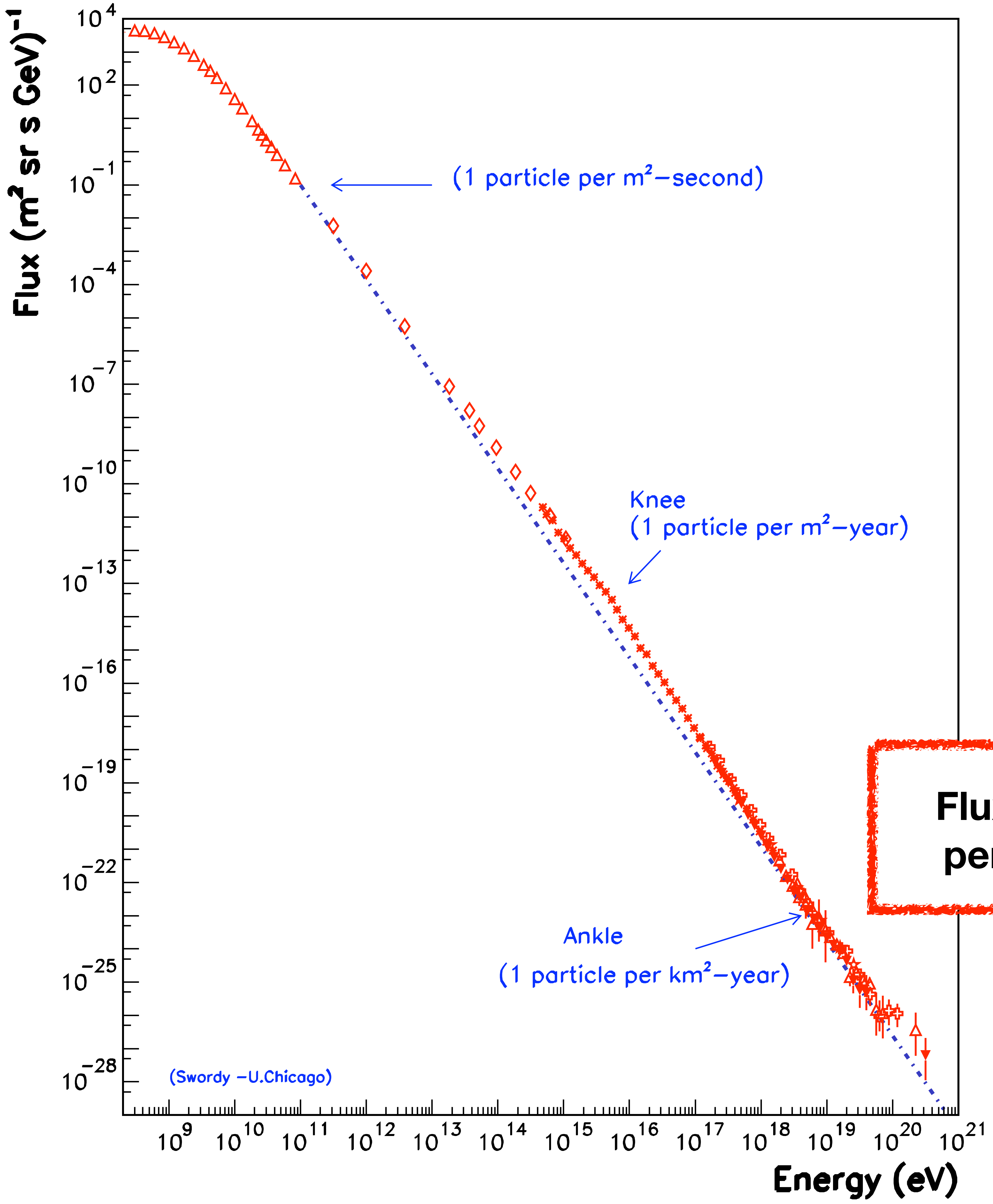
Cascade of secondary particles: extensive air shower



E = 10^{20} eV

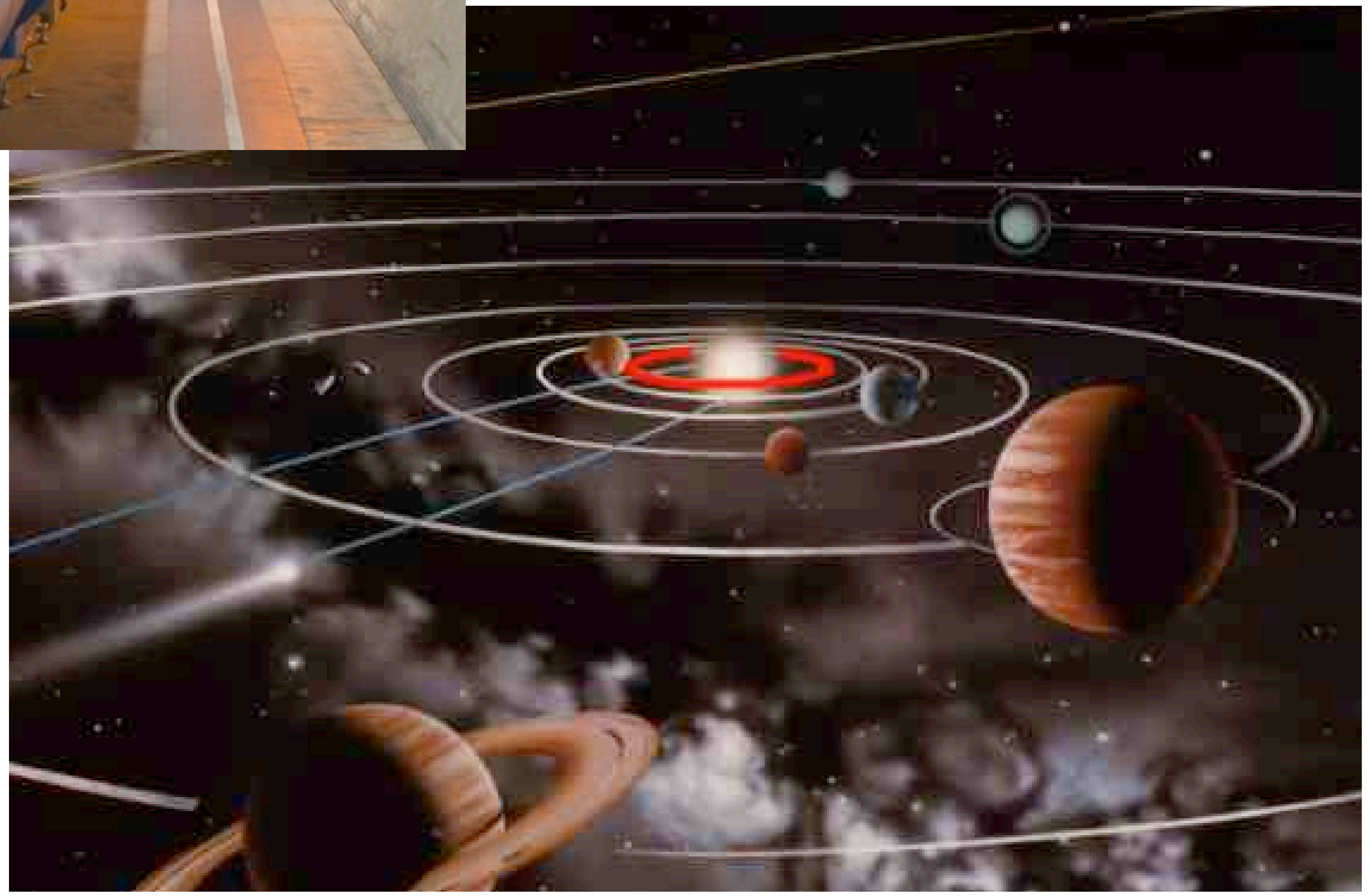
Energy conservation, overall energy estimate robust

Energy spectrum of cosmic rays – 10^{20} eV



Flux below 1 particle per km² per century

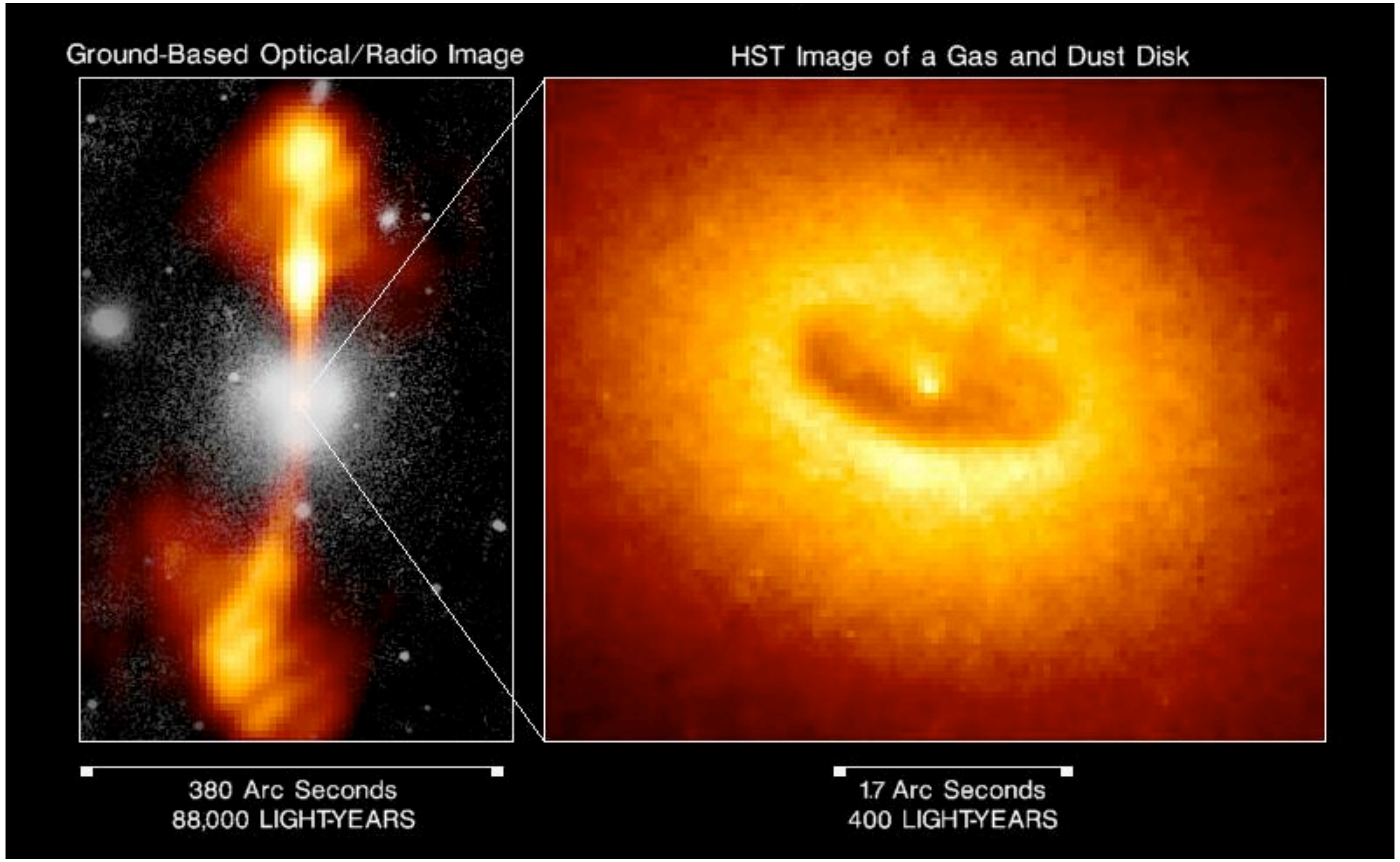
Large Hadron Collider (LHC), 27 km circumference, superconducting magnets



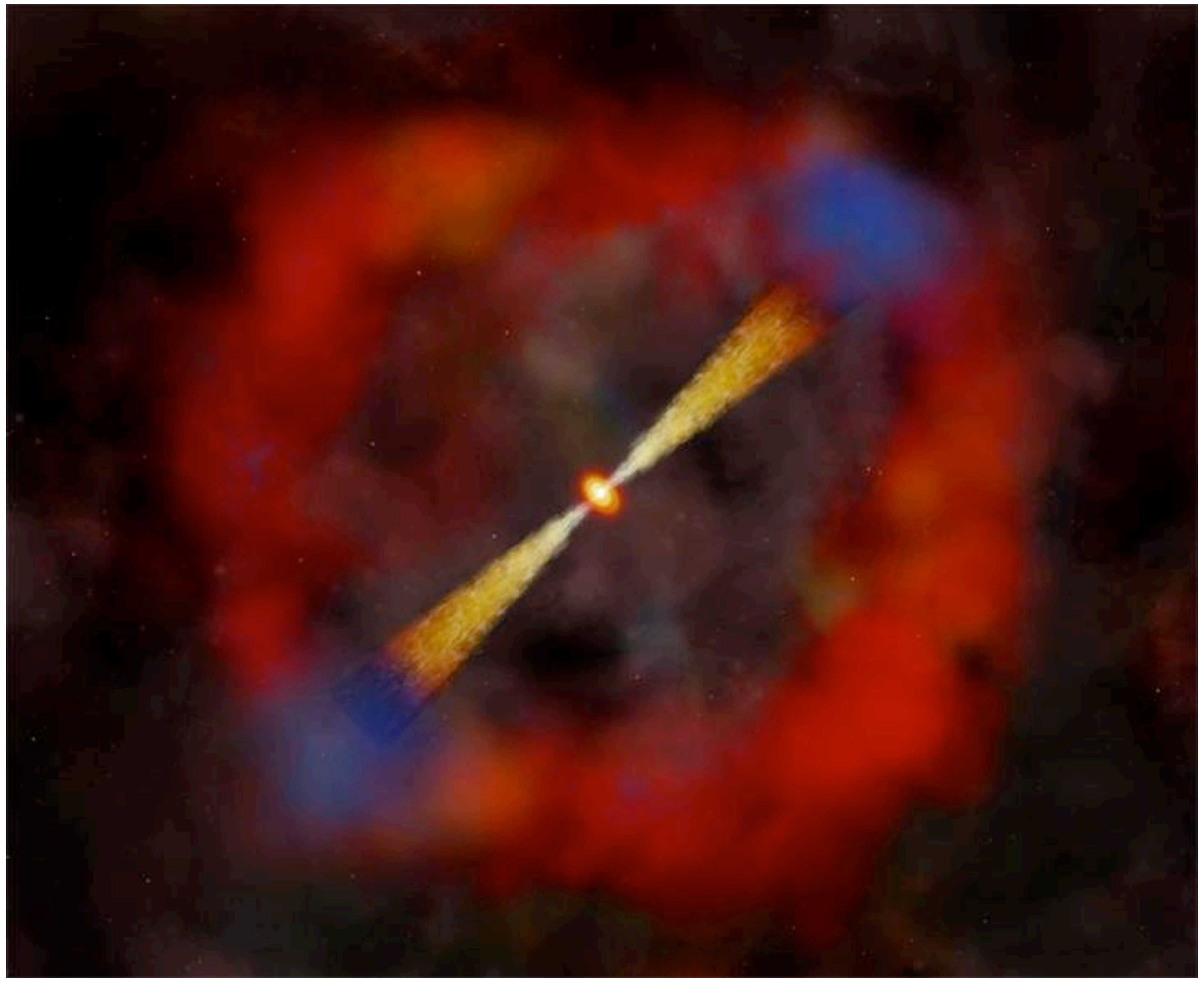
Gamma factor ~10^{11}

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

Classic models: Diffusive shock acceleration



Active Galactic Nuclei (in jets or in radio lobes)



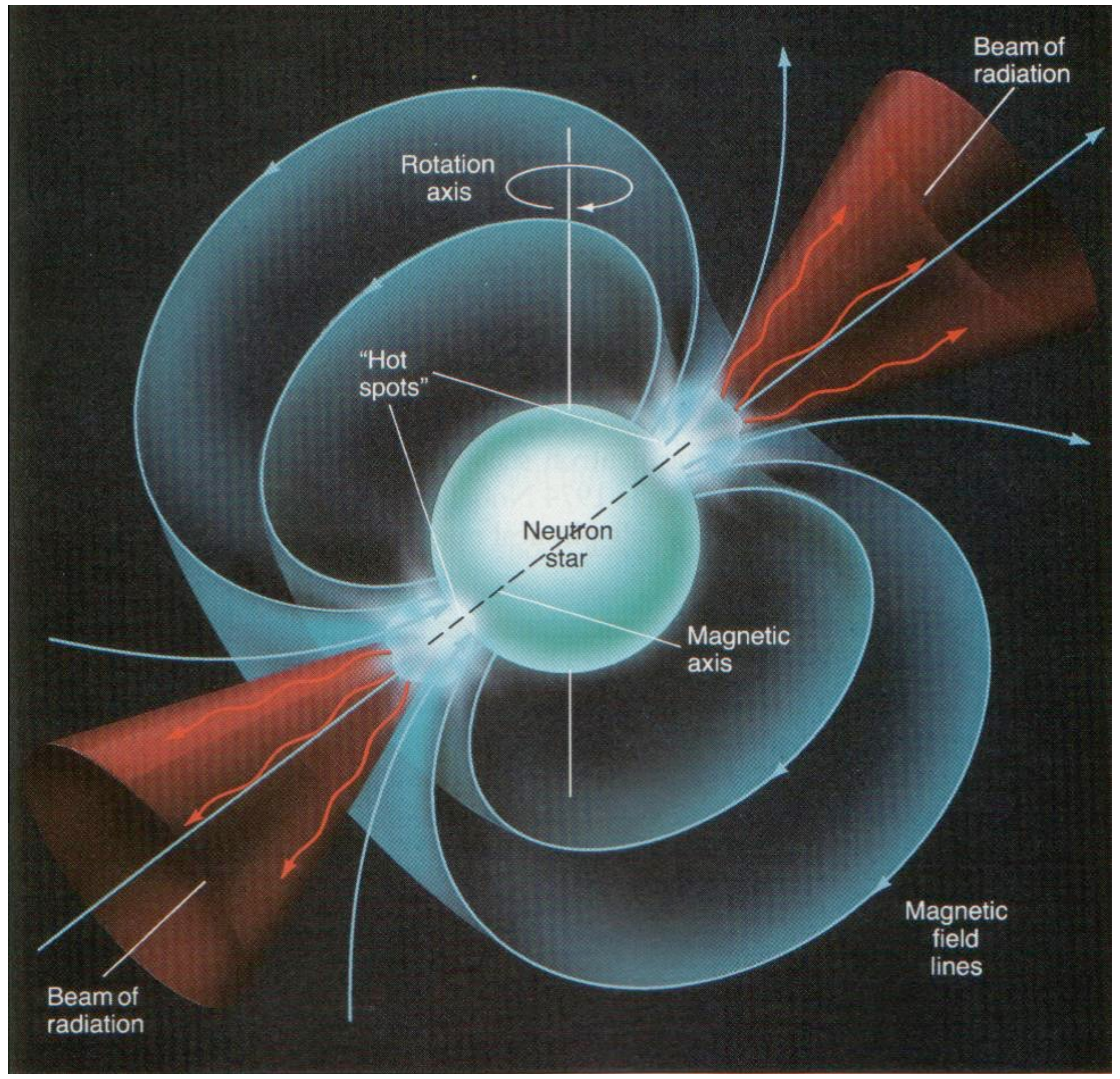
Gamma ray bursts (GRBs)

Fermi acceleration at shock fronts of plasmas

$$\frac{\mathrm{d}N_{\mathrm{inj}}}{\mathrm{d}E} \sim E^{-2}$$

Alternative source scenarios

Inductive acceleration

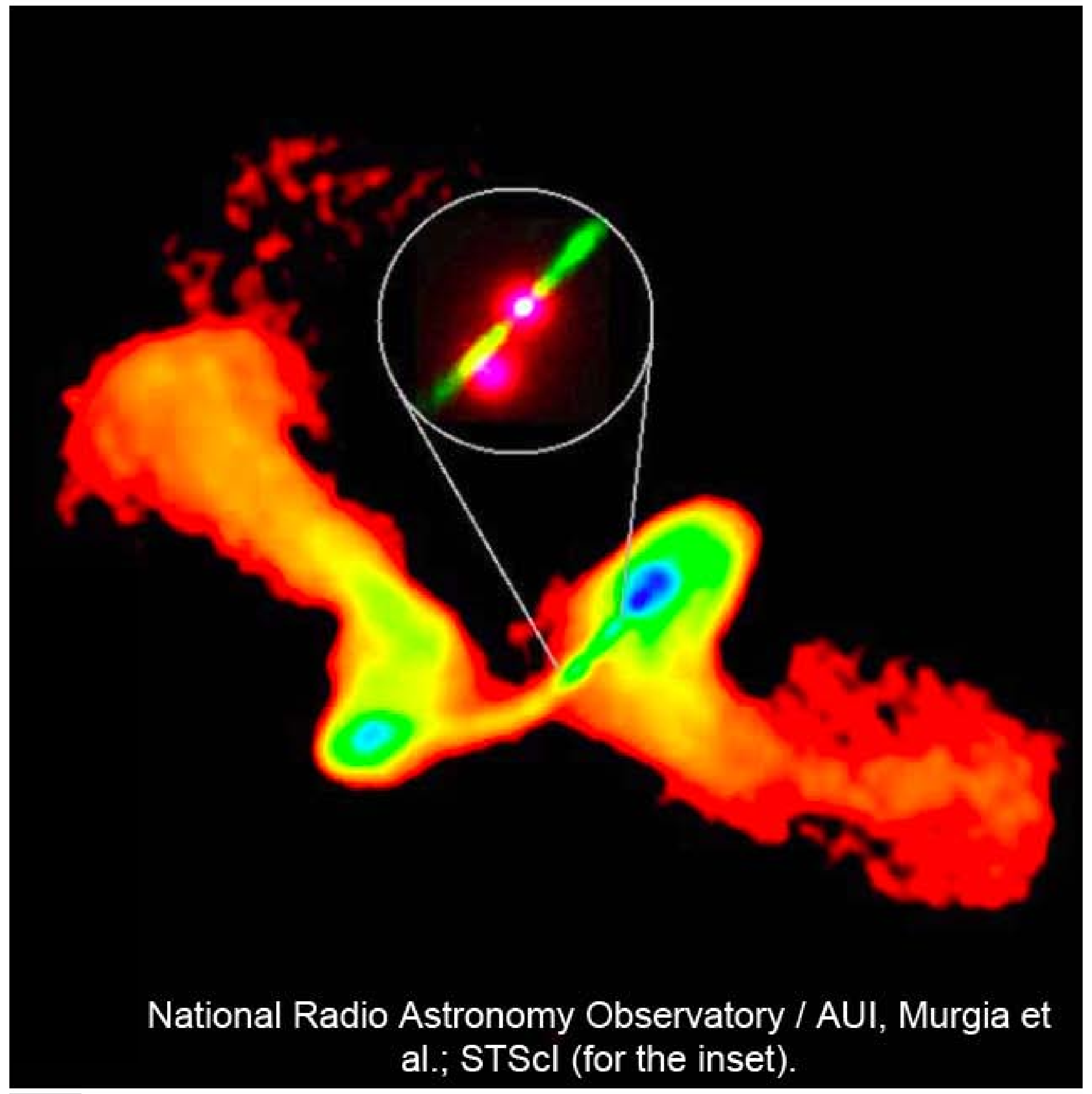


Rapidly spinning neutron stars

$$\frac{dN_{inj}}{dE} \sim E^{-1} \left(1 + \frac{E}{E_g}\right)^{-1}$$

Wake field acceleration in plasma jets

Single (relativistic) reflection



Spin flip of BH in AGN

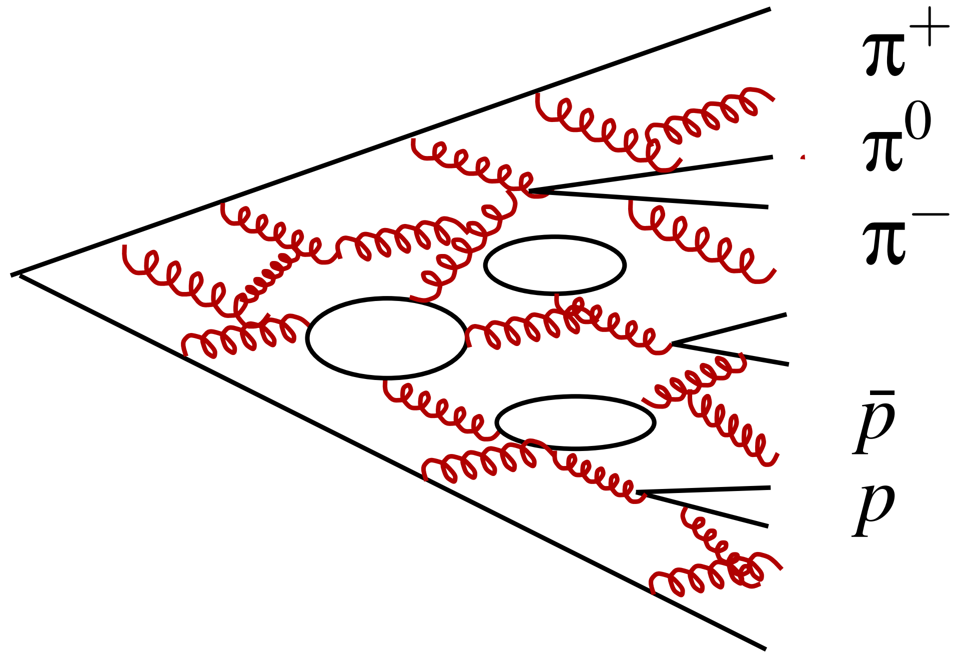
Tidal disruption events (TDEs)

$$E_{max} \sim \Gamma^2 E_{inj}$$

New particle physics (top-down scenarios)

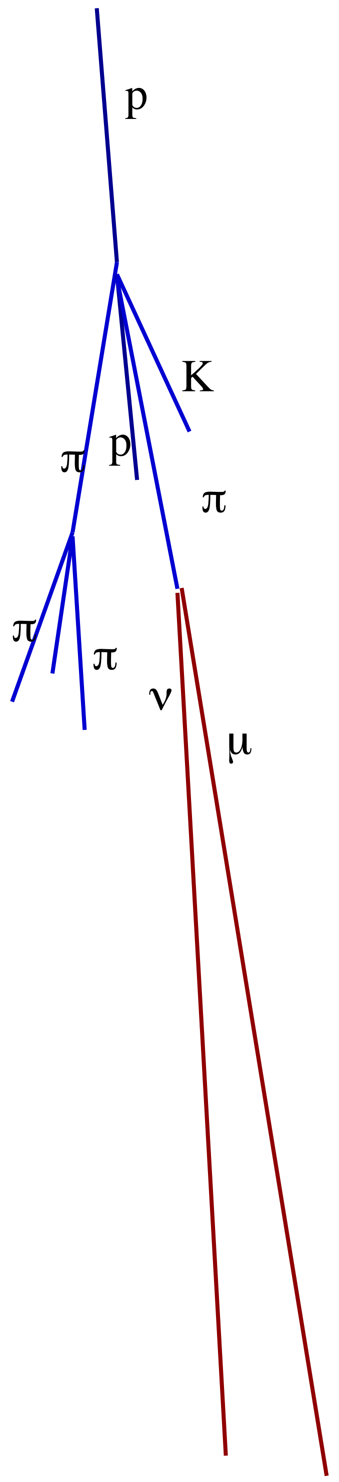
X particles from:
- topological defects
- monopoles
- cosmic strings
- cosmic necklaces
- .....

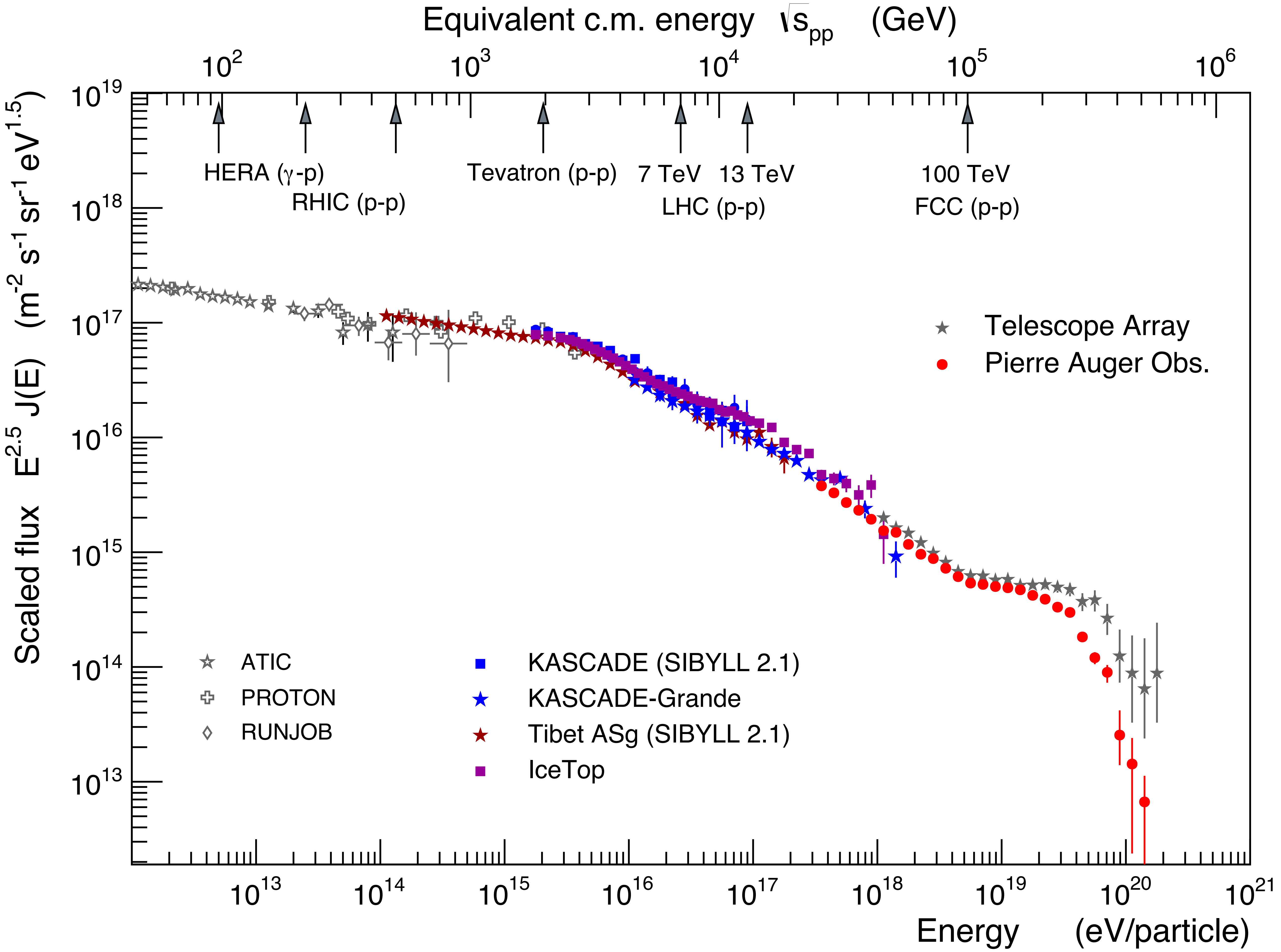
Super-heavy objects from Early Universe that decay slowly (by construction)
M_X ~ 10^{23} - 10^{24} eV

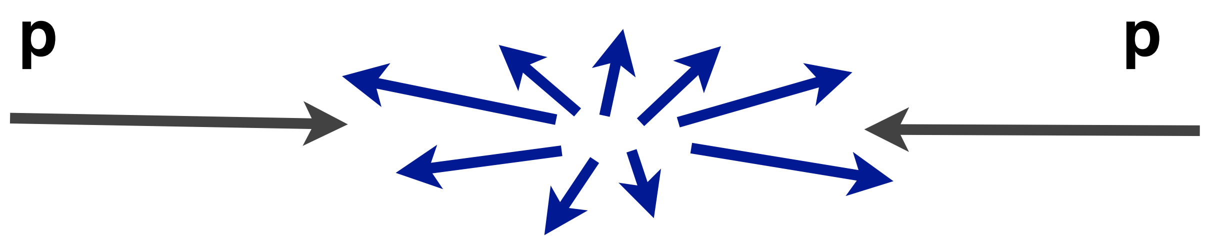


large fluxes of photons and neutrinos

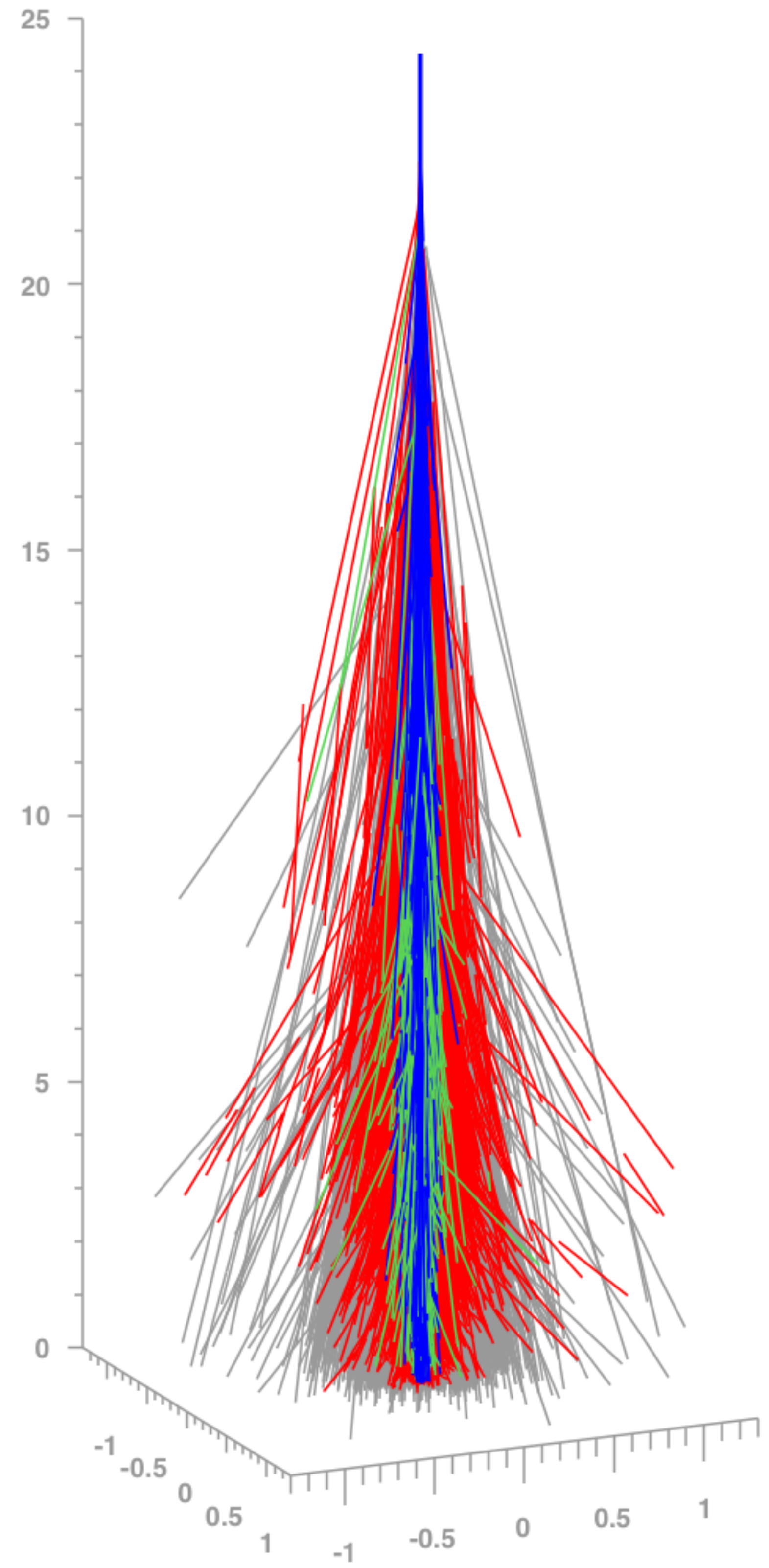
Cosmic ray flux and interaction energies



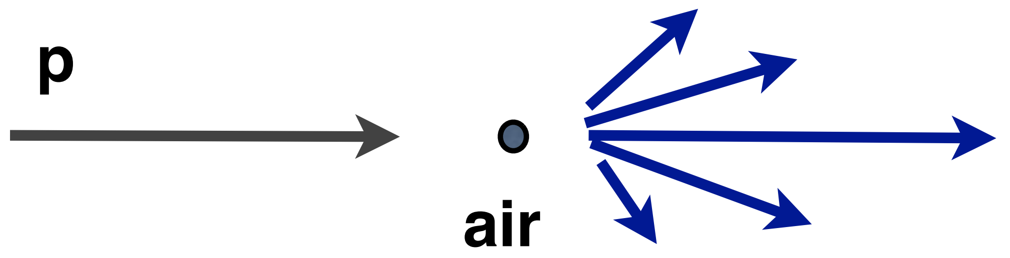




Center-of-mass energy

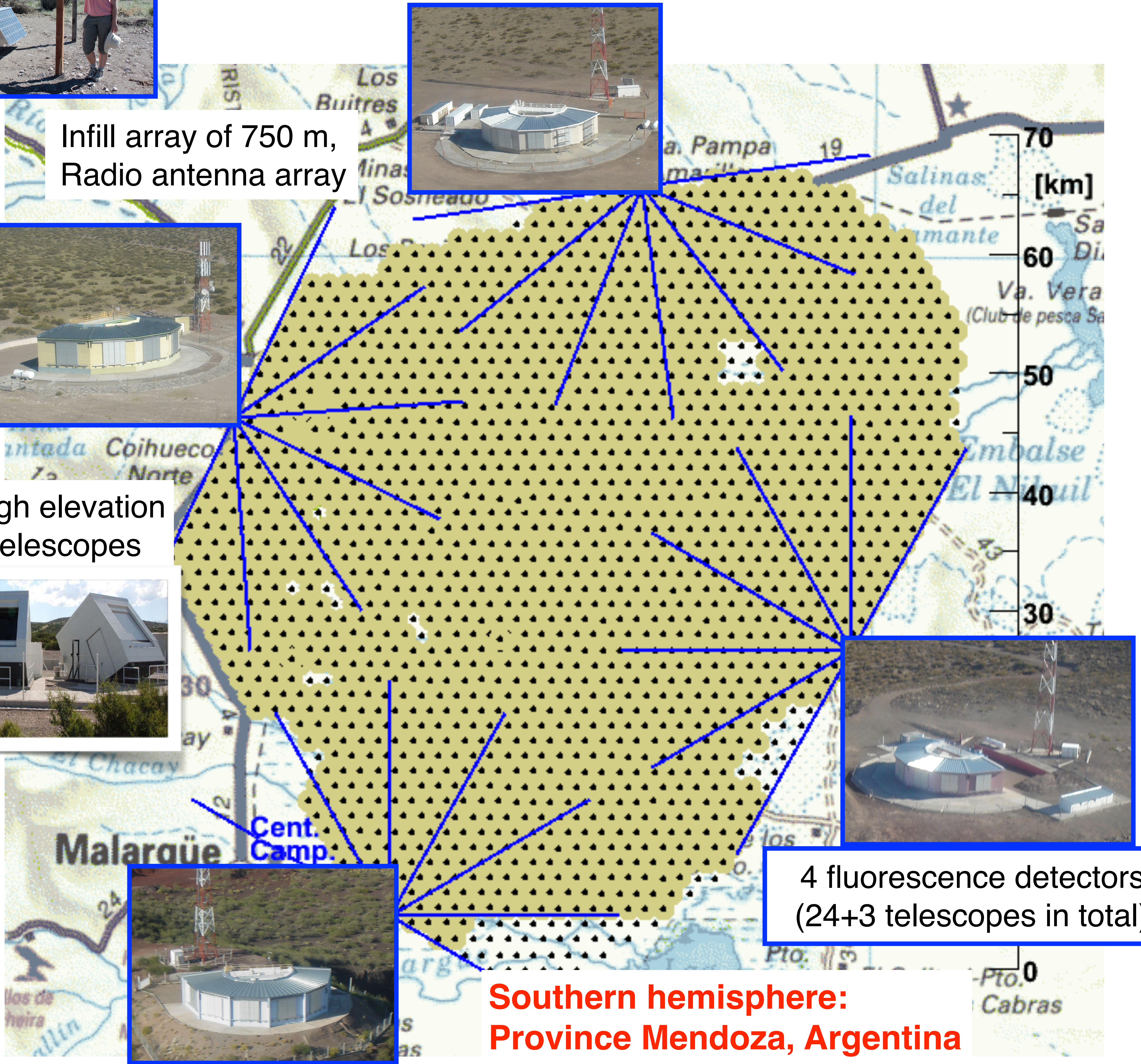


Laboratory energy



The Pierre Auger Observatory (3000 km^2)

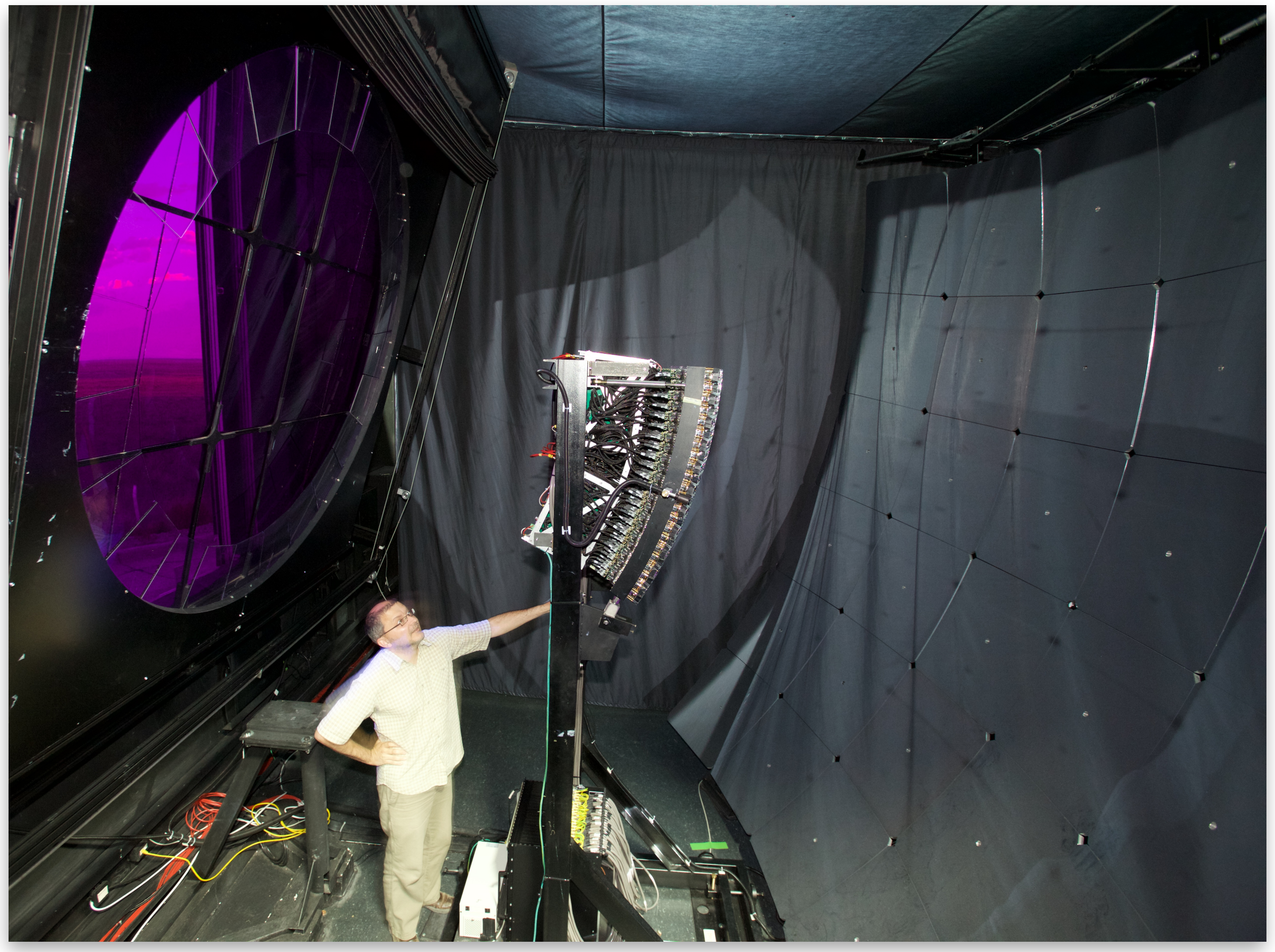
Infill array of 750 m,
Radio antenna array



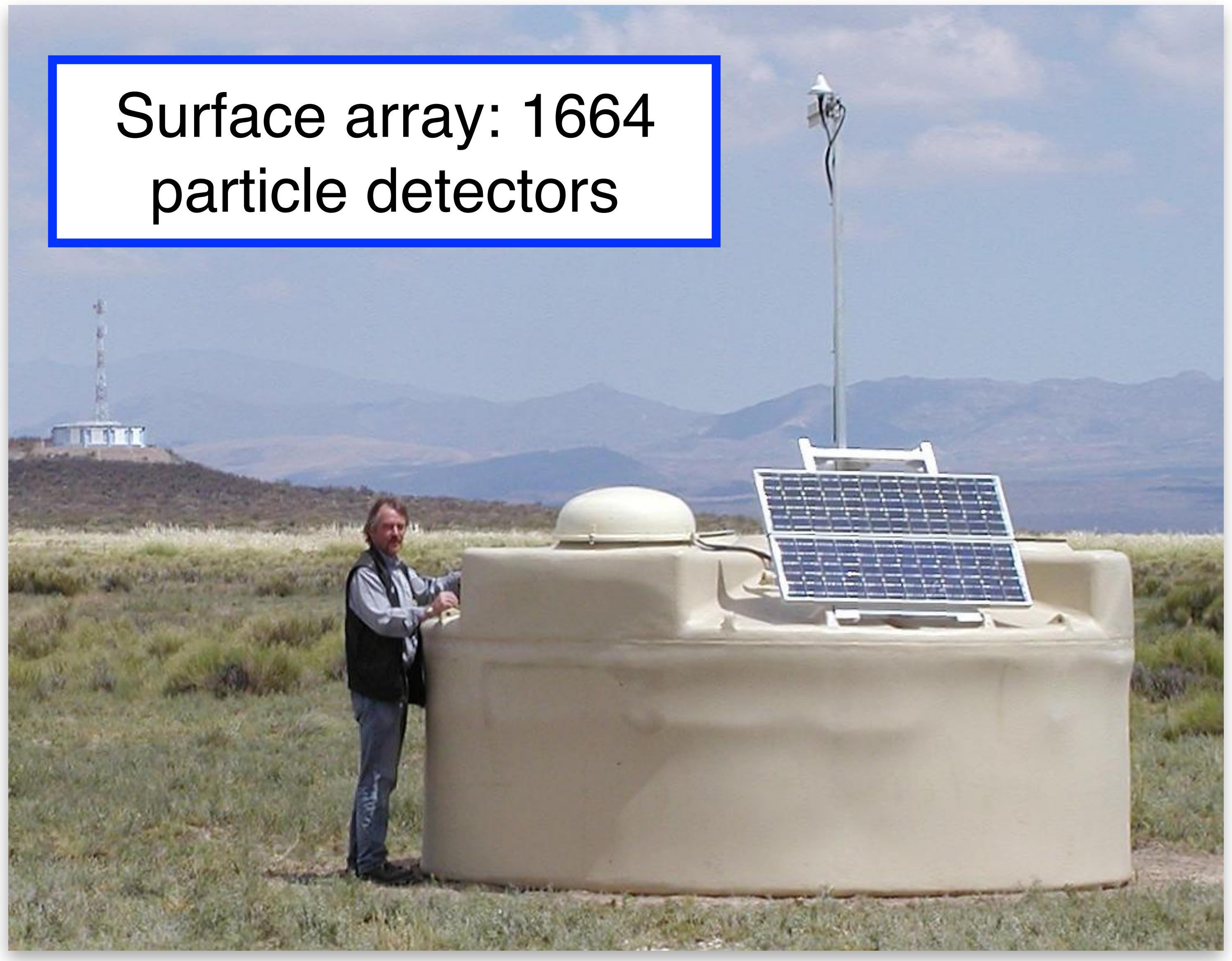
High elevation telescopes

4 fluorescence detectors (24+3 telescopes in total)

Southern hemisphere: Province Mendoza, Argentina



Surface array: 1664 particle detectors




1.5 km


Fluorescence telescopes
Particle detectors
10 m² area, 1.20 m high
12 tons of water

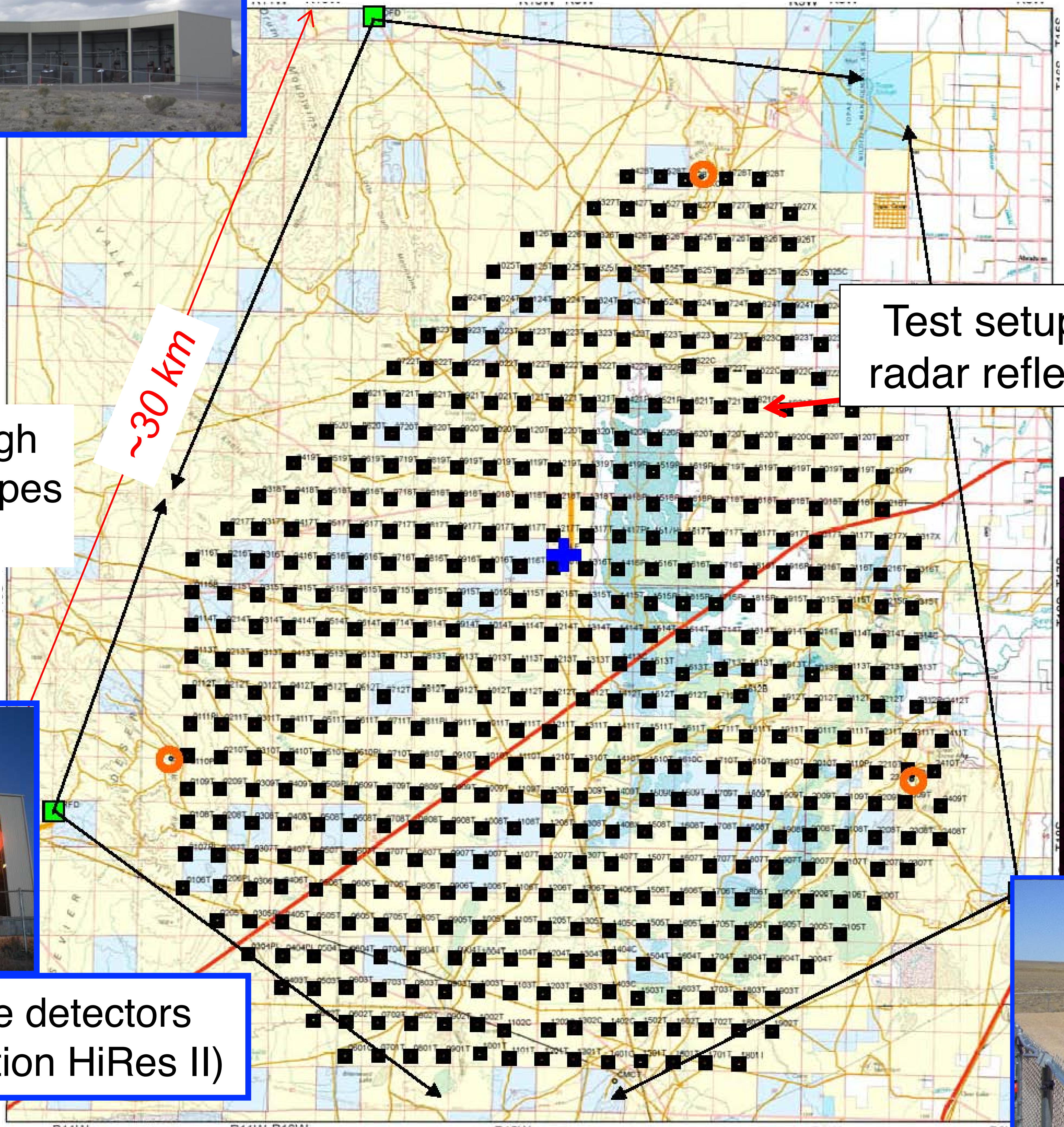
Telescope Array (TA, 700 km²)

Middle Drum: based on HiRes II

TALE (TA low energy extension)

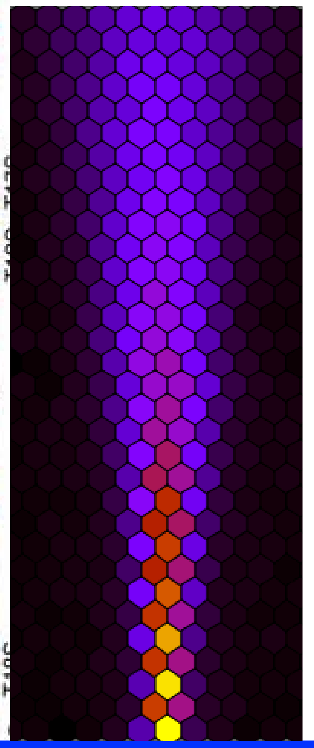
LIDAR
Laser facility

Infill array and high
elevation telescopes

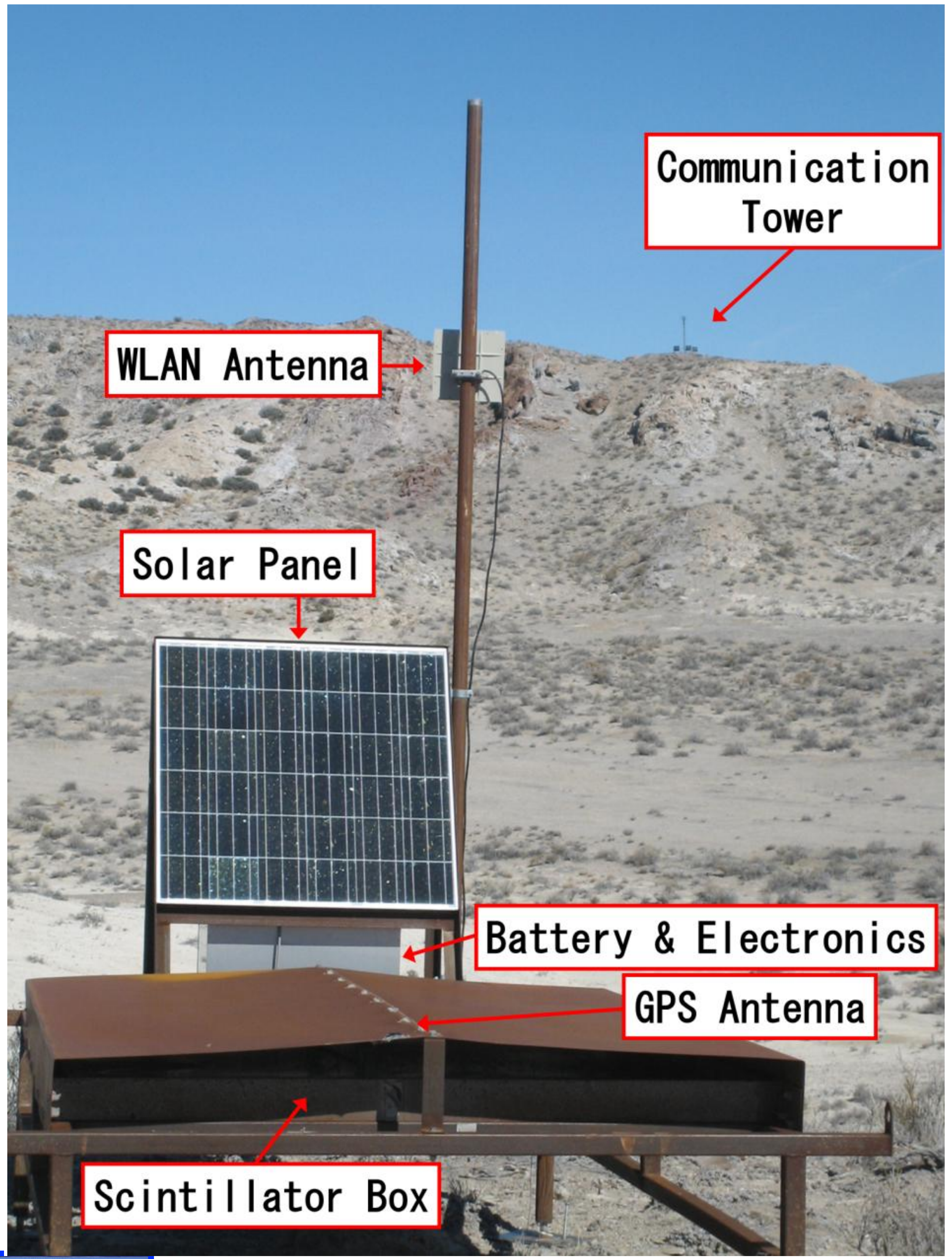


Test setup for
radar reflection

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



Electron light
source (ELS):
~40 MeV



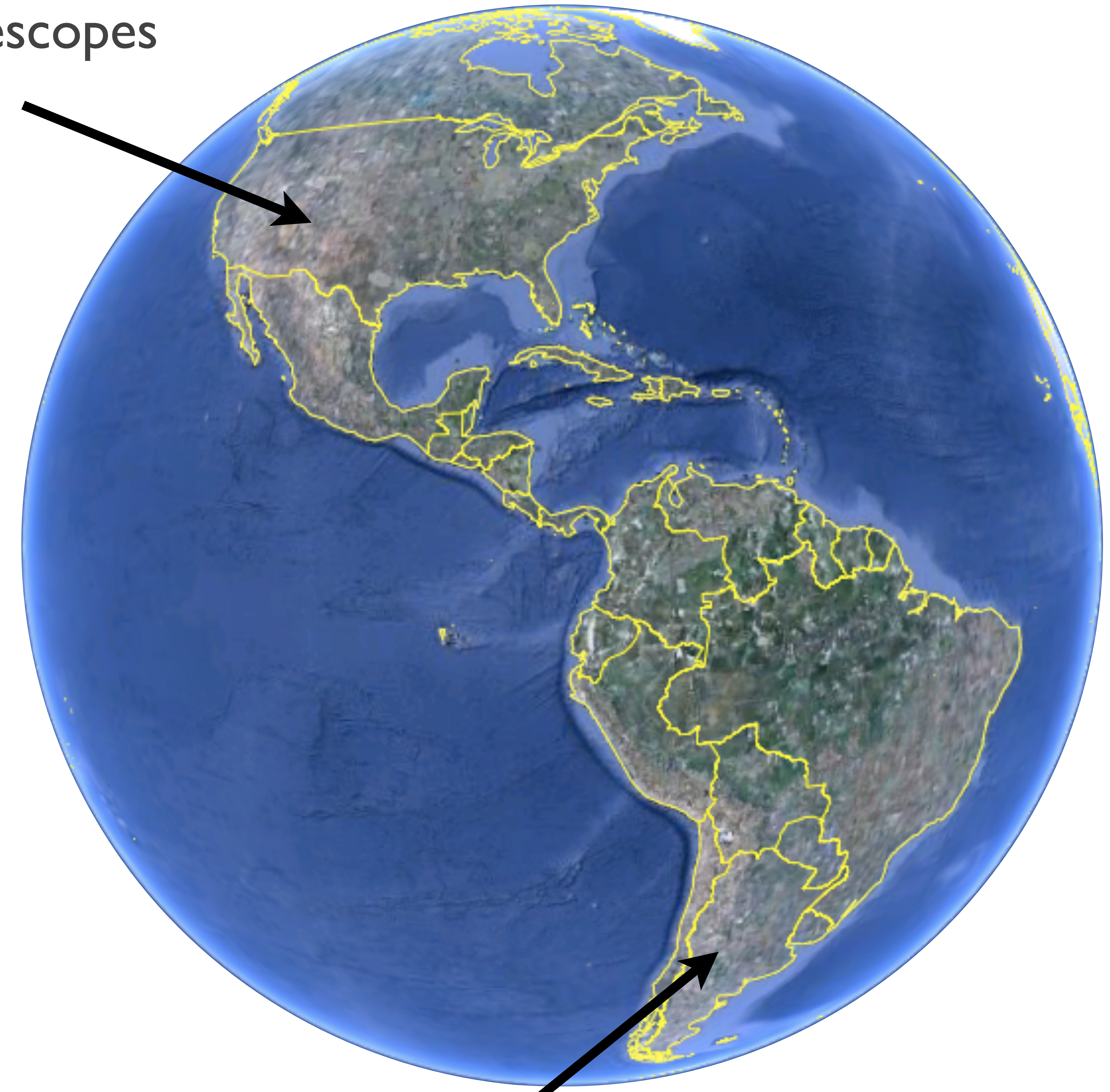
507 surface detectors:
double-layer scintillators
(grid of 1.2 km, 680 km²)

Northern hemisphere: Utah, USA

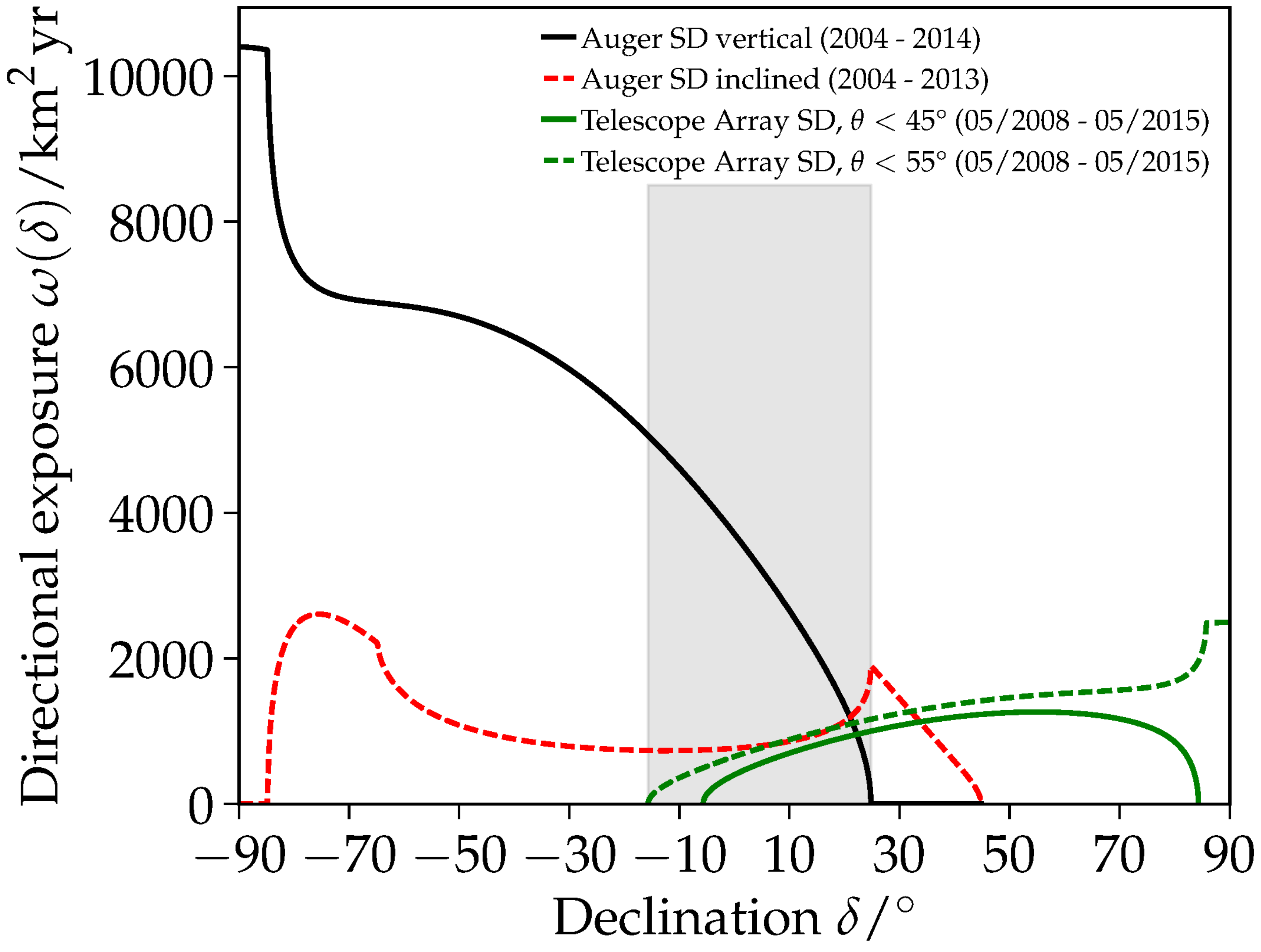
Pierre Auger Observatory and Telescope Array

Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km²
36 fluorescence telescopes

HiRes I (mono) ~ 5 x 10³ km² sr yr @ 10²⁰ eV
AGASA: 1.6 x 10³ km² sr yr



Together full sky coverage



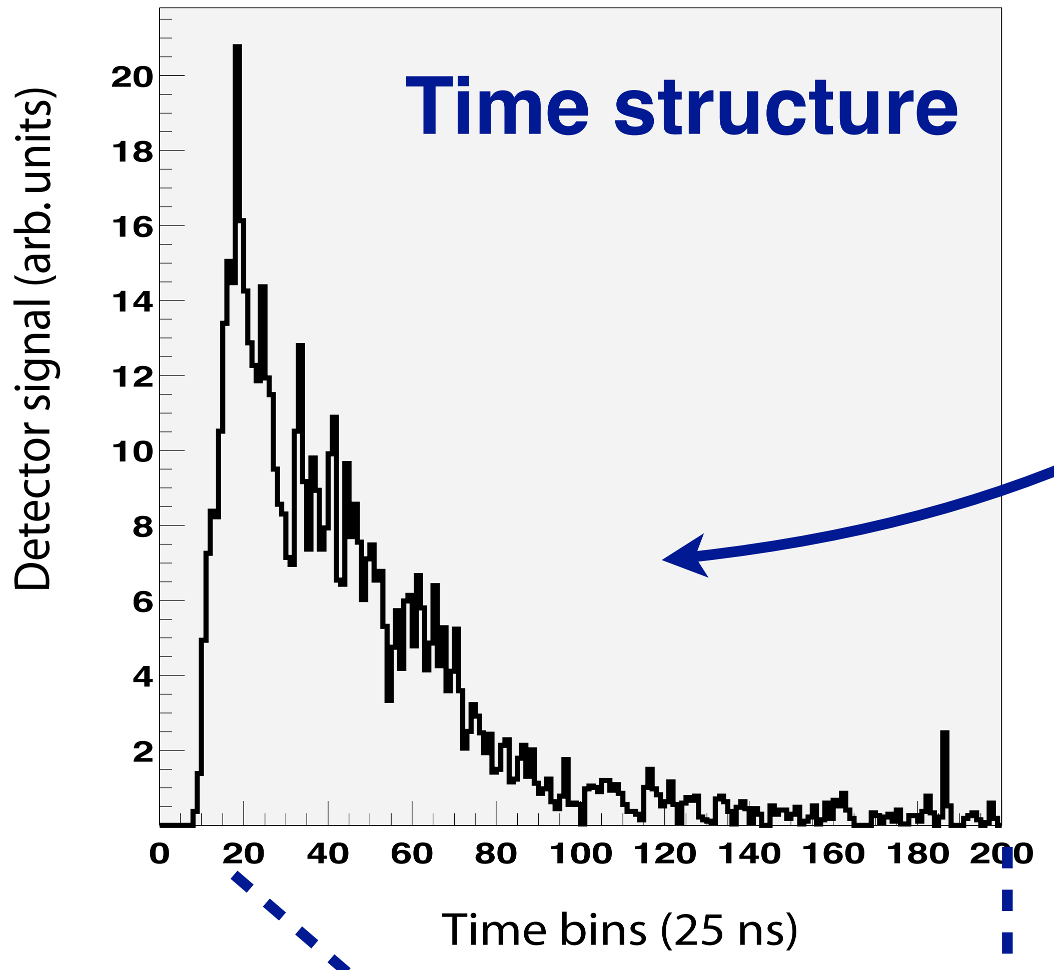
Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km²
27 fluorescence telescopes

Auger:
- 6.7 x 10⁴ km² sr yr (spectrum)
- 9 x 10⁴ km² sr yr (anisotropy)

TA:
- 8.1 x 10³ km² sr yr (spectrum)
- 8.6 x 10³ km² sr yr (anisotropy)

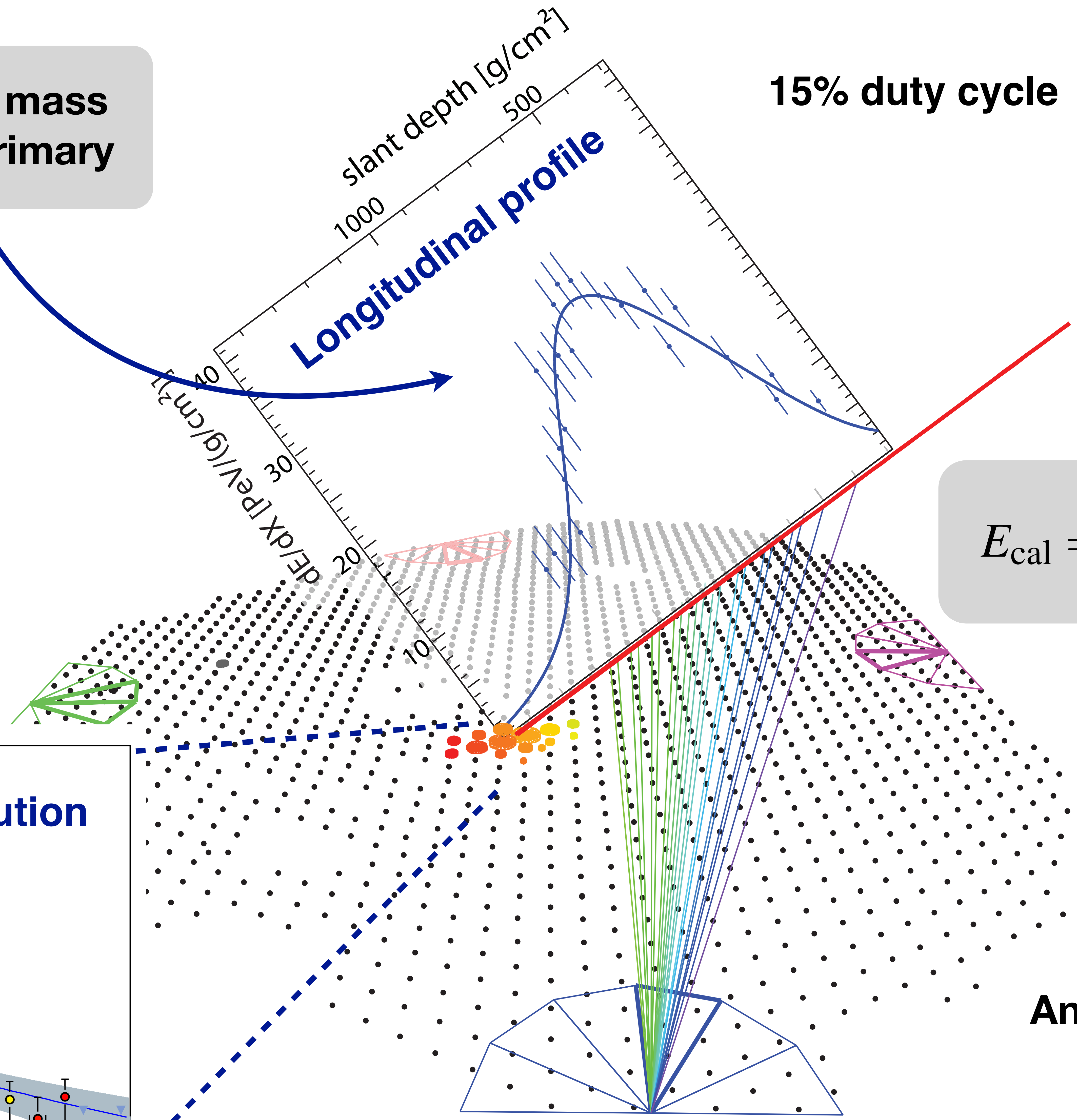
Current state of the art of UHE cosmic ray detection

Sensitivity to mass and type of primary

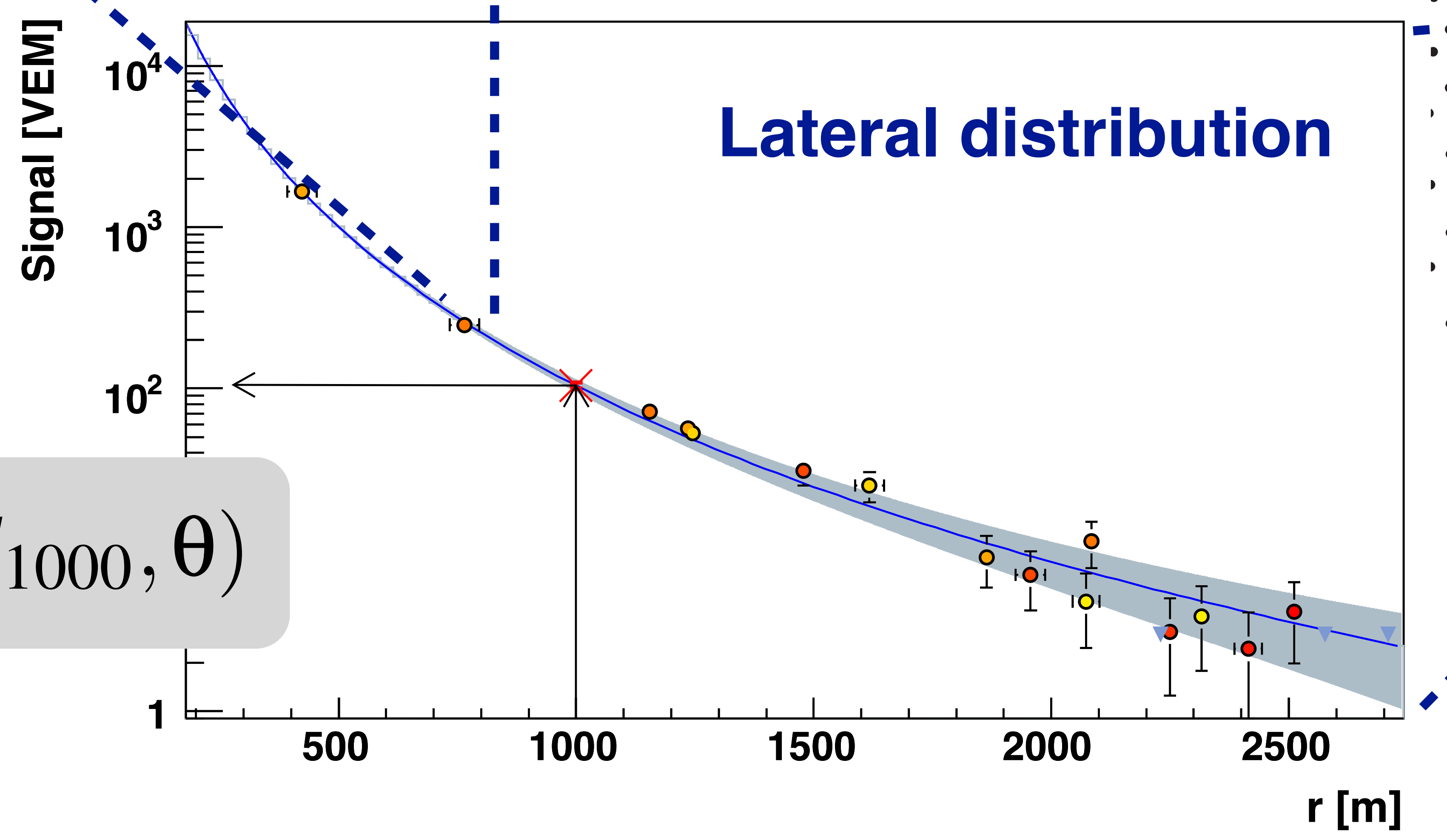


100% duty cycle

15% duty cycle



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



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

Angular resolution ~ 1.5° – 0.5°

Example: event observed with Auger Observatory

Air showers: electromagnetic and hadronic components

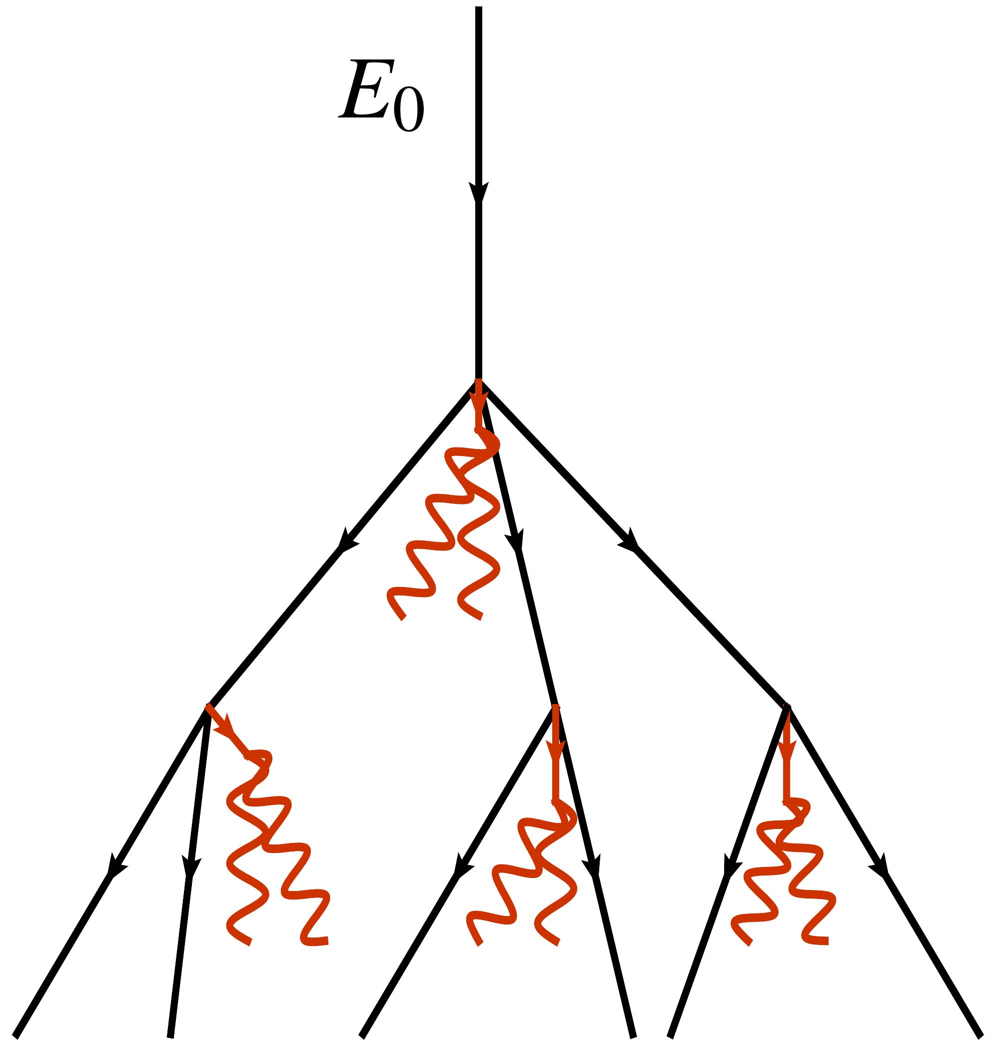
Hadronic energy

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

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

o
o
o

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



After n generations ...

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

Electromagnetic energy

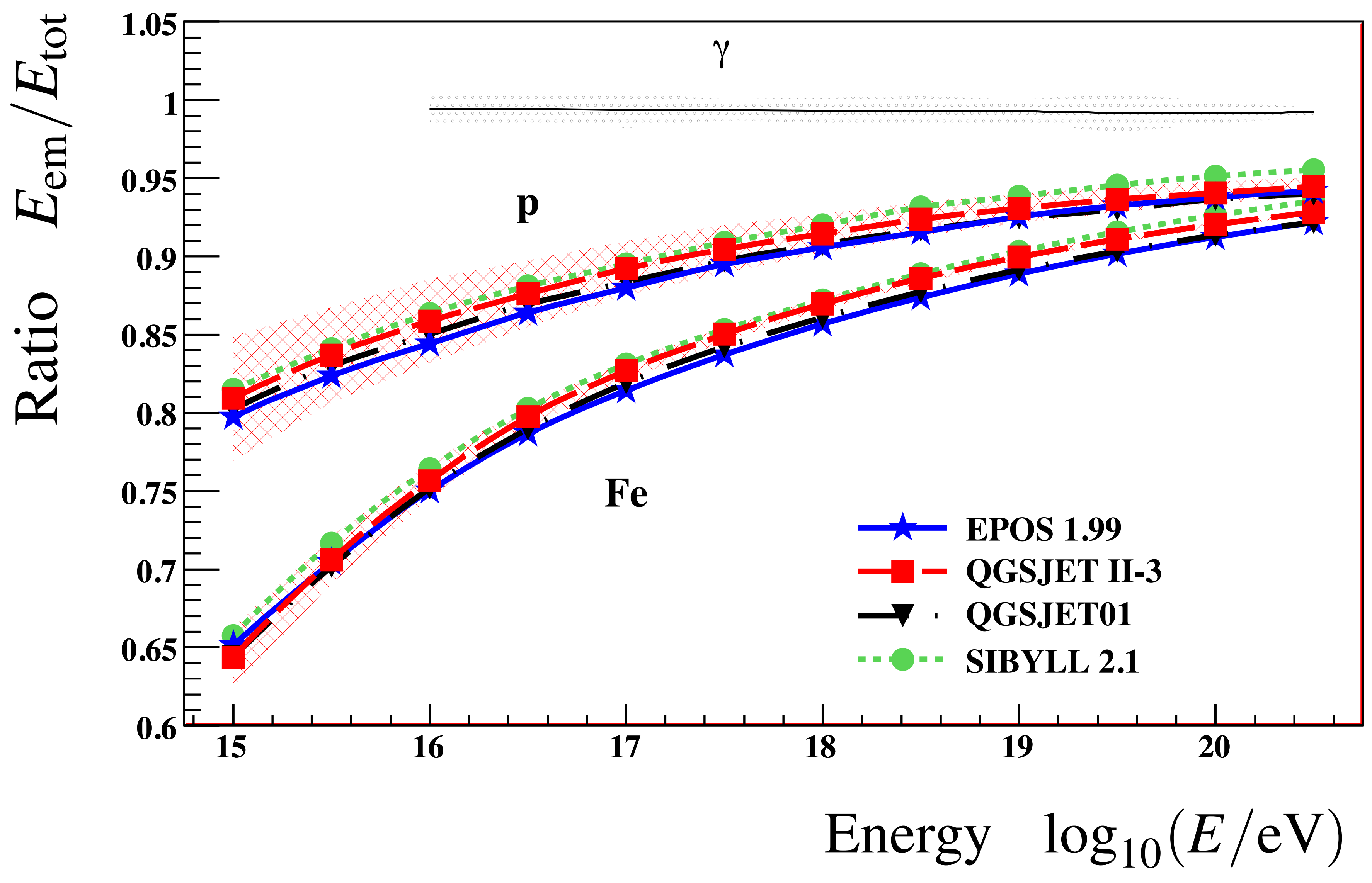
$$\frac{1}{3}E_0$$

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

o
o
o

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

(RE, Pierog, Heck, ARNPS 2011)

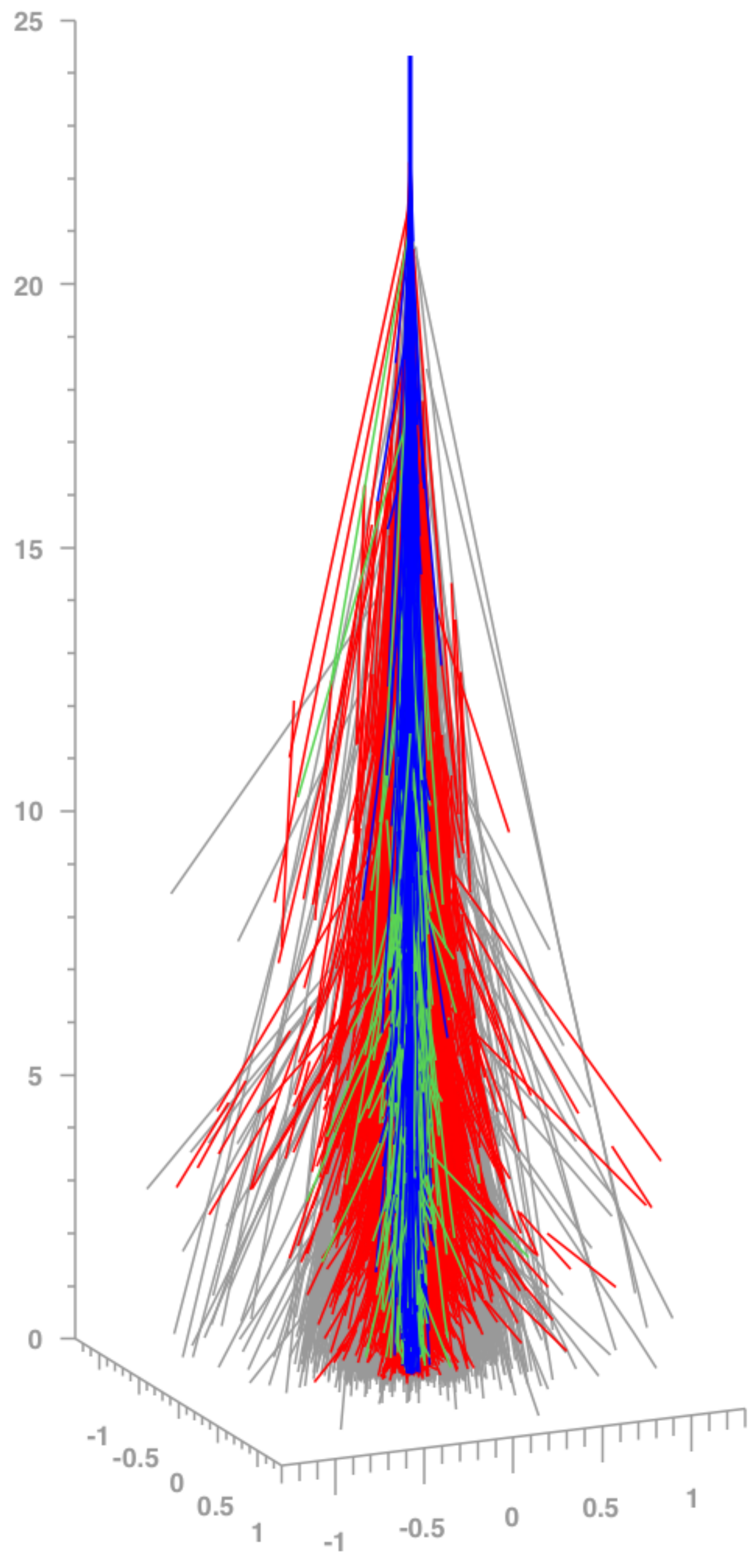


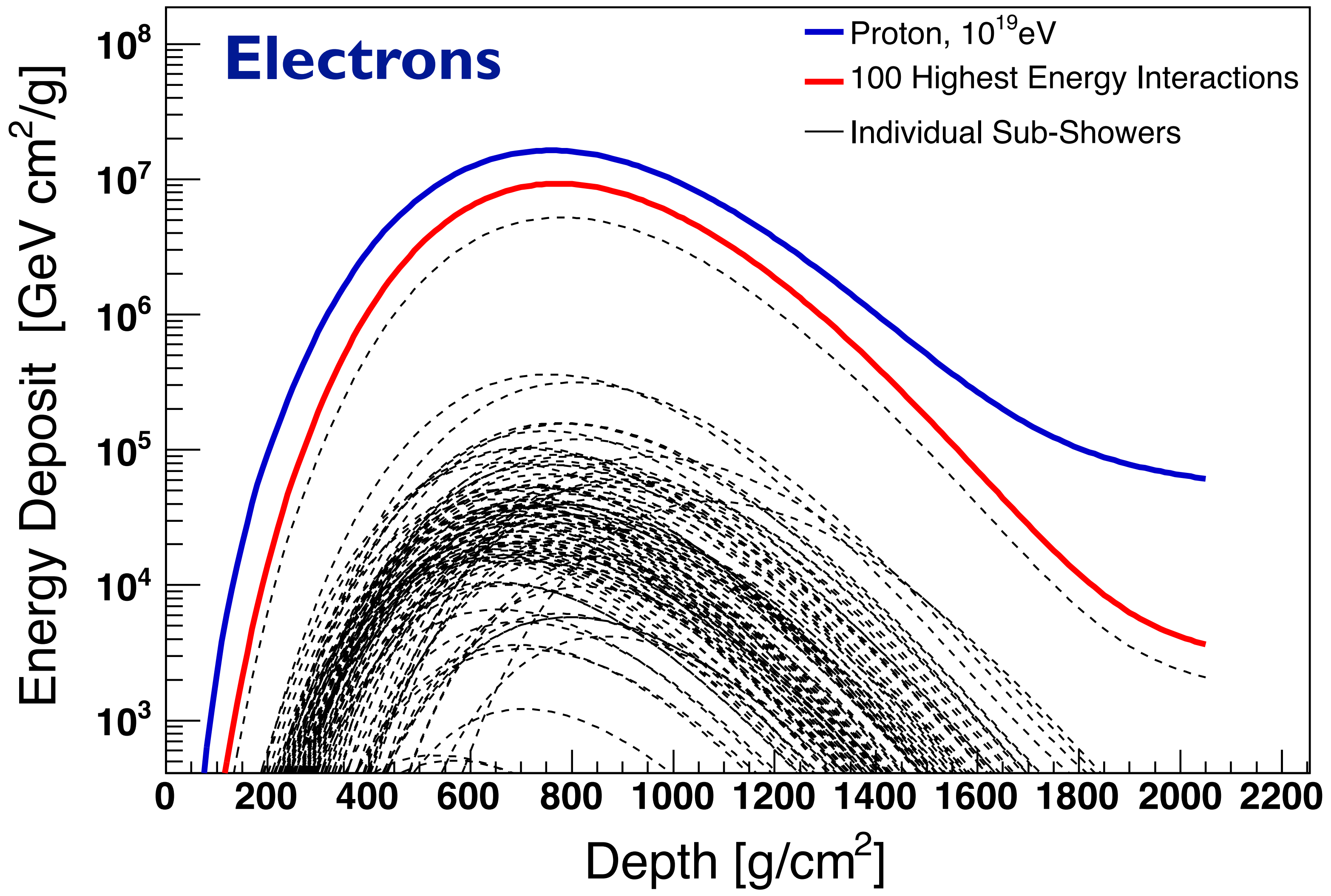
Very efficient transfer of hadronic energy to em. component

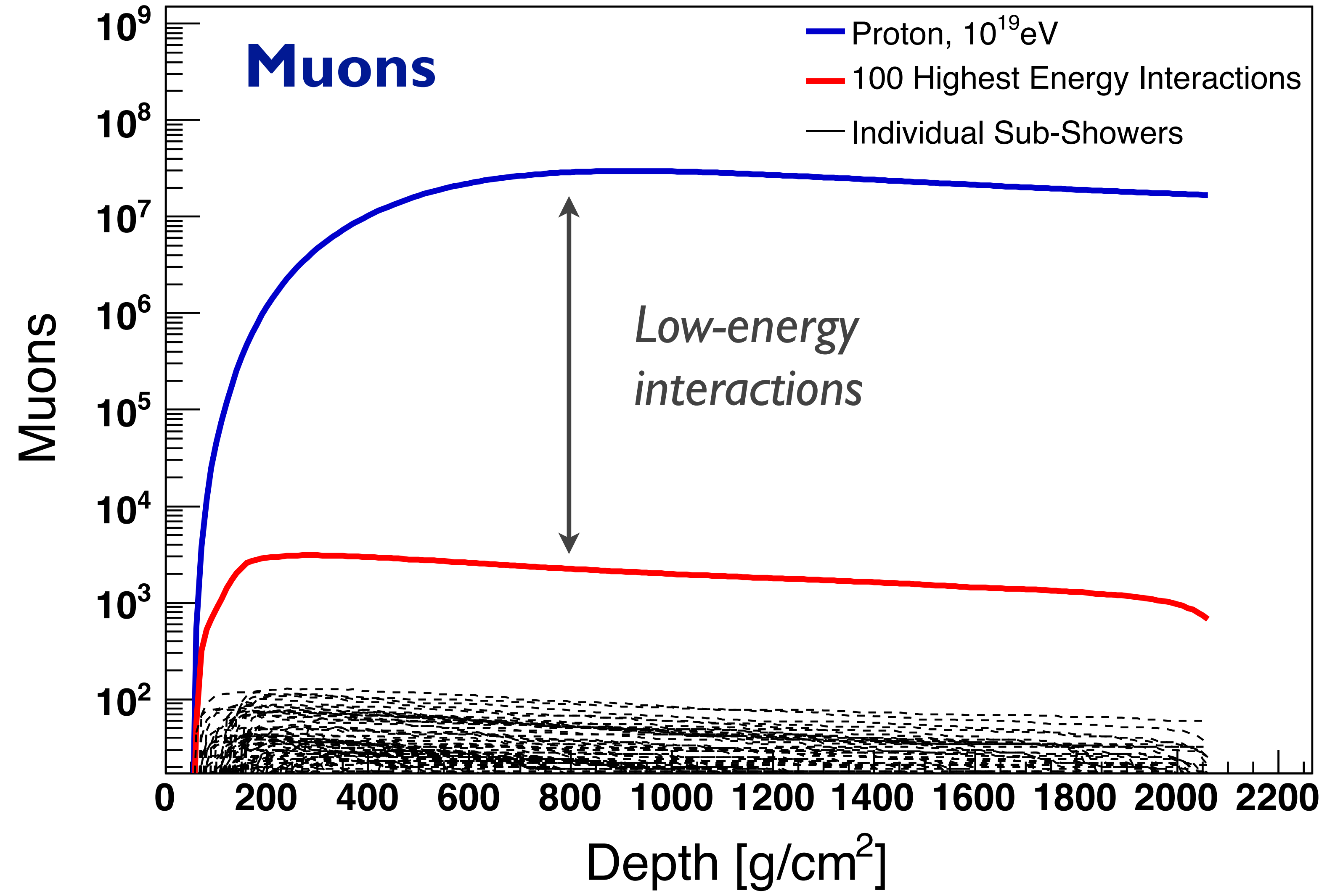
High-energy interactions most important

(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

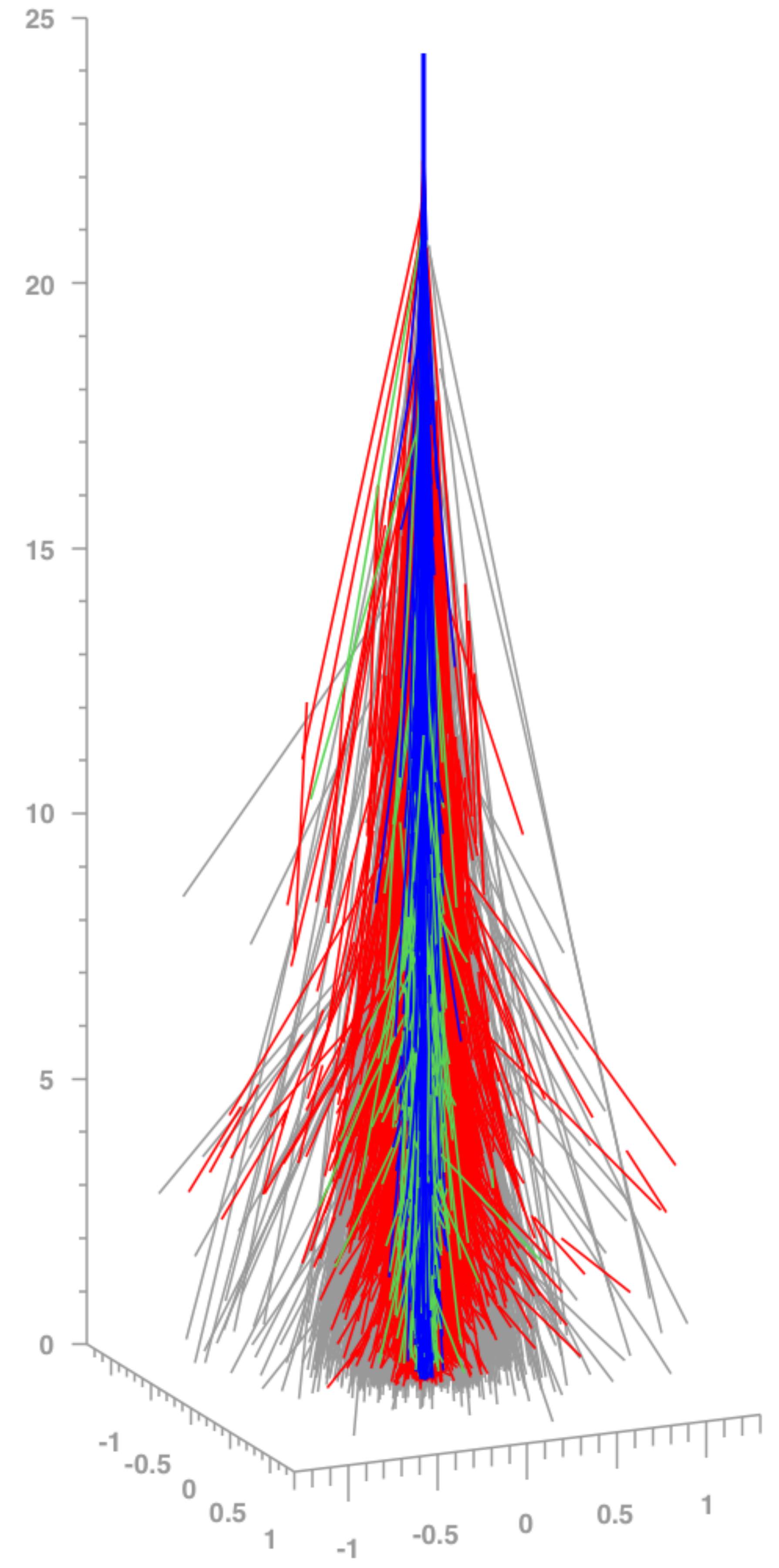
Muons/hadrons:
low-energy interactions

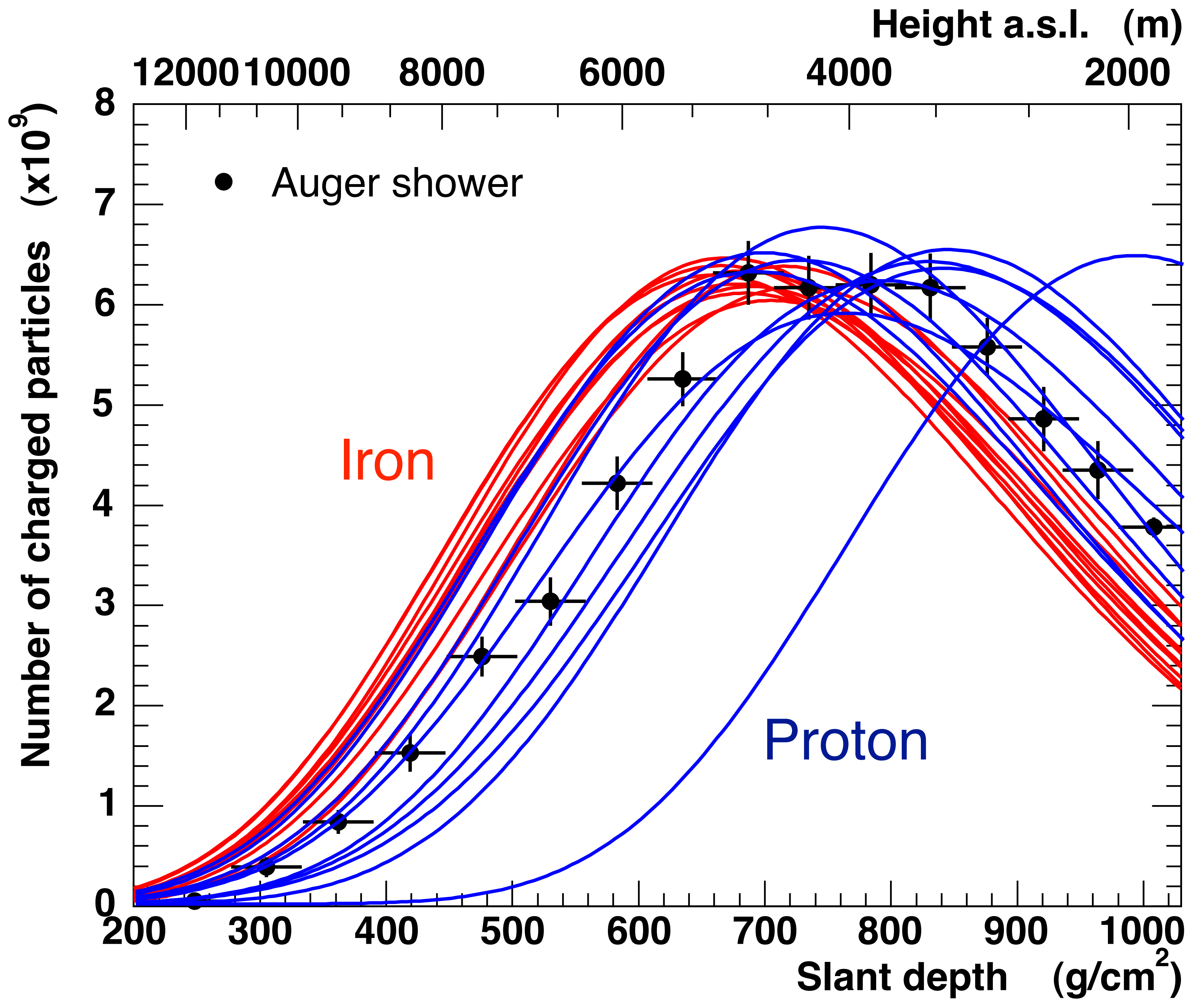
Muons: majority produced in ~30 GeV interactions

Hadron production at very high energy:

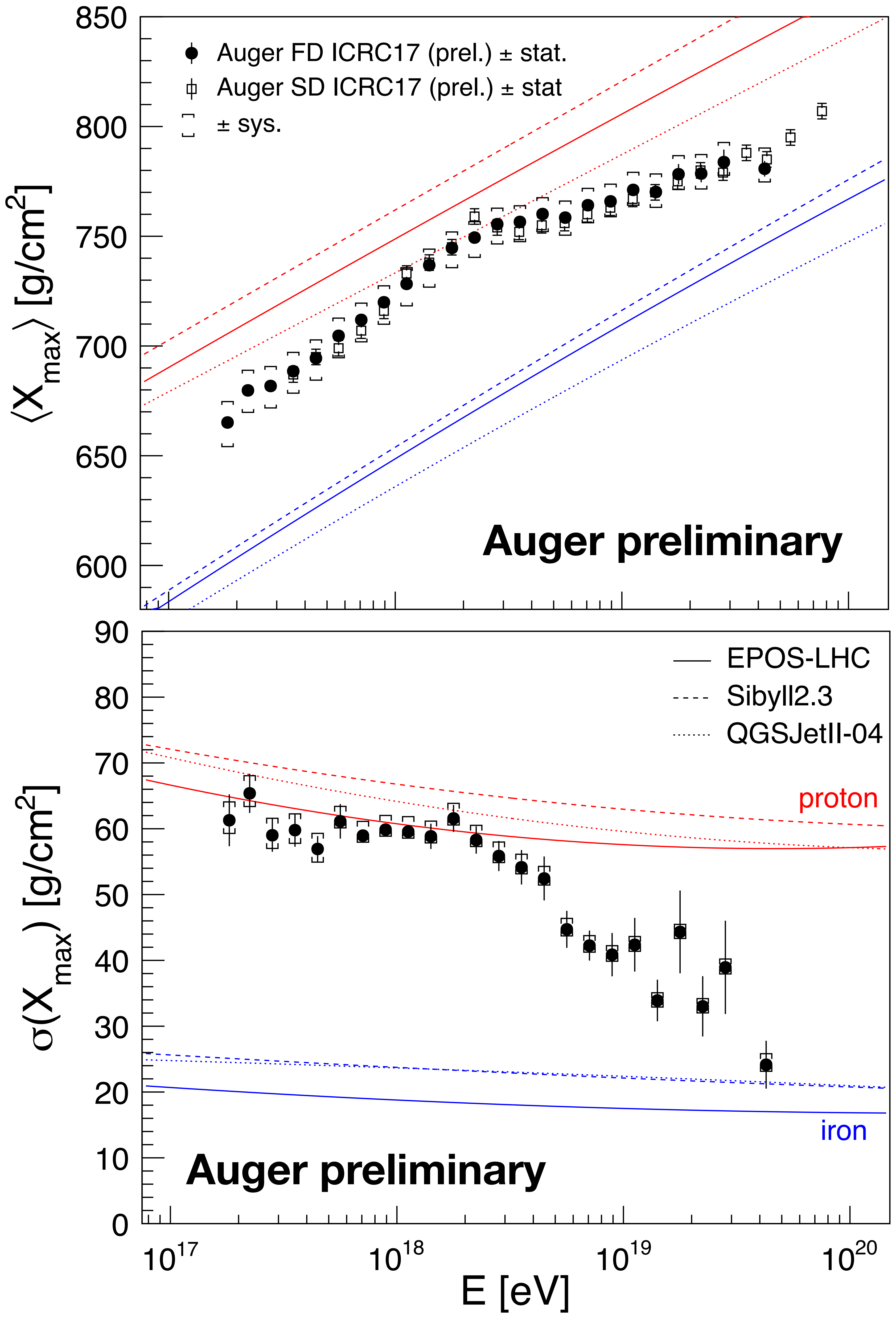
Mass composition of cosmic rays

Composition from longitudinal shower profile



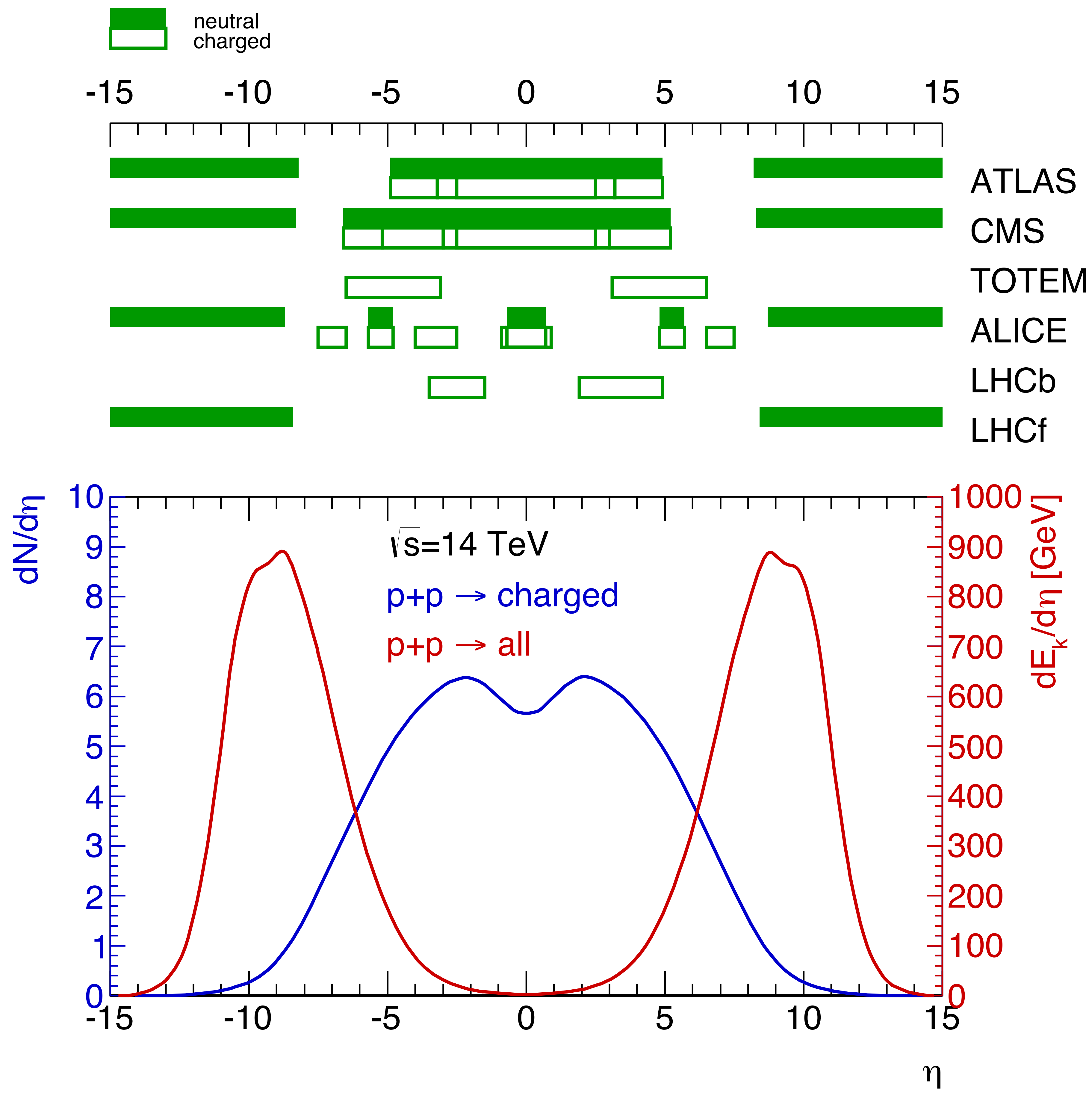


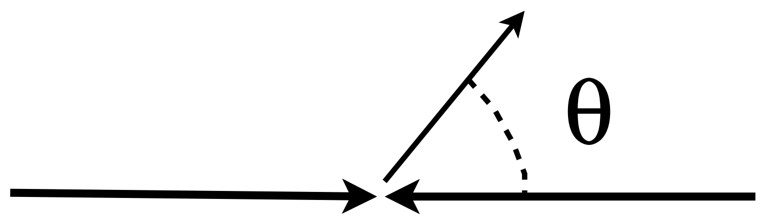
Example: event measured by Auger Collab.



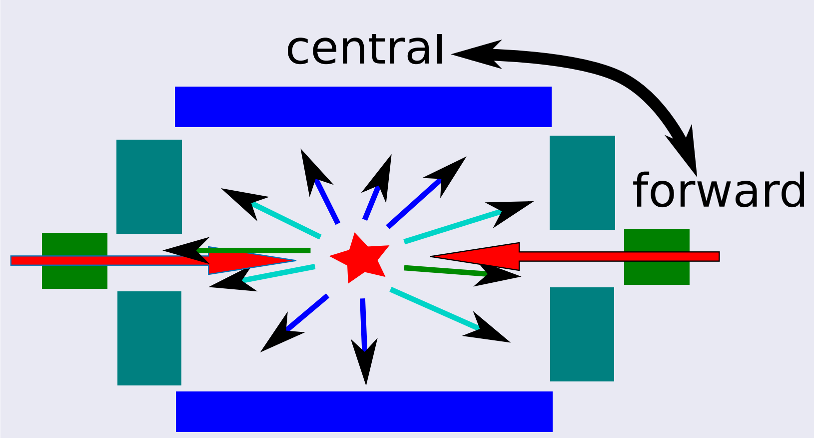
(Auger ICRC2017)

Challenge of limited phase space coverage – model extrapolations



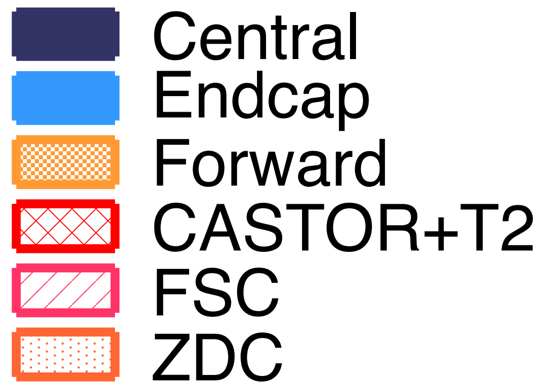


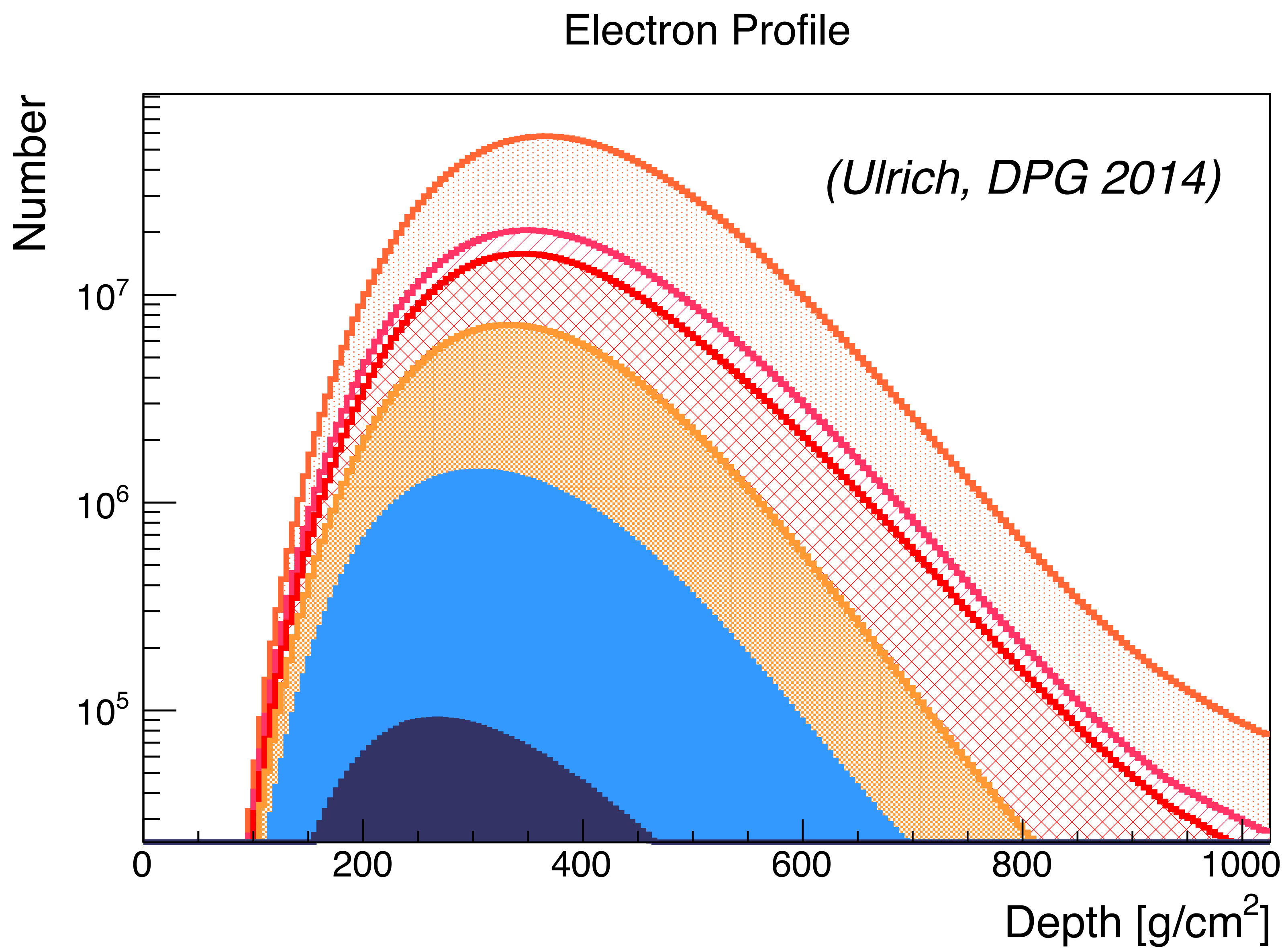
$$\eta = -\ln \tan \frac{\theta}{2}$$



- 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



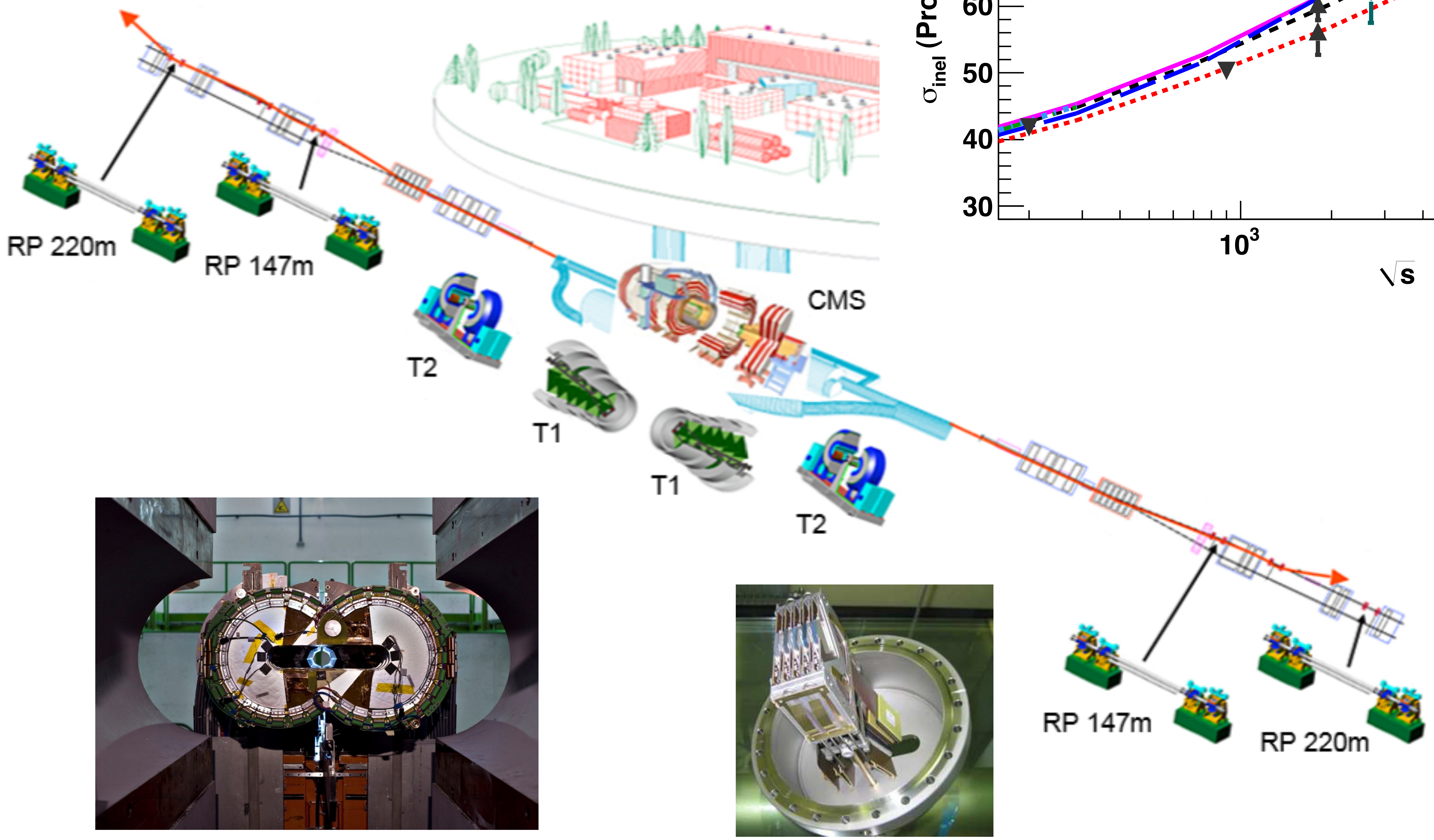


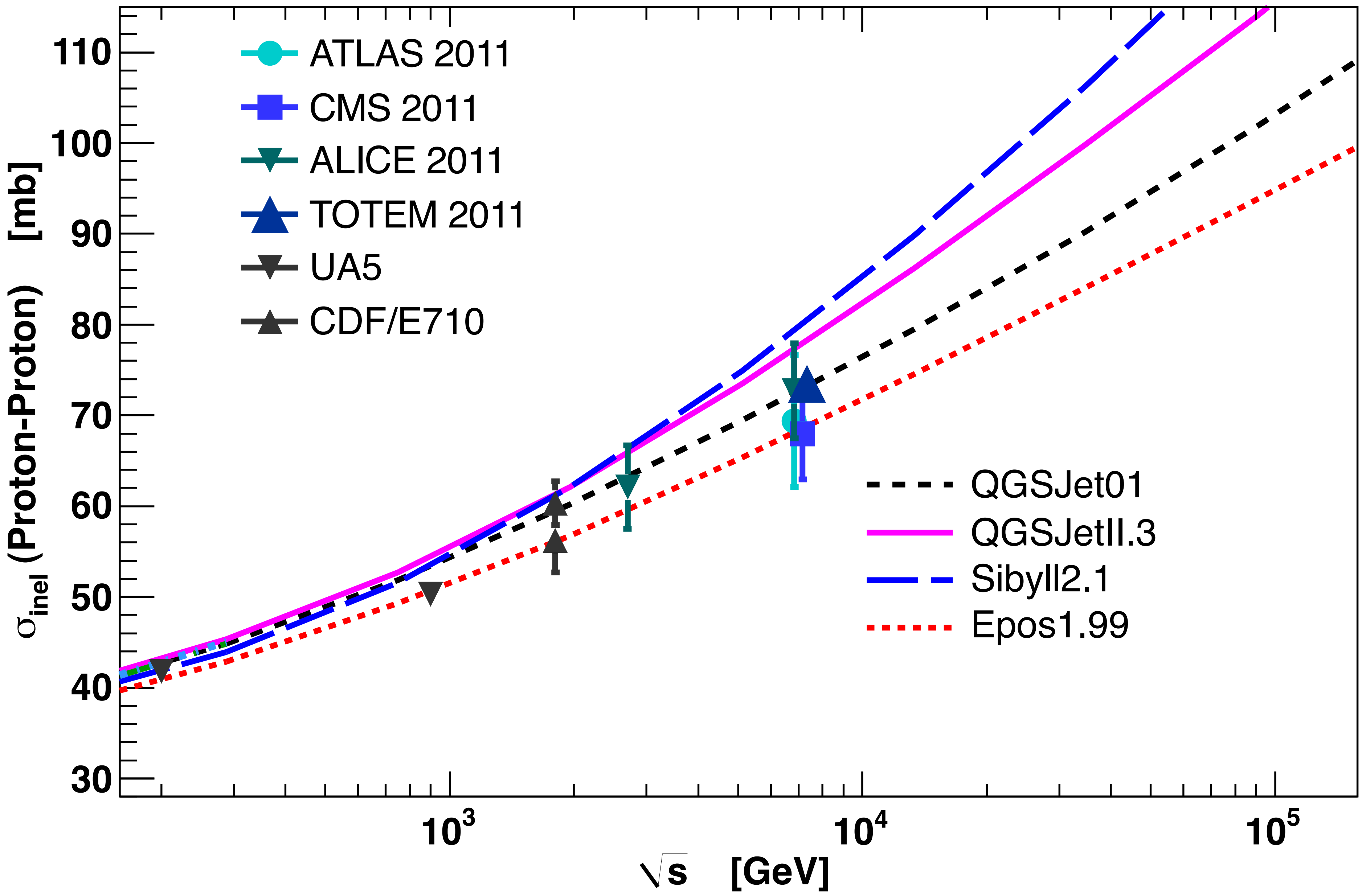
More than 50% of shower from η > 8

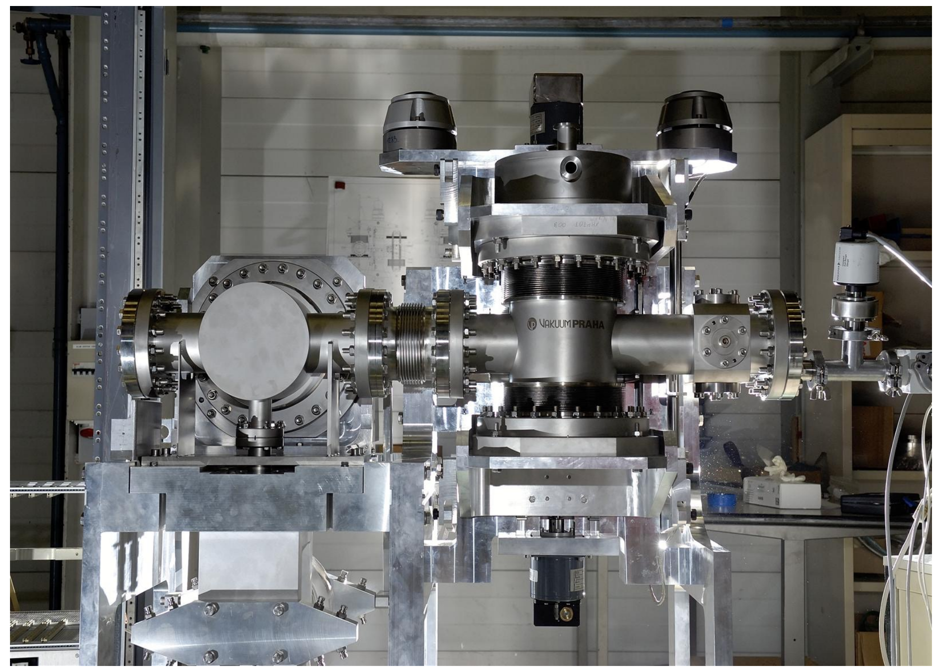
(Salek et al., 2014)

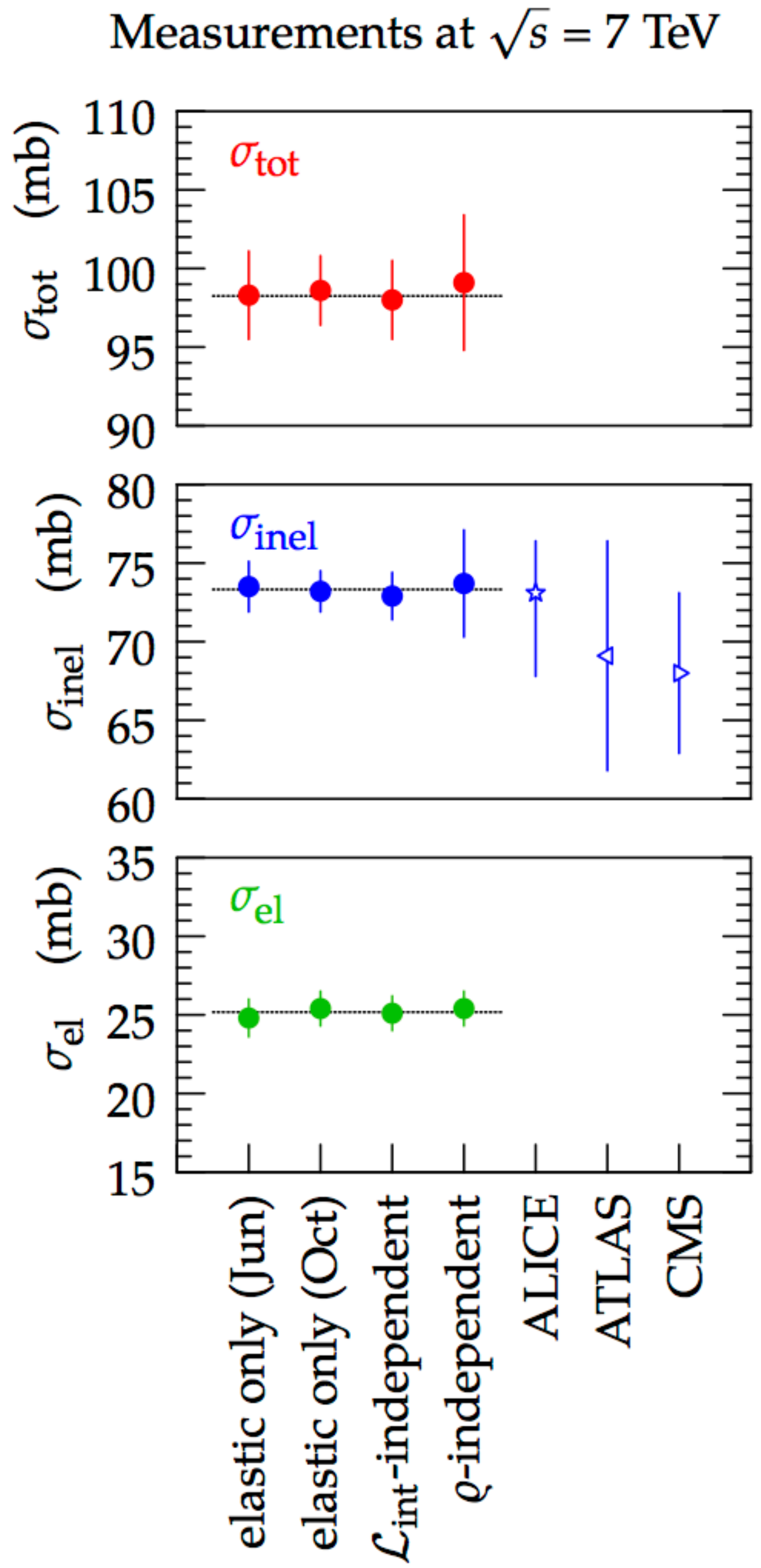
Cross section measurements at LHC

(Cafagna, ICRC 2015)



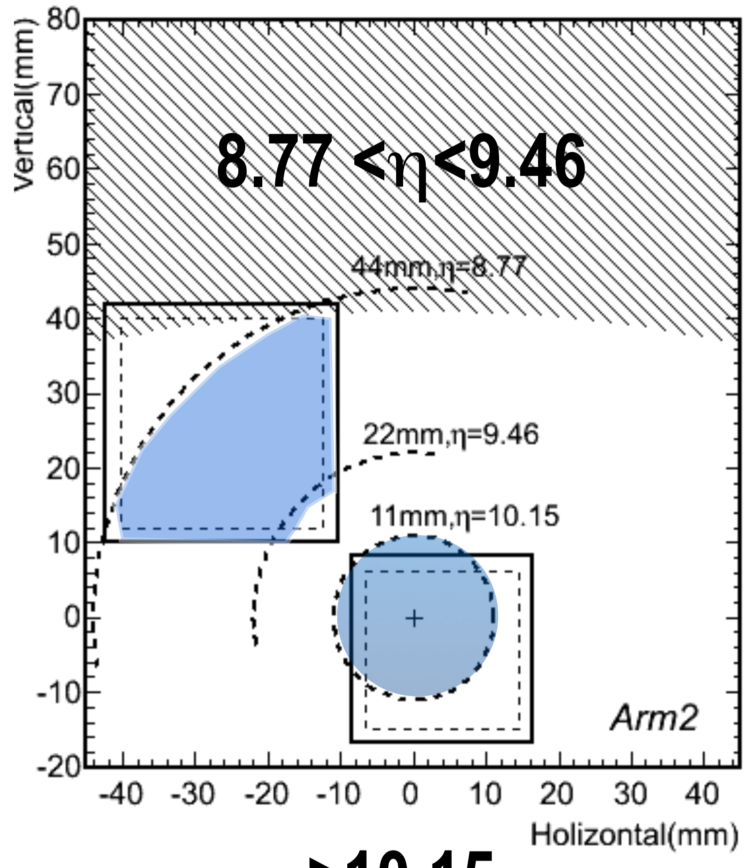




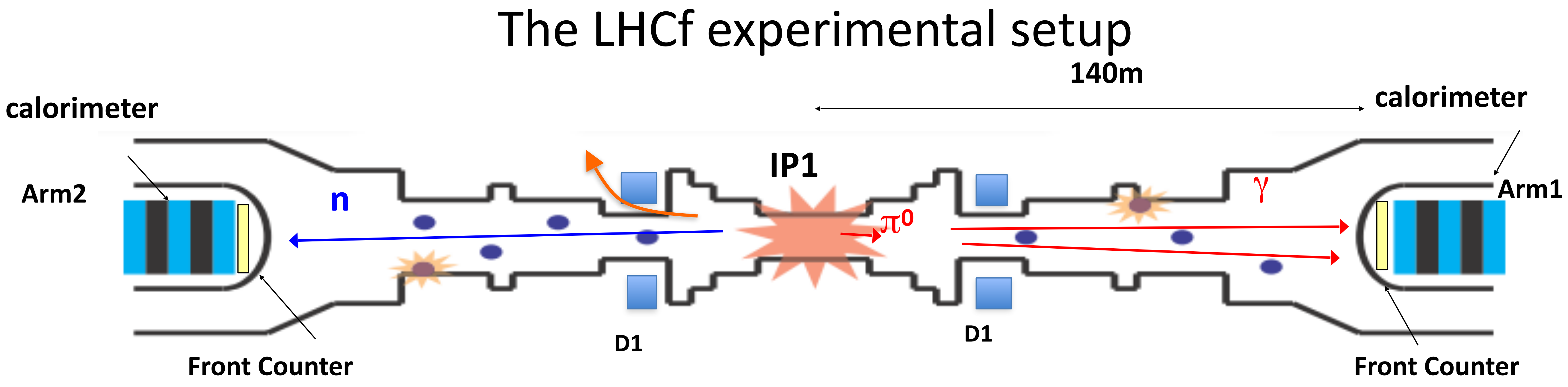


LHCf: very forward photon production at 7 TeV

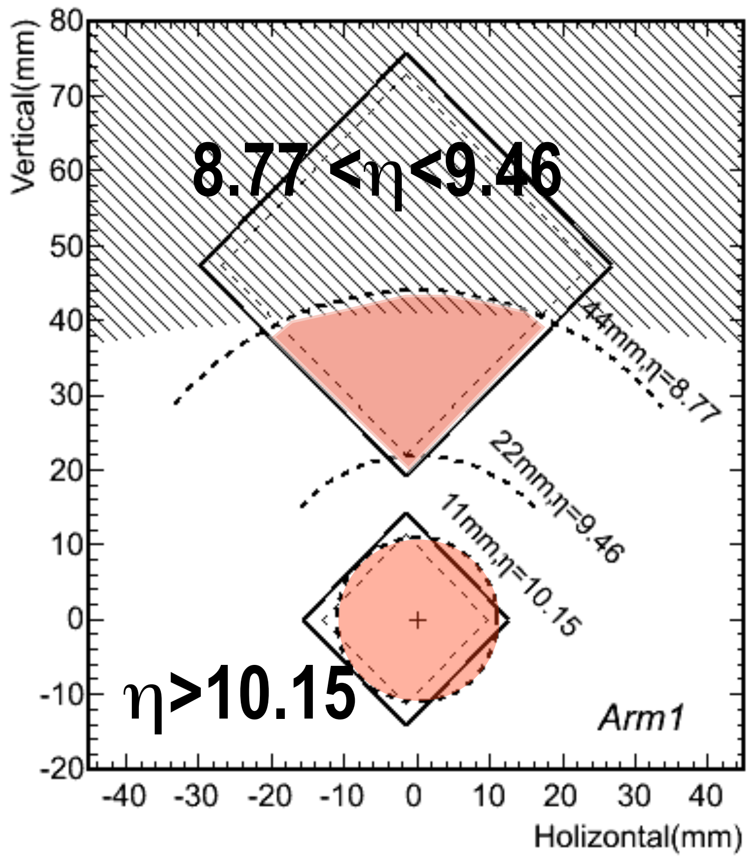
Arm 2



η>10.15

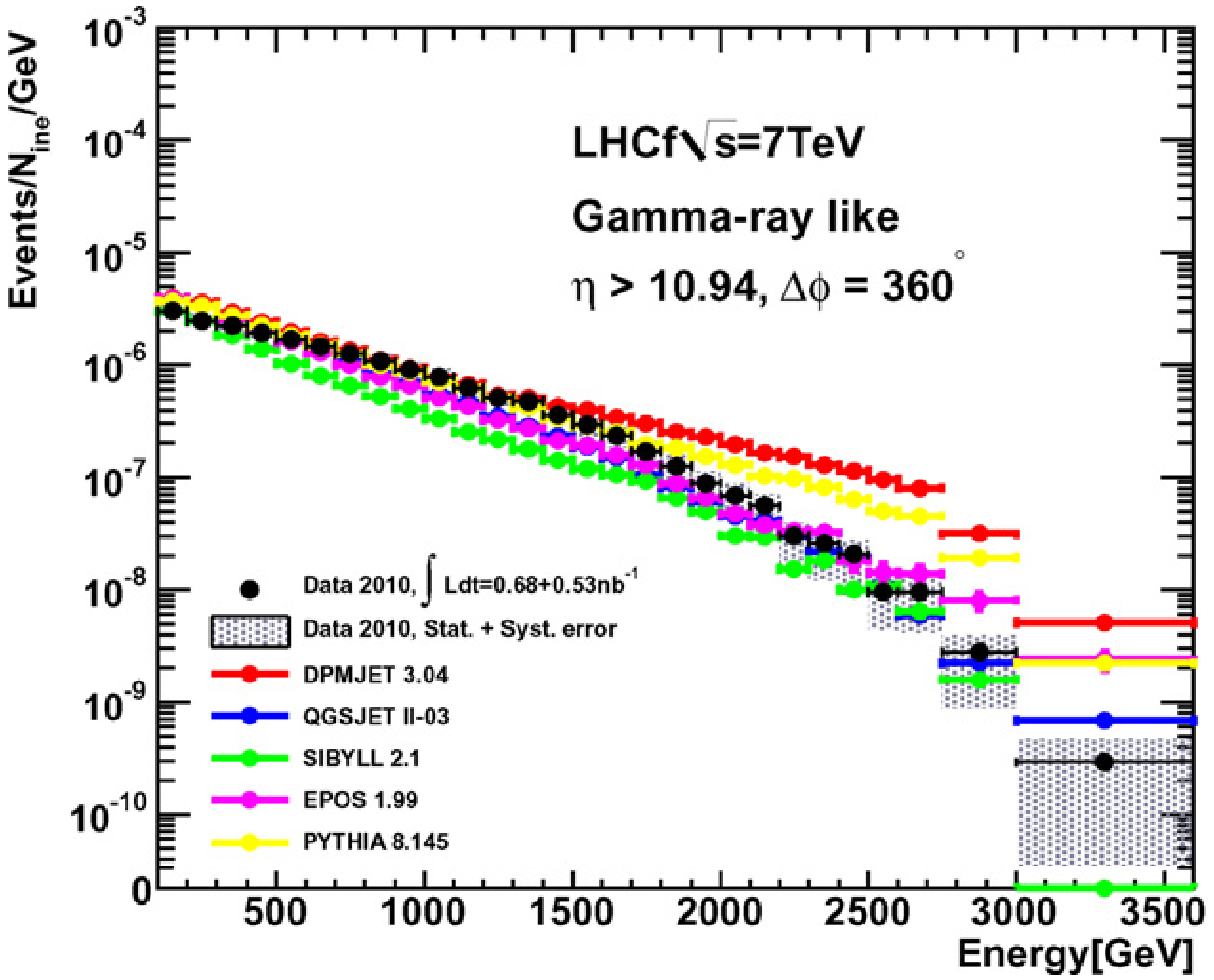


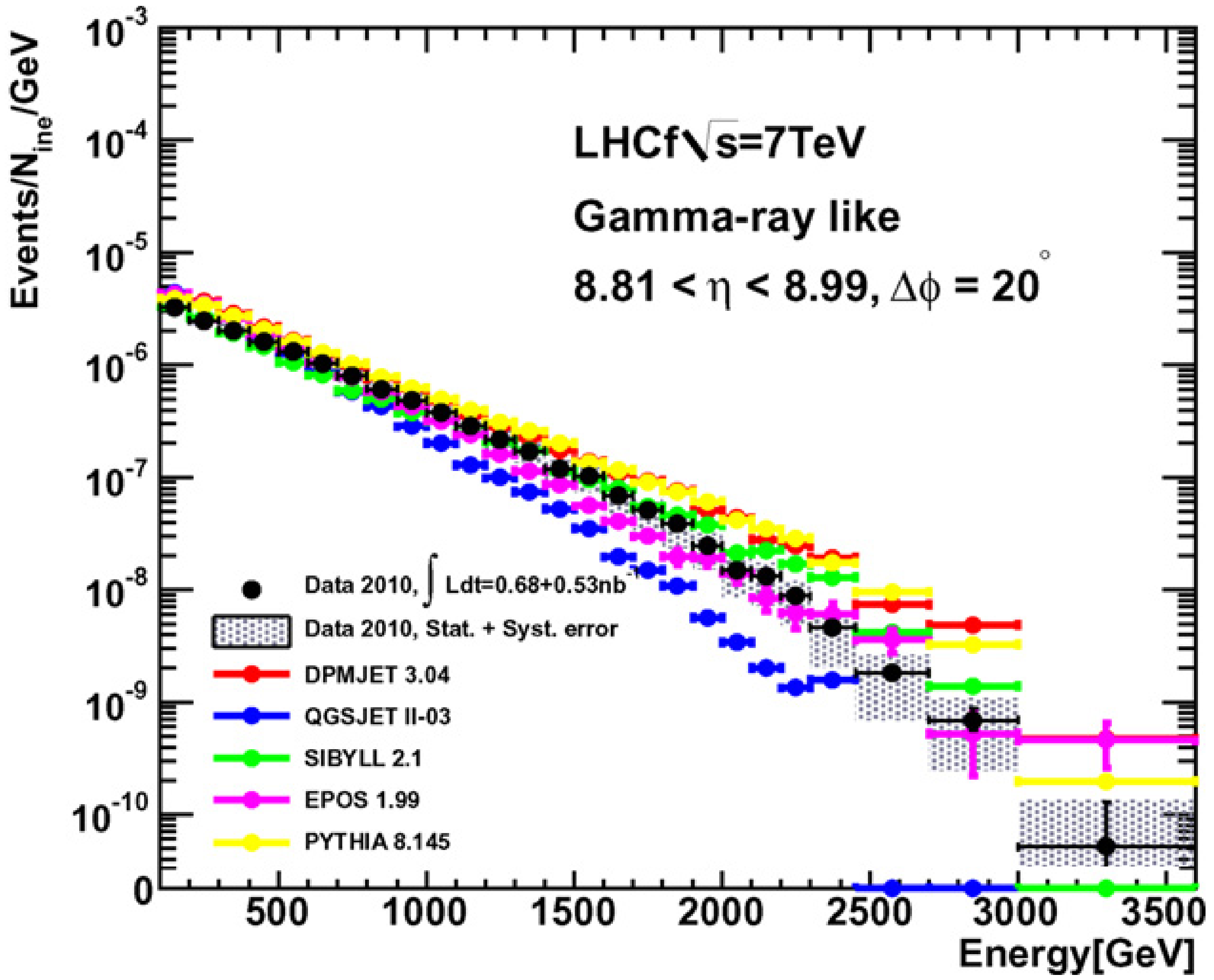
Arm 1

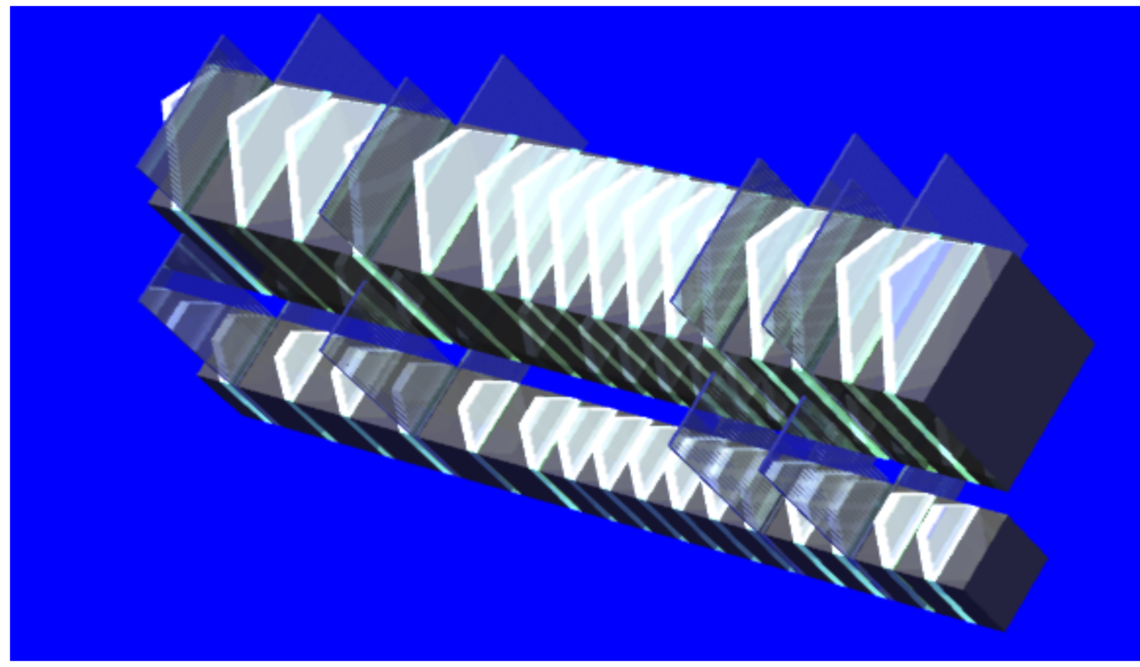


$$pp \to \gamma X$$

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

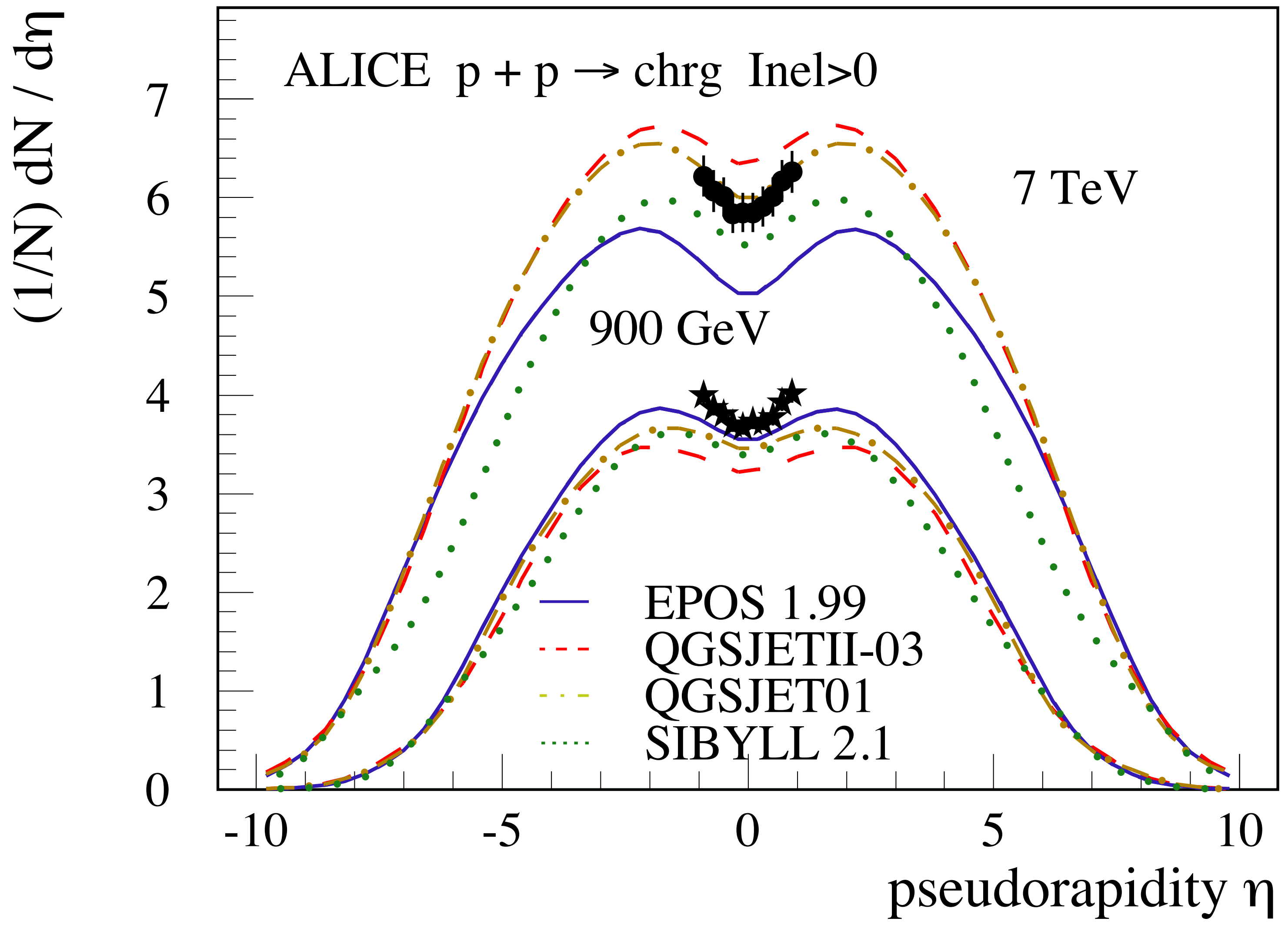


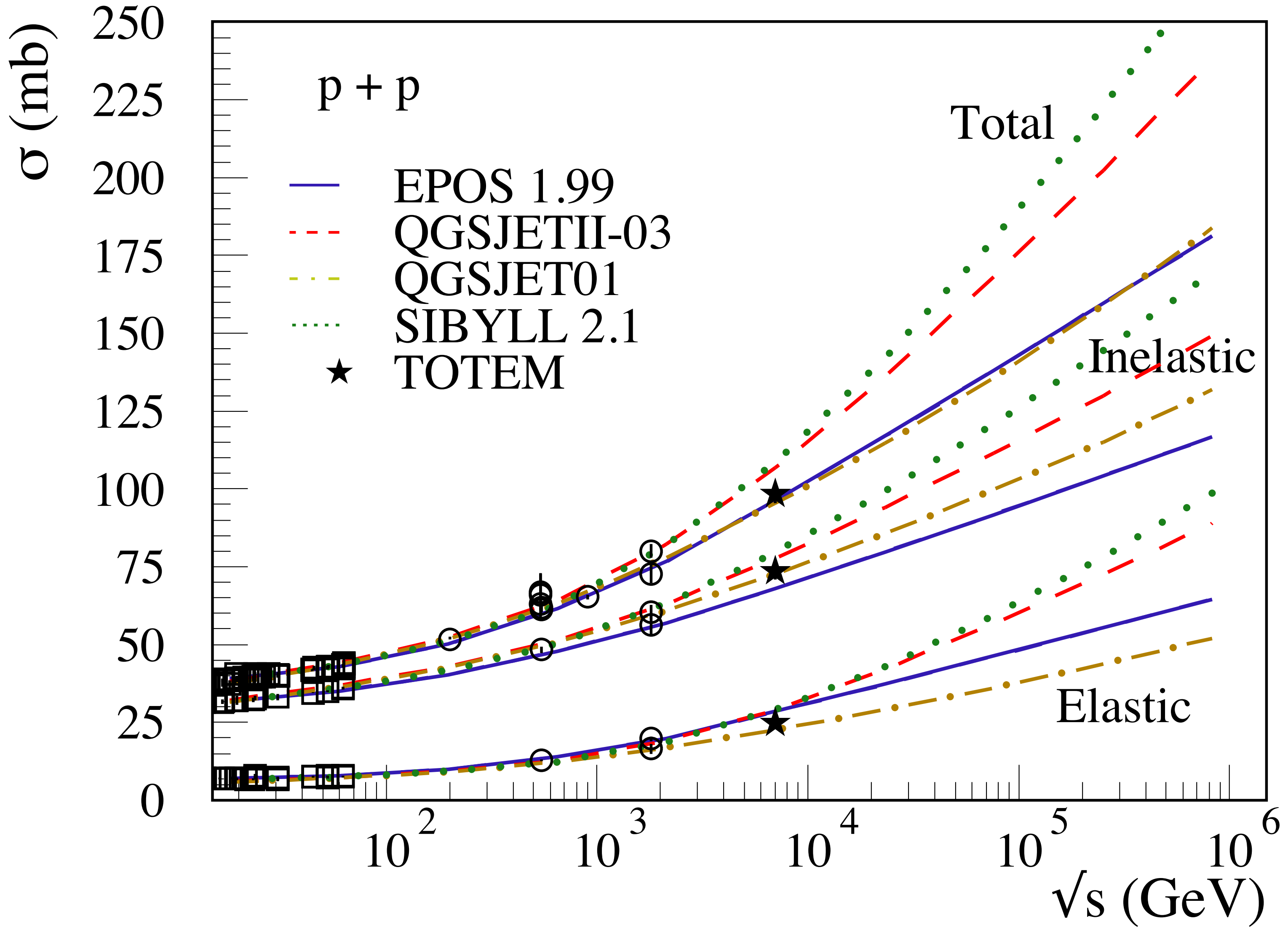


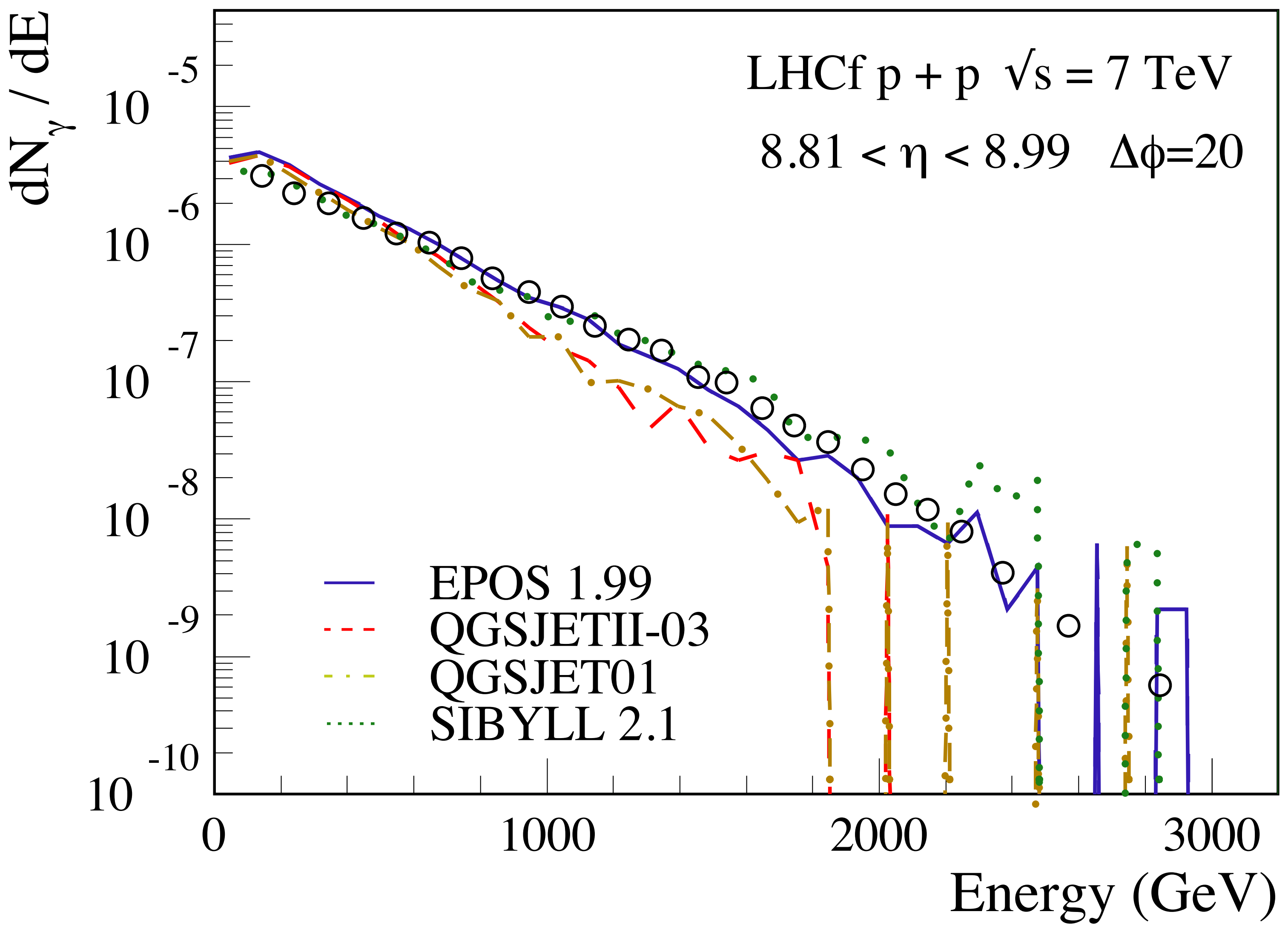


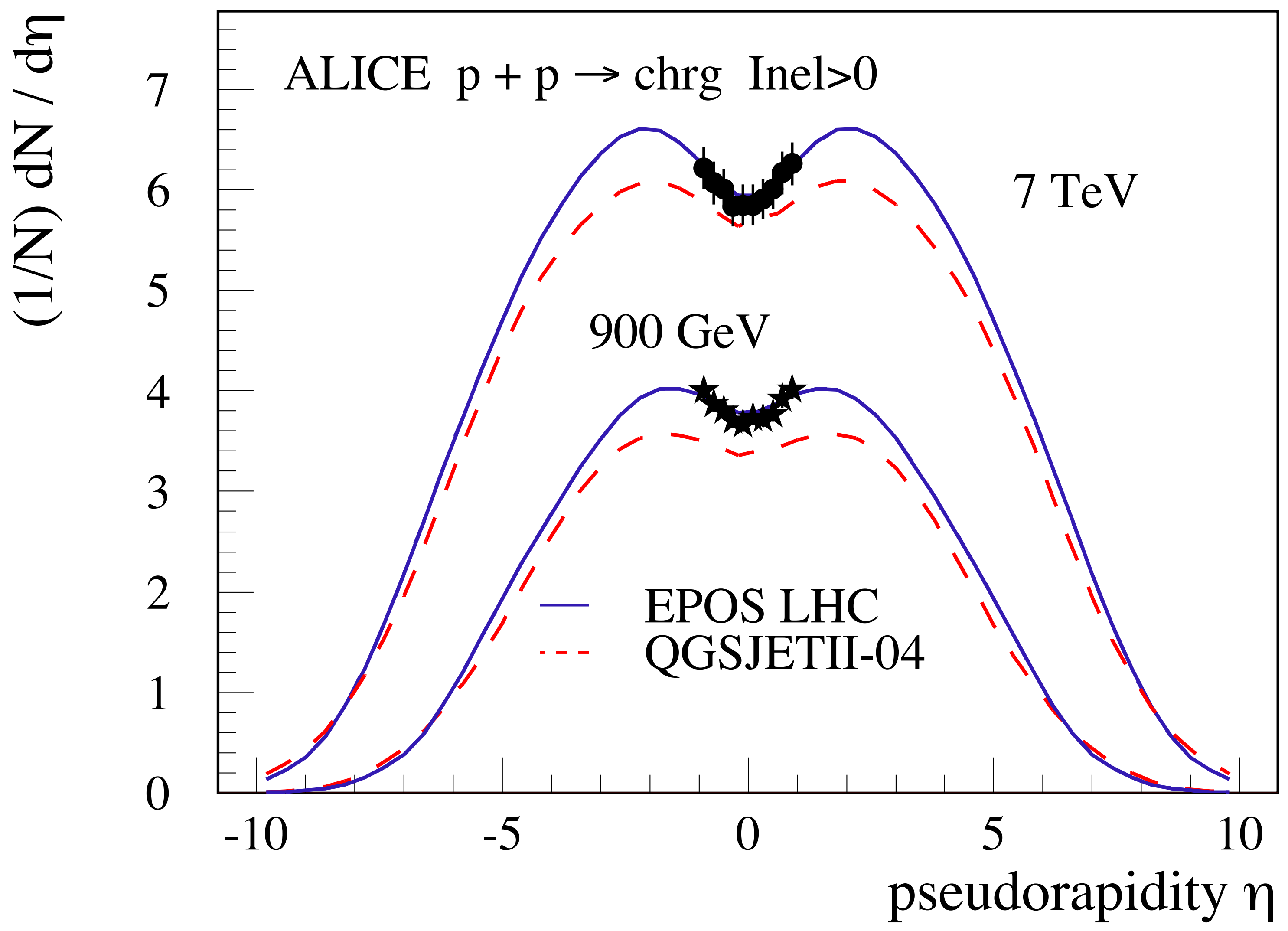
(Itow, ICRC 2015)

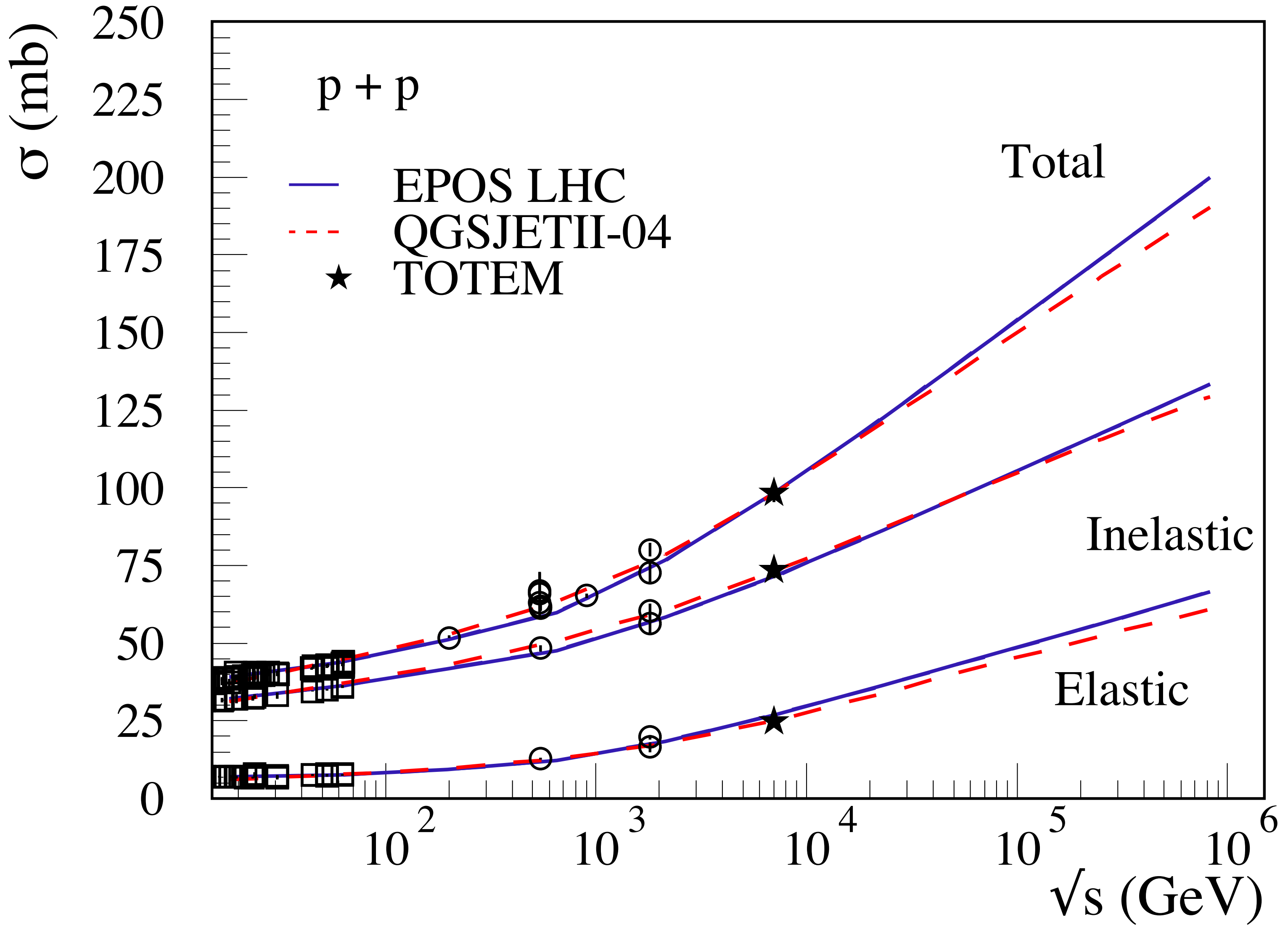
Examples of tuning interaction models to LHC data

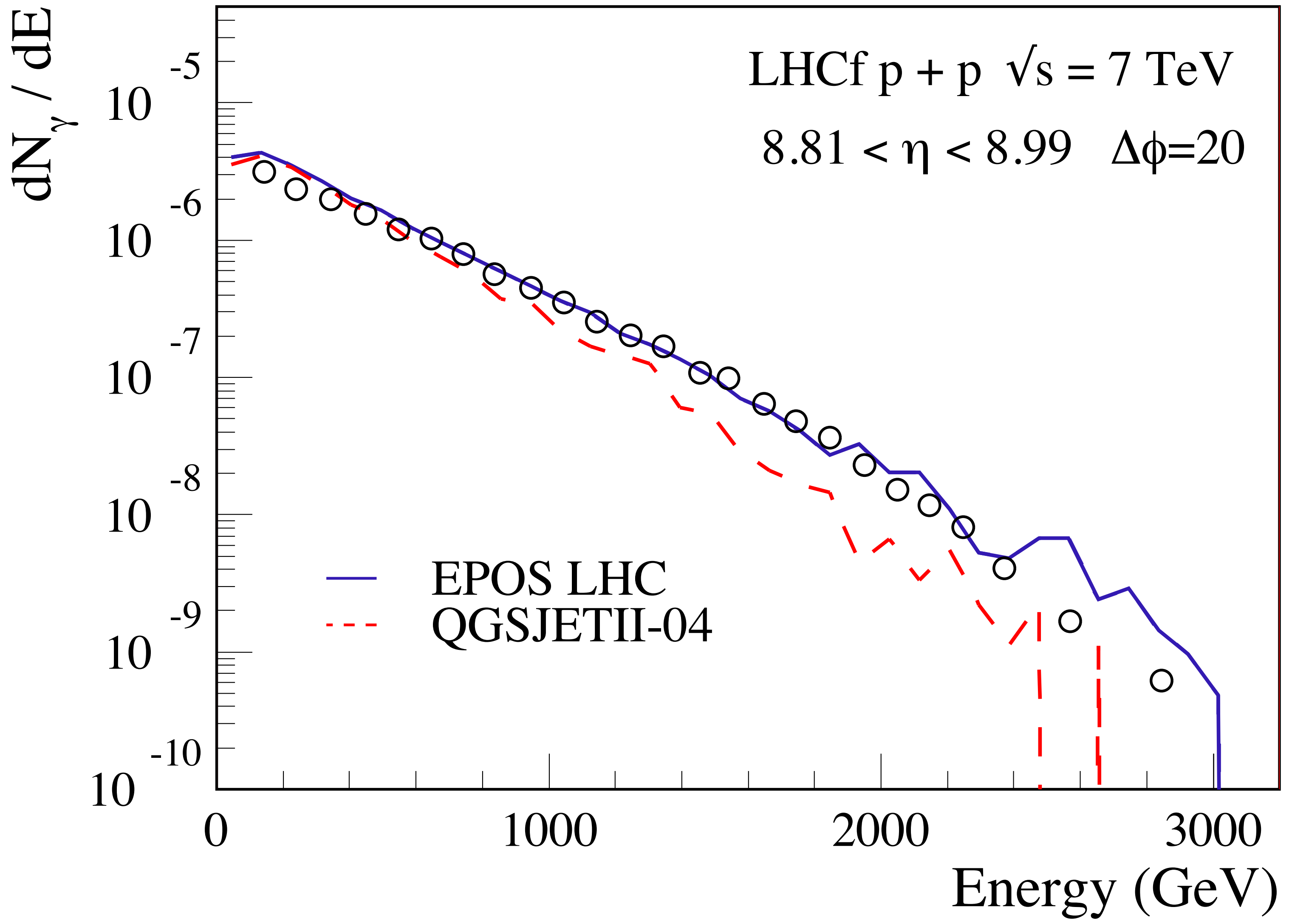






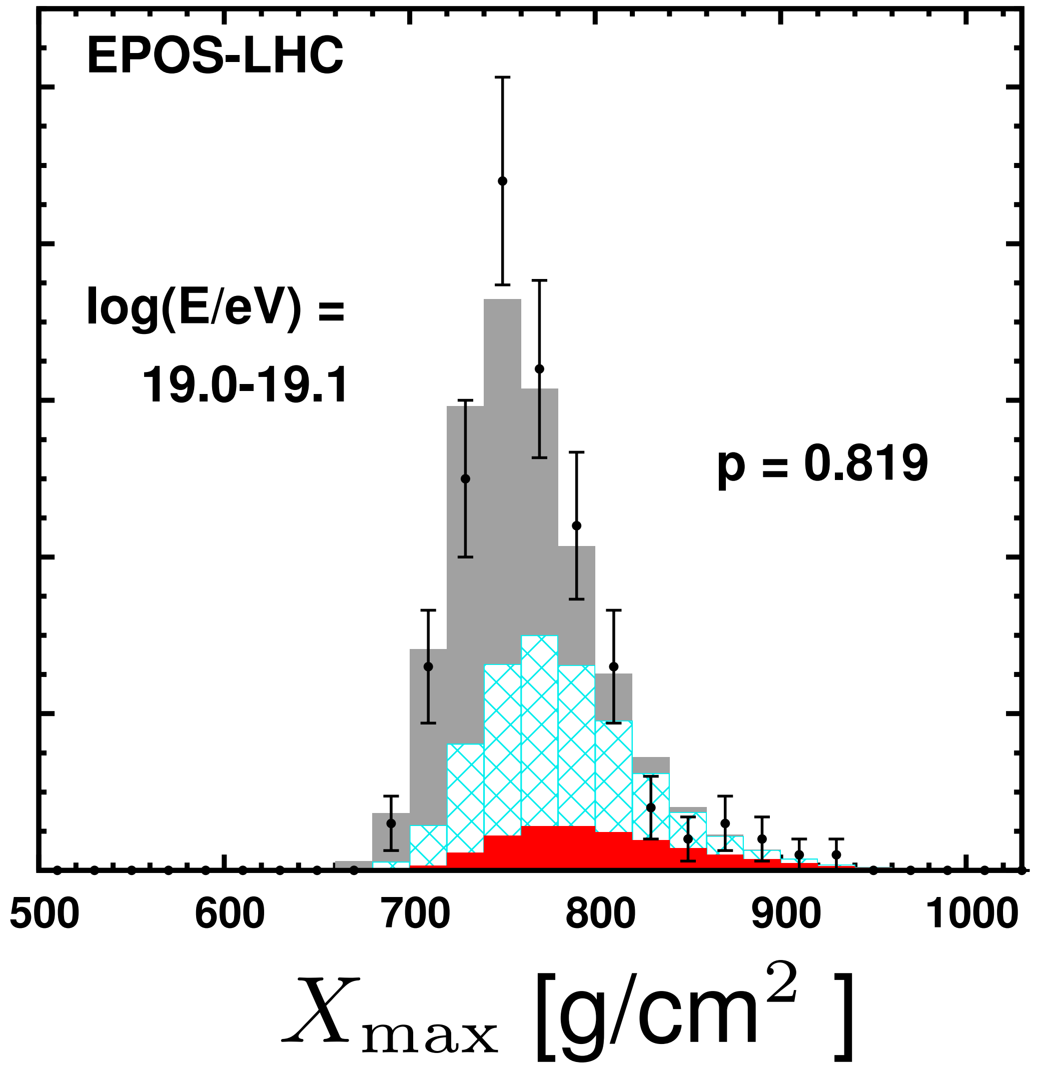






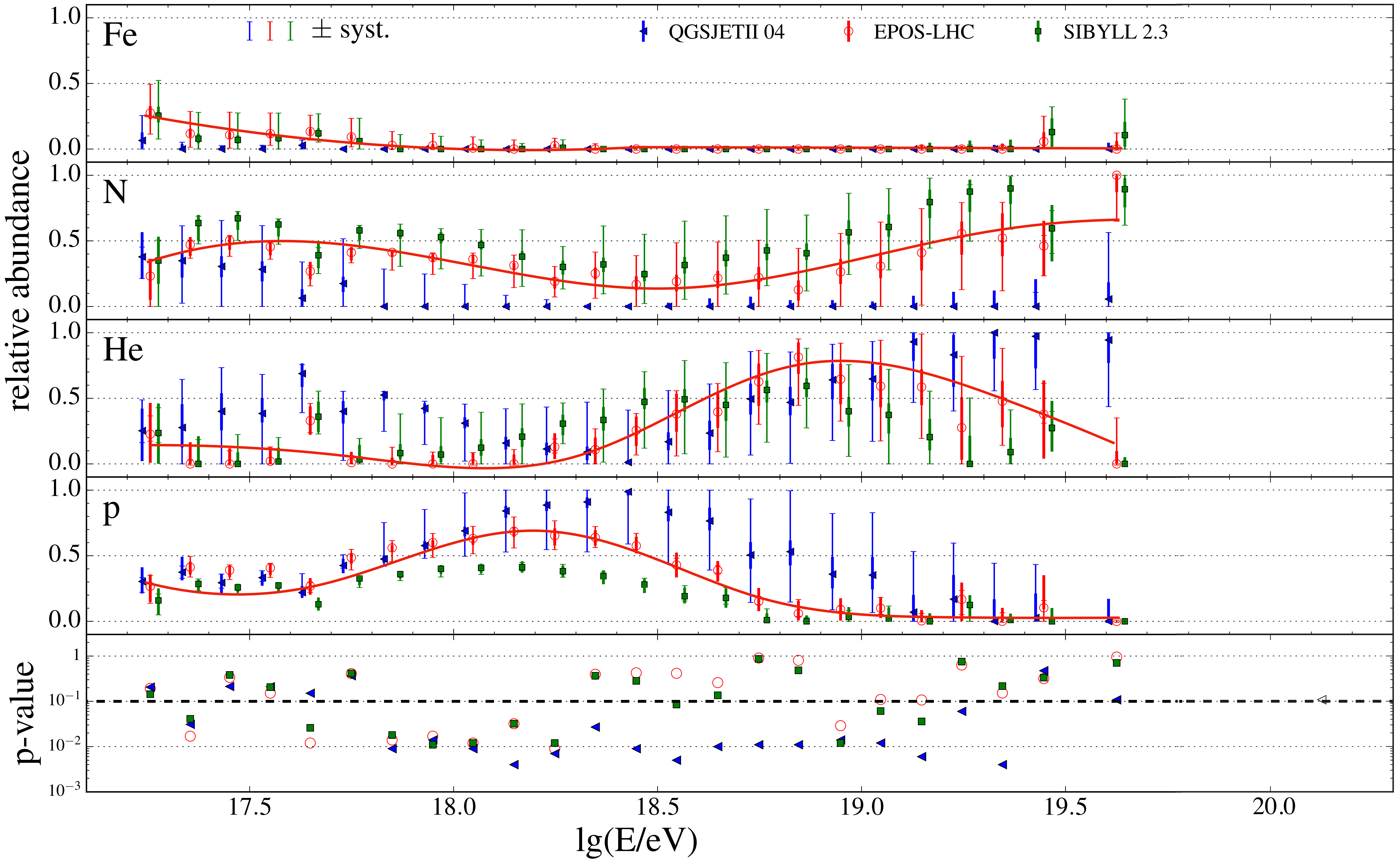
(Pierog 2013, 2014)

Puzzle: Unexpected change of mass composition



p He N Fe

Composition based on fluorescence telescope data (15% duty cycle)



LHC-tuned interaction models

Fit quality not always good

No iron needed for interpretation

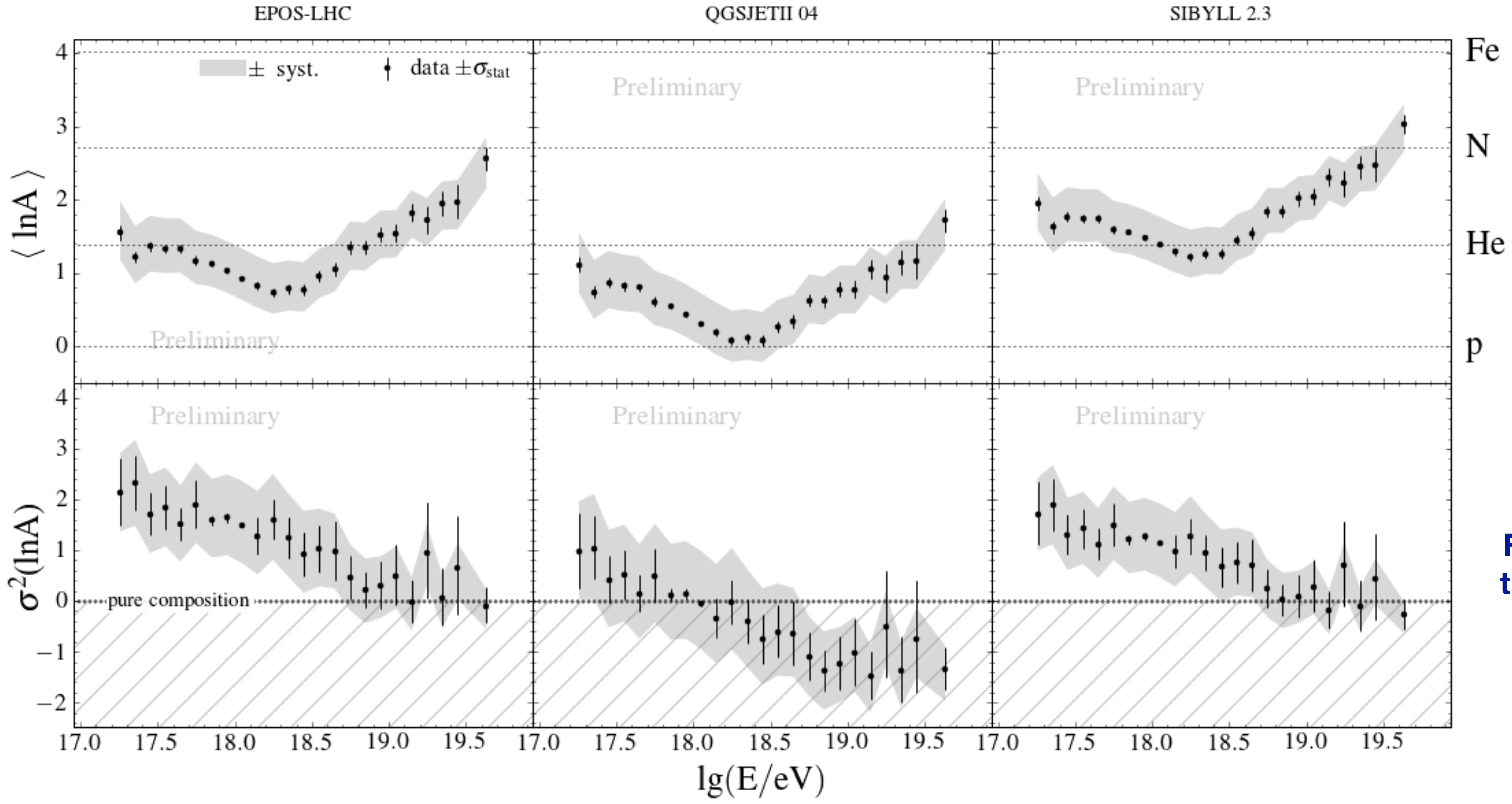
Large proton fraction below ankle

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



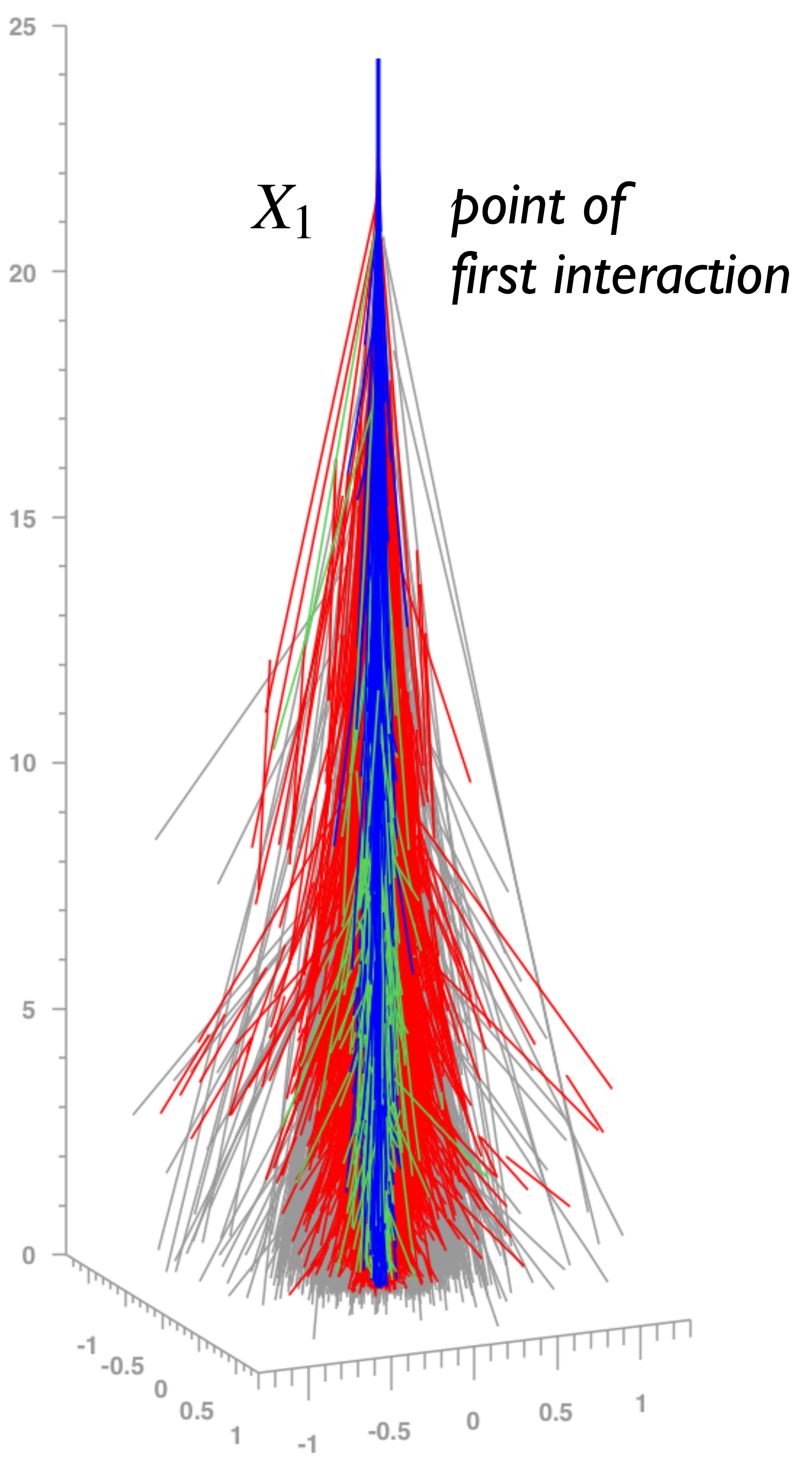
Fluctuations due only to mix of composition

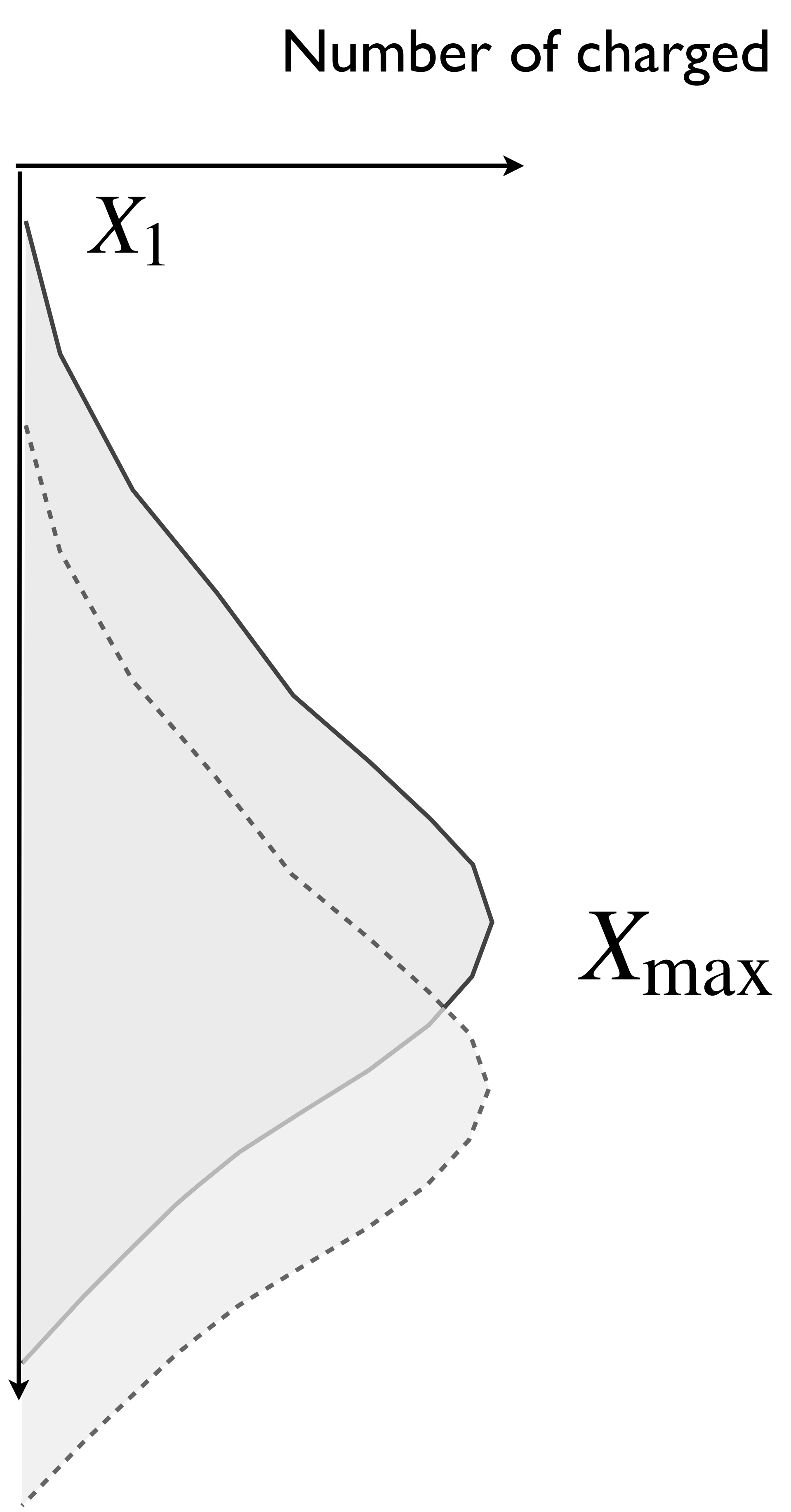
(Bellido, ICRC 2017)

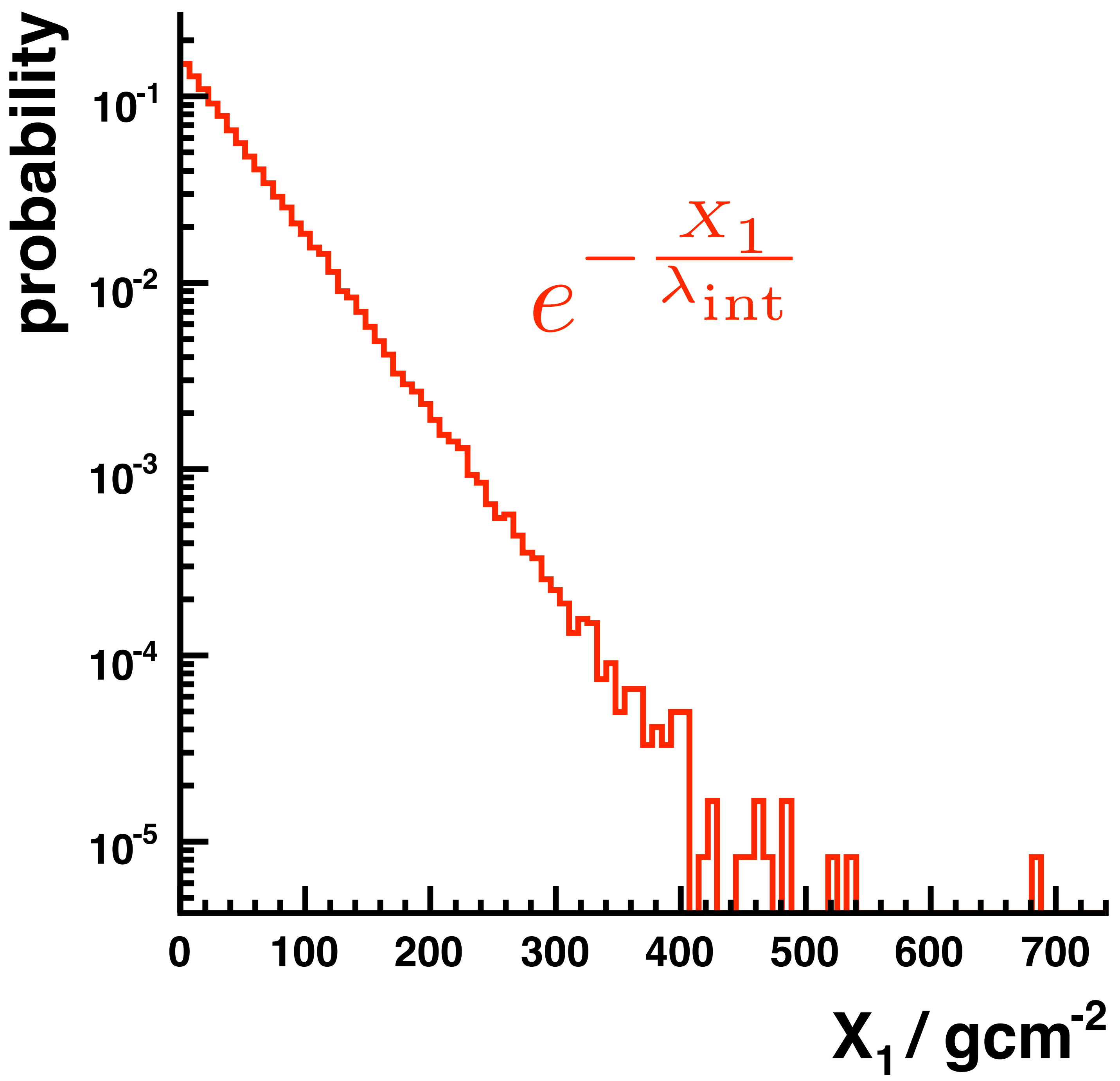
Hadron production at very high energy:

Measurement of proton-air cross section

Relation between depth of maximum and p-air cross section



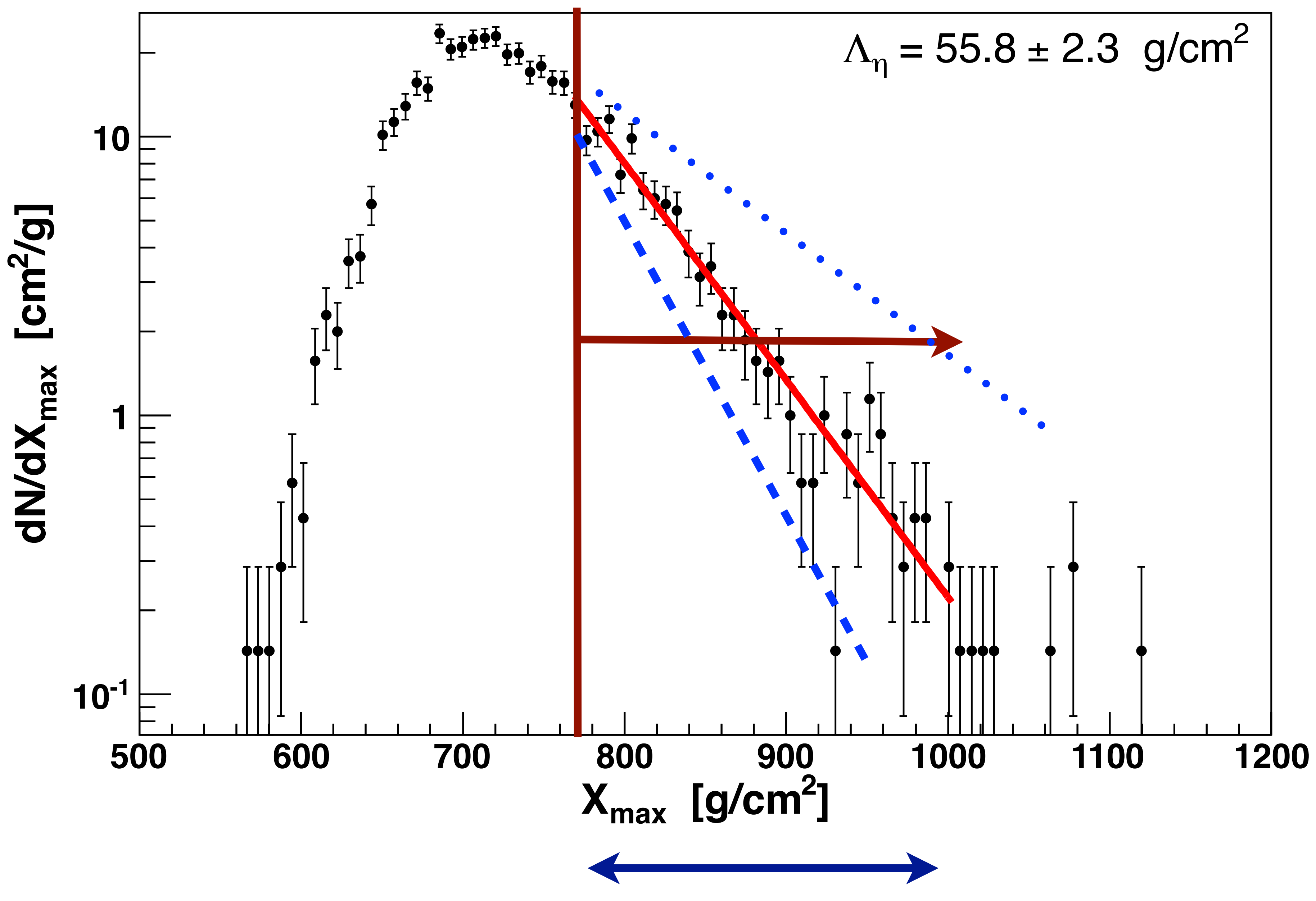




$$\lambda_{int} = \frac{\langle m_{air} \rangle}{\sigma_{p-air}}$$

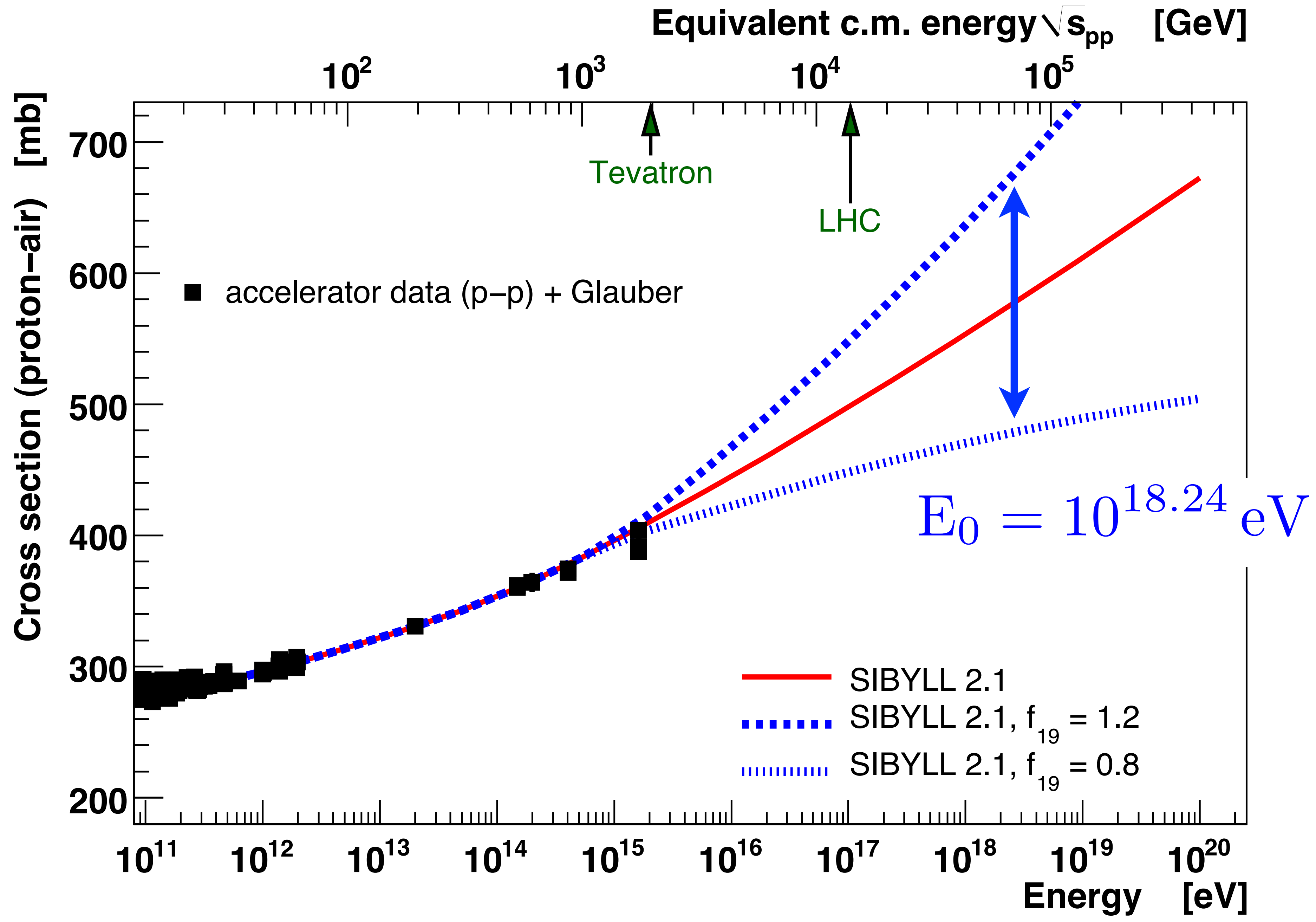
$$\sigma_{X_1} = \lambda_{int}$$

Cross section measurement: distribution of deep showers



Depth range of analysis

(Auger Collab. PRL 2012)

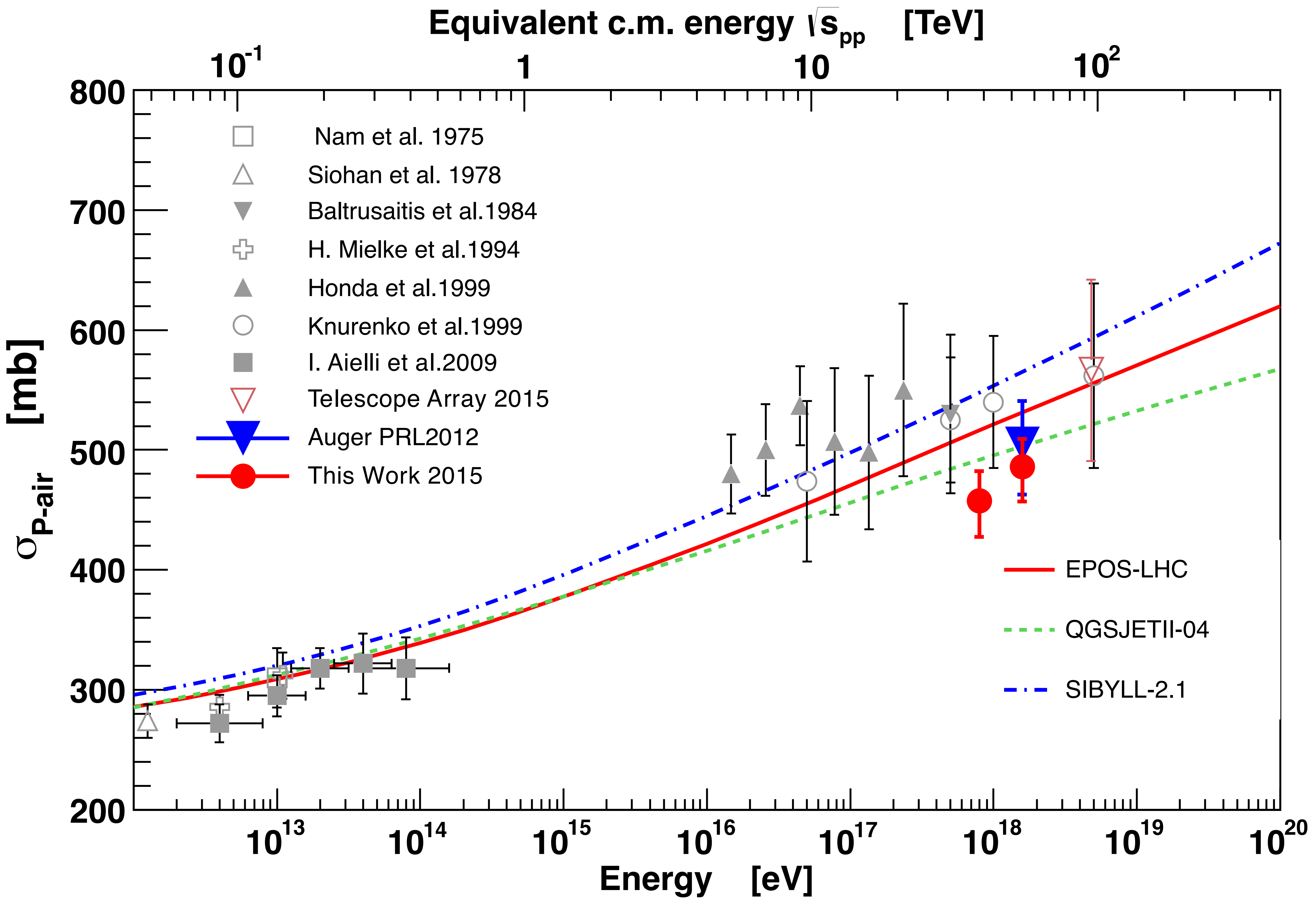


Cross section accepted if simulated slope fits measured slope of X_{max} distribution

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

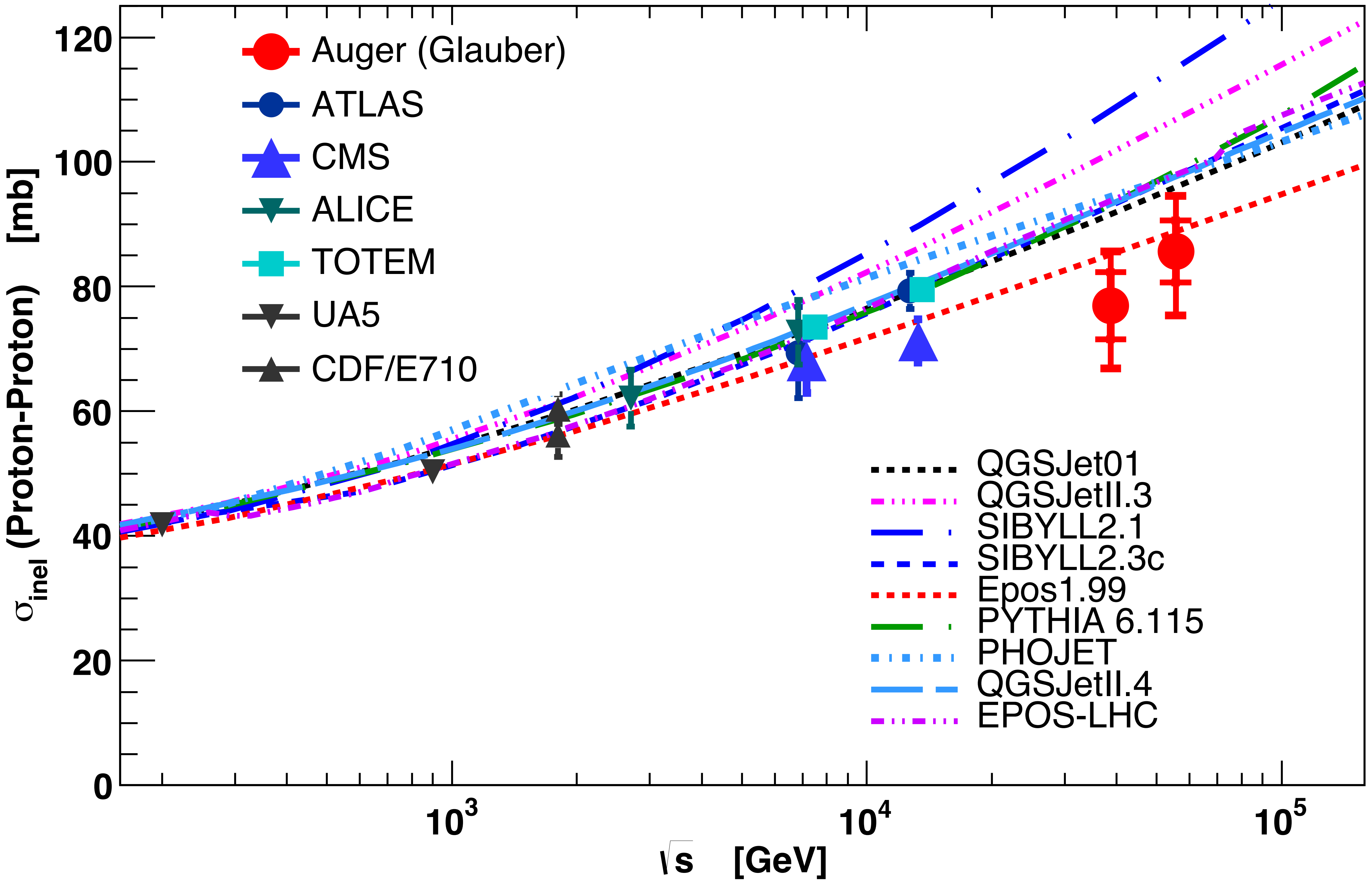
$$\sigma_{p\text{-air}} = \left(505 \ \pm 22_{\rm stat} \ \left({}^{+26}_{-34}\right)_{\rm sys}\right) \ \mathrm{mb}$$

Proton-air and proton-proton cross sections



Models, collider data, Auger (derived) cross sections

Glauber model (multiple scattering approximation)



(Ulrich, Auger, ICRC 2017)

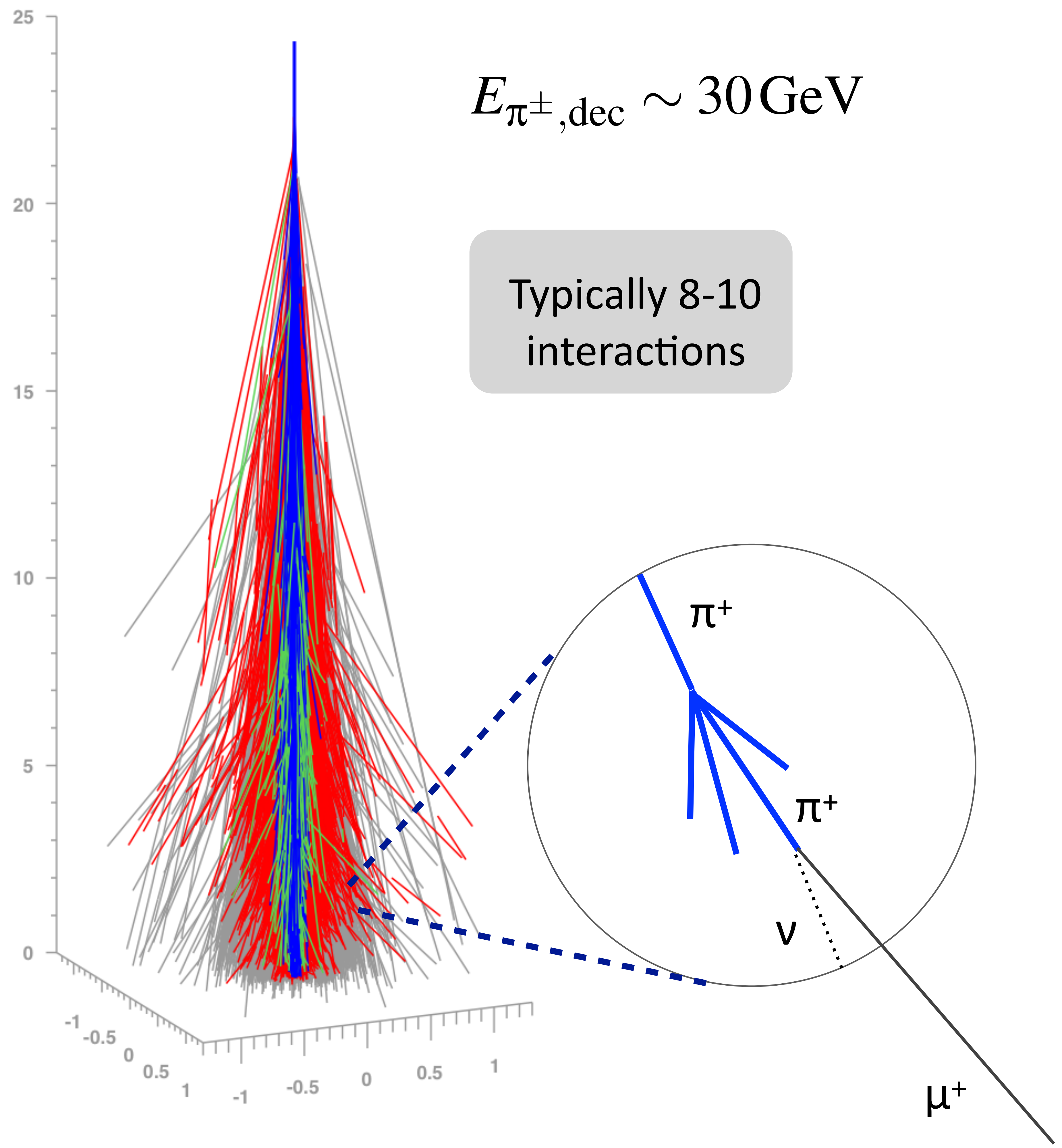
Hadron production at all energies energy:

Muons as tracer of the hadronic shower core

Muon production at large lateral distance

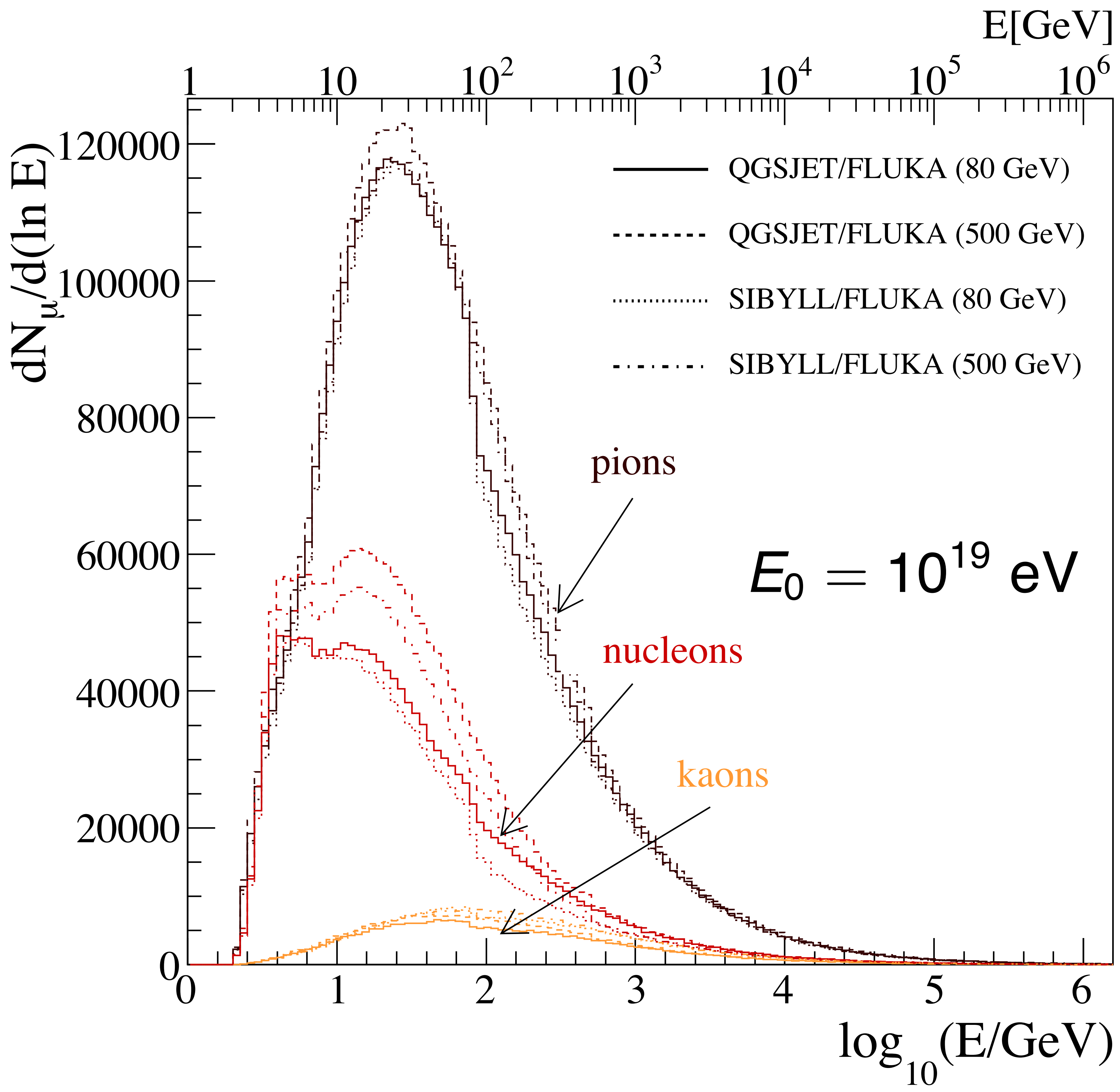
$E_{\pi^{\pm},\mathrm{dec}} \sim 30\,\mathrm{GeV}$

Typically 8-10 interactions



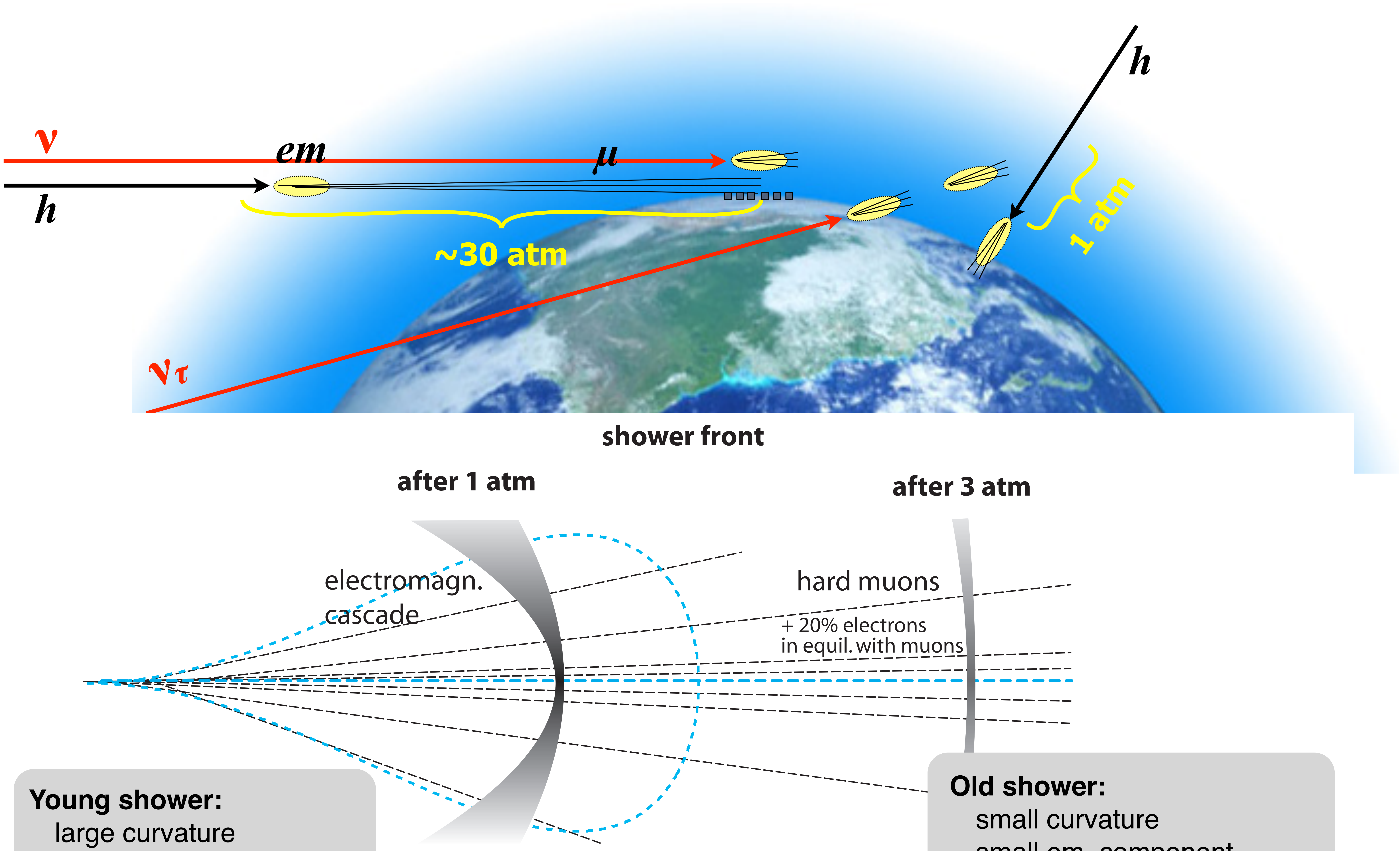
Muon observed at 1000 m from core

Energy distribution of last interaction that produced a detected muon



(Maris et al. ICRC 2009)

Measuring muons with highly inclined showers

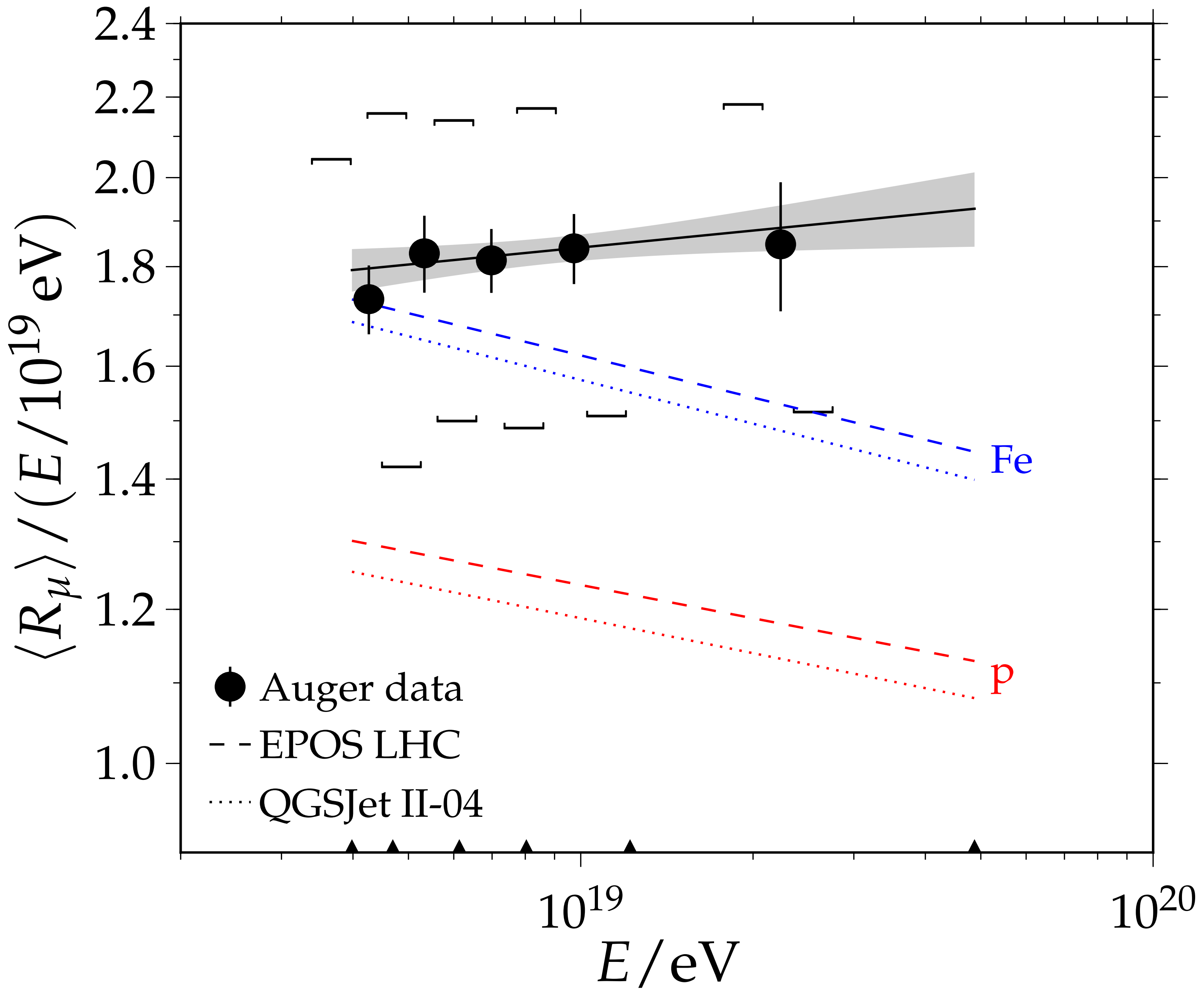


Young shower:
large curvature
large em. component
extended time structure

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

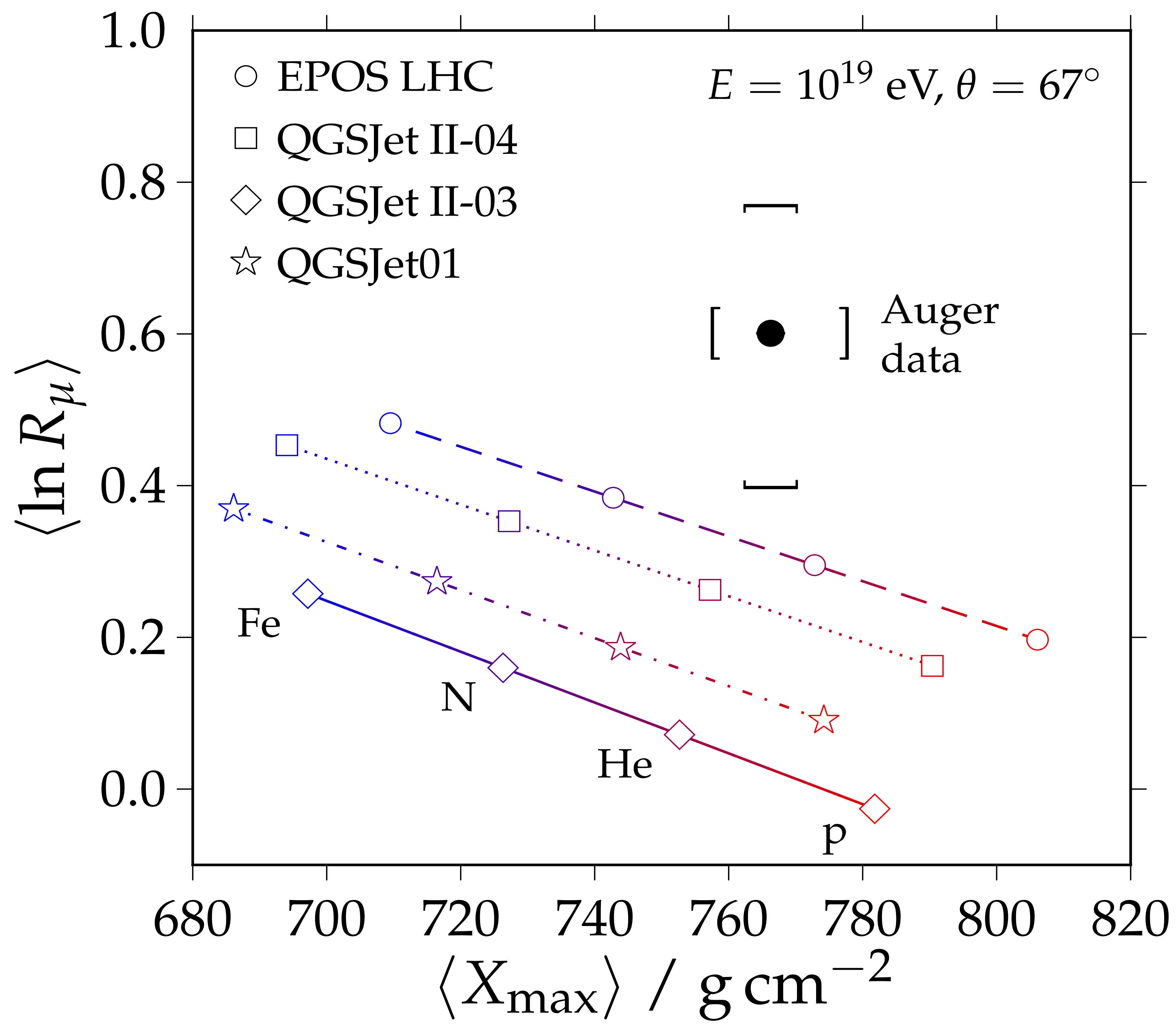
Discrepancy: Muon number in inclined showers

Number of muons in showers with θ>60°



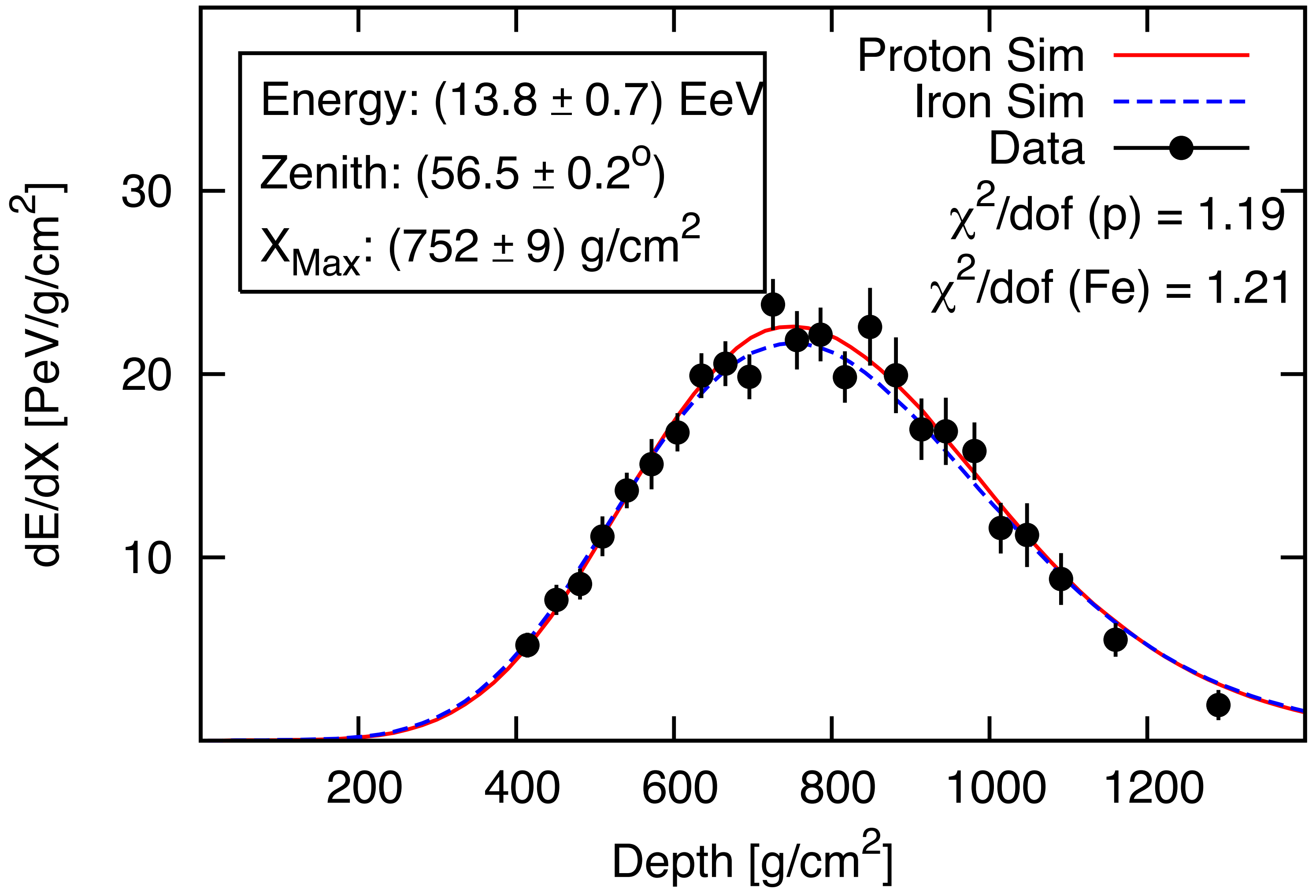
(Auger, PRD91, 2015)

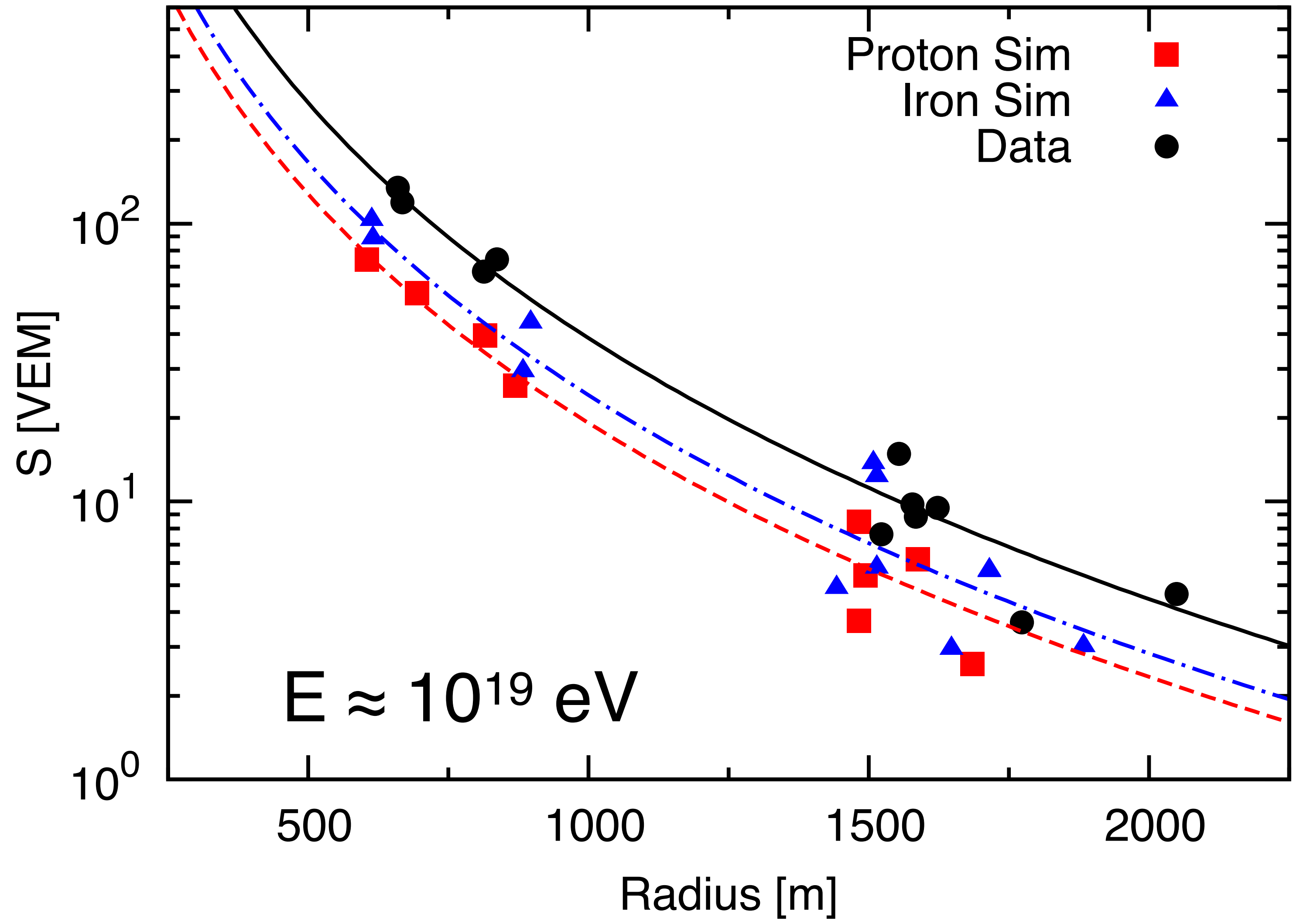
Combination of information on mean depth of shower maximum and muon number at ground



Several measurements: indications for muon discrepancy

Ultimative test: simulation of individual events



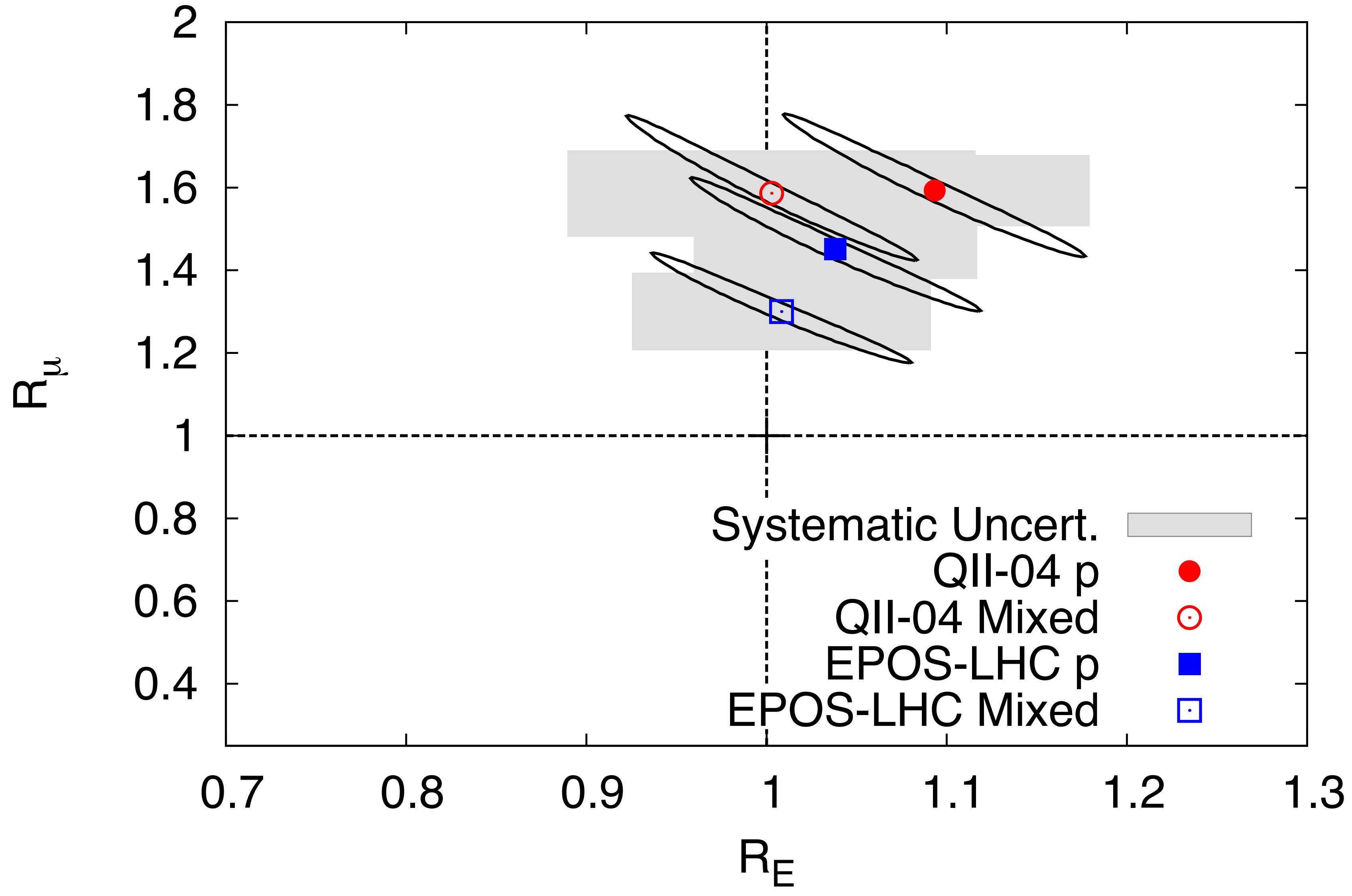


Phenomenological model ansatz

Energy scaling: em. particles and muons

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

Full detector simulation after re-scaling

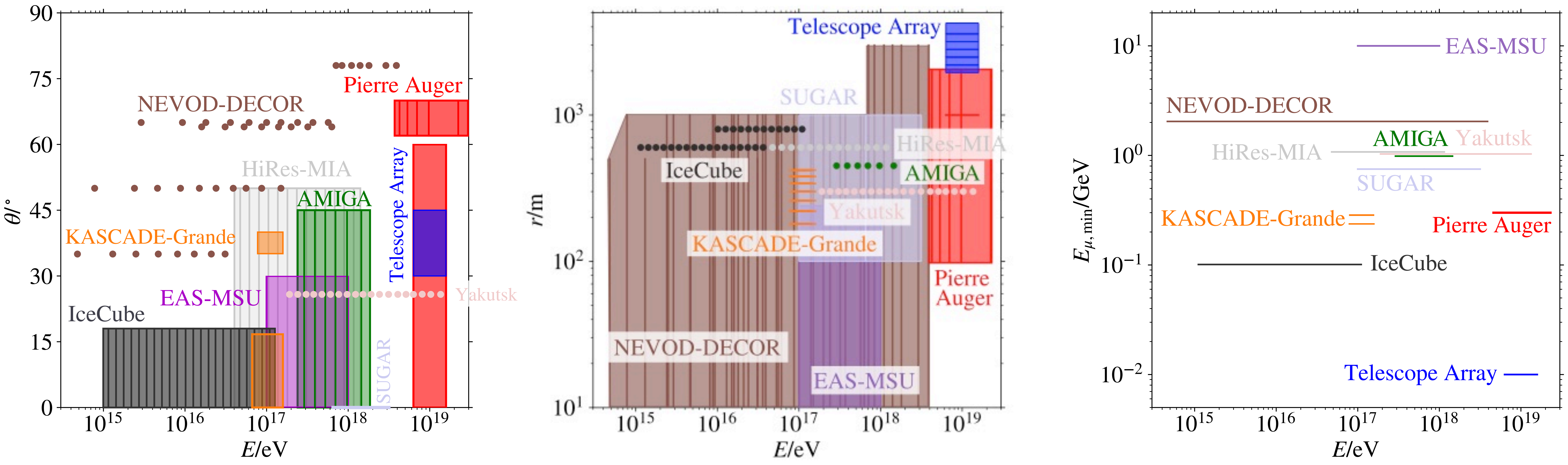


None of the models gives an acceptable description

(Auger, PRL 2016)

Muon number measured by many cosmic ray experiments

lines & boxes: result integrated over range



E = 0.5 PeV ... 20 EeV **θ** = 0 ... 78 deg **r** = 0 ... 4 km $\mathbf{E_{\mu,threshold}}$ = 0.01 ... 10 GeV

Pierre Auger	AMIGA preliminary: S. Müller poster ID 204; PRL 117 (2016) 192001; PRD 91 (2015) 032003
Telescope Array	PRD 98 (2018) 022002
IceCube	ISVHECRI 2018 preliminary
KASCADE-Grande	Astropart. Phys. 95 (2017) 25
NEVOD-DECOR	Phys. Atom. Nucl. 73 (2010) 1852, Astropart. Phys. 98 (2018) 13
SUGAR	PRD 98 (2018) 023014
EAS-MSU	Astropart. Phys. 92 (2017) 1
Yakutsk	Unpublished preliminary results
HiRes-MIA	PRL 84 (2000) 4276; not part of WG, only included for comparison

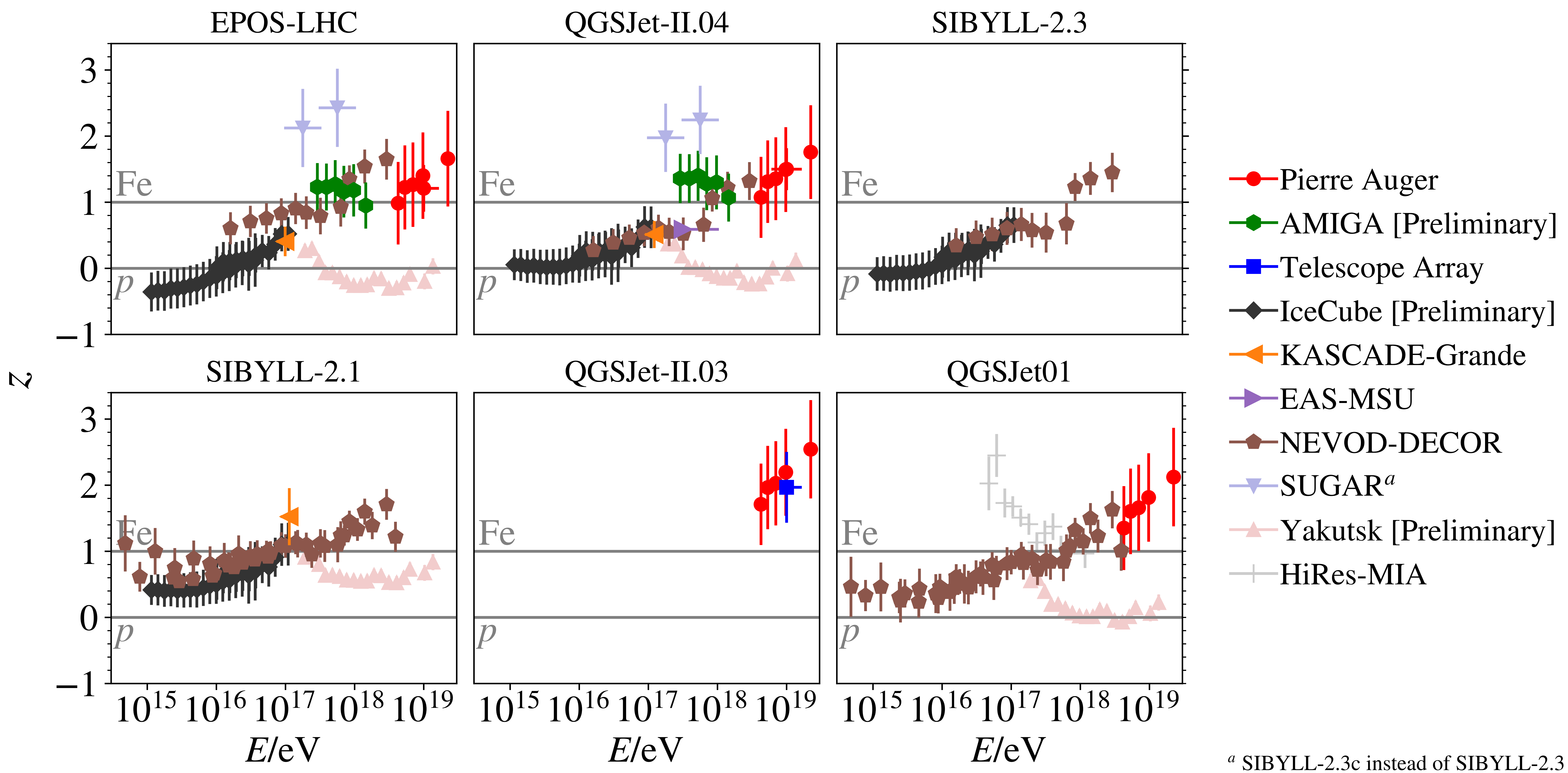
(Dembinski et al.
Hadronic interactions
working group, UHECR 2018)

Comparison of muon measurements: 1. Universal reference scale

Step 1: Convert all measurements to z-scale $z = \dfrac{\ln N_{\mu}^{\det} - \ln N_{\mu,p}^{\det}}{\ln N_{\mu,\mathrm{Fe}}^{\det} - \ln N_{\mu,p}^{\det}}$

corrects simple biases;
$z_p = 0$ and $z_{Fe} = 1$

Potential divergence from differences in: **energy scale offsets**, shower age, lateral distances, muon energy thresholds



[a] SIBYLL-2.3c instead of SIBYLL-2.3

(Dembinski et al. Hadronic interactions working group, UHECR 2018)

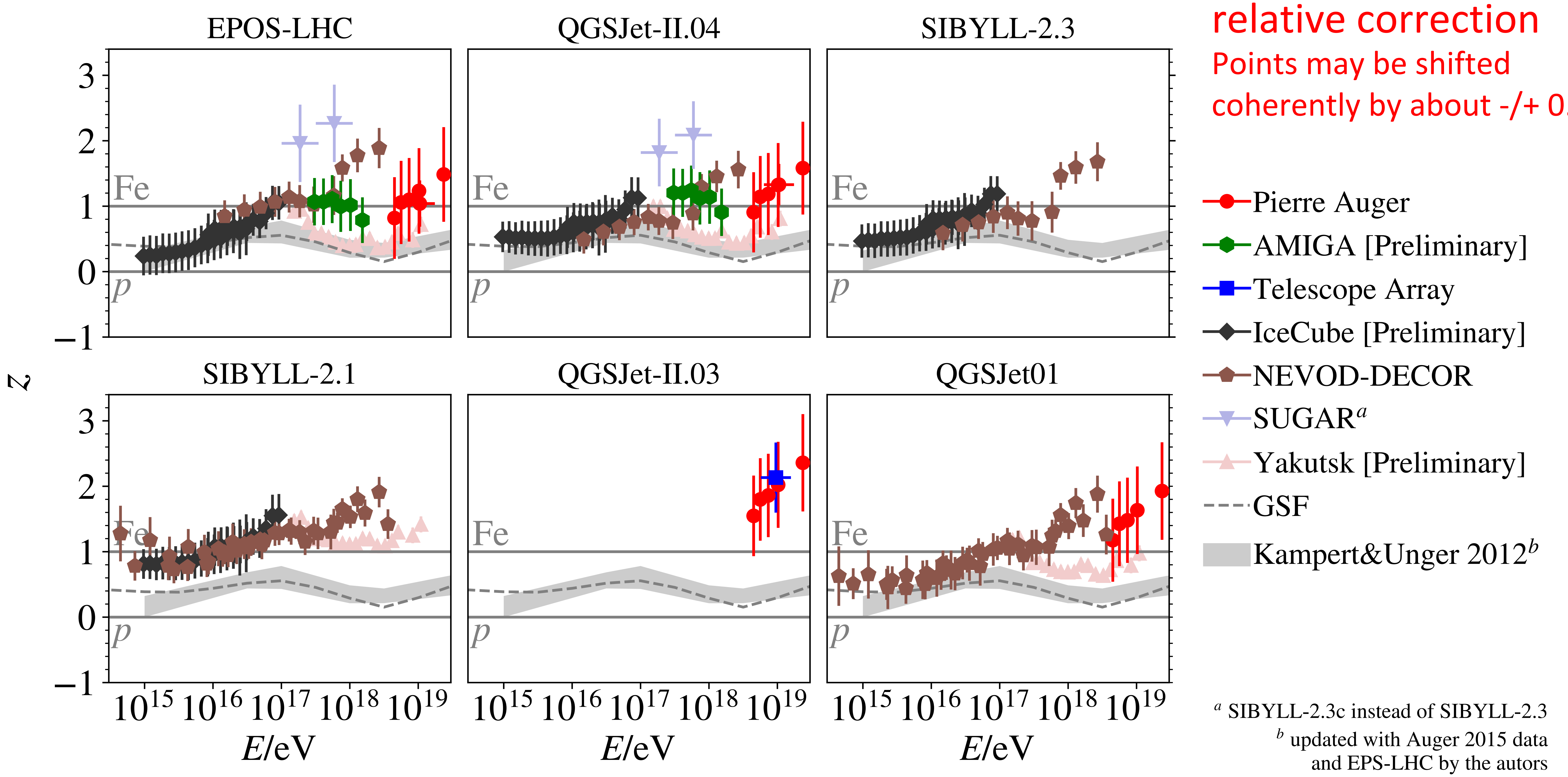
Comparison of muon measurements: 2. Energy scale correction

Step 2: Apply energy scale corrections (after, experiments with unknown scale not shown)

Still present: possible dependence on shower age, lateral distance, energy threshold

Absolute energy-scale still uncertain after relative correction

Points may be shifted coherently by about -/+ 0.25



(Dembinski et al. Hadronic interactions working group, UHECR 2018)

What is the origin of the muon discrepancies ?

Air showers: electromagnetic and hadronic components

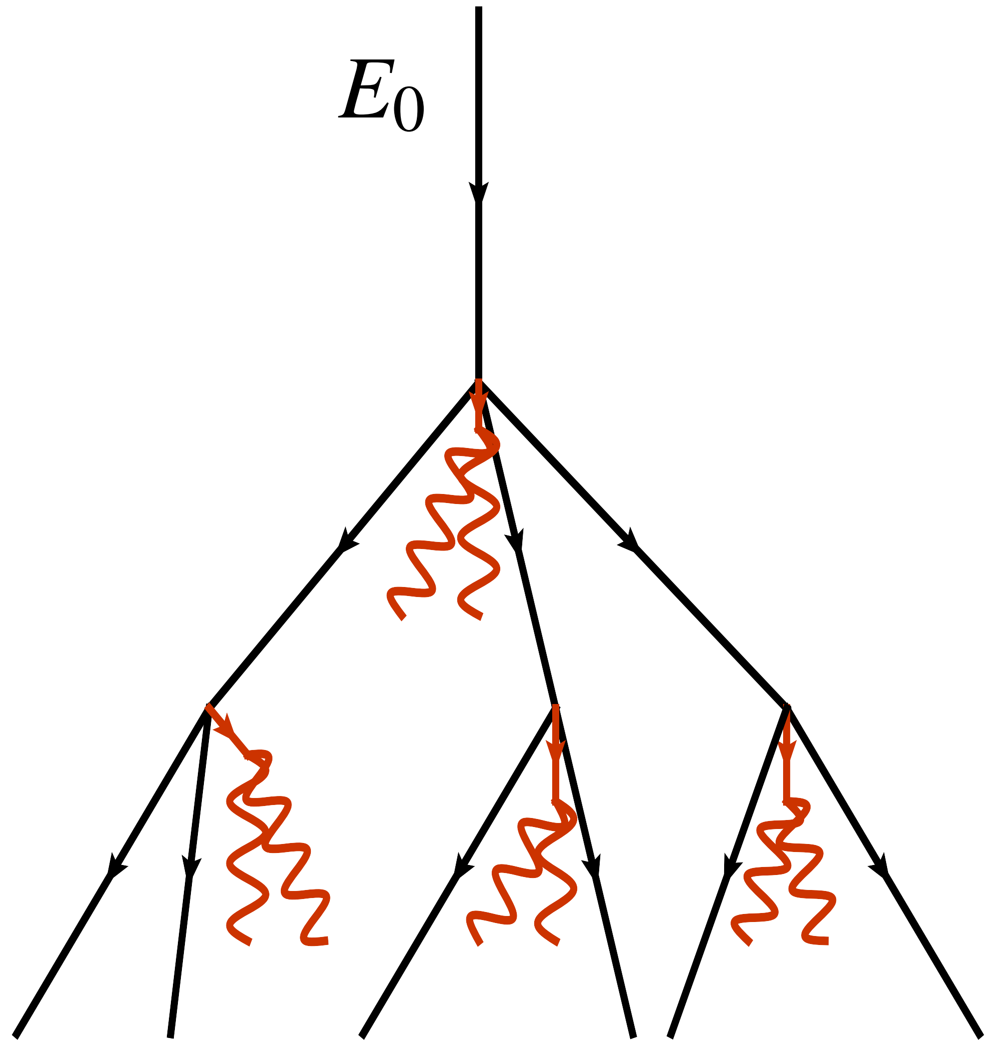
Hadronic energy

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

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

o
o
o

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



After n generations ...

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

Electromagnetic energy

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

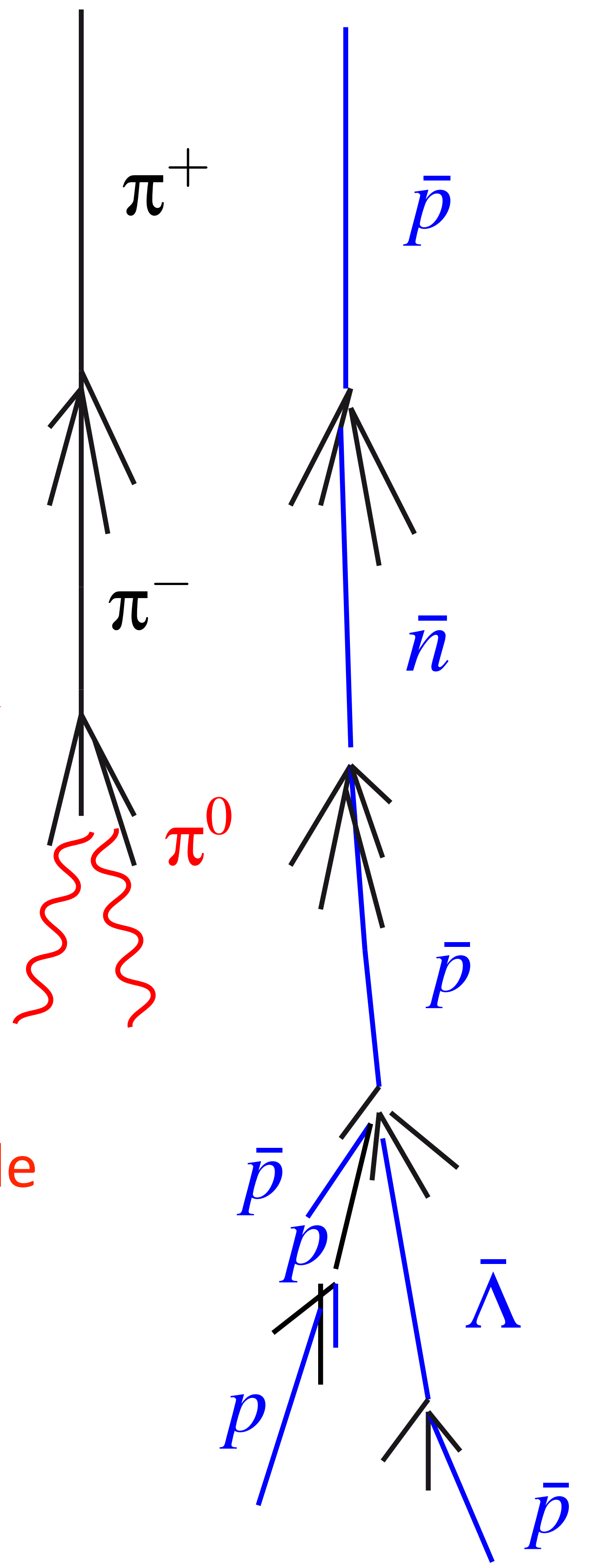
$$\frac{1}{3}E_0 + \frac{1}{3}\left(\frac{2}{3}E_0\right)$$

o
o
o

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

30% chance to have π^0 as leading particle

Meson sub-shower | **Baryon sub-shower**



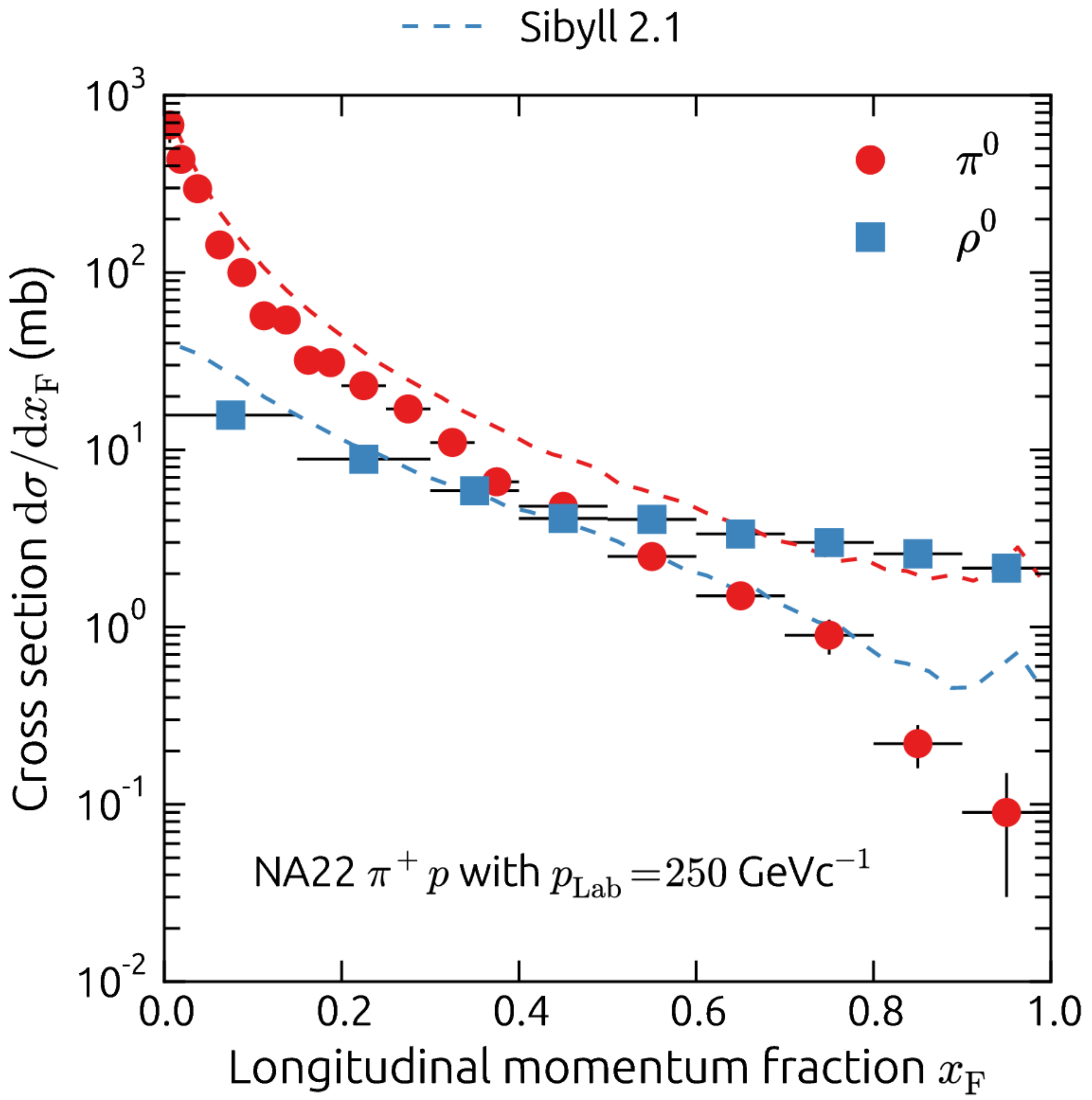
Decay of leading particle

(Matthews, APP22, 2005)

Realistic number of generations: 6-7 at 10^{15} eV, 10-12 at 10^{19} eV

(Pierog, Riehn)

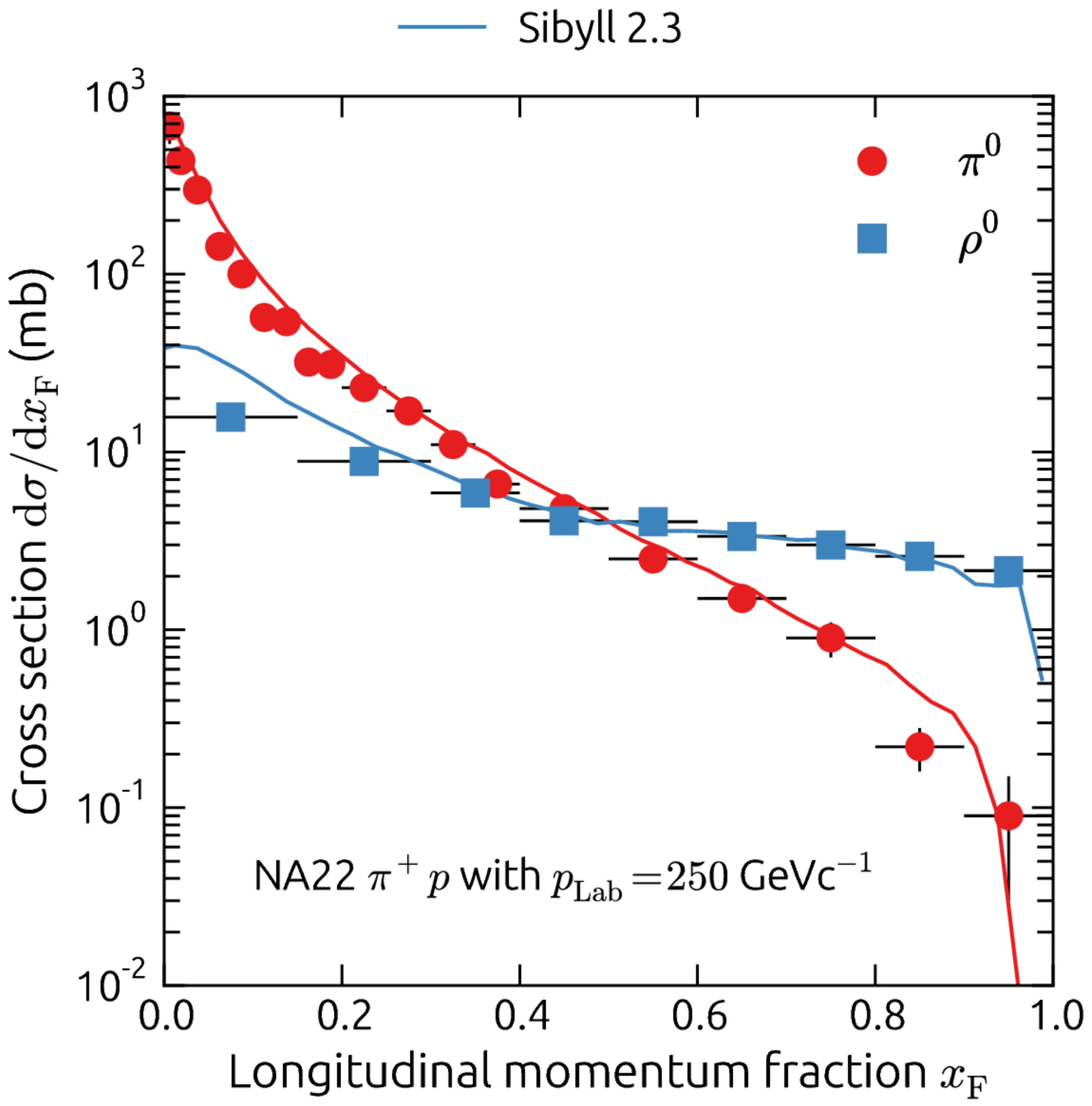
Rho production in π-p interactions (Sibyll 2.1 → Sibyll 2.3)



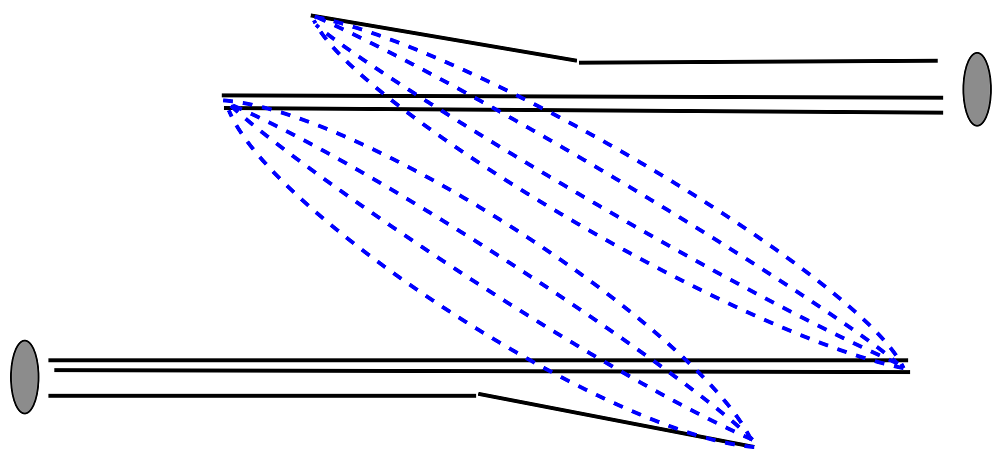
$$\pi^+ p \rightarrow \pi^0 \rightarrow 2\gamma$$

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

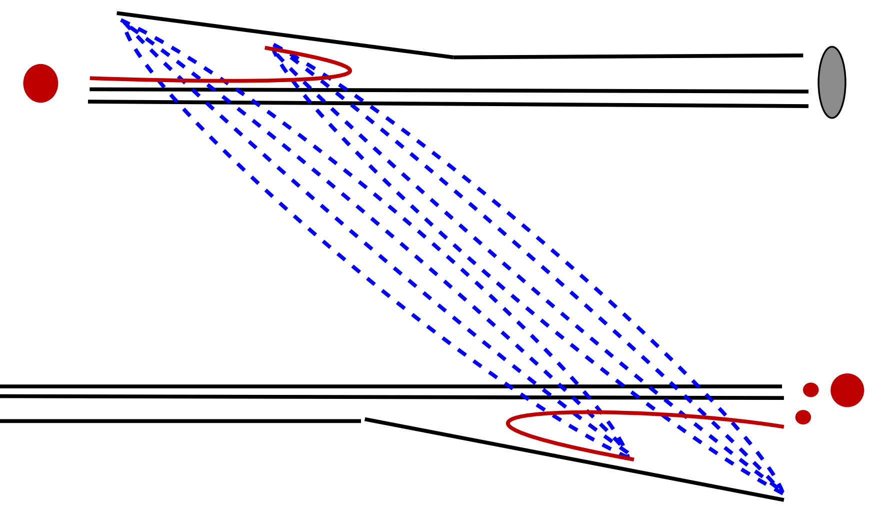
$$E_{\mathrm{lab}} = 250\,\mathrm{GeV}$$



$$x_{\mathrm{F}} = p_{\|}/p_{\mathrm{max}}$$



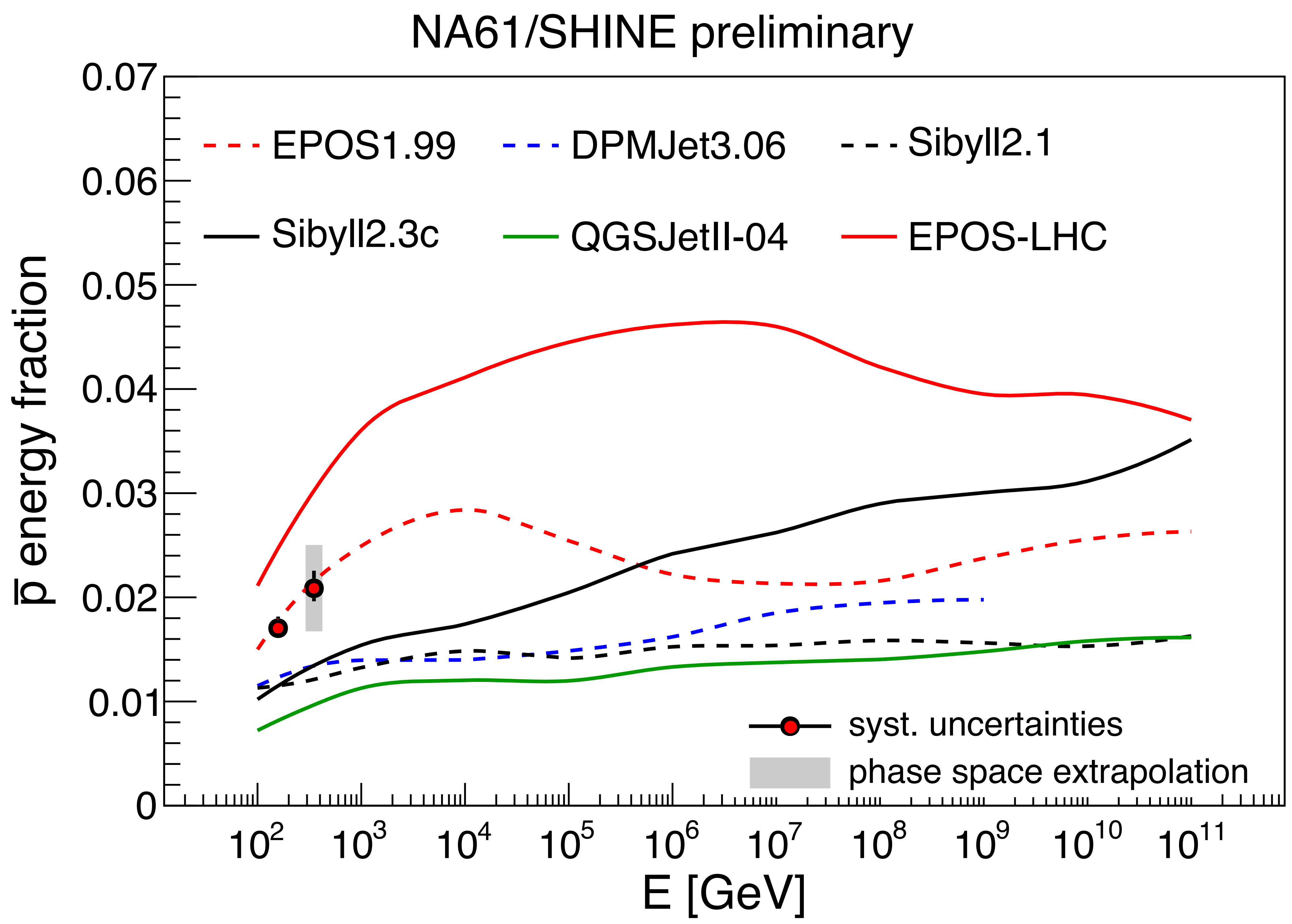
$$R_{\rho^0}/R_{\pi^0} = 0.3$$



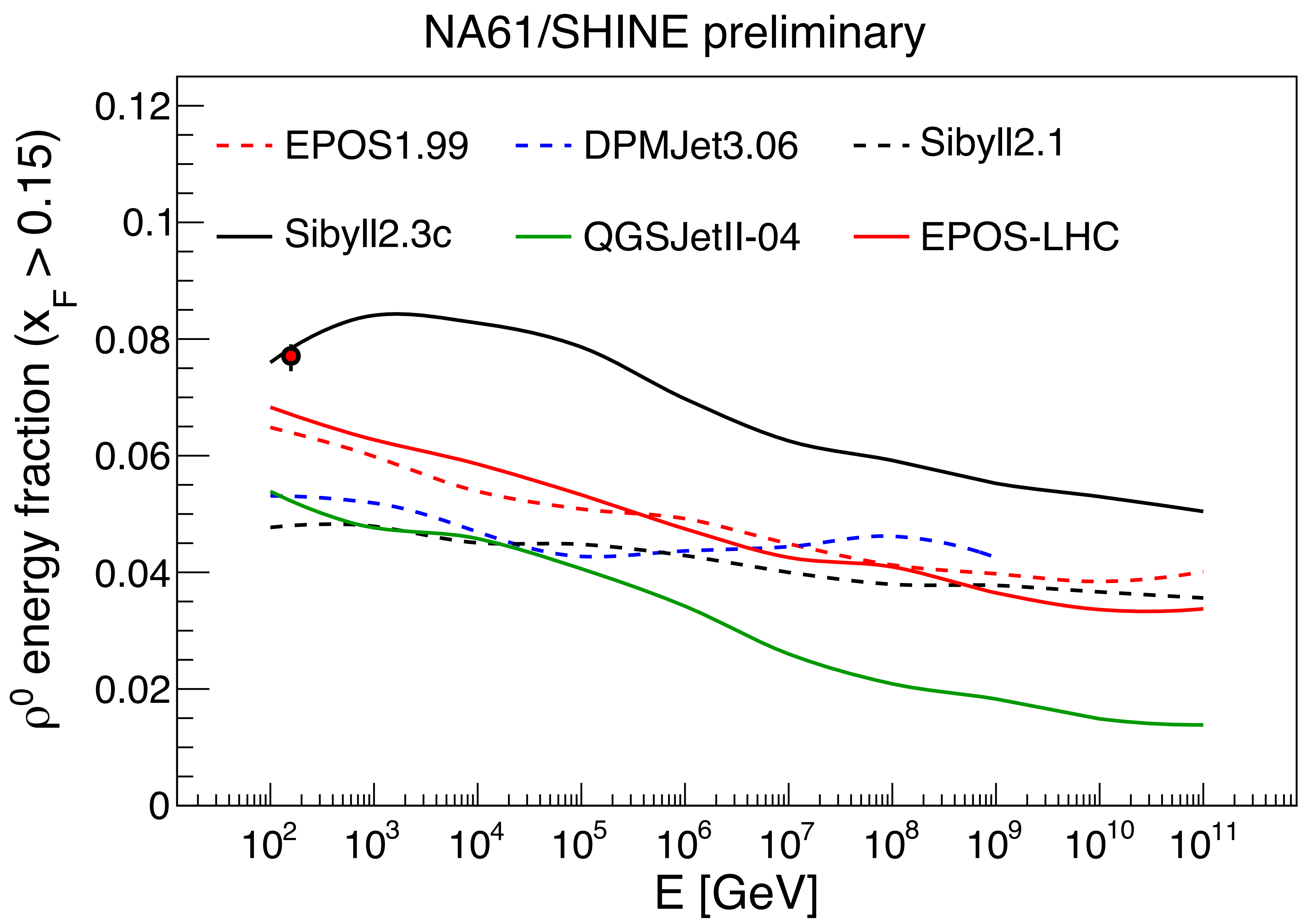
$$R_{\rho^0}/R_{\pi^0} = f(x_{\mathrm{F}})$$

(Riehn et al., ICRC 2015)

NA61 results and extrapolation to high energy



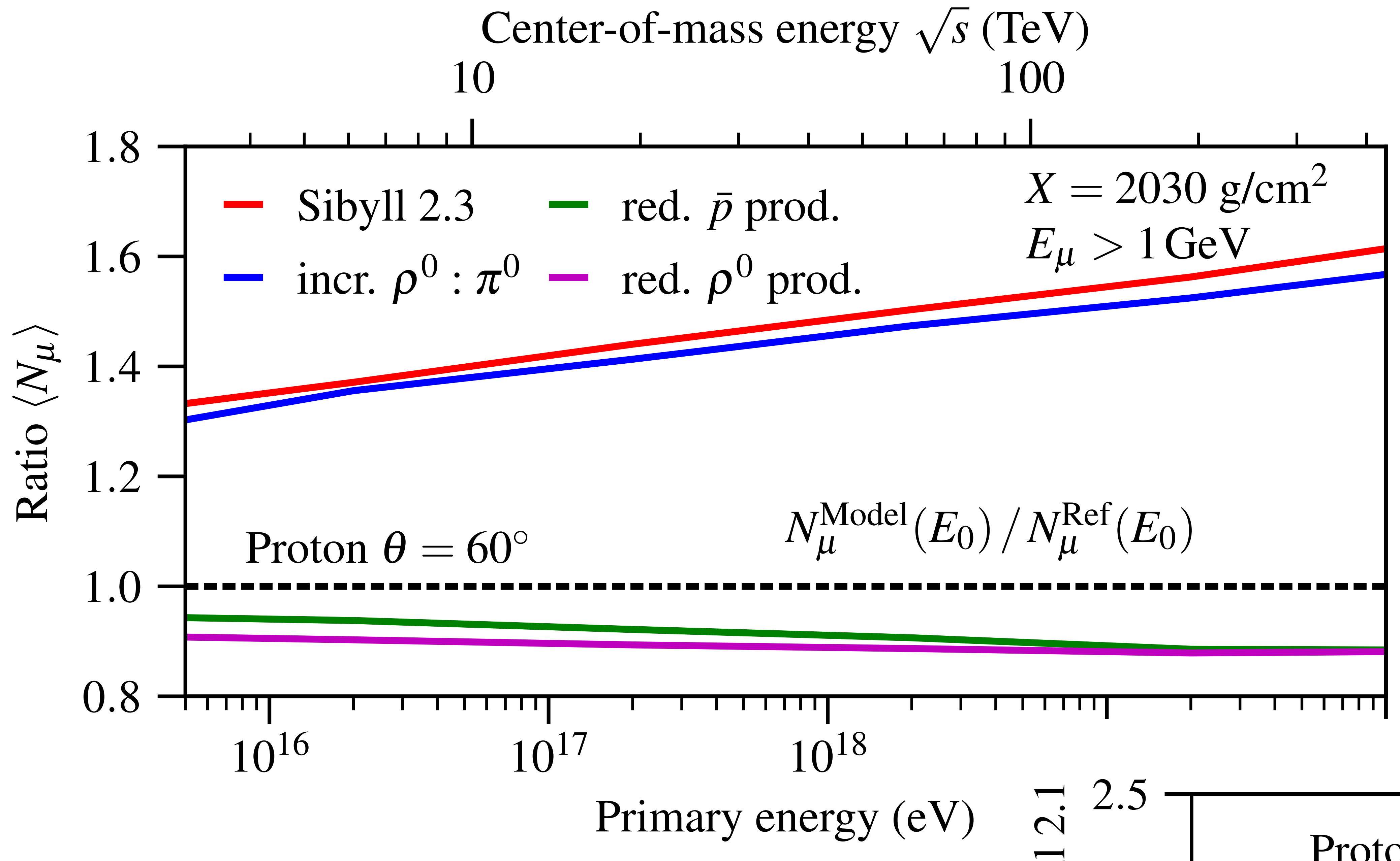
$\bar{p}$ energy fraction in π^-+C



ρ^0 energy fraction in π^-+C

(Prado, NA61, ICRC 2017)

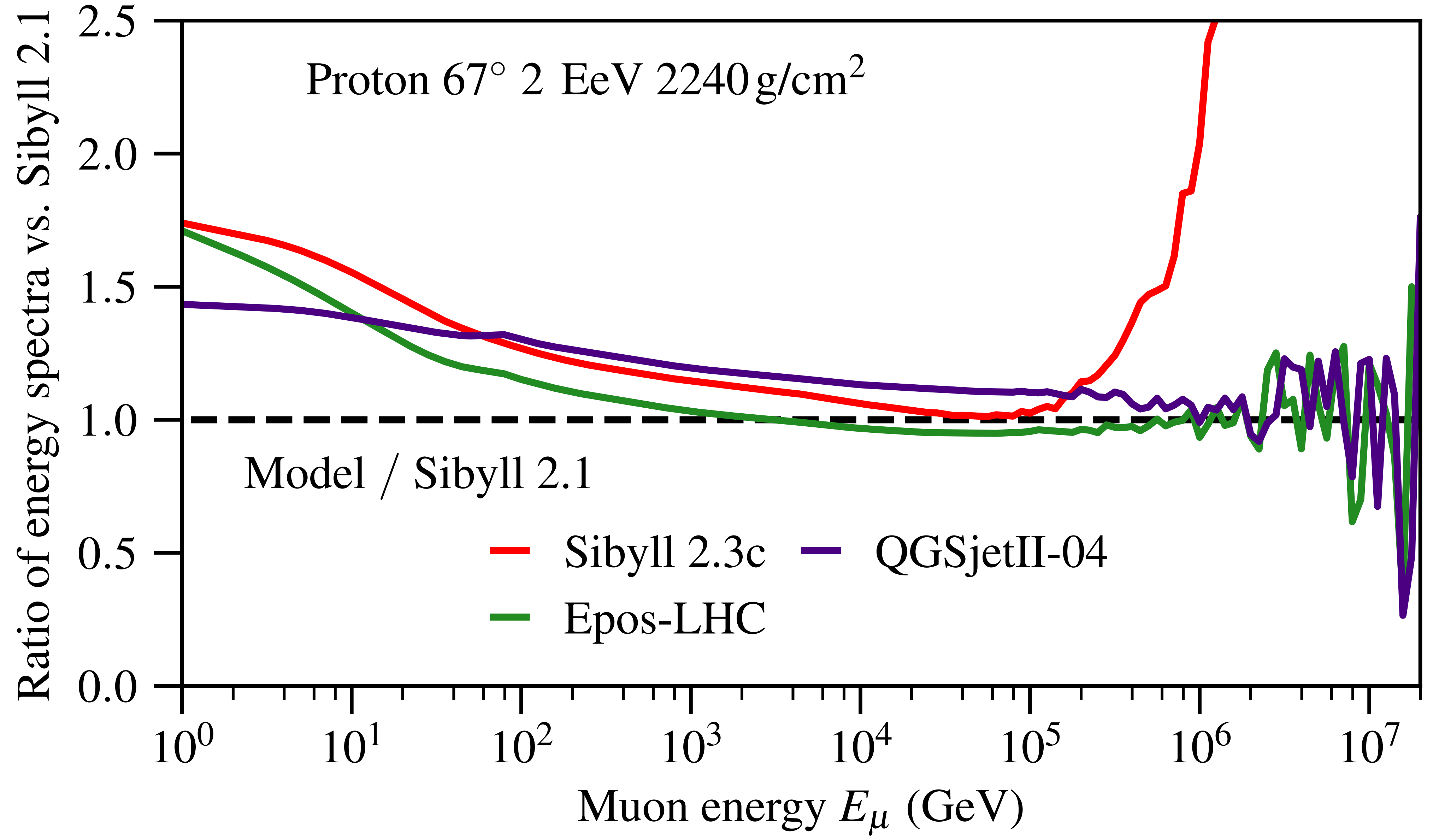
Air showers: electromagnetic and hadronic components

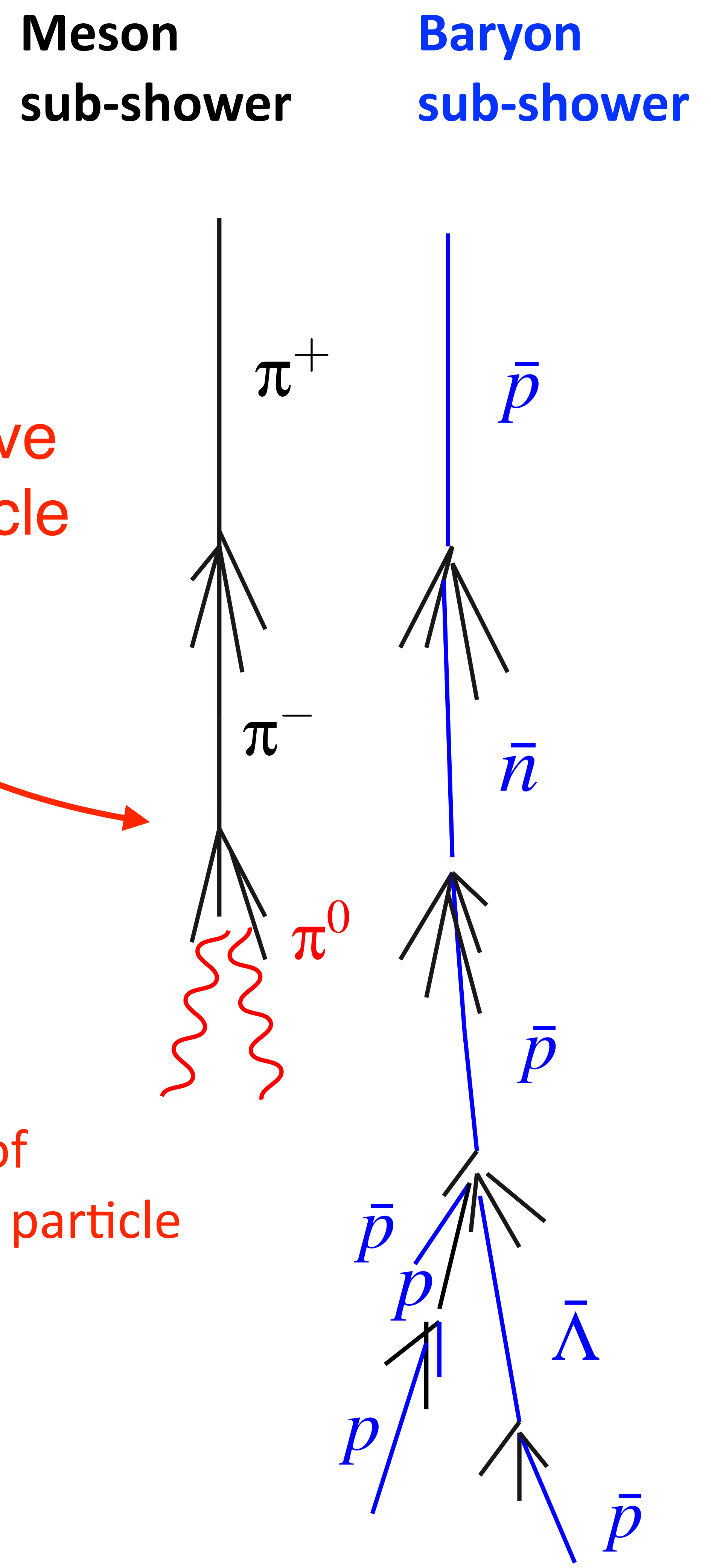


Factor 1.6

30% chance to have π^0 as leading particle

Relative energy spectrum





Decay of leading particle

Energy spectrum depends on contribution processes

Can be measured with IceCube (~500 GeV) and IceTop (~1 GeV)

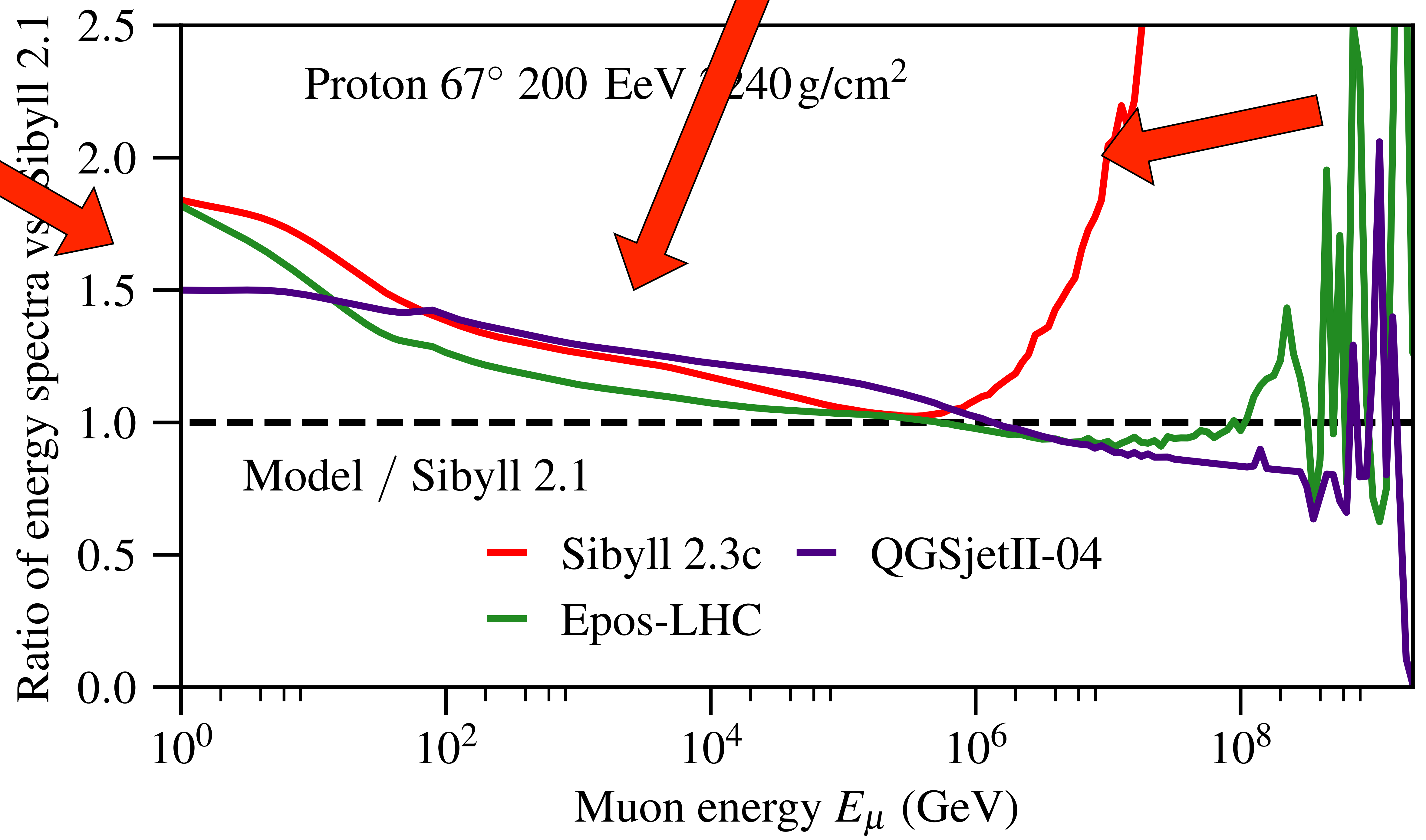
(Riehn et al. 2017 & 2018)

Energy spectrum of muons in EAS

Muon energy spectrum in EAS relative to that of Sibyll 2.1

Rho-0 production

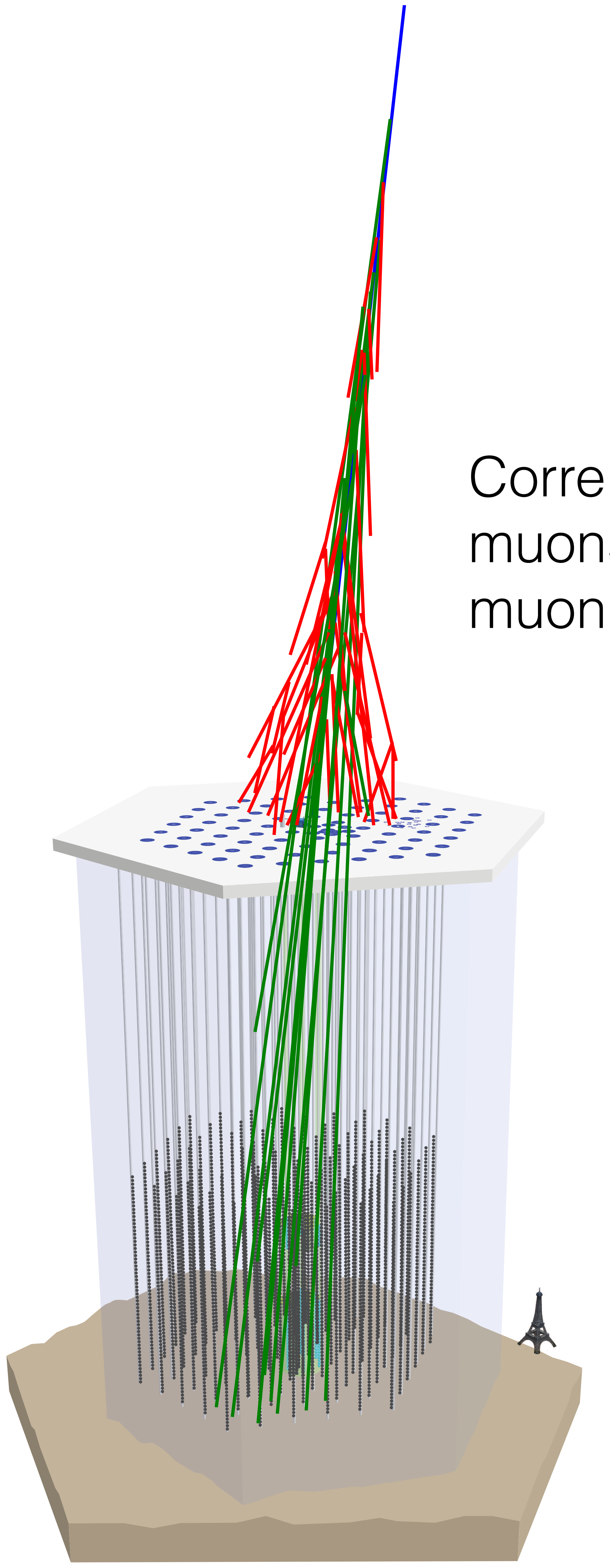
Low-energy enhancement due to baryon pair production



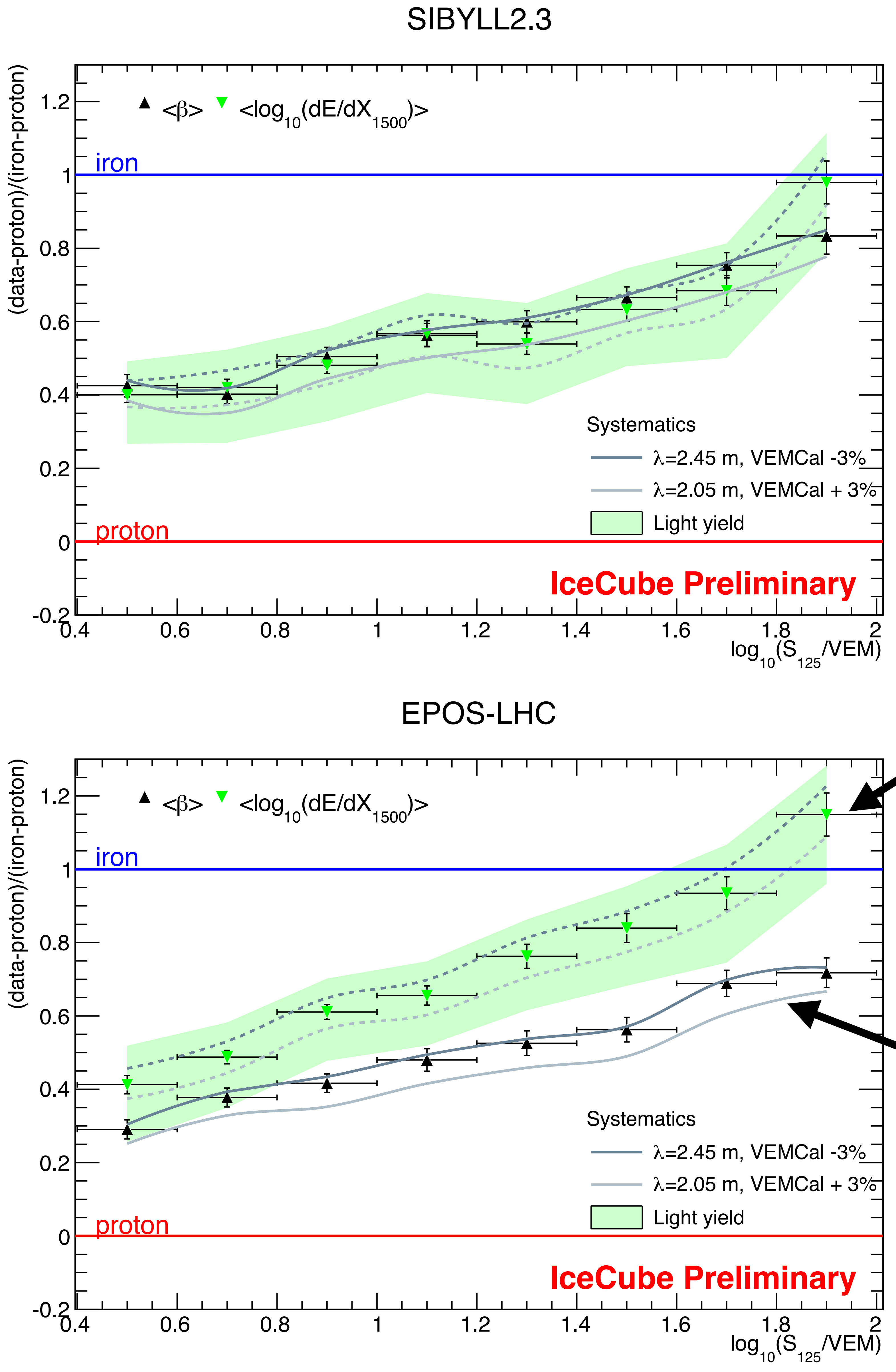
Charm particles (only Sibyll 2.3, and Sibyll 2.3c)

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

IceCube: discrimination of enhancement scenarios?



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



(de Ridder, Gaisser, IceCube, ICRC 2017)

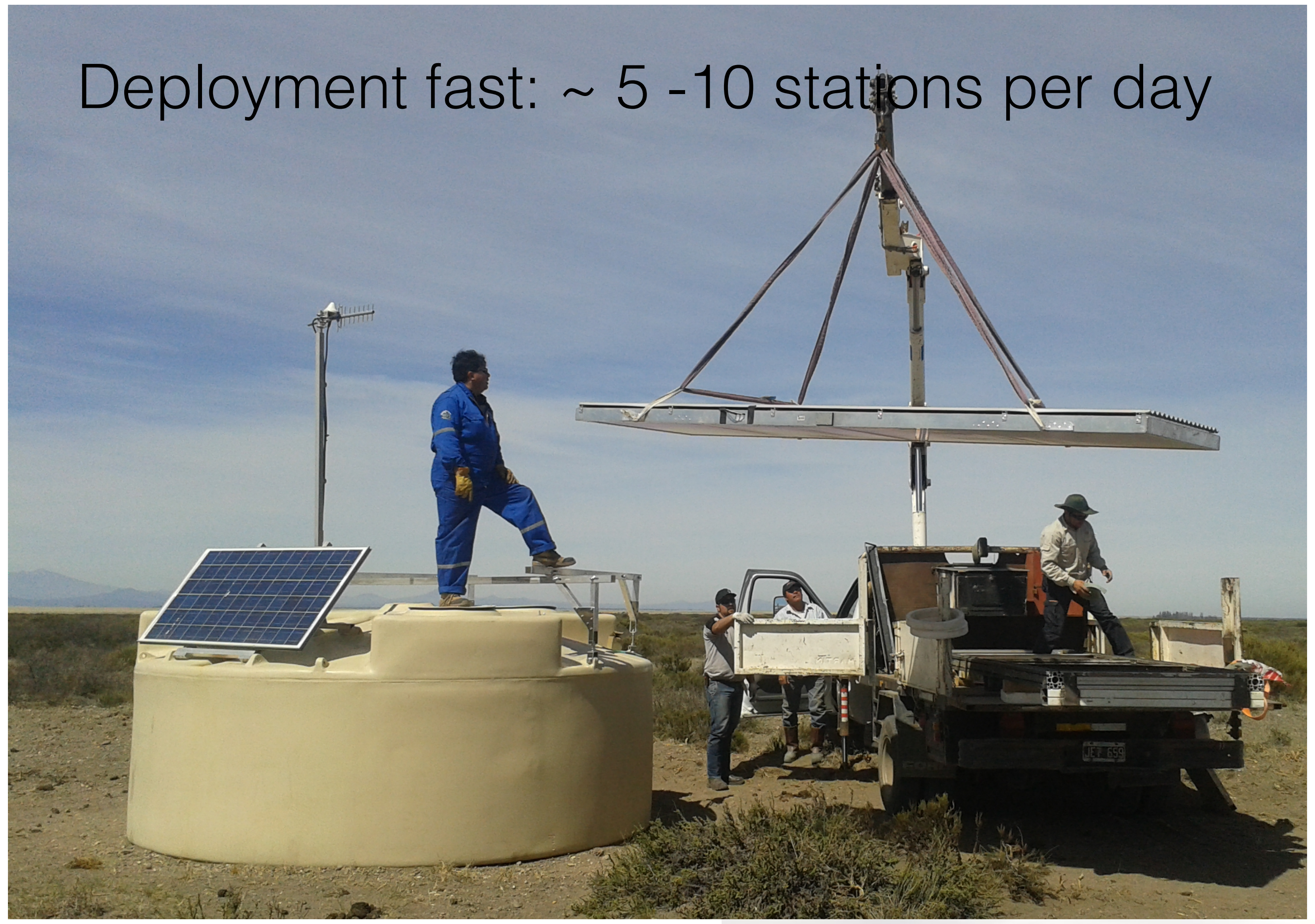
In-ice muons (~300 GeV)

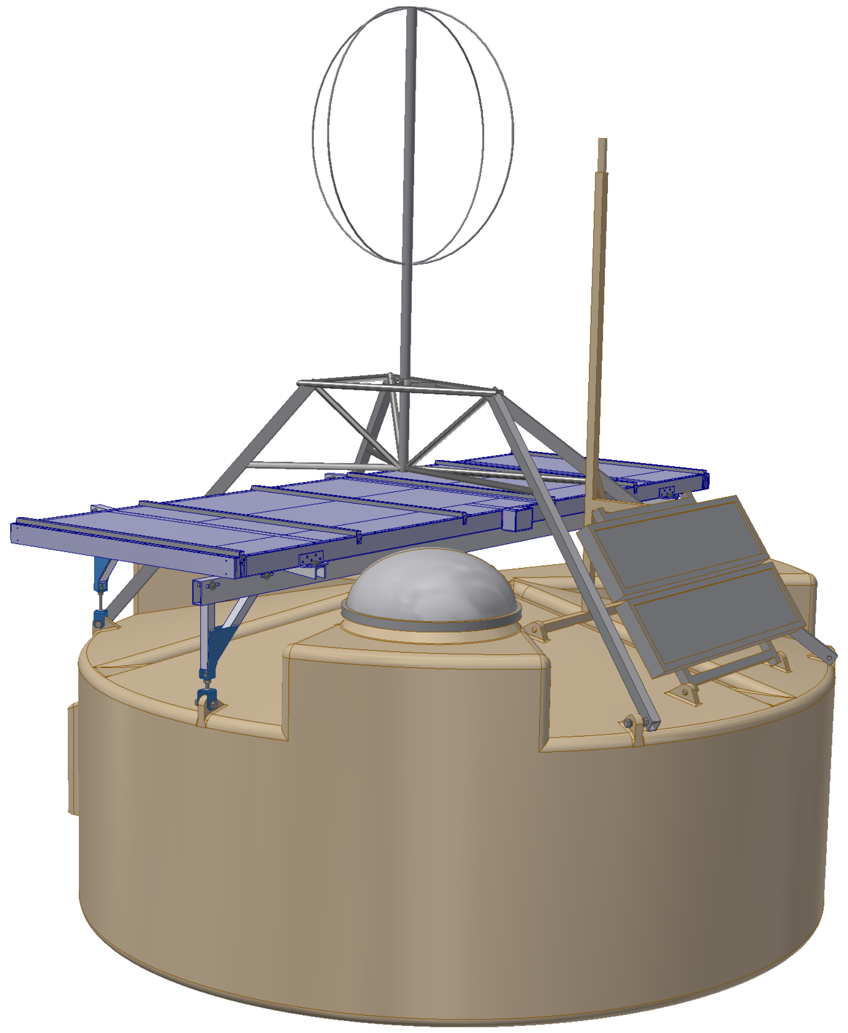
Surface muons (~1 GeV)

Outlook: Upgrade of Auger Observatory

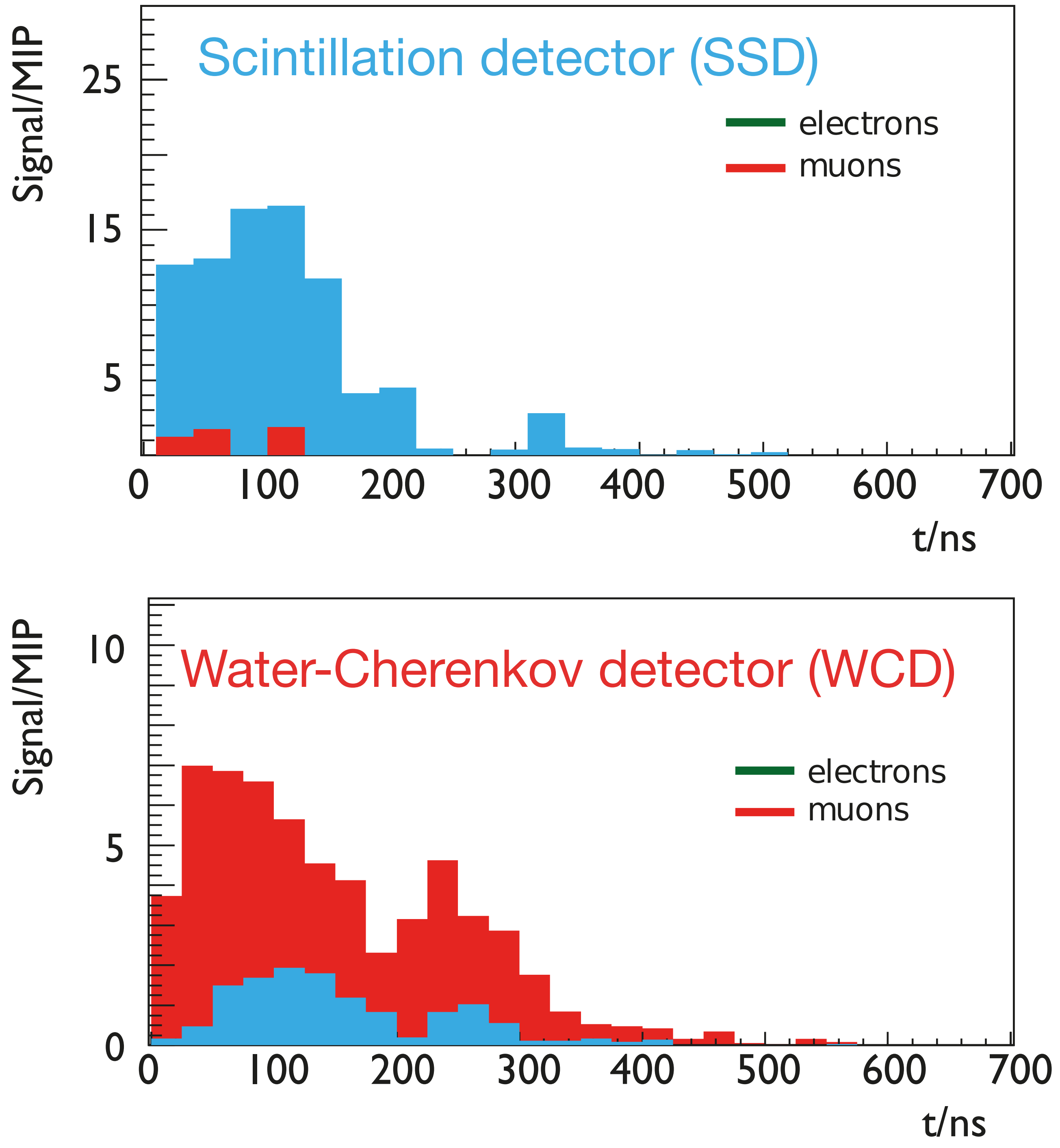
15% duty cycle

100% duty cycle

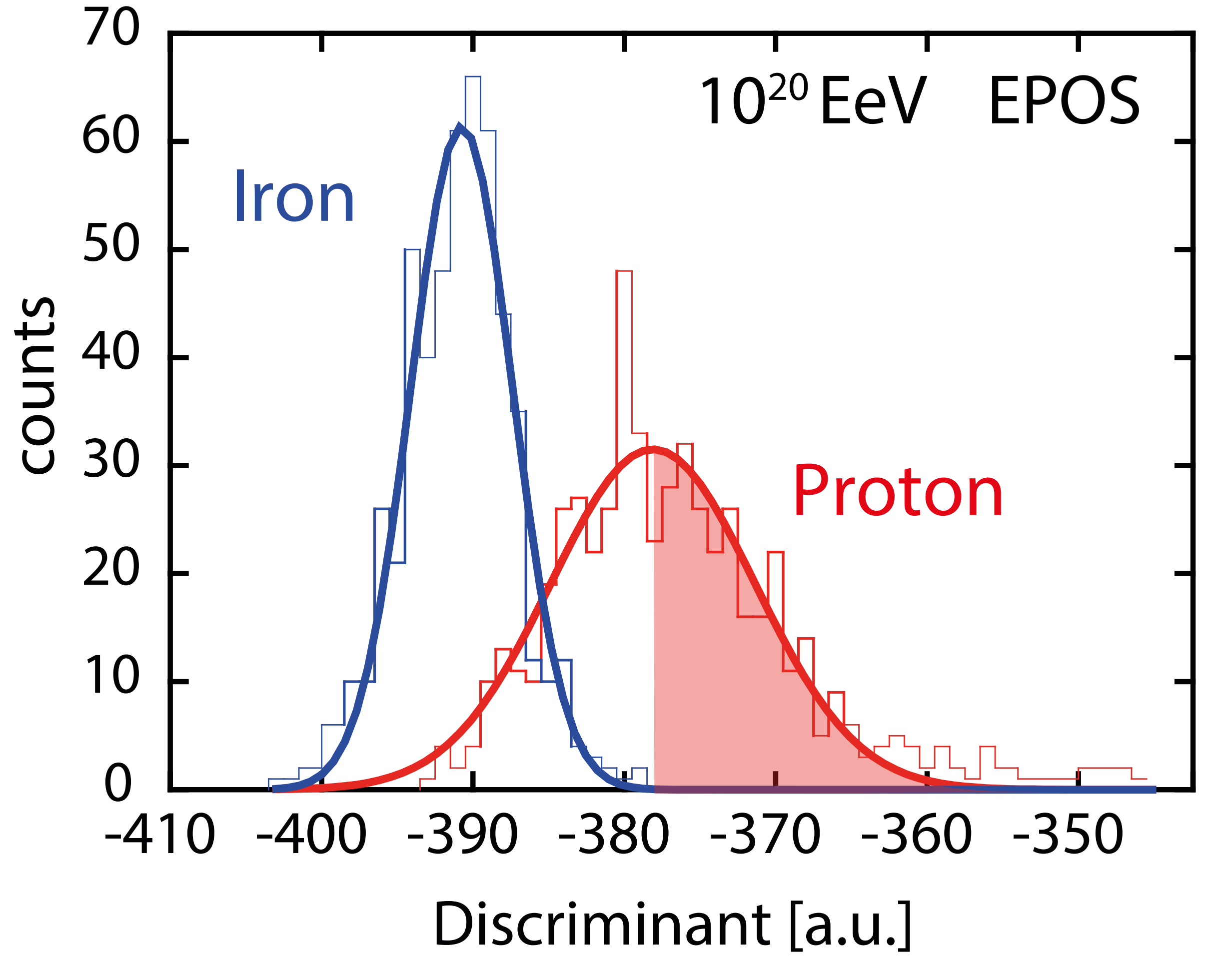




Radio antennas for inclined showers



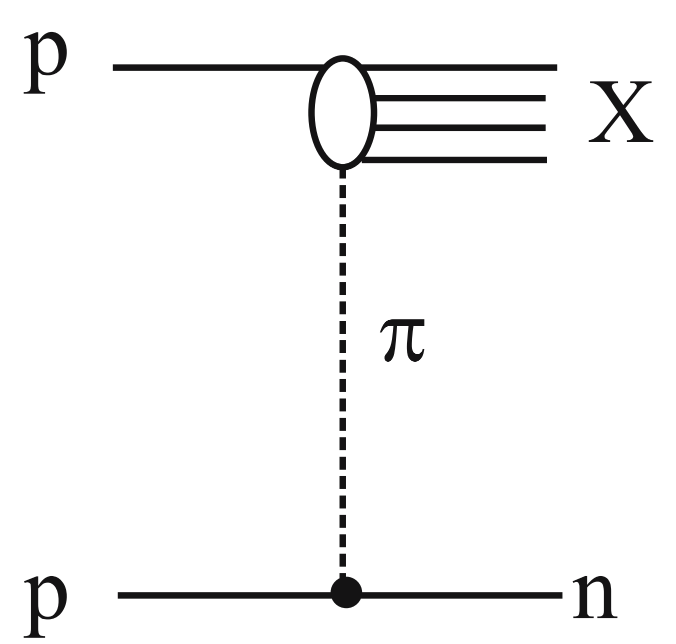
- **Scintillators (3.8 m²) and radio antenna on top of each array detector**
- **Composition measurement up to 10^{20} eV**
- **Composition selected anisotropy**
- **Particle physics with air showers**



(AugerPrime design report 1604.03637)

Outlook: pion-proton/nucleus interactions at high energy

Measurement of pion exchange at RHIC, LHC and EIC



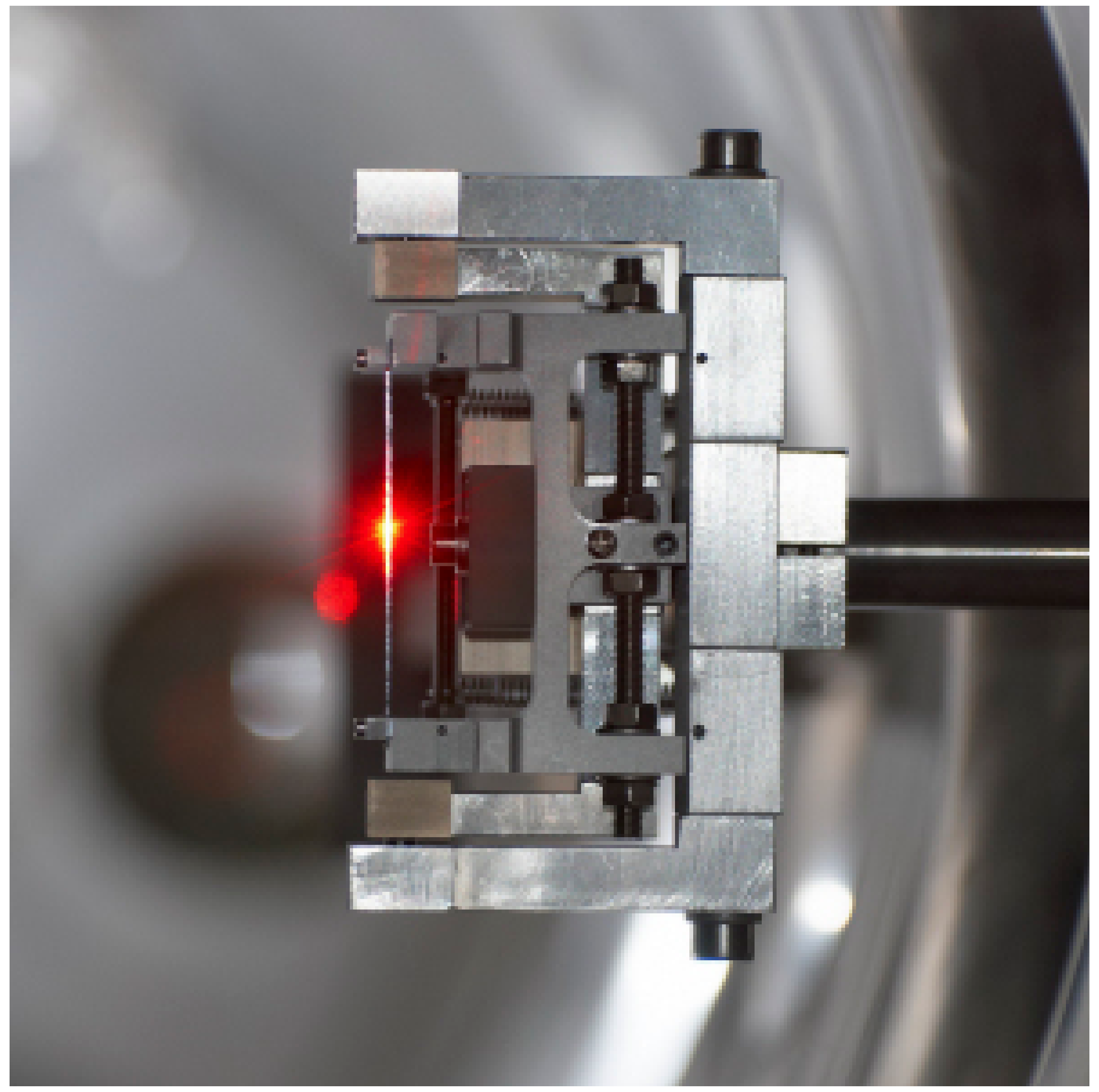
Pion fragmentation
region in ATLAS

Leading neutron in RHICf, 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.)

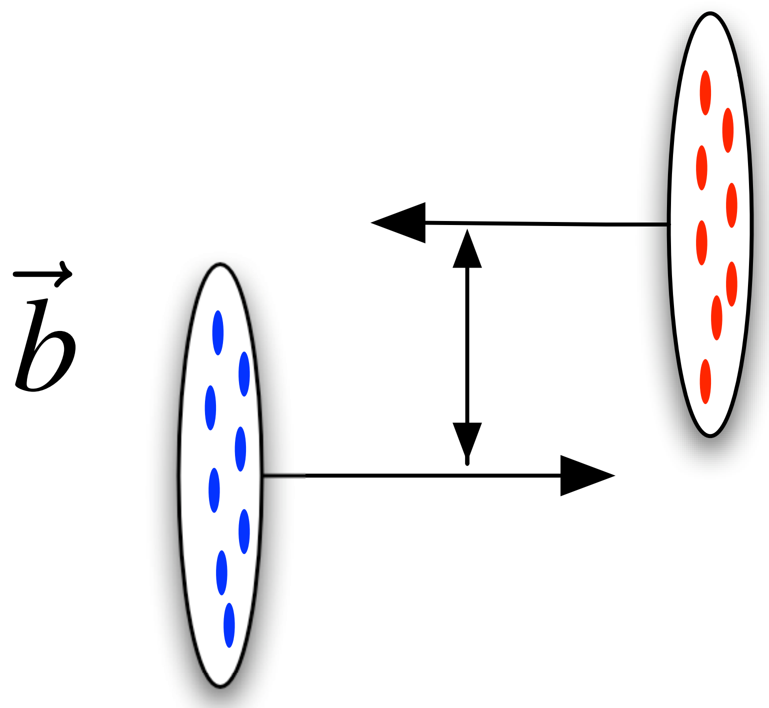
$$\frac{d\sigma(\gamma p \to Xn)}{dx_L\, dt} = S^2 \frac{G^2_{\pi^+ pn}}{16\pi^2} \frac{(-t)}{(t-m_\pi^2)^2} F^2(t) \times (1-x_L)^{1-2\alpha_\pi(t)} \sigma^{tot}_{\gamma\pi}(M^2)$$

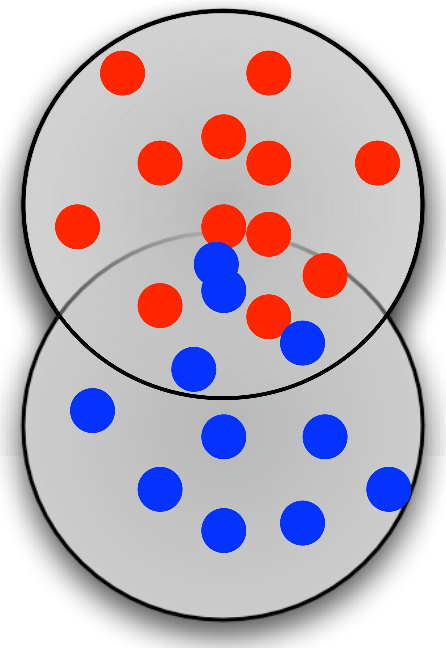
Fixed-target experiment at LHC?



Deflection of protons
of beam halo by crystal

Outlook: Importance of EIC for cosmic ray physics (i)





Simplified, qualitative view:

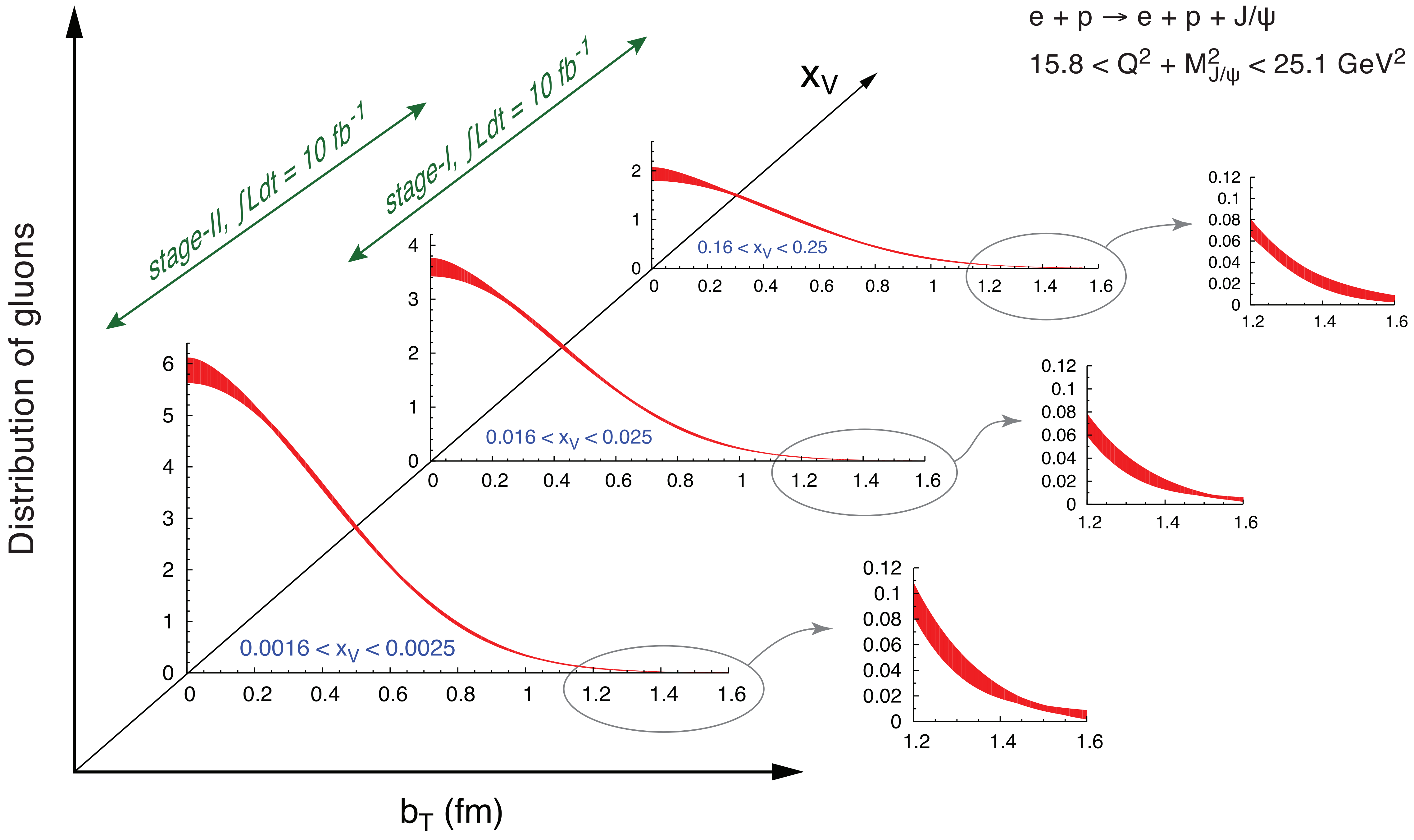
$$P_n = \frac{\langle n(\vec{b})\rangle^n}{n!} \exp\left(-\langle n(\vec{b})\rangle\right)$$

Overlap function, parton correlations?

$$\langle n(\vec{b})\rangle = \sigma_{\rm QCD}\, A(s,\vec{b})$$

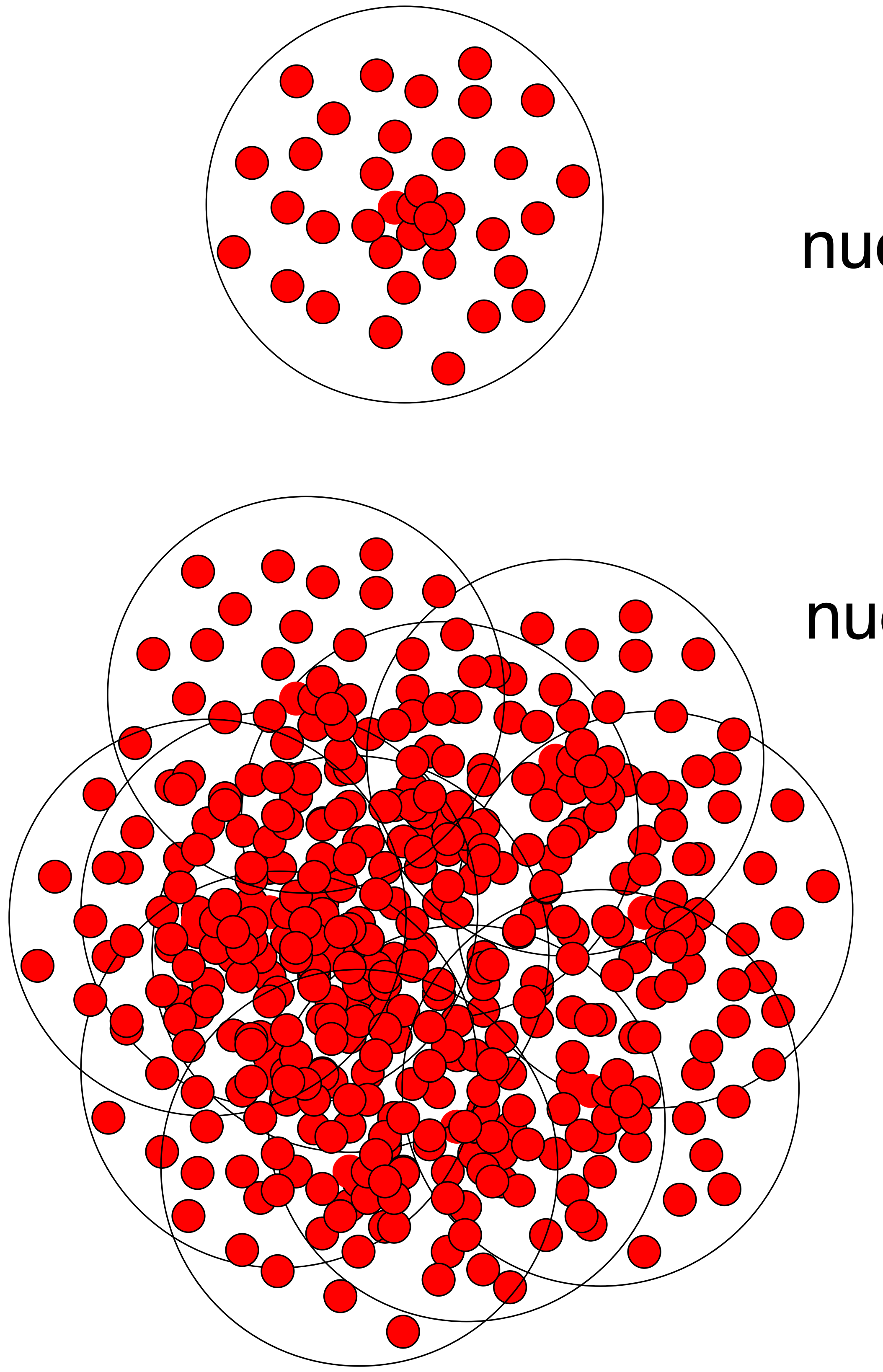
$$\sigma_{\rm ine} = \int d^2\vec{b} \sum_{n=1}^{\infty} P_n = \int d^2\vec{b} \left(1 - \exp\{-\sigma_{\rm QCD}\, A(s,\vec{b})\}\right)$$

Impact parameter distribution of partons

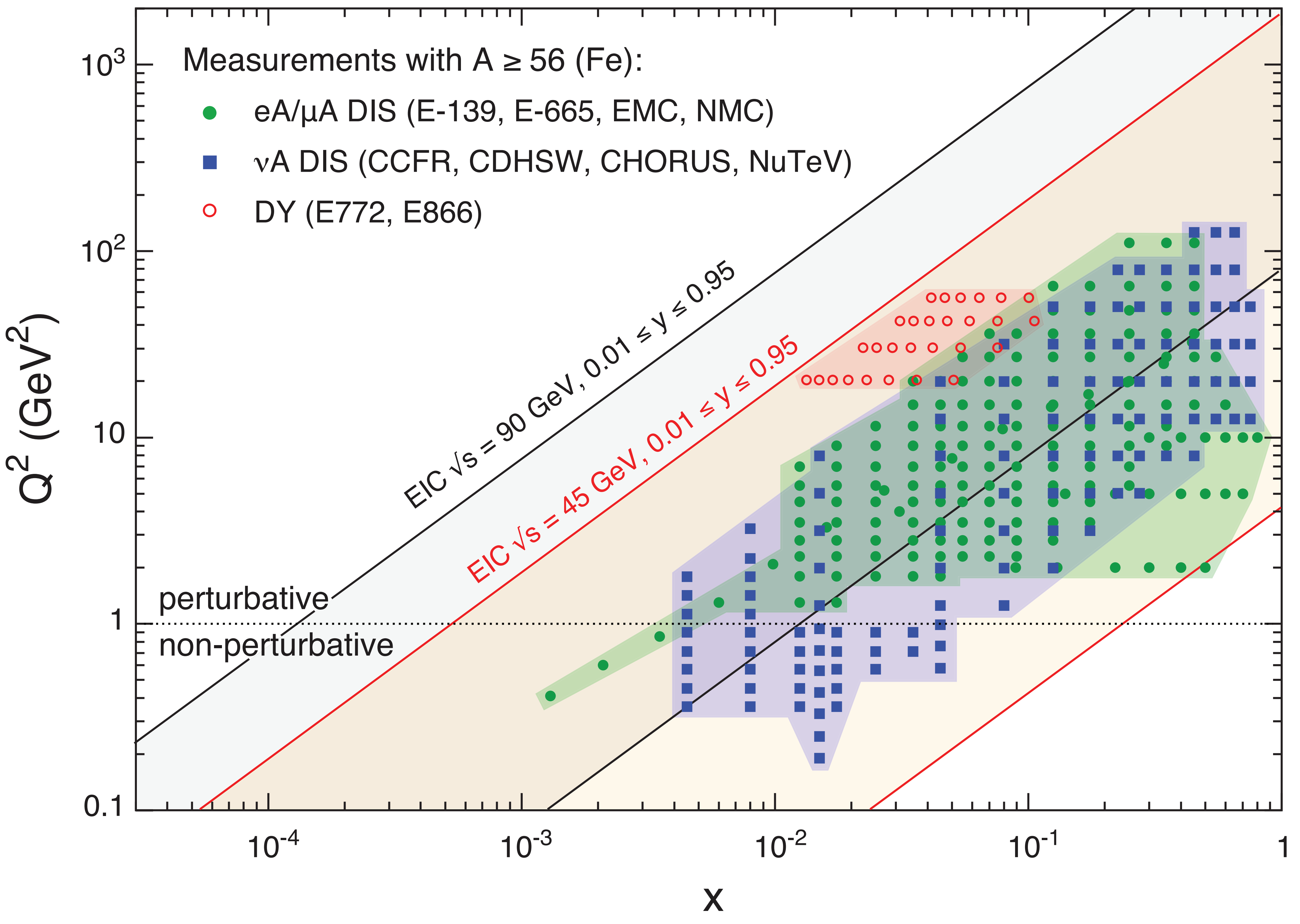


(EIC white paper 2012)

Outlook: Importance of EIC for cosmic ray physics (ii)



Different treatments of effects of high parton densities in models



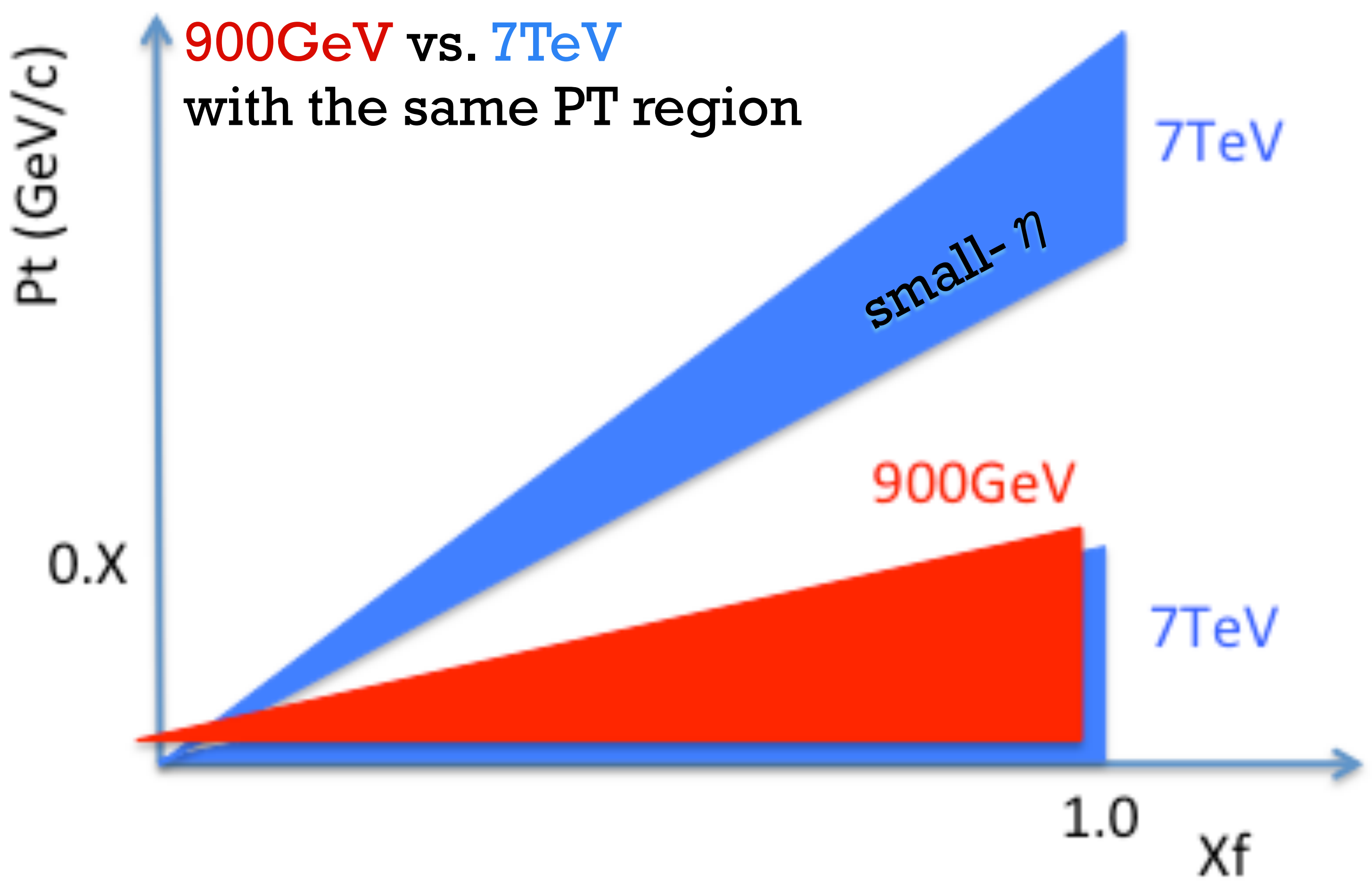
(EIC white paper 2012)

Saturation scale depends on impact parameter

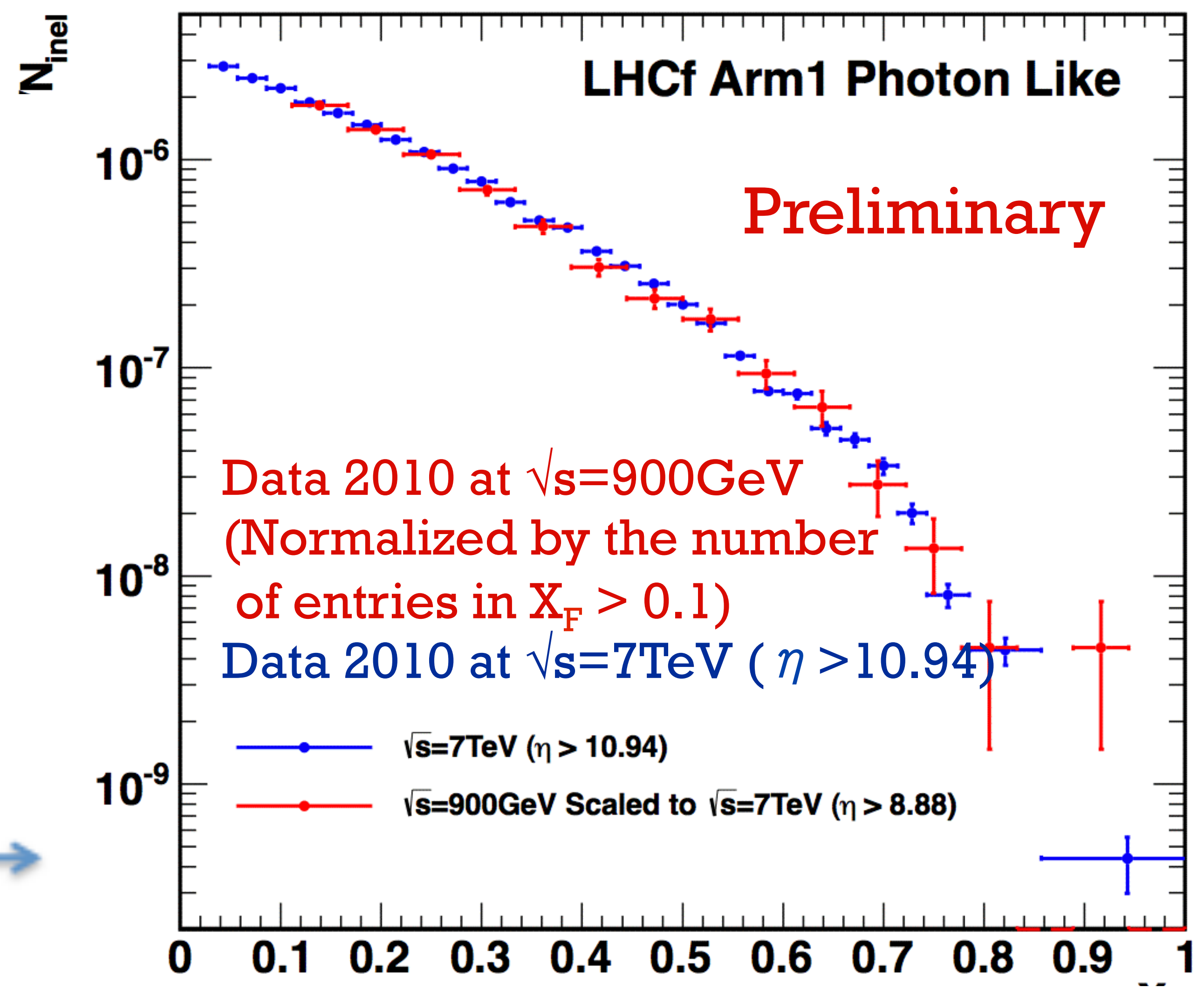
Parton density saturation vs. collective effects (string fusion, plasma), what is more important?

Outlook: Importance of EIC for cosmic ray physics (iii)

Coverage of 900GeV and 7TeV results in Feynman-X and P_T



X_F spectra : 900GeV data vs. 7TeV data

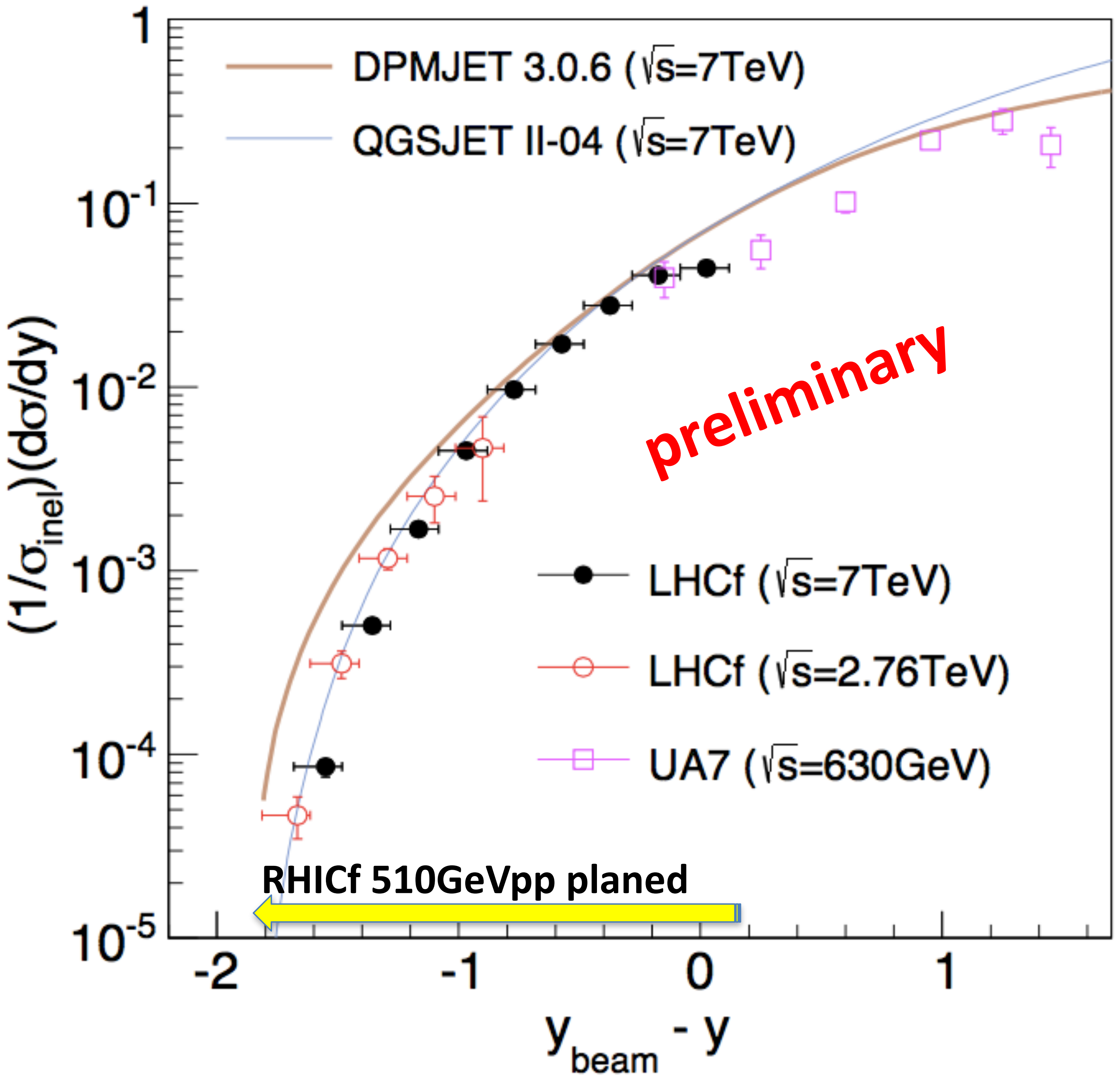


$$\left.\frac{1}{\sigma_{\rm inel}}\frac{d\sigma_\gamma}{dX_{\rm F}}\right|_{\eta<{\rm limited}} \propto \frac{1}{\sigma_{\rm inel}}\frac{d\sigma_\gamma}{p_{\rm T}dp_{\rm T}dX_{\rm F}}\langle p_{\rm T}\rangle dp_{\rm T}$$

(Oscar Adriani, LHCf Collab., QCD at Cosmic Energies 2012)

Feynman or rapidity scaling of forward particles ?

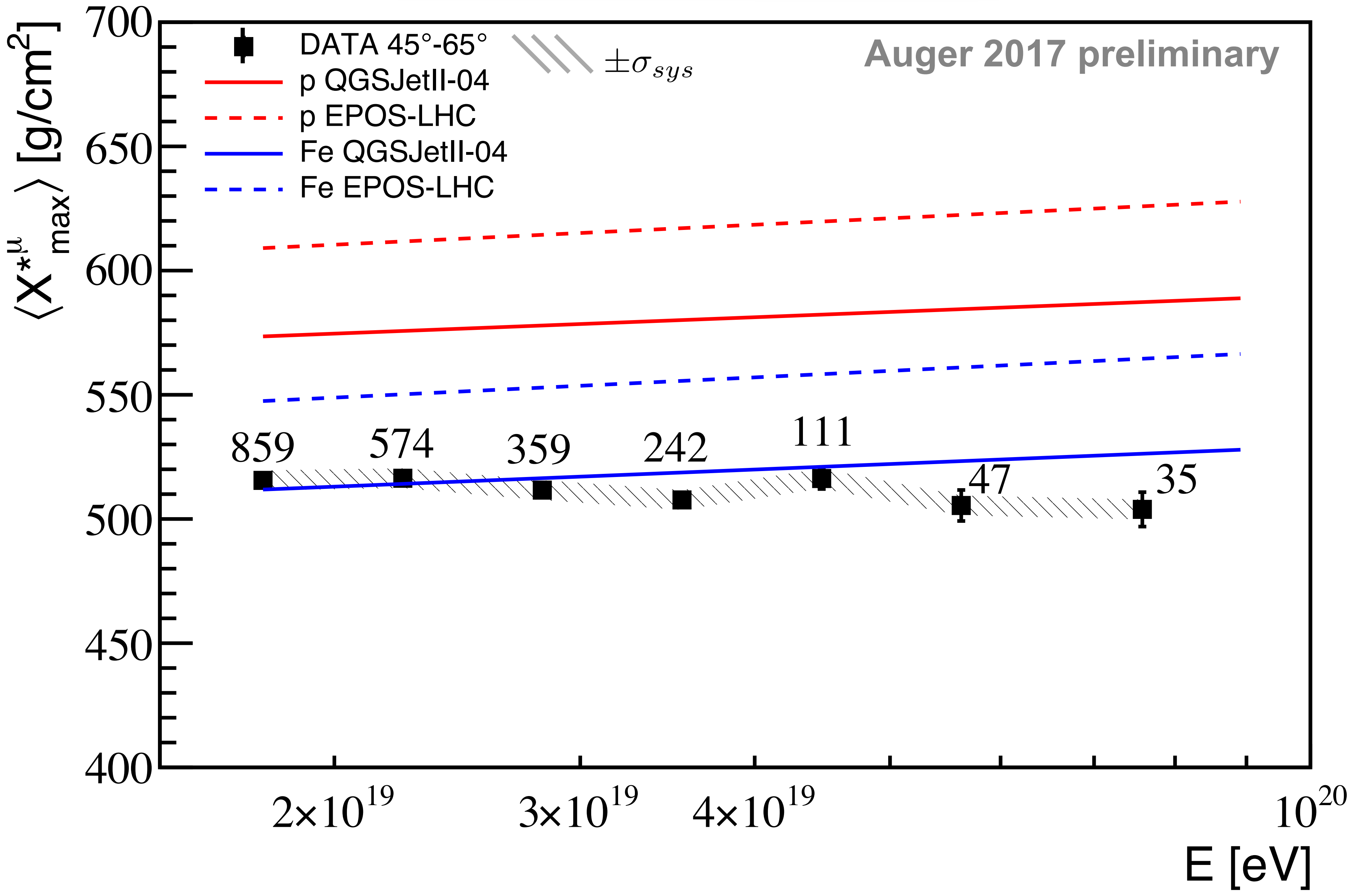
(LHCf, ICRC 2015)



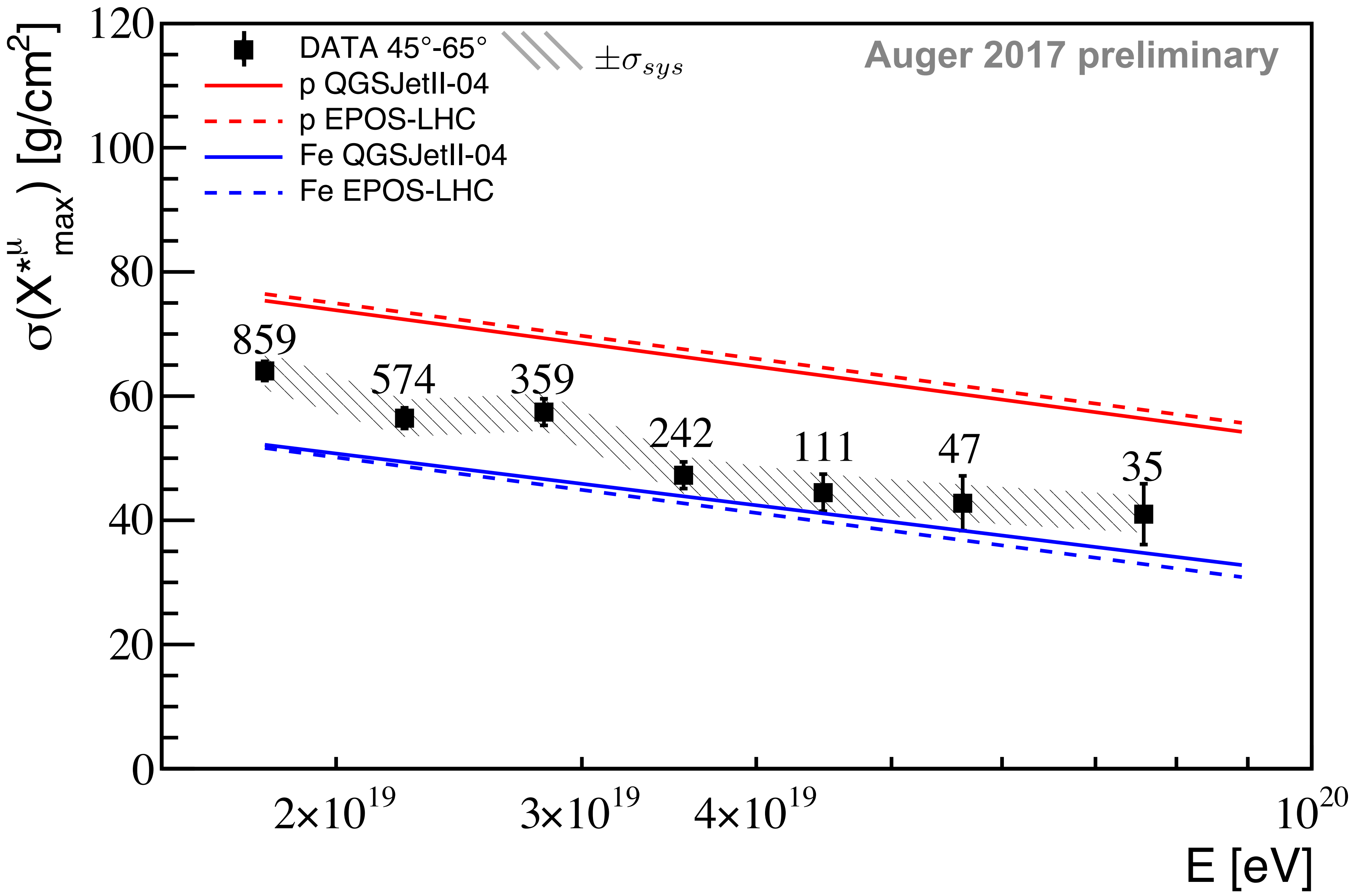
Additional (backup) slides

Discrepancy in muon production depth

Mean values



Shower-by-shower fluctuations

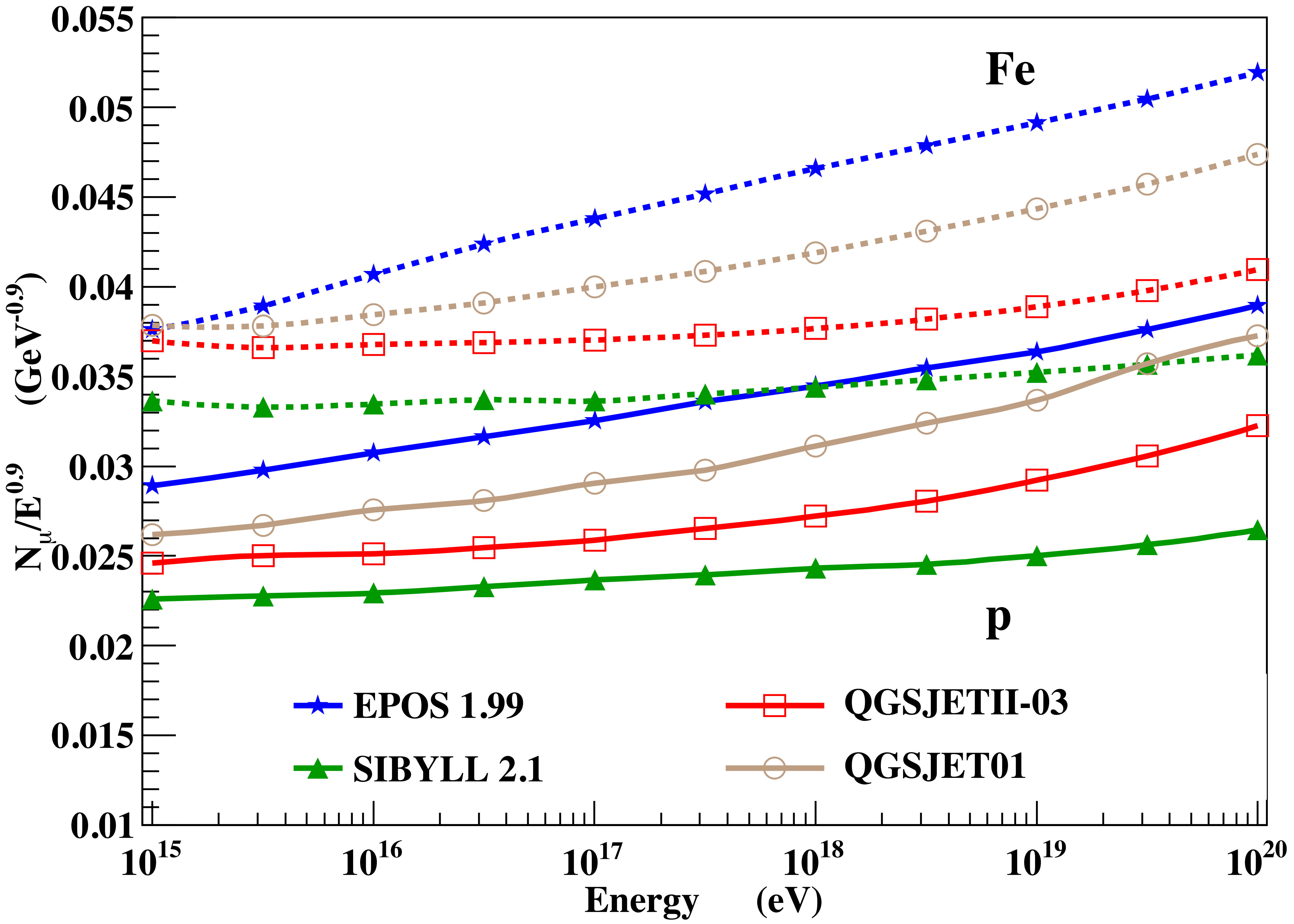


Model predictions of EPOS-LHC outside of expected range of composition

E>15 EeV
θ=45°-65
r>1200 m

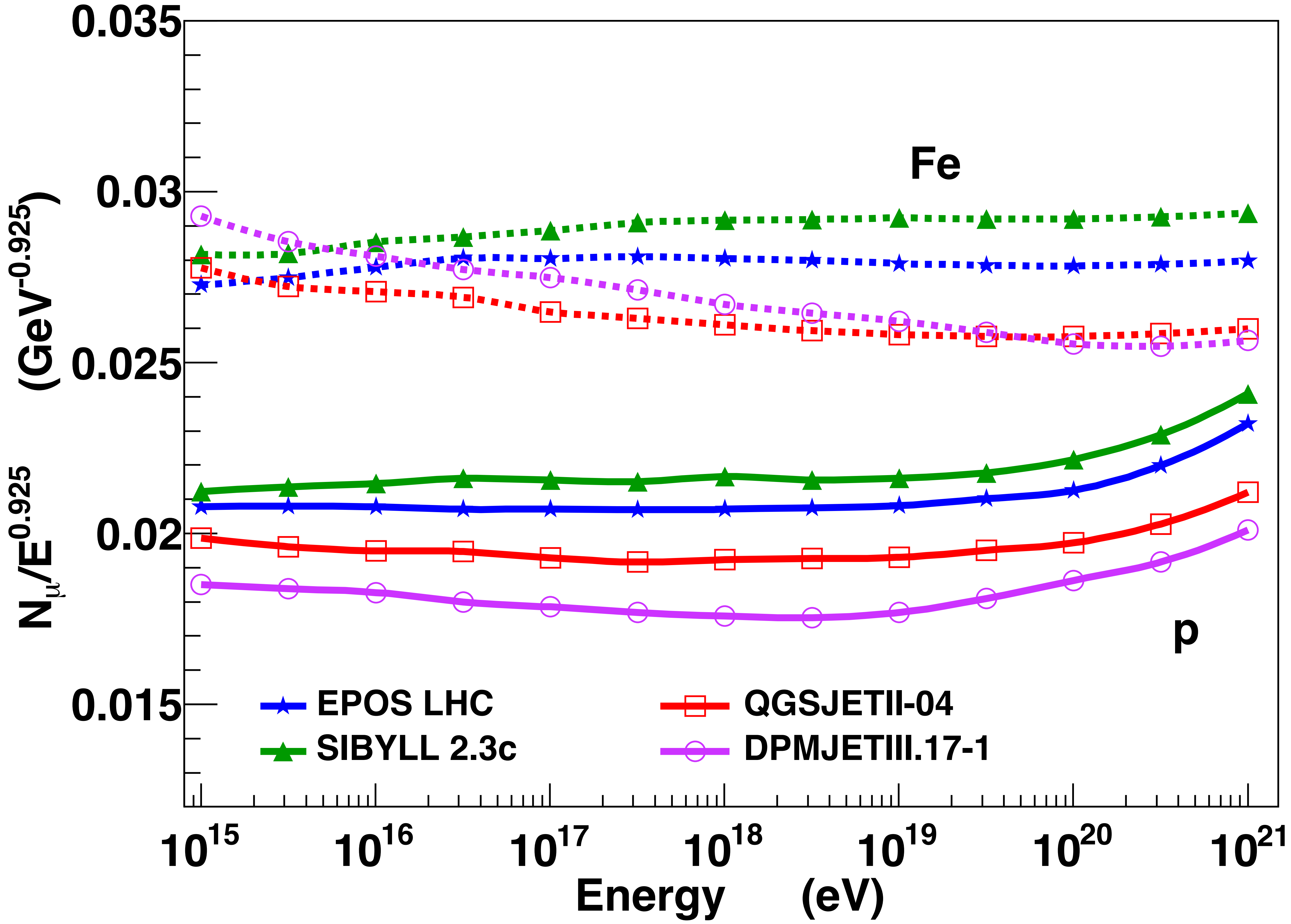
(Mallamaci, ICRC 2017)

Updated predictions for the muon number in air showers



pre-LHC models

post-LHC models

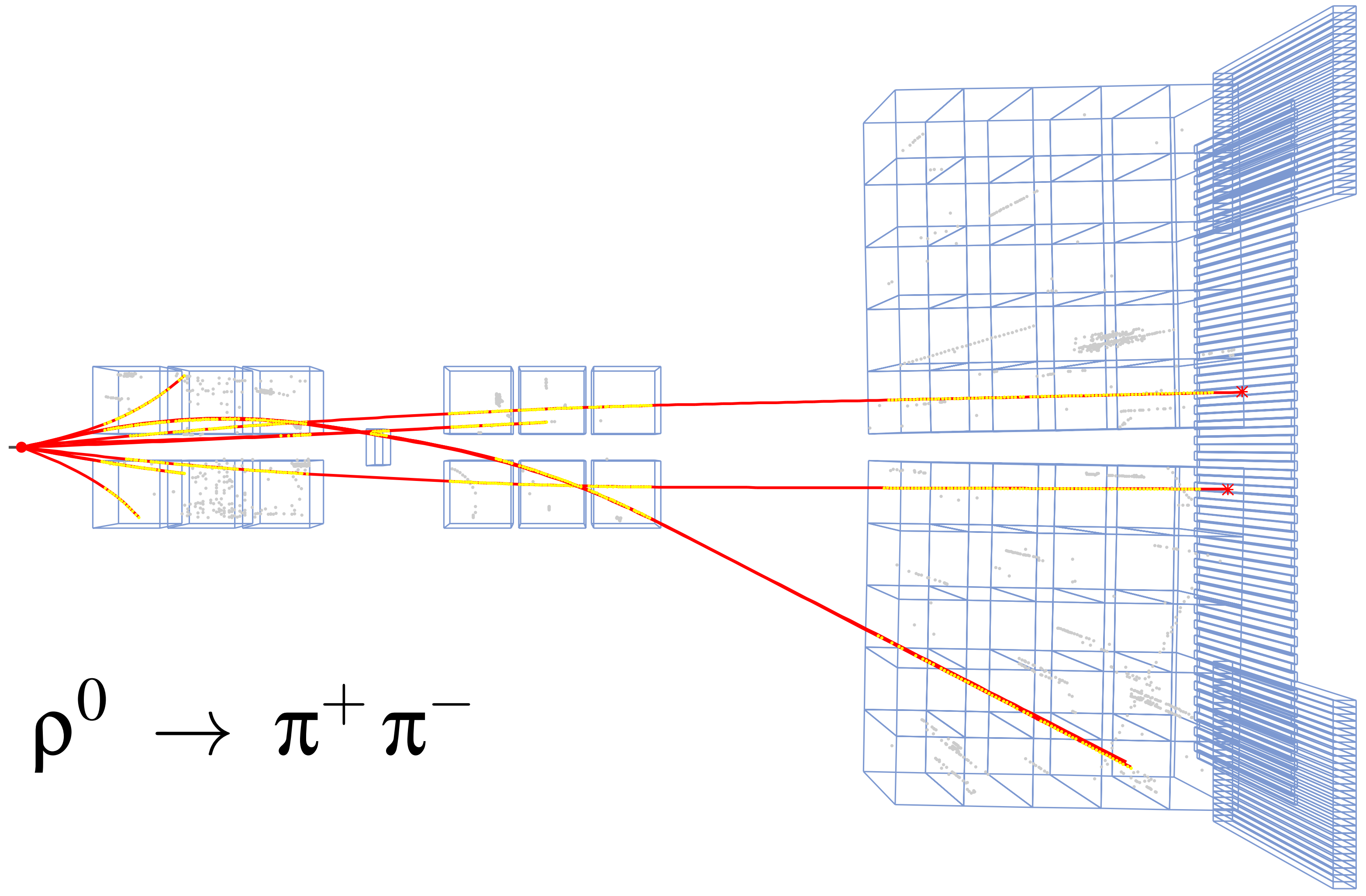


New models favor interpretation as lighter composition than before

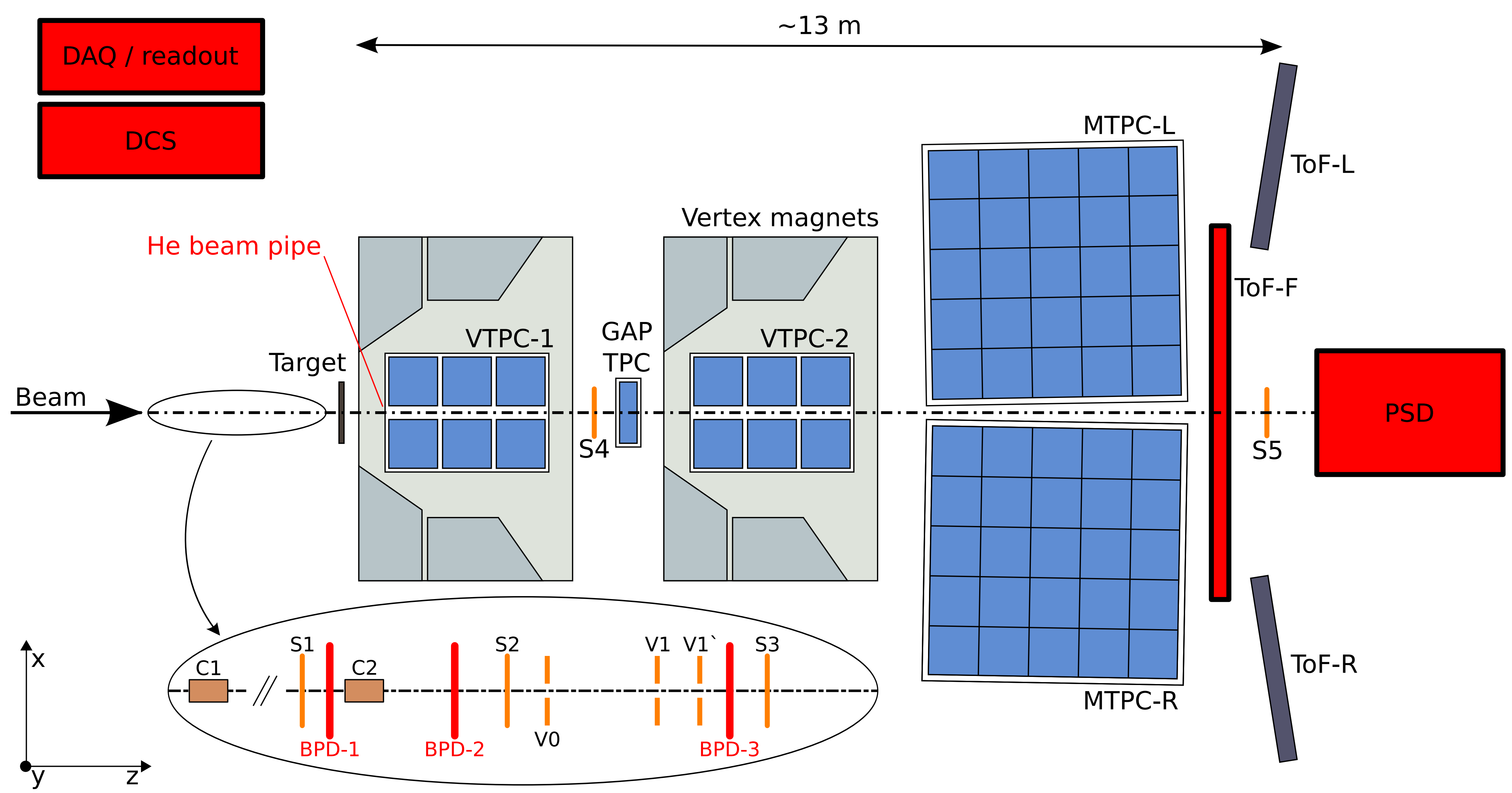
(Pierog 2017)

NA61 experiment at CERN SPS

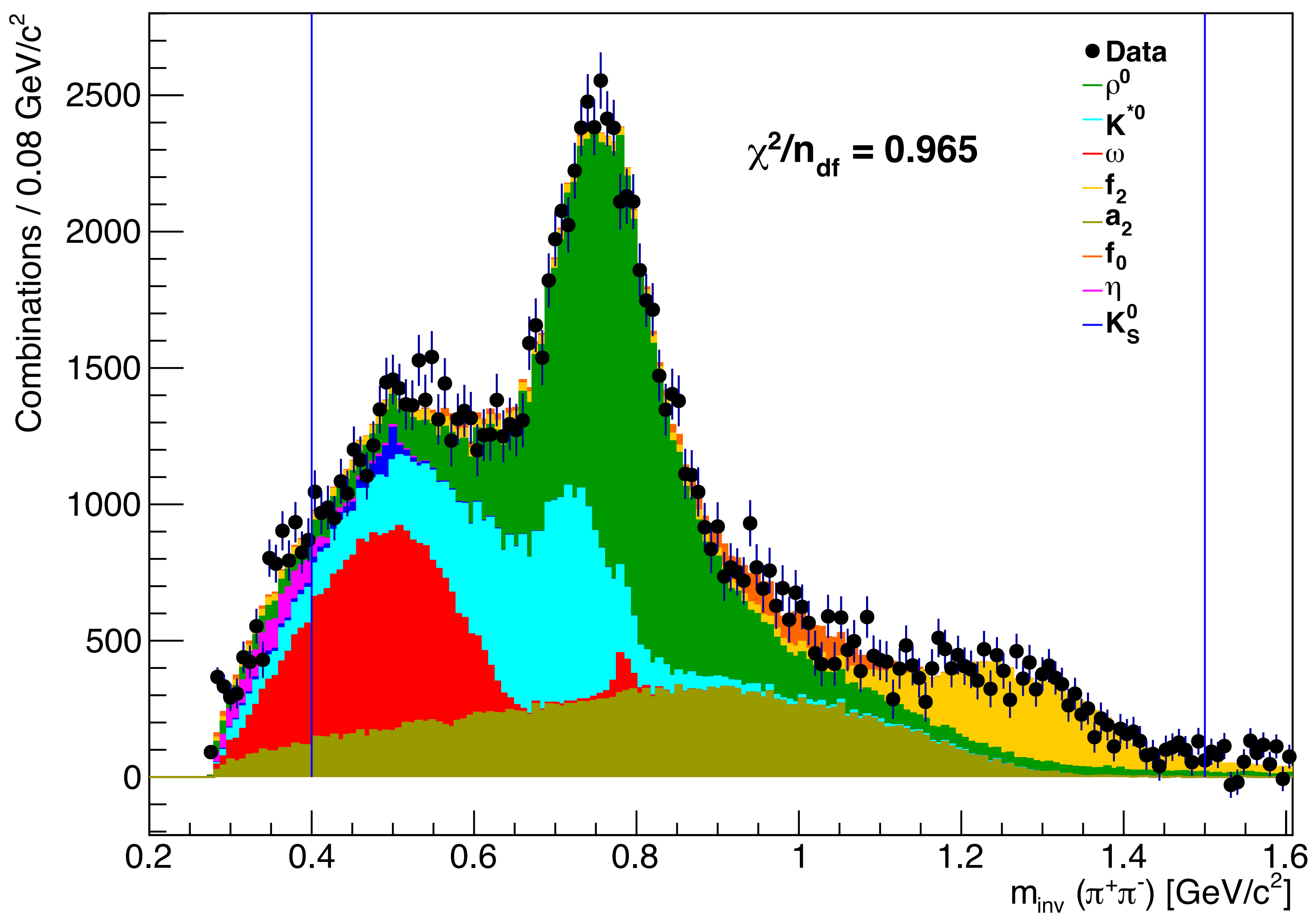
Dedicated cosmic ray runs (π-C at 158 and 350 GeV)



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



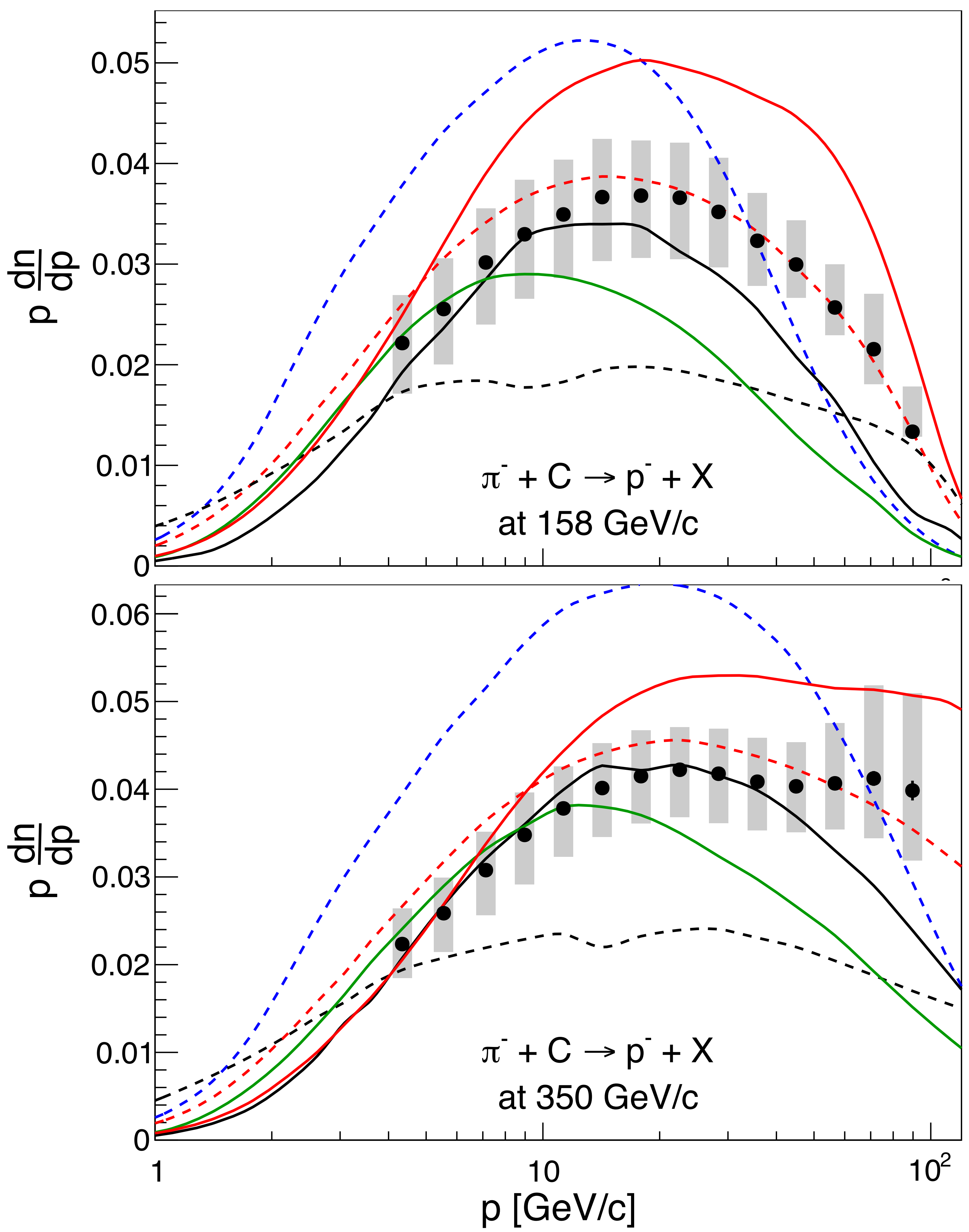
Invariant mass of two charged tracks



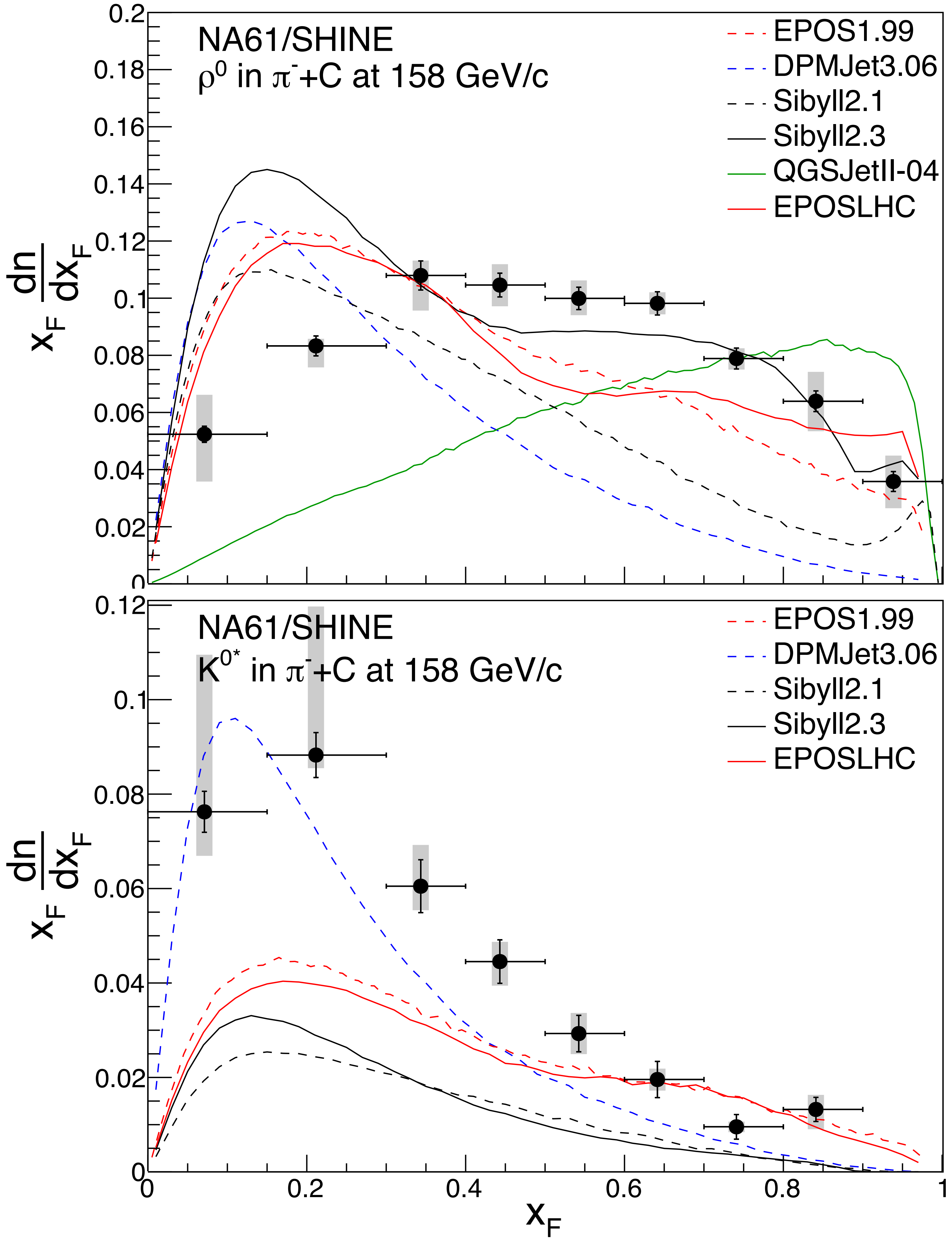
(former NA49 detector, extended)

Some NA61 results

antiproton production



rho-0 production



(Prado ICRC 2017, EPJ 2016)

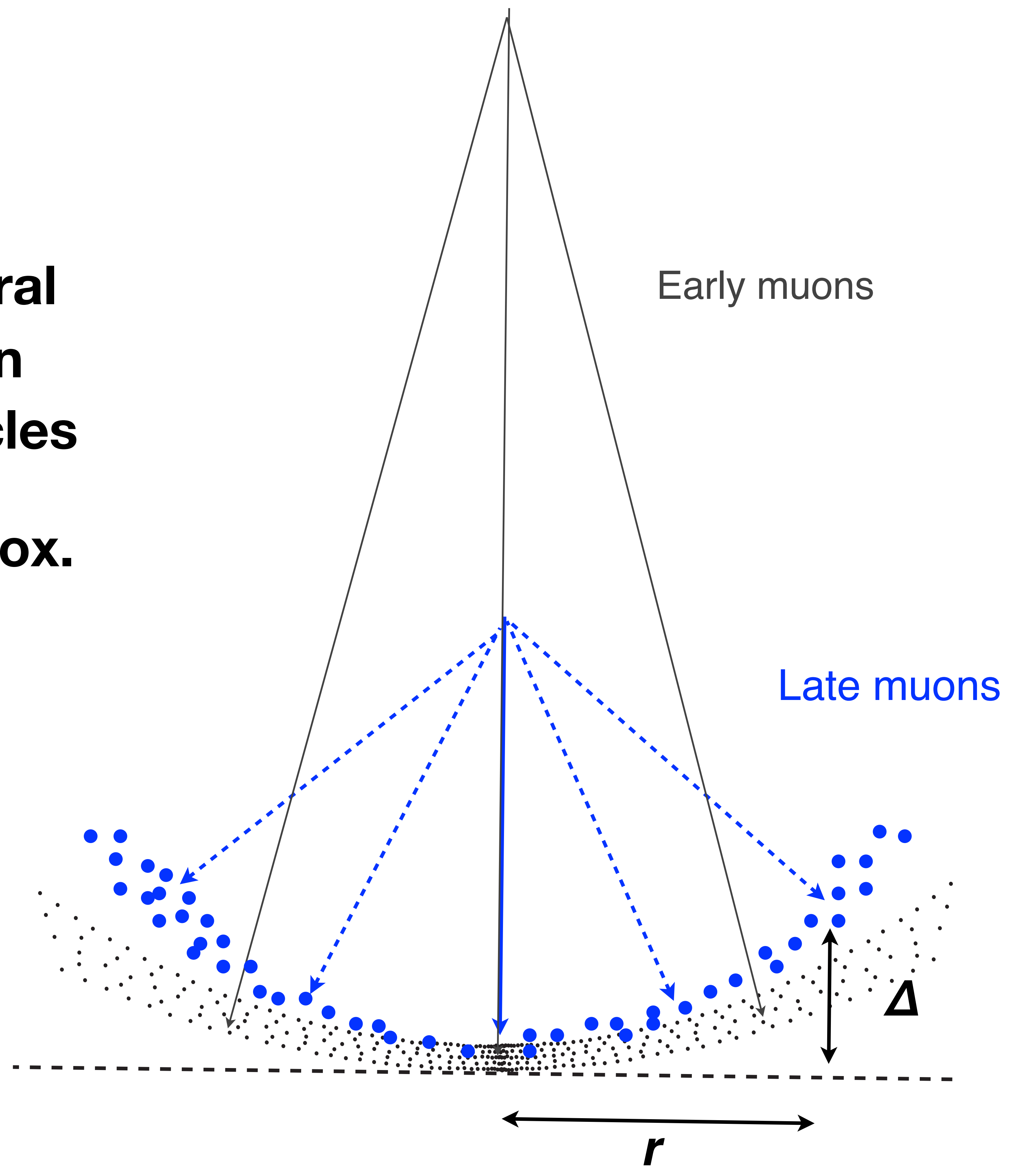
Muon production depth in showers

Distribution of muon production depth (MPD)

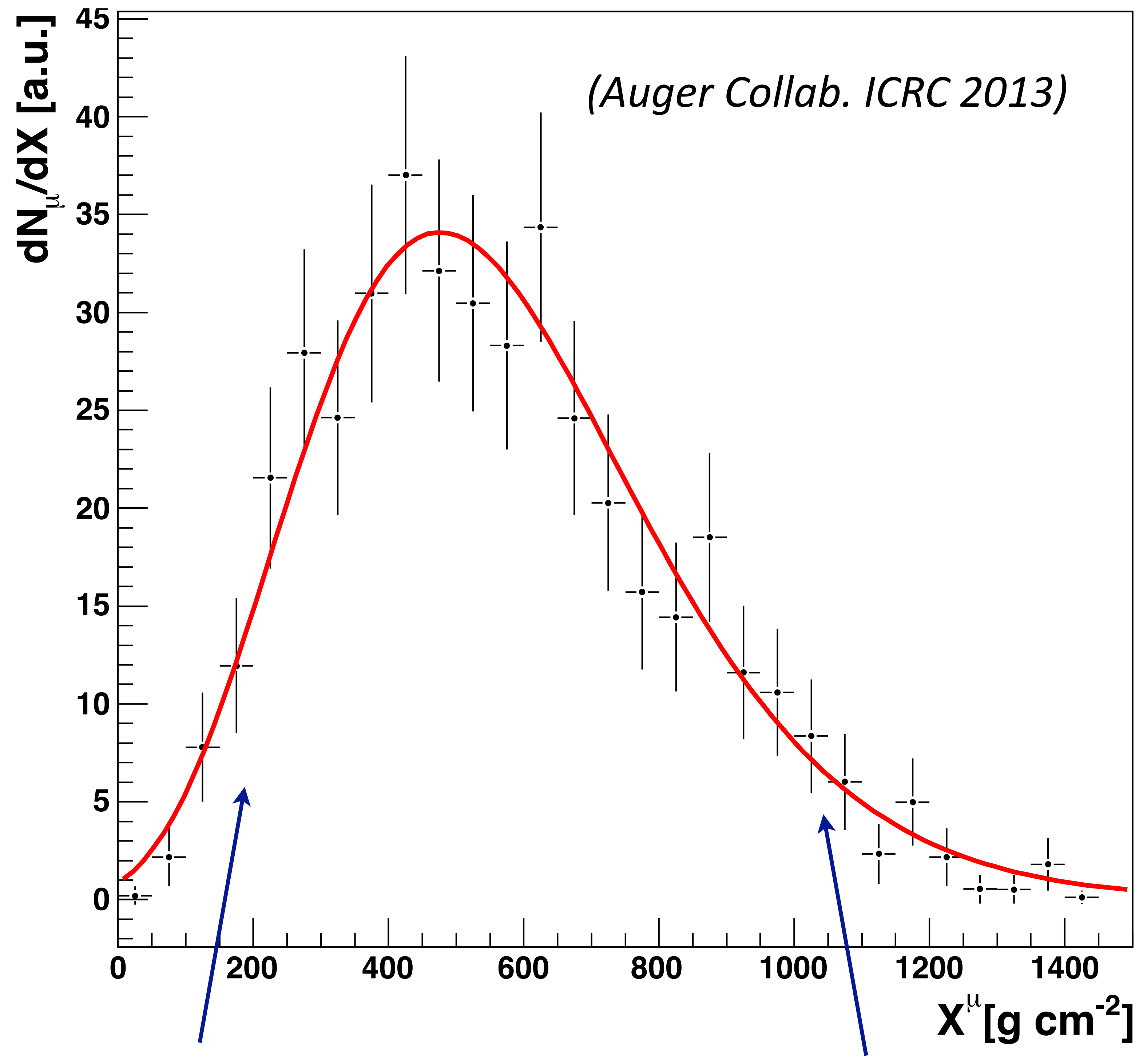
Two effects used:

1. **Muons have wider lateral (transverse) distribution than em. shower particles**

2. **Muons propagate approx. straight trajectories**

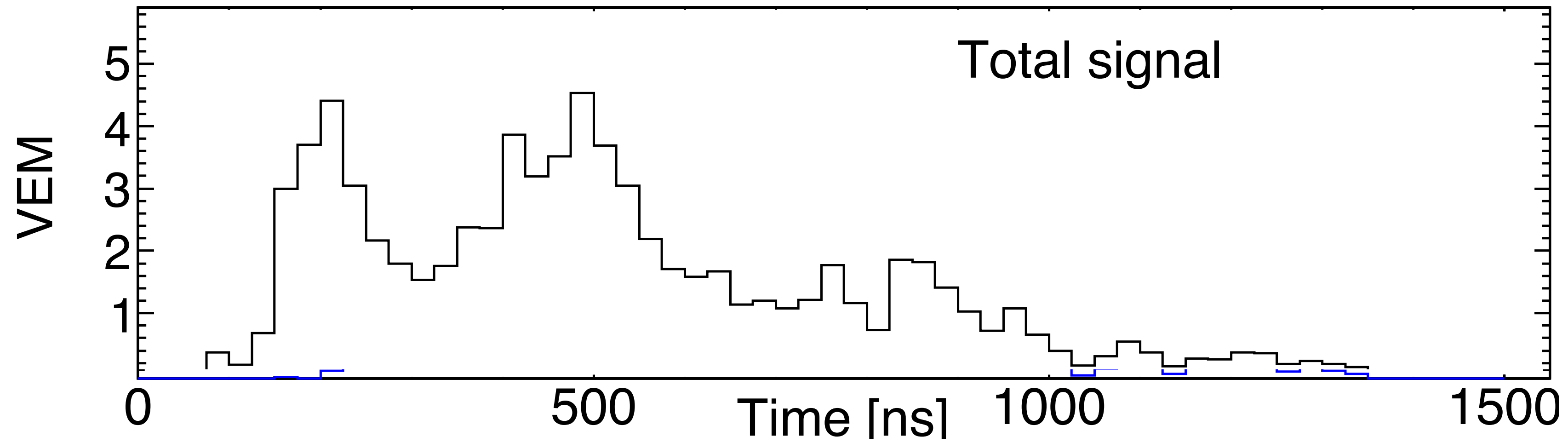


$$z \simeq \frac{1}{2}\left(\frac{r^2}{c(t-\langle t_\varepsilon \rangle)} - c(t-\langle t_\varepsilon \rangle)\right) + \Delta - \langle z_\pi \rangle$$

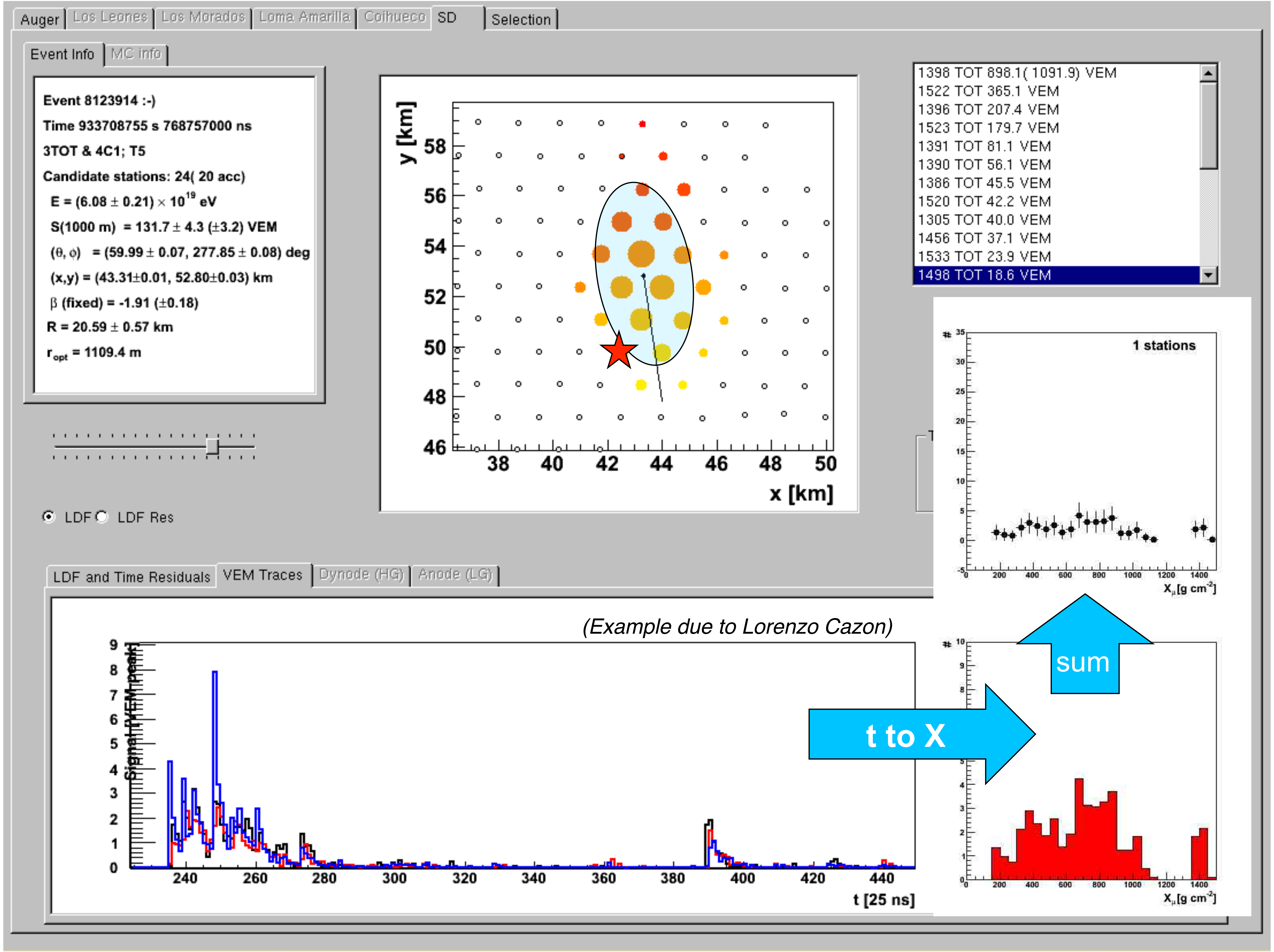


Muons from early interactions

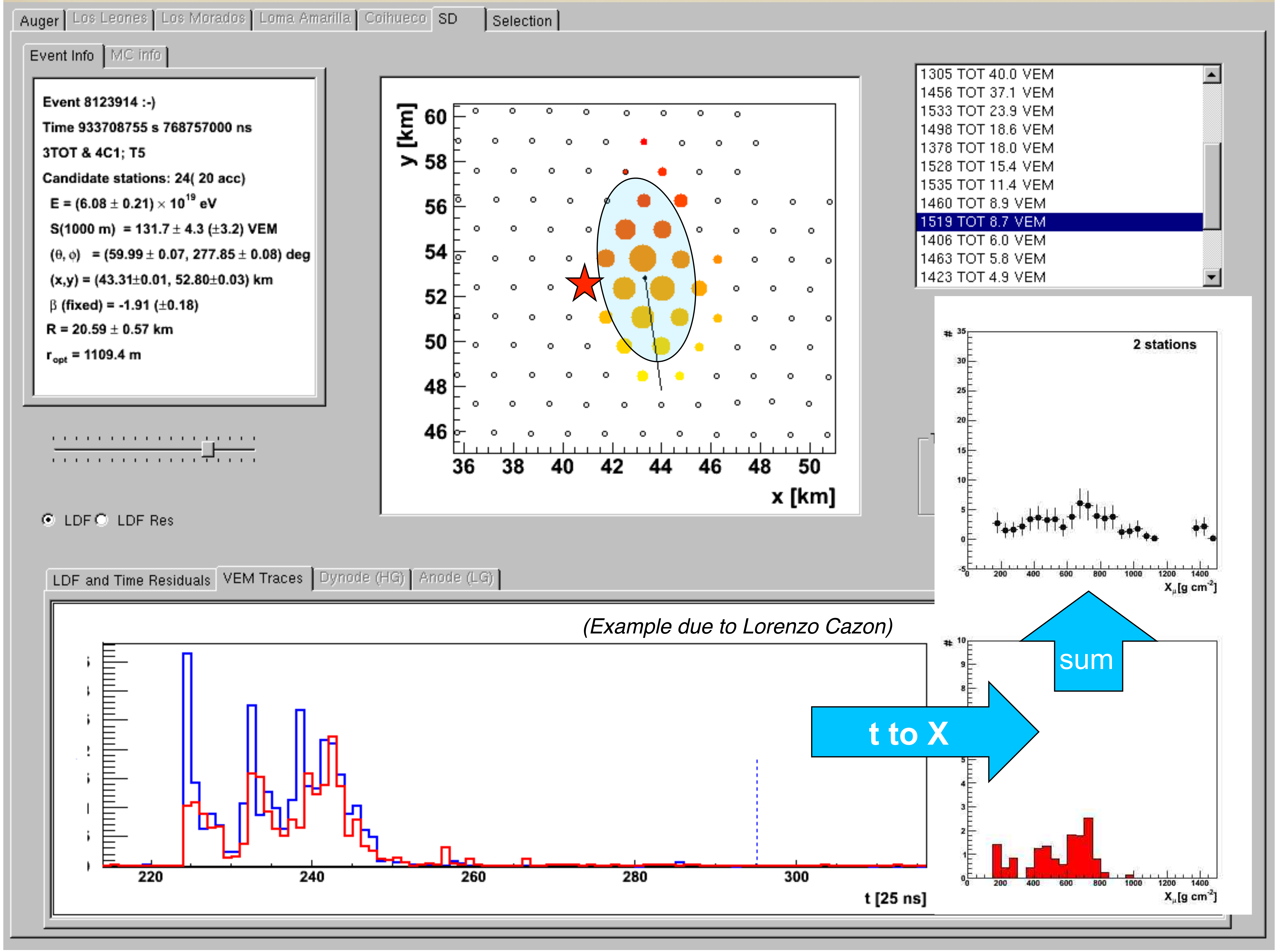
Muons from late interactions



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



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
1 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


Auger
Los Leones
Los Morados
Loma Amarilla
Coihueco
SD
Selection
Event Info
MC info
Event 8123914 :-)
Time 933708755 s 768757000 ns
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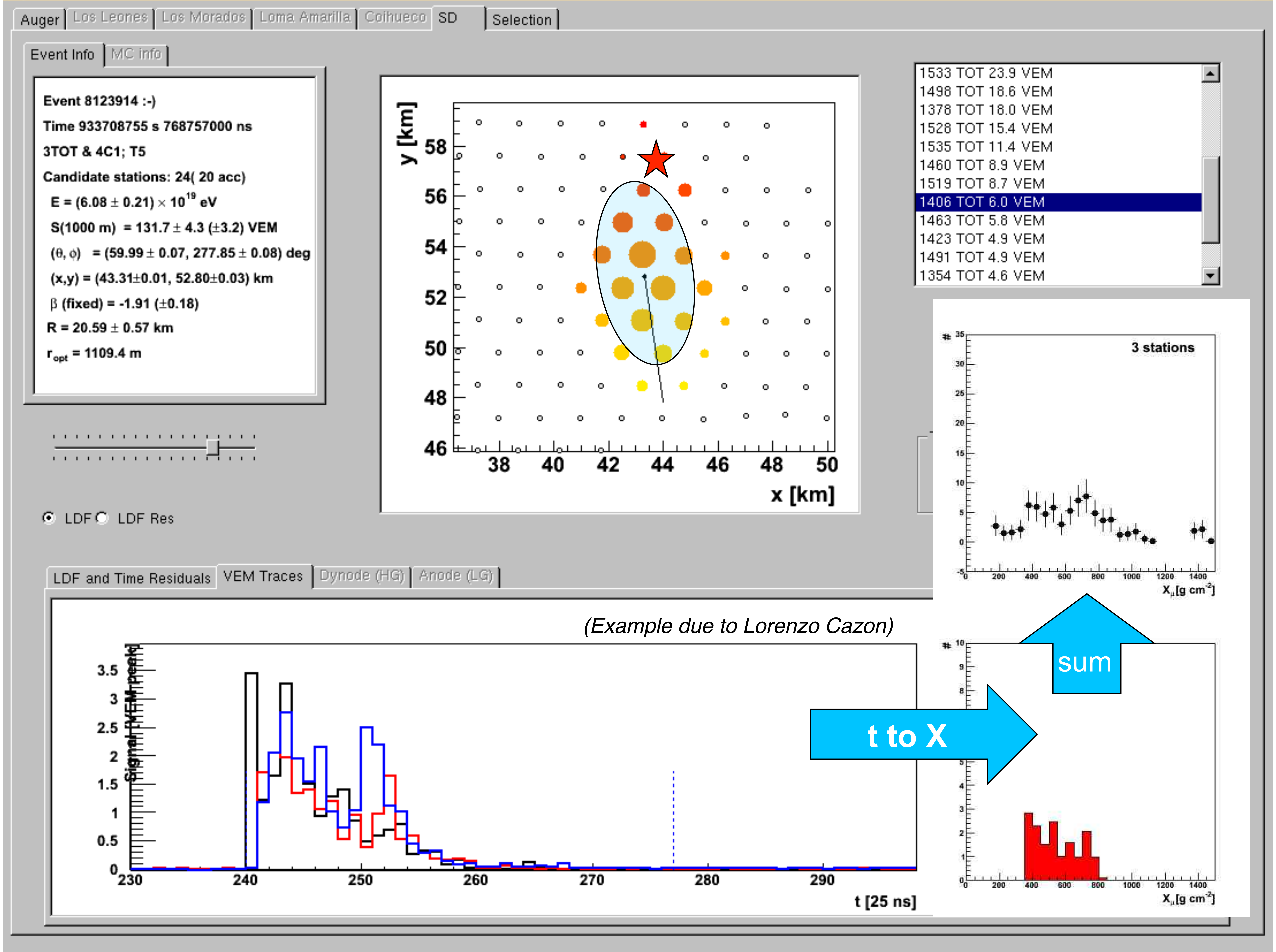
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
y [km]
x [km]
1305 TOT 40.0 VEM
1456 TOT 37.1 VEM
1533 TOT 23.9 VEM
1498 TOT 18.6 VEM
1378 TOT 18.0 VEM
1528 TOT 15.4 VEM
1535 TOT 11.4 VEM
1460 TOT 8.9 VEM
1519 TOT 8.7 VEM
1406 TOT 6.0 VEM
1463 TOT 5.8 VEM
1423 TOT 4.9 VEM
LDF
LDF Res
LDF 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
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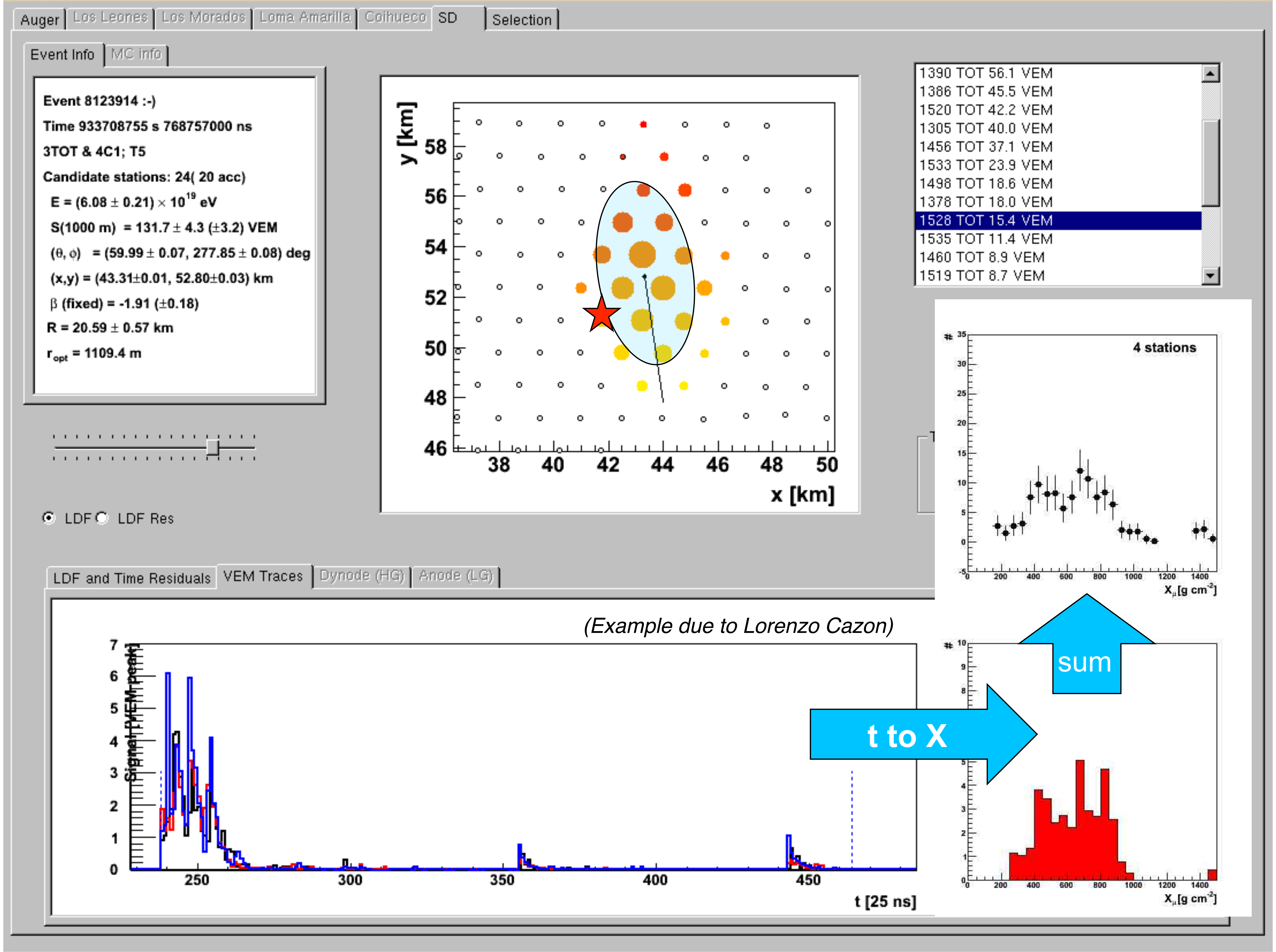
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
y [km]
x [km]
1533 TOT 23.9 VEM
1498 TOT 18.6 VEM
1378 TOT 18.0 VEM
1528 TOT 15.4 VEM
1535 TOT 11.4 VEM
1460 TOT 8.9 VEM
1519 TOT 8.7 VEM
1406 TOT 6.0 VEM
1463 TOT 5.8 VEM
1423 TOT 4.9 VEM
1491 TOT 4.9 VEM
1354 TOT 4.6 VEM
LDF
LDF Res
3 stations
X_μ [g cm^-2]
LDF and Time Residuals
VEM Traces
Dynode (HG)
Anode (LG)
(Example due to Lorenzo Cazon)
Signal [VEM peak]
t [25 ns]
sum
t to X
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)
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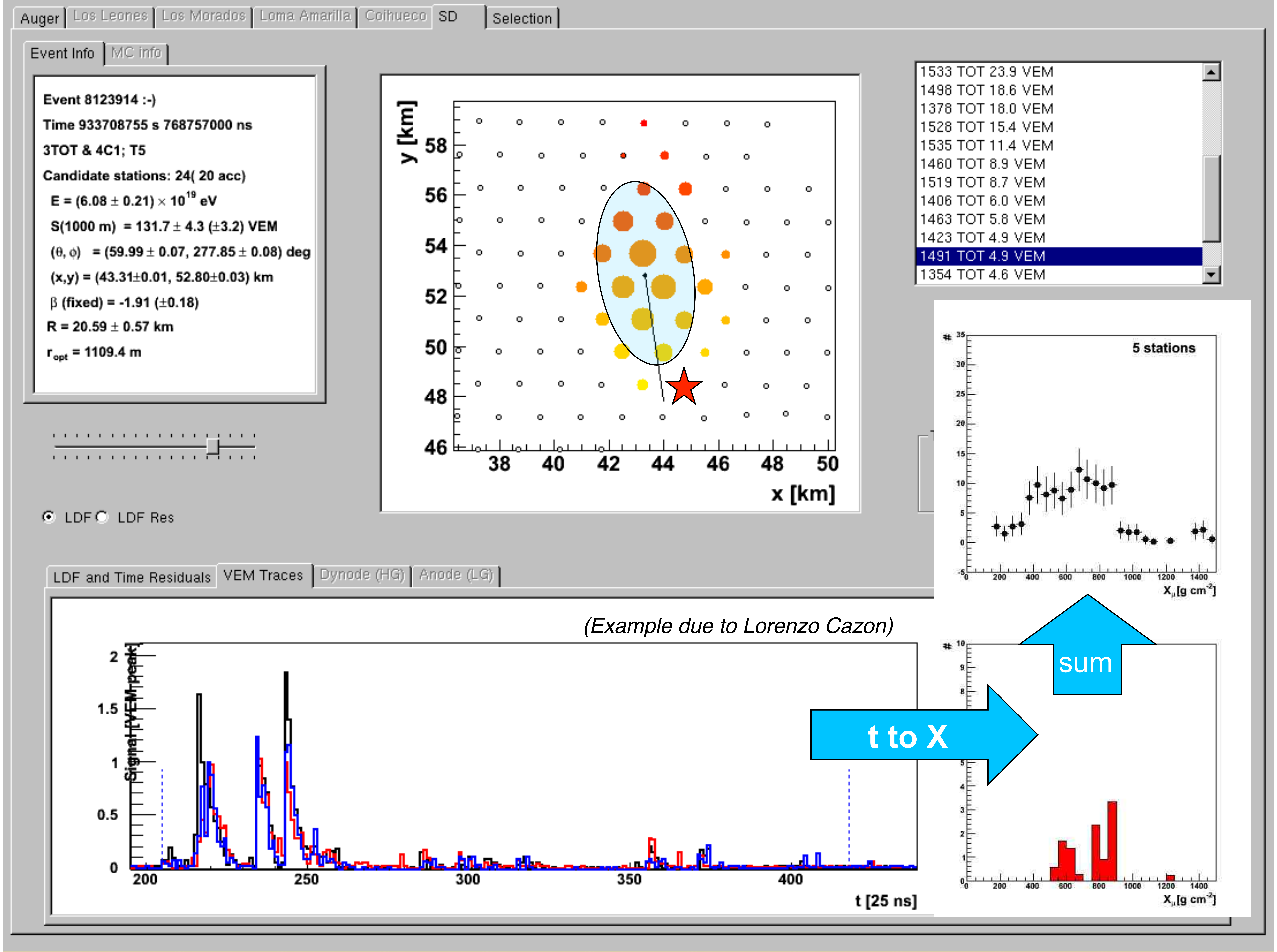
S(1000 m) = 131.7 ± 4.3 (±3.2) VEM
(θ, φ) = (59.99 ± 0.07, 277.85 ± 0.08) deg
(x,y) = (43.31±0.01, 52.80±0.03) km
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
y [km]
x [km]
1390 TOT 56.1 VEM
1386 TOT 45.5 VEM
1520 TOT 42.2 VEM
1305 TOT 40.0 VEM
1456 TOT 37.1 VEM
1533 TOT 23.9 VEM
1498 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
LDF
LDF Res
4 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
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
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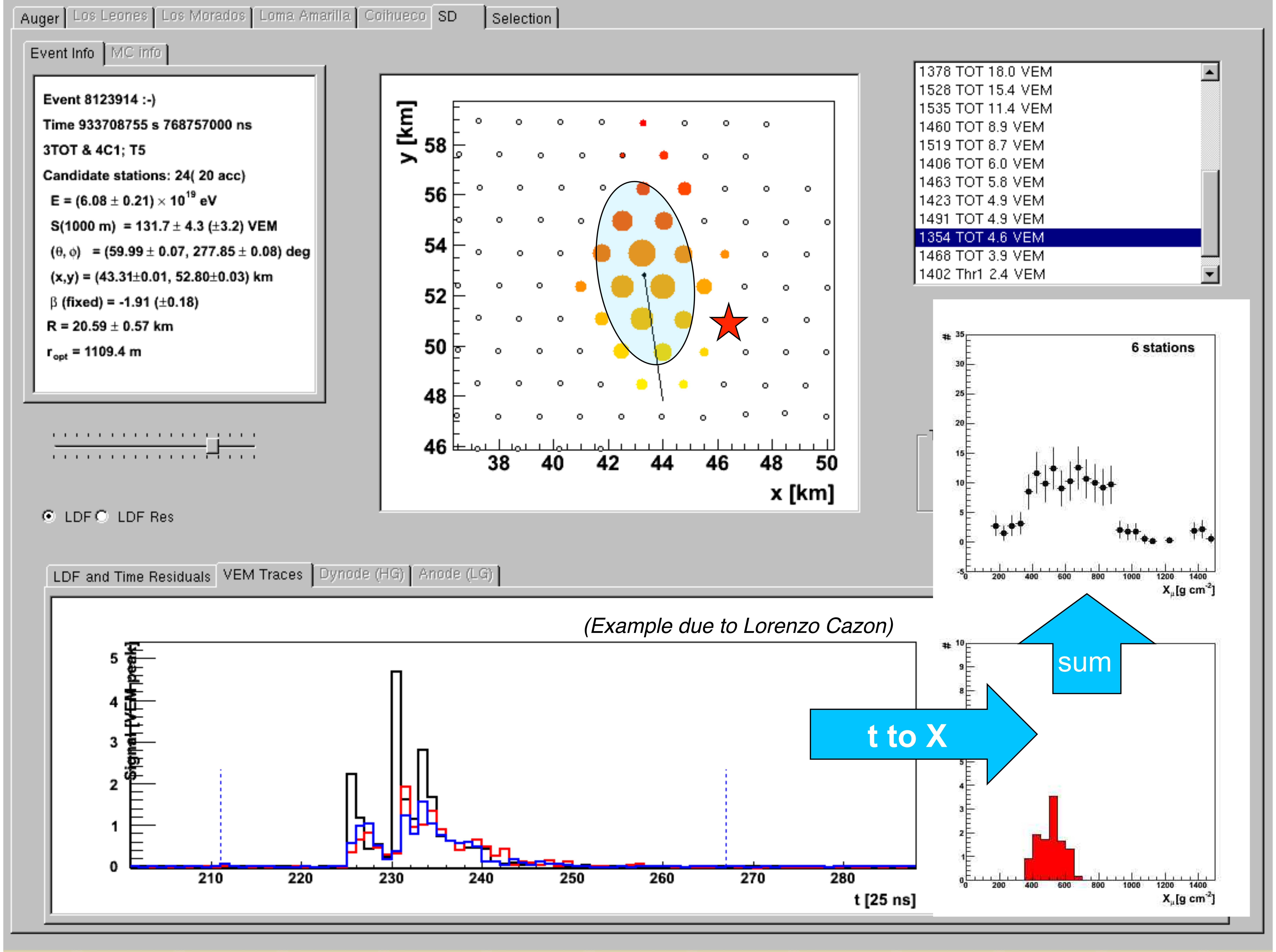
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
y [km]
x [km]
1533 TOT 23.9 VEM
1498 TOT 18.6 VEM
1378 TOT 18.0 VEM
1528 TOT 15.4 VEM
1535 TOT 11.4 VEM
1460 TOT 8.9 VEM
1519 TOT 8.7 VEM
1406 TOT 6.0 VEM
1463 TOT 5.8 VEM
1423 TOT 4.9 VEM
1491 TOT 4.9 VEM
1354 TOT 4.6 VEM
5 stations
X_μ [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
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
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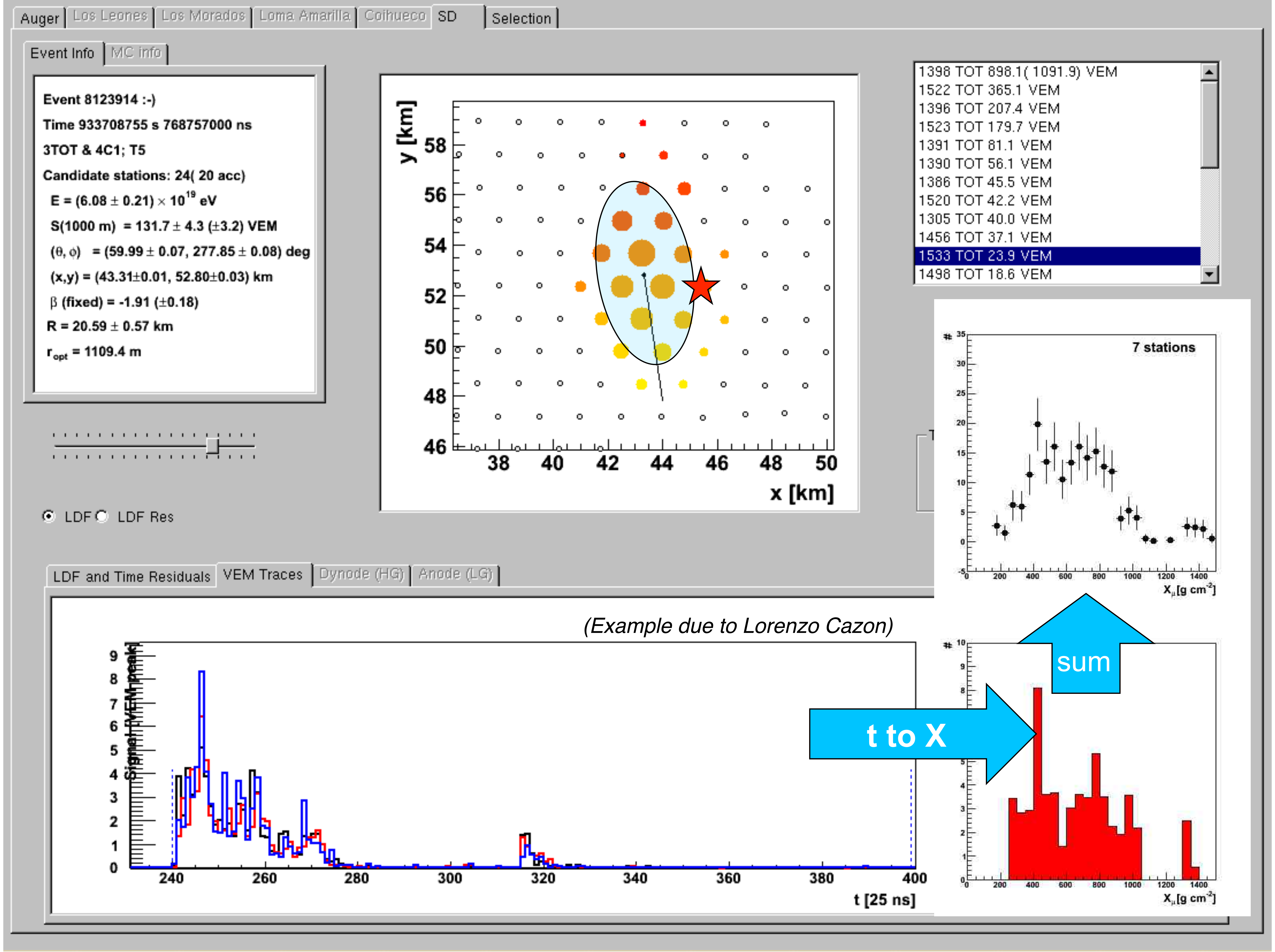
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
y [km]
x [km]
1378 TOT 18.0 VEM
1528 TOT 15.4 VEM
1535 TOT 11.4 VEM
1460 TOT 8.9 VEM
1519 TOT 8.7 VEM
1406 TOT 6.0 VEM
1463 TOT 5.8 VEM
1423 TOT 4.9 VEM
1491 TOT 4.9 VEM
1354 TOT 4.6 VEM
1468 TOT 3.9 VEM
1402 Thr1 2.4 VEM
6 stations
X_μ [g 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


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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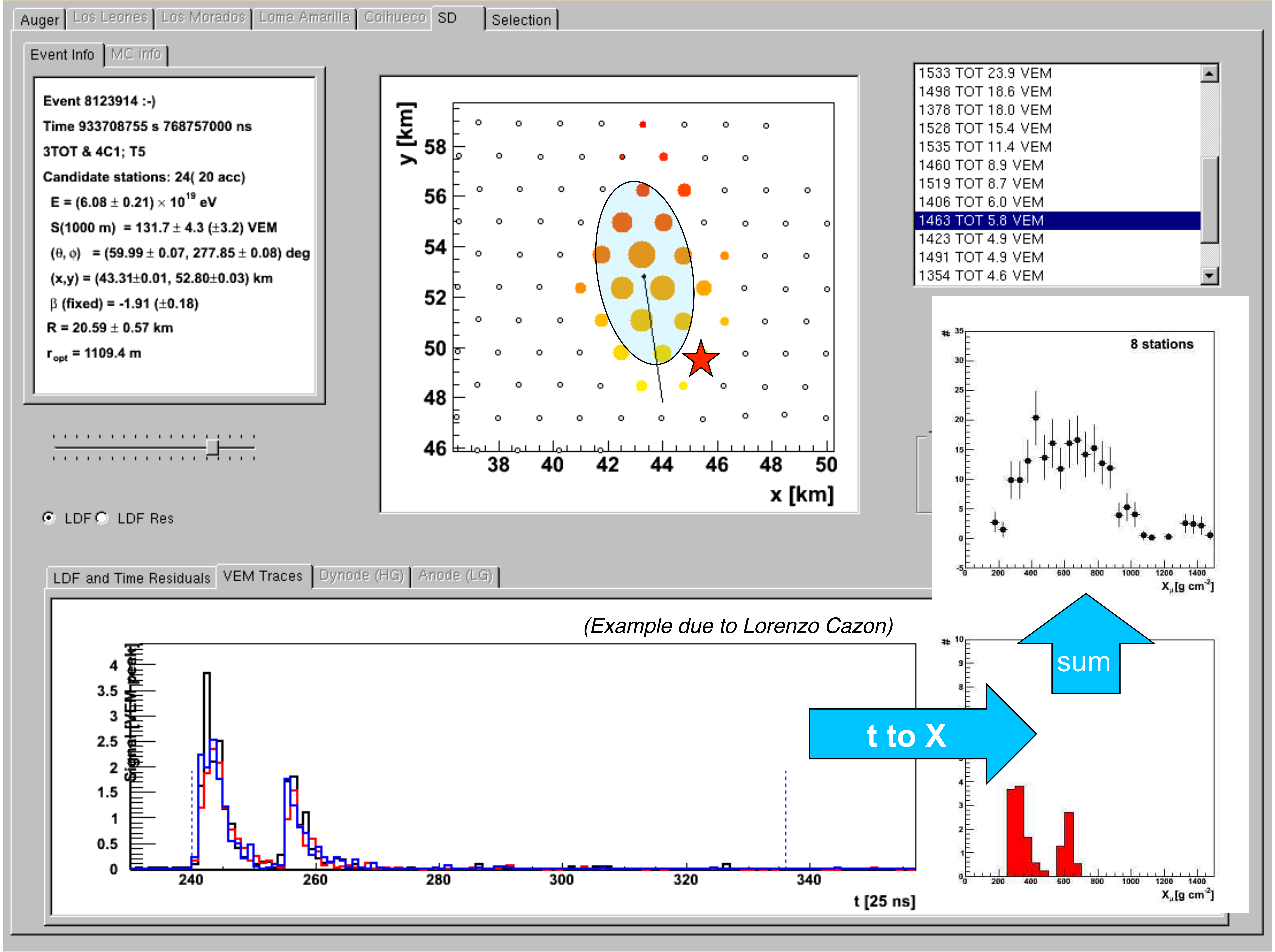
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
y [km]
x [km]
1398 TOT 898.1(1091.9) VEM
1522 TOT 365.1 VEM
1396 TOT 207.4 VEM
1523 TOT 179.7 VEM
1391 TOT 81.1 VEM
1390 TOT 56.1 VEM
1386 TOT 45.5 VEM
1520 TOT 42.2 VEM
1305 TOT 40.0 VEM
1456 TOT 37.1 VEM
1533 TOT 23.9 VEM
1498 TOT 18.6 VEM
7 stations
X_μ [g cm^-2]
LDF
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
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S(1000 m) = 131.7 ± 4.3 (±3.2) VEM
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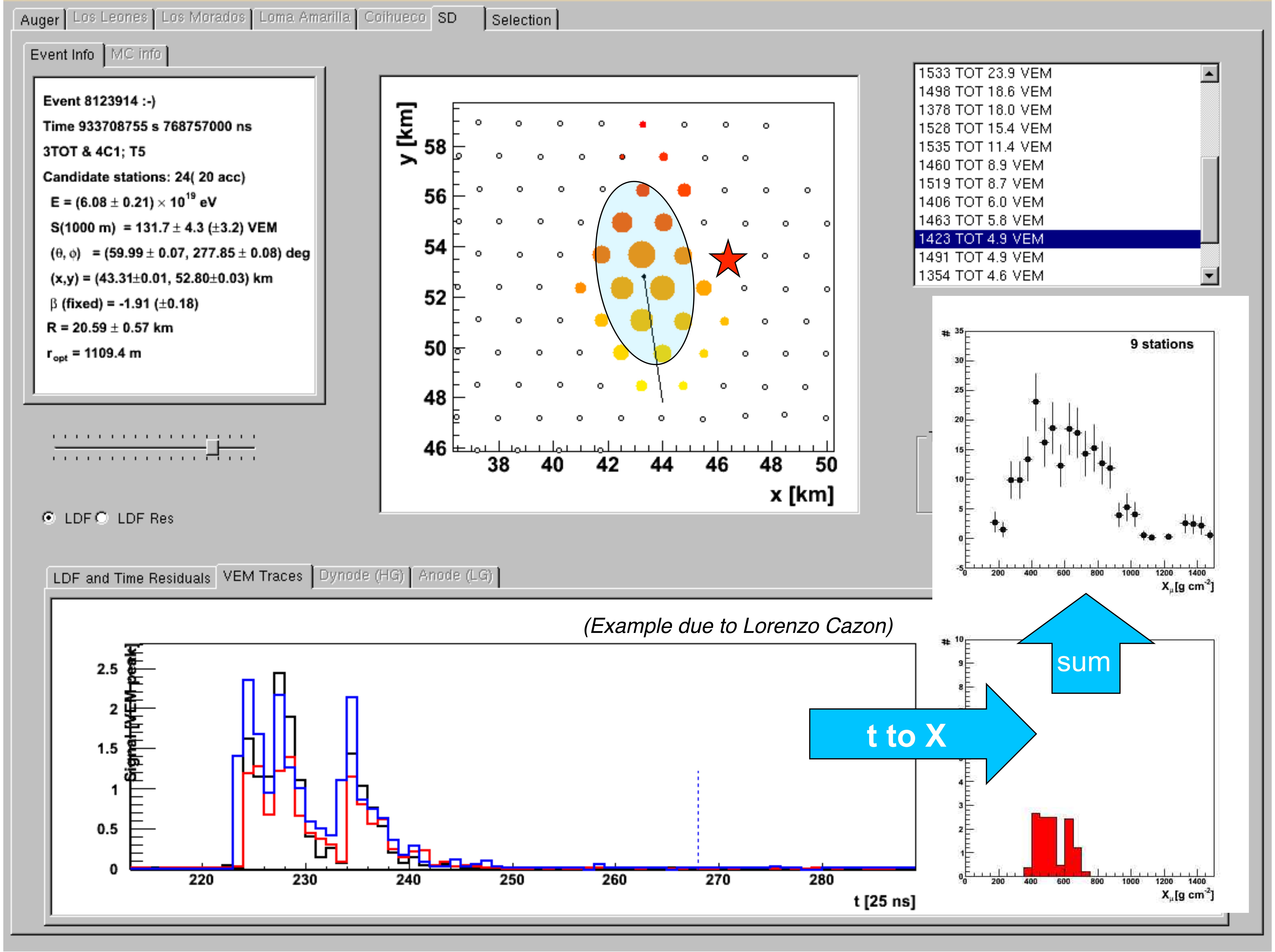
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
LDF
LDF Res
y [km]
x [km]
1533 TOT 23.9 VEM
1498 TOT 18.6 VEM
1378 TOT 18.0 VEM
1528 TOT 15.4 VEM
1535 TOT 11.4 VEM
1460 TOT 8.9 VEM
1519 TOT 8.7 VEM
1406 TOT 6.0 VEM
1463 TOT 5.8 VEM
1423 TOT 4.9 VEM
1491 TOT 4.9 VEM
1354 TOT 4.6 VEM
8 stations
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)
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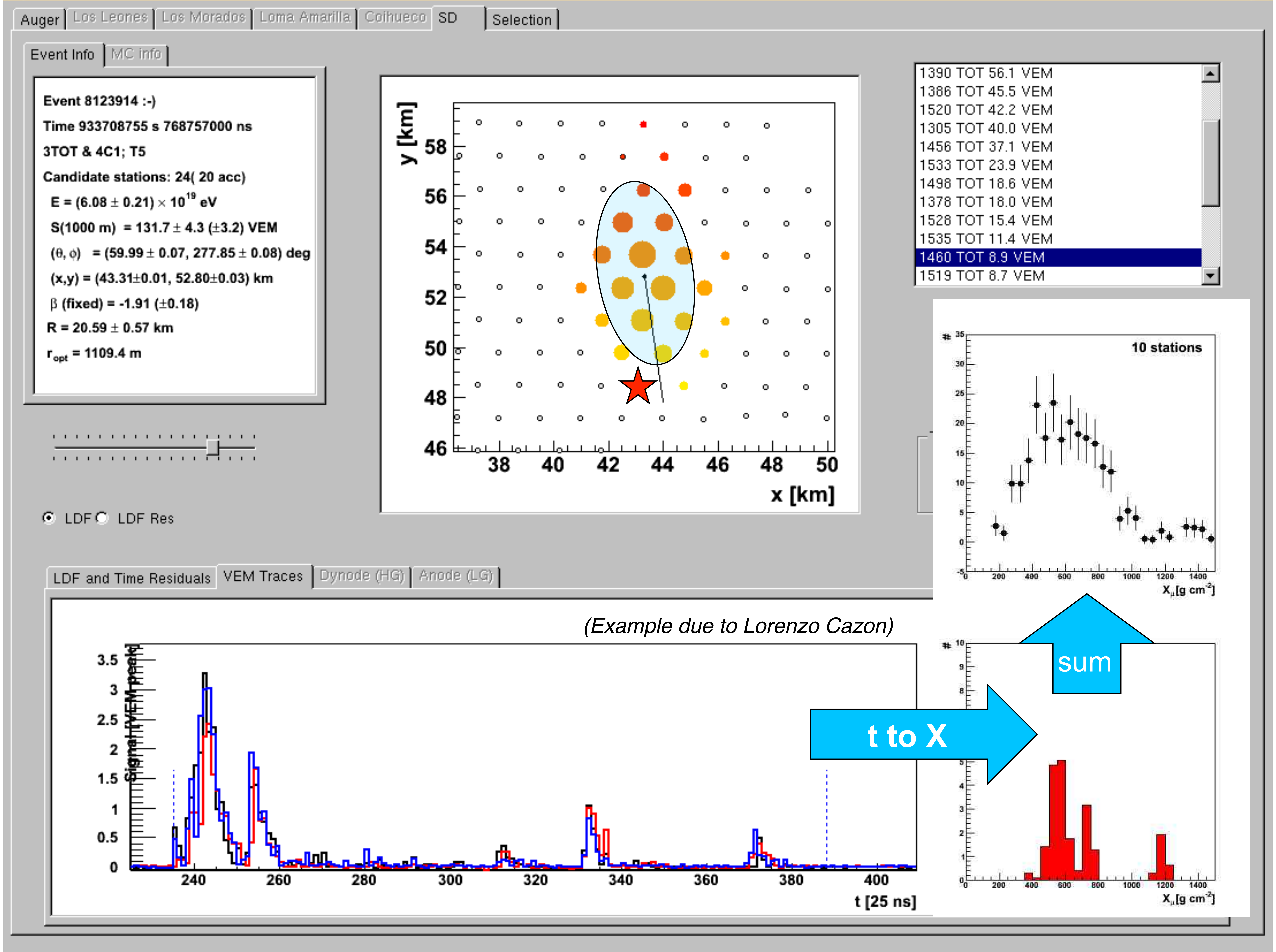
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
LDF
LDF Res
y [km]
x [km]
1533 TOT 23.9 VEM
1498 TOT 18.6 VEM
1378 TOT 18.0 VEM
1528 TOT 15.4 VEM
1535 TOT 11.4 VEM
1460 TOT 8.9 VEM
1519 TOT 8.7 VEM
1406 TOT 6.0 VEM
1463 TOT 5.8 VEM
1423 TOT 4.9 VEM
1491 TOT 4.9 VEM
1354 TOT 4.6 VEM
9 stations
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]
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
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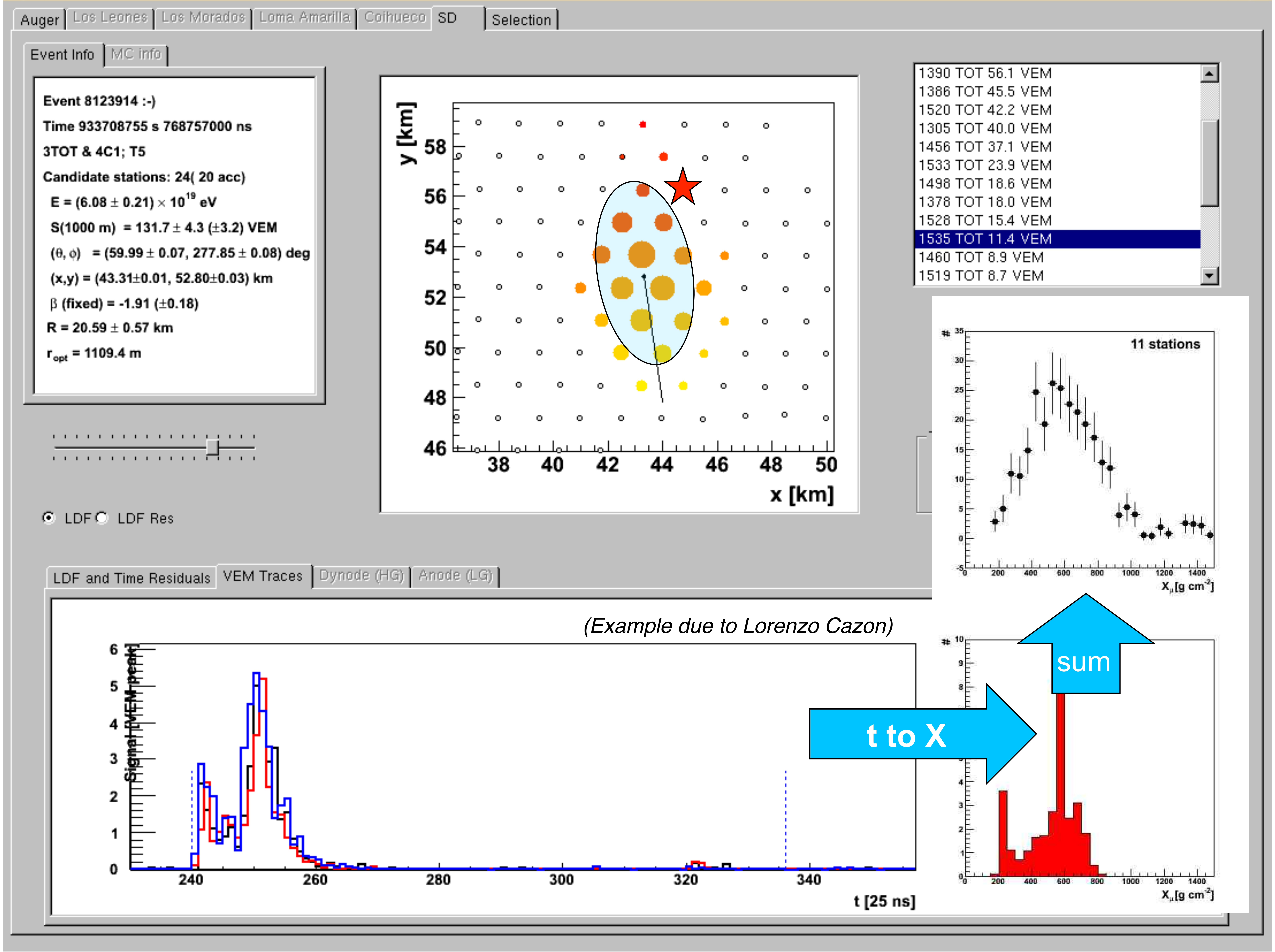
S(1000 m) = 131.7 ± 4.3 (±3.2) VEM
(θ, φ) = (59.99 ± 0.07, 277.85 ± 0.08) deg
(x,y) = (43.31±0.01, 52.80±0.03) km
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
y [km]
x [km]
1390 TOT 56.1 VEM
1386 TOT 45.5 VEM
1520 TOT 42.2 VEM
1305 TOT 40.0 VEM
1456 TOT 37.1 VEM
1533 TOT 23.9 VEM
1498 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]
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)
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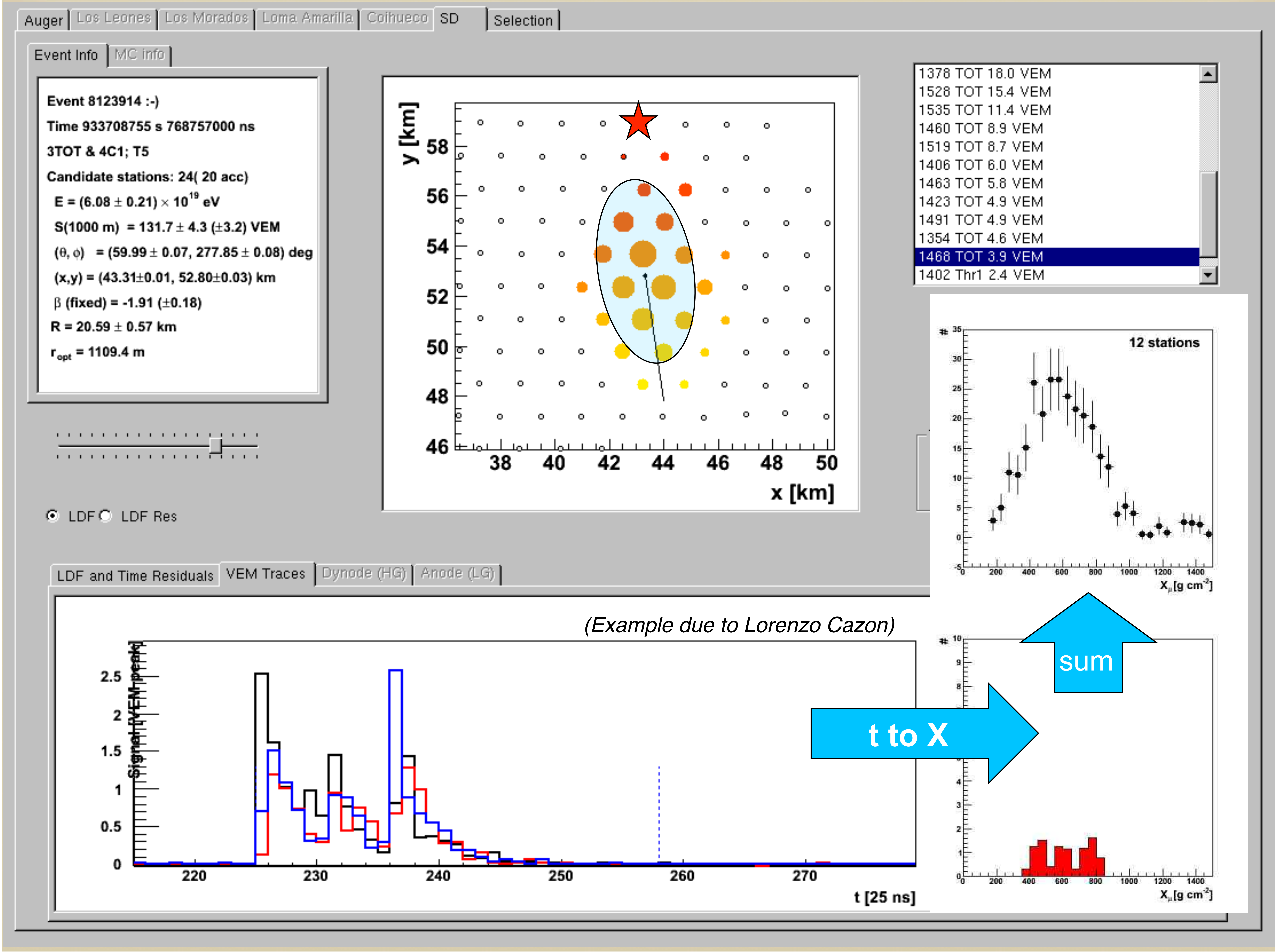
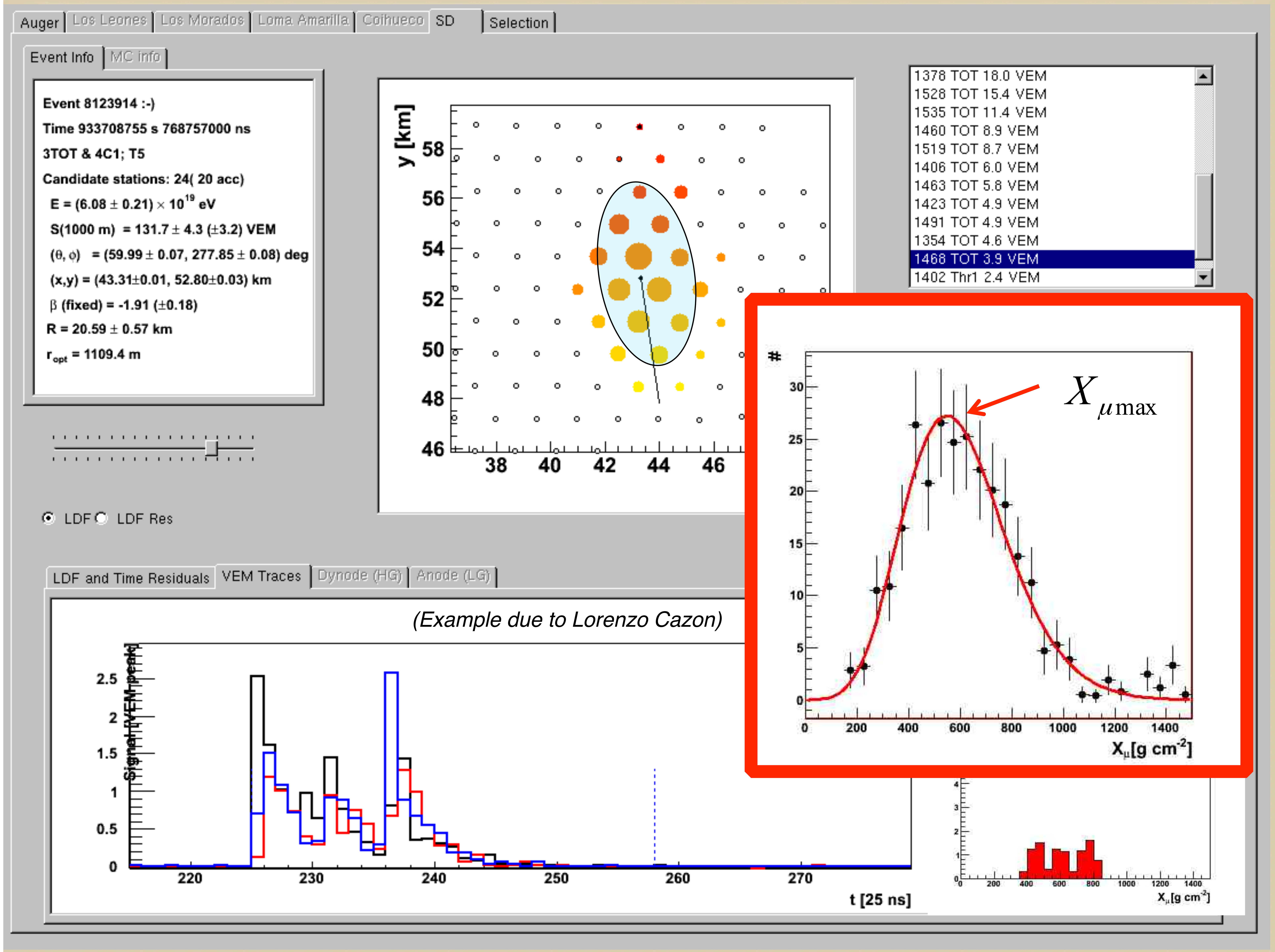
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
y [km]
x [km]
1390 TOT 56.1 VEM
1386 TOT 45.5 VEM
1520 TOT 42.2 VEM
1305 TOT 40.0 VEM
1456 TOT 37.1 VEM
1533 TOT 23.9 VEM
1498 TOT 18.6 VEM
1378 TOT 18.0 VEM
1528 TOT 15.4 VEM
1535 TOT 11.4 VEM
1460 TOT 8.9 VEM
1519 TOT 8.7 VEM
LDF
LDF Res
11 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
X_μ [g cm^-2]



(Example due to Lorenzo Cazon)


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)
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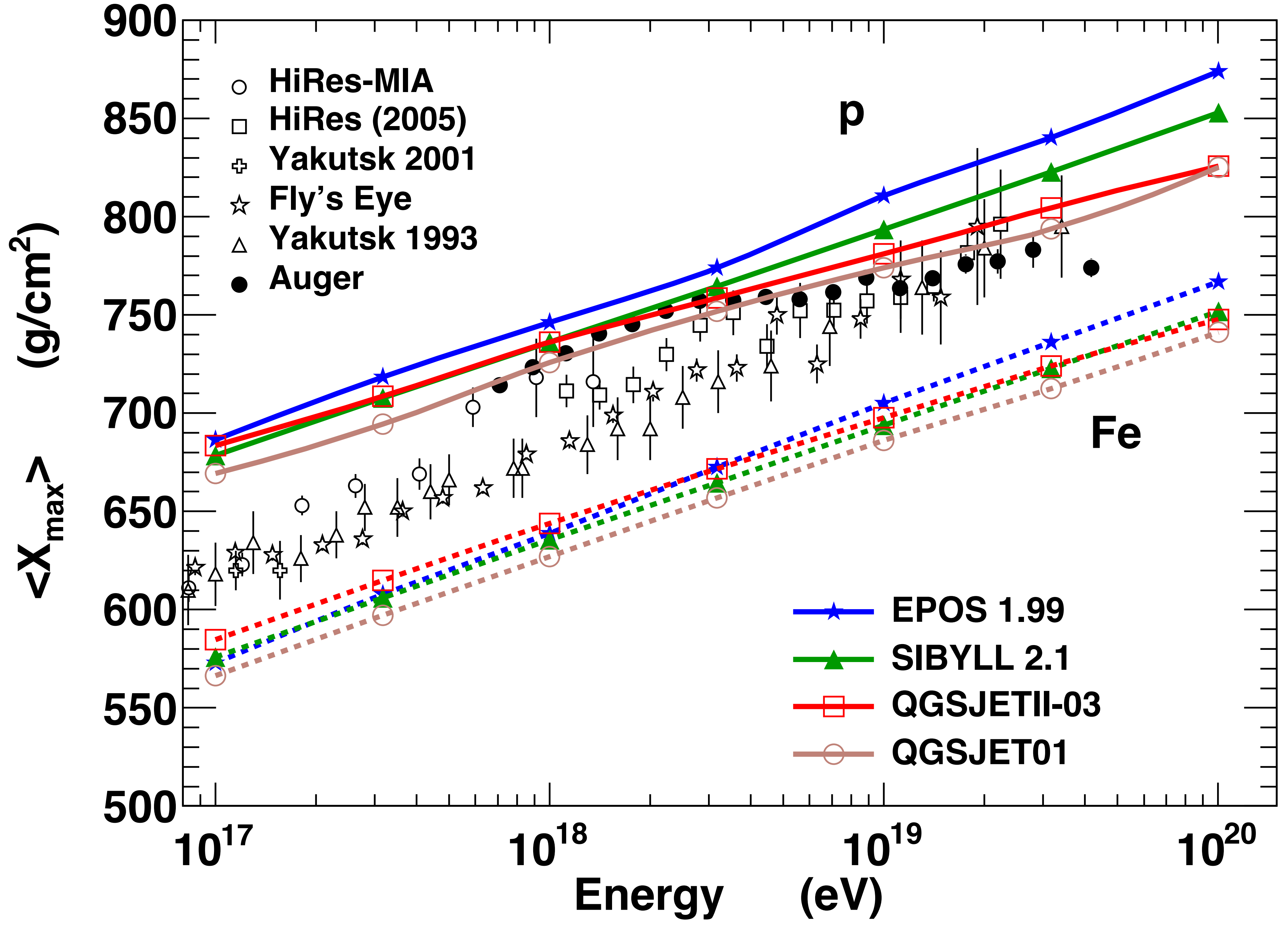
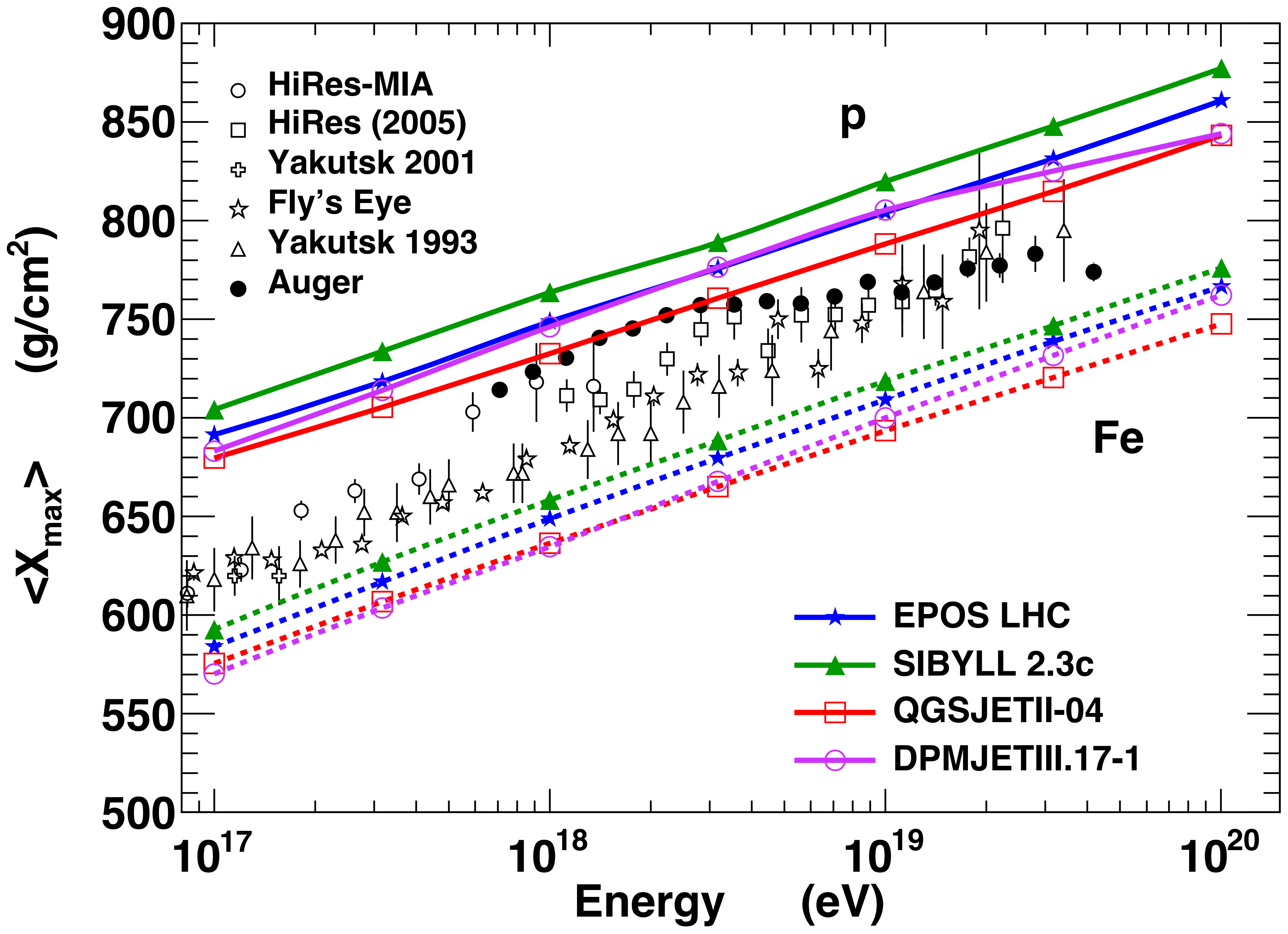
β (fixed) = -1.91 (±0.18)
R = 20.59 ± 0.57 km
r_opt = 1109.4 m
y [km]
1378 TOT 18.0 VEM
1528 TOT 15.4 VEM
1535 TOT 11.4 VEM
1460 TOT 8.9 VEM
1519 TOT 8.7 VEM
1406 TOT 6.0 VEM
1463 TOT 5.8 VEM
1423 TOT 4.9 VEM
1491 TOT 4.9 VEM
1354 TOT 4.6 VEM
1468 TOT 3.9 VEM
1402 Thr1 2.4 VEM
LDF
LDF Res
LDF and Time 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}]

Change of model predictions thanks to LHC data

pre-LHC models



post-LHC models



(Pierog, ICRC 2017)

Sys. X_{max} uncertainty Auger: $\Delta X_{max} = -10\,g/cm^2 \; +8\,g/cm^2$

TA: $\Delta X_{max} = \pm 20\,g/cm^2$

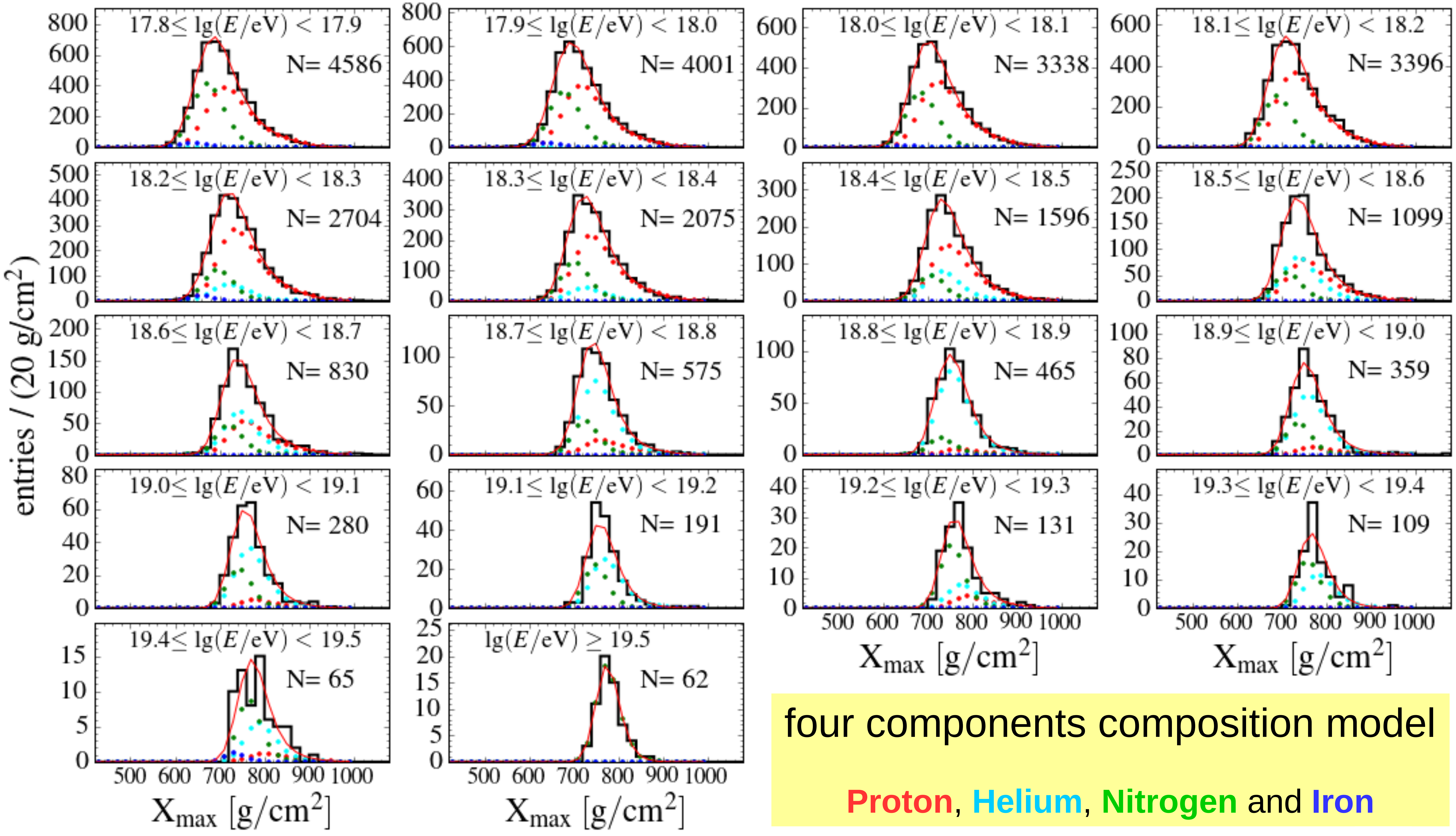
LHC-tuned models should be used for data interpretation

Hadron production at ultra-high energies:

Change of composition vs. change of hadronic interaction

X_{max} distributions (FD)

Interpreting X_{max} distributions with **EPOS-LHC**



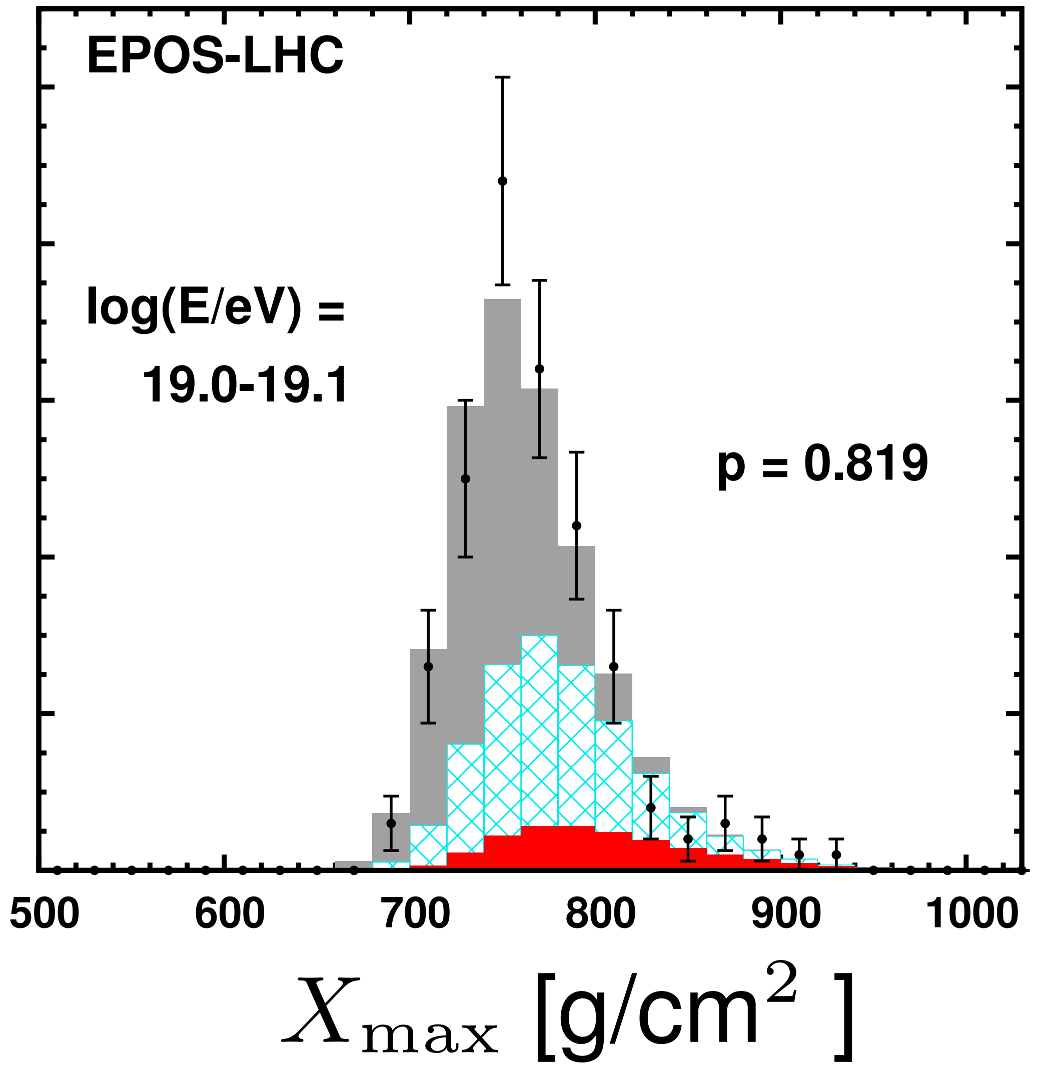
four components composition model

Proton, **Helium**, **Nitrogen** and **Iron**

Sum of four components

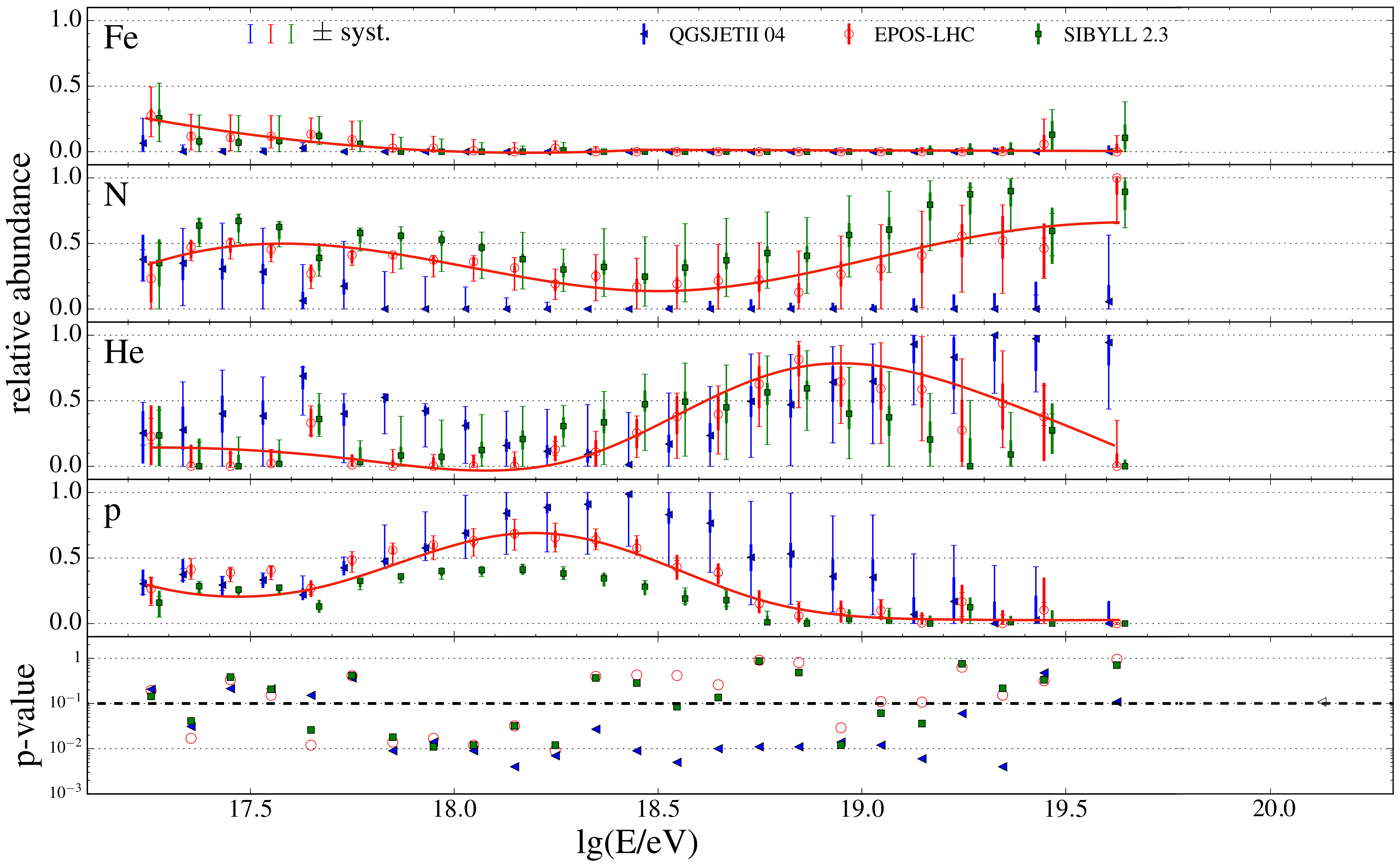
(Bellido, Auger, ICRC 2017)

Result 2: Unexpected change of mass composition



p He N Fe

Composition based on fluorescence telescope data (15% duty cycle)



LHC-tuned interaction models

Fit quality not always good

No iron needed for interpretation

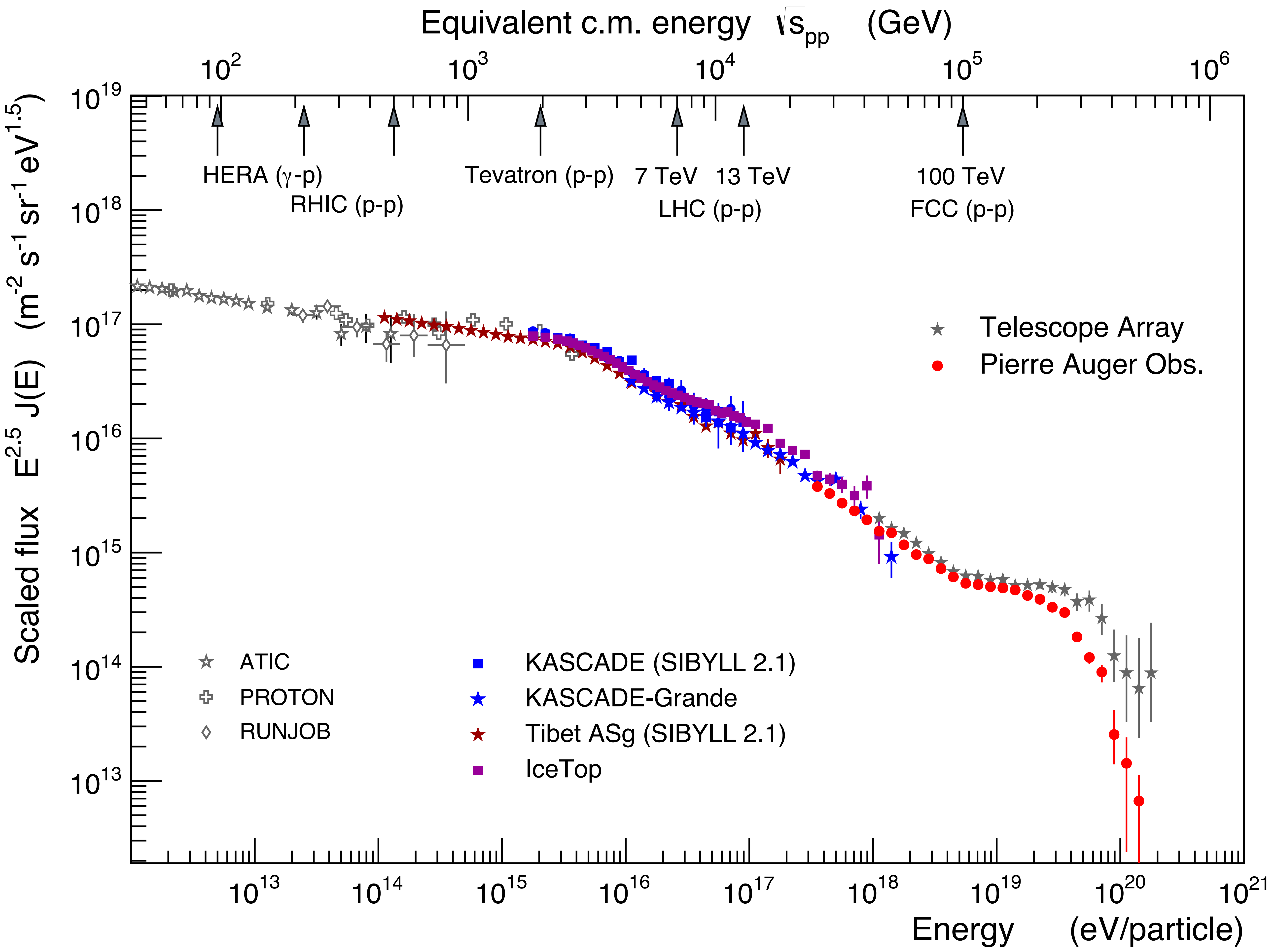
Large proton fraction below ankle

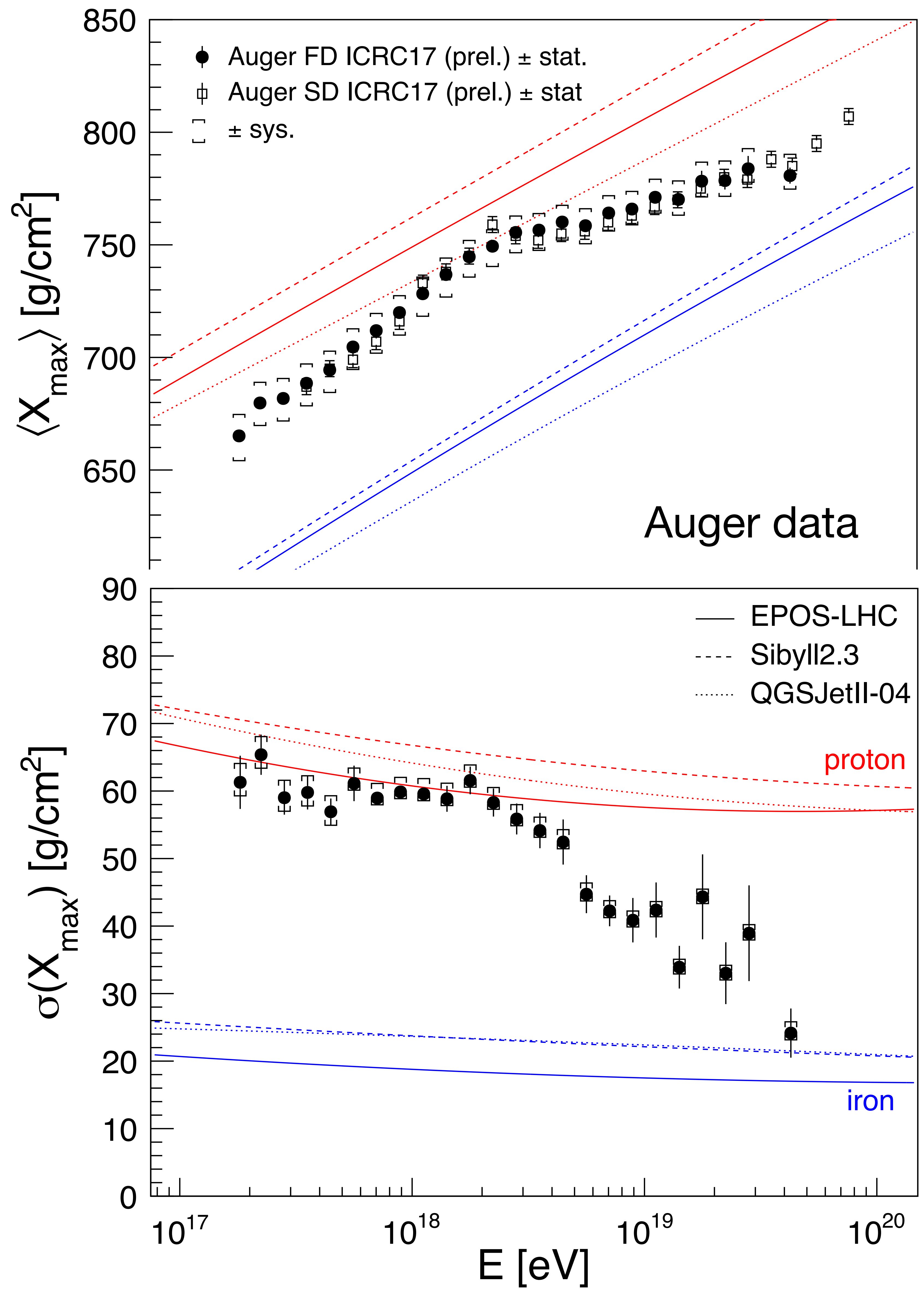
No obvious scaling with rigidity

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

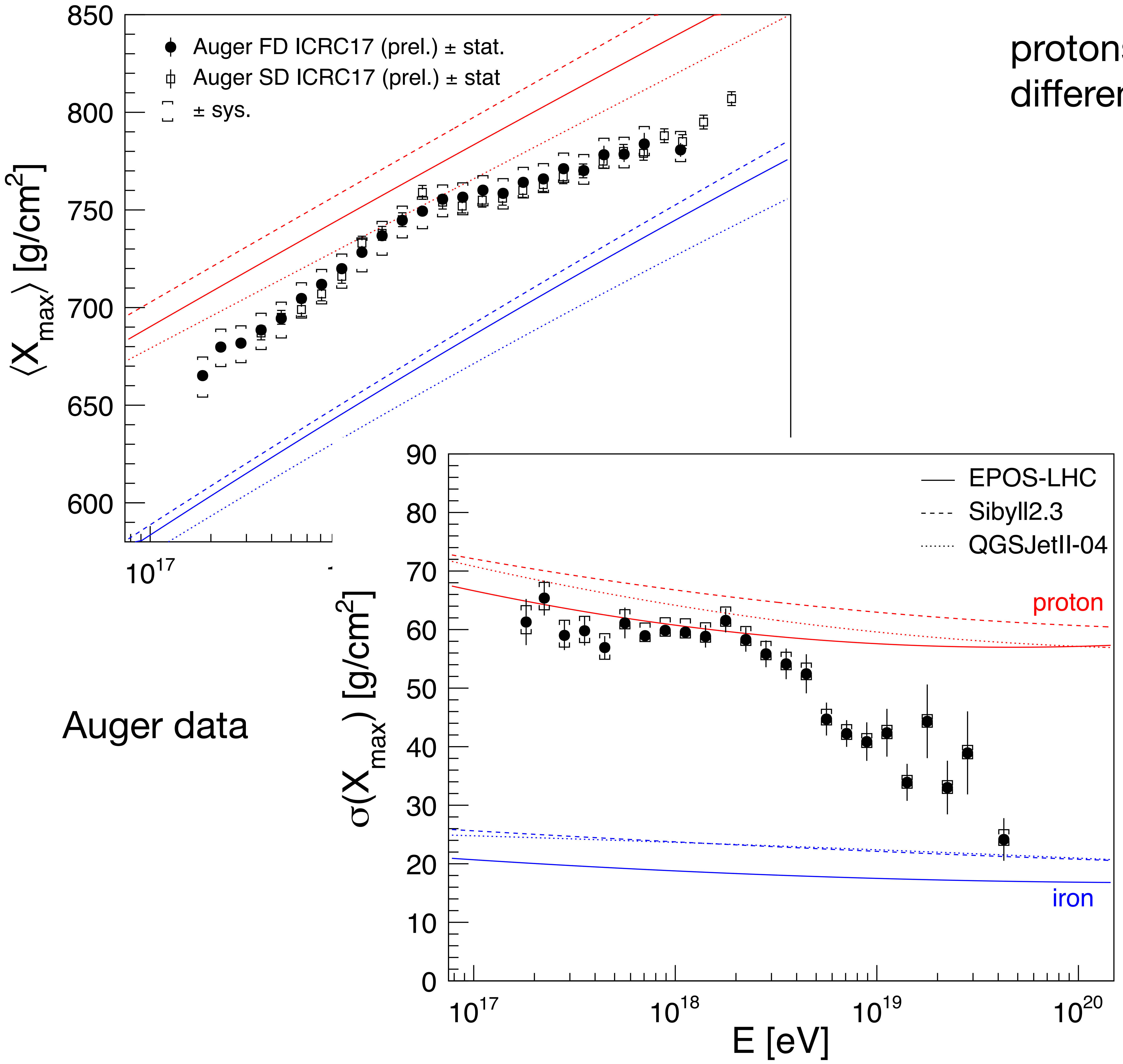
(Bellido ICRC 2017)

Energy scale of possible exotic physics



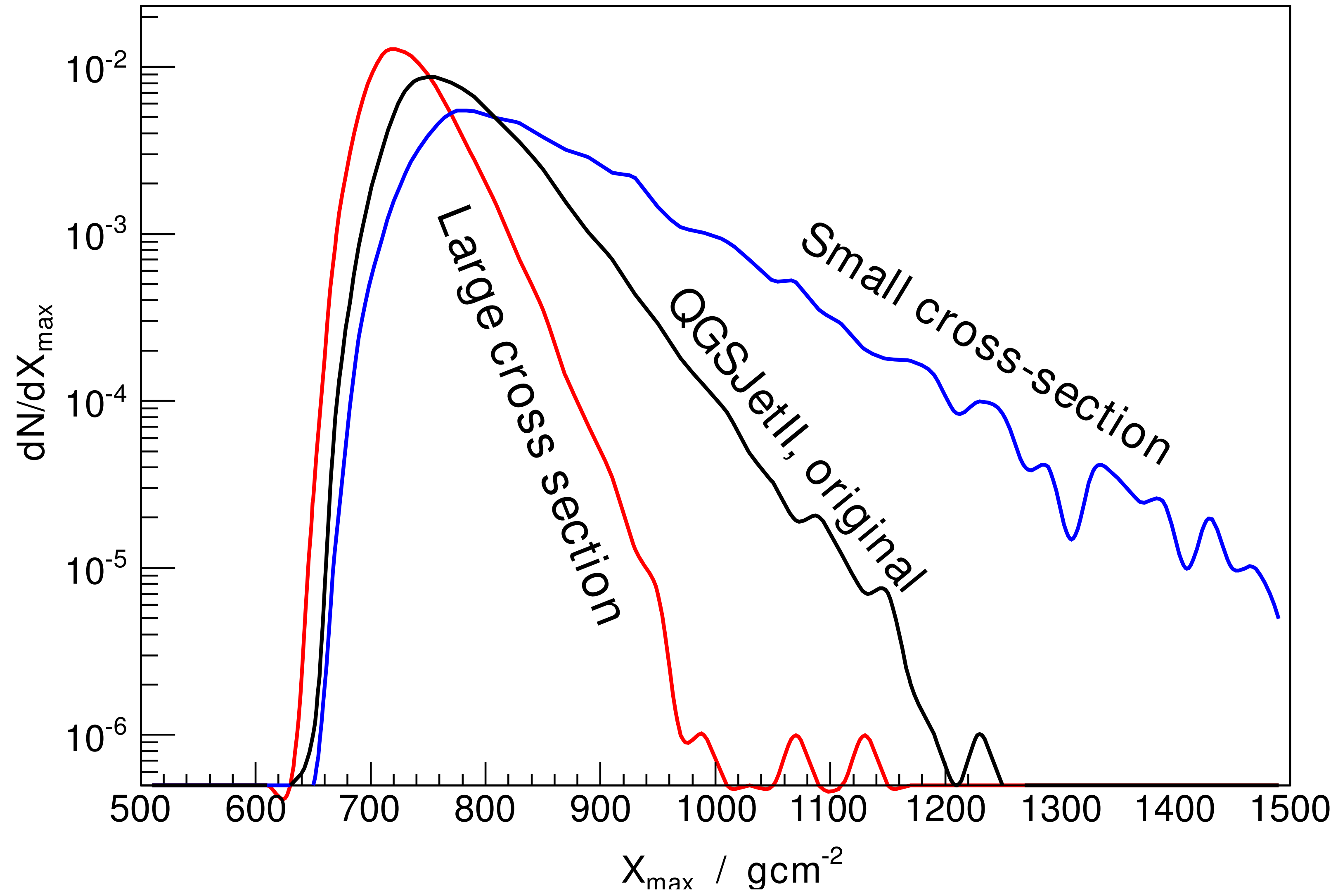


Chance of composition vs. change of hadronic interaction

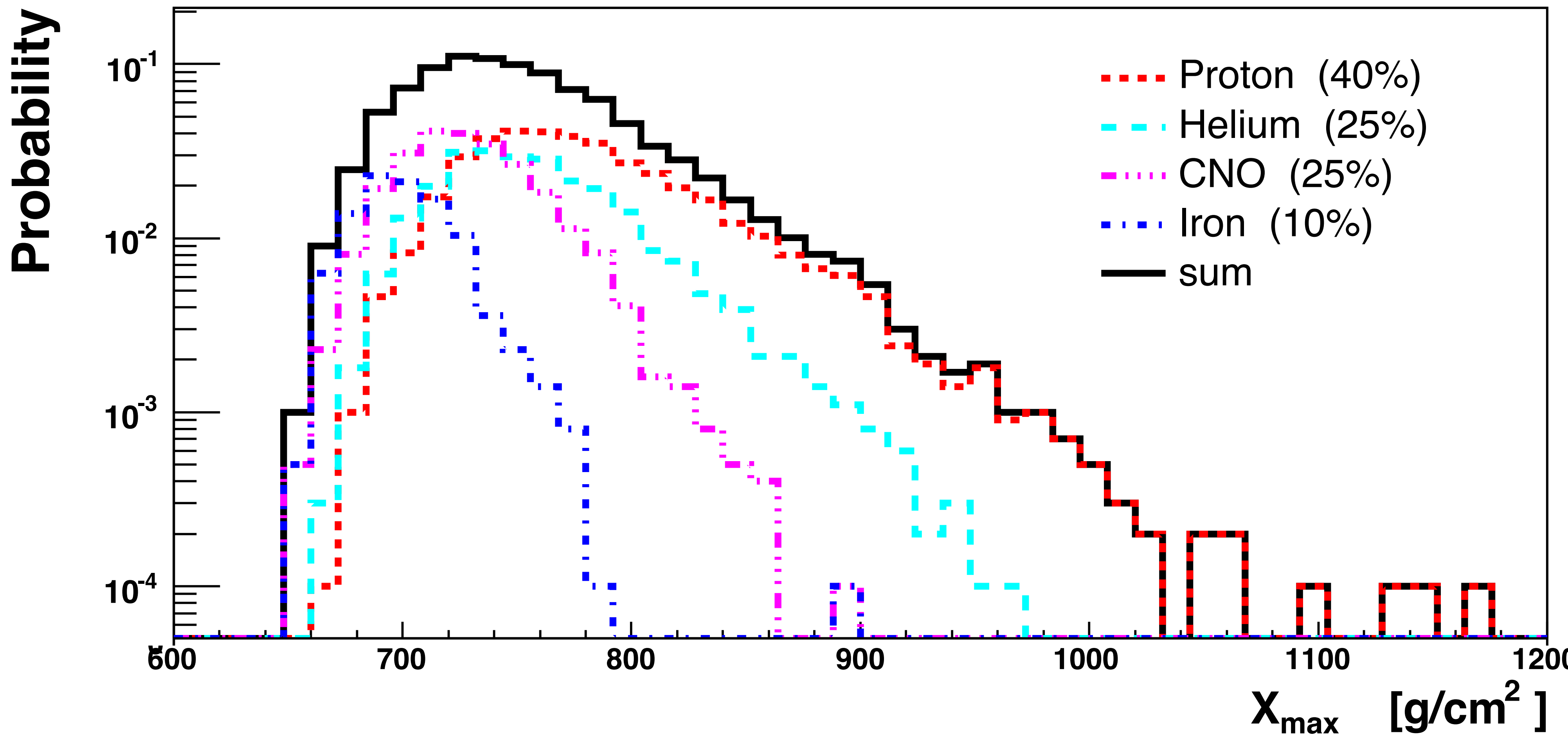


Auger data

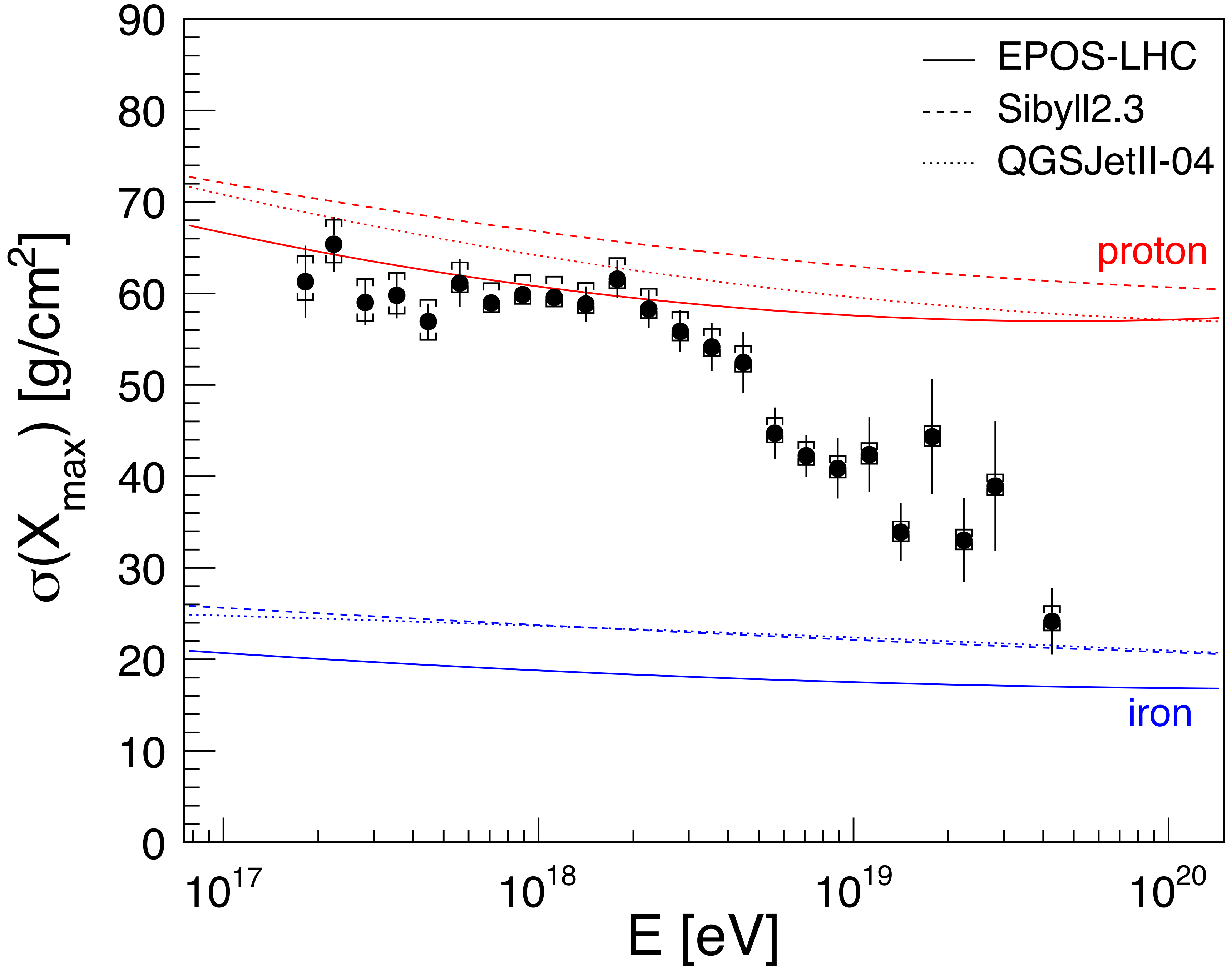
protons showers with different cross sections



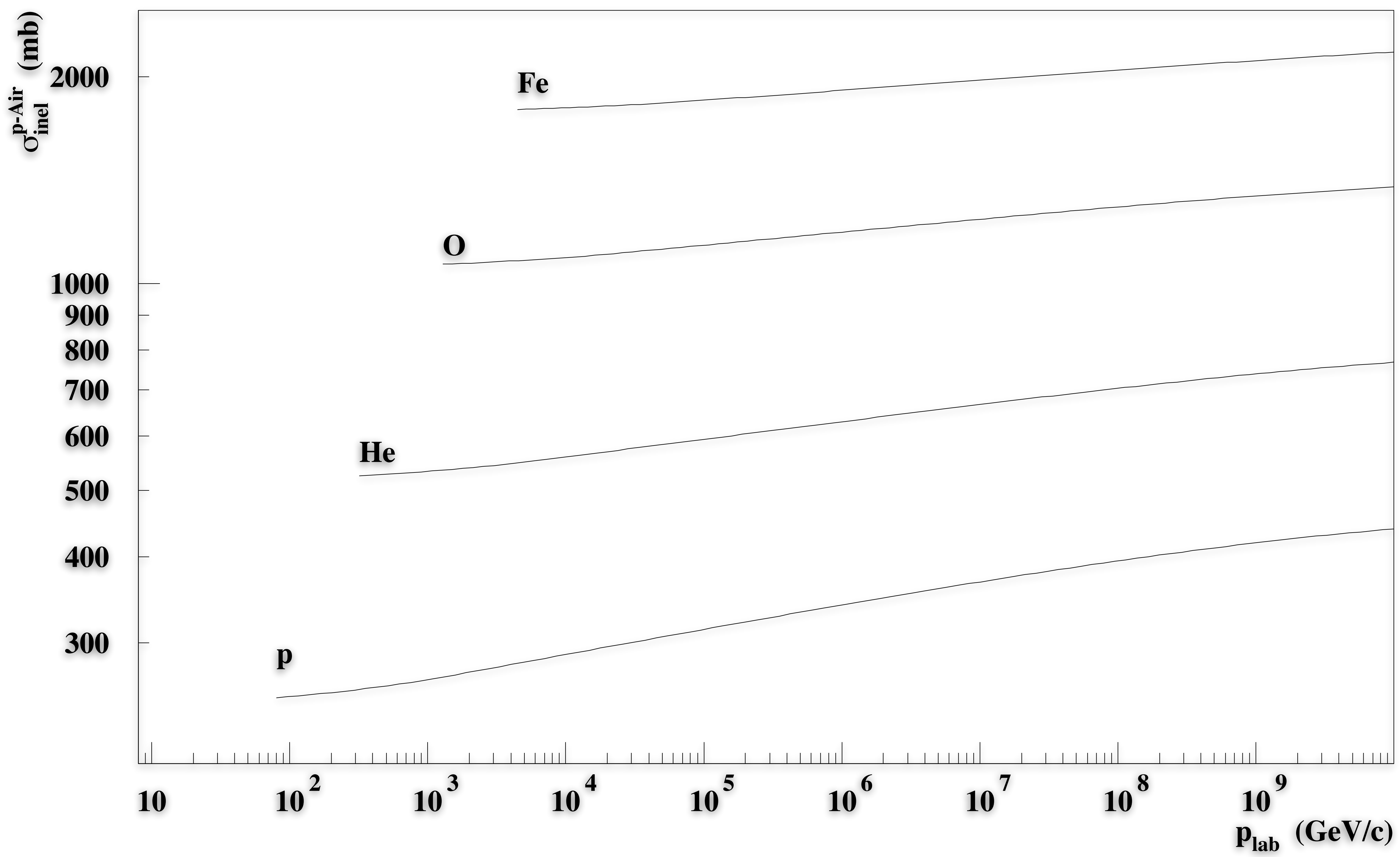
typical composition scenario



Comparison of order of magnitude



(Knapp, Heck, Schatz, FZKA 5828)



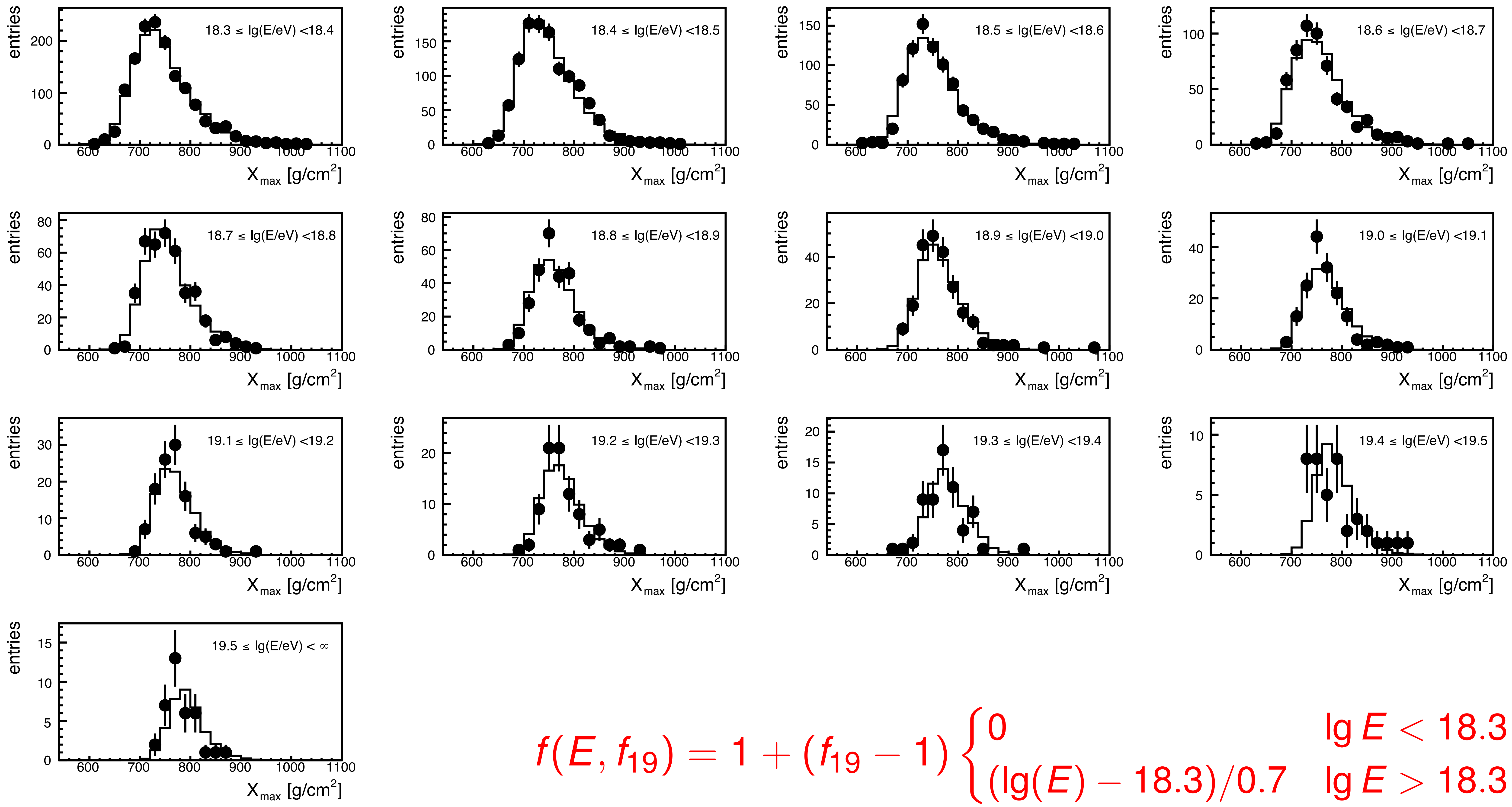
$$\sigma_{tot} = \sqrt{\sigma_{X_1}^2 + \sigma_{evol}^2}$$

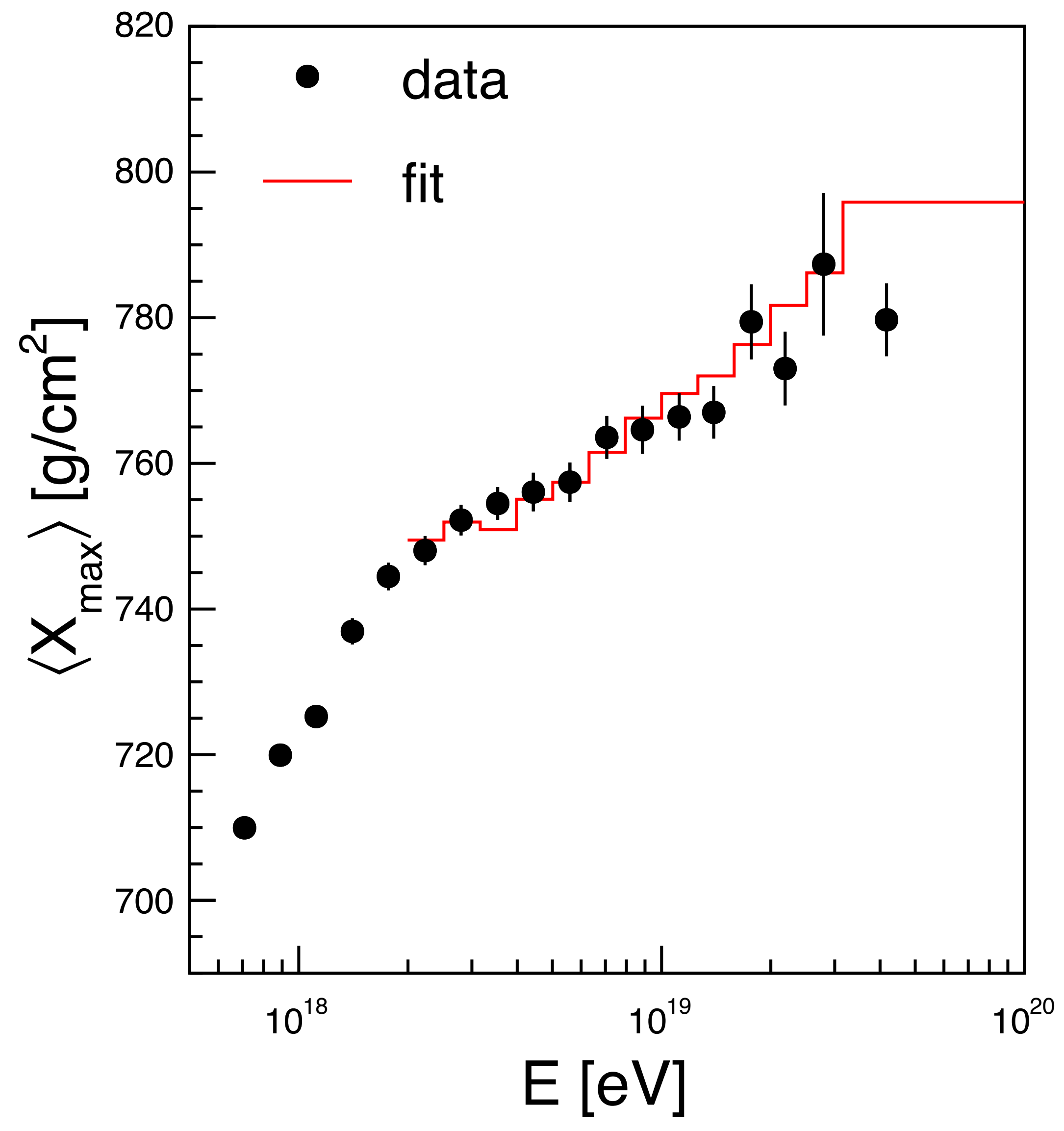
$$\sigma_{X_1} = \lambda_{int}$$

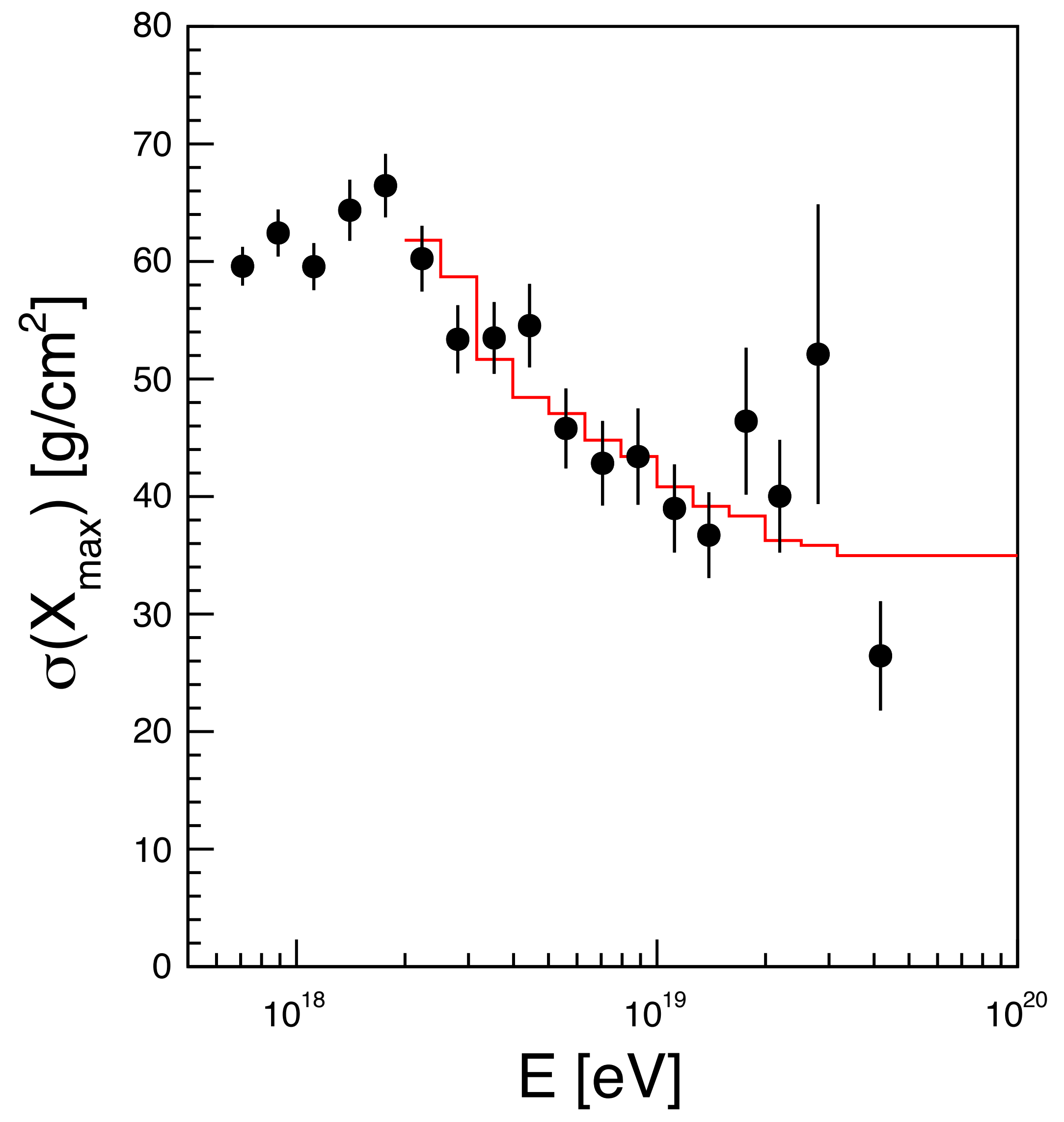
$$\lambda_{int} = \frac{24160\,\mathrm{mb\,g/cm^2}}{\sigma_{p-air}}$$

$$\sigma_{X_1,p} \sim 50 - 55\,\mathrm{g/cm^2}$$
$$\sigma_{X_1,Fe} \sim 10\,\mathrm{g/cm^2}$$

Toy model: fit of interaction properties







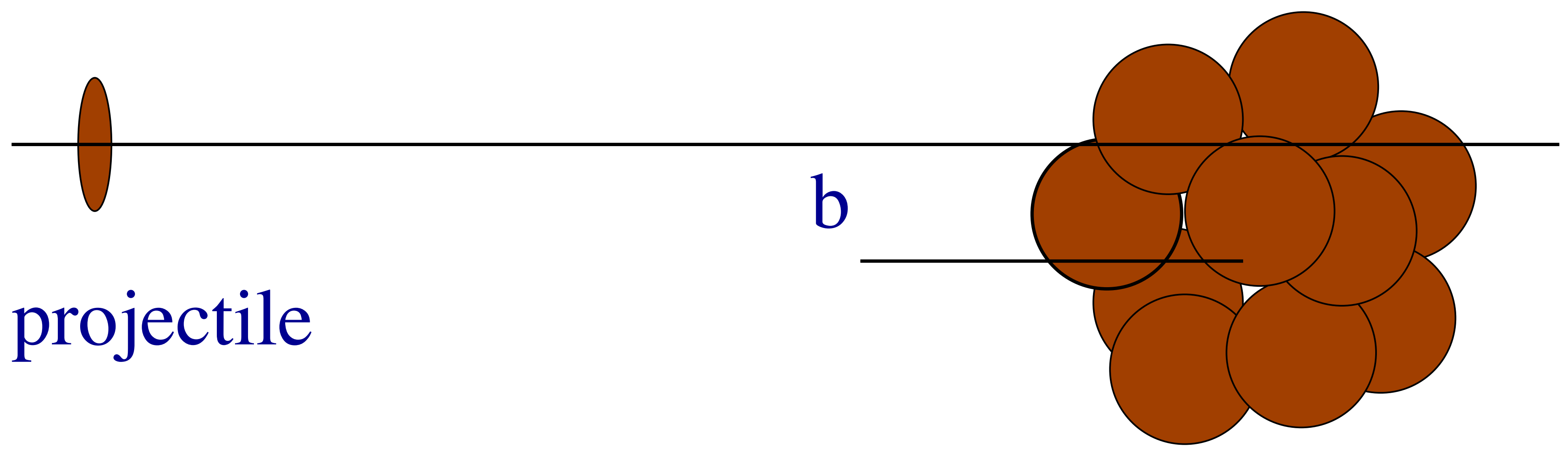
$$f(E, f_{19}) = 1 + (f_{19} - 1)\begin{cases} 0 & \lg E < 18.3 \\ (\lg(E) - 18.3)/0.7 & \lg E > 18.3 \end{cases}$$

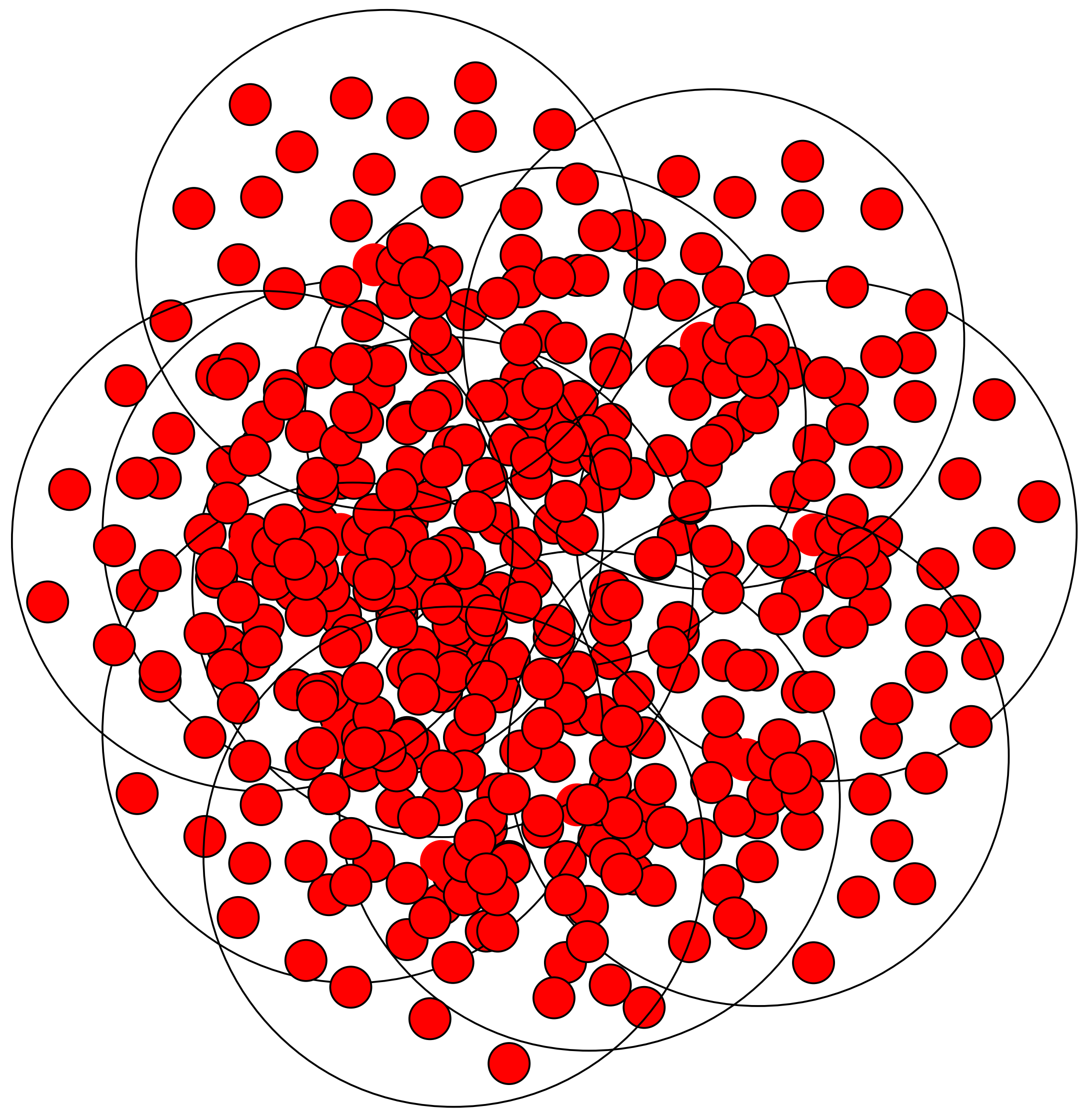
QGSJet II.04

$$f_{\rm mult} = 0.82 \pm 0.01, \quad f_{\rm cross} = 2.06 \pm 0.02$$

(Unger, unpublished 2015)

Black disk limit reached at LHC energies for p-p scattering





LHC: p-p scattering "black disk" at small impact parameters

$$\sigma_{\text{prod}} \approx \int d^2\vec{b} \left[1 - \exp\left\{-\sigma_{\text{ine}}^{NN} T_A(\vec{b})\right\}\right]$$

Cross section largely determined by geometry of nucleons in nucleus

Cross section can only grow at periphery

Example: total p-p cross section 160 mb, then p-air 560 mb
320 mb 630 mb (unitarity?)

Rapid increase of transverse size of protons required, otherwise factor of 2 not possible