59th Krakow School of Theoretical Physics
Zakopane June 2019

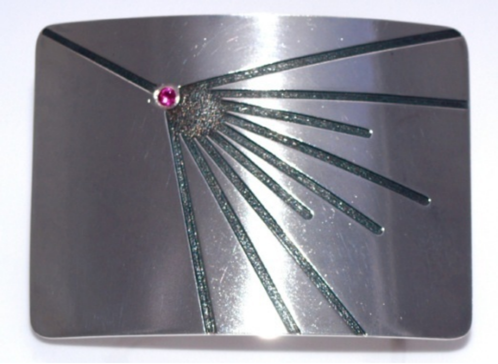
Probing the Violent Universe with multi-messenger eyes: gravitational waves, high-energy neutrinos, gamma rays, and cosmic rays

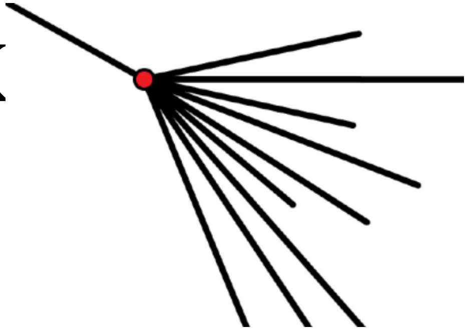
Ultra High-Energy Cosmic Rays
Lecture 3

Alan Watson

University of Leeds, UK

a.a.watson@leeds.ac.uk

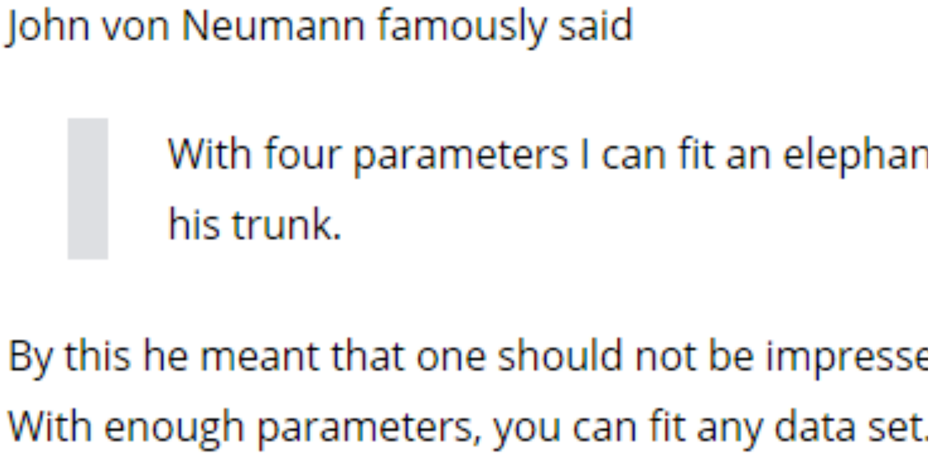




Lecture 3

Astrophysical Models to explain all of this

There are many and the data are not very constraining



John von Neumann famously said

> With four parameters I can fit an elephan
> his trunk.

By this he meant that one should not be impresse t well.
With enough parameters, you can fit any data set.

Truth ... is much too complicated to allow anything but approximations.

Implications of mass result for detection of cosmogenic neutrinos

(Ave, Busca, Olinto, aaw, Yamamoto 2005; Hooper, Taylor and Sarkar 2005)

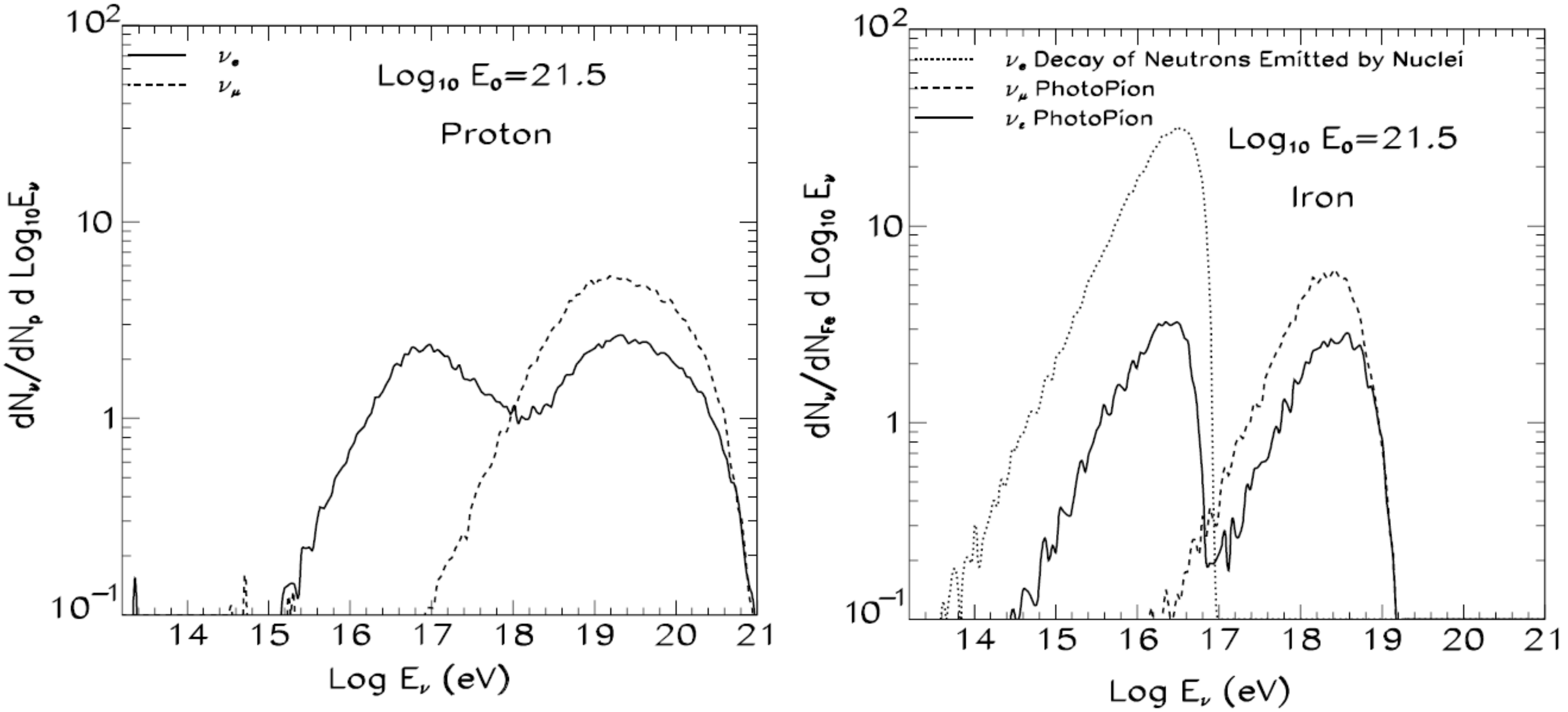


Figure 1: The neutrino yield for a proton primary (left) and an iron primary (right). In each case the initial energy was chosen as $10^{21.5}$ eV and the propagation distance was 300 Mpc. The different origins of the neutrinos are shown. The dotted line in the right-hand diagram shows the neutrino flux that arises from the decay of neutrons from photodisintegration processes. The figure is from [3].

Neutrino argument and the Ankle Region:
Heinze et al. arXiv 1512.05988 (ApJ 2016)

Assume that the TA spectrum measurement and interpretation of pure protons is correct

Scan simultaneously over

- **Spectral index at injection**
- **Source Evolution**
- **Maximum proton energy**

Predict the neutrino flux and compare with IceCube

3D best fit: log (E_{max}/GeV) = 10.7 +0.3 /0.1; **m = 4.3** +0.4/-0.8; **γ = 1.52** +0.35/-0.20

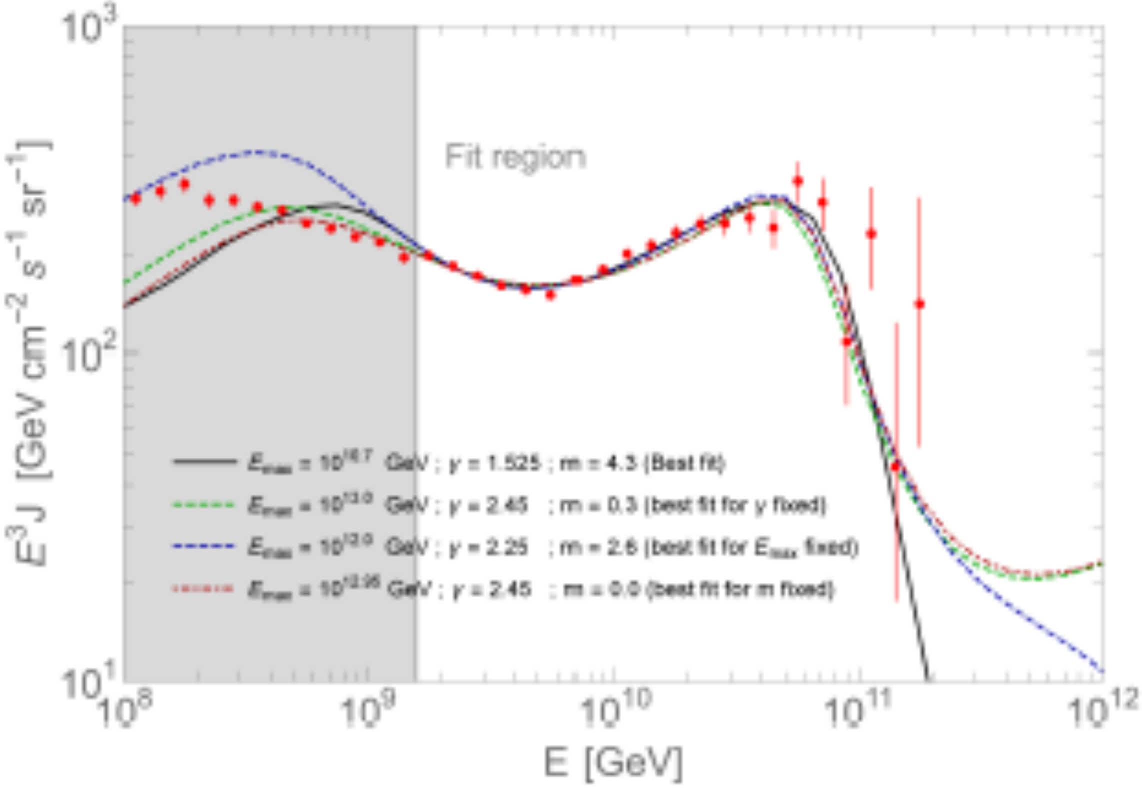
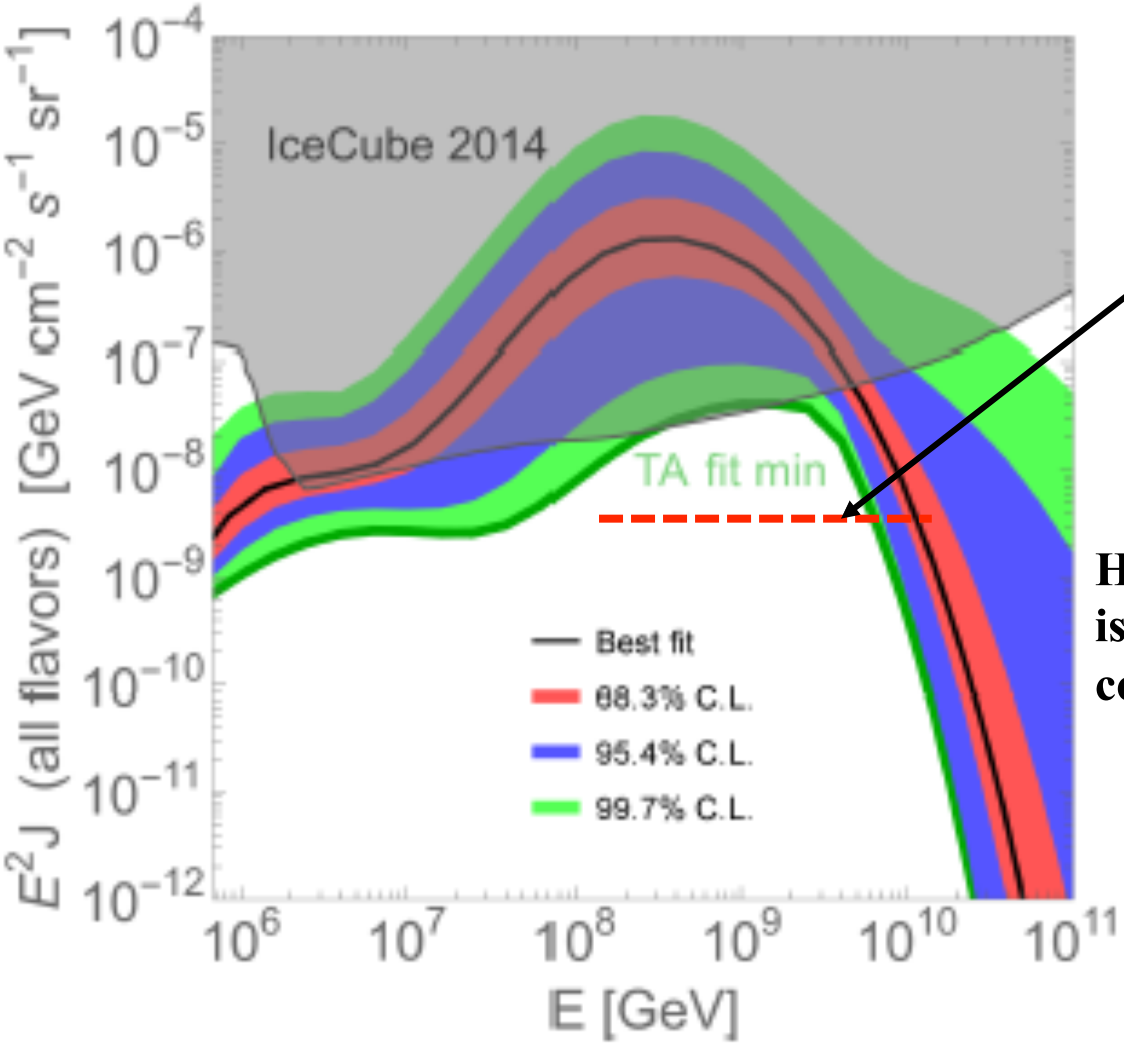


FIG. 3: Best-fit UHECR spectra for 3 and 2D scans (dashed/dotted curves), s TA 7-year data [2, 66]. Here the energ points is fixed while that of the models is by the best fit value.

	ν events
Best fit	180.6
68.3% C.L. min flux	62.7
95.4% C.L. min flux	12.4
99.7% C.L. min flux, **TA fit min**	4.9

TABLE I: Expected number of cosmogenic neutrino events in IceCube, corresponding to the 7-year UHECR TA best-fit, and to the minimal fluxes within the 68.3%, 95.4%, 99.7% C.L.



Auger neutrino limit 2019

Heavier composition, *à la Auger*, is favoured (or some additional component in ankle region)

FIG. 4: All-flavor flux of cosmogenic neutrinos predicted by the 3D fit to the TA 7-year UHECR spectrum reported in Sec. III. The IceCube experimental upper limit is taken from Ref. [63].

New York and Parisian Ideas: Extragalactic sources

Globus, Allard and Parizot: arXiv 1505.01377

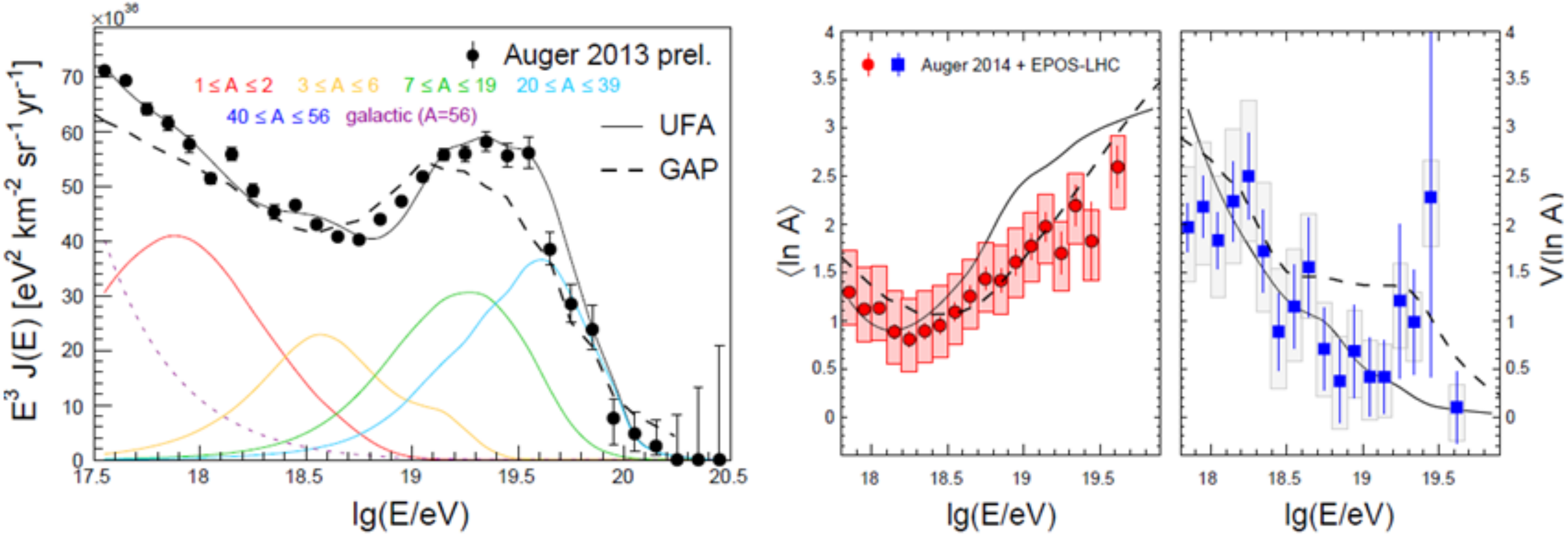
Unger, Farrar and Anchordoqui: arXiv 1505.02153

Acceleration in extragalactic sources surrounded by strong photon fields

Globus et al. Specific GRB model

Unger et al. More generic

Fragmentation and propagation studied

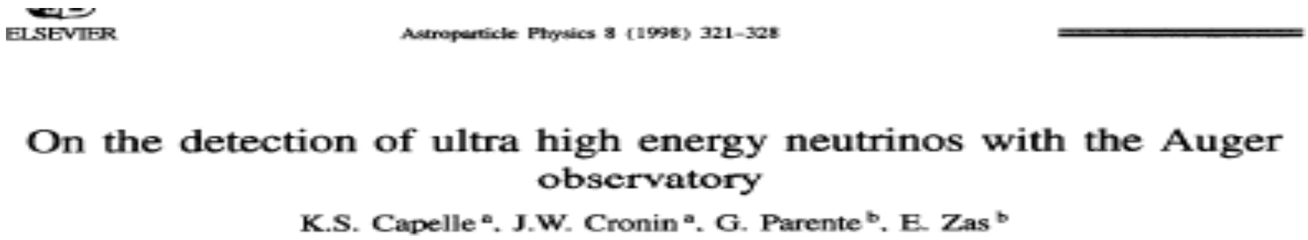

×10^36
Auger 2013 prel.
1 ≤ A ≤ 2
3 ≤ A ≤ 6
7 ≤ A ≤ 19
20 ≤ A ≤ 39
40 ≤ A ≤ 56
galactic (A=56)
UFA
GAP
E^3 J(E) [eV^2 km^-2 sr^-1 yr^-1]
0
10
20
30
40
50
60
70
17.5
18
18.5
19
19.5
20
20.5
lg(E/eV)
Auger 2014 + EPOS-LHC
⟨ln A⟩
V(ln A)
0
0.5
1
1.5
2
2.5
3
3.5
4
18
18.5
19
19.5
lg(E/eV)
18
18.5
19
19.5
lg(E/eV)

An earlier solution?

National Gallery London

Carlo Crivelli (1430 – 1490): ‘The Annuciation with St Edimus’

Search for UHE neutrinos at the Auger Observatory



ELSEVIER

Astroparticle Physics 8 (1998) 321–328

On the detection of ultra high energy neutrinos with the Auger observatory

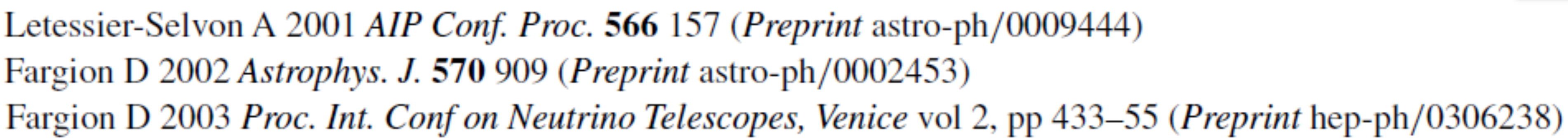
K.S. Capelle[a], J.W. Cronin[a], G. Parente[b], E. Zas[b]

Parente and Zas: Venice Meeting 1996, arXiv 960609

τ at EeV may decay before reaching the ground

→ Secondary shower (Double Bang event)

Also interactions in mountains or upward-going in earth

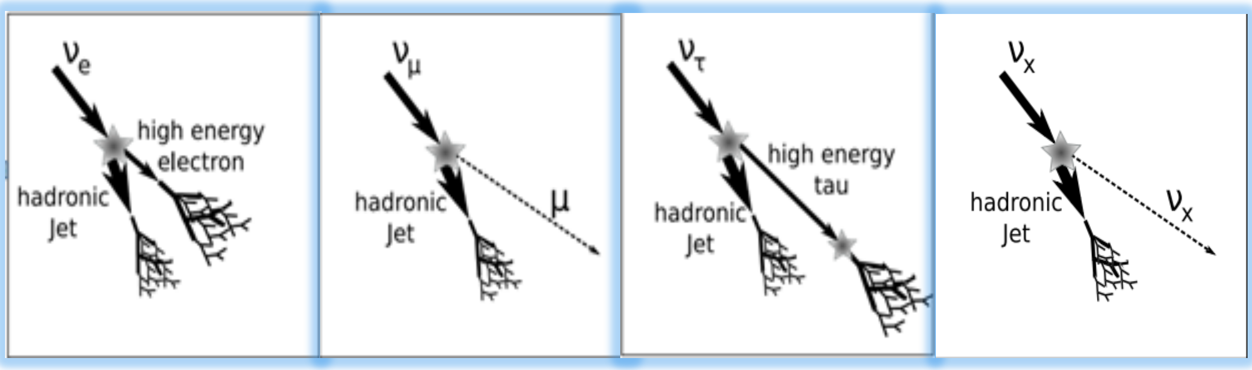


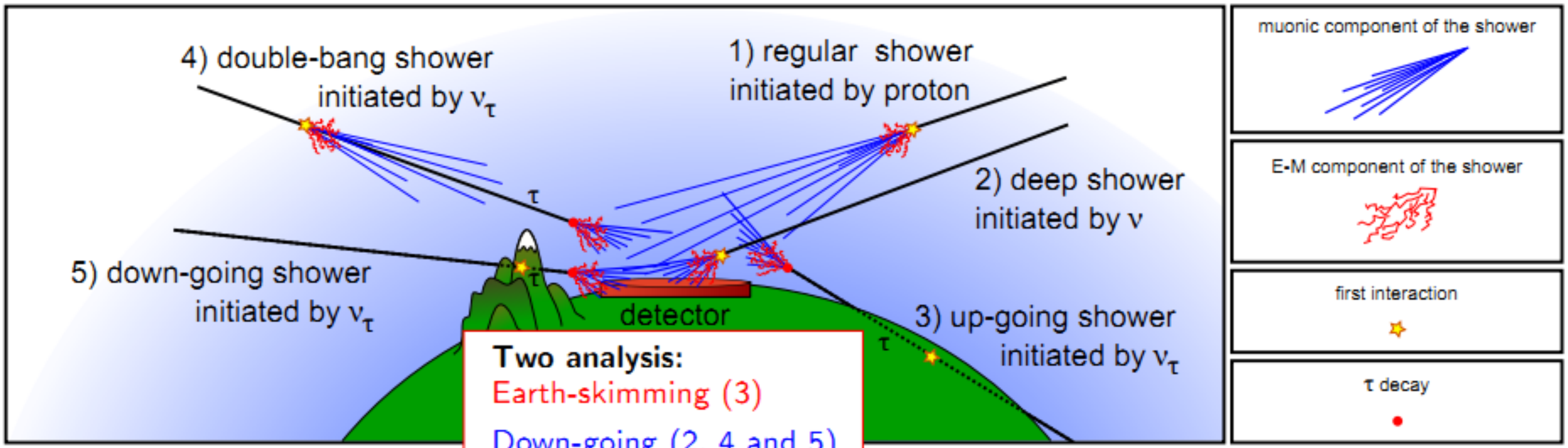
Letessier-Selvon A 2001 *AIP Conf. Proc.* **566** 157 (*Preprint* astro-ph/0009444)

Fargion D 2002 *Astrophys. J.* **570** 909 (*Preprint* astro-ph/0002453)

Fargion D 2003 *Proc. Int. Conf on Neutrino Telescopes, Venice* vol 2, pp 433–55 (*Preprint* hep-ph/0306238)

$$p + \gamma_{CMB} \rightarrow \pi \rightarrow \nu$$

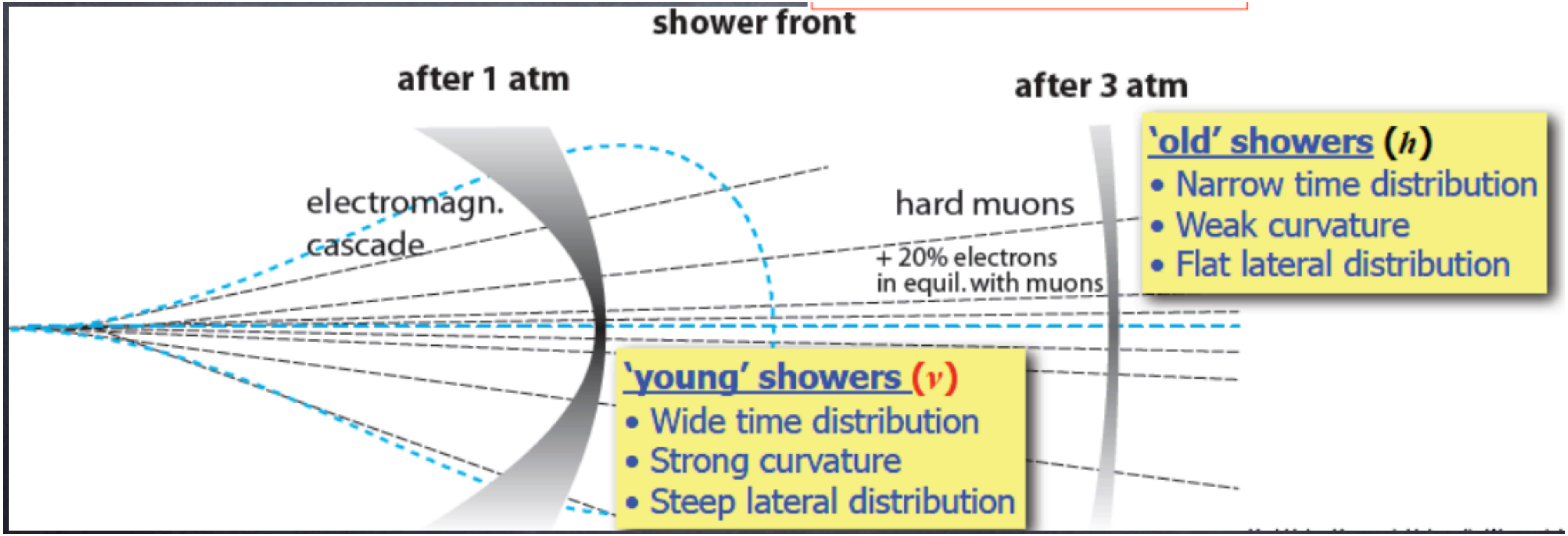




Two analysis:
Earth-skimming (3)
Down-going (2, 4 and 5)

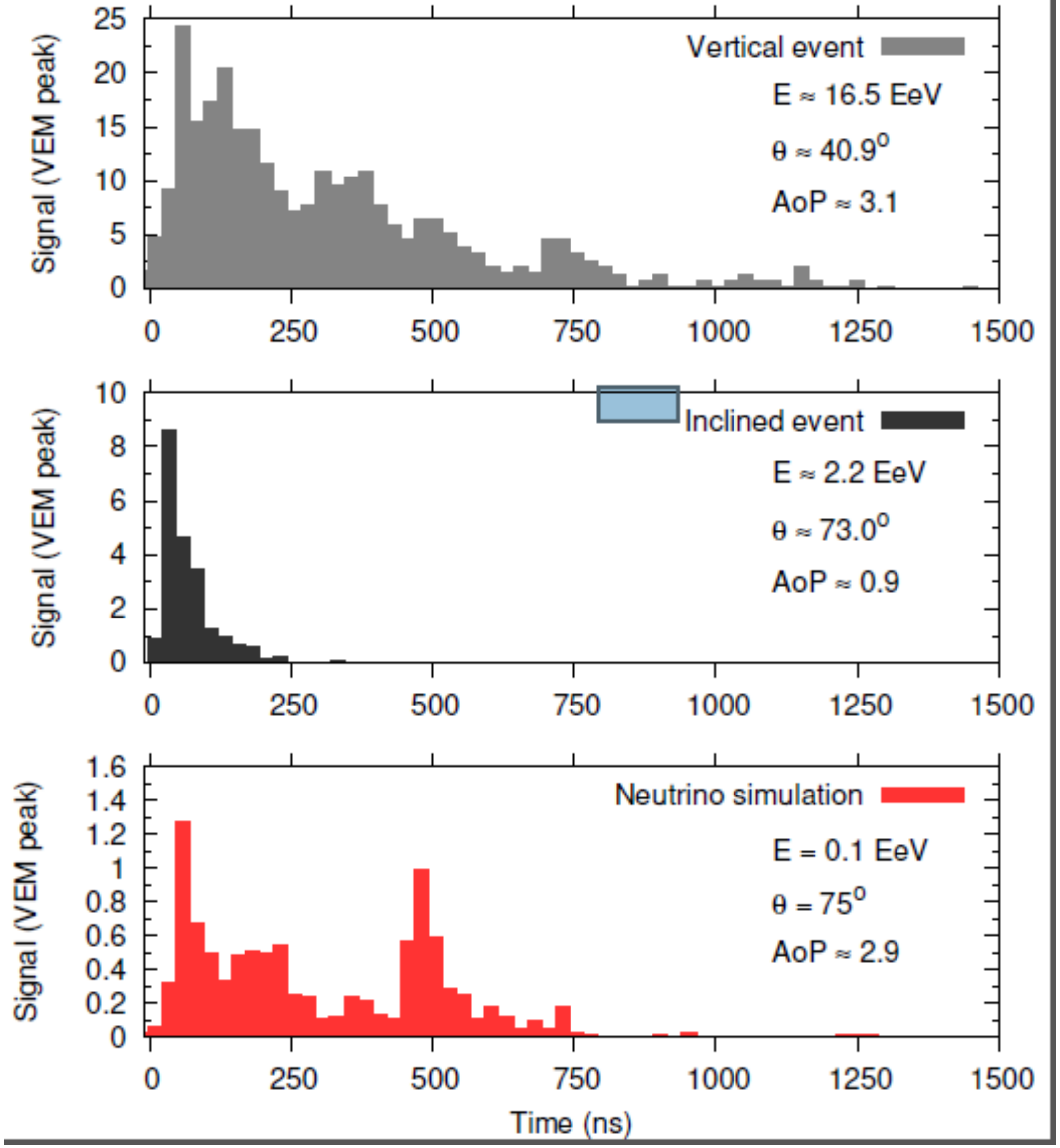
Search Method for neutrinos

Look for inclined, BUT young, showers



'old' showers (h)
- Narrow time distribution
- Weak curvature
- Flat lateral distribution

'young' showers (ν)
- Wide time distribution
- Strong curvature
- Steep lateral distribution


Vertical event
E ≈ 16.5 EeV
θ ≈ 40.9°
AoP ≈ 3.1
Inclined event
E ≈ 2.2 EeV
θ ≈ 73.0°
AoP ≈ 0.9
Neutrino simulation
E = 0.1 EeV
θ = 75°
AoP ≈ 2.9
Signal (VEM peak)
Time (ns)
0
250
500
750
1000
1250
1500
25
20
15
10
5
0
10
8
6
4
2
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2

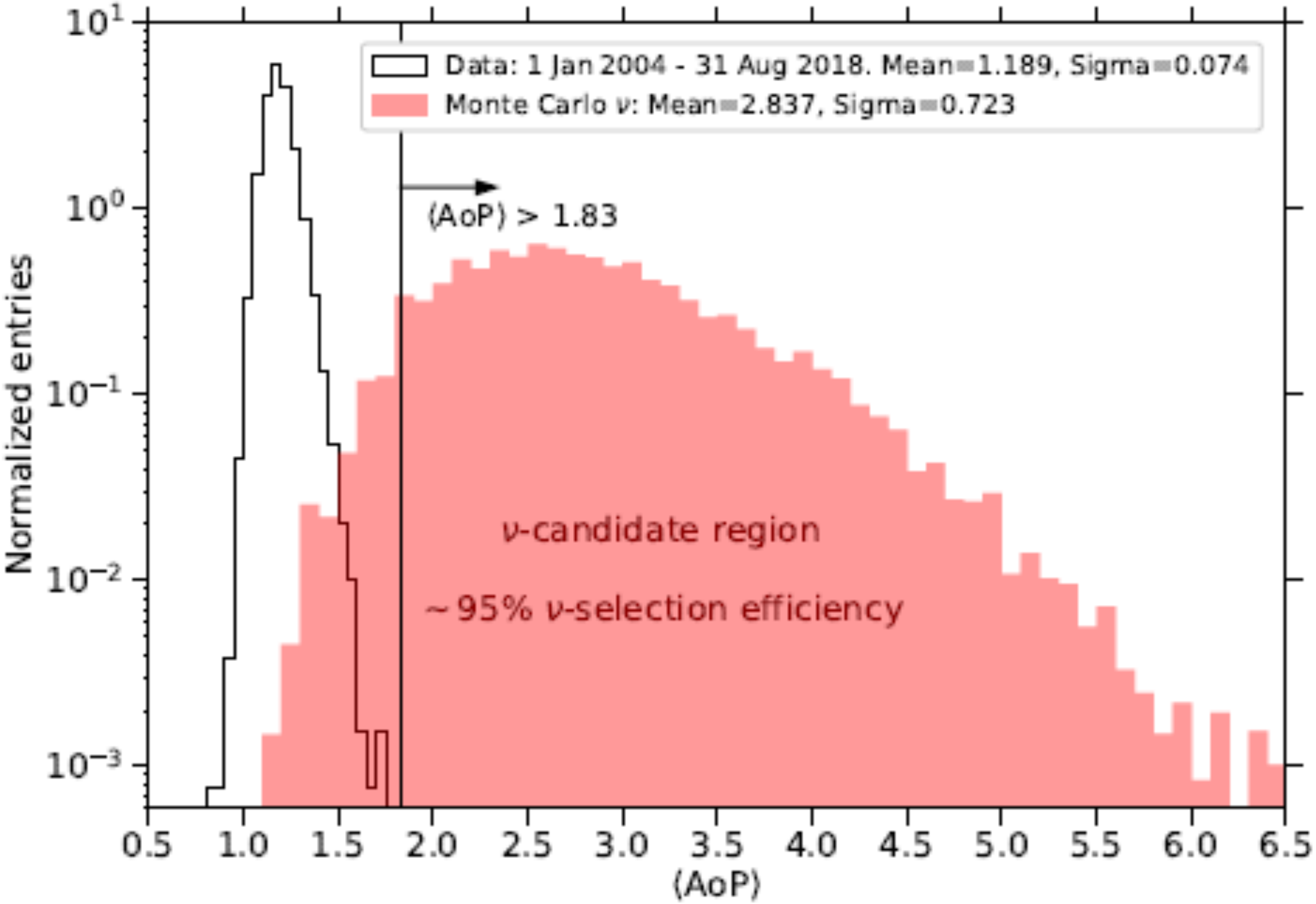


Figure 1. Distribution of ⟨AoP⟩ after the Earth-skimming inclined selection. Black histogram: full data set up to 31 August 2018. Red-shaded histogram: Monte Carlo simulated ES ν_τ events.

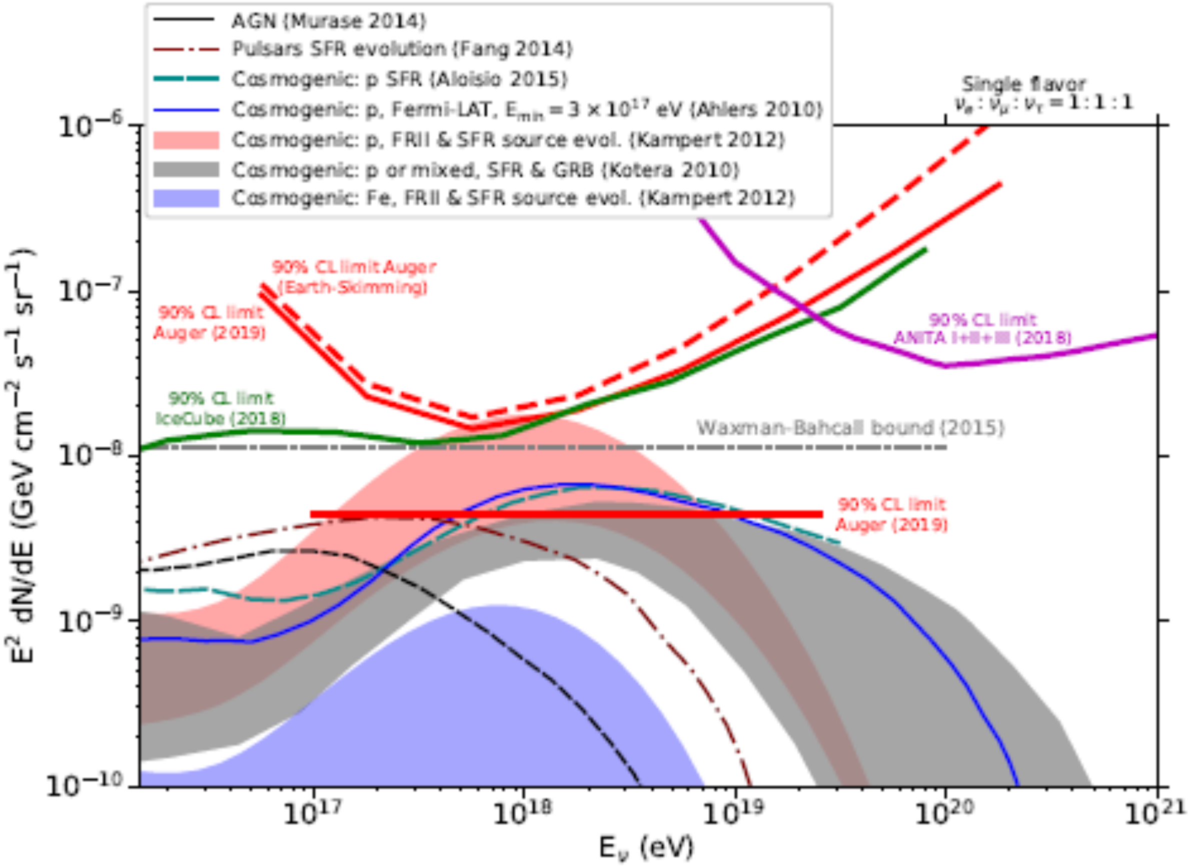
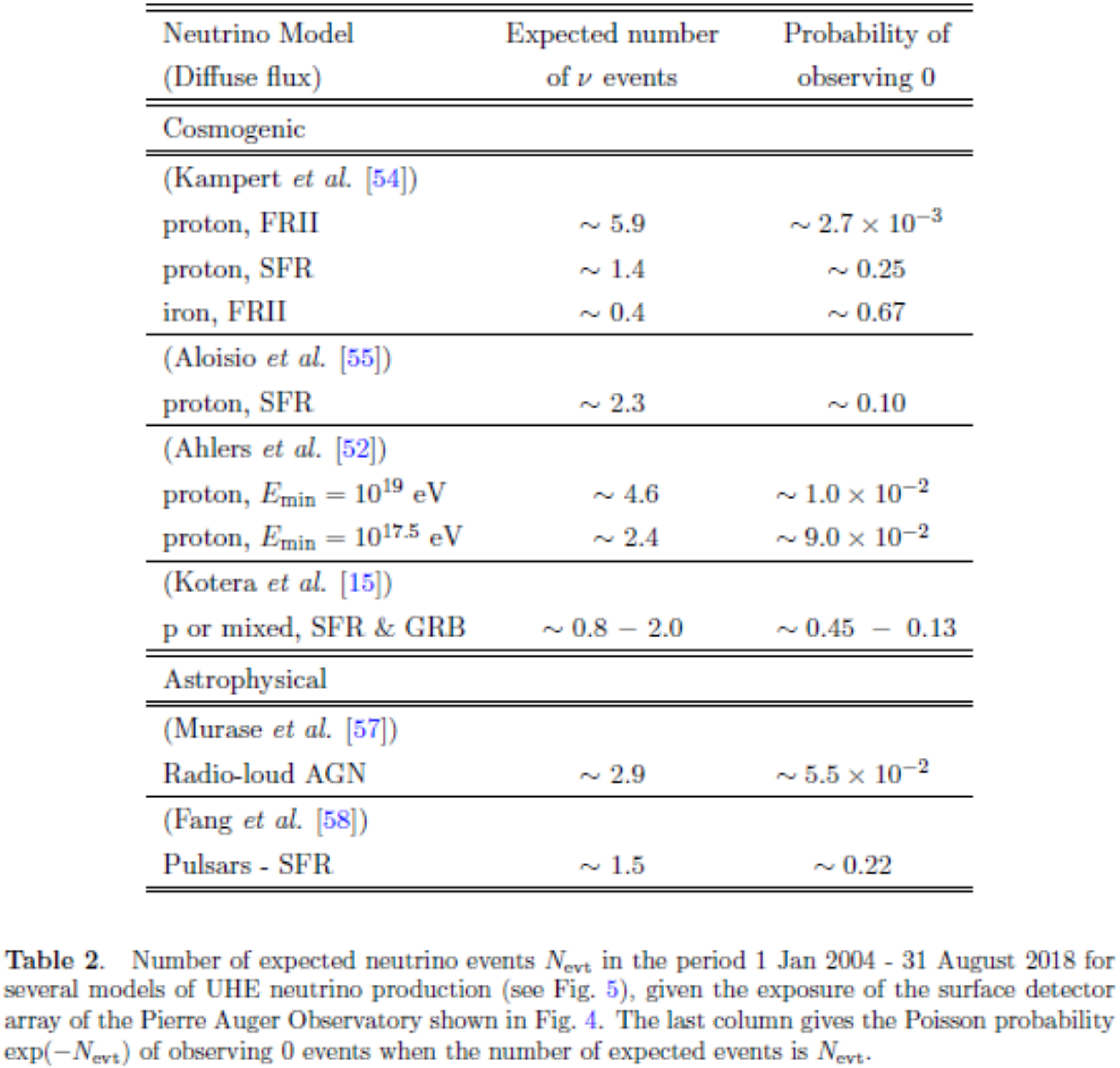


Figure 5. Pierre Auger Observatory upper limit (90% C.L.) to the normalization k of the diffuse flux of UHE neutrinos $\phi_\nu = k\ E_\nu^{-2}$ as given in Eqs. (4.2) and (4.3) (solid straight red line). Also plotted are the upper limits to the normalization of the diffuse flux (differential limits) when integrating the denominator of Eq. (4.2) in bins of width 0.5 in $\log_{10} E_\nu$ (solid red line - Auger all channels and flavours; dashed red line - Auger Earth-skimming ν_τ only). The differential limits obtained by IceCube [28] (solid green) and ANITAI+II+III [27] (solid dark magenta) are also shown. The expected neutrino fluxes for several cosmogenic [15, 52, 54, 55] and astrophysical models of neutrino production, as well as the Waxman-Bahcall bound [56] are also plotted. All limits and fluxes are converted to single flavor.



Neutrino Model (Diffuse flux)	Expected number of ν events	Probability of observing 0
Cosmogenic		
(Kampert *et al.* [54])		
proton, FRII	~ 5.9	$\sim 2.7 \times 10^{-3}$
proton, SFR	~ 1.4	~ 0.25
iron, FRII	~ 0.4	~ 0.67
(Aloisio *et al.* [55])		
proton, SFR	~ 2.3	~ 0.10
(Ahlers *et al.* [52])		
proton, $E_{\rm min} = 10^{19}$ eV	~ 4.6	$\sim 1.0 \times 10^{-2}$
proton, $E_{\rm min} = 10^{17.5}$ eV	~ 2.4	$\sim 9.0 \times 10^{-2}$
(Kotera *et al.* [15])		
p or mixed, SFR & GRB	$\sim 0.8 - 2.0$	$\sim 0.45 - 0.13$
Astrophysical		
(Murase *et al.* [57])		
Radio-loud AGN	~ 2.9	$\sim 5.5 \times 10^{-2}$
(Fang *et al.* [58])		
Pulsars - SFR	~ 1.5	~ 0.22

Table 2. Number of expected neutrino events $N_{\rm evt}$ in the period 1 Jan 2004 - 31 August 2018 for several models of UHE neutrino production (see Fig. 5), given the exposure of the surface detector array of the Pierre Auger Observatory shown in Fig. 4. The last column gives the Poisson probability $\exp(-N_{\rm evt})$ of observing 0 events when the number of expected events is $N_{\rm evt}$.

Searching neutrinos in coincidence with other ‘happenings’

1. GW170817 Superbly positioned for Auger neutrino searches
-but only upper limits – joint paper with ~4000 others!

2. **TXS0506+056**
Again no neutrinos seen. Joint paper with IceCube, ANTARES and Auger

No coincidences - YET

The Astrophysical Journal Letters, 850:L35 (18pp), 2017 December 1
https://doi.org/10.3847/2041-8213/aa9aed

Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory

ANTARES Collaboration, IceCube Collaboration, The Pierre Auger Collaboration,
and LIGO Scientific Collaboration and Virgo Collaboration
(See the end matter for the full list of authors.)

Received 2017 October 15; revised 2017 November 9; accepted 2017 November 10; published 2017 November 29

Abstract

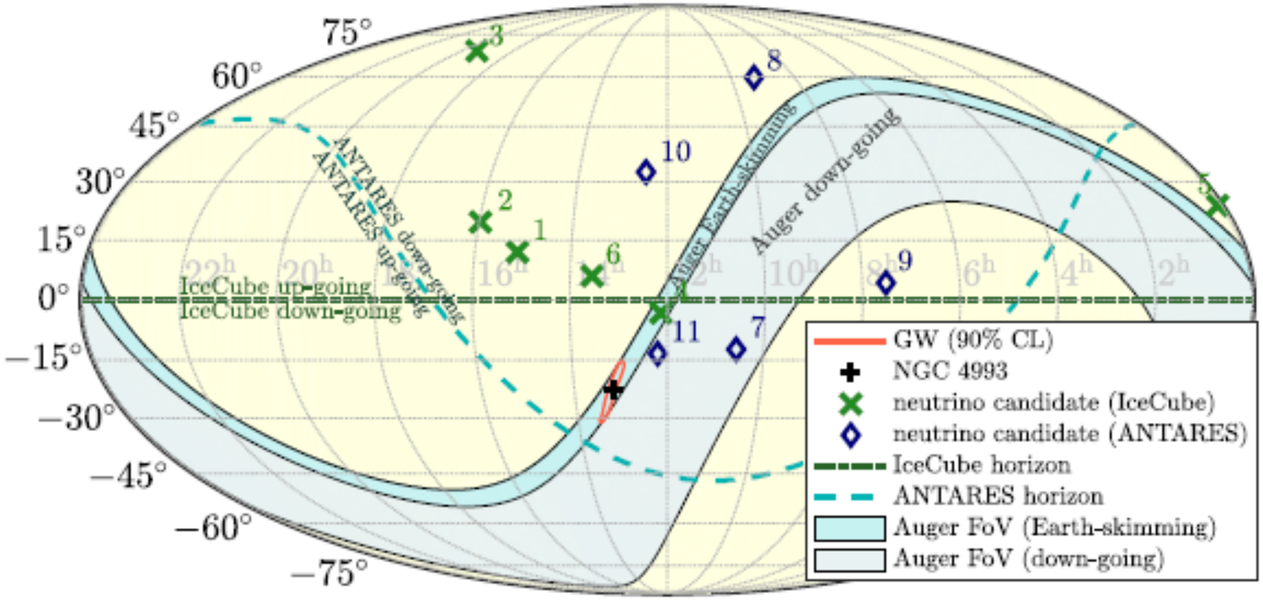
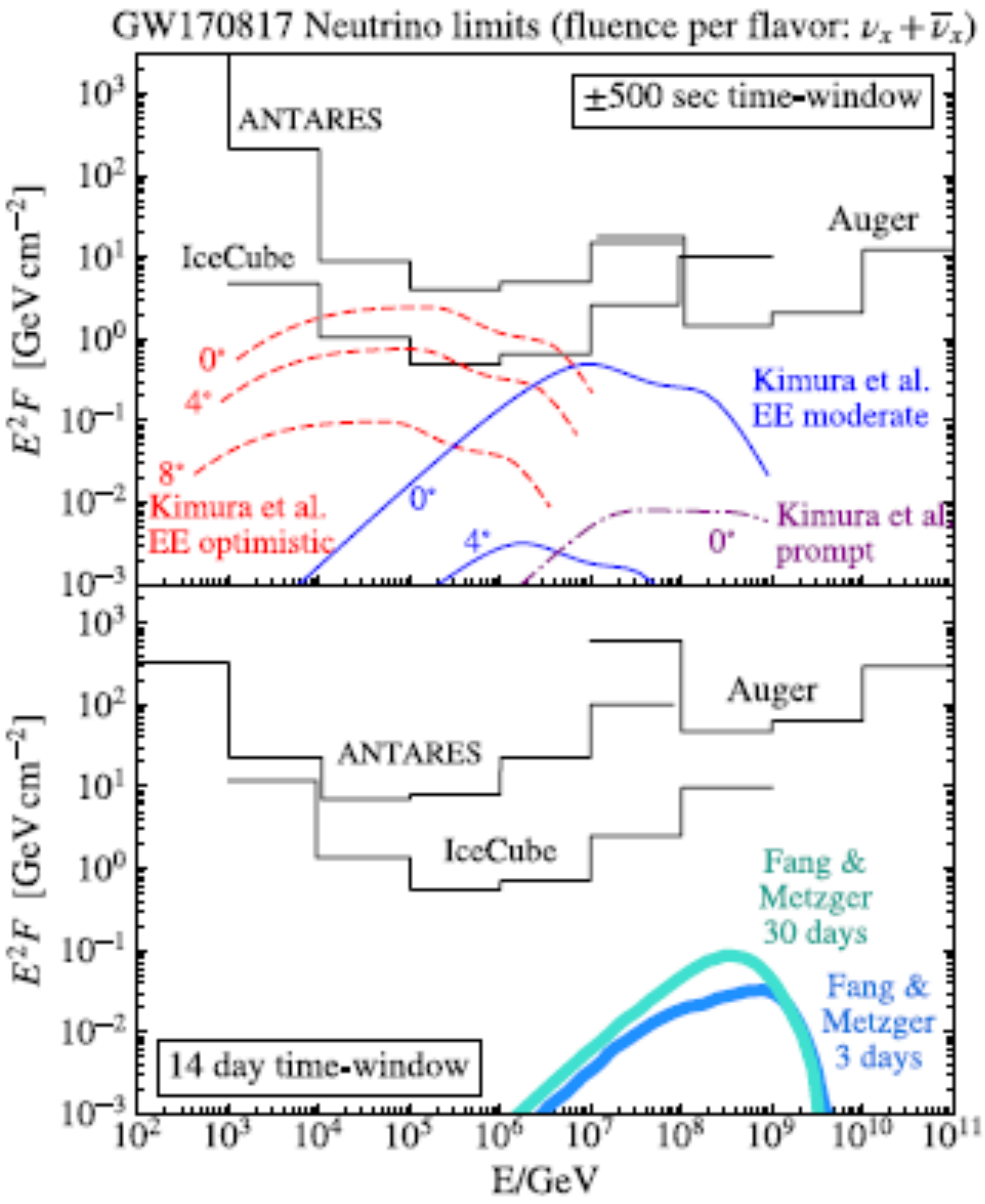


Figure 1. Localizations and sensitive sky areas at the time of the GW event in equatorial coordinates: GW 90% credible-level localization (red contour; Abbott et al. 2017b), direction of NGC 4993 (black plus symbol; Coulter et al. 2017b), directions of IceCube's and ANTARES's neutrino candidates within 500 s of the merger (green crosses and blue diamonds, respectively), ANTARES's horizon separating down-going (north of horizon) and up-going (south of horizon) neutrino directions (dashed blue line), and Auger's fields of view for Earth-skimming (darker blue) and down-going (lighter blue) directions. IceCube's up-going and down-going directions are on the northern and southern hemispheres, respectively. The zenith angle of the source at the detection time of the merger was 73°.8 for ANTARES, 66°.6 for IceCube, and 91°.9 for Auger.


GW170817 Neutrino limits (fluence per flavor: $\nu_x + \overline{\nu}_x$)
±500 sec time-window
ANTARES
IceCube
Auger
Kimura et al. EE moderate
Kimura et al. EE optimistic
Kimura et al. prompt
0°
4°
8°
E^2F [GeV cm^{-2}]
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
14 day time-window
Fang & Metzger 30 days
Fang & Metzger 3 days
E/GeV
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}

Search for photons

Main source is decay of neutral pions

Or from exotic ways of producing UHECR

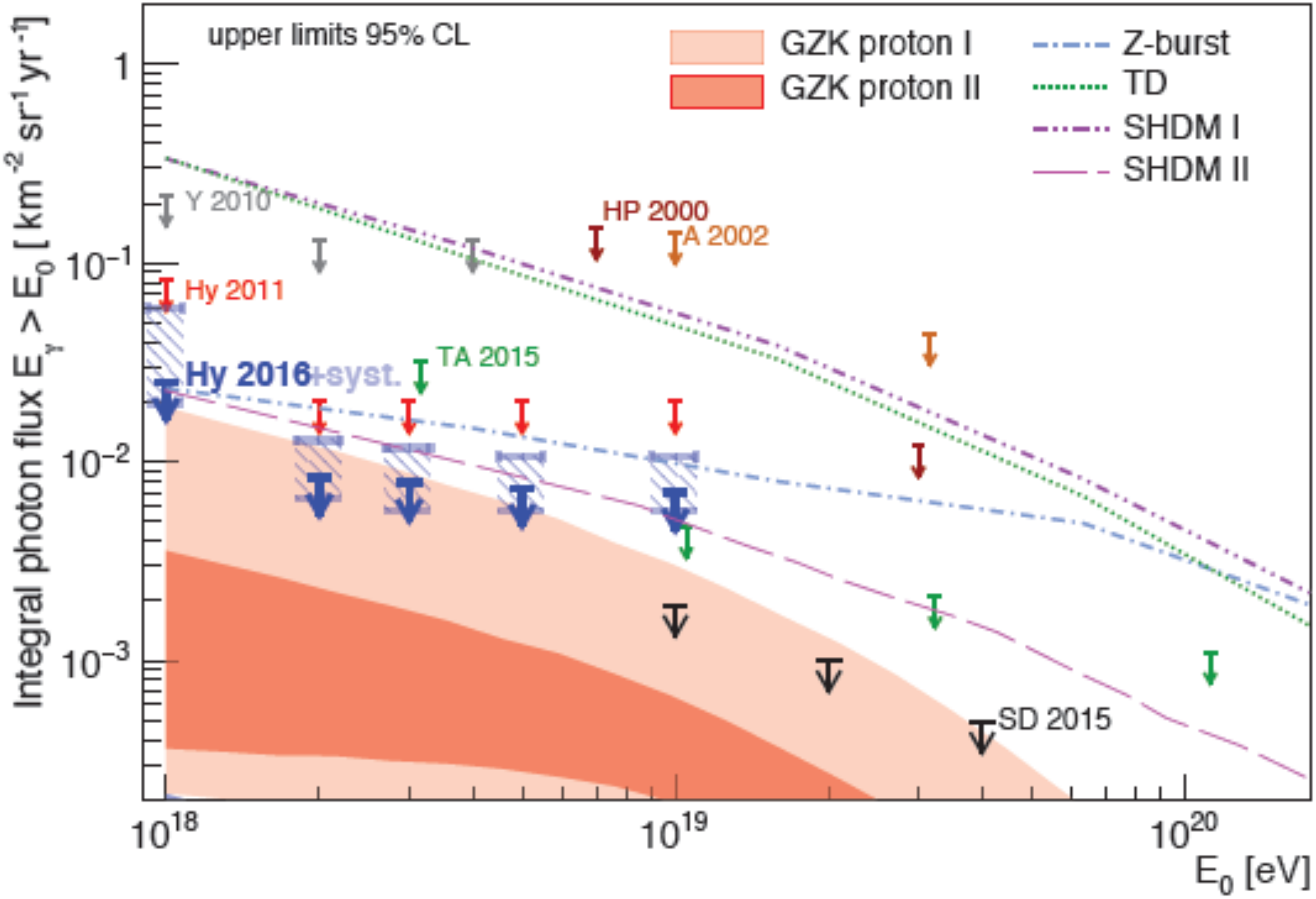
Showers with

lateral distribution function steeper unusually steep

X_{max} unusually deep

Shower front unusually curved

Risetime unusually slow


upper limits 95% CL
GZK proton I
GZK proton II
Z-burst
TD
SHDM I
SHDM II
Y 2010
HP 2000
A 2002
Hy 2011
Hy 2016
+syst.
TA 2015
SD 2015
Integral photon flux E_γ > E_0 [km^-2 sr^-1 yr^-1]
1
10^-1
10^-2
10^-3
10^18
10^19
10^20
E_0 [eV]

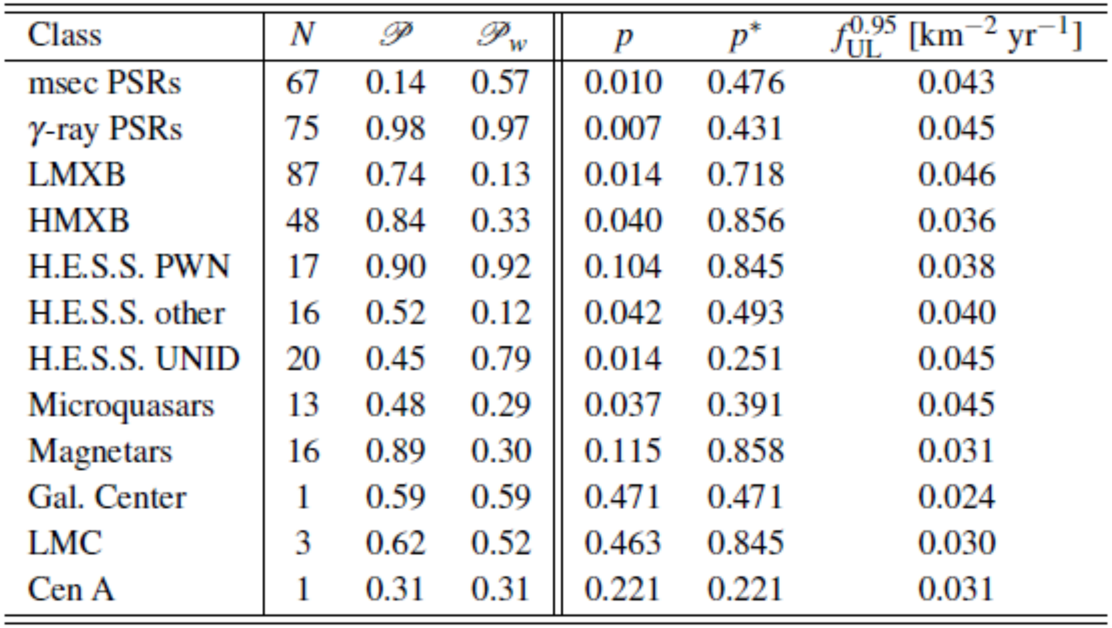
Limits rule out exotic models

Beginning to test models where protons dominate

No signals from specific objects

Work continuing to devise more clever methods

Searches from specific sources



Class	N	$\mathscr{P}$	$\mathscr{P}_w$	p	p^*	$f_{\mathrm{UL}}^{0.95}$ [km^{-2} yr^{-1}]
msec PSRs	67	0.14	0.57	0.010	0.476	0.043
γ-ray PSRs	75	0.98	0.97	0.007	0.431	0.045
LMXB	87	0.74	0.13	0.014	0.718	0.046
HMXB	48	0.84	0.33	0.040	0.856	0.036
H.E.S.S. PWN	17	0.90	0.92	0.104	0.845	0.038
H.E.S.S. other	16	0.52	0.12	0.042	0.493	0.040
H.E.S.S. UNID	20	0.45	0.79	0.014	0.251	0.045
Microquasars	13	0.48	0.29	0.037	0.391	0.045
Magnetars	16	0.89	0.30	0.115	0.858	0.031
Gal. Center	1	0.59	0.59	0.471	0.471	0.024
LMC	3	0.62	0.52	0.463	0.845	0.030
Cen A	1	0.31	0.31	0.221	0.221	0.031

Table 1: Combined unweighted probabilities $\mathscr{P}$ and weighted Probabilities $\mathscr{P}_w$ for the 12 target sets [6].

Hadronic Interactions

Some success

- and of some problems

Bristol: Conference on Very High Energy Interactions, January 1963

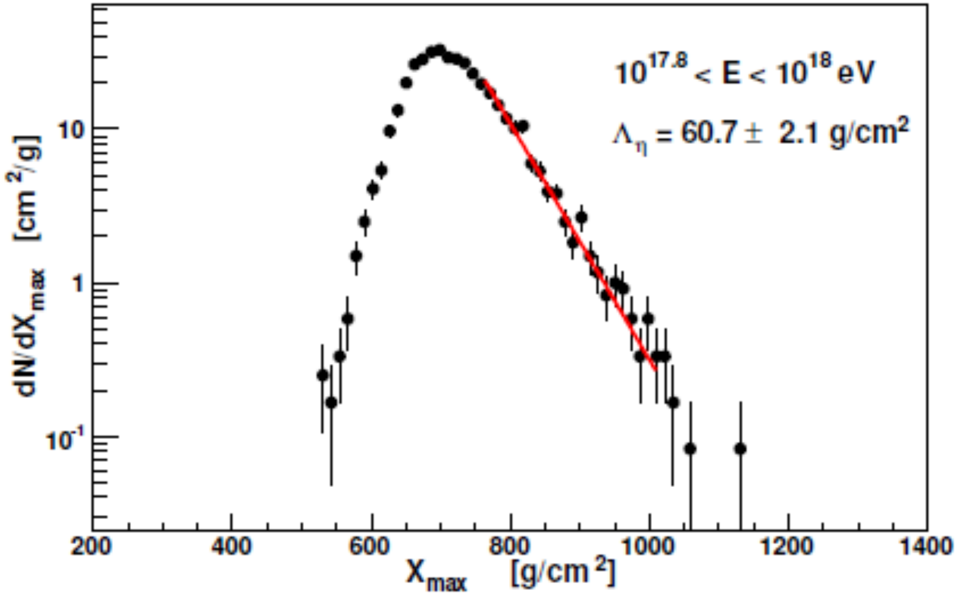
Trying to get information about particle interactions from studying Extensive Air Showers is like trying to get information about the workings of the British Cabinet by reading the Daily Mirror

J G Wilson

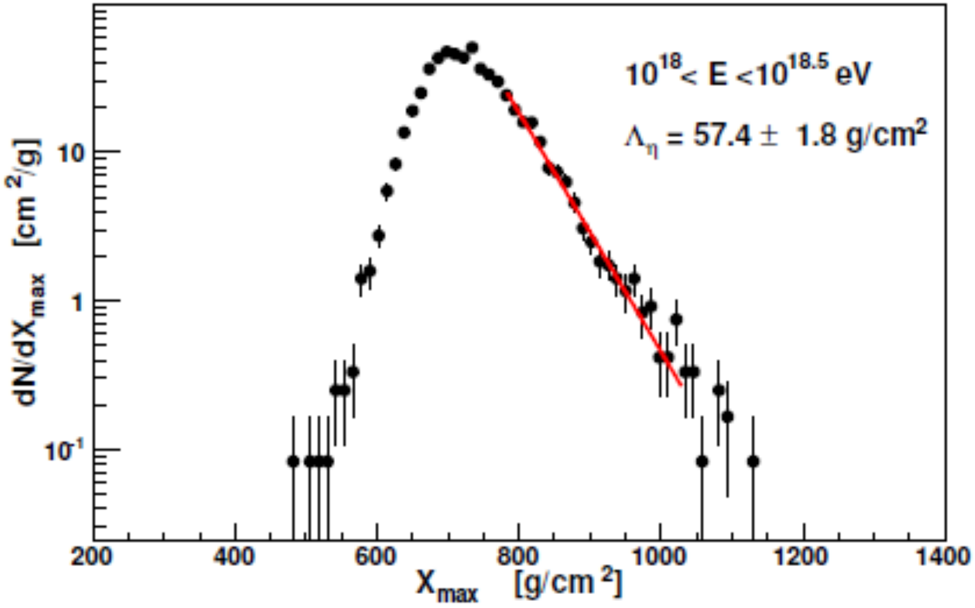
AGS
33 GeV
CERN PS
28 GeV

Distribution of X_{max} for two energy ranges ICRC 2015

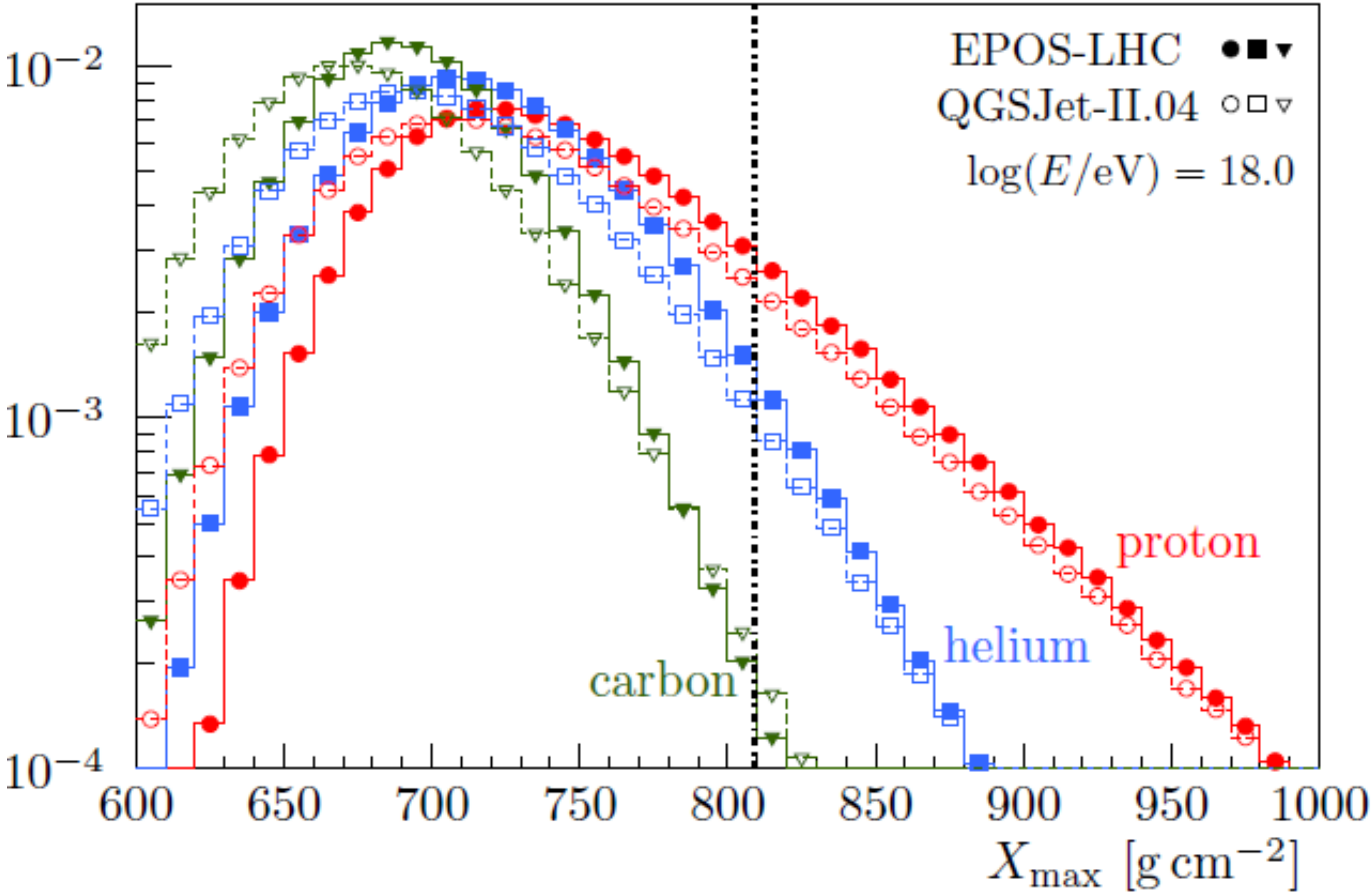
Λ_η, the attenuation length, is found from the 20% most penetrating events



$\underline{1196}$/18090



$\underline{1384}$/21270


EPOS-LHC ● ■ ▼
QGSJet-II.04 ○ □ ▽
$\log(E/\mathrm{eV}) = 18.0$
proton
helium
carbon
10^{-2}
10^{-3}
10^{-4}
600
650
700
750
800
850
900
950
1000
X_{max} [g cm^{-2}]

Relationship between Λ_η and proton-air cross-section

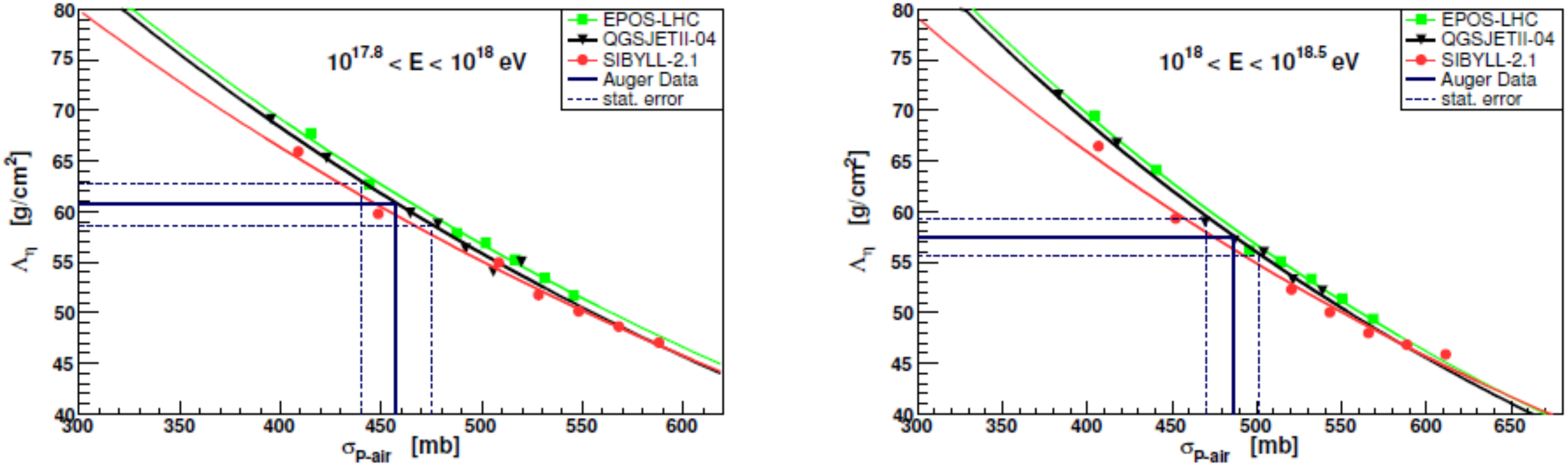
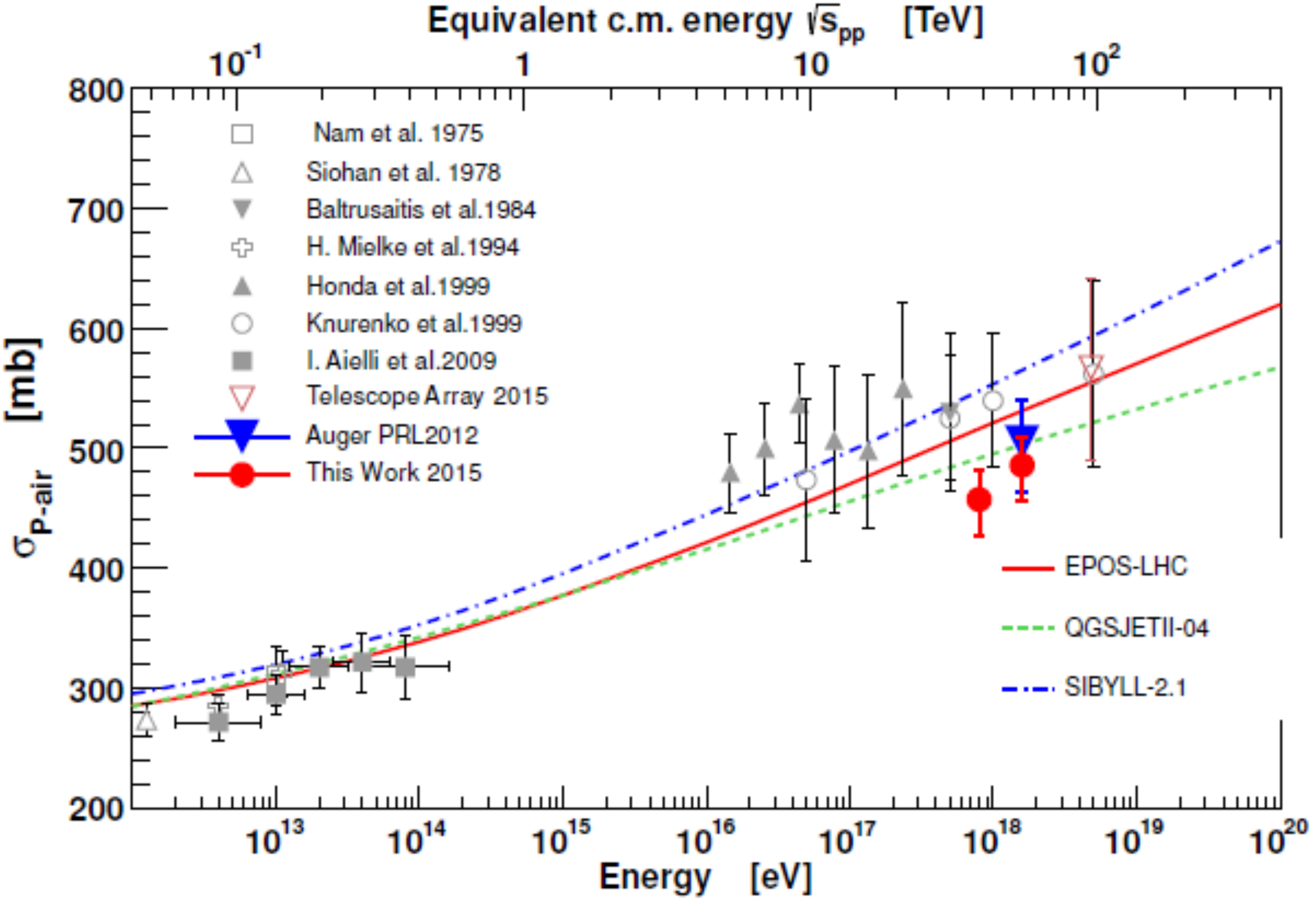


Figure 2: Conversion of Λ_η to $\sigma_{p-\mathrm{air}}$. The simulations includes all detector resolution effects, while the data is corrected for acceptance effects. The solid and dashed lines show the Λ_η measurement and its projection to $\sigma_{p-\mathrm{air}}$ as derived using the average of all models.

25% Helium contamination: σ reduced by -17 and – 16 mb

Proton-air cross-section as function of energy

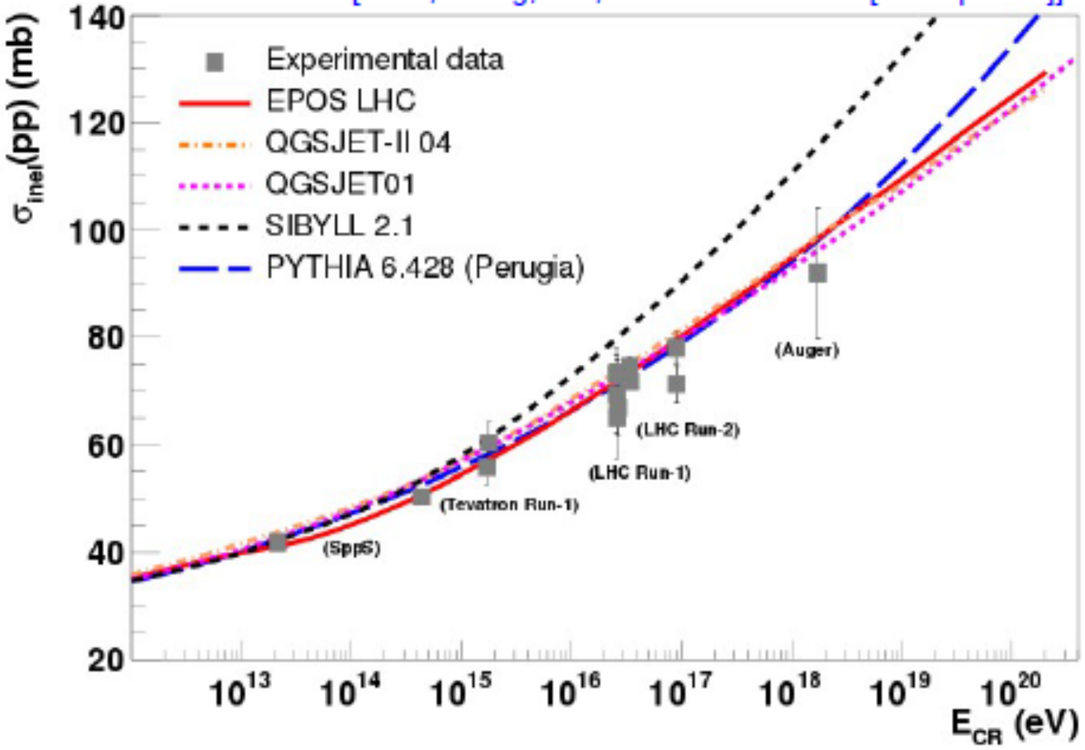


Impact of 25% He is included as systematic uncertainty (- 16 mb)

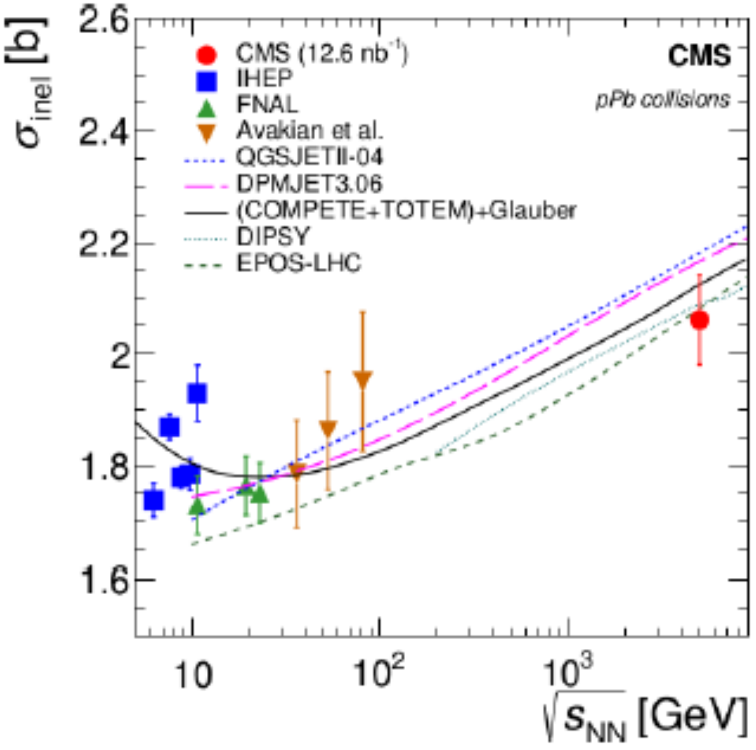
Photons have been shown to be < 0.5% at energies of interest:

contamination would raise σ by ~ 4.5 mb

Inelastic p-p, p-Pb cross sections (LHC)



[Dd'E,Pierog,Sun, arXiv:1809.06406 [astro-ph.HE]]



- All retuned MCs predictions are now ~consistent up to GZK cutoff.
- Measured σ(p-Pb) at 5.16 TeV confirms Glauber-scaling of σ(p-p) to σ(p-Air)
- Measured σ(p-p) at LHC, slightly below pre-LHC MC predictions, leads to reduced σ(p-Air): Deeper shower X_{max} position.

‘The Muon Problem’

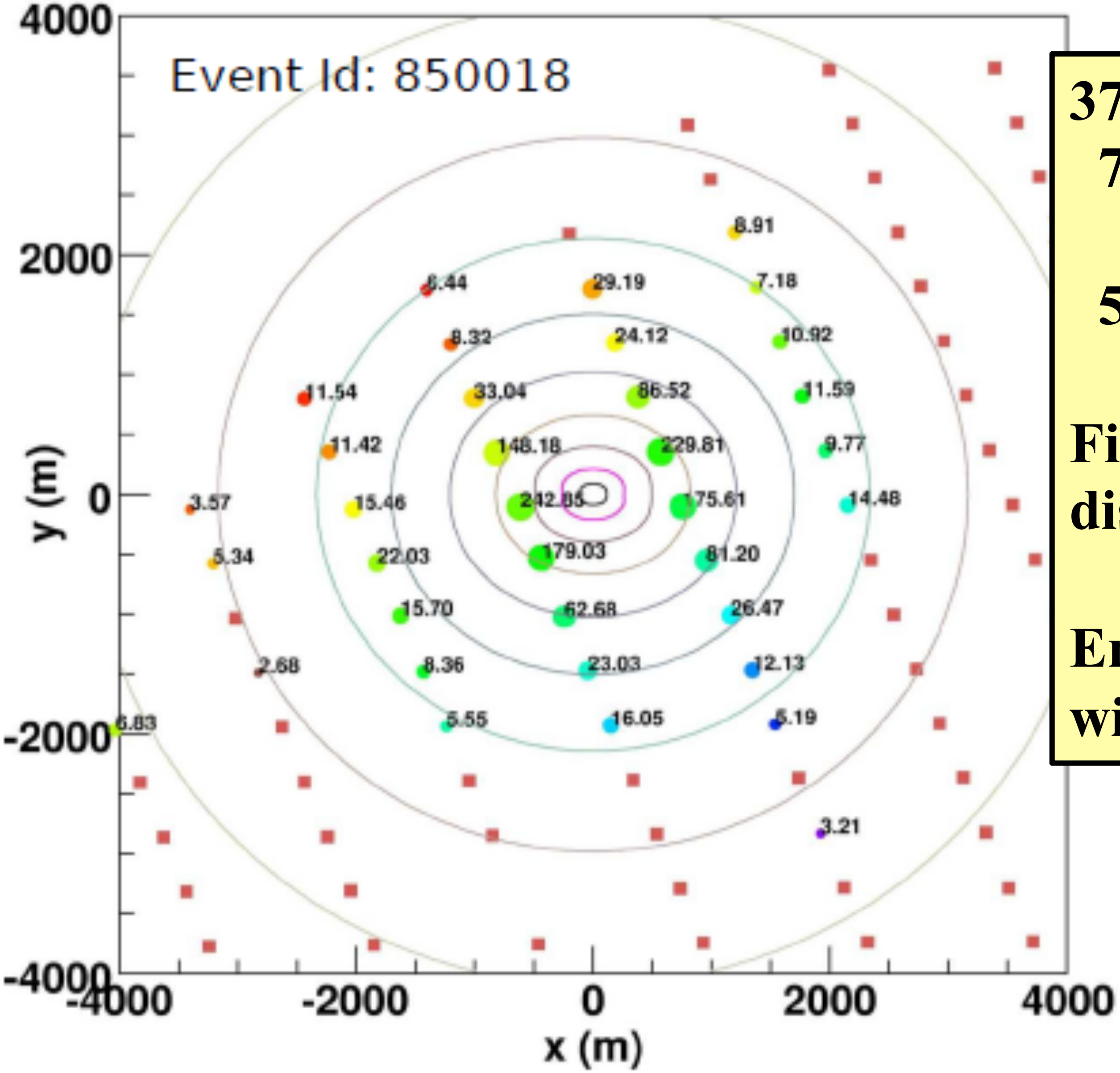
$$N_\mu = A \left(\frac{E/A}{\epsilon_c} \right)^\beta ,$$

$\beta = 0.9$

ε_c = energy at which pion interaction becomes less probable than decay (~10 GeV)

N_μ increases with energy
increases with A at given energy

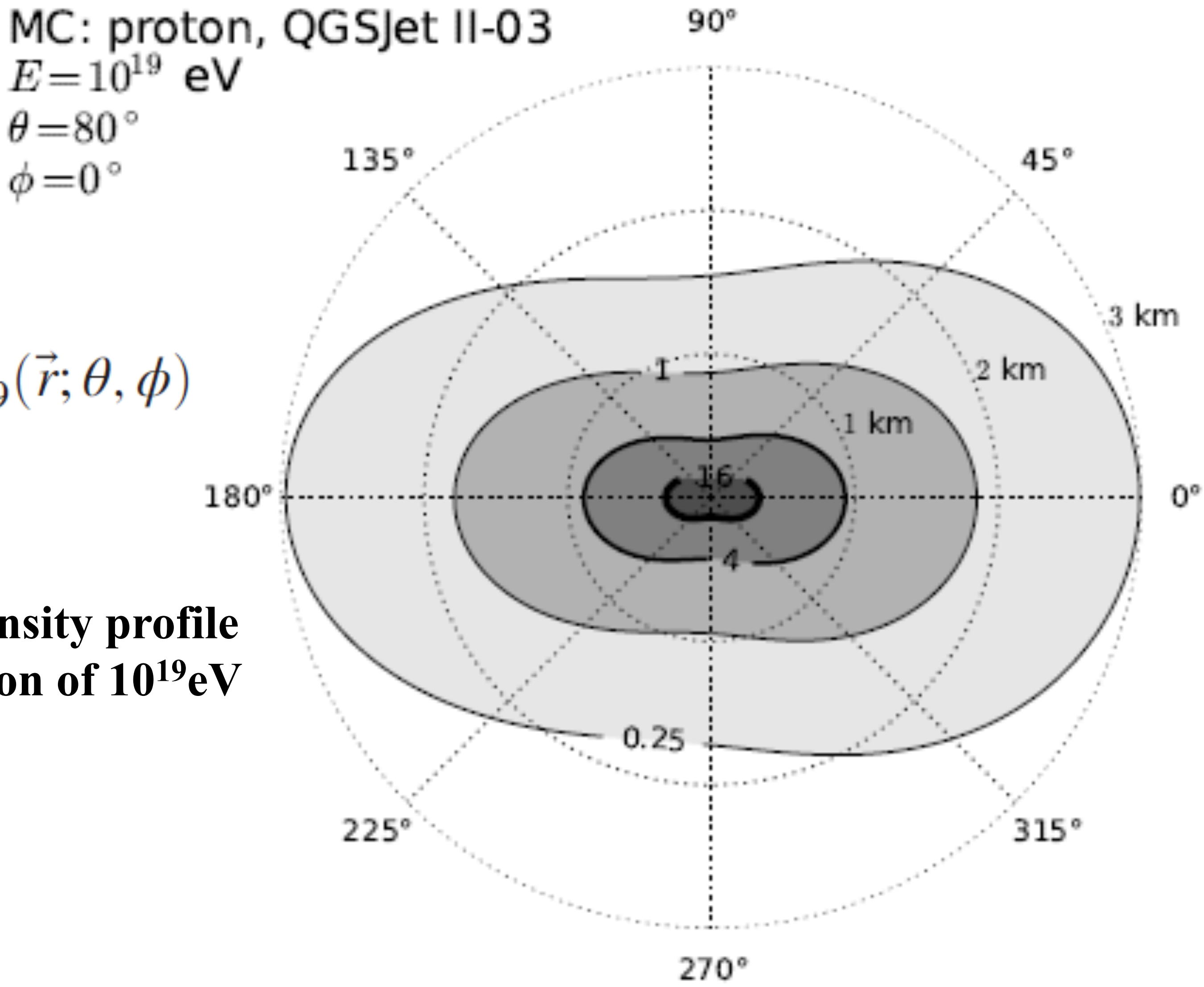
Inclined showers are useful to test models – muons dominate



37 stations
71°
3200 g cm^{-2}
54 EeV

Fit made to density distribution

Energy measured with ~20 % accuracy



$$\rho_\mu(\vec{r}) = N_{19}\rho_{\mu,19}(\vec{r};\theta,\phi)$$

Average muon density profile of simulated-proton of 10^{19}eV

Maps such as these are compared and fitted to the observations so that the number of muons, N_μ, can be obtained

R_μ in highly inclined events

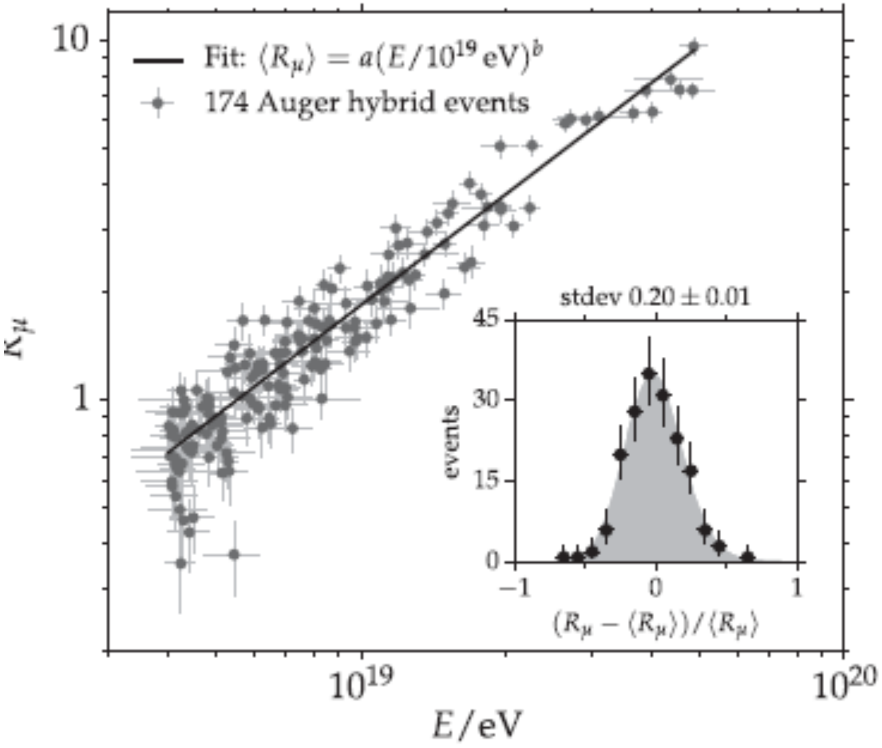
$$N_\mu = A\left(\frac{E/A}{\xi_c}\right)^\beta \qquad R_\mu = \frac{N_\mu^{data}}{N_{\mu,19}^{MC}}$$

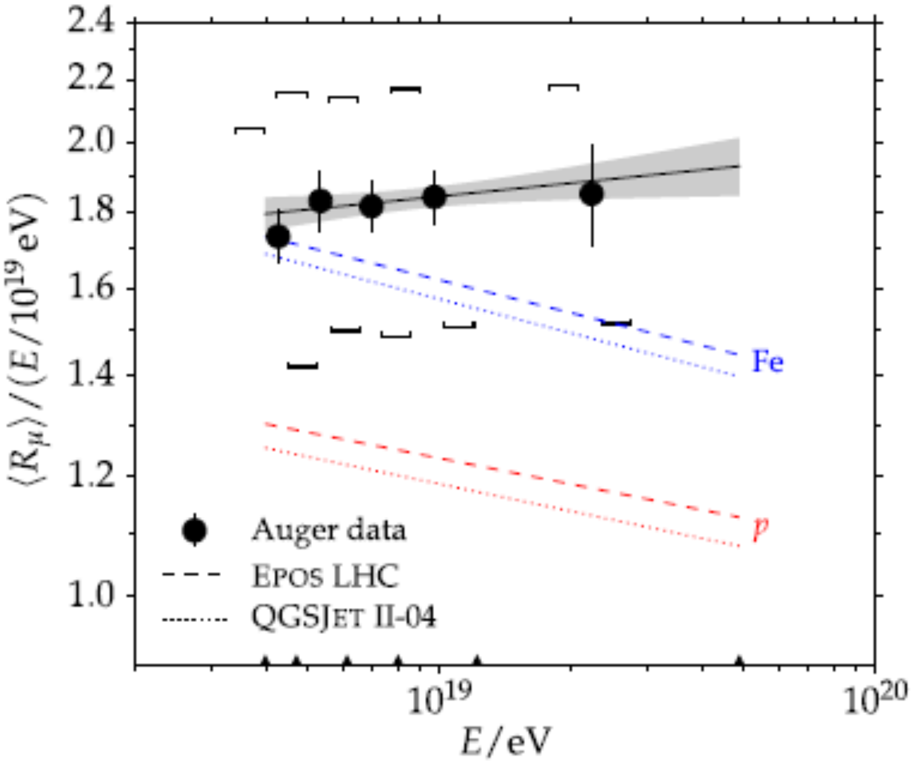
$$\langle R_\mu \rangle = a(E/10^{19}\text{ eV})^b$$

$$a = \langle R_\mu \rangle(10^{19}\text{ eV}) = (1.841 \pm 0.029 \pm 0.324(\text{sys})),$$

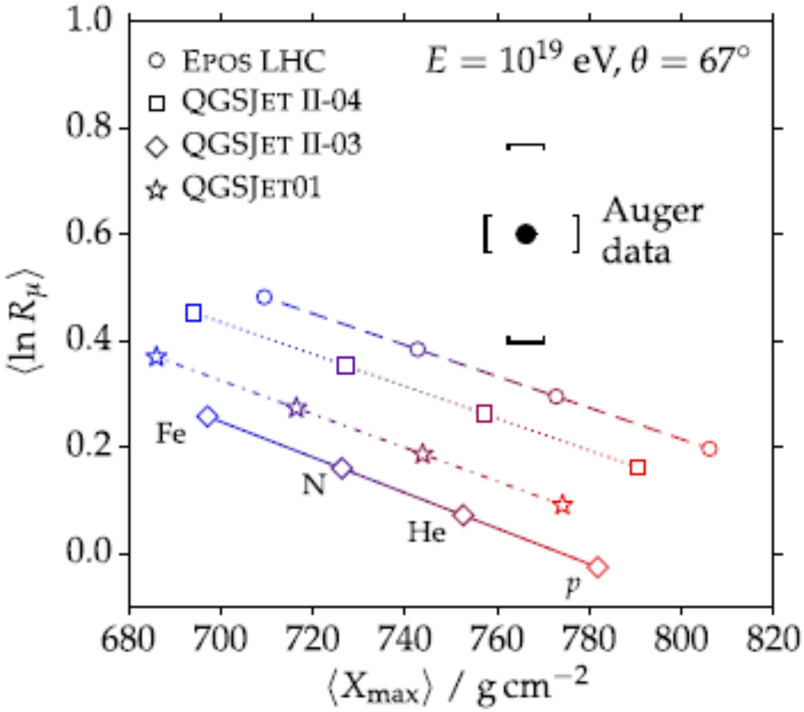
$$b = \mathrm{d}\langle \ln R_\mu \rangle/\mathrm{d}\ln E = (1.029 \pm 0.024 \pm 0.030(\text{sys})),$$

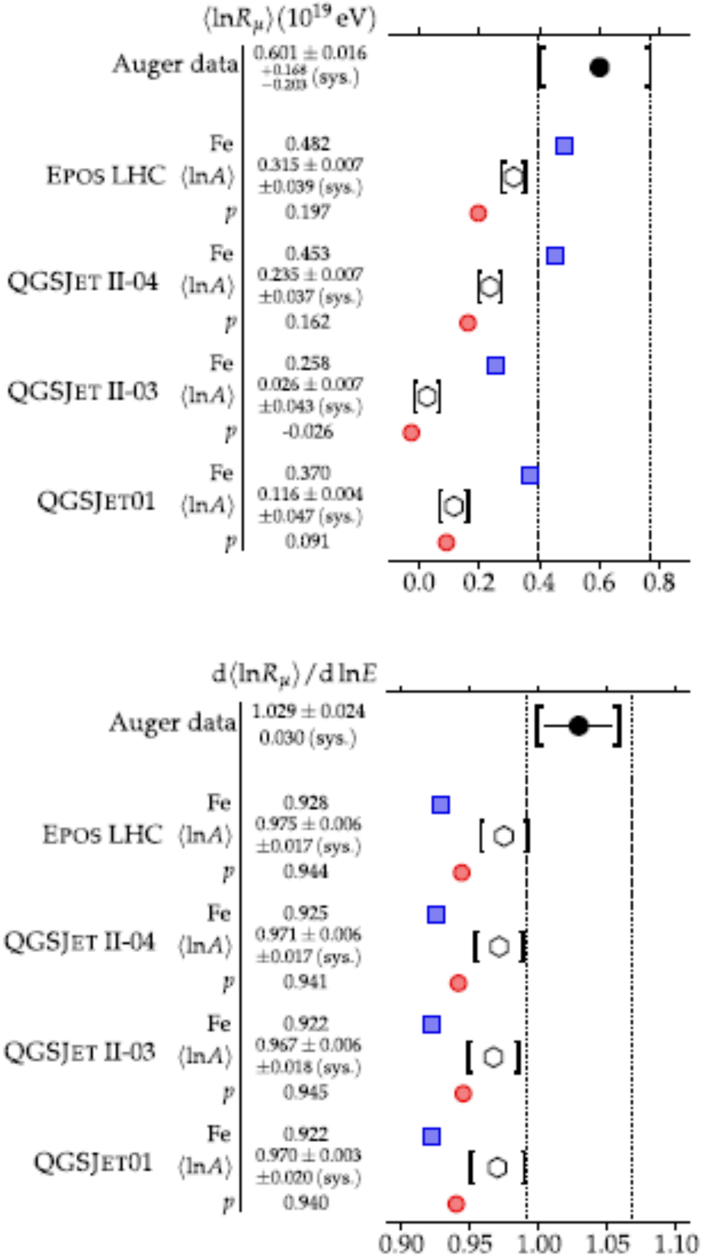
$$\sigma[R_\mu]/R_\mu = (0.136 \pm 0.015 \pm 0.033(\text{sys})).$$





Results on $\langle \ln R_\mu \rangle$

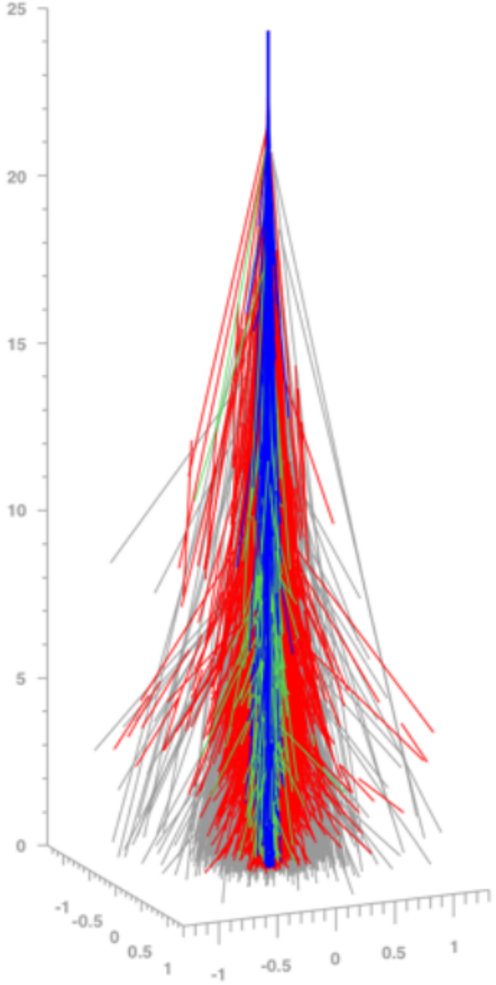




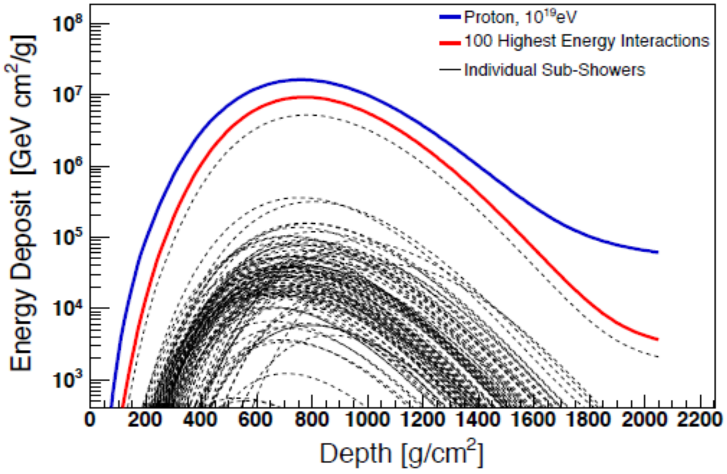
Muon deficit in sims,
and also deficit on
energy derivative (muon gain)

Predicted muon numbers are under-estimated by 30 to 80% (20% systematic)

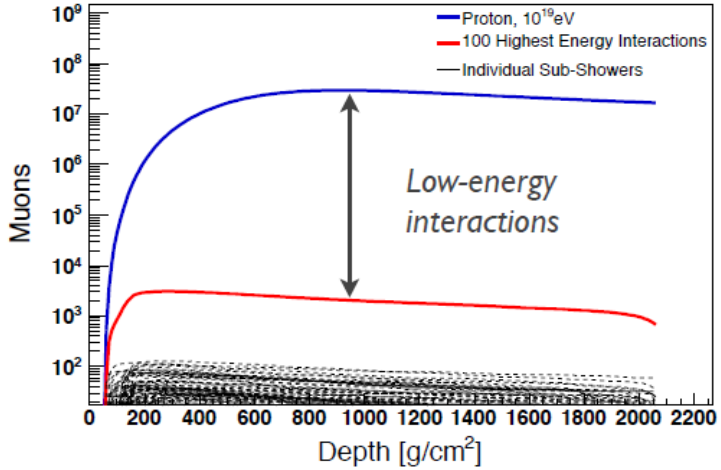
Importance of different interaction energies



Electrons



Muons



Shower particles produced i
100 interactions of highest
energy

Electrons/photons:
high-energy interactions

(Ulrich, APS 2012)

Muons/hadrons:
low-energy interactions

Muons: majority produced in low energy interactions (30-200 GeV lab.)

- Data suggest few leading neutral pions in meson interactions

$$\pi^{\pm} + p \not\to \pi^0_{\text{lead}} + X$$

Instead

$$\pi^{\pm} + p \to \rho^0_{\text{lead}} + X$$

Pion-Carbon Interactions Measured by NA61/SHINE Alexander E

NA62/SHINE

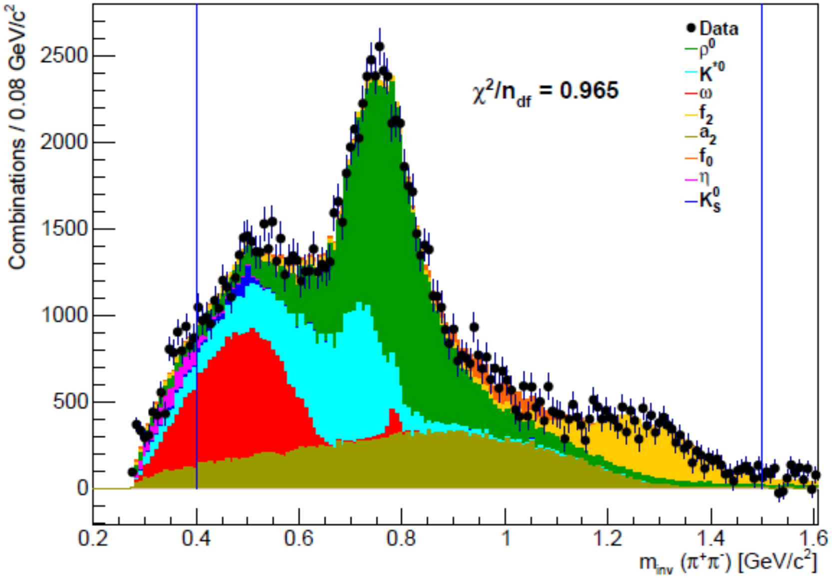


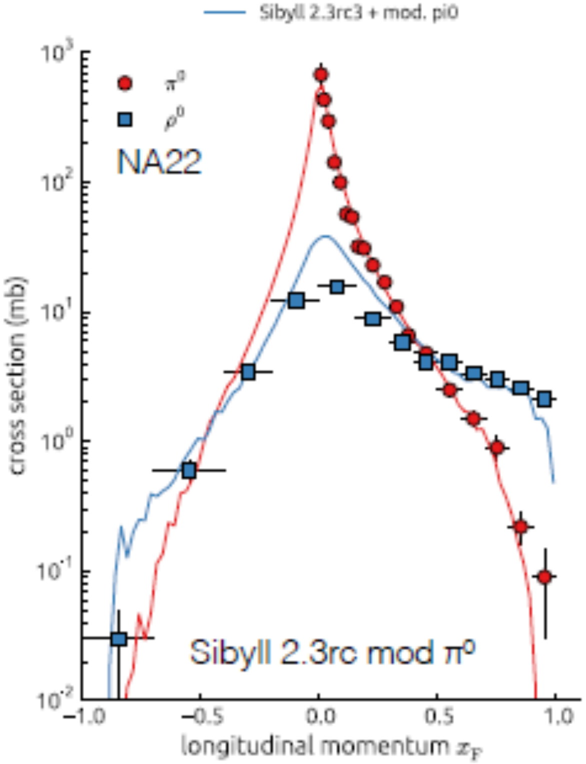
Figure 4: $\pi^+\pi^-$ mass distribution in π^-+C interactions at 158 GeV/c in the range $0.4 < x_F < 0.5$. D
error bars denote the data and the fitted resonance templates are shown as filled histograms. The
lines indicate the range of the fit.

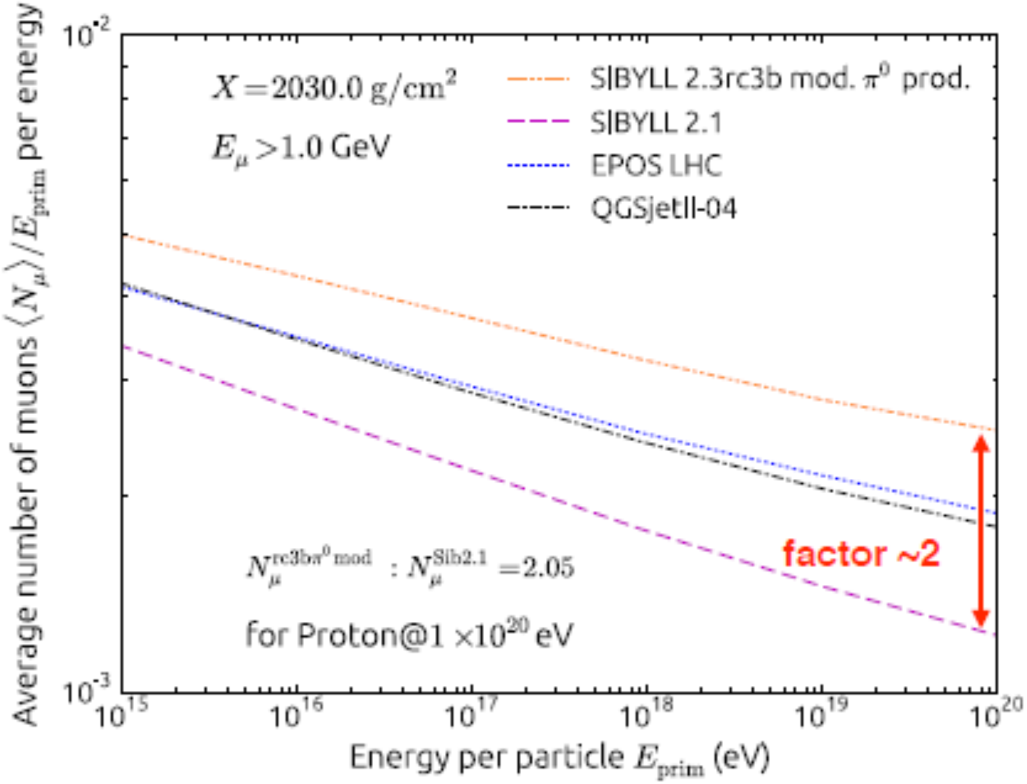
$$\rho^0 \to \pi^+ + \pi^-$$

Thus there is a channel to enhance muon production

Taking energy out of electromagnetic channel will raise depth of shower maximum - slightly lighter primaries

Rho production in pion-proton interactions (iii)



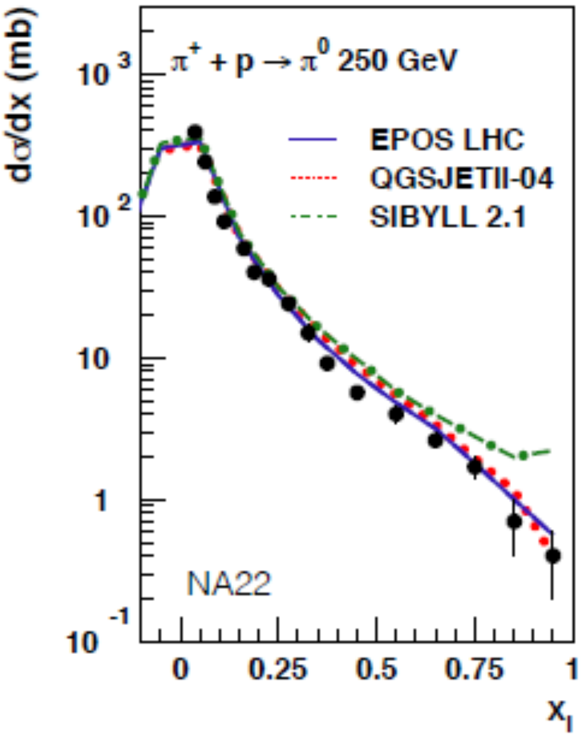


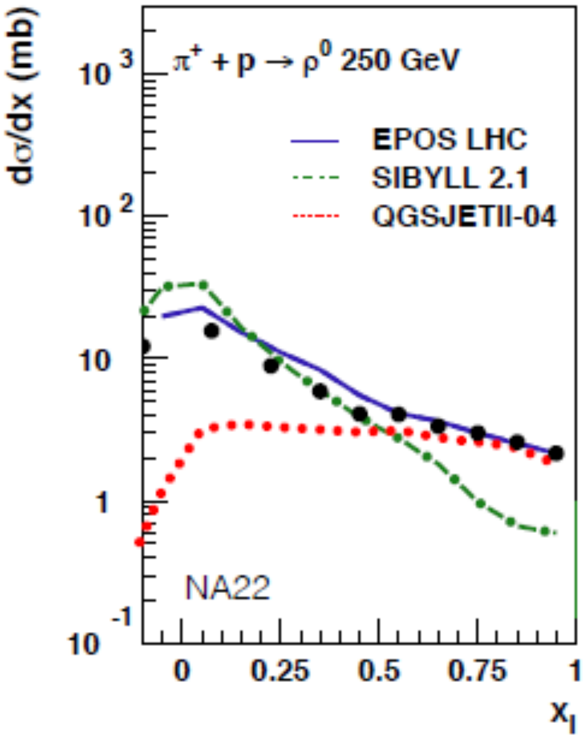
Ad hoc modified ρ^0 and π^0 production

Sibyll 2.3rc mod π^0

(Riehn et al., ICRC 2015)

Open questions related to rho production



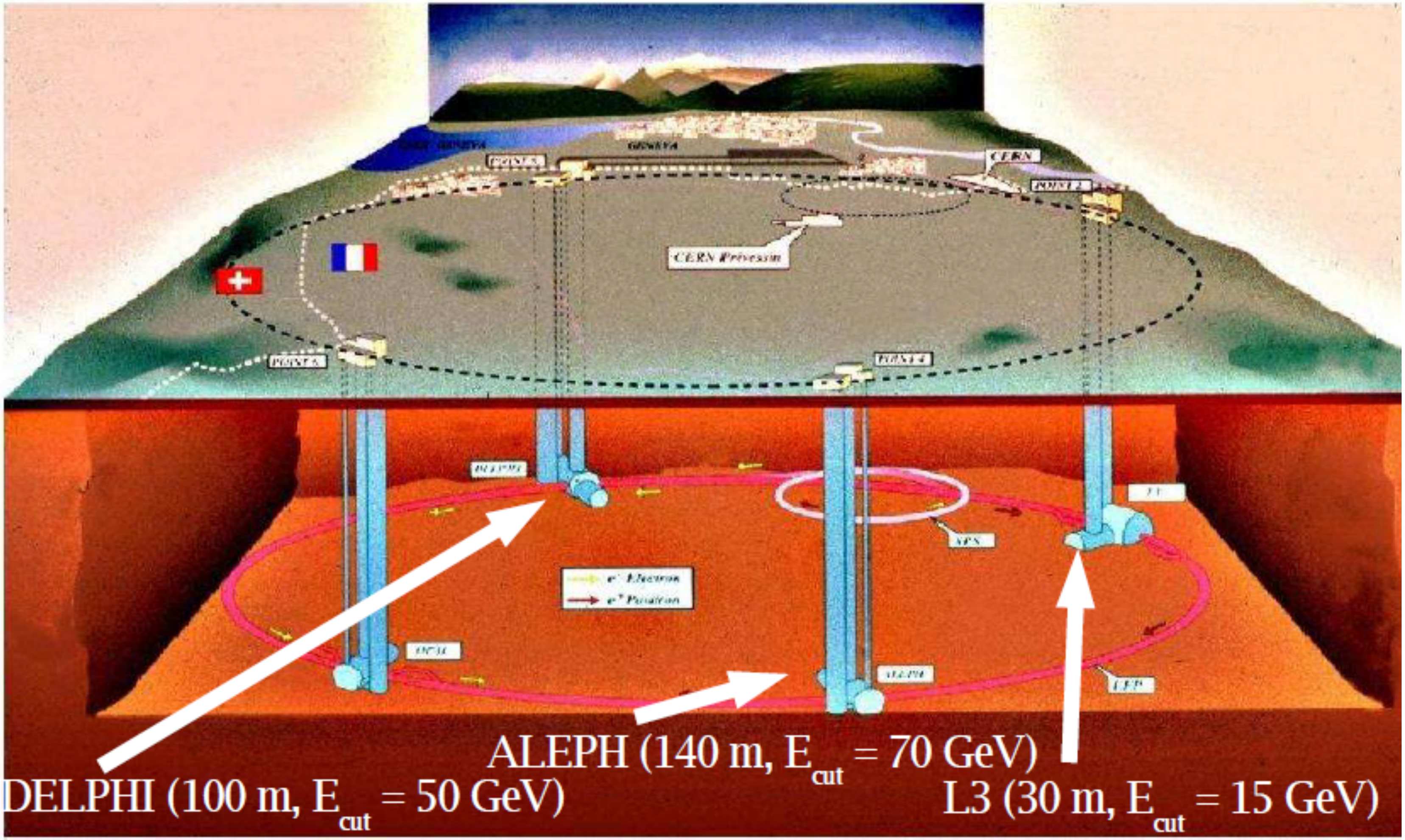


- EPOS and QGSJet tuned to reproduce π-p data
- Apparently origin of rho production not understood
- Suppression of π^0 production rather strong
- Energy dependence of these effects could be important

(Pierog 2015)

Similar muon problem to what was seen at LEP?

Detection of CR by LEP experiments



ALEPH (140 m, $E_{cut} = 70$ GeV)

DELPHI (100 m, $E_{cut} = 50$ GeV)

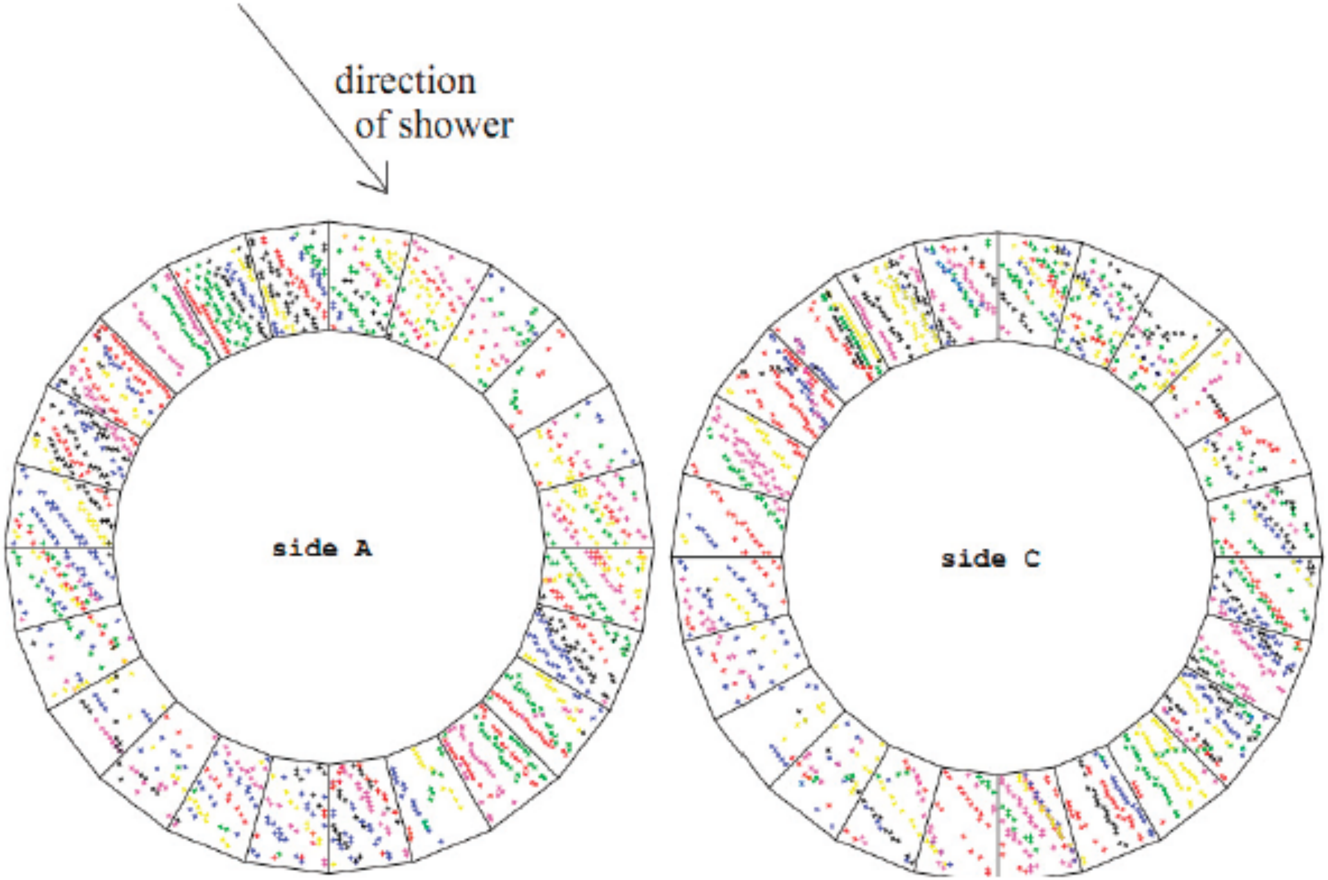
L3 (30 m, $E_{cut} = 15$ GeV)

DELPHI as a cosmic ray detector

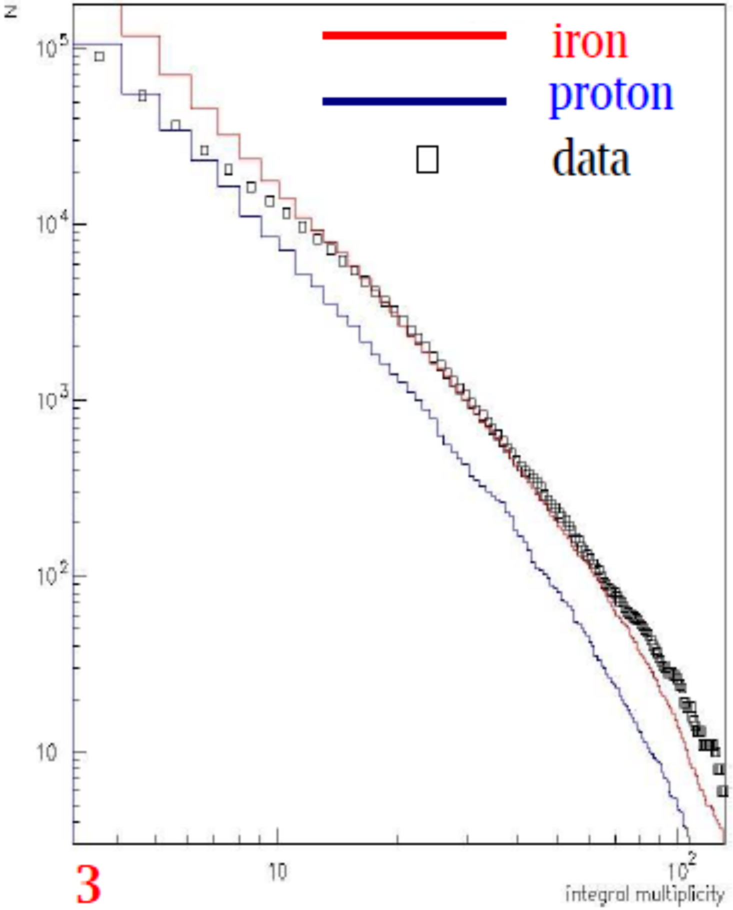
- rock overburden: vertical cutoff ~ 52 GeV
- cosmic measurement in concurence with normal run: effective uptime ~ 18 days

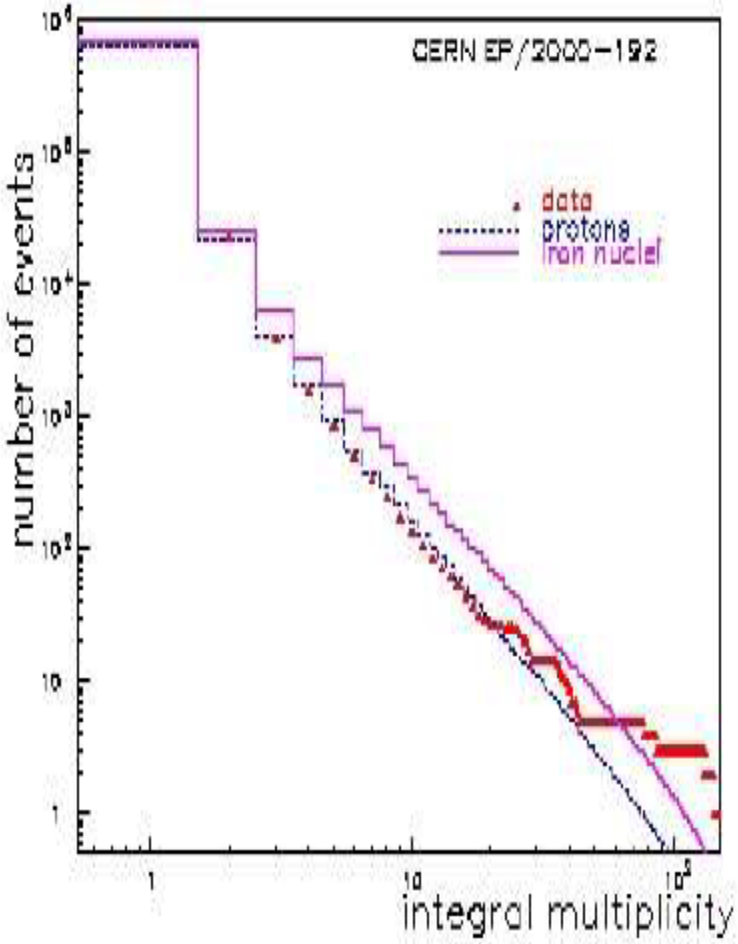
Bundles of parallel tracks in HCAL

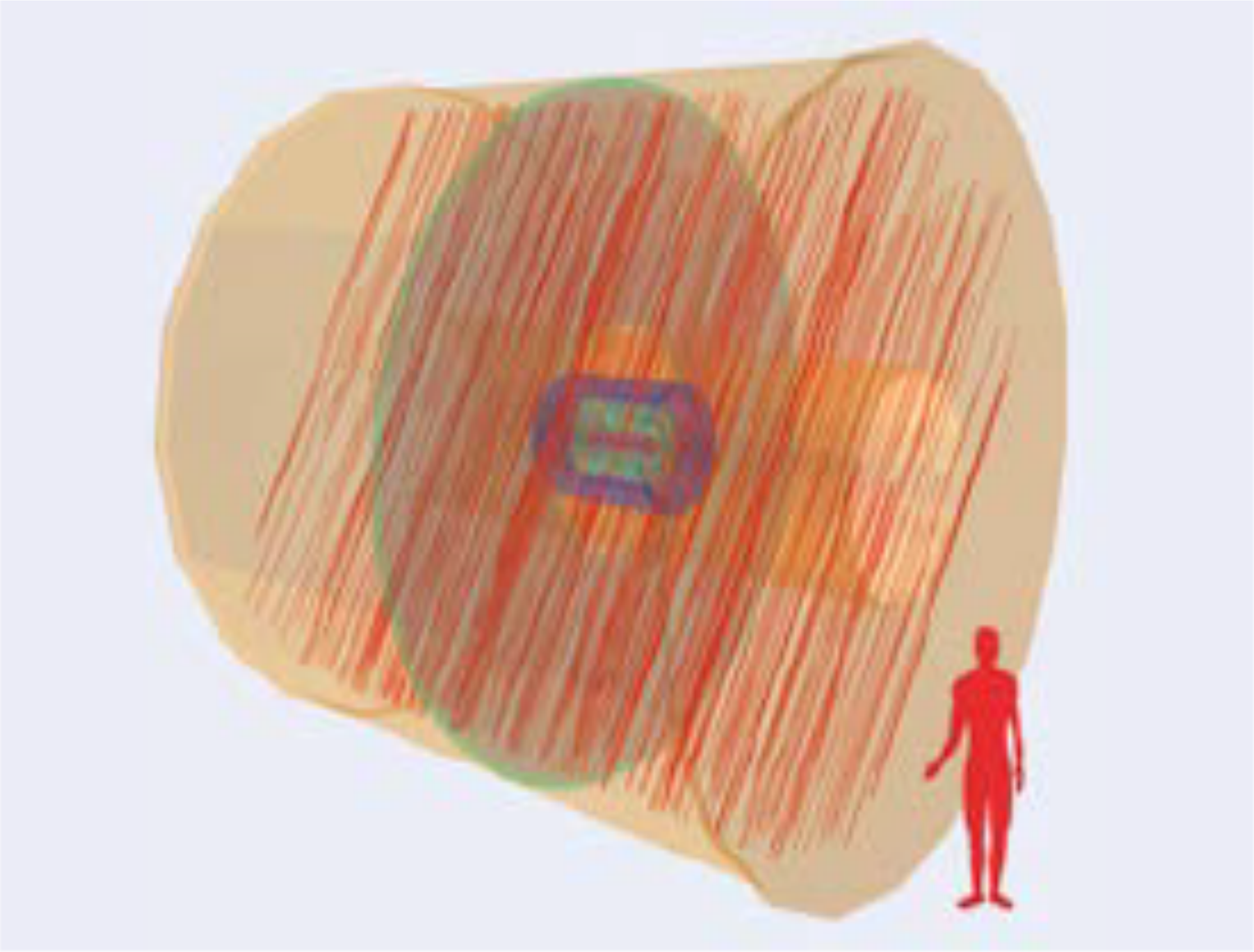
- not every muon reconstructed (shadowing, saturation, non-active areas)
- high-multiplicity events mainly from EAS between 10^{15}–$10^{17.5}$ eV
- excess w.r.t contemporary simulations



Results


Delphi

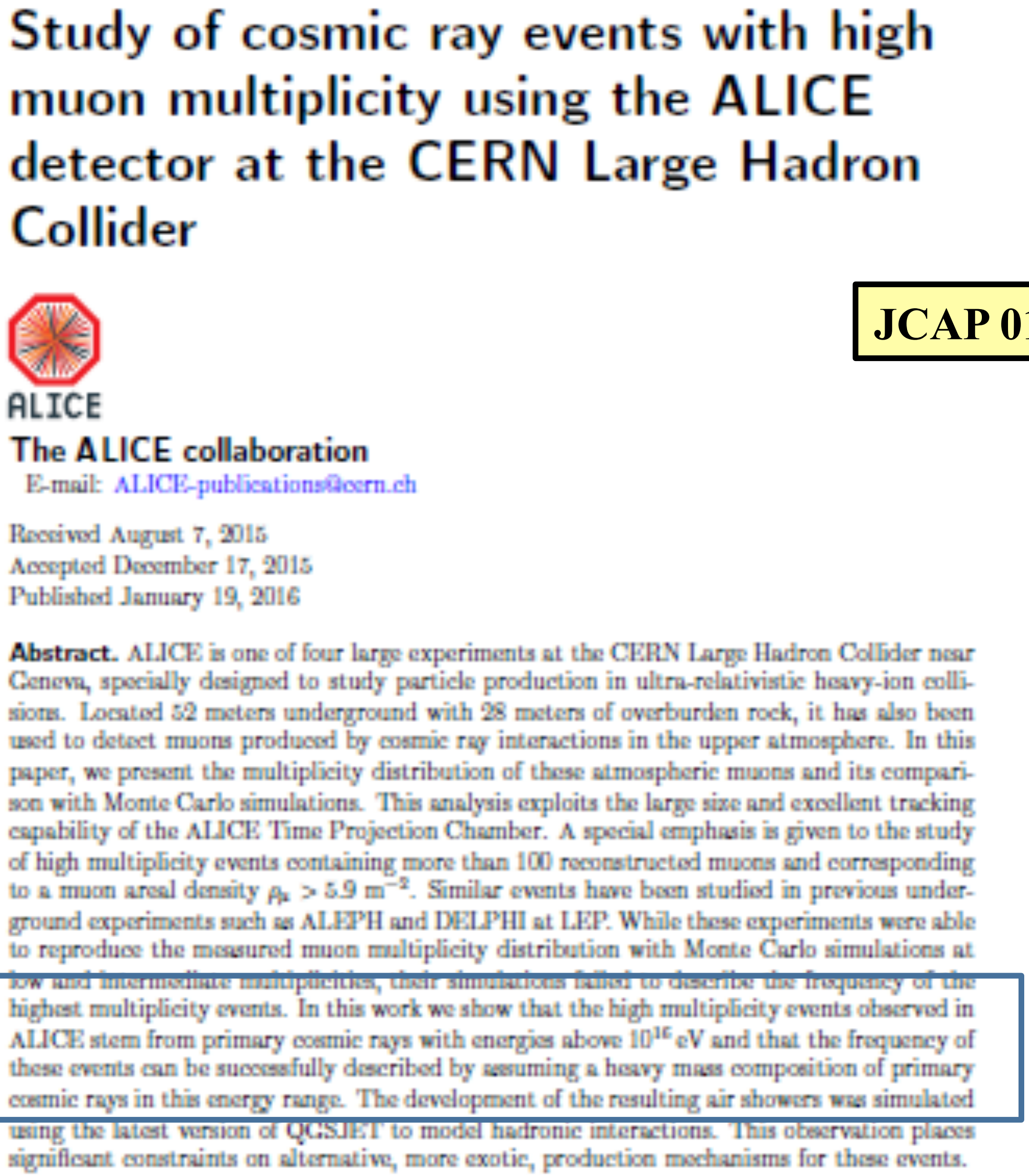

Aleph



Event display of a multi-muon event with 276 reconstructed muons crossing the TPC.

CERN Courier
December 2015

ALICE



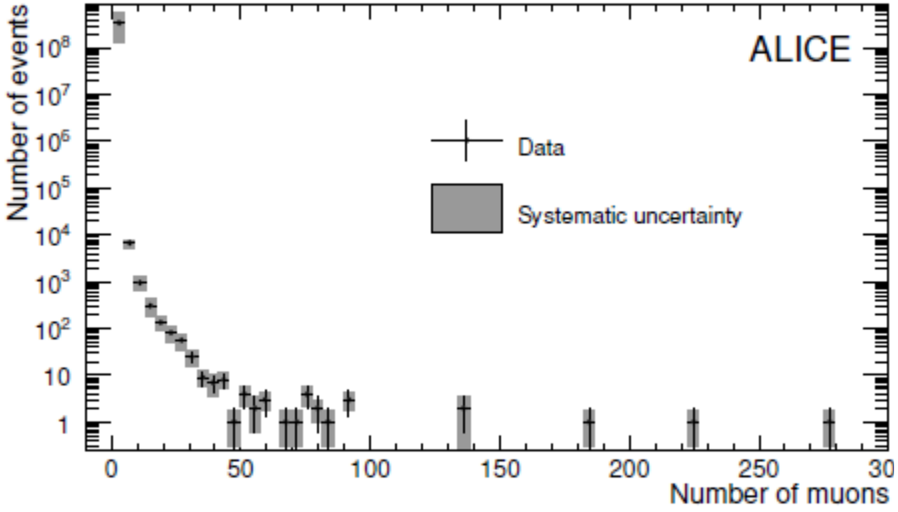
Study of cosmic ray events with high muon multiplicity using the ALICE detector at the CERN Large Hadron Collider

The ALICE collaboration
E-mail: ALICE-publications@cern.ch

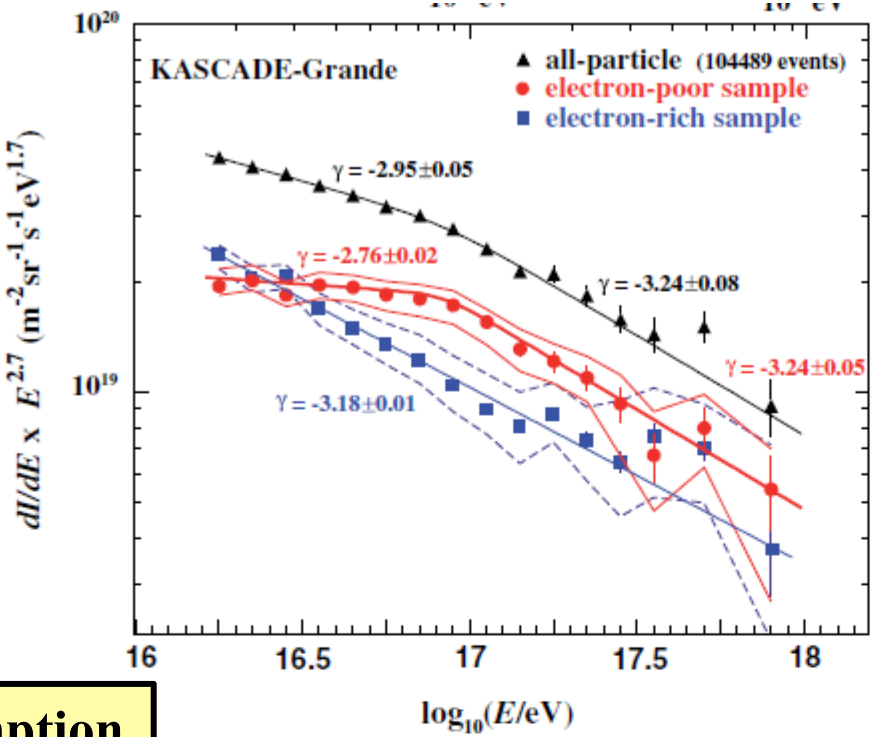
Received August 7, 2015
Accepted December 17, 2015
Published January 19, 2016

Abstract. ALICE is one of four large experiments at the CERN Large Hadron Collider near Geneva, specially designed to study particle production in ultra-relativistic heavy-ion collisions. Located 52 meters underground with 28 meters of overburden rock, it has also been used to detect muons produced by cosmic ray interactions in the upper atmosphere. In this paper, we present the multiplicity distribution of these atmospheric muons and its comparison with Monte Carlo simulations. This analysis exploits the large size and excellent tracking capability of the ALICE Time Projection Chamber. A special emphasis is given to the study of high multiplicity events containing more than 100 reconstructed muons and corresponding to a muon areal density $\rho_\mu > 5.9$ m^{-2}. Similar events have been studied in previous underground experiments such as ALEPH and DELPHI at LEP. While these experiments were able to reproduce the measured muon multiplicity distribution with Monte Carlo simulations at low and intermediate multiplicities, their simulations failed to describe the frequency of the highest multiplicity events. In this work we show that the high multiplicity events observed in ALICE stem from primary cosmic rays with energies above 10^{16} eV and that the frequency of these events can be successfully described by assuming a heavy mass composition of primary cosmic rays in this energy range. The development of the resulting air showers was simulated using the latest version of QGSJET to model hadronic interactions. This observation places significant constraints on alternative, more exotic, production mechanisms for these events.

JCAP 01 032 2016

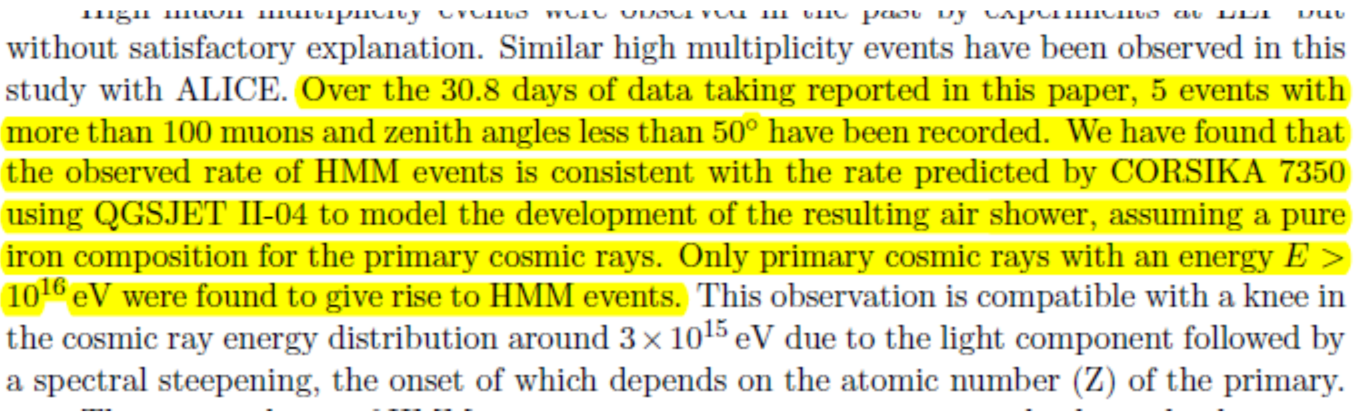


Iuon multiplicity distribution of the whole sample of data (2010-2013)



or online). Reconstructed energy spectrum of the
or and electron-rich components together with the
spectrum for the angular range 0°–40°. The error

Conclusion in ALICE paper makes assumption about mass composition, in contradiction with cosmic ray data



High muon multiplicity events were observed in the past by experiments at LEP but without satisfactory explanation. Similar high multiplicity events have been observed in this study with ALICE. Over the 30.8 days of data taking reported in this paper, 5 events with more than 100 muons and zenith angles less than 50° have been recorded. We have found that the observed rate of HMM events is consistent with the rate predicted by CORSIKA 7350 using QGSJET II-04 to model the development of the resulting air shower, assuming a pure iron composition for the primary cosmic rays. Only primary cosmic rays with an energy $E > 10^{16}$ eV were found to give rise to HMM events. This observation is compatible with a knee in the cosmic ray energy distribution around 3×10^{15} eV due to the light component followed by a spectral steepening, the onset of which depends on the atomic number (Z) of the primary.

Next steps:

On the ground

TA x4:

this will increase area of TA to that of Auger.
Operational in next year or so. Fully
Sensitive above ~ 30 EeV. Main aim is to increase
Statistics on Hot Spot

Auger to Auger Prime:

4 m^2 of scintillator to allow muon separation:
event-by-event mass at highest energies

Radio antenna on every tank

(ii) 4 m^2 Scintillators above Water-Cherenkov detectors

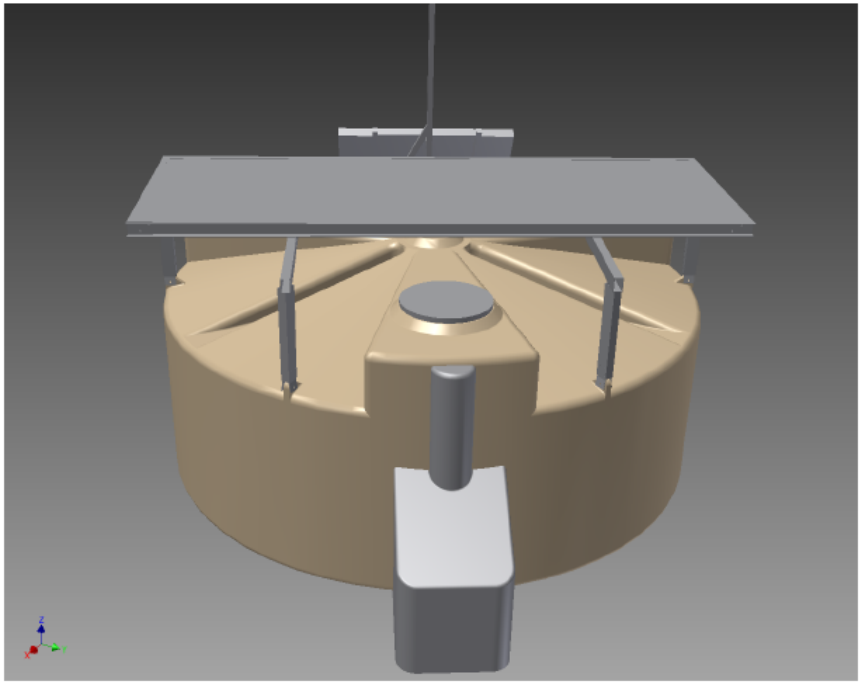
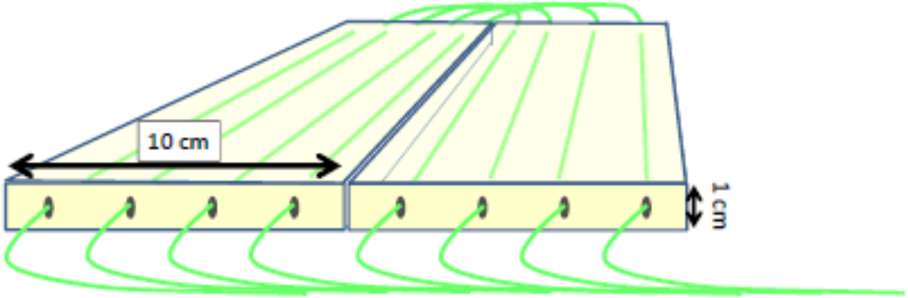


Figure 4.1: 3D view of a water-Cherenkov detector with a scintillator unit on top.

Scintillators respond to muons and electromagnetic component

Water-Cherenkov detectors absorb all of the em component and are fully sensitive to muons

It has been demonstrated with simulations that techniques exist to separate out the muon component



(iii) Buried Muon Detectors (1.3 m below surface)

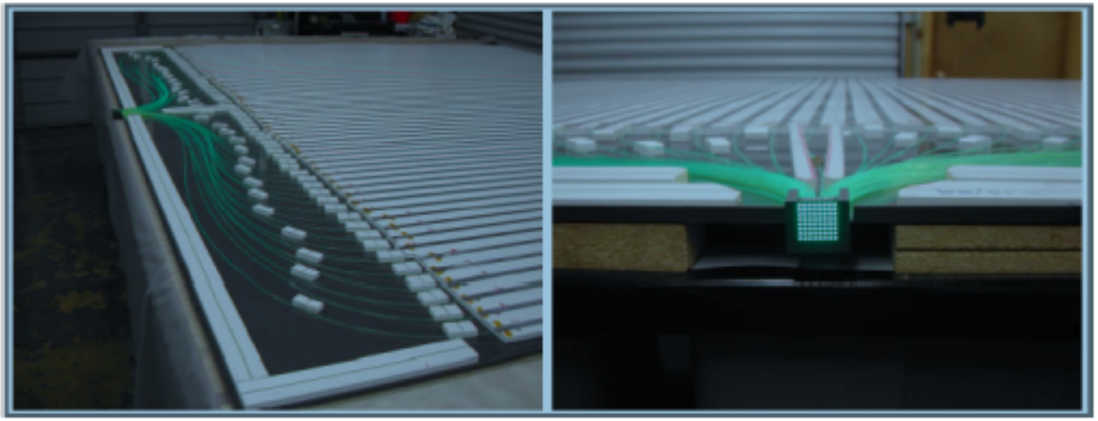


Figure 5.1: Scintillators strips: left: general mounting in the PVC housing, right: detail of the 64-pixel optical connectors.

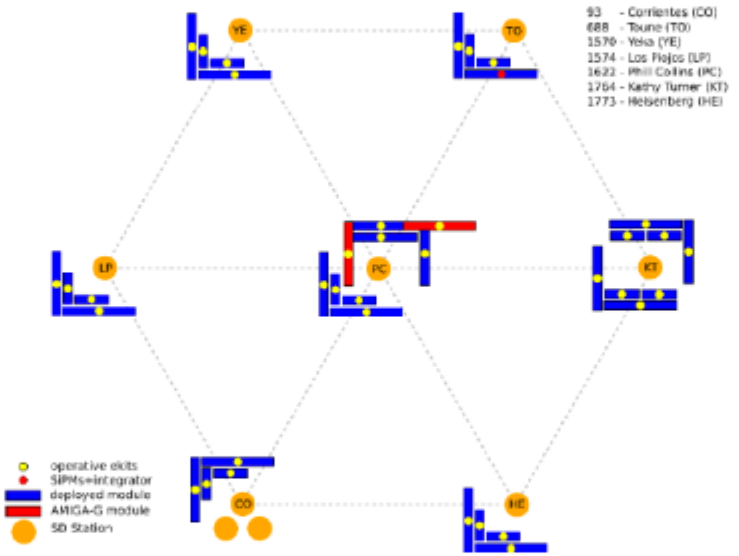


Figure 5.2: AMIGA unitary cell.

60 x 20 m^2

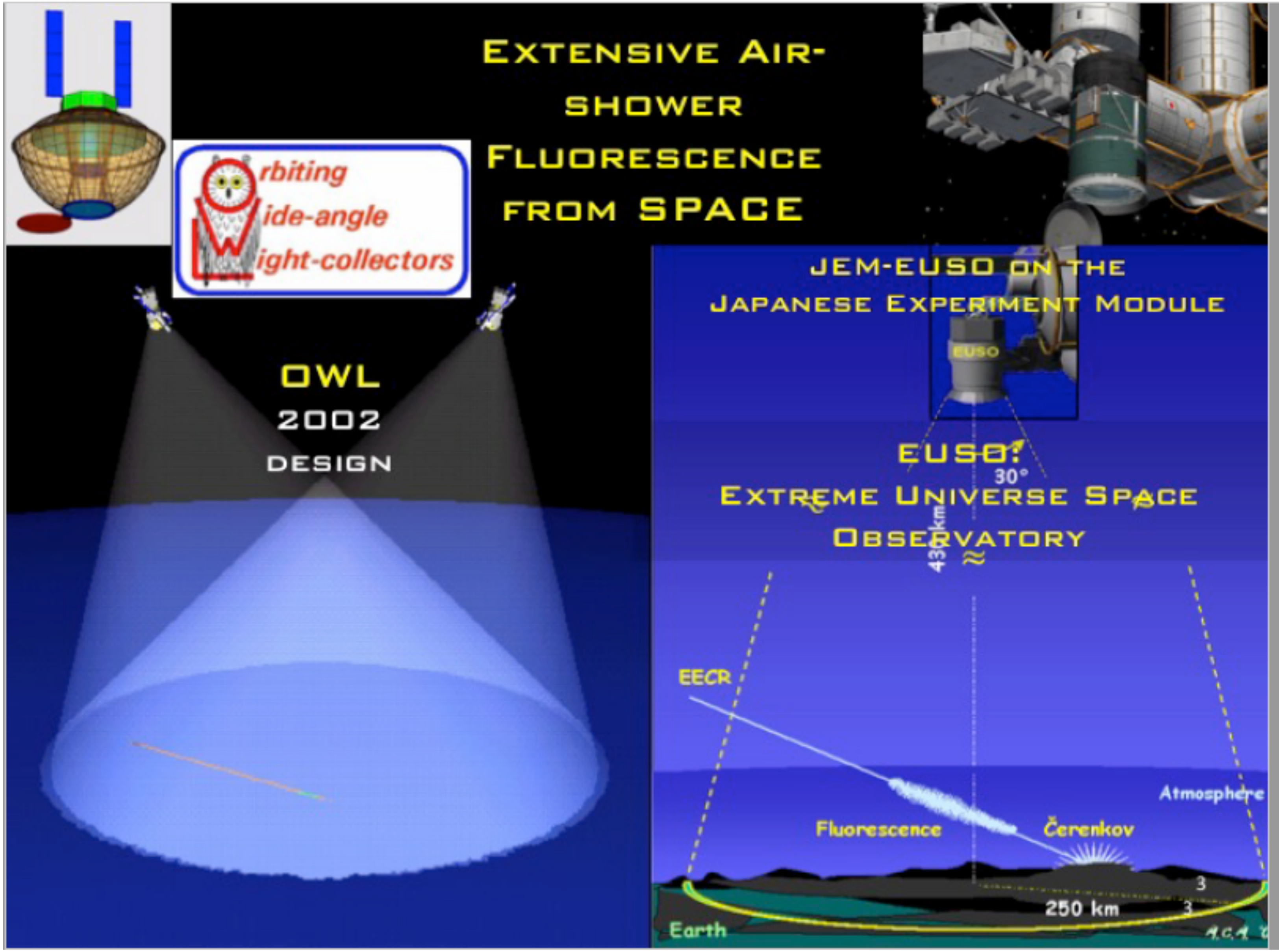
Linsley proposed (1979) that a fluorescence
detector should be put into space
Eventually led to EUSO (ESA phase A (with Livio Scarsi))

and then to JEM-EUSO

Currently module at TA
and super-pressure balloon test flights

ISS flight

Twin satellites:
POEMMA: Probe of Extreme Multi-Messenger Astrophysics



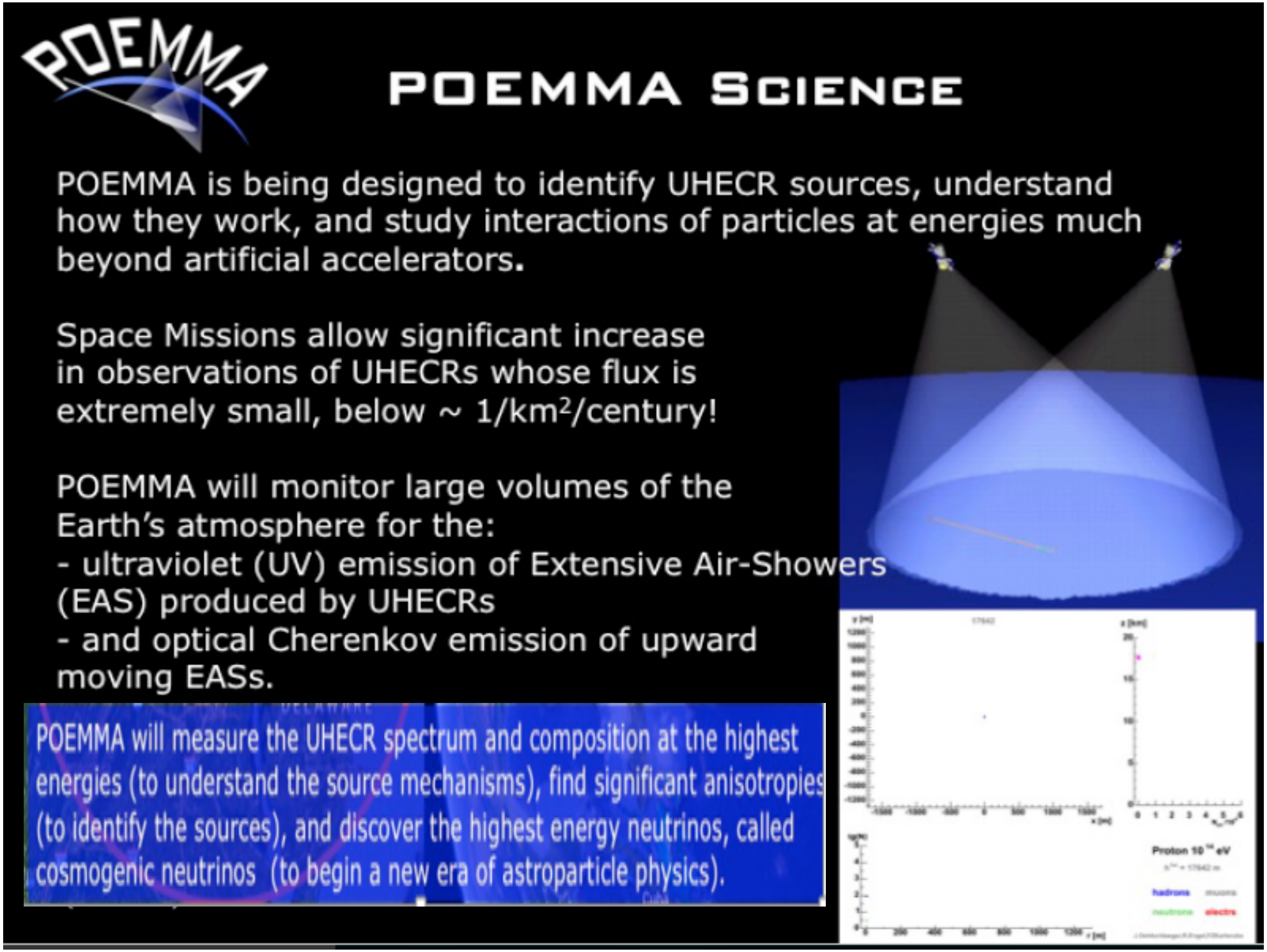
EXTENSIVE AIR-SHOWER FLUORESCENCE FROM SPACE

Orbiting
Wide-angle
Light-collectors

OWL
2002
DESIGN

JEM-EUSO on the
Japanese Experiment Module

EUSO:
Extreme Universe Space
Observatory



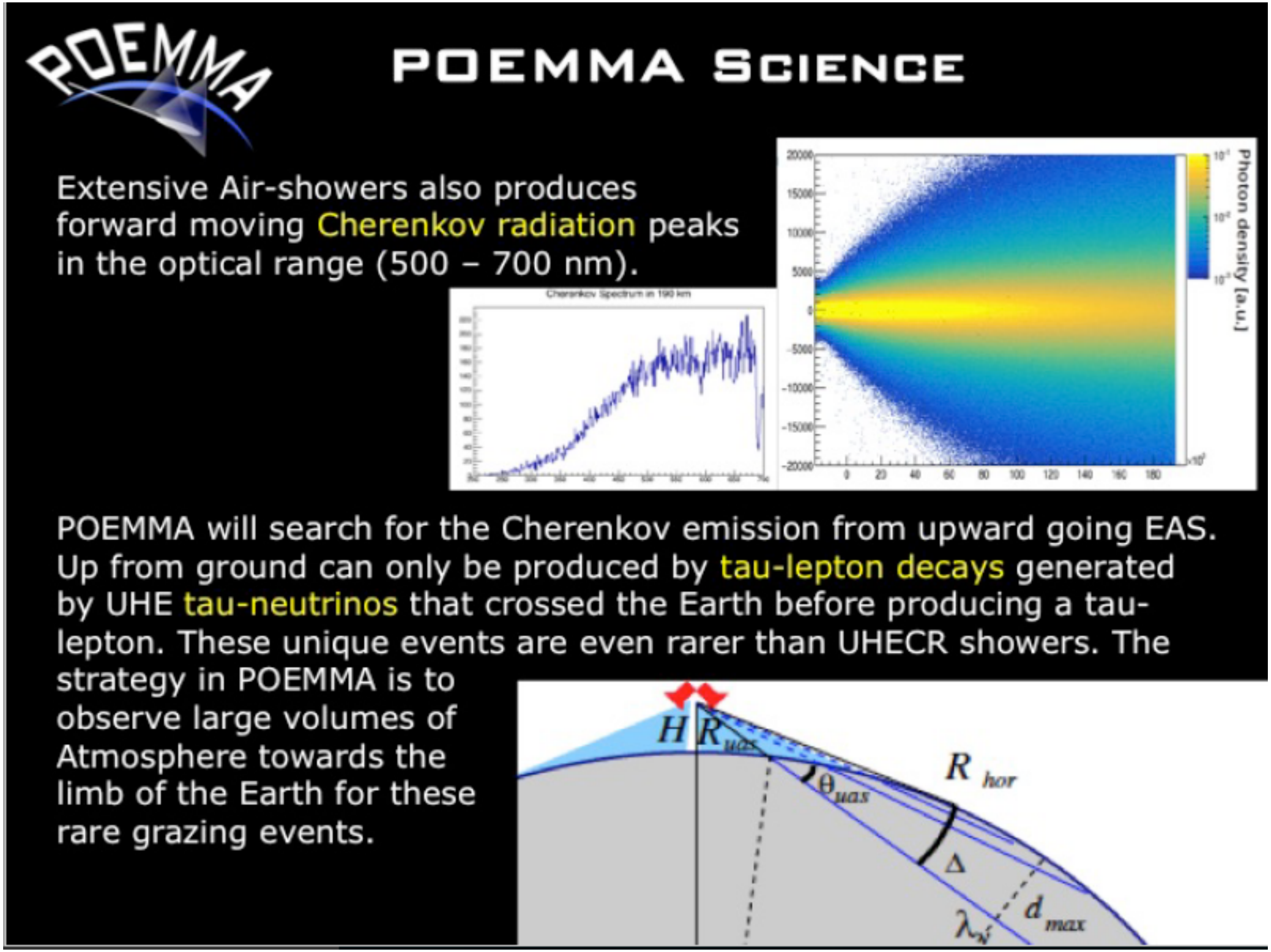
POEMMA SCIENCE

POEMMA is being designed to identify UHECR sources, understand how they work, and study interactions of particles at energies much beyond artificial accelerators.

Space Missions allow significant increase in observations of UHECRs whose flux is extremely small, below ~ 1/km^2/century!

POEMMA will monitor large volumes of the Earth's atmosphere for the:
- ultraviolet (UV) emission of Extensive Air-Showers (EAS) produced by UHECRs
- and optical Cherenkov emission of upward moving EASs.

POEMMA will measure the UHECR spectrum and composition at the highest energies (to understand the source mechanisms), find significant anisotropies (to identify the sources), and discover the highest energy neutrinos, called cosmogenic neutrinos (to begin a new era of astroparticle physics).



POEMMA SCIENCE

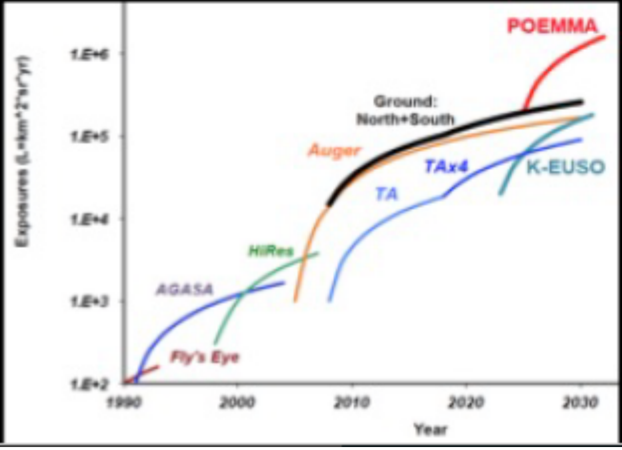
Extensive Air-showers also produces forward moving Cherenkov radiation peaks in the optical range (500 – 700 nm).

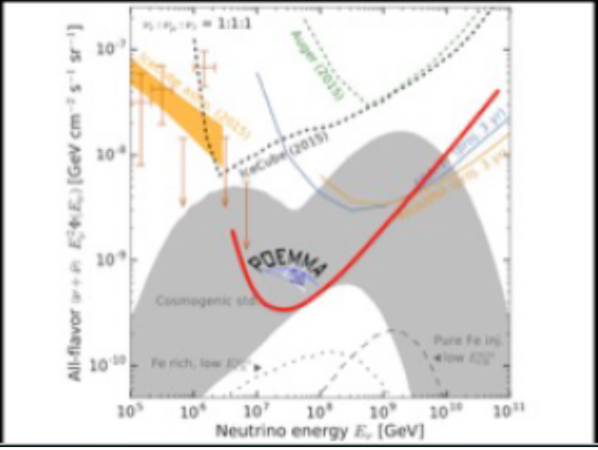
POEMMA will search for the Cherenkov emission from upward going EAS. Up from ground can only be produced by tau-lepton decays generated by UHE tau-neutrinos that crossed the Earth before producing a tau-lepton. These unique events are even rarer than UHECR showers. The strategy in POEMMA is to observe large volumes of Atmosphere towards the limb of the Earth for these rare grazing events.

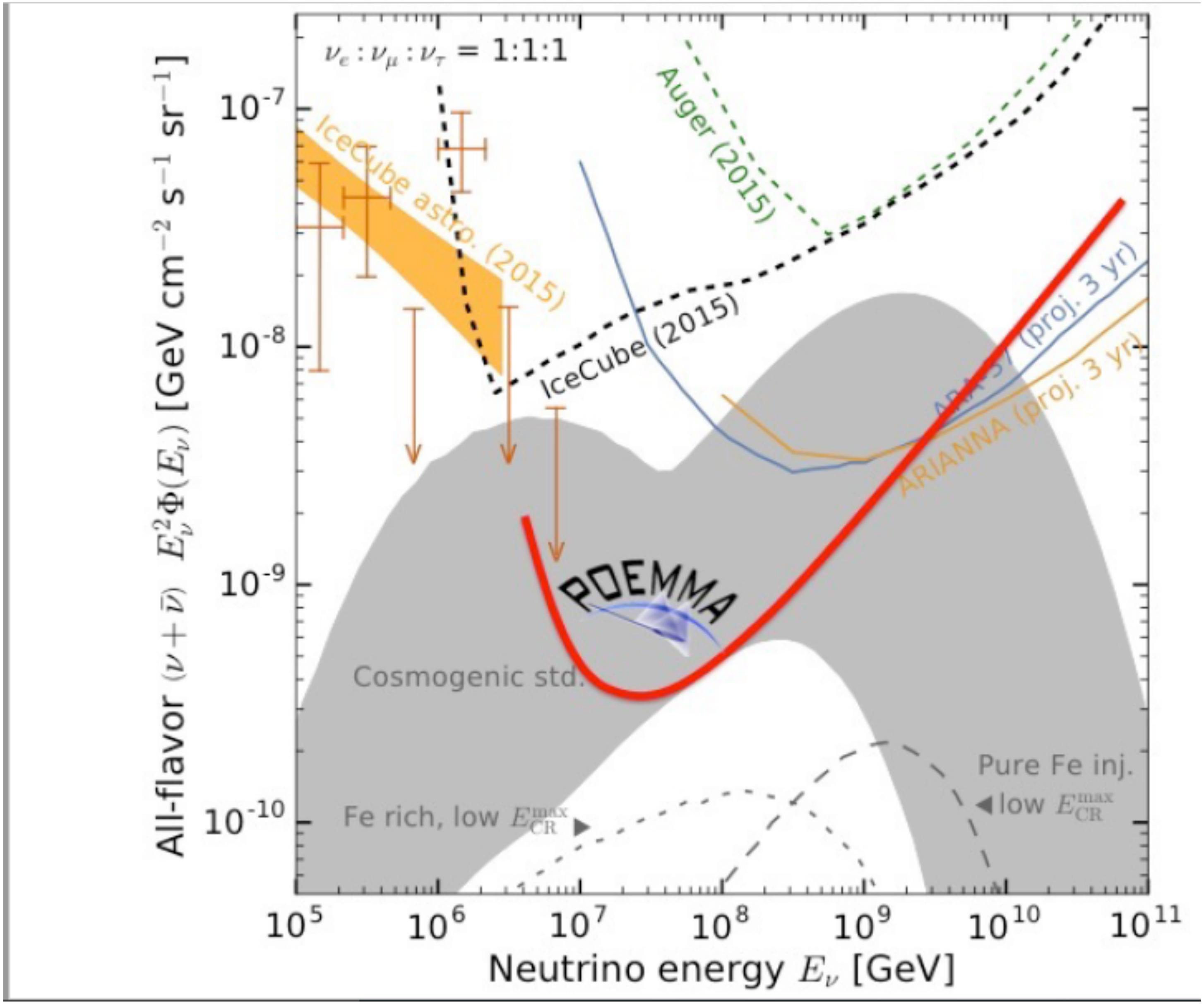
POEMMA SCIENCE

Giant Ground Arrays of detectors and fluorescence telescopes covering areas as large as 3,000 km^2 have measured the spectrum and composition just above 10^{19} eV. They find low significance hints (3 to 4σ) of anisotropies and no neutrinos.

POEMMA will monitor 100 times the atmospheric volume at a time. A 5 year mission will deliver a 10 fold increase overall (compared to ground arrays) and 100 times the composition measurements (compared to ground fluorescence). (Fluorescence ~ 10% duty cycle compared to ground arrays, but more direct information.) The neutrino search will be the most sensitive at the optimum energy for discovery ~10^{17}eV.






$\nu_e : \nu_\mu : \nu_\tau$ = 1:1:1
IceCube astro. (2015)
Auger (2015)
IceCube (2015)
ARA-37 (proj. 3 yr)
ARIANNA (proj. 3 yr)
POEMMA
Cosmogenic std.
Pure Fe inj.
◀ low $E_{\mathrm{CR}}^{\mathrm{max}}$
Fe rich, low $E_{\mathrm{CR}}^{\mathrm{max}}$ ▶
All-flavor $(\nu+\bar{\nu})$ $E_\nu^2\Phi(E_\nu)$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
Neutrino energy E_ν [GeV]

The Future at the Highest Energies – immediate future

- **Separate particles as function of development for anisotropy studies:**
  - **FADC parameters with water-Cherenkov detectors**
  - **Radio detection to measure X_{max} , 24 hours per day**

- **Achieve greater exposures:**
  - **TA x 4 Continued operation of Auger Observatory**
  - **JEM-EUSO and derivatives**

- **Composition on shower-by-shower basis at highest energy with AugerPrime**

Summary of experimental data

- Ankle at ~ 4 EeV and steepening at ~ 50 EeV clearly established

- Strong evidence for dipole anisotropy in Auger data above 8 EeV

- Weaker evidences (~4 sigma) for coincidence with starburst galaxies above 39 EeV and some evidence (~2.5 sigma) for γAGNs above 60 EeV

- Mass composition getting heavier above the ankle (still some dispute)

- No diffuse neutrinos seen (at level similar to IceCube) nor any from specific events (GW170817 or TX0506+56)

- Hadronic Interactions – more muons seen than predicted

Remains a fascinating field with very exciting prospects!