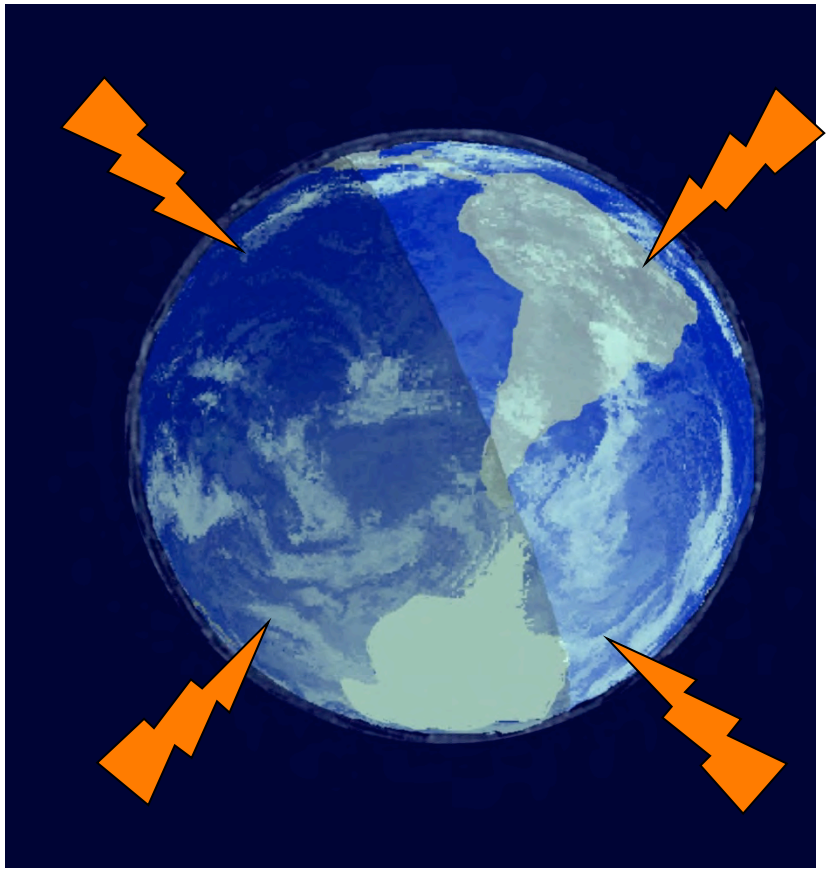
Astroparticle Physics_4



Cosmic rays

Charged particles

Gamma rays

Neutrinos

Gravitational Waves

???

Alessandro De Angelis
Mário Pimenta

6/2017 Asiago

Cosmic ray detection in space

'96 '97 '98 '99 '00 '01 '02 '03 '04 '05 '06 '07 '08 '09 '10 '11

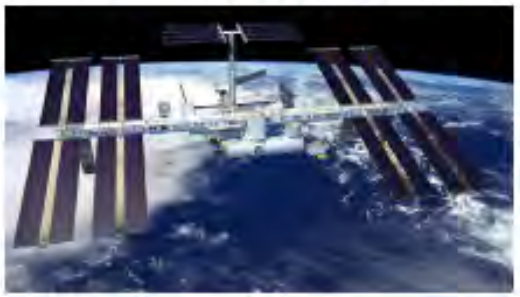
STS-91 flight (Jun 98)

BESS-POLAR (2004, 2007-08)

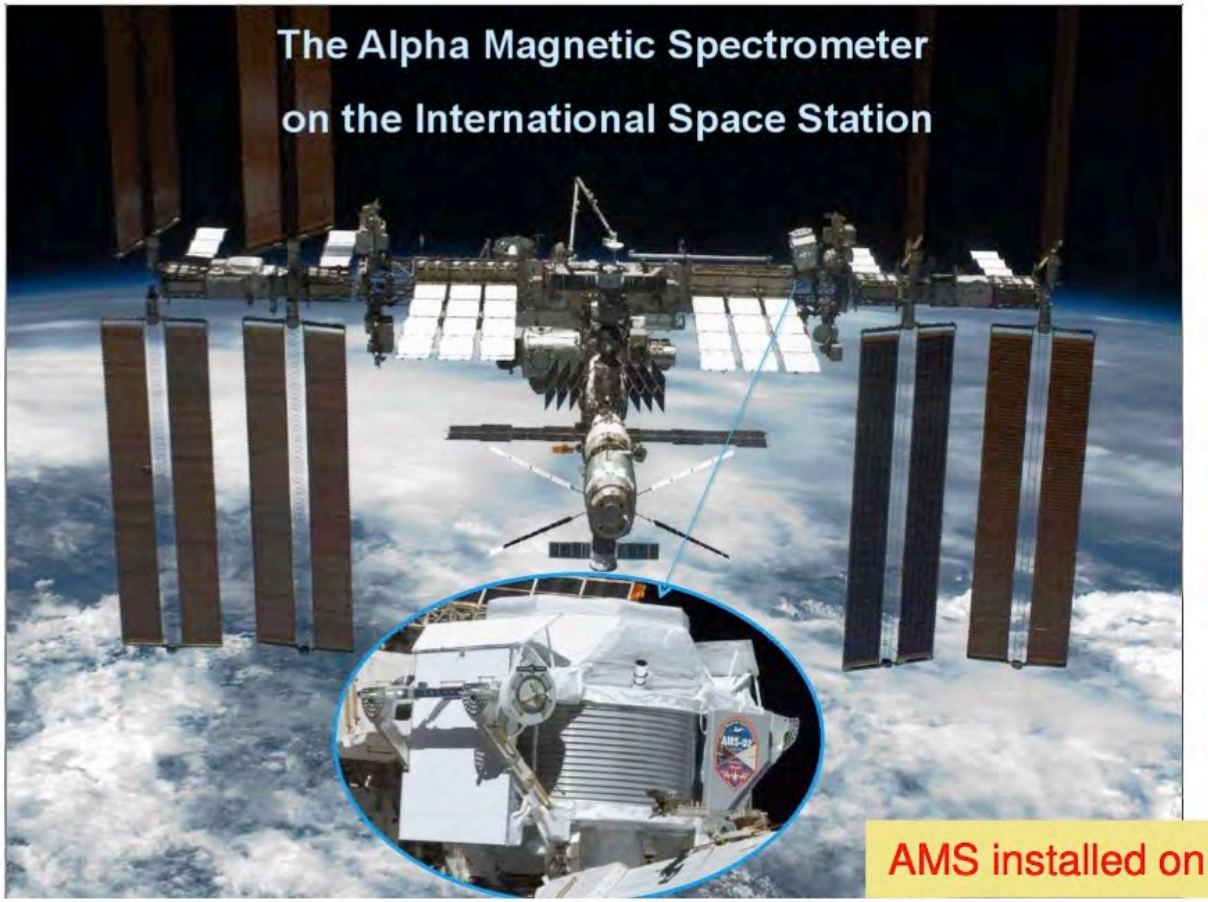
FERMI (June 2008)

PAMELA (June 2006)

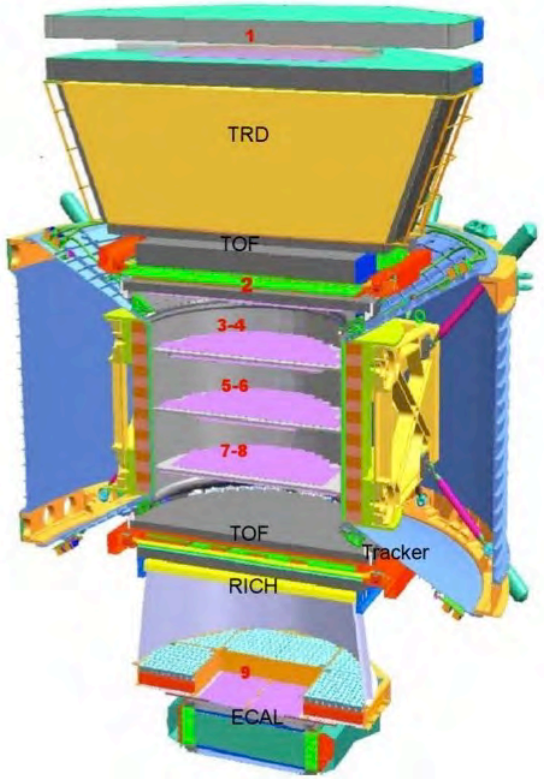
AMS to ISS (Feb-Apr/2011)



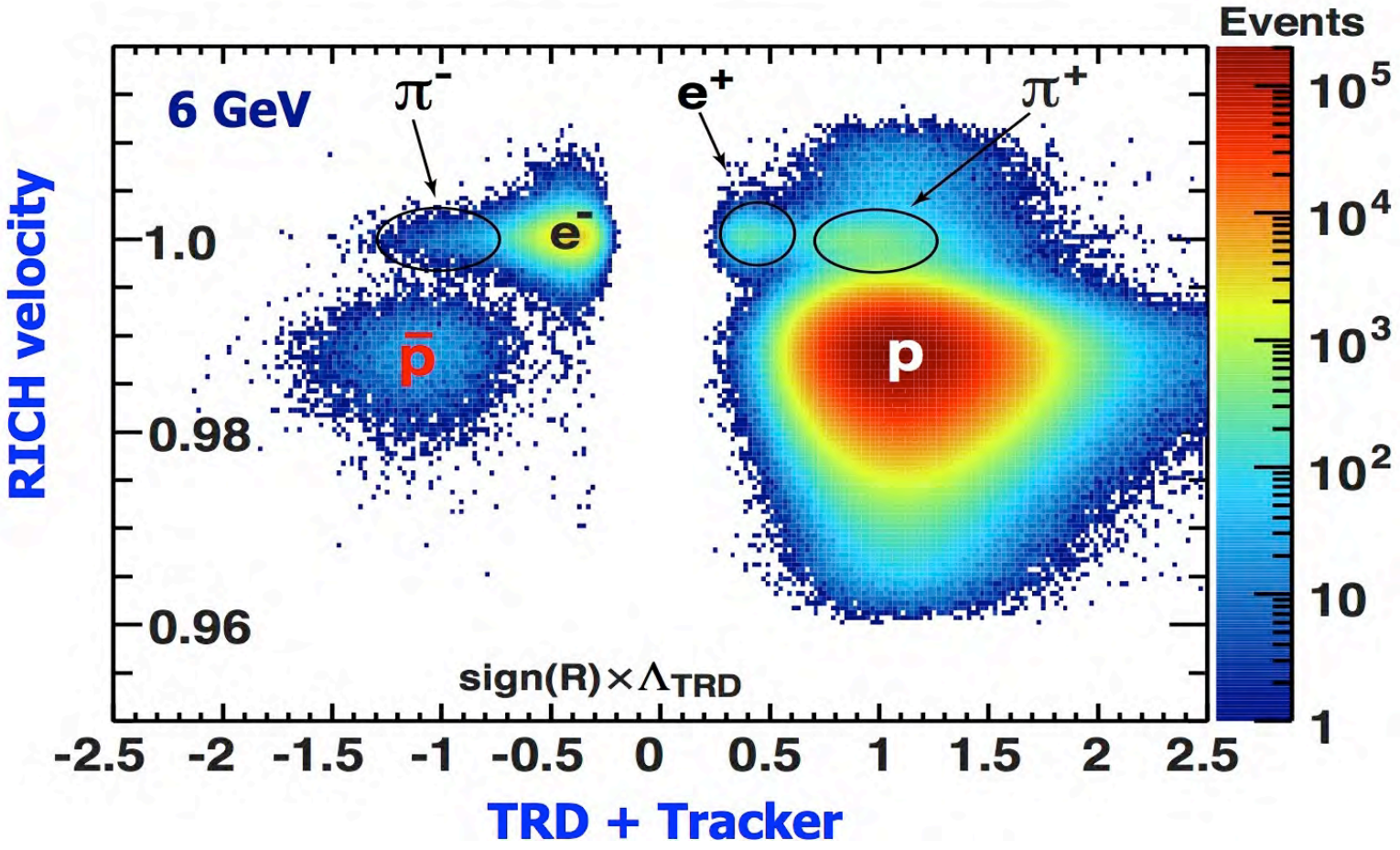
AMS



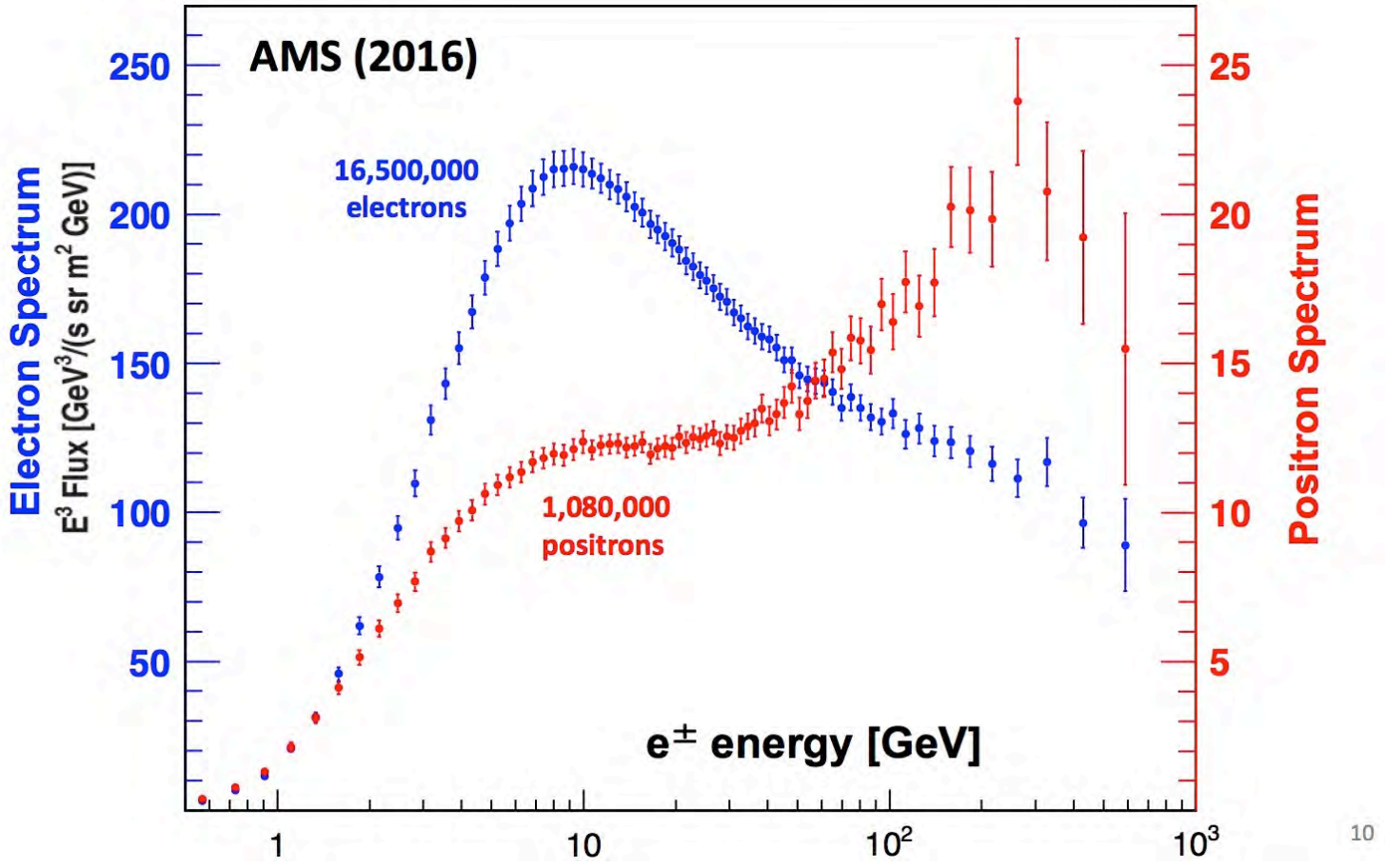
AMS installed on ISS



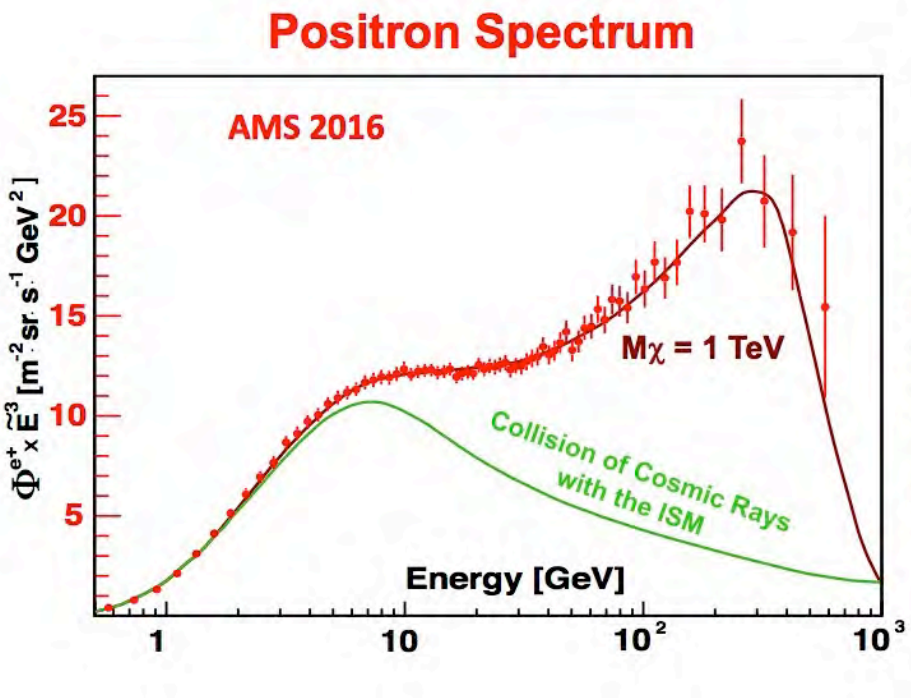
Particle identification

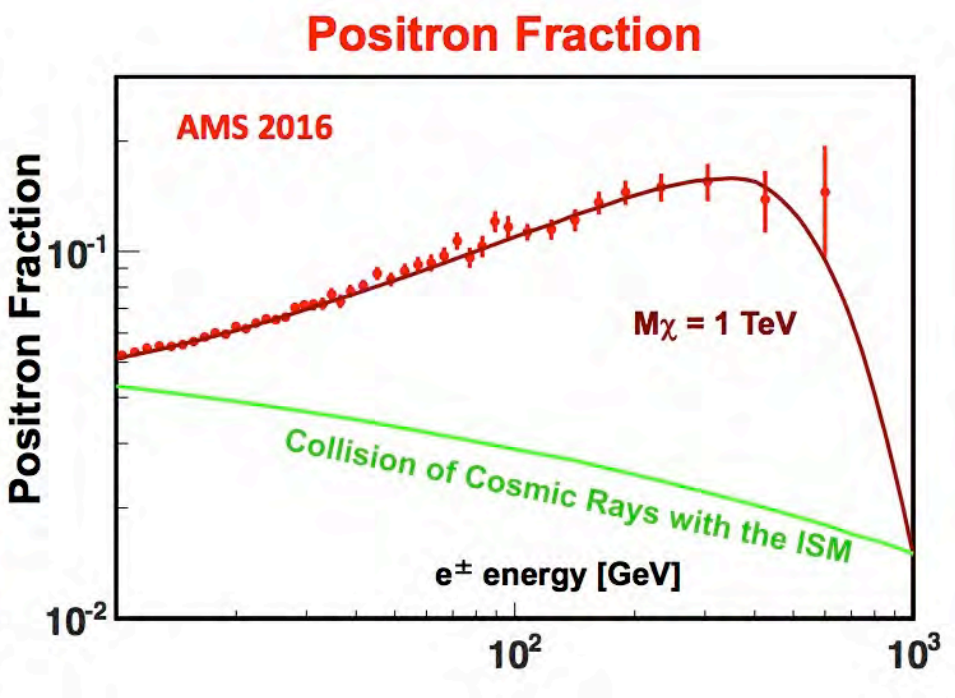


Electron, positron spectrum

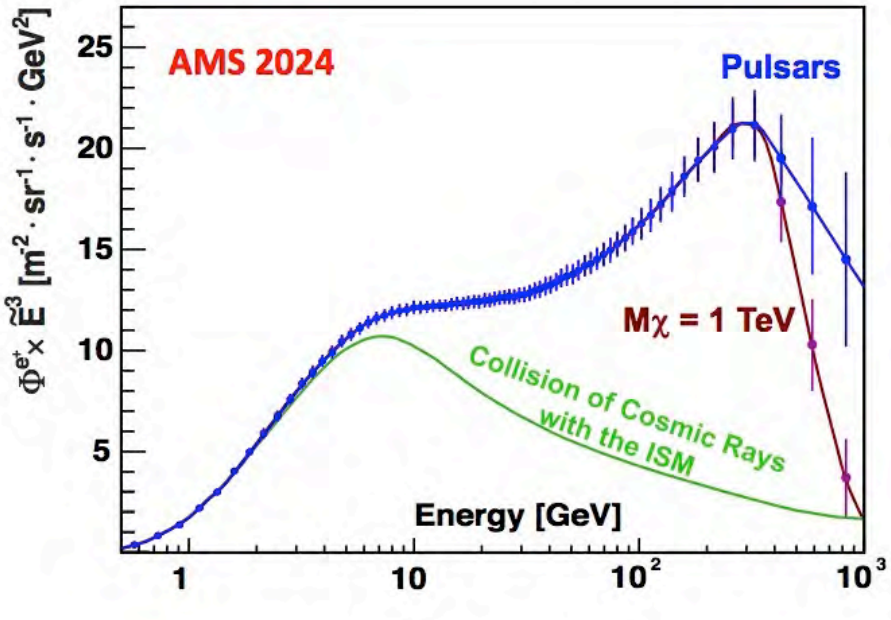


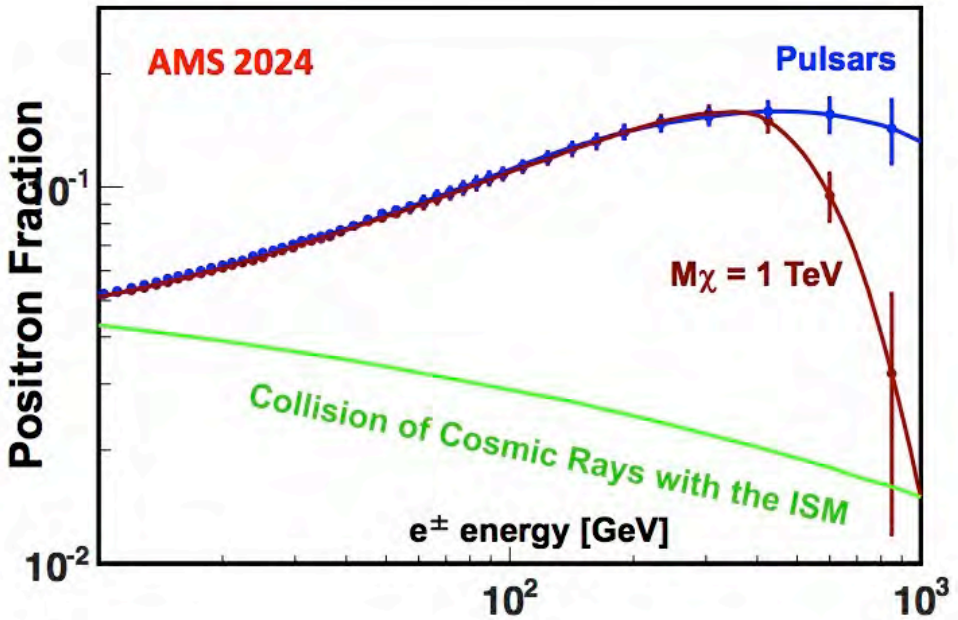
Dark matter signal?



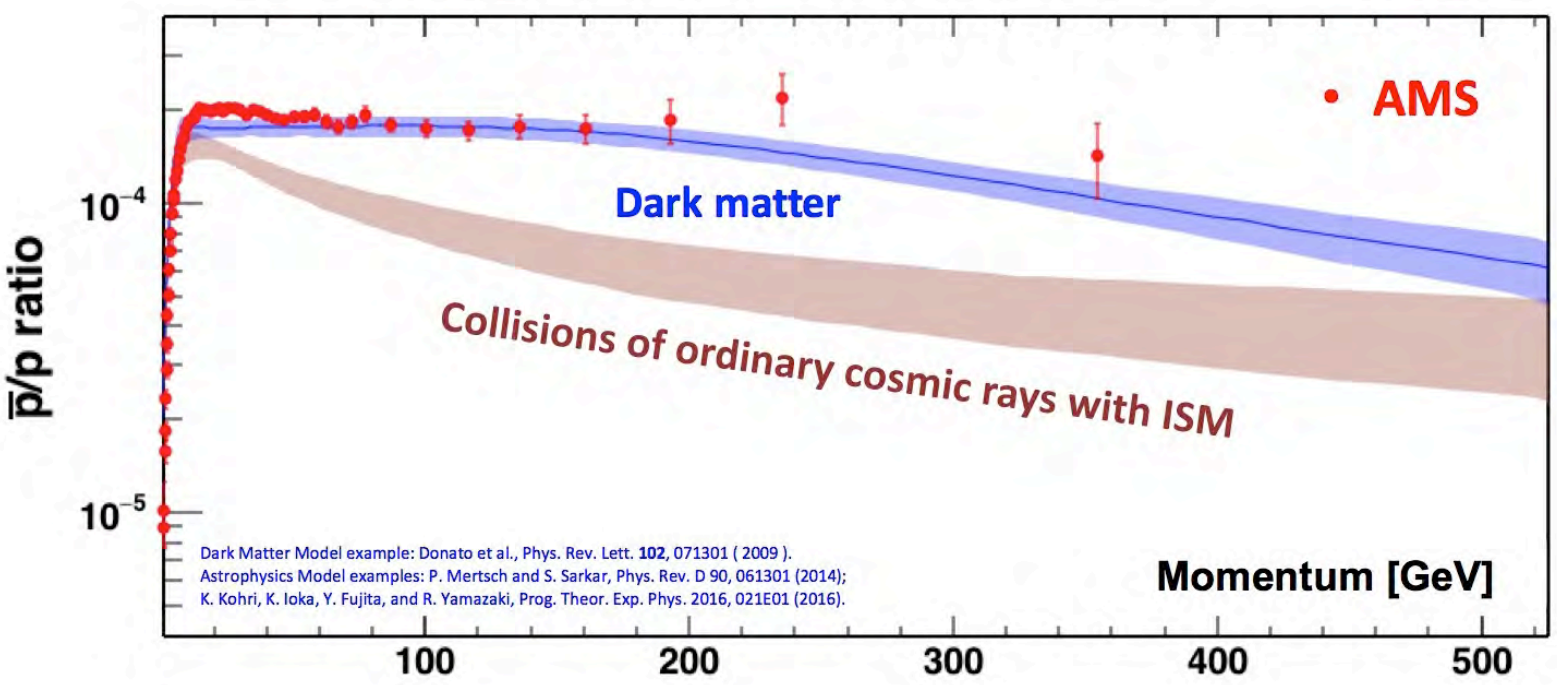


Wait for 2024 …



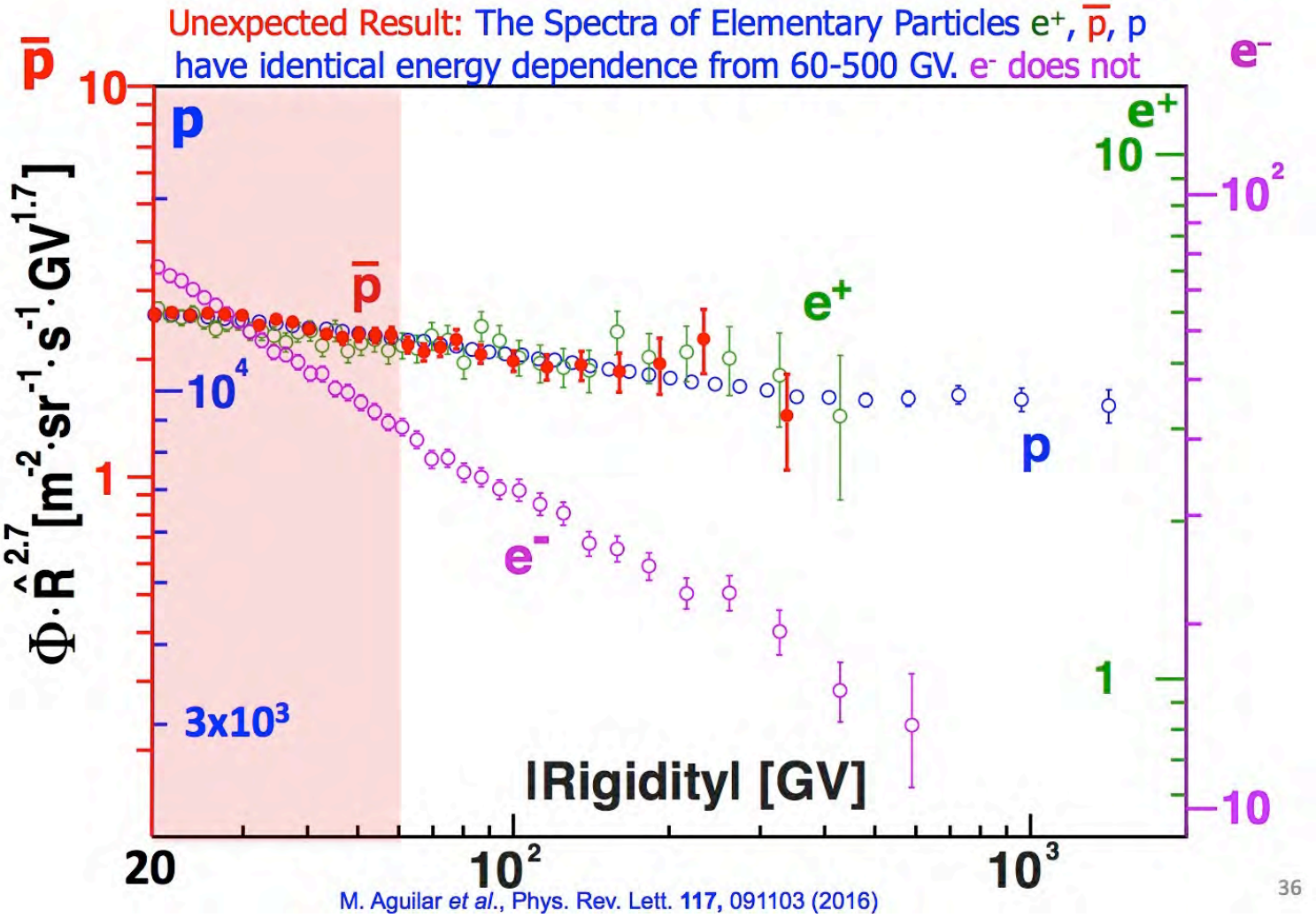


anti-proton/proton ratio

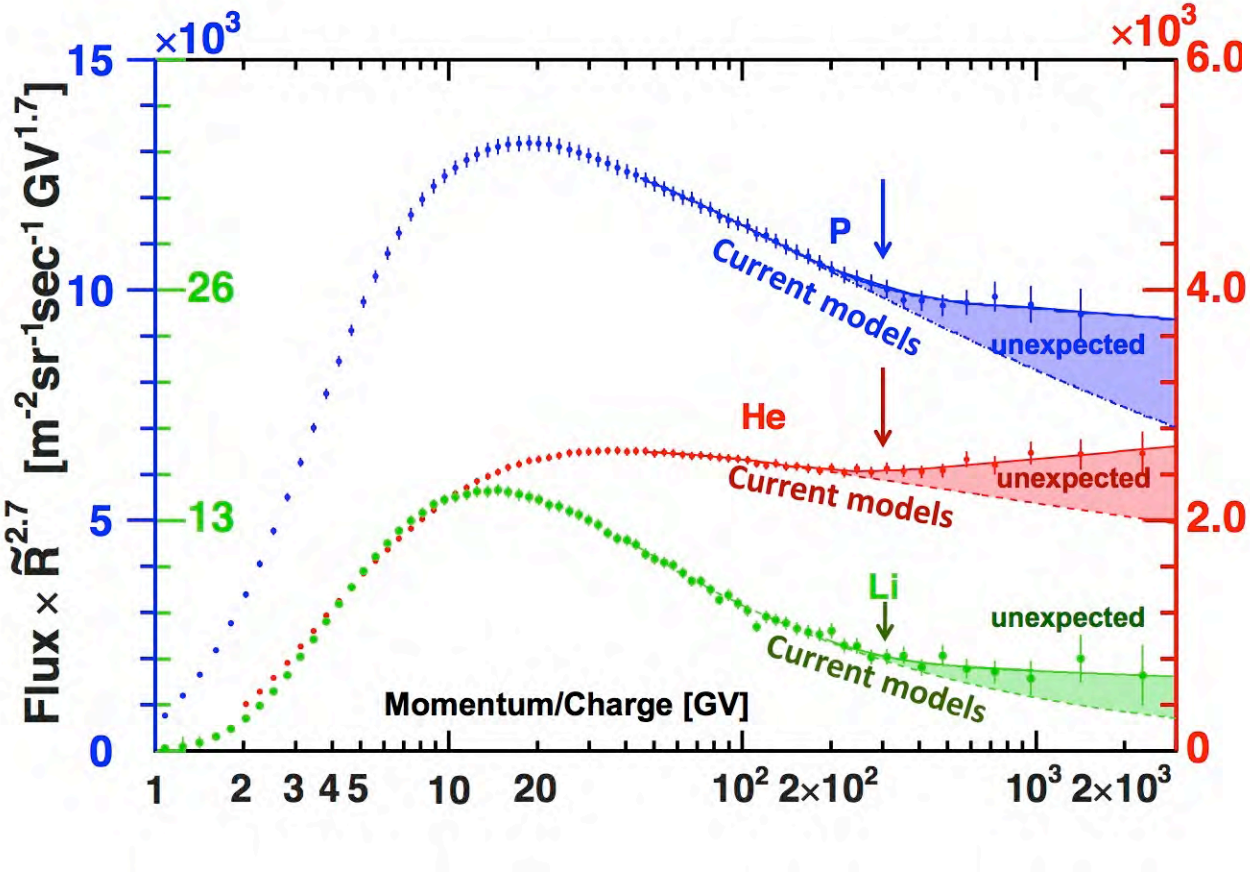


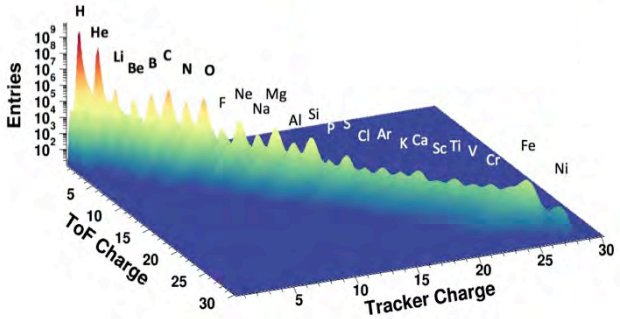
Not easily explained by pulsars ...

elementary particles spectra

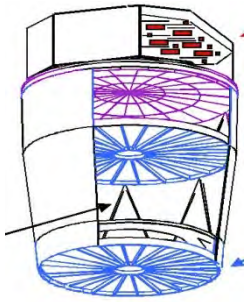


Nuclei …


×10³
15
10
5
0
26
13
×10³
6.0
4.0
2.0
0
Flux × R̃^2.7 [m^-2 sr^-1 sec^-1 GV^1.7]
P
Current models
unexpected
He
Current models
unexpected
Li
Current models
unexpected
Momentum/Charge [GV]
1
2
3
4
5
10
20
10²
2×10²
10³
2×10³

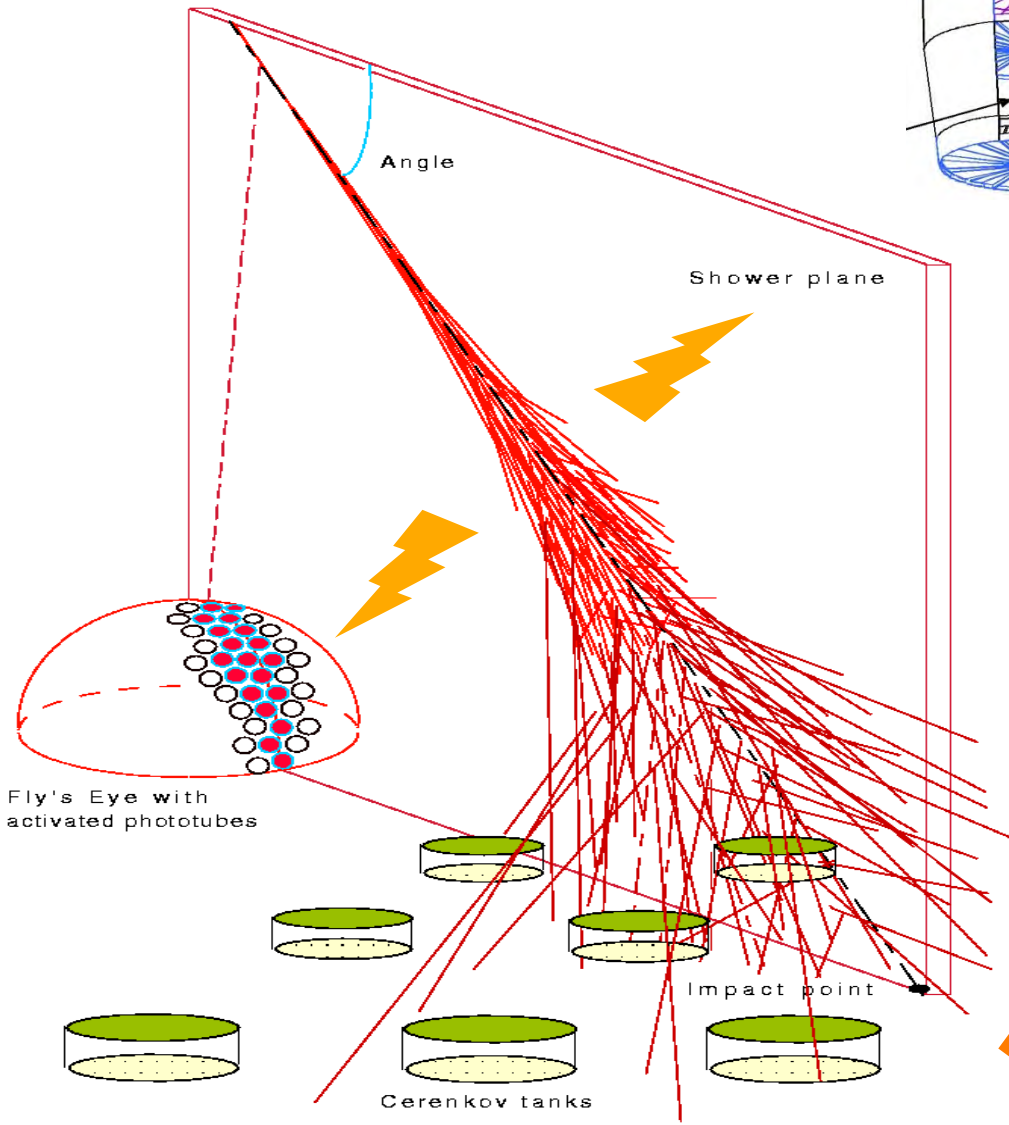

Entries
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Fe
Ni
ToF Charge
Tracker Charge

EAS detection



Fluorescence

electrons excite
N_2 molecules



Cherenkov

Particles

Fluorescence

•EAS electrons moving in the atmosphere excite N_2 molecules

•de-excitation → fluorescence light

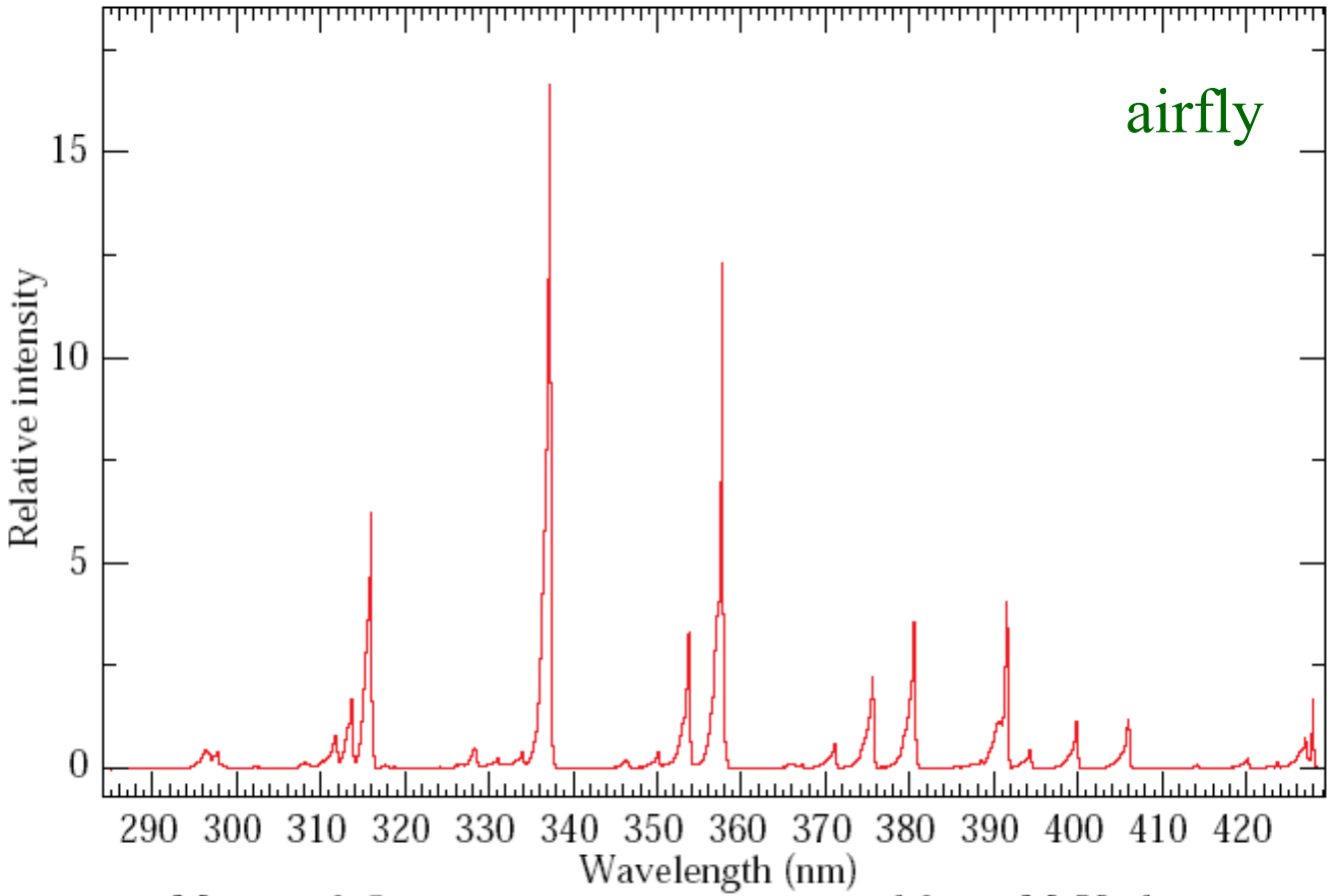


Figure 32.1: Measured fluorescence spectrum excited by 3 MeV electrons in dry air at 800 hPa and 293 K [9].

Fluorescence detectors measurements

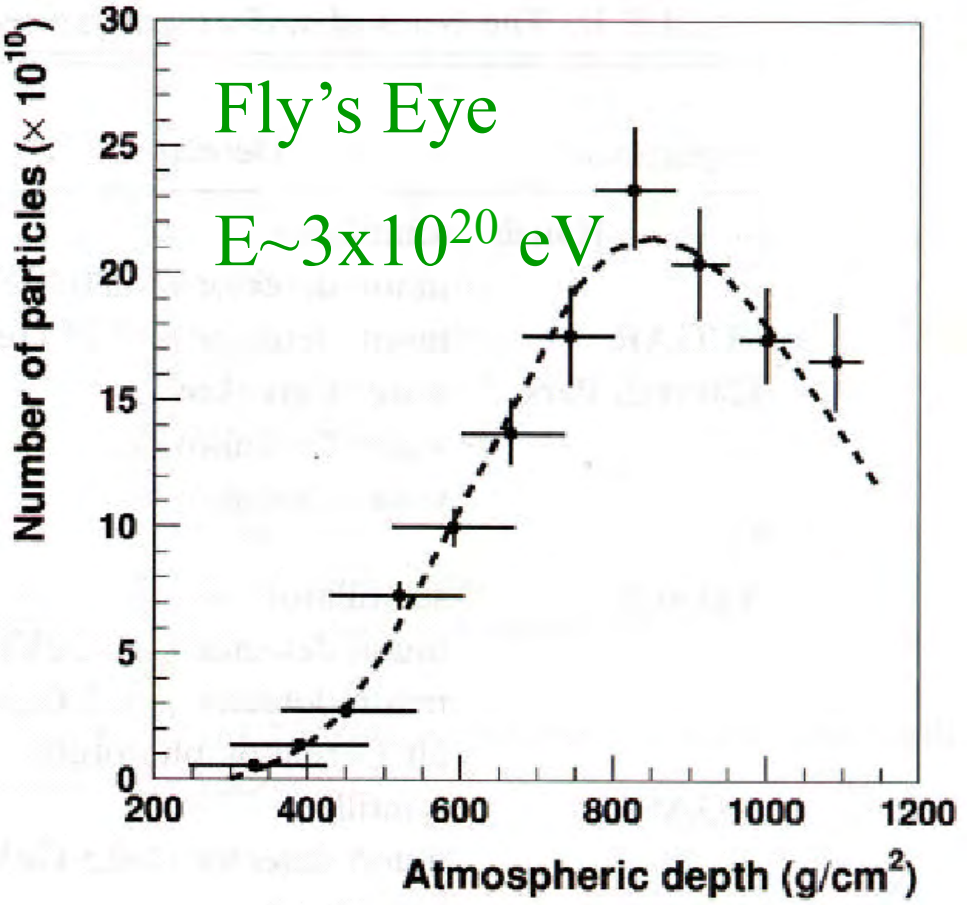
The direction

The X_{max}

The Energy

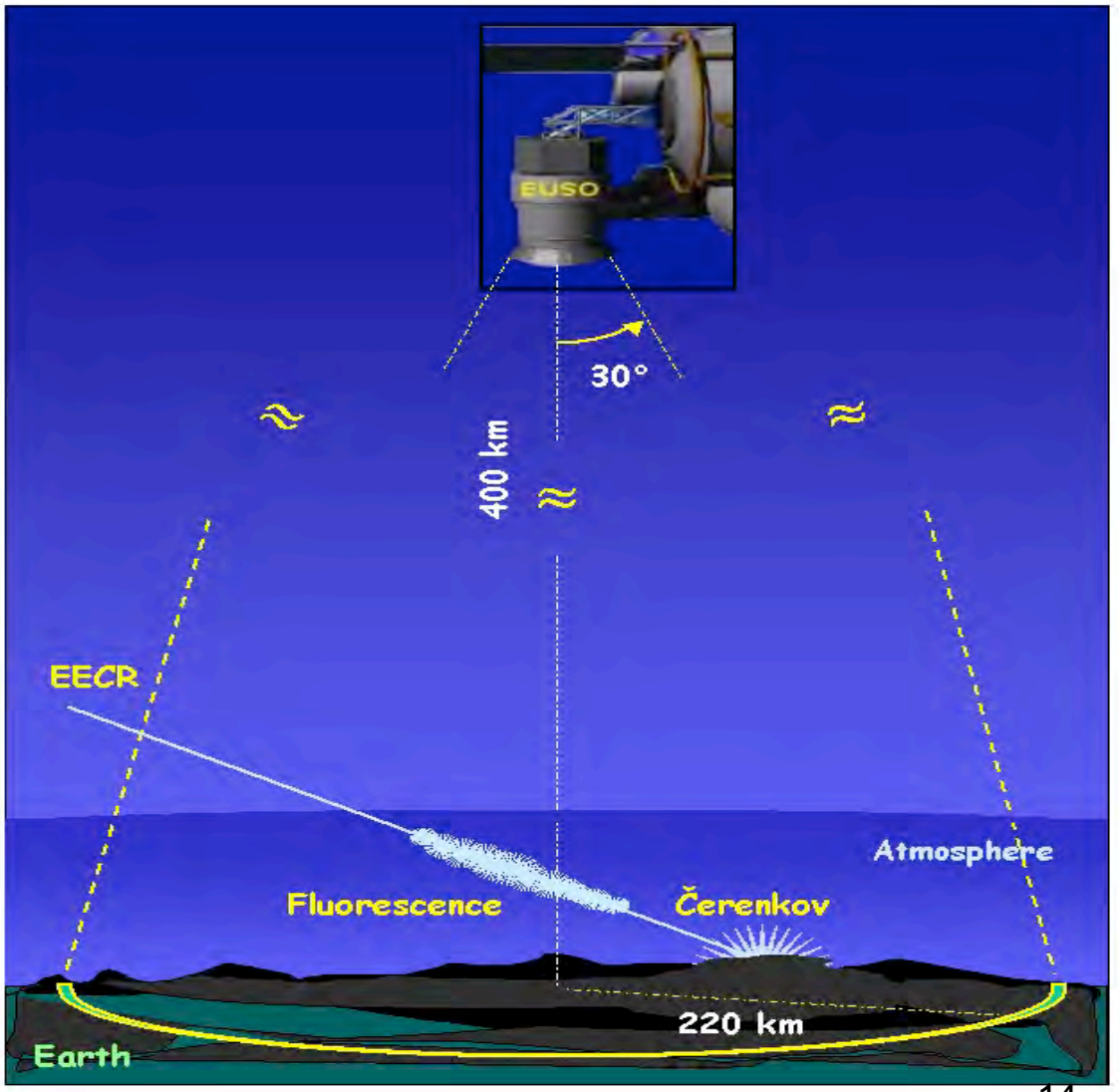
$E \propto Ne$

$\propto \int N(t)$



Fluorescence from space

JEM-EUSO

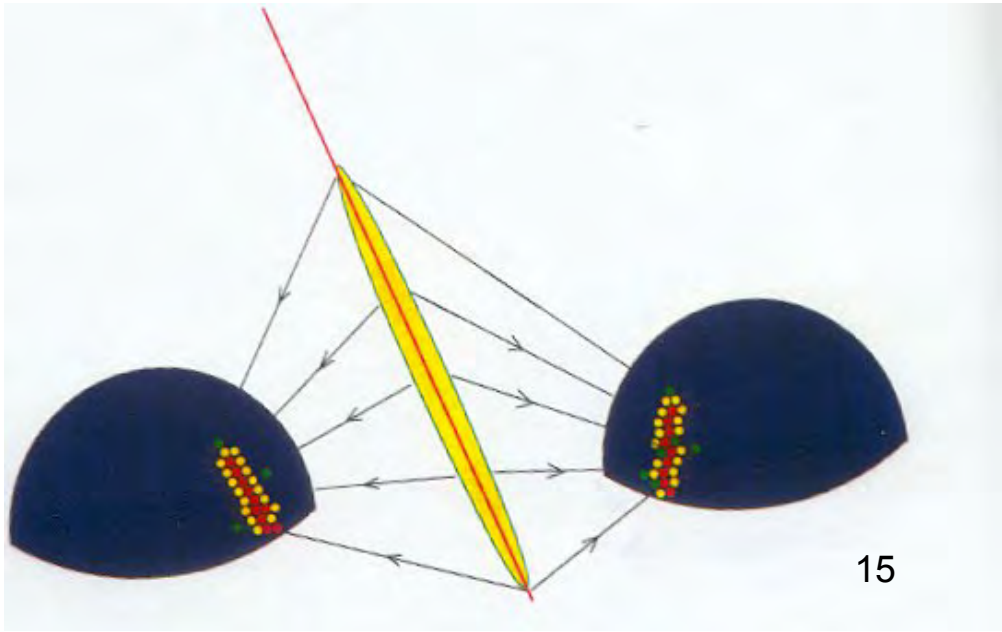


Fluorescence from Earth

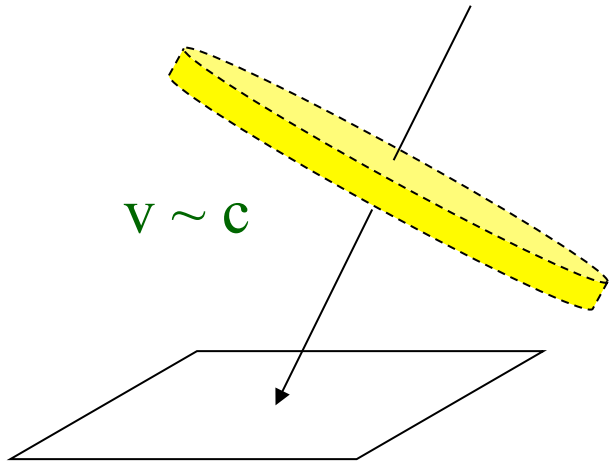
Fly's Eye

HiRes

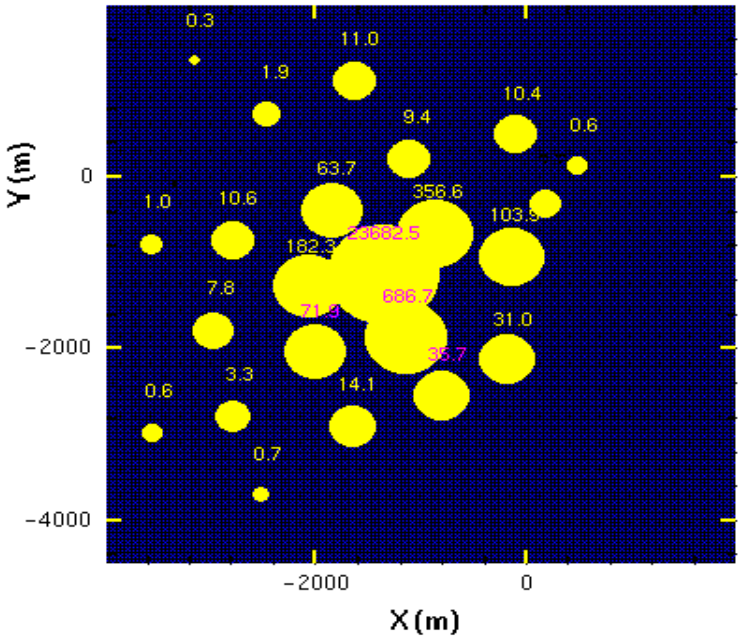
Air shower
stereo image



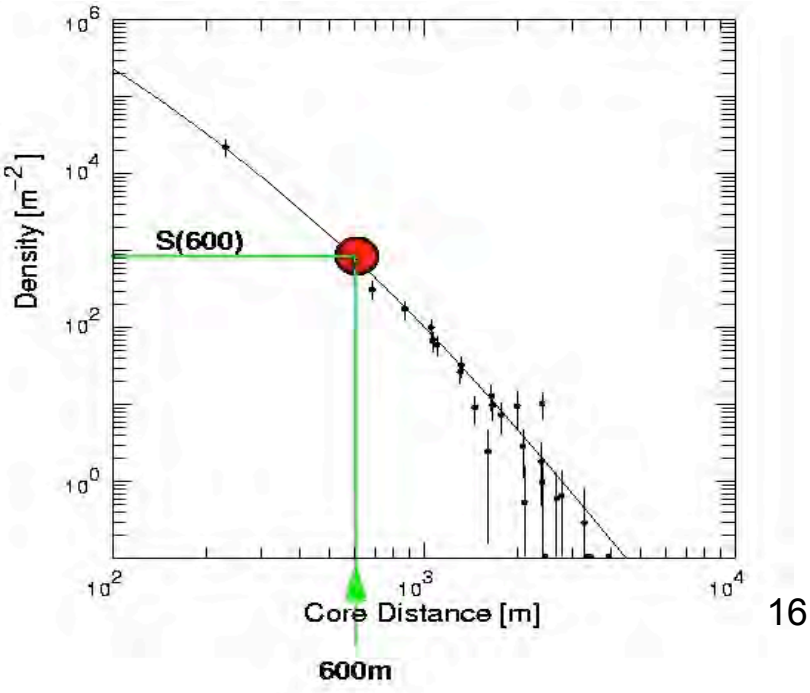
Ground arrays measurements



From (n_i, t_i):
The direction
The core position
The Energy



The LDF



The Pierre Auger Observatory

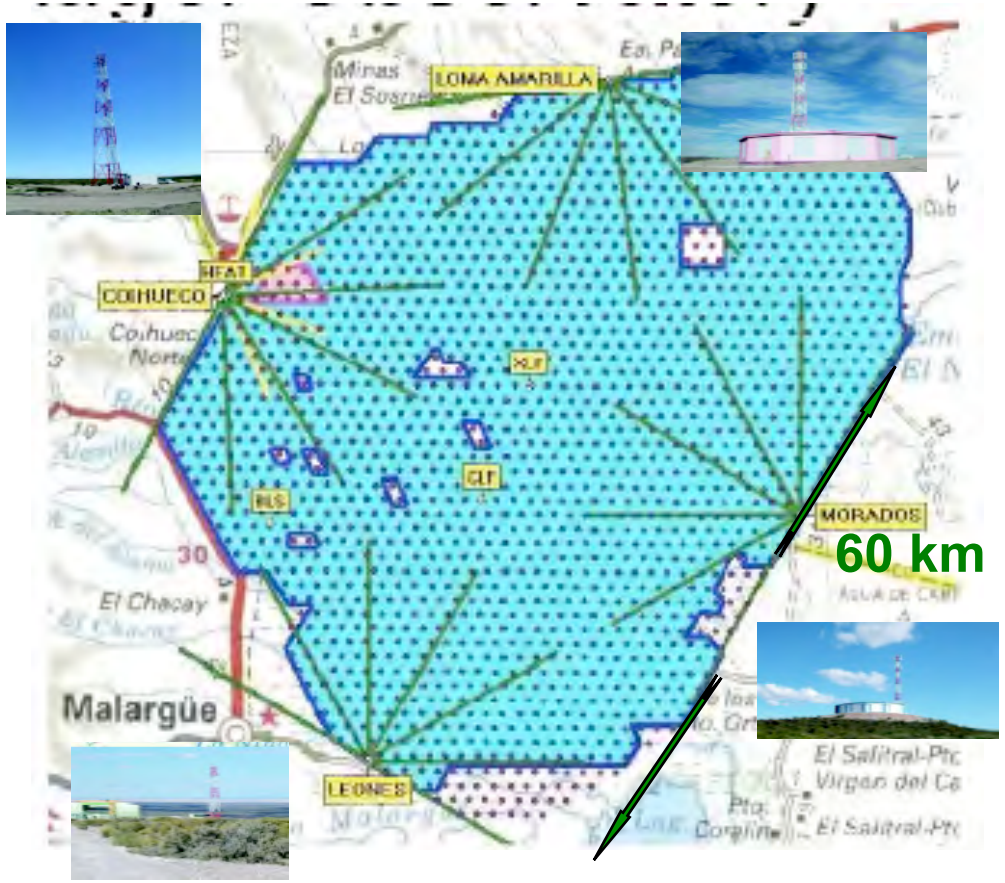
PIERRE AUGER OBSERVATORY

South Hemisphere

Area ~ 3000 km2

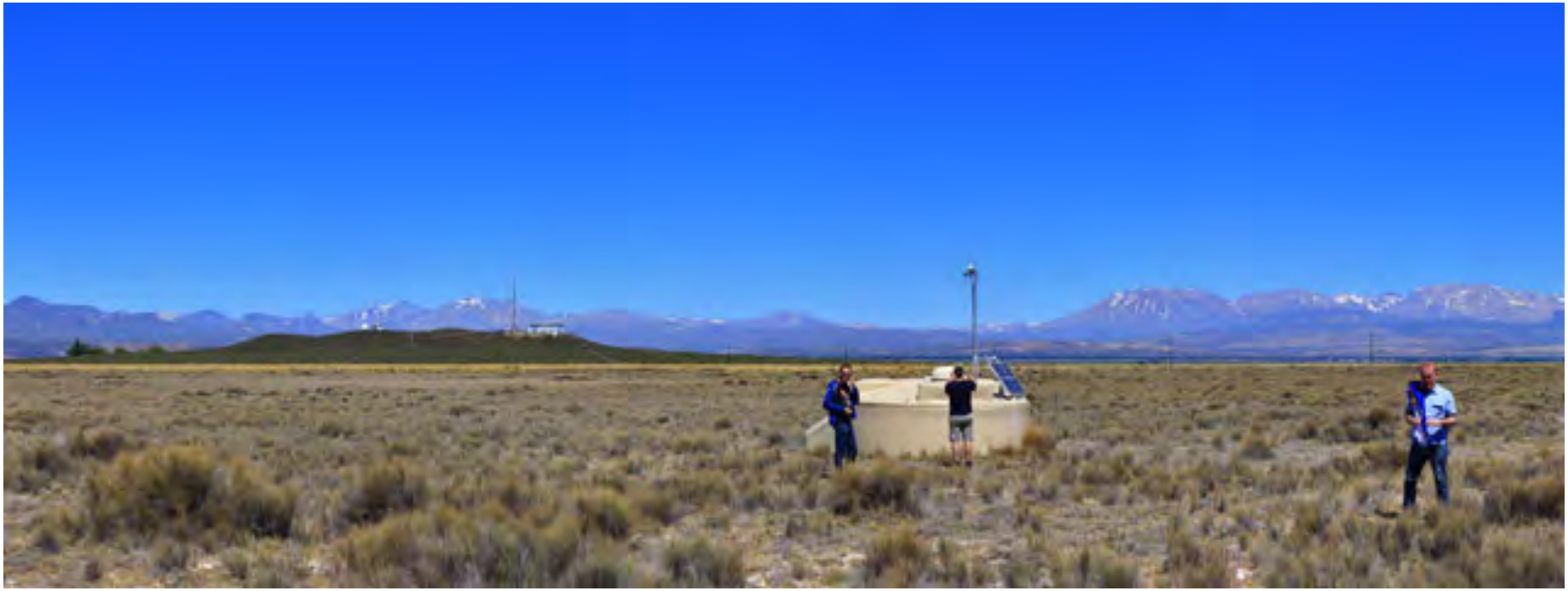
24 fluorescence telescopes

1600 water Cerenkov detectors



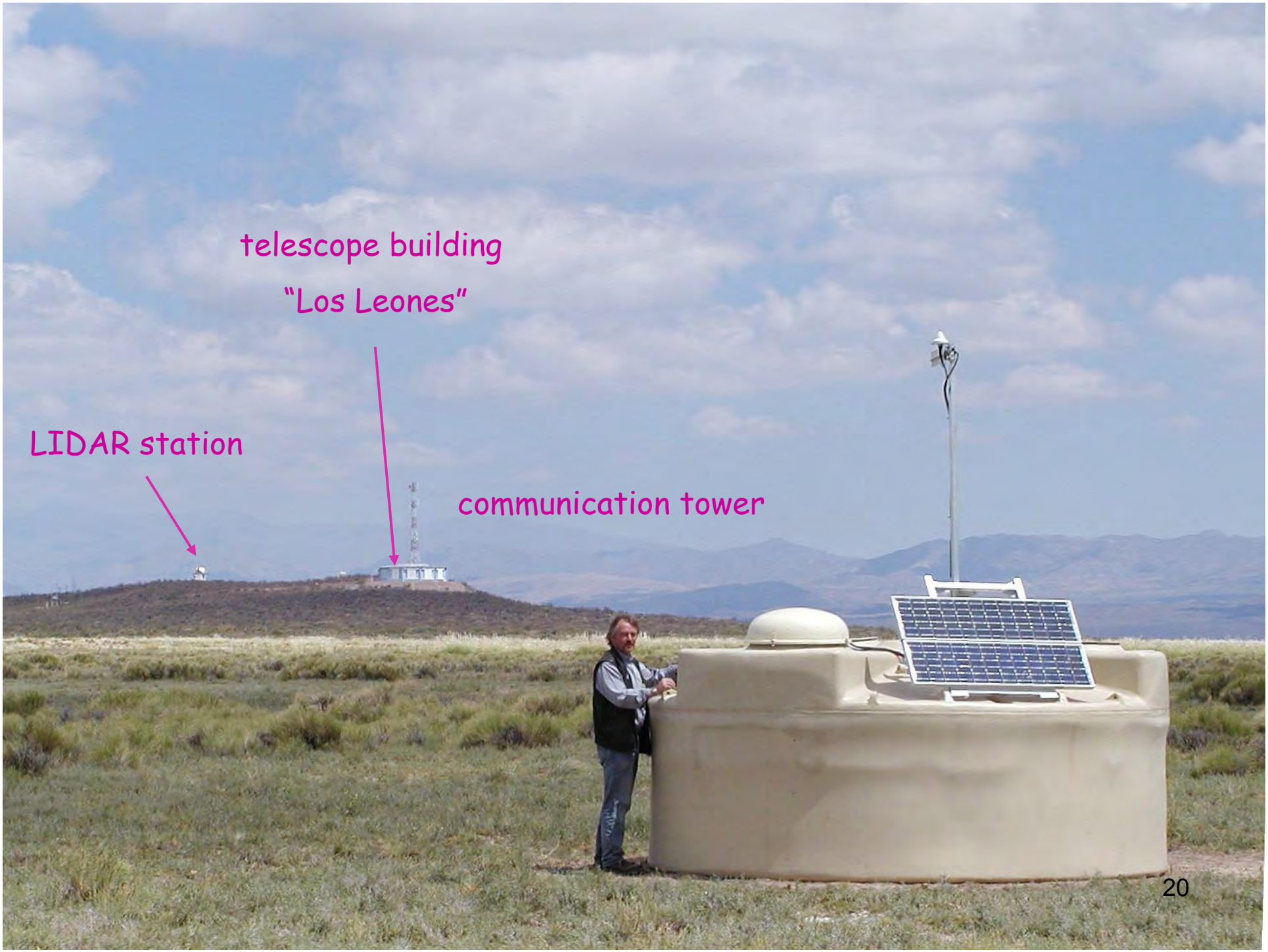
Malargüe, Argentina

Nov 2009




Escuela Nº 4-190
Dr. James W. Cronin
MALARGÜE - MENDOZA

Tanks aligned seen from Los Leones

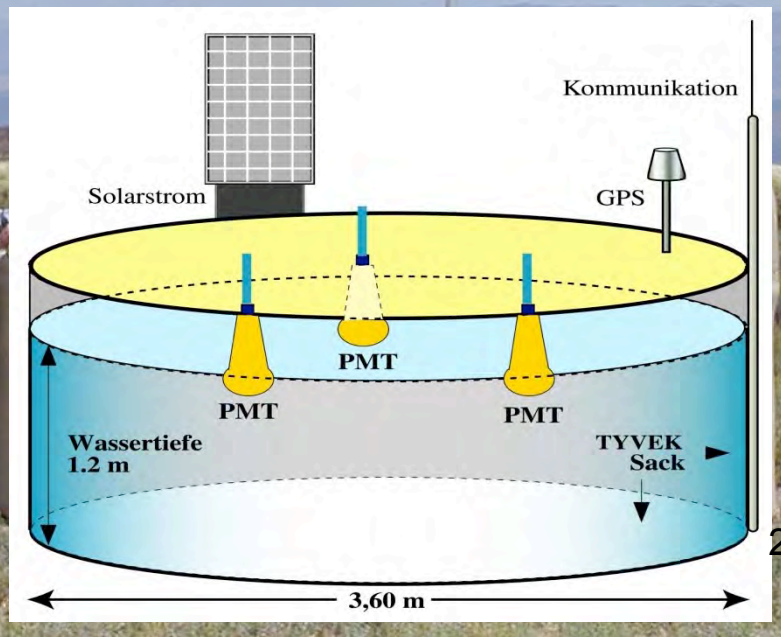

telescope building
"Los Leones"
LIDAR station
communication tower

telescope building

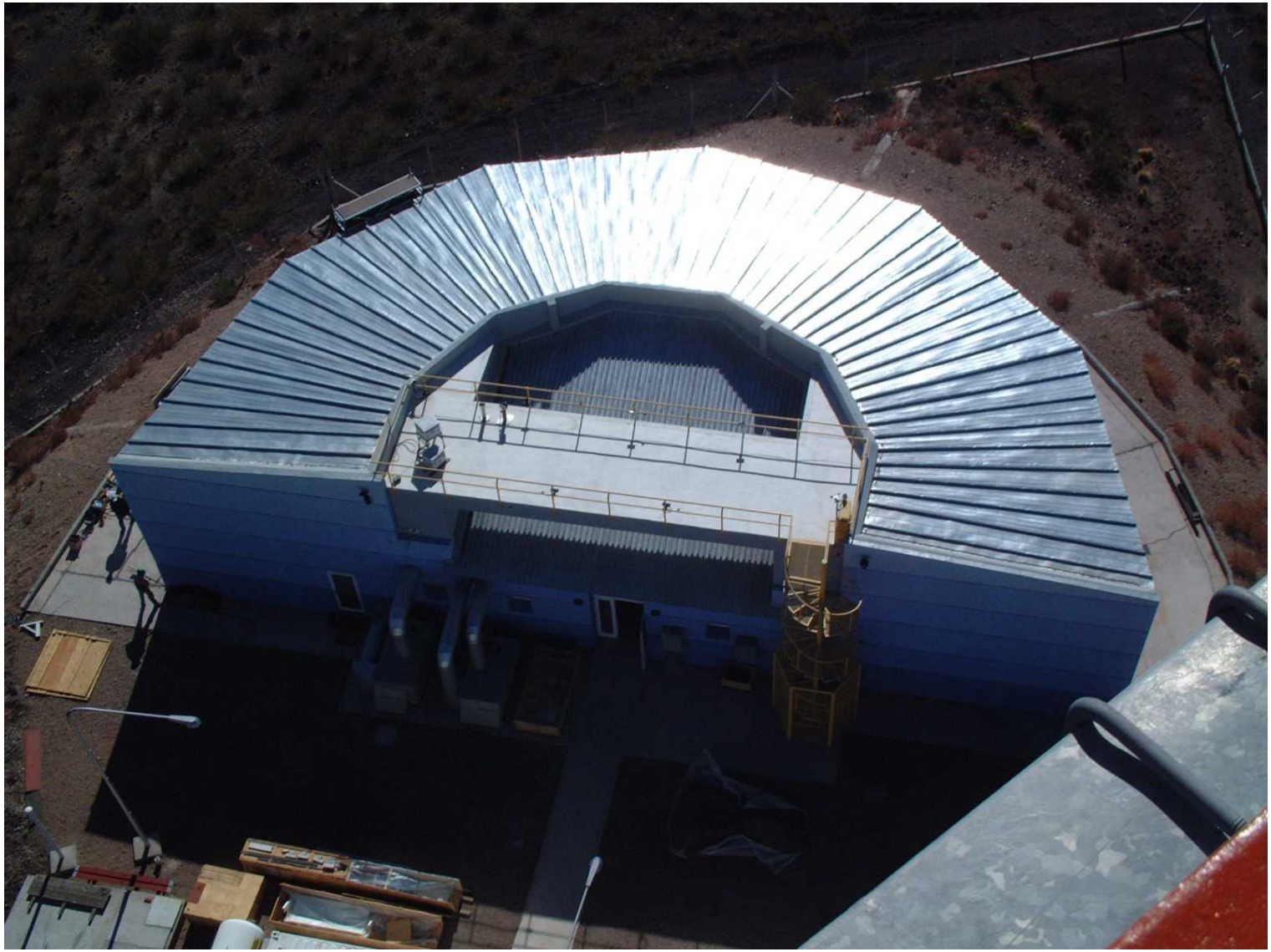
"Los Leones"

LIDAR station

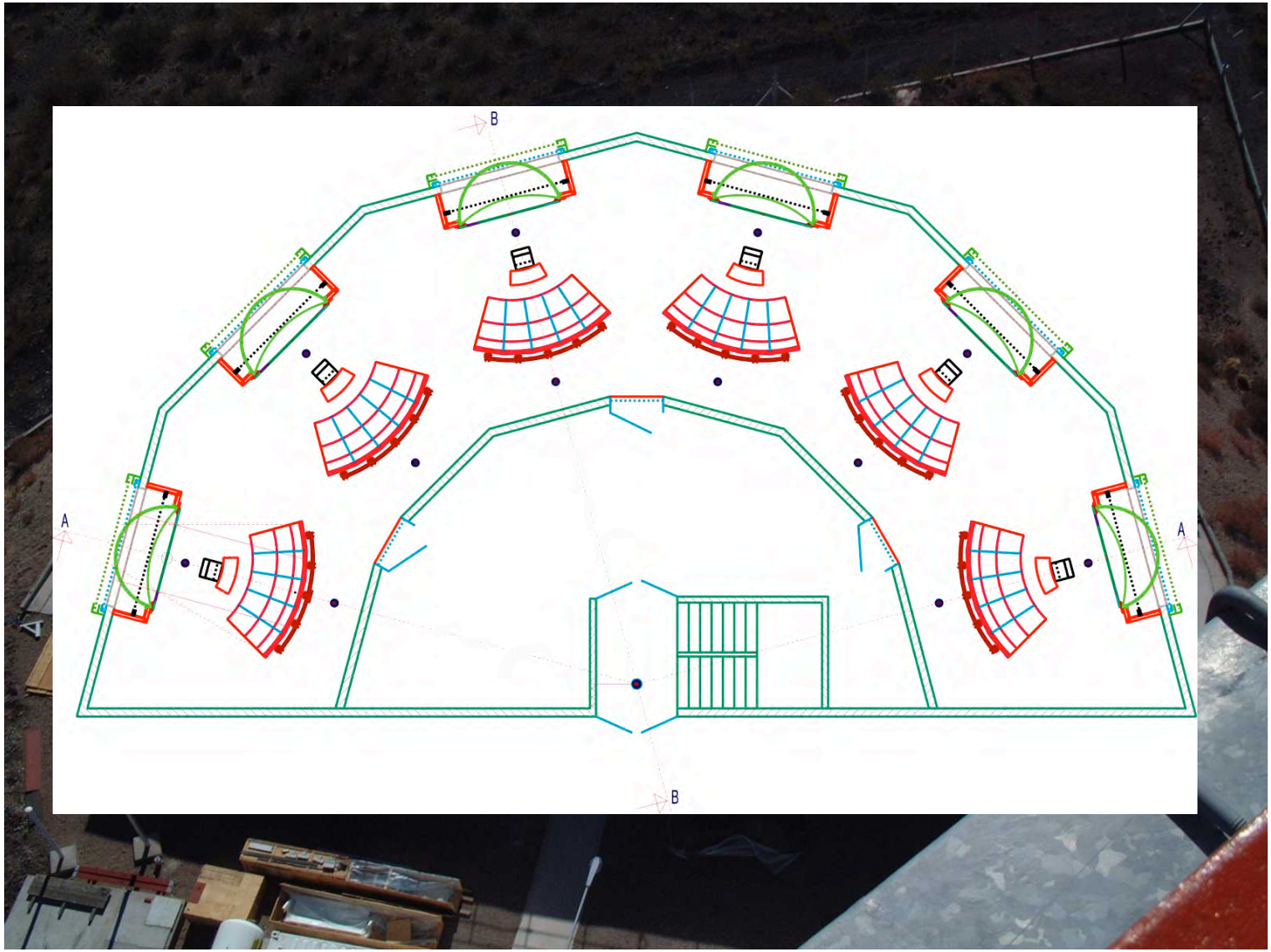
communication tower



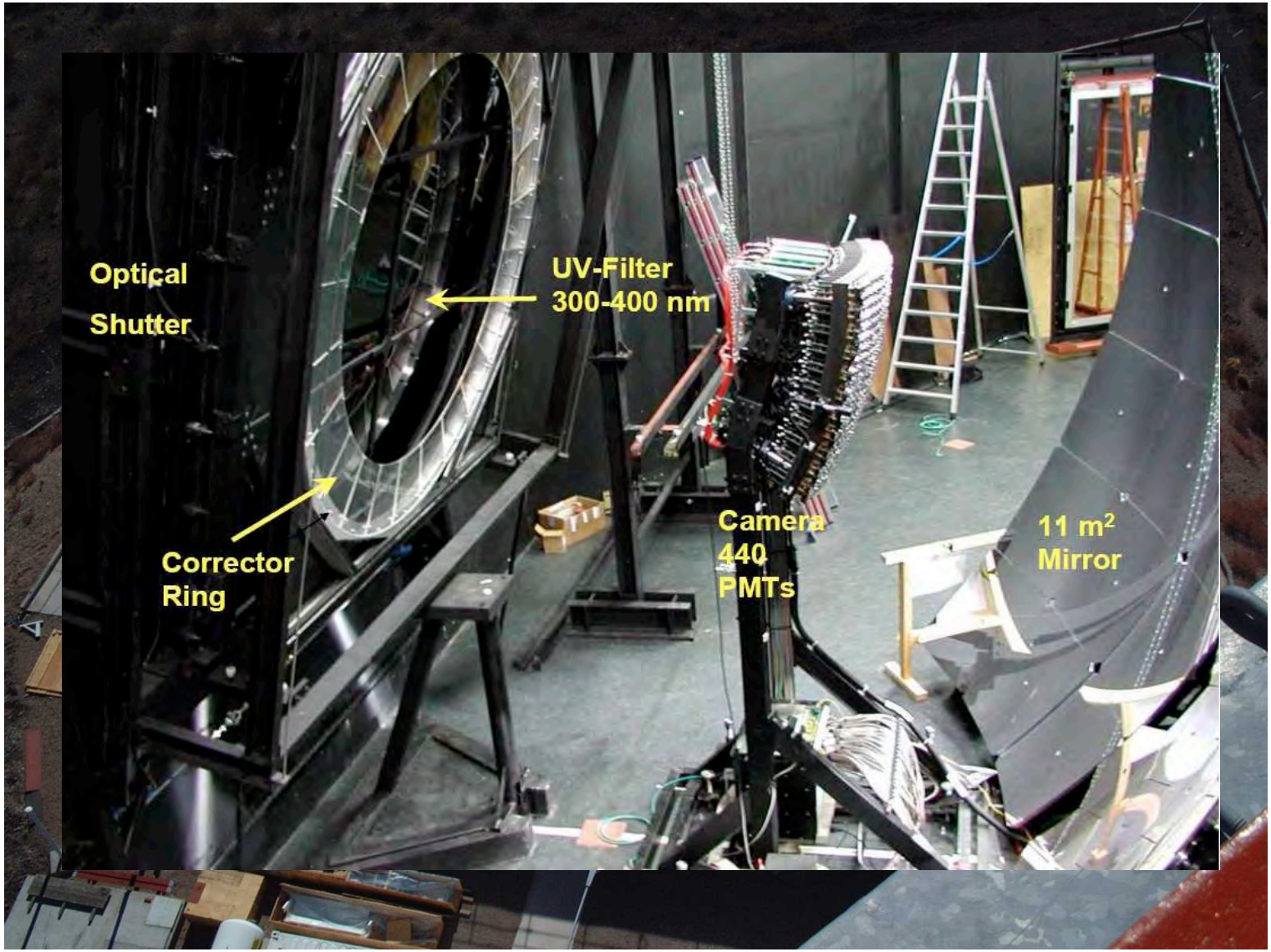
The fluorescence detectors (FD)



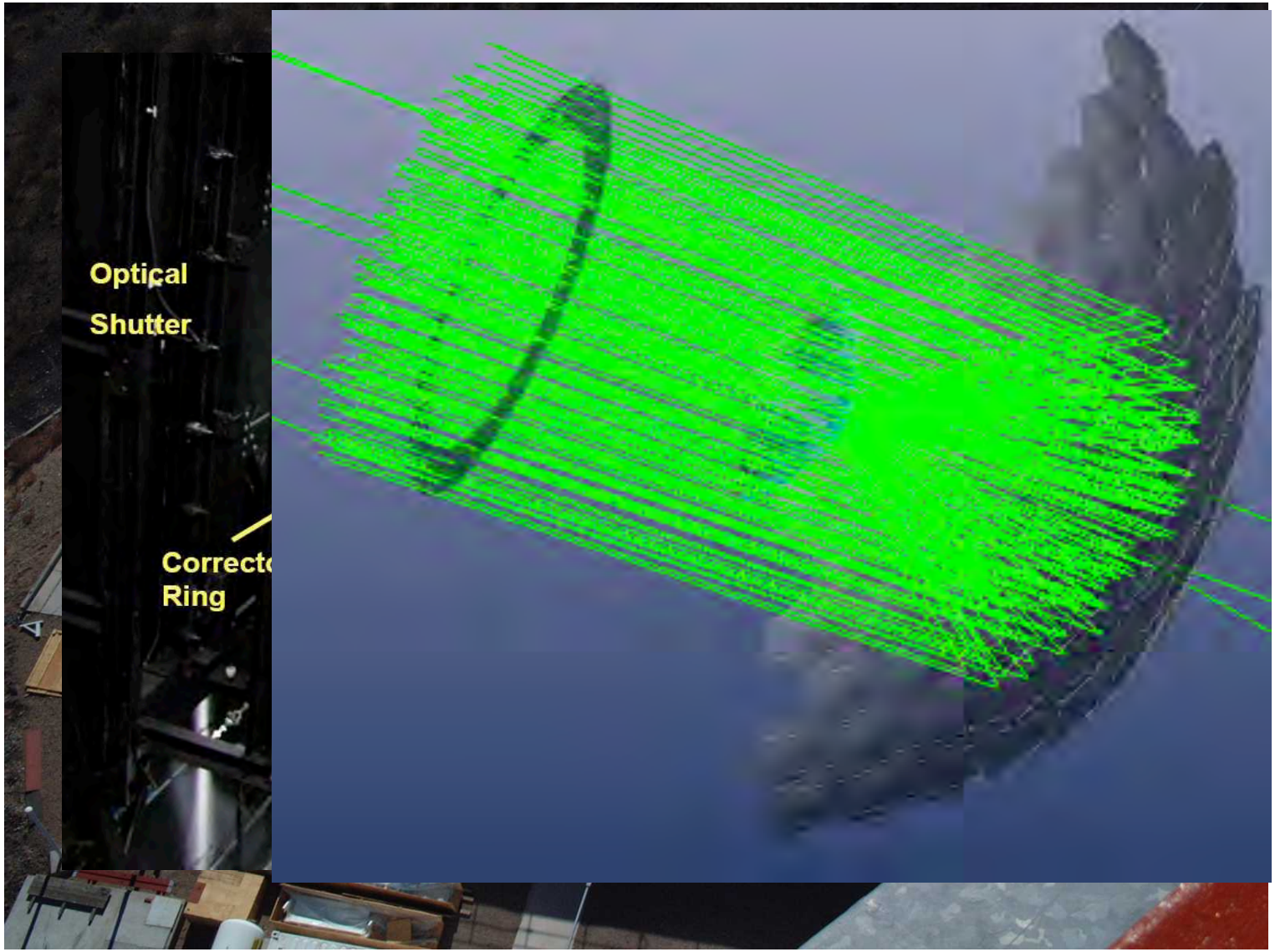
The fluorescence detectors (FD)



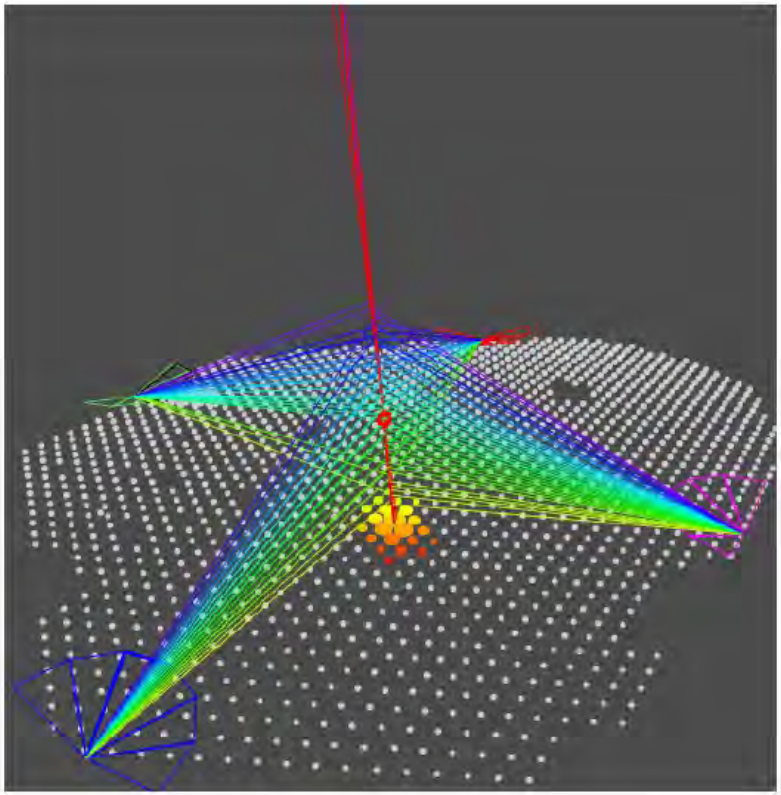
The fluorescence detectors (FD)

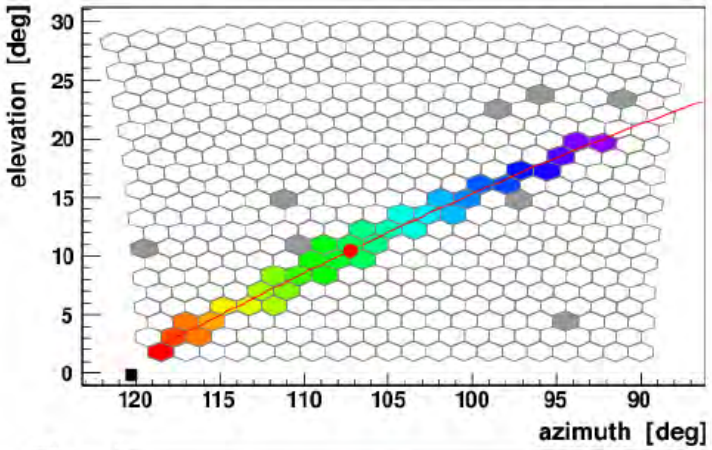


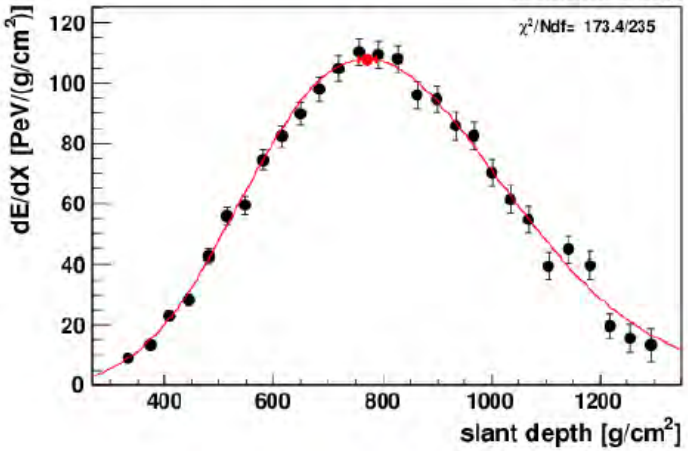
The fluorescence detectors (FD)

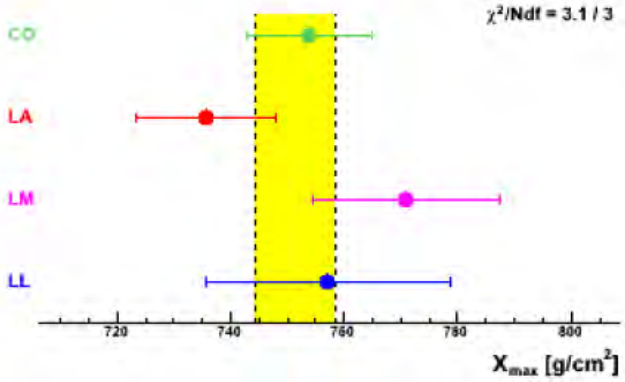


A 4 eyes hybrid event !









Energy

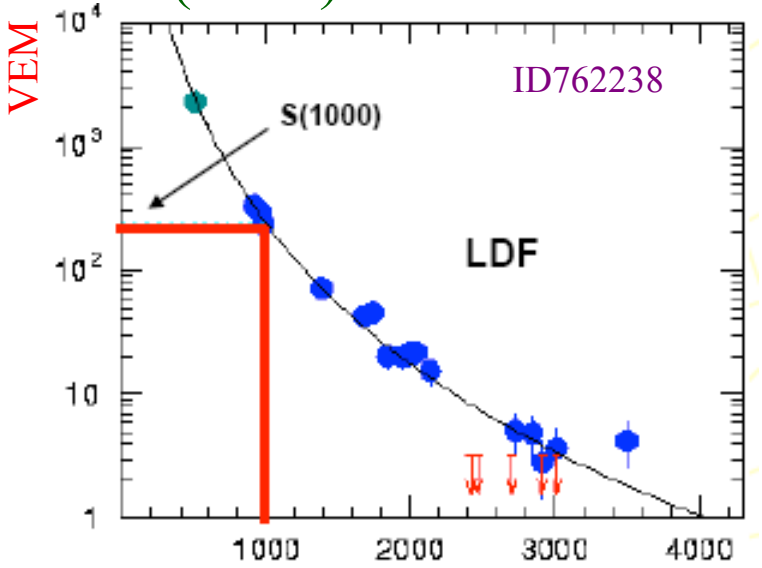
E = (7.1± 0.2) 10^{19} eV

Depth of the maximum

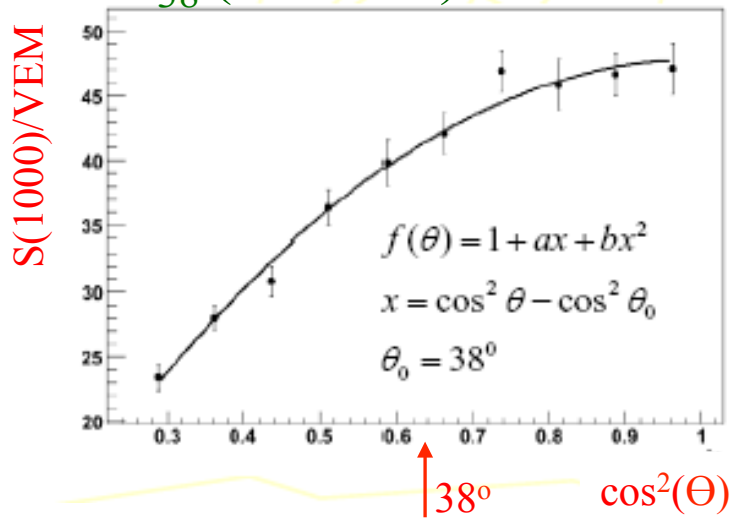
X_{max} = (752 ± 7) g/cm²

Energy determination in Auger

S(1000)



S_{38} (das CIC)



Calibration

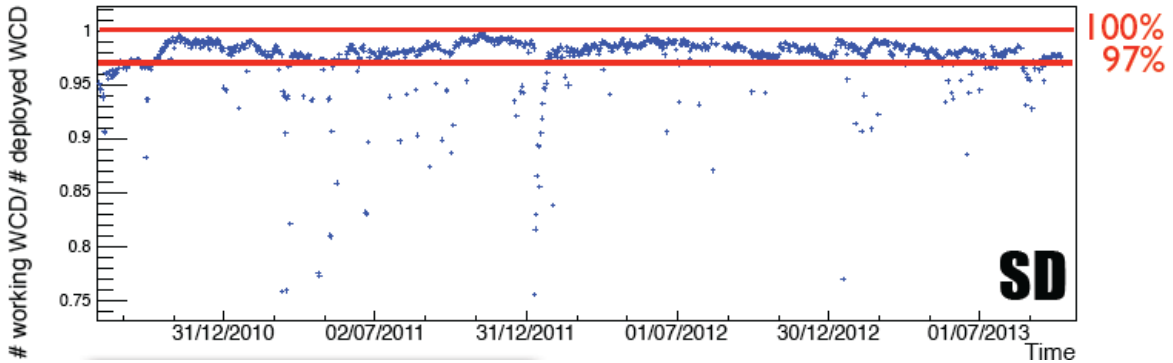
Impossibile visualizzare l'immagine. La memoria del computer potrebbe essere insufficiente per aprire l'immagine oppure l'immagine potrebbe essere danneggiata. Riavviare il computer e aprire di nuovo il file. Se viene visualizzata di nuovo la x rossa, potrebbe essere necessario eliminare l'immagine e inserirla di nuovo.

$\sigma_E \sim 10\%$

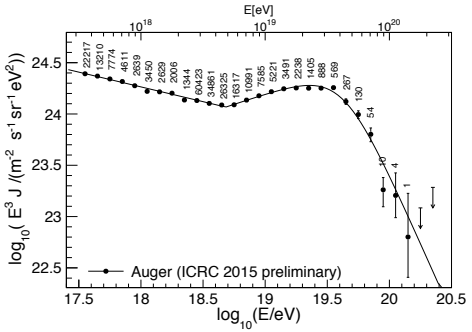
Auger is running smoothly

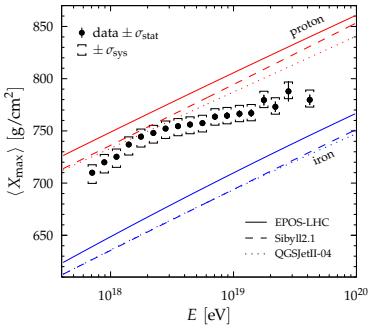
The Swiss clock!

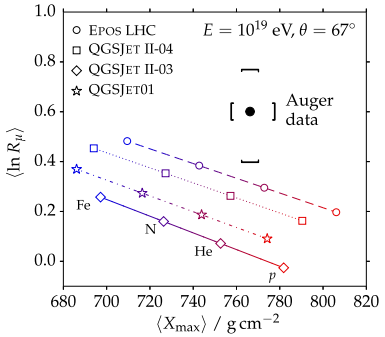
Fraction of Water Cherenkov Tanks in operation

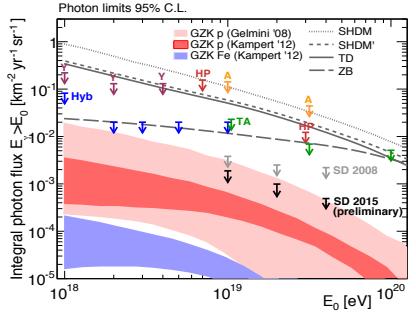


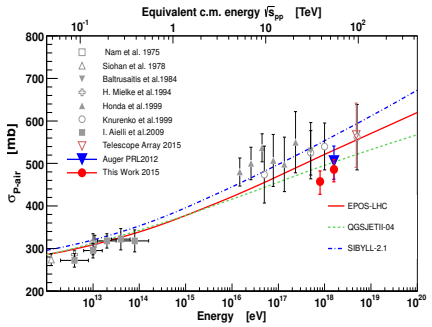
Many and important results !

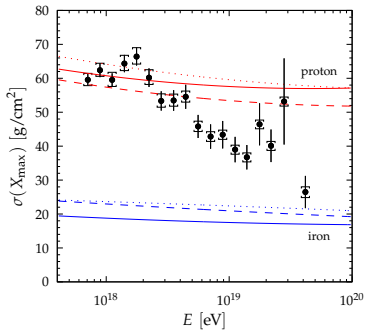


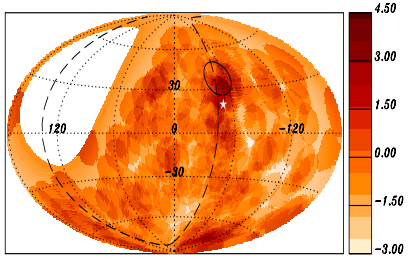


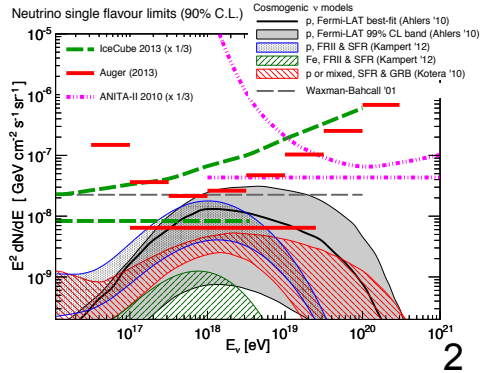




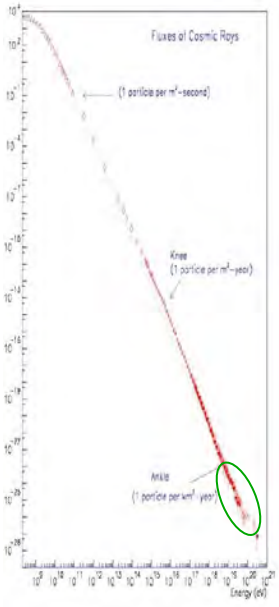


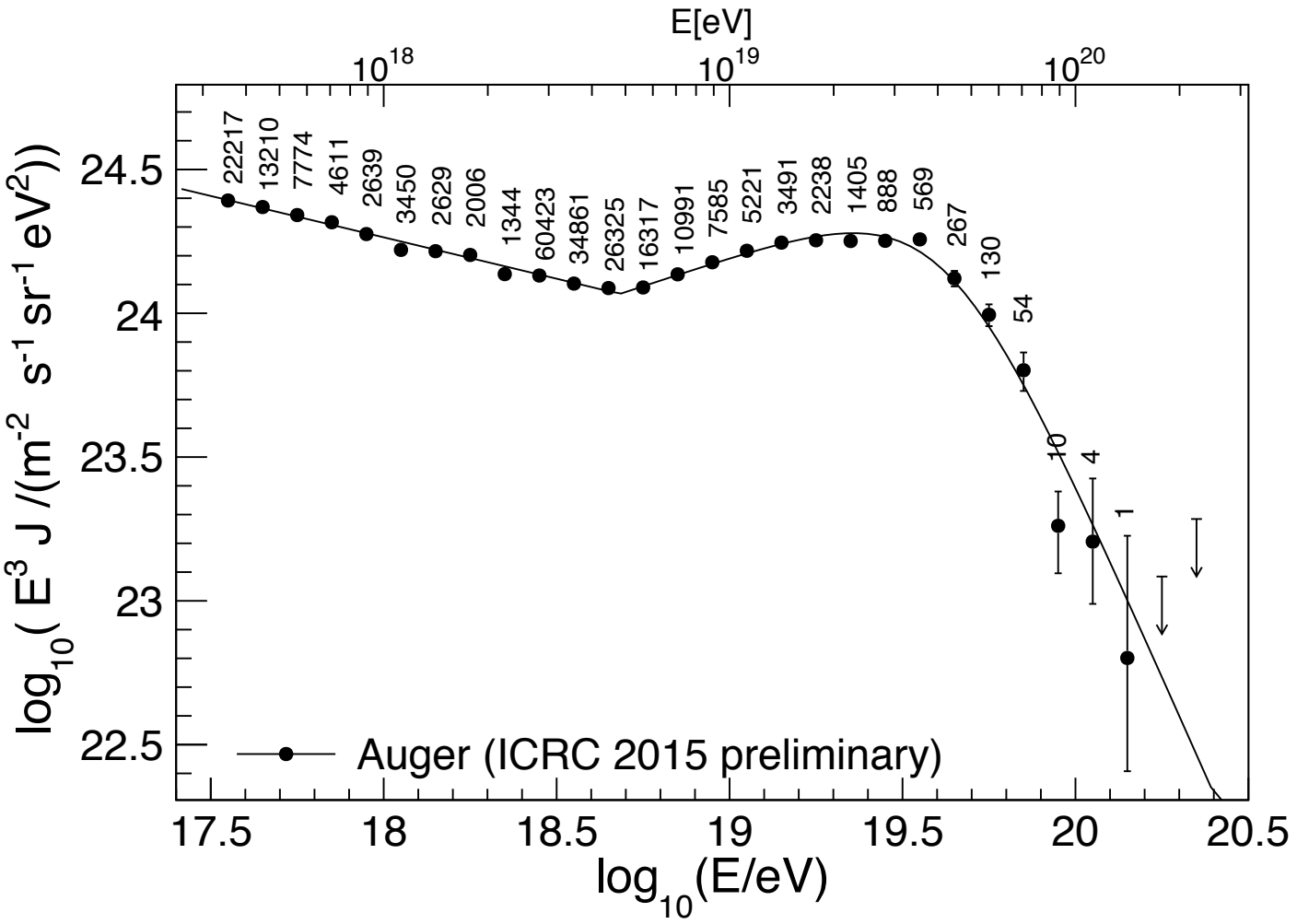




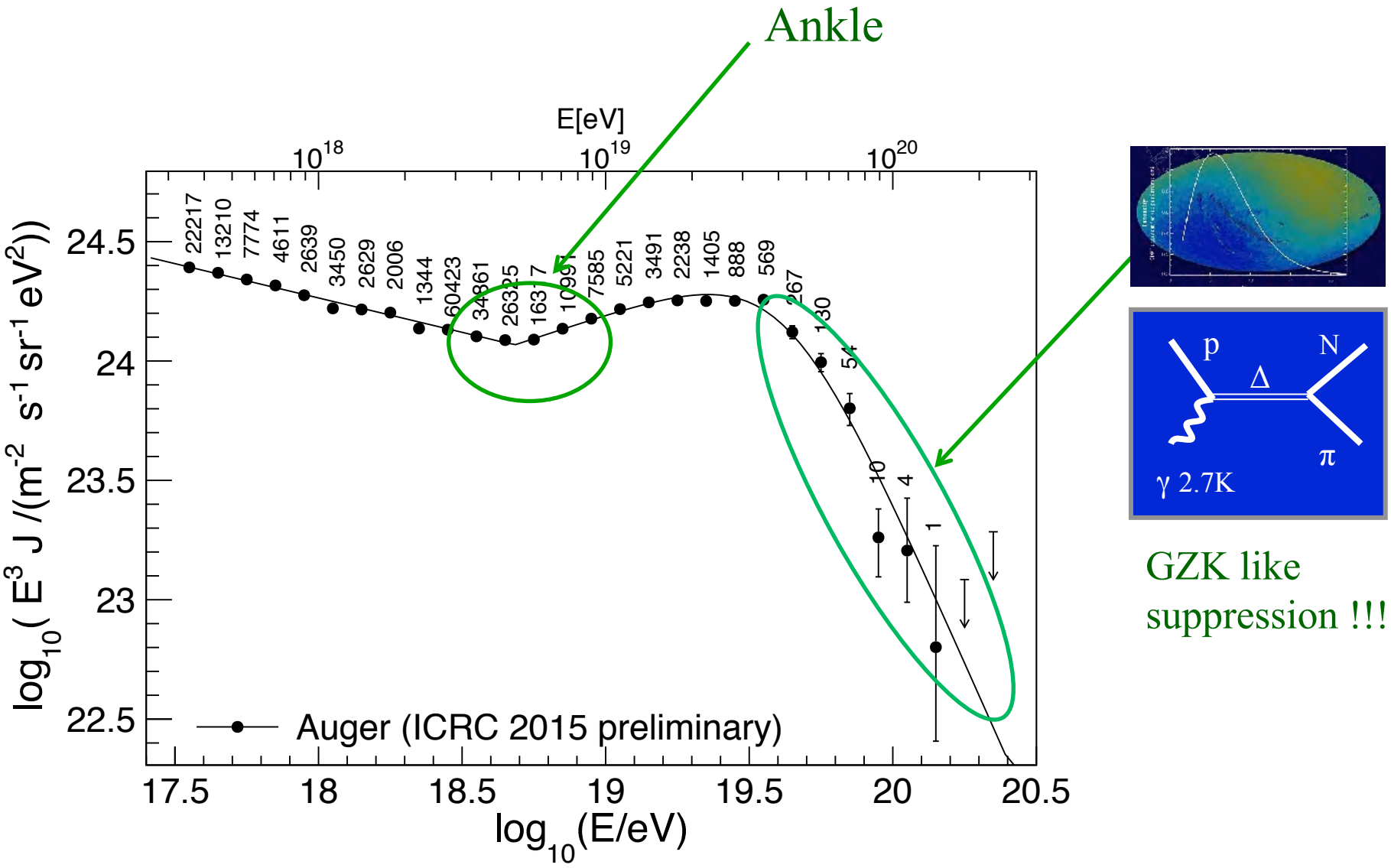


Energy spectrum

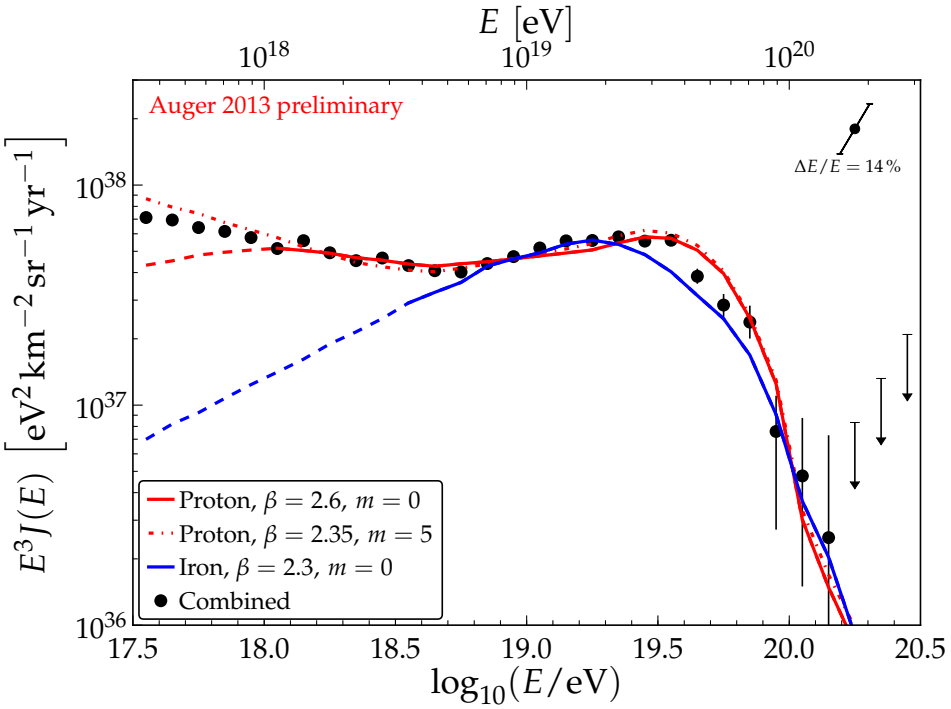


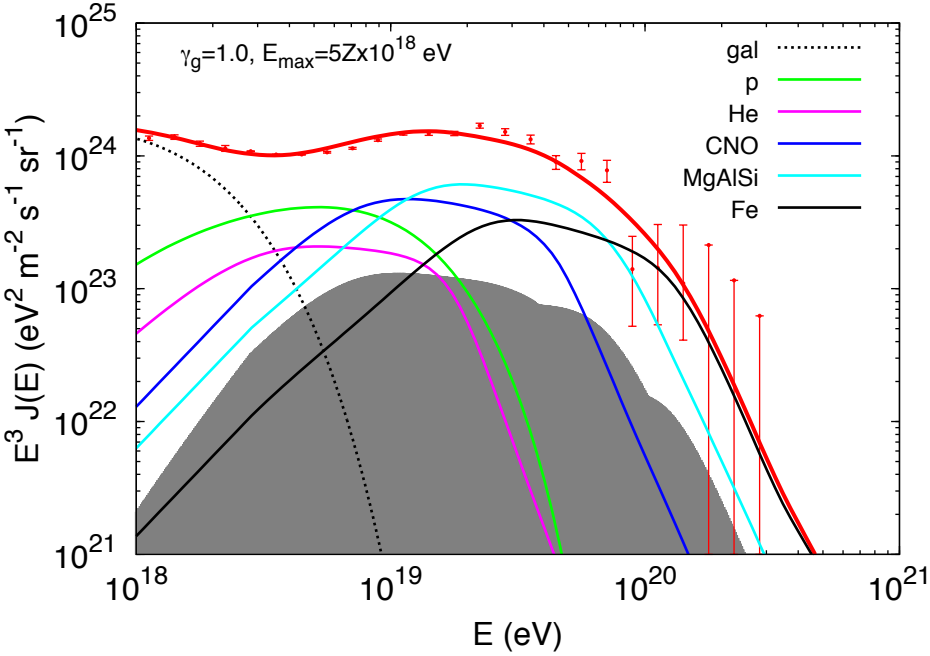


Energy spectrum



GZK or the exhaustion of sources ???





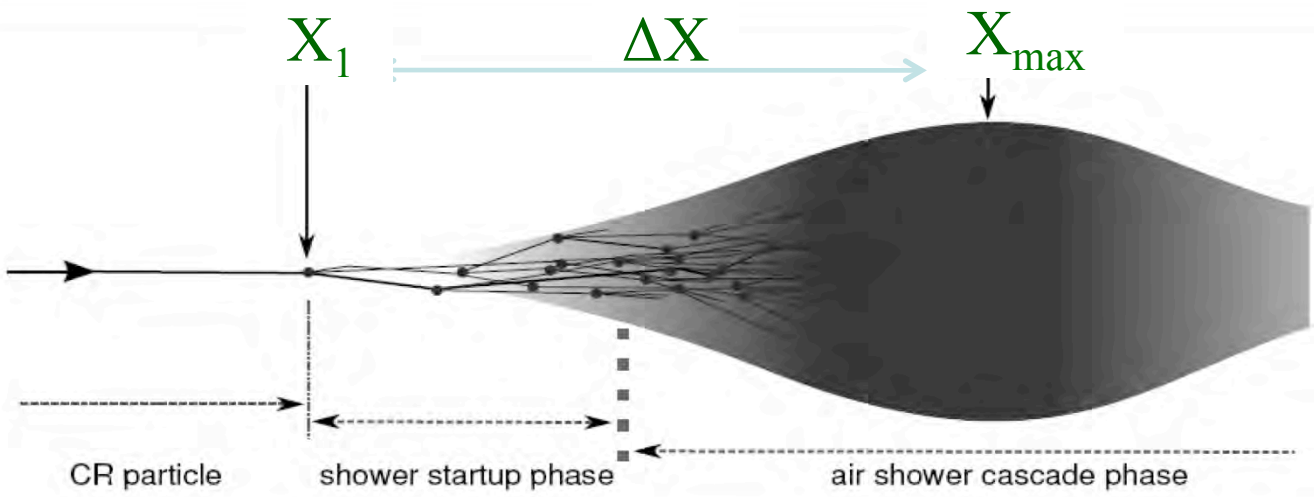
Composition is the key to disentangle the two scenarios!

X_{max} and the “beam composition”

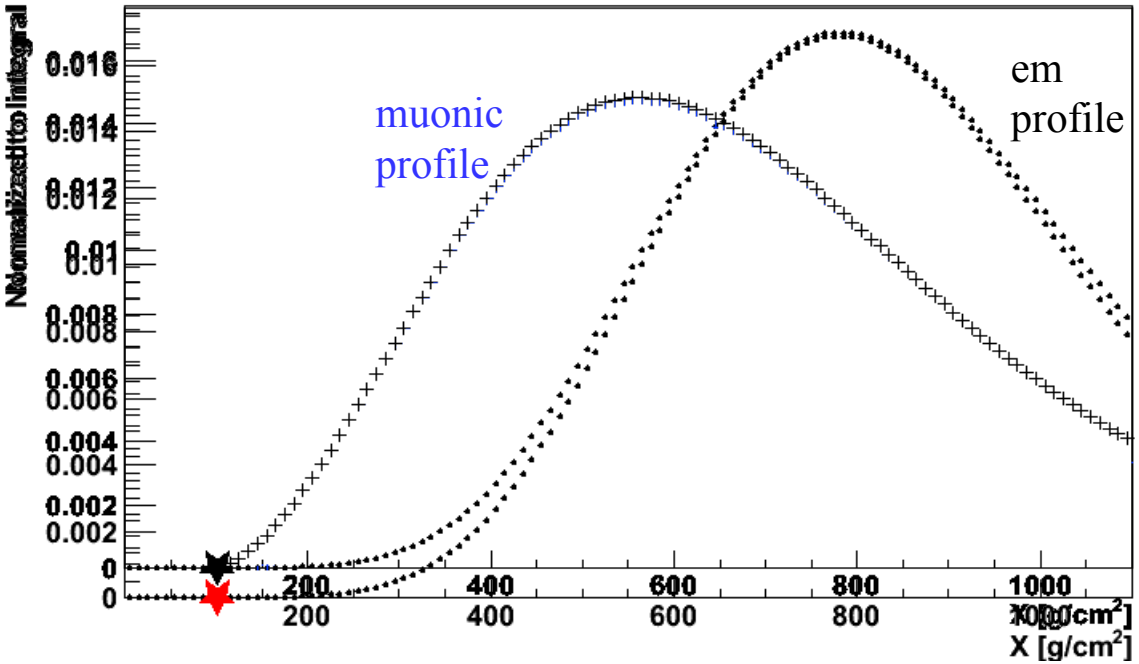
Proton

Nuclei
(Iron, …)

Shower development



$$X_{max} = X_1 + \Delta X$$



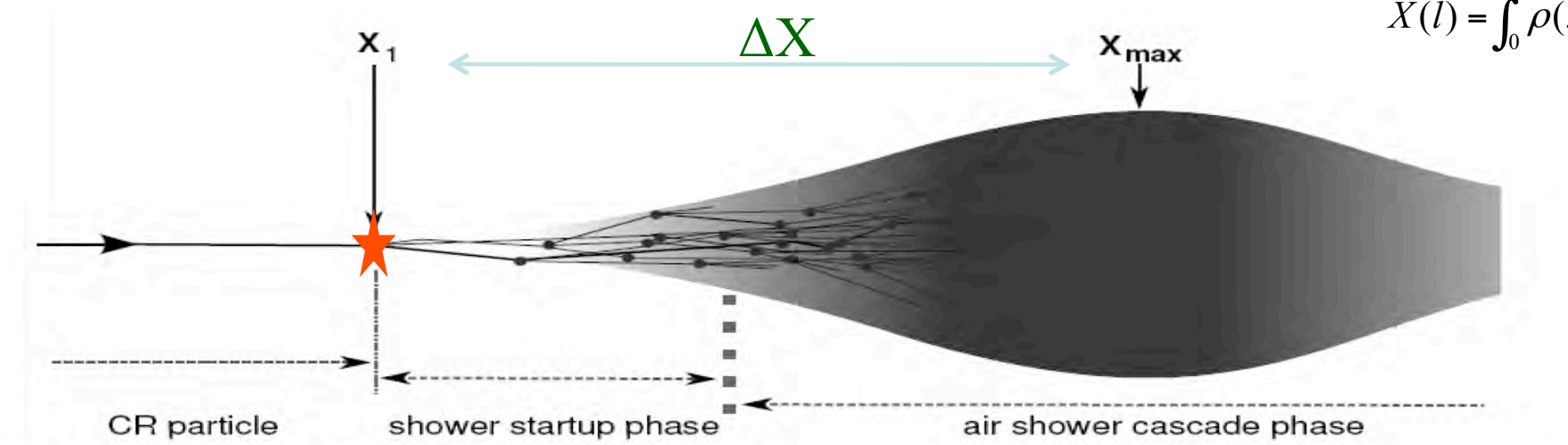
$$E \propto Ne$$

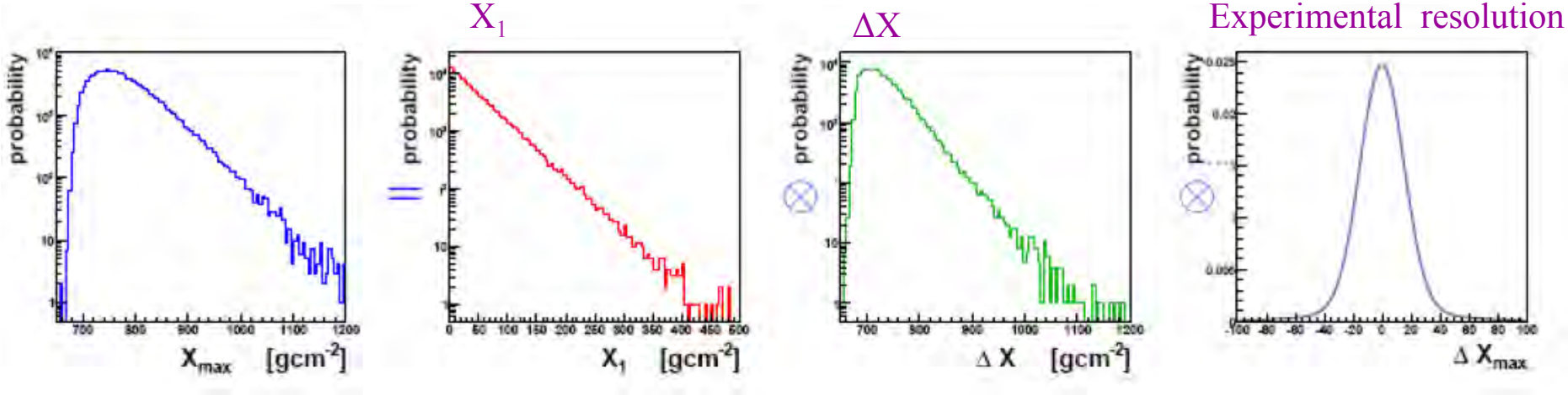
$$\propto \int \frac{dN_e}{dX} dX$$

$$N_\mu \propto \int \frac{dN_\mu}{dX} dX$$

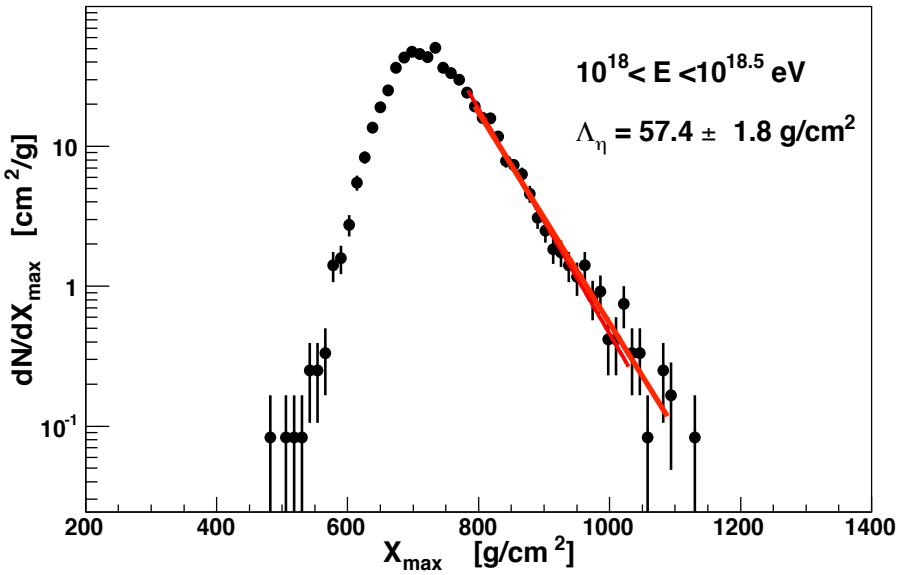
The "X_{max} distributions"

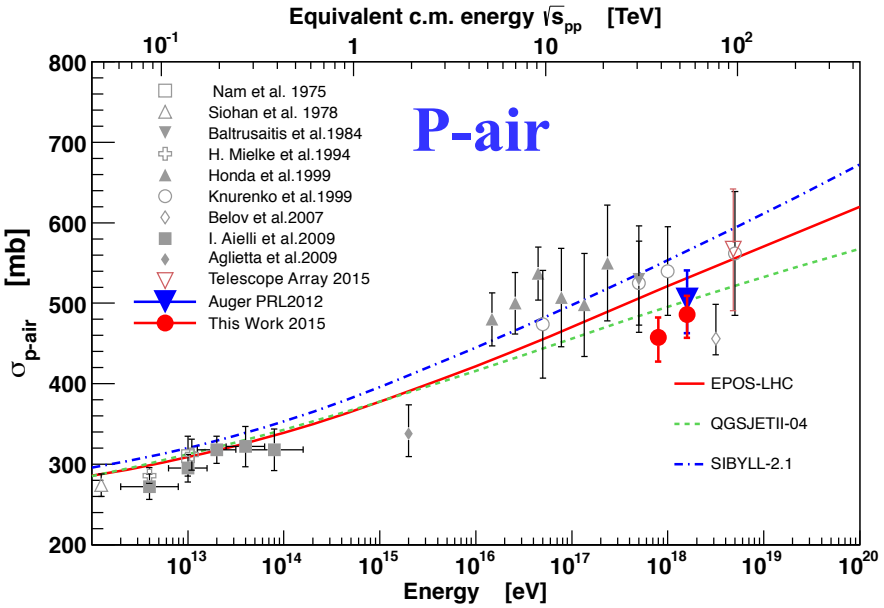
$$X(l) = \int_0^l \rho(x)dx$$





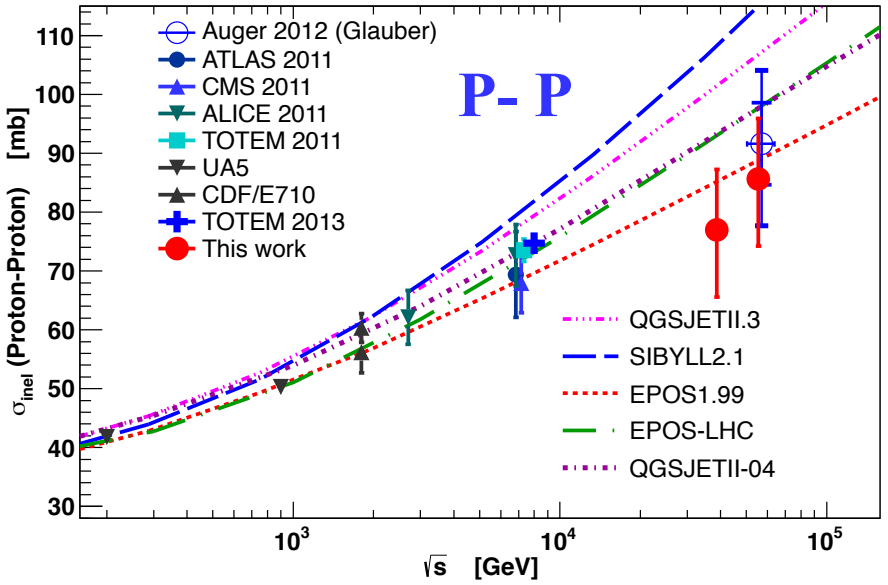
Proton cross-section





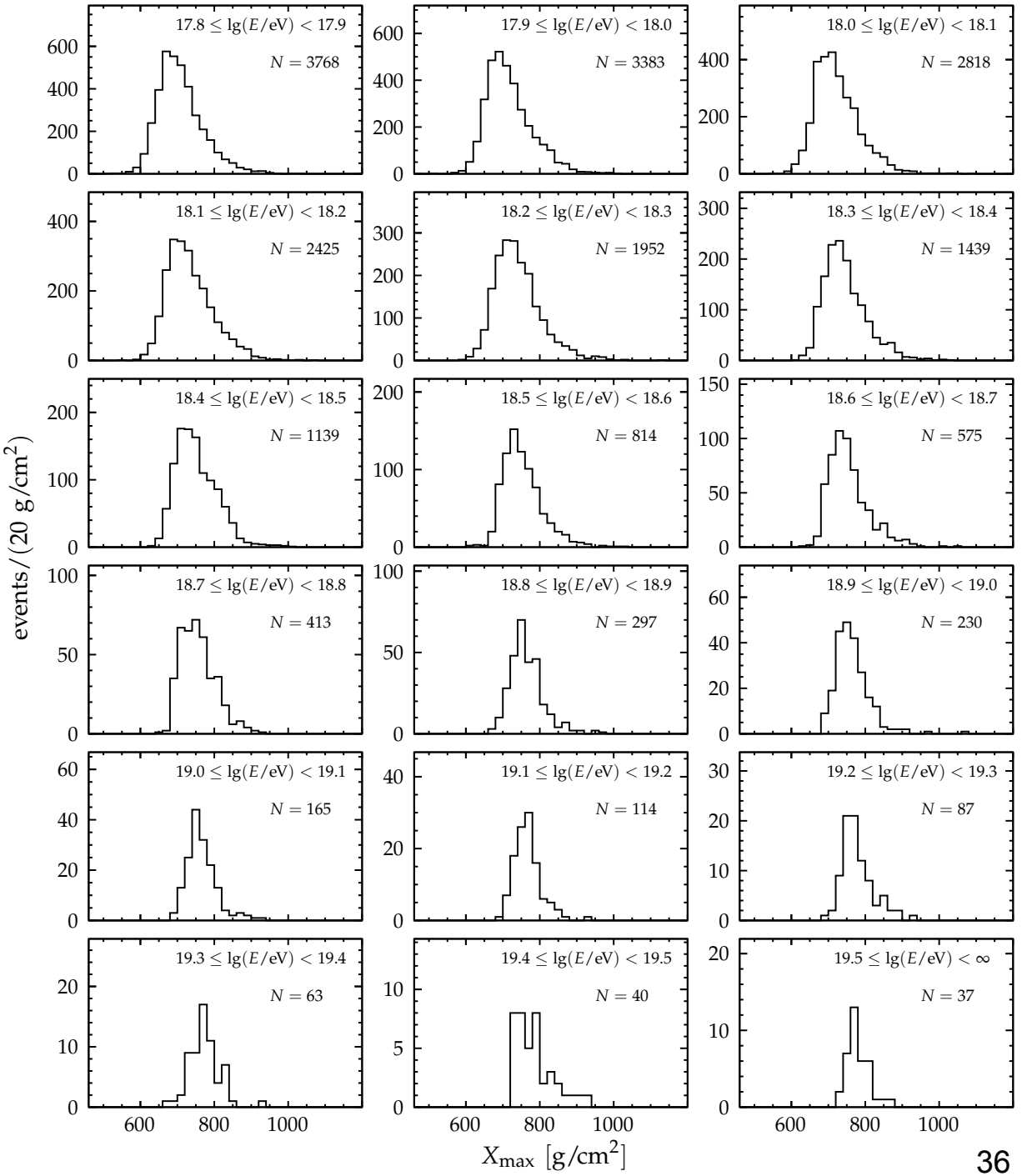
If % p > 20%, % He < 25%

Slightly lower than it was expected at the time by most of the models, but in good agreement with recent LHC data.

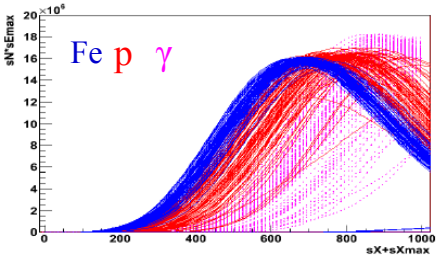


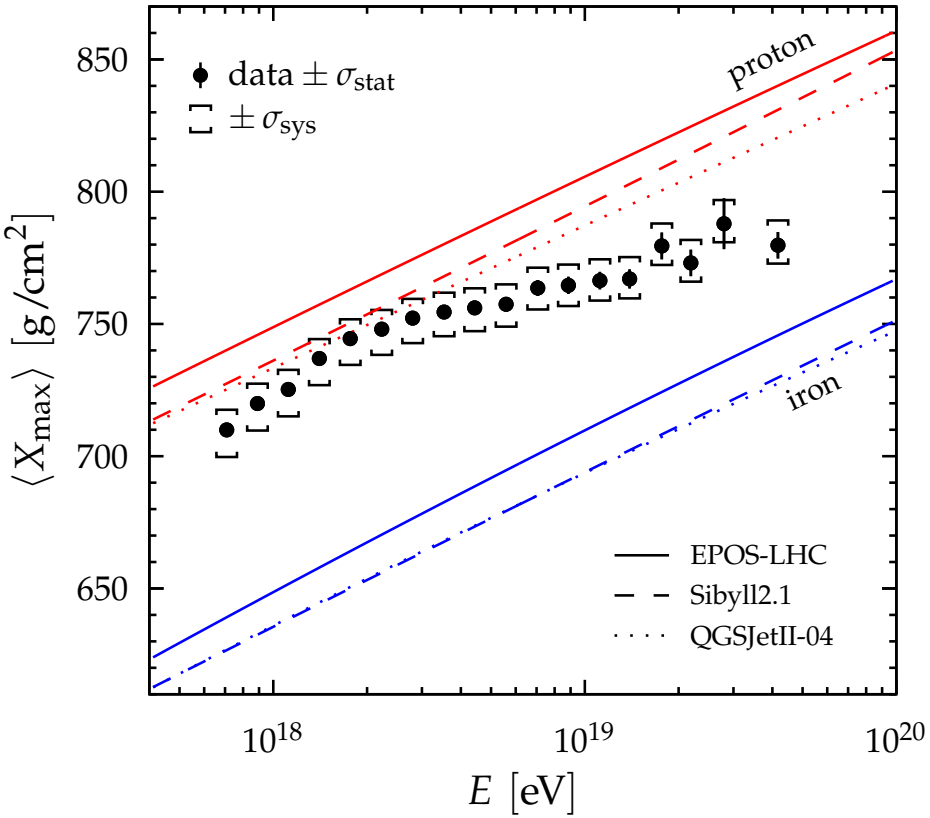
X_{max} distributions

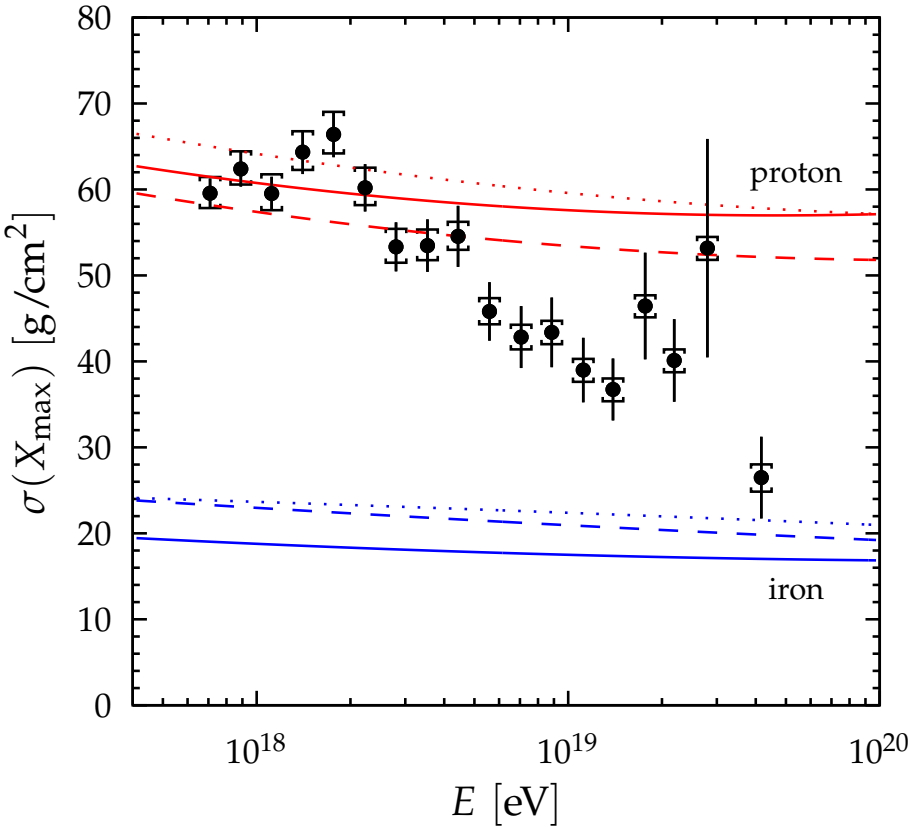
As the energy increases the distributions become narrower !!!



<X_{max}> and RMS(X_{max})







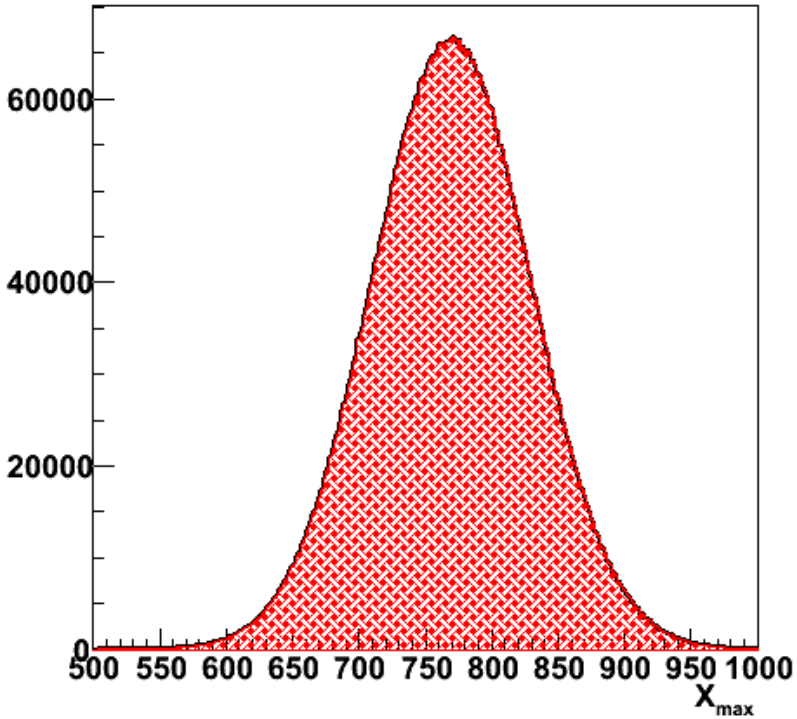
A clear change above 3 10^{18} eV

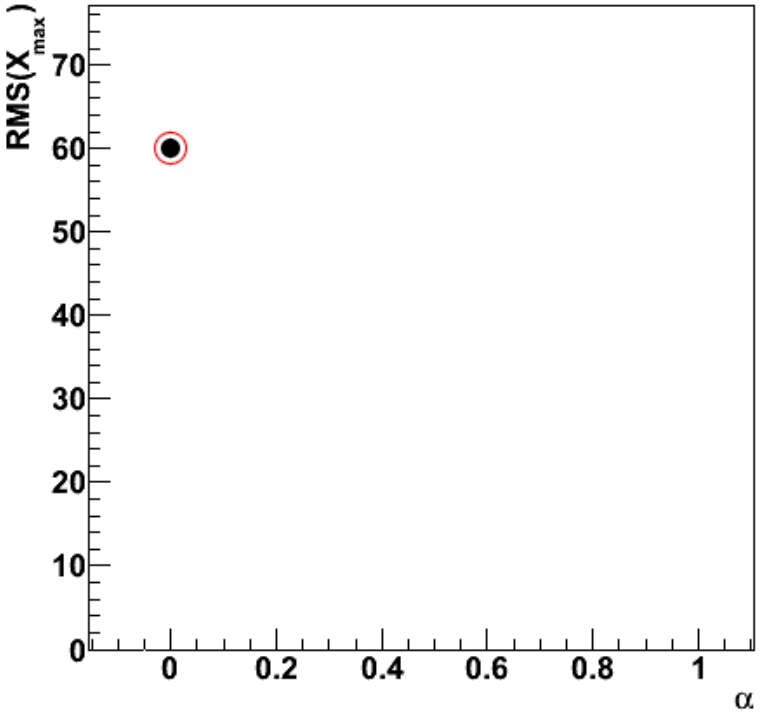
Beam composition ??? Hadronic interactions???

But if just proton and iron …

Xmax distribution and RMS

α : iron fraction ; (1-α): proton fraction





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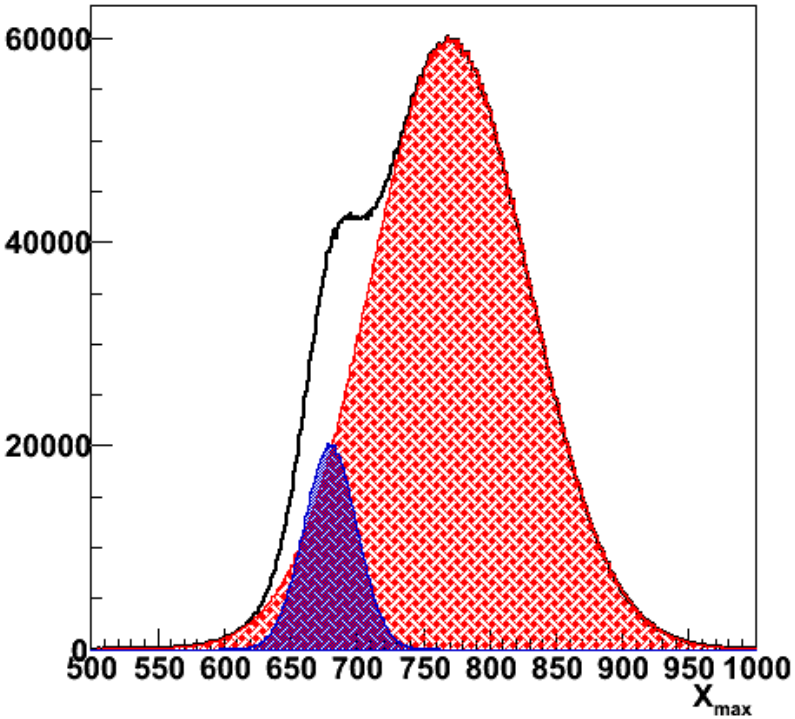

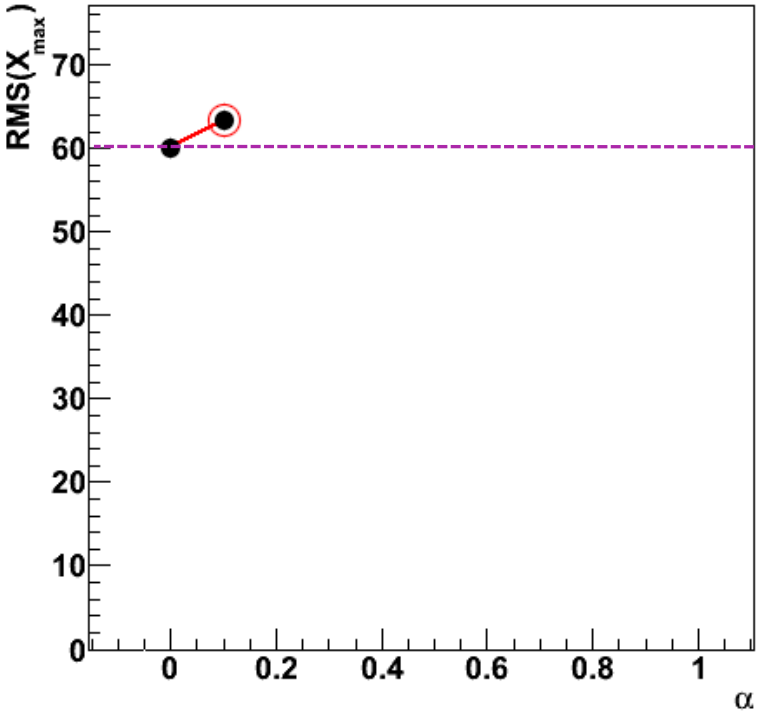

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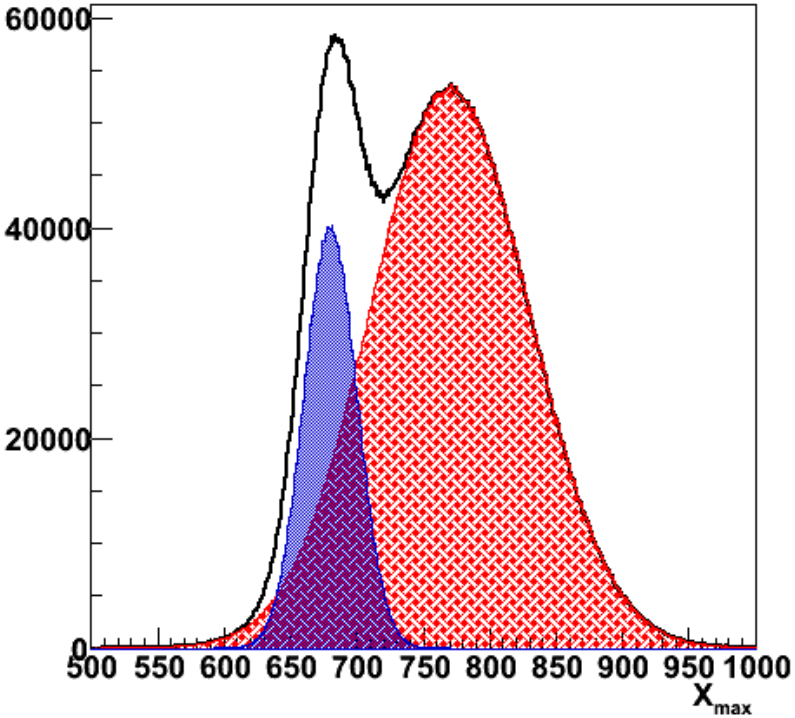

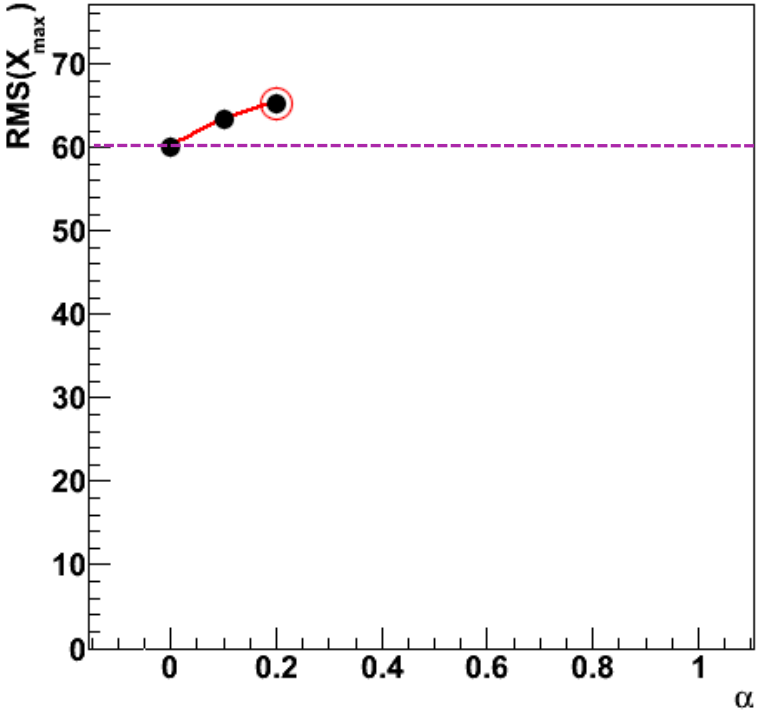

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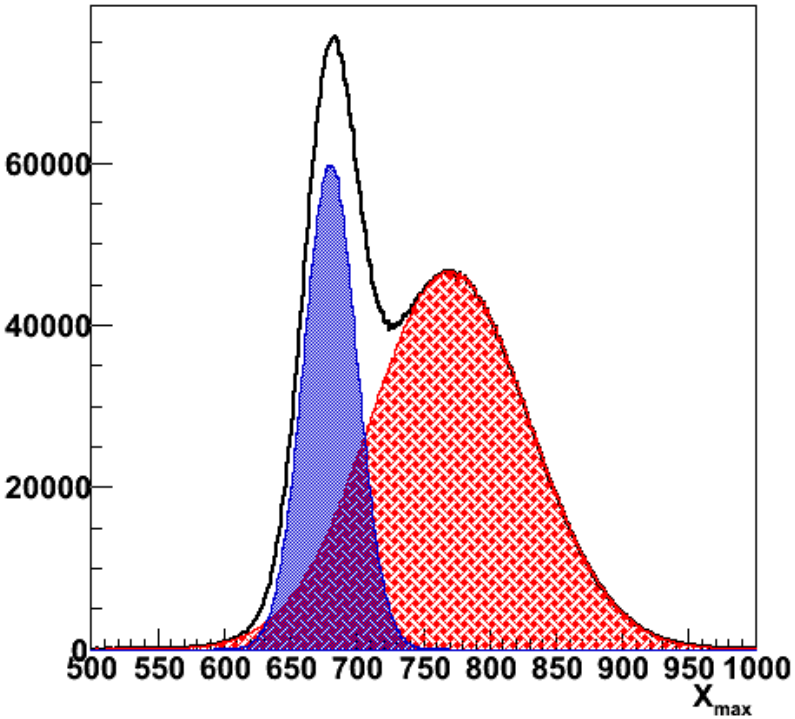
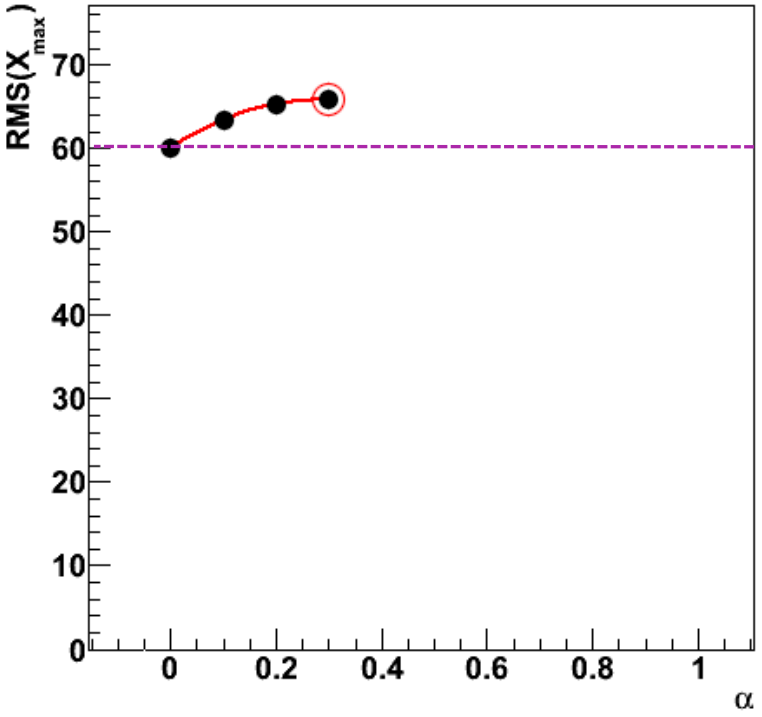
Xmax distribution and RMS

α : iron fraction ; (1-α): proton fraction

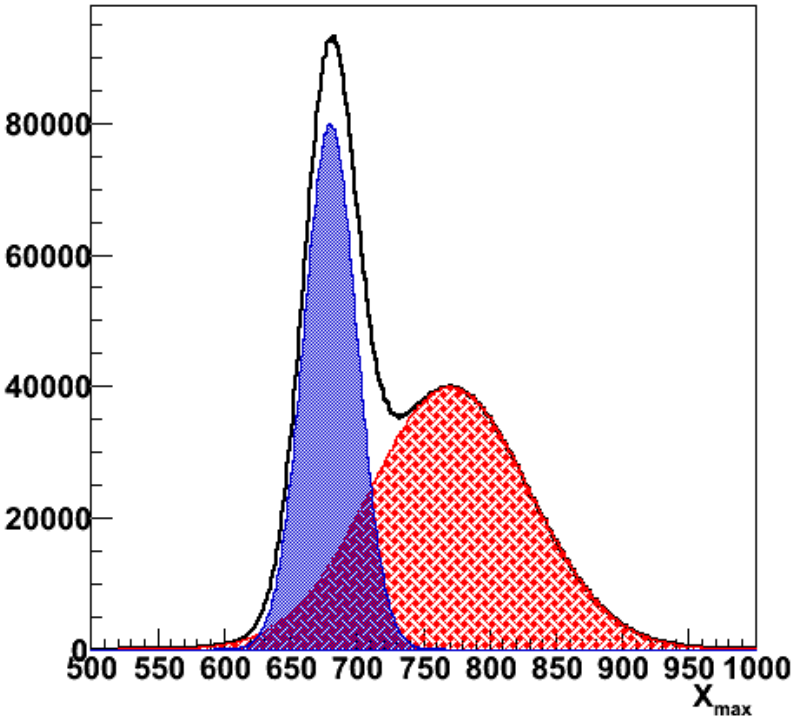


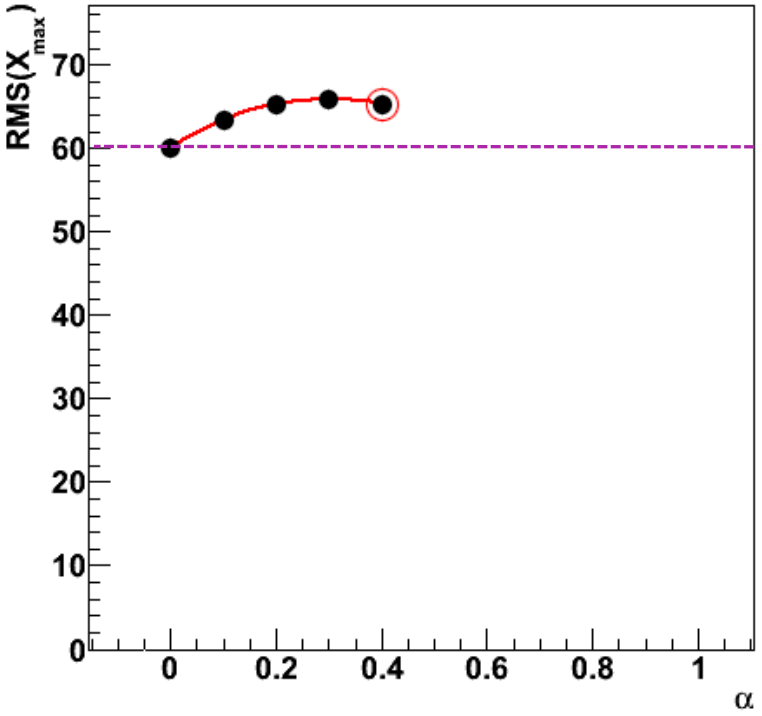


But if just proton and iron …

Xmax distribution and RMS

α : iron fraction ; (1-α): proton fraction

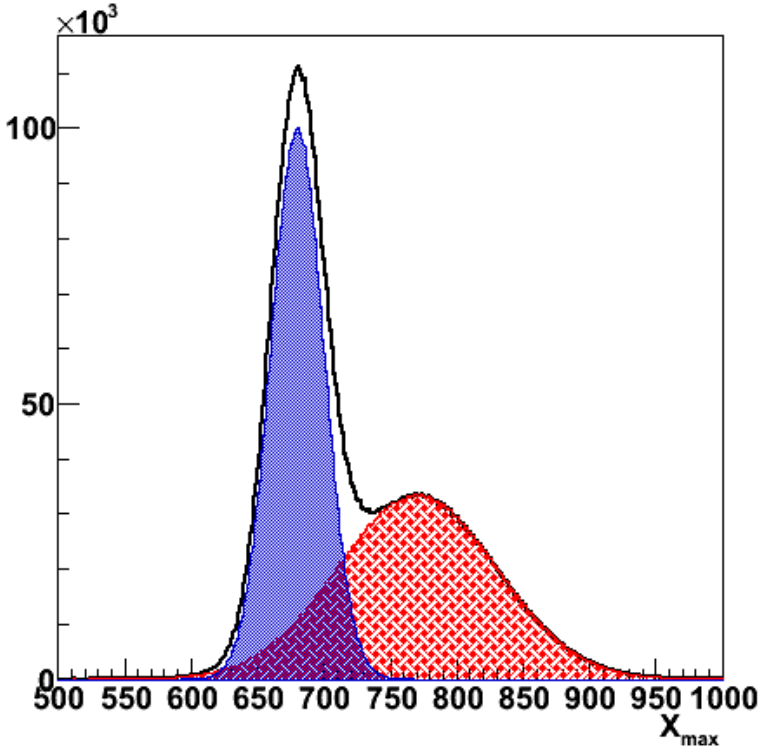


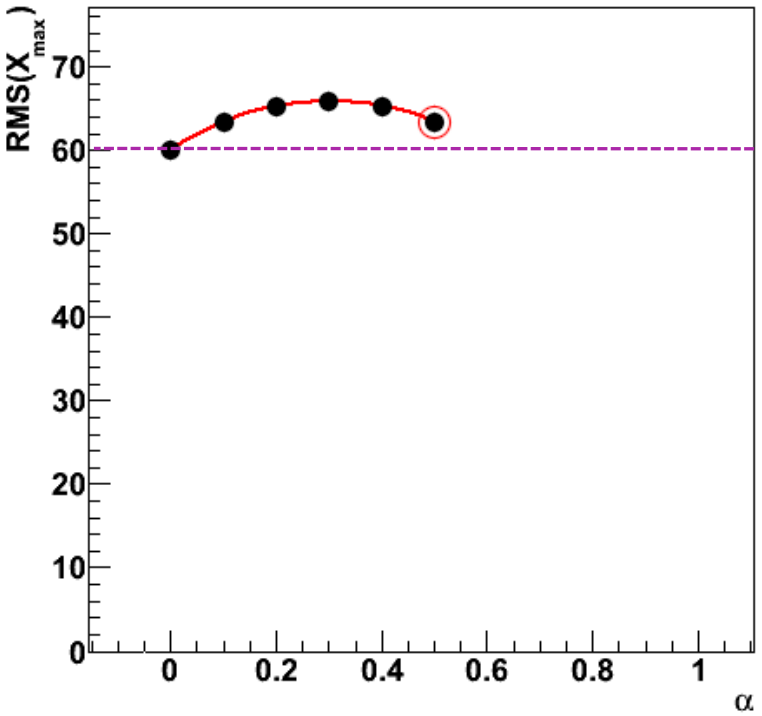


But if just proton and iron …

Xmax distribution and RMS

α : iron fraction ; (1-α): proton fraction





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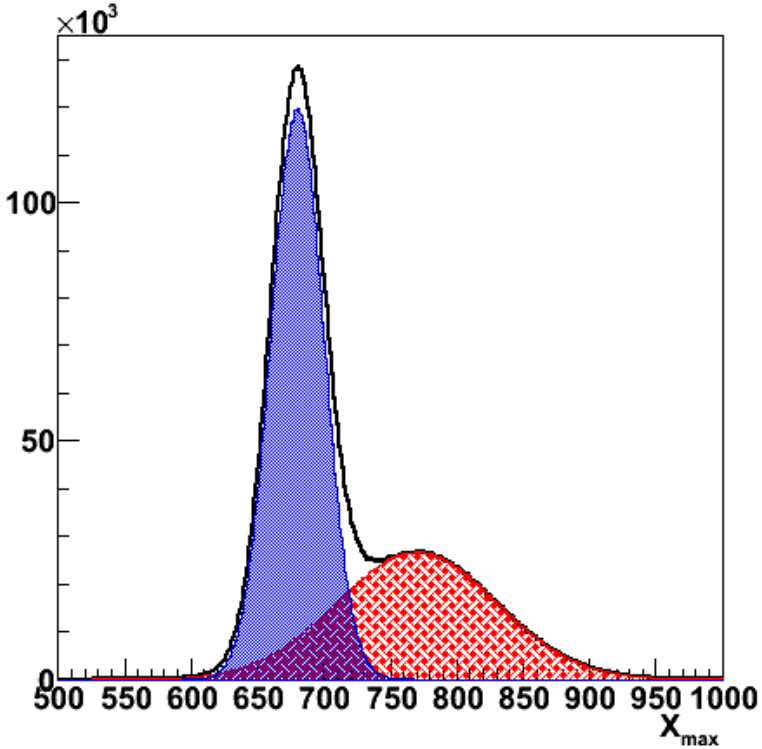
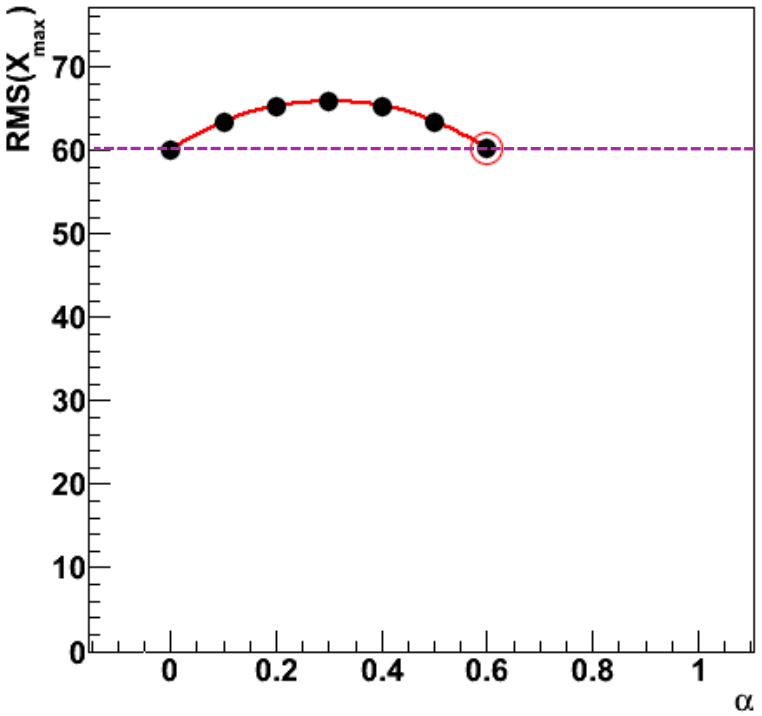
Xmax distribution and RMS

α : iron fraction ; (1-α): proton fraction





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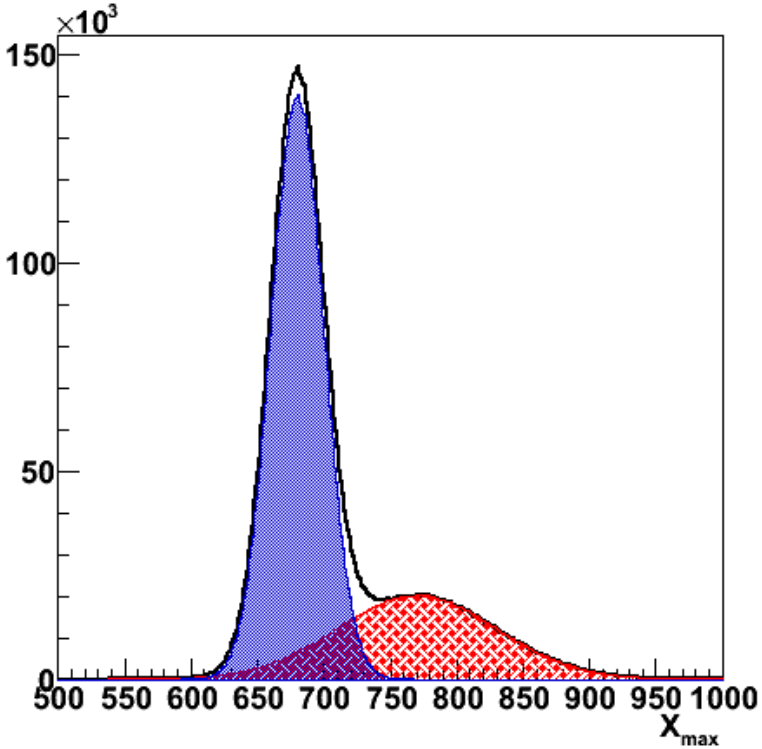
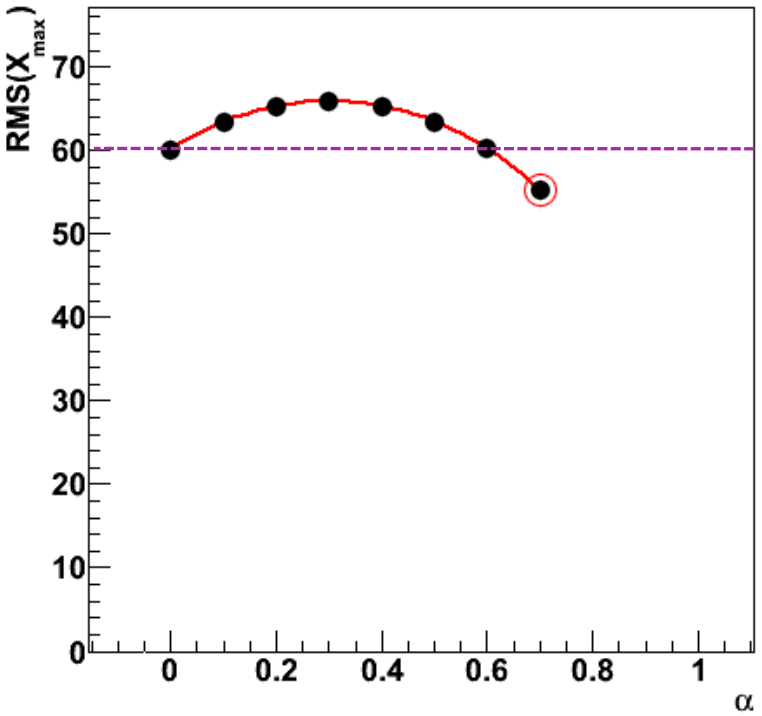
Xmax distribution and RMS

α : iron fraction ; (1-α): proton fraction





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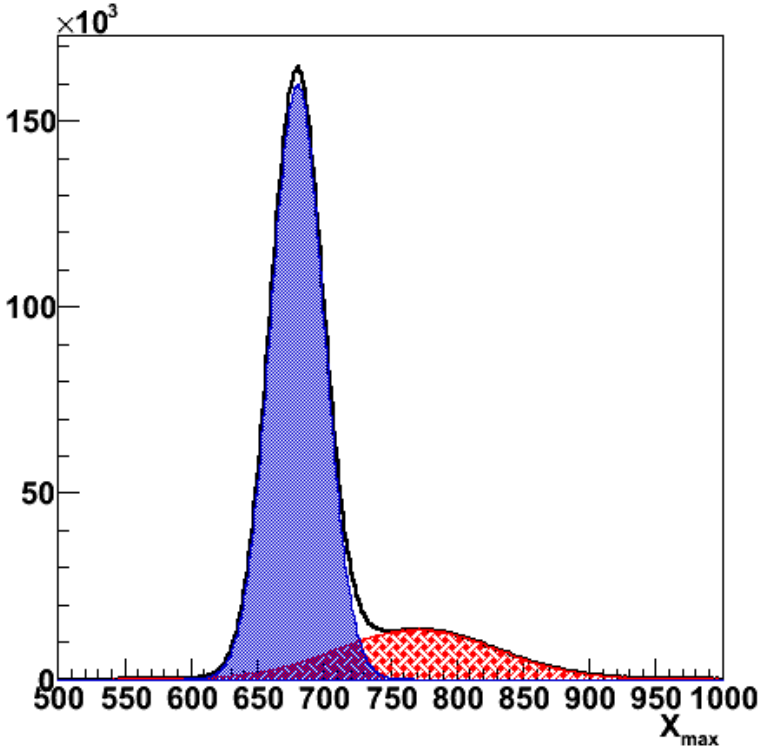
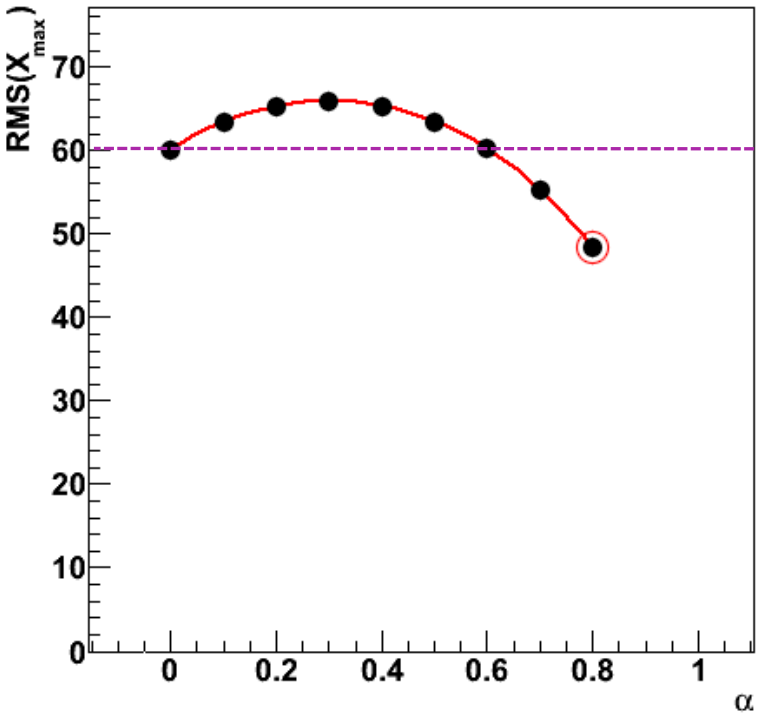
Xmax distribution and RMS

α : iron fraction ; (1-α): proton fraction

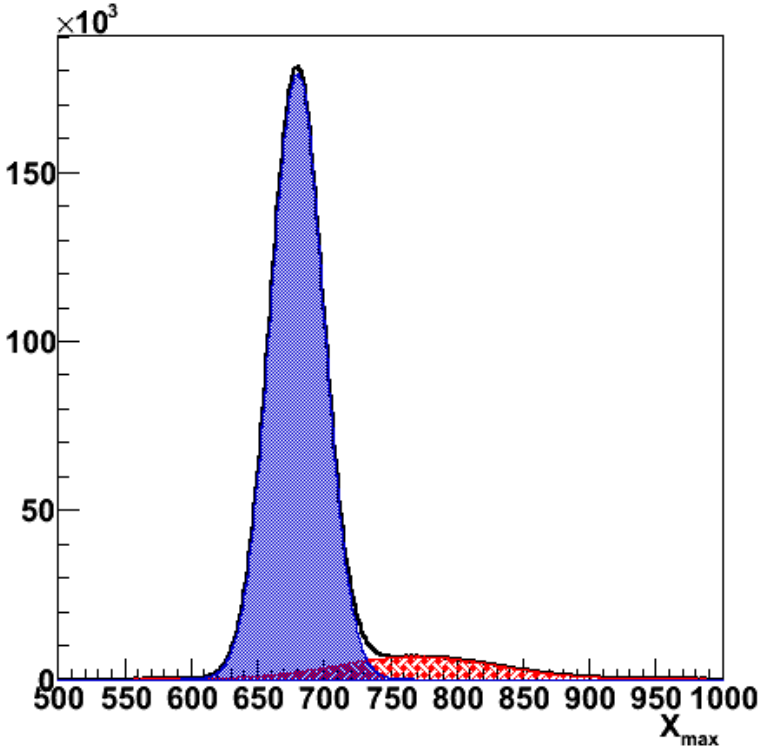


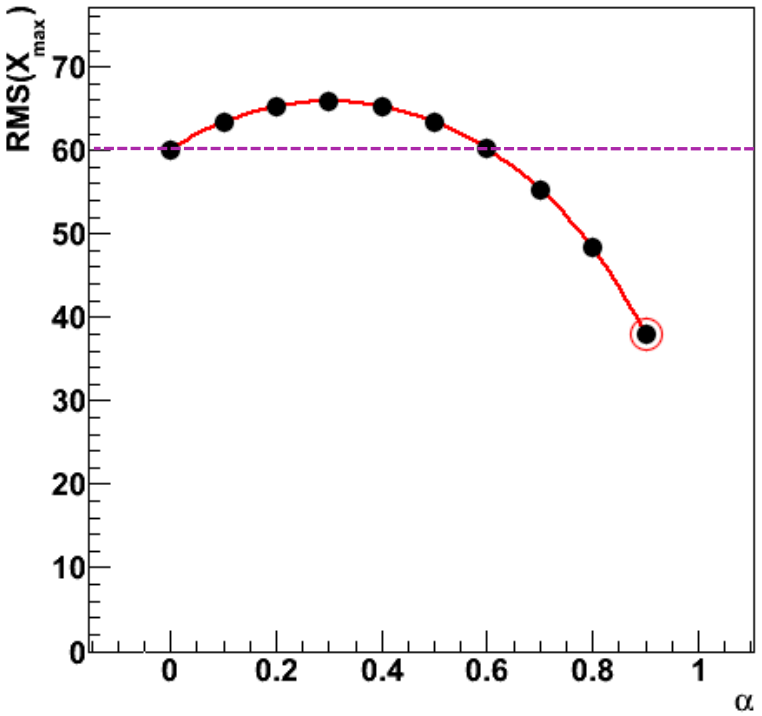


But if just proton and iron …

Xmax distribution and RMS

α : iron fraction ; (1-α): proton fraction

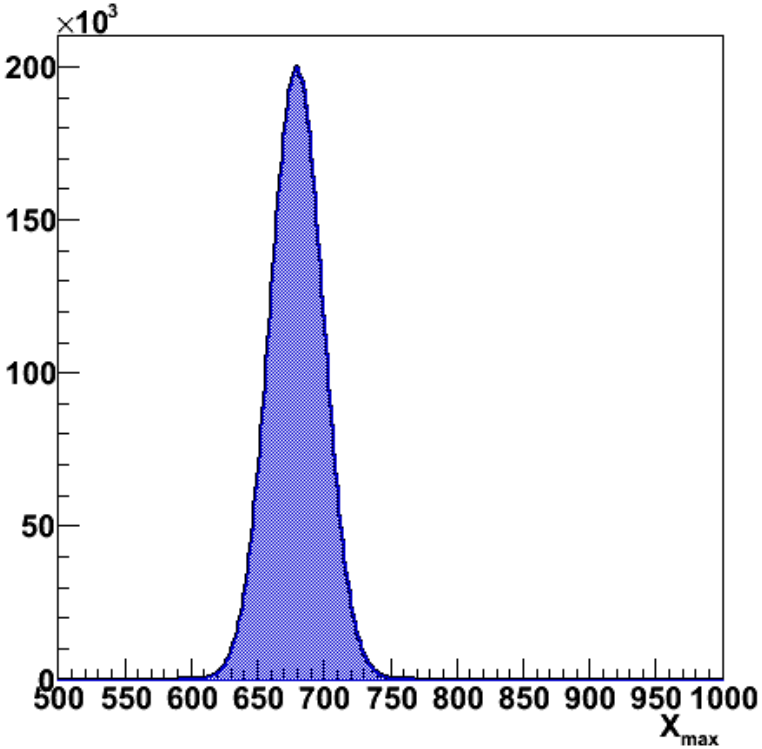


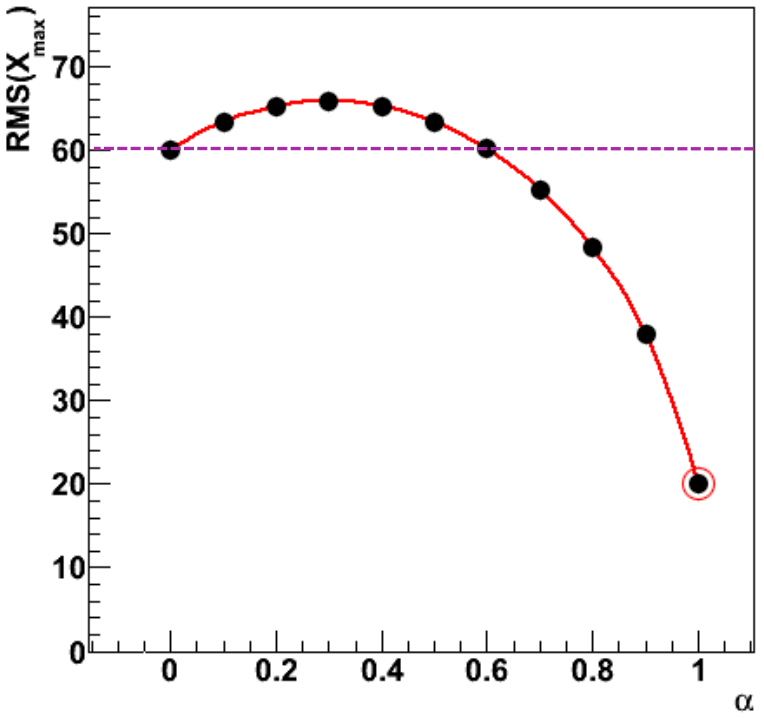


But if just proton and iron …

Xmax distribution and RMS

α : iron fraction ; (1-α): proton fraction

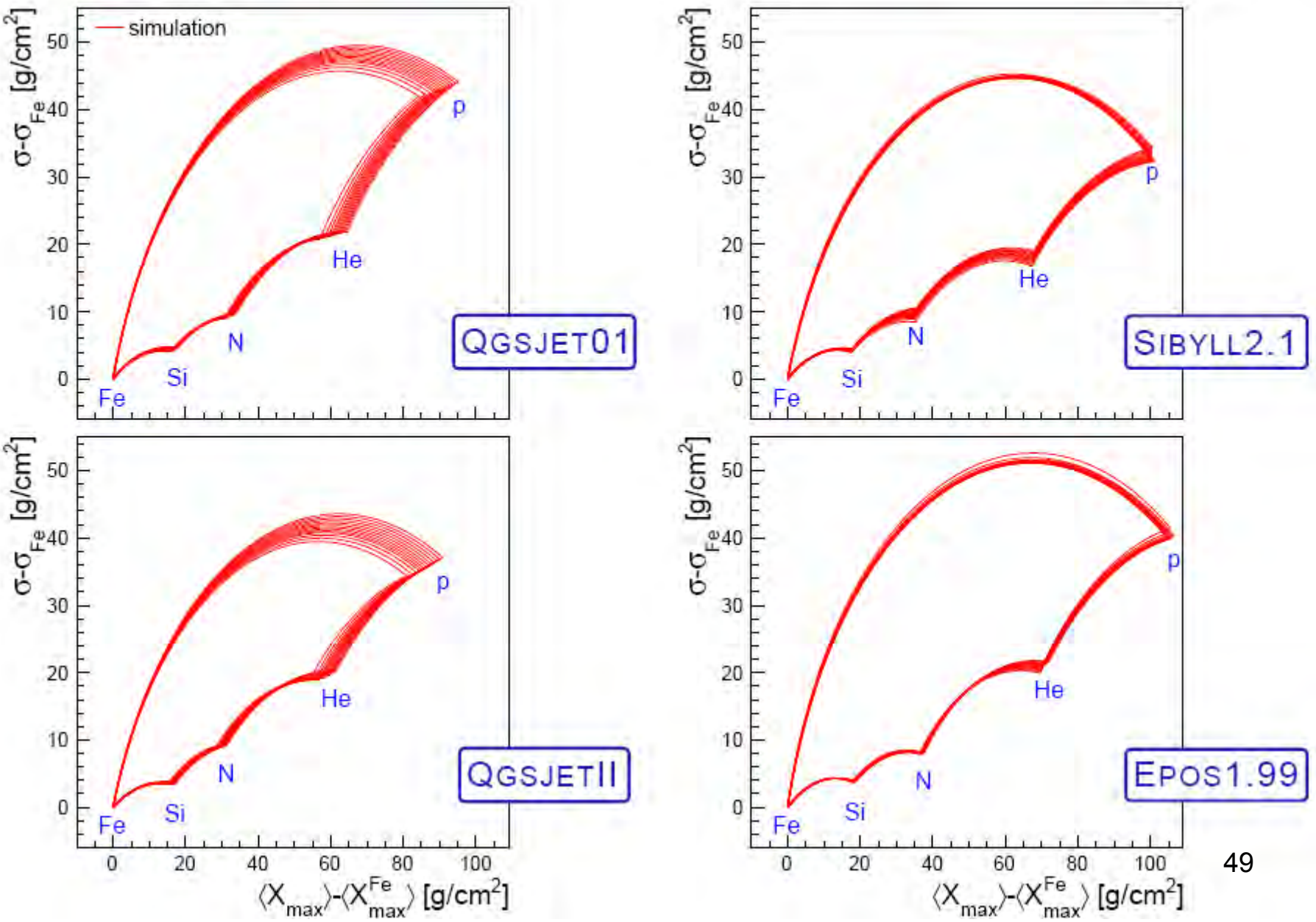




$$RMS^2(X_{max})(\alpha) = (1-\alpha)\,RMS^2(X_{max})_p + \alpha\,RMS^2(X_{max})_{Fe} + \alpha(1-\alpha)\left(\langle X_{max}\rangle_p - \langle X_{max}\rangle_{Fe}\right)^2,$$

$\langle X_{max} \rangle$ vs. RMS

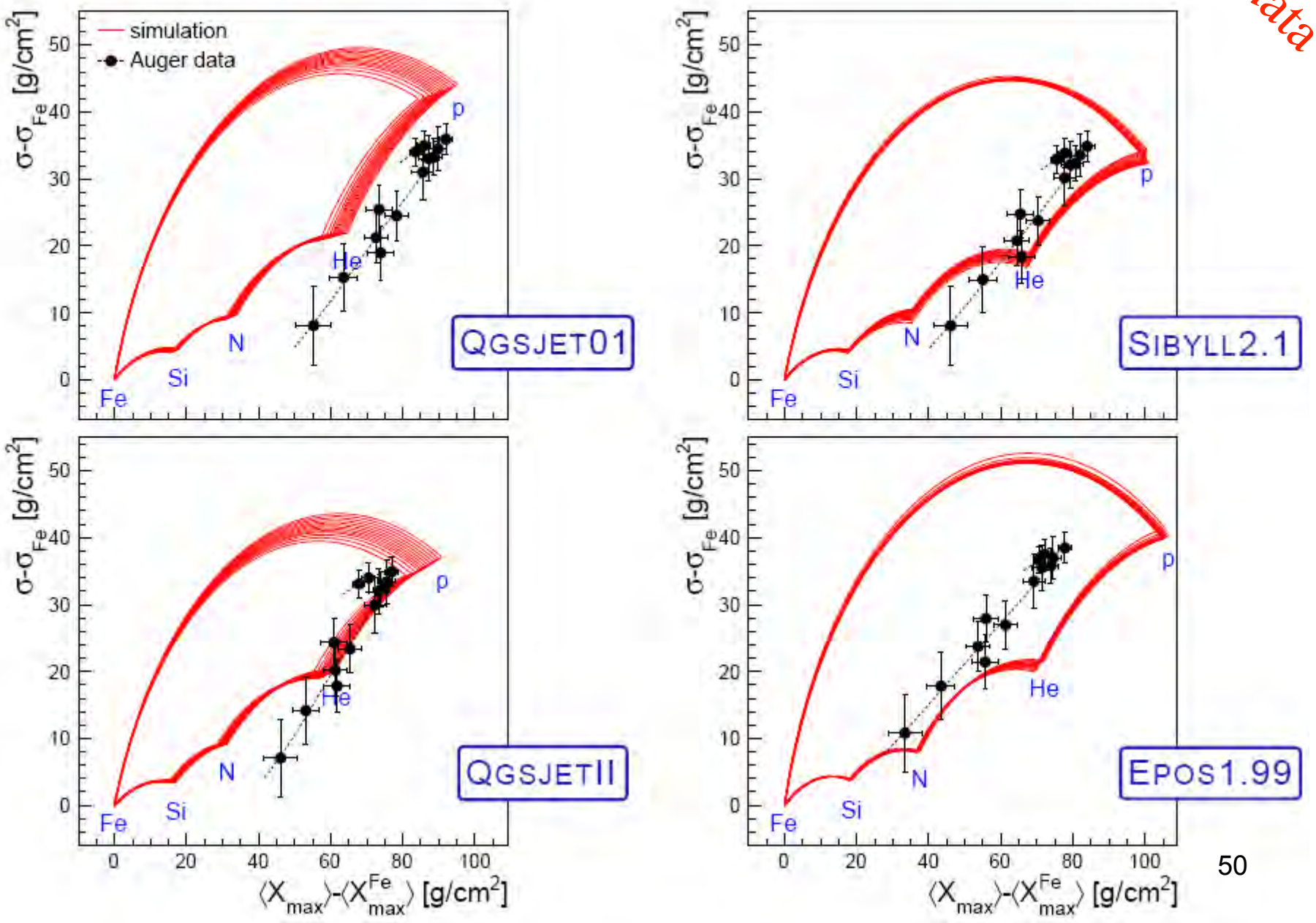
arXiv:1201.0018



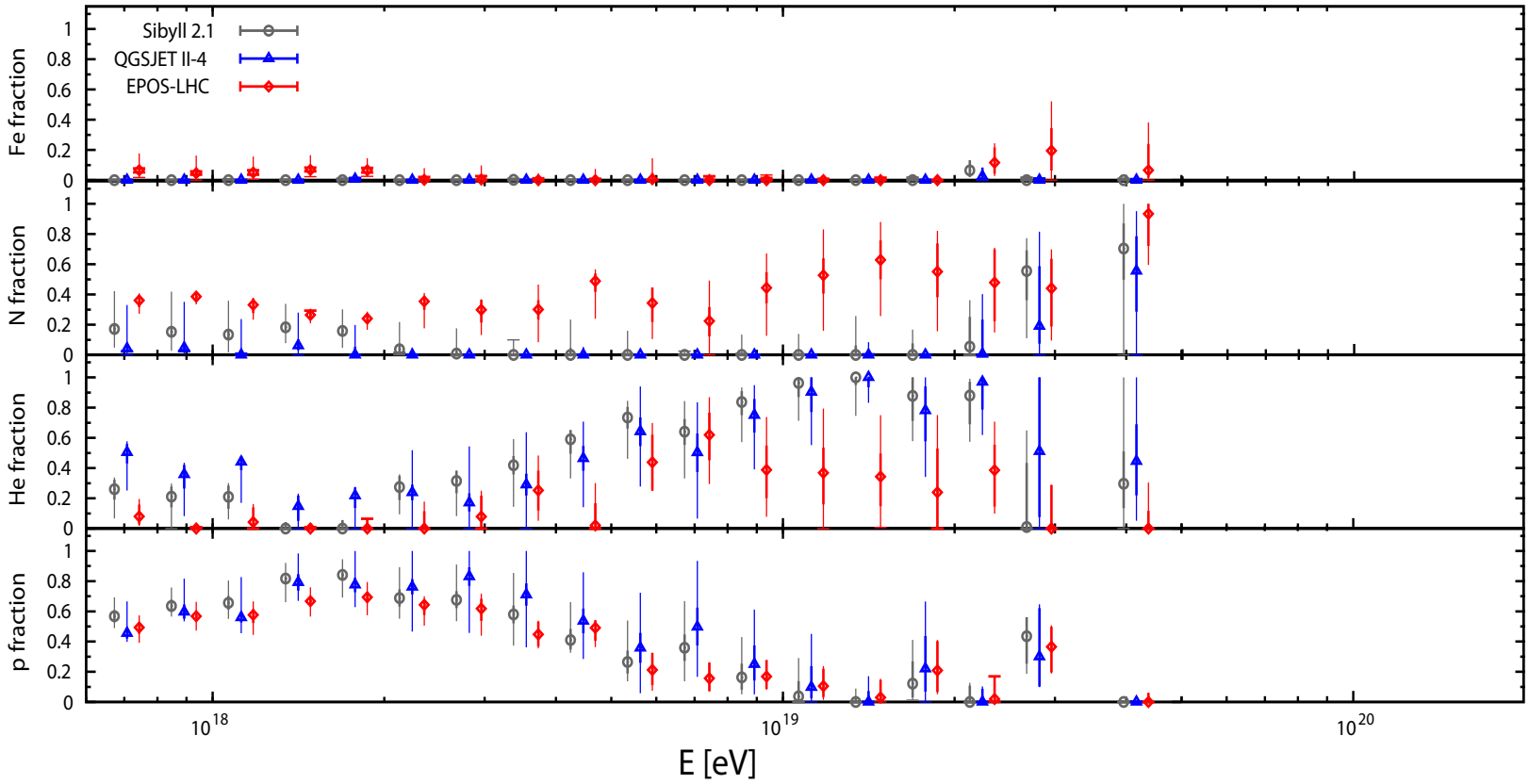
$\langle X_{max} \rangle$ vs. RMS

arXiv:1201.0018

Old data



Nuclei fraction from X_{max} distributions



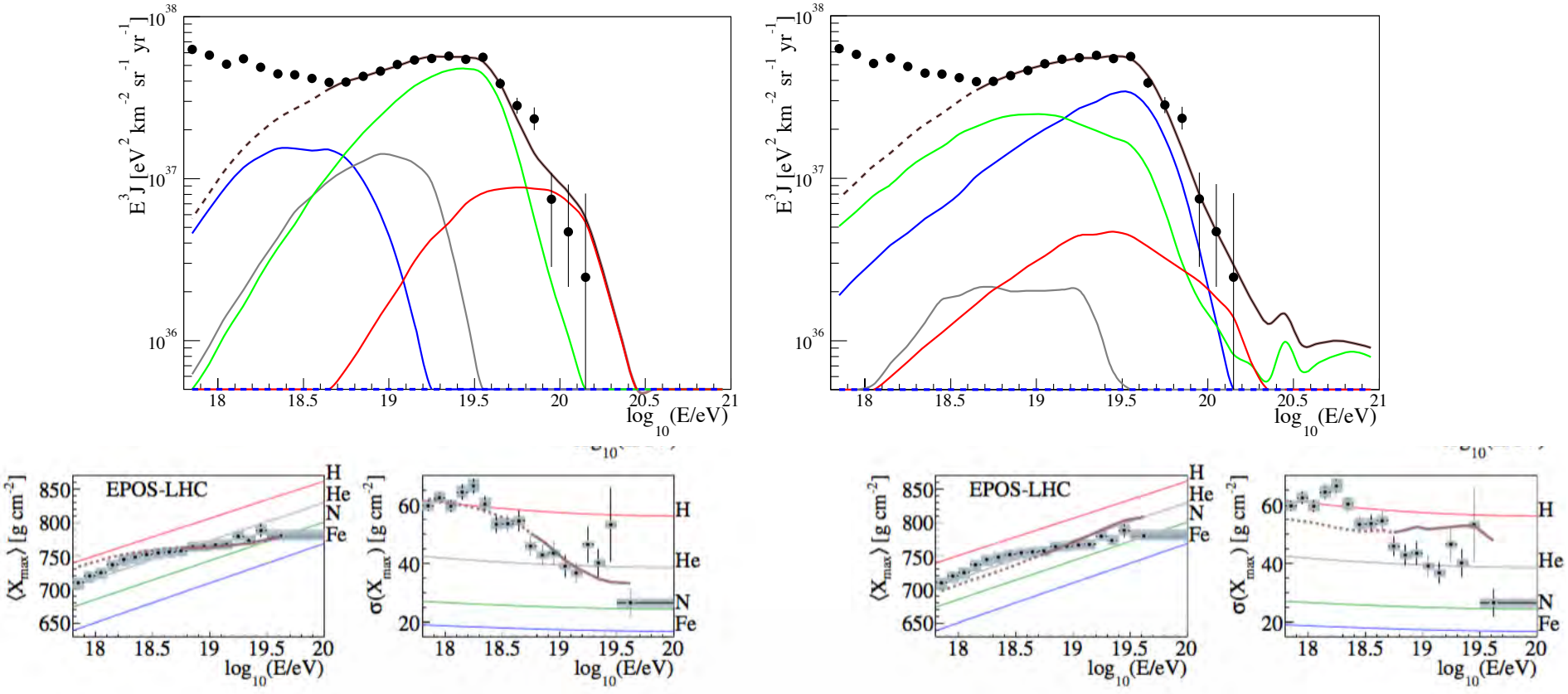
almost no Fe and <10% of p at the highest energies

a no "standard" astrophysics scenario !

Combined fits

Protons (blue)
Helium (gray)
Nitrogen (green)
Iron (red)

A. di Matteo for the Pierre Auger Coll., Proc 34th ICRC (2015)



A Fit (spectrum, $<X_{max}>$, RMS(X_{max})) is always possible but it requires a very unusual metallicity of the sources!

The “Particle Physics” interpretation …

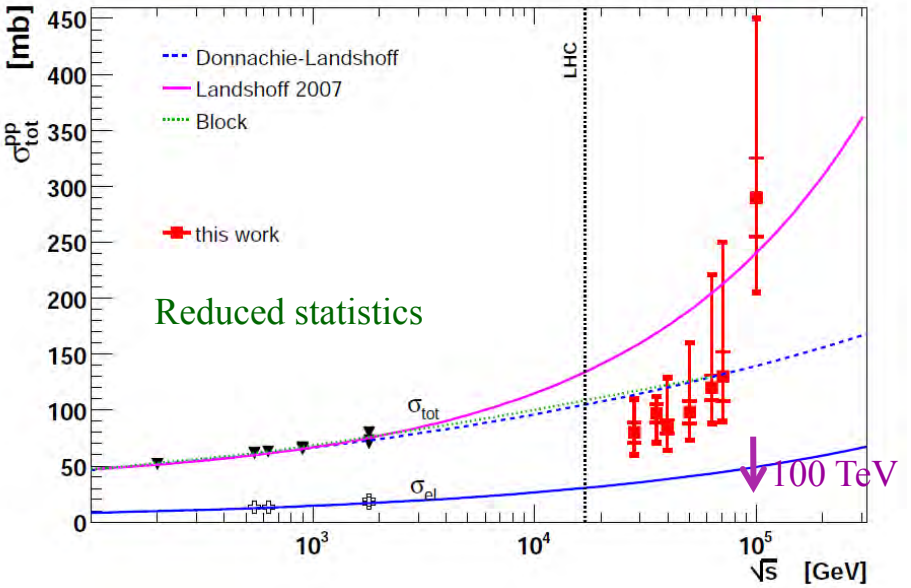
If just proton …

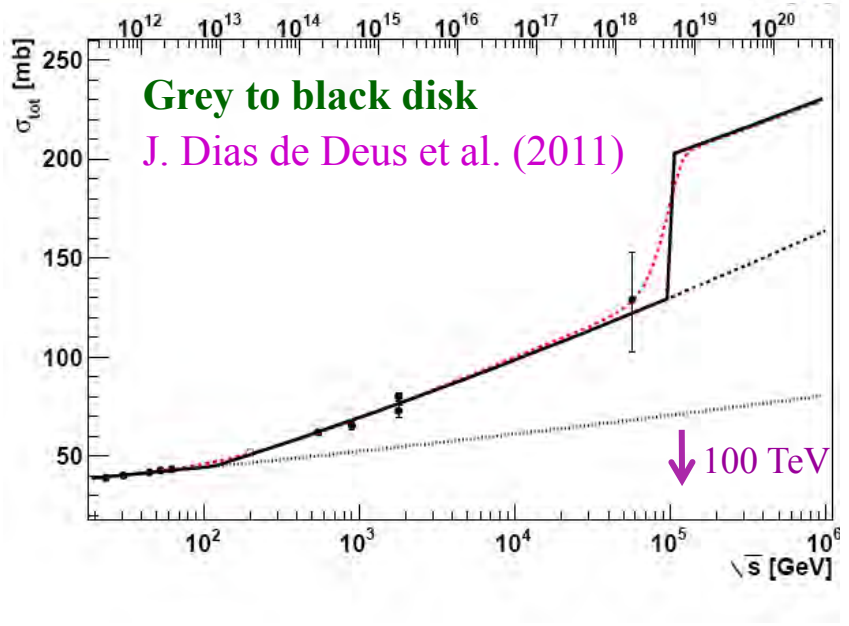
$\sqrt{s}$ = 100 TeV !!!

A dramatic increase in the proton-proton cross section

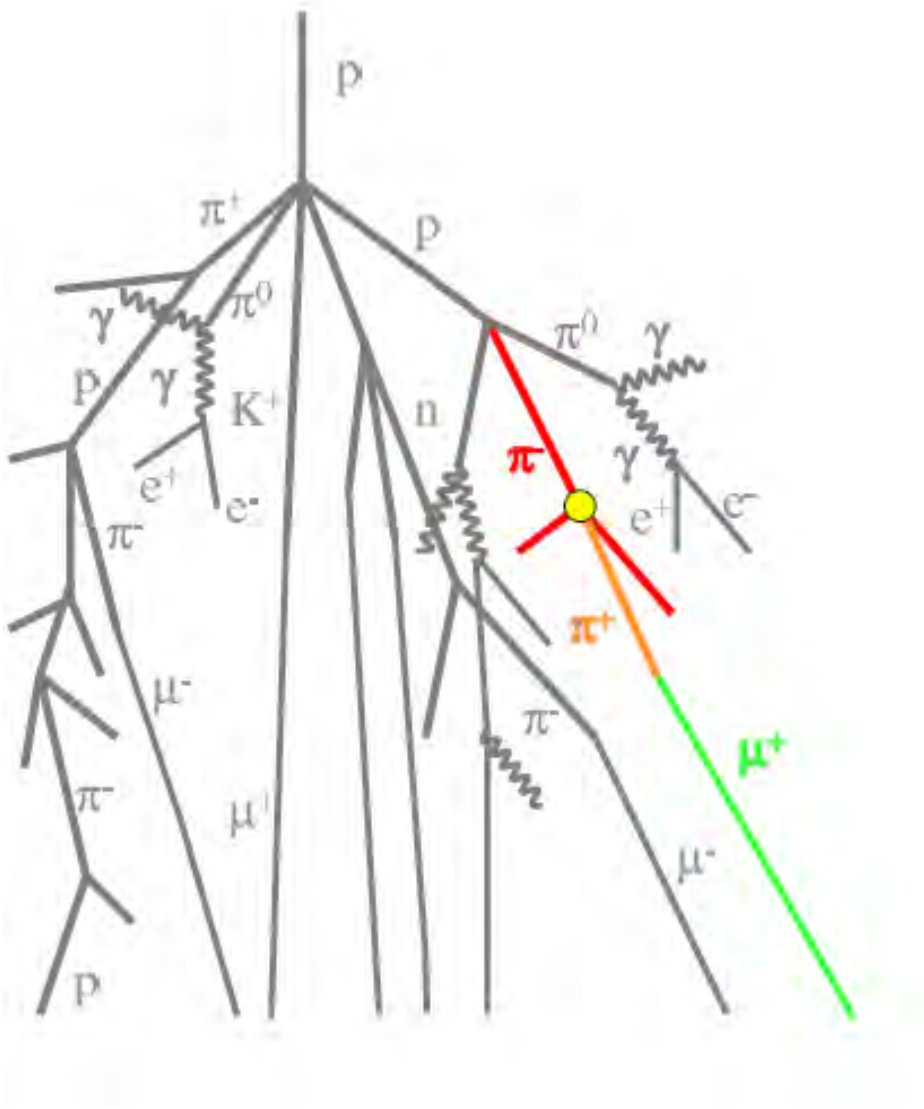
But no violation of the Froissart bound

R.Ulrich (2008)



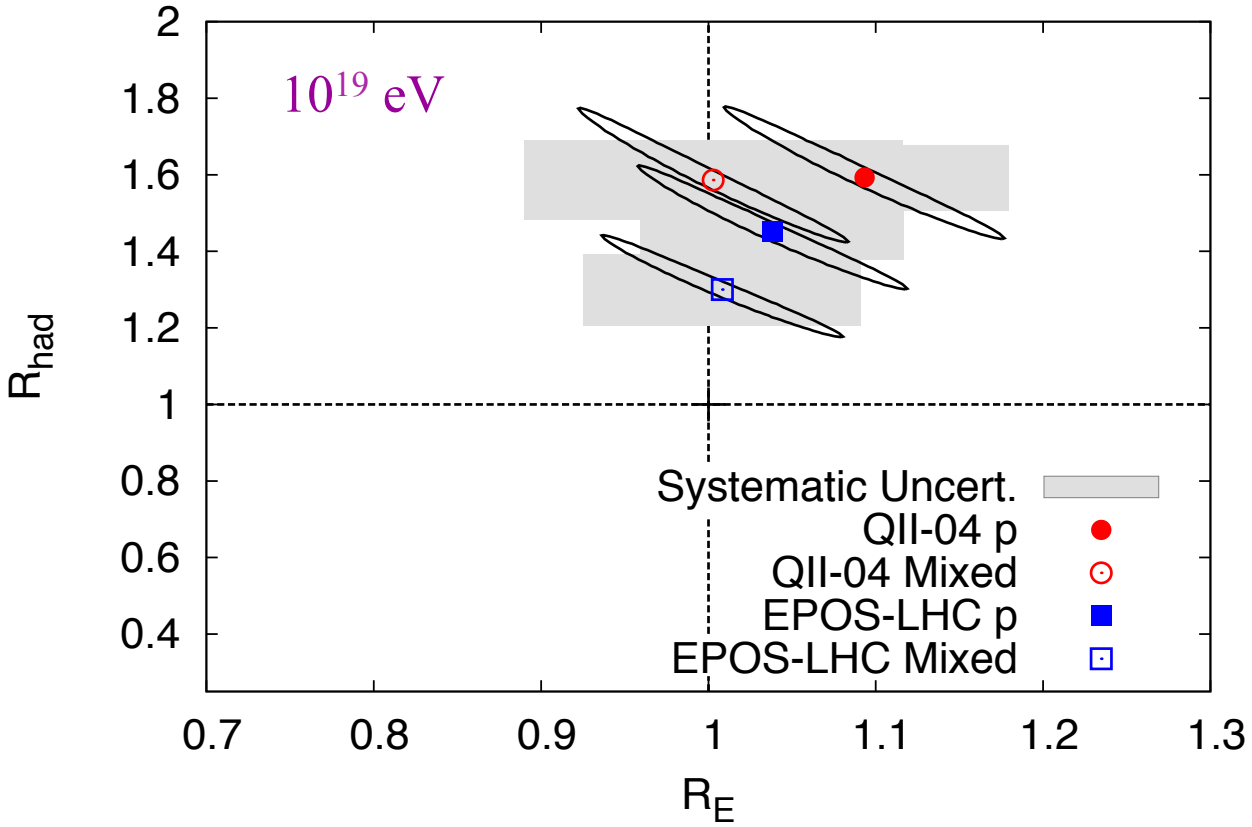


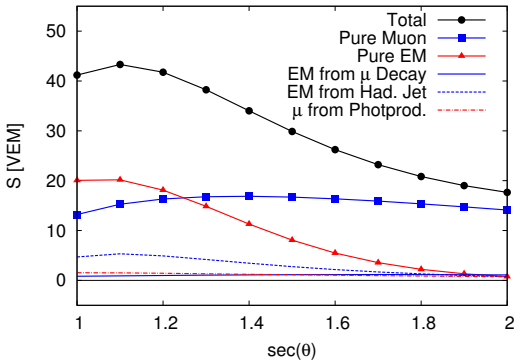
The “number of μ_s



The "number of μ_s

$$S_{\rm resc}(R_E, R_{\rm had})_{i,j} \equiv R_E\, S_{EM,i,j} + R_{\rm had}\, R_E^{\alpha}\, S_{{\rm had},i,j}$$

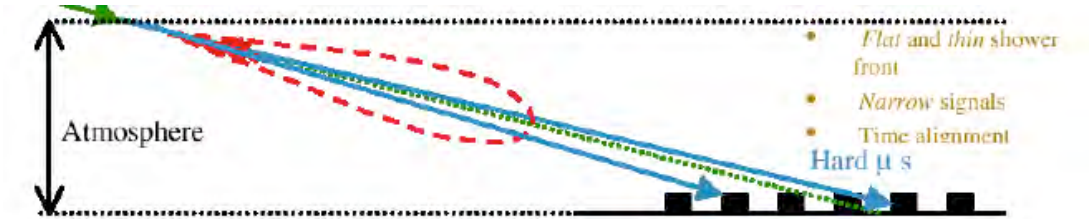


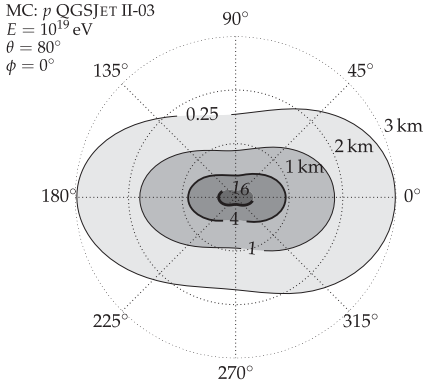


Model	R_E	$R_{\rm had}$
QII-04 p	$1.09 \pm 0.08 \pm 0.09$	$1.59 \pm 0.17 \pm 0.09$
QII-04 Mixed	$1.00 \pm 0.08 \pm 0.11$	$1.61 \pm 0.18 \pm 0.11$
EPOS p	$1.04 \pm 0.08 \pm 0.08$	$1.45 \pm 0.16 \pm 0.08$
EPOS Mixed	$1.00 \pm 0.07 \pm 0.08$	$1.33 \pm 0.13 \pm 0.09$

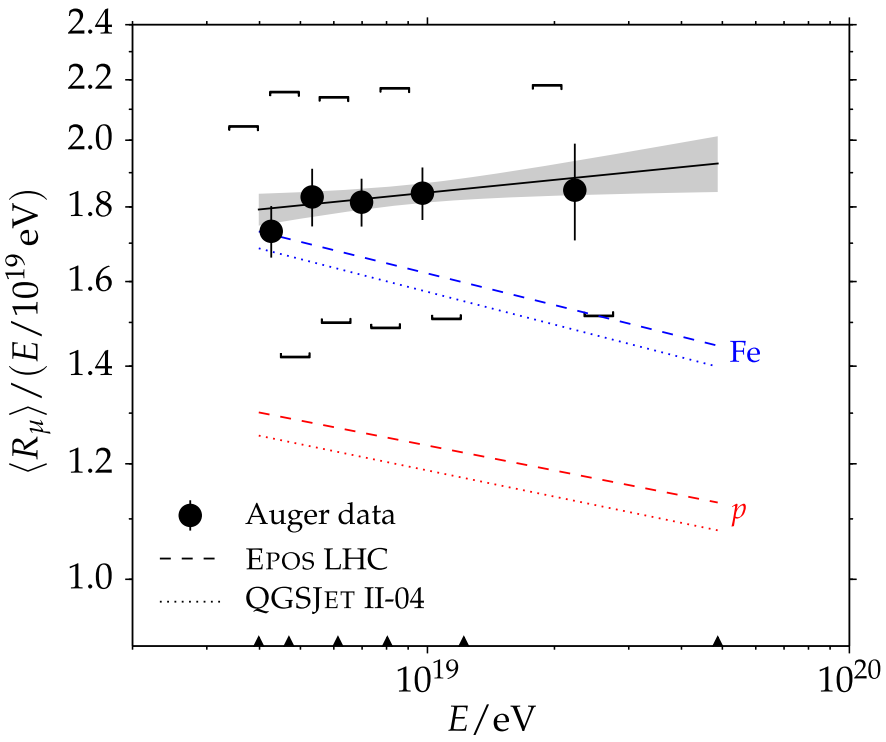
Hadronic signal in data is significantly larger

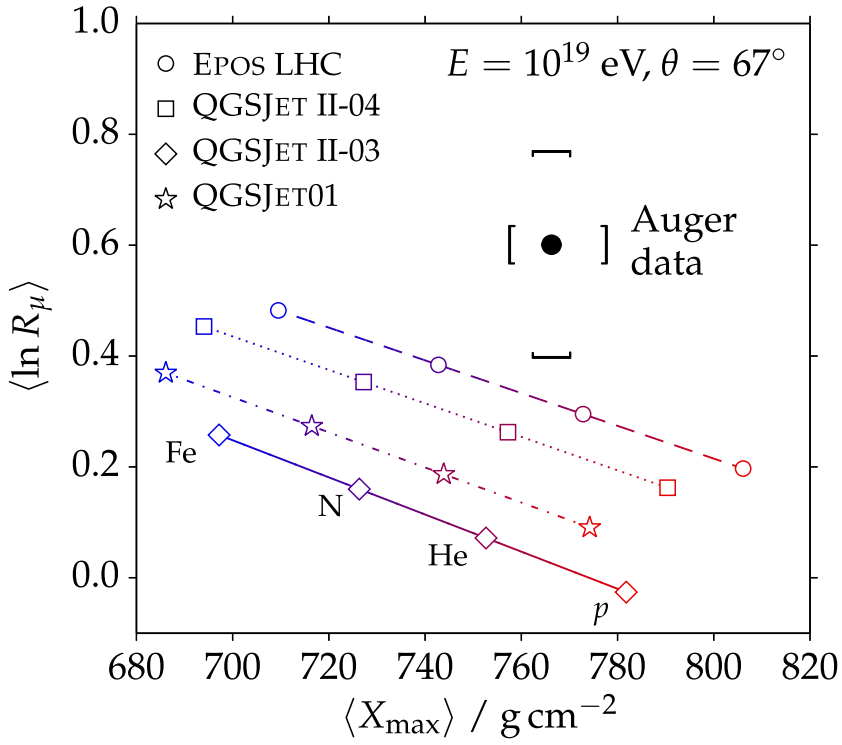
The “number of μ_s (inclined showers)





$$R_\mu = N_\mu^{true}/N_\mu^{map}(\theta,\phi) = N_{19}^{true}$$

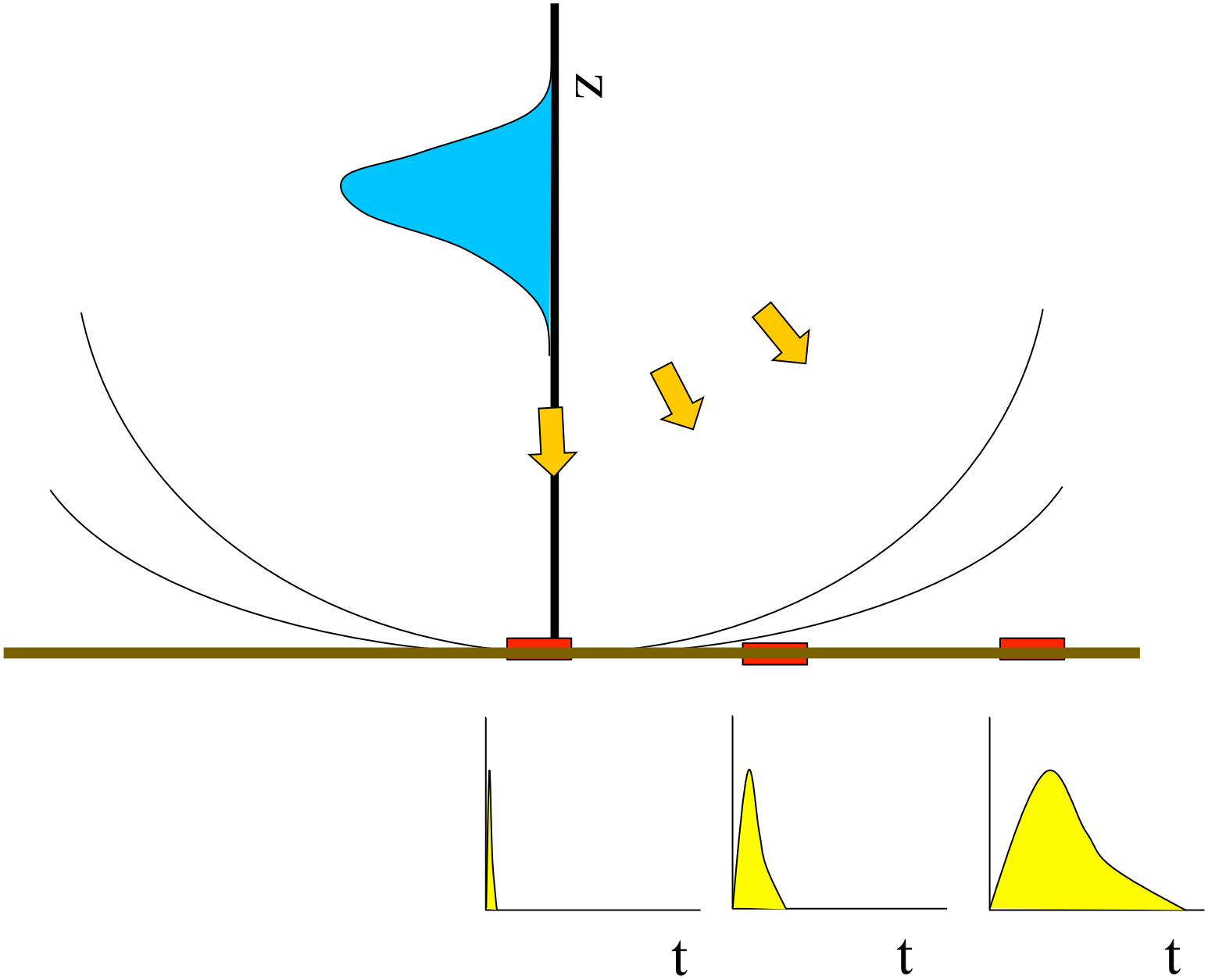




Tension between data and all hadronic interaction models !!!

Muon Production Depth (MPD)

L. Cazon, R.A. Vazquez, A.A. Watson, E. Zas,
Astropart.Phys.**21**:71-86 (2004)
L.Cazon, PhD Thesis (USC 2005)



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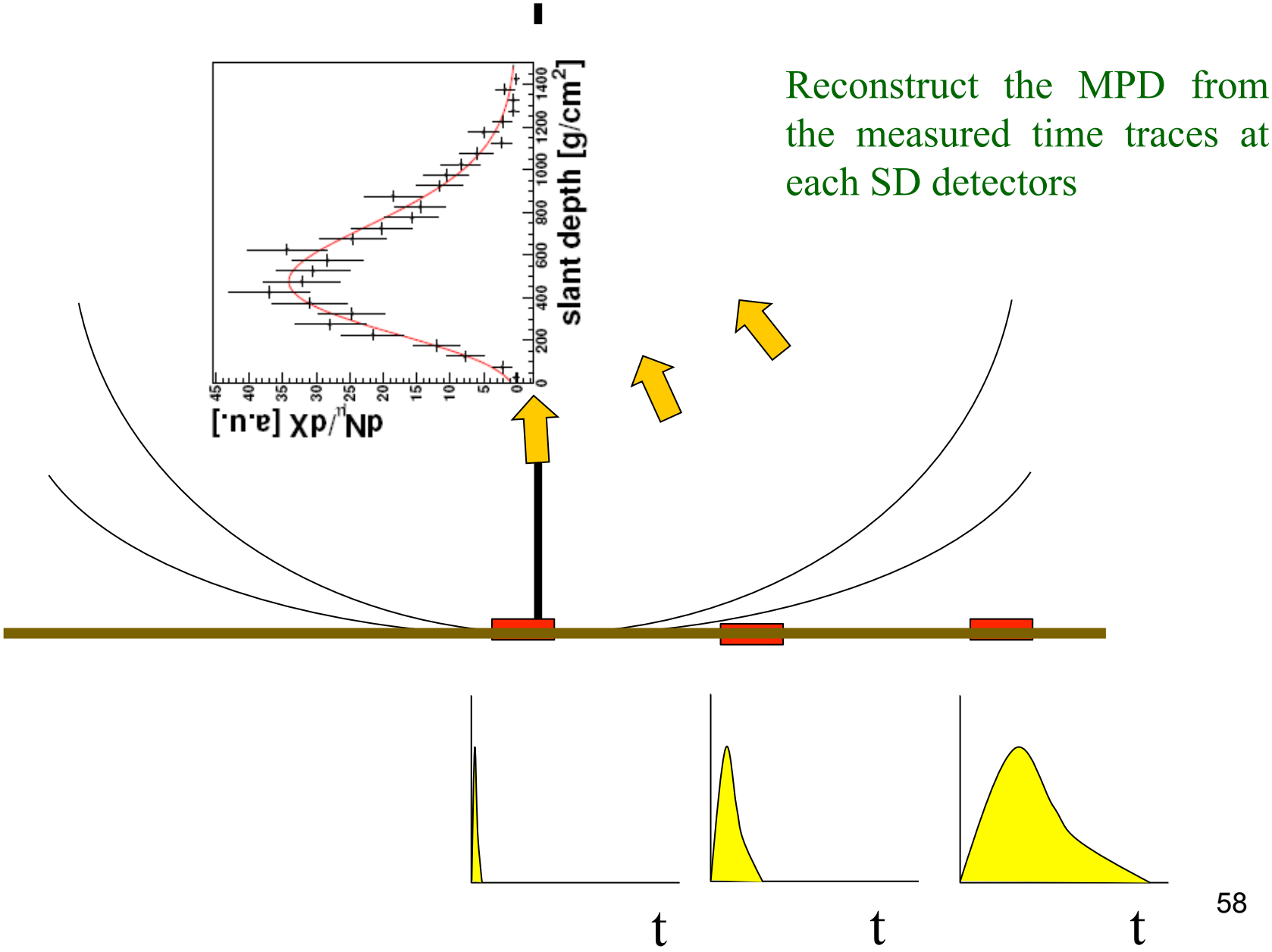
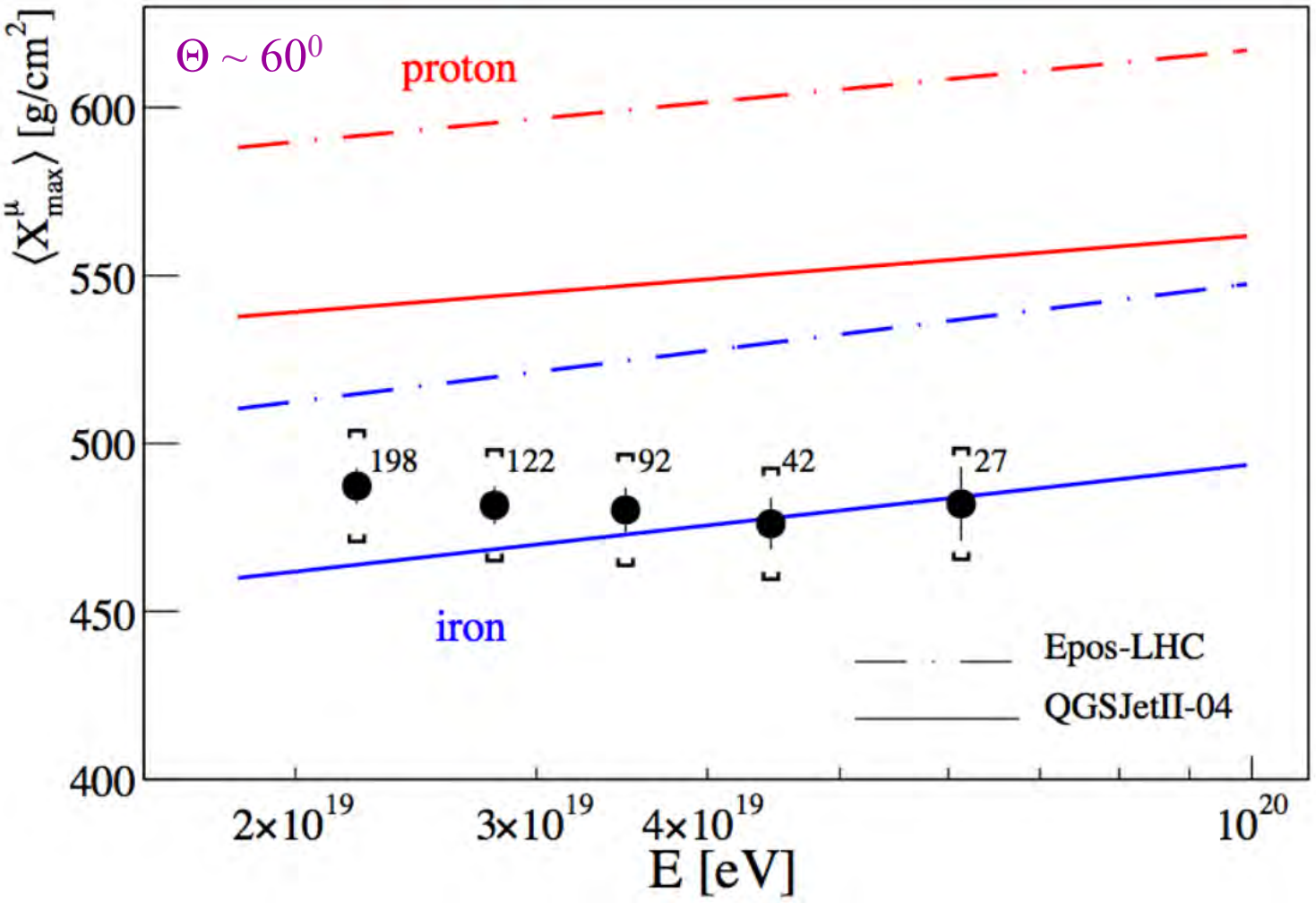
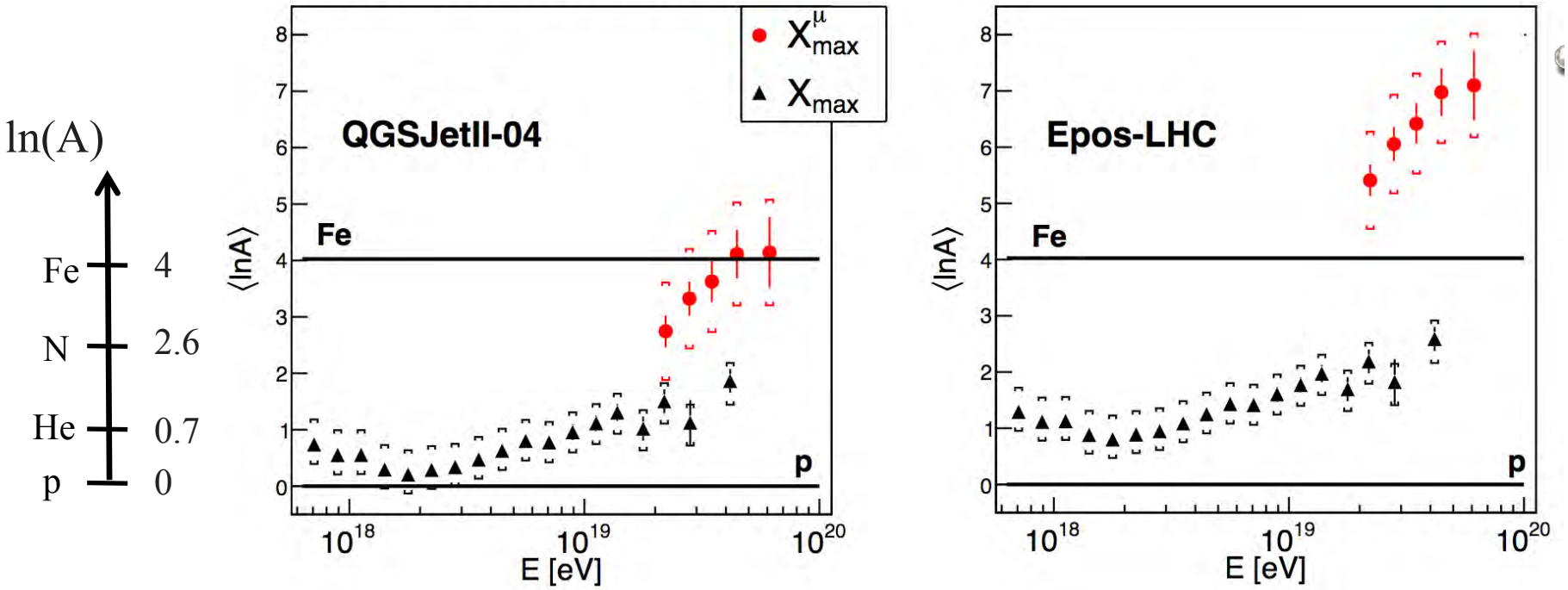


Reconstruct the MPD from the measured time traces at each SD detectors

$\langle X^{\mu}_{max} \rangle$

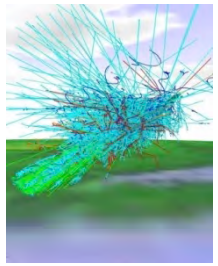


<ln A> from X_{max} and X^{μ}_{max}



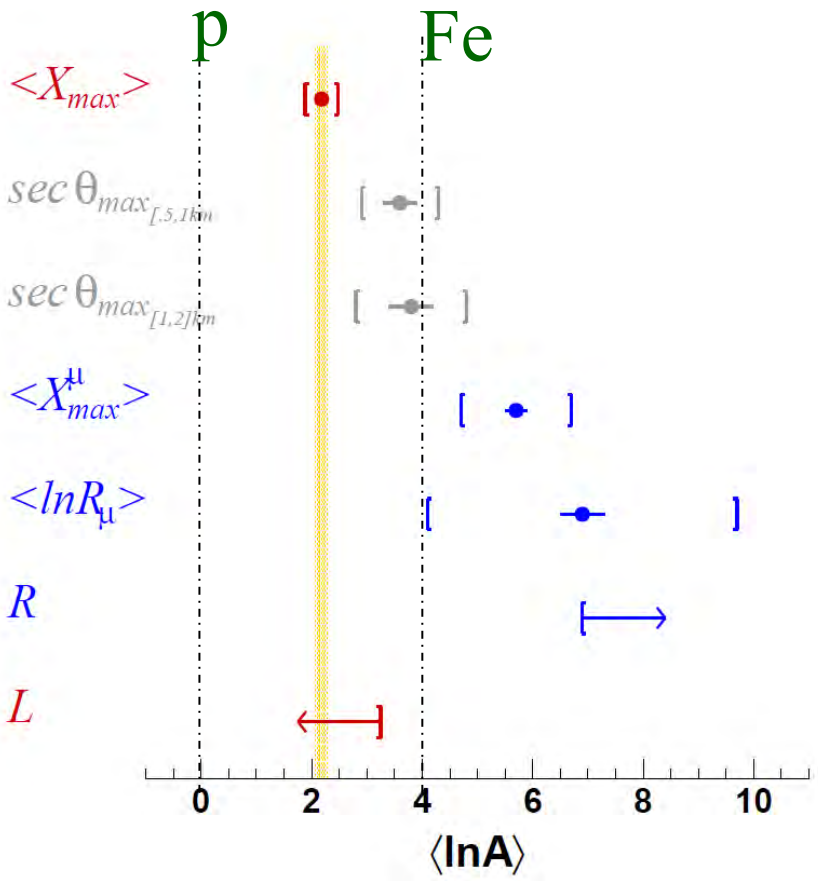
(X_{max} , X^{μ}_{max}) is sensitive to hadronic development of the shower (rapidity distributions, …)

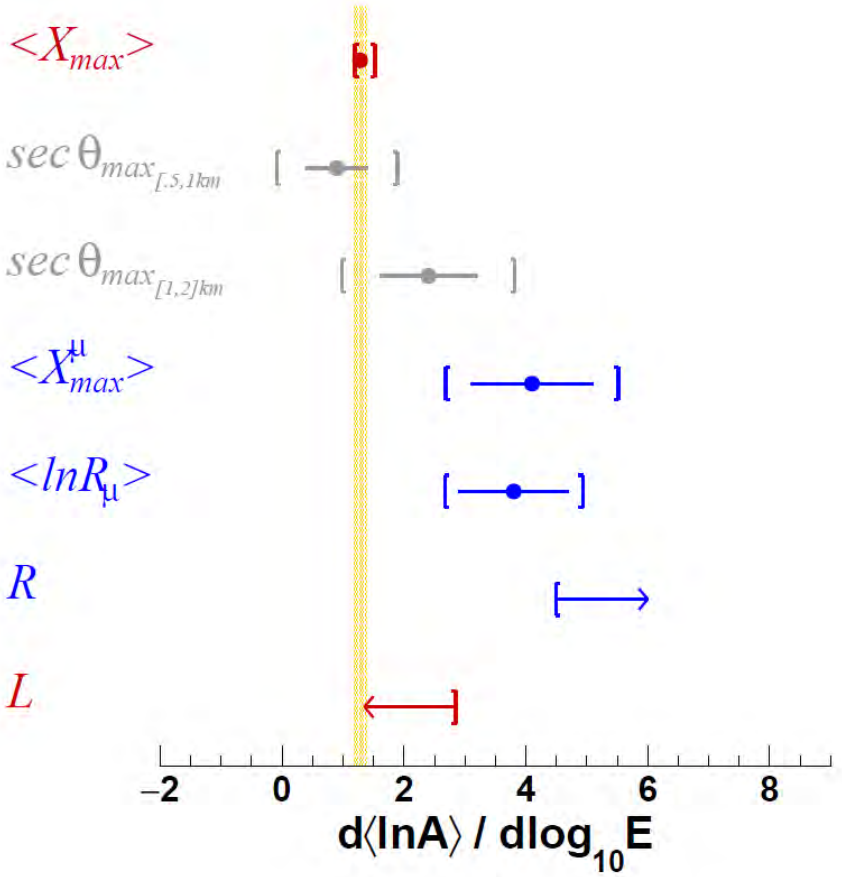
The Physics puzzle



Are we understanding our showers?

EPOS-LHC model, E ~ $10^{19.4}$ eV





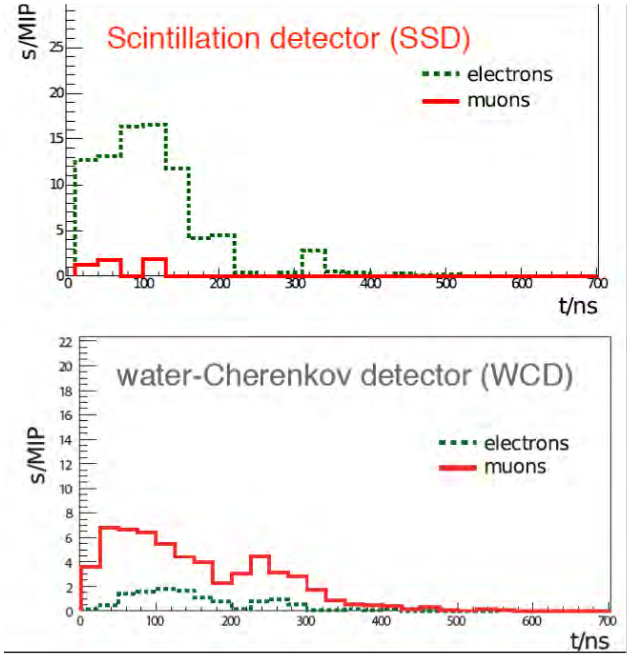
None of the present hadronic interaction models can describe fully our measurements at sqrt(s) ~ 100 TeV !!!

Auger Prime

- "Primary cosmic Ray Identification through Muons and Electrons"

- Two complementary detectors:
  - Scintillator on top of the tank: signal dominated by e.m. component
  - WCD sensitive to e.m. + muons

- The goal:
  - Enhance primary identification
  - Improve shower description
  - Reduce systematic uncertainties



Exciting times ahead us