Particle physics with the Pierre Auger Observatory

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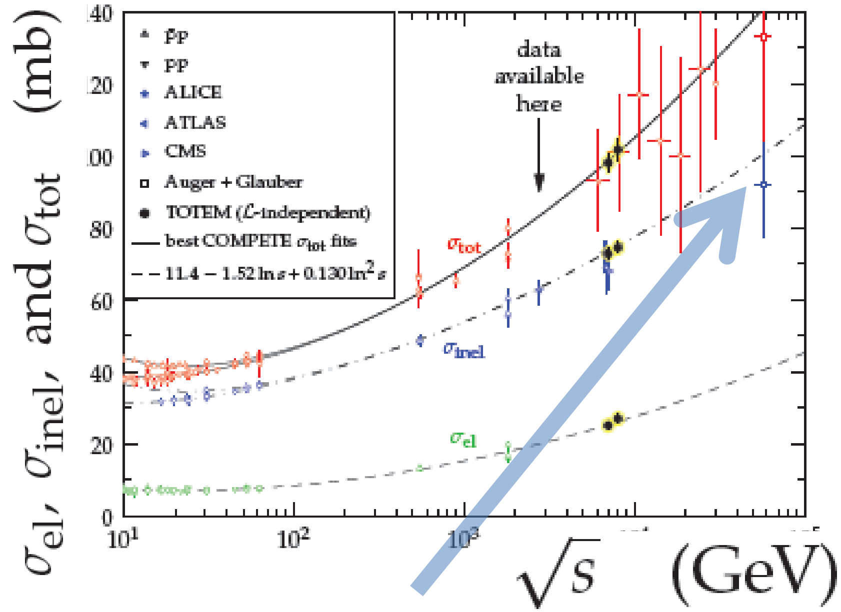
Outline



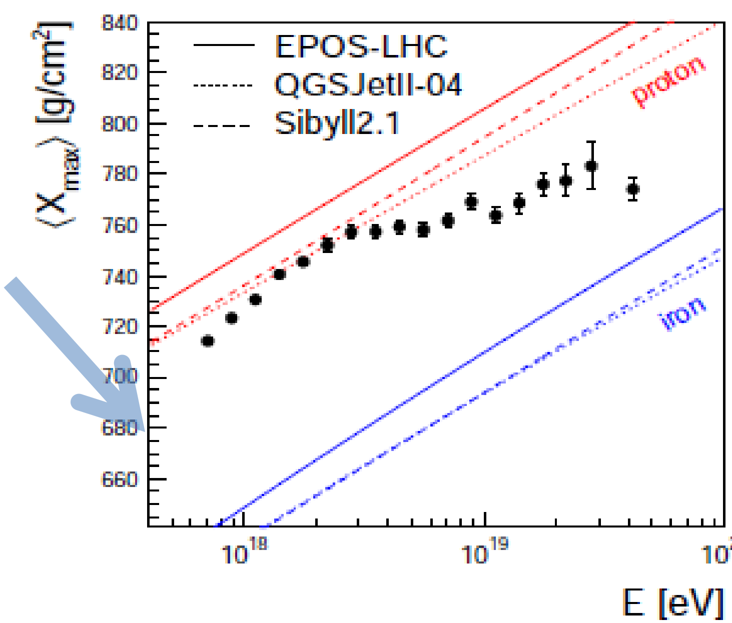
- **Cosmic rays and Observatory**
  - UHECR
  - FD (fluorescence detector)
  - SD (surface detector)
- p-air (p-p@57 TeV) production **cross-section measurement**

Primary CR composition

- Information in X_{max} and RMS(X_{max})
- Information in X^{μ}_{max}
- Other SD parameters

Hadronic interaction models

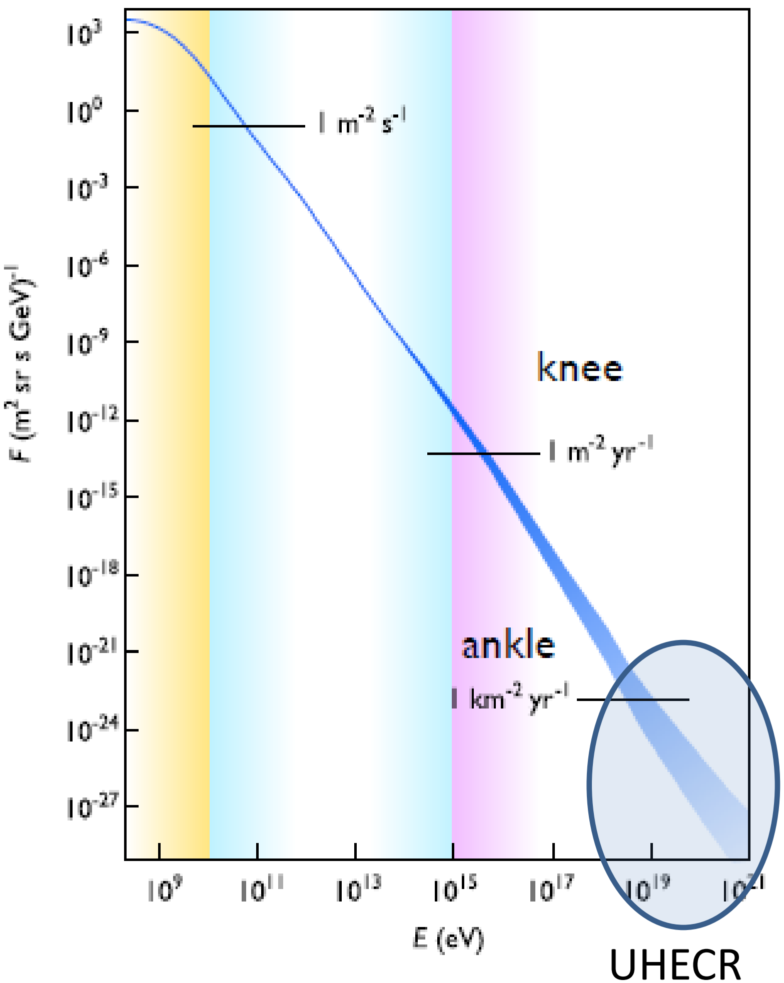
- consistency in Xmax vs. RMS(Xmax)
- muon component measurement
- consistency in Xmax vs. #muons

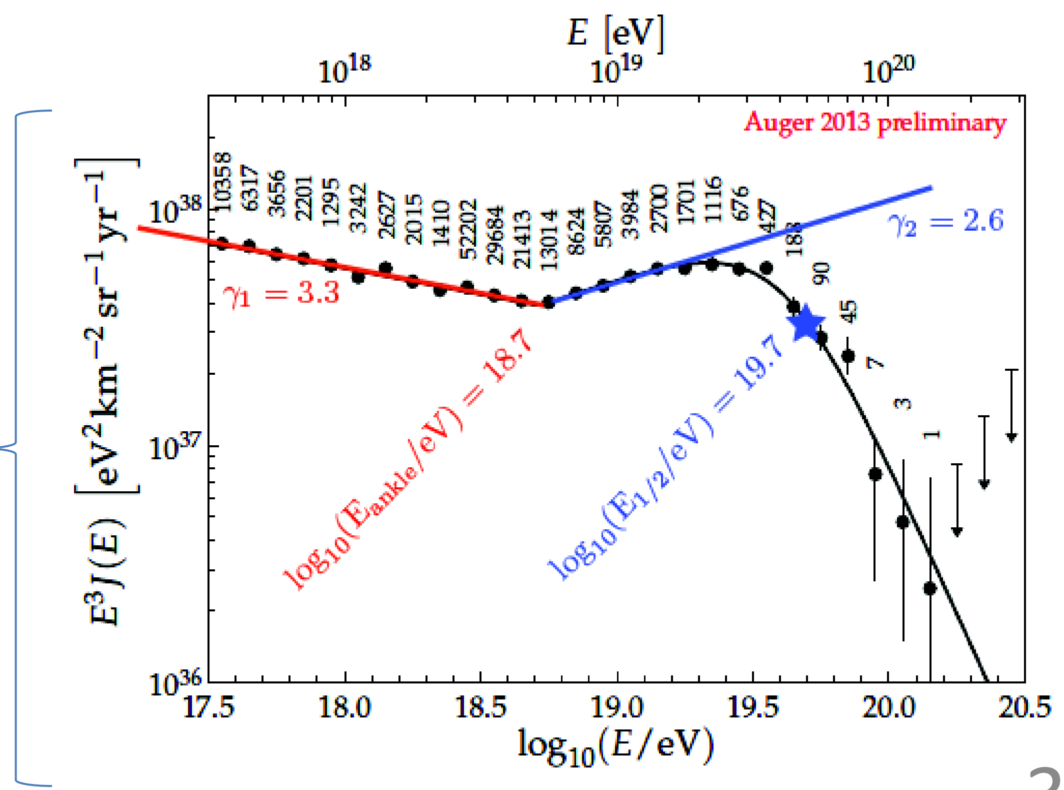


Cosmic rays and Pierre Auger Observatory

Energies far from reach of accelerators
Rare events - large observatory needed

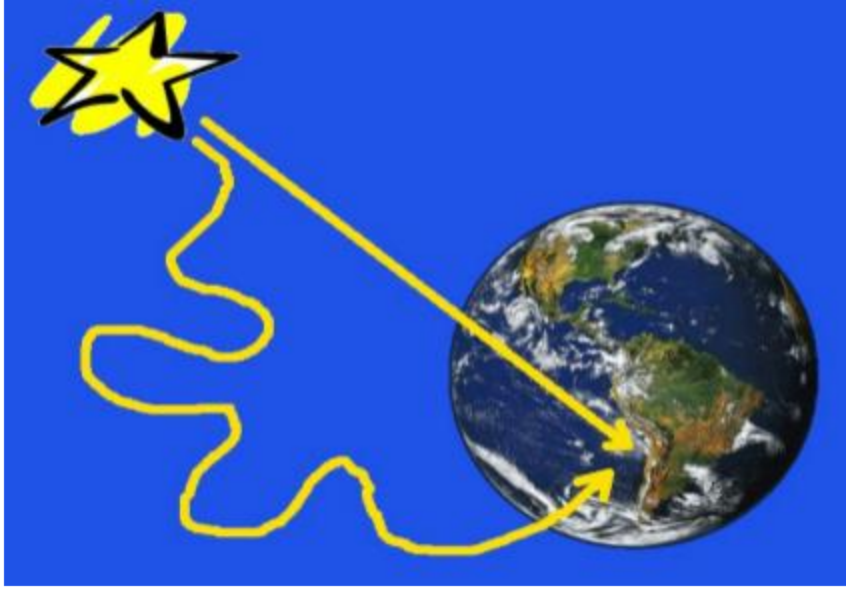
Note more than 125 000 events in the plot!





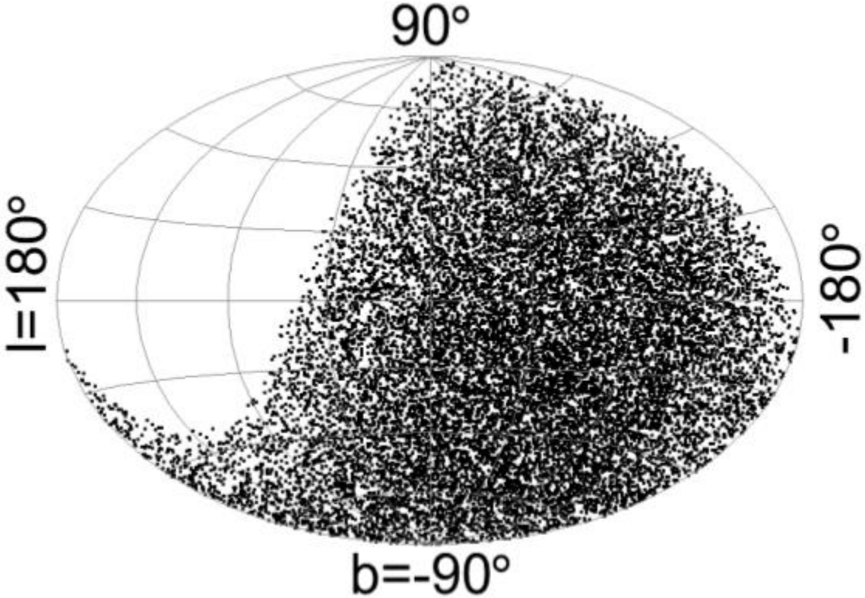
Flux suppression@$10^{19.5}$eV confirmed

Cosmic rays and magnetic field

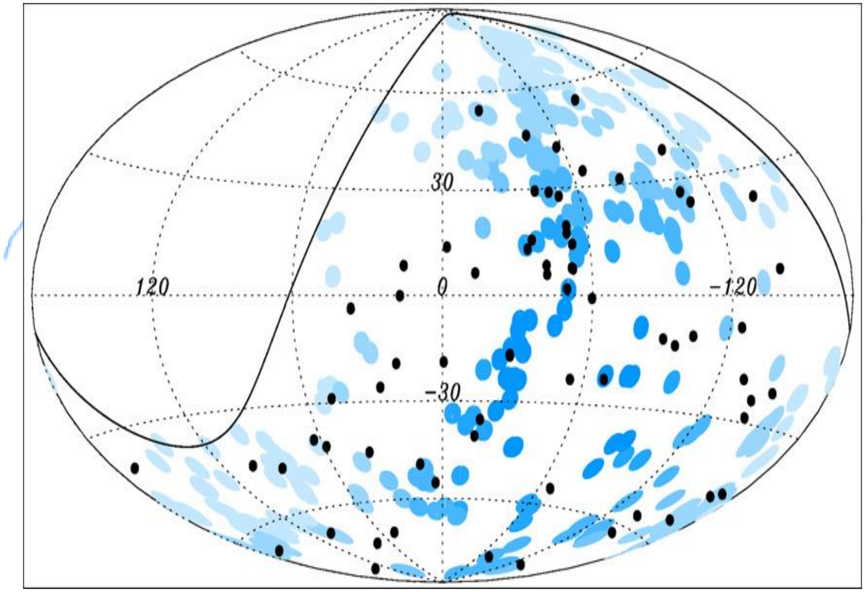


Protons

10^{18}eV



10^{20}eV



protons correlate?, heavy do not?

Observatory

Were do UHECRs come from?
What are they?
How are they accelerated?
Does their spectrum end?

Extensive Air Shower:
- Indirect measurement,
- Shape and particle content of showers

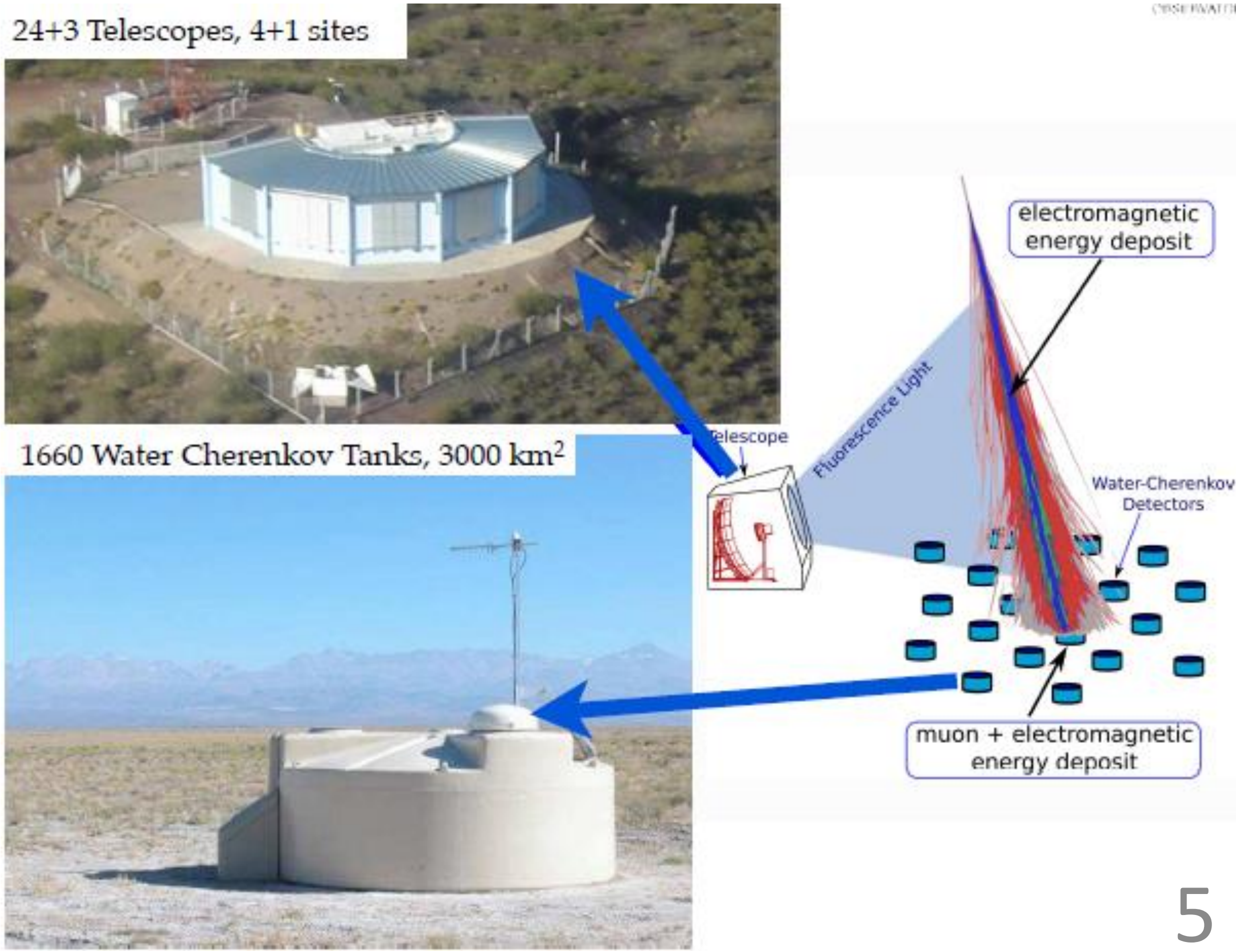
Hybrid Detector

24 Fluorescence telescopes
- 30°×30° FoV
- UV light from excited N2
- 13% duty cycle

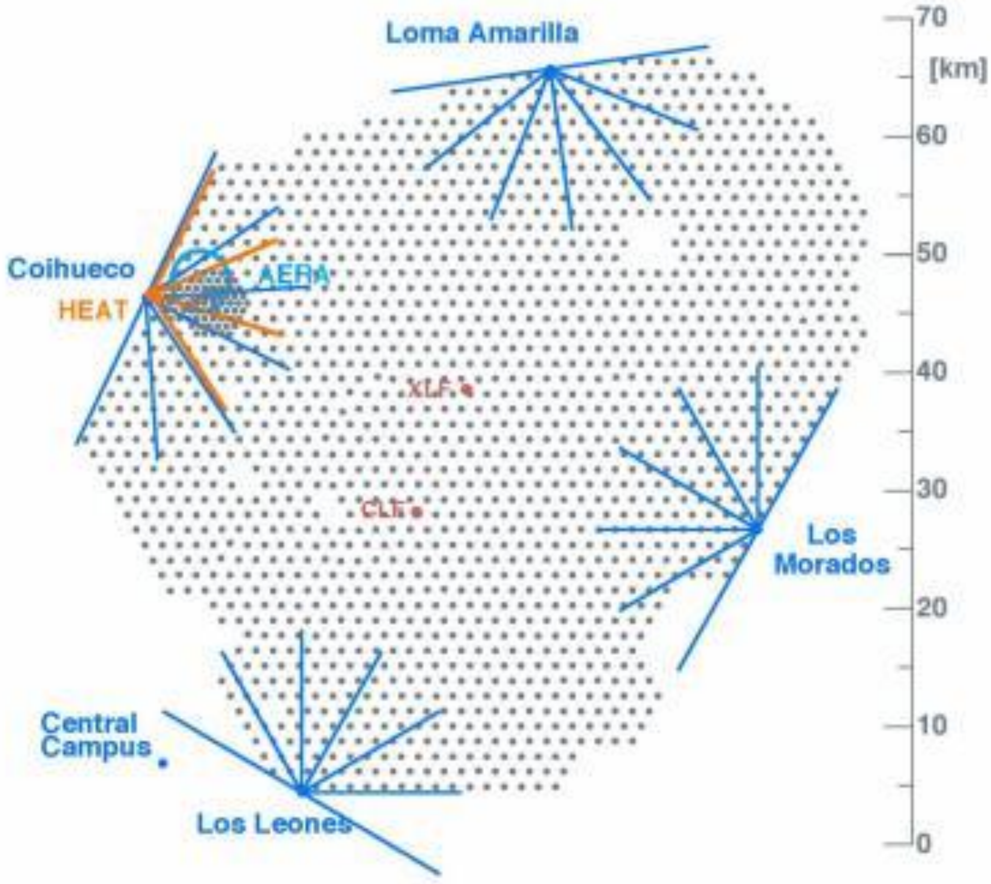
Good energy resolution

Array of 1600 water Cherenkov detectors
- On 3000 km^2,
- 100% duty cycle,

Well-known aperture



Observatory

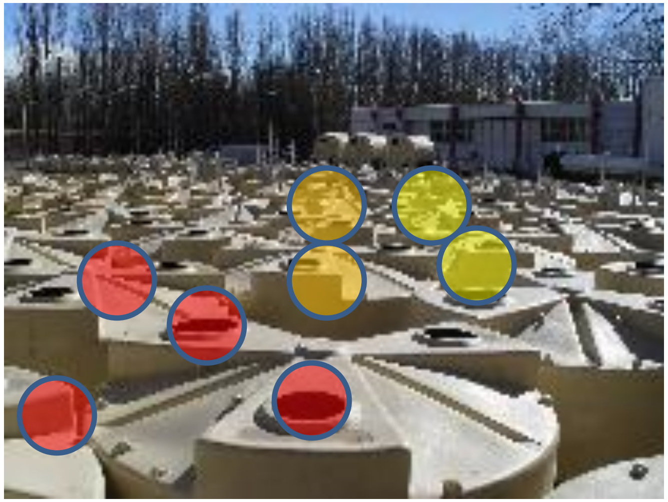


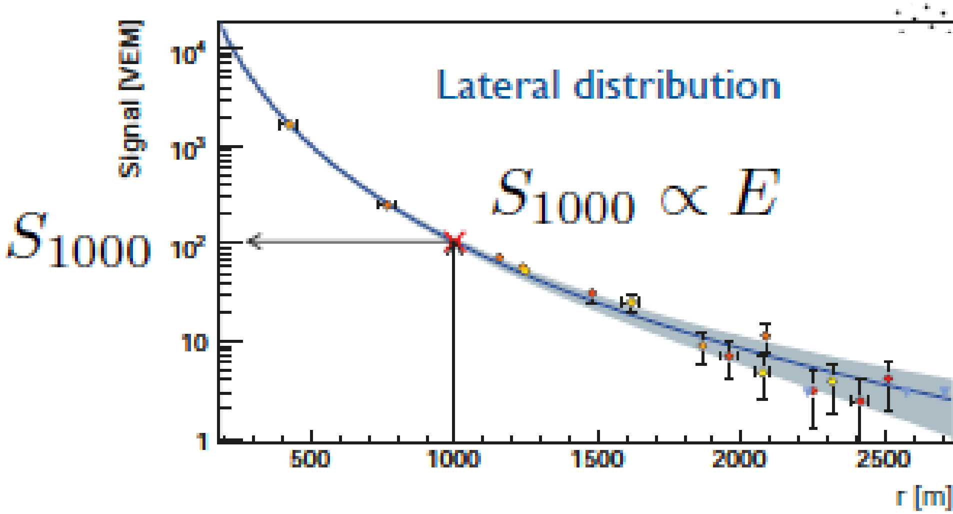
FD - Fluorescence detector
E>10^{18} eV
- Loma Amarilla
- Coihueco
- Los Morados
- Los Leones
- HEAT: E>10^{17} eV

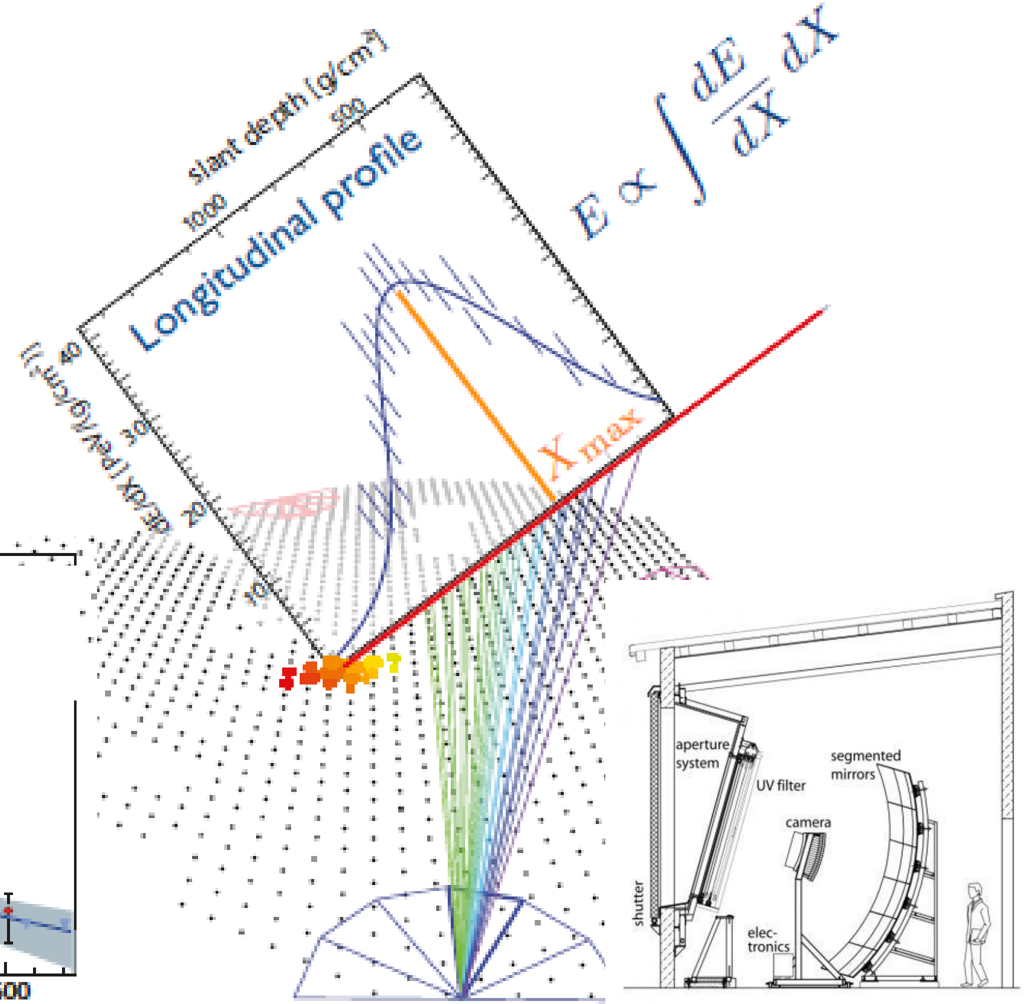
SD - Surface detector array
- 1500 m: E>$10^{18.5}$ eV
- 750 m (AMIGA): E>$10^{17.5}$ eV

Other detector systems (RADIO): AERA (MHz), AMBER (GHz), EASIER (MHz, GHz), MIDAS (GHz)

Observatory – measurement principle



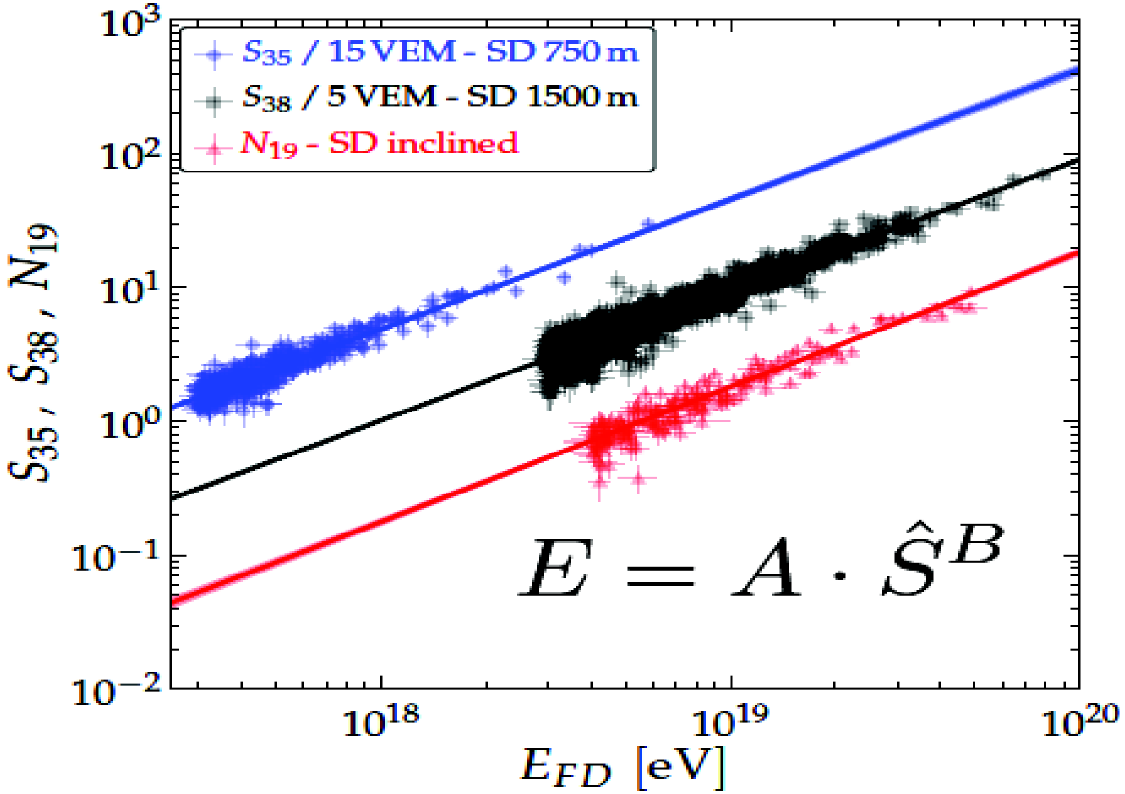




SD

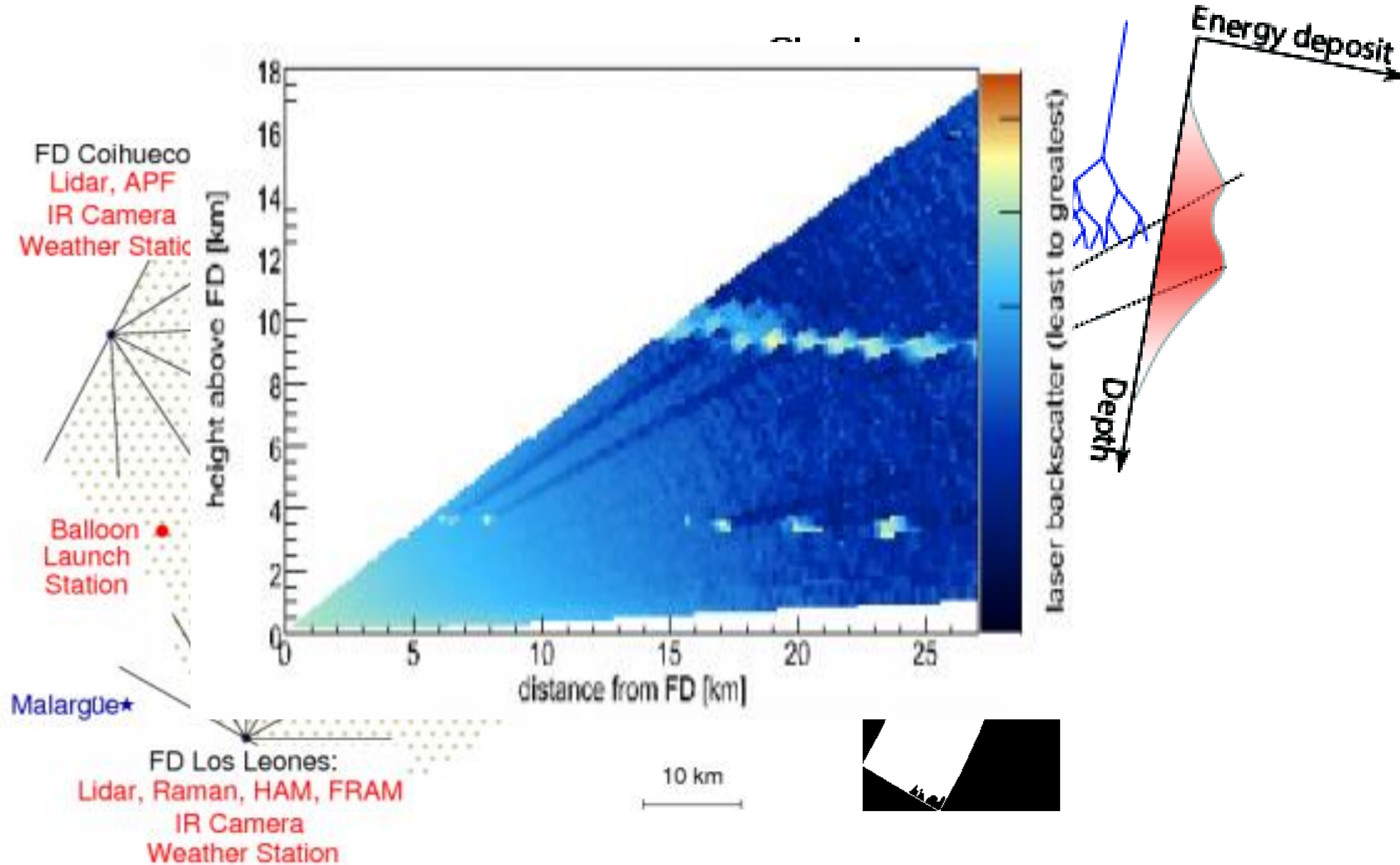
FD

Observatory – energy calibration



Systematic uncertainty on the energy scale:
14% (before update 22%)
Energy resolution: 7 - 8 % (FD), 17 - 12 % (SD)

Observatory – atmospheric measurements



p-air cross-section @ $E_{lab}/eV = 10^{18}$-$10^{18.5}$

Method:

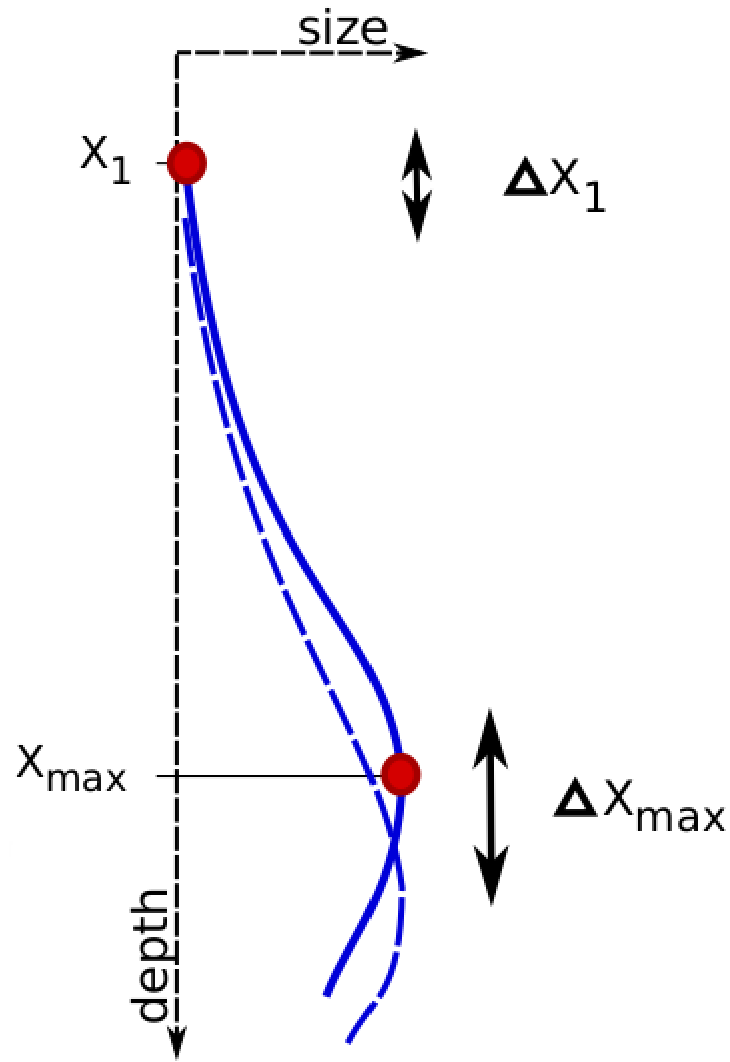
- X_{max} tail sensitive to $\sigma_{p\text{-}air}$

$dN/dX_1 \approx \exp(-X_1/\Lambda_{int})$

$\sigma_{int} = \langle m_{air} \rangle / \Lambda_{int}$

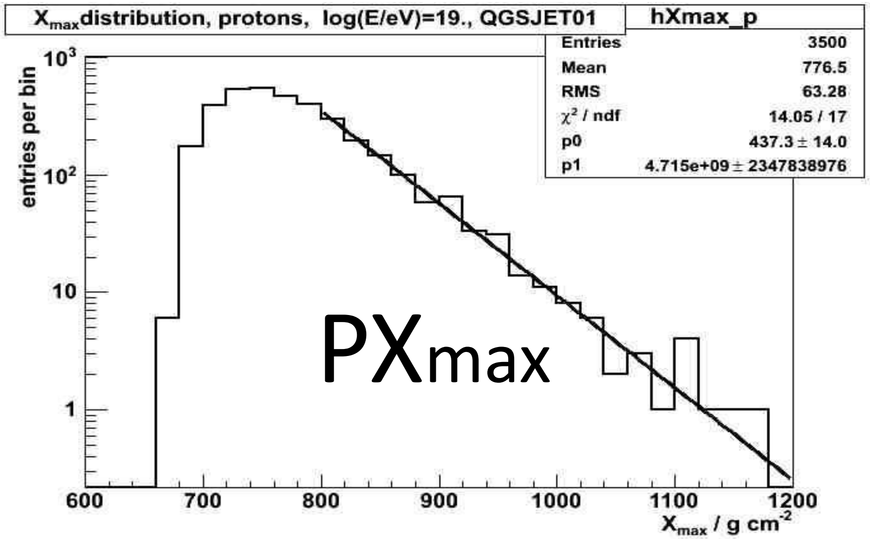
$dN/dX_{max} \approx \exp(-X_{max}/\Lambda_\eta)$

Λ_{int} is related to Λ_η



X_{max} distribution

Problems:
- unbiased X_{max} dist. needed
- $RMS(X_1) \approx RMS(X_{max}-X_1)$ - model
- Unknown composition



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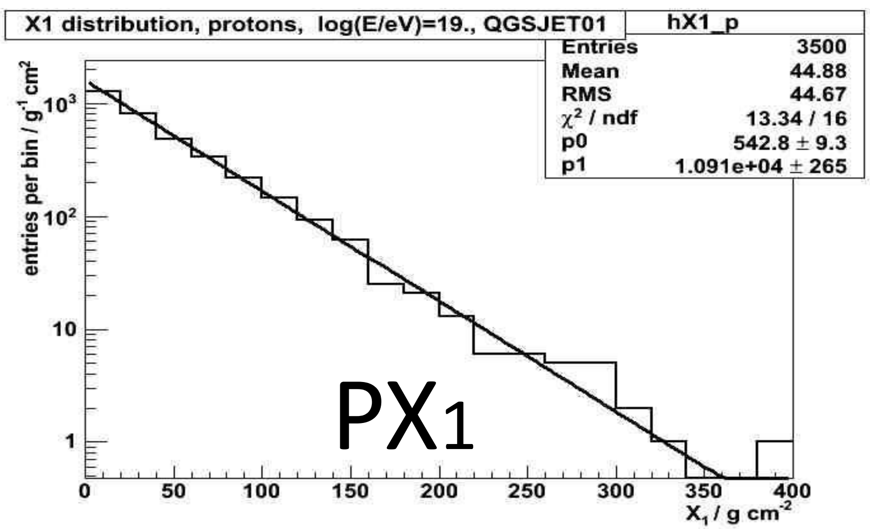

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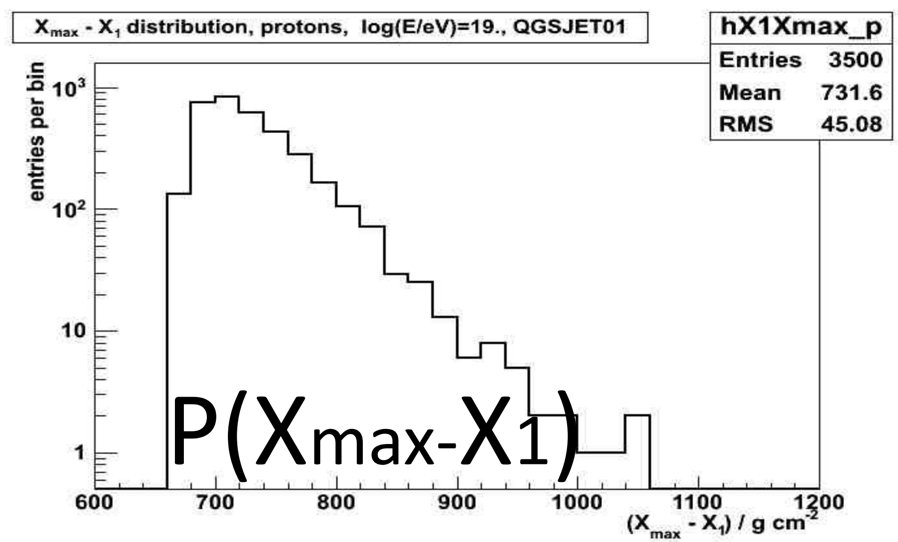
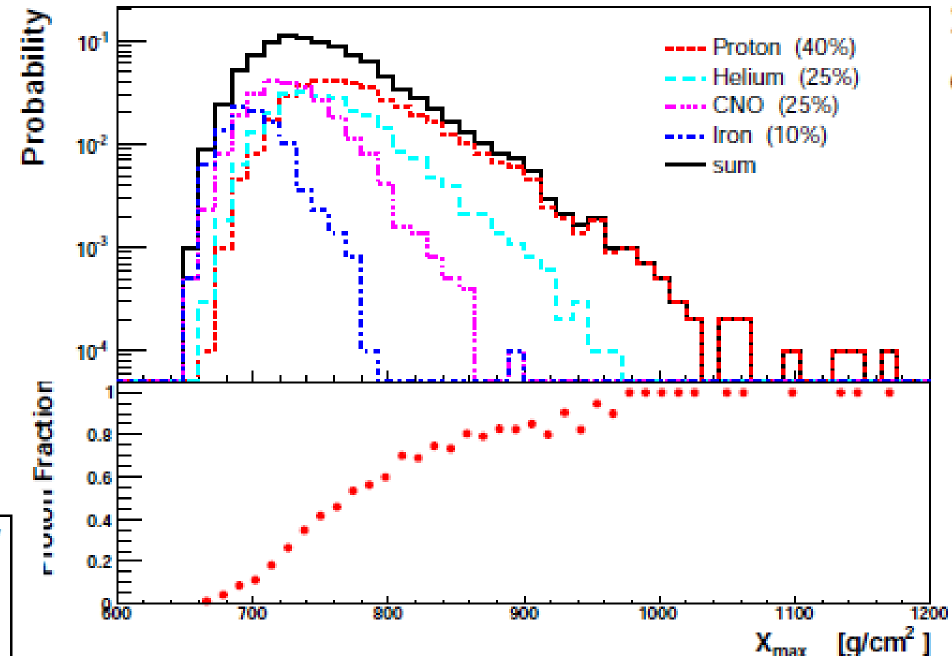
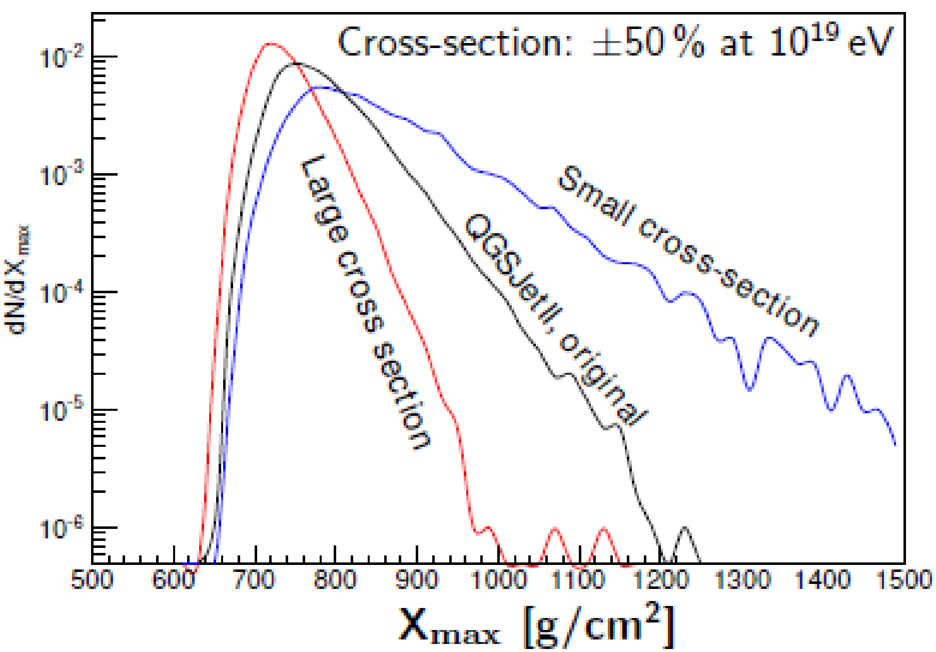


Cross-section – tail of X_{max}

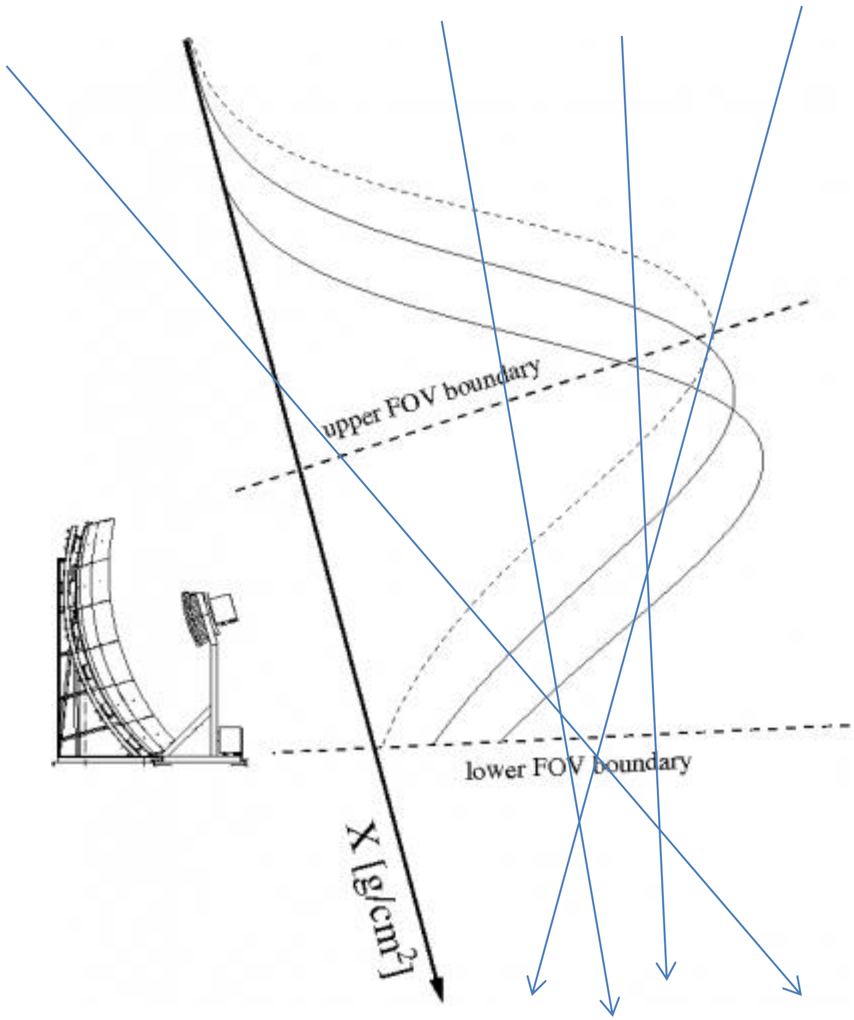
- proton contribution strongly enhanced in X_{max} tail
- protons should be in CR at $E_{lab}/eV = 10^{18}$-$10^{18.5}$





- X_{max} tail very sensitive to production cross-section

X_{max} distribution - observation bias



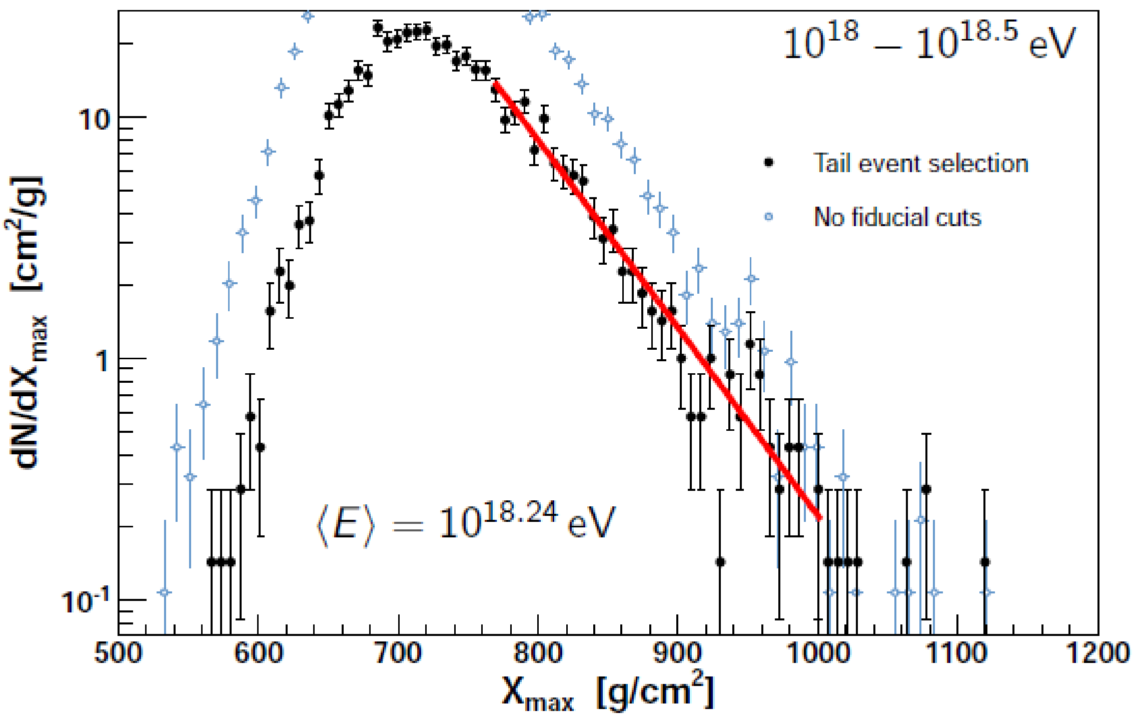
Range of the observable X_{max} depends on shower direction and core location wrt. FD

Select those geometries that allow for large range of observable X_{max}

⇩

Fiducial volume cuts

X_{max} distribution - unbiased



- -fiducial cuts - tail optimized
- -keep as much events as possible
- - 3082 events remain wrt. 1635 events with strict cuts

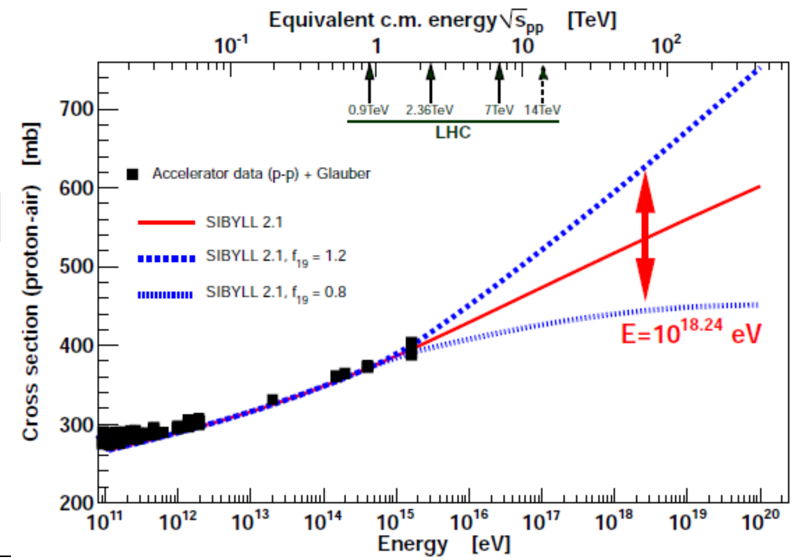
Λ_η / g cm^{-2} = 55.8 ± 2.3$_{stat}$ ± 1.6$_{sys}$

@ $10^{18.24 \pm 0.005_{stat}}$ eV => $\sqrt{s}$ = 57 ± 0.3 TeV

p-air cross-section

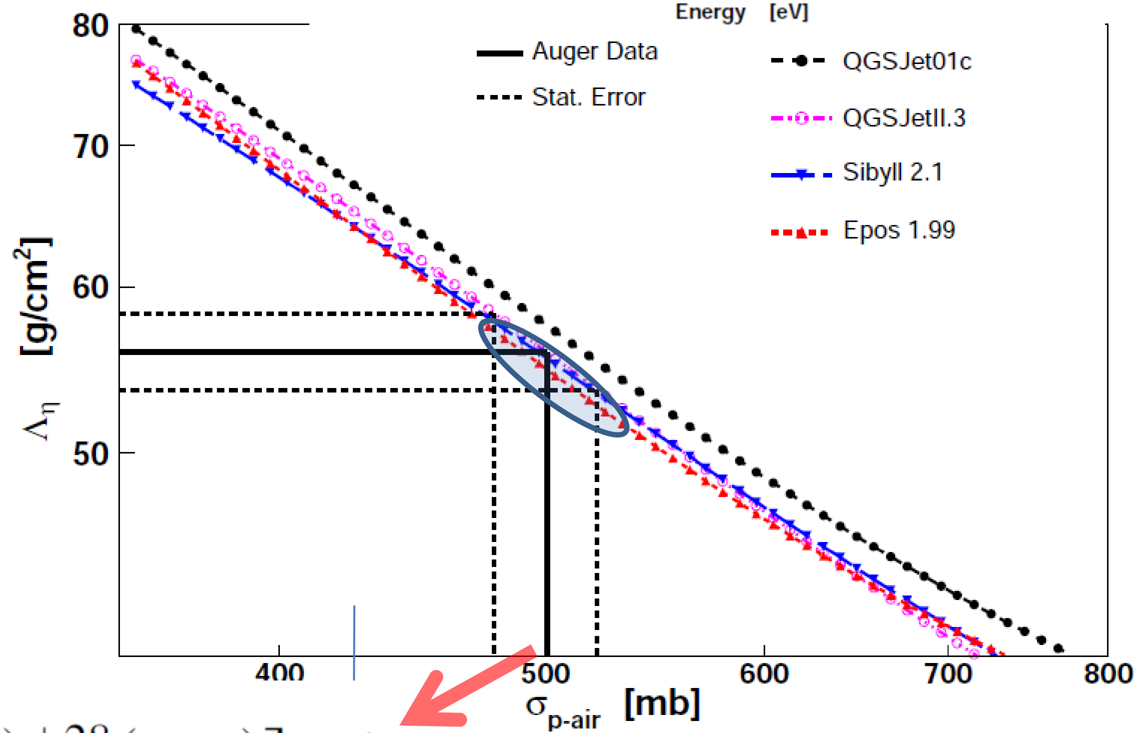
Convert Λ_η to σ_{int} – models needed

MC resampling with modified σ_{int}



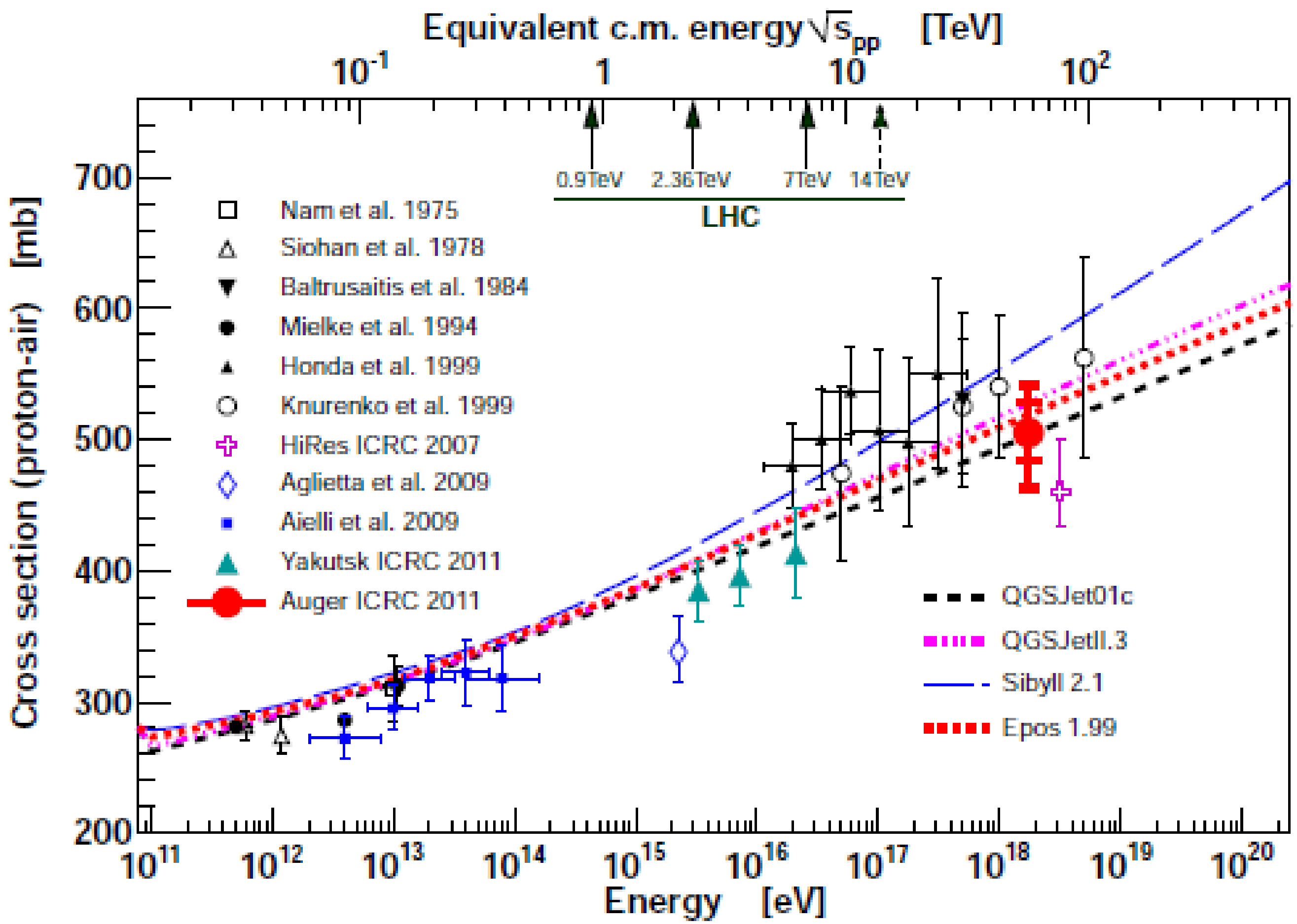
$$f(E,\, f_{19}) = 1 + (f_{19} - 1)\; F(E)$$

$$F(E) = \frac{\lg\left(E/10^{15}\,\text{eV}\right)}{\lg\left(10^{19}\,\text{eV}/10^{15}\,\text{eV}\right)}$$



$$\sigma_{p\text{-air}}^{\text{prod}} = [505 \pm 22(\text{stat})^{+28}_{-36}(\text{syst})]\ \text{mb}$$

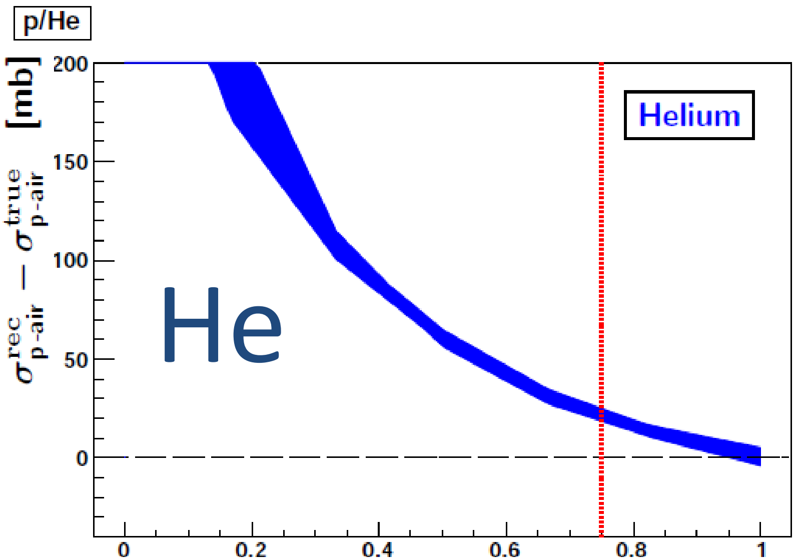
p-air cross-section

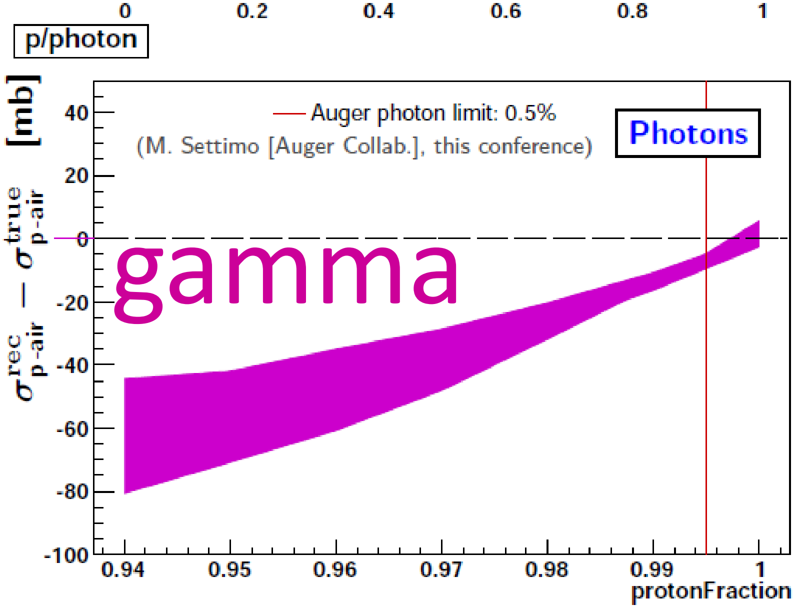


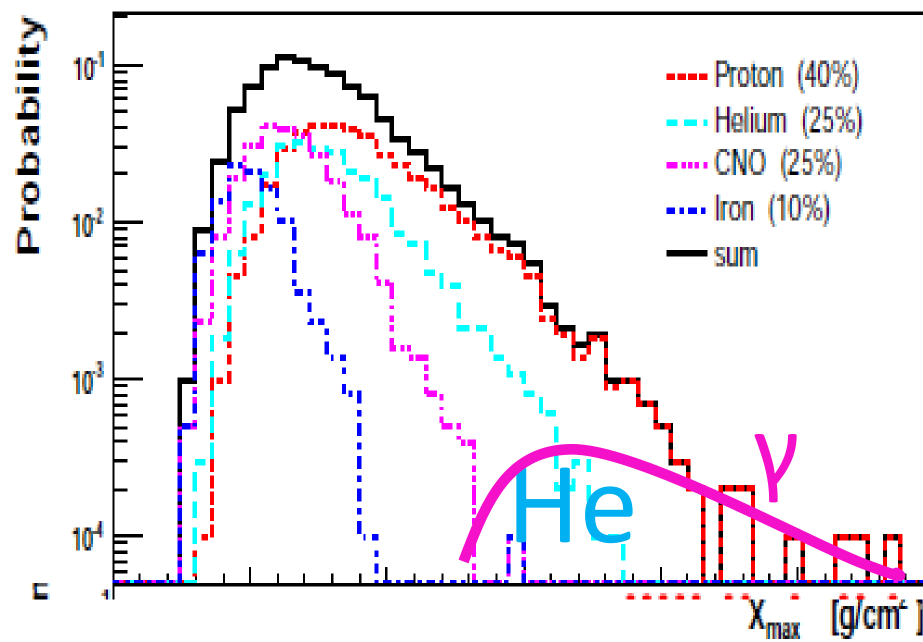
$$\sigma_{p\text{-air}}^{\text{prod}} = [505 \pm 22(\text{stat})^{+28}_{-36}(\text{syst})] \text{ mb}$$

Systematics $\sigma_{\text{p-air}}$

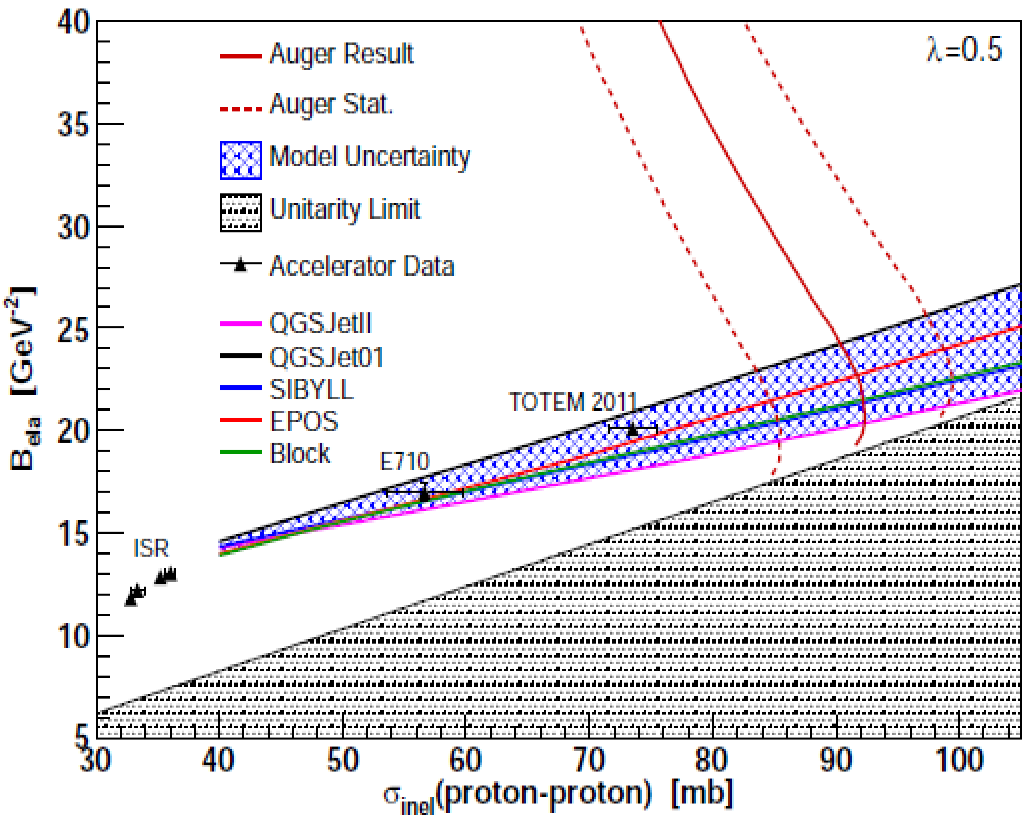
Description	Impact on $\sigma_{\text{p-air}}$
Λ_η systematics	± 15 mb
Hadronic interaction models	$^{+19}_{-8}$ mb
Energy scale	± 7 mb
Conversion of Λ_η to $\sigma^{\text{prod}}_{p\text{-air}}$	± 7 mb
Photons, $<0.5\,\%$	$< +10$ mb
Helium, 10 %	-12 mb
Helium, 25 %	-30 mb
Helium, 50 %	-80 mb
Total (25 % helium)	-36 mb, $+28$ mb







Conversion to $\sigma_{p\text{-}p}$



- Glauber with diffractive intermediate states included

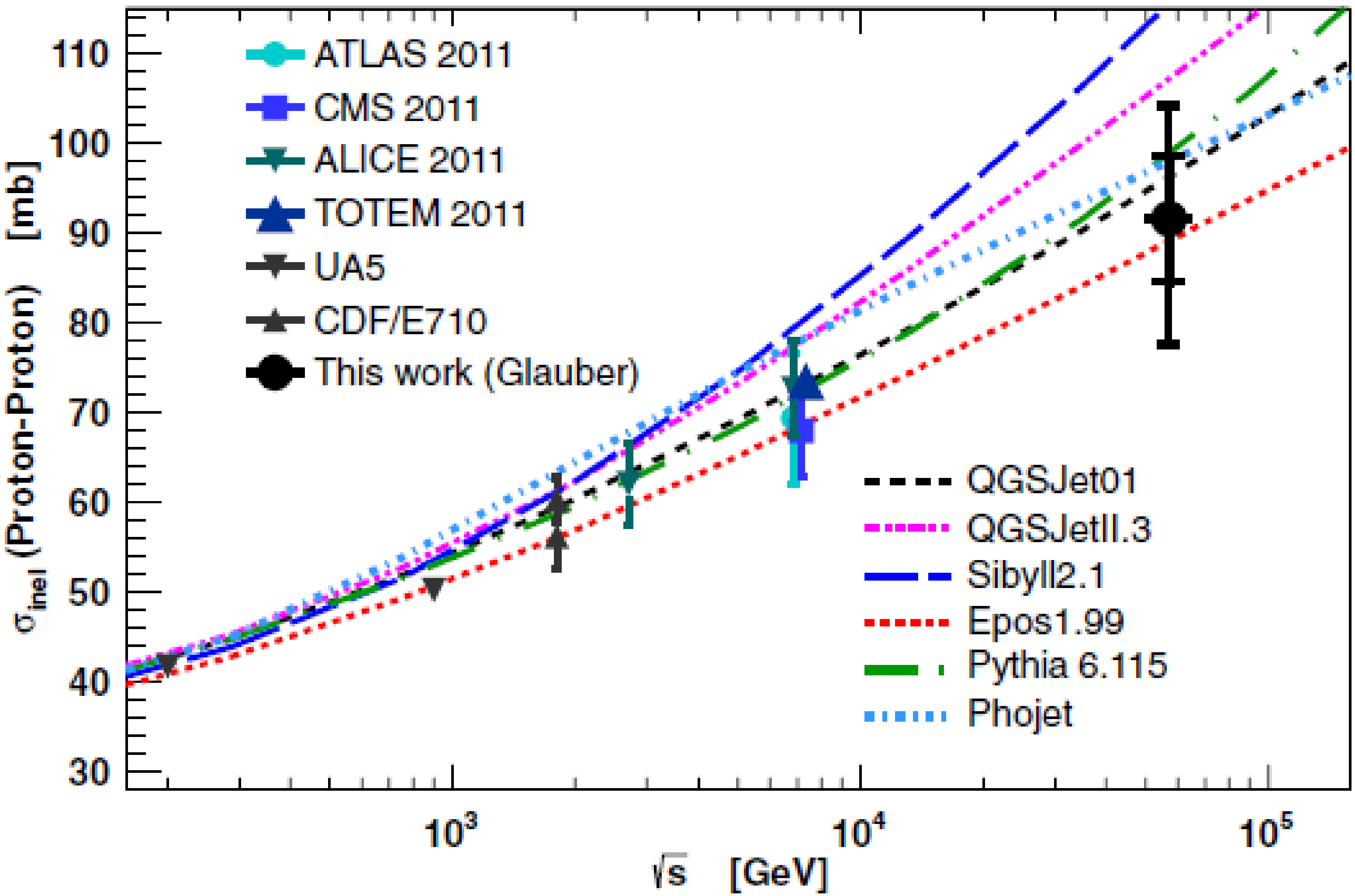
- additional parameter λ: ratio of diffractive and elastic amplitudes

- systematical errors of the conversion derived

$$\sigma_{pp}^{\mathrm{inel}} = [92 \pm 7(\mathrm{stat})^{+9}_{-11}(\mathrm{syst}) \pm 7(\mathrm{Glauber})]\ \mathrm{mb}$$

$$\sigma_{pp}^{\mathrm{tot}} = [133 \pm 13(\mathrm{stat})^{+17}_{-20}(\mathrm{syst}) \pm 16(\mathrm{Glauber})]\ \mathrm{mb}$$

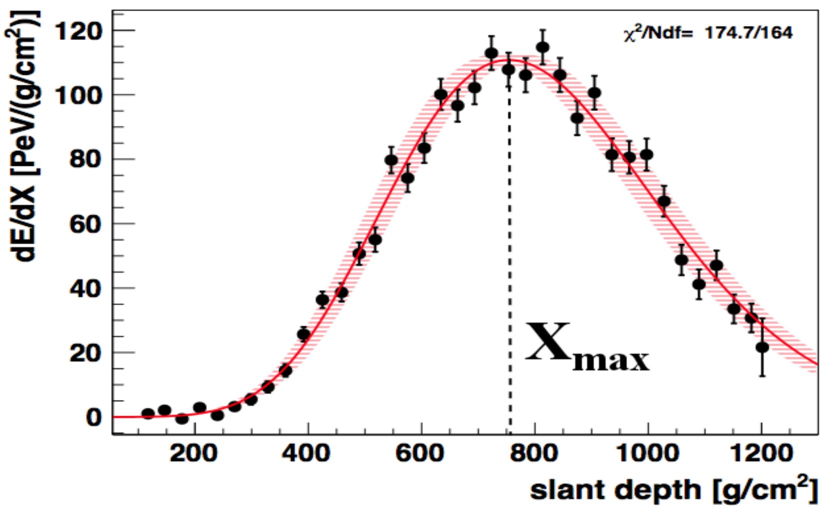
Conversion to $\sigma_{p\text{-}p}$

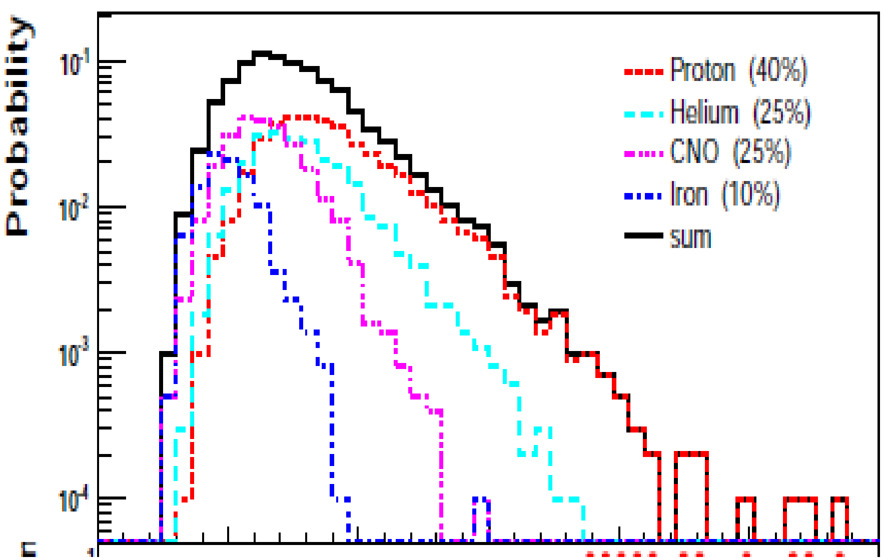


Primary cosmic ray composition

Hadronic interaction models

CR composition





Mass sensitive variables:

FD

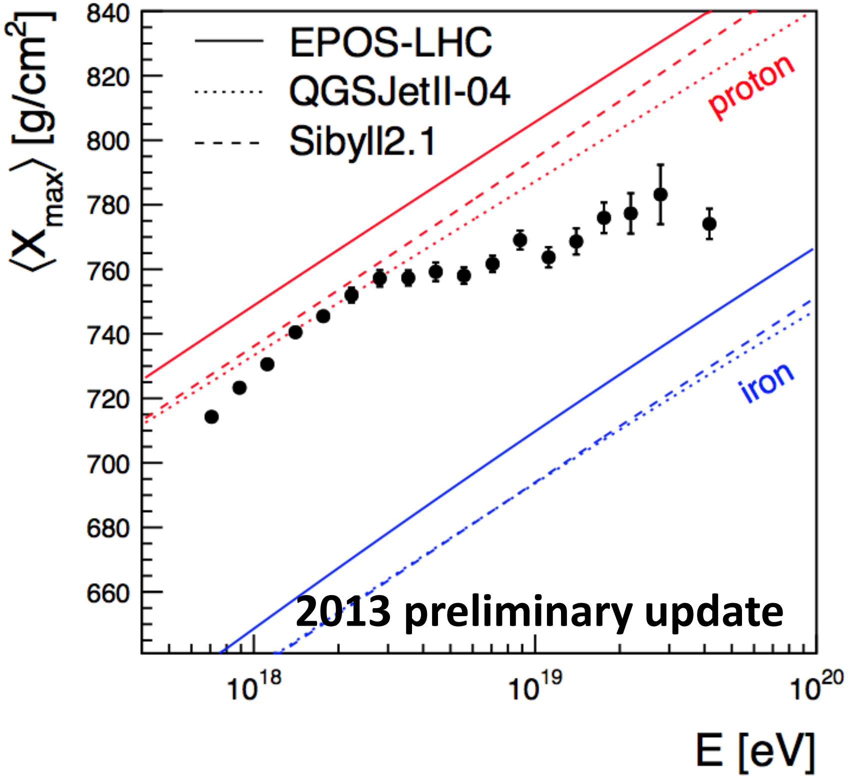
X_{max} ($<X_{max}>$,RMS(X_{max})):
Light nuclei - deep showers - high Xmax
Heavy nuclei – shallow showers – low Xmax

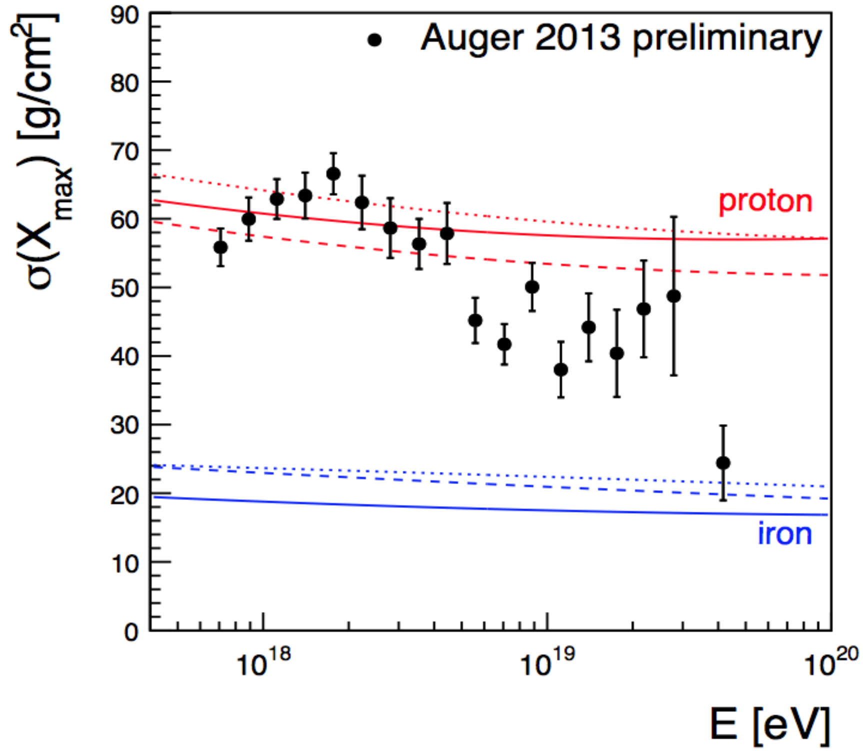
SD

X^{μ}_{max} ,Asymmetry (θ_{max})
($<X^{\mu}_{max}>$,$<\theta_{max}>$)

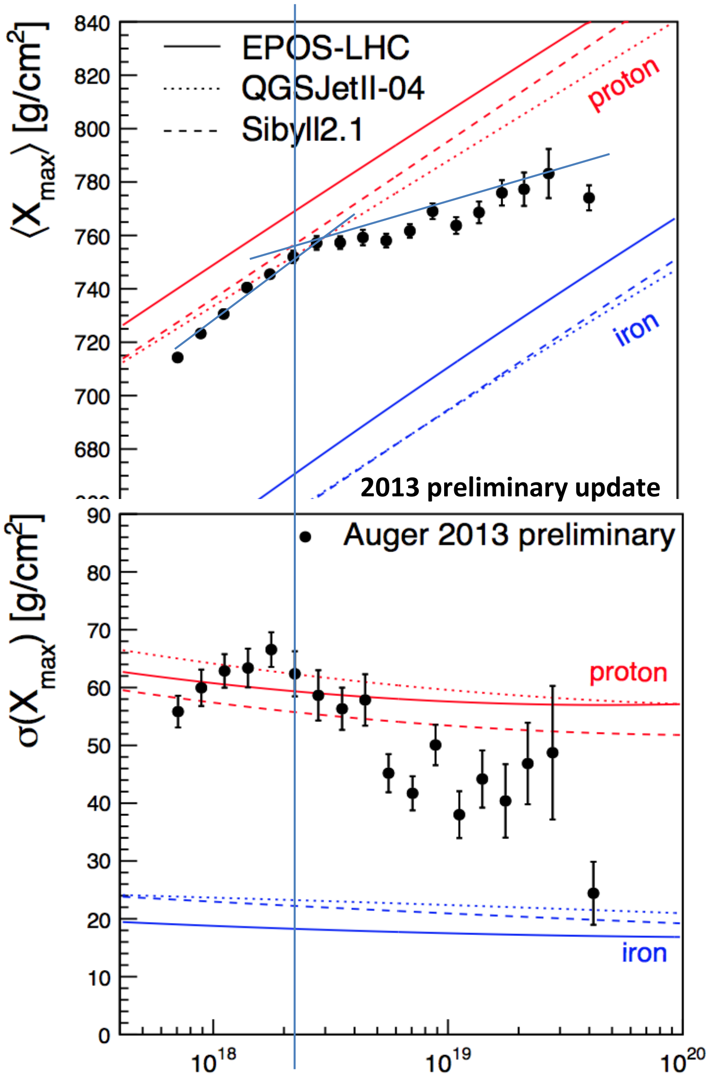
$\langle X_{max} \rangle$, RMS(X_{MAX})

2013 preliminary (ICRC) results confirmed published data
- note improved energy scale and reconstruction





$<X_{max}>$,RMS(X_{MAX})



$<X_{max}>$ slope changes at E≈$10^{18.45}$ eV

RMS(X_{max}) decreases at E≈$10^{18.45}$ eV

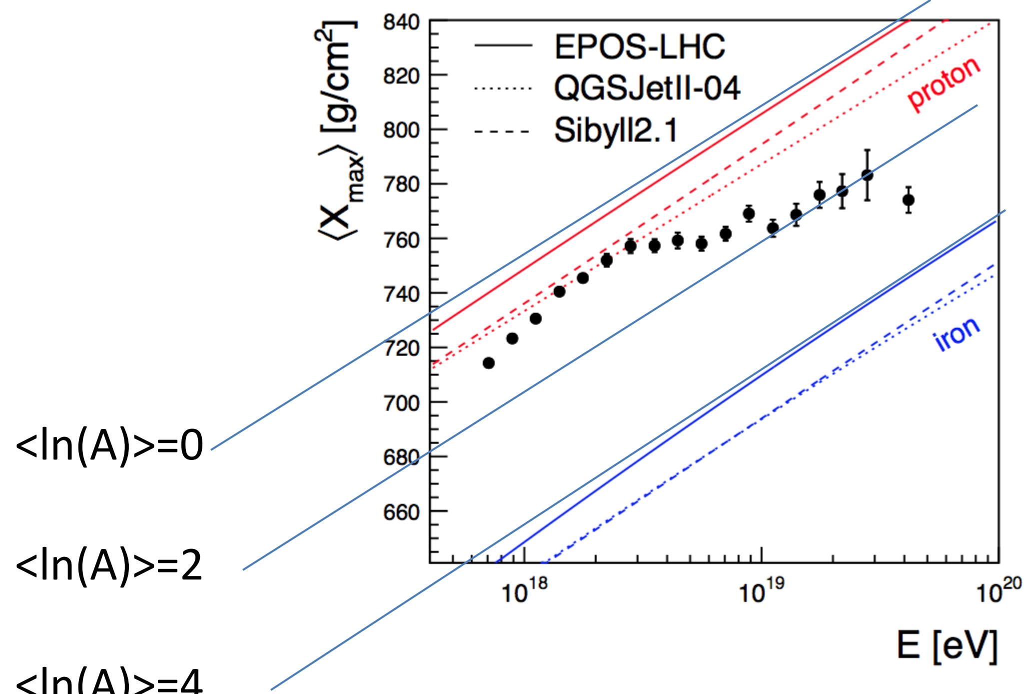
Explanations:

- Composition gets heavier

- Hadronic interactions “change” (eg. cross-section increases much faster with energy)

ln(A), σ²(lnA)

$$\langle X_{\max} \rangle = \langle X^{p}_{\max} \rangle - D_p \, \langle \ln A \rangle$$
$$\sigma^2(X_{\max}) = \langle \sigma_i^2 \rangle + D_p^2 \sigma^2 \left(\ln A\right)$$



D_p: elongation rate $(\mathrm{d}\langle X_{\max}\rangle / \mathrm{d}\log_{10}(E))$ - from data

$\langle X^{p}_{\max} \rangle$: average depth of protons - from proton simulation

$\langle \sigma_i^2 \rangle$: mass-averaged shower fluctuations - from simulations

$$\langle \ln \mathrm{A} \rangle = \sum \mathrm{f_i} \ln \mathrm{A_i}$$

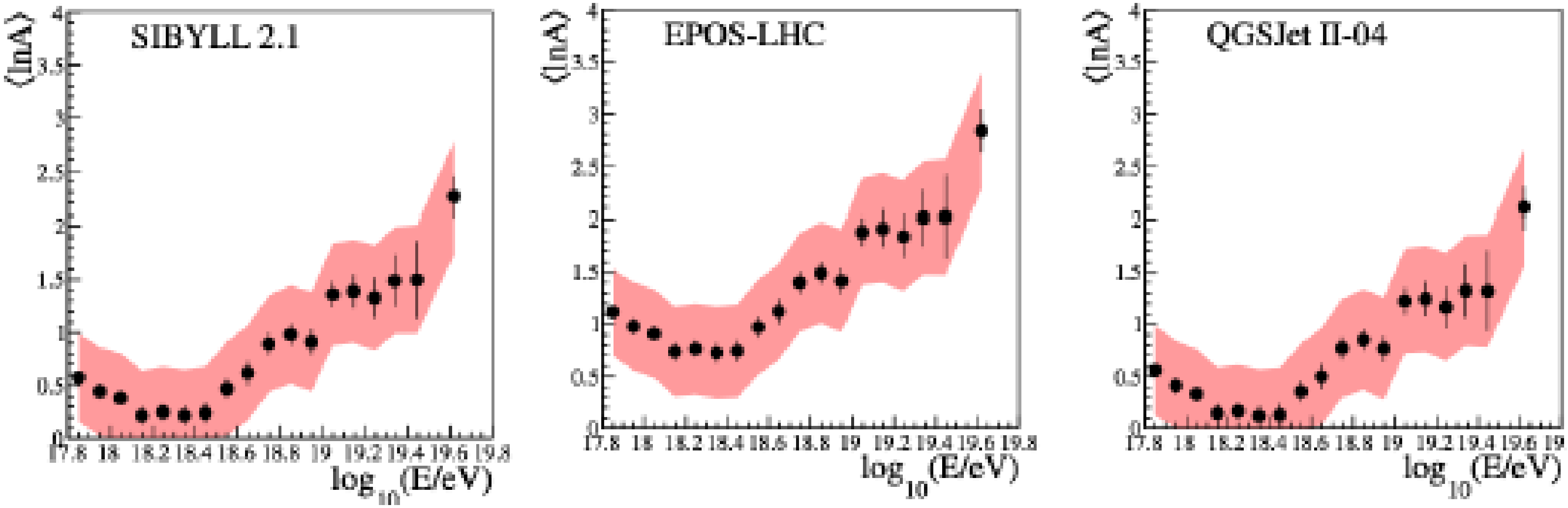
e.g. pure $p \rightarrow \langle \ln A \rangle = 0$, pure $Fe \rightarrow \langle \ln A \rangle \approx 4$, $50:50\, p/Fe \rightarrow \langle \ln A \rangle \approx 2$

$$\sigma^2(\ln \mathrm{A}) = \langle \ln^2 \mathrm{A} \rangle - \langle \ln \mathrm{A} \rangle^2$$

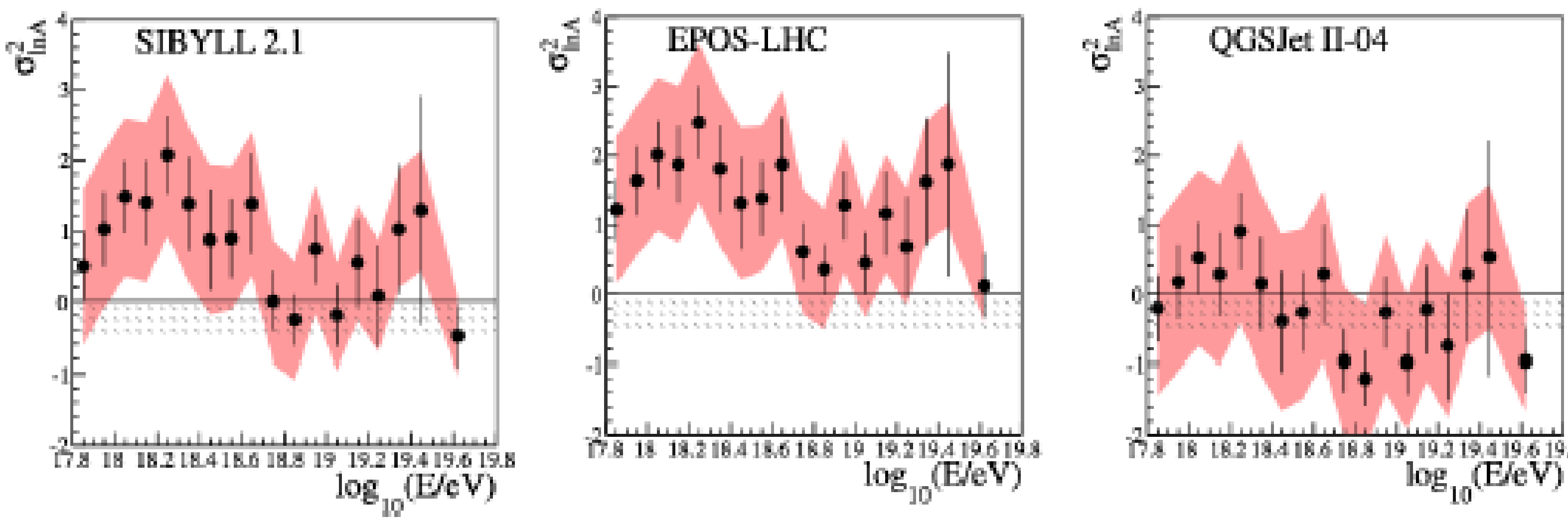
e.g. pure $p/Fe \rightarrow \sigma^2(\ln A) = 0$, $50:50\, p/Fe \rightarrow \sigma^2(\ln A) \approx 4$

ln(A), σ^2(ln(A)) from X_{max}

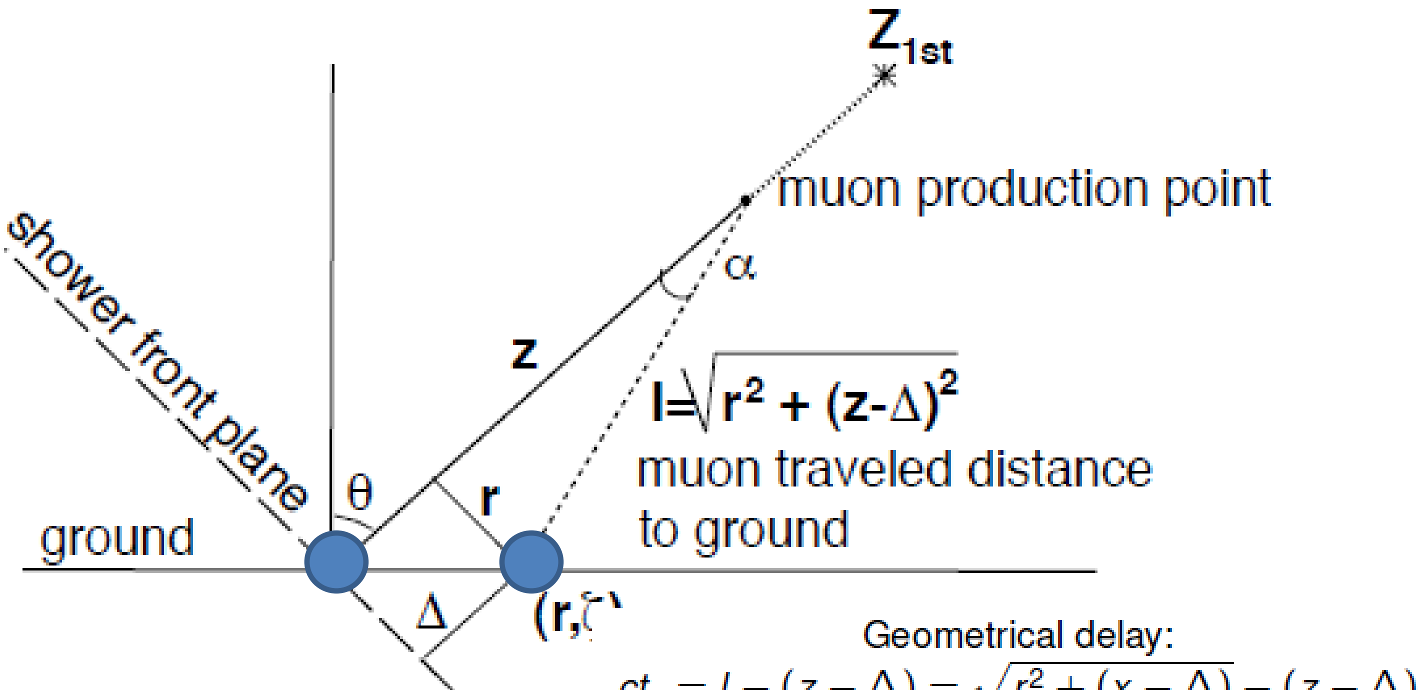
ln *A*



σ^2(ln *A*)



X^{μ}_{max} - muon production depth (MPD)



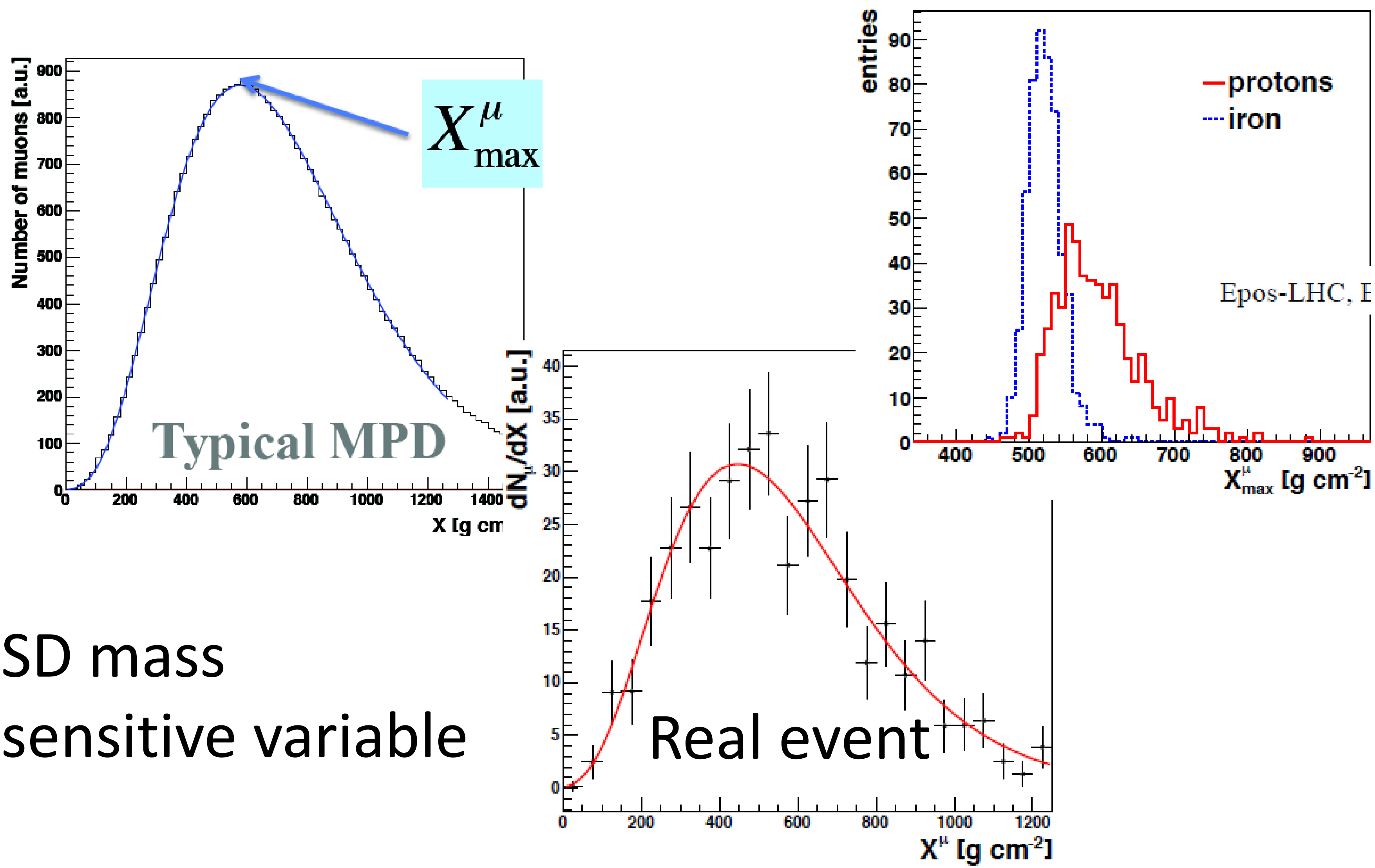
Shower direction

Zenith angles ≈ 60 deg

Muon arrival times from VEM traces in SD stations

Production depth of individual muons from time delay

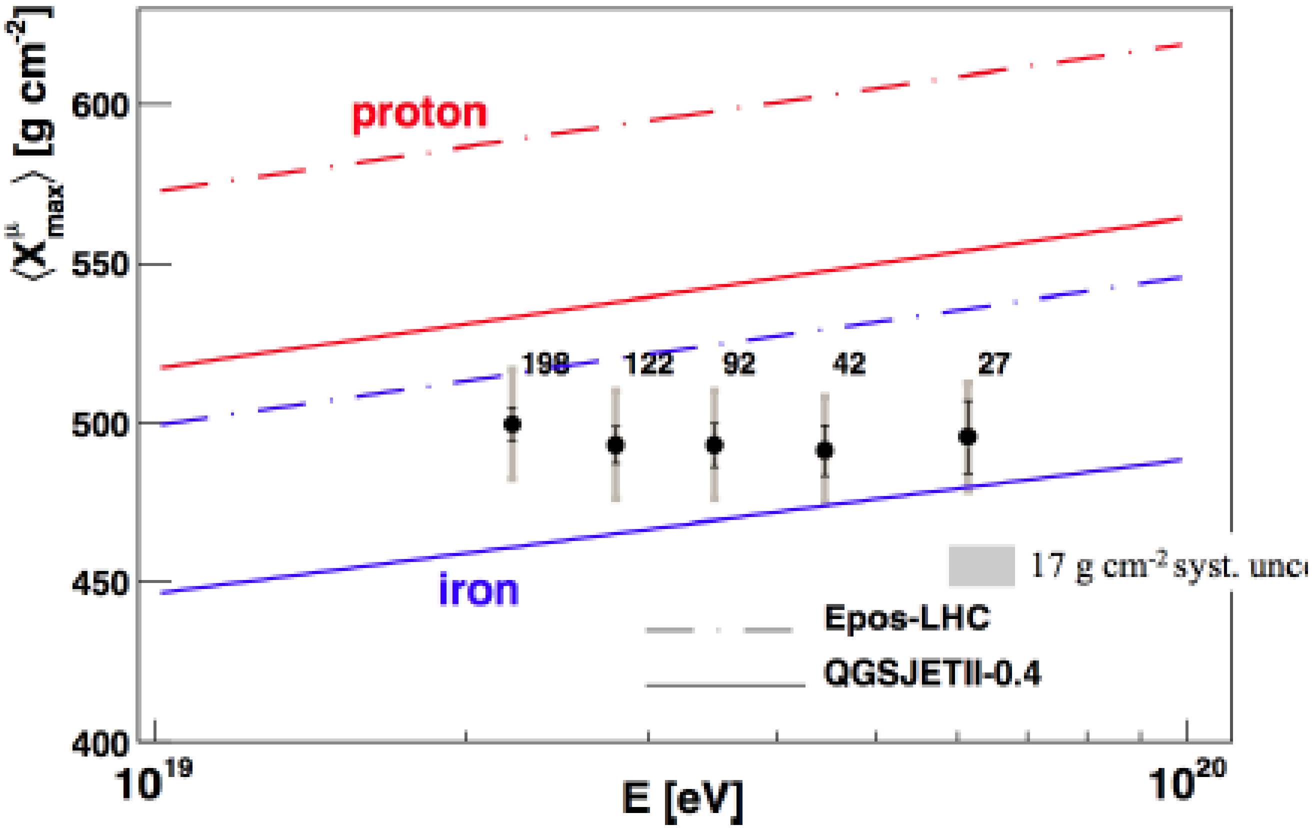
X^{μ}_{max} - muon production depth (MPD)



SD mass
sensitive variable

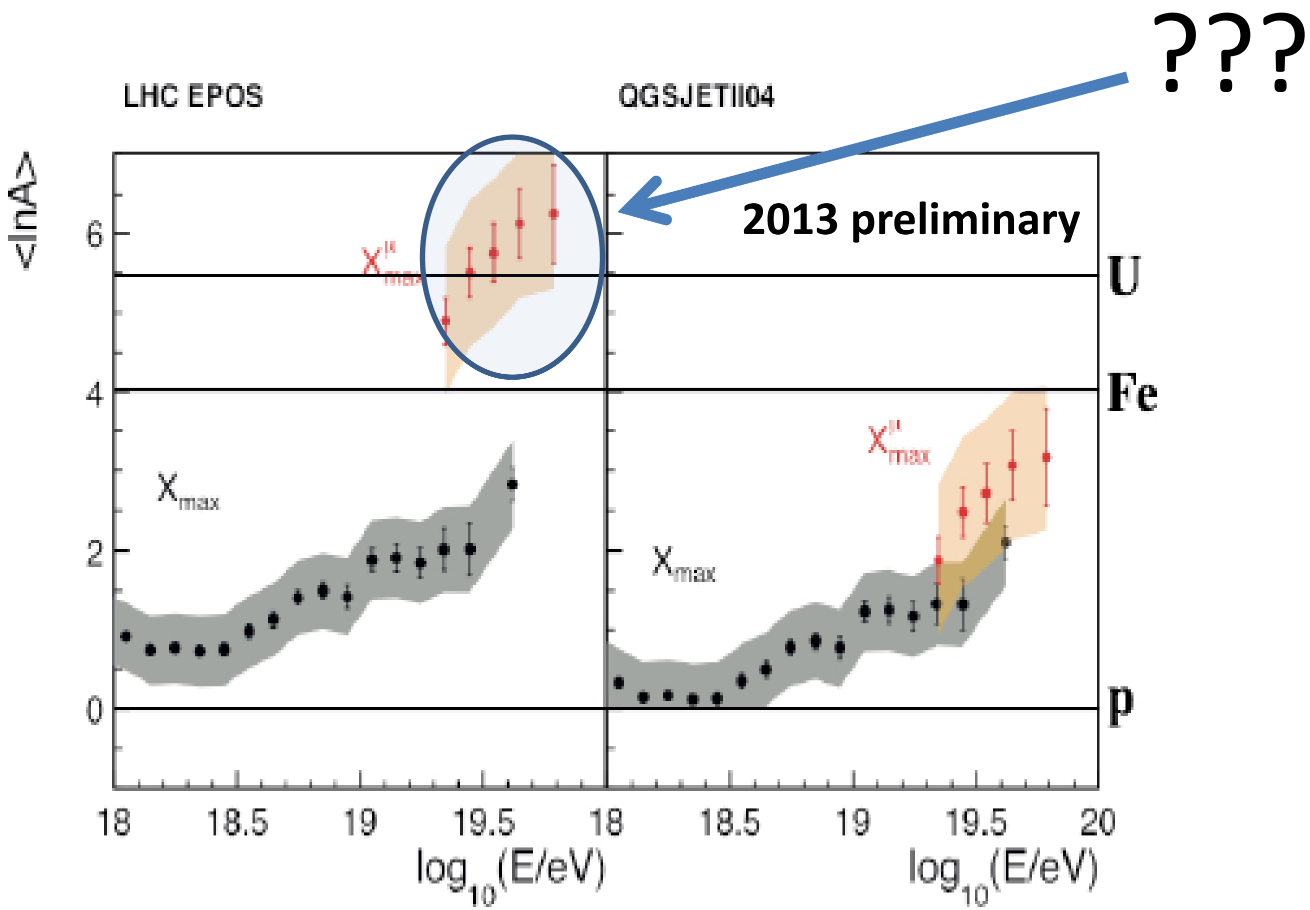
X^{μ}_{max} _muon production depth (MPD)

2013 preliminary



Larger differences between hadronic models compared to the X_{max}

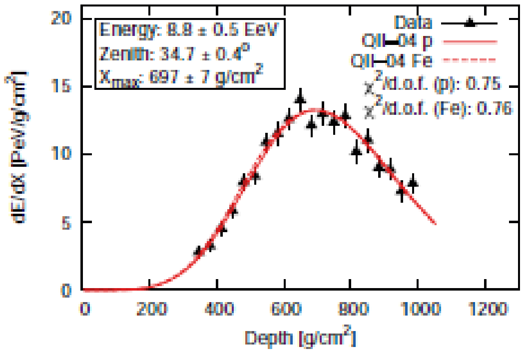
ln(A) from X^{μ}_{max}

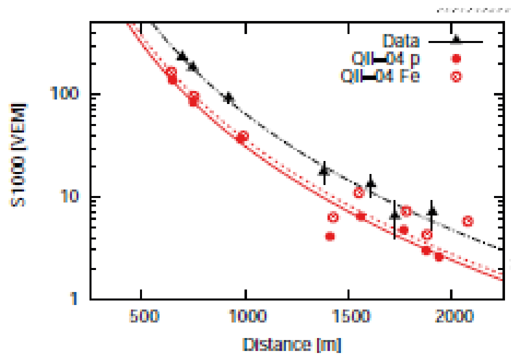


Model discrepancy – needs to be further investigated

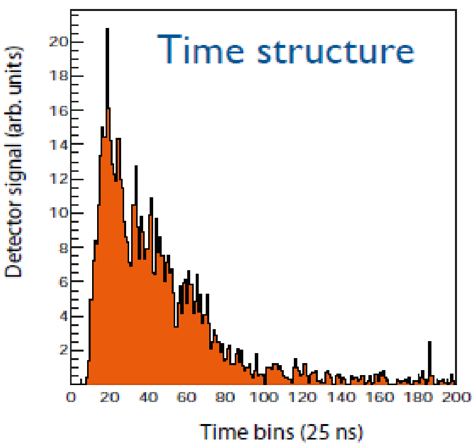
Muonic signals

How much “artificially” increase muon signal in simulations to describe measured SD signals?

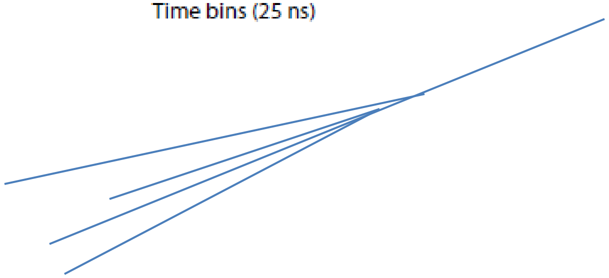




Hybrid events

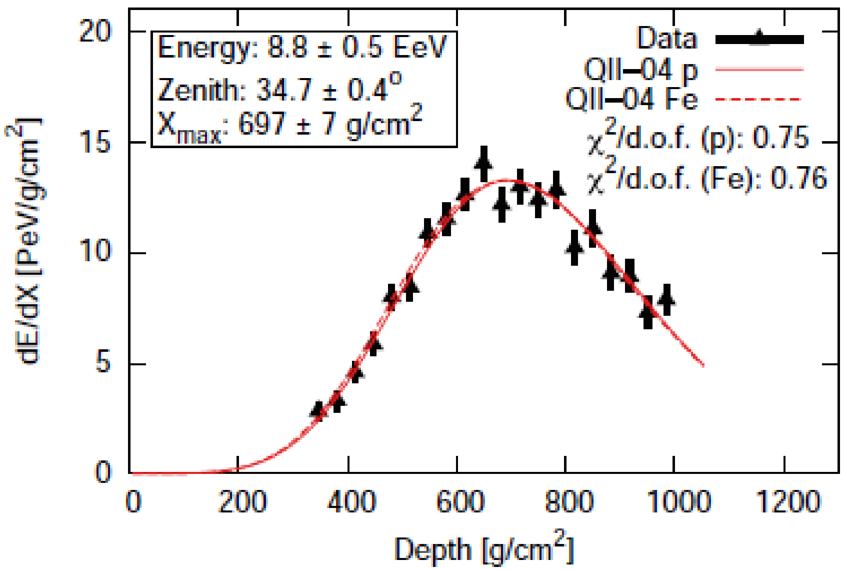


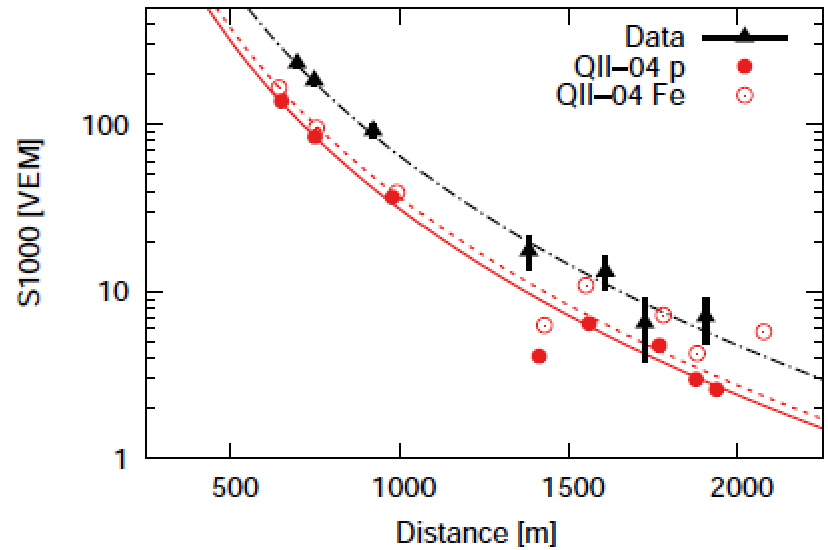
FADC time structure
extraction of muonic component



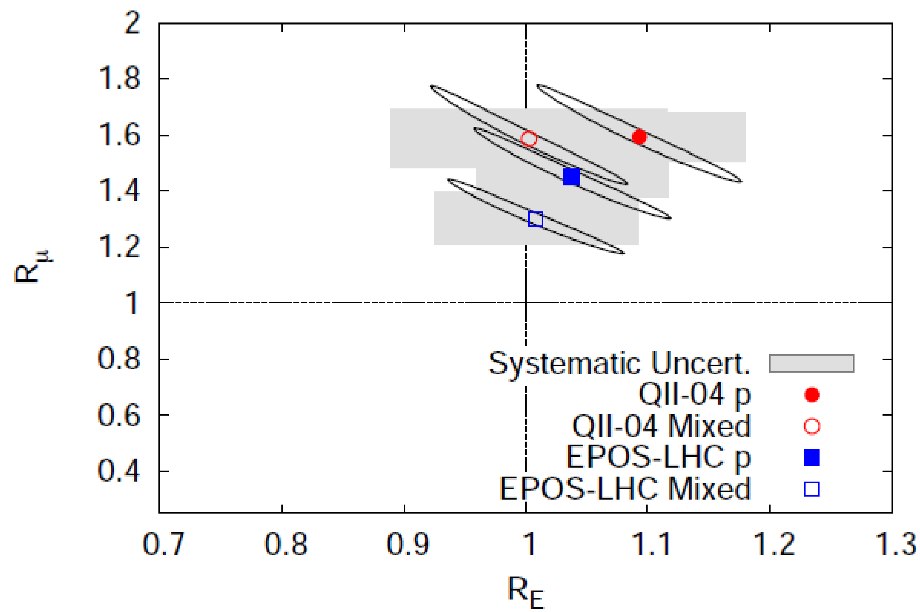
Inclined showers
muon component dominates

μ - Hybrid events



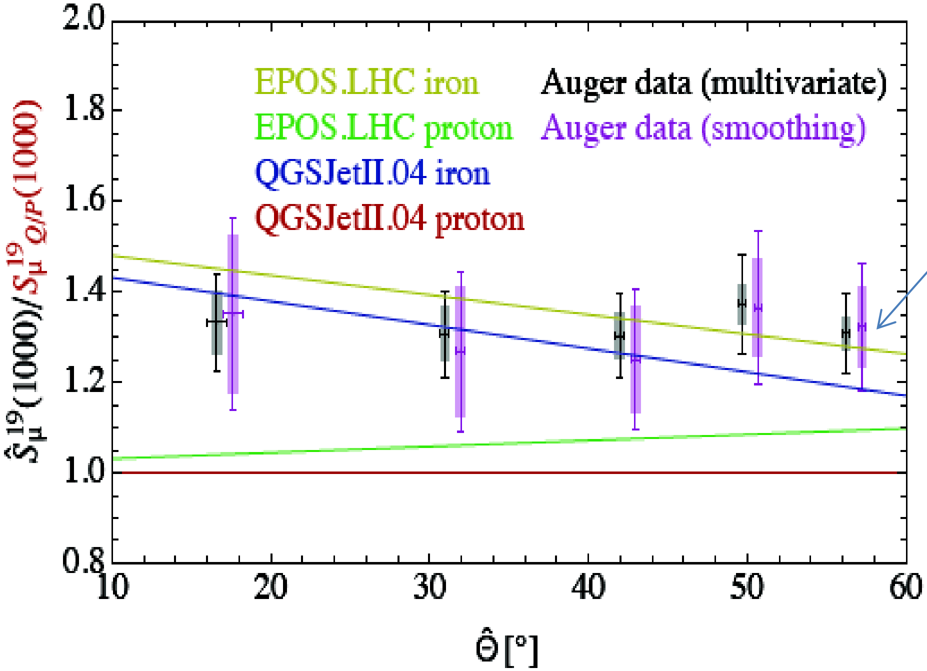


Rμ,R_E

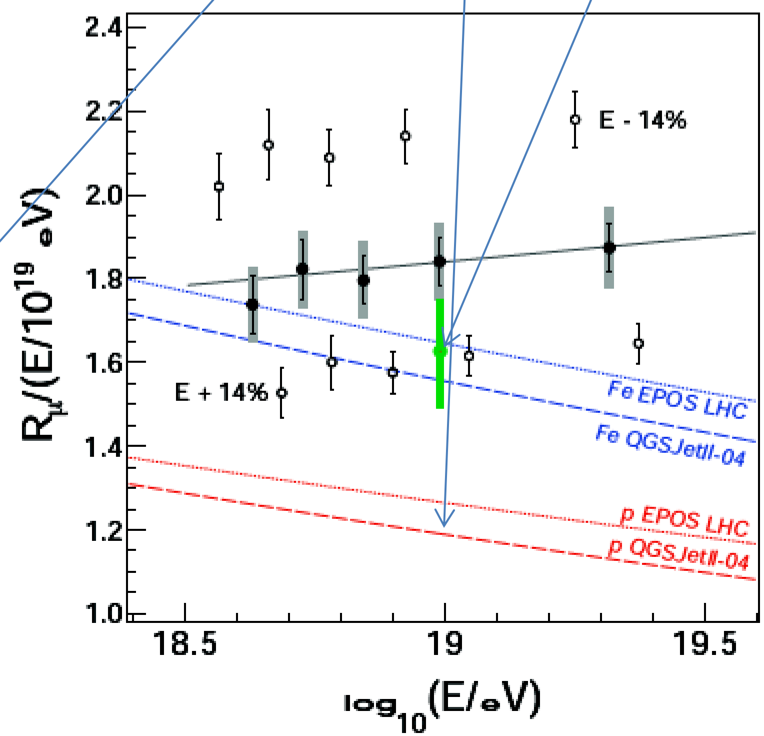


μ – FADC traces, inclined

1.35 x 1.2 = 1.6



Vertical, FADC traces
analysis@10^{19}eV
Reference QGSJETII.04 (proton)



Inclined events
Reference QGSJETII.03 (proton)

Conclusions 1/2

- Inelastic p-air cross-section measured @E_{lab}=$10^{18.24}$ eV
- Inelastic p-p(Glauber) cross-section estimated @57 TeV

- All composition related results - with increasing energy clear trend from light to heavier component at E_{lab}>$10^{18.4}$eV

- μ – direct (indirect) results comparable with Fe-like prediction of current hadronic interaction models
- EM – observed X_{max} distribution not compatible with Fe only

- Hadronic interaction models cannot be consistently used to interpret all data in terms of CR composition

Conclusions 2/2

Primary cosmic ray composition

Hadronic interaction models

How to disentangle? Ever?

- Test/tune models at LHC

- Try to define beam of light (correlating) particles on the sky (highest energies needed)
    - simultaneous composition and anisotropy searches
    - large aperture needed (>= AUGER)
    - better muon detector on ground