Mass composition studies and photon fraction limits of UHECR with the Pierre Auger Observatory

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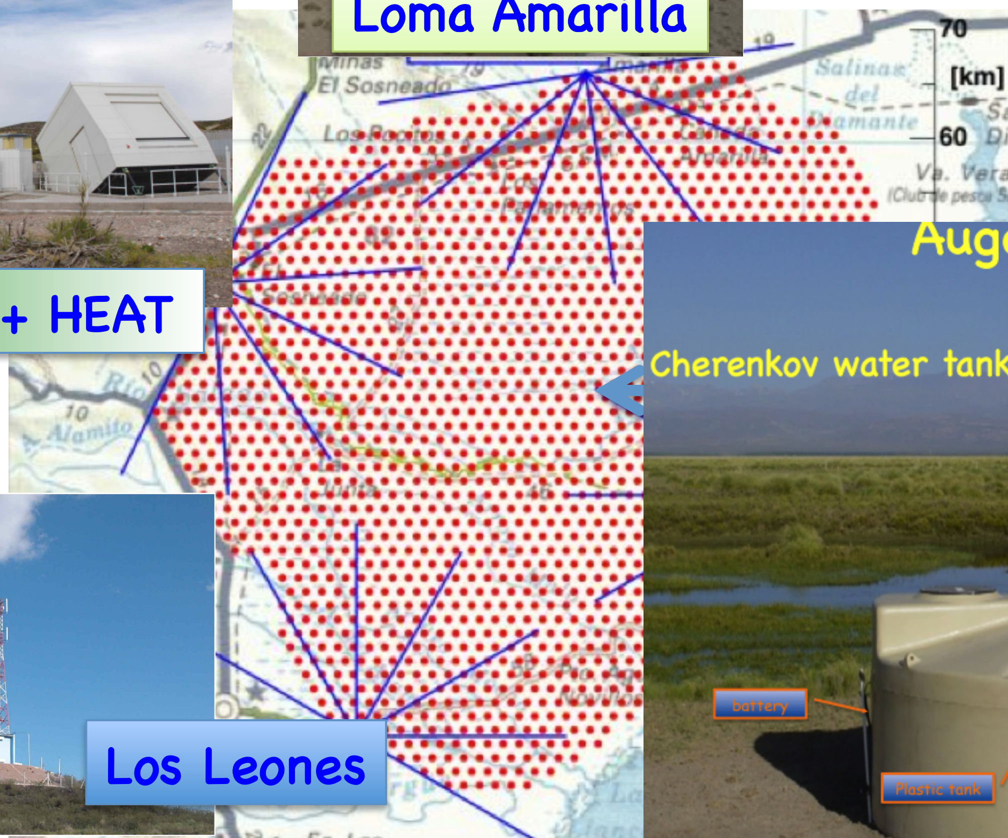
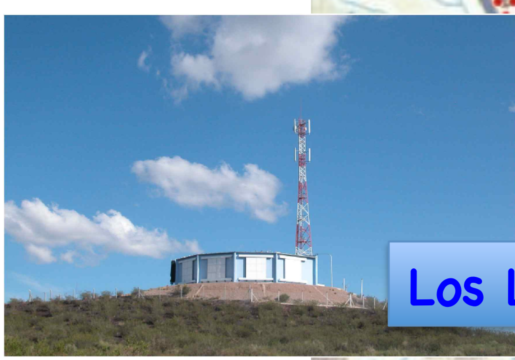
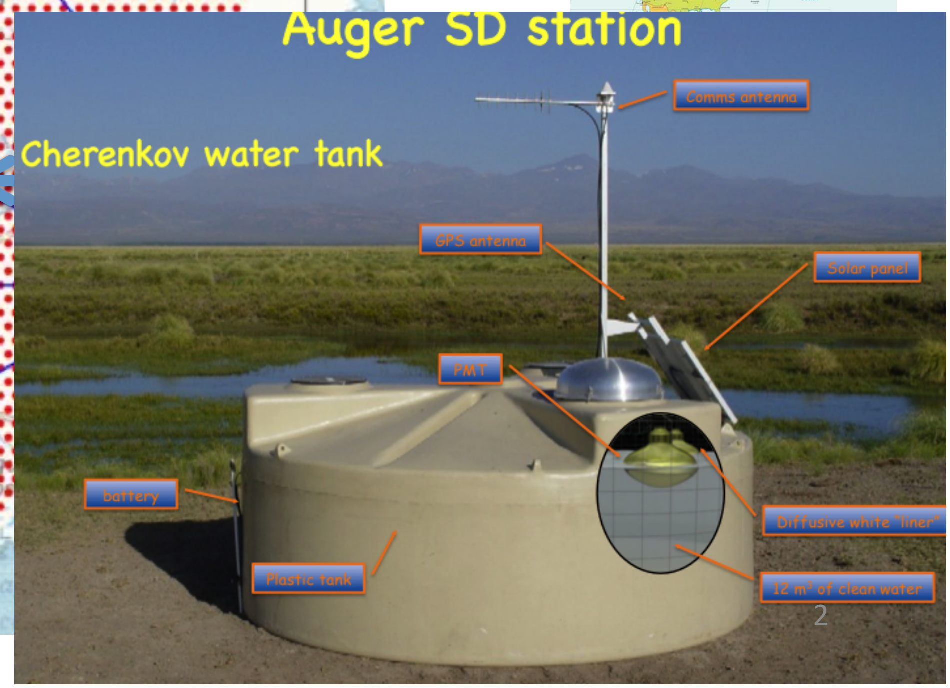
Pierre Auger Observatory

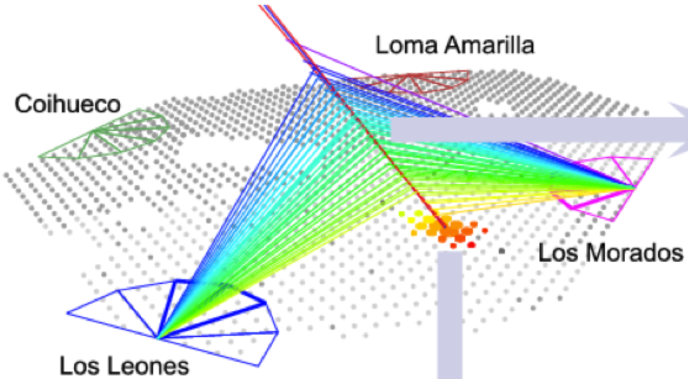
- **Hybrid** detector:
  - **Surface Detector**: array of 1660 Cherenkov detectors; 3000 km^2
  - **Fluorescence Detector**: 27 fluorescence telescopes overlooking the array from 4 locations

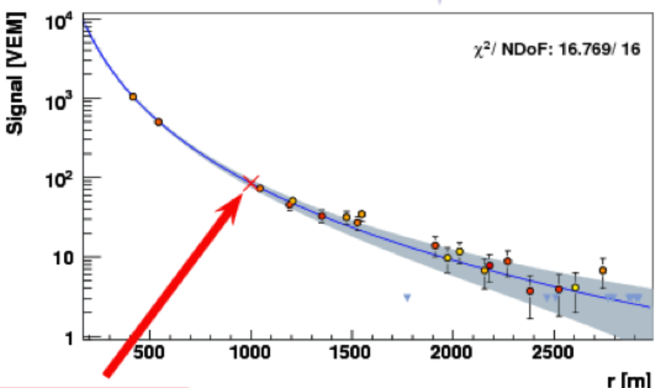


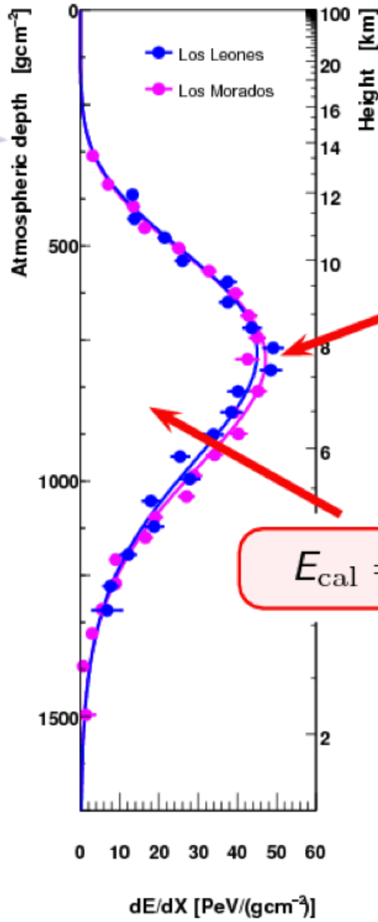




Auger events

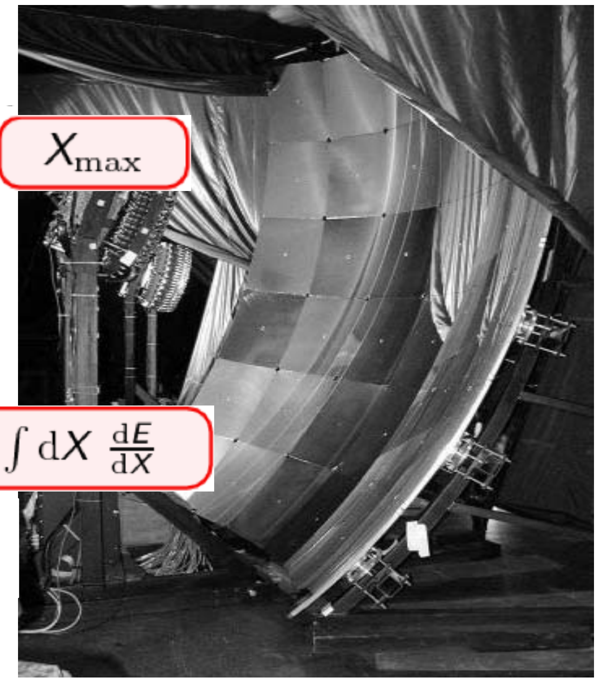






X_{max}

$E_{\mathrm{cal}} = \int \mathrm{d}X \, \frac{\mathrm{d}E}{\mathrm{d}X}$



S_{1000}

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

SD event

- Large statistics (100% duty cycle)
- Full efficiency above 3 EeV

Hybrid: FD+1 SD station

- Precise geometry and lower energy threshold (~ 10^{18} eV)
- Calorimetric energy and direct measurement of X_{max}

Golden: FD+SD

Good for calibration and cross-checks

Why is it important to study the composition of UHECRs?

• Combined with other measurements such as energy spectrum and distribution of arrival directions will help us to separate the different scenarios of **origin** and **propagation** of UHECRs.

• Understanding the origin of UHECRs:

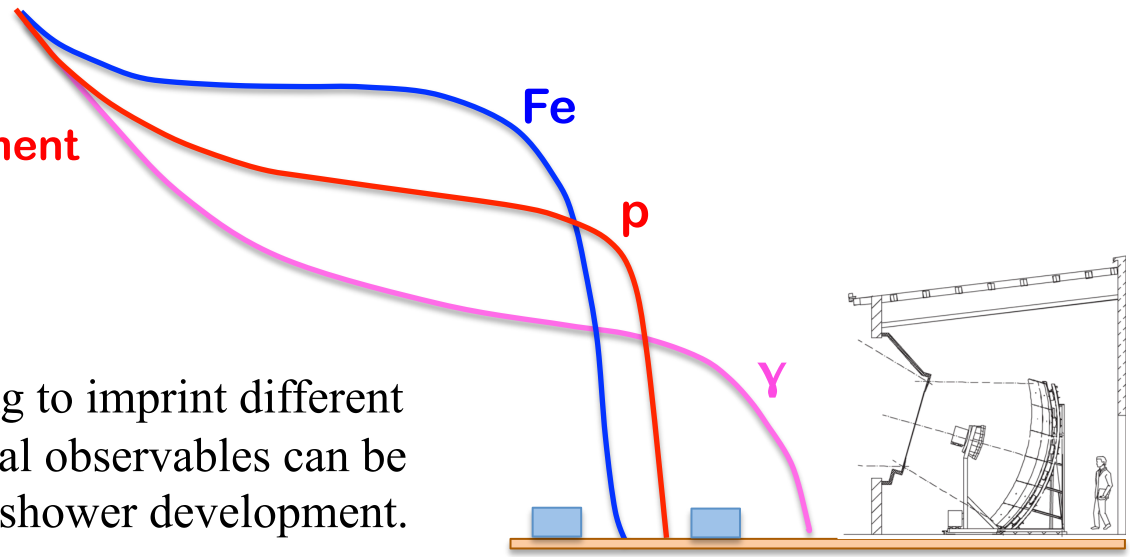
  • **Bottom-up models**: acceleration mechanisms depend on Z.
  • **Top-down models**: predict large fluxes of photons and neutrinos.

• Determining a possible “contamination” with UHE photons will reduce the systematic uncertainties on mass composition, energy spectrum and cross section.

How can we study composition with Auger?

The **first interaction** of a hadronic shower is expected to be **shallower as the primary mass increases**. For photons, the small multiplicity of EM interactions also induces deeper showers.

Determine the **longitudinal development** of the shower in the atmosphere.

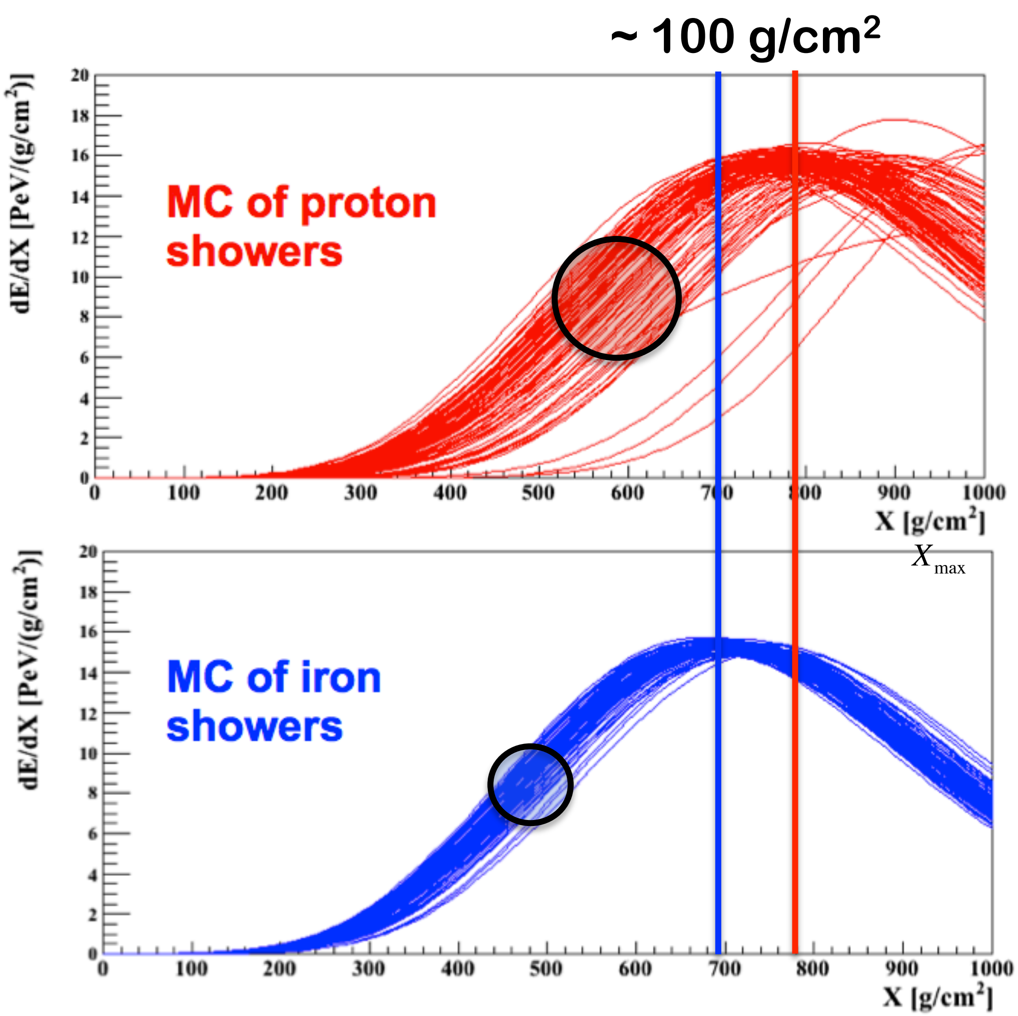


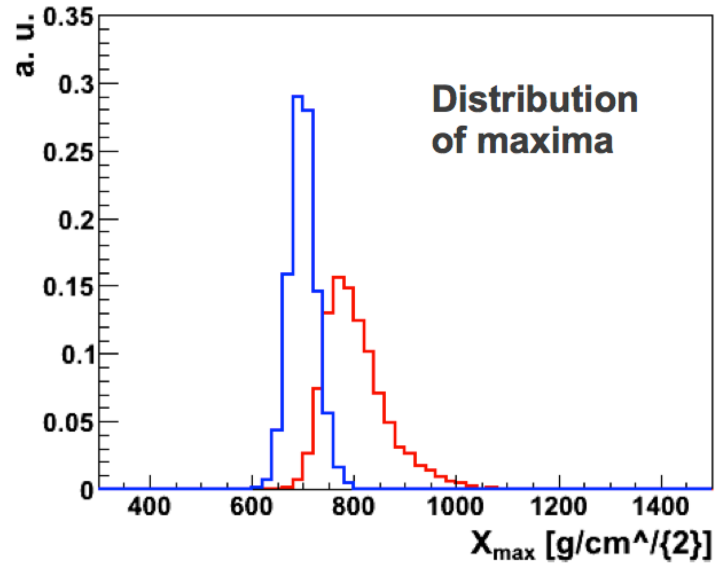
Different shower developments are going to imprint different signatures in the recorded signals. Several observables can be defined to extract information about the shower development.

- **FD:**
  - X_{max} main shower observable sensitive to primary composition.
  - RMS(X_{max}).
- **SD:**
  - Azimuthal asymmetry of the risetime.
  - Maximum depth of muon production.
  - Shape of the lateral distribution at ground level.

•These observables can be combined to strengthen the sensitivity or to cross-check results.

Longitudinal profile of air showers





$$\langle X_{max} \rangle = \alpha\left(\ln E - \langle \ln A \rangle\right) + \beta$$

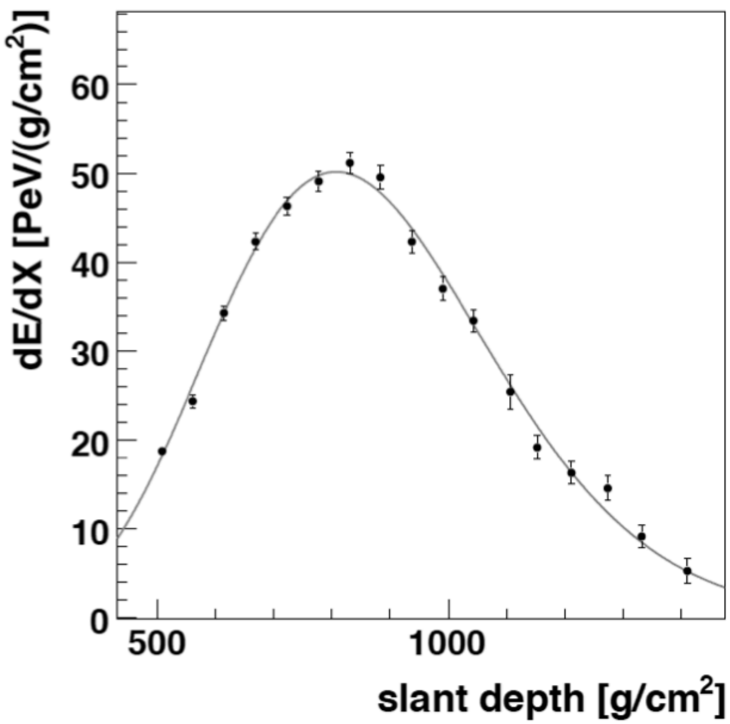
$$\mathrm{RMS} \propto 1/\sqrt{\mathrm{A}}$$

$$\langle X_{max} \rangle_p > \langle X_{max} \rangle_{Fe}$$

$$\mathrm{RMS}(X_{max})_p > \mathrm{RMS}(X_{max})_{Fe}$$

- X_{max} reflects the properties of the first interaction.
- Distributions for heavy primaries, as iron, are expected to be narrower and shallower. Lighter primaries, like protons, have a characteristic tail towards deep X_{max}.

Data sample for the FD analysis

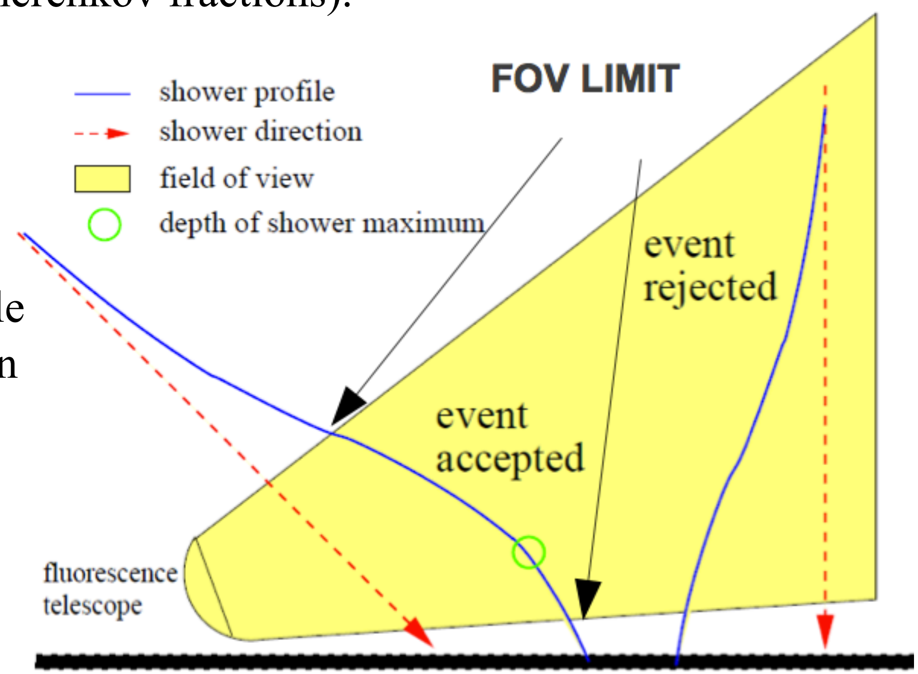


Selection of high quality hybrid events:

- X_{max} observed.
- Low aerosol content & cloud coverage.
- χ^2/Ndf < 2.5 for Gaisser-Hillas profile fit.
- Statistical uncertainty X_{max} < 40 g/cm^2.
- Angle between shower and telescope > 20° (avoid high Cherenkov fractions).

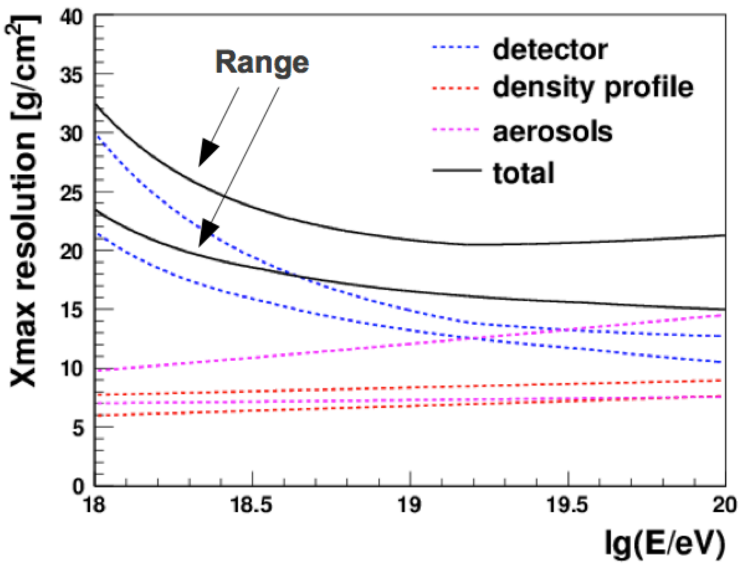
Unbiased selection:

- Select the distance to the SD station, and zenith angle so that the tank trigger probability does not depend on the mass of primary.
- Select event geometries that allow to sample the whole X_{max} distribution (from measurement).



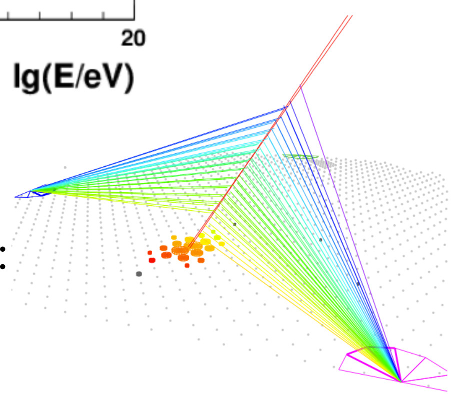
X_{max} resolution

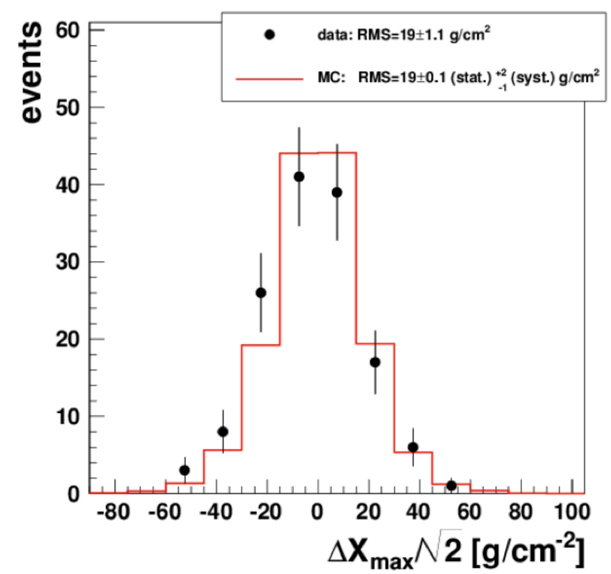
Good X_{max} resolution required for a **good mass discrimination** and to allow measurements of **narrow distributions characteristic of heavy primaries**.



- From simulations with a realistic description of the DAQ conditions.
- **X_{max} resolution** including the detector resolution and fluctuations of the atmospheric conditions from simulations **~ 20 g/cm²**.

Validated with 'stereo' events:

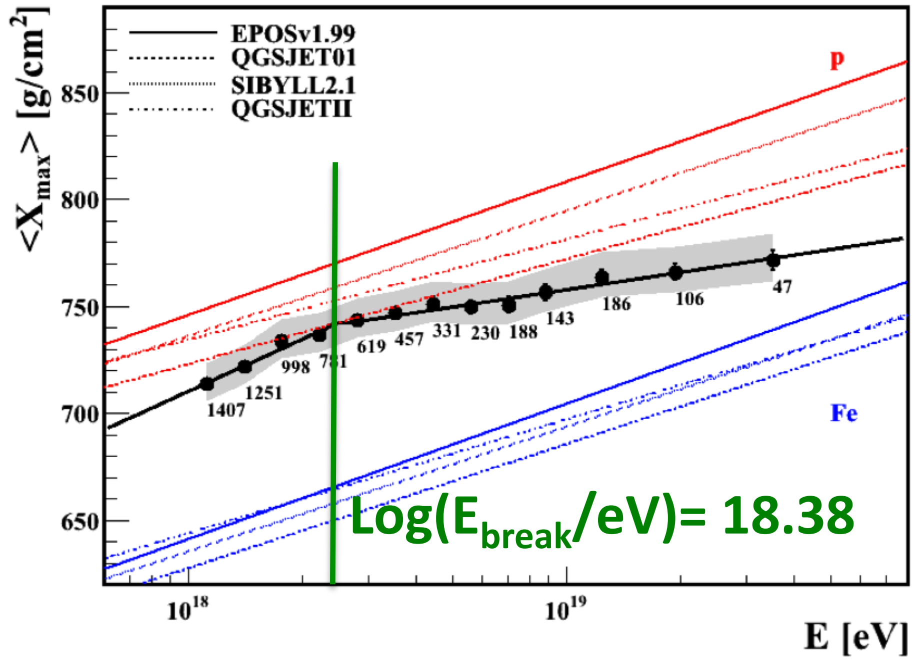


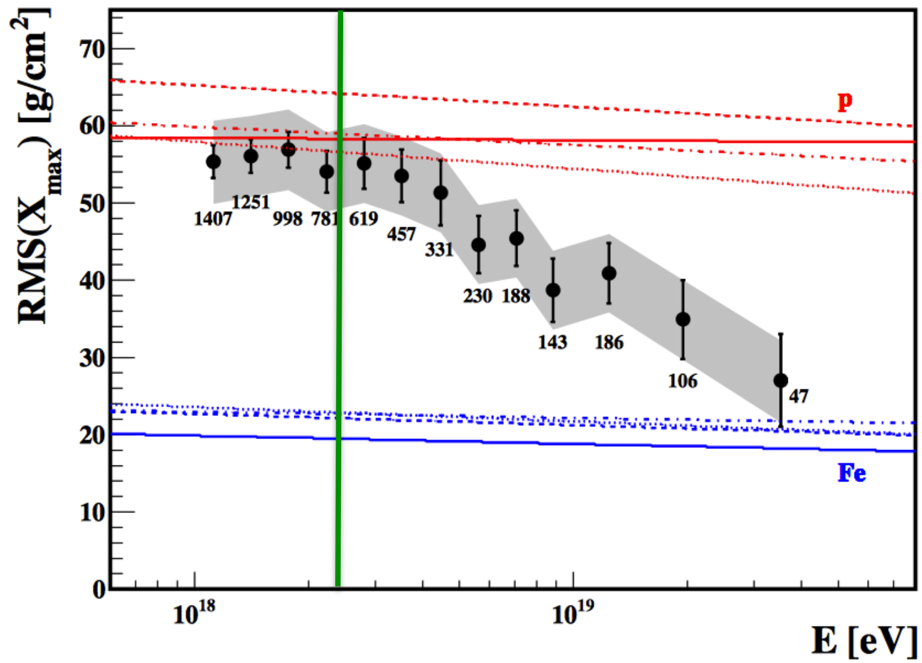


Systematics (analysis, reconstruction, atmosphere, calibration): $\langle X_{max} \rangle \leq 13$ g/cm²

RMS(X_{max}) ≤ 5 g/cm²

$\langle X_{max} \rangle$ and RMS from FD





Elongation rate: $$D_{10} = \frac{\mathrm{d}\langle X_{\max} \rangle}{\mathrm{d}\log E}$$

Low energy — $D_{10} = 82^{+48}_{-8}$ g/cm²/decade

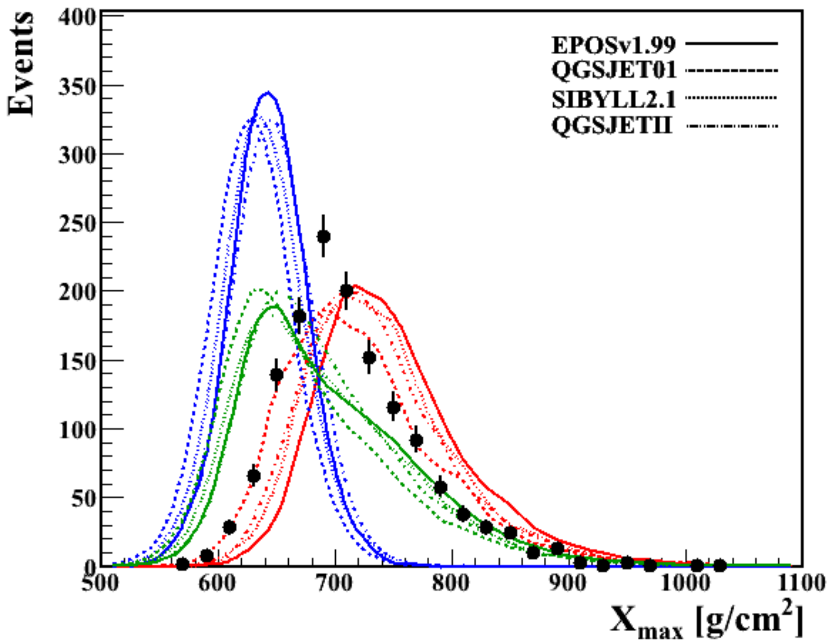
High energy — $D_{10} = 27^{+3}_{-8}$ g/cm²/decade

- Data is best described using two different slopes.
- At high energies $\langle X_{max} \rangle$ increases slowly with energy.
- The decrease of RMS becomes stepper at the joint of the 2 fits towards values expected for heavy primaries.

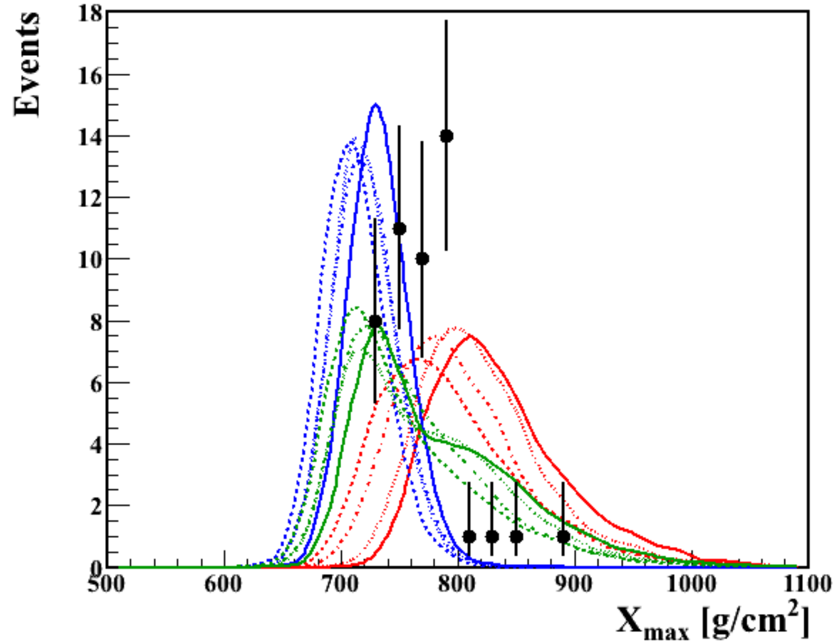
X_{max} distributions

Fe
p
50% Fe+ 50% p

18.0 < logE < 18.1



logE > 19.4



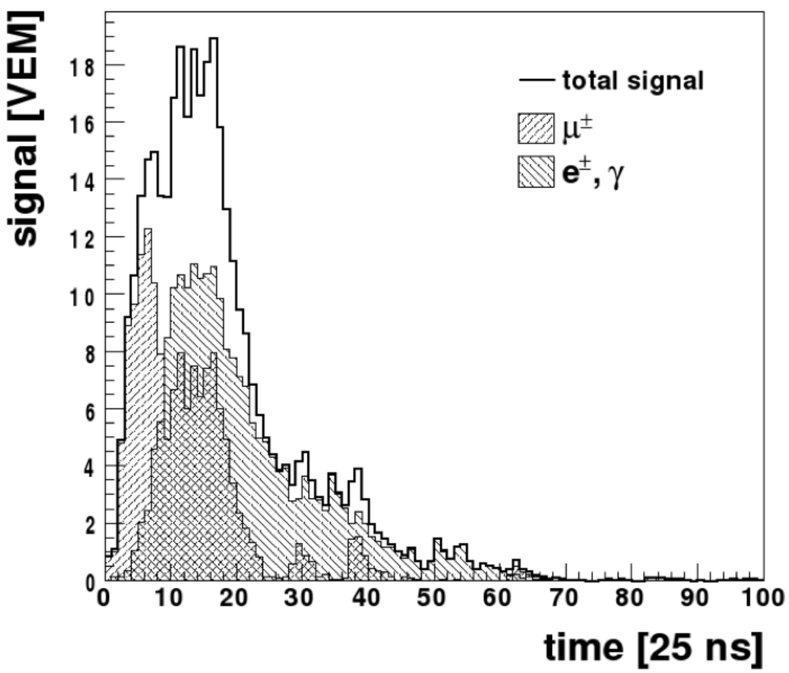
As energy increases:

- narrower distributions.
- deep X_{max} tail less evident, more symmetric distributions.
- For low energies shape compatible with a significant fraction of protons.
- The shape of the distributions (and the RMS) is heavy-like at high energy.

Any interpretation, especially at high energies, is difficult since it would rely on the extrapolation provided by the different models.

Composition using the azimuthal asymmetry in SD signals

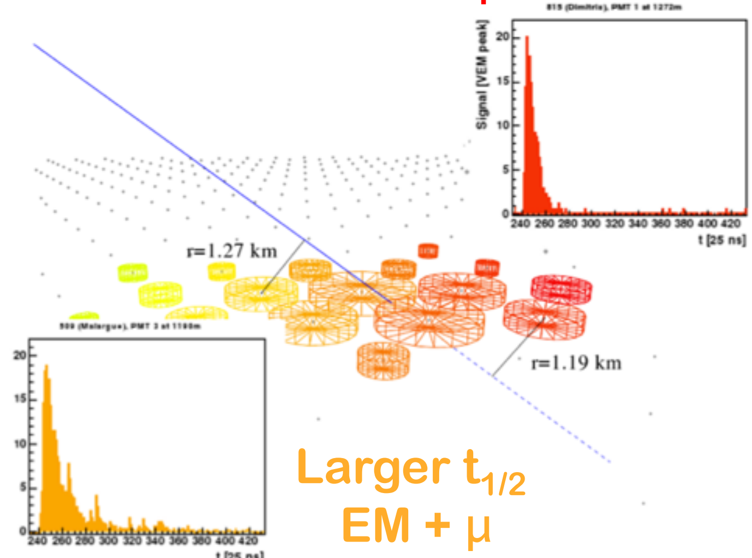
The time structure of SD signals has information about shower development:



μ: less interacting. Dominate first portion of the signal.

EM: multiple scattering. Spread out in time.

LATE REGION
Shorter $t_{1/2}$
μ dominated



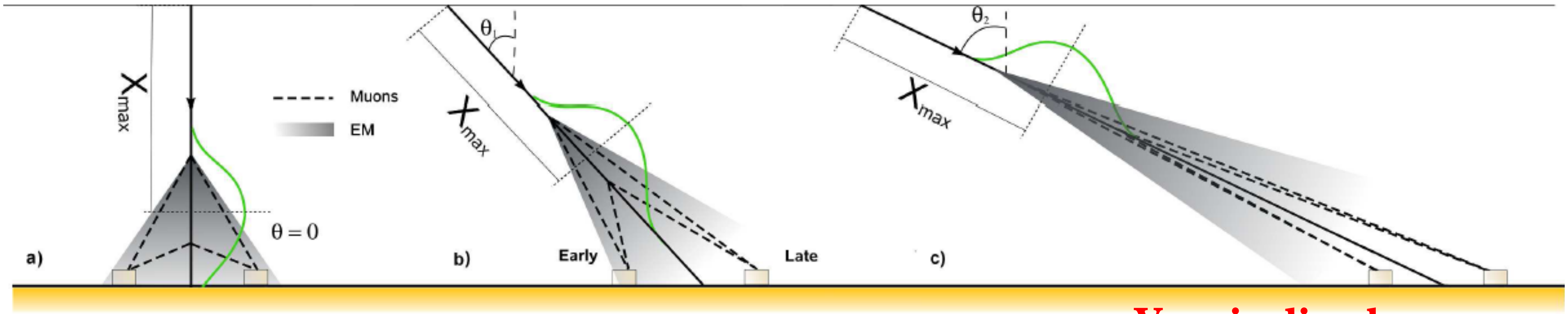
Larger $t_{1/2}$
EM + μ

EARLY REGION

Risetime ($t_{1/2}$): time required to go from 10% to 50% of the total signal.

For non-vertical showers particles striking detectors in the different regions will have different stages of development because of the different path travelled.

Azimuthal asymmetry in SD signals



Vertical
symmetry in the signals

Inclined
asymmetry!!

Very inclined
no asymmetry

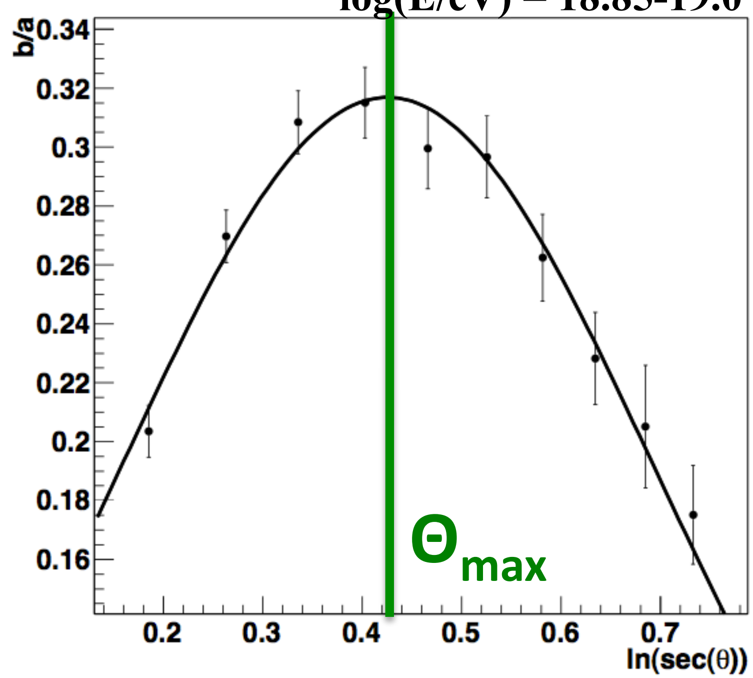
The early-late asymmetry as function of the zenith angle is expected to have a maximum which is correlated with X_{max}

Observable: Θ_{max} : secθ for which b/a is maximum

Different primaries will have different asymmetry profiles.

Event selection:

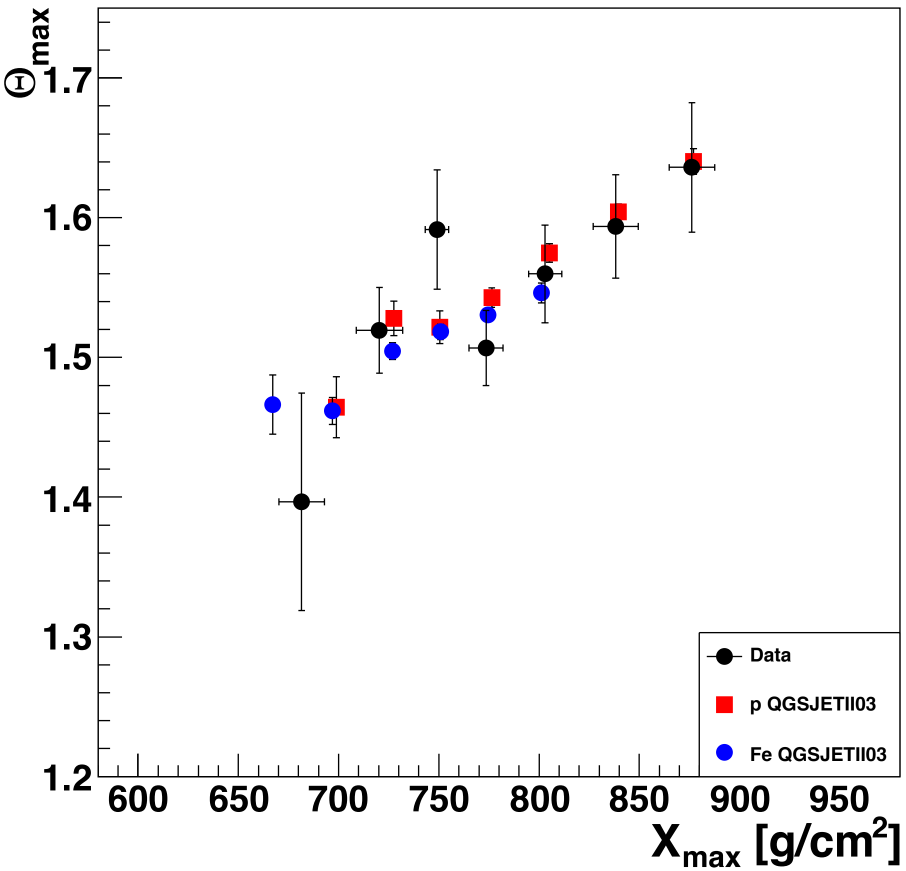
- $30^o < \theta < 60^o$
- 500 m < r < 2000 m



Systematic uncertainty ≈ 10% of p-Fe separation

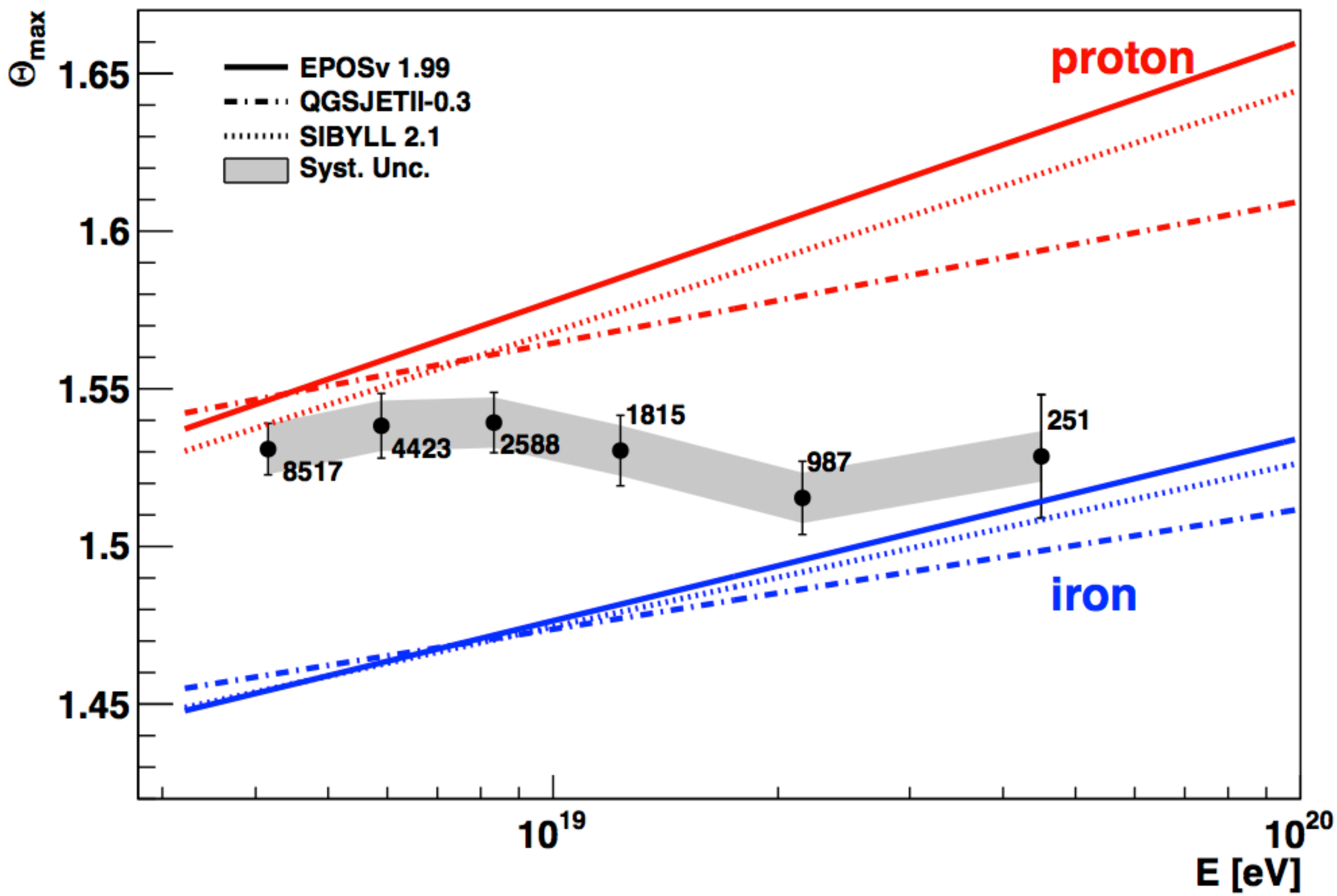
Correlation of Θ_{max} with X_{max}

- As expected, the asymmetry is correlated with the stage of development and therefore with X_{max}.
- From golden hybrid events: **Θ_{max} and X_{max} are correlated**.
- From simulations: The **correlation is independent of the primary**.



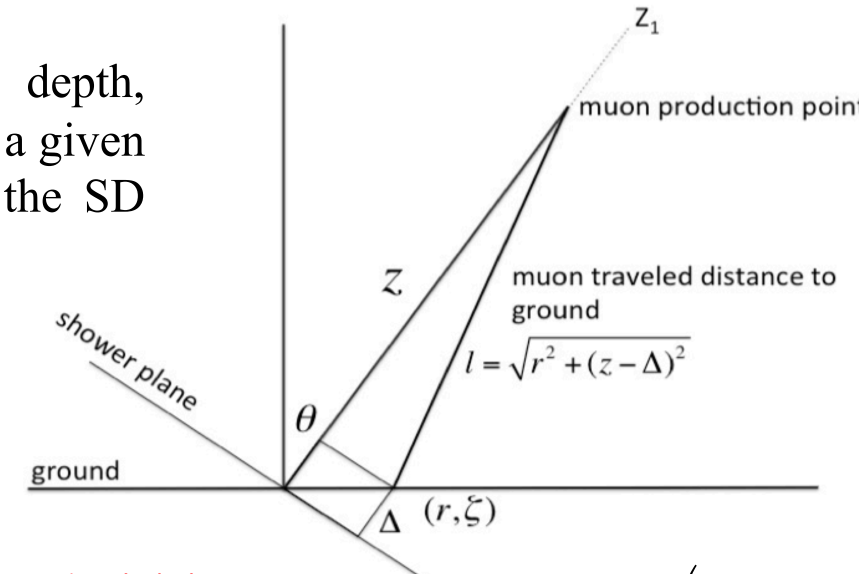
Θ_{max} vs logE

15851 SD events (Jan 2004 – Dec 2010)
E >3.16 EeV and 30º< θ <60º



Muon Production Depth

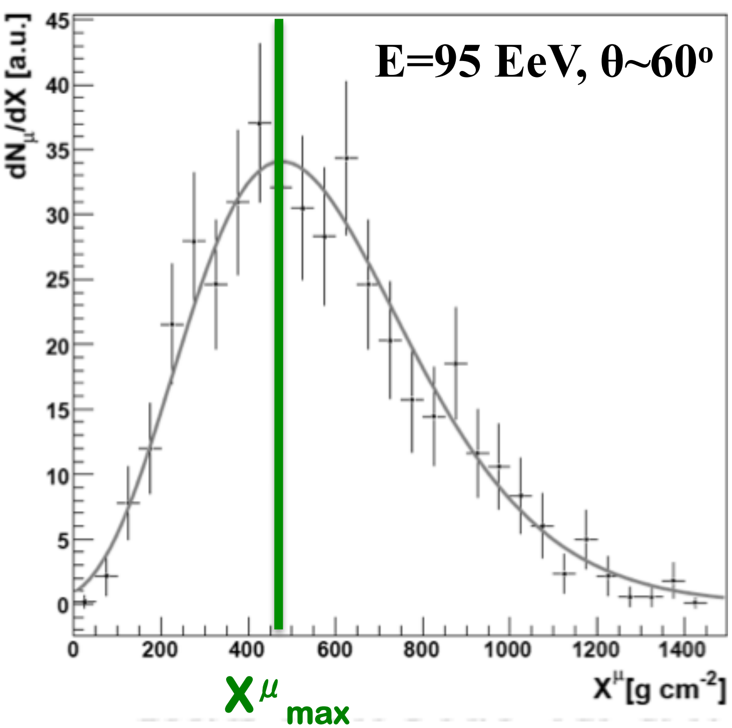
Muons are produced within a narrow cylinder centered at the shower axis. They travel along straight lines, practically unaffected by multiple scattering and bremsstrahlung.



Muon Production Depth (MPD): the depth, measured parallel to the shower axis, at which a given muon is produced. It can be obtained from the SD signals.

$t_{g,}$ geometrical delay: the time difference between the arrival time of the muon and that of the time-reference shower plane.

$$z = \frac{1}{2}\left(\frac{r^2}{ct_g} - ct_g\right) + \Delta$$

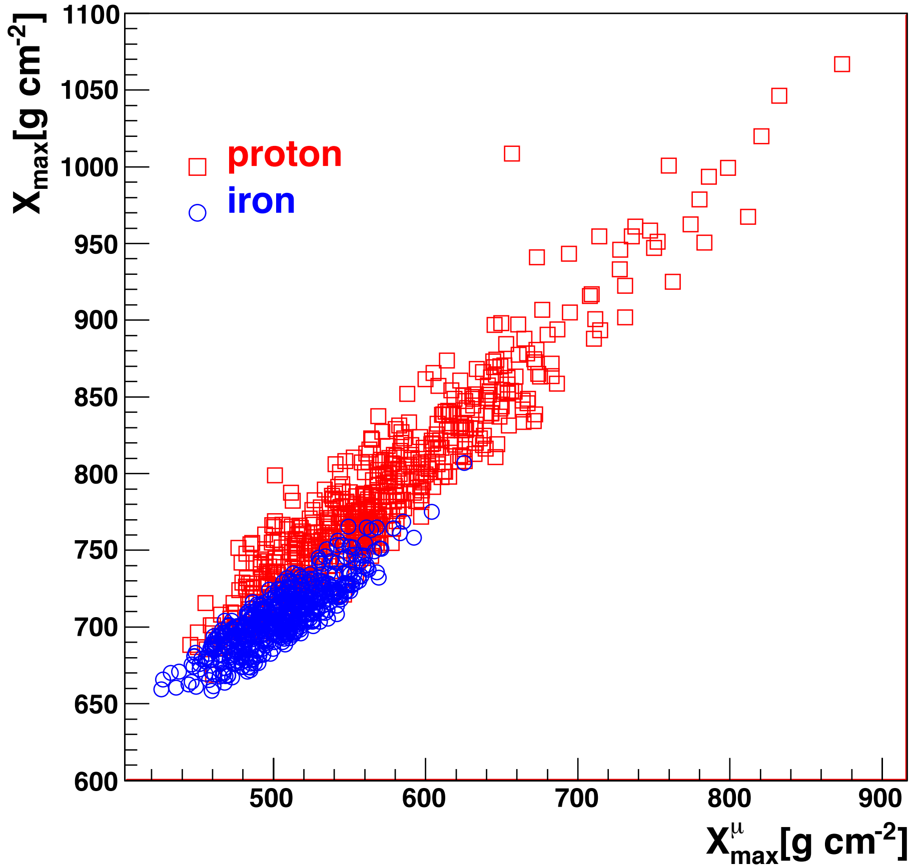


Event selection:

- $55^o < \theta < 65^o$
- r > 1800 m
- E > 20 EeV
- Gaisser-Hillas fit ⇨ X^μ_{max} (depth of maximum number of produced muons)
- Systematic uncertainty ≤ 11 g/cm^2

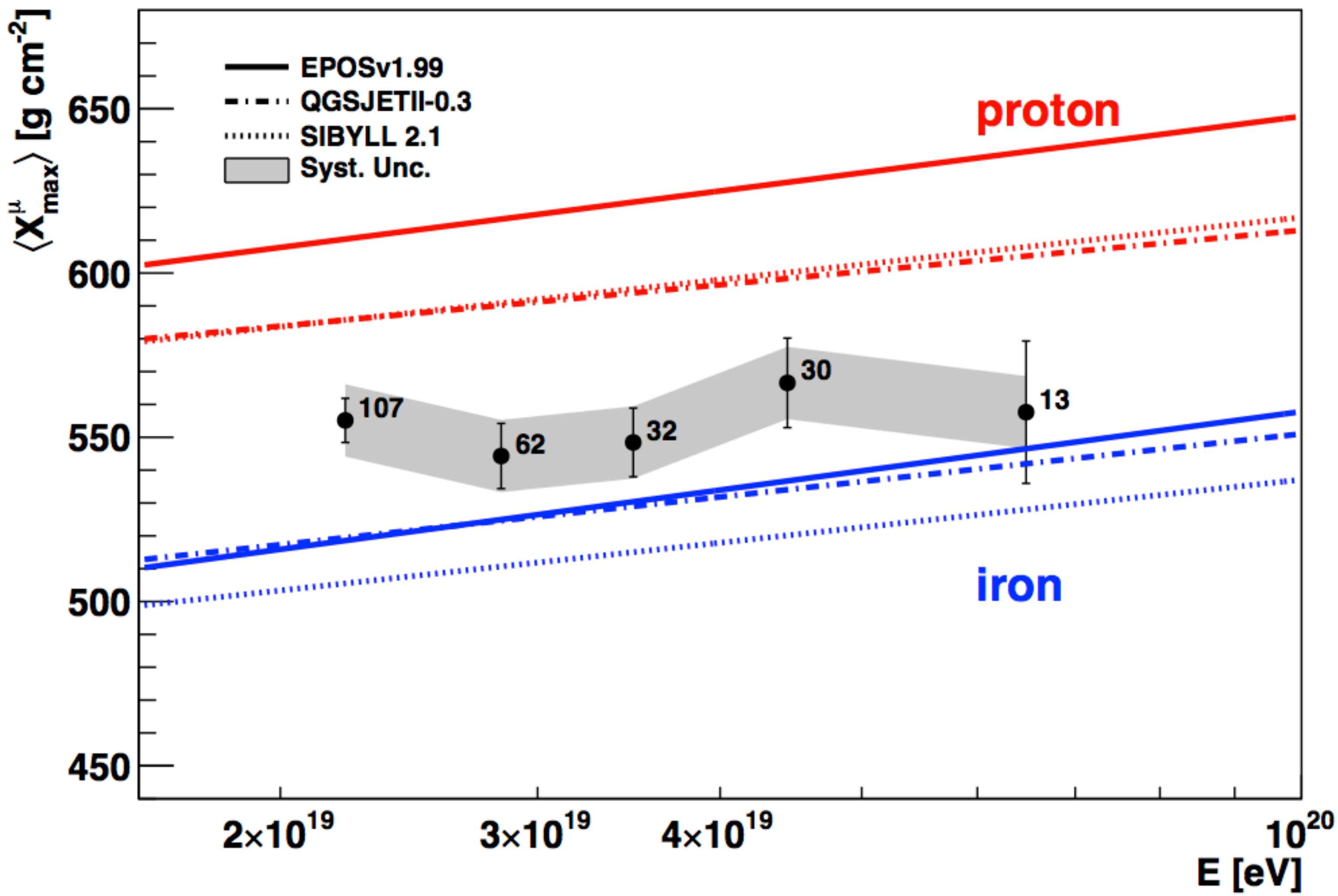
Correlation of X^{μ}_{max} with X_{max}

X^{μ}_{max} depends on the primary and it is correlated with X_{max}

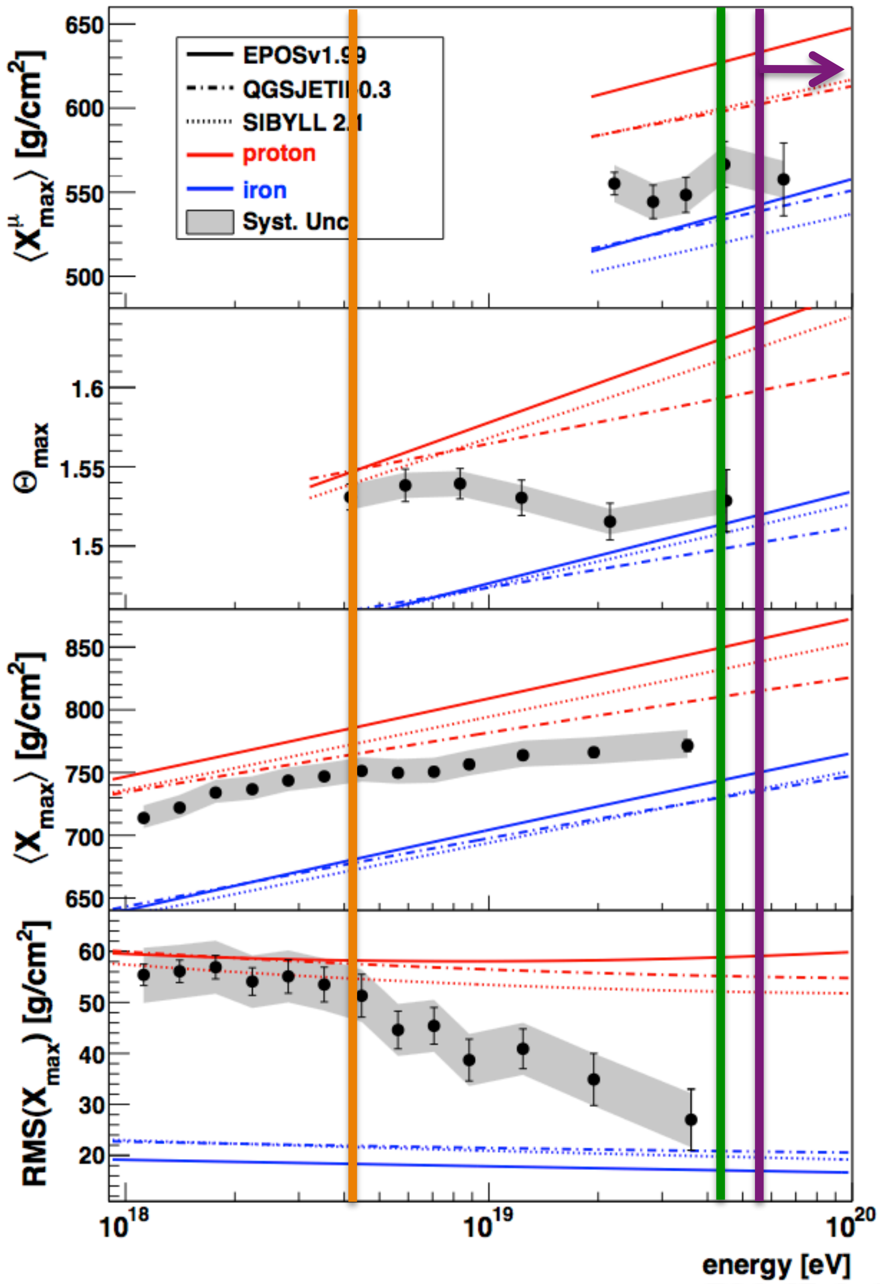


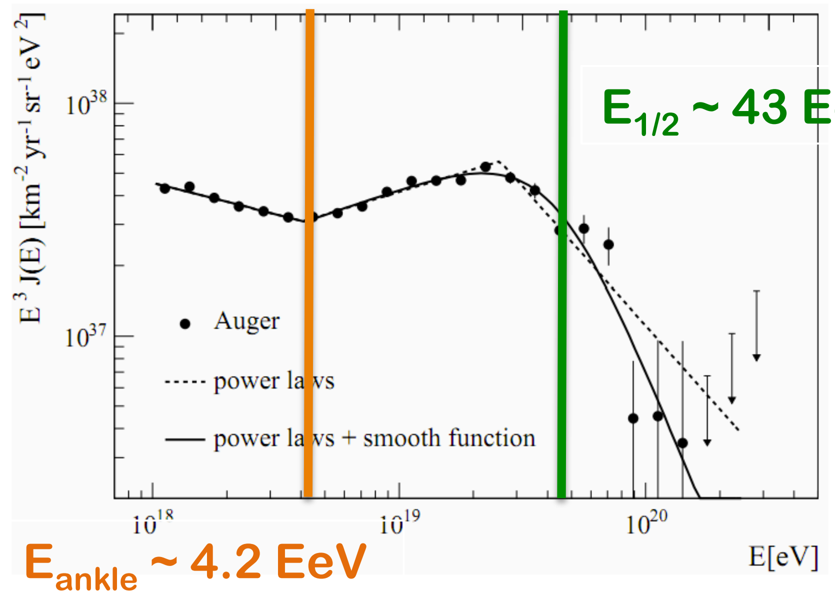
$\langle X^{\mu}_{max} \rangle$ vs logE

244 SD events (Jan 2004 – Dec 2010)
E > 20 EeV, 55º< θ < 65º



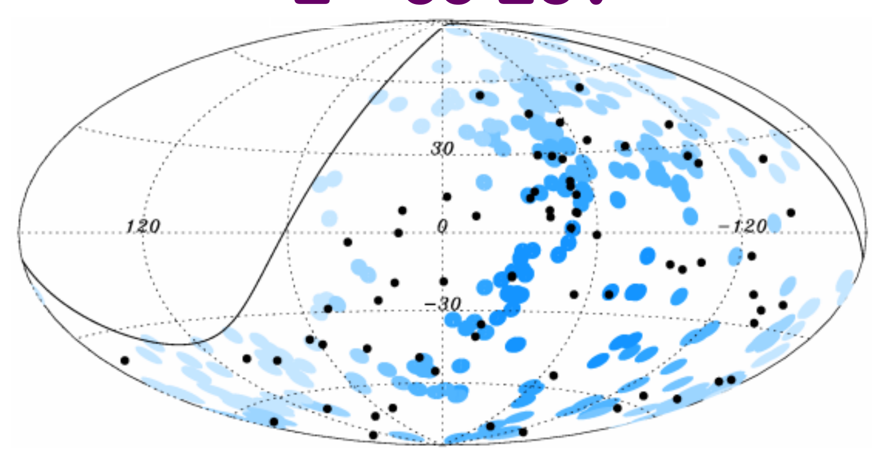
Combining all the information…





see L. Perrone talk

E > 55 EeV



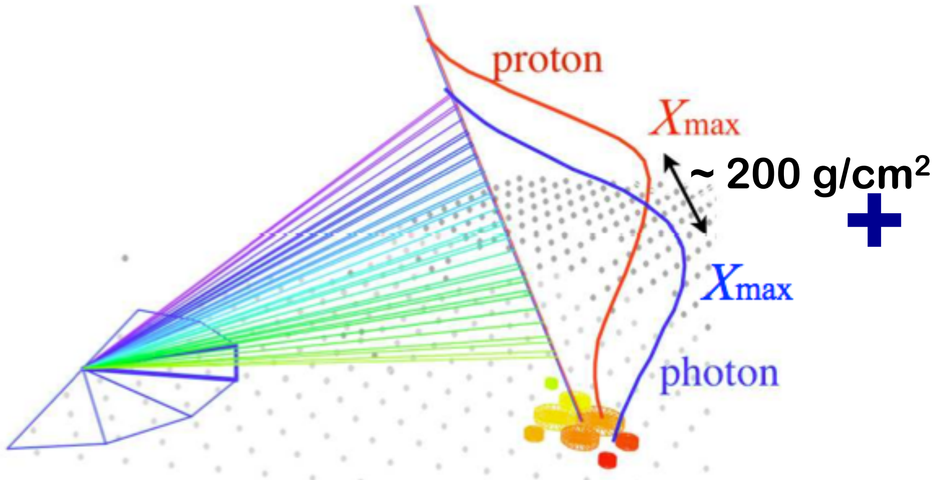
see D. Allard talk

Search for photons

- Previous analyses were done using X_{max} or SD observables (rise-time, radius of curvature) independently.
- New analysis using hybrid events to combine the strength of FD and SD observables:

X_{max}

Photons develop deeper showers

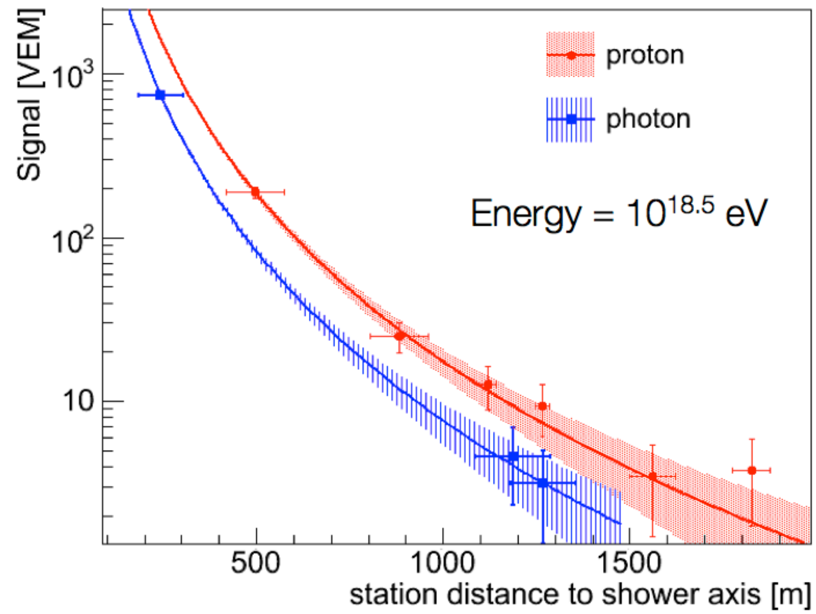


$X_{max}(\gamma) > X_{max}$ (p)

+

LDF

Photon showers produce smaller signals at a given distance and trigger fewer stations

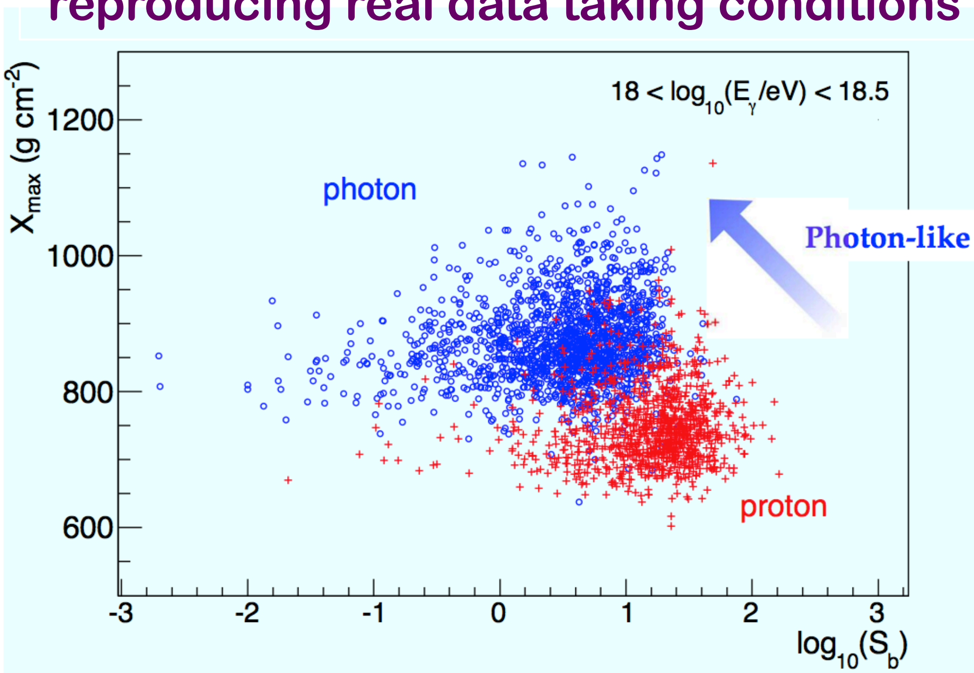


SD observable: $S_4 = \sum_i S_i \left(\frac{R_i}{R_{ref}} \right)^4$,, $R_{ref} = 1000$ m

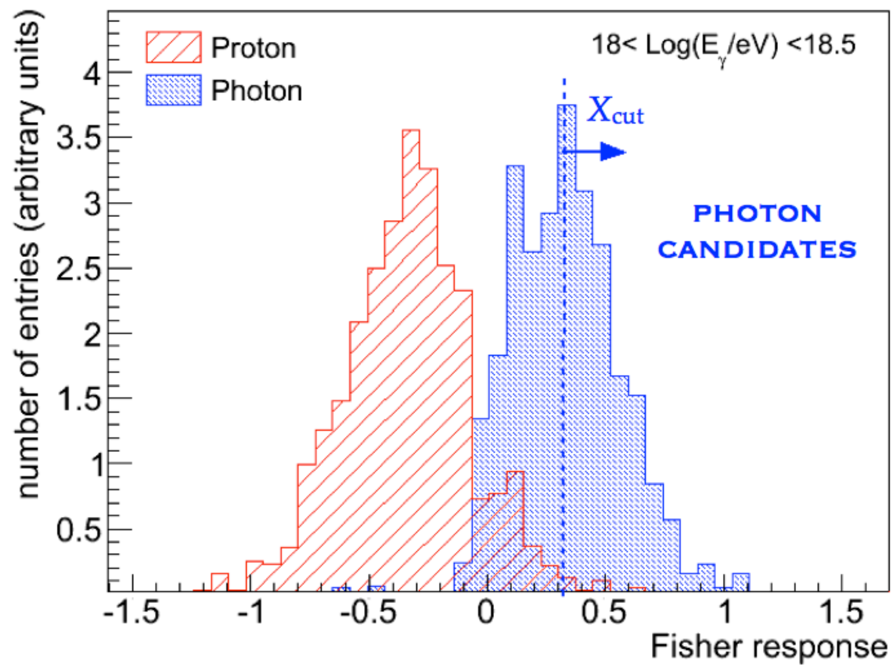
$S_4(\gamma) < S_4$ (p)

X_{max}-S_4 analysis

Photon and proton simulations reproducing real data taking conditions



Fisher analysis



- **Photon-like events:** $X > X_{cut}$ ⇨ **photon detection efficiency** ~ 50%
- Proton background ≤ 1%

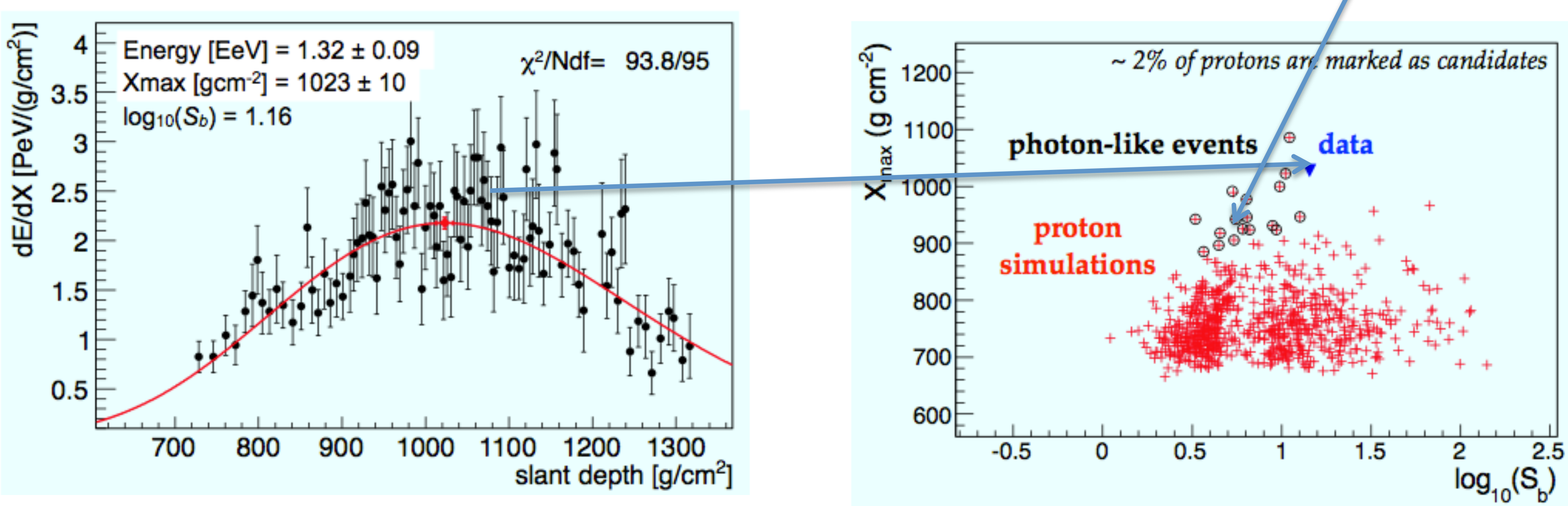
X_{max}-S_4 analysis

Analysis applied to Hybrid data between January 2005- September 2010

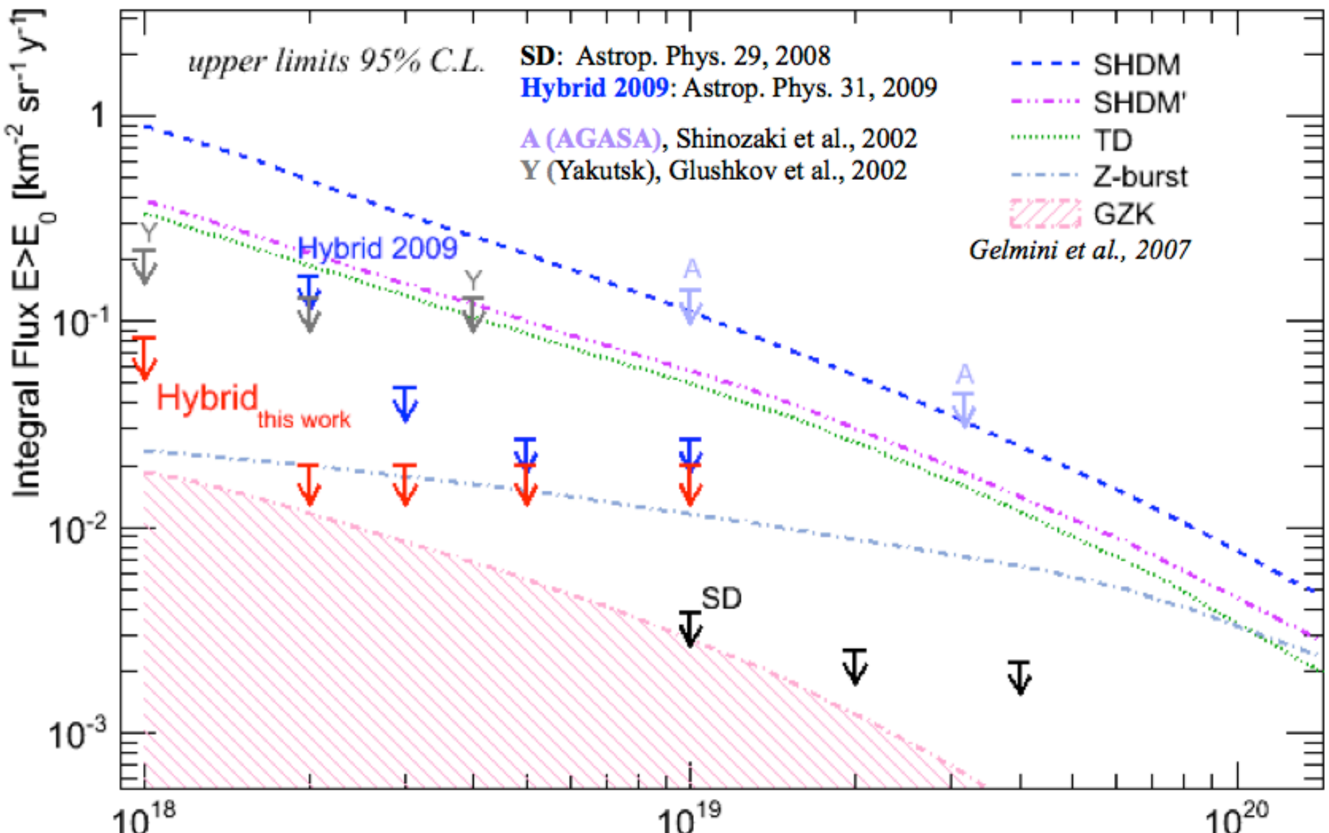
6, 0, 0, 0 and 0 candidates above 1, 2, 3, 5 and 10 EeV

Compatible with the expected nuclear background

protons passing the cut on the Fisher observable



Photon upper limits



• Systematic uncertainties from exposure, hadronic interaction model and mass composition assumptions: $^{+20\%}_{-64\%}$ for 1 EeV and $^{+15\%}_{-36\%}$ for E>1 EeV.

• As previous Auger results, they disfavor exotic models.

• Upper limits to the integral photon fraction assuming the Auger spectrum:
0.4%, 0.5%, 1.0%, 2.6% and 8.9% for E> 1, 2, 3, 5 and 10 EeV

Conclusions

- **From the FD and the SD** data of the Pierre Auger observatory, several **observables** carrying information about the shower development **useful for composition studies** can be defined.

- Different **analyses with independent systematic** uncertainties show **compatible results**.

- Assuming that **the hadronic interaction models are correct**:
    - At **low energy**, data is consistent with a **significant number of protons**.
    - Comparison of the data and simulation leads to the conclusion that **the mean mass increases with energy**.
    - Data have to be **adjusted within their systematic** uncertainties to simultaneously **match both $\langle X_{max} \rangle$ and its RMS**.

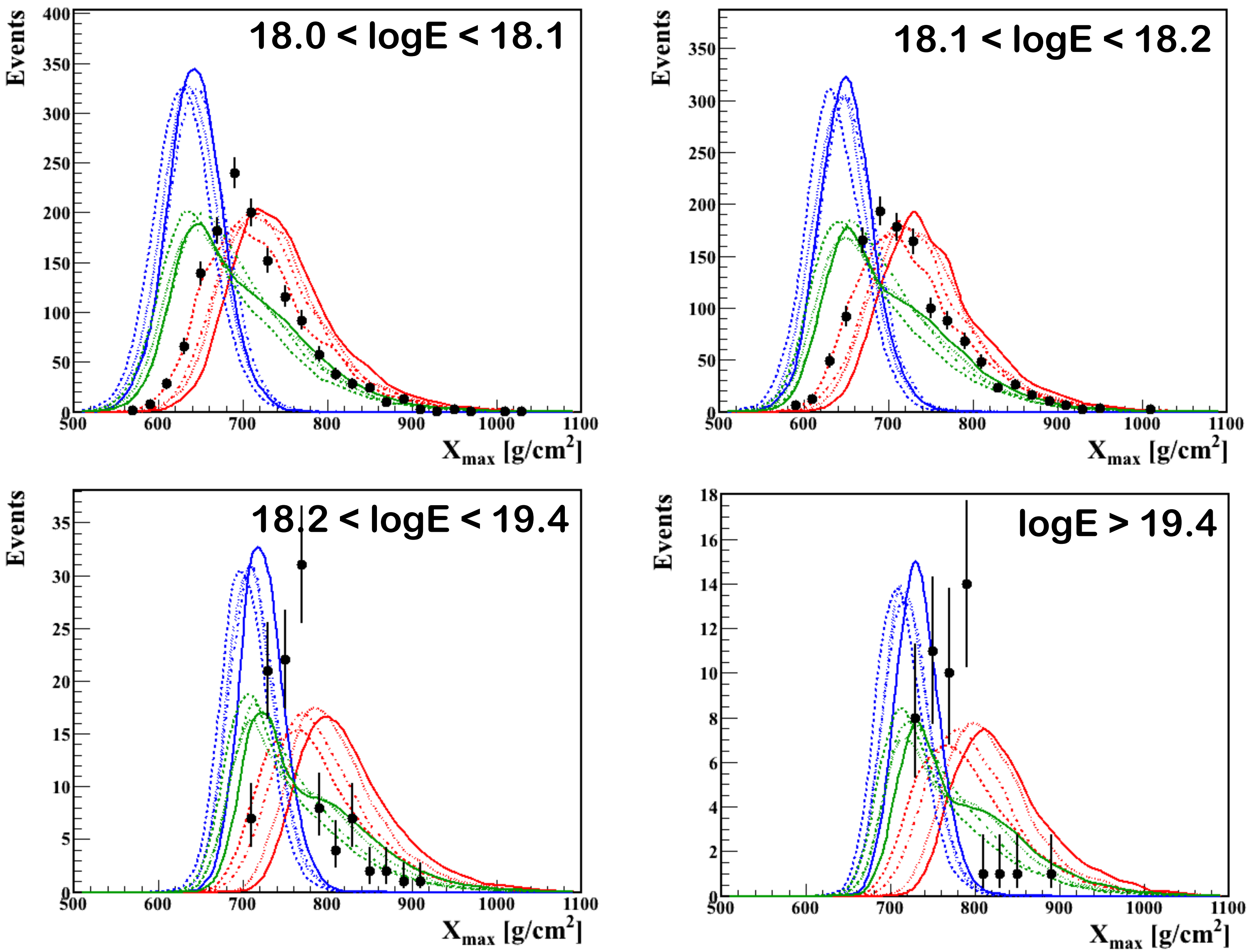
- Any significant departure from the predictions of hadronic models would modify the interpretation in terms of primary mass.

- **FD and SD** observables have been also **combined to look for photons**.

- New photon limits **provide tighter constraints for models**. **GZK region within reach** combining both SD and FD observables.

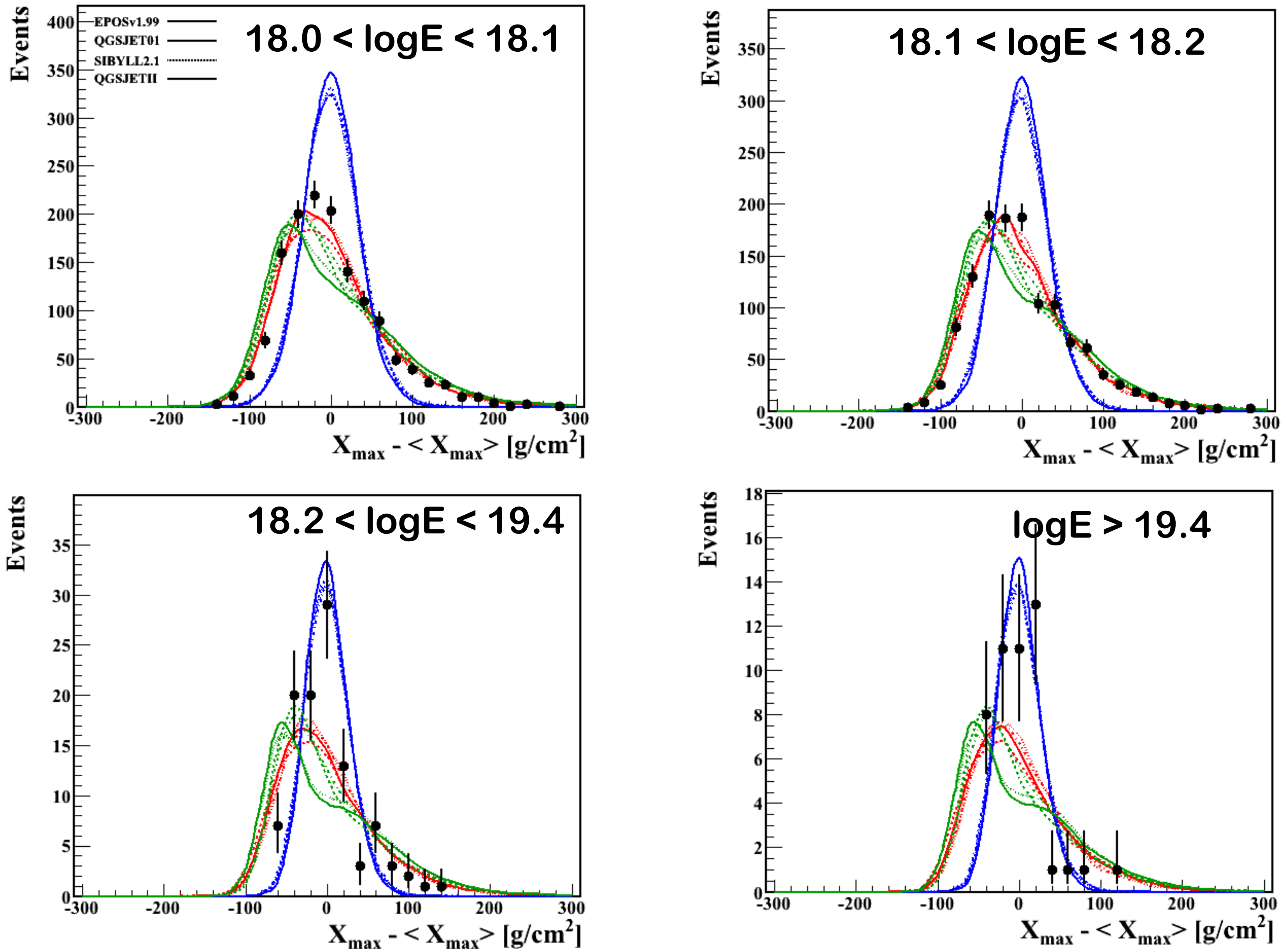
Back up slides

X_{max} distributions

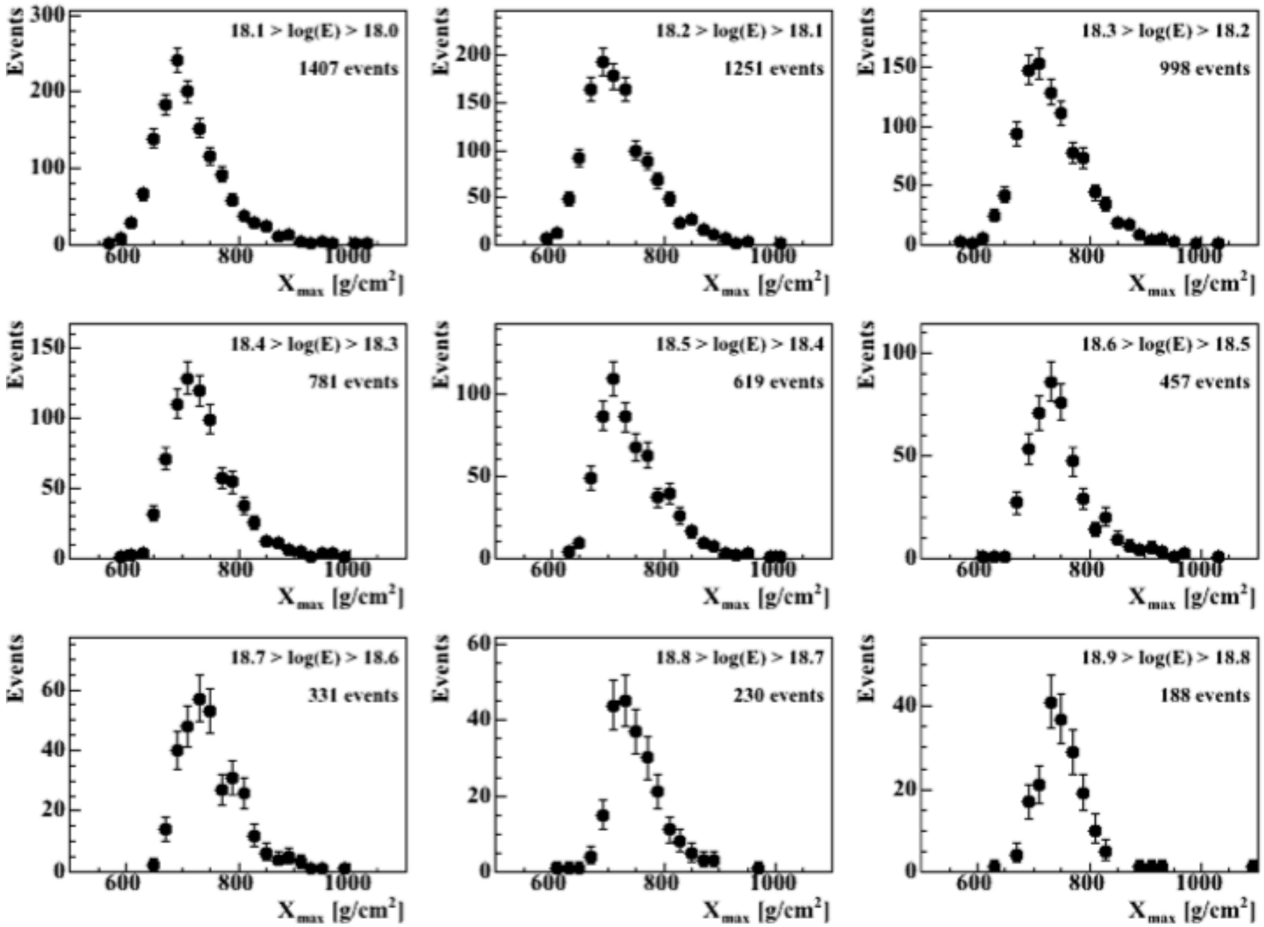


X_{max} distributions

Subtract $\langle X_{max} \rangle$ to each of the distributions and compare only the shapes

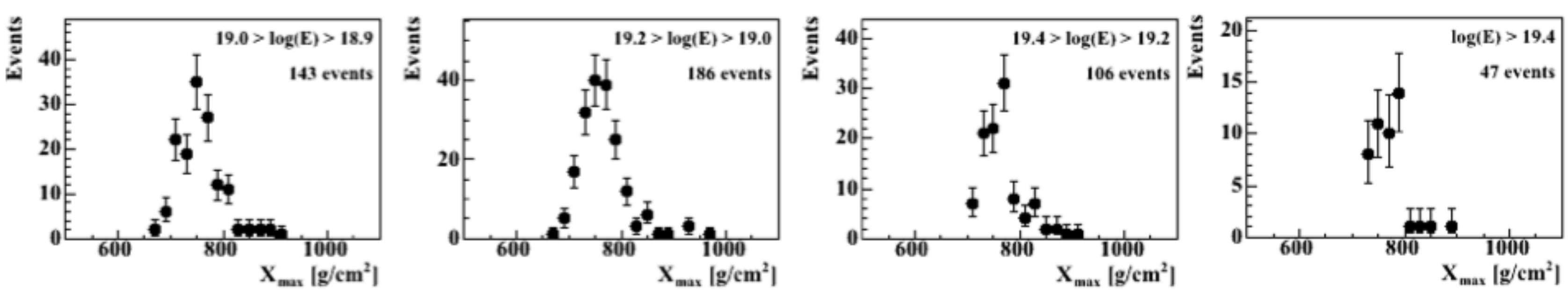


X_{max} distributions



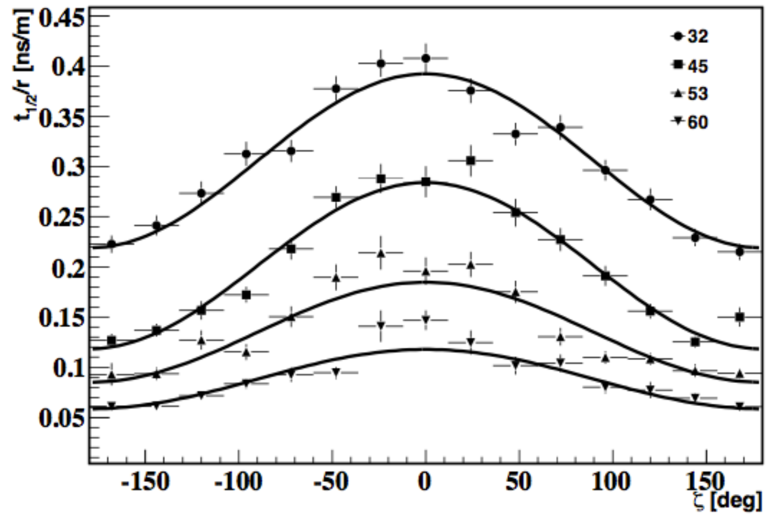
As the energy increases:

- distributions become narrower
- deep Xmax tail becomes less evident

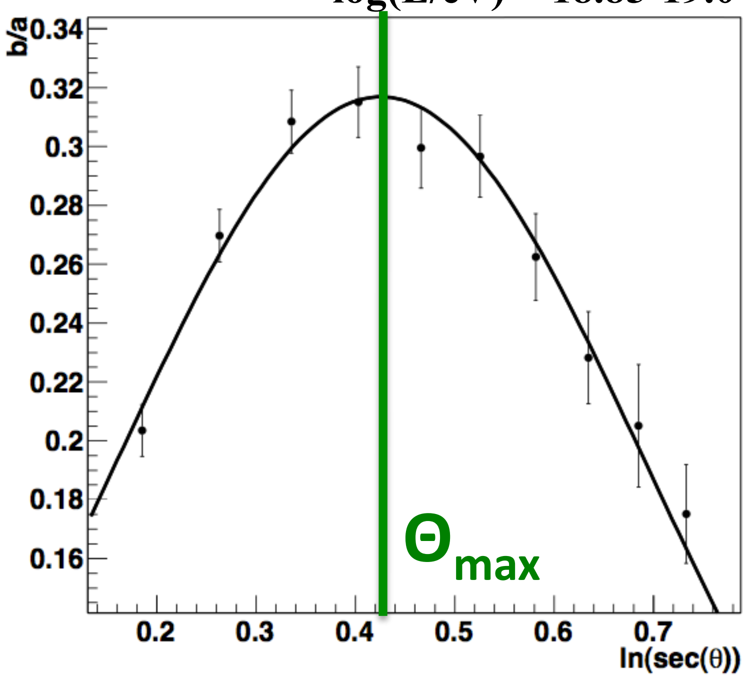


Azimuthal asymmetry. Method

I. The risetime asymmetry from all SD detectors for all events in a given (E, secθ) bin ⇨ fit to $\langle t_{1/2}/r \rangle = a + b\cos\zeta$



log(E/eV) = 18.85-19.0

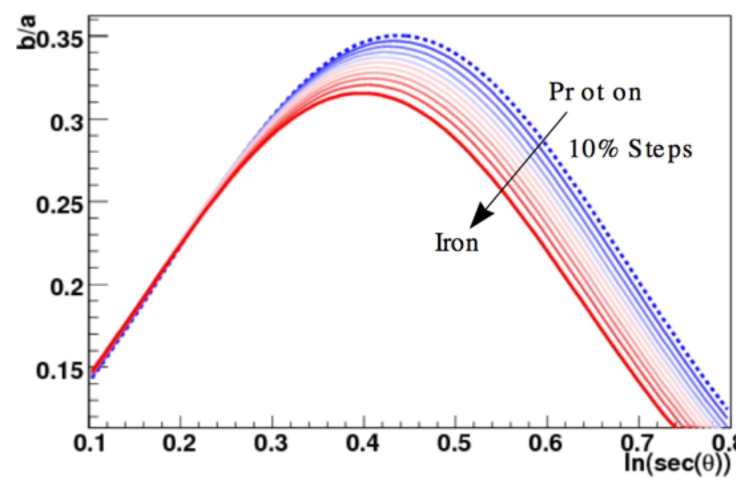


II. b/a vs ln(secθ) in a E bin.

III. Fit to a gaussian function.

Observable: Θ_{max} : secθ for which b/a is maximum.

Since the asymmetry at ground level depends on the shower development, different primaries will have different asymmetry profiles:



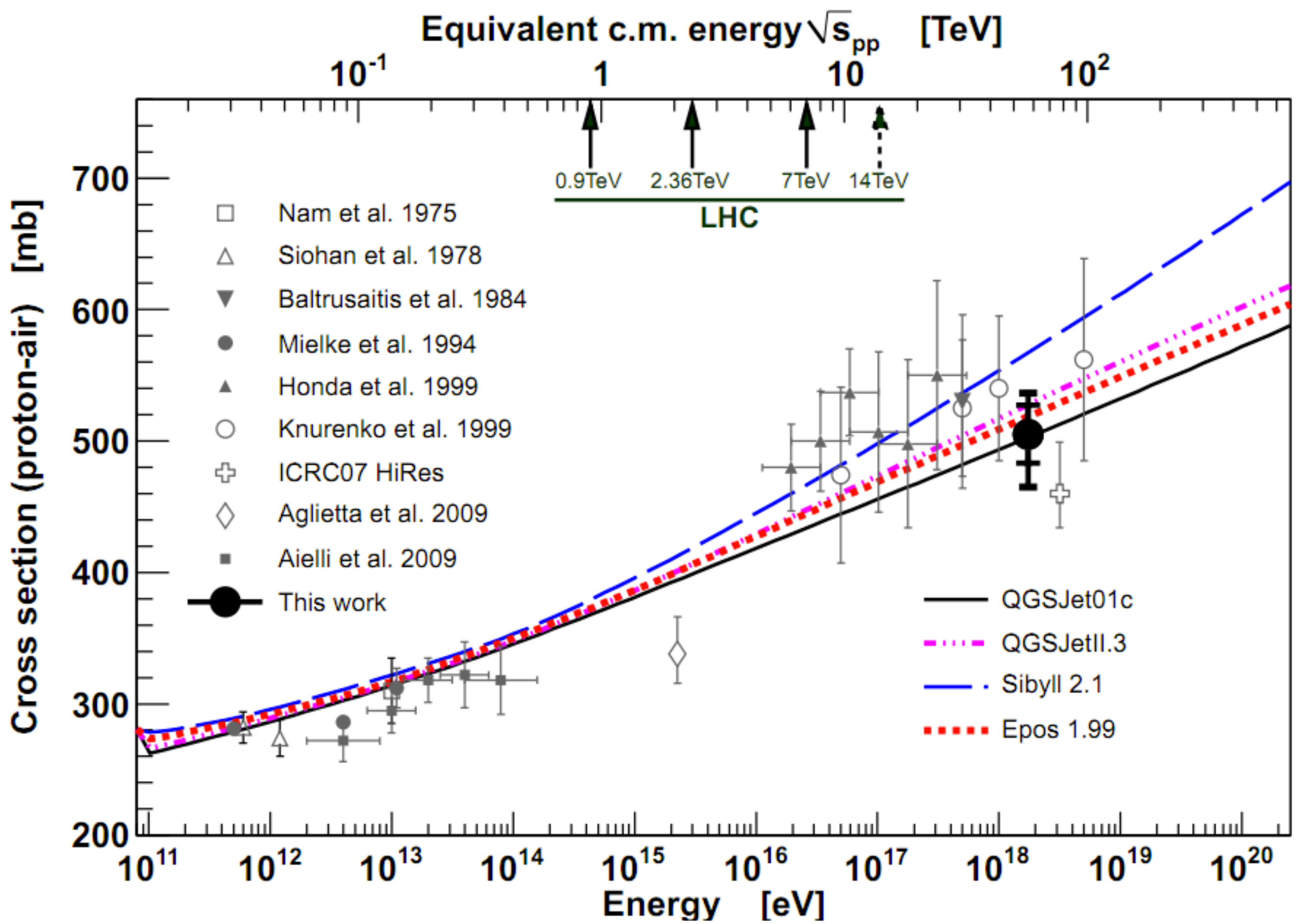
Systematic uncertainty ≈ 10% of p-Fe separation

Systematics

X_{max}	Atmosphere, FD reconstruction.
$RMS(X_{max})$	FD resolution, event selection.
Θ_{max}	SD geometrical reconstruction.
$X^{\mu}{}_{max}$	MPD reconstruction.

p-air cross section

Assumption: at E~1EeV composition mainly dominated by protons.



Result favours a moderately slow rise of the cross-section towards higher energies.