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IAEA International Atomic Energy Agency

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International Workshop on QCD at Cosmic Energies III

28 May - 1 June, 2007

The Pierre Auger Observatory: Results and Prospects at the Interface of QCD

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The Pierre Auger Observatory: Results and Prospects at the Interface of QCD

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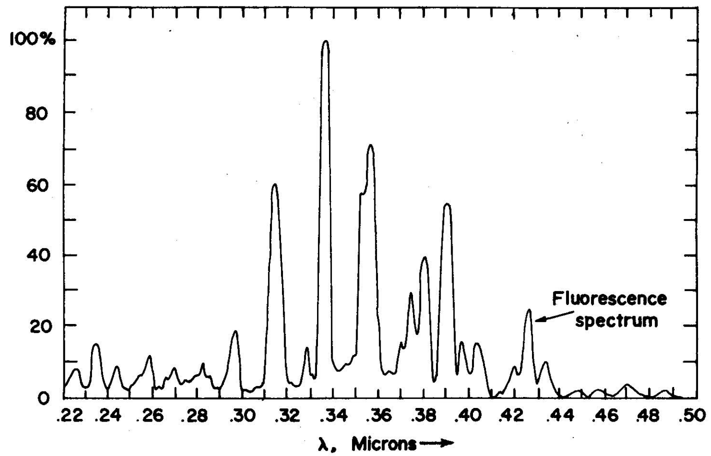
Workshop on QCD at Cosmic Energies - III
ICTP Trieste, May 28 – June 1, 2007

- **the Observatory (reminder)**
- **search for photons**
- **elongation rate**
- **shower muon content**
- **(some) prospects**

PIERRE AUGER OBSERVATORY

BERGISCHE UNIVERSITÄT WUPPERTAL

Pierre Auger Observatory – a hybrid detector



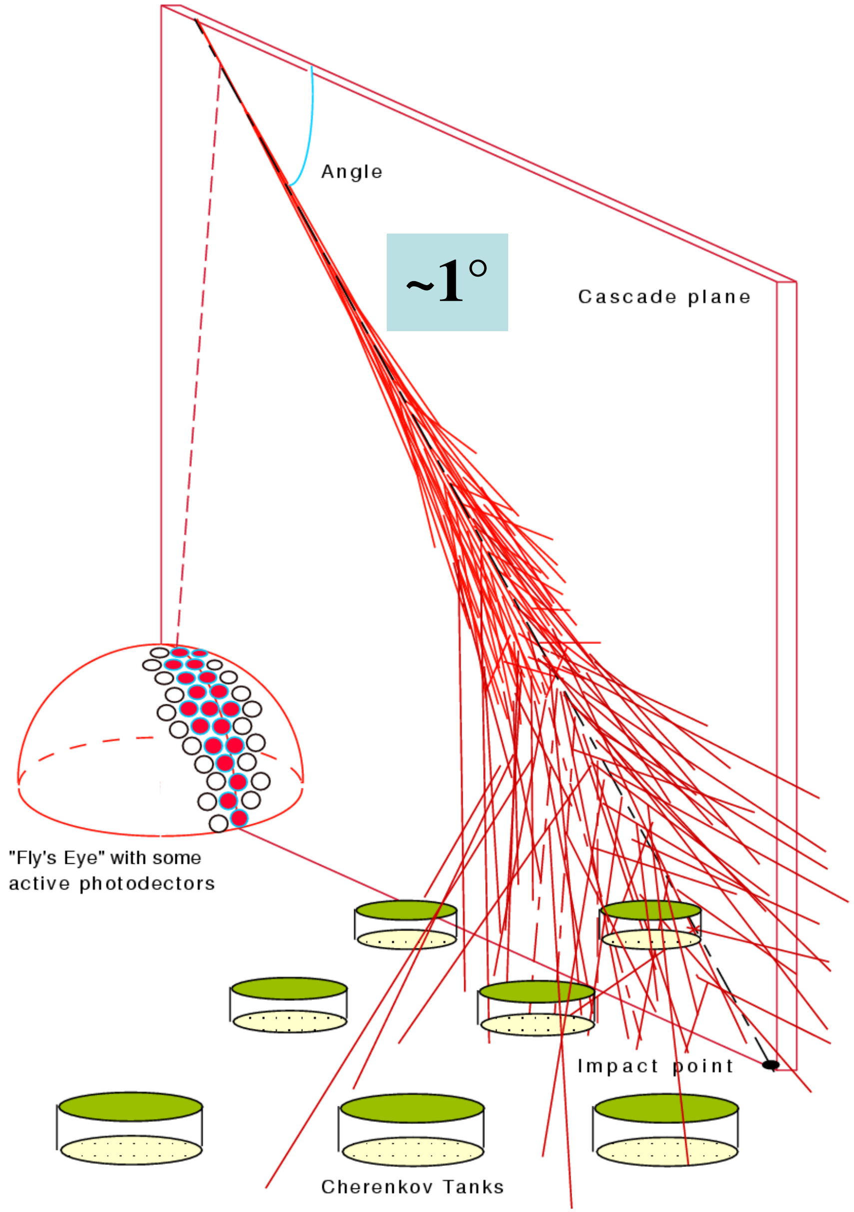
300 – 400 nm

- UV fluorescence light

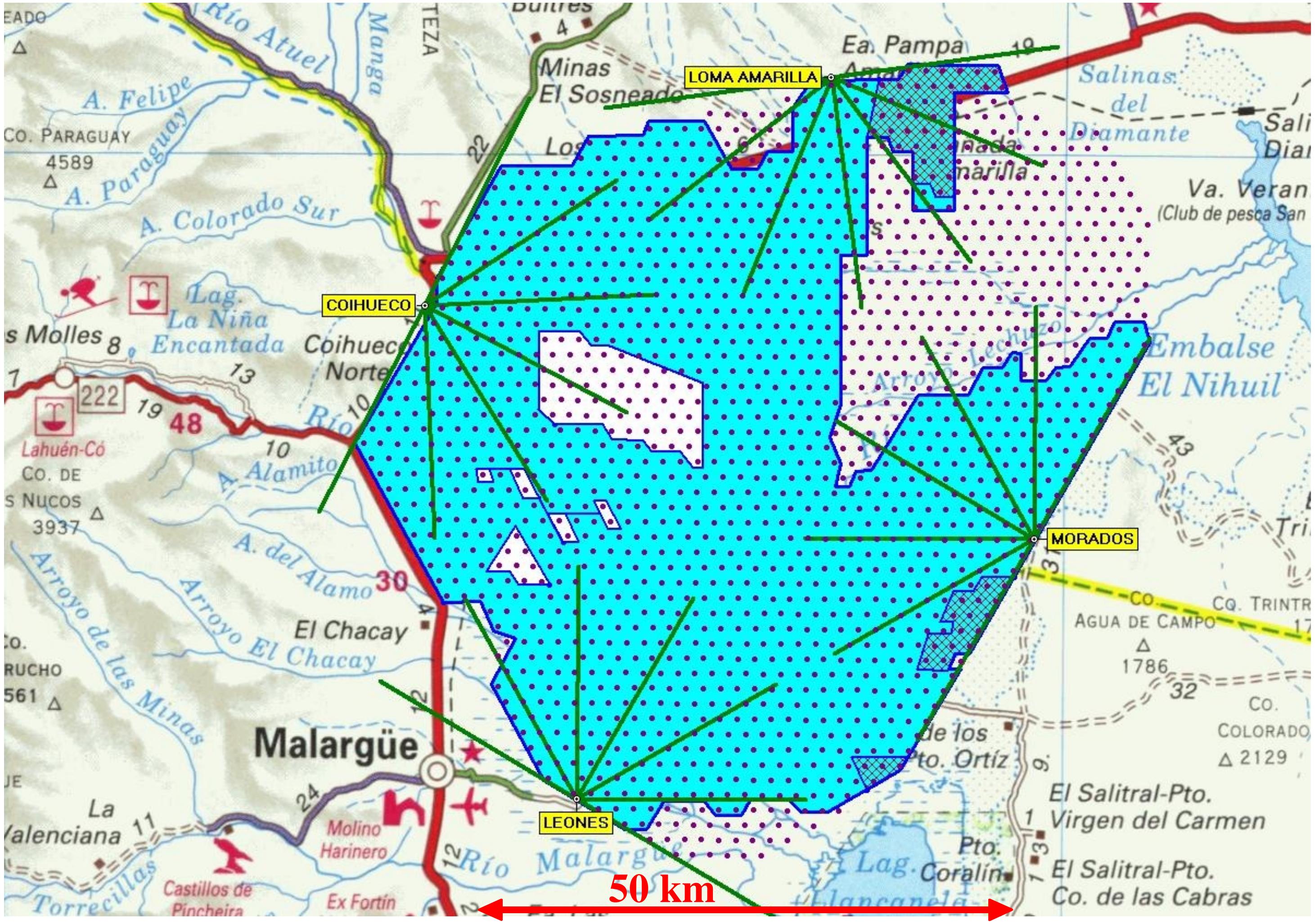
➔ *longitudinal shower profile*

- ground array of water Cherenkov detectors

➔ *particle lateral distributions*



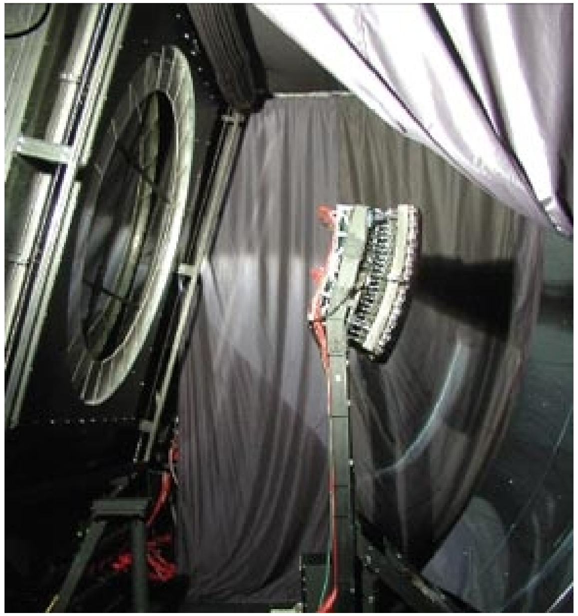
Pierre Auger Observatory – status (May 11, 2007)



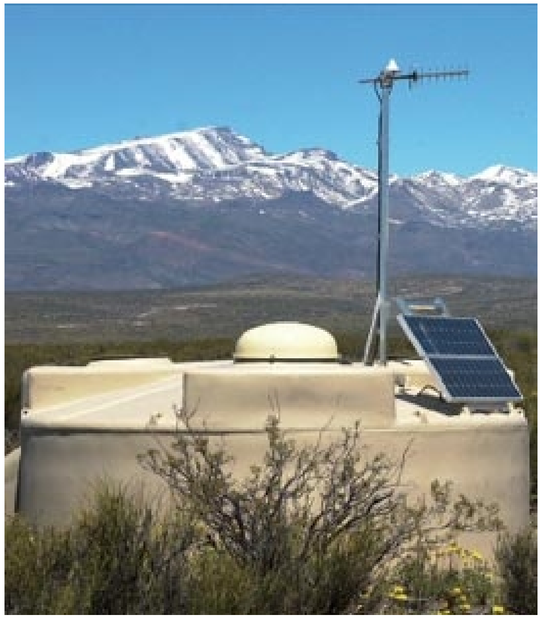
- array: 1376 stations deployed (1338 filled), **1201** taking data (finally **1600**)
  - 1.5 km distance, total area 3000 km^2
- telescopes: all 4 sites taking data, 6 telescopes each (30 deg x30 deg each)

Pierre Auger Observatory – impressions

hybrid =

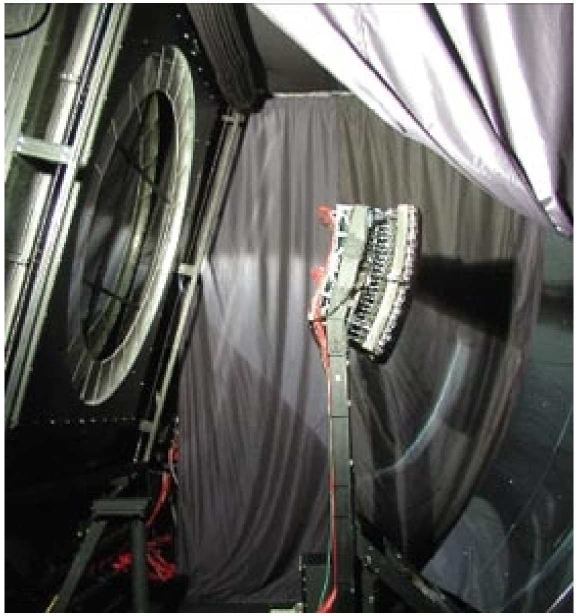


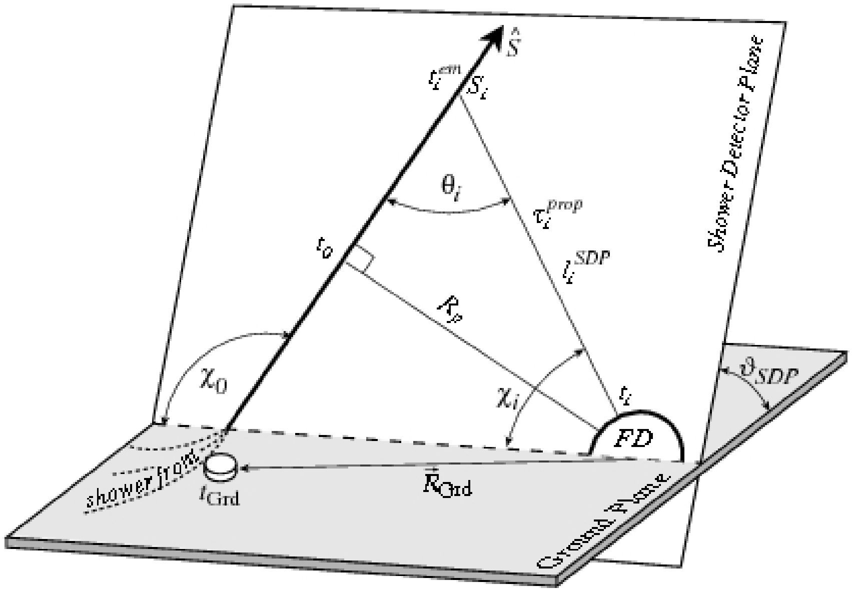
+



~10% duty cycle

Fluorescence telescopes

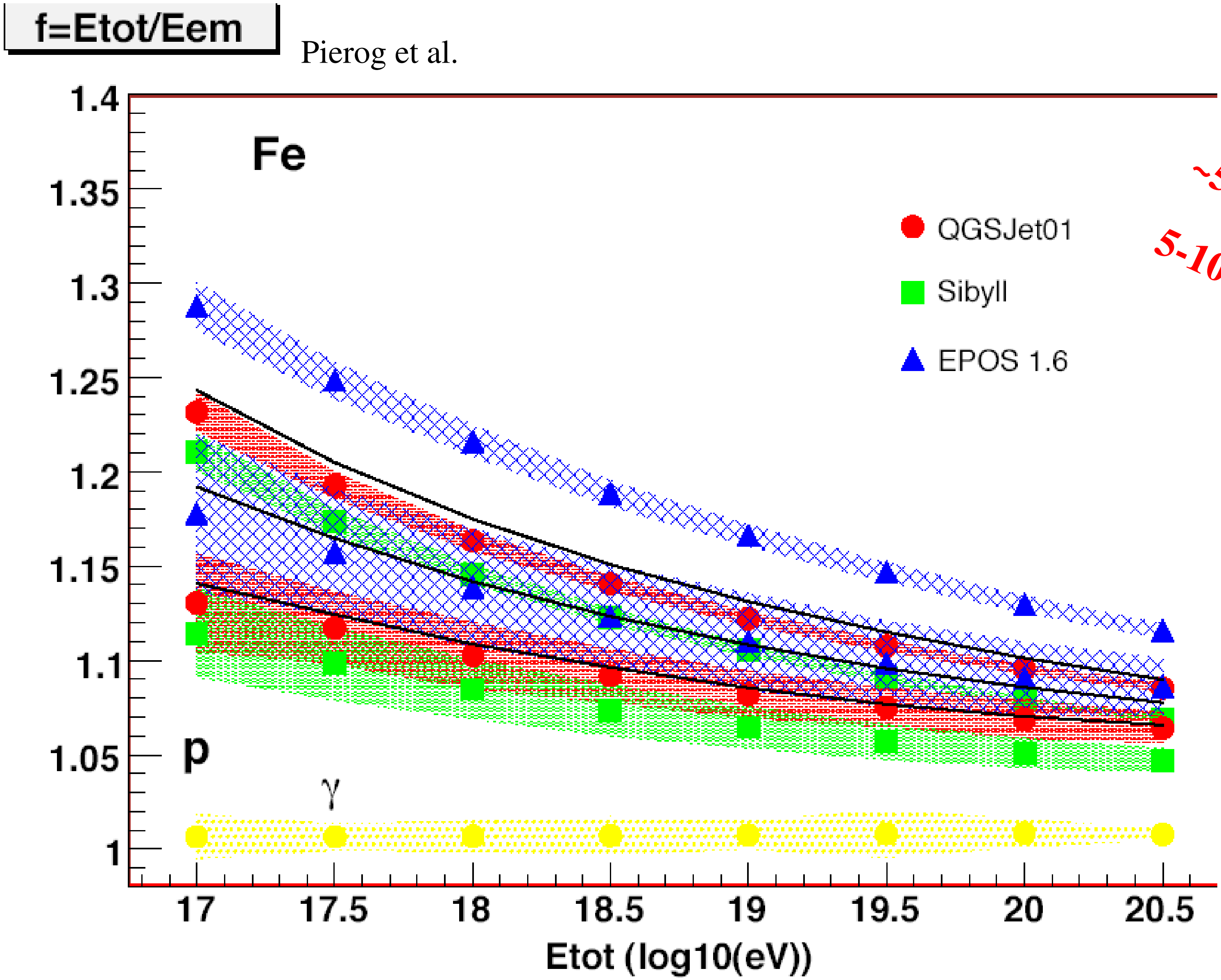




- **geometry**: angular-time correlation of triggered PMTs
- **profile**: PMT signal -> light at aperture -> light at shower -> dE/dX at shower
- $\mathbf{X_{max}}$ and **energy** (integrating dE/dX plus -> *missing energy correction*)

Fluorescence reconstruction: missing energy correction

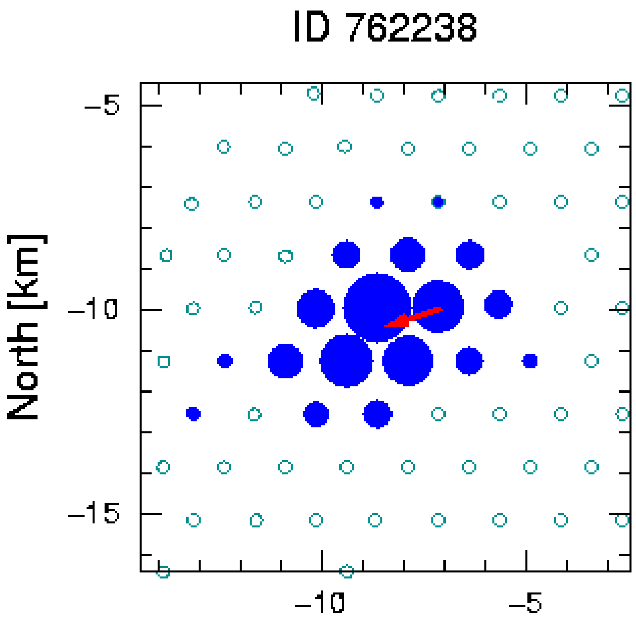
Pierog et al.

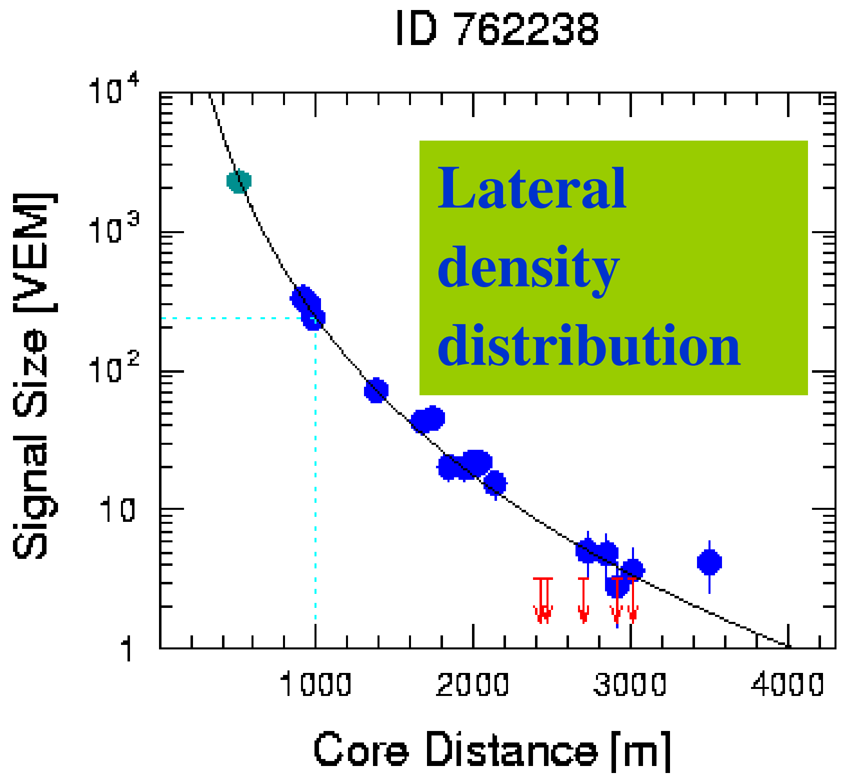


~5% model uncertainty

5-10% difference p-Fe

Ground array





- geometry from timing
- lateral distribution => **S(1000)**
  - sensitive to elmagn and muonic component
- also: 25 ns sampling => signal **risetime**

Disclaimer!

Results shown are PRELIMINARY.

Plots and numbers may differ slightly from those in the ICRC papers submitted this week.

Search for UHE photons

There are 10^{20} eV (= 100 EeV) events ! Origin ??

- **acceleration models (astrophysics):**
  - active galactic nuclei, gamma-ray bursts, ...
  - ➔ not easy to reach >100 EeV; no obvious correlations

photon fractions typically < ~1%

- **non-acceleration models (particle physics):**
  - super-heavy dark matter, topological defects
  - ➔ hypothetical massive objects produce normal particles

photon fractions typically > ~10%

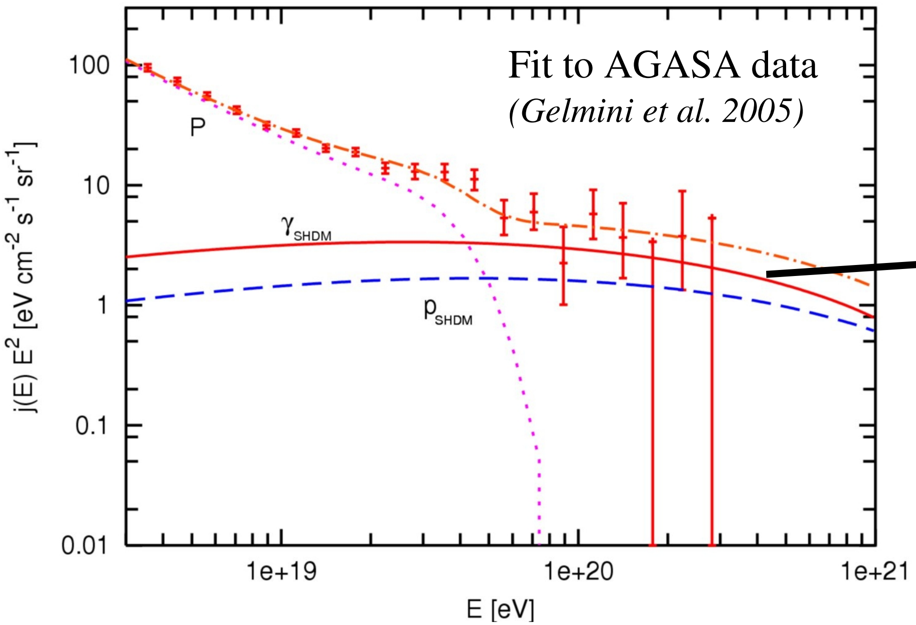
- to avoid GZK cut-off also for distant sources:
  - neutrinos in Z-Burst scenario (cosmology)
  - violation of Lorentz invariance (fundamental physics)

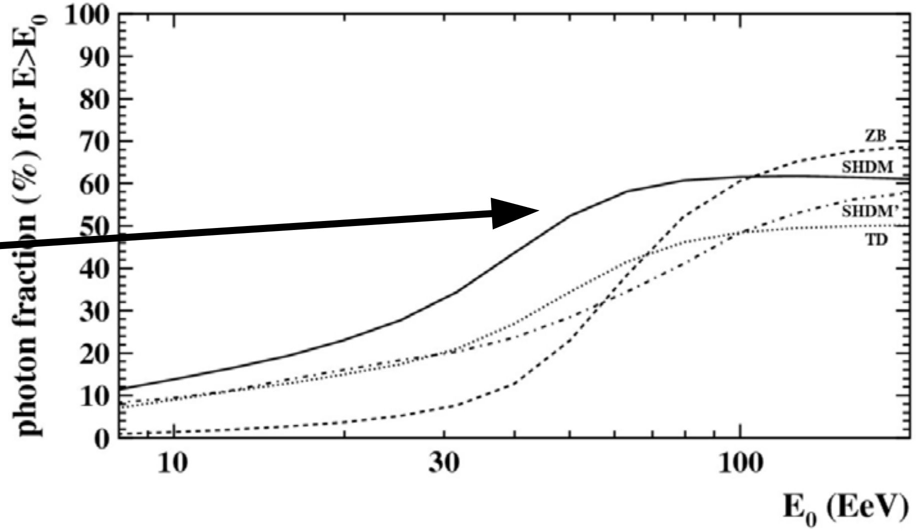
Super Heavy Dark Matter (SHDM)

- produced during inflation; **M_x~10^{23} eV**, clumped in **galactic halo** (overdensity ~10^5)
- lifetime ~10^{20} y: **decay** *(SUSY-QCD)* => pions => **UHE photons** (and neutrinos)

➔ little processing during propagation: **decay spectrum** at Earth

(integral photon fraction)





Berezinsky, Kachelrieß 1998; Birkel, Sarkar 1998; Ellis et al. 2005, Aloisio et al. 2006 ...

➔ **photons dominate >50-80 EeV**

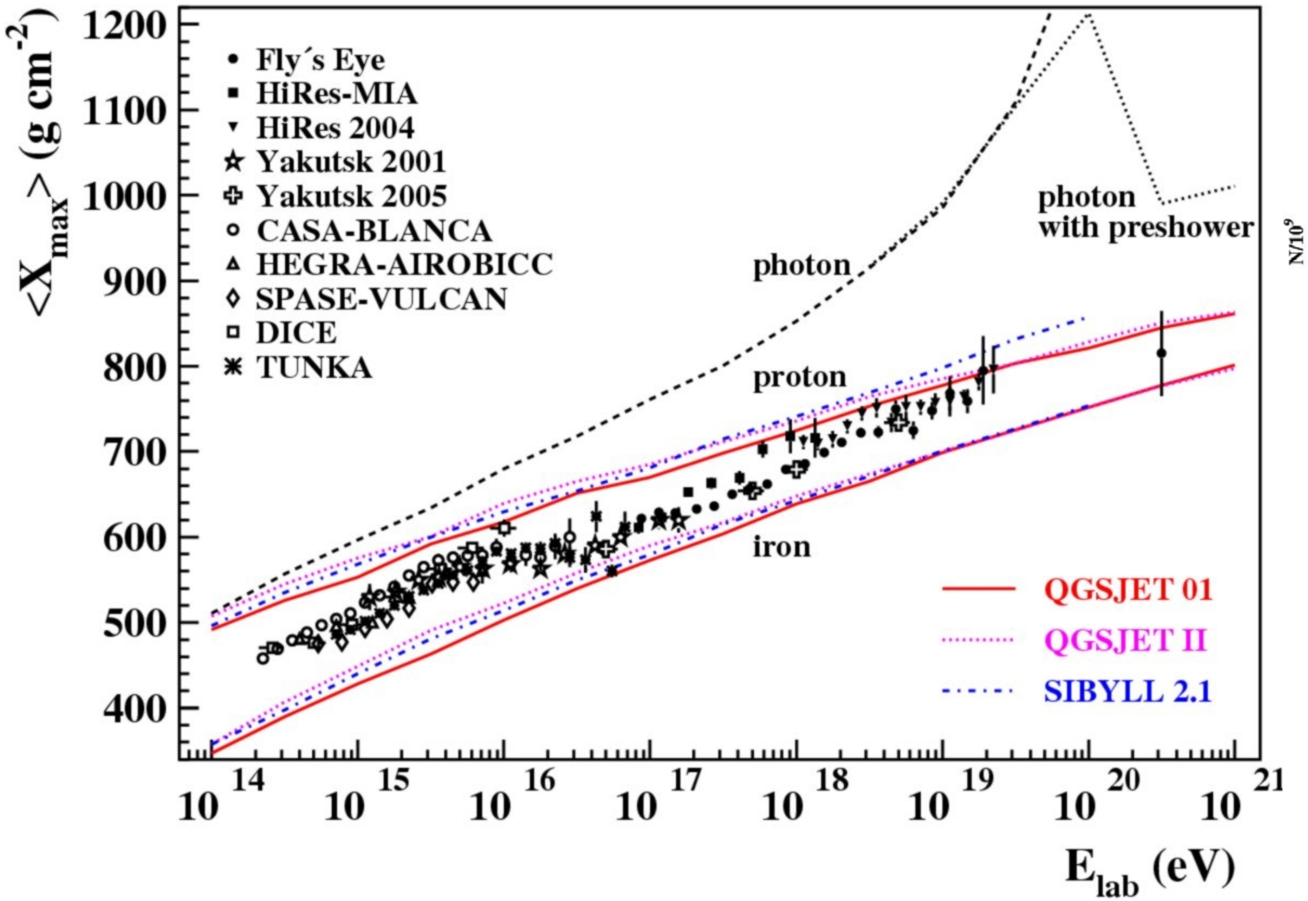
➔ similar shapes for ZB *(Weiler 1982, ...)* and TD *(Hill 1983, ...)* models

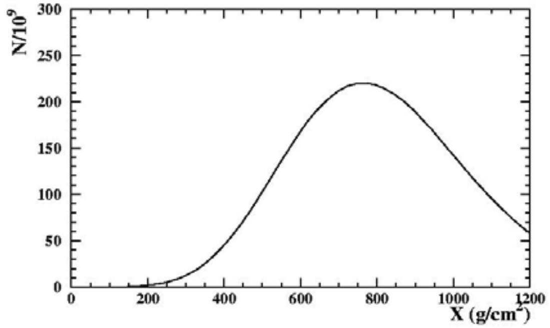
➔ **signature for exotics !**

Can we see the decay products (via SUSY-QCD) of the SHDM ?

The Auger Observatory is well suited to search for UHE photons.

Photon discrimination with X_{max}

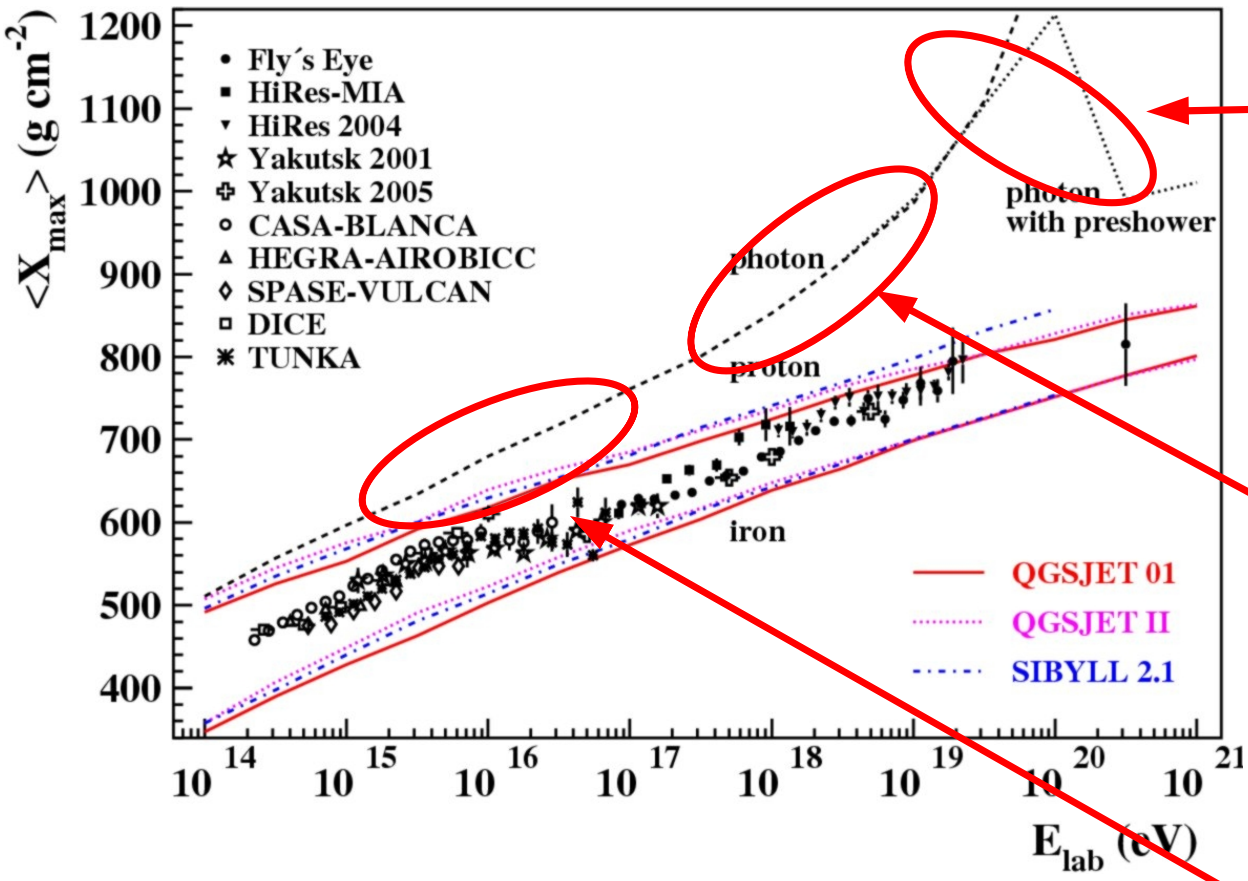




X_{max}
(depth of shower maximum)

- photons vs hadrons: **~200 g cm^{-2} difference** at 10^{19} eV
- **slope** (ΔX_{max} / per energy decade) is changing !?

Photon showers: high-energy effects



preshower

photon conversion and elmag. cascade in geomagnetic field

LPM

suppression of pair production and bremsstrahlung cross-sections

“standard“

slope ~ 85 g cm^{-2} / energy decade

(-> toy model: equal energy splitting and λ_{rad})

Photon search using high-quality hybrids (X_{max})

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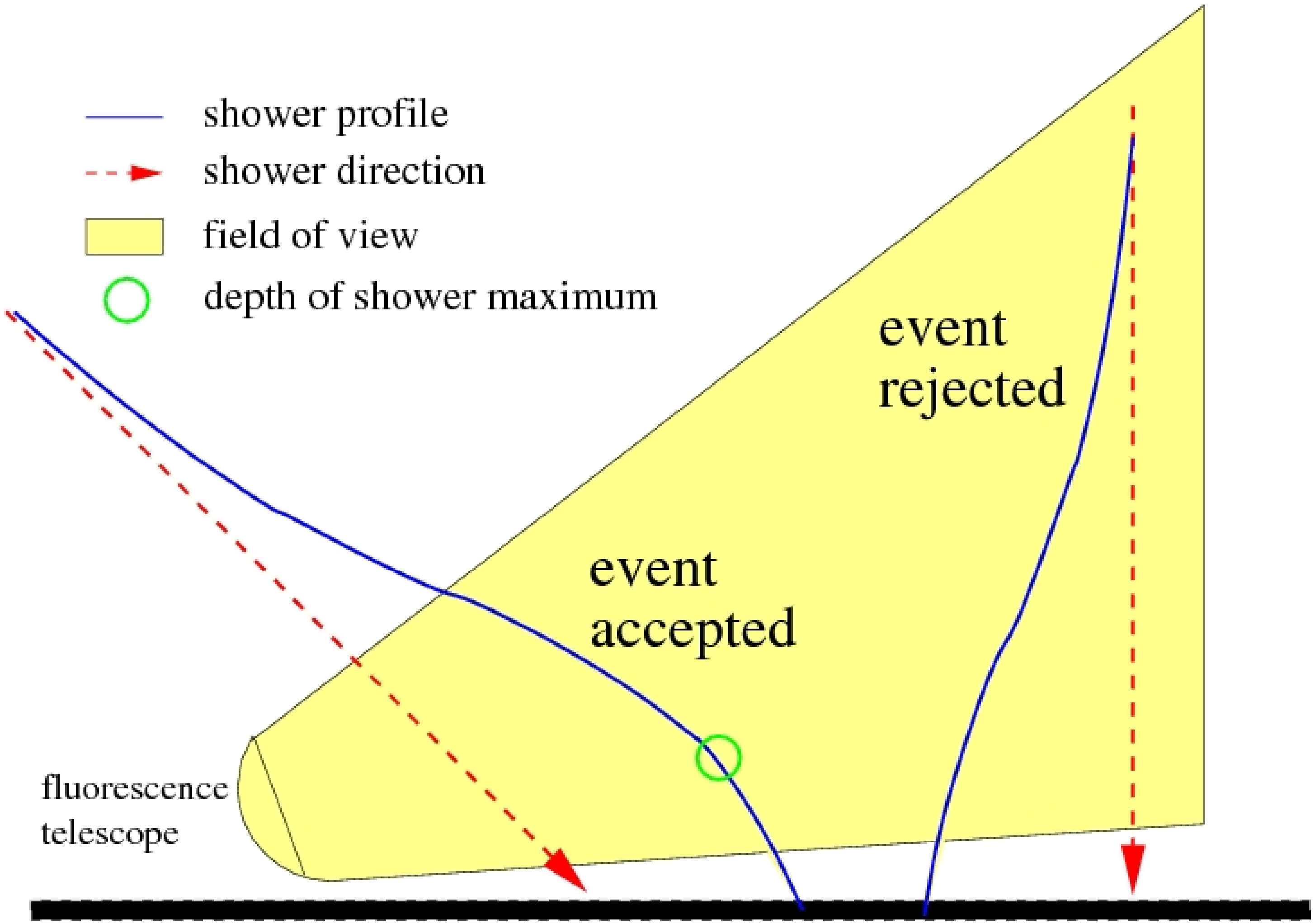
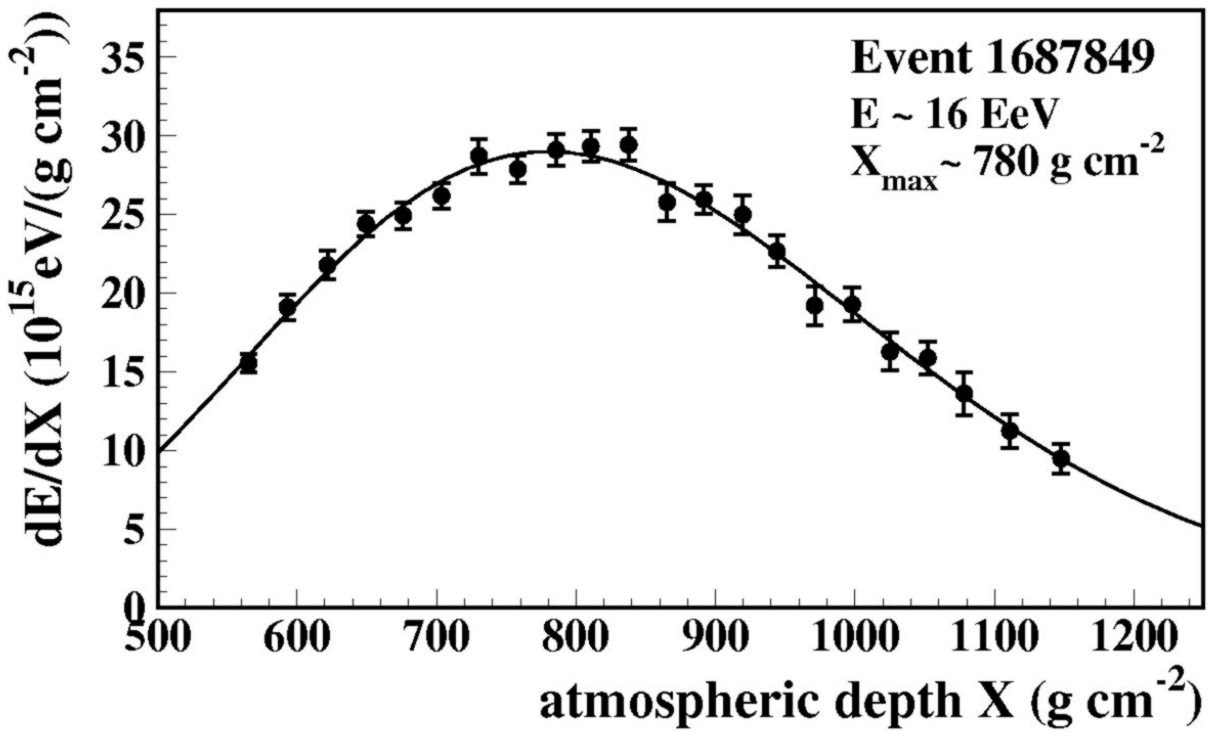
- data set: 01/2004 – 02/2006
- anti-bias cuts needed *because of* large X_{max} (e.g. exclude near-vertical events)



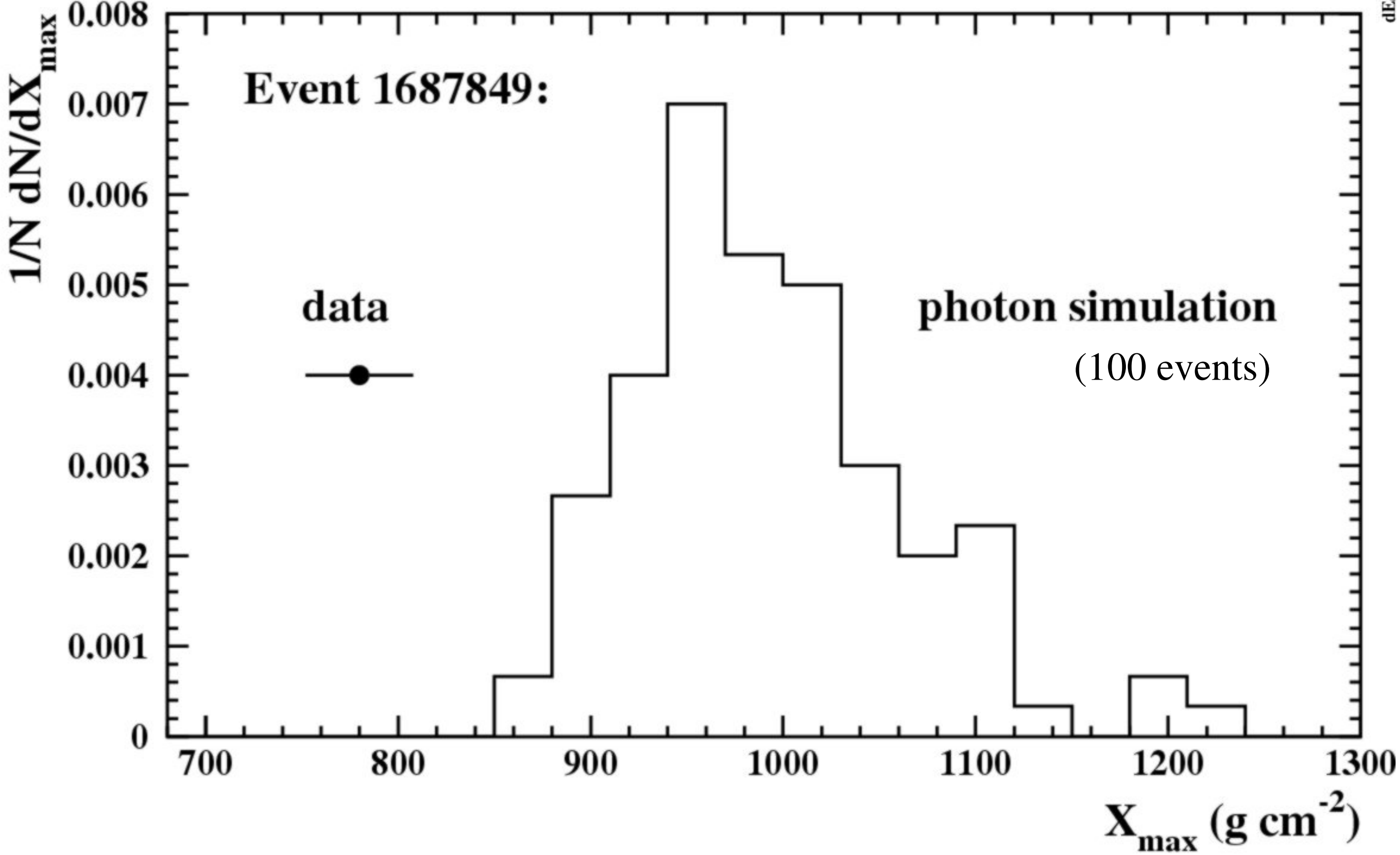
Example of observed profile

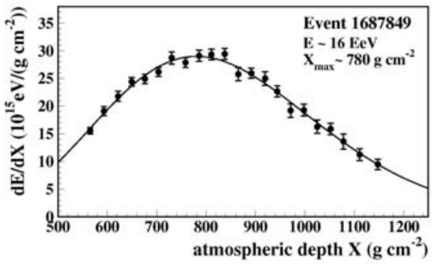


Gaisser-Hillas fit

- **calorimetric energy** from integration
- 1% **missing energy** correction, suitable for primary photons
  - energy scale for photons
  - *underestimates* slightly (~7-14%) energy of hadron primaries
  - conservative photon limit! (data sample slightly *depleted* from hadron primaries)

Example: data vs photon simulation





- event: X_{max} = 780 ± 28 (stat) ± 23 (syst) g cm^{-2}
- photons: $<X_{max}>$ = 1000 g cm^{-2} , rms = 71 g cm^{-2}

➔ **observed X_{max} well below expectation for photons**

The data set: overview

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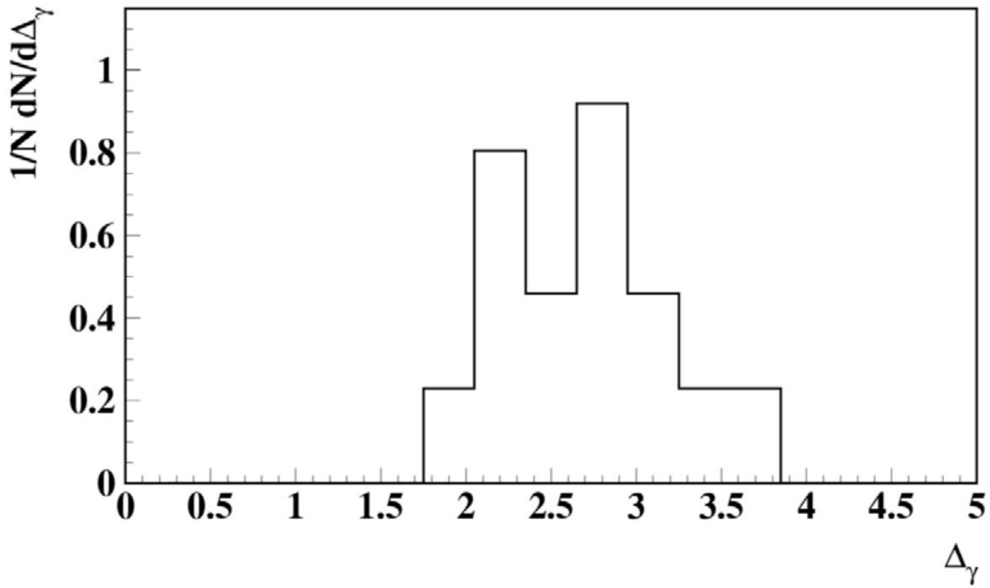
Event ID	Energy [x10^{18} eV]	X_{max} [g cm^{-2}]	$<X^{\gamma}_{max}>$ [g cm^{-2}]	ΔX^{γ}_{max} [g cm^{-2}]	Δ_{γ} [std. dev.]
668949	17	765	985	71	2.9
673409	12	760	996	82	2.7
705583	11	678	973	77	3.6
737165	202	821	948	27	3.3
828057	13	805	978	68	2.4
829526	12	727	996	85	3.0
850018	54	774	1050	120	2.2
931431	24	723	1022	89	3.2
935108	14	717	992	68	3.8
986990	15	810	1000	87	2.1
1109855	16	819	1019	95	2.0
1171225	15	786	993	74	2.6
1175036	17	780	1001	100	2.1
1257649	10	711	971	76	3.2
1303077	13	709	992	85	3.1
1337921	18	744	1029	93	2.9
1421093	25	831	1028	93	2.0
1535139	15	768	998	77	2.8
1539432	12	787	975	76	2.3
1671524	13	806	978	77	2.1
1683620	20	824	1035	80	2.5
1683856	18	763	981	92	2.3
1684651	12	753	991	79	2.8
1687849	16	780	1001	71	2.9
1736288	10	726	981	71	3.3
1826386	17	747	994	84	2.8
1978675	10	740	978	76	2.9
2035613	11	802	998	90	2.1
2036381	27	782	1057	101	2.6

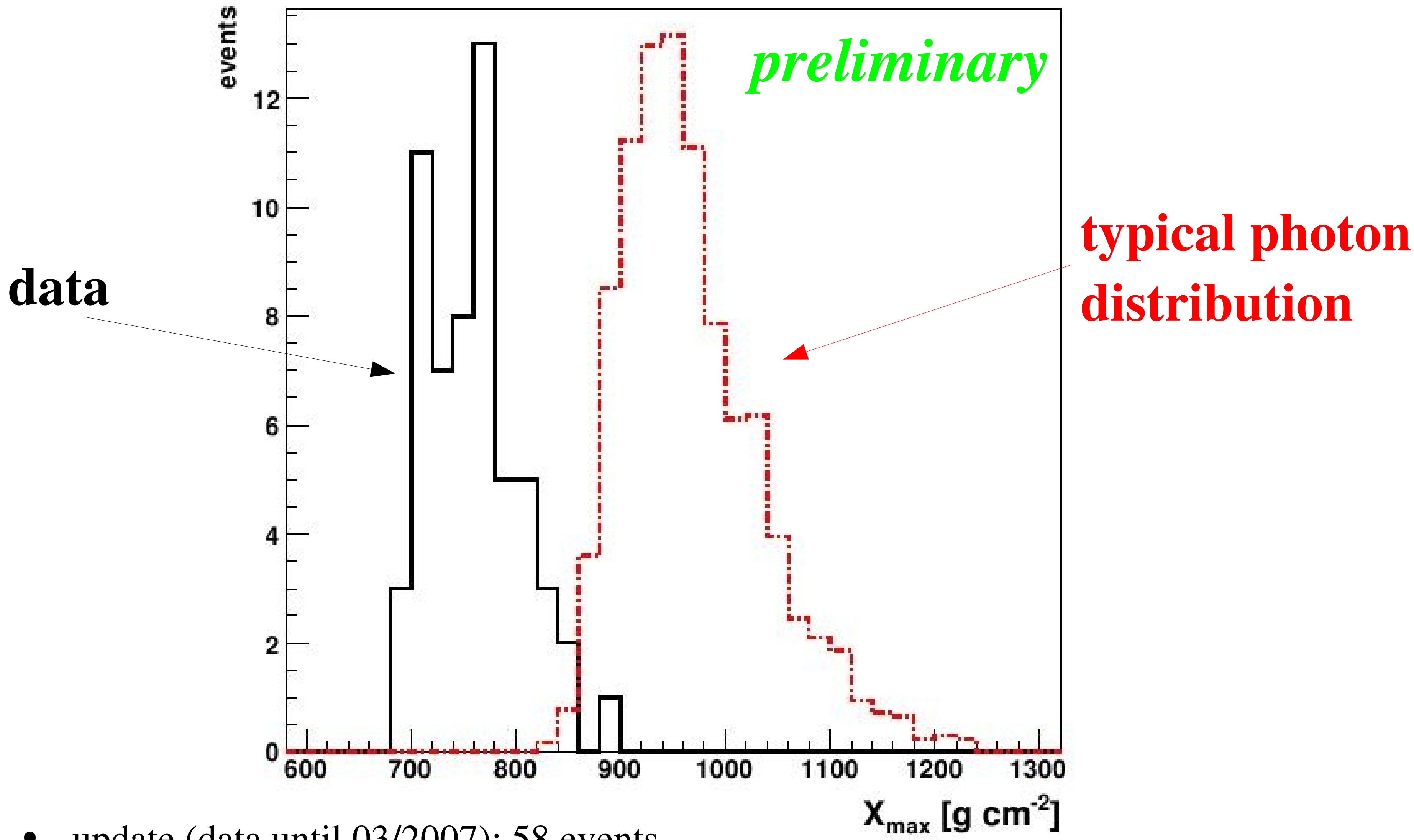


photon vs data:
2.0-3.8 st.dev.

$$\Delta_{\gamma} = \frac{< X^{\gamma}_{\rm max} > - X_{\rm max}}{\sqrt{(\Delta X^{\gamma}_{\rm max})^2 + (\Delta X^{\rm stat}_{\rm max})^2}}$$

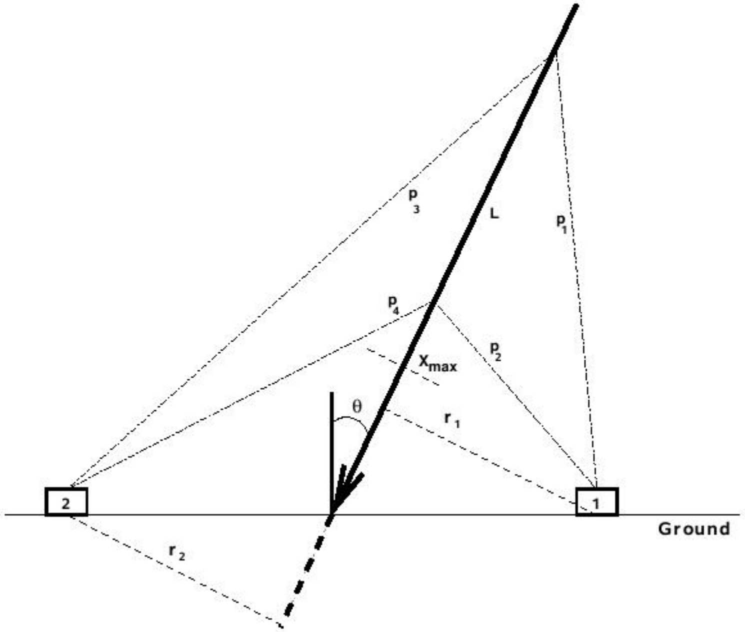
- ➔ probability (29x photons) << 10^{-10}
- ➔ set limit to photon fraction
- ➔ **<16%** (95% c.l.) **above 10^{19} eV**

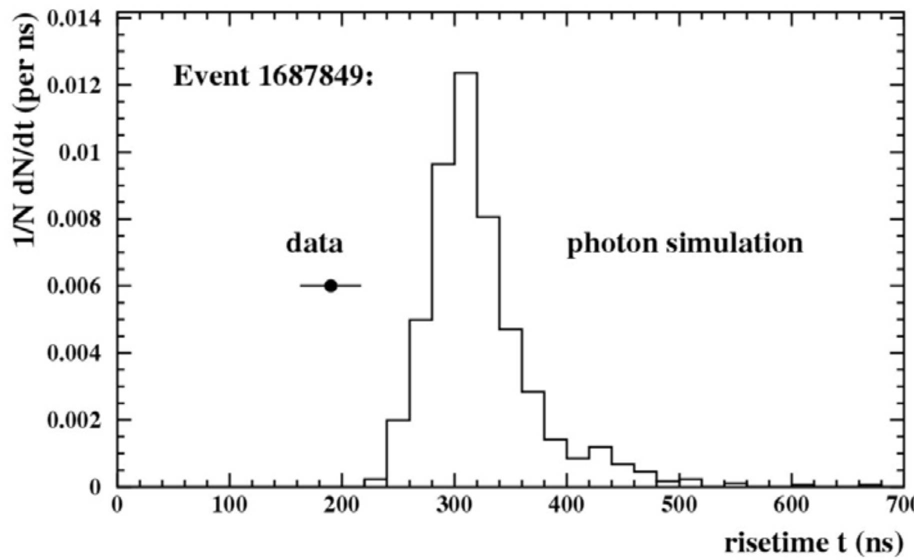
Photon search using hybrids: update

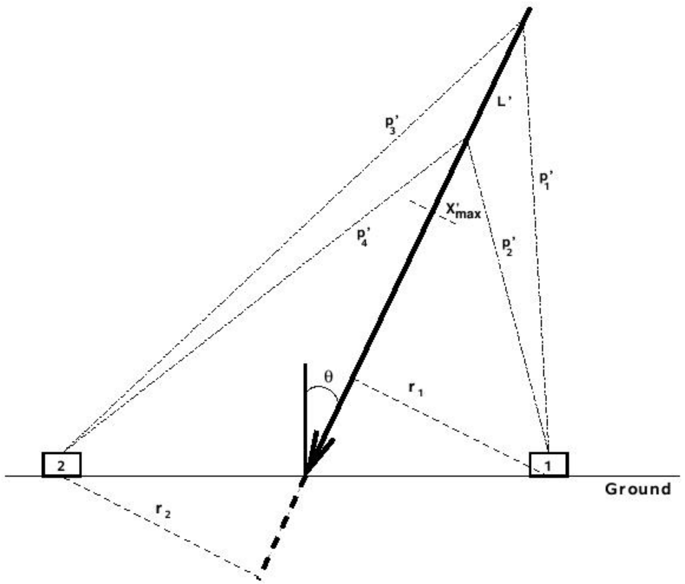


- update (data until 03/2007): 58 events
- largest X_{max} ~900 g/cm^2: still below average photon X_{max}
- current limit from hybrid X_{max} data: **<13%** (95% c.l.) **above 10^{19} eV**

Photon search using the ground array: factor ~10 more data!





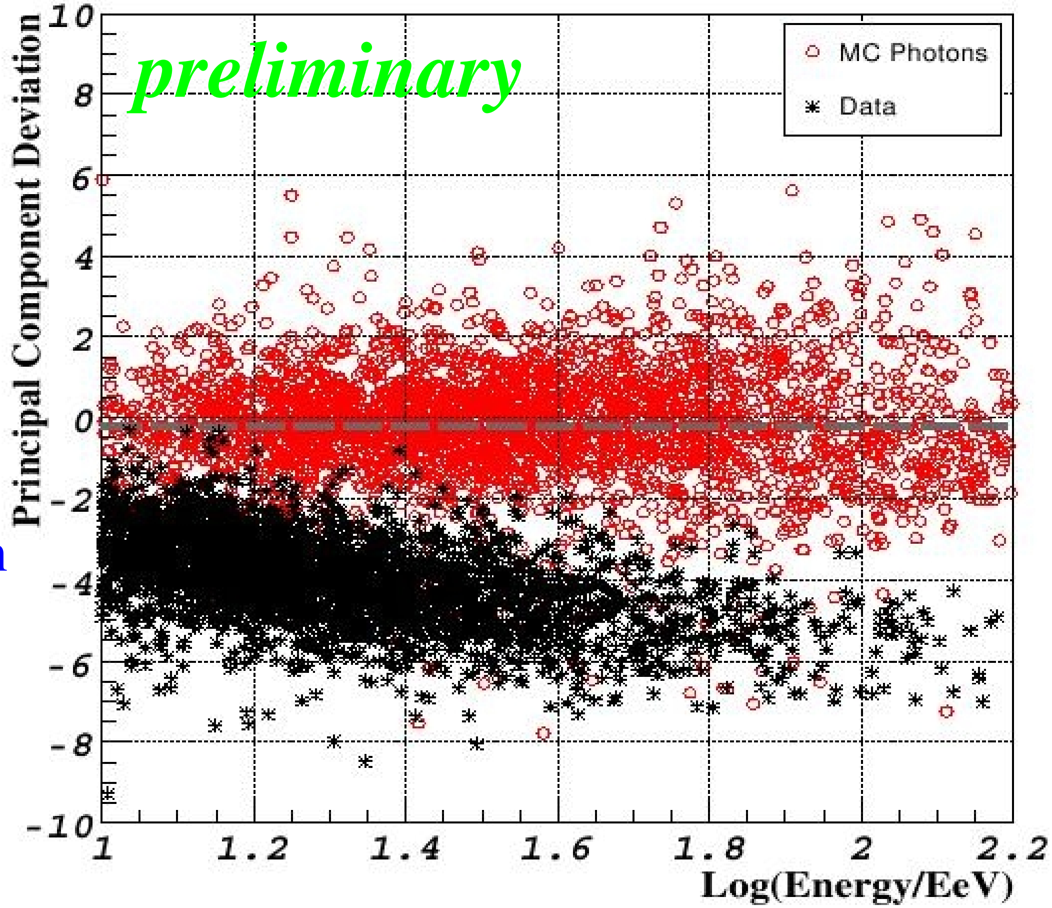


- **risetime** of signal at 1000 m core distance
- larger X_{max} -> larger risetime
  - path length differences, elmagn dominates
- similar: shower front **curvature** (from timing)
- larger X_{max} -> larger curvature

Photon search using the ground array

combination of risetime and curvature (PCA)

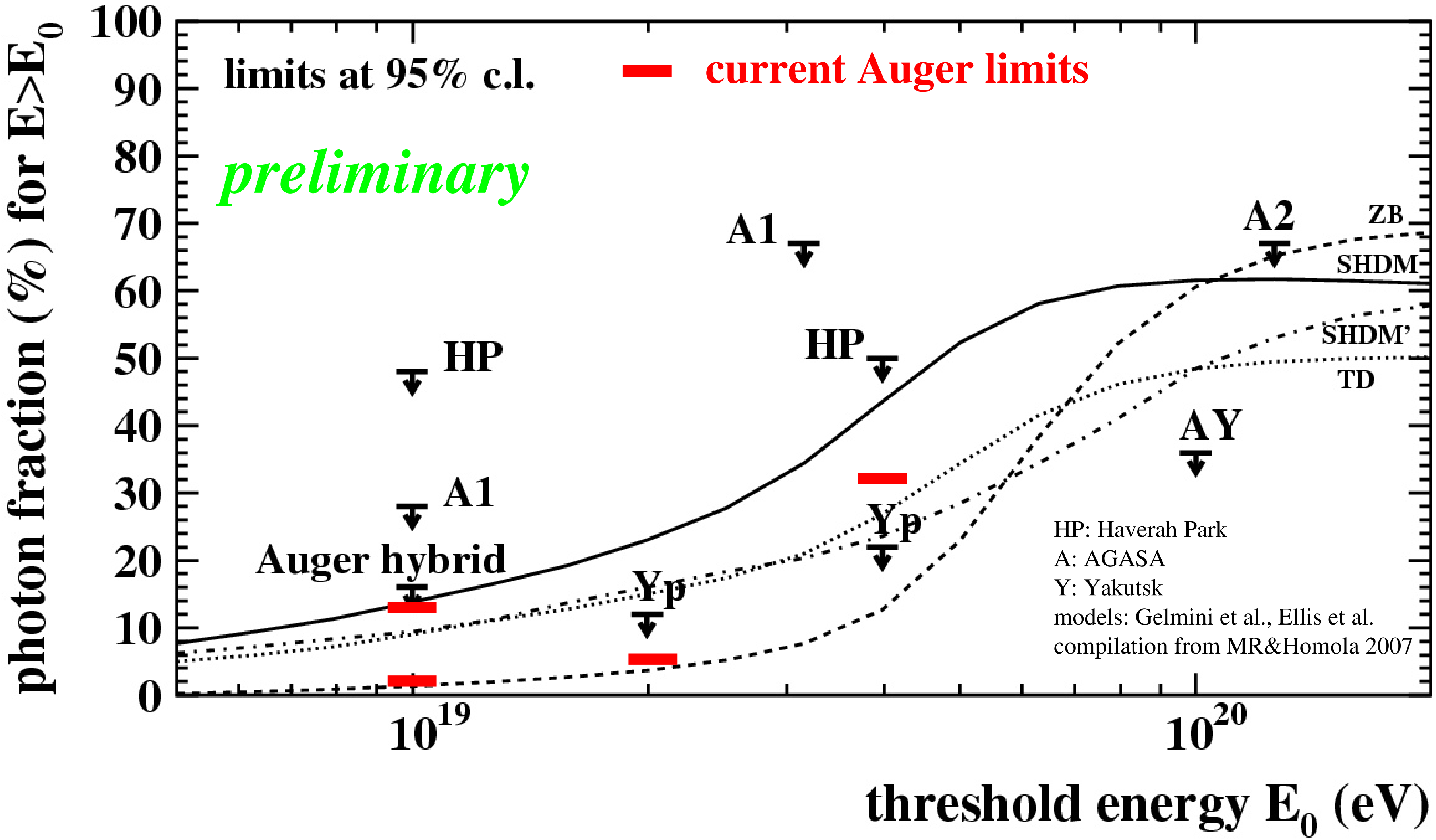
shown: deviation to photon expectation



energy scale for photons!

- **cut in S_{38}(1000)** corresponding to photon energies of 10 (20, 40) EeV
- **cut in combined observable** such that 50% photons were accepted
- **count surviving events: zero** (2761 / 570 events above 10 EeV photon/hadron energy scale)
  => flux limit to photons (from this also fraction limit => **2% above 10 EeV**)

Auger photon limits



- upper limits of **2%** (hybrid: 13%), **5%, 31%** (95% c.l.) above 1, 2 ,4 * 10^{19} eV

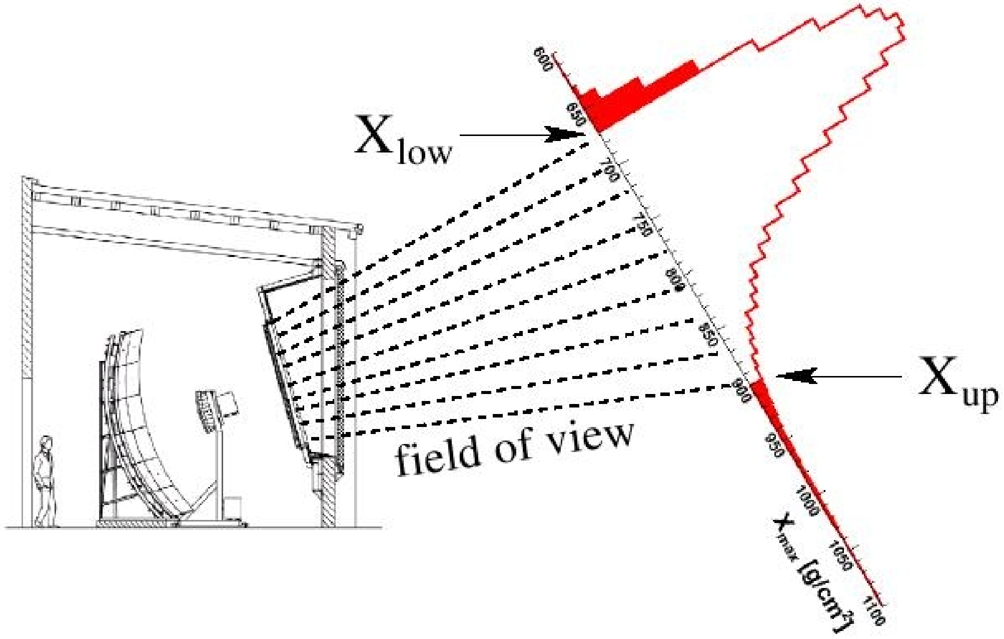
➔ *SHDM (top-down) models strongly disfavoured*

High-energy events look hadronic.

X_{max} is a key shower characteristics with sensitivity to inelastic (non-diffractive) cross-section and elasticity.

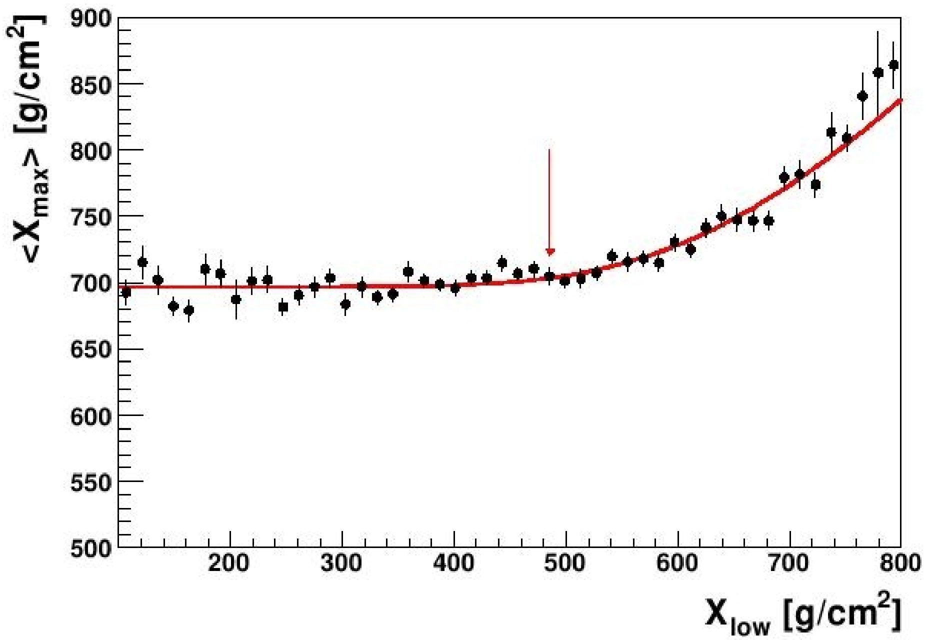
Here: measurement of $\langle X_{max} \rangle$ as fct of energy

$<X_{max}>$ vs energy: anti-bias cuts



profile fit: $\chi^2 / n < 2.5$
χ^2(line) minus χ^2(Gaisser-Hillas) > 4
dXmax < 40 g/cm2, dE/E < 20%
X_{max} observed!

check on data possible
where bias starts



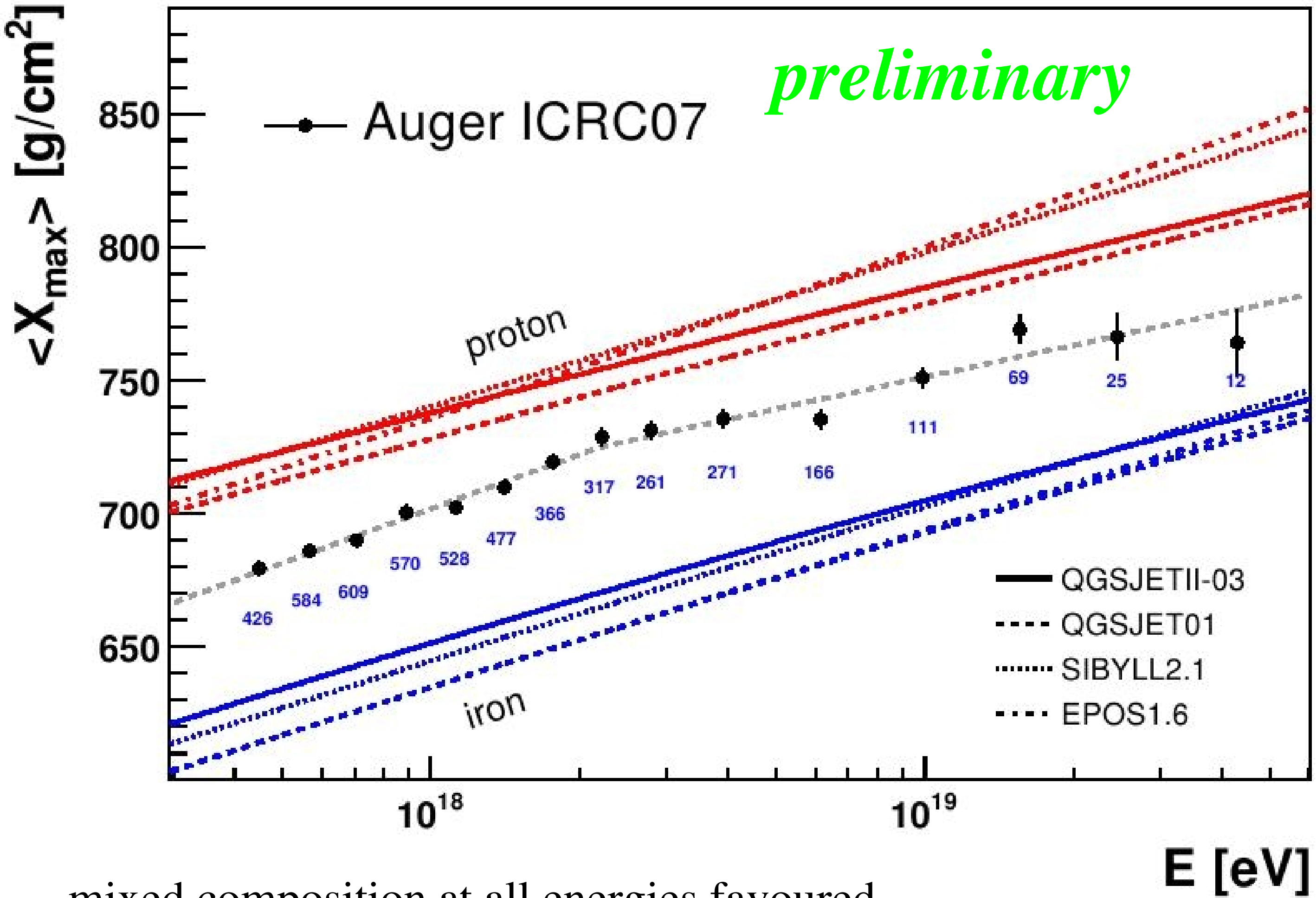
- events with X_{max} outside the f.o.v. are rejected by the *quality cut*
- *fiducial volume cuts* for unbiased $<X_{max}>$

$<X_{max}>$ systematics (preliminary)

- atmospherics (monthly averaged density profiles) ~6 g/cm^2
- profile reconstruction algorithm <5 g/cm^2
- multiple-scattered light 5 g/cm^2
- geometry reconstruction <6 g/cm^2
- below 10^{18} eV, acceptance difference proton-iron <10 g/cm^2

- **total: 11 (15) g/cm^2 above (below) 10^{18} eV**

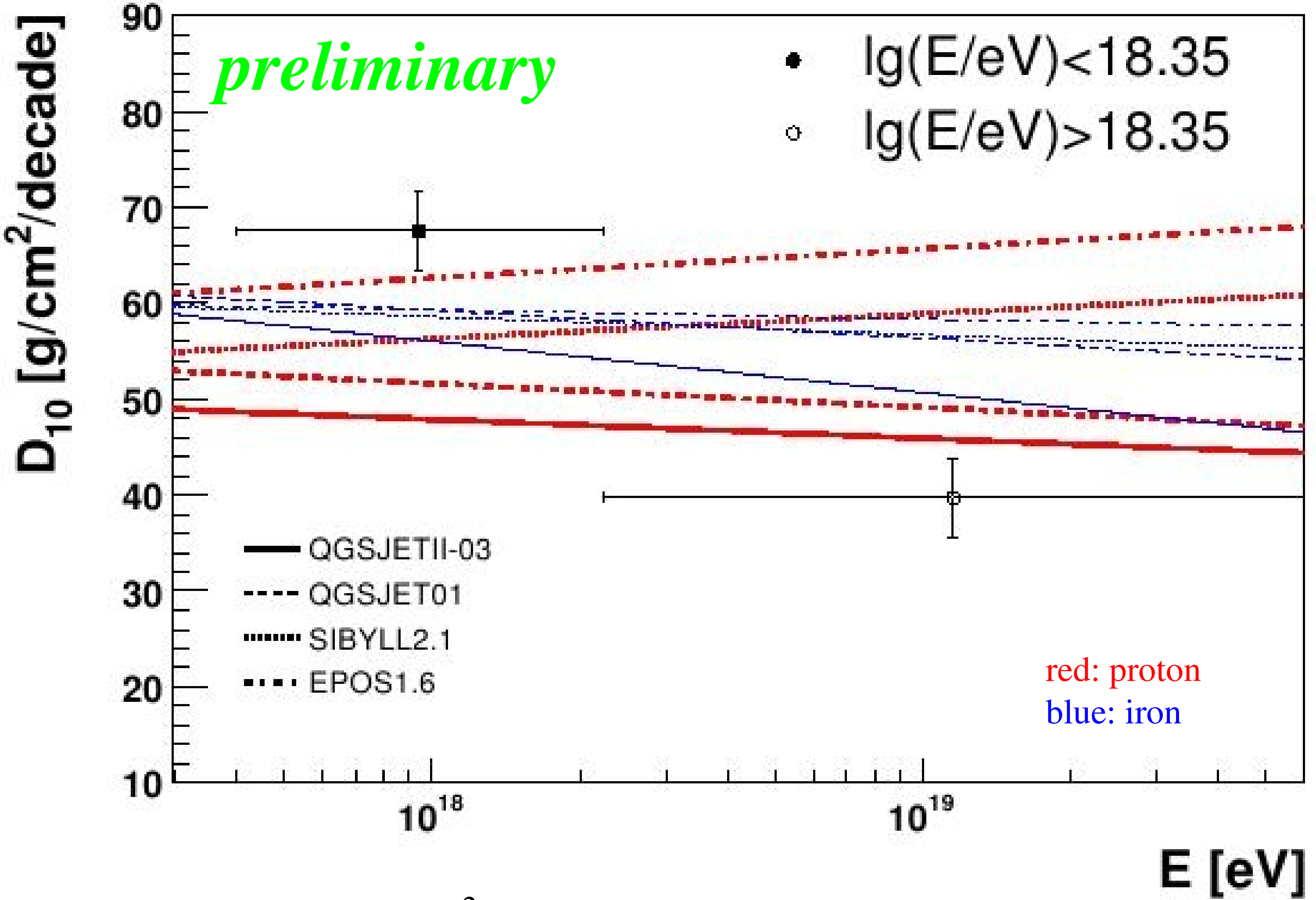
$<X_{max}>$ vs energy



4792 events

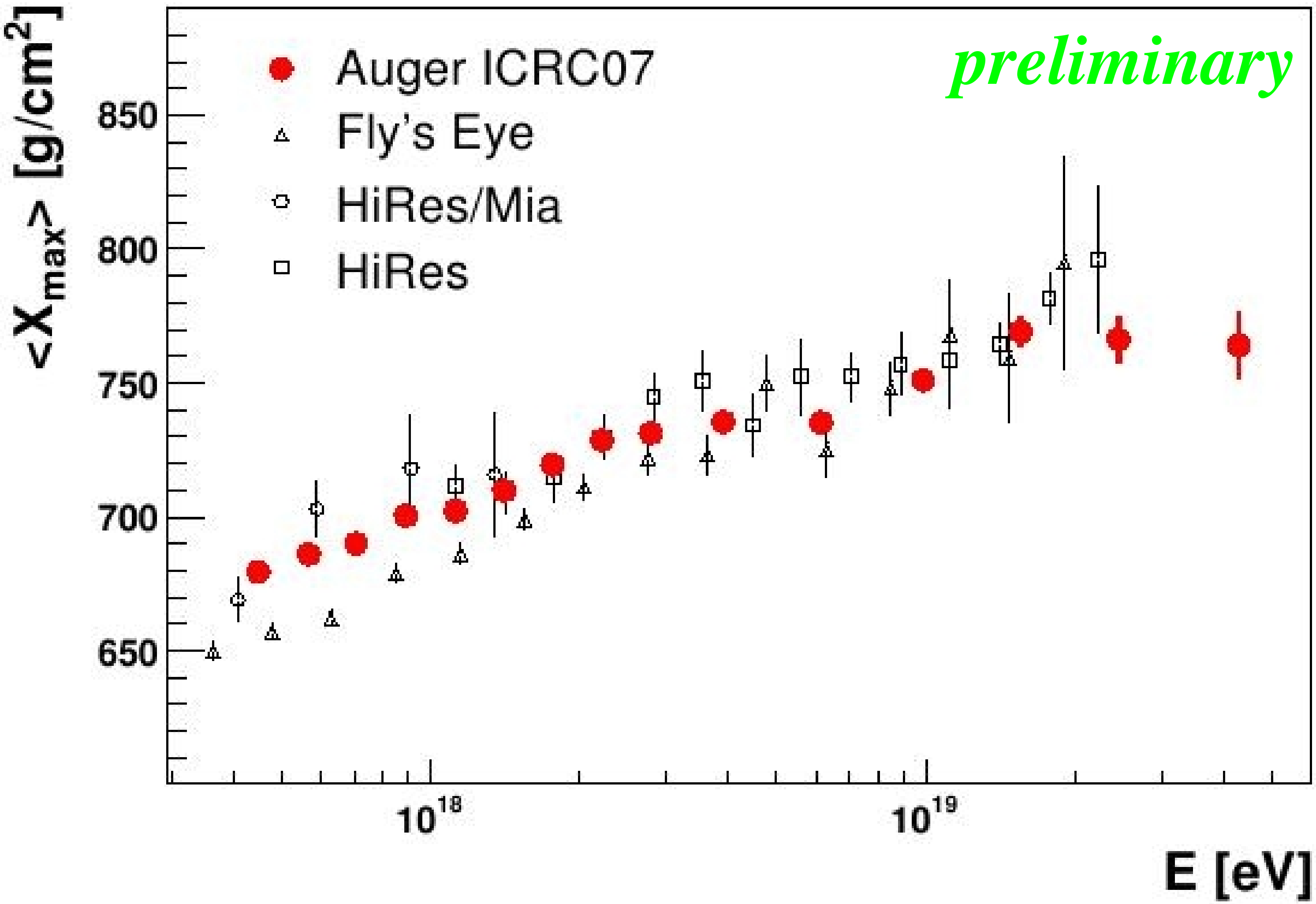
- ~mixed composition at all energies favoured
- not too much room for “exotic“ high-energy interactions that influence $<X_{max}>$?
- linear fit: El.Rate 52 ± 2 g/cm^2 per dec., but $\chi^2/n = 29/13$ (P<1%)
- break at 2-3*10^{18} eV: $\chi^2/n = 14/11$ (P=24%), El.Rate 68±4, 40±4 g/cm^2 per dec

$\langle X_{max} \rangle$ vs energy: elongation rate



- $(68 \pm 4, 40 \pm 4)$ g/cm^2 per dec
- QGSJET II (solid lines): trend to light at small E, ~ constant at high E
- EPOS (dash-dot): ~constant at small E, trend to heavier at high E

$<X_{max}>$ vs energy: previous experiments



- agreement within systematic uncertainties
  - note: already best statistics -> data also at higher E
- on-going: also X_{max} fluctuation analysis

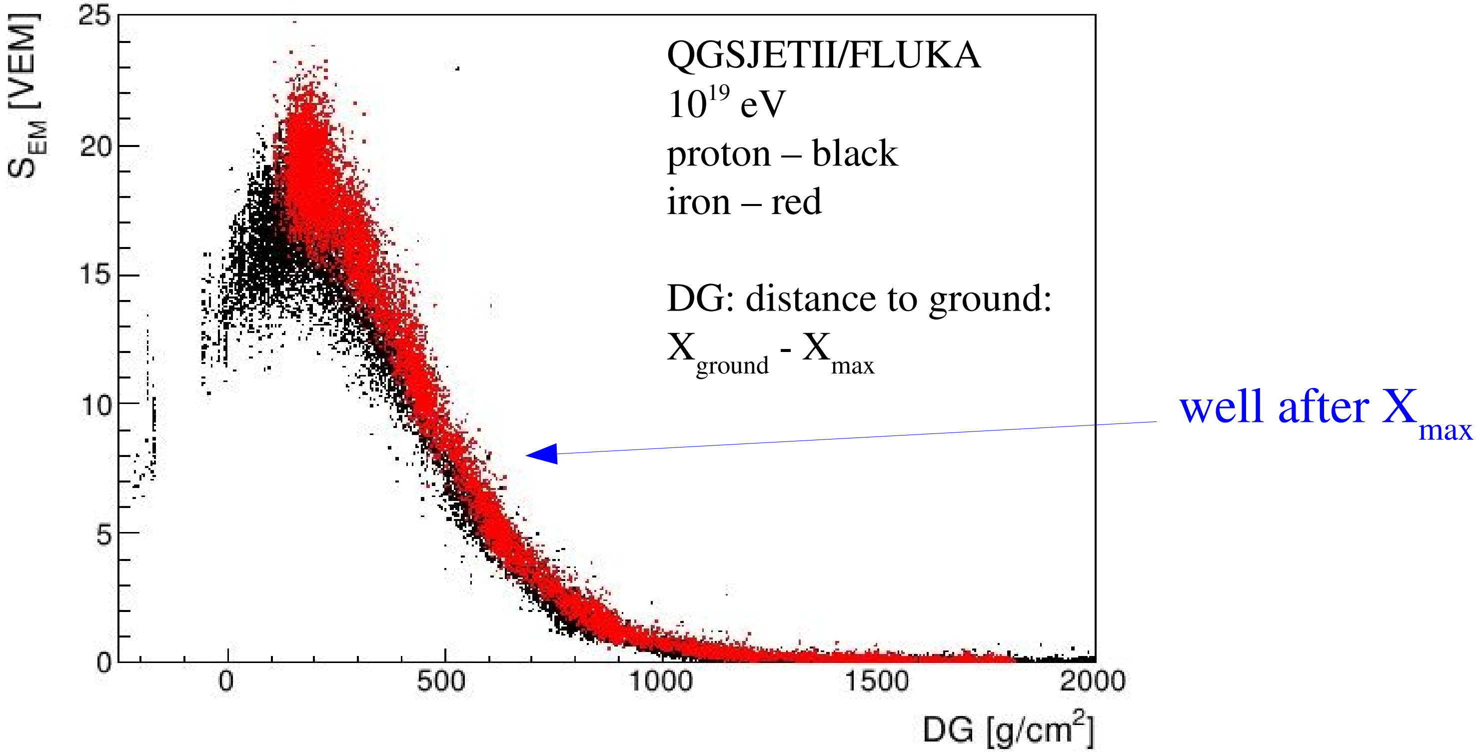
High-energy events look hadronic between p-Fe.

Shower muons are tracers of high-energy hadron interactions: secondary particle production.

The Auger ground array (of water Cherenkov detectors) is sensitive also to muons.

Aim: disentangle muon component

- **measured S(1000) = S_{em} + S_{mu}**
- simulations: after X_{max}, EM component behaves **"universal"**, i.e. little dependence on composition (~13%) and model (~5%)



➔ subtract S_{em} to obtain S_{mu} which can be compared to simulations

➔ *here: 2 independent ways to subtract S_{em}*

Shower muons using hybrids

- FD => E_{FD}, X_{max} => calculate ground signal S_{em}

→ S_{mu} exceeds by factor 1.92 ± 0.08 QGSJETII proton simulations (at ~10 EeV)

Shower muons using hybrids

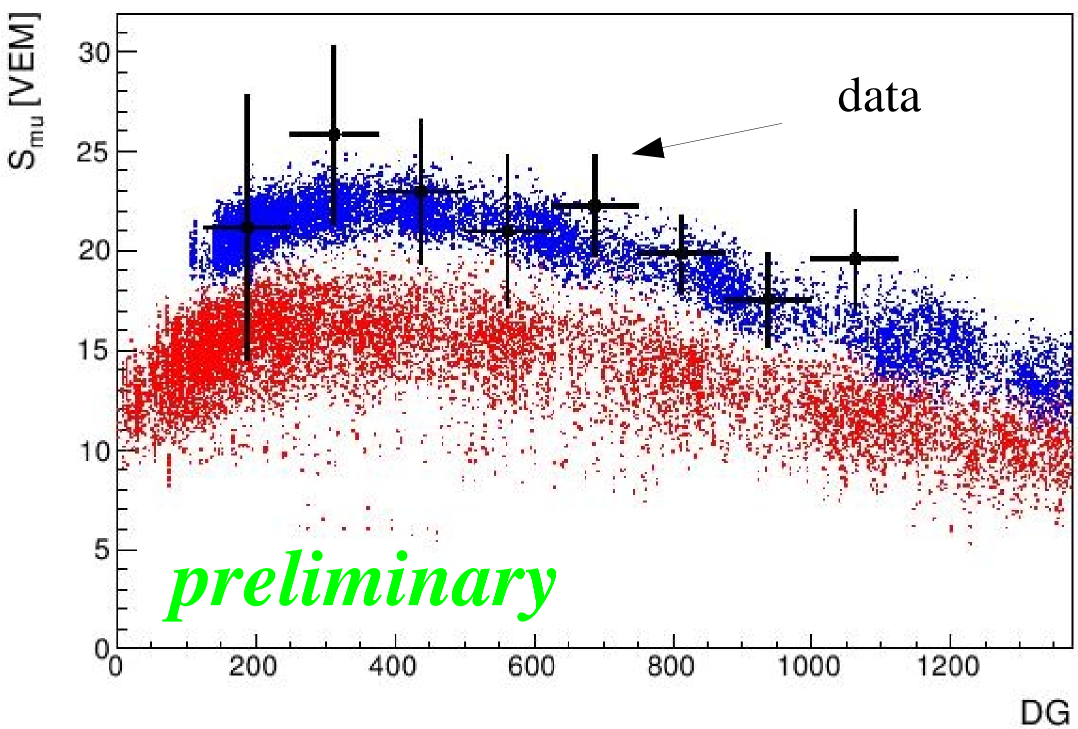
- FD => E_{FD}, X_{max} => calculate ground signal S_{em}

➔ S_{mu} exceeds by factor 1.92 ± 0.08 QGSJETII proton simulations (at ~10 EeV)

- caveat: ~24% systematics in E_{FD} (~15% from fluor. yield)

➔ **factor 1.55 ± 0.06** for shifted energy scale $E = 1.28\ E_{FD}$ (see plot)

➔ composition >Fe contradicts X_{max} data => too few muons in simulations ?



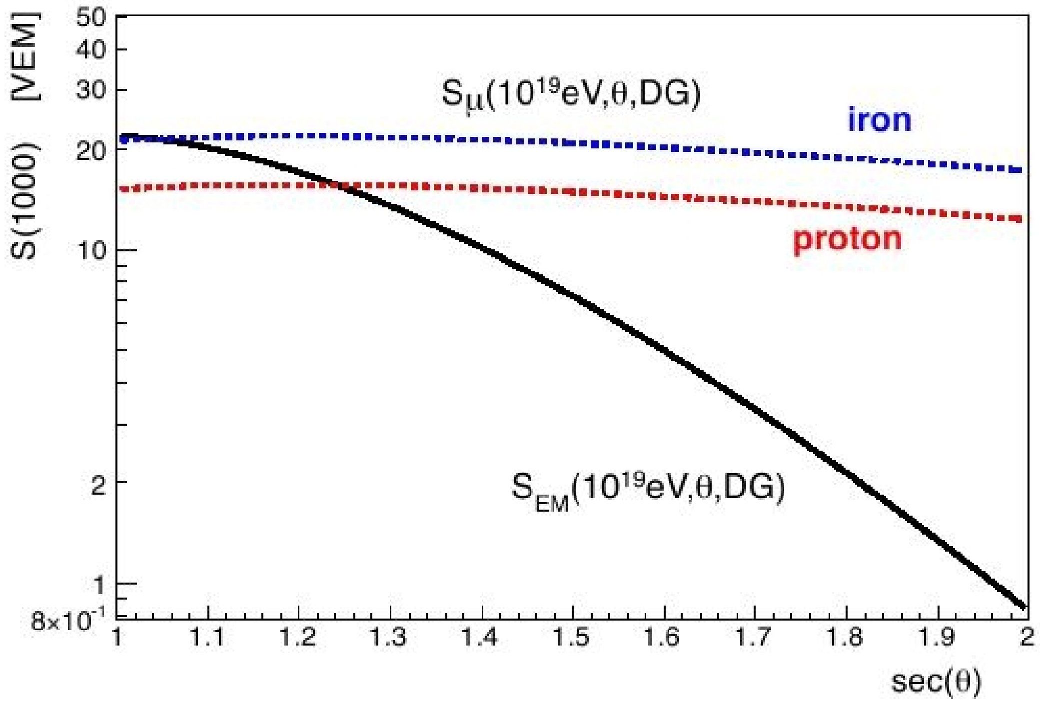
QGSJETII/FLUKA
proton – red
iron – blue

DG: distance to ground:
$X_{ground} - X_{max}$

energy scale $E = 1.28\ E_{FD}$

Shower muons using the array alone

- EM component is absorbed faster => ratio S_{mu}/S_{EM} changes with zenith
  - moreover, shapes of muon curves are similar for p-Fe; normalisation differs



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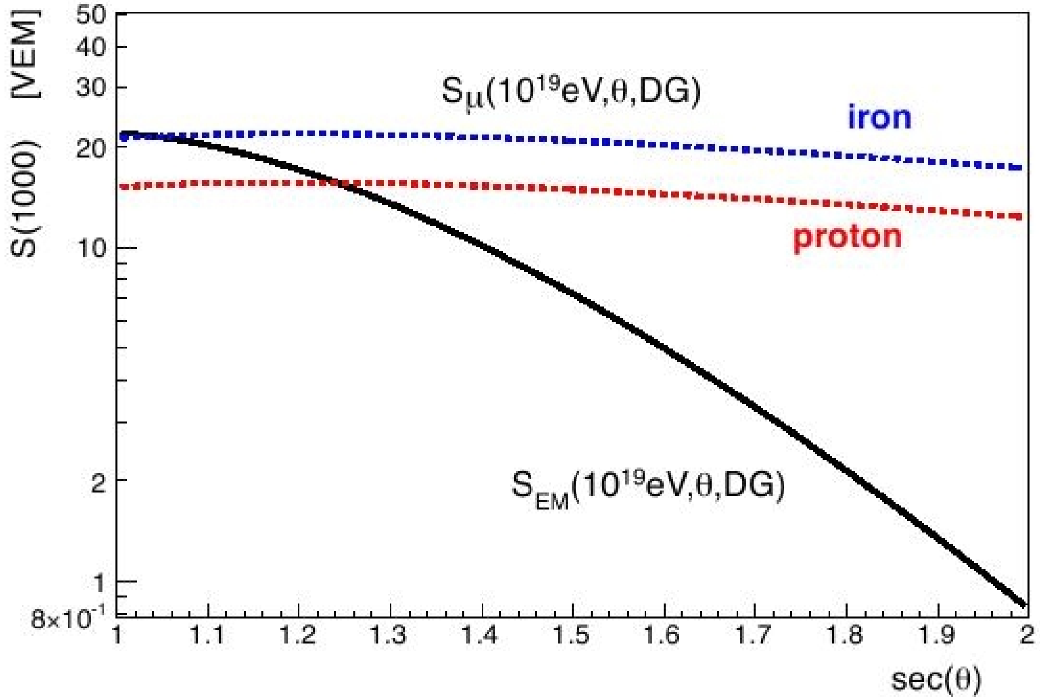
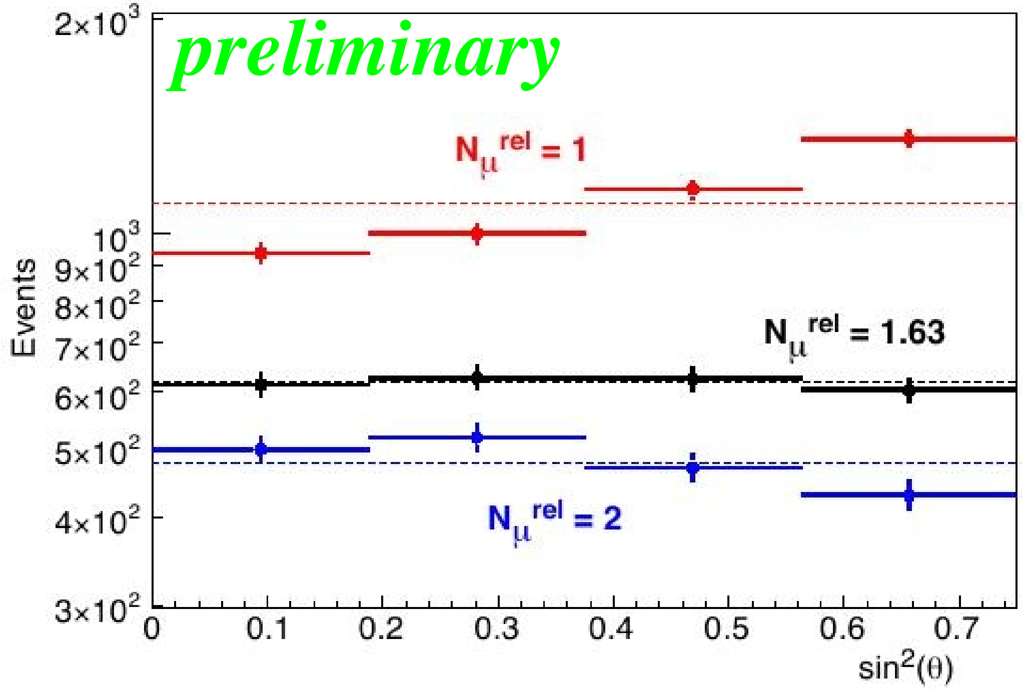


- isotropic flux => number of events (above minimum E) vs $\sin^2(\theta)$ should be flat
- S_{MC} <-> E from MC: if wrong, not flat! $$\left.\frac{dN_{\rm ev}}{d\sin^2\theta}\right|_{S(1000)>S_{\rm MC}(E,\theta,\langle X_{\rm max}\rangle,N_\mu^{\rm rel})} = \text{const.}$$
- to make distribution flat, adjust muon normalisation

Shower muons using the array alone

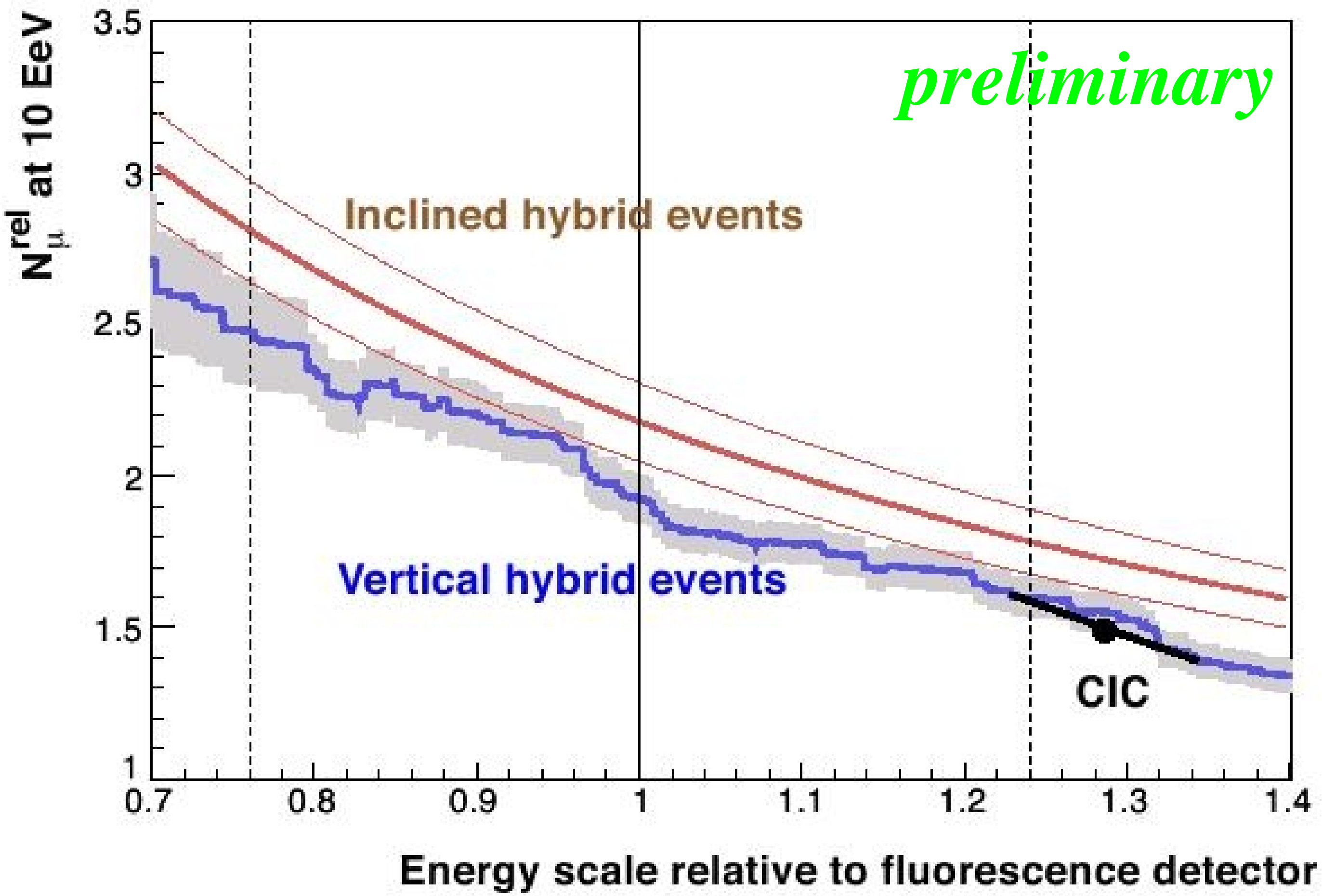
- adjust muon normalisation such that distribution gets flat => factor ~1.63
  - measured <Xmax> used as input => correction from fluctuations

→ **factor 1.5 ± 0.1**



→ note: then, array energy scale E ~ 1.28 E_{FD} (allowed within systematics!)

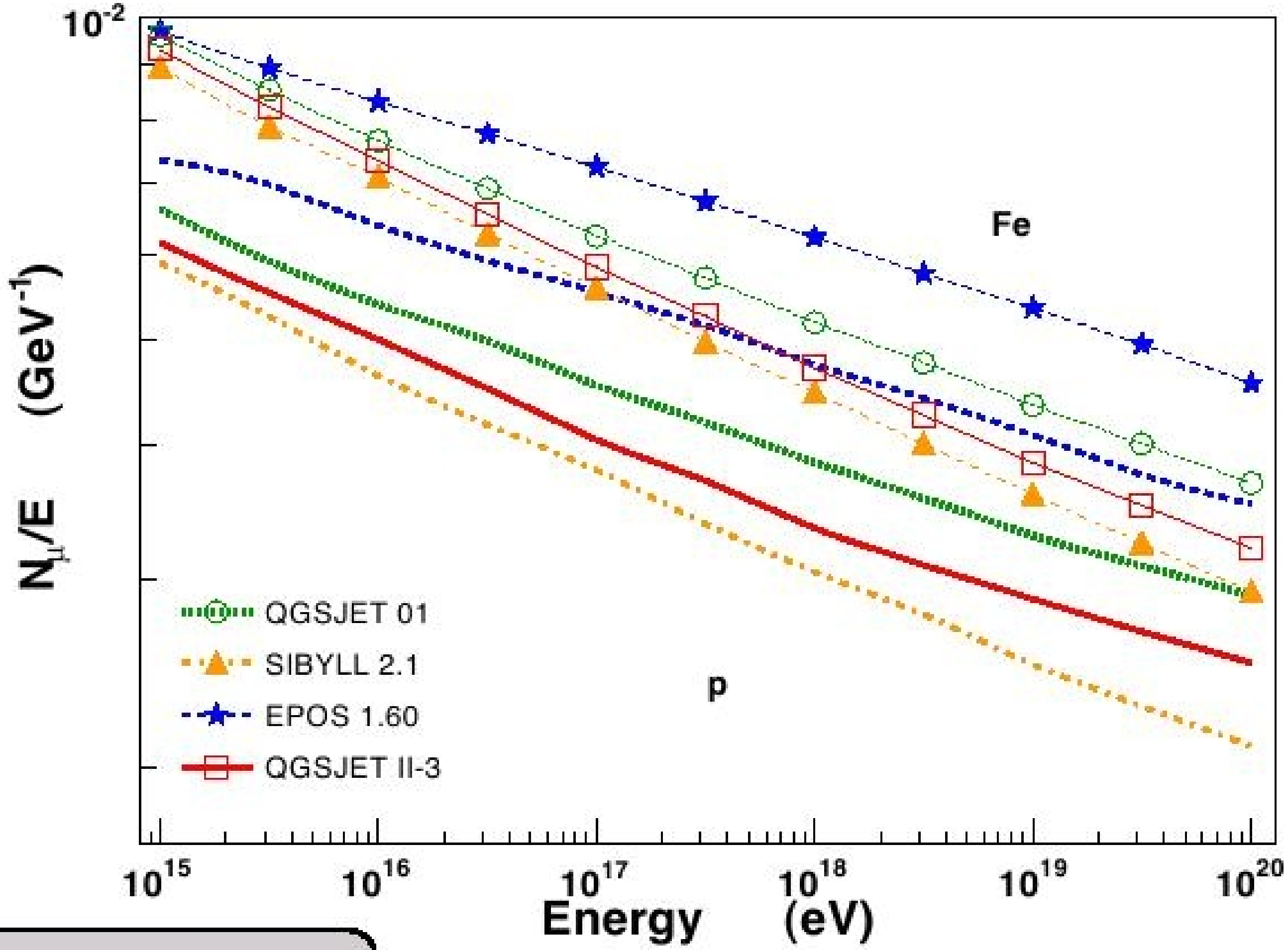
Shower muons: summary



- consistent description of data possible for E ~ 1.28 E_{FD}
- factor ~1.5 more muons compared to QGSJETII-protons (at 10 EeV)
- **more muons in simulations** might give also consistent description of <X_{max}>

EPOS and number of muons

surprise!
EPOS:
+ ~30%



Iron (QGSJET) = proton (EPOS)

(at 10^{18} eV)

from Engel (Aspen 2007); see also Pierog & Werner 2006

EPOS: more baryon-antibaryon production; more re-interaction -> more muons.
Confirmed by artificial increase of b-ab production in SIBYLL.

Prospects

- more data (helps also to reduce systematics)
- X_{max} fluctuation analysis (fluctuations less model dependent?)
- methods of direct muon counting (muons: early, larger signal)

➔ ***consistent description of data – the challenge for models***

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- if source identification such that protons seem most likely primary (because higher Z particles were deflected larger)

➔ compare measured proton shower features to proton simulations

➔ ***"top-down" calibration of models***

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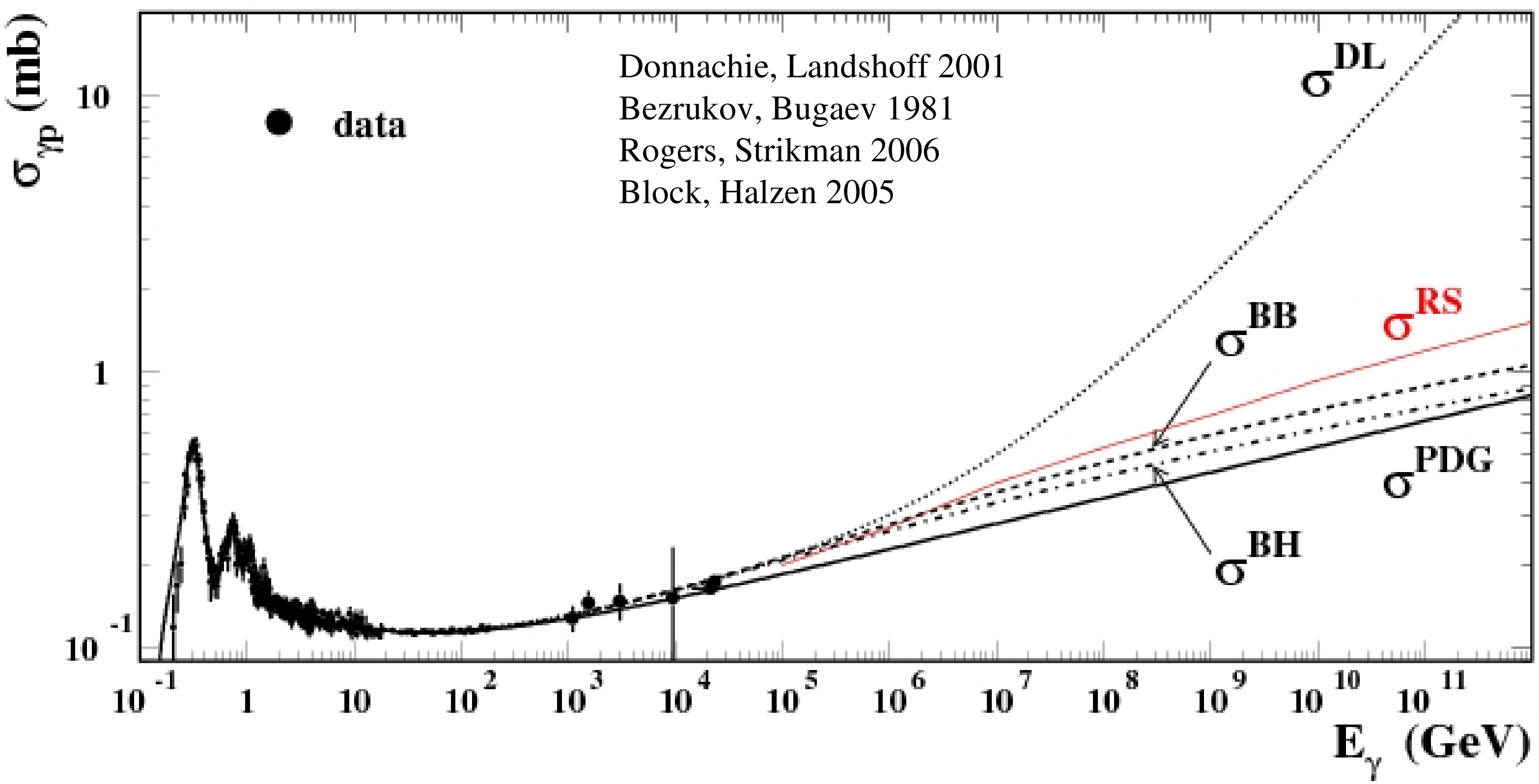
→ compare measured proton shower features to proton simulations

→ ***"top-down" calibration of models***

- if photon observation => handle on photonuclear cross-section

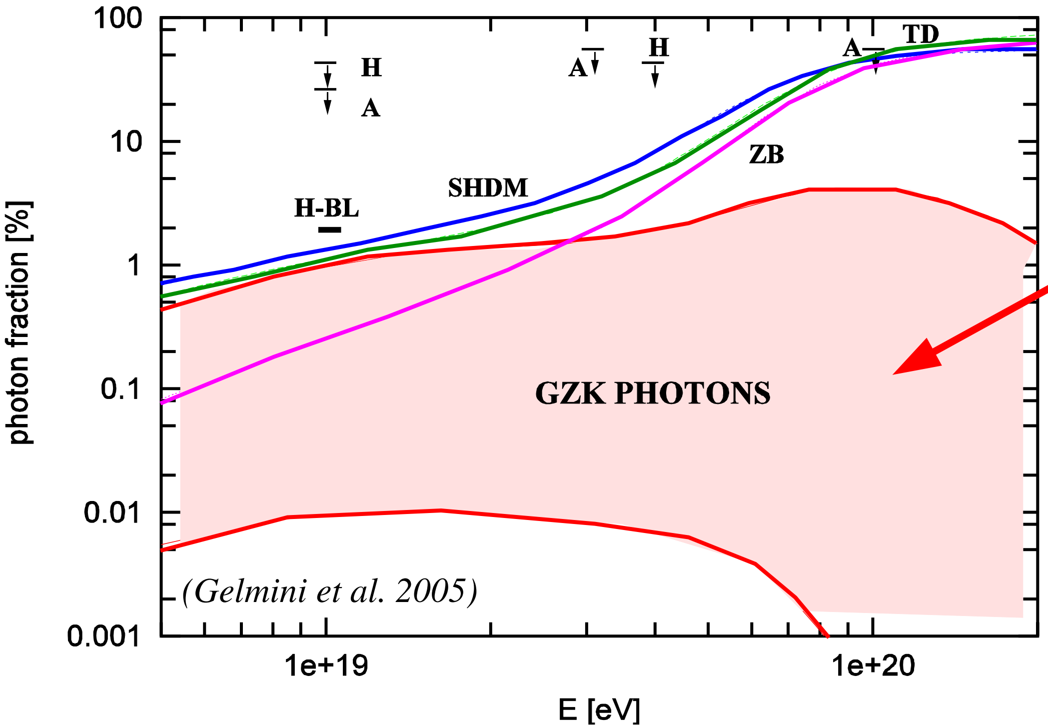
Prospects

- σ^{DL} theoretically disfavored (=> σ^{RS}!) *(Roger & Strikman 2006)*
- σ^{DL} => factor ~1.8 more muons and 30...>100 g/cm^2 smaller X_{max} compared to σ^{PDG} *(MR et al. 2005)*
- if photon observation "as expected" => upper limit to cross-section



Photons in acceleration models: GZK photons

- $N\gamma_{2.7}$ –> Δ –> $N\pi$ –> **UHE (“GZK“) photons** (and neutrinos)



shaded region: source and propagation parameters varied

further calculations (Gelmini et al. 2007, Sigl 2007) give 0.01–0.1% above 10 EeV

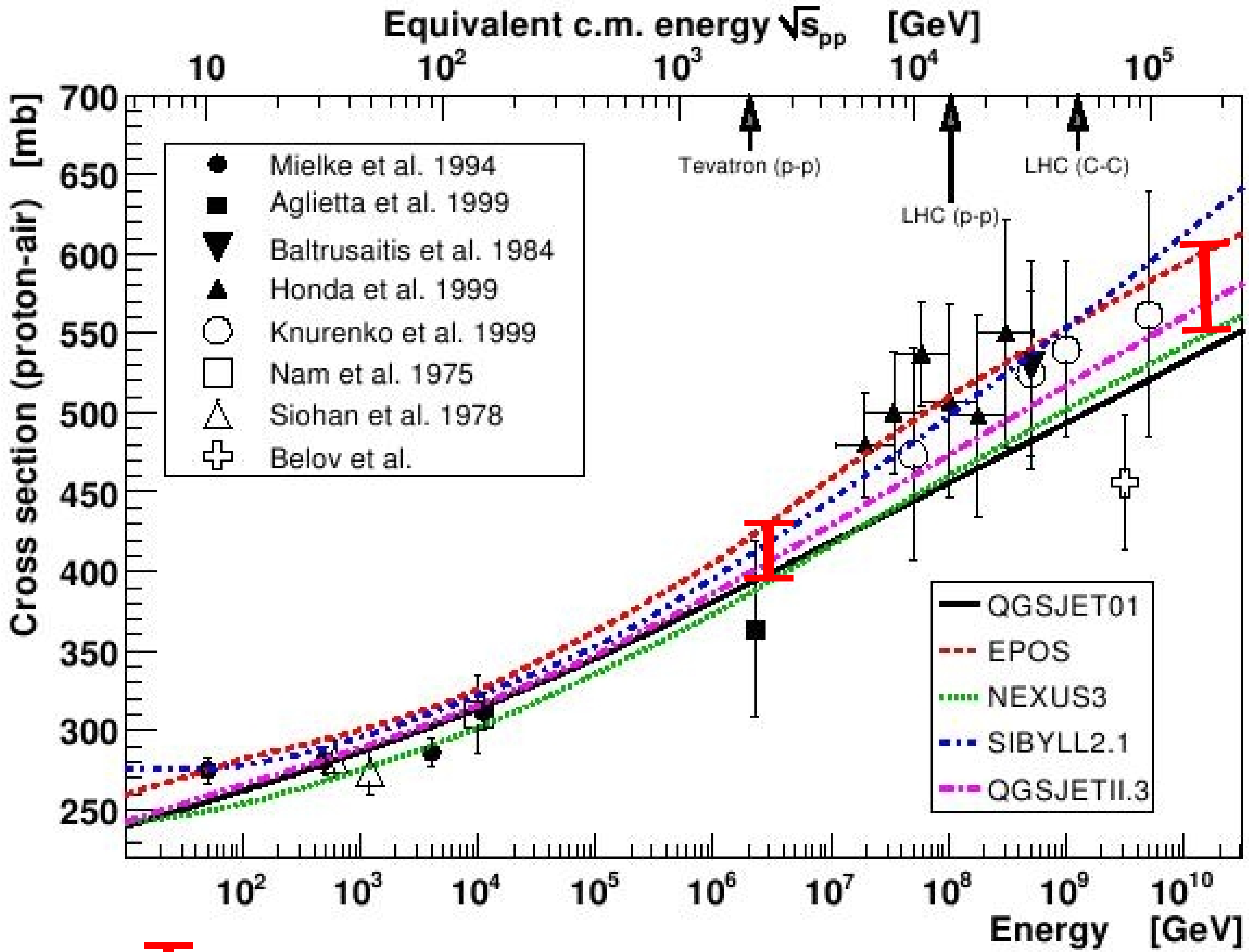
- **benchmark: 0.1%**

➔ photons/year (>10 EeV): **~2 (Auger South), ~10 (North plus South)**

Auger Observatory & QCD: conclusions

- **search for photons**
  - upper limits constrain top-down models (unfortunately no SUSY-QCD seen)
  - photon observations could constrain photonuclear cross-section
- **$<X_{max}>$ vs energy**
  - shower look hadronic (between proton and iron)
  - seems no “exotic“ inelastic cross-section and elasticity
- **shower muons**
  - there seems to be a muon deficit in the simulations at high energy
- **prospects**
  - this is just the beginning ...

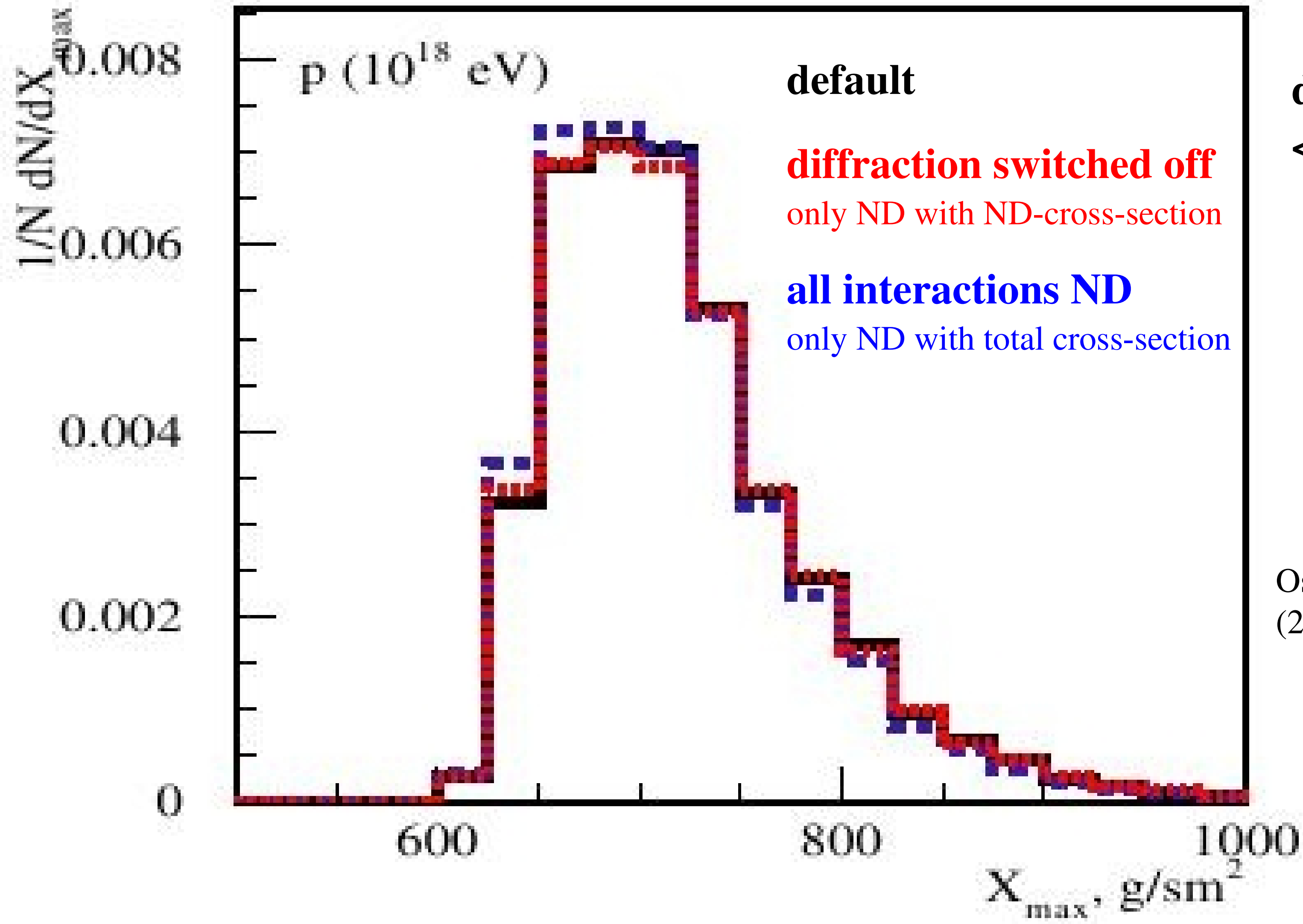
Models vs shower data: cross-section



I indicates 10% difference

(Ulrich, Aspen 2007)

Sensitivity study: which cross-section?

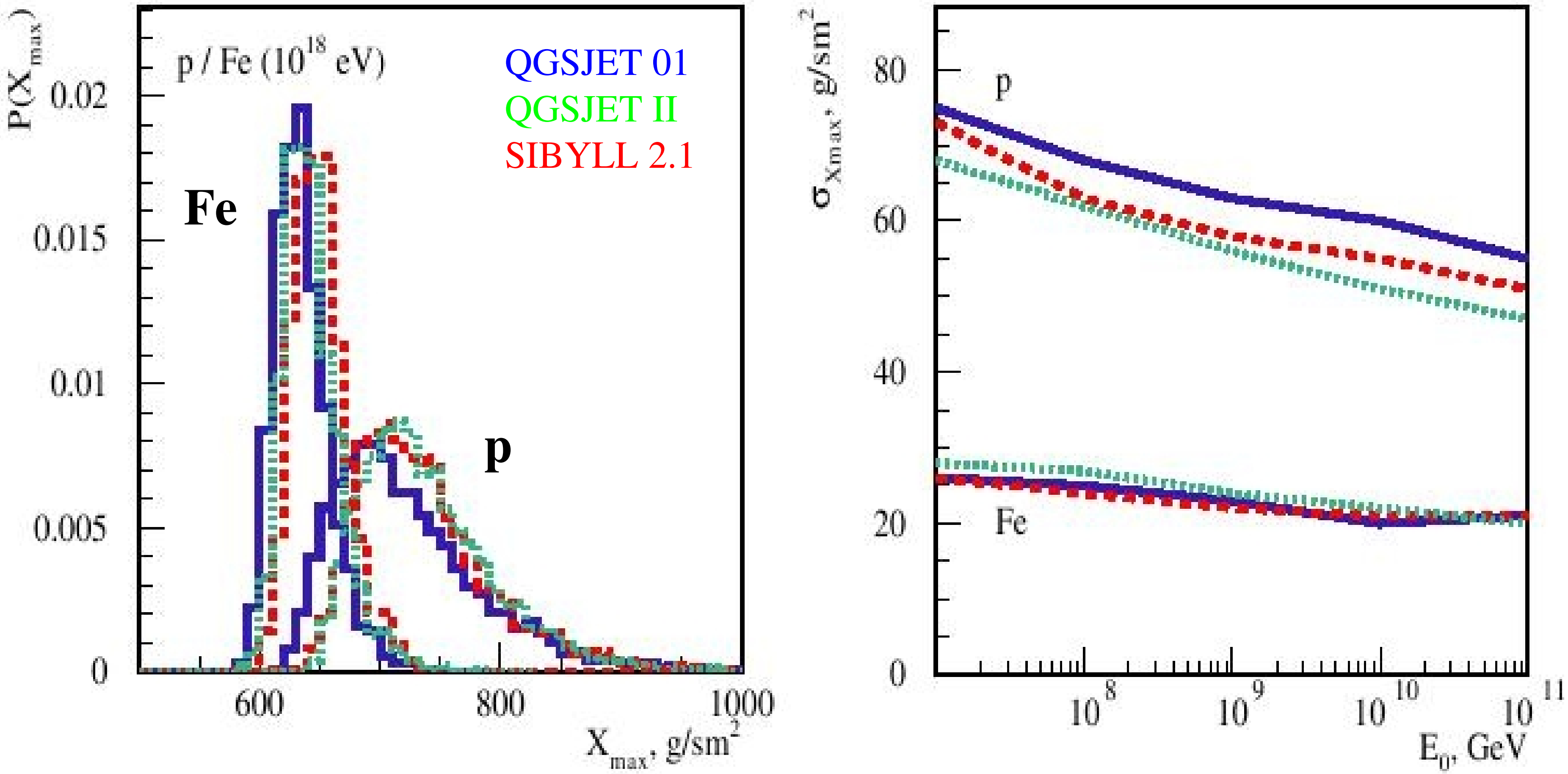


diffraction
<-> $k_{inel} < 0.1$

Ostapchenko (2007)

- sensitivity to non-diffractive (ND) part of inelastic cross-section
  - see also KASCADE Collab. 2001: trigger vs hadron rates

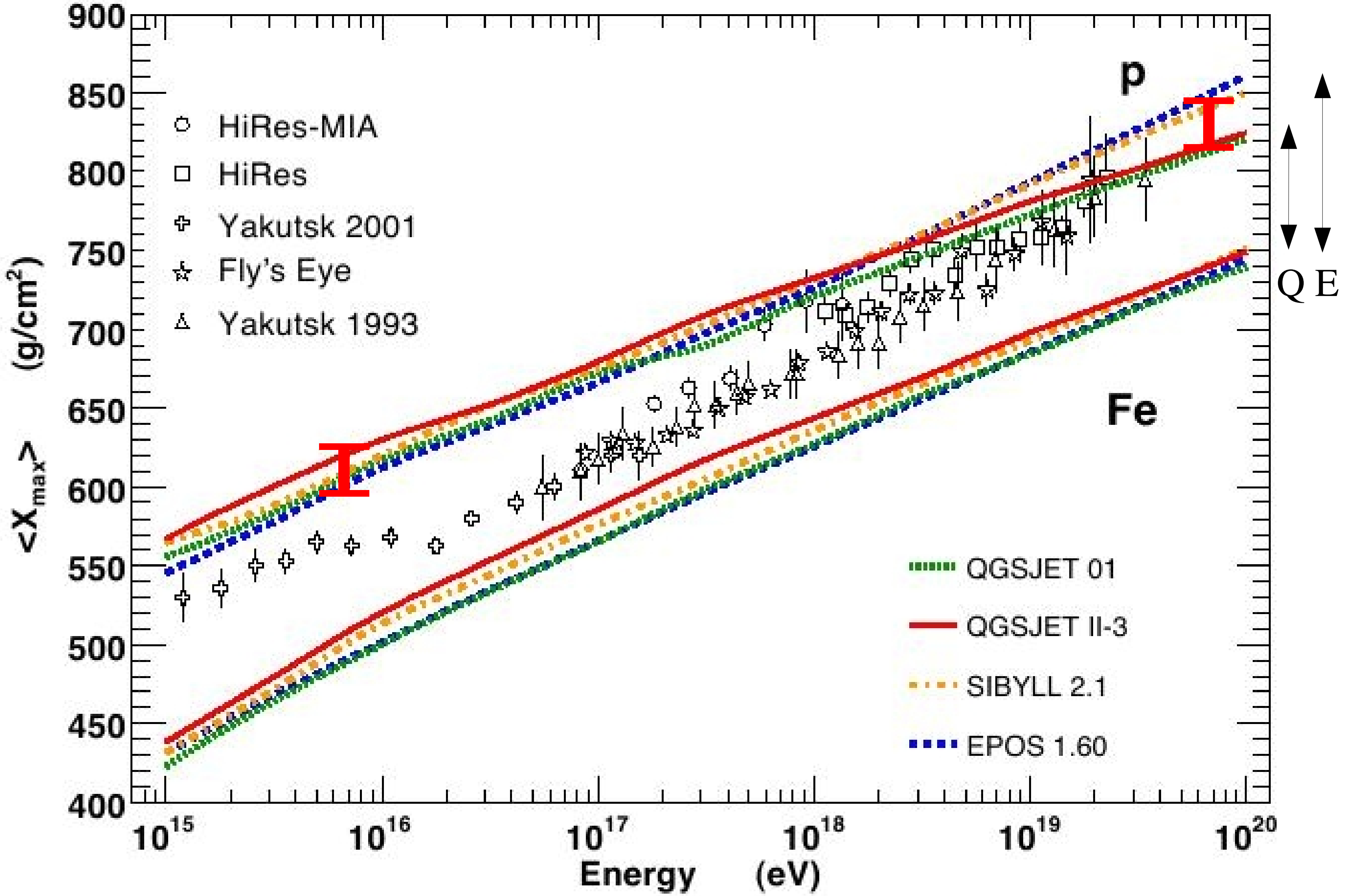
X_{max} and fluctuations



Ostapchenko (2007)

- width of X_{max} distribution is
  - good indicator of composition
  - less model dependent!

Models vs shower data: X_{max}



indicates 30 g cm^{-2} difference

from [1]

Prospects (3): Auger South vs North

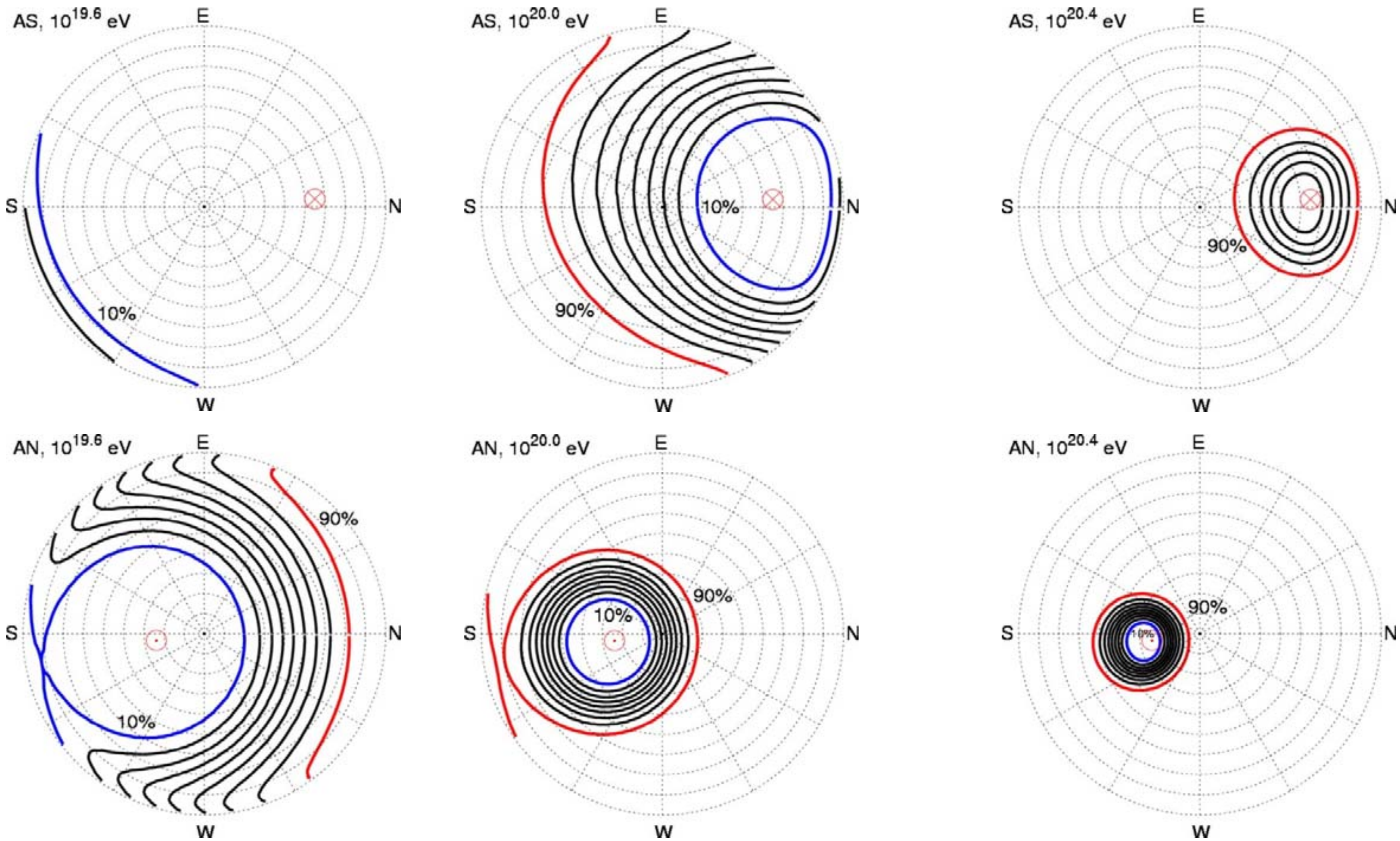
Homola et al.
astro-ph/0608101

probability for preshower from UHE photons at ...

40 EeV **100 EeV** **250 EeV**

Auger South

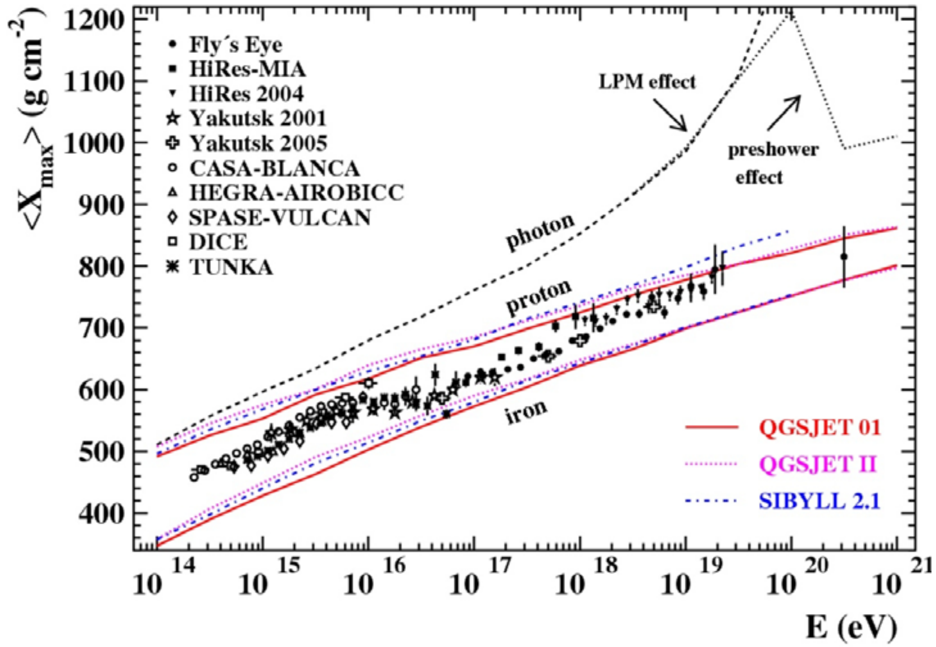
Auger North

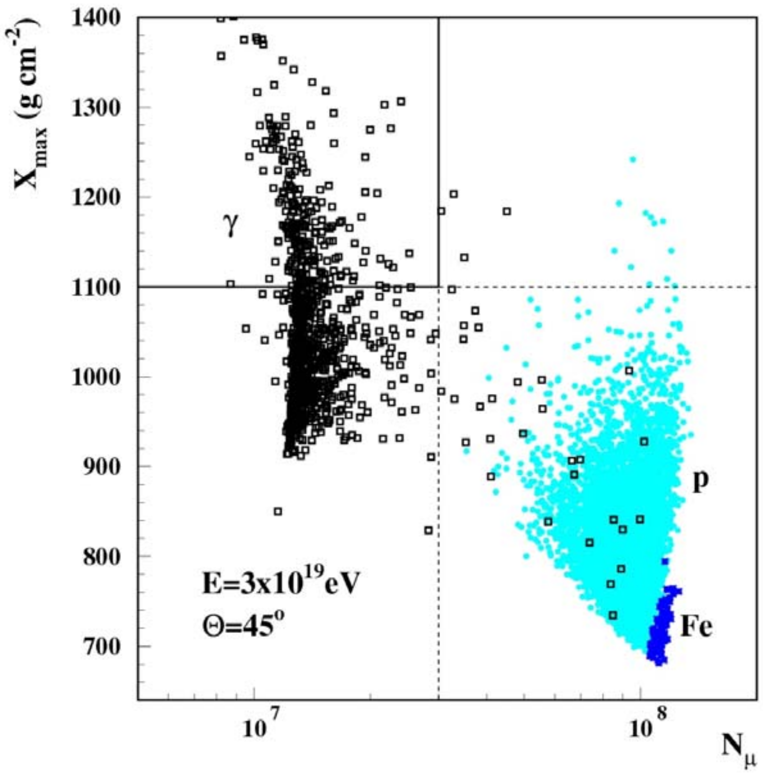


preshower at North ...

"starts" at smaller energy	**shift of sky pattern**	**"ends" at higher energy**
(factor 2 stronger field)	(different field direction)	(field line less curved)

Plots





MR & Homola 2007

X_{max} uncertainty

- here: conservative estimate used for all 29 selected events

Auger Collab.

Astropart. Phys. 2007

Data	ΔX_{max}^{stat} [g cm^{-2}]	ΔX_{max}^{syst} [g cm^{-2}]
Profile fit	20	10
Atmosphere	12	8
Geometry reconstruction	10	5
Others	10	5
Simulation		
Reconstructed energy of event	5	13
Photo-nuclear cross-section	-	10
Hadron generator	-	5
Total	28	23

energy *(input for photon simulation):* ***~25% syst. unc.***

a big advantage of this analysis!

→ well below photon shower fluctuations (~80 g cm^{-2})

→ analysis **not limited by measurement uncertainty**

Statistical treatment

- account for events statistics, shower fluctuations and shower properties changing with primary energy and arrival direction *(-> MR et al., PRL 2005)*

- chance probability for hypothetical F_γ to get χ^2 values ≥ than found in data:

$$P(F_\gamma) = \sum_{n_\gamma=0}^{n_\mathrm{m}} q(F_\gamma, n_\gamma, n_\mathrm{m}) \cdot p_\gamma(n_\gamma) \cdot p_{\overline{\gamma}}(n_\mathrm{m} - n_\gamma)$$

probability that ...

... data set contains n_γ photons

... n_γ "photons" yield χ^2 values ≥ than in data

... n_γ-n_m "non-photons" yield χ^2 values ≥ than in data

$$q(F_\gamma, n_\gamma, n_\mathrm{m}) = F_\gamma^{n_\gamma}(1 - F_\gamma)^{n_\mathrm{m}-n_\gamma}\binom{n_\mathrm{m}}{n_\gamma}$$

$$\chi_j^2 = \frac{(X_\mathrm{max}^j - < X_\mathrm{max}^{j,\mathrm{s}} >)^2}{(\Delta X_\mathrm{max}^j)^2 + (\Delta X_\mathrm{max}^{j,\mathrm{s}})^2}$$

$p_{\overline{\gamma}}(n_\mathrm{m} - n_\gamma)$: are set to unity (no test on "non-photons")

$p_\gamma(n_\gamma)$: take n_γ most photon-like looking events => $\sum_{i=1}^{n_\gamma} \chi_{k_i}^2$ is minimal;
determine $p_\gamma(\chi^2 \geq \sum_{i=1}^{n_\gamma} \chi_{k_i}^2)$ with MC technique (non-Gaussian fluct.)

➔ **with confidence 1-P(F_γ), photon fractions ≥ F_γ/ε can be rejected**

ε=0.80: efficiency correction from photon acceptance (conservative: minimum ratio)