Photon air showers at highest energies and the photonuclear cross-section

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in collaboration with
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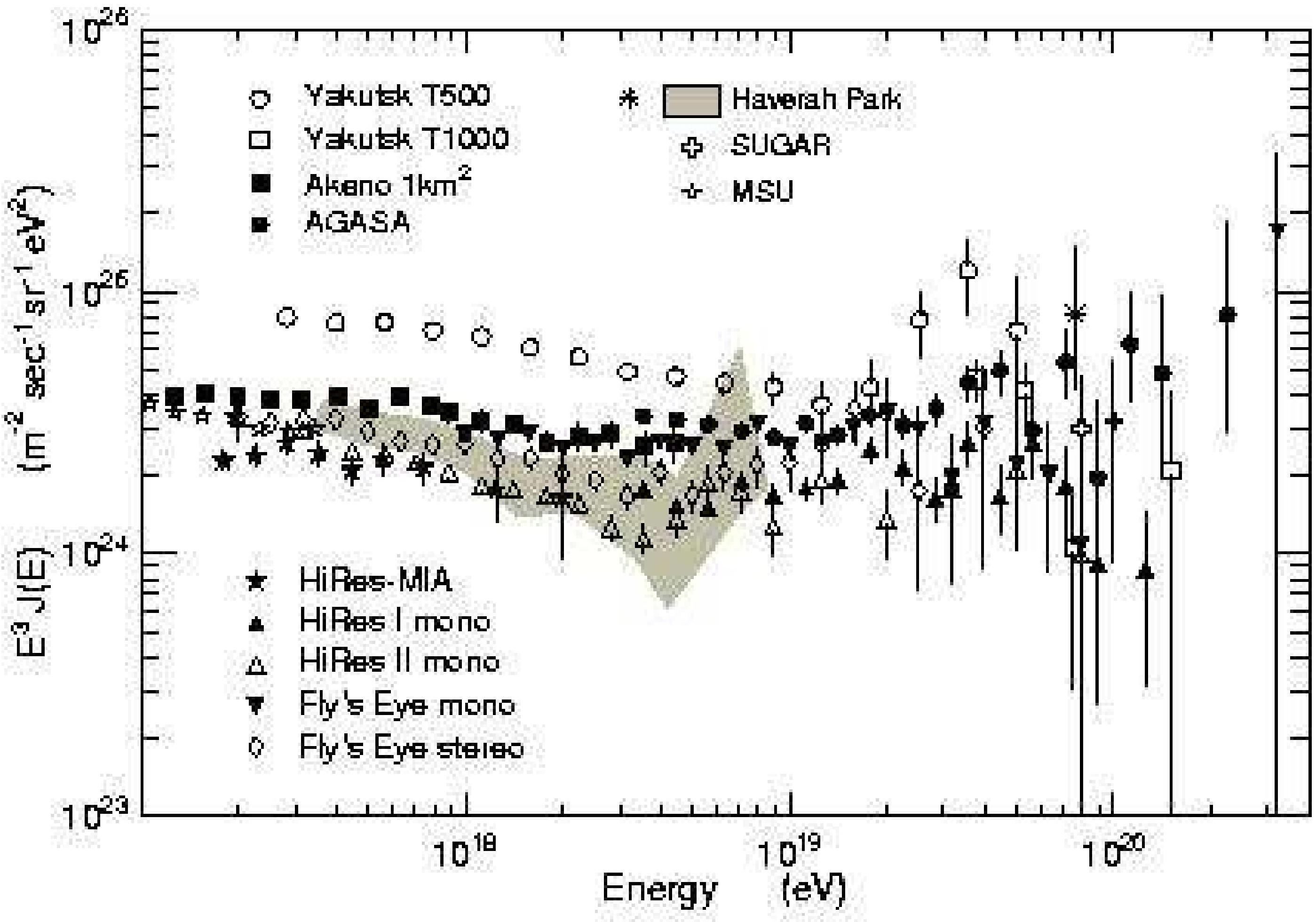
C2CR, Prague, September 2005

- **Why searching for photon primaries ?**
- **Features of photon-induced showers**
- **Shower data & photons: Upper limits**
- **Influence of & sensitivity to photonuclear cross-section**

Highest energies: CR spectrum

flux scaled by E^3 !



(Engel & Klages, 2004)

- There are events >100 EeV ! What are their sources??

Theoretical status

- **acceleration models (astrophysics):**
  - active galactic nuclei, gamma-ray bursts, jets in radio galaxies, pulsars, ...
  - ➔ not easy to accelerate particles to >100 EeV

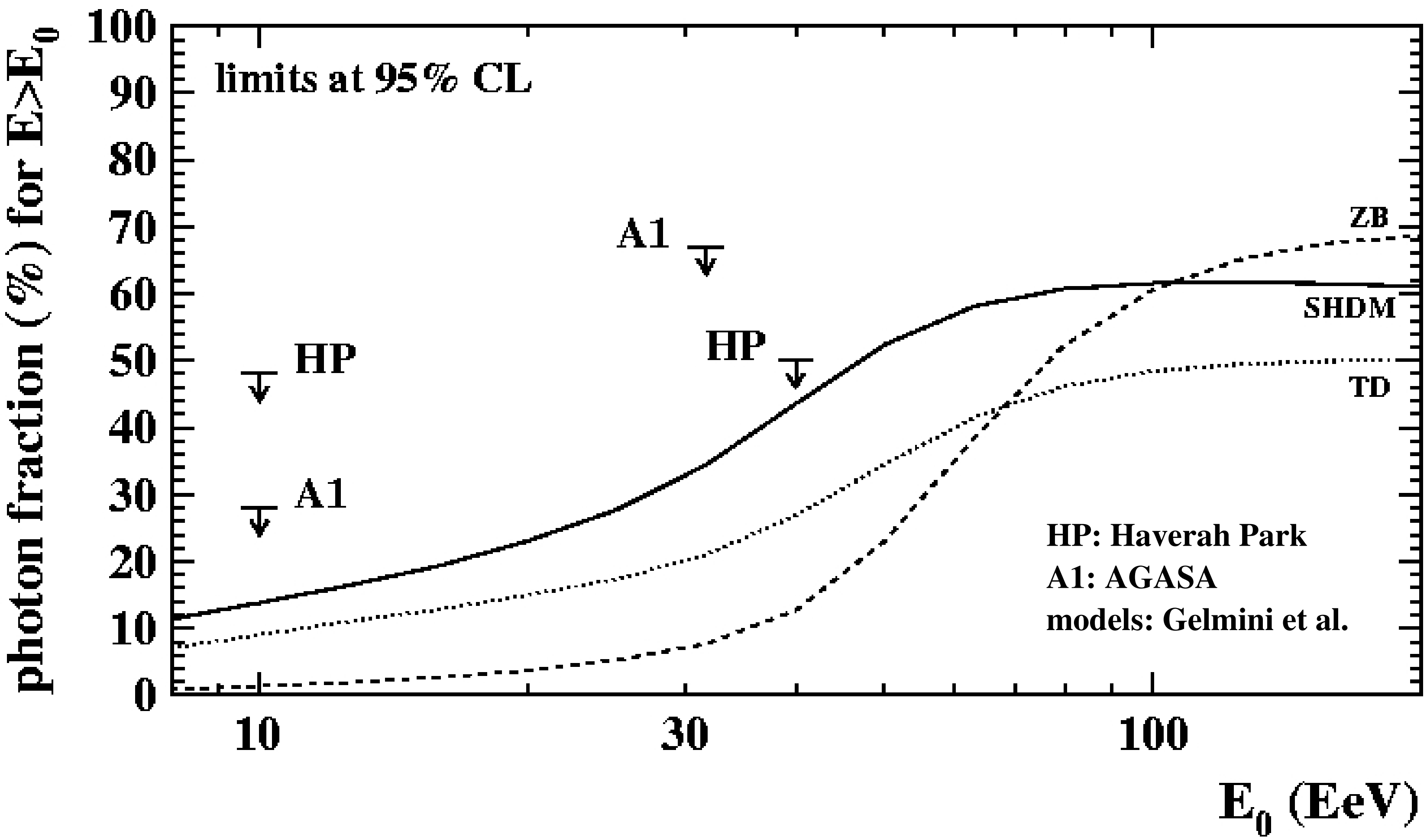
photon fractions < ~1%

- **non-acceleration models (particle physics):**
  - super-massive dark matter, monopoles, cosmic strings, necklaces, WIMPZILLAS, ...
  - ➔ hypothetical objects that produce normal particles

photon fractions > ~10%

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

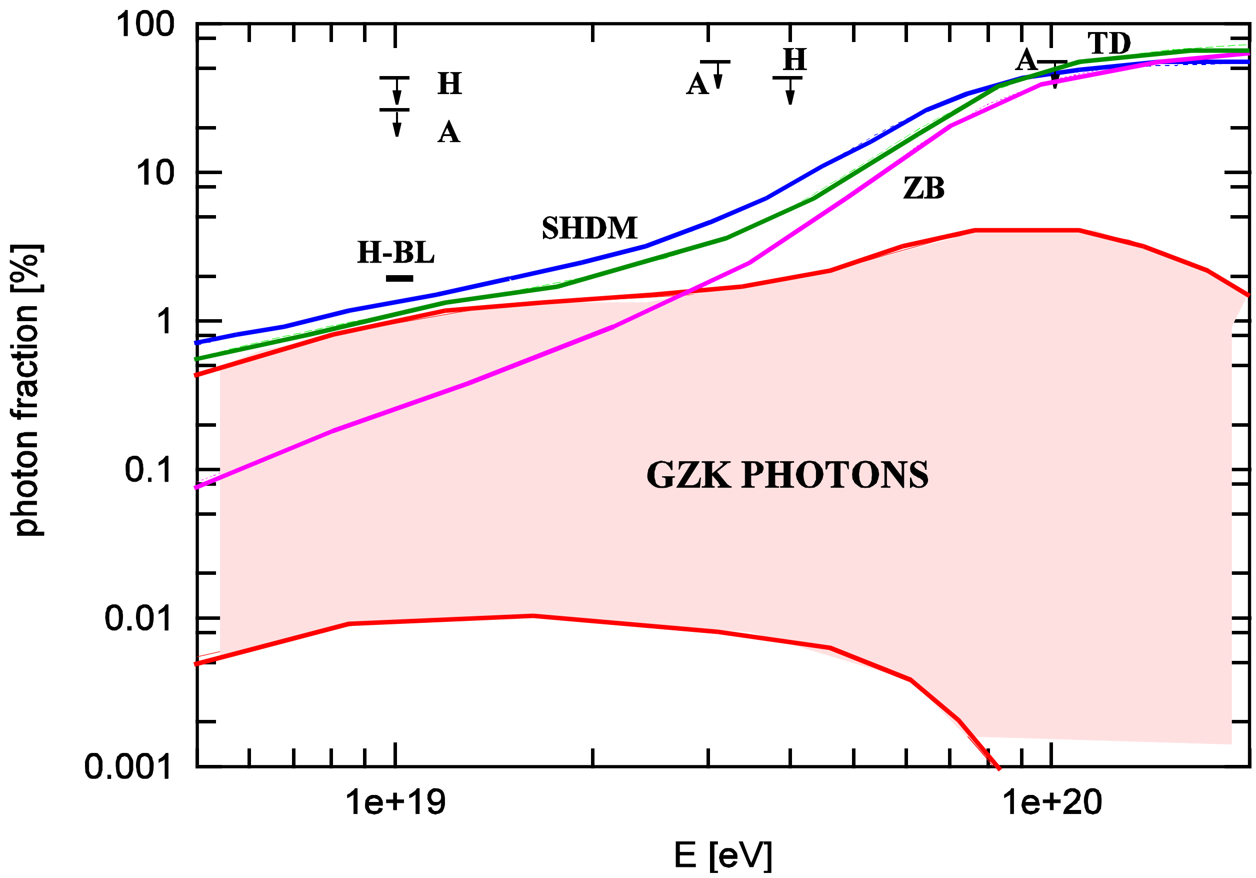
Non-acceleration models & photons



(2004)

- significant photon fractions predicted
- previous limits up to 40 EeV

Acceleration models & GZK photons



Based on HiRes spectrum
=> conservative;
much larger for AGASA !

Shaded region: variation of source and propagation parameters

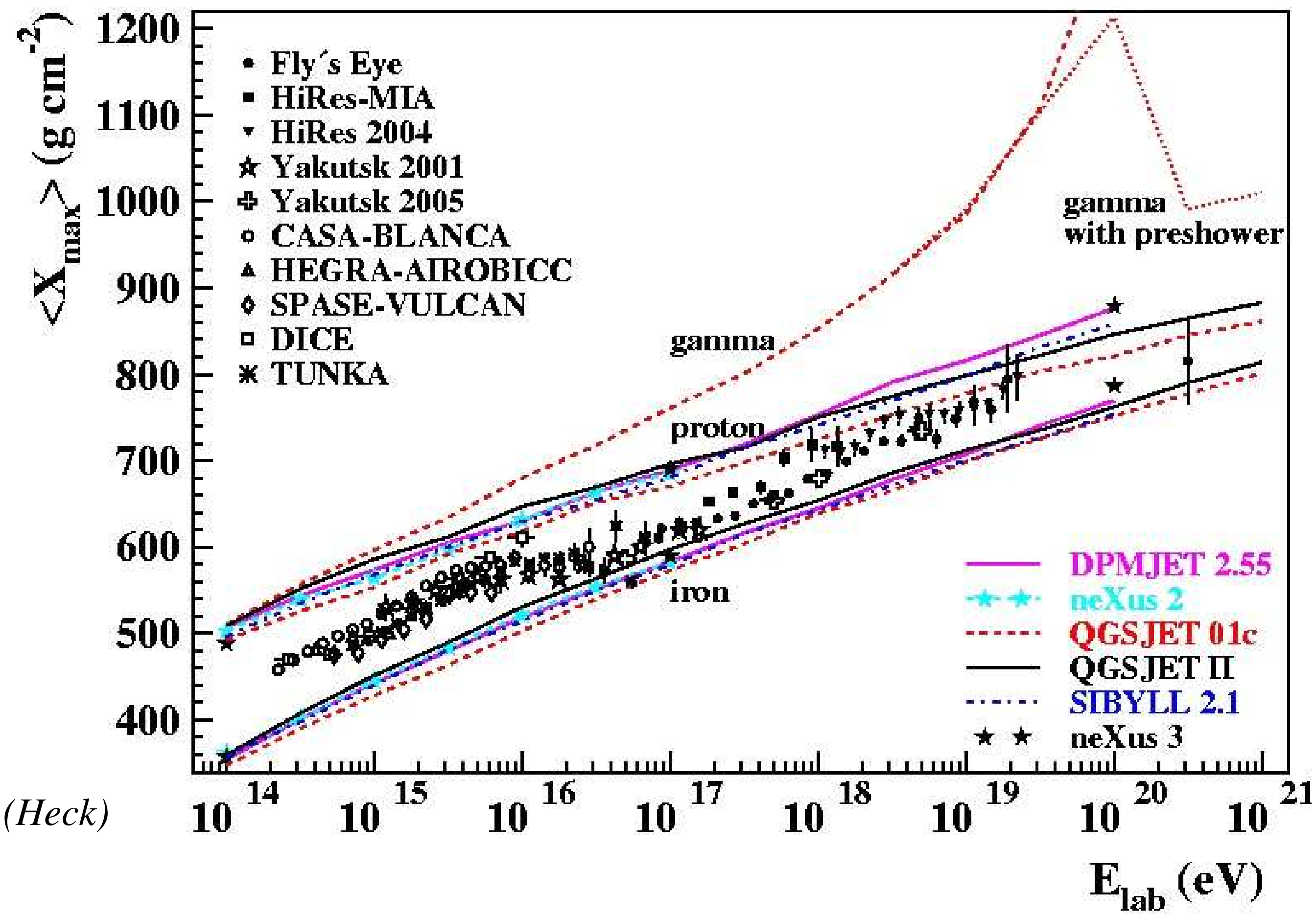
(Gelmini, Kalashev,Semikoz, astro-ph/0506128)

- **Auger N+S, photons/year: Up to ~60 (>10 EeV), ~2-3 (>100 EeV)**

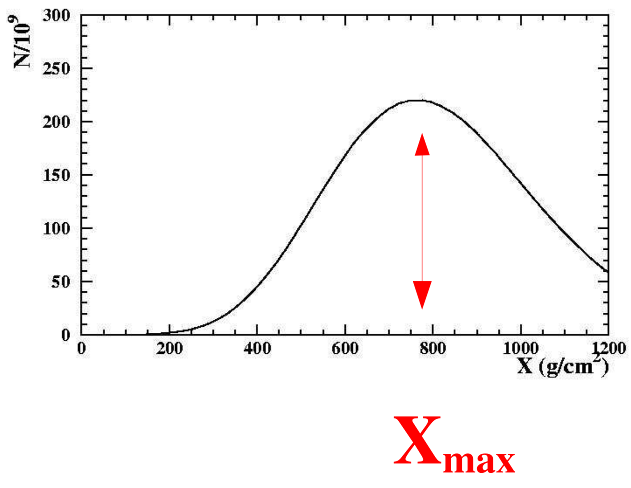
(absence of photons -> model constraints)

=> How to "identify" photon showers ?

Photon *vs* hadron: Fewer muons, deeper X_{max}

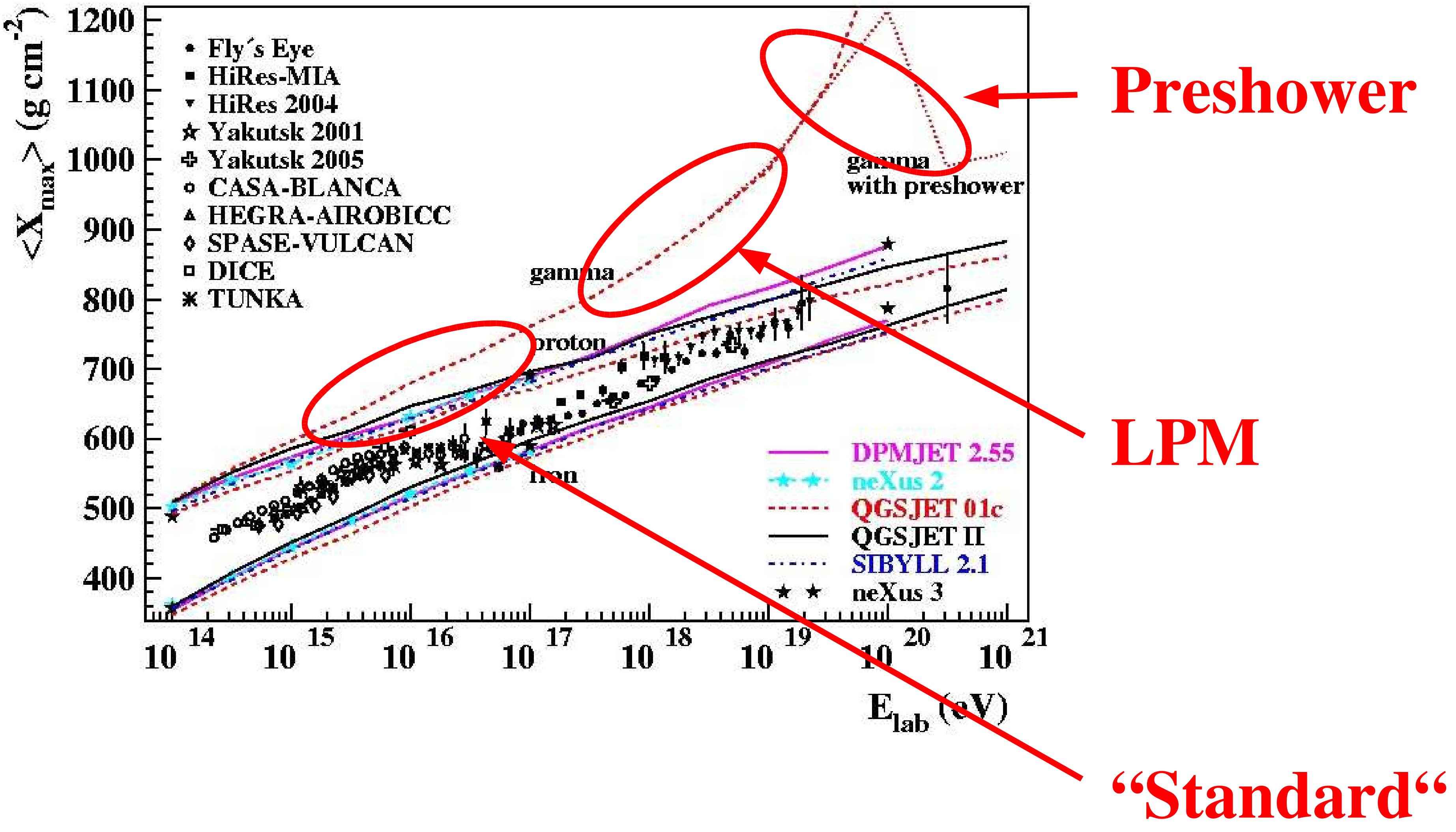


(Heck)



- At 10^{19} eV: $\Delta<X_{max}>$ (photon, hadron) > 200 g cm^{-2}
- **Elongation rate**: ΔX_{max} / per energy decade is changing !?

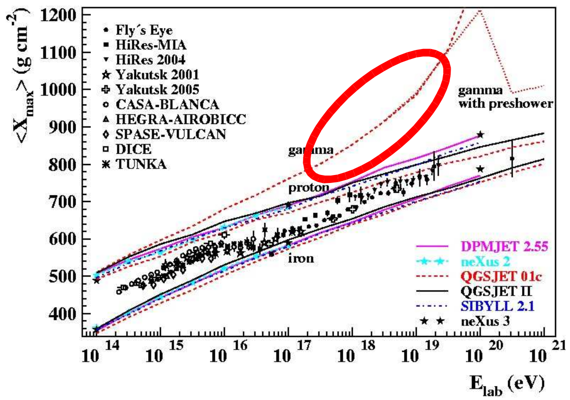
Photon shower: High-energy effects



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

(-> Toy model: Equal energy splitting and λ_{rad})

Photon shower: LPM effect



- Landau, Pomeranchuk (1953), Migdal (1956)
- Matter effect: Interference when formation length becomes macroscopic

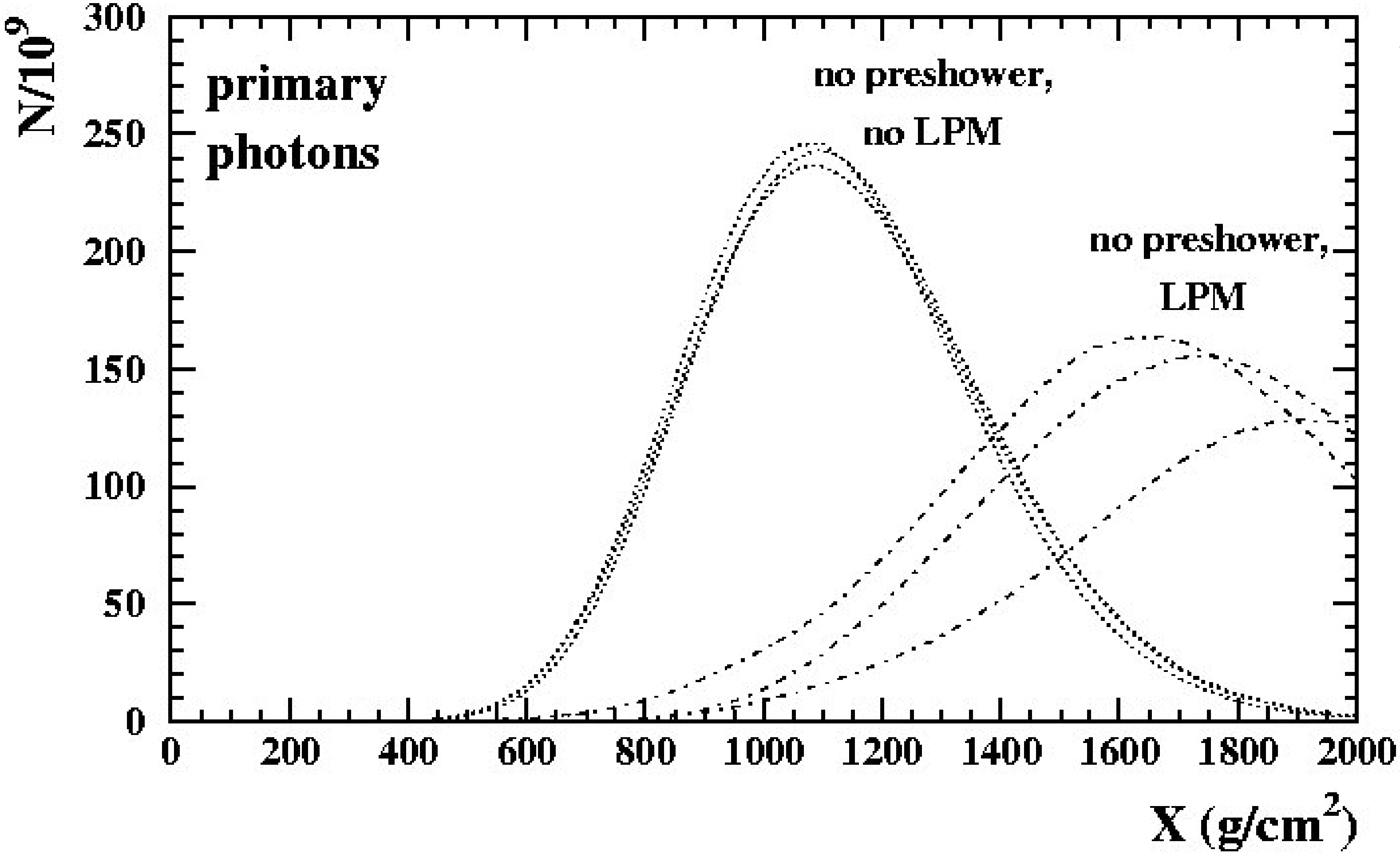
- Pair production and bremsstrahlung **cross-sections** reduced **~1/sqrt(ρE)** (in h.e. limit)
- **Asymmetric energy distribution** favoured

➔ Effect increases with **air density** and **particle energy**

  ➔ If photon survives the first 50 g cm^{-2}, then larger probability to survive the next 50 g cm^{-2} etc.

➔ *Influence on air showers ...*

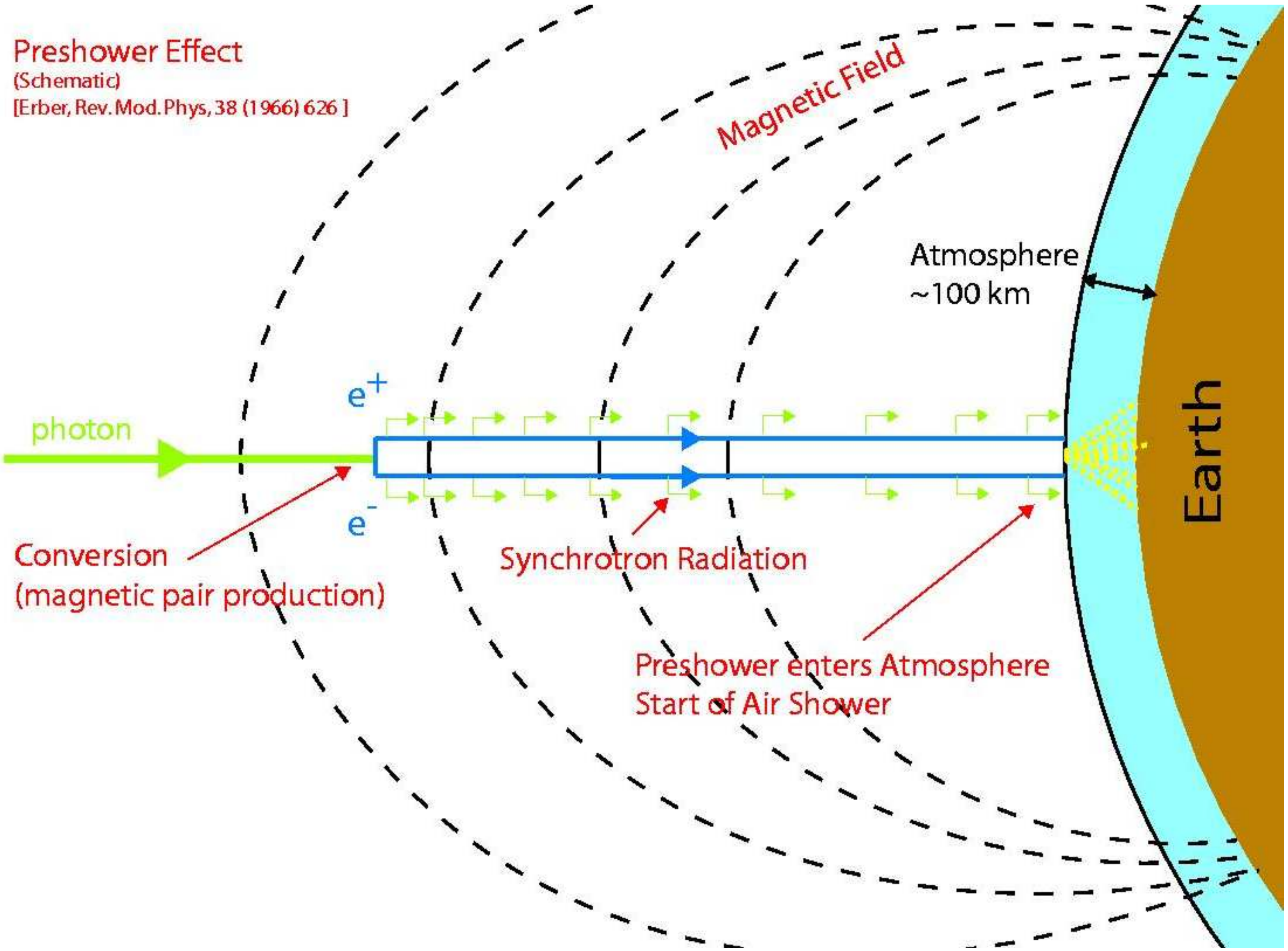
Photon shower: LPM effect



320 EeV photons (Fly's Eye event)

- Delayed shower development due to LPM !
- Large shower-to-shower fluctuations

Photon shower: Preshower effect

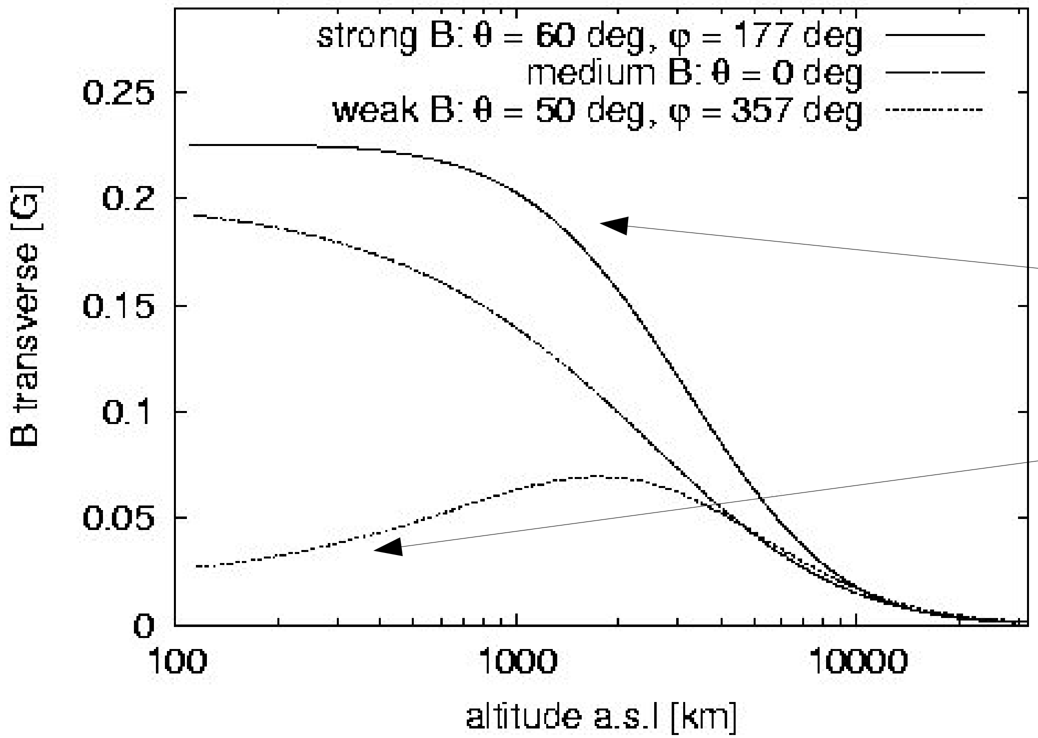


- Cascade in geomagnetic field before "normal" air shower

  -> PRESHOWER code: Homola et al., CPC, in press; astro-ph/0311442

Geomagnetic field

- Both conversion and synchr.emission = f($\mathbf{B_t}$, E_{part})
  - ➔ Precise field calculation required: **IGRF**



Example:
Auger South,

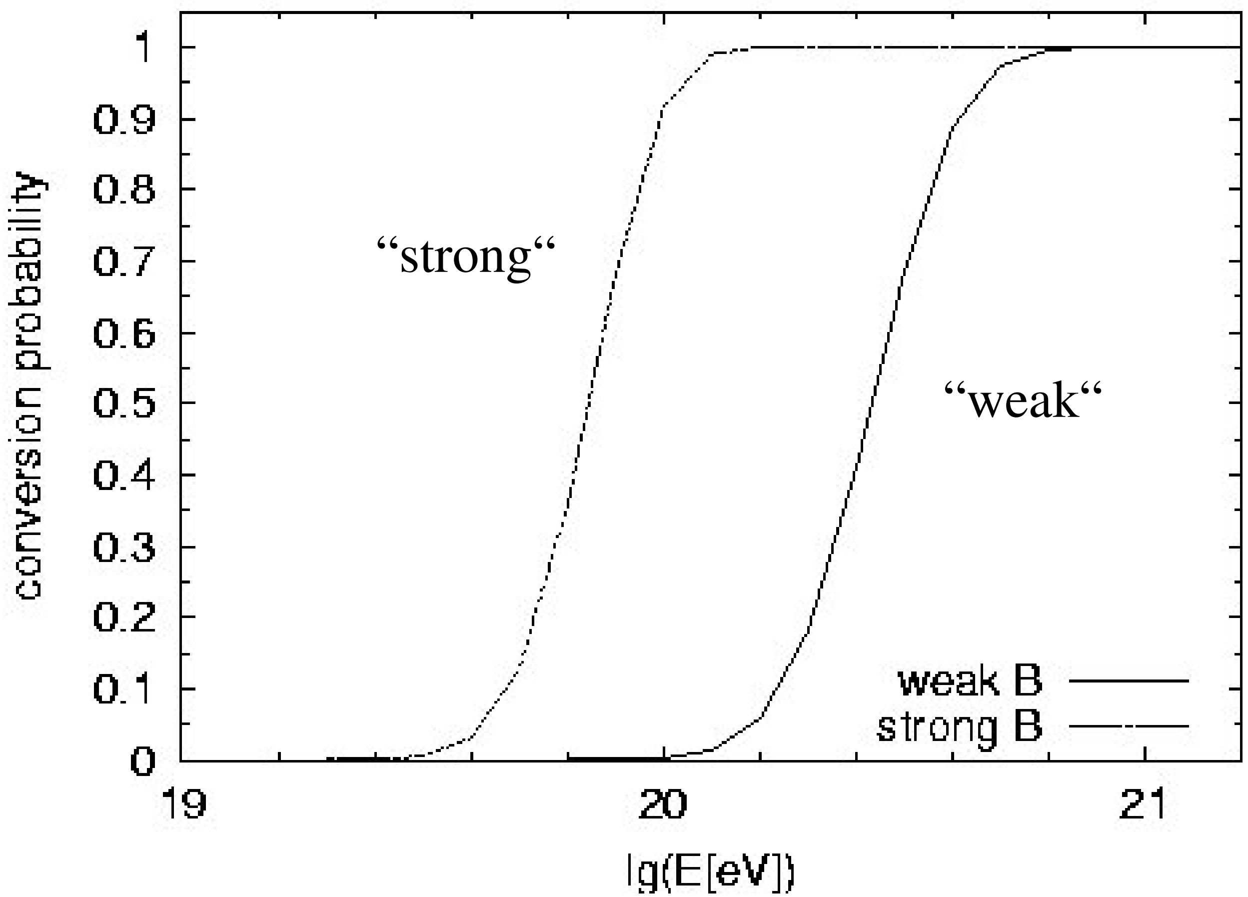
direction 1: large B_t

direction 2: small B_t

➔ **Preshower effect: Depends strongly on direction !**

Photon conversion: Different directions

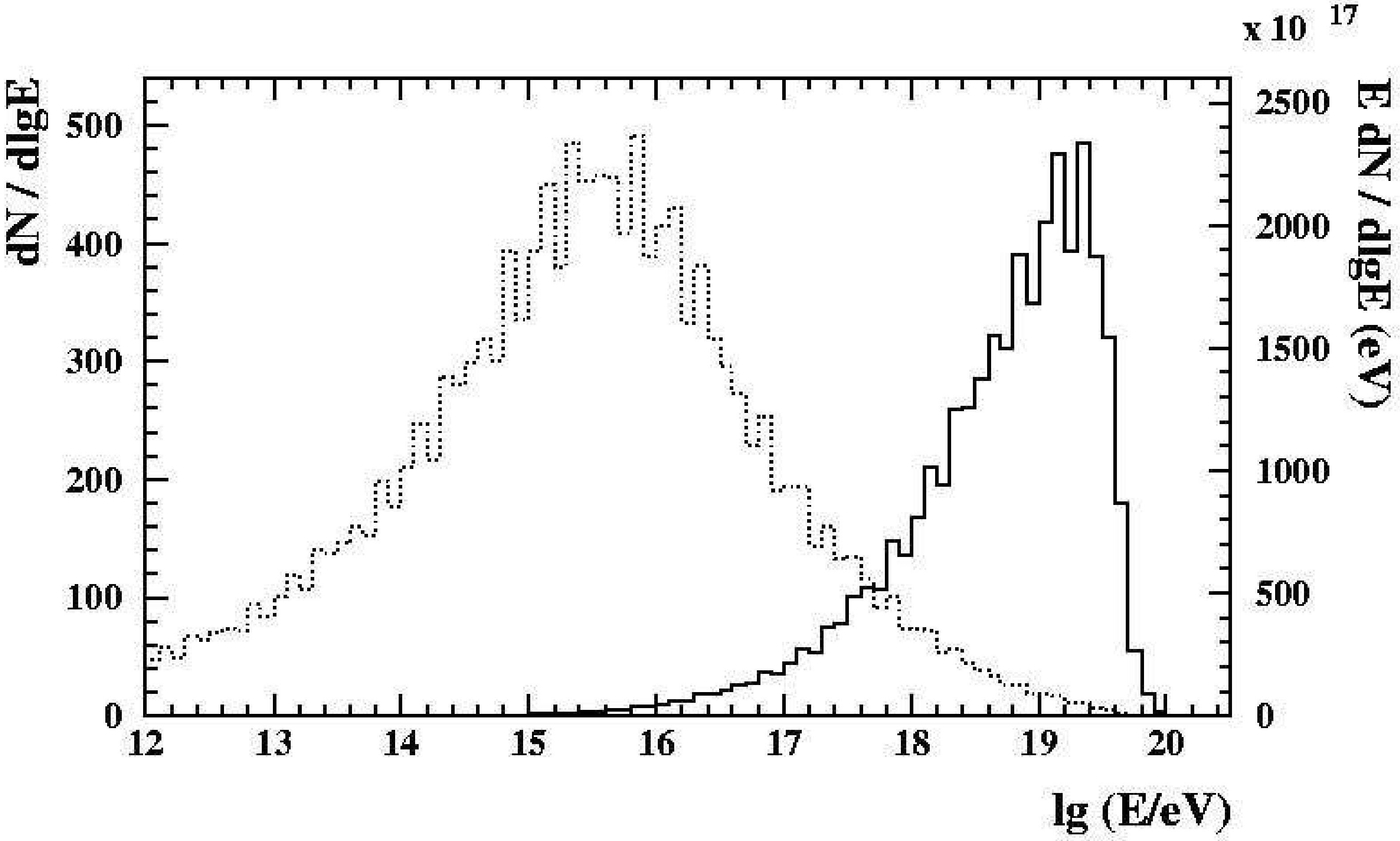
- Primary photons from “weak and strong B_t“ direction



➔ E.g. at 10^{20} eV: Almost always *vs* no conversion

Preshower particle spectra

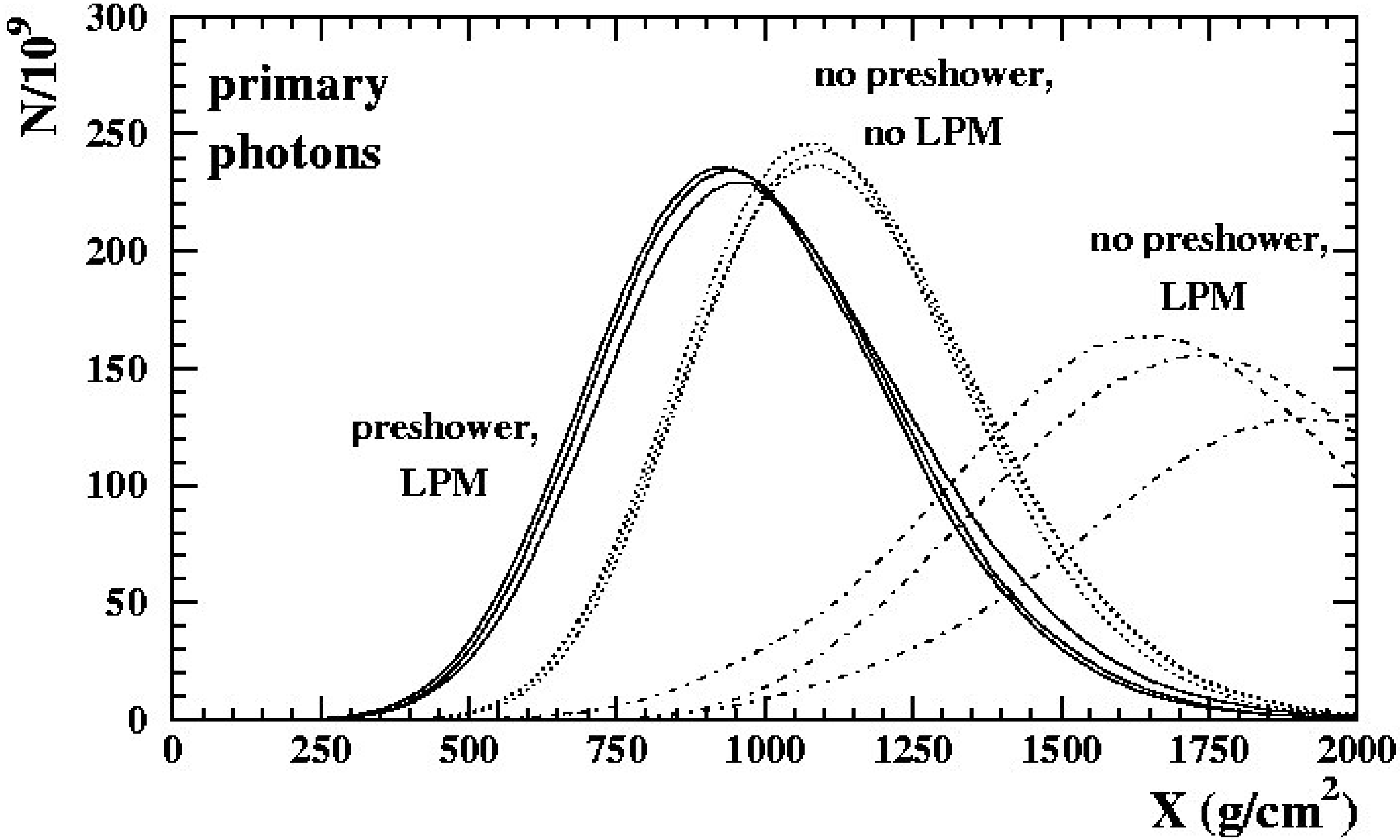
(320 EeV photons, 1000 showers averaged, top of atmosphere)



→ instead of 1 photon of energy $3.2 * 10^{20}$ eV:

~1400 low-energy particles; most energy ~10^{19} eV

Photon shower: Preshower effect

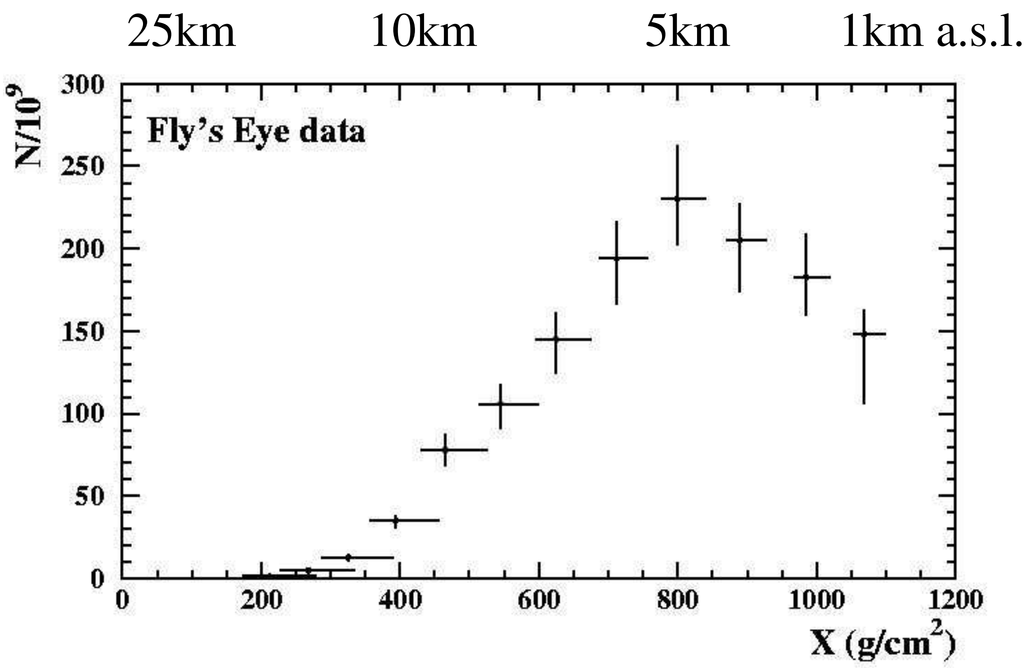


320 EeV photons (Fly's Eye event)

- Faster shower development, smaller fluctuations

→ **Competition of LPM and preshower !**

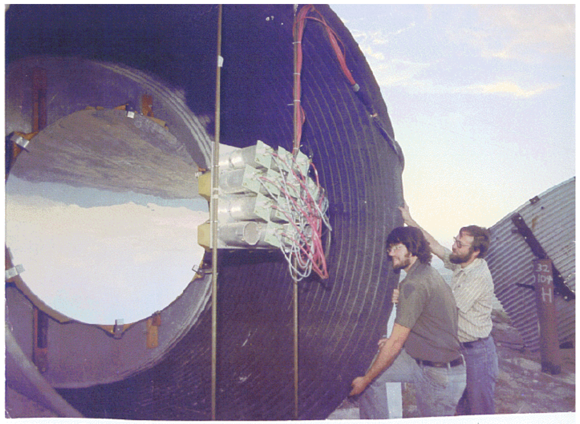
The most energetic Fly's Eye shower



- October 15, 1991
- "World record" (so far)!

(Bird et al., 1995)

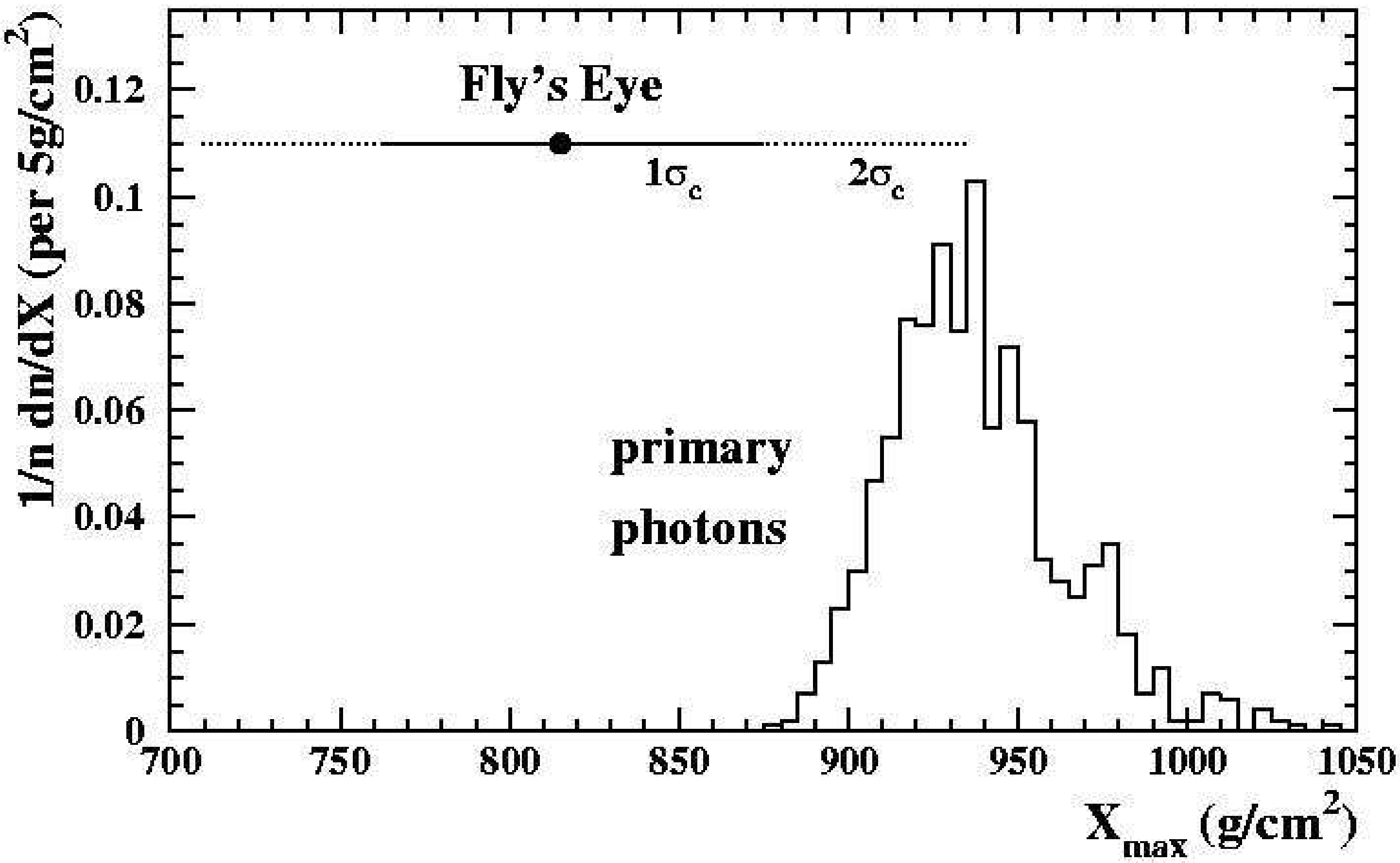
Parameter	Best-Fit Value	Statistical Uncertainty	Systematic Uncertainty	Combined Uncertainty
Energy [10^{18} eV]	320	$^{+35}_{-40}$	±85	$^{+92}_{-94}$
X_{max} [g/cm^2]	815	$^{+45}_{-35}$	±40	$^{+60}_{-53}$
zenith angle [deg]	43.9	$^{+1.4}_{-0.6}$	±1.2	$^{+1.8}_{-1.3}$
azimuth angle [deg]	31.7	$^{+4.0}_{-6.0}$	±1.2	$^{+4.2}_{-6.1}$



Utah, USA

-> Compare photon simulation (PRESHOWER+CORSIKA) to data

Fly's Eye event & photon: X_{max}

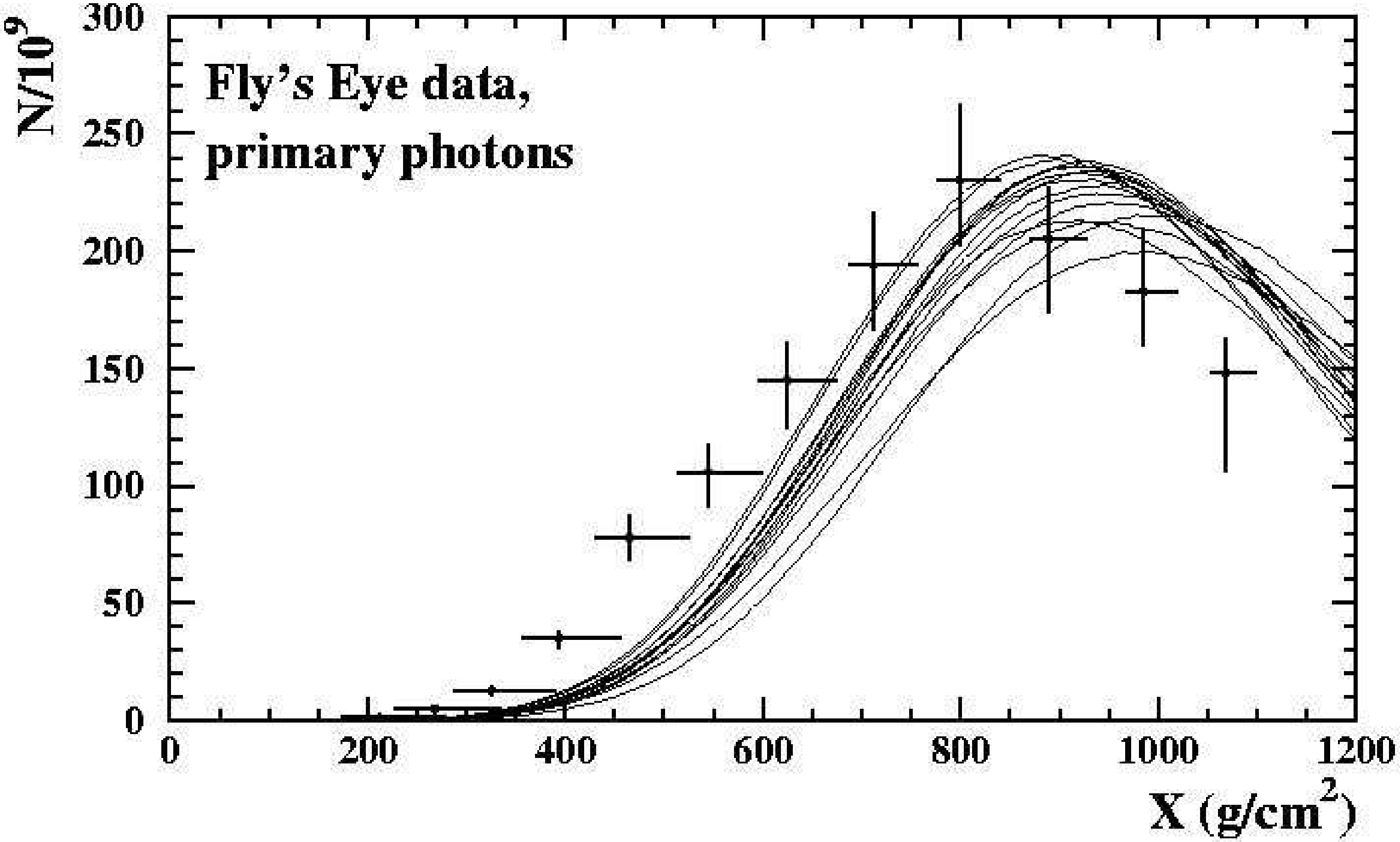


- Data: 815+-60 g/cm^2 < photon: 937+-26 g/cm^2

→ Discrepancy < 2 sigma

→ **Photon origin possible (though not favoured)**

Fly's Eye event & photons: Profile



note: X errors correlated !!!
(common geometry fit)

(MR et al., 2004)

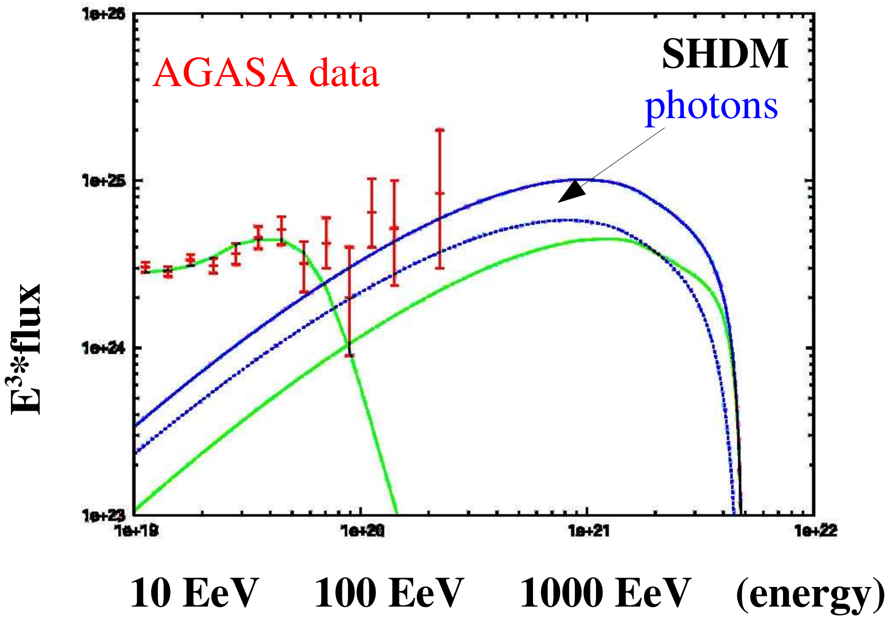
- Calculate probability of primary photon hypothesis

→ **Photon: 1.5 sigma (13% probability)**

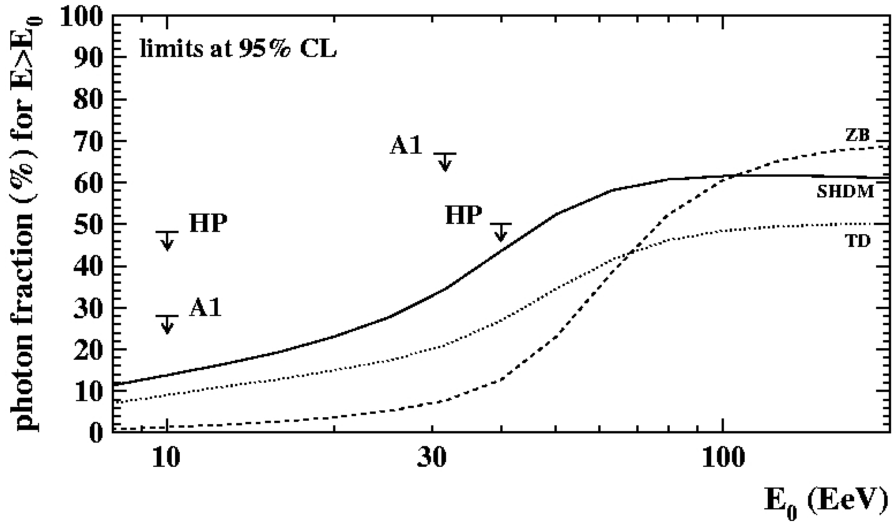
→ **The most energetic event could have been a photon !**

AGASA events >100 EeV

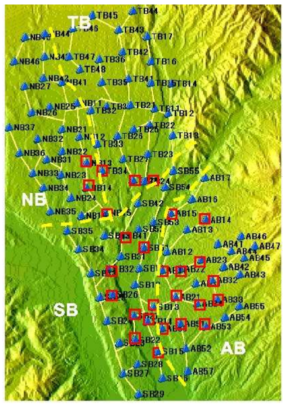
- **Non-acceleration models try to explain AGASA excess !**



(Kachelriess et al., 2004)



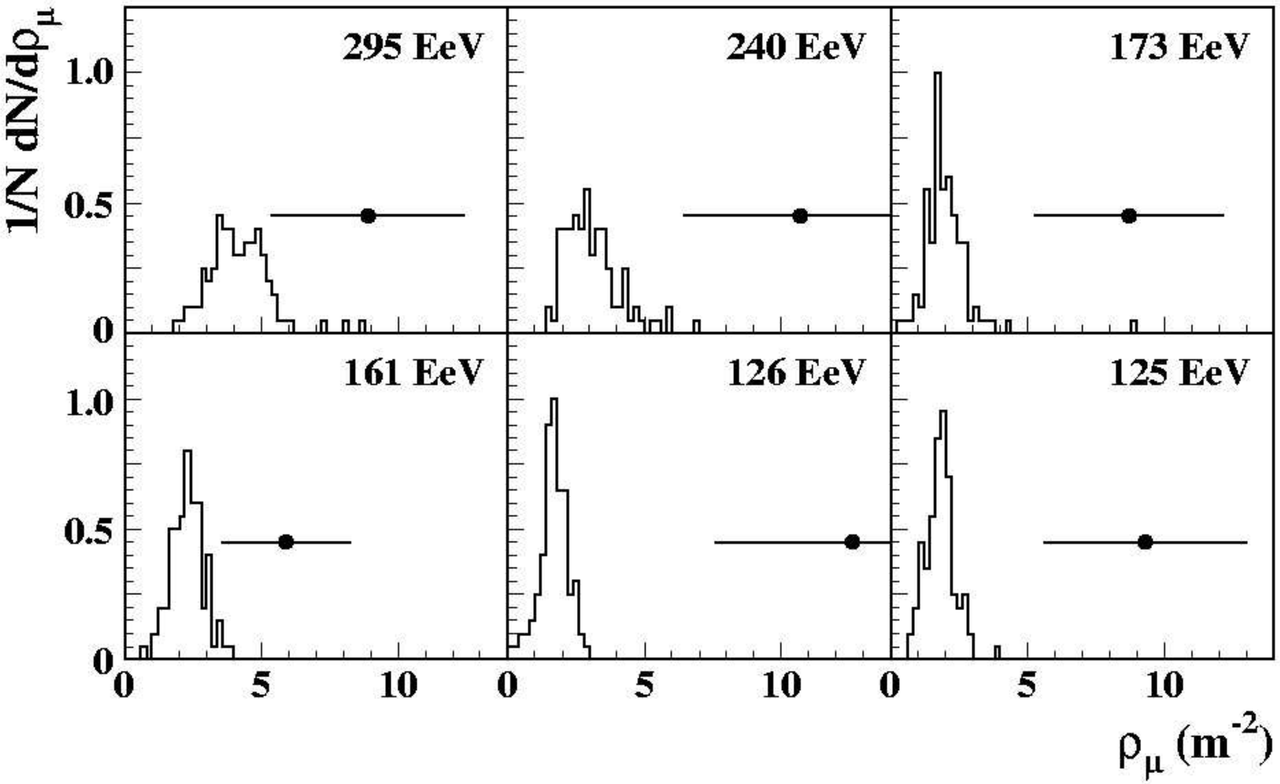
111 scintillator and
27 muon detectors
on ~100 km^2



Akeno Observatory
35.7°N 138.5°E 900m asl. 920g/cm^2

-> Check these events!

AGASA events >100 EeV and photons

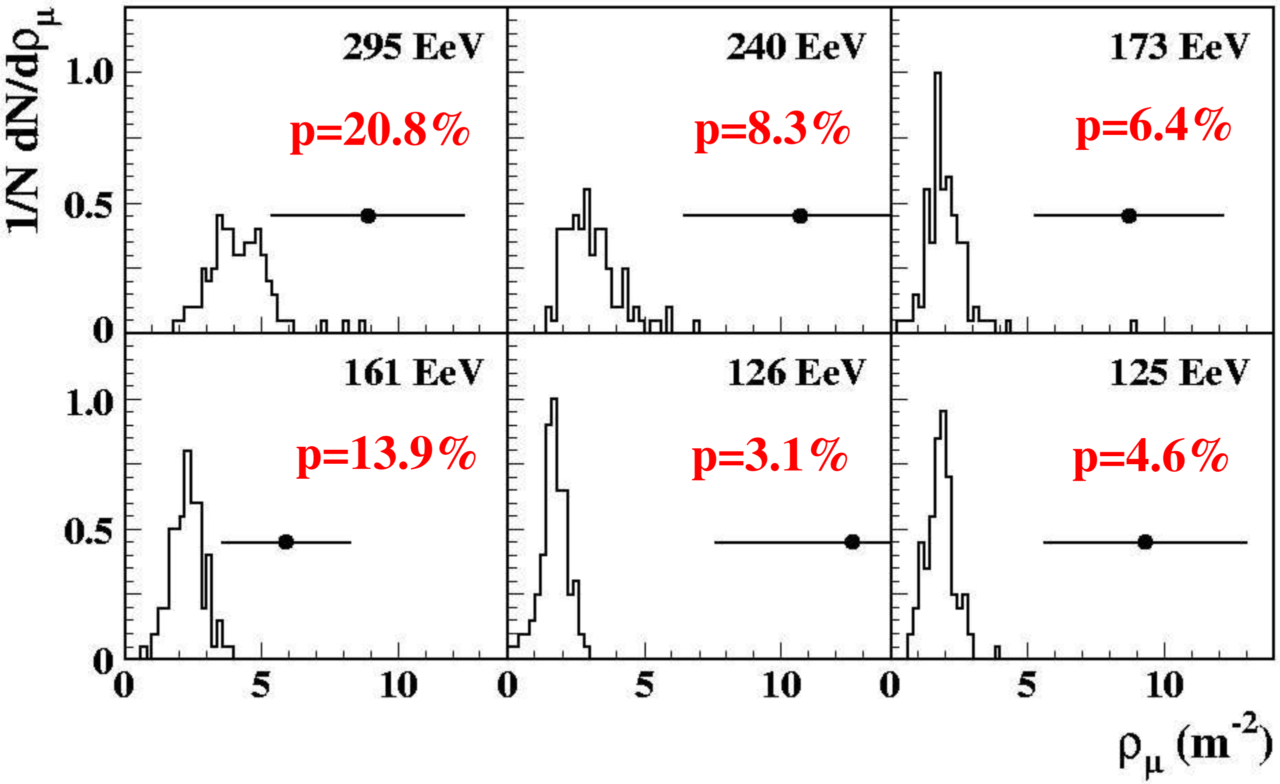


AGASA data:
Shinozaki et al., 2002

- In six AGASA events >100 EeV: muon density at 1000 m measured
  - Data: Points with error bars
  - Photon simulation: Histograms

➔ *Calculate consistency between data & photon prediction*

AGASA events >100 EeV and photons



AGASA data:
Shinozaki et al., 2002

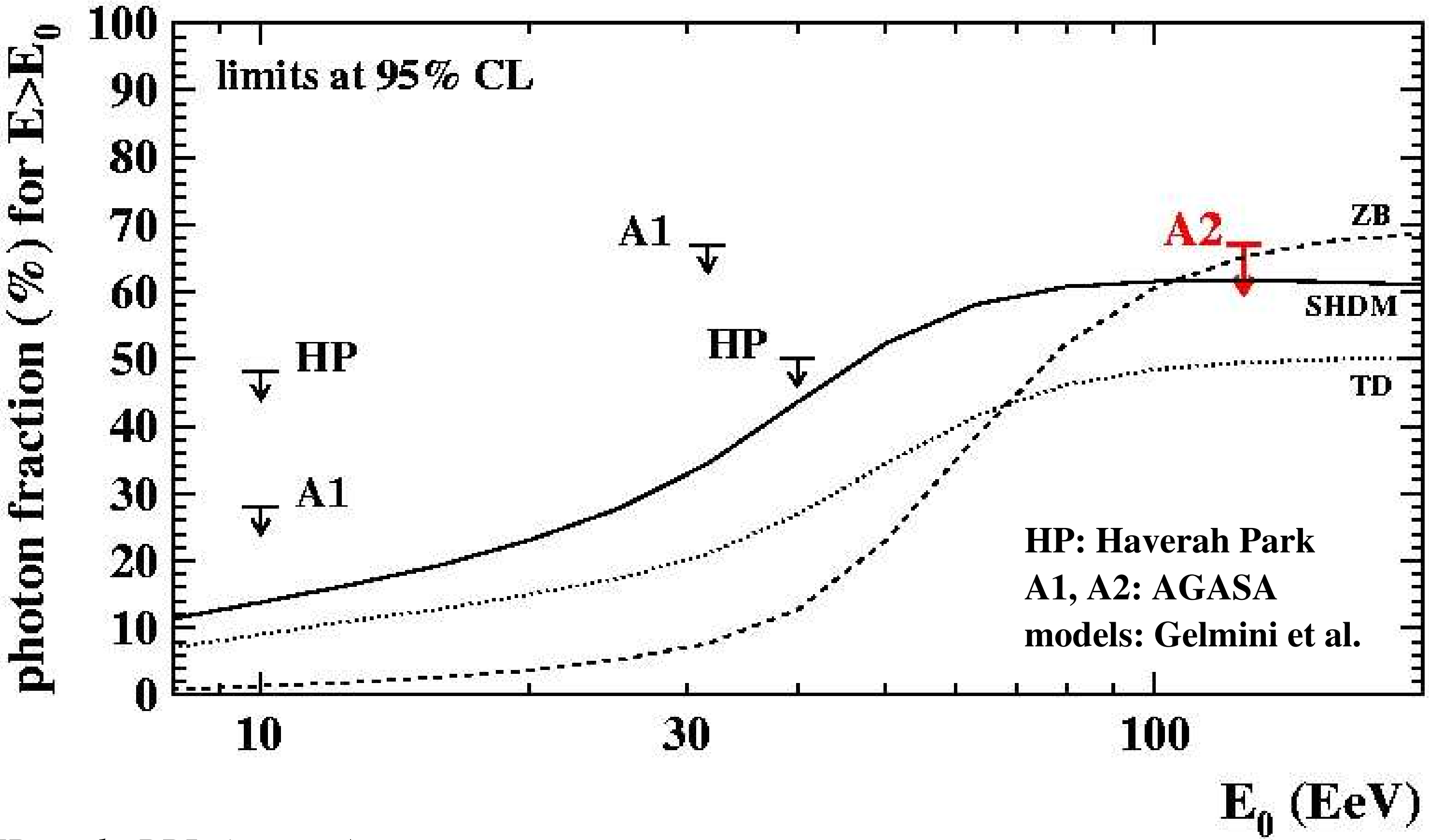
Prob. that photons produce chi2 larger than measured (from MC)

- **Prob., all 6 are photons: 0.5%**

→ **Derive limit on photon fraction**

→ **Stat. method** accounts for small statistics, shower fluctuations, shower properties varying from event to event: PRL 2005, in press

Photon Upper Limit



1st limit above GZK cutoff energy

predictions shown with minimum values

(MR et al., PRL, in press)

- Models with dominant photon fraction disfavoured:
  upper limit 51% (90% CL), 67% (95% CL) above 125 EeV

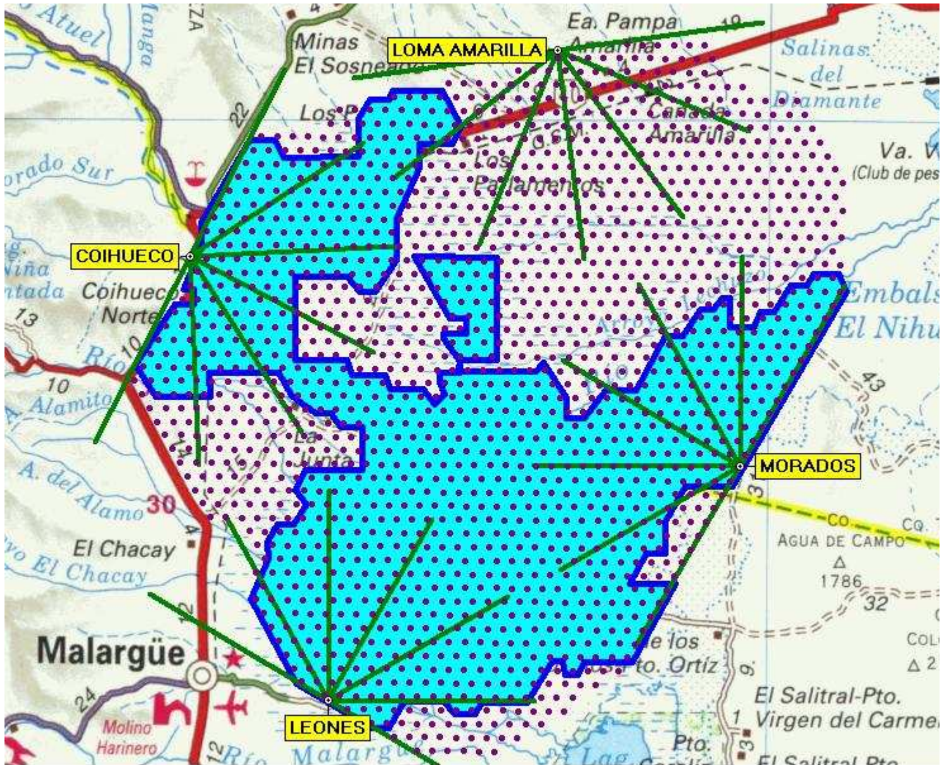
➔ Method (limit from small shower statistics) -> **Auger**, HiRes ...

Auger South & Photons

(ICRC 2005, Pune)

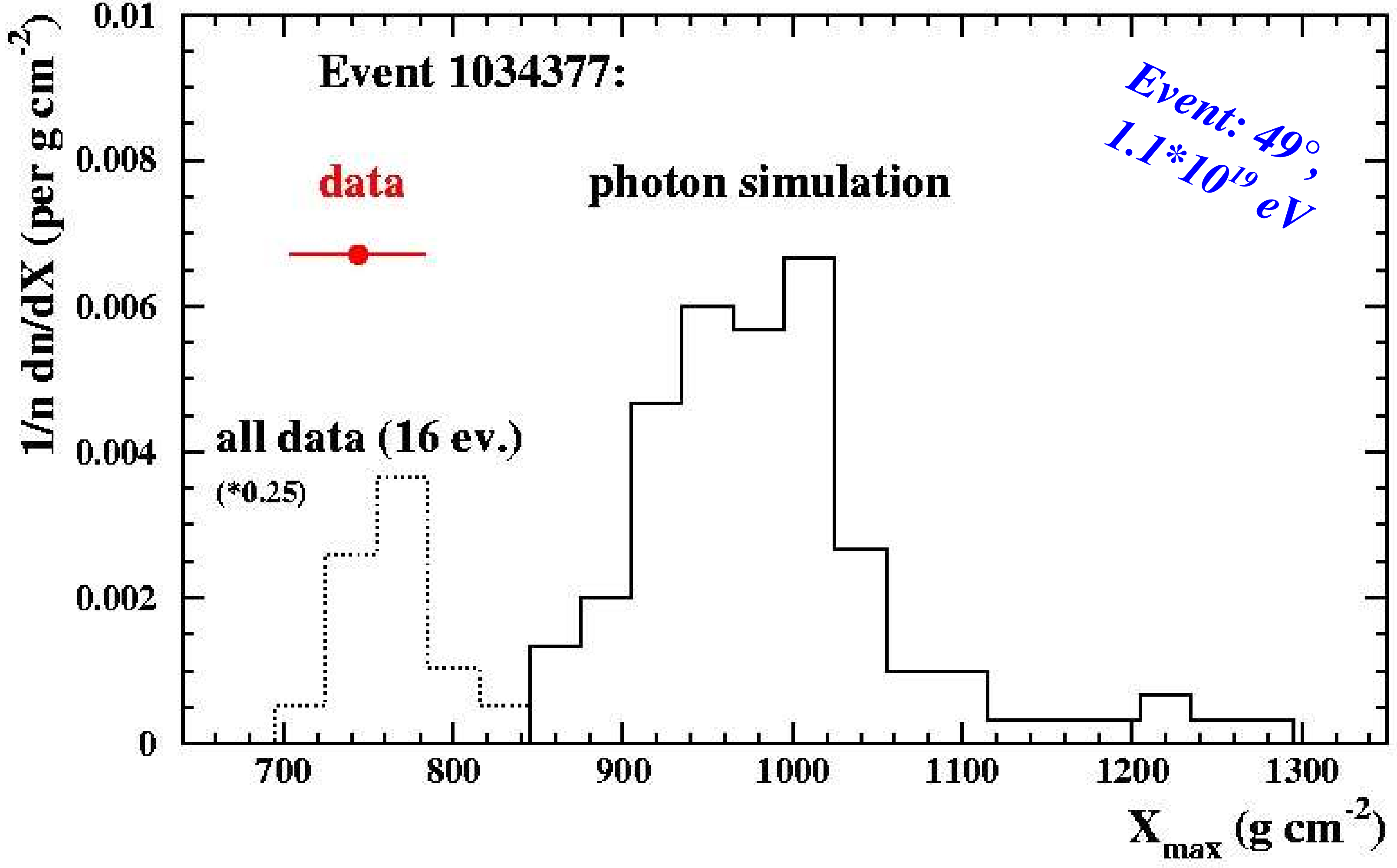
- **Hybrid events** (telescope **and** array): Improved geometry
- High-quality selection criteria
- $\Delta X_{max} \sim 40$ g cm^{-2}

→ **16 events** above 10 EeV



total:
4x6 telescopes
1600 array stations

Example: Auger event

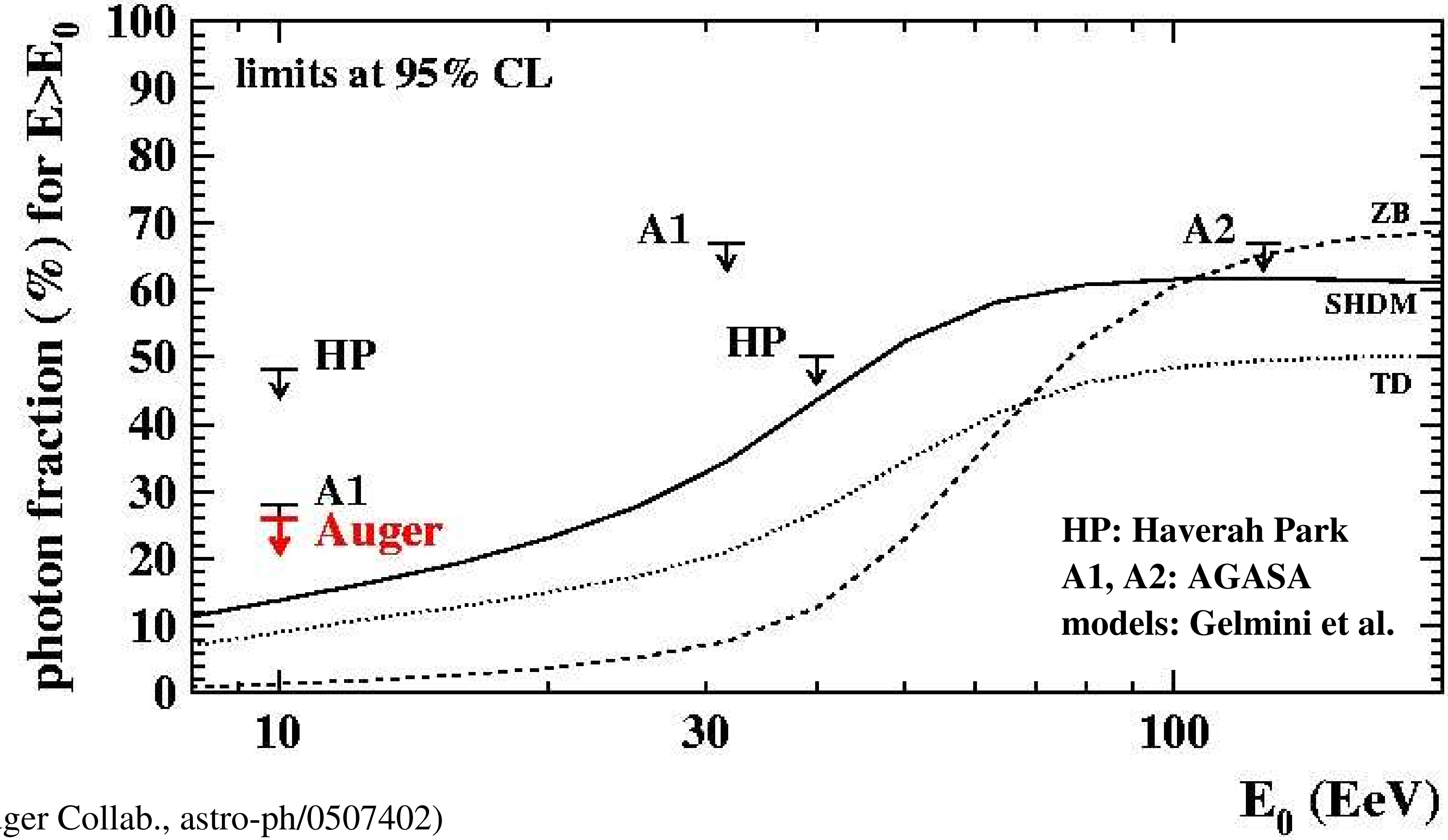


(Auger Collab., astro-ph/0507402)

- Event: $X_{max} = 744 \pm 40$ g cm^{-2}
- Photons: $\langle X_{max} \rangle = 1020$ g cm^{-2} , rms = 80 g cm^{-2}

→ Observed X_{max} well below photon expectation

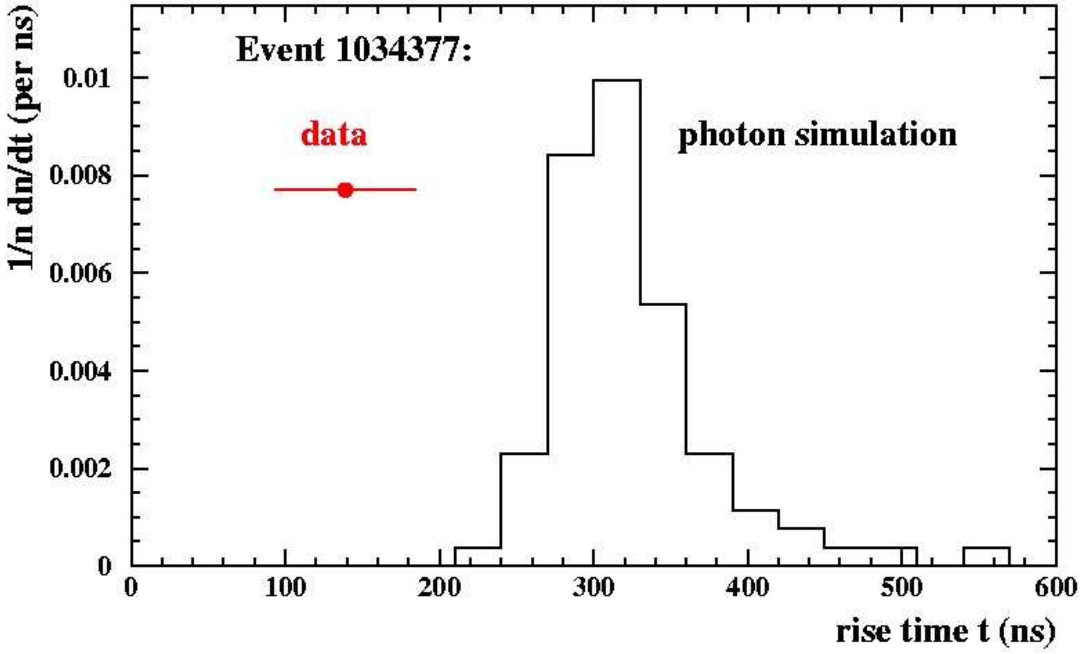
Auger photon limit

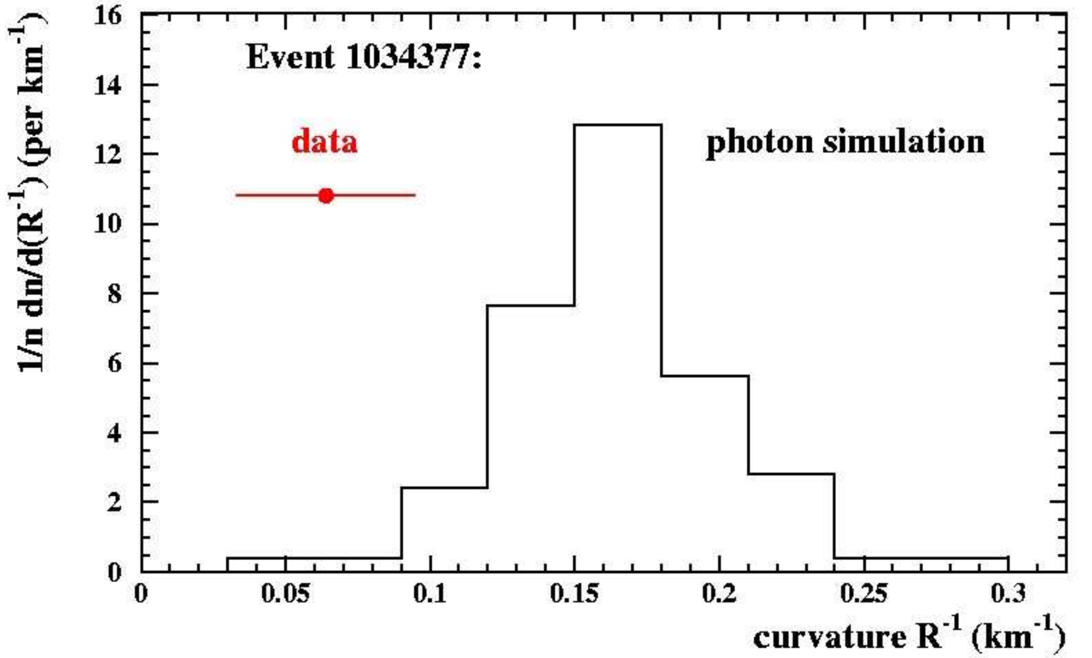


(Auger Collab., astro-ph/0507402)

- **26% upper limit** (95% CL) on cosmic-ray photon fraction
- Confirms and improves previous limits above 10^{19} eV

Discrimination power of Auger array data





- Standard array reconstruction:
  - → **Rise time** of detector signal at 1000 m core distance
  - → **Curvature** of shower front
  - → Observed values below photon prediction
  - → Observables sensitive to shower muons !

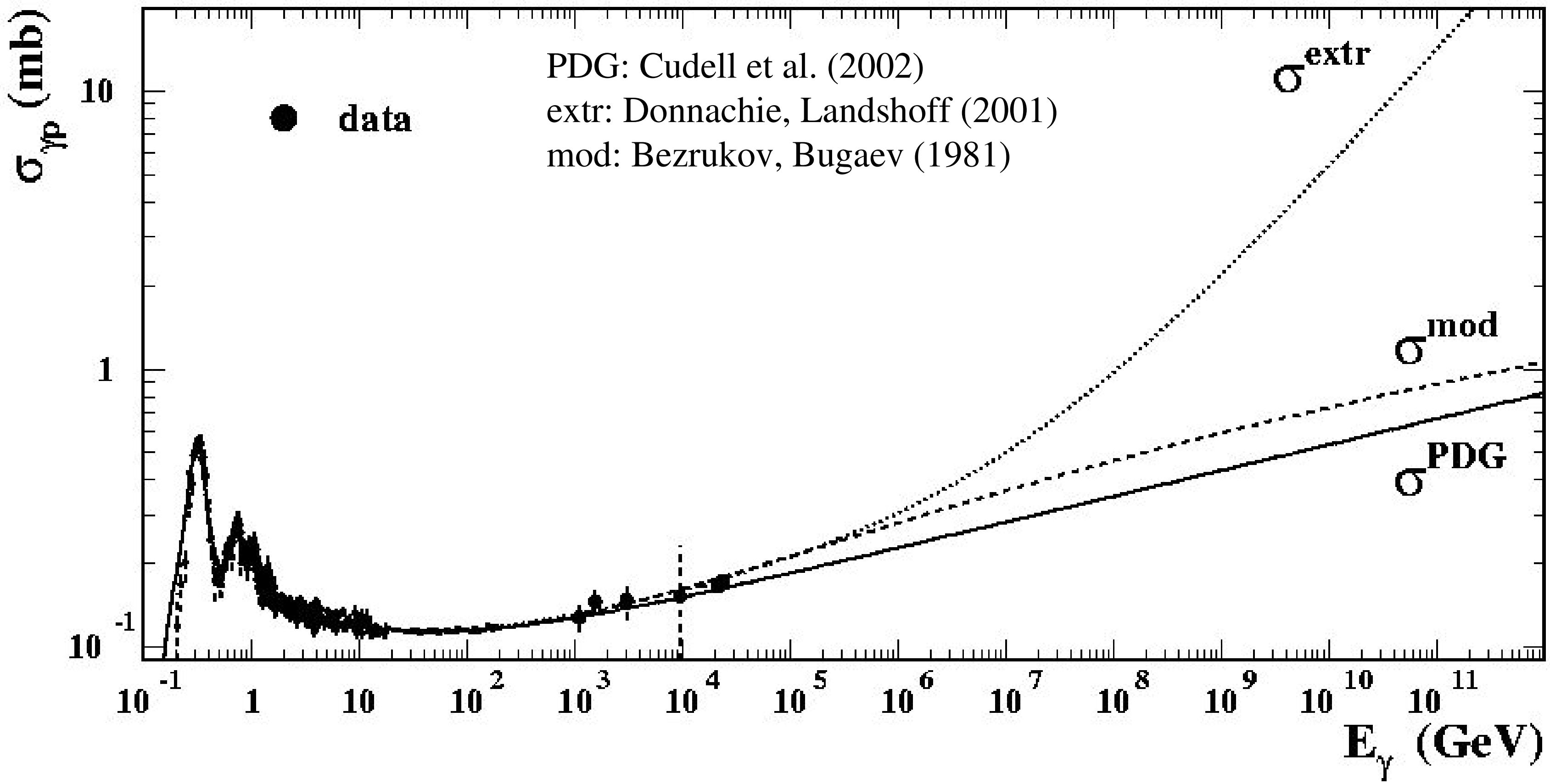
(Auger Collab., astro-ph/0507402)

Photon future at Auger

- Hybrid statistics factor ~10 larger within ~2 years
- Array-only analysis:
  - ➔ Factor ~10 more events than hybrid
  - ➔ Caveat: acceptance to photons
- **Much lower photon fractions (also at higher energy) tested soon**

- **Northern site:** Different geomagnetic field (orientation & strength)
  - ➔ **Different preshower pattern !**
  - ➔ E.g.: Check possible photon signal from Southern site (prediction of different shower features for North)

High-energy photonuclear cross-section

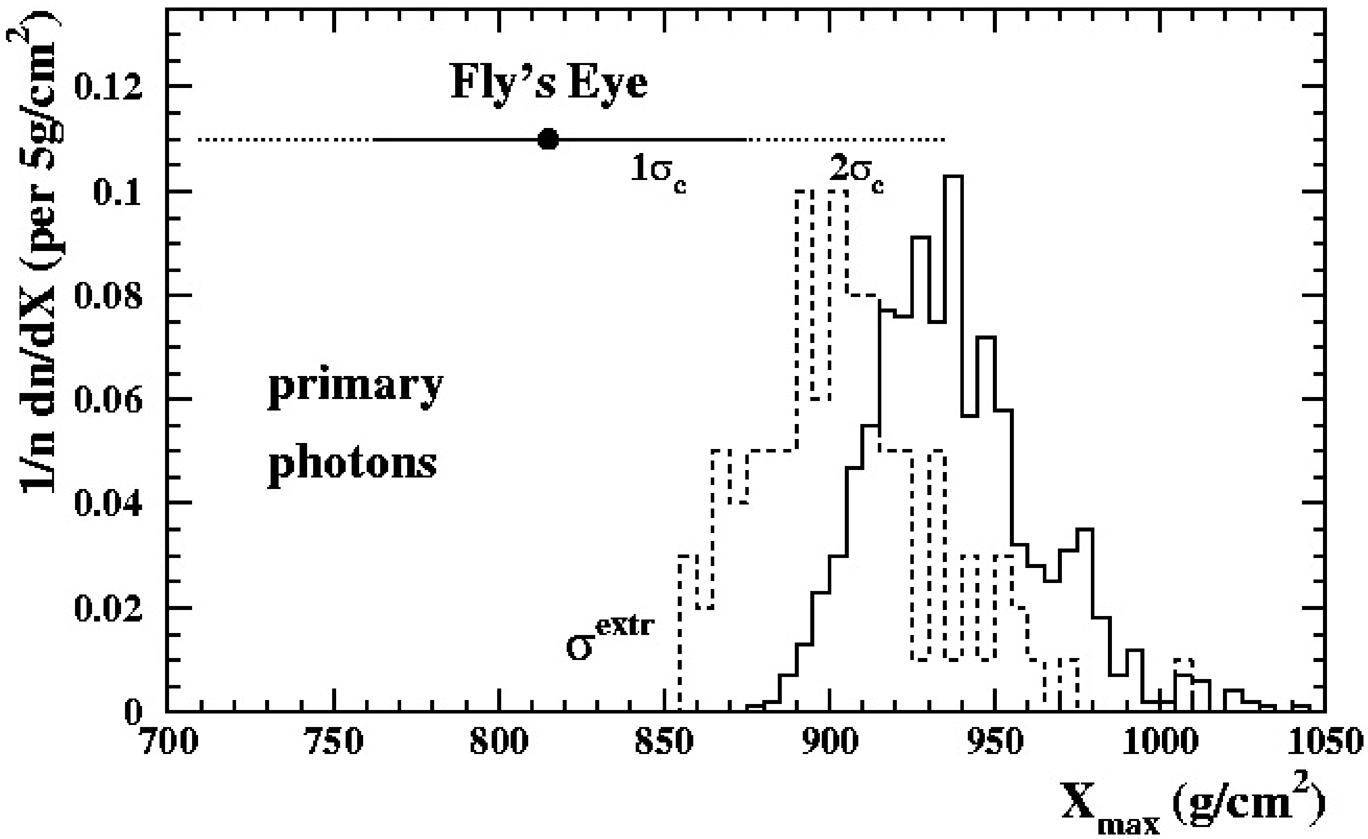


- **Effect on photon showers if, e.g., σ_{PDG} -> σ_{extr} ?**

→ Qualitatively: Photon showers more hadron-like

→ **Question to theoreticians: How large is allowed ??**

Effect on 320 EeV Fly's Eye event

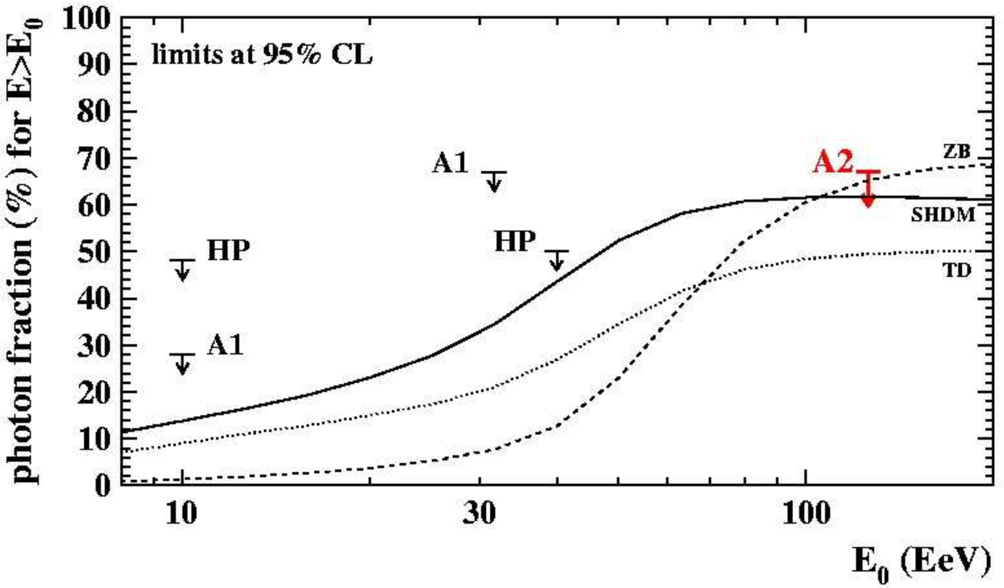


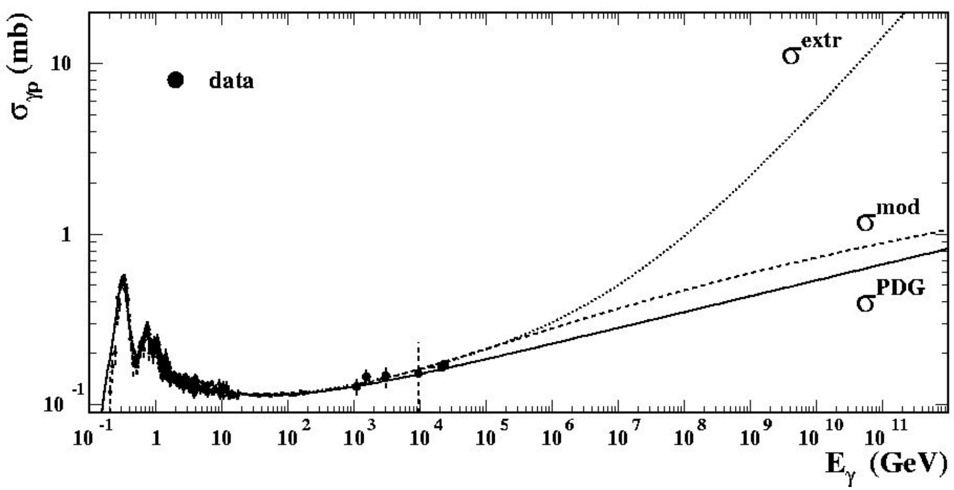
- **For σ_{extr}: <X_{max}>: 937 --> 905 g cm^{-2}**

➔ Photon discrepancy: 1.5 --> ~1.2 sigma

➔ ~ modest effect due to preshowering

Effect on AGASA events





- For σ_{mod} : upper limit 67% -> 75% (95% CL)
- For σ_{extr} : **no upper limit can be set!** (all 6 are photons: 15%)
  - ➔ Muon densities increase by ~70-80%

➔ Note: Also previous upper limits affected !

➔ ***Could primary photons “hide“ behind a large cross-section?***

A critical scenario:

Would a photon component be observable even with large cross-section (e.g. σ_{extr}) ?

➔ More difficult ... but still photons deeper and with fewer muons compared to protons:

$\Delta\langle X_{max}\rangle$	~(180 ... 50) g cm^{-2}
ratio $\langle N_{\mu}\rangle$	factor ~2

➔ *Let's turn it around now:*
Photon shower features are sensitive to the cross-section; so ...

Experimental limit on photonuclear cross-section !?

- **In case of photon observation (necessary condition!)**

➔ Different photon shower features for σ_{PDG} and σ_{extr}:

$\Delta\langle X_{max}\rangle$	~(>100 ... 30) g cm^{-2}
ratio $\langle N_\mu \rangle$	factor ~1.8

➔ Special sub-classes of photon events, e.g.:
Deeply starting photon w/o photonuclear interaction
-> suppressed for σ_{extr}: mean free path ~150 g cm^{-2} at ~100 EeV

(Work in progress ...)

Conclusion: Photons at highest energies ...

- Even **absence** interesting to constrain source models !

  ➔ $\sigma_{\gamma\text{-air}}$: systematic uncertainty in photon upper limit

  ➔ Q: How large could $\sigma_{\gamma\text{-air}}$ be?

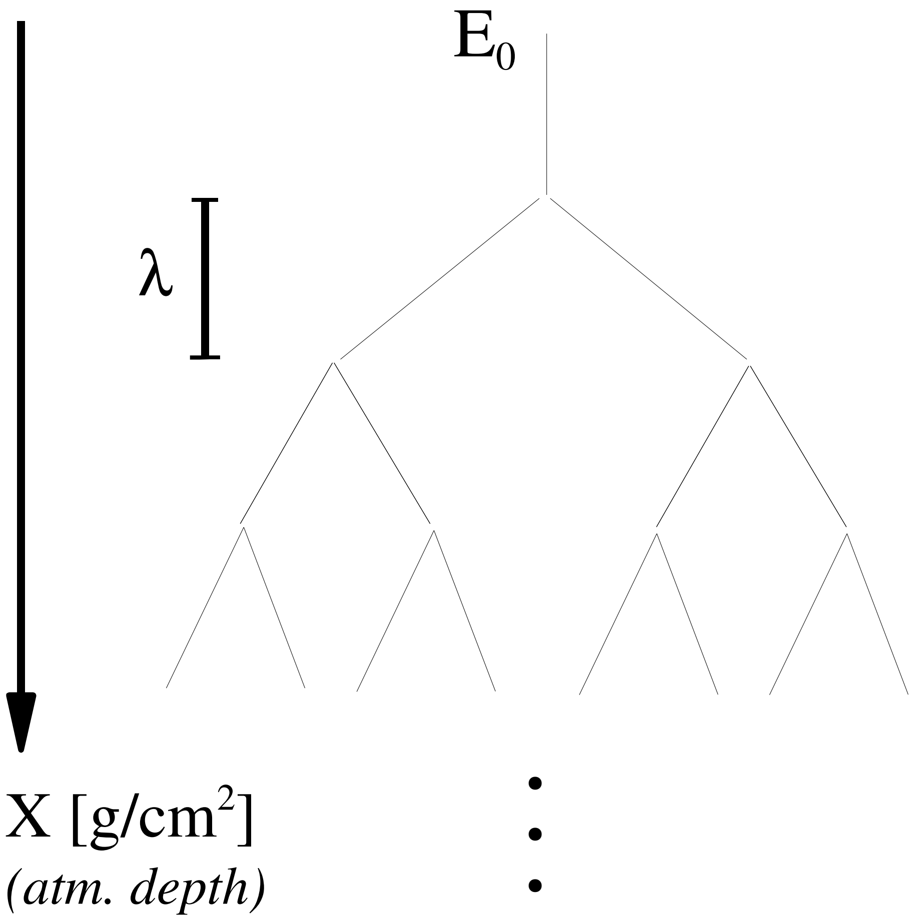
- **If observed:** Even more interesting ...

  ➔ Limit on $\sigma_{\gamma\text{-air}}$ might be placed; e.g. from

  - Shower features (X_{max}, N_{μ})

  - Special event sub-classes

“Standard“ elongation rate: toy model



each vertex: equal energy splitting

=> after $n=X/\lambda$ steps: $N(X) = 2^{X/\lambda}$

particles with $E(X) = E_0 / N(X)$

particle multiplication stops at

$E(X) = E_L$ => **shower maximum:**

$$N(X_{max}) = E_0 / E_L$$

$$X_{max} = \lambda/\ln 2 * \ln(E_0 / E_L)$$

=> elongation rate:

$$\Delta\, \mathbf{X_{max}} = X_{max}(10E_0)\text{-}X_{max}(E_0) = \lambda/\ln 2 * \ln(10)$$

$$= 37\ \mathrm{g/cm^2} * 2.30\ \ \mathbf{= 85\ g/cm^2} \quad \text{with } \lambda_{rad}=\lambda/\ln 2$$

(Heitler 44)

Addendum: Statistical treatment

astro-ph/0502418

- chance probability for hypothetical F_γ to get χ^2 values $\geq$ 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 $\geq$ than in data

... n_γ-n_m ``non-photons´´ yield χ^2 values $\geq$ than in data

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

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

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

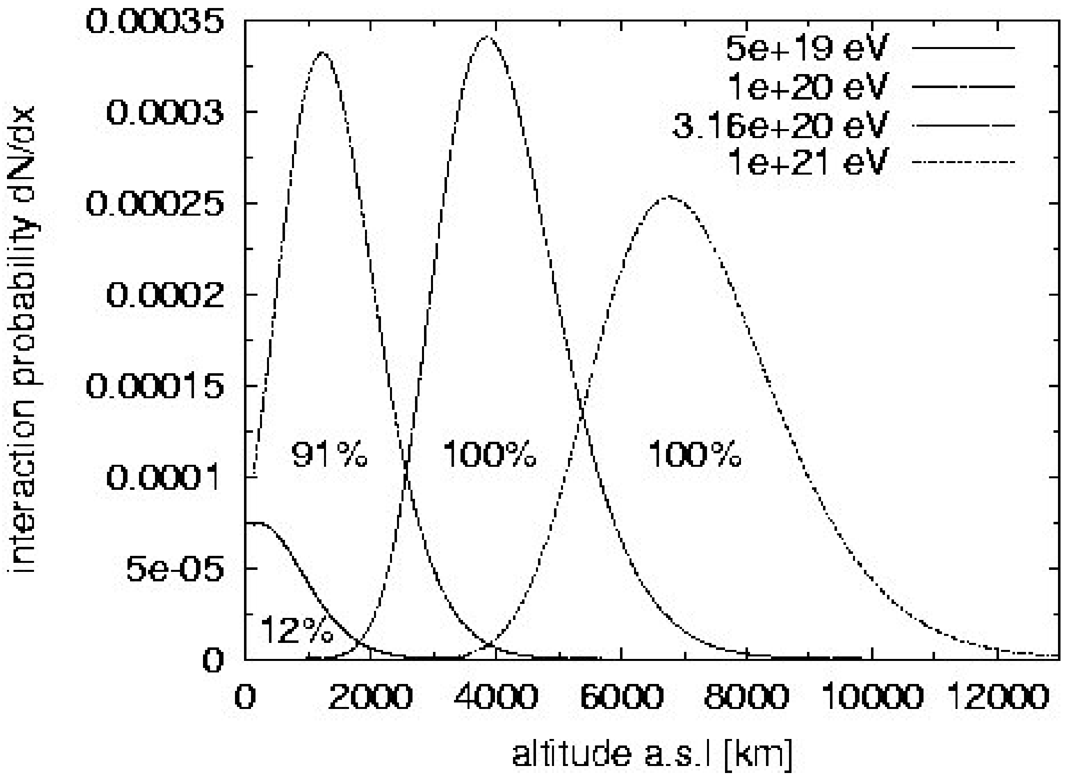
$p_\gamma(n_\gamma)$: take n_γ most photon-like looking events => $\sum_{i=1}^{n_\gamma} \chi^2_{k_i}$ is minimal;

determine $p_\gamma(\chi^2 \geq \sum_{i=1}^{n_\gamma} \chi^2_{k_i})$ with MC technique (non-Gaussian fluct.!)

→ **with confidence 1- P(F_γ) , photon fractions $\geq \varepsilon F_\gamma$ can be rejected**

Photon conversion altitudes

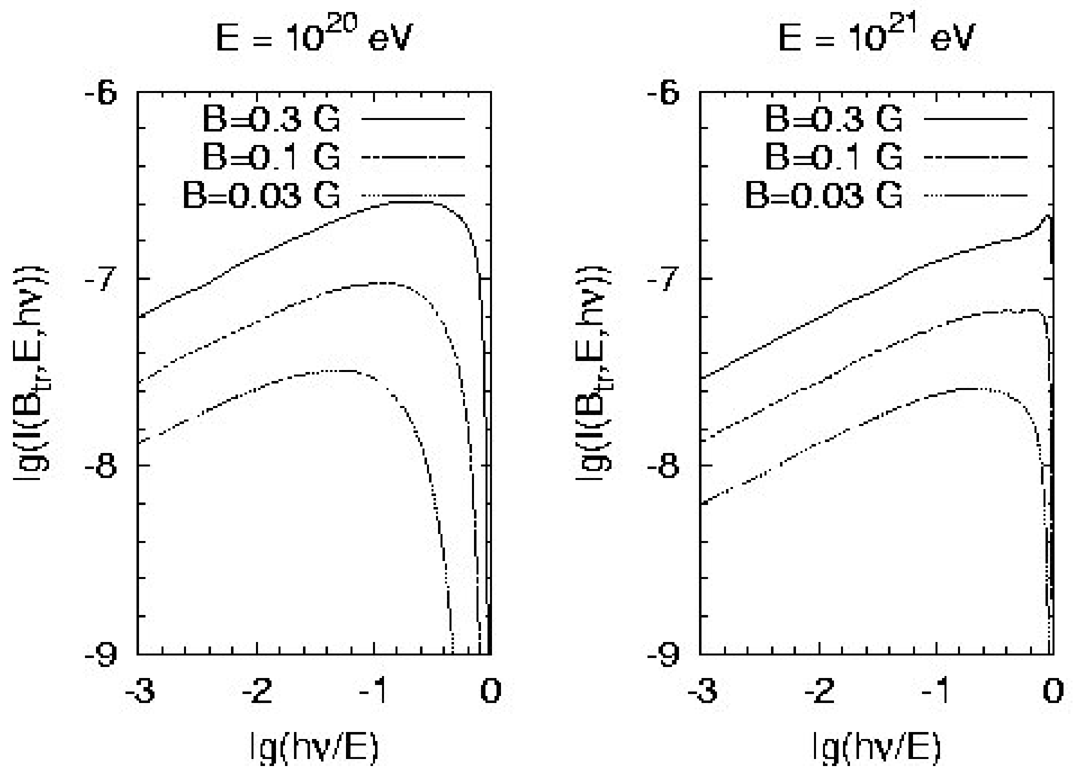
- primary photons from "strong B_t" direction



→ smaller energy <=> closer to atmosphere (if at all)

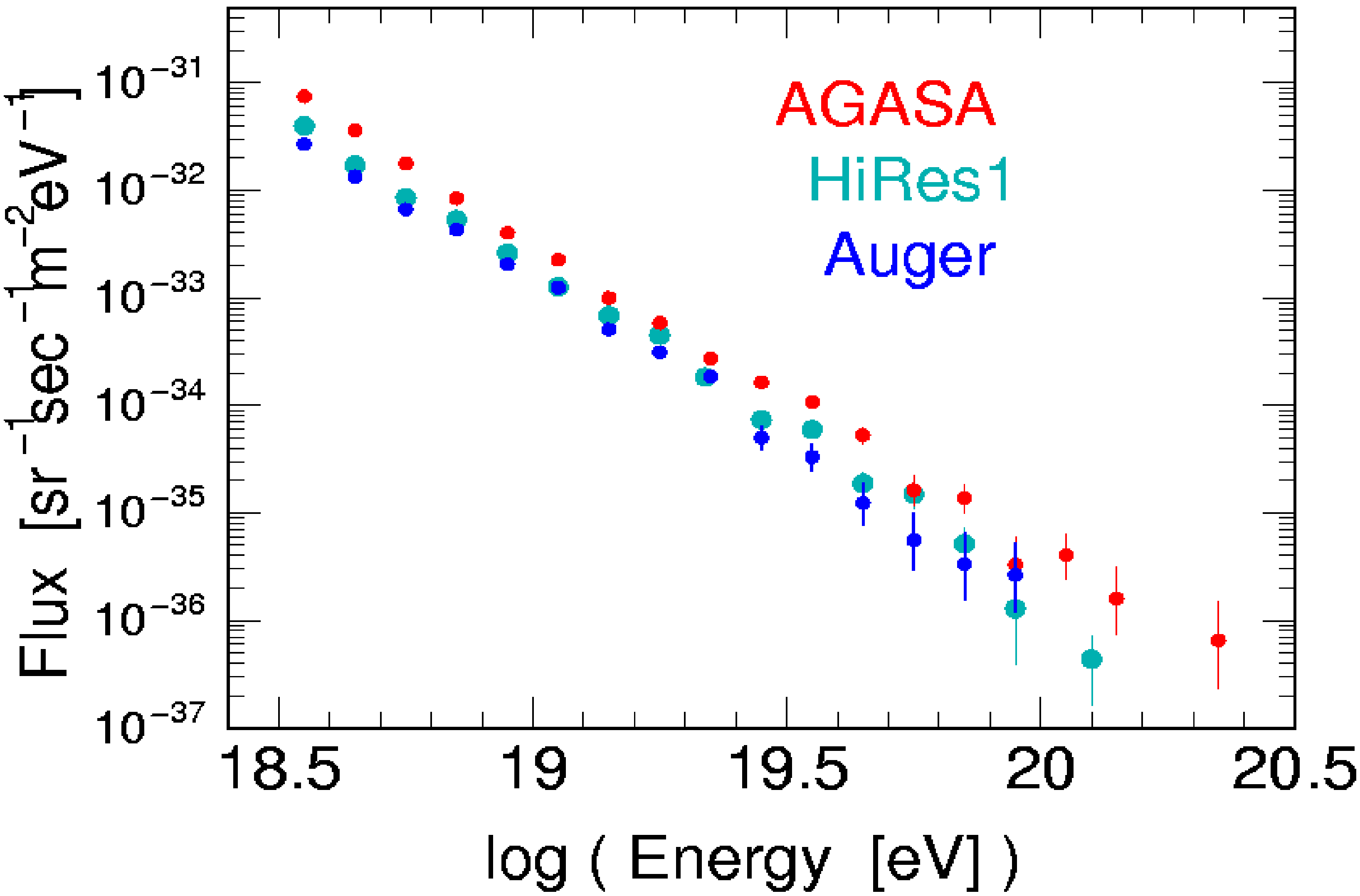
Synchrotron emission

- prob. distribution of emitted photon vs fractional energy



→ **increasing B_t and E: more and harder emission**

Highest energies: CR spectrum



(Mantsch, ICRC 2005)

- **There are events >100 EeV !! What are their sources??**