An upper limit to photons from first Auger data

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for the Pierre Auger Collaboration

Challenges in Particle Astrophysics
6th Rencontres du Vietnam, Hanoi, August 6-12, 2006

- **UHE photons $>10^{19}$ eV**
  - production, propagation; air showers
- **photon limit** (astro-ph/0606619)
  - method & cuts; first limit using X_{max}
- **prospects**
  - more data, ground array, Auger North vs South

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

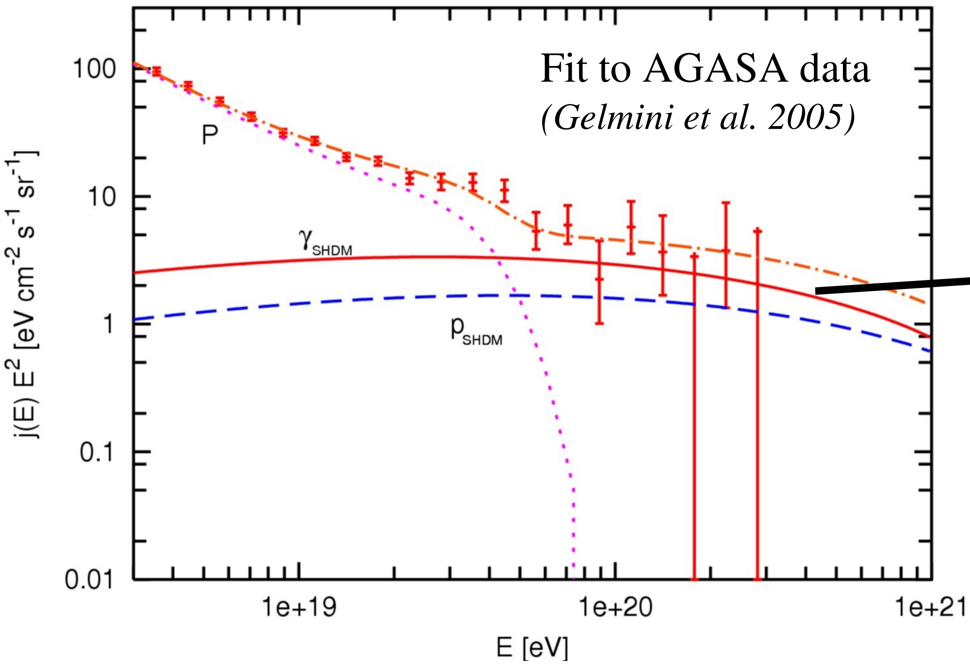
photon fractions typically > ~10 %

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

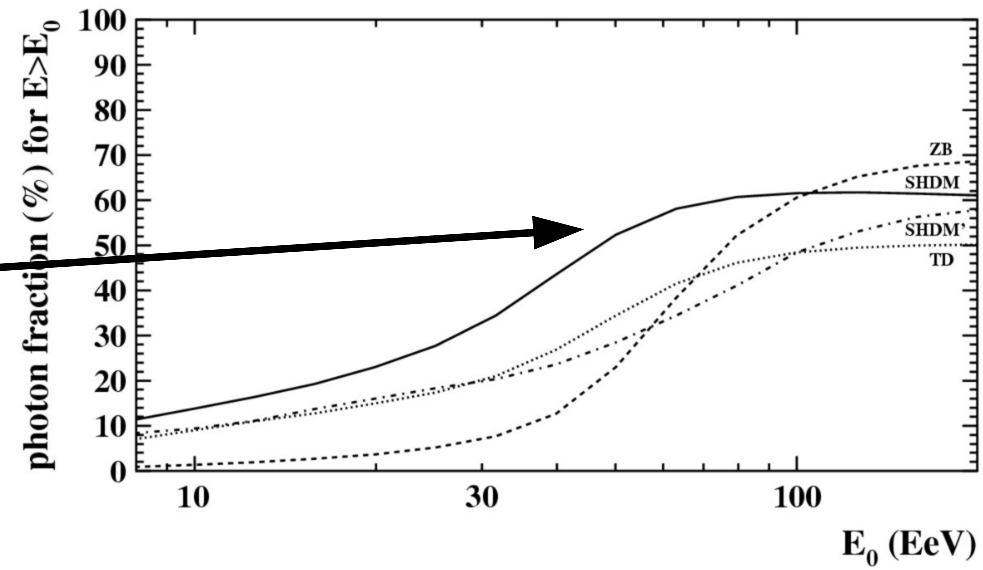
Super Heavy Dark Matter (SHDM)

- 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 !**

Acceleration models: “GZK photons“

- nucleons from astrophysical source (>100 EeV nucleons: λ_{loss}~ 50 Mpc)
  - ➔ $N\gamma_{2.7}$ –> Δ –> $N\pi$ –> **UHE (“GZK“) photons** (and neutrinos)
- pair production on ~MHz radio background (10-100 EeV photons: λ_{loss}~3-15 Mpc)

  – *note: multimessenger observations, complementary features !*

UHE photons --- UHE neutrinos

↓

GeV-TeV photons

GZK: Greisen; Zatsepin, Kuzmin 1966

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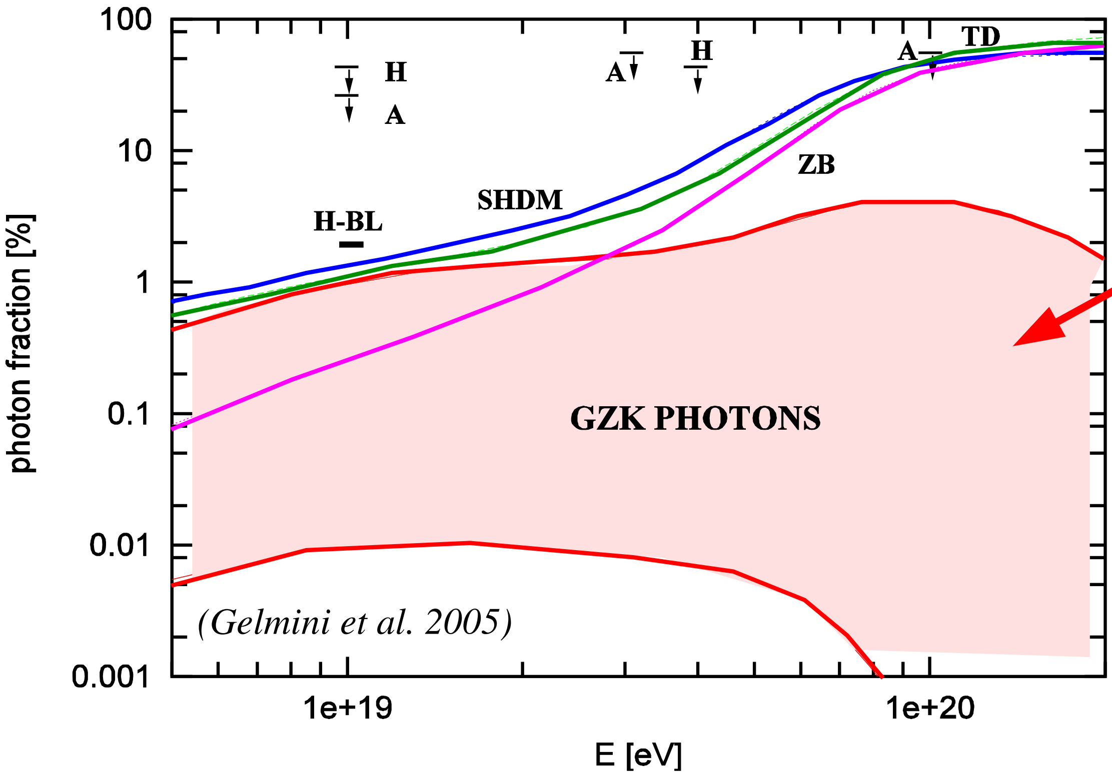


shaded region: source and propagation parameters varied (HiRes spectrum)

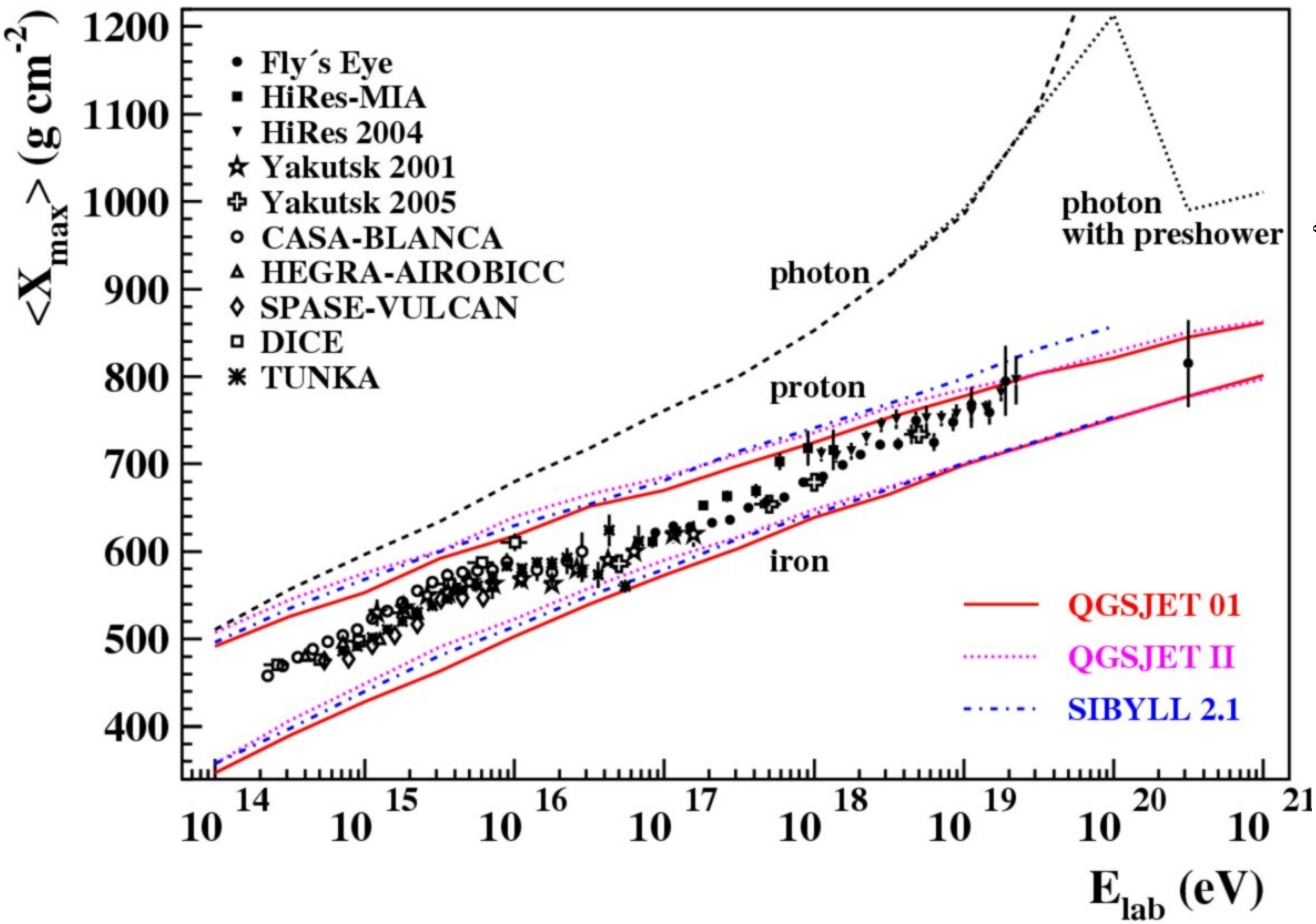
- **typically <1%**
- Auger North+South, photons/year: **up to ~40 (>10 EeV), ~2 (>100 EeV)**

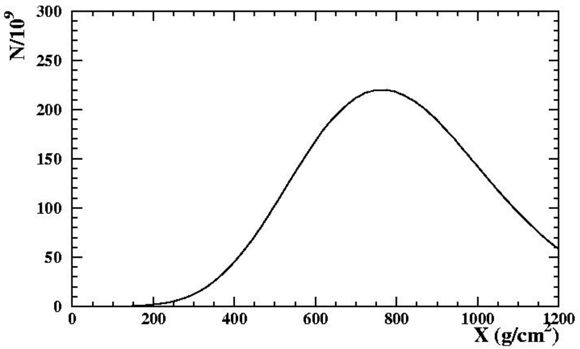
→ absence of photons => constraints

GZK: Greisen; Zatsepin, Kuzmin 1966

-> air showers: how to “identify“ photons?

Photon discrimination with X_{max}



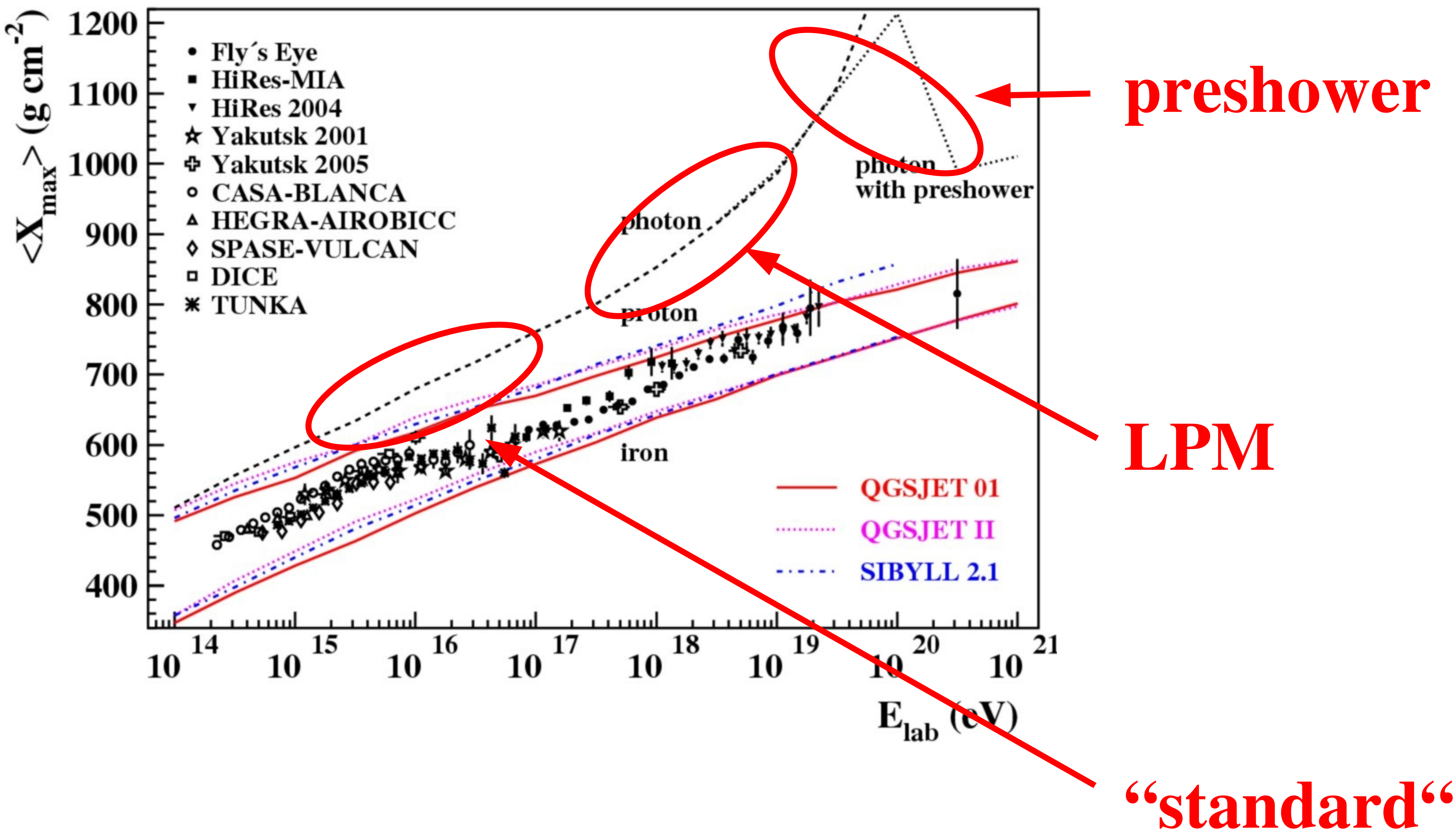


X_{max}

(depth of shower maximum)

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

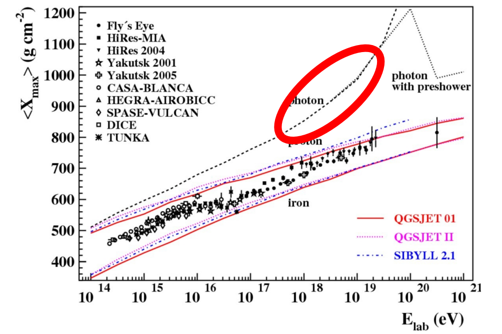
Photon showers: high-energy effects



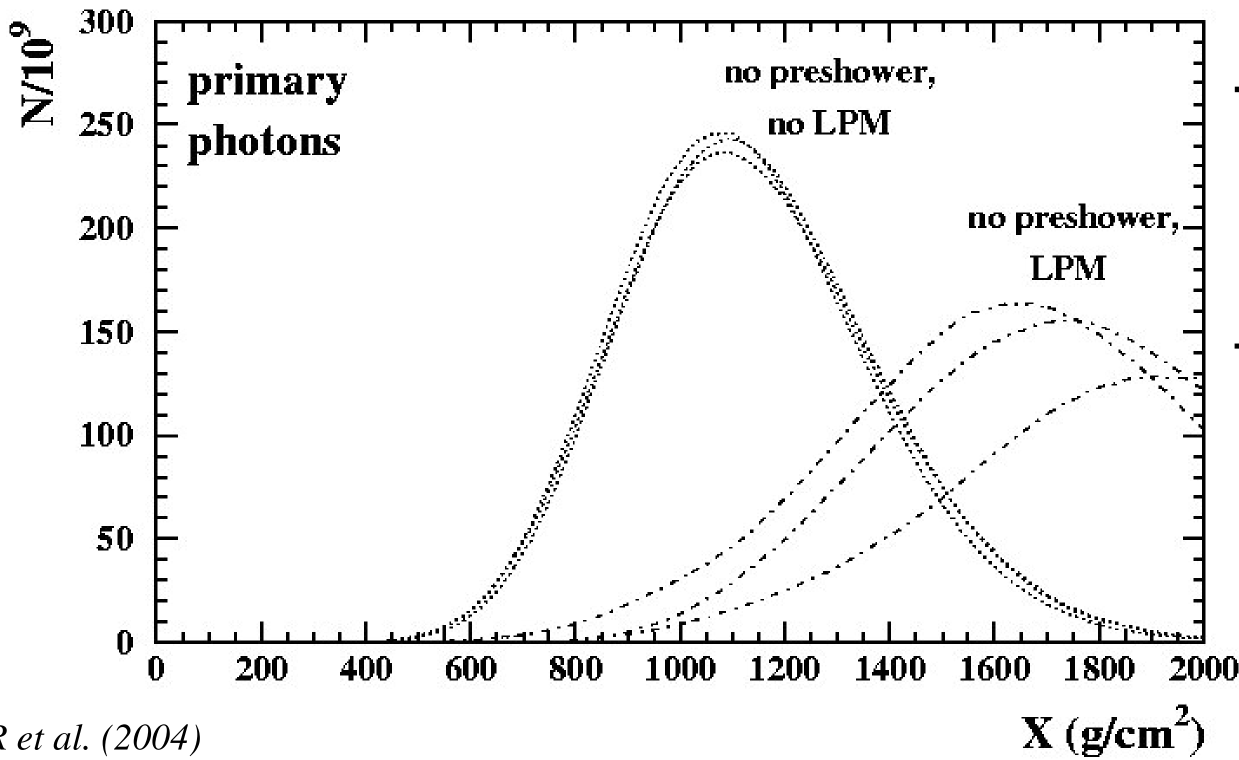
slope ~ 85 g cm^{-2} / energy decade

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

Photon shower: LPM effect



- Landau, Pomeranchuk (1953), Migdal (1956)
- in matter: interference if formation length gets macroscopic
- pair production and bremsstrahlung **cross-sections reduced**:
  ~1/sqrt(ρE) (h.e. limit); larger air density -> stronger reduction
- **asymmetric energy distribution** favoured

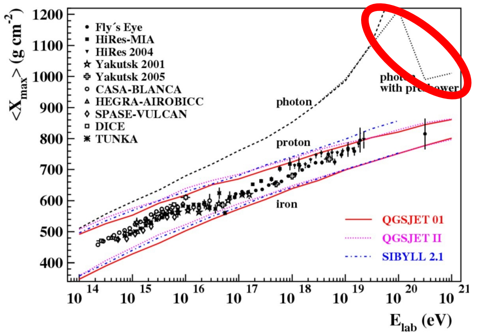


➔ *CORSIKA code (Heck et al. 1998), conditions of 320 EeV Fly's Eye event*

➔ **delayed shower development and large fluctuations !**

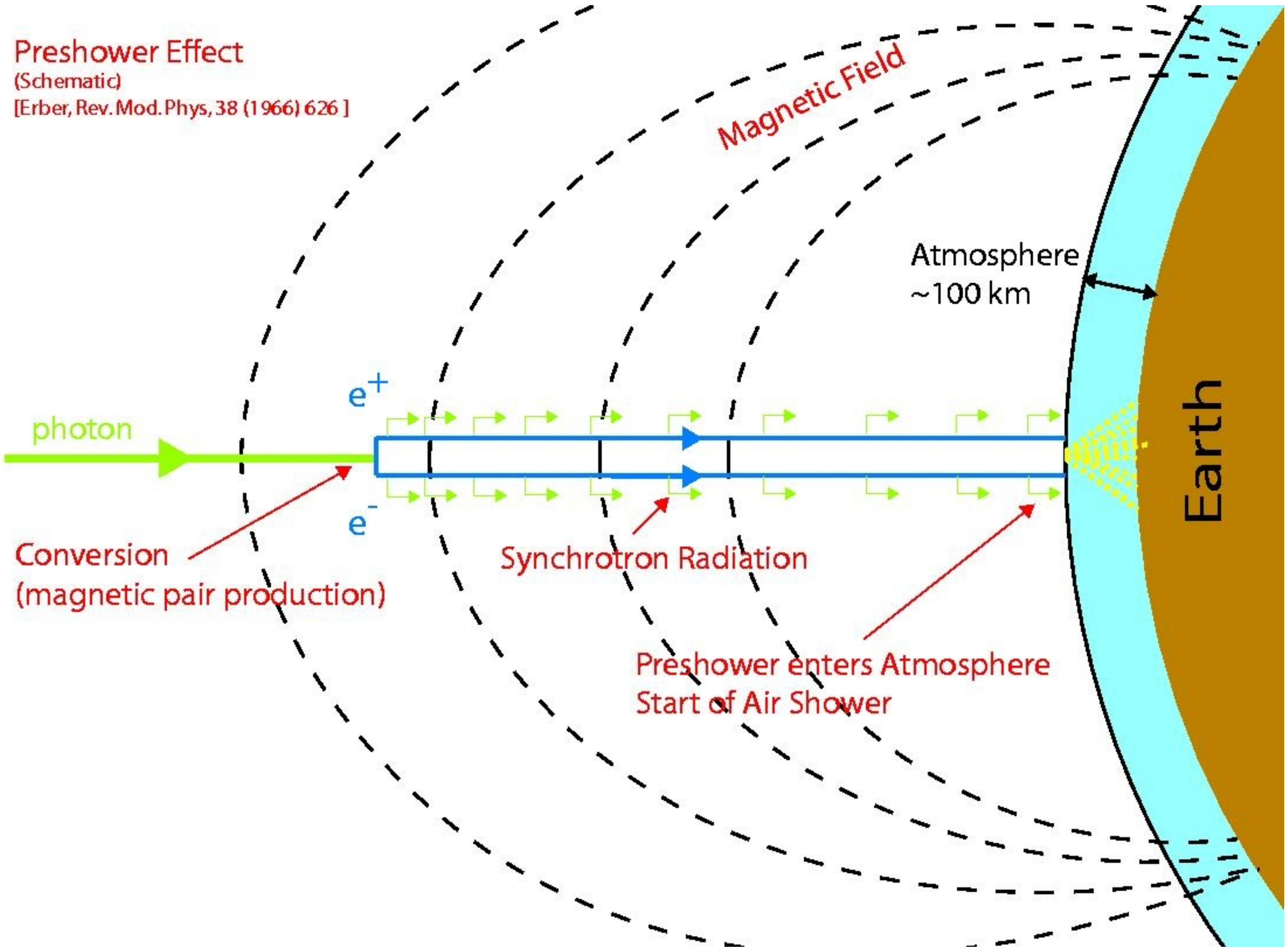
MR et al. (2004)

Photon showers: preshower effect



- **cascade in geomagnetic field** before “normal“ air shower
- **depends on photon energy and arrival direction!**

  -> PRESHOWER code: Homola et al. 2005



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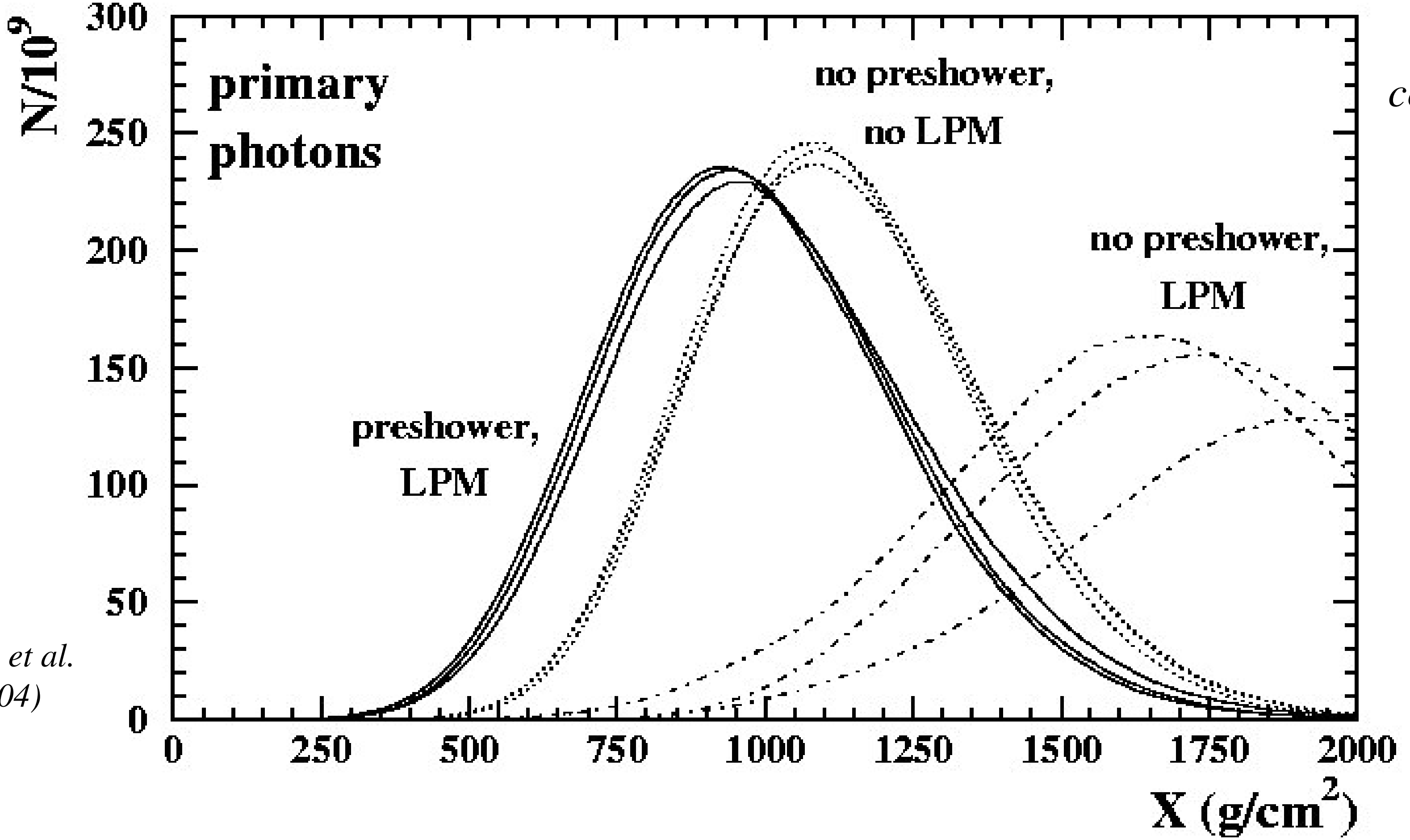


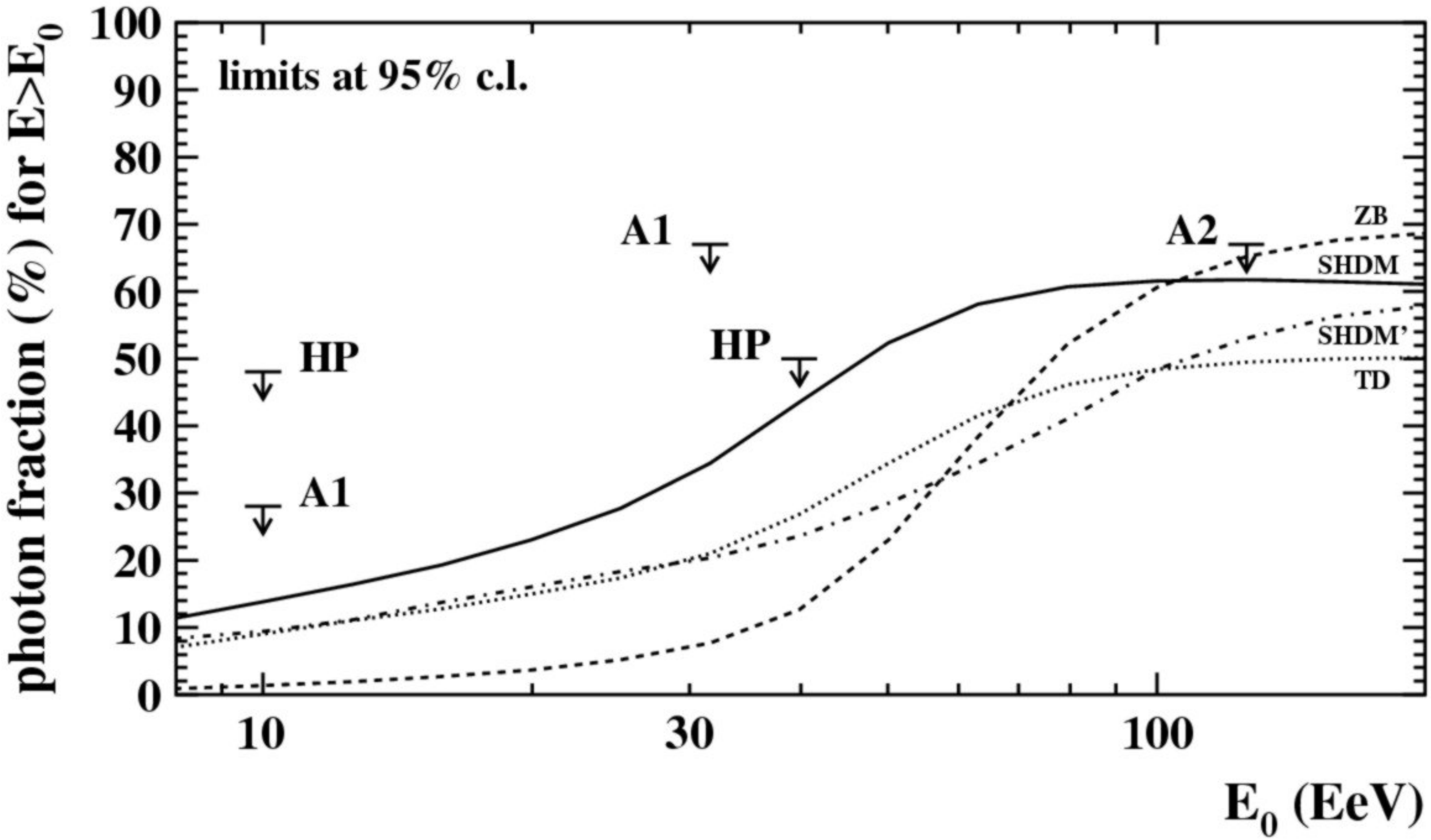
conditions of 320 EeV Fly's Eye event

MR et al. (2004)

- faster shower development, smaller fluctuations
- → **competition of LPM and preshower !**
- → precise calculations needed for individual event

-> experimental status ...

UHE photons: status in 2005



HP: Haverah Park
Ave et al.,2000; event rates

A1, A2: AGASA
muons @ 1000 m
Shinozaki et al., 2002;
MR et al., 2005

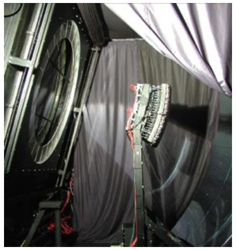
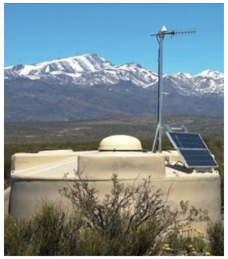
Models:
ZB,SHDM,TD-Gelmini et al. 2005
SHDM' – Ellis et al., 2005

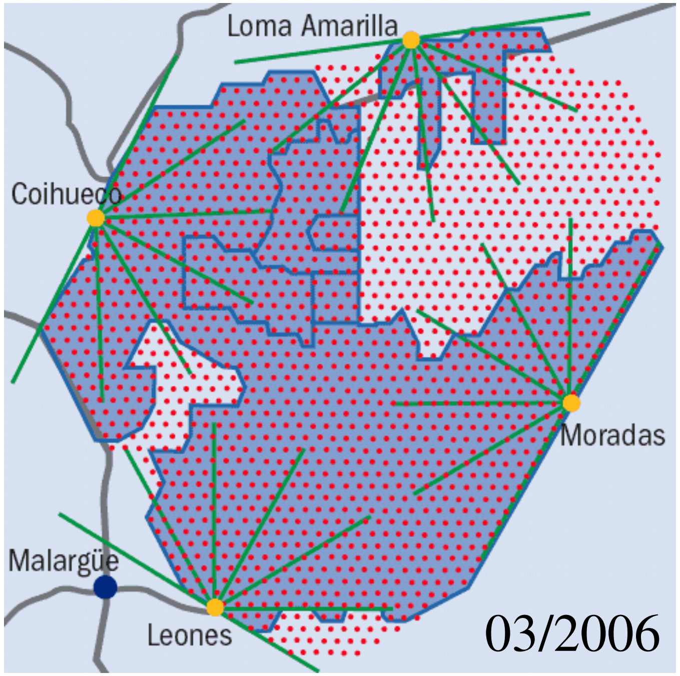
- cosmic-ray photon fraction: check non-acceleration models
- upper limits so far: **surface detectors only** !?
- needed: **cross-check by fluorescence technique** (X_{max} in *hybrids*)

Analysis overview (1)

Auger, astro-ph/0606619

- data set: 01/2004 – 02/2006 (150 -> 950 tanks, total 12 telescopes)
- hybrid reconstruction (geometry, energy, X_{max})

hybrid =  + 



- quality cuts (but: bias to photons)
- fiducial volume cuts

→ *29 events above 10 EeV*

reconstruction based on ...

-> end-to-end calibration of telescopes *(Brack et al. 2005)*

-> monitoring of local atmosphere *(Roberts et al., Keilhauer et al. 2005)*

- monthly density profiles

- average aerosol model

- no clouds

Analysis overview (2)

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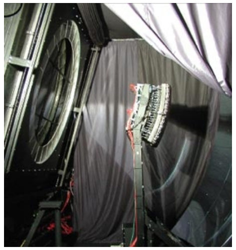
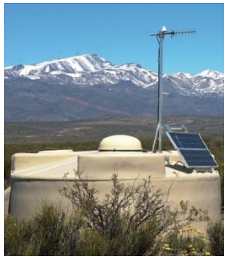
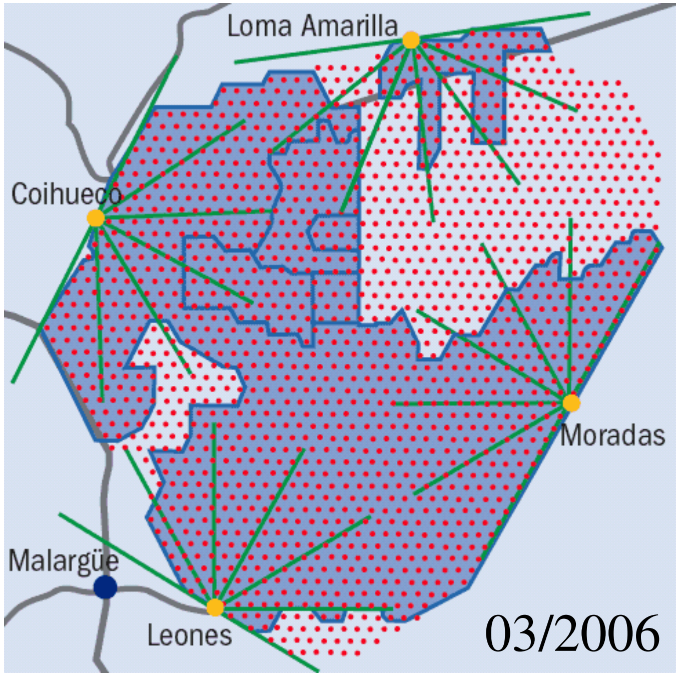
hybrid =  + 



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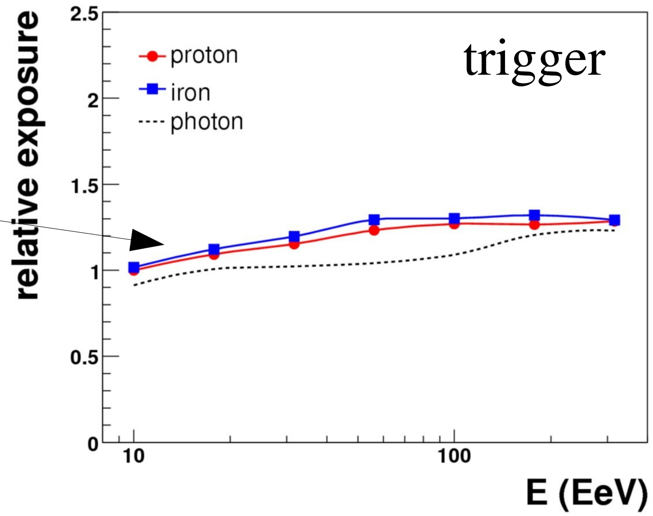
➔ *29 events above 10 EeV*

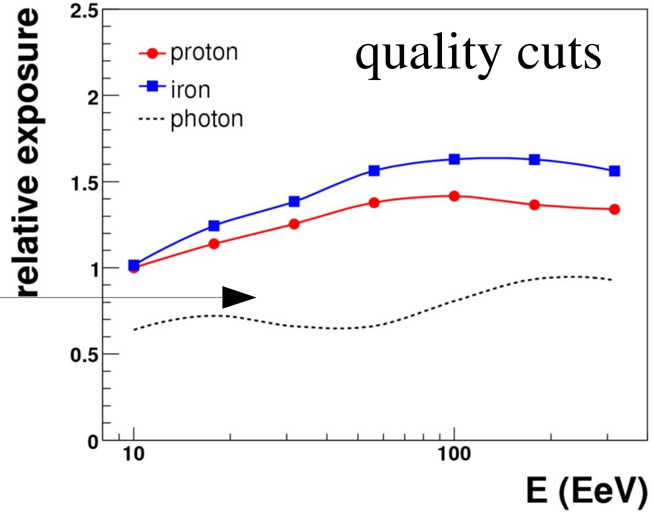
- for each event: simulate photon X_{max} distribution (PRESHOWER+CORSIKA)
- compare data & simulation => (statistical method:) photon limit
- correction of limit for detector acceptance

Data cuts & bias to photons

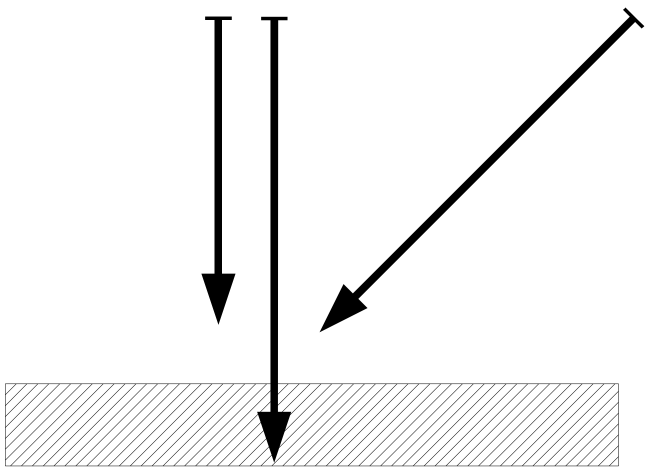
- after **trigger** ~OK: no large bias to photons



- **quality cuts:**
  - d(axis-tank) < 1.5 km, dt(SD,FD) < 300 ns
  - >5 phototubes triggered by shower
  - profile fit: $\chi^2 / n < 6$
  - χ^2(Gaisser-Hillas) / χ^2(line) < 0.9
  - minimum viewing angle >15 deg
  - **X_{max} observed:** necessary, but bias to photons !



- **X_{max} (~1000 g cm^{-2}) below ground (~880 g cm^{-2}) for near-vertical photons !**



- **fiducial volume cuts ...**

Data cuts & bias to photons

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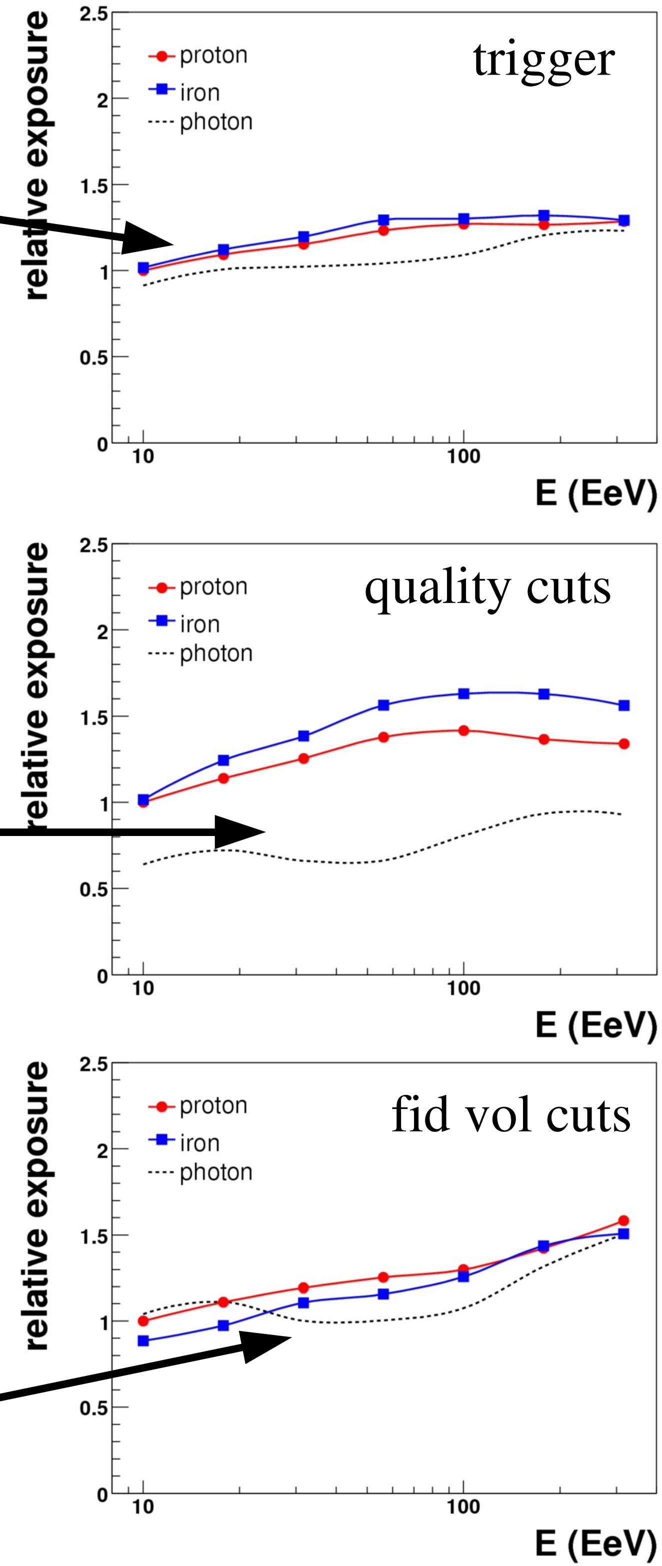
  - **X_{max} observed:** necessary, but bias to photons !
- **fiducial volume cuts:**

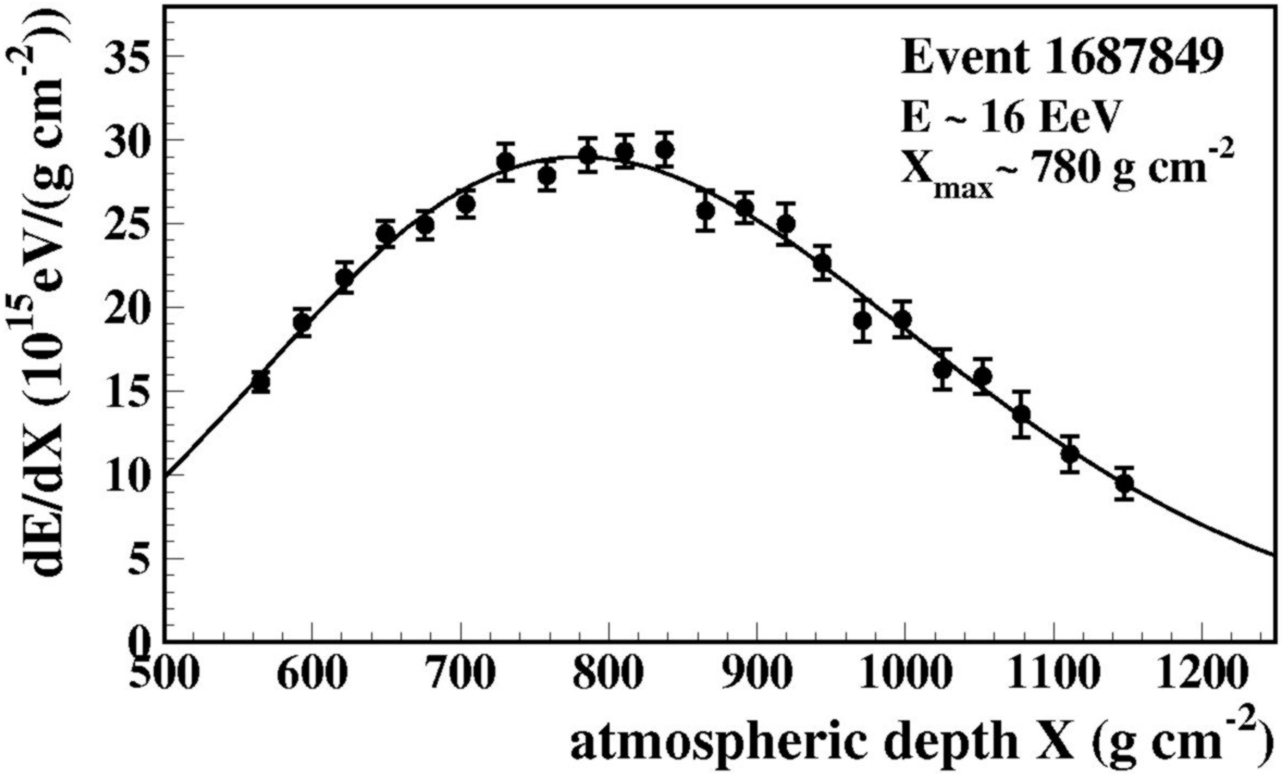
$$\theta > 35^\circ + g_1(E),$$
with $g_1(E) = 10^\circ \cdot (\lg E/\mathrm{eV} - 19.0)$ for $\lg E/\mathrm{eV} \leq 19.7$, else $g_1(E) = 7^\circ$

$$d\ (\text{eye-core}) < 24\ \text{km} + g_2(E),$$
with $g_2(E) = 12\ \text{km} \cdot (\lg E/\mathrm{eV} - 19.0)$.

- no large bias to photons, acceptance ~ flat
- minimum ratio (photon / nuclear primaries) ~ 0.80



Example of observed profile



constrained 4-param.
Gaisser-Hillas fit
(Unger et al., in prep.)

- **calorimetric energy** from integration
- 1% **missing energy** correction, suitable for primary photons *(Pierog et al., 2005)*
  - energy scale for photons
  - *underestimates* slightly (~7-14%) energy of hadron primaries
  - conservative photon limit! (data sample slightly *depleted* from hadron primaries)

X_{max} uncertainty

- here: conservative estimate used for all 29 selected events

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

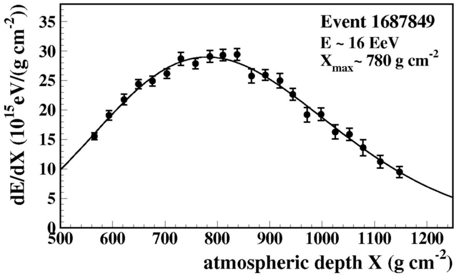
energy *(input for photon simulation):* ***~25% syst. unc.*** (→ Reconstructed energy of event, 13)

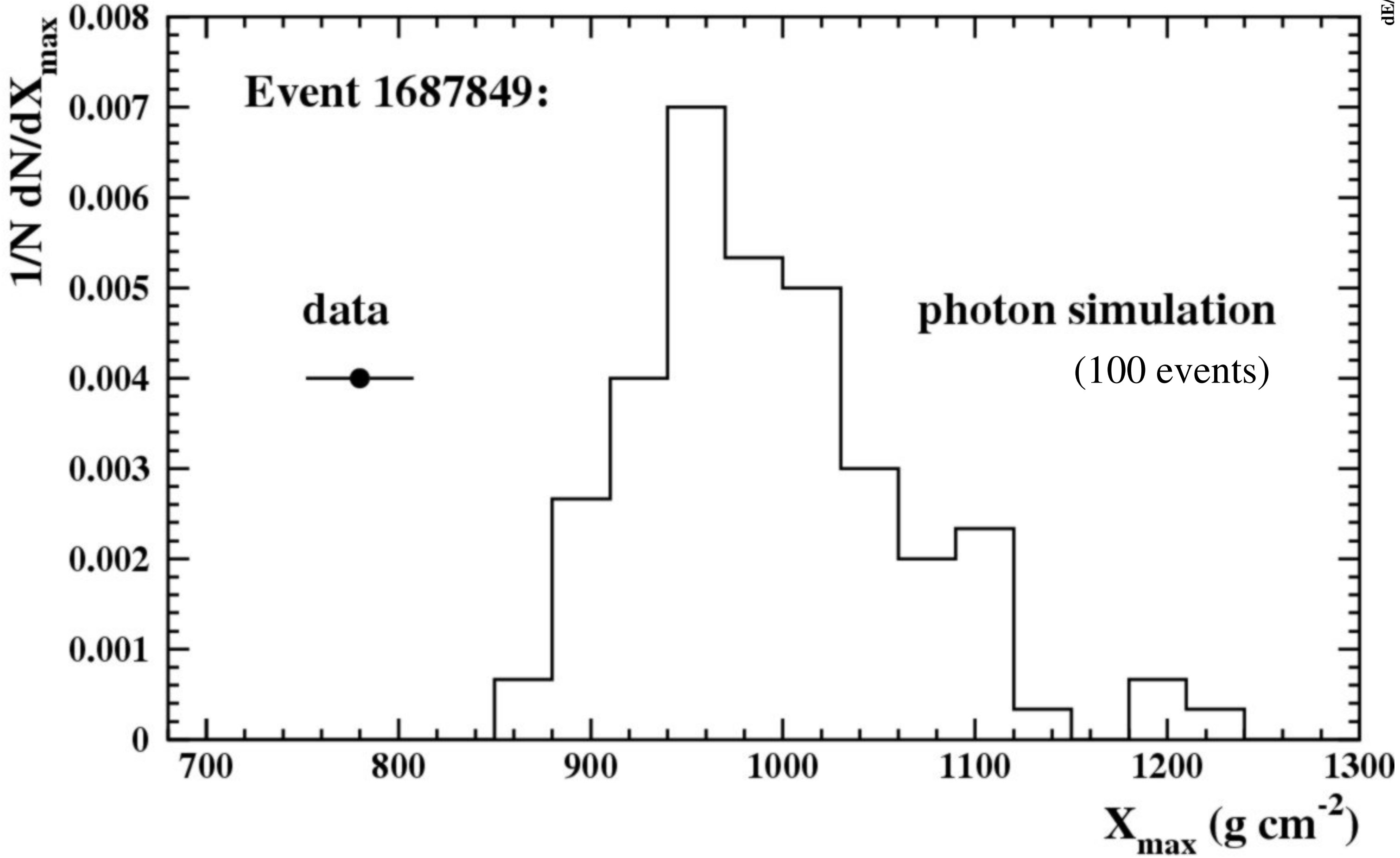
a big advantage of this analysis! (→ Hadron generator, 5)

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

→ analysis **not limited by measurement uncertainty**

Example: data vs photon simulation





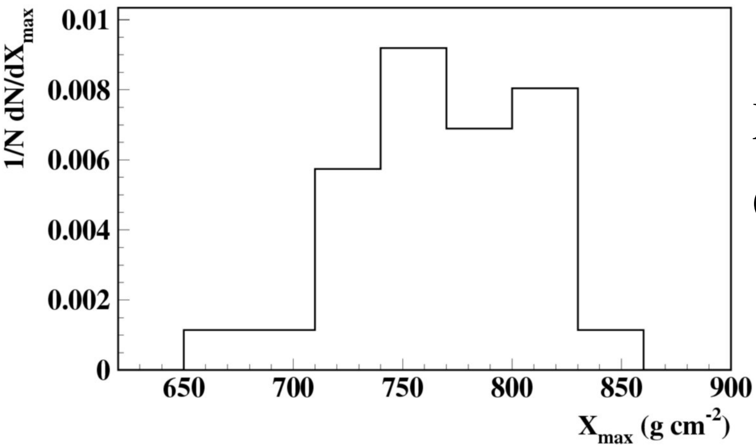
- event: $X_{max} = 780 \pm 28$ (stat) ± 23 (syst) g cm^{-2}
- photons: $\langle X_{max} \rangle = 1000$ g cm^{-2} , rms = 71 g cm^{-2}

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

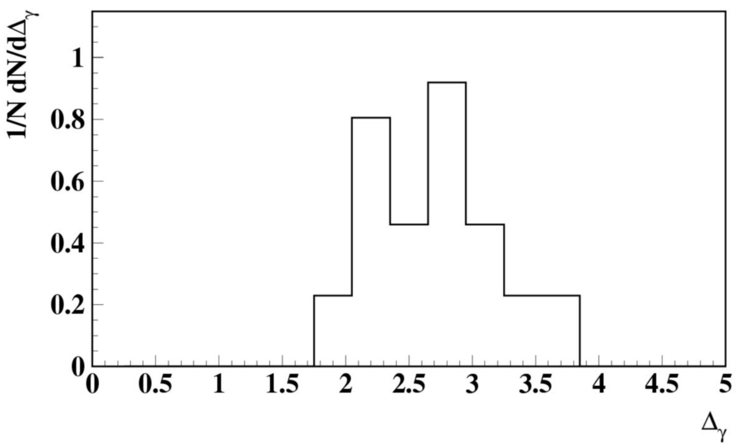
The data set: overview

(astro-ph/0606619)

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



X_{max} range: 678-831 g cm^{-2}



photon vs data: 2.0-3.8 st.dev.

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

- probability (29x photons) << 10^{-10}
- set limit to photon fraction

Statistical treatment

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

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

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

probability that ...

... data set contains n_γ photons

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

... n_γ-$n_{\rm m}$ "non-photons" yield χ^2 values ≥ than in data

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

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

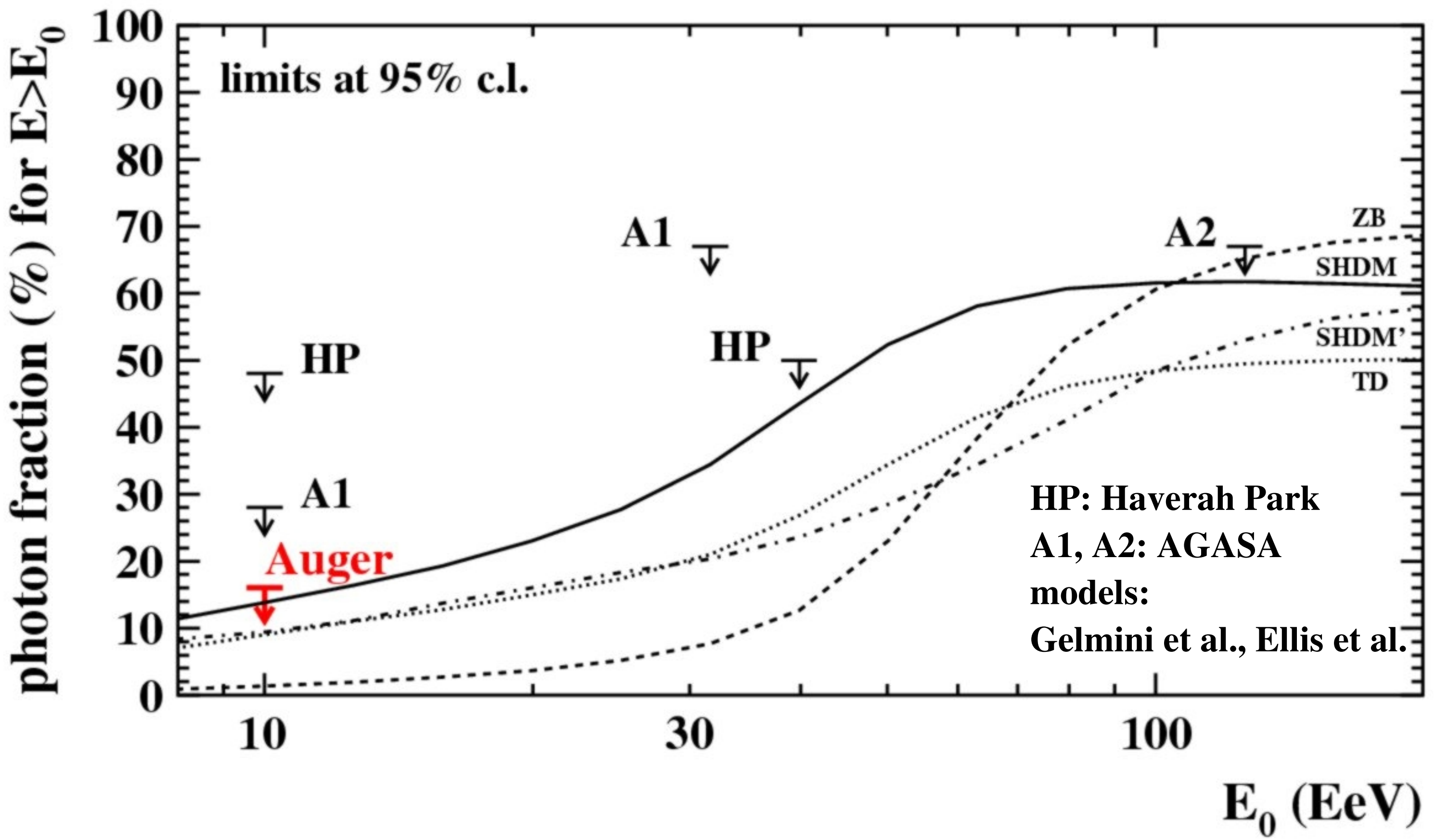
$p_{\overline{\gamma}}(n_{\rm m} - n_\gamma)$: are set to unity (no test on "non-photons")

$p_\gamma(n_\gamma)$: 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**

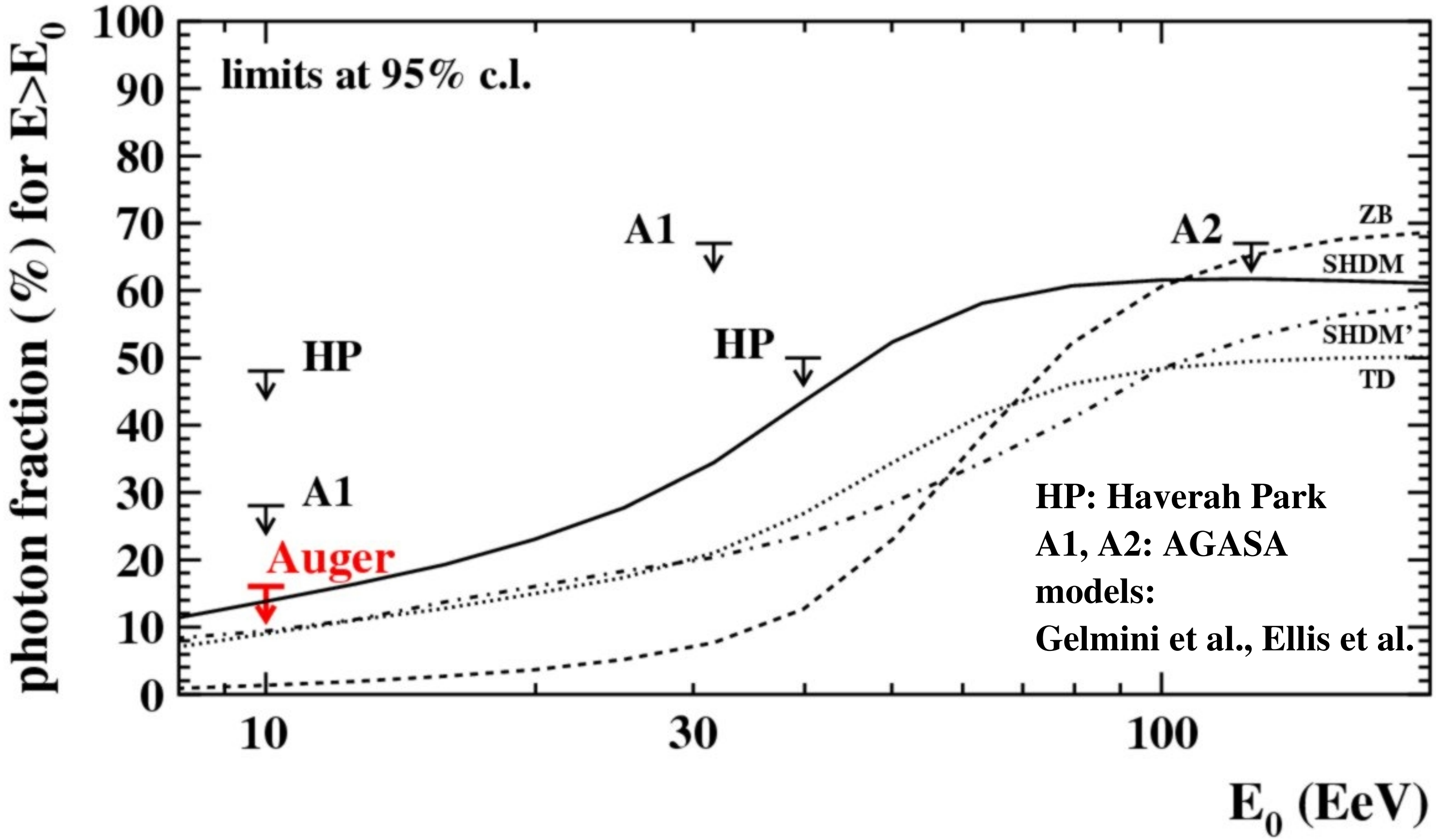
ε=0.80: efficiency correction from photon acceptance (conservative: minimum ratio)

Auger photon limit



- **16% upper limit** (95% c.l.) to cosmic-ray photon fraction
- confirms and improves on previous limits above 10^{19} eV

Prospects (1): same method, more data



- factor ~10 more hybrid data within 2-3 years
- assume similar X_{max} distribution as observed so far

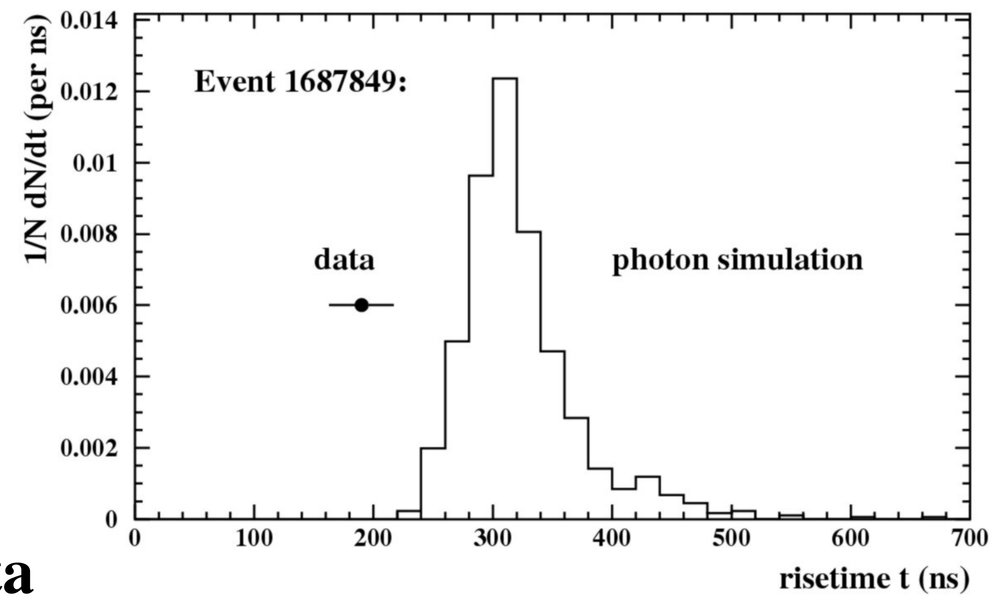
→ sensitivity down to photon fractions of **~5%** above 10 EeV

→ similar statistics and sensitivity as now **(~16%)** above 30-35 EeV

Prospects (2): data from ground array

- here: array only for geometry reconstruction in *hybrids*
- for ≥3 detectors, standard array reconstruction possible; e.g.:
  - ➔ **risetime** of detector signal at 1000 m core distance
    - *plot: data below photon prediction*

➔ photon discrimination with array



- array alone: **factor ~10 more data**
  - *caveat:* acceptance and energy reconstruction of photons
  - *work in progress*

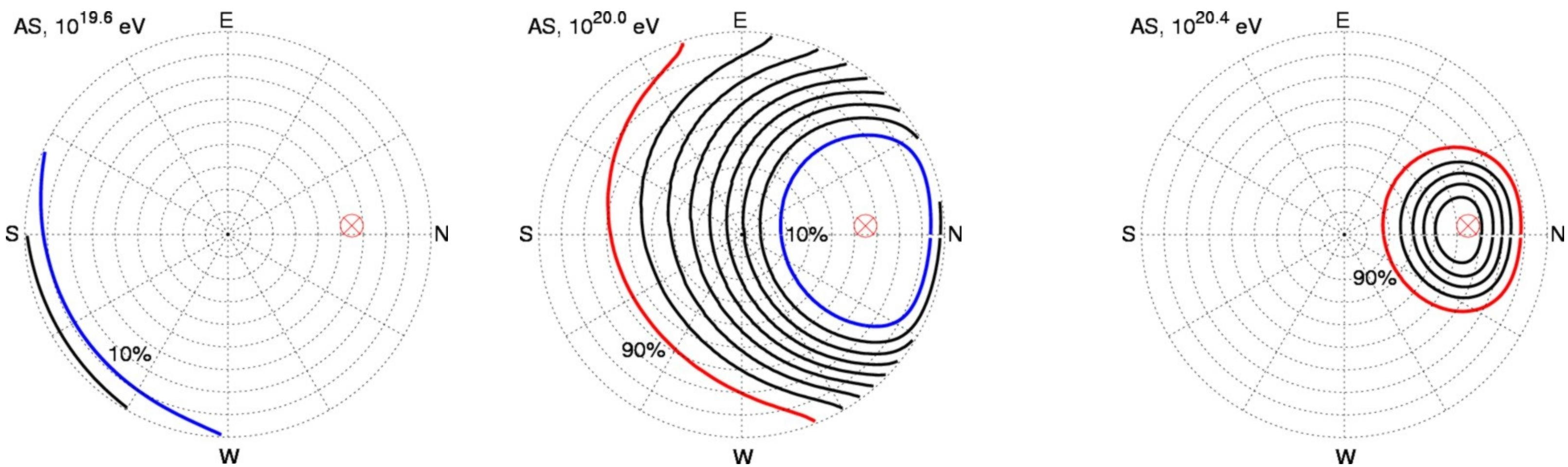
Prospects (3): Auger South vs North

Homola et al. astro-ph/0608101

probability for preshower from UHE photons at ...

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

Auger South



Auger North (Colorado): **full sky coverage**

also: *magnetic fields differ* between Auger South and North

➔ *preshower characteristics of UHE photons differ !*

Prospects (3): Auger South vs North

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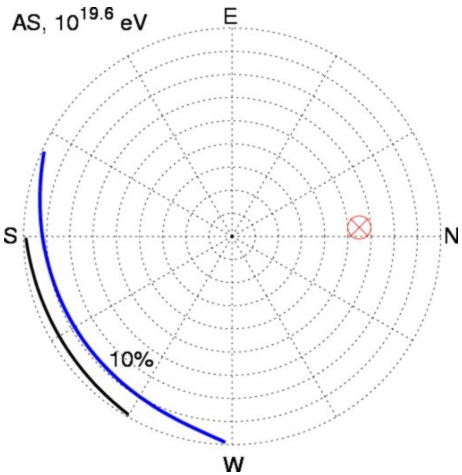
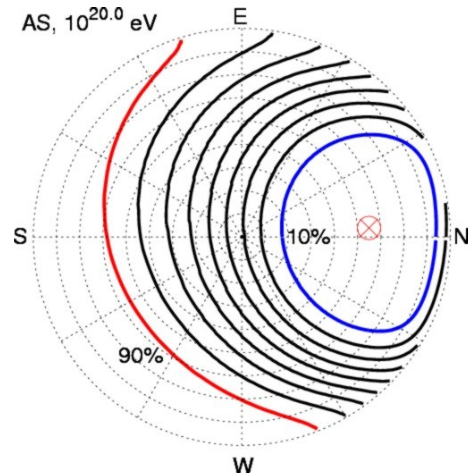
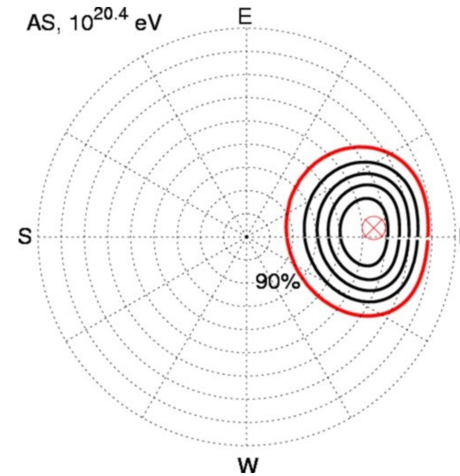
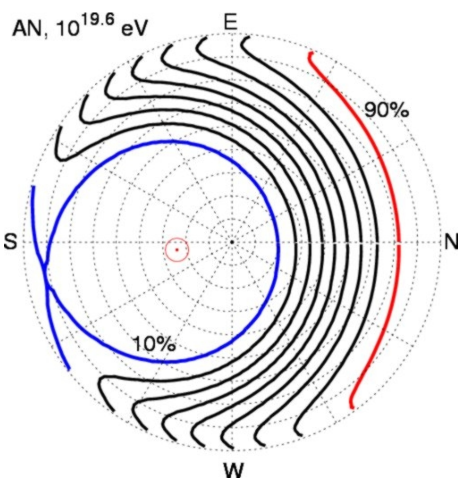
Auger South







Auger North



preshower at North ...

"starts" at smaller energy

(factor 2 stronger field)

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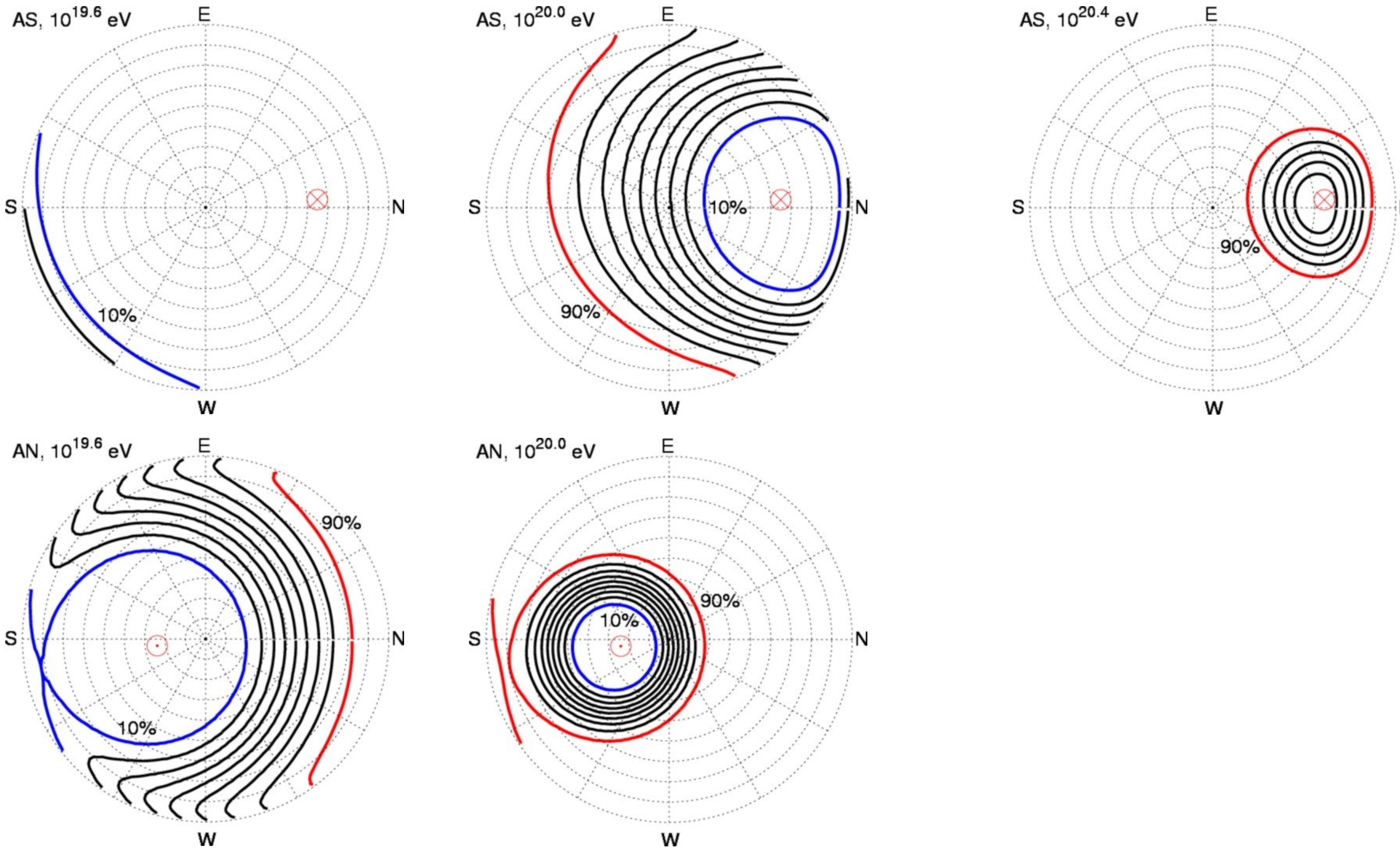
Auger South

Auger North



preshower at North ...

“starts“ at smaller energy
(factor 2 stronger field)

shift of sky pattern
(different field direction)

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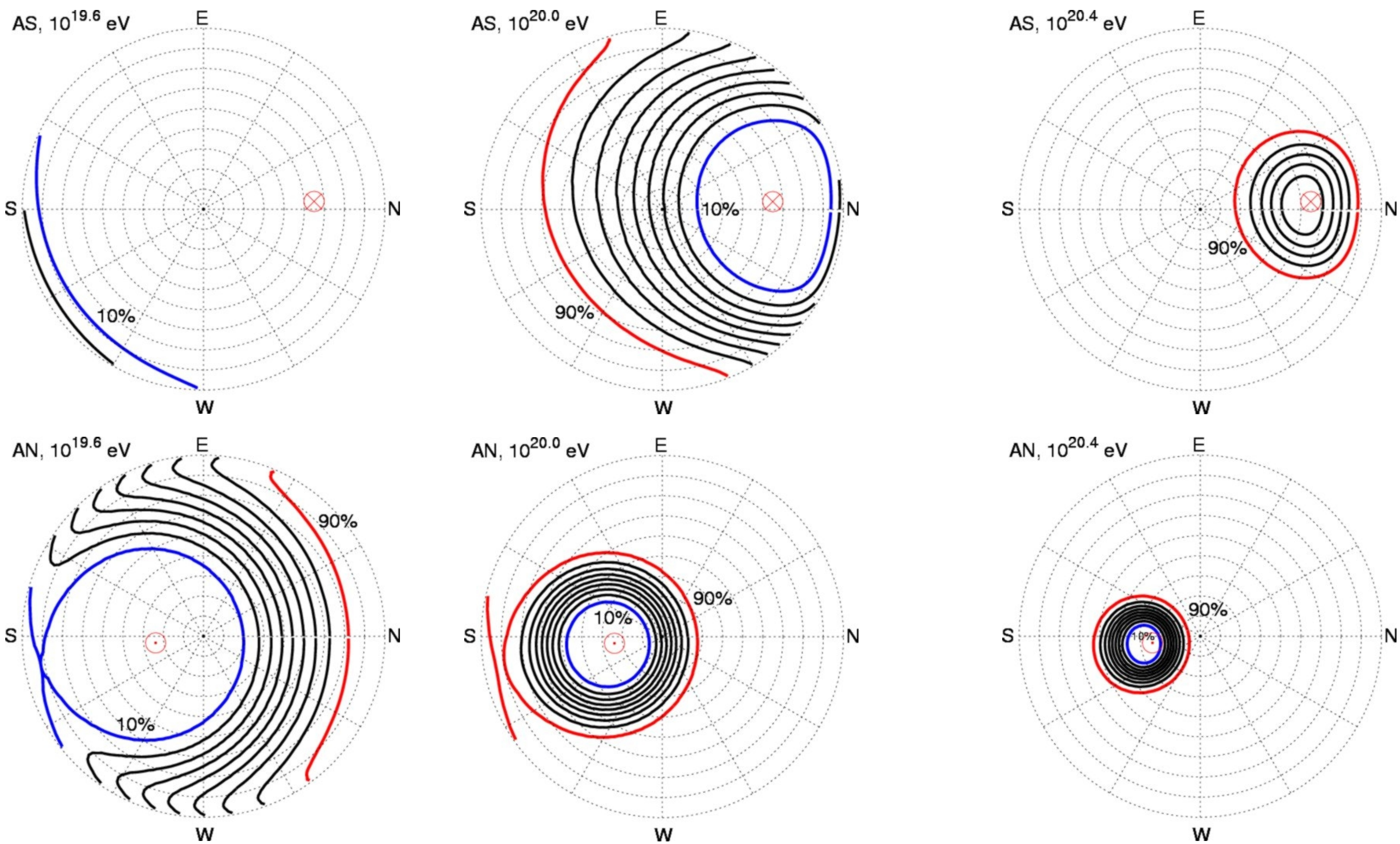
Auger South

Auger North



preshower at North ...

“starts“ at smaller energy
(factor 2 stronger field)

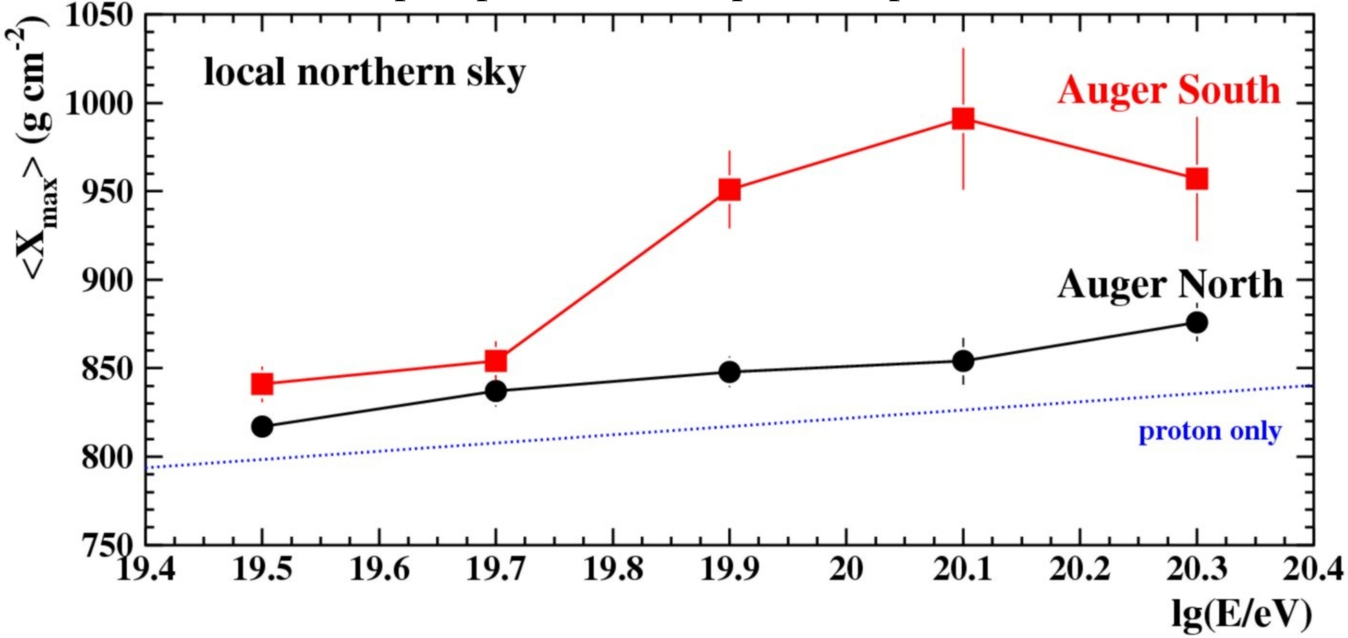
shift of sky pattern
(different field direction)

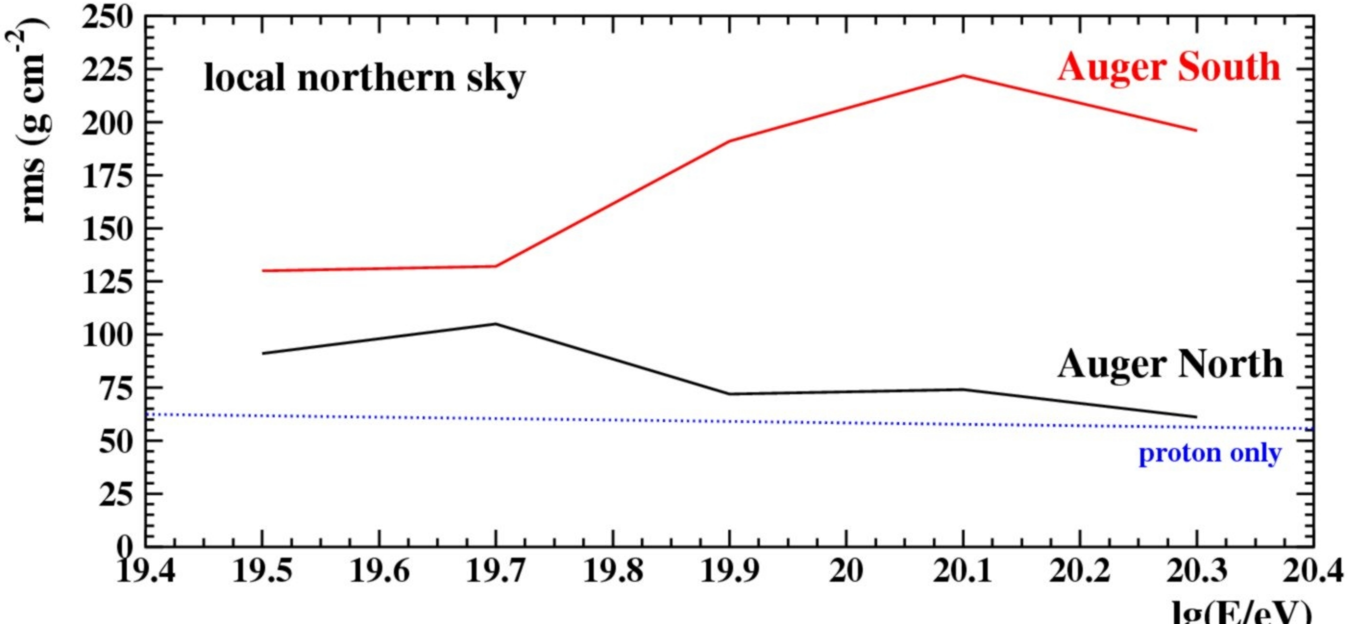
“ends“ at higher energy
(field line less curved)

Auger North and South: take local northern sky

Homola et al.
astro-ph/0608101

input spectra: diffuse proton + photons from TD model





- here: more converted photons at Auger North
- smaller X_{max} + rms
- opposite for other sky regions
- **same cuts, different signal**
- if photons at Auger South, possible **confirmation** with Auger North using preshowering

Conclusions

- **UHE photons**
  - “smoking gun“ for *exotic scenarios*
  - at a smaller level, *GZK photons* expected
- **Auger data analysis**
  - careful study of cuts and possible bias to photons
- **16% upper limit** (95% c.l.) to photon fraction $>10^{19}$ eV
  - first photon limit using fluorescence technique (X_{max})
  - confirms and improves (factor ~2) on previous limits from arrays
- **prospects** for photons are bright at Auger ...
  - hybrid statistics: factor ~10 within ~2-3 years
  - array alone: factor ~10 more data (work in progress)
  - Auger North vs South: complementary search for UHE photons

Acceptance correction

diff. fluxes $\Phi_\gamma(E), \Phi_i(E),\ i = p, He, \ldots$

We want: upper limit UL to true photon fraction above E_0 :

$$UL \ > \ F_\gamma = \int_{E_0} \Phi_\gamma(E)dE \ / \ (\int_{E_0} \Phi_\gamma(E)dE + \sum_i \int_{E_0} \Phi_i(E)dE)$$

however, from data: upper limit UL' to measured fraction :

$$F'_\gamma = \int_{E_0} A_\gamma(E)\Phi_\gamma(E)dE \ / \ (\int_{E_0} A_\gamma(E)\Phi_\gamma(E)dE + \sum_i \int_{E_i} A_i(E)\Phi_i(E)dE)$$

with acceptances $A_\gamma(E), A_i(E)$,
and effective threshold $E_i = E_0 \cdot \frac{m_i}{m_\gamma}$, (missing energies m_γ, m_i)

$\Rightarrow$ need correction ϵ such that $\quad UL'/\epsilon = UL > F_\gamma$

Acceptance correction

Upper limit UL' to measured fraction :

$$UL' > \int_{E_0} A_\gamma(E)\Phi_\gamma(E)dE / (\int_{E_0} A_\gamma(E)\Phi_\gamma(E)dE + \sum_i \int_{E_i} A_i(E)\Phi_i(E)dE)$$

Since $E_i = E_0 \cdot \frac{m_i}{m_\gamma} > E_0$, with $m_\gamma \simeq 1.01, m_i \simeq 1.07 - 1.14$:

$$> \int_{E_0} A_\gamma(E)\Phi_\gamma(E)dE / (\int_{E_0} A_\gamma(E)\Phi_\gamma(E)dE + \sum_i \int_{E_0} A_i(E)\Phi_i(E)dE)$$

Define efficiency ratio $\epsilon_i(E) = A_\gamma(E)/A_i(E)$:

$$= \int_{E_0} A_\gamma(E)\Phi_\gamma(E)dE / (\int_{E_0} A_\gamma(E)\Phi_\gamma(E)dE + \sum_i \int_{E_0} \frac{A_\gamma(E)}{\epsilon_i(E)}\Phi_i(E)dE)$$

With $A_\gamma \simeq$ const (fiducial volume cuts!) :

$$\simeq \int_{E_0} \Phi_\gamma(E)dE \ / \ (\int_{E_0} \Phi_\gamma(E)dE + \sum_i \int_{E_0} \frac{1}{\epsilon_i(E)}\Phi_i(E)dE)$$

Take minimum ratio $\epsilon_{\min} \simeq 0.80 \leq \epsilon_i(E)$:

$$> \int_{E_0} \Phi_\gamma(E)dE \ / \ (\int_{E_0} \Phi_\gamma(E)dE + \frac{1}{\epsilon_{\min}} \sum_i \int_{E_0} \Phi_i(E)dE)$$

Since $1/\epsilon_{\min} > 1$:

$$> \int_{E_0} \Phi_\gamma(E)dE \ / \ (\frac{1}{\epsilon_{\min}} \int_{E_0} \Phi_\gamma(E)dE + \frac{1}{\epsilon_{\min}} \sum_i \int_{E_0} \Phi_i(E)dE)$$

$$= \epsilon_{\min} \int_{E_0} \Phi_\gamma(E)dE \ / \ (\int_{E_0} \Phi_\gamma(E)dE + \sum_i \int_{E_0} \Phi_i(E)dE)$$

$$= \epsilon_{\min} \cdot F_\gamma$$

$$\Leftrightarrow UL = UL'/\epsilon_{\min} > F_\gamma \quad \text{(conservative)}$$

Conservative correction for detector acceptance

-> limit independent of specific input spectra !

-> for given model, (smaller) correction can be calculated.

Not much smaller, since epsilon_min~0.8