Was the highest energy cosmic ray a photon?

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contents:

- studies on photons as UHECR: motivation
- analysis tools for identification of photons
- the Fly's Eye highest energy cosmic ray: a photon?
- applications to the future UHECR data (AUGER)

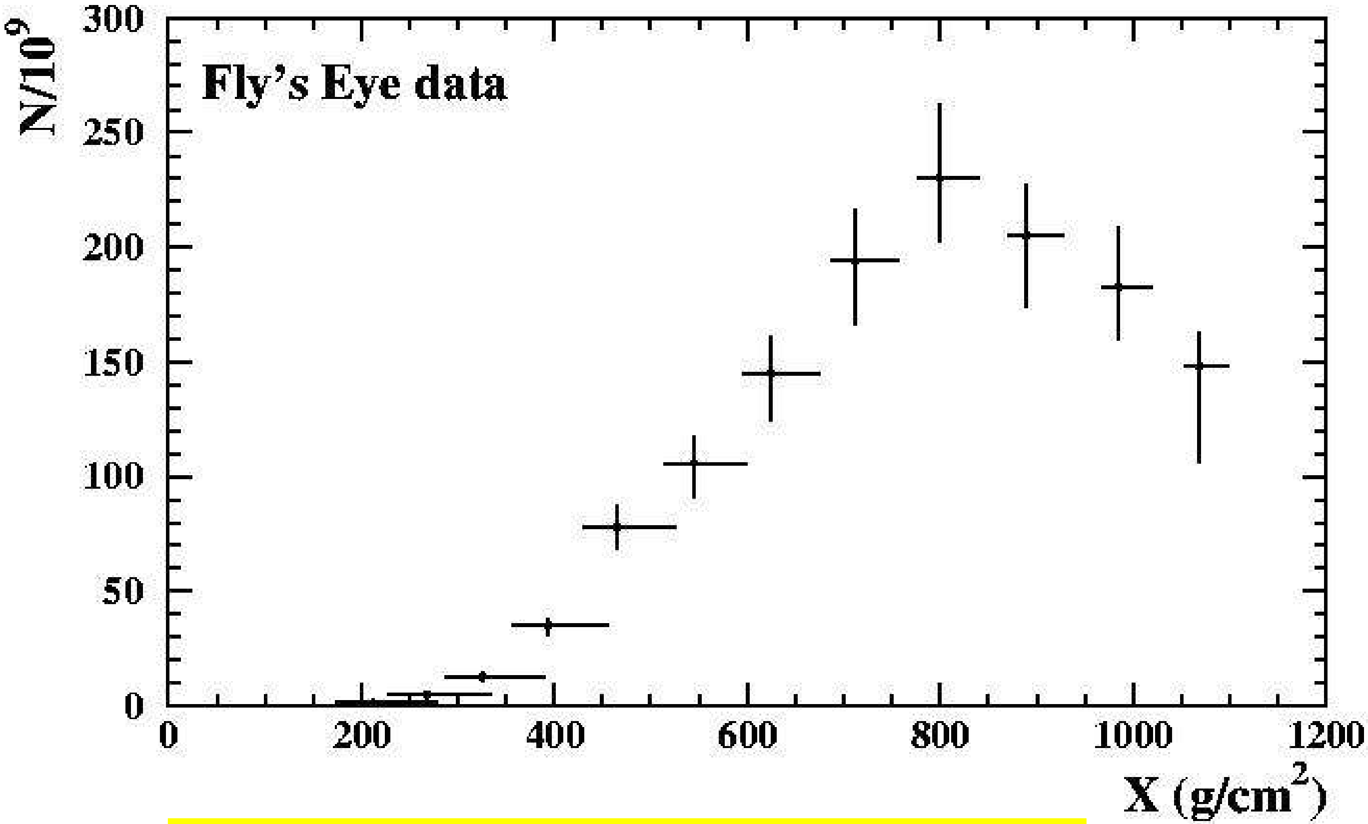
Studies on photons as UHECR: motivation

- if UHE photons reach Earth
  → indication of an exotic “top-down” model of cosmic ray origin (e.g. annihilation of topological defects)

- if no UHE photons in cosmic ray flux
  → indication for an acceleration scenario

- identification of photon primaries, measurment of the UHE photon flux, or specifying the upper limit for it
  → excellent test for the models of cosmic-ray origin

The highest energy shower : Fly's Eye, Utah, 15 Oct 1991



Bird et al., ApJ 441 (1995) 144:

- final reconstruction
- best fit: mid size nucleus
- any hadron OK

Halzen et al., Astropart. Phys. 3 (1995) 151 :

- "event not initiated by γ"

this work:

- PRESHOWER + CORSIKA simulations
- photon primary not excluded

Energy [10^{18} eV]:	320^{+92}_{-94}
X_{max} [g/cm^2]:	815^{+60}_{-53}
zenith angle [deg]:	$43.9^{+1.8}_{-1.3}$
azimuth angle [deg]:	$31.7^{+4.2}_{-6.1}$

Identification of photons as UHECR: how to proceed?

- Simulations of UHE photons before they enter the Earth's atmosphere: accounting for creation of preshowers
- Monte-Carlo extensive air shower (EAS) simulations including the Landau-Pomeranchuk-Migdal (LPM) effect
- Search for features of EAS characteristic only for UHE photons as cosmic ray primaries
- Analysis of real data (e.g. collected by Pierre Auger Experiment – good statistics at energies > 10^{20} eV is expected in next few years)

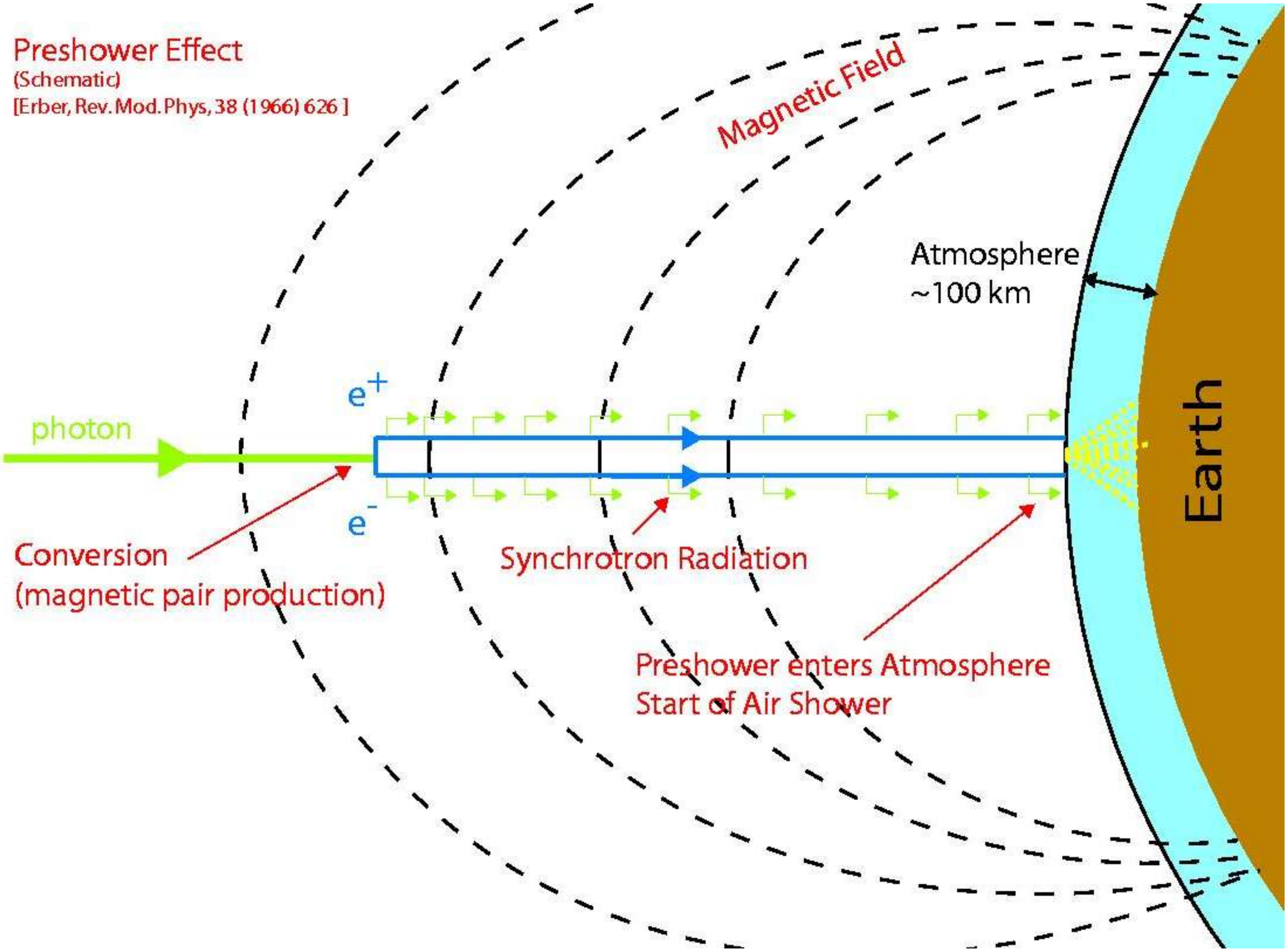
Preshower calculation: important points

details: astro-ph/0311442

- Exact model of the geomagnetic field (here: IGRF Model)
- UHE gamma conversion: $\gamma \rightarrow e^{+}e^{-}$
- Synchrotron radiation: $e^{+/-} \rightarrow \gamma e^{+/-}$
- Negligible effects:
  - deflection of $e^{+/-}$ trajectories in B,
  - γ conversion in Sun's magnetosphere,
  - influence of solar wind,
  - time delay of particles with velocities < c.
- Good approximation: preshower particles have the same trajectory and arrival time at the top of atmosphere.

Note: preshower effect is dependent on $B_{\perp}$ and E_0.

Preshower effect: schematic view



PRESHOWER functionality: Fly's Eye & Auger North

Preshowers at the top of atmosphere above Utah:

	E_0 [eV]	arrival direction	fraction of converted	$\langle N_{part} \rangle$	$\langle N_{e+e-} \rangle$
	5×10^{19}	strong $B_\perp$	984 / 1000	718 ± 296	2.0 ± 0.3
	10^{20}	weak $B_\perp$	0 / 1000	1	0
	10^{20}	strong $B_\perp$	1000 / 1000	1304 ± 256	2.3 ± 0.7
FE ➔	3×10^{20}	$\theta = 43.9^\circ$, $\varphi = 31.7^\circ$	1000 / 1000	1434 ± 332	4.7 ± 1.6
	10^{21}	weak $B_\perp$	918 / 1000	170 ± 72	2.1 ± 0.3
	10^{21}	strong $B_\perp$	1000 / 1000	9865 ± 1224	20.9 ± 3.5

weak $B_\perp$: $\theta = 24^\circ$, $\varphi = 255^\circ$ ($\parallel$ to local **B**); strong $B_\perp$: $\theta = 66^\circ$, $\varphi = 75^\circ$ ($\perp$ to local **B**)

NOTE: gamma conversion probability and N_{part} depend on the arrival direction and E_0.

➔ EAS properties are expected to depend on arrival direction.

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Complete simulation tool: PRESHOWER + CORSIKA

PRESHOWER:
photon propagation and the preshower effect above the atmosphere

Returns energies and types of all the preshower particles at the top of atmosphere (112 km); all the particles have the same trajectory and arrival time.

CORSIKA:
LPM effect included; hadronic interactions: QGSJET 01 and SIBYLL 2.1

Each preshower particle initiates an atmospheric subshower, final EAS is a superposition of all the subshowers induced by preshower particles.

Simulations

Parameters:

Utah, $E_0 = 3\times10^{20}$ eV, $\theta = 43.9^\circ$, $\varphi = 31.7^\circ$, different primaries A_0

➔ only longitudinal profile studied

CORSIKA:

1000 profiles for p, C and Fe (QGSJET 01 & SIBYLL 2.1)

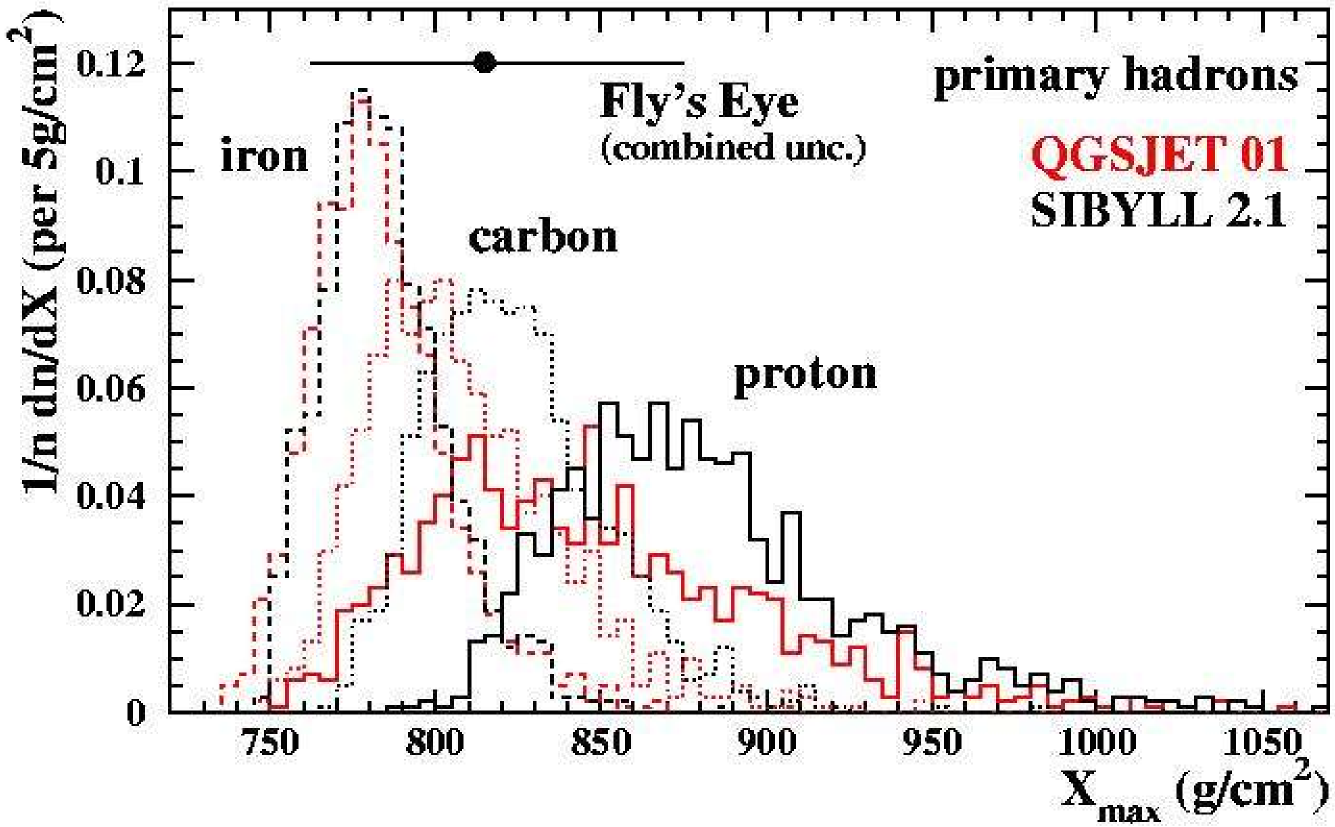
PRESHOWER+CORSIKA:

1000 profiles for γ

➔ compare simulated profiles with data

➔ try to conclude: are any A_0 (dis)favoured?

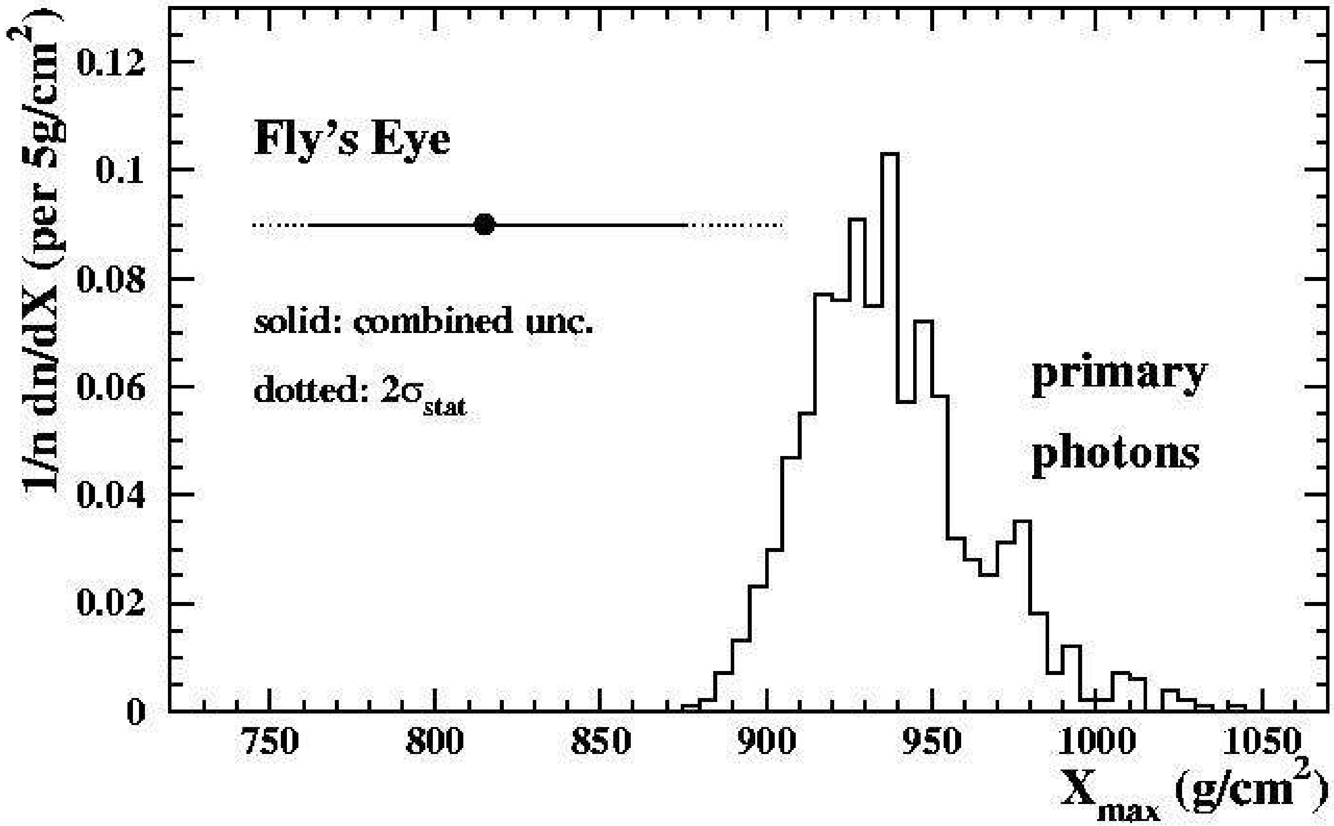
X_{max} – primary hadrons



➔ within experimental uncertainties and shower fluctuations:

every hadron-model combination possible

X_{max} – primary photons



Expected:
$\langle X_{max} \rangle = 937 \pm 26$ g/cm^2

Measured:
$X_{max} = 815^{+60}_{-53}$ g/cm^2

X_{max} – primary photon probability P(γ)

$X_{max} = 815^{+60}_{-53}$ g/cm^2 consistent with photon ?

➔ average X_{max} + experimental statistical uncertainty:

P ($<X_{max}> = 937, \sigma_{stat} = 45$) = 0.7%

➔ shower fluctuations, $P = \frac{1}{n}\sum P_i$:

P (X_{max}-distr., $\sigma_{stat} = 45$) = 1.5%

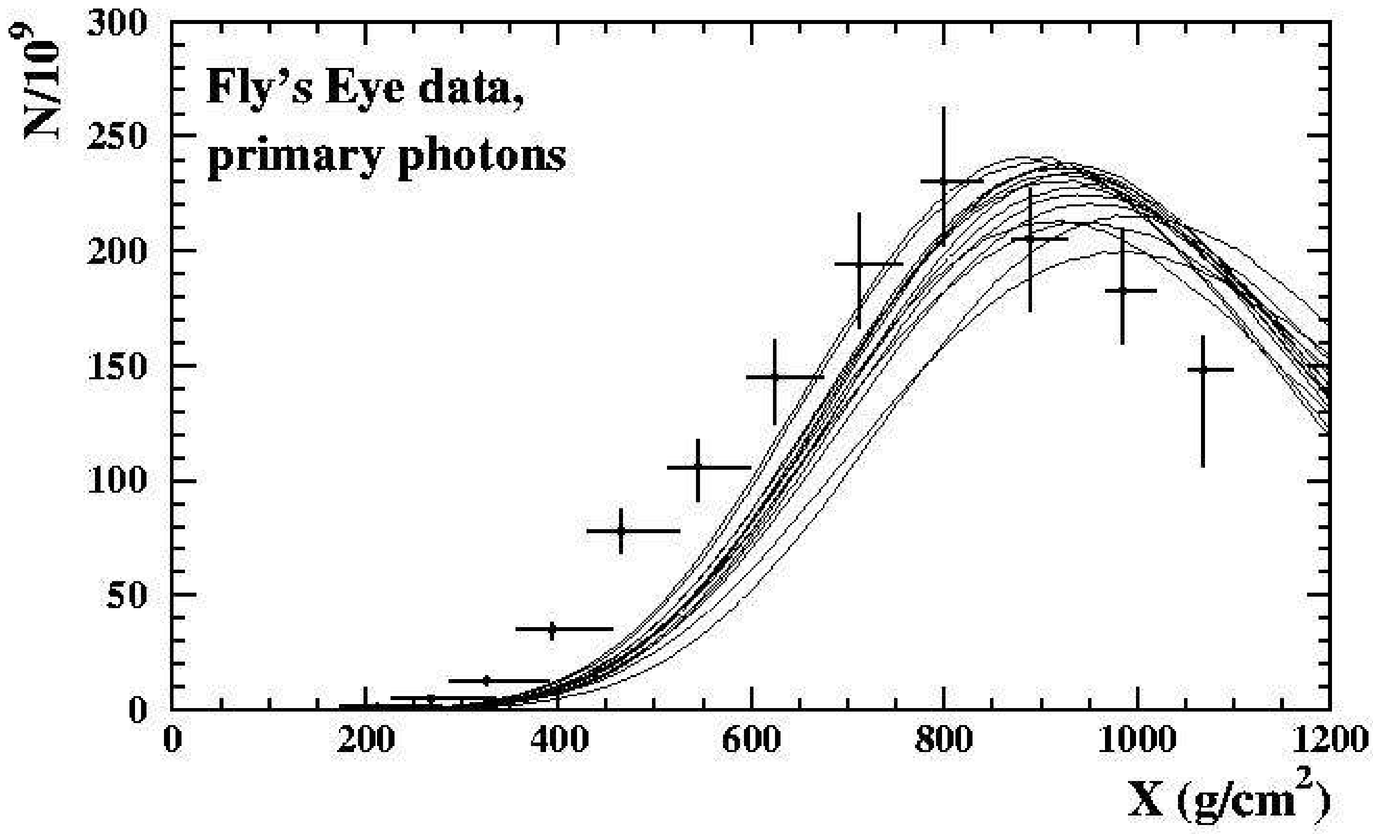
➔ systematic uncertainty:

P(X_{max}-distr., $\sigma = \sqrt{\sigma^2_{syst} + \sigma^2_{stat}} = 60$) = 5.8%

➔ within experimental uncertainties and shower fluctuations:

P(γ) ~ few % : small, but non-negligible!

Complete profile: safe conclusion



Sensitivity to A_0:

X_{max} – yes

N_{max} – no

profile shape – no

safe conclusion:

➔ any hadron/model combination consistent with data,

➔ primary photon hypothesis not favoured by data, but not excluded !

PRESHOWER + CORSIKA: applications for AUGER

profiles of photon-induced EAS for conditions of Malargüe (Auger South):

E_0 [eV]	arrival direction	fraction of converted	$\langle X_{max} \rangle$ [g/cm²]	$\langle RMS(X_{max}) \rangle$ [g/cm²]
5×10^{19}	strong $B_\perp$	1 / 50	1065	90
10^{20}	weak $B_\perp$	1 / 100	1225	175
10^{20}	strong $B_\perp$	91 / 100	940	85
10^{21}	weak $B_\perp$	100 / 100	1040	40
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strong $B_\perp$: $\theta = 53^\circ$, $\varphi = 267^\circ$; weak $B_\perp$: $\theta = 53^\circ$, $\varphi = 87^\circ$

proton: $E_0 = 10^{20}$ eV $\rightarrow X_{max} = 820\pm60$ g/cm²

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- small or negative elongation rates $dX_{max} / dlogE$

Conclusions for Pierre Auger Experiment

good signatures of primary photon:

- very deep X_{max} and large X_{max} fluctuations if photon unconverted
- directional anisotropy in X_{max} and $RMS(X_{max})$
- small or negative elongation rates $dX_{max} / dlogE$

estimate of Auger-FD sensitivity to photon flux (few years' data):

- assume around 40 events at $E_0 > 10^{20}$ eV, no γ detected, primary photon probability $P(\gamma) \cong$ 3% for each event
- hence upper limit of γ flux in cosmic rays ~ 10% (99% c.l.)

➔ <u>serious constraint for exotic CR models</u>!

Identification of photons as UHECR seems possible for AUGER !

SUMMARY and OUTLOOK

Was the highest energy cosmic ray a photon?
Probably not, but this hypothesis cannot be excluded.

We are ready to look for photons in the forthcoming ultra-high energy data.