HELMHOLTZ GEMEINSCHAFT

Allianz für Astroteilchenphysik

RWTH AACHEN UNIVERSITY

bmb+f - Förderschwerpunkt

Astroteilchenphysik

Großgeräte der physikalischen Grundlagenforschung

Search for ultra-high energy photons with the Pierre Auger Observatory

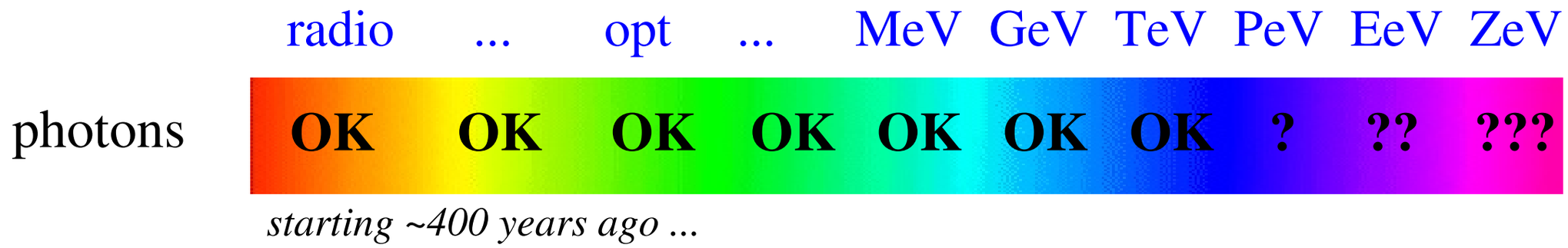
PIERRE AUGER OBSERVATORY

Daniel Kuempel

RWTH Aachen University

HAP Workshop **The Non-Thermal Universe** *Erlangen September 2016*

Search for photons at ultra-high energies



- Photons, as the gauge bosons of the EM force, at such enormous energy are unique messengers and probes of extreme and, possibly, new physics

- UHE photons are a *smoking gun* for non-acceleration models

- UHE photons are important when trying to constrain interaction parameters such as the proton-air-cross-section at energies far beyond LHC energies

- UHE photons point back to the location of their production. Arrival directions may correlate to possible sources

- UHE photons play a role in fundamental physics:
  E.g. they help to constrain Lorentz invariance violation (LIV)

$$\gamma_{\mathrm{UHE}} + \gamma_{\mathrm{b}} \not\Rightarrow e^+ + e^-$$ (more photons expected in LIV)

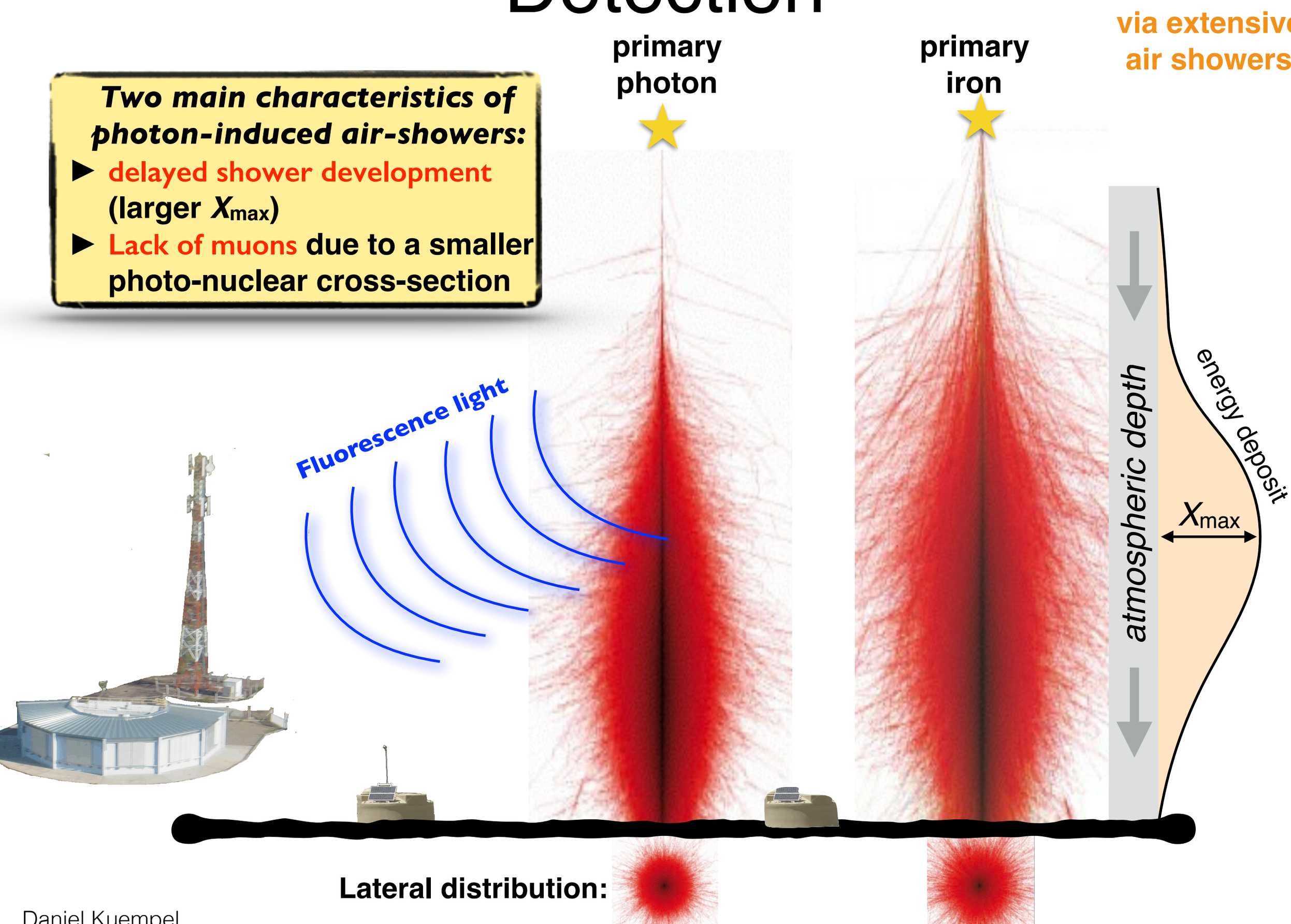
- UHE photons may help to interpret TeV observations

Detection

Measurement via extensive air showers

Two main characteristics of photon-induced air-showers:

- delayed shower development (larger X_{max})
- Lack of muons due to a smaller photo-nuclear cross-section



Auger Photon Searches

1. Diffuse photon searches
2. Directional searches for photon point sources

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1 Search for photons with $E > 10^{19}$ eV

(C. Bleve for the Pierre Auger Collaboration ICRC 2015)

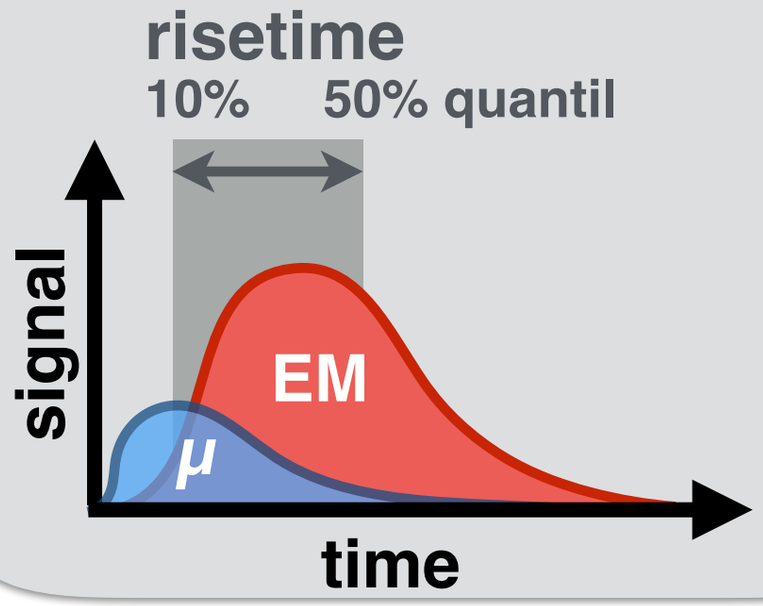
Experimental observables (surface detector)

Risetime:

Time difference between 10% and 50% quantile of signal in surface detector

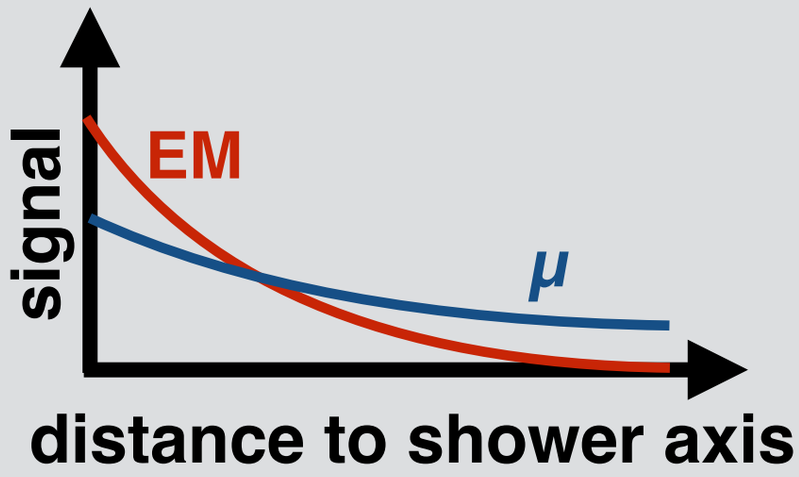
Larger for:

- Signals dominated by EM component
- Deep developing showers



Lateral distribution:

Lateral distribution function (LDF) of EM rich events is steeper compared to average.



For photon searches select events with large risetimes and steep LDF

1 Analysis and photon identification

Observables

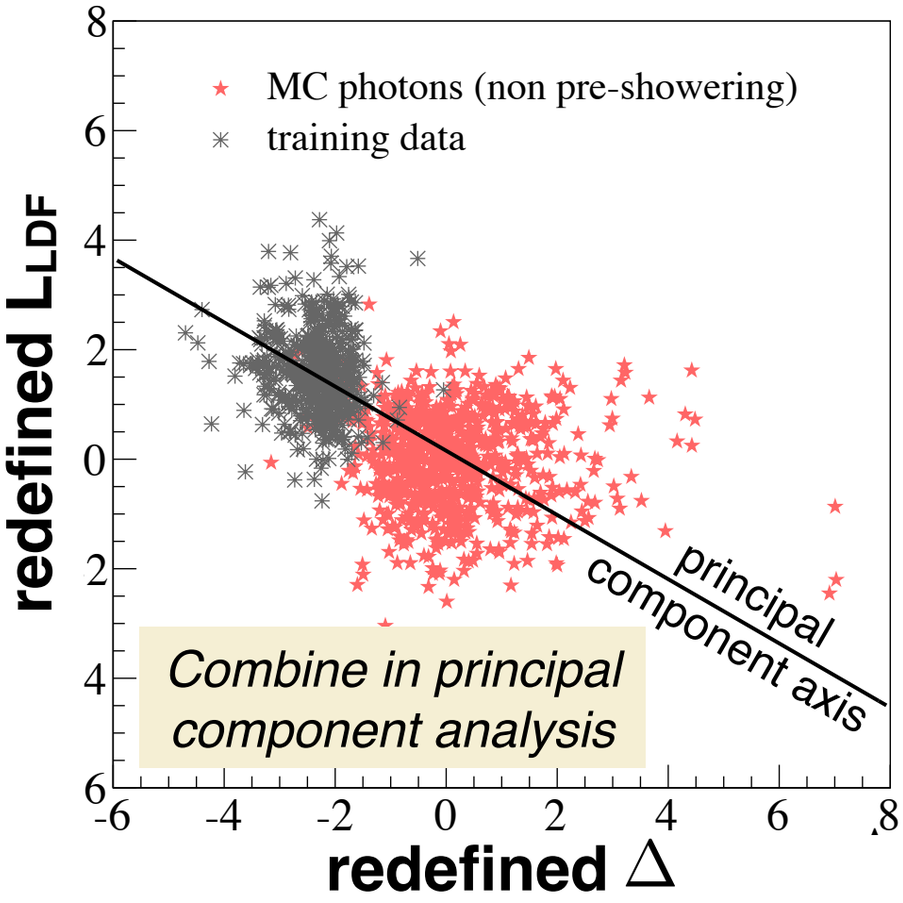
- $L_{\mathrm{LDF}} = \log_{10}\left(\frac{1}{N}\sum_i \frac{S_i}{\mathrm{LDF}(r_i)}\right)$

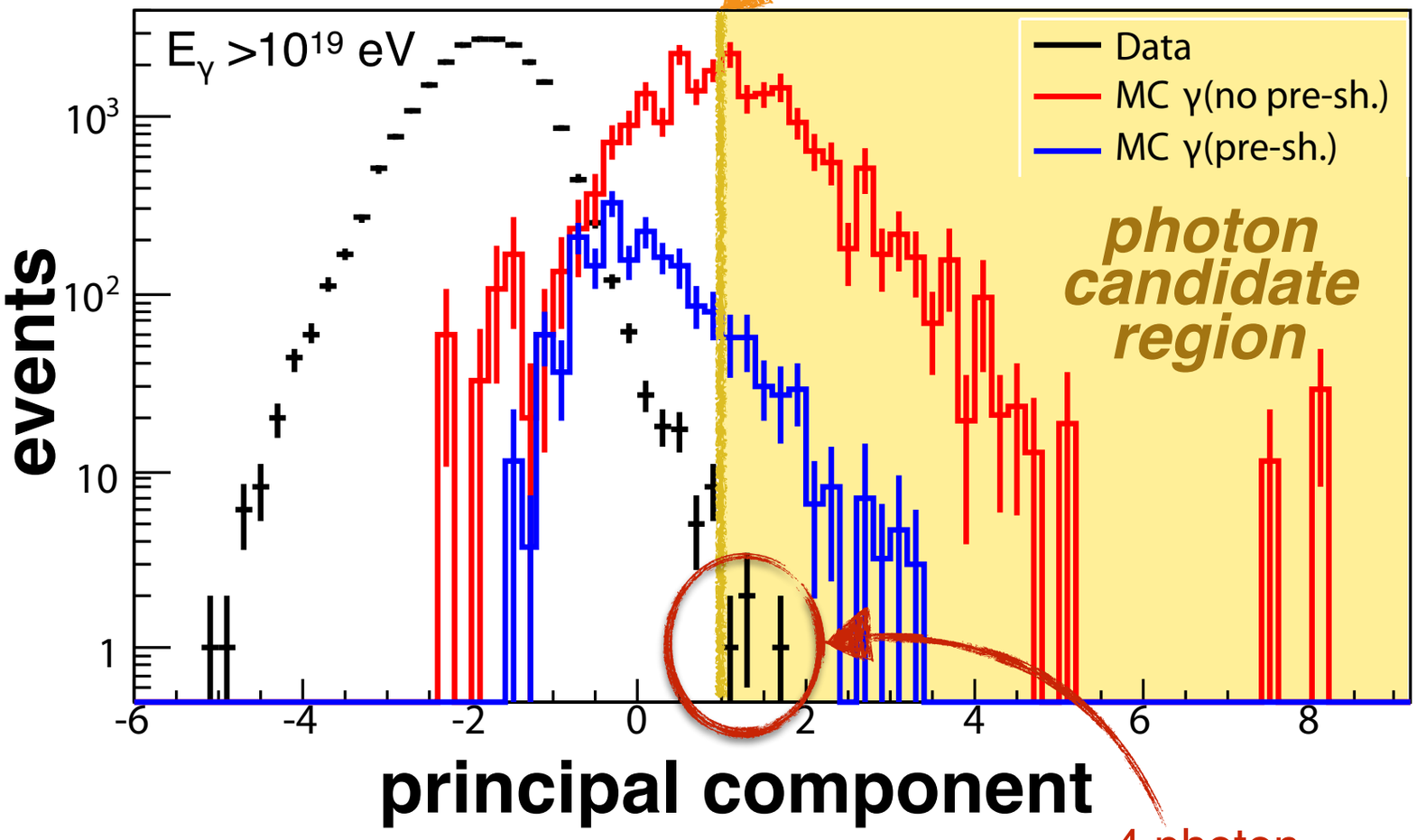
  S_i: total signal in station *i*; $\mathrm{LDF}(r_i)$: expected signal at distance r_i

„Deviation from average data LDF“

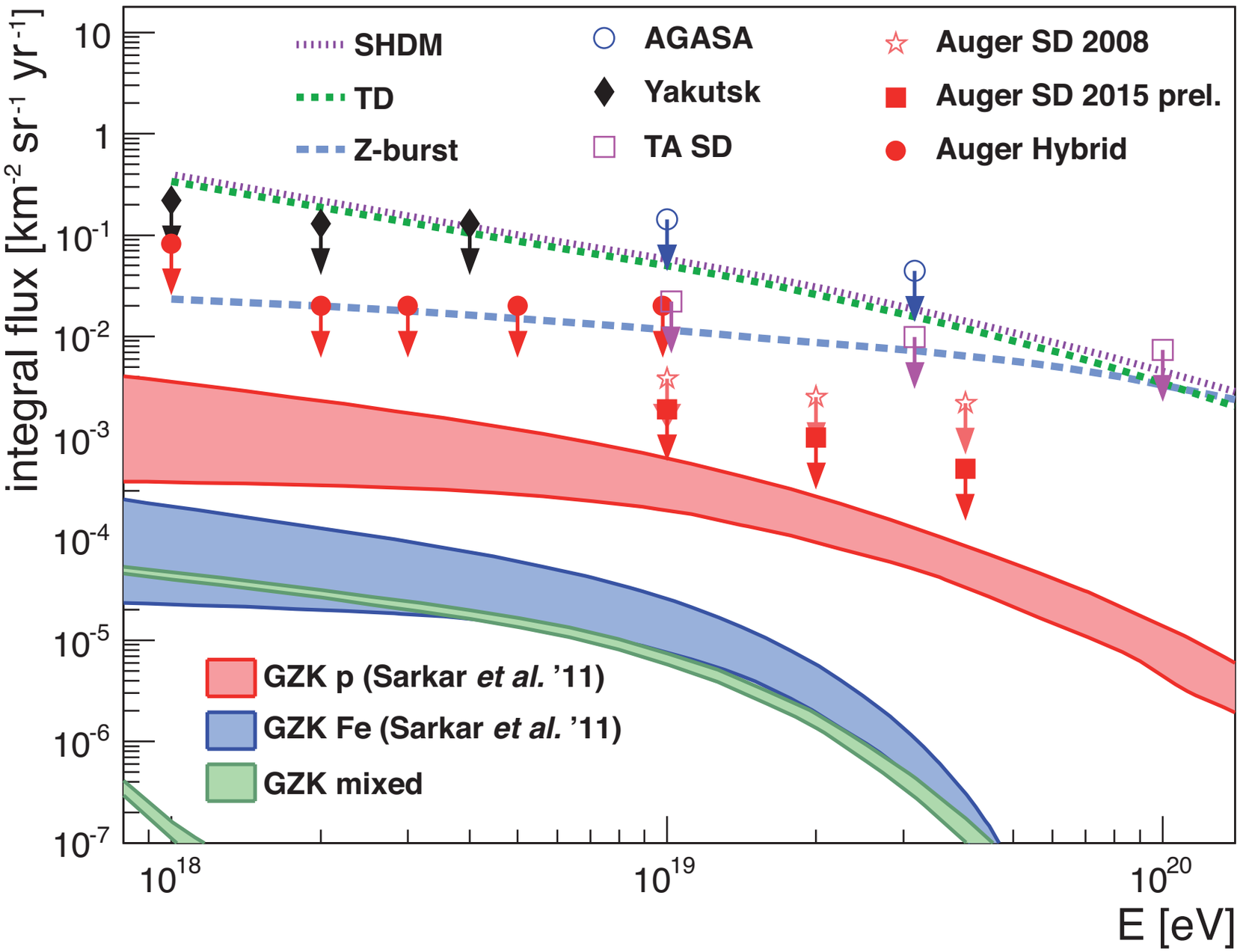
- $\Delta = \frac{\sum_i \delta_i}{N}$ ← $\delta_i = \frac{t_{1/2} - t^{\mathrm{bench}}}{\sigma_{t_{1/2}}}$

„Deviation from the data benchmark“





Results



Feldman-Cousins upper limit number of photons

$$F_\gamma(E_\gamma > E_0) = \frac{N_\gamma}{< \mathcal{E} >}$$

E^{-2} spectrum weighted average exposure

- **No photon detection at ultra-high energies**
- **Top-down models severely constraint by current limits**
- **Start to constrain optimistic GZK scenarios**

Idea directional searches

2 Directional searches for photon point sources

(A. Aab et al. ApJ 789 (2014) 160)

The signature is an

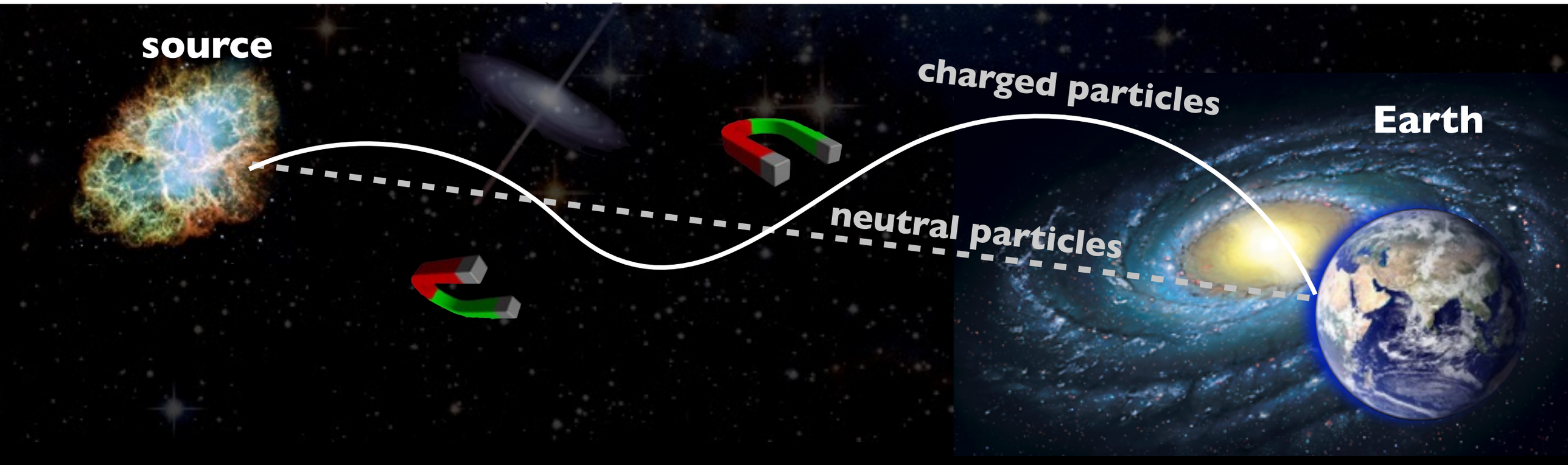
accumulation of events

from a specific direction in the sky

(neutral particles are not deflected in magnetic fields)

Idea:

Select photon-like air showers and search for an accumulation of events



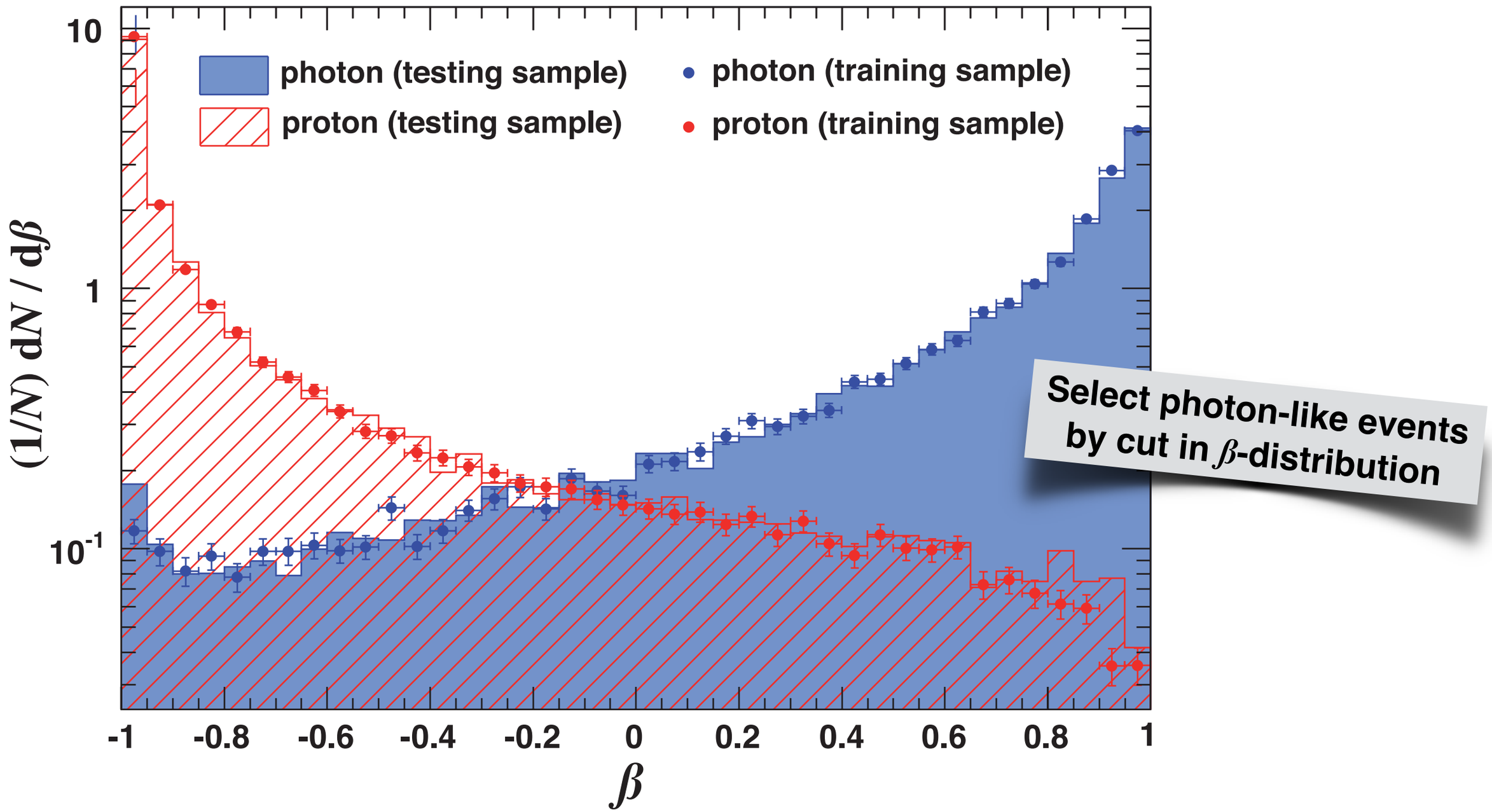
2

Background rejection

5 input observables
(fluorescence and surface detector)

X^2 Greisen, $E_{Greisen}$ / E_{FD}, X_{max},
S_b, *shape parameter*

Boosted decision trees → β

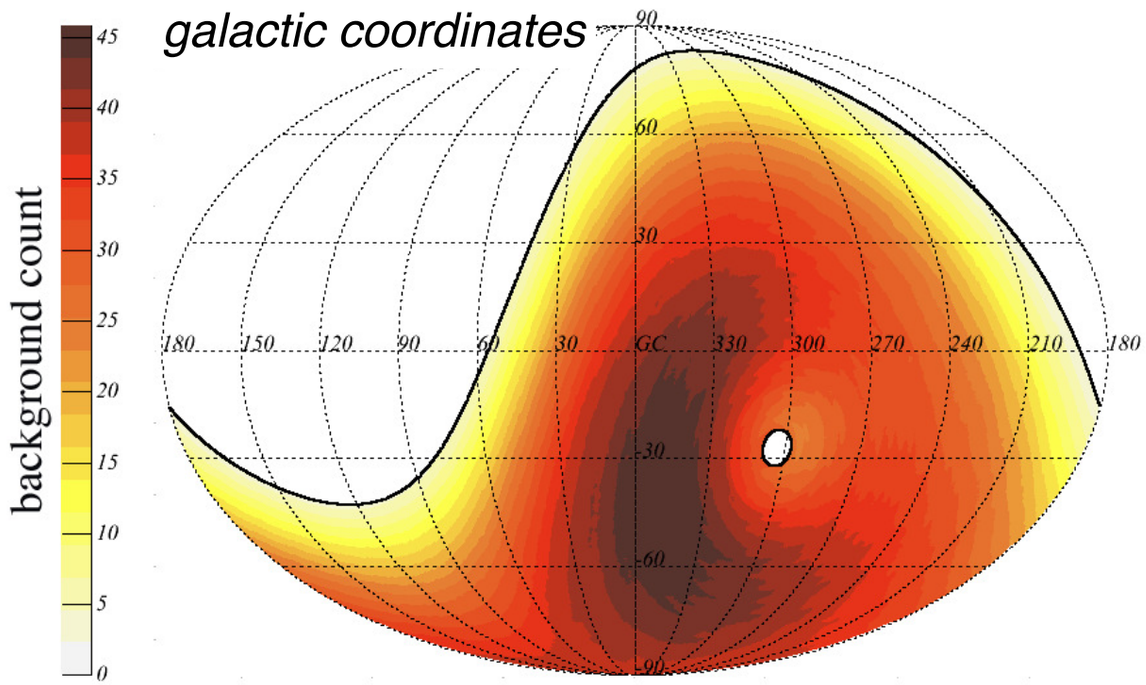


Select photon-like events by cut in β-distribution

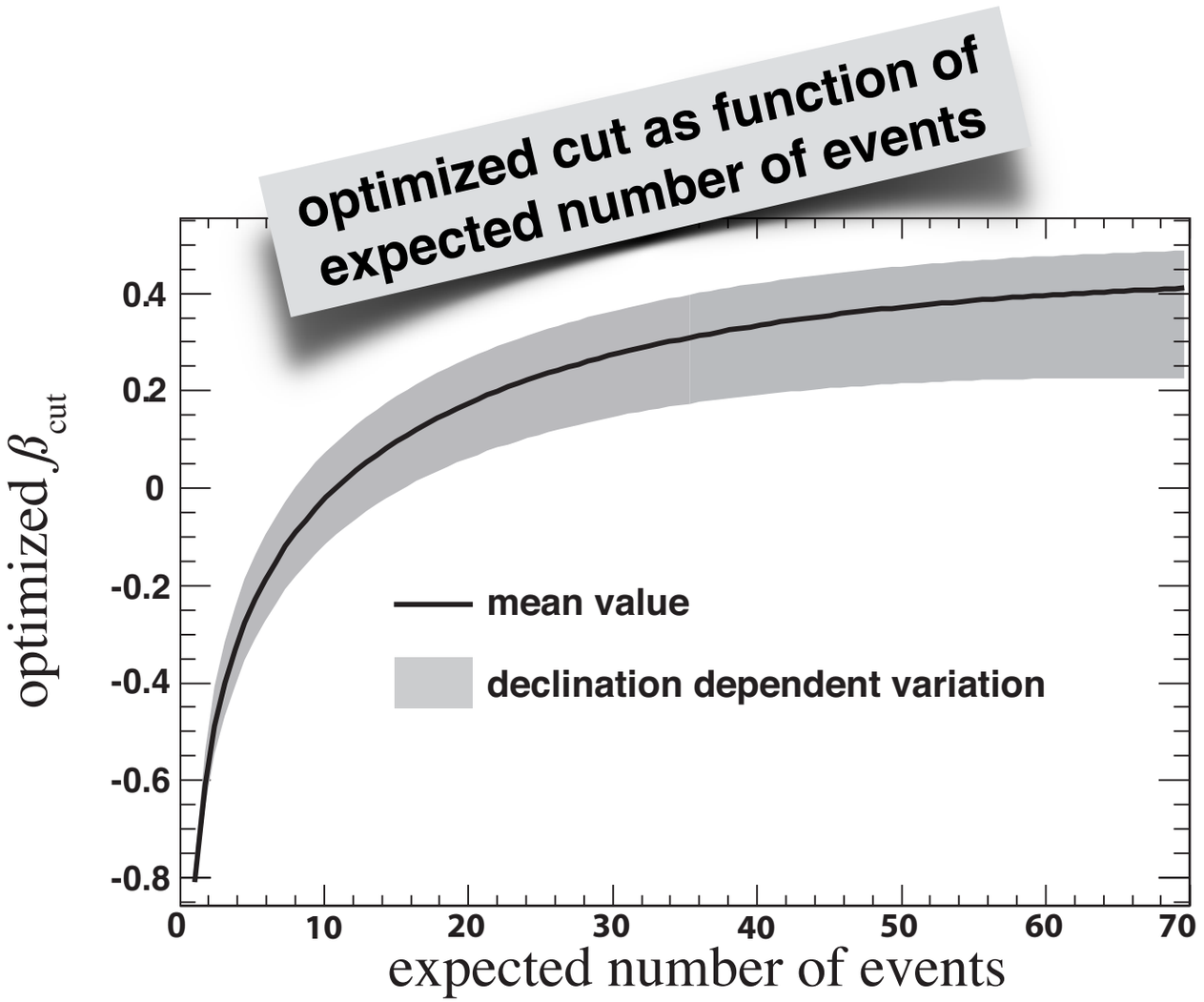
2

Analysis details

- **Blind search:** 526200 target directions between declination -85° and +20°.
- Optimized β_{cut} is determined by minimizing upper limit using Zech's method
  G. Zech, NIM A277, 608-610 (1989)
- **Data:**
  - Energy range $10^{17.3} < E/\text{eV} < 10^{18.5}$
  - Zenith angle range: 0° - 60°
  - Angular resolution: 0.7°
  - Top-hat counting with radius 1°



Obtained using scrambling method
Cassiday *et al.* Nucl. Phys. Proc. Suppl. **14A**, 291 (1990)



Results

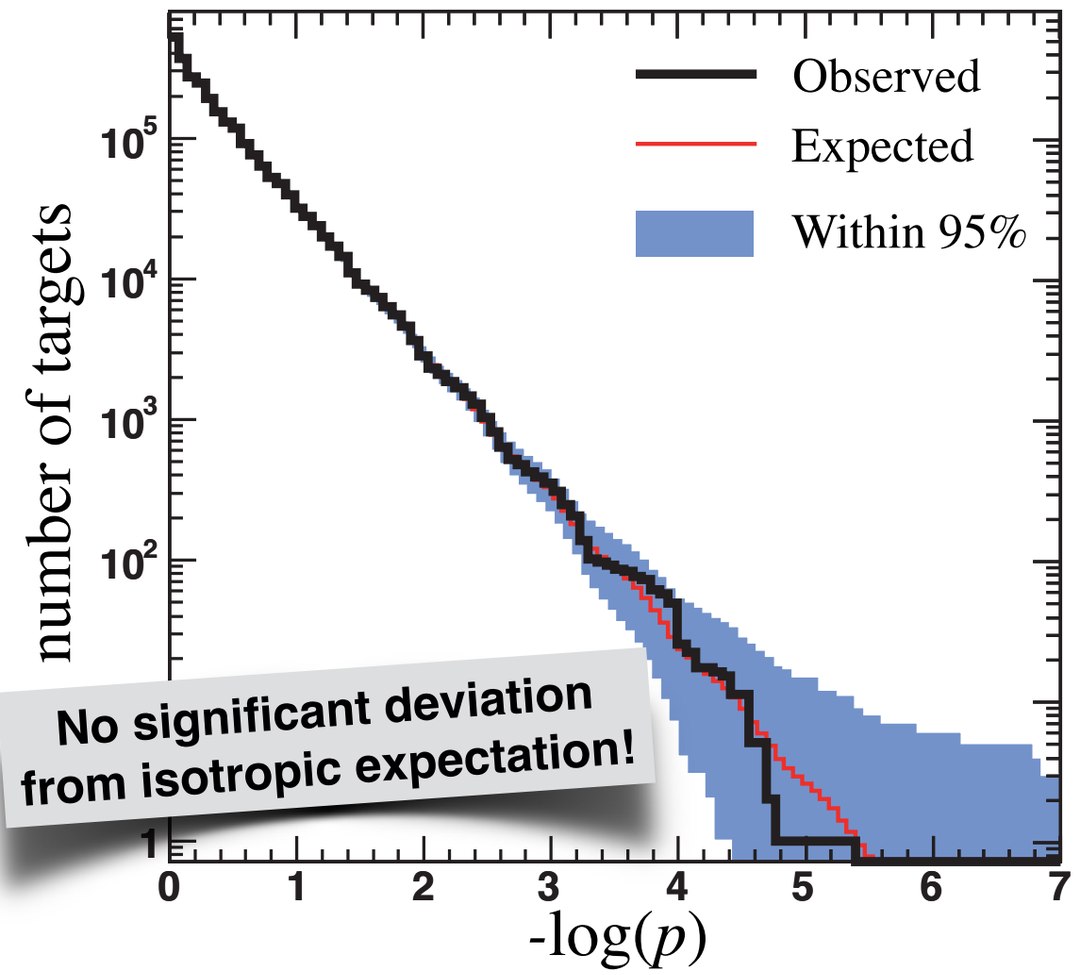
2

Calculate p-value of observation

$$p = \mathrm{Poiss}(\geq n^{\beta}_{\mathrm{data}} | n^{\beta}_{b})$$

expected number

observed number



Chance probability that p_{min} is observed anywhere in the sky: 36%

2

Results

Calculate p-value of observation

$$p = \mathrm{Poiss}(\geq n^{\beta}_{\mathrm{data}} | n^{\beta}_{b})$$

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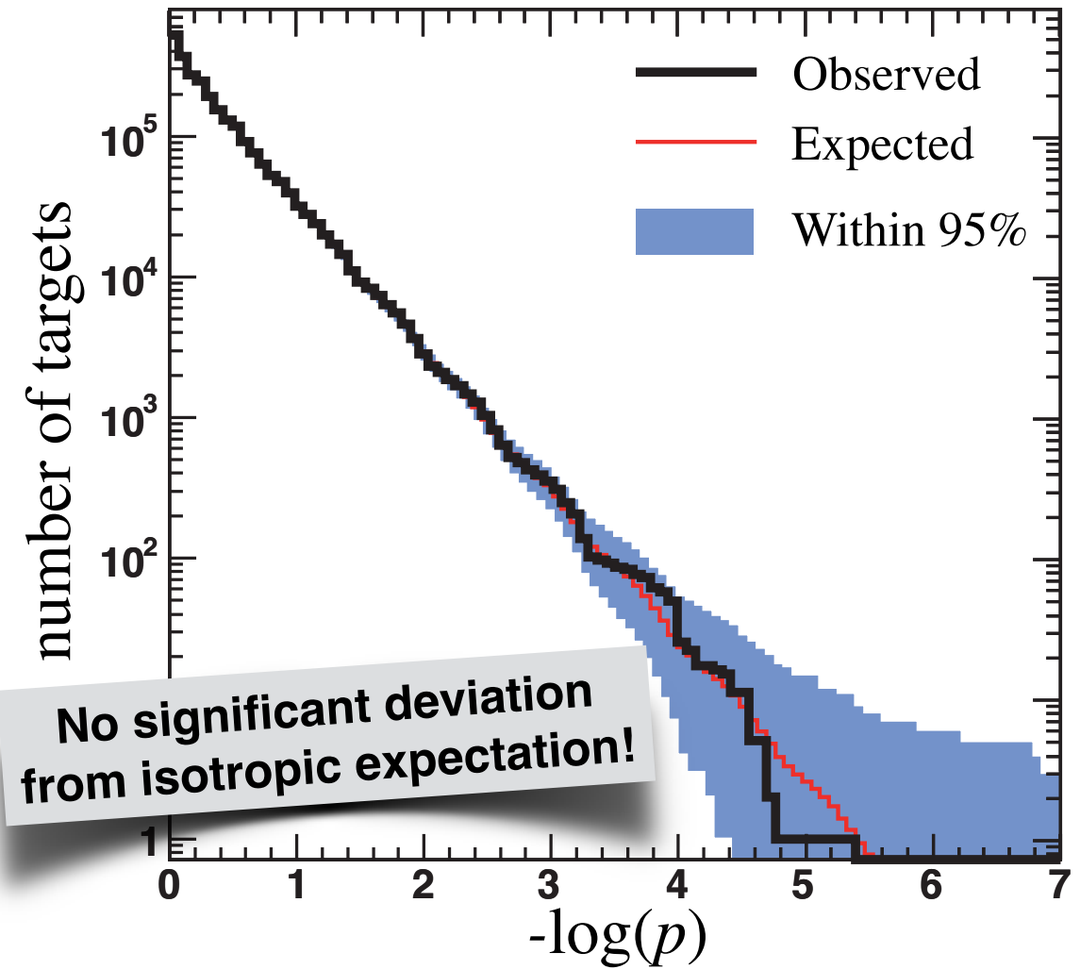


No significant deviation from isotropic expectation!

Chance probability that p_{min} is observed anywhere in the sky: 36%

Derive flux upper limits

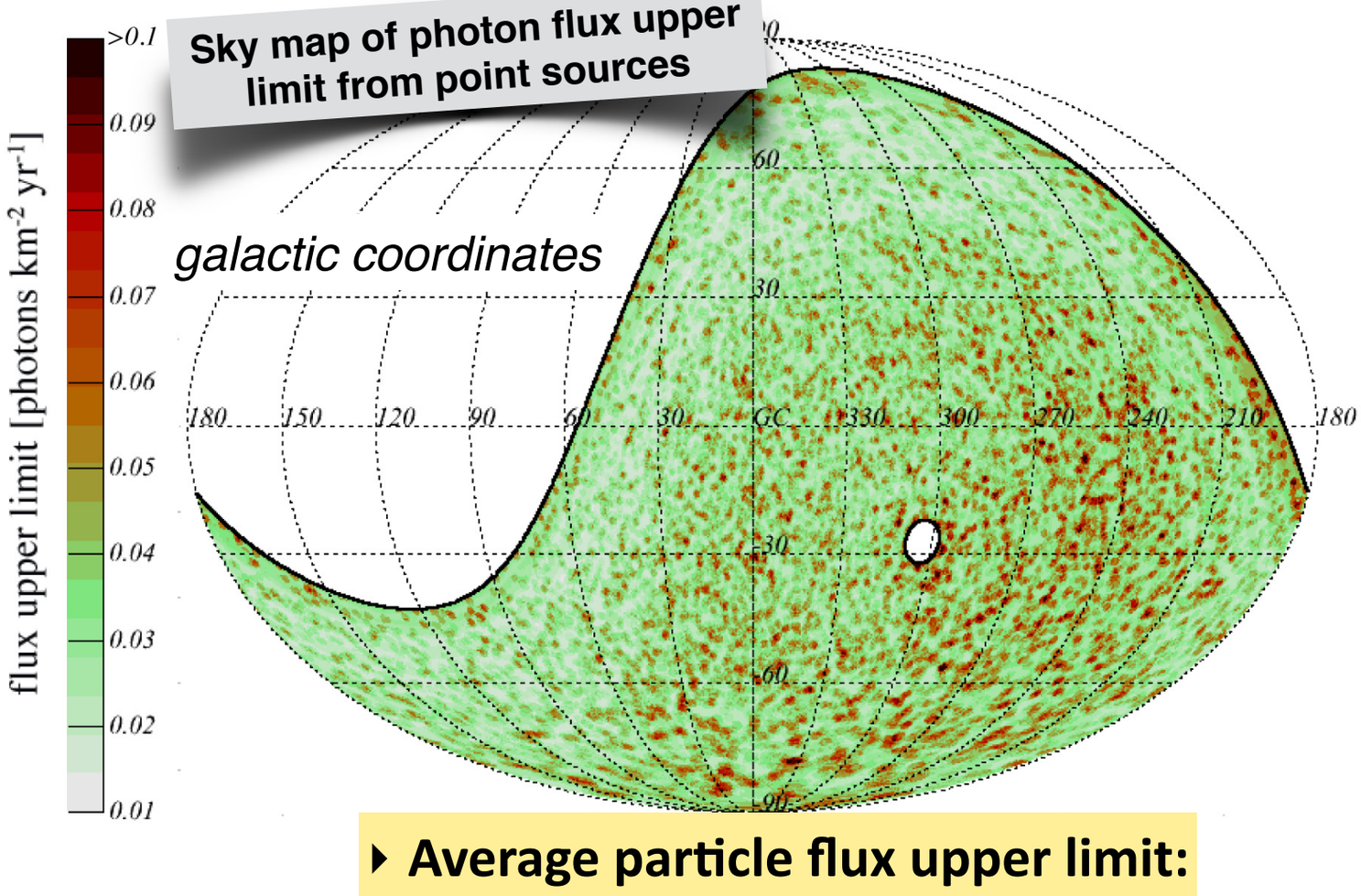
$$f^{\mathrm{UL}} = \frac{n_s^{\mathrm{Zech}}}{n_{\mathrm{inc}} \cdot \mathcal{E}_{\beta}}$$

particle upper limit

photon exposure (from time-dependent detector simulations)

correction factor for top-hat choice (=0.9)

Sky map of photon flux upper limit from point sources

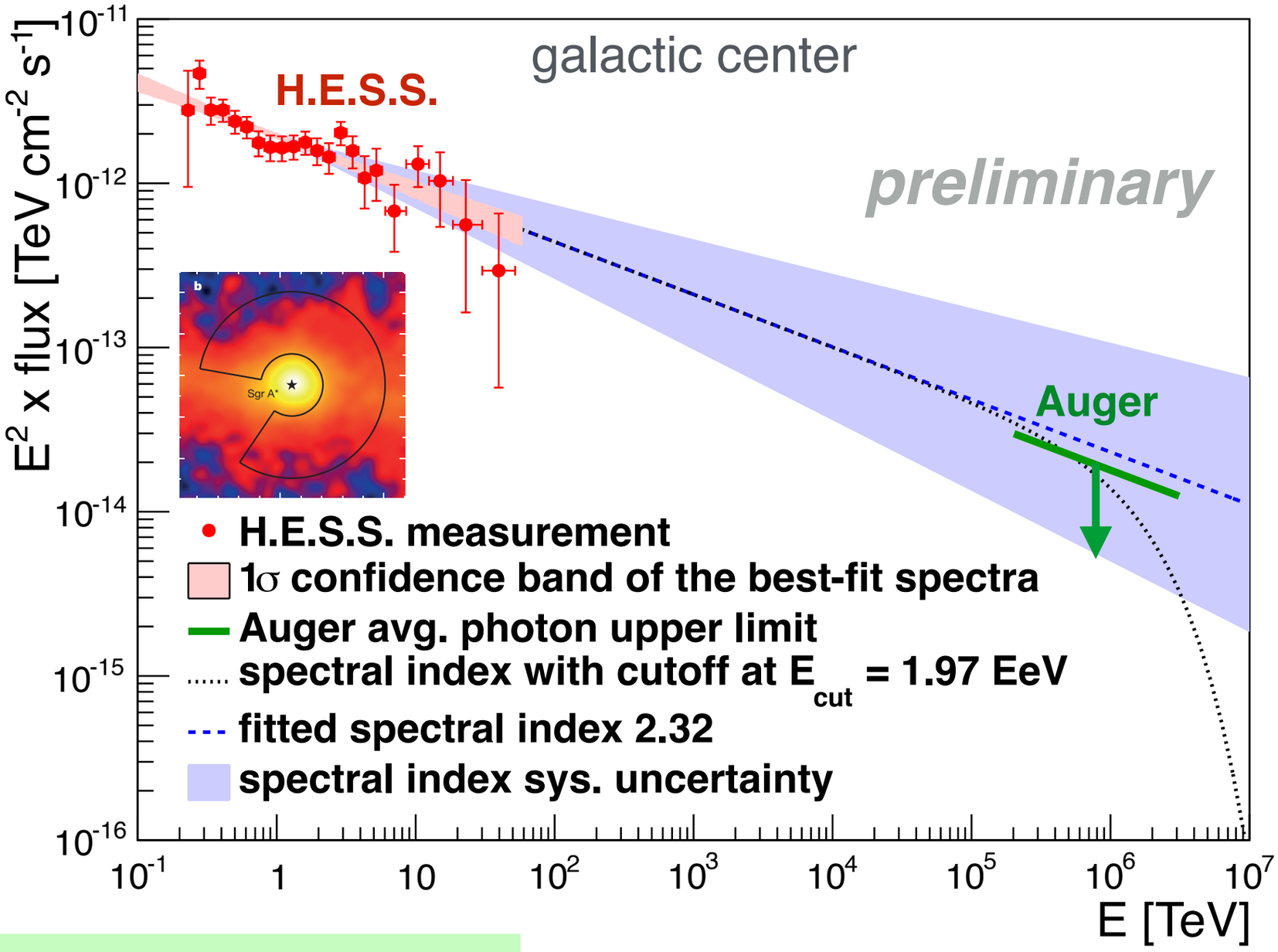


- **Average particle flux upper limit: 0.035 photons km^{-2} yr^{-1}**
- **Average energy flux upper limit: 0.06 eV cm^{-2} s^{-1} (energy spectral index -2)**

2

Interpretation

Example: Naive extrapolation of recent H.E.S.S. galactic center results



Furthermore:
Auger limit of **neutron** flux from galactic center of 0.014 km^{-2} yr^{-1} above 1 EeV enables additional constraints!
(Aab et al. ApJ 789 (2014) L34)

Average particle flux upper limit of photon point sources in the region of H.E.S.S. extrapolation. A paper targeting the galactic center is in preparation.

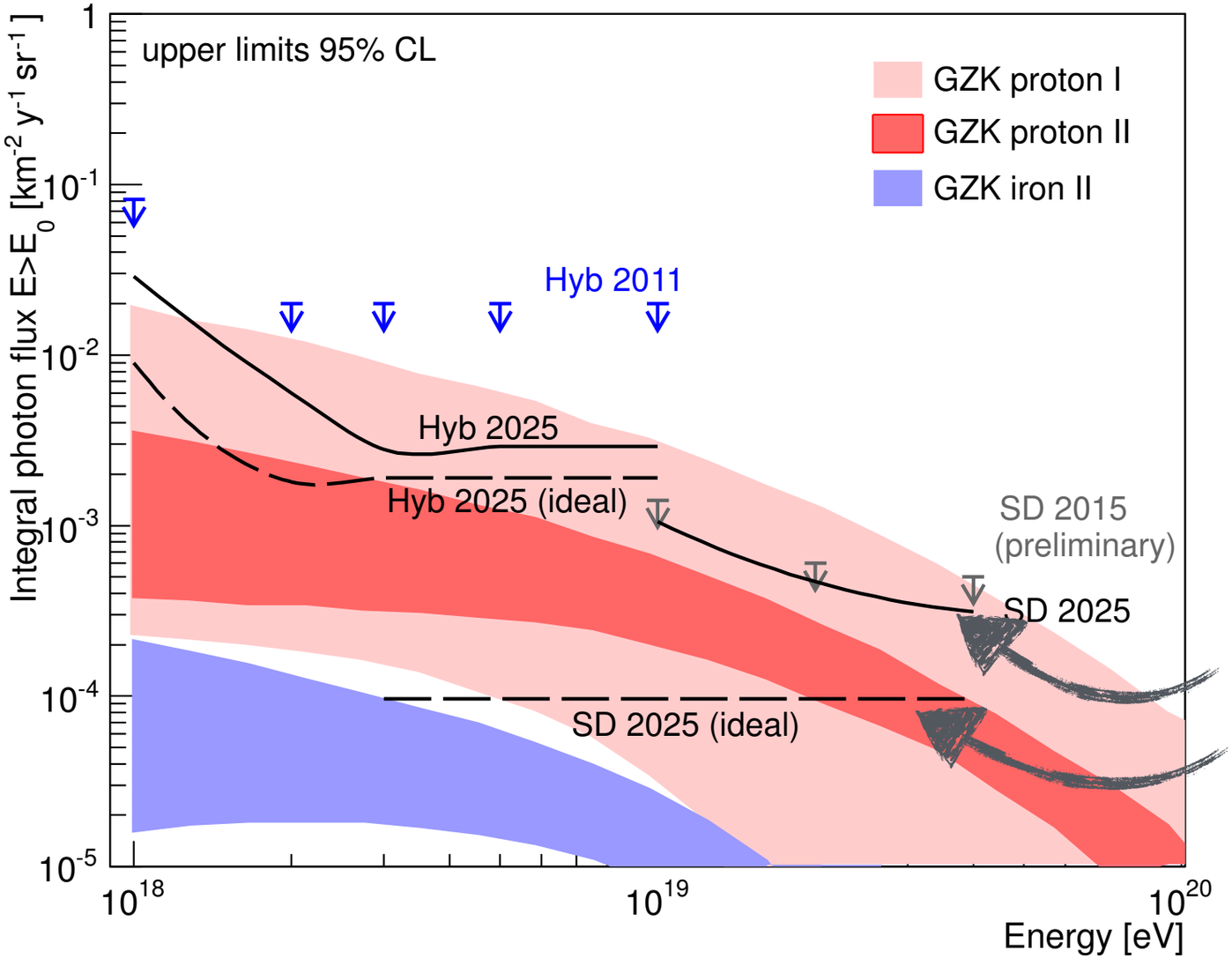
Auger upgrade

AugerPrime

Main goals:

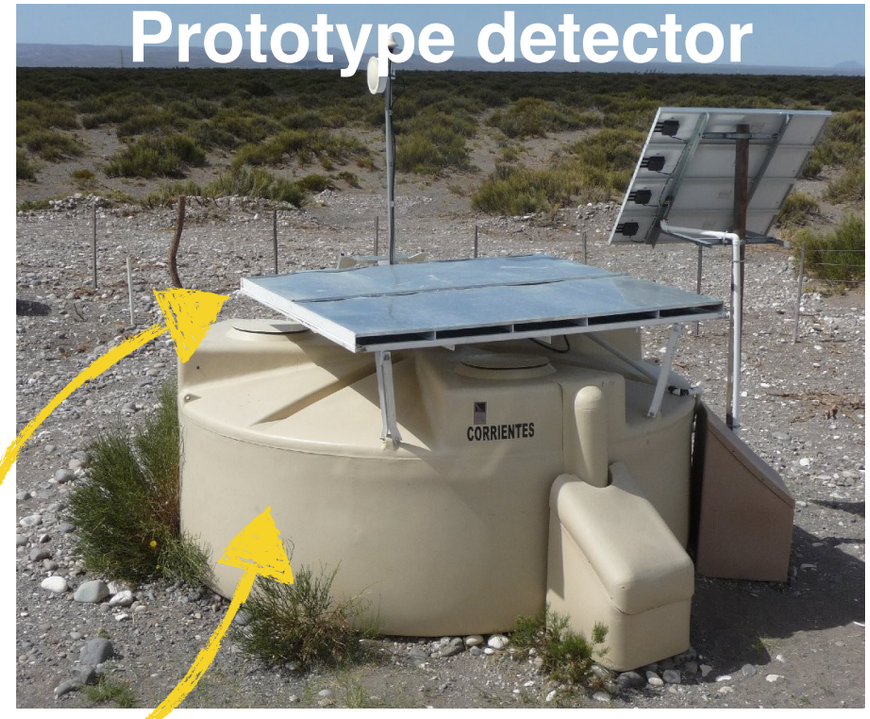
- Origin of the flux suppression
- Proton contribution in the flux suppression region
- Fundamental particle physics

→ increase sensitivity to mass composition



conservative estimate

ideal estimate (no background)



10 m² water Cherenkov counter
(mainly μ component)

3.8 m² scintillator
(mainly EM component)

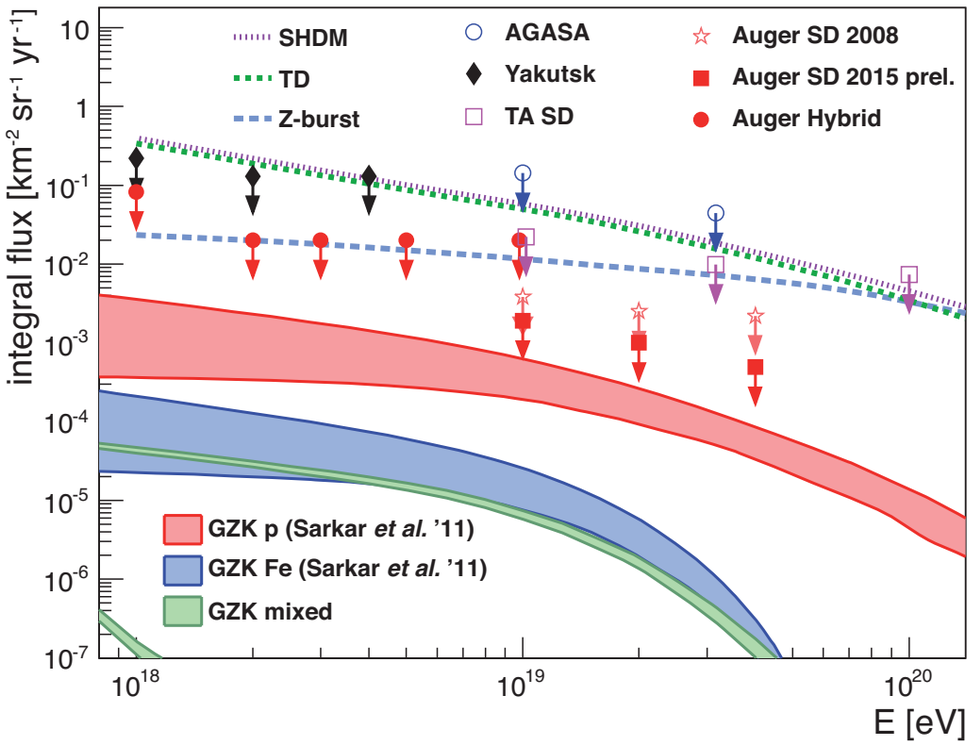
expect improvement for diffuse and directional searches

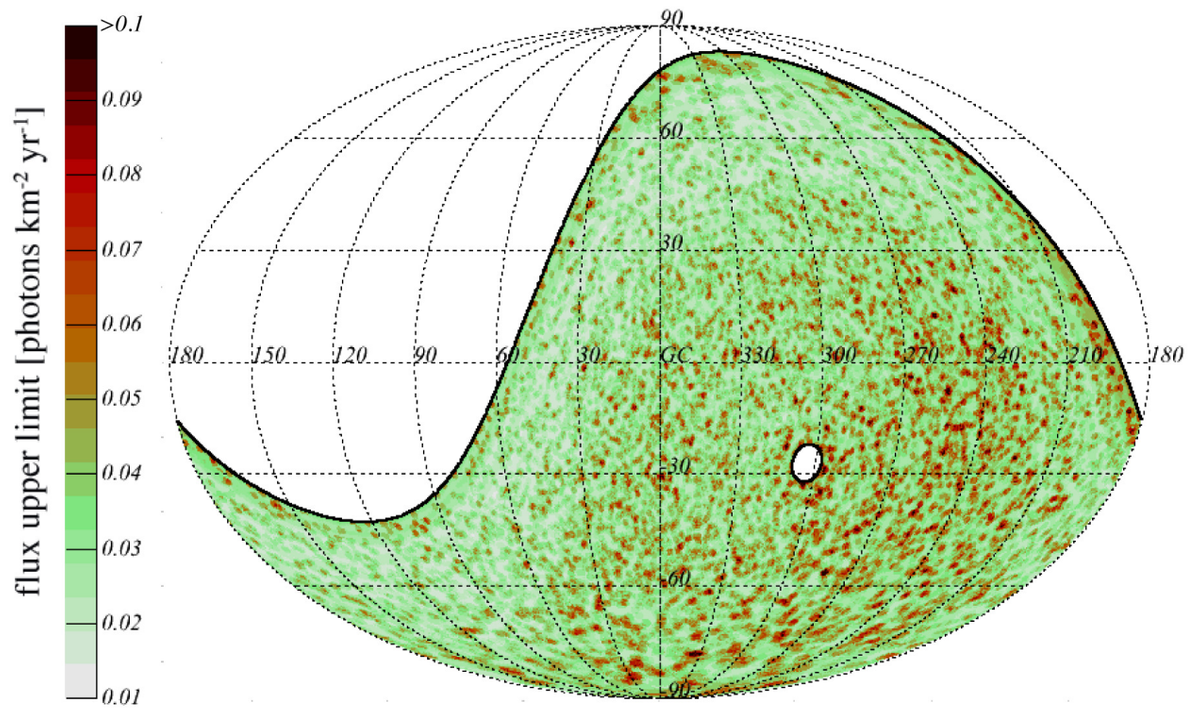
Summary

Search for UHE photons with the Pierre Auger Observatory

- **Search for ultra-high energy photons is an interesting field with high discovery potential**
- **No photons in EeV range observed so far**

- **Diffuse searches:**
  - Top-down models are strongly disfavored
  - Upper limits start to constrain optimistic GZK-scenarios
- **Directional searches:**
  - First particle and energy flux upper limits of photon point sources in the EeV range
  - Severe constraints on the continuation of measured TeV fluxes

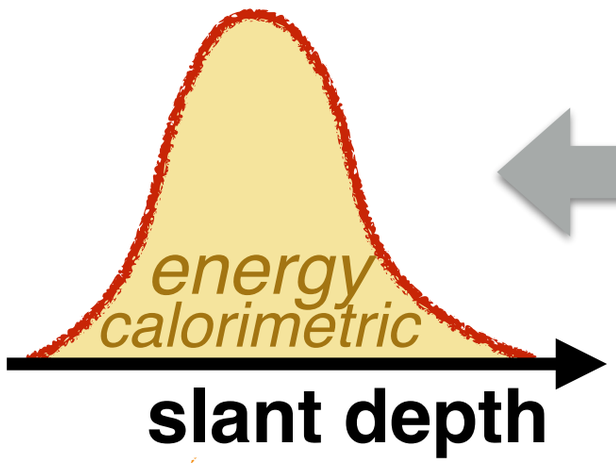




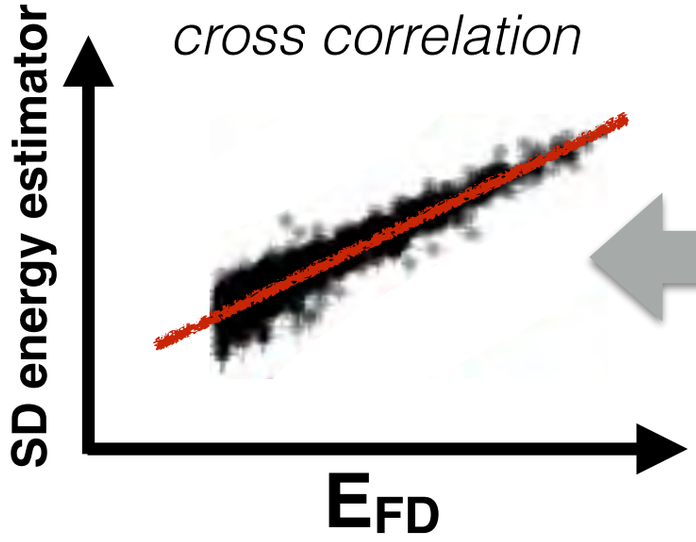
Backup slides

Hybrid detector

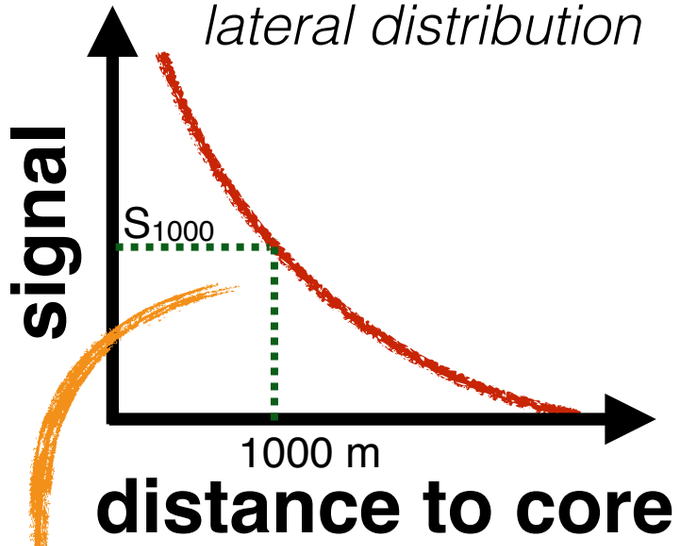
longitudinal profile

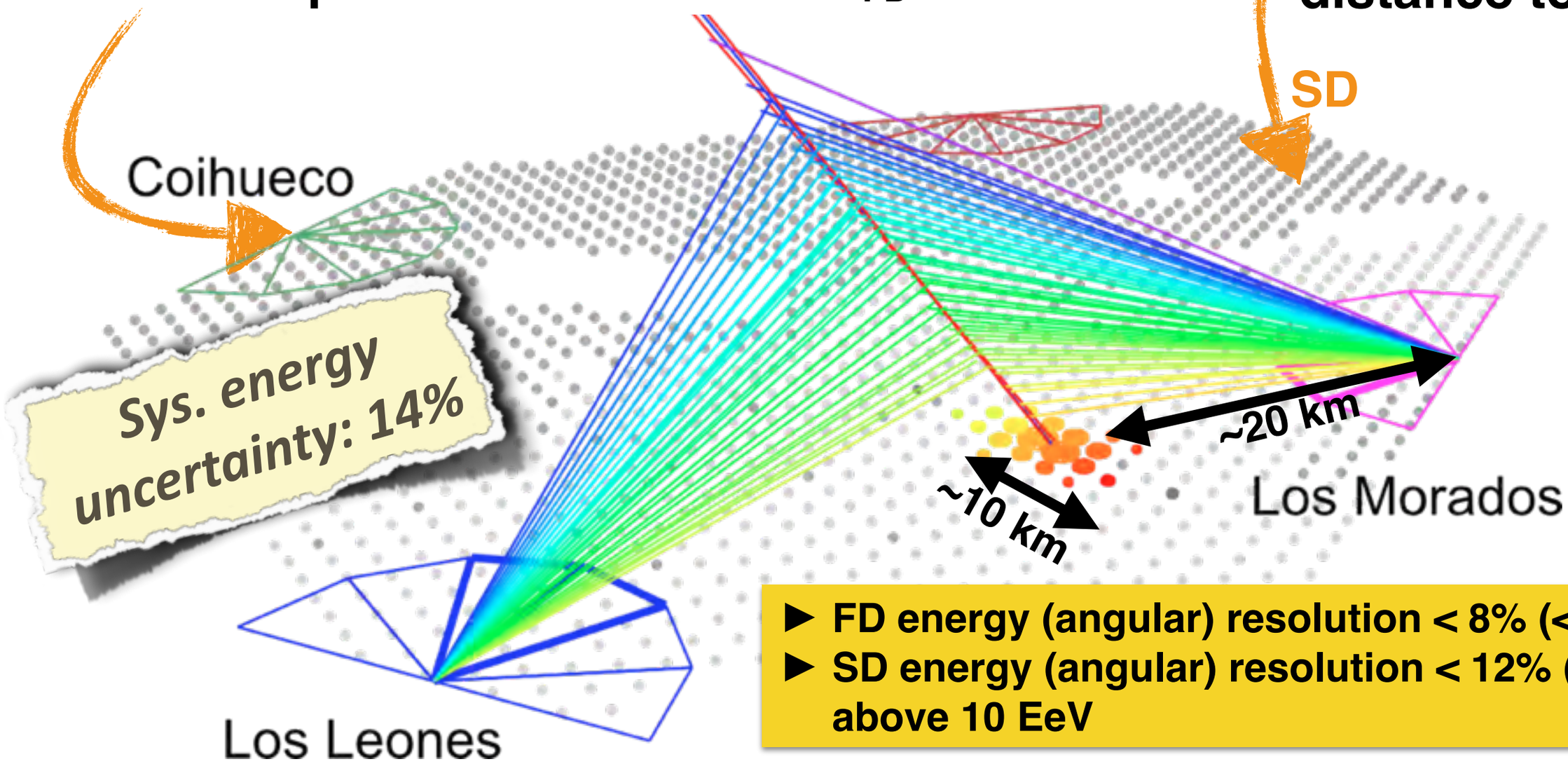


cross correlation



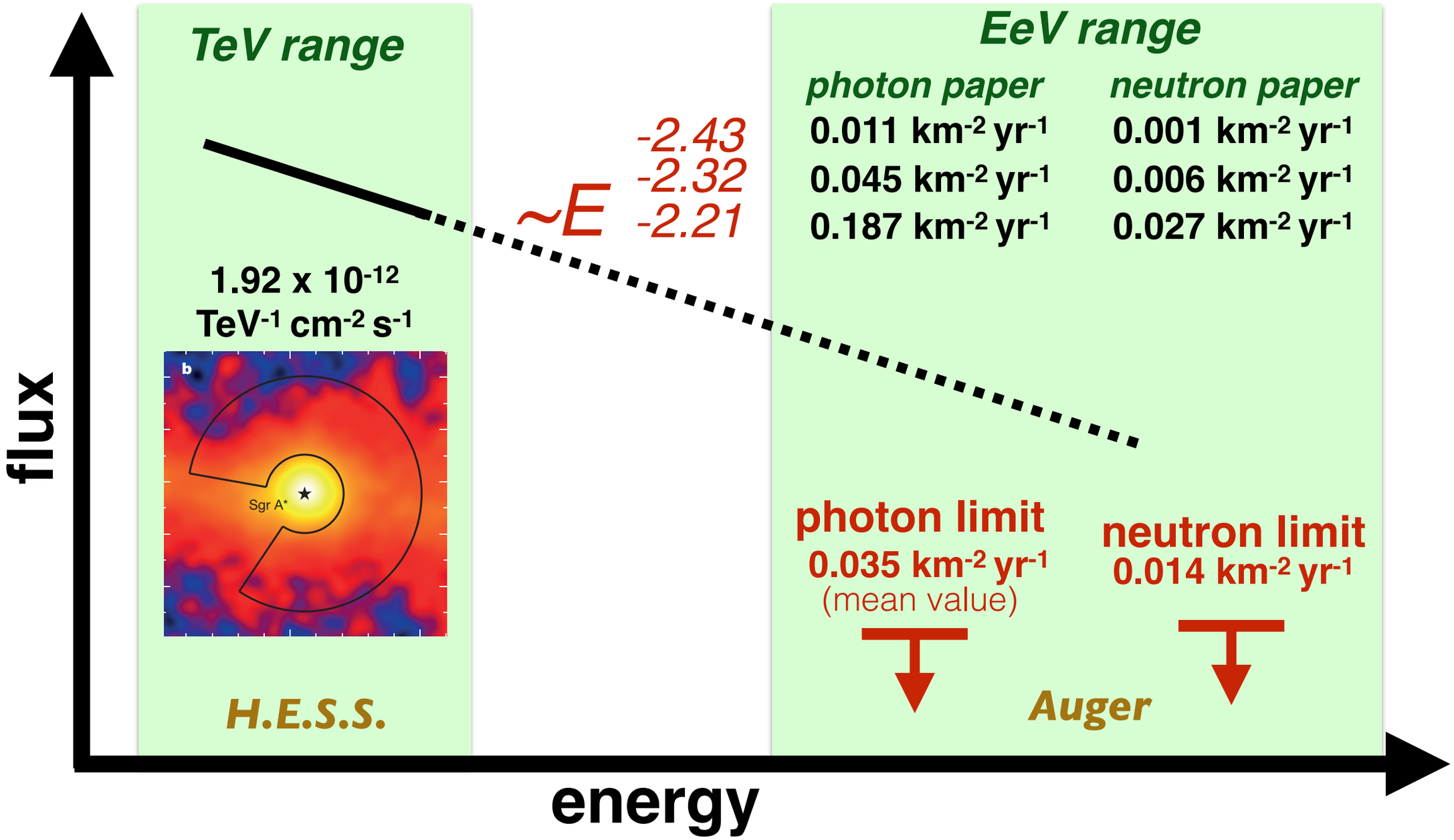
lateral distribution





- **FD energy (angular) resolution < 8% (<1°)**
- **SD energy (angular) resolution < 12% (<1°) above 10 EeV**

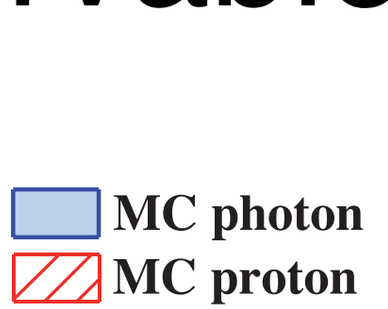
Galactic center extrapolation

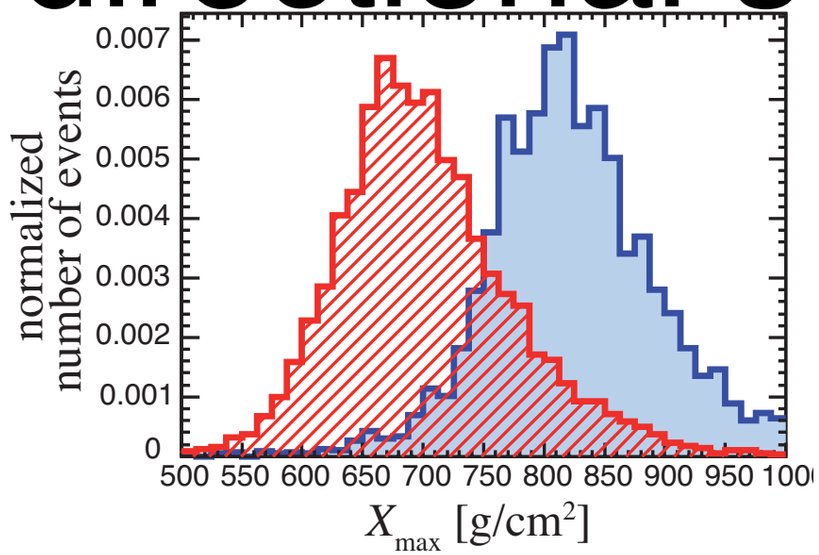


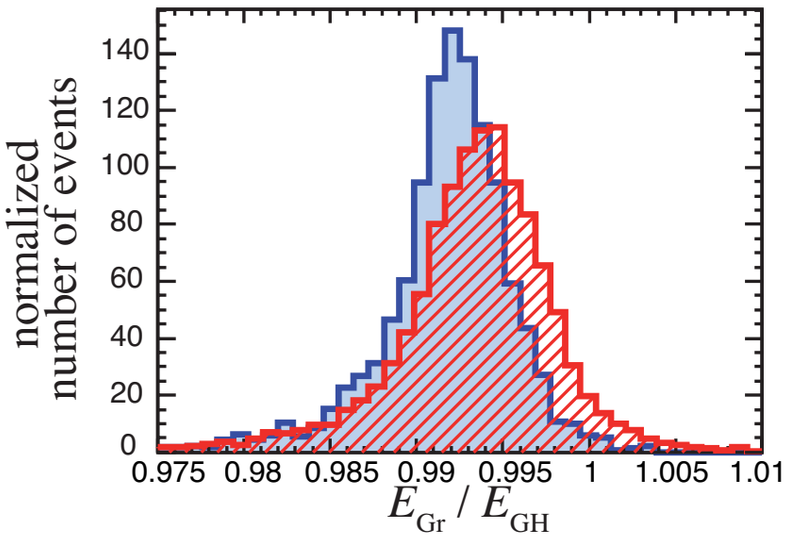
Input observables directional search

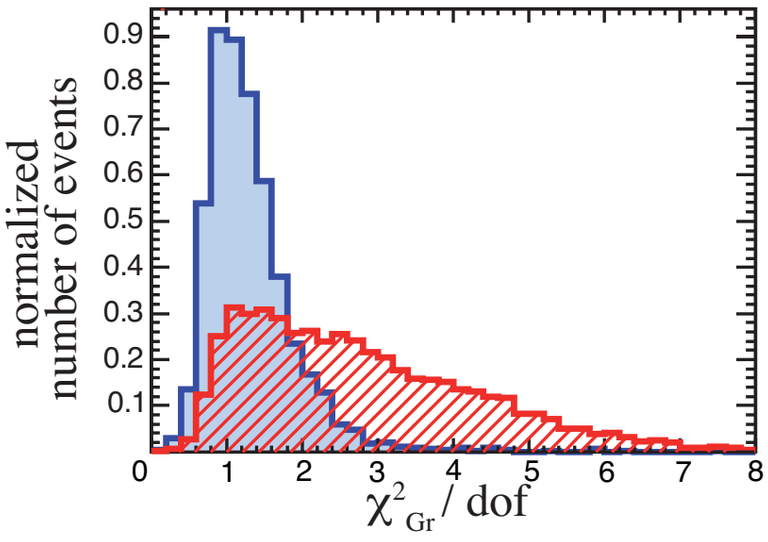
Observables

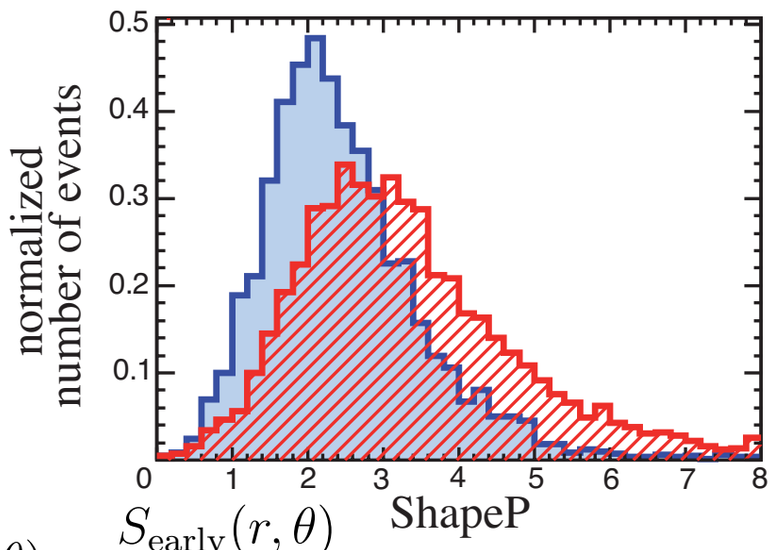
targeted search
FD + SD



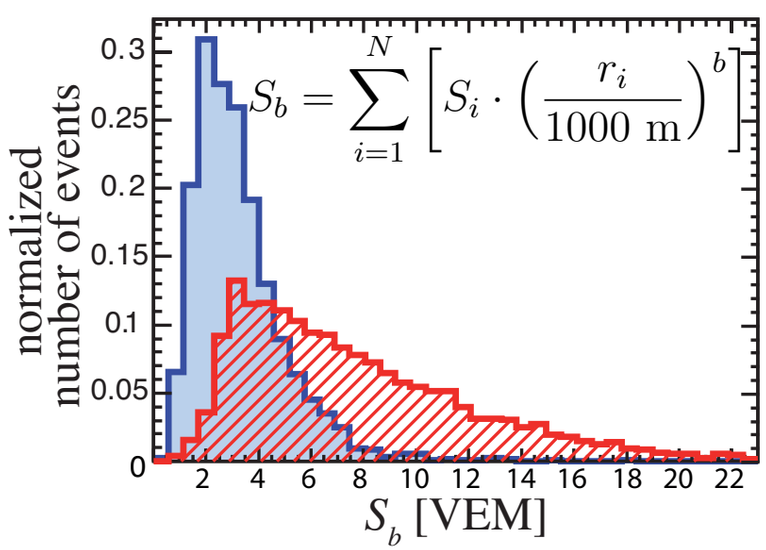




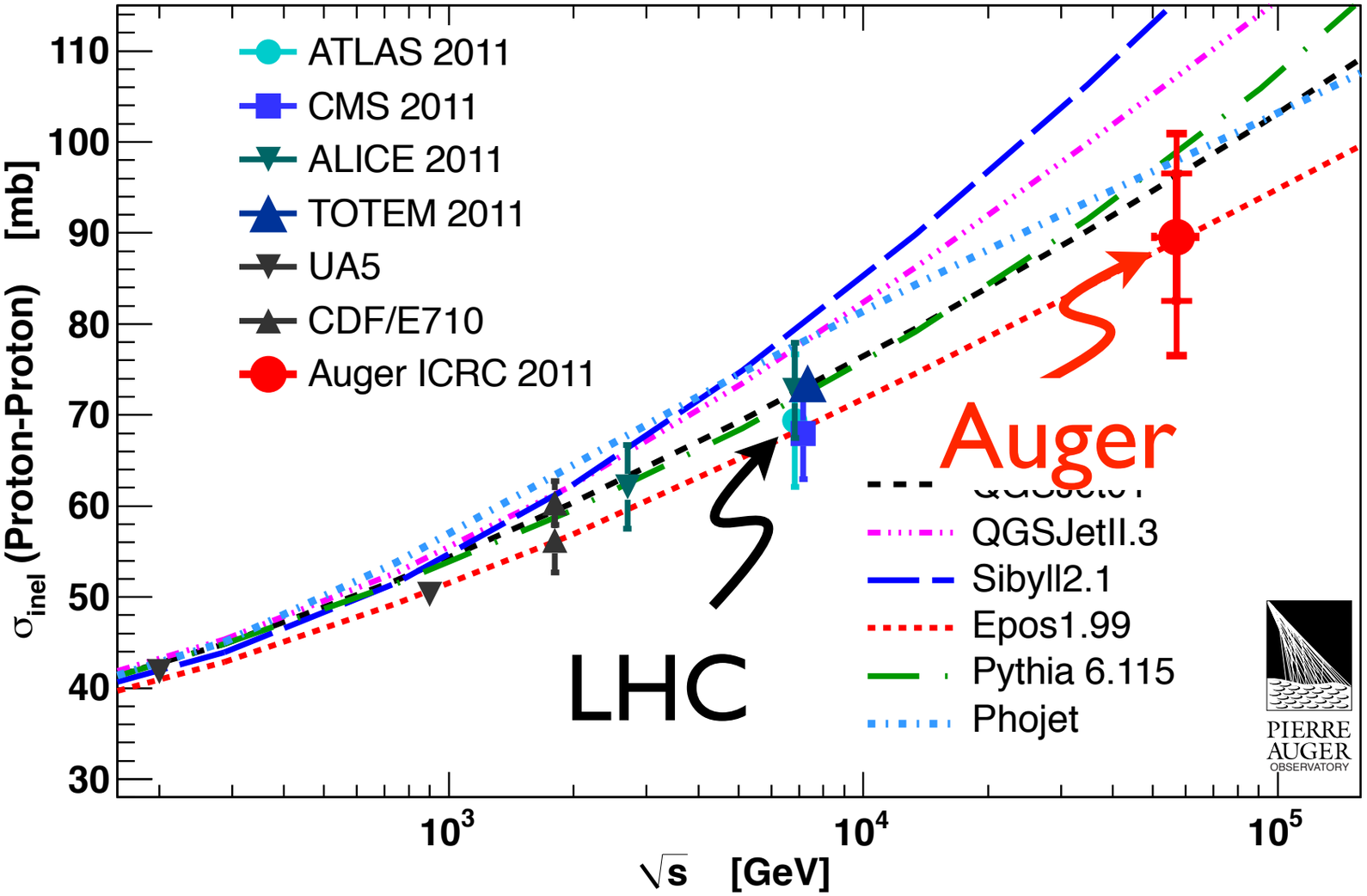




$$\mathrm{ShapeP}(r,\theta) = \frac{S_{\mathrm{early}}(r,\theta)}{S_{\mathrm{late}}(r,\theta)}$$



Auger pp cross section



Auger Collaboration, PRL 109, 062002 (2012)

pp cross section @ 57 TeV