Monte Carlo Simulation and System Layout

by

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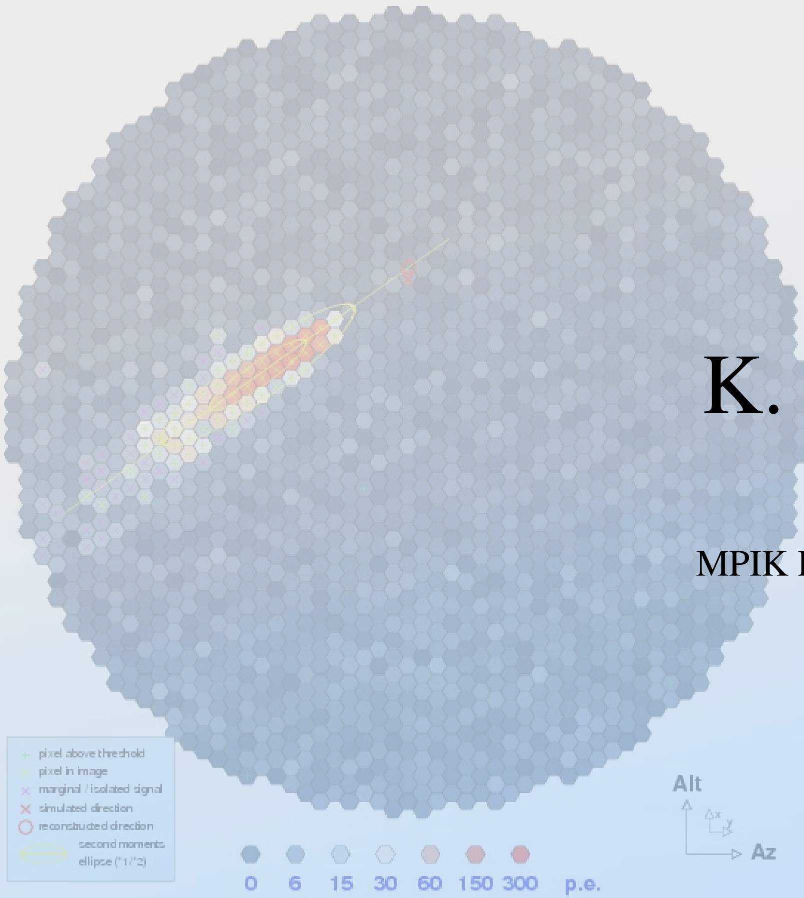
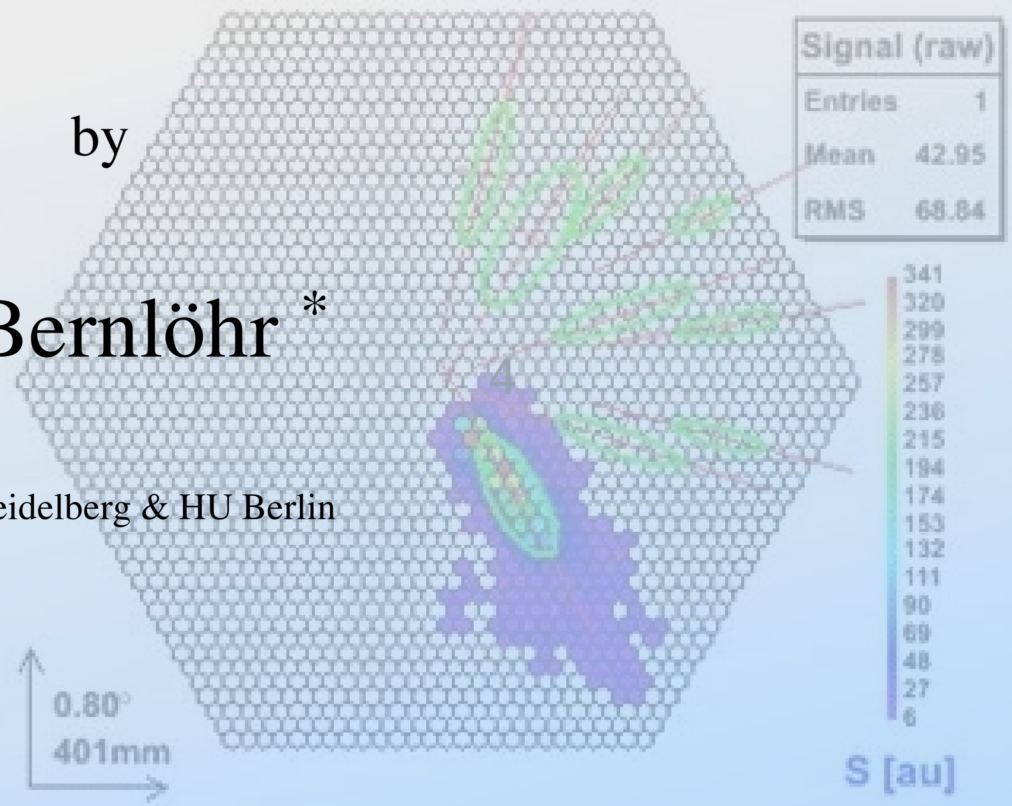




*) with contributions by E. Carmona

A word of warning

- No simulations of anything that would make a full CTA installation. Don't quote results as "CTA sensitivity".
- We tested a number of specific configurations, with specific questions in mind. This is far from a full design study.
- We made no attempt at simulating the "high energy" part of the array (km^2) component, due to lack of CPU power to get enough hadrons.

Back of the envelope calculation

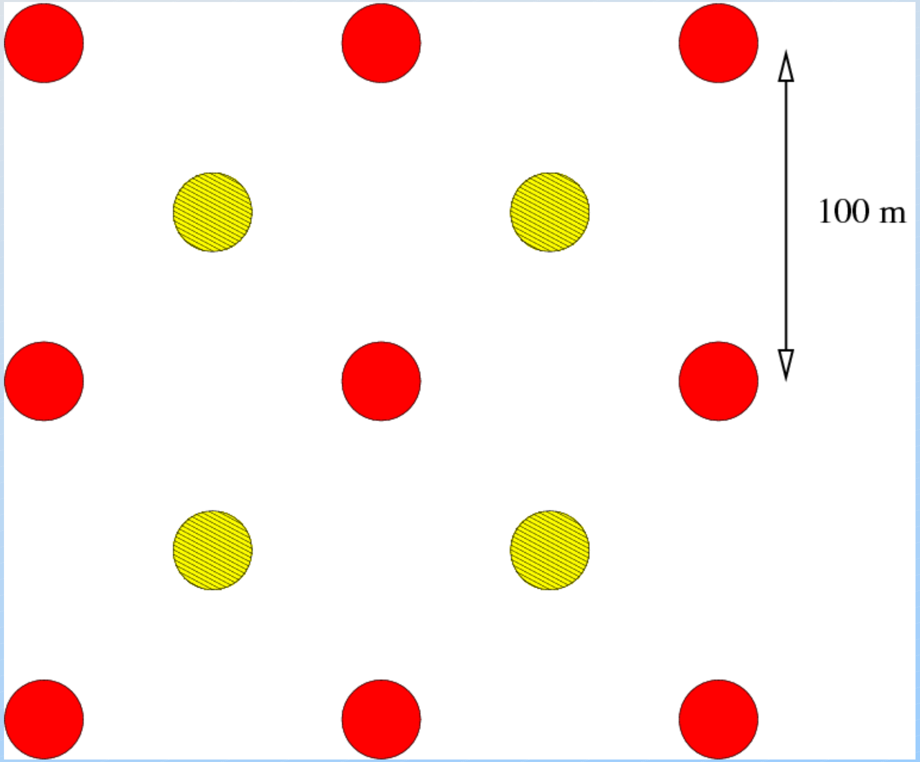
With a 1 km² effective area (neglecting cut efficiencies) you can see 10 events in 50 hours from

- a 0.01 Crab source above 10 TeV,
- a 0.1 Crab source above 40 TeV,
- a 1 Crab source above 200 TeV,

(assuming HEGRA power-law Crab spectrum).

Reminder: Munich configurations

- 9-telescope benchmark system (23 m diameter)
- 13-telescope extension
- subsets of it
- cameras with different pixel size



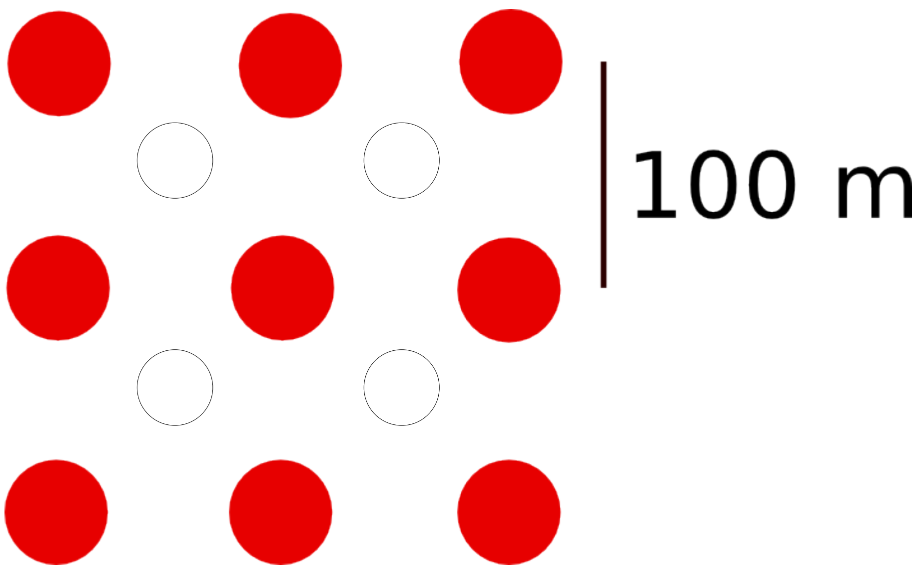
Munich analysis

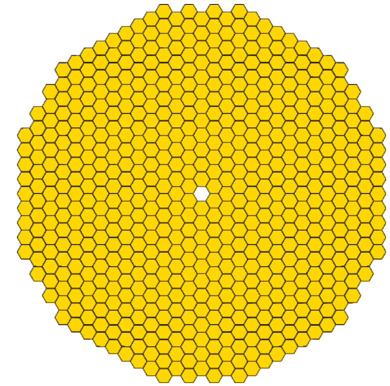
- Signal extraction from FADC pulse shape (less NSB on average but with bias and potential for background systematics in case of non-uniform sky).
- Two-level image cleaning + second moments.
- Stereo reconstruction, including Hmax.
- Scaling of width + length. Energy lookup similar.
- Gamma-hadron separation by *Random Forest* using combined parameters. Needs enough hadrons looking gamma-like for efficient training.

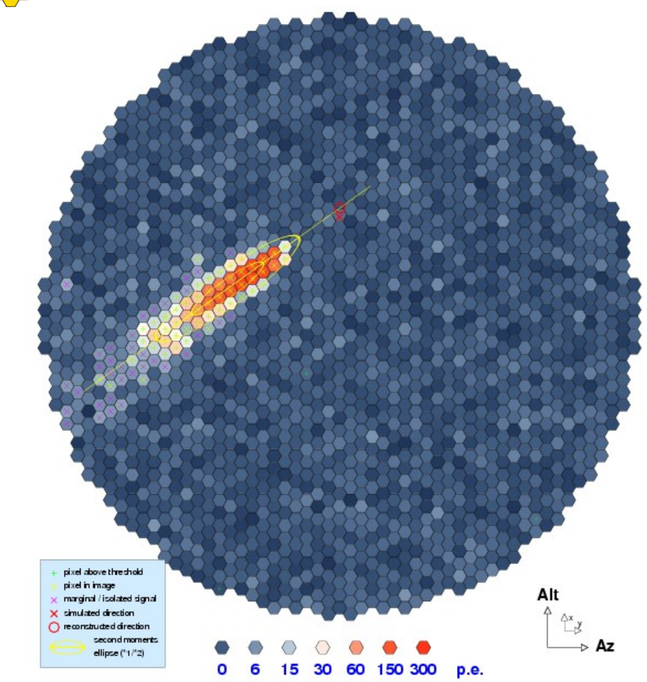
Reminder: Heidelberg configurations

- Benchmark array: 9 telescopes of 23 m diameter in 100 m grid at 2000 m altitude (long. 0°, lat. 0°).
- Like benchmark array but at 5000 m altitude and with 80 m telescope grid.
- 41 “small” telescopes (HESS-1 type) in a graded array, starting with 60 m telescope separation.
- 97 telescope mixed array with 600 m² telescopes at the centre and 100 m² telescopes surrounding them, larger f.o.v. and higher Q.E. than current system.

Configurations: benchmark system

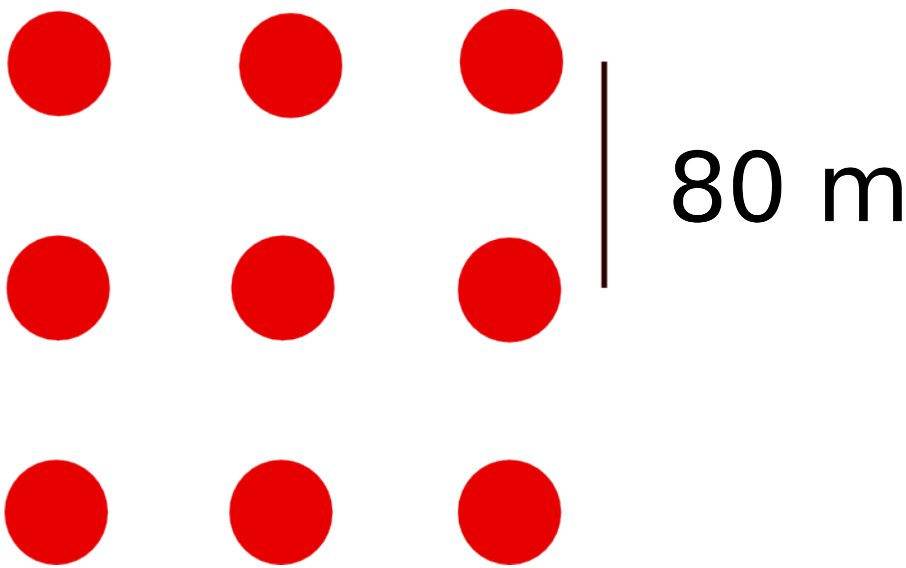






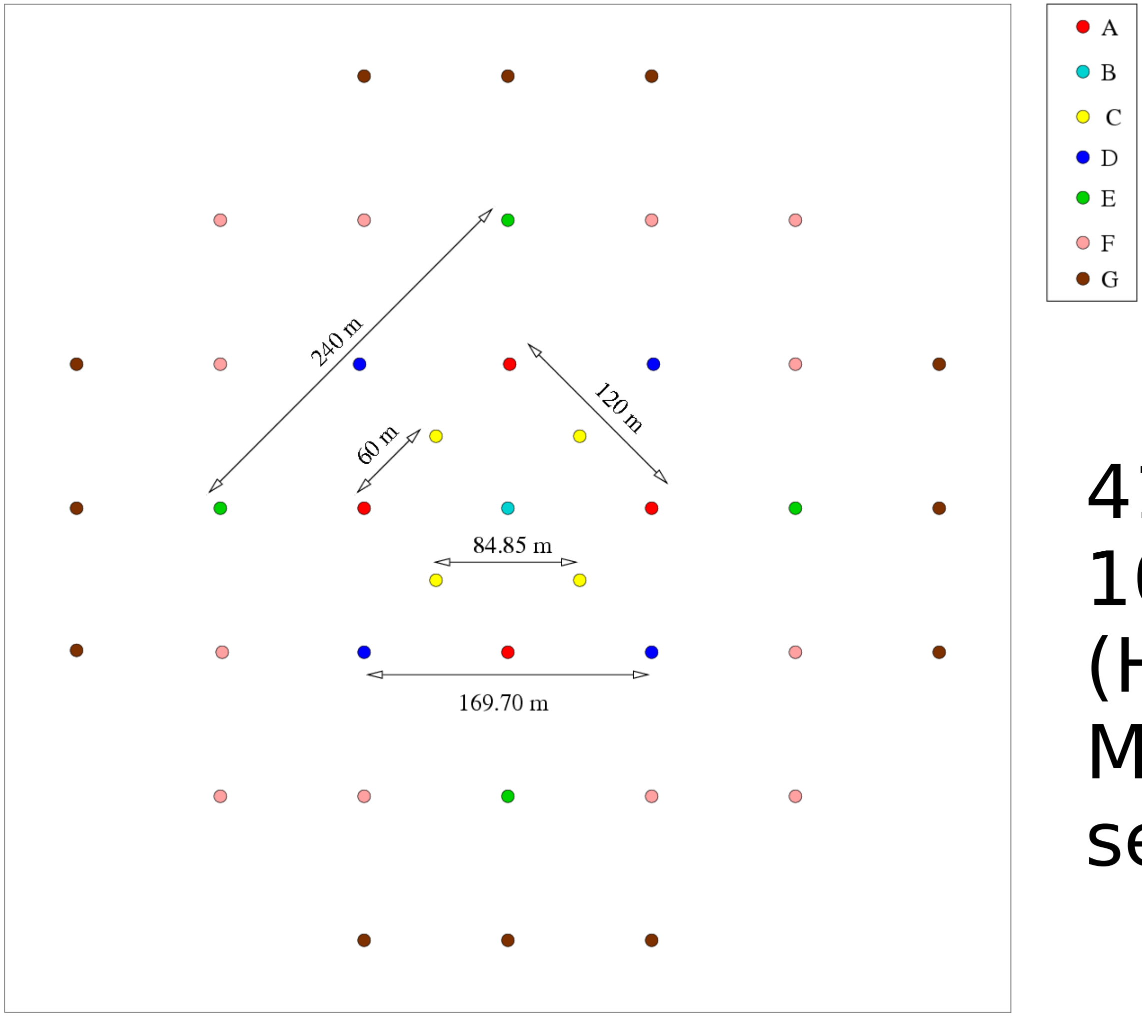
9 telescopes of 23 m diameter, f=28 m, 80% mirror reflectivity, 2029 pixels of 0.1°, HESS-I Q.E.

Configurations: 5000 m alt. system



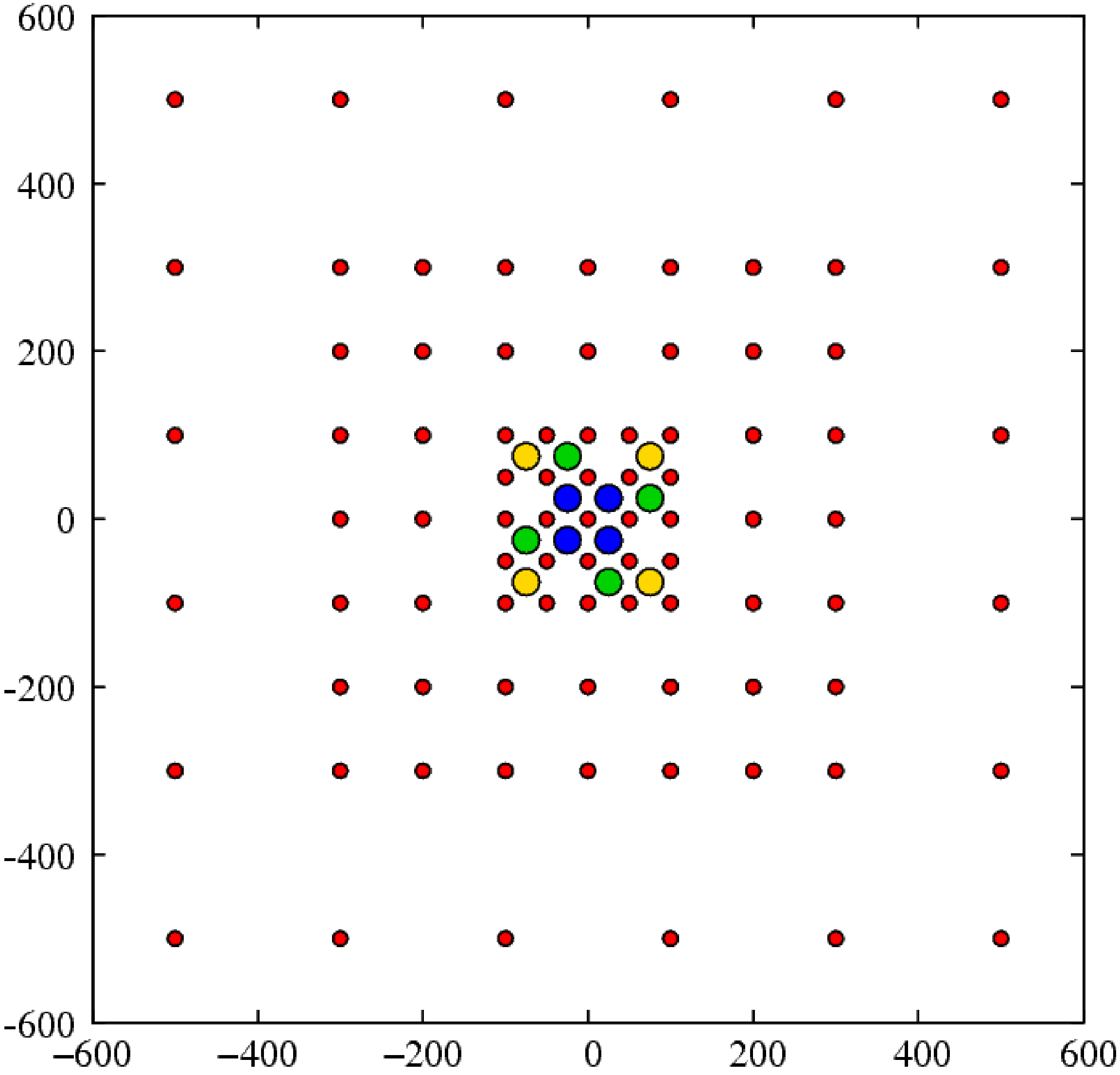
Like benchmark system but smaller telescope separation (light pool is smaller at high altitude).

Configurations: 41 “small” telescopes



41 telescopes of
100 m² mirror area
(H.E.S.S. phase 1 type).
Many different subsets
selectable.

Configurations: 97 tel. hybrid system



Hybrid system of
- 12 600 m² class tel.
- 85 100 m² class tel.

with 1.4* larger f.o.v. and 50% higher Q.E. compared to HESS.

Current MPIK simulation statistics

Configuration	*Showers simulated*	*Events simulated*	*Events triggered*	
Benchmark @ 2000	8.2 mio.	164 mio.	2.3 mio.	gammas
	77 mio.	1920 mio.	3.4 mio.	protons
Benchmark @ 5000	30 mio.	590 mio.	5.3 mio.	gammas
	252 + 14 mio.	6300 + 360 mio.	5.2 + 0.5 mio.	p + e
41-telescope	7.2 mio.	72 mio.	3.0 mio.	gammas
	52 mio.	1300 mio.	3.5 mio.	protons
97-telescope	54 mio.	270 mio.	6.2 mio.	gammas
	39 + 4 mio.	970 + 22 mio.	2.3+0.2 mio.	p + e

All simulation at 20° zenith angle.

Heidelberg Analysis 1

- Simple analysis (with updates since last meeting):
  - Cleaning: 4/7, 5/10, 8/12 p.e. tail-cuts and other scheme;
  - Image amplitude > 30 p.e., up to 200 p.e.
  - Image c.o.g. radius + image length < 0.85 R_{cam} and variations of it (“edge cut”). Potential problem at high *E*.
  - Geometrical shower reconstruction (direction and core position) from Hillas parameters, using mean of weighted pair-wise intersections of image major axes.

Heidelberg Analysis 2

- Generating lookup tables width+length of gamma rays.
- Using the lookups, get mean reduced scaled width+length

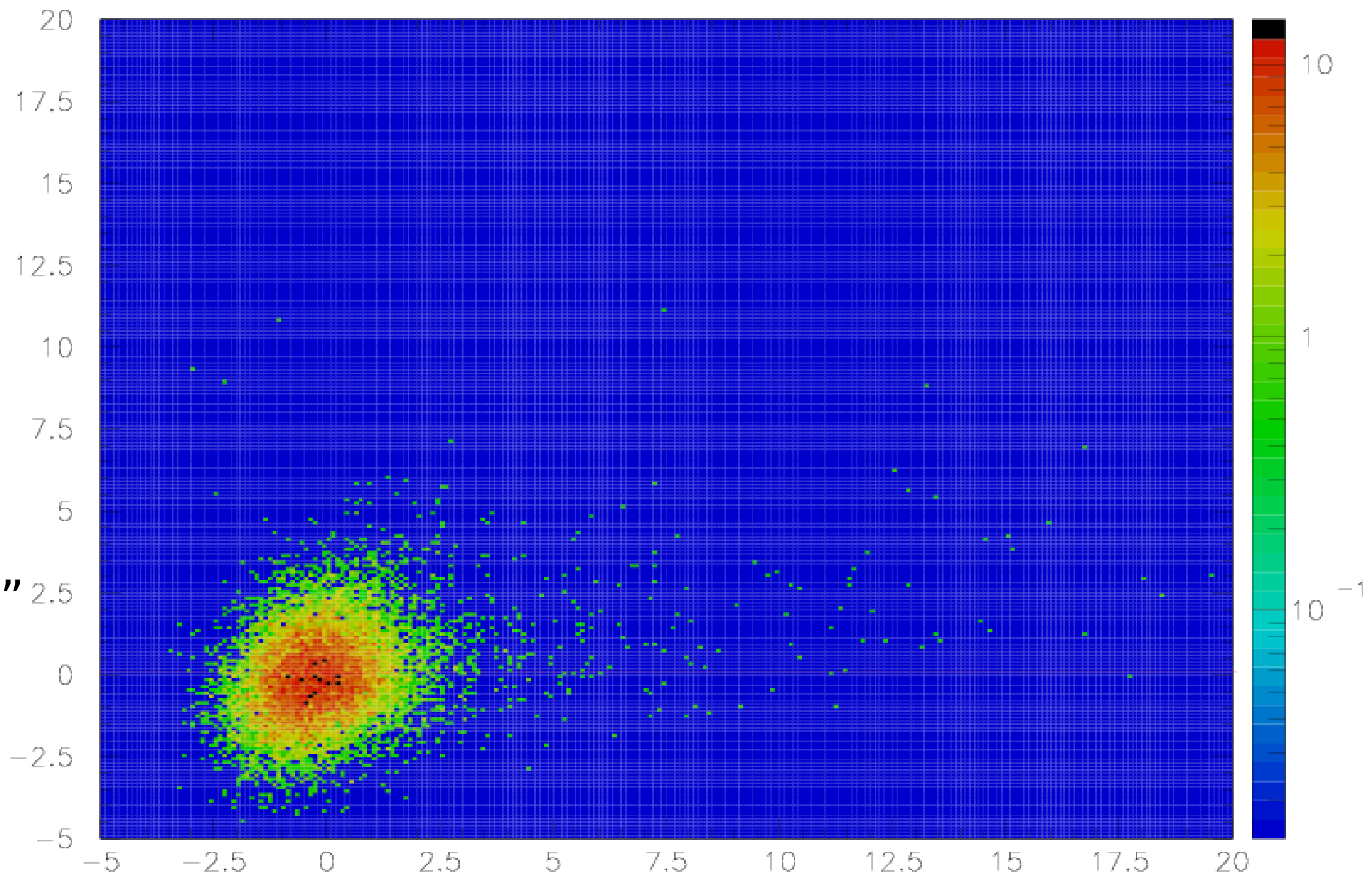
$$mrscw = \frac{1}{N} \sum_{i=1,N} \frac{(w_i - \bar{w}(r_c, A, z))}{\sigma_w}$$

  and cut on *mrscw* and *mrscl* for gammas and protons ("shape cuts").
- Get angular resolution and apply point source selection ("angle cut"):
  - Now with multiplicity-dependent cut.

Heidelberg Analysis 3

- Generating lookup tables for image amplitude / energy (*I/E*) as with width and length.
- Using that lookup an energy estimate and estimate of its fluctuation for each telescope is obtained.
- Get energy E, energy accuracy σ_E/E, and χ^2/n.d.f.
- Discard showers with bad σ_E/E ("dE cut").
  Rejects also gammas at large (but energy dependent) R_c.
- Discard showers with bad χ^2/n.d.f. ("dE2 cut").
- Calculate distance of shower maximum and discard showers inconsistent with gammas ("hmax cut").

Shape cuts: gammas 2 – 5 TeV

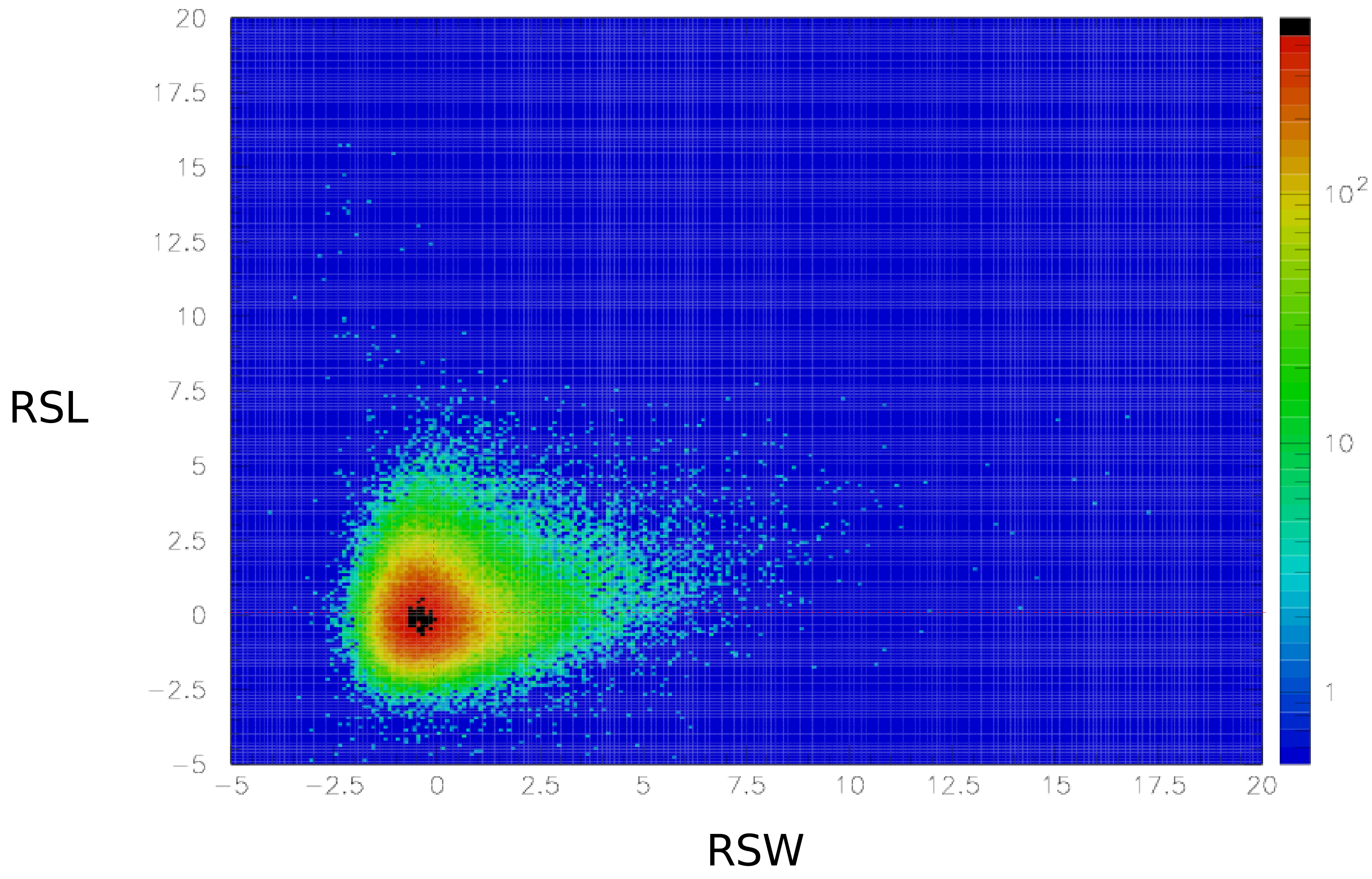


RSL

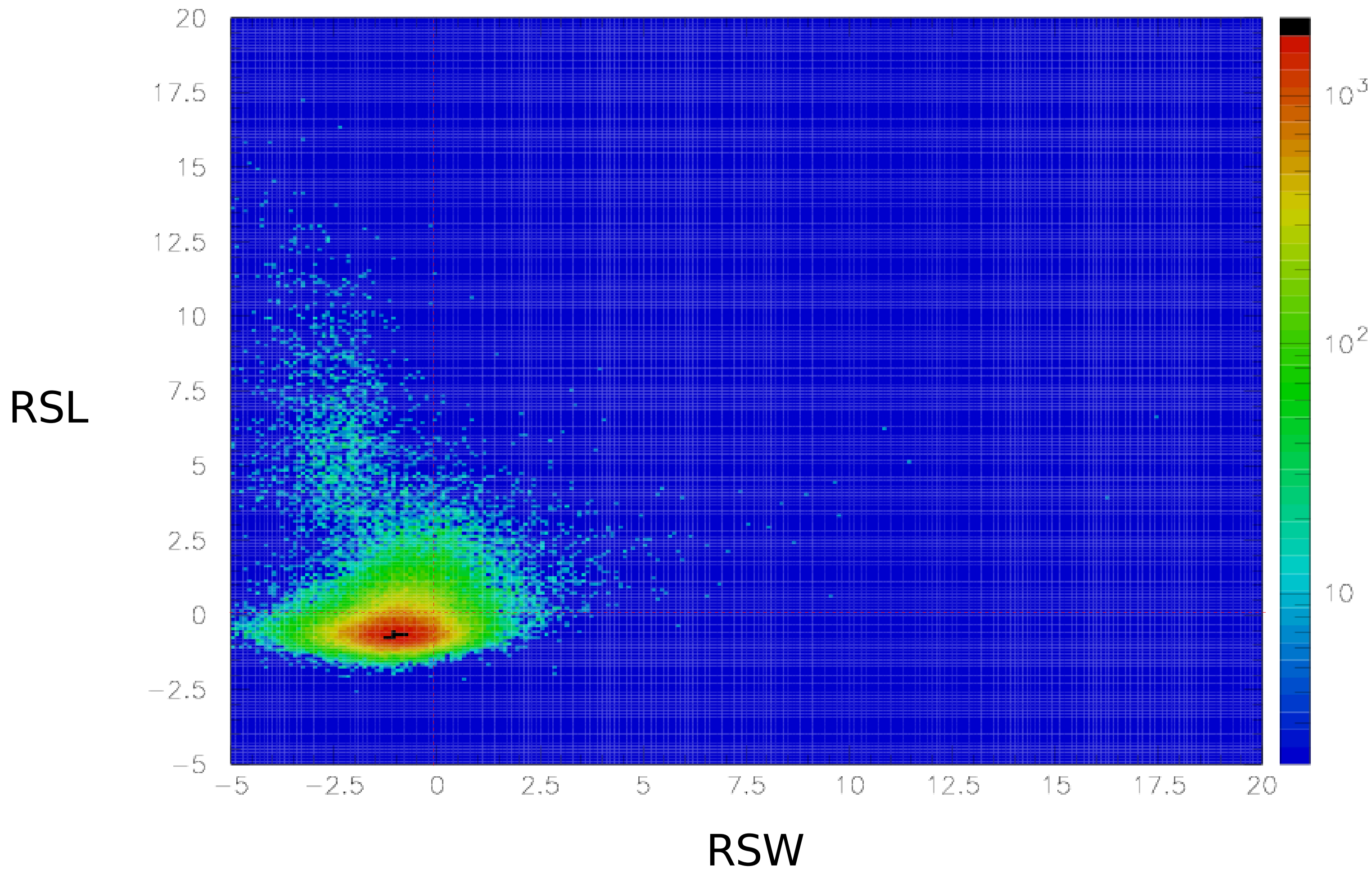
= "reduced scaled length"

RSW = "reduced scaled width"

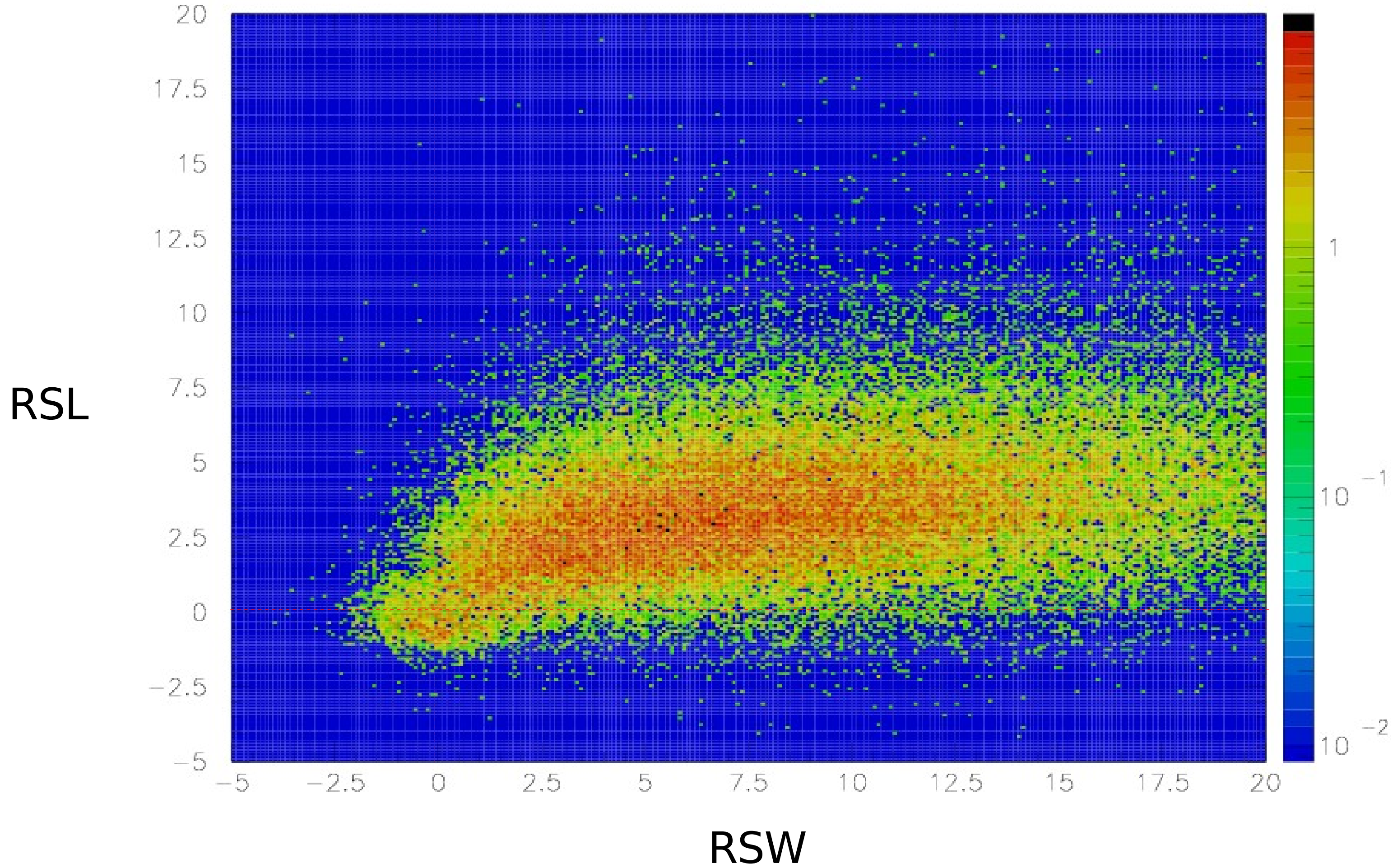
Shape cuts: gammas 200 – 500 GeV



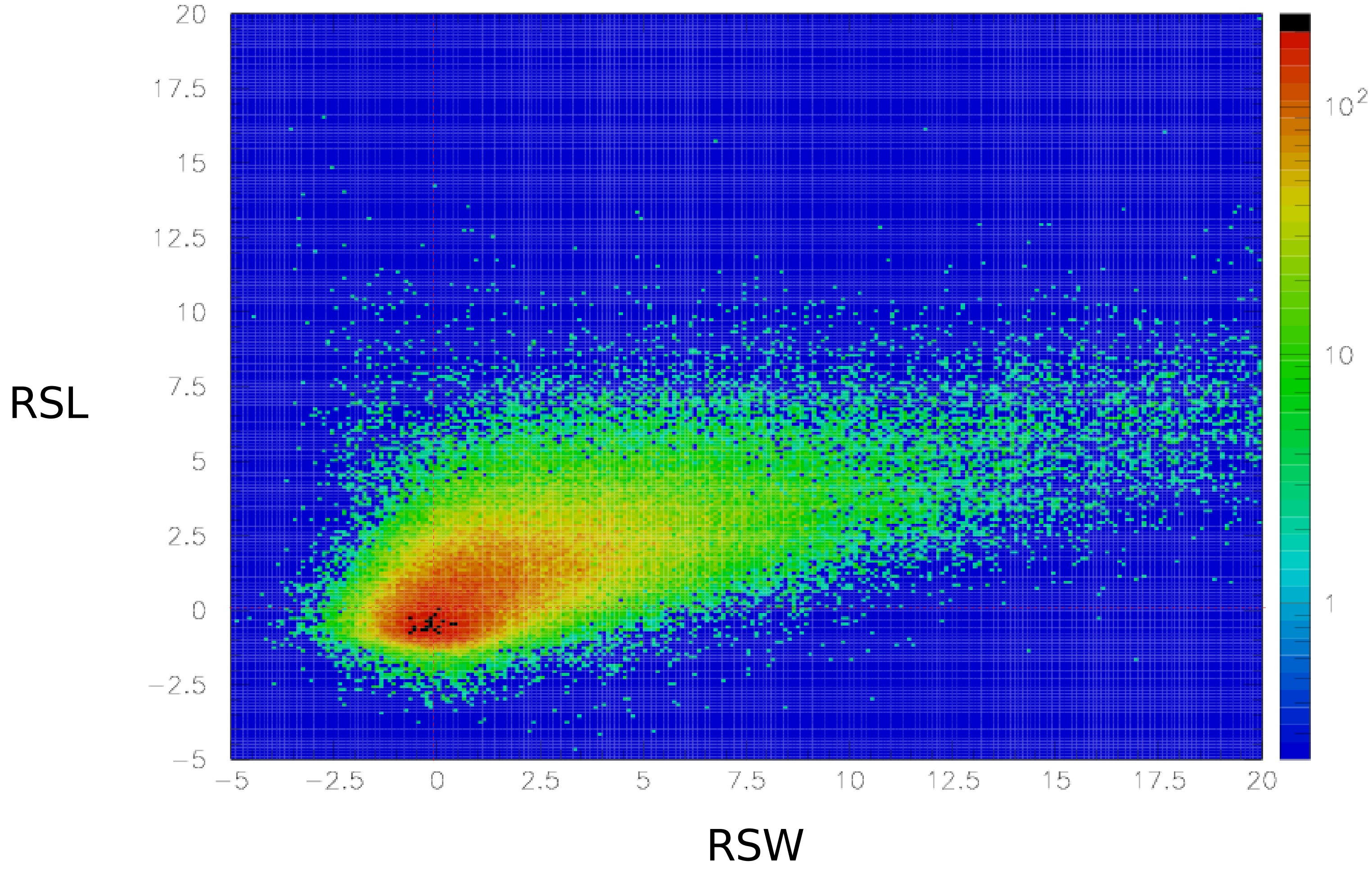
Shape cuts: gammas 20 – 50 GeV



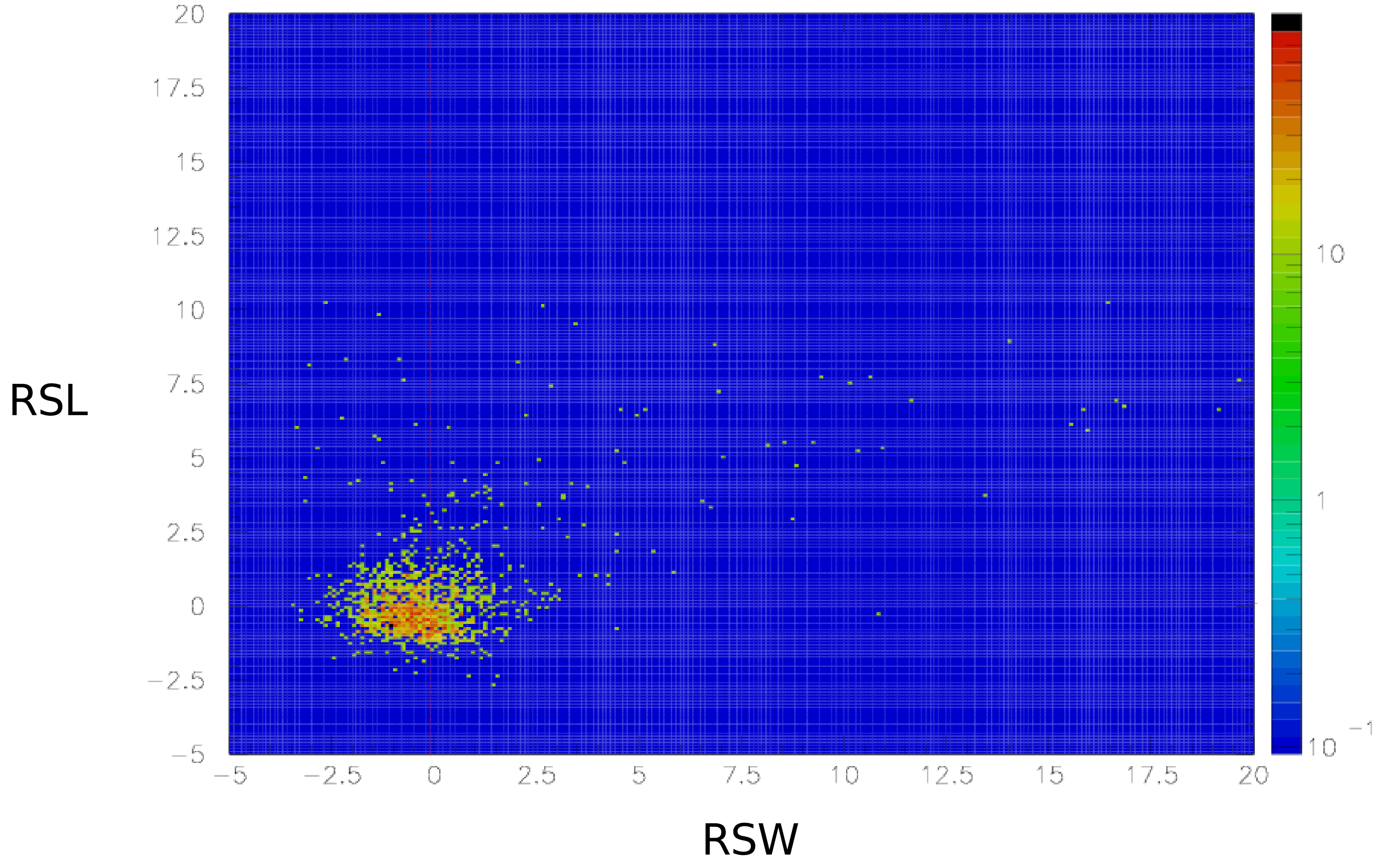
Shape cuts: protons 2 – 5 TeV



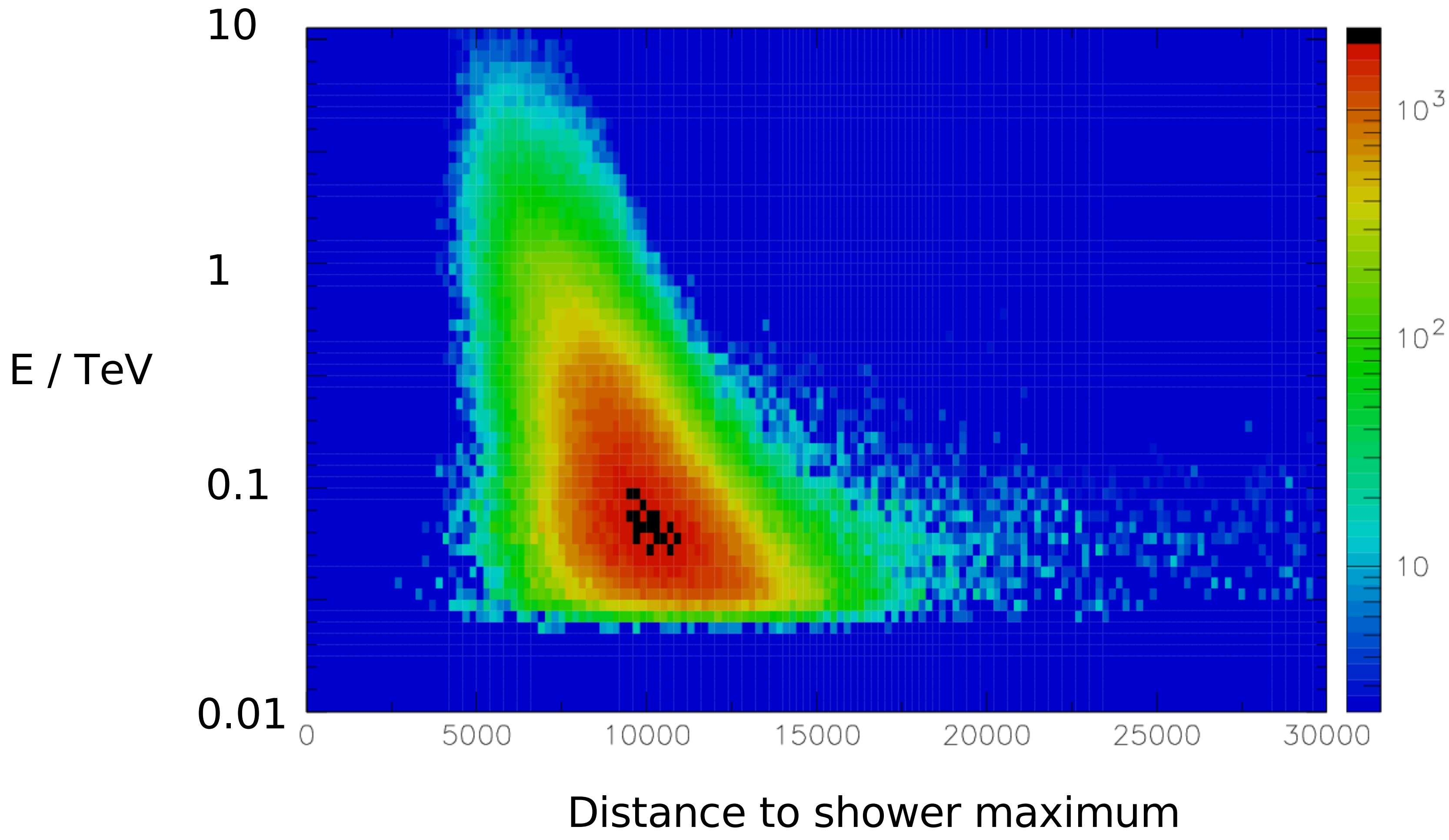
Shape cuts: protons 200 – 500 GeV



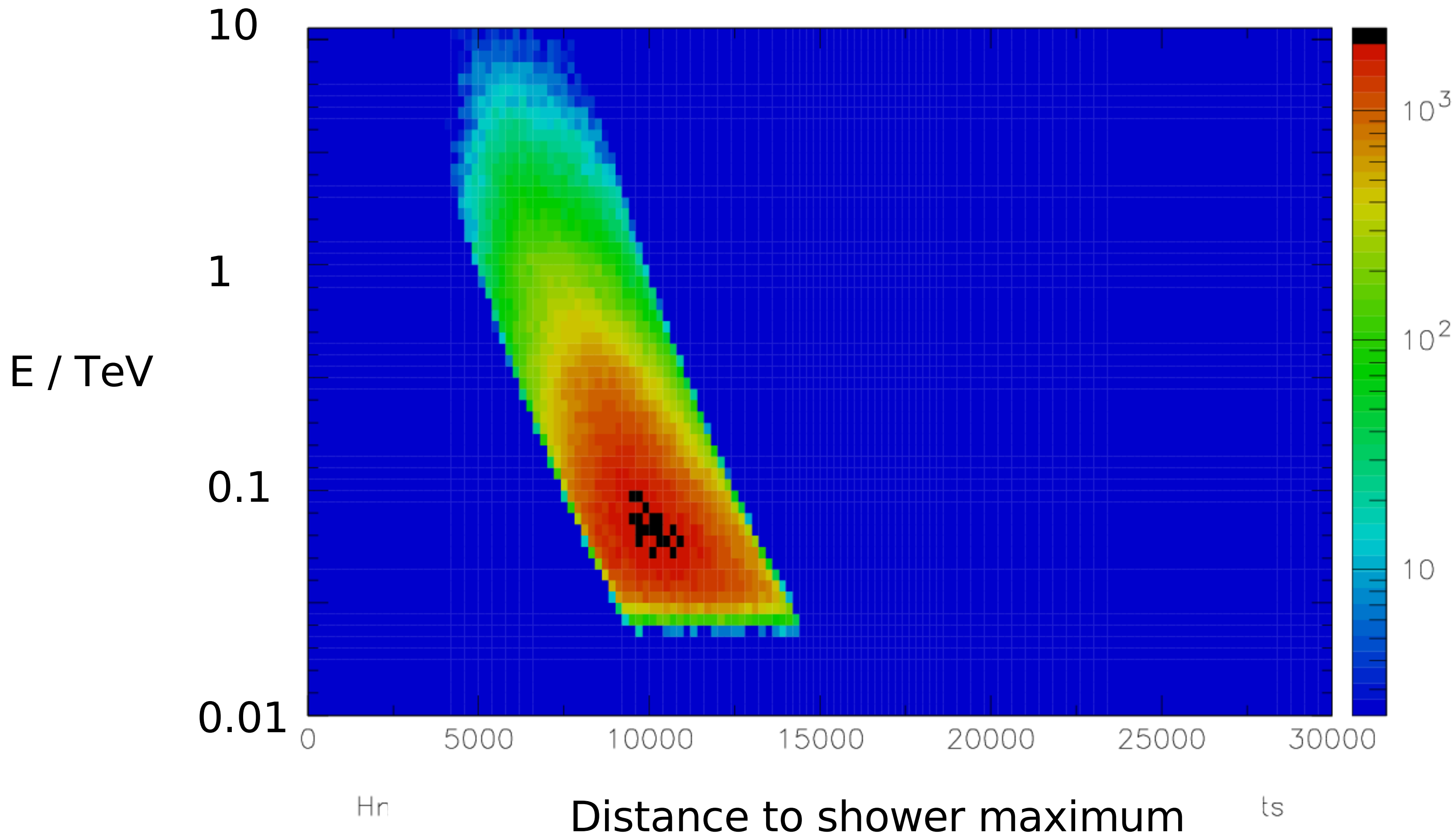
Shape cuts: protons 20 – 50 GeV



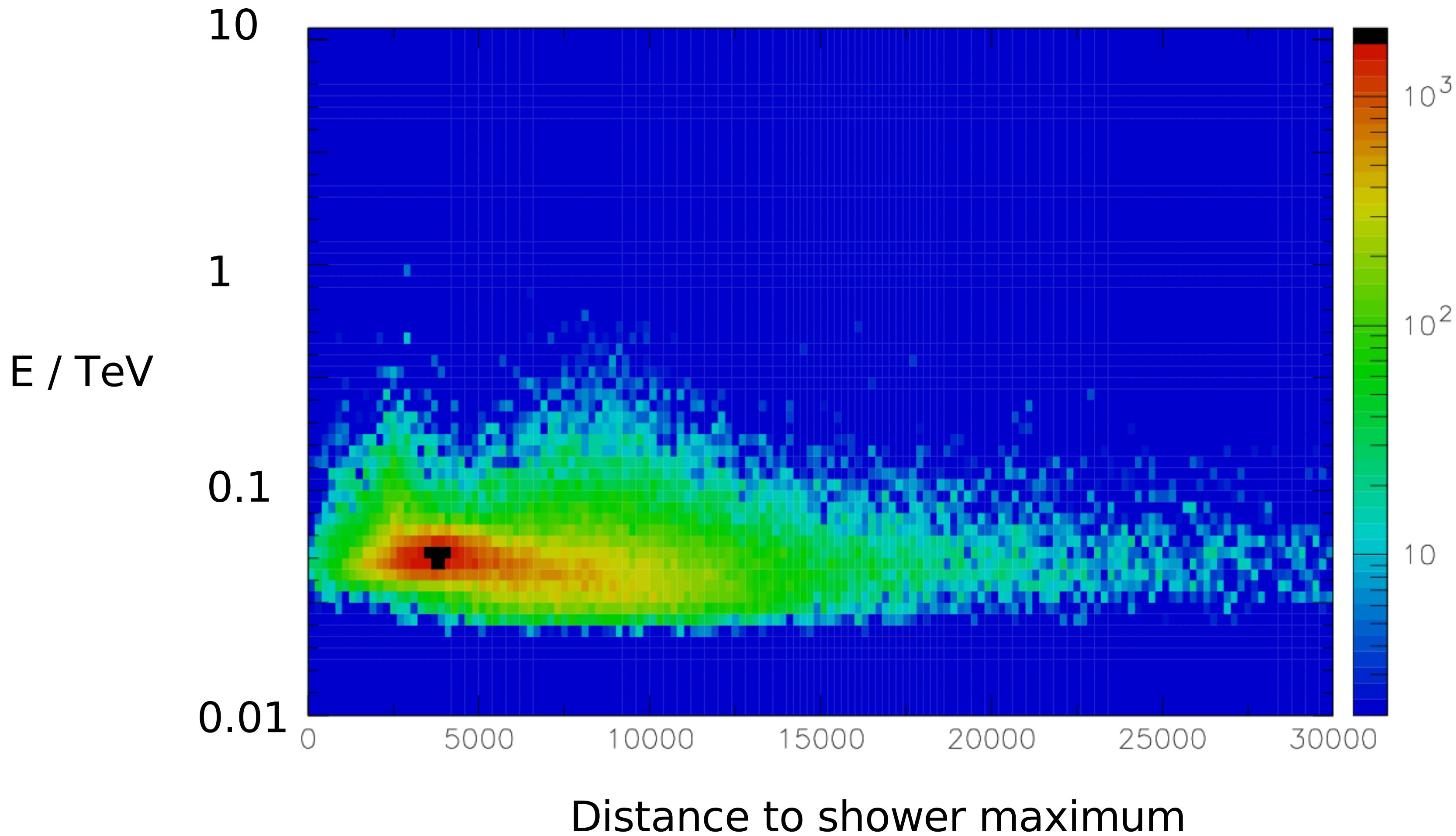
Hmax cut (gammas)



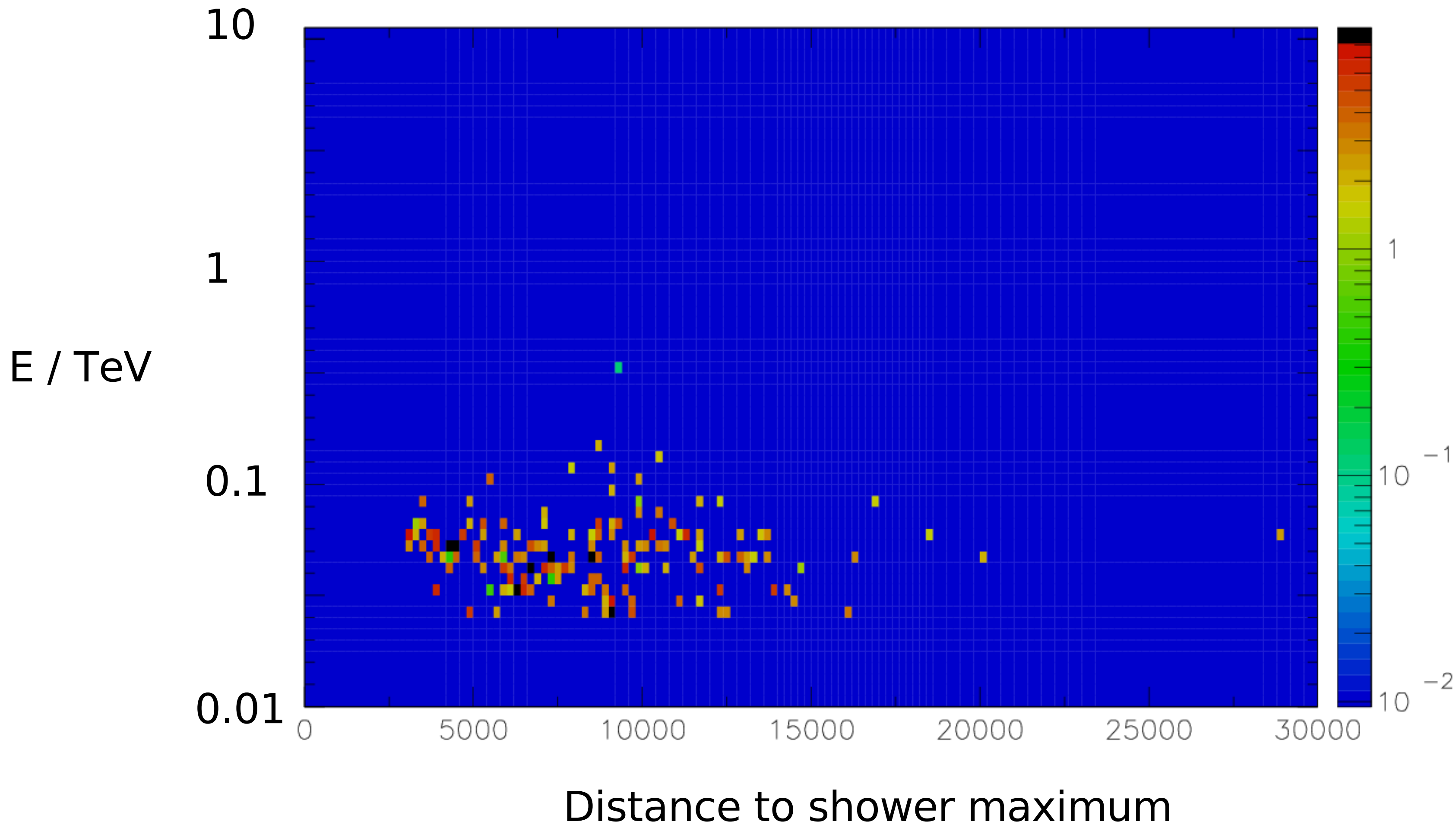
Hmax cut (gammas)



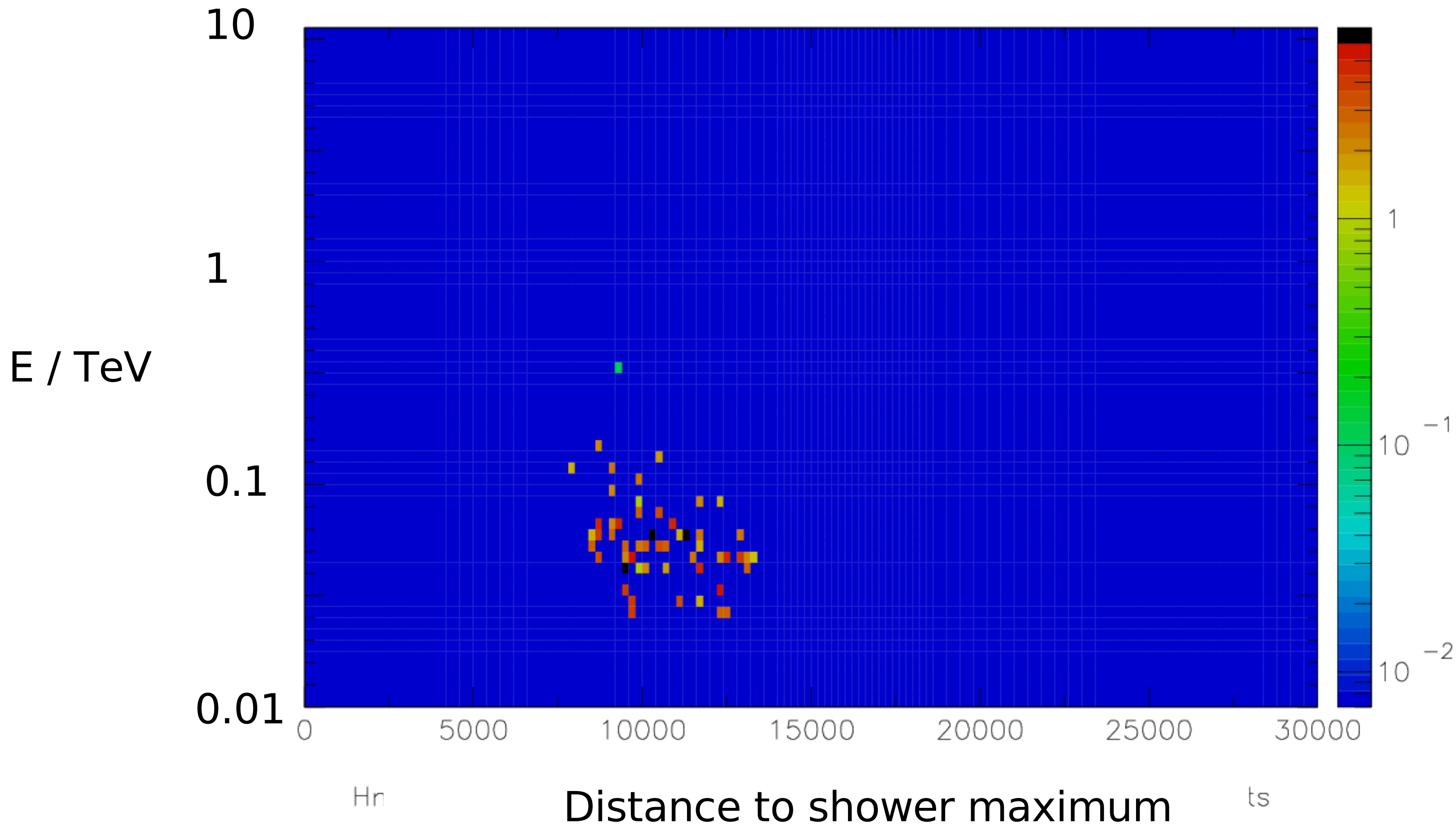
Hmax cut (protons)



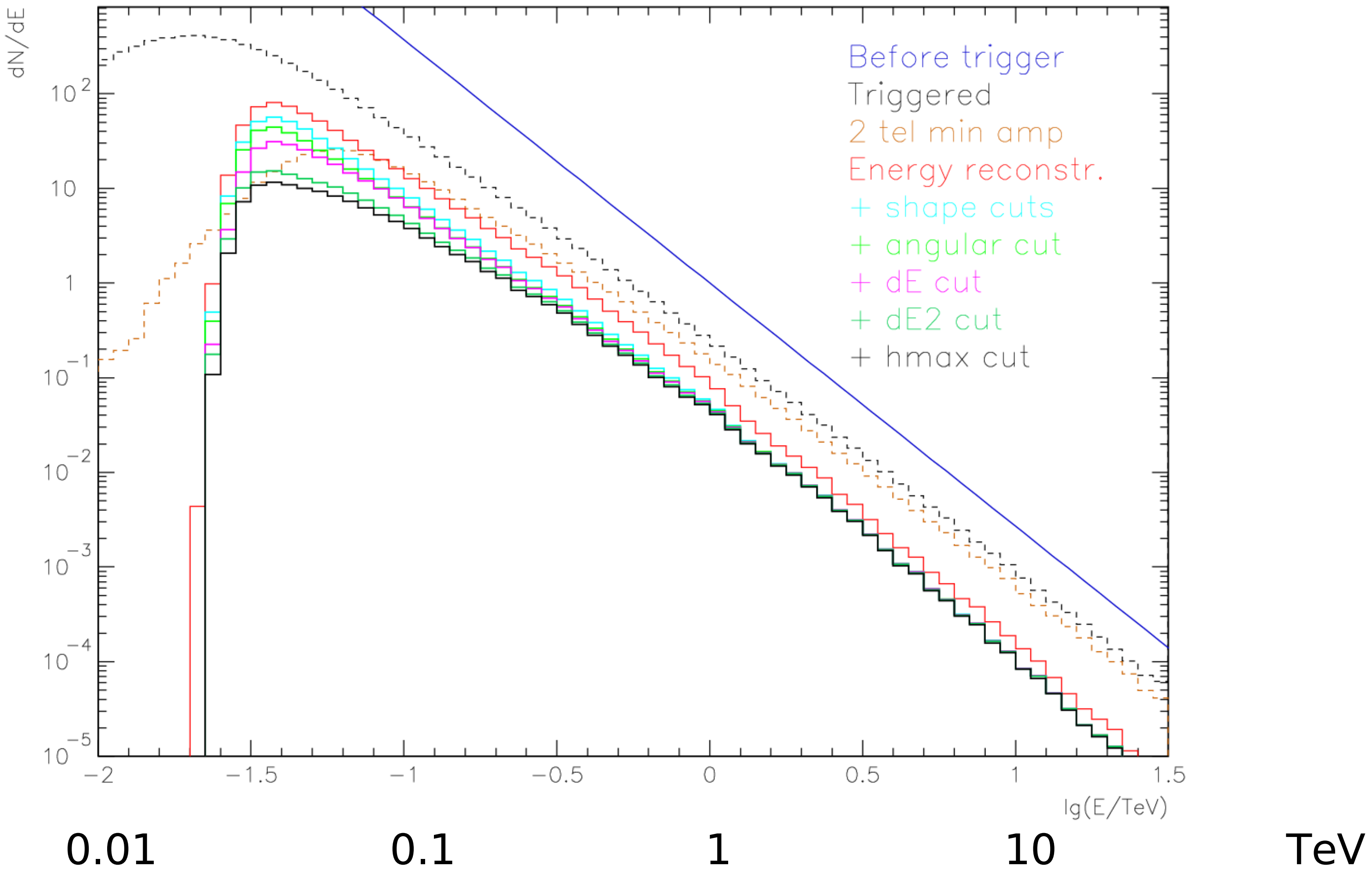
Hmax cut (protons)



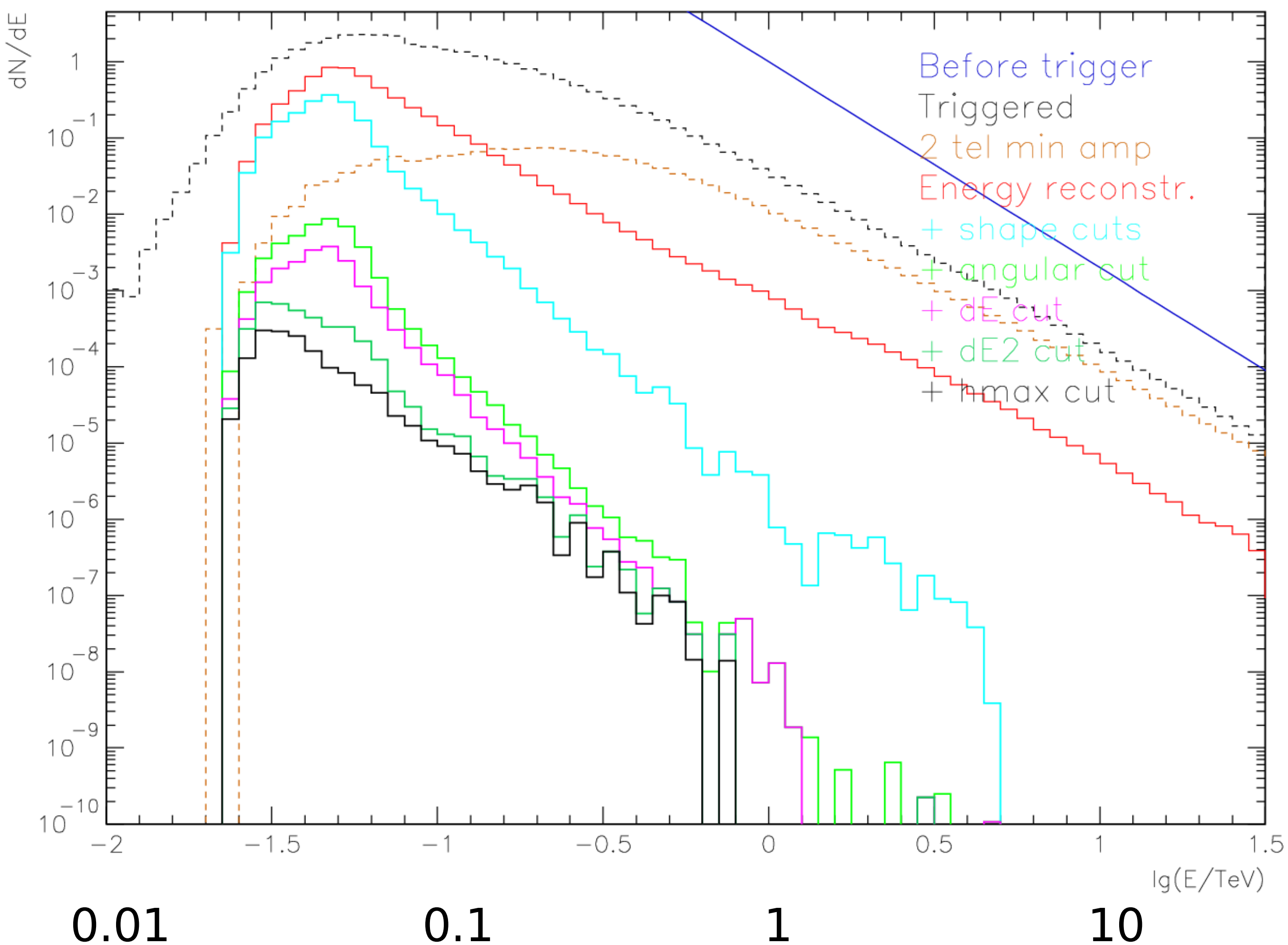
Hmax cut (protons)



Cut efficiencies (gammas)



Cut efficiencies (protons)



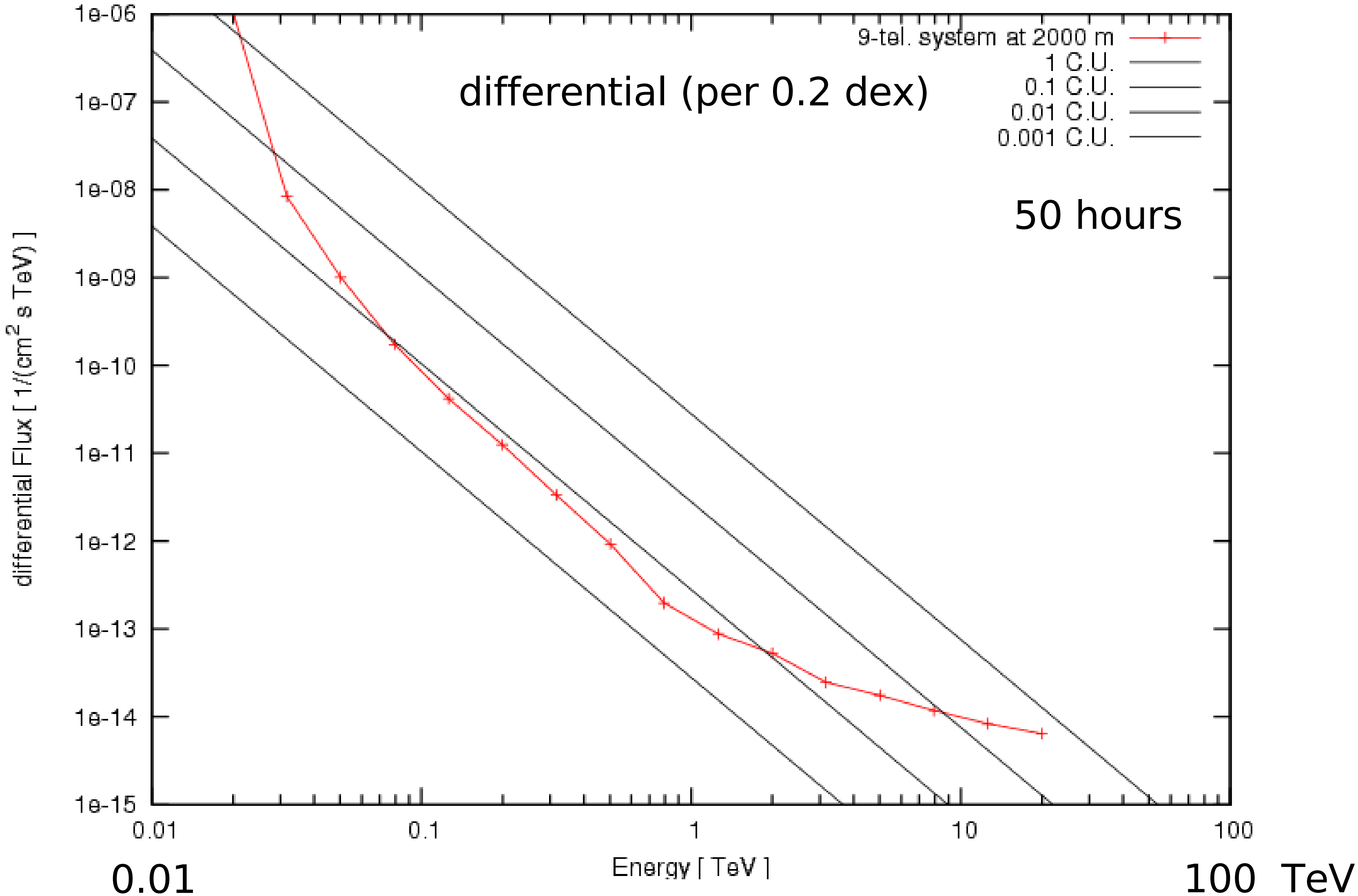
Since meetings last autumn

- Immediately after Munich CTA-MC meeting: Stricter *hmax* cut resulting in almost factor 2 improvement for benchmark array below 100 GeV.
- More conservative sensitivity threshold: 5σ Li&Ma, resulting in (up to 25%) worse limits in the intermediate energy range. Low energies and high energies not affected.
- Systematic search of best sensitivity in tail-cuts, telescopes, pixels, image amplitude, ...
- Search for more gamma-hadron separation criteria.

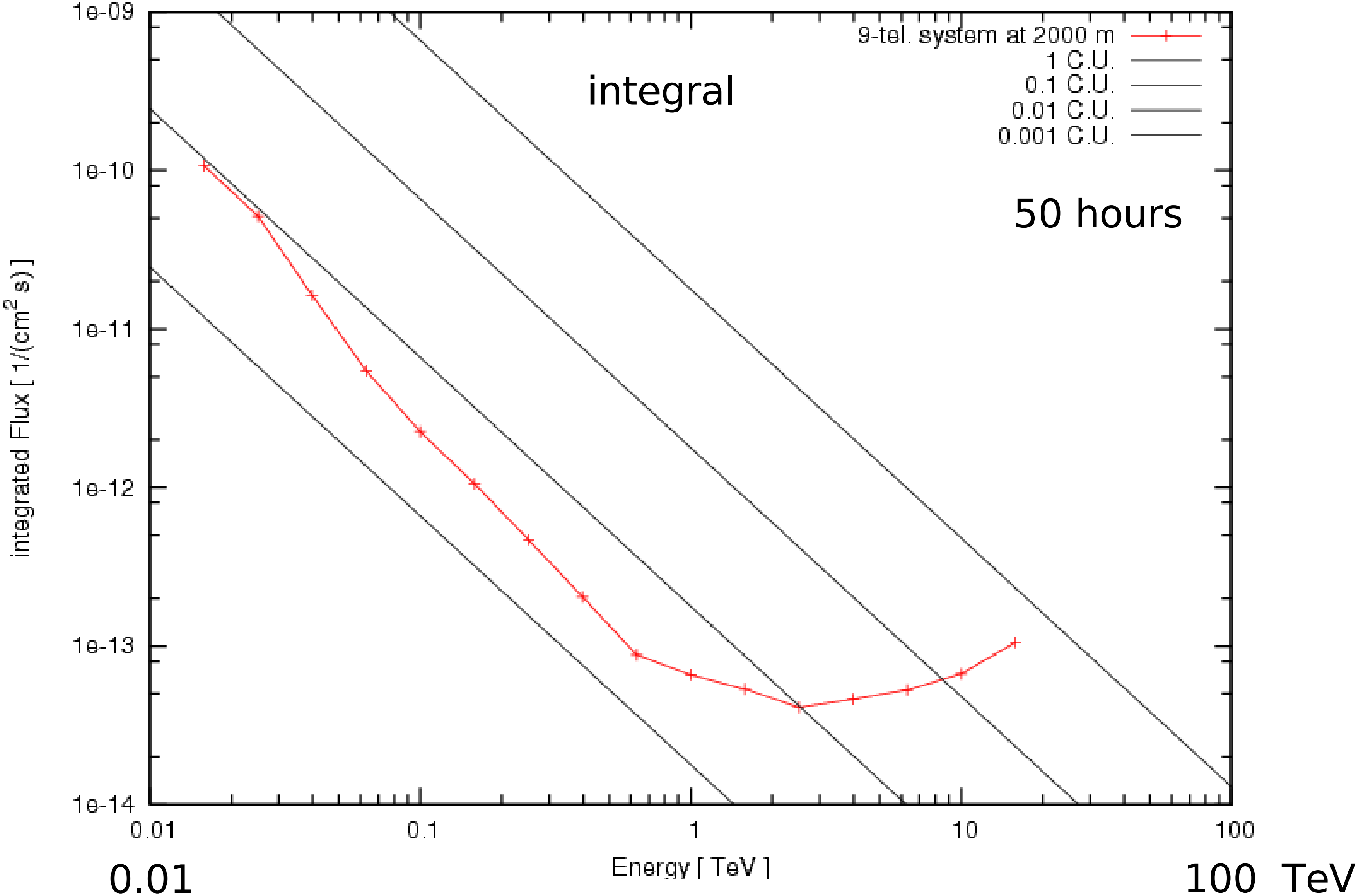
Optimizing shape cuts etc.

- Background falls off rapidly at higher energies.
- Optimum shape cuts are, compared to fixed cuts:
  - more strict at low energies (better hadron rejection)
  - less strict at high energies (more gamma signal)
- Similar for *dE* cut, even though acceptable relative energy error estimate was already larger at low energies.
- The *dE2* and *hmax* cuts were pretty much at optimum value already.

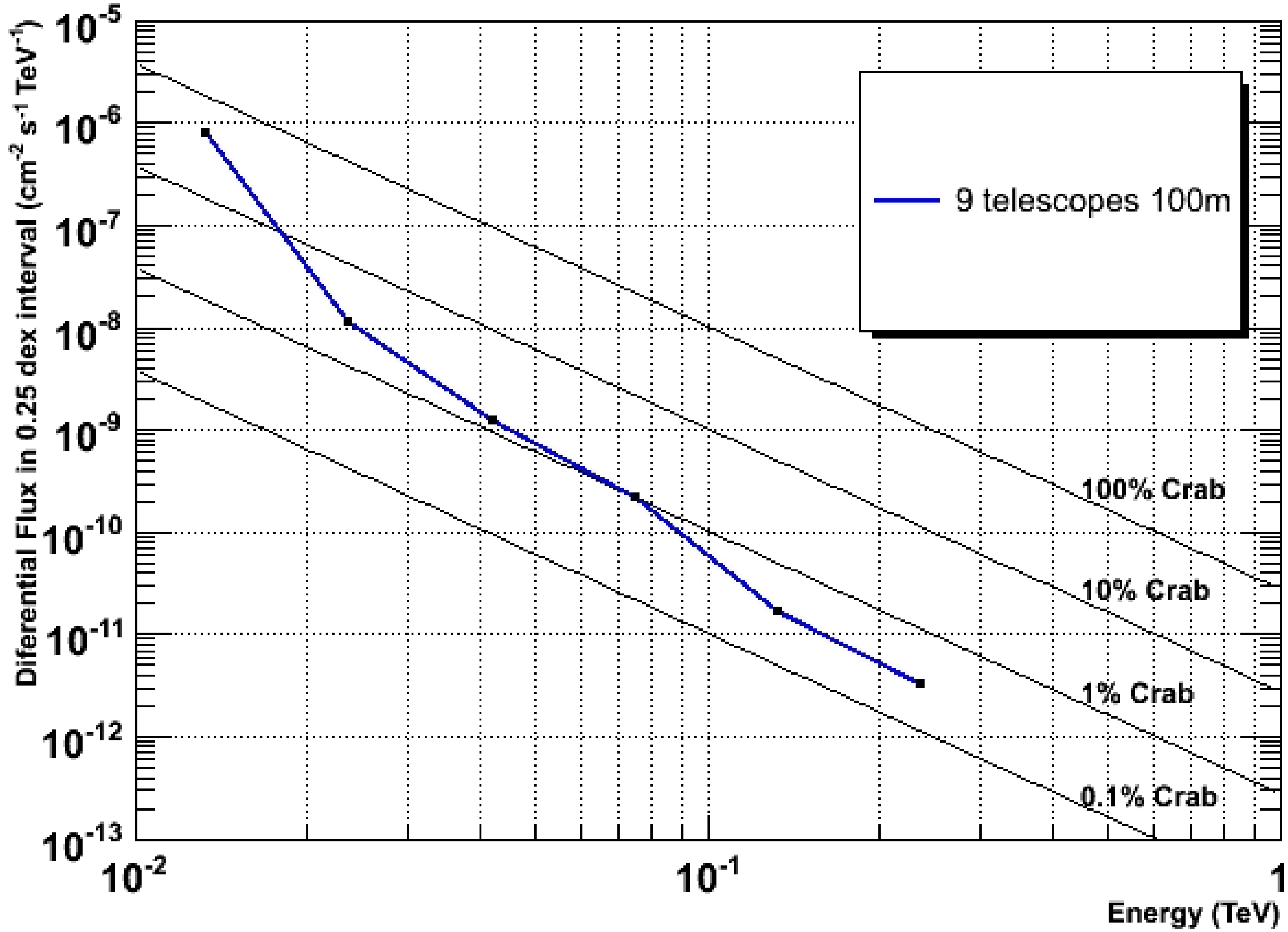
Sensitivity of benchmark array



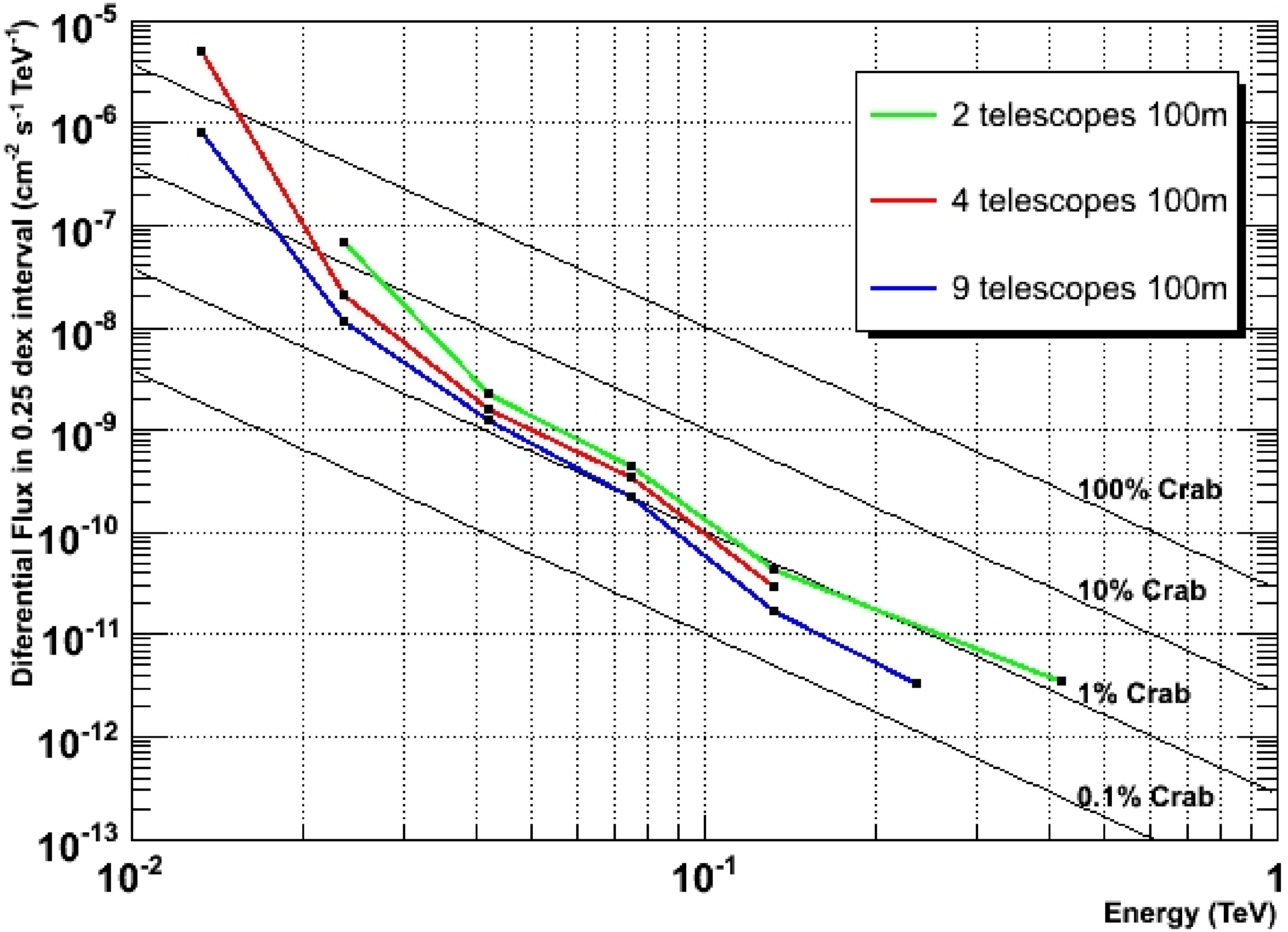
Sensitivity of benchmark array



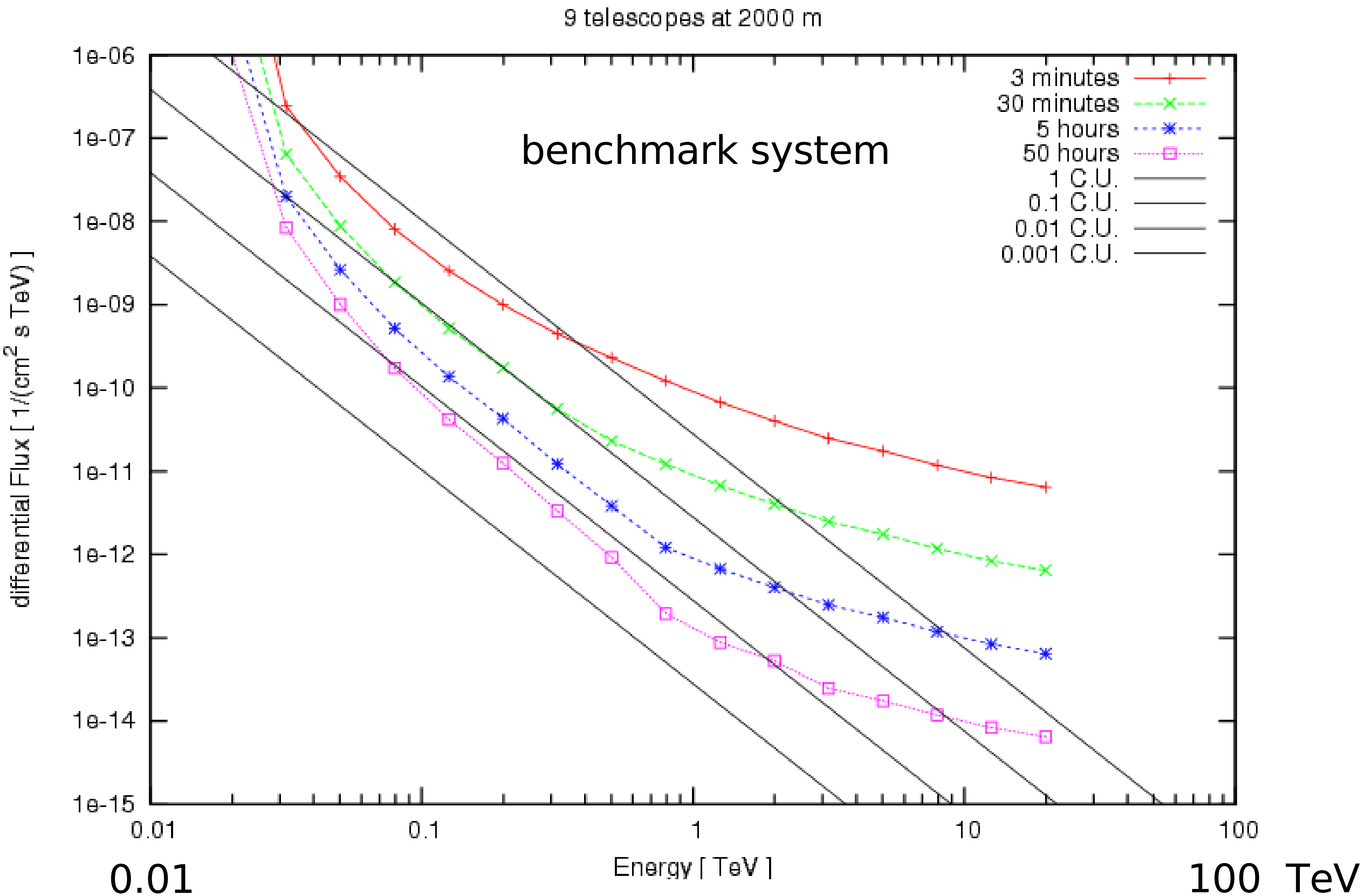
Benchmark array: Munich analysis



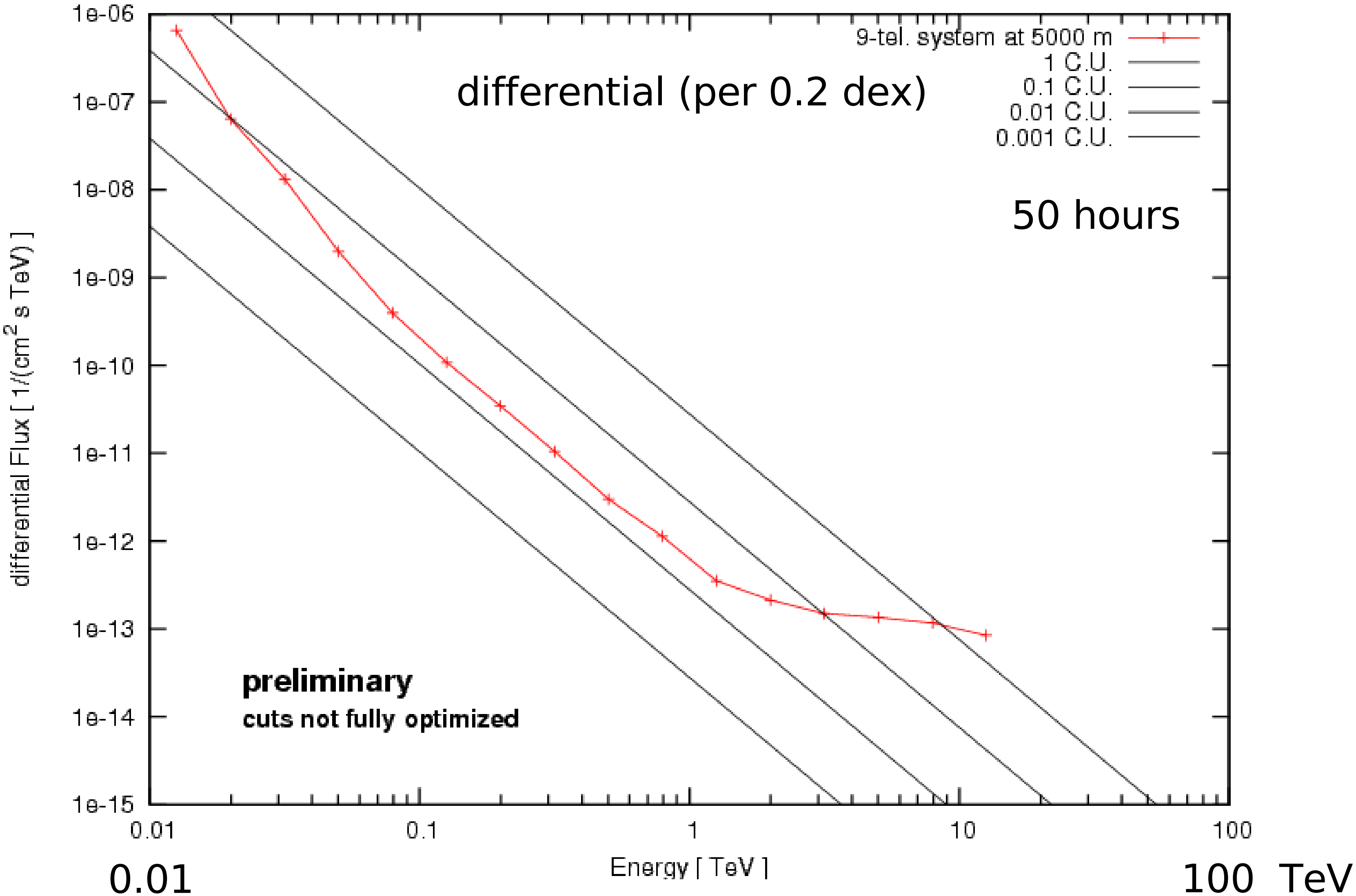
Benchmark array: Munich analysis



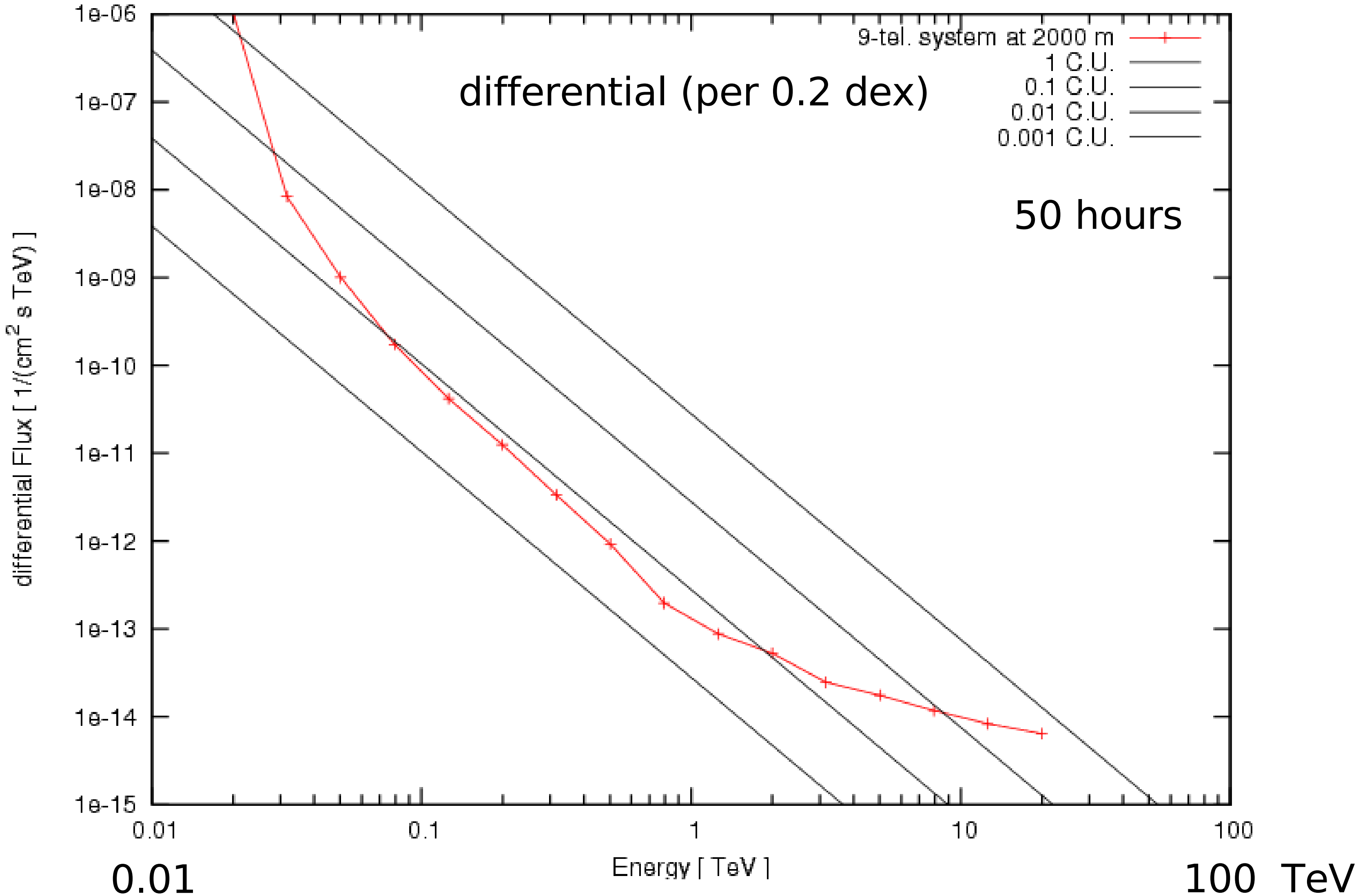
Different exposure times



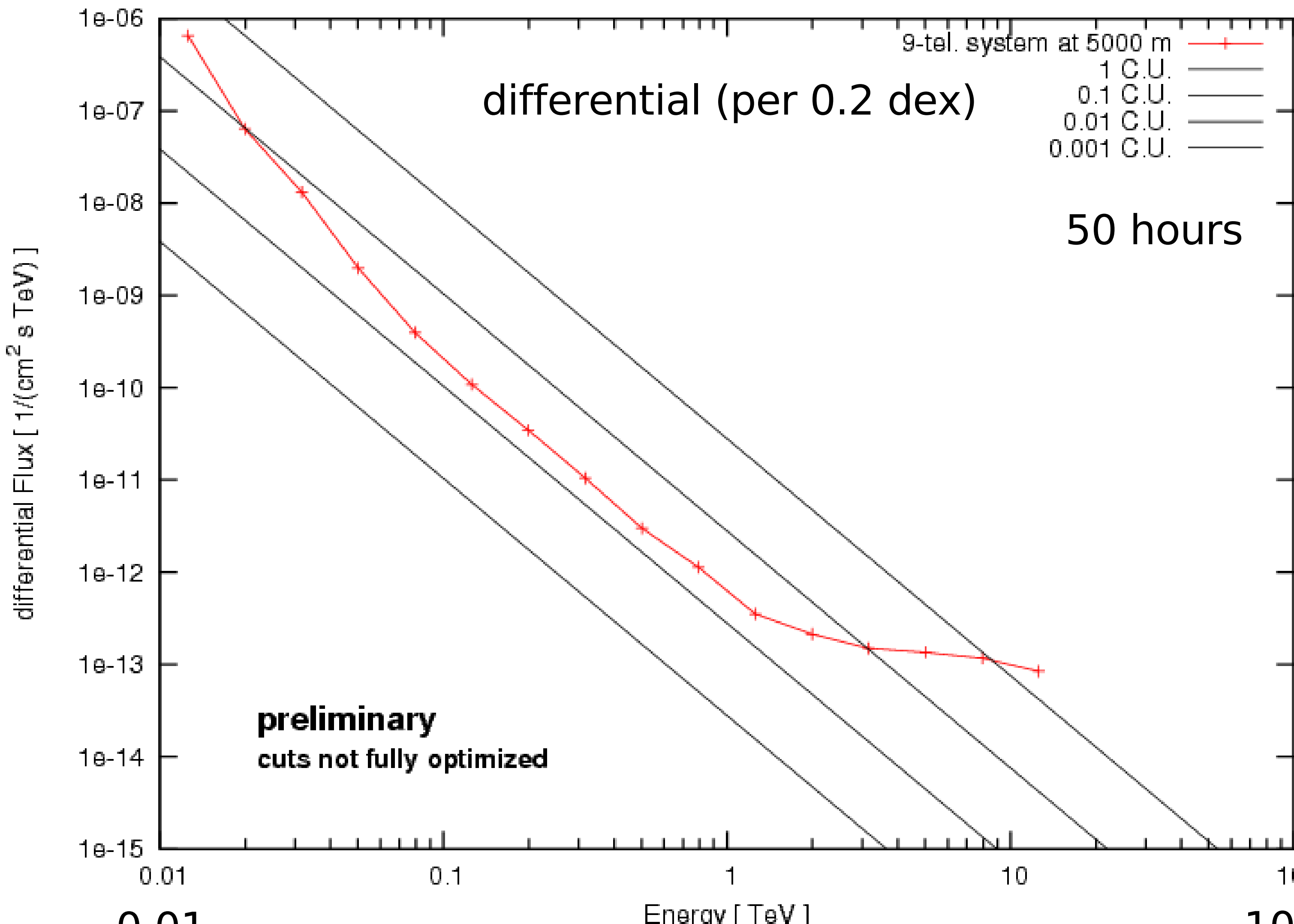
Sensitivity of 5000 m array



Sensitivity of benchmark array



Sensitivity of 5000 m array



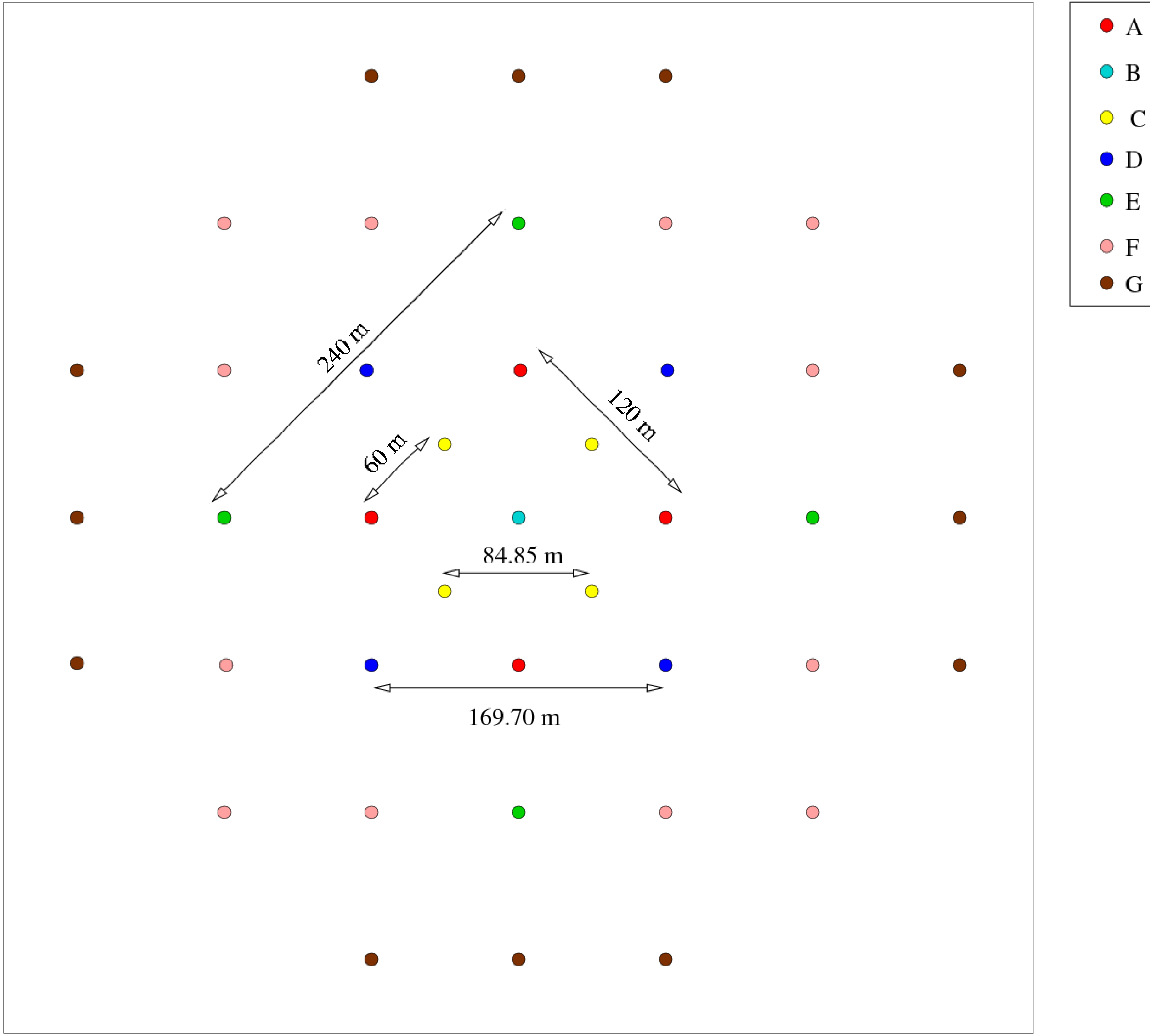
0.01 100 TeV

Sensitivity of 5000 m array

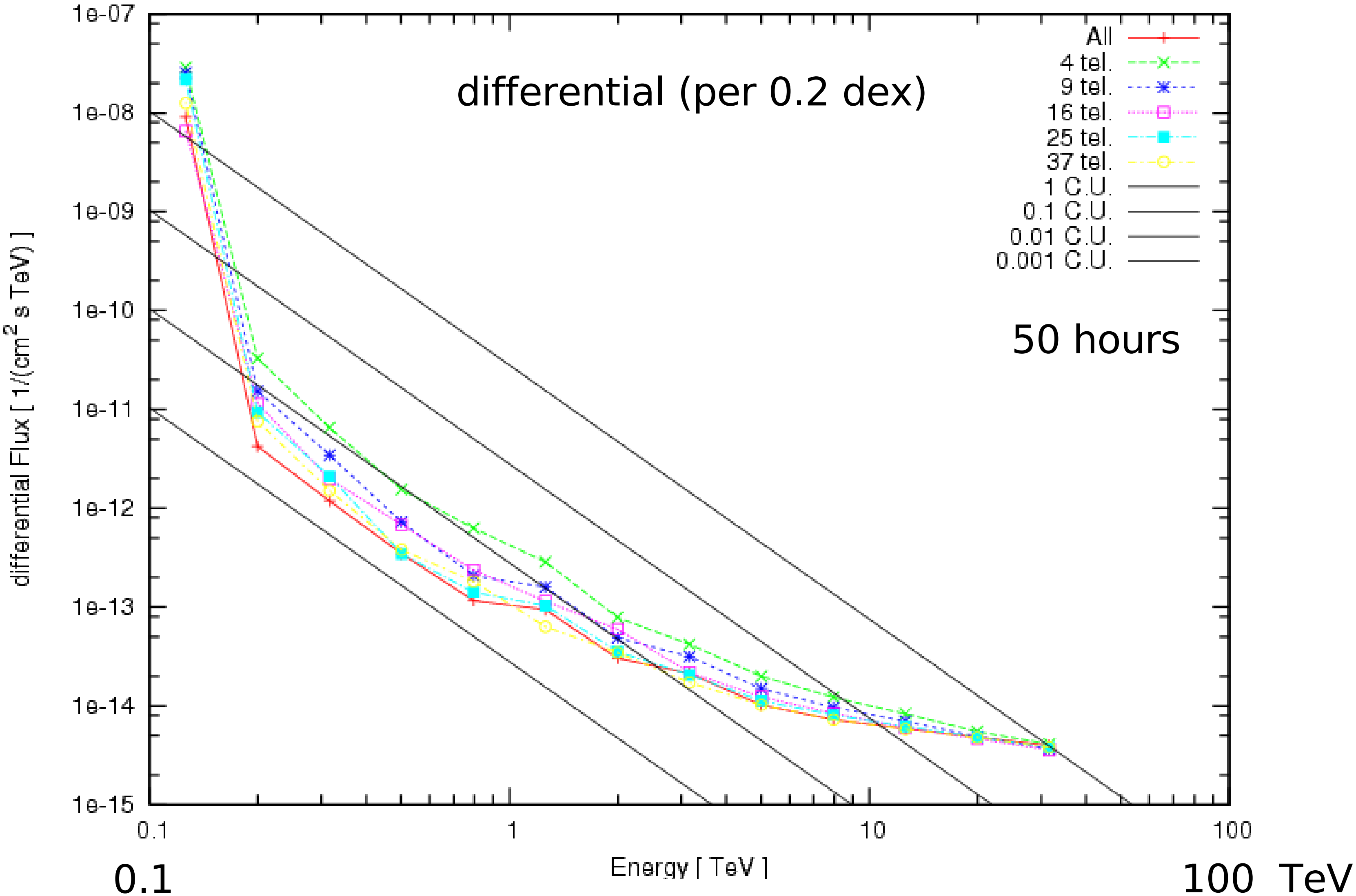
- The energy threshold is lowered by about a factor of two when moving from 2000 m to 5000 m because of smaller dilution of Cherenkov light close to shower maximum.
- At 30 GeV and above the array at 5000 m is less sensitive than that at 2000 m because of inferior gamma-hadron rejection. Gamma showers look more irregular when the detector is not well behind the shower.

41 telescopes
of 106 m²

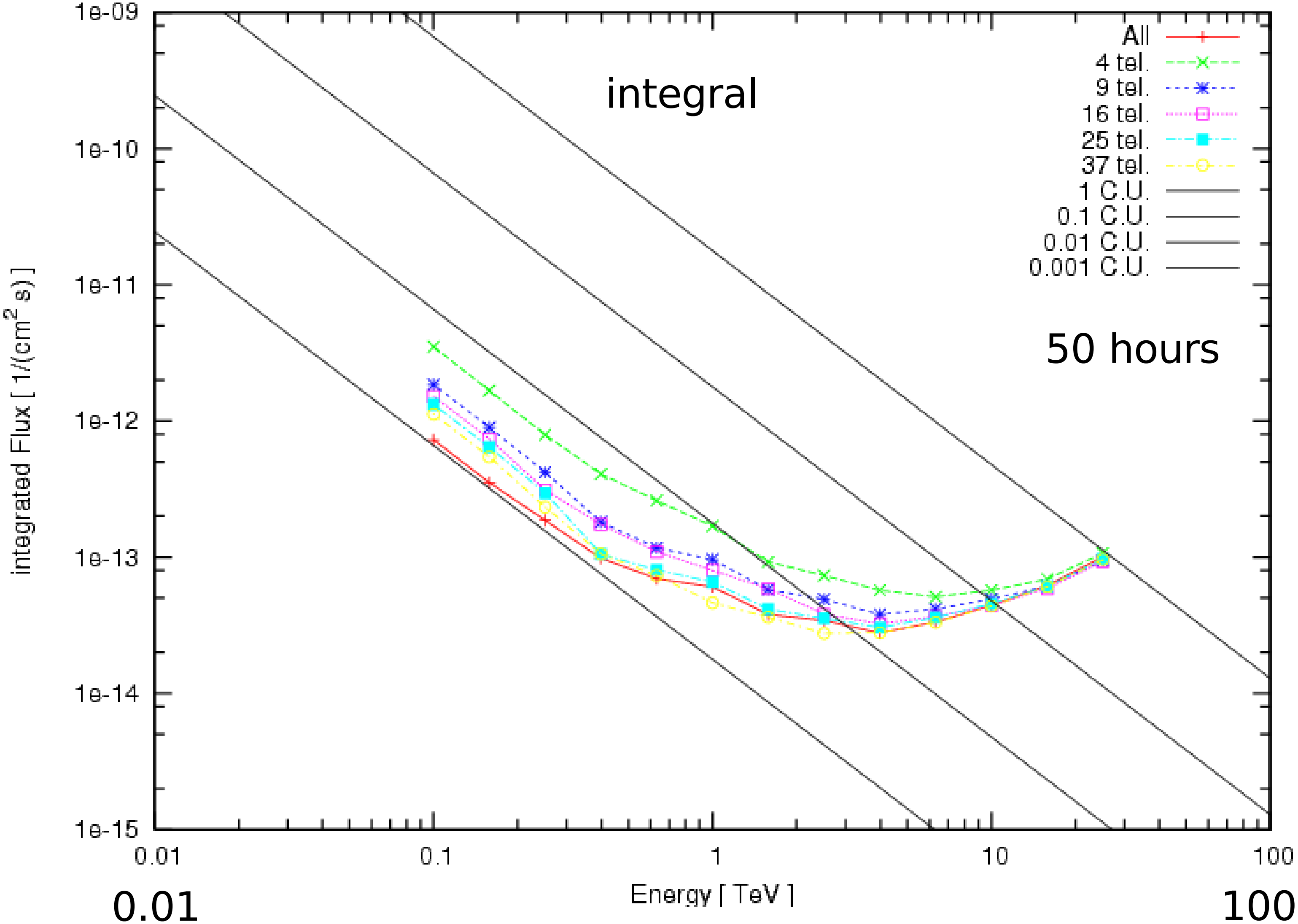
Sub-array A
is H.E.S.S. 1



Sensitivity of 41-telescope system



Sensitivity of 41-telescope system

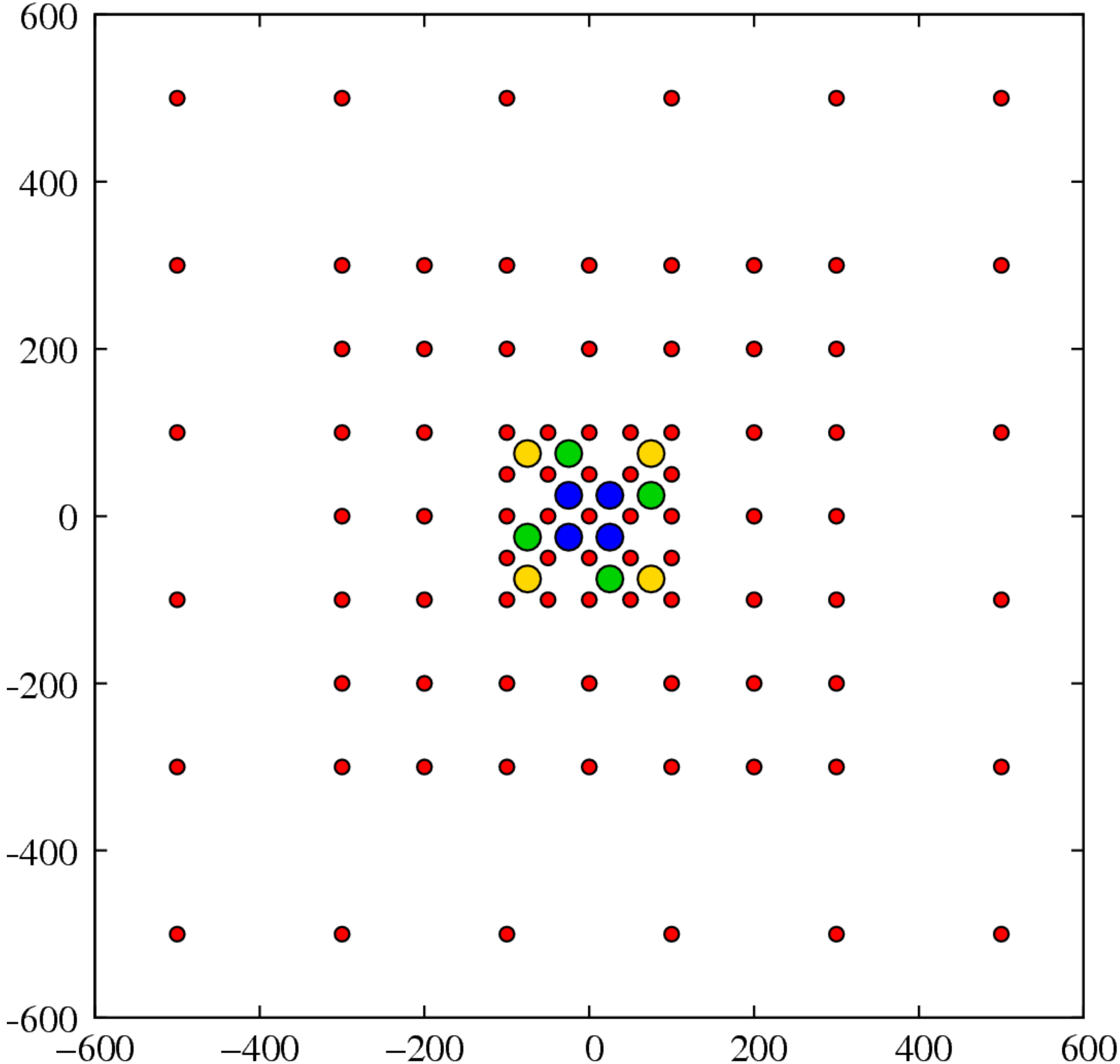


0.01 100 TeV

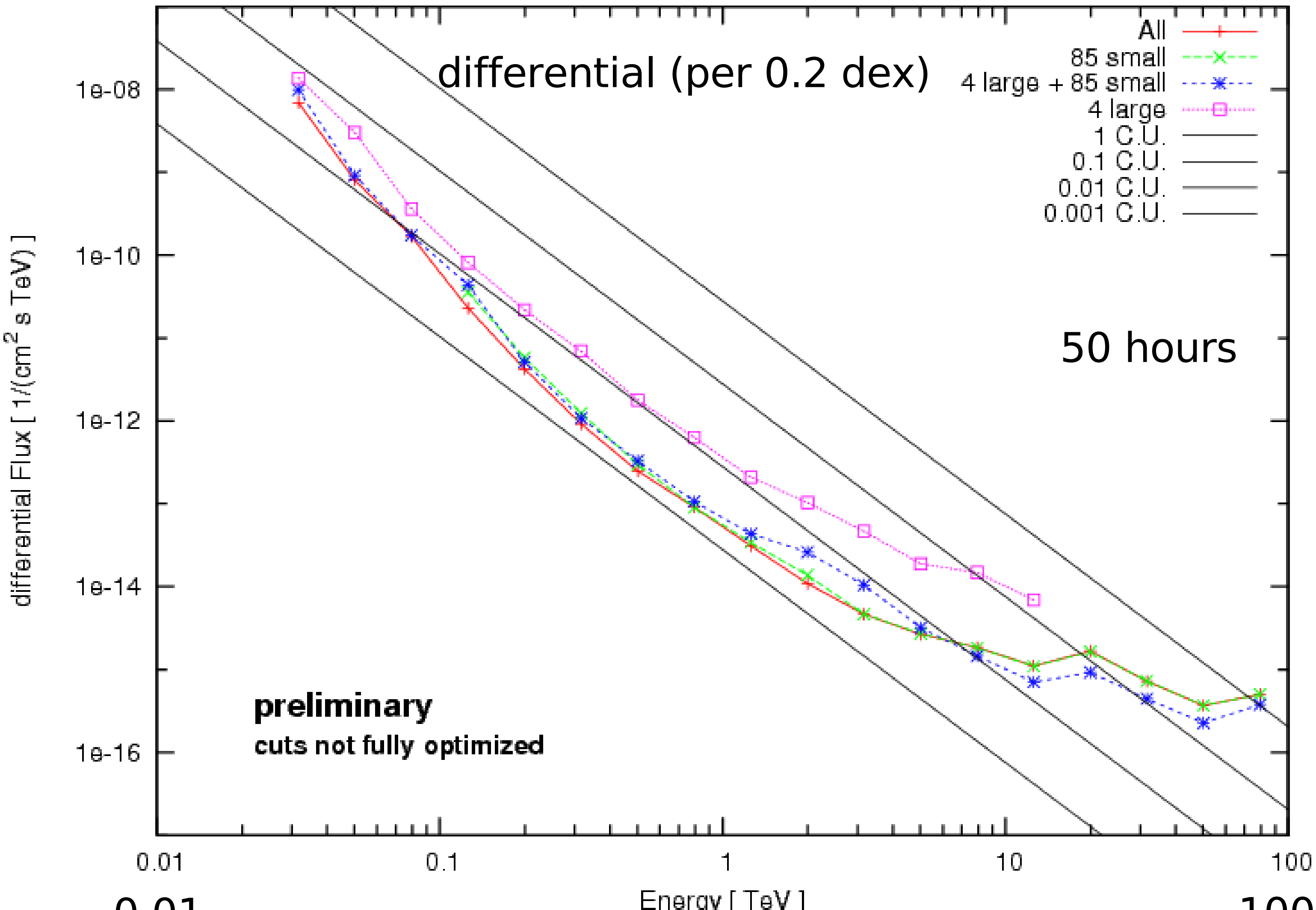
Sensitivity of 41-telescope system

- Factor of 7 improvement in sensitivity (7 mCrab to **1 mCrab** integral) when increasing no. of telescopes from 4 to 41. That is faster than $\sqrt{N}$.
- Largest improvement seen below 1 TeV.
- Very noticeable improvement from 37 to 41 tel. (adding central 4 telescopes fill-in).
- At highest energies little to no improvement in sensitivity (background-free; complete array illuminated) but in angular and energy resolution.

97 telescopes:
3 * 4 tel. with 600 m²
(with 5° f.o.v.),
85 tel. with 100 m²
(with 7° f.o.v.),
both 50% higher QE.

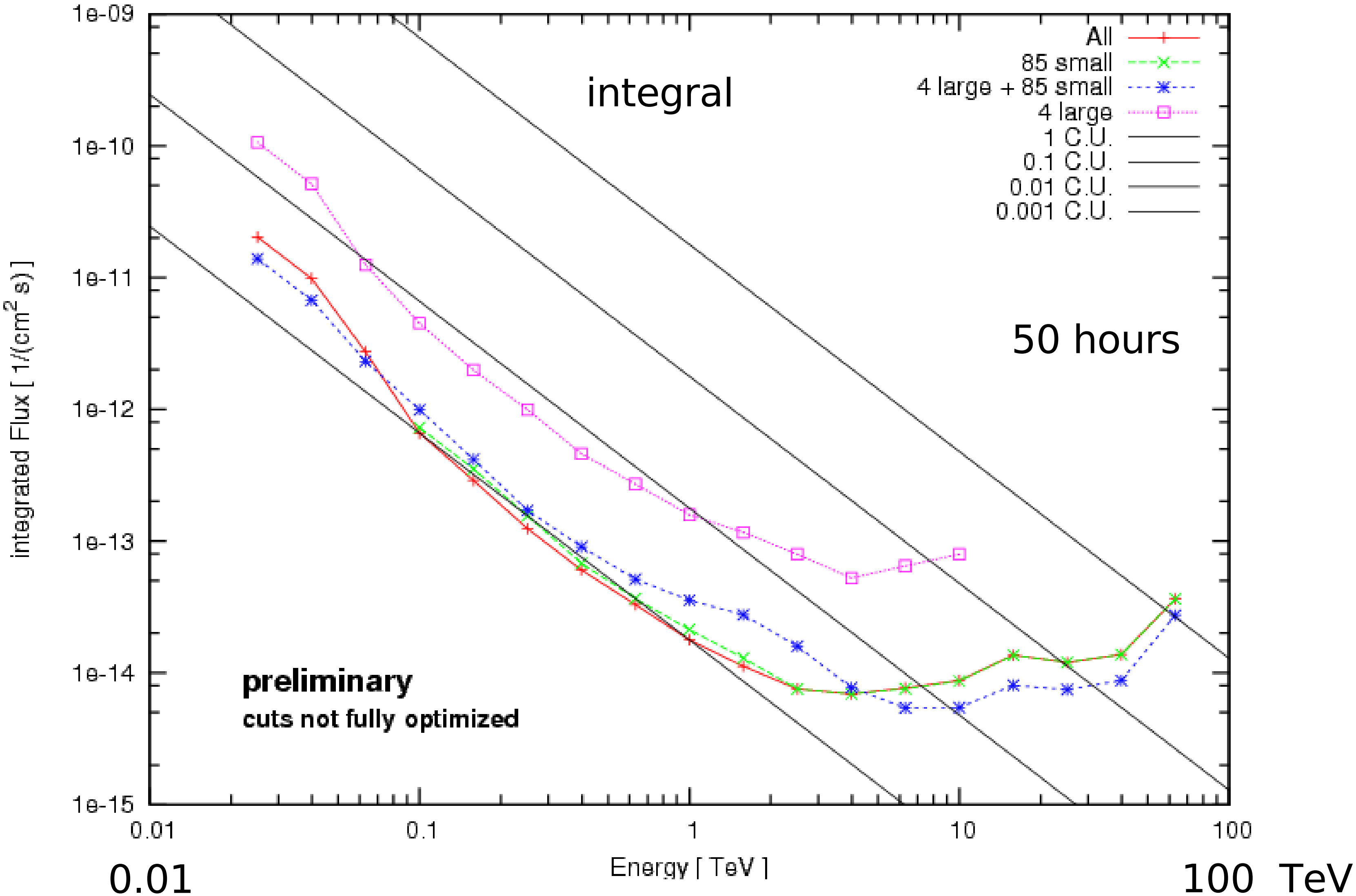


Sensitivity of 97-telescope system



0.01 100 TeV

Sensitivity of 97-telescope system

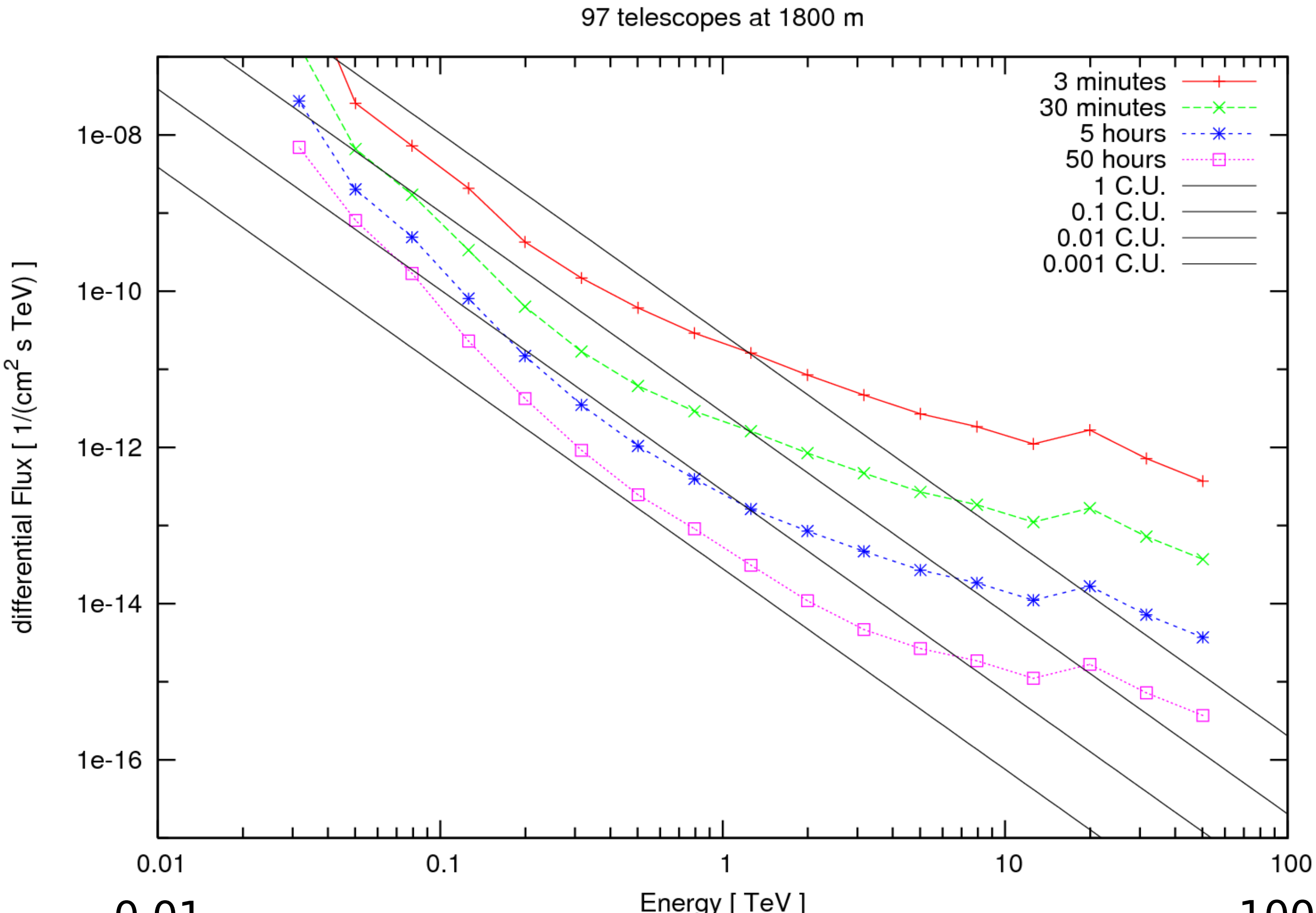


Sensitivity of 97-telescope system

- Sensitivity at low energies is improving from
  - 4 large telescopes to
  - 4 large + 85 small

  by factors of 2-3 at energies where the small telescopes are not sensitive at all!
- Veto-counter effect of surrounding small telescopes to high-energy protons mis-interpreted as low-E gammas with the 4 large telescopes alone.
- But how much veto-counter area is needed?

97 tel.: different exposure times

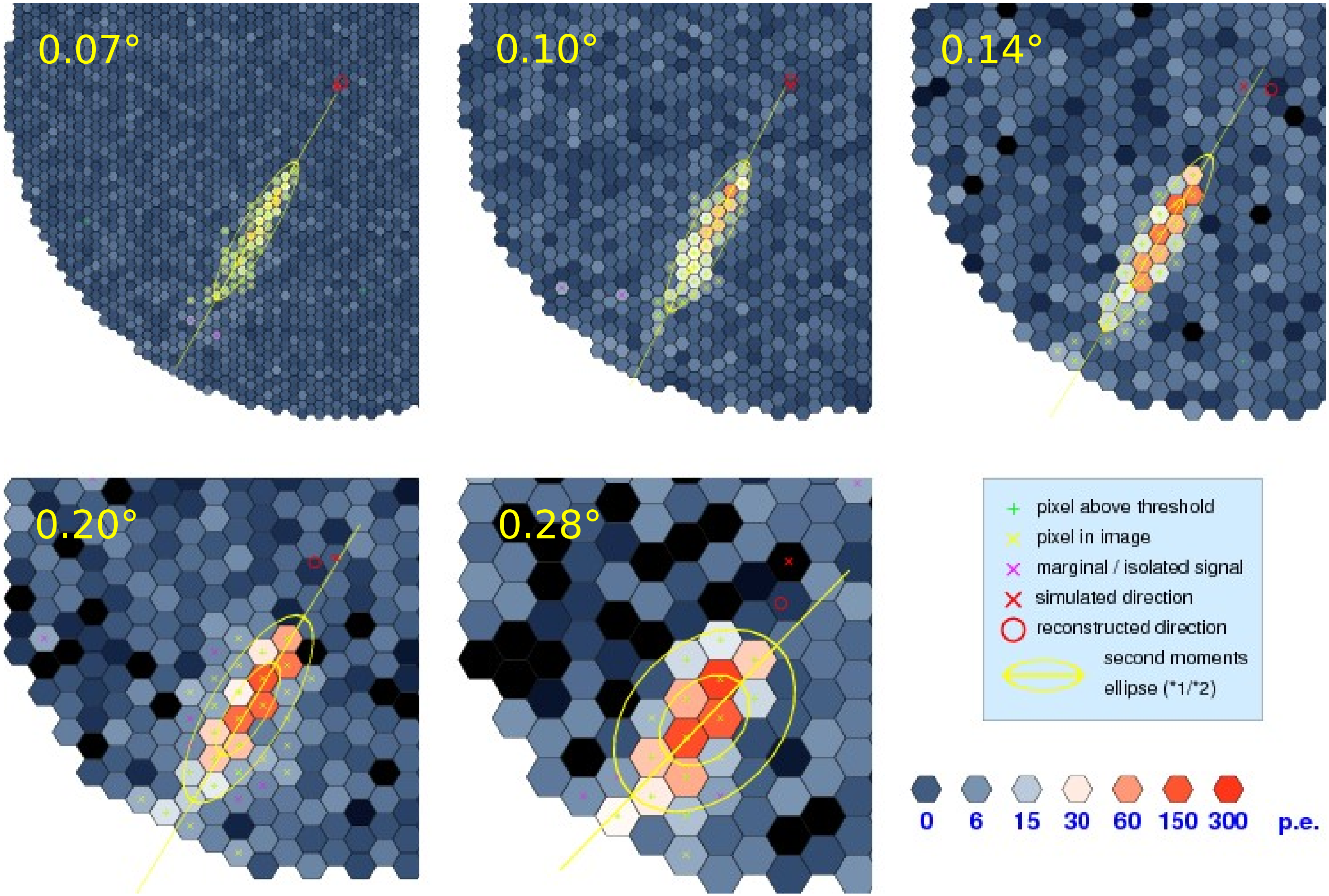


0.01 100 TeV

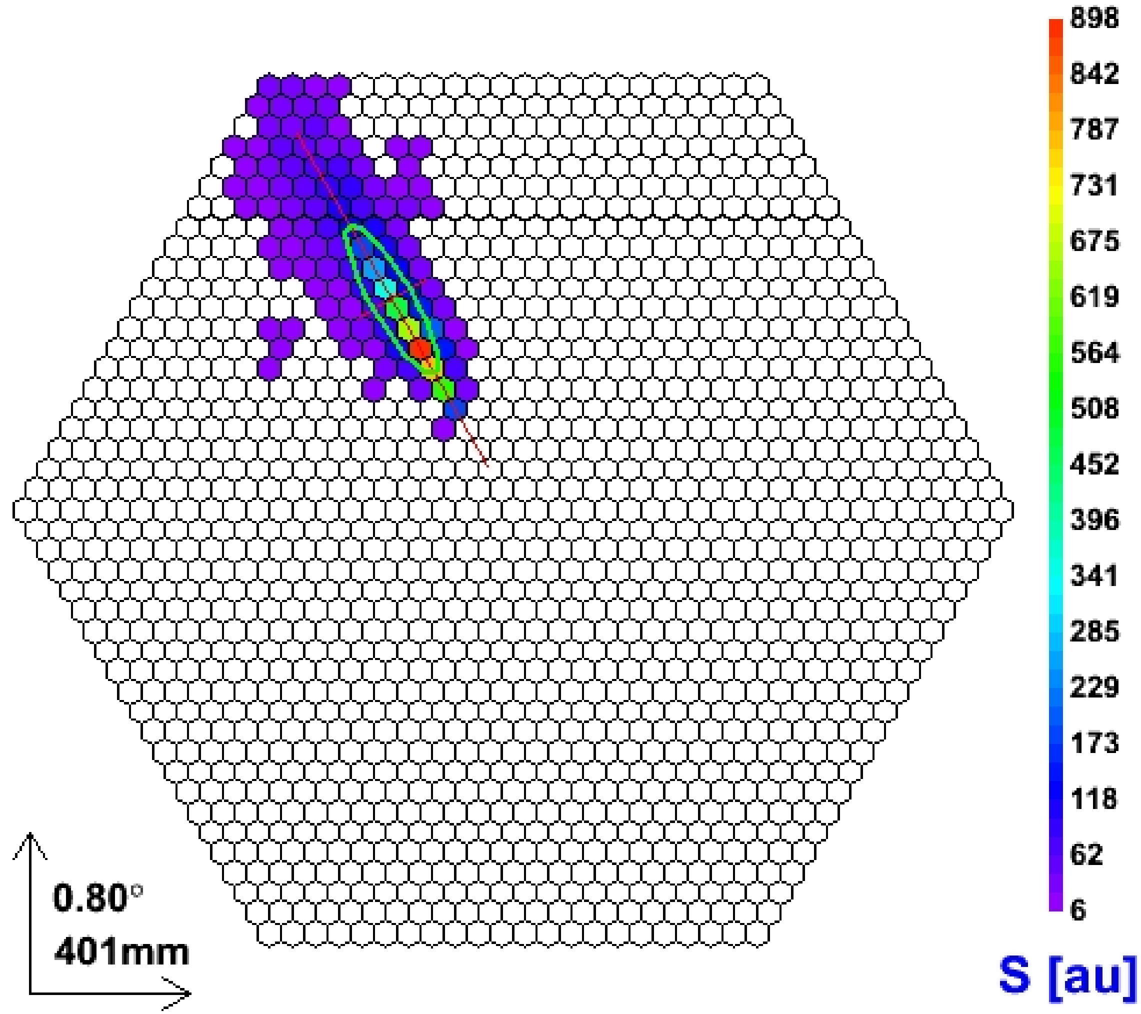
97 tel.: different exposure times

- For a 1 Crab source, you can get spectra over
  - almost 4 orders of magnitude in E in 50 hours,
  - 3 orders of magnitude in E in 5 hours,
  - more than 2 orders of magnitude in 30 minutes,
  - 1.5 order of magnitude in 3 minutes.
- For a 0.01 Crab source, you can still get spectra over
  - 1 order of magnitude in E within 5 hours,
  - 2 orders of magnitude in E within 50 hours.
- A 0.001 Crab source is detected in 50 hours.

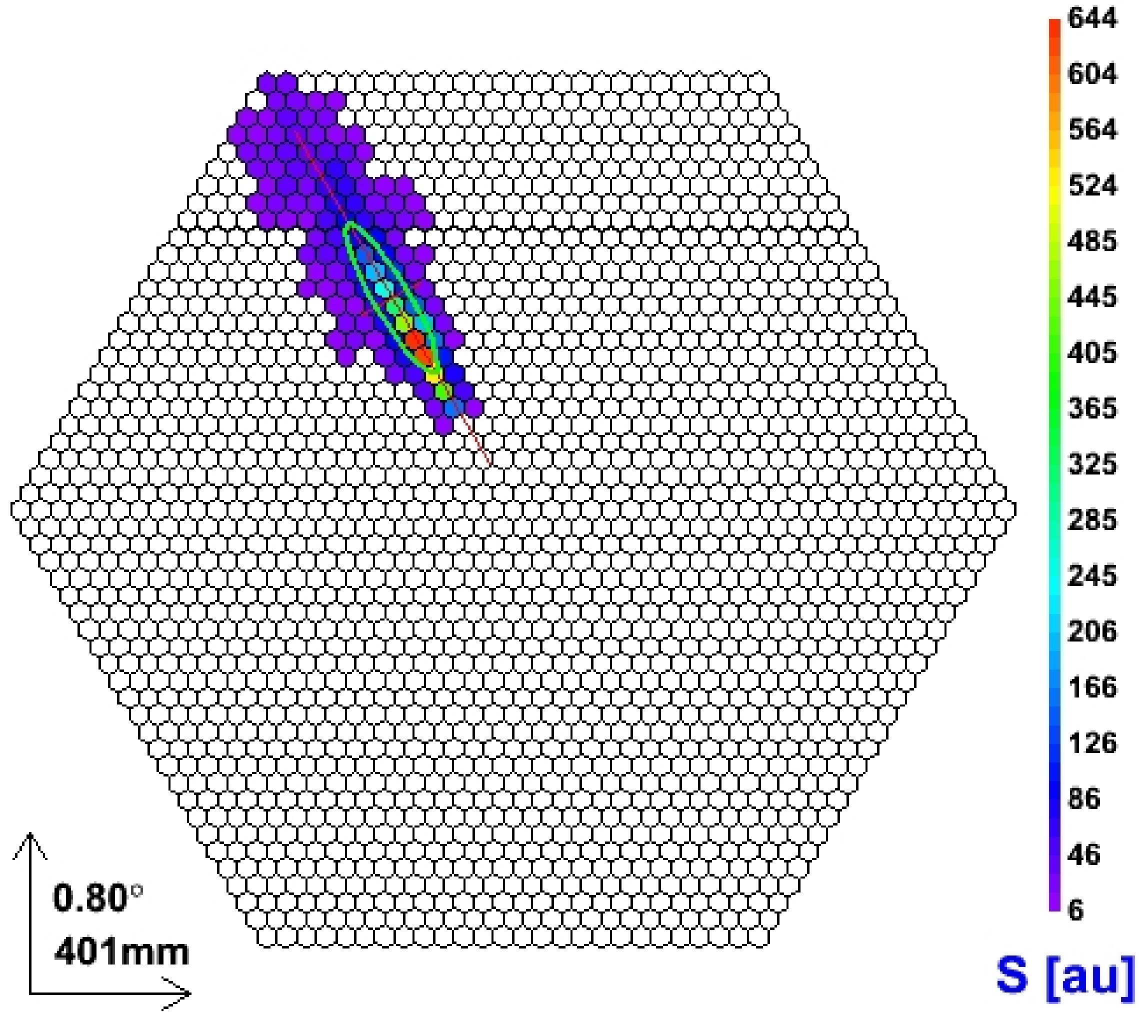
Impact of pixel size (in progress)



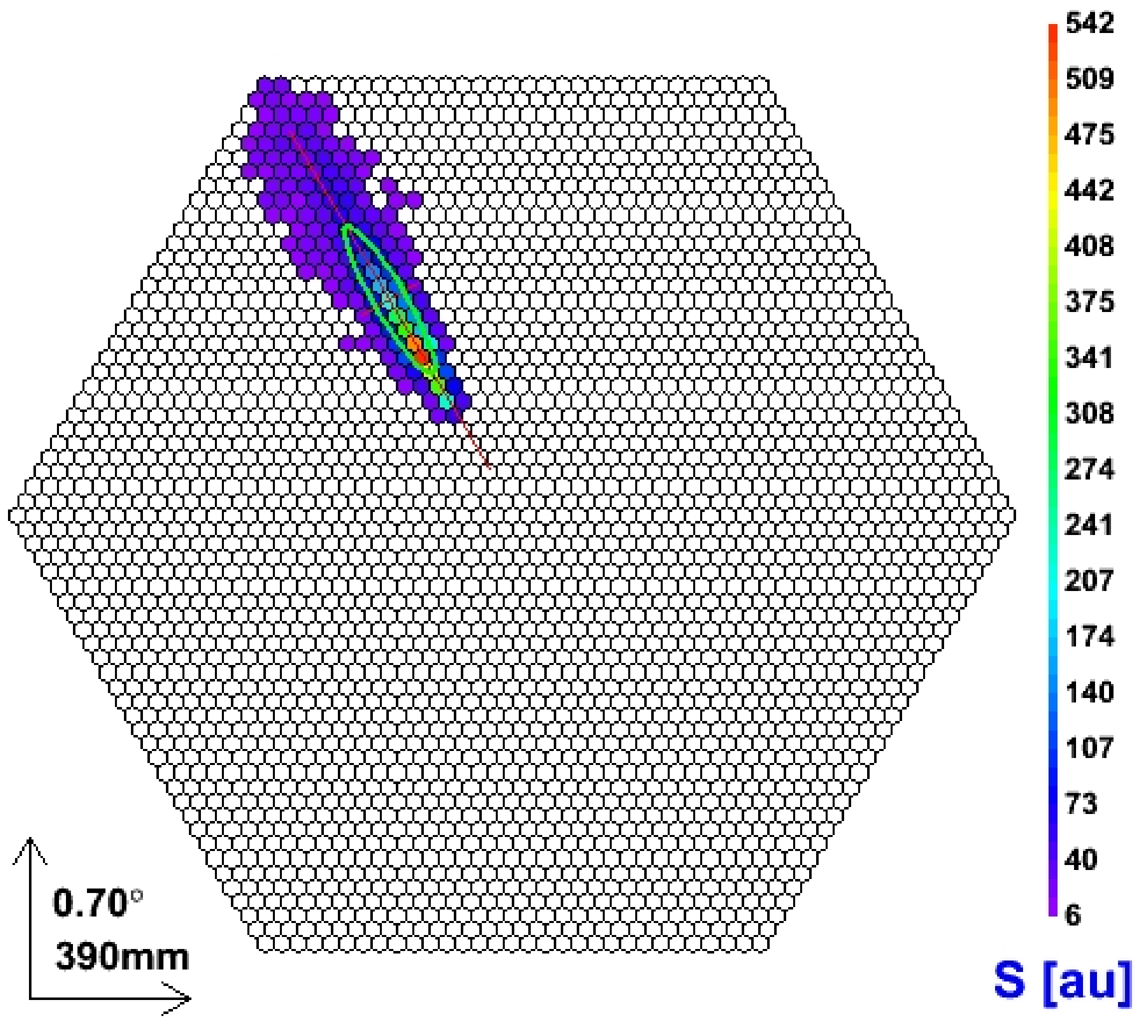
Example with 0.08° pixels



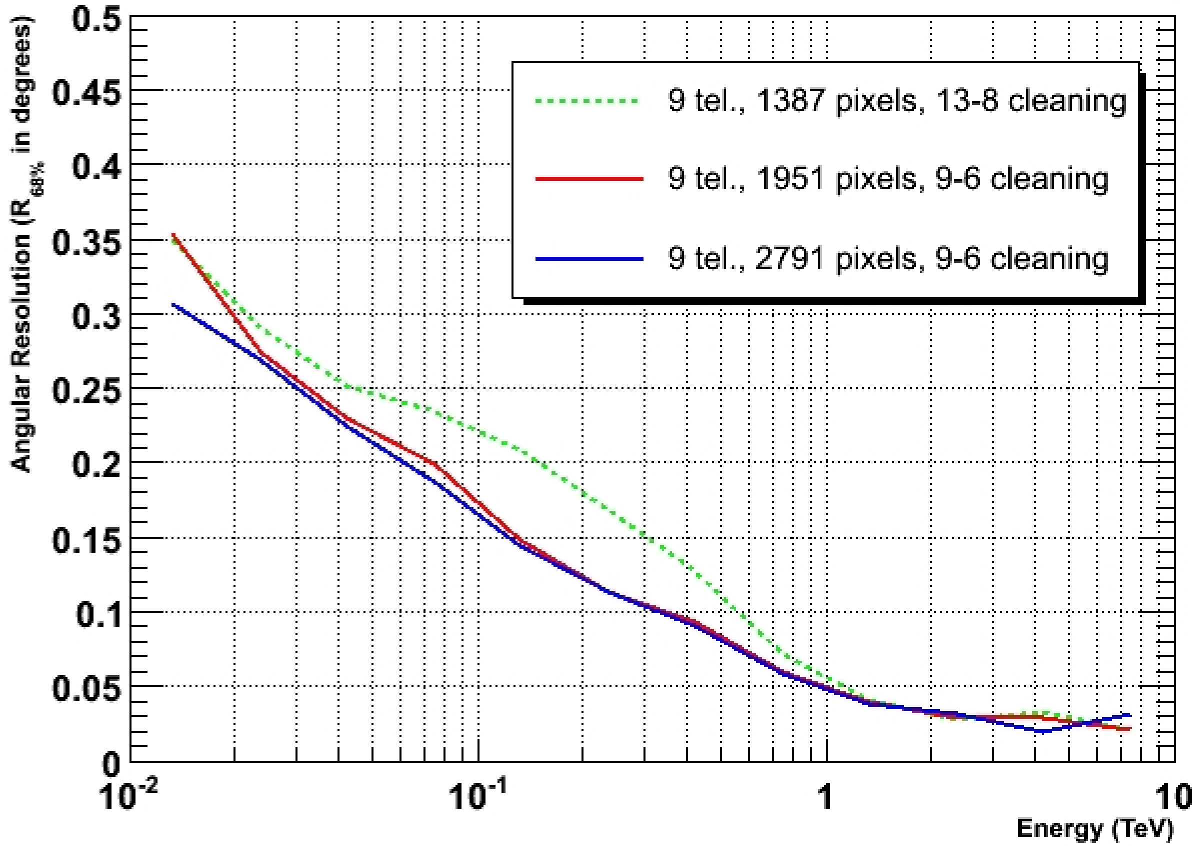
Example with 0.10° pixels



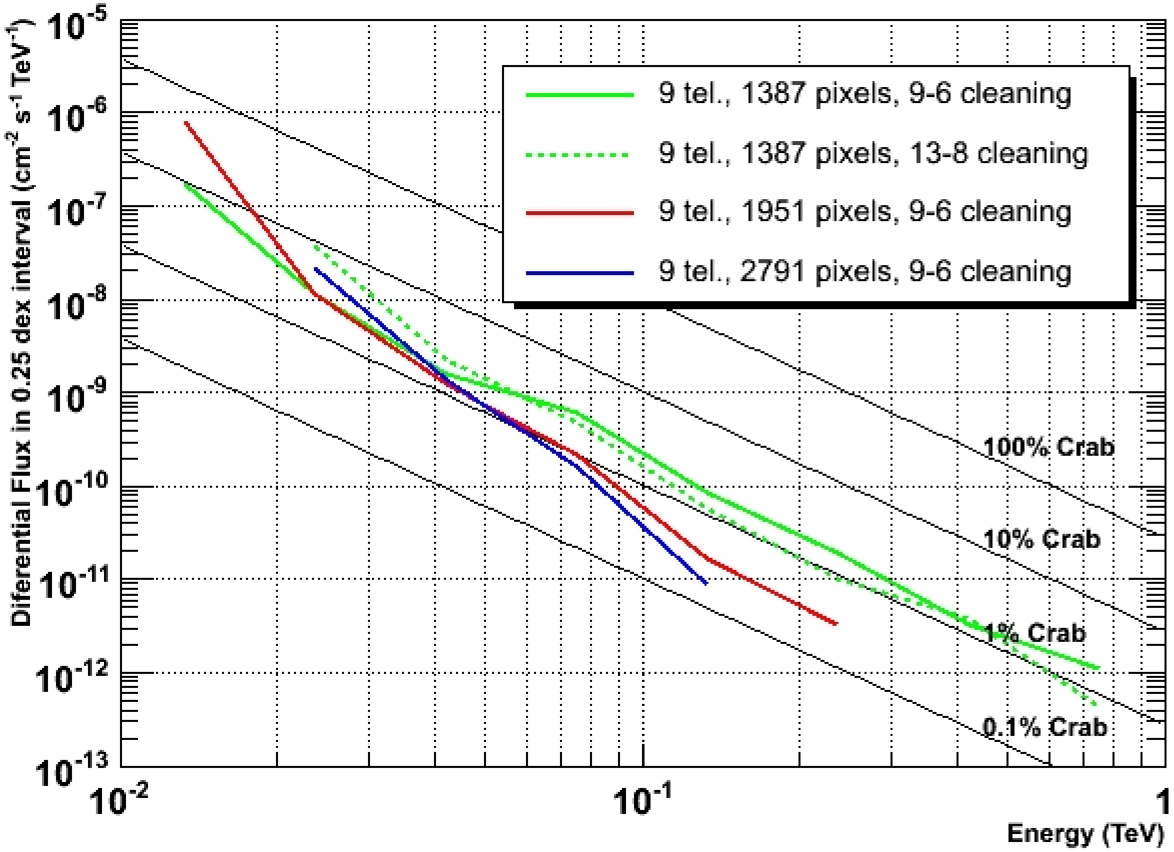
Examples with 0.12° pixels



Pixel size: Angular resolution



Pixel size: Sensitivity



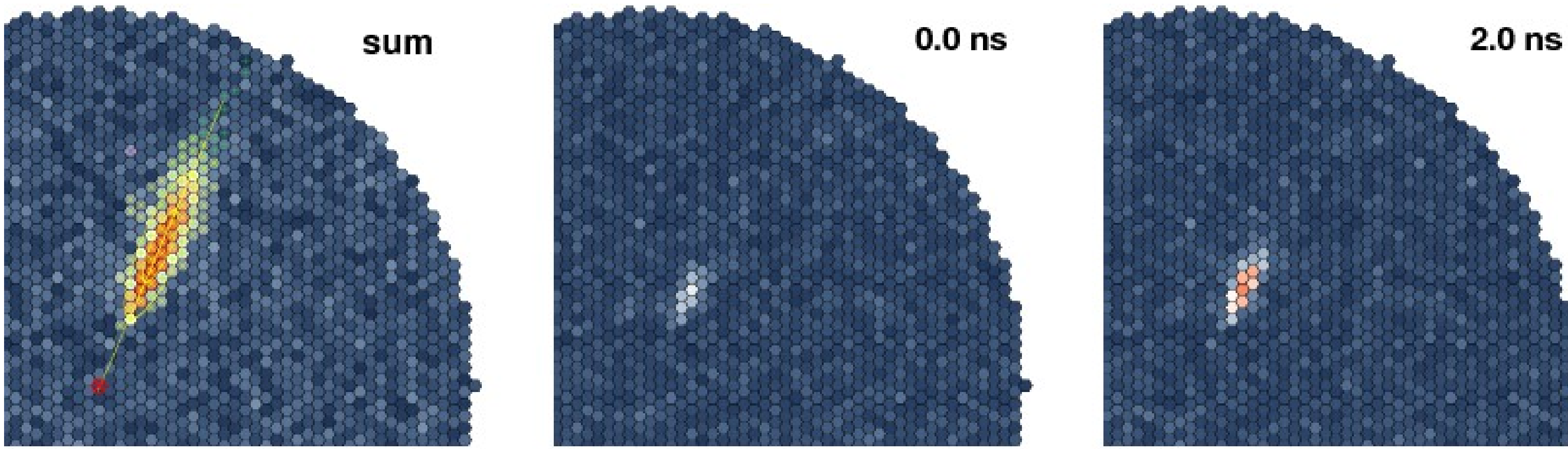
Optimum pixel size ?

- Results are, so far, inconclusive. Investigation is in progress.
- Smaller pixels resulting in slightly better angular resolution – but image cleaning must really be optimized separately for each pixel size.
- At least, we are in the right ball park with 0.10° pixels for the large telescopes.

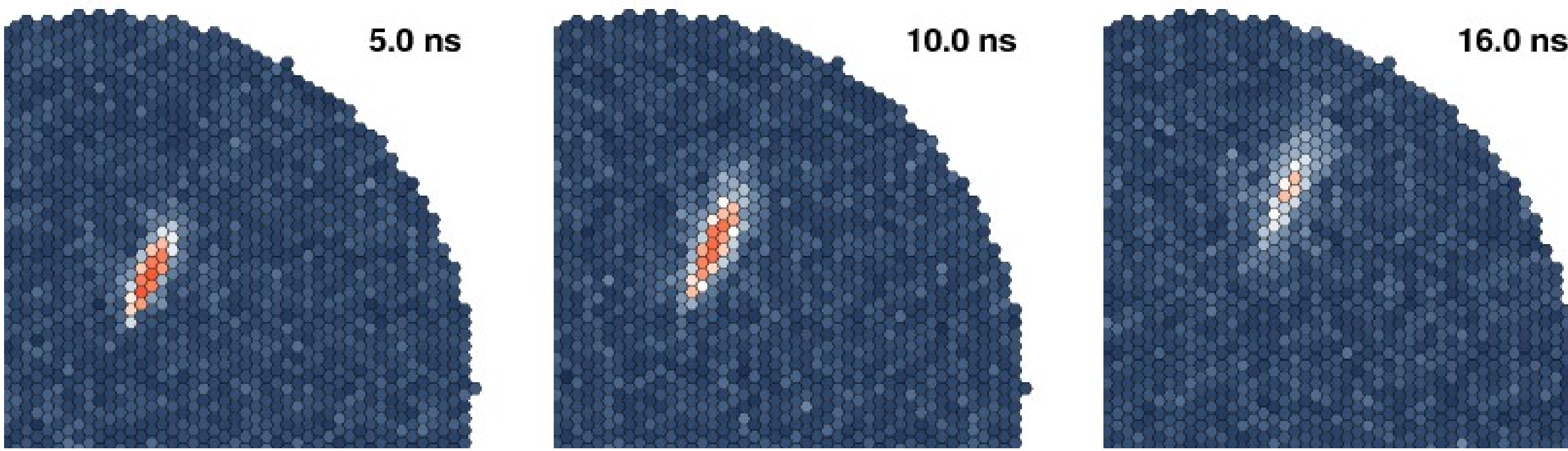
Wide-angle telescopes ?

- Not fully addressed by current simulations.
- For proper use of wide angles, need more advanced "read-out" and/or analysis scheme for images of showers with distant impact point.
- Time-profile in distant impact images may add further constraint on core location – but stereo reconstruction is almost always much better.

Image development in wide-angle tel.



10 TeV gamma at 250 m core distance seen in 10° camera



Cost-saving by wide-angle telescopes?

- Generally, no saving when camera dominates cost:
  - 4 tel. of 5° cover the same field as 1 tel. of 10° with same number of pixels.
  - Tel. of 5° every 200 m see (at least) all showers seen by 10° tel. every 400 m. Again same number of pixels.
- Mechanics of wide-angle telescopes may be demanding (large *f* ratio, heavy camera).
- Thus, optimum angle depends on dish and pixel costs and the right pixel size for a given telescope size.

Conclusions (1)

- Below 100 GeV, gamma-hadron separation by shape cuts gets less and less effective.
  - Supplemented by Hmax and energy estimate quality.
  - 4-fold or higher telescope multiplicity improves separation.
- Veto-counter by surrounding smaller telescopes:
  - Factor 2-3 improvement in energy domain of large tels.
  - May require different read-out scheme (same shower triggers non-contiguous parts of array).

Conclusions (2)

- Excellent gamma-hadron discrimination requires high-quality data (high telescope multiplicity, perhaps finer pixels).
- In the threshold regime, telescopes in array centre should be packed densely enough that a shower can be seen in 4-5 telescopes (little increase in total number with large improvement in sensitivity).

Conclusions (3)

- Adding more and more telescopes to a uniform array only helps where background is important and showers illuminate only a fraction of the array.
- In background-free regime with showers illuminating whole array, adding more telescopes may give little improvement in sensitivity.
  - Use wider separations (wider f.o.v. ?) or
  - "clusters" of a few telescopes each (enough for stereo reconstruction and sufficient gamma-hadron separation at high energies).

Two possible array layouts

One quadrant
only shown.