Results from the simulations of the ALTO observatory

http://alto-gamma-ray-observatory.org

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--- for the ALTO group ----
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Linnæus University

The ALTO project

- Project born in 2014 at Linnaeus University after we received a research grant from the Crafoord Foundation (Sweden)

- A Wide Field-of-View (~ 2 sr) gamma-ray observatory:

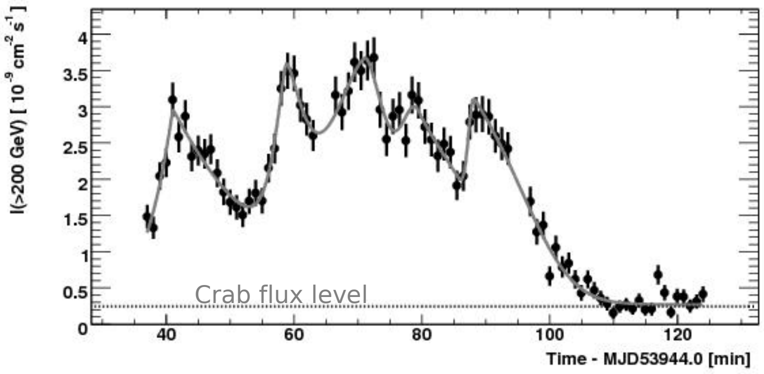
  - In the Southern hemisphere → Daily observations of Southern sources
  - At high altitude (~ 5 km) → Low threshold E ≥ 200 GeV
  - Particle detectors → Observations may be done 24h per day
  - Hybrid detectors → Improved S/B discrimination
  - Excellent timing accuracy → Improved angular resolution (~ 0.1° at few TeV)
  - Modular design → Phased construction and easy maintenance
  - Simple to construct → Minimize human intervention at high-altitude
  - Long duration → Should operate for 30 years
  - "Open Observatory" → Distribute data to the community "à la Fermi-LAT"

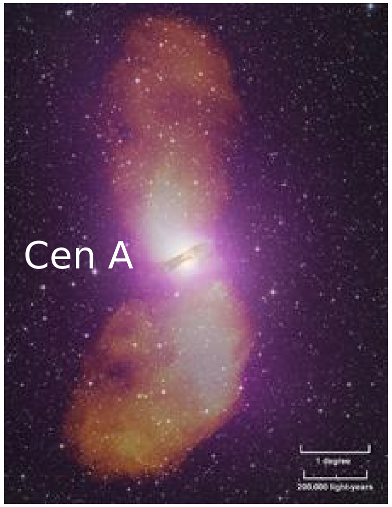
ALTO Science Goals

Daily monitoring of Southern targets:

- Transients and variable sources;
- Active Galactic Nuclei, Gamma-Ray Bursts (if spectra favourable), X-ray binaries;
- Galactic centre and central region;
- Alerts to other observatories;
- Multi-year light-curves;
- High-end of the sources' spectra;
- Search for Pevatrons;

H.E.S.S. PKS 2155-304 (blazar) flare





Study of extended sources:

Fermi Bubbles,
Vela SNR,
AGN radio lobes;

Credit: NASA/DOE/Fermi LAT Collaboration, Capella Observatory, and Ilana Feain, Tim Cornwell, and Ron Ekers (CSIRO/ATNF), R. Morganti (ASTRON), and N. Junkes (MPIfR)

Other accessible goals:

- Search in past data if detections of:
  - gravitational waves or
  - neutrinos;
- Study of the cosmic-ray composition and anisotropy;
- Dark matter searches;
- EBL studies (if threshold low enough);
- Search for Lorentz invariance violation;
- Axion-like particles from distant AGNs.

Current Collaboration

Sweden

- Department of Physics and Electrical Engineering, Linnaeus University (LnU), Växjö
  - PI Yvonne Becherini
  - Post-doc Satyendra Thoudam
  - Two PhD students
    - Mohanraj Seniappan: MVA Rejection
    - Tomas Bylund: DAQ & Control, Energy NN
- Industry: TBS Yard AB, Torsås
  - Industrial construction, responsible Lars Tedehammar

France

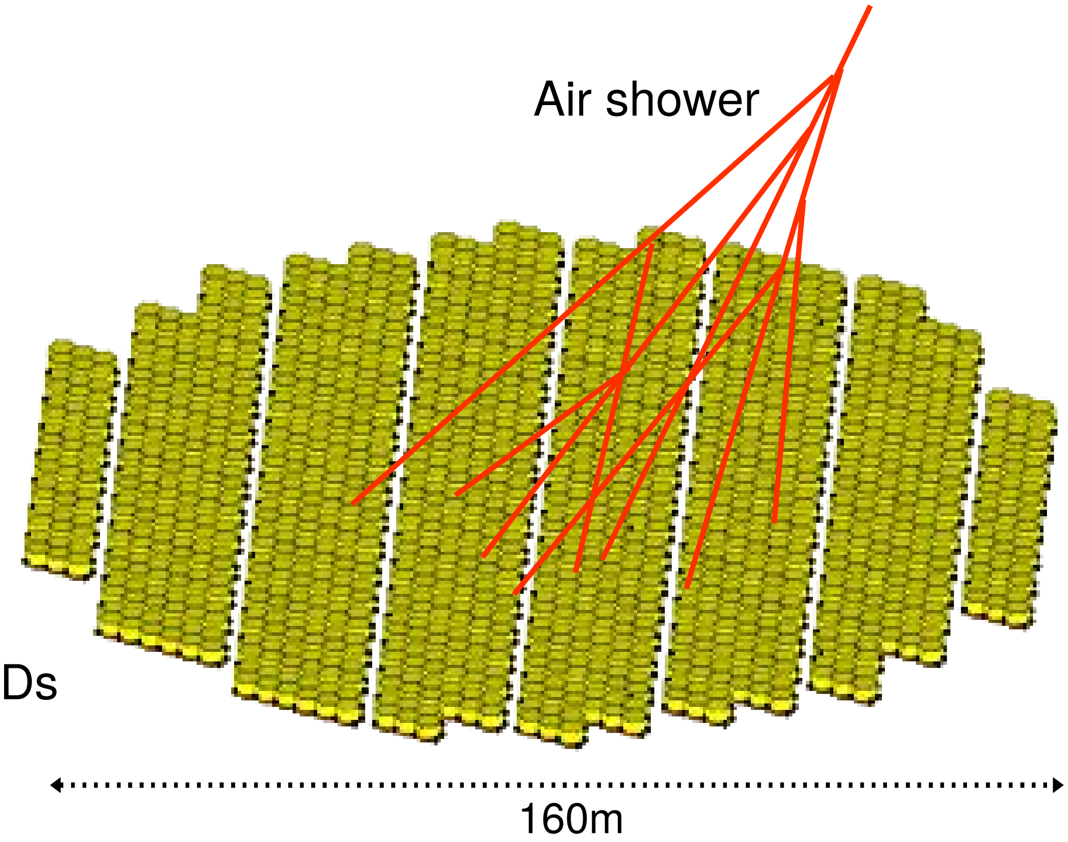
- APC Laboratory, IN2P3/CNRS, Paris
  - Michael Punch
  - Contacts with Jean-Christophe Hamilton (discussions about the site)
- Aix-Marseille University
  - Jean-Pierre Ernenwein (key work on proto, regular visits to LnU)
- LAL/Orsay
  - Dominique Breton, Jihane Maalmi (work on WaveCatcher electronics)
- CEA/Saclay
  - Eric Delagnes (past discussions on electronics)

ALTO
Observatory
Essentials

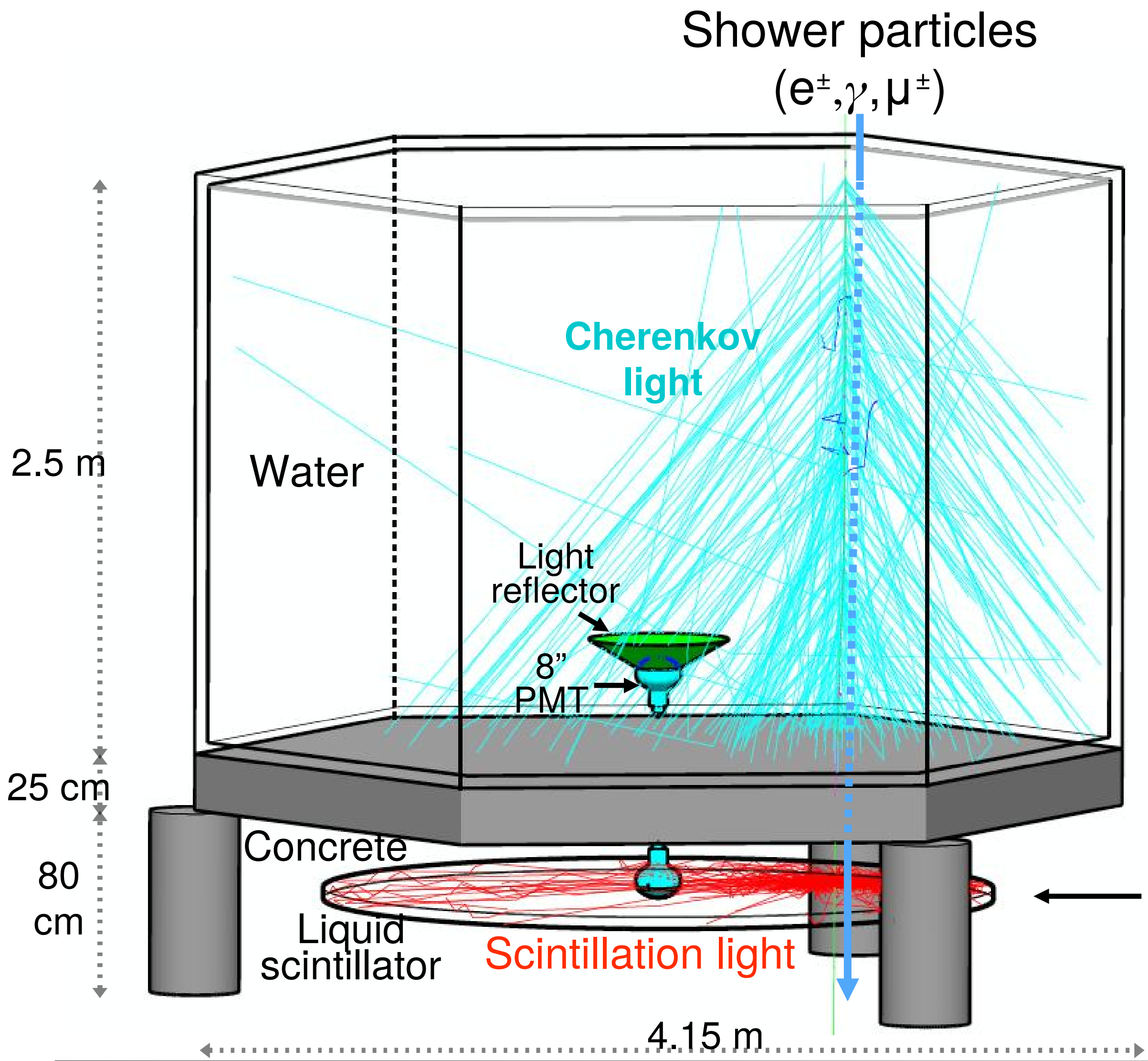
ALTO array layout and aims

- Southern Hemisphere (Chile/Argentina)
- Altitude ~5 km a.s.l
- Energy range $\gtrsim$ 200 GeV
- ~1200 detector units

- Advanced electronics:
  - WaveCatcher + White Rabbit timing system
- Sub-ns timing
- Small-sized, closed-packed WCDs
  - Low dead-space ("packing factor" ~70%)
- Scintillation detectors



An ALTO detector unit



Water Cherenkov Detector

- Carbon fibre sandwich + PVC foam
- Non-reflective walls
- Sensitive to $e^{\pm},\gamma,\mu^{\pm}$

Scintillation Detector

- Aluminium
- Highly-reflective walls
- Liquid scintillator: LAB+PPO+POPOP
- $\mu^{\pm}$ detector

An ALTO "cluster"

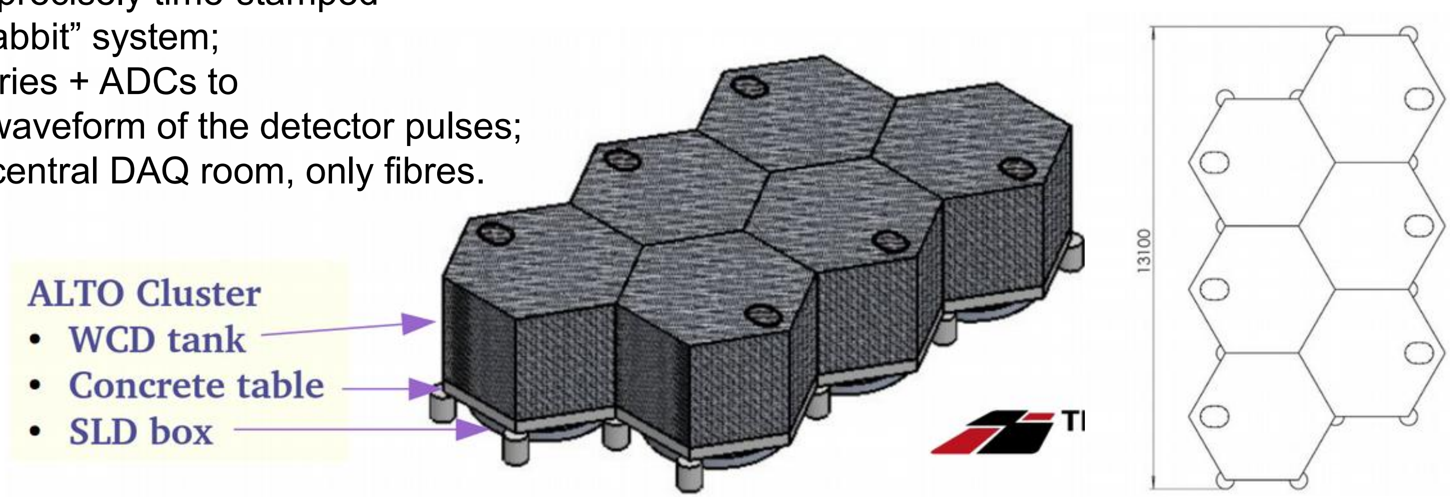
Cluster = Group of 6 Units
= 6 x (WCD + SLD)

- WCDs on concrete "table"
- SLDs below "table",
  on telescopic rails

Each cluster to have common:

- Electronics readout unit
- Solar panel + battery
- Communication/data
  to central DAQ room by fibre only

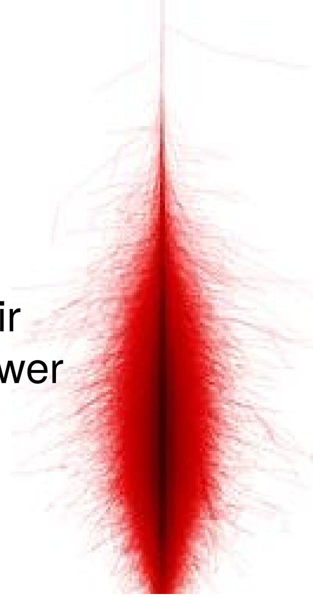
- Advanced electronics for 6-tank "cluster",
  WaveCatcher + White Rabbit:
- Trigger channel precisely time-stamped
  with "White Rabbit" system;
- Analogue memories + ADCs to
  measure the waveform of the detector pulses;
- No cables from central DAQ room, only fibres.



SEE TOMORROW FOR DETAILS ON PROTOTYPE ELECTRONICS

ALTO
Monte Carlo Simulations

Monte-Carlo simulations



Air shower simulation: CORSIKA (version 7.4000)

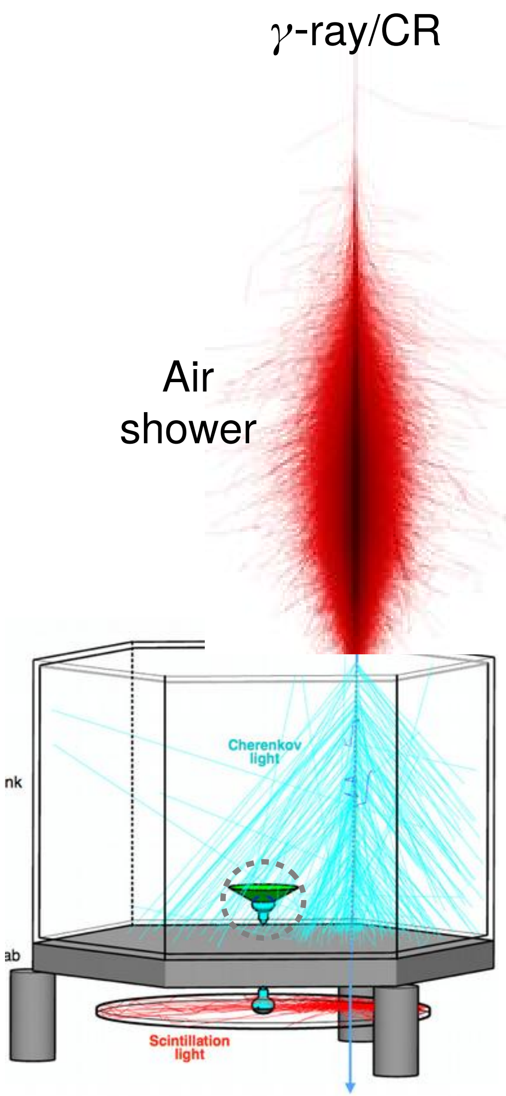
- Realistic model of Earth's atmosphere, magnetic field, refractive index, ….
- Electromagnetic and hadronic interactions based on particle physics models.

Parameter	Gamma rays	Proton
Observation height	5.1 km	Same
Energy	10 GeV-100 TeV	158 GeV-100 TeV
Spectral slope	-2.0	-2.7
Zenith angle	Fixed at 18°	0-30°
Azimuth angle	Fixed at 180°	0-360°
Magnetic field	ALMA site	Same
Core position (from array centre)	0-100 m (square)	Same
No. of showers	~17 million	~21 million (→ 12 minutes!)

Note:
- No reuse of Corsika showers currently

Future: planning for
- protons simulations up to 48°
- gamma-ray simulation at multiple zenith angles (18, 32, 41°)

Monte-Carlo simulations



Air shower simulation: CORSIKA (version 7.4000)

- Realistic model of Earth's atmosphere, magnetic field, refractive index, ….
- Electromagnetic and hadronic interactions based on particle physics models.

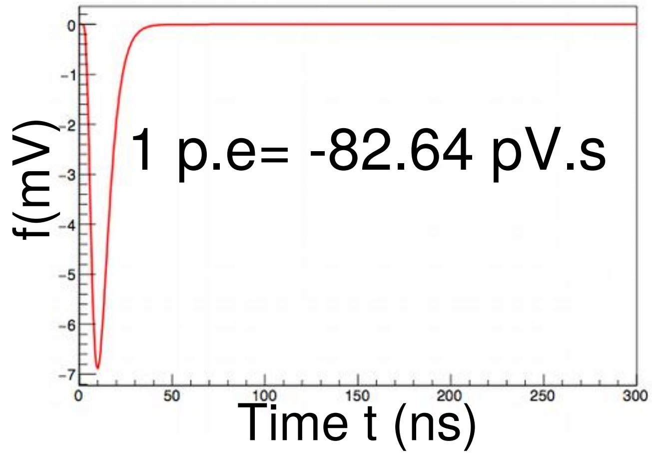
Detector simulation: GEANT4 (version 10.2)

- **All material properties included:**
  - Density, refractive index as function of wavelength.
  - Photon reflectivity, absorption and scattering coeff. as function of wavelength.
- **All important physical processes included:**
  - Electro-magnetic processes:
    - γ's: Photoelectric effect, Compton scattering, Pair production, Rayleigh scattering.
    - $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, nuclei: Multiple scattering, ionisation, bremsstrahlung, annihilation (positrons)
    - Unstable particles: Decay
  - Optical processes:
    - Cherenkov and Scintillation photons production.
    - Their emission spectrum, absorption, scattering …
- **Particle tracking**
  - All particles completely tracked by GEANT4 except for photons inside WCD.
  - ~10^5 photons (Cherenkov/Scintillation) produced in each tank.
  - For optical photons inside water tank:
    - Only those that are likely to hit the PMT are tracked.
- **Signal propagation inside photomultiplier tubes:**
  - Include signal time spread (TTS) and PMT gain fluctuations.

New p.e. to mV
for better trigger verisimilitude

*Based on Test bench measurement on real PMT in our lab

Single photoelectron pulse

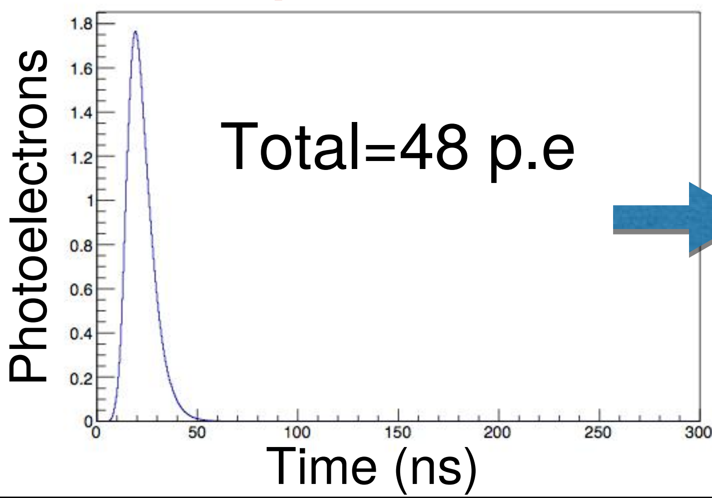


Modelled with FRED

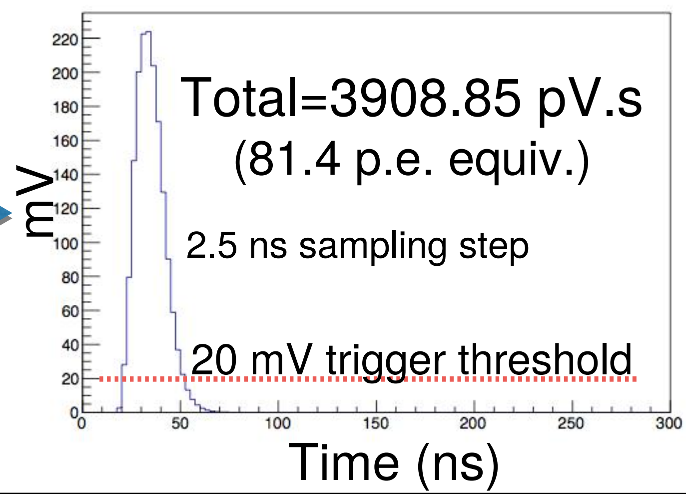
f=p0*exp(-p1/t-t/p2)

p0= -956.721
p1= 24.4760
p2= 4.02169

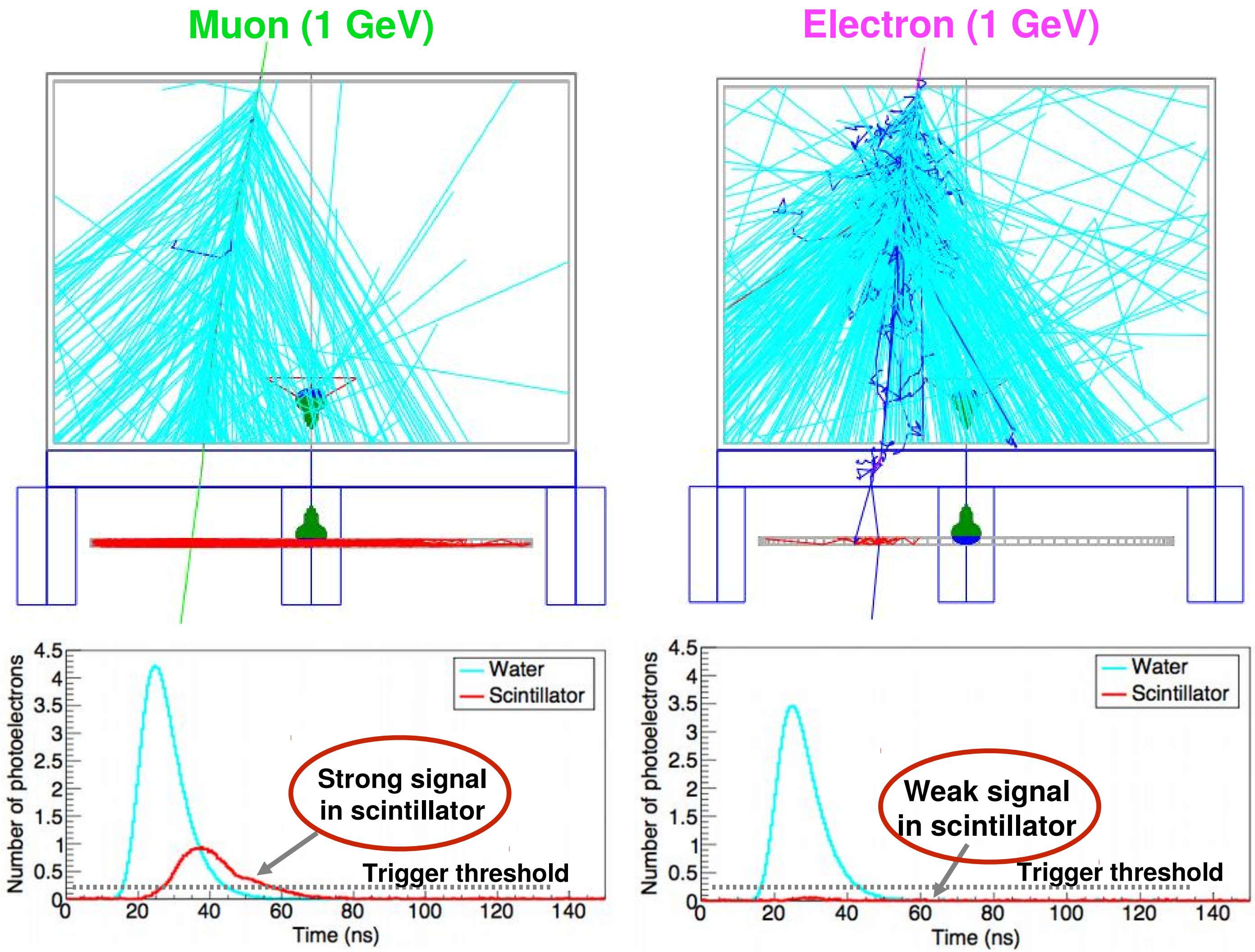
Example waveform



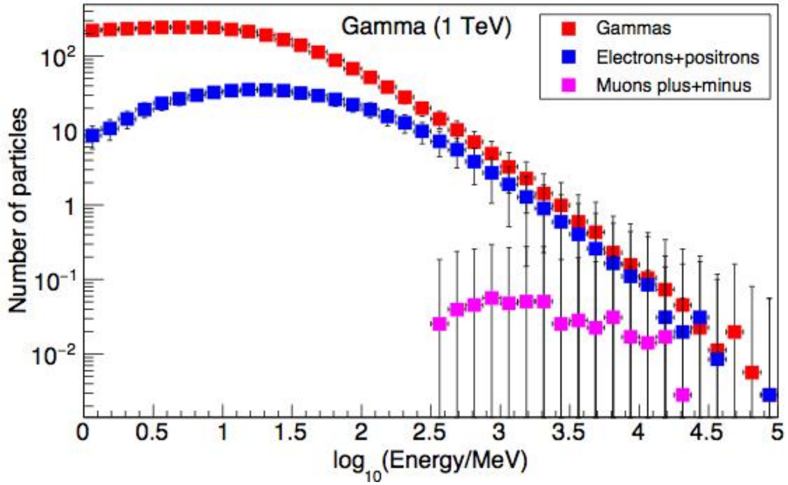
(Using measured function)

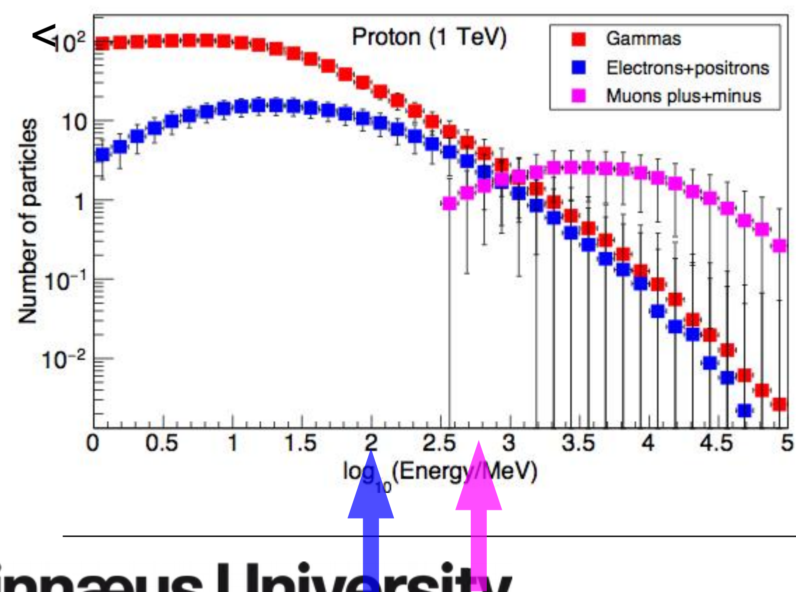


ALTO Unit response to single particles



Single particles from Air Showers
Energy Distribution





- Shower Muons have median energy a factor of several hundred higher than Shower Gammas/Electrons
- Factor >100 more Muons at median in Proton vs. Gamma showers

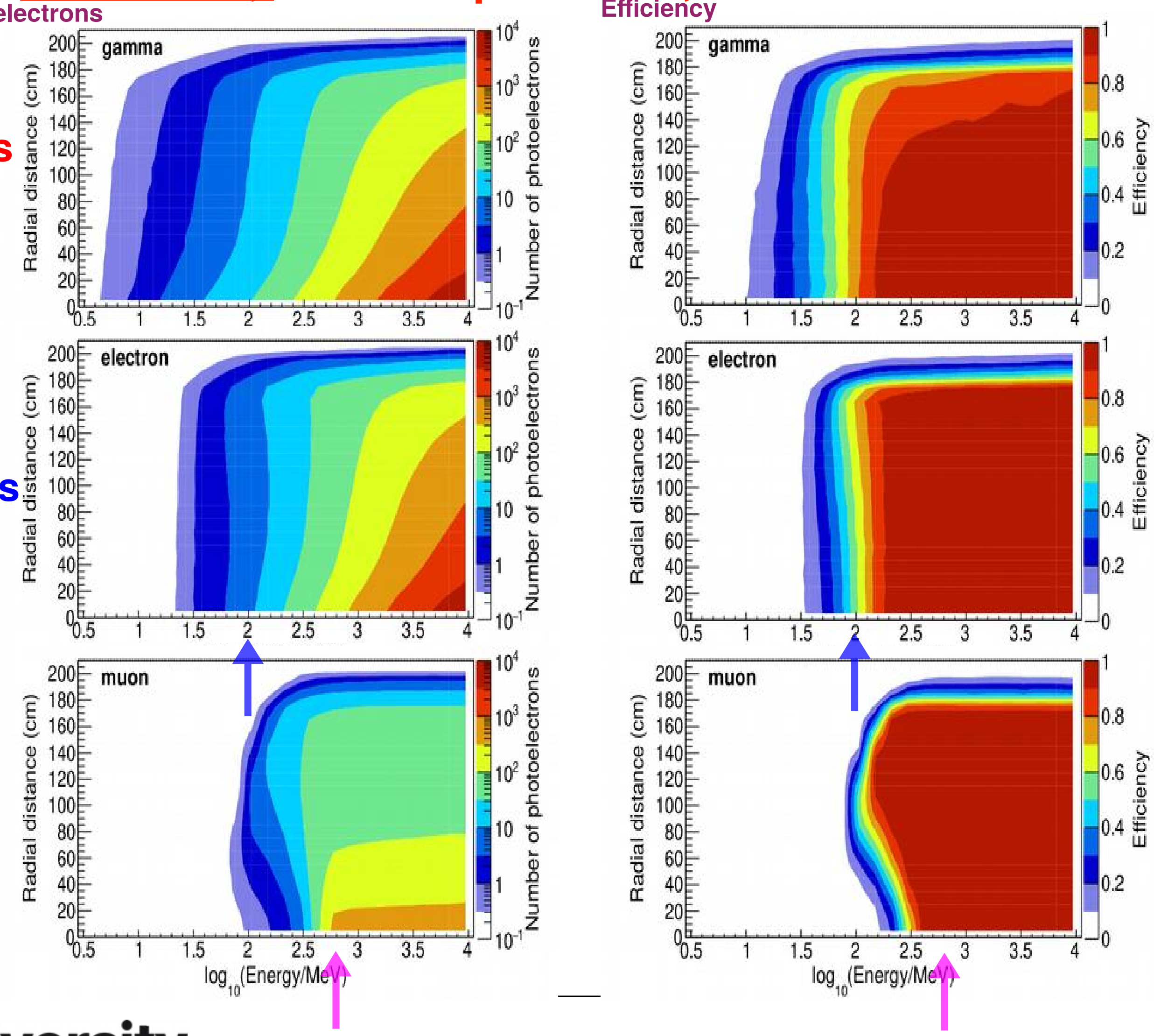
ALTO Water tank, **updated** response to Single particles

Water tank, Radial dependence, 0° incidence

Gammas

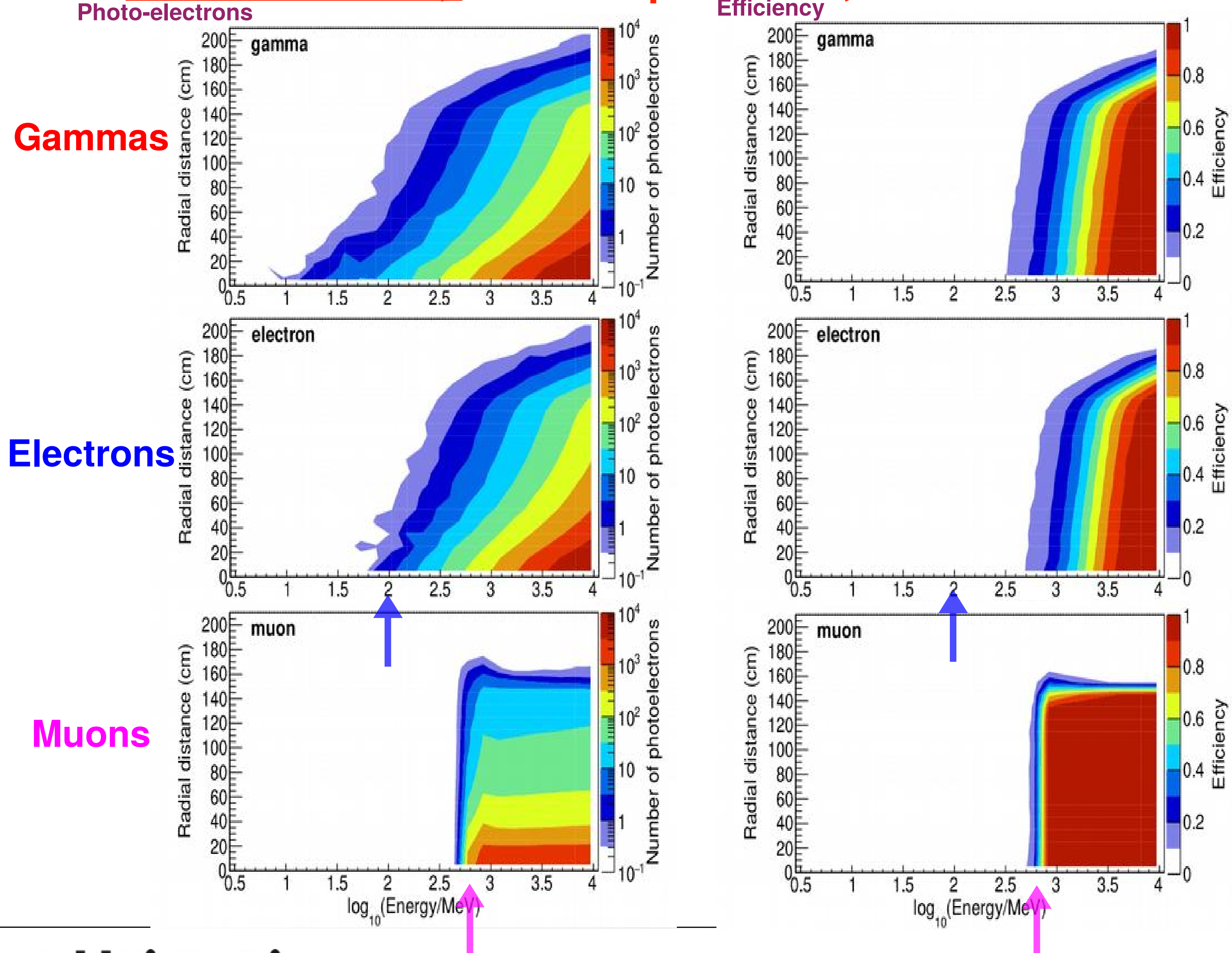
Electrons

Muons



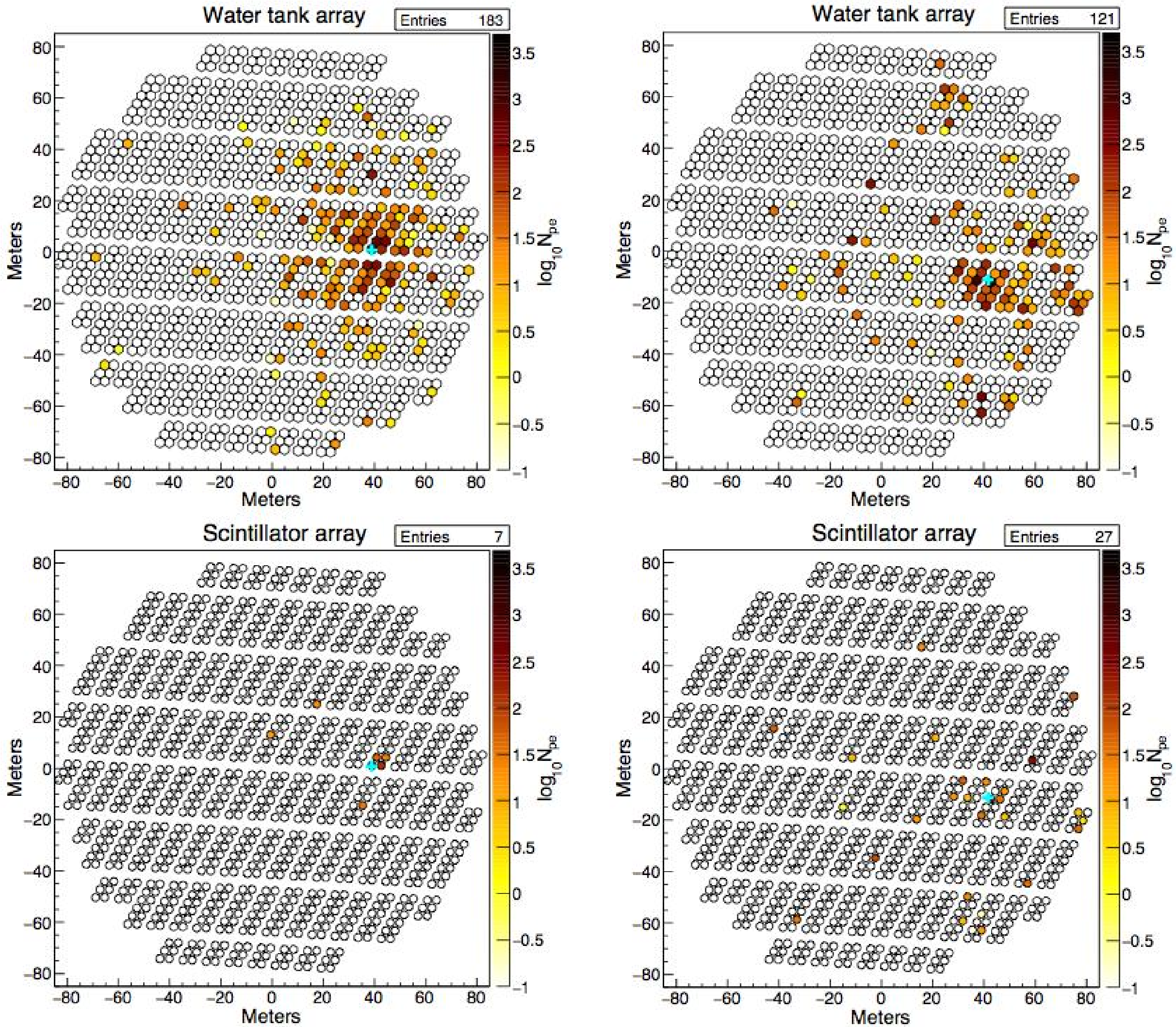
ALTO Scintillator tank, **updated** response to Single particles

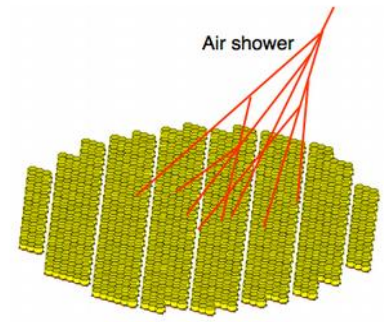
Scintillator tank, Radial dependence, 0° incidence



ALTO Array response to Air Showers

Gamma ray | **Cosmic-ray proton**





Gamma ray

-More compact

-Regular pattern

Cosmic ray

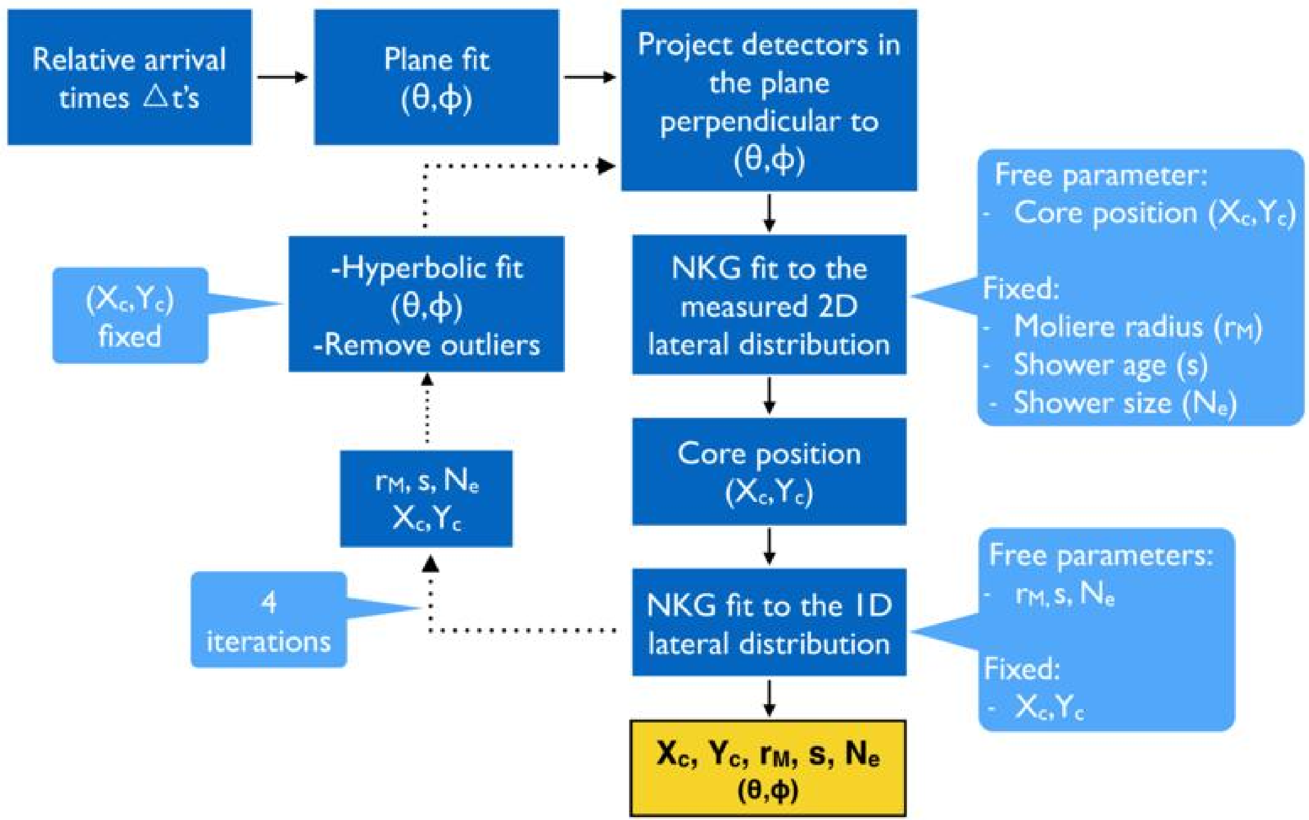
-Clumpy

-Hot spots in the scintillators at large distance from the core

ALTO Event Reconstruction

A multi-fit process for core + size, direction

Reconstruction flow chart

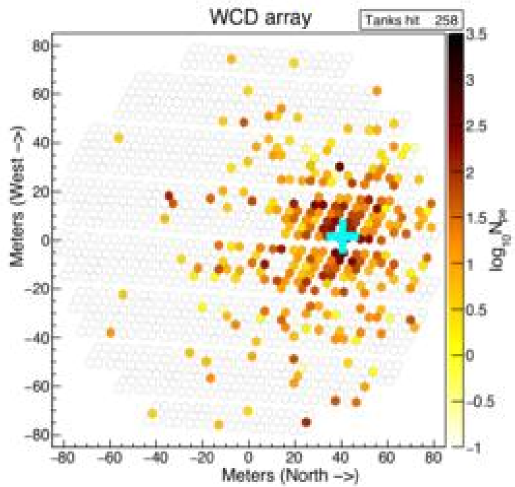


A multi-fit process for core + size, direction

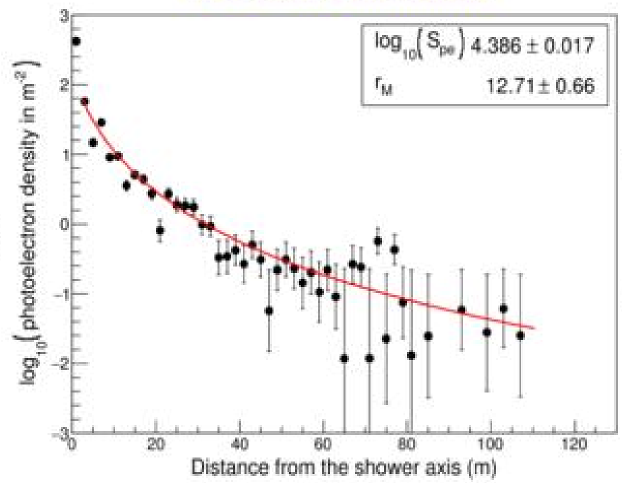
Shower core reconstruction

Gamma ray (1 TeV, 18°)

Shower footprint



1-D Lateral distribution



TCore = (40, 0) m
RCore= (39.3,1.5)m
dCore = 2.3 m

NKG function:

$$\rho(r') = S_{\rm pe} C(s) \left(\frac{r'}{r_{\rm M}}\right)^{s-2} \left(1 + \frac{r'}{r_{\rm M}}\right)^{s-4.5}$$

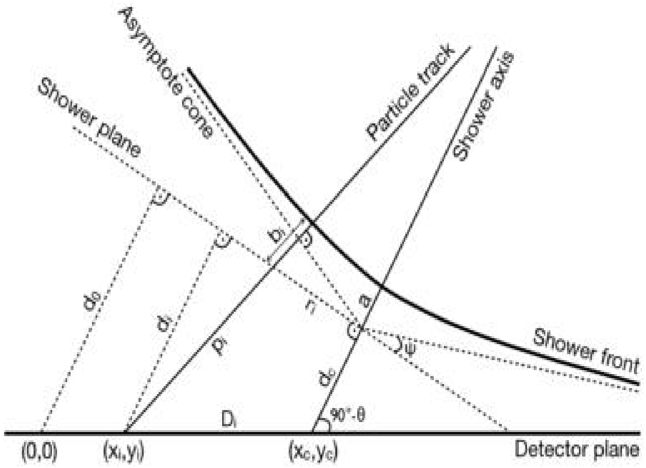
$$C(s) = \frac{\Gamma(4.5 - s)}{2\pi r_{\rm M}^2 \Gamma(s) \Gamma(4.5 - 2s)}.$$

- S_{pe}: Shower Size or "RSize"
- r': Shower core position (x_c,y_c)
- r_M: Moliere radius or "RrM"
- s: Shower age

A multi-fit process for core + size, direction

Arrival direction reconstruction

Hyperbolic fit to the wavefront



Minimize the signal delay times with:

$$ct_i = \frac{d_i}{\cos\psi} + \frac{r_i}{\sin\psi} - \frac{\cos\psi}{(\cot^2\psi - 1)} \times \left\{ r_i \cot^3\psi - \sqrt{a^2\cot^4\psi + r_i^2\cot^2\psi - a^2} \right\},$$

$$d_i = d_0 - l x_i - m y_i,$$

$$r_i = \sqrt{D_i^2 - (d_i - d_c)^2} - \frac{d_i}{\cot\psi},$$

$$D_i = \sqrt{(x_c - x_i)^2 + (y_c - y_i)^2},$$

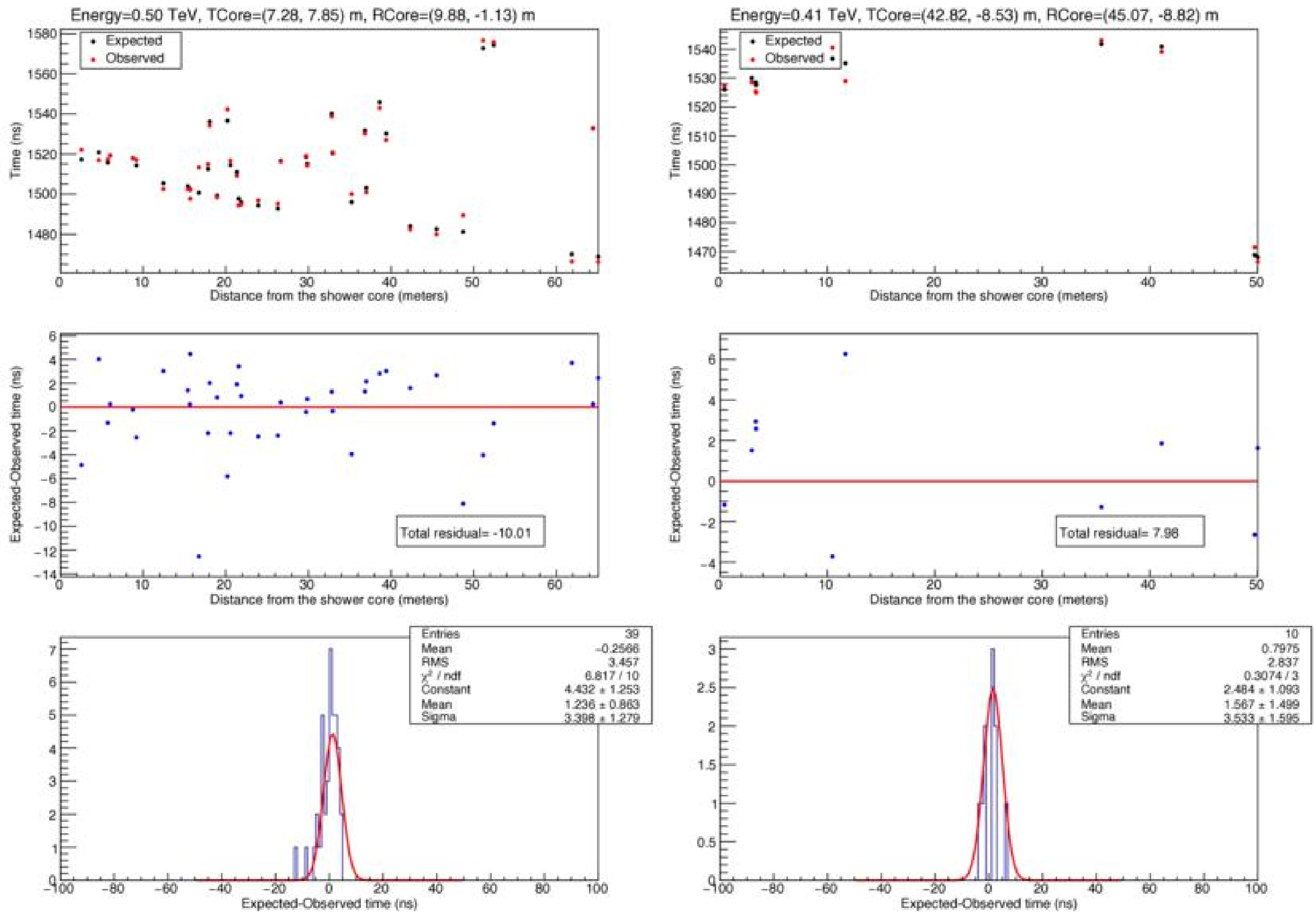
$$d_c = d_0 - l x_c - m y_c.$$

*Outliers outside 6 ns removed.

A multi-fit process for core + size, direction

Examples of time profiles

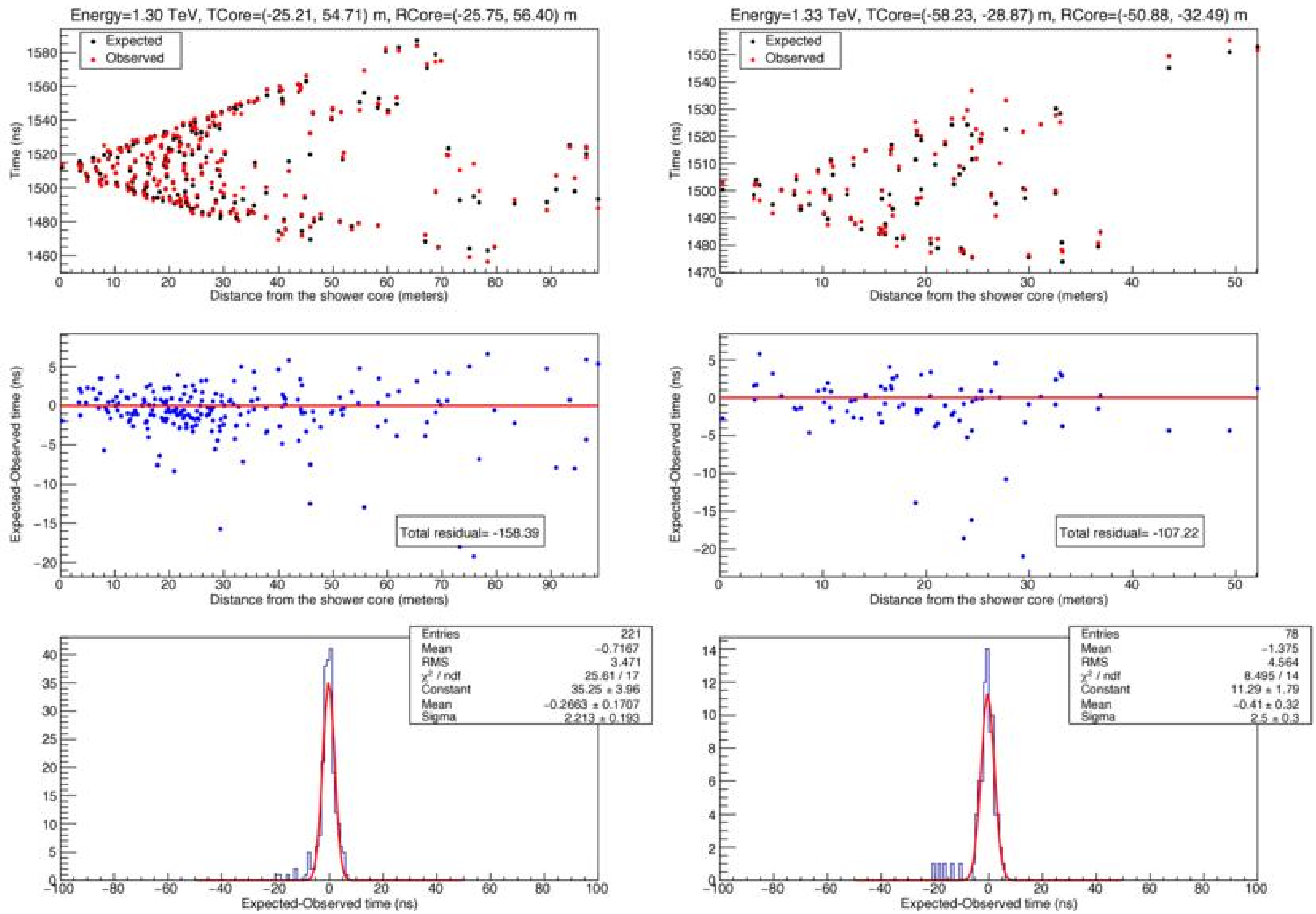
log10(TEnergy)=2.6-2.8



A multi-fit process for core + size, direction

Examples of time profiles

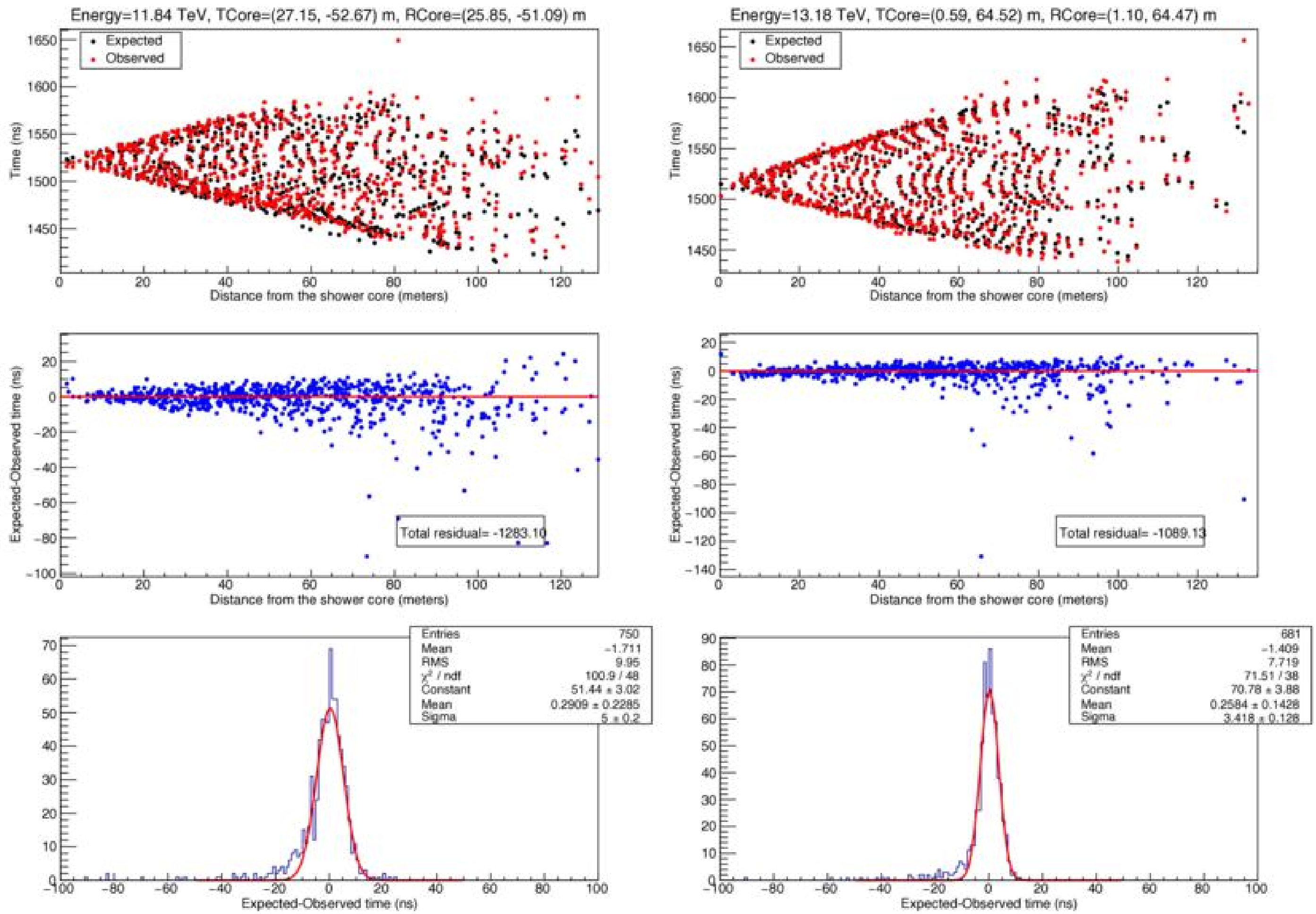
log10(TEnergy)=3-3.2



A multi-fit process for core + size, direction

Examples of time profiles

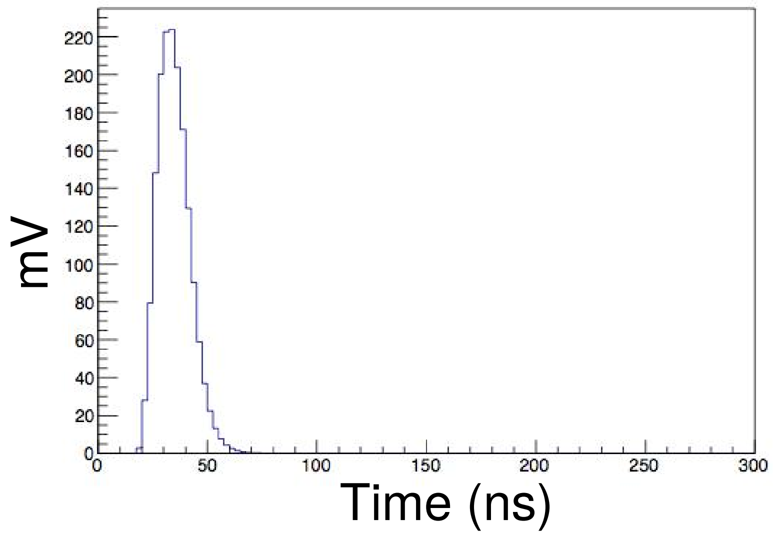
log10(TEnergy)=4-4.2



ALTO
Waveforms

Reduction in waveform sampling for lower dead-time & read-out data rate

- Waveform sampling step:
  - Initially with 0.5ns, max of cell
  - (checked also time reaching threshold)
- Lowered based response for
  - Shower core reconstruction accuracy
  - Arrival direction accuracy
- Interpolation to max based on 3 cells



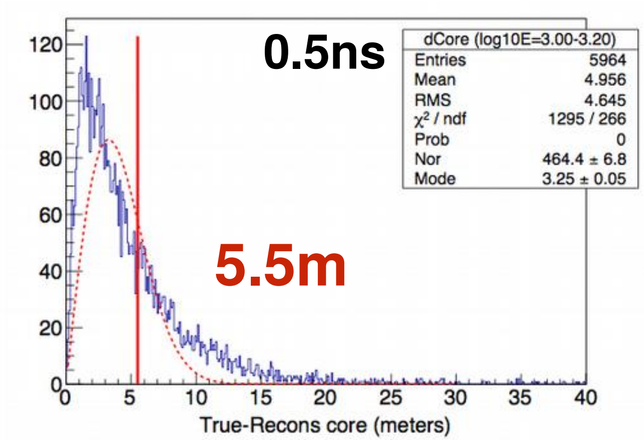
- Checked at various energies
  - With minimum number of WCDs
    - Ndet_water >= 20
  - With condition fitted core is <60m from array centre
    - Otherwise, reconstruction is bad
  - Results, illustrated in next slides
    - No effect on core reconstruction
    - Slight effect on direction accuracy
- **→ we choose to use 2.5ns sampling**

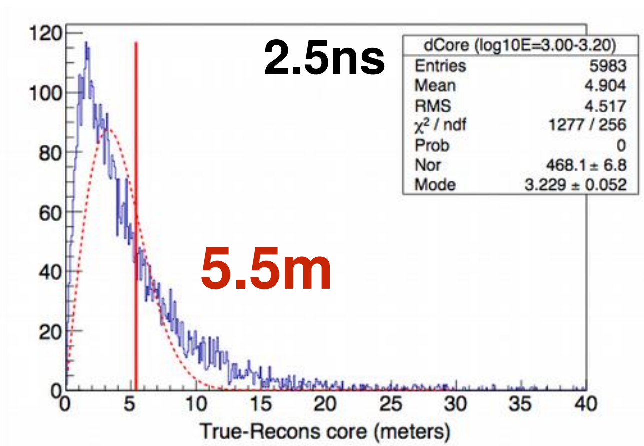
Energy	1 TeV		10 TeV	
Sampling	0.5ns	2.5ns	0.5ns	2.5ns
Core accuracy	5.5m	5.5m	0.9m	1.0m
Direction accuracy	0.7°	0.7°	0.175°	0.20°

Reduction in waveform sampling for lower dead-time & read-out data rate

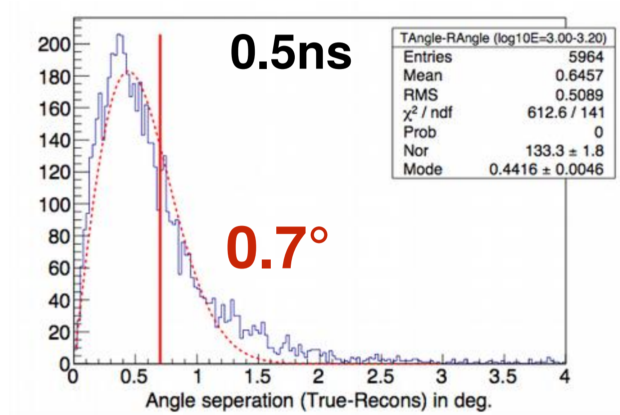
1 TeV gamma showers (Zenith=18°, RCore<60m)

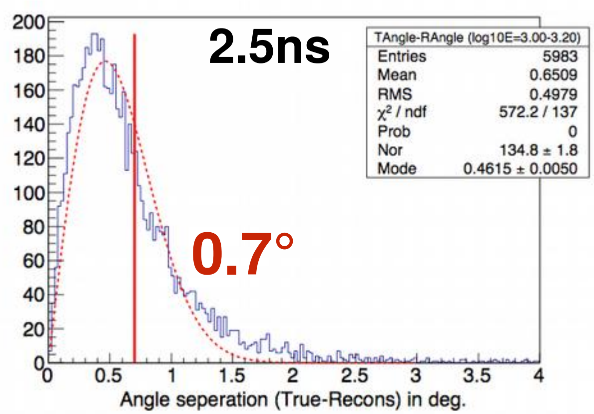
Core position accuracy





Arrival direction accuracy

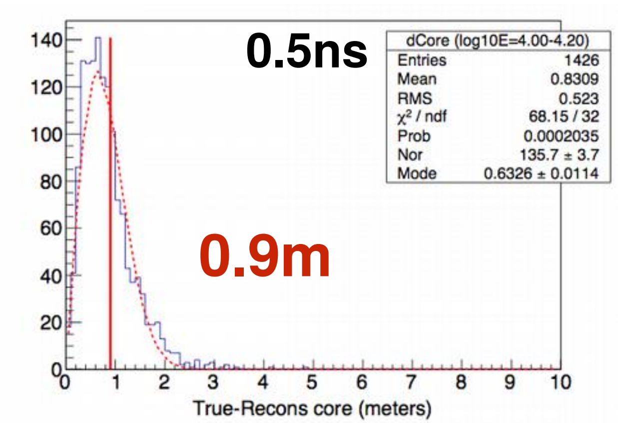


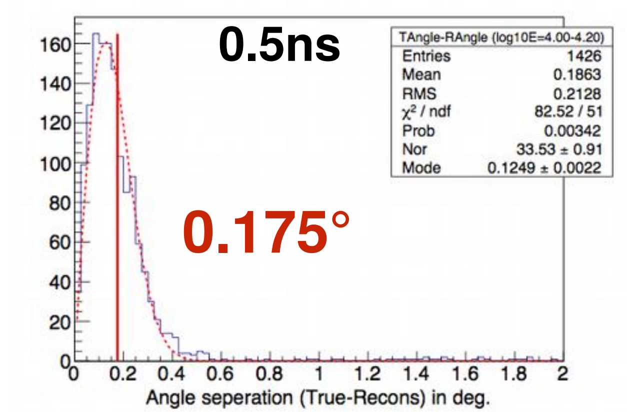


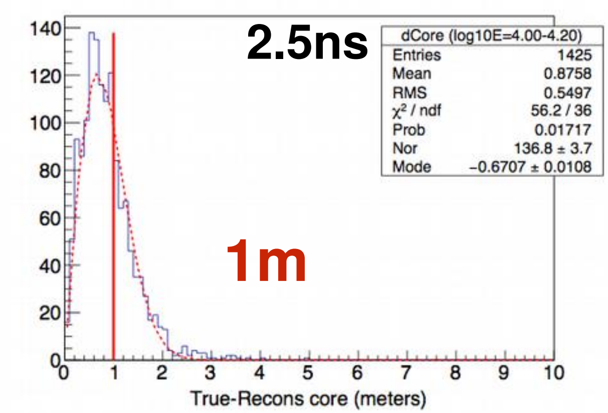
Reduction in waveform sampling for lower dead-time & read-out data rate

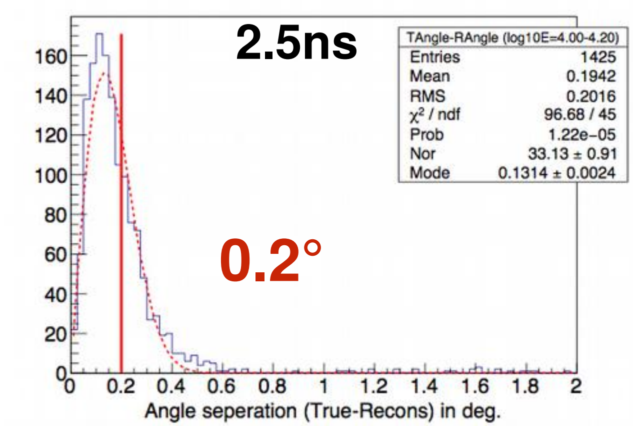
10 TeV gamma showers (Zenith=18°, RCore<60m)

Core position accuracy | **Arrival direction accuracy**









ALTO
Analysis

Parameters used or developed for ALTO

- **9 parameters** chosen from a wider list of tested ones. These parameters:
  - have distributions which differ between proton and gamma events
  - don't show a strong (anti-)correlation with others
  - are not ranked lowest in the BDT analysis in all the bins (i.e. used often in nodes)

- **Parameters:**
  - **Charge Residual RMS** and **mean**,
    from charge Observed – Expected (from NKG fit) in triggered WCDs
  - **Compactness**: ratio of total number of WCDs triggered
    to the max. charge 20m beyond reconstructed core in shower plane
  - Parameters from the Hillas fit on the :
    - Reconstructed **Length** of Hillas Ellipse
    - **Hillas Ellipse Ratio**: expected charges in the Hillas ellipse for all WCDs
      to that in the Hillas ellipse for triggered WCDs
  - **Radial density**: ratio of # WCDs triggered to
    the sum of the products of {charge by distance} beyond 10 m.
  - Parameters involving information from the scintillators:
    - **SCMdist**: The distance between the reconstructed core position
      and Centroid of triggered scintillators in the shower plane
    - **WCD/SD number ratio**: # scintillator tanks triggered to the # WCDs triggered.
    - **WCD/SD charge ratio**: total charge seen in scintillators to the total charge seen in WCDs.

ALTO Pre-cuts

- Some of these parameters are used for "**Pre-cuts**" to remove badly reconstructed events, essentially high impact parameters beyond array edge

- **Precuts foreseen for AGN-observations**:
  - N_Det >= 5
  - $\log_{10}$(err_RSize/RSize) < 0
    - (aka, low energy cut / Rsize cut)
  - $\log_{10}$(RrM)/(-1.075*$\log_{10}$(MaxExpRadius)+3.53) < 1
    - (aka, high energy cut / RrM cut)
  - **CAVEAT**: The precuts values applied here were developed for an earlier reconstruction → Re-optimization needed

- Precuts foreseen monitoring purposes, N_Det >= 3

- Precuts forseen for Galactic sources,
  - All the above AGN cuts
  - NDet_water few tens of WCDs (TBD)

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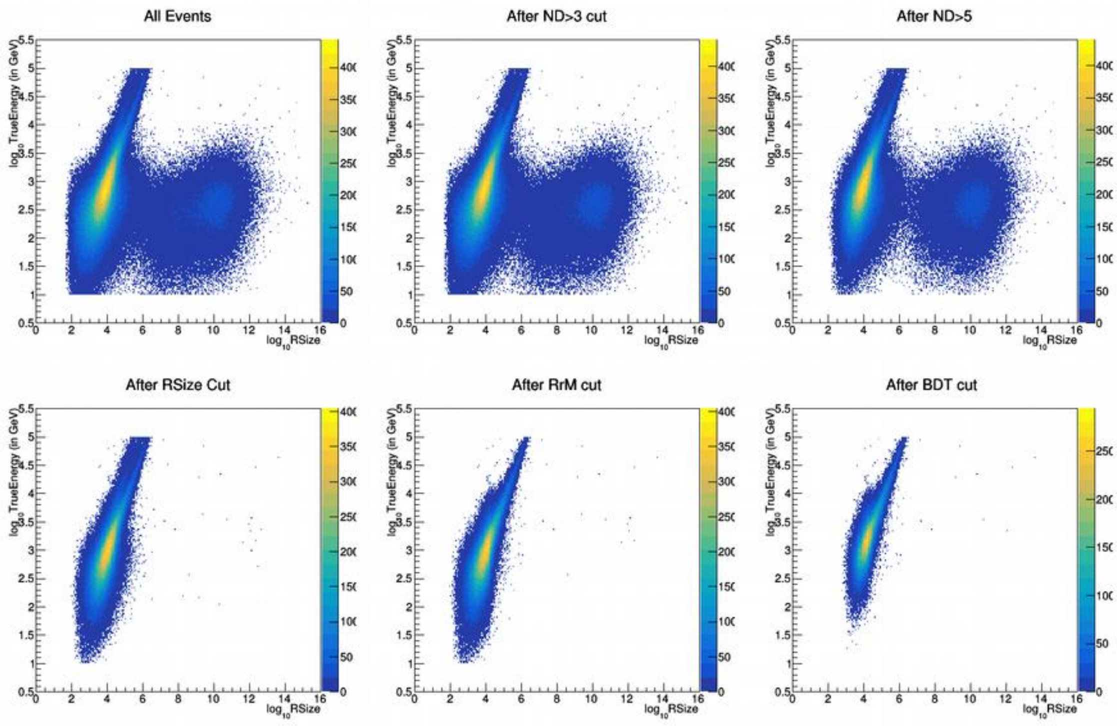
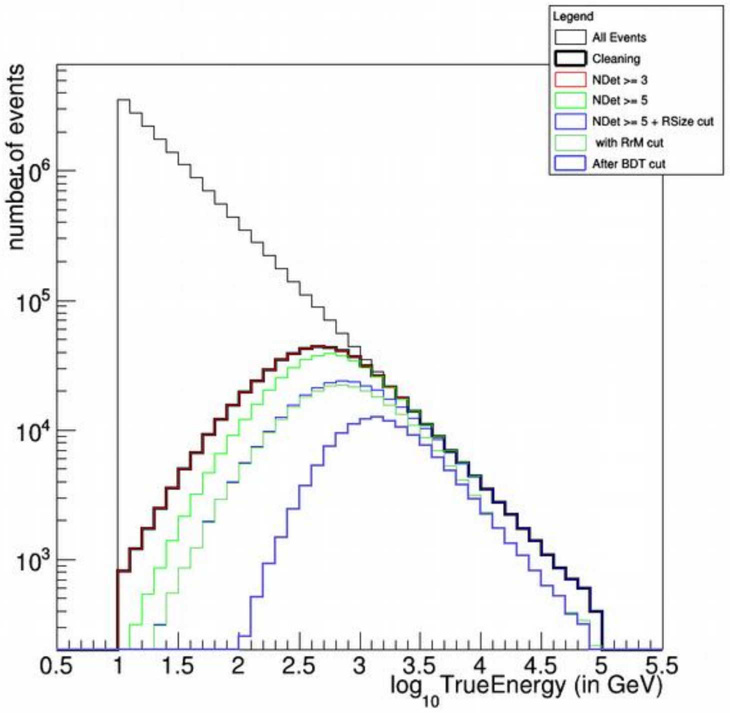
ALTO Pre-cuts Effect

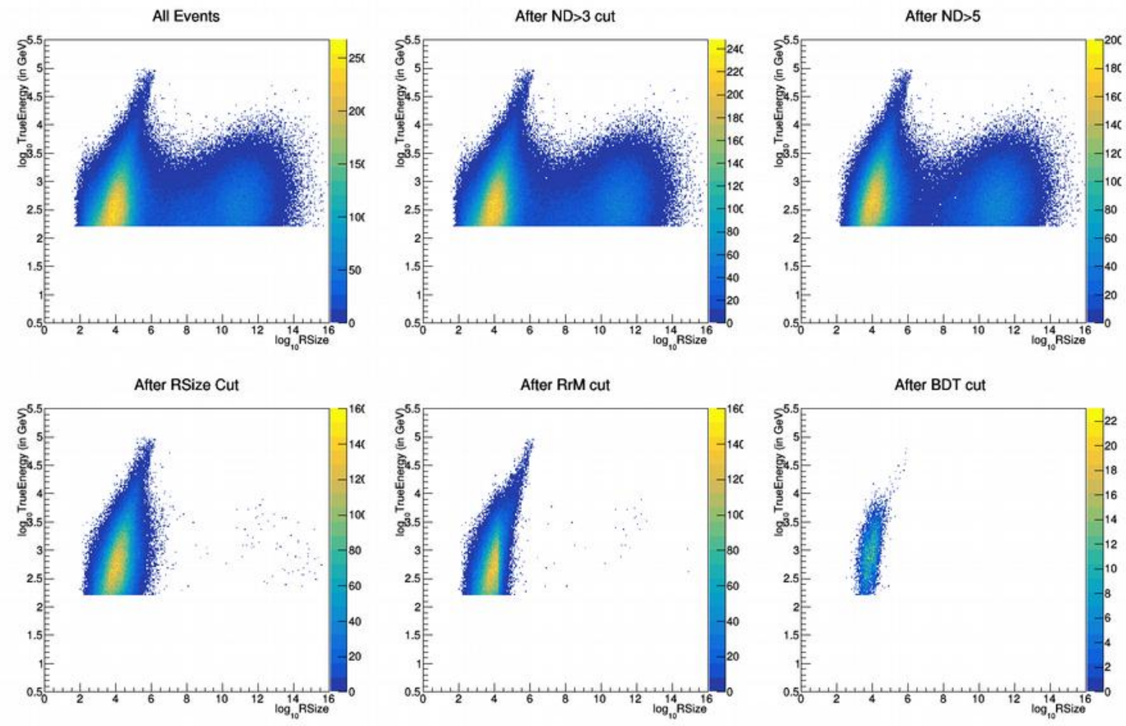
For Gammas

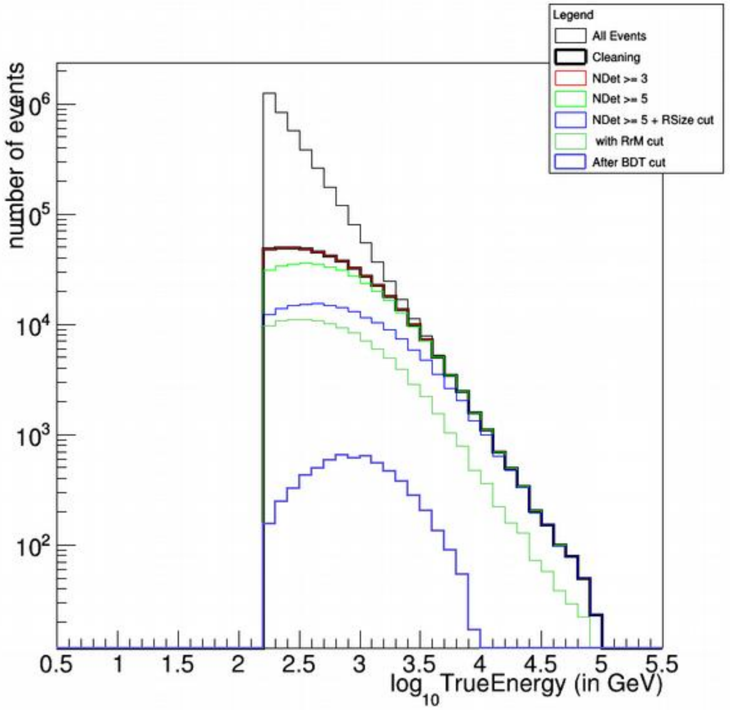




ALTO Pre-cuts Effect

For Protons





ALTO Analysis bins

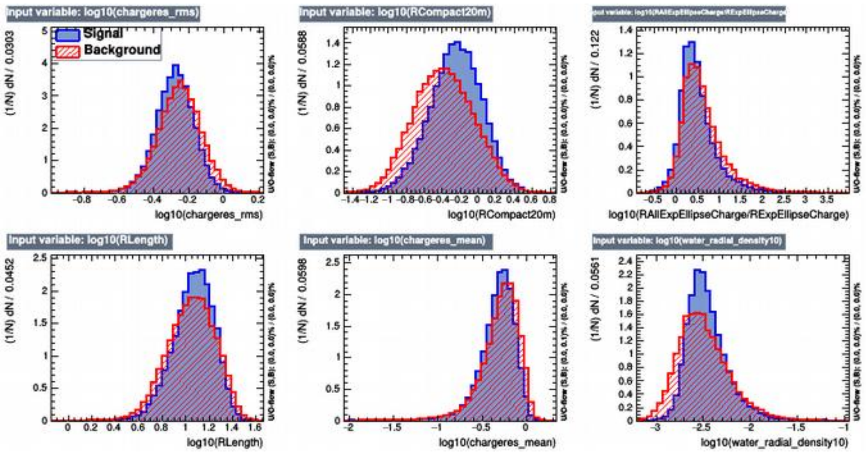
- **Sample divided into 4 increasing RSize ranges (bins)**
  - Independent analysis developed for each bin (using MVA-BDT)
  - For each, a gamma efficiency was required
  - Training applied gave the proton efficiency shown.

Bin No.	RSize limit (Number of events trained)	True Energy Mean (in GeV)	Gamma Efficiency	Proton Efficiency
1	1.00 - 3.78 (31605)	343	0.4	0.130
2	3.78 - 4.08 (31208)	729	0.6	0.110
3	4.08 - 4.40 (28351)	1273	0.8	0.099
4	4.40 - 7.00 (26803)	4874	0.9	0.039

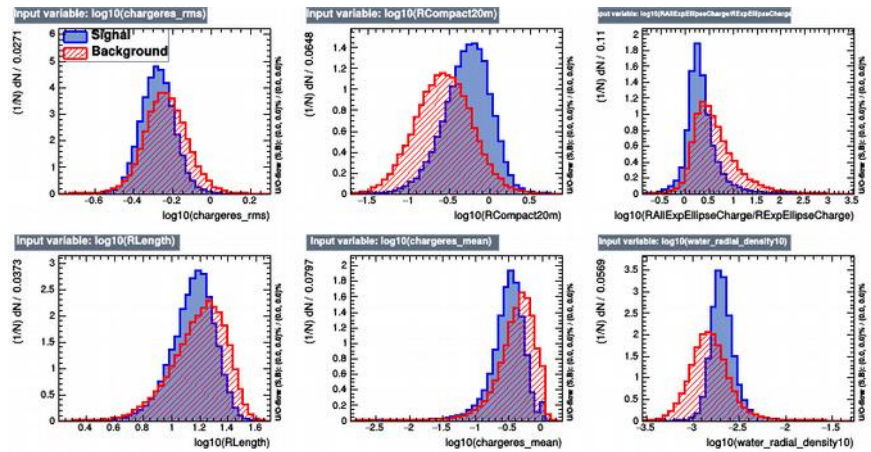
Parameters used or developed for ALTO

Distributions for 4 bins in RSize, (low to high → worst to best

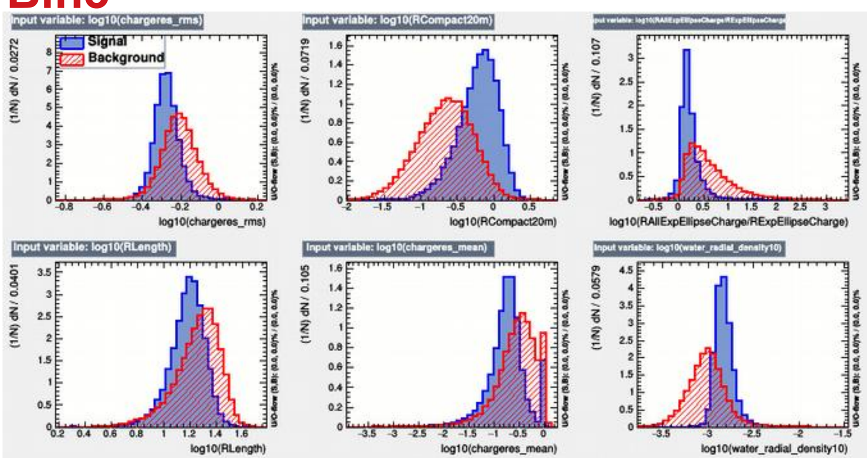
Bin1



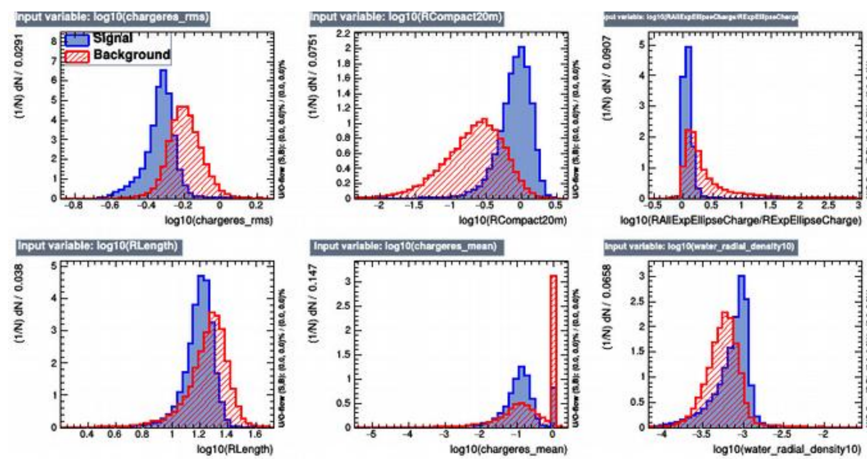
Bin2



Bin3



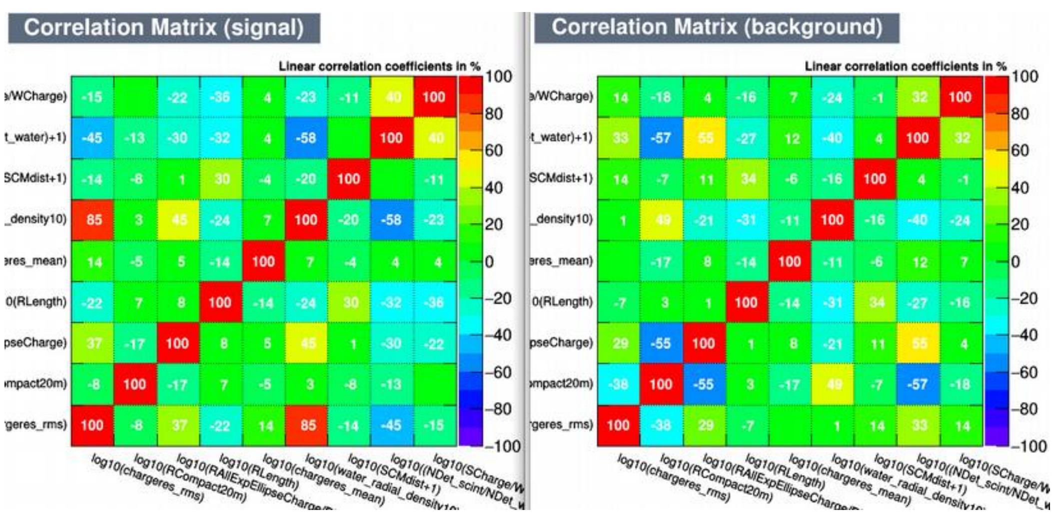
Bin4



Multi-Variate Analysis – Boosted Decision Trees

- The Decision Trees based on sequence of binary conditions on discriminating variables. Final leaves labelled Signal or Background
- Boosting by re-weighting events to form many trees, which can then be pruned to give best results

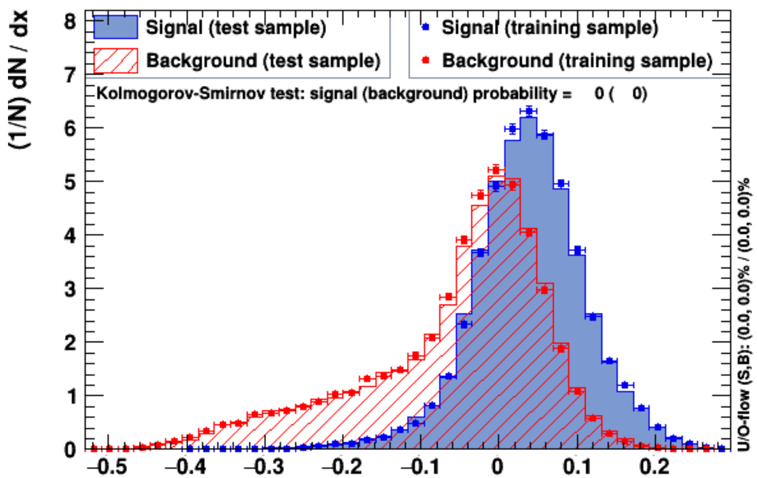
- ROOTs MVA-BDT software provides many features
  - e.g. check of the correlations between parameters
  - See result for bin4 in RSize (after removal of highly (anti-) correlated params):



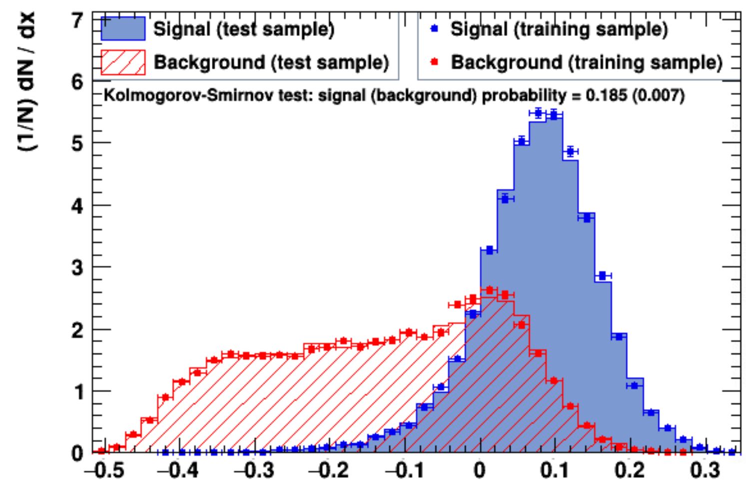
Multi-Variate Analysis – Boosted Decision Trees

BDT Classifier outputs for 4 bins in RSize, low to high → worst to best

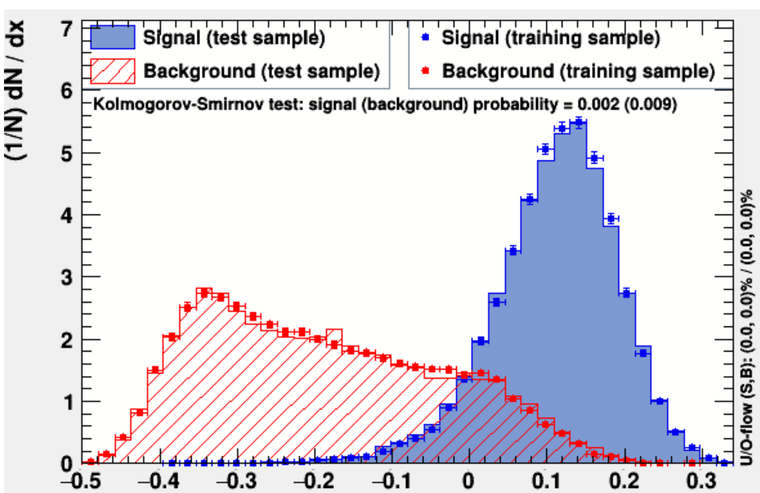
Bin1



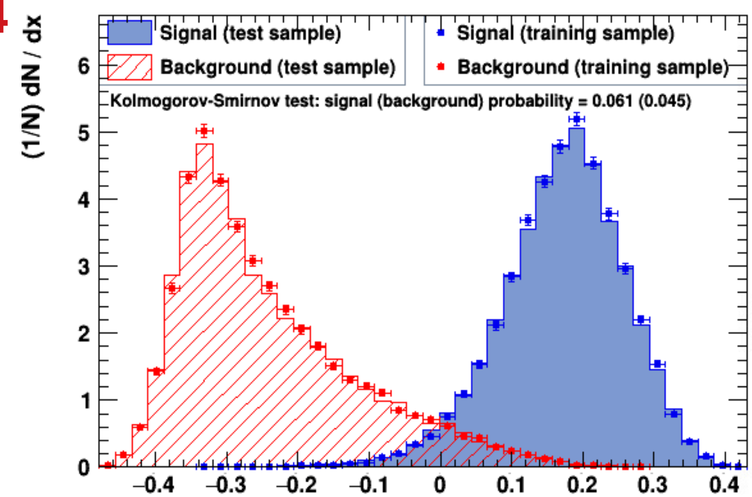
Bin2



Bin3



Bin4

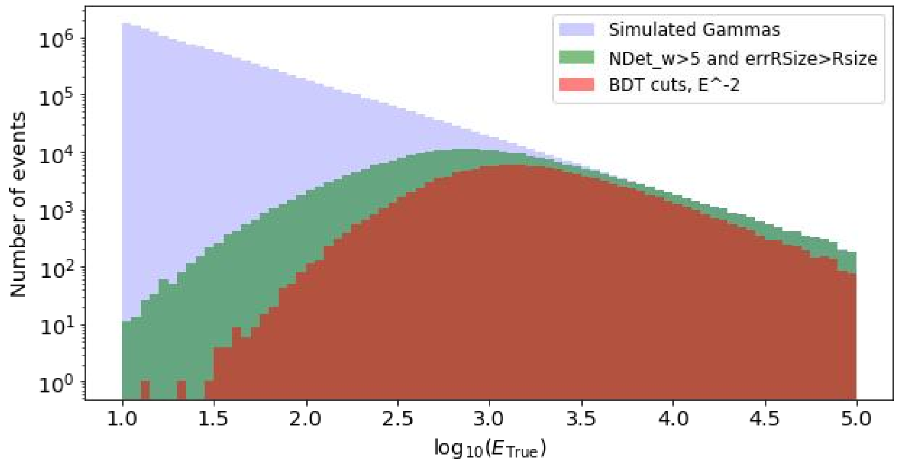


ALTO
Results from
Simulations, Reconstruction, Analysis

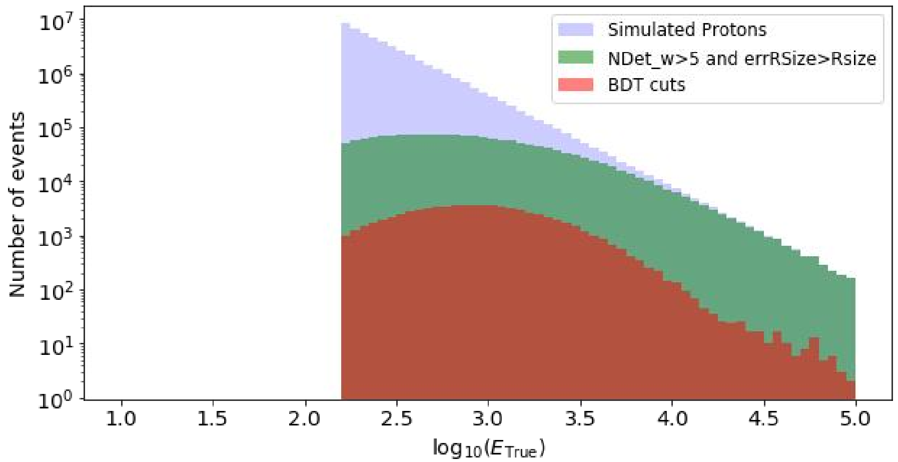
Simulations, Reconstruction, Analysis results

- **Application of BDT** to full set of Monte Carlos

Gammas



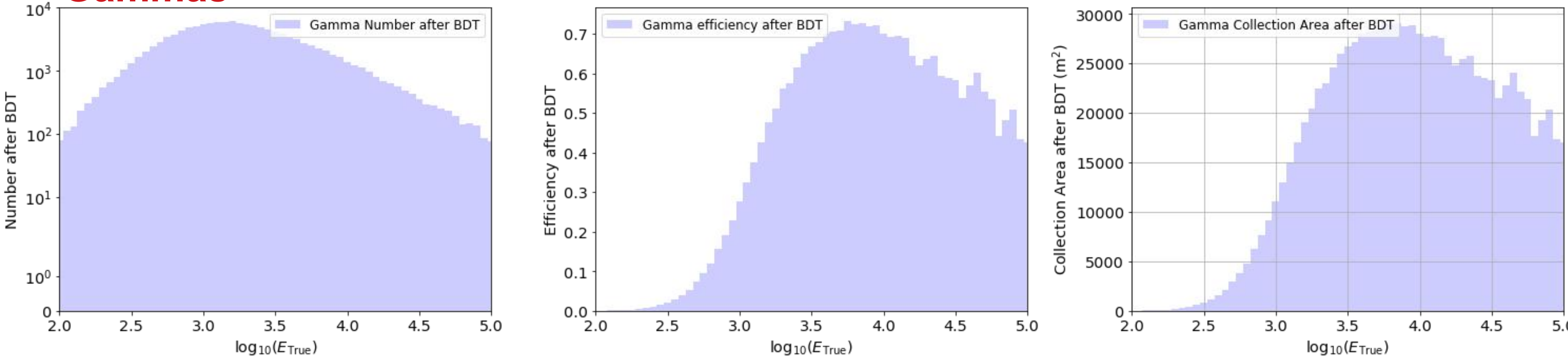
Protons



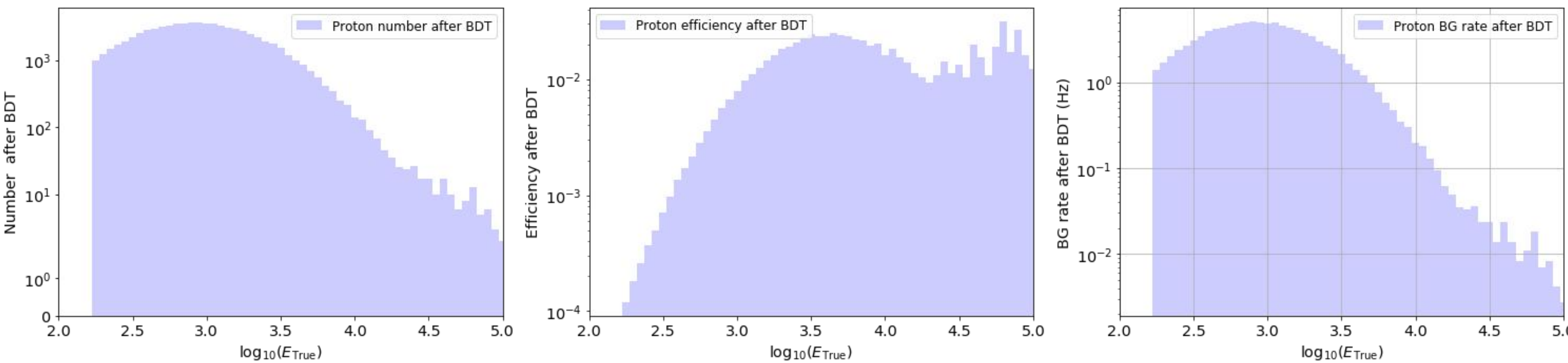
Simulations, Reconstruction, Analysis results

- **Application of BDT** to full set of Monte Carlos

Gammas

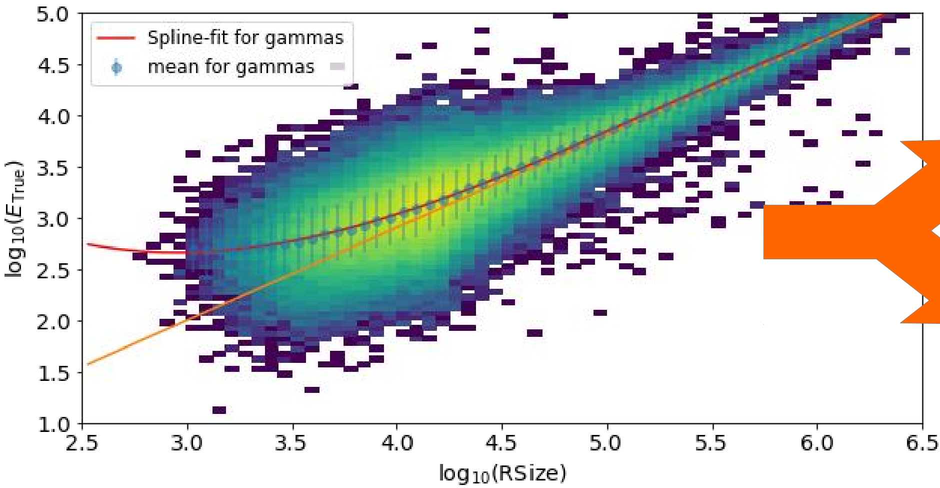


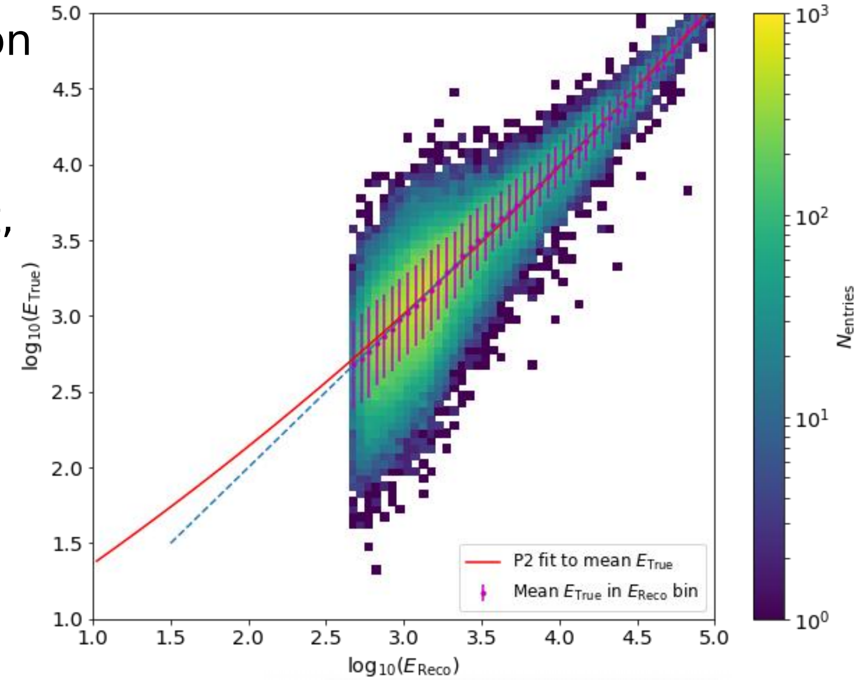
Protons

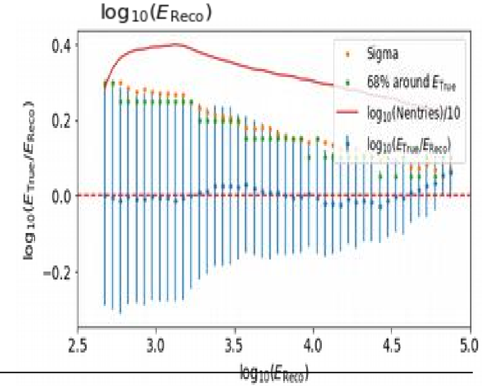


Simulations, Reconstruction, Analysis results

- **Energy reconstruction:**
  - Based on fitted “Rsize” from NKG function
    - Spline fit to the mean, to provide estimate of energy given RSize
  - Neural-Net currently under development, should be better

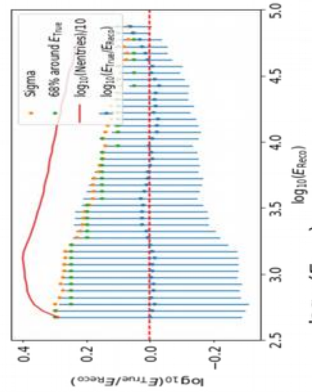


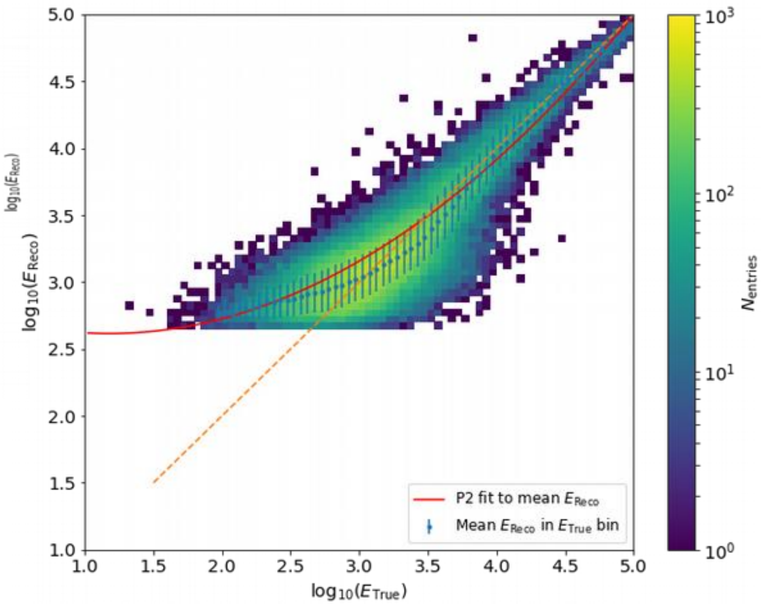


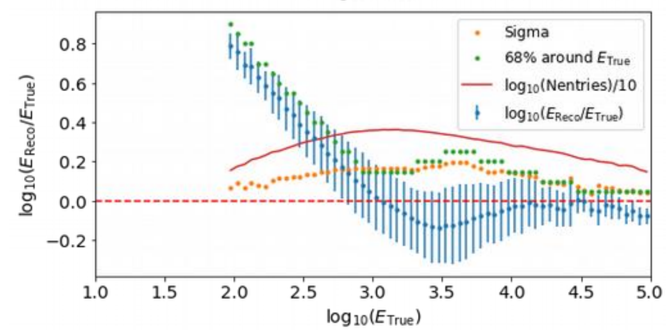


Simulations, Reconstruction, Analysis results

- (Two asides)
  - What counts for the sensitivity plot is the **bias in E_{reco}**
  - 68% containment of error around E_{True}, used by CTA, nicely combines bias and sigma

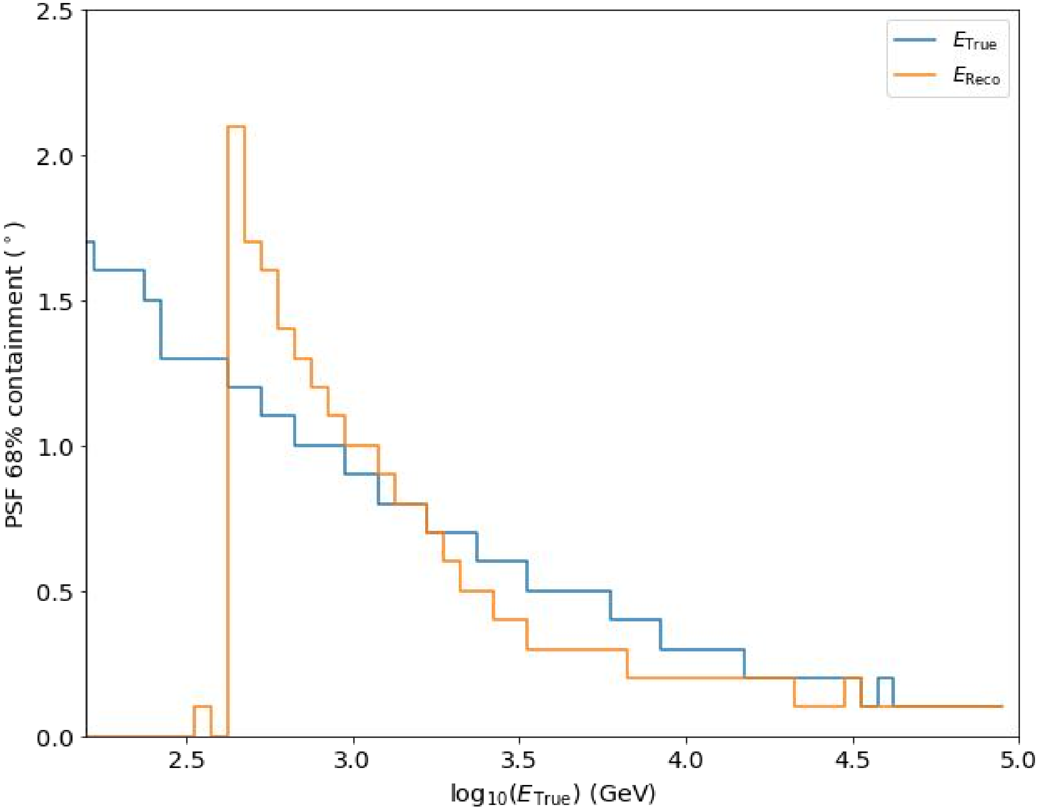






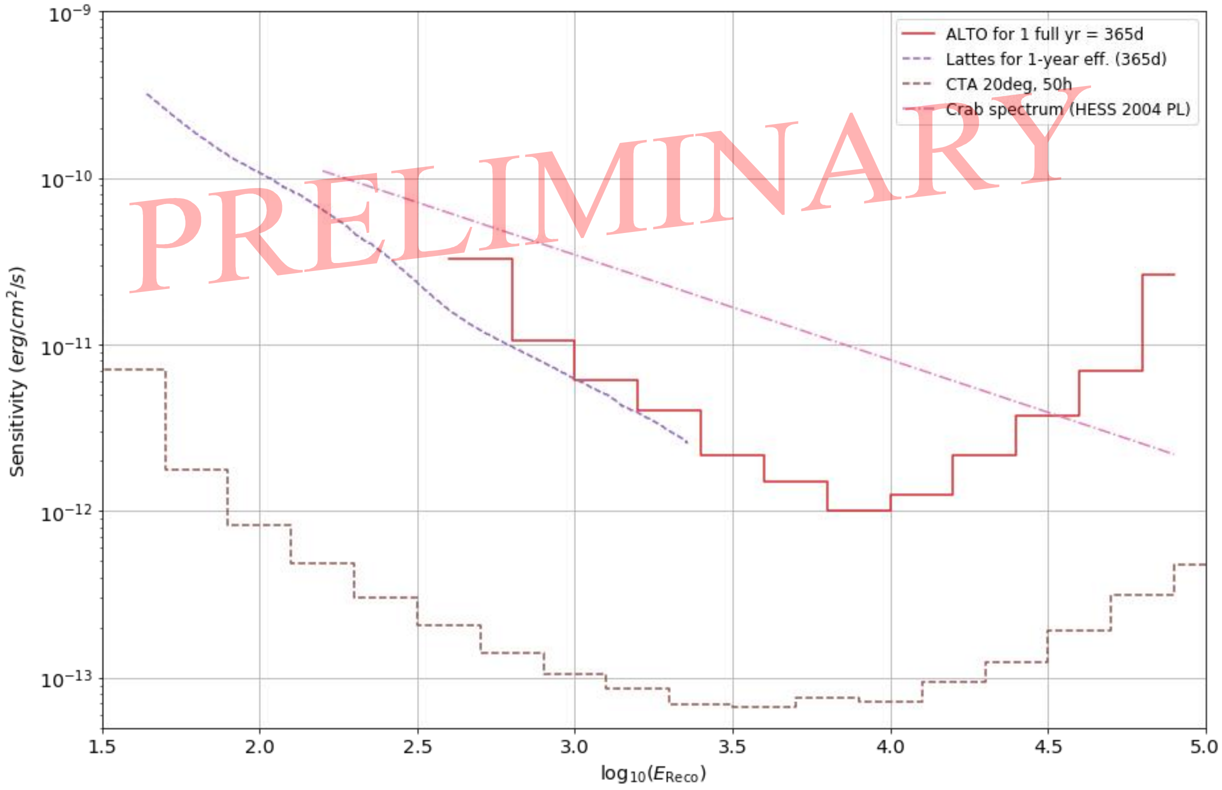
Simulations, Reconstruction, Analysis results

- **PSF**
  - Determining cut for 68% containment of Gammas



Simulations, Reconstruction, Analysis results

- **Sensitivity** for 1yr live-time on a source at 18°:



- **CAVEATs**:
  - High-energy response will be improved when using pre-cuts adapted to reconstruction
  - Further improvements overall expected now that the chain is complete

Conclusions

- ALTO simulations and Analysis now quite mature
  - We have a complete and detailed simulation of a realizable detector
  - We have completed the full chain up to the sensitivity curves
    - Many parameters developed and tested
    - MVA- BDT machinery in place and working
    - → Now, some time for optimizations based on full chain

  - Note: we are not convinced on the validity of the “strawman” approach
    - Even if it helps to estimate performance of different array types relatively
    - → Need full realistic simulations and a complete reconstruction / analysis chain

- ALTO planned publication(s) before the EOY on this basis
  - Including the response at different Zenith angles, and to a “moving source”
  - Background work on gain given by the use of the Scintillator layer muon tagging
  - Effect of “cluster trigger”, versus no cluster trigger

- Future steps
  - Extend detector by either/both:
    - Outrigger clusters, clearly will improve for a slightly increased cost
    - Graded array, with more distant clusters further away
      → possibly overall improvement for similar cost

- Status of the project with further information can be found at the website:
  → http://alto-gamma-ray-observatory.org/
- For enquiries about the project, please contact yvonne.becherini@lnu.se