A Proposal for a Low-Energy Trigger

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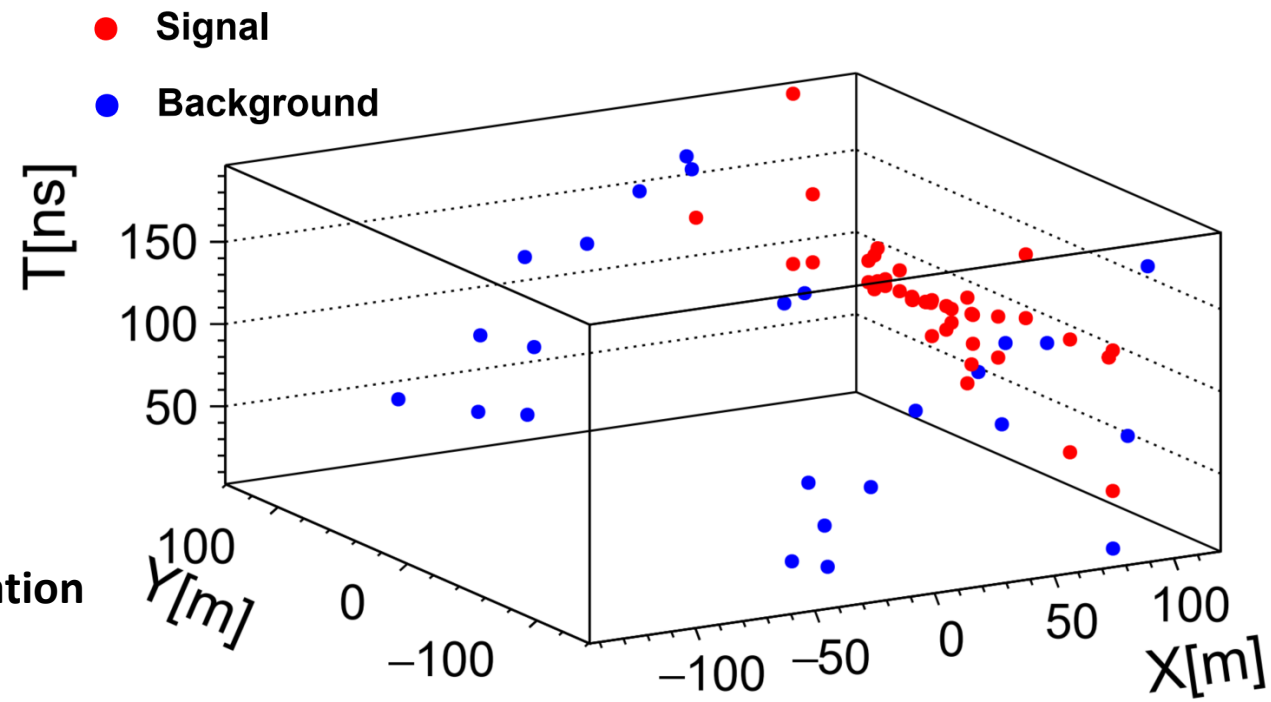
Original Procedure

Simulated events, CORSIKA (version 7.5600)**:**

- Altitude: 4.7 km;
- Primary particles: proton, gamma;
- $\boldsymbol{\theta = 10°, 30°;}$
- Energy spectrum E^{-1}, from ~**10 to 250 GeV**

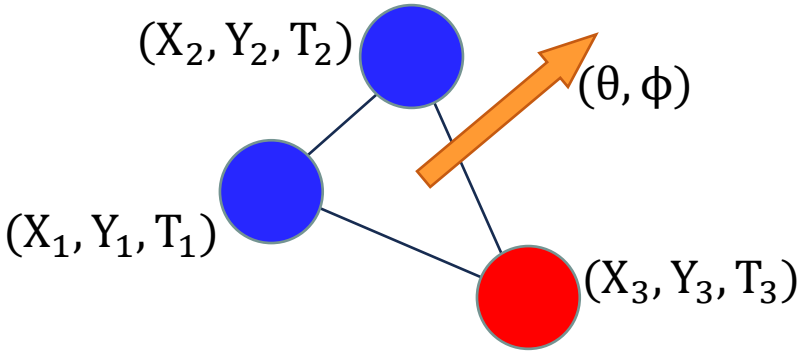
Detector configuration:

- Array area: $80\ 000\ \mathrm{m}^2$;
- Fill factor: 80%;
- Energy to signal parametrization from **single layer station** with **Mercedes configuration**

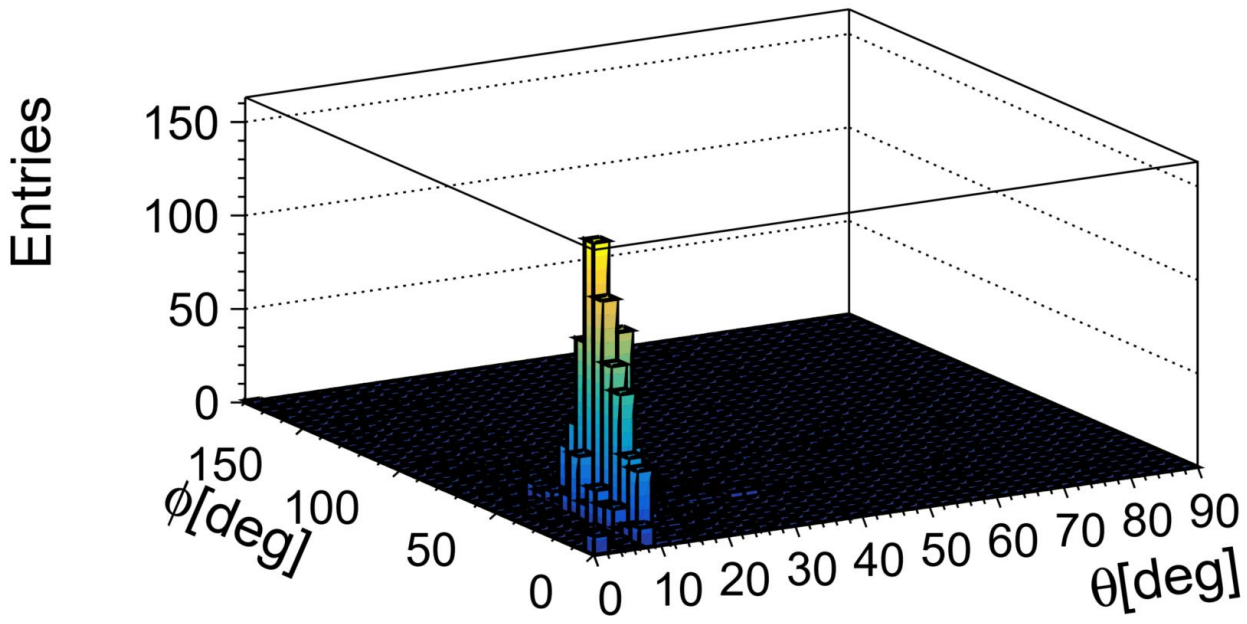


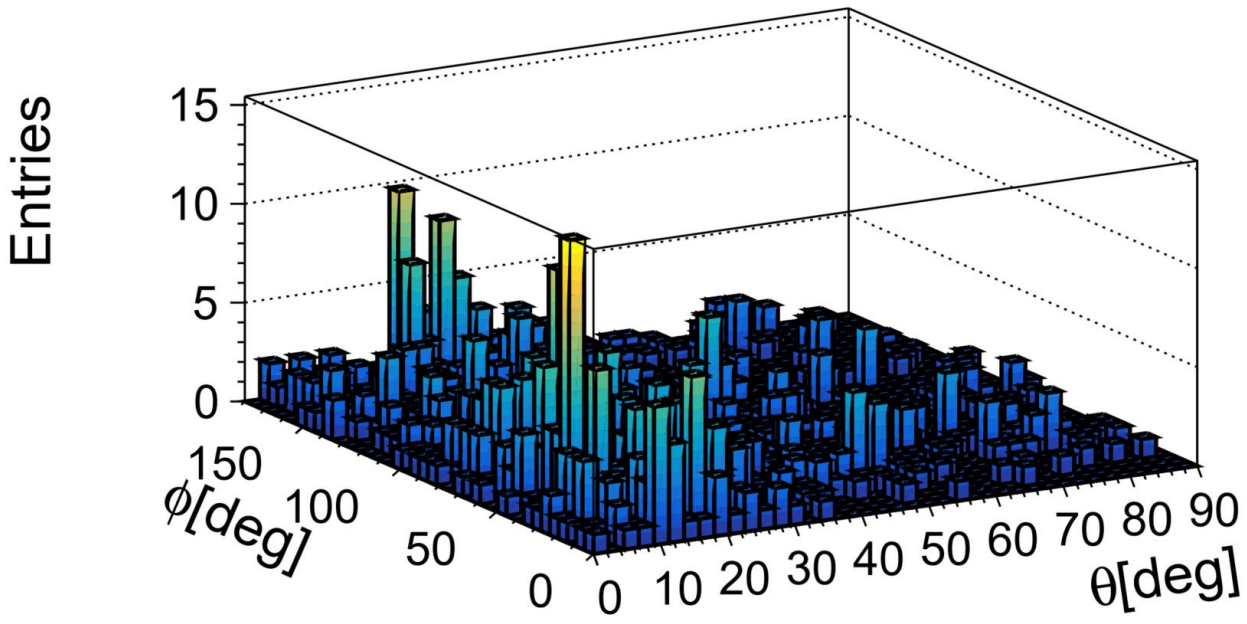
Procedure - Base principle:

- Particles in shower front lay approximately in a plane;
- 3 triggered stations define plane in (X, Y, T) space, normal vector points to a direction (θ, ϕ) ;
- Go over all 3-station combinations in **200 ns window** to reconstruct shower direction



Original Procedure





Signal event

- Normal vectors point in a clear direction, **well defined peak in (θ, ϕ) plane** matching the reconstructed particle direction.

Background event
(superposition of tens of low energy cosmic rays)

- No clear direction stands out.
  Broad accumulation near vertical direction.

Improved Procedure

Sky semi-hemisphere histogram with equal-area cells filled with **direction of normal vectors** (θ, ϕ)

- **Each cell**: number of normal vectors whose direction falls within the cell

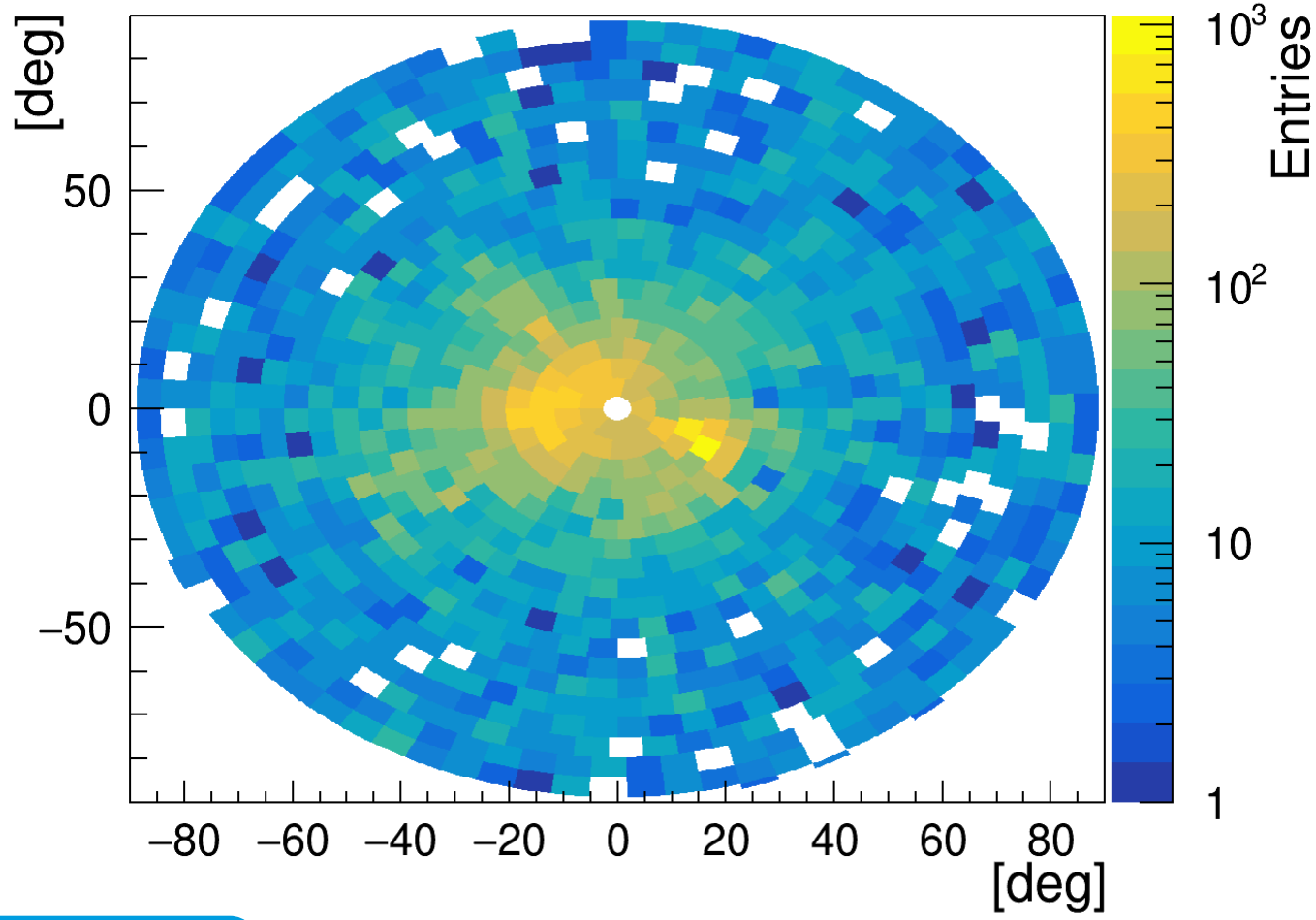
Cells clustered into "jets"

- **QCD jet inspired algorithm**[1] used to improve signal direction reconstruction

Size of a jet direction (C_{3j}^{N}):

- Number of vectors forming a clustered jet

Sky semi-hemisphere histogram filled with the directions (θ, ϕ) of normal vectors/jets.



[1] ***Successive combination jet algorithm for hadron collisions***, S.D. Ellis, D.E. Soper, Phys. Rev. D 48, 3160 (1993). DOI 10.1103/PhysRevD.48.3160

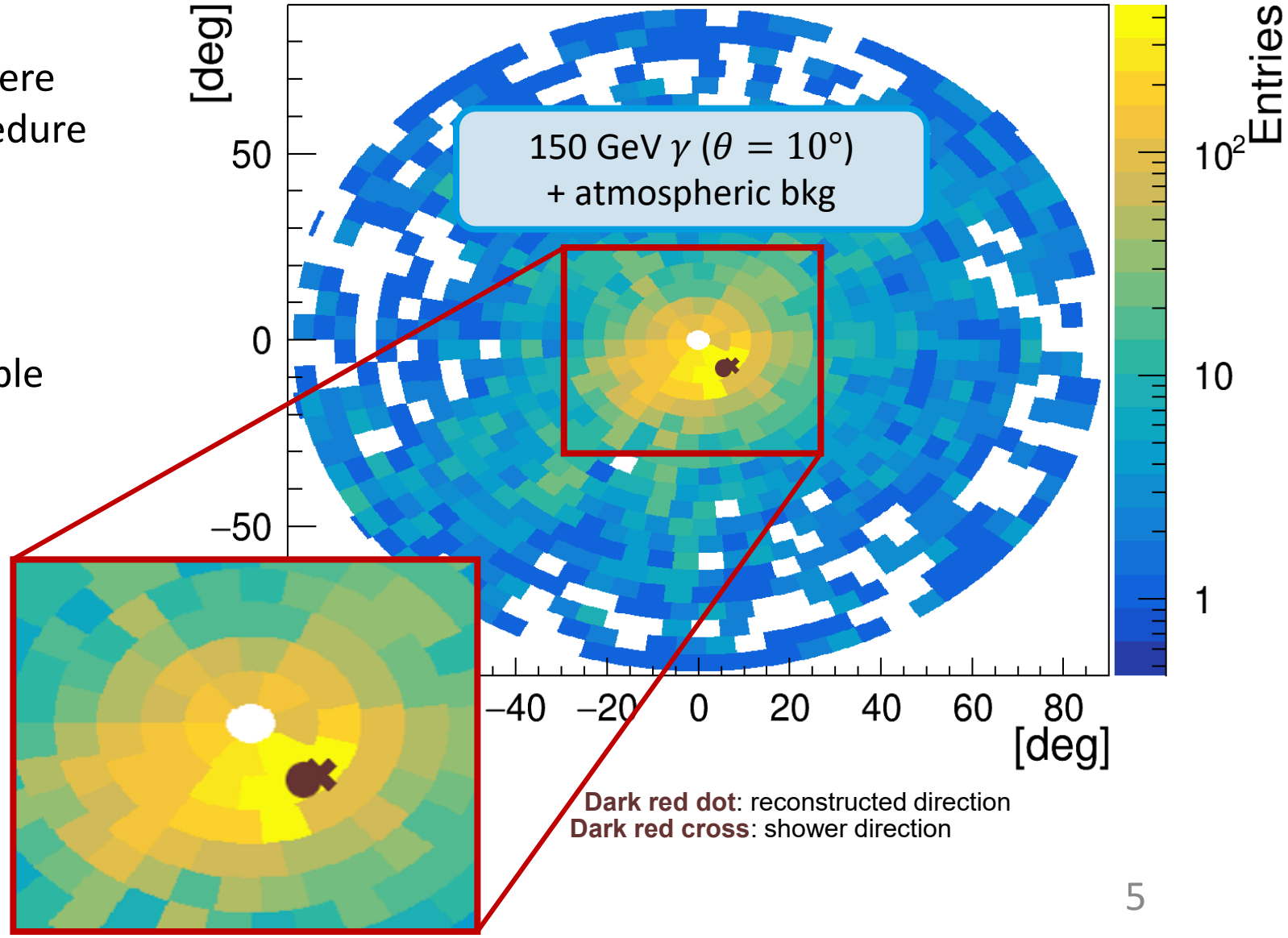
Improved Procedure

Number of cells in sky semi-hemisphere (typically 1000 or 5000) affects procedure performance

Selected clustered jet directions

- Update cumulative lookup table of sky directions.

Alert emitted when lookup table cell **surpasses a threshold**.

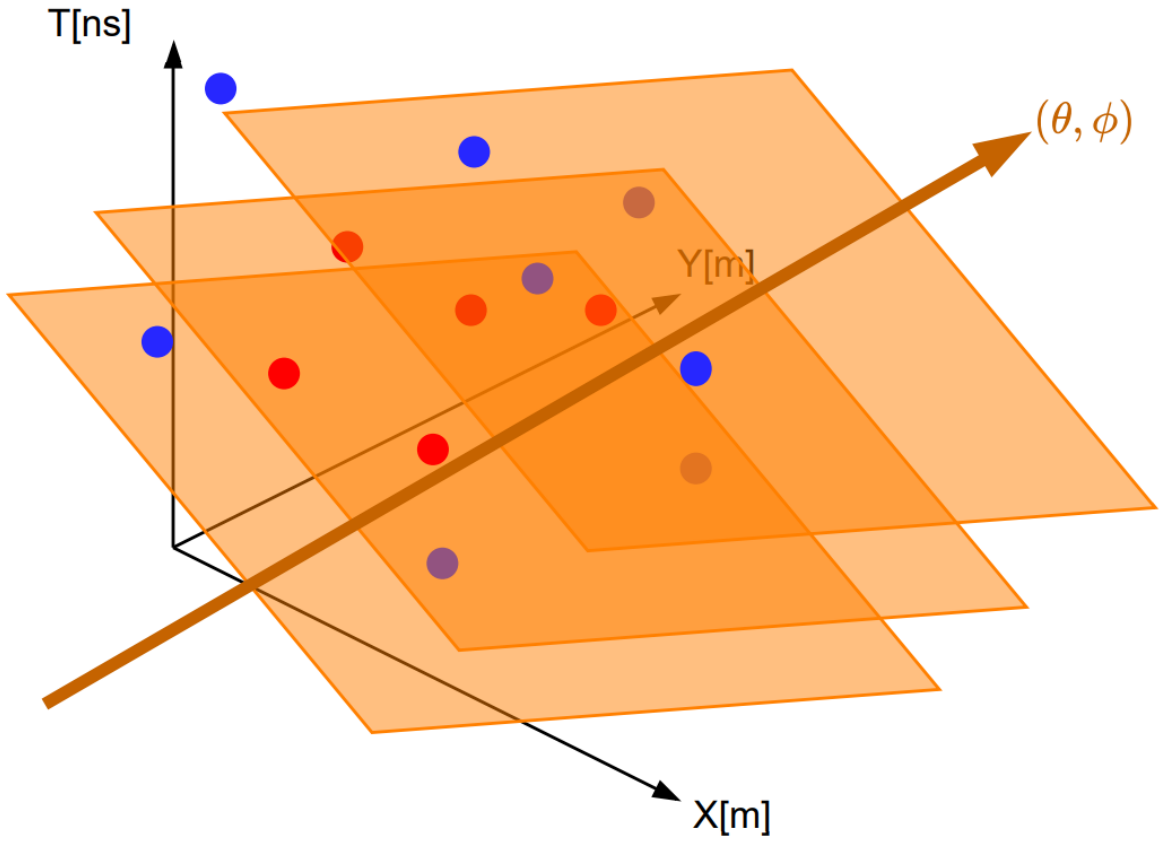


Improved Procedure

Shower direction estimate (θ, ϕ)
obtained from **largest jet cluster**

- **Infinite number of planes** can be drawn from this normal vector

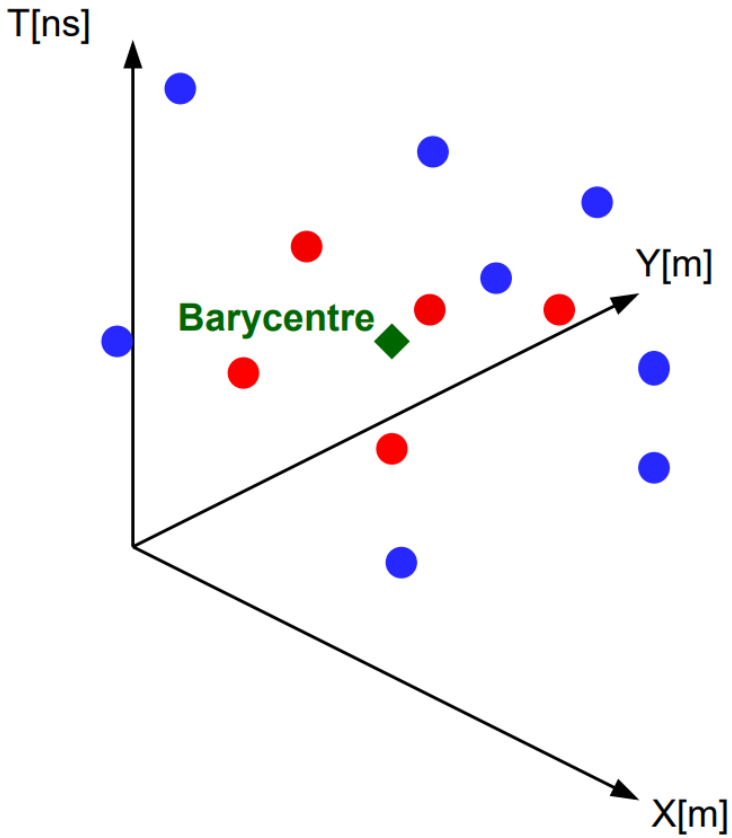
Shower plane definition incomplete:
a **reference point** is **required**



Improved Procedure

Reference point definition:

1. Take spatial coordinates of **barycentre**: (X, Y)

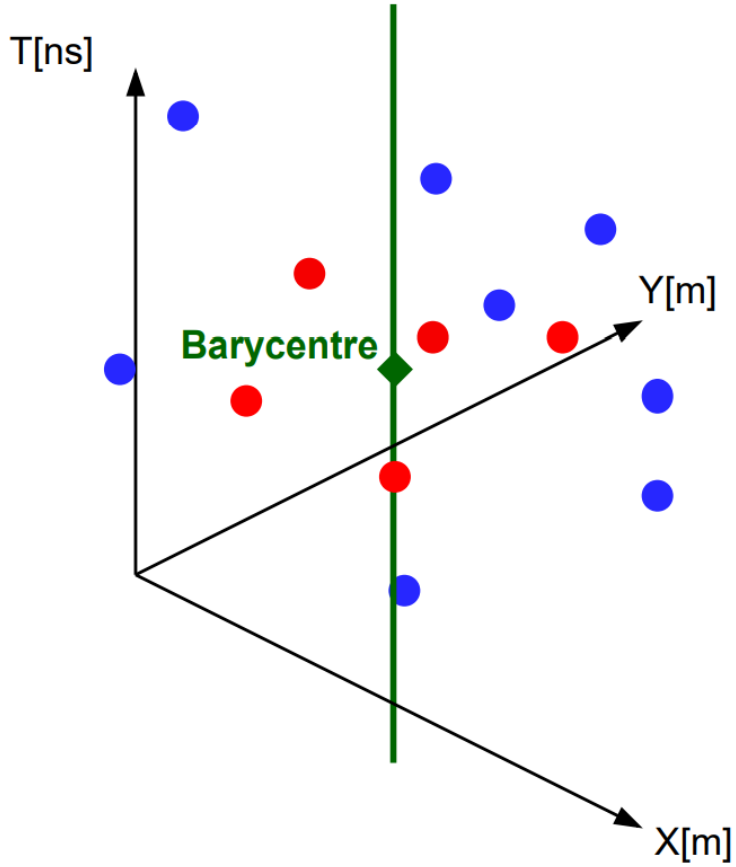


Improved Procedure

Reference point definition:

1. Take spatial coordinates of **barycentre**: (X, Y)

2. Define a **vertical line** in the (X, Y, T) space passing through barycentre



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1. Take spatial coordinates of **barycentre**: (X, Y)

2. Define a **vertical line** in the (X, Y, T) space passing through barycentre

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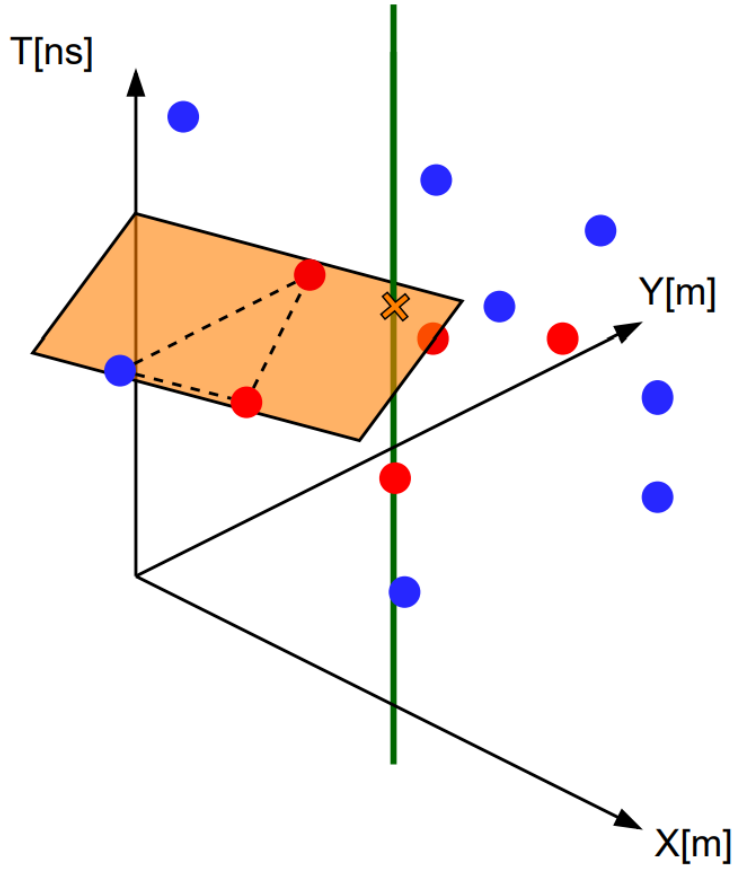

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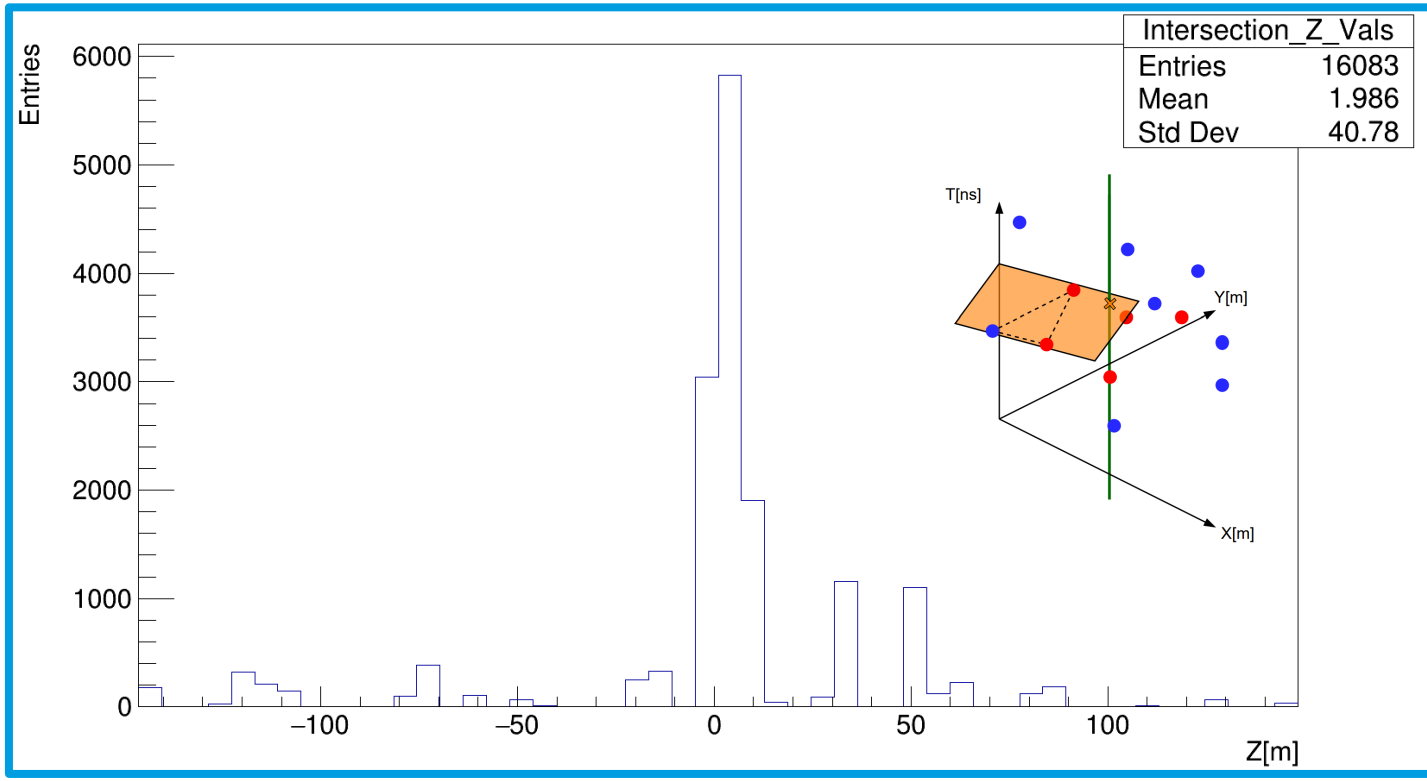
4. Take **most frequent value of Z**. Define interval containing values of Z with **frequency higher or equal than** 10% of maximum frequency.



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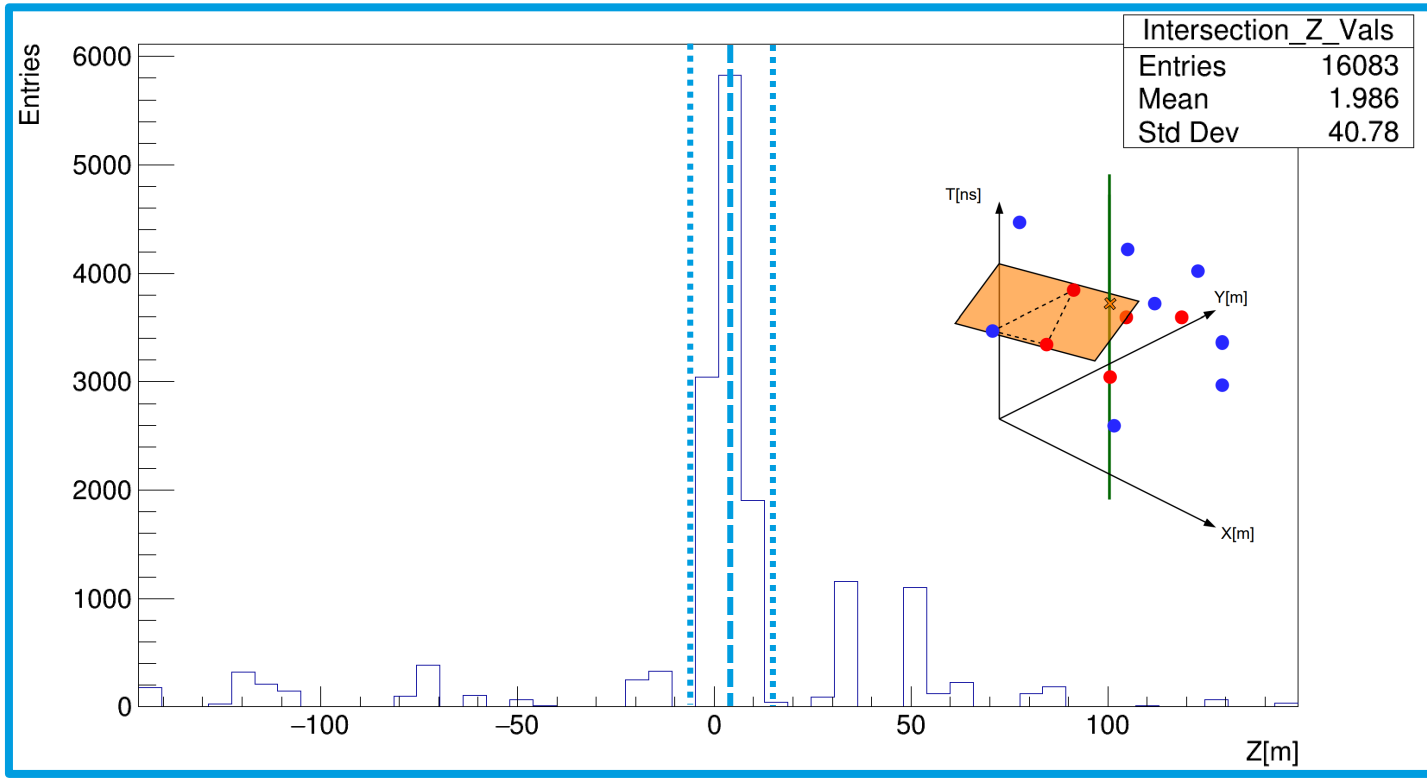


Improved Procedure

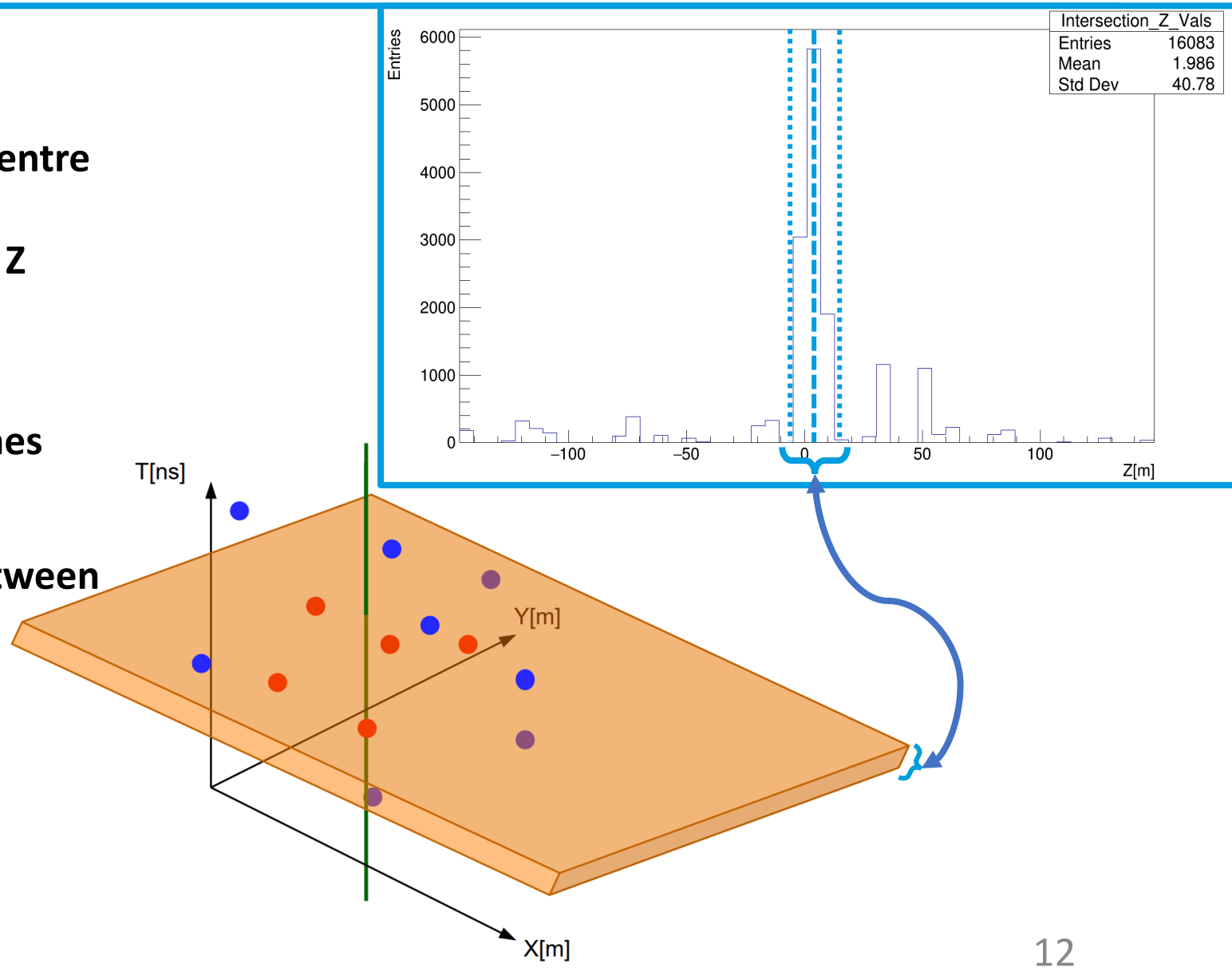
Define **2 reference points** using:

- Spatial **coordinates of the barycentre** (X,Y)
- **Edges** of the computed **range of Z values**

From the reference points define **2 planes**

Account only for **stations contained between the 2 planes**

Reapply jet clustering algorithm, only with normal vectors from combinations of **selected stations**



Trigger Procedure

Per event,
take **jet of maximum size**
(after removing background):
C_3^N

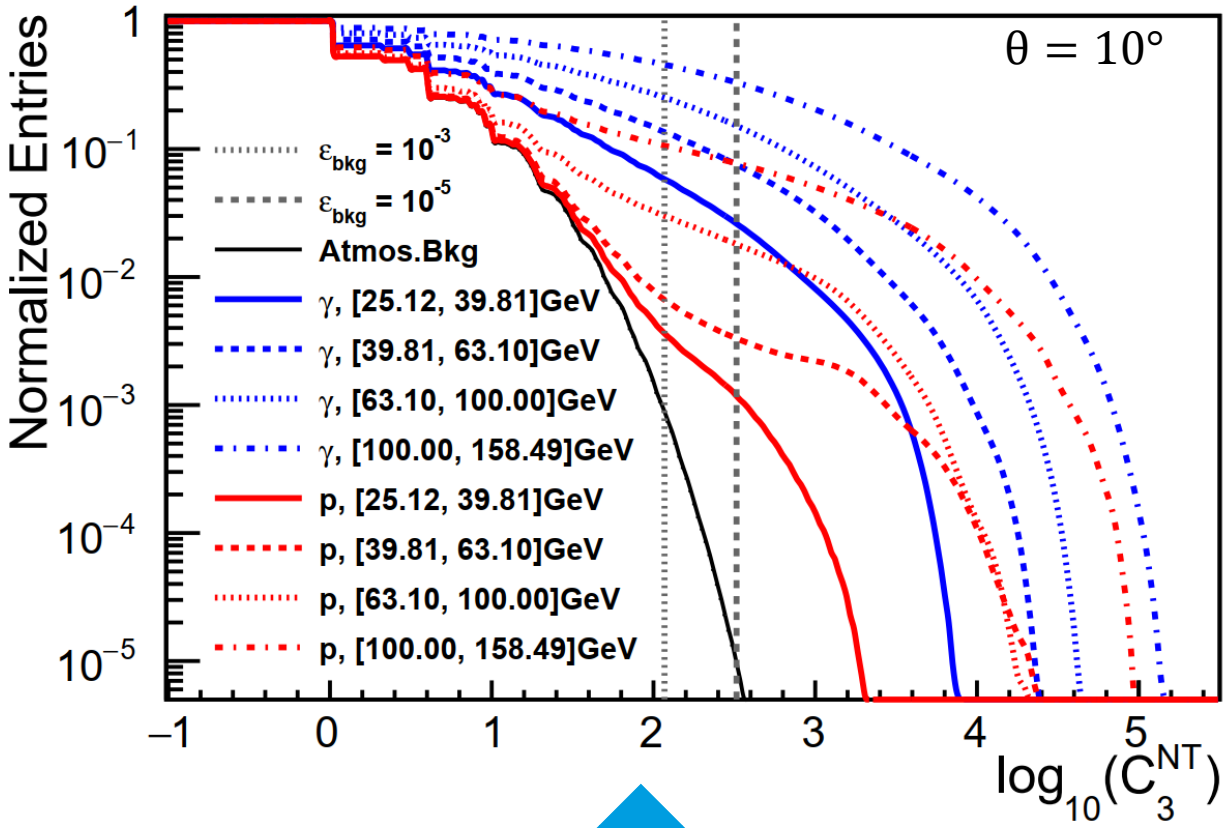
Reconstructed direction
of signal source
⇓
Direction of jet

Trigger Variable
Content of jet cluster corresponding to reconstructed direction

Used in **logarithmic form**:
$\log(C_3^N)$

Set a **threshold value, $\log(C_3^{NT})$**
above which an event is triggered

Gamma and Proton shower tagging efficiency curves



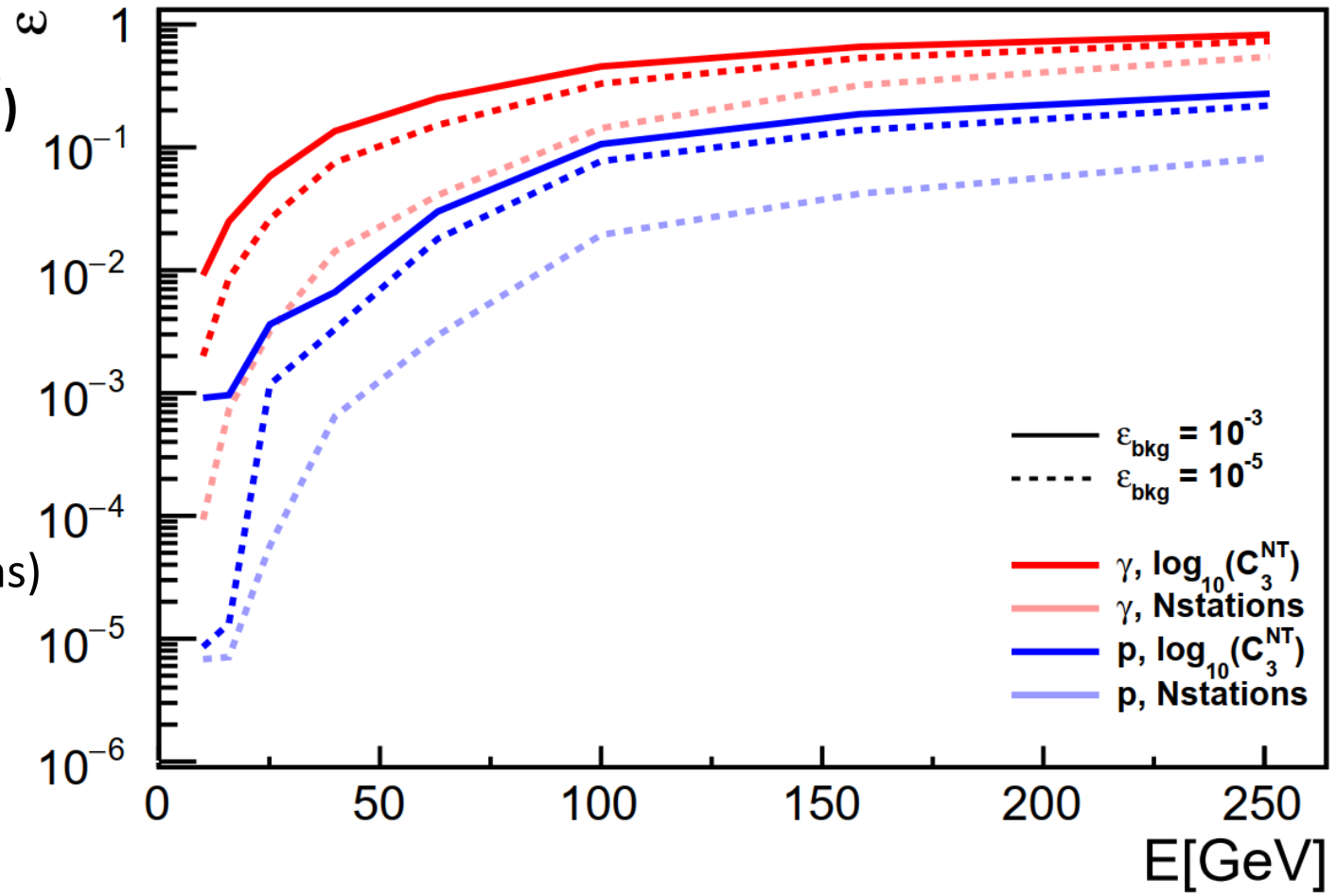
Trigger Efficiency

Define a cut in $\log(C_3^N)|_{max}$

- **C_3^N higher than threshold value (C_3^{NT}) triggers the event**
- C_3^{NT} determines atmospheric background rejection factors

For $\theta = 10°$ and $\varepsilon_{bkg} = 10^{-3}$, trigger efficiency of **20%** for gammas (protons) with energies of about **50 GeV** (150 GeV).

Trigger efficiencies as a function of shower energy (including atmospheric background)



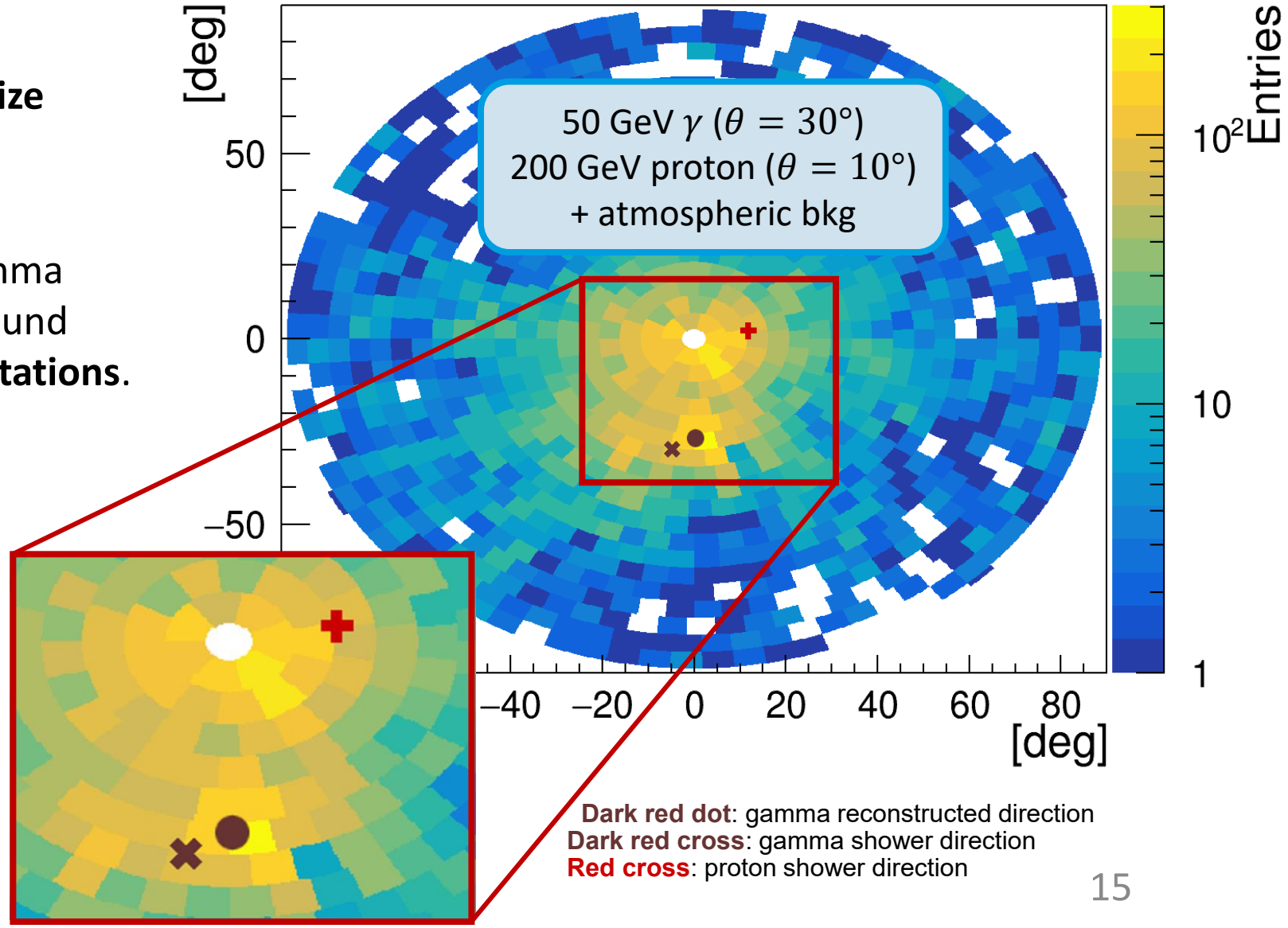
Alert Generation

Alerts sent to the **global network of Astrophysics Observatories**

- Stringent standards to **minimize false alerts**.

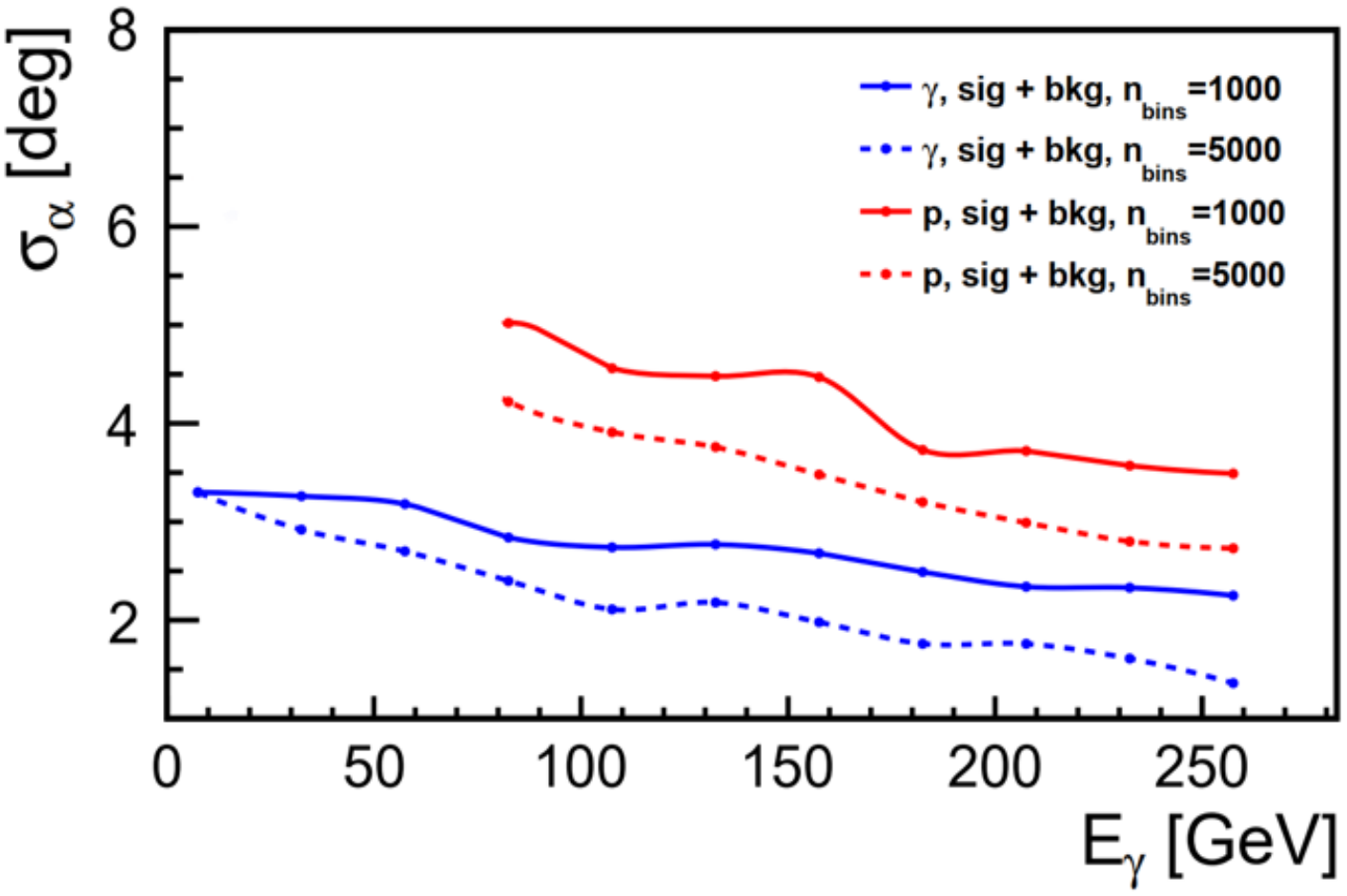
Angular accuracy maintained for gamma sources with **proton shower** background with **comparable number of active stations**.

- Proton showers with energy >100/200 GeV should not hinder gamma source alerts;
- **Gamma source** has **well-defined direction**; protons have erratic distribution.



Angular Resolution

Angular resolution as a function of shower energy



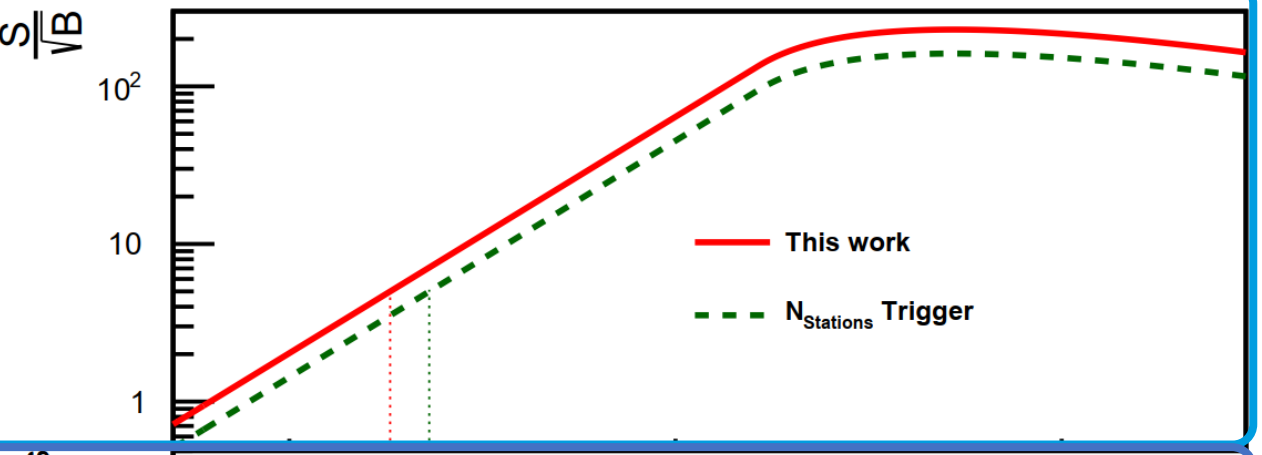
- **Angular accuracy:**
  $2° - 3°$ for **gammas** with energies as low as a **few tens of GeV**

- **Trigger flexibility:**
  Possibility of temporarily **downgrading** requirements to save events from region linked to **external alerts**.

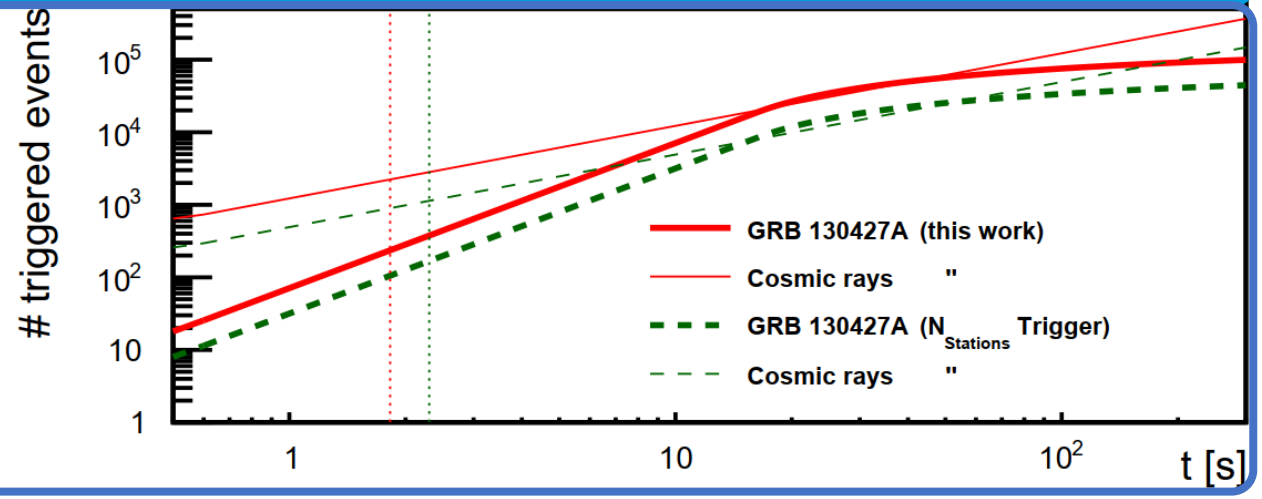
- **Alert issuance:**
  Based on pre-defined criteria for observed events from a region in the sky.

Alert Issuance Example

- Significance ($S/\sqrt{B}$) of signal from GRB 130427A[1] as a function of integrated time ($\varepsilon_{bkg} = 10^{-3}$)
  - **Vertical dashed lines** indicate time at which $\boldsymbol{S = 5\sqrt{B}}$.



- Integrated number of triggered events from cosmic rays and the GRB as a function of time
  - **Alert** could be issued after **less than 2 seconds**, with the accumulation of **over 100 counts**



[1]**Gamma-ray burst detection prospects for next generation ground-based VHE facilities**
G. La Mura et al., Mon. Not. Roy. Astron. Soc. 508(1), 671 (2021), DOI 10.1093/mnras/stab2544

Alert Issuance Example

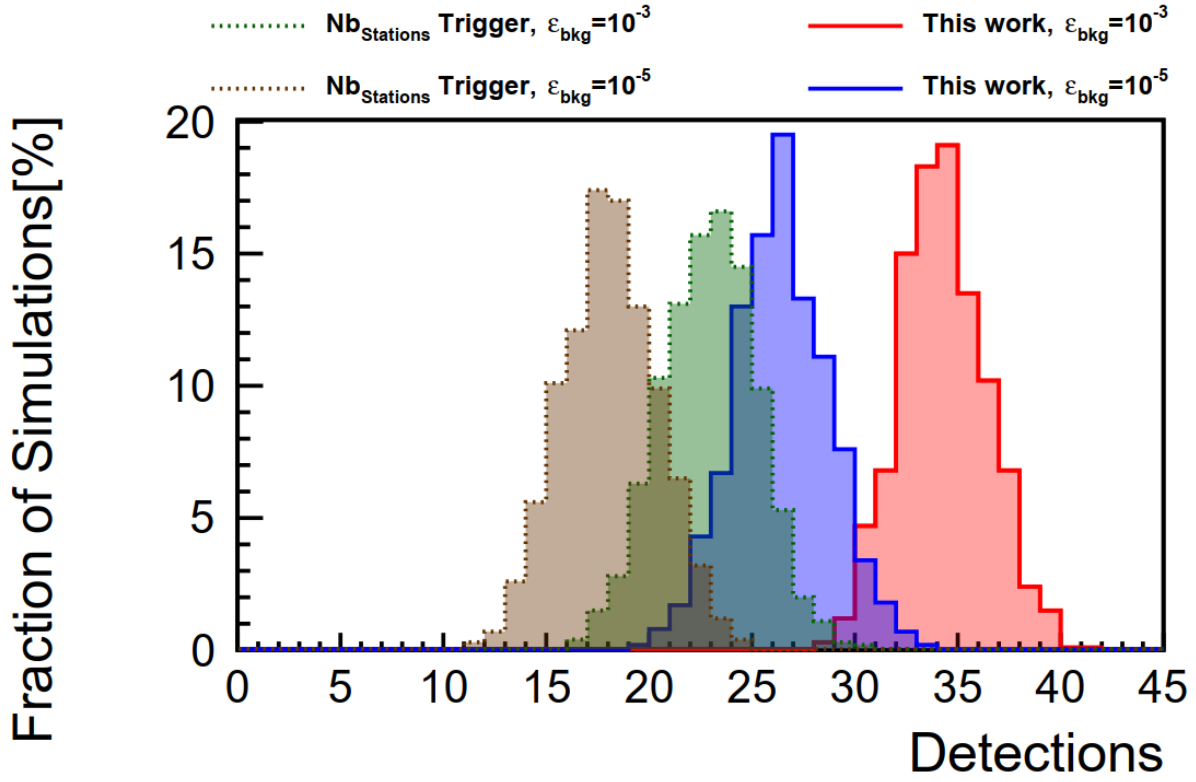
Detectable fraction of simulated gamma-ray bursts (GRBs) redshift distributions

- Based on 1000 random redshift distributions from 140 GRBs without measured redshifts[1] (observed by Fermi -LAT over 10 years)

Improvement in **expected number of detections**, ~50% of simulations predict:

Nb.Detections	$\varepsilon_{bkg} = 10^{-3}$	$\varepsilon_{bkg} = 10^{-5}$
New Trigger[2]	>34	>26
Nb.Stations Trigger	>23	>17

[2]energy threshold: E_{low} = 125 GeV



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Summary

- **Low-energy trigger strategy** shows strong potential for SWGO operation:
  - Energy thresholds down to **tens of GeV**
  - Background rejection factors of **10^3–10^5**
  - Angular resolution of **2°–3°** at trigger level

- Enables **continuous sky surveillance** and rapid alert dissemination:
  - Critical for detecting **transients** (GRBs, flares)
  - Improves statistics on **extended and diffuse sources**

- Article describing this work published in JCAP:
  - **Identification of low energy neutral and charged cosmic ray events in large wide field observatories**, L.Apolinário et al., *JCAP* 04 (2025) 029, DOI: 10.1088/1475-7516/2025/04/029

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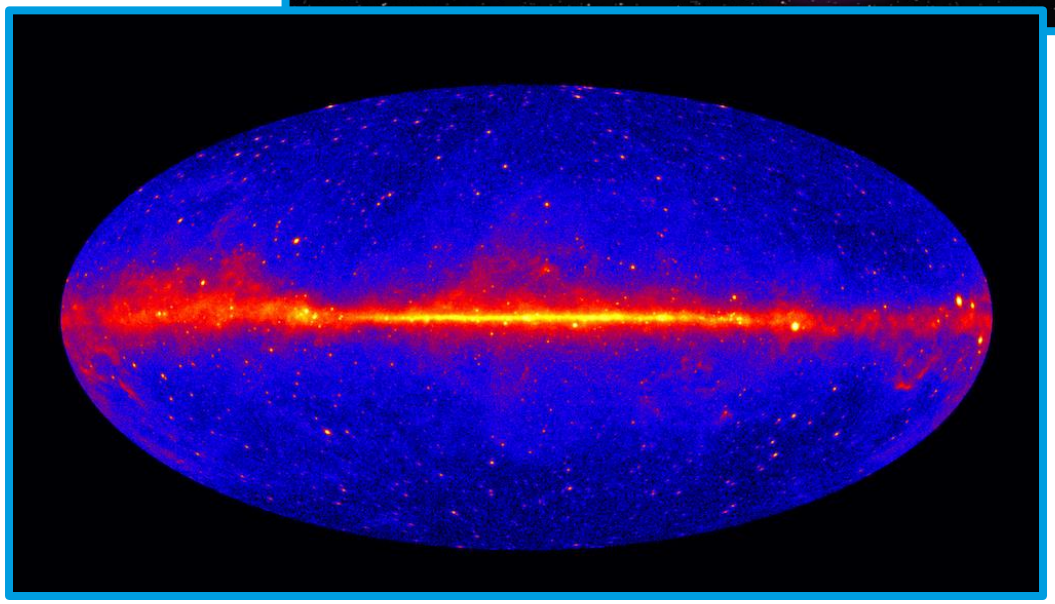
Backup Slides

Low Energy Trigger Motivation

- Low energy thresholds critical to collect reasonable statistics on:
  - **Transients** (e.g. VHE emission from GRBs and flares);
  - **Extended sources** (e.g. Fermi bubbles), and diffuse gamma emission.

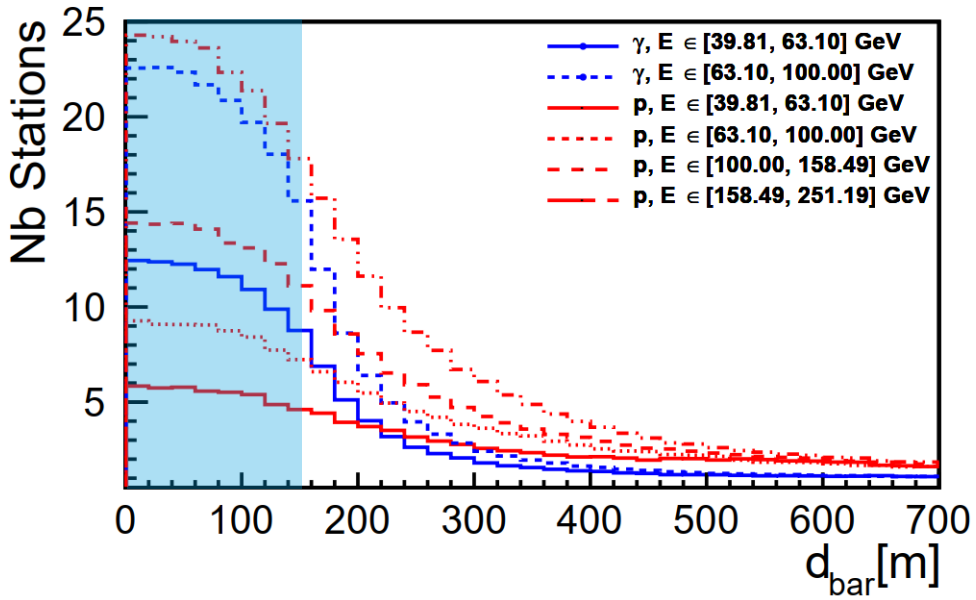
- Low energy trigger system needs rejection factors of the order of $\mathbf{10^3}$ - $\mathbf{10^5}$.

- Trigger strategy based on a small number of hit stations saturates Data Acquisition (DAQ) system.

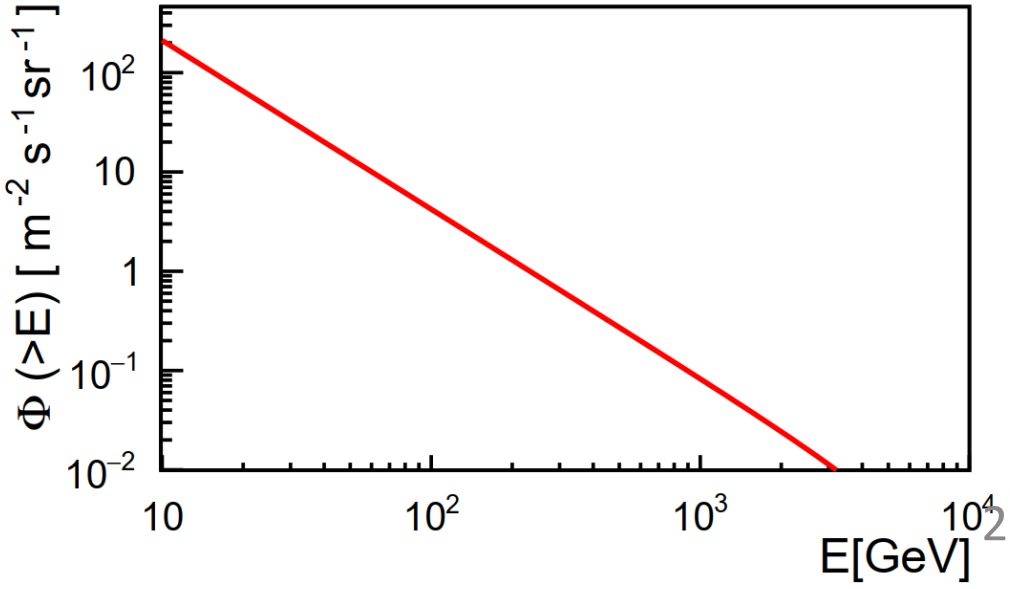


Signal, Background & Simulations

- If shower core located within the array ($\mathbf{d_{bar} \in [0, 150]m}$):
  - **Factor of 2-3 between energy values/bins with similar number of active stations and different primary particles:**
    - Proton $[100, 158]$GeV - gamma $[40, 63]$GeV
    - Proton $[158, 251]$GeV - gamma $[63, 100]$GeV



- Rate of charged cosmic-rays with $E > 100(200)$ GeV :
  - For a **field of view of 2 sr**, **$\sim$500(130) kHz**.
  - For 200 ns time window, **1 event with every 10(38) time windows**
  - Not a significant source of background for a source of continuous gamma emission

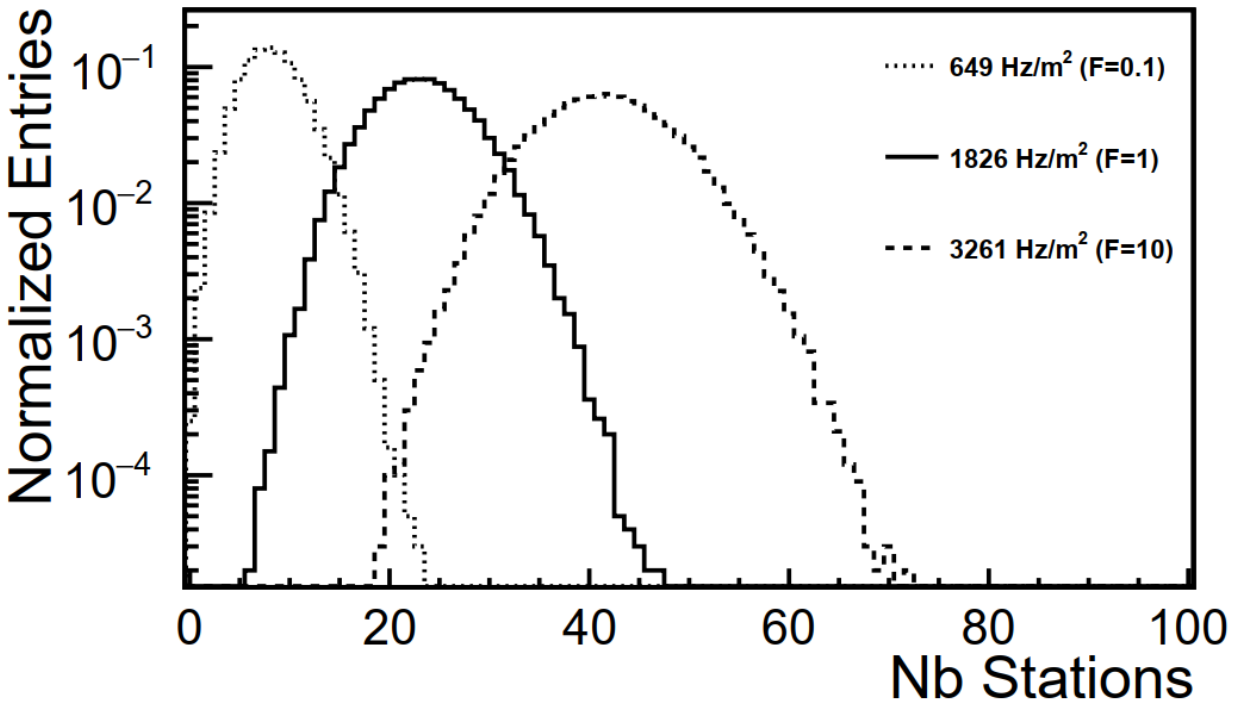


Signal, Background & Simulations

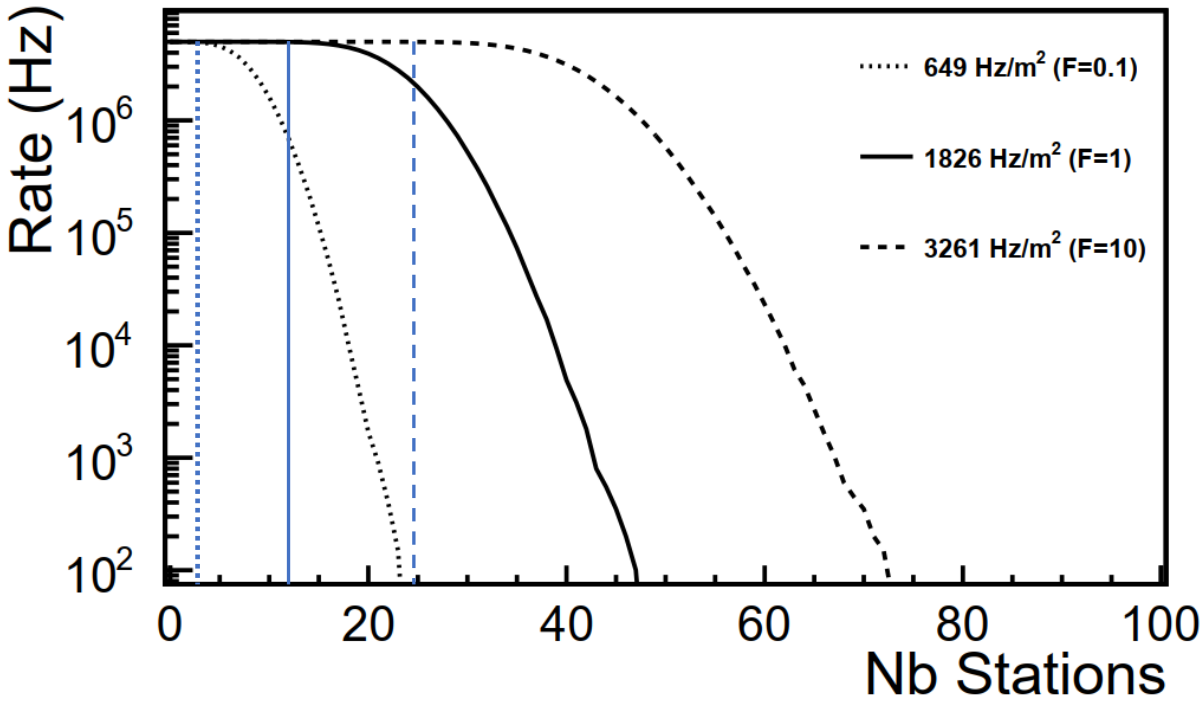
- Main source of background at high altitude: **atmospheric muons**
- Probability of a particle triggering a detector unit:

$$1-\exp(-F\,k\,E),\ \text{scale factor } F$$

- F **= 1**, mean number of background stations ~**23**;
  - Fluctuate number of background stations with Poisson distribution.



Number of **stations triggered by atmospheric muons in a 200 ns time window**



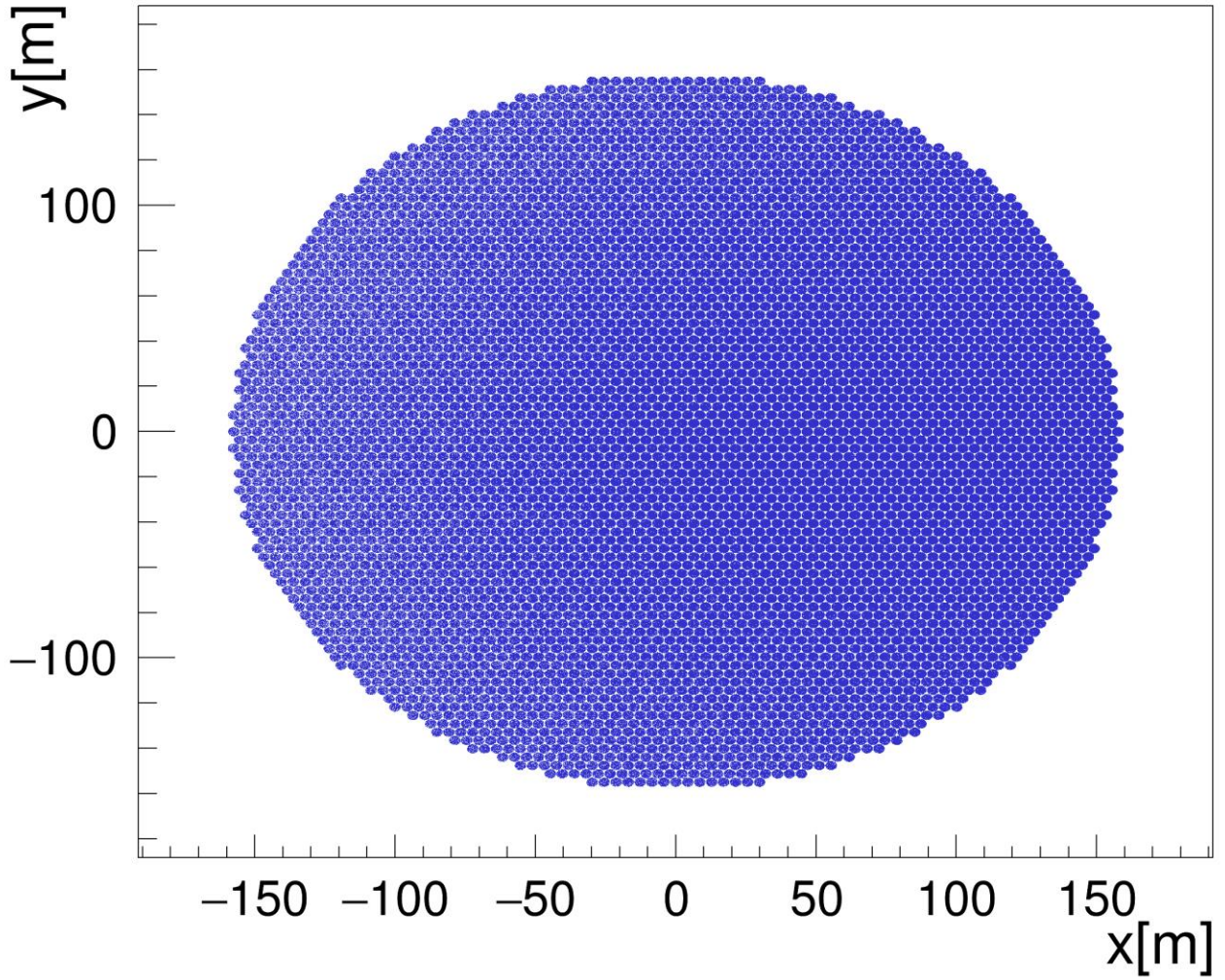
Trigger rate as a function of the threshold on **number of active stations. Point of saturation**

HAP-20-003 - *Impact of altitude and Cherenkov photon detection efficiency on the energy threshold of SWGO-like arrays* - W. Hofmann

Signal, Background & Simulations

- **Simulated events:**
  - **CORSIKA** (version 7.5600),
  - Altitude: 4.7 km;
  - Primary particles: proton, gamma;
  - $\theta = 10°$ ($\sim$25 000 files), $30°$($\sim$6000 files)
  - Energy spectrum E^{-1}, from $\sim$10 to 250 GeV
  - Values of ϕ follow uniform distribution
  - Low-energy hadronic interaction model: **FLUKA;**
  - High-energy hadronic interaction model: **QGSJet-II.04;**
  - Shower core position randomized uniformly within the array area multiple times per file;

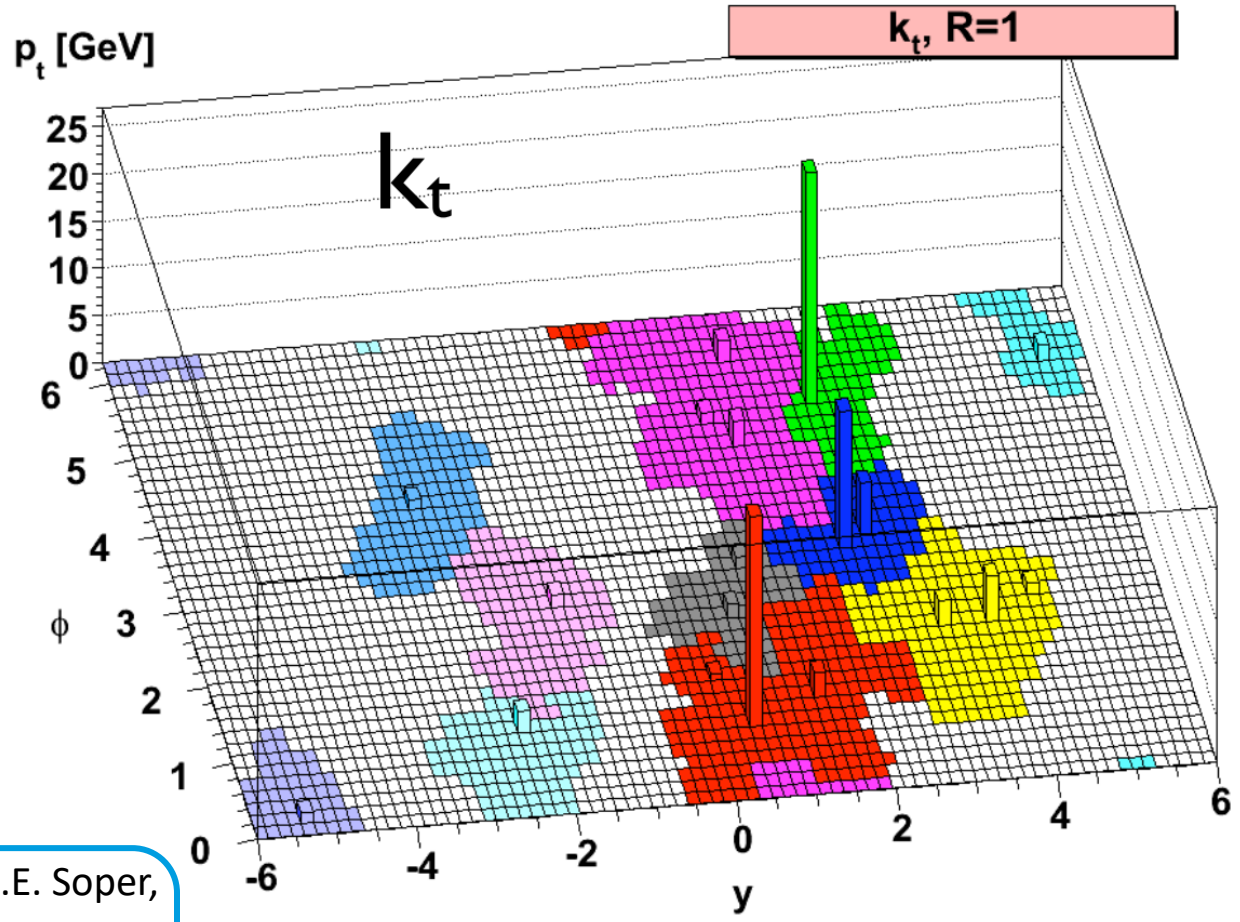
- **Detector configuration:**
  - Array area: $80\,000\ m^2$;
  - Fill factor: 80%;
  - Altitude: $5000\ m$;
  - Energy to signal parametrization from **single layer station** with **Mercedes configuration** (E1)



Improved Procedure

- Direction of normal vectors clustered into “jets” using a **QCD jet inspired algorithm**[1] to improve signal direction reconstruction

Example of application of jet clustering algorithm[2]
Clusters highlighted with different colours



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[2] ***The anti-kt jet clustering algorithm***, M. Cacciari et al, JHEP04(2008)063. DOI 10.1088/1126-6708/2008/04/063

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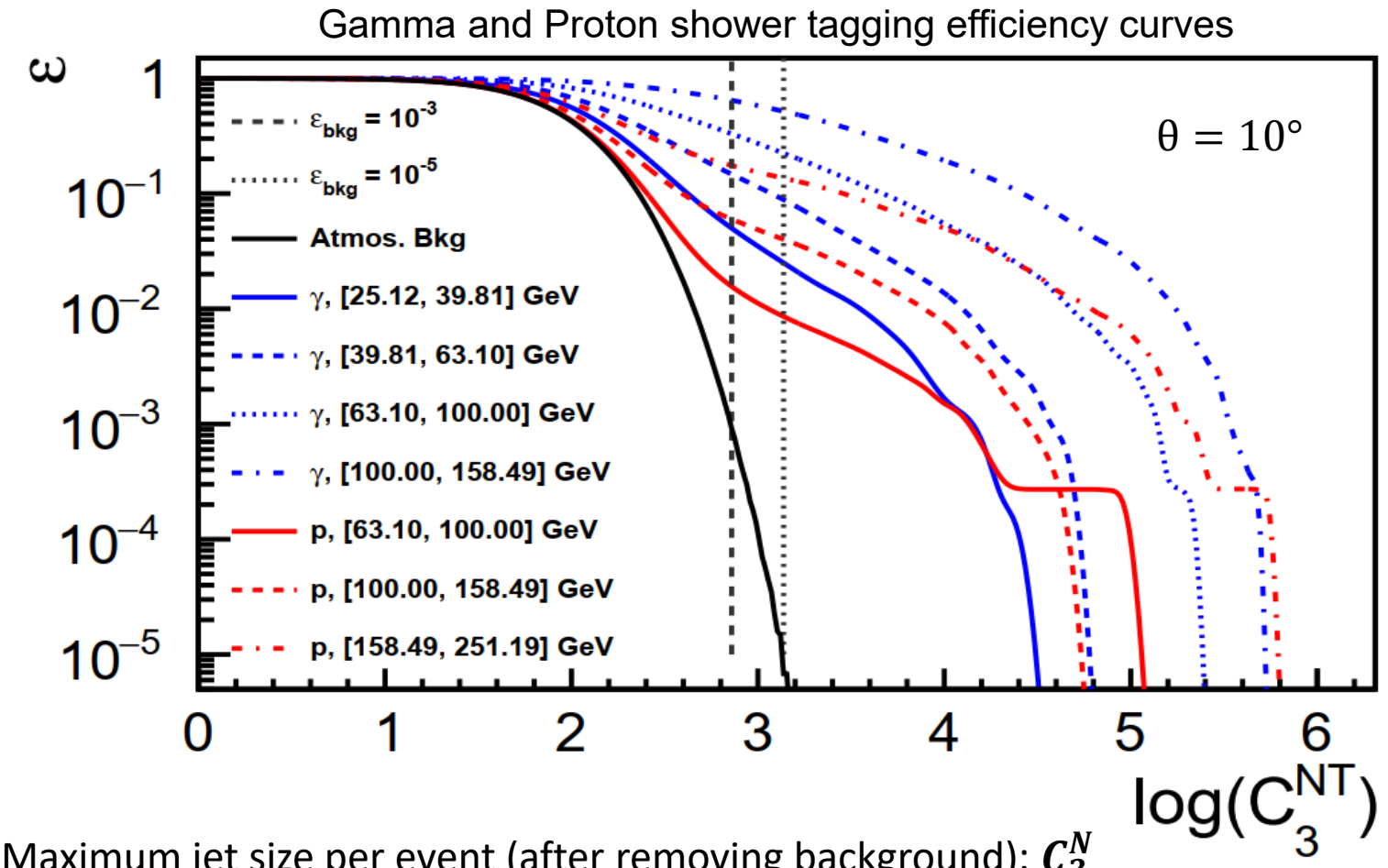
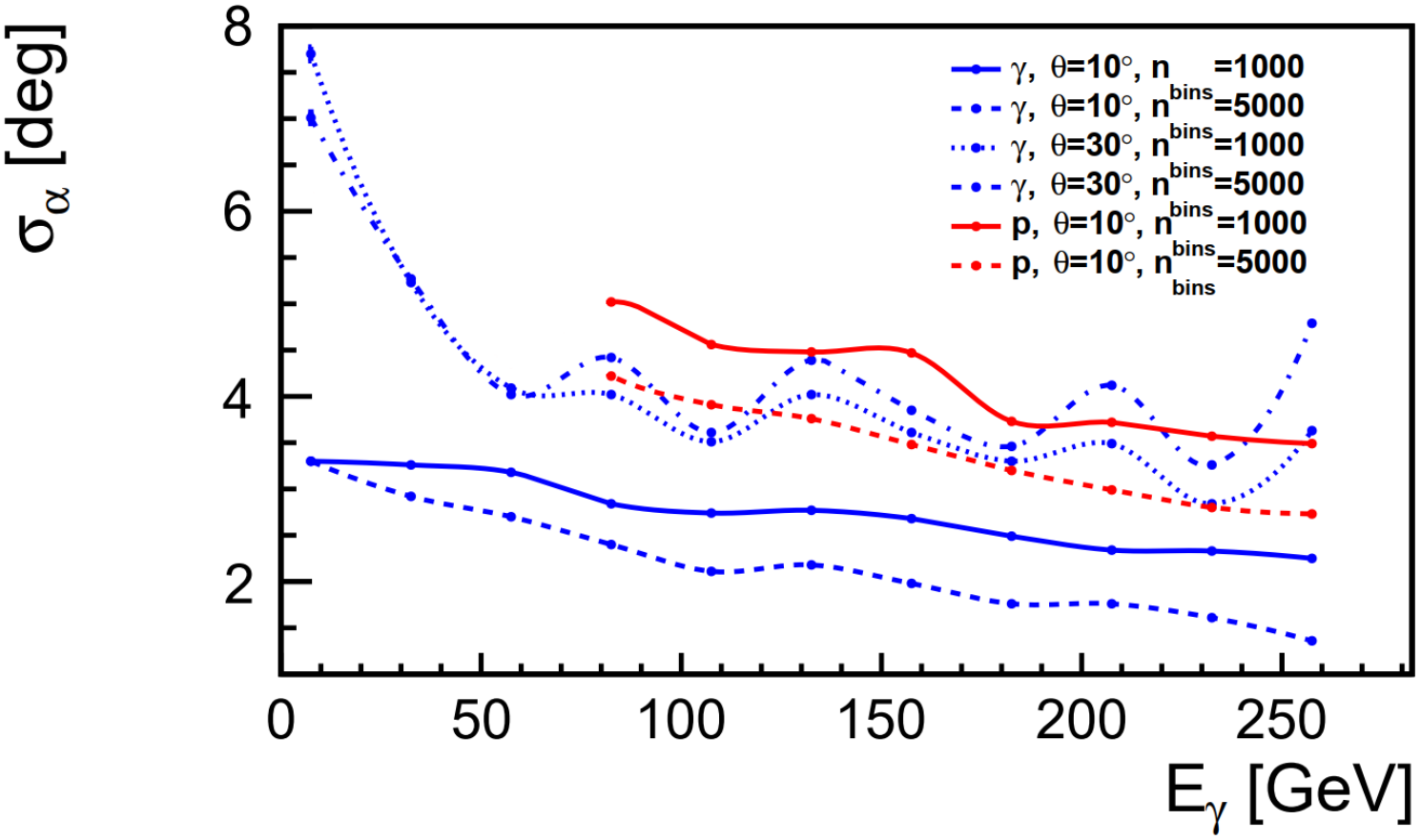


- Maximum jet size per event (after removing background): $\boldsymbol{C_3^N}$
  - Direction of jet taken as **reconstructed direction** of signal source
  - Content of cell corresponding to reconstructed direction (also accounting for background) taken as **event trigger variable,** in logarithmic form, $\boldsymbol{\log(C_3^N)|_{max}}$
  - Set a **threshold value ($\boldsymbol{C_3^{NT}}$)** above which an event is triggered

Signal, Background & Simulations

Angular resolution as a function of shower energy



- **Reasonably high angular accuracy** $(2° - 3°)$ for **gammas** with energies as low as a **few tens of GeV**
- Possibility of **downgrading trigger** requirements during a time period to save events from region corresponding to **an external alert**.
- Alerts should be issued based on pre-defined criteria for observed events from a region in the sky.