Swiss Physical Society Annual Meeting 2024, ETH Zürich

Indirect search for dark matter in γ-ray fluxes with DAMPE

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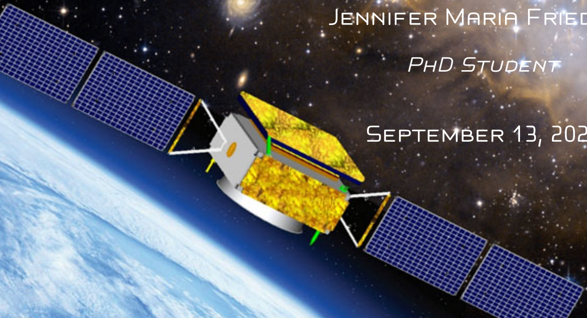


Motivation

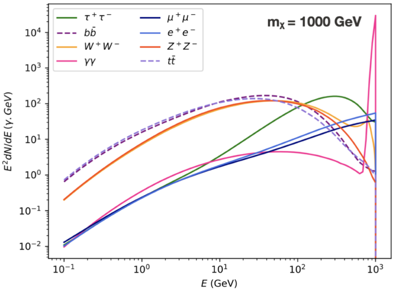
- Only **15.6%** of the matter in the universe consists of baryonic matter!
- Dark matter particles must be **massive**, **neutral** and **stable**
- Focus on neutralino (χ) annihilation: $\chi\chi \rightarrow X\gamma$, with $X = \gamma, Z$ or H

$\Longrightarrow E_\gamma = m_\chi \left(1 - \frac{m_X^2}{4m_\chi^2}\right)$, i.e. for $X = \gamma$, $E_\gamma = m_\chi$

- The neutralino annihilation leads to a monoenergetic γ-ray emission

  $\Longrightarrow$ observe a **narrow peak** in the γ-ray energy spectrum

- In particular, **nearby galaxy clusters** are used as target, such as: Centaurus, Coma, Virgo, Perseus, Fornax

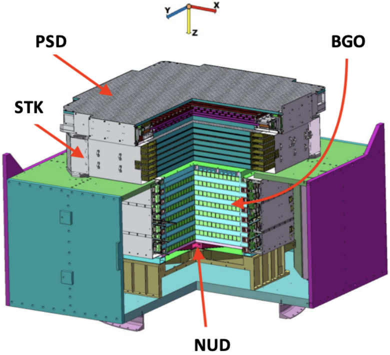


Plot: C. Armand, *Dark matter search program with CTA*, 12.01.2022

Introduction to the DAMPE experiment

The DArk Matter Particle Explorer

- Launched on 17th December 2015
- Measure cosmic-ray spectrum and composition, indirect search for DM signatures in e/γ spectra, HE γ-ray astronomy
- Consists of 4 subdetectors:
  - **P**lastic **S**cintillator **D**etector (**PSD**)
  - **S**ilicon-tungsten **T**rac**K**er-converter (**STK**)
  - **B**ismuth **G**ermanium **O**xide (**BGO**) calorimeter
  - **N**e**U**tron **D**etector (**NUD**)

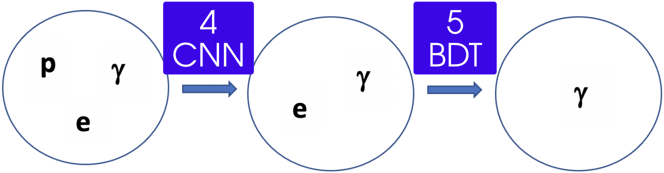


STK+PSD $\sim 1X_0$
BGO $\sim 31X_0$

Image: C. Perrina et al., *Performance of the DAMPE silicon-tungsten tracker-converter during the first 5 years of in-orbit operations*, 15-22th.07.2021

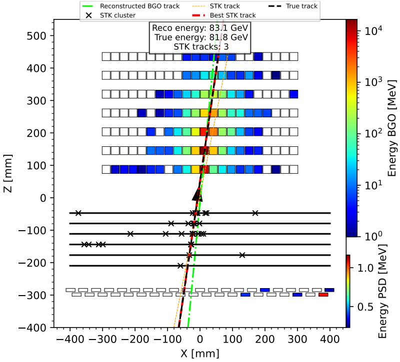
γ-ray selection

1. **Skim** and **fiducial** cuts: detector geometry and BGO segmentation
2. **STK track selection** among the track set given by the Kalman filter
3. **Cleaning cuts** based on the geometry and charge of the reco track
4. **Proton rejection:** using **CNN** developed for γ/p separation
5. **Electron rejection:** using the **BDT** developed for γ/e separation

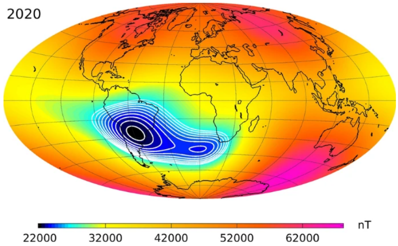


1. Skim and fiducial cuts

- **Skim cuts:**
  - Reconstructed energy $\geq$ 1 GeV
  - E.m. shower shape: $Ecore_3/E_{rec} \geq 0.9$
  - BGO track well contained in PSD



- **Fiducial cuts:**
  - SAA rejection & High Energy Trigger activation
  - At least 1 STK track that is well contained in PSD



*thanks to Parzival Nussbaum for the event display tool

2./3. STK γ-ray track selection & Cleaning cuts

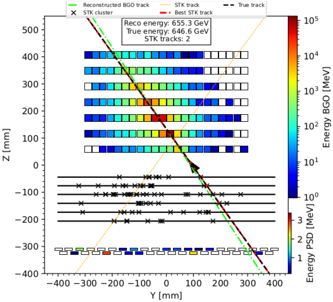
2 STK γ-ray track selection

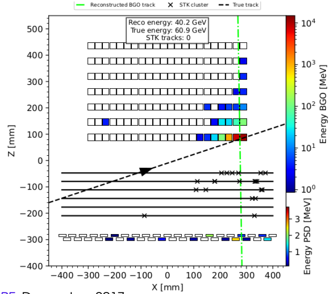
- Select best track among the set of STK tracks given by the Kalman filter (at least 3 aligned clusters)
- Define Track Quality (TQ) and take maximum value: [1]:

$$TQ = \frac{1 + E_r}{\ln(D_{sum}/mm)} \cdot \left(1 + \frac{N_{tr} - 3}{12}\right)$$

3 Cleaning cuts:

- Reject horizontal events entering the BGO
- Discard not well contained showers
- Reject high-charge events



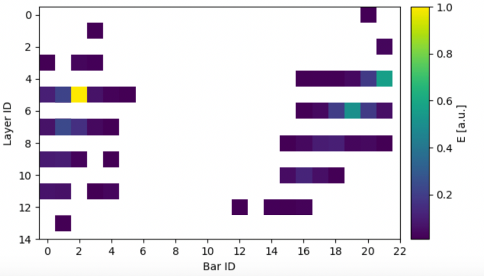


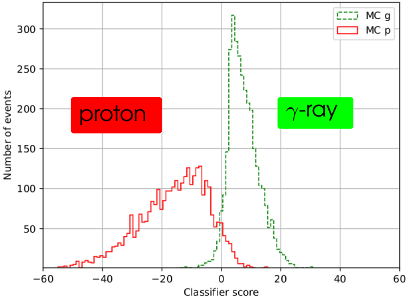
[1] Z. L. Xu et al. *An algorithm to resolve γ-rays from charged cosmic rays with DAMPE*, December 2017

4. Proton rejection

- **Proton** being the main component of cosmic rays
  $\Longrightarrow$ powerfull discrimination tool needed
- Use a CNN trained to classify γ and p showers in the BGO
- **Input:** BGO images, **Output:** score between -∞ and +∞

Input image: 14 layers $\times$ 22 bars
$\Longrightarrow$ 14 $\times$ 22 pixel image



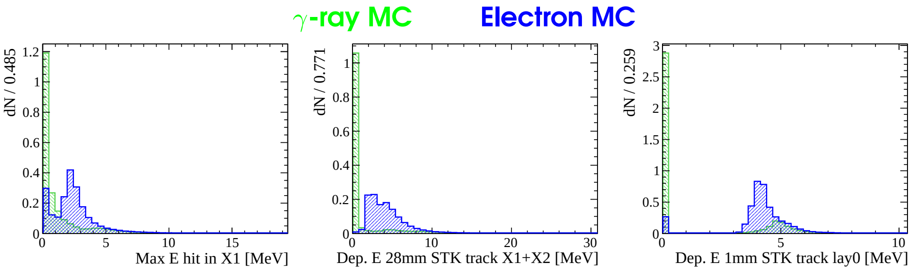


$\Longrightarrow$ **Applied cut : CNN score > 0**

*thanks to Loïs Niggli for the development and training of this CNN

5. Electron rejection: BDT input variables

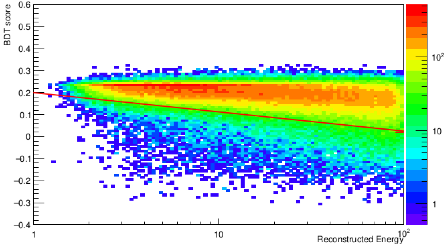
- Can be distinguished **before** γ-ray conversion
  $\Longrightarrow$ in the **PSD** and the first 2 layers of **STK**
- A total of **22 variables** have been chosen to train the **BDT** (14 in PSD and 8 in STK)
- The behaviour of γ-rays varies a lot with energy E
  $\Longrightarrow$ **3 BDTs** for 3 different E ranges have been trained



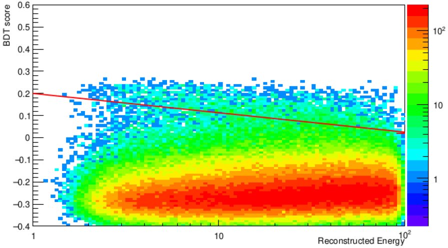
5. Electron rejection: BDT score cut

- As γ-ray flux follows a decreasing power law, an **energy dependant cut** is more efficient than a rectangular cut
- BDT score as a function of the reconstructed energy

MC Gamma



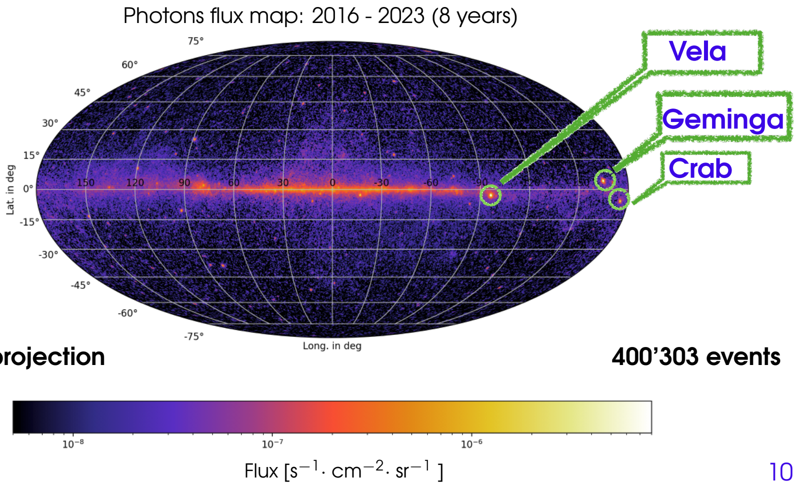
MC Electron



- **1 - 100 GeV:** BDT > 0.2 - 0.038 · log(E_{rec}) AND BDT > 0.02
- **0.1 - 1 TeV:** BDT > 0.1 - 0.06 · log(0.01*E_{rec}) AND BDT > -0.06
- **1 - 10 TeV:** BDT > 0.05 - 0.05 · log(0.001*E_{rec}) AND BDT > -0.03

Photon flux map

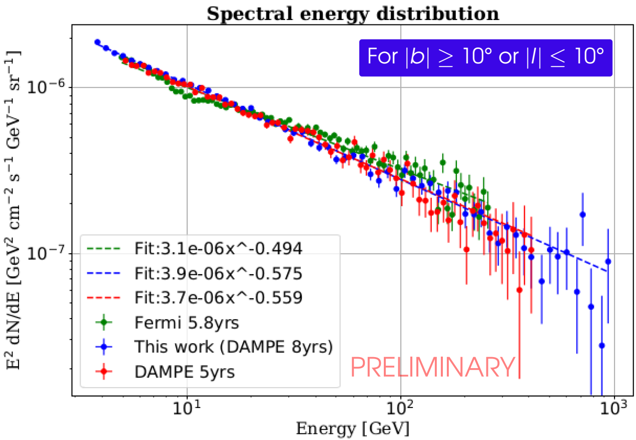
- Selected events in galactic coordinates for 8 years of flight data (2016-2023) with $E_{rec} \in [1, 10^4]$ GeV



Mollweide projection **400'303 events**

Spectral Energy Distribution (SED)

- The Spectral Energy Distribution (SED) is defined as: $E^2 \cdot \frac{N_\gamma}{\Delta E} \frac{1}{T \cdot A_{\text{geom}} \cdot \epsilon_\gamma}$

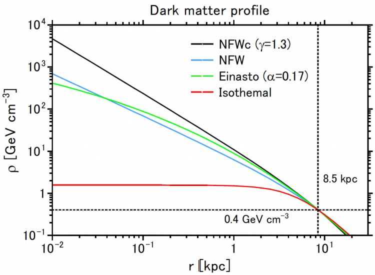


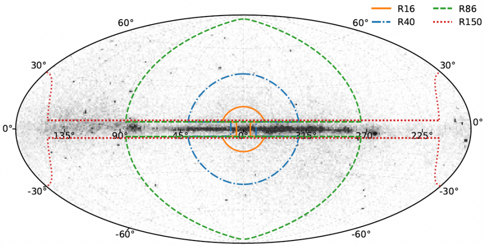
[1] F. Alemanno et al. *Search for gamma-ray spectral lines with the DArk Matter Particle Explorer* , April 2022

[2] M. Ackermann et al. *Fermi LAT Search for Dark Matter in Gamma-ray Linesand the Inclusive Photon Spectrum* , May 2012

Search for DM line signatures

- The cosmic γ rays consists of common produced γ-rays and **DM produced** γ-rays
- DM halo is associated with our Galaxy and distributes spherically
- Different **DM density profiles** ρ exist that are optimised for different **Regions Of Interests (ROIs)**

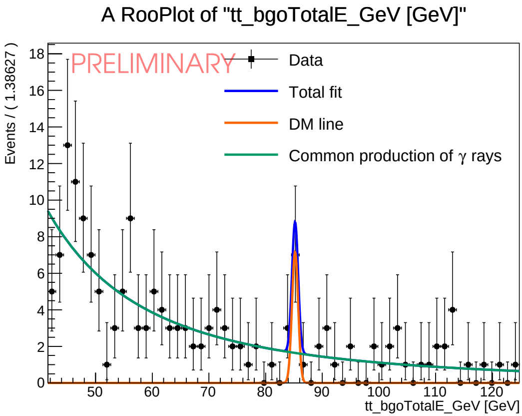




$\Longrightarrow$ the Einasto profile is treated in this work for R16

Search for DM line signatures

- A sliding energy window technique is used to estimate the number of γ-rays produced by DM annihilation in R16



The total fit consists of:

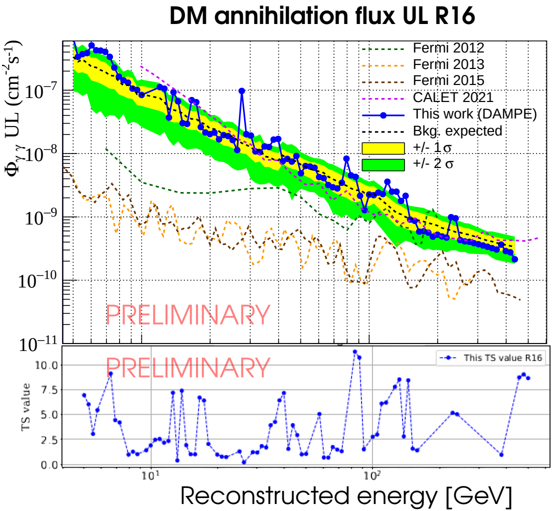
Common production of γ rays modeled as a power law

DM line modeled as a gaussian distribution

$\Longrightarrow$ Did we discovered DM?

Search for DM line signatures

- The **Test Statistics (TS)** shows no significant discovery of DM line in R16 and therefore an **upper limit** is set on the γ-ray flux in this ROI



$$TS = -2 \ln \frac{\hat{L}_{null}}{\hat{L}_{sig}}$$

$\hat{L}_{null}$ being the max. likelihood for the null hypothesis

$\hat{L}_{sig}$ being the max. likelihood for the DM line hypothesis

Summary and outlooks

- **Summary:**
  - An **efficient γ-ray selection algorithm** was developed using **ML tools** and the SED is in agreement with other published results
  - The DM annihilation-induced γ-ray flux was evaluated in the R16 ROI and **no significant line** has been observed

    $\Longrightarrow$ an **upper limit** was set on the DM annihilation-induced γ-ray flux
- **Outlook:**
  - **More ROIs** and especially **targets** will be considered for DM line searches
  - From the flux upper limit, the **speed-averaged cross section of DM annihilation** will be constraint under the assumptions of each ROI
  - Future space experiments are developed to increase the acceptance of γ-ray events, for ex. HERD $\Longrightarrow$ see next talk by *Dr Chiara Perrina*


Thank you for your attention!

Backup slides

2. STK photon track selection

- `STKKalmanFilter` returns a set of tracks that have at least 3 aligned clusters in STK
- If more than 1 STK track, choose the one with the highest **quality**
- Track Quality (TQ) definition [1]:

$$TQ = \frac{1 + E_r}{\ln(D_{sum}/mm)} \cdot \left(1 + \frac{N_{tr} - 3}{12}\right)$$

  - E_r: Ratio of energy deposited in a 5 mm cylinder around the considered track in STK and the total energy deposited in STK
  - D_{sum}: Distance between the STK track and the center of mass energy deposit in the 4 first BGO layers
  - N_{tr}: Number of STK clusters used for the track reconstruction

[1] Z. L. Xu et al. *An algorithm to resolve γ-rays from charged cosmic rays with DAMPE*, December 2017

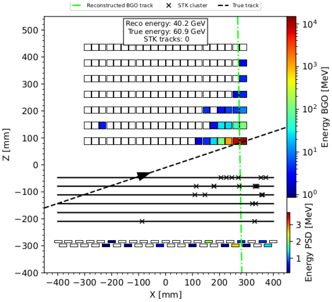
3. Cleaning cuts

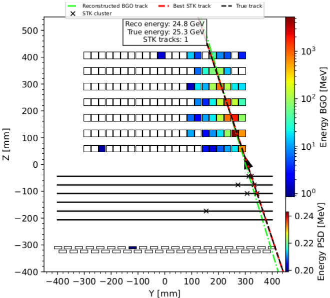
- Horizontal events entering the BGO:
  - $E_{lay1}/E_{reco} < 40\ \%$
  - $E_{lay2}/E_{reco} < 50\ \%$
- Discard not well contained showers:

  $\Longrightarrow$ $|\texttt{ProjSTK\_track\_Xi}| < 400$ mm for i= 1,2 and same for Y
- Reject high-charge events:

  $\Longrightarrow$ sum of E deposited in the 4 PSD bars (2X & 2Y) is lower than 80% E_{reco}

  $\Longrightarrow$ Number of hits in PSD is maximum 1.8 x E_{reco}





5. Electron rejection: BDT input variables

Input variables:

PSD

- The 4 maximum energy deposits in the 4 PSD layers (X1, X2, Y1, Y2): **4 variables**
- Sum of the distances between the STK track and the closest PSD hit in X1 and X2: **1 variable**
  Same for Y: **1 variable**
- Total charge on the X layers of PSD: **1 variable** Same for Y: **1 variable**
- Sum of deposited energy in PSD bars in 28 mm, 42 mm, 56 mm, around the STK track in X1 and X2: **3 variables** Same for Y: **3 variables**

STK

- Energy deposited in 1st STK X layer in distances 0.2 mm, 1.0 mm, 5.0 mm, 10.0 mm around STK track: **4 variables**
  Same for 1st STK Y layer: **4 variables**

Number of variables: 22

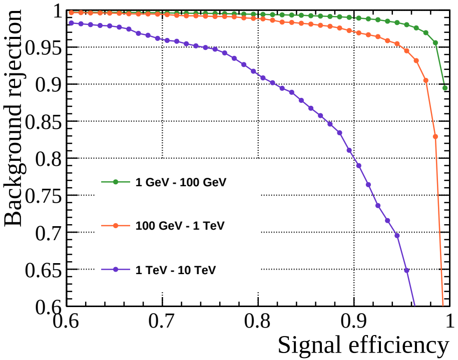
Training:

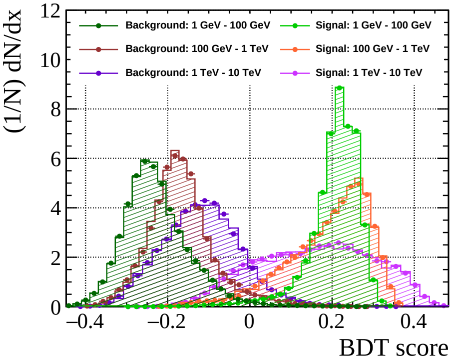
3 different BDTs for

3 different E_{rec} ranges

5. Electron rejection: BDT training

- The results of the training of the 3 different energy ranges showed that the higher the energy, the more difficult is the separation between γ/e





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- BDT score as a function of the reconstructed energy

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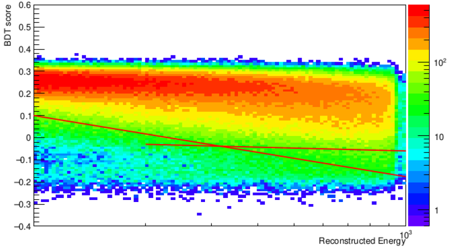
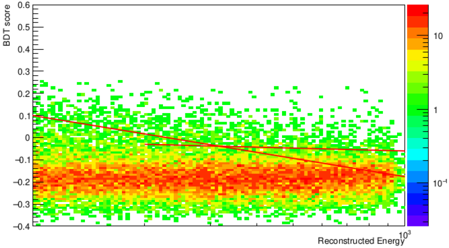


MC Electron



- **0.1 - 1 TeV:** BDT > 0.1 - 0.06 · log(0.01*E_{rec}) AND BDT > -0.06

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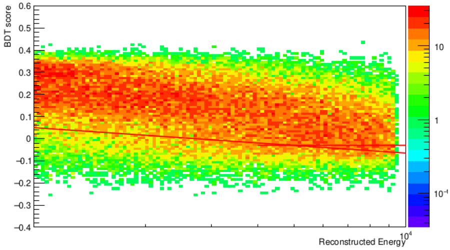

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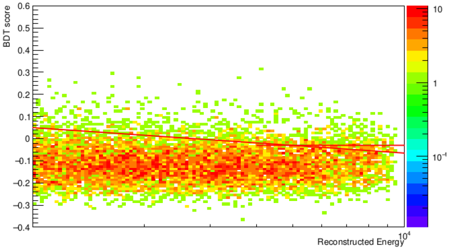

- **1 - 10 TeV:** BDT > 0.05 - 0.05 $\cdot$ log(0.001*E_{rec}) AND BDT > -0.03