Reconstruction Software of the Silicon Tracker of DAMPE

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Outline

• Introduction: DAMPE mission
• Track reconstruction software: combined-2D vs 3D
• Implementation of detector geometry: CAD-2-GDML
• Alignment of tracker: method of varying-$\chi^2$
DAMPE mission

DAMPE is designed to detect

5 GeV to 10 TeV e/γ

50 GeV - 100 TeV protons and nuclei

with excellent energy resolution, tracking precision and particle identification capabilities

- Plastic scintillator (anti-coincidence unit)
- Silicon tracker
  6.6 m² of silicon sensors
- BGO calorimeter
  32 radiation lengths
- Neutron Detector

Andrii Tykhonov

Reconstruction software of DAMPE mission
DAMPE successfully launched on December 17, 2015

Jiuquan Satellite Launch Center
Gobi desert, China
Steps of the track reconstruction

• Seeding
• Propagation (Kalman filter)
• Removal of ghost and duplicates
• **Track seeds:**
  1. Direction from calorimeter (Calorimeter-seed) - baseline
  2. Blind seeds (on-ground tests only)

• **Calorimeter seed:**
  • $x$ and $y$ track candidates are reconstructed separately (Kalman filter)
  • Combined $xy$ tracks are refitted again with Kalman algorithm
Particle track reconstruction in DAMPE

• Iterative track reconstruction:
  • If a good track is found - first hit in is removed from “seeding points”
  • Track-finding repeated until all seeding points are exhausted

• Reconstructing tracks in XZ and YZ is \(O(100)\) faster than 3D reconstruction

• Allows to remove per-event limit of maximum number of iterations

10 % higher efficiency in finding the best possible track in event
DAMPE geometry implementation: CAD-2-GDML

- GEANT4 geometry model of DAMPE is obtained as GDML from CAD drawings using an in-house conversion tool:
  
  https://github.com/tihonav/cad-to-geant4-converter

- The same GDML geometry is used in the reconstruction

- Supporting structures are included

Files in STL format (tessellated solids) from CAD are used to convert into GEANT4 geometry
CAD-2-GDML converter

https://github.com/tihonav/cad-to-geant4-converter

- A standalone python tool
- Does not require GEANT4 or any other additional software
- Based on conversion of CAD into meshed (tessellated) objects
- Base set of materials implemented, should be easy to extend further

... possible application for ATLAS IBL is now being investigated, in particular could aid simulations used for B-tagging
CAD-2-GDML: performance tests

DAMPE GDML geometry:

- ~ 50 MB total
- ~ 150k vertices

<table>
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<tr>
<th>Protons:</th>
<th>Tessellated [s/event]</th>
<th>Simple Geometry [s/event]</th>
<th>Factor</th>
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<td>0.085</td>
<td>5.5</td>
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<td>2.6</td>
<td>0.61</td>
<td>4.2</td>
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<tr>
<td>10-1000 GeV</td>
<td>24.9</td>
<td>4.8</td>
<td>5.2</td>
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<table>
<thead>
<tr>
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<th>Simple Geometry [s/event]</th>
<th>Factor</th>
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<td>0.14</td>
<td>8.7</td>
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<tr>
<td>10-100 GeV</td>
<td>8.9</td>
<td>1.16</td>
<td>7.7</td>
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<tr>
<td>10-1000 GeV</td>
<td>88.9</td>
<td>13.22</td>
<td>6.7</td>
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</tbody>
</table>

For comparison, simple geometry was used - only sensitive volumes (defined as simple boxes)
Silicon Tracker of DAMPE

Tracker:
- 6 tracking double layers (x and y measurement)
- 768 total silicon sensors (SSD), 9.5 x 9.5 cm
- 121 μm silicon-strip pitch
- Every 2nd strip is read-out
- Total active area ~ 6.6 m²
- Expected position resolution: ~40 micron
Alignment of DAMPE Silicon Tracker

Track-hit residue VS track coordinate for one of the STK layers:

Position resolution of silicon sensors ~ 40 μm

Assembly precision ~ 100 μm

Precise alignment is crucial in order to fully exploit angular resolution of the instrument
Alignment of DAMPE Silicon Tracker: method

- 5 (2 offsets, 3 rotations) alignment parameters assigned to each silicon sensor = \(768 \times 5 = 3840\) alignment parameters
Alignment of DAMPE Silicon Tracker: method

Aligned track coordinates

Non-aligned track coordinates

\[
\begin{align*}
  x_a &= x + \Delta x - y \cdot \theta_z \\
  y_a &= y + \Delta y + x \cdot \theta_z \\
  z_a &= z + \Delta z - x \cdot \theta_y + y \cdot \theta_x
\end{align*}
\]

Alignment is based on minimisation of \( \chi^2 \) of tracks in the alignment data sample:

\[
\chi^2 = \sum_{t \in \{ \text{tracks} \}} \left( \sum_{p \in \{ \text{points} \}} \left( \frac{\left( x_{t,p}^{\text{fit}} - x_{t,p}^{\text{hit}} \right)^2}{N_{x \text{tracks},s}} + \sum_{p \in \{ \text{points} \}} \frac{\left( y_{t,p}^{\text{fit}} - y_{t,p}^{\text{hit}} \right)^2}{N_{y \text{tracks},s}} \right) \right),
\]

\[s = \text{sensor}\|\text{id}(t, p)\]
Alignment of DAMPE Silicon Tracker: method

- $\chi^2$ is affected by the noise (mis-reconstructed track hits, multiple scattering) - imposes limitations on precision of alignment

- To reduce noise contribution to $\chi^2$, at each iteration of algorithm, we use only those tracks that pass residue cuts for the hits - this implies that $\chi^2$ evaluation sample changes from one iteration to another

Figure 4: Development of the deviation of the residual mean at each iteration of the alignment correction. The deviation is defined as the RMS of the residual mean distribution for 768 silicon sensors of the tracker. Two methods are illustrated, the one shown on the left uses fixed track sample to perform the alignment and is performed first; the one on the right is performed afterwards and uses a variable track sample, as described in Section 5.3.
Alignment of DAMPE Silicon Tracker: method

- Optimisation of $\chi^2$ is not a merely minimisation any more (in some iteration $\chi^2$ can also increase )

- Instead, optimisation is performed by moving in a phase space of alignment parameters in the direction opposite to derivatives vector, until the modulus of this vector become small enough

![Graph showing position resolution at this iteration/baseline position resolution vs iteration of alignment algorithm for different ranges of $\theta$.]
Alignment of DAMPE Silicon Tracker: results

The method of varying-\(\chi^2\) improves quality of alignment and as a result - position resolution.

Alignment: fixed \(\chi^2\)

Alignment: variable \(\chi^2\)

Effective resolution (\(\mu m\))

Track inclination (deg)
Alignment of DAMPE Silicon Tracker: results

Good agreement is achieved between position resolution in the aligned and ideal (Simulation) model.

Figure 8: Effective position resolution for $x$- and $y$-plane so that tracker, estimated as RMS of double-Gaussian fit to the track residue (five point fit to the sixth plane). For non-aligned model residue can not be fit with simple formula, so the effective resolution is estimated as RMS of residue in the region $0.25; 0.25$ mm.
• DAMPE is powerful high-energy particle detector satellite mission, successfully launched in the end of 2015

• Tracking detector consist of about 6.6 m² of silicon-strip sensors.

• Track finding is done separately in XZ and YZ with Kalman filter, then tracks are combined in 3D and Kalman-refitted again.

• Geometry of the detector is implemented through CAD-2-GDML converter; the same geometry is used in both simulation and reconstruction.

• Alignment of tracker is done using the technique which employs varying $X^2$ sample, outperforming the standard minimisation of $X^2$. 
Thank you!

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Spare slides
Alignment as a function of time
Change of position resolution (fixed alignment)
Change of position resolution (**realigned**)

- $0^\circ < \Theta < 10^\circ$
- $10^\circ < \Theta < 20^\circ$
- $20^\circ < \Theta < 30^\circ$
- $30^\circ < \Theta < 40^\circ$
- $40^\circ < \Theta < 50^\circ$
- $\Theta_x > 50^\circ$
- $10^\circ < \Theta < 20^\circ$
- $20^\circ < \Theta < 30^\circ$
- $30^\circ < \Theta < 40^\circ$
- $40^\circ < \Theta < 50^\circ$
- $\Theta_y > 50^\circ$
Alignment as a function of time

Date

Position change (m)

Temperature (deg)

0 y tray7
0 x tray6
1 y tray6
1 x tray5
2 y tray5
2 x tray4
3 y tray4
3 x tray3
4 y tray3
4 x tray2
5 y tray2
5 x tray1

Temperature

Jan-01 Jan-31 Mar-01 Mar-31 Apr-30 May-30 Jun-29 Jul-29 Aug-28
Comparison with AMS-02 and FERMI

<table>
<thead>
<tr>
<th>Comparison</th>
<th>DAMPE</th>
<th>AMS-02</th>
<th>Fermi LAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>e/γ Energy res.@100 GeV (%)</td>
<td>1.5</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>e/γ Angular res.@100 GeV (°)</td>
<td>0.1</td>
<td>0.3</td>
<td>0.1</td>
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<tr>
<td>e/p discrimination</td>
<td>$10^5$</td>
<td>$10^5 - 10^6$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>Calorimeter thickness ($X_0$)</td>
<td>32</td>
<td>17</td>
<td>8.6</td>
</tr>
<tr>
<td>Geometrical accep. (m$^2$sr)</td>
<td>0.29</td>
<td>0.09</td>
<td>1</td>
</tr>
</tbody>
</table>

Mass: 1400 Kg  
Power: ~ 400 W  
Livetime: > 3 years
The DAMPE satellite

**PSD**: double layer of scintillating strip detector acting as anti-coincidence unit

**STK**: 6 tracking double layers of Silicon-Strip Detectors (SSD) + 3 mm tungsten plates (used for photon conversion)

**BGO**: the calorimeter made of 308 Bismuth-Germanium-Oxide bars in hodoscopic arrangement (~32 radiation length). Performs both energy measurements and trigger

**NUD**: boron-doped plastic scintillator - complementary to the BGO by measuring the thermal neutron shower activity
The Physics Goals of the DAMPE mission

- Study of the cosmic electron and photon spectra
- Study of cosmic ray protons and nuclei: spectrum and composition
- High-energy gamma ray astronomy: AGN, Pulsars, GRBs, …
- Search for dark matter signatures in electron spectra