CMS Timing

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Searches for long-lived particles at the LHC: Second workshop of the LHC LLP Community
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Upgrade of electromagnetic calorimeters

Barrel: New electronics, lower temperature
- Shorter pulse shaping
- Increased sampling rate 40 MHz→160 MHz
- Noise term in timing resolution improves ×5
- Expect photon timing of ∼ 30 ps for $p = 20$ GeV at the beginning of HL-LHC

Endcap: new calorimeter, HGCal
- Excellent intrinsic timing resolution for Si sensors for high amplitude signals
- Design to achieve ∼ 50 ps resolution per layer in EM showers
- Multiple layers can be combined within a shower for better resolution
- Hadrons with sufficient high energy give good timing resolution

Timing resolution for photons of 20-30 GeV is 30 ps
MIP timing detector (MTD)

- A thin LYSO+SiPM layer in the barrel, LGAD layer in the endcap
- Just outside the tracker, coverage $|\eta| < 3.0$, tracks with $p_T > 0.7$ GeV
- Converted photons (25% of photons in the barrel)
- **Timing resolution $\sim 30$ ps, almost full efficiency**
Primary and Secondary vertex position and timing

- Each track has timing measurement at the MTD: $t_1, t_2, \ldots$
- Calculate time of flight from the vertex position to MTD for each track, taking into account trajectory length, momentum etc.
- Timing of a track $i$ at the vertex is $t_i - \text{ToF}_i$
- Timing of all tracks at the vertex should converge to the same value: $T_P$ or $T_S$. Good constrain against background.
- Each vertex has both position and time measurement → 4D vertex, $(\vec{X}_P, T_P)$ or $(\vec{X}_S, T_S)$
Reconstruction of LLP decaying into visible(s) + invisible

- Invisible particle \((M_P, \vec{P}_p)\)
  - travels from primary vertex with measured coordinates and time \((\vec{X}_0, T_0)\)
  - and decays at secondary vertex with measured coordinates and time \((\vec{X}_v, T_v)\)
  - into a visible particle(s) with measured combined mass and momentum \((M_V, \vec{P}_V)\) (no need to be a resonance)
  - and an invisible particle \((M_I, \vec{P}_I)\)

Precision timing gives \(\vec{\beta}\) of LLP

\[
\vec{\beta}_P^{LAB} = \frac{1}{c} \cdot \frac{\vec{D}}{T_v - T_0} = \frac{\vec{P}_P^{LAB}}{E_P^{LAB}}
\]
Reconstruction of LLP decaying into visible(s) + invisible

We assume we have measured
\[ \vec{\beta}_P^{\text{LAB}} \] - velocity of parent particle in the lab
\[ E_V^{\text{LAB}}, \vec{P}_V^{\text{LAB}} \] - energy and momentum of visible decay products

Can boost visible system to LLP rest frame

\[ E_V^P = \gamma_P \left( E_V^{\text{LAB}} - \vec{P}_V^{\text{LAB}} \cdot \vec{\beta}_P^{\text{LAB}} \right) \]

Energy of visible system in LLP rest frame

\[ E_V^P = \frac{m_P^2 - m_I^2 + m_V^2}{2m_P} \]

Can assume invisible system mass to calculate LLP mass

\[ m_P = E_V^P + \sqrt{E_V^P^2 + m_I^2 - m_V^2} \]
“GMSB” SUSY
Illustration how this works in SUSY (GMSB)

An exercise to test neutralino reconstruction in the following SUSY scenario:

- reconstruction of $\tilde{\chi}_1^0 \rightarrow Z + \tilde{G}$
- neutralino $\tilde{\chi}_1^0$ is long-lived
- gravitino $\tilde{G}$ mass is negligible

Production

- from top-squark pairs
- $M(\tilde{t}) = 1000$ GeV, $M(\tilde{\chi}_1^0) = 700$ GeV
Generator-level study with PYTHIA8

- top squark pair production 14 TeV p-p collisions
- top squark decays to top and neutralino promptly
- top quark decays to bottom and $W$ (not used in the analysis)
- neutralino is long-lived with $c\tau = 0.3, 1.0, 3.0, 10.0\text{ cm}$
- neutralino decays to $Z$ and gravitino (mass = 1 MeV)
- $Z$ decays to electron-positron pair

Smearing

- Track resolution: 10$\mu$m and 30$\mu$m in transverse and longitudinal impact parameter (JINST 9 P10009, 2014) $\rightarrow$ use 30$\mu$m for simplicity
- PV resolution: 10-12um in each of three dimensions (JINST 9 P10009, 2014)
- Electron momentum resolution is 2%
- Timing resolution for tracks is 30 ps
Generated $\beta$ of neutralinos
Generated $\eta$ for electrons

most of the signal is in the barrel ($|\eta| < 1.5$)
Reconstructed invariant mass of neutralino assuming timing resolution of MTD
\[ \sigma_t = 30 \text{ps} \]
and mass of invisible (\(\tilde{G}\)) is zero

A nice observable to distinguish signal from background!
“compressed” SUSY
A case of two neutralinos with small mass difference

- $\tilde{\chi}_2^0$ travels between two separated vertices
- $e^+e^-$ pair does not need to be a resonance; $m_{ee}$ can be continuum distribution
- escaping $\tilde{\chi}_1^0$ does not need to be invisible; it can decay to whatever, right away, or later
- This can be just a short segment in a long and complicated decay chain
- Production of $\tilde{\chi}_1^\pm - \tilde{\chi}_2^0$ pairs. Three mass points tested

<table>
<thead>
<tr>
<th>$M(\tilde{\chi}_1^\pm)$</th>
<th>$M(\tilde{\chi}_2^0)$</th>
<th>$M(\tilde{\chi}_2^0) - M(\tilde{\chi}_1^0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>100</td>
<td>10</td>
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<tr>
<td>400</td>
<td>400</td>
<td>10</td>
</tr>
<tr>
<td>250</td>
<td>250</td>
<td>50</td>
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</tbody>
</table>
Beta of decaying neutralino
Eta of electrons from neutralino decay (in the barrel!)

- $M = 10$ GeV, $\Delta M = 100$ GeV
- $M = 10$ GeV, $\Delta M = 400$ GeV
- $M = 50$ GeV, $\Delta M = 250$ GeV

Legend:
- Blue line: $M = 100$ GeV, $\Delta M = 10$ GeV
- Red line: $M = 400$ GeV, $\Delta M = 10$ GeV
- Green line: $M = 250$ GeV, $\Delta M = 50$ GeV
**Measured values:**

- primary vertex position and time \((\vec{X}_0, T_0)\)
- displaced \(e^+e^-\) vertex position and time \((\vec{X}_V, T_V)\)
- invariant mass and momentum of \(e^+e^-\) \((M_V, \vec{P}_V)\)

**Observable** = \(M(\tilde{\chi}_2^0) - M(\tilde{\chi}_1^0)\)

- First, calculate mass of decaying particle \(M_P\) assuming mass of invisible particle \(M_I = 0\) as described in previous slides
- Then, take a wild guess for mass of invisible particle \(M_{\text{guess}}\) and calculate mass difference \(\Delta M = M(\tilde{\chi}_2^0) - M(\tilde{\chi}_1^0)\)

\[
\Delta M = \frac{1}{2M_0} \cdot \left(M_0^2 + m_{ee}^2 + \sqrt{\left(M_0^2 - m_{ee}^2 \right)^2 + 4M_0^2M_{\text{guess}}^2}\right) - M_{\text{guess}}
\]

**What are the good values for** \(M_{\text{guess}}\)?

*Taking* \(M_{\text{guess}} \gg M(\tilde{\chi}_2^0)\) *is as good as using the truth, almost*
Reconstructed $\Delta M$ using $M_{\text{guess}} = 5000$

Reconstructed mass splitting with MTD timing resolution of 30 ps
With enough signal statistics, fit for $M_{\text{guess}} \to M(\tilde{\chi}_2^0)$
Other possibilities
Toy Simulations for following exercises

Event generation with RestFrames

- PDF parameterizations
- non-zero particle widths
- phase-space effects
- \( M(\tilde{\chi}^0_2) = 700 \text{ GeV} \), \( M(\tilde{\chi}^0_1) = 500 \text{ GeV} \)

Gross detector effects represented

- PV's smeared by 12 \( \mu \text{m} \) in 3D
- SV's smeared by 65 \( \mu \text{m} \) in 3D
- timing resolution assumes 30 ps
- electron momentum smeared by 2% in 3D
- MET smeared by 15 GeV in 2D
**Scenario 1a**

Assume one LLP, semi-invisible decay, 4D reco of PV and SV

If visible system is resonant, energy of visible system in LLP frame will **peak** at distinct value

\[
E_V^P = \gamma_P \left( E_V^{LAB} - \vec{p}_V^{LAB} \cdot \vec{\beta}_P^{LAB} \right)
\]

Peaking signal with **no** prior assumptions
Scenario 1b

Assume one LLP, semi-invisible decay, 4D reco of PV and SV

Further, assume MET corresponds solely to invisible decay product(s) from this LLP

Extra constraint → can solve for parent and invisible masses even when visible system is not resonant

If we can assume that $\vec{E}_T = \vec{p}^{LAB}_{I,T}$, then

$$E_P^{LAB} \beta_P^{LAB} = \vec{p}^{LAB}_{P,T} = \vec{E}_T + \vec{p}^{LAB}_{V,T}$$

Two equations can be solved for unknown $E_P^{LAB}$

$$m_P = \left(\gamma_P^{LAB}\right)^{-1} E_P^{LAB} = \frac{\beta_P^{LAB} \cdot \left(\vec{E}_T + \vec{p}^{LAB}_{V,T}\right)}{\gamma_P^{LAB} |\beta_P^{LAB}|}$$

Can measure LLP mass with no prior assumptions
Scenario 1b

Assume one LLP, semi-invisible decay, 4D reco of PV and SV

Further, assume MET corresponds solely to invisible decay product(s) from this LLP

Extra constraint → can solve for parent and invisible masses

even when visible system is not resonant

Can measure invisible particle mass

\[ m_I = \sqrt{m_p^2 - 2m_P E_V^P + m_V^2} \]

with no prior assumptions
Scenario 2a

Assume two LLPs, semi-invisible decay, 4D reco of PV and SV

Two mass-sensitive observables from LLP measurements

If visible system is resonant (like $Z \to ee$), will peak at distinct value in 2D
Scenario 2a for various $cT$
Scenario 2b

Assume two LLP, semi-invisible decay, 4D reco of PV and SV
Further, assume MET corresponds solely to invisible decay product(s) from these LLPs

If we assume

\[ E_T = \vec{p}_{Va,T}^{LAB} + \vec{p}_{Vb,T}^{LAB} \]

then

\[ E_{Pa}^{LAB} \beta_{Pa,T}^{LAB} + E_{Pb}^{LAB} \beta_{Pb,T}^{LAB} = \vec{E}_T + \vec{p}_{Va,T}^{LAB} + \vec{p}_{Vb,T}^{LAB} \]

two equations, two unknowns, \( E_{Pa}^{LAB} \) and \( E_{Pb}^{LAB} \). Defining

\[ \hat{n}_{\parallel} = \frac{\vec{E}_T + \vec{p}_{Va,T}^{LAB} + \vec{p}_{Vb,T}^{LAB}}{|\vec{E}_T + \vec{p}_{Va,T}^{LAB} + \vec{p}_{Vb,T}^{LAB}|}, \quad \hat{n}_{\perp} = \hat{n}_{\parallel} \times \hat{z} \]

We can calculate

\[ m_{Pa} = \frac{|\vec{E}_T + \vec{p}_{Va,T}^{LAB} + \vec{p}_{Vb,T}^{LAB}| \hat{\beta}_{Pb}^{LAB} \cdot \hat{n}_{\perp}}{\gamma_{Pa}^{LAB} (\hat{\beta}_{Pa}^{LAB} \cdot \hat{n}_{\parallel} \beta_{Pb}^{LAB} \cdot \hat{n}_{\perp} - \hat{\beta}_{Pb}^{LAB} \cdot \hat{n}_{\parallel} \beta_{Pa}^{LAB} \cdot \hat{n}_{\perp})} \]

\[ m_{Pb} = \frac{|\vec{E}_T + \vec{p}_{Va,T}^{LAB} + \vec{p}_{Vb,T}^{LAB}| \hat{\beta}_{Pa}^{LAB} \cdot \hat{n}_{\perp}}{\gamma_{Pb}^{LAB} (\hat{\beta}_{Pb}^{LAB} \cdot \hat{n}_{\parallel} \beta_{Pa}^{LAB} \cdot \hat{n}_{\perp} - \hat{\beta}_{Pa}^{LAB} \cdot \hat{n}_{\parallel} \beta_{Pb}^{LAB} \cdot \hat{n}_{\perp})} \]

Can solve for both LLP and both invisible masses
Scenario 2b

Assume two LLP, semi-invisible decay, 4D reco of PV and SV
Further, assume MET corresponds solely to invisible decay product(s) from these LLPs
Scenario 2b

Assume two LLP, semi-invisible decay, 4D reco of PV and SV

Further, assume MET corresponds solely to invisible decay product(s) from these LLPs

Can measure **both LLP** and **both invisible** particle masses, even if they are different, even if visible systems in decays are not resonant
Summary

- Precision timing for tracks allows to reconstruct time-of-flight of LLP → β of LLP

- With this new info, one can fully constrain kinematics of some semi-visible decays → mass reconstruction. Or dramatically improve discovery potential for LLP

- Many interesting scenarios where LLPs are heavy. Decays result in barrel tracks.

- Hermetic timing layer (emphasis on barrel) is crucial for assigning timing to vertexes.