CMS Timing

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on behalf of CMS MIP Timing Detector Group

Searches for long-lived particles at the LHC: Second workshop of the LHC LLP Community
Oct 17-20, 2017, ICTP, Trieste, Italy

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

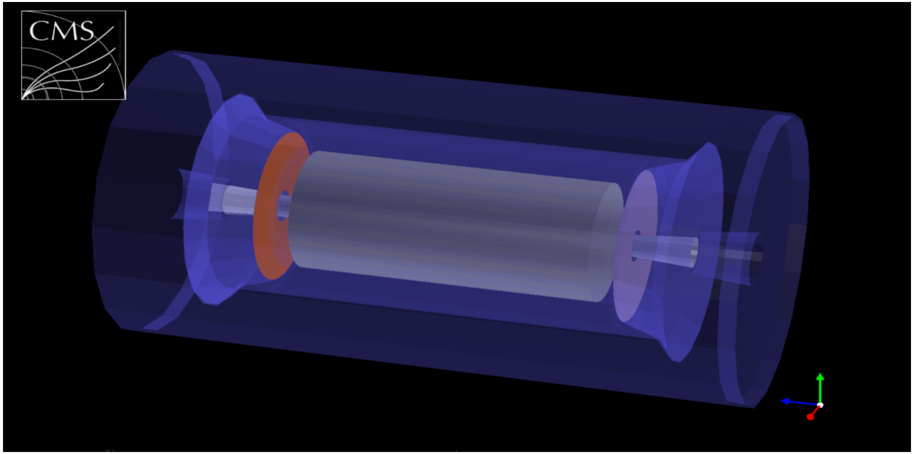
Endcap: new calorimeter, HGCal

- 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

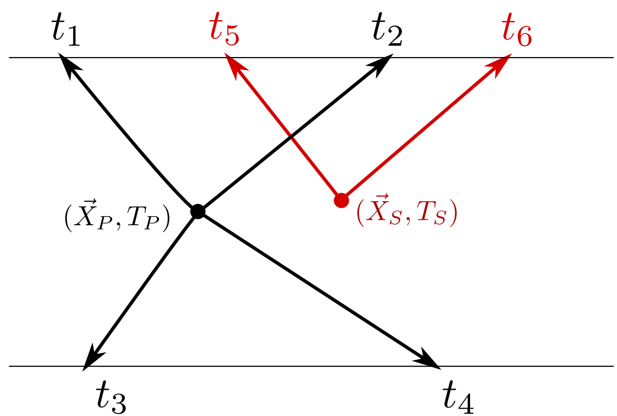
MIP timing detector (MTD)

- 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 ~ 30 ps, almost full efficiency**



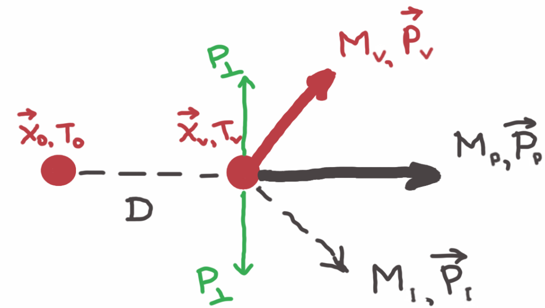
Primary and Secondary vertex position and timing

- 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 trajector length, momentum etc
- Timing of a track i at the vertex is $t_i - \mathrm{ToF}_i$
- 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

$\vec{\beta}_P^{LAB}$ - velocity of parent particle in the lab

E_V^{LAB}, $\vec{P}_V^{LAB}$ - energy and momentum of visible decay products

Can boost visible system to LLP rest frame

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

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

$$m_P = E_V^P + \sqrt{E_V^{P2} + m_I^2 - m_V^2}$$

1 "GMSB" SUSY

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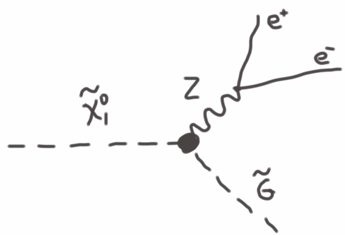
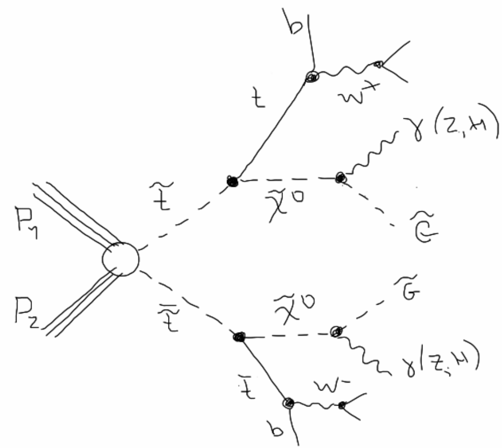
Illustration how this works in SUSY (GMSB)

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

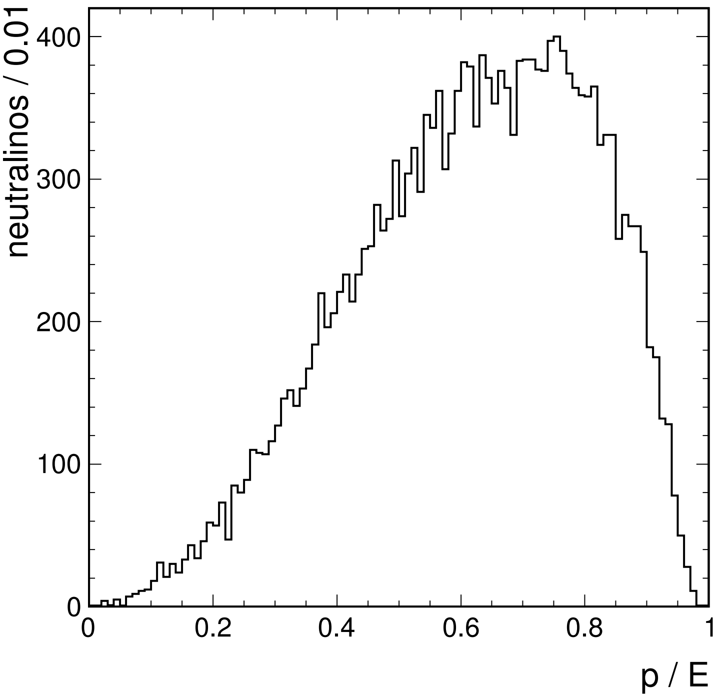
- from top-squark pairs
- $M(\tilde{t})$ = 1000 GeV, $M(\tilde{\chi}_1^0)$ = 700 GeV

Generator-level study with PYTHIA8

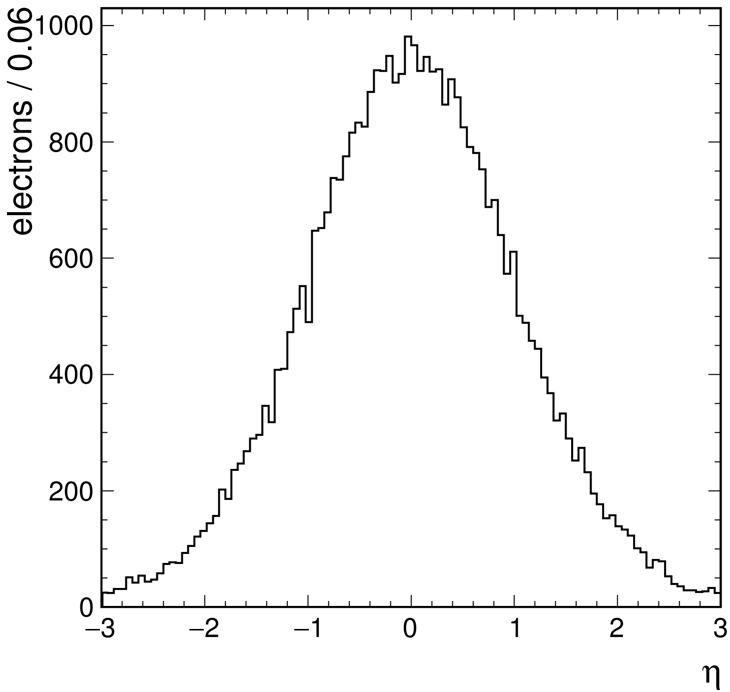
- top squark pair production 14 TeV p-p collisions
- top squark decays to top and neutralino promptly
- top quark decays to bottom and W (not used in the analysis)
- neutralino is long-lived with $c\tau$ = 0.3, 1.0, 3.0, 10.0 cm
- neutralino decays to Z and gravitino (mass = 1 MeV)
- Z decays to electron-positron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

Smearing

- Track resolution: 10μm and 30μm in transverse and longitudinal impact parameter (JINST 9 P10009, 2014) $\rightarrow$ use 30μm 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

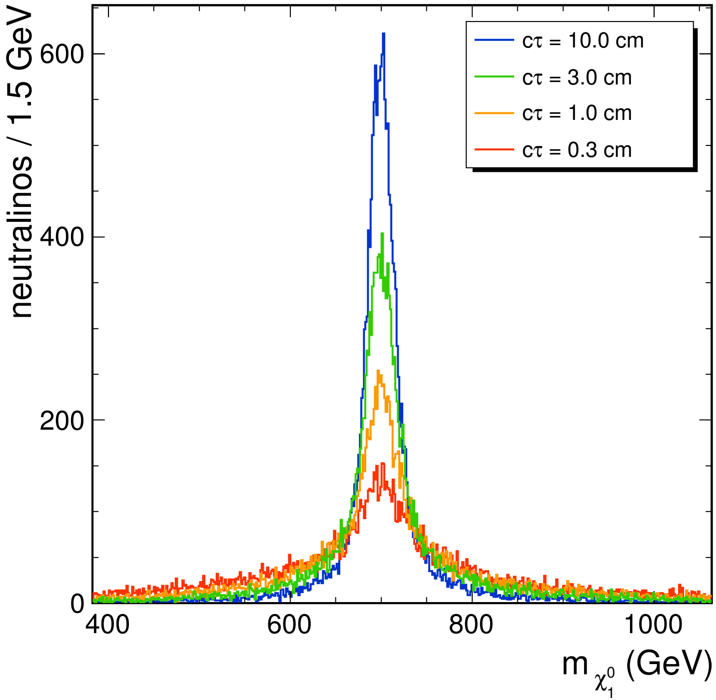


Generated β of neutralinos



Generated η for electrons

most of the signal is in the barrel $(|\eta| < 1.5)$



Reconstructed invariant mass of neutralino assuming timing resolution of MTD

$$\sigma_t = 30ps$$

and mass of invisible ($\tilde{G}$) is zero

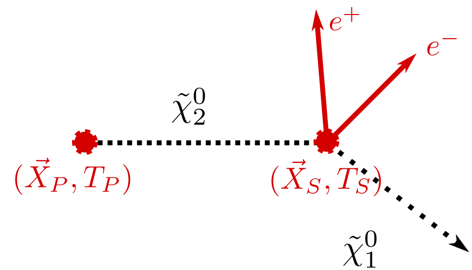
A nice observable to distinguish signal from background!

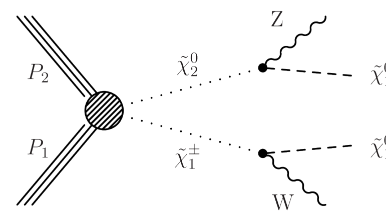
“compressed” SUSY

A case of two neutralinos with small mass difference

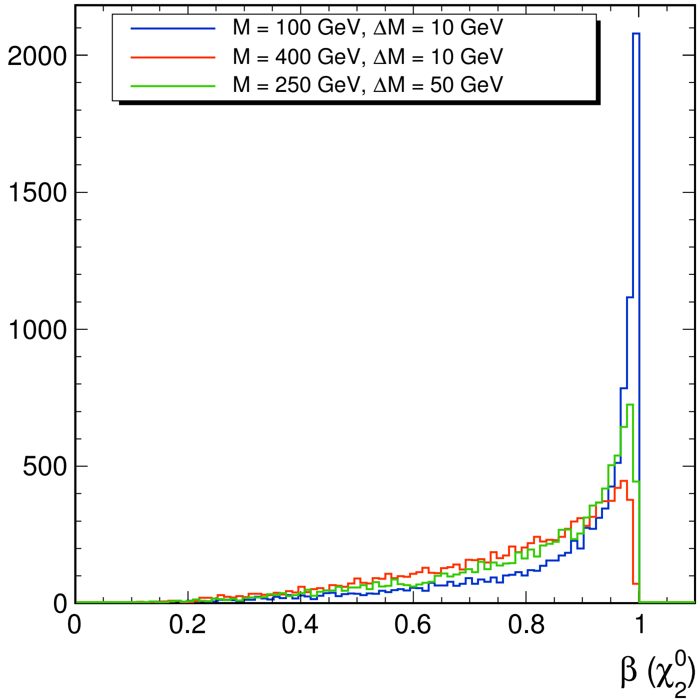
- $\tilde{\chi}_2^0$ travels between two separated vertecies
- e^+e^- pair *does not* need to be a resonance; m_{ee} can be continuum distribution
- escaping $\tilde{\chi}_1^0$ *does not* need ot be invisible; it can decay to *whatever*, right away, or later
- This can be just a short segment in a long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

$M(\tilde{\chi}_1^{\pm})$	$M(\tilde{\chi}_2^0)$	$M(\tilde{\chi}_2^0) - M(\tilde{\chi}_1^0)$
100	100	10
400	400	10
250	250	50

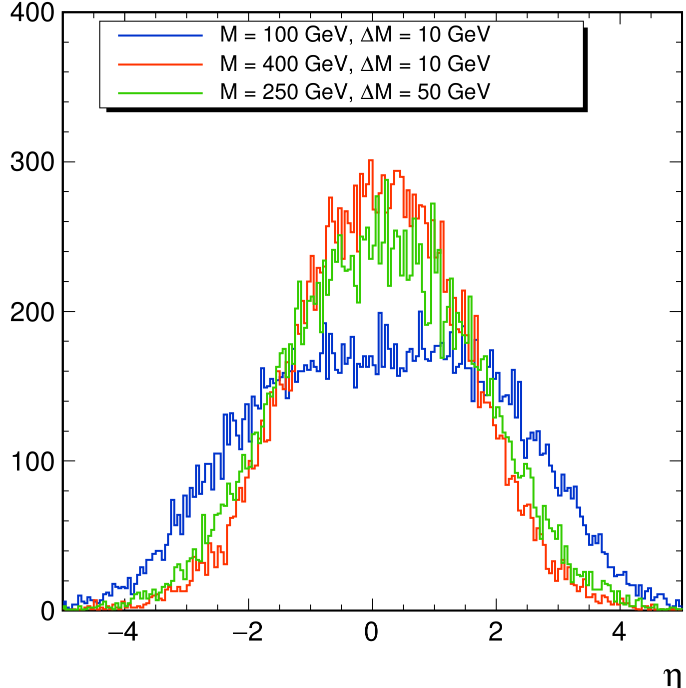




Beta of decaying neutralino

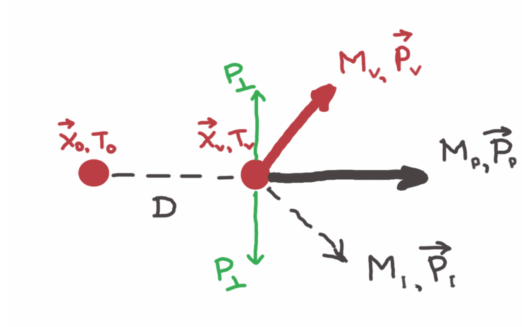


Eta of electrons from neutralino decay (in the barrel!)



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_{guess} and calculate mass difference $\Delta M = M(\tilde{\chi}_2^0) - M(\tilde{\chi}_1^0)$

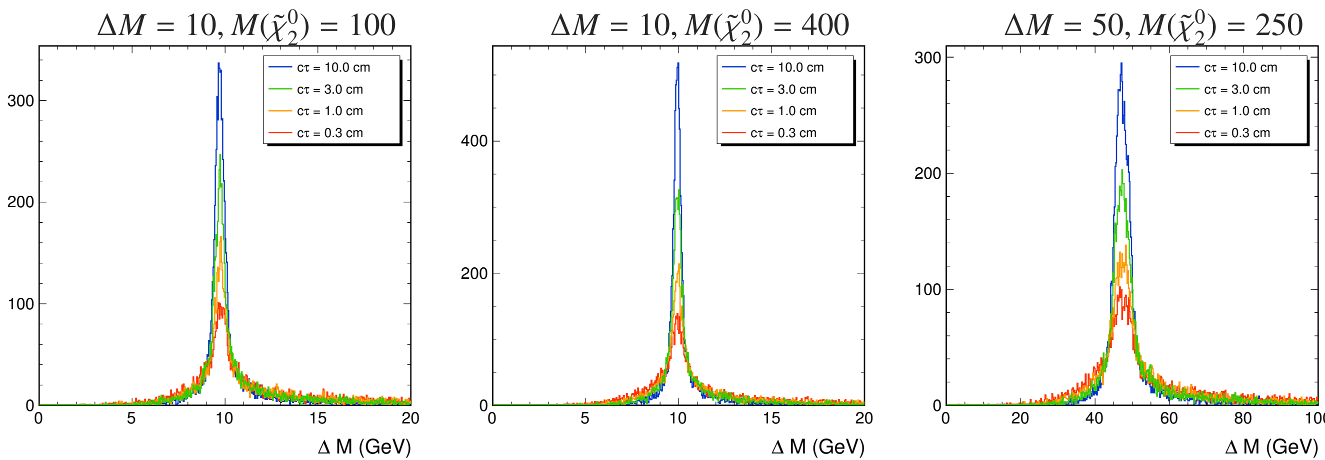
$$\Delta M = \frac{1}{2M_0} \cdot \left(M_0^2 + m_{ee}^2 + \sqrt{\left(M_0^2 - m_{ee}^2\right)^2 + 4M_0^2 M_{guess}^2} \right) - M_{guess}$$

What are the good values for M_{guess}?
Taking $M_{guess} \gg M(\tilde{\chi}_2^0)$ is as good as using the truth, almost

Reconstructed ΔM using $M_{guess} = 5000$

Reconstructed mass splitting with MTD timing resolution of 30 ps

With enough signal statistics, fit for $M_{guess} \to M(\tilde{\chi}_2^0)$



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Other possibilities

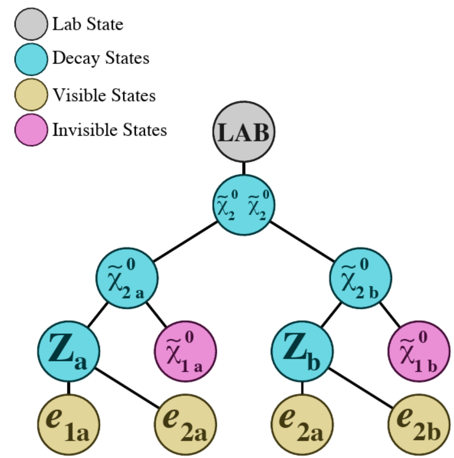
Toy Simulations for following exercises

Event generation with `RestFrames`

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

Gross detector effects represented

- PV's smeared by 12 μm in 3D
- SV's smeared by 65 μm in 3D
- timing resolution assumes 30 ps
- electron momentum smeared by 2% in 3D
- MET smeared by 15 GeV in 2D



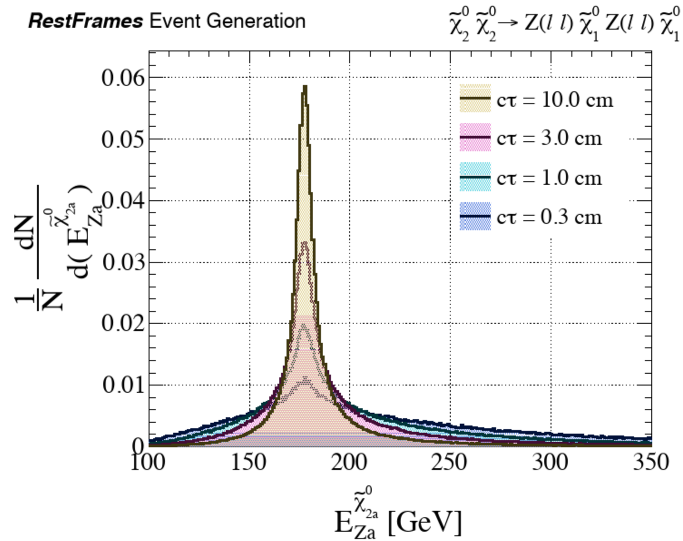
Scenario 1a

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

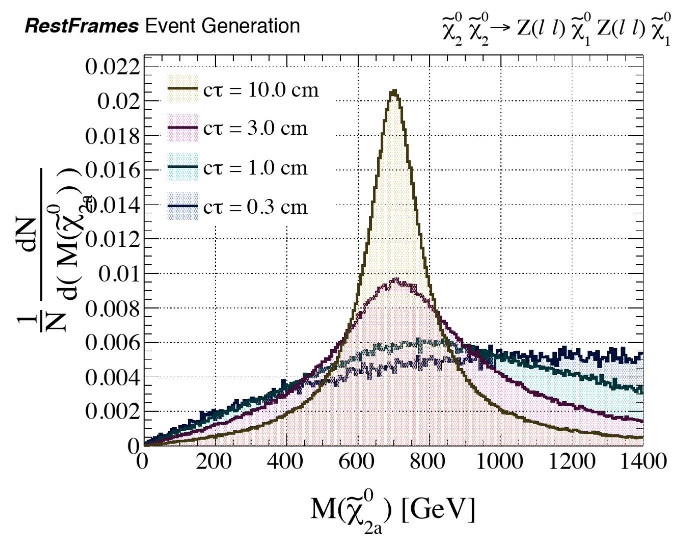
If we can assume that $\vec{\not{E}}_T = \vec{p}_{I,T}^{LAB}$, then

$$E_P^{LAB}\vec{\beta}_{P,T}^{LAB} = \vec{p}_{P,T}^{LAB} = \vec{\not{E}}_T + \vec{p}_{V,T}$$

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

$$m_P = \left(\gamma_P^{LAB}\right)^{-1} E_P^{LAB} = \frac{\vec{\beta}_{P,T}^{LAB} \cdot \left(\vec{\not{E}}_T + \vec{p}_{V,T}^{LAB}\right)}{\gamma_P^{LAB} \mid \vec{\beta}_{P,T}^{LAB} \mid}$$

Can measure LLP mass with **no** prior assumptions



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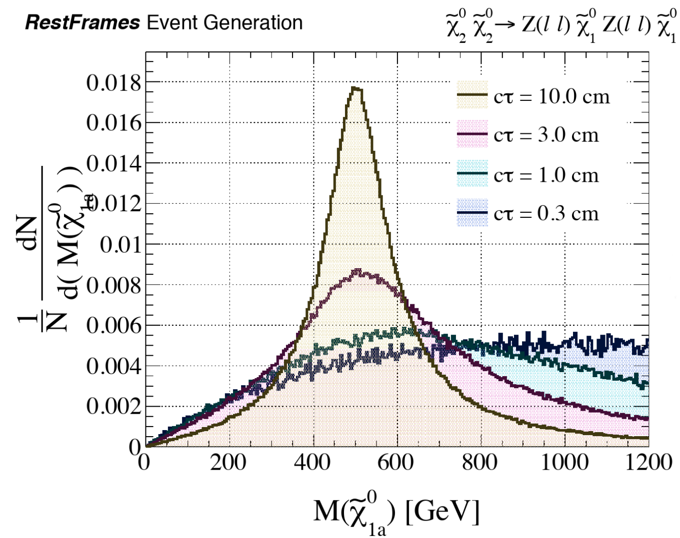
Scenario 1b

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

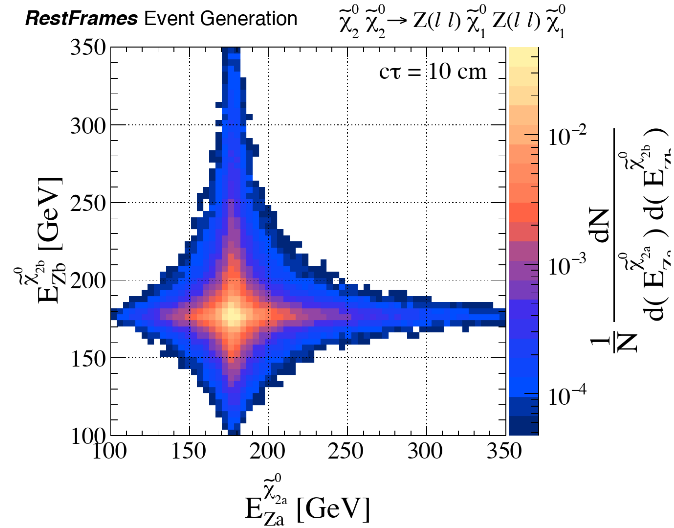


Scenario 2a

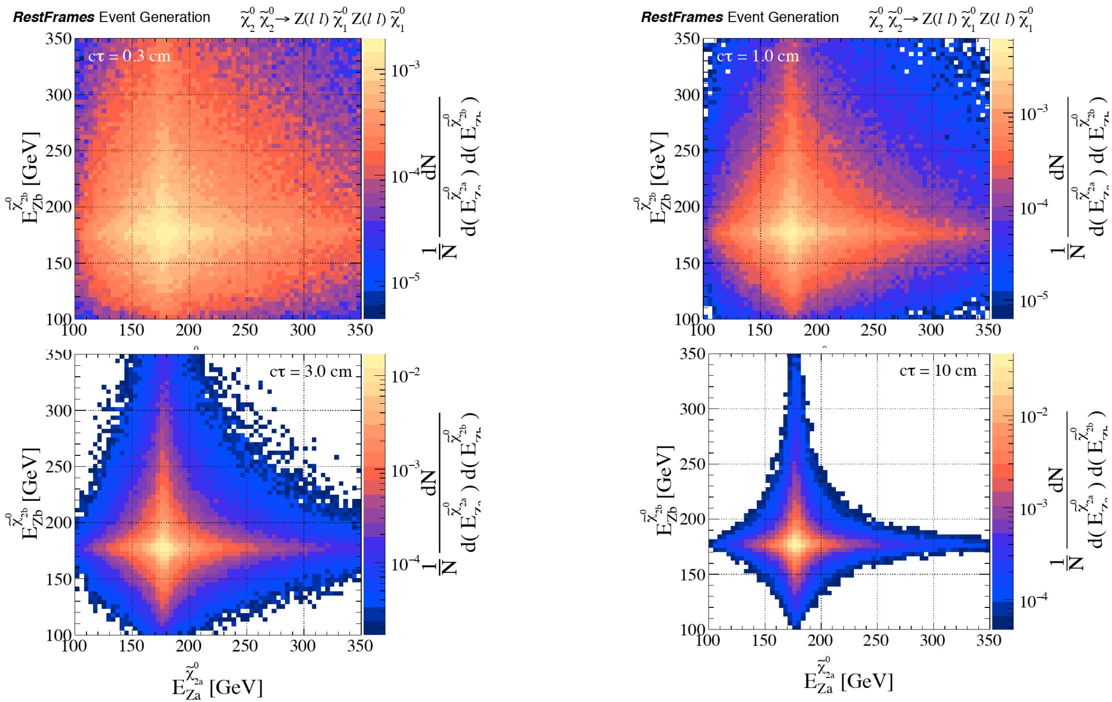
Assume two LLPs, semi-invisible decay, 4D reco of PV and SV

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 $c\tau$



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

$$\vec{E}_T = \vec{P}^{LAB}_{Ia,T} + \vec{P}^{LAB}_{Ib,T}$$

then

$$E^{LAB}_{Pa}\vec{\beta}^{LAB}_{Pa,T} + E^{LAB}_{Pb}\vec{\beta}^{LAB}_{Pb,T} = \vec{\not{E}}_T + \vec{P}^{LAB}_{Va,T} + \vec{P}^{LAB}_{Vb,T}$$

two equations, two unknowns, E^{LAB}_{Pa} and E^{LAB}_{Pb}. Defining

$$\hat{n}_{\parallel} = \frac{\vec{\not{E}}_T + \vec{P}^{LAB}_{Va,T} + \vec{P}^{LAB}_{Vb,T}}{\left|\vec{\not{E}}_T + \vec{P}^{LAB}_{Va,T} + \vec{P}^{LAB}_{Vb,T}\right|}, \quad \hat{n}_{\perp} = \hat{n}_{\parallel} \times \hat{z}$$

We can calculate

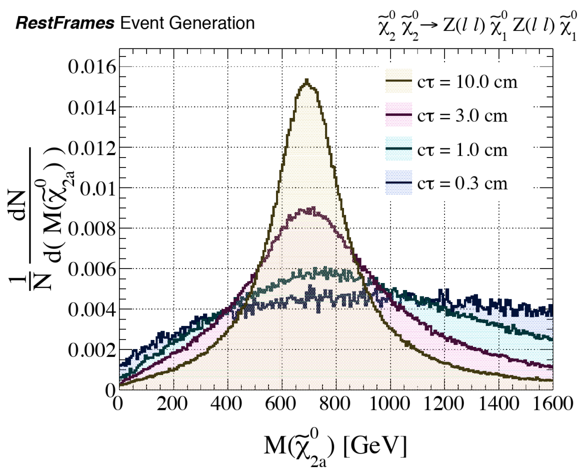
$$m_{Pa} = \frac{\left|\vec{\not{E}}_T + \vec{P}^{LAB}_{Va,T} + \vec{P}^{LAB}_{Vb,T}\right| \vec{\beta}^{LAB}_{Pb} \cdot \hat{n}_{\perp}}{\gamma^{LAB}_{Pa}\left(\vec{\beta}^{LAB}_{Pa} \cdot \hat{n}_{\parallel}\, \vec{\beta}^{LAB}_{Pb} \cdot \hat{n}_{\perp} - \vec{\beta}^{LAB}_{Pb} \cdot \hat{n}_{\parallel}\, \vec{\beta}^{LAB}_{Pa} \cdot \hat{n}_{\perp}\right)}$$

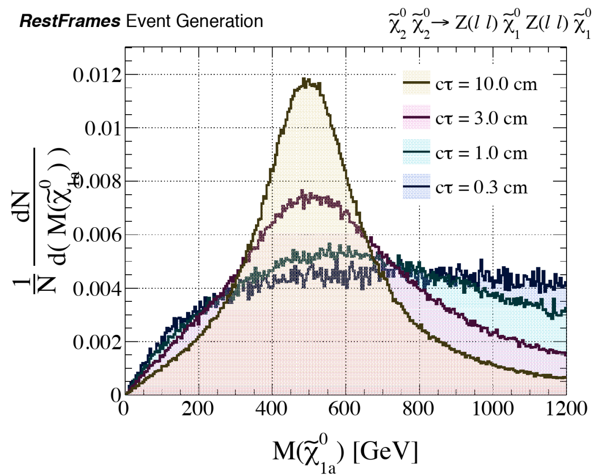
$$m_{Pb} = \frac{\left|\vec{\not{E}}_T + \vec{P}^{LAB}_{Va,T} + \vec{P}^{LAB}_{Vb,T}\right| \vec{\beta}^{LAB}_{Pa} \cdot \hat{n}_{\perp}}{\gamma^{LAB}_{Pb}\left(\vec{\beta}^{LAB}_{Pb} \cdot \hat{n}_{\parallel}\, \vec{\beta}^{LAB}_{Pa} \cdot \hat{n}_{\perp} - \vec{\beta}^{LAB}_{Pa} \cdot \hat{n}_{\parallel}\, \vec{\beta}^{LAB}_{Pb} \cdot \hat{n}_{\perp}\right)}$$

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





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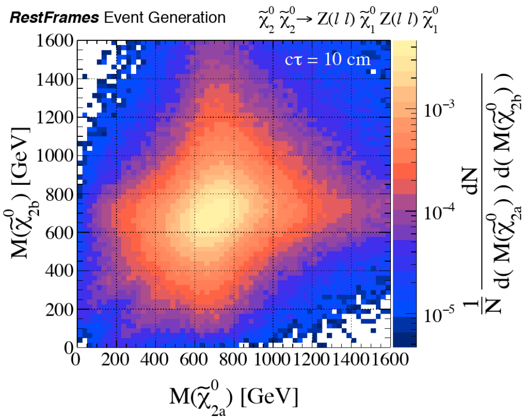

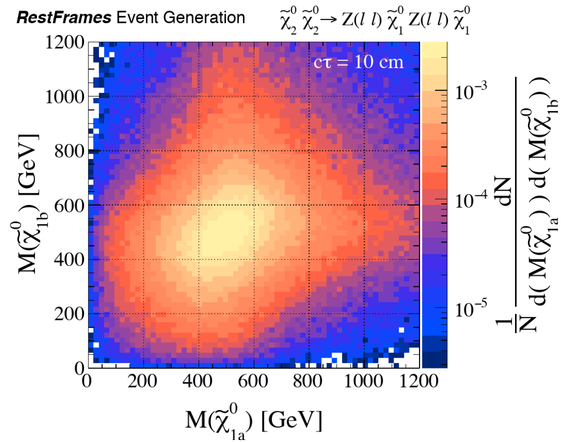

Can measure **both LLP** and **both invisible** particle masses, even *if they are different*, even if visible systems in decays are *not resonant*

Summary

- Precision timing for tracks allows to reconstruct time-of-flight of LLP $\rightarrow$ β of LLP
- With this new info, one can fully constrain kinematics of some semi-visible decays $\rightarrow$ 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 crutial for assigning timing to vertecies..