Long Lived Particle Search with timing information at the HL-LHC

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Based on arXiv:1903.05825

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LLP searches @ collider

- Missing transverse energy
- Displaced vertices
- Non-pointing events (Large impact parameter)
- Disappearing tracks
- Initial state radiation

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- Disappearing tracks
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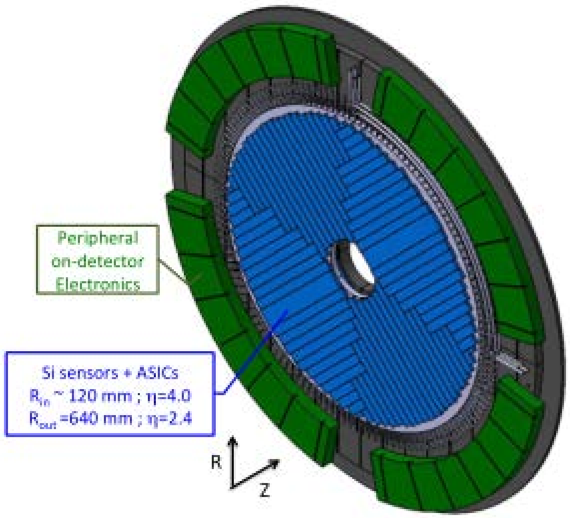
What else?

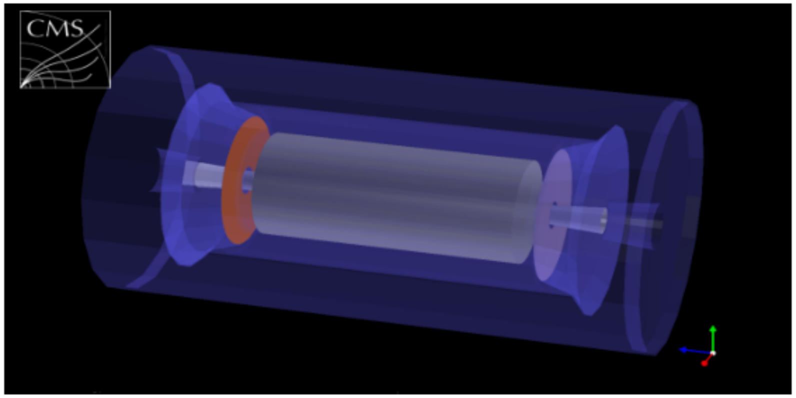
Timing detector @ HL-LHC

- ATLAS
  - High-Granularity Timing Detector at the endcap region
  - ~30 ps resolution
  - Coverage $2.4 < |\eta| < 4.0$



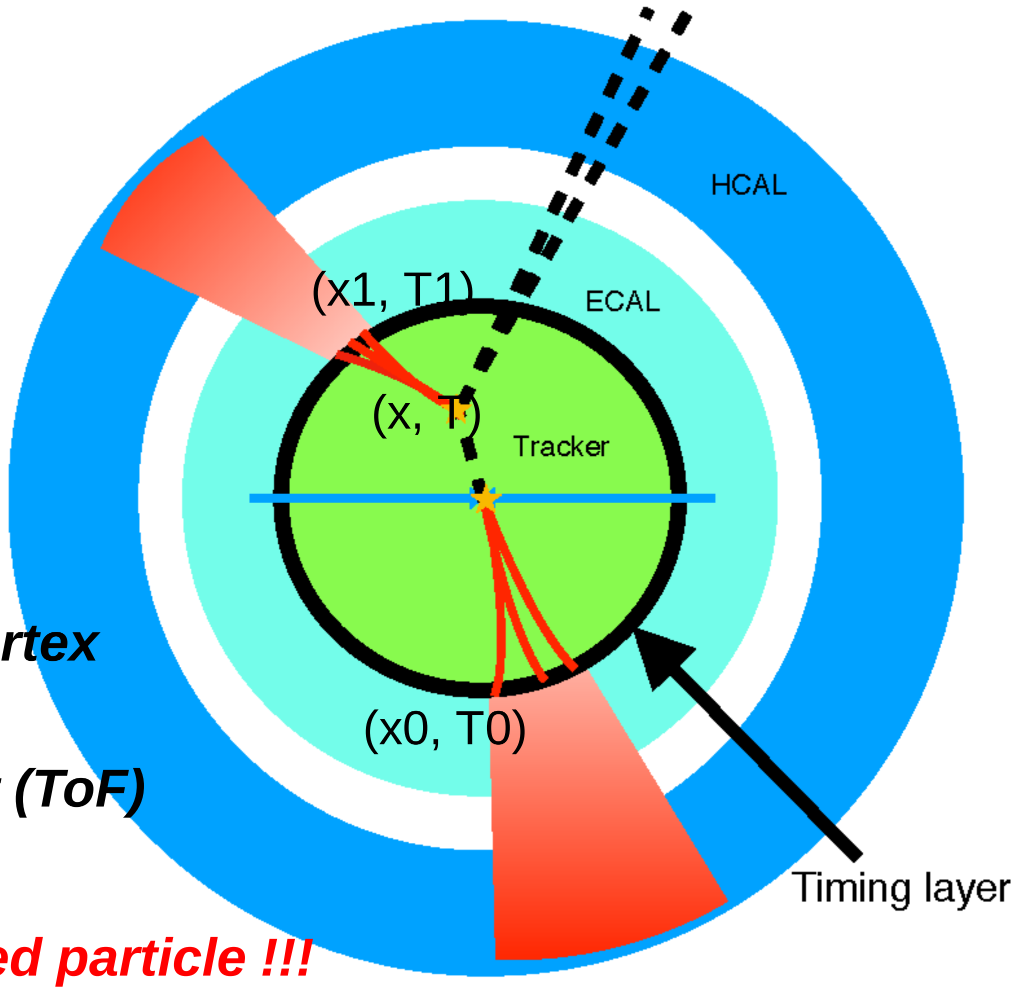
[ATL-LARG-PROC-2018-003]

- CMS
  - Minimum ionizing particles (MIPs) Timing Detector (MTD) between tracker and ECAL
  - ~30 ps resolution for charged tracks
  - Coverage $|\eta| < 3.0$



[CERN-LHCC-2017-027/LHCC-P-009]

Timing detector @ HL-LHC



- We can measure ***displaced vertex***

  \+

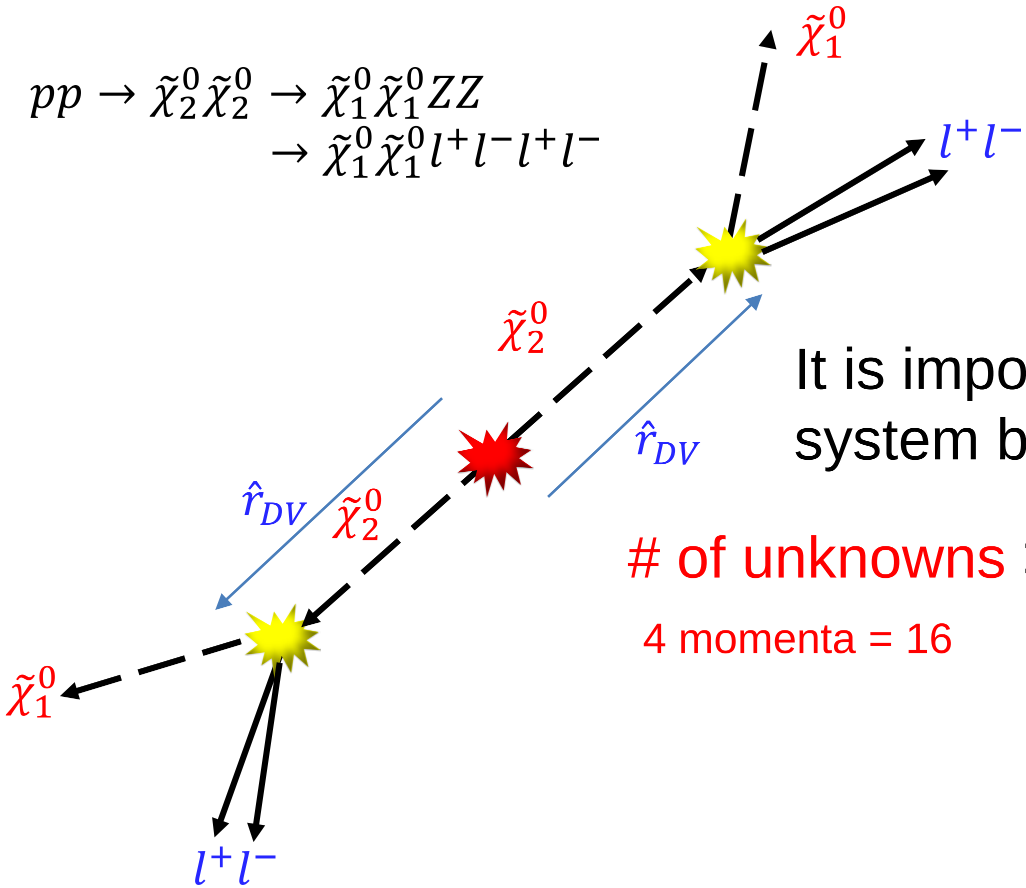
- We can measure ***time of flight (ToF)***

  ↓

- We can measure β of ***long-lived particle !!!***

Neutral LLP search example

$$pp \to \tilde{\chi}_2^0 \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 ZZ$$
$$\to \tilde{\chi}_1^0 \tilde{\chi}_1^0 l^+ l^- l^+ l^-$$



It is impossible to fully reconstruct the system by conventional method. Why?

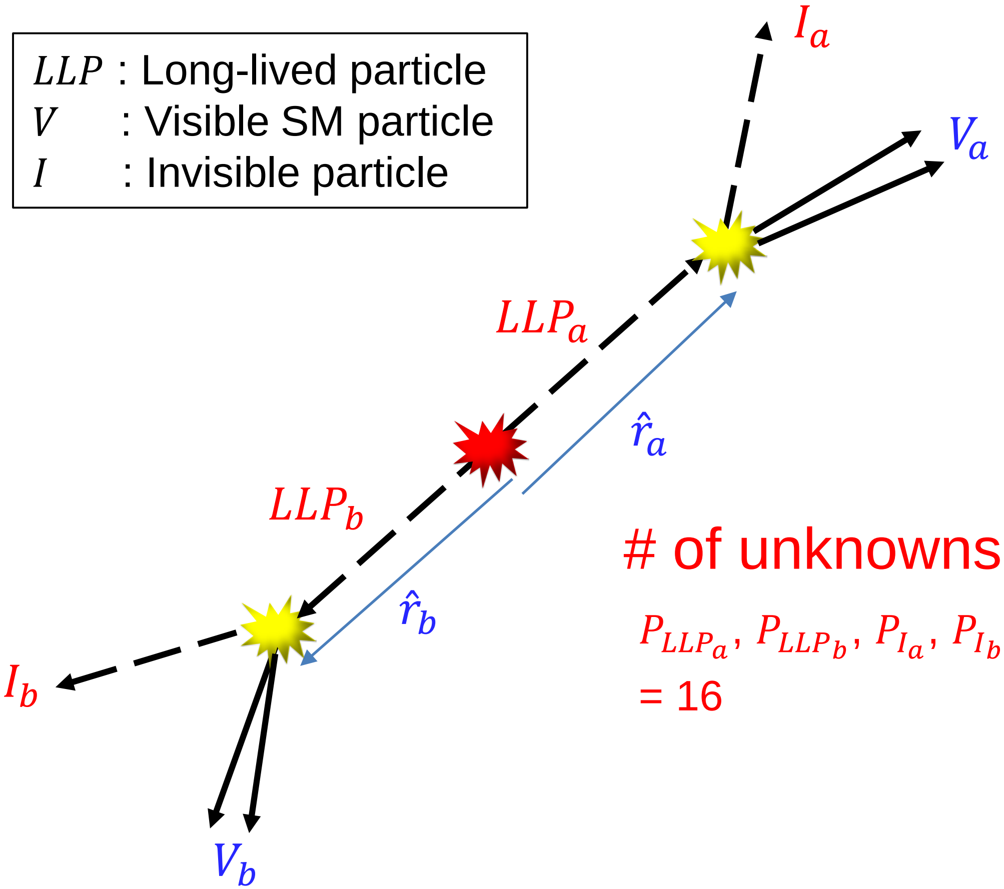
# of unknowns > # of knowns

4 momenta = 16

2 momenta = 8
p_T^{miss} = 2
2 displaced vertices = 4

How can we solve this kind of system?

Sol1: Reconstruction without timing



\# of unknowns = # of knowns + # of constraints

$P_{LLP_a}, P_{LLP_b}, P_{I_a}, P_{I_b}$ = 16

P_{V_a}, P_{V_b} = 8

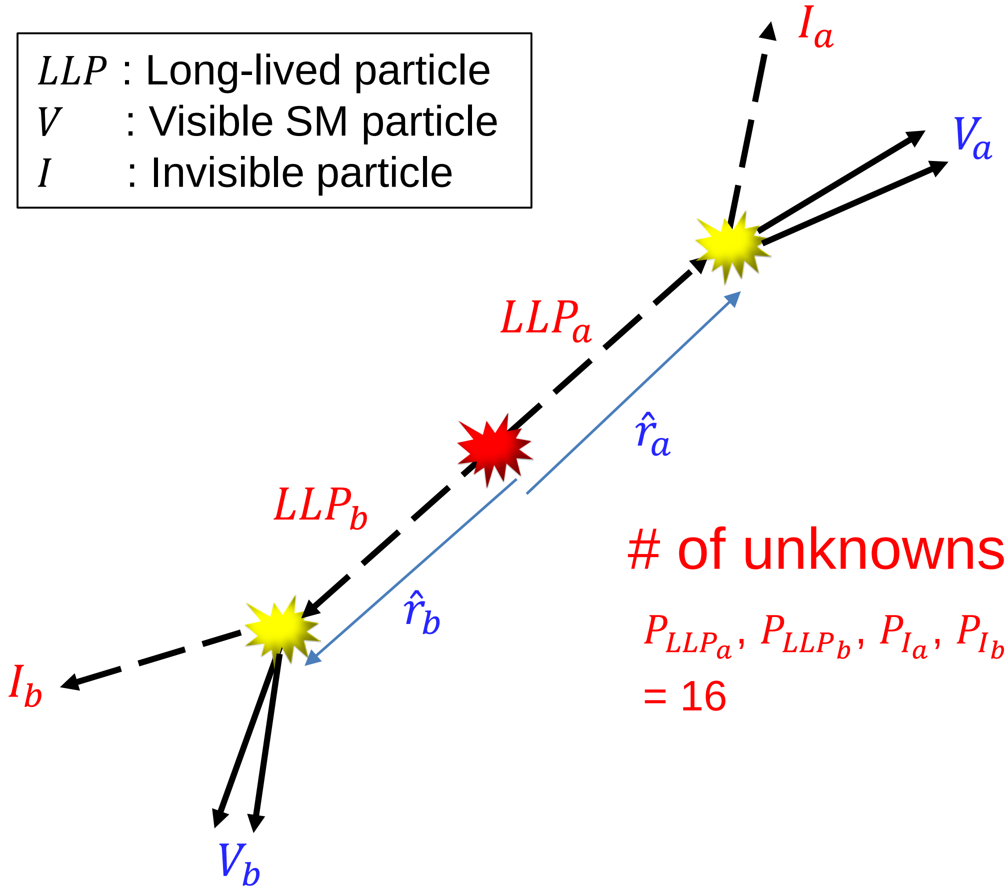
p_T^{miss} = 2

$\hat{r}_a, \hat{r}_b$ = 4

Sol1: 2 assumptions

$M_{LLP_a} = M_{LLP_b}, M_{I_a} = M_{I_b}$

Sol2: Reconstruction with timing



# of unknowns = # of knowns + # of new inputs

$P_{LLP_a}, P_{LLP_b}, P_{I_a}, P_{I_b}$
= 16

P_{V_a}, P_{V_b}	= 8
p_T^{miss}	= 2
$\hat{r}_a, \hat{r}_b$	= 4

Sol2: 2 timing information
T_a, T_b

Sol1: Reconstruction without timing

[M. Park and Y. Zhao, 1110.1403]
[G. Cottin, 1801.09671]

- 6 d.o.f become two 3-momenta
  - $\hat{r}_a, \hat{r}_b$ 4 d.o.f
  - p_T^{miss} 2 d.o.f
- 3-momenta of LLPs

$$\boldsymbol{p}_a = \frac{\hat{r}_b \times (\boldsymbol{p}_I + \boldsymbol{p}_{V_a} + \boldsymbol{p}_{V_b}) \cdot \hat{\boldsymbol{k}}}{\hat{r}_b \times \hat{r}_a \cdot \hat{\boldsymbol{k}}} \hat{r}_a$$

$$\boldsymbol{p}_b = \frac{\hat{r}_a \times (\boldsymbol{p}_I + \boldsymbol{p}_{V_a} + \boldsymbol{p}_{V_b}) \cdot \hat{\boldsymbol{k}}}{\hat{r}_a \times \hat{r}_b \cdot \hat{\boldsymbol{k}}} \hat{r}_b$$

- 3-momenta of invisible particles

$$\boldsymbol{p}_{I_a} = \boldsymbol{p}_a - \boldsymbol{p}_{V_a}$$

$$\boldsymbol{p}_{I_b} = \boldsymbol{p}_b - \boldsymbol{p}_{V_b}$$

- 4-momentum conservation

$$m_a^2 = m_{I_a}^2 + m_{V_a}^2 + 2E_{V_a}\sqrt{m_{I_a}^2 + |\boldsymbol{p}_{I_a}|^2} - 2\boldsymbol{p}_{V_a} \cdot \boldsymbol{p}_{I_a}$$

$$m_b^2 = m_{I_b}^2 + m_{V_b}^2 + 2E_{V_b}\sqrt{m_{I_b}^2 + |\boldsymbol{p}_{I_b}|^2} - 2\boldsymbol{p}_{V_b} \cdot \boldsymbol{p}_{I_b}$$

- We can find **1 or 2 positive mass pairs** with ***2 assumptions***

$$m_a = m_b,\ m_{I_a} = m_{I_b}$$

Sol2: Reconstruction with timing

- 6 d.o.f become two 3-momenta
  - $\hat{r}_a, \hat{r}_b$ 4 d.o.f
  - p_T^{miss} 2 d.o.f
- 3-momenta of LLPs

$$\boldsymbol{p}_a = \frac{\boldsymbol{\beta}_b \times (\boldsymbol{p}_I + \boldsymbol{p}_{V_a} + \boldsymbol{p}_{V_b}) \cdot \hat{\boldsymbol{k}}}{\boldsymbol{\beta}_b \times \boldsymbol{\beta}_a \cdot \hat{\boldsymbol{k}}} \boldsymbol{\beta}_a$$

$$\boldsymbol{p}_b = \frac{\boldsymbol{\beta}_a \times (\boldsymbol{p}_I + \boldsymbol{p}_{V_a} + \boldsymbol{p}_{V_b}) \cdot \hat{\boldsymbol{k}}}{\boldsymbol{\beta}_a \times \boldsymbol{\beta}_b \cdot \hat{\boldsymbol{k}}} \boldsymbol{\beta}_b$$

- 3-momenta of invisible particles

$$\boldsymbol{p}_{I_a} = \boldsymbol{p}_a - \boldsymbol{p}_{V_a}$$

$$\boldsymbol{p}_{I_b} = \boldsymbol{p}_b - \boldsymbol{p}_{V_b}$$

- 2 Timing information
  - $\boldsymbol{\beta}_a = \hat{r}_a / T_a$, $\boldsymbol{\beta}_b = \hat{r}_b / T_b$

$$E_a = \frac{\boldsymbol{\beta}_b \times (\boldsymbol{p}_I + \boldsymbol{p}_{V_a} + \boldsymbol{p}_{V_b}) \cdot \hat{\boldsymbol{k}}}{\boldsymbol{\beta}_b \times \boldsymbol{\beta}_a \cdot \hat{\boldsymbol{k}}}$$

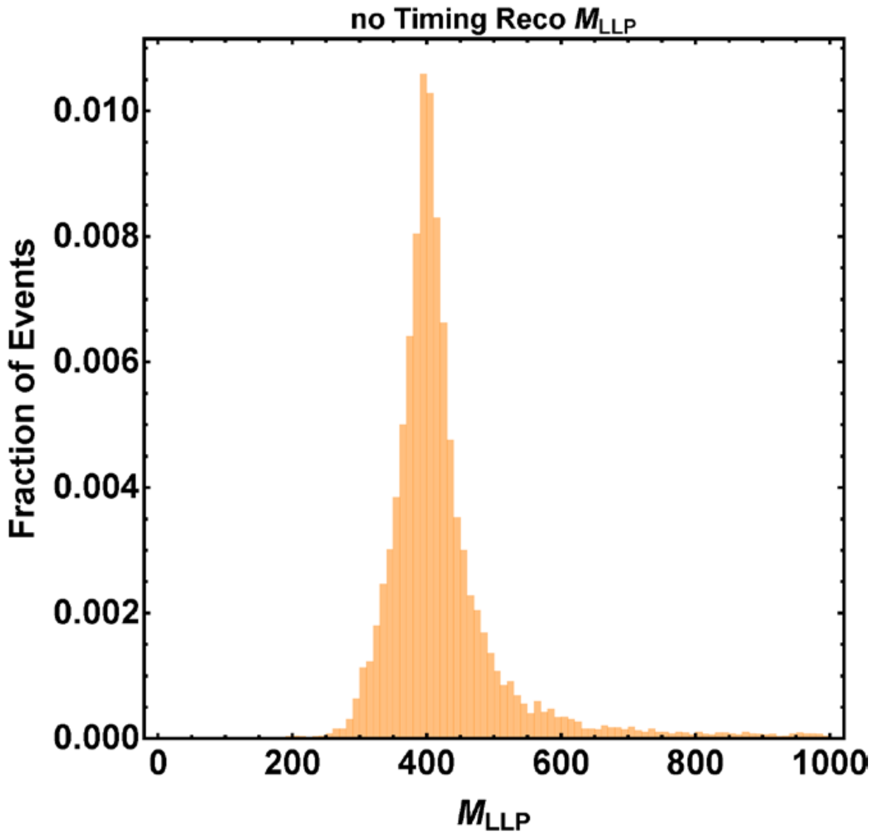
$$E_b = \frac{\boldsymbol{\beta}_a \times (\boldsymbol{p}_I + \boldsymbol{p}_{V_a} + \boldsymbol{p}_{V_b}) \cdot \hat{\boldsymbol{k}}}{\boldsymbol{\beta}_a \times \boldsymbol{\beta}_b \cdot \hat{\boldsymbol{k}}}$$

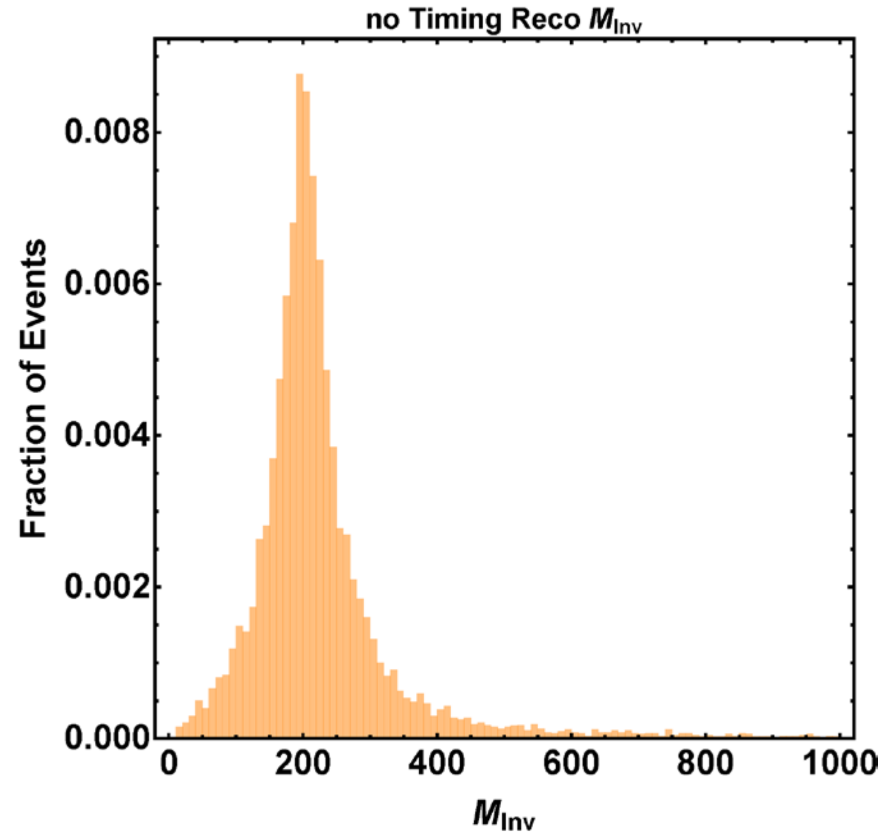
- We can find **unique mass pairs *without assumptions***

Case1: $LLP_a = LLP_b, I_a = I_b$

MC result: Sol1

$M_{LLP_a} = M_{LLP_b} = 400$ GeV
$M_{I_a} = M_{I_b} = 200$ GeV

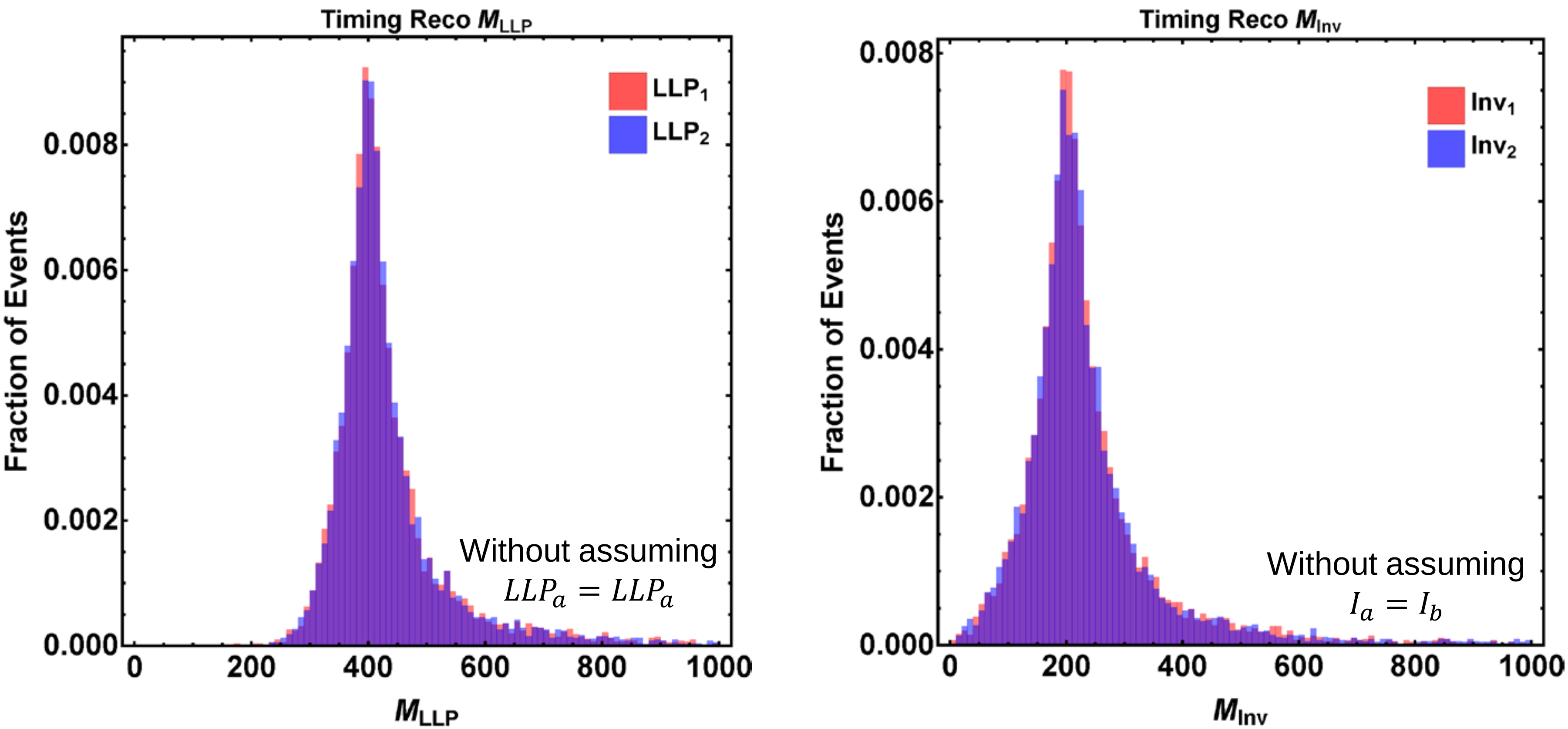




		m_{LLP_a}	m_{LLP_b}	m_{I_a}	m_{I_b}
Case 1	w/o timing	397.6 ± 1.2	397.6 ± 1.2	206.0 ± 1.5	206.0 ± 1.5

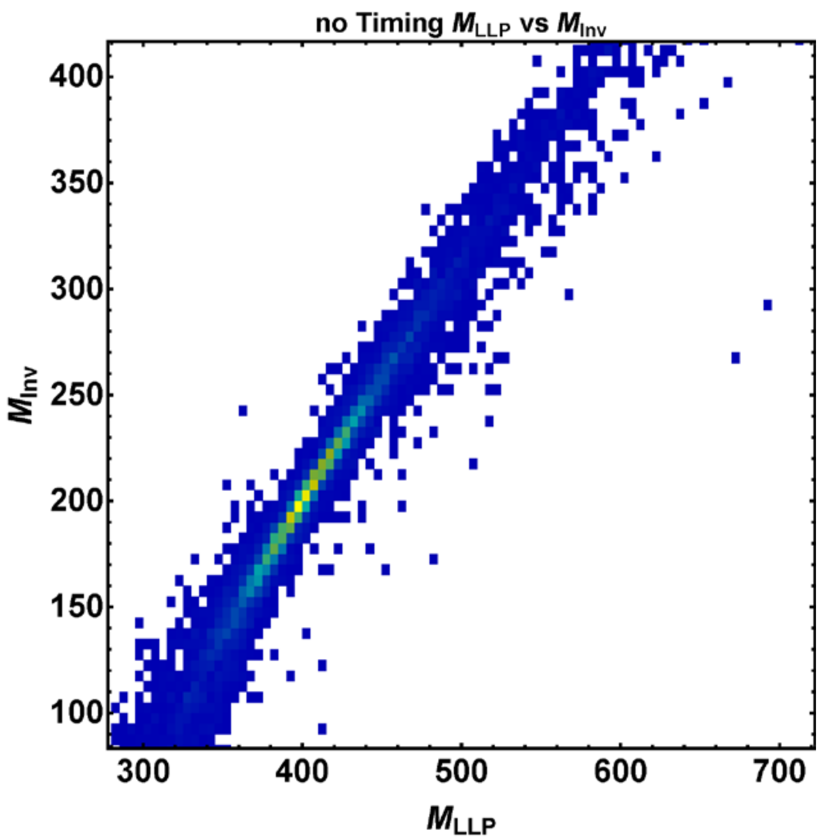
MC result: Sol2

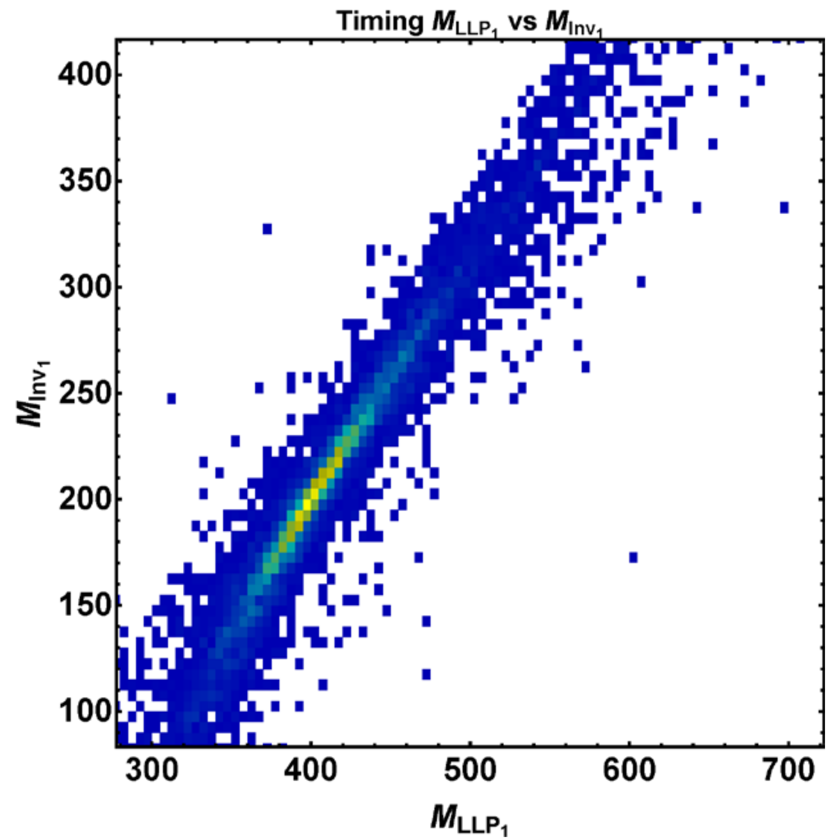
$M_{LLP_a} = M_{LLP_b} = 400$ GeV
$M_{I_a} = M_{I_b} = 200$ GeV



		m_{LLP_a}	m_{LLP_b}	m_{I_a}	m_{I_b}
Case 1	w/o timing	397.6 ± 1.2	397.6 ± 1.2	206.0 ± 1.5	206.0 ± 1.5
	timing	400.91 ± 0.35	400.77 ± 0.35	201.53 ± 0.49	201.53 ± 0.49

MC result: Sol1 vs Sol2



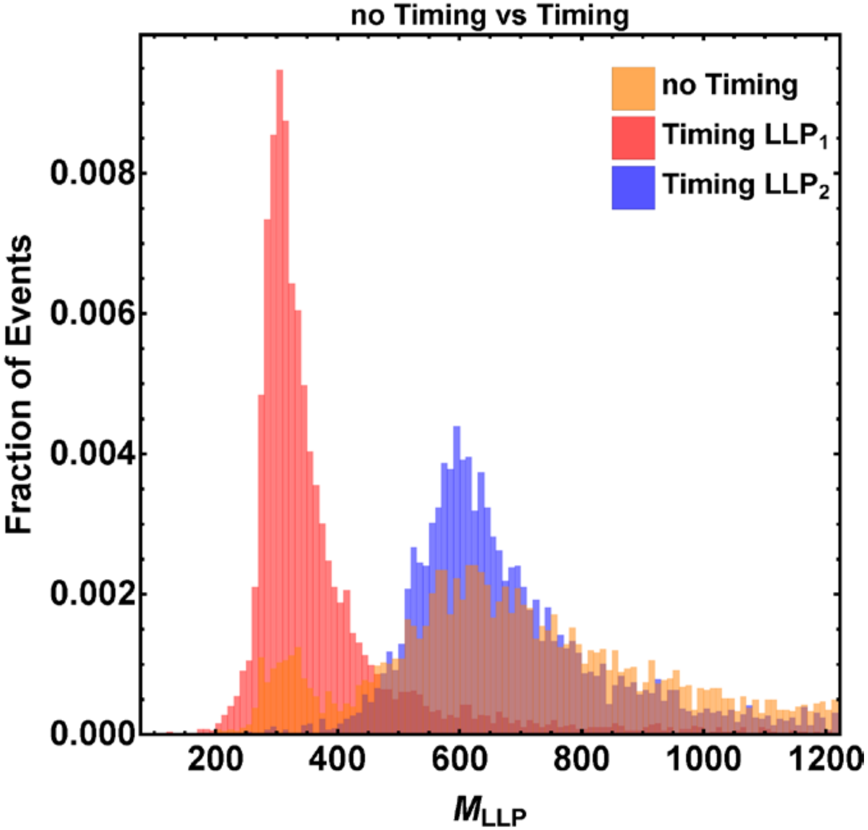


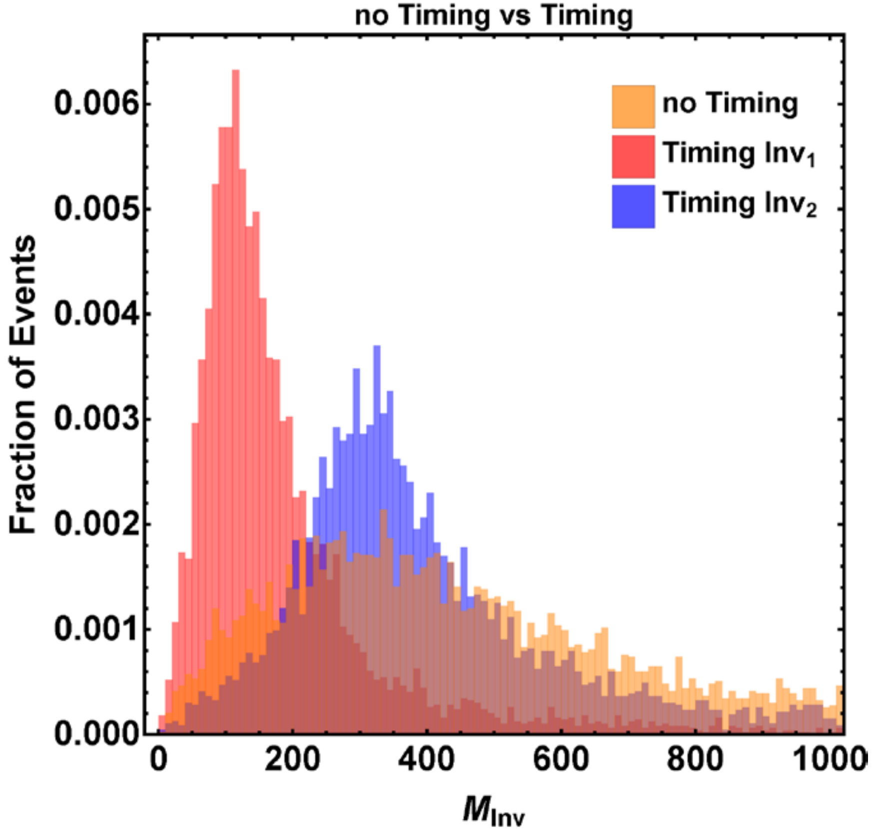
		m_{LLP_a}	m_{LLP_b}	m_{I_a}	m_{I_b}
Case 1	w/o timing	397.6 ± 1.2	397.6 ± 1.2	206.0 ± 1.5	206.0 ± 1.5
	timing	400.91 ± 0.35	400.77 ± 0.35	201.53 ± 0.49	201.53 ± 0.49

Case2: $LLP_a \neq LLP_b, I_a \neq I_b$

MC result: Sol2

M_{LLP_a}: 300 GeV, M_{LLP_b}: 600 GeV
M_{I_a} : 100 GeV, M_{I_a} : 300 GeV

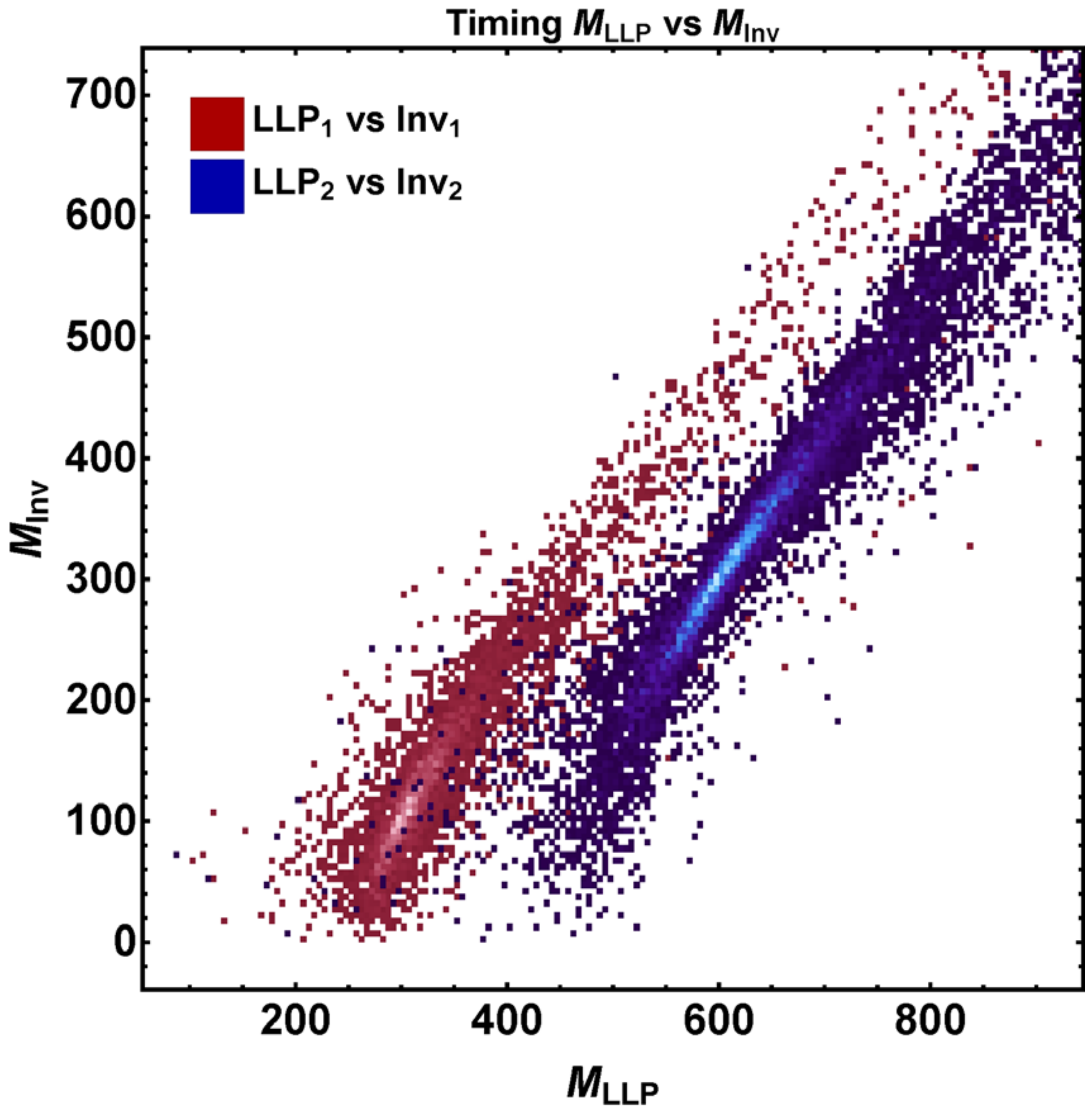




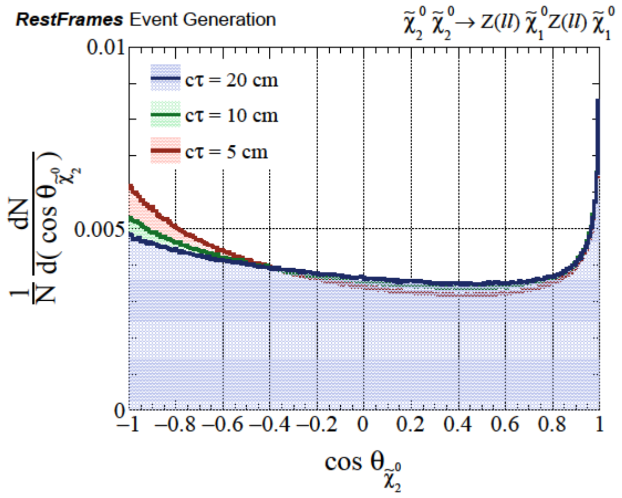
		m_{LLP_a}	m_{LLP_b}	m_{I_a}	m_{I_b}
Case2	w/o timing	-	-	-	-
	timing	307.25 ± 0.38	612.18 ± 0.72	118.54 ± 0.89	319.1 ± 1.1

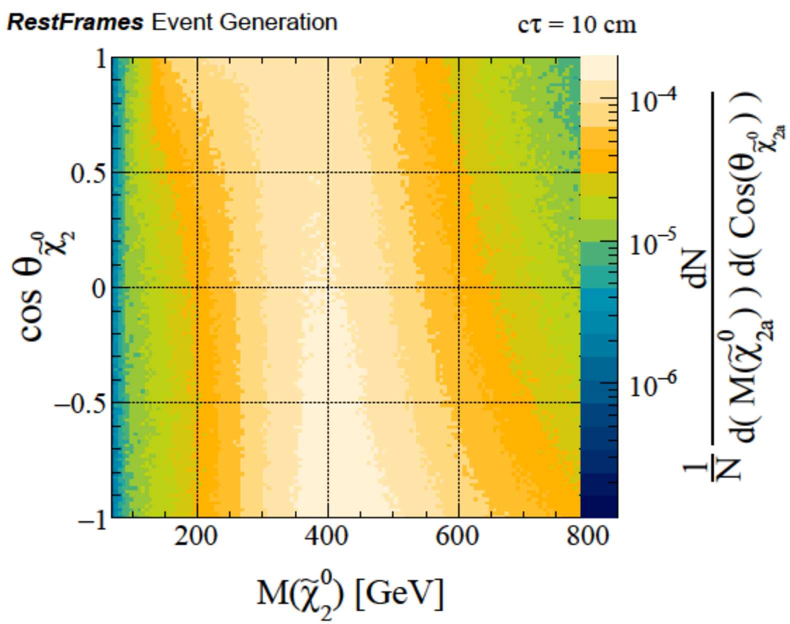
MC result: Sol2

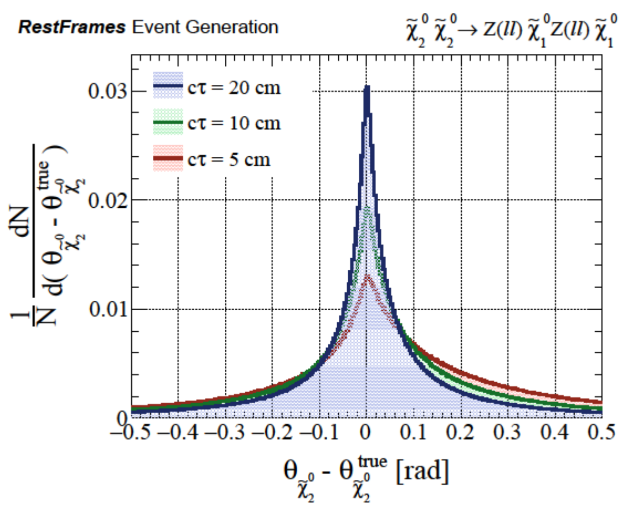
M_{LLP_a}: 300 GeV, M_{LLP_b}: 600 GeV
M_{I_a} : 100 GeV, M_{I_a} : 300 GeV



LLP decay angle







- We can reconstruct the entire event including the LLP decay angle, which can be used to remove poorly-measured events

Summary

		m_{LLP_1}	m_{LLP_2}	m_{I_1}	m_{I_2}	p_{LLP_1}	p_{LLP_2}	p_{I_1}	p_{I_2}
Case 1	no timing	△	△	△	△	○	○	○	○
$LLP_a = LLP_b, I_a = I_b$	timing	○	○	○	○	○	○	○	○
Case2	no timing	×	×	×	×	○	○	○	○
$LLP_a \neq LLP_b, I_a \neq I_b$	timing	○	○	○	○	○	○	○	○

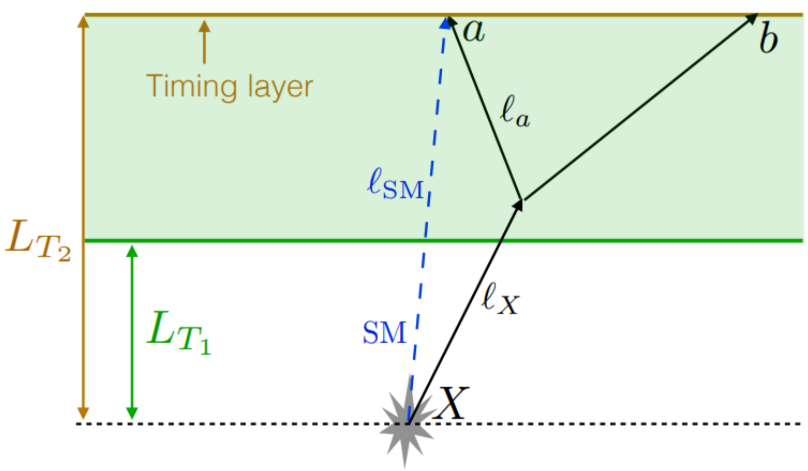
- Using timing information at HL-LHC we can measure the $\boldsymbol{\beta}$ of the long-lived particles.
- We can fully reconstruct the LLP events even if they decay to visible and invisible particles.
- Timing reconstruction method will flash the LLP searches at HL-LHC.

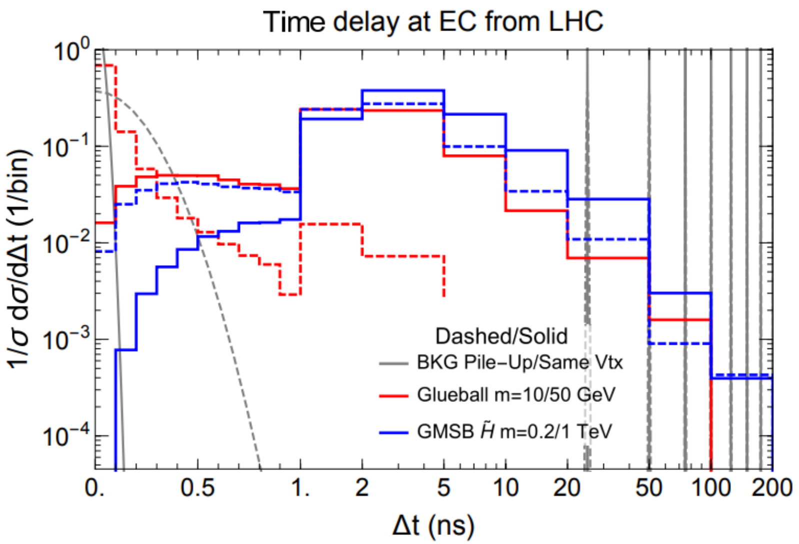
backup

Primary vertex uncertainty

- Time stamping

[J. Liu, Z. Liu and L. Wang, 1805.05957]

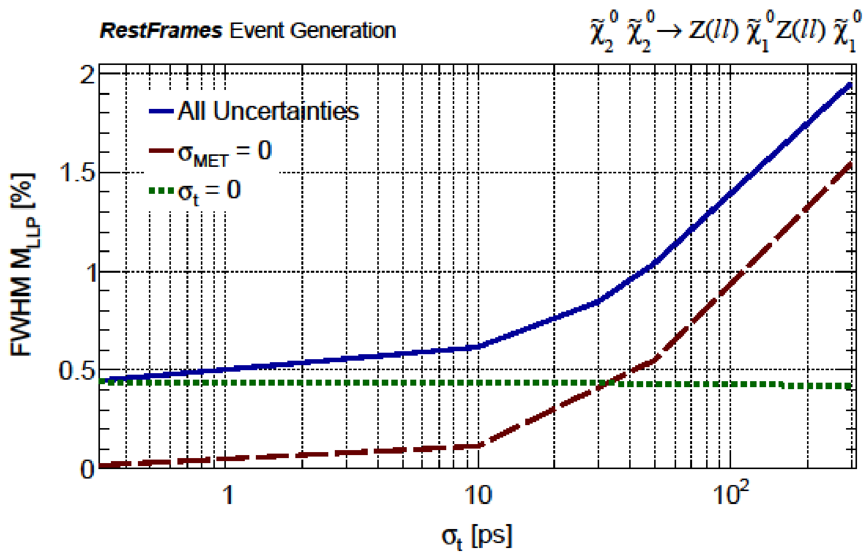


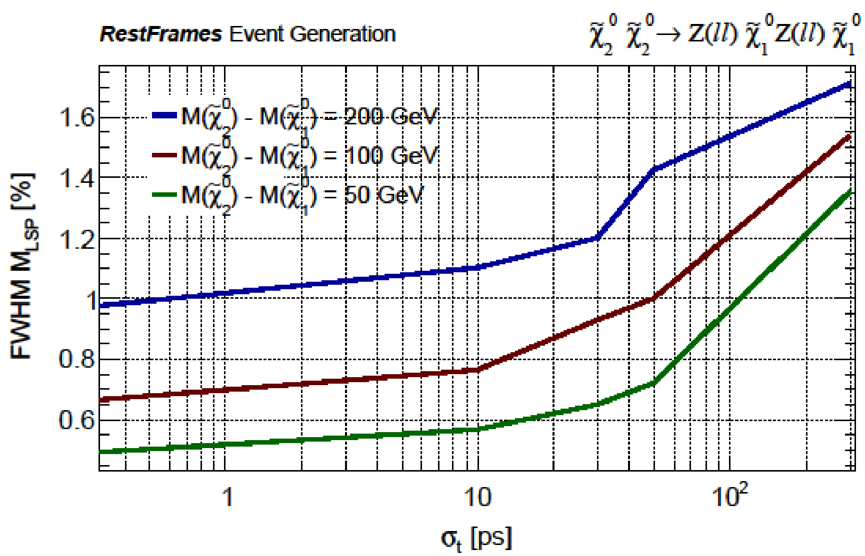


[M. Drewes, A. Giammanco, J. Hajer, M. Lucente, O. Mattelaer 1810.09400]

- For heavy ion collision, there is no Pile-up.
  - All tracks come from the same vertex.
  - → No uncertainty in primary vertex position.

Timing detector resolution





Monte Calro Simulation

- Event simulation with MG5_aMC+Pythia8
- Smearing
  - Position 12 μm
  - Momentum 2%
  - Timing 30ps
- Case1: $LLP_a = LLP_b, I_a = I_b$

  $M_{LLP_a} = M_{LLP_b} =$ 400 GeV

  $M_{I_a} = M_{I_b} =$ 200 GeV
- Case2: $LLP_a \neq LLP_b, I_a \neq I_b$

  M_{LLP_a}: 300 GeV, M_{LLP_b}: 600 GeV

  M_{I_a} : 100 GeV, M_{I_a} : 300 GeV