Time-Information at Colliders

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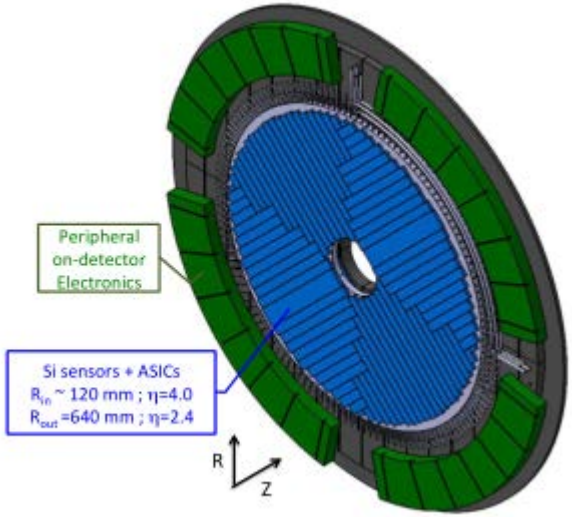
LHC / HL-LHC Plan

	LHC	HL-LHC
Bunch spacing	25 ns	25 ns
Vertex line density	~0.4 events/mm	~1.3 or 1.9 events/ mm
Pile up	30-50	140-200

ATLAS and CMS plan to install the new detector components during LS3 to resolve the pile-up issue

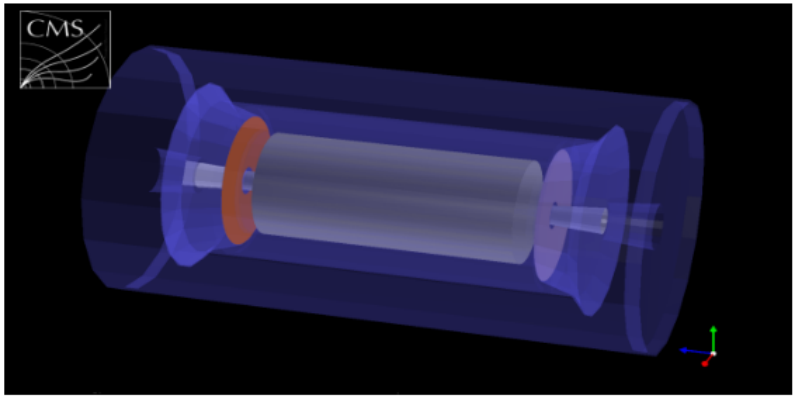
Timing detector @ HL-LHC

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



[ATL-LARG-PROC-2018-003]

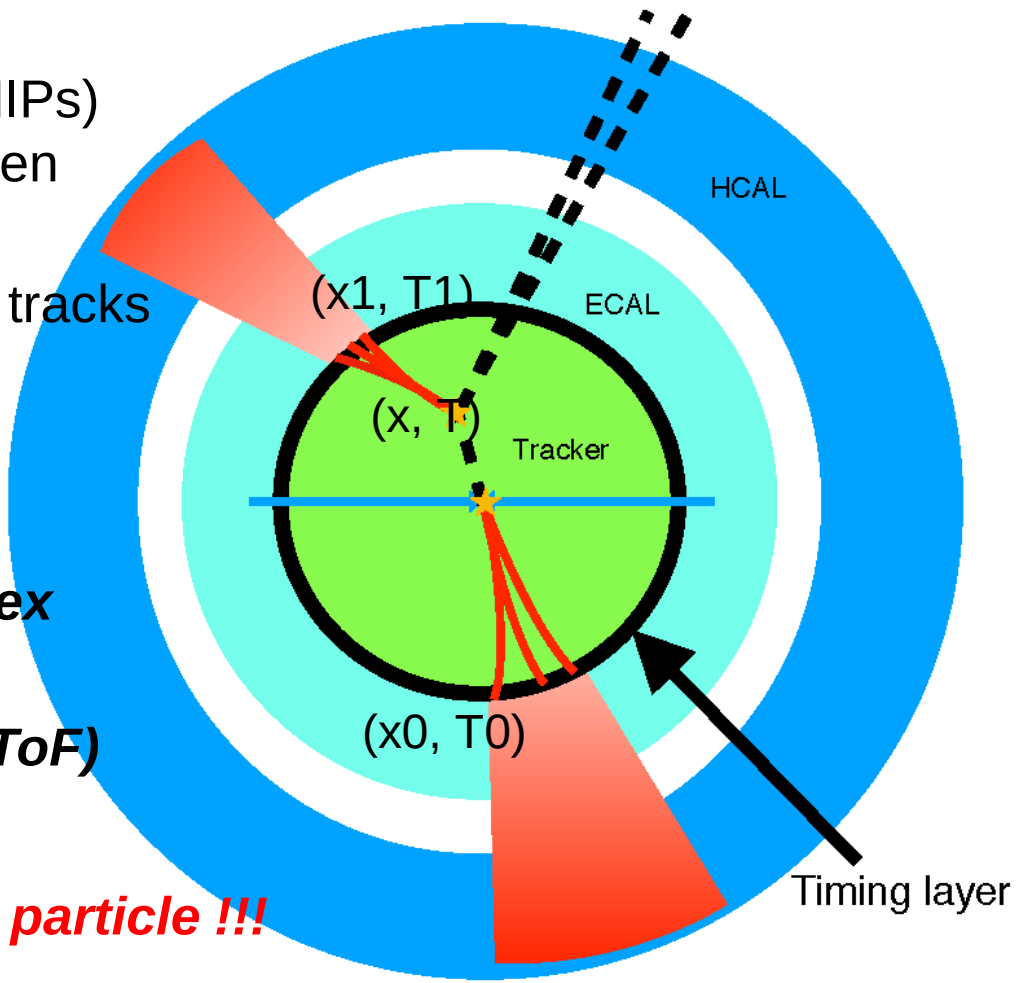
- CMS
  - Minimum ionizing particles (MIPs) Timing Detector (MTD) between tracker and ECAL
  - ~30 ps resolution for charged tracks
  - Coverage $|\eta| < 3.0$



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

Timing detector @ HL-LHC

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



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

+

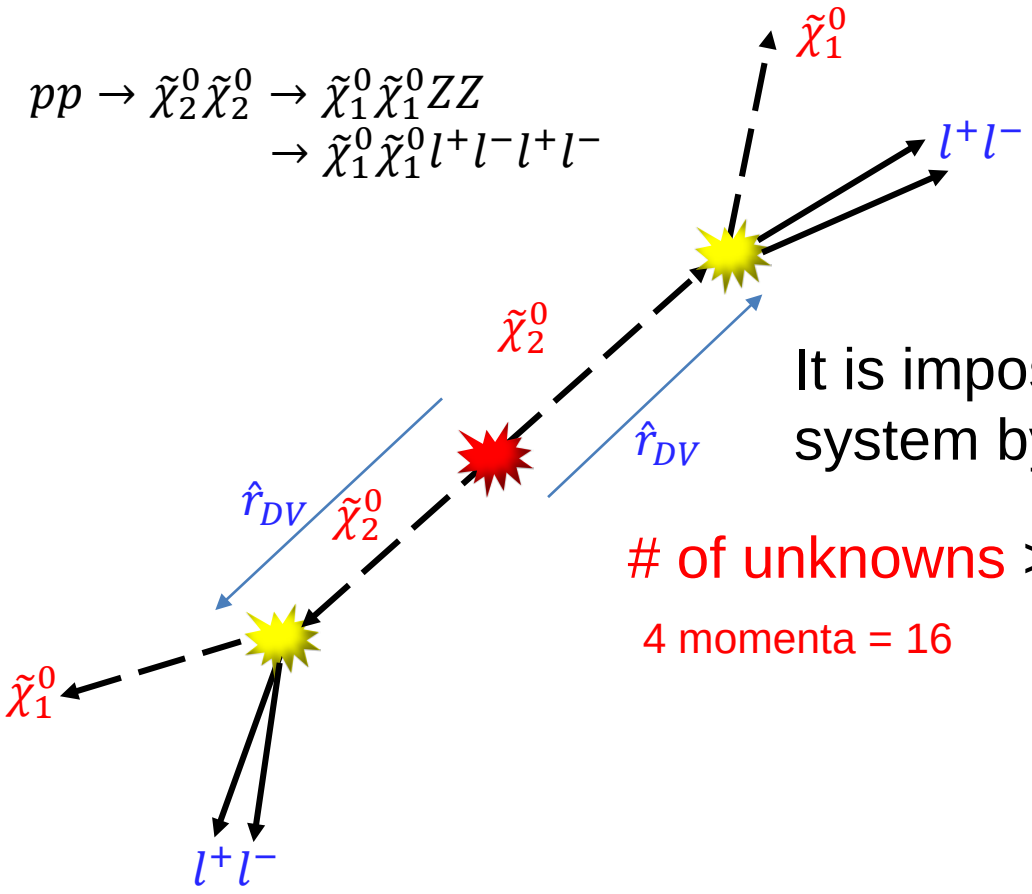
- We can measure ***time of flight (ToF)***

↓

- 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

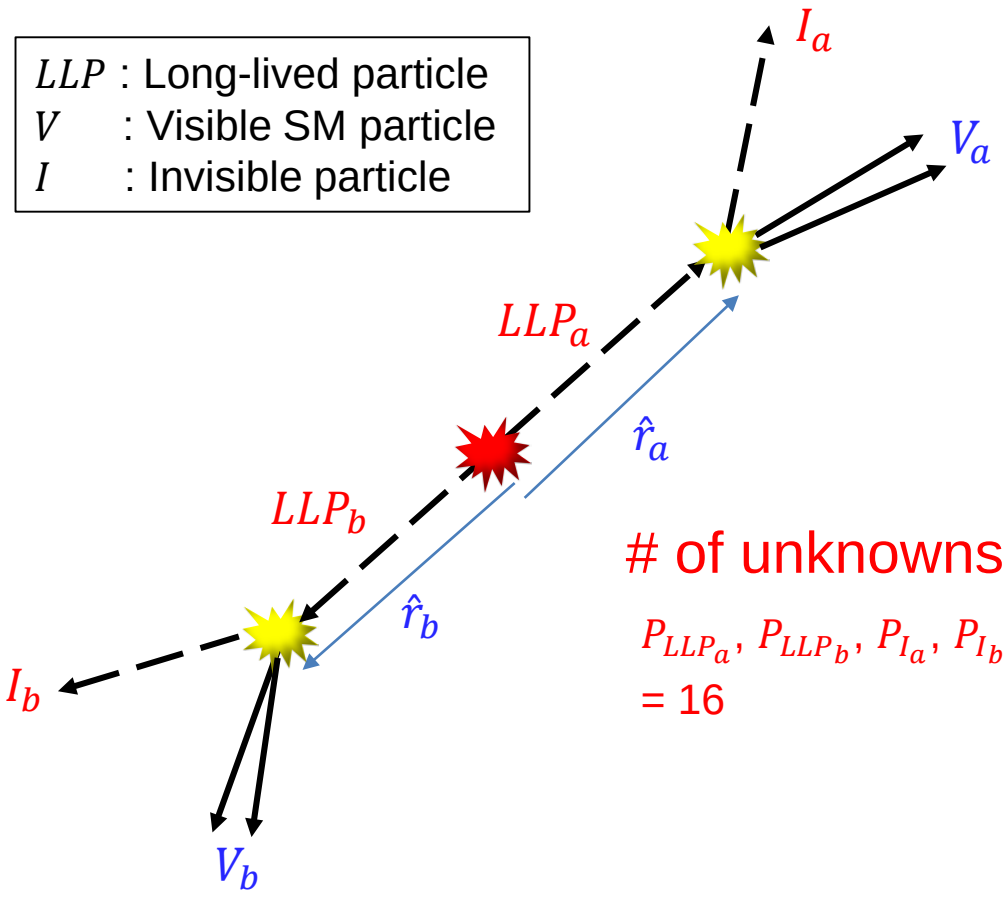
p_T^{miss} = 2

2 displaced vertices = 4

How can we solve this kind of system?

Sol1: Reconstruction without timing

LLP : Long-lived particle
V : Visible SM particle
I : Invisible particle



# of unknowns = # of knowns + # of constraints

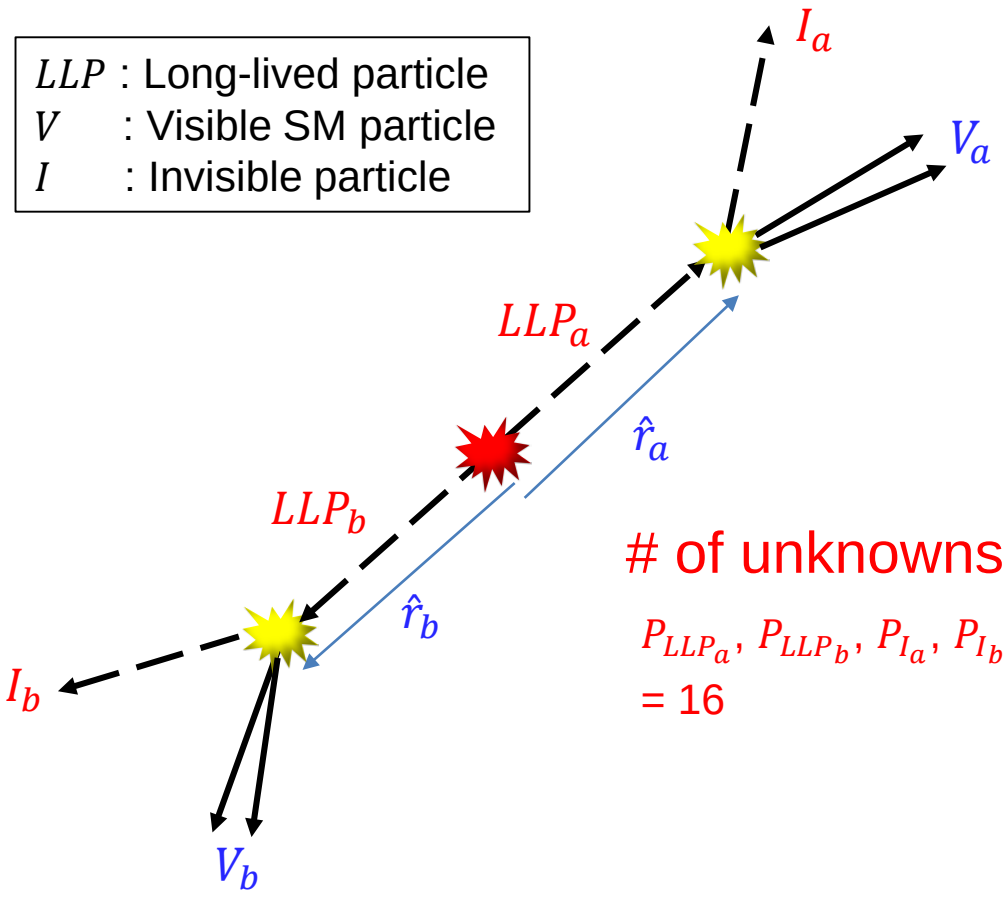
P_{LLP_a}, P_{LLP_b}, P_{I_a}, P_{I_b} = 16	P_{V_a}, P_{V_b}	= 8
	p_T^{miss}	= 2
	$\hat{r}_a$, $\hat{r}_b$	= 4

Sol1: 2 assumptions

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

Sol2: Reconstruction with timing

LLP : Long-lived particle
V : Visible SM particle
I : Invisible particle



# 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

- 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

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

- 3-momenta of LLPs

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

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

- 4-momentum conservation

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

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

- 3-momenta of invisible particles

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

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

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

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

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***

Is this really useful?

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

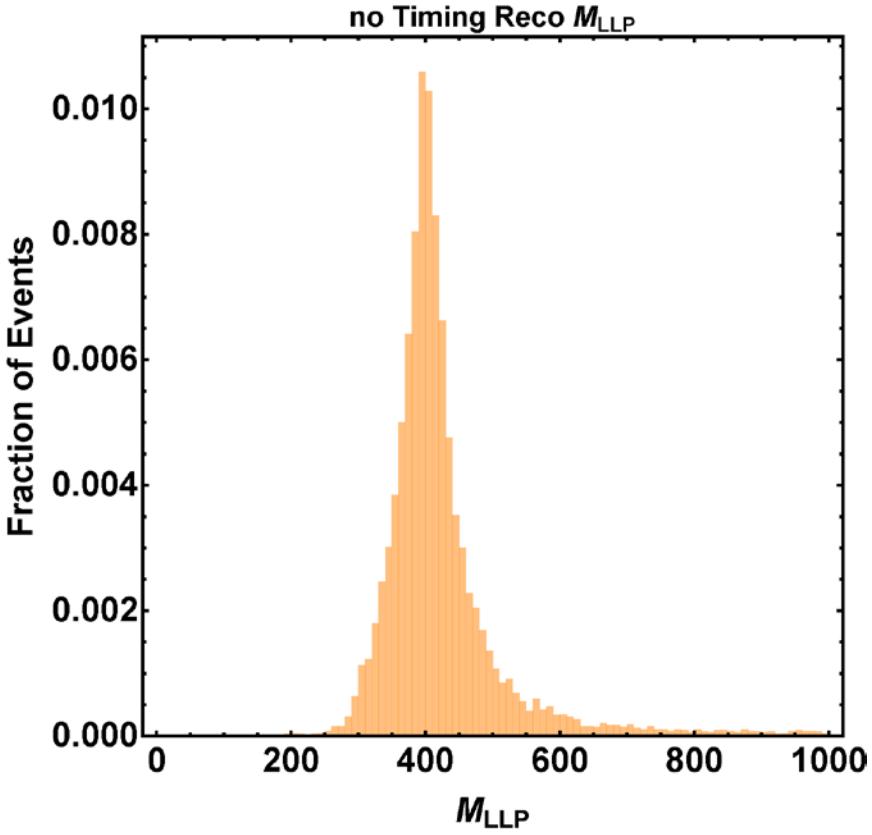
  M_{LLP_a}: 300 GeV, M_{LLP_b}: 600 GeV

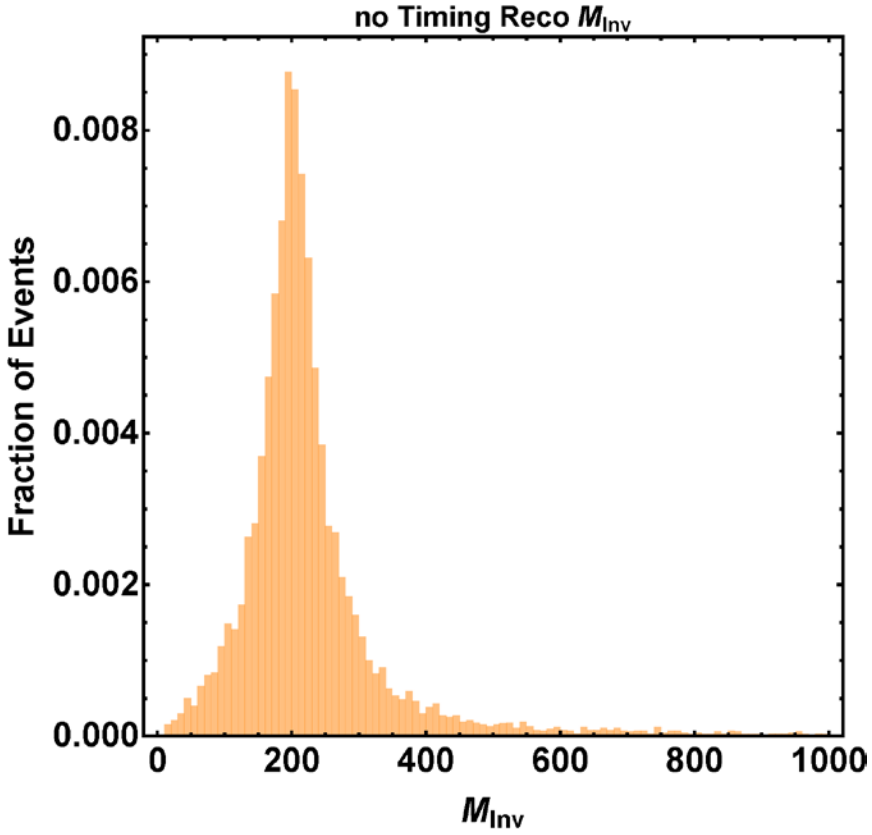
  M_{I_a} : 100 GeV, M_{I_a} : 300 GeV

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

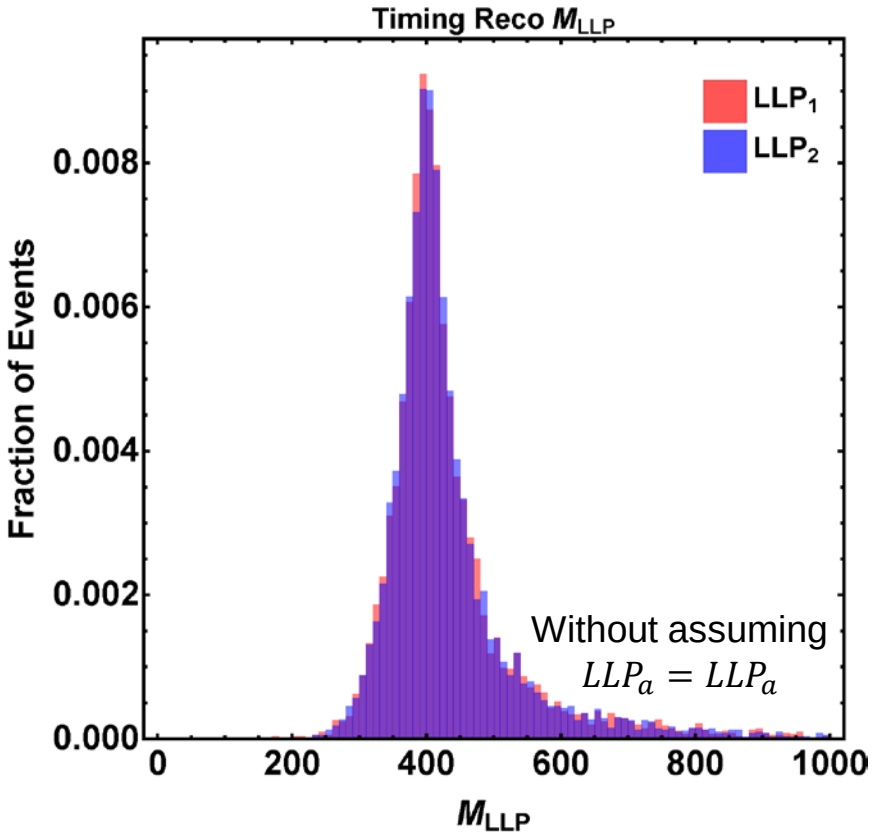


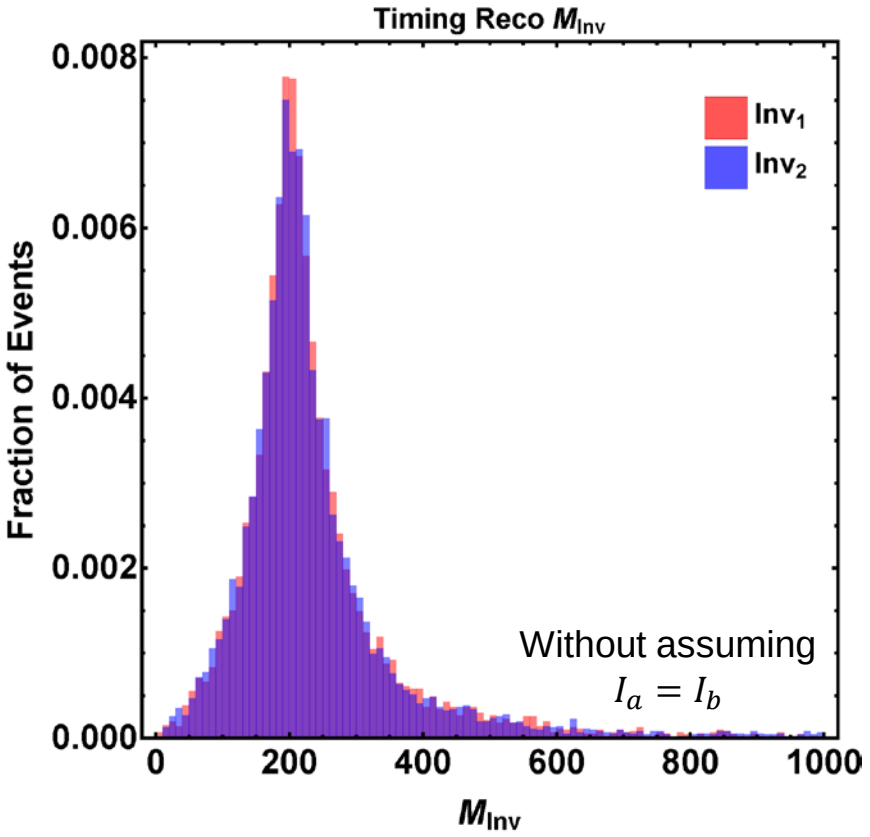


		m_{LLP_1}	m_{LLP_2}	m_{I_1}	m_{I_2}
Case 1	no timing	401.309	401.309	202.248	202.248

MC result: Sol2

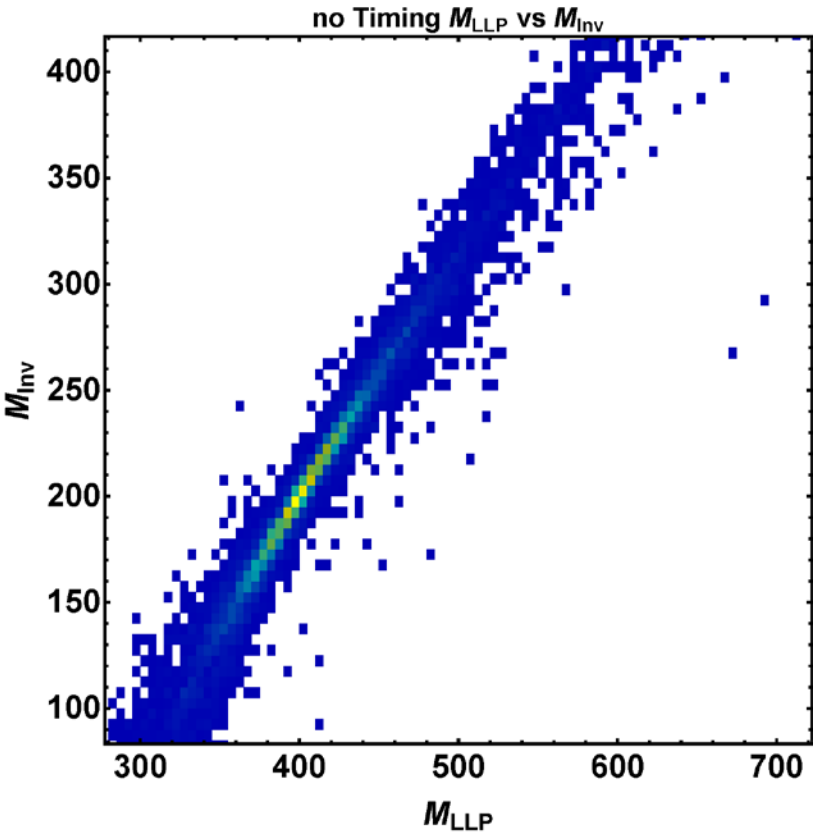
$M_{LLP_a} = M_{LLP_b} = 400$ GeV
$M_{I_a} = M_{I_b} = 200$ GeV

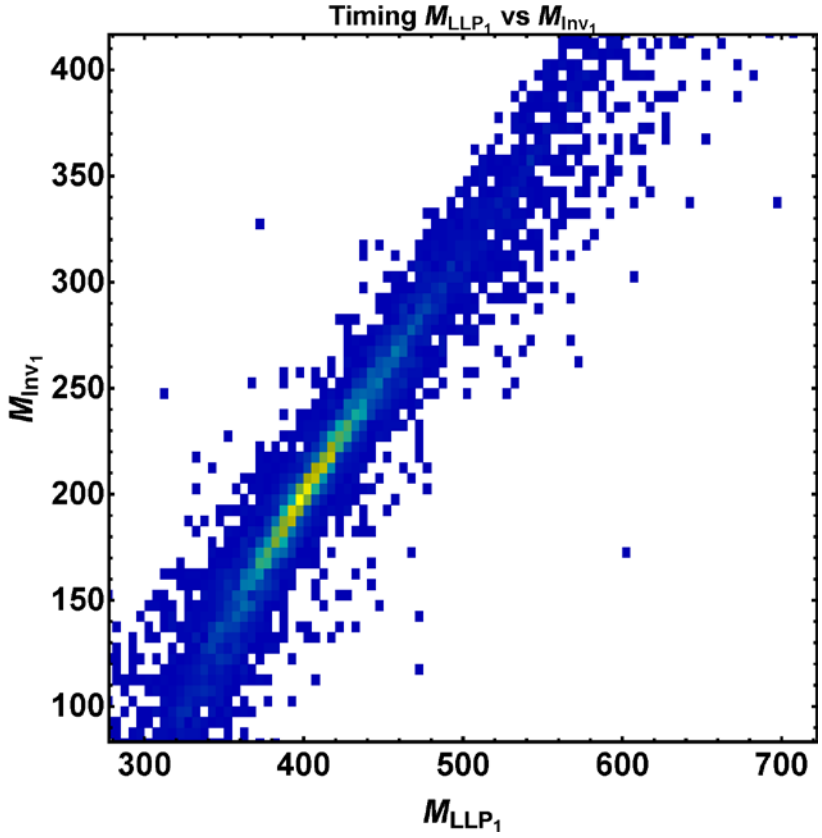




		m_{LLP_1}	m_{LLP_2}	m_{I_1}	m_{I_2}
Case 1	no timing	401.309	401.309	202.248	202.248
	timing	404.506	404.343	206.347	205.872

MC result: Sol1 vs Sol2



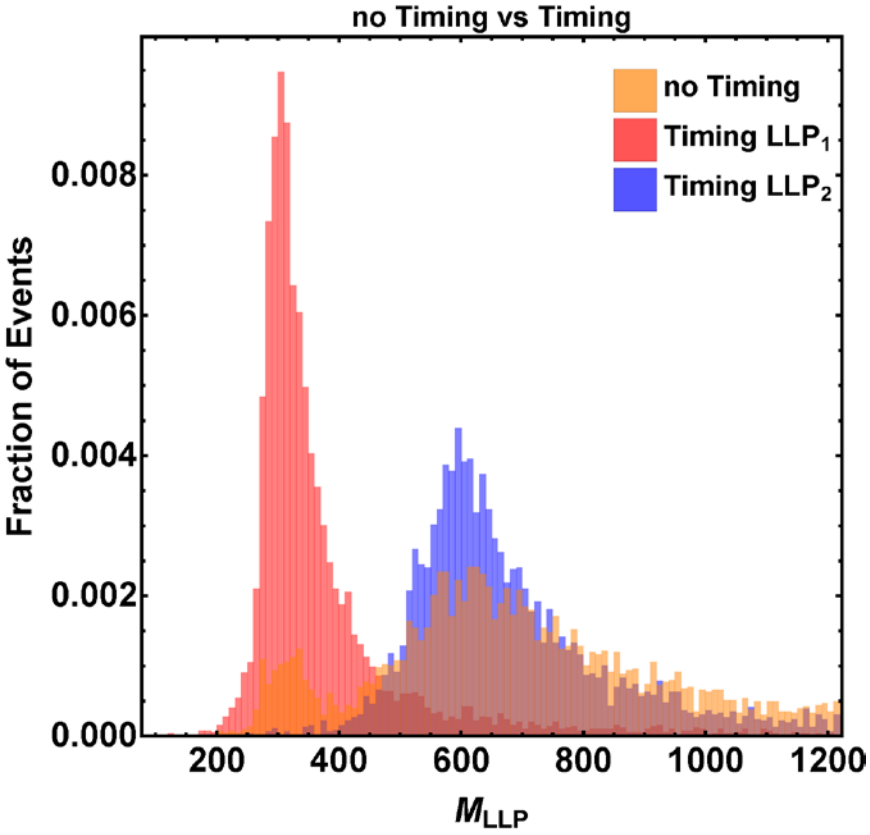


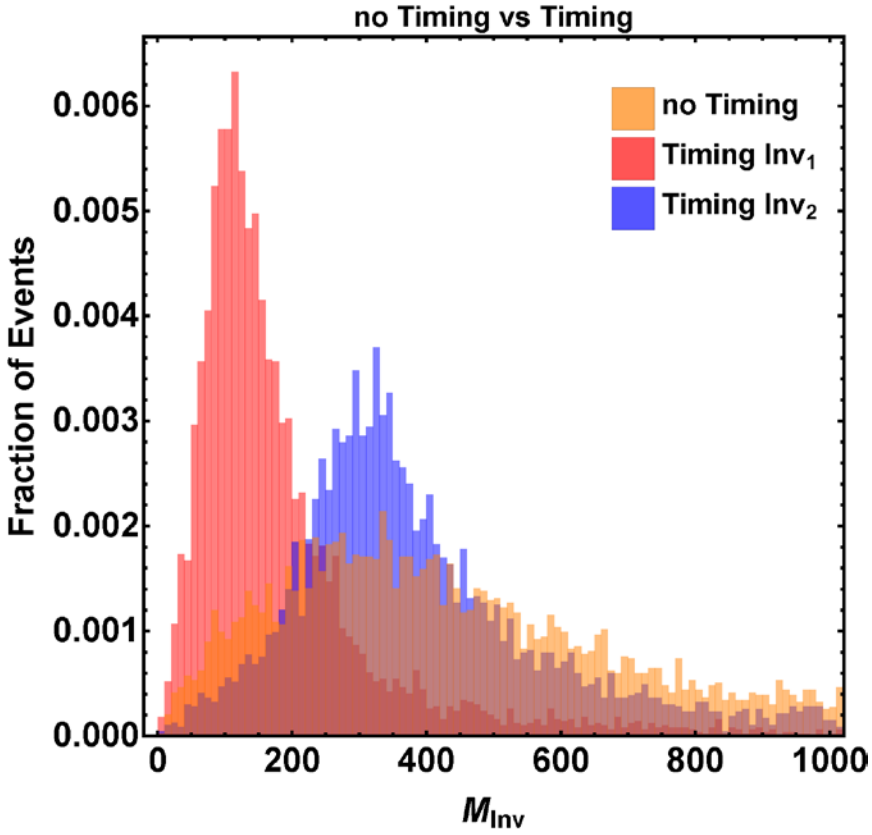
		m_{LLP_1}	m_{LLP_2}	m_{I_1}	m_{I_2}
Case 1	no timing	401.309	401.309	202.248	202.248
	timing	404.506	404.343	206.347	205.872

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

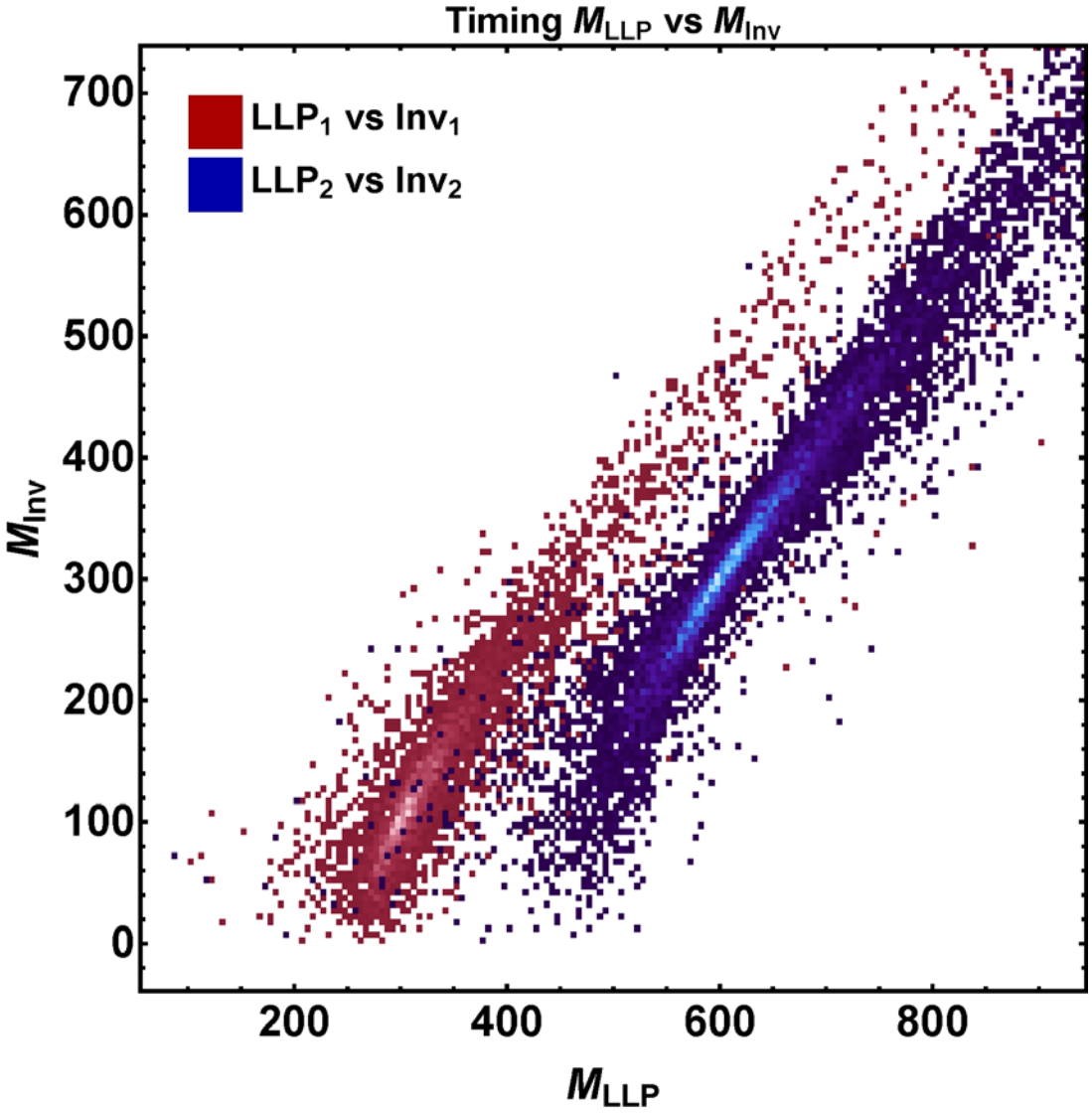




		m_{LLP_1}	m_{LLP_2}	m_{I_1}	m_{I_2}
Case2	no timing	-	-	-	-
	timing	319.307	633.317	132.094	341.503

MC result: Sol2

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



Summary

	m_{LLP_1}	m_{LLP_2}	m_{I_1}	m_{I_2}	$\boldsymbol{p}_{LLP_1}$	$\boldsymbol{p}_{LLP_2}$	$\boldsymbol{p}_{I_1}$	$\boldsymbol{p}_{I_2}$
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	○	○	○	○	○	○	○	○

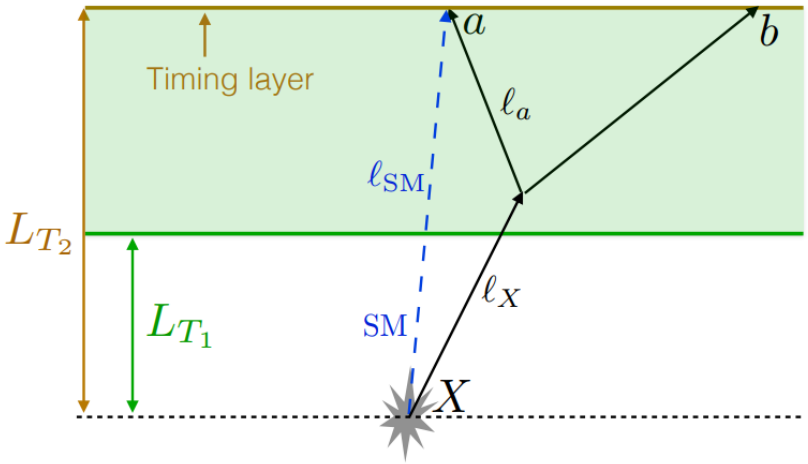
- Using timing information at HL-LHC we can measure the $\boldsymbol{\beta}$ of the long-lived particles.
- We can fully reconstruct the LLP events even if they decay to visible and invisible particles.
- Timing reconstruction method will flash the LLP searches at HL-LHC.

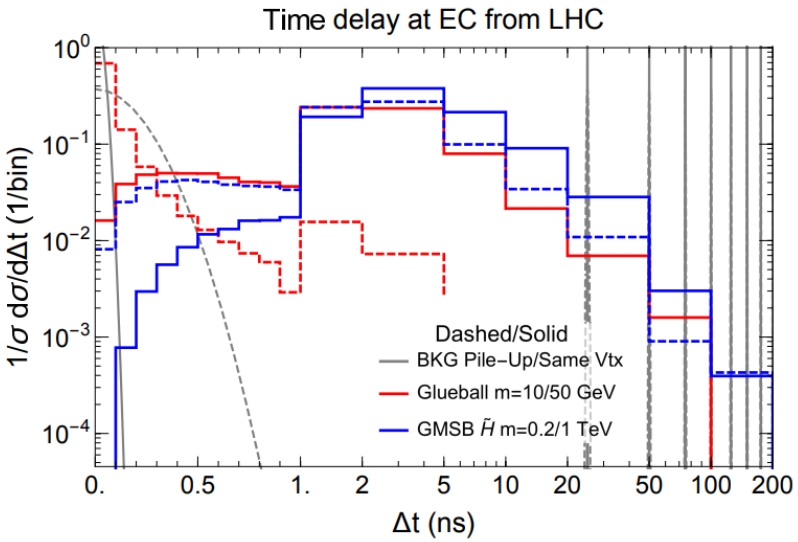
backup

Primary vertex uncertainty

- Time stamping

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

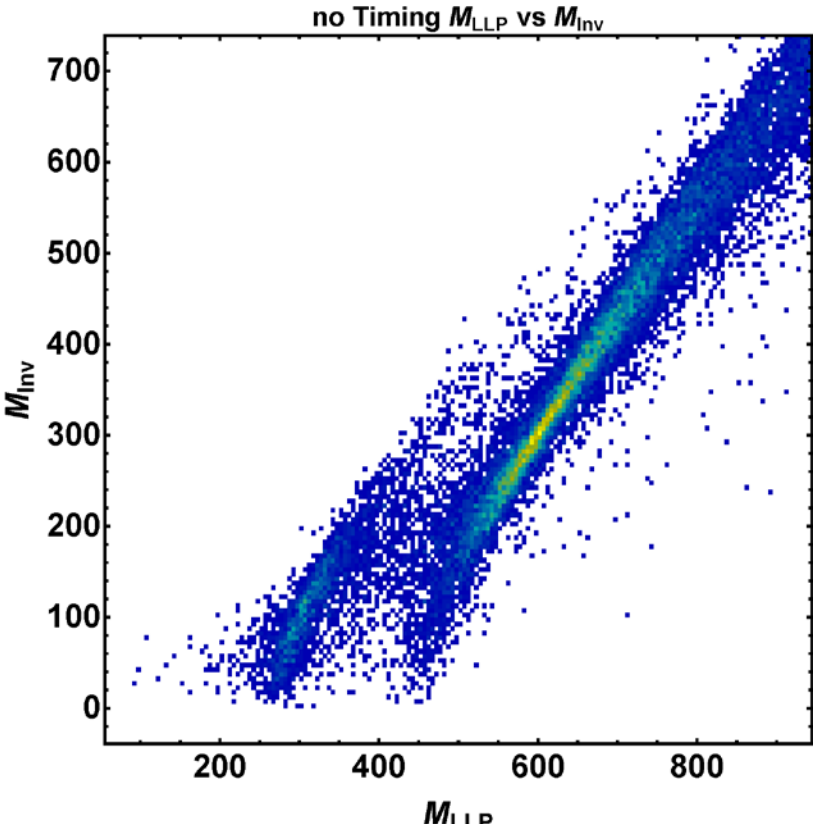


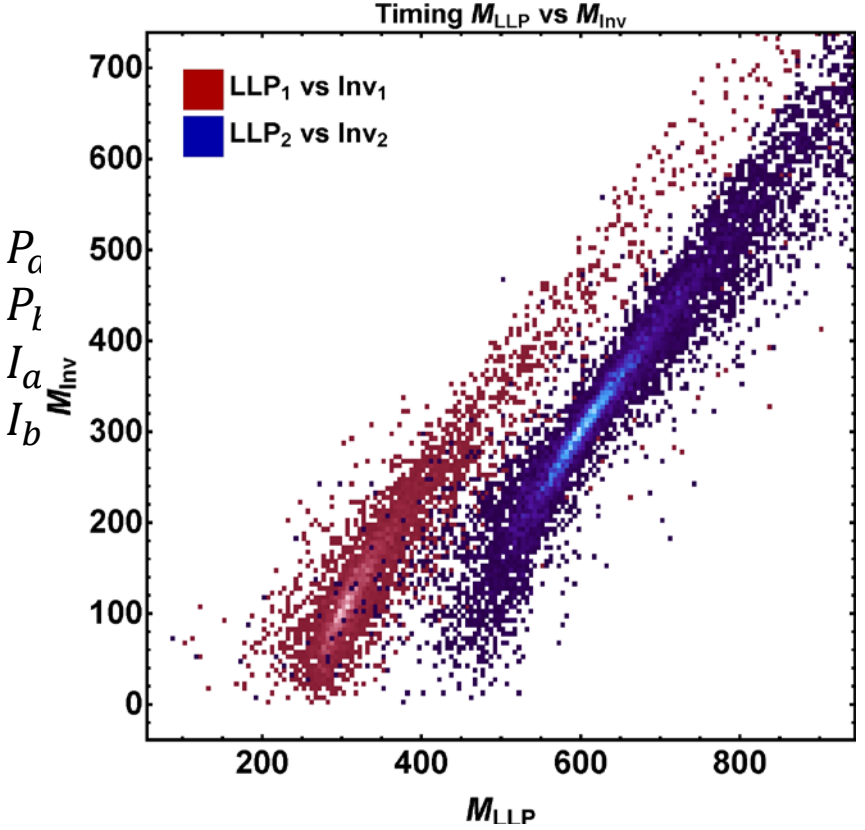


[M. Drewes, A. Giammanco, J. Hajer, M. Lucente, O. Mattelaer 1810.09400]

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

MC result: Sol1 vs Sol2





		m_{LLP_1}	m_{LLP_2}	m_{I_1}	m_{I_2}
Case2	no timing	-	-	-	-
	timing	319.307	633.317	132.094	341.503