KIAS 고등과학원 KOREA INSTITUTE FOR ADVANCED STUDY

Long-lived particle search using timing detector at HL-LHC

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Based on arXiv:1903.05825
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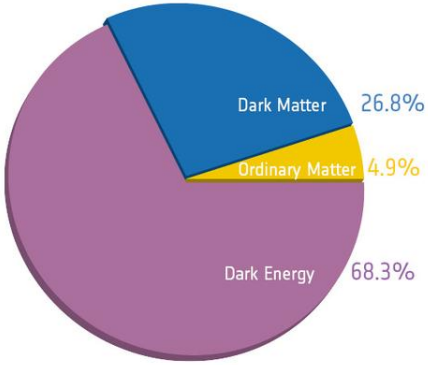
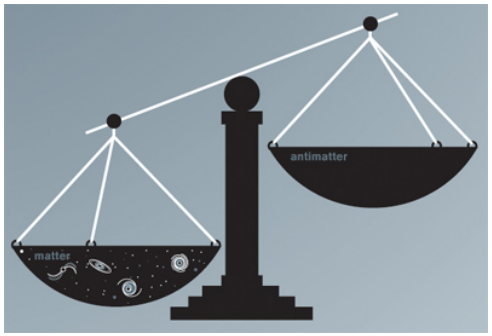
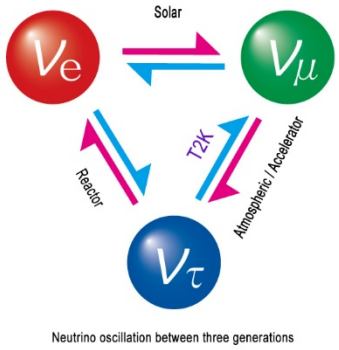
Where is new physics?

Observational Evidences

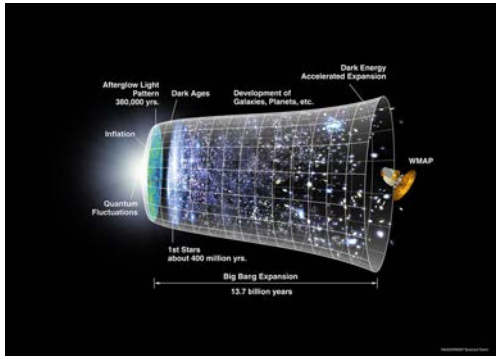
- Dark Matter problem
- Matter-Antimatter asymmetry
- Neutrino mass
- …







Neutrino oscillation between three generations



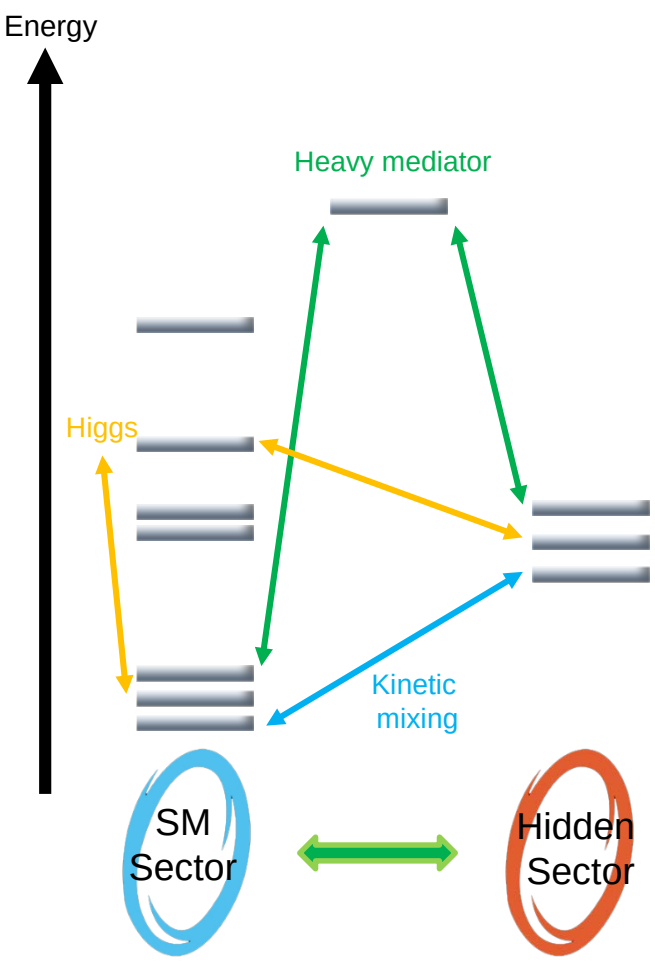
All of these problems imply that the SM is not a complete model.

We need new physics beyond the SM.

“Hidden” area?

- The new physics may “hidden” in high scale (e.g. SUSY or Extra dimension or Composite dynamics).
- “Hidden” in hidden sector.
- “Hidden” in experimentally unreachable area.

Hidden Sector



- Hidden sector typically have mediator particle
- Without the portal coupling, the hidden sector particles are stable themselves
- The portal coupling makes hidden sector particles unstable and they decay back to SM with relatively long life time

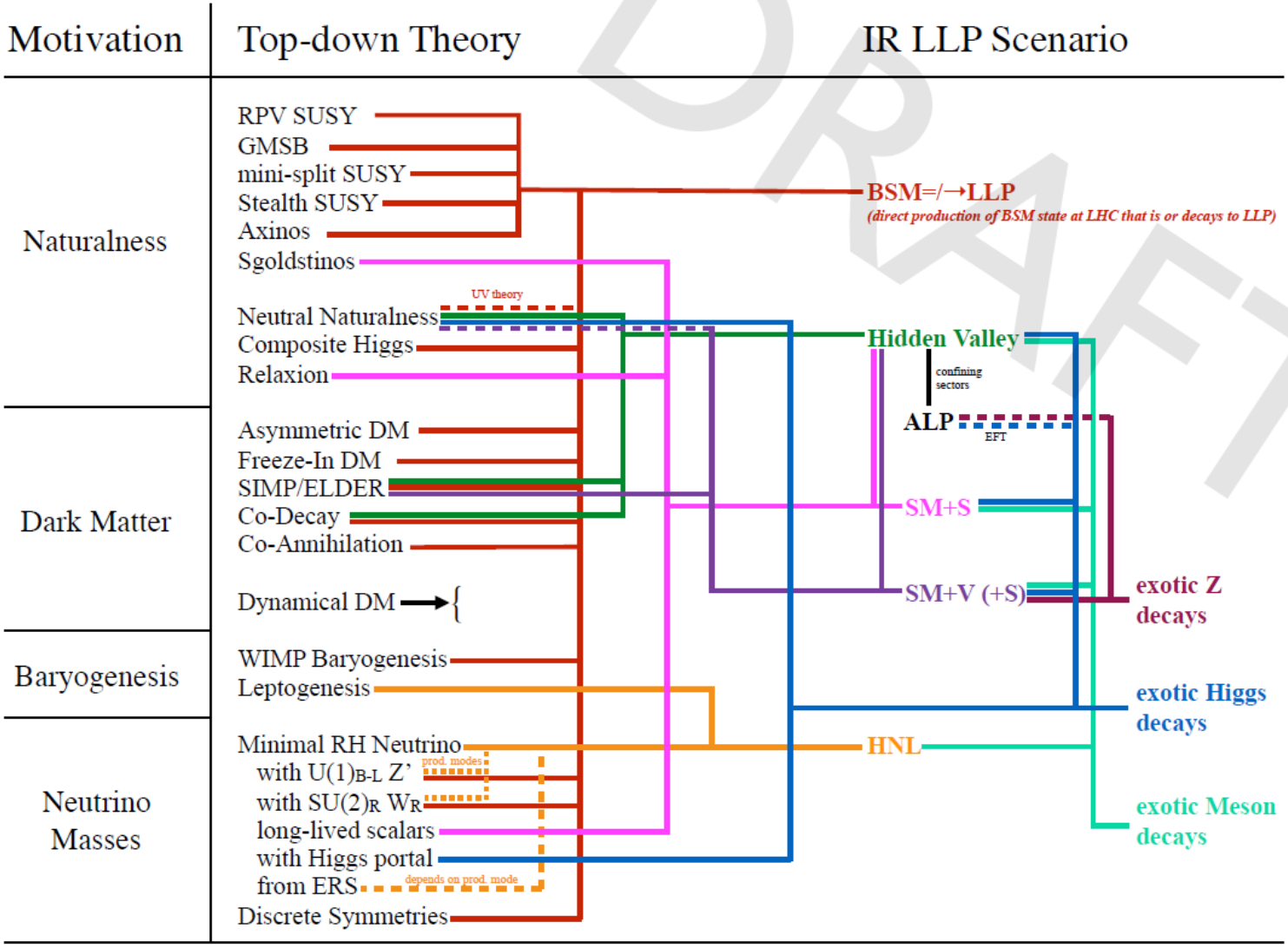
Approximate symmetry Small coupling
Heavy mediator Lack of phase space

$$c\tau \approx \frac{1.2\,\mathrm{fm}}{g^4}\left(\frac{M_{mediator}}{M_{LLP}}\right)^4\left(\frac{1\,\mathrm{TeV}}{M_{LLP}}\right)$$

- This Long Lived Particles (LLPs) can produced at colliders and decay back to the SM after flying some distance

LLP search can reveal the mysteries of our nature

LLP is well motivated



DRAFT

Advantage of Hidden Sector

- Such hidden sector can be explored in both high energy frontier and intensity frontier.
- Also new detector for LLP search is on the discussion.

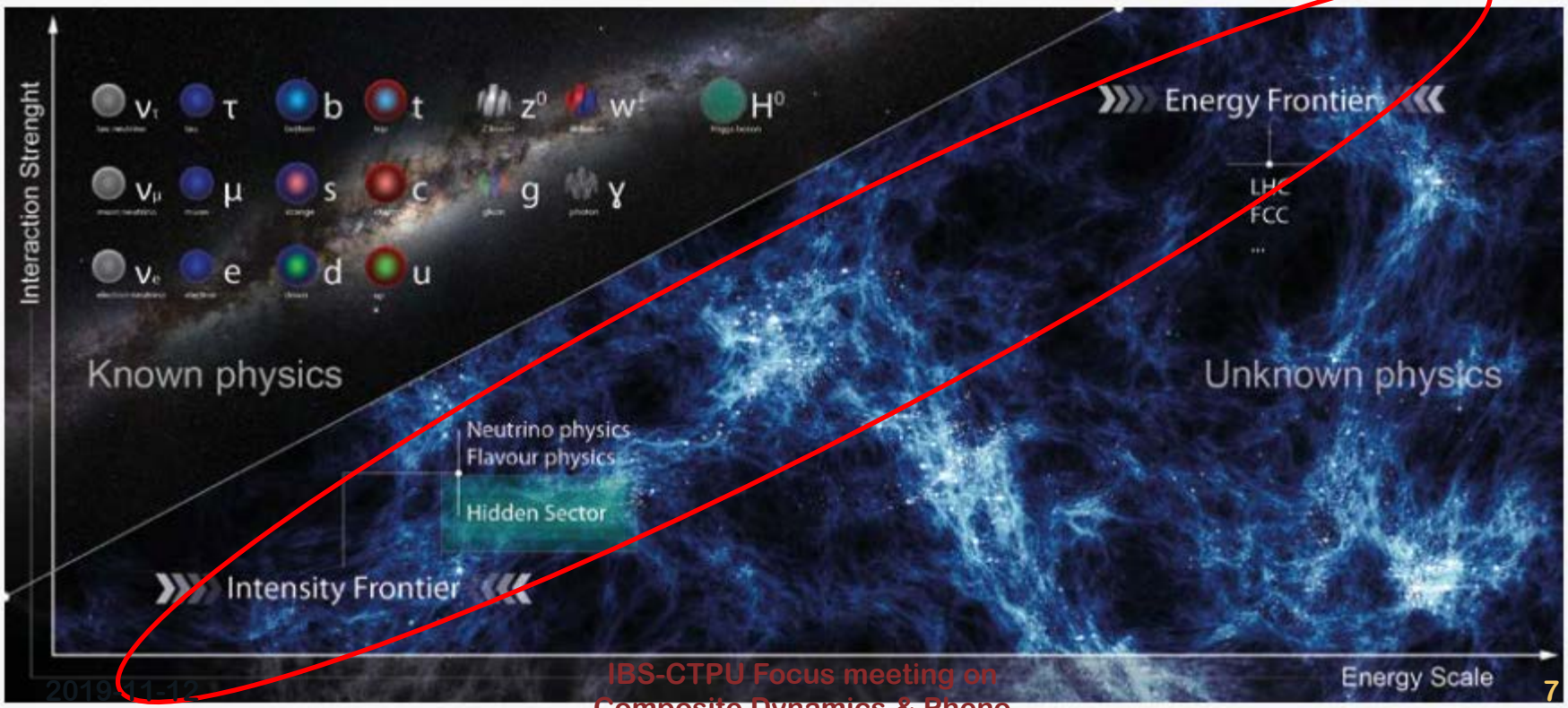


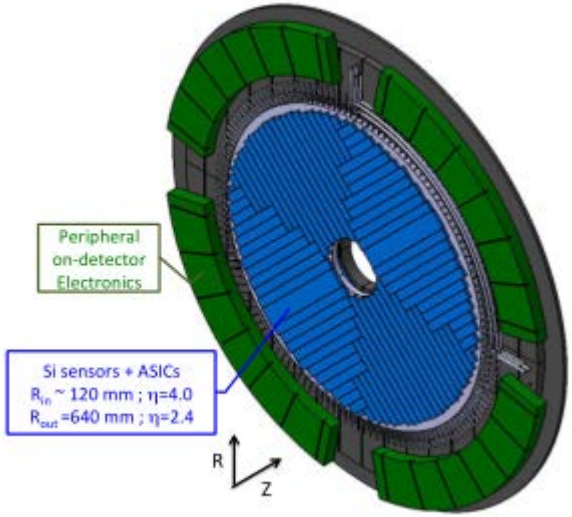
Image: CERN Courier 2/2016

Timing detector @ HL-LHC

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

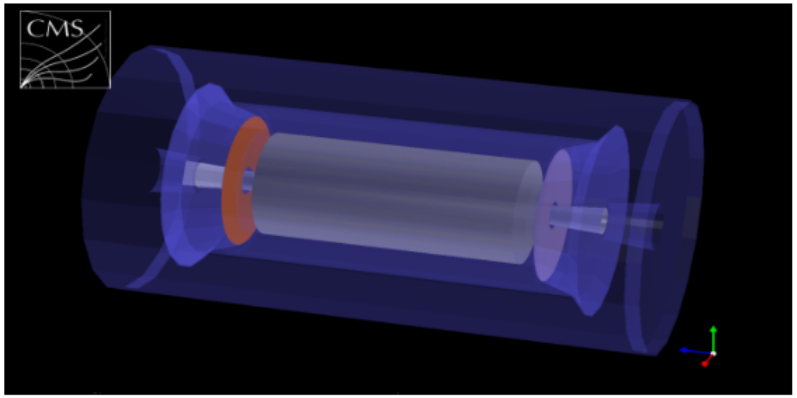
Timing detector @ HL-LHC

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



[ATL-LARG-PROC-2018-003]

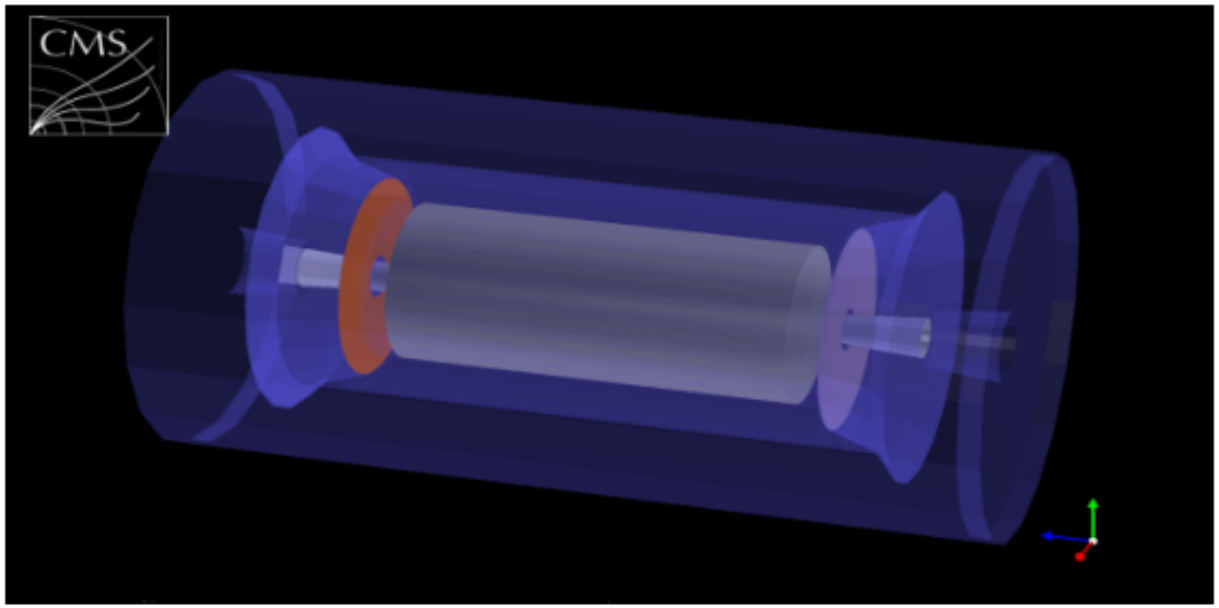
- CMS
  - Minimum ionizing particles (MIPs) Timing Detector (MTD) between tracker and ECAL
  - ~30 ps resolution for charged tracks
  - Coverage $|\eta| < 3.0$



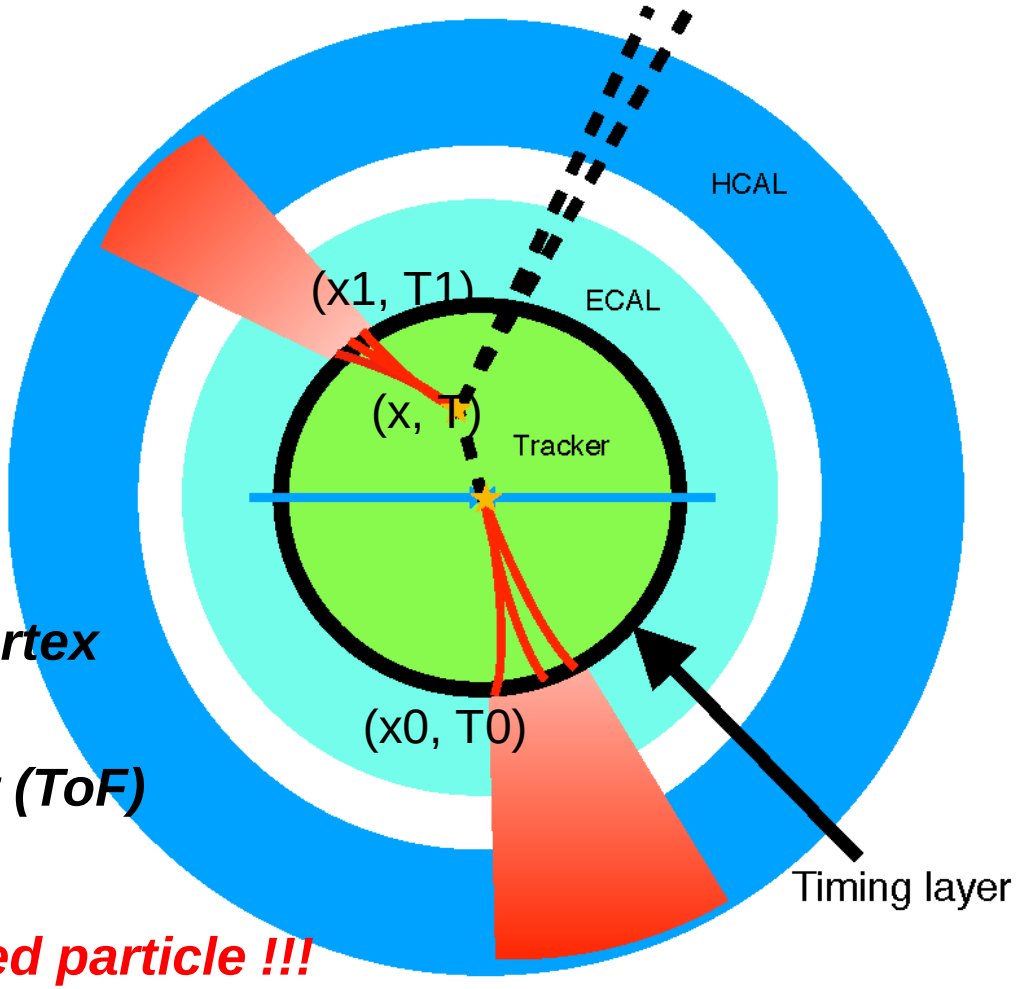
[CERN-LHCC-2017-027/LHCC-P-009]

MIP Timing detector (MTD)

- Barrel Timing Layer (BTL)
  - A thin LYSO+SiPM layer
- Endcap Timing Layer (ETL)
  - Low-gain Avalanche Diode (LGAD) layer
- Timing resolution 30ps & 99% efficiency



Timing detector @ HL-LHC



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

+

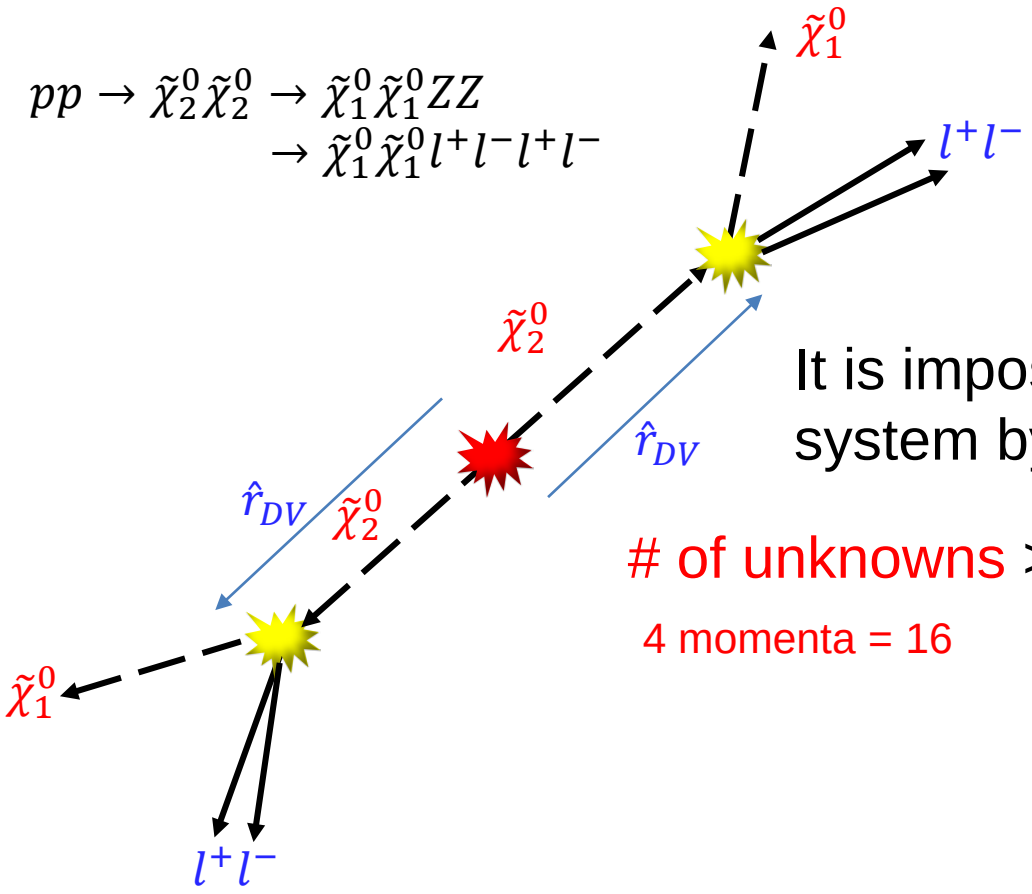
- We can measure ***time of flight (ToF)***

↓

- 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

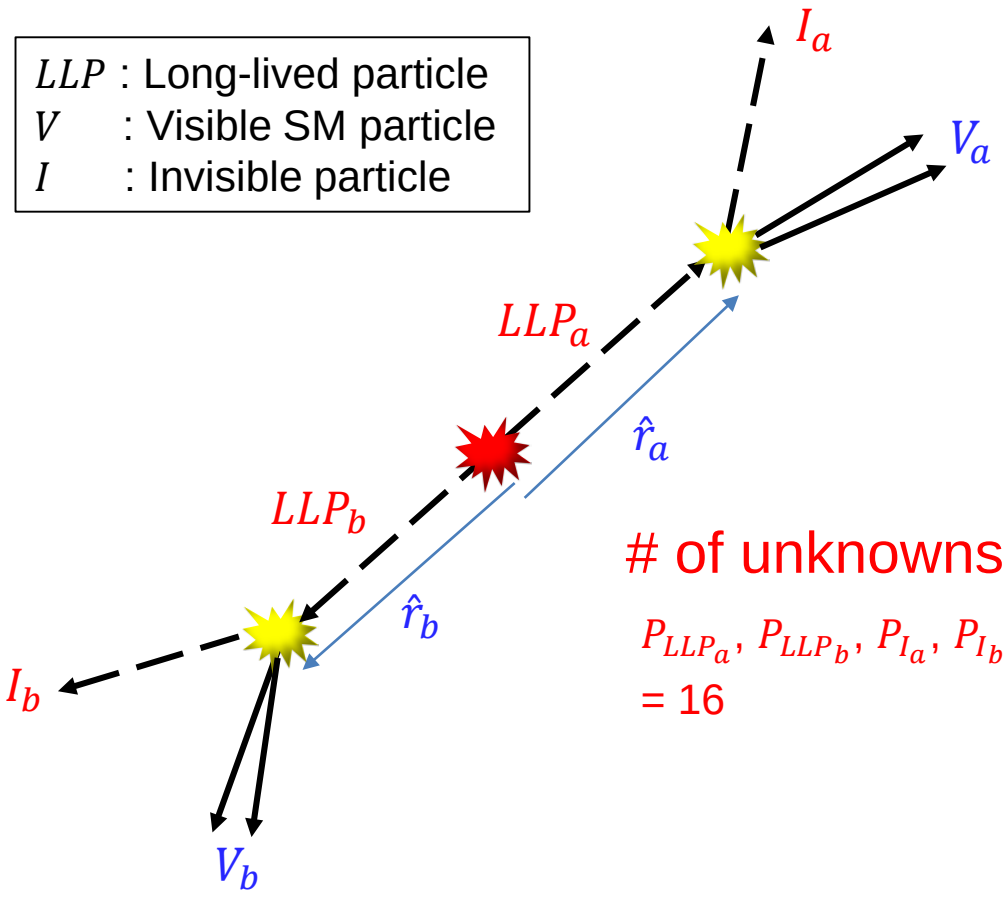
p_T^{miss} = 2

2 displaced vertices = 4

How can we solve this kind of system?

Sol1: Reconstruction without timing

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



What if ?

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

2 assumptions

# 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

Now we can solve system !

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

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

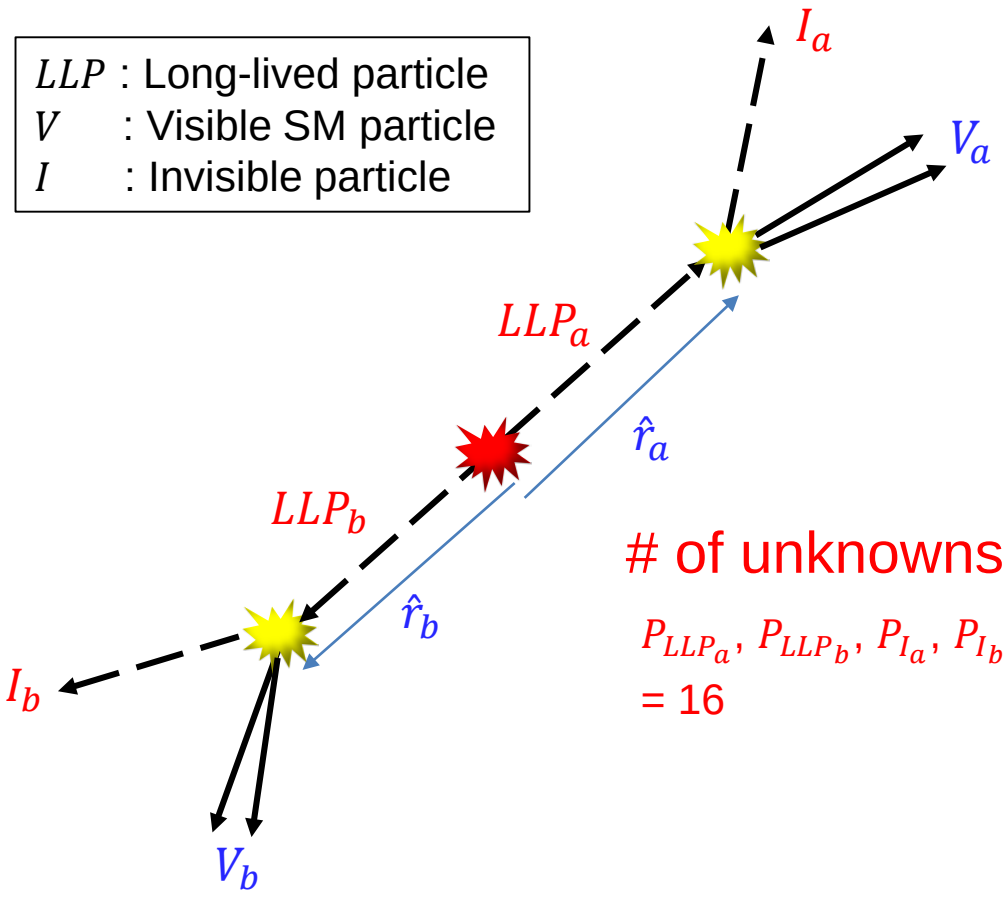
$$\boldsymbol{p}_{I_b} = \boldsymbol{p}_b - \boldsymbol{p}_{V_b}$$

- 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

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

2 timing information
T_a, T_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***

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

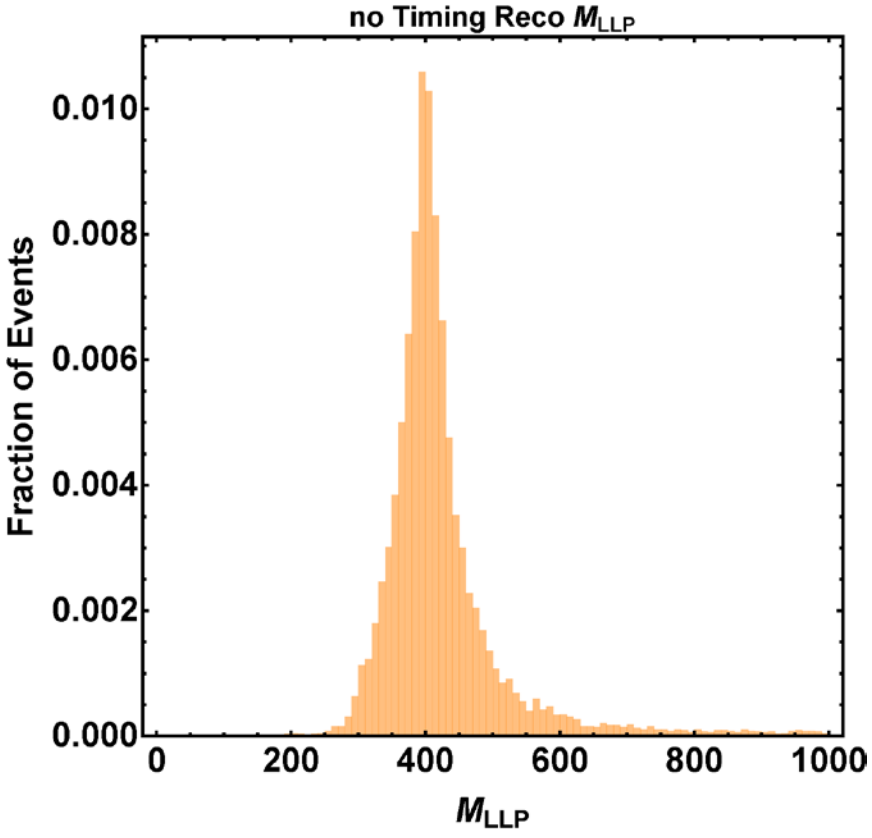
  M_{LLP_a}: 300 GeV, M_{LLP_b}: 600 GeV

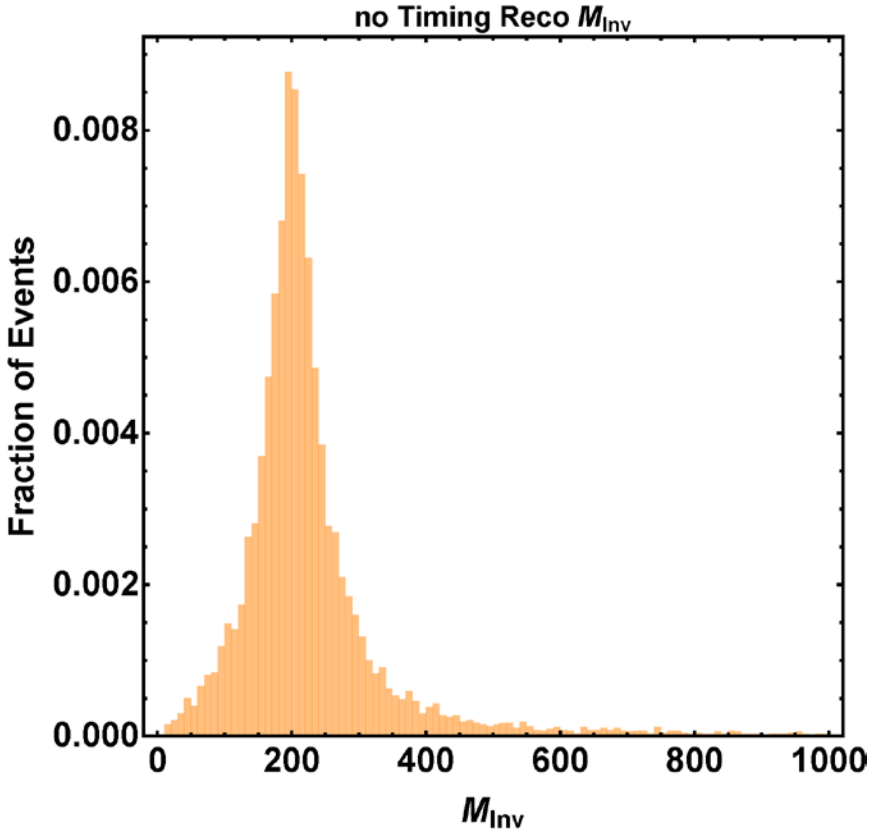
  M_{I_a} : 100 GeV, M_{I_a} : 300 GeV

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

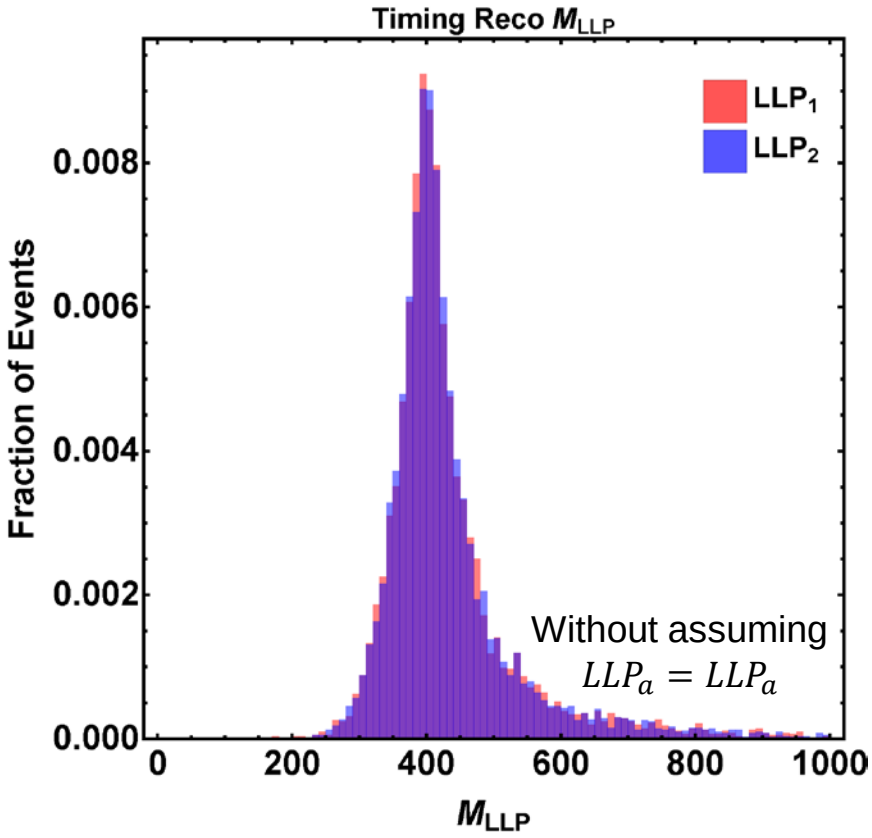


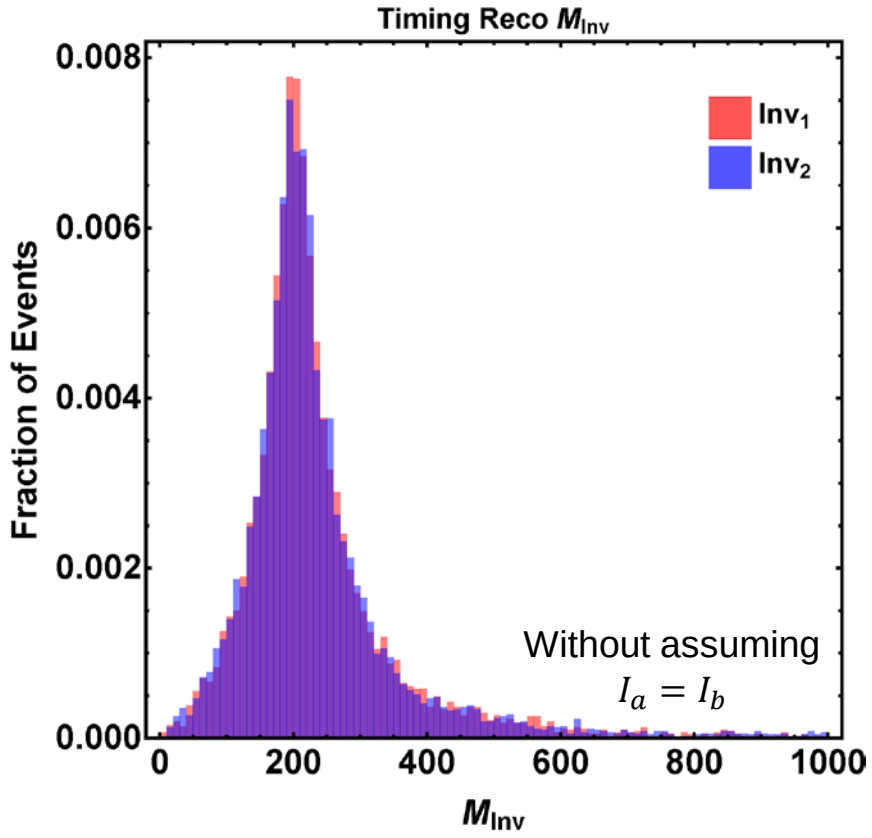


		m_{LLP_a}	m_{LLP_b}	m_{I_a}	m_{I_b}
Case 1	w/o timing	397.6 ± 1.2	397.6 ± 1.2	206.0 ± 1.5	206.0 ± 1.5

MC result: Sol2

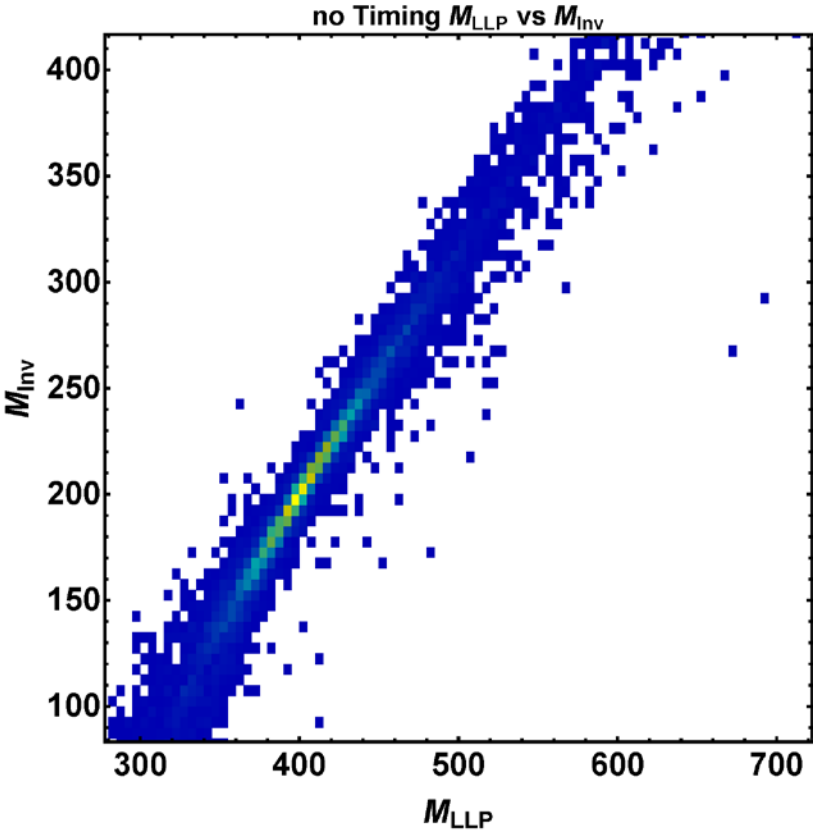
$M_{LLP_a} = M_{LLP_b} = 400$ GeV
$M_{I_a} = M_{I_b} = 200$ GeV

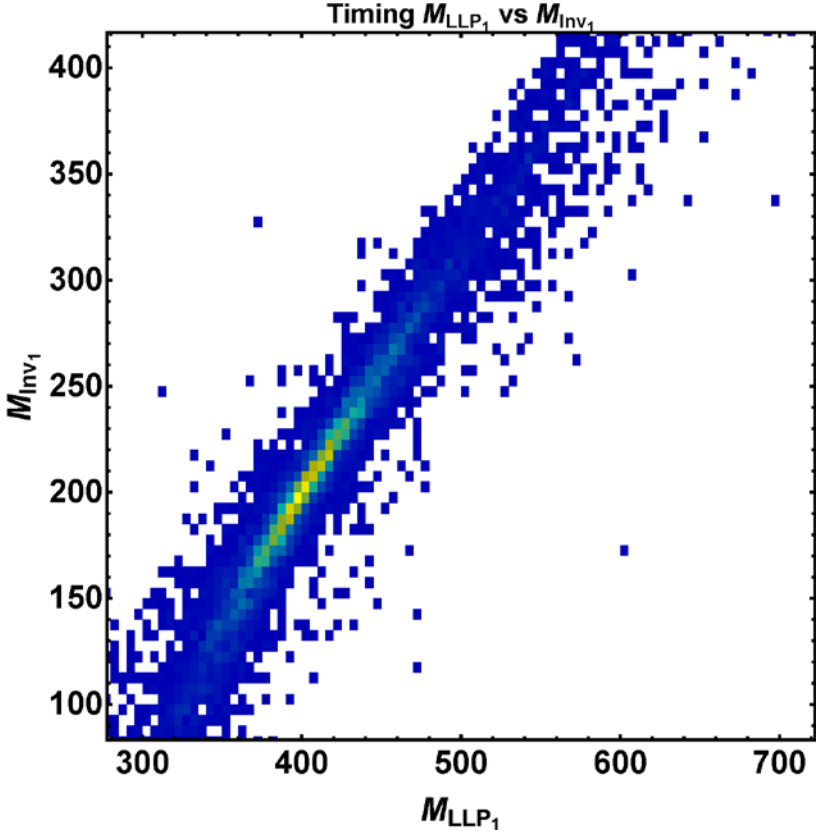




		m_{LLP_a}	m_{LLP_b}	m_{I_a}	m_{I_b}
Case 1	w/o timing	397.6 ± 1.2	397.6 ± 1.2	206.0 ± 1.5	206.0 ± 1.5
	timing	400.91 ± 0.35	400.77 ± 0.35	201.53 ± 0.49	201.53 ± 0.49

MC result: Sol1 vs Sol2



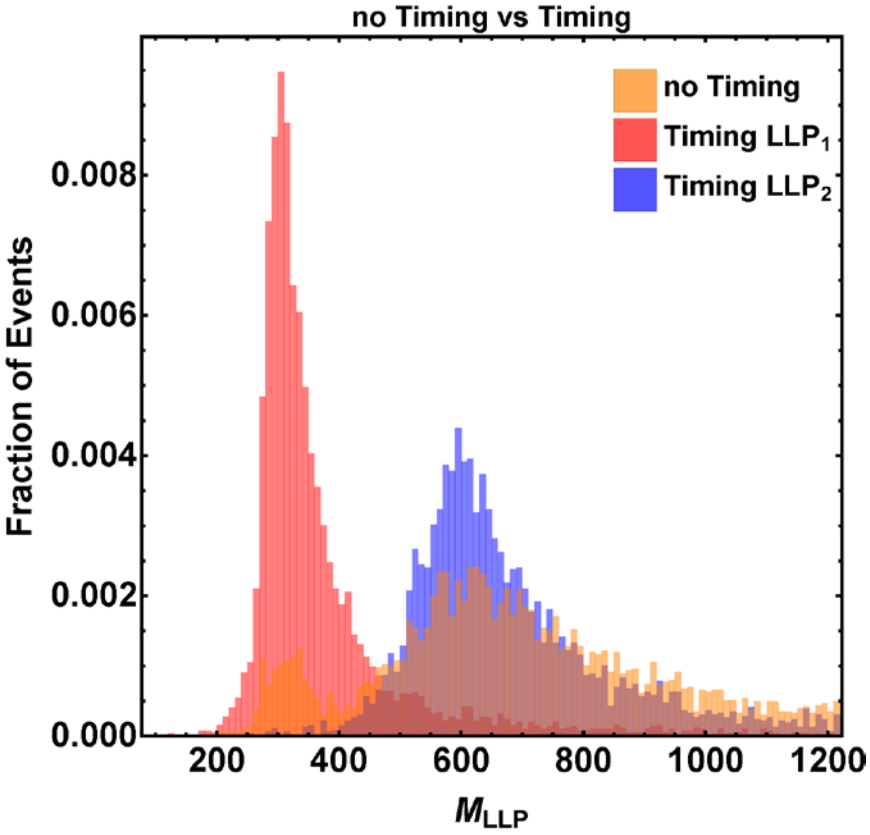


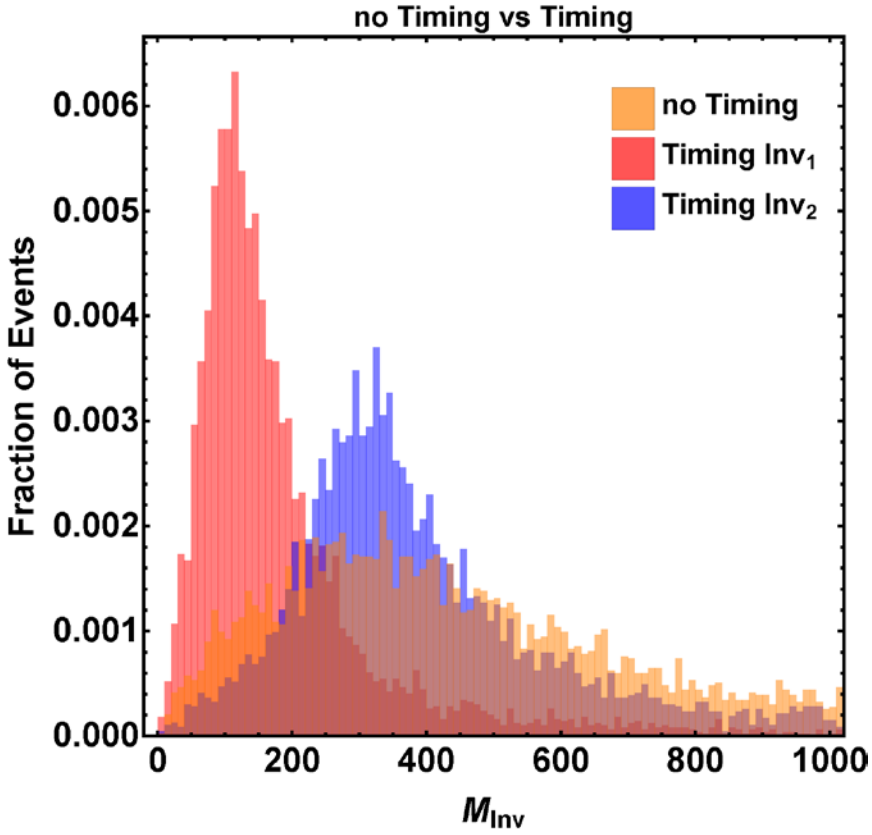
		m_{LLP_a}	m_{LLP_b}	m_{I_a}	m_{I_b}
Case 1	w/o timing	397.6 ± 1.2	397.6 ± 1.2	206.0 ± 1.5	206.0 ± 1.5
	timing	400.91 ± 0.35	400.77 ± 0.35	201.53 ± 0.49	201.53 ± 0.49

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

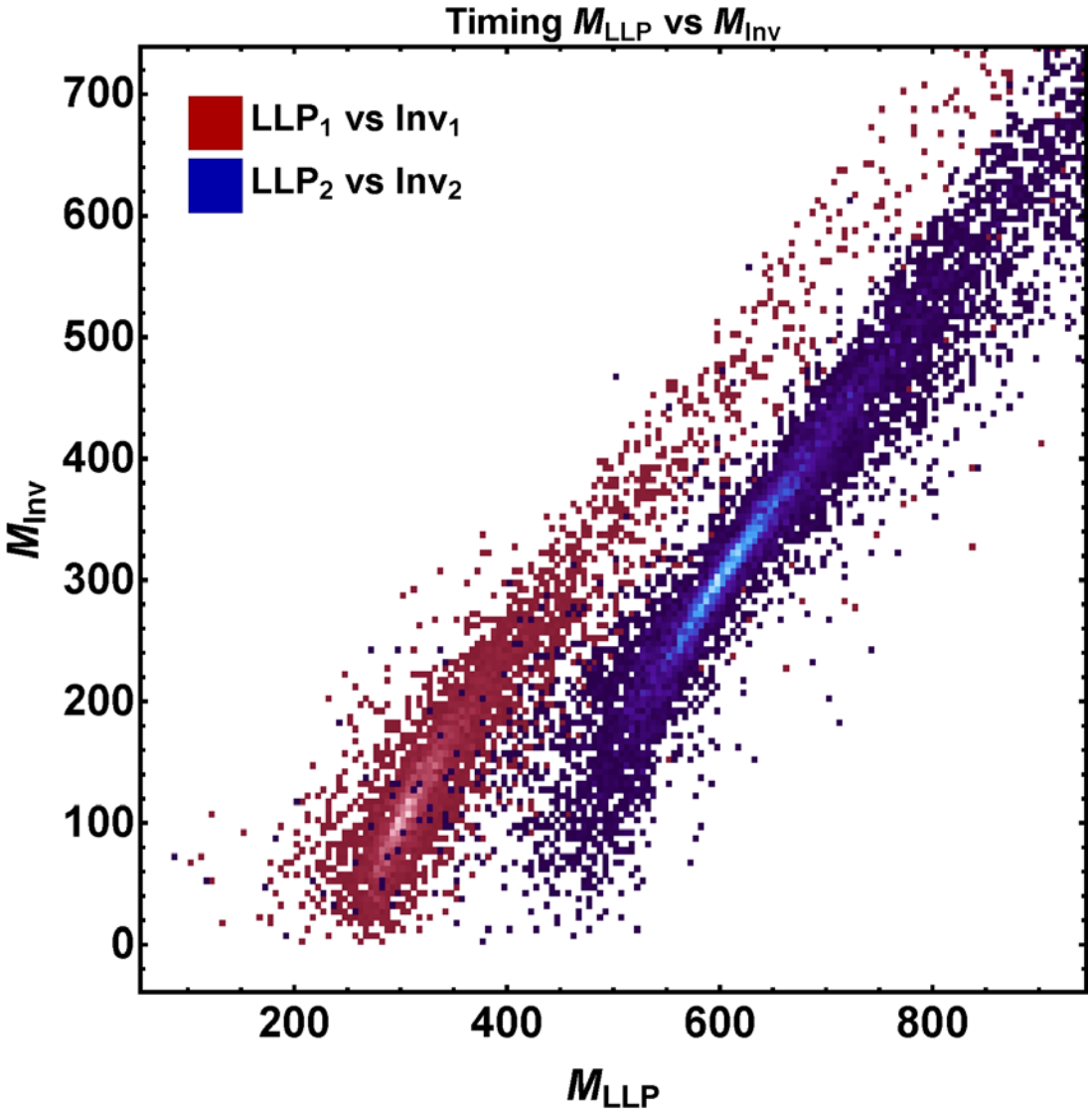




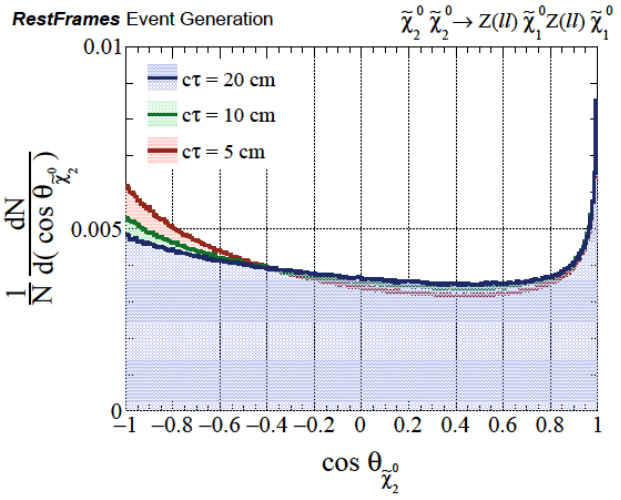
		m_{LLP_a}	m_{LLP_b}	m_{I_a}	m_{I_b}
Case2	w/o timing	-	-	-	-
	timing	307.25 ± 0.38	612.18 ± 0.72	118.54 ± 0.89	319.1 ± 1.1

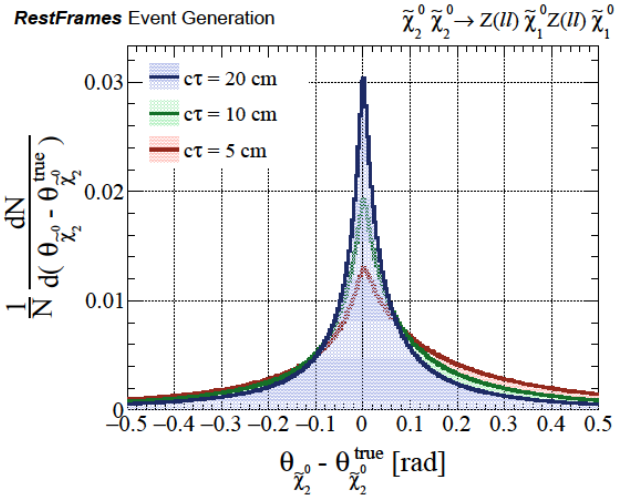
MC result: Sol2

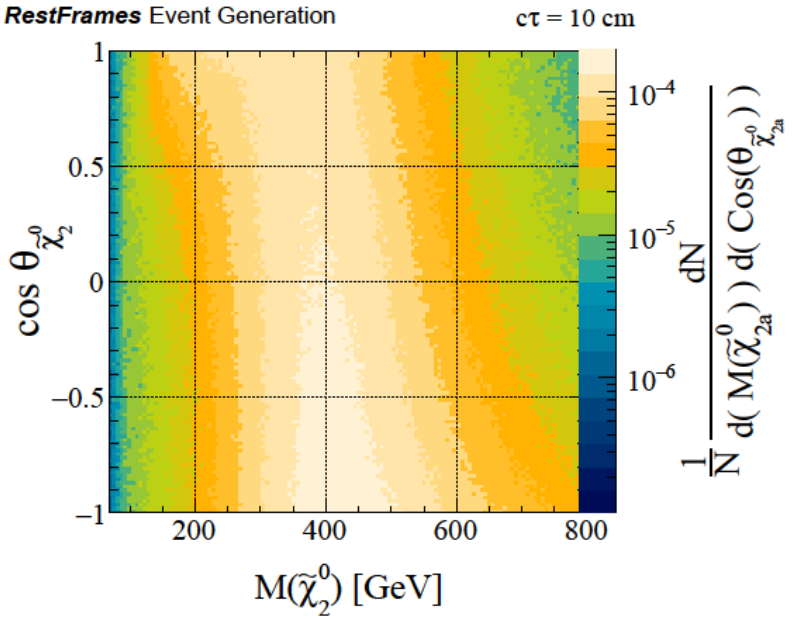
M_{LLP_a}: 300 GeV, M_{LLP_b}: 600 GeV
M_{I_a} : 100 GeV, M_{I_a} : 300 GeV



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}	$\boldsymbol{p}_{LLP_1}$	$\boldsymbol{p}_{LLP_2}$	$\boldsymbol{p}_{I_1}$	$\boldsymbol{p}_{I_2}$
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.
- w/o using timing information, we can find 3-momenta but we cannot find masses w/o any assumptions.
- Using timing information, we can fully reconstruct 4-momenta of the system even if the LLP decay to visible and invisible particles.

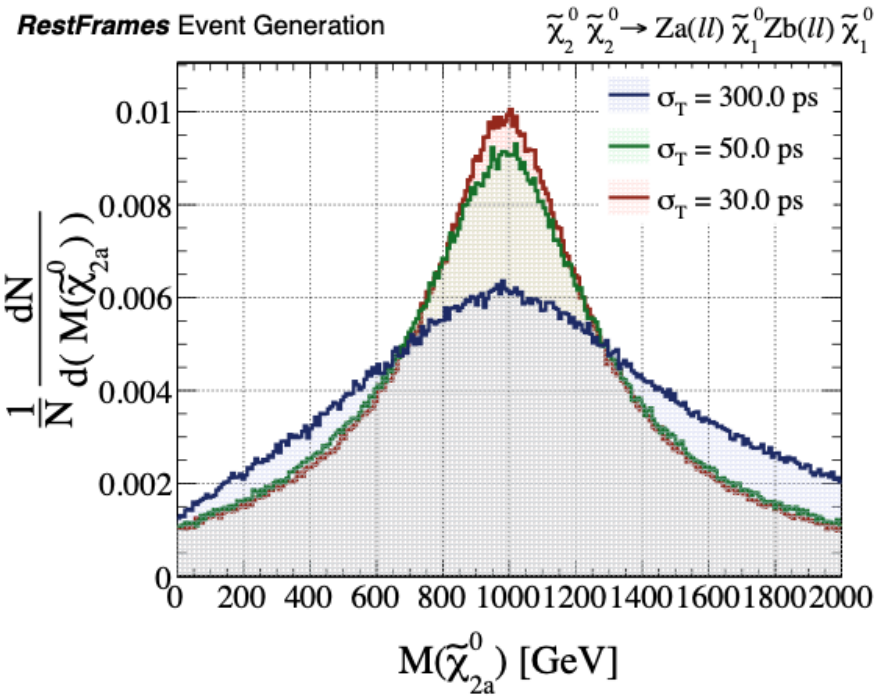
Conclusion

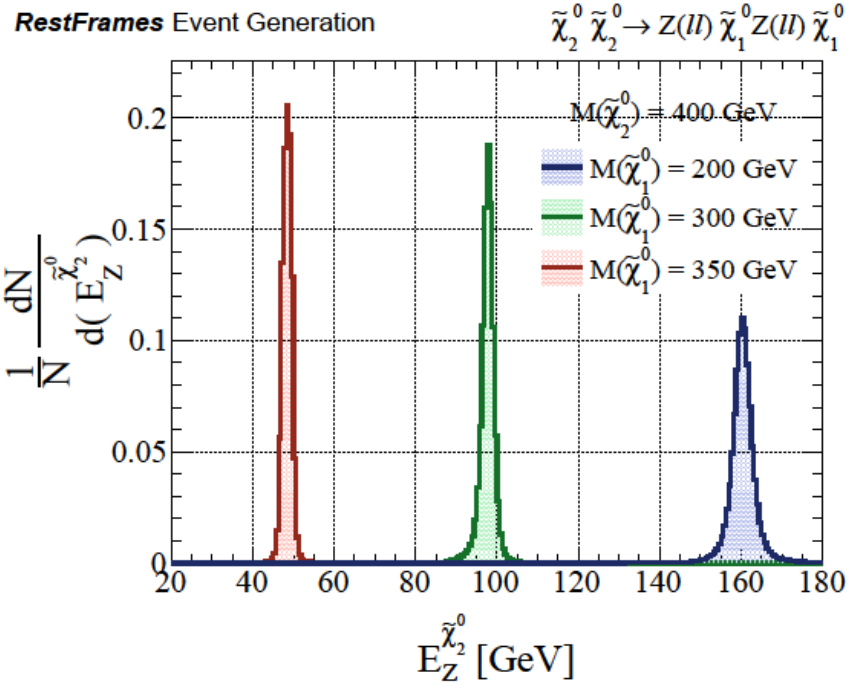
- New physics may buried in the hidden sector.
- LLPs are naturally generated and they play a crucial role in solving the problems in particle physics.
- HL-LHC is very good environment to search the LLPs in both intensity and high energy frontier.
- Using the timing information, we can fully reconstruct the events.
- The timing detectors will flash the hidden sector and LLP searches.

backup

Impact of timing resolution on mass resolution

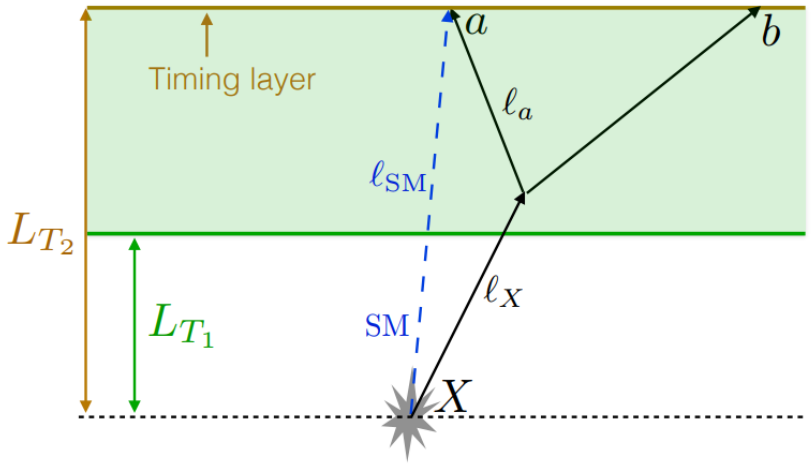
- With improved timing resolution we can better improve the mass resolution of LLPs



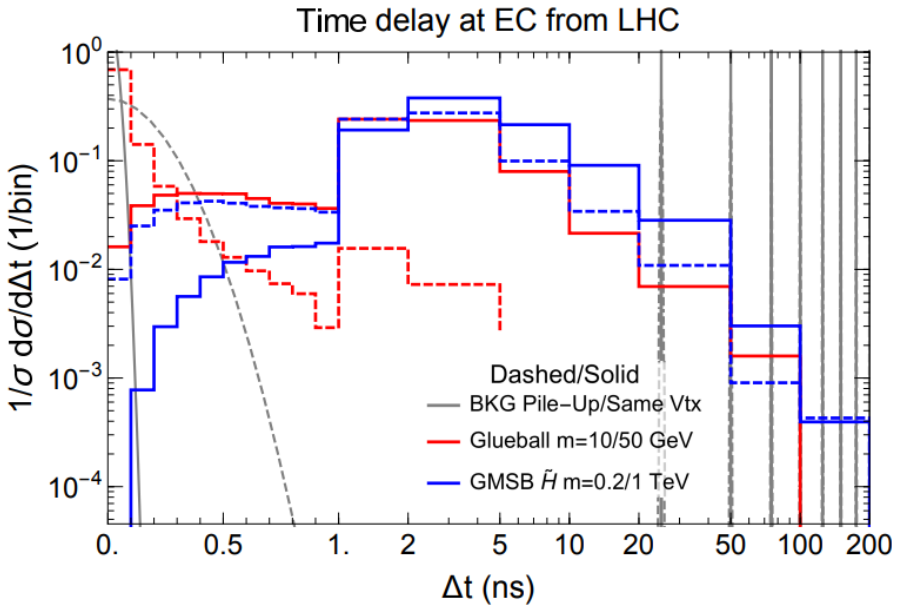


Time stamping

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



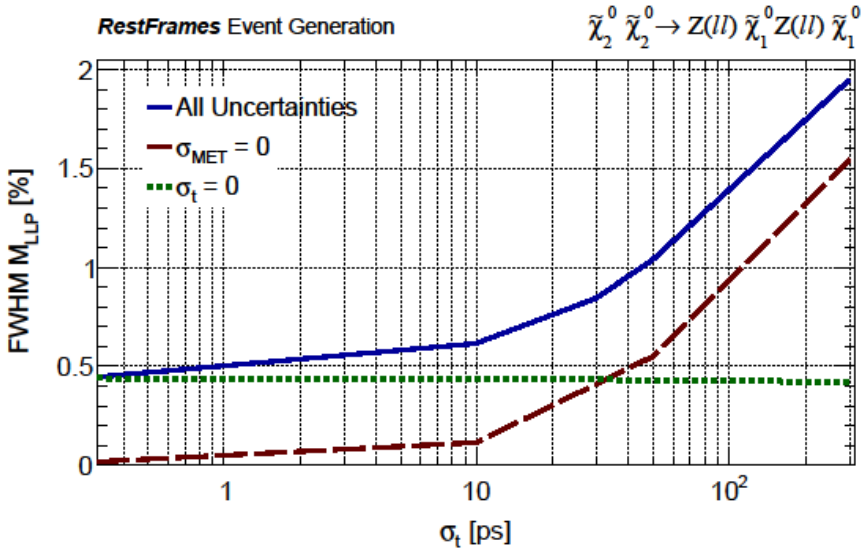
$$\Delta t^i_{\rm delay} = \frac{\ell_X}{\beta_X} + \frac{\ell_i}{\beta_i} - \frac{\ell_{\rm SM}}{\beta_{\rm SM}}$$

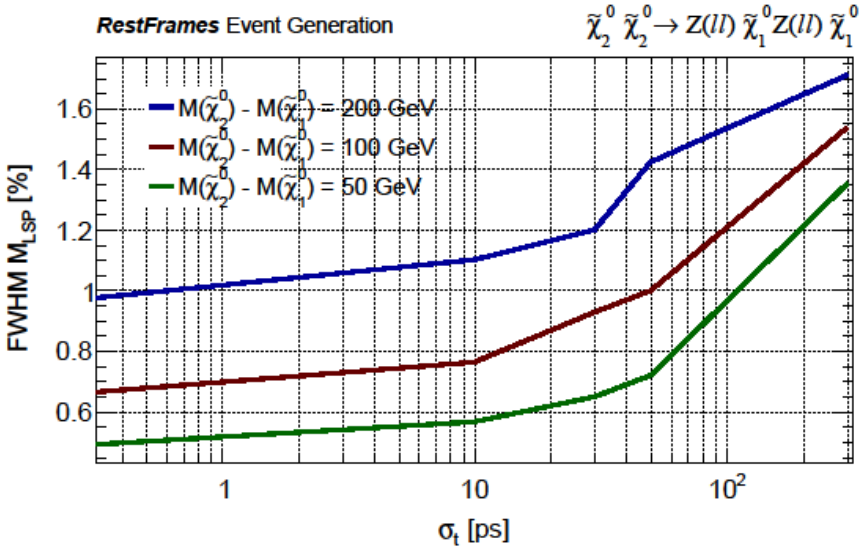


SigA : $pp \to h + j\ ,\ h \to X + X,\ X \to \mathrm{SM},$

SigB : $pp \to \tilde{\chi}\tilde{\chi} + j,\ \tilde{\chi}^0_1 \to h + \tilde{G} \to \mathrm{SM} + \tilde{G}.$

Timing detector resolution





LLP signatures at collider

- Displaced vertex
- Disappearing tracks
- Non-pointing photon
- Emerging jets
- Stopped particles
- Large dE/dx slow
- Late decaying

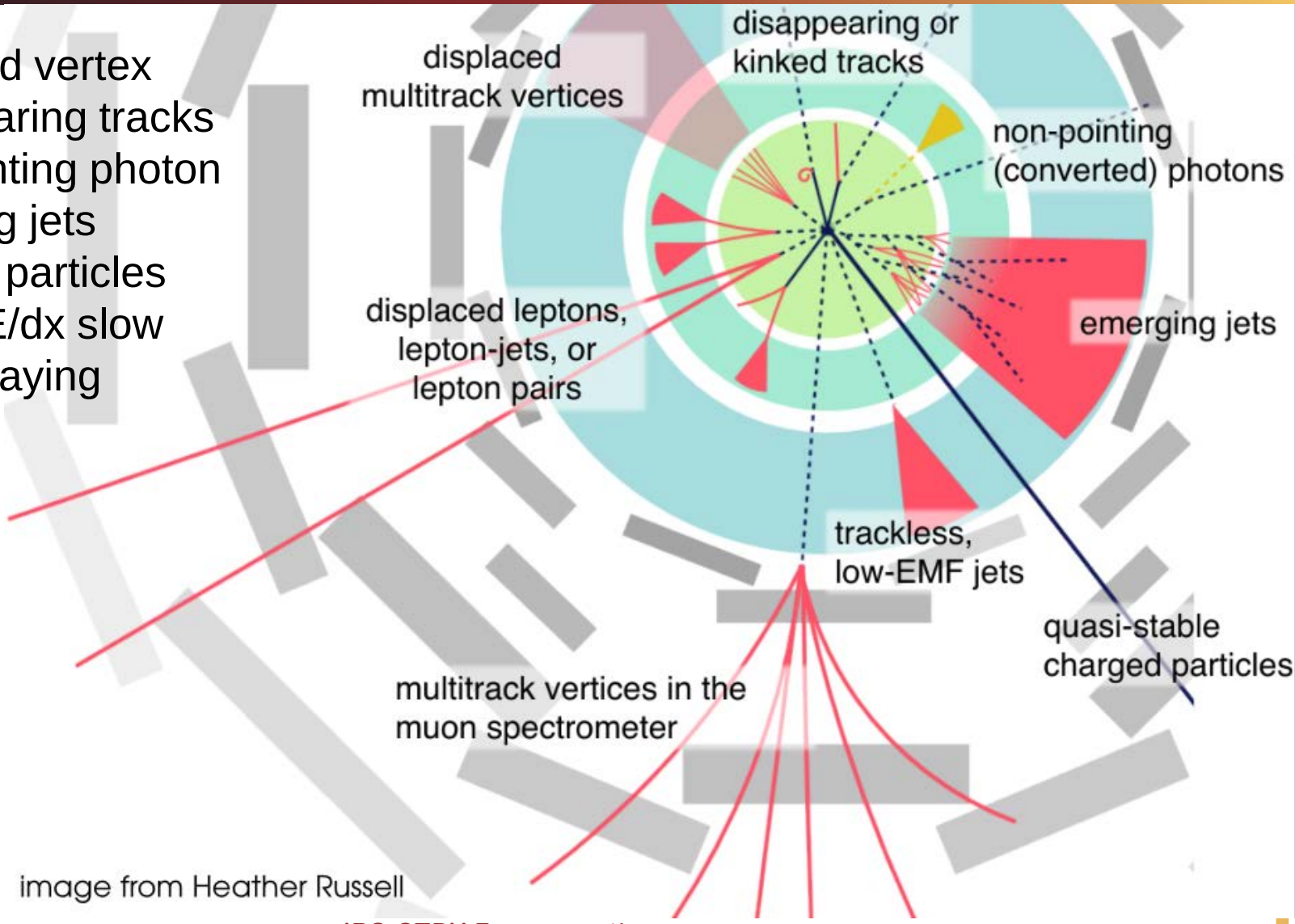
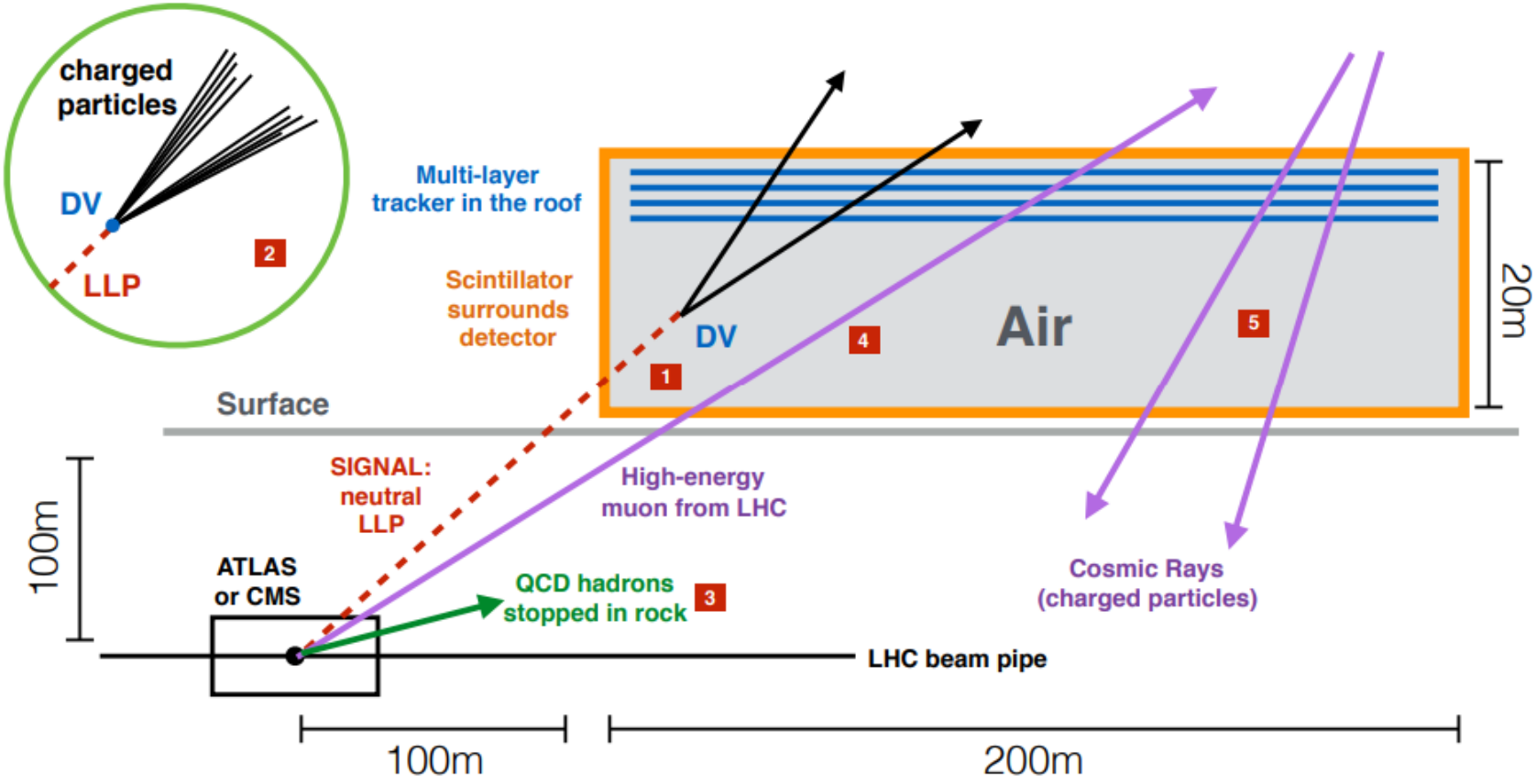


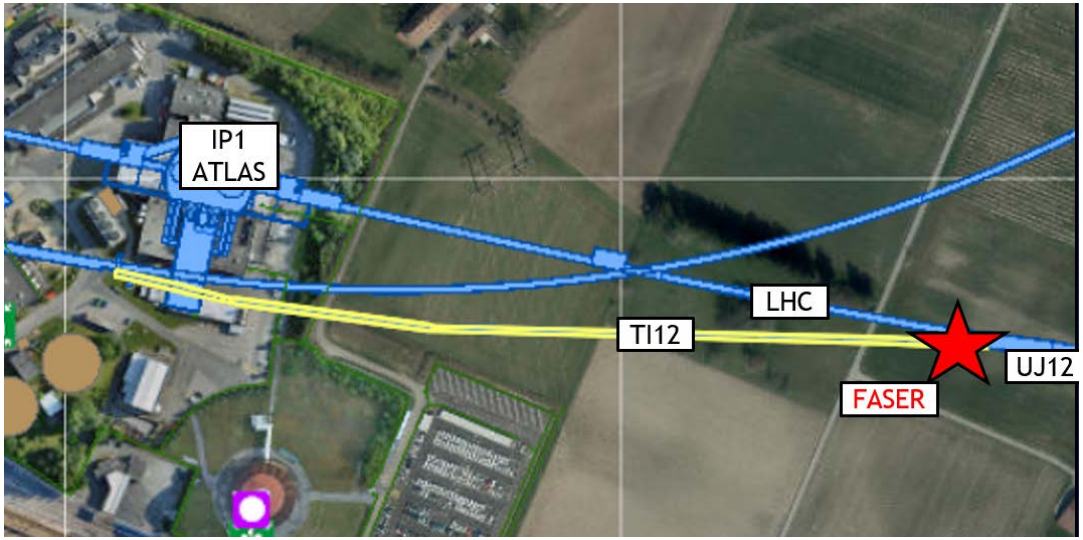
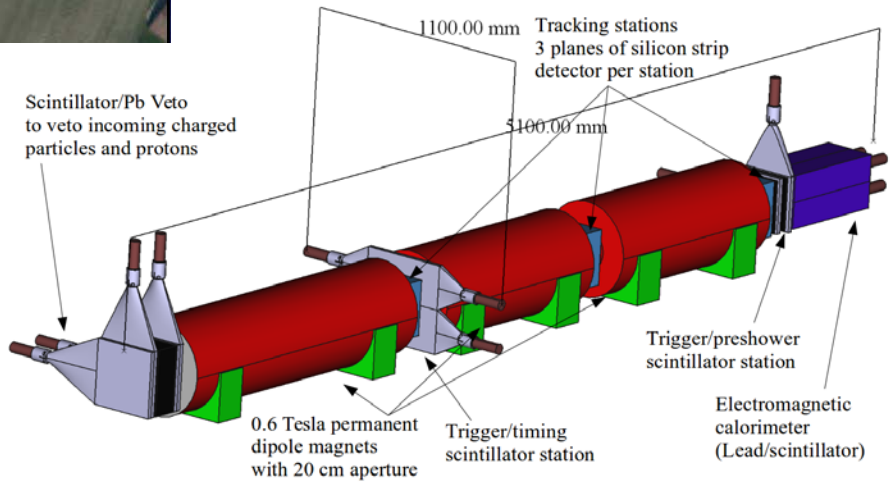
image from Heather Russell

MATHUSLA

[J. P. Chou, D. Curtin, H. J. Lubatti 1606.06298]

- MAssive Timing Hodoscope for Ultra-Stable neutraL pArticles



FASER

- ForwArd Search ExpeRiment at the LHC