Exploring properties of Long-lived particle at colliders

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Based on

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arXiv:2101.02503

DWK, P. Ko, Chih-Ting Lu

Contents

Long lived particle

The Standard Model

We have $\mu, \pi^{\pm}, K_L, B^{\pm}, n, \ldots \ldots$.

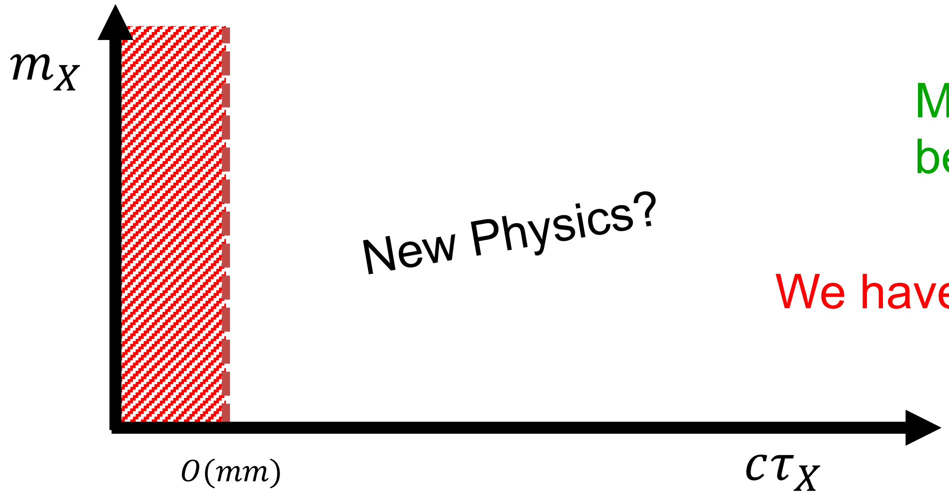
What makes particle long-lived?

Approximate symmetry Small coupling
Heavy mediator Lack of phase space

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

Beyond the Standard Model

- Long-lived particles commonly appears as a natural prediction in many well-motivated frameworks of new physics beyond the SM
- Searches for such LLPs is a very interesting and important research direction.



Most of the searches at LHC has been focused on prompt regime.

We have huge parameter space to investigate!

LLP signatures at collider

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

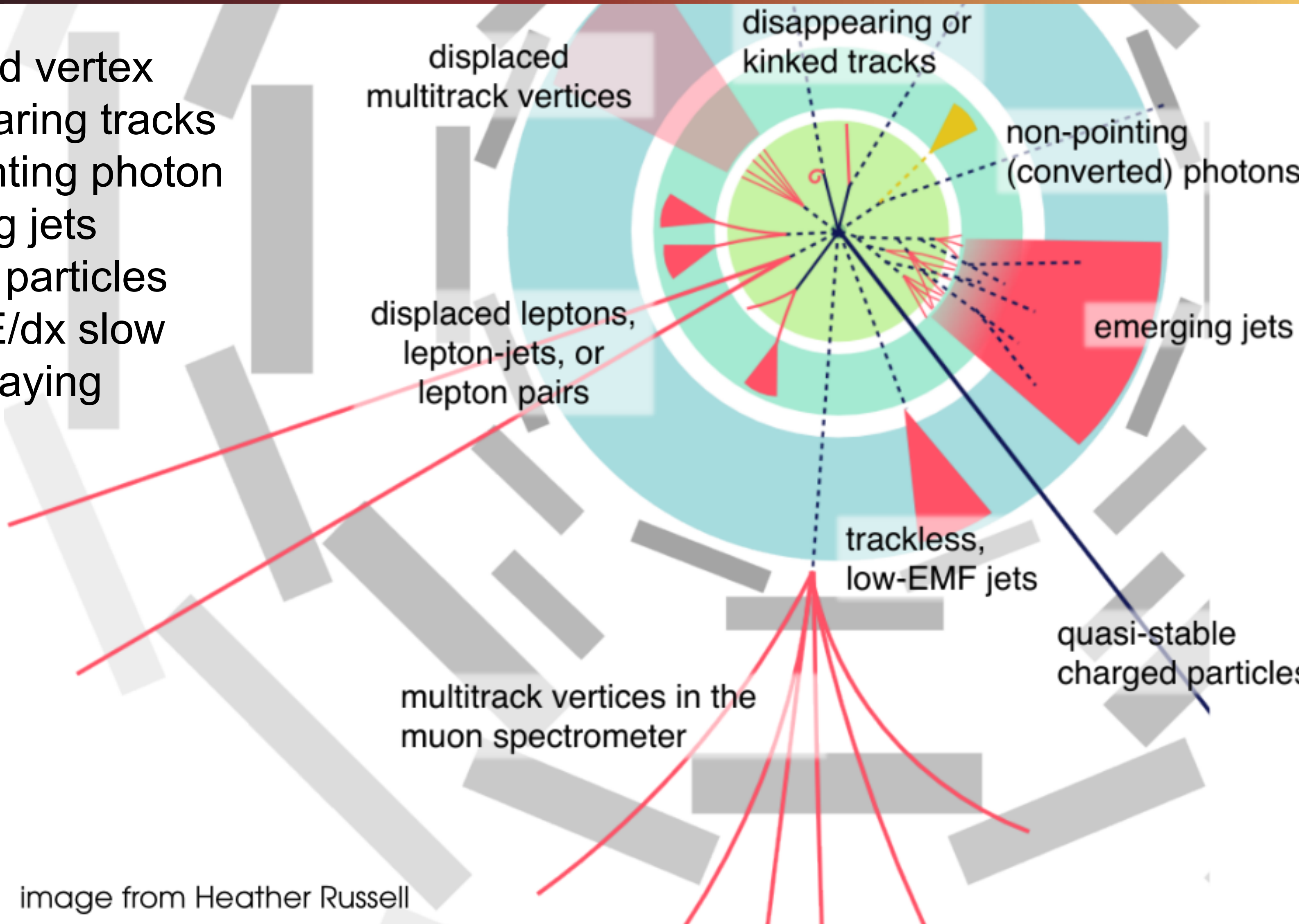
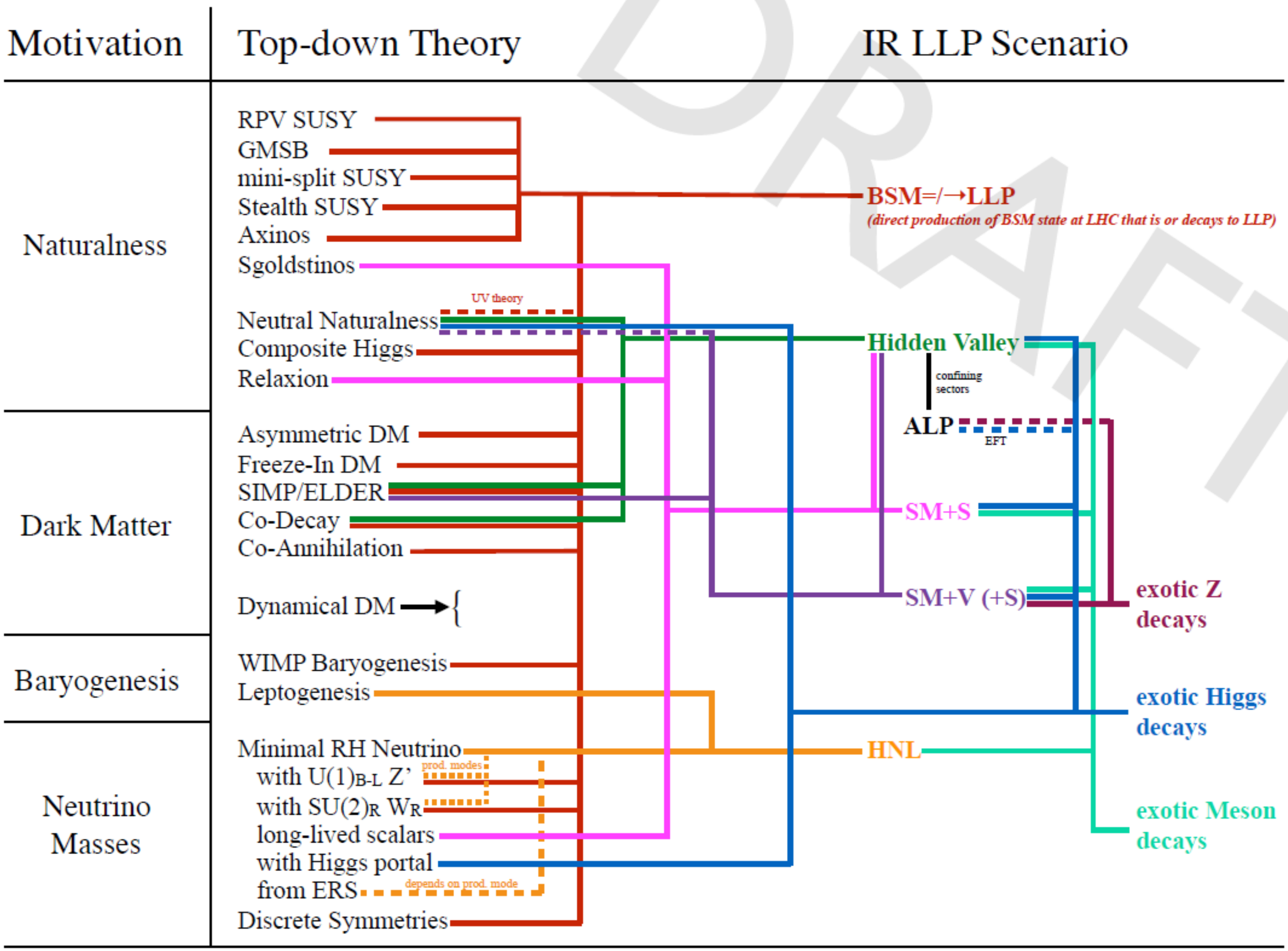


image from Heather Russell

LLP is well motivated



MATHUSLA Physics Case, June 2018

LLP searches at colliders and beyonds

CMS

ATLAS EXPERIMENT

LHCb

FASER

SHiP
Search for Hidden Particles

HiLumi
HL-LHC PROJECT

FCC
hh ee he

CODEX-b

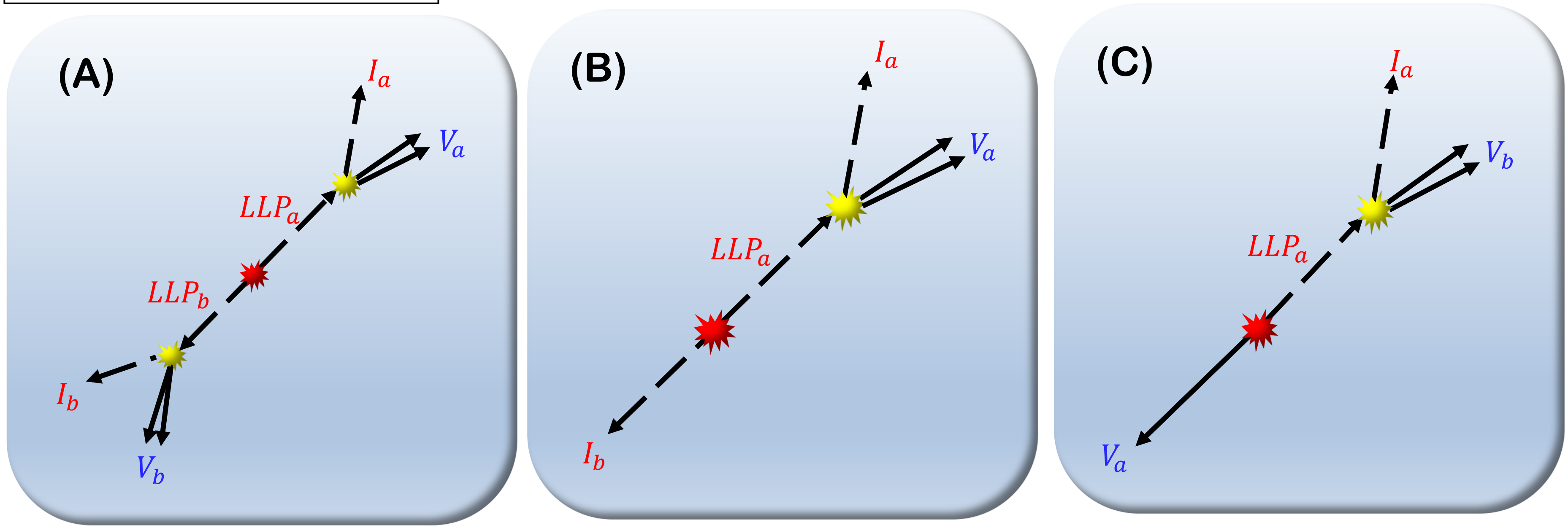
MATHUSLA

Belle II

And more …..

LLP event topology

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

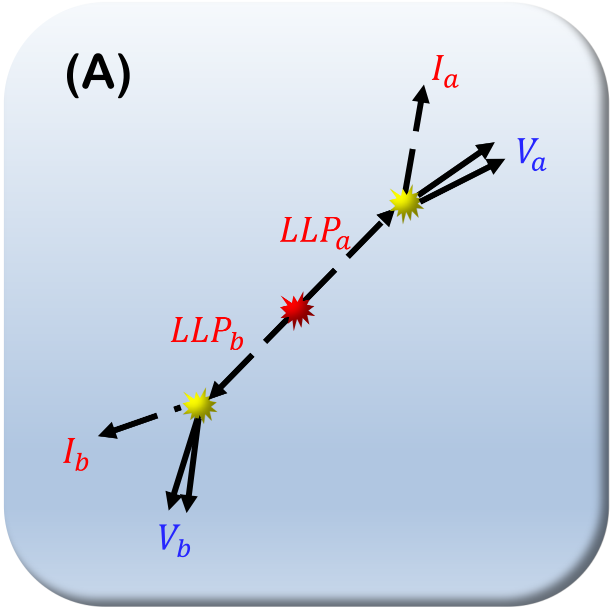


(A) Pair produced BSM LLPs

(B) Compressed neutralino, Inelastic DM, …

(C) Long-lived right-handed neutrino, HNL, RPV SUSY, …

Neutral LLP search example (A)



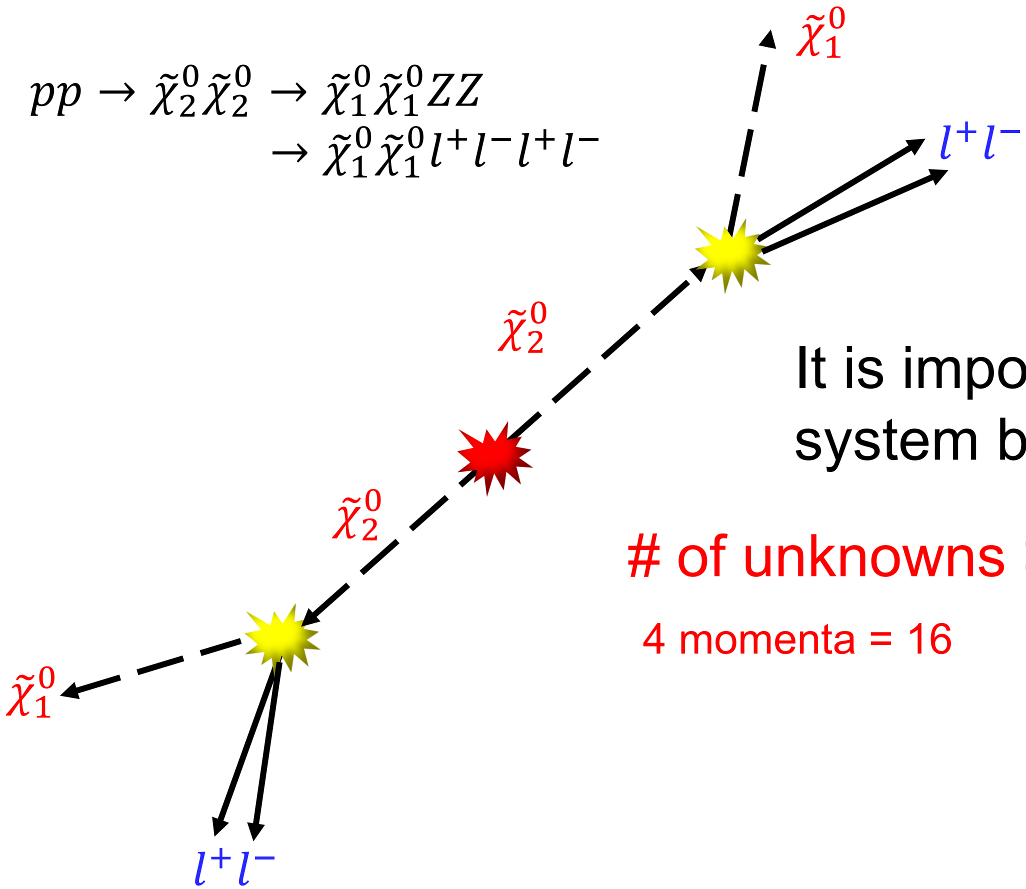
$$pp \to \tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to h + \tilde{G} \to \mathrm{SM} + \tilde{\mathrm{G}}$$

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

And many BSM models …..

Neutral LLP search example (A)

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



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

# of unknowns > # of knowns

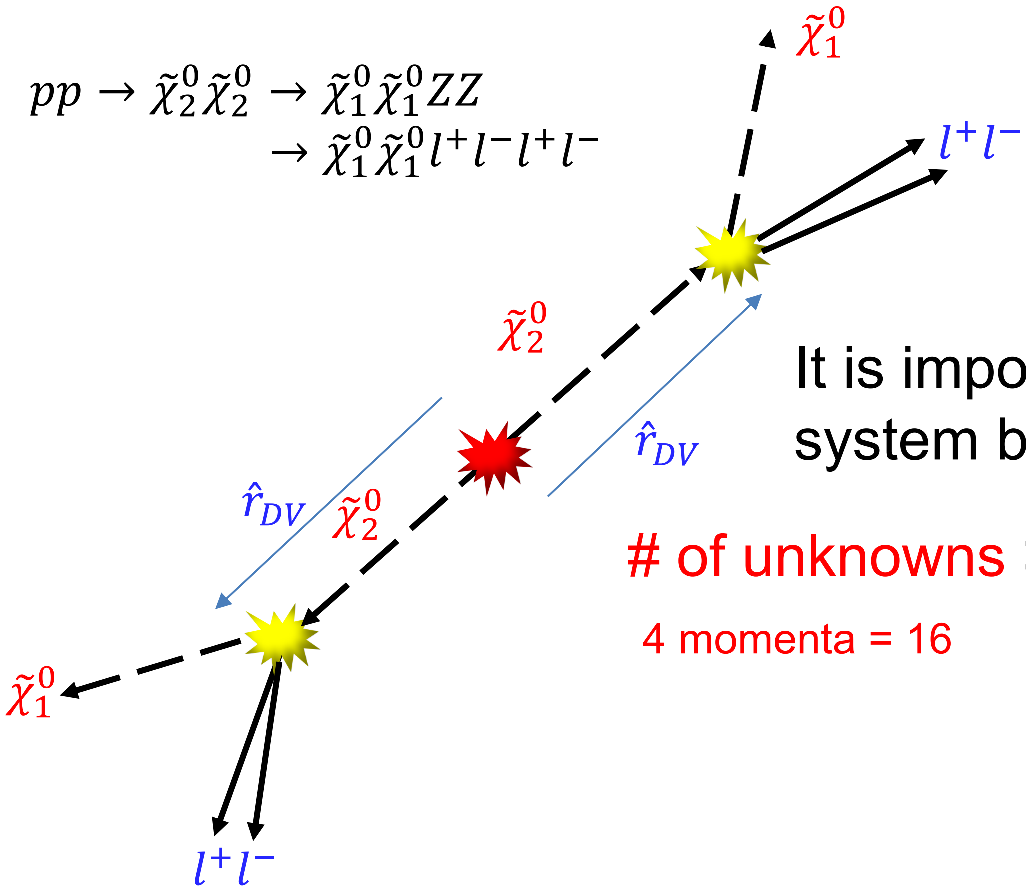
4 momenta = 16

2 momenta = 8

p_T^{miss} = 2

Neutral LLP search example (A)

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



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

# of unknowns > # of knowns

4 momenta = 16

2 momenta = 8

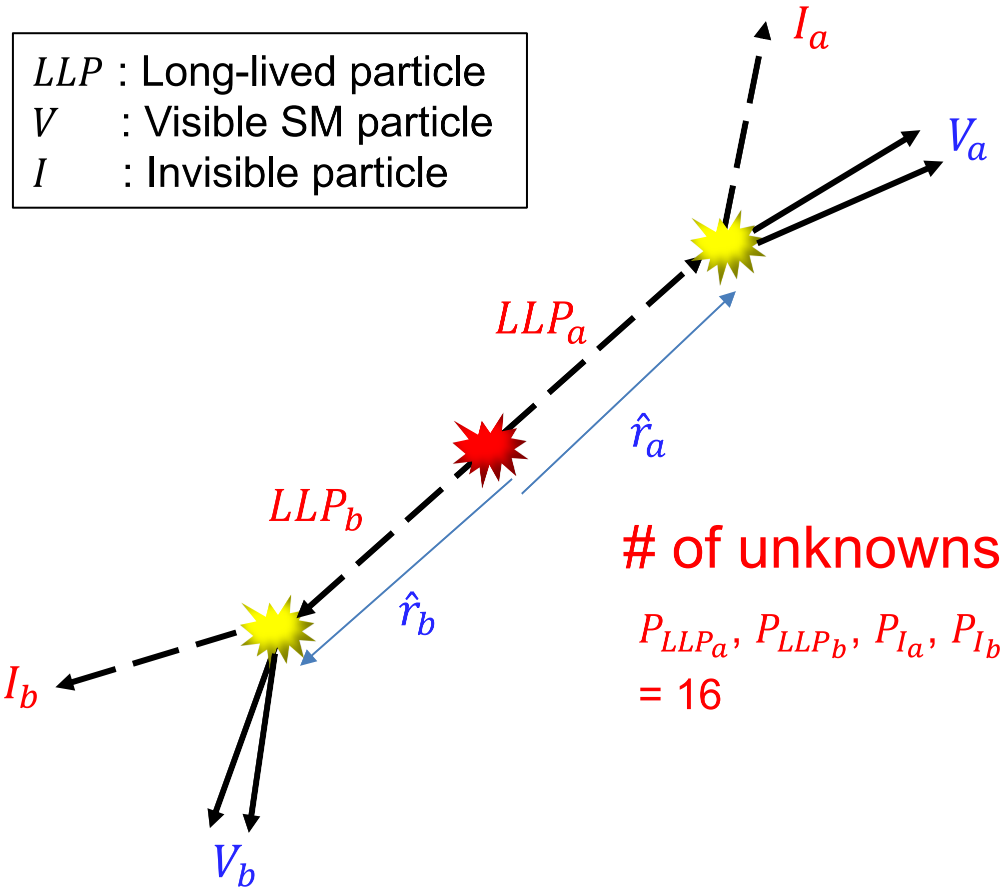
p_T^{miss} = 2

2 displaced vertices = 4

How can we solve this kind of system?

Reconstruction with assumptions

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 !

Reconstruction with assumptions

[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

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

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

Reconstruction with assumptions

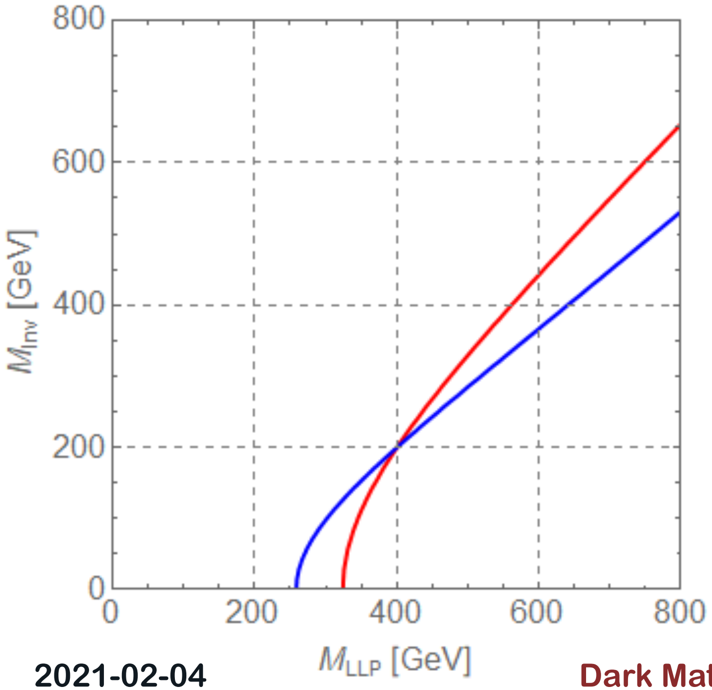
- 4-momentum conservation

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

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

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

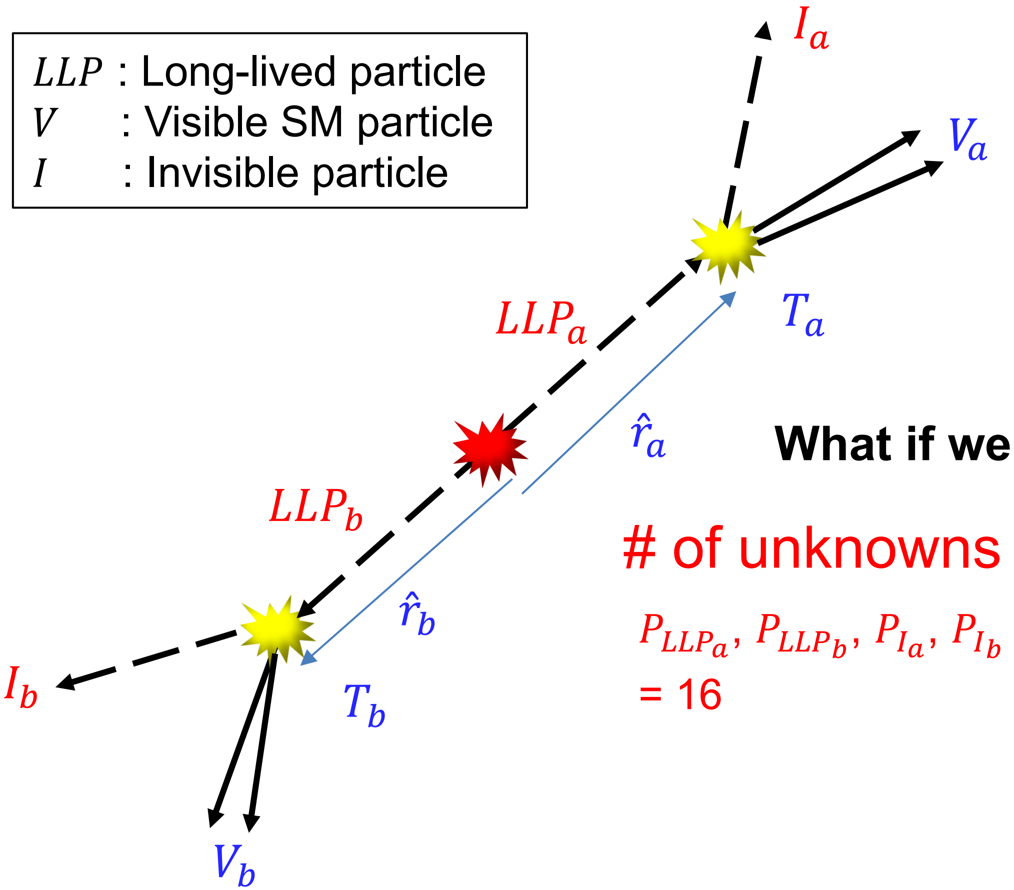
- For each event we can find



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

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

Reconstruction with timing information



What if we can measure decay time T_a, T_b ?

# 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

Reconstruction with timing information

- 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

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

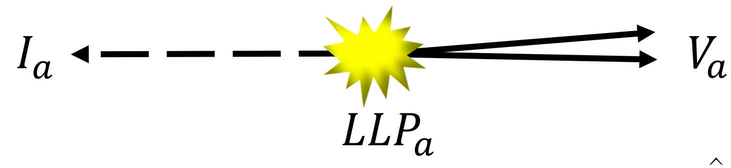
$$\boldsymbol{p}_b = \frac{\boldsymbol{\beta}_a \times (\boldsymbol{p}_I + \boldsymbol{p}_{V_a} + \boldsymbol{p}_{V_b}) \cdot \hat{\boldsymbol{k}}}{\boldsymbol{\beta}_a \times \boldsymbol{\beta}_b \cdot \hat{\boldsymbol{k}}} \boldsymbol{\beta}_b$$

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



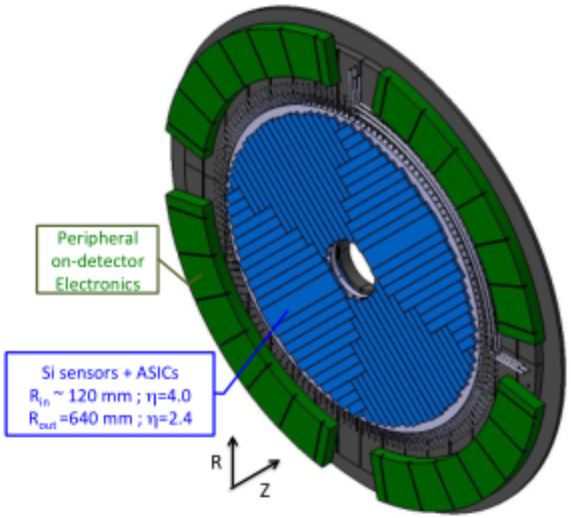
$$E_a = \frac{\boldsymbol{\beta}_b \times (\boldsymbol{p}_I + \boldsymbol{p}_{V_a} + \boldsymbol{p}_{V_b}) \cdot \hat{\boldsymbol{k}}}{\boldsymbol{\beta}_b \times \boldsymbol{\beta}_a \cdot \hat{\boldsymbol{k}}}$$

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

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

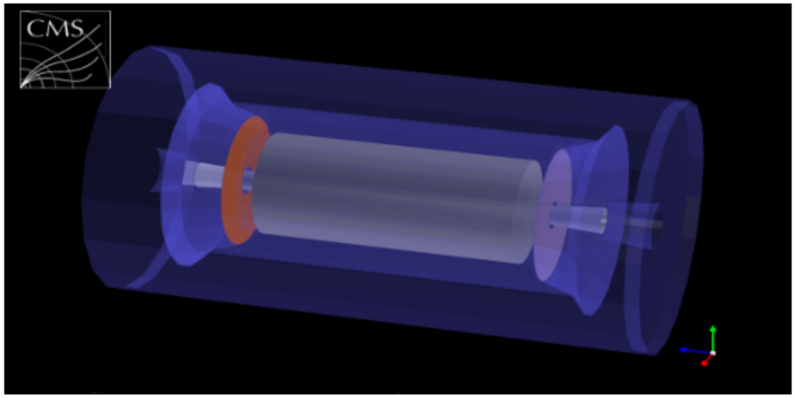
Timing detector @ HL-LHC

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



[ATL-LARG-PROC-2018-003]

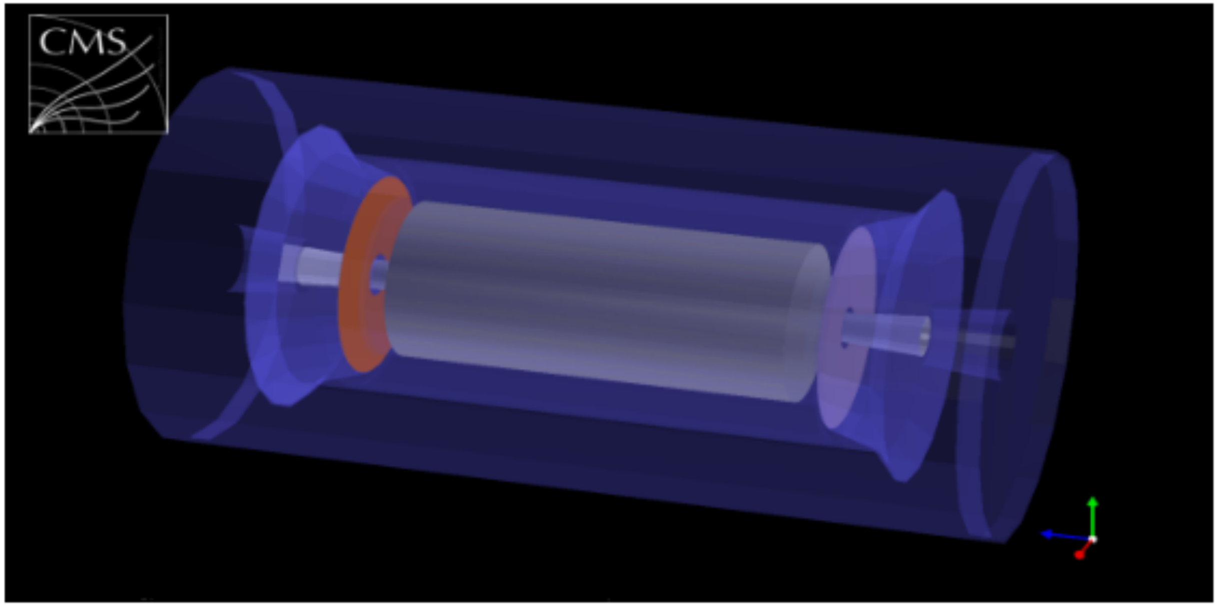
- CMS
  - Minimum ionizing particles (MIPs) Timing Detector (MTD) between tracker and ECAL
  - ~30 ps resolution for charged tracks
  - Coverage $|\eta| < 3.0$



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

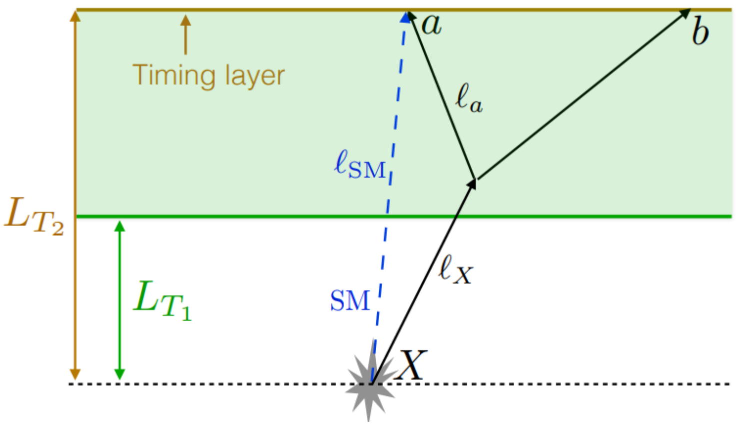
MIP Timing detector (MTD)

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

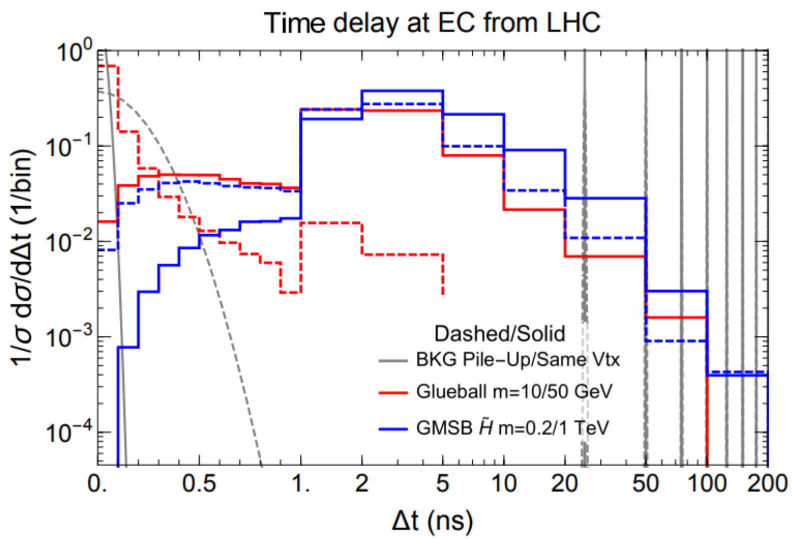


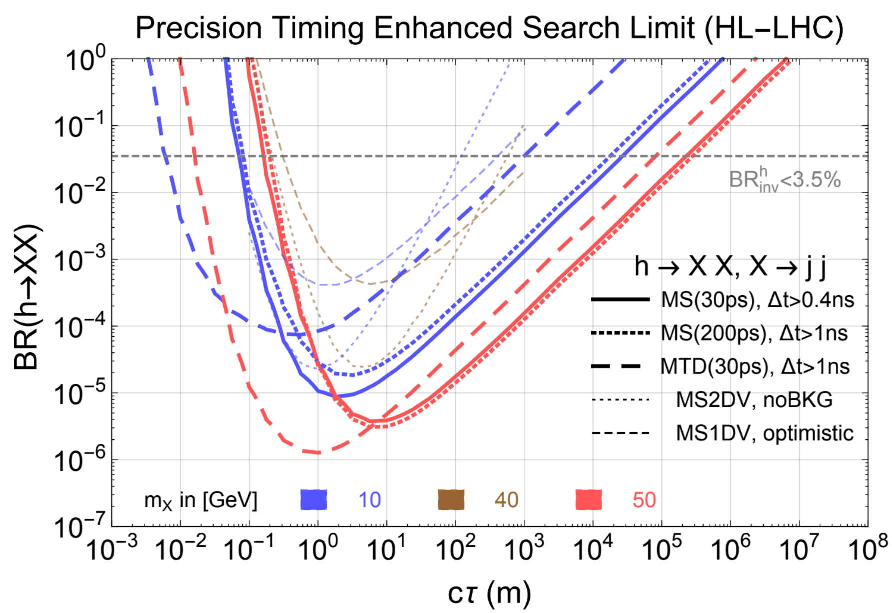
Time stamping

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



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

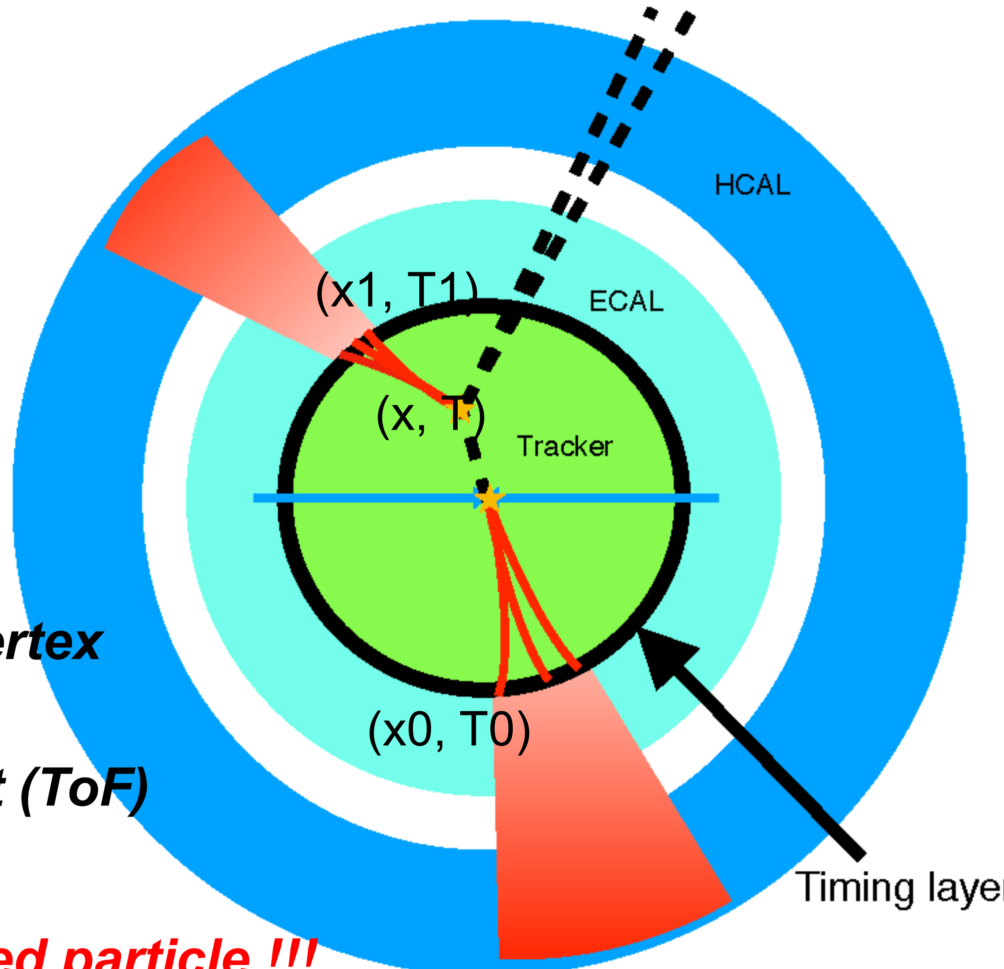




$$\text{SigA}: \quad pp \to h + j\ ,\ \ h \to X + X,\ \ X \to \text{SM},$$

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

Timing detector @ HL-LHC



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

  +

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

  ↓

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

Reconstruction Summary

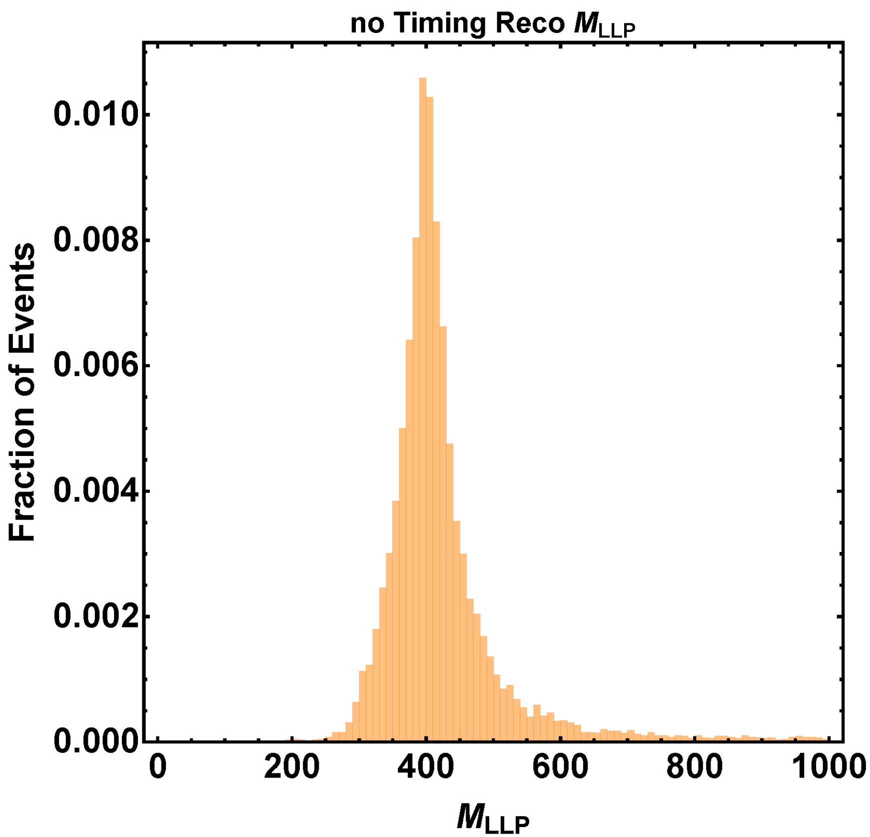
		m_{LLP_1}	m_{LLP_2}	m_{I_1}	m_{I_2}	$\mathbf{p}_{LLP_1}$	$\mathbf{p}_{LLP_2}$	$\mathbf{p}_{I_1}$	$\mathbf{p}_{I_2}$
Case 1	no timing	△	△	△	△	○	○	○	○
$LLP_a = LLP_b$, $I_a = I_b$	timing	○	○	○	○	○	○	○	○
Case2	no timing	×	×	×	×	○	○	○	○
$LLP_a \neq LLP_b$, $I_a \neq I_b$	timing	○	○	○	○	○	○	○	○

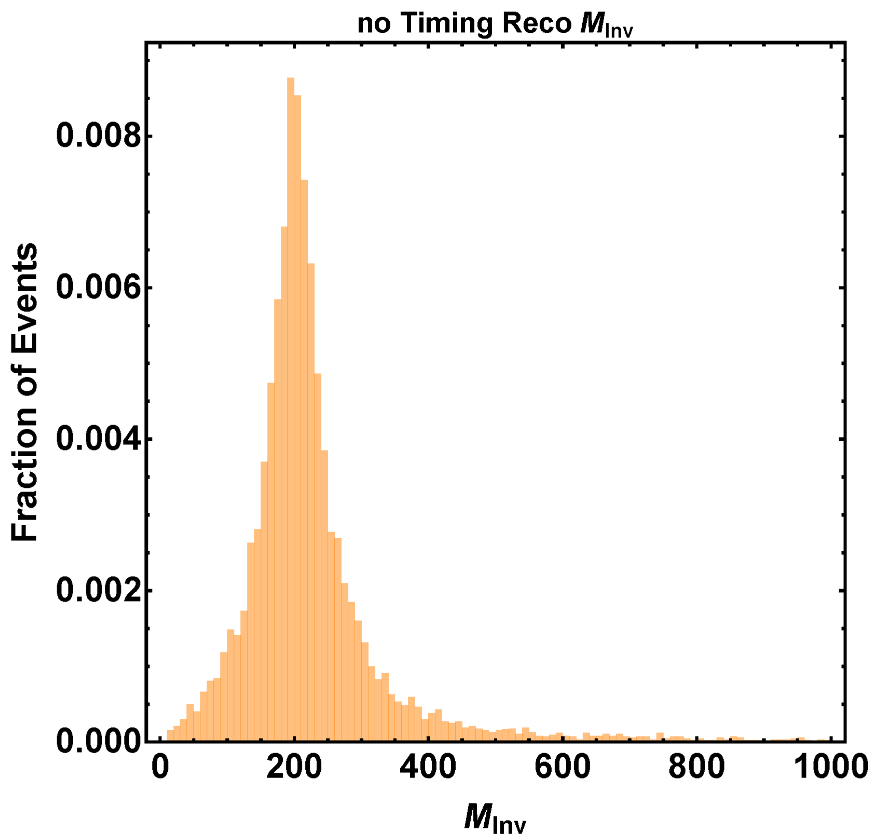
- Using timing information at HL-LHC we can measure the β of the long-lived particles.
- w/o using timing information, we can find 3-momenta but we cannot find masses w/o any assumptions.
- Using timing information, we can fully reconstruct 4-momenta of the system even if the LLP decay to visible and invisible particles.

Case1: $LLP_a = LLP_b, I_a = I_b$

MC result: w/o timing

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

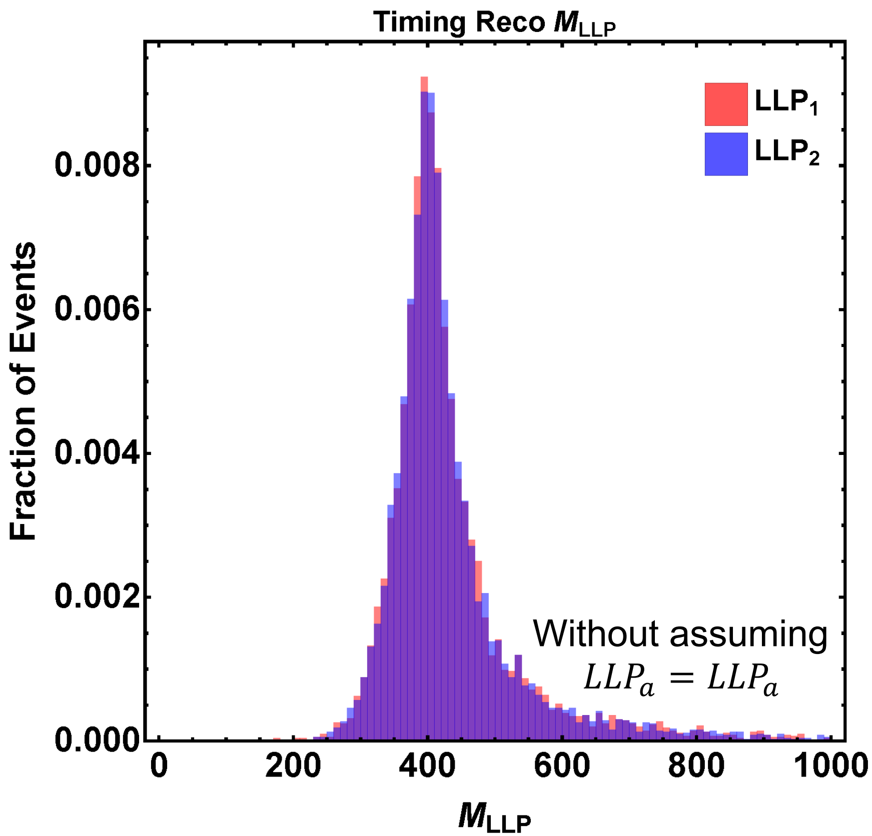


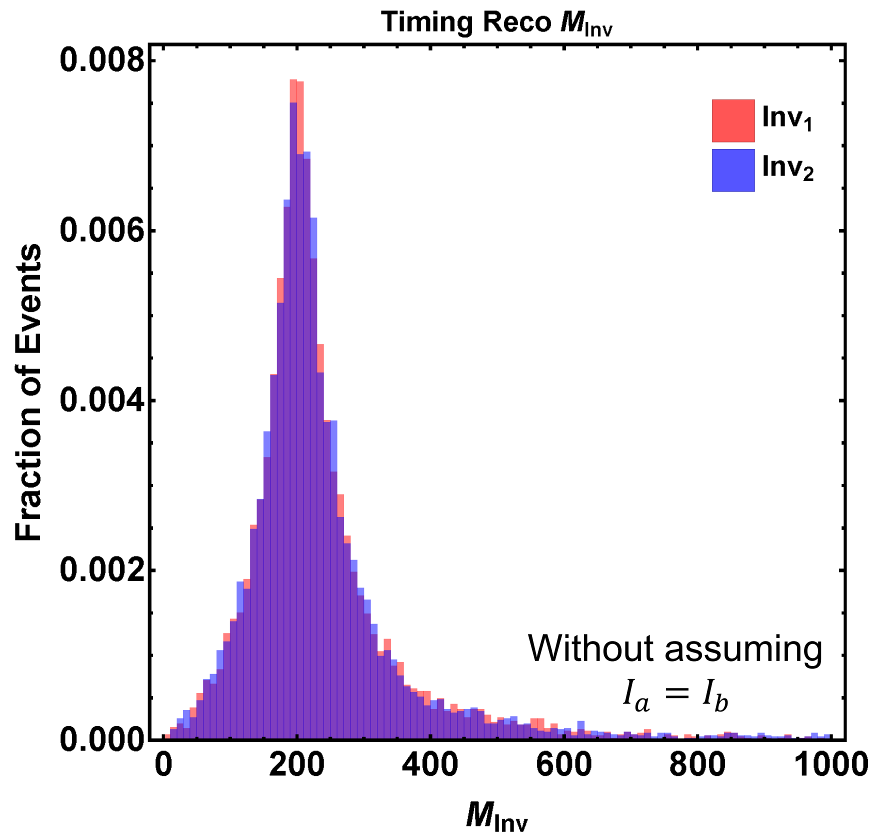


		m_{LLP_a}	m_{LLP_b}	m_{I_a}	m_{I_b}
Case 1	w/o timing	397.6 ± 1.2	397.6 ± 1.2	206.0 ± 1.5	206.0 ± 1.5

MC result: w/ timing

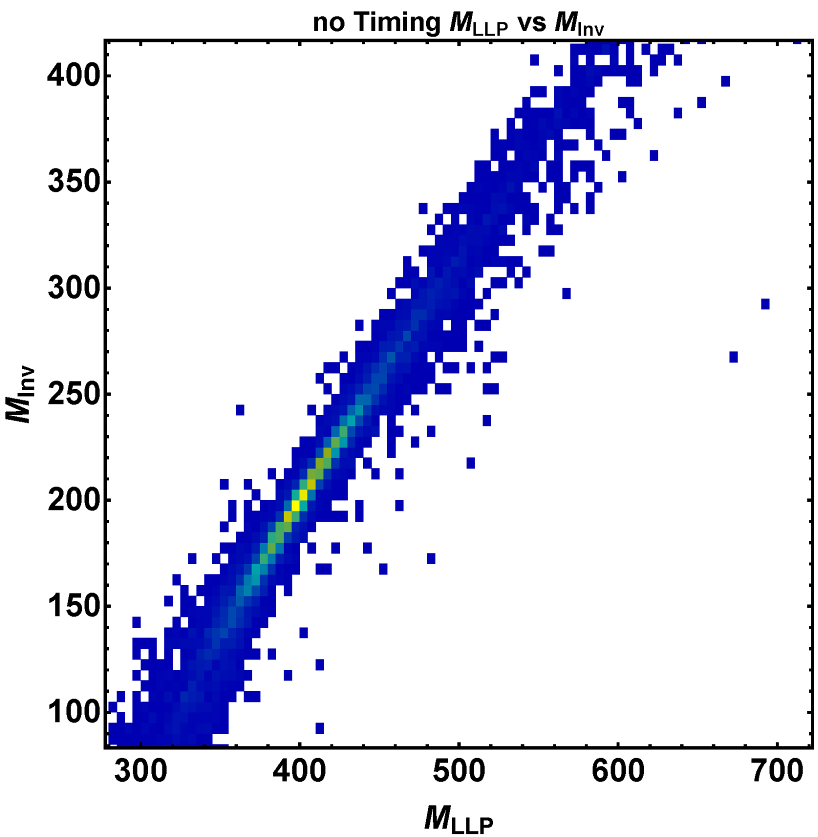
$M_{LLP_a} = M_{LLP_b} = 400$ GeV
$M_{I_a} = M_{I_b} = 200$ GeV

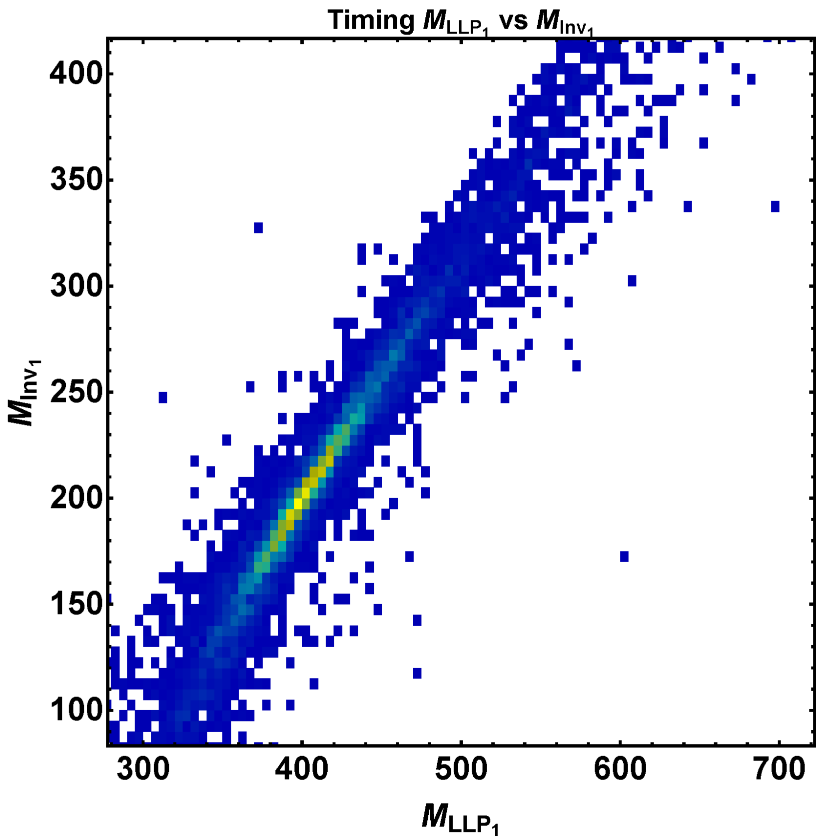




		m_{LLP_a}	m_{LLP_b}	m_{I_a}	m_{I_b}
Case 1	w/o timing	397.6 ± 1.2	397.6 ± 1.2	206.0 ± 1.5	206.0 ± 1.5
	timing	400.91 ± 0.35	400.77 ± 0.35	201.53 ± 0.49	201.53 ± 0.49

MC result:



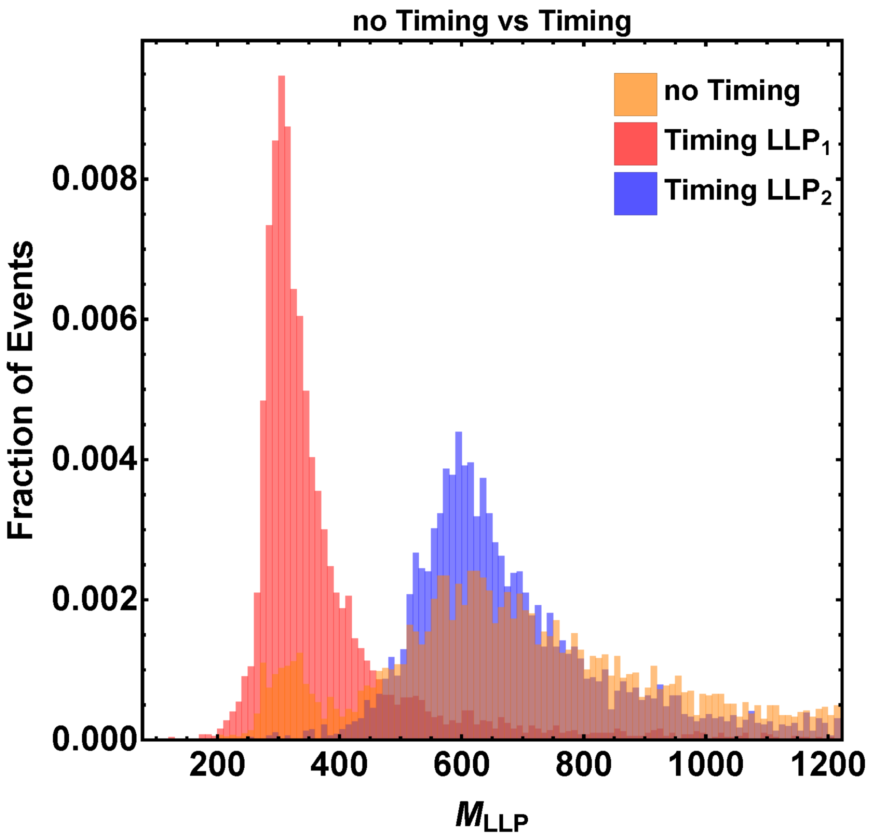


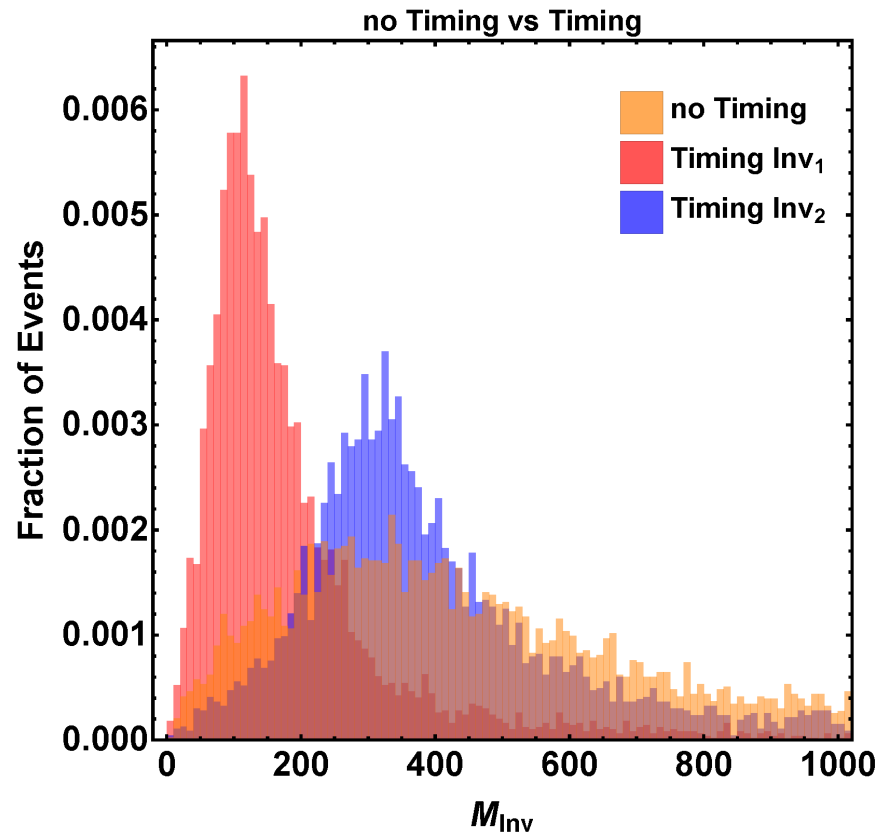
		m_{LLP_a}	m_{LLP_b}	m_{I_a}	m_{I_b}
Case 1	w/o timing	397.6 ± 1.2	397.6 ± 1.2	206.0 ± 1.5	206.0 ± 1.5
	timing	400.91 ± 0.35	400.77 ± 0.35	201.53 ± 0.49	201.53 ± 0.49

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

MC result

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

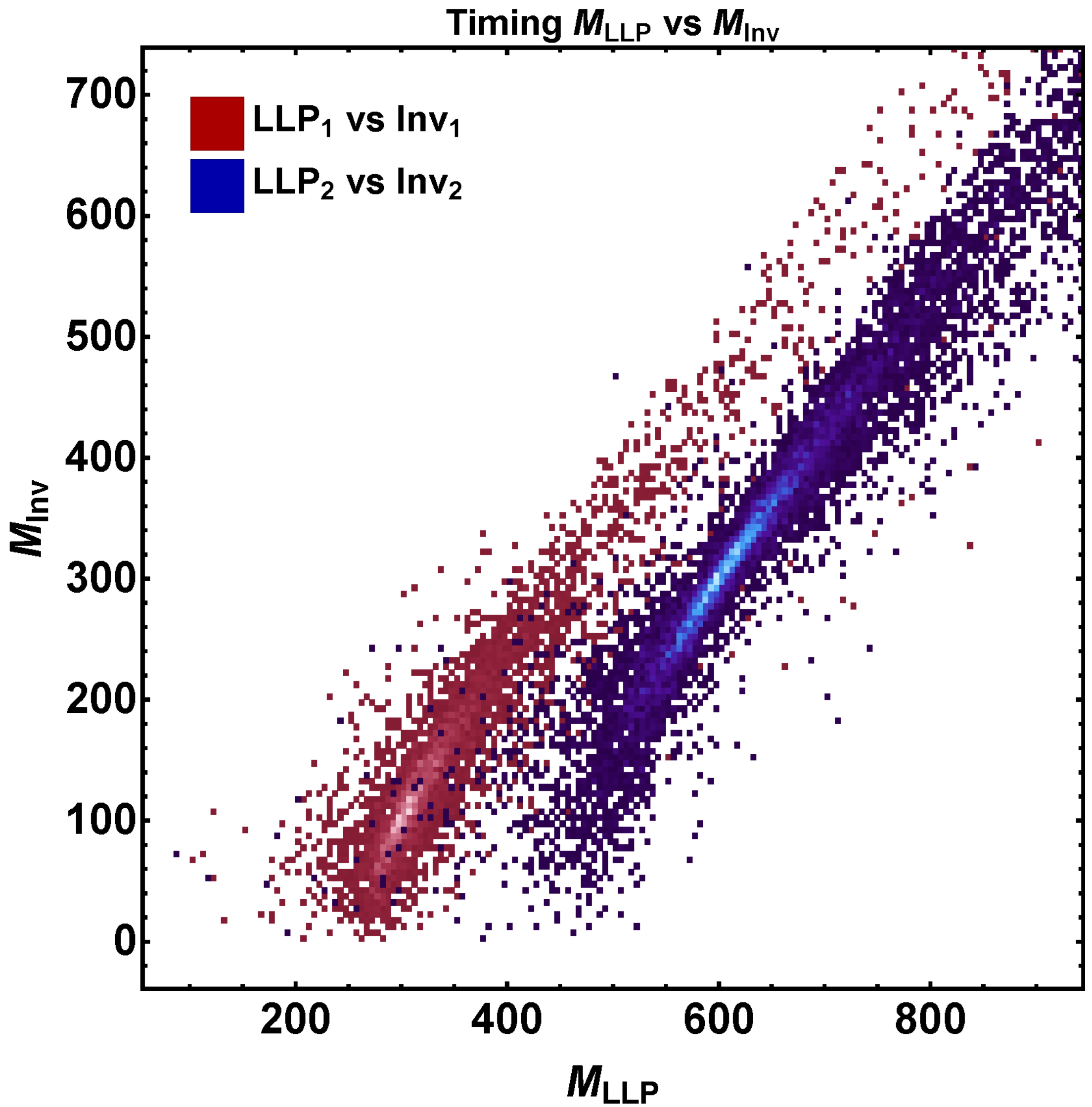




		m_{LLP_a}	m_{LLP_b}	m_{I_a}	m_{I_b}
Case2	w/o timing	-	-	-	-
	timing	307.25 ± 0.38	612.18 ± 0.72	118.54 ± 0.89	319.1 ± 1.1

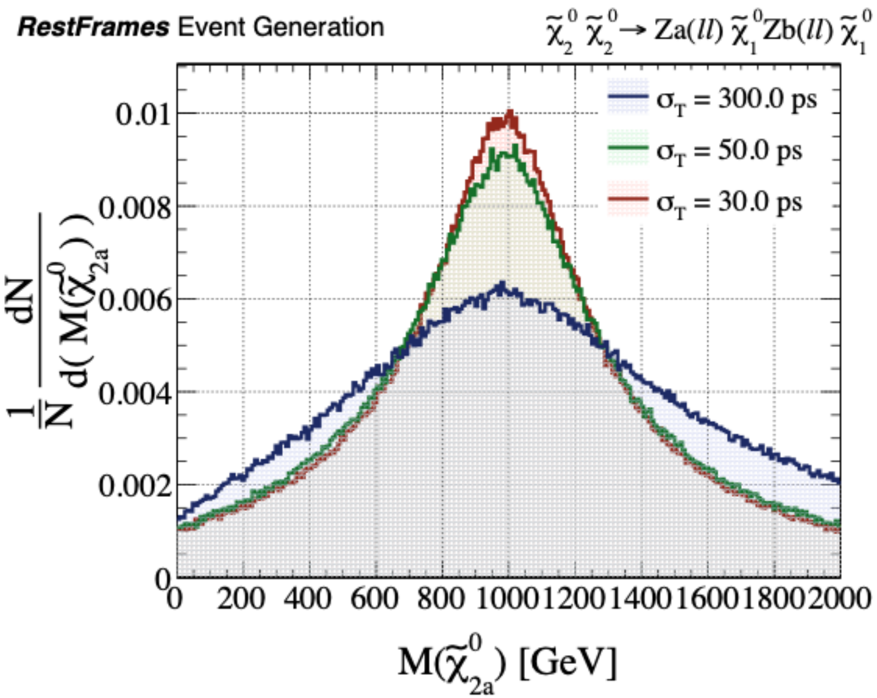
MC result

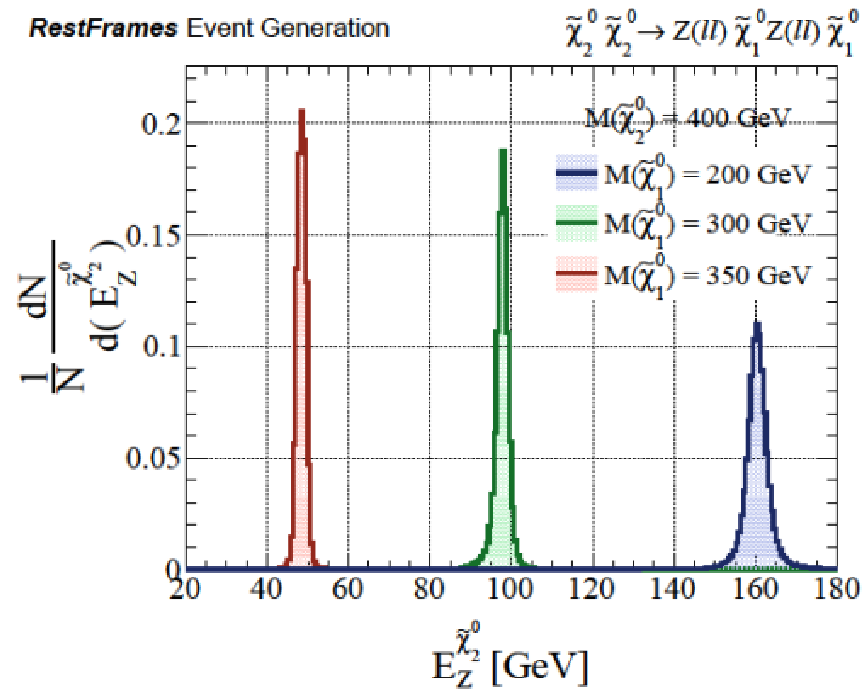
M_{LLP_a}: 300 GeV, M_{LLP_b}: 600 GeV
M_{I_a} : 100 GeV, M_{I_a} : 300 GeV



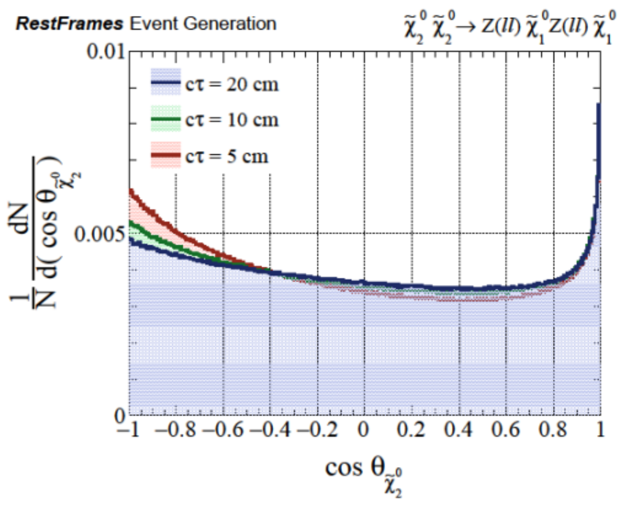
Impact of timing resolution on mass resolution

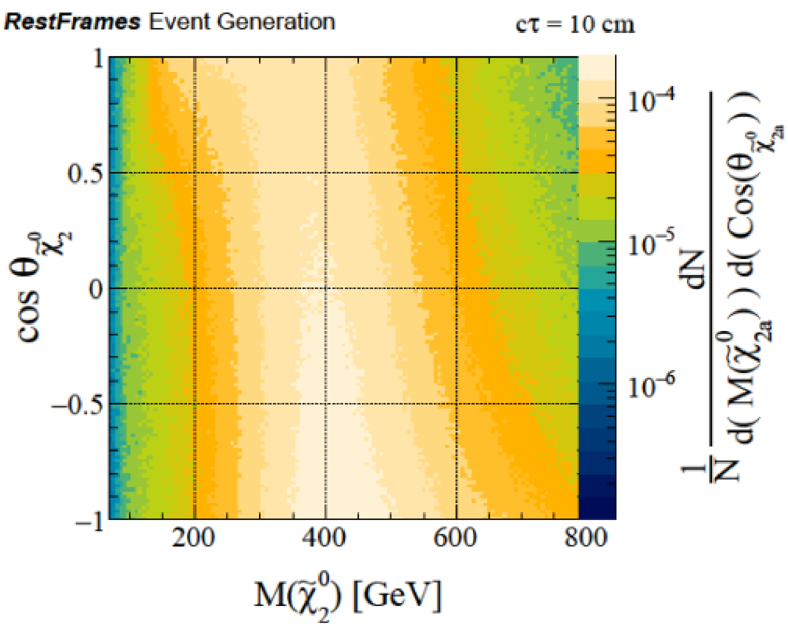
- With improved timing resolution we can better improve the mass resolution of LLPs

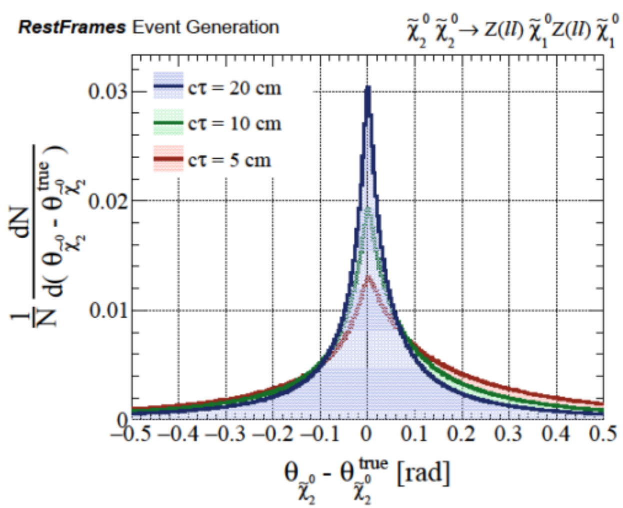




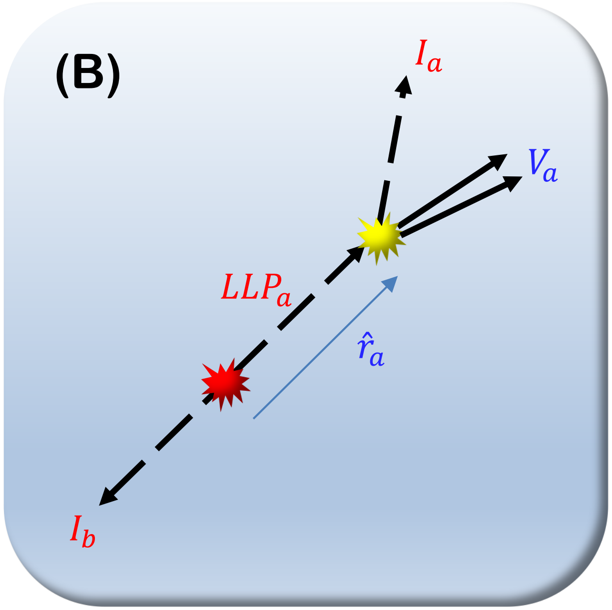
LLP decay angle







Neutral LLP search example (B)



- e+ e- > Z' -> chi1 chi2 -> chi1 chi1 l+ l-
- E+ e- > W'->nu N -> nu nu l+ l-
- ….

\# of unknowns > # of knowns + # of constraints

2 momenta = 8

1 momenta = 4

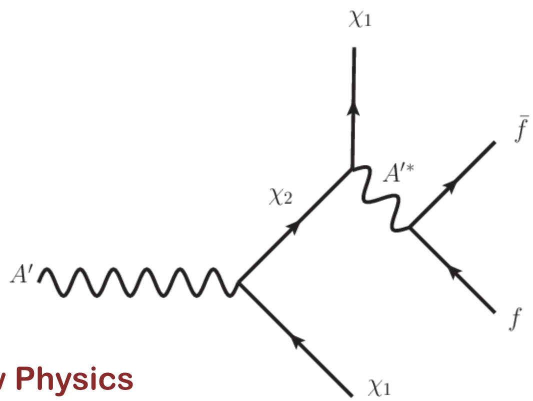
1 displaced vertices = 2

$I_a = I_b$

- Therefore, we cannot get the unique solution for 8 unknown values. We need to find other way to determine the mass of DM and mass splitting!

Inelastic dark matter model

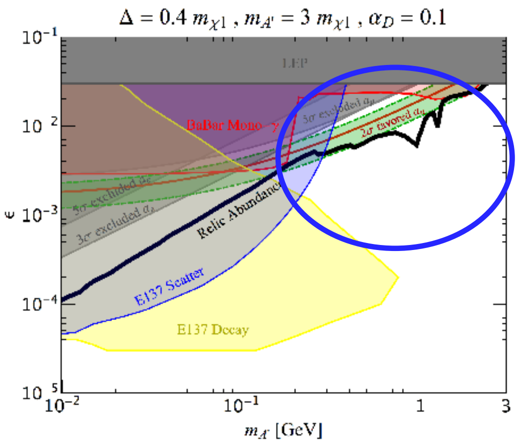
- We consider the inelastic (or excited) DM with extra $U(1)_D$ gauge symmetry.
- There are at least two states in the dark sectors and there is an inelastic transition between them via the new $U(1)_D$ gauge boson.
- The small mass splitting between two states, arise the co-annihilation channel to be the dominant one of DM relic density in early universe.
- The co-annihilation production for light DM via thermal freeze out is still consistent with the CMB constraint for the amount of parameter space.
- The constraint from DM and nuclear inelastic scattering is much weaker than the elastic one in the direct detection experiments.
- The excited DM state can naturally become long-lived and leave displaced vertex inside detector after it has been produced such that we can search for such novel signatures!



Inelastic dark matter model

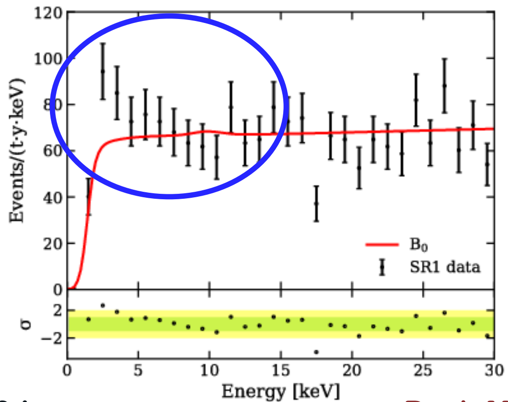
- Muon g-2 anomaly

[G. Mohlabeng, 1902.05075]
[M. Duerr, T. Ferber, c. earty, F. Kahlhoefer, K. Schmidt-Hoberg, 1911.03176]



- Xenon1T excess

[K. Harigaya, Y.Nakai, M. Suzuki,, 2006.11938]
[H. M. Lee, 2006.13183]
[S. Baek,J.Kim, P.Ko , 2006.16876]



Inelastic dark matter models

$$\mathcal{L}_{X,gauge} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\sin\epsilon}{2}B_{\mu\nu}B^{\mu\nu}$$

$$\Phi(x) = \frac{1}{\sqrt{2}}(v_D + h_D(x))$$

$$H(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

$$\mathcal{L}_{Z'f\bar{f}} = -\epsilon e c_W \sum_f x_f \bar{f} \not{Z}' f$$

$$m_{Z'} \simeq g_D Q_D(\Phi) v_D$$

Scalar model

	Q_D
Φ	$+2$
ϕ	$+1$

$$\begin{aligned} V(H,\Phi,\phi) = & -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 - \mu_\Phi^2 \Phi^*\Phi + \lambda_\Phi(\Phi^*\Phi)^2 \\ & -\mu_\phi^2\phi^*\phi + \lambda_\phi(\phi^*\phi)^2 + (\mu_{\Phi\phi}\Phi^*\phi^2 + H.c.) \\ & + \lambda_{H\Phi}(H^\dagger H)(\Phi^*\Phi) + \lambda_{H\phi}(H^\dagger H)(\phi^*\phi) + \lambda_{\Phi\phi}(\Phi^*\Phi)(\phi^*\phi) \end{aligned}$$

$$g_D X_\mu (\phi_2 \partial^\mu \phi_1 - \phi_1 \partial^\mu \phi_2)$$

$$M_{\phi_{1,2}} = \sqrt{\frac{1}{2}(-\mu_\phi^2 + \lambda_{H\phi}v^2 + \lambda_{\Phi\phi}v_D^2) \mp \mu_{\Phi\phi}v_D}$$

$$\Delta_\phi = M_{\phi_2} - M_{\phi_1} = \frac{2\mu_{\Phi\phi}v_D}{M_{\phi_1} + M_{\phi_2}}$$

Fermion model

	Q_D
Φ	$+2$
χ	$+1$

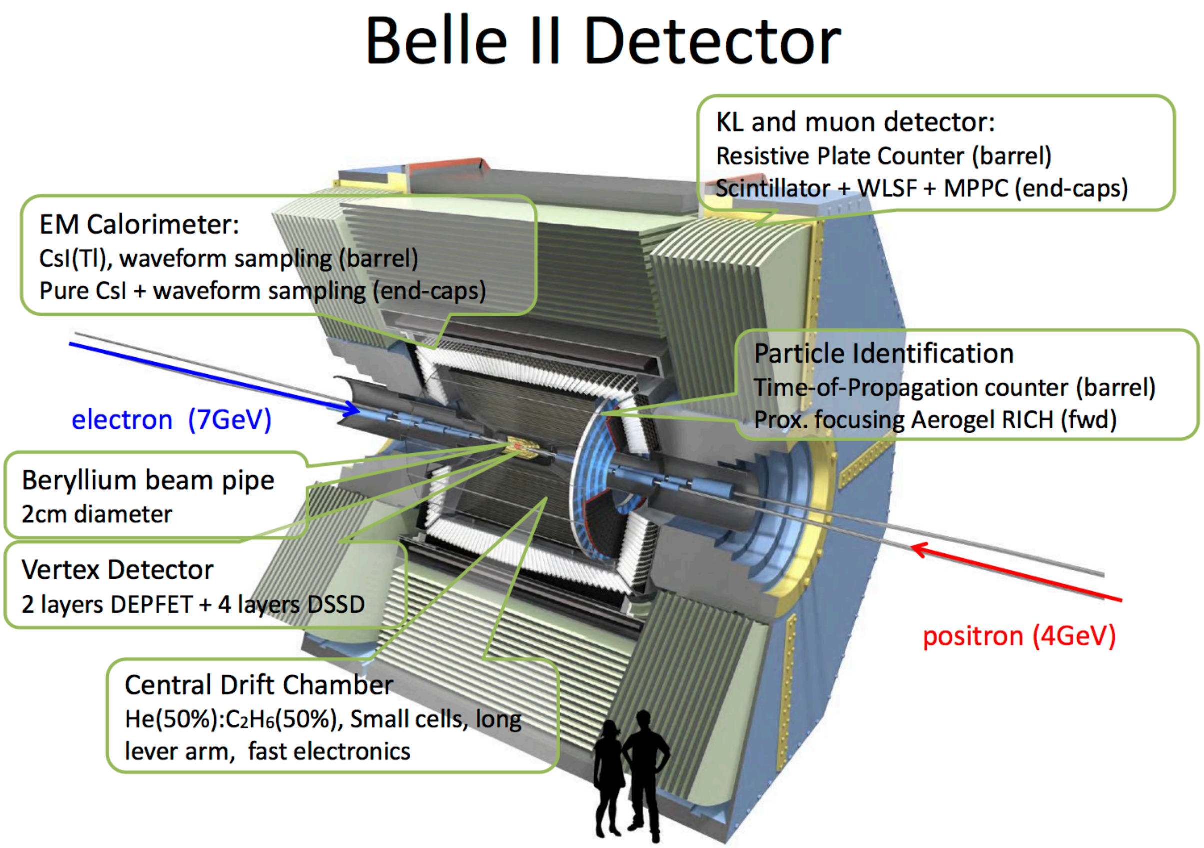
$$\begin{aligned} V(H,\Phi,\phi) = & -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 - \mu_\Phi^2 \Phi^*\Phi + \lambda_\Phi(\Phi^*\Phi)^2 \\ & + \lambda_{H\Phi}(H^\dagger H)(\Phi^*\Phi) \quad -(\frac{f}{2}\bar{\chi}^c\chi\Phi^* + H.c.) \end{aligned}$$

$$-i\frac{g_D}{2}(\bar{\chi}_2 \not{X} \chi_1 - \bar{\chi}_1 \not{X} \chi_2)$$

$$M_{\chi_{1,2}} = M_\chi \mp f v_D$$

$$\Delta_\chi \equiv (M_{\chi_2} - M_{\chi_1}) = 2 f v_D$$

Search for LLPs in inelastic DM models at Belle2



The tracking resolution of e/mu momenta in the drift chamber detector is given by

$$\sigma_{p_{\ell^\pm}}/p_{\ell^\pm} = 0.0011 p_{\ell^\pm}[\mathrm{GeV}] \oplus 0.0025/\beta$$

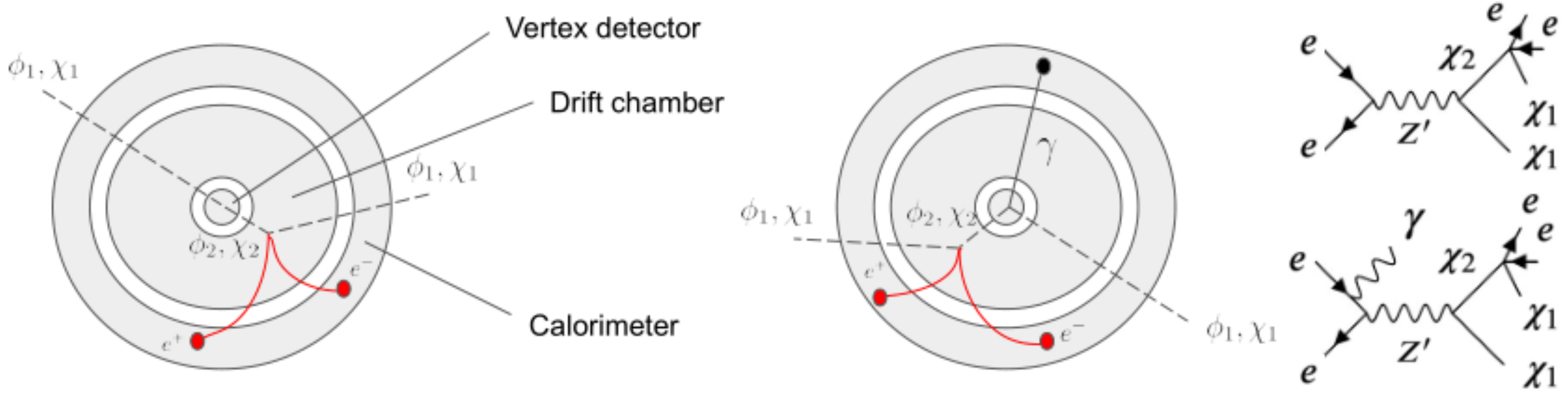
The resolution of photon momenta in the calorimeter

$$\sigma_{E_\gamma}/E_\gamma = 2\%$$

The resolution for the displaced vertex of lepton pair

$$\sigma_{r_{DV}} = 26\mu\mathrm{m}$$

Displaced signature in Belle2 detector

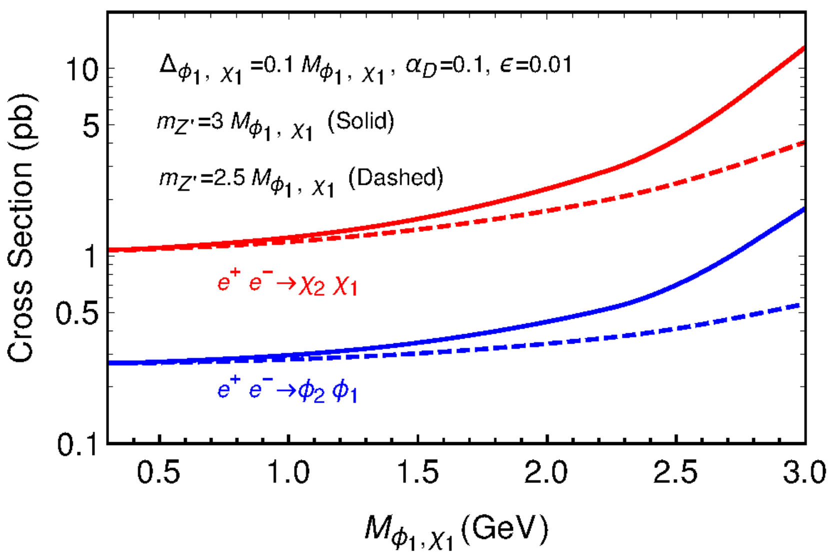


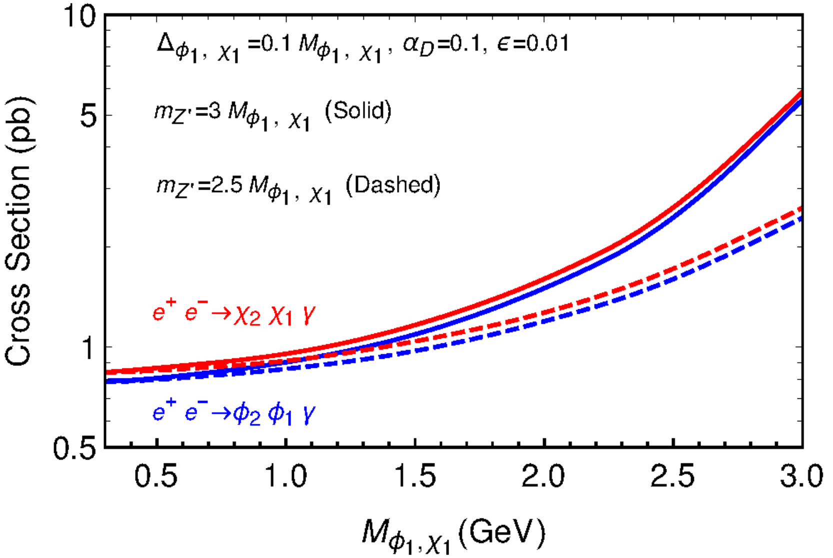
$$e^+e^- \to \phi_1\phi_2 \to \phi_1\phi_1 e^+e^-$$
$$e^+e^- \to \chi_1\chi_2 \to \chi_1\chi_1 e^+e^-$$

$$e^+e^- \to \phi_1\phi_2\gamma \to \phi_1\phi_1 e^+e^-\gamma$$
$$e^+e^- \to \chi_1\chi_2\gamma \to \chi_1\chi_1 e^+e^-\gamma$$

Production cross section

- The cross sections for fermion and scalar pair productions are scale by $\beta^{1/2}$ and $\beta^{3/2}$ respectively, where beta is the velocity of the final state particle in the CM frame
- Hence, one can expect the production of the scalar pair is suppressed by an extra factor of β compared with the fermionic case.





Event selections

We only conservatively consider the following two background-free regions after event selections in our analysis

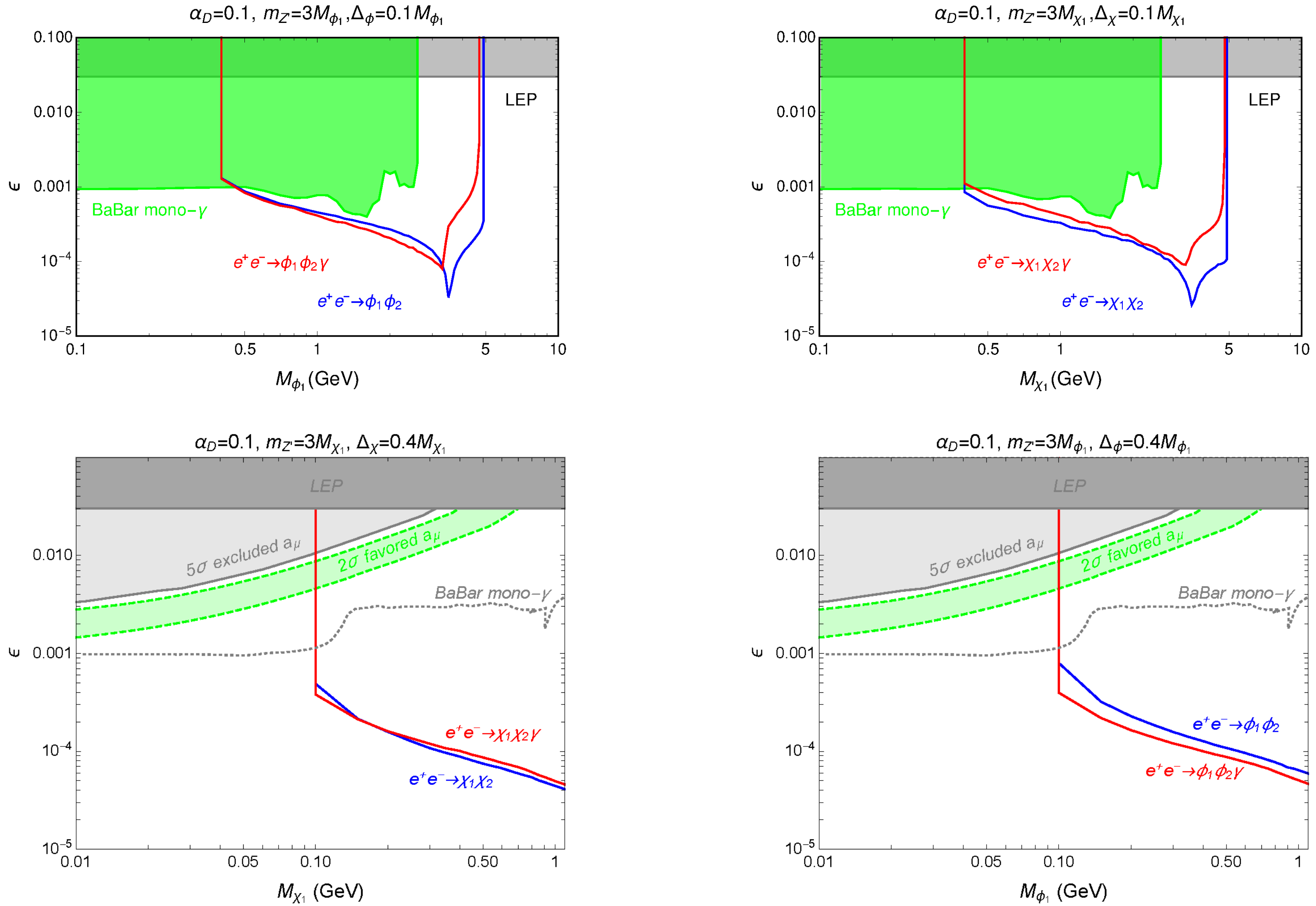
- Low R_{xy} region (100% efficiency) :
  0.2 < R_{xy} < 0.9 (17.0)
- High R_{xy} region (30% efficiency) :
  17.0 < R_{xy} < 60.0

Objects	Selections
displaced vertex	(i) $-55\,\text{cm} \leq z \leq 140\,\text{cm}$ (ii) $17° \leq \theta_{\text{LAB}}^{\text{DV}} \leq 150°$
electrons	(i) both $E(e^+)$ and $E(e^-) > 0.1\,\text{GeV}$ (ii) opening angle of pair $\theta_{ee} > 0.1$ rad (iii) invariant mass of pair $m_{ee} > 0.03\,\text{GeV}$
muons	(i) both $p_{\text{T}}(\mu^+)$ and $p_{\text{T}}(\mu^-) > 0.05\,\text{GeV}$ (ii) opening angle of pair $\theta_{\mu\mu} > 0.1$ rad (iii) invariant mass of pair $m_{\mu\mu} > 0.03\,\text{GeV}$ (iv) veto $0.48\,\text{GeV} \leq m_{\mu\mu} \leq 0.52\,\text{GeV}$
photons	(i) $E_{\text{LAB}}^{\gamma} > 0.5\,\text{GeV}$ (ii) $17° \leq \theta_{\text{LAB}}^{\gamma} \leq 150°$

Benchmark points

- (I) $M_{\phi_1,\chi_1} = 0.3$ GeV, $\Delta_{\phi_1,\chi_1} = 0.4 M_{\phi_1,\chi_1}$, $m_{Z'} = 3 M_{\phi_1,\chi_1}$ and $\epsilon = 2 \times 10^{-2}$
- (II) $M_{\phi_1,\chi_1} = 3.0$ GeV, $\Delta_{\phi_1,\chi_1} = 0.1 M_{\phi_1,\chi_1}$, $m_{Z'} = 3 M_{\phi_1,\chi_1}$ and $\epsilon = 2 \times 10^{-3}$
- (III) $M_{\phi_1,\chi_1} = 1.0$ GeV, $\Delta_{\phi_1,\chi_1} = 0.4 M_{\phi_1,\chi_1}$, $m_{Z'} = 2.5 M_{\phi_1,\chi_1}$ and $\epsilon = 10^{-3}$
- (IV) $M_{\phi_1,\chi_1} = 2.0$ GeV, $\Delta_{\phi_1,\chi_1} = 0.2 M_{\phi_1,\chi_1}$, $m_{Z'} = 2.5 M_{\phi_1,\chi_1}$ and $\epsilon = 10^{-3}$

Future sensitivity



Scalar vs fermion: Angular distribution

- In the CM frame, the normalized differential cross section can be written as

Scalar

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \frac{3}{4}(1-\cos^2\theta)$$

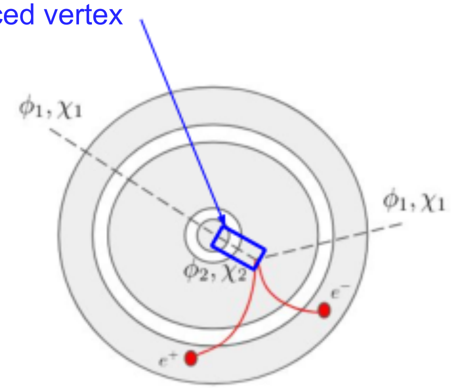
Fermion

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \frac{\left(1-\frac{(M_{\chi_2}^2-M_{\chi_1}^2)^2}{s^2}+\frac{4M_{\chi_1}M_{\chi_2}}{s}\right)\xi+\xi^{3/2}\cos^2\theta}{2\left(1-\frac{(M_{\chi_2}^2-M_{\chi_1}^2)^2}{s^2}+\frac{4M_{\chi_1}M_{\chi_2}}{s}\right)\xi+\frac{2}{3}\xi^{3/2}}$$

Massless limit → $\frac{3}{8}(1+\cos^2\theta)$

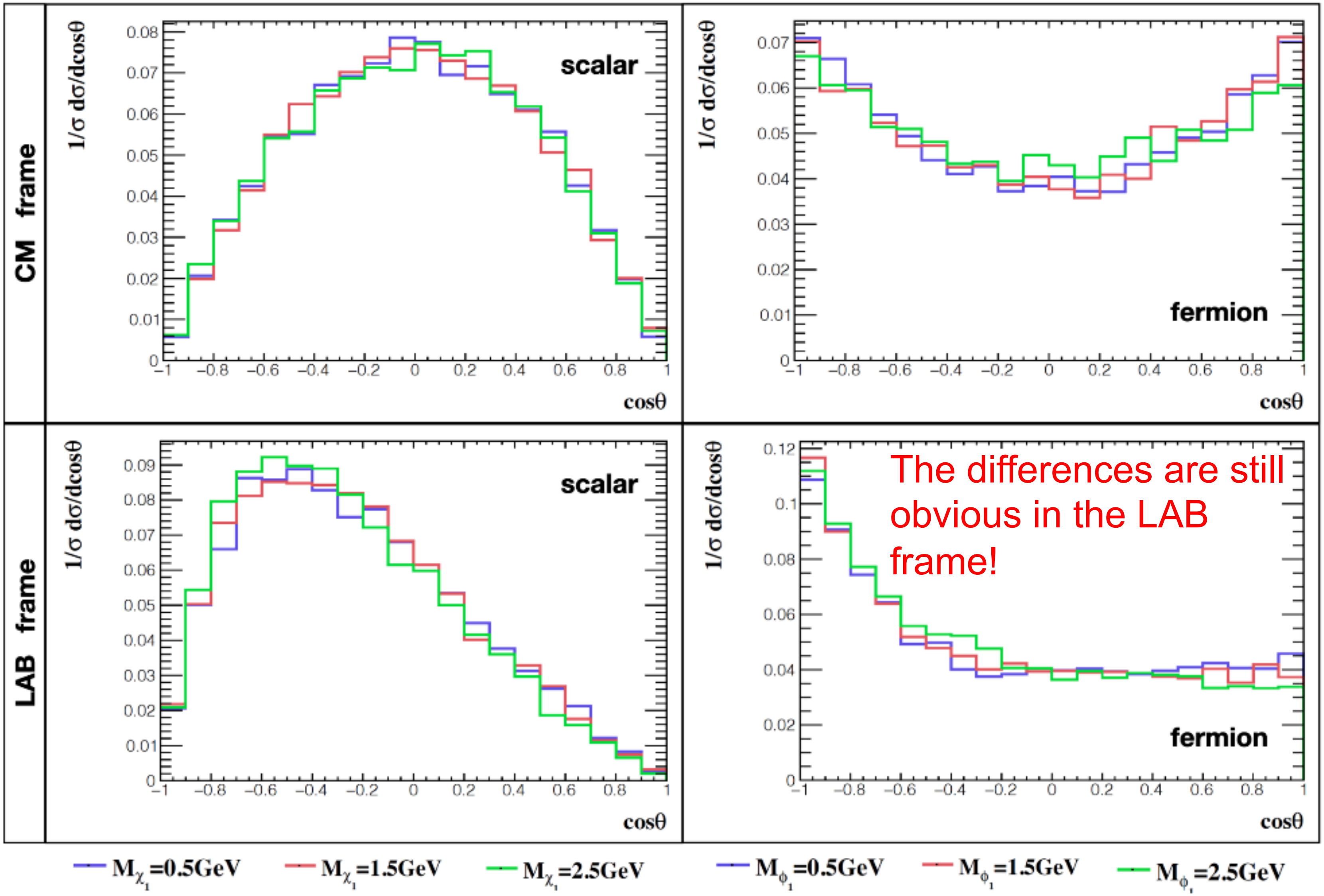
Where $\xi = \sqrt{1-\frac{2(M_{\chi_2}^2+M_{\chi_1}^2)}{s}+\frac{(M_{\chi_2}^2-M_{\chi_1}^2)^2}{s^2}}$

We need to know the direction of displaced vertex



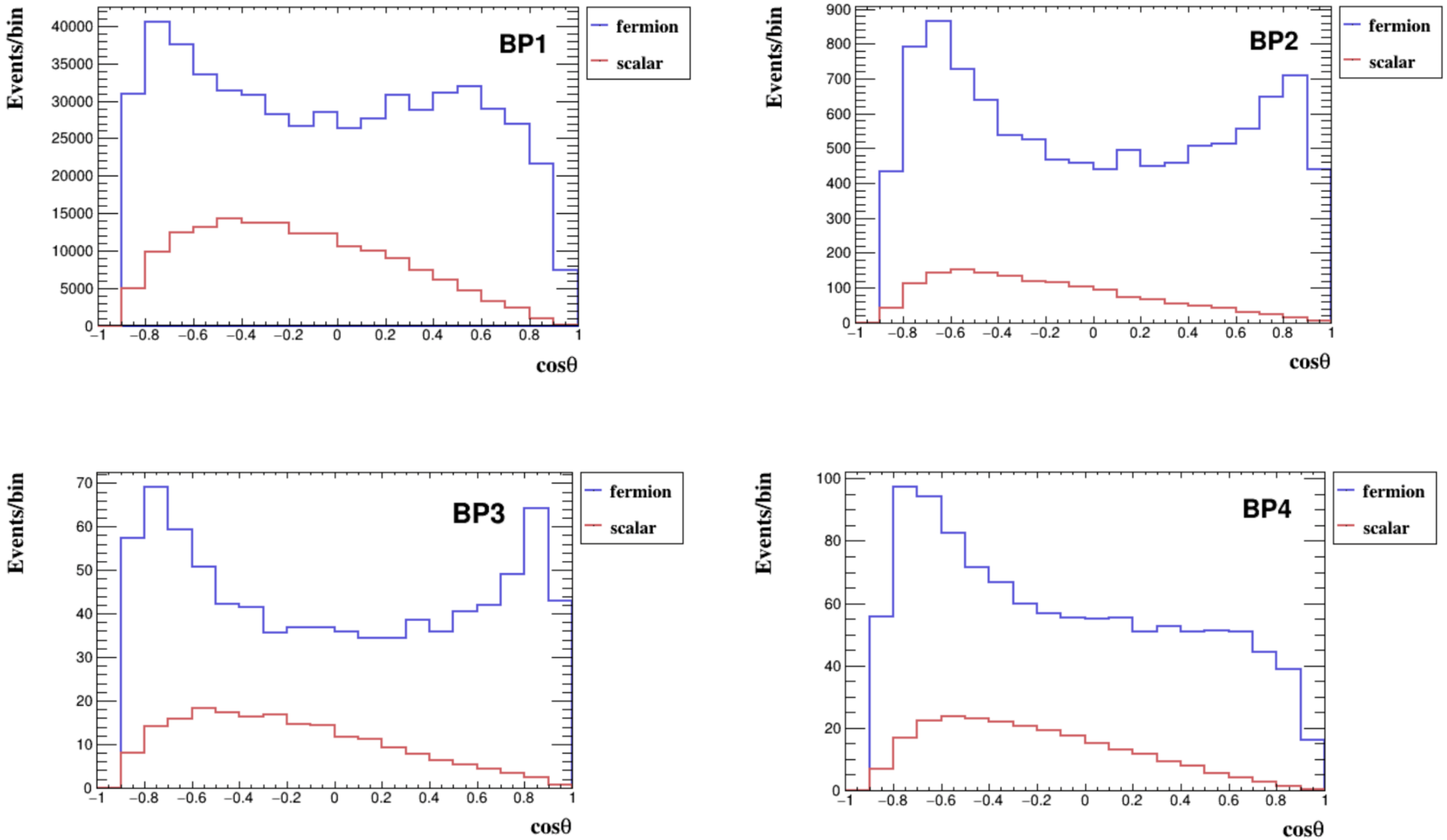
Note θ is the direction of ϕ_2, χ_2 relative to the positive beam direction

Angular distribution w/o ISR

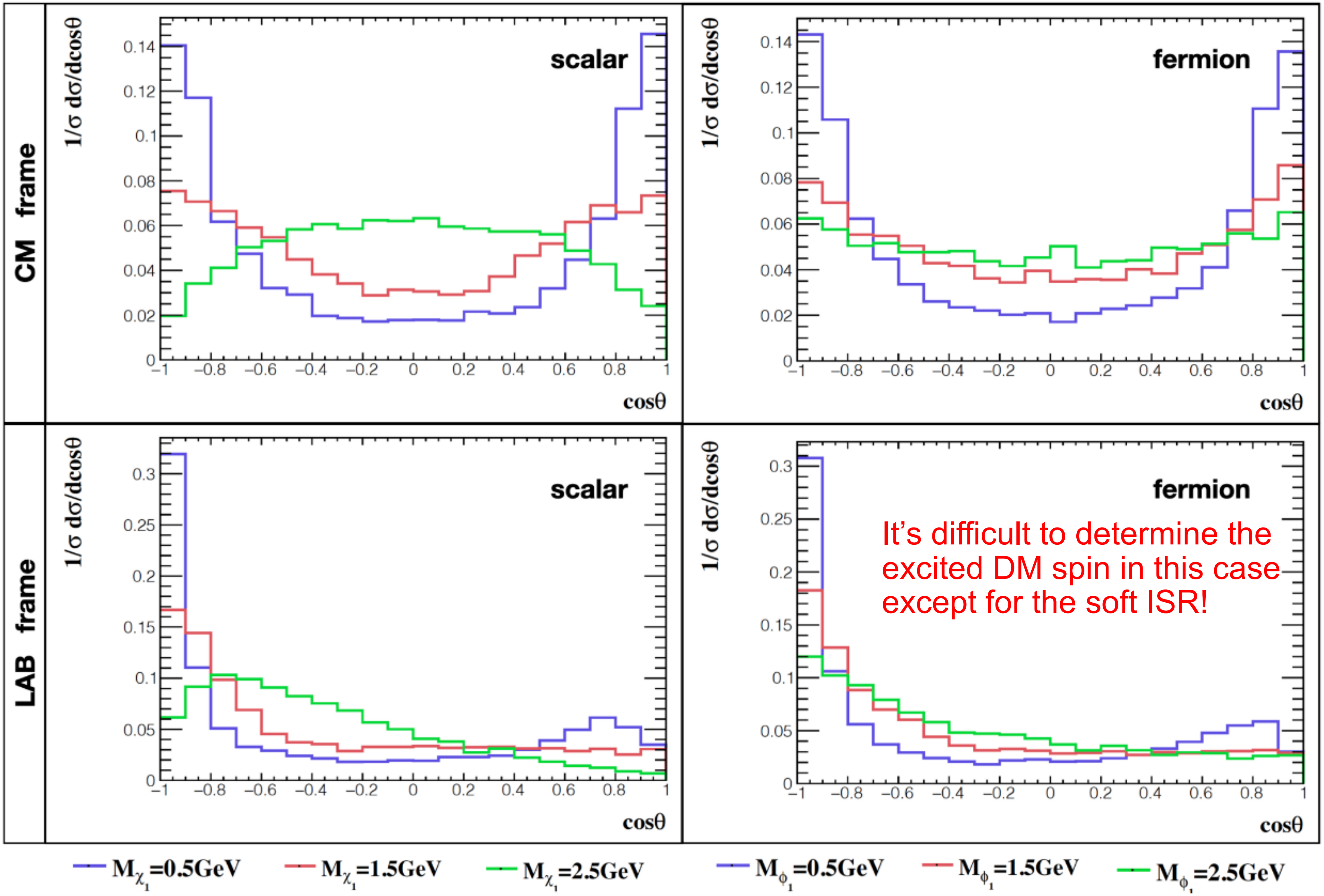


Angular distribution w/o ISR

After event selection

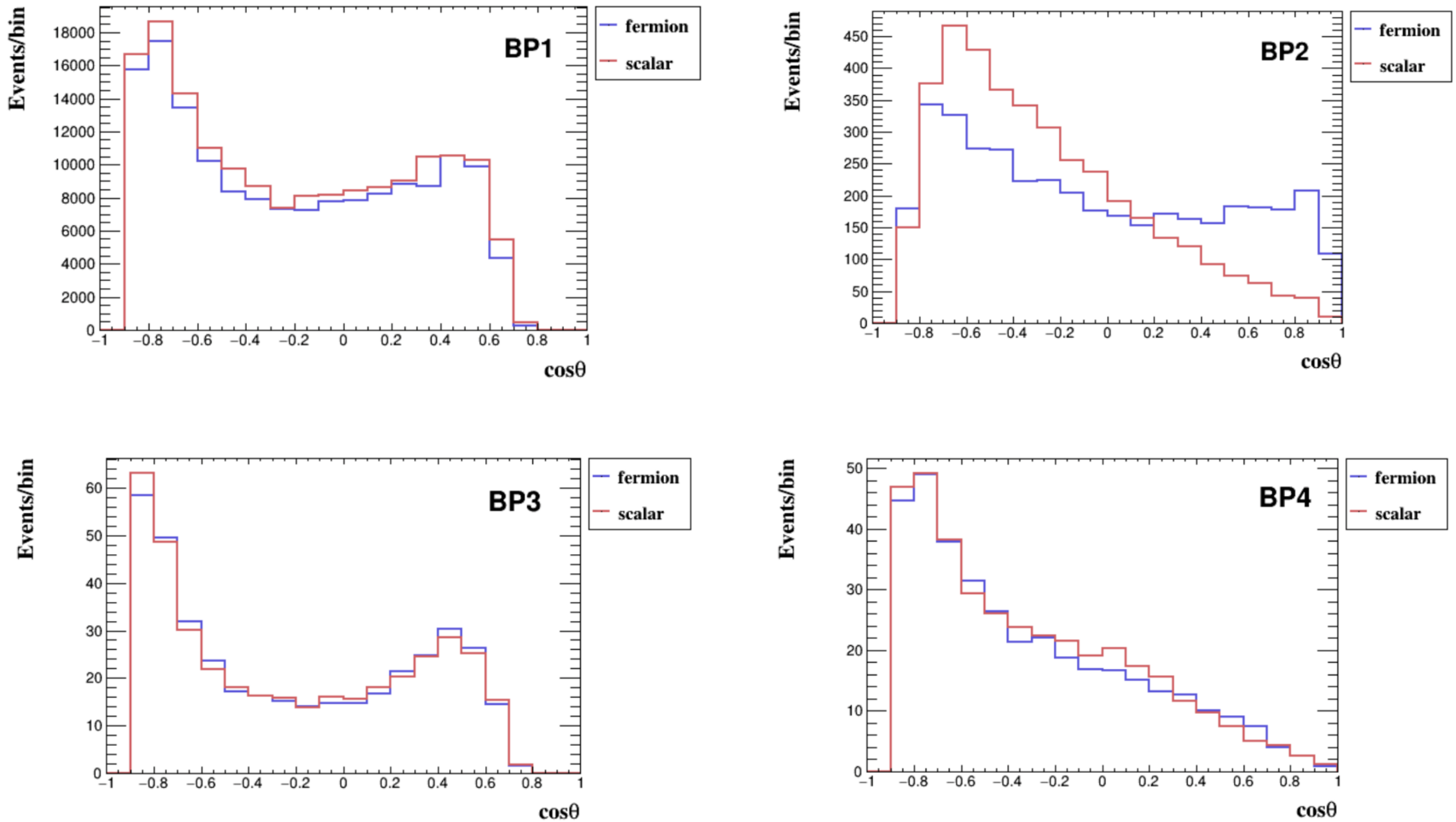


Angular distribution w/ ISR

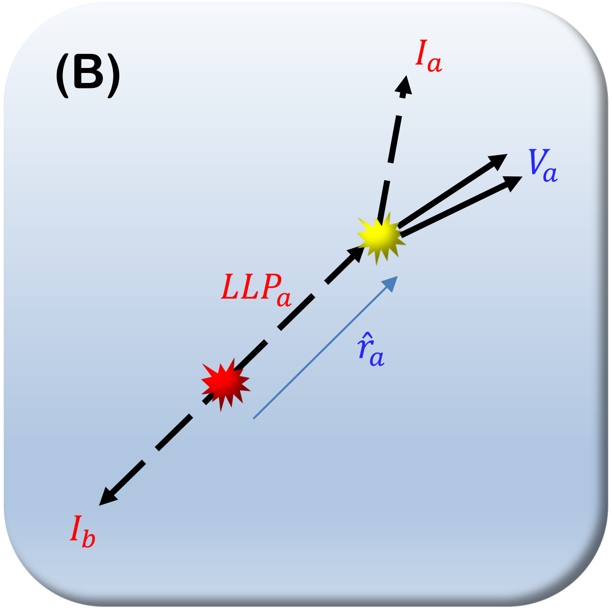


Angular distribution w/ ISR

After event selection



Mass & mass gap



# of unknowns > # of knowns + # of constraints

2 momenta = 8

1 momenta = 4
1 displaced vertices = 2

$I_a = I_b$

- Therefore, we cannot get the unique solution for 8 unknown values. We need to find other way to determine the mass of DM and mass splitting!

For each event, we can find a relation between the mass of DM and mass splitting from the four-momentum conservation.

$$m_{\chi 2}^2 - m_{\chi 1}^2 - 2E(1+\alpha)E_{V'} + E_{V'}^2 - |\vec{p}_{V'}|^2 + 2\sqrt{(E(1+\alpha))^2 - m_{\chi 2}^2}(\hat{r}_{DV}\cdot\vec{p}_{V'}) = 0$$

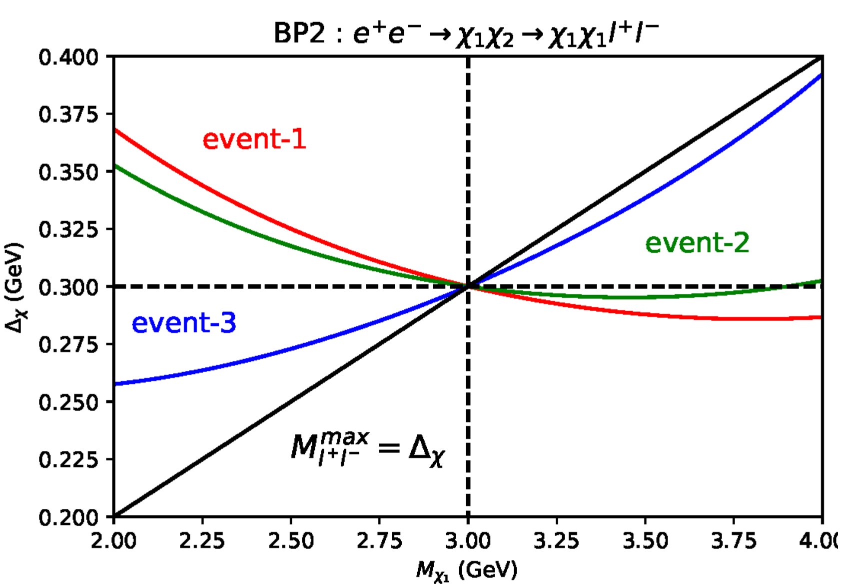
$\hat{r}_{DV}$ is the direction of displaced vertex, E is half of the CM energy, $E_{V'}$, $\hat{p}_{V'}$ are visible energy and three-momentum in the final states, and $\alpha = \frac{m_{\chi 2}^2 - m_{\chi 1}^2}{4E^2}$

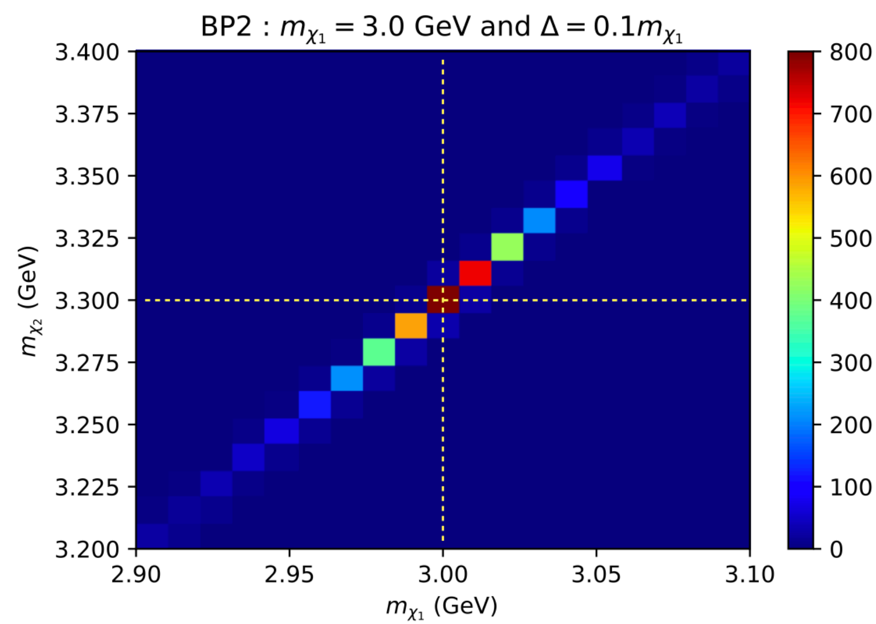
Mass & mass gap

The crossing point from these events and kinematic endpoint measurement can help us to determine the mass of DM and mass splitting.

This method is based on “Kinematic focus point” [D. Kim, K. Matchev, P. Shyamsundar, 1906.02821]

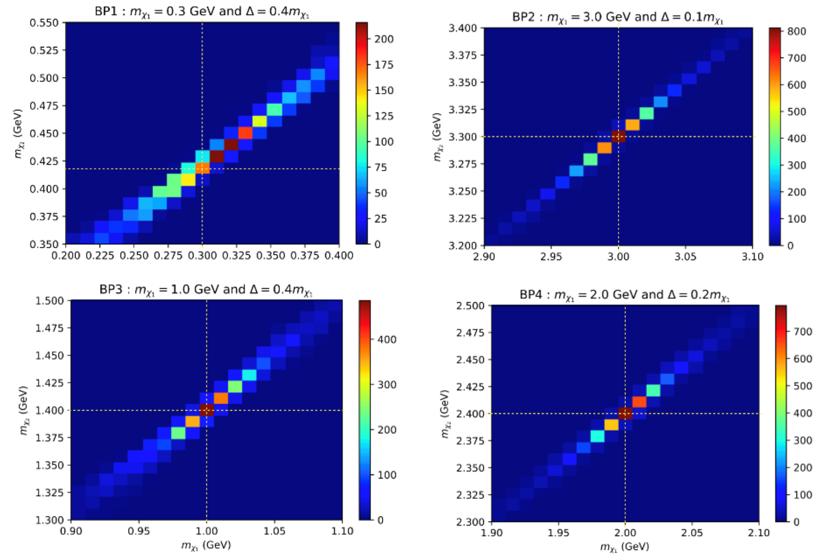
- Assume we can have 100 signal events at the Belle2, then we will get 4950 solutions from each two events!





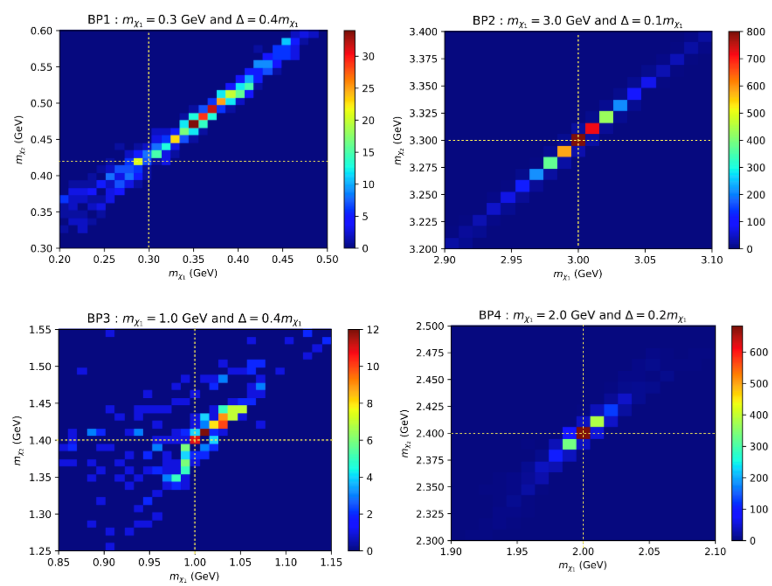
$$e^+e^- \to \chi_1\chi_2 \to \chi_1\chi_1\ell^+\ell^-$$

BP	N_{phys}	$(M_{\chi_2}, M_{\chi_1})^{\rm true}$ / $(M_{\chi_2}, M_{\chi_1})^{\rm peak}$	rms
BP1	4473	(0.42, 0.30)	(0.168, 0.175)
		(0.43, 0.32)	
BP2	4915	(3.30, 3.00)	(0.175, 0.190)
		(3.30, 3.00)	
BP3	4856	(1.40, 1.00)	(0.172, 0.192)
		(1.40, 1.00)	
BP4	4918	(2.40, 2.00)	(0.155, 0.170)
		(2.40, 2.00)	



$$e^+e^- \to \chi_1\chi_2\gamma \to \chi_1\chi_1\ell^+\ell^-\gamma$$

BP	N_{phys}	$(M_{\chi_2}, M_{\chi_1})^{\rm true}$ / $(M_{\chi_2}, M_{\chi_1})^{\rm peak}$	rms
BP1	901	(0.42, 0.30)	(0.114, 0.138)
		(0.47, 0.35)	
BP2	4914	(3.30, 3.00)	(0.121, 0.128)
		(3.30, 3.00)	
BP3	377	(1.40, 1.00)	(0.216, 0.402)
		(1.41, 1.01)	
BP4	2824	(2.40, 2.00)	(0.126, 0.173)
		(2.40, 2.00)	



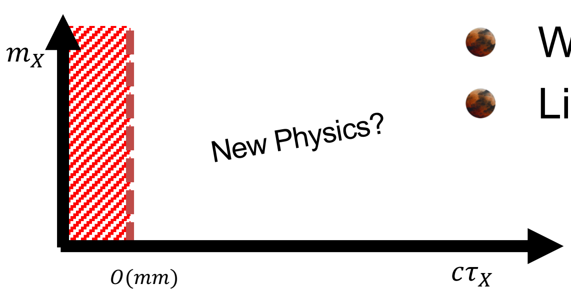
Conclusion

Timing detector @ HL-LHC

- 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/dark sector and LLP searches.

Inelastic DM @ Belle2

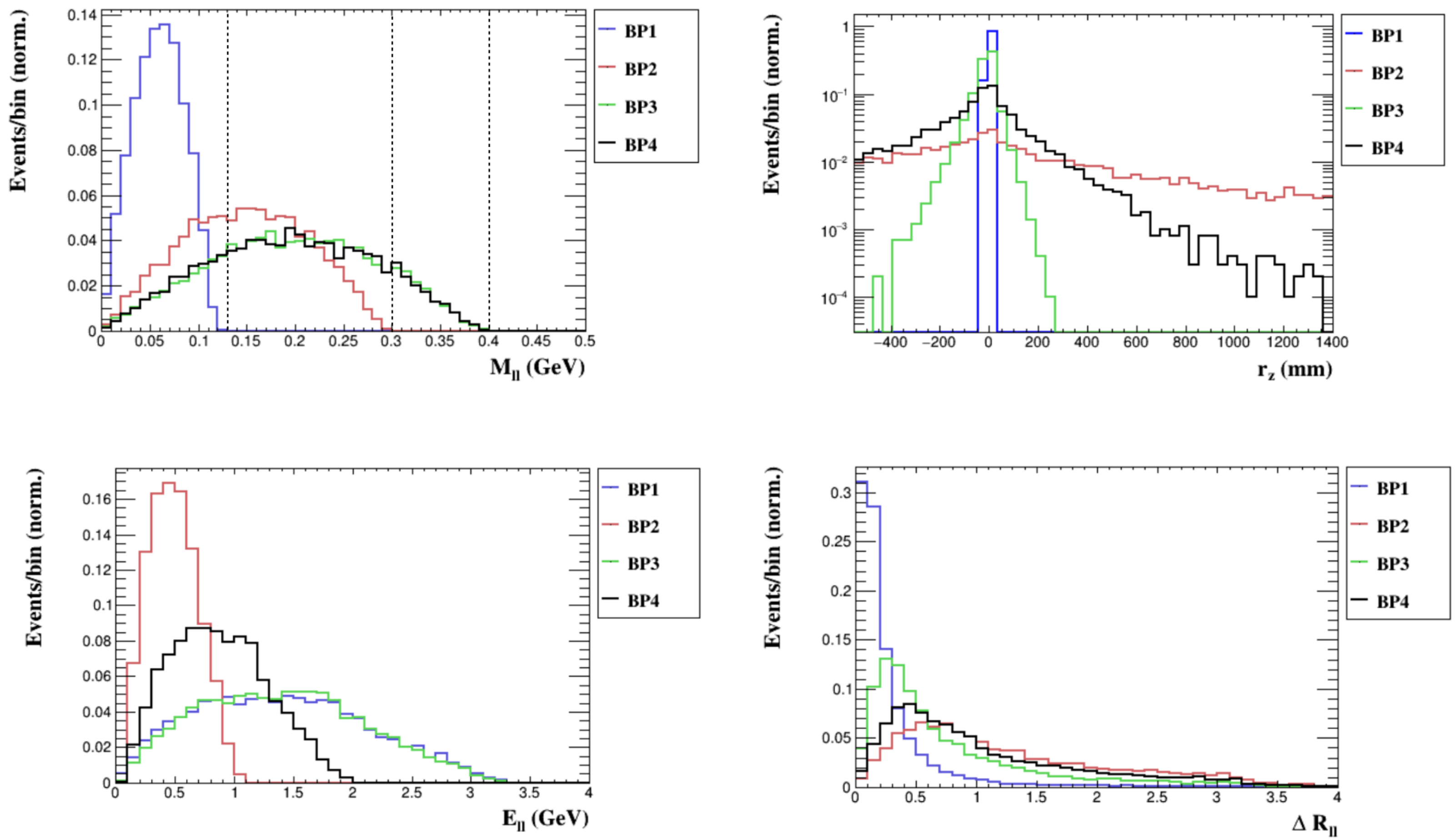
- The inelastic DM with extra $U(1)_D$ gauge symmetry is an interesting dark sector models with light DM.
- With the help of precise displaced vertex detection ability at Belle2, we can explore the DM spin, mass and mass splitting between DM excited and ground states
- Furthermore, the allowed parameter space to explain the excess of muon $(g-2)_\mu$ is also studied and it can be covered in our displaced vertex analysis during the early stage of Belle2 experiment.



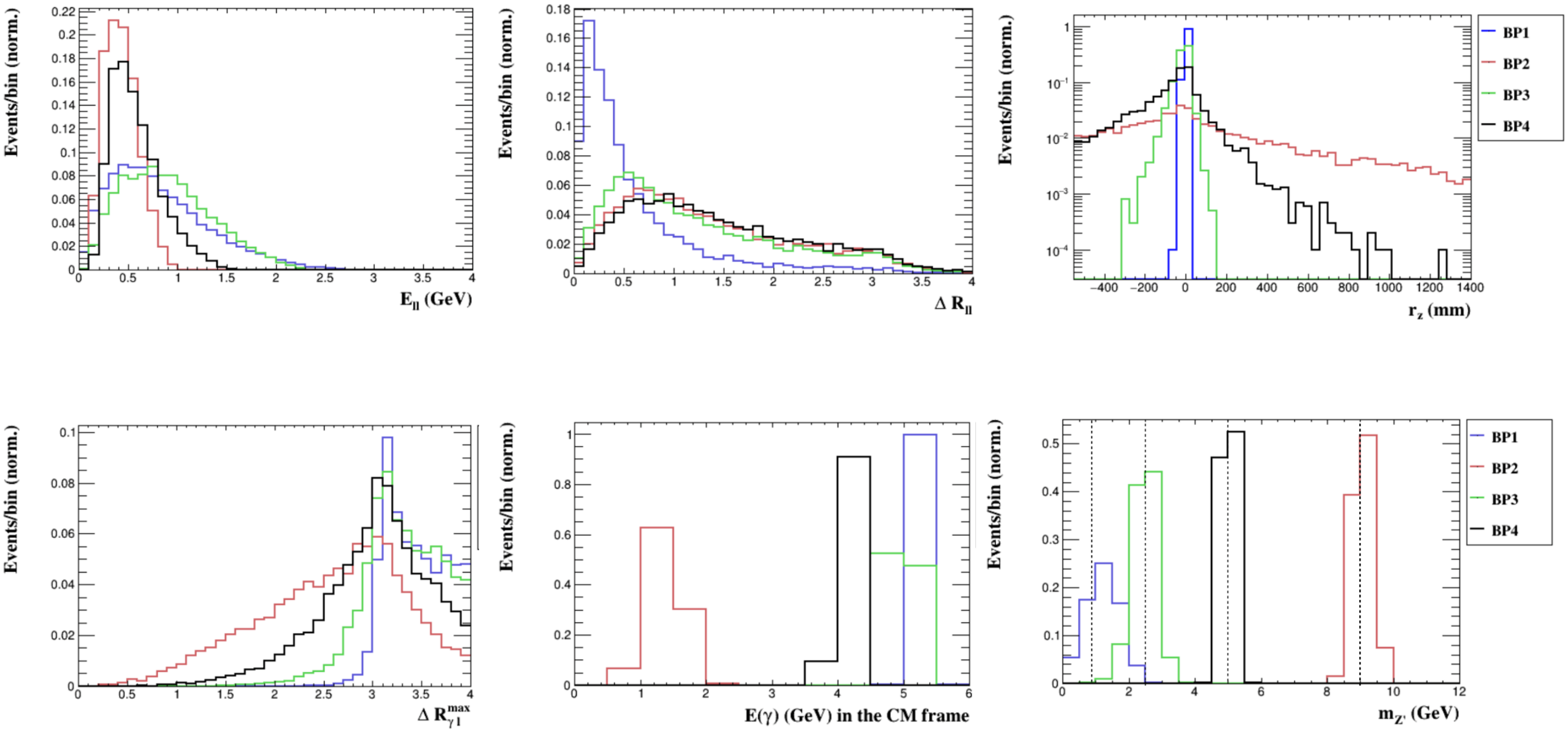
- BSM LLP search have potential to reveal new symmetries & scale
- We need more dedicated, signature-based searches for LLP.
- Lifetime era is coming!

backup

Kinematic distributions w/o ISR



Kinematic distributions w/ ISR



Analysis results

Without ISR

Type	BP	σ (fb)	Eff.(low R_{xy})	Eff.(high R_{xy})	N_{event}
scalar	BP1e	948.14	16.98	0%	1.61×10^5
	BP2e	58.39	0.15%	2.48%	1.54×10^3
	BP2μ	6.15	0.21%	3.33%	217.71
	BP3e	1.86	10.06%	0.70%	200.09
	BP3μ	0.61	11.25%	0.74%	73.14
	BP4e	2.23	1.56%	9.34%	243.26
	BP4μ	0.74	1.72%	10.78%	92.50
fermion	BP1e	3856.00	14.26%	0%	5.50×10^5
	BP2e	422.80	0.17%	2.35%	1.07×10^4
	BP2μ	44.63	0.22%	2.97%	1.42×10^3
	BP3e	7.99	10.20%	0.42%	848.54
	BP3μ	2.69	11.20%	0.46%	313.65
	BP4e	11.71	1.57%	7.82%	1.10×10^3
	BP4μ	3.88	1.69%	8.75%	405.07

With ISR

Type	BP	σ (fb)	Eff.(low R_{xy})	Eff.(high R_{xy})	N_{event}
scalar	BP1e	2472.70	6.70%	0%	1.66×10^5
	BP2e	159.85	0.16%	2.27%	3.88×10^3
	BP2μ	16.85	0.20%	2.87%	517.30
	BP3e	5.13	7.64%	0.02%	392.96
	BP3μ	1.69	8.83%	0.03%	149.73
	BP4e	7.14	1.86%	3.29%	367.71
	BP4μ	2.35	2.02%	2.87%	114.92
fermion	BP1e	2503.60	6.14%	0%	1.54×10^5
	BP2e	167.10	0.16%	2.16%	3.87×10^3
	BP2μ	17.66	0.18%	2.67%	503.31
	BP3e	5.05	7.77%	0.02%	393.40
	BP3μ	1.70	8.89%	0.02%	151.47
	BP4e	7.14	1.95%	3.14%	363.43
	BP4μ	2.37	2.05%	3.44%	130.11

Timing detector resolution