Exploring long-lived particles and its properties at colliders

Dong Woo Kang (KIAS)

Based on

Z. Flowers, Q. Meier, C. Rogan, **DWK**, S. C. Park, JHEP 03 (2020) 132

DWK, P. Ko, Chih-Ting Lu, JHEP 04 (2021) 269

Asia-Pacific Workshop on Particle Physics and Cosmology 2021

Long lived particle

The Standard Model

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

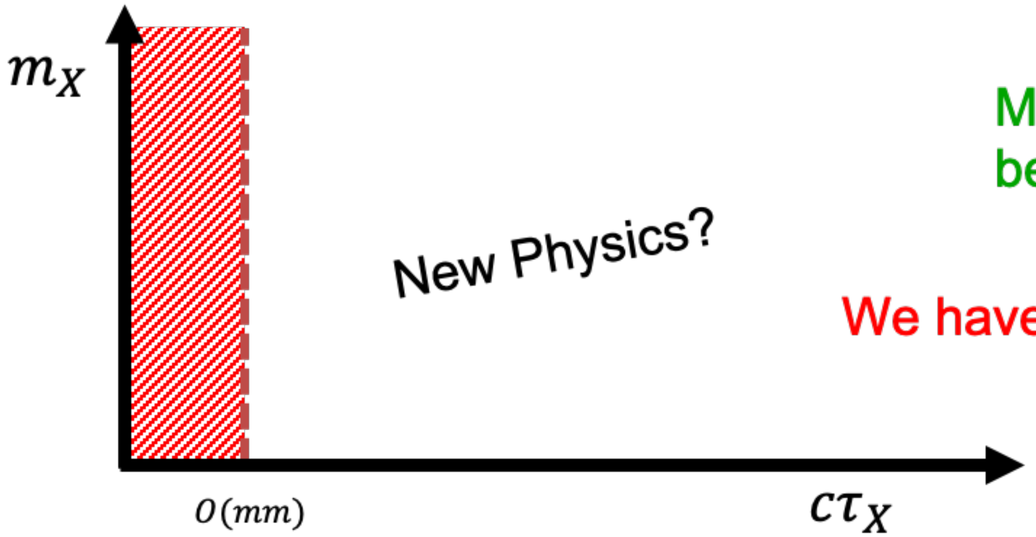
What makes particle long-lived?

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.

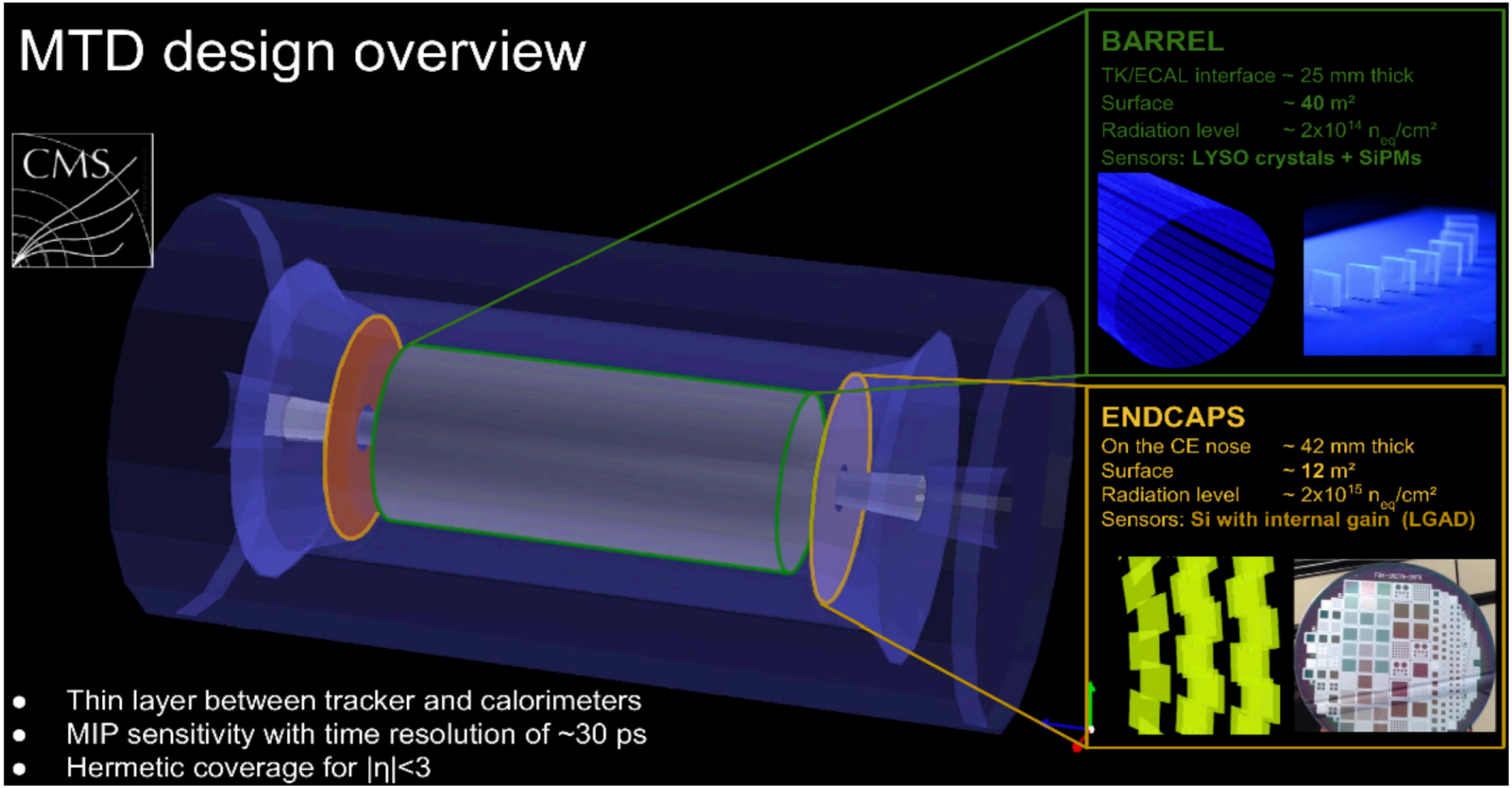
We have huge parameter space to investigate!

LLP searches at colliders and beyonds

And more …..

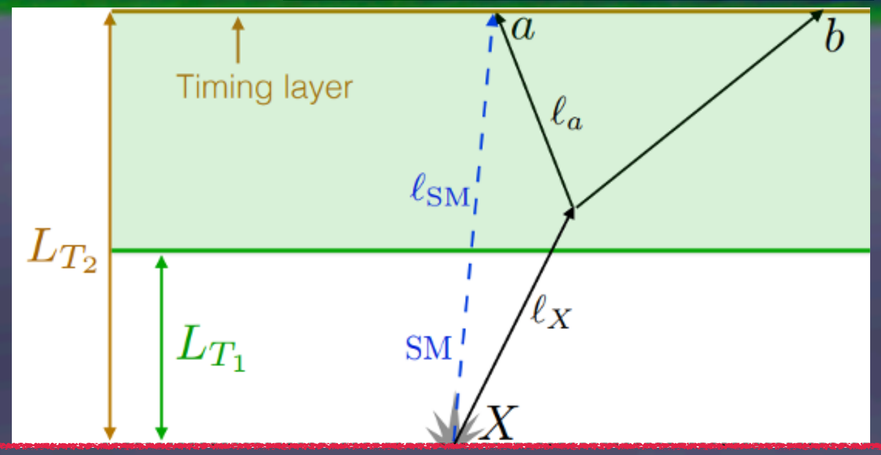
Timing detector @ HL-LHC

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



Time stamping

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

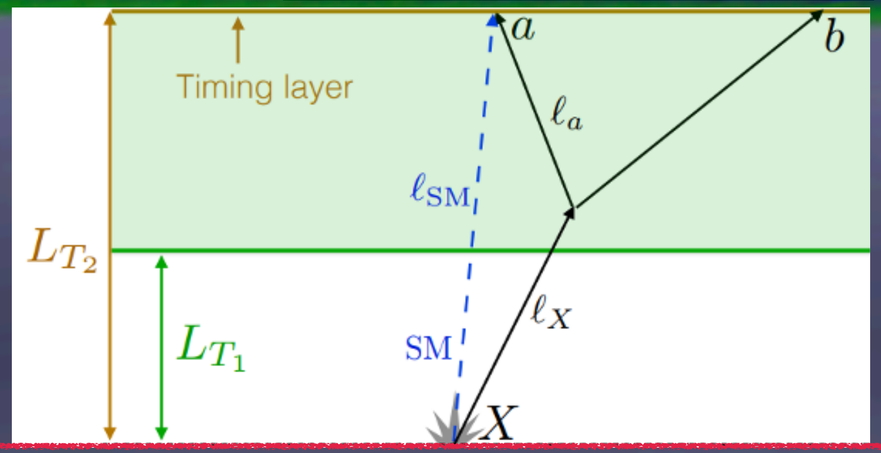


$$\Delta t^i_{\rm delay} = \frac{\ell_X}{\beta_X} + \frac{\ell_i}{\beta_i} - \frac{\ell_{\rm SM}}{\beta_{\rm SM}}$$

Beam axis

Time stamping

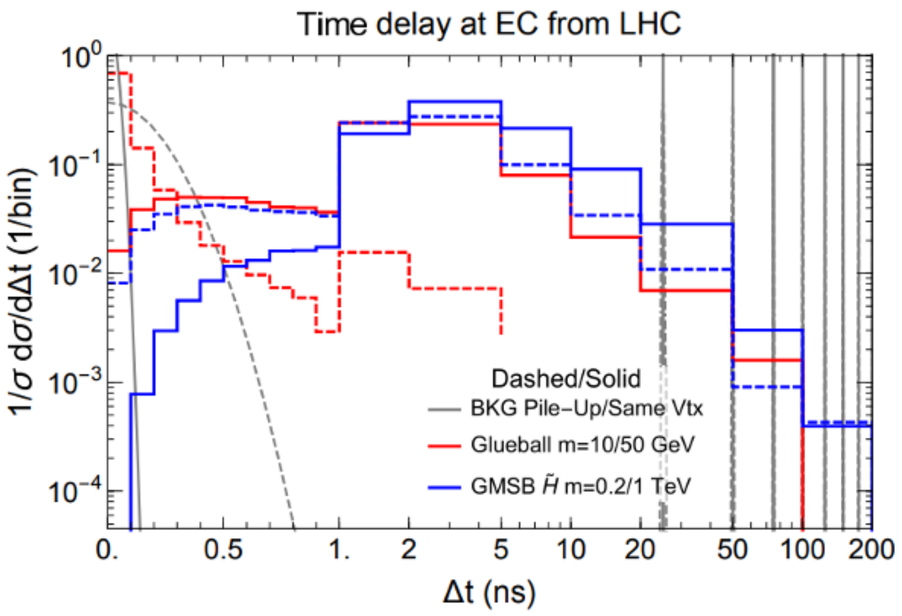
[J. LIU, Z. Liu and L. Wang, 1805.05957]

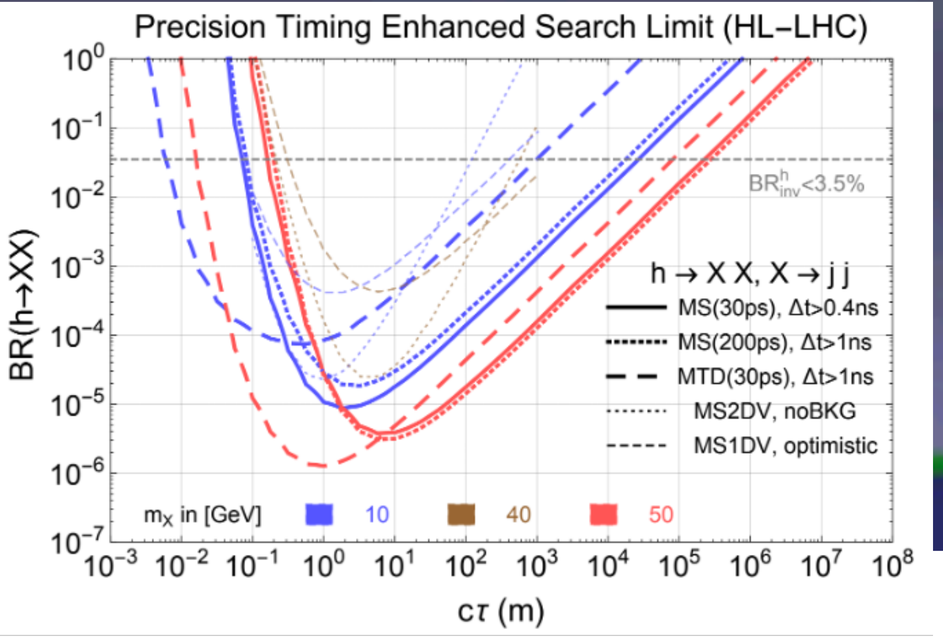


$$\Delta t^i_{\rm delay} = \frac{\ell_X}{\beta_X} + \frac{\ell_i}{\beta_i} - \frac{\ell_{\rm SM}}{\beta_{\rm SM}}$$

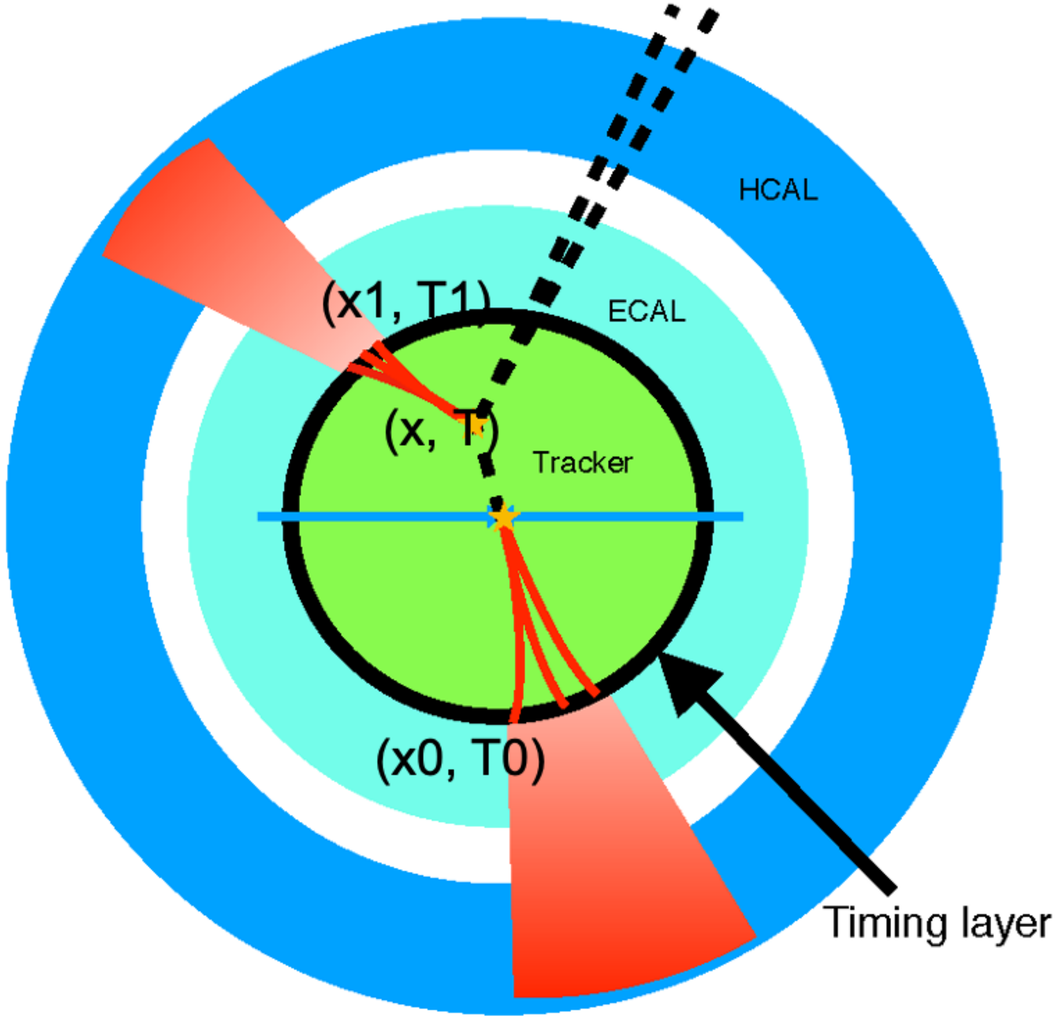
Beam axis

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





Timing detector @ HL-LHC



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

  +

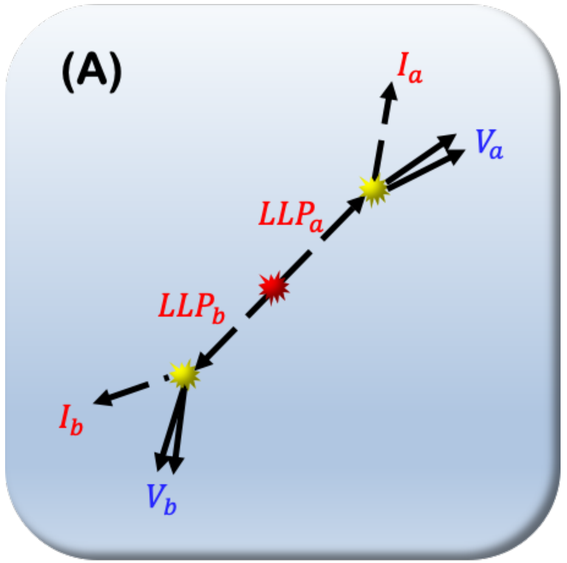
- We can measure ***time of flight (ToF)***

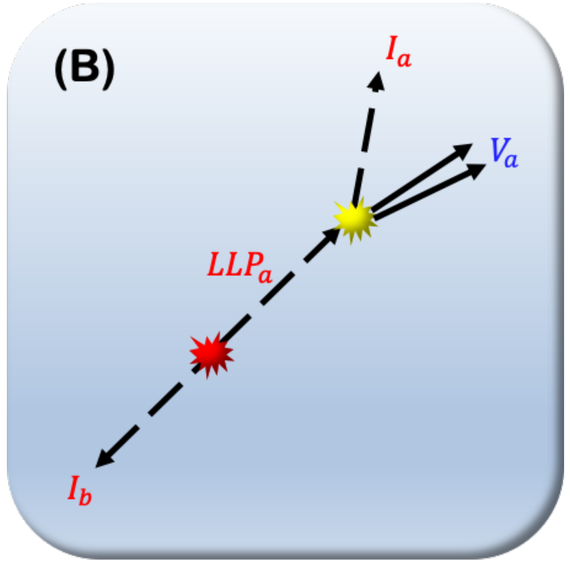
  ↓

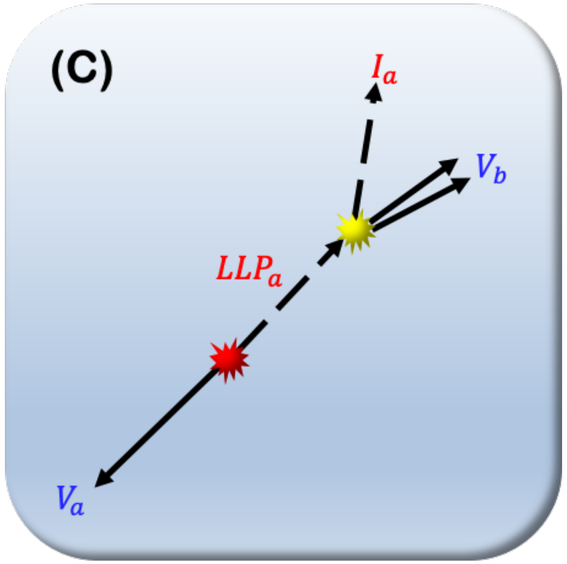
- We can measure ***β*** of ***long-lived particle !!!***

LLP event topology

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







(A) Pair produced BSM LLPs

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

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

[Z. Flowers, Q. Meier, C. Rogan, **DWK**, S. C. Park, JHEP 03 (2020) 132]

(B) Compressed neutralino, Inelastic DM, ...

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

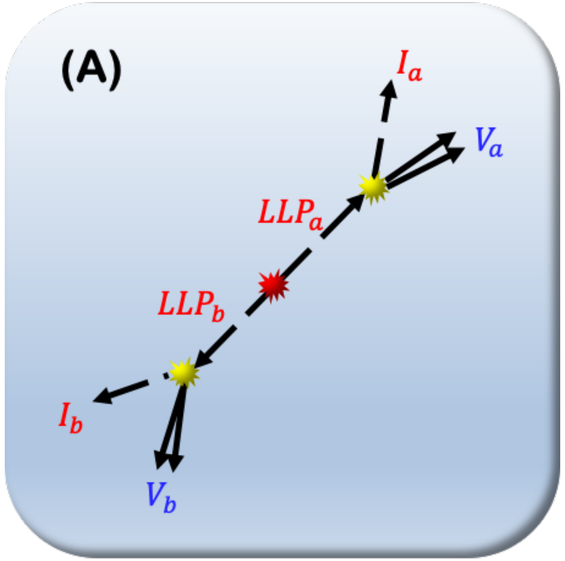
[**DWK**, P. Ko, Chih-Ting Lu, JHEP 04 (2021) 269]

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

See also Zeren Simon Wang 's talk

Neutral LLP search example (A)

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



# 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

- 4-momentum conservation

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

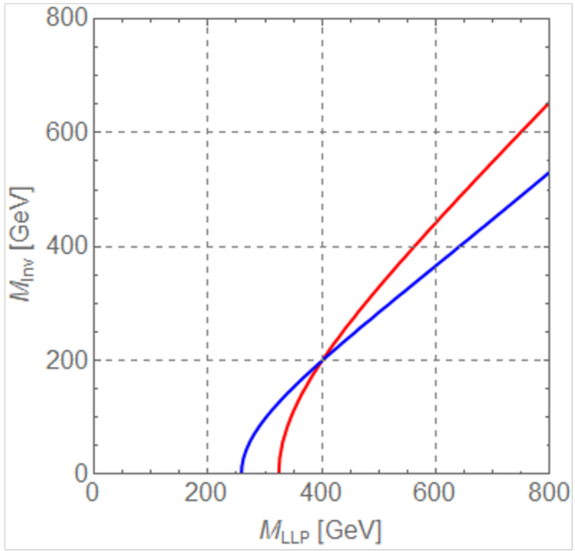
$$m_b^2 = m_{I_b}^2 + m_{V_b}^2 + 2E_{V_b}\sqrt{m_{I_b}^2 + |\boldsymbol{p}_{I_b}|^2} - 2\boldsymbol{p}_{V_b}\cdot\boldsymbol{p}_{I_b}$$

3-momenta reconstruction

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

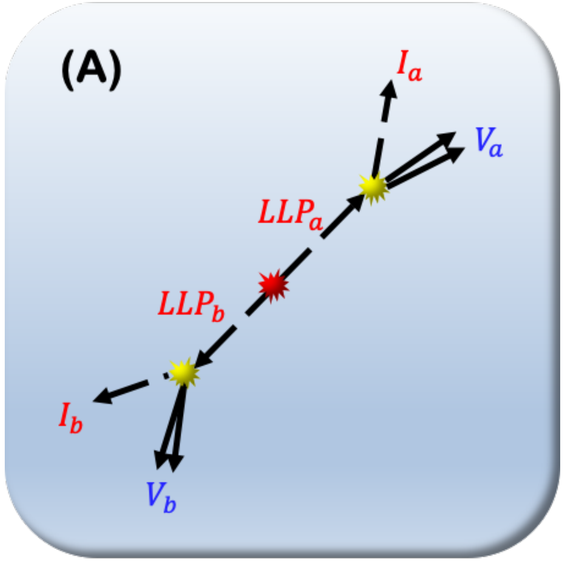
$$\boldsymbol{p}_{LLP_b} = \frac{\hat{r}_a \times (\boldsymbol{p}_I + \boldsymbol{p}_{V_a} + \boldsymbol{p}_{V_b})\cdot\hat{\boldsymbol{k}}}{\hat{r}_a \times \hat{r}_b \cdot \hat{\boldsymbol{k}}}\hat{r}_b \qquad \boldsymbol{p}_{I_b} = \frac{\hat{r}_a \times (\boldsymbol{p}_I + \boldsymbol{p}_{V_a} +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

- For each event we can find



- We can find **1 or 2 positive mass pairs with 2 assumptions**
  $\boldsymbol{m_a = m_b,\ m_{I_a} = m_{I_b}}$

Neutral LLP search example (A)



# 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

$$\beta_a = r_a/T_a, \qquad \beta_b = r_b/T_b$$

3-momenta reconstruction

$$p_{LLP_a} = \frac{\beta_b \times (p_I + p_{V_a} + p_{V_b}) \cdot \hat{k}}{\beta_b \times \beta_a \cdot \hat{k}} \beta_a \qquad p_{I_a} = \frac{\beta_b \times (p_I + p_{V_a} + p_{V_b}) \cdot \hat{k}}{\beta_b \times \beta_a \cdot \hat{k}} \beta_a - p_{V_a}$$

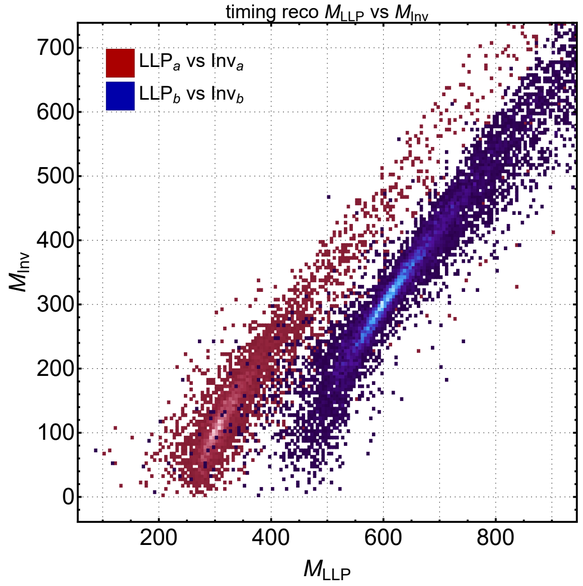
$$p_{LLP_b} = \frac{\beta_a \times (p_I + p_{V_a} + p_{V_b}) \cdot \hat{k}}{\beta_a \times \beta_b \cdot \hat{k}} \beta_b \qquad p_{I_b} = \frac{\beta_a \times (p_I + p_{V_a} + p_{V_b}) \cdot \hat{k}}{\beta_a \times \beta_b \cdot \hat{k}} \beta_b - p_{V_b}$$

$$E_{LLP_a} = \frac{\beta_b \times (p_I + p_{V_a} + p_{V_b}) \cdot \hat{k}}{\beta_b \times \beta_a \cdot \hat{k}} \qquad E_{LLP_b} = \frac{\beta_a \times (p_I + p_{V_a} + p_{V_b}) \cdot \hat{k}}{\beta_a \times \beta_b \cdot \hat{k}}$$

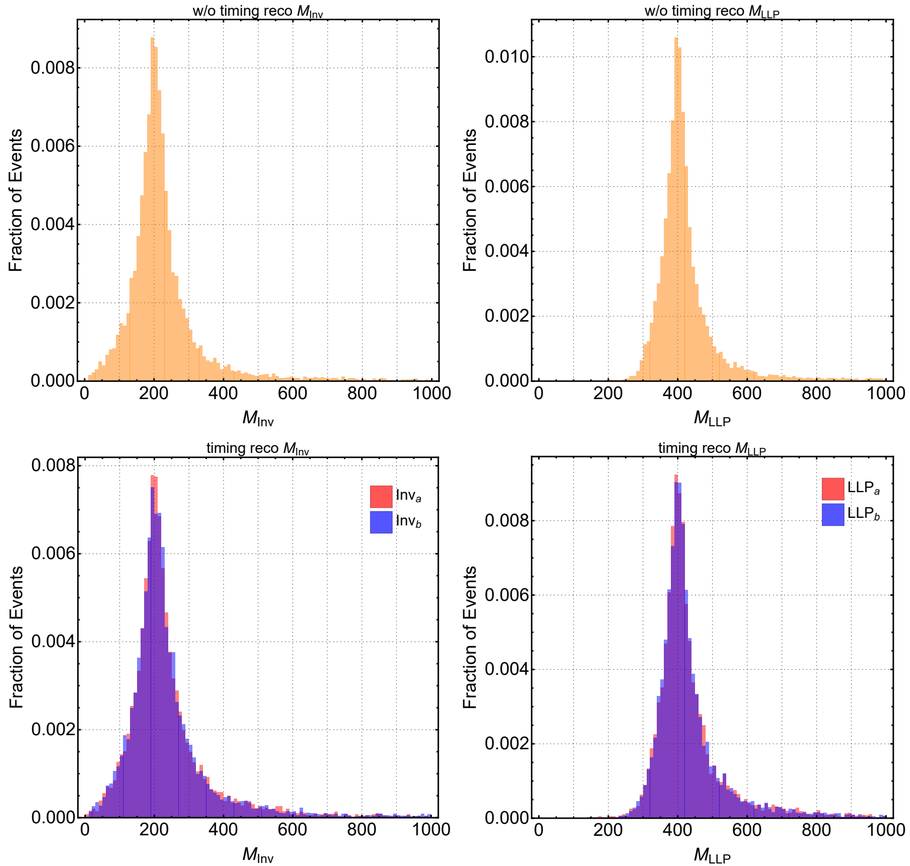
We can find **unique mass pairs without assumptions**

Reconstruction Summary

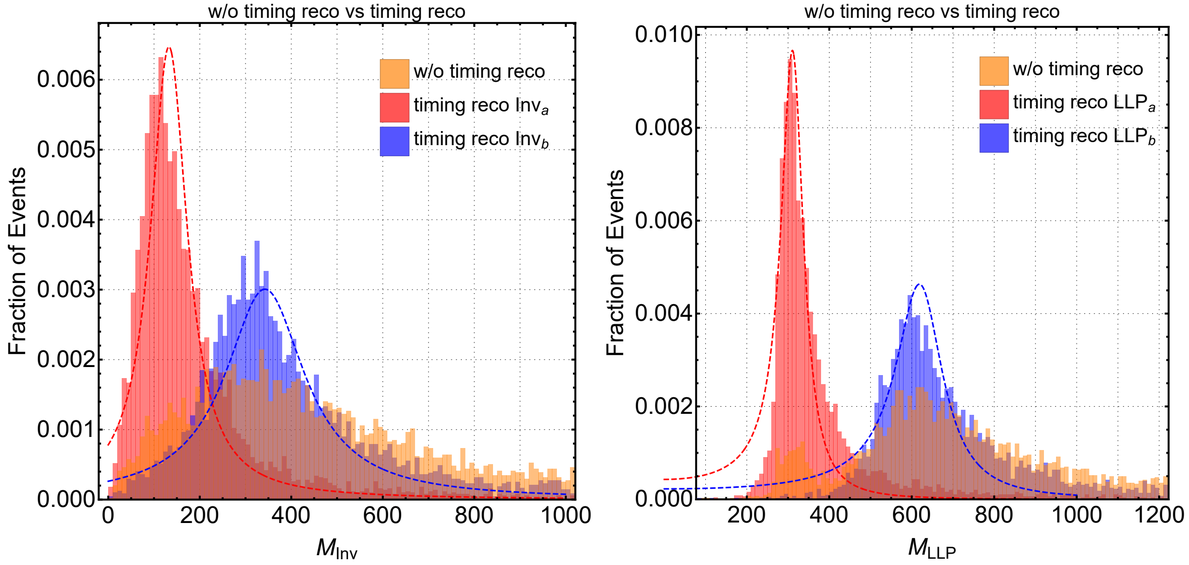
		m_{LLP_a}	m_{LLP_b}	m_{I_a}	m_{I_b}	$\boldsymbol{p}_{LLP_a}$	$\boldsymbol{p}_{LLP_b}$	$\boldsymbol{p}_{I_a}$	$\boldsymbol{p}_{I_b}$
Identical LLPs	w/o timing	△	△	△	△	○	○	○	○
	timing	○	○	○	○	○	○	○	○
Non-identical LLPs	w/o timing	×	×	×	×	○	○	○	○
	timing	○	○	○	○	○	○	○	○



Case1: $LLP_a = LLP_b, I_a = I_b$

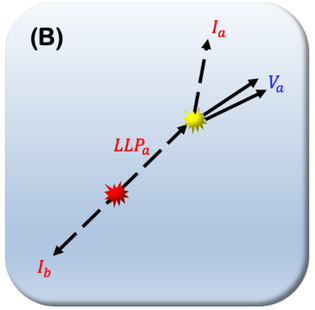


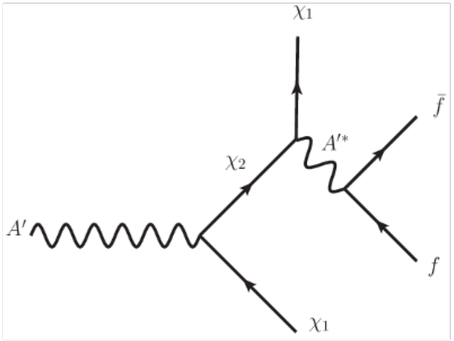
Case2: $LLP_a \neq LLP_b, I_a \neq I_b$



		m_{LLP_a}	m_{LLP_b}	m_{I_a}	m_{I_b}	ϵ_{reco}
$a = b$	w/o timing	397.6±1.2	397.6±1.2	206.0±1.5	206.0±1.5	0.86
	timing	400.91±0.35	400.91±0.35	201.53±0.49	201.53±0.49	0.72
$a \neq b$	w/o timing	-	-	-	-	-
	timing	307.25±0.38	612.18±0.72	118.54±0.89	319.1±1.1	0.51

Neutral LLP search example (B)





Inelastic dark matter model

$$\mathcal{L}_{X,gauge} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\sin\epsilon}{2}B_{\mu\nu}B^{\mu\nu} \qquad \Phi(x) = \frac{1}{\sqrt{2}}(v_D + h_D(x)) \qquad H(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

$$\mathcal{L}_{Z'f\bar{f}} = -\epsilon e c_W \sum_f x_f \bar{f} \not{Z}' f \qquad m_{Z'} \simeq g_D Q_D(\Phi) v_D$$

Scalar model

	Q_D
Φ	$+2$
ϕ	$+1$

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

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

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

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

Fermion model

	Q_D
Φ	$+2$
χ	$+1$

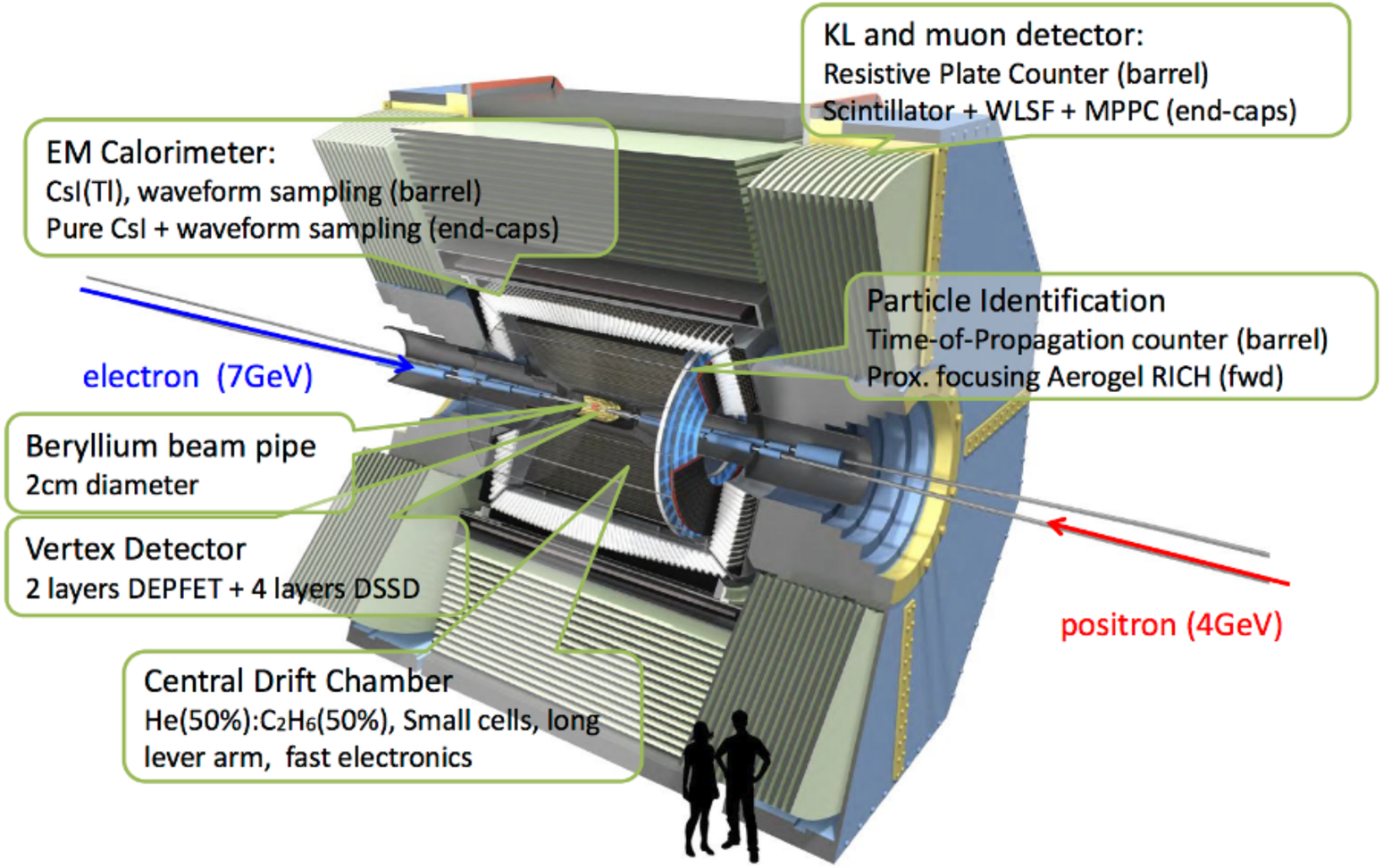
$$V(H,\Phi,\phi) = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 - \mu_\Phi^2 \Phi^*\Phi + \lambda_\Phi(\Phi^*\Phi)^2 + \lambda_{H\Phi}(H^\dagger H)(\Phi^*\Phi) \quad -(\frac{f}{2}\bar{\chi}^c\chi\Phi^* + H.c.)$$

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

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

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

Displaced signature in Belle2 detector



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

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

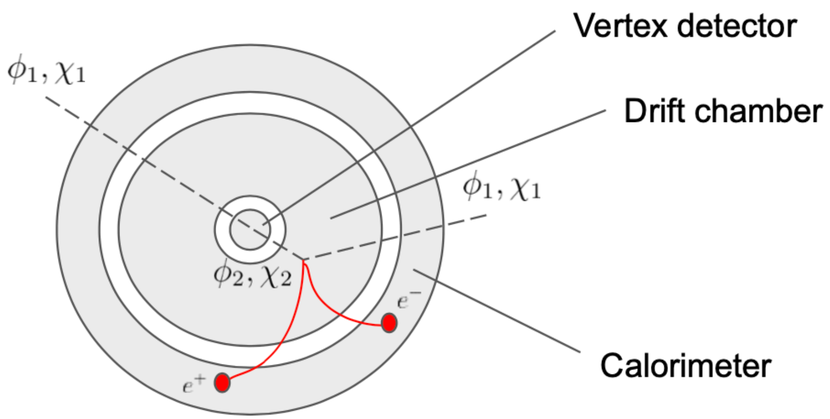
The resolution of photon momenta in the calorimeter

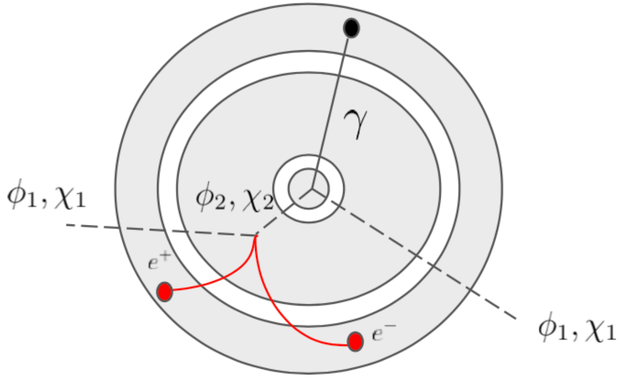
$$\sigma_{E_\gamma}/E_\gamma = 2\%$$

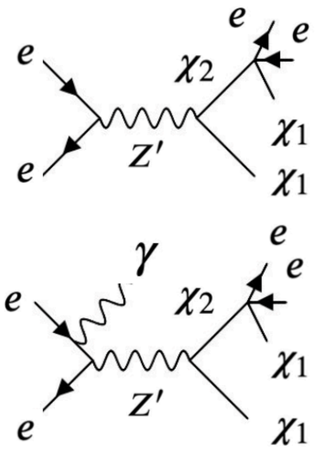
The resolution for the displaced vertex of lepton pair

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

Displaced signature in Belle2 detector







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

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

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

Low R_{xy} region (100% efficiency) : $0.2 < R_{xy} < 0.9\ (17.0)$

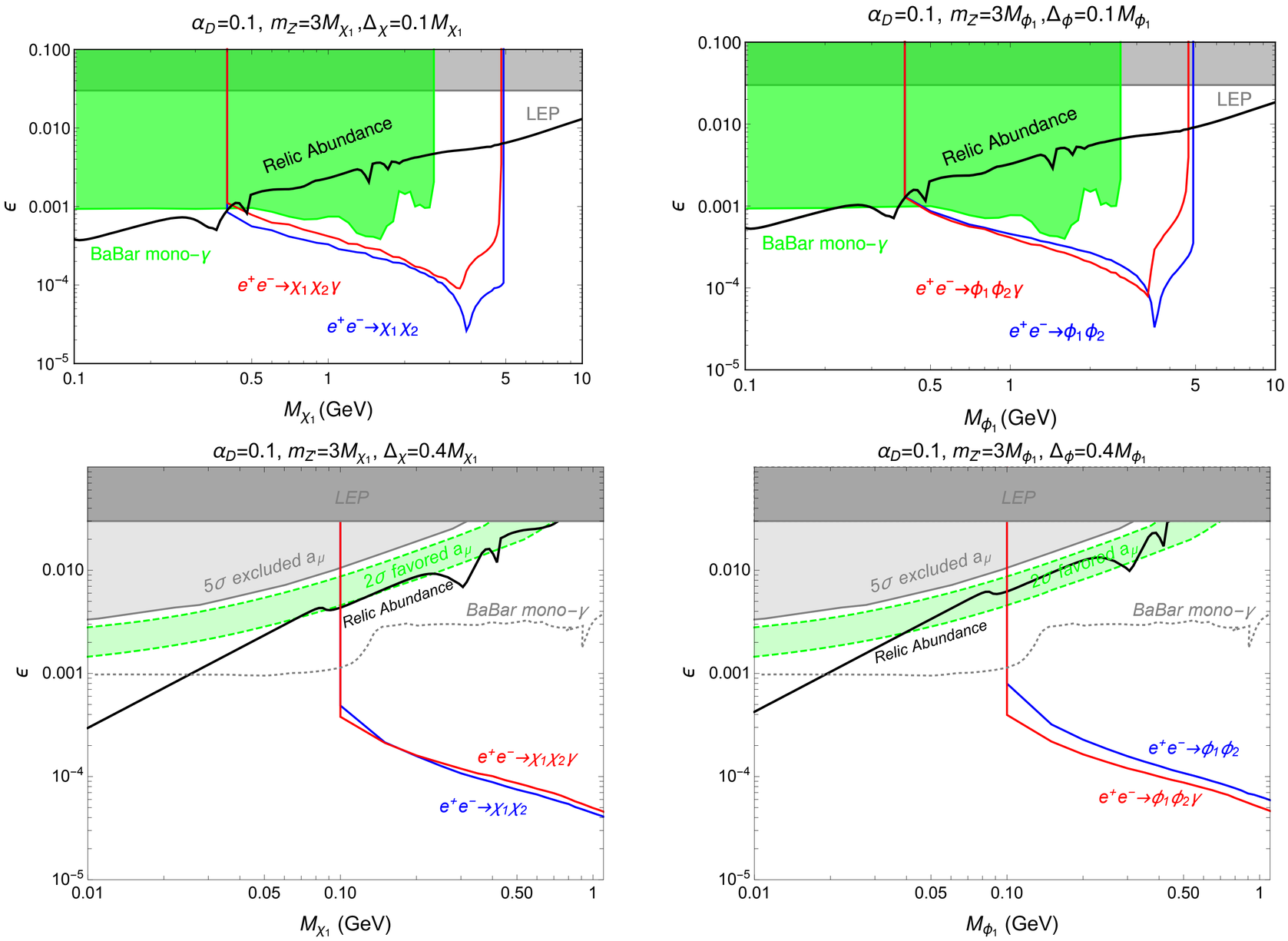
High R_{xy} region (30% efficiency) : $17.0 < R_{xy} < 60.0$

Benchmark points

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

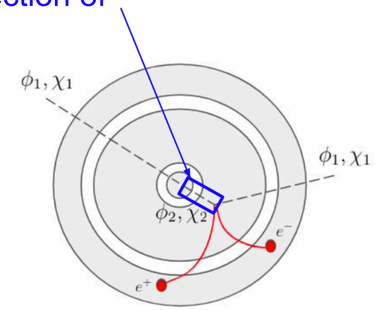
Objects	Selections
displaced vertex	(i) $-55\,\text{cm} \le z \le 140\,\text{cm}$ (ii) $17^\circ \le \theta^{\text{DV}}_{\text{LAB}} \le 150^\circ$
electrons	(i) both $E(e^+)$ and $E(e^-) > 0.1\,\text{GeV}$ (ii) opening angle of pair $\theta_{ee} > 0.1$ rad (iii) invariant mass of pair $m_{ee} > 0.03\,\text{GeV}$
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 $0.48\,\text{GeV} \le m_{\mu\mu} \le 0.52\,\text{GeV}$
photons	(i) $E^{\gamma}_{\text{LAB}} > 0.5\,\text{GeV}$ (ii) $17^\circ \le \theta^{\gamma}_{\text{LAB}} \le 150^\circ$

Future sensitivity



Scalar vs fermion: Angular distribution

We need to know the direction of displaced vertex



If ϕ_2, χ_2 are long-lived, can we determine their spin ?

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

Scalar

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

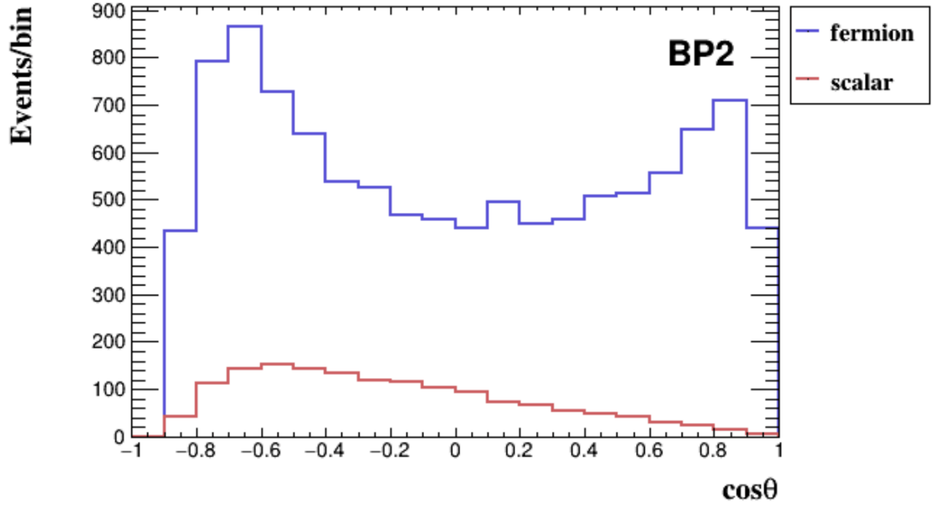
Fermion

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

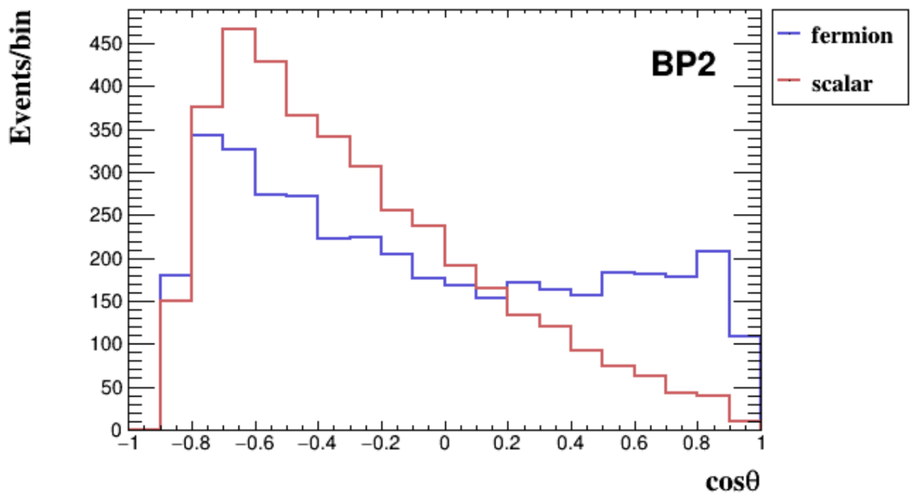
Where $\xi = \sqrt{1-\frac{2(M_{\chi_2}^2+M_{\chi_1}^2)}{s}+\frac{(M_{\chi_2}^2-M_{\chi_1}^2)^2}{s^2}}$

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

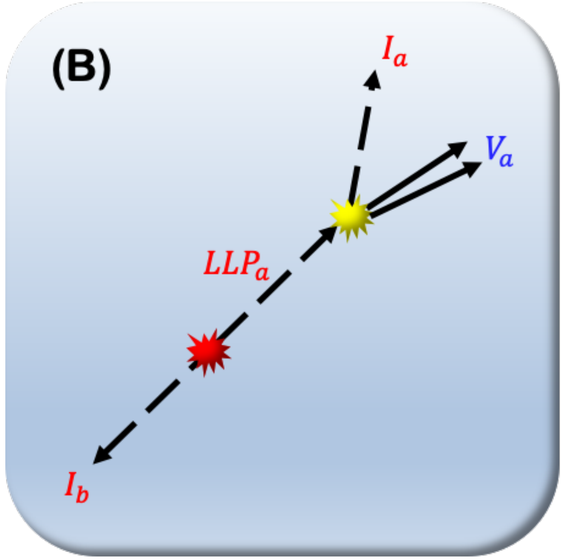
Angular distribution w/o ISR



Angular distribution w/ ISR



Reconstruct mass & mass gap



# of unknowns > # of knowns + # of constraints

2 momenta = 8 1 momenta = 4 $I_a = I_b$

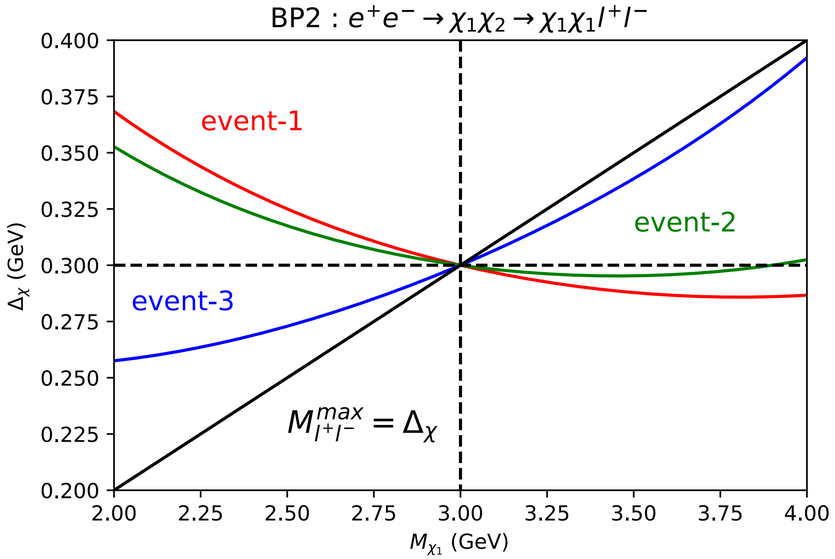
Therefore, we cannot get the unique solution

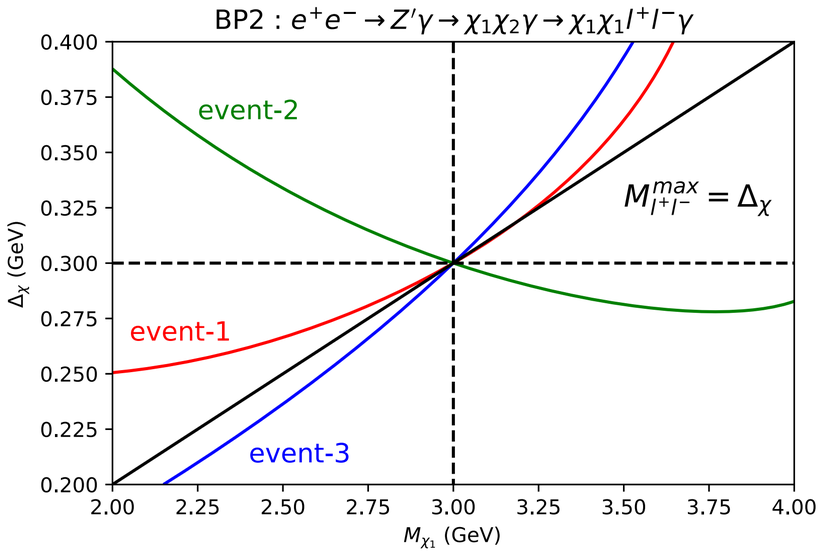
4-momentum conservation

$$m_{\chi^2}^2 - m_{\chi^1}^2 - 2E(1+\alpha)E_V + E_V^2 - |\boldsymbol{p}_V|^2 + 2\sqrt{(E(1+\alpha))^2 - m_{\chi^2}^2}(\hat{r}_{DV}\cdot\boldsymbol{p}_V) = 0$$

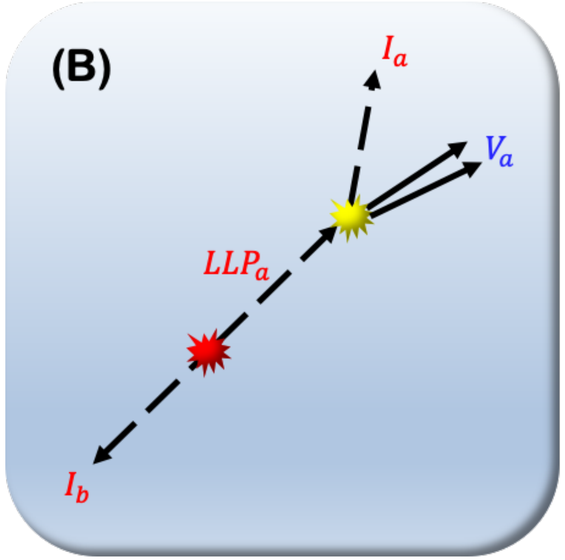
$$\alpha = \frac{m_{\chi^2}^2 - m_{\chi^1}^2}{4E^2}$$

The crossing point from these events and kinematic endpoint measurement can help us

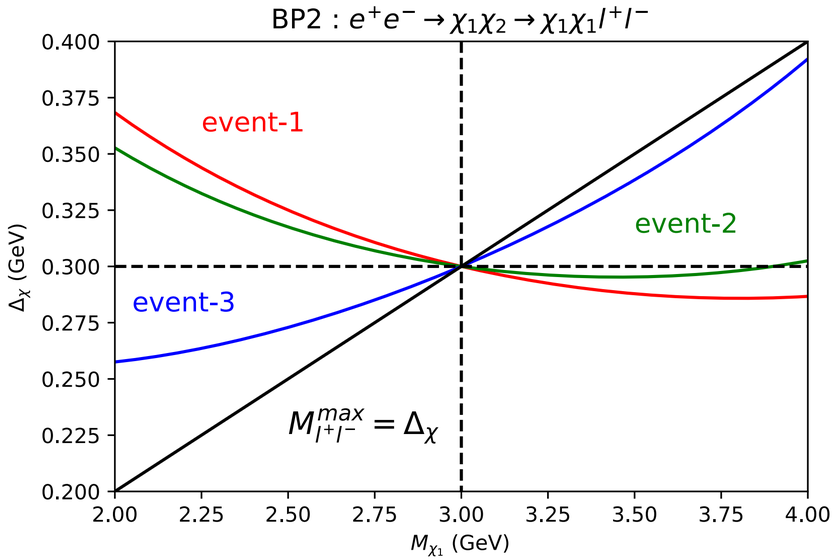




Reconstruct mass & mass gap

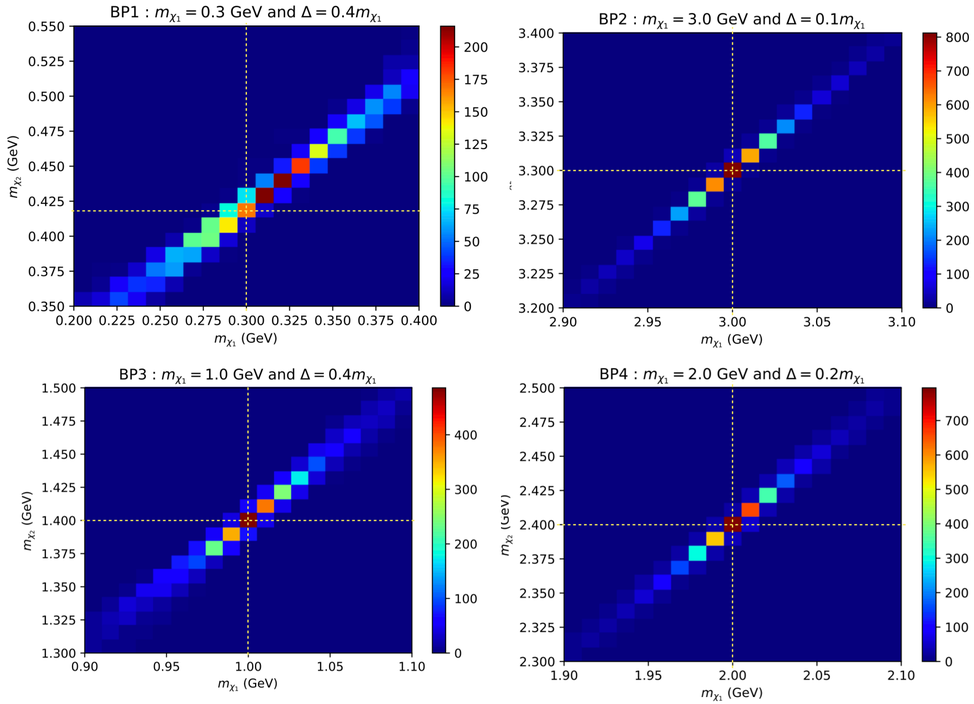


Assume we can have 100 signal events at the Belle2, then we will get ${}_{100}C_2 = 4950$ solutions from each two events!



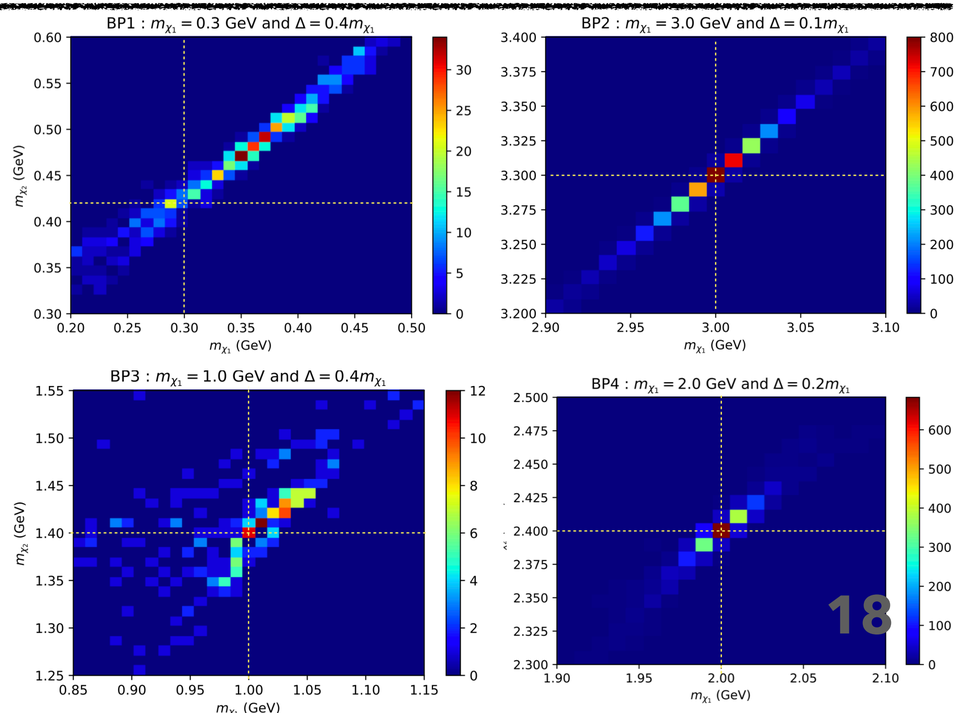
$$e^+e^- \to \chi_1\chi_2 \to \chi_1\chi_1\ell^+\ell^-$$

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



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

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



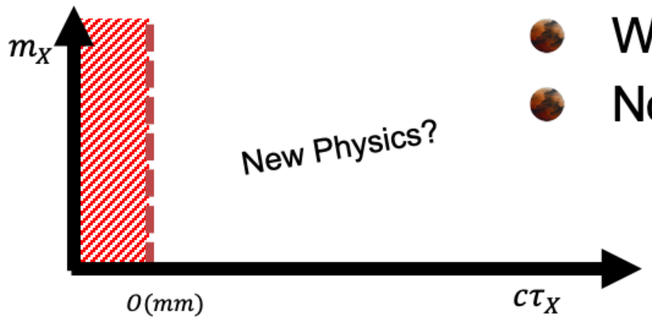
Conclusion

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.
- Now we are in the lifetime era!

Thank You!