Investigating the Long-lived particles and its properties at colliders

: Kinematics & future prospects

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

Workshop on particle physics and cosmology 2021 (27th Nov 2021)

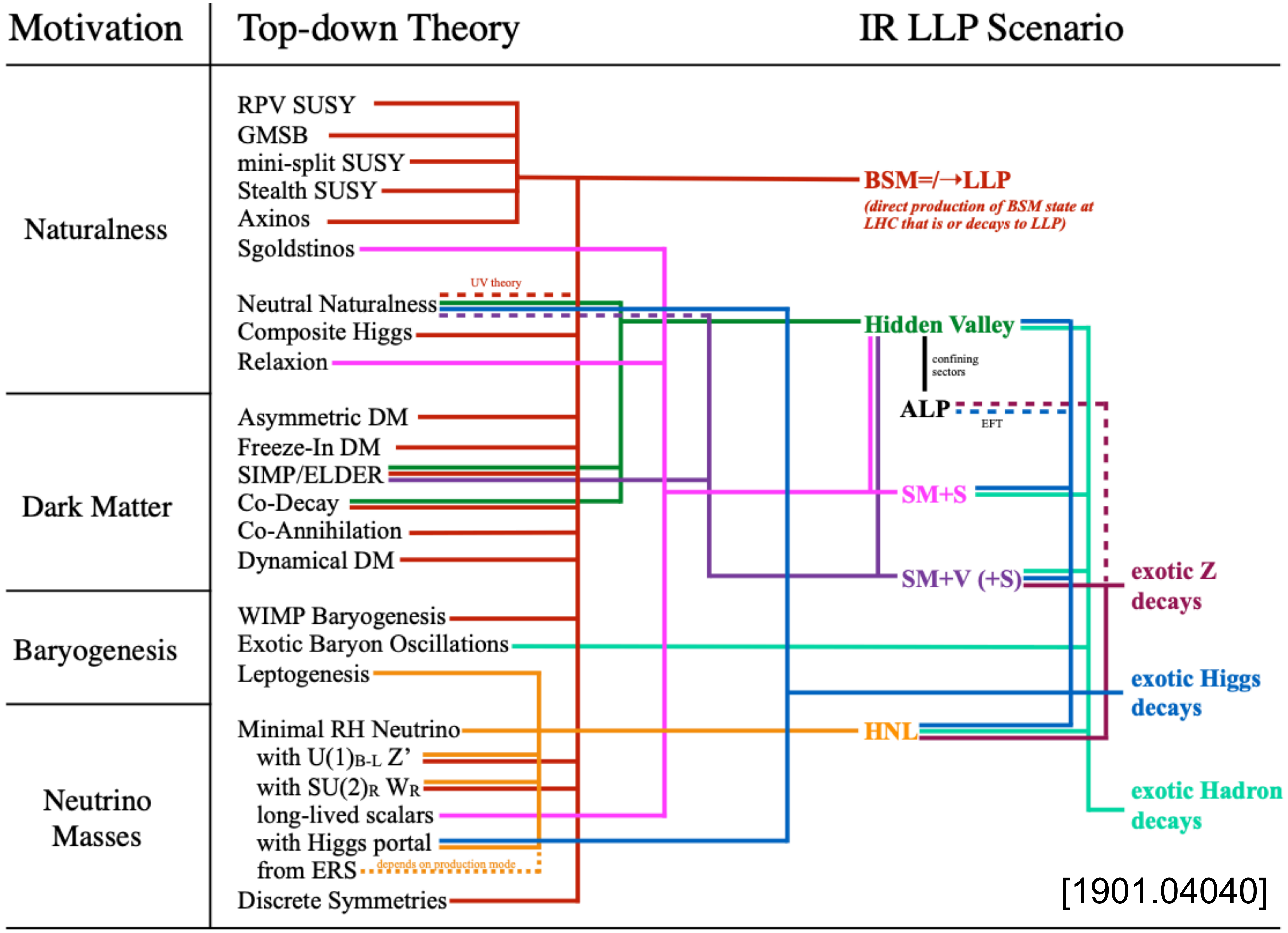
Contents

Long lived particle

The Standard Model

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

Beyond the Standard Model



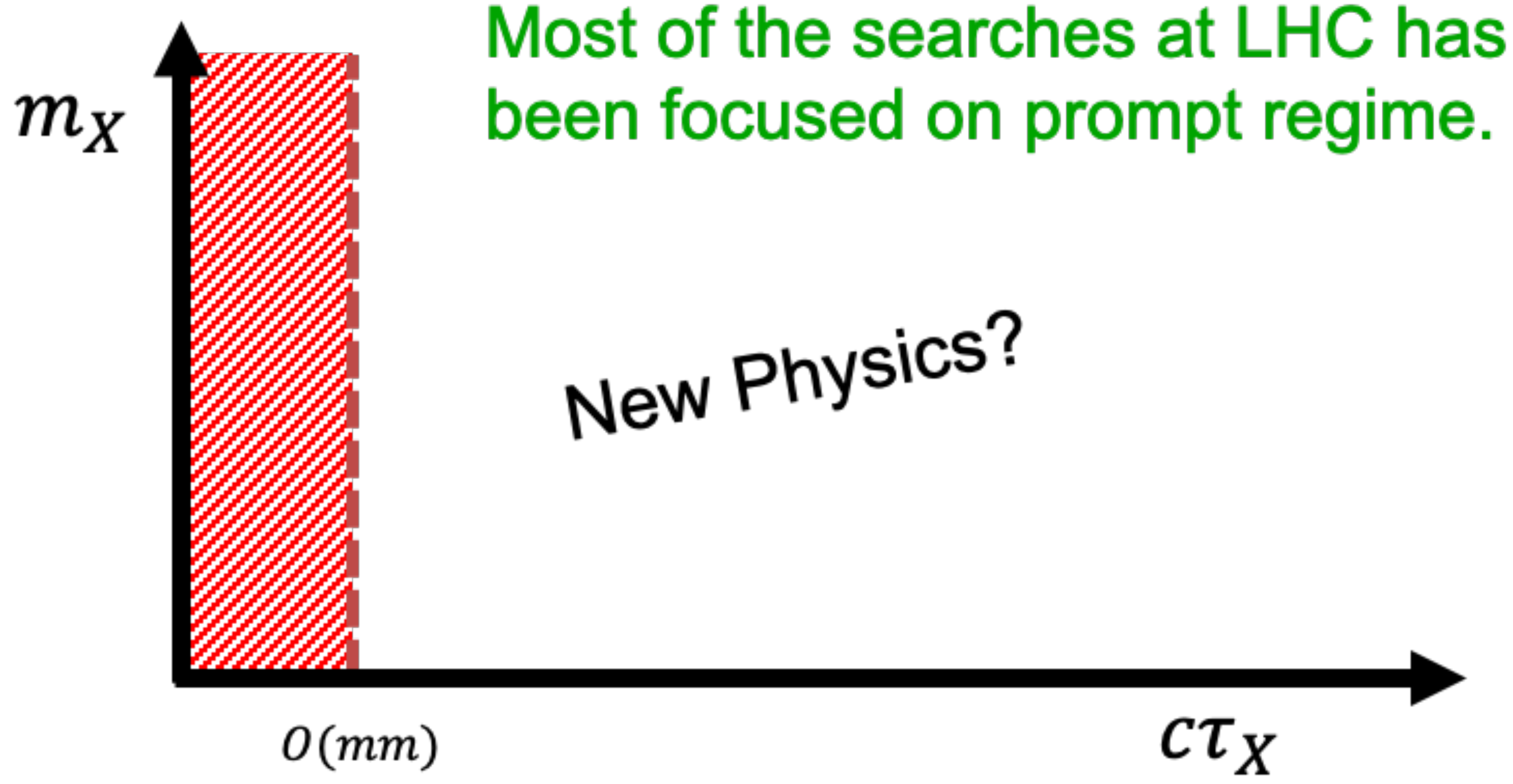
[1901.04040]

What makes particle long-lived?

Approximate symmetry Small coupling
Heavy mediator Lack of phase space

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

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

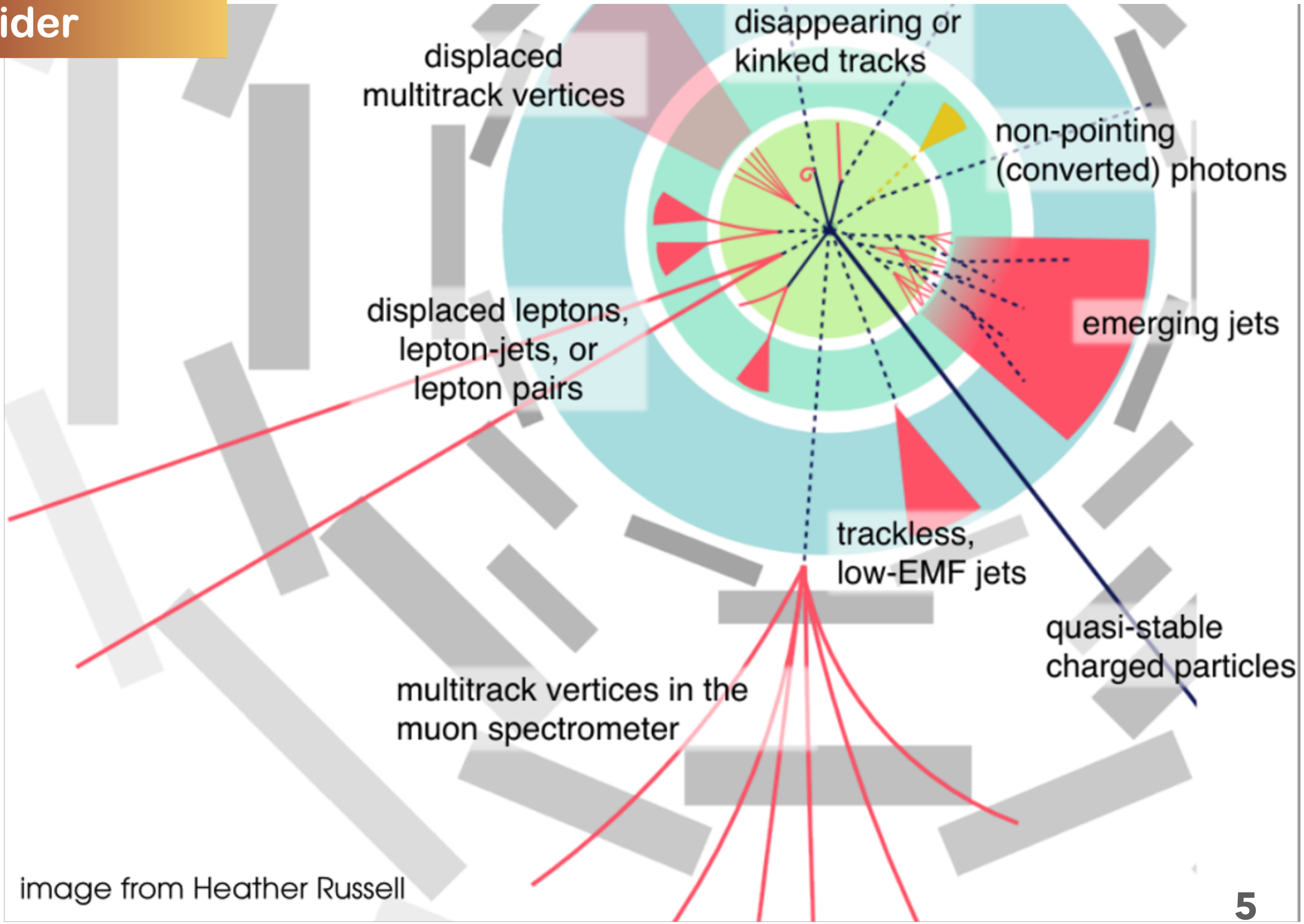
[from LLPX James's slide]

LHCb
ATLAS EXPERIMENT
CMS
Theory/pheno
MoEDAL
FASER
THE MILLIQAN EXPERIMENT
CODEX-b
AL3X
ANUBIS
NA62
NA64
SHiP Search for Hidden Particles
MATHUSLA
Belle II
BaBar
FCC hh ee he
T2K
MiniBooNE
MAGIX
MAMI MAINZER MIKROTRON
SoLid
IceCube
SUPER KAMIOKANDE
NASA esa LISA
SeaQuest E906
CLIC
BDX
ANITA

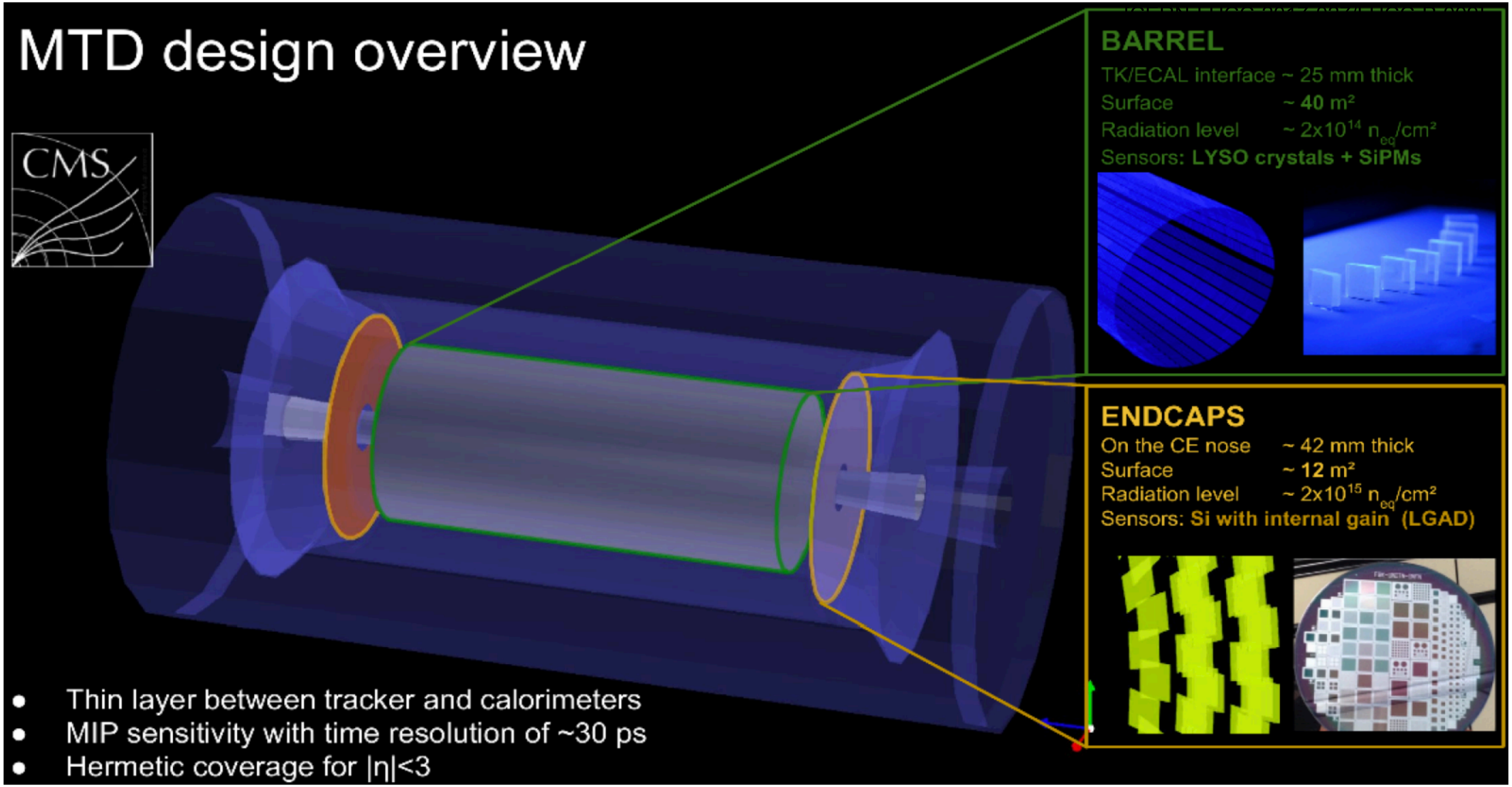
SHADOWS
SUBMET
LUXE
SND@LHC Scattering and Neutrino Detector at the LHC
FPF Forward Physics Facility

And more ….

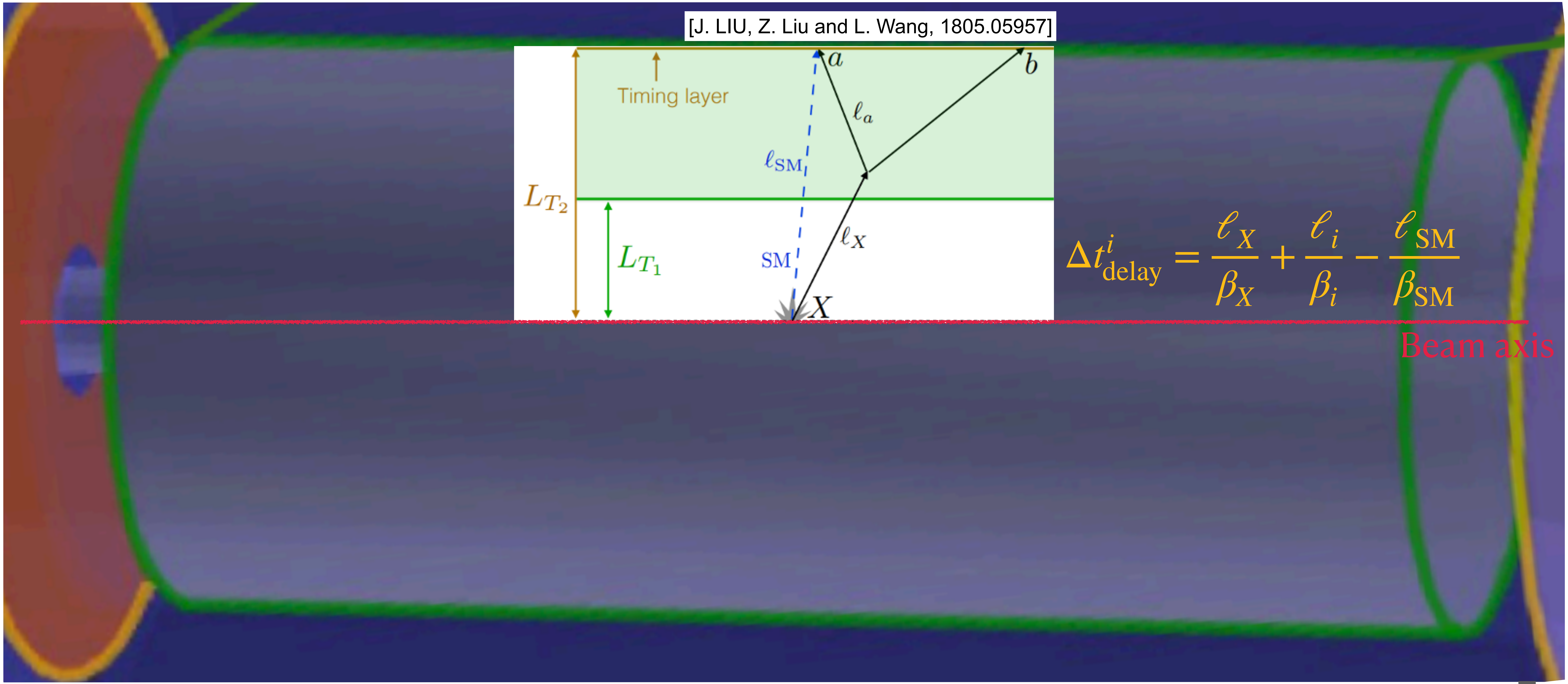
LLP signatures at collider



Timing detector @ HL-LHC



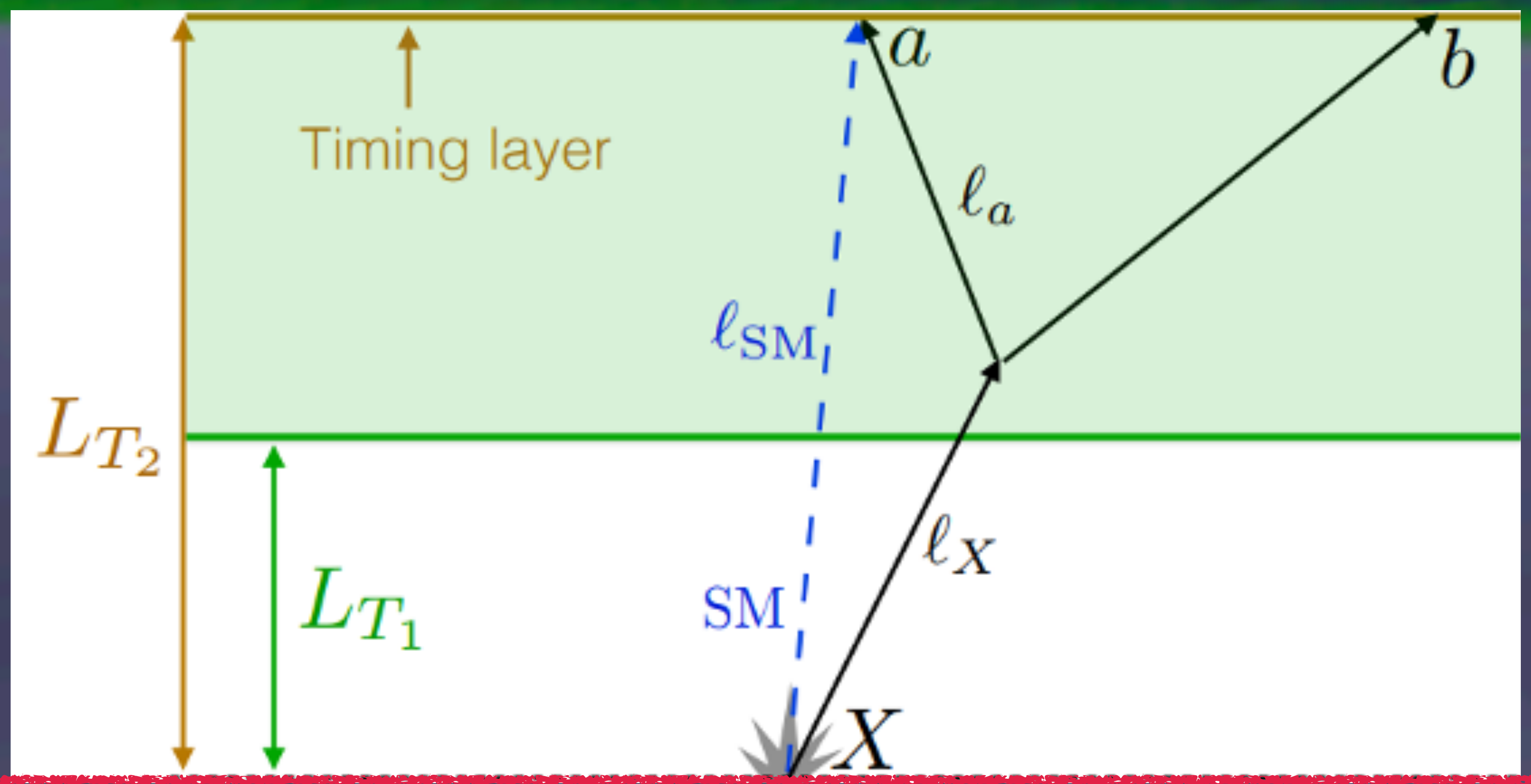
Time stamping



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

Time stamping

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

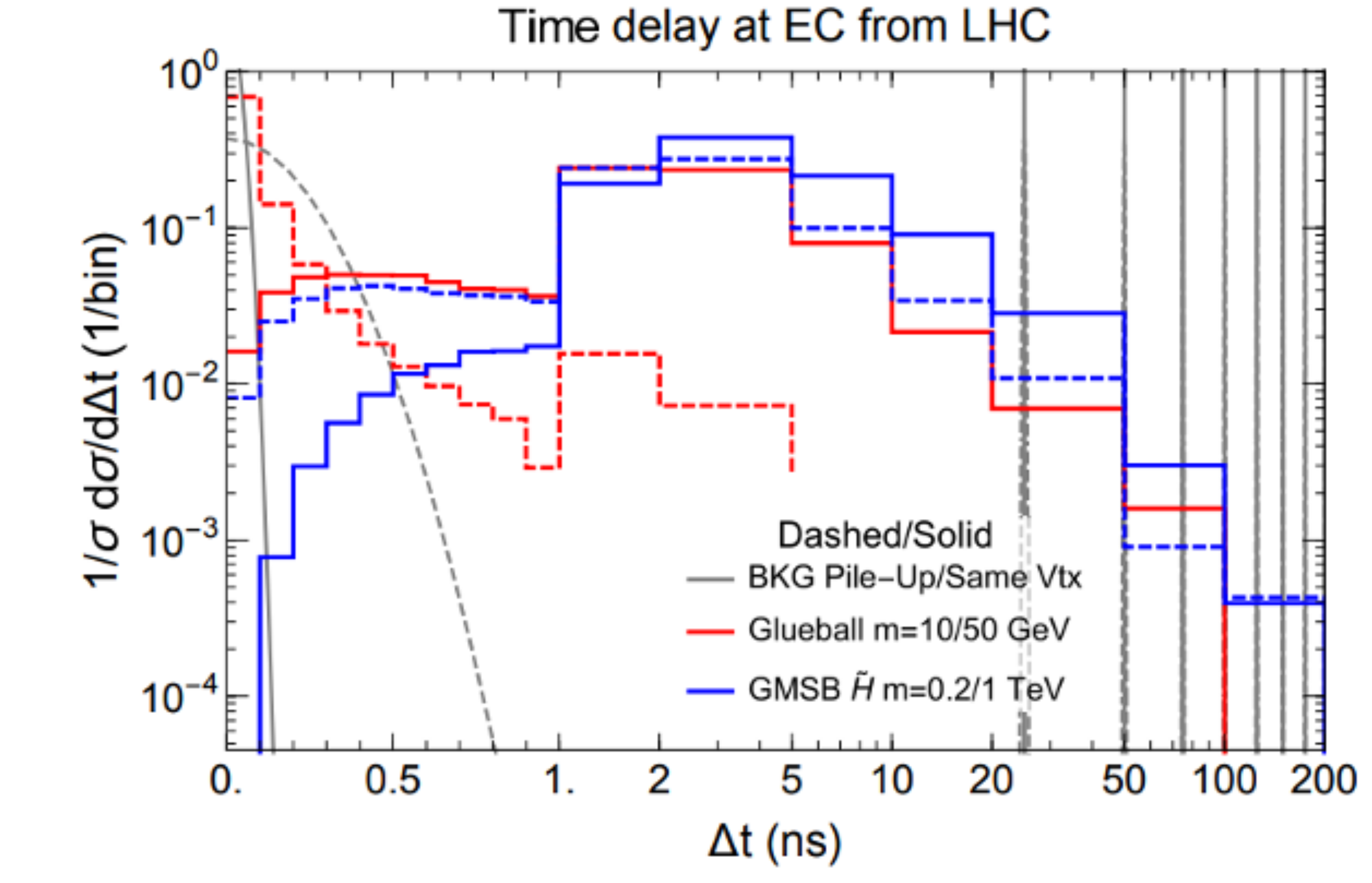


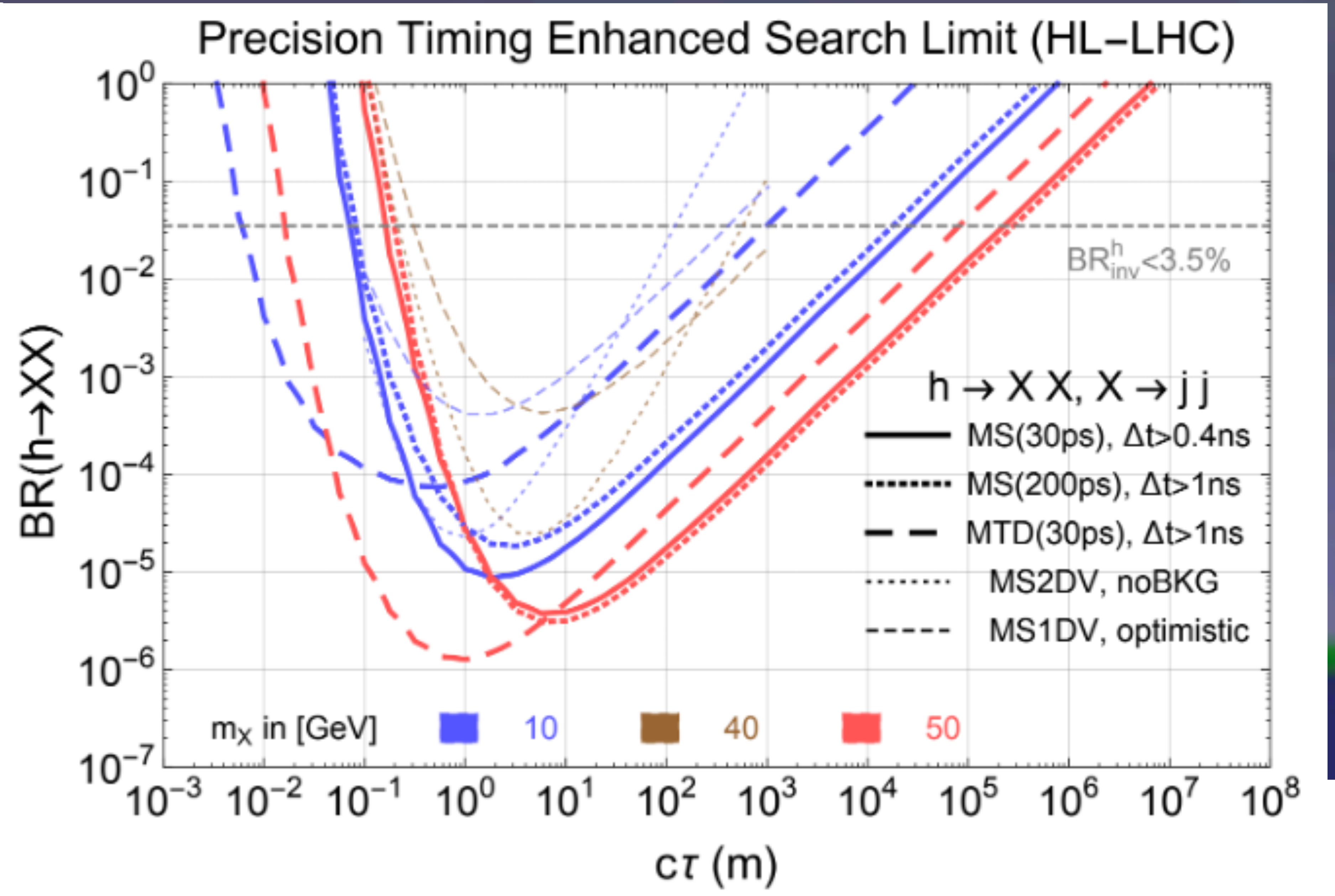
$$\Delta t^i_{\rm delay} = \frac{\ell_X}{\beta_X} + \frac{\ell_i}{\beta_i} - \frac{\ell_{SM}}{\beta_{SM}}$$

Beam axis

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

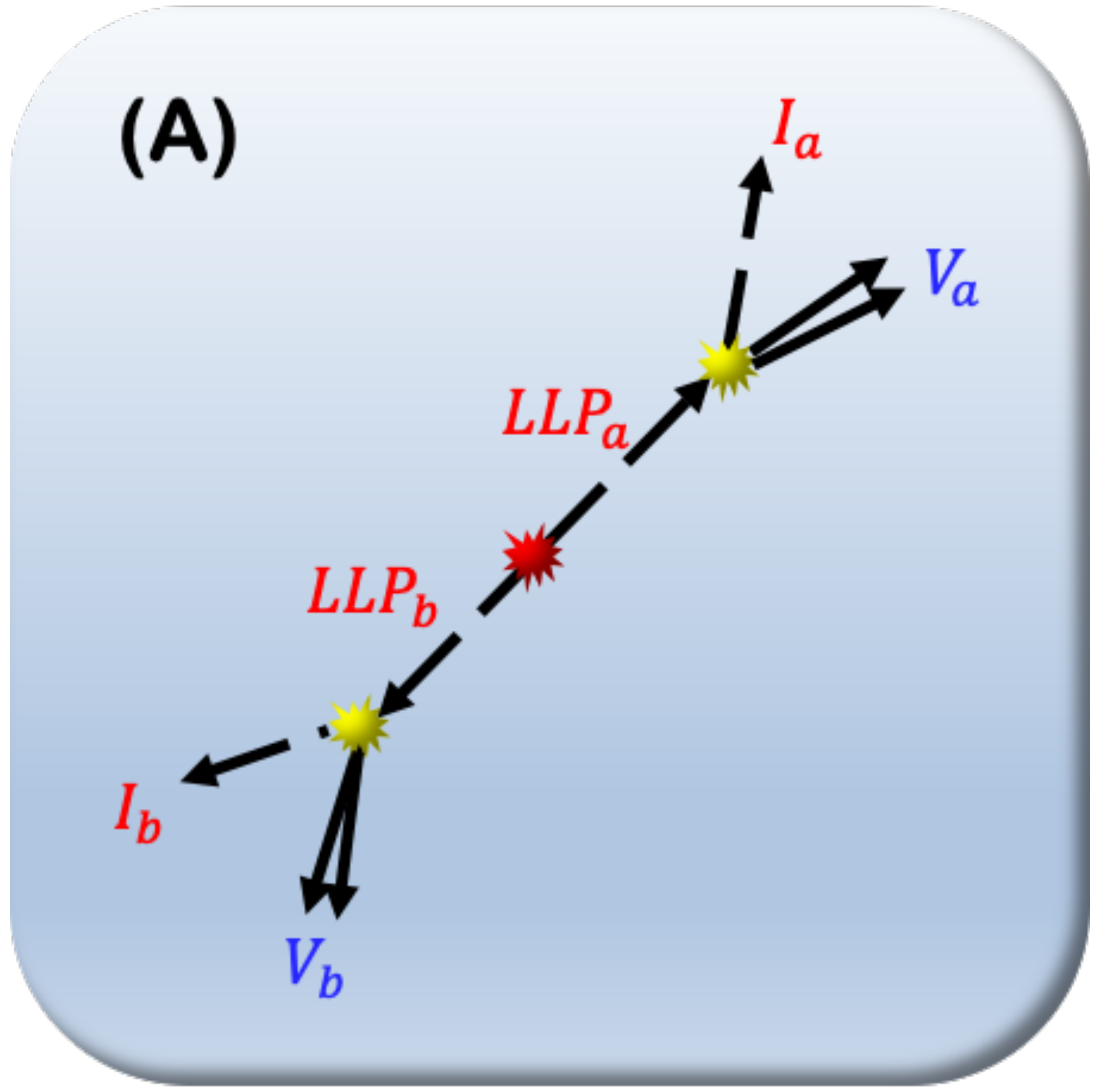
$\mathrm{SigB}: pp \to \tilde{\chi}\tilde{\chi} + j,\; \tilde{\chi}^0_1 \to h + \tilde{G} \to \mathrm{SM} + \tilde{G}.$

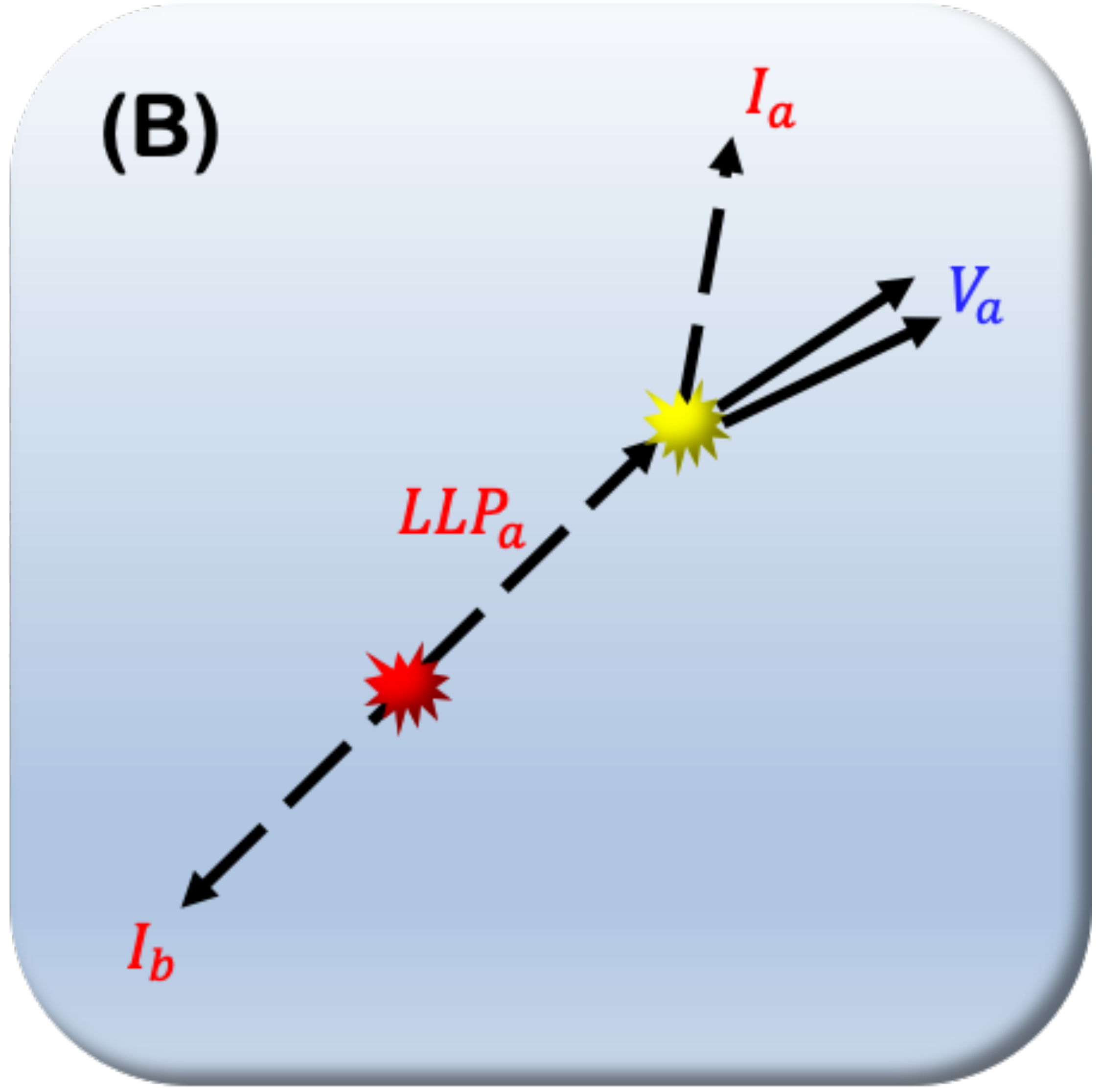


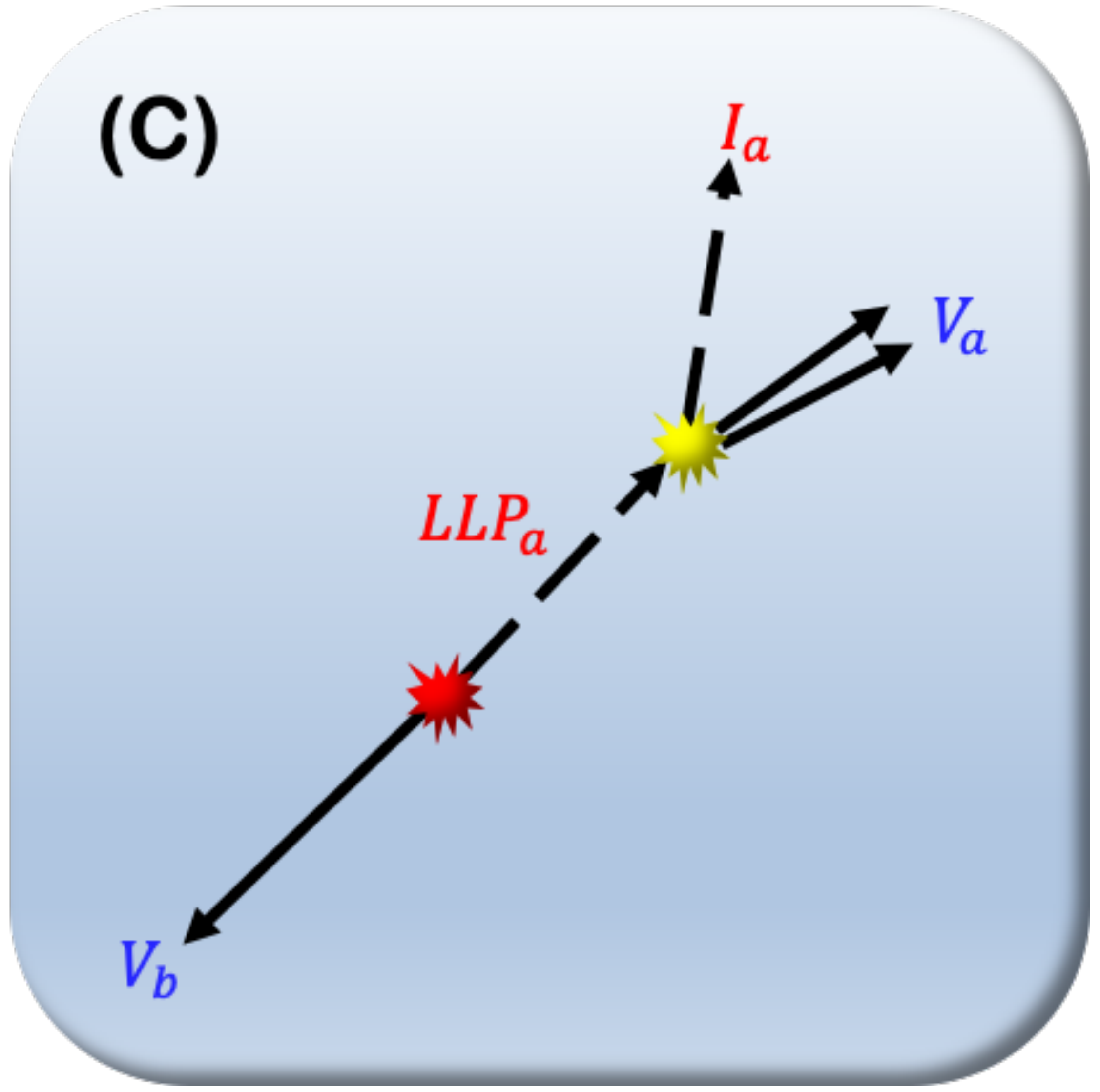


LLP event topology

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







... and more

(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]

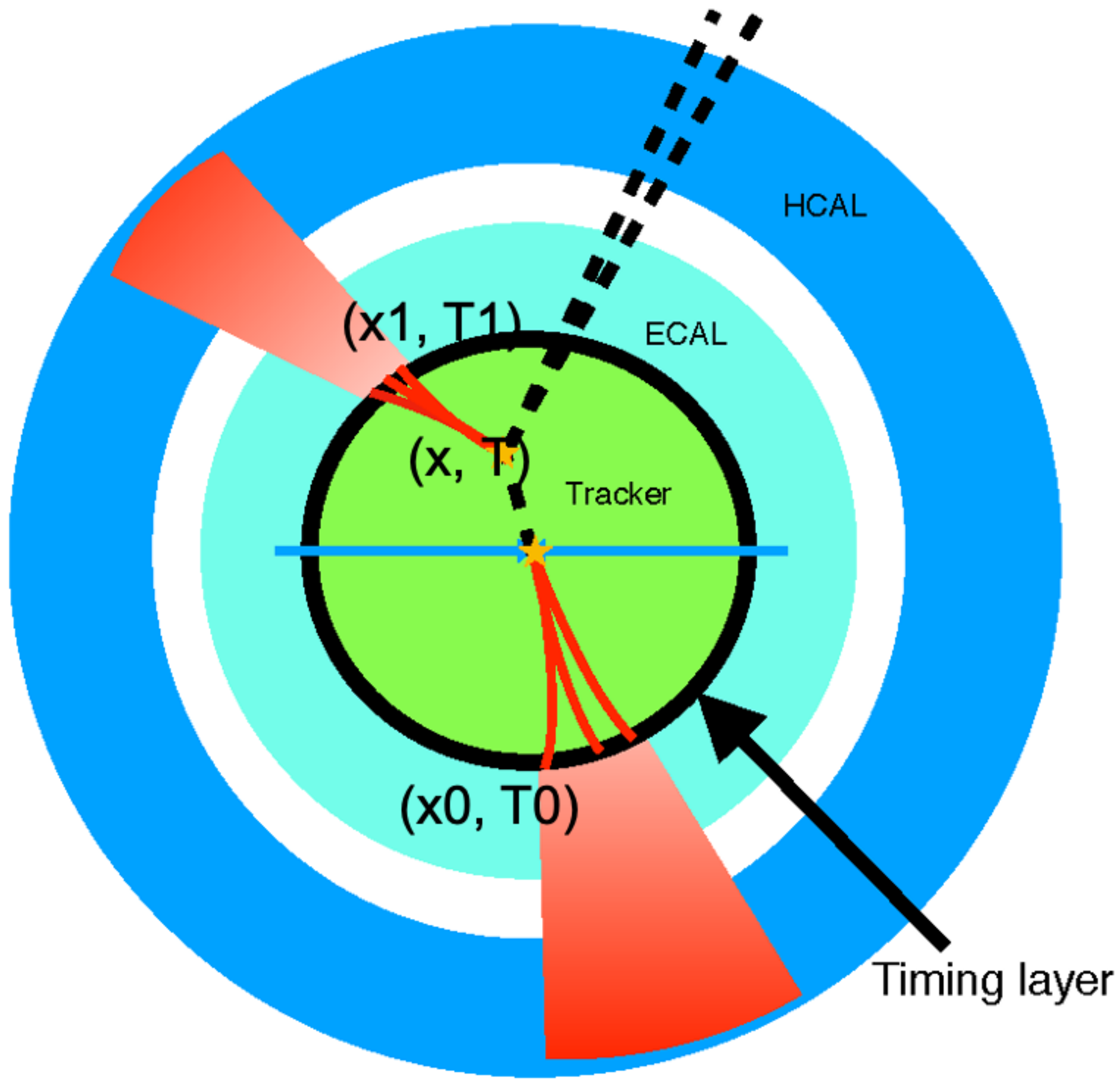
(B) Compressed neutralino, Inelastic DM, ...

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

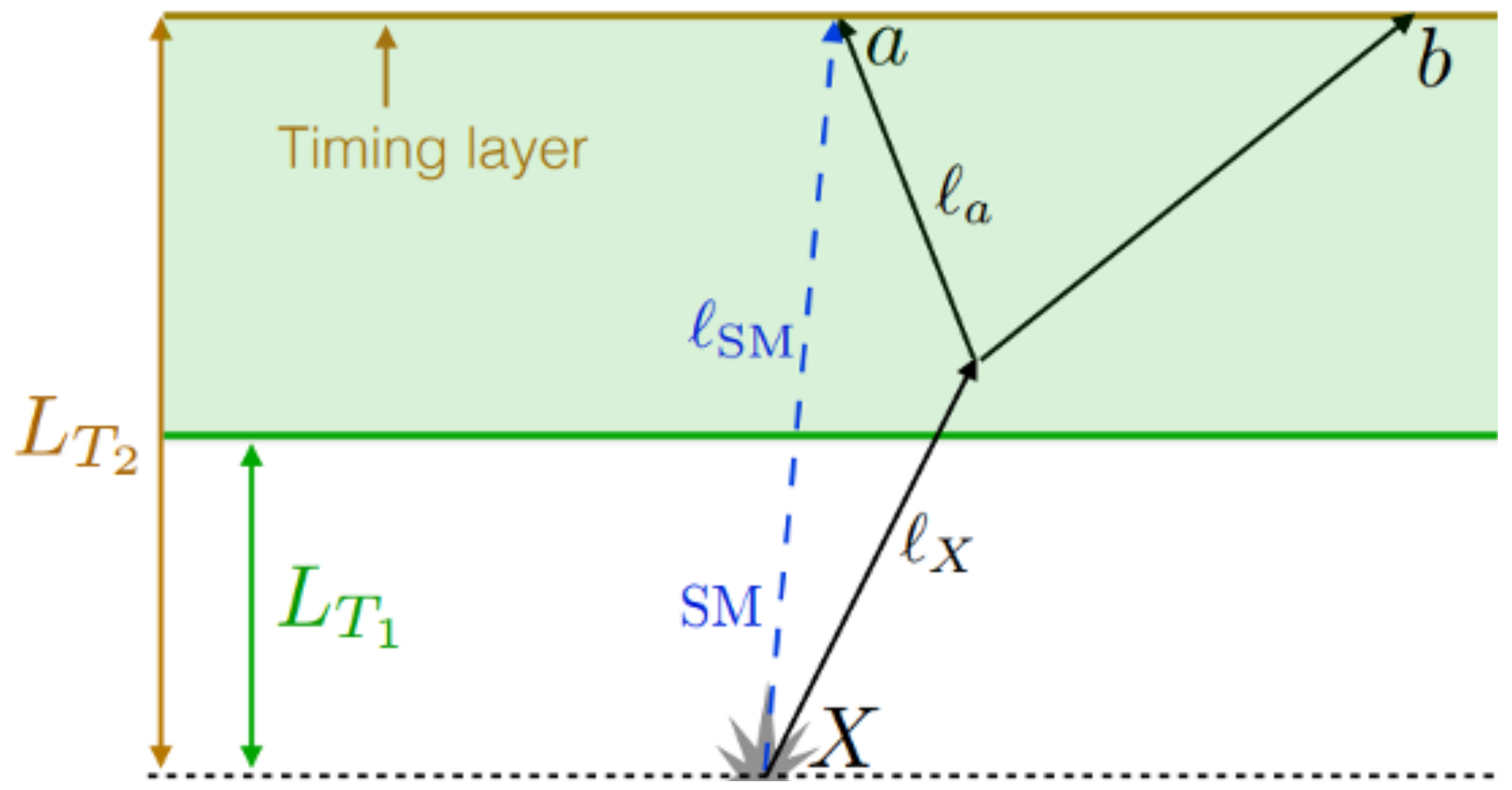
[**DWK**, P. Ko, Chih-Ting Lu, JHEP 04 (2021) 269]

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

Timing detector @ HL-LHC



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



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

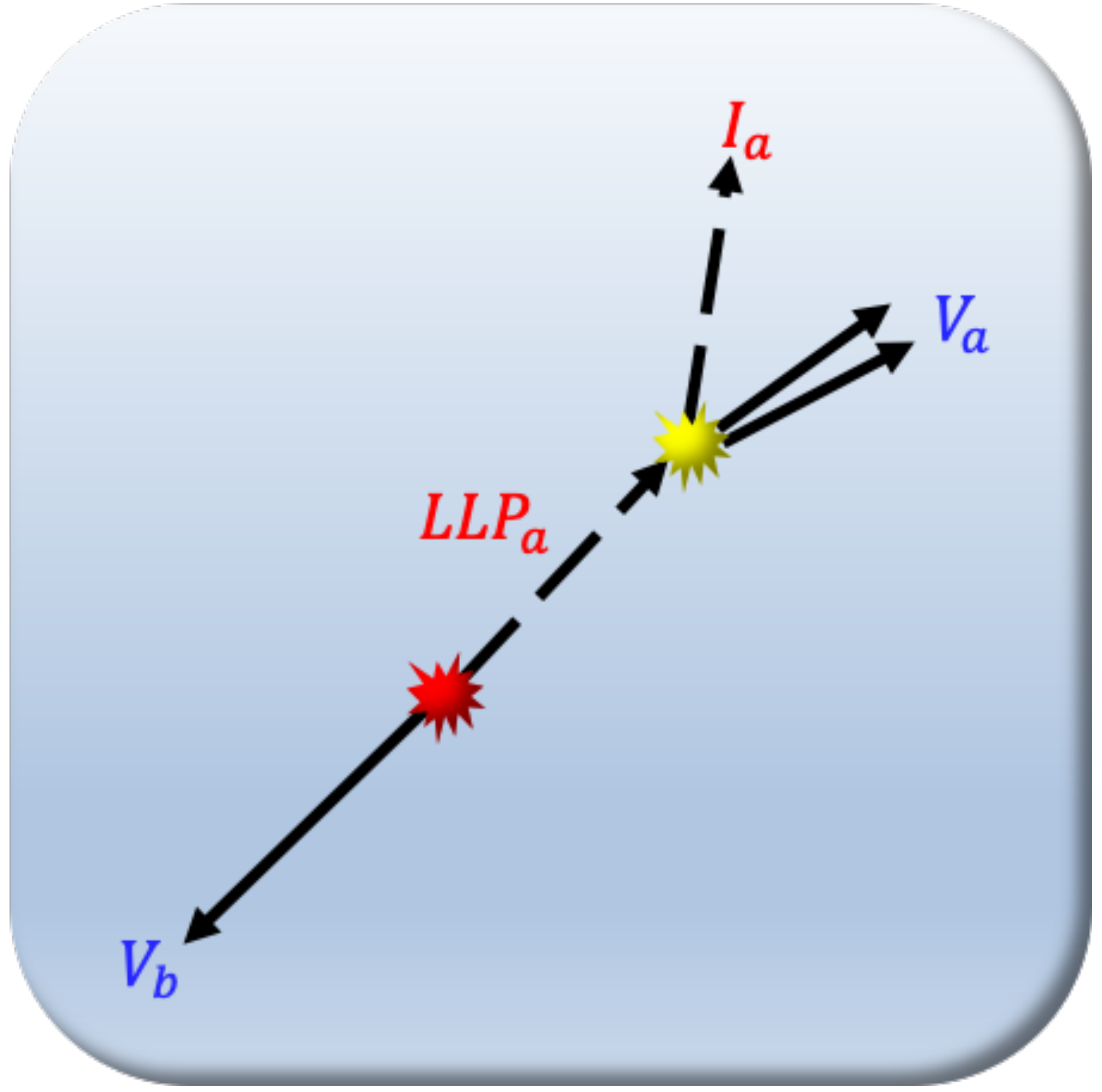
  \+

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

  ↓

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

Reconstruction with timing information



Lab frame

$$E_V^{LLP} = \gamma_P^{\text{lab}} \left(E_V^{\text{lab}} - \boldsymbol{p}_V^{\text{lab}} \cdot \boldsymbol{\beta}_{LLP}^{\text{lab}} \right)$$

$$\begin{aligned} \boldsymbol{p}_{LLP,T}^{\text{lab}} &= \boldsymbol{p}_{I,T}^{\text{lab}} + \boldsymbol{p}_{V,T}^{\text{lab}} \\ &= E_{LLP}^{\text{lab}} \boldsymbol{\beta}_{LLP,T}^{\text{lab}} \end{aligned}$$

$$\Rightarrow E_{LLP}^{\text{lab}} = \frac{\boldsymbol{\beta}_{LLP,T}^{\text{lab}} \cdot \left(\boldsymbol{p}_{I,T}^{\text{lab}} + \boldsymbol{p}_{V,T}^{\text{lab}} \right)}{|\boldsymbol{\beta}_{LLP,T}^{\text{lab}}|^2}$$

$$\begin{aligned} m_{LLP} &= \left(\gamma_{LLP}^{\text{lab}} \right)^{-1} E_{LLP}^{\text{lab}} \\ &= \frac{\sqrt{1 - \left(\boldsymbol{\beta}_{LLP}^{\text{lab}} \right)^2}}{|\boldsymbol{\beta}_{LLP,T}^{\text{lab}}|^2} \boldsymbol{\beta}_{LLP,T}^{\text{lab}} \cdot \left(\boldsymbol{p}_{I,T}^{\text{lab}} + \boldsymbol{p}_{V,T}^{\text{lab}} \right) \end{aligned}$$

$$m_I = \sqrt{m_{LLP}^2 - 2 m_{LLP} E_V^{LLP} + m_V^2}$$

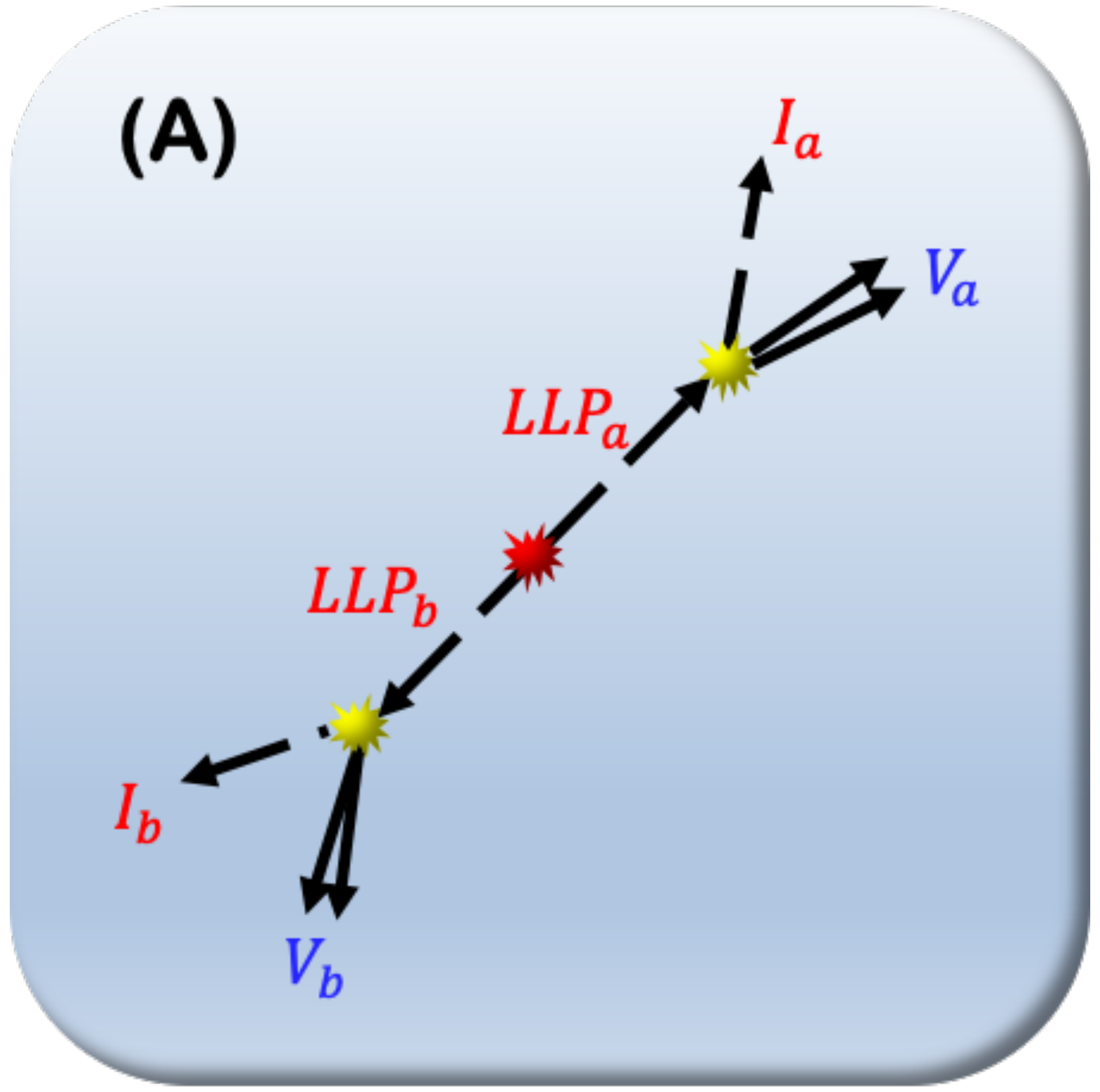
LLP rest frame

$$\boldsymbol{p}_I^{LLP} = -\boldsymbol{p}_V^{LLP}$$

$$p_{LLP}^{\mu} = p_V^{\mu} + p_I^{\mu} = (m_P, 0)$$

$$E_V^{LLP} = \frac{m_{LLP}^2 - m_I^2 + m_V^2}{2 m_{LLP}}$$

Neutral LLP search example (A)



# of unknowns = # of knowns + timing information

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

P_{V_a}, P_{V_b} = 8

p_T^{miss} = 2

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

T_a, T_b = 2

$$\boldsymbol{\beta}_a = r_a/T_a, \qquad \boldsymbol{\beta}_b = r_b/T_b$$

$$\boldsymbol{p}_{a,T} + \boldsymbol{p}_{b,T} = \boldsymbol{p}_{I,T} + \boldsymbol{p}_{V_a,T} + \boldsymbol{p}_{V_b,T}$$

$$\Rightarrow E_a\boldsymbol{\beta}_{a,T} + E_b\boldsymbol{\beta}_{b,T} = \boldsymbol{p}_{I,T} + \boldsymbol{p}_{V_a,T} + \boldsymbol{p}_{V_b,T}$$

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

3-momenta reconstruction

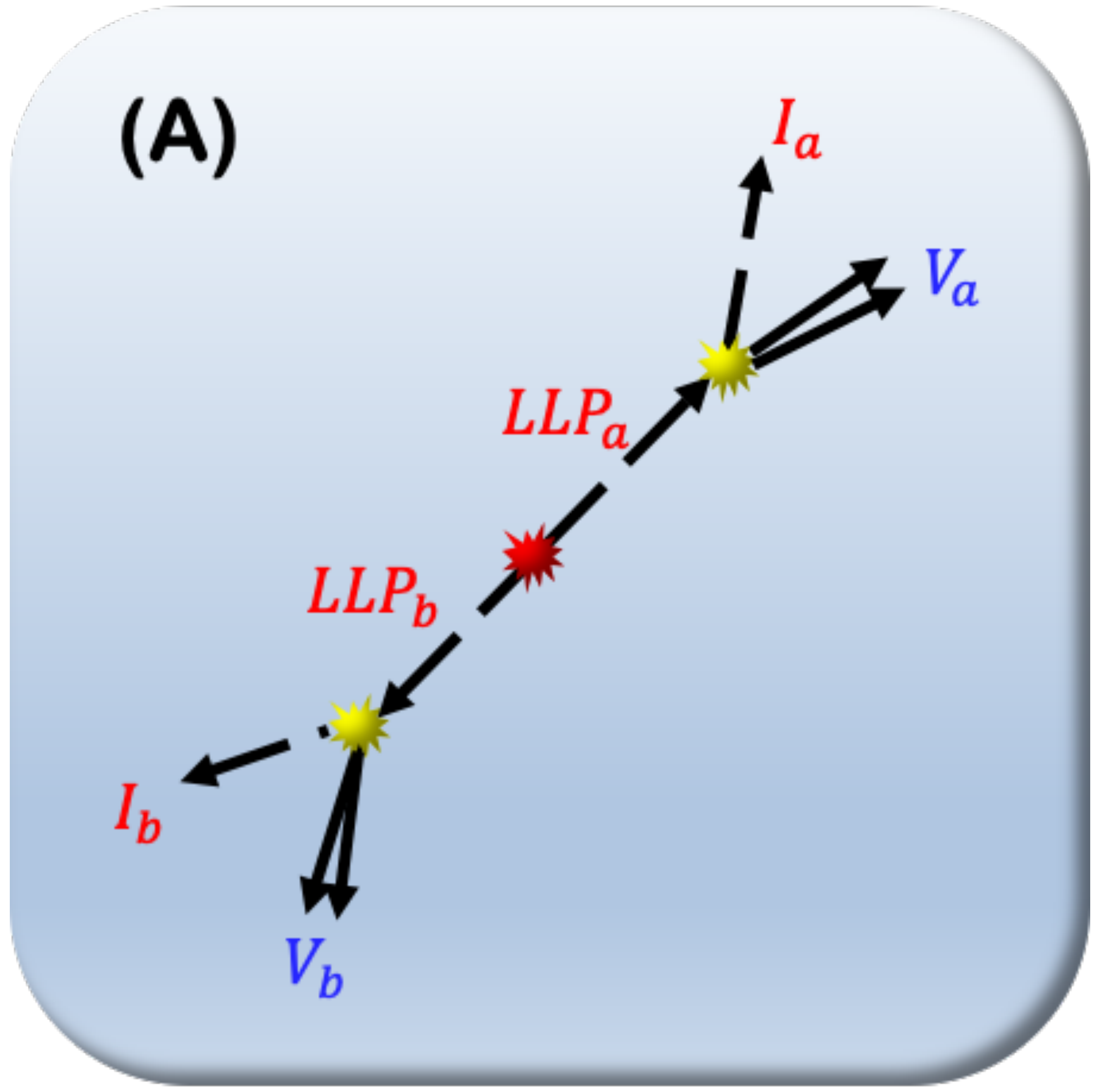
$$\boldsymbol{p}_{LLP_a} = \frac{\boldsymbol{\beta}_b \times (\boldsymbol{p}_I + \boldsymbol{p}_{V_a} + \boldsymbol{p}_{V_b}) \cdot \hat{\boldsymbol{k}}}{\boldsymbol{\beta}_b \times \boldsymbol{\beta}_a \cdot \hat{\boldsymbol{k}}}\boldsymbol{\beta}_a \qquad \boldsymbol{p}_{I_a} = \frac{\boldsymbol{\beta}_b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

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

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

Neutral LLP search example (A)

[M. Park and Y. Zhao, 1110.1403]
[G. Cottin, 1801.09671]
See also [K. Bae, M. Park, and M. Zhang, 2001.02142]



# 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

$m_a = m_b$

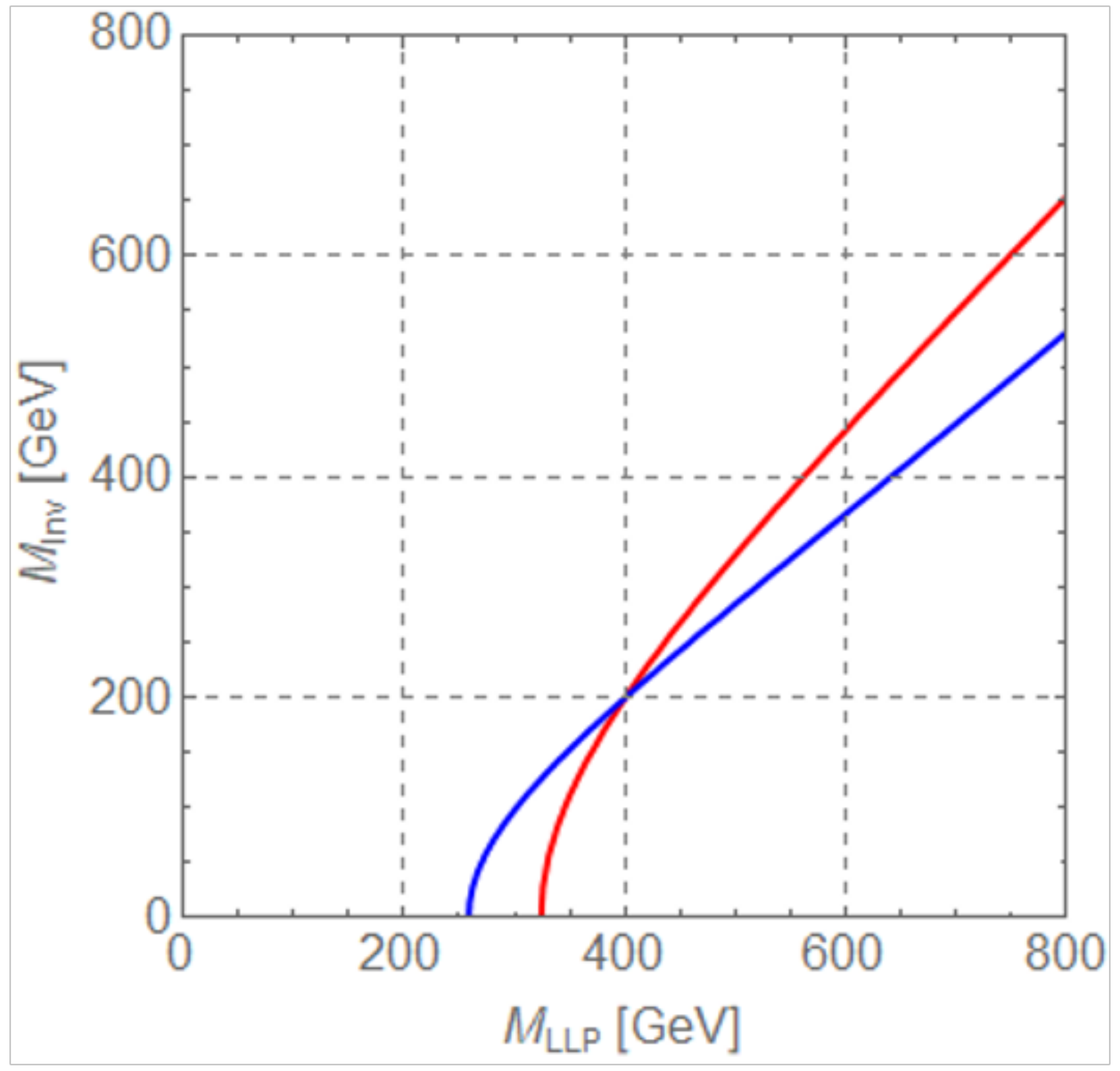
$m_{I_a} = m_{I_b}$

- 4-momentum conservation

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

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

- For each event we can find



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

$$\boldsymbol{p}_{a,T} + \boldsymbol{p}_{b,T} = \boldsymbol{p}_{I,T} + \boldsymbol{p}_{V_a,T} + \boldsymbol{p}_{V_b,T}$$

$$\Rightarrow E_a\boldsymbol{\beta}_{a,T} + E_b\boldsymbol{\beta}_{b,T} = \boldsymbol{p}_{I,T} + \boldsymbol{p}_{V_a,T} + \boldsymbol{p}_{V_b,T}$$

3-momenta reconstruction

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

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

Monte Calro Simulation

Event simulation with MG5 + Pythia8

$$pp \to LLP_a\, LLP_b \to V_a\ I_a\ V_b\, I_b$$

- Case1: $LLP_a = LLP_b,\ I_a = I_b$

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

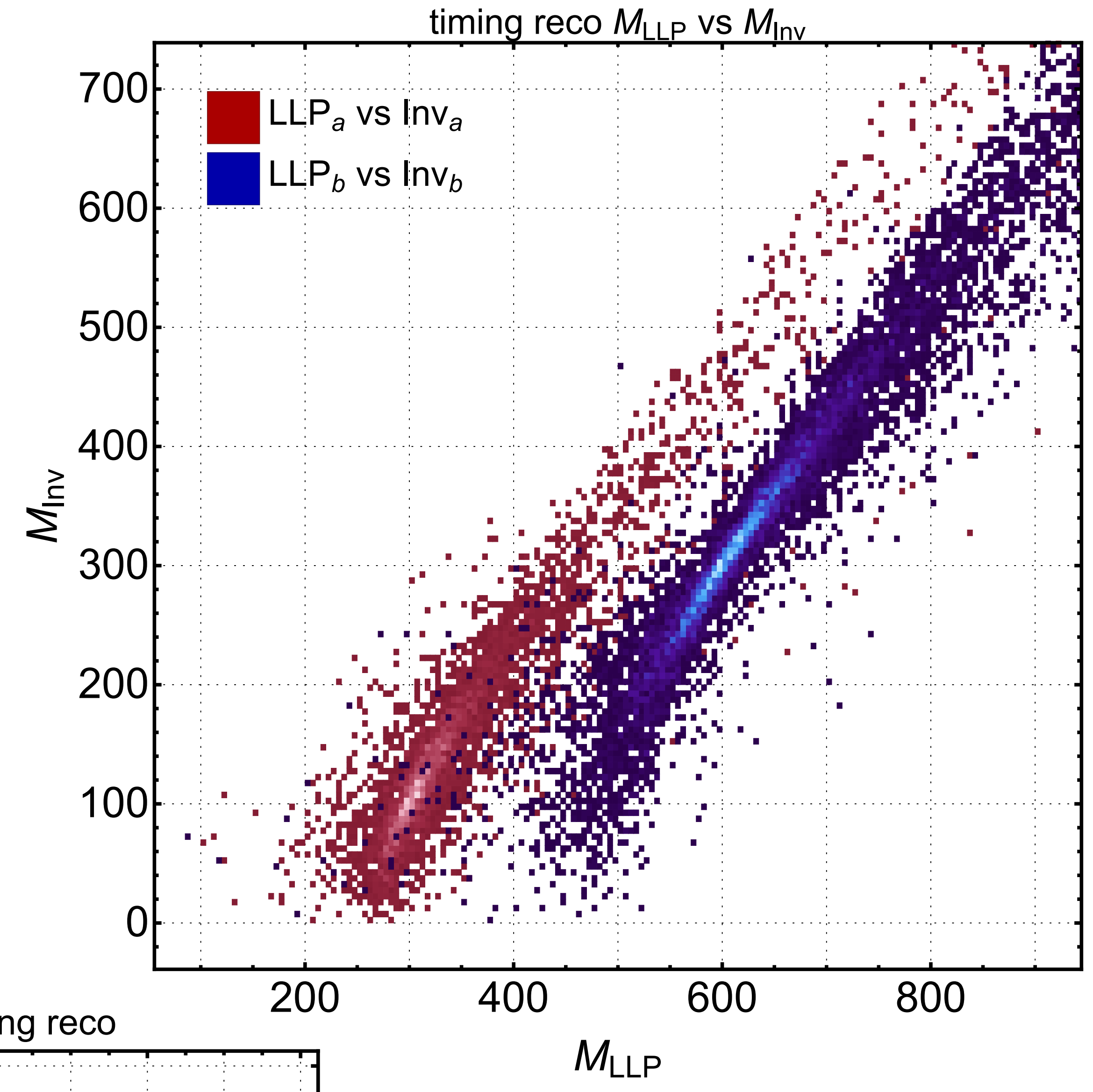
- Case2: $LLP_a \neq LLP_b,\ I_a \neq I_b$

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

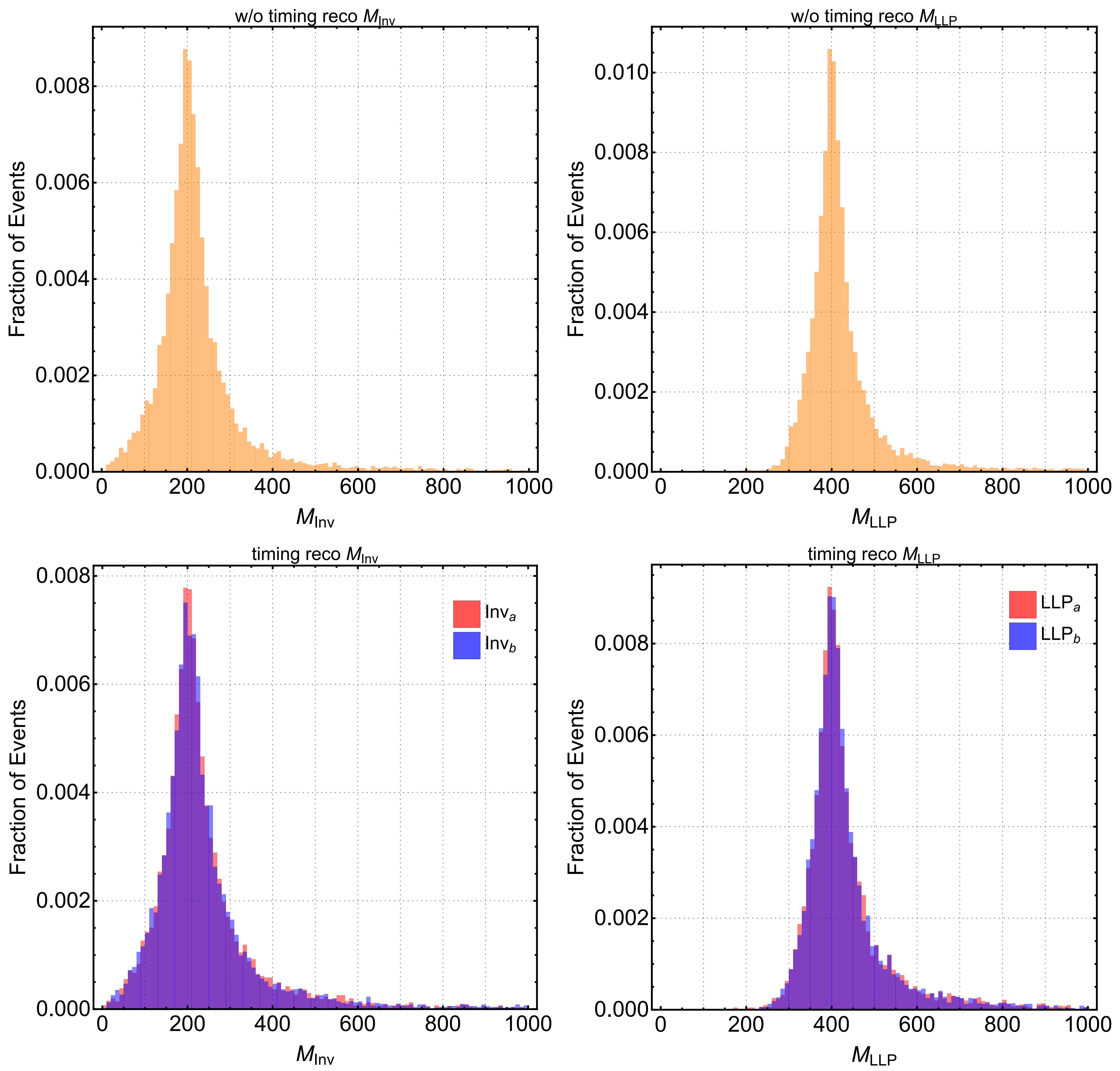
Detector effects are simulated with gaussian smearing

Reconstruction Summary

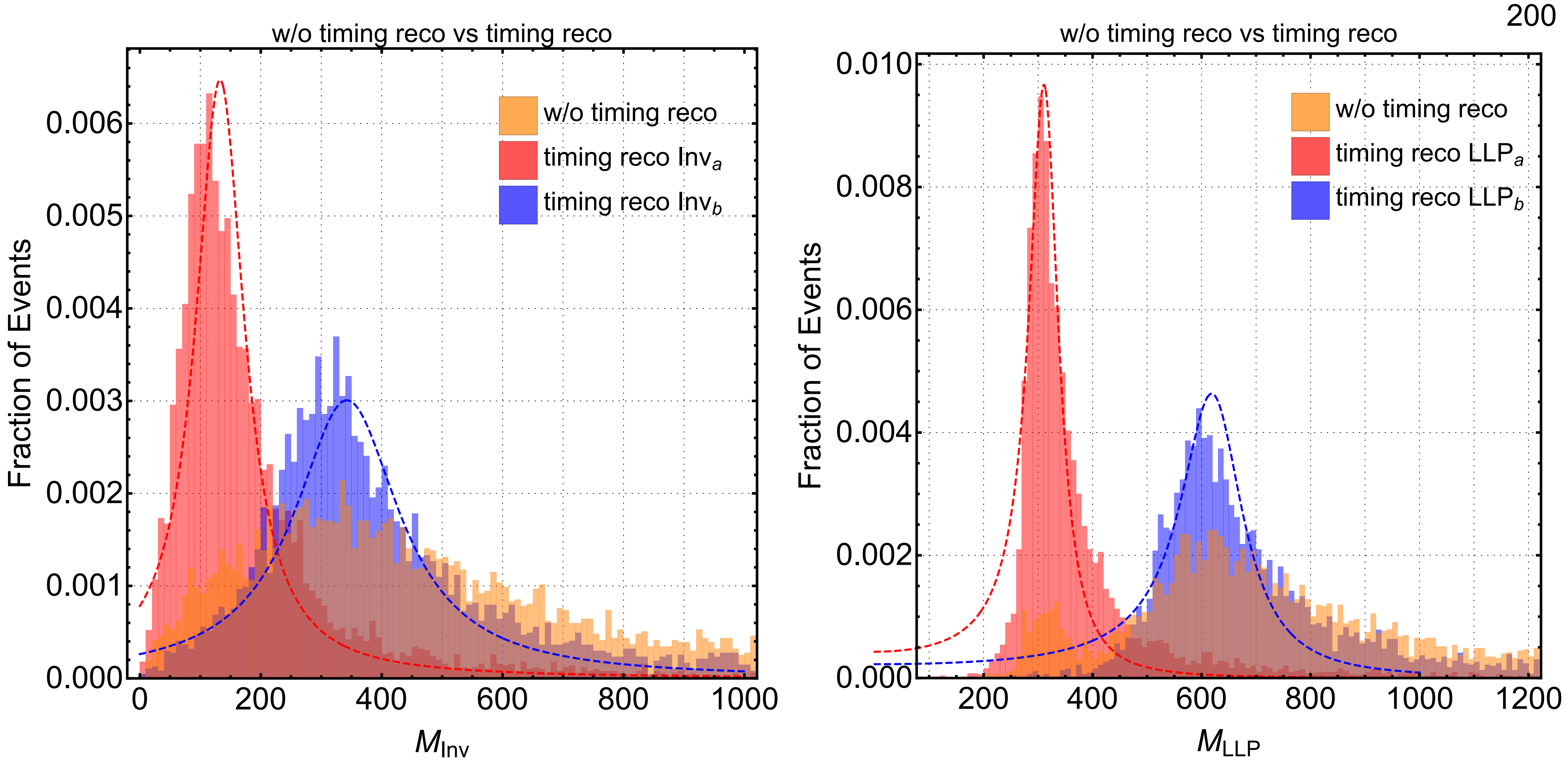
		m_{LLP_a}	m_{LLP_b}	m_{I_a}	m_{I_b}	$\boldsymbol{p}_{LLP_a}$	$\boldsymbol{p}_{LLP_b}$	$\boldsymbol{p}_{I_a}$	$\boldsymbol{p}_{I_b}$
Identical LLPs	w/o timing	△	△	△	△	◯	◯	◯	◯
	timing	◯	◯	◯	◯	◯	◯	◯	◯
Non-identical LLPs	w/o timing	×	×	×	×	◯	◯	◯	◯
	timing	◯	◯	◯	◯	◯	◯	◯	◯



Case1: $LLP_a = LLP_b, I_a = I_b$



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

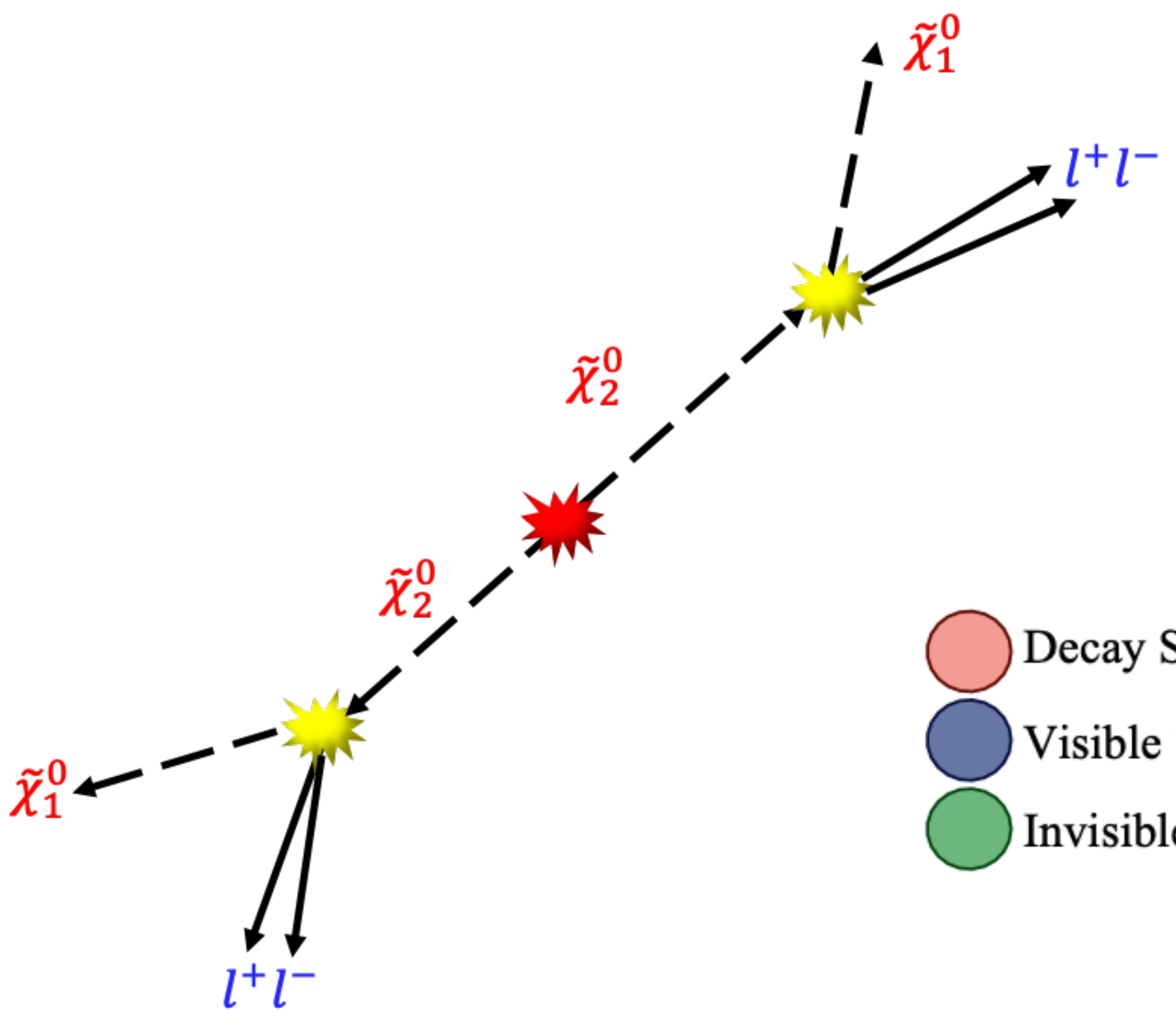


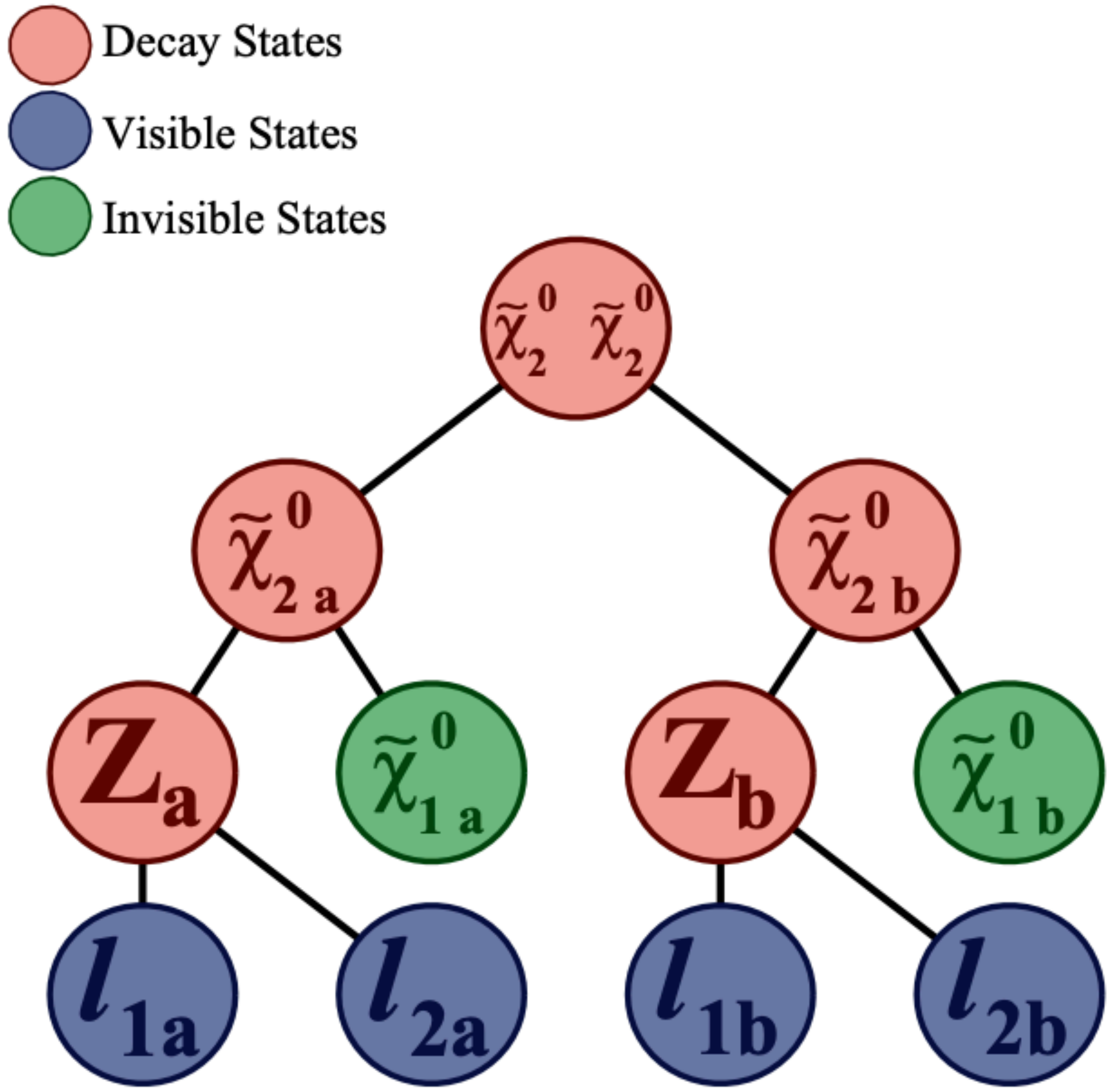
		m_{LLP_a}	m_{LLP_b}	m_{I_a}	m_{I_b}	ϵ_{reco}
$a = b$	w/o timing	397.6±1.2	397.6±1.2	206.0±1.5	206.0±1.5	0.86
	timing	400.91±0.35	400.91±0.35	201.53±0.49	201.53±0.49	0.72
$a \neq b$	w/o timing	-	-	-	-	-
	timing	307.25±0.38	612.18±0.72	118.54±0.89	319.1±1.1	0.51

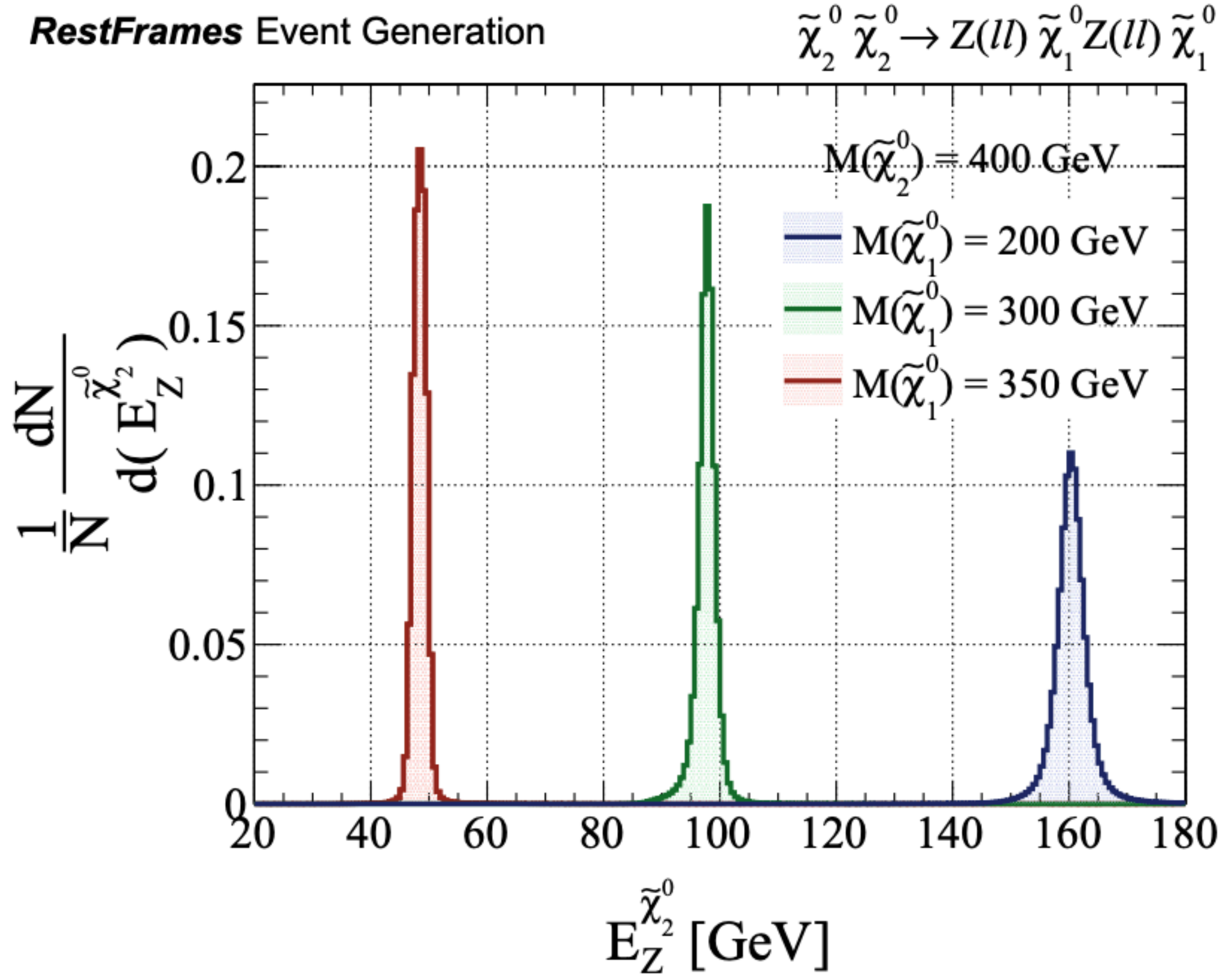
Timing reconstruction of neutral LLP decays

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

MG5+Pythia8+Delphes with 200 pile up

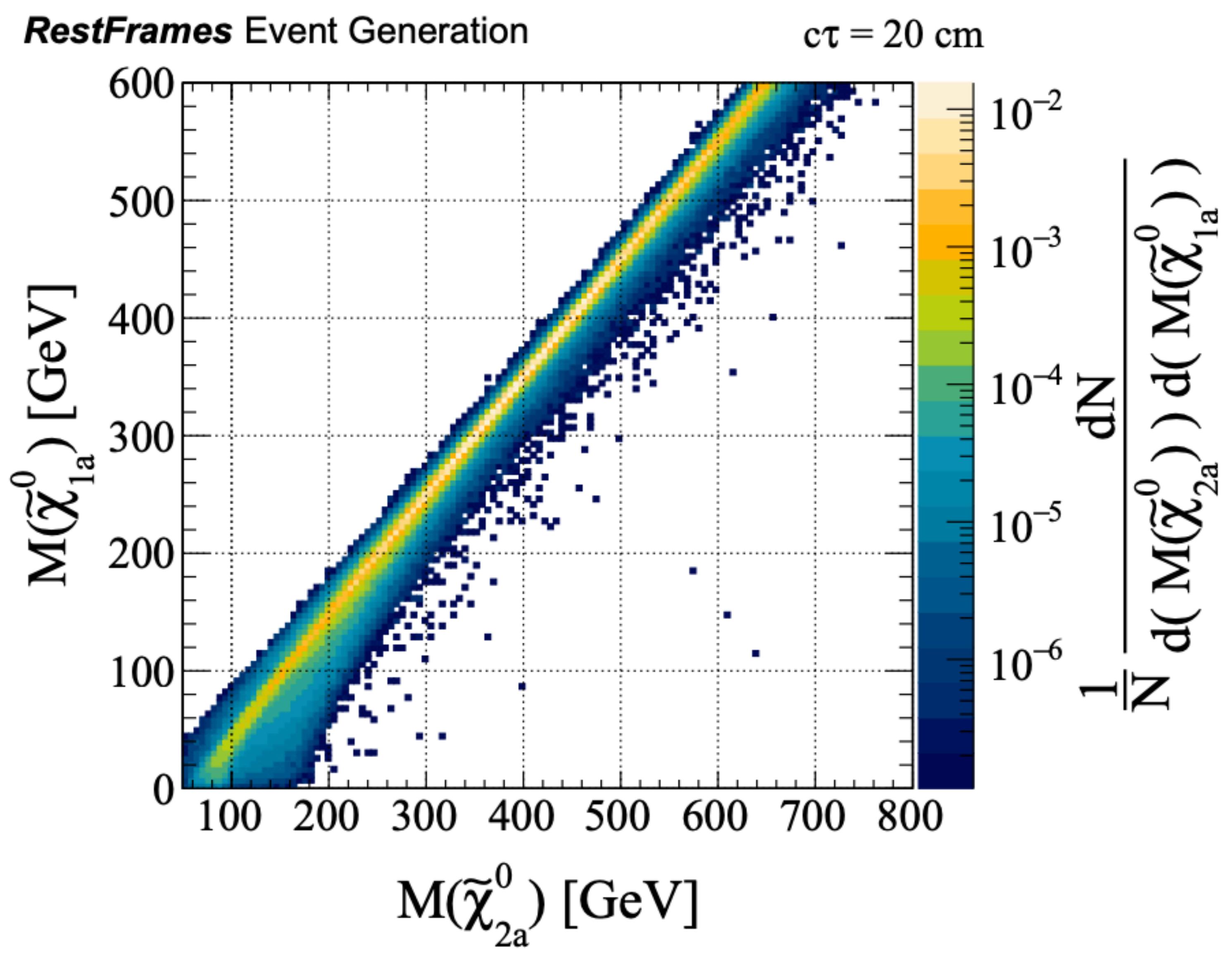




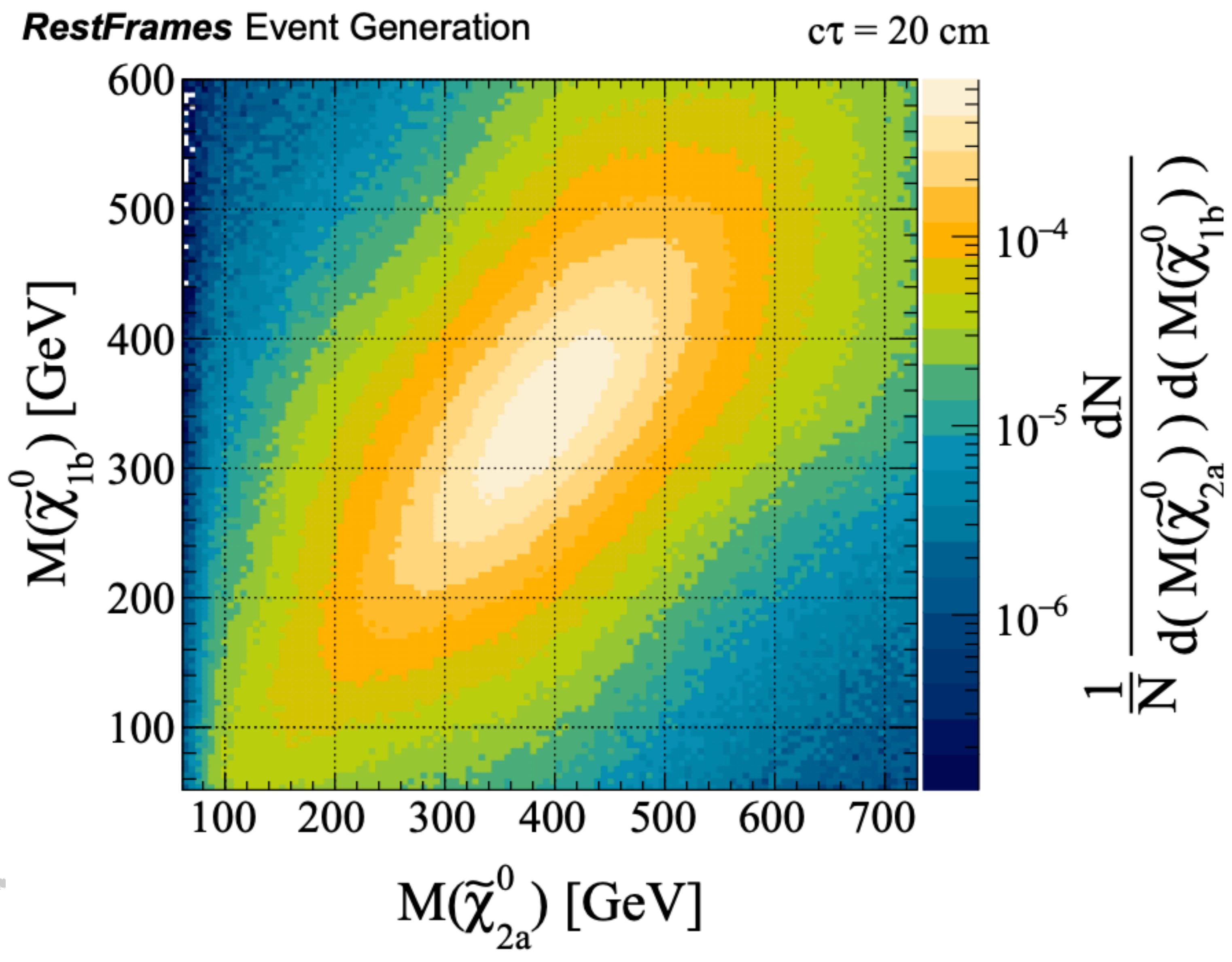


Timing reconstruction of neutral LLP decays

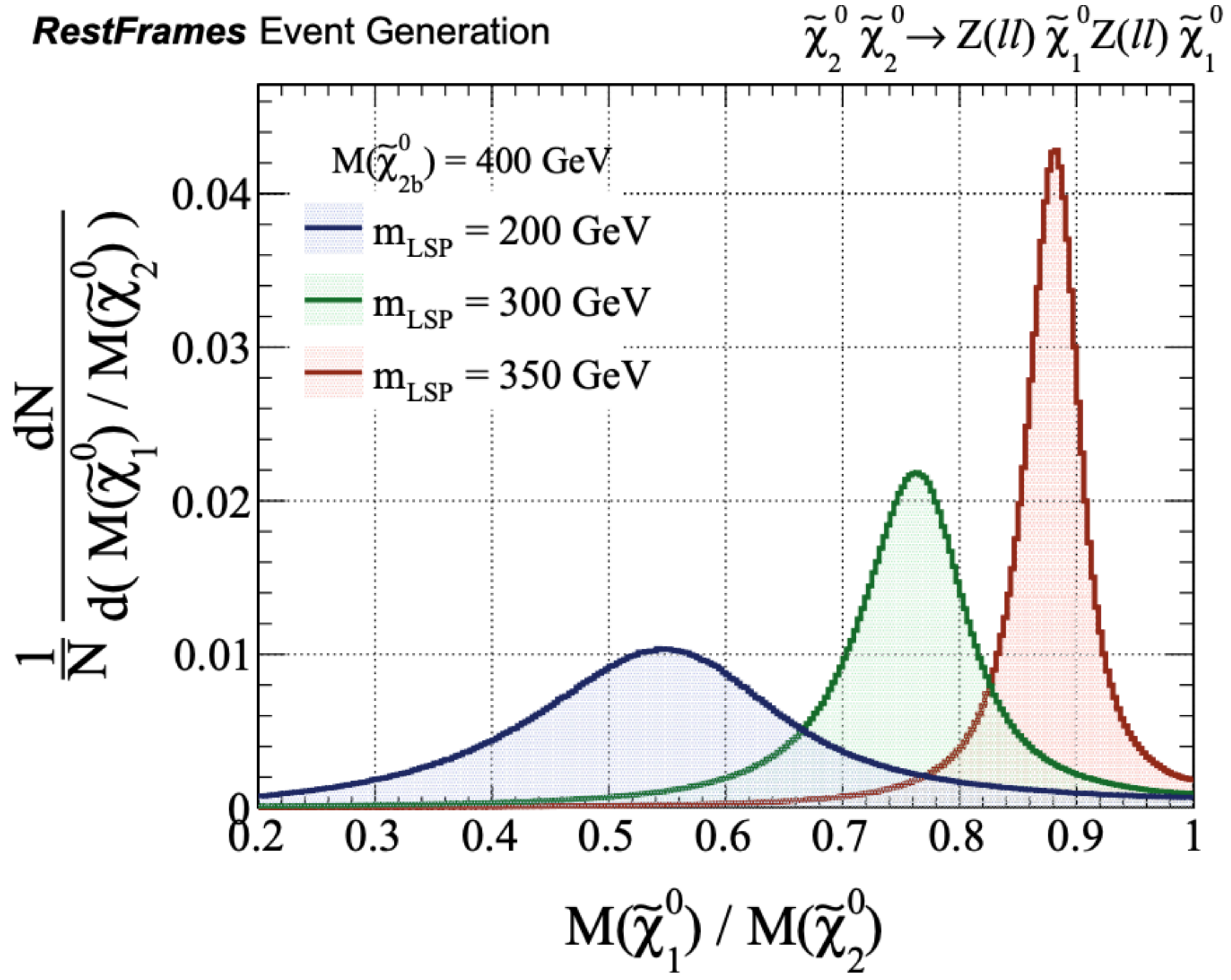
$$pp \rightarrow \tilde{\chi}_2\tilde{\chi}_2 \rightarrow \tilde{\chi}_1\tilde{\chi}_1 ZZ \rightarrow \tilde{\chi}_1\tilde{\chi}_1 \ell^+\ell^-\ell^+\ell^-$$



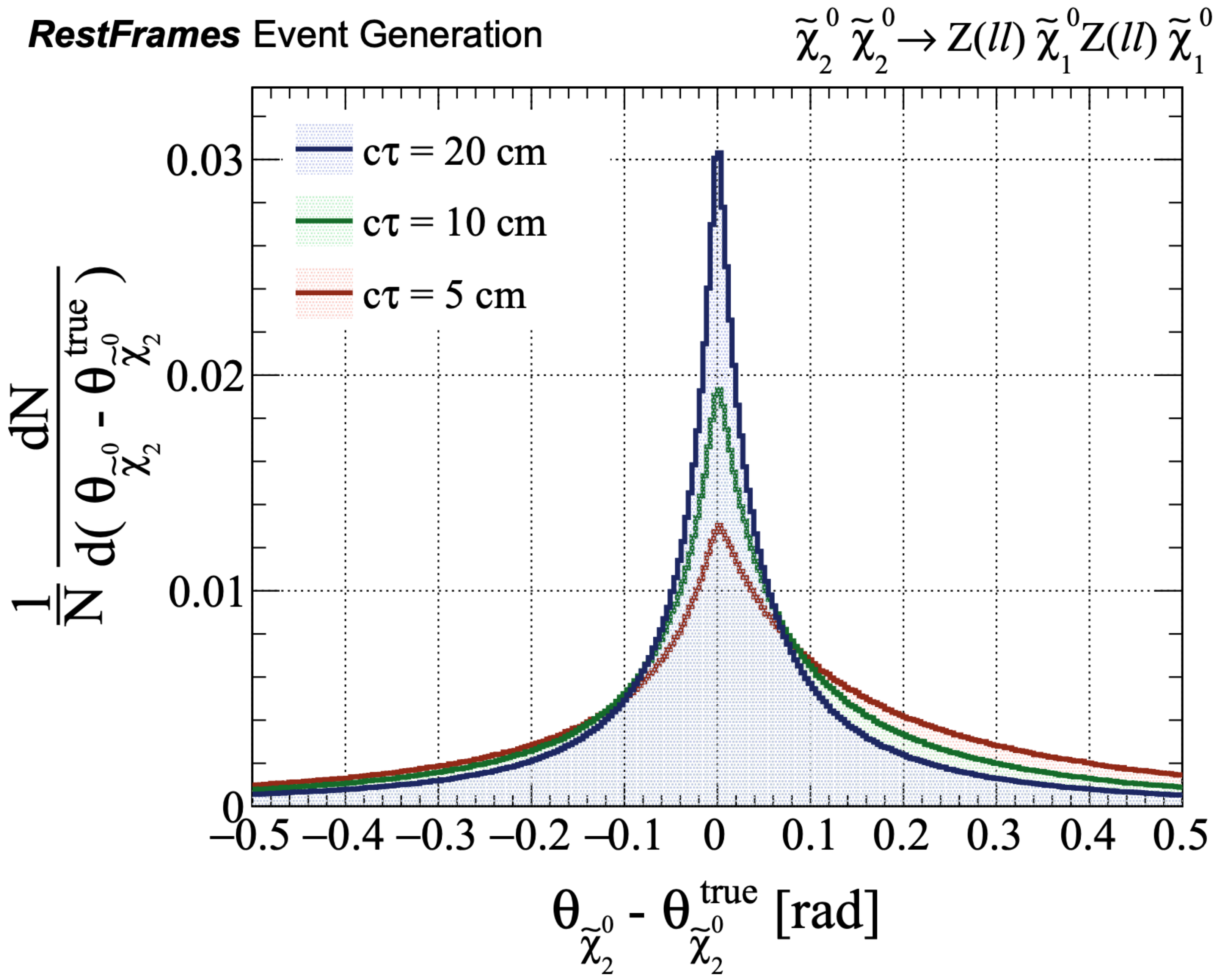
← Same decay



← Separate decay

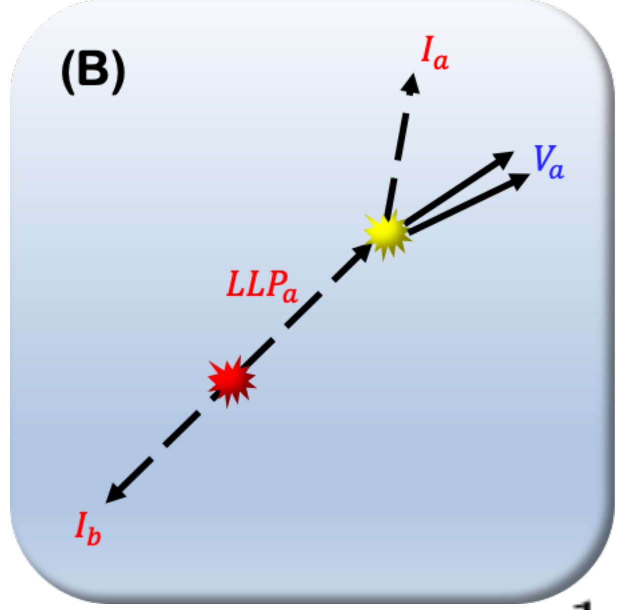


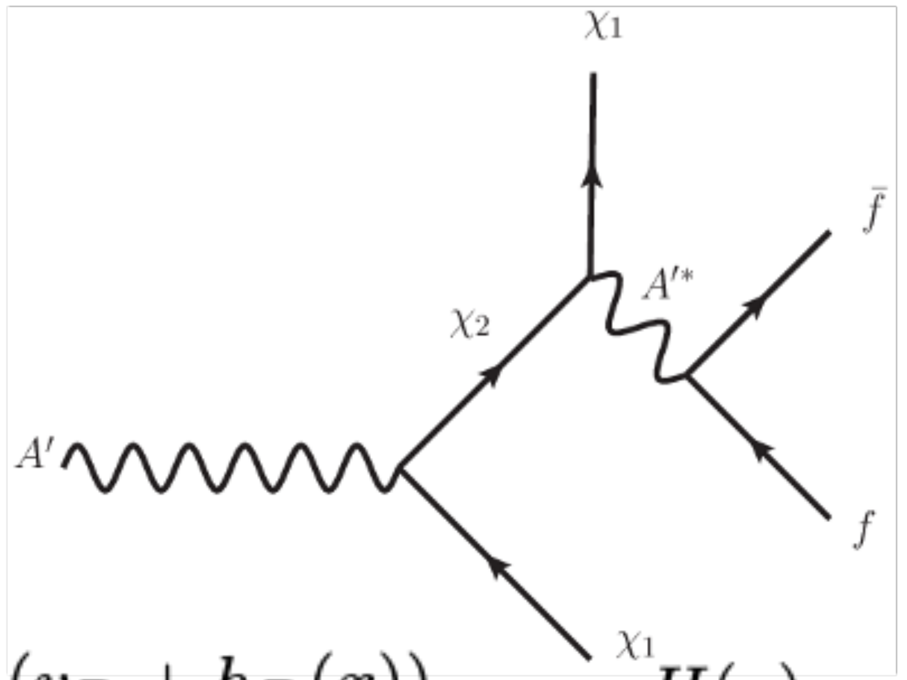
← Resolution is much better for compressed mass spectra



← Possibility to get spin information

Neutral LLP search example (B)





Inelastic dark matter model

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

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

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

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

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

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	$+1$

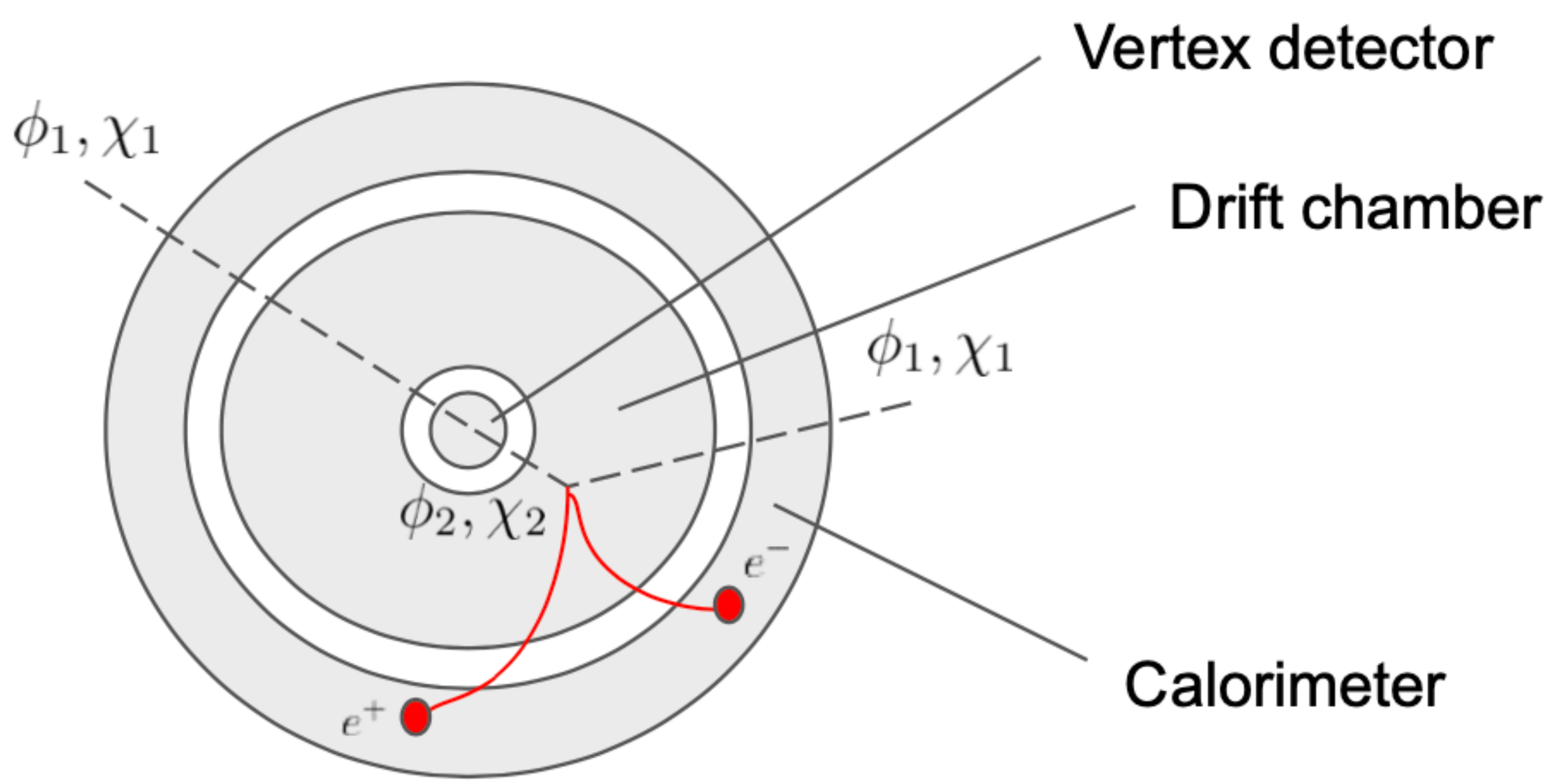
$$\begin{aligned} V(H,\Phi,\phi) = & -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 - \mu_\Phi^2 \Phi^*\Phi + \lambda_\Phi(\Phi^*\Phi)^2 \\ & + \lambda_{H\Phi}(H^\dagger H)(\Phi^*\Phi) \quad -(\frac{f}{2}\bar{\chi}^c\chi\Phi^* + H.c.) \end{aligned}$$

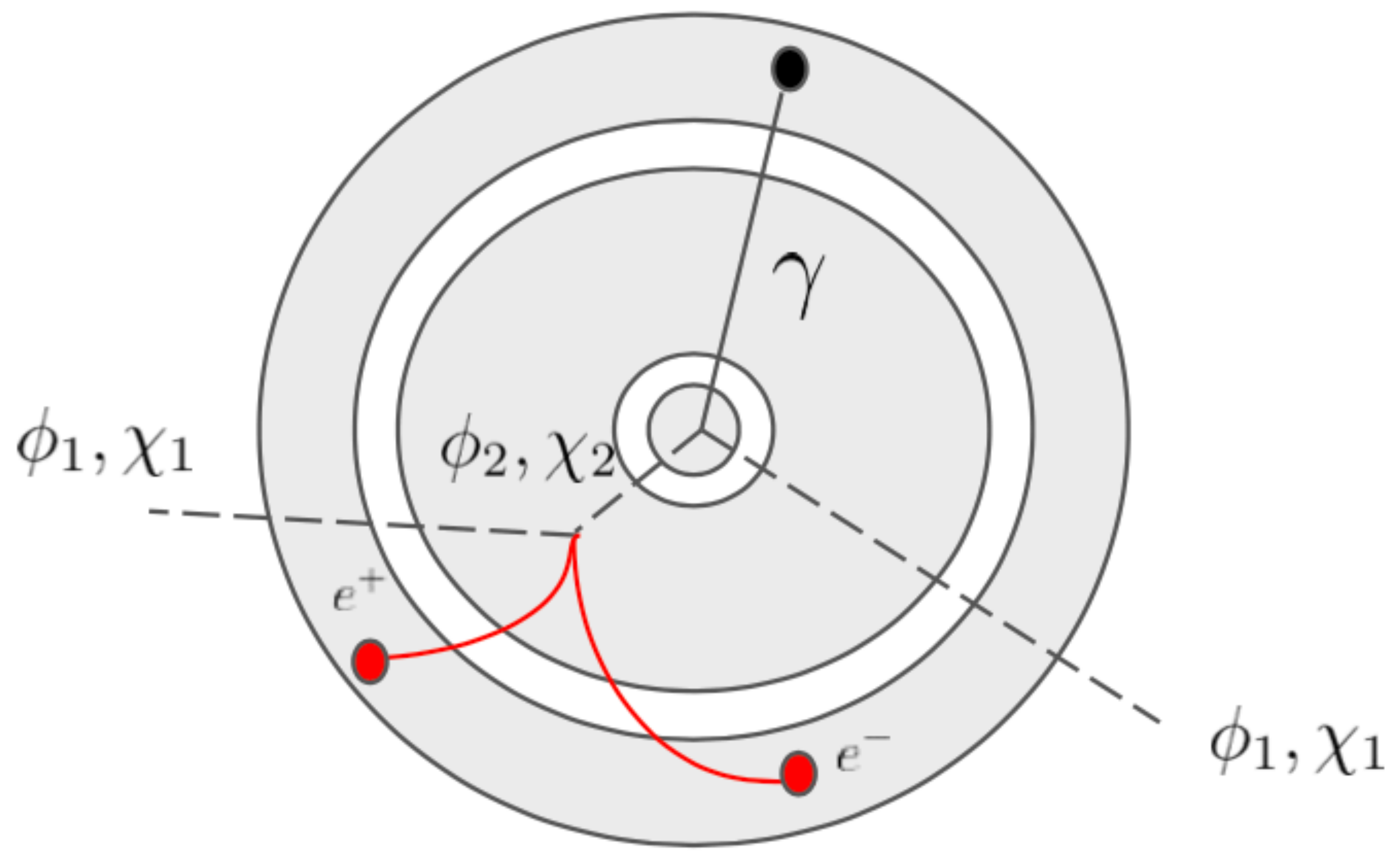
$$-i\frac{g_D}{2}(\bar{\chi}_2 \not{X}\chi_1 - \bar{\chi}_1 \not{X}\chi_2)$$

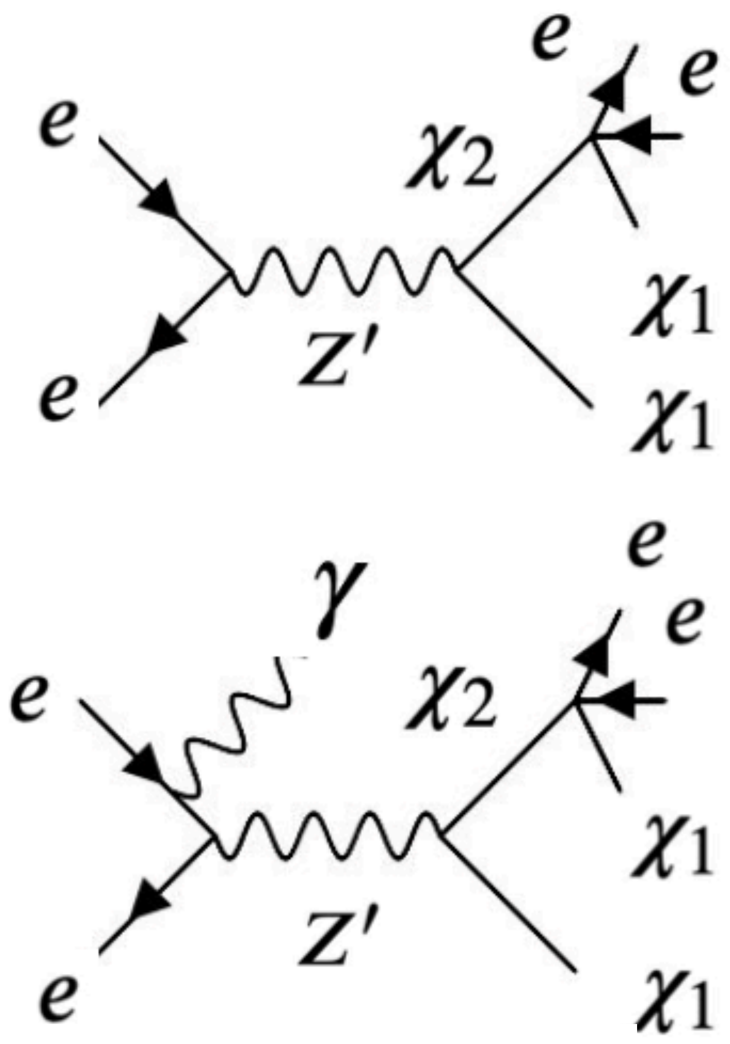
$$M_{\chi_{1,2}} = M_\chi \mp f v_D$$

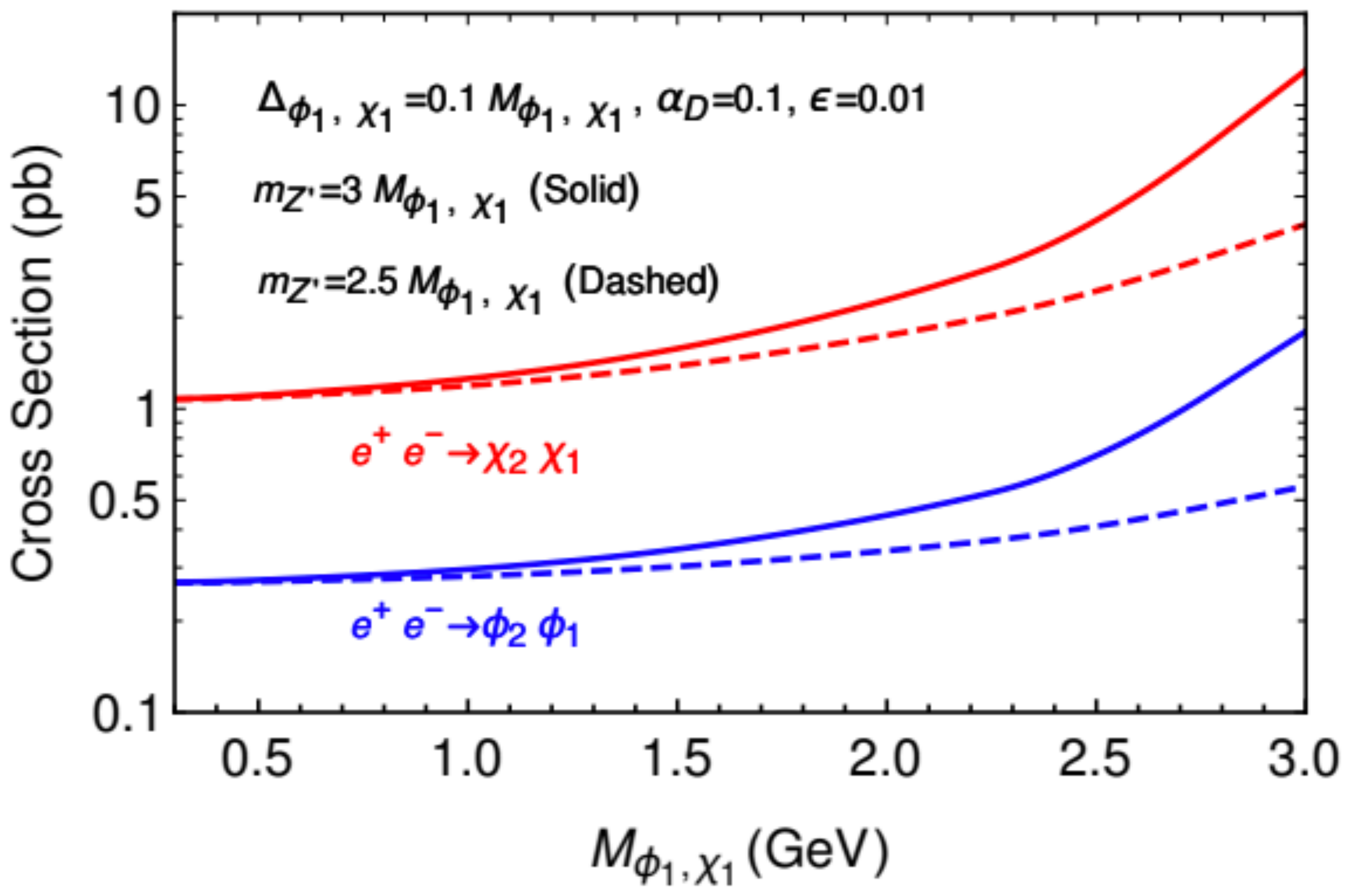
$$\Delta_\chi \equiv (M_{\chi_2} - M_{\chi_1}) = 2 f v_D$$

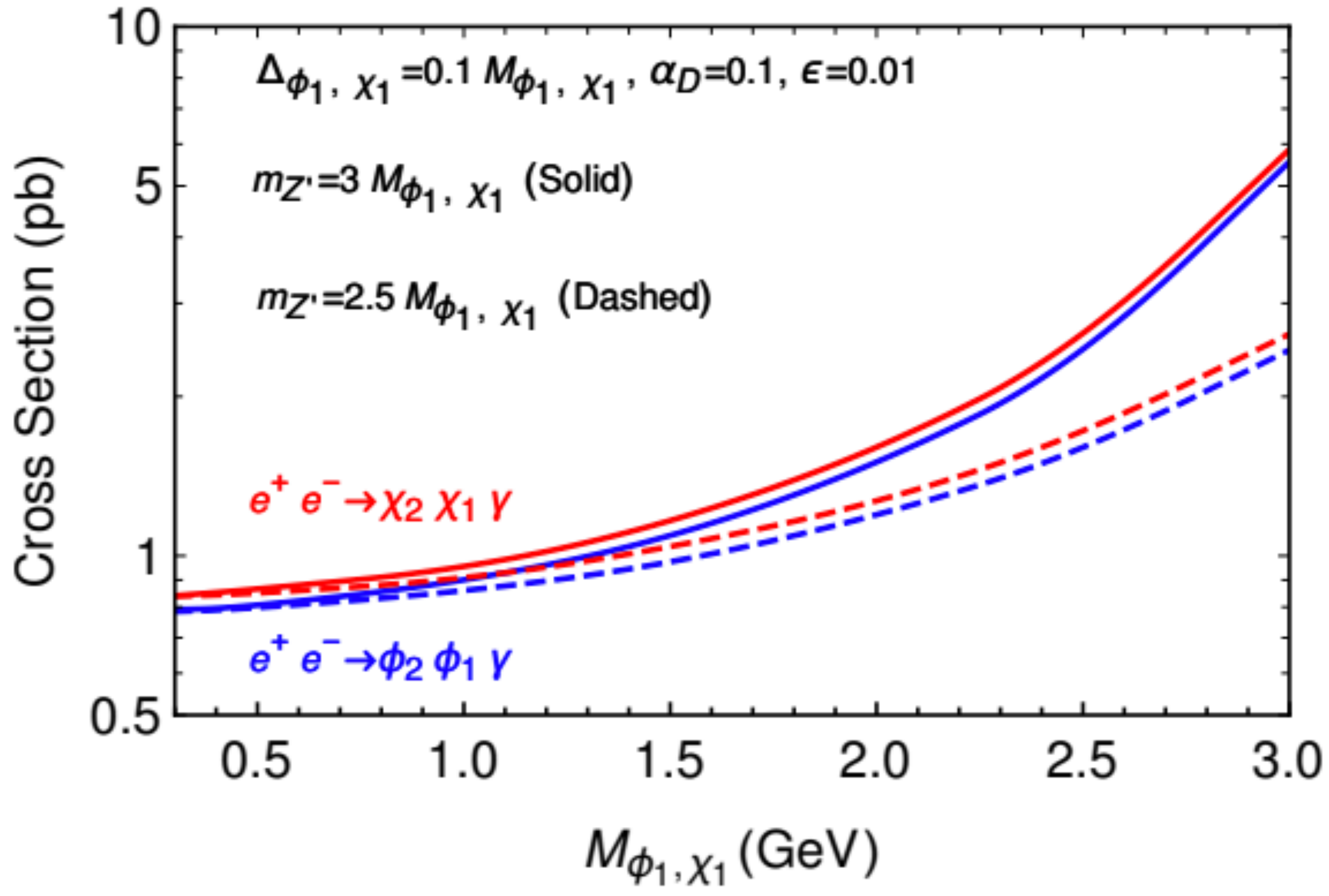
Displaced signature in Belle2 detector



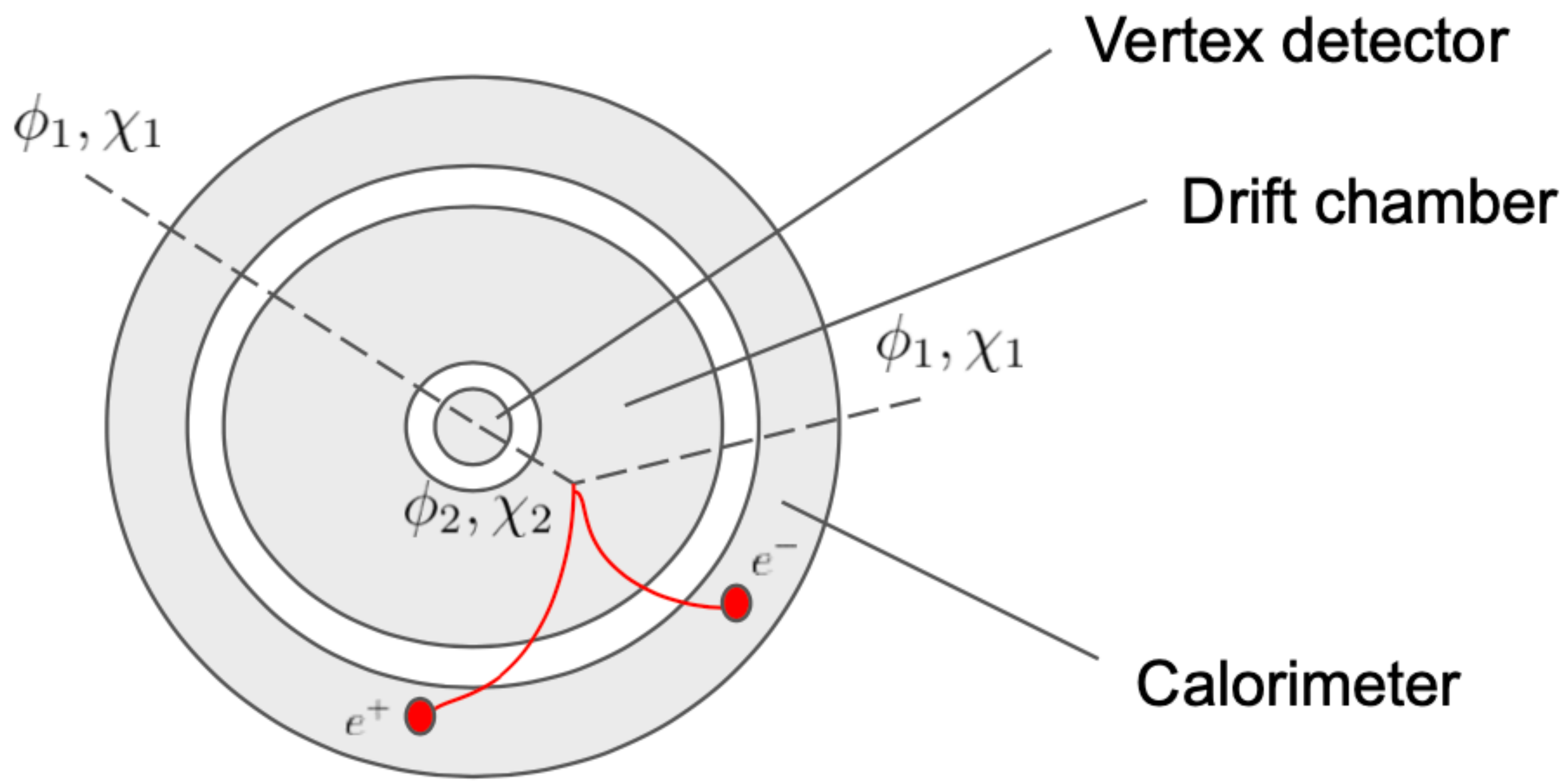


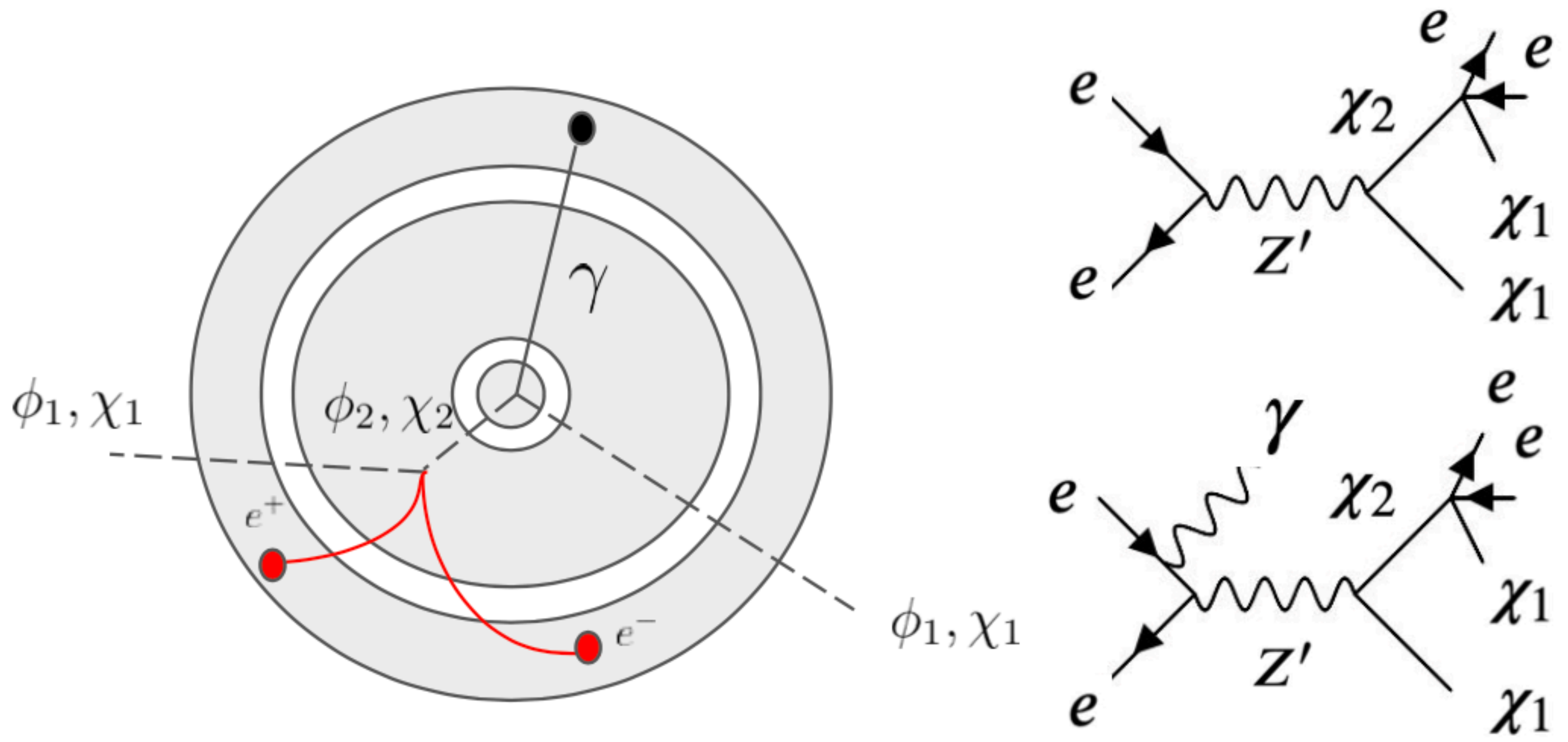






Displaced signature in Belle2 detector





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

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

* Mono-γ : $\phi_2(\chi_2)$ decay outside the detector or decay products are too soft

* Mono-γ with prompt lepton pair : $\phi_2(\chi_2)$ prompt decay

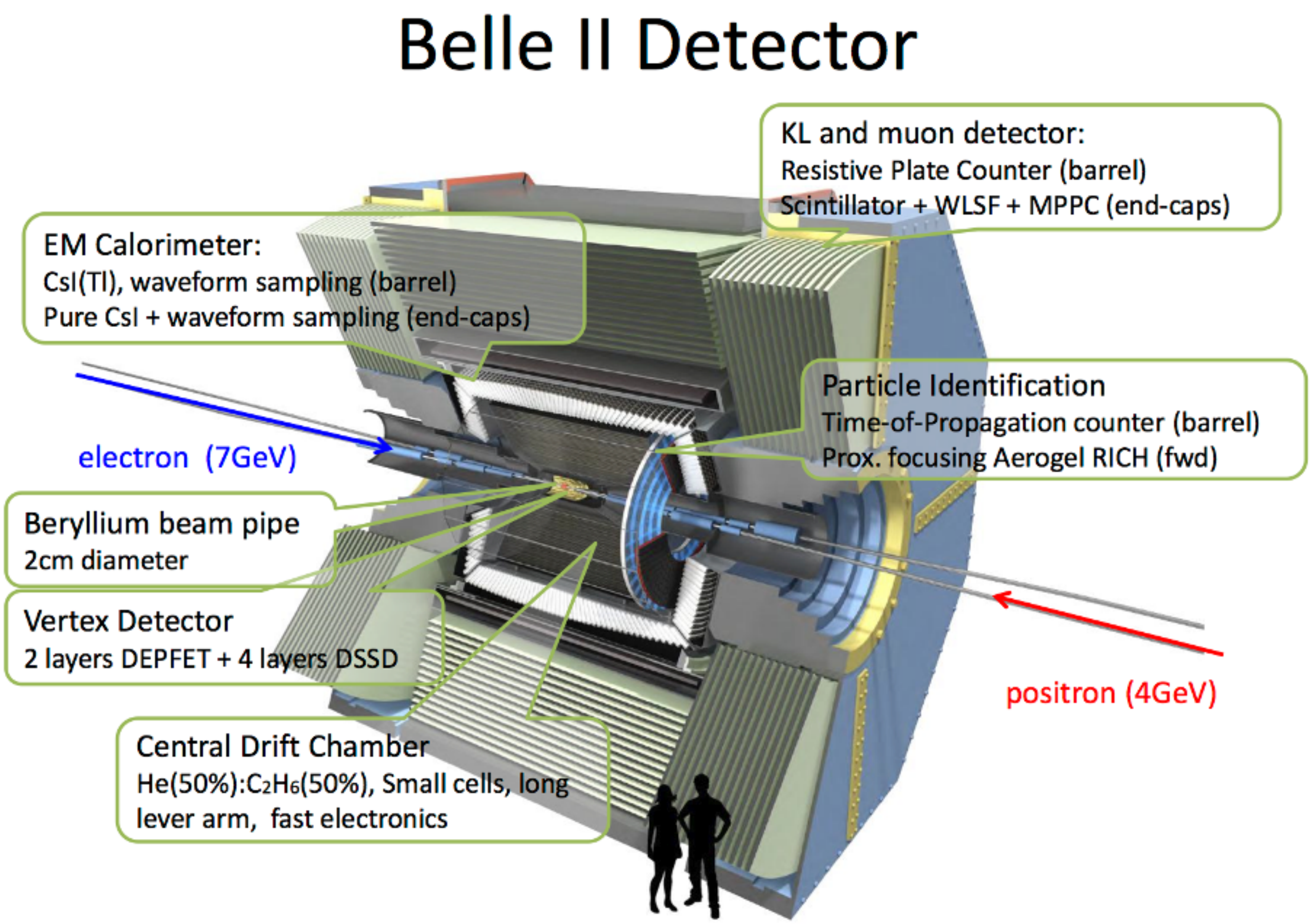
* Mono-γ with displaced lepton pair : $\phi_2(\chi_2)$ long-lived and decay inside the detector

Only prompt lepton pair: $\phi_2(\chi_2)$ prompt decay

Only displaced lepton pair: $\phi_2(\chi_2)$ long-lived and decay inside the detector

Displaced signature in Belle2 detector

MG5+Pythia8



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

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

The resolution of photon momenta in the calorimeter

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

The resolution for the displaced vertex of lepton pair

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

Displaced signature in Belle2 detector

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) $17^\circ \leq \theta^{\text{DV}}_{\text{LAB}} \leq 150^\circ$
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 $0.48\,\text{GeV} \leq m_{\mu\mu} \leq 0.52\,\text{GeV}$
photons	(i) $E^{\gamma}_{\text{LAB}} > 0.5\,\text{GeV}$ (ii) $17^\circ \leq \theta^{\gamma}_{\text{LAB}} \leq 150^\circ$

Benchmark points

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

Future sensitivity

with $L = 1\, ab^{-1}$

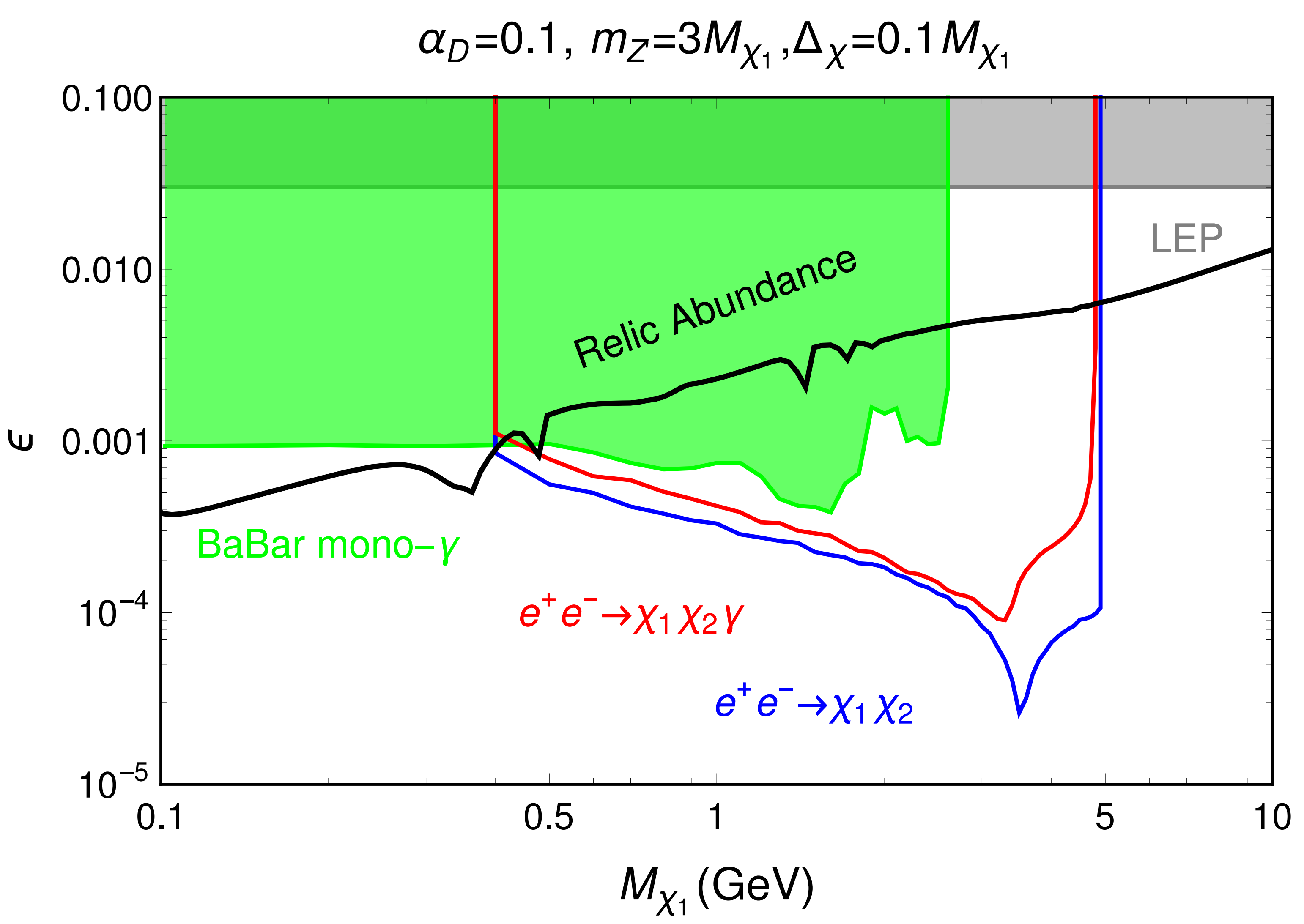
$$e^+e^- \to \phi_1\phi_2 \to \phi_1\phi_1 e^+e^-$$
$$e^+e^- \to \chi_1\chi_2 \to \chi_1\chi_1 e^+e^-$$

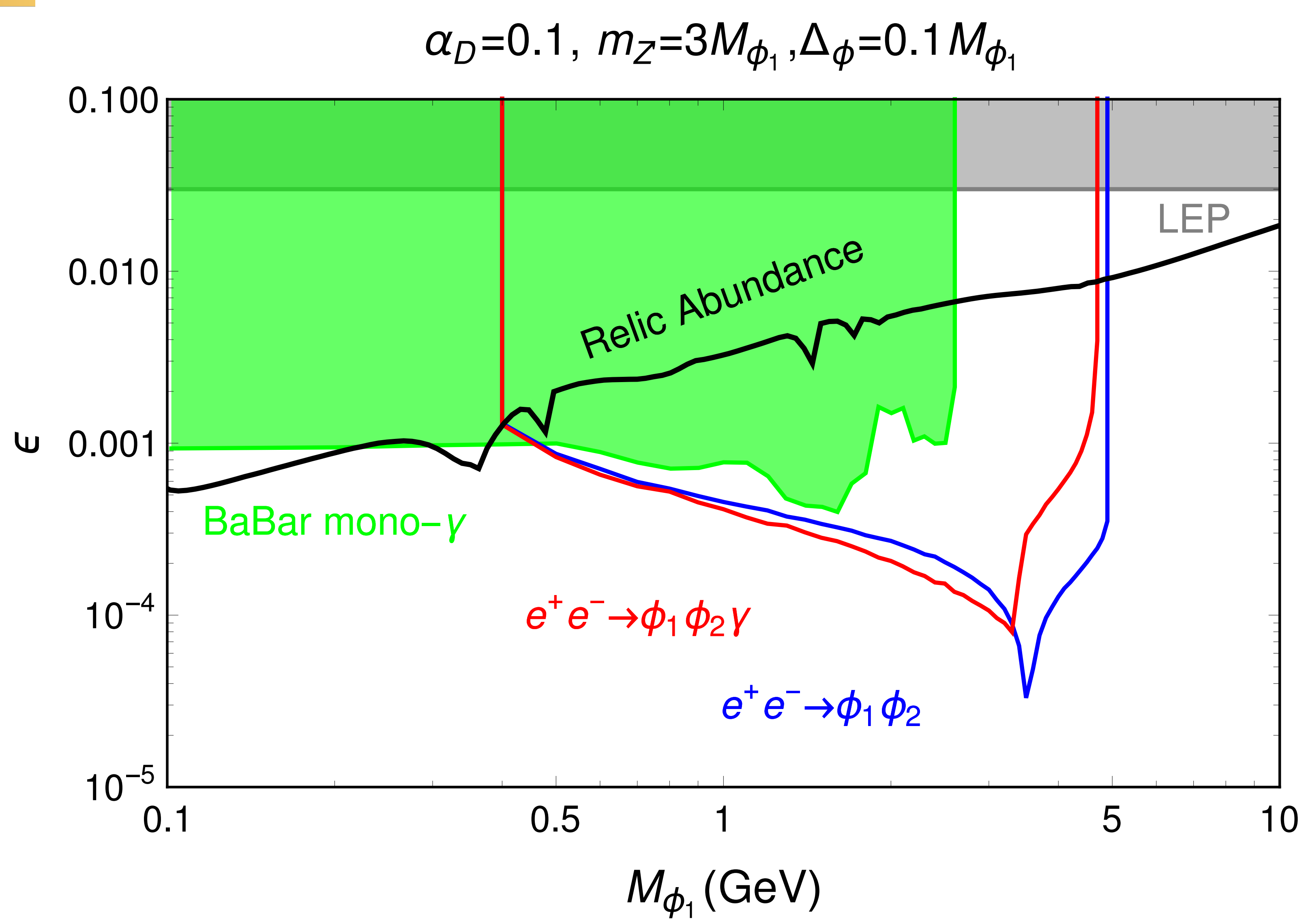
Type	BP	σ (fb)	Eff.(low R_{xy})	Eff.(high R_{xy})	N_{event}
scalar	BP1e	948.14	16.98	0%	1.61×10^5
	BP2e	58.39	0.15%	2.48%	1.54×10^3
	BP2μ	6.15	0.21%	3.33%	217.71
	BP3e	1.86	10.06%	0.70%	200.09
	BP3μ	0.61	11.25%	0.74%	73.14
	BP4e	2.23	1.56%	9.34%	243.26
	BP4μ	0.74	1.72%	10.78%	92.50
fermion	BP1e	3856.00	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

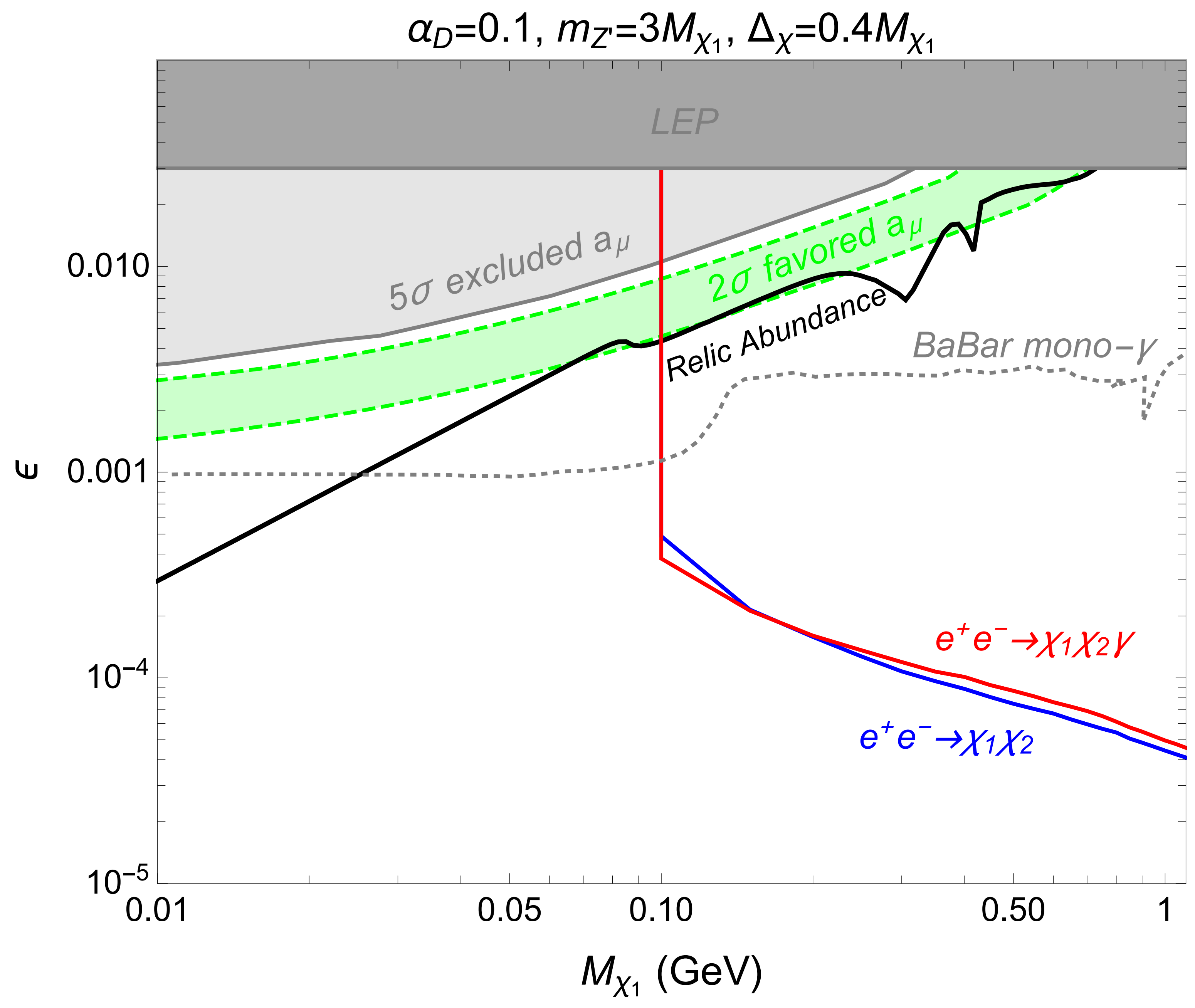
$$e^+e^- \to \phi_1\phi_2\gamma \to \phi_1\phi_1 e^+e^-\gamma$$
$$e^+e^- \to \chi_1\chi_2\gamma \to \chi_1\chi_1 e^+e^-\gamma$$

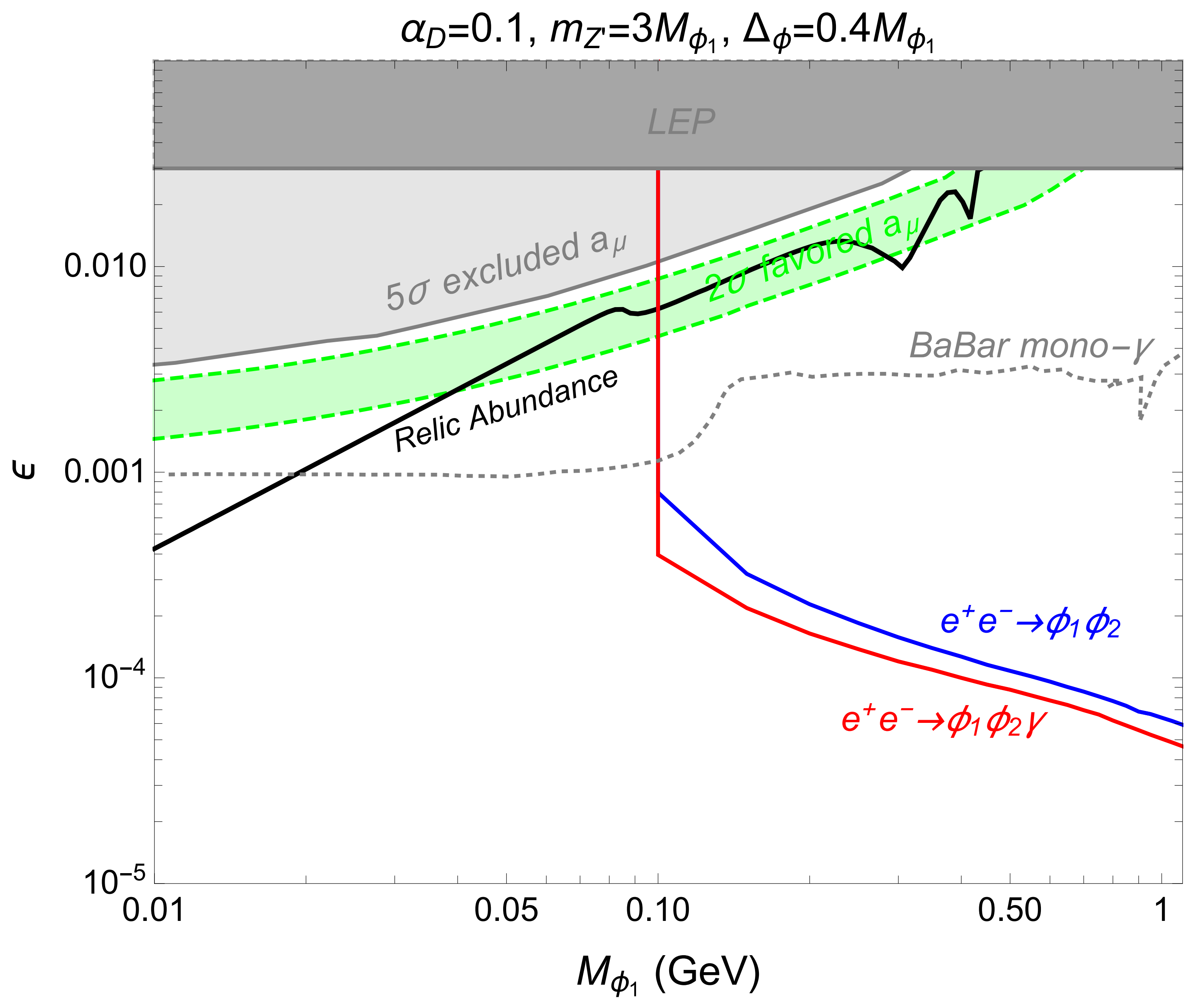
Type	BP	σ (fb)	Eff.(low R_{xy})	Eff.(high R_{xy})	N_{event}
scalar	BP1e	2472.70	6.70%	0%	1.66×10^5
	BP2e	159.85	0.16%	2.27%	3.88×10^3
	BP2μ	16.85	0.20%	2.87%	517.30
	BP3e	5.13	7.64%	0.02%	392.96
	BP3μ	1.69	8.83%	0.03%	149.73
	BP4e	7.14	1.86%	3.29%	367.71
	BP4μ	2.35	2.02%	2.87%	114.92
fermion	BP1e	2503.60	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

Future sensitivity

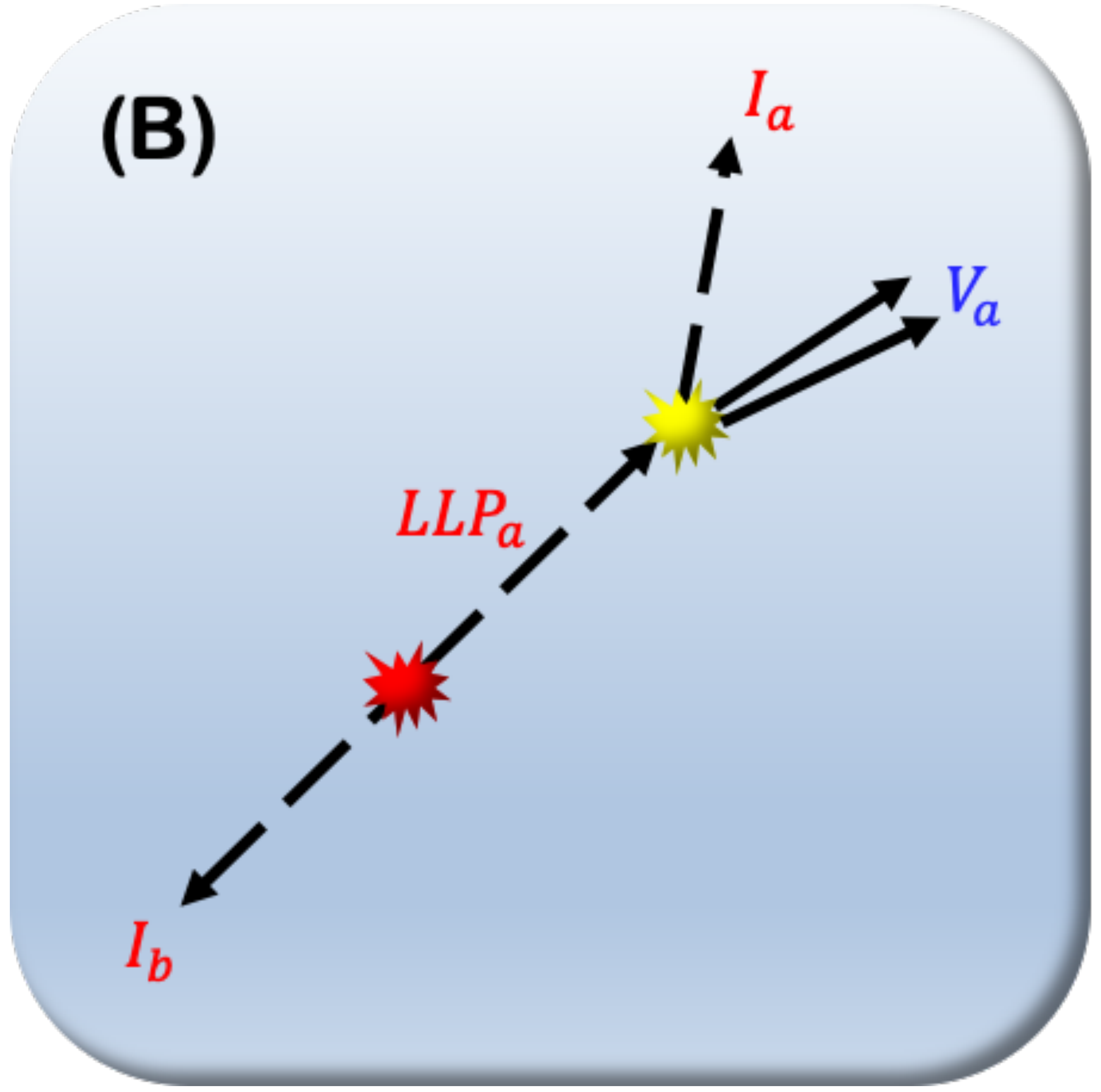








Reconstruct mass & mass gap



# of unknowns > # of knowns + # of constraints

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

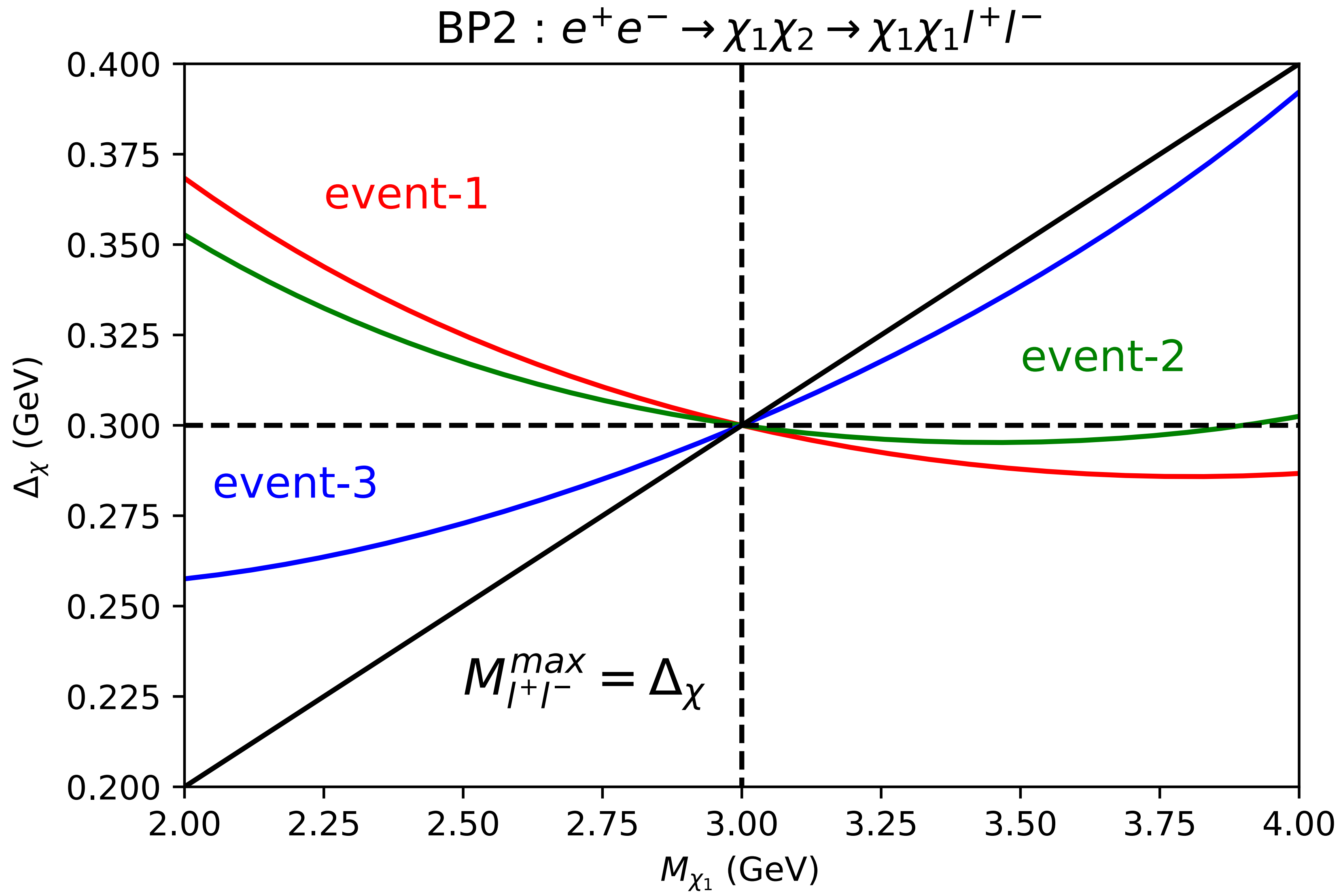
Therefore, we cannot get the unique solution

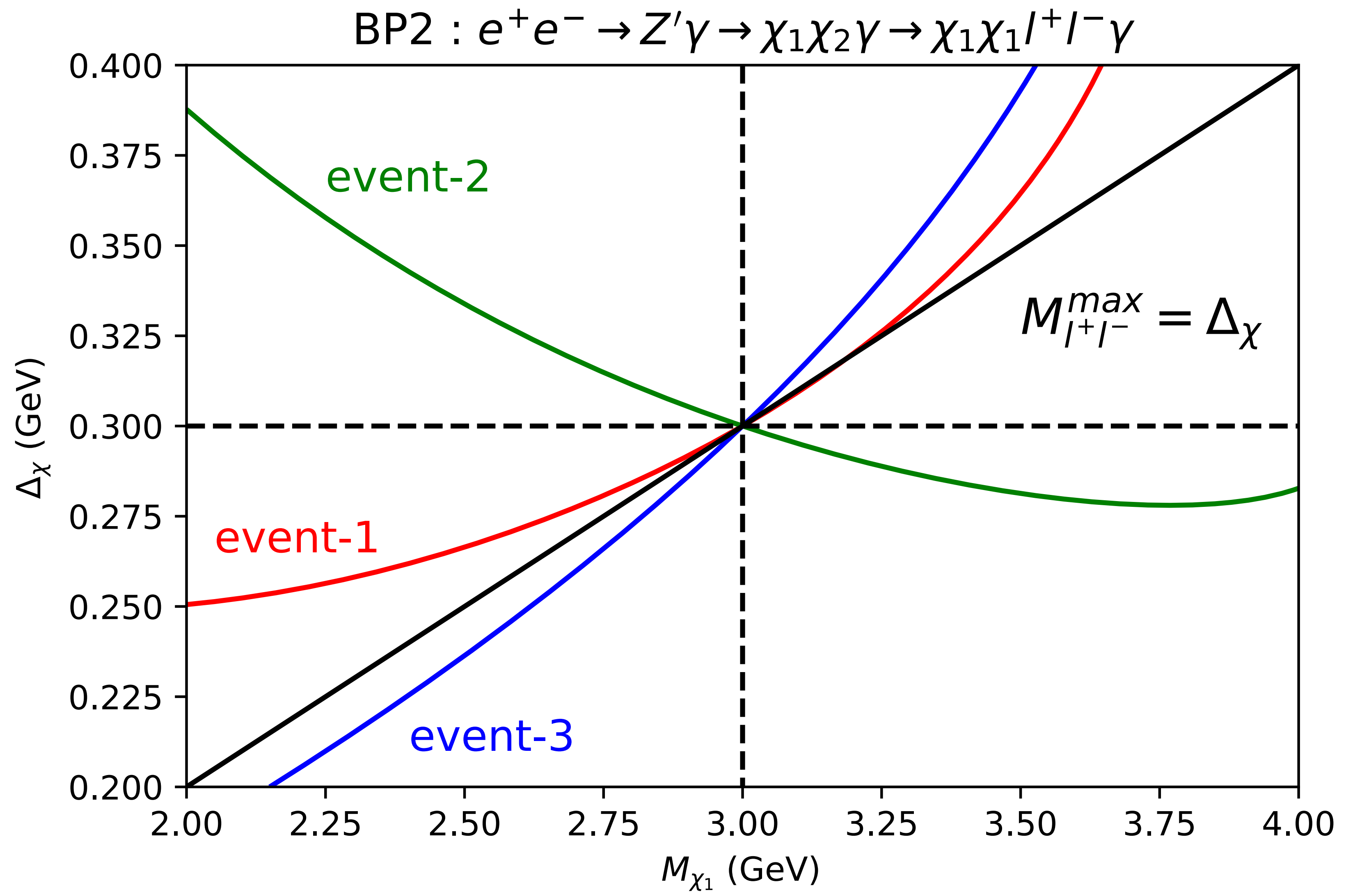
where, $\alpha = \dfrac{m_{\chi^2}^2 - m_{\chi^1}^2}{4E^2}$

4-momentum conservation

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

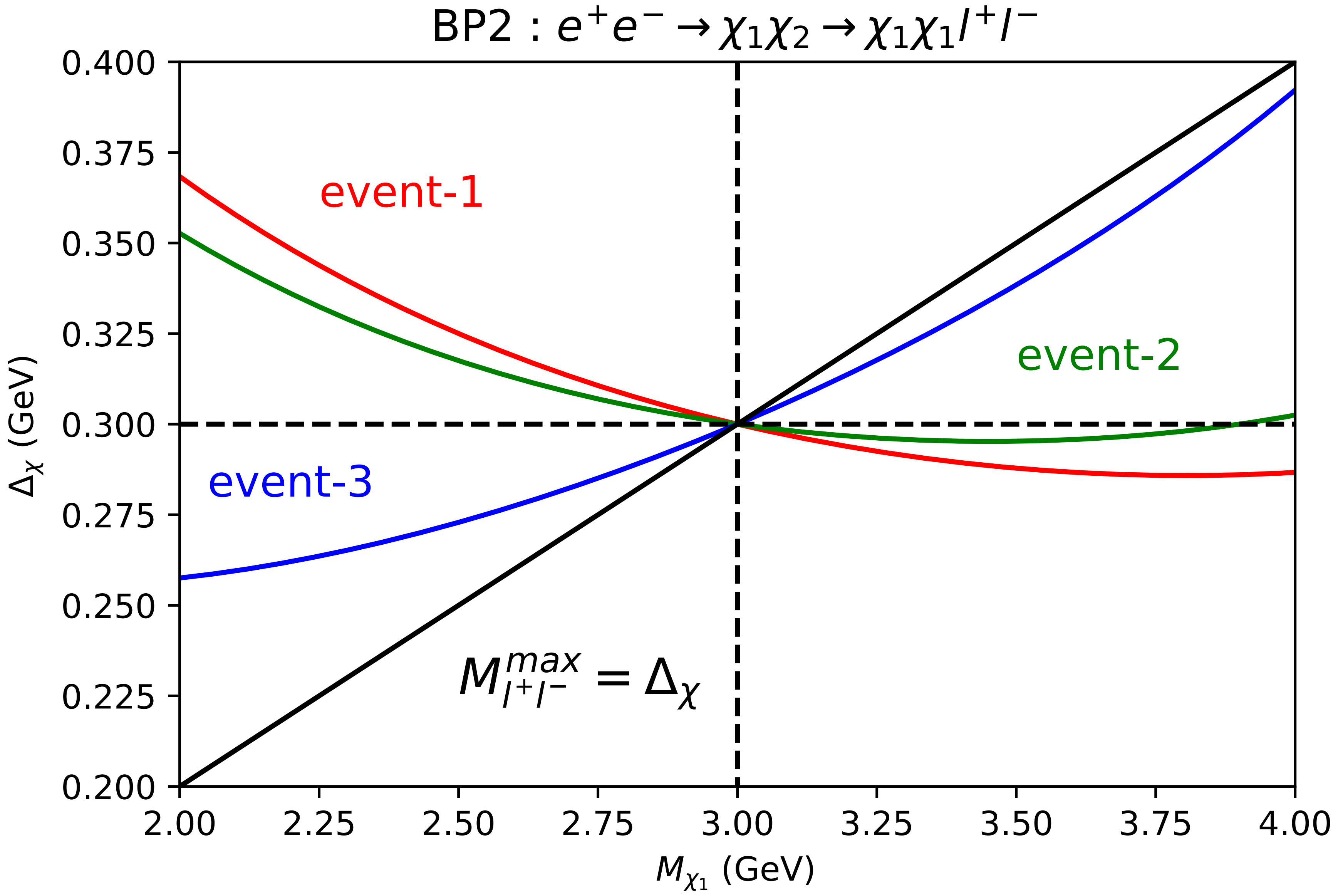
The crossing point from these events and kinematic endpoint measurement can help us





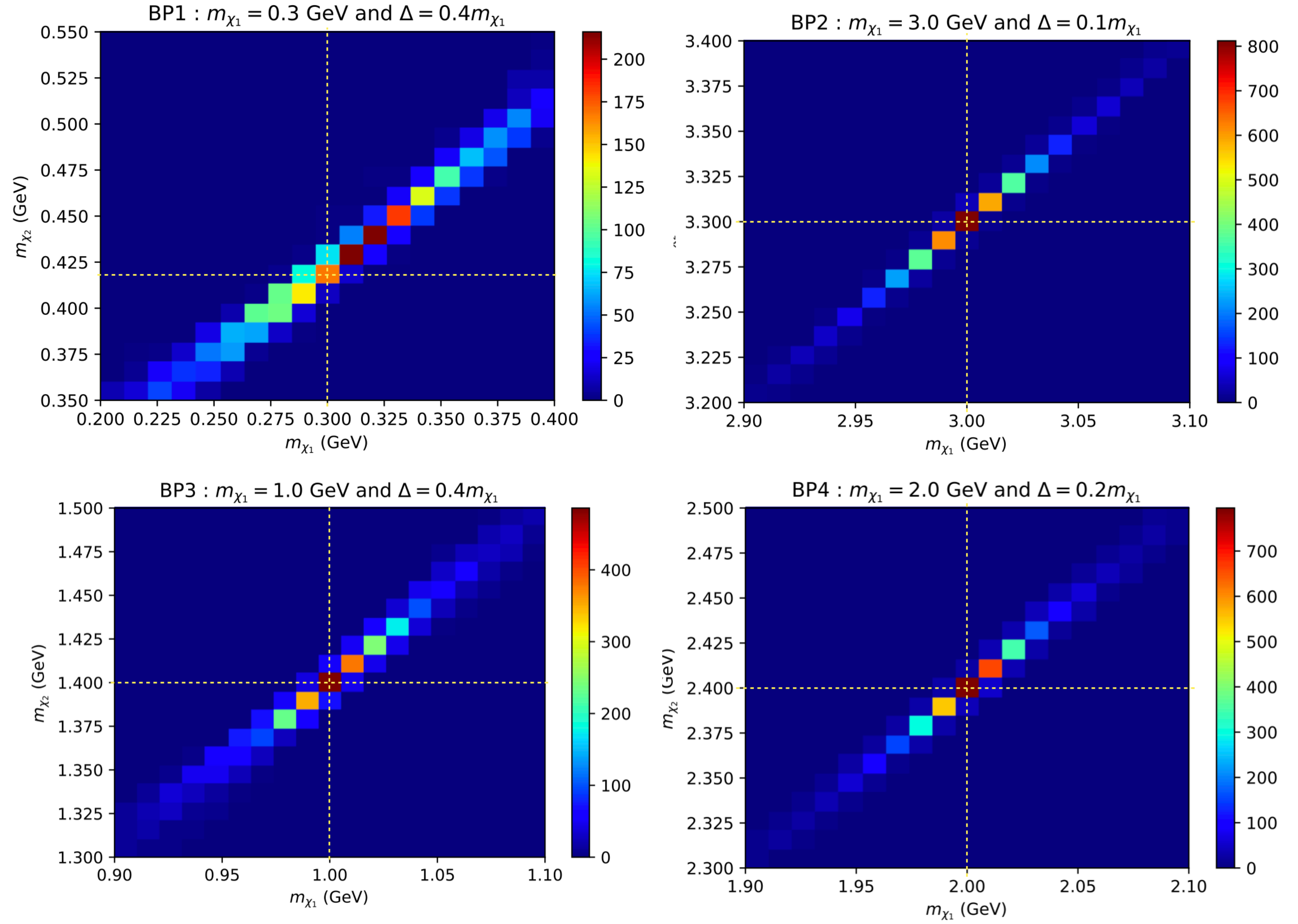
Reconstruct mass & mass gap

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



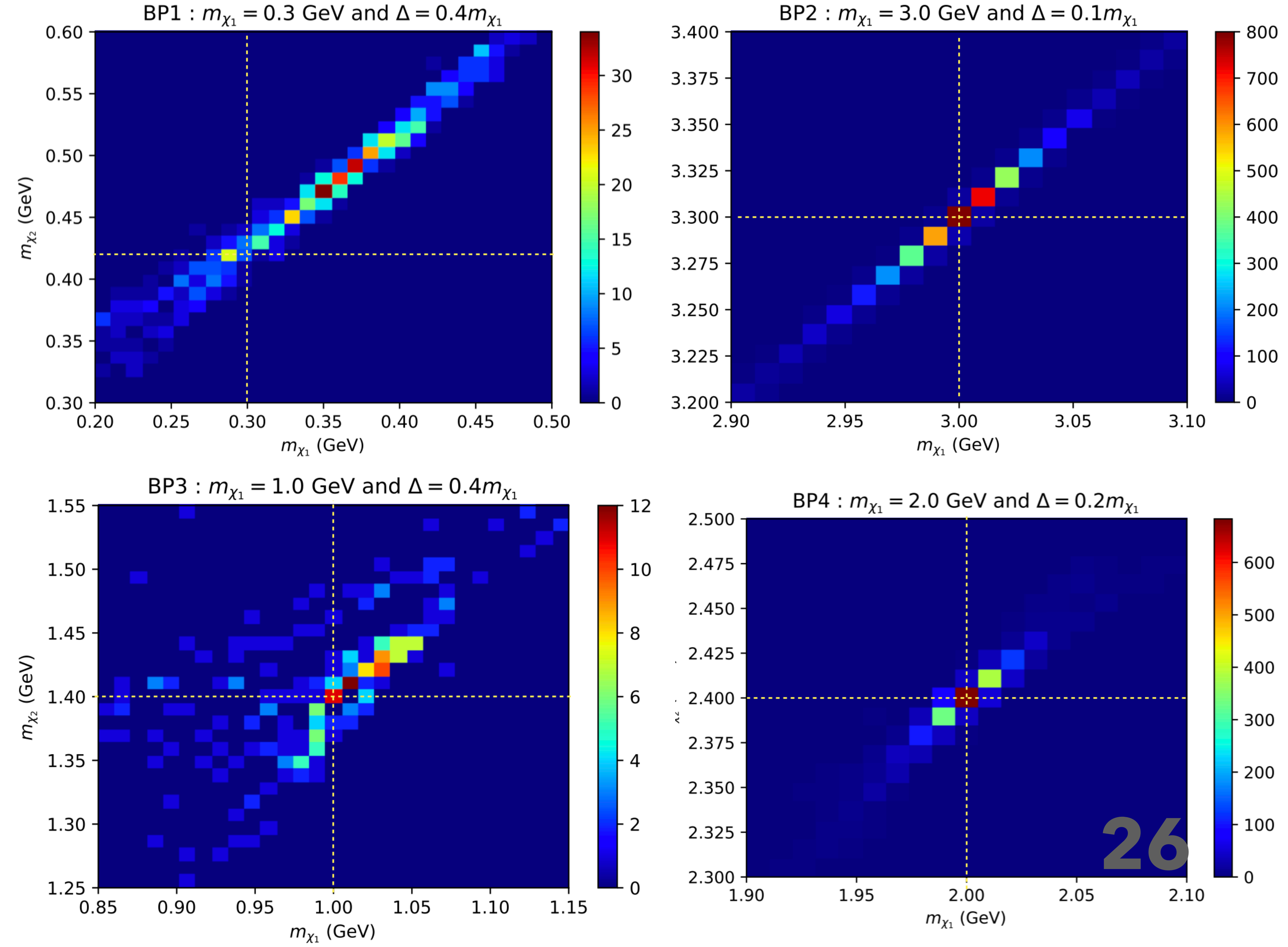
$$e^+e^- \to \chi_1\chi_2 \to \chi_1\chi_1\ell^+\ell^-$$

BP	N_{phys}	$(M_{\chi_2}, M_{\chi_1})^{\rm true}$ / $(M_{\chi_2}, M_{\chi_1})^{\rm peak}$	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)	



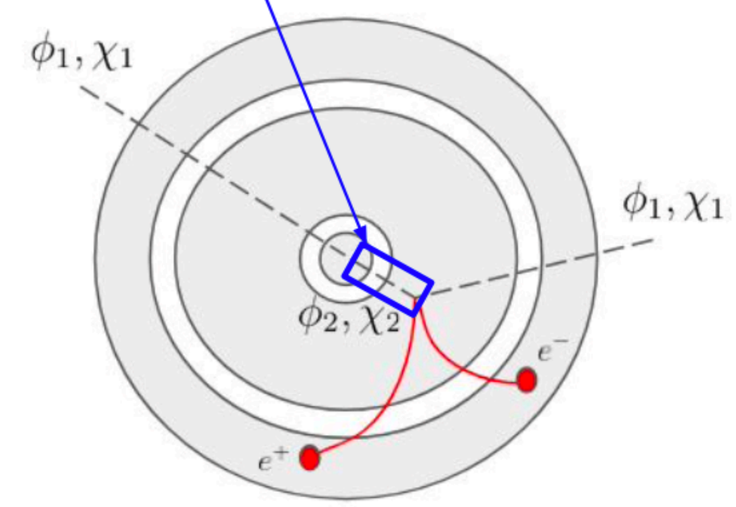
$$e^+e^- \to \chi_1\chi_2\gamma \to \chi_1\chi_1\ell^+\ell^-\gamma$$

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)	



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

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

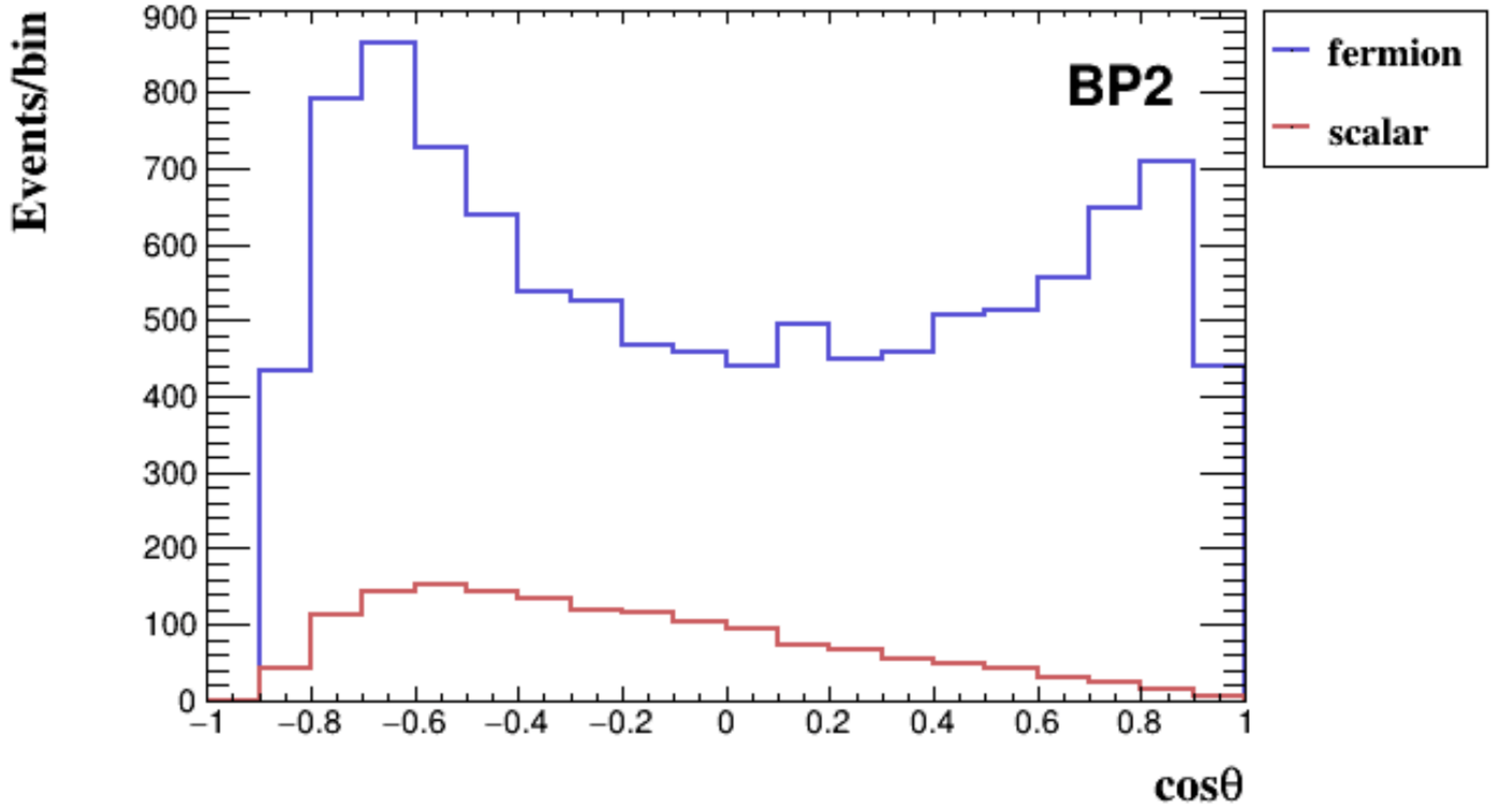
Fermion

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

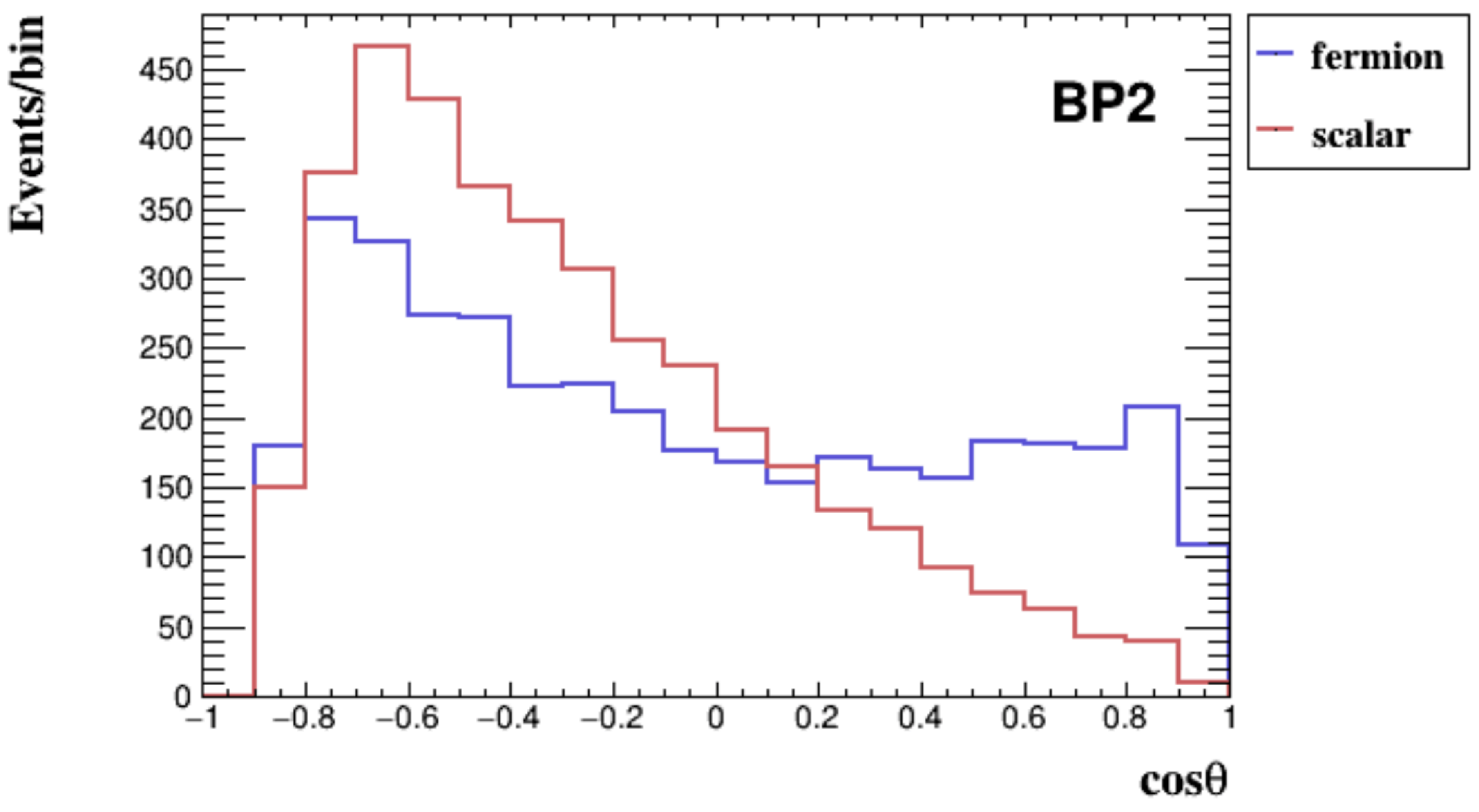
Massless limit → $\frac{3}{8}(1+\cos^2\theta)$

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

Angular distribution w/o ISR



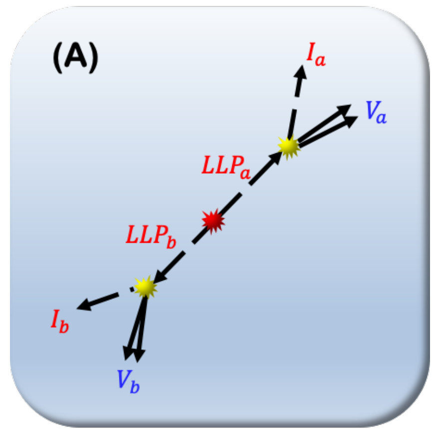
Angular distribution w/ ISR



Summary

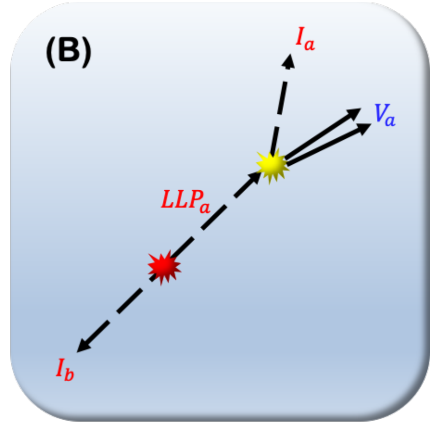
We discuss how to reconstruct the event with neutral LLP decays based on displaced vertex and missing energy which can provide the understanding for the underlying new physics.

Our methods are generally applicable to any model with similar decay topology which can cover wide class of lifetimes and masses at the colliders and beyonds.



Timing detector @ HL-LHC

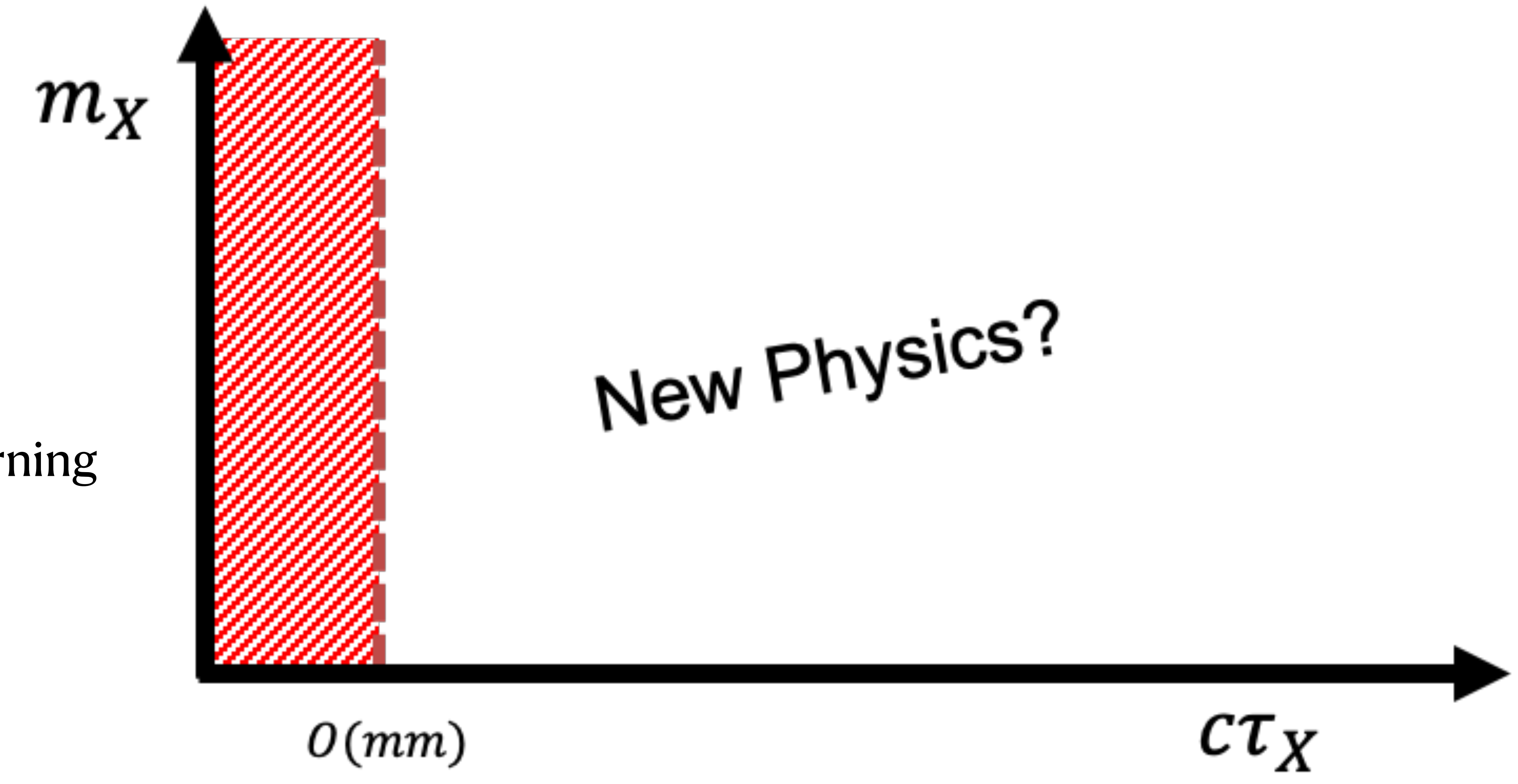
- HL-LHC is very good environment to search the LLPs in both intensity and high energy frontier.
- Using the timing information, we can fully reconstruct the events.
- The timing detectors will flash the hidden/dark sector and LLP searches.



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.

Outlooks



Background estimation

ABCD methods for LLP searches using machine learning

Simulation for Hidden Valleys / Dark Sectors

Dedicated detector simulation for LLP searches

Dedicatd Delphes Module for Neutral Long-lived Particle Decaying in the CMS Endocarp Muon Detector.

Recasting the LLP searches

CheckMATE2, MadAnalysis5, ...

Machine learning for LLP searches at the LHC and beyonds

Long-lived jet tagging using the CNN

non-pointing photon search using the CNN

Searched based on DGCNN

Unsupervised SUEP

New types of collider signatures

Tumblers

Thank You!