New particle searches @ Belle II

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Inelastic DM ~ XDM

Flavor Physics Mini-Workshop 2025
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Contents

- General Remarks on DM with massive dark photon
- Dark gauge models for inelastic DM models and phenomenology
- Inelastic DM searches @ Belle II
- ATOMKI 17 MeV Boson

Based On

- “Singlet portal extensions of the standard seesaw models to a dark sector with local dark symmetry,” with S. Baek, W.I.Park, arXiv:1303.4280, JHEP
- “Local Z2 scalar dark matter model confronting galactic center γ-ray excess,” with S. Baek, W.I. Park, arXiv:1407.6588 [hep-ph], PLB
- “Dark matter bound state formation in fermionic Z2 DM model with light dark photon and dark Higgs boson,” with Toshinori Matsui, Yi-Lei Tang, arXiv:1910.04311, JHEP
- “XENON 1T excess in local Z2 DM models with light dark sector,” with S. Baek, Jongkuk Kim, arXiv:2006.16876, PLB
- “Exploring properties of long-lived particles in inelastic DM models at Belle II,” with Dong Woo Kang, Chih-Ting Lu, arXiv:2101.02503, JHEP

Motivations for XDM

- In the usual real scalar DM with Z_2 symmetry, DM stability is not guaranteed in the presence of high dim op's induced by gravity effects

- Better to have local gauge symmetry for absolutely stable DM
  (Baek,Ko,Park,arXiv:1303.4280)

- XDM : phenomenologically interesting possibility, used for interpretation of DAMA, 511 keV γ-ray & PAMELA e^+ excesses, and XENON1T excess, muon (g-2), etc

- Usually the mass difference btw XDM & DM is put in by hand, by dim-2 for scalar and dim-3 for fermions DM cases, and dark photon is introduced

- However such theories are mathematically inconsistent and unitarity will be violated in some channels, when (X)DM couples to dark photon

Z2 real scalar DM

$$\mathcal{L} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_S^2 S^2 - \frac{\lambda_S}{4!}S^4 - \frac{\lambda_{SH}}{2}S^2 H^\dagger H.$$

- Simplest DM model with Z2 symmetry : $S \to -S$
- Global Z2 could be broken by gravity effects (higher dim operators)
- e.g. consider Z2 breaking dim-5 op : $\dfrac{1}{M_{\rm Planck}} S O^{(4)}_{\rm SM}$
- Lifetime of EW scale mass “S” is too short to be a DM
- Similarly for singlet fermion DM

Local dark gauge symmetry

- Better to use local gauge symmetry for DM stability (Baek,Ko,Park,arXiv:1303.4280)

- Success of the Standard Model of Particle Physics lies in “local gauge symmetry” without imposing any internal global symmetries
- Electron stability : U(1)em gauge invariance, electric charge conservation, massless photon
- Proton longevity : baryon # is an accidental sym of the SM
- No gauge singlets in the SM ; all the SM fermions chiral

- Dark sector with (excited) dark matter, dark radiation and force mediators might have the same structure as the SM
- “Chiral dark gauge theories without any global sym”
- Origin of DM stability/longevity from dark gauge sym, and not from dark global symmetries, as in the SM
- Just like the SM (conservative)

In QFT

- DM could be absolutely stable due to unbroken local gauge symmetry (DM with local Z_2, Z_3 etc.) or topology (hidden sector monopole + vector DM + dark radiation)
- Longevity of DM could be due to some accidental symmetries (hidden sector pions and baryons)
- Or DM is long lived for kinematic reaons, namely very light (axion, ν_s , etc)

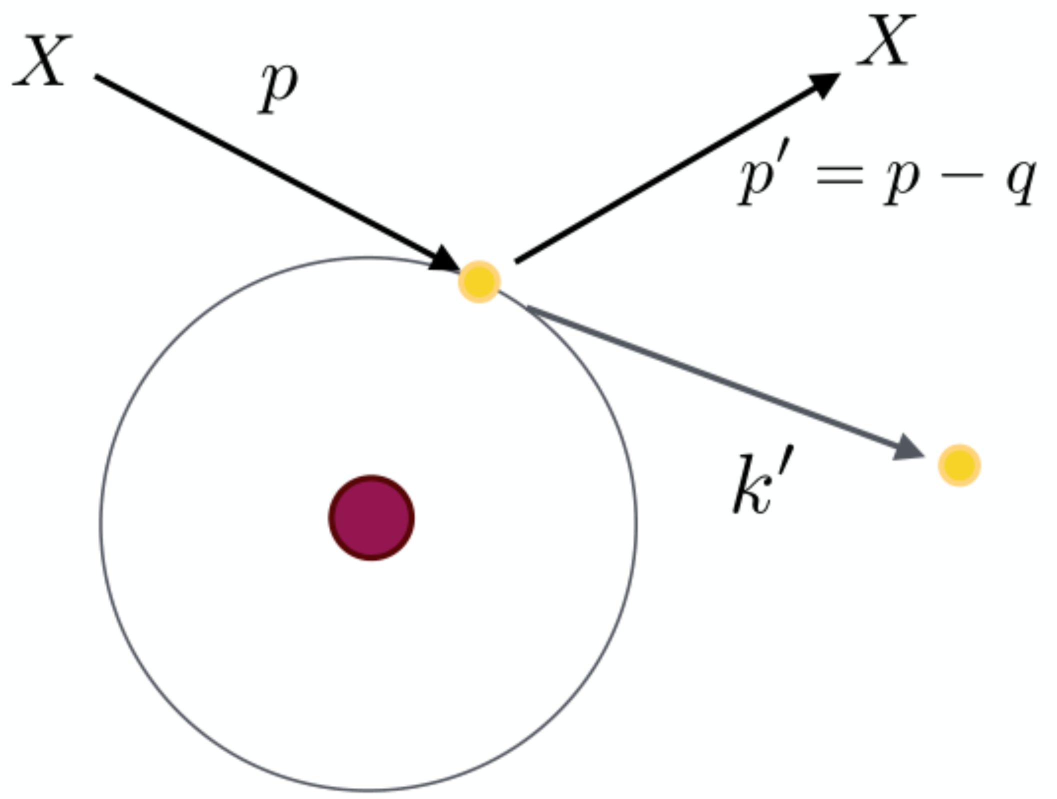
XENON1T Excess
In inelastic DM models

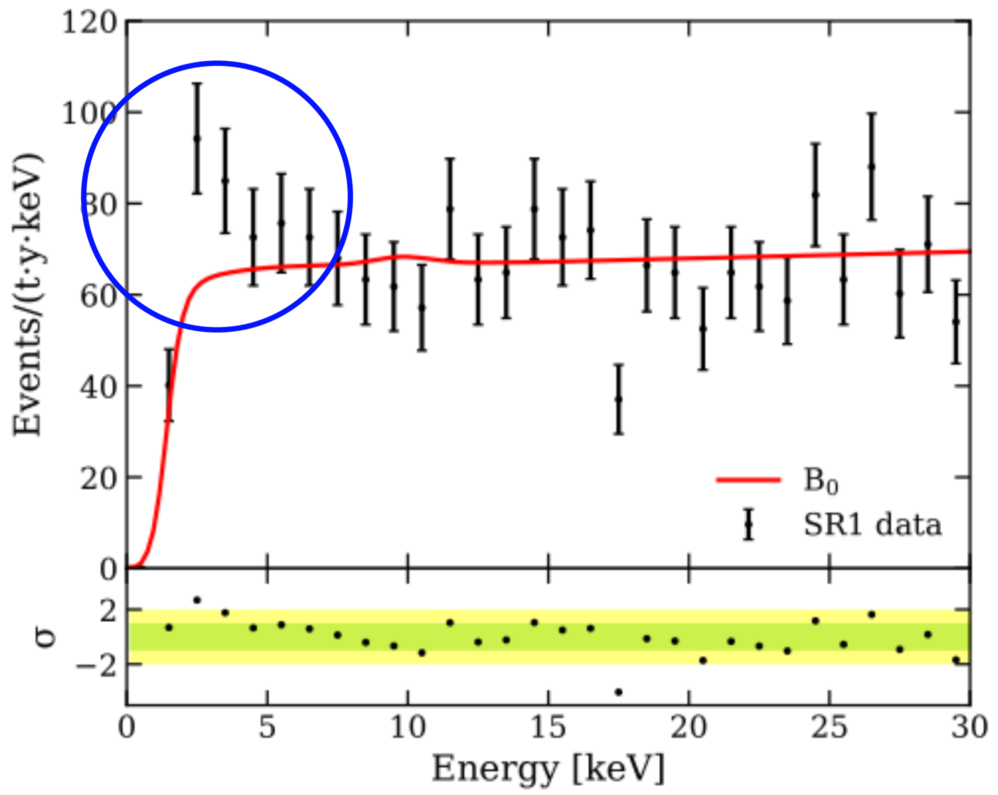
(Talk by Jongkuk Kim)

XENON1T Excess

- Excess between 1-7 keV
  - Expectated : 232 ± 15 , Observed : 285
  - Deviation ~ 3.5 σ
- Tritium contamination
  - Long half lifetime (12.3 years)
  - Abundant in atmosphere and cosmogenically produced in Xenon
- Solar axion
  - Produced in the Sun
  - Favored over bkgd @ 3.5 σ
- Neutrino magnetic dipole moment
  - Favored @ 3.2 σ

Electron recoil

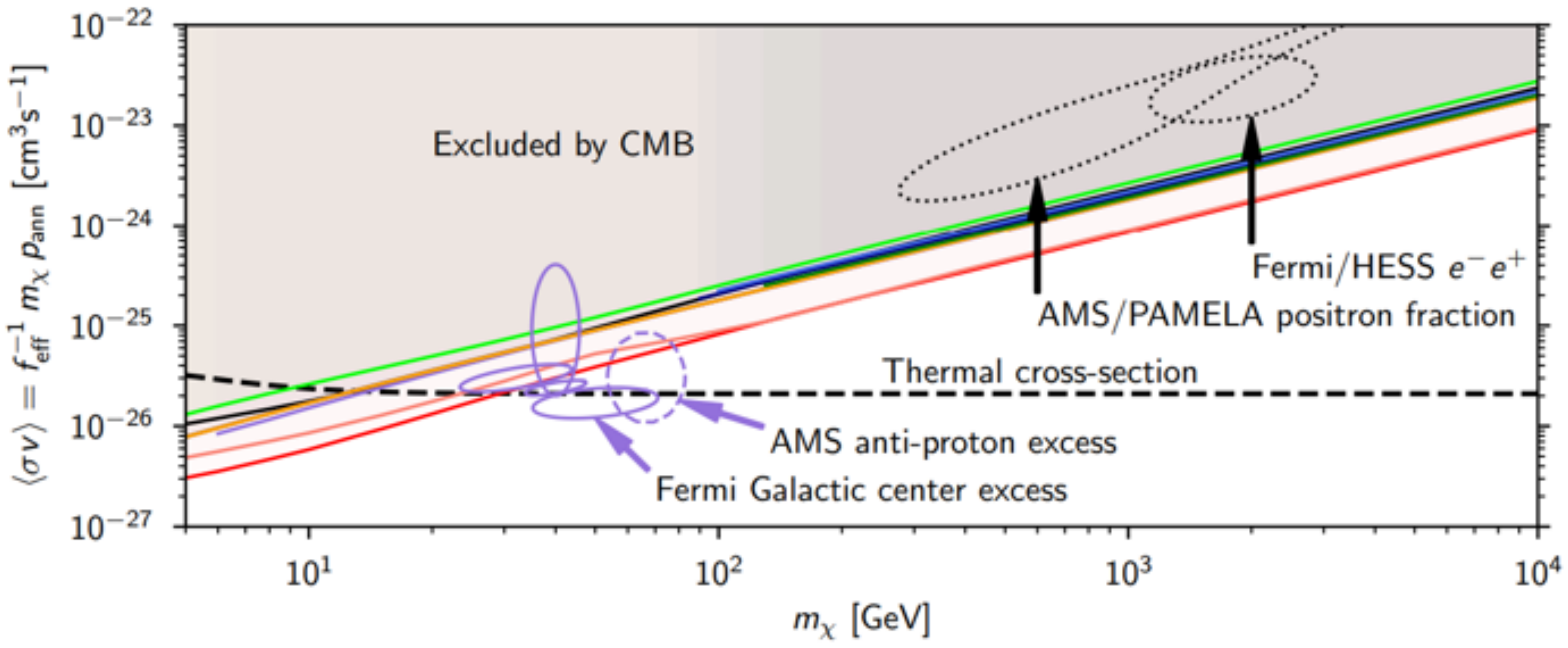




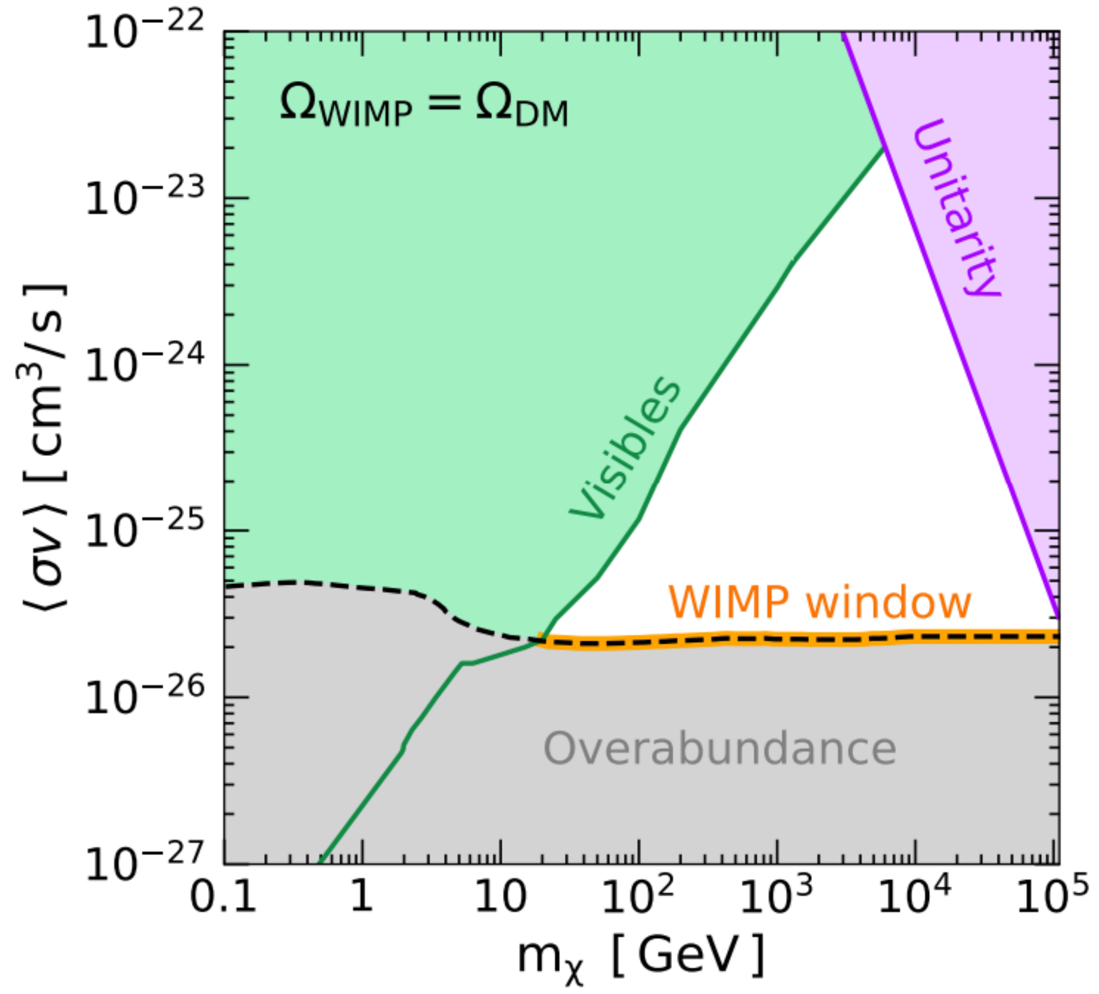
DD/CMB Constraints

- To evade stringent bounds from direct detection expt’s : sub GeV DM
- CMB bound excludes thermal DM freeze-out determined by S-wave annihilation : DM annihiliation should be mainly in P-wave

$$\boxed{\langle \sigma v \rangle \sim \cancel{a} + b v^2}$$



Planck 2018
R.K.Leane 35 al, PRD2018



Exothermic DM

- Inelastic exothermic scattering of XDM
- $XDM + e_{\text{atomic}} \to DM + e_{\text{free}}$ by dark photon exchange + kinetic mixing
- Excess is determined by $E_R \sim \delta = m_{XDM} - m_{DM}$
- Most works about XENON1T excess are based on effective/toy models where δ is put in by hand [Kannike et al; Harigaya et al; HM Lee; Bramante et al, etc.]
- dim-2 op for scalar DM and dim-3 op for fermion DM : soft and explicit breaking of local gauge symmetry), and include massive dark photon as well → theoretically inconsistent !

Z2 DM models with dark Higgs

- We solve this inconsistency and unitarity issue with Krauss-Wilczek mechanism

- By introducing a dark Higgs, we have many advantages:

  - Dark photon gets massive

  - Mass gap δ is generated by dark Higgs mechanism

  - We can have DM pair annihilation in P-wave, unlike in other works

Usual Approaches

For example, Harigaya, Nagai, Suzuki, arXiv:2006.11938

$$V(\phi) = m^2|\phi|^2 + \boxed{\Delta^2\left(\phi^2 + \phi^{*2}\right)}, \qquad (1)$$

This term is problematic

$$\mathcal{L} = g_D A'^{\mu}\left(\chi_1 \partial_\mu \chi_2 - \chi_2 \partial_\mu \chi_1\right) + \epsilon e A'_\mu J^\mu_{\mathrm{EM}},$$

Similarly for the fermion DM case

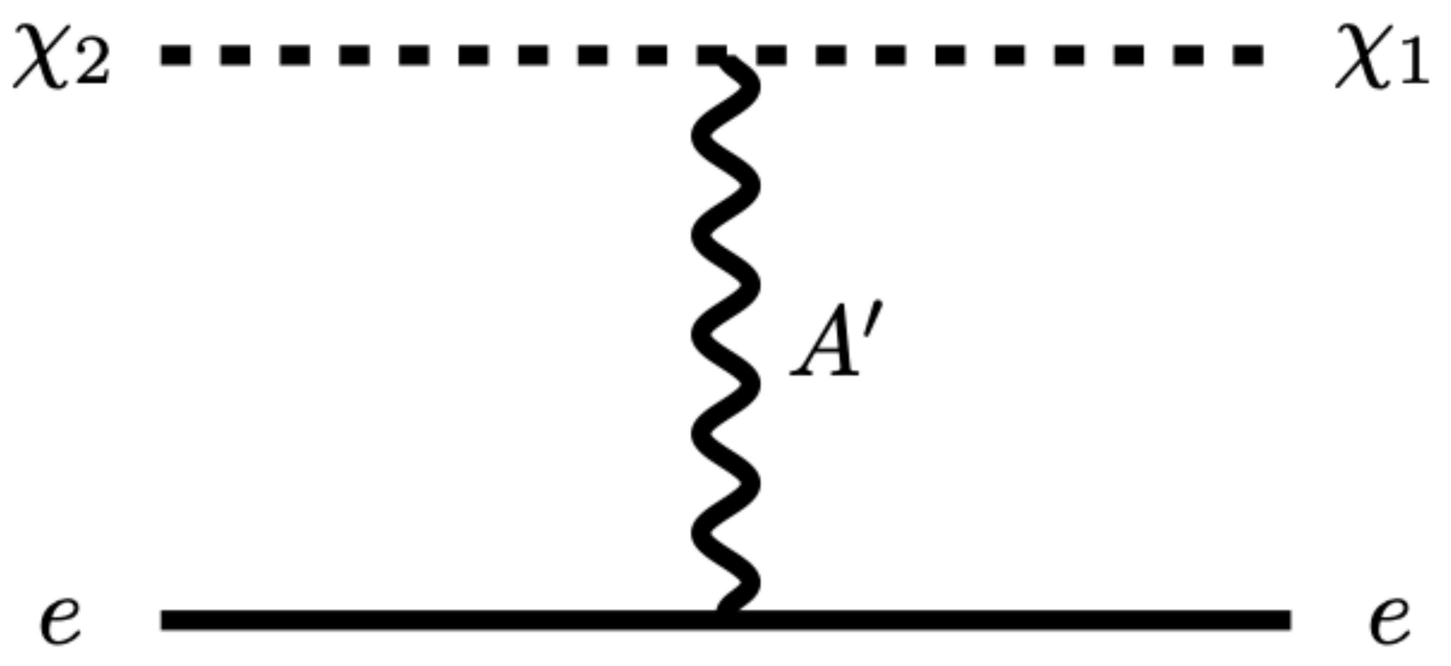


FIG. 1. Inelastic scattering of the heavier DM particle χ_2 off the electron e into the lighter particle χ_1, mediated by the dark photon A'.

- The model is not mathematically consistent, since there is no conserved current a dark photon can couple to in the massless limit
- The second term with Δ^2 breaks $U(1)_X$ explicitly, although softly

Relic Density from $XX^{\dagger} \to Z^{'\,*} \to f\bar{f}$
(P-wave annihilation)

For example, Harigaya, Nagai, Suzuki, arXiv:2006.11938

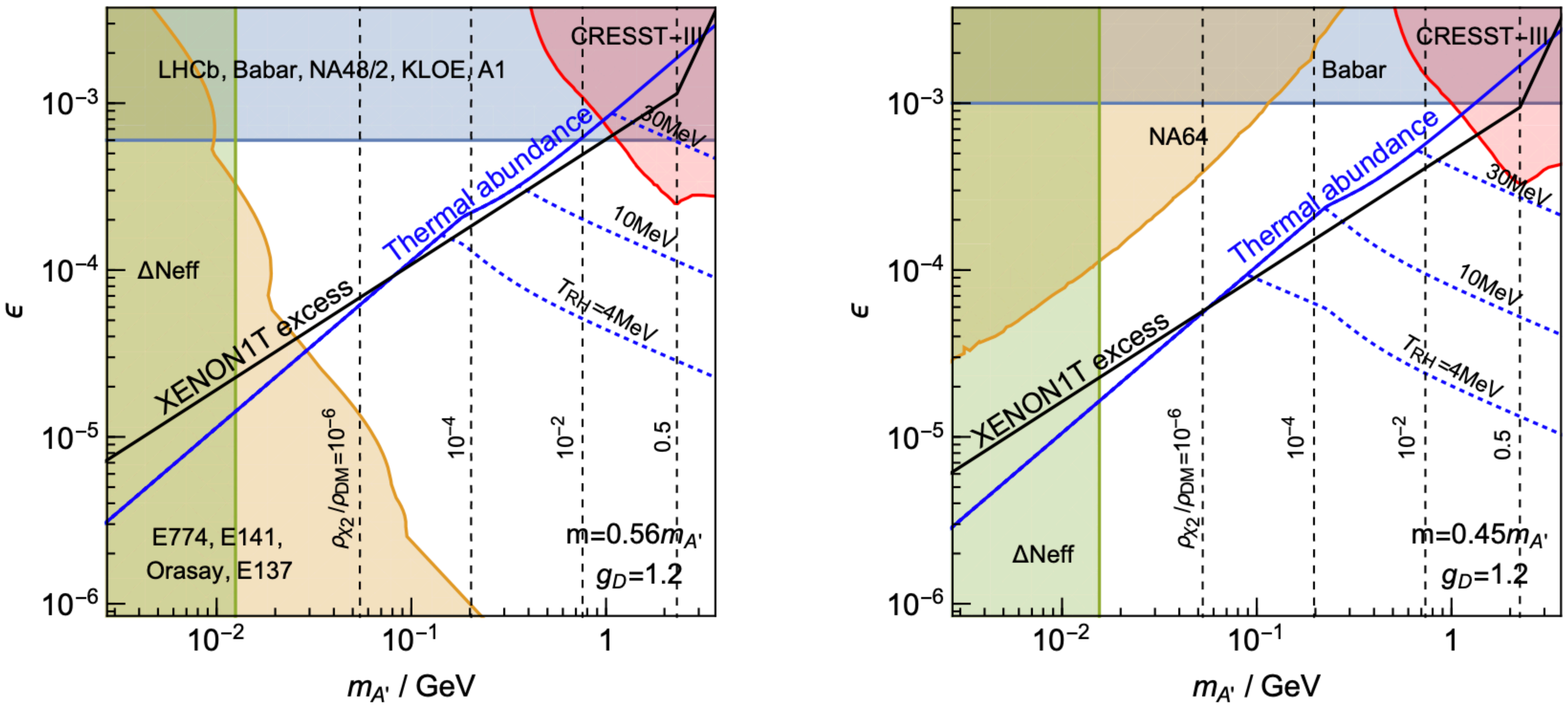
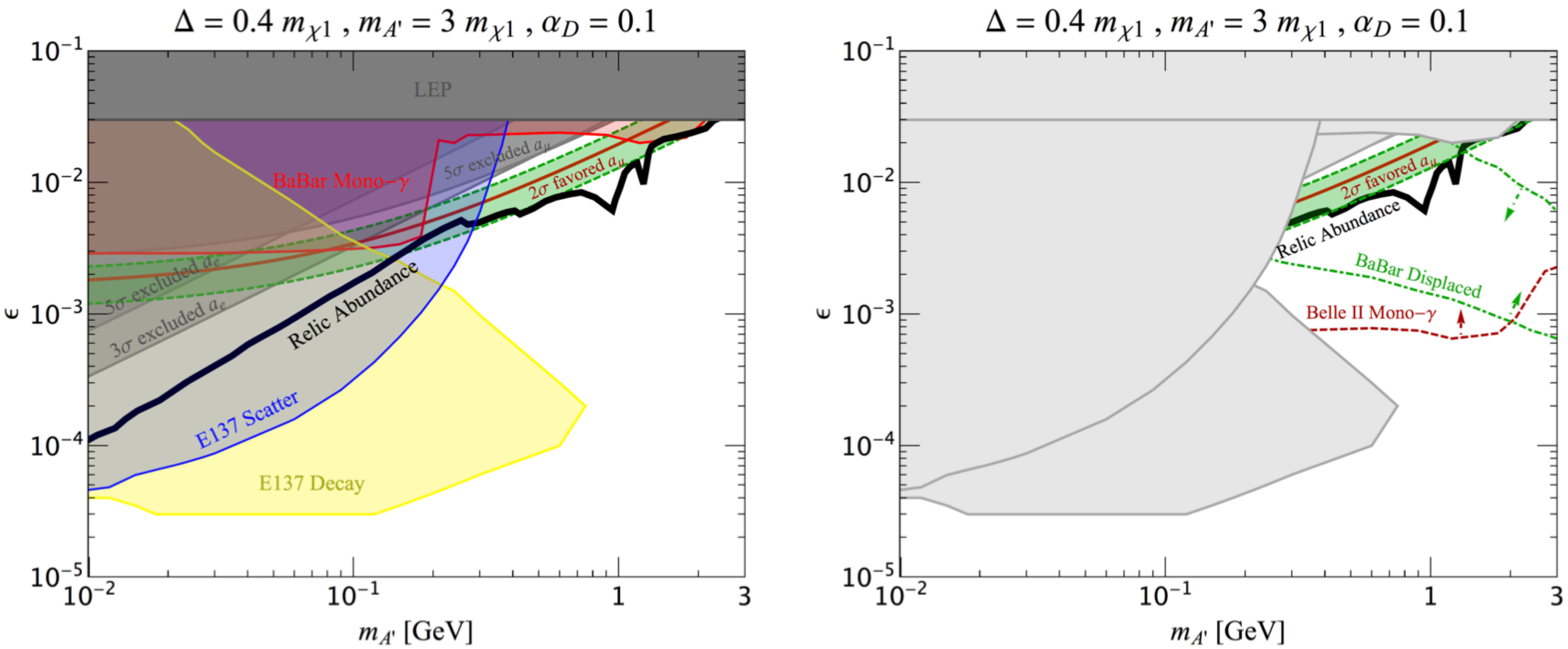


FIG. 4. The required value of ϵ to explain the observed excess of events at XENON1T in terms of the dark photon mass $m_{A'}$ (black solid lines). The left and right panels correspond to the cases of $m > m_{A'}/2$ and $m < m_{A'}/2$ respectively. We assume $g_D = 1.2$ in both cases. The blue lines denote the required value of ϵ to obtain the observed DM abundance by the thermal freeze-out process, discussed in Sec. IV. The solid lines correspond to the case without any entropy production. The dashed lines assume freeze-out during a matter dominated era and the subsequent reheating at $T_{\rm RH}$, which suppresses the DM abundance by a factor of $(T_{\rm RH}/T_{\rm FO})^3$. The black dashed lines denote the mass density of χ_2 normalized by the total DM density. The shaded regions show the constraints from dark radiation and various searches for the dark photon A' which are discussed in Sec. V.

Muon g-2, Dark photon, XDM

Mohlabeng, arXiv:1902.05075


$\Delta = 0.4\, m_{\chi 1}$, $m_{A'} = 3\, m_{\chi 1}$, $\alpha_D = 0.1$

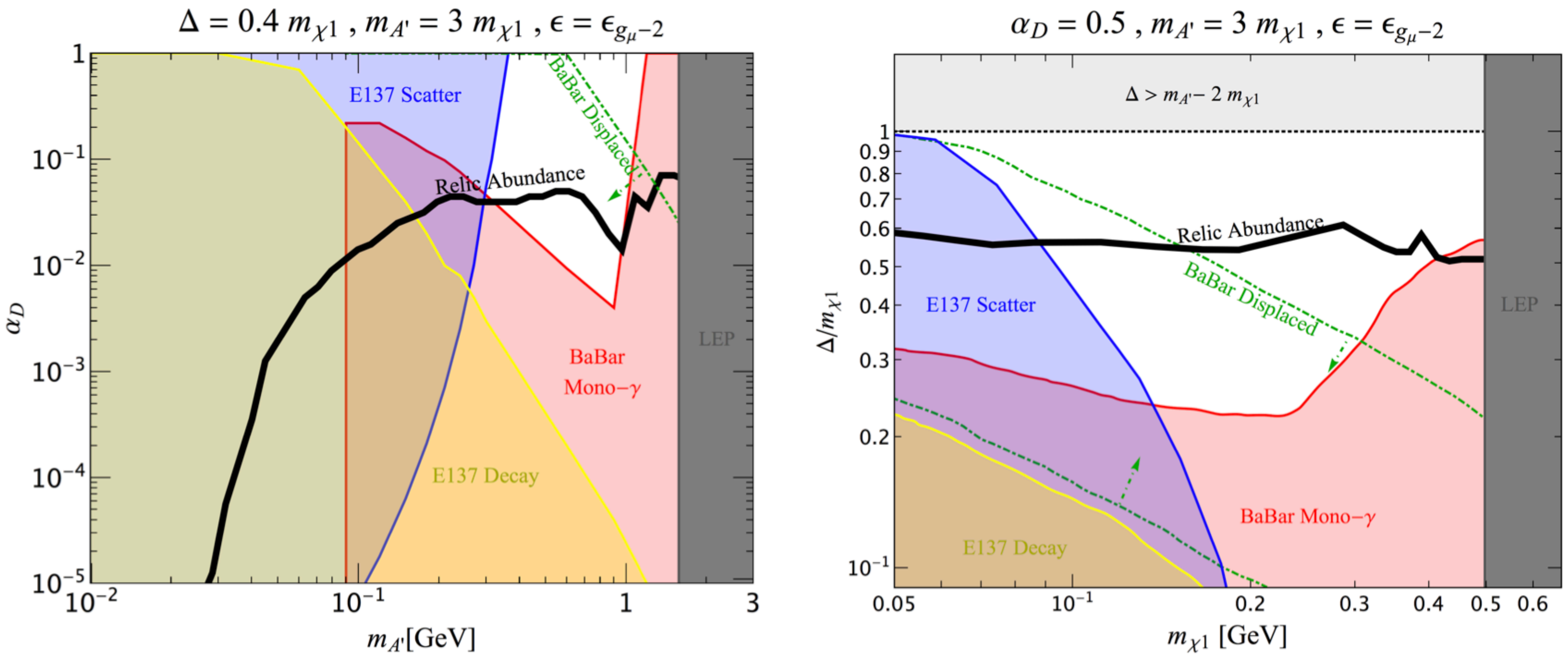
$\Delta = 0.4\, m_{\chi 1}$, $m_{A'} = 3\, m_{\chi 1}$, $\alpha_D = 0.1$

FIG. 2: Current limits on the dark photon semi-visible decay parameter space with benchmark parameters $\Delta = 0.4\ m_{\chi 1}$, $m_{A'} = 3\ m_{\chi_1}$ and $\alpha_D = 0.1$. On the left panel we place constraints on the ϵ vs $m_{A'}$ parameter space. On the right panel we include projections for a `BELLE II` monophoton search as well as a `BABAR` displaced track re-analysis. We also color the various experimental constraints in grey for clarity and to bring attention to our region of parameter space. See text for details on the various bounds and projections.

Relic abundance calculations will change if we include dark Higgs

Muon g-2, Dark photon, XDM

Mohlabeng, arXiv:1902.05075


$\Delta = 0.4\ m_{\chi 1}\ ,\ m_{A'} = 3\ m_{\chi 1}\ ,\ \epsilon = \epsilon_{g_\mu - 2}$

$\alpha_D = 0.5\ ,\ m_{A'} = 3\ m_{\chi 1}\ ,\ \epsilon = \epsilon_{g_\mu - 2}$

FIG. 3: Parameter space compatible with a dark photon decaying into thermal inelastic DM as an explanation for the Muon g-2 anomaly. On the left panel we plot α_D vs $m_{A'}$ for a 40% mass splitting and $m_{A'} = 3\ m_{\chi_1}$. On the right panel we plot the ratio of mass splitting to m_{χ_1} as a function of m_{χ_1} for benchmark parameters $\alpha_D = 0.5$ and $m_{A'} = 3\ m_{\chi_1}$. See text for details.

What if we don’t have dark Higgs ?

P.Ko, T.Matsui, Yi-Lei Tang, arXiv:1910.04311, Appendix A

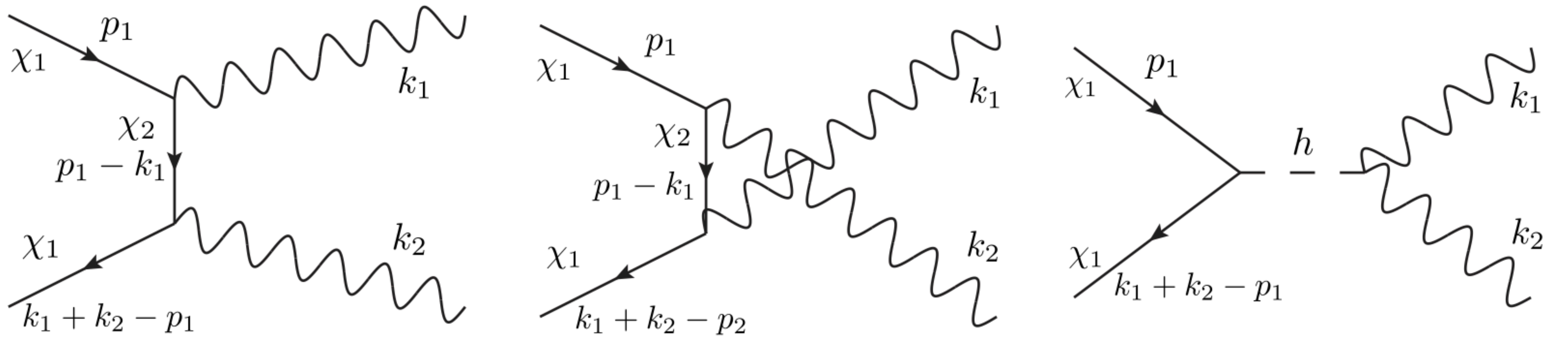


Figure 9: $\chi_1\chi_1 \to \gamma'\gamma'$ diagrams. Compared with the Higgsless soft-breaking model, the third diagram arises in our model

- Only the first two diagrams if the mass gap is given by hand
- The third diagram if the mass gap is generated by dark Higgs mechanism
- Without the last diagram, the amplitude violates unitarity at large $E_{\gamma'}$
- Also true in amplitude methods, independent of Lagrangian models (work in progress)

Inelastic DM models with dark gauge symmetry

Scalar XDM (X_R & X_I)

Field	ϕ	X	χ
U(1) charge	2	1	1

$$\begin{aligned}\mathcal{L} \;=\; & \mathcal{L}_{\rm SM} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon\hat{X}_{\mu\nu}\hat{B}^{\mu\nu} + D^{\mu}\phi^{\dagger}D_{\mu}\phi + D^{\mu}X^{\dagger}D_{\mu}X - m_X^2X^{\dagger}X + m_{\phi}^2\phi^{\dagger}\phi \\ & -\lambda_{\phi}\left(\phi^{\dagger}\phi\right)^2 - \lambda_X\left(X^{\dagger}X\right)^2 - \lambda_{\phi X}X^{\dagger}X\phi^{\dagger}\phi - \lambda_{\phi H}\phi^{\dagger}\phi H^{\dagger}H - \lambda_{HX}X^{\dagger}XH^{\dagger}H \\ & -\mu\left(X^2\phi^{\dagger} + H.c.\right), \qquad (1)\end{aligned}$$

$$X = \frac{1}{\sqrt{2}}(X_R + iX_I),$$

$$H = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v_H + h_H) \end{pmatrix}, \quad \phi = \frac{1}{\sqrt{2}}(v_{\phi} + h_{\phi}),$$

$$\mathcal{L} \supset \epsilon g_X s_W Z^{\mu}(X_R\partial_{\mu}X_I - X_I\partial_{\mu}X_R) - \frac{g_Z}{2}Z_{\mu}\overline{\nu}_L\gamma^{\mu}\nu_L$$

$$\mathcal{L} \supset g_X Z'^{\mu}(X_R\partial_{\mu}X_I - X_I\partial_{\mu}X_R) - \epsilon\, e c_W Z'_{\mu}\overline{e}\gamma^{\mu}e,$$

$$U(1) \to Z_2 \text{ by } v_{\phi} \neq 0 : X \to -X$$

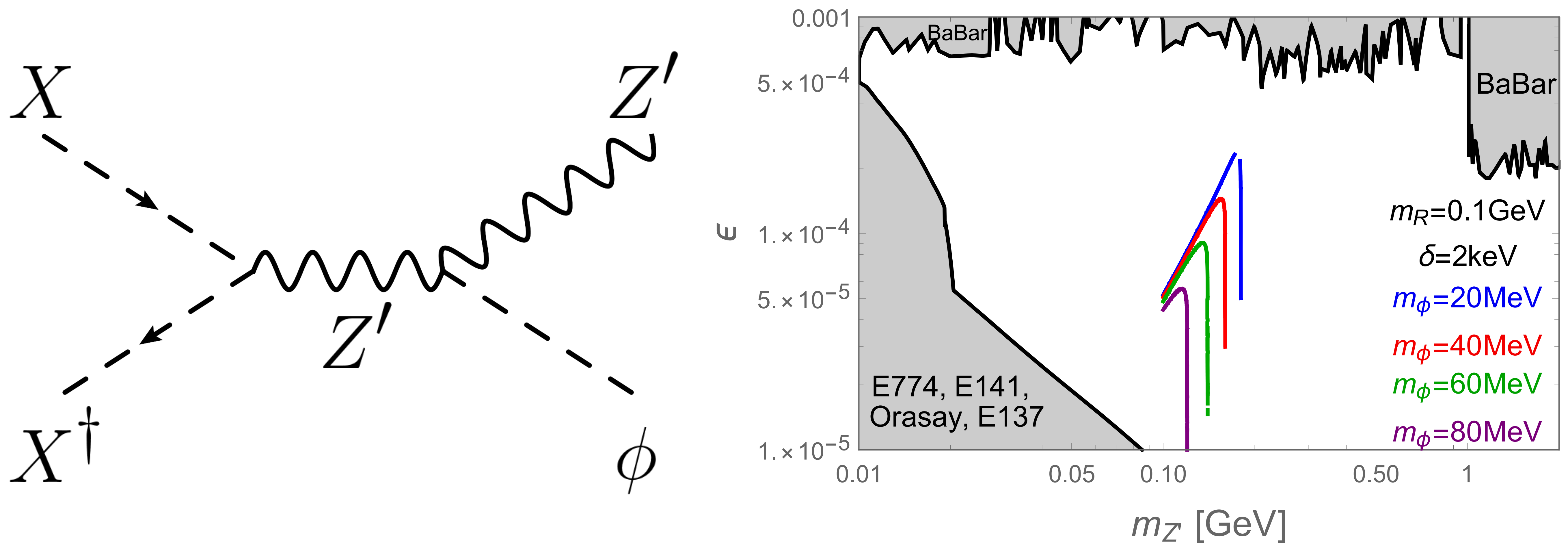


FIG. 1: (*left*) Feynman diagrams relevant for thermal relic density of DM: $XX^\dagger \to Z'\phi$ and (*right*) the region in the $(m_{Z'}, \epsilon)$ plane that is allowed for the XENON1T electron recoil excess and the correct thermal relic density for scalar DM case for $\delta = 2$ keV : (a) $m_{\rm DM} = 0.1$ GeV. Different colors represents $m_\phi = 20, 40, 60, 80$ MeV. The gray areas are excluded by various experiments, from BaBar [61], E774 [62], E141 [63], Orasay [64], and E137 [65], assuming $Z' \to X_R X_I$ is kinematically forbidden.

P-wave annihilation cross sections

Scalar DM : $XX^\dagger \to Z'^* \to Z'\phi$

$$\sigma v \simeq \frac{g_X^4 v^2}{384\pi\, m_X^4 (4m_X^2 - m_{Z'}^2)^2}\left(16m_X^4 + m_{Z'}^4 + m_\phi^4 + 40m_X^2 m_{Z'}^2 - 8m_X^2 m_\phi^2 - 2m_{Z'}^2 m_\phi^2\right)$$
$$\times \left[\left\{4m_X^2 - (m_{Z'} + m_\phi)^2\right\}\left\{4m_X^2 - (m_{Z'} - m_\phi)^2\right\}\right]^{1/2} + \mathcal{O}(v^4), \tag{10}$$

Fermion XDM (χ_R & χ_I)

$$\begin{aligned}\mathcal{L} &= -\frac{1}{4}\hat{X}^{\mu\nu}\hat{X}_{\mu\nu} - \frac{1}{2}\sin\epsilon\hat{X}_{\mu\nu}B^{\mu\nu} + \overline{\chi}\left(i\not{D} - m_\chi\right)\chi + D_\mu\phi^\dagger D^\mu\phi \\ &- \mu^2\phi^\dagger\phi - \lambda_\phi|\phi|^4 - \frac{1}{\sqrt{2}}\left(y\phi^\dagger\overline{\chi^C}\chi + \text{h.c.}\right) - \lambda_{\phi H}\phi^\dagger\phi H^\dagger H\end{aligned}$$

$$\begin{aligned}\chi &= \frac{1}{\sqrt{2}}(\chi_R + i\chi_I), \\ \chi^c &= \frac{1}{\sqrt{2}}(\chi_R - i\chi_I), \\ \chi_R^c &= \chi_R, \quad \chi_I^c = \chi_I,\end{aligned}$$

$$\begin{aligned}\mathcal{L} &= \frac{1}{2}\sum_{i=R,I}\overline{\chi_i}\left(i\not{\partial} - m_i\right)\chi_i - i\frac{g_X}{2}(Z'_\mu + \epsilon s_W Z_\mu)\left(\overline{\chi_R}\gamma^\mu\chi_I - \overline{\chi_I}\gamma^\mu\chi_R\right) \\ &- \frac{1}{2}yh_\phi\left(\overline{\chi_R}\chi_R - \overline{\chi_I}\chi_I\right),\end{aligned}$$

$U(1) \to Z_2$ by $v_\phi \neq 0 : \chi \to -\chi$

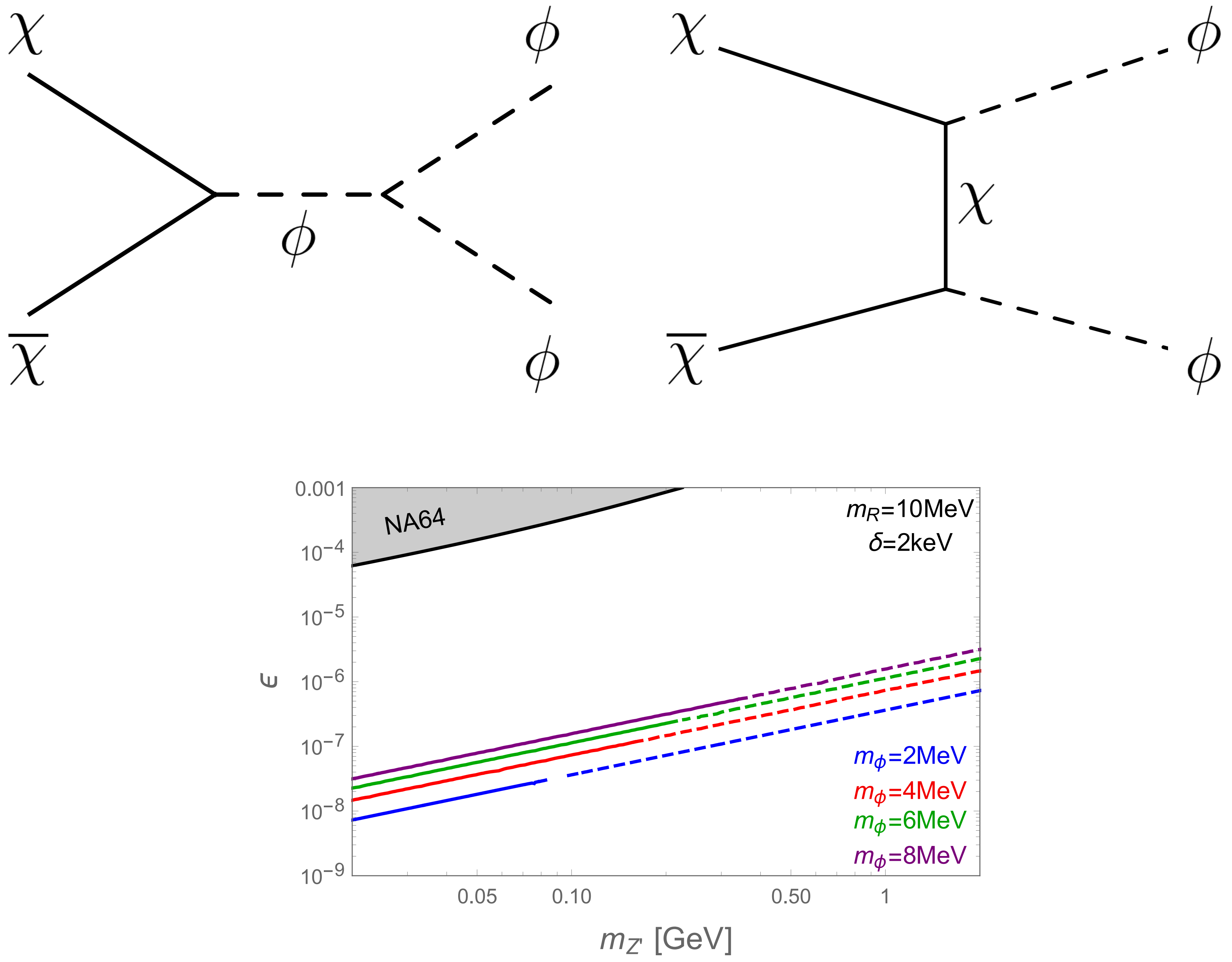


FIG. 2: (*top*) Feyman diagrams for $\chi\bar{\chi} \to \phi\phi$. (*bottom*) the region in the $(m_{Z'}, \epsilon)$ plane that is allowed for the XENON1T electron recoil excess and the correct thermal relic density for fermion DM case for $\delta = 2$ keV and the fermion DM mass to be $m_R = 10$ MeV. Different colors represents $m_\phi = 2, 4, 6, 8$ MeV. The gray areas are excluded by various experiments, assuming $Z' \to \chi_R \chi_I$ is kinematically allowed, and the experimental constraint is weaker in the ϵ we are interested in, compared with the scalar DM case in Fig. 1 (right). We also show the current experimental bounds by NA64 [66].

P-wave annihilation cross sections

Scalar DM : $XX^{\dagger} \to Z'^{*} \to Z'\phi$

$$\sigma v \simeq \frac{g_X^4 v^2}{384\pi\, m_X^4 (4m_X^2 - m_{Z'}^2)^2} \left(16m_X^4 + m_{Z'}^4 + m_\phi^4 + 40m_X^2 m_{Z'}^2 - 8m_X^2 m_\phi^2 - 2m_{Z'}^2 m_\phi^2\right) \times \left[\left\{4m_X^2 - (m_{Z'} + m_\phi)^2\right\}\left\{4m_X^2 - (m_{Z'} - m_\phi)^2\right\}\right]^{1/2} + \mathcal{O}(v^4), \qquad (10)$$

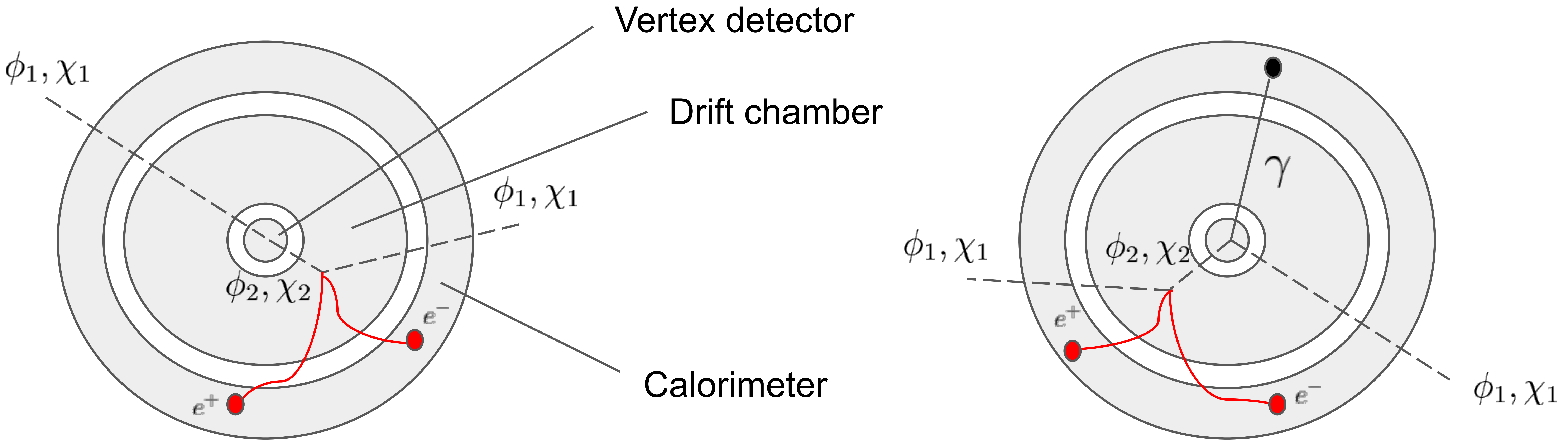
Fermion DM : $\chi\bar{\chi} \to \phi\phi$

$$\sigma v = \frac{y^2 v^2 \sqrt{m_\chi^2 - m_\phi^2}}{96\pi m_\chi} \left[\frac{27\lambda_\phi^2 v_\phi^2}{(4m_\chi^2 - m_\phi^2)^2} + \frac{4y^2 m_\chi^2 (9m_\chi^4 - 8m_\chi^2 m_\phi^2 + 2m_\phi^4)}{(2m_\chi^2 - m_\phi^2)^4}\right] + \mathcal{O}(v^4), \qquad (28)$$

Determination of (M,spin) @ Belle2

(Talk by Chih-Ting Lu)

Displaced signature examples in Belle II detector (xy-plane)


Vertex detector

Drift chamber

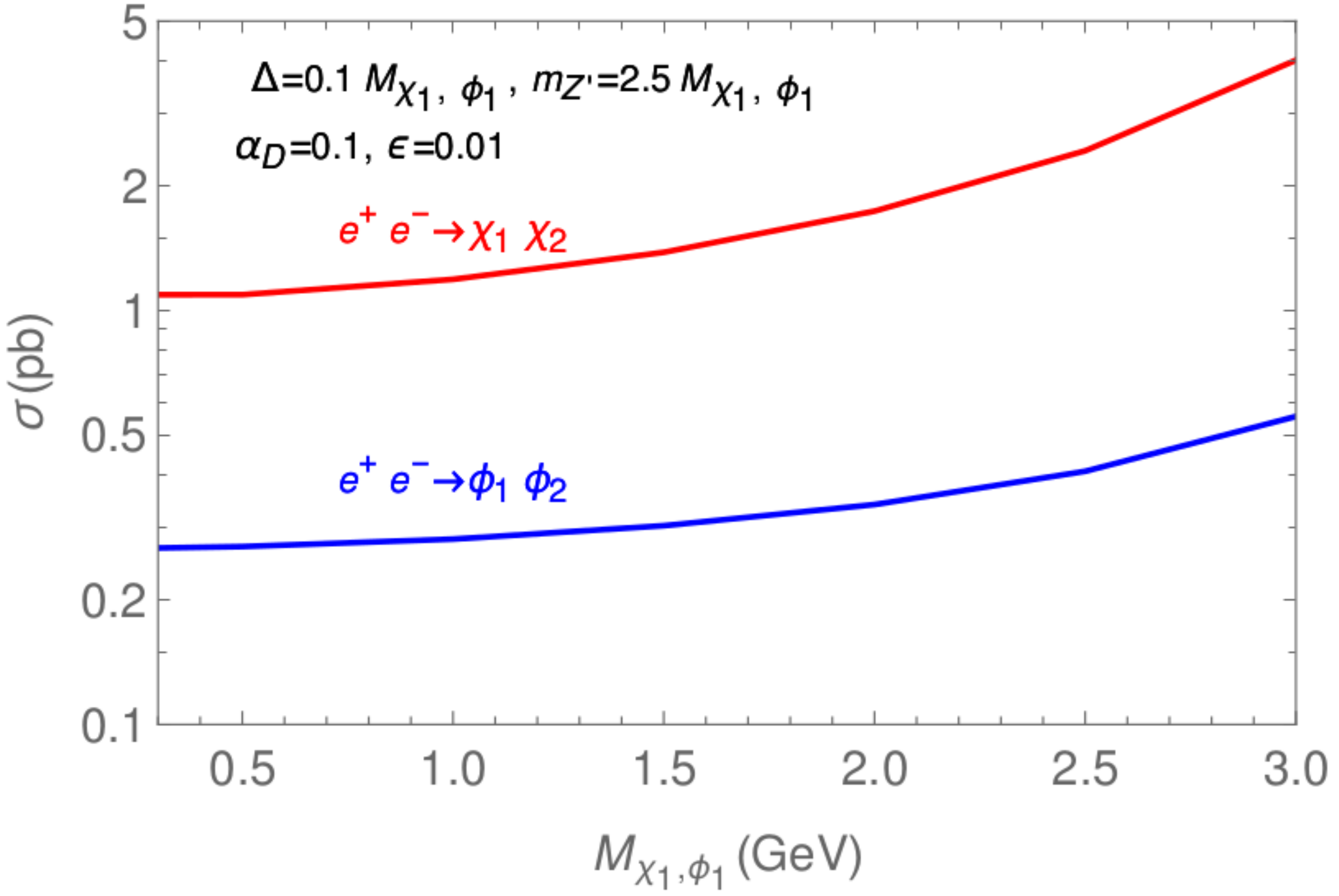
Calorimeter

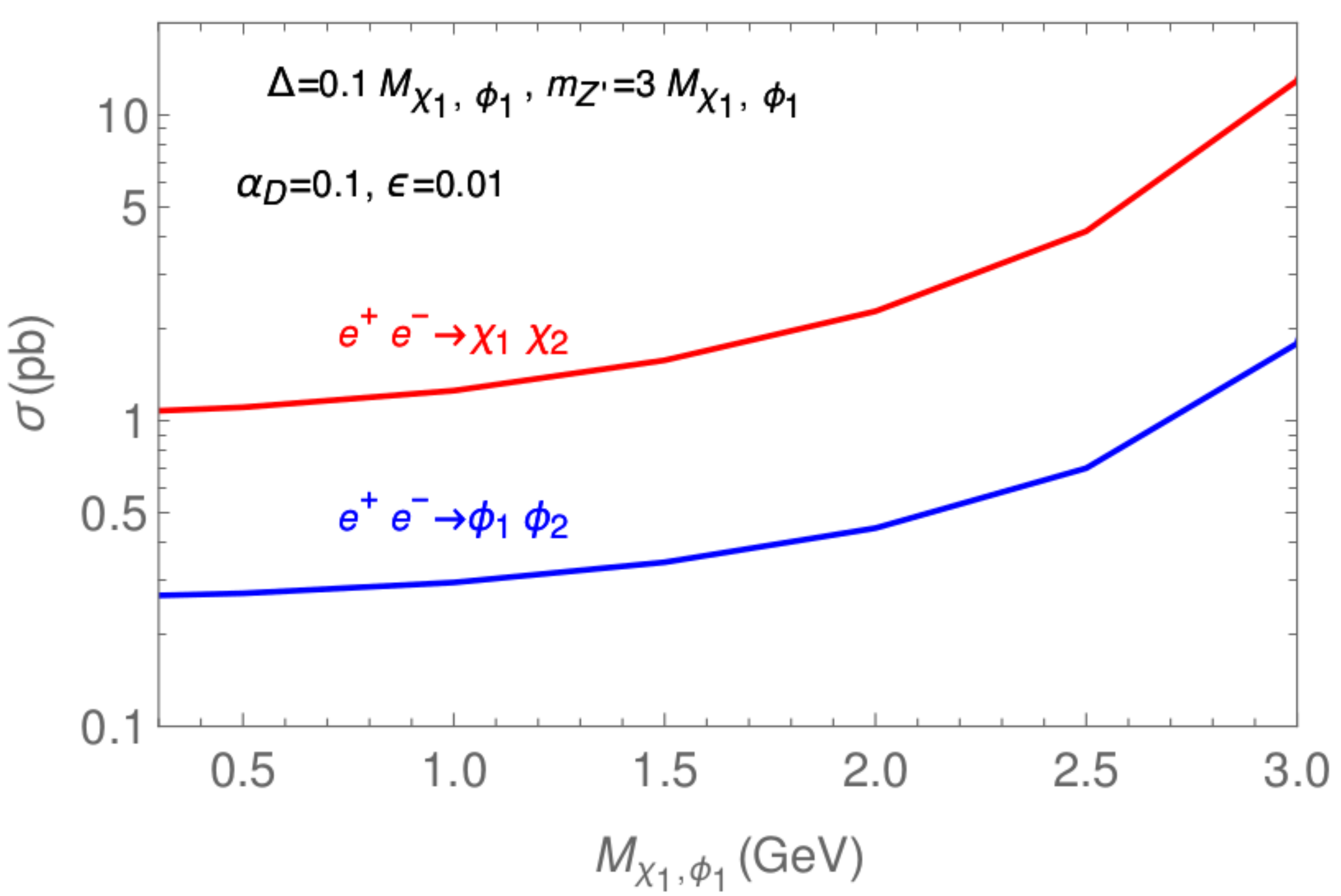
$$e^+e^- \to \phi_1\phi_2 \to \phi_1\phi_1e^+e^-$$
$$e^+e^- \to \chi_1\chi_2 \to \chi_1\chi_1e^+e^-$$

$$e^+e^- \to \phi_1\phi_2\gamma \to \phi_1\phi_1e^+e^-\gamma$$
$$e^+e^- \to \chi_1\chi_2\gamma \to \chi_1\chi_1e^+e^-\gamma$$

Can we tell the difference for fermion and scalar boson pair productions at colliders ?

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





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

In the center of mass (CM) frame, the normalized differential cross section can be written as

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

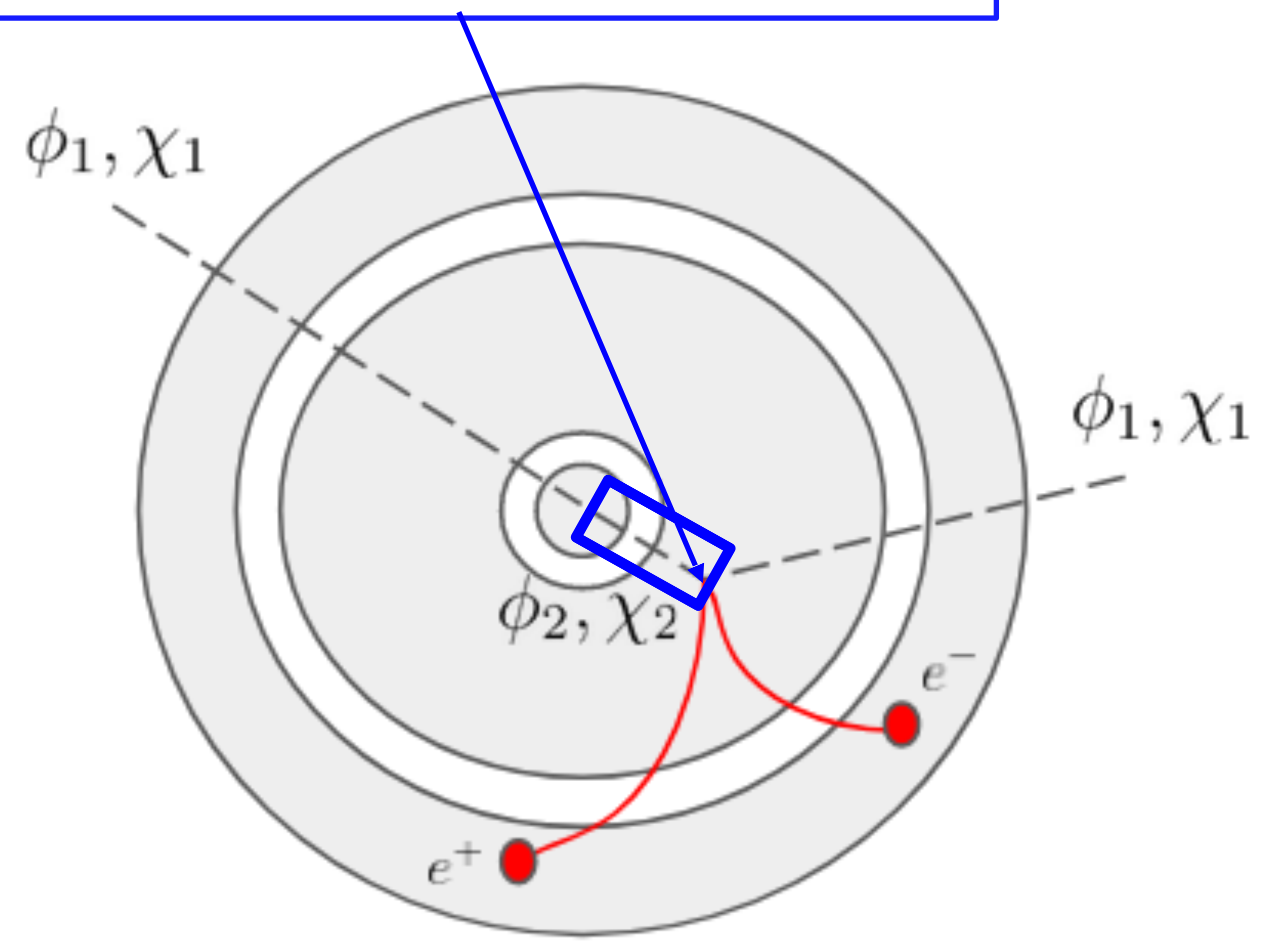
for the scalar case $(e^+e^- \to \phi_2\phi_1)$

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

for the fermion case $(e^+e^- \to \chi_2\chi_1)$

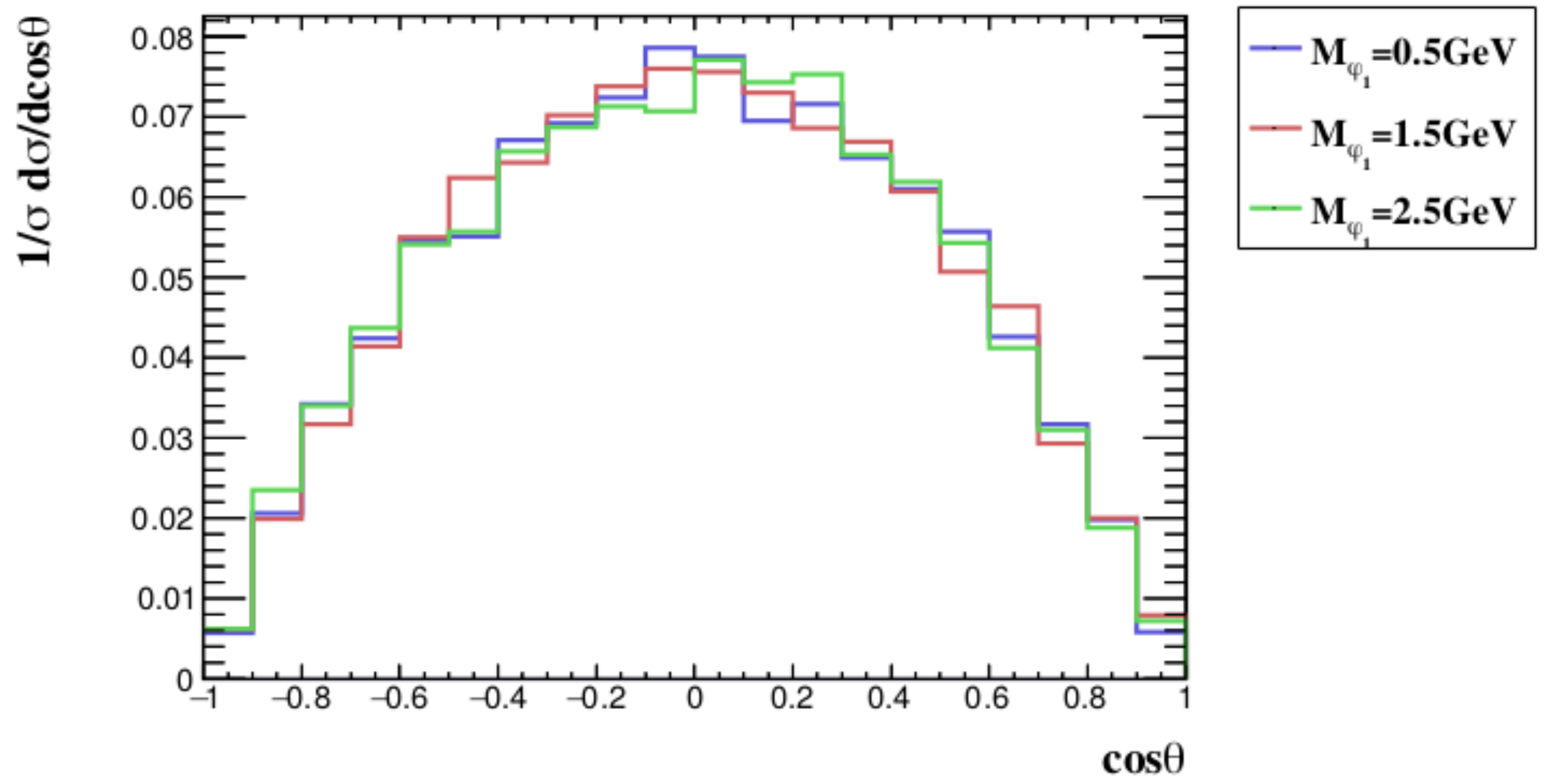
where $\xi = \sqrt{1 - \frac{2(M_{\chi_2}^2 + M_{\chi_1}^2)}{s} + \frac{(M_{\chi_2}^2 - M_{\chi_1}^2)^2}{s^2}}$

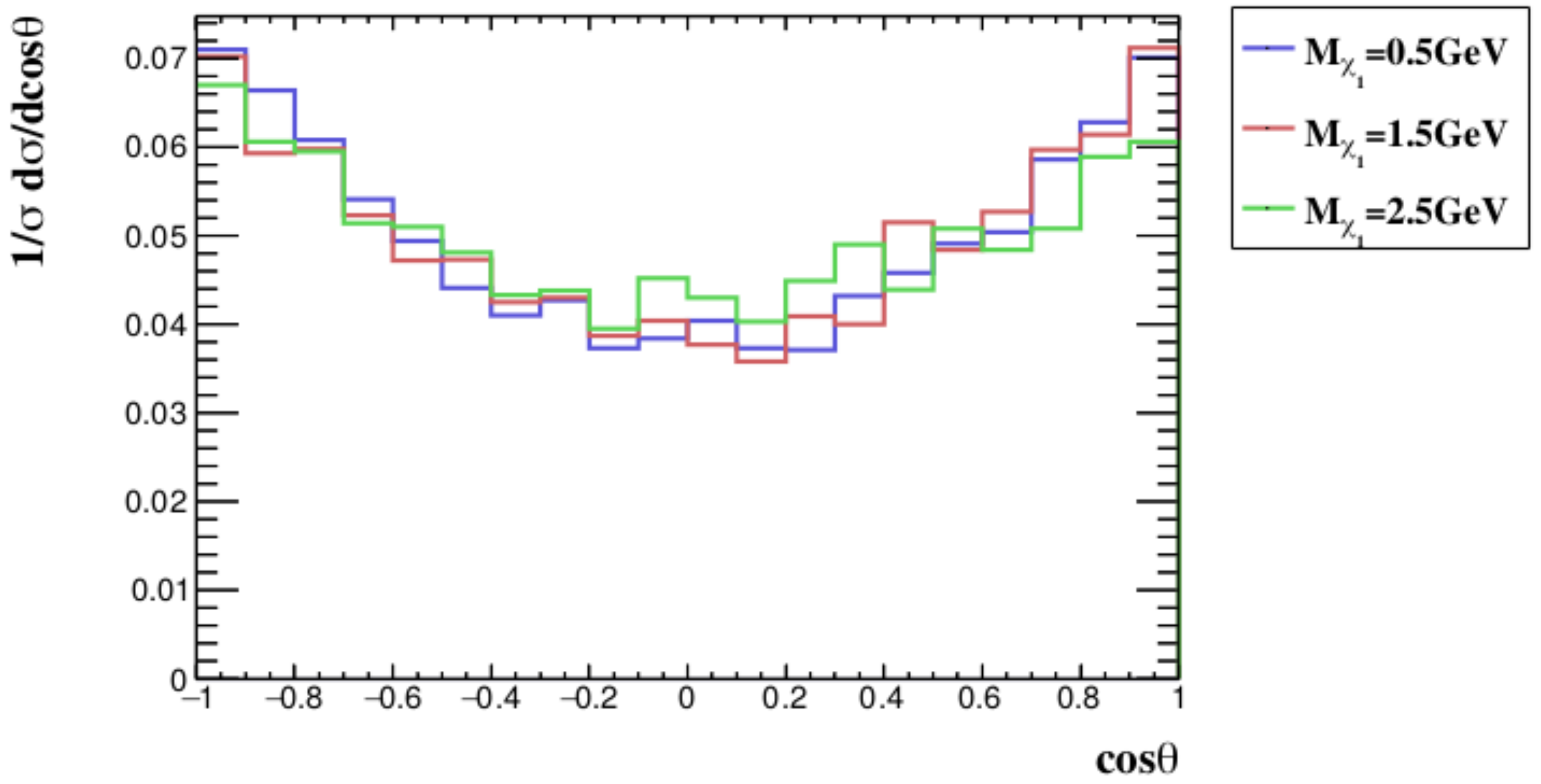
Note θ is the direction of ϕ_2 , χ_2 relative to the beam direction.


We need to know the direction of the displaced vertex

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

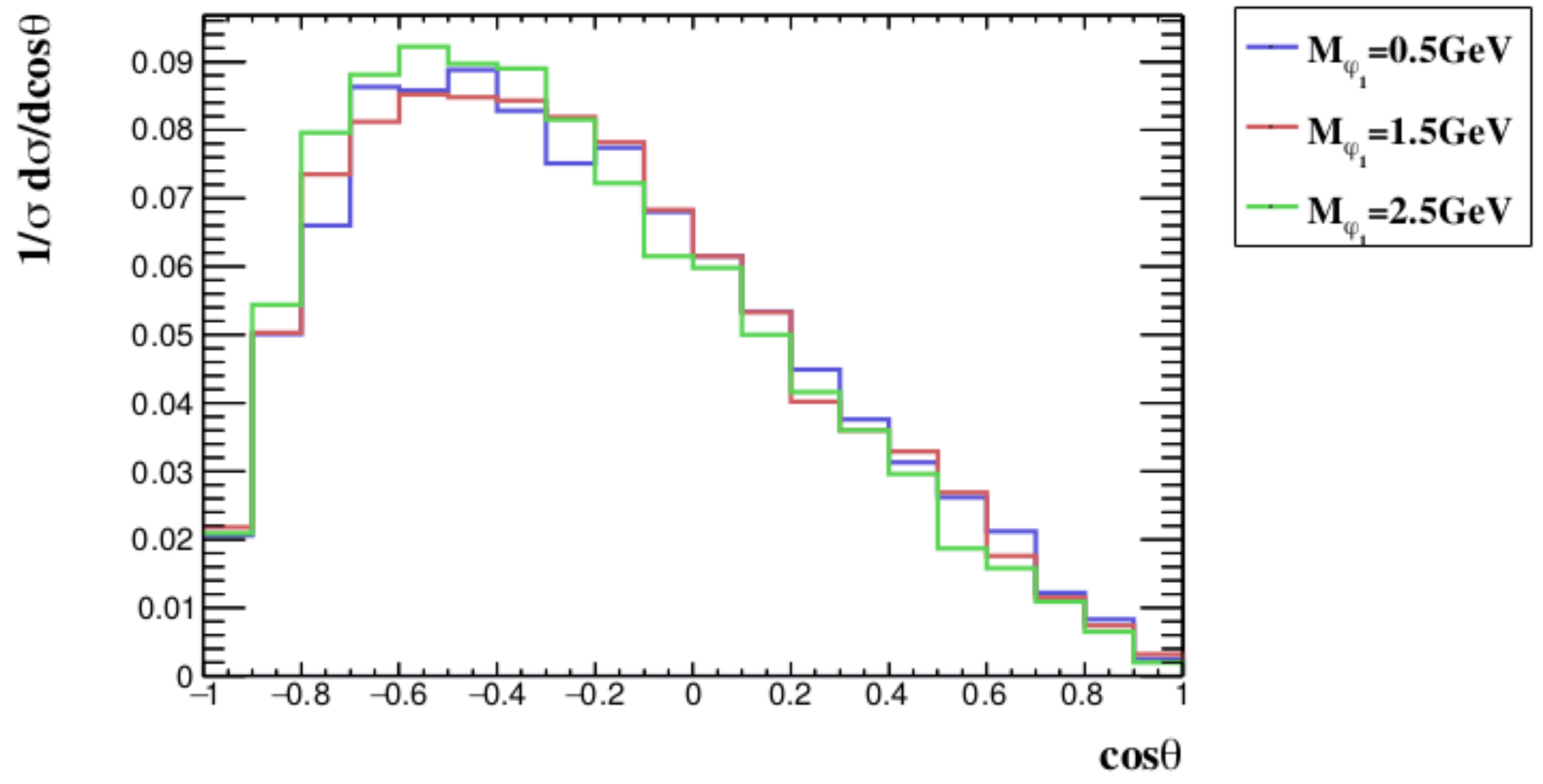
In the center of mass (CM) frame

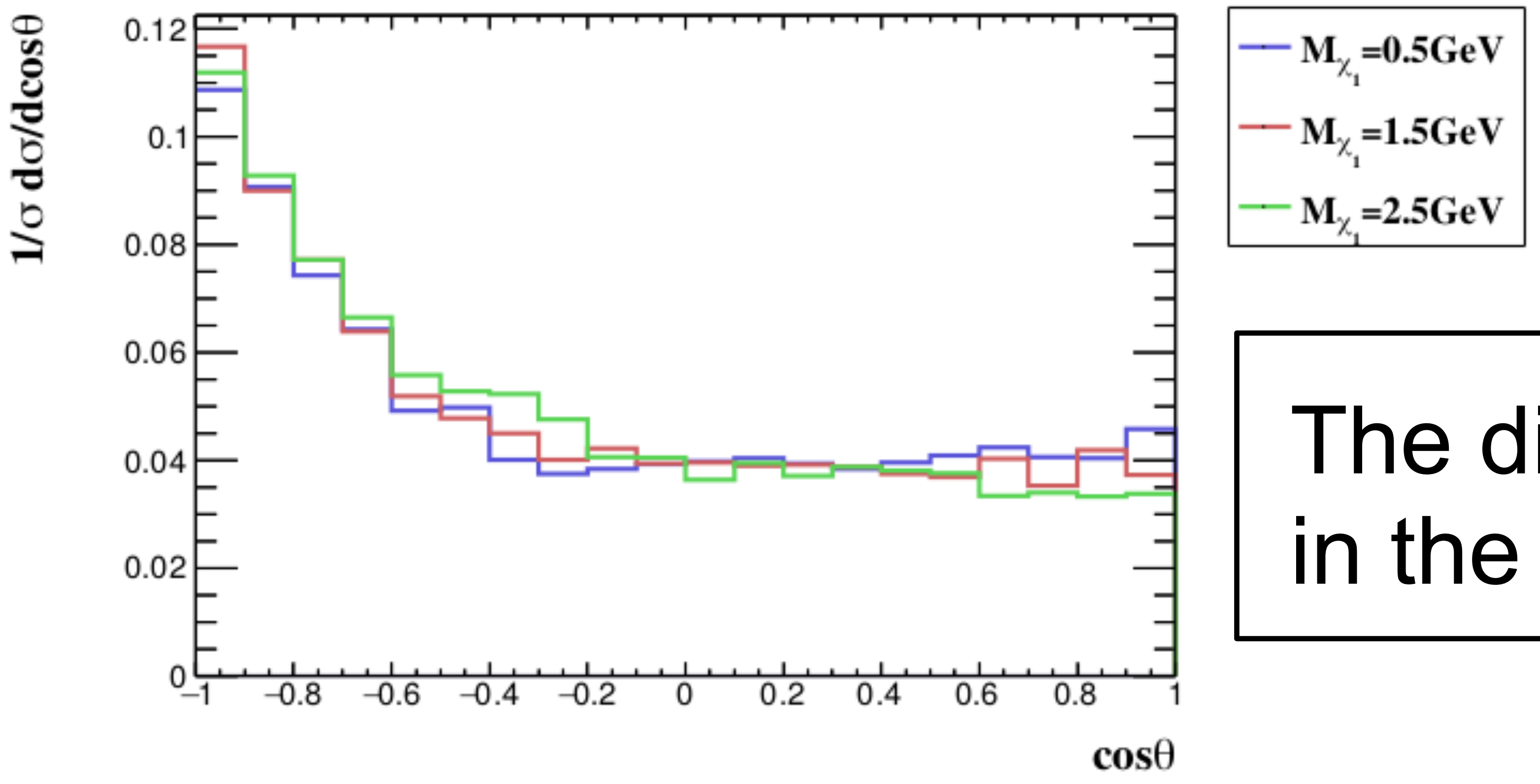




In the laboratory (LAB) frame

Fix $\alpha_D = 0.1$, $\epsilon = 0.01$, $\Delta = 0.1 M_{\phi_1,\chi_1}$, and $m_{Z'} = 3.0 M_{\phi_1,\chi_1}$

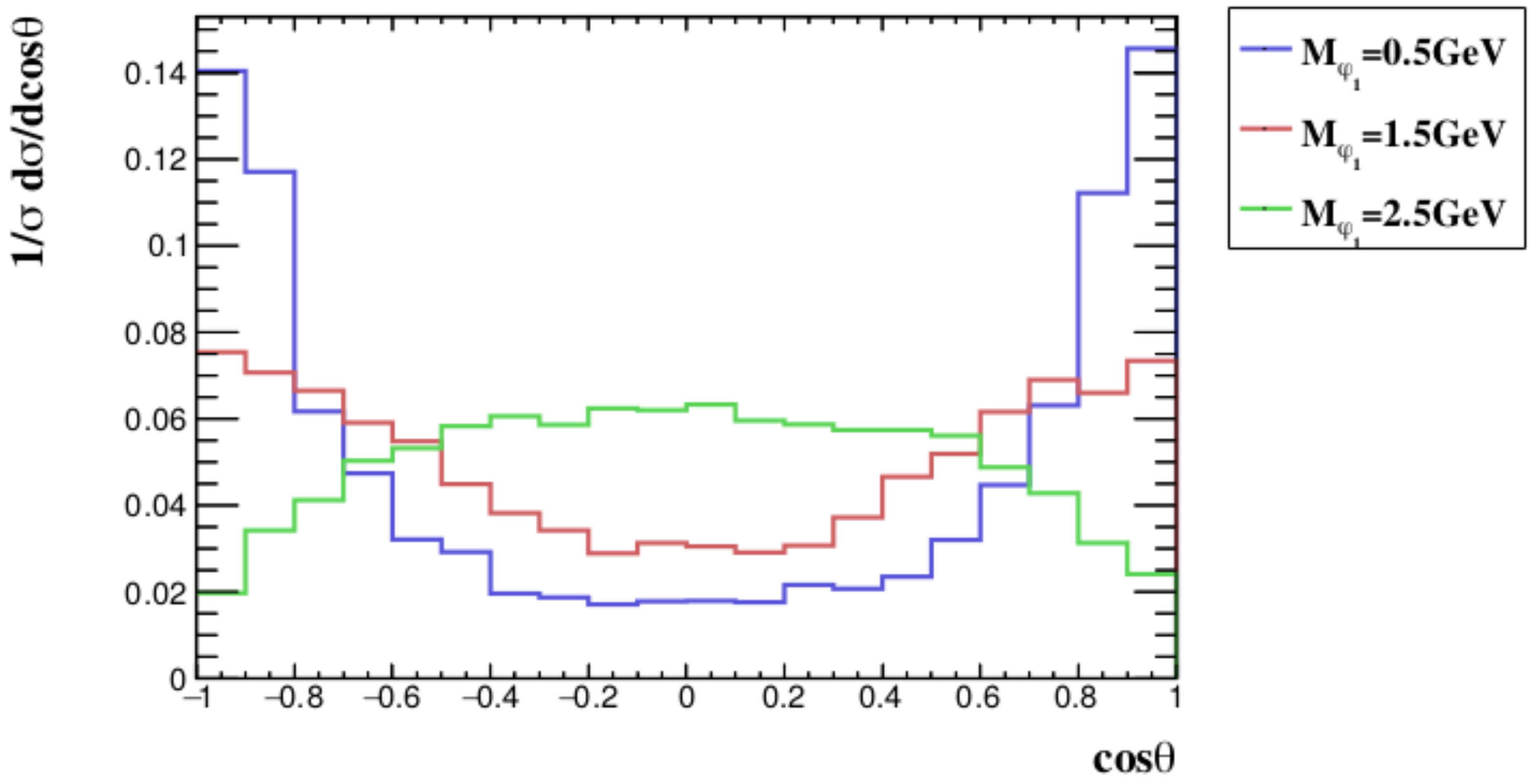


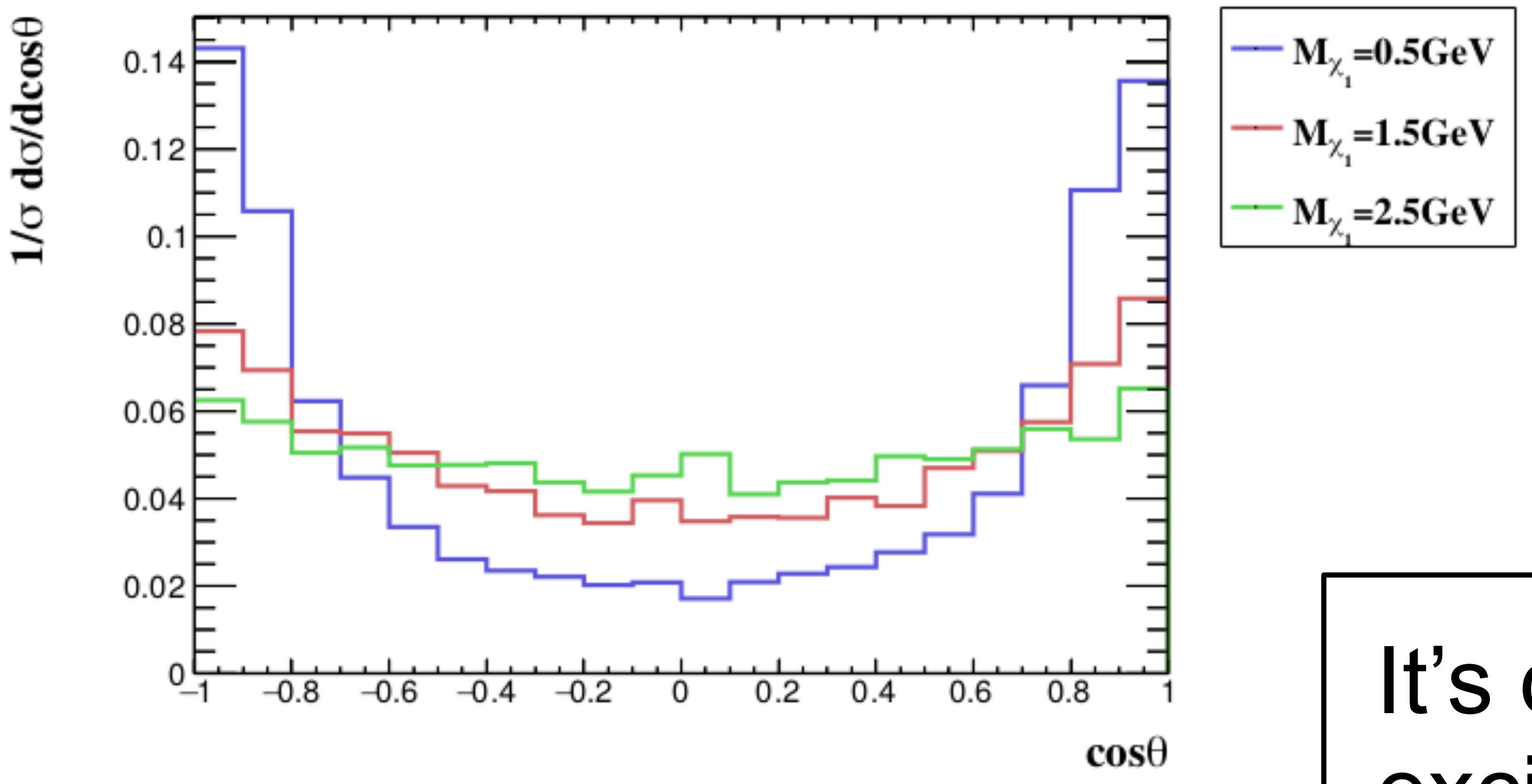


The differences are still obvious in the LAB frame !

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

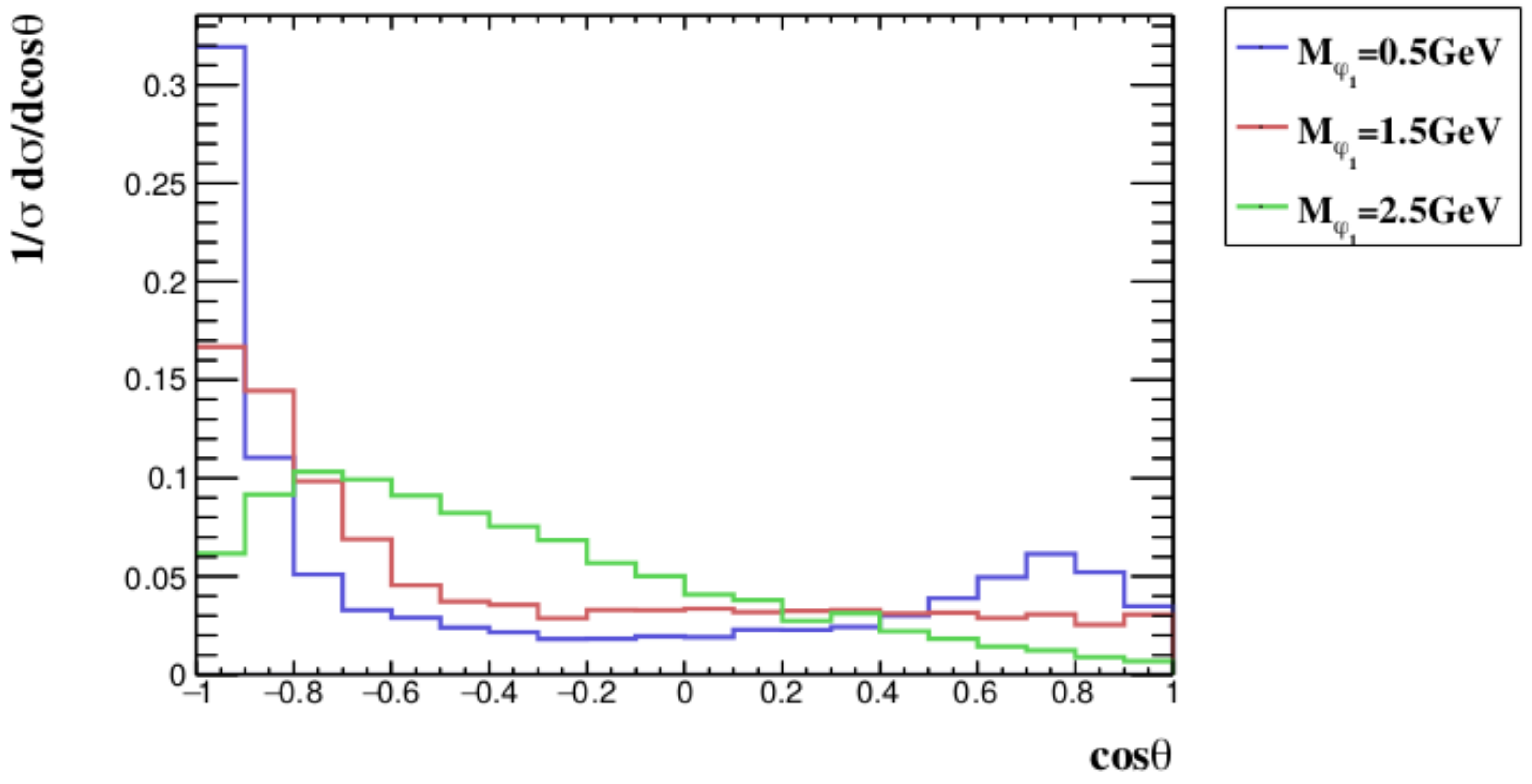
In the center of mass (CM) frame with initial state radiation (ISR)

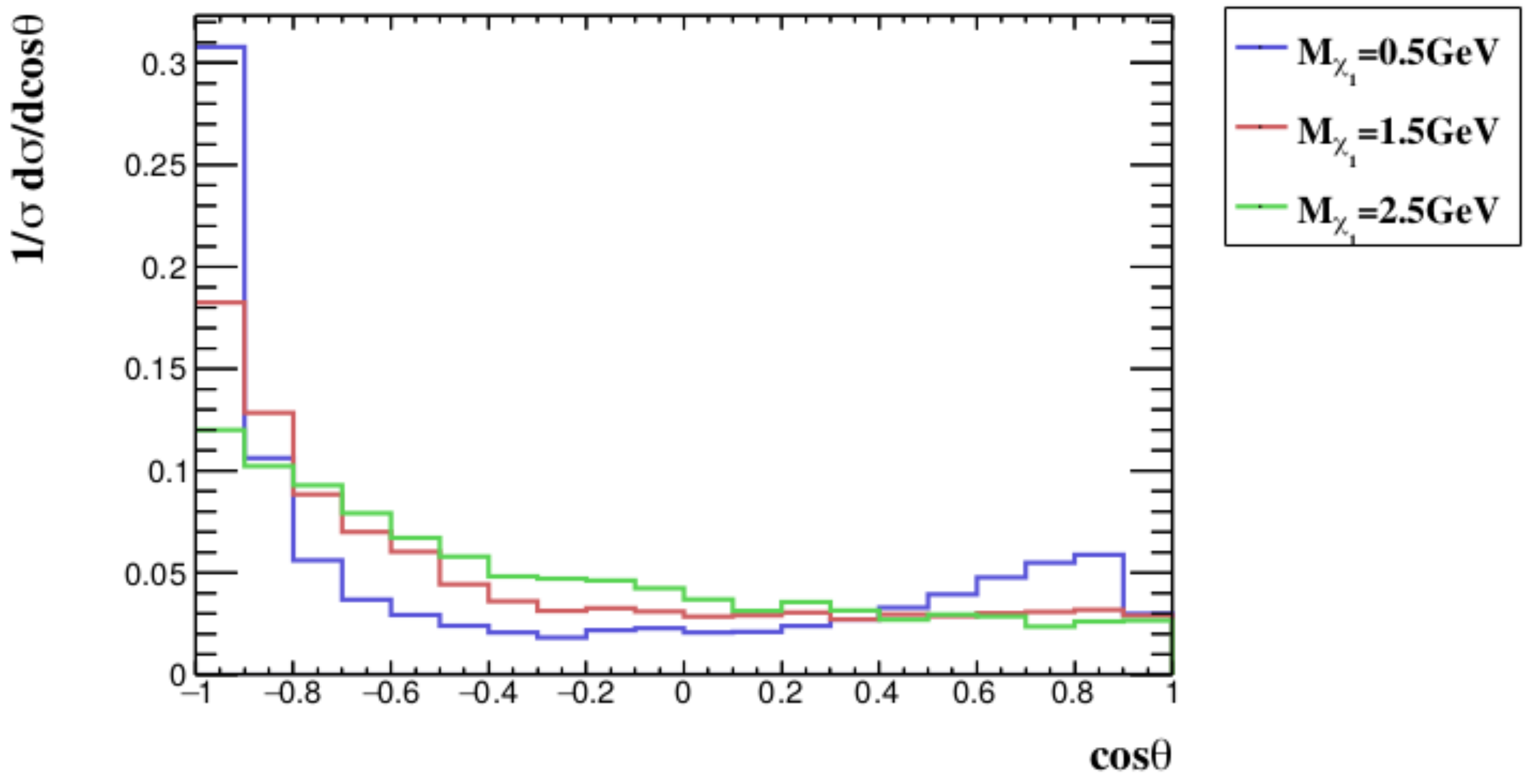




It's difficult to determine the excited DM spin in this case except for the soft ISR !

In the laboratory (LAB) frame with initial state radiation (ISR)





Future bounds @ 50ab^{-1}

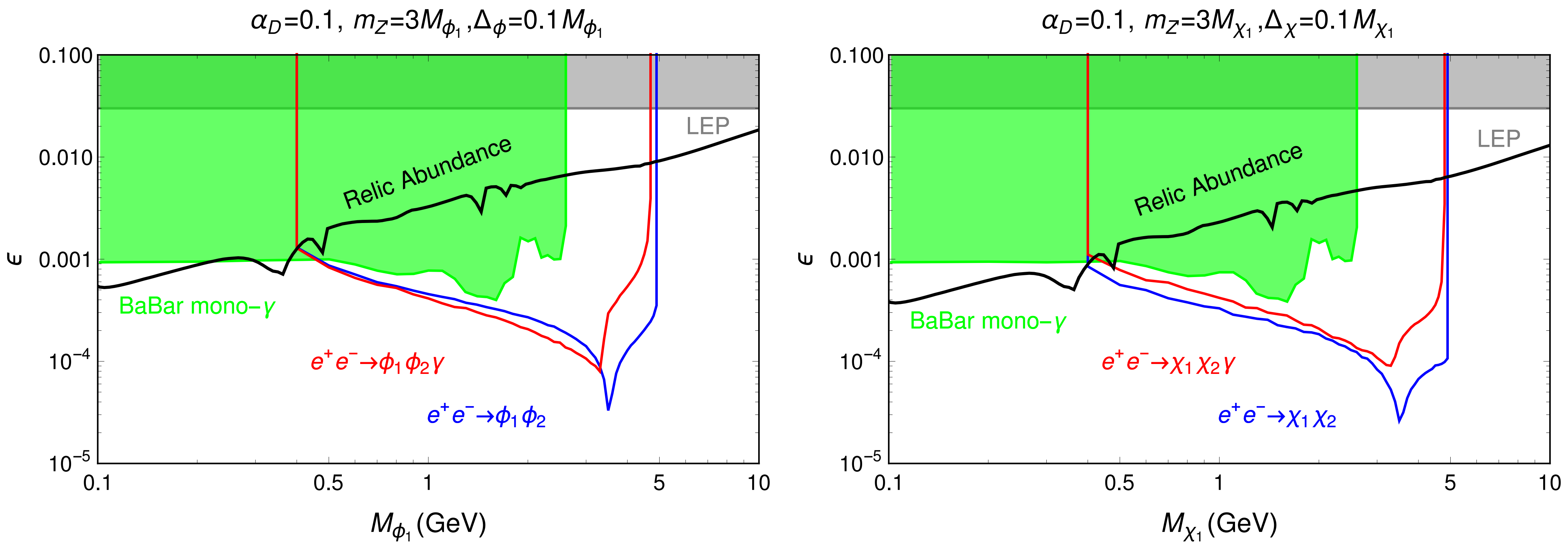


FIG. 6: The future bounds from $e^+e^- \to \phi_1\phi_2(\chi_1\chi_2)$ and $e^+e^- \to \phi_1\phi_2(\chi_1\chi_2)\gamma$ processes for event selections in Table I with the integrated luminosity of 50 ab^{-1}. Here parameters $\alpha_D = 0.1$, $m_{Z'} = 3M_{\phi_1,\chi_1}$ and $\Delta_{\phi,\chi} = 0.1M_{\phi_1,\chi_1}$ are fixed and 90% C.L. contours which correspond to an upper limit of 2.3 events with the assumption of background-free are applied. The model-independent LEP bound [79], BaBar mono-γ bound [23] and correct relic abundance lines are also shown.

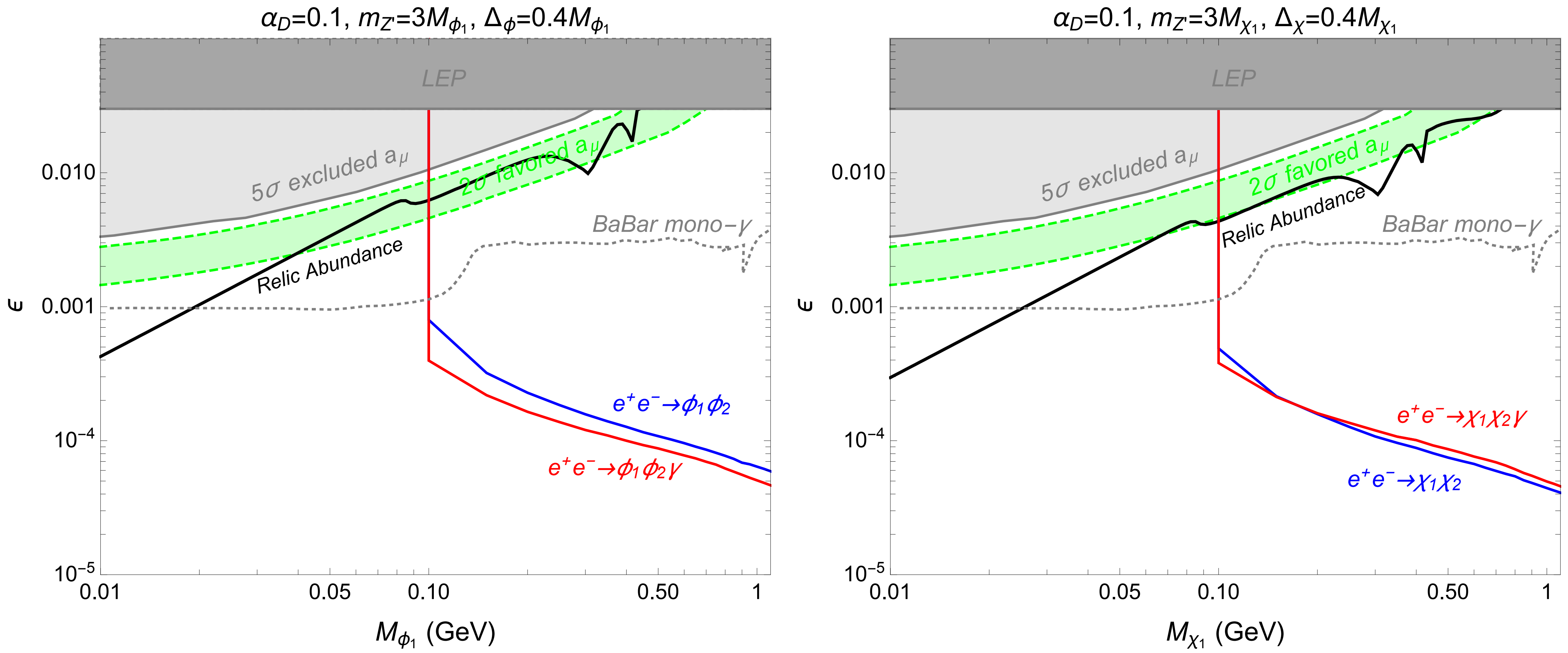


FIG. 7: The same as Fig. 6 but for $m_{Z'} = 3M_{\phi_1,\chi_1}$ and $\Delta_{\phi,\chi} = 0.1M_{\phi_1,\chi_1}$. The green shaded region bounded by the green dashed lines is the 2σ allowed region for the $(g-2)_\mu$ excess and the lighter gray region excluded by the $(g-2)_\mu$ at 5σ C.L.

See the paper for more details

If the excited DM is long-lived, can we determine its mass at colliders ?

In the center of mass (CM) frame for the process $e^+e^- \to \chi_1\chi_2 \to \chi_1\chi_1 e^+e^-$

There are 8 unknown values from four-momentum of two dark matters in the final states.

However, we have 7 constraints for this process :

1. four-momentum conservation (4)
2. two dark matters with the same mass (1)
3. because of the charge neutrality of the excited DM, a three-momentum vector is proportional to the displaced vertex (2)

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

If the excited DM is long-lived, can we determine its mass at colliders ?

In the center of mass (CM) frame for the process $e^+e^- \to \chi_1\chi_2 \to \chi_1\chi_1 e^+e^-$

We can first write down the following equation with the help of four-momentum conservation,

$$m_{\chi_2}^2 - m_{\chi_1}^2 - 2E(1+\alpha)E_{V'} + E_{V'}^2 - |\overrightarrow{p_{V'}}|^2 + 2\sqrt{(E(1+\alpha))^2 - m_{\chi_2}^2}(\hat{r_{DV}} \cdot \overrightarrow{p_{V'}}) = 0$$

where $\hat{r_{DV}}$ is the direction of displaced vertex, E is half of the center of mass energy,

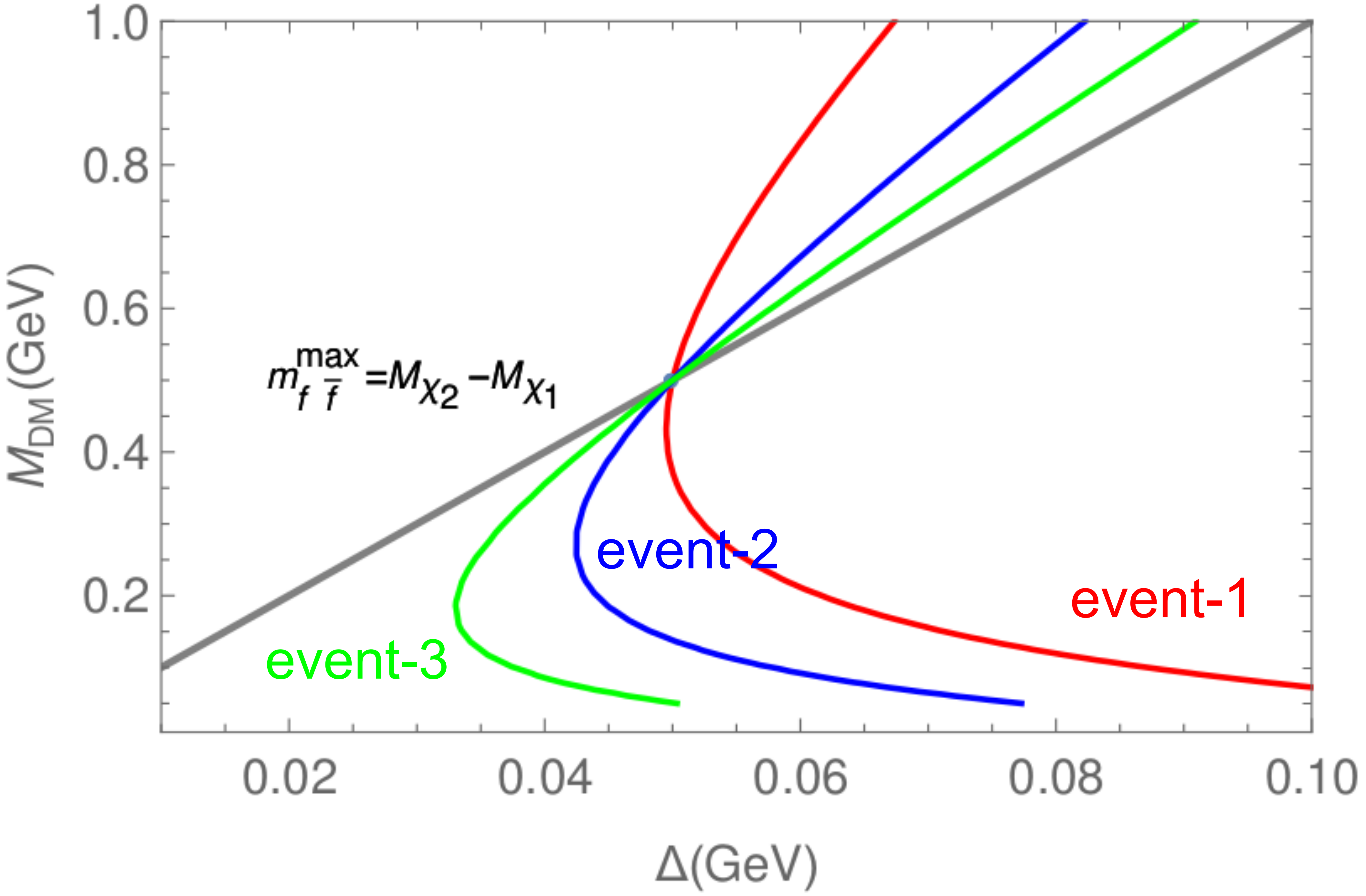
$E_{V'}$, $\overrightarrow{p_{V'}}$ are the visible energy and three-momentum in the final states, and

$$\alpha = \frac{m_{\chi_2}^2 - m_{\chi_1}^2}{4E^2}$$

For each event, we can receive a relation between the mass of DM and mass splitting.

If the excited DM is long-lived, can we determine its mass at colliders ?

The crossing point from these events and kinematic endpoint measurement $m_{f\bar{f}}^{max}$ can help us to determine the mass of DM and mass splitting. This method is based on “Kinematic focus point” from arXiv:1906.0282 (Kim,Matchev,Shyamsundar).



$$(\Delta, M_{DM}) = (0.05, 0.5)$$

If the excited DM is long-lived, can we determine its mass at colliders ?

In the LAB frame for the process $e^+e^- \to \chi_1\chi_2 \to \chi_1\chi_1 e^+e^-$

We can still write down the following equation with the help of four-momentum conservation,

$$\boxed{m_{\chi_2}^2 - m_{\chi_1}^2 - 2E_{\chi_2}E_{V'} + E_{V'}^2 - |\overrightarrow{p_{V'}}|^2 + 2\sqrt{E_{\chi_2}^2 - m_{\chi_2}^2}(\widehat{r}_{DV} \cdot \overrightarrow{p_{V'}}) = 0}$$

where $\widehat{r}_{DV}$ is the direction of displaced vertex, E is half of the center of mass energy,

$E_{V'}$, $\overrightarrow{p_{V'}}$ are the visible energy and three-momentum in the final states, and

$$E_{\chi_2} = \frac{1}{2\left[sin^2\theta(E_-^2 + E_+^2) + 2(1 + cos^2\theta)E_-E_+\right]} \times$$
$$\left[(E_- + E_+)(4E_-E_+ + m_{\chi_2}^2 - m_{\chi_1}^2) - (E_- - E_+)cos\theta \times\right.$$
$$\left.\sqrt{(m_{\chi_1}^2 - 4E_-E_+)^2 - 2(2sin^2\theta(E_-^2 + E_+^2) + 4cos^2\theta E_-E_+ + m_{\chi_1}^2) + m_{\chi_1}^4}\right]$$

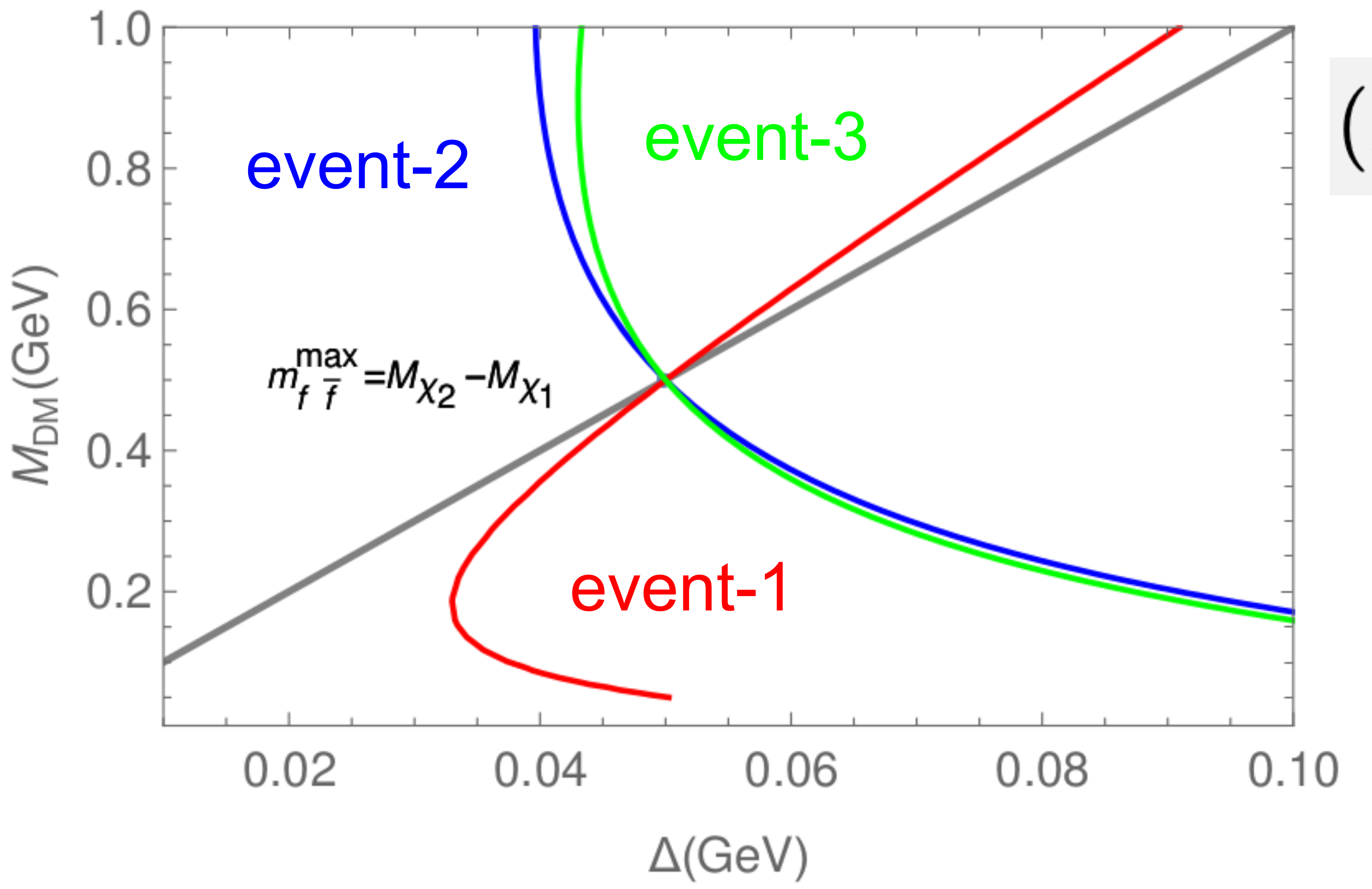
If the excited DM is long-lived, can we determine its mass at colliders ?

where $\widehat{r}_{DV} = (sin\theta cos\phi, sin\theta sin\phi, cos\theta)$

$$p_{e^-} = (E_-, 0, 0, E_-)$$

$$p_{e^+} = (E_+, 0, 0, -E_+)$$

Again, the crossing point from these events and kinematic endpoint measurement $m_{f\bar{f}}^{max}$ can help us to determine the mass of DM and mass splitting.

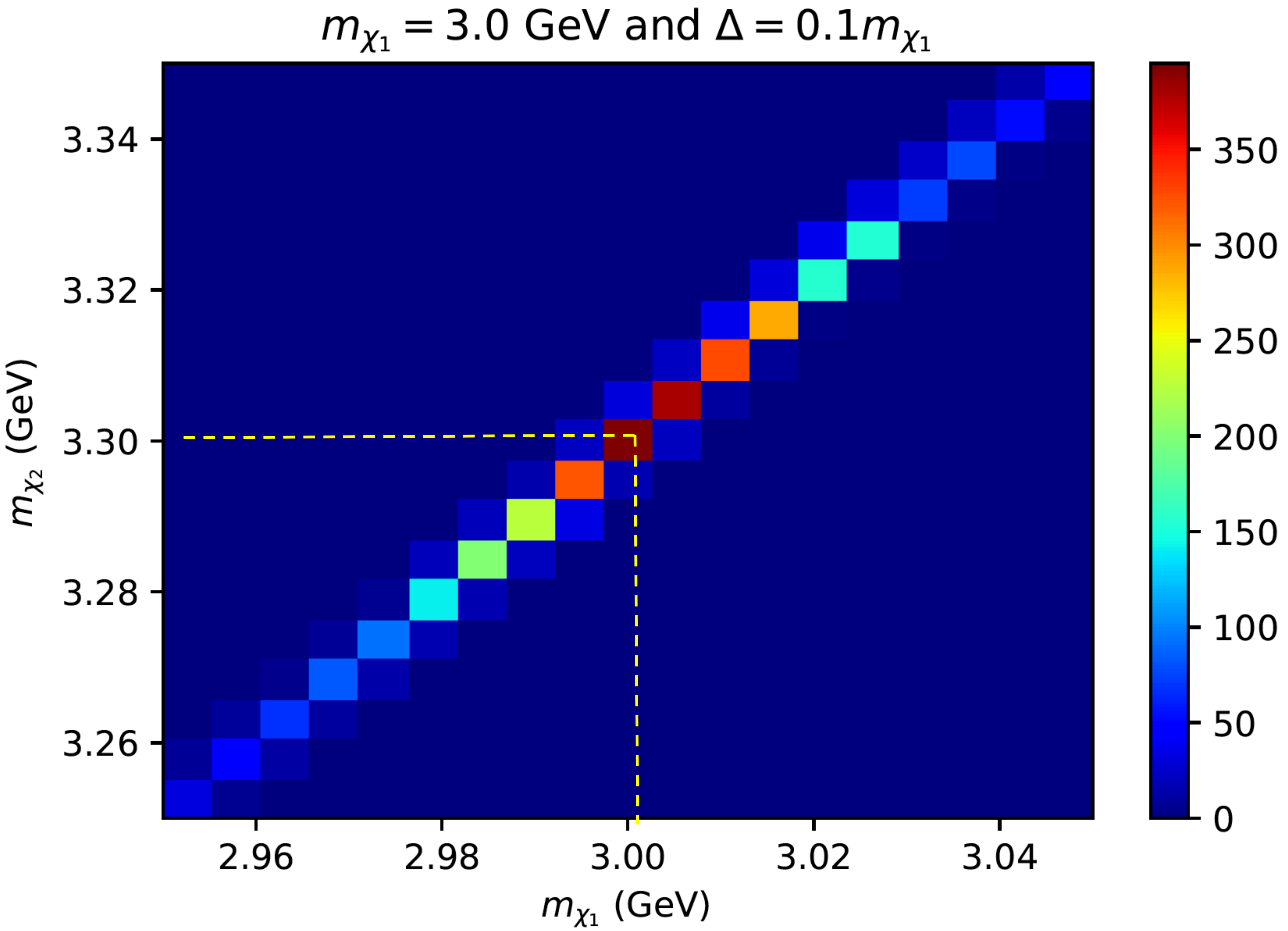


$$(\Delta, M_{DM}) = (0.05, 0.5)$$

How about the impact of the detector resolution ?

If the excited DM is long-lived, can we determine its mass at colliders ?

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

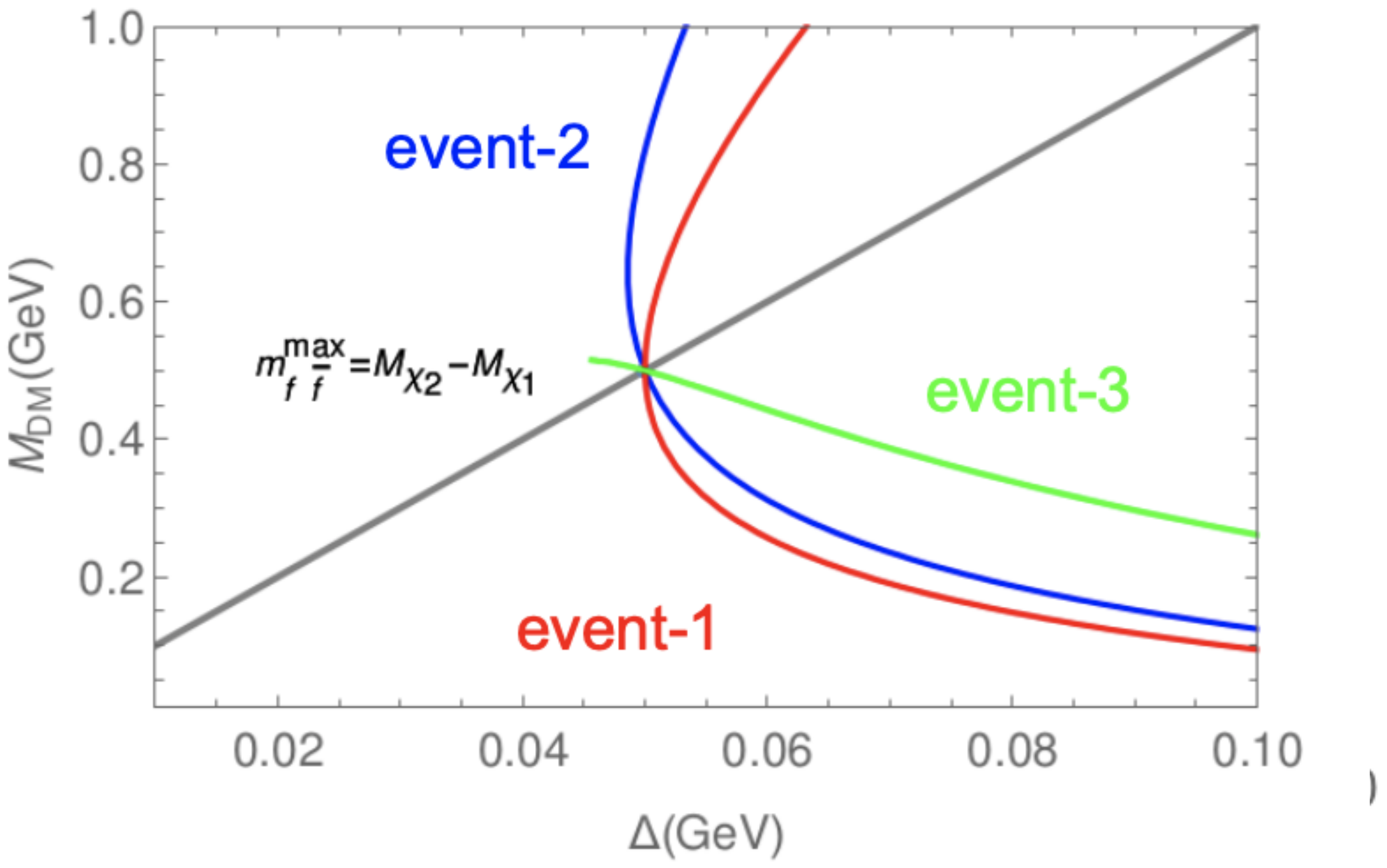


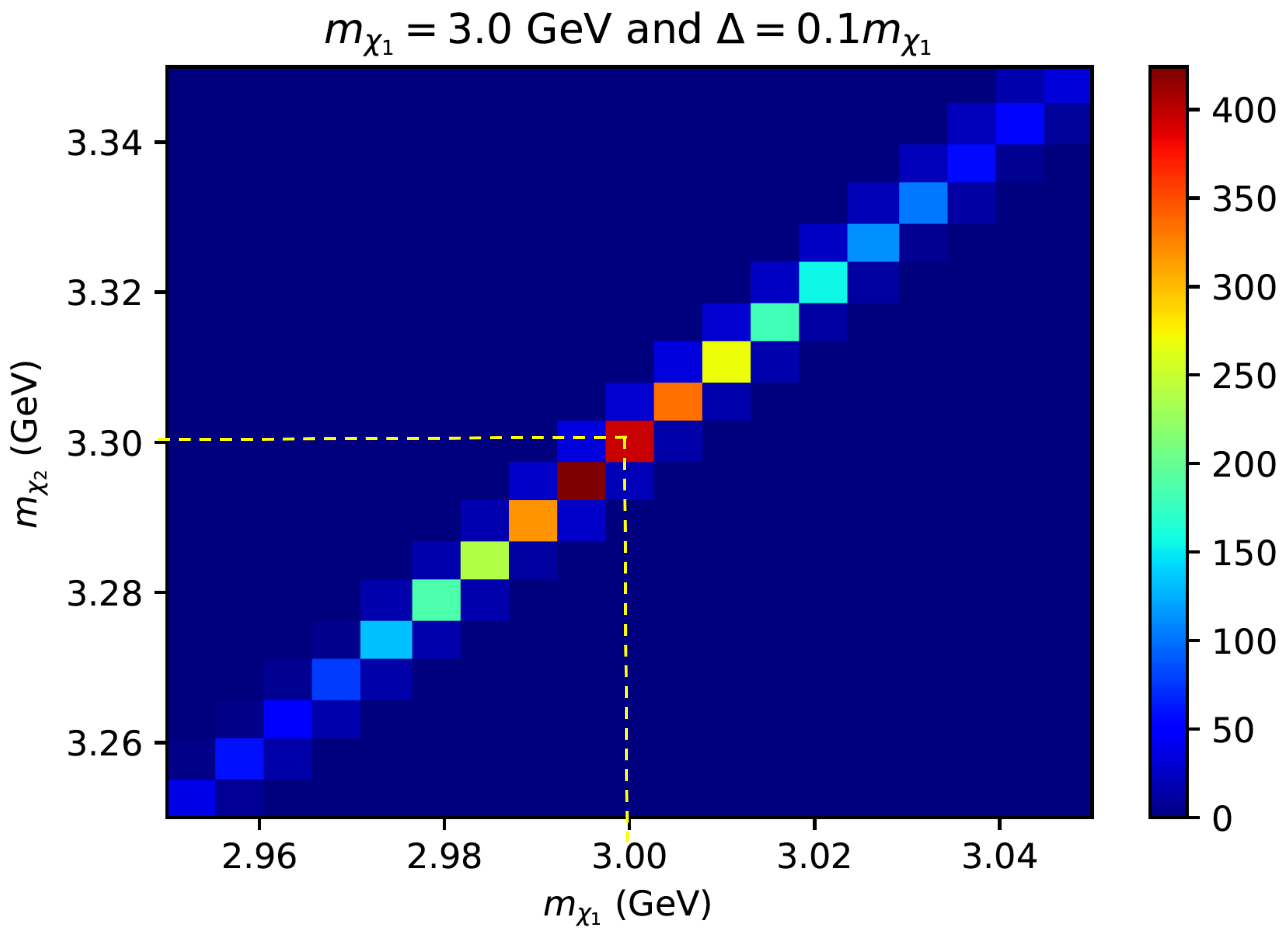
If the excited DM is long-lived, can we determine its mass at colliders ?

Similarly,

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

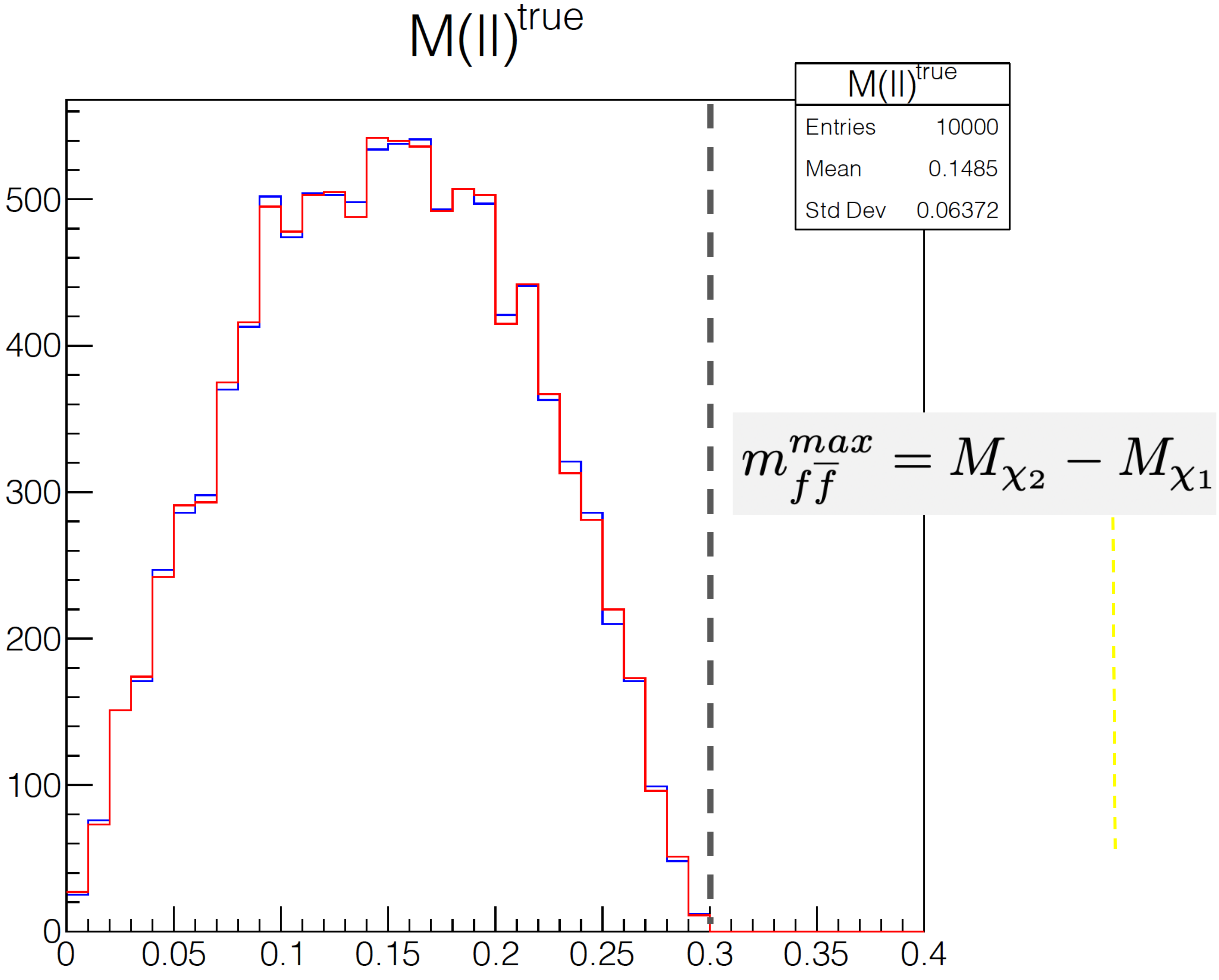
In the LAB frame $(\Delta, M_{DM}) = (0.05, 0.5)$





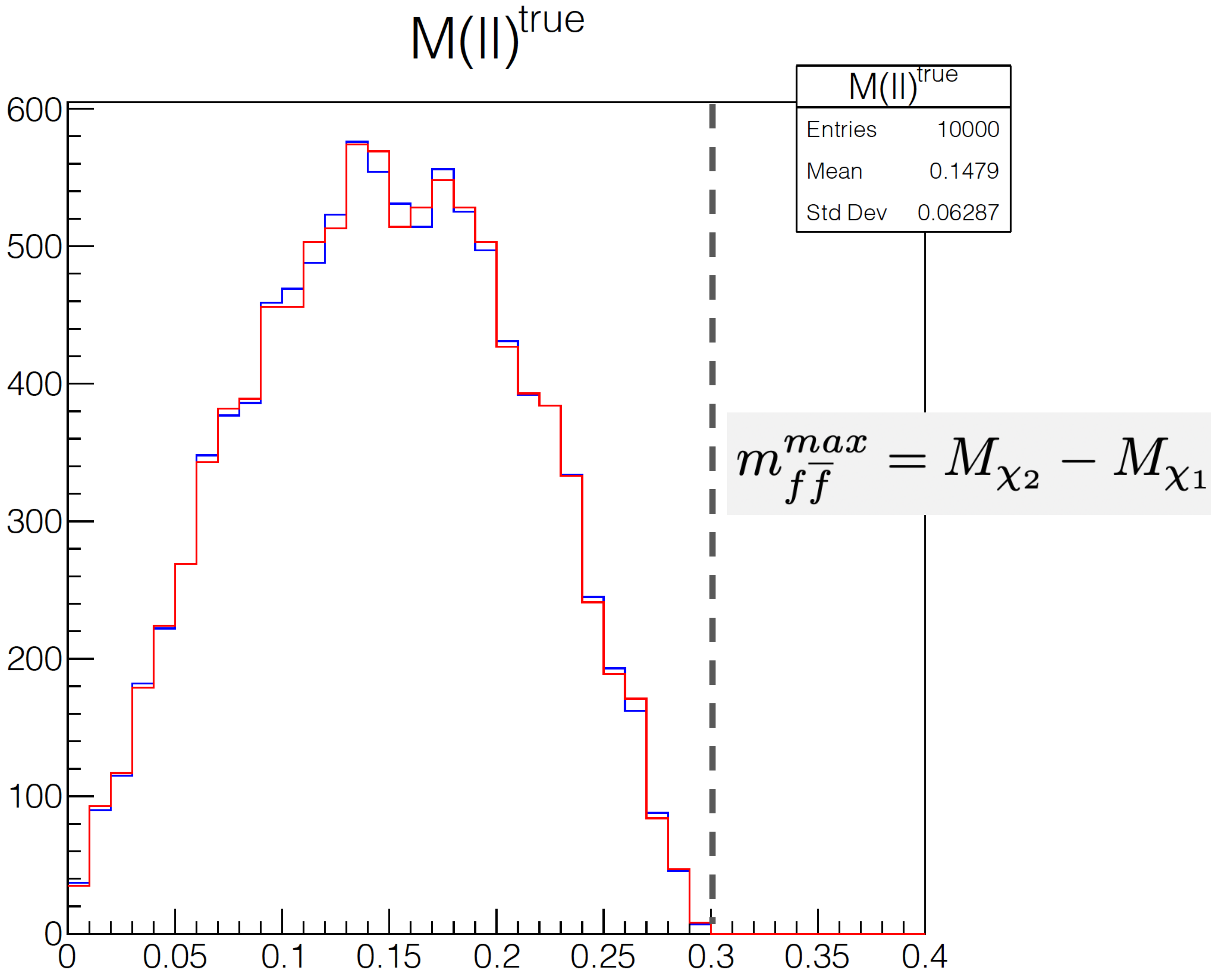
If the excited DM is long-lived, can we determine its mass at colliders ?

$$\boxed{e^+e^- \to \chi_1\chi_2 \to \chi_1\chi_1 e^+e^-}$$



$$m_{f\bar{f}}^{max} = M_{\chi_2} - M_{\chi_1}$$

$$\boxed{e^+e^- \to \chi_1\chi_2\gamma \to \chi_1\chi_1 e^+e^-\gamma}$$



$$m_{f\bar{f}}^{max} = M_{\chi_2} - M_{\chi_1}$$

Conclusion

1. The inelastic DM with extra $U(1)_D$ gauge symmetry is an interesting dark sector models with light DM.
2. If ϕ_2, χ_2 are long-lived, the size of cross sections for $\phi_1\phi_2(\chi_1\chi_2)$ productions and their angular distributions can give us some hints for the spin of DM.
3. If ϕ_2, χ_2 are long-lived, we can apply the "Kinematic focus point" method, the mass of DM and its mass splitting can be determined within a few percent for some parameter space.

Summary

- Local Z2 scalar/fermion DM : theoretically well defined & mathematically consistent models for XDM
- Can explain a number of phenomena including the recent XENON1T data
- One can discriminate the spin of (X)DM at Belle2 from the polar angle distributions of the decaying points (DM mass and the Δm can be determined with the focus point method)
- Similar studies at ILC, CEPC, HL-LHC and FCC-hh in progress (The current version of FCC CDR does not include this interesting case.)

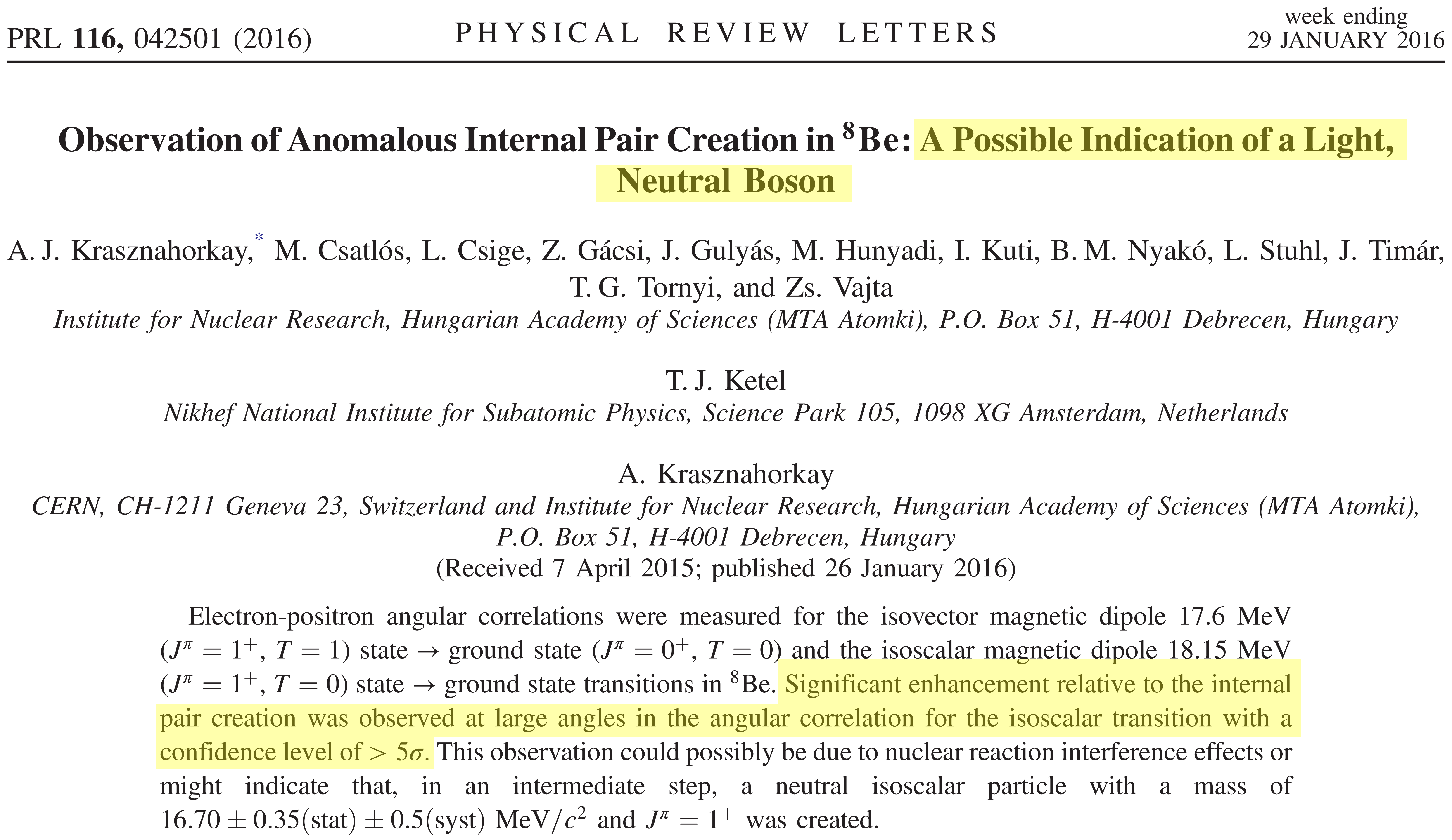
X(17MeV)
ATOMKI Boson?

Sumit Ghosh, P.Ko, arXiv:2311.14099 [hep-ph]

Work in progress with Jinheung Kim, (Y.J.Kwon + ??)

Some slides taken from the CERN seminar by Luigi Delle Rose

ATOMKI X(17 MeV) Boson



PRL **116,** 042501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson

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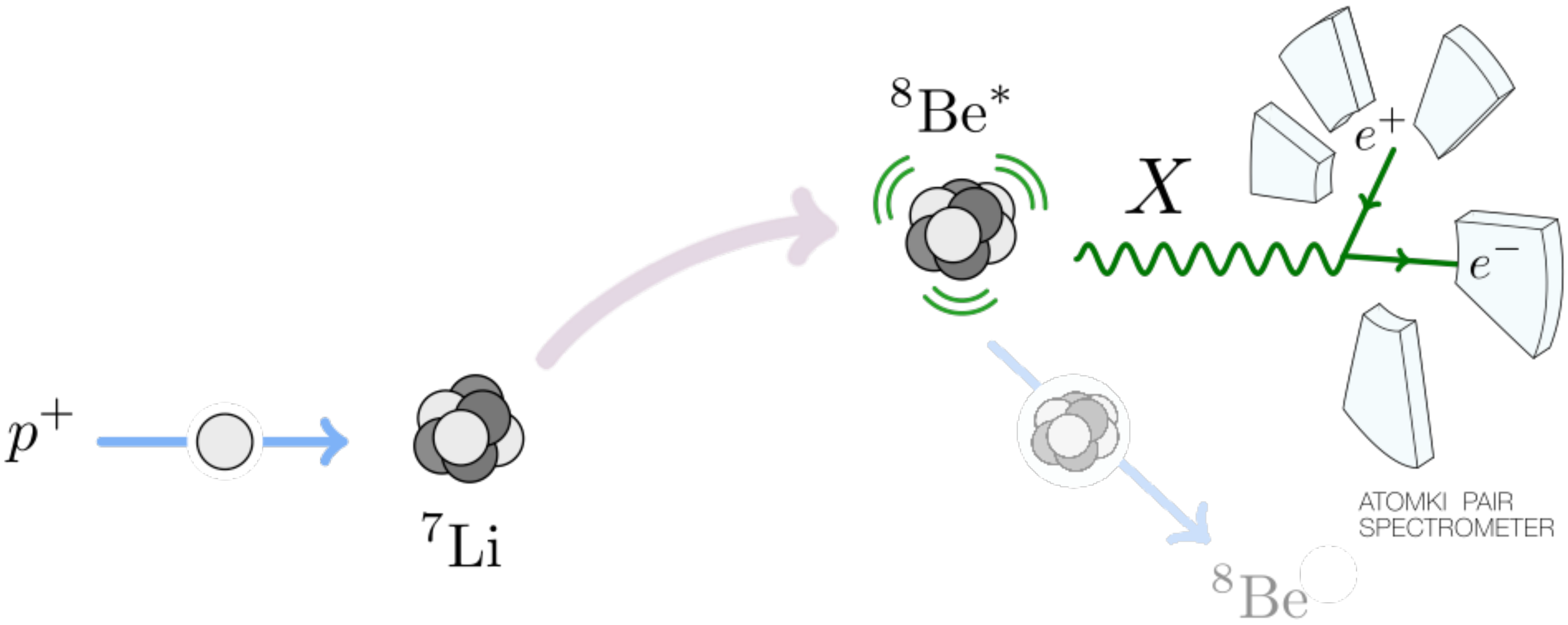
(Received 7 April 2015; published 26 January 2016)

Electron-positron angular correlations were measured for the isovector magnetic dipole 17.6 MeV ($J^\pi = 1^+$, $T = 1$) state → ground state ($J^\pi = 0^+$, $T = 0$) and the isoscalar magnetic dipole 18.15 MeV ($J^\pi = 1^+$, $T = 0$) state → ground state transitions in ^{8}Be. Significant enhancement relative to the internal pair creation was observed at large angles in the angular correlation for the isoscalar transition with a confidence level of $> 5\sigma$. This observation could possibly be due to nuclear reaction interference effects or might indicate that, in an intermediate step, a neutral isoscalar particle with a mass of $16.70 \pm 0.35(\mathrm{stat}) \pm 0.5(\mathrm{syst})$ MeV/c^2 and $J^\pi = 1^+$ was created.



arXiv:1608.03591

The Atomki pair spectrometer experiment was set up for searching e$^+$e$^-$ internal pair creation in the decay of excited ^{8}Be nuclei, the latter being produced with help of a beam of protons directed on a ^{7}Li target. The proton beam was tuned in such a way that the different ^{8}Be excitations could be separated with high accuracy.

$^8\mathrm{Be}$ Decay Modes

- Hadronic decay (BR ~ 1)

$$^8\mathrm{Be}^* \to {}^7\mathrm{Li} + p$$

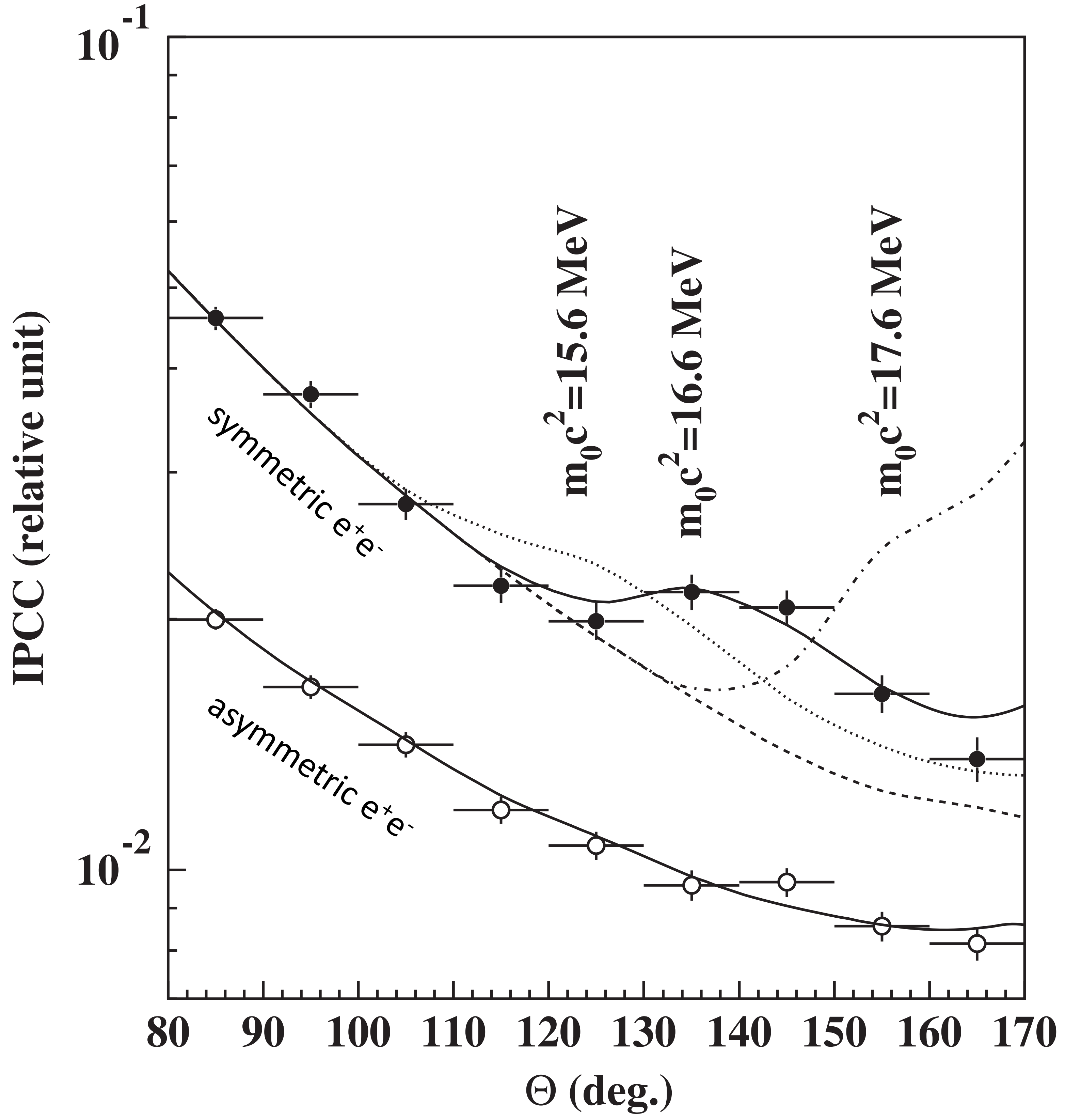
- Electromagnetic decay (BR ~ 1.5 x 10^{-5})

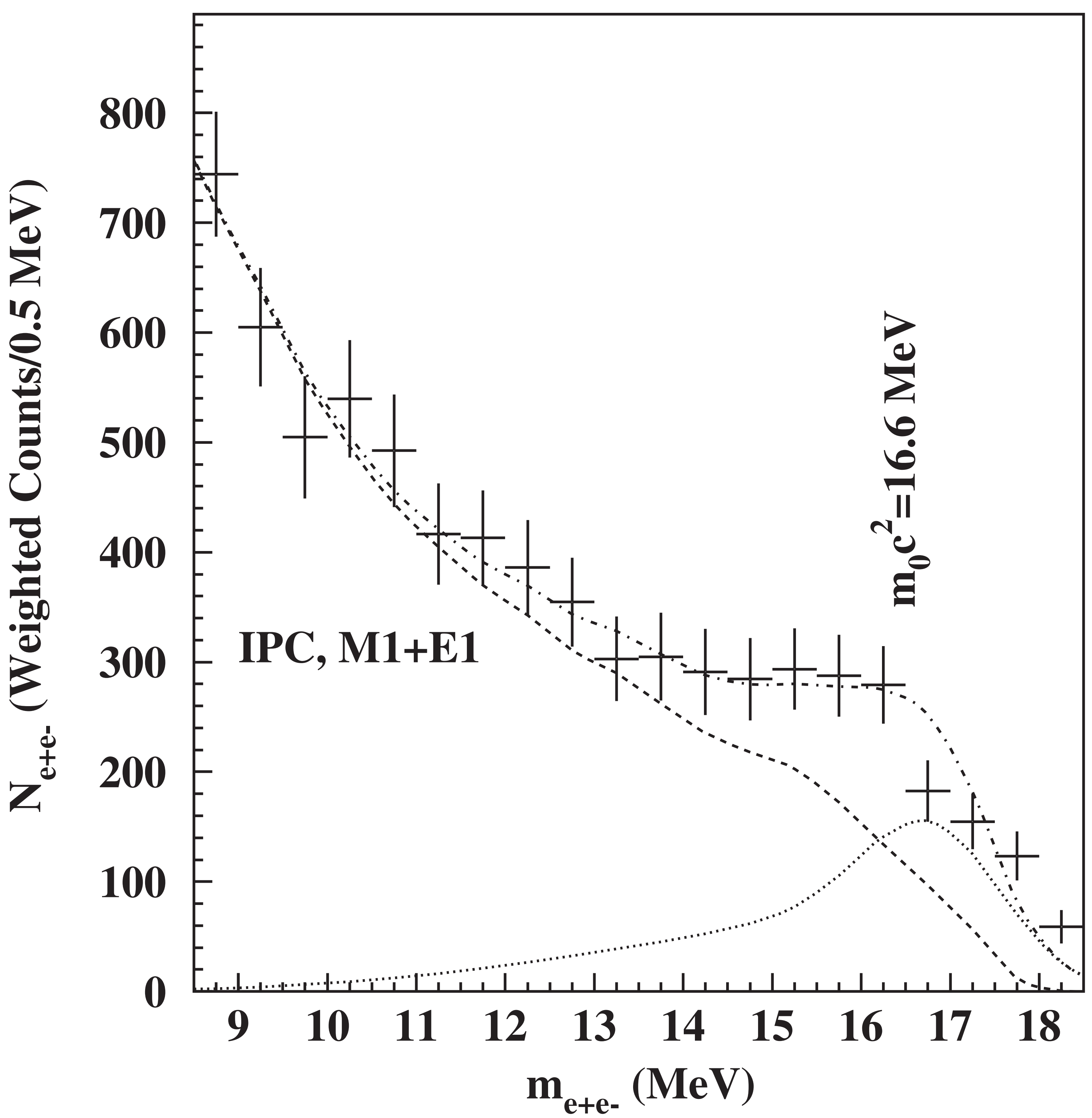
$$^8\mathrm{Be}^* \to {}^8\mathrm{Be} + \gamma$$

- Internal pair creation (BR ~ 5.5 x 10^{-8})

$$^8\mathrm{Be}^* \to {}^8\mathrm{Be} + \gamma^* \to {}^8\mathrm{Be} + e^+ e^-$$

^{8}Be Anomaly





arXiv:1504.01527

$$M_X = 16.7 \pm 0.35 \text{ (stat) } \pm 0.5 \text{ (sys) MeV}$$

$$\frac{\mathrm{BR}(^8\mathrm{Be}^* \to X + {}^8\mathrm{Be})}{\mathrm{BR}(^8\mathrm{Be}^* \to \gamma + {}^8\mathrm{Be})} \times \mathrm{BR}(X \to e^+e^-) = 5.8 \times 10^{-6}$$

Statistical significance of the excess of about 6.8 σ

Possible Explanations

1. The $X \to e^+e^-$ decay implies that X is a boson

2. Candidates:

   a) **Scalars** $(J^P = 0^+)$
   not allowed since $1^+ \to 0^+0^+$ *would imply L = 1 and* $(-1)^L$

   b) **Pseudoscalars** $(J^P = 0^-)$
   decay width $\sim |k|^3/m_X^3$ implies new Yukawa couplings $Y \sim 0.3\ Y_{SM}$

   c) **Vectors** $(J^P = 1^-)$
   decay width $\sim |k|^3/m_X^3$ implies g' ~ 10^{-3}

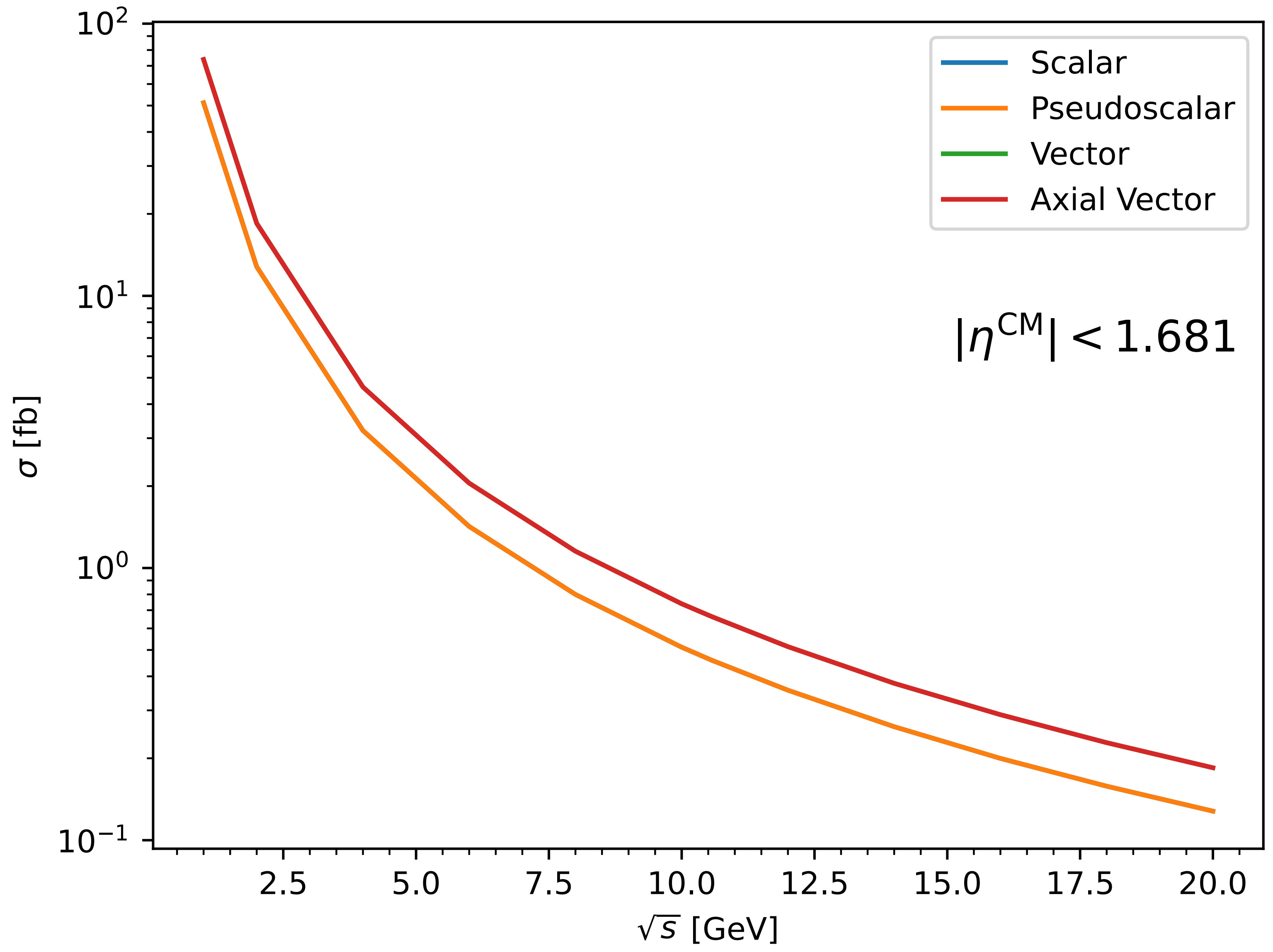
   d) **Axial-vectors** $(J^P = 1^+)$
   nuclear matrix elements have been computed only recently (arXiv:1612.01525)
   decay width $\sim |k|/m_X$ implies g' ~ 10^{-4}

   e) **Vector + Axial-vector spin-1 bosons**
   strongly constrained by atomic parity violation

X(17MeV) @ Belle II ?

- $e^+e^- \to \gamma X(17\mathrm{MeV})$, followed by $X \to e^+e^-, q\bar{q}$
- $$^8\mathrm{Be}^*(18.15) \to {}^8\mathrm{Be} + X(X \to e^+e^-)$$
- $$m_X = 16.70 \pm 0.35(stat) \pm 0.5(sys)\ \mathrm{MeV}$$
  $$\frac{\Gamma\left({}^8\mathrm{Be}^*(18.15) \to {}^8\mathrm{Be}\ X\right)}{\Gamma\left({}^8\mathrm{Be}^*(18.15) \to {}^8\mathrm{Be}\ \gamma\right)} Br(X \to e^+e^-) = 5.8 \times 10^{-6}$$
- However this excess has not been seen by MEG@PSI (still consistent w/ ATOMKI @ 1.5 σ level) !
- 2HDM w/ U(1) Higgs gauge symmetry: Sumit Ghosh, P.Ko, arXiv:2311.14099 [hep-ph]
- Can we search for it @ Belle II, BEPC, Phi factory, etc.?

$$\sigma(e^+e^- \to \gamma X)$$



- If we consider $X \to e^+e^-$ for the vector case, there could be interference with photon exchange, which has not been included in this plot
- Huge background from QED
- Can we reduce bkgd and see the signal?
- Will ML, DL help?
- Any suggestions/collaborations are welcome!

Polar angle distributions