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Dark Higgs-strahlung at Belle II

A distinctive dark sector signature with displaced vertices and missing energy

Launching the Second Century of Quantum Physics - Brookhaven Forum 2025

From 2508.09247 - FA, Felix Kahlhöfer

In this talk

- A model for a Dark Sector
- A promising signal... or two!
- Background: where are you?
- Event selection
- Results

Dark Higgs

$$\mathscr{L}_\Phi = \left[\left(\partial^\mu + ig' q_\Phi A'^\mu\right)\Phi\right]^\dagger \left[\left(\partial_\mu + ig' q_\Phi A'_\mu\right)\Phi\right] - V(\Phi, H)$$

$$V(\Phi, H) \supset \lambda_{h\phi} |\Phi|^2 |H|^2$$

$$\Phi = \frac{\phi + w}{\sqrt{2}}$$

$$h \to \cos\theta\, h + \sin\theta\, \phi,$$
$$\phi \to -\sin\theta\, h + \cos\theta\, \phi\,.$$

$$\theta \approx \frac{\lambda_{h\phi} v w}{m_h^2 - m_\phi^2}$$

Dark Photon

$$\mathscr{L}_{A'} = -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu}$$

$U(1)'$ SBS $\rightarrow m_{A'} = q_\Phi g' w$

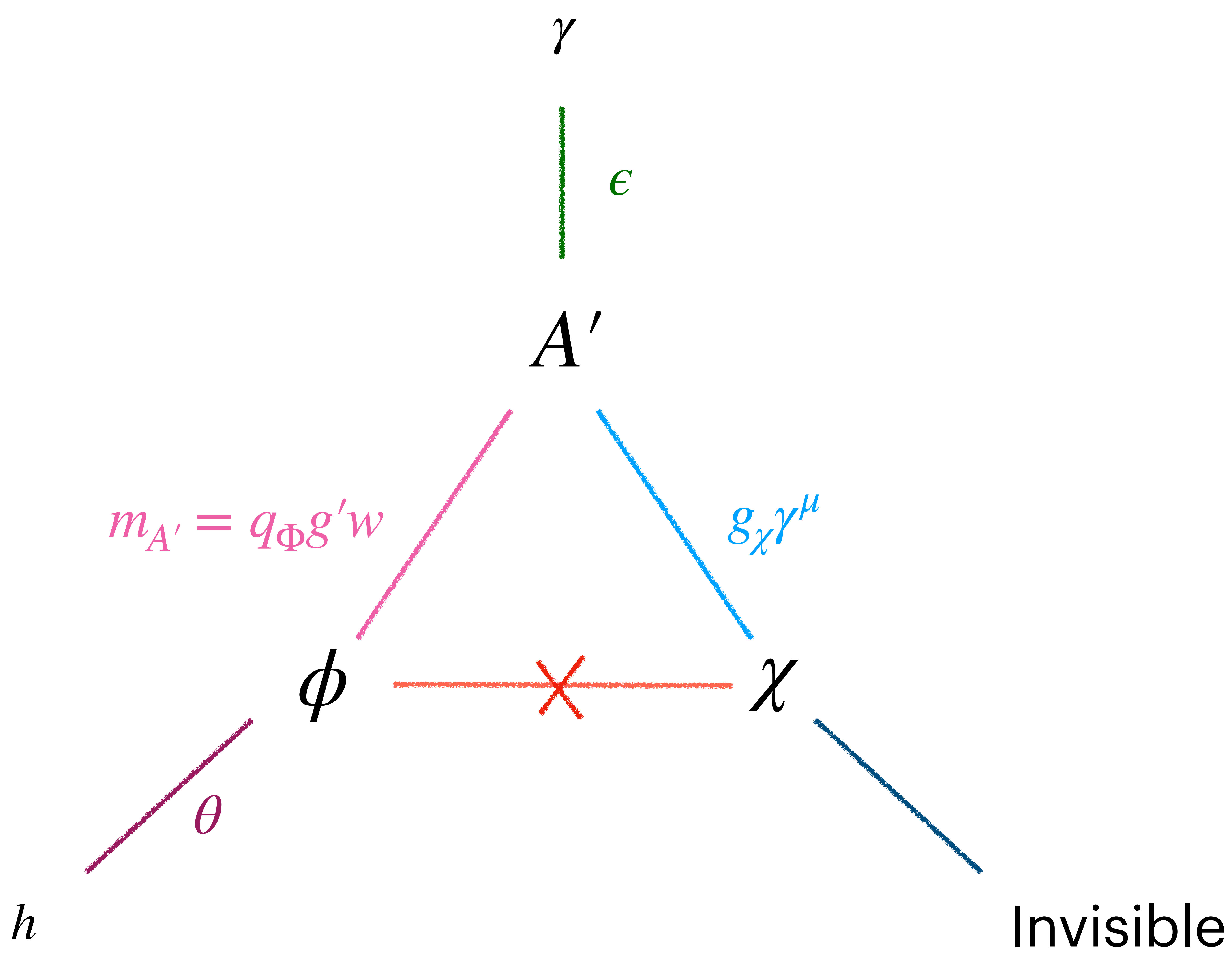
$$\epsilon \ll 1$$

Dark Matter

$$\mathscr{L}_\chi = \bar{\chi}\left(i\partial_\mu\gamma^\mu - g_\chi A'_\mu\gamma^\mu - m_\chi\right)\chi$$

$$g_\chi = q_{\chi_L} g' = q_{\chi_R} g'$$

Forbidden Yukawa


γ
ϵ
A'
$m_{A'} = q_\Phi g' w$
$g_\chi \gamma^\mu$
ϕ
χ
θ
h
Invisible

So many parameters!

$$\boxed{\theta, \epsilon, g_\chi, m_{A'}, m_\chi, m_\phi}$$

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$$\mathbf{B2}\ :(m_{A'}, m_\chi, m_\phi) = m_{A'}\left(1, \frac{1}{4}, \frac{1}{6}\right),$$

$$\mathbf{B3}\ :(m_{A'}, m_\chi, m_\phi) = m_{A'}\left(1, \frac{1}{4}, \frac{1}{8}\right).$$

So many parameters!

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- Use $g_\chi = 1$

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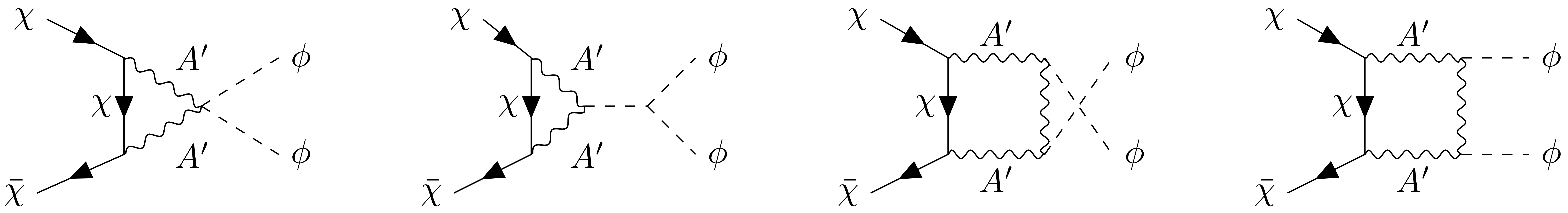
Dark matter relic density



- If you allow $\phi - \chi$ coupling, a sub-GeV DM annihilation would be too efficient in the early universe
- Could pick tiny couplings but then impossible to probe experimentally
- Instead consider only loop-level

- In NR limit: $\sigma v = \dfrac{A\, g_\chi^8 m_\chi^2}{128\pi^5 m_{A'}^4} v^2,\ A \sim \mathcal{O}(1)$ depending on masses ratios

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- $$\mathbf{B1}: m_\chi^{\text{relic}} = (0.89\,\text{GeV})\, g_\chi^4,$$
  $$\mathbf{B2}: m_\chi^{\text{relic}} = (0.07\,\text{GeV})\, g_\chi^4,$$
  $$\mathbf{B3}: m_\chi^{\text{relic}} = (0.66\,\text{GeV})\, g_\chi^4\,.$$
- Kinematic distributions are almost completely independent of g_χ if $\epsilon e \ll g_\chi \ll 4\pi$ because BR$(A' \to \chi\bar{\chi}) \approx 1$ and the narrow-width approximation holds.

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- $$\begin{aligned}\mathbf{B1}&: m_\chi^{\text{relic}} = (0.89\,\text{GeV})\, g_\chi^4,\\ \mathbf{B2}&: m_\chi^{\text{relic}} = (0.07\,\text{GeV})\, g_\chi^4,\\ \mathbf{B3}&: m_\chi^{\text{relic}} = (0.66\,\text{GeV})\, g_\chi^4\,.\end{aligned}$$

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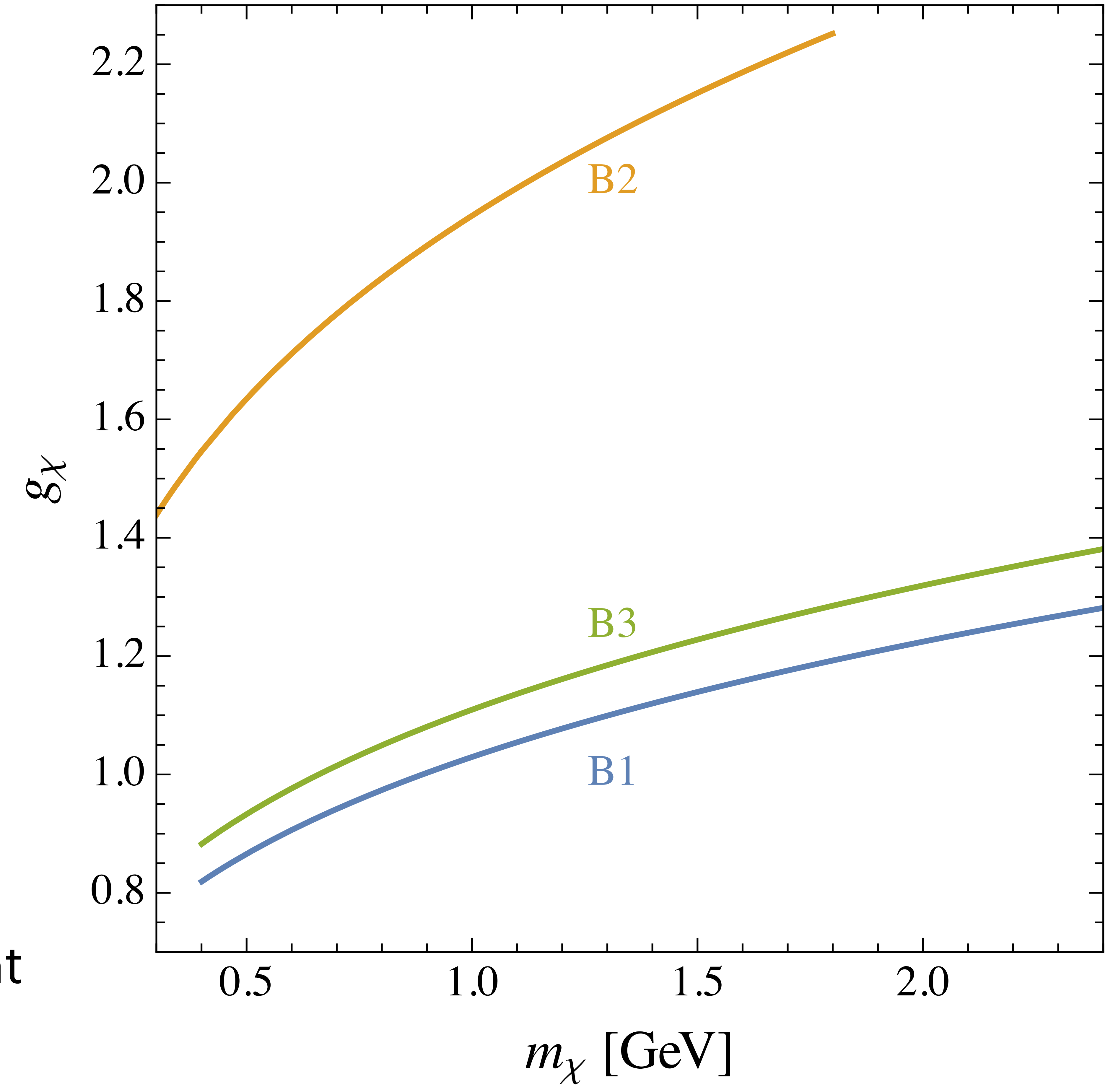
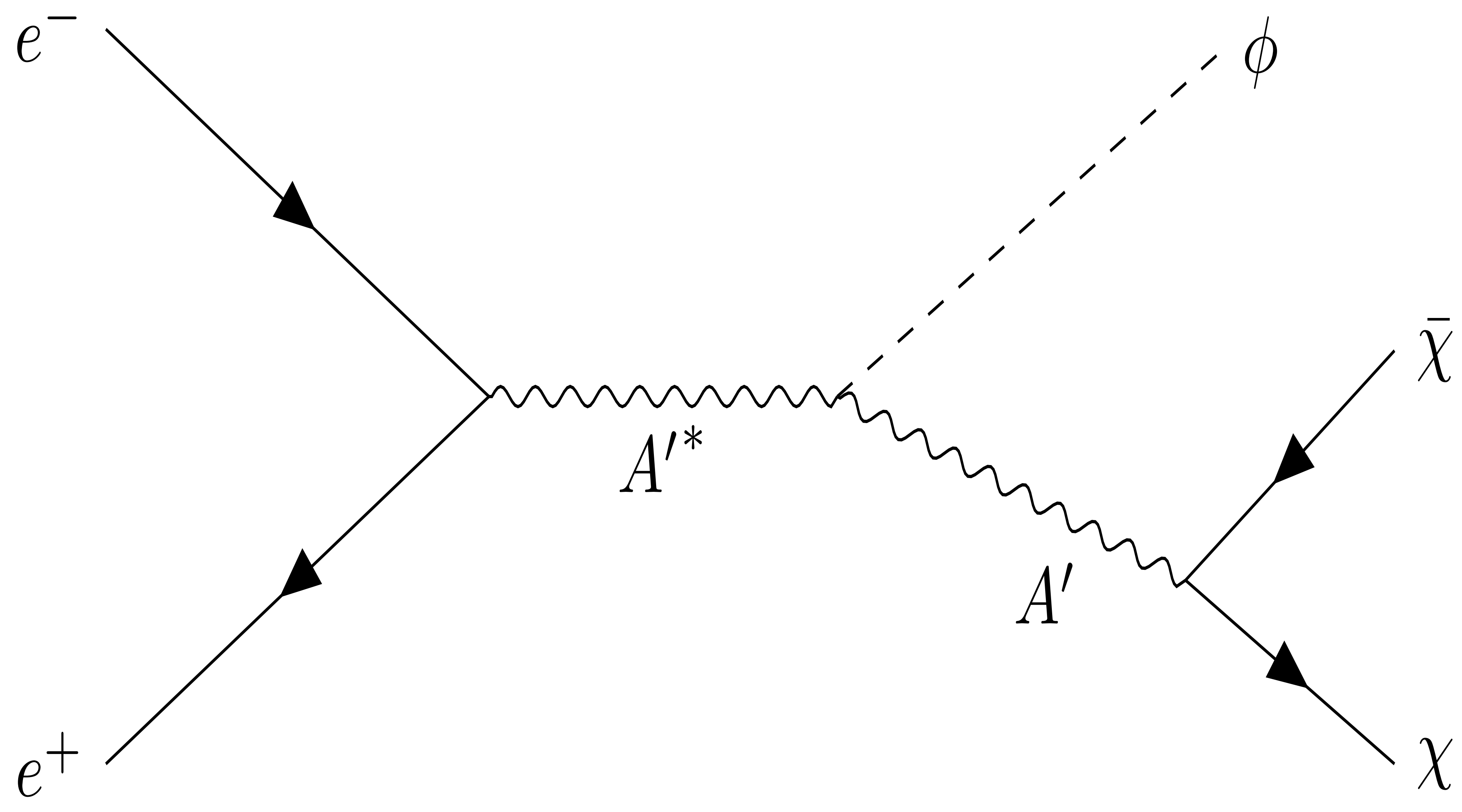
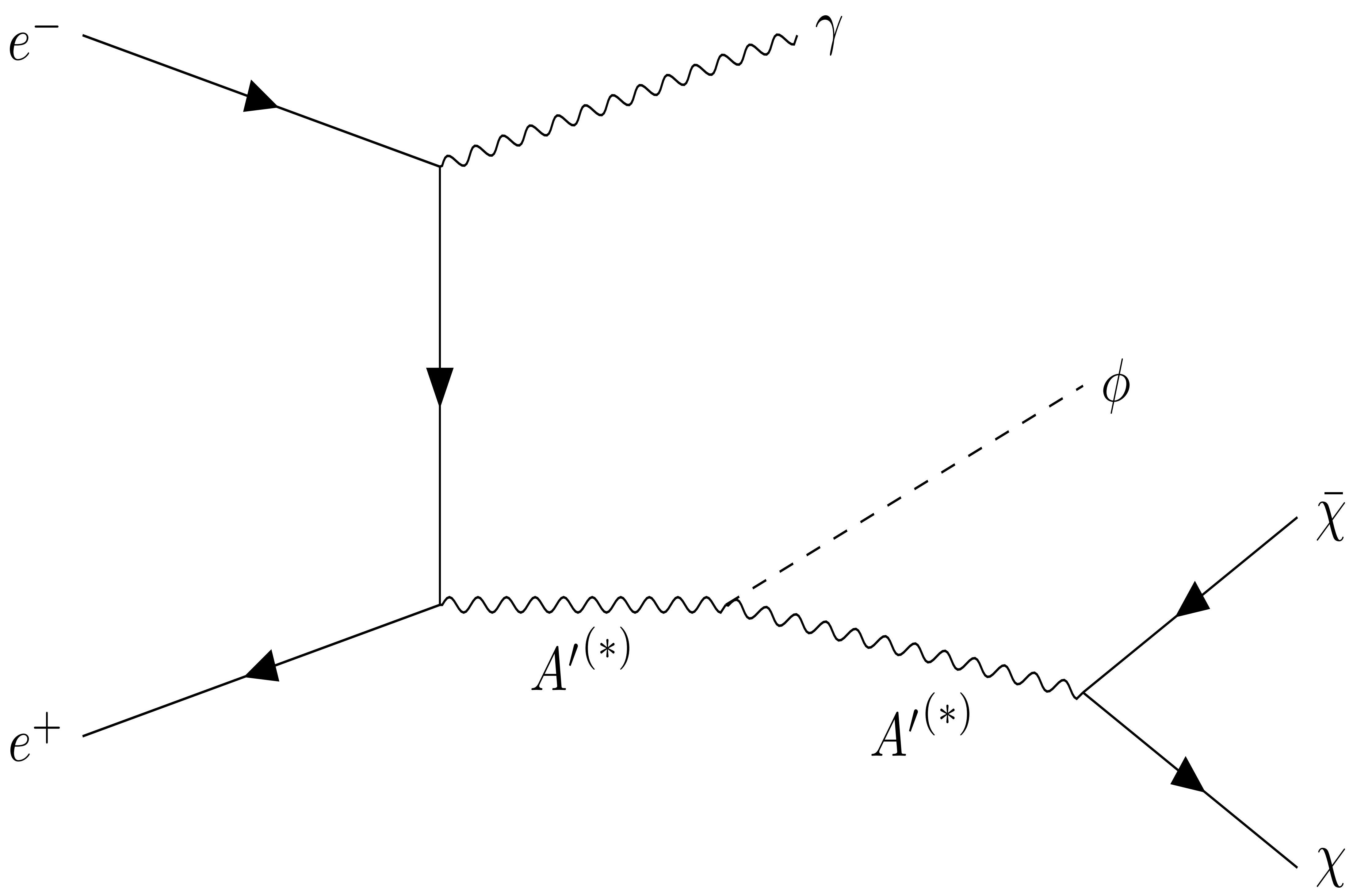


A promising signal... or two!

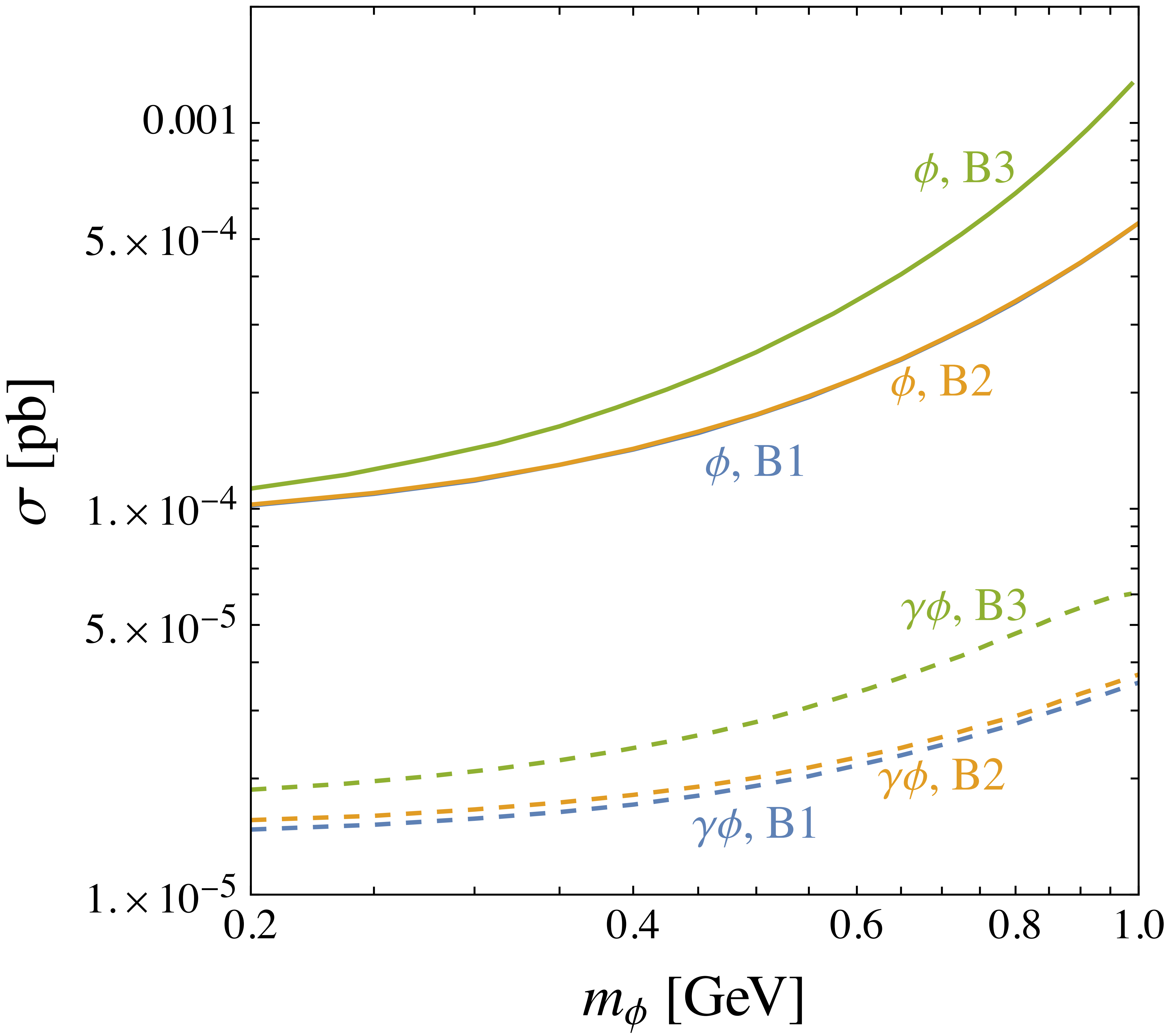


ϕ

- $\phi \to$ SM SM
- Invisible χ
- σ is θ independent but $\Gamma_\phi \sim \theta^2$
- BR$(A' \to \chi\bar{\chi}) \approx 1 \to \epsilon$ independent
- $\sigma \sim \epsilon^2$


e^-
γ
ϕ
$\bar{\chi}$
$A'^{(*)}$
$A'^{(*)}$
e^+
χ

$\gamma\phi$

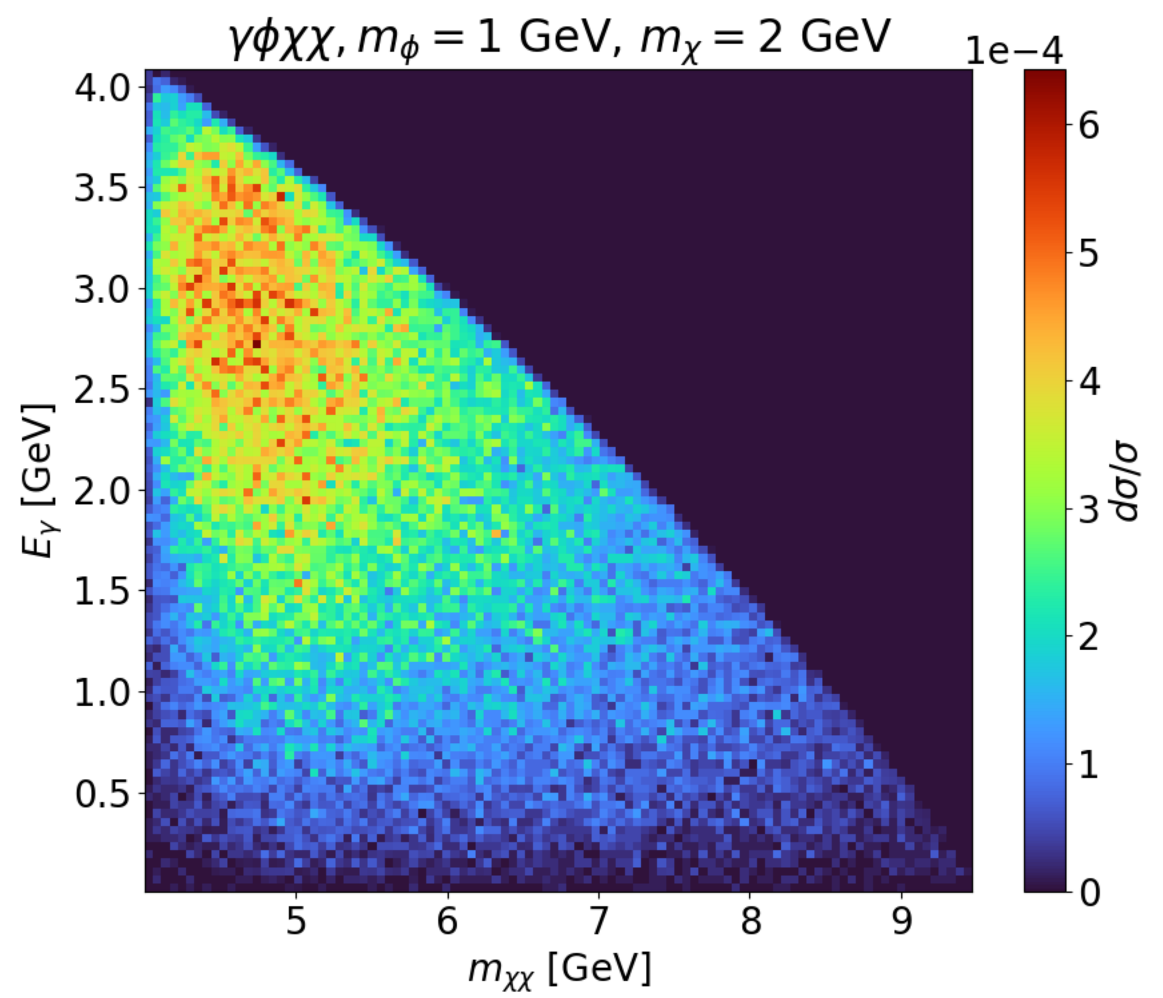

0.001
$5.\times 10^{-4}$
$1.\times 10^{-4}$
$5.\times 10^{-5}$
$1.\times 10^{-5}$
0.2
0.4
0.6
0.8
1.0
σ [pb]
m_ϕ [GeV]
ϕ, B3
ϕ, B2
ϕ, B1
$\gamma\phi$, B3
$\gamma\phi$, B2
$\gamma\phi$, B1

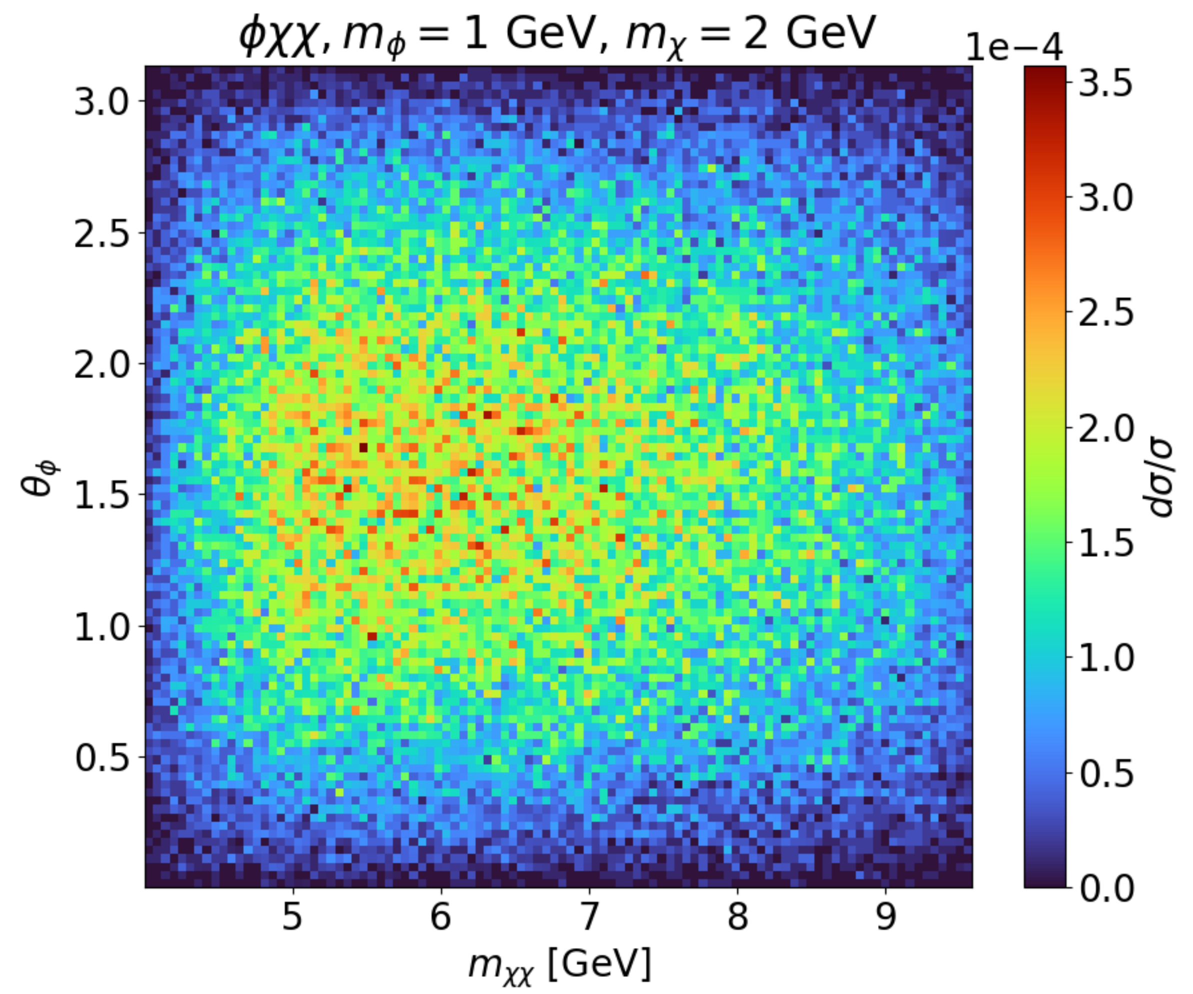
Background: where are you?

- QED processes with missed particle? No displaced vertex
- EW process with neutrinos? No displaced vertex
- A photon conversion? Not in uninstrumented
- A displaced K_S and a missed K_L? Would only have $m_\phi, m_{\chi\chi} \sim 0.5$ GeV.
- Yet $\mathscr{L} = 50\ \mathrm{ab}^{-1}$ and few sig events: very rare decays or scatterings, misidentified final states or misreconstructed vertices

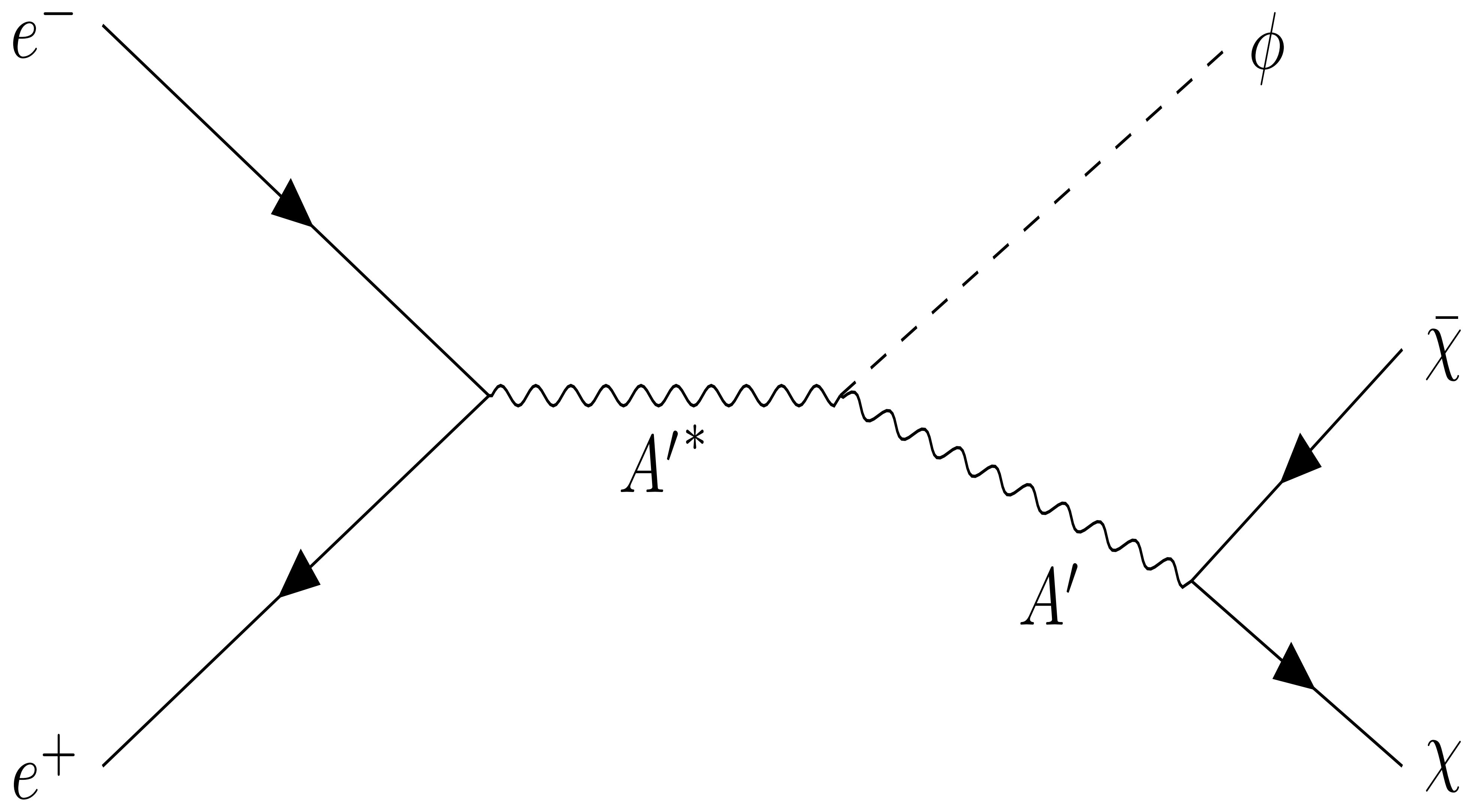
Random Momenta Beautifully Organized

- $\phi \to$ SM SM is detected with efficiency 1
- Trigger efficiency is (realistically) assumed 1
- $$\frac{\sigma_{\text{BG}}(\gamma\phi)}{\sigma_{\text{BG}}(\phi)} = \frac{\sigma_{\text{SM}}(3\gamma)}{\sigma_{\text{SM}}(2\gamma)} = 0.22$$
- $$1 \leq N_B \leq 10^4$$
- Bg always displaced

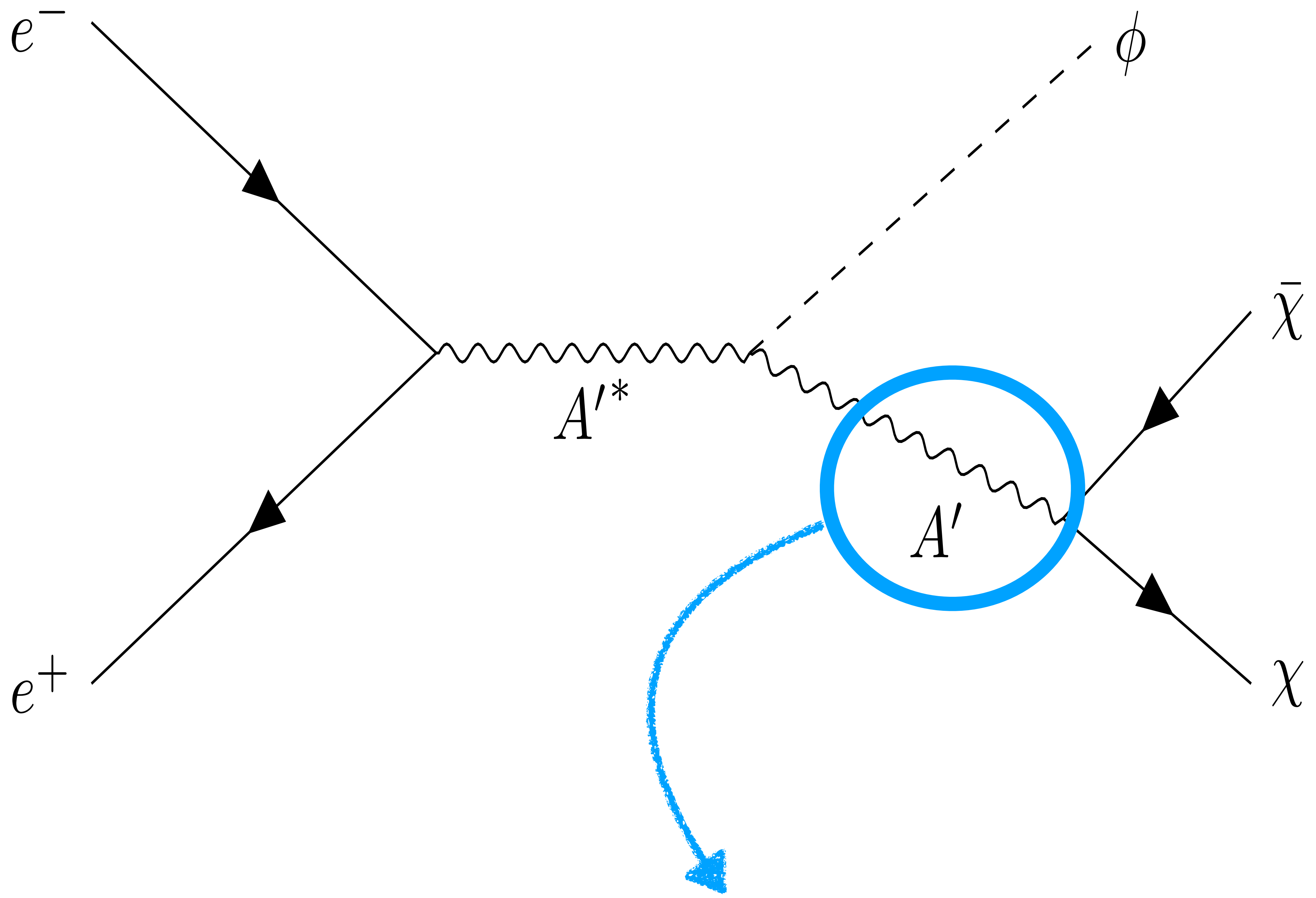


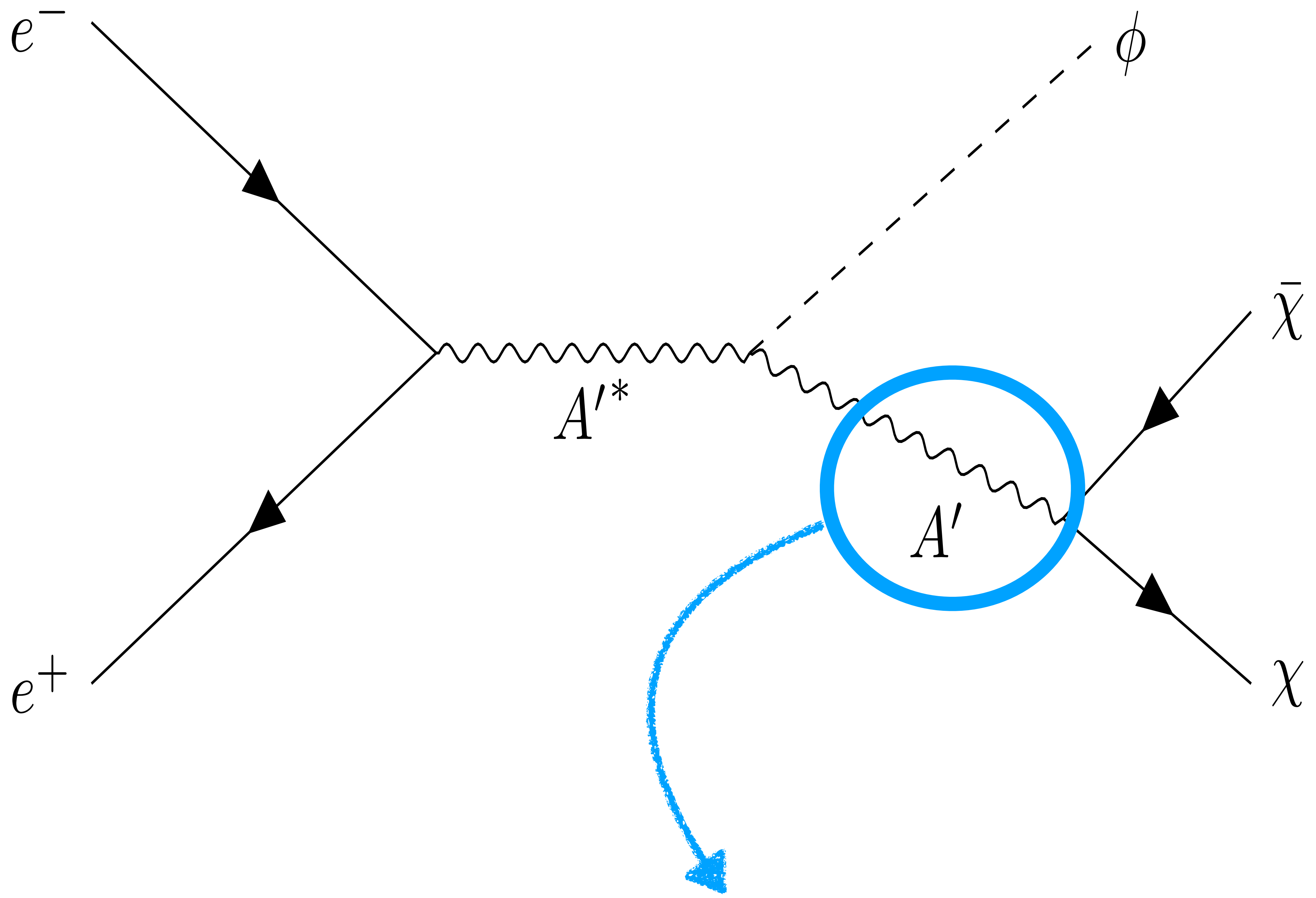


Event selection

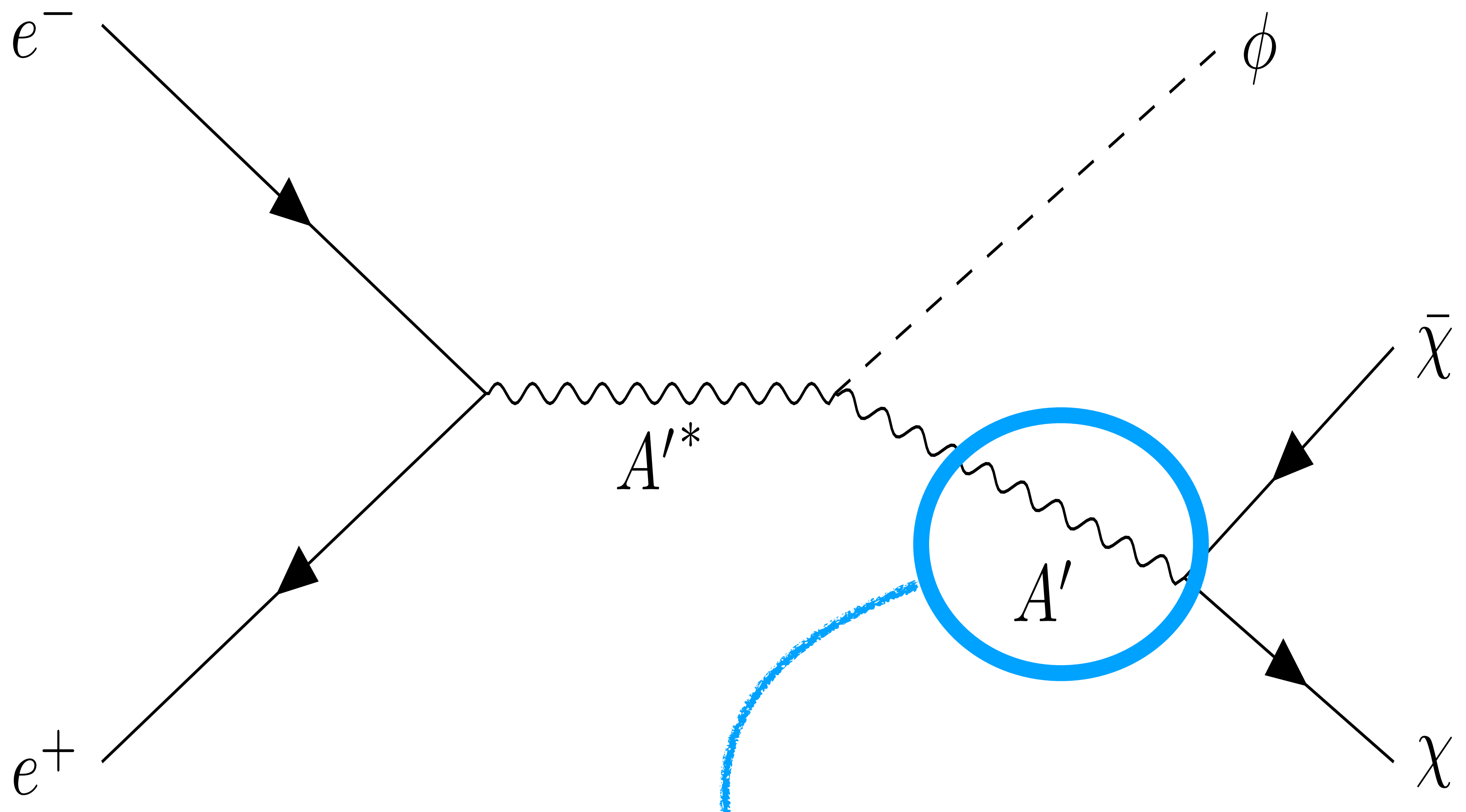


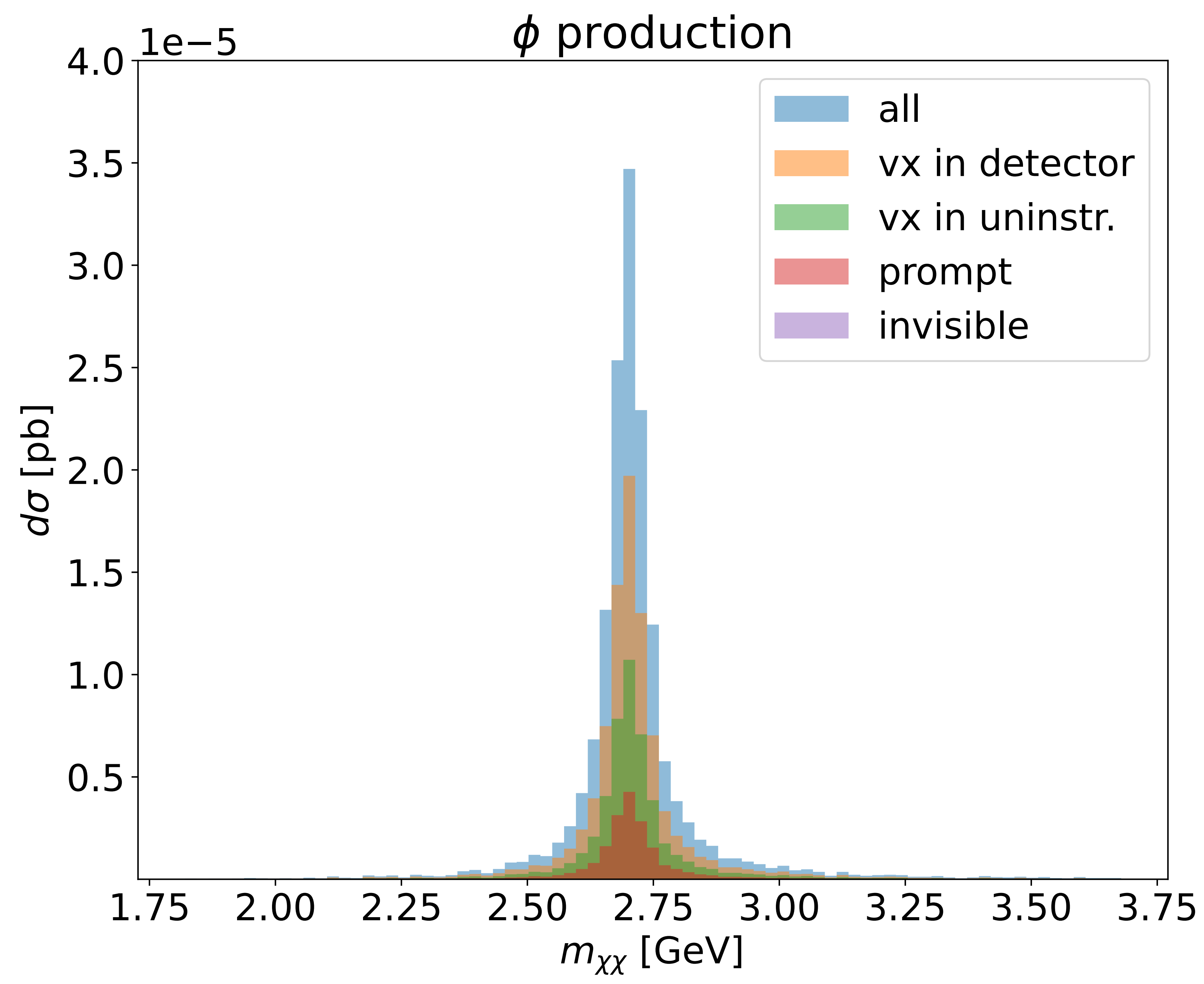
e^-
ϕ
$\bar{\chi}$
A'^*
A'
e^+
χ


e^-
ϕ
$\bar{\chi}$
A'^*
A'
e^+
χ



$$\frac{1}{m_{\chi\chi}^2 - m_{A'}^2 + i m_{A'} \Gamma}$$





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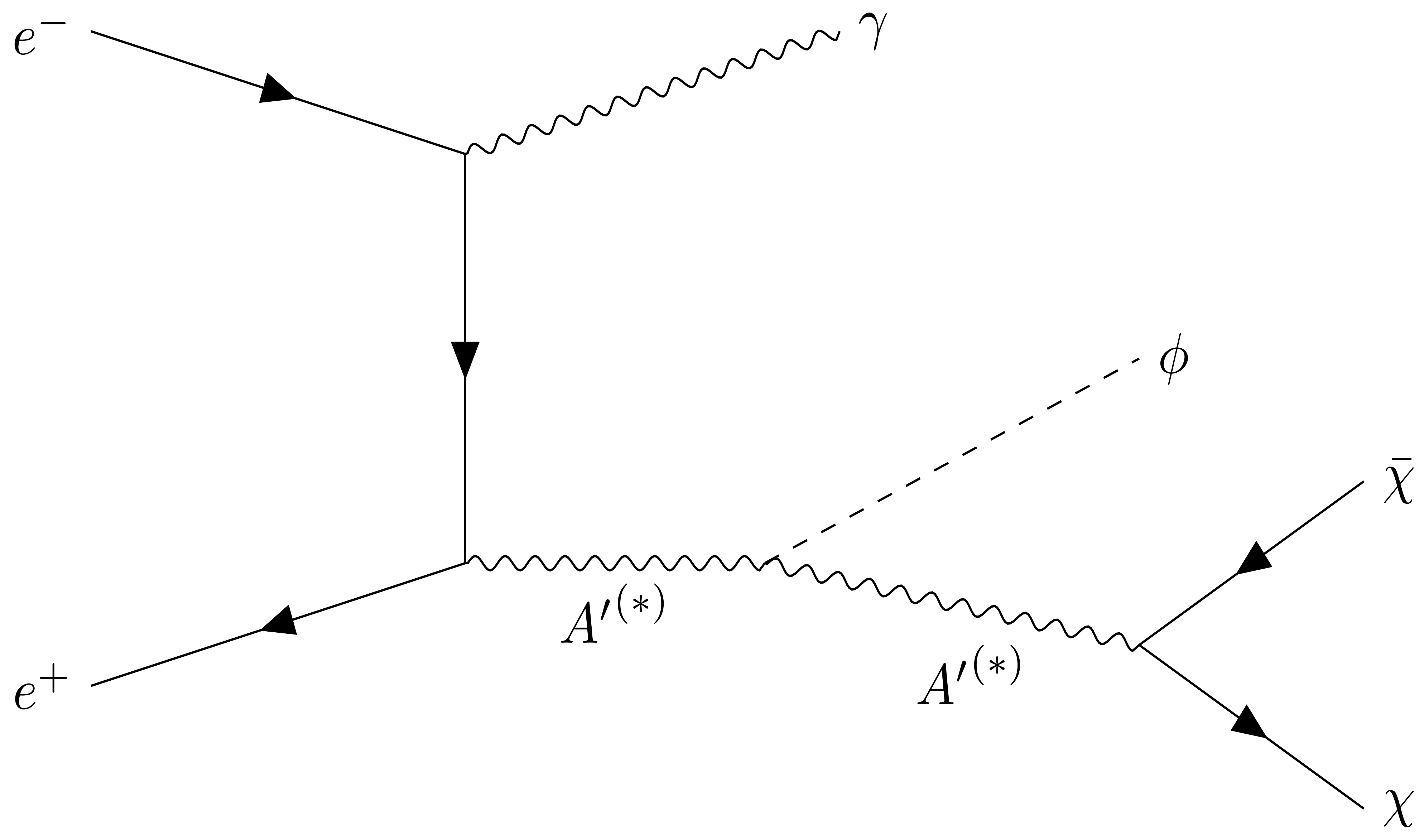
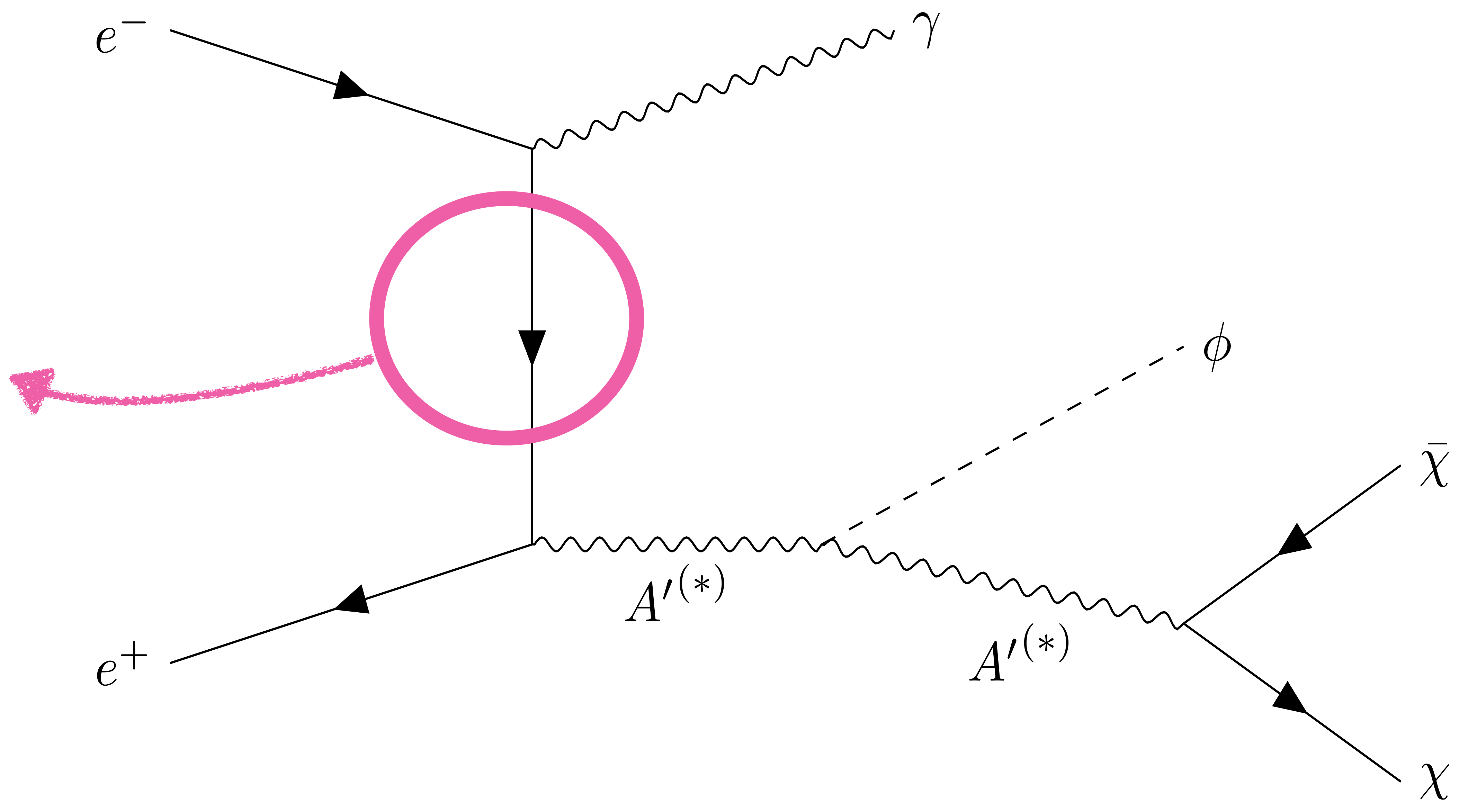
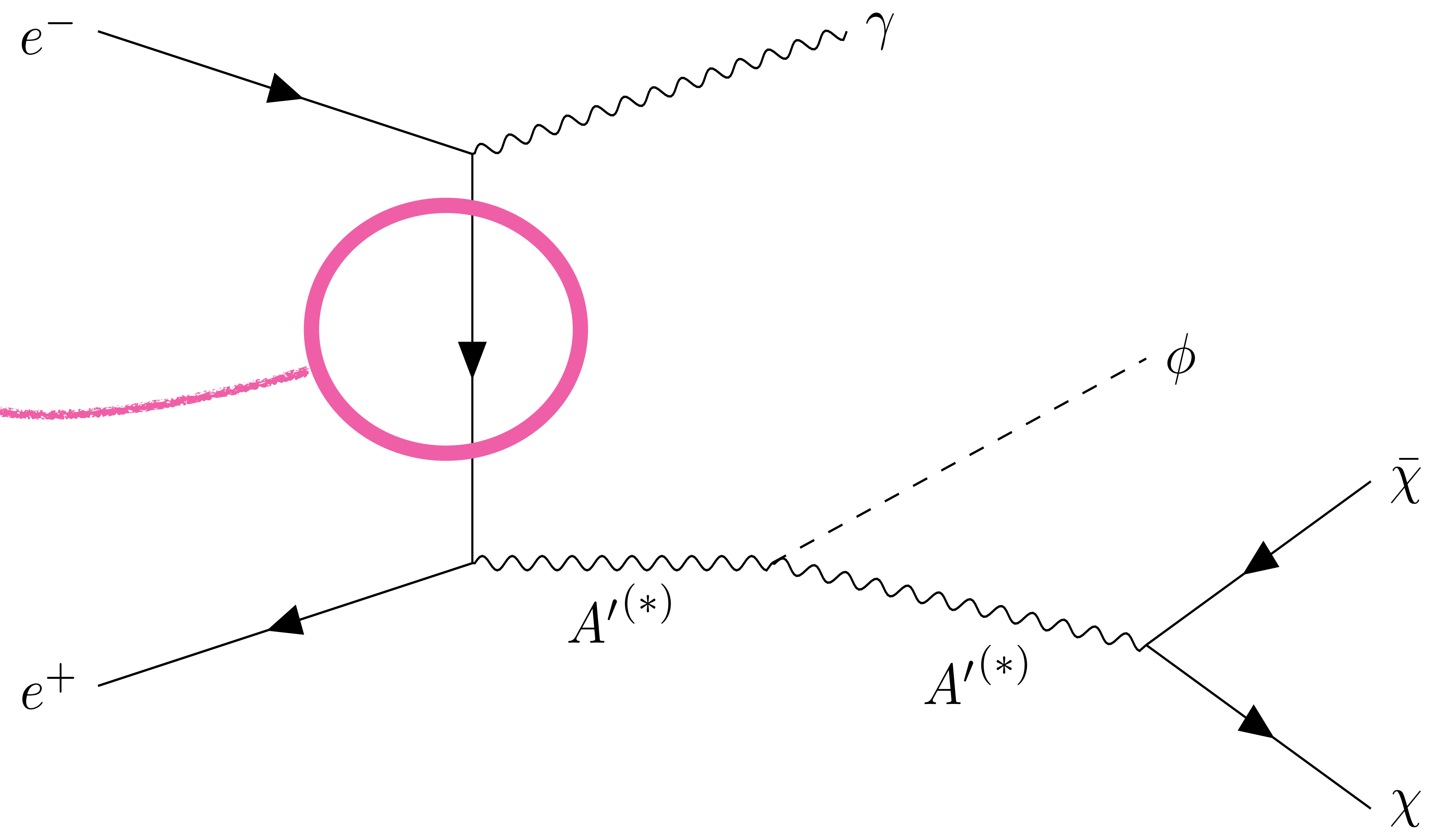

e^-
γ
ϕ
$\bar{\chi}$
e^+
$A'^{(*)}$
$A'^{(*)}$
χ

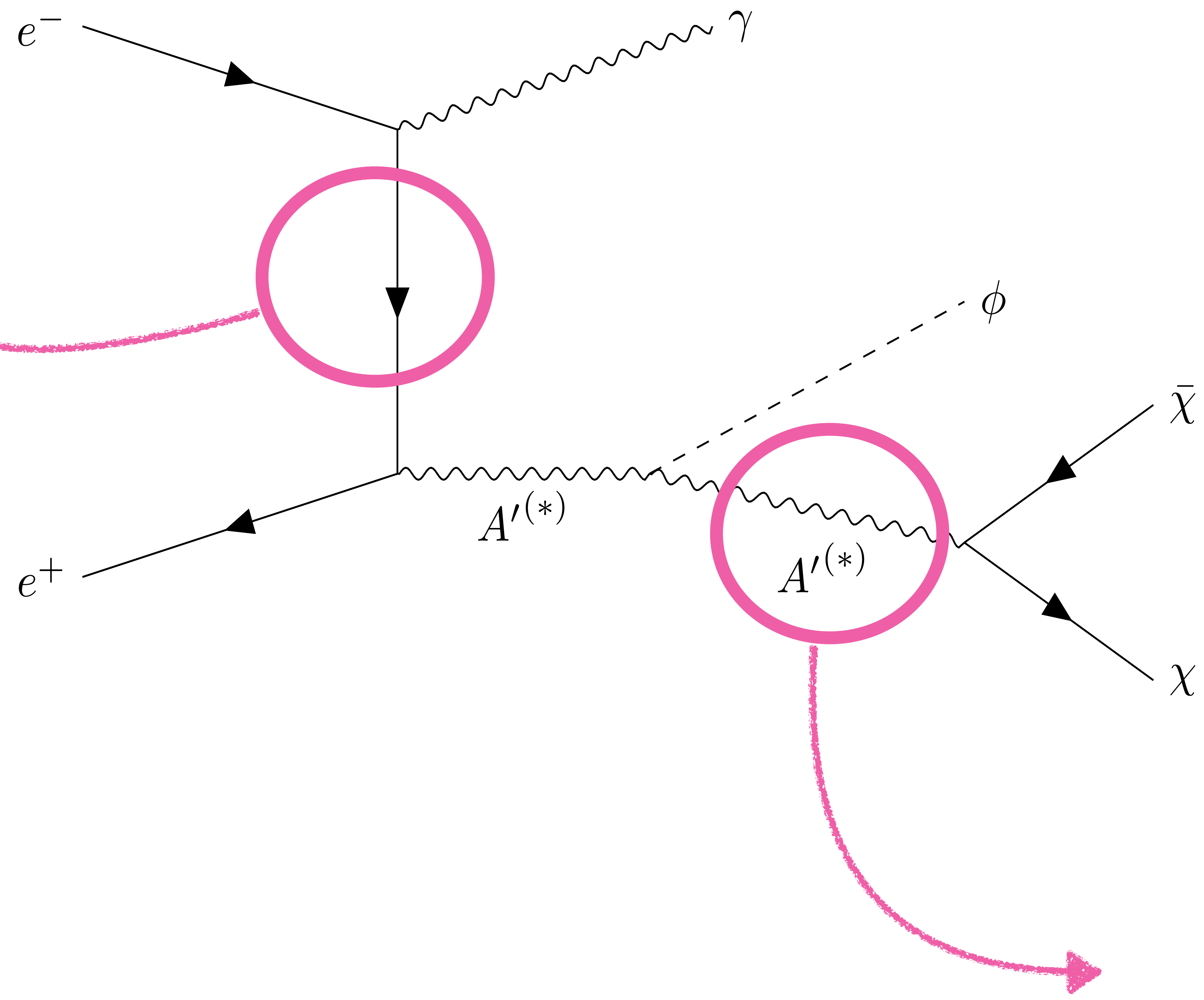


e^-
γ
ϕ
$\bar{\chi}$
$A'^{(*)}$
e^+
$A'^{(*)}$
χ

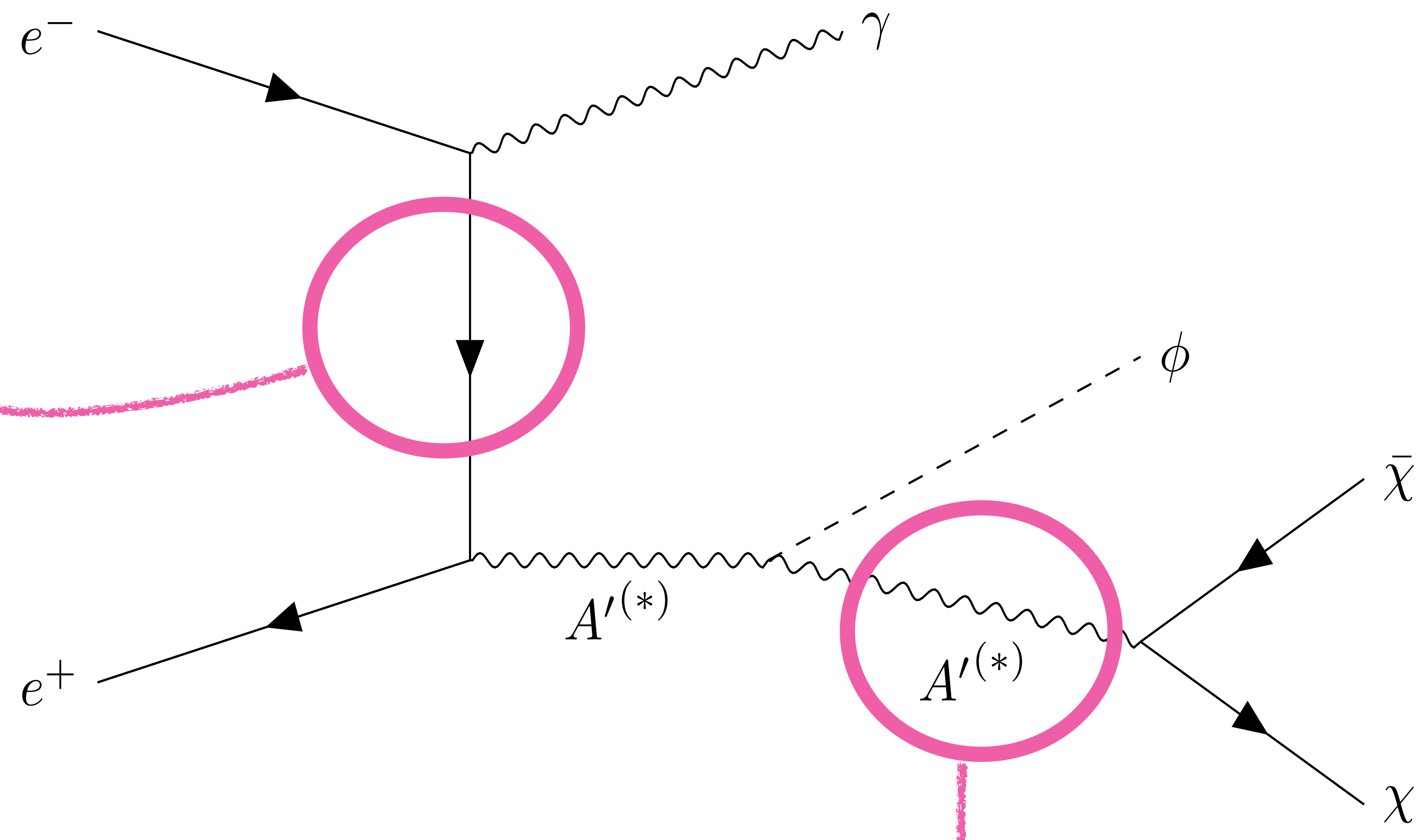
$$\frac{1}{-\sqrt{s}E_\gamma(1-\cos\theta_\gamma)}$$



$$\frac{1}{-\sqrt{s}E_\gamma(1-\cos\theta_\gamma)}$$

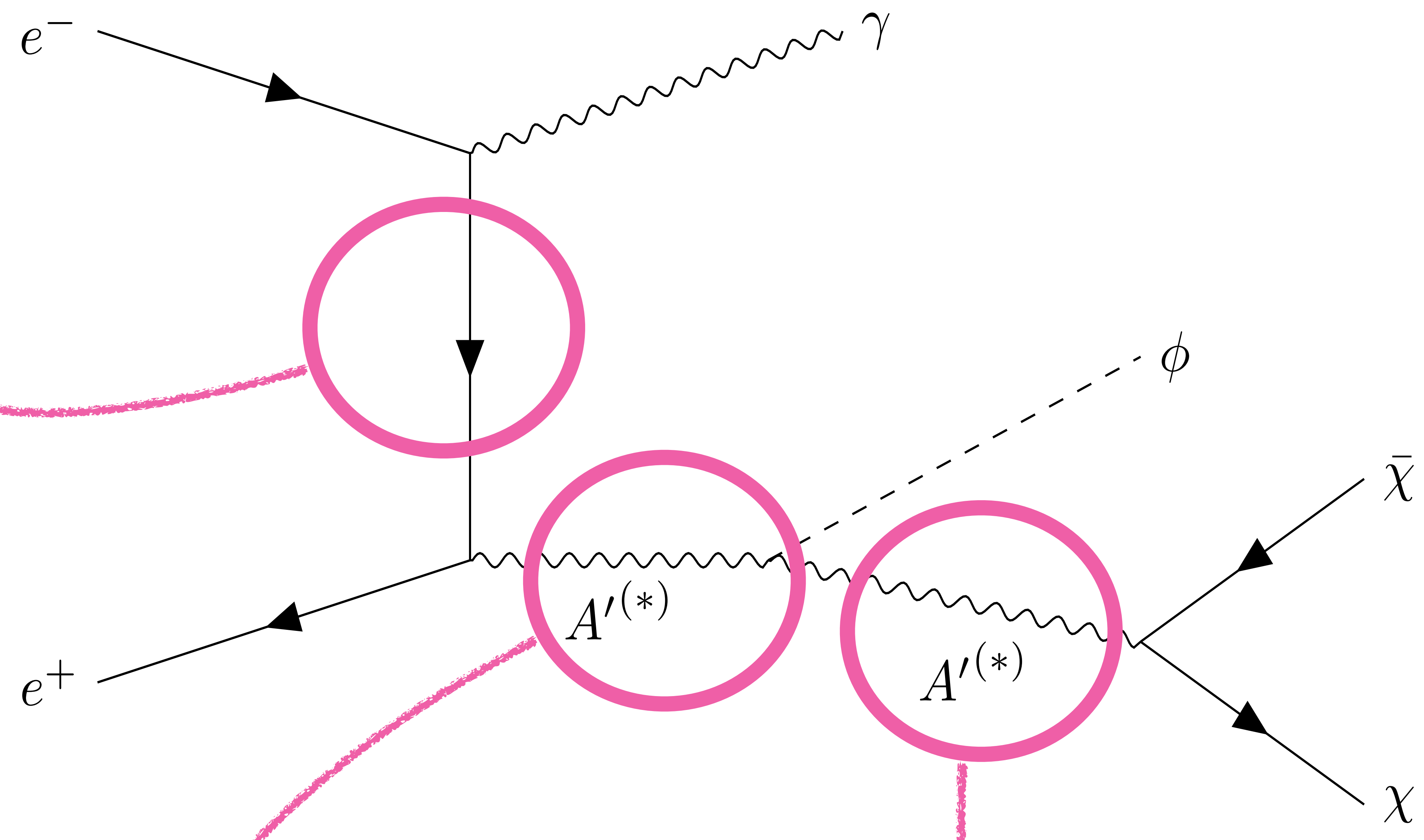


$$\frac{1}{-\sqrt{s}E_\gamma(1-\cos\theta_\gamma)}$$



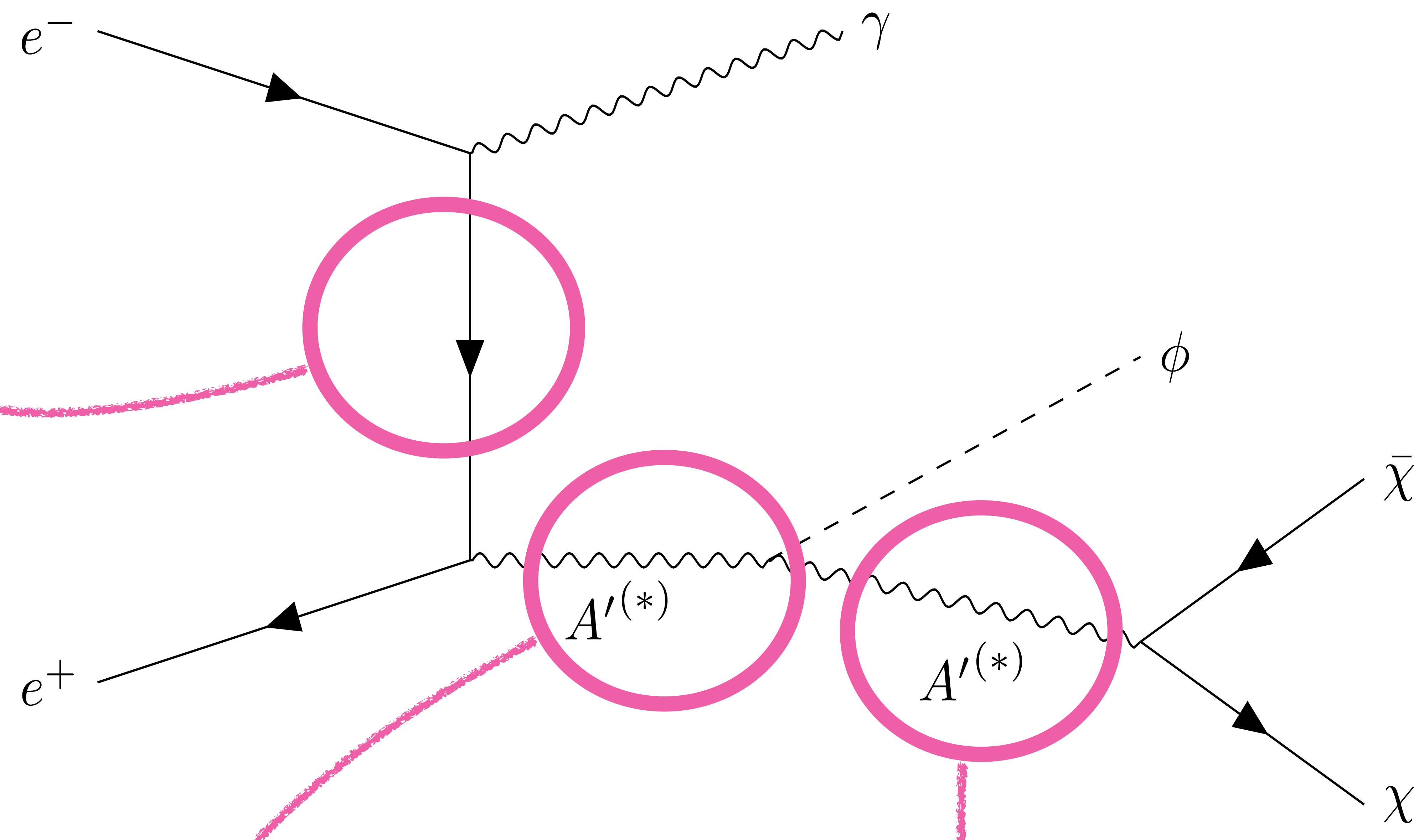
$$\frac{1}{m_{\chi\chi}^2 - m_{A'}^2 + i m_{A'}\Gamma}$$

$$\frac{1}{-\sqrt{s}E_\gamma(1-\cos\theta_\gamma)}$$



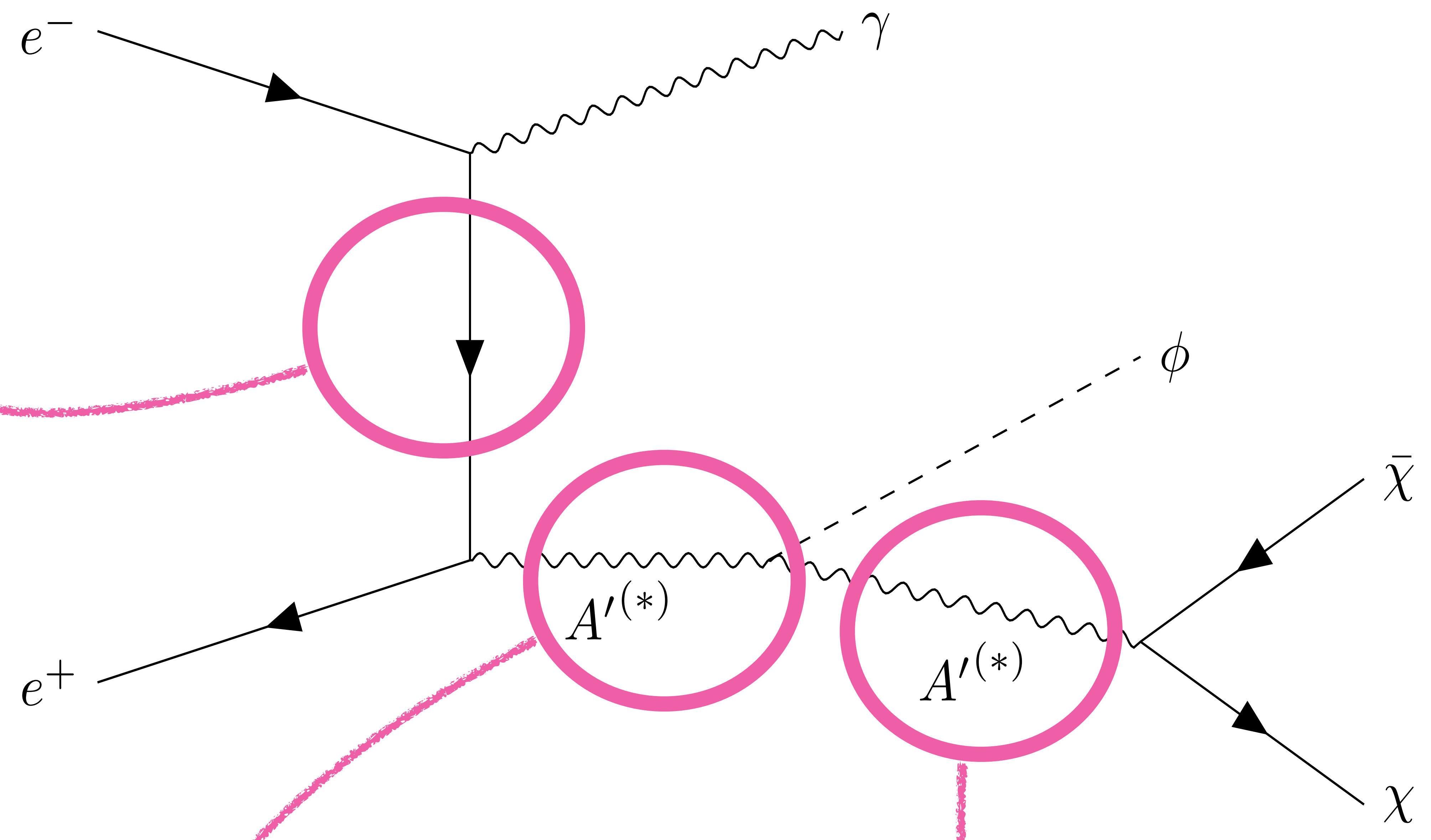
$$\frac{1}{m^2_{\chi\chi}-m^2_{A'}+im_{A'}\Gamma}$$

$$\frac{1}{-\sqrt{s}E_\gamma(1-\cos\theta_\gamma)}$$



$$\frac{1}{(p_1+p_2-p_\gamma)^2-m_{A'}^2+im_{A'}\Gamma_{A'}}$$

$$\frac{1}{m_{\chi\chi}^2-m_{A'}^2+im_{A'}\Gamma}$$

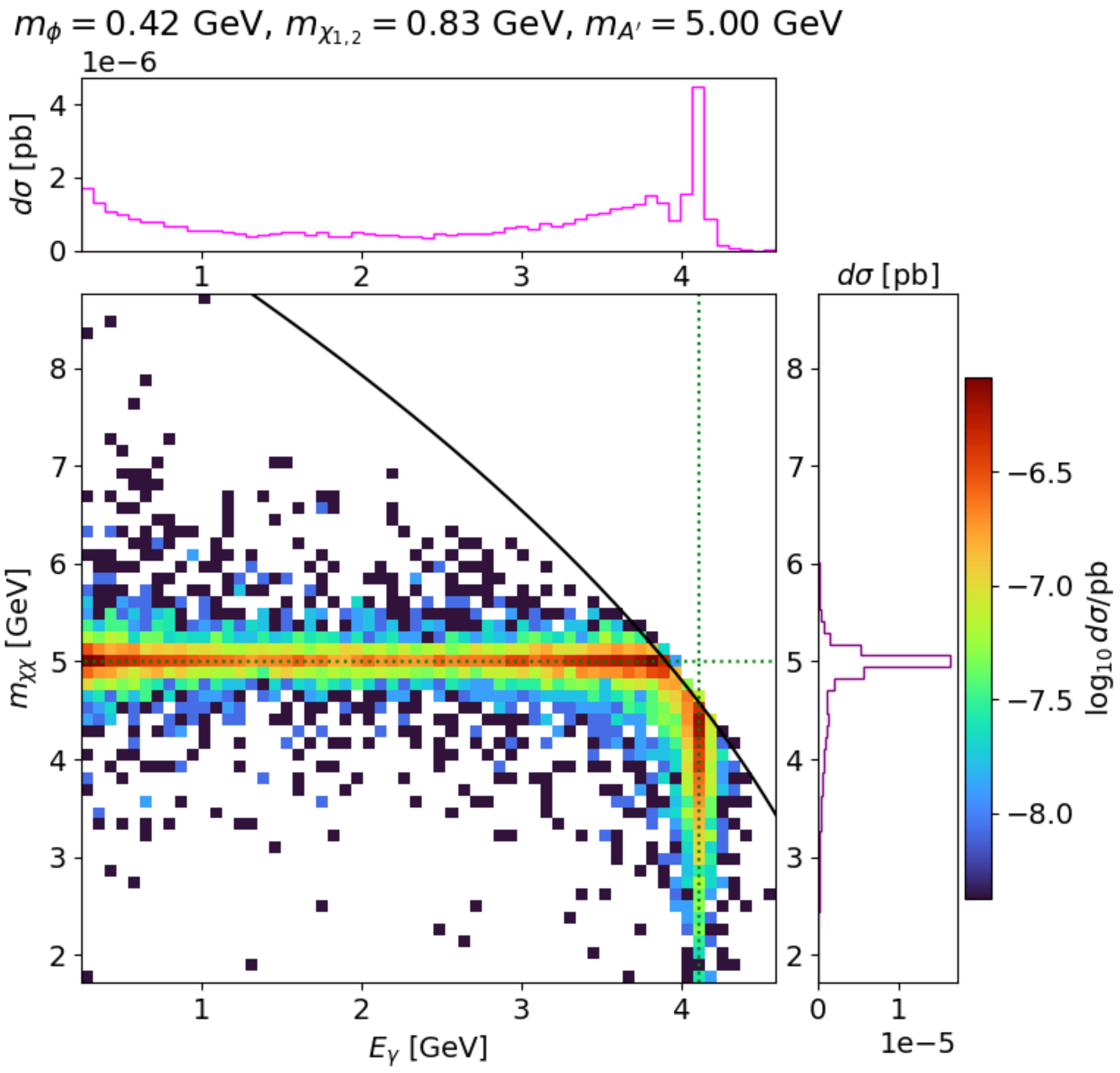


$$\frac{1}{-\sqrt{s}E_\gamma(1-\cos\theta_\gamma)}$$

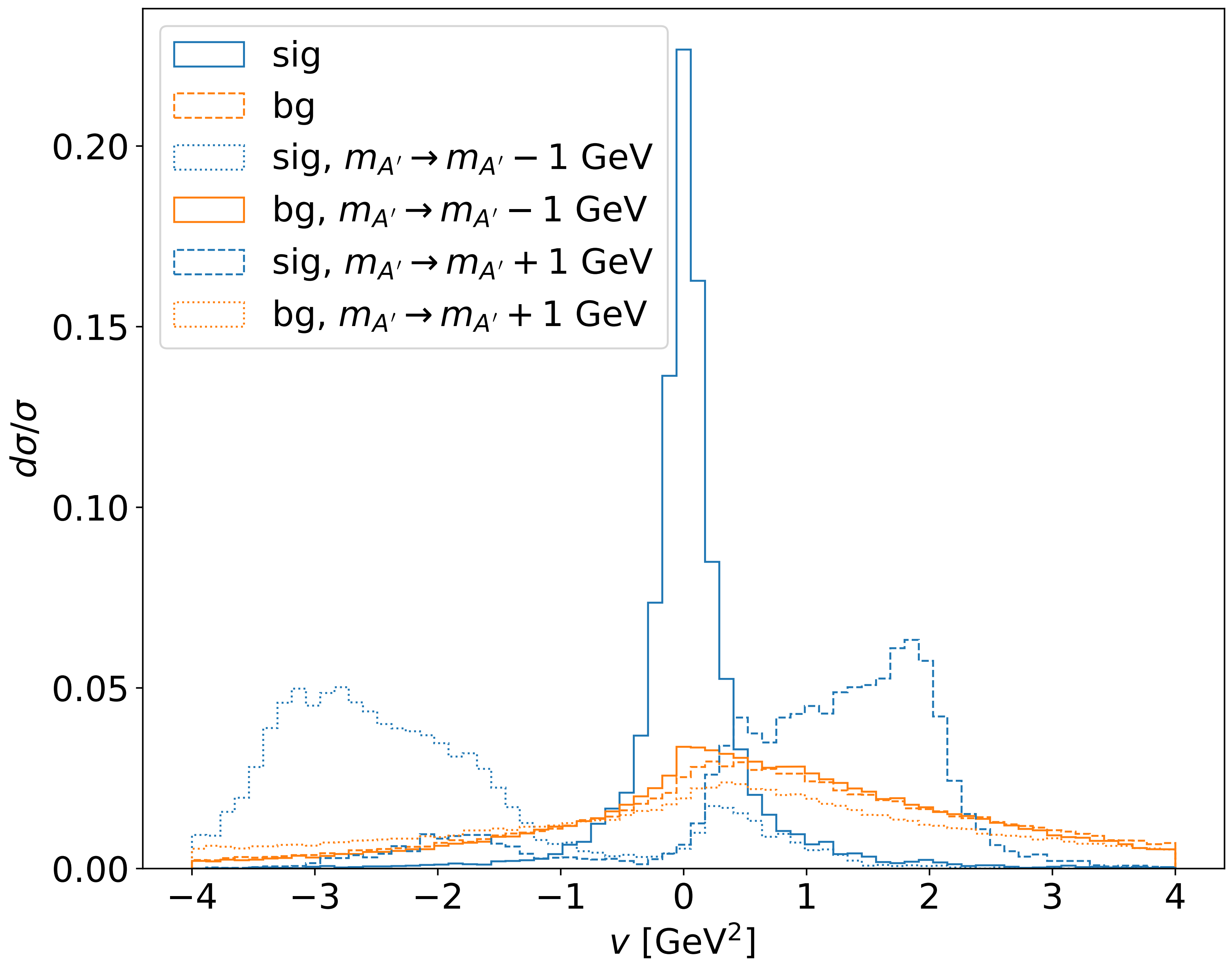
$$\frac{1}{(p_1+p_2-p_\gamma)^2-m_{A'}^2+im_{A'}\Gamma_{A'}}$$

$$\frac{1}{m_{\chi\chi}^2-m_{A'}^2+im_{A'}\Gamma}$$

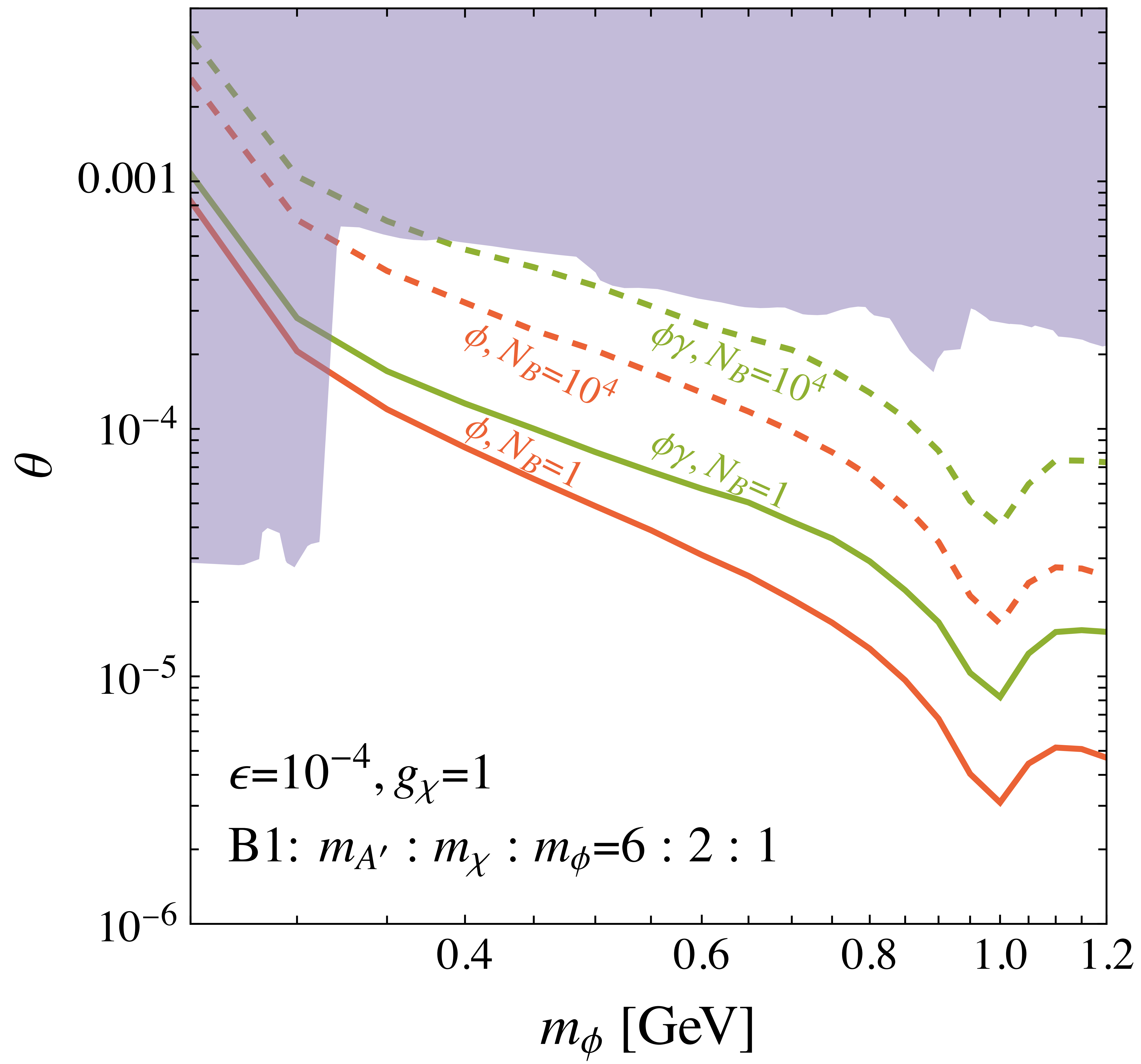
$$E_\gamma \sim \frac{s-m_{A'}^2}{2\sqrt{s}}$$



$$v := \left(E_\gamma - \frac{s - m_{A'}^2}{2\sqrt{s}}\right) \cdot \left(m_{\chi\chi} - m_{A'}\right)$$

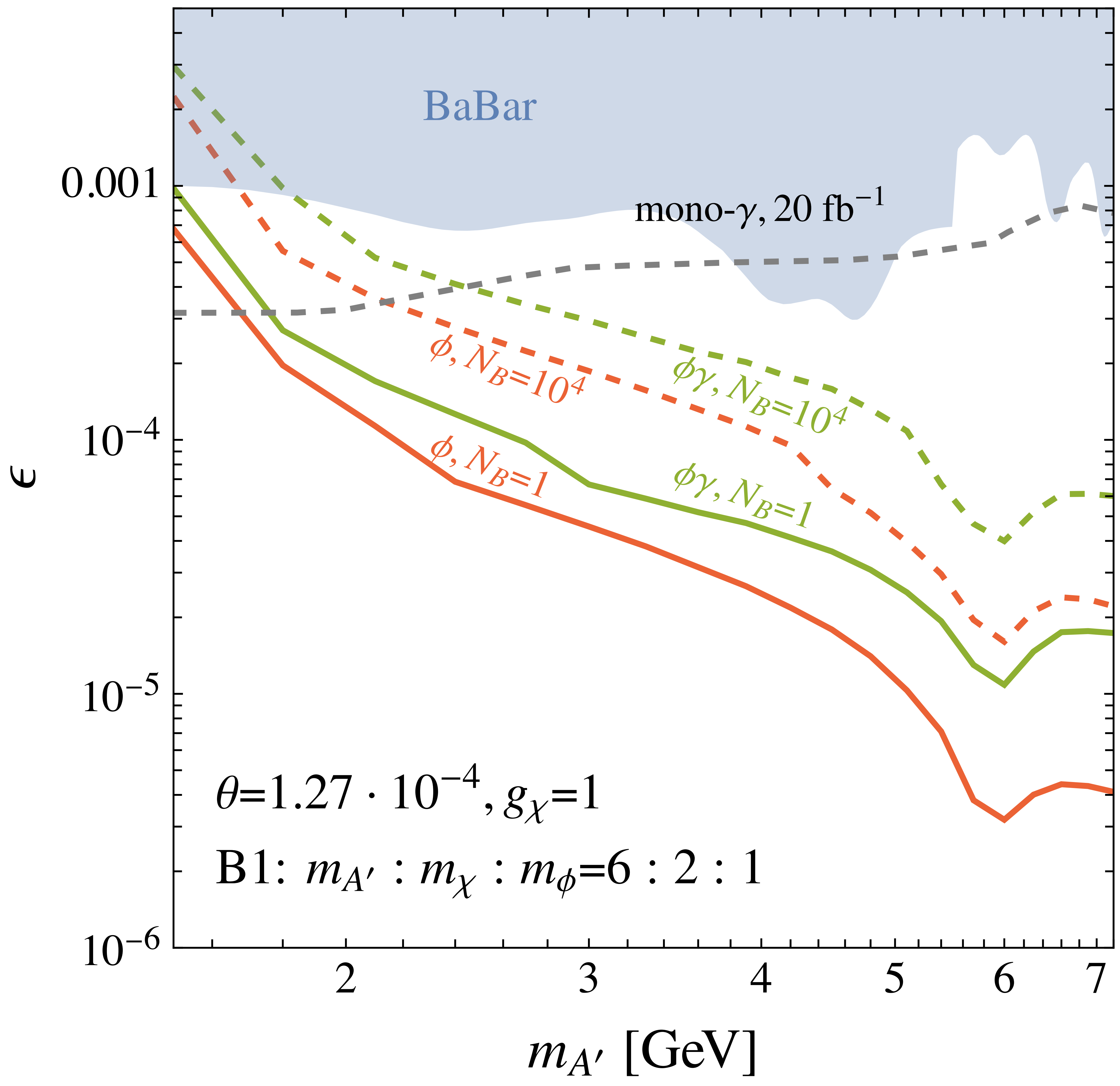


Results



0.001
10^{-4}
10^{-5}
10^{-6}
θ
0.4
0.6
0.8
1.0
1.2
m_ϕ [GeV]
$\phi\gamma, N_B=10^4$
$\phi, N_B=10^4$
$\phi\gamma, N_B=1$
$\phi, N_B=1$
$\epsilon=10^{-4}, g_\chi=1$
B1: $m_{A'} : m_\chi : m_\phi=6 : 2 : 1$

- Going down because of increasing cross section, and Γ_ϕ
- Follows θ because dominated by disp. vert. loss
- Could expand to disp. instr. region but would need more precise bg simulation if want to keep $\mathscr{L} = 50\,\text{ab}^{-1}$



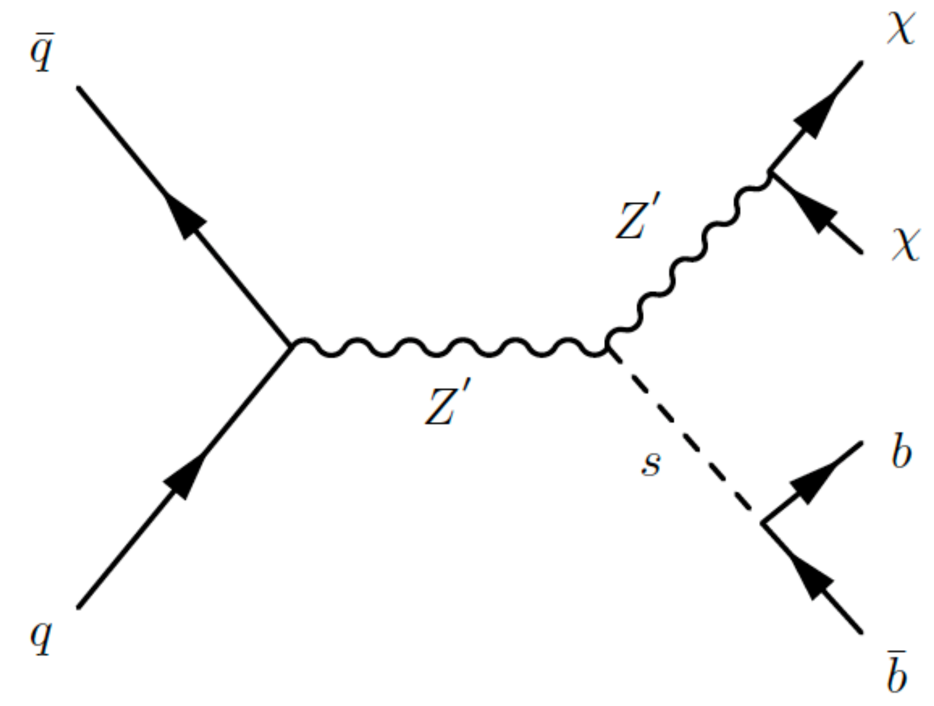
Thank you!

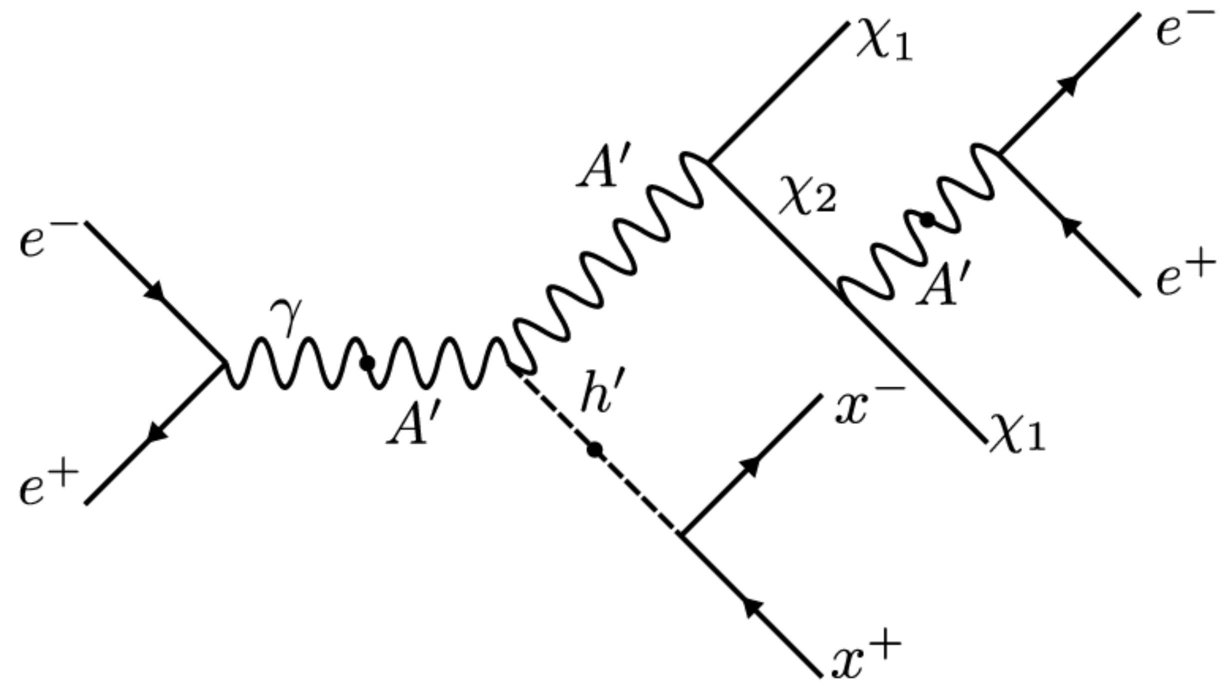
Questions?

Backup slides

Similar searches

- ATLAS and CMS looked into a signature of $pp \to \phi A', A' \to \chi\bar{\chi}, \phi \to b\bar{b}, W^+W^-, ZZ, hh$ but they have much broader miss. en. distribution
- Belle II: $\phi +$ a semi-visibly decaying A' (inelastic dark matter)
- Various searches for light scalars with Higgs mixing but no DP. Example: rare B meson decays $B \to K\phi, \phi \to$ SM SM





Belle II simulation specifics

- Symmetric e^+e^- collider
- $\sqrt{s} = 10.58$ GeV.
- $\gamma\phi$ process: γ within Belle II acceptance:

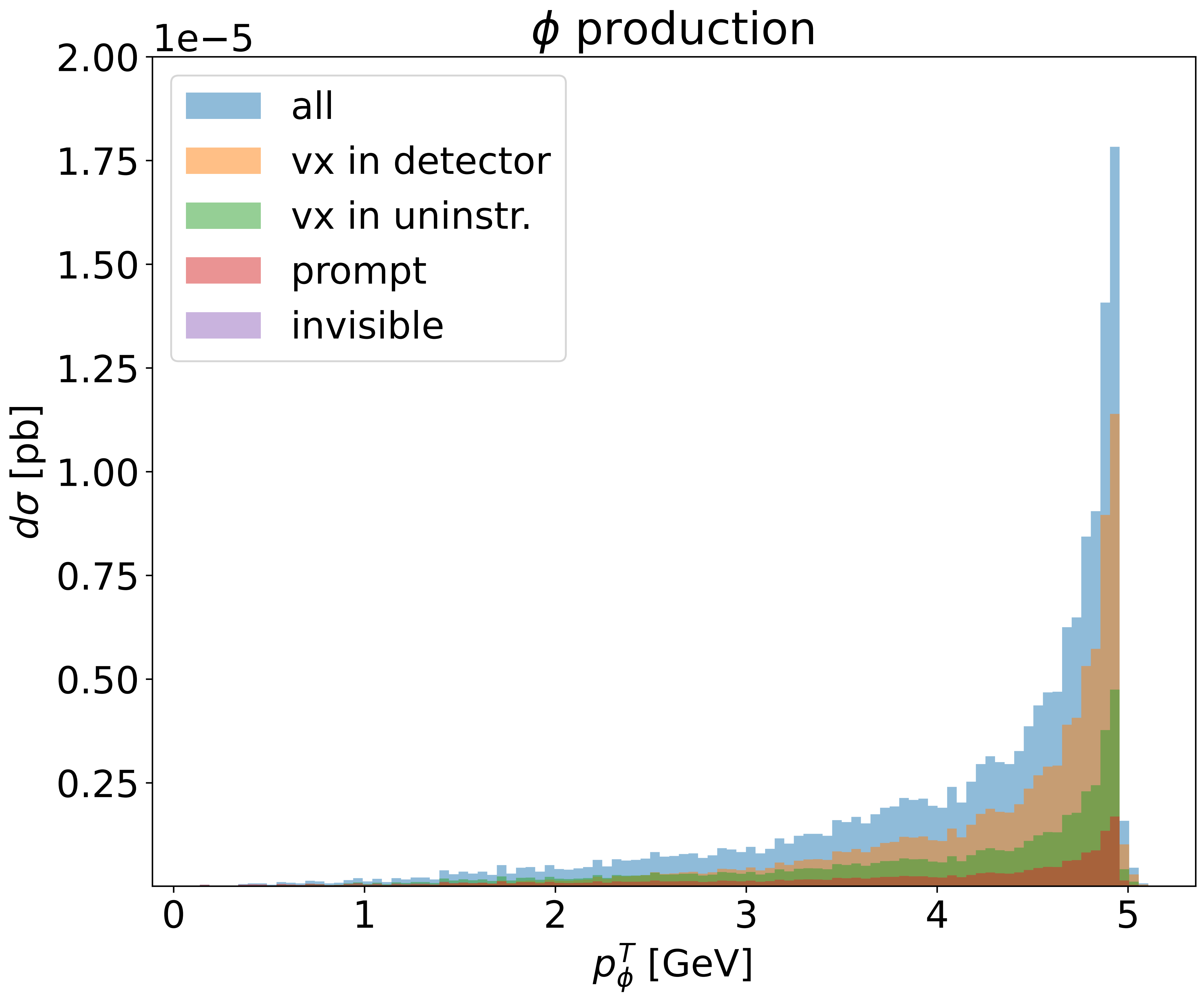
$$E_\gamma \geq E_0 = 0.25 \text{ GeV}, \qquad 22^o \leq \theta_\gamma \leq 180^o - 22^o$$

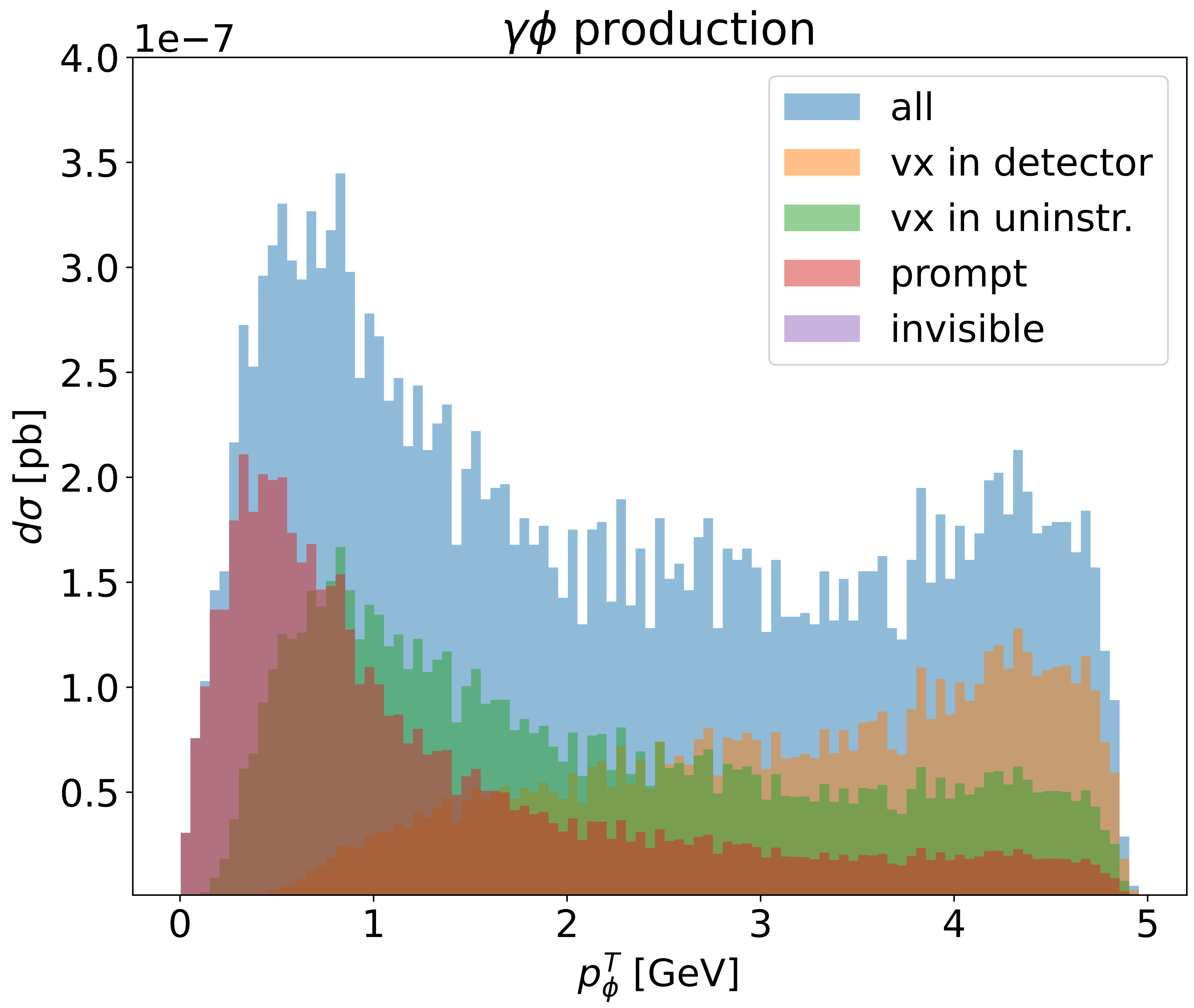
- To study the dark Higgs displacement boost events to the lab frame:
    - e^- beam: energy 7 GeV and tilt around the y axis =0.0415 rad
    - e^+ beam: energy 4 GeV and tilt around the y axis =-0.0415 rad

More on the analysis

- Logarithmic binning: $e_0 = 0,\ e_1 = 0.01$ GeV, $\dfrac{e_{i+1} - e_i}{\frac{1}{2}(e_{i+1} + e_i)} = 30\,\%$

- Smearing: $\dfrac{\delta E}{E} = \sqrt{\left[\dfrac{0.066\,\%}{E/\text{GeV}}\right]^2 + \left[\dfrac{0.81\,\%}{(E/\text{GeV})^{1/4}}\right]^2 + \left[1.34\,\%\right]^2}$



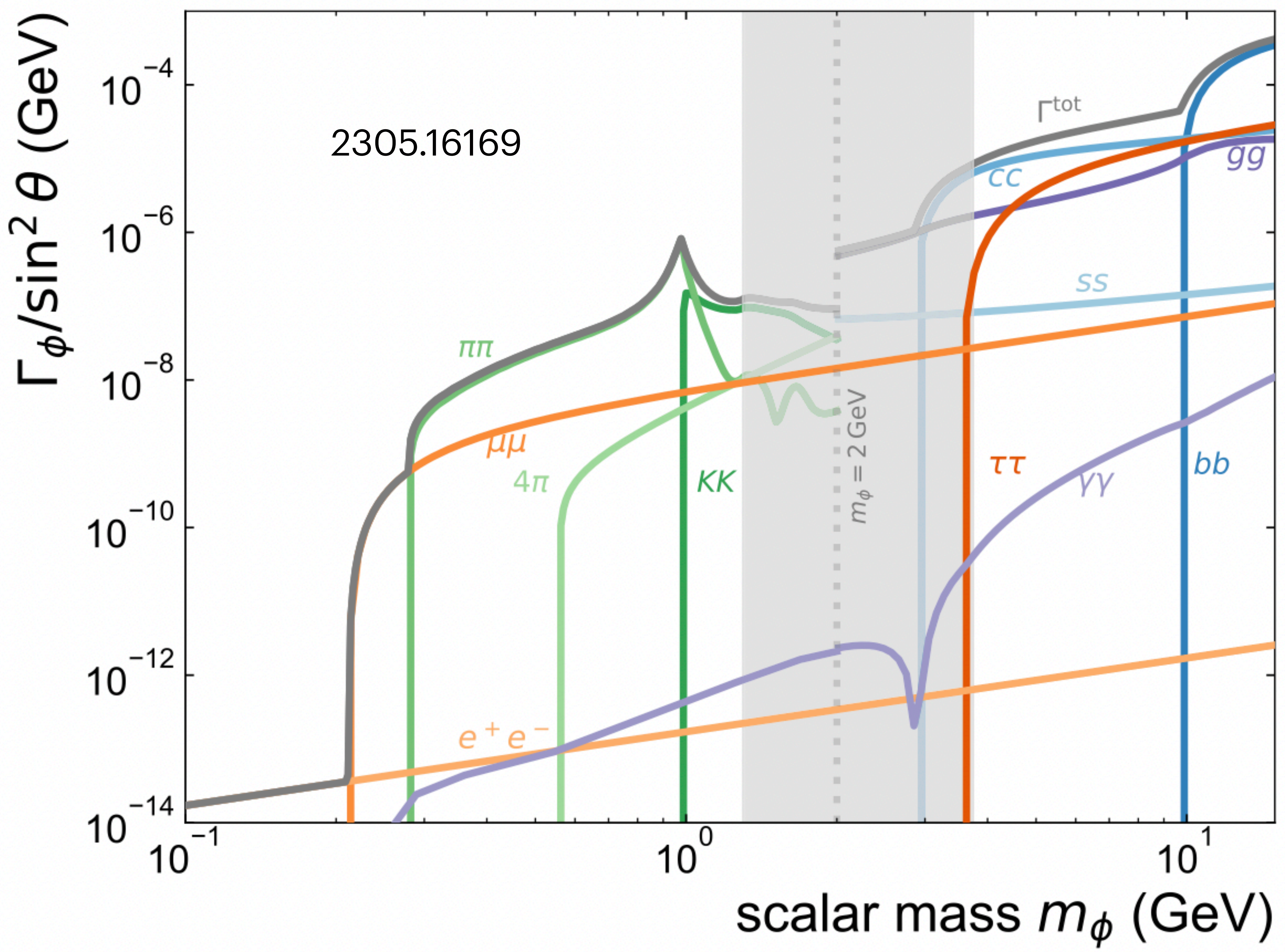


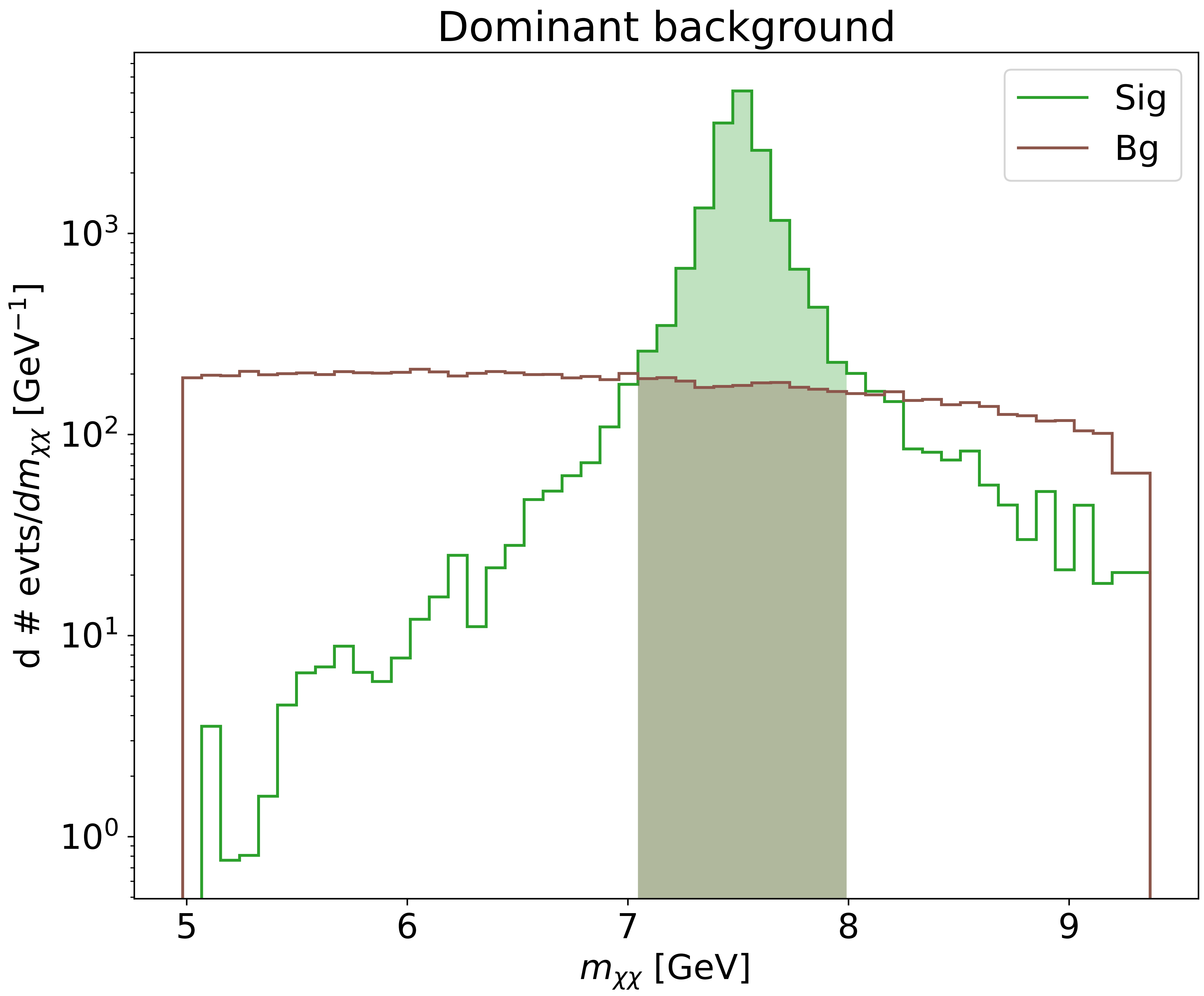
$m_{A'} = 2.7$ GeV, $\epsilon = 10^{-4}$, $\theta = 10^{-4}$

Decay probability

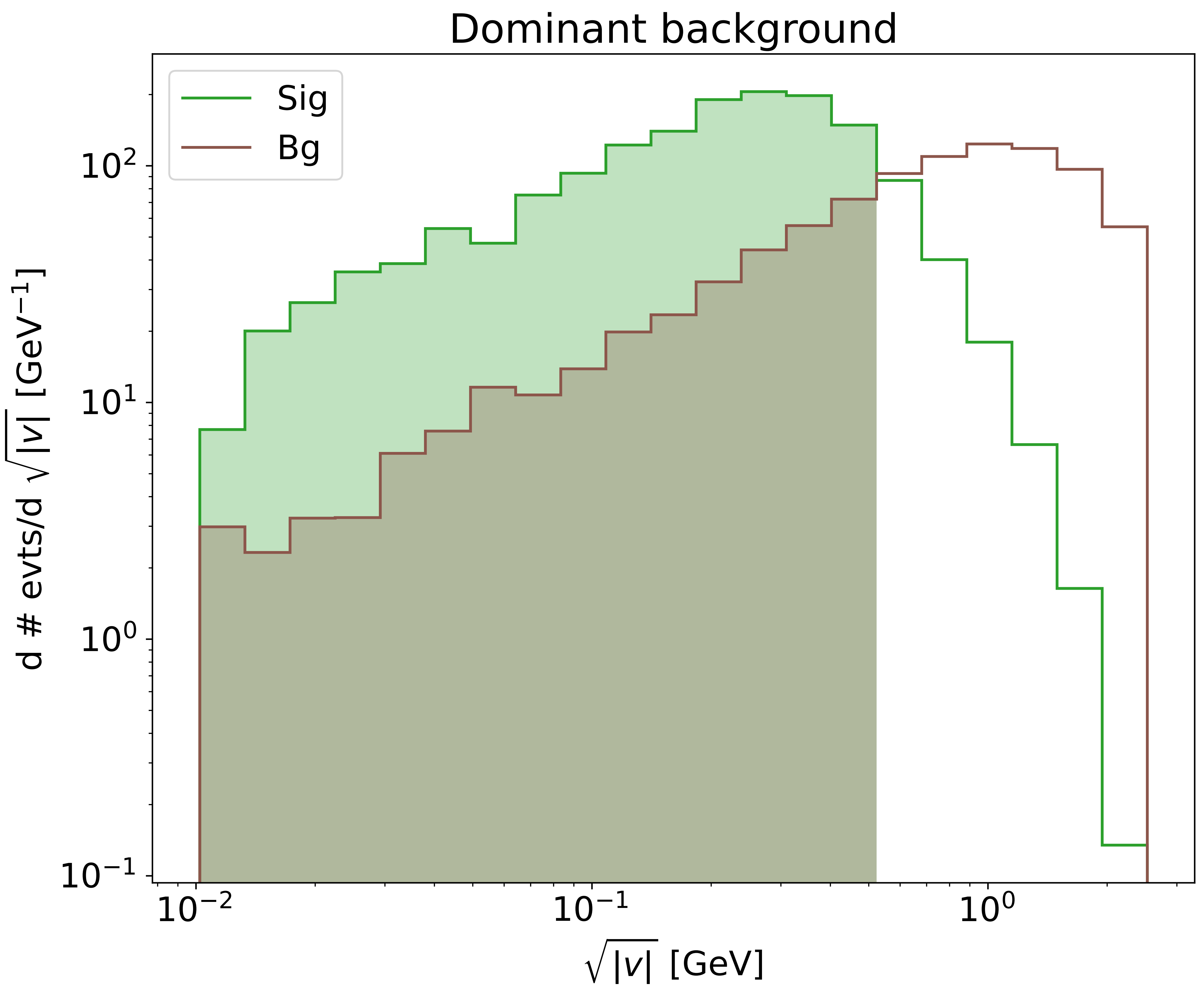
$$p_i \equiv \exp\left(-\frac{r_{\text{in}}}{d_i}\right) - \exp\left(-\frac{r_{\text{out}}}{d_i}\right),$$

- $d_i \equiv \dfrac{p_i^T(\phi)}{\Gamma_\phi(\theta) m_\phi}$.

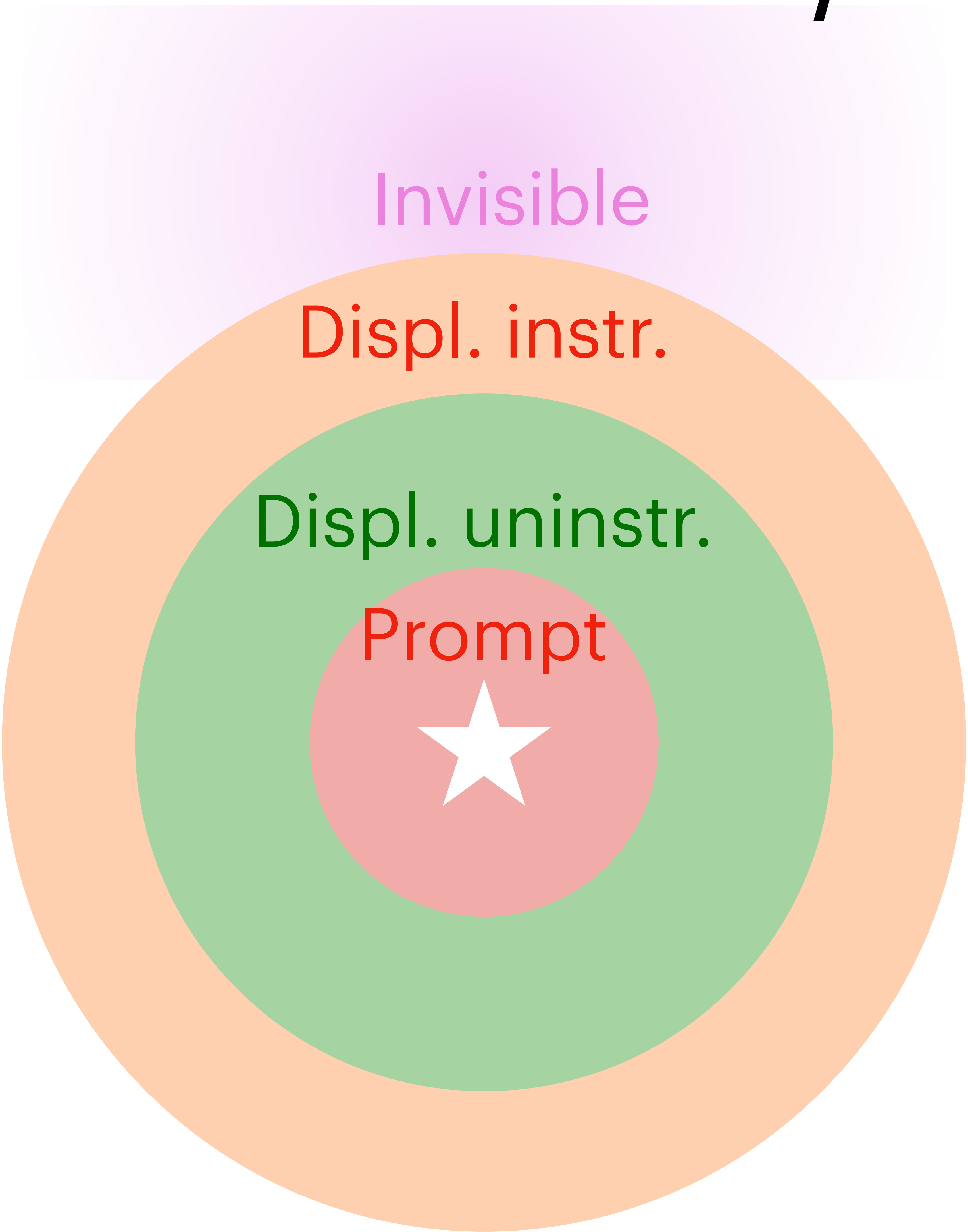




Dominant background
Sig
Bg
10^3
10^2
10^1
10^0
d # evts/$dm_{\chi\chi}$ [GeV^{-1}]
5
6
7
8
9
$m_{\chi\chi}$ [GeV]

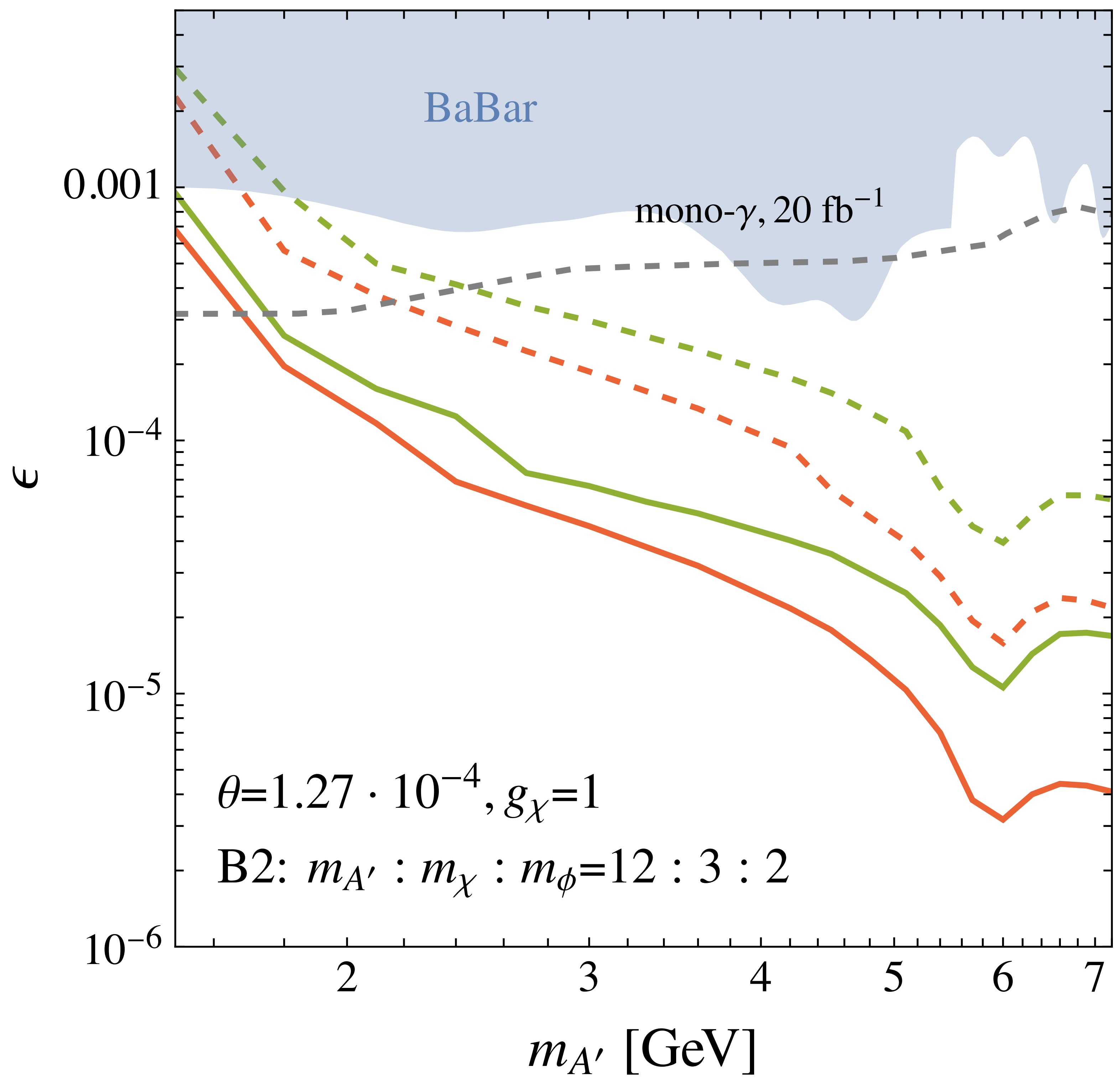

Dominant background
Sig
Bg
d # evts/d $\sqrt{|v|}$ [GeV^{-1}]
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-1}
10^{0}
$\sqrt{|v|}$ [GeV]

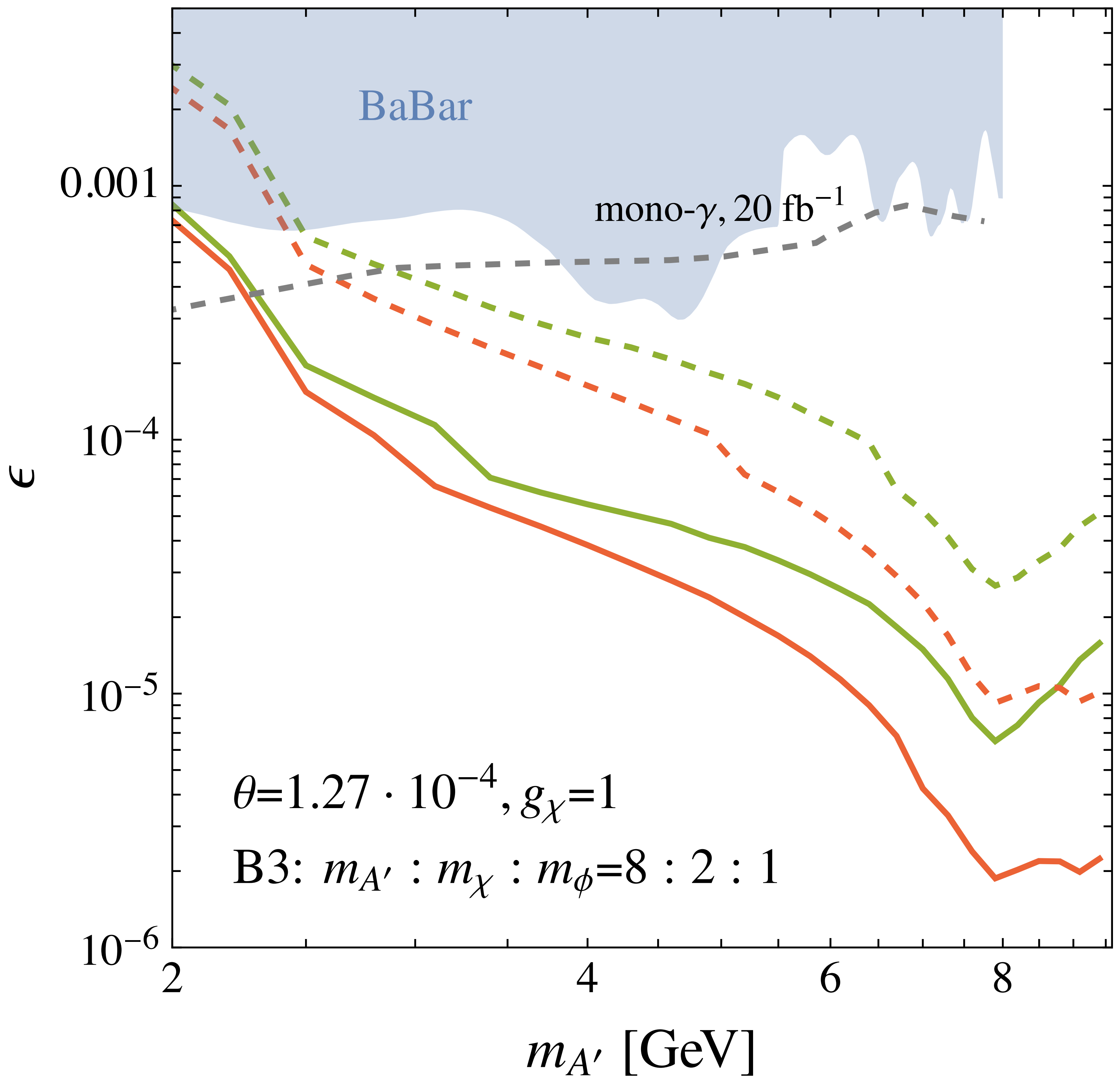
ϕ displaced vertex



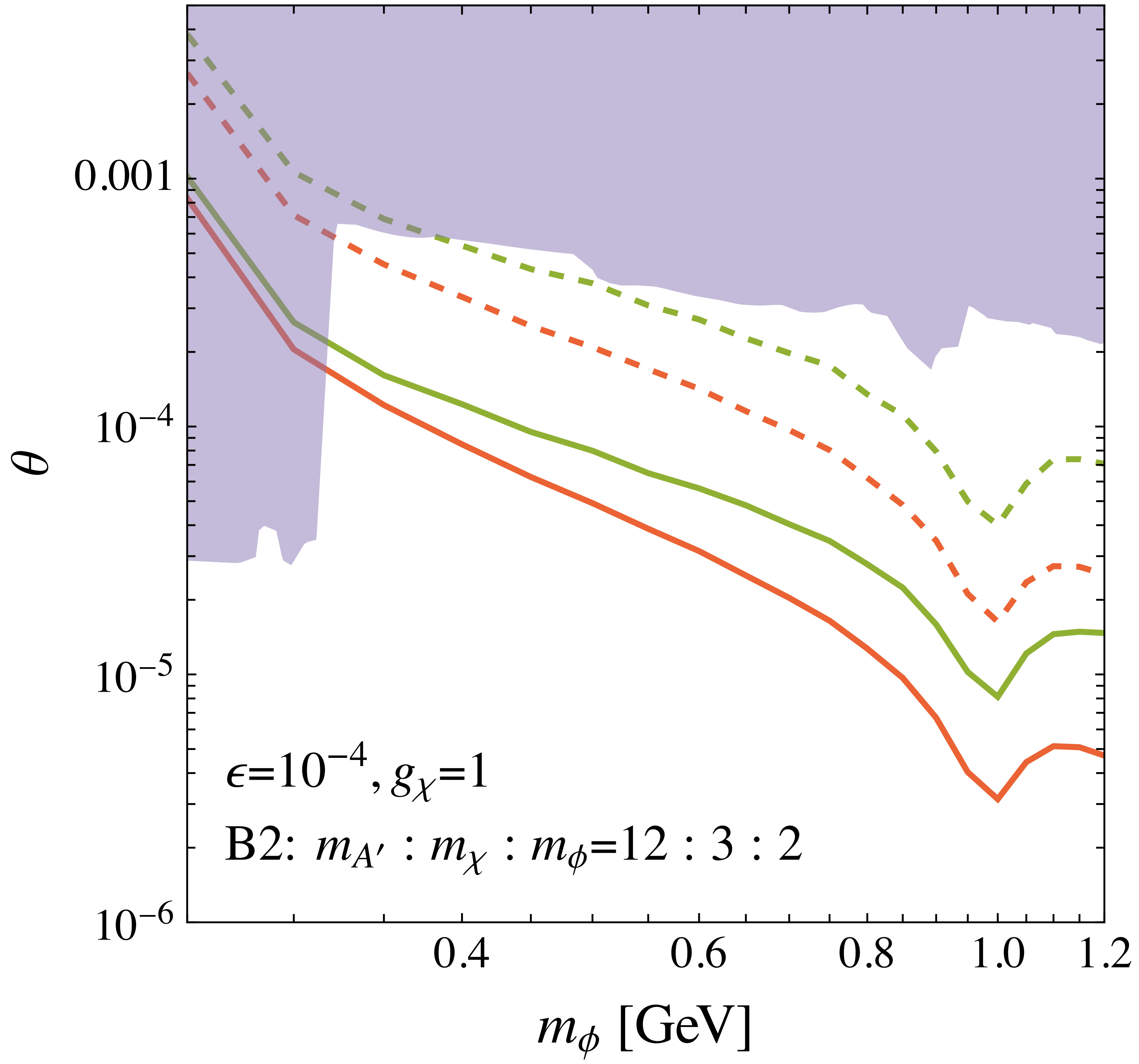
Name	r_{in} [mm]	r_{out} [mm]
Prompt	0	2
Displaced (uninstrumented)	2	9
Displaced (instrumented)	9	$2 \cdot 10^3$
Invisible	$2 \cdot 10^3$	∞
All	0	∞

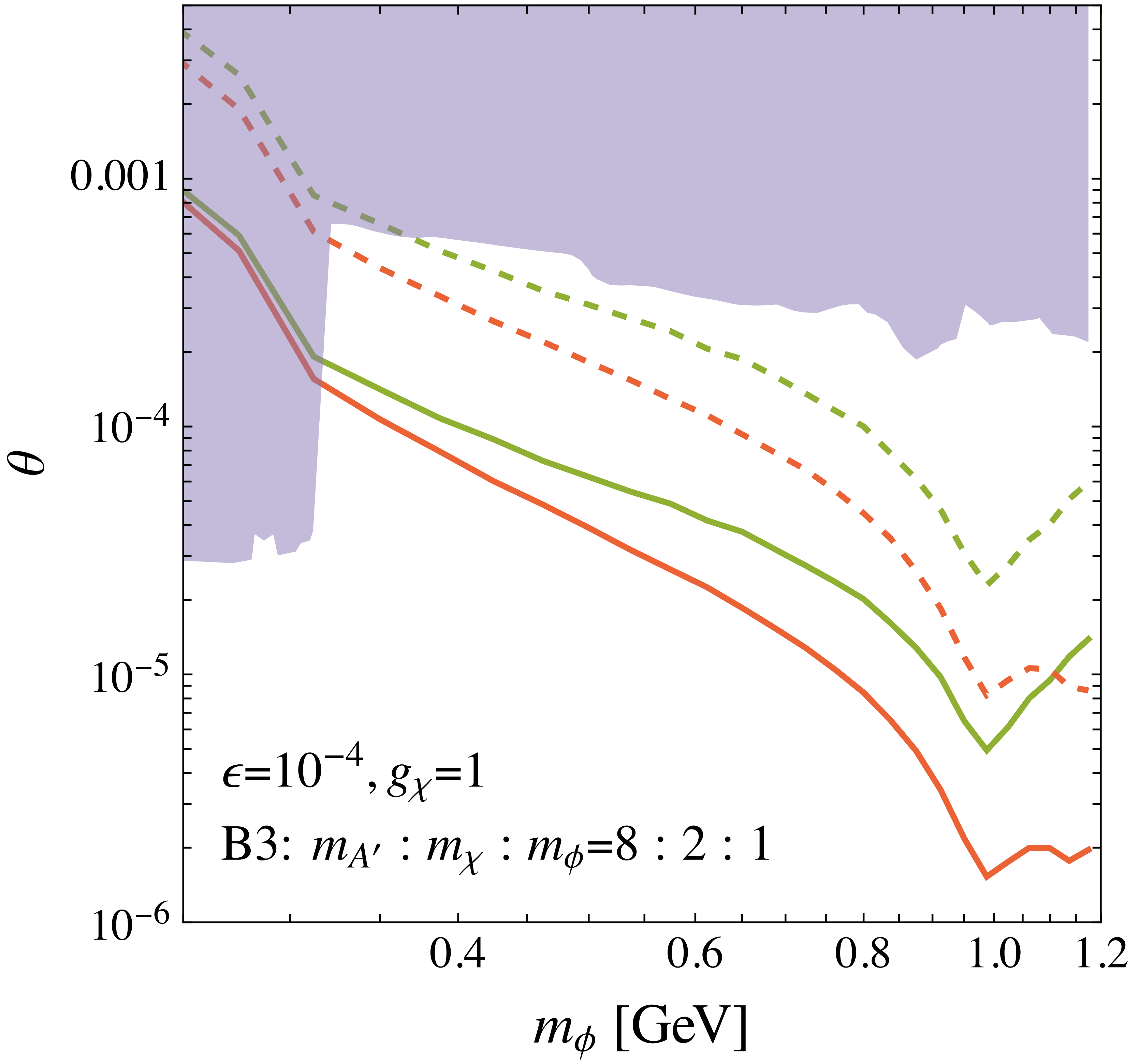
Benchmark 2 and 3 - ϵ reach



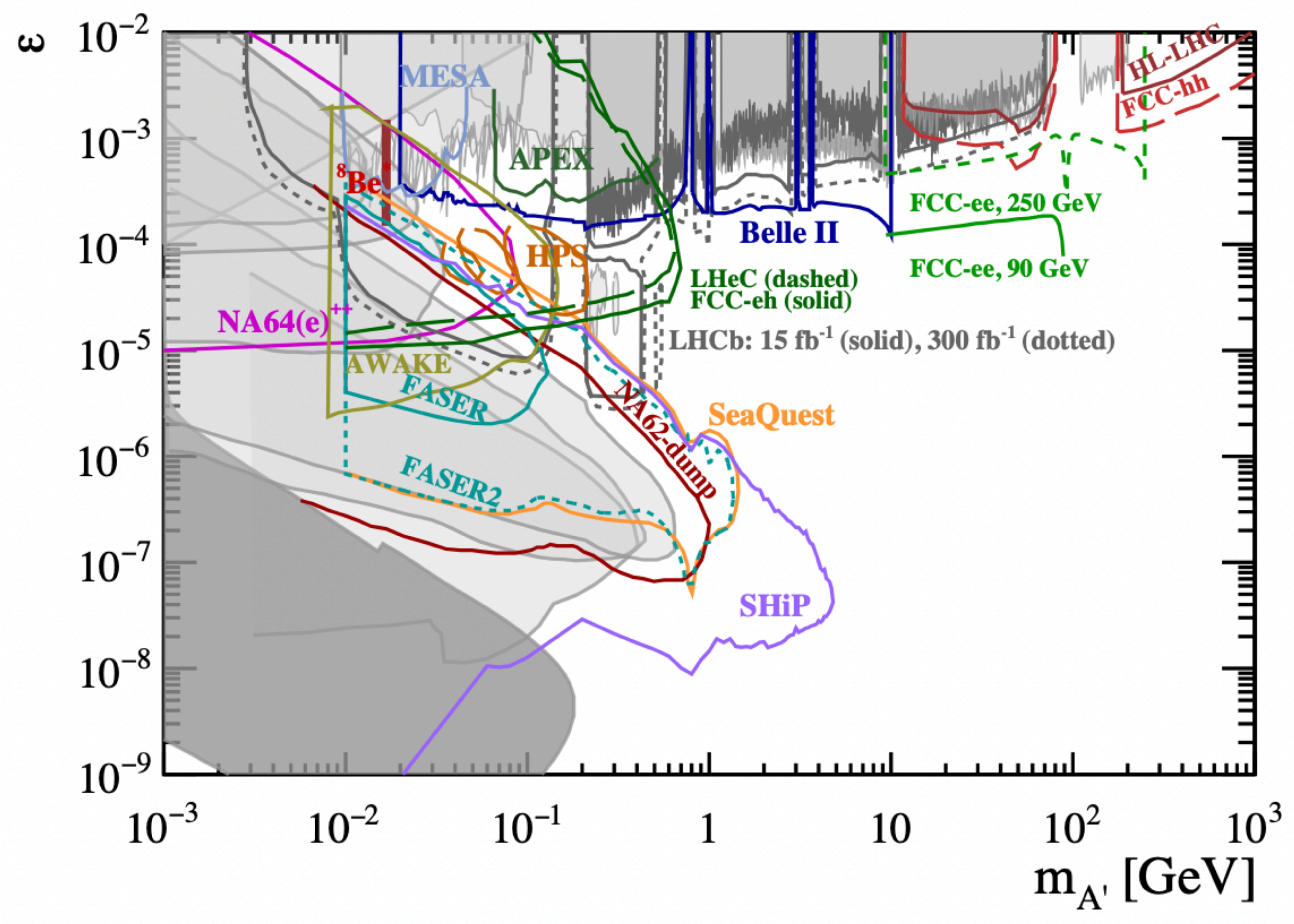


Benchmark 2 and 3 - θ reach





Existing and projected limits on $(\epsilon, m_{A'})$



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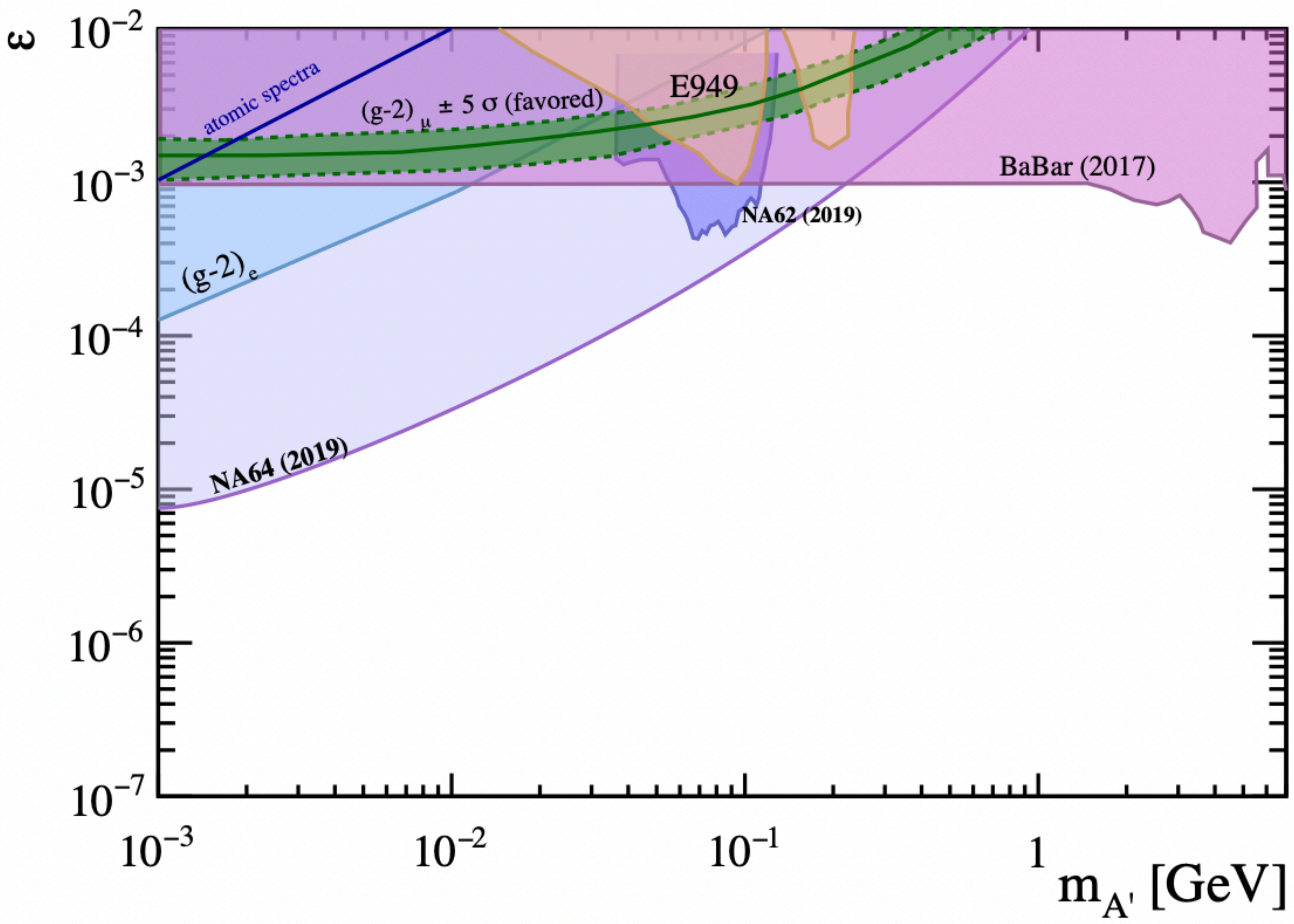
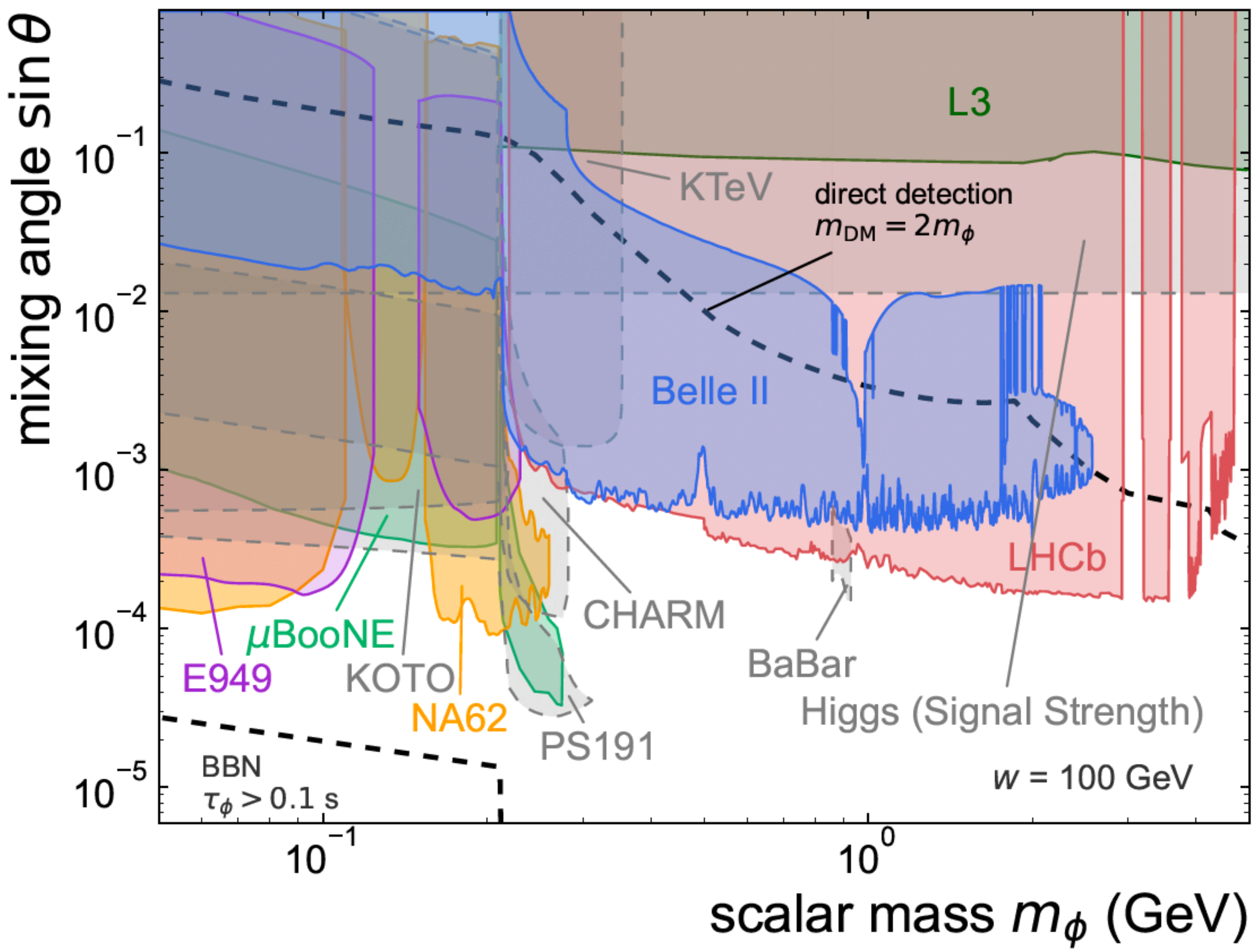
Existing limits on $(\epsilon, m_{A'})$



2005.01515

Limits on (m_ϕ, θ)



E949: $K^+ \to \pi^+ \phi(\to \text{inv.})$
Phys. Rev. D 79 (2009) 092004

KOTO: $K_L^0 \to \pi^0 \phi(\to \text{inv.})$
Phys. Rev. Lett. 126 (12) (2021) 121801

μBooNE: $K^+ \to \pi^+ \phi(\to e^+e^-, \mu^+\mu^-)$
Phys. Rev. Lett. 127 (15) (2021) 151803, Phys. Rev. D 106, 092006 (2022)

NA62: $K^+ \to \pi^+ \phi(\to \text{inv.})$
JHEP 02 (2021) 201, JHEP 06 (2021) 093

PS191: $K^\pm \to \pi^\pm \phi(\to e^+e^-, \mu^+\mu^-)$
Phys. Lett. B 203(1988) 332–334, Phys. Lett. B 820 (2021) 136524

CHARM: $K^\pm \to \pi^\pm \phi(\to e^+e^-, \mu^+\mu^-)$
Phys. Lett. B 203(1988) 332–334, Phys. Lett. B 820 (2021) 136524

Belle II: $B \to K^{(*)} \phi(\to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-)$
arXiv:2306.02830 [hep-ex] 2023

KTeV: $K_L^0 \to \pi^0 \phi(\to \mu^+\mu^-)$
Phys. Rev. Lett. 84(2000) 5279–5282, Phys. Rev. D 99 (1) (2019) 015018

BaBar: $B \to X_s \phi(\to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-)$
Phys. Rev.Lett. 114 (17) (2015) 171801, Phys. Rev. D 99 (1) (2019) 015018

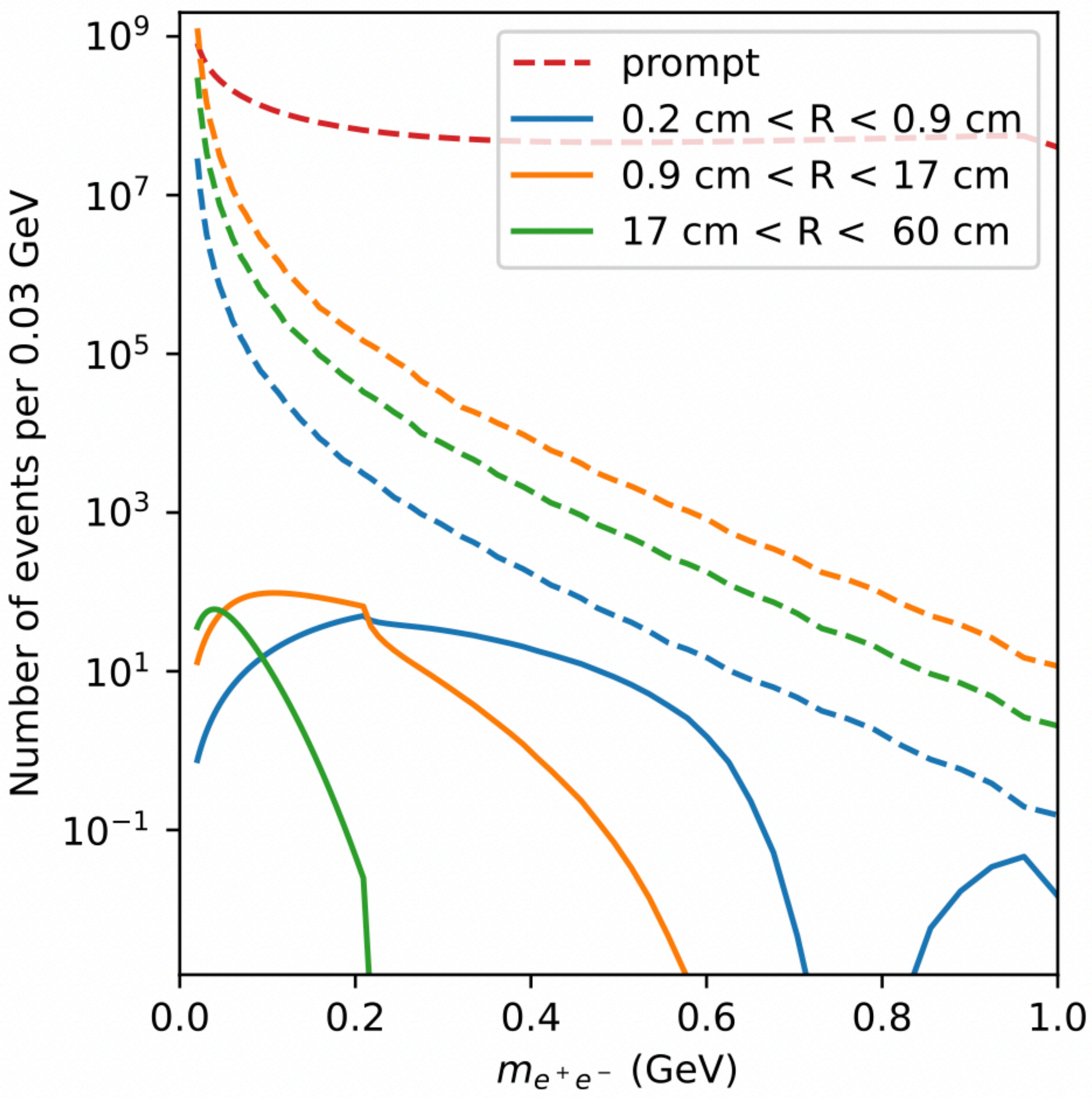
L3: $e^+e^- \to Z^* \phi$
Phys. Lett. B 385 (1996) 454–470

LHCb: $B \to K^{(*)} \phi(\to \mu^+\mu^-)$
Phys. Rev.Lett. 115 (16) (2015) 161802, Phys. Rev. D 95 (7) (2017) 071101, Phys. Rev. D 99 (1) (2019) 015018

2305.16169

Photon conversion

- 2312.12522
- Sig: $e^+e^- \to A'\gamma, A' \to l^+l^-$ displaced. Solid
- Bg: $e^+e^- \to \gamma\gamma_{\text{conv}}, \gamma_{\text{conv}} \to l^+l^-$ displaced; dashed
- $\epsilon = 2 \cdot 10^{-5}, \mathscr{L} = 50$ ab^{-1}



Inelastic Dark Matter

- Setup as above but chiral fermions $\chi_{L,R}$ with charges $\pm q_{DM}$; DH charge $= -2q_{DM} \rightarrow$ Yukawa is allowed $\rightarrow$ Majorana masses $m_{L,R}$
- Add a Dirac mass m_D
- Diagonalized mass matrix to $\chi_{1,2}$ eigenstates
- Assume $m_L \approx m_R \rightarrow$ small mass splitting Δ

Uncertainties on Γ_ϕ

- The most widely adopted approach does dispersive analysis before 2 GeV and perturbative spectator model after but has discontinuity
- $\phi \to$ SM SM with $m_\phi \lesssim 2$ GeV is expected to be dominated by $\pi\pi$ and KK.
- Chiral Perturbation Theory is not applicable in the whole energy range
- Perturbative QCD is also not applicable
- Dispersive techniques relying on unitarity and analyticity properties of amplitudes are most useful
- A key input in these representations are the pion and kaon scattering phase shifts.
- Experimental information enters the computation. Their error must be taken into account and propagated down to Γ_ϕ