Recasting Dark Photon Searches

Yotam Soreq

Roadmap of Dark Matter model for Run 3, May 15, 2024

Portals to hidden sector

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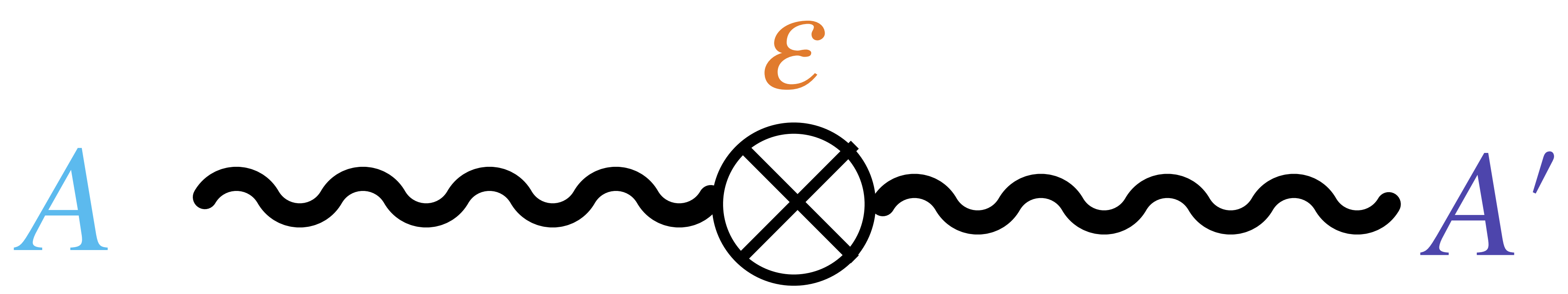
Portals to hidden sector

dark photons, $B-L$, $L_\mu - L_\tau$

Higgs mixing, axion or axion-like-particles….

Dark photon - kinetic mixing



$$-\frac{1}{2}\varepsilon F'_{\mu\nu}F^{\mu\nu}$$

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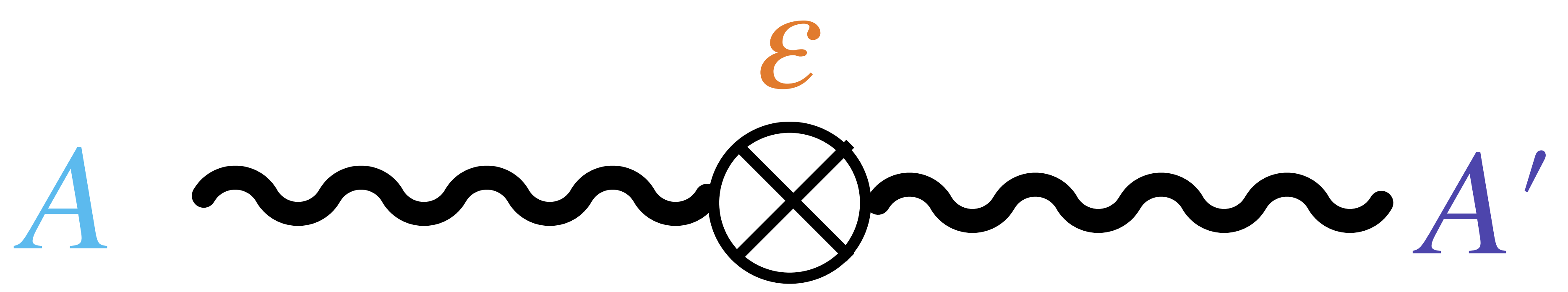

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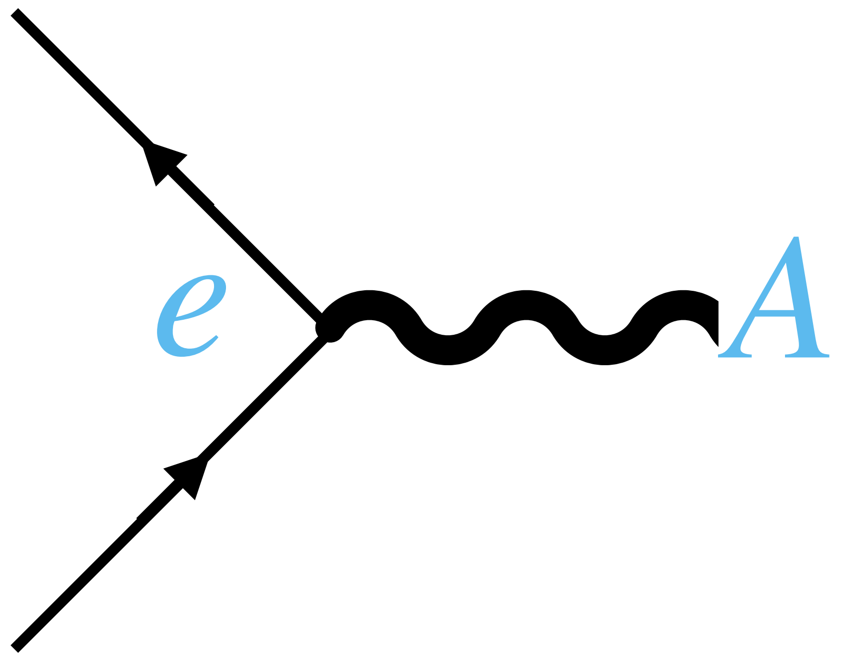
electromagnetic process



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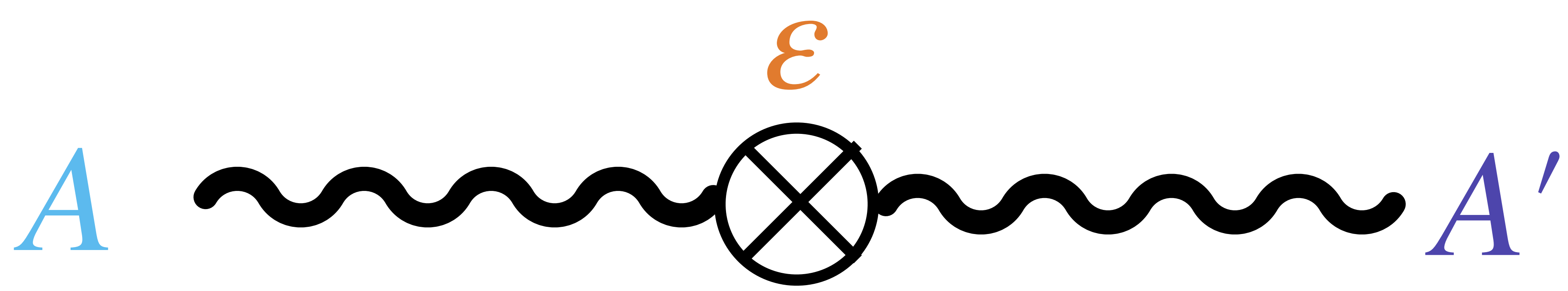

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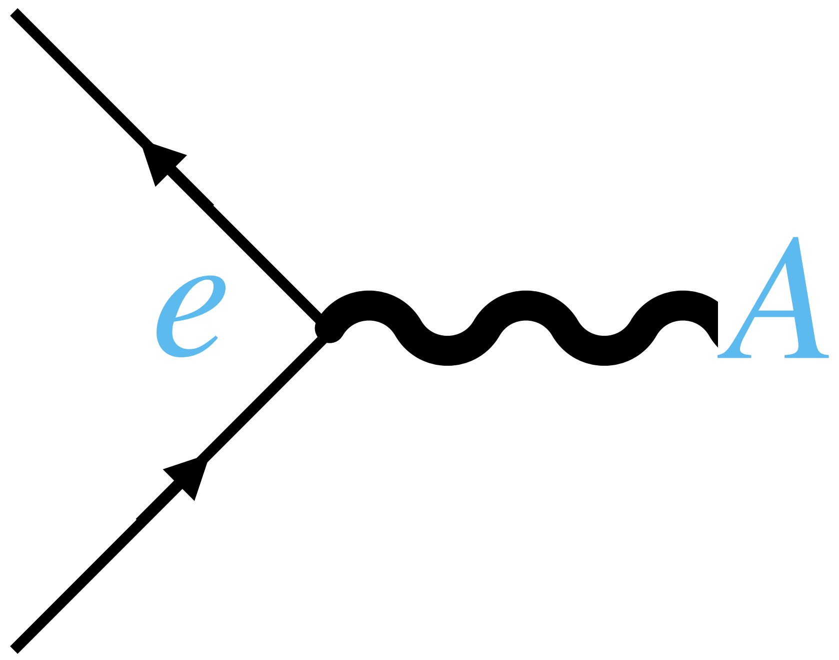
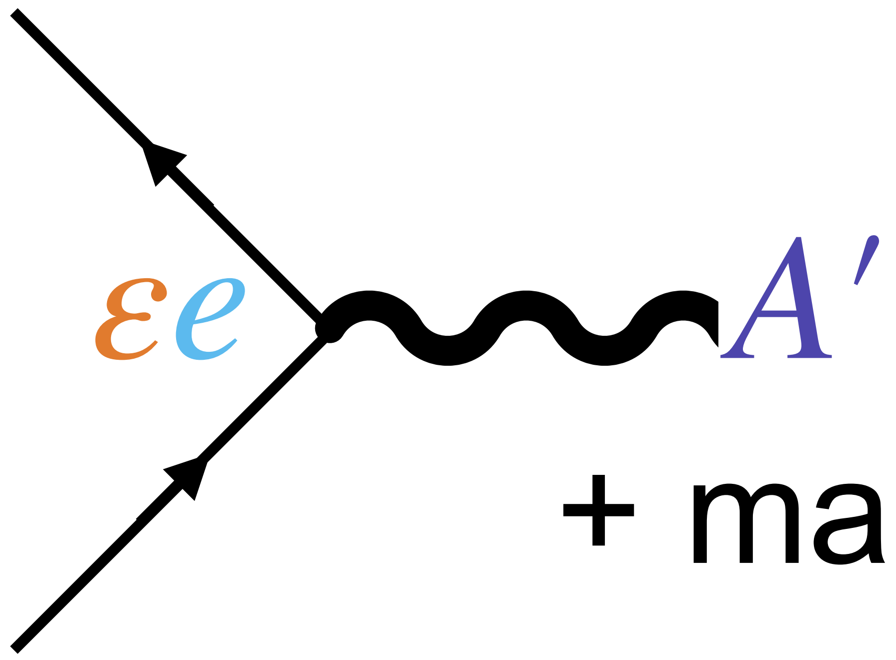


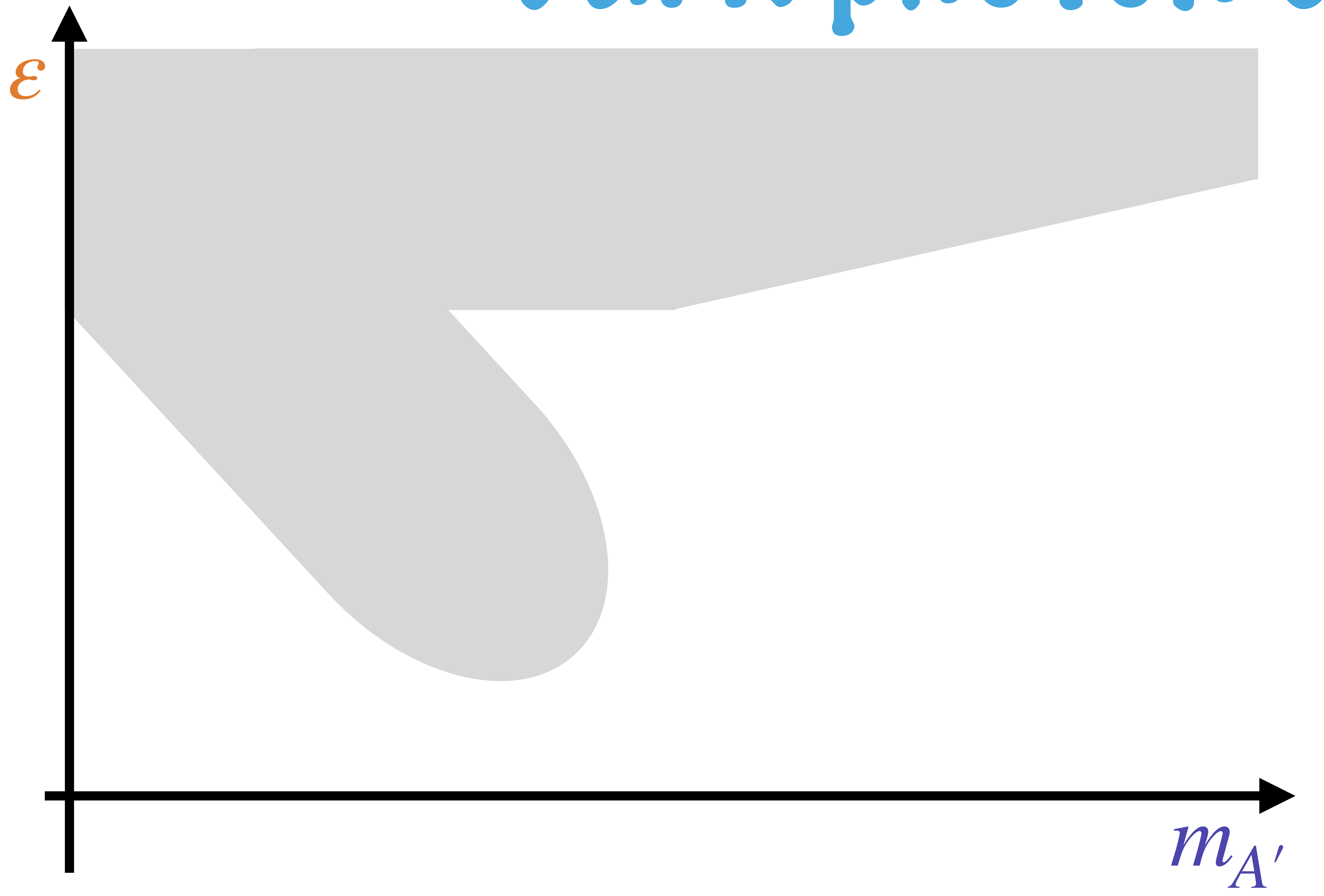
dark-photon process



+ mass effect

Dark photon searches

Dark photon searches



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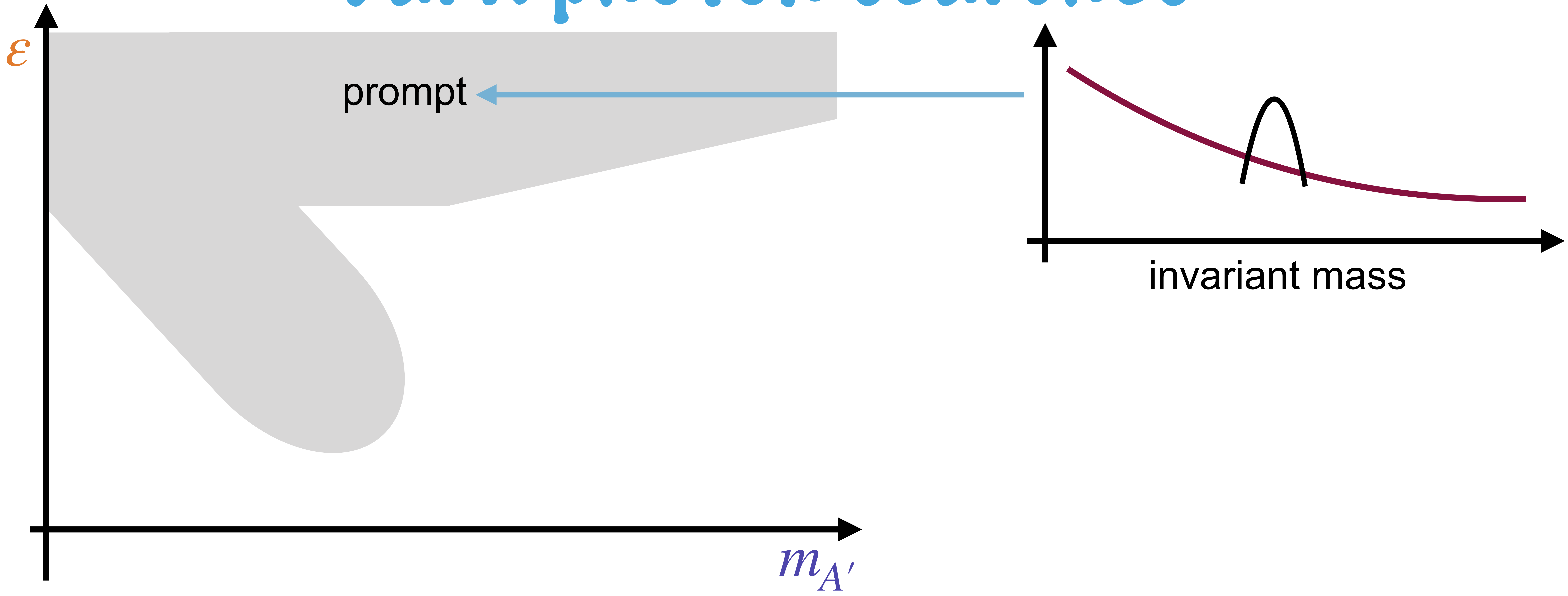

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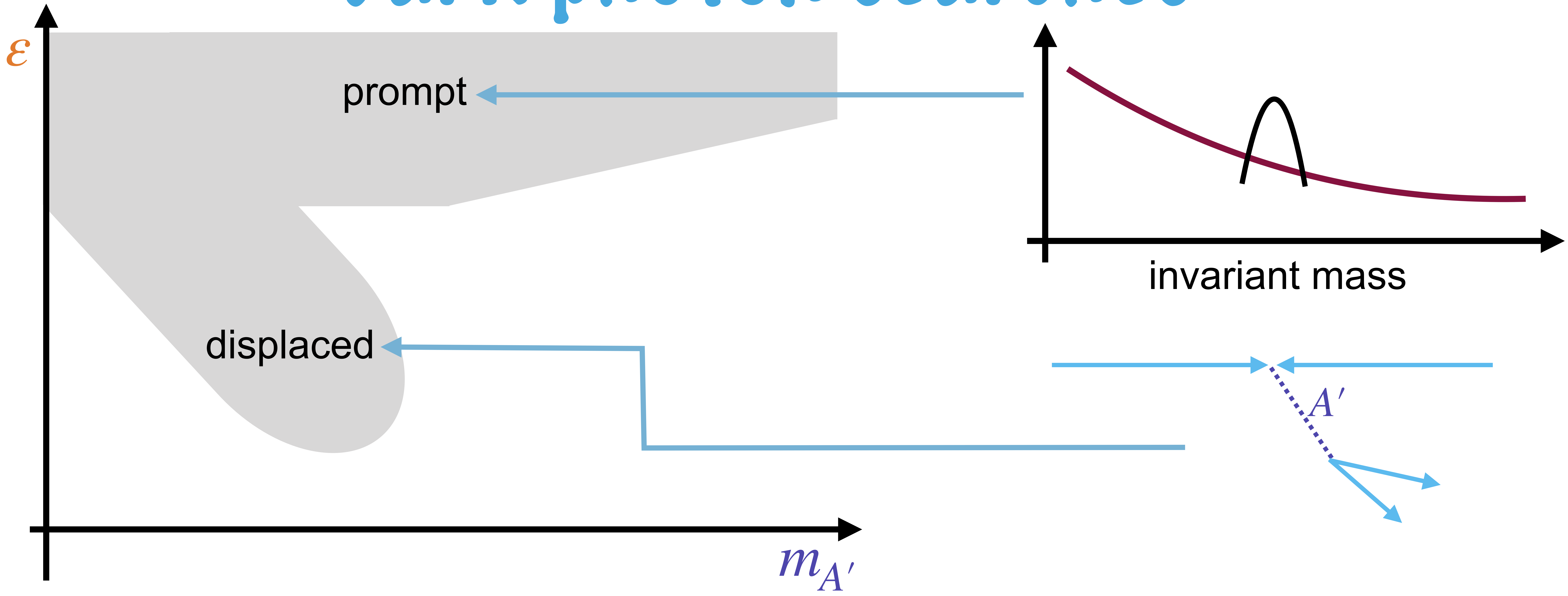
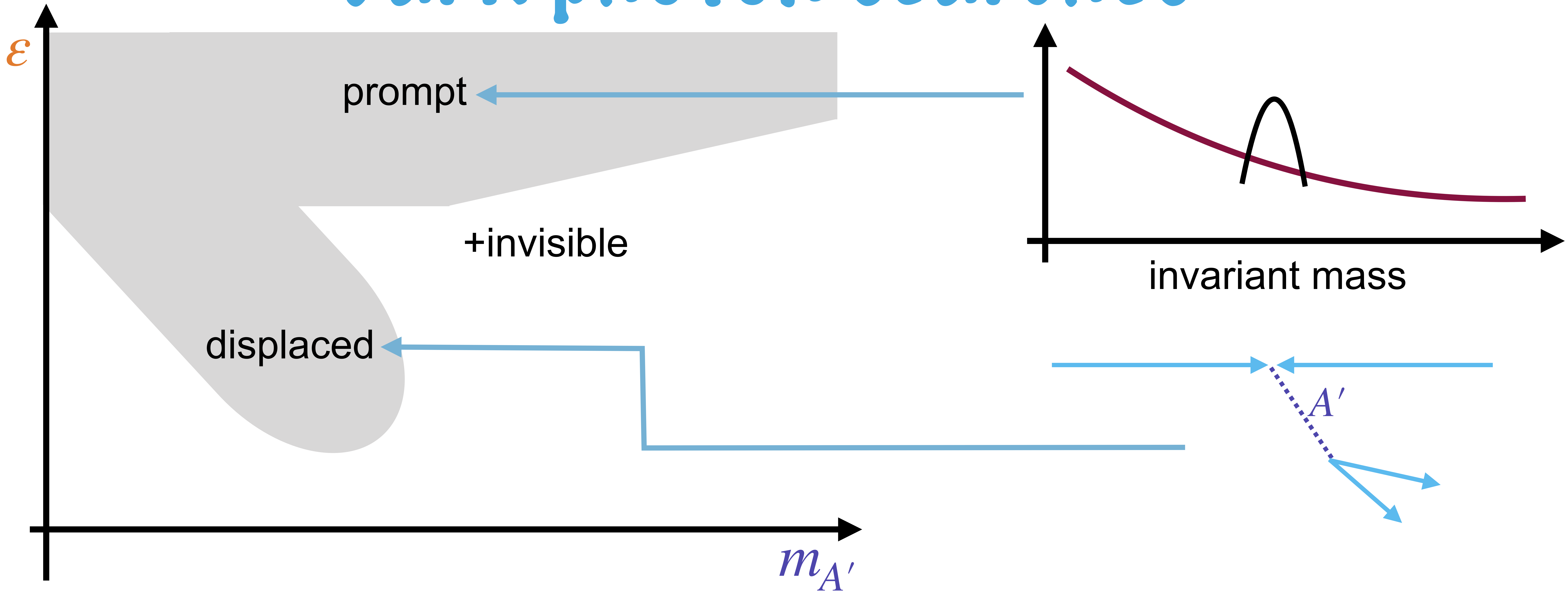


Dark photon searches



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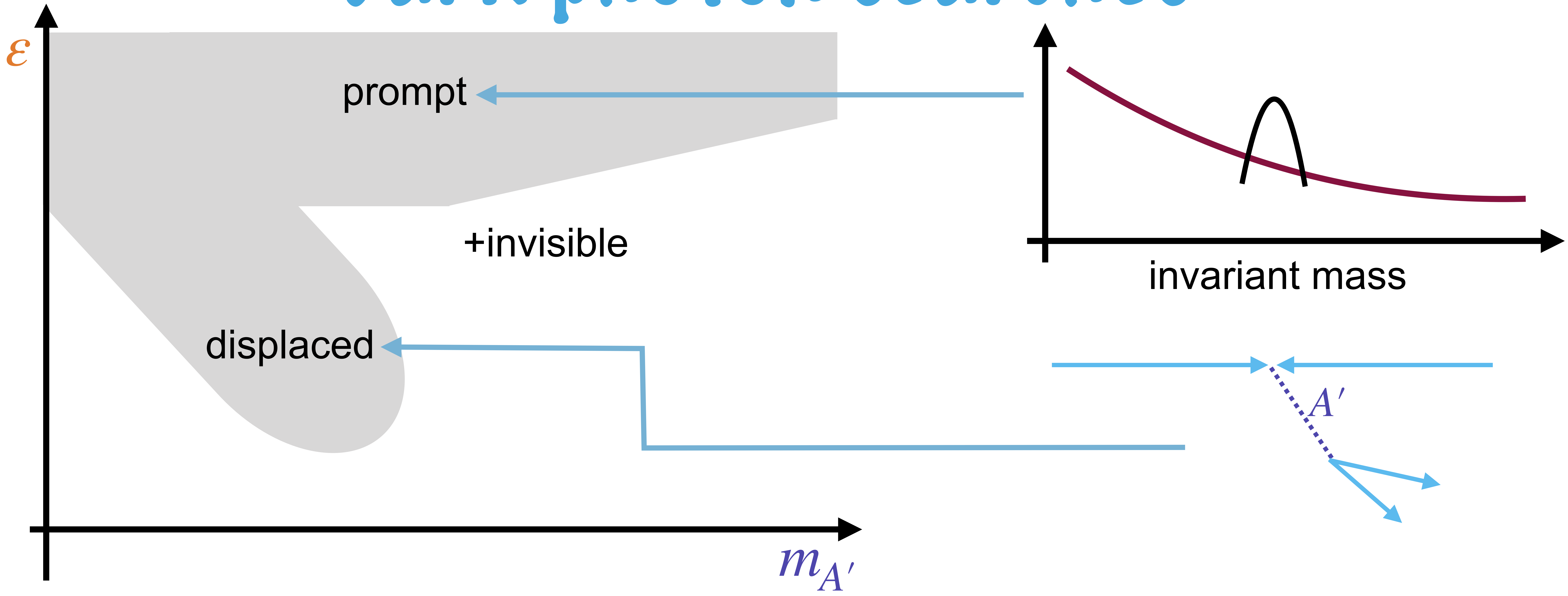
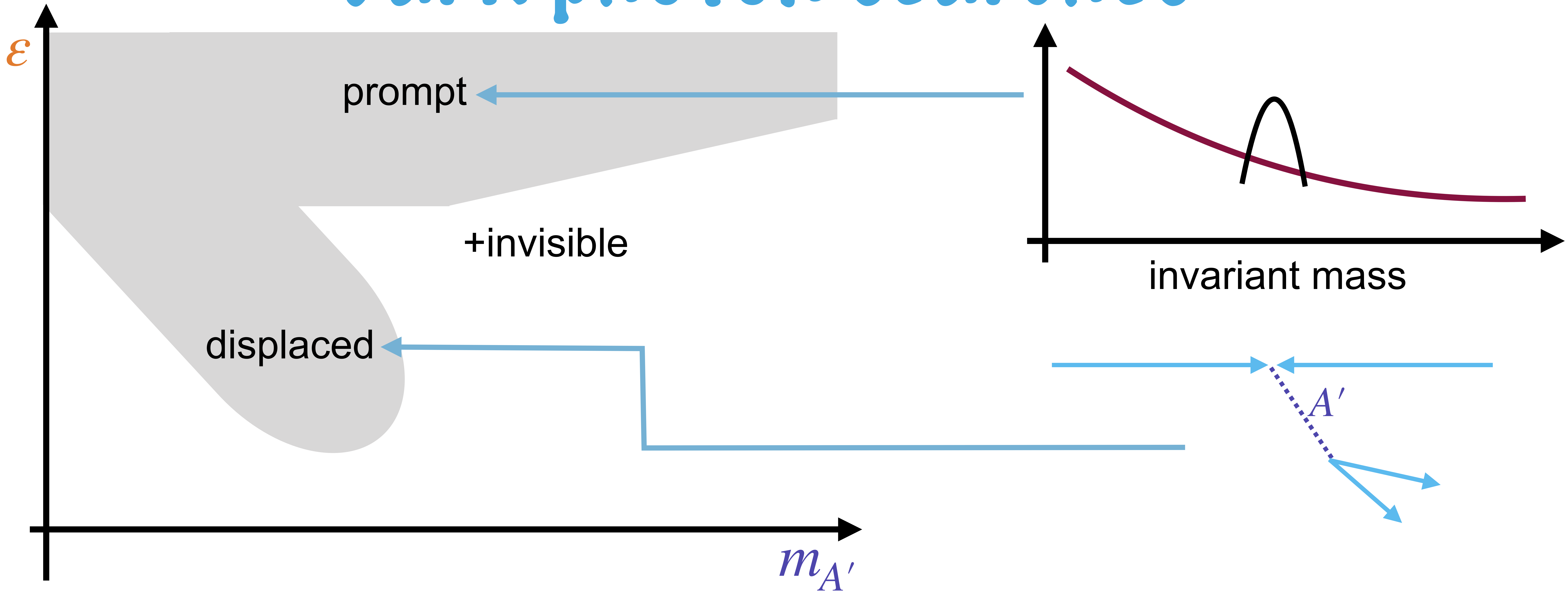


collider: B-factories, LHCb/ATLAS/CMS, CLOE

Dark photon searches



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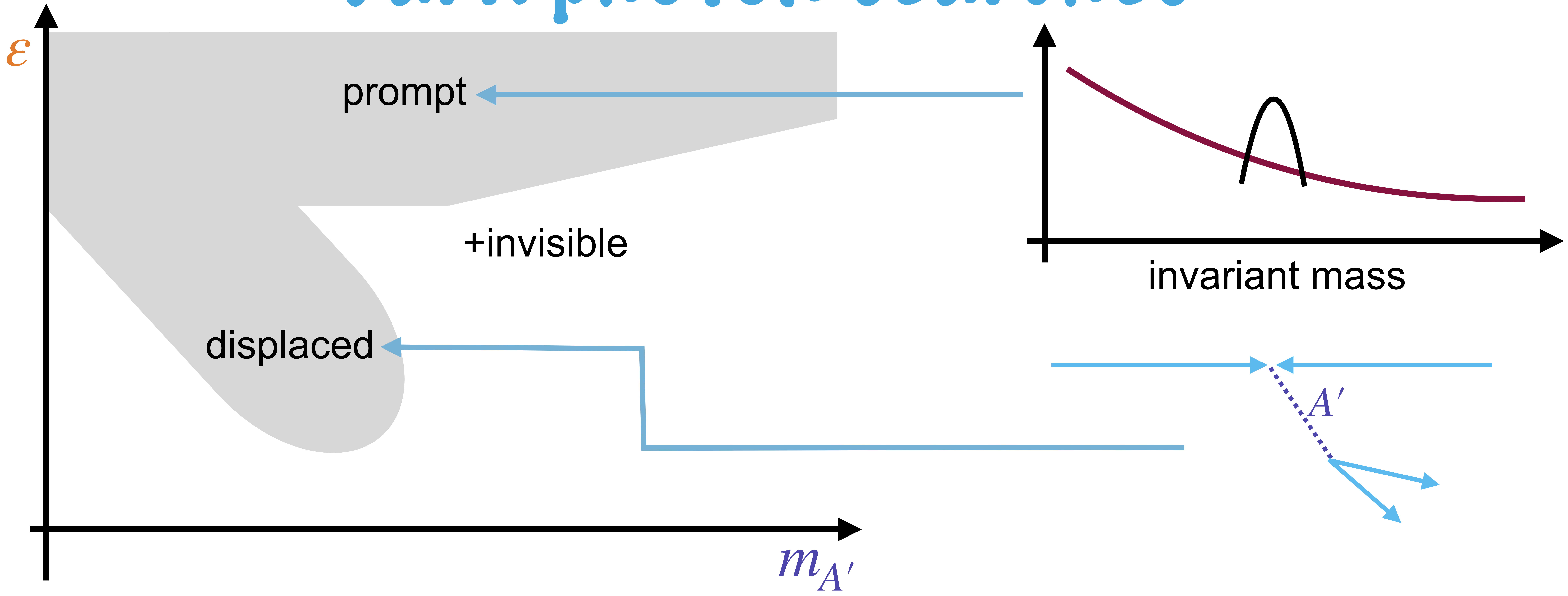
Dark photon searches

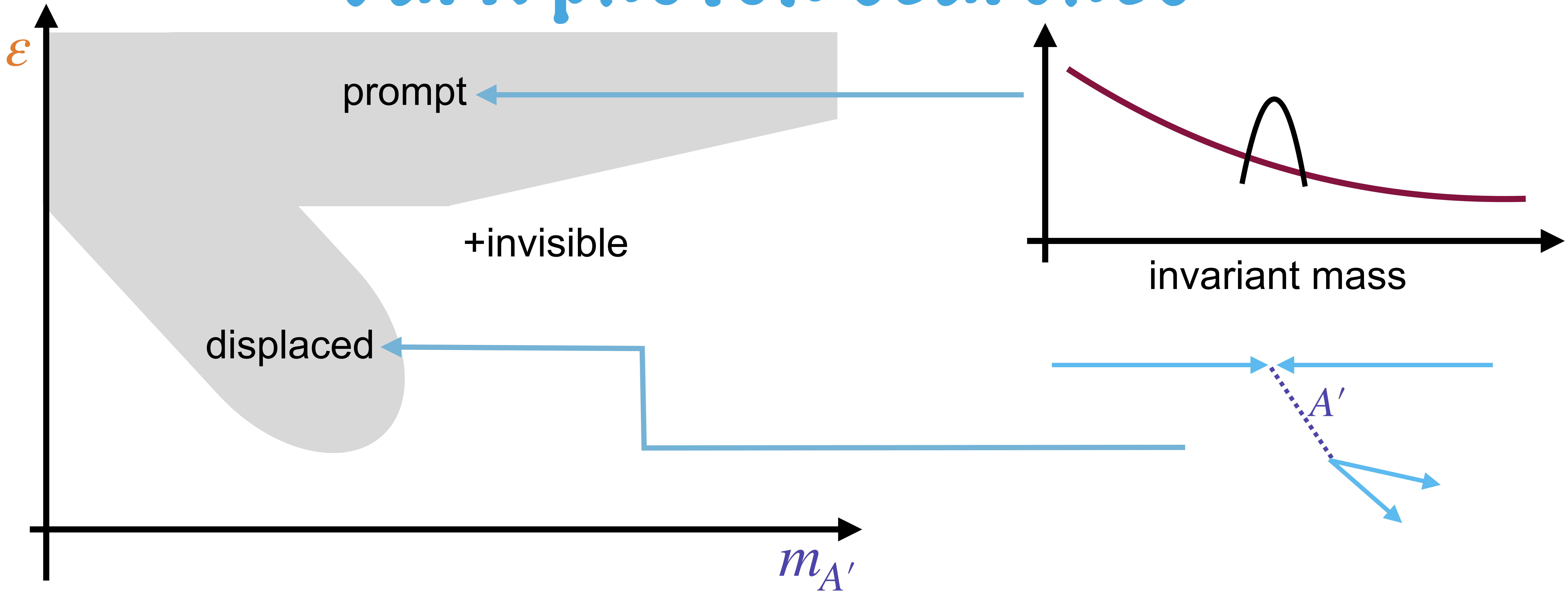


collider: B-factories, LHCb/ATLAS/CMS, CLOE

rare decays: NA48, NA62, B-factories, LHCb, Mu3e

fixed target: HPS, PrimEx, GlueX

Dark photon searches



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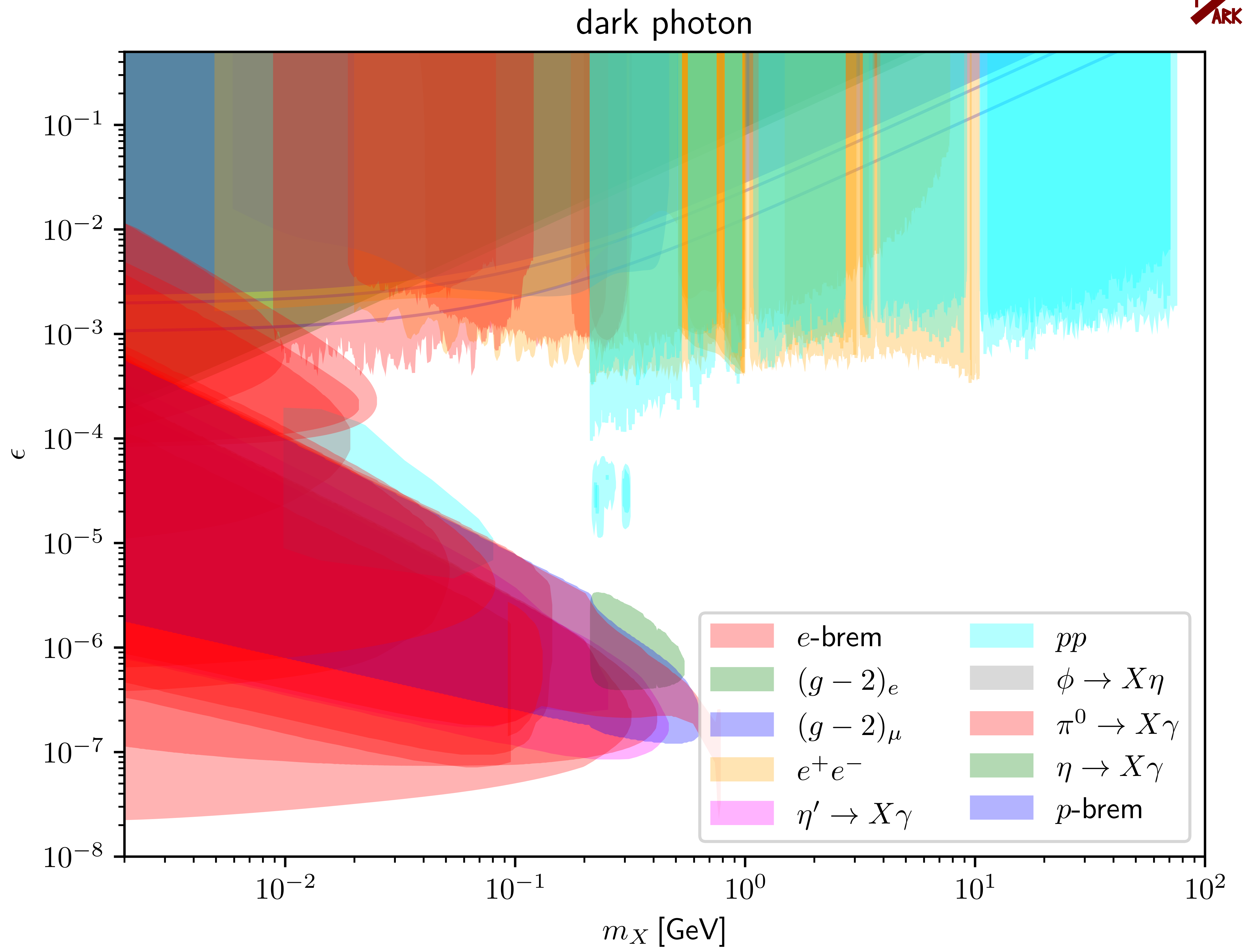
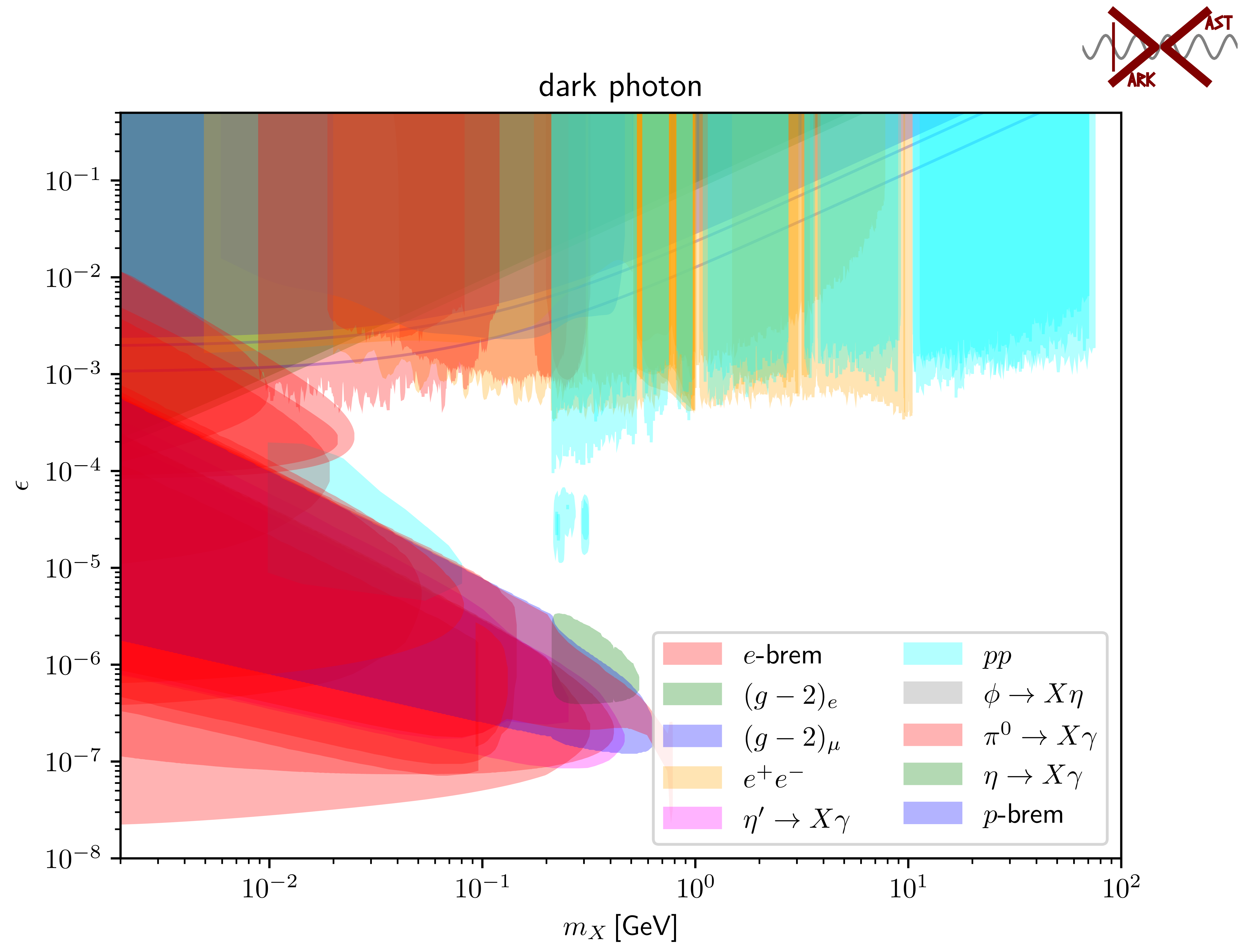
beam-dump: E774, NA64, E141, KE, Orsay, E137, NOMAD, PS191, muCAL, FASER, CHARM, LUXE

Dark photon searches



visible final states

Dark photon searches



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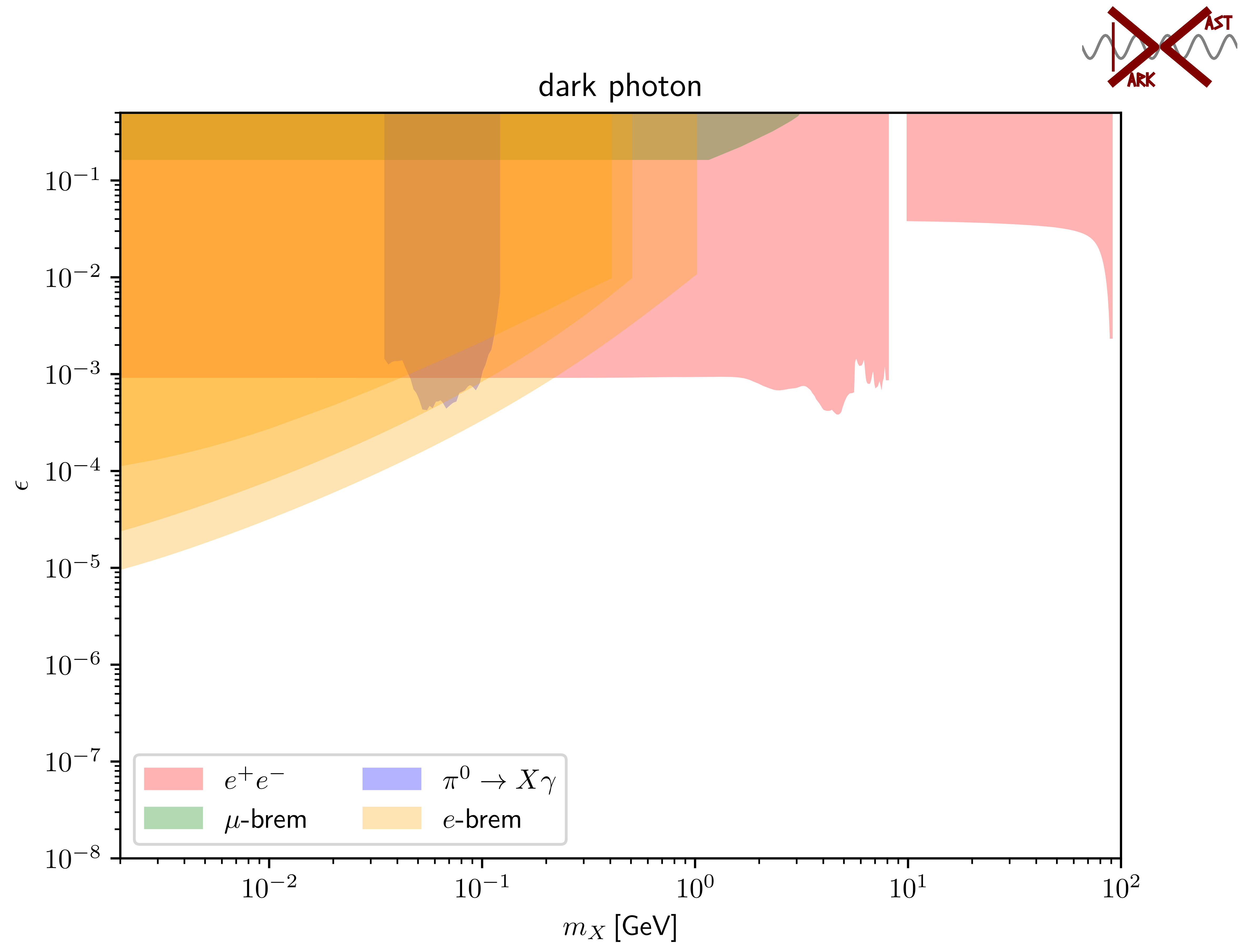
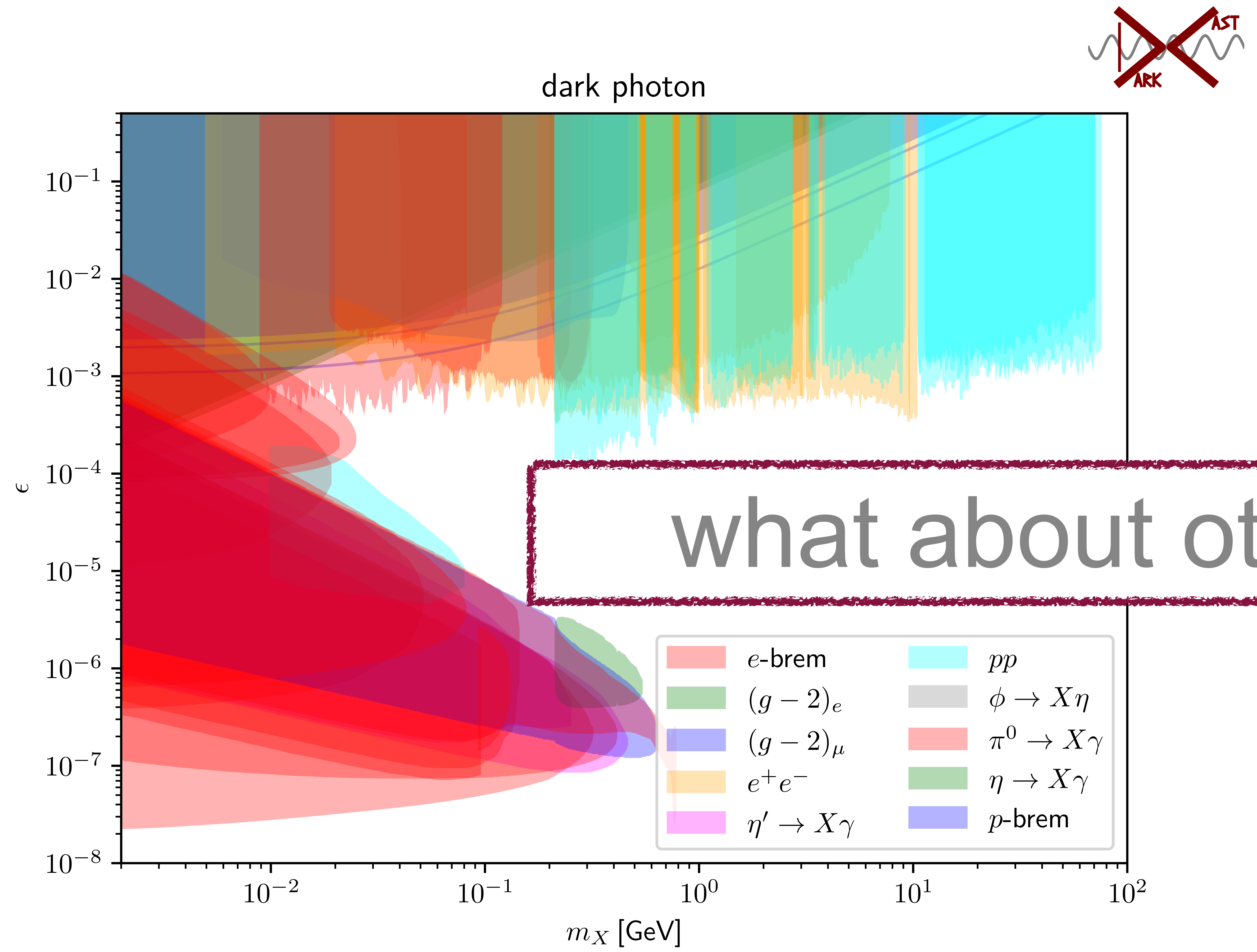
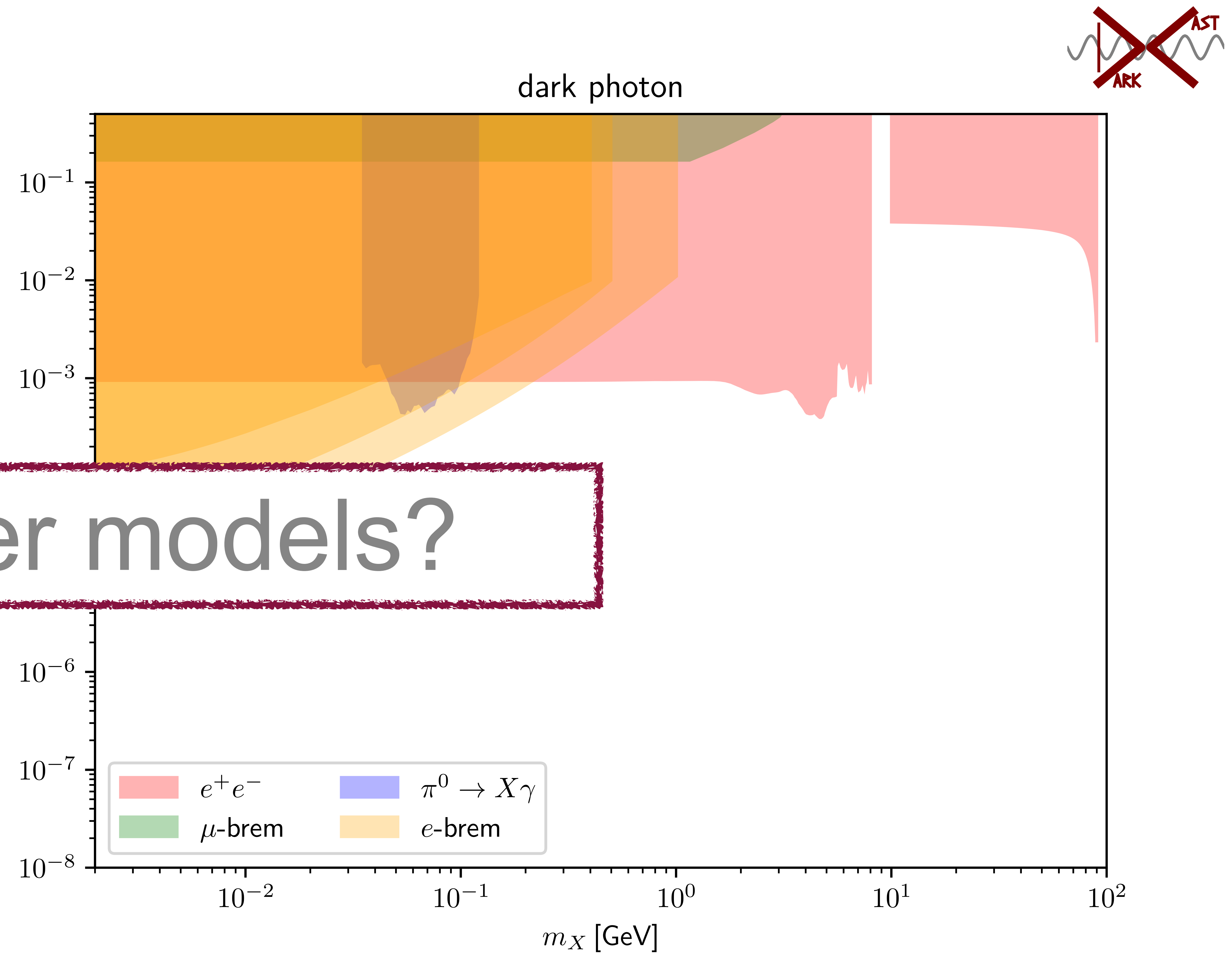


invisible final state

Dark photon searches





what about other models?

visible final states

invisible final state

DarkCast
recasting dark photon searches for generic spin-1 models

Ilten, YS, Williams, Xue, 1801.04847
Baruch, Ilten, YS, Williams, 2206.08563
https://gitlab.com/darkcast/

Beyond the dark photon

assume that the dark photon (kinetic bounds)
bounds are given $m_{A'}$, ε

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↓

generic spin-1 model: $g_X \sum_f \bar{f} \gamma^\mu \left(x_V^f + \gamma_5 x_A^f \right) f \, X_\mu + \sum_\chi \mathscr{L}_{X_{\chi\bar{\chi}}}$

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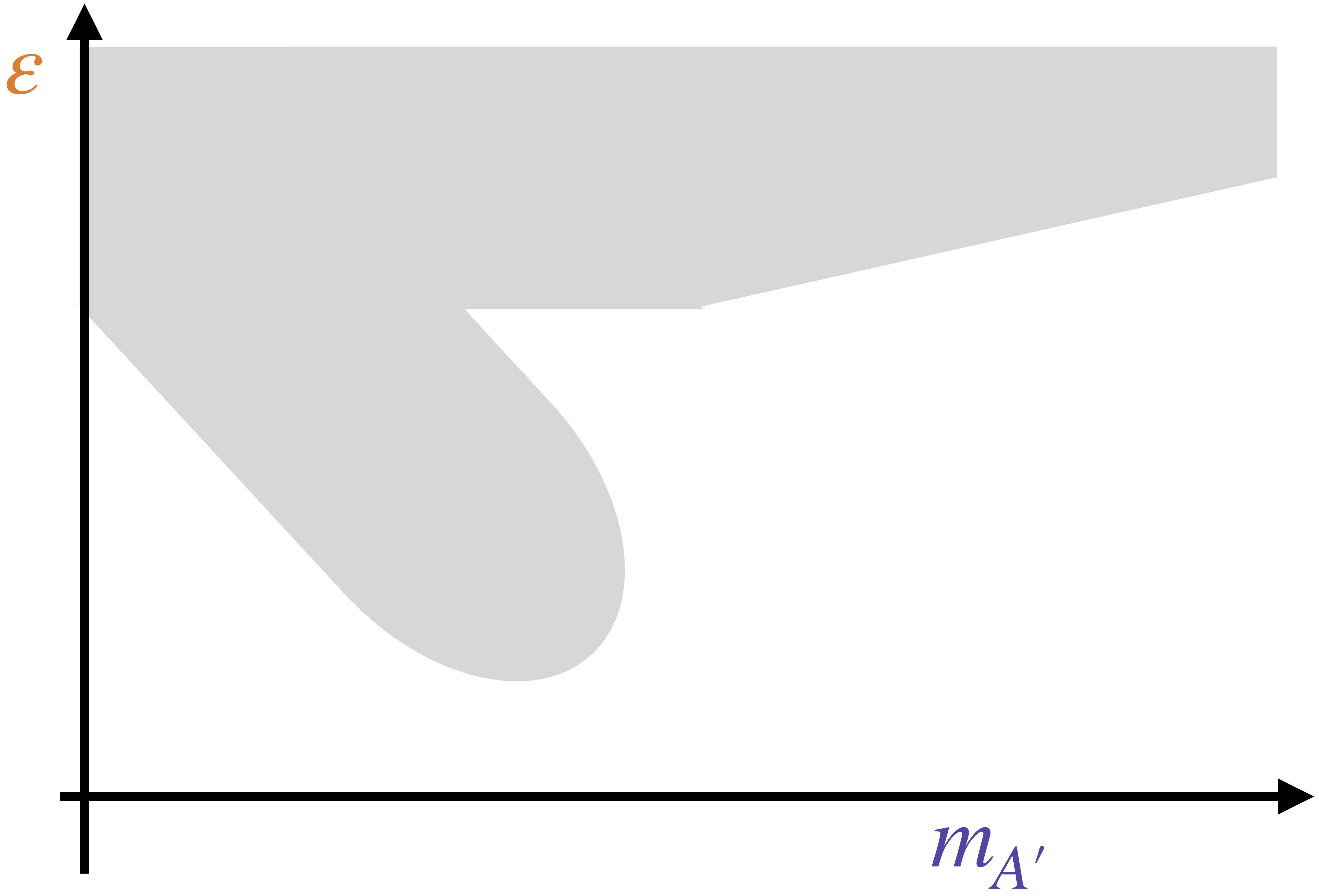
in principle, can go from any model to any model

Beyond the dark photon

$A' \to X$



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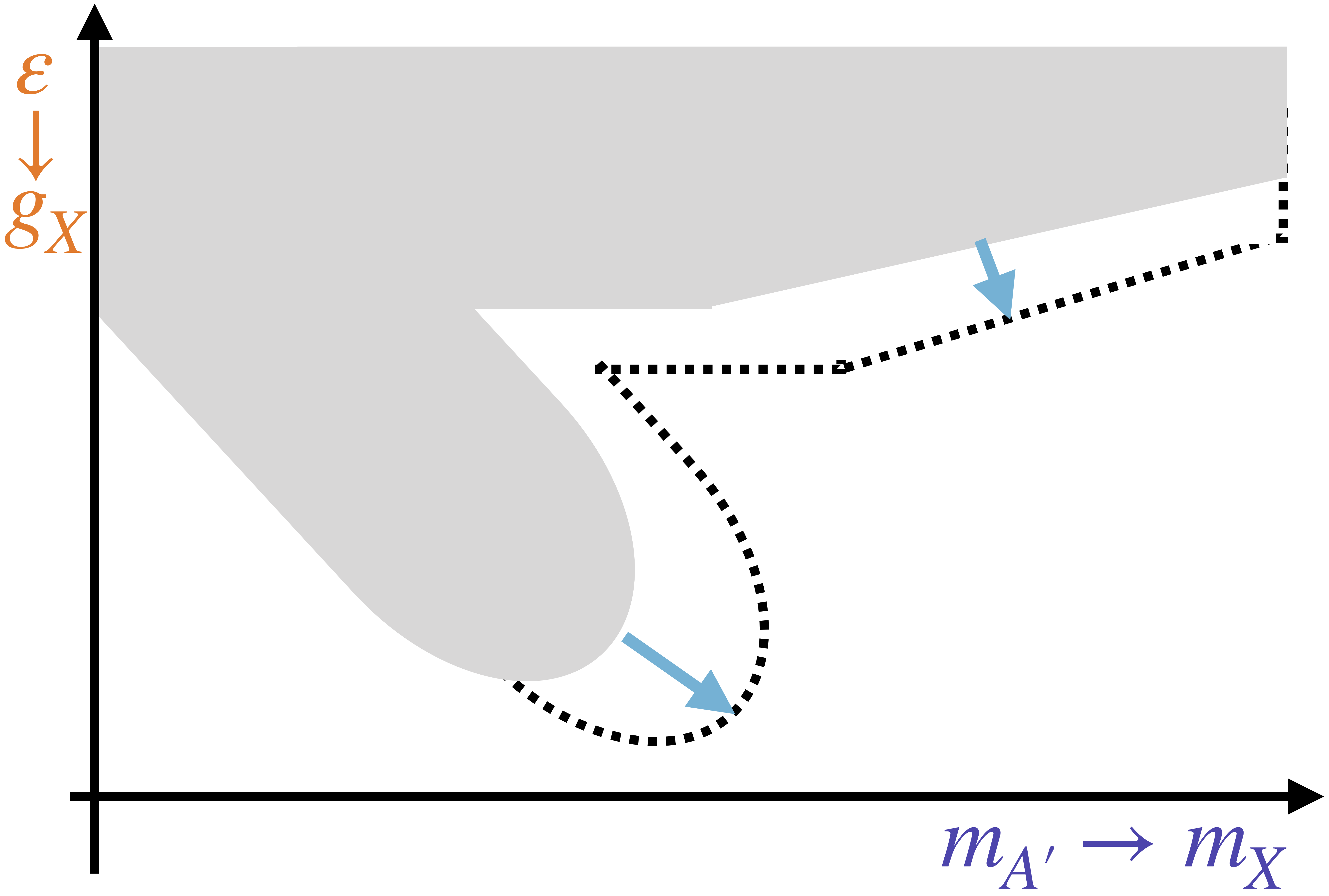

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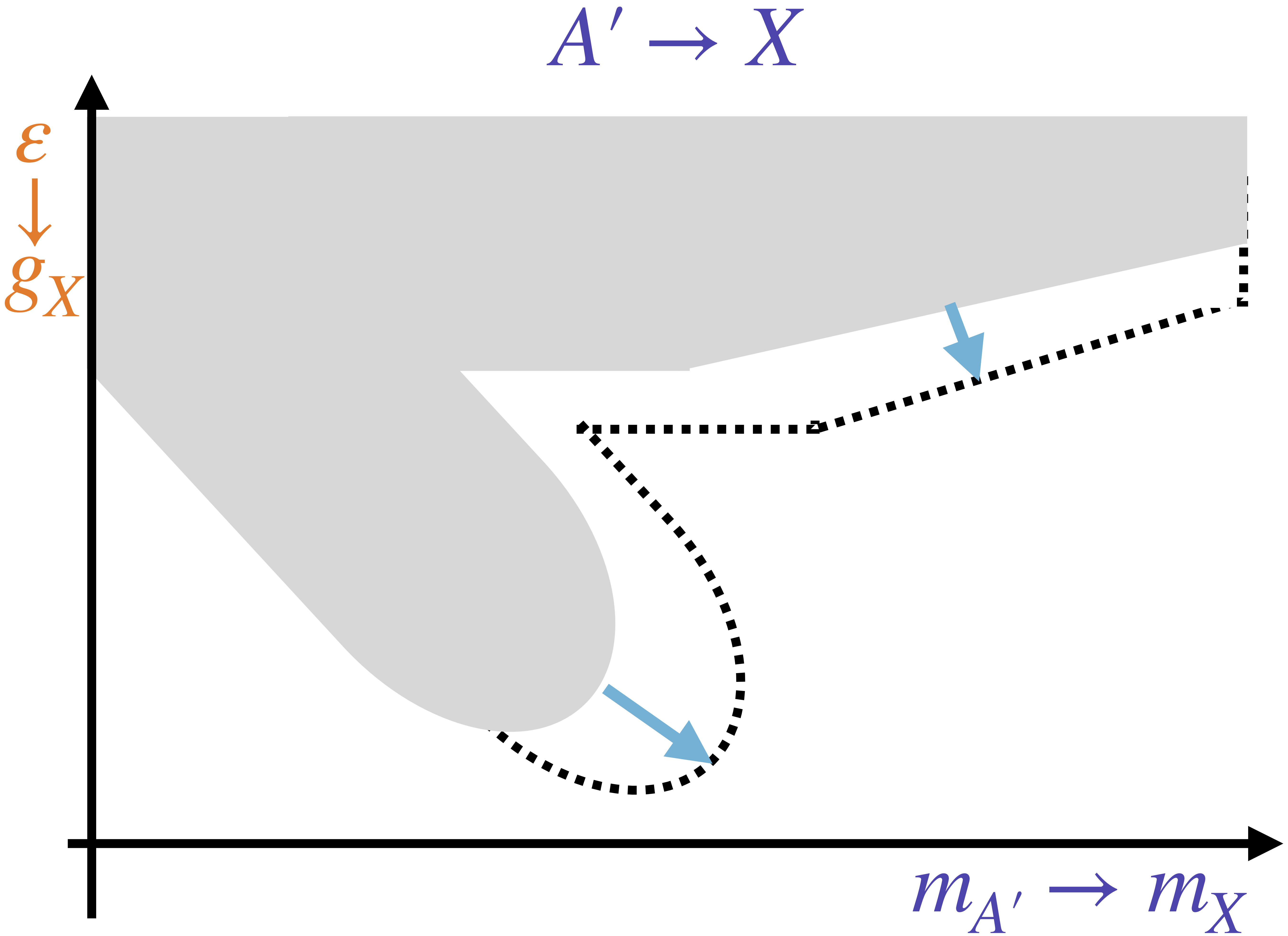
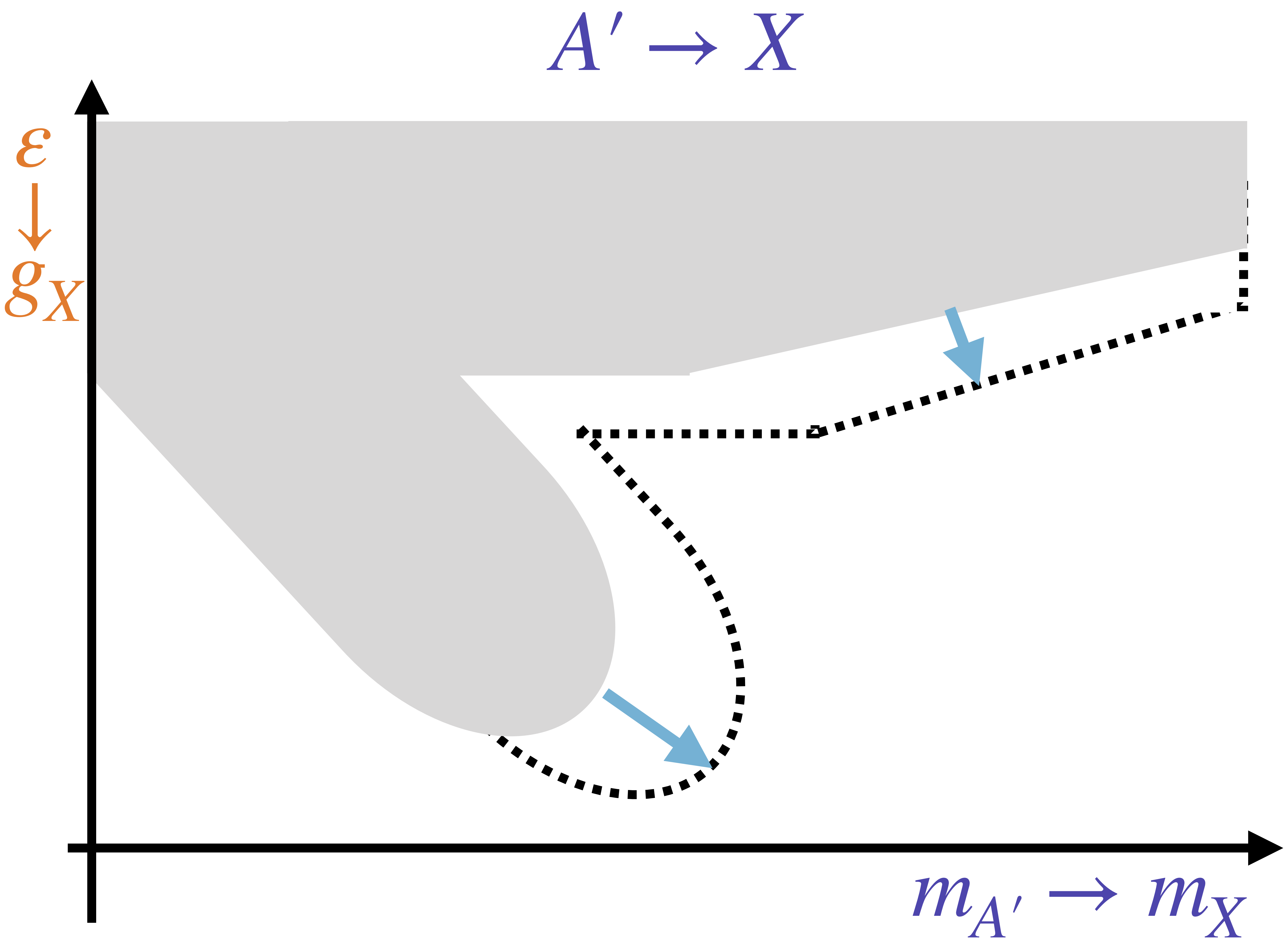


master equation:

$$\frac{\sigma_X(m, g_X)\,\mathrm{BR}_{X\to\mathcal{F}}(m)\,\varepsilon(\tau_X(m, g_X))}{\sigma_{A'}(m, g_{A'})\,\mathrm{BR}_{A'\to\mathcal{F}}(m)\,\varepsilon(\tau_{A'}(m, g_{A'}))} = 1$$

Beyond the dark photon



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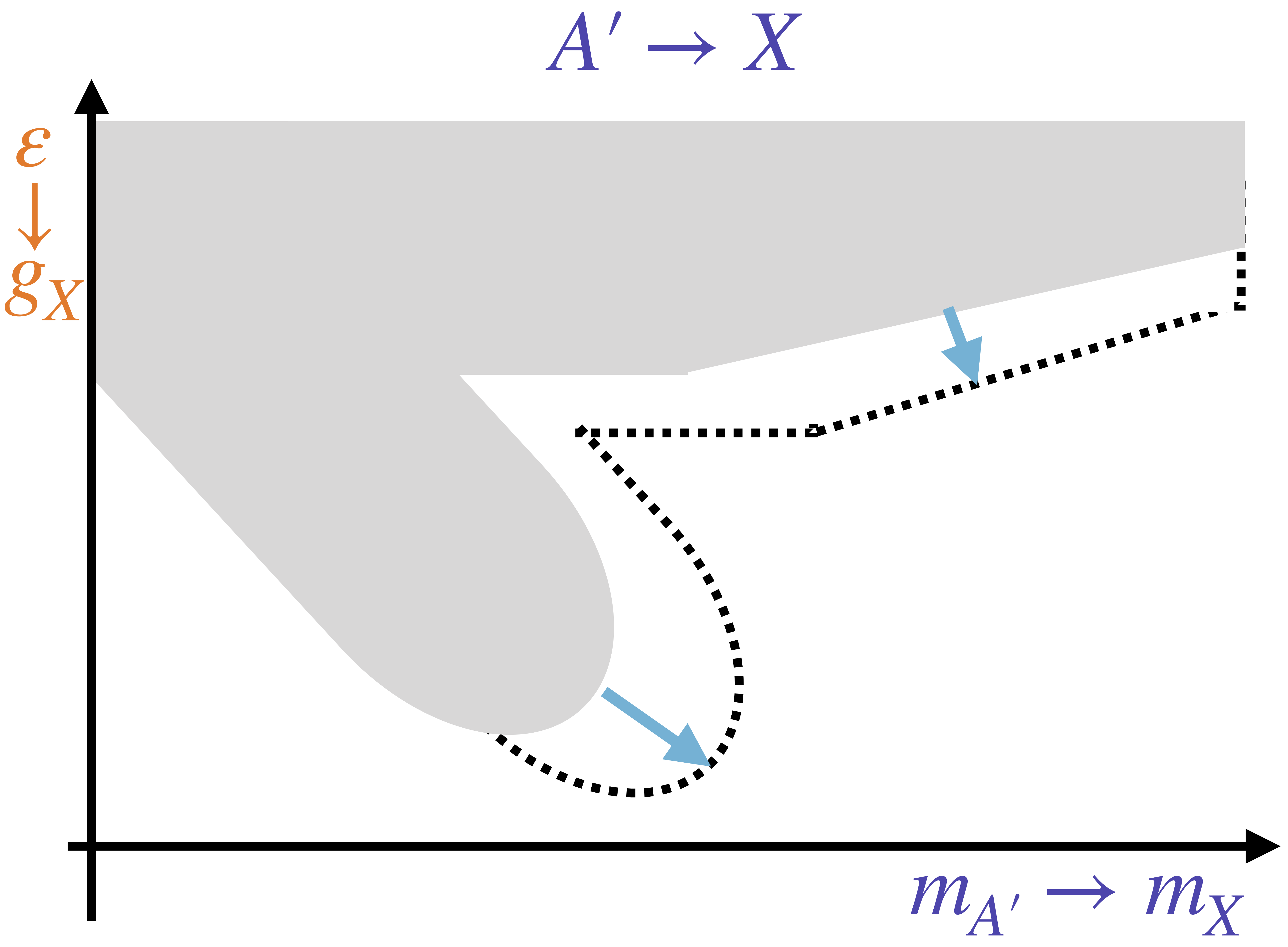
$$\frac{\varepsilon(\tau_X(m, g_X))}{\varepsilon(\tau_{A'}(m, g_{A'}))} \qquad \frac{\sigma_X(m, g_X)}{\sigma_{A'}(m, g_{A'})}$$

X and the experiment

Beyond the dark photon



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X and the experiment

$$\frac{\mathrm{BR}_{X\to\mathcal{F}}(m)}{\mathrm{BR}_{A'\to\mathcal{F}}(m)}$$

only X dependent

Ratio of branching ratios

perturbative $(m_X \gg m_f)$: $\Gamma_{X\to f\bar{f}} = \dfrac{\mathscr{C}_f g_X^2}{12\pi} m_x \left[\left(x_V^f\right)^2 + \left(x_A^f\right)^2\right]$

leptons + quarks for $m_X > 2\,\mathrm{GeV}$

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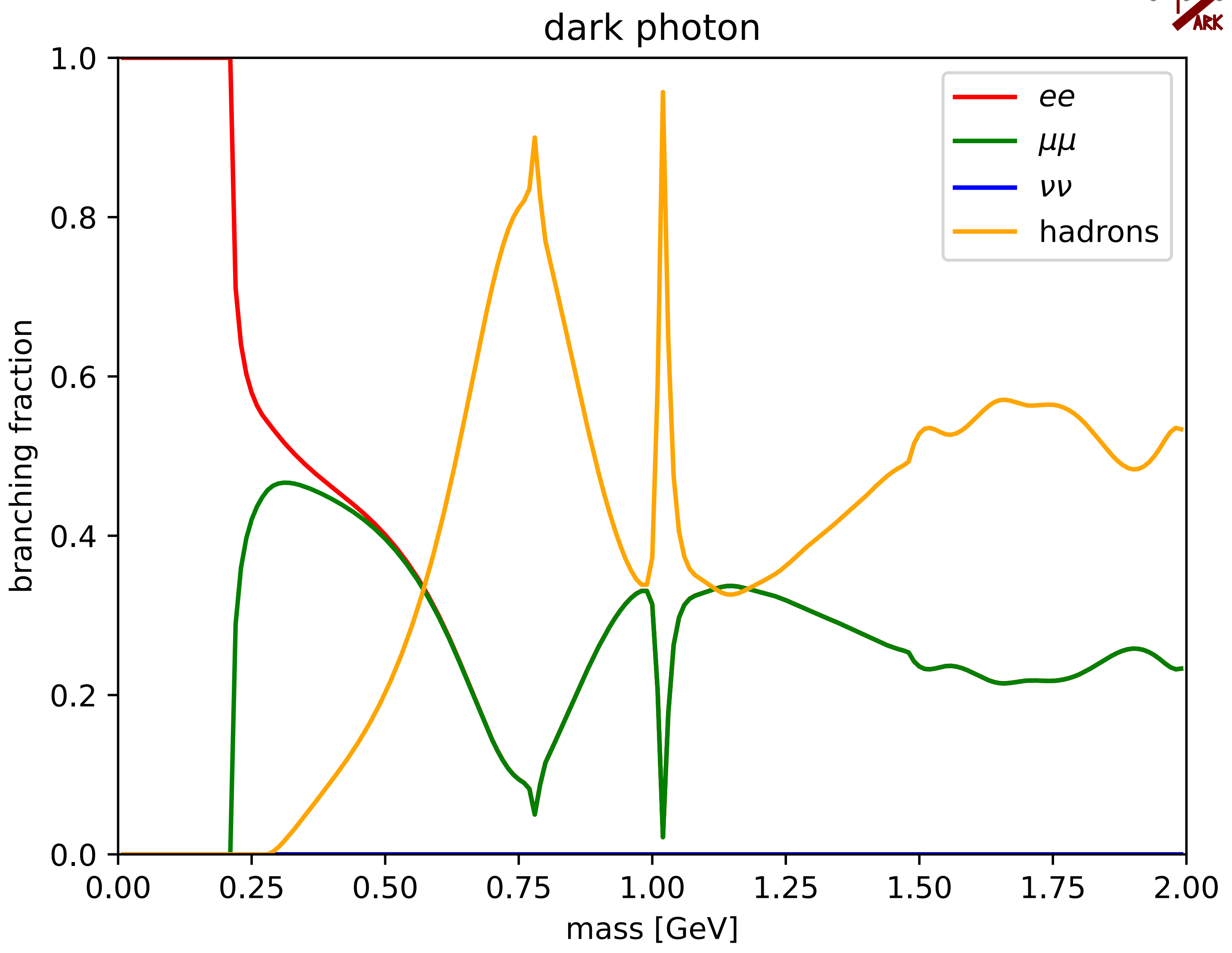
vector current - $\bar{q}\gamma_\mu q$: $e^+e^- \to \mathrm{hadrons}$

axial current - $\bar{q}\gamma_\mu\gamma_5 q$: hadronic τ decays + $U(3)_{\mathrm{flavor}}$

Ratios of branching ratios



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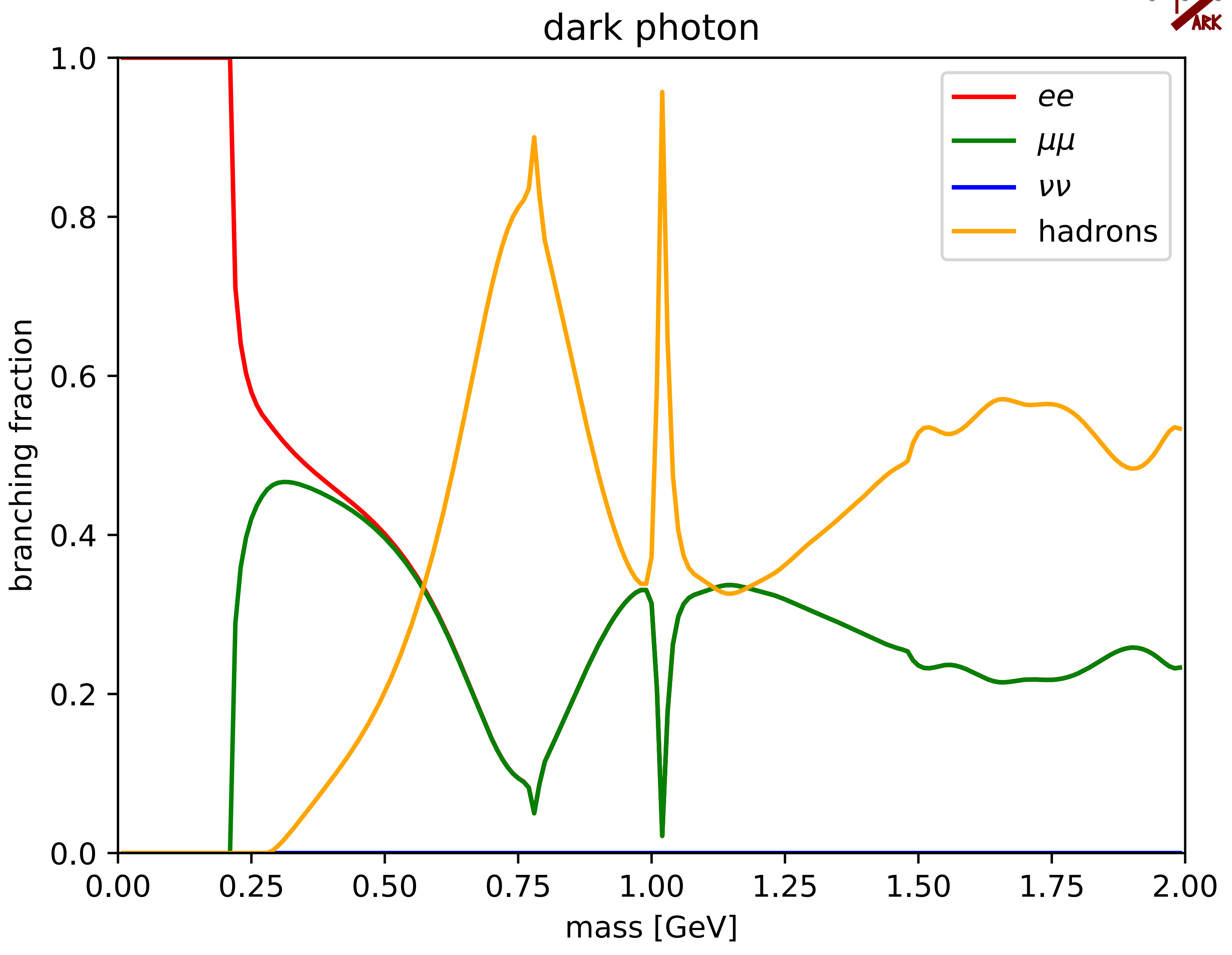

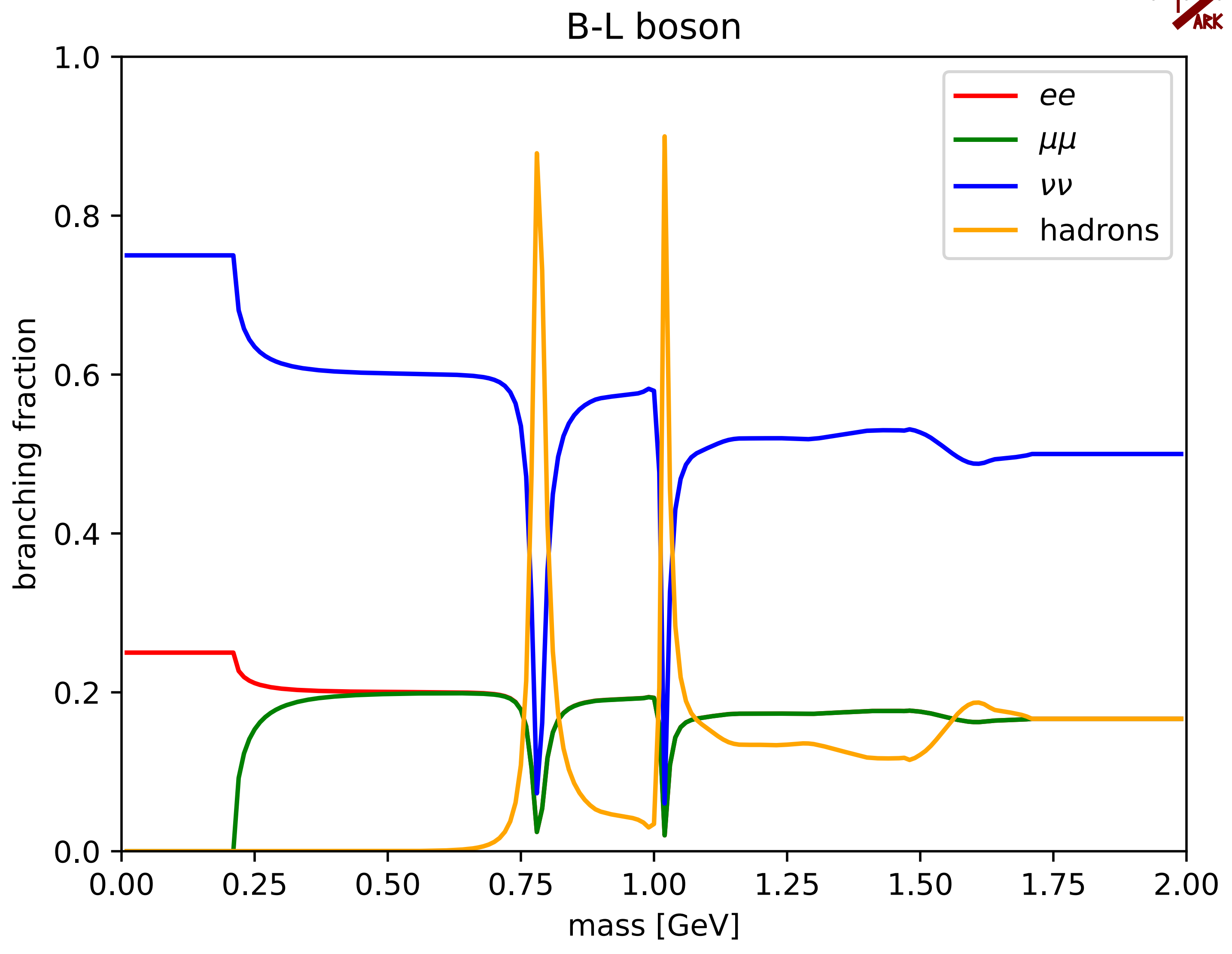

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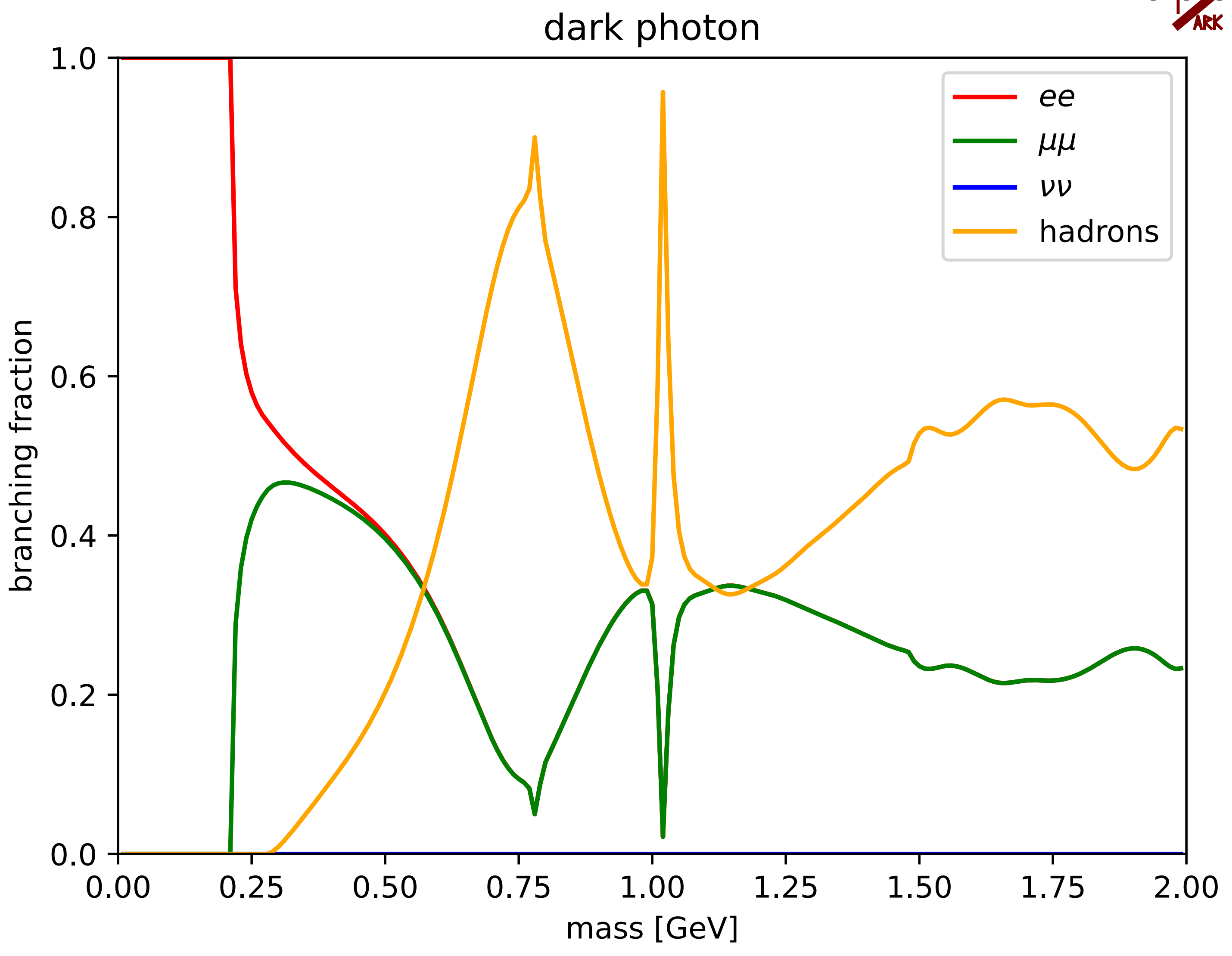

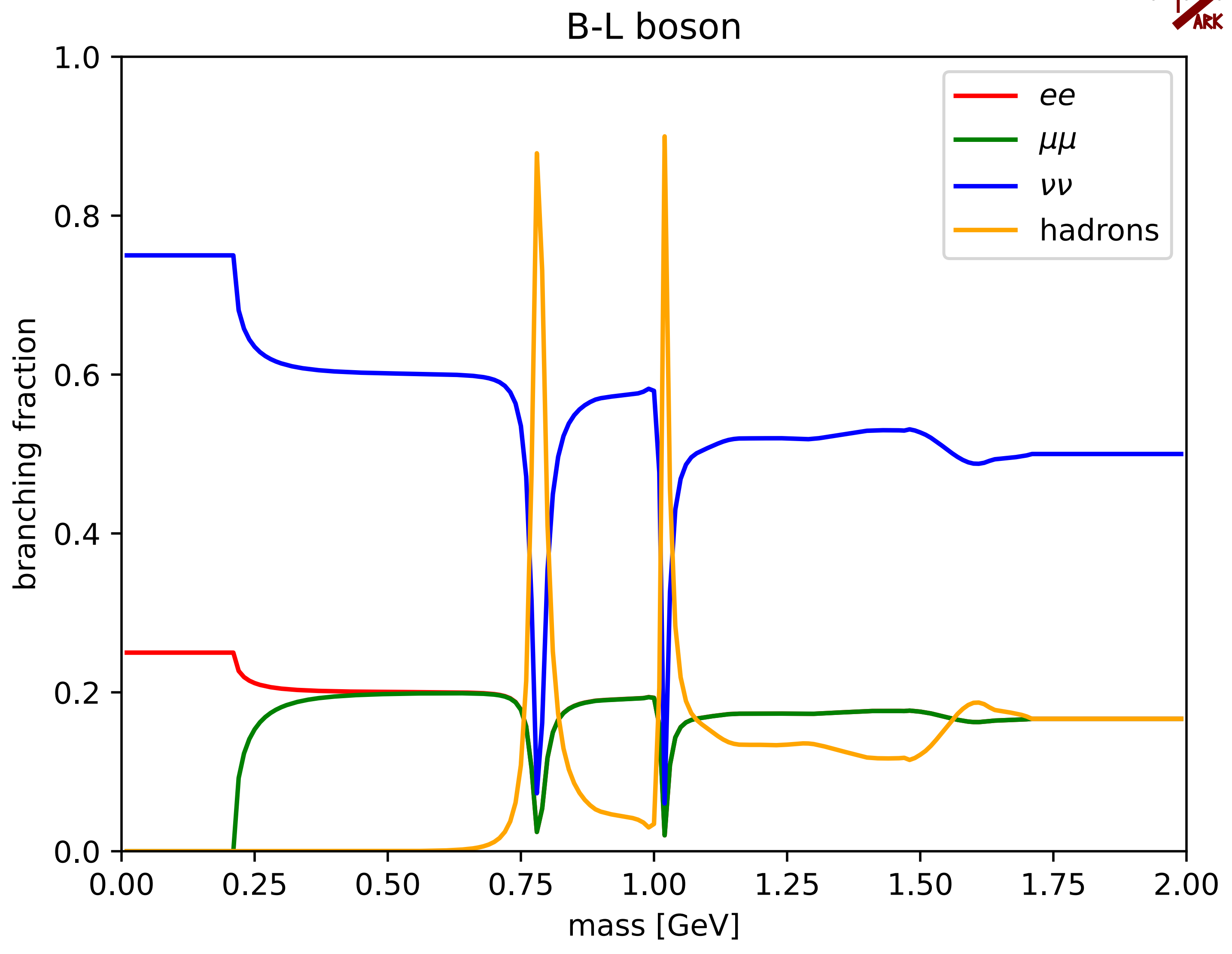

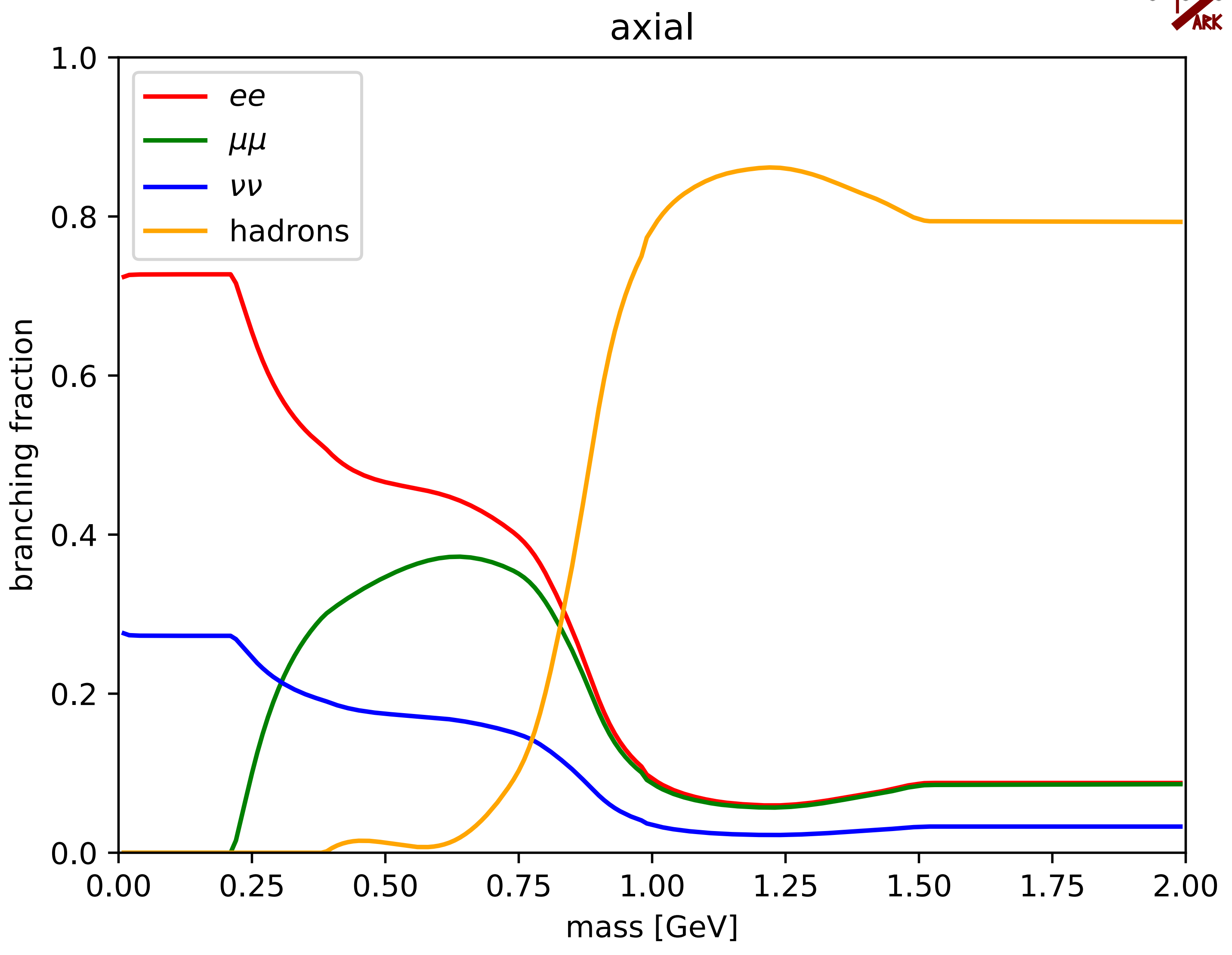

Production ratios

e-bream+annihilation: $$\frac{\sigma(e^+e^- \to \gamma X)}{\sigma(e^+e^- \to \gamma A')} = \frac{\sigma(eZ \to eZX)}{\sigma(eZ \to eZX)} = \frac{g_X^2}{(\varepsilon e)^2}\left[(g_A^e)^2 + (g_V^e)^2\right]$$

neglecting $\mathcal{O}\left(m_e^2/m_X^2\right)$

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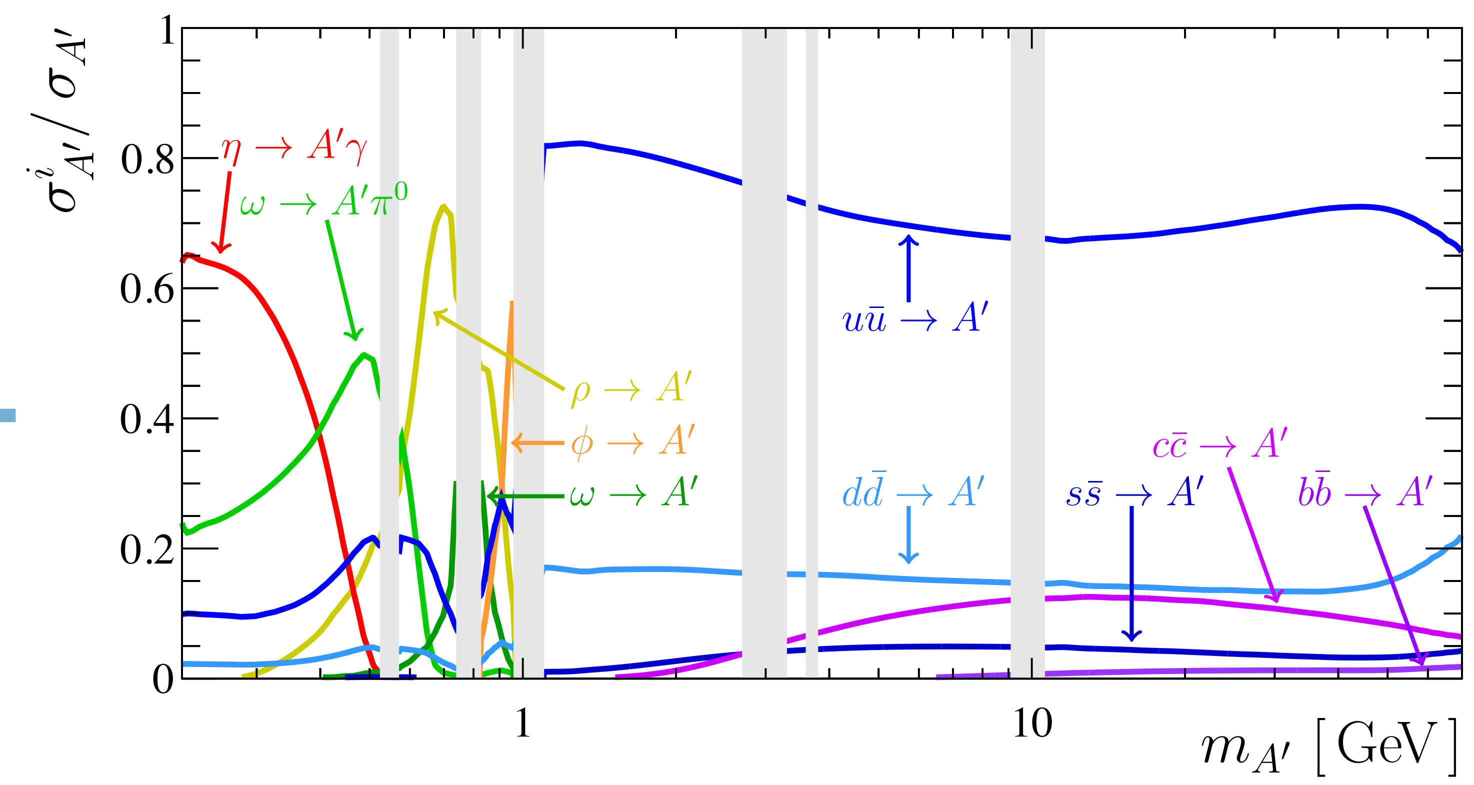
relative fractions from MC



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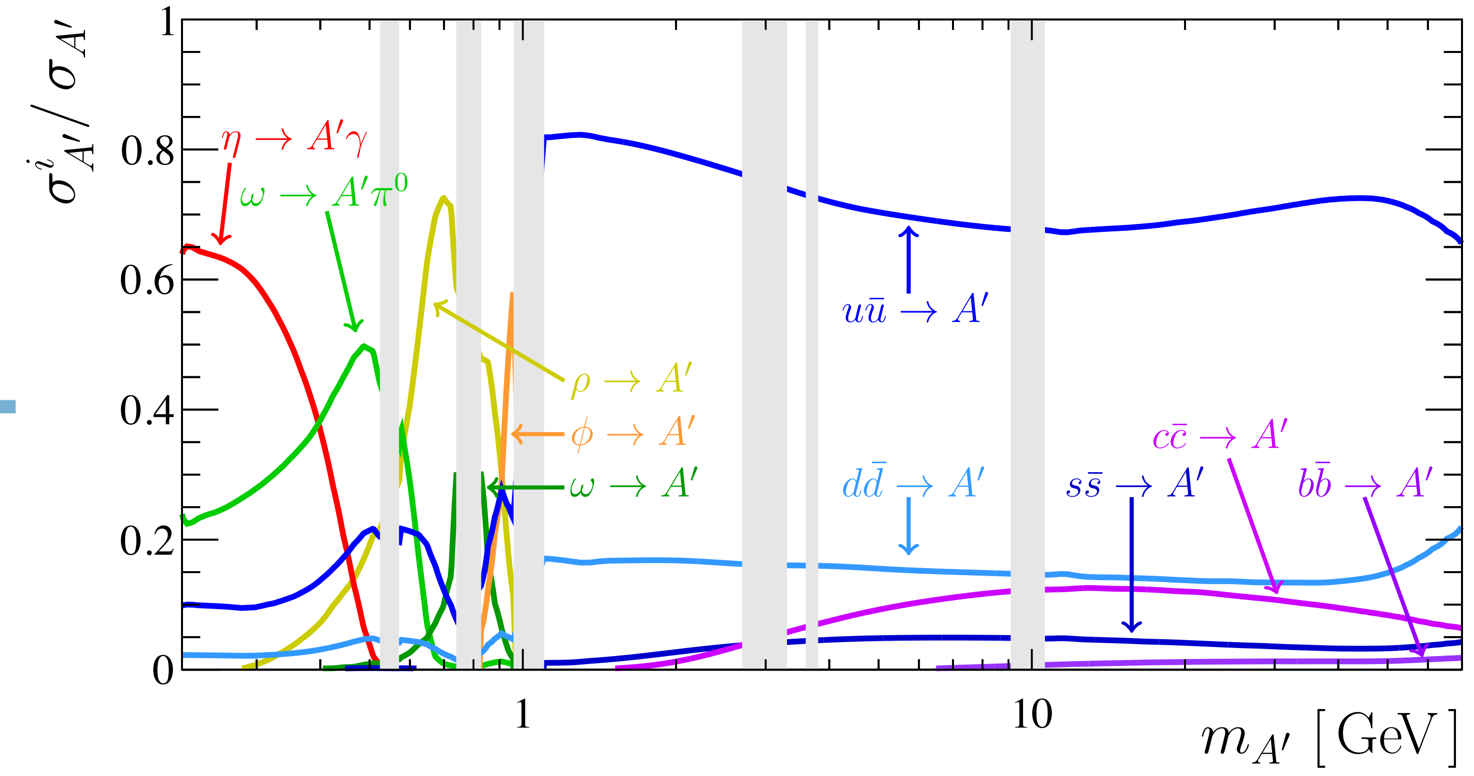
$$\frac{9g_X^2}{(e\varepsilon Q_q)^2}\left[(x_V^q)^2 + (x_A^q)^2\right]$$

relative fractions from MC



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Production ratios

vector meson decay $V \to XP$: $$\frac{\Gamma_{V\to XP}}{\Gamma_{V\to A'P}} = \frac{g_X^2}{(\varepsilon e)^2}\frac{\left|\sum_{V'}\mathrm{Tr}[T_V T_P T_{V'}]\mathrm{Tr}[T_{V'}Q_X]\mathrm{BW}_{V'}(m_X)\right|^2}{\left|\sum_{V'}\mathrm{Tr}[T_V T_P T_{V'}]\mathrm{Tr}[T_{V'}Q]\mathrm{BW}_{V'}(m_X)\right|^2}$$

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$U(3)_{\text{flavor}}$ mixing

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$U(3)_{\text{flavor}}$ mixing

Bright-Wigner

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$U(3)_{\text{flavor}}$ mixing — Bright-Wigner

radiative meson decay $V \to XP$: $$\frac{\Gamma_{P\to X\gamma}}{\Gamma_{P\to A'\gamma}} = \left(\frac{g_X}{\varepsilon e}\right)^2\frac{\left|\sum_{V}\mathrm{Tr}[T_P Q T_V]\mathrm{Tr}[T_V Q_X]\mathrm{BW}_V(m)\right|^2}{\left|\sum_{V}\mathrm{Tr}[T_P Q T_V]\mathrm{Tr}[T_V Q]\mathrm{BW}_V(m)\right|^2}$$

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$U(3)_{\text{flavor}}$ mixing

Bright-Wigner

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$V - X$ mixing: $$\frac{\sigma_{V\to X}}{\sigma_{V\to A'}} = \frac{g_X^2}{(\varepsilon e)^2} \times \begin{cases} (x_V^u - x_V^d)^2 & \text{for } V = \rho, \\ 9(x_V^u + x_V^d)^2 & \text{for } V = \omega, \\ 9(x_V^s)^2 & \text{for } V = \phi, \end{cases}$$

Efficiencies ratios

signature	$\frac{\varepsilon(\tau_X(m, g_X))}{\varepsilon(\tau_{A'}(m, g_{A'}))}$	
invisible		
prompt		
displaced (long-lived)		

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invisible	≈ 1	
prompt	$1 - e^{-\tilde{t}/\tau_X}$	$\varepsilon(\tau_A') \approx 1$
displaced (long-lived)		

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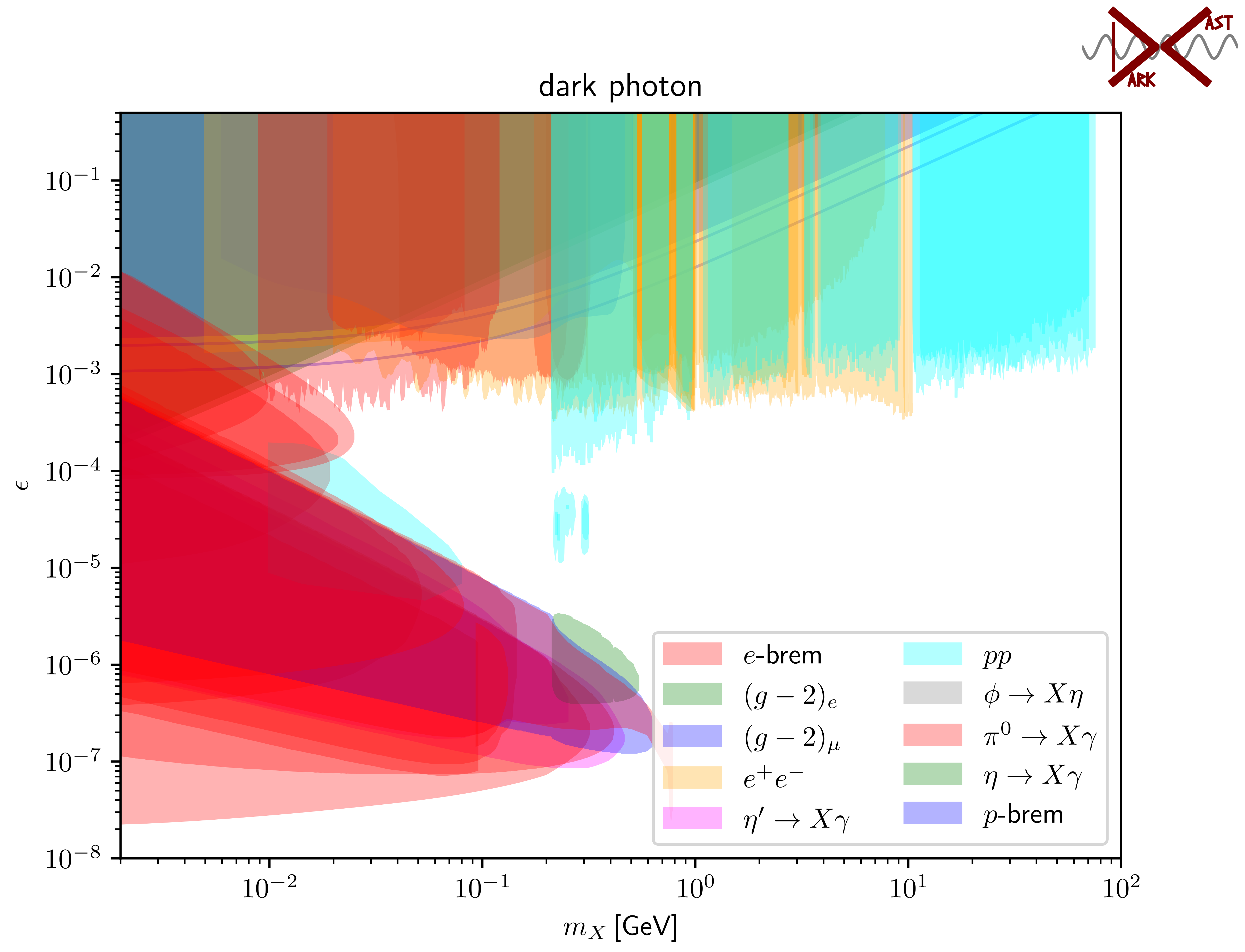
invisible	≈ 1	
prompt	$1 - e^{-\tilde{t}/\tau_X}$	$\varepsilon(\tau_A') \approx 1$
displaced (long-lived)	$\dfrac{e^{-\tilde{t}_0/\tau_X} - e^{-\tilde{t}_1/\tau_X}}{e^{-\tilde{t}_0/\tau_{A'}} - e^{-\tilde{t}_1/\tau_{A'}}}$	$\tilde{t}_1 = \tilde{t}_0(1 + L_{\rm dec}/L_{\rm sh})$ $\varepsilon^2_{\rm max}\epsilon[\tau_{A'}(\varepsilon^2_{\rm max})] = \varepsilon^2_{\rm min}\epsilon[\tau_{A'}(\varepsilon^2_{\rm min})]$

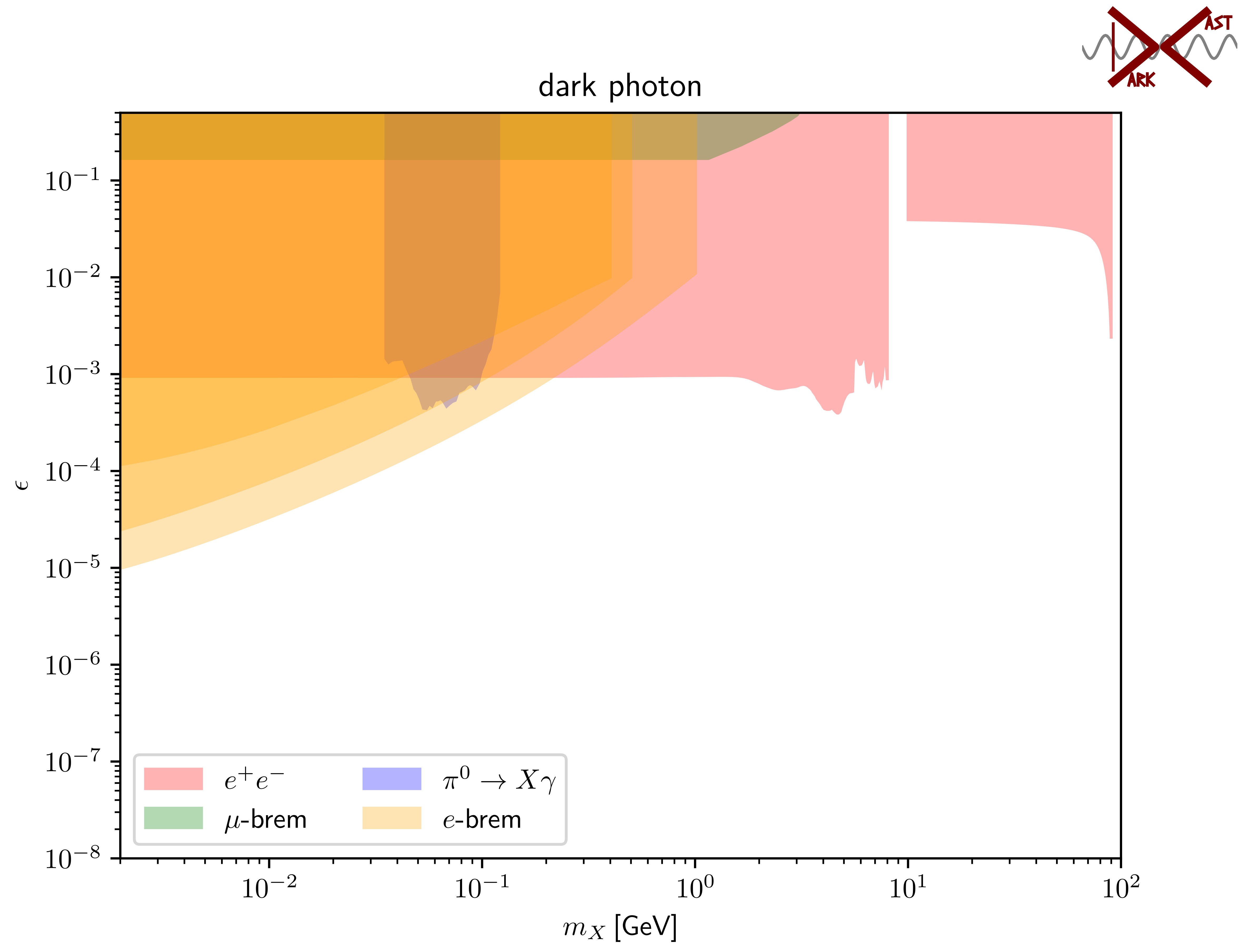
(finding the average boost)
LHCb provides the expected limits

Examples

Dark photon

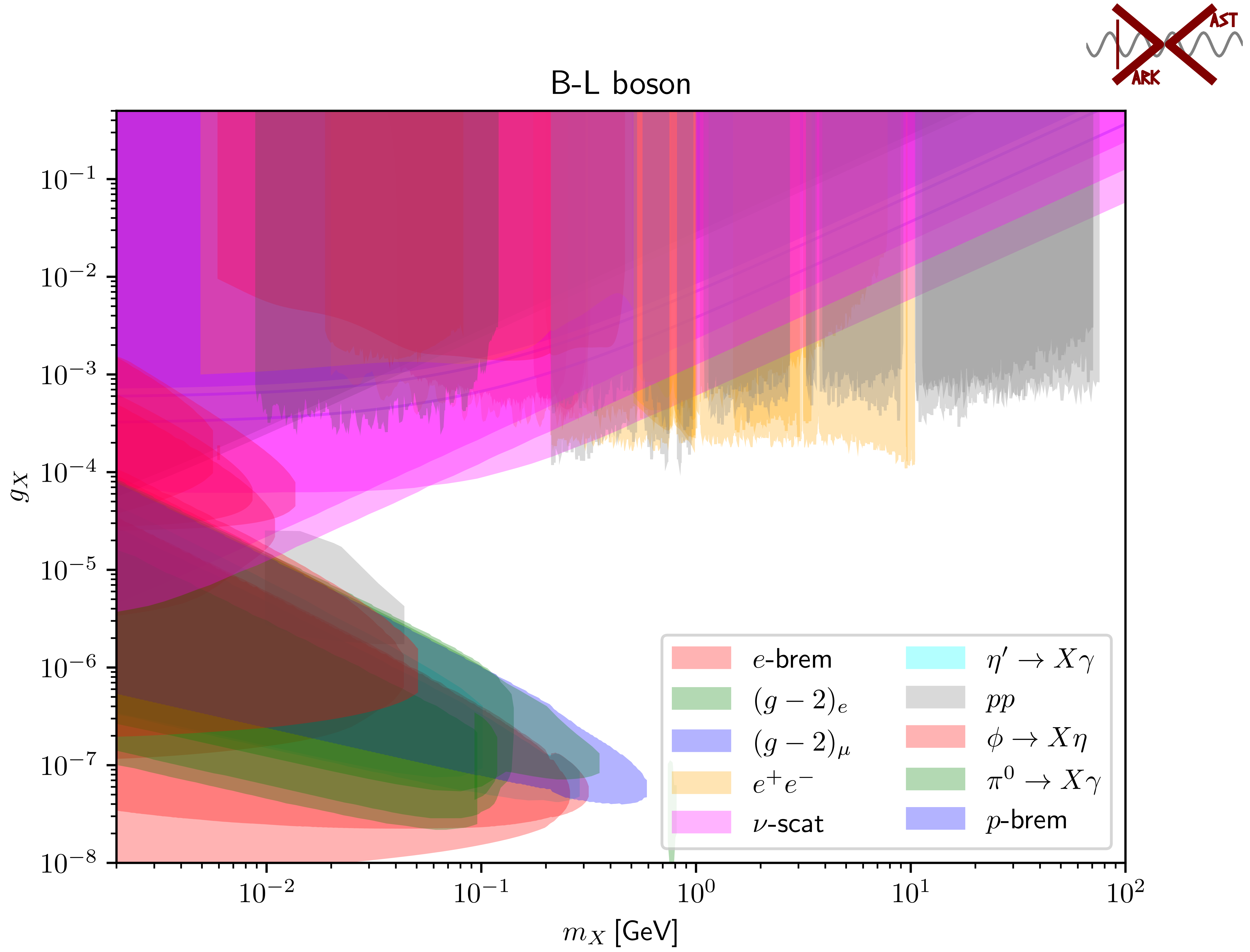


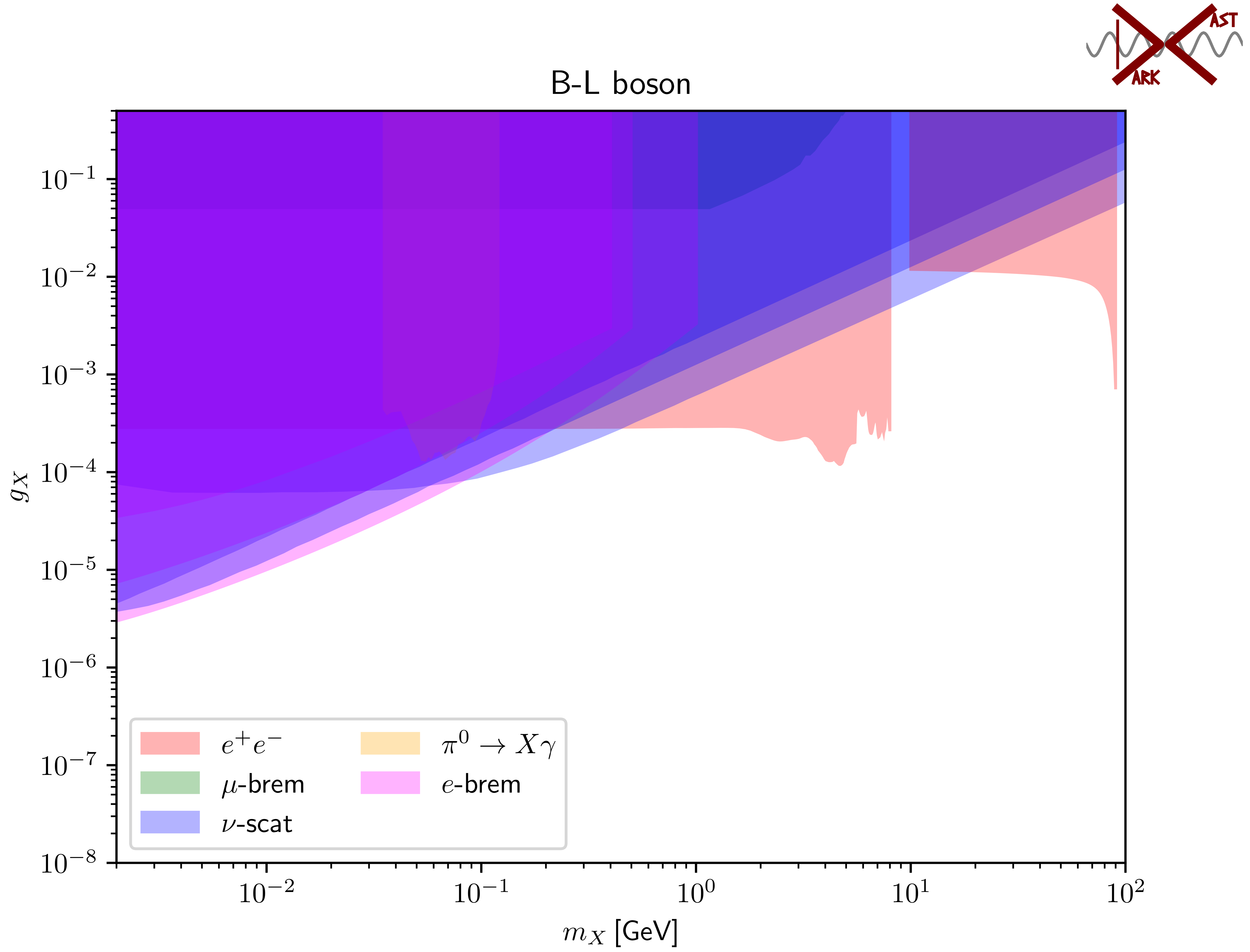
visible final states



invisible final state

B-L gauge boson

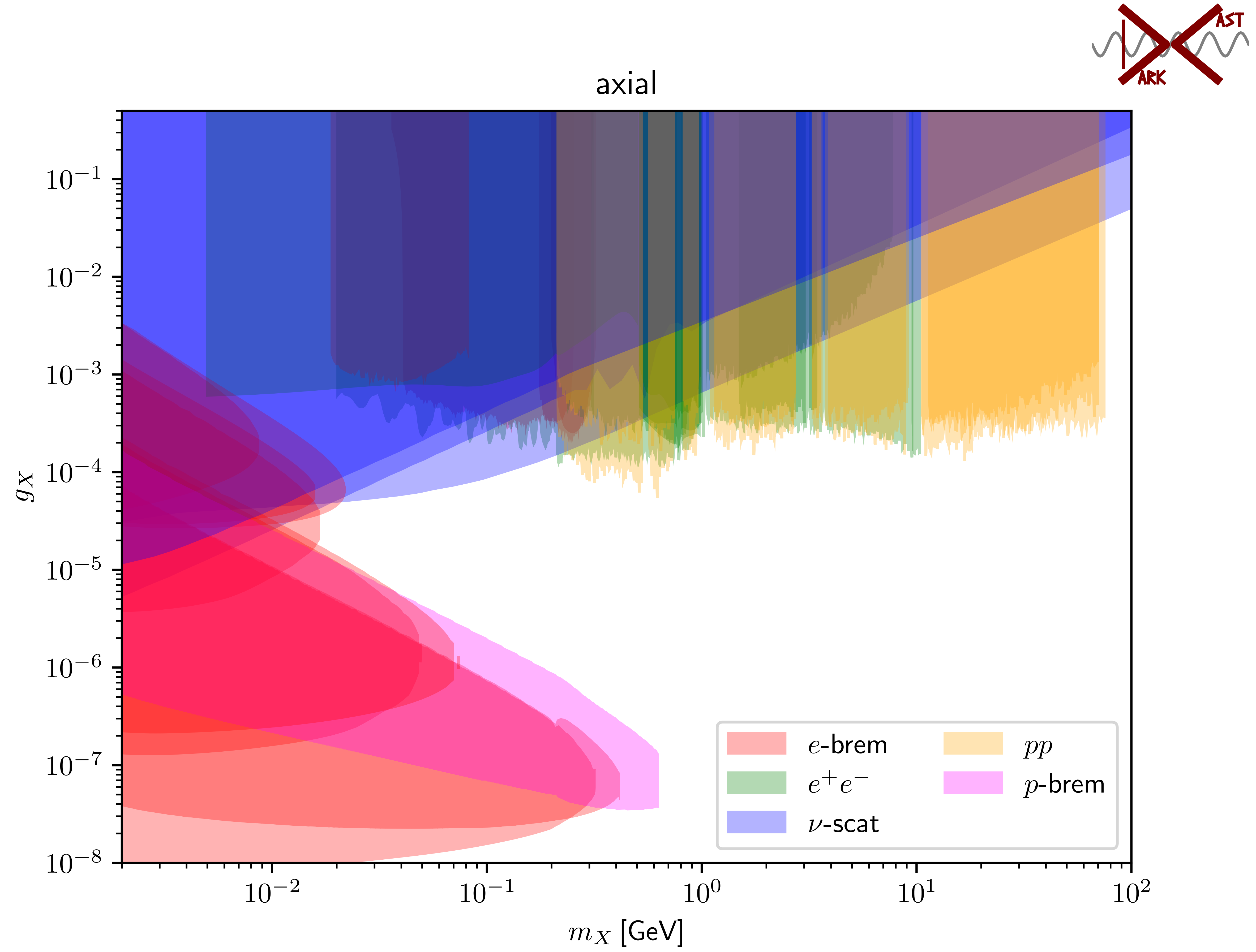




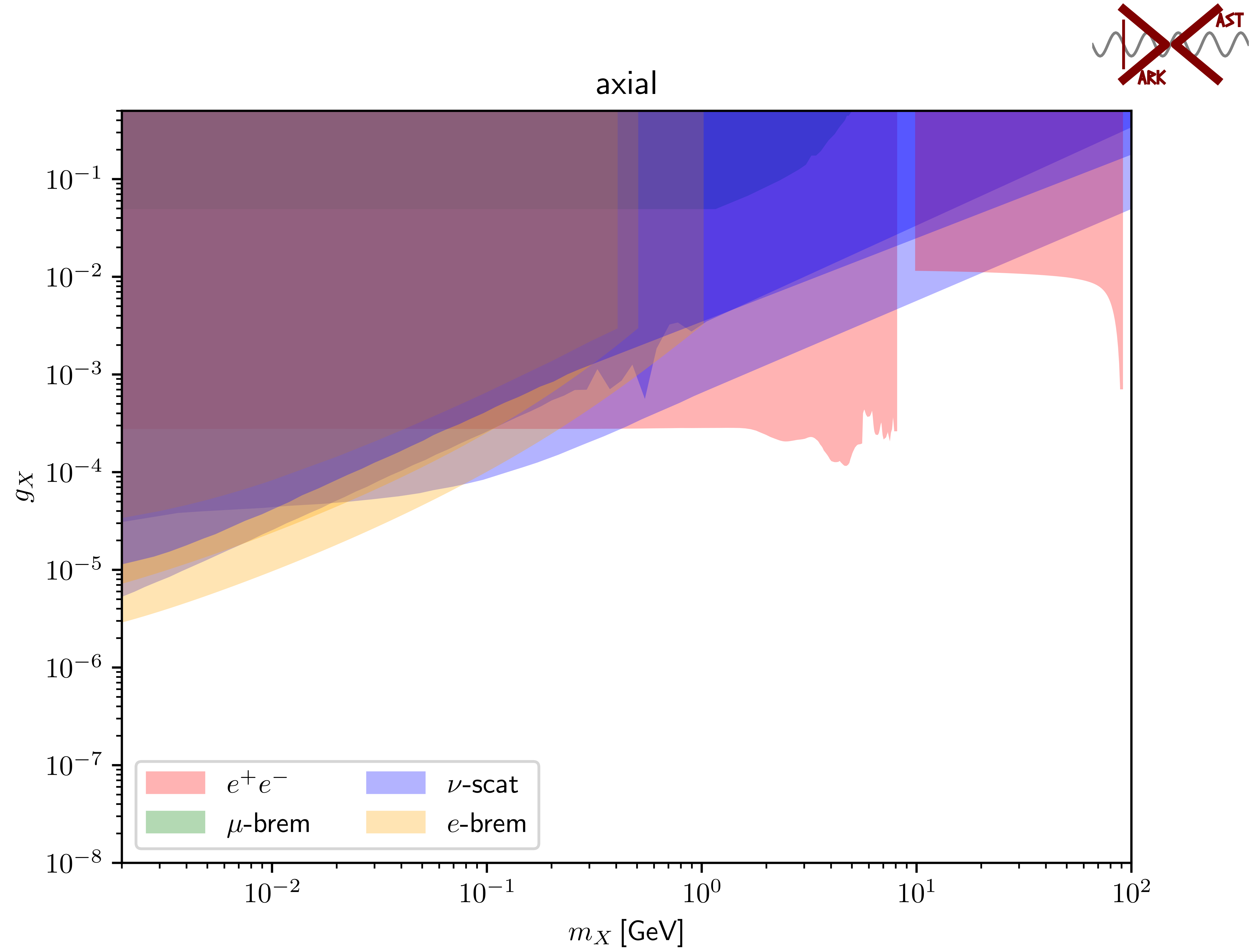
visible final states

invisible final state

Axial coupling



visible final states



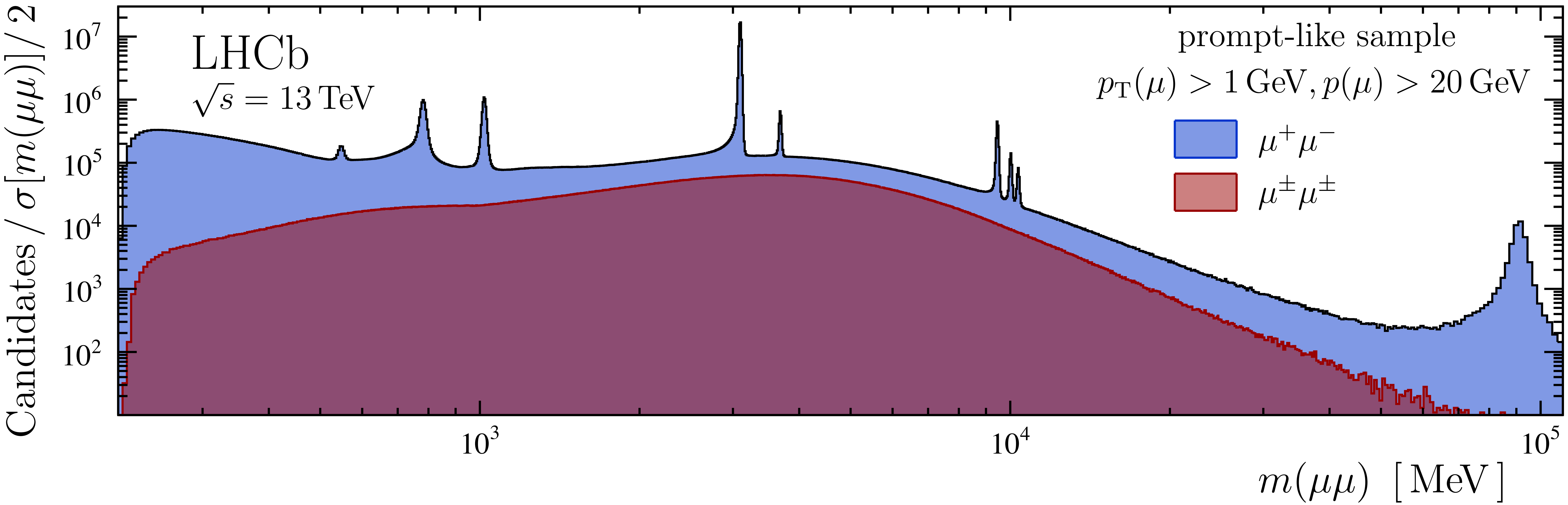
invisible final state

Summary

- Recasting of dark photon searches can be easily done by DarkCast for spin-1 models.
- Can be also use for assign projection for different models based on dark photon reach.
- In principle, other BSM scenarios can be recasting on similar way.

https://gitlab.com/darkcast/

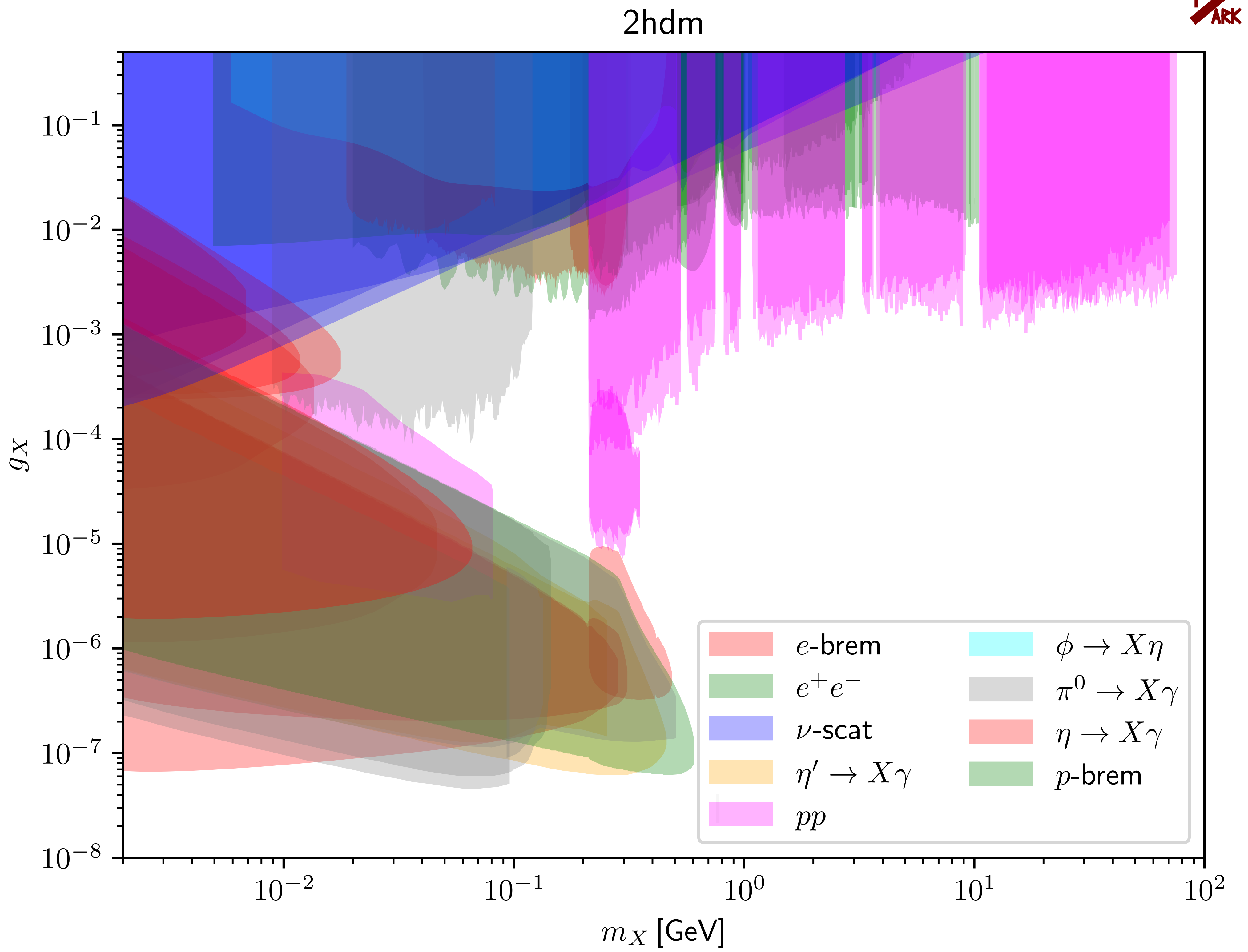
backups



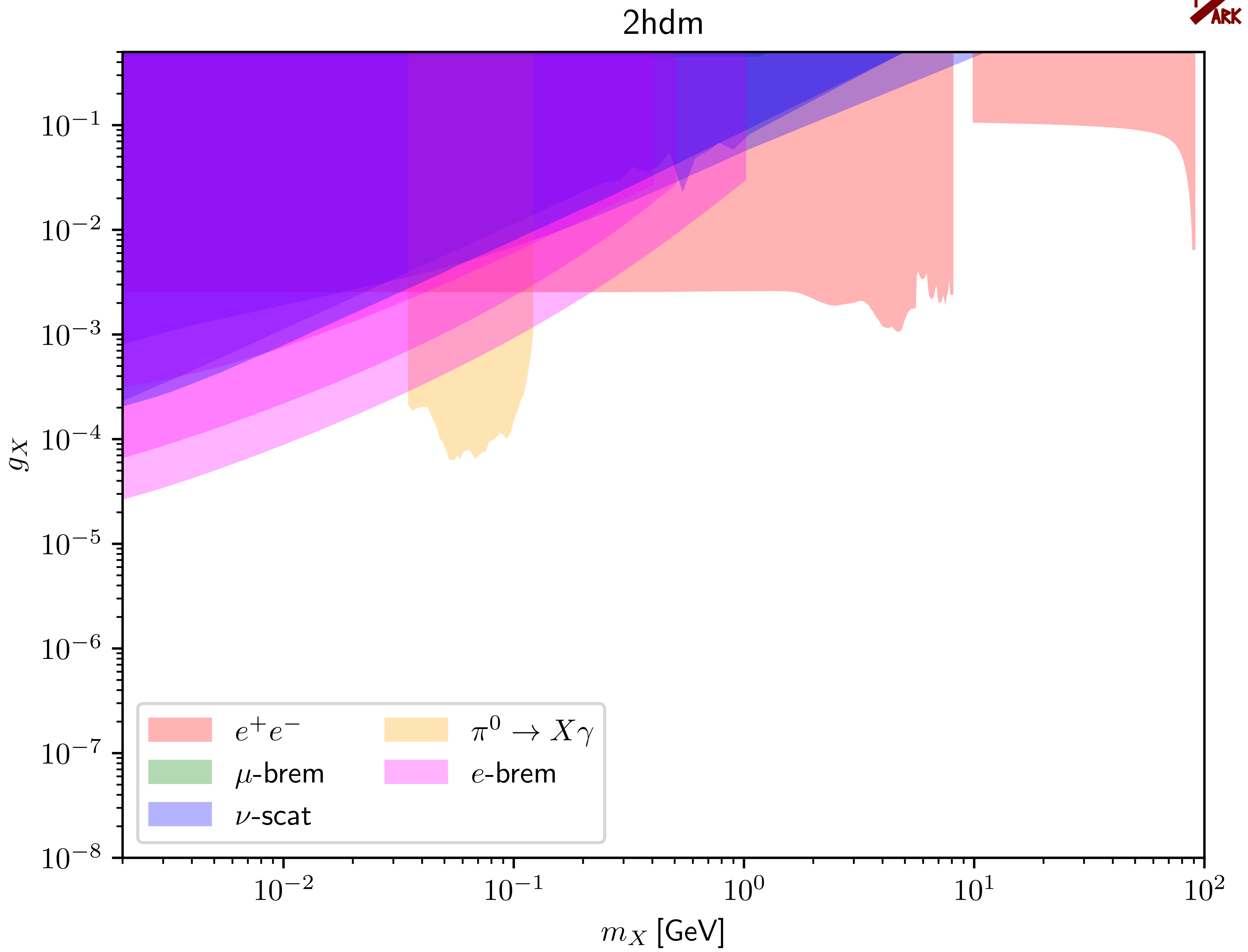
LHCb, 1710.02867

more models

2HDM

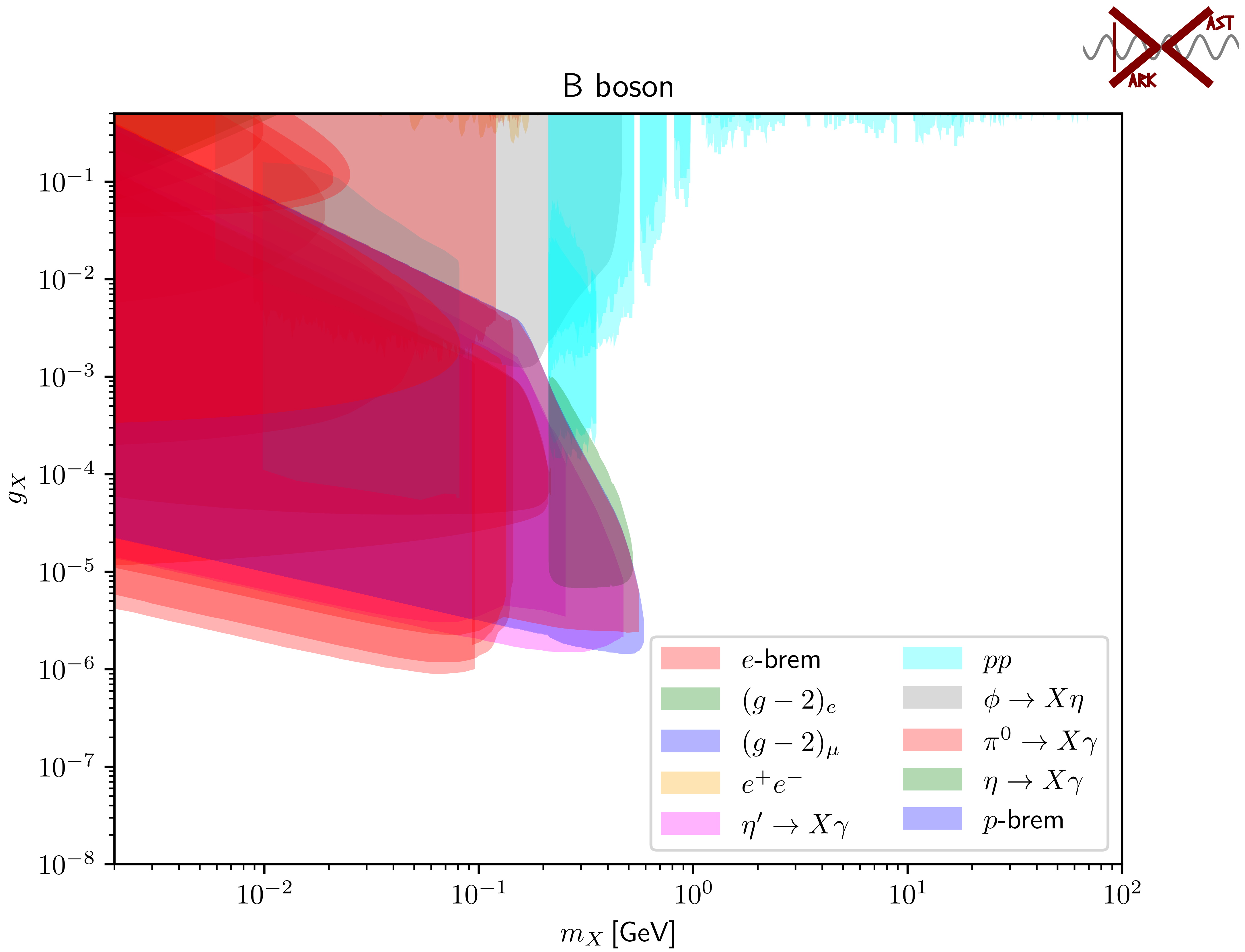


visible final states

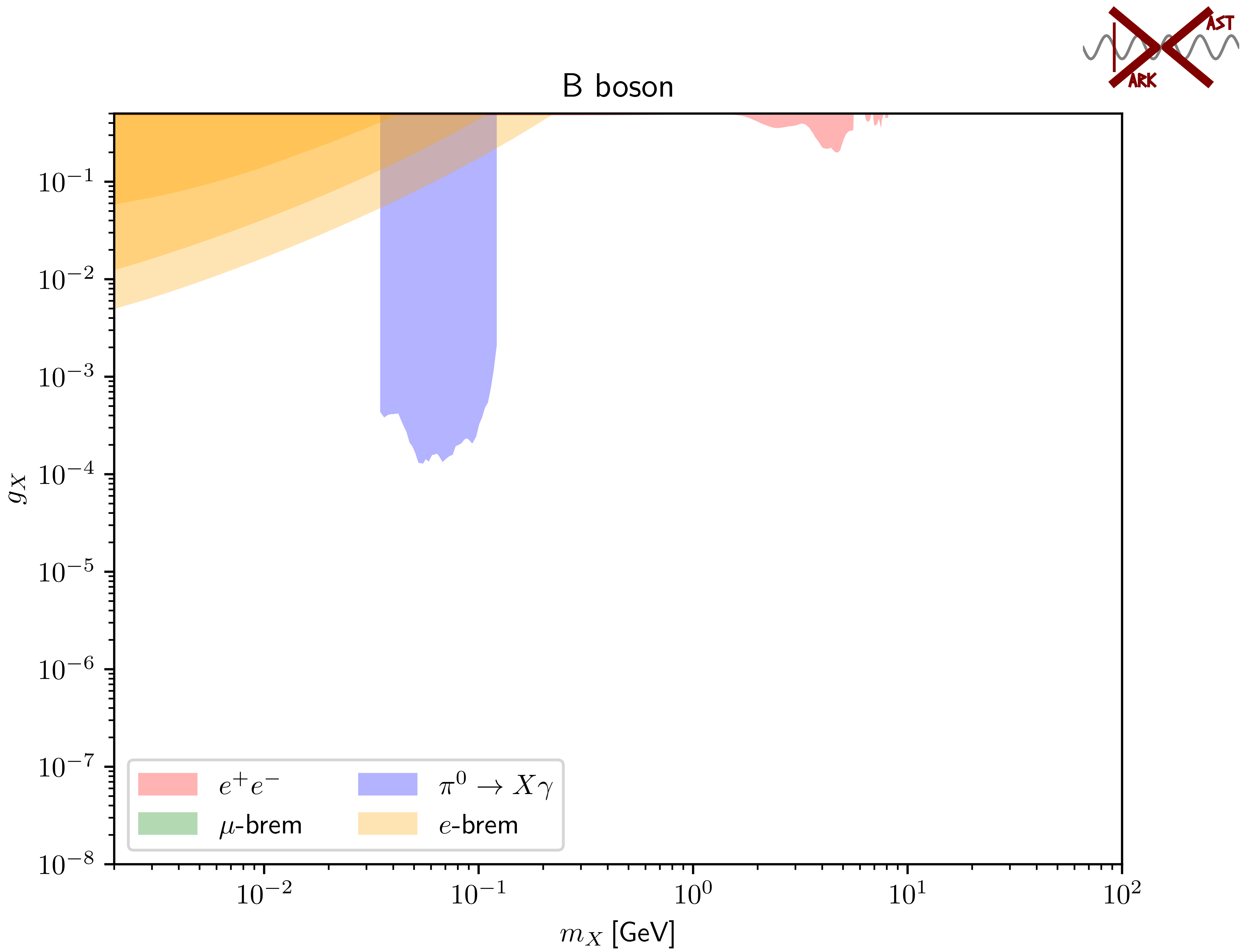


invisible final state

B-Boson

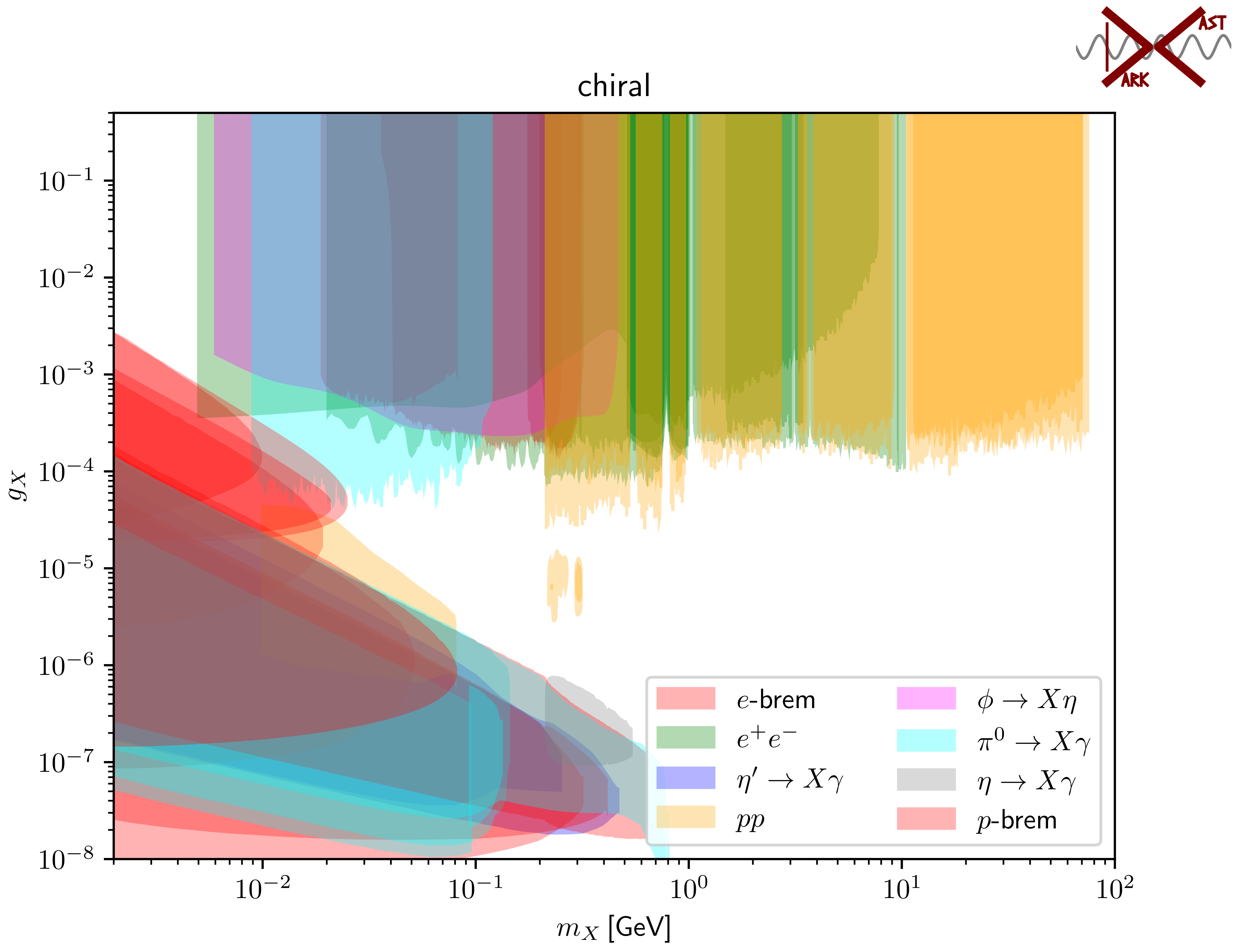


visible final states

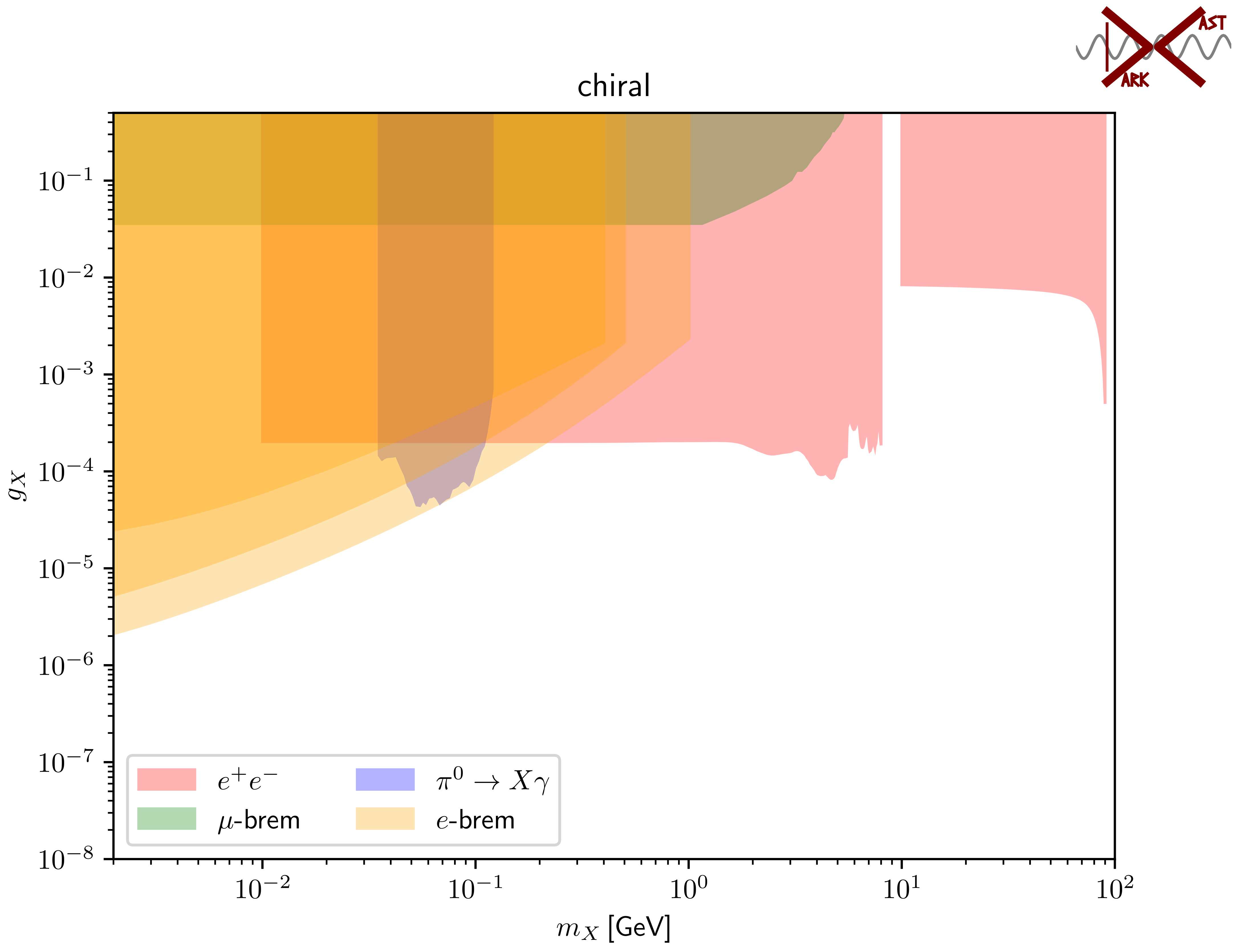


invisible final state

Chiral-couplings

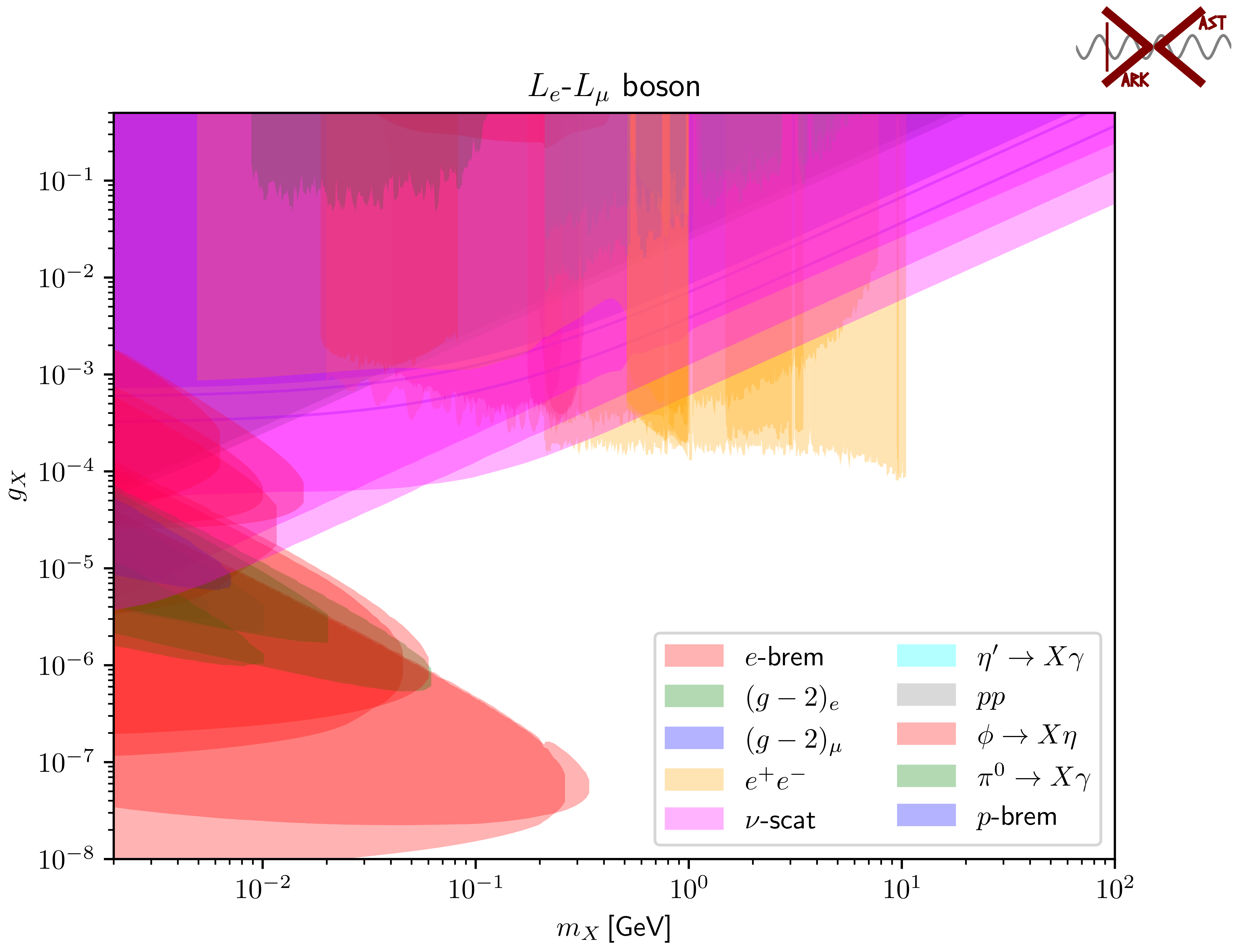


visible final states

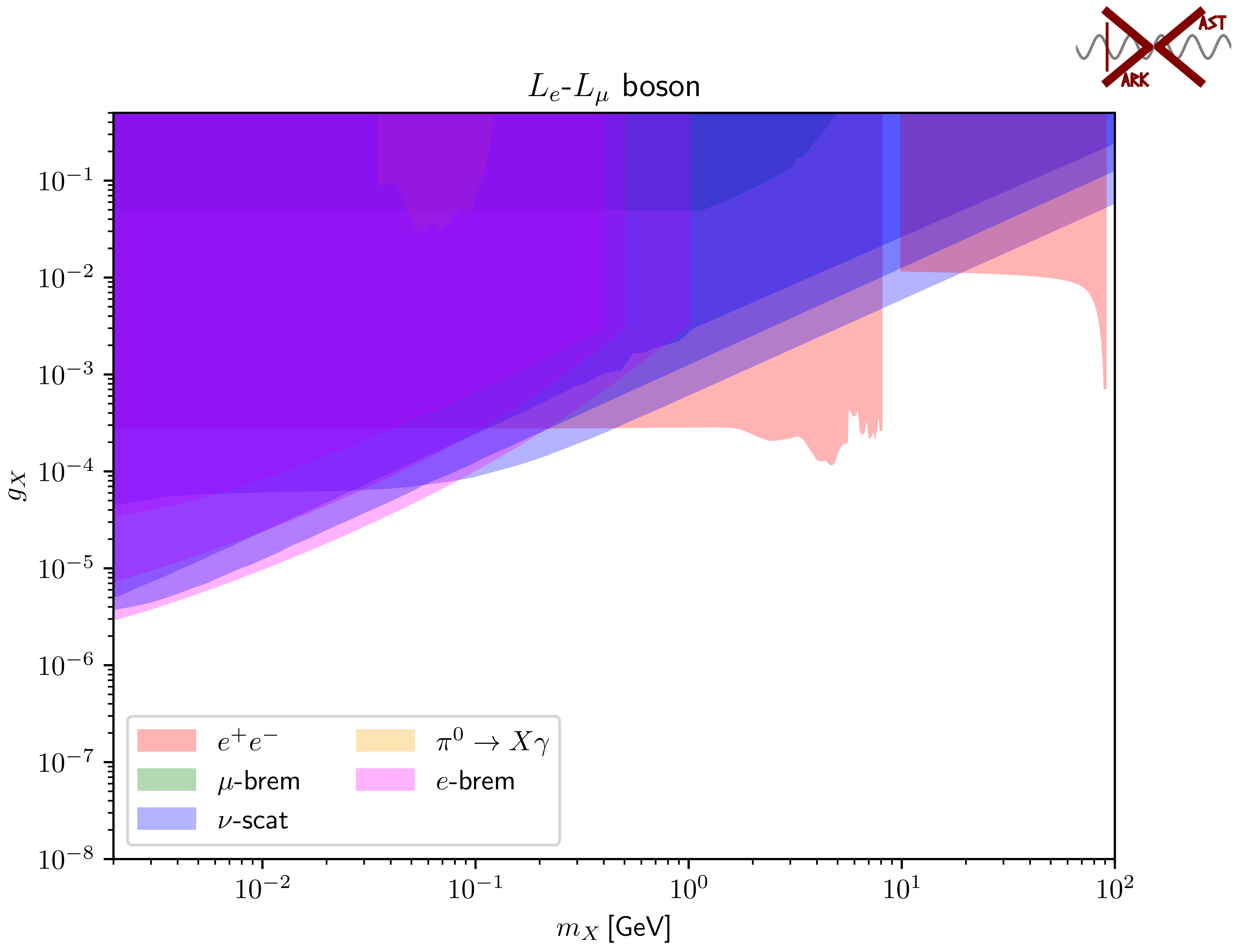


invisible final state

Le-Lmu coupling

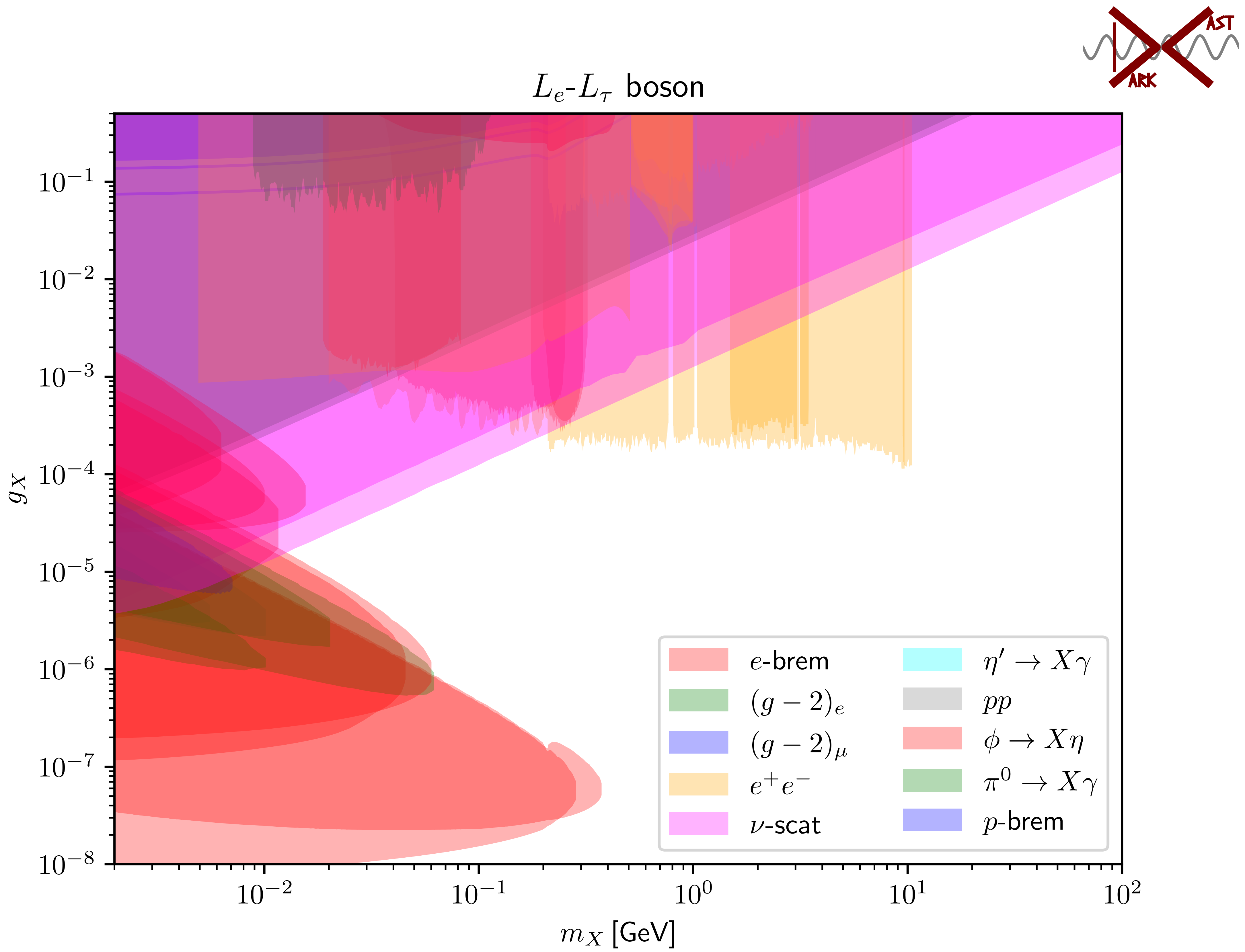


visible final states

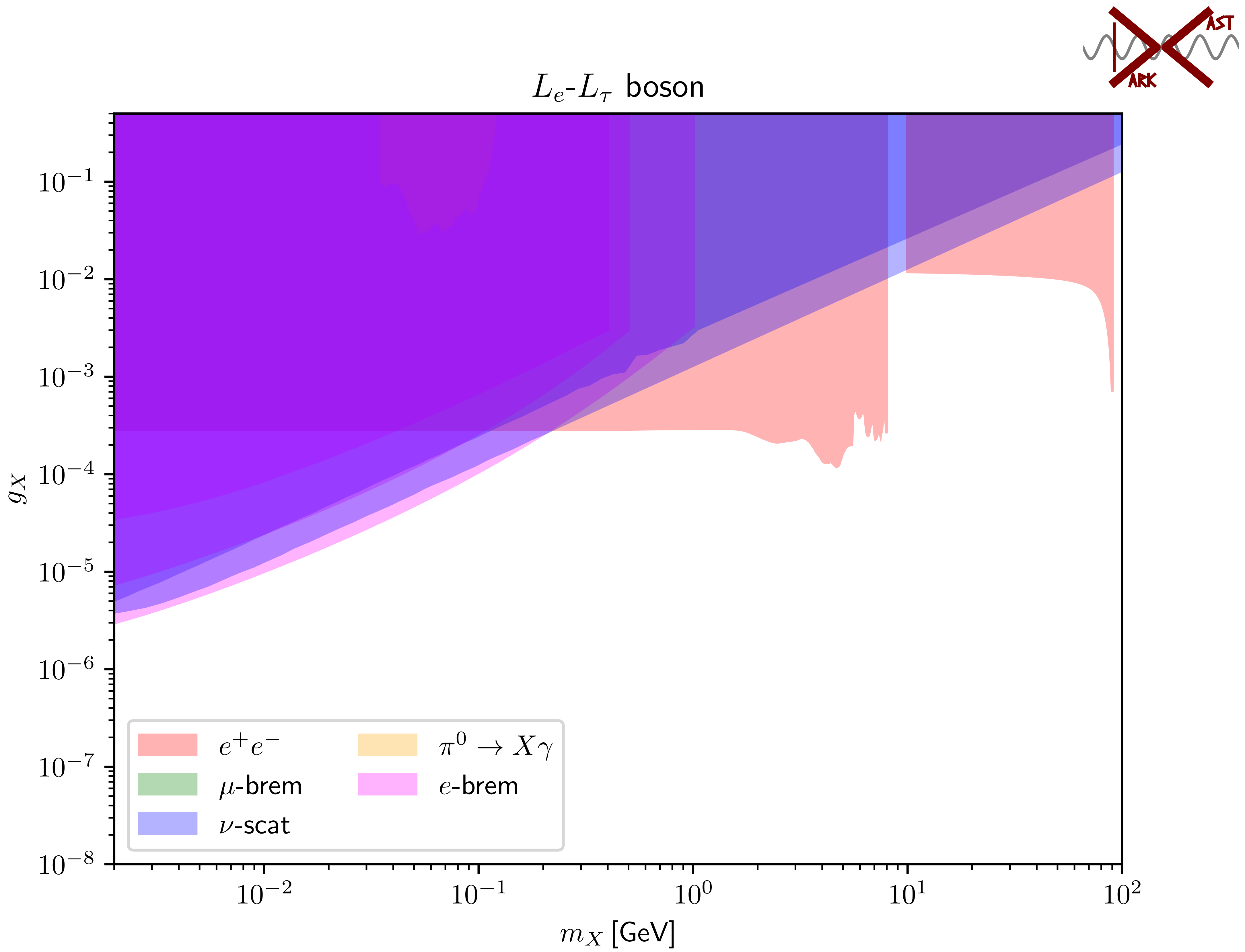


invisible final state

Le-Ltau coupling

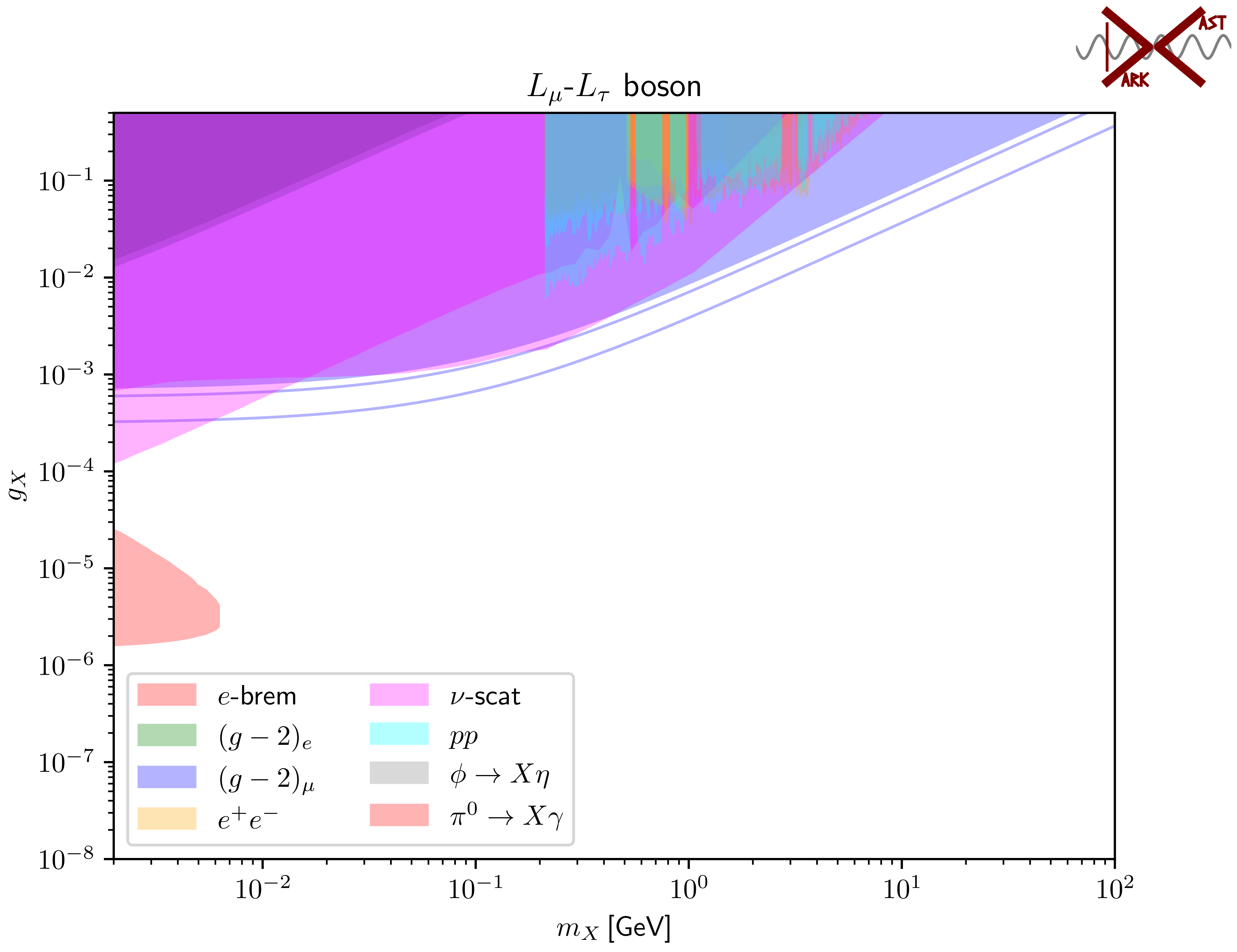


visible final states

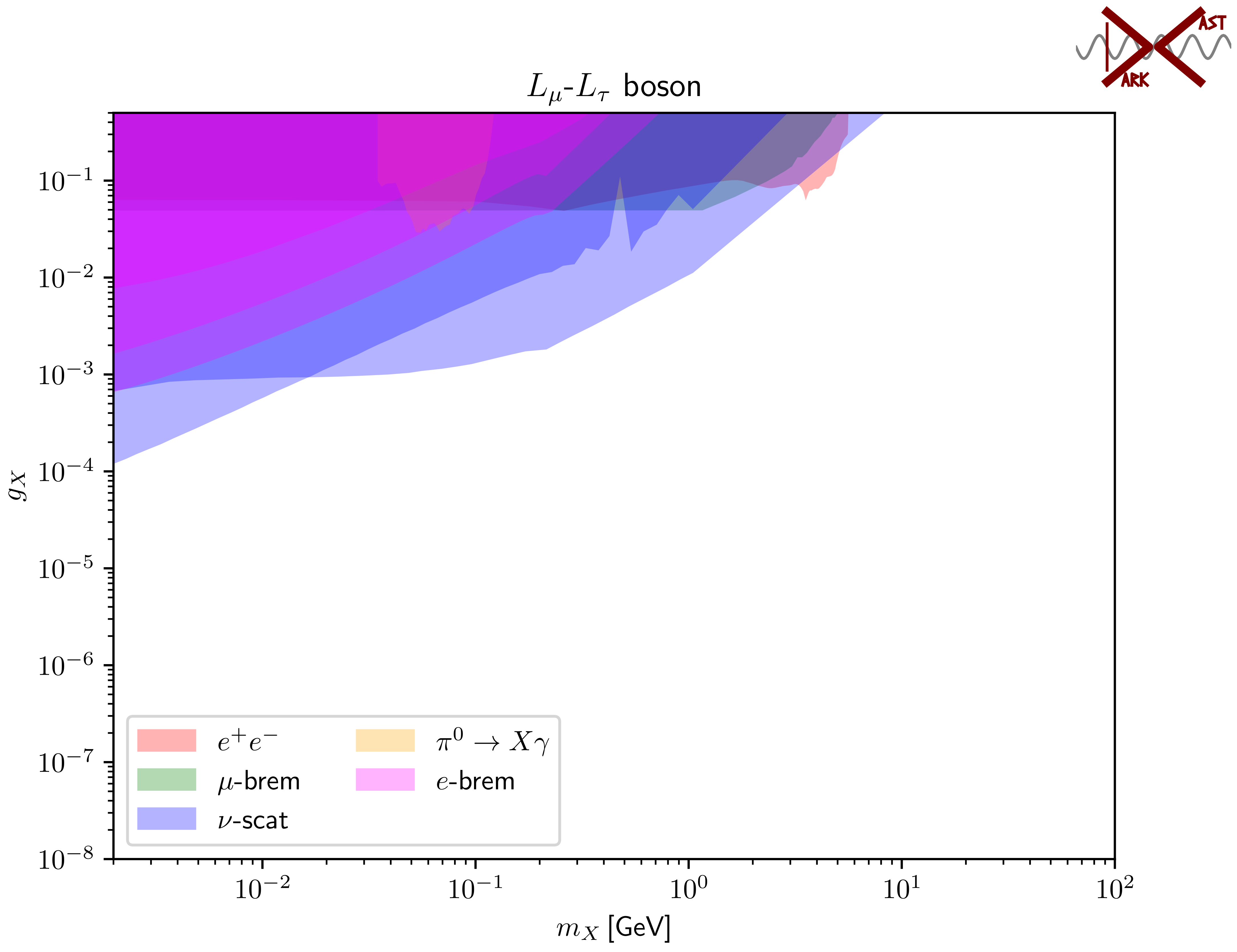


invisible final state

Lmu-Ltau coupling

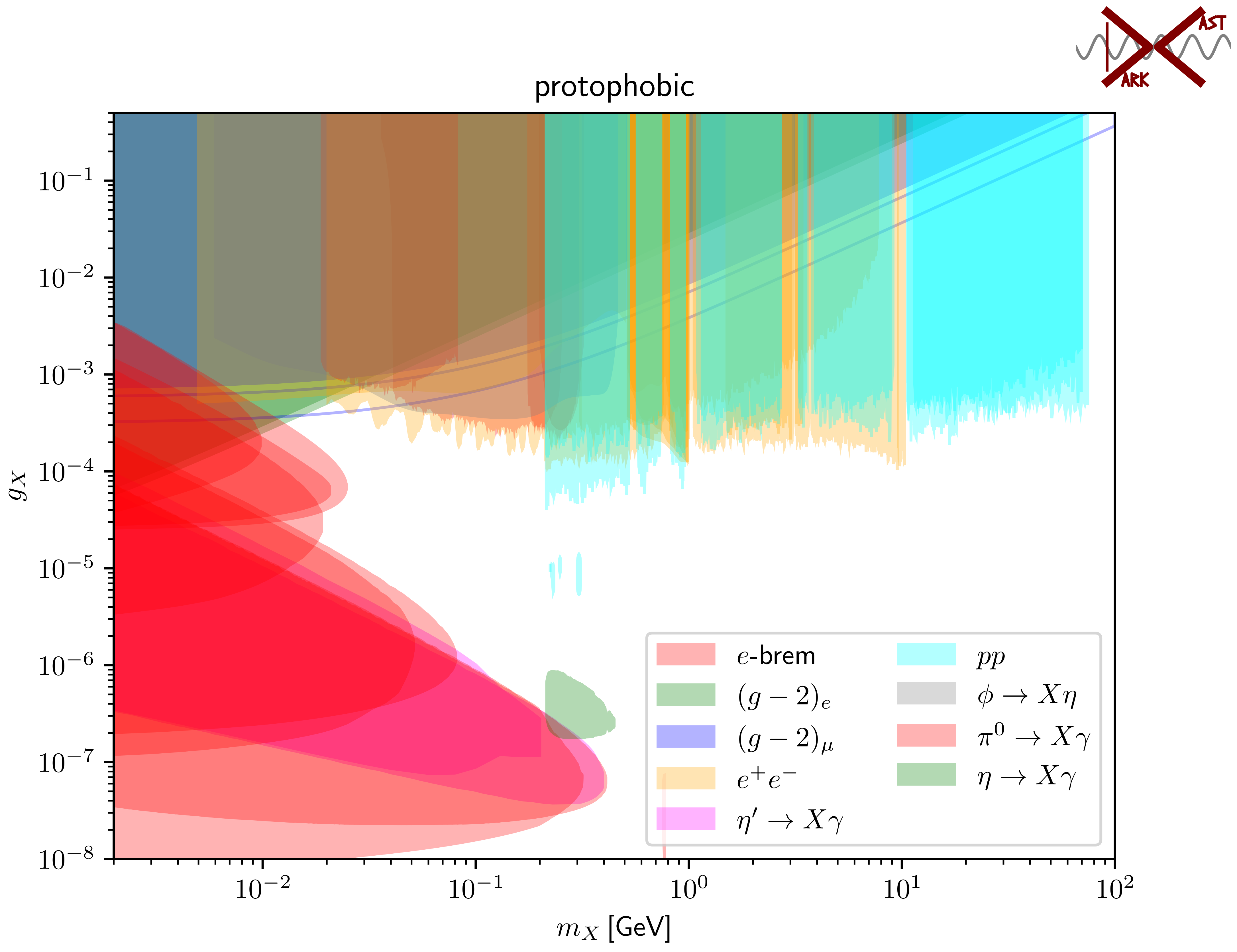


visible final states

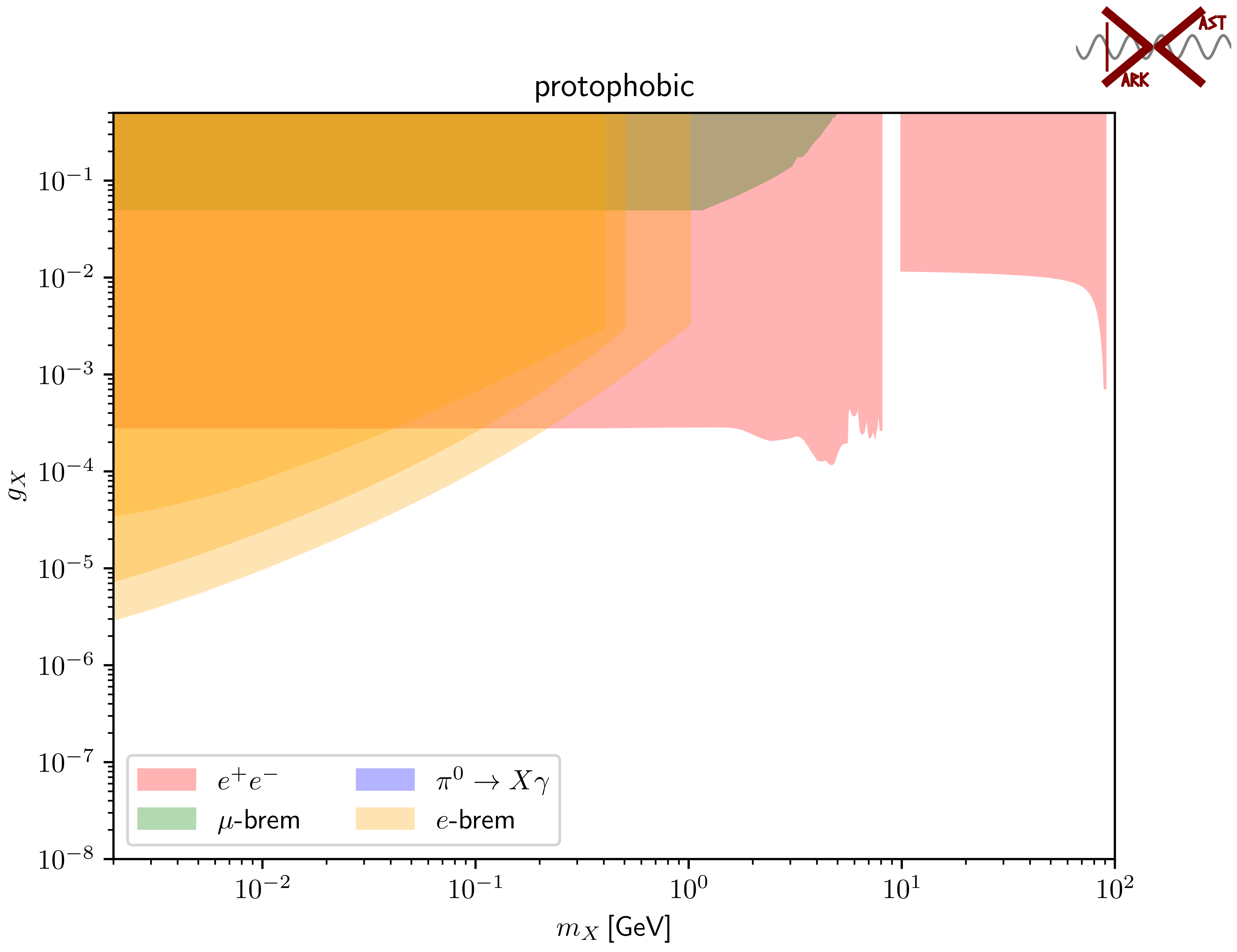


invisible final state

Protophobic boson



visible final states



invisible final state

True muonium

True muonium at LHCb

true muonium ($\mathscr{TM}$) = $\mu^+\mu^-$ bound state

Never observed!

Cid Vidal, Ilten, Plews, Shuve, YS, PRD 19

True muonium at LHCb

true muonium ($\mathcal{TM}$) = $\mu^+\mu^-$ bound state

Never observed!

the 1^3S_1 state (spin-1) is a "dark photon" like state

$$m_{\mathcal{TM}} = 2m_\mu - B_E \approx 211\,\mathrm{MeV}$$

$$\varepsilon_{\mathcal{TM}} = \alpha^2/2 \approx 2.7 \times 10^{-5}$$

$$\mathscr{L} \supset \frac{\varepsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

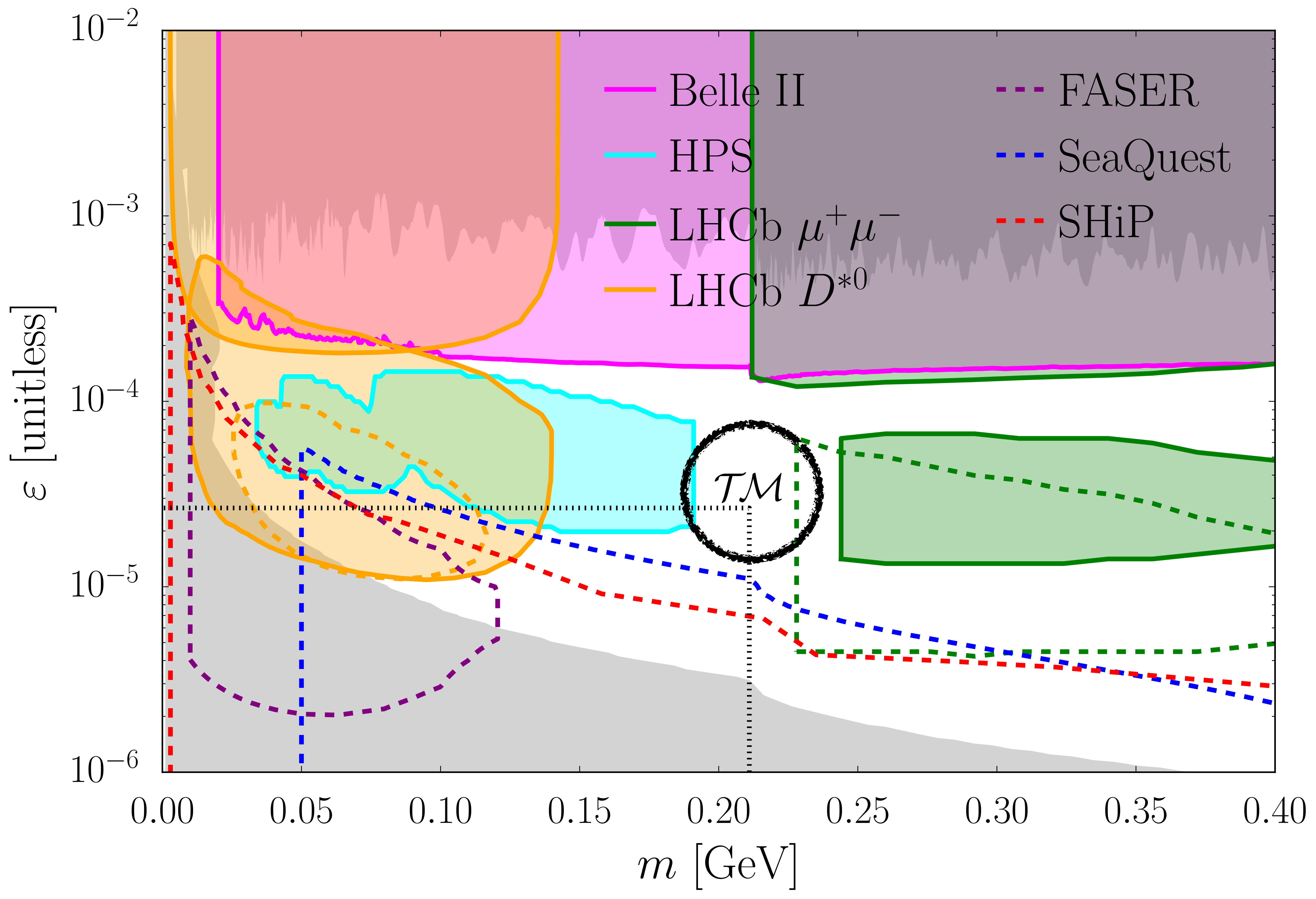
but it is dissociated due to muons detector material interaction

→ similar search strategy as dark photon

Cid Vidal, Ilten, Plews, Shuve, YS, PRD 19

True muonium at LHCb

true muonium ($\mathcal{TM}$) = $\mu^+\mu^-$ bound state



→ similar search strategy as dark photon

Cid Vidal, Ilten, Plews, Shuve, YS, PRD 19

True muonium at LHCb

dominant production

$$\eta \to \gamma \, \mathcal{TM} \to \gamma \, e^+ e^-$$

$$c\tau_{\mathcal{TM}} \approx 0.53 \, \text{mm} \, , \; \sigma_{m_{ee}} \approx 20 \, \text{MeV}$$

Cid Vidal, Ilten, Plews, Shuve, YS, PRD 19

True muonium at LHCb

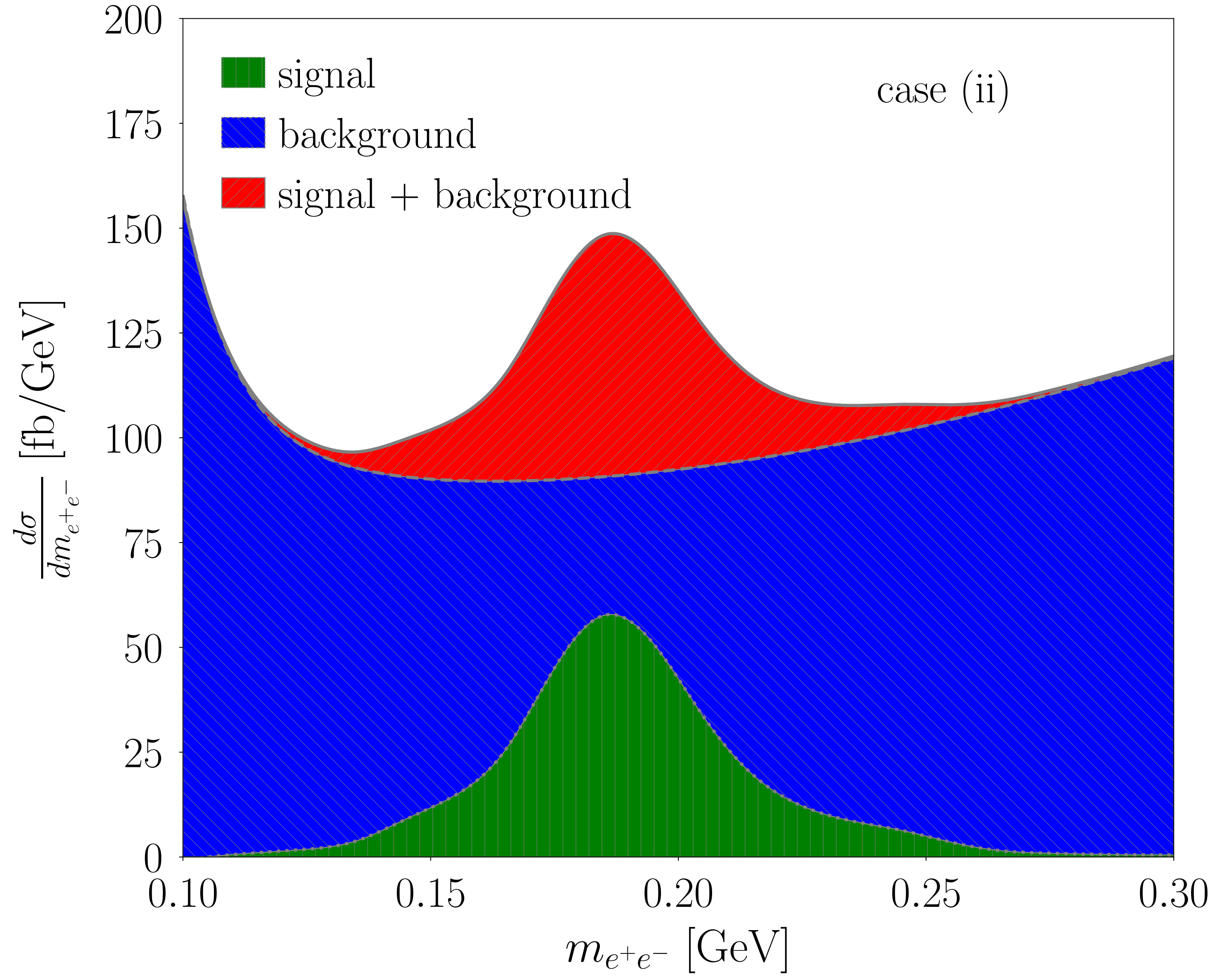
dominant production

$\eta \to \gamma\, \mathcal{TM} \to \gamma\, e^+ e^-$

$c\tau_{\mathcal{TM}} \approx 0.53\,\mathrm{mm}\,,\ \sigma_{m_{ee}} \approx 20\,\mathrm{MeV}$

displaced e^+e^- resonance

reconstruct: $e^+e^-\gamma$



expect $5\sigma_{\mathrm{stat}}$ (discovery) within next LHCb run ($15\,\mathrm{fb}^{-1}$)

Cid Vidal, Ilten, Plews, Shuve, YS, PRD 19