Dark sector searches with leptons

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UC Santa Cruz

2024 Belle II Physics Week

October 15, 2024

Outline

- <u>Introduction</u>:

Leptons are a very common signature of dark sector models

- <u>What's done</u>:

Searches already performed by Belle II

- <u>Future opportunities</u>:

Next steps in the search for dark sectors with leptonic signatures

- minimal models: dark photon
- non minimal models:
  * Inelastic Dark Matter (IDM)
  * Leptonically coupled axions
  * Strongly interacting massive particles (SIMPs)

Leptons are a prominent signature of dark sectors

Minimal models

$\epsilon Z^{\mu\nu} A'_{\mu\nu}$ Dark photon

$y H L N$ Neutrino

$\kappa |H|^2 |S|^2$ Higgs

The portals induce the decay of the dark particle to leptons

Gauging anomaly free approximate symmetries of the Standard Model:
e.g., L_μ-L_τ: the corresponding Z' will decay to either muons, or taus, or neutrinos

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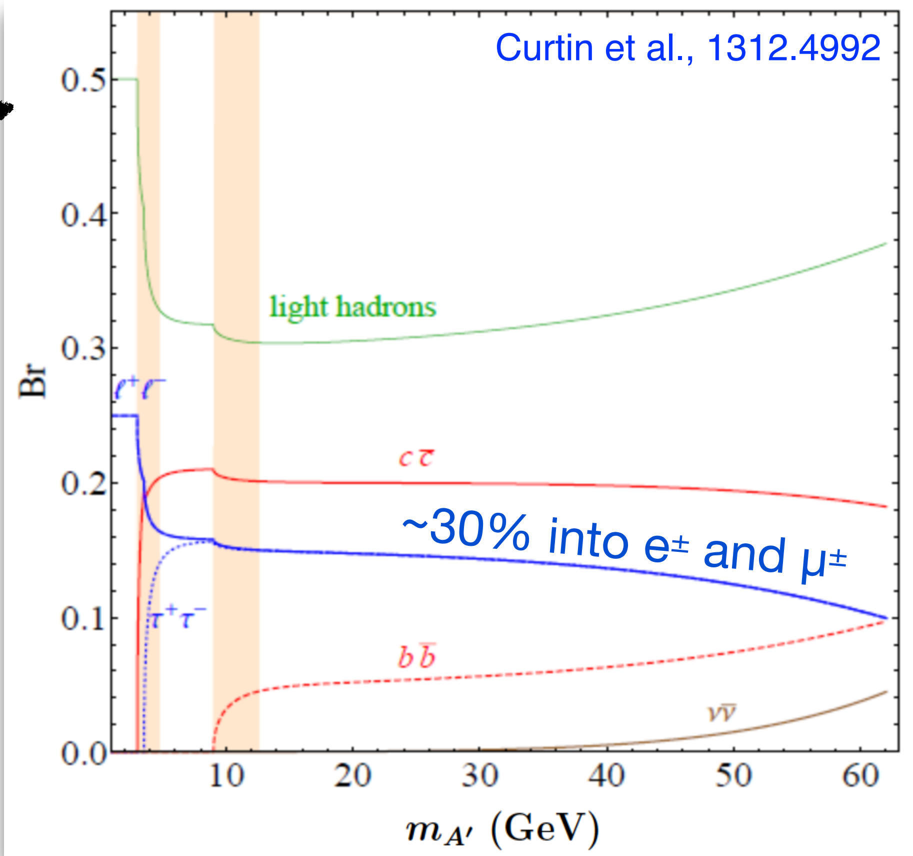
Curtin et al., 1312.4992

~30% into $e^\pm$ and $\mu^\pm$

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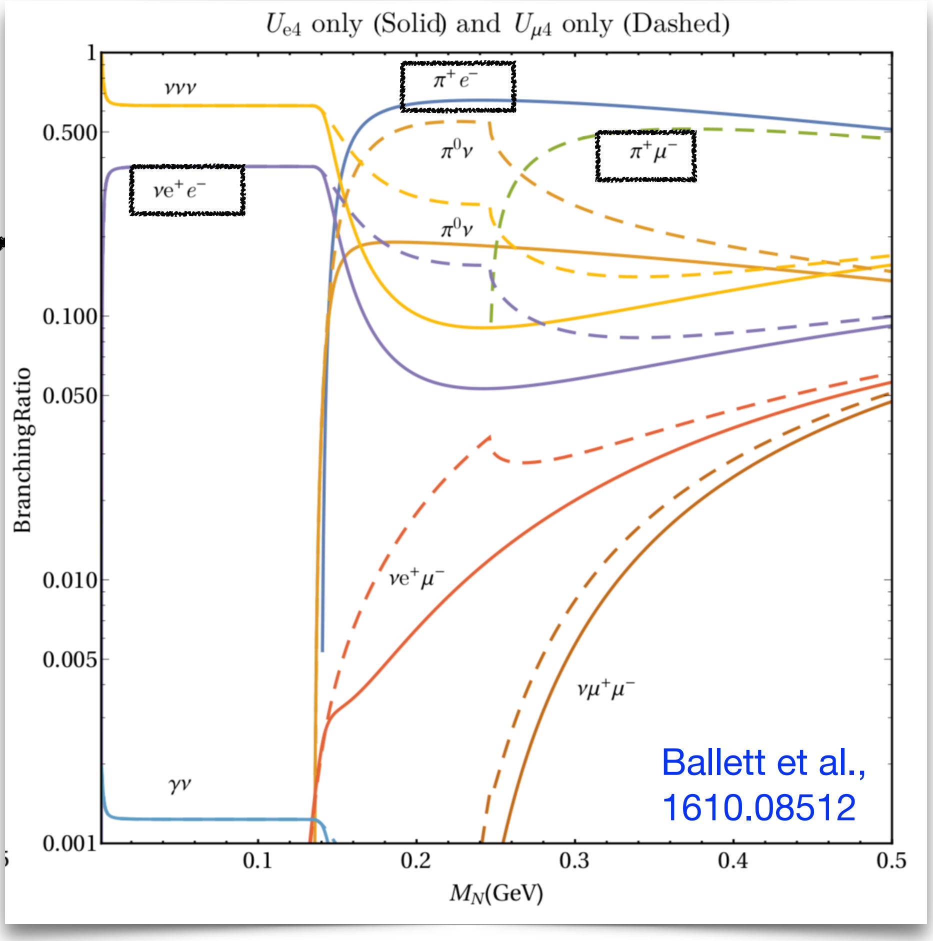

Ballett et al., 1610.08512

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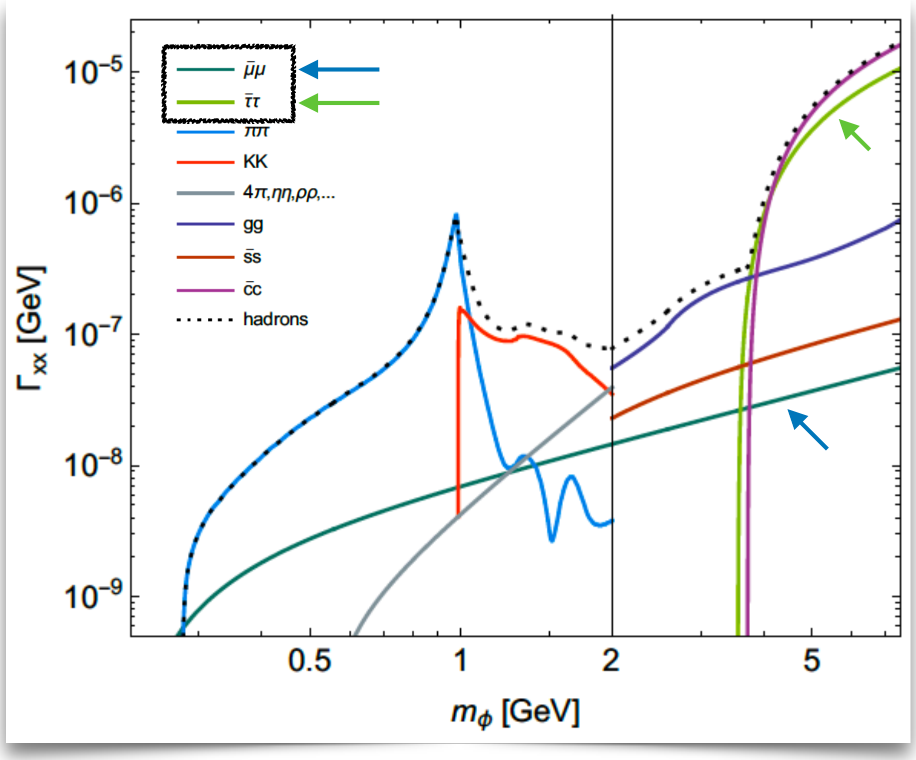
large theory uncertainties in this calculation



Winkler, 1809.01876

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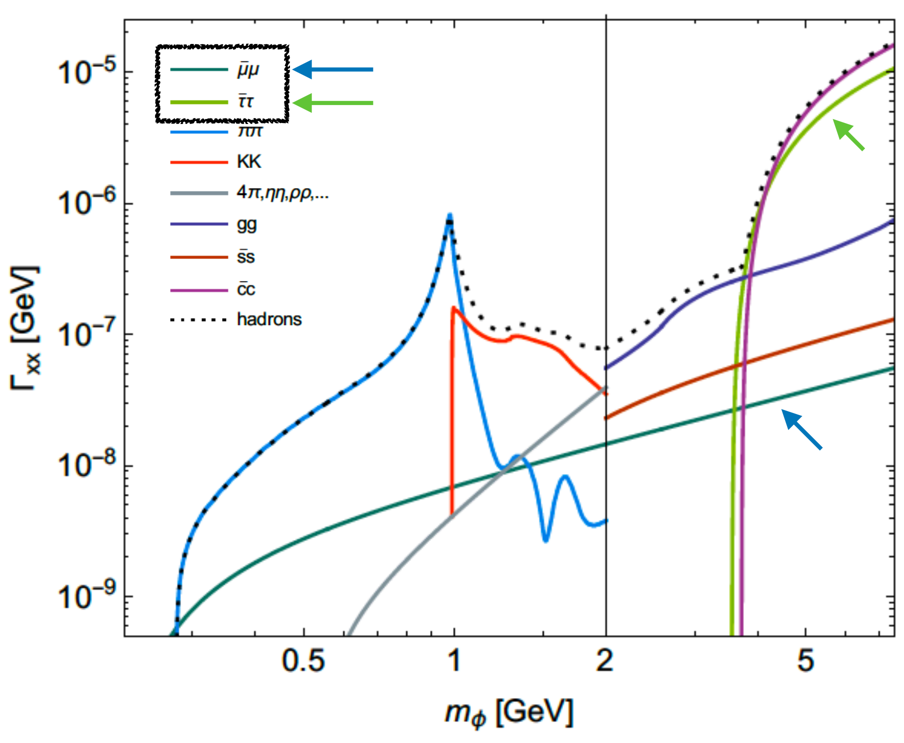

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Gauging anomaly free approximate symmetries of the Standard Model:
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+ dark sector particles can be produced in association with leptons

Leptons are a prominent signature of dark sectors

Non minimal models

Dark Matter (DM) models with DM excited states or additional dark particles:

e.g.,

- Inelastic DM: $A' \to \chi_1 \chi_2, \quad \chi_2 \to \chi_1 \ell^+ \ell^-$ (X$_1$ is the DM state)
- Strongly Interacting Massive Particles (SIMPs): $A' \to \chi_1 V_D, \quad V_D \to \ell^+ \ell^-$
- models with both a dark photon and a dark scalar: dark Higgs-strahlung

Axion/axion-like-particles (ALPs) with flavor-specific couplings:

e.g.,

$$2 g_{\mu\mu} \frac{(\partial_\mu a)}{m_\mu} \bar{\mu} \gamma^\mu P_R \mu \quad \text{or} \quad 2 g_{ee} \frac{(\partial_\mu a)}{m_e} \bar{e} \gamma^\mu P_R e$$

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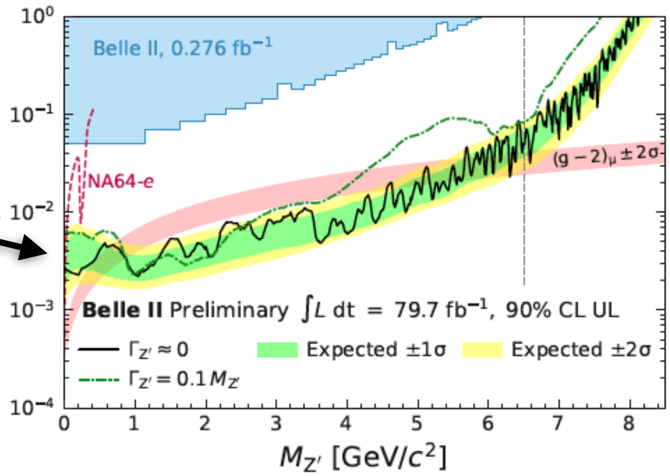
Searches currently performed by Belle II, invisible

- 1912.11276: 276/pb; 2212.03066 79.7/fb

$$e^+e^- \to e\mu Z', \quad e^+e^- \to \mu\mu Z', \qquad Z' \to \text{invisible}$$

Interpretation:
L_μ-L_τ model



World-leading bounds

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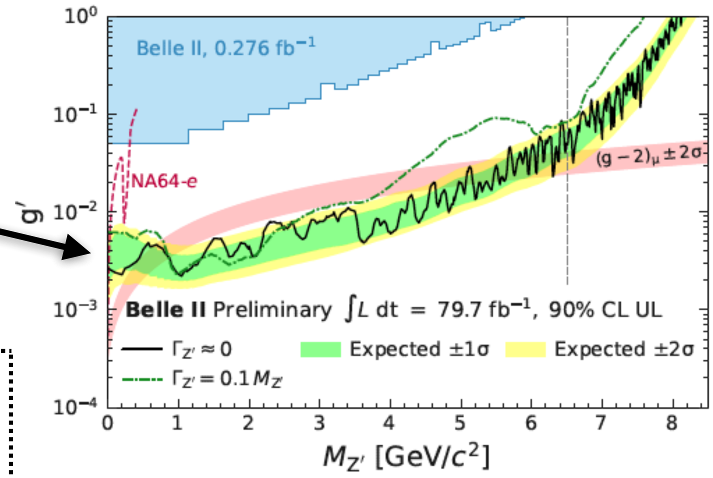
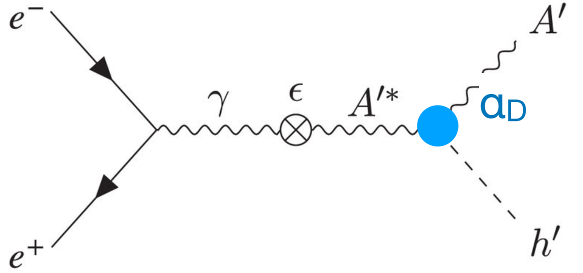


- 2207.00509: 8.34/fb

$$e^+e^- \to A'h', \qquad A' \to \mu\mu, \; h' \to \text{invisible}$$

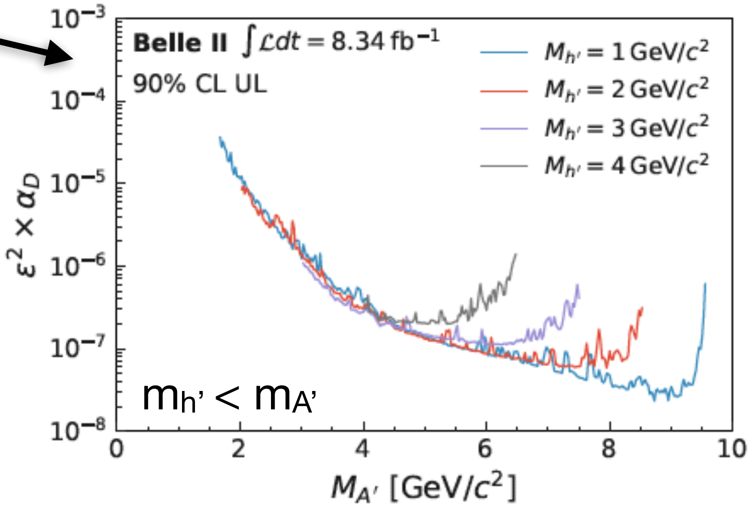
$M_{\mu\mu}$ $\qquad$ M_{Recoil}

Dark Higgs-strahlung



Interpretation:
dark photon model

Batell, Pospelov, Ritz,
0903.0363



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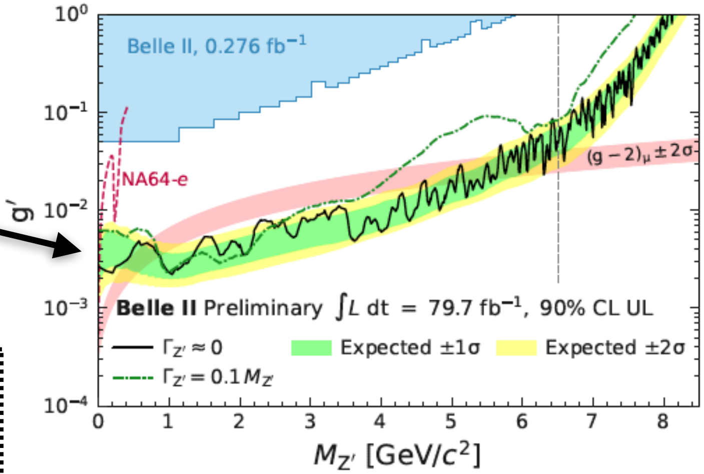

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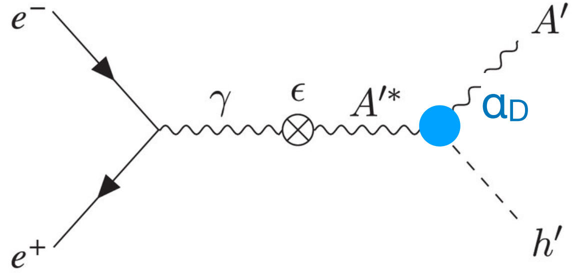

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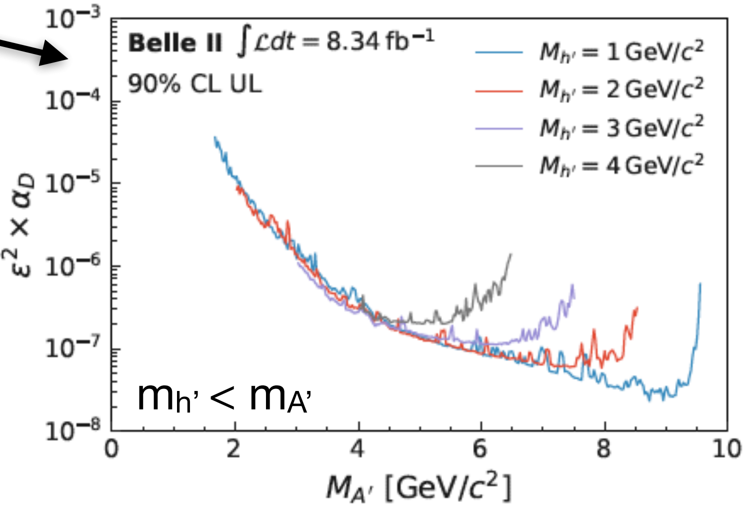

- 2212.03634: 62.8/fb

$$\frac{\text{BR}(\tau \to e a, \quad a \to \text{invisible})}{\text{BR}(\tau \to e\nu\nu)}$$

$$\frac{\text{BR}(\tau \to \mu a, \quad a \to \text{invisible})}{\text{BR}(\tau \to \mu\nu\nu)}$$

Interpretation:
model independent
BR<O(10^{-3})

World-leading bounds

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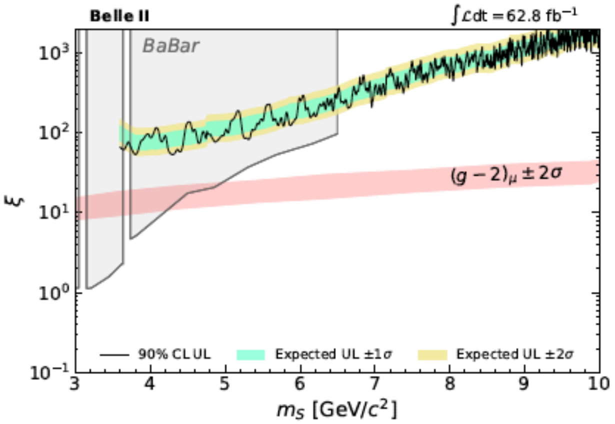
- 2306.12294: 62.8/fb

$$e^+e^- \to \mu\mu X,$$
$$X \to \tau\tau$$

Interpretation:

- L_μ-L_τ Z’ gauge bosons
- Axion coupled to leptons
- **leptophilic scalar**



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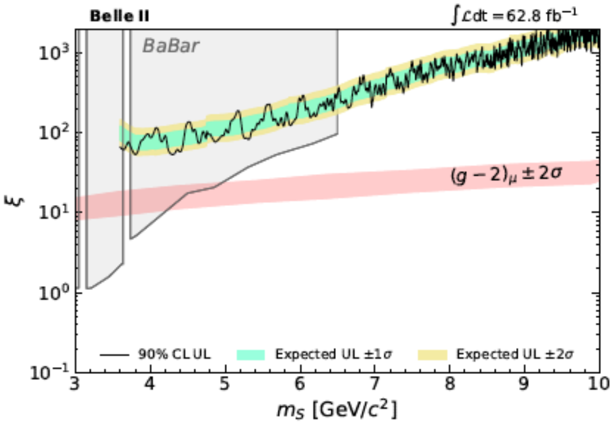


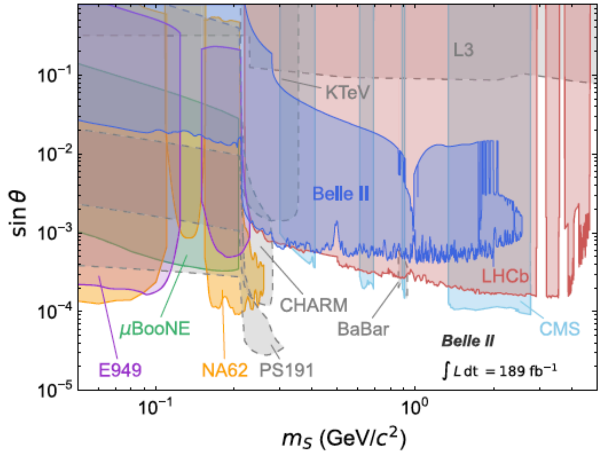
- 2306.02830: 189/fb

$$B \to KS, \quad S \to ee, \mu\mu, \pi\pi, KK$$

B^0 and B^+

charged states
(including leptons)

Interpretation:
Dark scalar mixed with the SM Higgs



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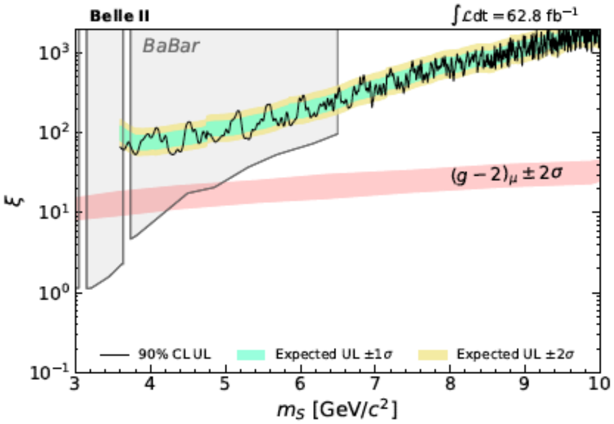

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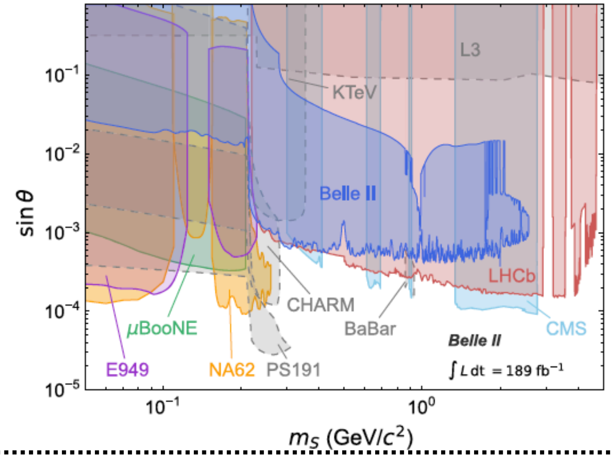


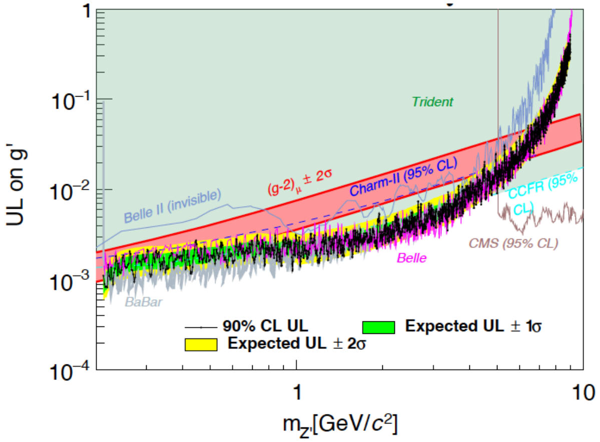
World-leading bounds

- 2403.02841: 178/fb

$$e^+e^- \to \mu\mu X, \quad X \to \mu\mu$$

Interpretation:

- **L_μ-L_τ Z' gauge bosons**
- muon philic scalar



Additional new searches for leptonic dark sectors?

Four examples:

1. Minimal visible dark photon
2. Leptonically coupled axions
3. Inelastic Dark Matter (IDM) **reminders from this morning lecture**
4. Strongly interacting massive particles (SIMPs)

Some additional missing signature?

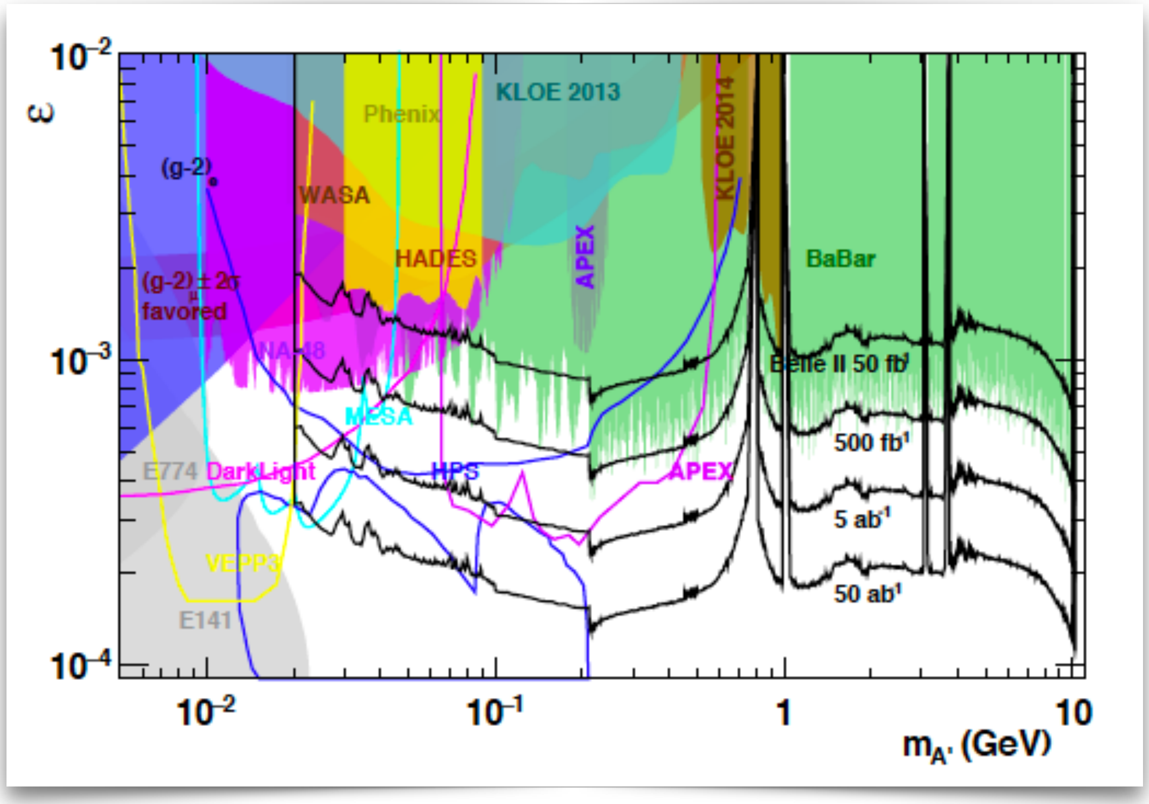
Can one do a systematic (more model independent) coverage of leptonic signatures?

1.

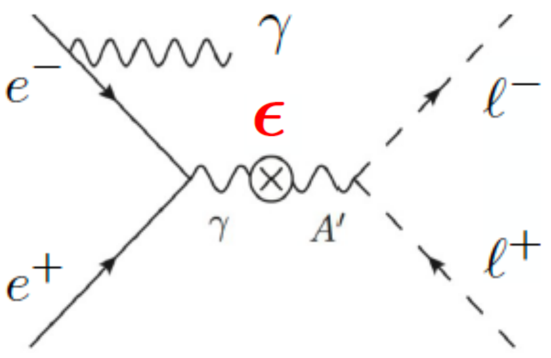
Other minimal models to look for

Dark photon decaying visibly to leptons

$$\boxed{\frac{\epsilon}{2\cos\theta}\widehat{Z}_{D\mu\nu}\widehat{B}_{\mu\nu}}$$



The Belle II physics book, 1808.10567



photon + di-lepton resonance

Search done by Babar with 514 fb^{-1}
1406.2980

Projected limits scaled from BaBar, assuming:

- twice as good mass resolution
- better trigger efficiency for both muons (~ factor 1.1) and electrons (~ factor 2)

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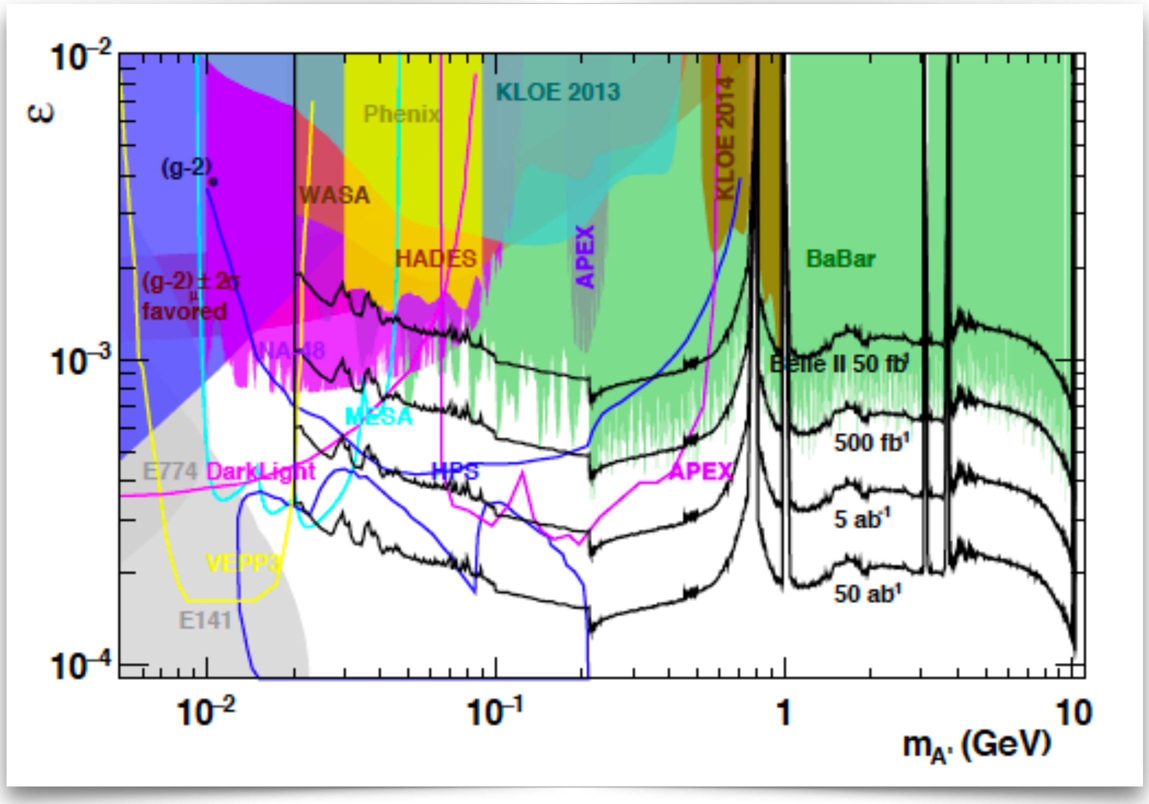

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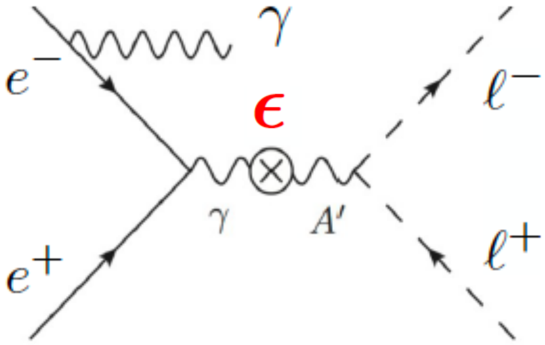
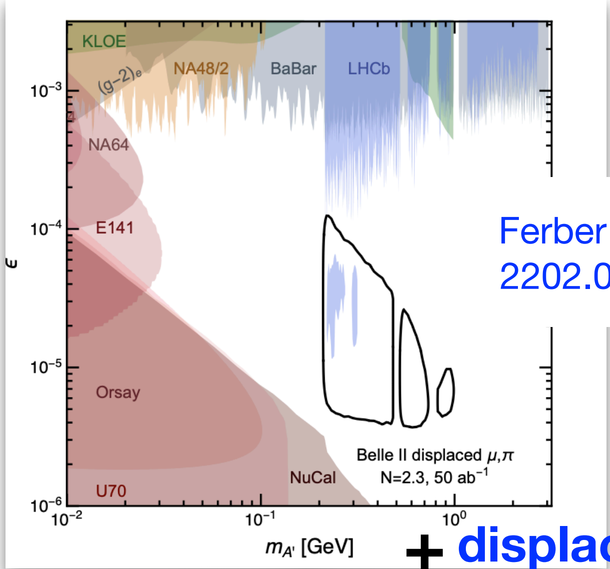


photon + di-lepton resonance

Search done by Babar with 514 fb^{-1}

1406.2980

displaced di-muons/pions resonance



Ferber et al, 2202.03452

see also Jaeckel Phan, 2312.12522, Bandyopadhyay et al., 2203.03280

+ displaced di-electrons

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2.

Weak violating axions coupled to leptons

This morning, we saw the most general ALP EFT.

Let us focus on these couplings:

$$\frac{(\partial_\mu a)}{m_e}\left[\bar{e}\gamma^\mu\left(\bar{g}_{ee}+g_{ee}\gamma_5\right)e+g_\nu\bar{\nu}\gamma^\mu P_L\nu\right]$$

2.

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The SM SU(2) symmetry would lead to $\bar{g}_{ee}-g_{ee}-g_\nu=0$

If SU(2) is violated by the axion interactions, $\bar{g}_{ee}-g_{ee}-g_\nu\neq 0$, some meson, M, decay modes to axions are enhanced:

SU(2) conserving

$$\Gamma(M^+\to e^+\nu a)\propto g_{ee}^2\frac{m_M^3 f_M^2}{m_W^4}$$

Helicity suppressed

SU(2) violating

$$\Gamma(M^+\to e^+\nu a)\propto \frac{m_M^2}{m_e^2}g_{ee}^2\frac{m_M^3 f_M^2}{m_W^4}$$

No helicity suppression

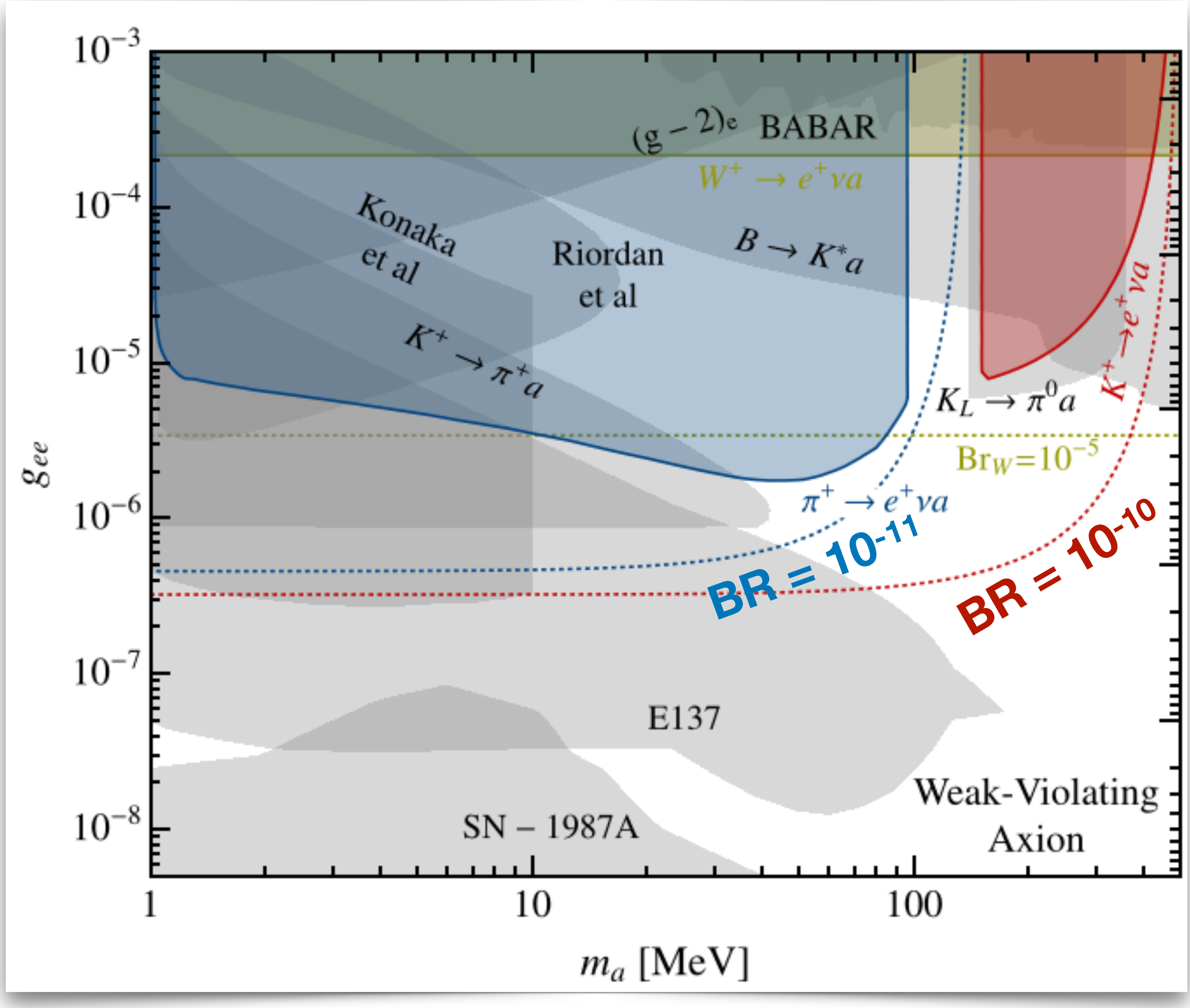
Altmannshofer, Dror, SG, 2209.00665

New searches can be done at meson factories (PIONEER, NA62, KOTO, Belle II)

2.

The reach on the parameter space

Altmannshofer, Dror, SG, 2209.00665



— neutral current decays
e.g., K →π a

— SINDRUM search for
π → eνs, s →ee
Physics Letters B 175 (1986), no. 1 101–104

— Reinterpretation of the
E865 measurement of
K → eνee, 0204006

$$\frac{(\partial_\mu a)}{m_e}\left[\bar{e}\gamma^\mu\left(\bar{g}_{ee}+g_{ee}\gamma_5\right)e+g_\nu\bar{\nu}\gamma^\mu P_L\nu\right]$$

$$\bar{g}_{ee}=g_\nu=0,\ g_{ee}\neq 0$$

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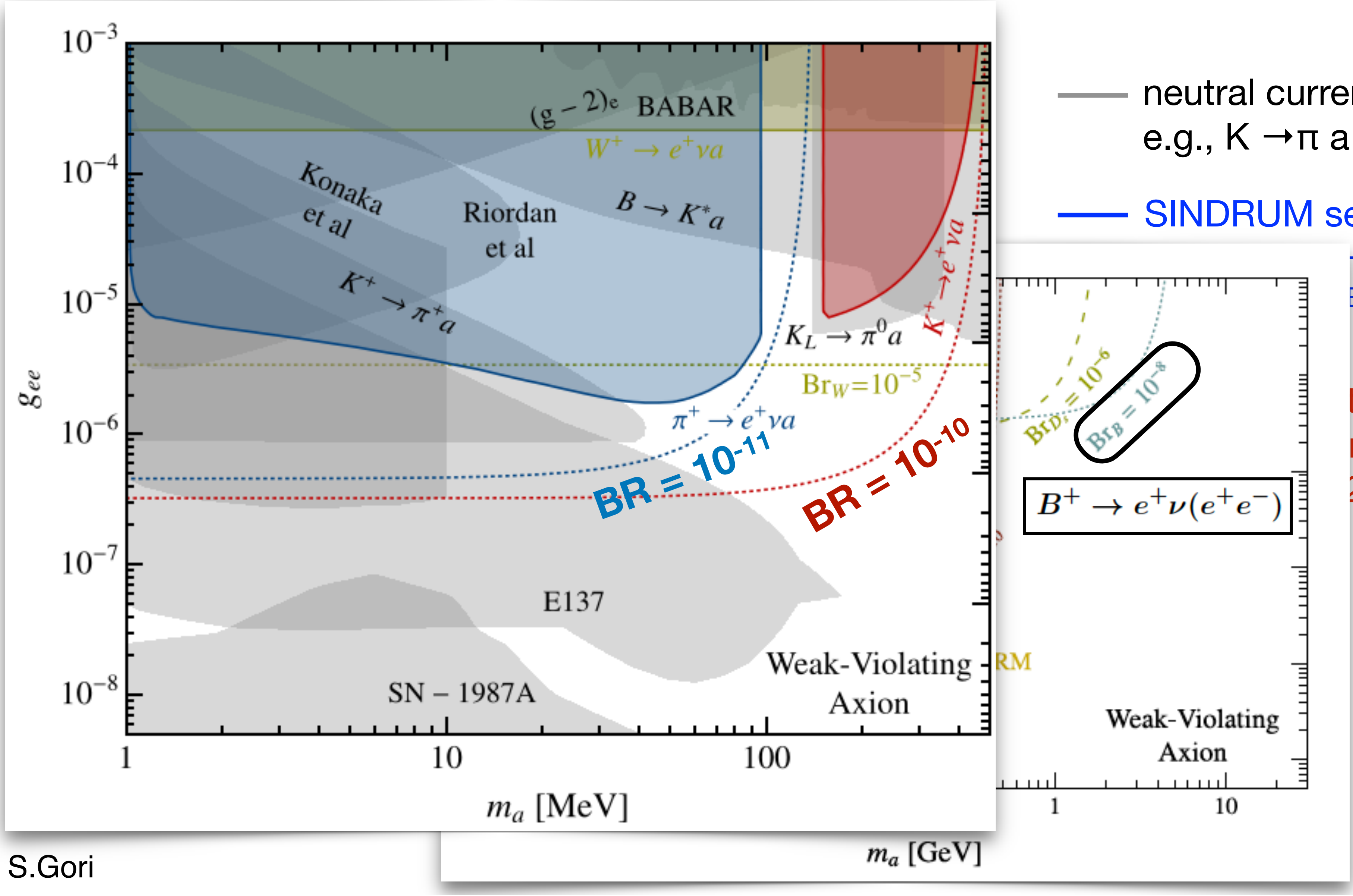
Altmannshofer, Dror, SG, 2209.00665



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→ee
B 175 (1986),

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204006

3.

Beyond minimal models: inelastic dark matter (IDM)

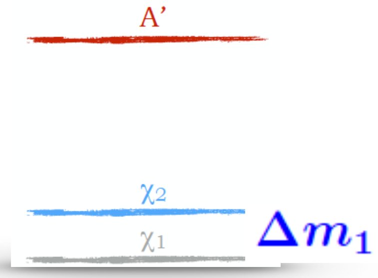
Inelastic DM (IDM) models were initially proposed to explain the DAMA anomaly, while being consistent with Dark Matter direct detection bounds from CDMS

Tucker-Smith, Weiner, 0101138

$$-\mathcal{L} \supset m_D\,\eta\,\xi + \frac{1}{2}\,\delta_\eta\,\eta^2 + \frac{1}{2}\,\delta_\xi\,\xi^2 + \text{h.c.}$$

2-component Weyl spinors
with opposite charge under U(1)'

$$\chi_1 = i(\eta - \xi)\sqrt{2}\,,$$
$$\chi_2 = (\eta + \xi)\sqrt{2}$$



The only relevant interaction is inelastic:

$$\mathcal{L} \supset \frac{i e_D\, m_D}{\sqrt{m_D^2 + (\delta_\xi - \delta_\eta)^2/4}}\, A'_\mu\, (\bar{\chi}_1\gamma^\mu\chi_2 - \bar{\chi}_2\gamma^\mu\chi_1)$$

The elastic piece is very small $(\delta_{\eta,\xi} \ll m_D)$:

$$\mathcal{L} \supset \frac{e_D\, (\delta_\xi - \delta_\eta)}{\sqrt{4m_D^2 + (\delta_\xi - \delta_\eta)^2}}\, A'_\mu\, (\bar{\chi}_2\gamma^\mu\chi_2 - \bar{\chi}_1\gamma^\mu\chi_1)$$

Two states close in mass: $\Delta \equiv \frac{m_2 - m_1}{m_1} \sim \frac{\delta_\xi + \delta_\eta}{m_D} \ll 1$

Easy to get it small since it is a U(1)' breaking effect

Abundance of χ_1 and χ_2 is determined by two coupled Boltzmann equations, that keep into account:

- $\chi_1\,\chi_2$ co-annihilation,
- $\chi_2\, f \rightarrow \chi_1\, f$ inelastic scattering,
- $\chi_2 \rightarrow \chi_1$ + SM decays

3.

New opportunities for B-factories

New proposed search for Belle-II:

(Photon) + displaced tracks + missing energy

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New proposed search for Belle-II:

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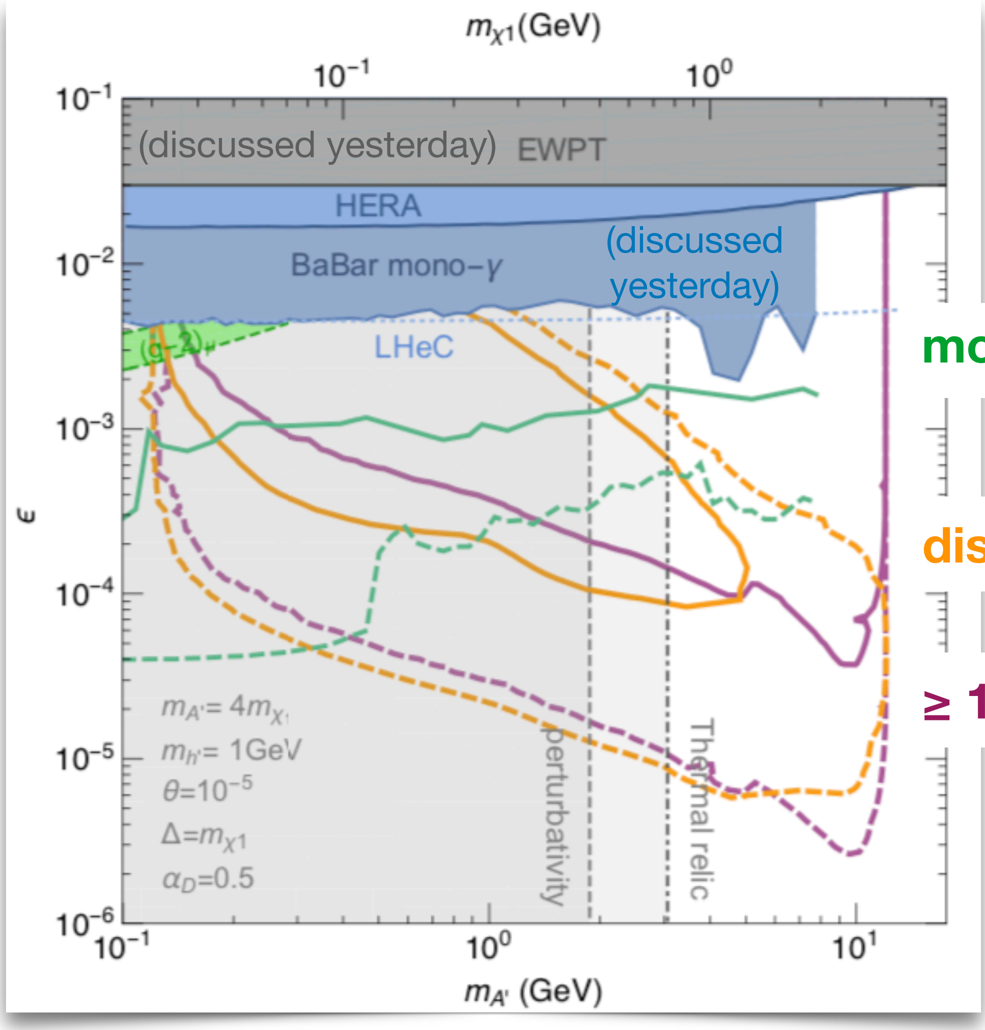


Duerr et al. 2012.08595

—— 100/fb

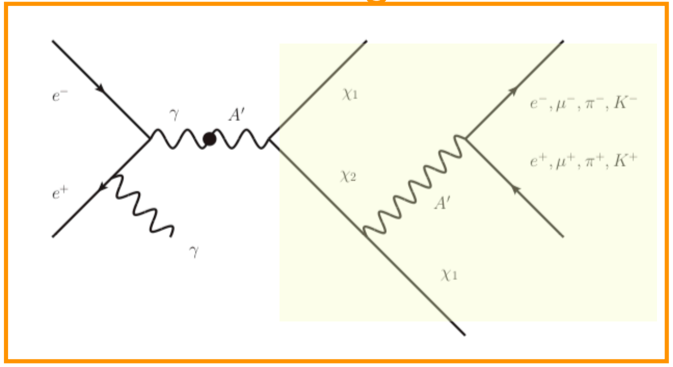
········ 50/ab

mono-photon

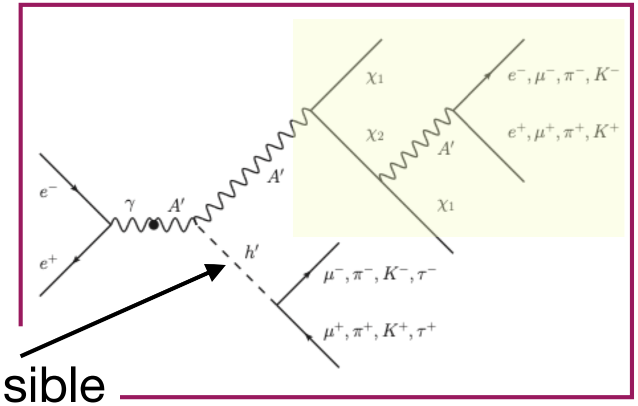
displaced+photon

≥ 1 displaced

“minimal signature”



“non-minimal signature”



Higgs responsible for the A’ mass

Higgs-strahlung

Displaced vertex trigger is very important

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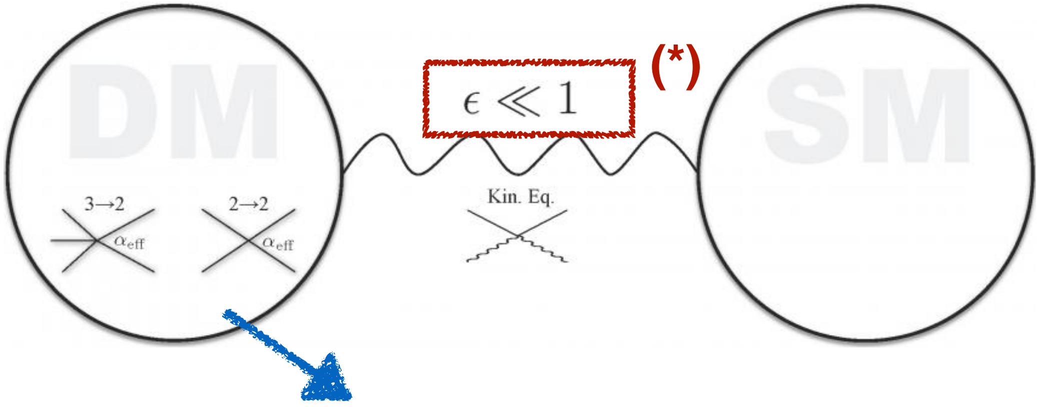
4.

Strongly interacting massive particles in a nutshell



Hochberg, Kuflik, Volansky, Wacker, 1402.5143,

Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727

(*) Needed to maintain thermalization between the two sectors

A new scale for DM?

(

WIMP

DM DM $2 \to 2$ **SM SM**

$m_{\rm DM} \sim \alpha_{\rm ann}(T_{\rm eq}M_{\rm pl})^{1/2} \sim {\rm TeV}$

)

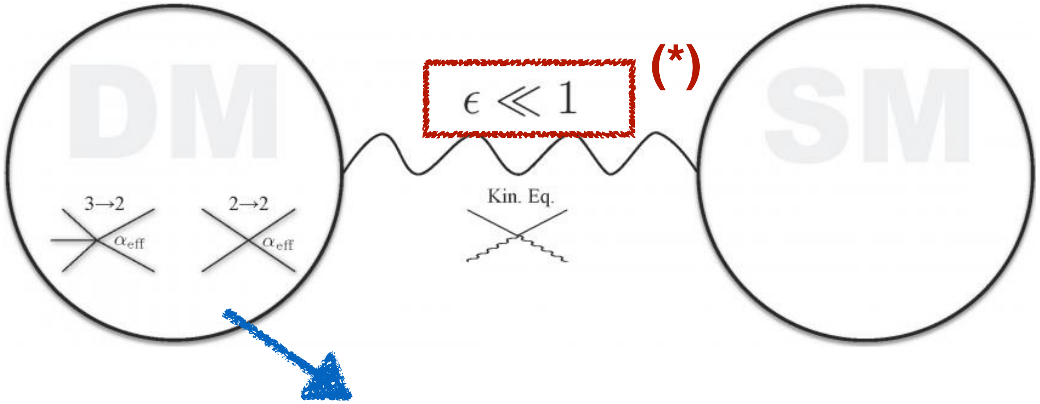
SIMP

DM DM DM $3 \to 2$ **DM DM**

$m_{\rm DM} \sim \alpha_{\rm ann}(T_{\rm eq}^2 M_{\rm pl})^{1/3} \sim 100~{\rm MeV}$

4.

Strongly interacting massive particles in a nutshell



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(**WIMP**

DM DM $2 \to 2$ **SM SM**

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SIMP

DM DM DM $3 \to 2$ **DM DM**

$m_{\rm DM} \sim \alpha_{\rm ann} (T_{\rm eq}^2 M_{\rm pl})^{1/3} \sim 100\ {\rm MeV}$

Possibly realized in a QCD-like theory with

$$SU(N_f) \times SU(N_f) \to SU(N_f)$$

N_f^2-1 pions Light pions

$$\mathcal{L}_{\rm WZW} = \frac{2N_c}{15\pi^2 f_\pi^5} \epsilon^{\mu\nu\rho\sigma} {\rm Tr}(\pi \partial_\mu \pi \partial_\nu \pi \partial_\rho \pi \partial_\sigma \pi)$$

(*) If the portal operator is not too small, the dark pions can be in thermal equilibrium with the SM → **Detection?**

4.

Spectrum and portal to the SM

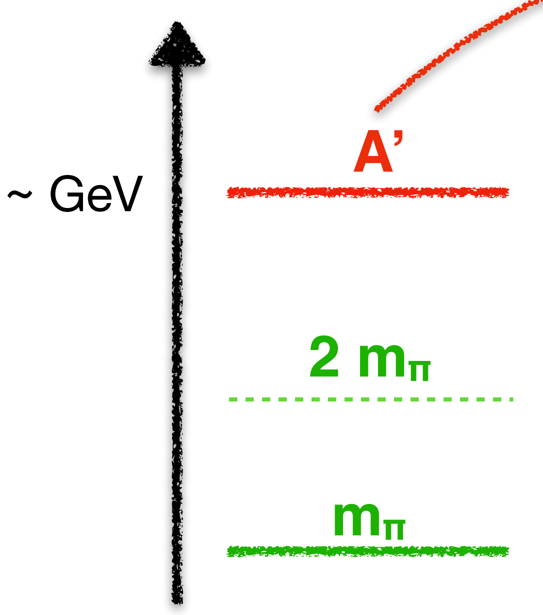
A concrete realization for SIMPs

Berlin, Blinov, SG,
Schuster, Toro, 1801.05805

$$\frac{\epsilon}{2\cos\theta_W}A'_{\mu\nu}B^{\mu\nu}$$

DM is kept in thermal equilibrium

SM



prevent

$$\pi\pi \to A'A'$$

(CMB)

N_f^2-1 = 8 dark pions:

$$\frac{1}{\sqrt{2}}\begin{pmatrix} \frac{\pi^0}{\sqrt{2}}+\frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}}+\frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \overline{K^0} & -\sqrt{\frac{2}{3}}\,\eta \end{pmatrix}$$

$$SU(3)_L \times SU(3)_R \to SU(3)_D \supset U(1)_D$$

$$N_f = 3$$

4.

Spectrum and portal to the SM

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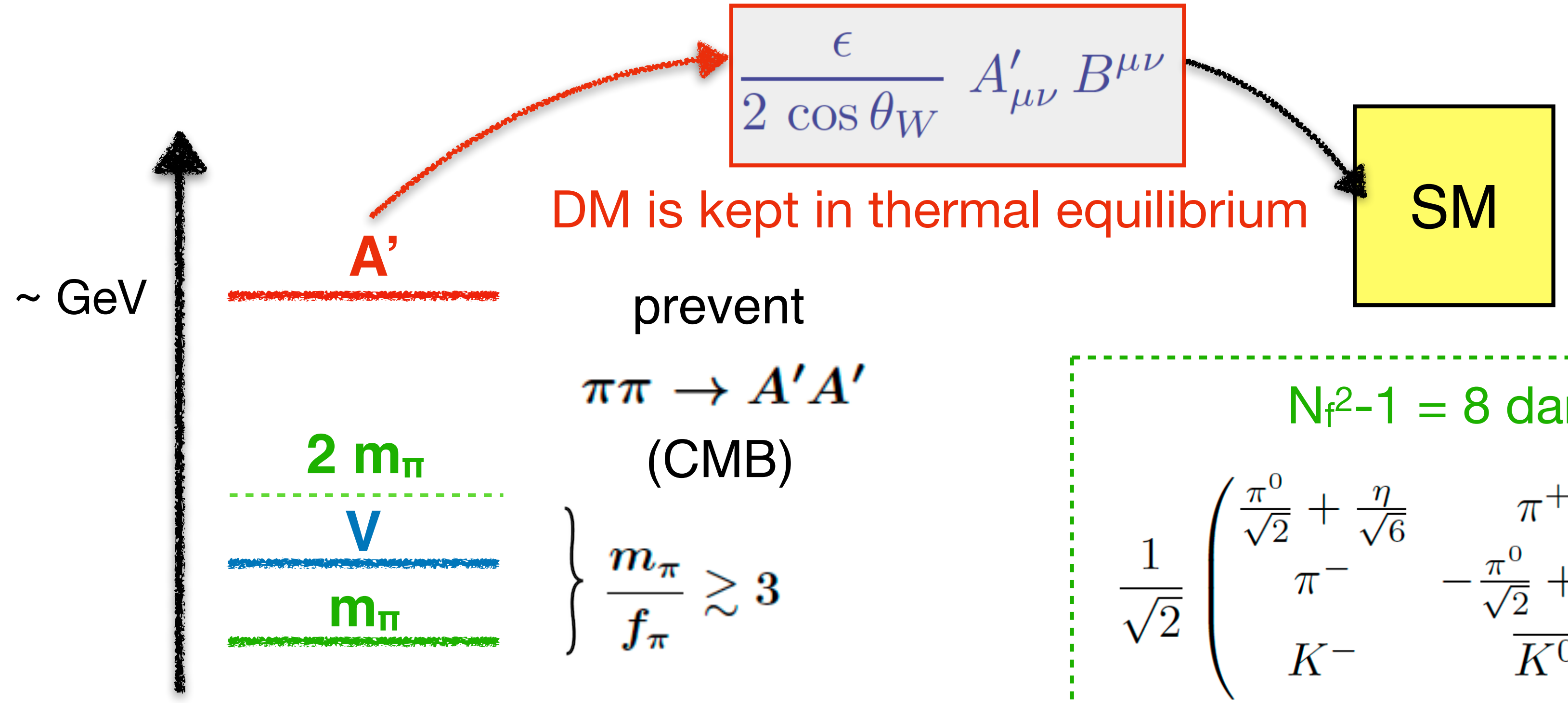
Berlin, Blinov, SG,
Schuster, Toro, 1801.05805

$$\frac{\epsilon}{2\cos\theta_W} A'_{\mu\nu} B^{\mu\nu}$$

DM is kept in thermal equilibrium

SM



prevent

$$\pi\pi \to A'A'$$

(CMB)

$$\frac{m_\pi}{f_\pi} \gtrsim 3$$

$$SU(3)_L \times SU(3)_R \to SU(3)_D \supset U(1)_D$$

$$N_f = 3$$

$N_f^2 - 1 = 8$ dark pions:

$$\frac{1}{\sqrt{2}}\begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \overline{K^0} & -\sqrt{\frac{2}{3}}\,\eta \end{pmatrix}$$

dark vector mesons, V:

$$\frac{1}{\sqrt{2}}\begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+_\mu & K^{*+}_\mu \\ \rho^-_\mu & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0}_\mu \\ K^{*-}_\mu & \overline{K^{*0}_\mu} & \phi \end{pmatrix}$$

4.

The dark pion relic abundance

Berlin, Blinov, SG, Schuster, Toro, 1801.05805

Several processes can contribute to the dark pion annihilation:

1. $3\pi_D \to 2\pi_D$ annihilation $\Gamma(3 \to 2) = n_\pi^2 \langle \sigma v^2 \rangle \ , \ \langle \sigma v^2 \rangle \sim \left(\frac{m_\pi}{f_\pi}\right)^{10} \frac{1}{m_\pi^5}$

④

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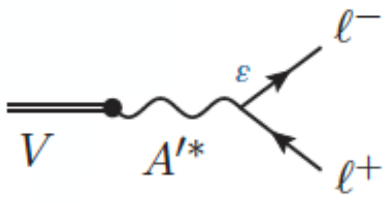
2. $\pi_D \pi_D \to V_D \pi_D$ semi-annihilation



$m_V < 2m_\pi$

(If the dark vectors (V) have a mass close to the mass of the dark pions)

$$\langle \sigma v \rangle \sim \frac{e^{-(m_V - m_\pi)/T}}{m_\pi^2} \gtrsim \frac{e^{-m_\pi/T}}{m_\pi^2}$$

4.

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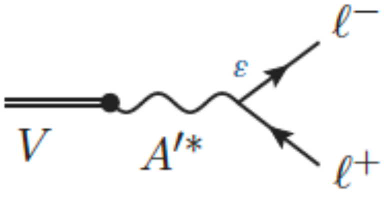

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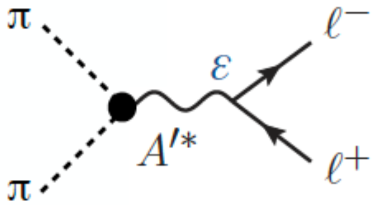

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Berlin, Blinov, SG, Schuster, Toro, 1801.05805

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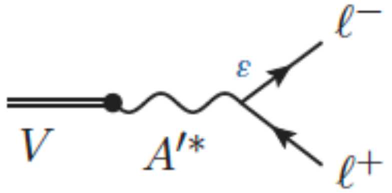

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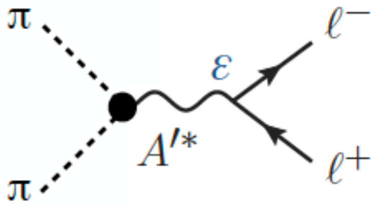
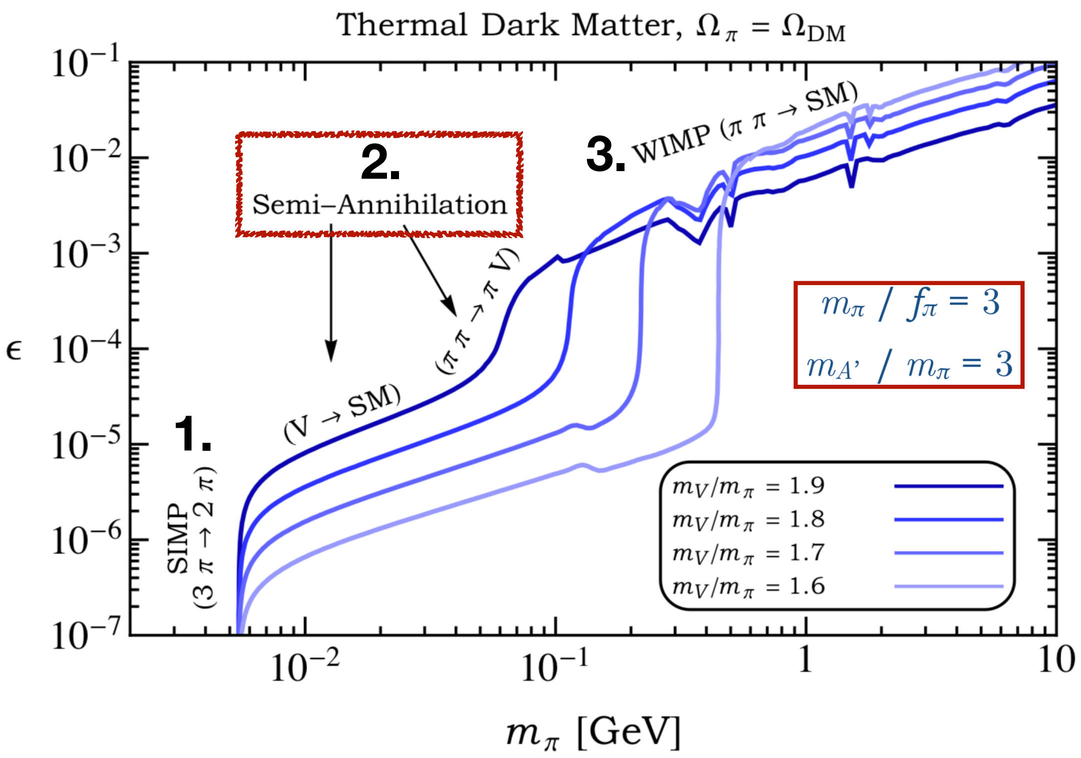
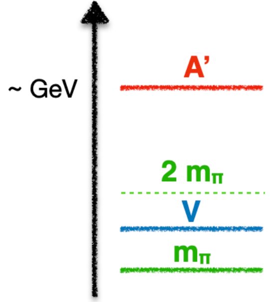




Broad range of values of m_π are possible

4. Dark photon production to access SIMPs



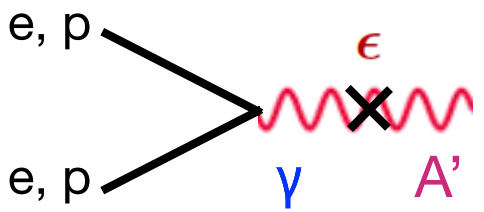
(At low mass) Z' couples proportionally to the electric charge

⇨ Whenever there is a γ, there will be a A'

From my lecture of yesterday

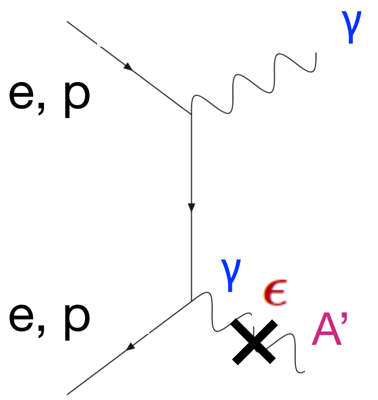
Collider experiments

1) Drell-Yan production:



3) Meson decays:
e.g., D* → D A'

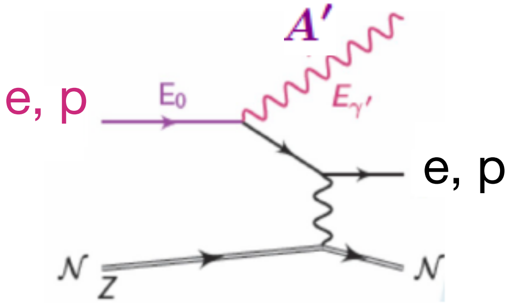
2) Associated production:



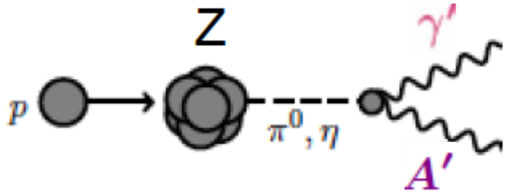
$$\sigma \propto \frac{\varepsilon^2 \alpha_{\mathrm{em}}^2}{E^2}$$

Good for low energy colliders

Fixed target experiments



brems-strahlung



meson decay

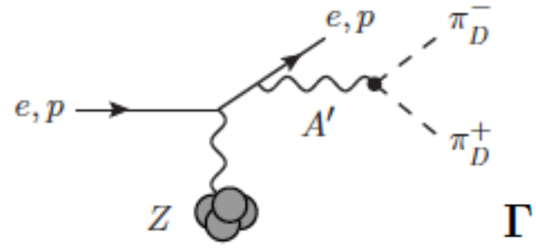
$\sigma \sim \alpha_{\mathrm{em}}\, \epsilon^2 \times \sigma_{pp}$ proton

$\sigma \sim \frac{\alpha_{\mathrm{em}}^3\, \epsilon^2}{m_{A'}^2}\, Z^2$ electron

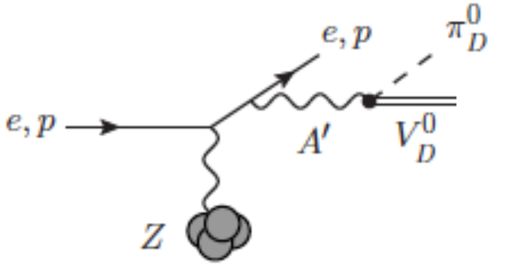
④

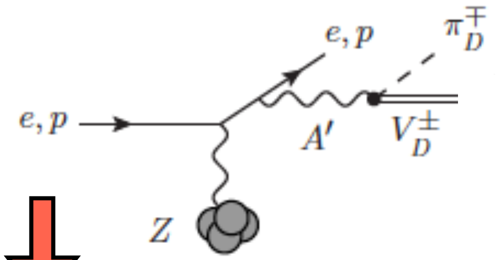
Dark photon decays to SIMPs

$A' \to \pi_D^+\pi_D^-$ (DM)



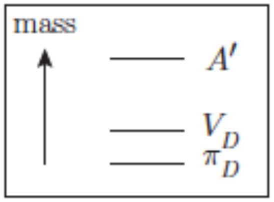
$\Gamma \propto \alpha_D m_{A'}$



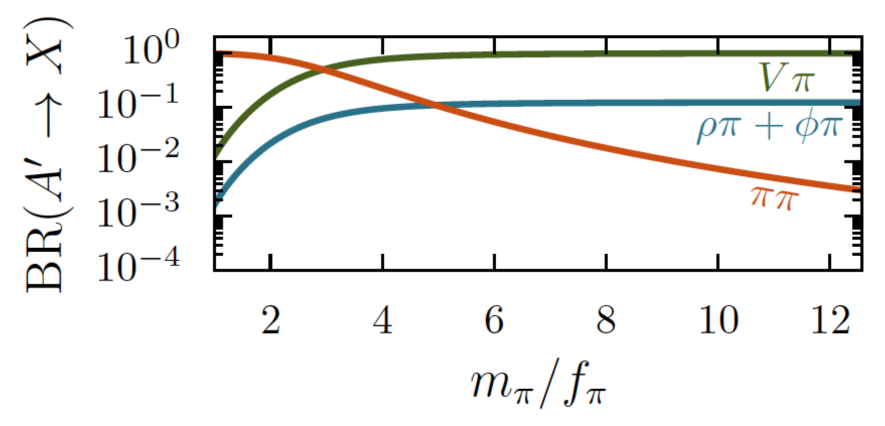


$A' \to \pi_D V_D$

$$\Gamma \propto \alpha_D \frac{m_{A'}^3 m_V^2}{f_\pi^4}$$



Berlin, Blinov, SG, Schuster, Toro, 1801.05805

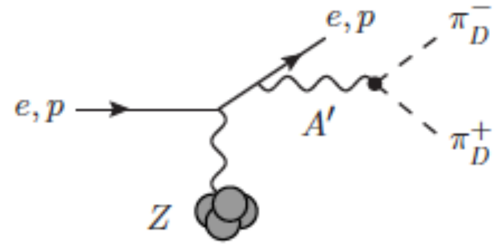


$\alpha_D = 10^{-2}, \quad \epsilon = 10^{-3}$

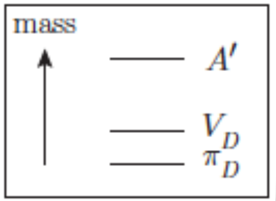
4.

Dark photon decays to SIMPs

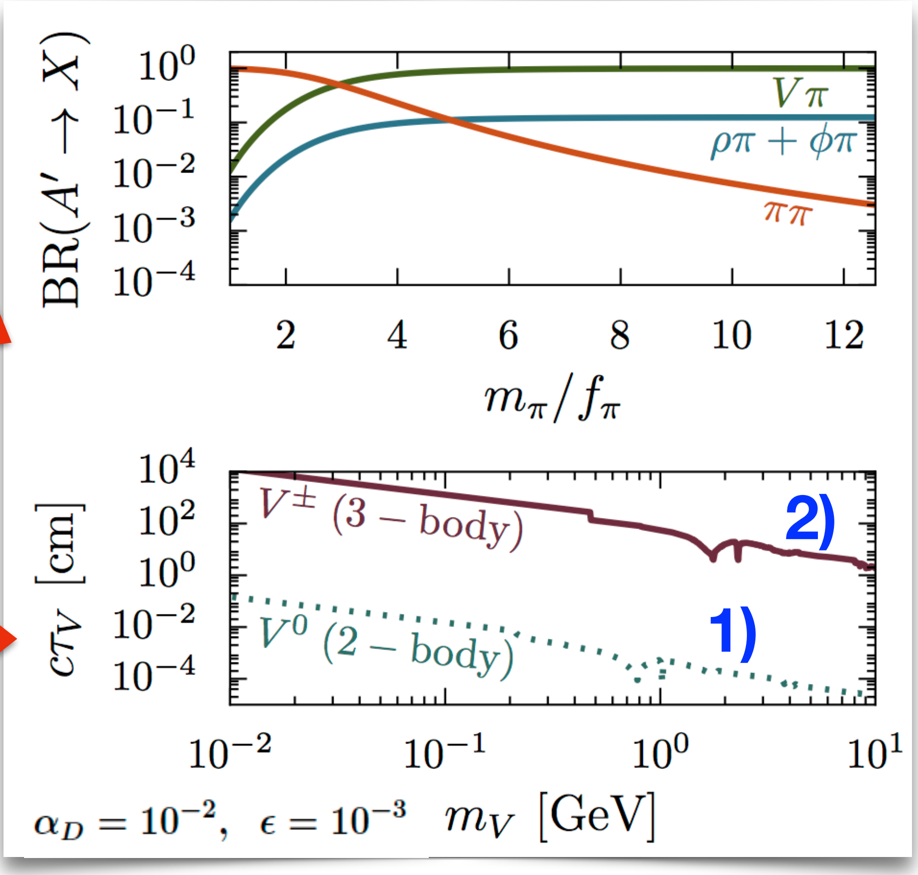
$A' \to \pi_D^+\pi_D^-$ (DM)

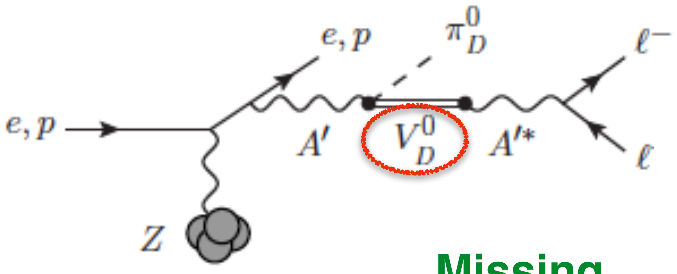


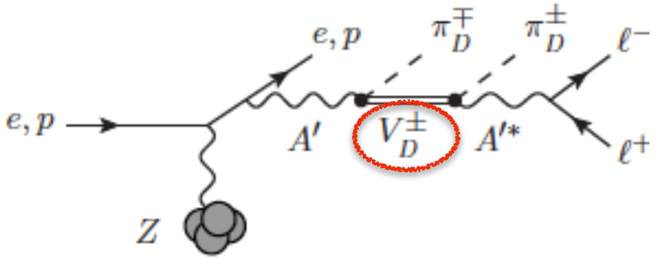
Invisible
A' decay



Berlin, Blinov, SG, Schuster, Toro, 1801.05805







Missing energy

Visible
A' decay

$A' \to \pi_D V_D \to \pi_D(\ell^+\ell^-)$ **1)** New

$\to \pi_D(\ell^+\ell^-\pi_D)$ **2)**

Displaced decays of the dark vector

Similar to the IDM $\chi_1\chi_2 \to \chi_1(\chi_1\ell^+\ell^-)$

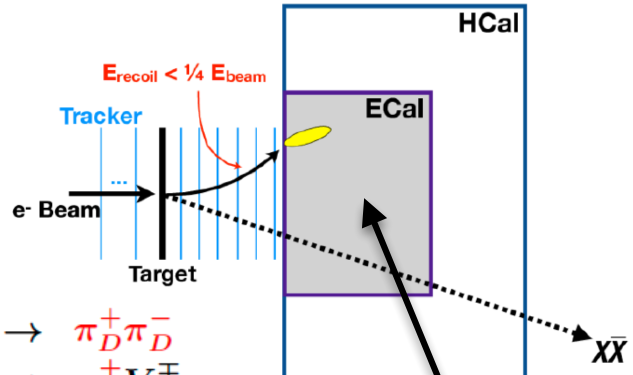
④

DarkQuest and LDMX

Let us focus on two proposed experiments:

1. Invisible

LDMX @ SLAC



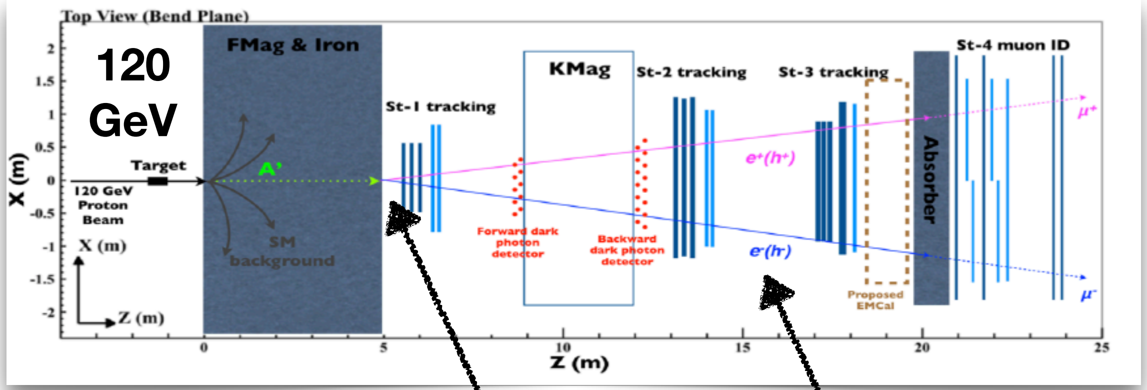
$$A' \to \pi_D^+ \pi_D^-$$
$$A' \to \pi_D^\pm V_D^\mp$$
$$V_D^\pm \to \pi_D^\pm \ell^+ \ell^-$$

can also look for visible decays

4 x 10^{14} electrons on target, 4 GeV beam (phase 1)
10^{16} electrons on target, 8 GeV beam (phase 2)

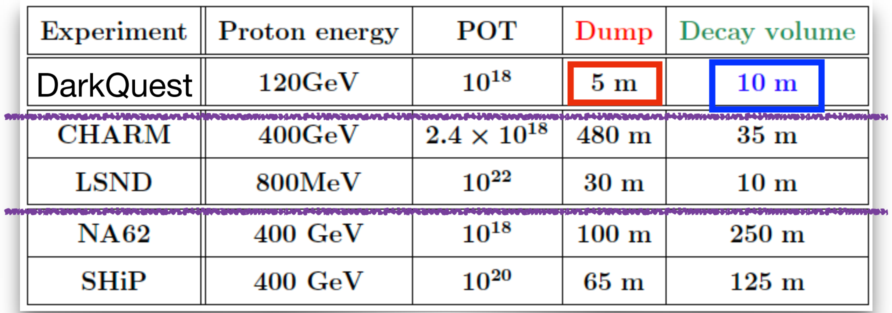
2. Visible

DarkQuest @ Fermilab



decay of
the dark vector

$$V_D^\pm \to \pi_D^\pm \ell^+ \ell^-$$
$$V_D^0 \to \ell^+ \ell^-$$

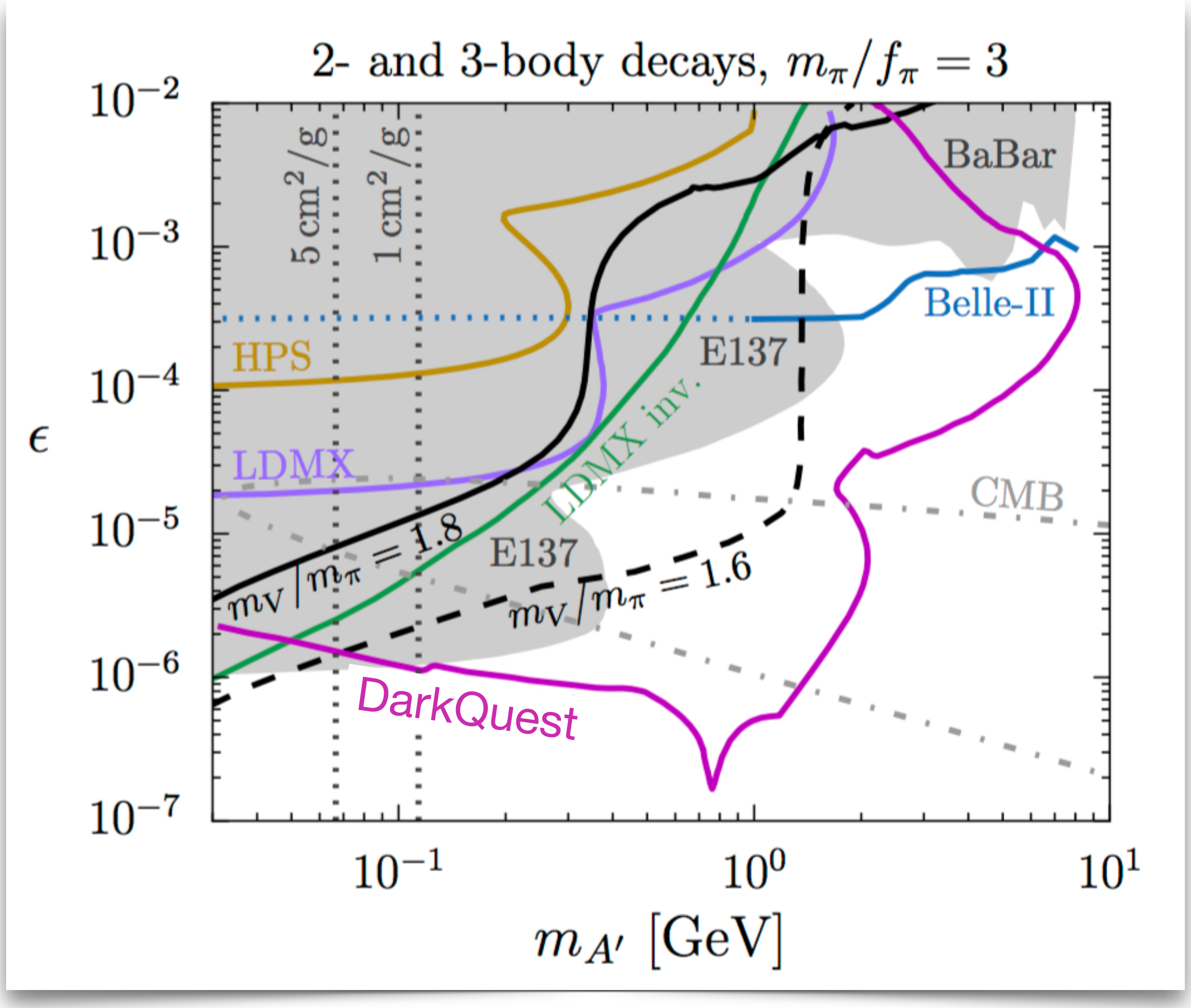


Experiment	Proton energy	POT	Dump	Decay volume
DarkQuest	120GeV	10^{18}	5 m	10 m
CHARM	400GeV	2.4×10^{18}	480 m	35 m
LSND	800MeV	10^{22}	30 m	10 m
NA62	400 GeV	10^{18}	100 m	250 m
SHiP	400 GeV	10^{20}	65 m	125 m

4.

The reach for SIMPs (2+3 body decays)

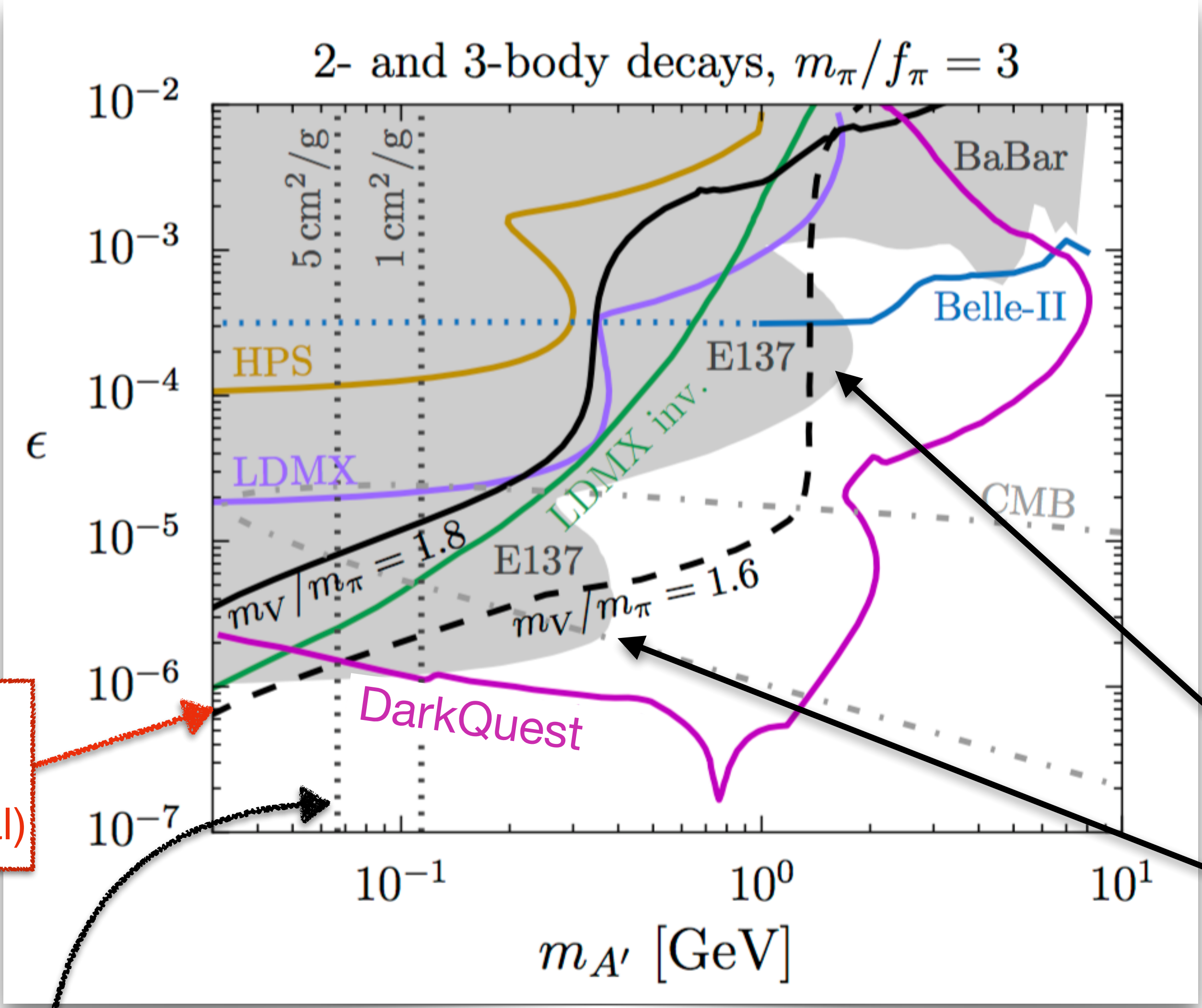
Berlin, Blinov, SG, Schuster, Toro, 1801.05805



$\alpha_D = 10^{-2},\ m_{A'}/m_\pi = 3$

4. The reach for SIMPs (2+3 body decays)

Berlin, Blinov, SG, Schuster, Toro, 1801.05805



$\alpha_D = 10^{-2}$, $m_{A'}/m_\pi = 3$

Relic line (our goal)

Bound from DM self-interaction

Gray:

reach of past experiments:

- Babar:

$e^+e^- \to \gamma A'$, $A' \to \mathrm{inv}$

- E137:

past electron beam dump experiment. Search for visibly decaying A'

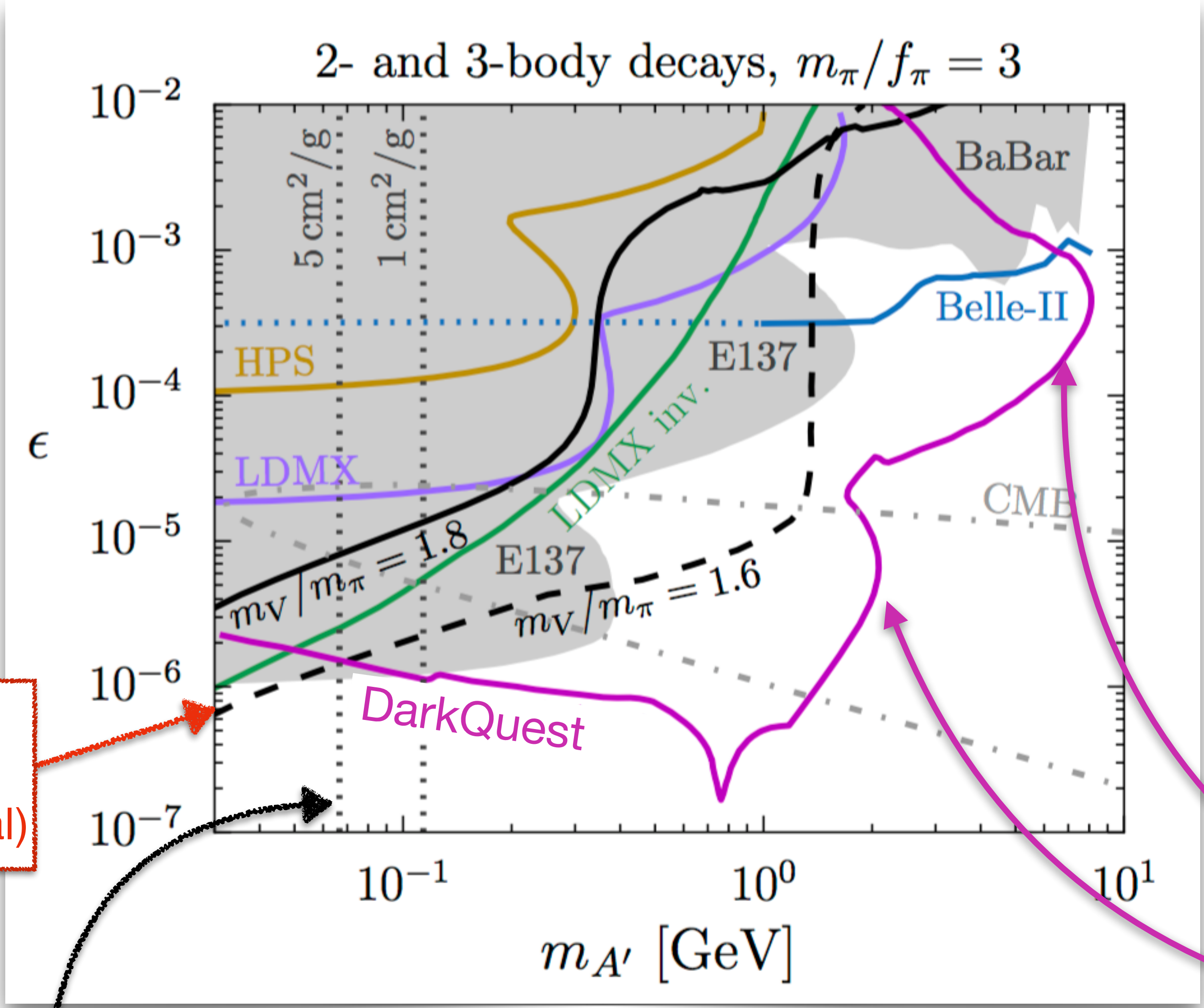
$A' \to \pi_D V_D$

$V_D^\pm \to \pi_D^\pm \ell^+\ell^-$

$V_D^0 \to \ell^+\ell^-$

4. The reach for SIMPs (2+3 body decays)

Berlin, Blinov, SG, Schuster, Toro, 1801.05805



Relic line (our goal)

Bound from DM self-interaction

$\alpha_D = 10^{-2}$, $m_{A'}/m_\pi = 3$

In color:

reach of future experiments:

- Belle II: (same Babar signature)

$$e^+e^- \to \gamma A', \quad A' \to \text{inv}$$

- LDMX: invisible A'
- LDMX: visible A'
- HPS: electron beam dump experiment. Search for visibly decaying A'
- DarkQuest

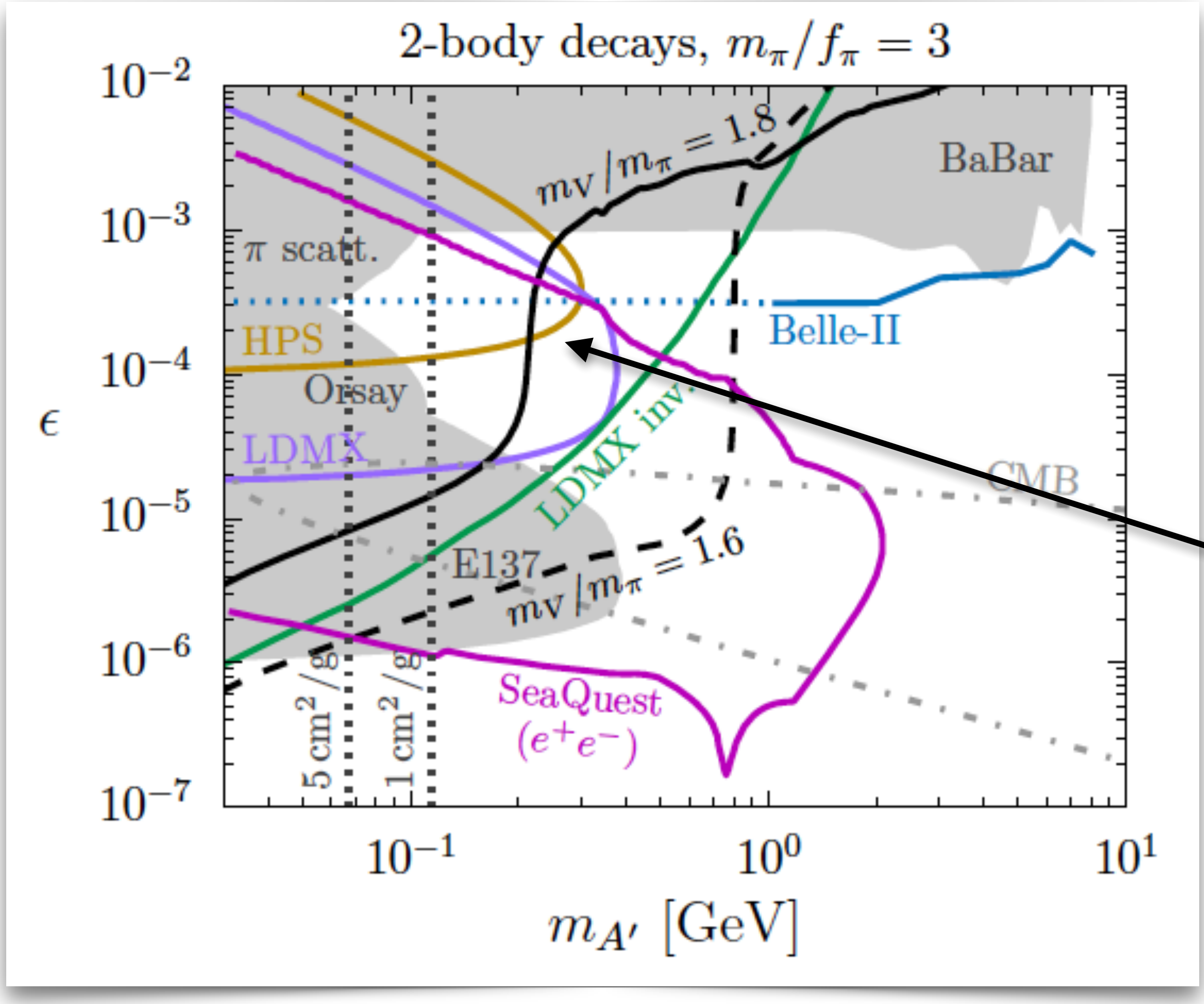
$$A' \to \pi_D V_D$$

$$V_D^\pm \to \pi_D^\pm \ell^+\ell^-$$

$$V_D^0 \to \ell^+\ell^-$$

What about searching for this at Belle II?

4. The reach for SIMPs (2 body decays)



$\alpha_D = 10^{-2}$, $m_{A'}/m_\pi = 3$

If the charged vectors are heavier than $2m_\pi$, then only the neutral vectors will appreciably decay visibly:

$$A' \to \pi_D V_D \to \pi_D (\ell^+\ell^-)$$

E137 (past) bounds are relaxed since the experiment had a long baseline (~400 m).

➡ Larger regions of parameter space are open

Outlook

Many different leptonic signatures arise in dark sector models

Several searches have been already performed at Belle II probing new interesting regions of parameter space

Several new signatures to look for

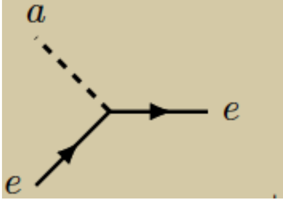
- 1photon + 2 charged tracks (prompt or displaced) **dark photon**
- 3 charged leptons from B meson decays **axions**
- broader coverage of 1 photon+missing + 2 (or more) displaced charged tracks **IDM + SIMP**

Rewriting the ALP interaction

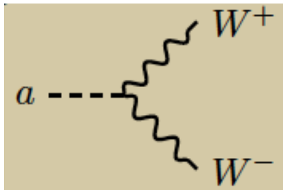
$$\mathcal{L} = -a\partial_\mu j^\mu_{PQ}$$

$$\begin{aligned}\partial_\mu j^\mu_{\rm PQ} = {} & g_{\ell\ell}(\bar\ell i\gamma_5\ell) \\ & + \frac{e^2}{16\pi^2 m_\ell}\frac{\bar g_{\ell\ell} - g_{\ell\ell} + g_{\nu_\ell}}{4s_W^2} W^+_{\mu\nu}\tilde W^{-,\mu\nu} \\ & + \frac{e^2}{16\pi^2 m_\ell}\frac{\bar g_{\ell\ell} - g_{\ell\ell}(1-4s_W^2)}{2c_W s_W} F_{\mu\nu}\tilde Z^{\mu\nu} - g_{\ell\ell}F_{\mu\nu}\tilde F^{\mu\nu} + \\ & + \frac{e^2}{16\pi^2 m_\ell}\frac{\bar g_{\ell\ell}(1-4s_W^2) - g_{\ell\ell}(1-4s_W^2+8s_W^4) + g_\nu}{8s_W^2 c_W^2} Z_{\mu\nu}\tilde Z^{\mu\nu} \\ & + \frac{ig}{2\sqrt{2}m_\ell}(g_{\ell\ell} - \bar g_{\ell\ell} + g_{\nu_\ell})(\bar\ell\gamma^\mu P_L\nu)W^-_\mu\end{aligned}$$

“Standard” vertex

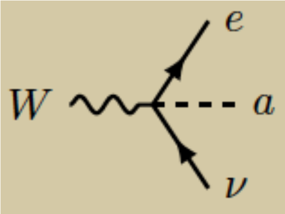


Anomaly terms



Weak vertex

(only present for weak violating models)



Our work:

- **importance of the weak vertex**
- new bounds on the “standard” vertex

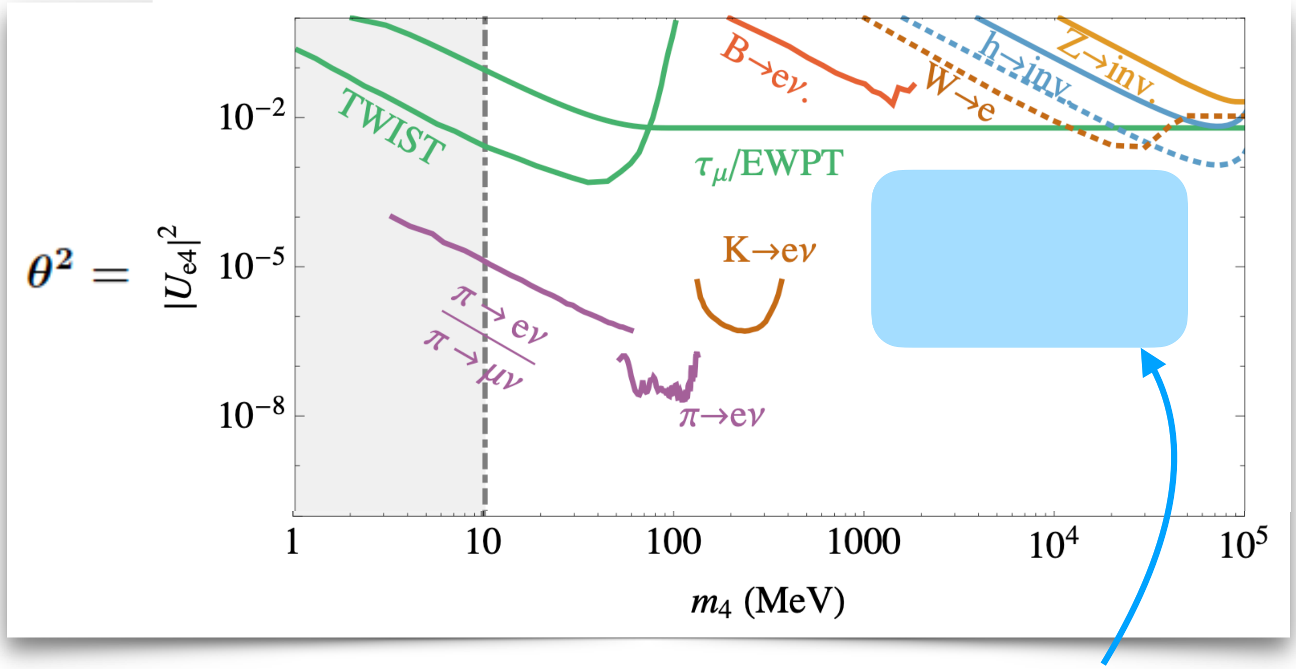
$$\boxed{\frac{(\partial_\mu a)}{m_e}\left[\bar e\gamma^\mu\left(\bar g_{ee} + g_{ee}\gamma_5\right)e + g_\nu\bar\nu\gamma^\mu P_L\nu\right]}$$

SU(2) violating models

$$\mathcal{L} \supset -yHLN^c - Me^{ia/f_a}NN^c + \text{h.c.}$$

$$\Rightarrow \mathcal{L} \supset \frac{\theta^2}{f_a}\partial_\mu a(\bar{\nu}_e\gamma^\mu P_L\nu_e) \Rightarrow \begin{cases} g_\nu = \dfrac{2\theta^2 m_e}{f_a} = 1.0\times 10^{-5}\left(\dfrac{\theta}{0.1}\right)^2\left(\dfrac{\text{GeV}}{f_a}\right) \\ g_{ee} = \bar{g}_{ee} = 0 \end{cases}$$

Batell, et al, 1709.07001

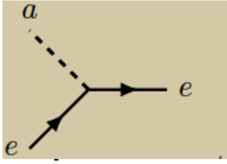


additional constraints from
visibly decaying HNL (less robust)

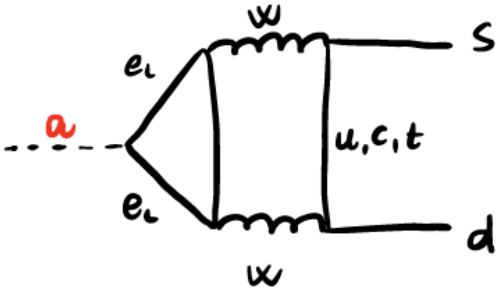
Complementarity with neutral current decays

Neutral current meson decays are also generated at the 2 or 3-loop level (suppressed by CKM elements as well)

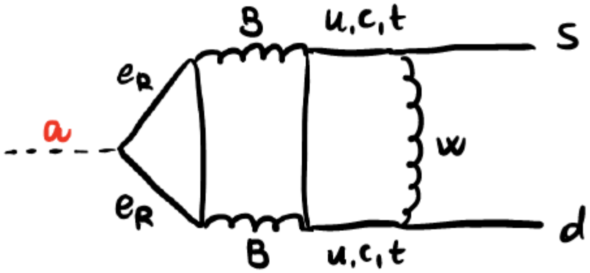
$K \to \pi a$

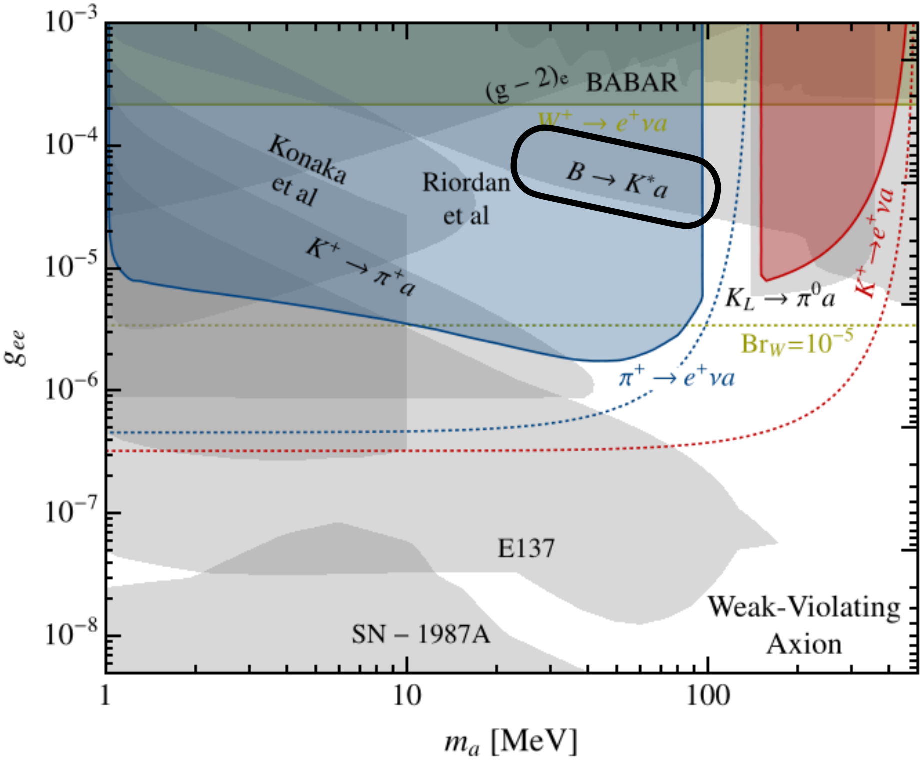


1. ALP with LH coupling



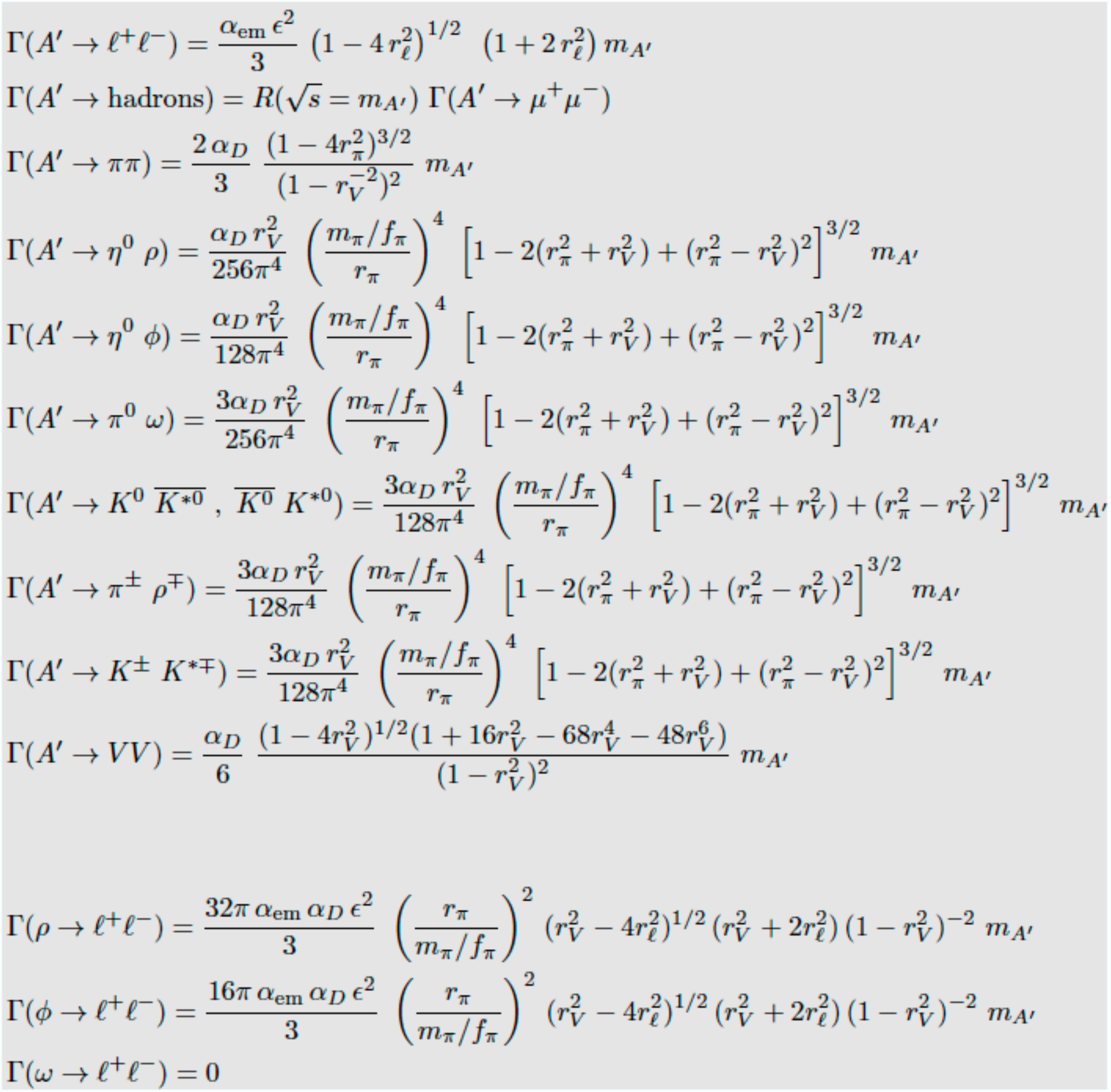
2. ALP with RH coupling





Similar diagrams for $B \to K^{(*)} a$

Dark sector decays



$$\Gamma(A' \to \ell^+\ell^-) = \frac{\alpha_{\rm em}\,\epsilon^2}{3}\,\left(1-4\,r_\ell^2\right)^{1/2}\,\left(1+2\,r_\ell^2\right) m_{A'}$$

$$\Gamma(A' \to {\rm hadrons}) = R(\sqrt{s} = m_{A'})\,\Gamma(A' \to \mu^+\mu^-)$$

$$\Gamma(A' \to \pi\pi) = \frac{2\,\alpha_D}{3}\,\frac{(1-4r_\pi^2)^{3/2}}{(1-r_V^{-2})^2}\,m_{A'}$$

$$\Gamma(A' \to \eta^0\,\rho) = \frac{\alpha_D\,r_V^2}{256\pi^4}\,\left(\frac{m_\pi/f_\pi}{r_\pi}\right)^4\,\left[1-2(r_\pi^2+r_V^2)+(r_\pi^2-r_V^2)^2\right]^{3/2}\,m_{A'}$$

$$\Gamma(A' \to \eta^0\,\phi) = \frac{\alpha_D\,r_V^2}{128\pi^4}\,\left(\frac{m_\pi/f_\pi}{r_\pi}\right)^4\,\left[1-2(r_\pi^2+r_V^2)+(r_\pi^2-r_V^2)^2\right]^{3/2}\,m_{A'}$$

$$\Gamma(A' \to \pi^0\,\omega) = \frac{3\alpha_D\,r_V^2}{256\pi^4}\,\left(\frac{m_\pi/f_\pi}{r_\pi}\right)^4\,\left[1-2(r_\pi^2+r_V^2)+(r_\pi^2-r_V^2)^2\right]^{3/2}\,m_{A'}$$

$$\Gamma(A' \to K^0\,\overline{K^{*0}}\,,\,\overline{K^0}\,K^{*0}) = \frac{3\alpha_D\,r_V^2}{128\pi^4}\,\left(\frac{m_\pi/f_\pi}{r_\pi}\right)^4\,\left[1-2(r_\pi^2+r_V^2)+(r_\pi^2-r_V^2)^2\right]^{3/2}\,m_{A'}$$

$$\Gamma(A' \to \pi^\pm\,\rho^\mp) = \frac{3\alpha_D\,r_V^2}{128\pi^4}\,\left(\frac{m_\pi/f_\pi}{r_\pi}\right)^4\,\left[1-2(r_\pi^2+r_V^2)+(r_\pi^2-r_V^2)^2\right]^{3/2}\,m_{A'}$$

$$\Gamma(A' \to K^\pm\,K^{*\mp}) = \frac{3\alpha_D\,r_V^2}{128\pi^4}\,\left(\frac{m_\pi/f_\pi}{r_\pi}\right)^4\,\left[1-2(r_\pi^2+r_V^2)+(r_\pi^2-r_V^2)^2\right]^{3/2}\,m_{A'}$$

$$\Gamma(A' \to VV) = \frac{\alpha_D}{6}\,\frac{(1-4r_V^2)^{1/2}(1+16r_V^2-68r_V^4-48r_V^6)}{(1-r_V^2)^2}\,m_{A'}$$

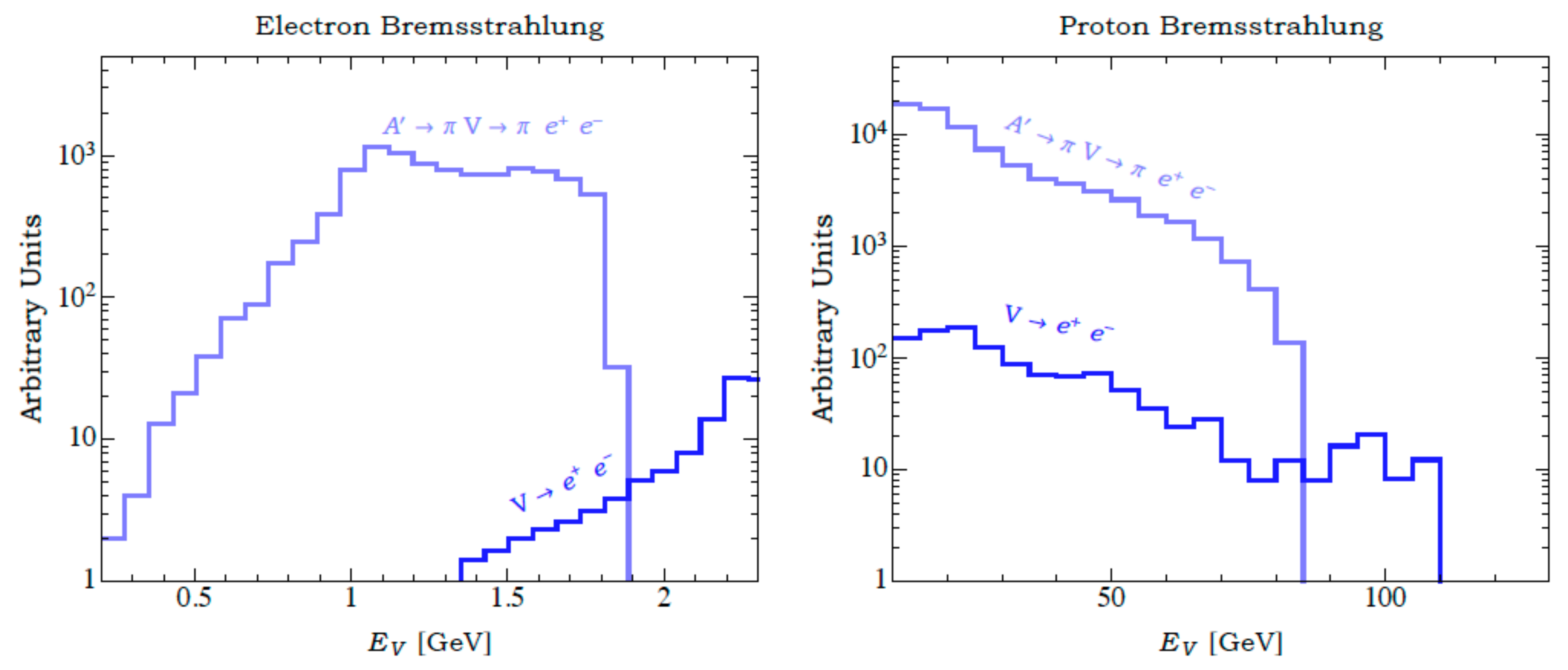
$$\Gamma(\rho \to \ell^+\ell^-) = \frac{32\pi\,\alpha_{\rm em}\,\alpha_D\,\epsilon^2}{3}\,\left(\frac{r_\pi}{m_\pi/f_\pi}\right)^2\,(r_V^2-4r_\ell^2)^{1/2}\,(r_V^2+2r_\ell^2)\,(1-r_V^2)^{-2}\,m_{A'}$$

$$\Gamma(\phi \to \ell^+\ell^-) = \frac{16\pi\,\alpha_{\rm em}\,\alpha_D\,\epsilon^2}{3}\,\left(\frac{r_\pi}{m_\pi/f_\pi}\right)^2\,(r_V^2-4r_\ell^2)^{1/2}\,(r_V^2+2r_\ell^2)\,(1-r_V^2)^{-2}\,m_{A'}$$

$$\Gamma(\omega \to \ell^+\ell^-) = 0$$

$$r_i \equiv m_i/m_{A'}$$

Kinematics of the decays



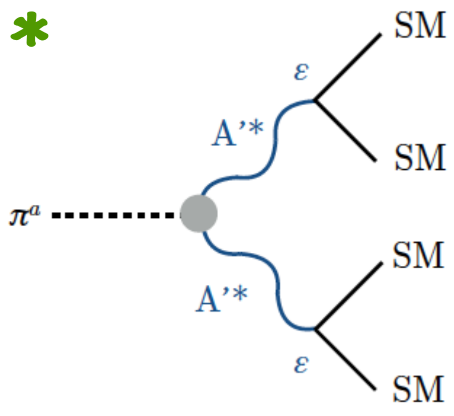
Berlin, Blinov, SG, Schuster, Toro, 1801.05805

for the darkquest experiment

The stability of pions

Pions need to be long-lived on timescales compared to freeze-out.

However, the **neutral pions:**

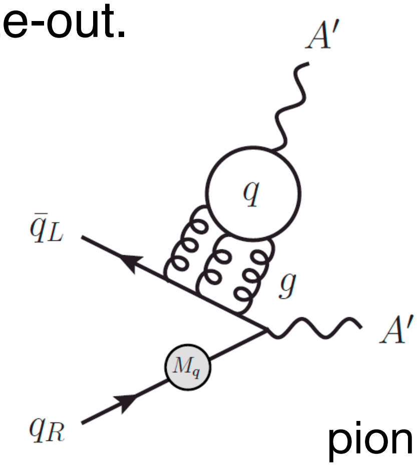
- 

If $Q^2 \propto \mathbf{I}_{3\times 3}$

e.g. $Q = (+1, -1, -1)$

no contribution to the neutral pion decay from the chiral anomaly.

- additional contribution:



pion matrix

$$\frac{\alpha_D}{4\pi f_\pi}\, i\,\epsilon^{\mu\nu\alpha\beta} A'_{\mu\nu} A'_{\alpha\beta}\,\mathrm{Tr}\,Q\;\mathrm{Tr}\left(Q\,M_q\,U^\dagger\right) + \mathrm{h.c.}$$

$$\Rightarrow \quad \Gamma(\pi \to 4\ell) \sim \frac{\alpha_D^2\,\alpha_{\rm em}^2\,\epsilon^4}{2048\,\pi^5}\,\frac{m_\pi^{11}}{f_\pi^2\,m_{A'}^8}$$

Lifetime can be comparable to the time of recombination.

OK if $m_{\pi 0} > m_{\pi +}$

U(1)$_D$ charged pions are stable → they can be DM