Overview of BSM theory on exotic particles

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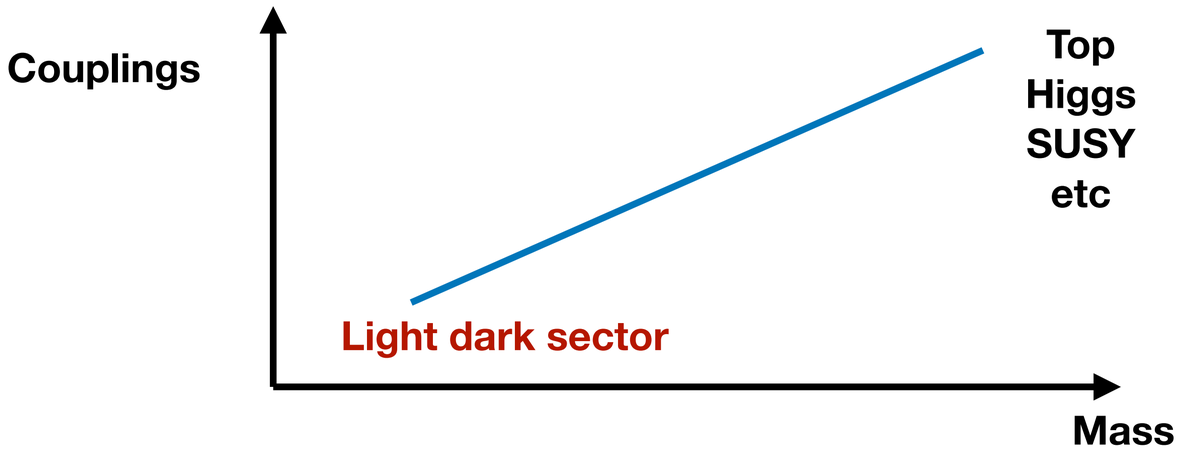
Outline

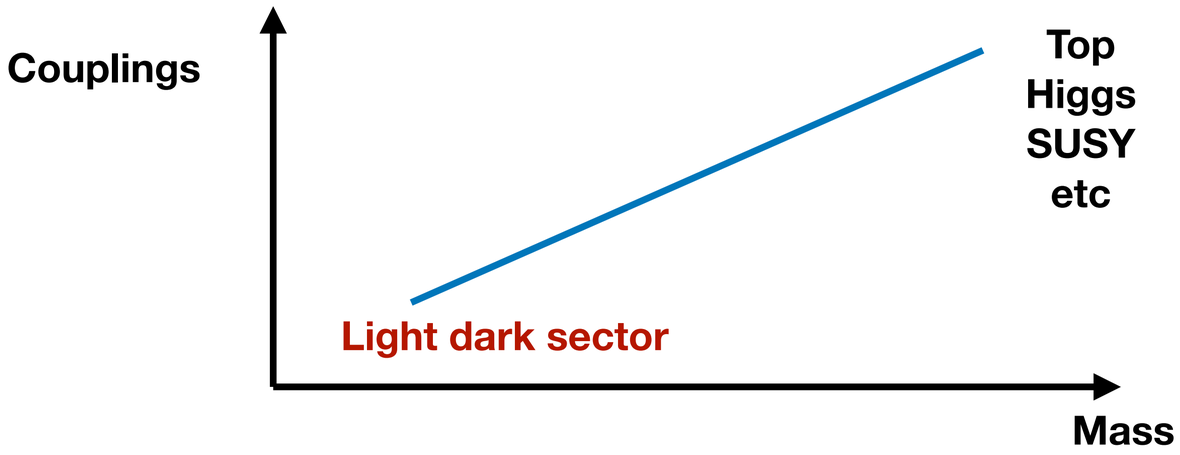
- Introduction
- Exotic Particles
  - Various Portals
- Exotic Features
  - Long-Lived Particles
  - Time-varying particles
- Conclusion

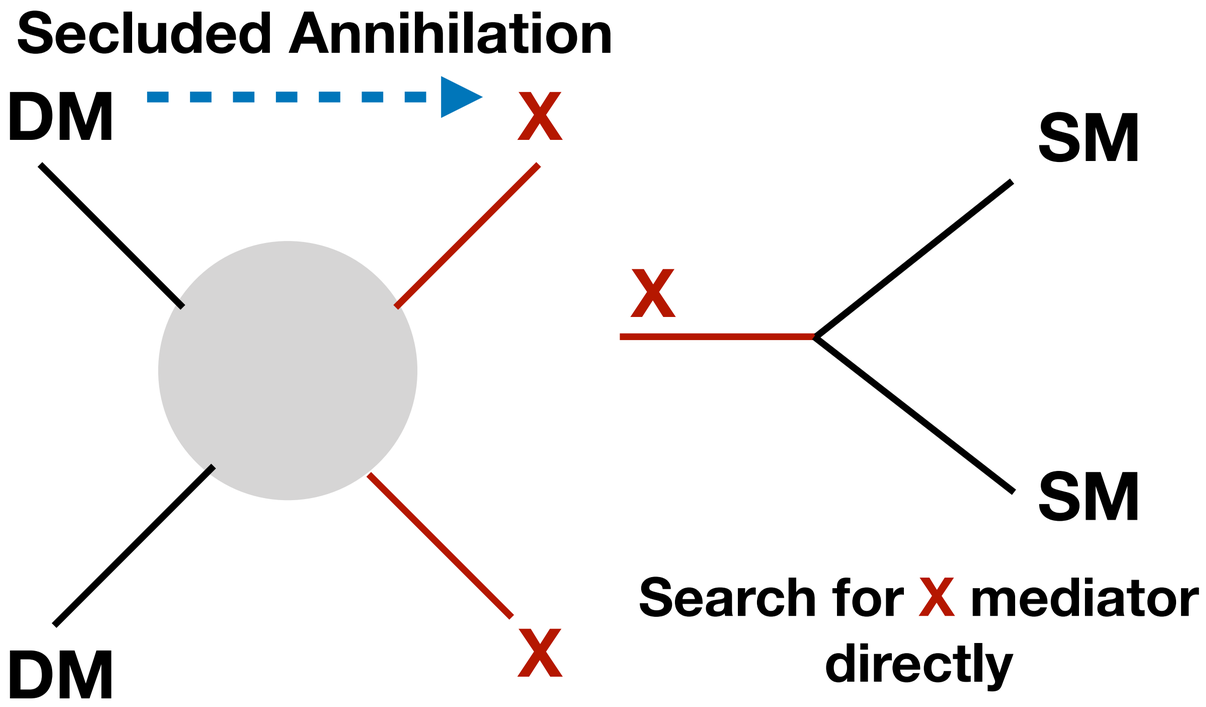
The target for the Intensity Frontier



- 1. It fits well with intensity frontier programs: beam dump, high-lumi searches from tau/charm factory, b factory, Z factory, Higgs factory
- 2. The low energy experiment hints
  - Lepton mu (e?) g-2 (light particles at ~ 100 MeV, coupling << 1)
  - Atomki: Be8/He4 decay into a 17 MeV ee resonance
  - ~~KOTO: neutral K decay into pi0 + MET (light scalar < 200 MeV)~~
  - ~~MiniBooNE: (dark neutrino/boson at 10~100MeV)~~
- 3. Secluded DM annihilation: light mediator $m_X < m_{DM}$, with small coupling

The target for the Intensity Frontier





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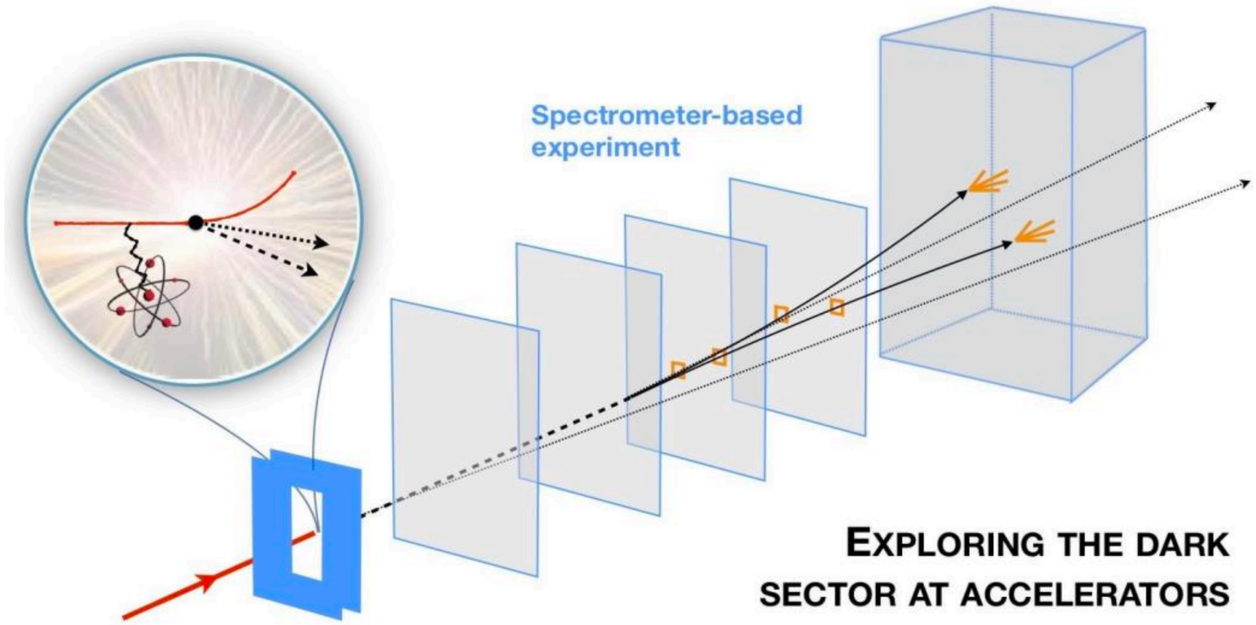
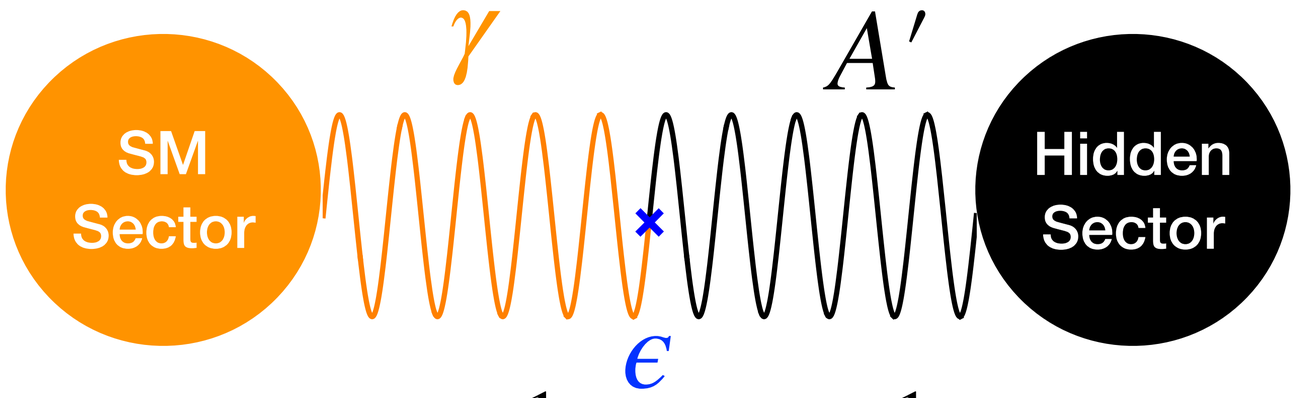
Exotic interactions: Various BSM portals

- Vector Portal: Kinetic Mixing Dark Photon
  $B_{\mu\nu}F'^{\mu\nu}$
- Pseudoscalar Portal: Axion, Axion-Like Particles $\frac{a}{\Lambda}\tilde{F}F$, $\frac{a}{\Lambda}\tilde{G}G$
- Scalar Portal (Higgs Portal): SM Higgs
  $\left(H^\dagger H\right)\left(\phi \text{ or } \phi^2\right)$
- Fermion Portal: Sterile neutrino, Vector-like Fermions
  $\left(\bar{L}H\right)N_R, \bar{L}\Phi\Psi, \bar{Q}\Phi\Psi$
- Millicharged Particles, Leptoquarks etc …



The Kinetic Mixing Portal

- Marginal operator: a single extension of SM at low energy
  - Integrating out heavy fermion charged under both SM and Dark sector



$$\epsilon \sim -\frac{gg'}{16\pi^2}\log\left(\frac{m_L^2}{\mu^2}\right)$$

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

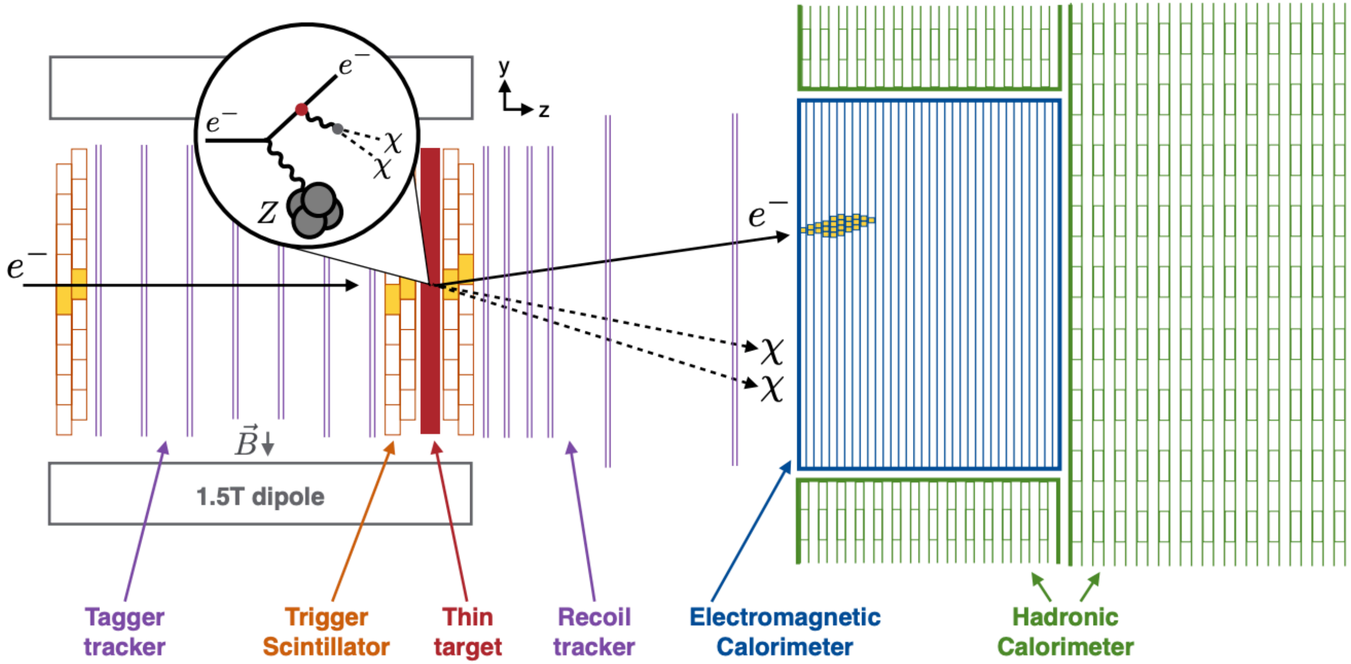
$$\mathscr{L}_{\text{mass}} \supset \frac{1}{2}m_{A'}{}^2A'^{\mu}A'\mu + eA_{\mu}j^{\mu}_{\text{em}} + A'_{\mu}\left(g'j^{\mu}_{D} + \epsilon e j^{\mu}_{\text{em}}\right)$$

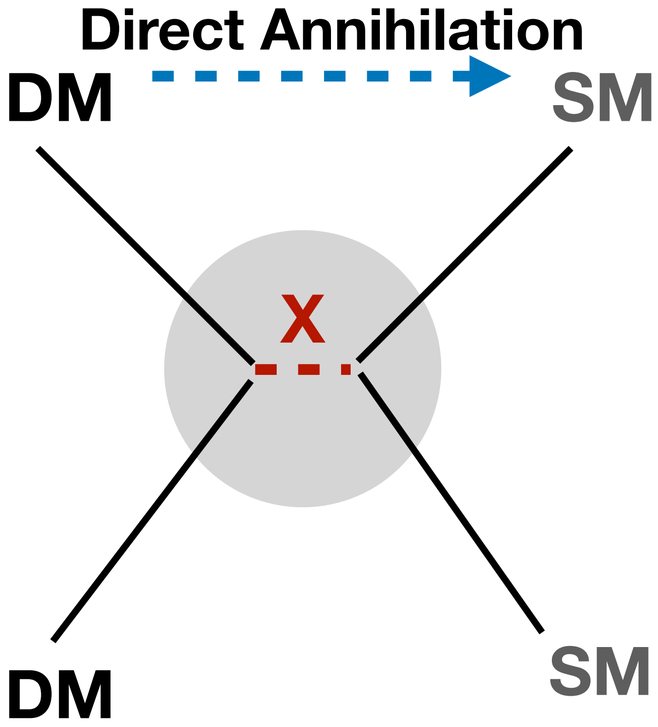
- Parameters: $m_{A'}$, ϵ, g', m_{DM}

A proper low energy model from UV physics
Log dependence of UV scale

The A' invisible benchmark at intensity frontier

- A dark mediator with direct annihilation
- Mass setup $m_{A'} > 2m_{\mathrm{DM}}$ to avoid secluded scenario
  - The thermal cross-section: $\langle \sigma v \rangle \approx \alpha' \epsilon^2 \alpha \frac{m_{\mathrm{DM}}^2}{m_{A'}^4}$
- Benchmark: $m_{A'} = 3m_{\mathrm{DM}}, \alpha' = 0.5$





See Bertrand Echenard's talk on LDMX
Benjamin Banto Oberhauser's talk on NA64 …

A variant in DM annihilation history

- Massive gauge boson has a varying mass in the early universe

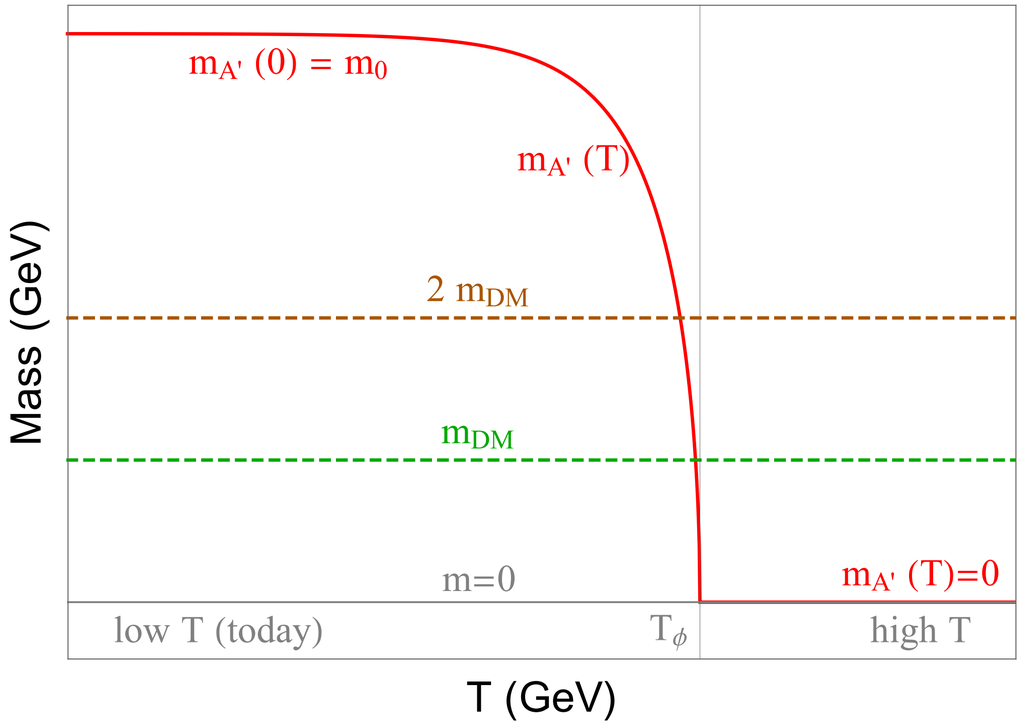
$$m^2_{A'}(T) = \begin{cases} 0 & T > T_\phi, \\ m^2_{A',0} - \kappa m^2_\psi \left(\frac{T}{m_\psi}\right)^n & T < T_\phi \end{cases}$$

- The annihilation channels divided into two categories:

Transient secluded: $(\bar{\psi}\psi \to A'A')$ $\quad m_{A'} = m_\psi,$

$(\bar{\psi}\psi \to A'\phi)$ $\quad m_{A'} = 2m_\psi - m_\phi,$

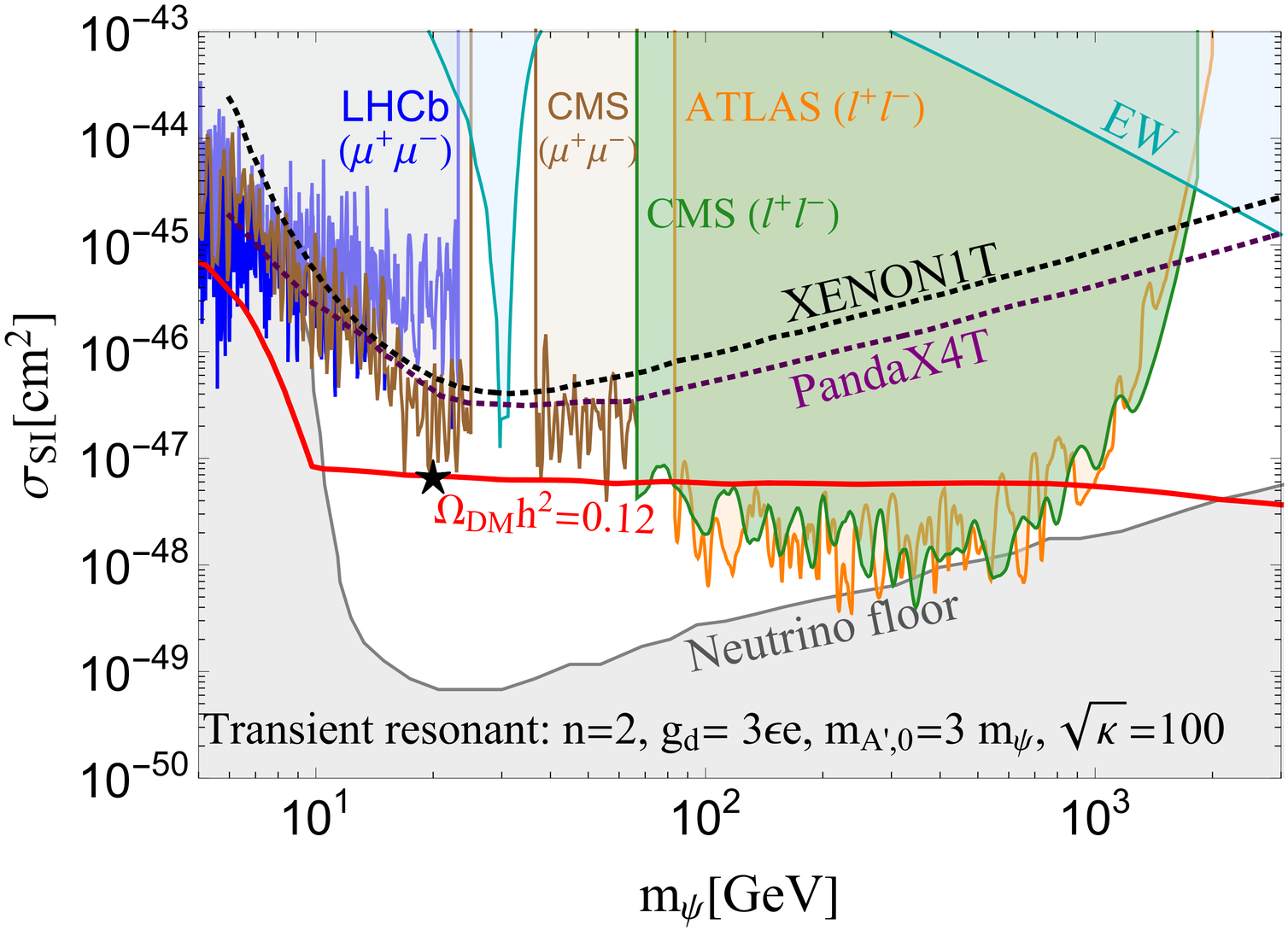
Transient resonant: $(\bar{\psi}\psi \to \bar{f}f)$ $\quad m_{A'} = 2m_\psi\,.$



K. Hashino, JL, X.P. Wang, K.P. Xie 2109.07479 PRD

A variant in DM annihilation history

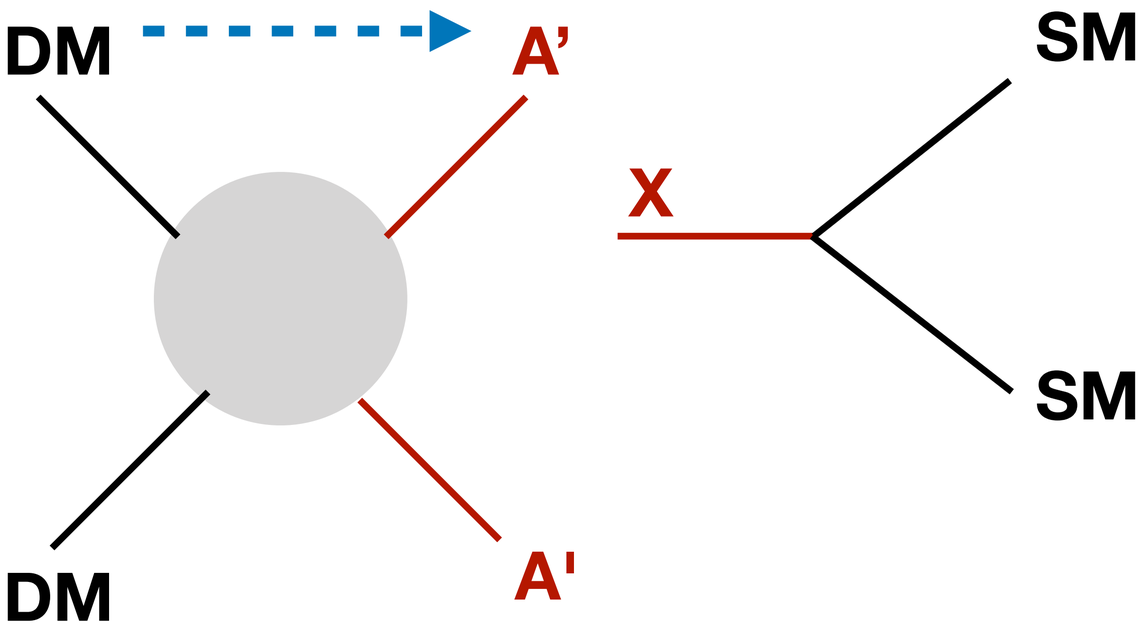
- Transient resonant annihilation only happens in the early universe
  - No indirect constraints
  - Collider and direct detection constraints are evaded
  - Can be soon tested in the future

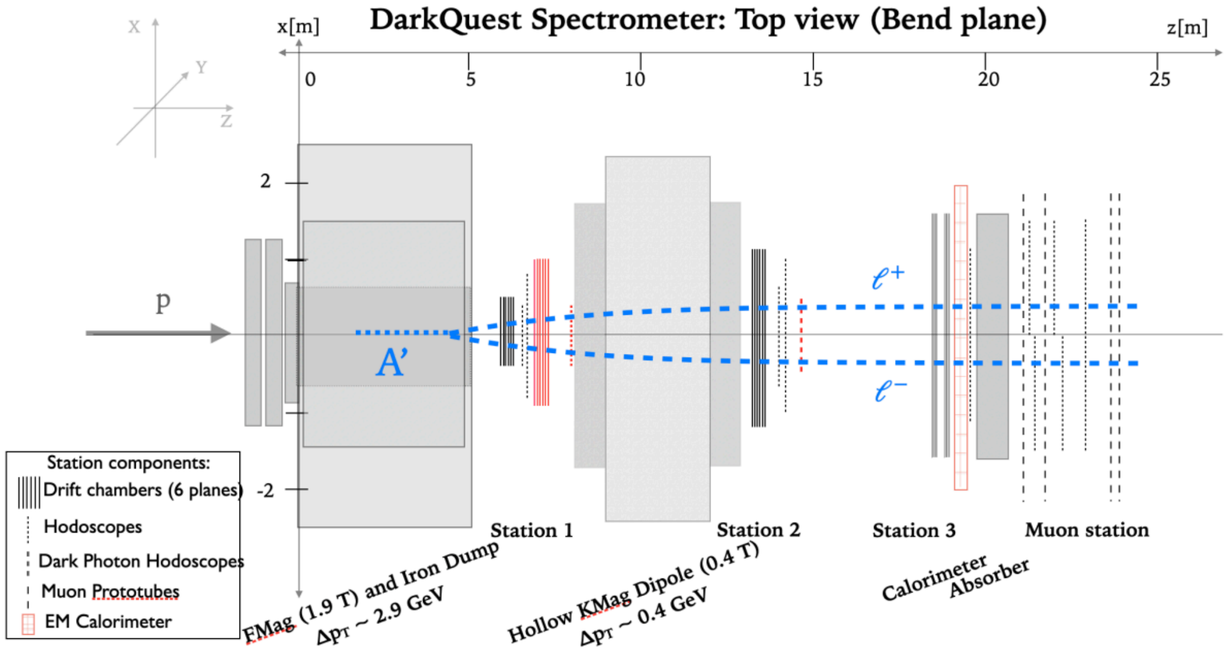


K. Hashino, JL, X.P. Wang, K.P. Xie 2109.07479 PRD

The A’ visible benchmark at intensity frontier

Secluded Annihilation

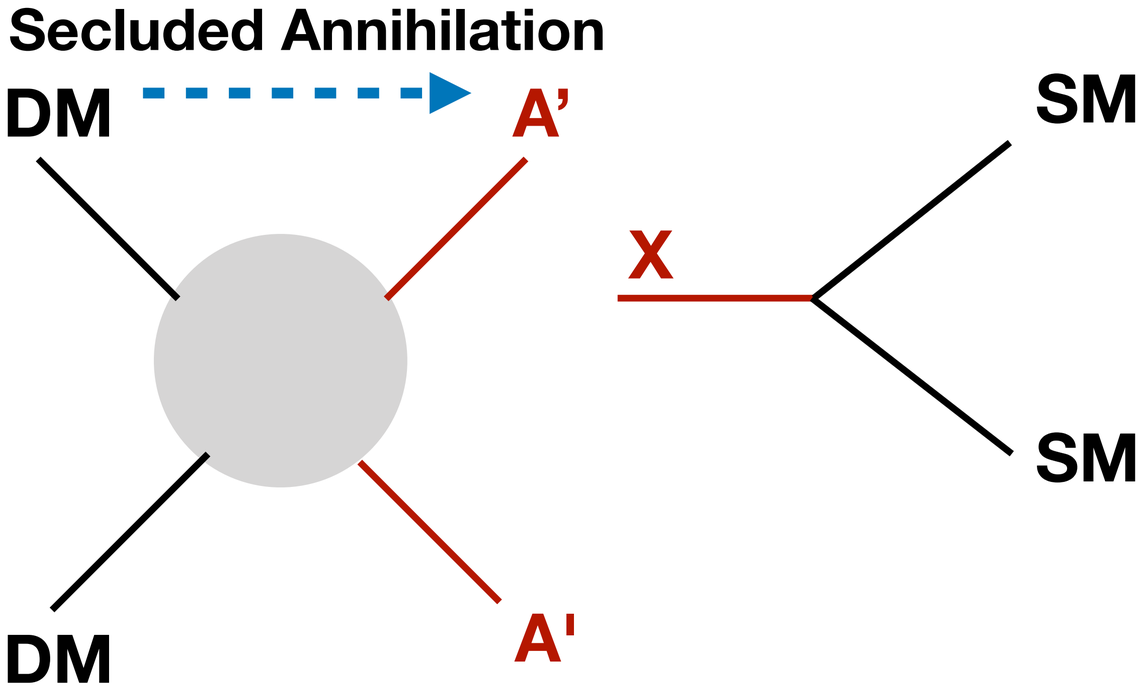




- A dark mediator with secluded annihilation
- Mass setup $m_{A'} < m_{\mathrm{DM}}$
  - The thermal cross-section: $\langle \sigma v \rangle \approx \alpha'^2 \frac{1}{m_{A'}^2}$
- Only two free parameters relevant: $m_{A'}$, ϵ
- Leading to visible A’ searches at intensity frontier

See Yongbin Feng’s talk on DarkQuest
Achim Denig’s talk on DarkMESA
Benjamin Banto Oberhauser’s talk on NA64
Jing Chen’s talk on DarkSHINE

The A' invisible benchmark at intensity frontier



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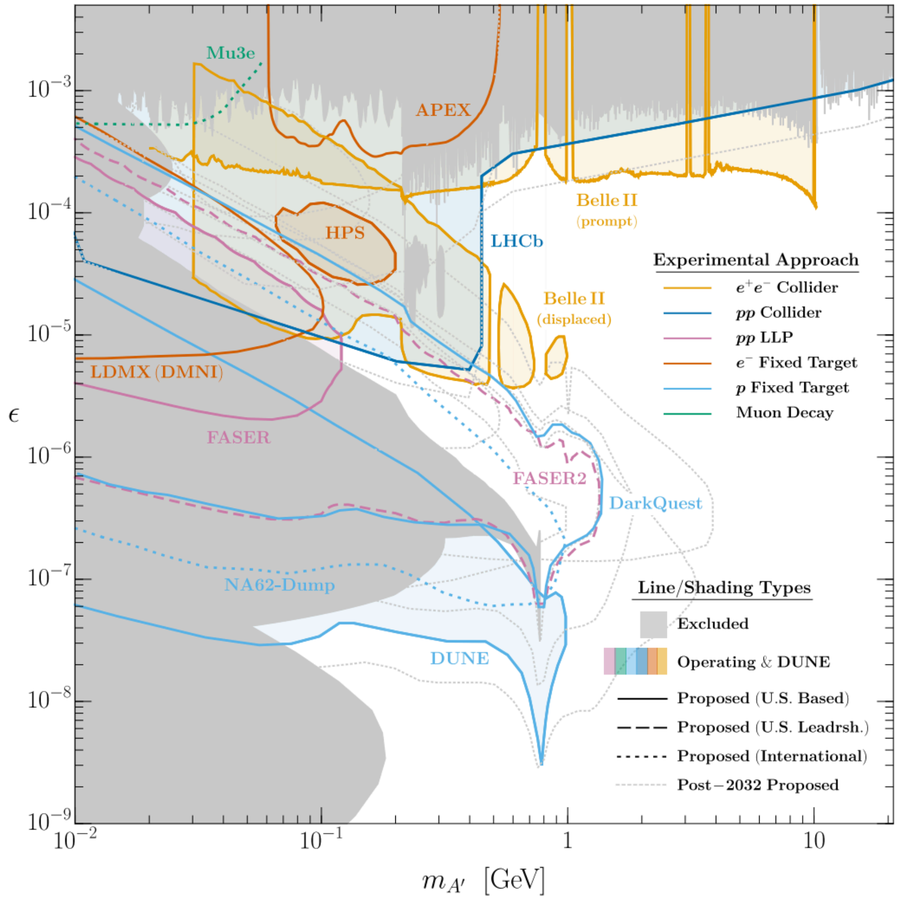

Batell, Blinov, Hearty, McGehee, 2207.06905

The Kinetic Mixing Portal

- The A' should actually kinetic mixing with Hypercharge field

$$\mathscr{L} = -\frac{1}{4}F'^{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}{}^2A'^{\mu}A'\mu - \frac{1}{2}\epsilon F'^{\mu\nu}B^{\mu\nu} + g'A'_{\mu}j^{\mu}_{D}$$

- Z gauge boson is involved (K denotes A')

$$\mathcal{L} \supset \frac{-1}{4}\begin{pmatrix} Z^{\mu\nu}_{\rm SM} & A^{\mu\nu}_{\rm SM} & K^{\mu\nu} \end{pmatrix}\begin{pmatrix} 1 & 0 & \epsilon t_W \\ 0 & 1 & -\epsilon \\ \epsilon t_W & -\epsilon & 1 \end{pmatrix}\begin{pmatrix} Z_{\mu\nu,\,\rm SM} \\ A_{\mu\nu,\,\rm SM} \\ K_{\mu\nu} \end{pmatrix}$$

$$+\frac{1}{2}\begin{pmatrix} Z^{\mu}_{\rm SM} & A^{\mu}_{\rm SM} & K^{\mu} \end{pmatrix}\begin{pmatrix} m^2_{Z,\,\rm SM} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m^2_K \end{pmatrix}\begin{pmatrix} Z_{\mu,\,\rm SM} \\ A_{\mu,\,\rm SM} \\ K_{\mu} \end{pmatrix},$$

JL, Xiao-Ping Wang, Felix Yu, 1704.00730 (JHEP)

The Kinetic Mixing Portal

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- After normalizing kinetic terms and diagonalizing 3x3 mass matrix

$$\begin{aligned}
\mathcal{L} \supset\ & gZ_{\mu,\,\mathrm{SM}}J^{\mu}_{Z} + eA_{\mu,\,\mathrm{SM}}J^{\mu}_{\mathrm{em}} + g_D K_\mu J^{\mu}_{D} \\
&= \tilde{Z}_\mu \left(gJ^{\mu}_{Z} - g_D \frac{m^2_{Z,\,\mathrm{SM}} t_W}{m^2_{Z,\,\mathrm{SM}} - m^2_K}\epsilon J^{\mu}_{D} + g\frac{m^2_{Z,\,\mathrm{SM}}(m^2_{Z,\,\mathrm{SM}} - 2m^2_K)t^2_W}{2(m^2_K - m^2_{Z,\,\mathrm{SM}})^2}\epsilon^2 J^{\mu}_{Z} - e\frac{m^2_{Z,\,\mathrm{SM}} t_W}{m^2_{Z,\,\mathrm{SM}} - m^2_K}\epsilon^2 J^{\mu}_{\mathrm{em}} \right) \\
&+ \tilde{K}_\mu \left(g_D J^{\mu}_{D} + g\frac{m^2_K t_W}{m^2_{Z,\,\mathrm{SM}} - m^2_K}\epsilon J^{\mu}_{Z} + e\epsilon J^{\mu}_{\mathrm{em}} + g_D \frac{(m^4_{Z,\,\mathrm{SM}} c^2_W - 2m^2_K m^2_{Z,\,\mathrm{SM}} + m^4_K)c^{-2}_W}{2(m^2_{Z,\,\mathrm{SM}} - m^2_K)^2}\epsilon^2 J^{\mu}_{D} \right) \\
&+ \tilde{A}_\mu e J^{\mu}_{\mathrm{em}}\,.
\end{aligned}$$

Vanish in the $m_{A'} \ll m_Z$ limit

JL, Xiao-Ping Wang, Felix Yu, 1704.00730 (JHEP)

The Kinetic Mixing Portal

- The A' should actually kinetic mixing with Hypercharge field

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- After normalizing kinetic terms and diagonalizing 3x3 mass matrix

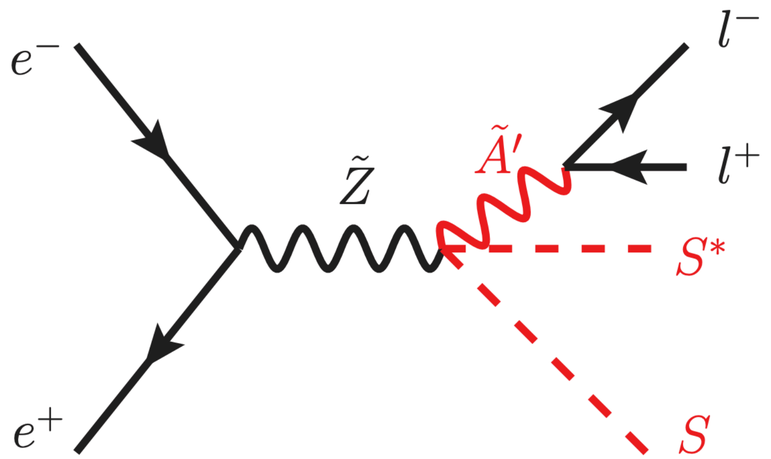
$$\mathcal{L} \supset gZ_{\mu,\,\mathrm{SM}}J_Z^{\mu} + eA_{\mu,\,\mathrm{SM}}J_{\mathrm{em}}^{\mu} + g_D K_{\mu}J_D^{\mu}$$

$$= \tilde{Z}_{\mu}\left(gJ_Z^{\mu} - g_D\frac{m_{Z,\,\mathrm{SM}}^2 t_W}{m_{Z,\,\mathrm{SM}}^2 - m_K^2}\epsilon J_D^{\mu} + g\frac{m_{Z,\,\mathrm{SM}}^2(m_{Z,\,\mathrm{SM}}^2 -\right.$$

$$+ \tilde{K}_{\mu}\left(g_D J_D^{\mu} + g\frac{m_K^2 t_W}{m_{Z,\,\mathrm{SM}}^2 - m_K^2}\epsilon J_Z^{\mu} + e\epsilon J_{\mathrm{em}}^{\mu} + g_D\frac{(m_{Z,\,\mathrm{SI}}^4\right.$$

$$+ \tilde{A}_{\mu}eJ_{\mathrm{em}}^{\mu}\,.$$

Exist but usually overlooked
Could be tested at future Z-factory (e.g. CEPC)



E.g. if dark scalar is contained in the current j_D

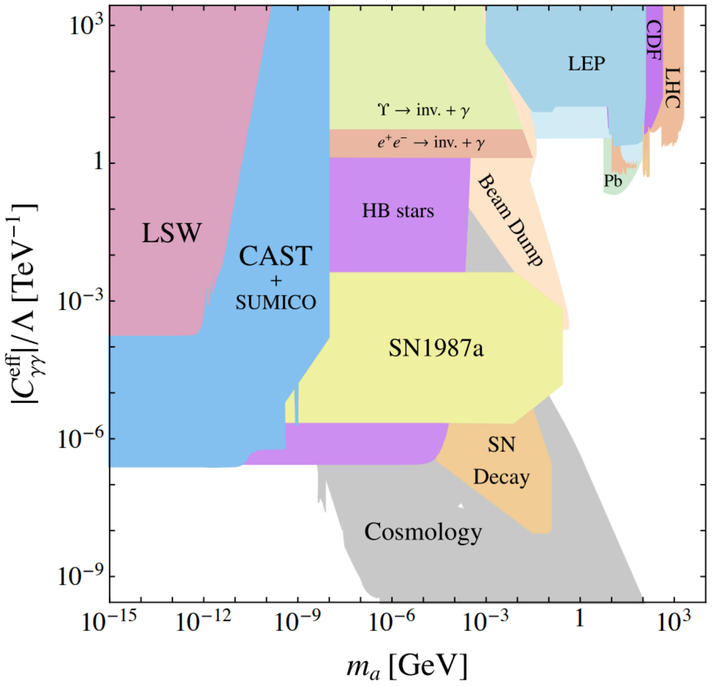
JL, Xiao-Ping Wang, Felix Yu, 1704.00730 (JHEP)

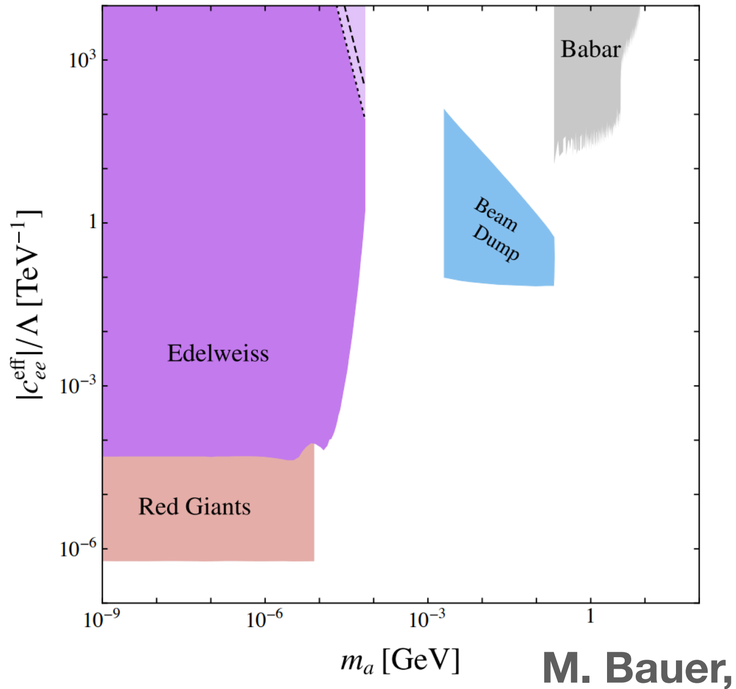
The Pseudoscalar Portal: Axion, ALP

- The general Lagrangian

$$\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + \frac{\partial^\mu a}{\Lambda}\sum_F \bar{\psi}_F \boldsymbol{C}_F \gamma_\mu \psi_F$$
$$+ g_s^2 C_{GG}\frac{a}{\Lambda}G^A_{\mu\nu}\tilde{G}^{\mu\nu,A} + g^2 C_{WW}\frac{a}{\Lambda}W^A_{\mu\nu}\tilde{W}^{\mu\nu,A} + g'^2 C_{BB}\frac{a}{\Lambda}B_{\mu\nu}\tilde{B}^{\mu\nu}$$

- Motivates searches at colliders and beam dump searches





M. Bauer, M. Neubert, A. Thamm, 1708.00443

The Pseudoscalar Portal: Axion, ALP

- A connection to muon g-2

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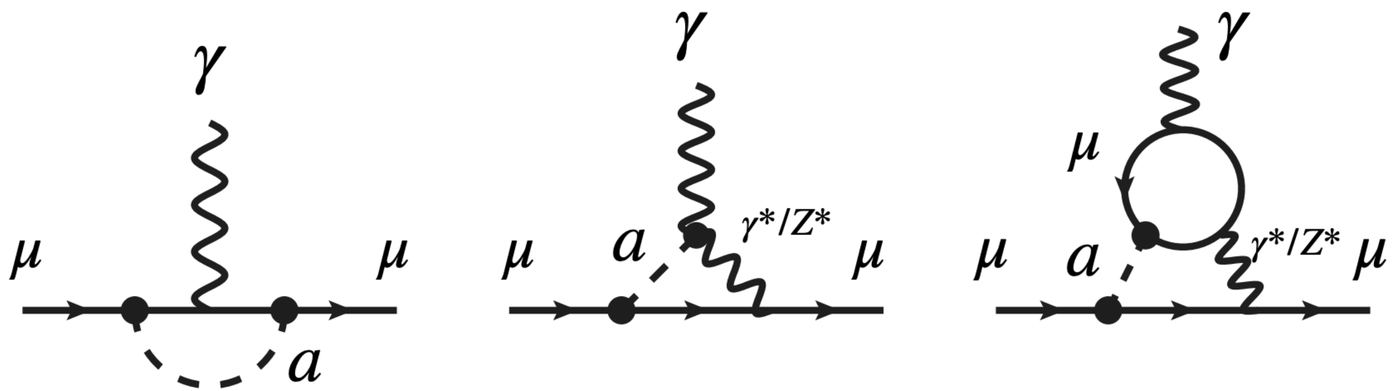
- Couplings to muon, Hypercharge field B, and SU(2) W



W.Y. Keung et al, hep-ph/0009292
W.J. Marciano et al. 1607.01022
M. Bauer, M. Neubert, A. Thamm, 1708.00443
M. A. Buen-Abad, J. Fan, M. Reece, C. Sun 2104.03267
JL, X. Ma, L.T. Wang, W.P. Wang 2210.09335 (PRD)

The Pseudoscalar Portal: Axion, ALP

- A connection to muon g-2 and future Z-factory

$$\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + \frac{\partial^\mu a}{\Lambda}\sum_F \bar{\psi}_F \boldsymbol{C}_F \gamma_\mu \psi_F$$
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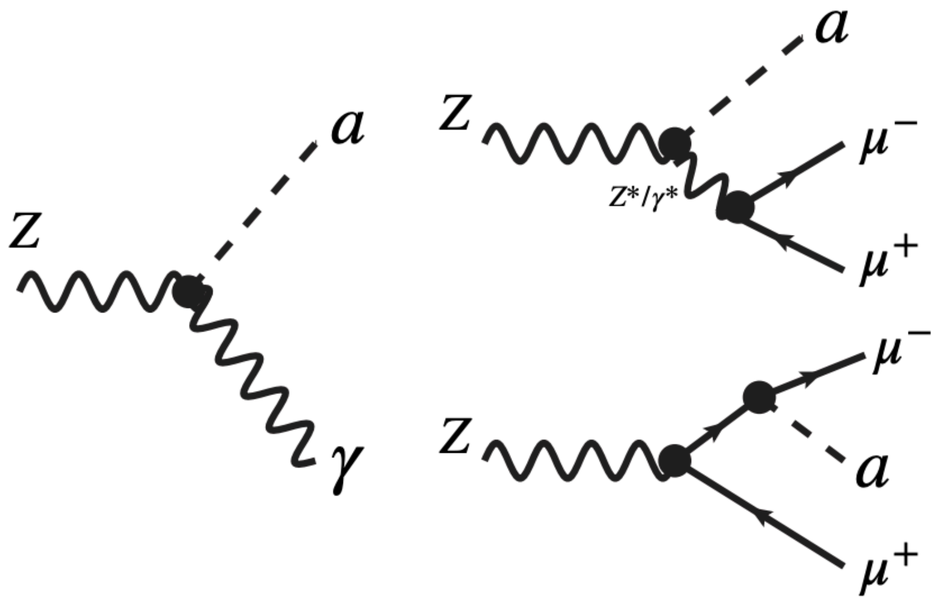
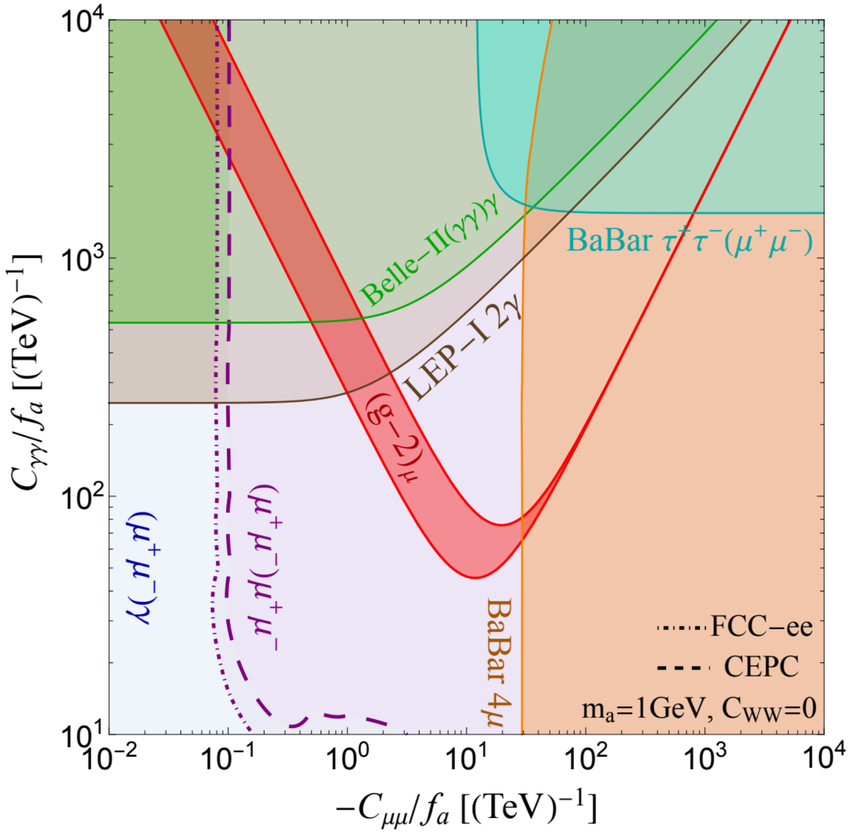
- Z exotic decays

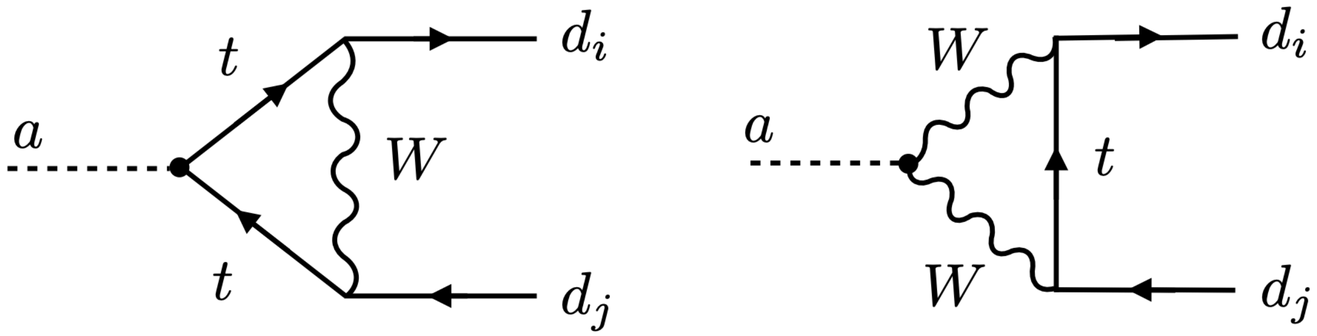




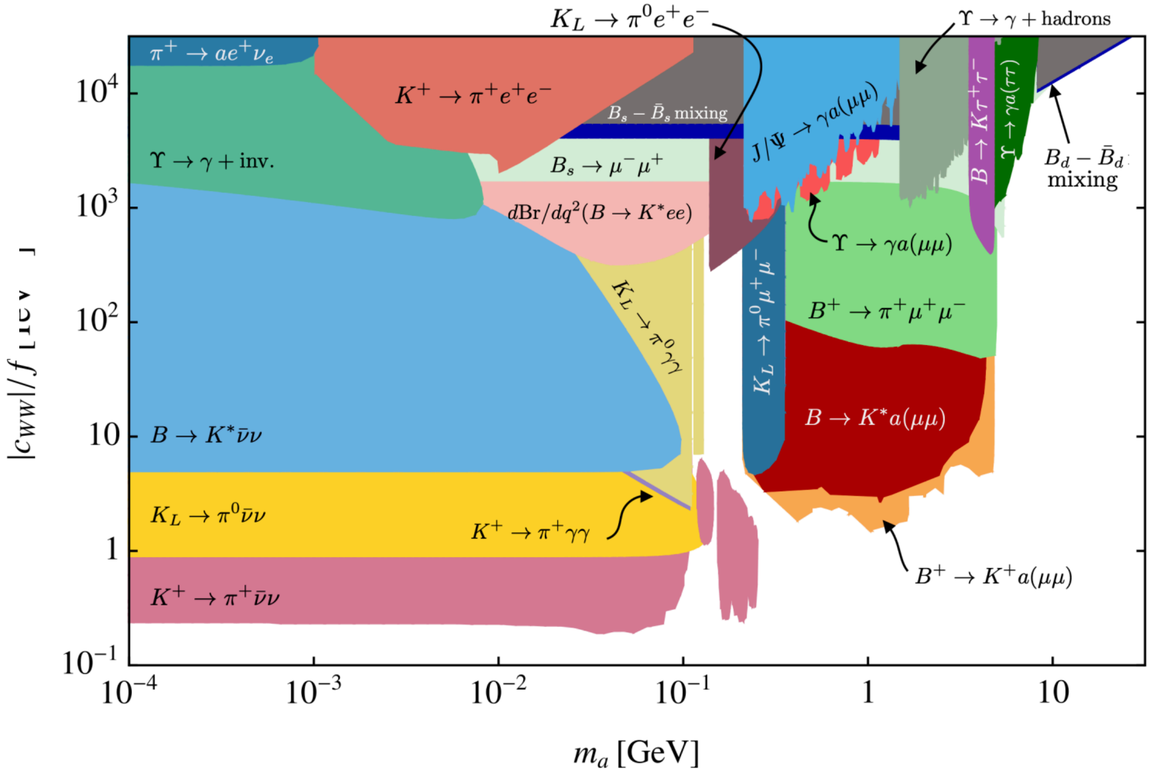
JL, X. Ma, L.T. Wang, W.P. Wang 2210.09335 (PRD)

The Pseudoscalar Portal: Axion, ALP

- The general Lagrangian (usually people consider flavor diagonal)
- However, if starting from high energy, it will end up with flavor off-diagonal interactions at low energy: $\mathbf{C}_F \to \mathbf{C}_F^{ij}$



- Providing ALP motivations to Flavor Searches at low energy, e.g. BES-III, Belle-II



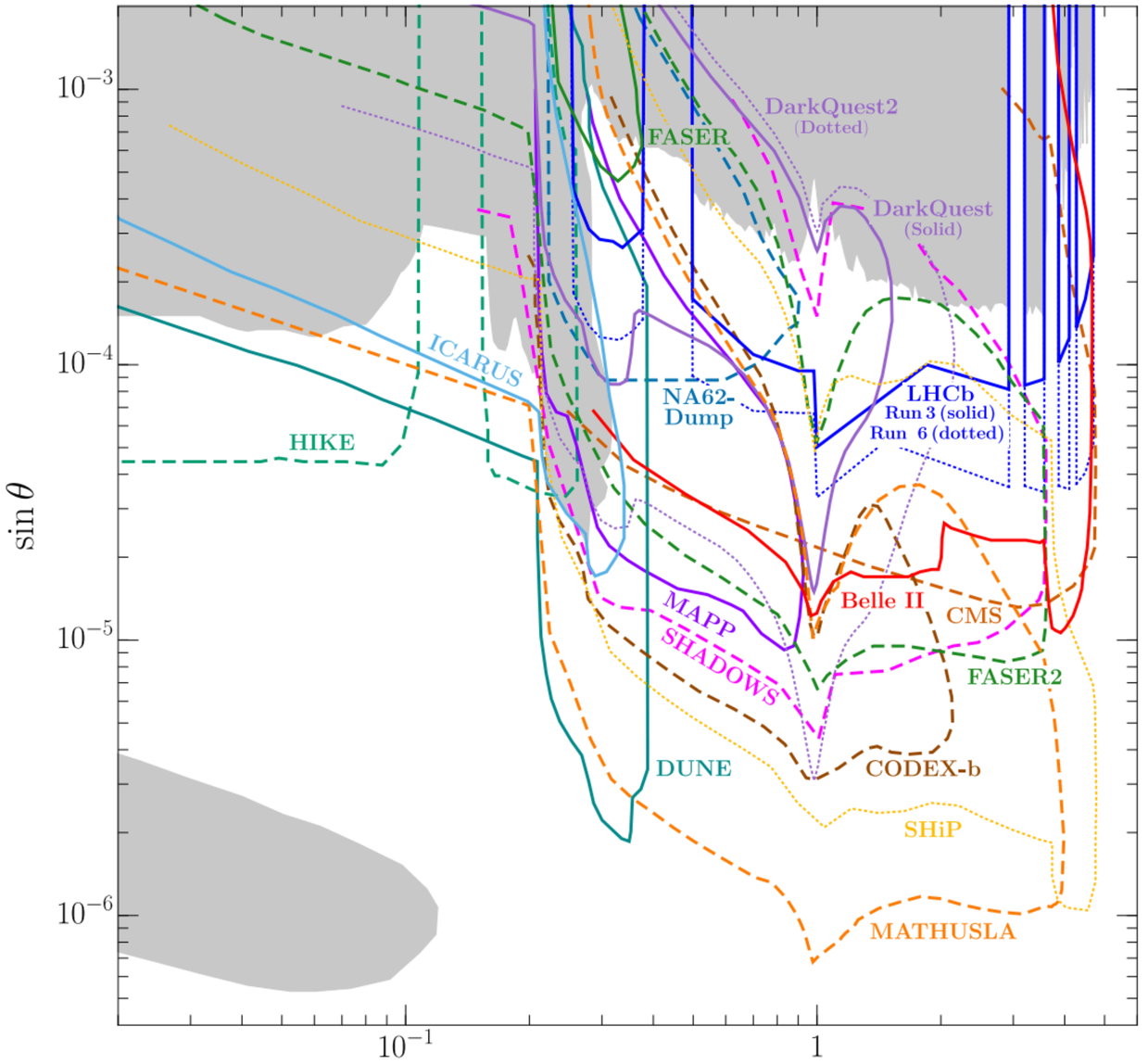
M. Bauer, M. Neubert, S. Renner, M. Schnubel, A. Thamm, 2110.10698

The Scalar Portal: SM Higgs and Singlet scalars

- The addition of a singlet scalar

$$-\mathcal{L} \supset (A\,S + \lambda\,S^2)\,H^\dagger H$$

- The addition of a singlet scalar
  - S-h mixing angle θ: $\sin\theta \dfrac{m_f}{v} S\bar{f}f$
  - Two parameters: m_S, $\sin\theta$



Batell, Blinov, Hearty, McGehee, 2207.06905

The Scalar Portal: SM Higgs and Singlet scalars

- More Baroque setup is possible
  - Different mixing angles to different fermions $\epsilon_q \approx \epsilon_W$

$$\mathcal{L}_{\text{eff}} \supset \sum_q \epsilon_q \frac{m_q}{v} \phi \bar{q} q + \sum_\ell \epsilon_\ell \frac{m_\ell}{v} \phi \bar{\ell} \ell + \epsilon_W \frac{2m_W^2}{v} \phi W_\mu^+ W^{\mu-}.$$

Type-X 2HDM + Singlet

$$\mathcal{L}_{\text{yuk}} = -\lambda_u \bar{Q} \tilde{\Phi}_2 u_R - \lambda_d \bar{Q} \Phi_2 d_R - \lambda_e \bar{L} \Phi_1 e_R + h.c.\,,$$

$$\begin{pmatrix} \sqrt{2}\text{Re}\left[\Phi_1^0\right] \\ \sqrt{2}\text{Re}\left[\Phi_2^0\right] \\ \phi_0 \end{pmatrix} \simeq \begin{pmatrix} \cos\alpha & -\sin\alpha & \sin\theta_{1\phi} \\ \sin\alpha & \cos\alpha & \sin\theta_{2\phi} \\ -\sin\theta_{1\phi} & -\sin\theta_{2\phi} & 1 \end{pmatrix} \cdot \begin{pmatrix} H \\ h \\ \phi \end{pmatrix}$$

$$\epsilon_q \simeq \frac{\sin\theta_{2\phi}}{\sin\beta}, \quad \epsilon_\ell \simeq \frac{\sin\theta_{1\phi}}{\cos\beta}.$$

$$\epsilon_W \simeq (\sin\theta_{1\phi}\cos\beta + \sin\theta_{2\phi}\sin\beta)$$

$$\approx \epsilon_\ell \cos^2\beta + \epsilon_q \sin^2\beta \approx \epsilon_q,$$

JL, N. McGinnis, C.E.M. Wagner, X.P. Wang, 2001.06522 (JHEP)

The Scalar Portal: SM Higgs and Singlet scalars

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    $\epsilon_q \approx \epsilon_W$

$$\mathcal{L}_{\rm eff} \supset \sum_q \epsilon_q \frac{m_q}{v}\phi\bar{q}q + \sum_\ell \epsilon_\ell \frac{m_\ell}{v}\phi\bar{\ell}\ell + \epsilon_W \frac{2m_W^2}{v}\phi W_\mu^+ W^{\mu-}.$$

- Coupling to specific flavor

$$\mathcal{L} \supset -g_u S\bar{u}u - g_\chi S\overline{\chi}\chi,$$

UV completed by Vector-like Fermions

$$\mathcal{L}_{\rm VLQ} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu S\partial^\mu S - \frac{1}{2}m_S^2 S^2 + \overline{U}' i\gamma^\mu D_\mu U' - M\,\overline{U}'U'$$
$$- \left[y_i\,\overline{Q}_L^i U'_R\,H_c + \lambda^i\,\overline{U}'_L u_{Ri}\,S + \text{h.c.}\right]$$

$$\longrightarrow \quad \mathcal{L} \supset \frac{y_i\,\lambda^j}{M} S\,\overline{Q}_L^i\,u_{Rj}\,H_c + \text{h.c.}$$

Batell et al, 2107.08059

Type-X 2HDM + Singlet

$$\mathcal{L}_{\rm yuk} = -\lambda_u \bar{Q}\tilde{\Phi}_2 u_R - \lambda_d \bar{Q}\Phi_2 d_R - \lambda_e \bar{L}\Phi_1 e_R + h.c.\,,$$

$$\begin{pmatrix} \sqrt{2}\text{Re}\left[\Phi_1^0\right] \\ \sqrt{2}\text{Re}\left[\Phi_2^0\right] \\ \phi_0 \end{pmatrix} \simeq \begin{pmatrix} \cos\alpha & -\sin\alpha & \sin\theta_{1\phi} \\ \sin\alpha & \cos\alpha & \sin\theta_{2\phi} \\ -\sin\theta_{1\phi} & -\sin\theta_{2\phi} & 1 \end{pmatrix} \cdot \begin{pmatrix} H \\ h \\ \phi \end{pmatrix}$$

$$\epsilon_q \simeq \frac{\sin\theta_{2\phi}}{\sin\beta}, \qquad \epsilon_\ell \simeq \frac{\sin\theta_{1\phi}}{\cos\beta}.$$

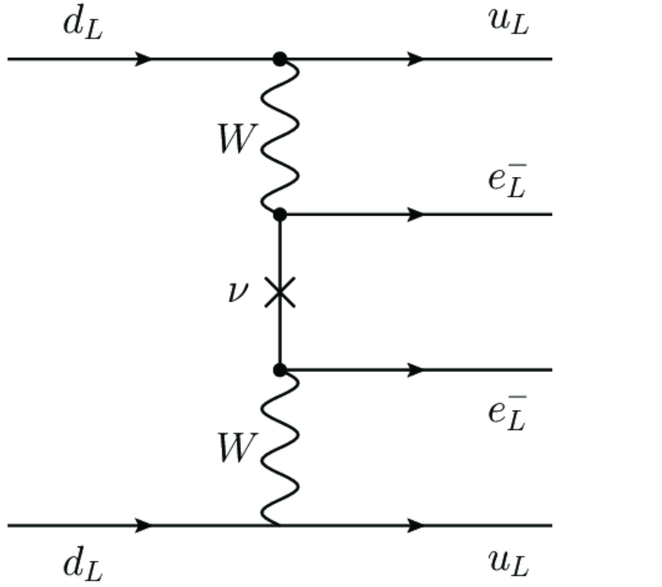
$$\epsilon_W \simeq (\sin\theta_{1\phi}\cos\beta + \sin\theta_{2\phi}\sin\beta)$$
$$\approx \epsilon_\ell \cos^2\beta + \epsilon_q \sin^2\beta \approx \epsilon_q,$$

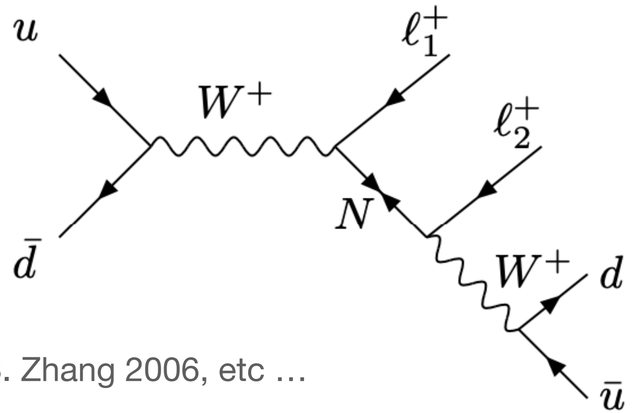
The Fermion Portal: Gauge singlets

- Sterile neutrino N/ν_s

$$\mathscr{L} \supset y(LH) \cdot N + m_D N \cdot N$$

- Lepton number violation via Majorana neutrino
  - Same sign lepton searches
  - 0νββ
  - Coherent production (on-shell)
  - Exotic meson/tau decays
    - $M^+ \to \ell^+ \ell'^+ M'^-$
  - Displaced searches for N (ν_s)





T. Han, B. Zhang 2006, etc …

Helo, Hirsch, Kovalenko 2013; A. Maiezza, Nemevsek, Nesti 2015 … etc

The Fermion Portal: Gauge non-singlets

Y. Bai, J. Berger [1402.6696, JHEP]

- The new vector-like fermion + Scalar

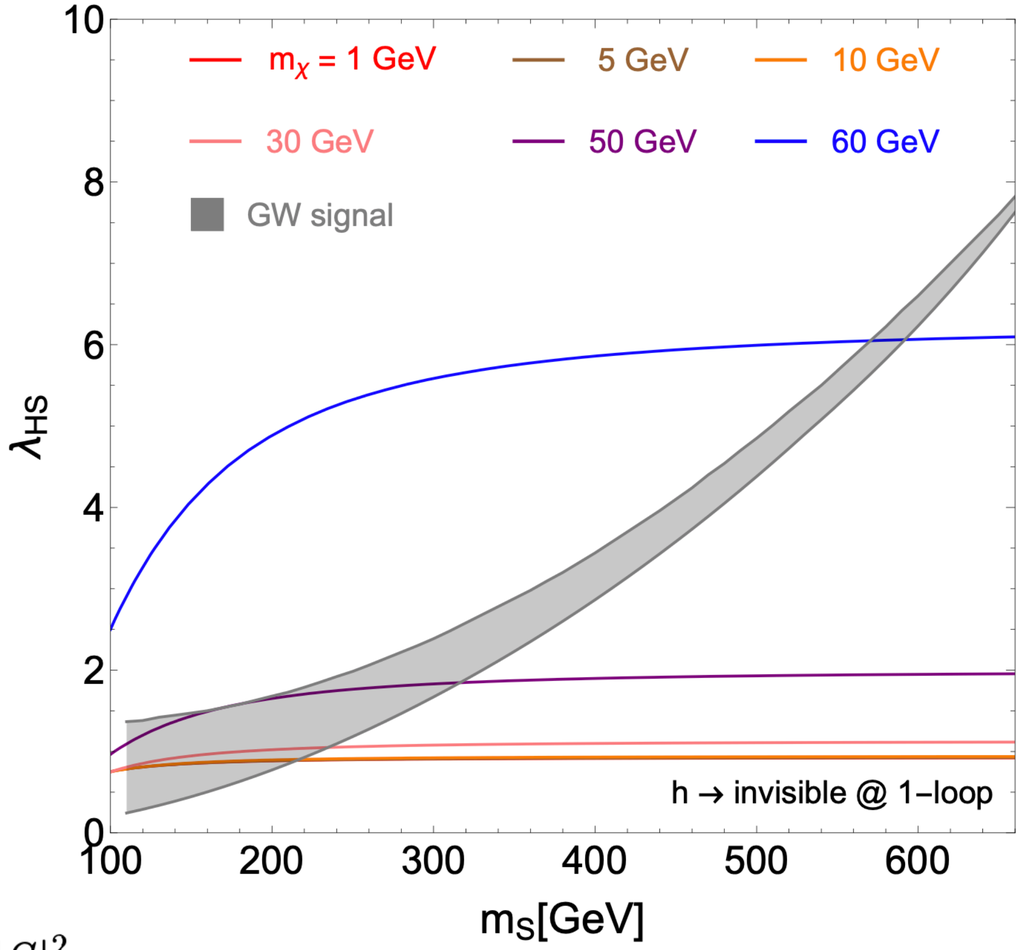
$$\mathscr{L} = y\left(\bar{f}_R \psi_L\right)\Phi + h\,.\,c\,.$$

- With Z_2 symmetry assigned to ψ/Φ, the lighter one can be DM
- The lepton portal example:
  $\mathscr{L} = y_\ell(\ell_R \cdot \chi)S^* + h\,.\,c\,.$
- The scalar S looks like slepton, can induce first order phase transition

$$\mathcal{L}_\chi = y_\ell \bar{\chi}_L S^\dagger \ell_R + \text{h.c.},$$

$$\mathcal{L}_S = (D^\mu S)^\dagger D_\mu S - V(H,S),$$

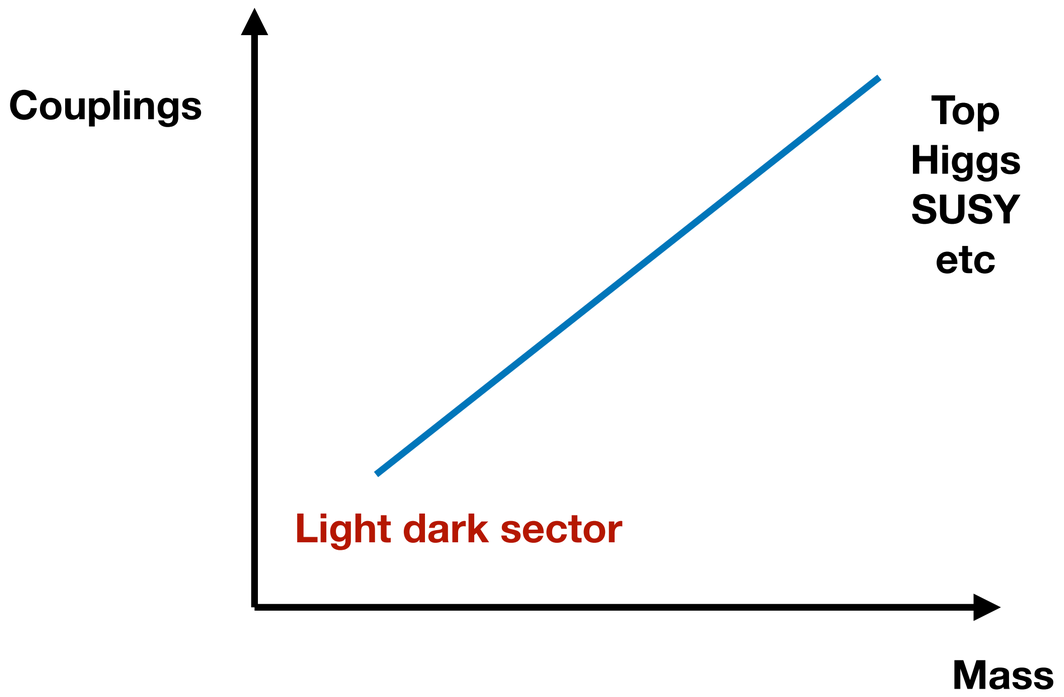
$$V(H,S) = \mu_H^2|H|^2 + \mu_S^2|S|^2 + \lambda_H|H|^4 + \lambda_S|S|^4 + 2\lambda_{HS}|H|^2|S|^2$$



JL, X.P. Wang, K.P. Xie, 2104.06421

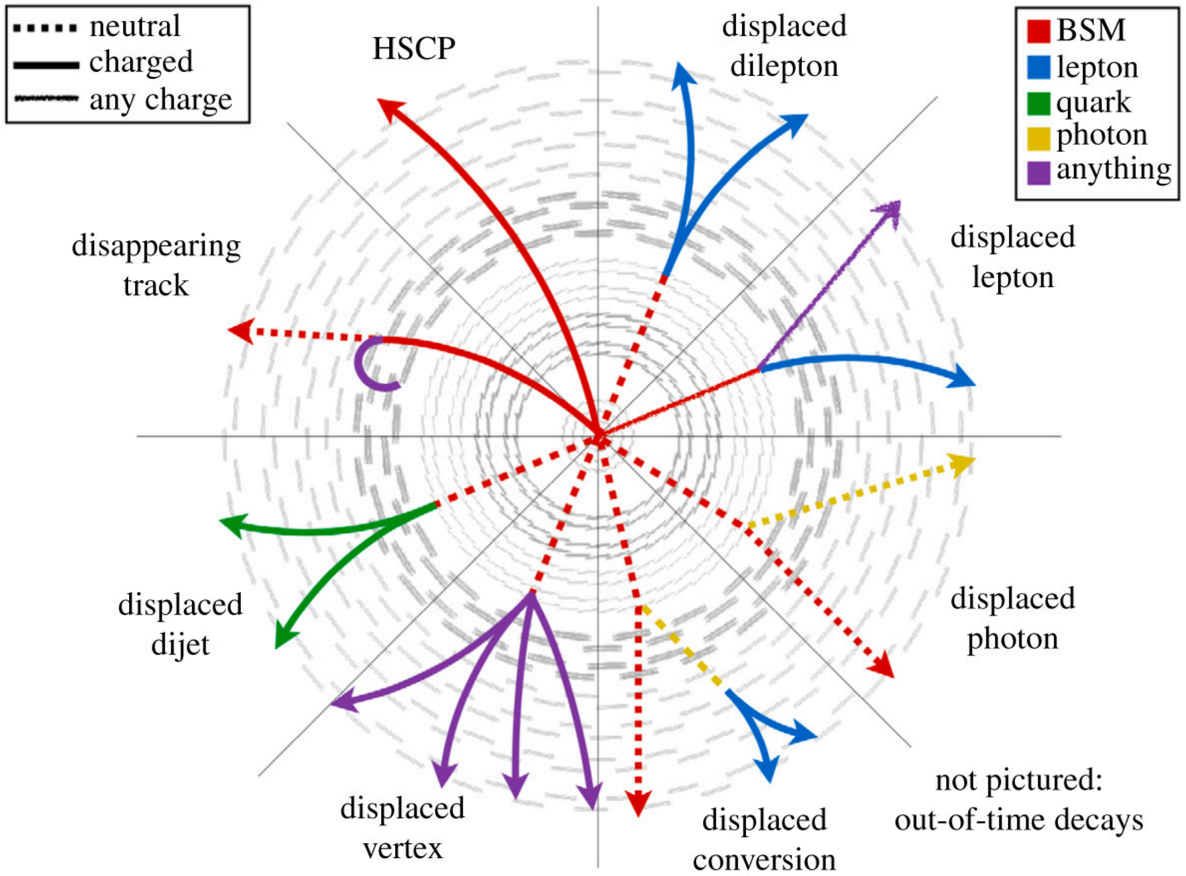
Exotic features: Long-Lived Particles

- Why being long-lived?
  - Feeble couplings:
    Dark sector models, R-parity violating Supersymmetry, sterile neutrinos
  - Suppression from heavy mass scale:
    muon/charged pion, gauge mediated spontaneous breaking Supersymmetry
  - Near degenerate state:
    higgsino-like chargino/neutralino, or anomaly-mediated spontaneous breaking Supersymmetry
  - Approximate symmetry:
    K_L to three pions (accidental PS suppression)

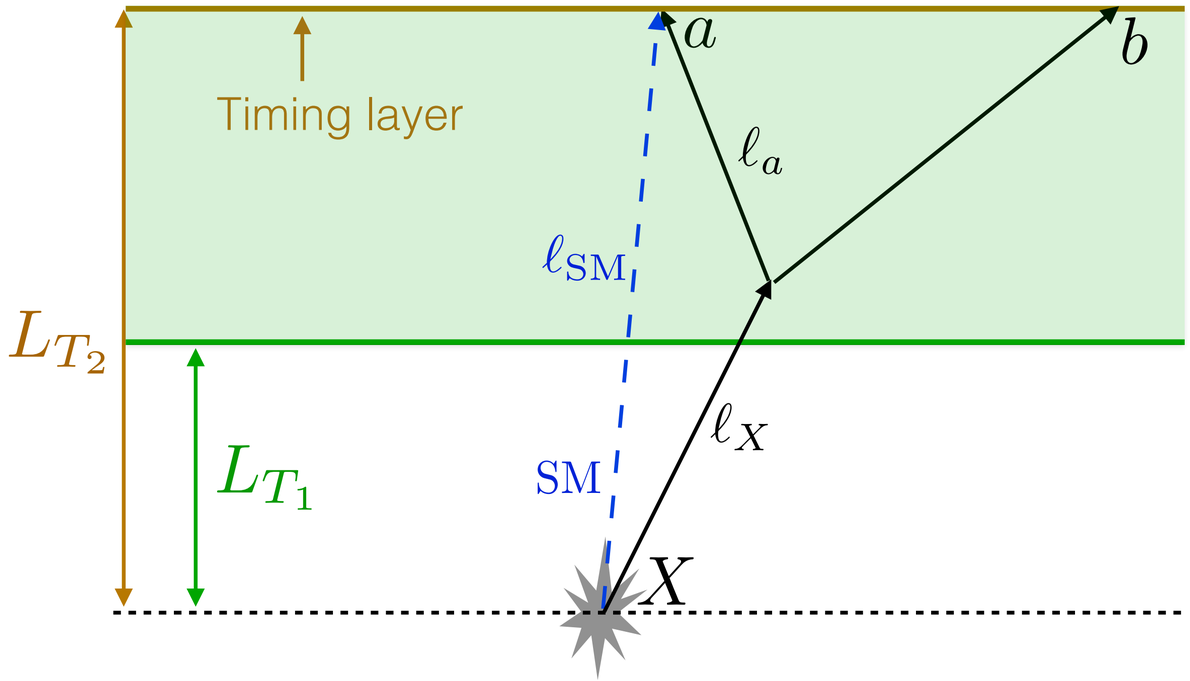


Exotic features: Long-Lived Particles

- Displacement as the feature



- Time-delay as the feature



Z. Liu, JL, L.T. Wang, PRL 122 (2019) 131801

Exotic features: time-varying particles

- Time-varying fundamental constants at AMO (e.g. electron mass/ fine structure constant)
- High physics energy scale (environmental effect)
  - Time-varying neutrino parameters
    - Dark MSW effect for neutrino oscillations

$$\mathcal{L}_{\text{scalar}} = \bar{\nu}_L^\alpha i\gamma^\mu \partial_\mu \nu_L^\alpha - \frac{1}{2} m_\nu^{\alpha\beta} \overline{(\nu_L^c)^\alpha} \nu_L^\beta - \frac{1}{2} y^{\alpha\beta} \phi \, \overline{(\nu_L^c)^\alpha} \nu_L^\beta$$

$$\mathcal{L}_{vector} = \bar{\nu}_L^\alpha i\gamma^\mu \partial_\mu \nu_L^\alpha - \frac{1}{2} m_\nu^{\alpha\beta} \overline{(\nu_L^c)^\alpha} \nu_L^\beta + g Q^{\alpha\beta} \phi^\mu \bar{\nu}_L^\alpha \gamma_\mu \nu_L^\beta$$

A. Berlin, 1608.01307
Krnjaic, Machado, Necib, 1705.06740
V. Brdar, J. Kopp, **JL**, P. Prass, X.P. Wang, 1705.09455

  - Time-varying mass at collider and beam dump

Time-varying particle mass at collider and beam dump

- Time-varying particle mass at collider and beam dump
  - UV Model: ultralight complex scalar DM charged under U(1)'
    - Massive A' has kinetic mixing with SM

$$\left(D_\mu\phi\right)^* D^\mu\phi \supset \left(g'Q_\phi\right)^2 \phi^*\phi A'_\mu A'^\mu \qquad \mathscr{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_0^2 A'_\mu A'^\mu + \epsilon e A'_\mu J^\mu_{\rm em}$$

- Ultralight ϕ DM obtain relic abundance via misalignment

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2\phi = 0 \quad \longrightarrow \quad \text{today}: \phi(t) \approx \phi_1\cos(m_\phi t) + \phi_2\sin(m_\phi t)$$

- The A' leads to time-varying invariant mass spectrum

$$m_{A'}^2(t) = \tilde{m}_0^2\left(1 + \kappa\cos^2\left(m_\phi t\right)\right)$$

Base value m_0 $\quad \tilde{m}_0^2 = m_0^2 + \left(g'Q_\phi\right)^2\left(\phi_1^*\phi_1 + \phi_2^*\phi_2 - \sqrt{\xi^2 + \eta^2}\right)$

Oscillation amplitude κ $\quad \kappa \equiv 2(g'Q_\phi)^2\sqrt{\xi^2+\eta^2}/\tilde{m}_0^2,$

Guo, He, JL, Wang, Xie, 2206.14221 (Comm. Phys.)

Summary

- There are extremely rich physics for exotic particles in BSM
- Exotic particles from various portal models
  - Vector, pseudo scalar, scalar, fermion portals
- Exotic particle physics
  - Long-Lived Particles
  - Time-varying particle parameters: mass, interaction strength etc…
- A joint search program from intensity/energy/cosmic frontiers is necessary to hunt for exotic particles.

Thank you!

Backup slides