Dark Matter and Flavor Violation

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Based on work done with
Jinrui Huang (Los Alamos) and Volodymyr Takhistov (→ UCLA)
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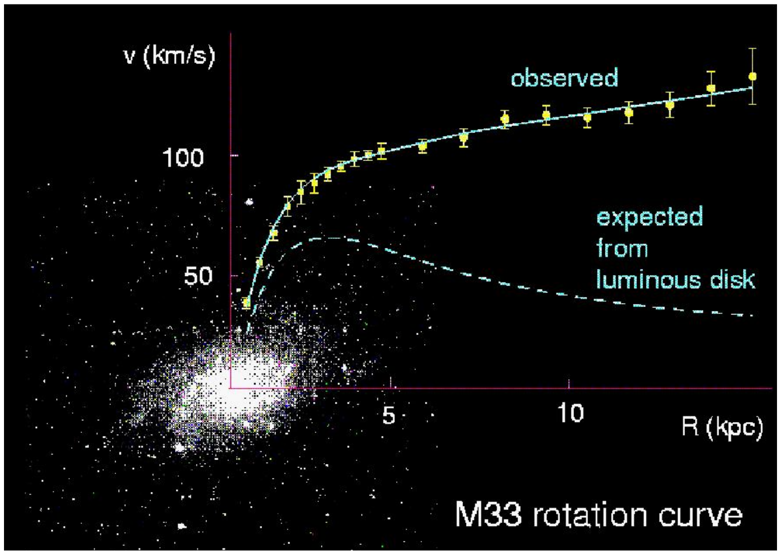
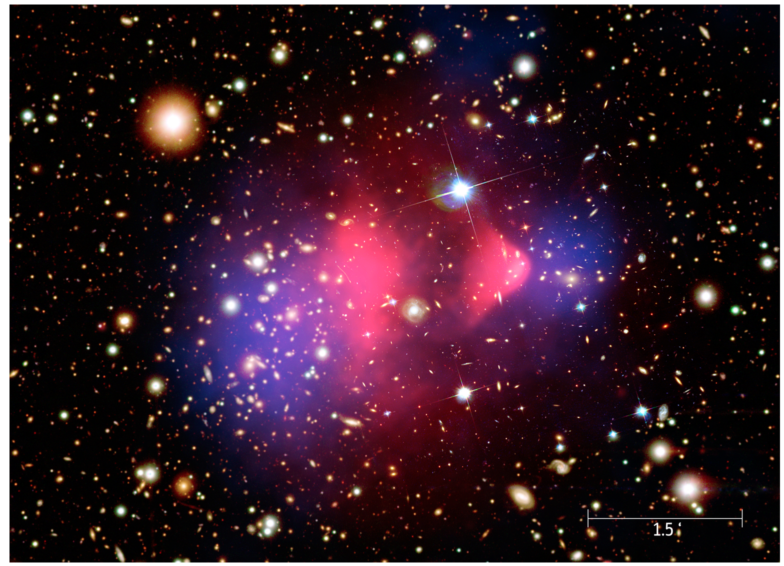
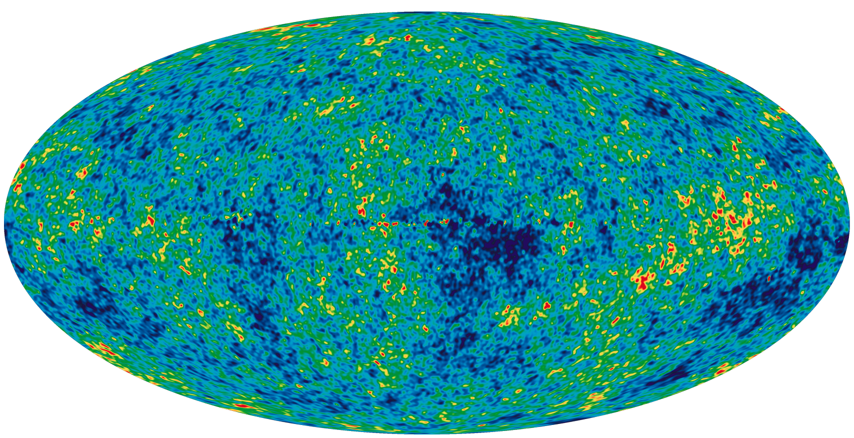
Dark Matter Evidence







Identity of dark matter?
What is its mass?
Possible interactions?

Flavored Dark Matter

- Dark matter come in multiple copies
- Non-trivial flavor structure in couplings to quarks and leptons
  - distinct signatures
- FCNC constraints
  - universal couplings
  - minimal flavor violation   Batell, Pradler, Spannowsky (2011)
  - beyond MFV: “dark minimal flavor violation”   Agrawal, Blanke, Gemmler (2014)
    - dark matter coupling: only new source of flavor violation
    - implemented in quark sector
    - lepton sector unexplored ⇒ this work

Minimal Flavor Violation with SM gauge group

$$G_F \equiv G_{QF} \times G_{LF}$$

$$G_{QF} \equiv SU(3)_Q \times SU(3)_u \times SU(3)_d$$

D'Ambrosio, Giudice, Isidori, Strumia (2002);
Bobeth, Ewerth, Krüger, Urban (2002)

$$G_{LF} \equiv SU(3)_L \times SU(3)_E \quad [m_\nu = 0]$$

Cirigliano, Grinstein, Isidori, Wise (2005)

lepton sector : complication from ν mass generation

* minimal particle content : G_{LF}
* extended particle content (N) : $G_{LF} \times SU(3)_N$

⇒ different spurion combinations

⇒ diff. implications for LFV

For simplicity : $m_\nu = 0$

Beyond Minimal Flavor Violation

Quark Flavored DM: $G_{QF} \times SU(3)_\chi$ Agrawal, Blanke, Gemmler (2014)

DM: Dirac fermion $\chi \sim 3$ of $SU(3)_\chi$

mediator: scalar $\phi \sim 1$ of $SU(3)_\chi$

coupling: $\lambda \bar{d}_R \chi \phi$, $\lambda \sim (3, \bar{3})$ of $SU(3)_d \times SU(3)_\chi$

constraints: meson-antimeson mixing, K, B decays, ...

Lepton Flavored DM: $G_{LF} \times SU(3)_\chi$ MCC, Huang, Takhistov (2015)

DM: Dirac fermion $\chi \sim 3$ of $SU(3)_\chi$

mediator: scalar $\phi \sim 1$ of $SU(3)_\chi$

coupling: $\lambda \bar{e}_R \chi \phi$, $\lambda \sim (3, \bar{3})$ of $SU(3)_E \times SU(3)_\chi$

constraints: cLFV processes ($\mu \to e\gamma$, ...)

The Model - Particle Content

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(3)_Q$	$SU(3)_U$	$SU(3)_D$	$SU(3)_L$	$SU(3)_E$	$SU(3)_\chi$
Q_L	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
u_R	$\mathbf{3}$	$\mathbf{1}$	$2/3$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
d_R	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
L_L	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$
e_R	$\mathbf{1}$	$\mathbf{1}$	-1	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$
H	$\mathbf{1}$	$\mathbf{2}$	$1/2$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
ϕ	$\mathbf{1}$	$\mathbf{1}$	-1	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
χ	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$
Y_U	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
Y_D	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
Y_E	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\overline{\mathbf{3}}$	$\mathbf{1}$
λ	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\overline{\mathbf{3}}$

The Model - Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\chi}\not{\partial}\chi - m_\chi \bar{\chi}\chi$$

$$- \left(\lambda_{ij} \bar{e}_{R_i} \chi_j \phi + h.c. \right)$$

$$+ (D_\mu \phi)^\dagger (D^\mu \phi) - m_\phi^2 \phi^\dagger \phi$$

$$+ \lambda_{H\phi} (\phi^\dagger \phi)(H^\dagger H) + \lambda_{\phi\phi} (\phi^\dagger \phi)^2$$

flavor violating interactions

Dark Matter Stability

$$\mathcal{O}_{DM} \sim \chi \cdots \bar{\chi} \cdots \phi \cdots \phi^\dagger \cdots L \cdots \bar{L} \cdots e_R \cdots \bar{e}_R$$
$$\cdots Y_E \cdots Y_E^\dagger \cdots \lambda \cdots \lambda^\dagger \cdots G$$

↳ $SU(3)_c$ inv rendering $\mathcal{O}_{DM}$ inv. under G_{EW}

Inv. under flavor $SU(3)$:

$$n_3 - n_{\bar{3}} = 0 \mod 3$$

$$SU(3)_L: \quad N_L - N_{\bar{L}} + N_{Y_E} - N_{Y_E^\dagger} = 0 \mod 3$$

$$SU(3)_E: \quad N_E - N_{\bar{E}} - N_{Y_E} + N_{Y_E^\dagger} + N_\lambda - N_{\lambda^\dagger} = 0 \mod 3$$

$$SU(3)_\chi: \quad N_\chi - N_{\bar{\chi}} + N_\lambda - N_{\lambda^\dagger} = 0 \mod 3$$

$$\Rightarrow \quad N_\chi - N_{\bar{\chi}} + N_L - N_{\bar{L}} + N_E - N_{\bar{E}} = 0 \mod 3$$

Dark Matter Stability

O_{decay} : $N_\chi = 1$, $N_{\bar{\chi}} = N_\phi = N_{\phi^\dagger} = 0$

$\Rightarrow$ $1 + N_L - N_{\bar{L}} + N_E - N_{\bar{E}} = 0 \mod 3$

can still be satisfied. $\Rightarrow$ DM Stability: need additional symm.

e.g. Z_2: ϕ, χ $-$

SM $+$

Cf. Quark flavored DM : Batell, Pradler, Spannowsky (2011); Agrawal, Blanke, Gemmler (2014)

inv. under QCD & G_{QF} & $SU(3)_\chi$

$\Rightarrow$ $N_\chi - N_{\bar{\chi}} - N_\phi - N_{\phi^\dagger} = 0 \mod 3$

For O_{decay} : $1 \neq 0 \mod 3$

$\Rightarrow$ automatic Z_3 stabilizing symmetry

- argument works for both MFV and BMFV

Model Assumptions

MFV limit:

(i) $SU(3)_\chi \equiv SU(3)_E$: $\lambda_{ij} = (\alpha \mathbb{1} + \beta [Y_E^\dagger Y_E])_{ij}$

$m_{ij} = (m_\chi \mathbb{1} + \Delta_m [Y_E^\dagger Y_E])_{ij}$

(ii) $SU(3)_\chi = SU(3)_L$: $\lambda_{ij} = (Y_E)_{ij}$

$m_{ij} = (m_\chi \mathbb{1} + \Delta_m [Y_E^\dagger Y_E])_{ij}$

BMFV

λ_{ij} : unrestricted

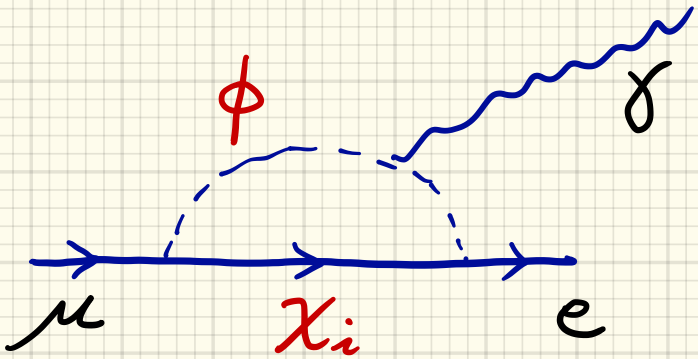
$m_{ij} = (m_\chi \mathbb{1} + \Delta_m [\lambda^\dagger \lambda])_{ij}$

RG induced mass splitting: $\Delta_m \sim \frac{1}{16\pi^2} \ln\left(\frac{m_\chi^2}{\Lambda^2}\right)$, Λ: $SU(3)_\chi$ breaking scale

assume near degenerate $m_{\chi_a} \simeq m_\chi$, $a = 1, 2, 3$

$m_\phi > m_\chi$ w/ $\phi \to \chi \bar{e}_R$ (100%)

Constraints: cLFV



Current exp limit:

$$Br(\mu \to e\gamma) < 5.7 \times 10^{-13}$$

(MEG @ PSI, 90% CL)

$$Br(\mu \to e\gamma) \propto \frac{1}{G_F^2 m_\phi^4} \left[\sum_{i=1}^{3} (\lambda_{1i}^* \lambda_{2i}) \, F\left(\frac{m_{\chi_i}^2}{m_\phi^2}\right) \right]^2$$

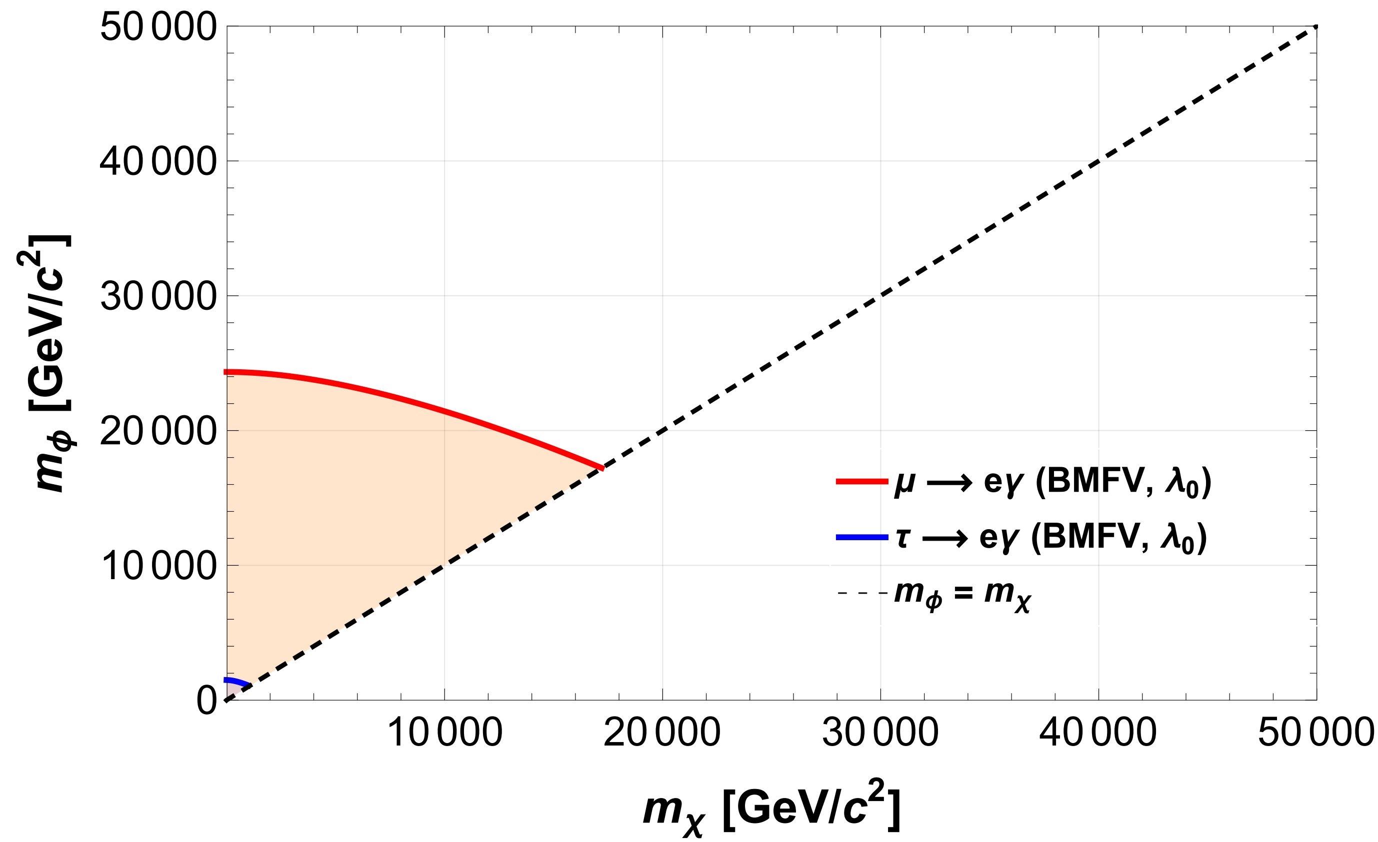
$$\chi = (\chi_1, \chi_2, \chi_3)$$

$$F(x) \sim (1 - 6x + \cdots)(1 - x)^{-4}$$

Constraints: cLFV

“democratic” coupling matrix:

$$\lambda_0 = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

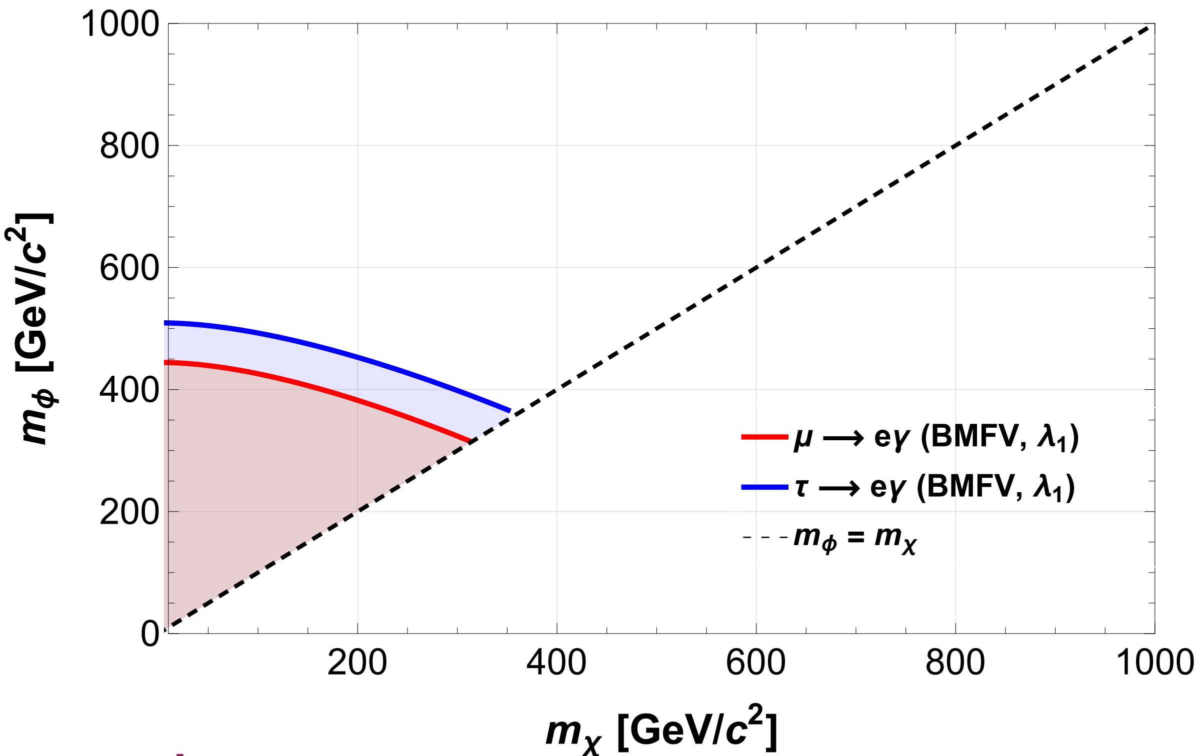


Rather tightly constrained

Constraints: cLFV

Special form of coupling matrix:

$$\lambda_1 = \begin{pmatrix} 1 & 0 & 10^{-\frac{3}{2}} \\ 0 & 1 & 10^{-\frac{3}{2}} \\ 10^{-\frac{1}{2}} & 10^{-\frac{1}{2}} & 1 \end{pmatrix}$$



Constraints can be loosened

O(1) off diagonal couplings possible, e.g.

$$\lambda_2 = \begin{pmatrix} 0 & 1 & 10^{-\frac{3}{2}} \\ 1 & 0 & 10^{-\frac{3}{2}} \\ 10^{-\frac{1}{2}} & 10^{-\frac{1}{2}} & 0 \end{pmatrix}$$

Constraints: Muon (g-2)

$$a_\mu^{\rm exp} \equiv \frac{g_\mu - 2}{2} \equiv \frac{\mu_\mu}{(e\hbar/2m_\mu)} - 1 = (11659208.9 \pm 6.3) \times 10^{-10}$$

$$a_\mu^{\rm SM} = (11659182.8 \pm 4.9) \times 10^{-10}$$

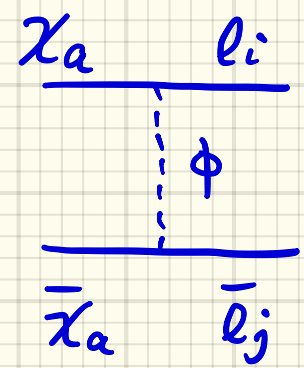
$$a_\mu^{\rm diff} = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (26.1 \pm 8.0) \times 10^{-10}$$

BMFV:

$$\delta a_\mu = -\frac{m_\mu^2}{192\pi^2 m_\phi^2}\Big[\sum_{i=1}^{3}(\lambda_{2i}^*\lambda_{2i})\Big]F_1(x)$$

contributions < 0 ⇒ increase the discrepancy

Constraints: Relic Abundance



multiple DM species w/ distinc masses:

self-annihilation $\chi_a \bar{\chi}_a \to l_i \bar{l}_j$

$$\langle \sigma v \rangle_{\chi_a \bar{\chi}_a} \sim \lambda_{ia}^* \lambda_{ja} \lambda_{ia} \lambda_{ja}^* \frac{m_{\chi_a}^2}{(m_{\chi_a}^2 + m_\phi^2)^2}$$

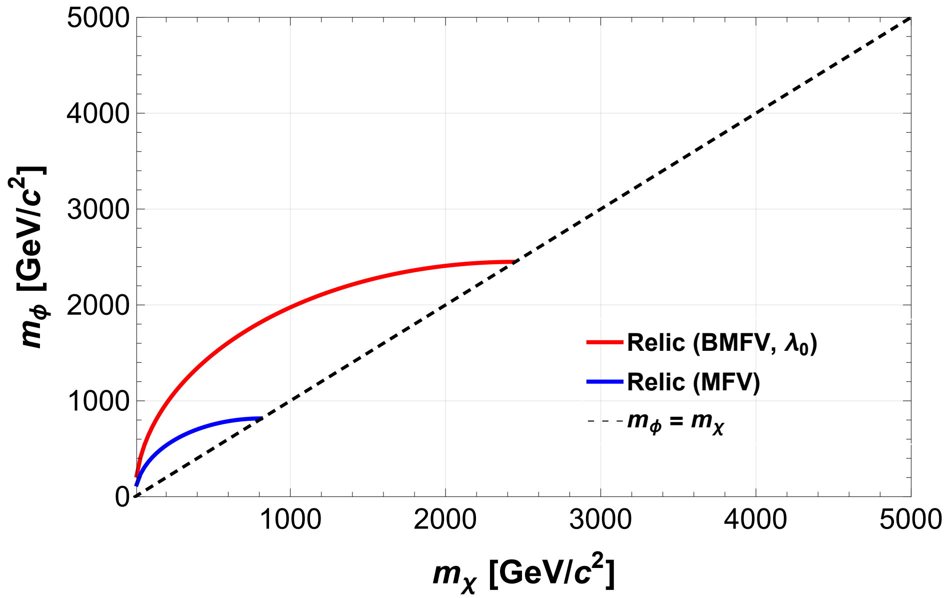
Highly degenerate DM species: $m_{\chi_a} \simeq m_{\chi_b} \simeq m_{\chi_c}$

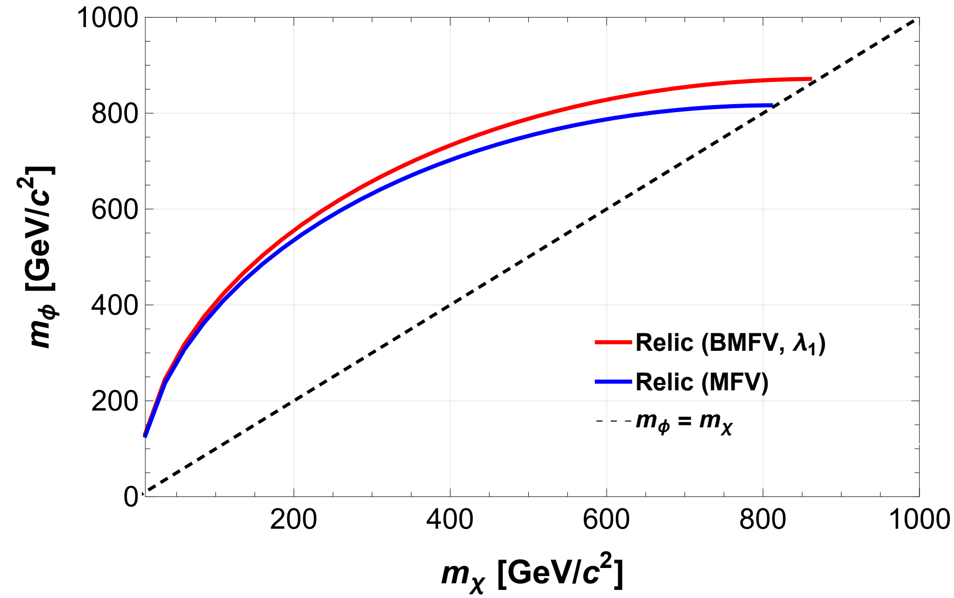
$\chi_a l_i \to \chi_b l_j$ fast $\Rightarrow$ co-annihilation dominates

$$\langle \sigma v \rangle_{eff} \sim \sum_{i,j=e,\mu,\tau} \left[\sum_{a,b=1,2,3} \langle \sigma v \rangle_{\chi_a \bar{\chi}_b \to l_i \bar{l}_j} \right]$$

correct relic abundance $\Rightarrow$ $\langle \sigma v \rangle_{eff} = 2.2 \times 10^{-26}\ cm^3/s$

Constraints: Relic Abundance



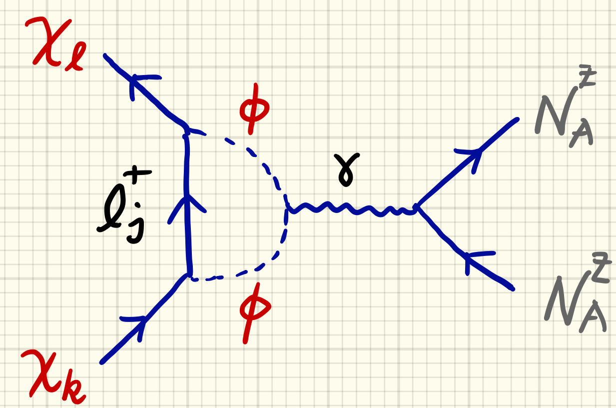


BMFV (λ_0): more channels opened up

BMFV (λ_1): similar to MFV

Constraints: DM Direct Detection

- no direct tree-level couplings of lepton flavored DM to target nucleus
  - DM scattering off target electrons at tree-level   Kopp, Niro, Schwetz, Zupan (2009)
  - through photon exchange at one loop: dominant!



DM-nucleon cross section:

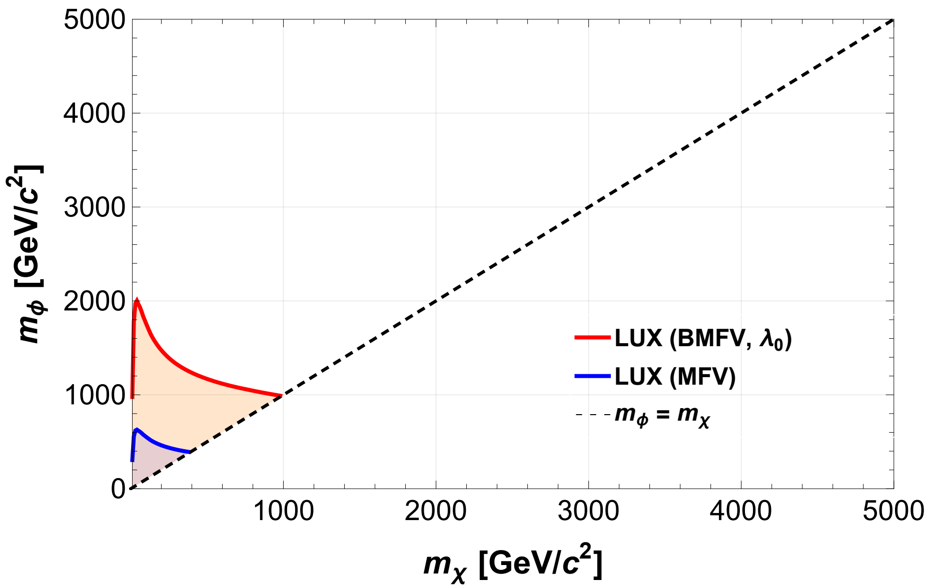
$$\sigma_\chi^N = \sum_{j=e,\mu,\tau} c_j^2 \, e^2 \left(\frac{Z}{A}\right)^2 \frac{\mu^2}{\pi}$$

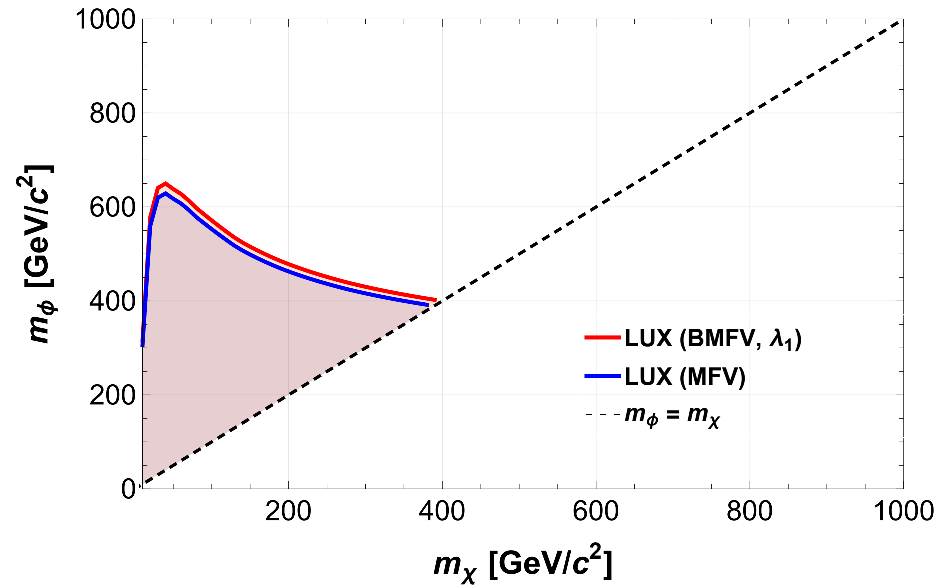
$$c_j \propto \frac{e}{m_\phi^2}\left[\sum_{k,\ell=1}^{3}\left(\lambda_{jk}^* \lambda_{j\ell}\right)\right]\left[1 + \frac{2}{3}\ln\left(\frac{m_{\ell_j}^2}{m_\phi^2}\right)\right]$$

$$\mu = \frac{m_\chi m_N}{(m_\chi + m_N)}$$

Constraints: DM Direct Detection

LUX: Xenon, A = 129, Z = 54





BMFV (λ_0): more channels opened up

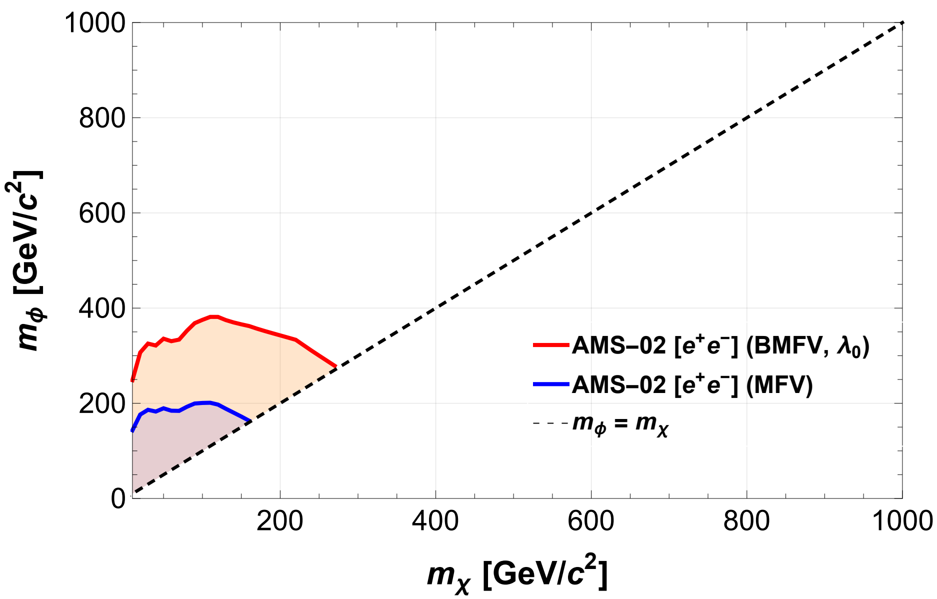
BMFV (λ_1): similar to MFV

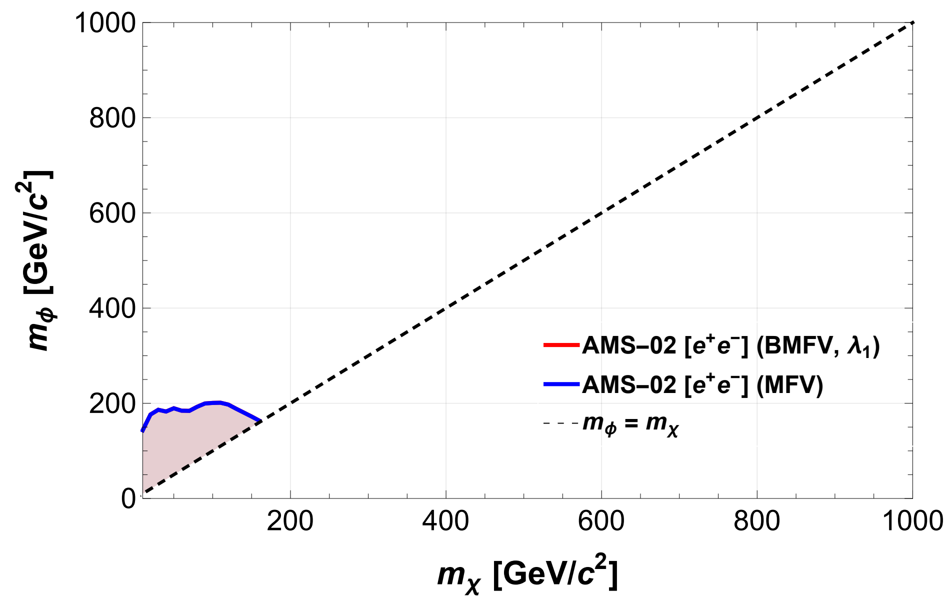
Constraints: Indirect Detection - AMS

AMS-02 positron excess:

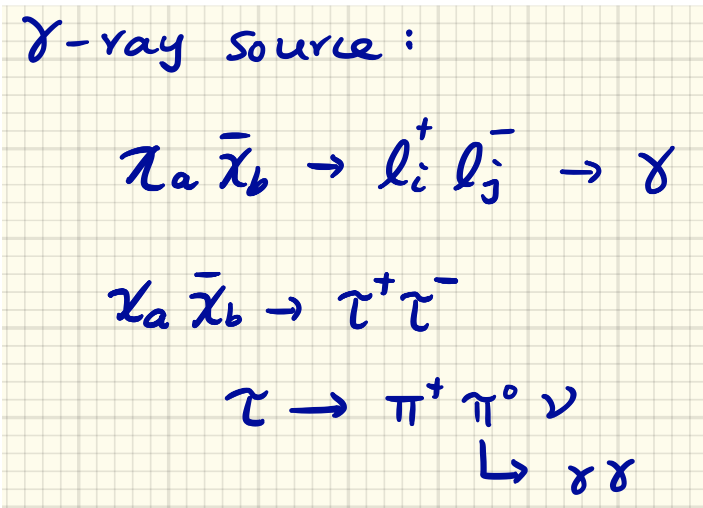
DM annihilation

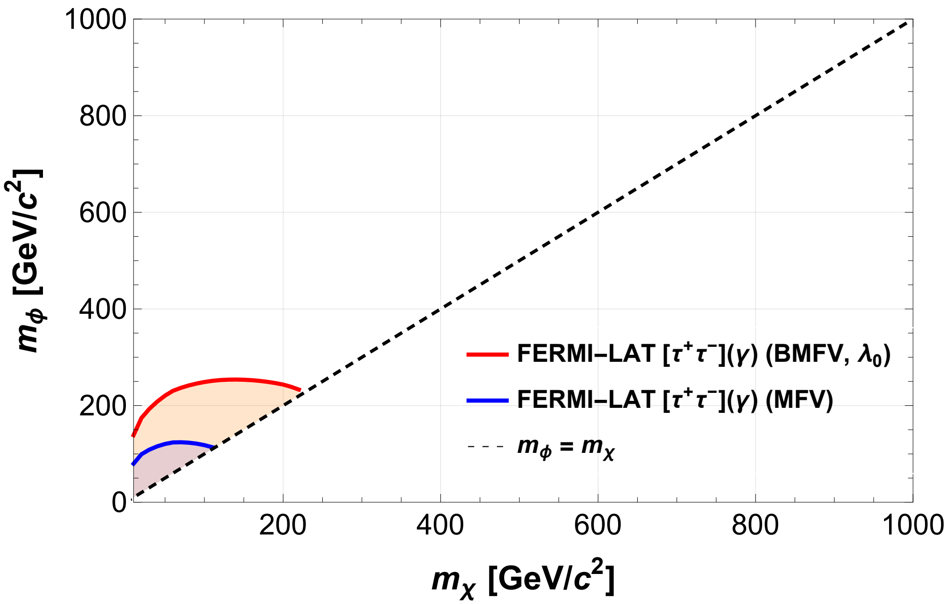
$$\chi_a \bar{\chi}_b \to e^+ e^-$$

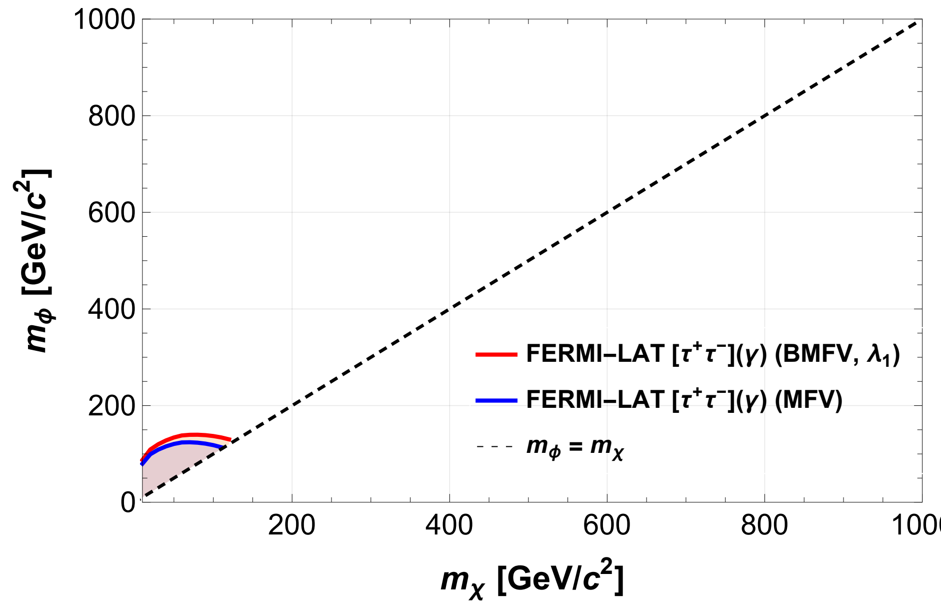




Constraints: Indirect Detection - Fermi-LAT







@ Hadron Collider

Drell-Yang Production of ϕ:

$$pp \to \chi\bar{\chi}\, \ell^+\ell^-$$

signature :

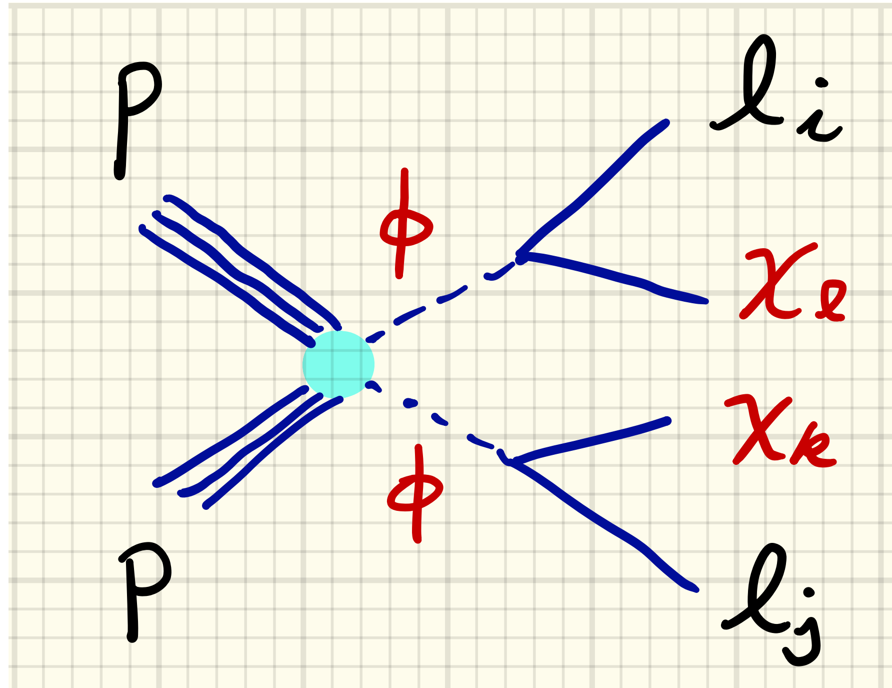
$\ell^+\ell^-$ + MET

cf. SUSY Slepton searches

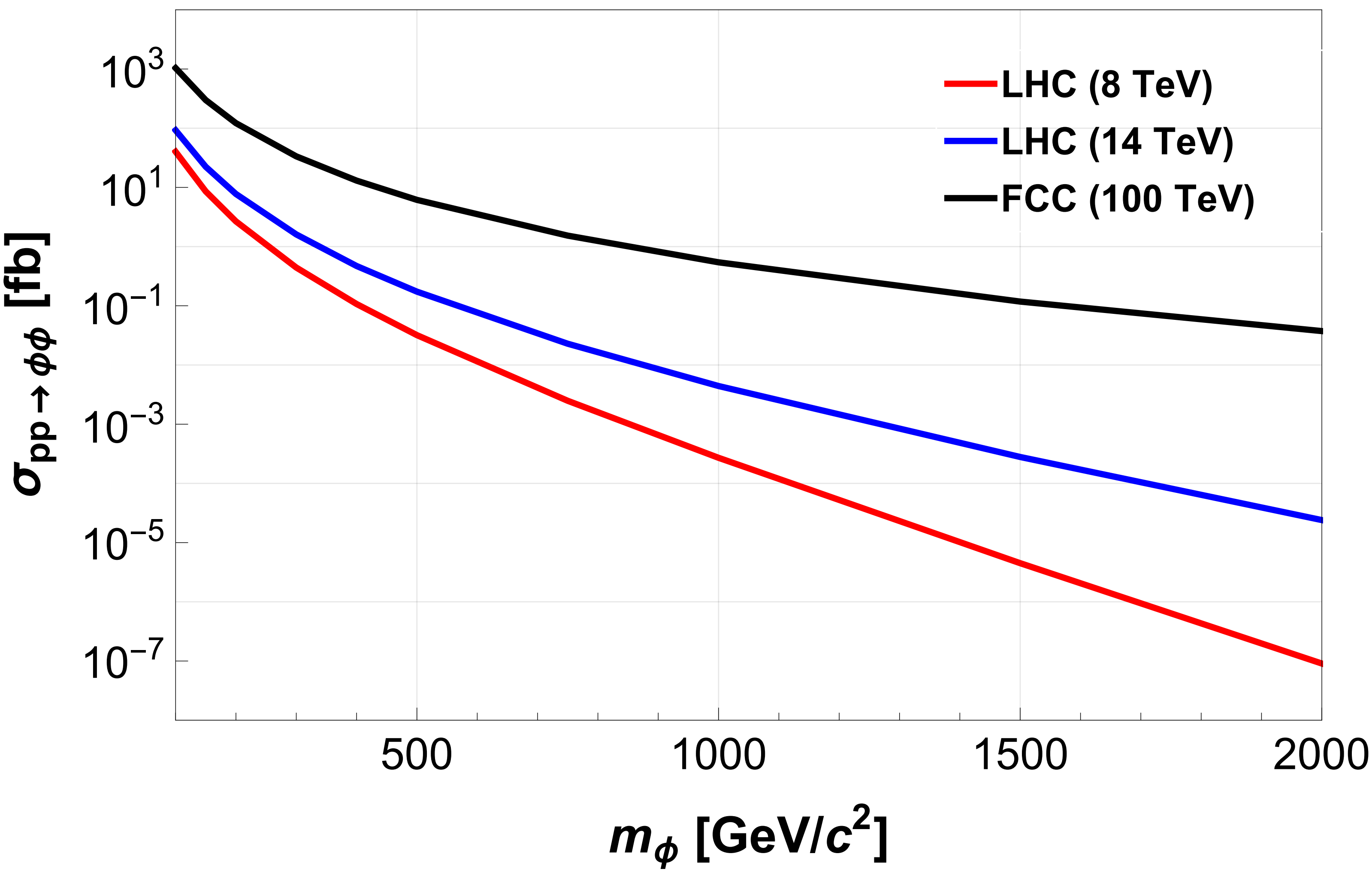
for multi-flavor final states (e.g. $e^\pm\mu^\mp$)

⇒ chargino production in SUSY

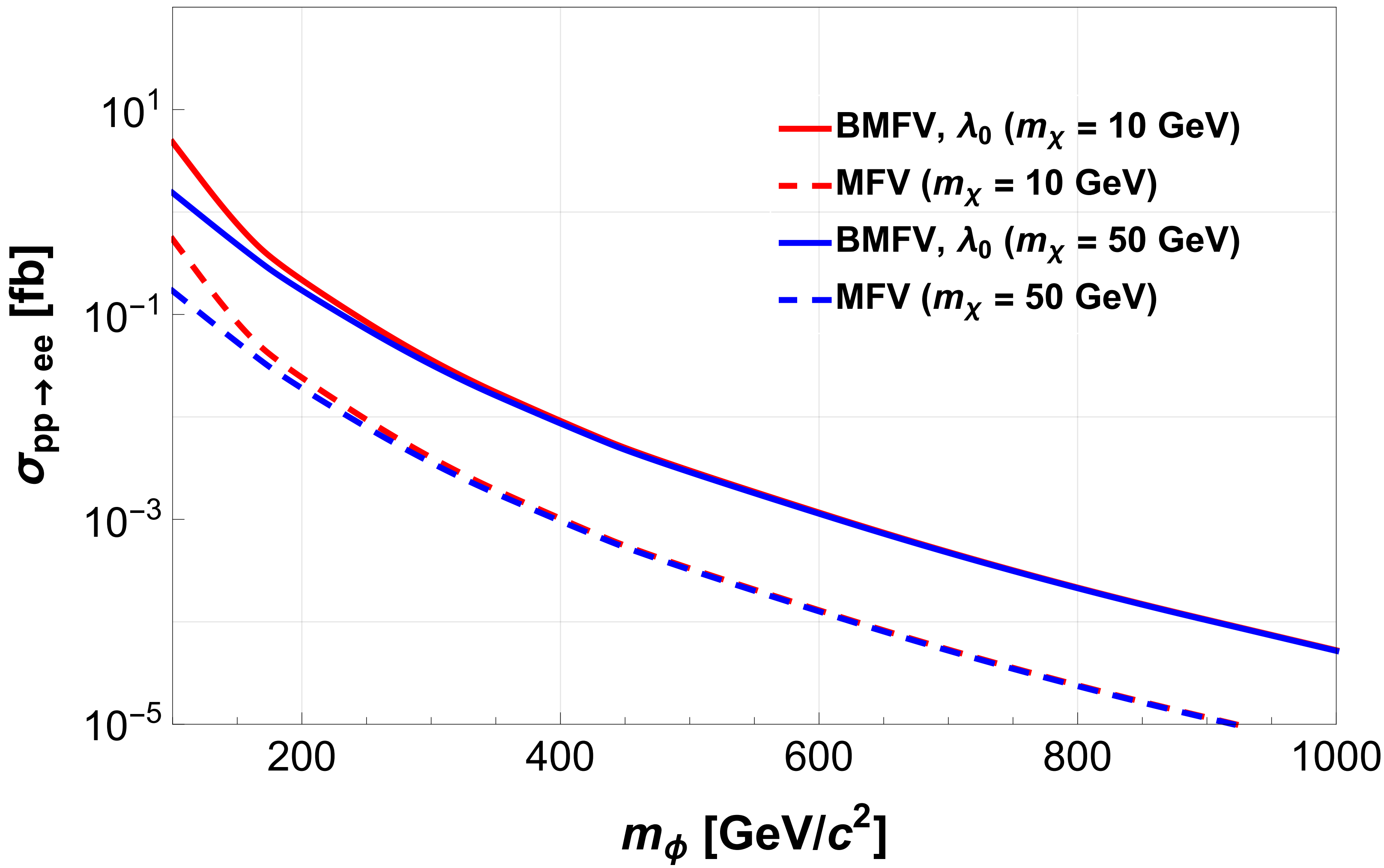
⇒ different event topologies



@ Hadron Collider



@ Hadron Collider



@ Lepton Collider

LEP

- best discovery channel

  $e^+e^- \to \chi\bar{\chi}\gamma$

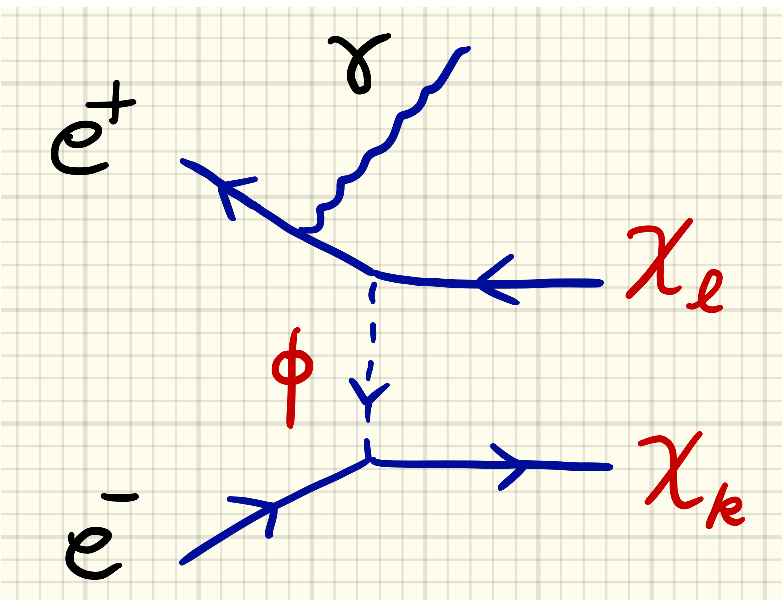
  signature: γ + MET

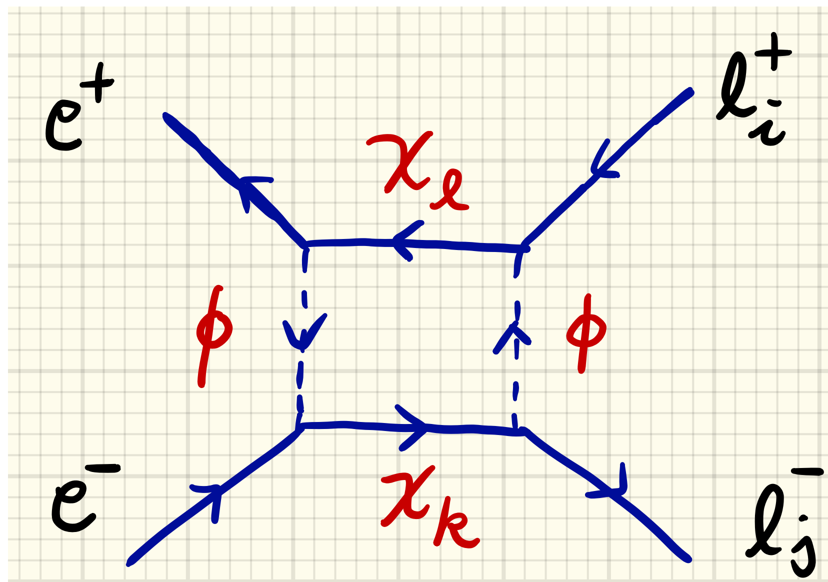
  background: $e^+e^- \to Z\gamma$, $Z \to \nu\bar{\nu}$

- fermion pair production

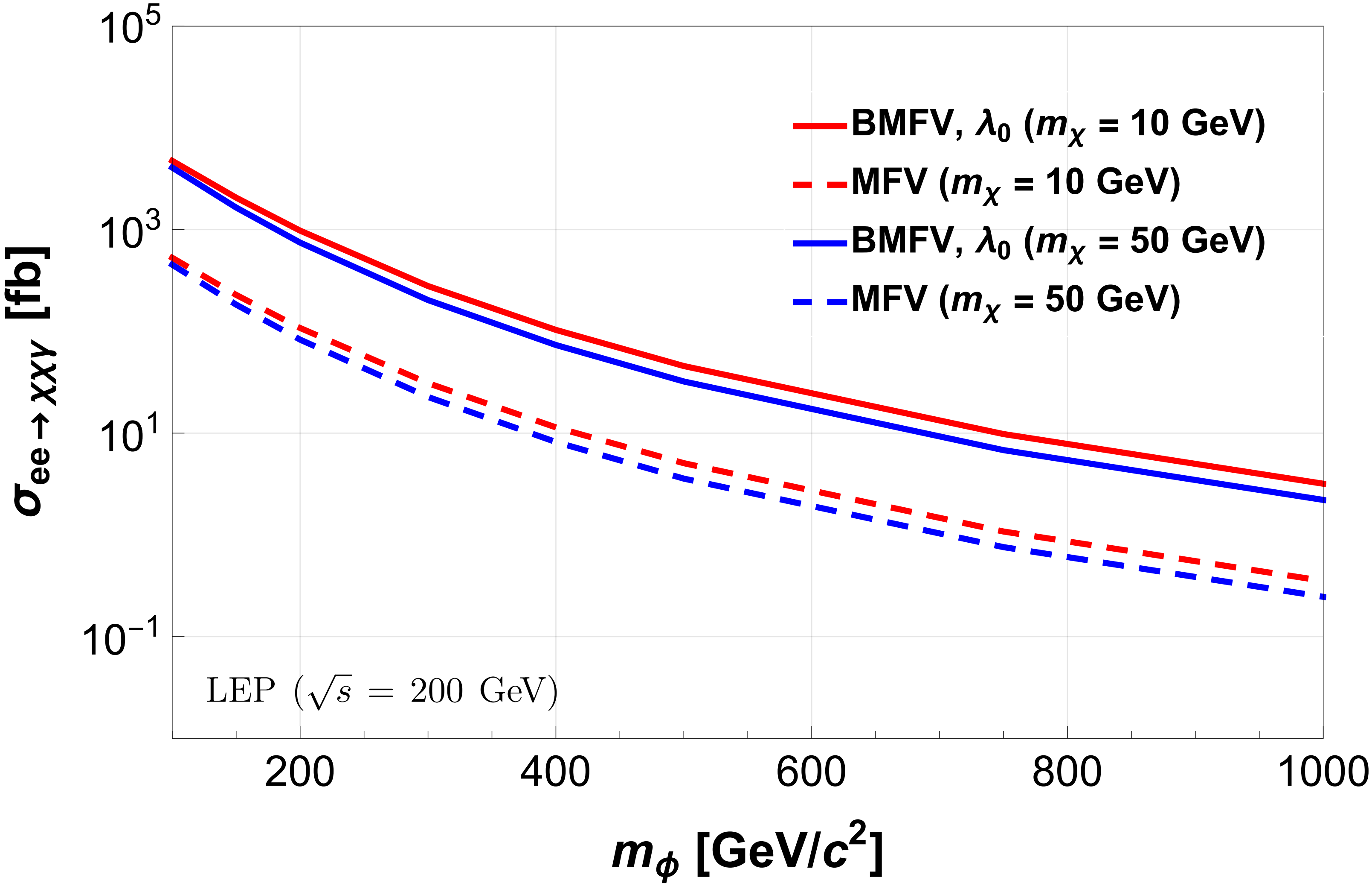
  ⇒ testing flavor violating couplings (e.g. $e^+e^- \to \mu^+e^-$)

  ⇒ signature: multi-flavor lepton final state





@ Lepton Collider



Decaying DM

- Without the additional stabilizing symmetry: $\chi \to \text{lepton} + \text{meson}$
- e.g.

$$\left(\frac{\lambda Y_D Y_U^\dagger}{\Lambda^2}\right)\chi\overline{e_R}d_R\overline{u_R} \implies \chi \to e^+\pi^-$$

$$\left(\frac{\lambda Y_E Y_D}{\Lambda^2}\right)\chi d_R\overline{LQ} = \left(\frac{\lambda Y_E Y_D}{\Lambda^2}\right)\chi d_R\{\overline{\nu_L}\overline{d_L} - \overline{e_L u_L}\} \implies \chi \to \overline{\nu}\pi^0\ ,\ \chi \to e^+\pi^-$$

$$\left(\frac{\lambda Y_E Y_U^\dagger}{\Lambda^2}\right)\chi\overline{u_R}\overline{L}Q = \left(\frac{\lambda Y_E Y_U^\dagger}{\Lambda^2}\right)\chi\overline{u_R}\{\overline{\nu_L}d_L - \overline{e_L}u_L\} \implies \chi \to \overline{\nu}\pi^0\ ,\ \chi \to e^+\pi^-$$

$$\left(\frac{\lambda Y_E^\dagger}{\Lambda^2}\right)\chi e_R\overline{LL} = \left(\frac{\lambda Y_E^\dagger}{\Lambda^2}\right)\chi e_R\{\overline{\nu_L e_L} - \overline{e_L\nu_L}\} \implies \chi \to \overline{\nu}e^+e^-$$

Mimic RPV neutralino decays

- DM lifetime

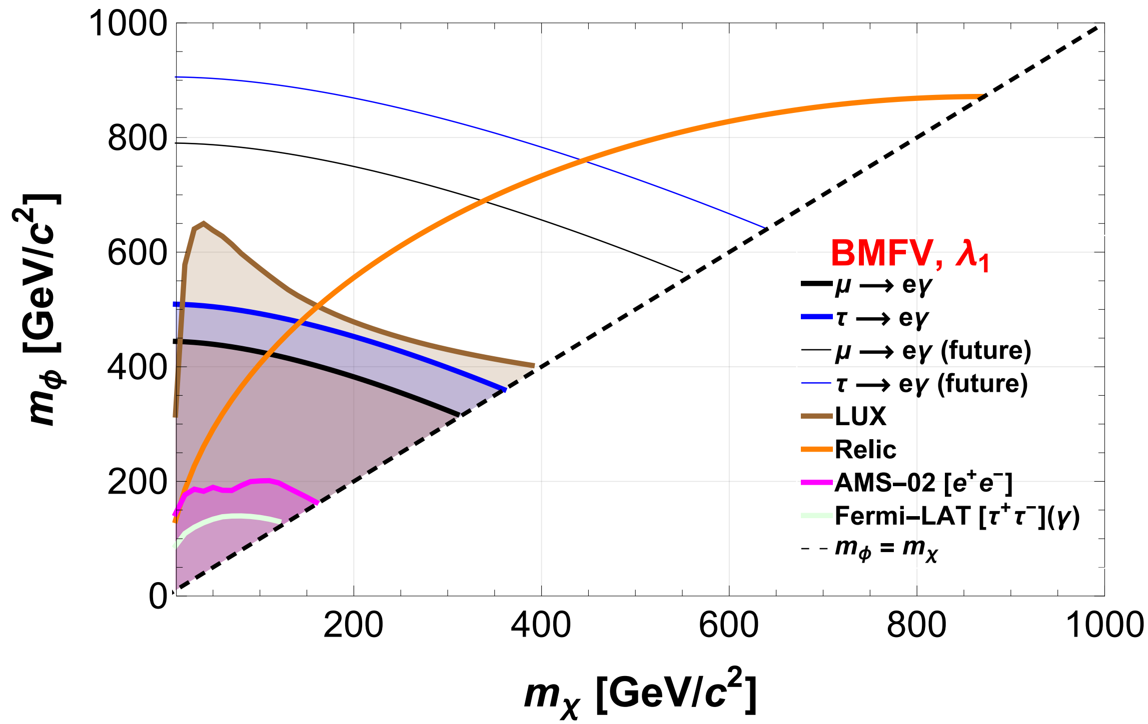
$$\tau_\chi \sim 10^{26}\text{s}\left(\frac{1}{f(\lambda,\lambda^\dagger,Y,Y^\dagger)}\right)^2\left(\frac{\text{TeV}}{m_\chi}\right)^5\left(\frac{\Lambda}{10^{15}\ \text{GeV}}\right)^4$$

- c.f. age of the universe

$$\tau_{univ.} \sim 4.3\times10^{17}\text{s}$$

Summary

- Lepton Flavored DM: beyond MFV with SU(3)χ
- Contrast to quark flavored DM case: no automatic stabilizing symmetry
- Most stringent constraints from cLFV processes
- Interesting collider signatures
- UV Theory of (B)MFV?



26th International Workshop on Weak Interactions and Neutrinos (WIN2017)

6/19 - 24/2017

University of California, Irvine

Please check back soon for details!

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