DM as a Portal to New Physics @ APCTP

Fermion portal dark matter and muon anomalies

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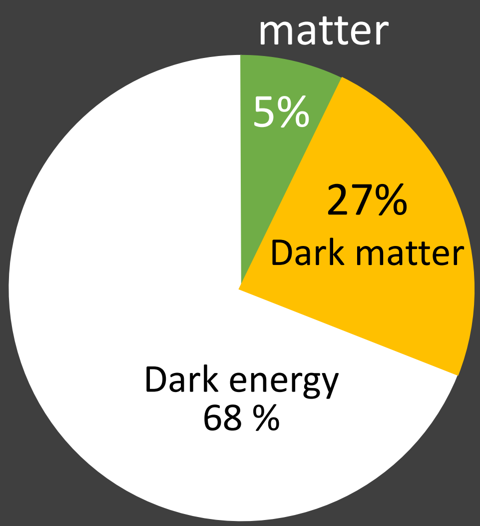
arXiv:2002.12534, 1706.04344
[JHEP] [PRD]

in collaboration with

Y.Omura [Kindai U., Japan] and S.Okawa [Victoria U., Canada]

Dark Matter [DM]

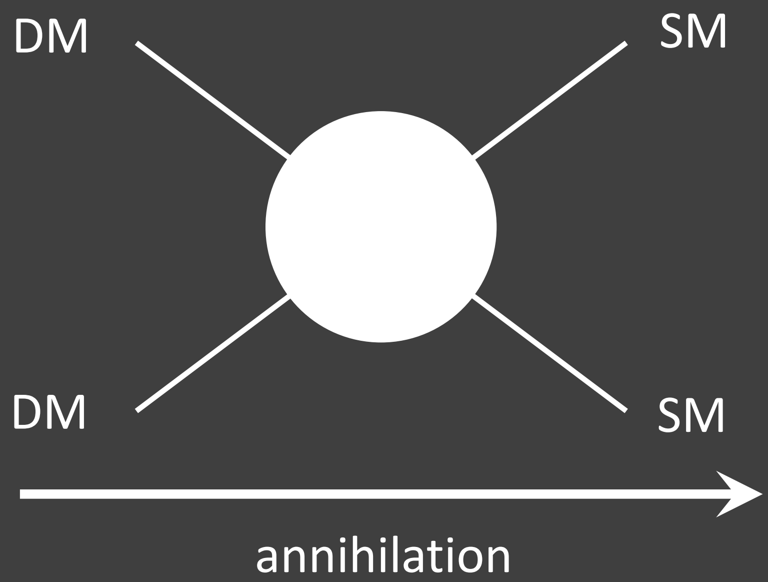
- dark matter
  - dark and cold (particle)
  - 27% of energy of the universe
  - discovered only by gravitational int.

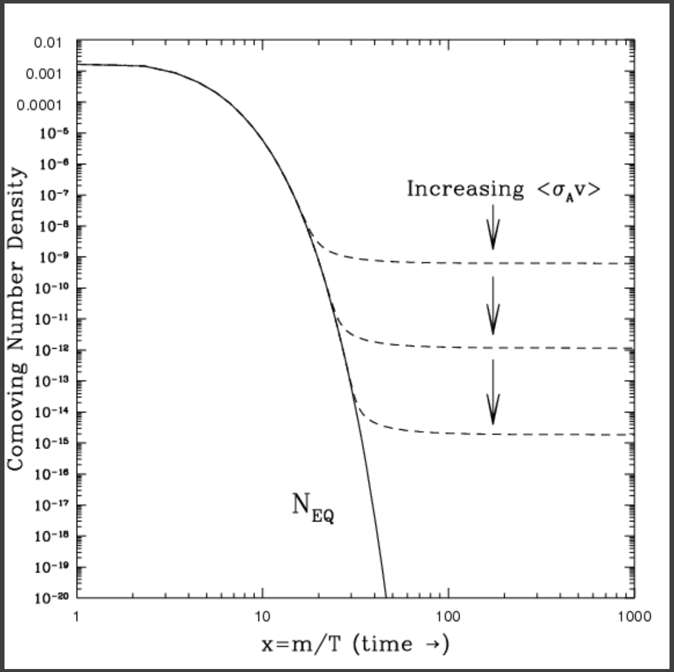


- particle candidates
  - Weakly Interacting Massive Particle [WIMP]
  - axion, ALP
  - SIMP, FIMP, asymmetric, self-interacting, …

WIMP is still an interesting candidate

Freeze-out of WIMP



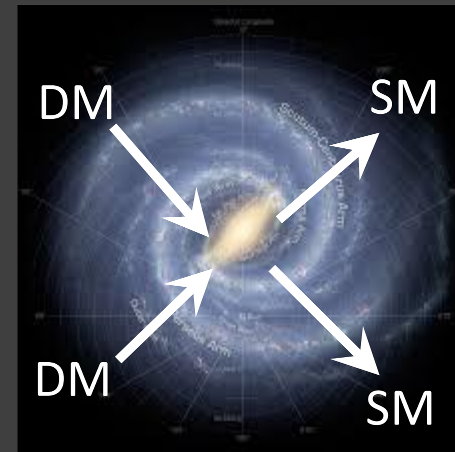


E.W.Kolb, M.S.Turner,
The Early Universe, `89

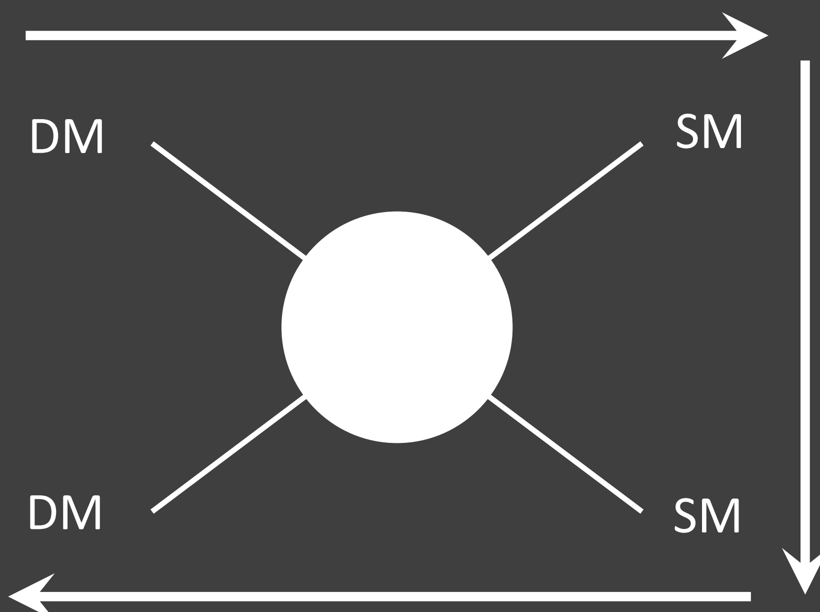
- DM decouples from thermal bath and “freeze-out”
- Electro-Weak [EW] coupling and mass can explain relic density
- WIMP can be in beyond SM e.g. models for muon anomalies

Probes of WIMP

- annihilation
  - indirect detection
  - annihilation in DM rich env.
  - e.g. Fermi-LAT, CTA, HESS,

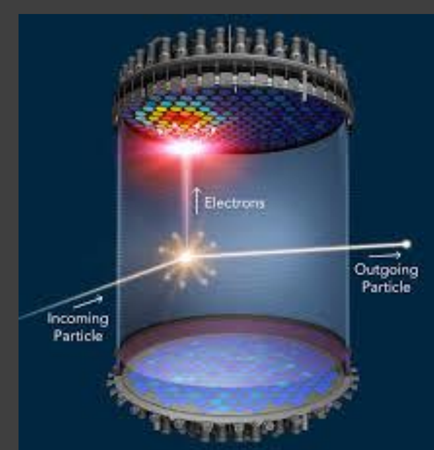


https://solarsystem.nasa.gov/



- scattering
  - direct detection
  - scattering with nucleus/e
  - e.g. XENON, PANDA, LZ

- production at collider
  - usually by mono-X searches
  - e.g. LHC, LEP, ILC(?) ⋯

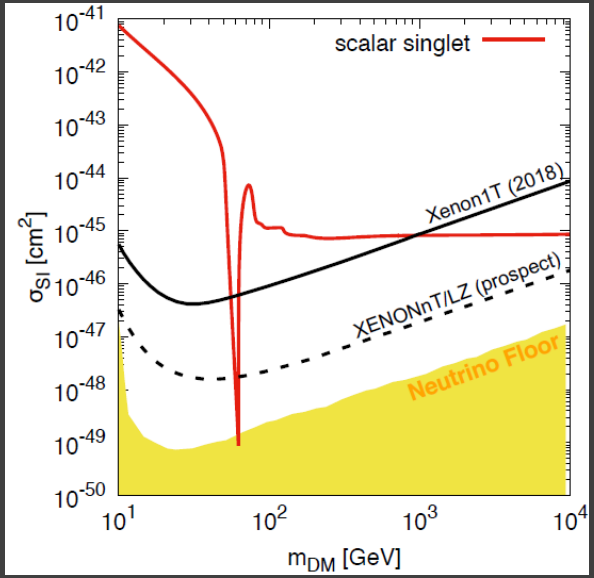


https://kipac.stanford.edu/

Minimal WIMP models

- SM + EW singlet DM

- quartic coupling $X^2 H^\dagger H$ and DM mass are the parameter
- direct detection excludes most region
- resonant or heavy region still alive

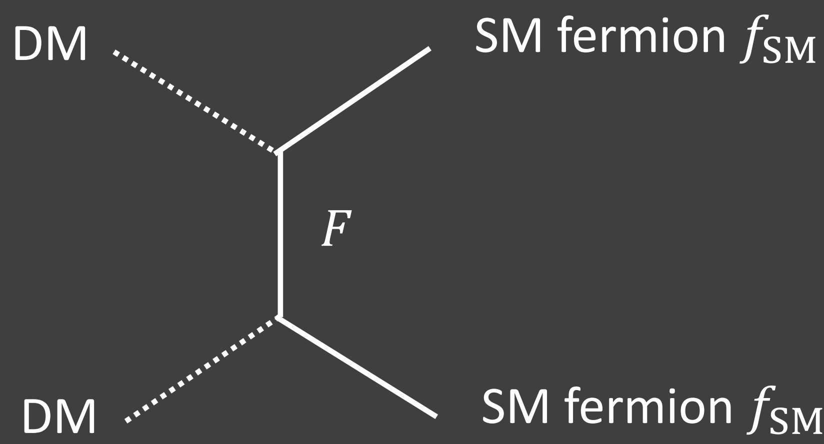


T.Abe's talk, SUSY2019

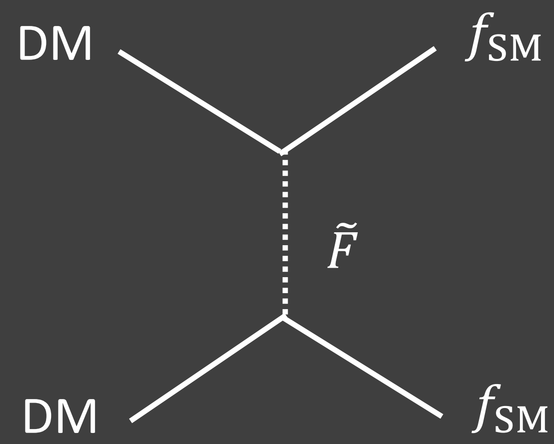
Fermion portal model

1308.0612, 1402.6696 Y.Bai, J.Berger

- SM + EW singlet DM + mediator



OR



- Yukawa coupling, DM and mediator masses are parameter
- co-annihilation of DM and mediator occurs if degenerate
- pure bino + slepton in SUSY is in this class
- We focus on EW singlet DM   cf. non-singlet case:

0512090 M.Cirelli, N.Fornengo, A.Strumia (DM)
1804.00009, L.Calibbi, R.Ziegler, J.Zupan (DM+g-2)

Outline

1. Introduction
2. minimal lepton portal dark matter
3. simultaneous explanation with muon anomalies
4. Conclusion

Minimal lepton portal model

- SM + EW singlet DM + 1 mediator (s)lepton

DM is

1.	scalar	a.	self-conjugate
2.	fermion	b.	complex

→

[1a] real scalar
1405.6917, A.Ibarra et.al

[1b] complex scalar
1812.07004, JK, S.Okawa et.al

[2a] Majorana fermion
1403.4634 Garny et.al ,
1401.6457 Kopp et.al

[2b] Dirac fermion
1503.03382 A.Ibarra, S.Wild

mediator is

1.	fermion	i.	EW singlet
2.	scalar	ii.	EW doublet

there are $2 \times 2 \times 2 = 8$ possibilities

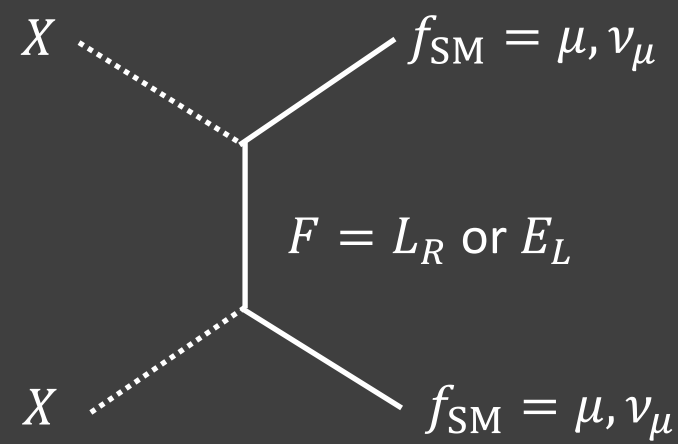
Scalar DM models

- singlet mediator E_L

  $\mathcal{L} \supset m_E\, \overline{E}_L E_R + \lambda_R \overline{E}_L\, X\, \mu_R$

- doublet mediator L_R

  $\mathcal{L} \supset m_L\, \overline{L}_L L_R + \lambda_L \overline{\ell_2}\, X\, L_R \quad \ell_2 = \begin{pmatrix} \mu_L \\ \nu_{\mu L} \end{pmatrix}$



  - fermion mediator should be vector-like
  - Yukawa coupling is non-zero only for muon
  - Higgs portal is neglected

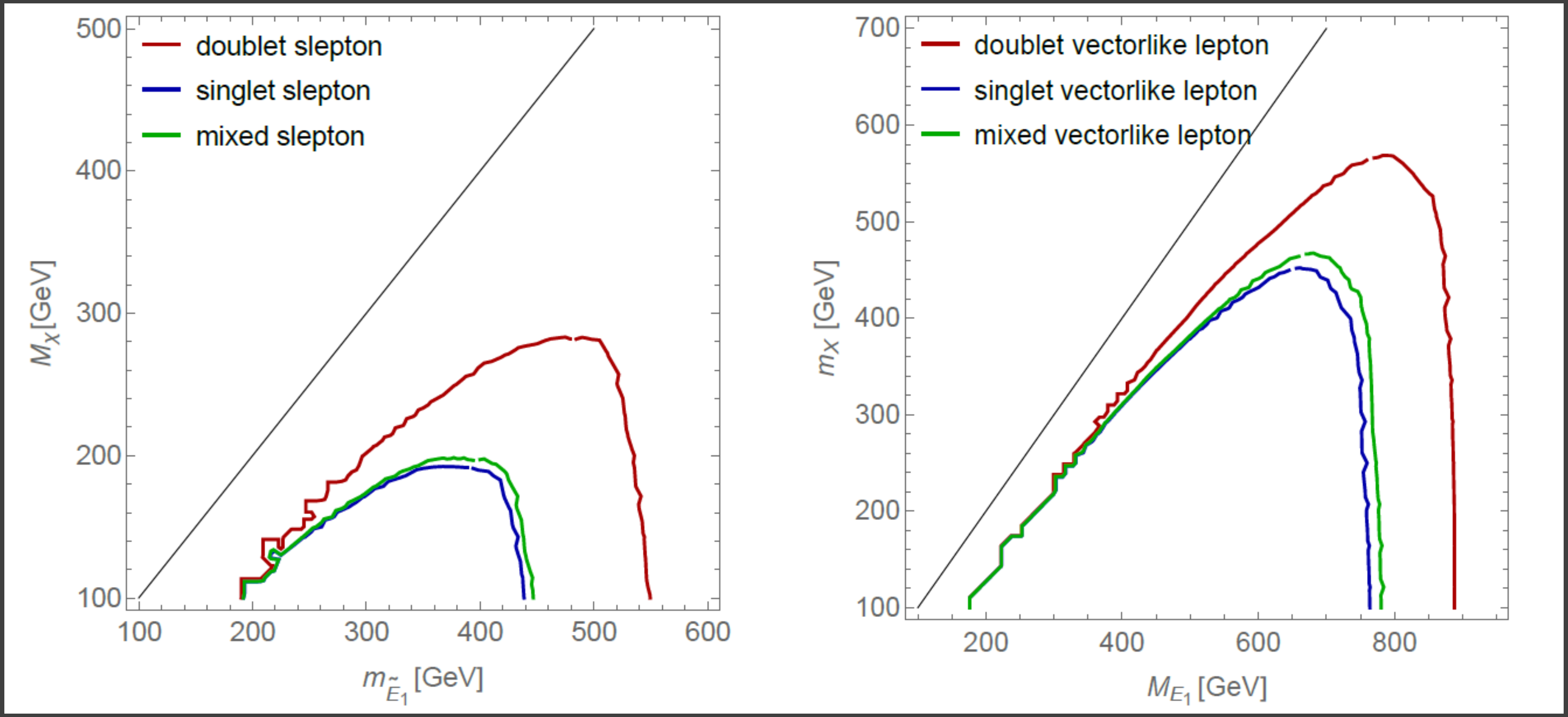
- Fermion DM models
  - mediator is "s"lepton (complex scalar)
  - special case of Majorana DM (= bino) is realized in SUSY

LHC limits

mediator decays to DM and muon

→ $p\,p \to L\,L \to \mu\,\mu + \mathrm{MET}$ is the same as SUSY slepton signal

limit from 139 fb^{-1} data at ATLAS [1908.08215]

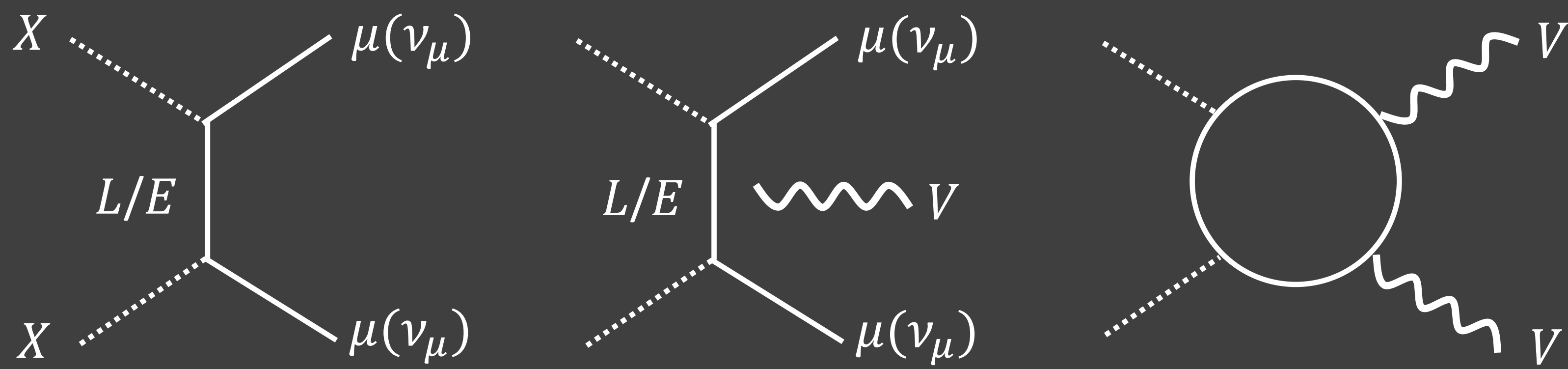


FeynRules, Madgraph5

Annihilation

- Processes

$V, V' = Z, W, \gamma$



$XX^{(\dagger)} \to \mu\mu$ $\quad XX^{(\dagger)} \to \mu\mu + V$ $\quad XX^{(\dagger)} \to VV'$

- 2-2 annihilation

velocity expansion: $\sigma v = a + b\, v^2 + c v^4 + \cdots$ (s-wave, p-wave, d-wave)

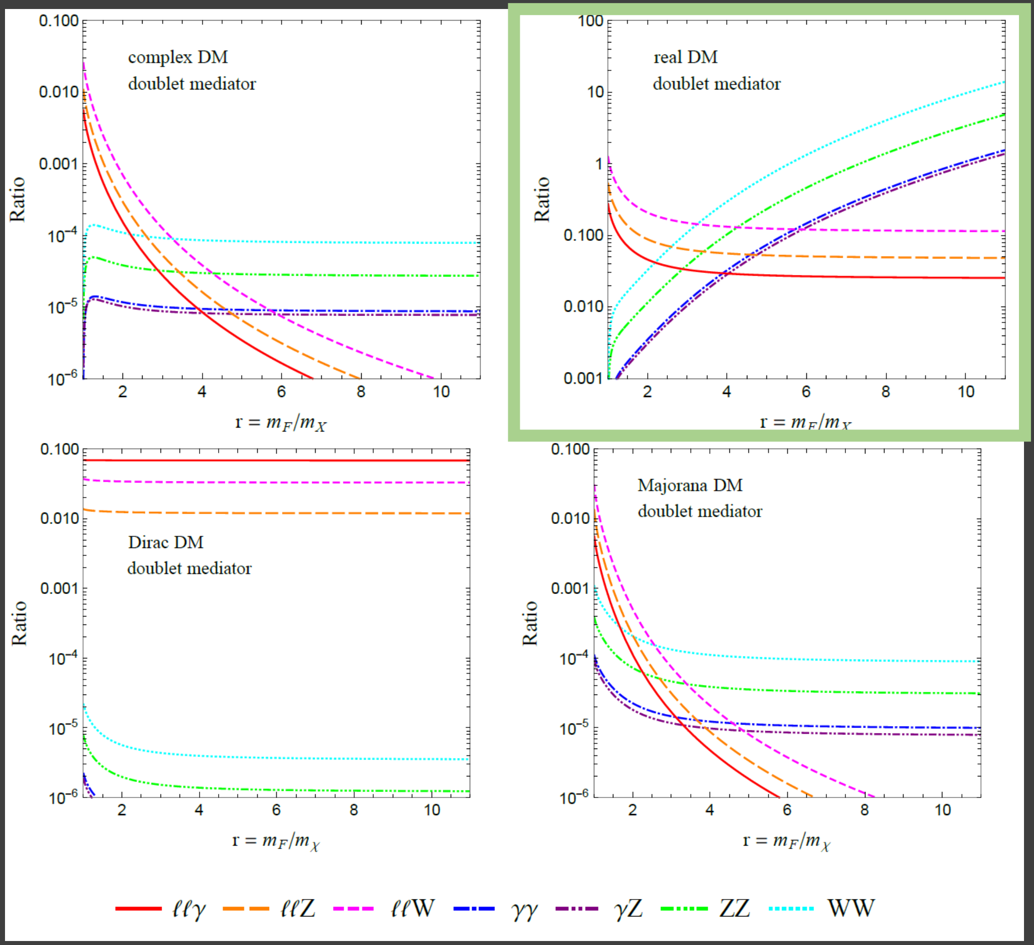
$\langle v^2 \rangle \simeq 0.24, \langle v^4 \rangle \simeq 0.1$ at freeze-out

- s-wave is helicity suppressed, i.e. $\propto m_\mu^2/m_X^2$, except Dirac DM
- p-wave is also helicity suppressed for real DM

Annihilation

relative importance of higher-order processes

$$\text{Ratio} = \frac{\langle \sigma(XX \to \mu\mu V / VV')v \rangle}{\langle \sigma(XX \to \mu\mu)v \rangle}$$



$m_X = 500$ GeV

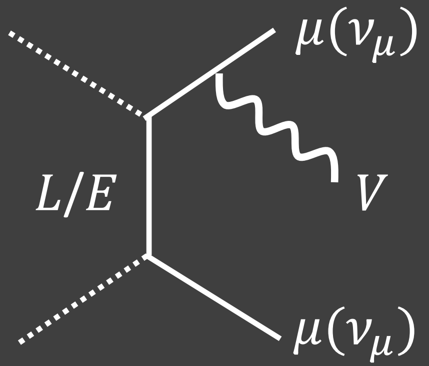
$r = m_L/m_X$

- higher-order processes can be sizable for real DM
- these are less than 0.1 for other cases

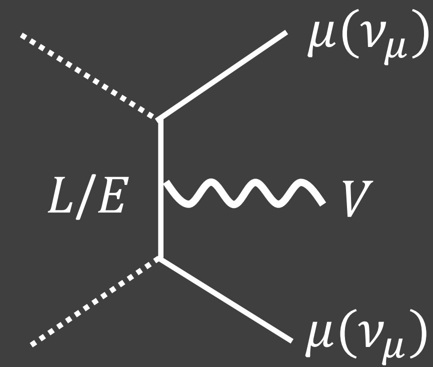
Virtual Internal Bremsstrahlung

e.g. 1203.1312
T.Bringmann, X.Huang et.al

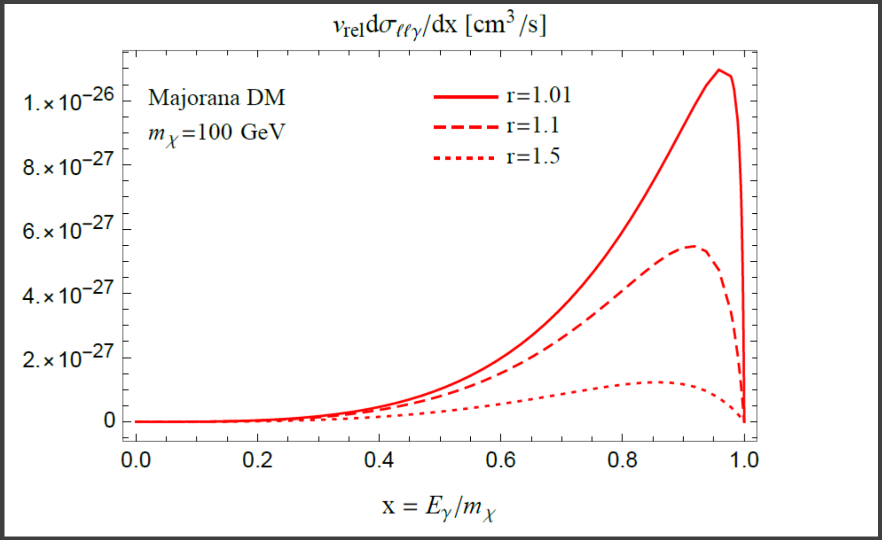
Final State Radiation [FSR]



Virtual Internal Bremsstrahlung [VIB]



➢ photon spectrum from VIB



$r = m_L/m_X$

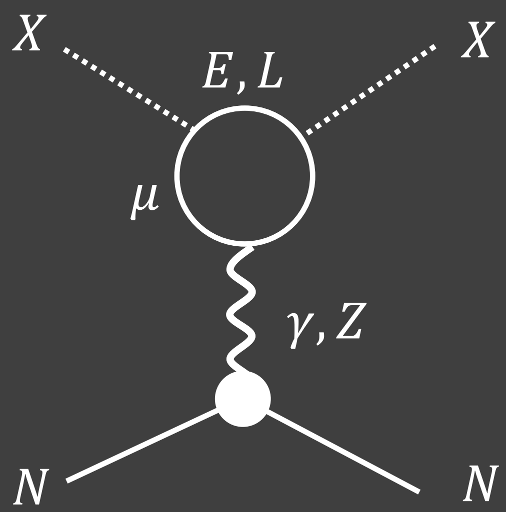
- peak at $E_\gamma \sim m_X$ if $m_L \sim m_X$
- γ from $XX \to \gamma\gamma, Z\gamma$ also has sharp spectral structure

1405.6917
A.Ibarra, T.Toma et.al

Direct detection

tree-level is absent

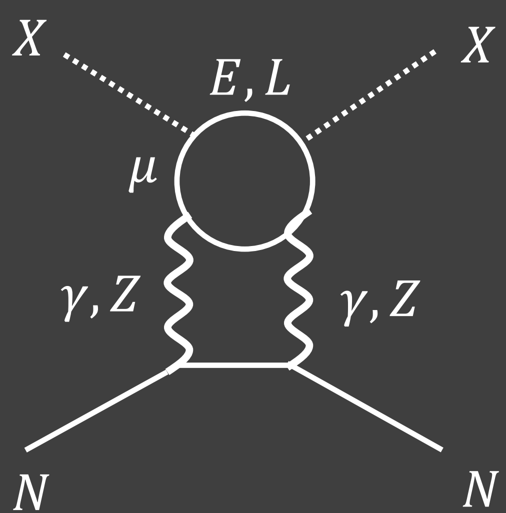
0907.3159, J.Kopp etl.al



- 1-loop penguin

$$\rightarrow \quad \mathcal{L}_{\mathrm{eff}} \supset C\, i \left(X^\dagger \partial_\mu X - \partial_\mu X^\dagger \cdot X \right) \overline{N} \gamma^\mu N$$

  - dominant in complex scalar DM
  - vanishing for real scalar DM

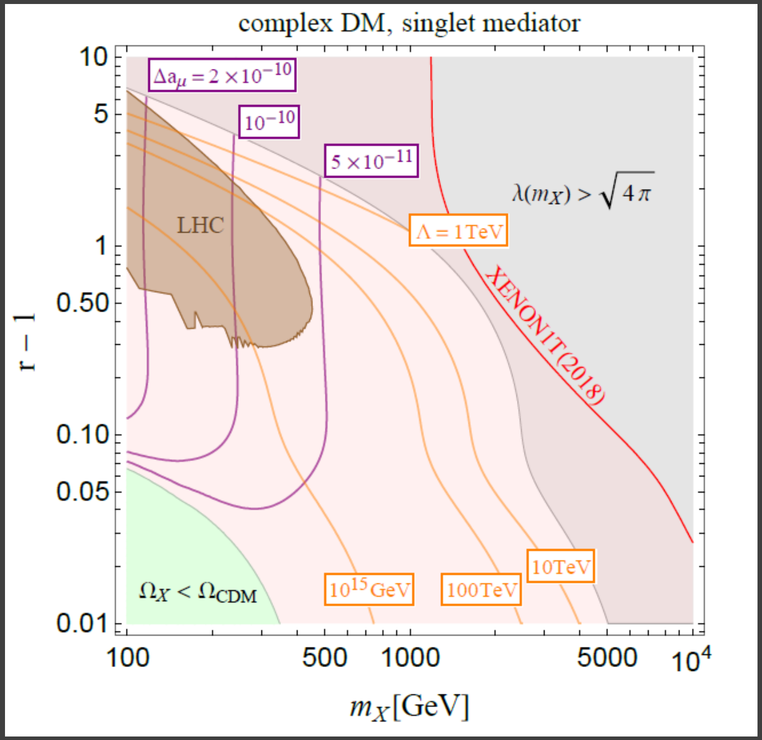


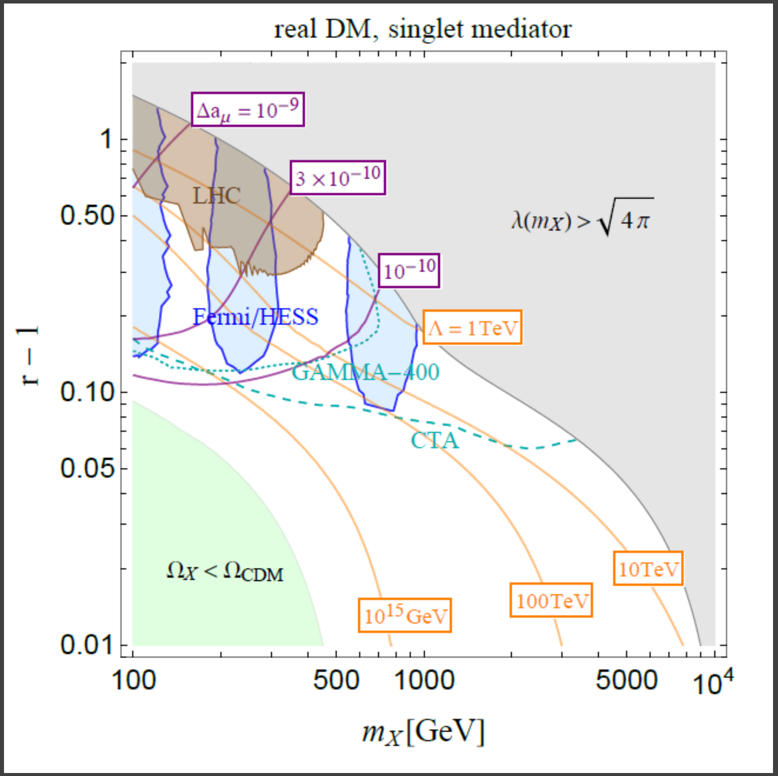
- 2-loop two photon exchange
  - dominant in real scalar DM
  - very much suppressed

Current status of scalar DM

$r = m_E/m_X$

Yukawa is fixed to explain thermal relic density via (co-)annihilation





MicrOmegas

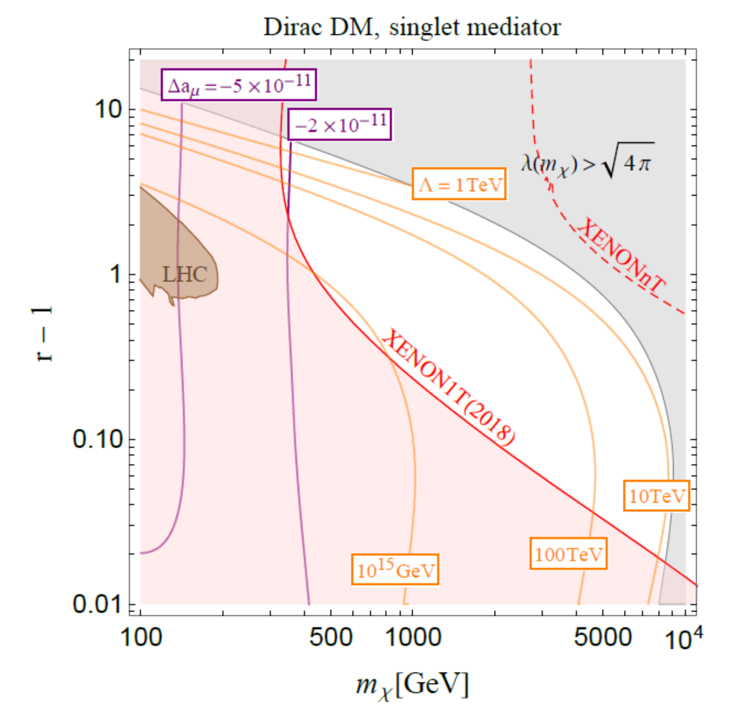
- ✓ excluded by direct detection
- ✓ Δa_μ is too small

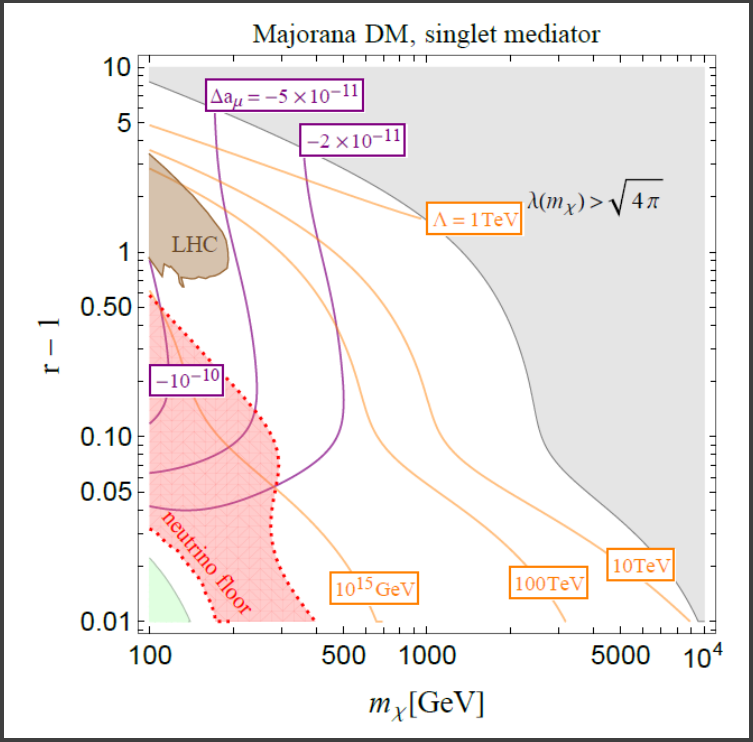
- co-annihilation is needed for abundance
- direct detection bound is absent
- indirect detections give bounds

Current status of fermion DM

$r = m_E/m_X$

Yukawa is fixed to explain thermal relic density via (co-)annihilation





MicrOmegas

- ✓ XENON excludes wide region
- ✓ Δa_μ is too small

- p-wave allows larger mass difference
- direct detection bound is absent
- indirect detections give no bound

Summary of minimal models

	real	**complex**	**Majorana**	**Dirac**
relic density $XX \to \mu\mu$	d-wave	p-wave	p-wave	s-wave
direct det. $XN \to XN$	2-loop	1-loop	1-loop v-suppressed	1-loop
indirect det. $\sigma_{\mu\mu\gamma}/\sigma_{\mu\mu}$	$\gtrsim 0.1$	$\lesssim 0.1$	$\lesssim 0.1$	$\lesssim 0.1$

- complex/Dirac DM is strongly constrained by XENON
- real DM is partially constrained by indirect detections
- Majorana DM is less constrained
- Analytic formulas are in paper

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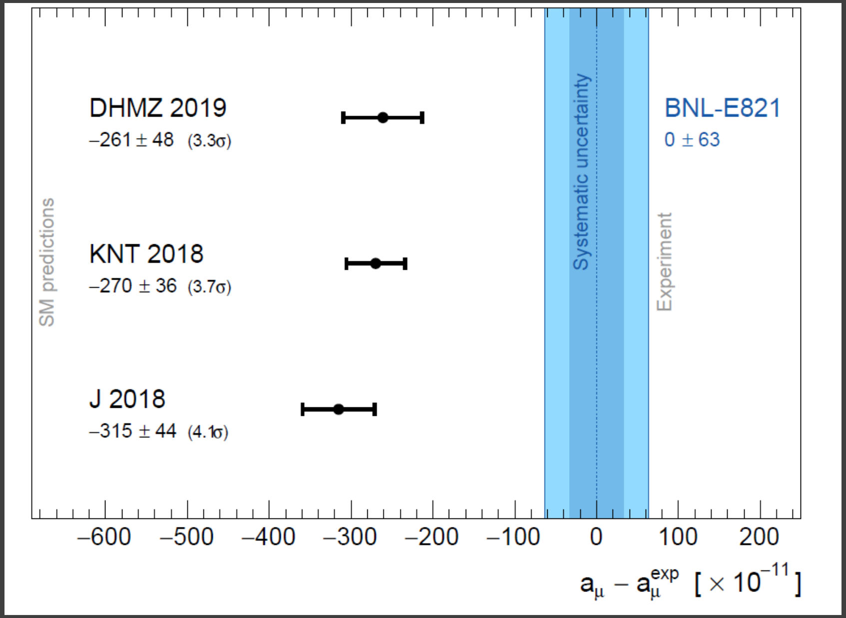
Muon $g-2$

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM}$$

$$= 2.61\,(63)(48) \times 10^{-9}$$

$$\sim 3.3\,\sigma$$

SM Exp.



PDG2020

- discrepancy is resolved if lattice result for hadronic contribution is true
- we would have new experimental result soon

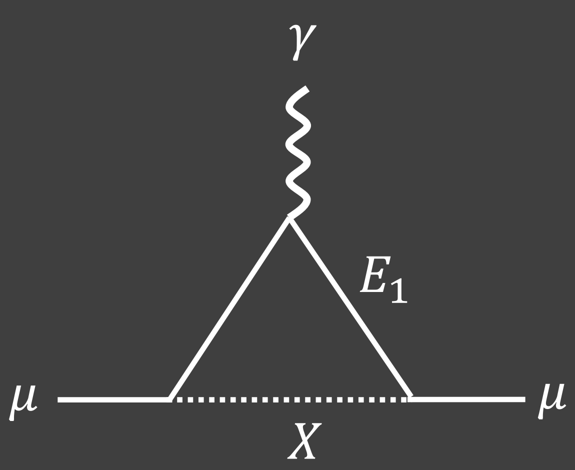
Δa_μ in lepton portal model

- SM + singlet DM + 2 mediator (s)leptons

$$\mathcal{L} \supset \lambda_L \overline{\ell_L}\, X\, L_R + \lambda_R \overline{E}_L X^* \mu_R + \kappa \overline{L}_L H E_R \qquad E'_{L(R)} \in L_{L(R)}$$

$$\rightarrow \quad \begin{pmatrix} E'_R \\ E_R \end{pmatrix} = \begin{pmatrix} c_R & s_R \\ -s_R & c_R \end{pmatrix} \begin{pmatrix} E_{R_1} \\ E_{R_2} \end{pmatrix}, \quad \begin{pmatrix} E'_L \\ E_L \end{pmatrix} = \begin{pmatrix} c_L & s_L \\ -s_L & c_L \end{pmatrix} \begin{pmatrix} E_{L_1} \\ E_{L_2} \end{pmatrix}$$

mixing is induced by Yukawa coupling κ



$$\Delta a_\mu \sim \frac{m_\mu}{16\pi^2 m_X^2}\left[\lambda_L \lambda_R\, c_R s_L m_{E_1} + \mathcal{O}(m_\mu)\right]$$

sizable Δa_μ comes only from mixing

Correlation to DM density

- Annihilation rate

$$\langle \sigma v \rangle \sim \frac{|\lambda_L \lambda_R|^2}{\pi} \left(\frac{c_R s_L m_{E_1}}{m_X^2 + m_{E_1}^2} - \frac{c_L s_R m_{E_2}}{m_X^2 + m_{E_2}^2} \right)^2$$

no suppression by muon mass in the s-wave contribution

- Correlation to Δa_μ

$\langle \sigma v \rangle \sim 3 \times 10^{-26}\ [\mathrm{cm}^3/s]$

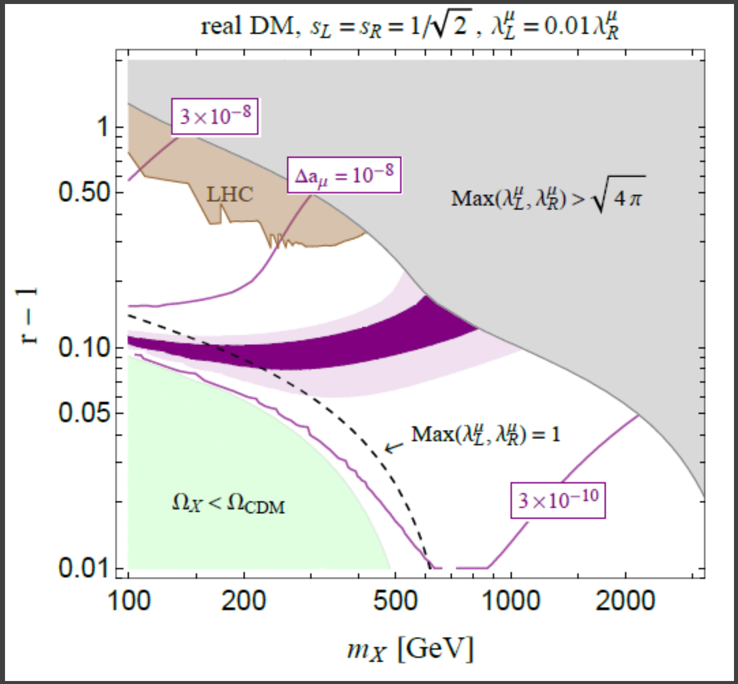
→ $\Delta a_\mu \sim \frac{m_\mu}{16\pi^2} \sqrt{2\pi \langle \sigma v \rangle} \sim 5 \times 10^{-8}$ is too large if maximal mixing

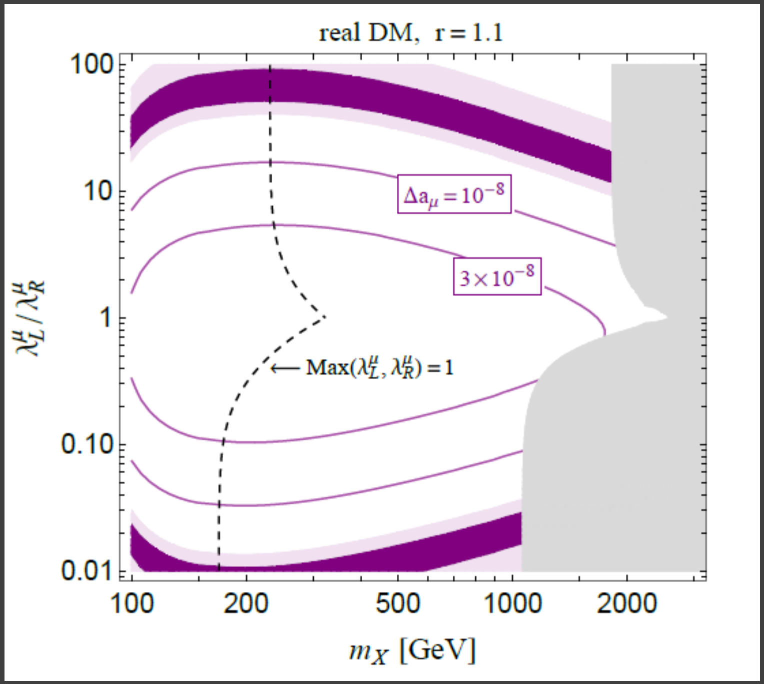
→ co-annihilation and/or $\lambda_L \ll \lambda_R$ ($\lambda_R \ll \lambda_L$)
and/or non-maximal mixing is/are needed

Result in real DM

$m_{E_2} - m_{E_1} = 100$ GeV
$r = m_{E_1}/m_X$

λ_R is fixed to explain relic density





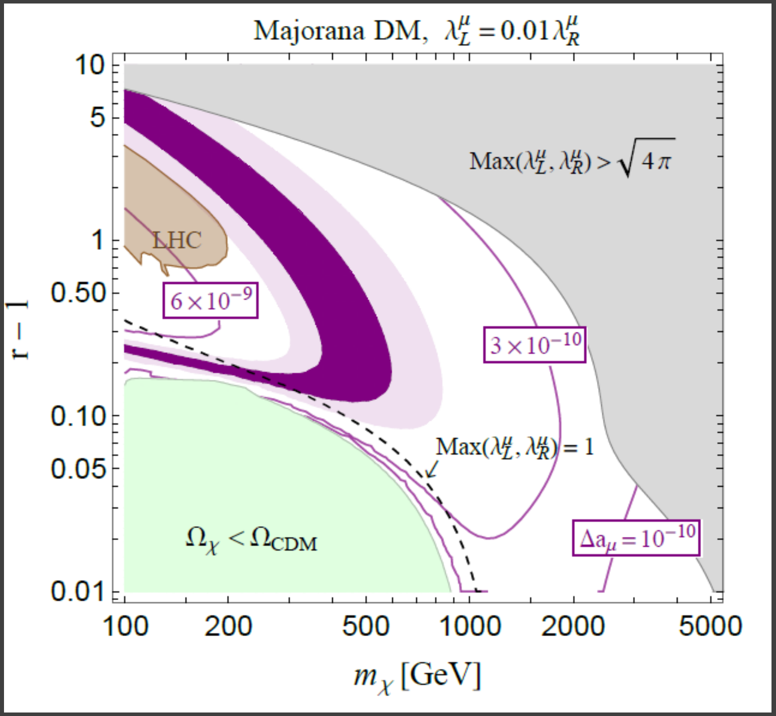
MicrOmegas

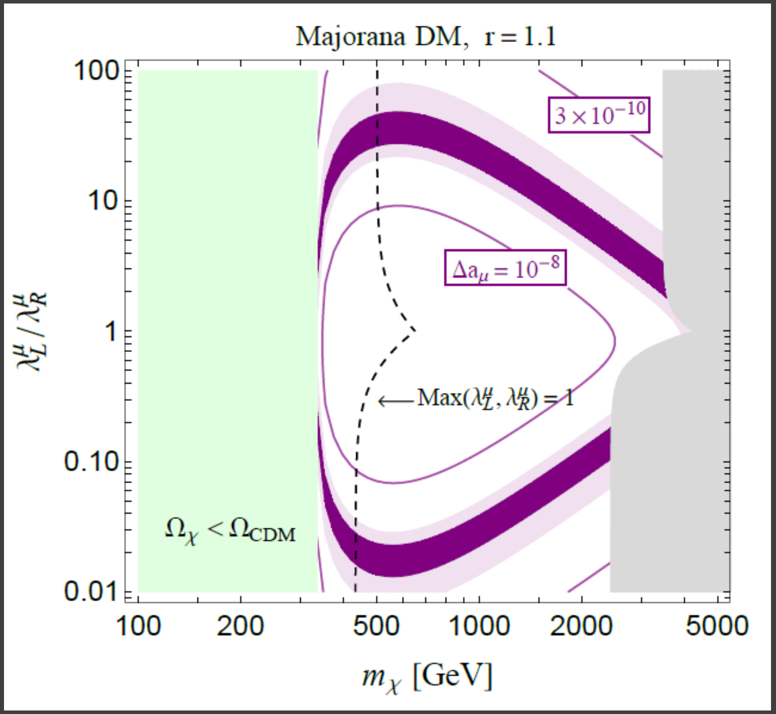
Δa_μ can be explained if $m_{E_1} \sim 1.1 \times m_X$ and $\lambda_L \sim 0.01 \times \lambda_R$

Result in Majorana DM

$m_{E_2} - m_{E_1} = 100$ GeV
$r = m_{E_1}/m_X$

λ_R is fixed to explain relic density





MicrOmegas

- Δa_μ can be explained if $m_{E_1} \sim 1.1 \times m_X$ and $\lambda_L \sim 0.01 \times \lambda_R$
- requirement for degeneracy is relaxed due to p-wave contribution

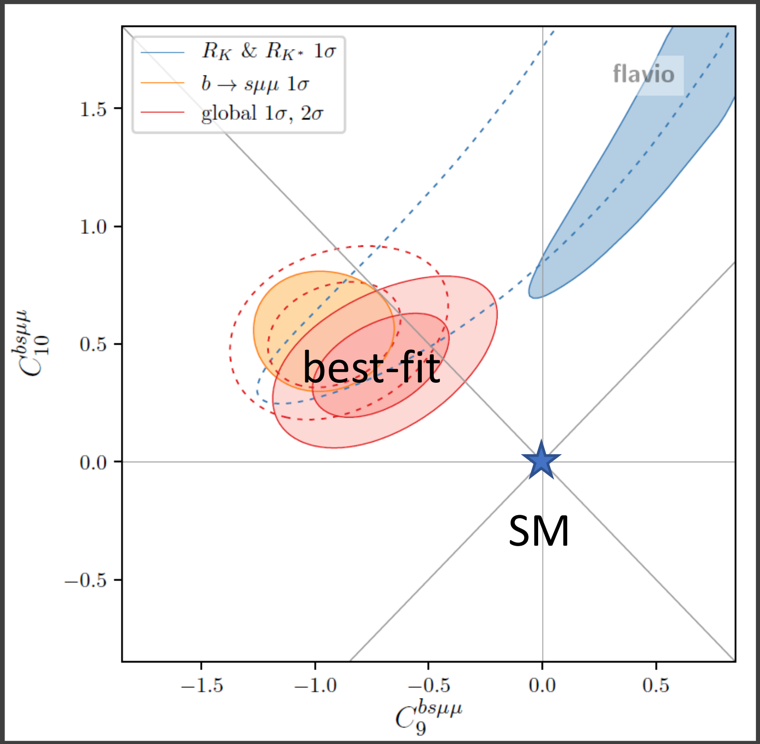
$b \to s\ell\ell$ anomaly

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \sum_{j=9,10} \left(C_j\, \mathcal{O}_j + C_j' \mathcal{O}_j' \right) + h.c.$$

$$\mathcal{O}_9^{(\prime)\mu} = \left(\bar{s}\gamma_\mu P_{L(R)} b\right)\left(\bar{\mu}\gamma^\mu \mu\right) \qquad \mathcal{O}_{10}^{(\prime)\mu} = \left(\bar{s}\gamma_\mu P_{L(R)} b\right)\left(\bar{\mu}\gamma^\mu \gamma_5 \mu\right)$$

- anomalies in B decays
  - $R_K = 0.846^{+0.060}_{-0.054}\ ^{+0.016}_{-0.014}$ is 2.5σ below the SM prediction
  - Branching ratios in $B \to \phi\mu\mu, K\mu\mu$ are $(2-3)\sigma$ below the SM pred.
  - discrepancy in angular observables

combined → $\sqrt{\chi^2_{SM} - \chi^2} > 6\,\sigma$



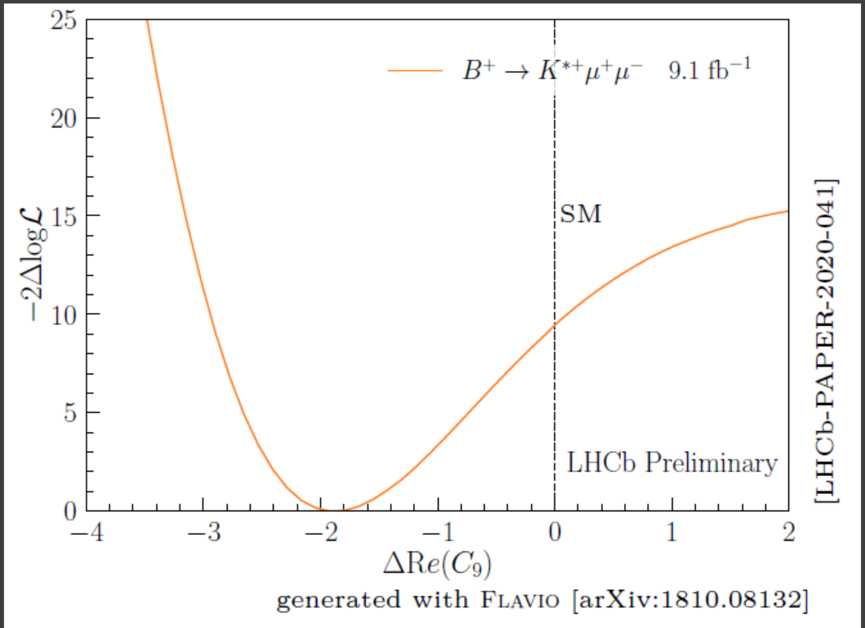
1903.10434 J. Aebischer et.al

$b \to s\ell\ell$ anomaly

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \sum_{j=9,10} \left(C_j\, \mathcal{O}_j + C_j' \mathcal{O}_j' \right) + h.c.$$

$$\mathcal{O}_9^{(\prime)\mu} = \left(\bar{s}\gamma_\mu P_{L(R)} b\right)(\bar{\mu}\gamma^\mu \mu) \qquad \mathcal{O}_{10}^{(\prime)\mu} = \left(\bar{s}\gamma_\mu P_{L(R)} b\right)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$

- anomalies in B decays



- new result on $B^+ \to K^{*+}\mu\mu$ also favors Re $C_9 \sim -1.9$
- Significance from SM is 3.1 σ

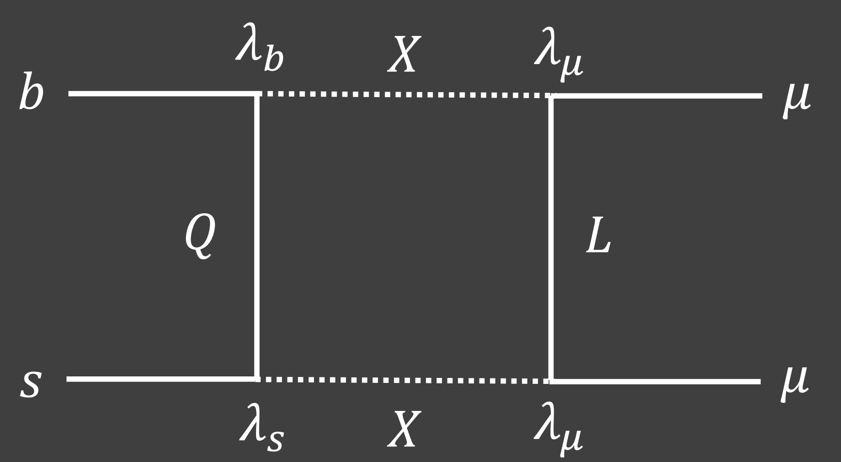
Explanation in fermion portal

preferred pattern may be LL-type: $C_9 = -C_{10} \sim -0.5$

$$\mathcal{O}_9^\mu = (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu) \qquad \mathcal{O}_{10}^\mu = (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$

- Complex DM X + doublet VL quark Q + VL lepton L

Yukawa coupling: $\mathcal{L} \supset \lambda_\mu \overline{\ell_2}\, X\, L_R + \lambda_b\, \overline{q}_3 X Q_R + \lambda_s\, \overline{q}_2 X Q_R$



$q_2 = \begin{pmatrix} c_L \\ s_L \end{pmatrix}$

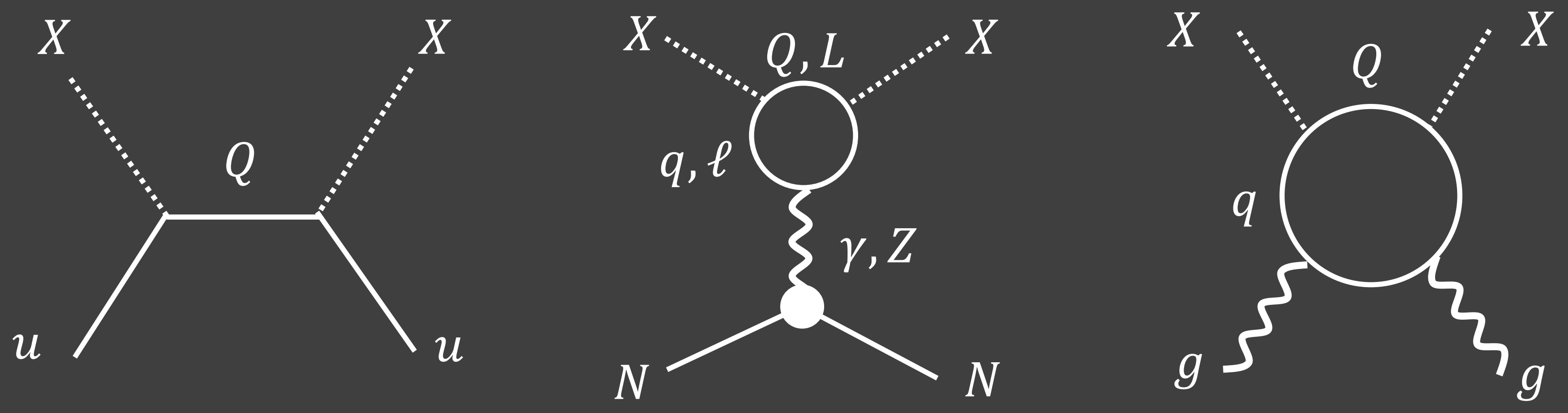
$q_3 = \begin{pmatrix} t_L \\ b_L \end{pmatrix}$

flavor violation is necessary in quark sector ➔ $B_s - \overline{B}_s$, $D - \overline{D}$ mixing

Direct detection

VL quark mediator affects to direct detection significantly

➢ Processes

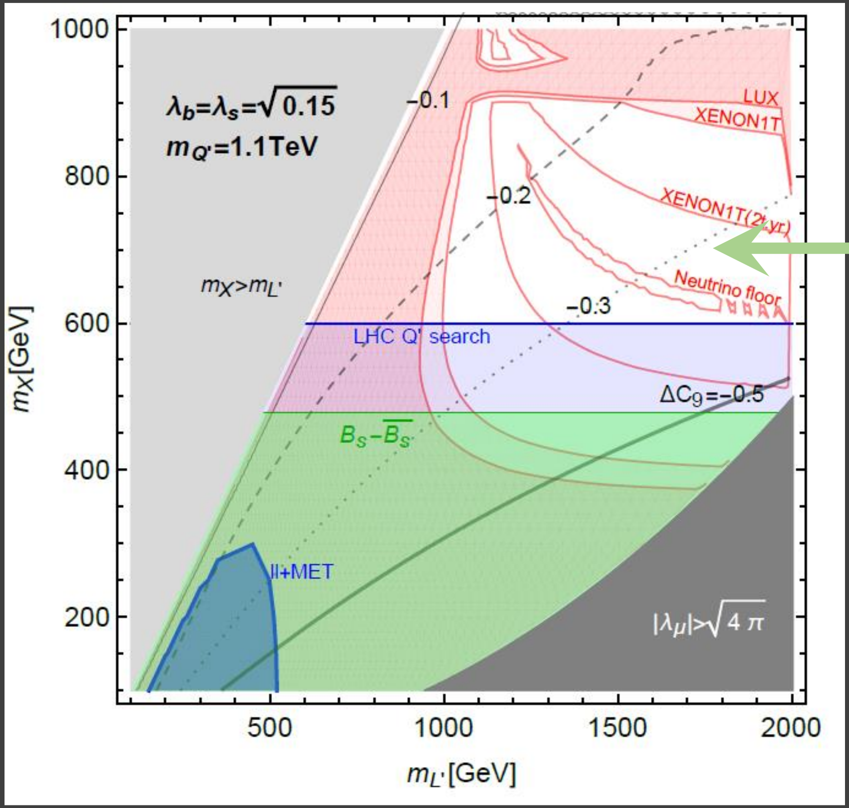


- there is, in general, tree-level scattering via CKM mixing $\propto \lambda_s V_{uc}$
- γ/Z penguin tends to dominate, Z-penguin enhanced by top mass
- γ and Z penguins are destructive
- gluon scattering is subdominant

Result

λ_μ is fixed to explain relic density. Typically $\lambda_\mu \sim 2$

1706.04344
JK, Y.Omura, S.Okawa



LHC limit: $36\ \mathrm{fb}^{-1}$

$C_9 = -0.3$

* complex DM

- $C_9 = -C_{10} \sim -0.3$ is compatible with LHC limit and direct detection
- cancellation in direct detection rate happens

Summary

➢ Muon $g-2$

- both singlet and doublet mediators are necessary for sizable Δa_μ
- can be explained with DM in real scalar and Majorana cases
- tends to be too big, mild tuning $O(0.1)$ may be needed

➢ $b \to s\ell\ell$

- both doublet VL quark and VL lepton are necessary
- we considered complex scalar DM
- $C_9 = -C_{10} \sim -0.3$ is possible where direct detection rate is canceled

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Conclusion

- Minimal lepton portal models
  - we studied real, complex, Majorana and Dirac singlet DM w/ 1 mediator
  - complex and Dirac DM are almost excluded by direct detection
  - real DM may predict peaked signal
  - Majorana DM is tough to be tested

- Simultaneous explanation with muon anomalies
  - Δa_μ can be explained in models with singlet and doublet mediators
  - $b \to s\mu\mu$ can be partially explained in narrow parameter space

Thank you !!

Backup

Direct detection of fermion DM

charge radius magnetic dipole anapole electric dipole

$$\mathcal{L}^F_{\rm multipole} = b_\chi \bar{\chi}\gamma^\mu \chi \partial^\nu F_{\mu\nu} + \frac{\mu_\chi}{2}\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} + a_\chi \bar{\chi}\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu} + i\frac{d_\chi}{2}\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu},$$

$$\mathcal{L}^F_{\rm eff} = \sum_{N=p,n}\left(C_{S,N}\bar{\chi}\chi\overline{N}N + C_{V,N}\bar{\chi}\gamma^\mu\chi\overline{N}\gamma_\mu N\right).$$

1503.03382 A.Ibarra et.al

→

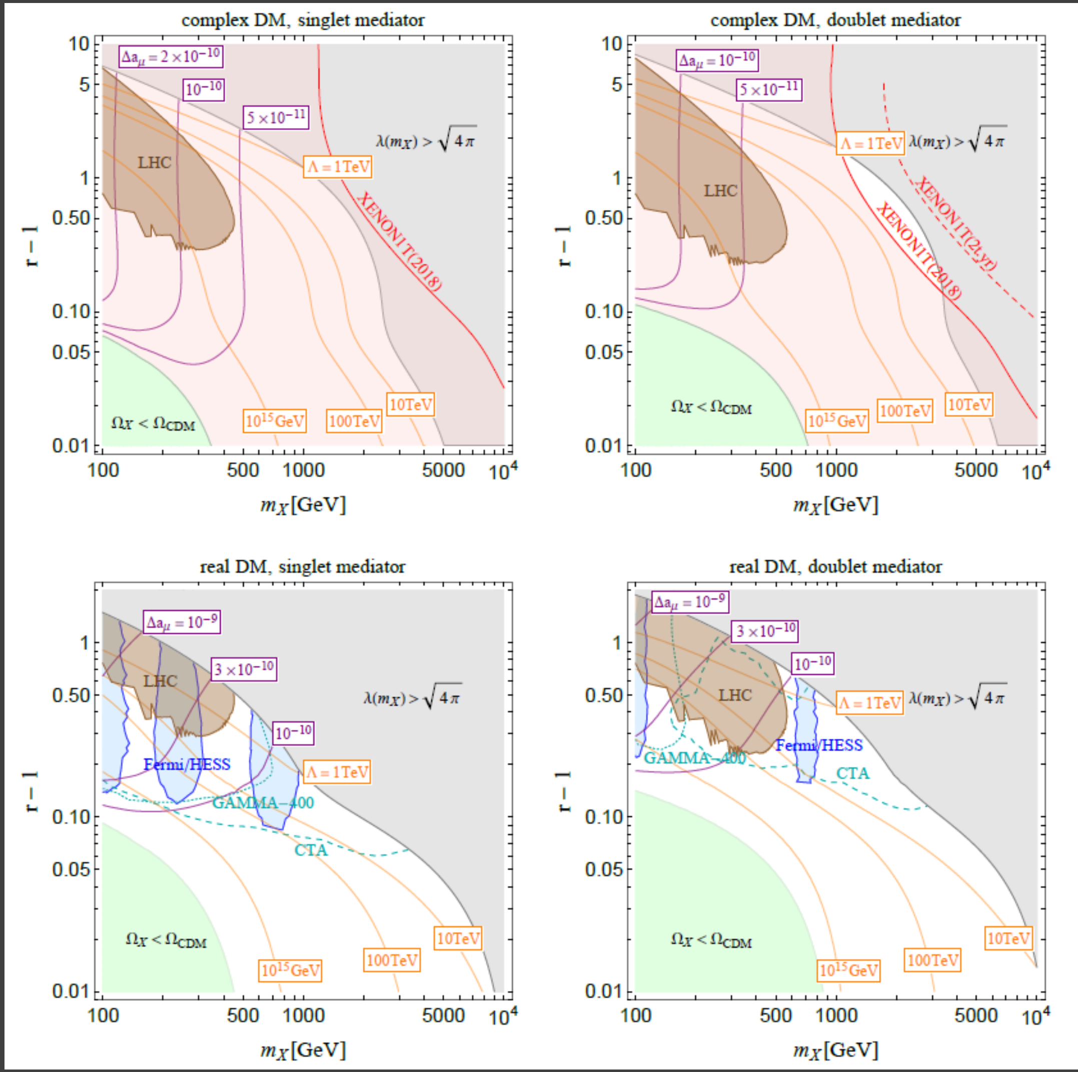
$$\frac{d\sigma}{dE_R} = \frac{\alpha Z^2}{v^2}\left[\mu_\chi^2\left(\frac{v^2}{E_R} - \frac{m_N}{2\mu^2_{\rm red}}\right) + d_\chi^2\left(\frac{1}{E_R} - \frac{1}{m_\chi}\right)\right]|F(E_R)|^2 + \frac{m_N f_A^2}{2\pi v^2}|F(E_R)|^2$$
$$+ \frac{\alpha Z^2}{v^2}a_\chi^2\left[2m_N v^2 - \frac{(m_N+m_\chi)^2}{m_\chi^2}E_R\right]|F(E_R)|^2$$
$$+ \frac{m_N\mu_A^2}{2\pi v^2}\left(2\mu_\chi^2 + d_\chi^2 v^2 + 4m_N E_R a_\chi^2\right)\frac{J_A+1}{3J_A}|F_{\rm spin}(E_R)|^2,$$

$$f_A = Z\left(C_{S,p} + C_{V,p} - eb_\chi - e\mu_\chi/(2m_\chi)\right) + (A-Z)\left(C_{S,n} + C_{V,n}\right)$$

- $b_\chi = \mu_\chi = d_\chi = 0$ for Majorana DM
- anapole a_χ contribution is suppressed by velosity v or recoil energy E_R

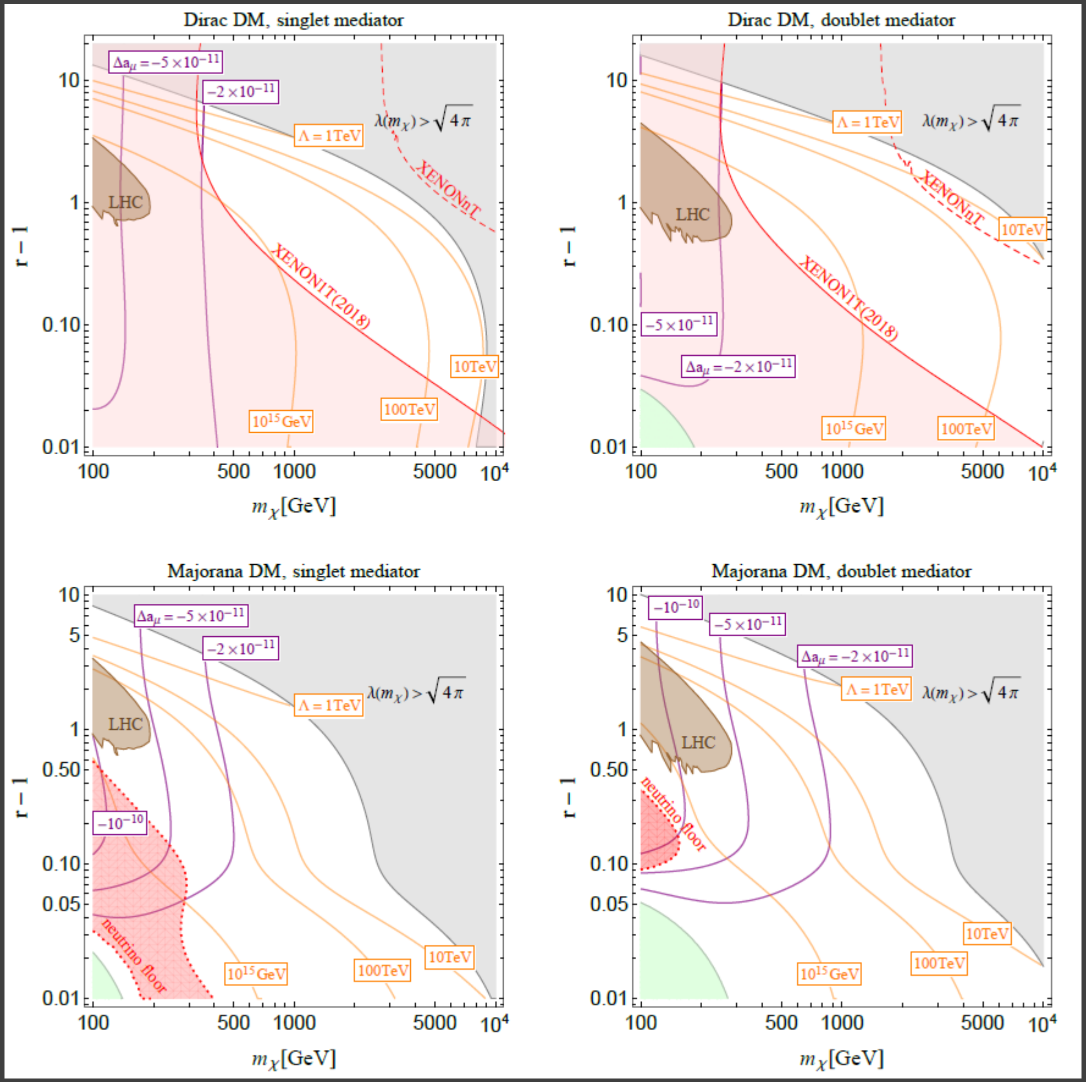
Current status of scalar DM

Yukawa is fixed to explain thermal relic density via (co-)annihilation



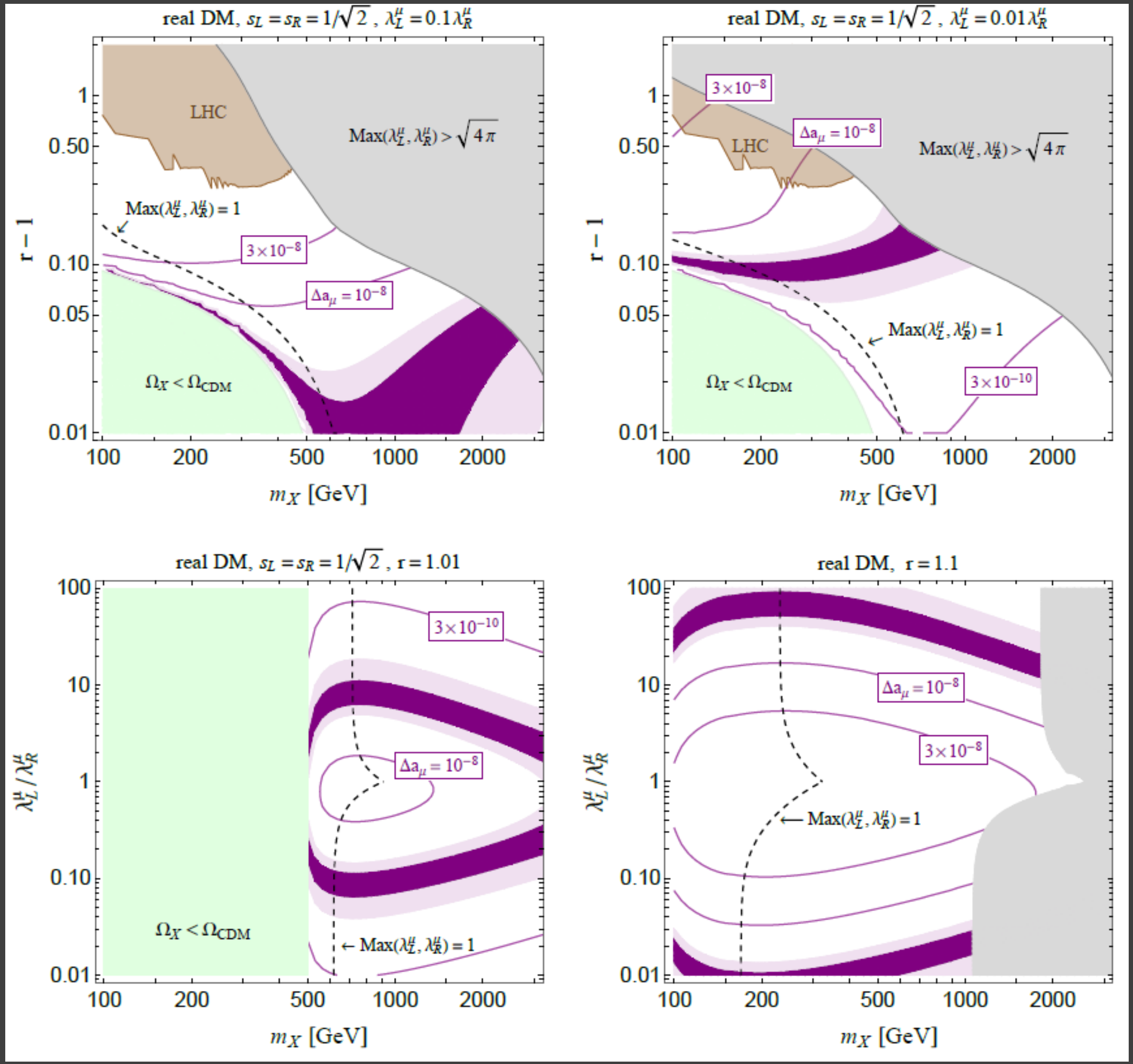
Current status of fermion DM

Yukawa is fixed to explain thermal relic density via (co-)annihilation



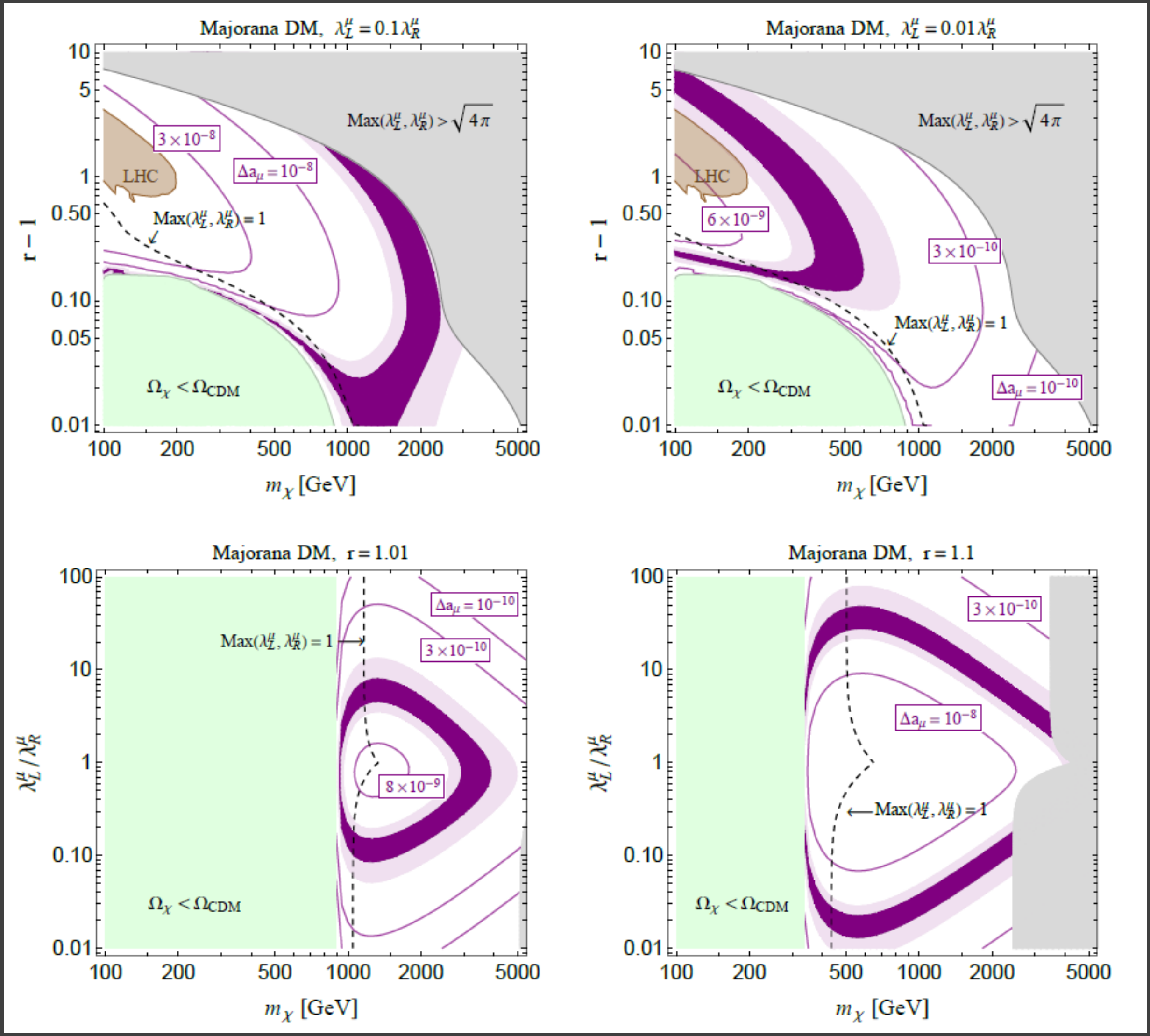
g-2 in scalar DM

Yukawa is fixed to explain thermal relic density via (co-)annihilation



g-2 in fermion DM

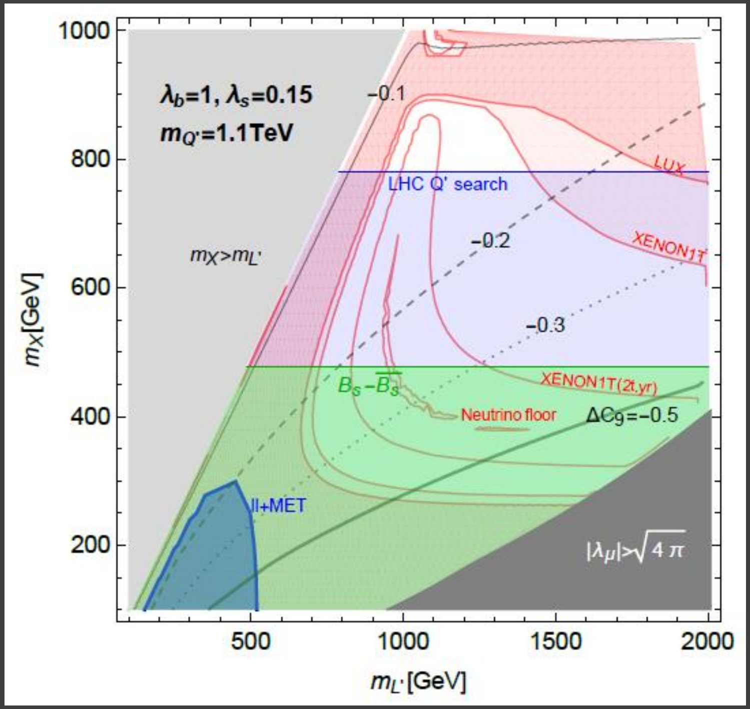
Yukawa is fixed to explain thermal relic density via (co-)annihilation

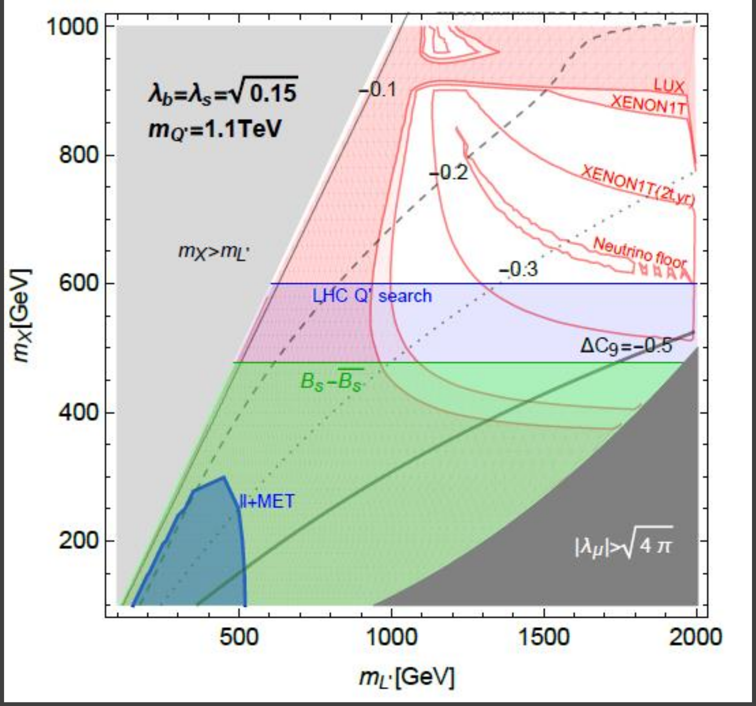


Result

λ_μ is fixed to explain relic density. Typically $\lambda_\mu \sim 2$

LHC limit: $36\ \mathrm{fb}^{-1}$

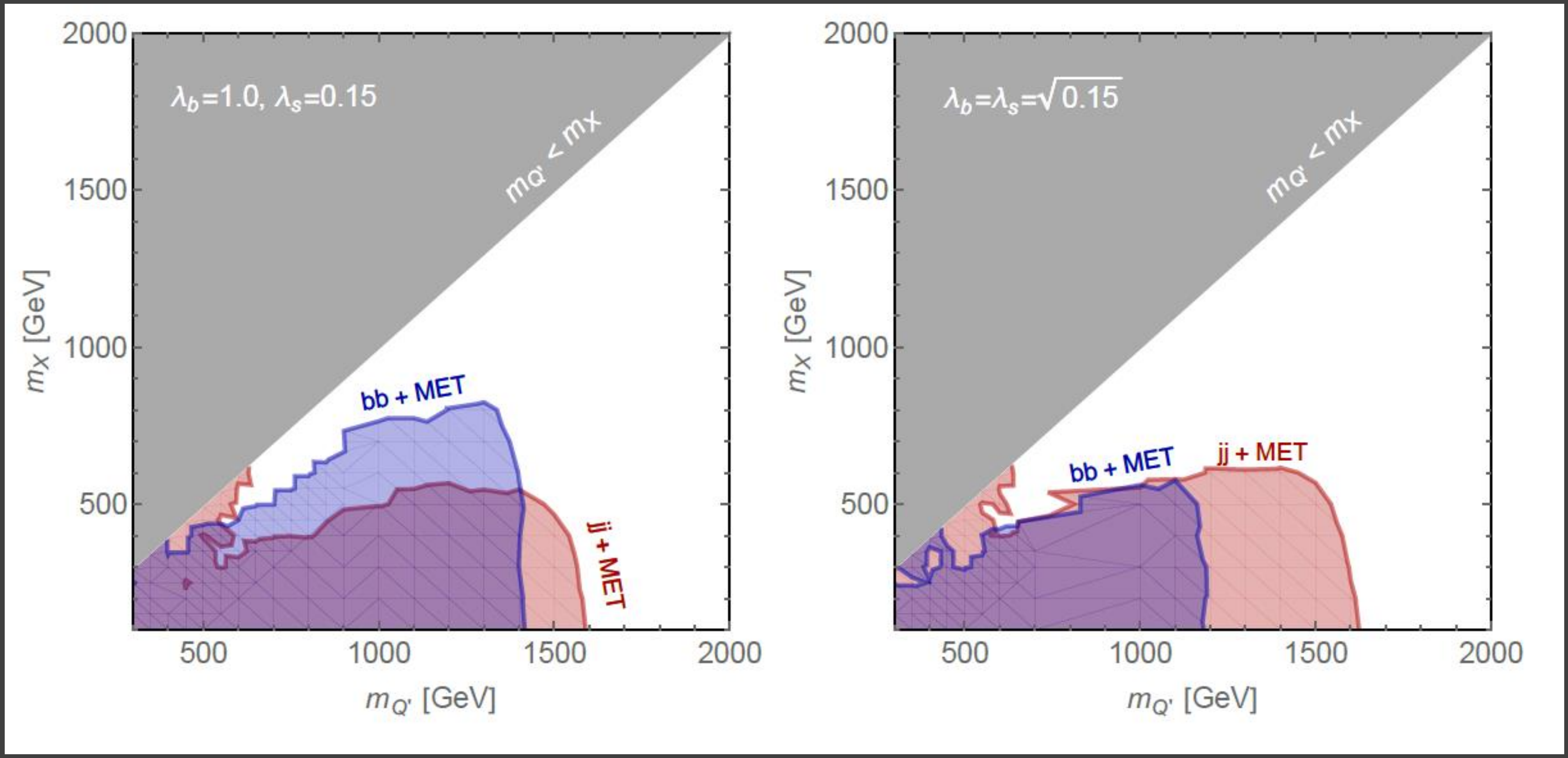




- $C_9 = -C_{10} \sim 0.3$ is compatible with LHC limit and direct detection
- cancellation in direct detection rate happens

LHC limit on VL quark

integrated luminosity is 36 fb^{-1}



ΔC_9 vs collider constraints

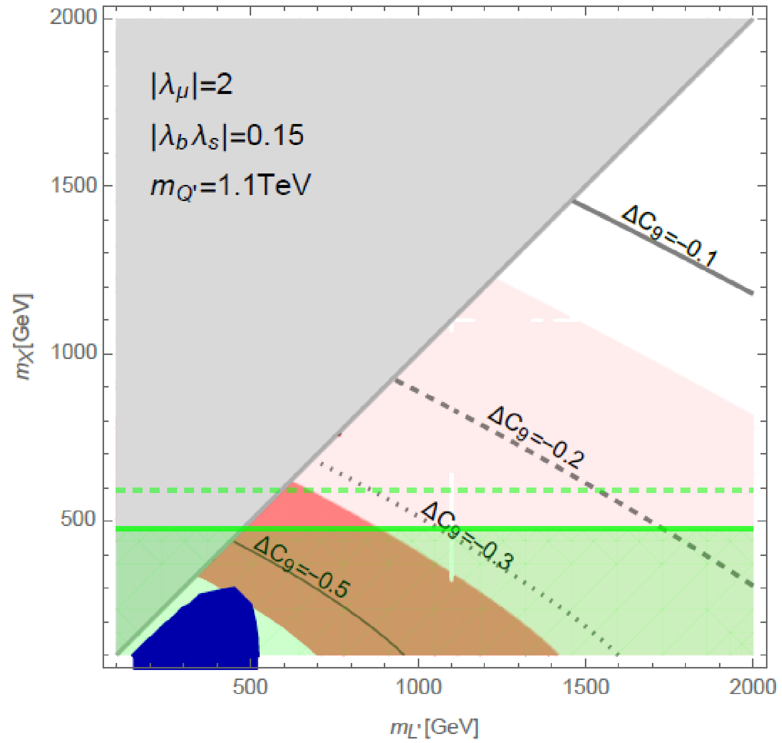


Figure 3: ΔC_9 on the plane of $m_{L'}$ and m_X with $|\lambda_\mu| = 2$, $|\lambda_b\lambda_s| = 0.15$ and $m_{Q'} = 1.1$ TeV. The size of $\Delta C_9 = -\Delta C_{10}$ on each black line is -0.1 (thick), -0.2 (dashed), -0.3 (dotted), and -0.5 (solid), respectively. The (light) red region is the 1σ (2σ) region of R_K. The (dashed) green line depicts the lower limit from $B_s - \overline{B_s}$ mixing in Eq. (7) at $m_{Q'} = 1.1$ TeV (1 TeV). The blue region is excluded by $\mu\mu + E_T^{\rm miss}$ at the LHC [31].