LEPTOPHILIC NEW PHYSICS: DARK MATTER AND THE MUON G-2

based on JHEP 1405(2014)145 with Ayres Freitas, Stefan Kell and Joe Lykken
and on JHEP 1410(2014)116 with Ayres Freitas

Susanne Westhoff

University of Pittsburgh

Seminar - December 18, 2014 - LAPTh Annecy

LEPTON MAGNETIC MOMENT

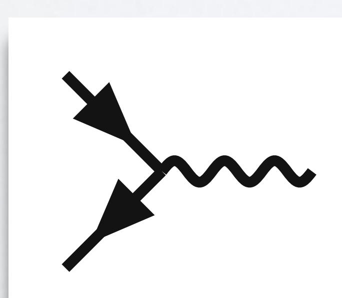
Pauli equation for lepton in electromagnetic field: [W. Pauli, 1927]

$$i\hbar\frac{\partial\varphi}{\partial t} = \Big(\frac{1}{2m_\ell}(\vec{p} - \frac{e}{c}\vec{A})^2 - \frac{e\hbar}{m_\ell c}\vec{s}\cdot\vec{B}\Big)\varphi$$

Lepton magnetic moment: $\vec{\mu}_\ell = g_\ell \dfrac{e\hbar}{2m_\ell c}\vec{s}$

Quantum corrections induce **anomalous magnetic moment**:

$$g_\ell = 2(1 + a_\ell)$$



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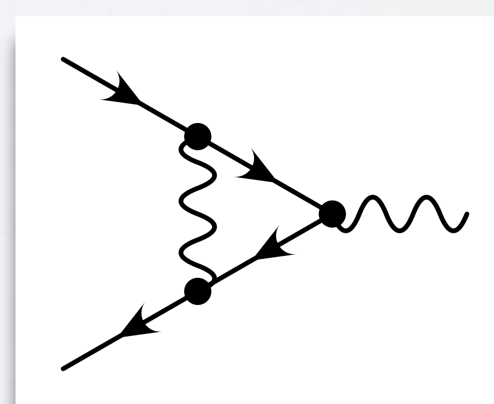
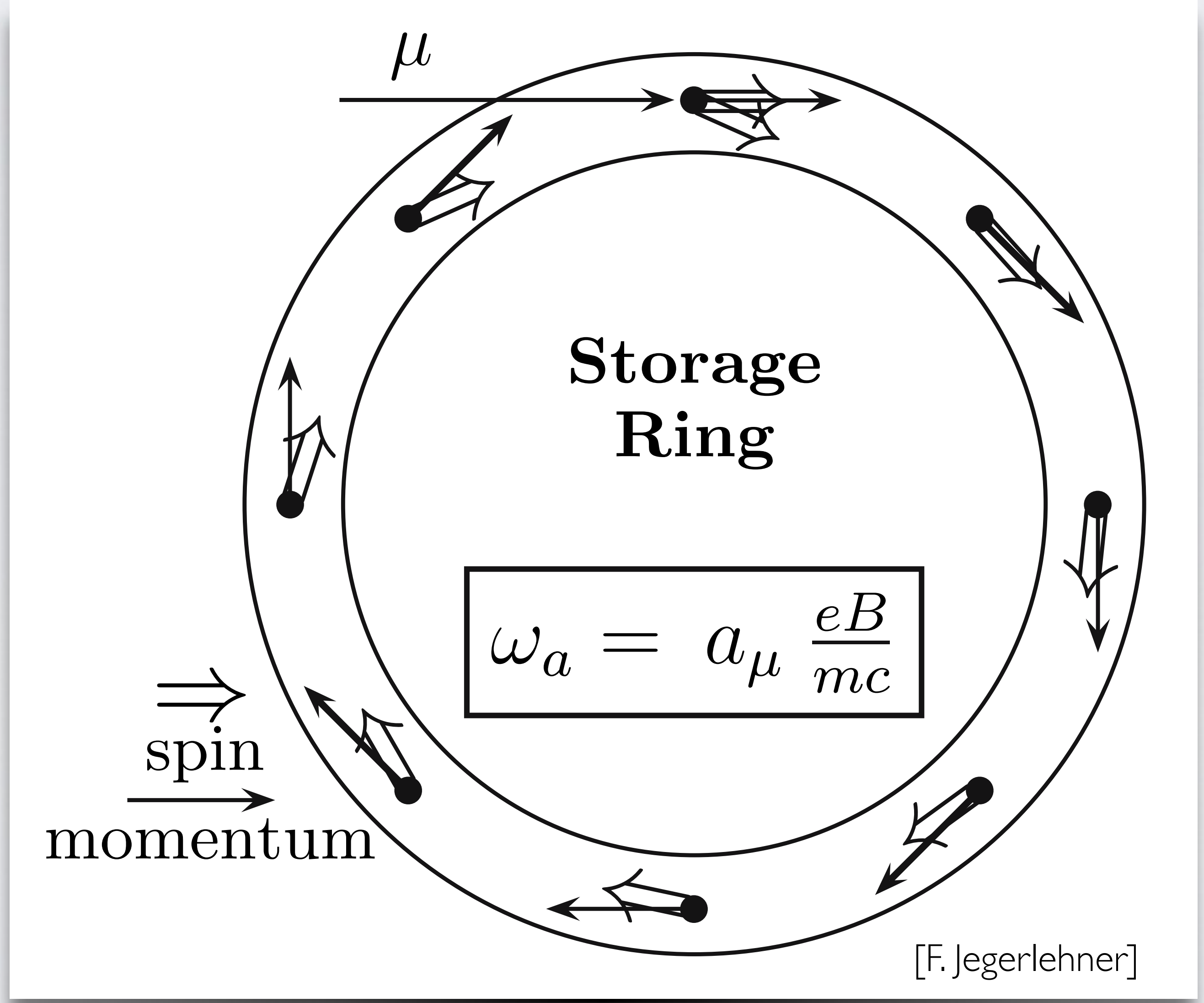


$$a_\ell = \frac{g_\ell - 2}{2}$$

MEASURING THE MUON G-2

Larmor precession of muon in magnetic field:

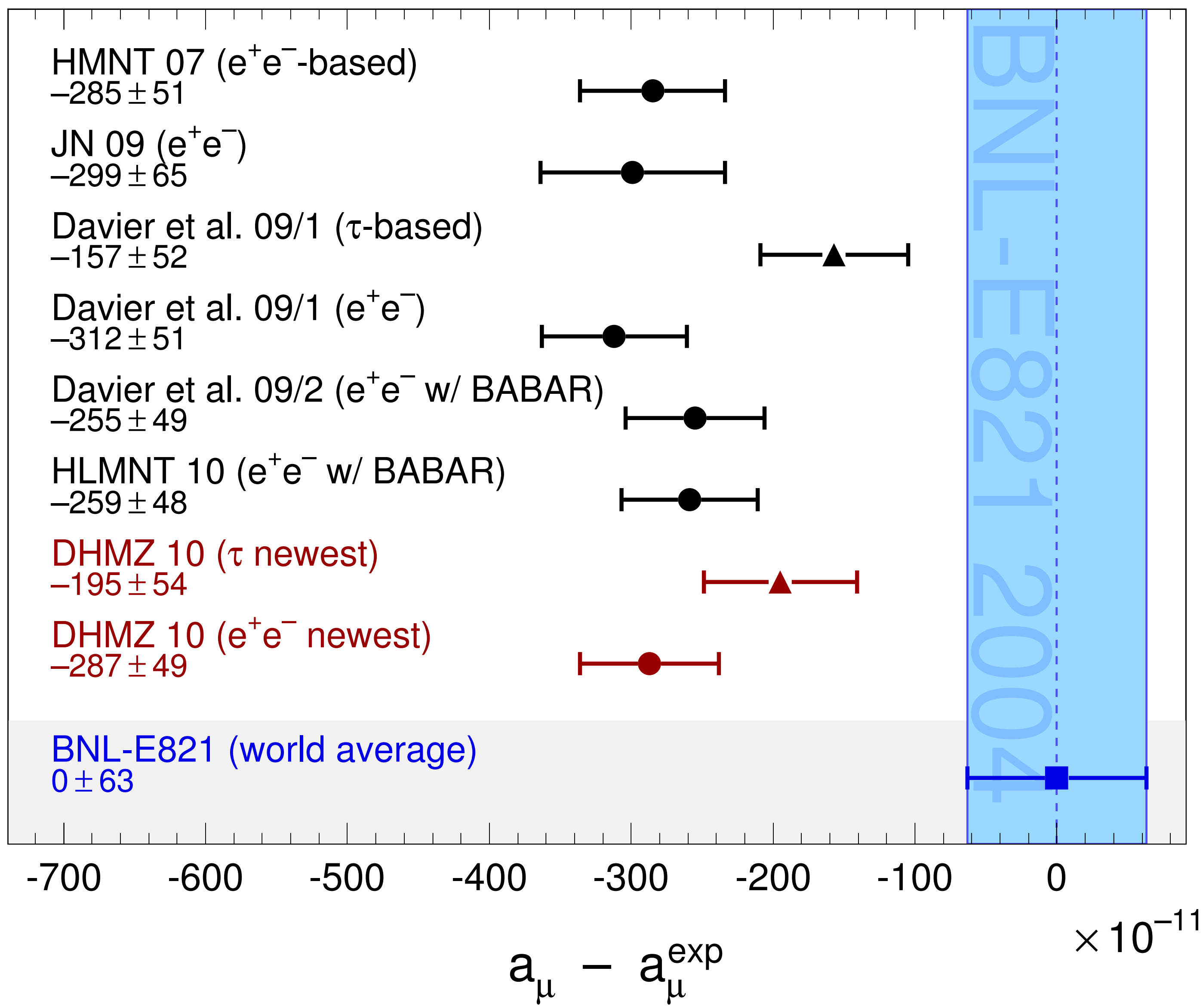
$$\omega_s - \omega_c = \frac{e}{m_\mu}\Big[a_\mu \vec{B} - \Big(a_\mu - \frac{1}{\gamma^2 - 1}\Big)\vec{\beta} \times \vec{E}\Big]_{E_\mu \approx 3.1\,\mathrm{GeV}} = \frac{e}{m_\mu} a_\mu \vec{B}$$



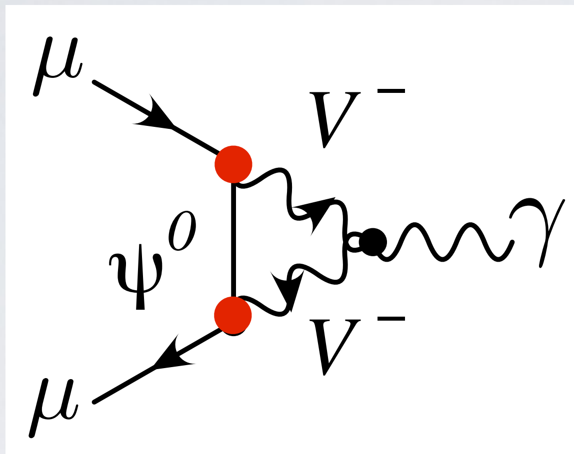
LEPTOPHILIC NEW PHYSICS?

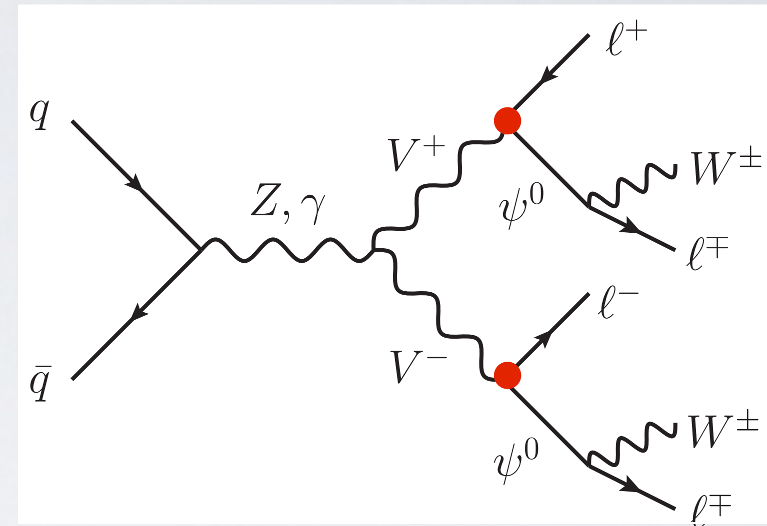
The measured muon g-2 differs from its prediction in the standard model:

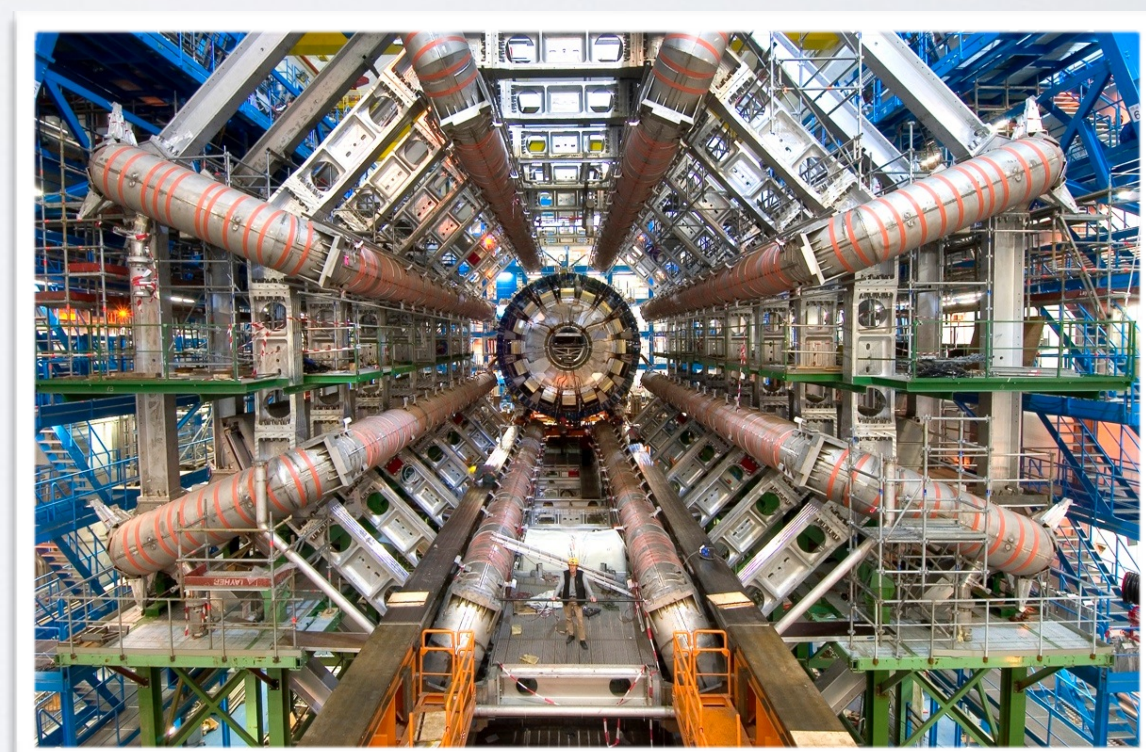
[Davier et al., Eur.Phys.J. C71(2011) 1515]



MUON G-2 AND THE LHC



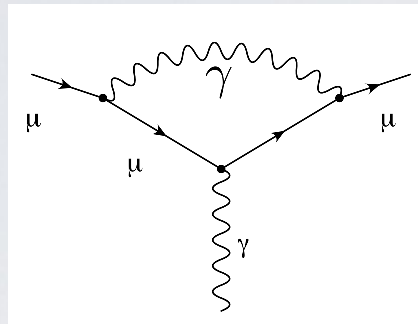




MUON G-2 IN THE STANDARD MODEL

[Davier et al., Eur.Phys.J. C71(2011) 1515]

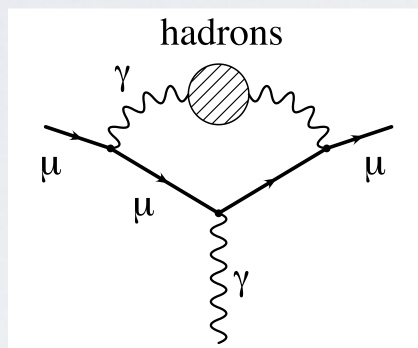
$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}}$$



$$\frac{\alpha}{2\pi} + \ldots \left(\frac{\alpha}{\pi}\right)^5 : \quad 116584718.951(10)$$

$[10^{-11}]$

$$+ a_\mu^{\mathrm{had}}$$

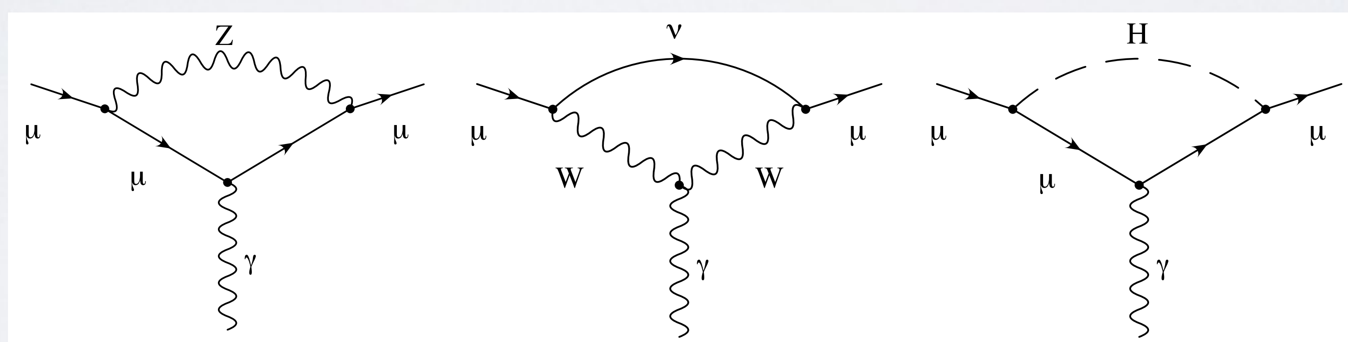


Leading order: $6923(42)$

Higher orders: $-97.9(0.9)$

Light-by-light sctg.: $105(26)$

$$+ a_\mu^{\mathrm{EW}}$$



$$\frac{G_F m_\mu^2}{8\sqrt{2}\pi^2}\left[\frac{5}{3} + \frac{1}{3}(1 - 4\sin^2\theta_W)^2 + \mathcal{O}\left(\frac{m_\mu^2}{M_{\mathrm{EW}}^2}\right)\right] + (2-\mathrm{loop}) : \quad 154(1)$$

$$\boxed{a_\mu^{\mathrm{SM,tot}} = 116591802(49) \times 10^{-11}}$$

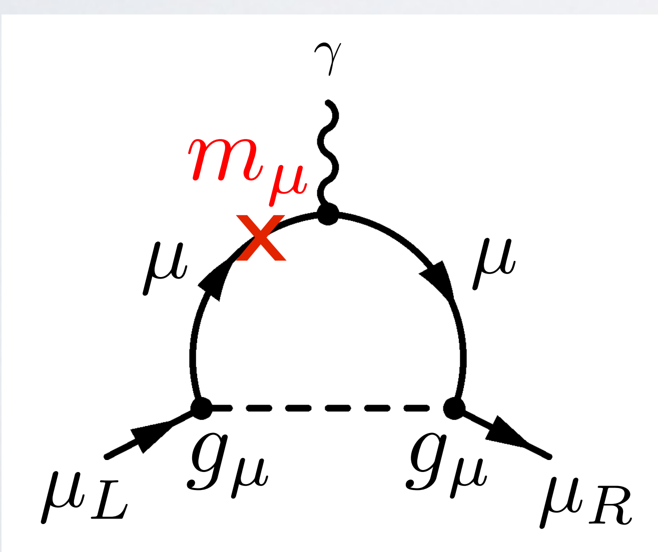
NEW PHYSICS IN G-2

$$\boxed{\Delta a_\mu \equiv a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (287 \pm 80) \times 10^{-11} \sim a_\mu^{\mathrm{EW}}}$$

[Jegerlehner, Nyffeler, arXiv:0902.3360]

Focus on mass range accessible in direct production at LHC:

$$\boxed{\begin{array}{c} M_{\mathrm{NP}} > 100\,\mathrm{GeV} \\ g_\mu = \mathcal{O}(1) \end{array}}$$



[cf. Agrawal, Chacko, Verhaaren, arXiv:1402.7369]

Need chiral symmetry breaking:

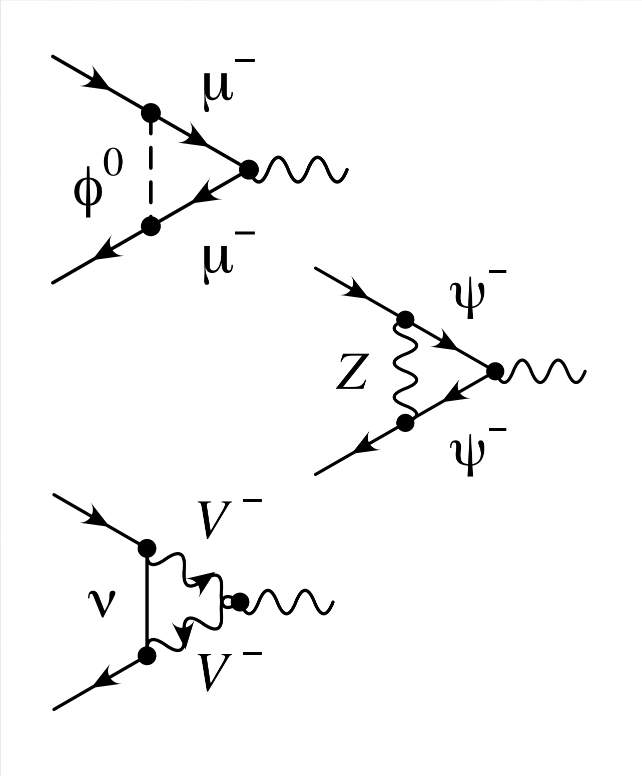
$$\Delta a_\mu^{\mathrm{NP}} \sim g_\mu^2 \frac{m_\mu^2}{M_{\mathrm{NP}}^2} \longrightarrow \frac{a_\mu}{a_e} \sim \frac{m_\mu^2}{m_e^2} \sim 4 \times 10^4$$

A MODEL-INDEPENDENT APPROACH

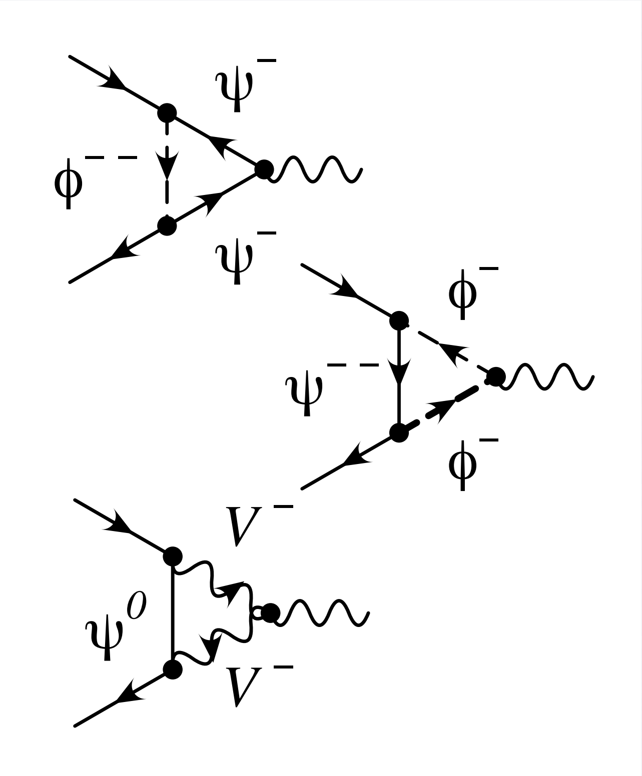
Consider new fields:

- spin 0,1/2,1 and integer electric charge
- weak singlets, doublets, triplets (all color singlets)

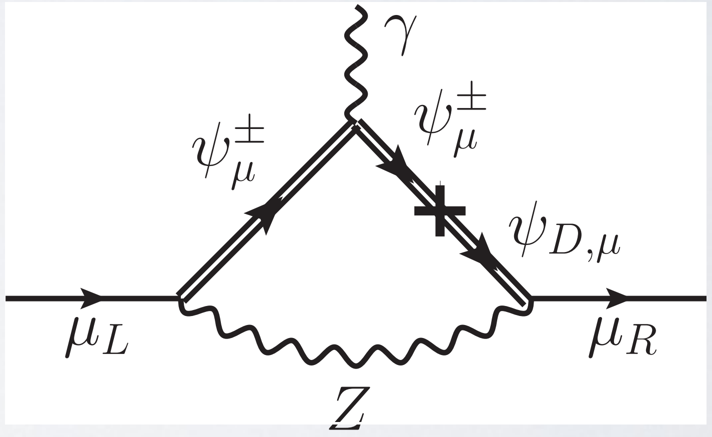
Three classes of one-loop contributions to a_μ :



One new field



Two new fields

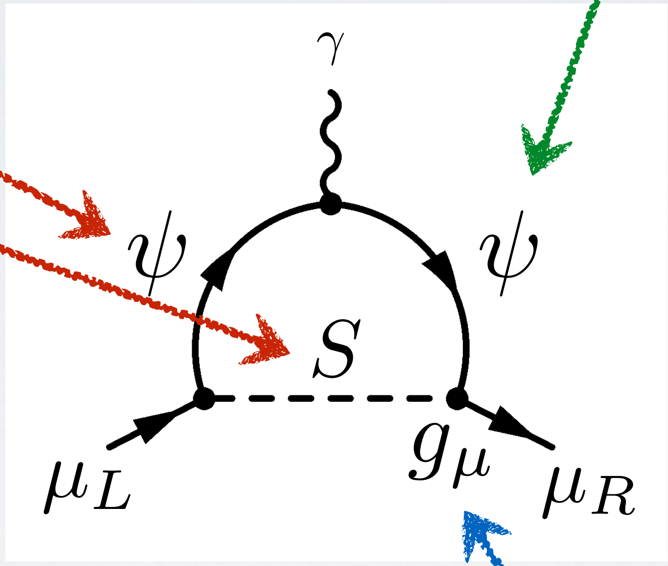


Two mixing fermions

GENERAL PARTICLE FEATURES

New fermions:
vector-like weak interactions.

Weak multiplet members
are **degenerate in mass**.

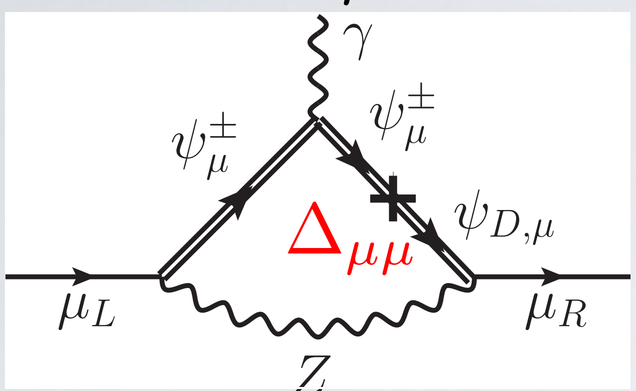


Real, perturbative couplings to leptons.

All interactions are **minimally flavor-violating**.

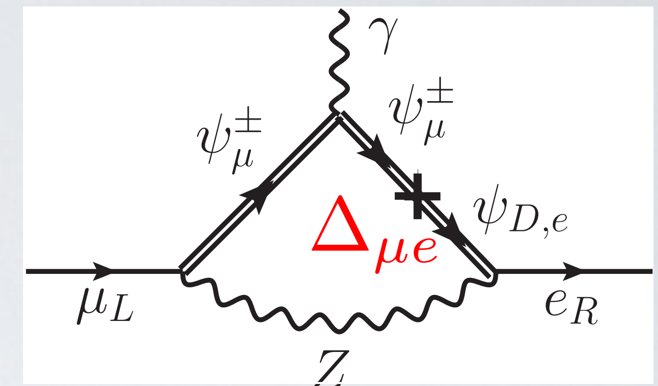
MINIMAL FLAVOR VIOLATION

a_μ



$$\mathcal{O}_{\mu\ell} = g y_\mu \Delta_{\mu\ell} H^\dagger \overline{\ell_R} \sigma^{\alpha\beta} A_{\alpha\beta} \mu_L$$

$\mu \to e\gamma$



Strong experimental bound on flavor violation $\sim \Delta_{\mu e}$:

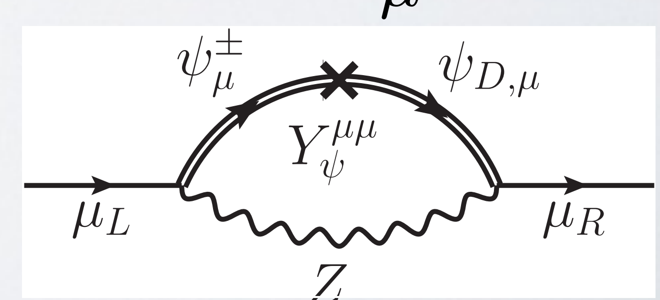
$$\mathcal{B}(\mu \to e\gamma) \approx 6.34 \times 10^{-7} \left(\frac{1\mathrm{TeV}^4}{\Lambda_{\mathrm{FV}}^4} \right) |\Delta_{\mu e}|^2 < 2.4 \times 10^{-12}$$

[Cirigliano et al., Nucl.Phys.B728 (2005) 121]

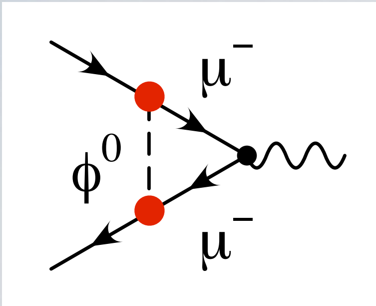
MFV implications for g-2 scenarios:

- Fermions in **fundamental** representation of $\mathcal{G}_F = \mathrm{SU}(3)_L \times \mathrm{SU}(3)_e$.
- Three **flavor copies** of new fermions.
- (At least) one Yukawa suppression, here: $\Delta_{\mu\mu} \sim y_\mu$.

m_μ

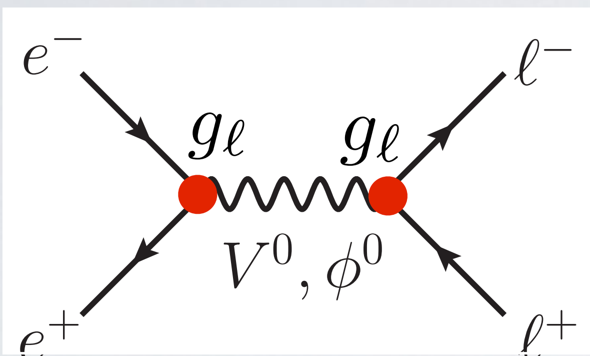


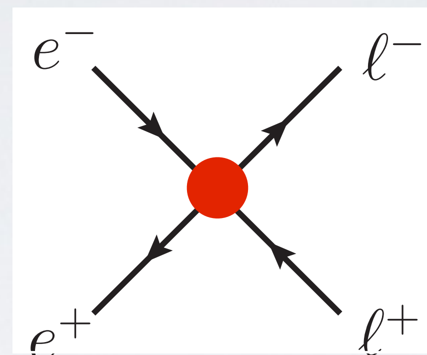
Muon mass protected: $m_\mu = y_\mu v(1 + \delta m_\mu)$



ONE NEW BOSON: LEP BOUNDS

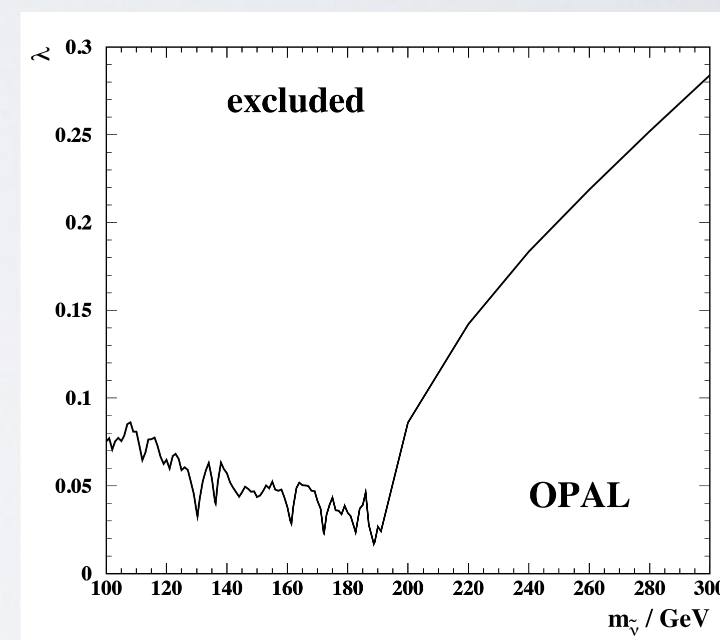
$M > \sqrt{s} \sim 200\,\mathrm{GeV}$: 4-lepton contact interactions





$$\sim \frac{g_\ell^2}{M_{V,\phi}^2} \lesssim (0.0003\,\mathrm{GeV}^{-1})^2$$

[LEP colls., hep-ex/0612034]



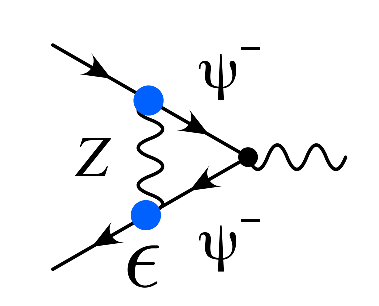
[OPAL coll., Eur.Phys.J. C13 (2000) 553]

$M < 200\,\mathrm{GeV}$: neutralino resonance searches

$$e^+e^- \to (V^0, \phi^0)\gamma \to \ell^+\ell^-\gamma$$

$$\to g_\ell / M_{V,\phi} \lesssim 0.0008\,\mathrm{GeV}^{-1}$$

Exclude neutral vector boson and scalar doublet or scalar adjoint triplet as explanations of Δa_μ.



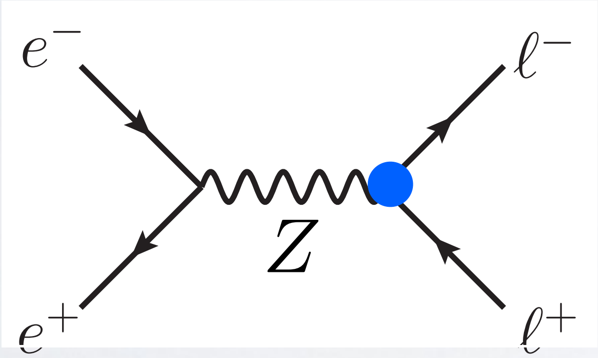
ONE NEW FERMION: LEP BOUNDS

New fermions mixing with SM leptons, $\epsilon = \dfrac{Y_\ell v}{M_\psi}$:

$$\mathcal{L} \supset -Y_\ell \overline{\psi_L} H \ell_R + \text{h.c.} \xrightarrow{\langle H \rangle} \quad \epsilon\, \overline{\psi_R} \gamma^\mu \ell_R Z_\mu \qquad (a_\mu)$$

and $(1 - \epsilon^2/2) \overline{\ell_R} \gamma^\mu \ell_R Z_\mu$ (LEP)

Global fit to LEP data: $|\epsilon| \lesssim 0.03$ [Aguila et al., PRD78 (2008) 013010]



$\sim (1 - \epsilon^2/2)$

Excludes explanation of Δa_μ by a fermion doublet or charged singlet (neutral singlet and triplet yield $\delta a_\mu < 0$).

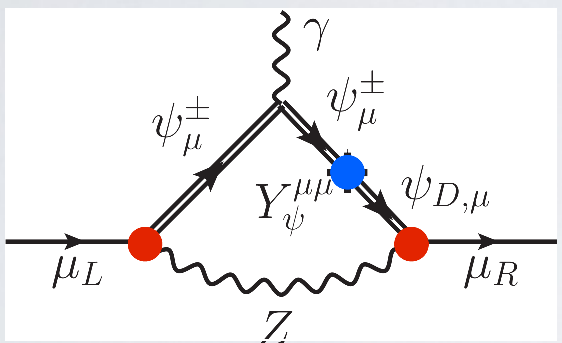
MIXING VECTOR FERMIONS

(Here: charged singlet $\psi^{\pm}$ and doublet ψ_D)

Two viable **minimally flavor-violating** scenarios:

a) $\psi^{\pm} = (3,1),\ \psi_D = (1,3)$

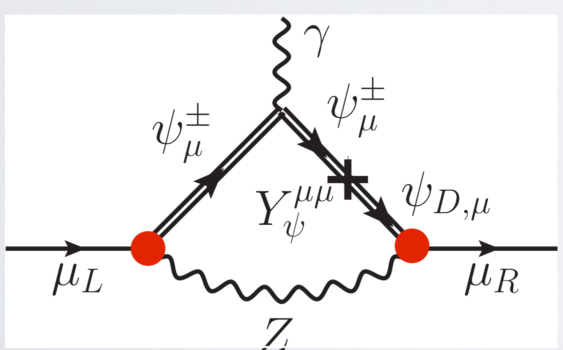
$$\delta a_\mu \sim m_\mu \cdot Y_\psi v \cdot \epsilon_1 \epsilon_2$$



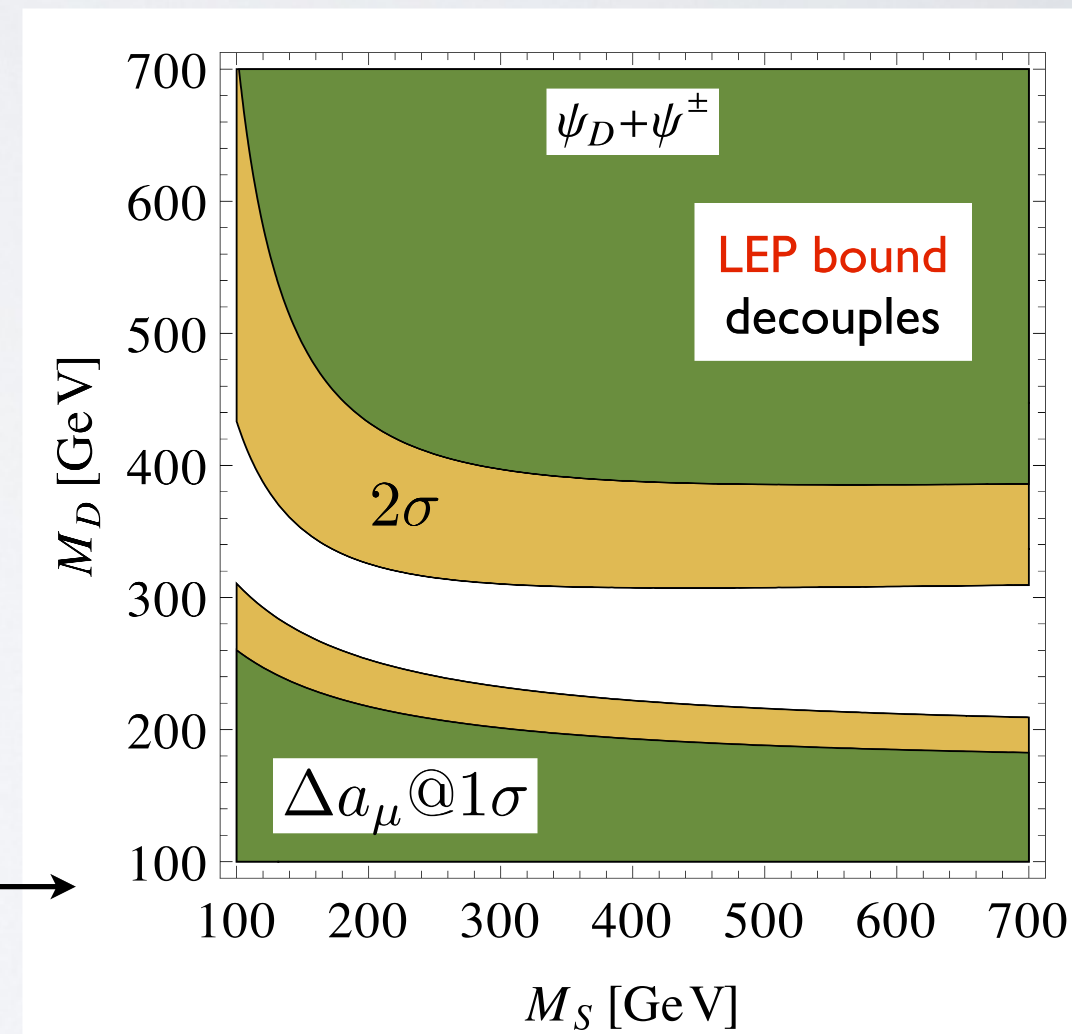
$|Y_\psi| \lesssim 0.2,\ |\epsilon| \lesssim 0.03$

$\longrightarrow\ \delta a_\mu \lesssim \mathcal{O}(10^{-10})$

b) $\psi^{\pm}, \psi_D = (1,3)$ or $(3,1)$



$|Y_\psi| \lesssim \sqrt{4\pi},\ |\epsilon| \lesssim 0.03$

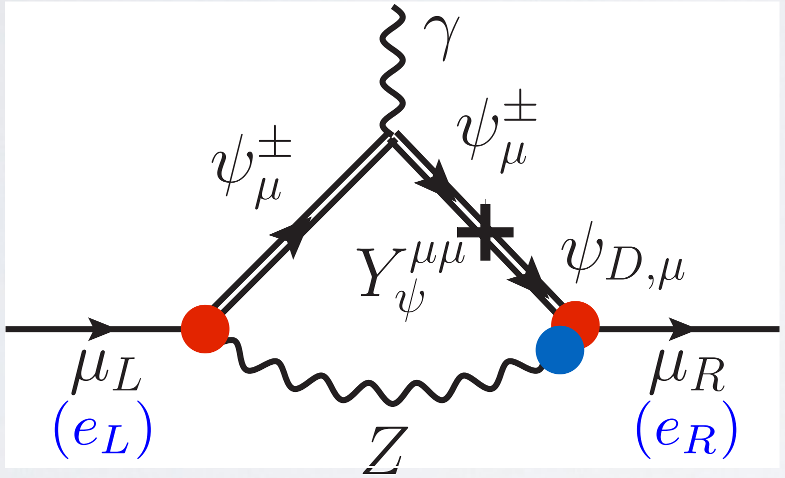


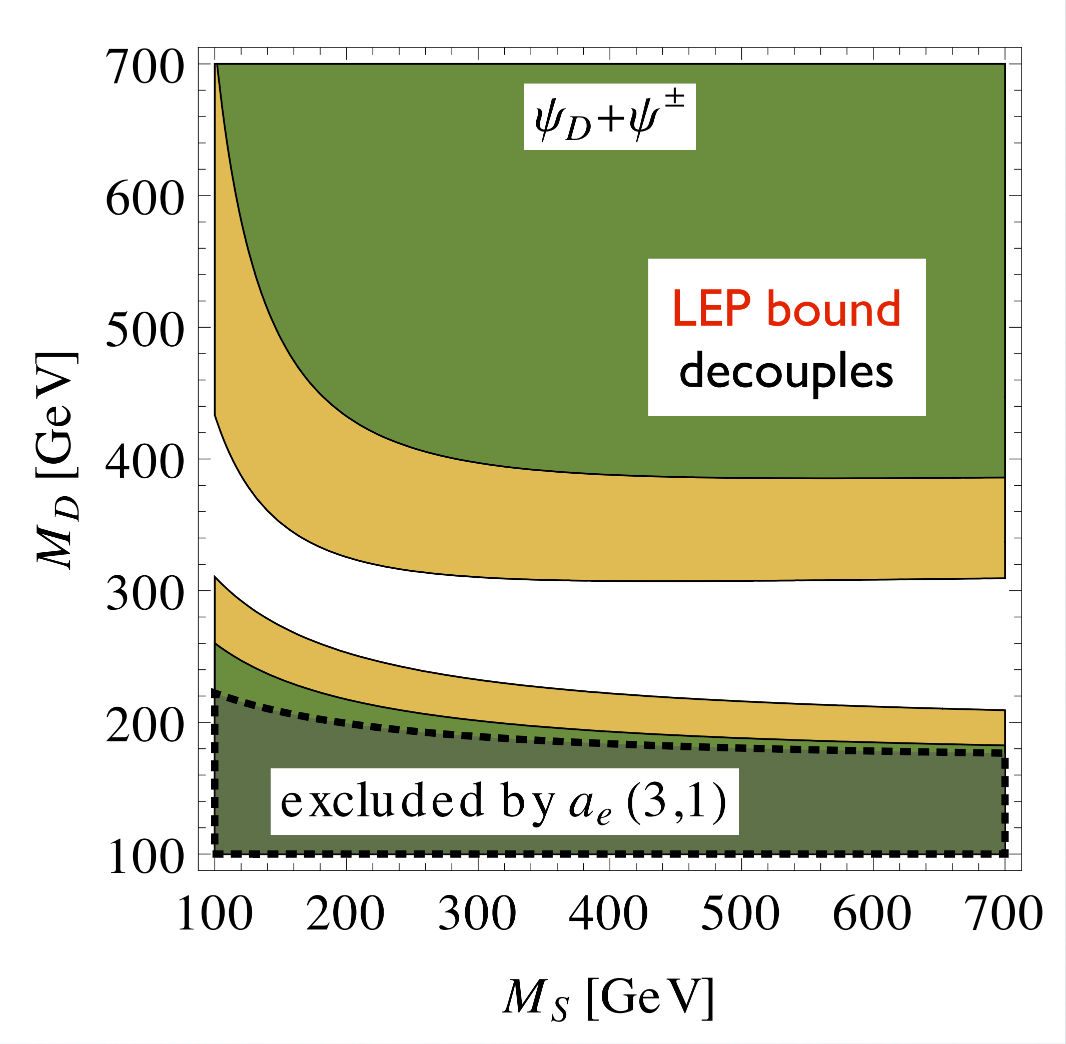
BOUNDS FROM ELECTRON MOMENT

(Here: charged singlet $\psi^\pm$ and doublet ψ_D)

Electron g-2: $a_e^{\rm exp} - a_e^{\rm SM} = (-1.06 \pm 0.82) \times 10^{-12}$ [Aoyama et al., PRL 109 (2012)111807]

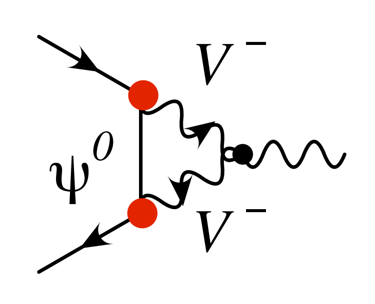
Consider $\psi^\pm = \psi_D = (3,1)$:





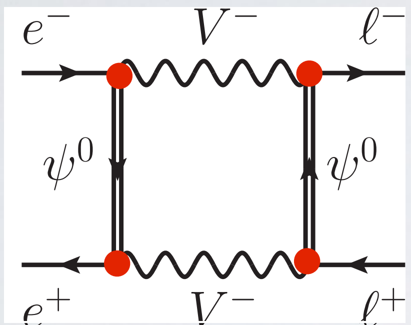
$$\boxed{\delta a_e = \frac{m_e^2}{m_\mu^2} \cdot \max\left\{\frac{\sqrt{4\pi} y_\mu / y_\tau}{0.03\, M_D / v}, 1\right\} \delta a_\mu}$$

$= \mathcal{O}(10^{-12})$ for $M_D \lesssim v$

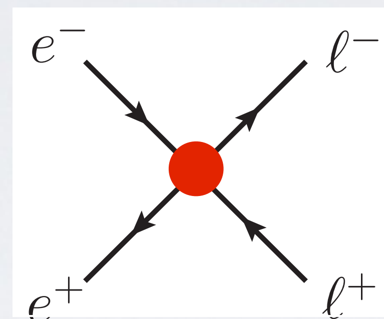


TWO NEW FIELDS: LEP BOUNDS

Indirect bound on SM-NP-NP couplings at one-loop level:



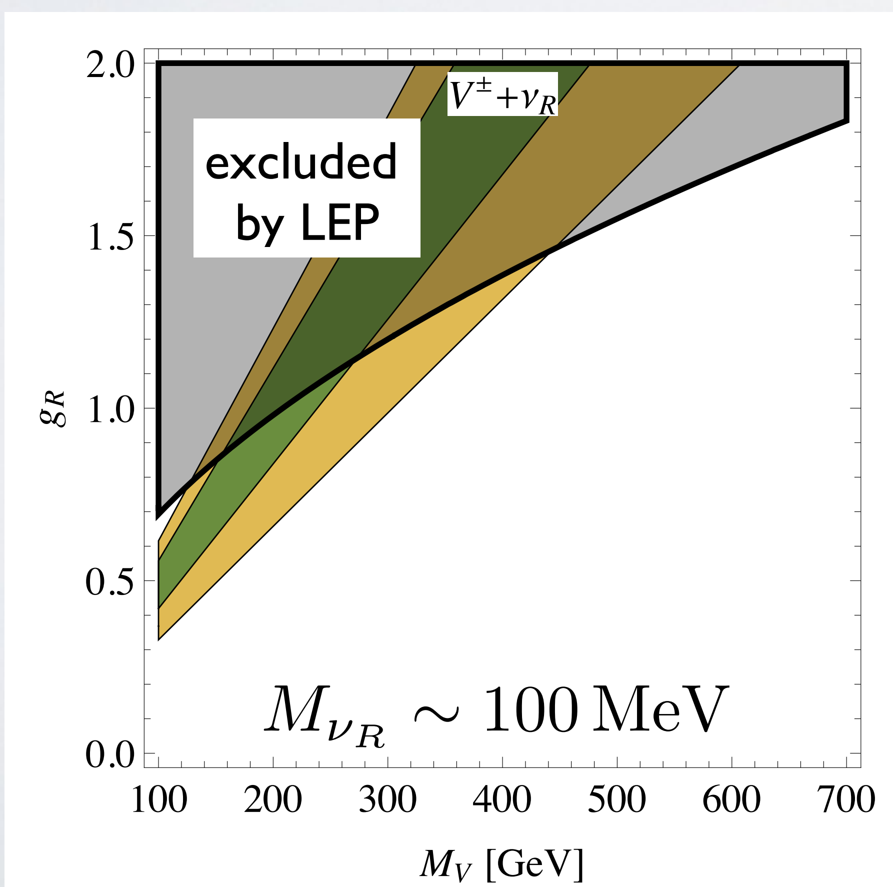
$$\xrightarrow{M \gtrsim \sqrt{s}}$$

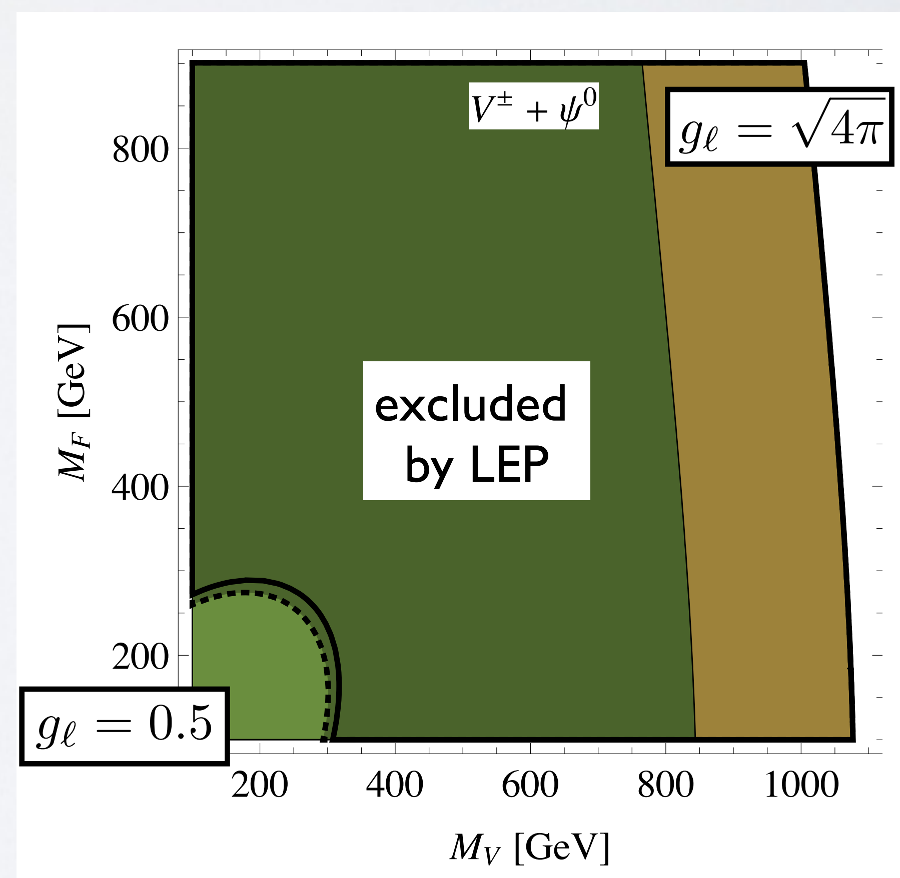


$$\sim \frac{g_\ell^4}{16\pi^2 M_V^2} \lesssim (0.0003\,\mathrm{GeV}^{-1})^2$$

[LEP colls., hep-ex/0612034]

LEP constraints on δa_μ in regions of strong couplings:

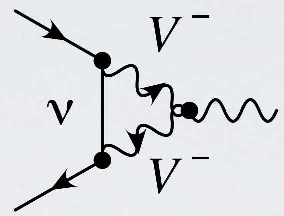




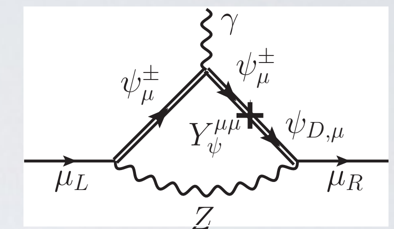
VIABLE G-2 CANDIDATES AFTER LEP

One new field

- charged vector singlet $V^{\pm}$

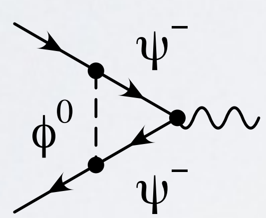


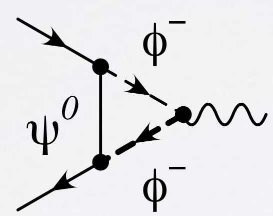
Mixing fermions

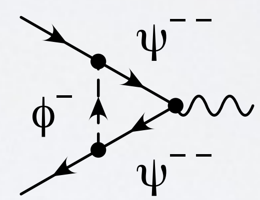


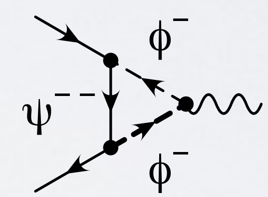
Two new fields

- $\phi^0 + \psi^{\pm}$: neutral scalar + charged fermion singlet
- $\phi_D + \psi_{A,T}$: scalar doublet & fermion triplets (Y=0 and Y=-1)
- $\phi_A + \psi_T$: scalar adjoint triplet & fermion triplet (Y=-1)

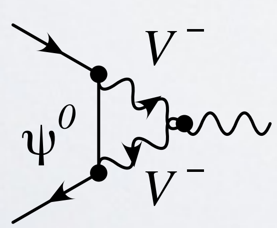


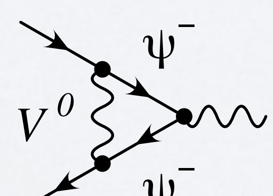






- $V^{\pm} + \psi^0$: charged vector singlet & neutral fermion
- $V_A + \psi_D$: vector adjoint triplet & fermion doublet



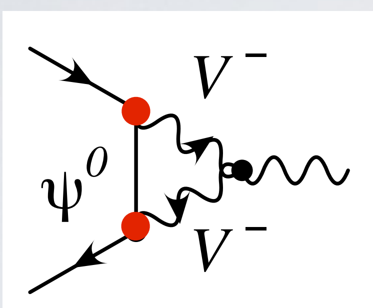


One-loop LEP bounds optional; may be relaxed by tree-level NP.

DIRECT TESTS AT THE LHC

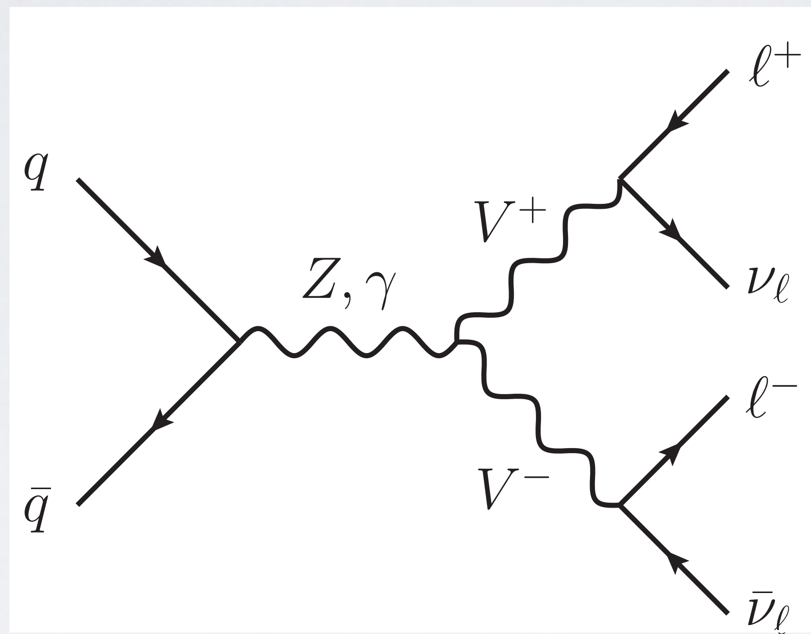
(Here: charged vector singlet & neutral fermion singlet)

$V^{\pm} + \psi^0$

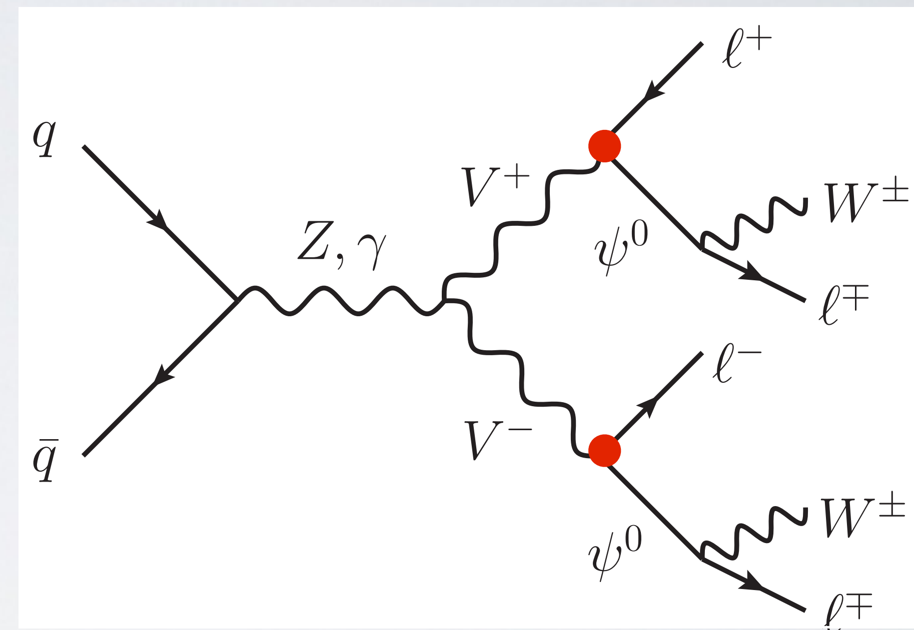


$\longleftrightarrow$

$M_V < M_\psi$



$M_V > M_\psi$

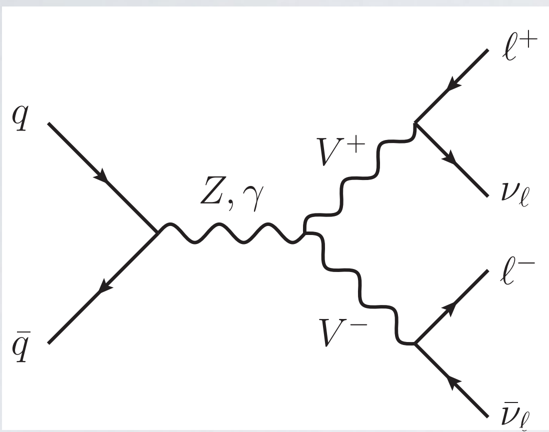


Assumptions

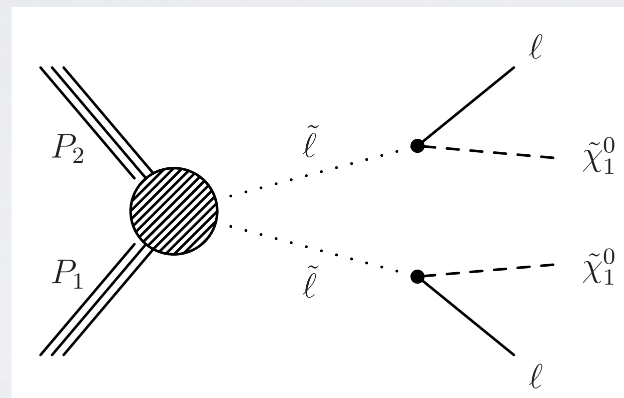
- Drell-Yan pair production (model-independent).
- Two new fields: constrain the lighter one (no cascades).
- If this is a SM singlet, look for cascade decays.
- Decay dominantly (and flavor-universally) into leptons.

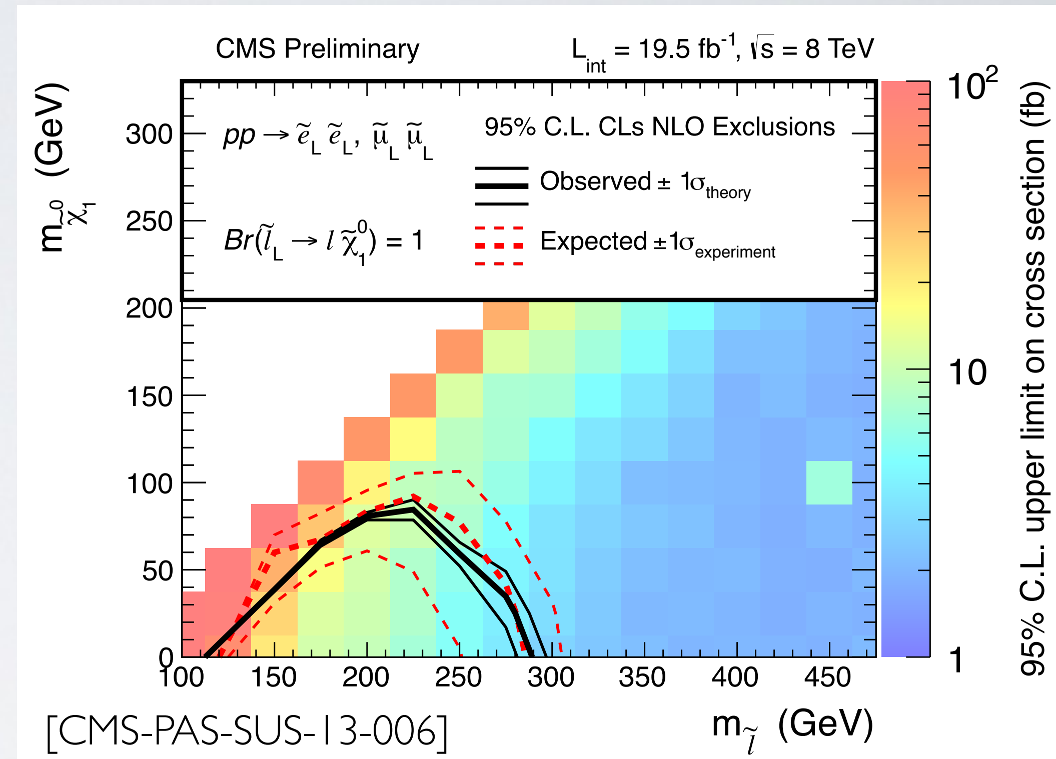
RECAST SEARCHES BY ATLAS & CMS
(charged vector singlet & neutral fermion singlet ctd.)

$M_V < M_\psi$: slepton production



$\longleftrightarrow$



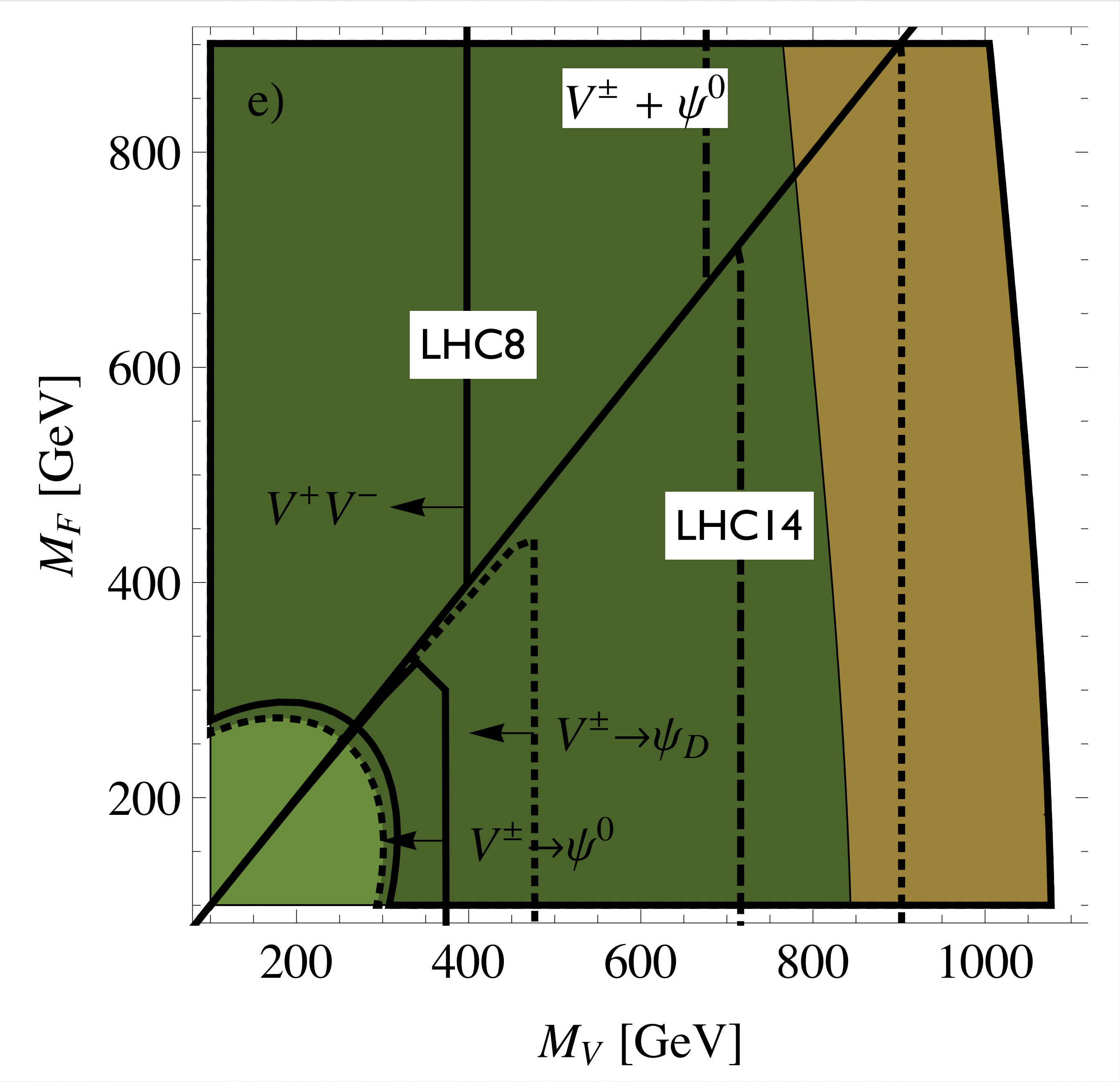


$\longrightarrow \quad M_V > 398\,\mathrm{GeV}$

$M_V > M_\psi$: multi-lepton search [ATLAS-CONF-2013-019]

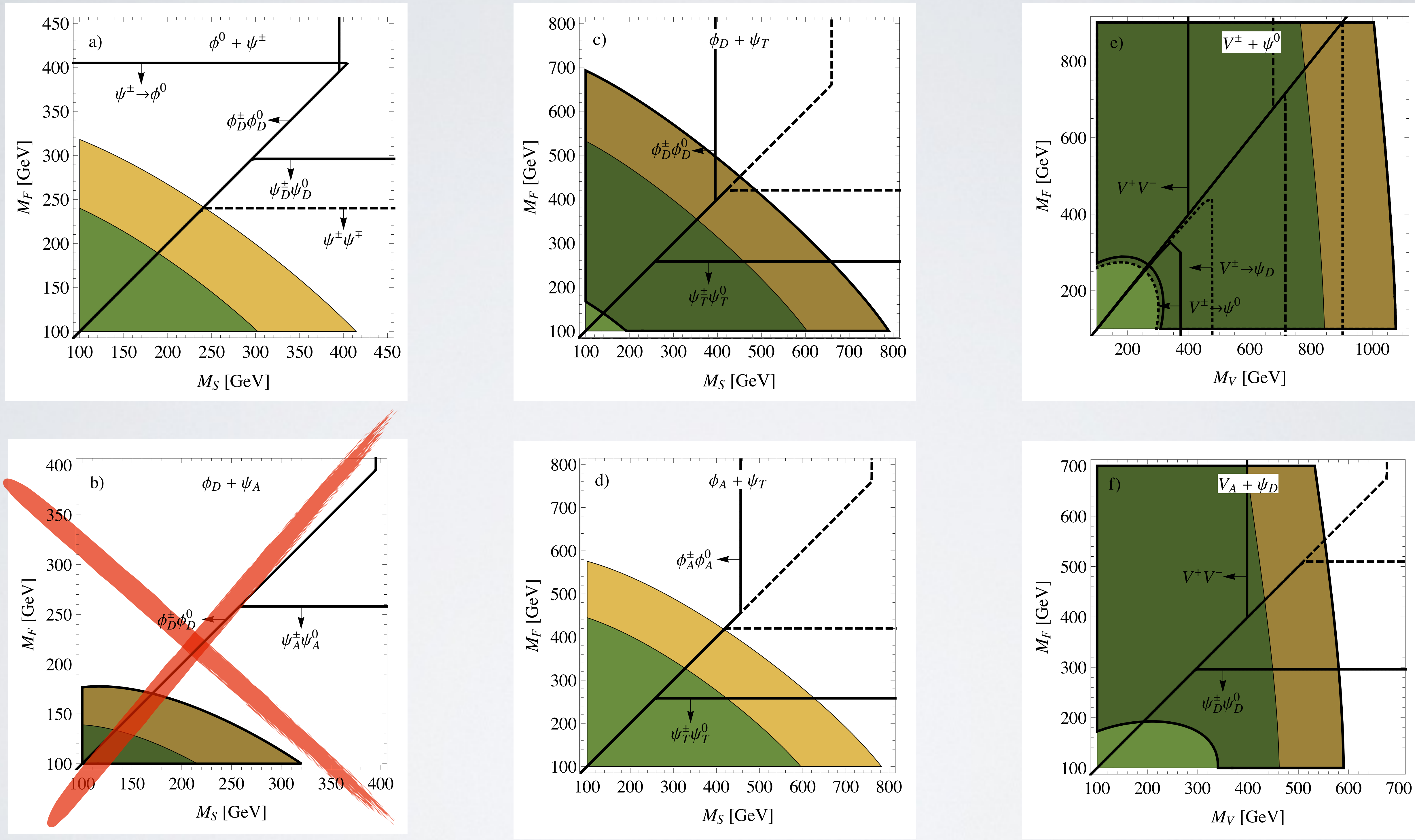
- ψ^0 is weak singlet: $\mathcal{B}(\psi^0 \to W^\pm \ell^\pm) = 1/2$ $\qquad M_V > 373\,\mathrm{GeV}$
- ψ^0 part of weak doublet: $\mathcal{B}(\psi^0 \to W^\pm \ell^\pm) = 1$ $\qquad M_V > 476\,\mathrm{GeV}$

LHC CONSTRAINTS ON G-2



LHC14: rescaled event yield $N_{14}(300\,\mathrm{fb}^{-1}) = N_8(20\,\mathrm{fb}^{-1})\dfrac{\sigma(14\,\mathrm{TeV})}{\sigma(8\,\mathrm{TeV})}$

G-2 CANDIDATES AFTER LHC8



Mixing fermions for g-2 cannot be excluded at the LHC.

PROSPECTS: ORIGIN OF G-2 ANOMALY?

- Current g-2 uncertainties:

$$\delta a_\mu^{\rm exp} \approx \pm 63 \times 10^{-11} \qquad \delta a_\mu^{\rm SM} \approx \pm 49 \times 10^{-11}$$

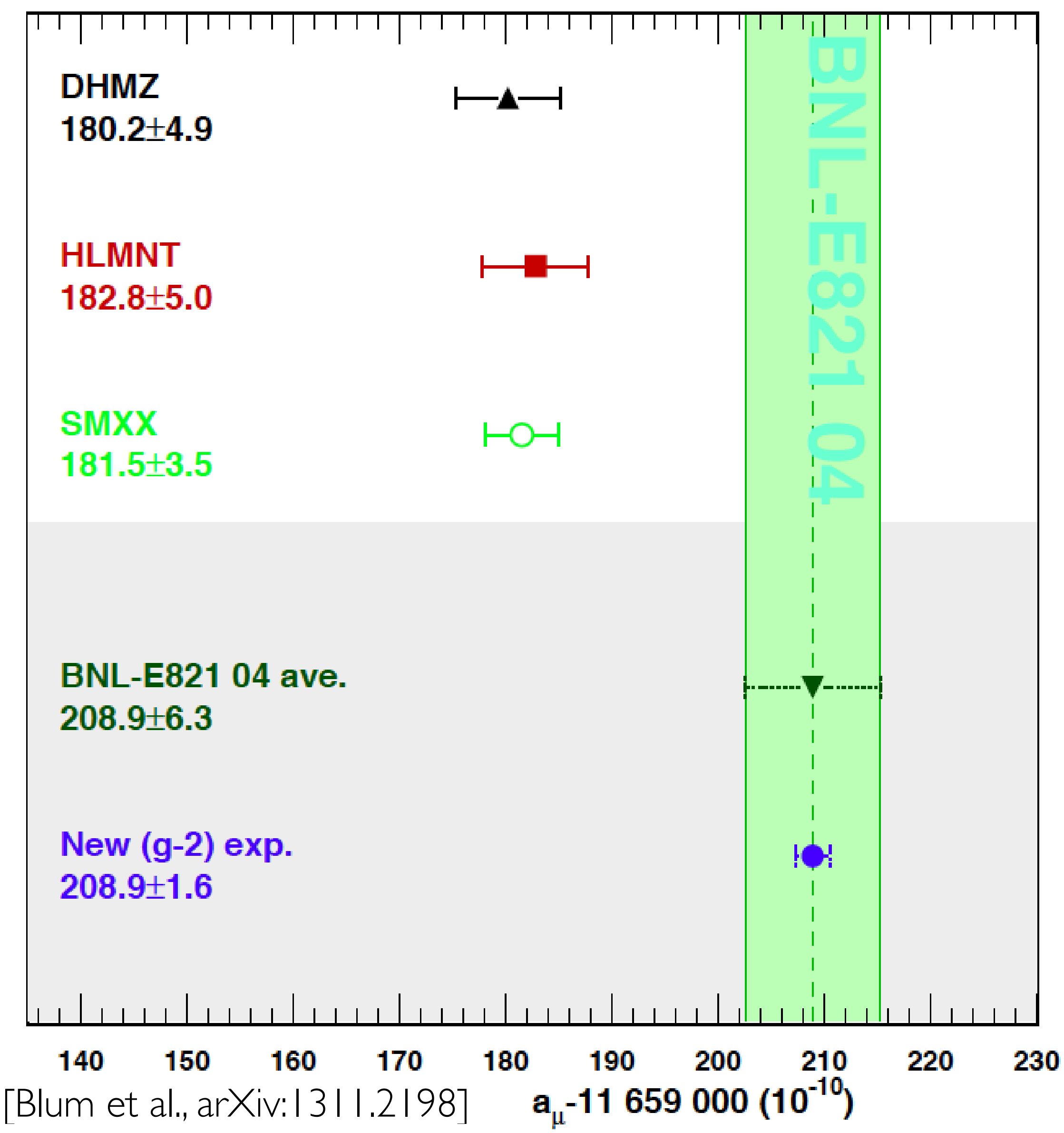
- Fermilab´s E989 and J-PARC:

$$\delta a_\mu^{\rm exp} \approx \pm 16 \times 10^{-11}$$

- Expected reduced SM error:

$$\delta a_\mu^{\rm SM} \approx \pm 35 \times 10^{-11}$$

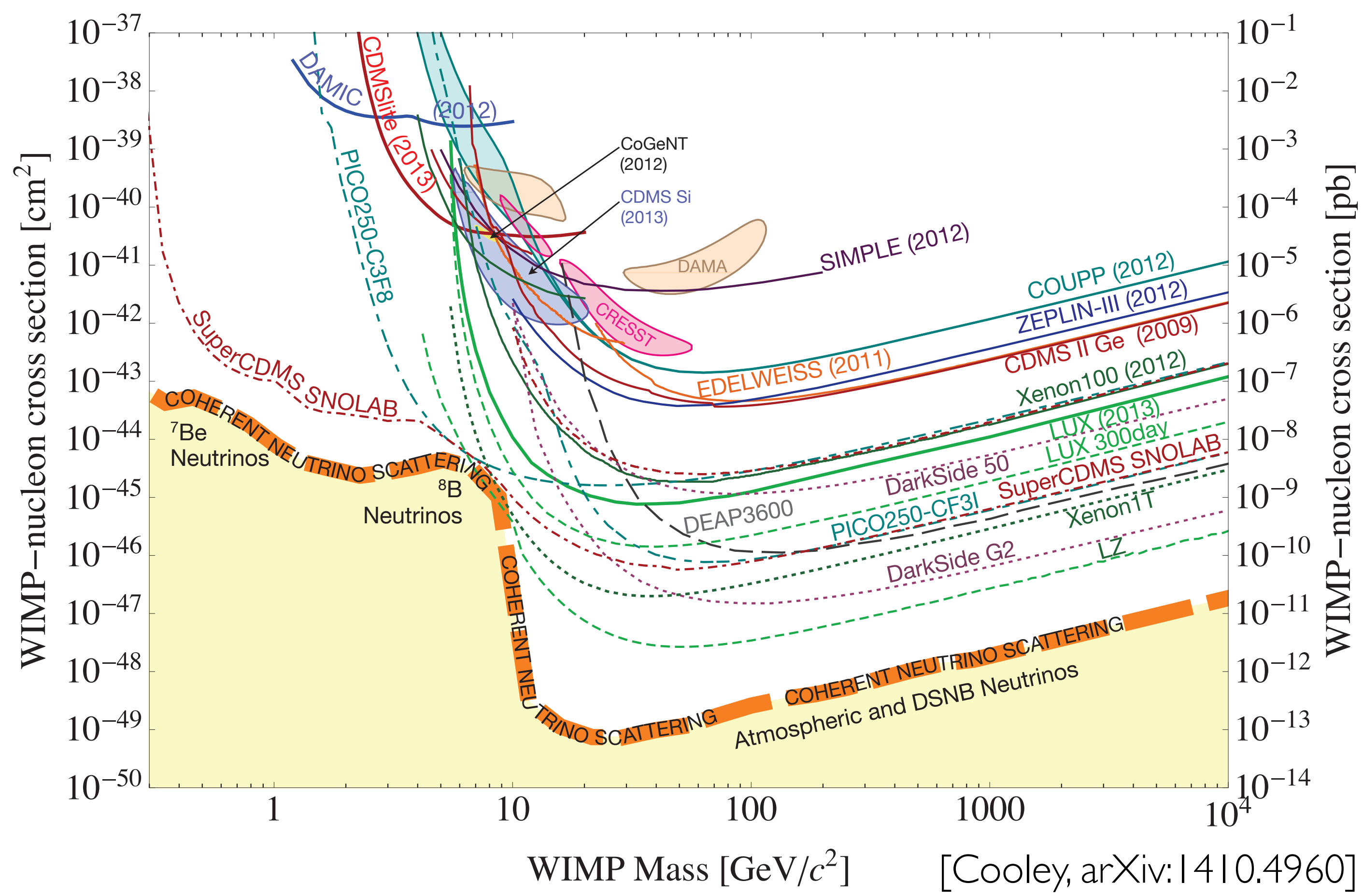
Total uncertainty may be reduced by a factor of 2.



[Blum et al., arXiv:1311.2198]

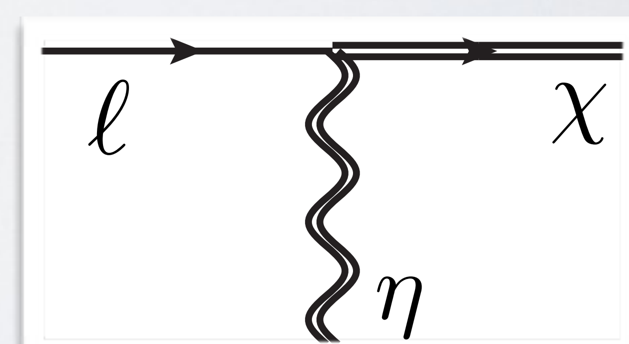
LEPTOPHILIC DARK MATTER

No observed dark matter scattering off nuclei:



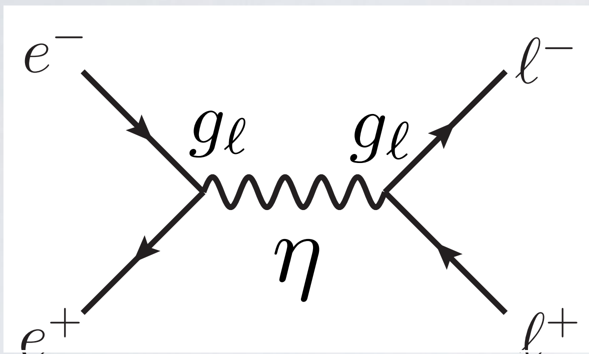
[Cooley, arXiv:1410.4960]

Maybe dark matter interacts only with leptons:

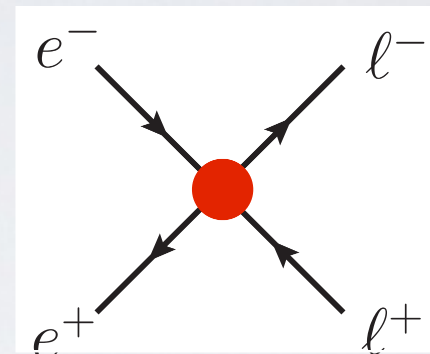


SIGNATURES OF LEPTOPHILIC DARK MATTER

s-channel mediation:

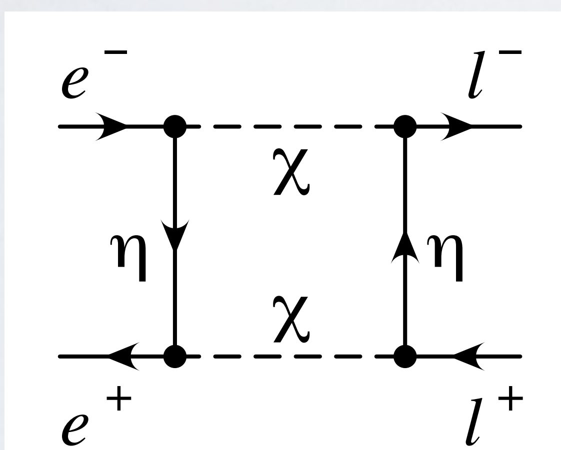


$\xrightarrow{M_\eta > \sqrt{s}}$

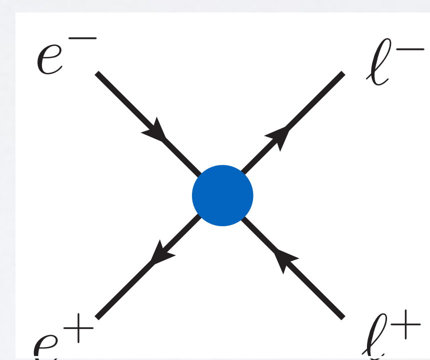


$$\mathcal{C} \sim \frac{g_\ell^2}{M_\eta^2}$$

t-channel mediation:



$\xrightarrow{M_{\chi,\eta} > \sqrt{s}}$



$$\mathcal{C} \sim \frac{g_\ell^4}{M_\eta^2} F_S\left(\frac{M_\chi^2}{M_\eta^2}\right)$$

Chiral couplings: t-channel med. reduces to vector operators

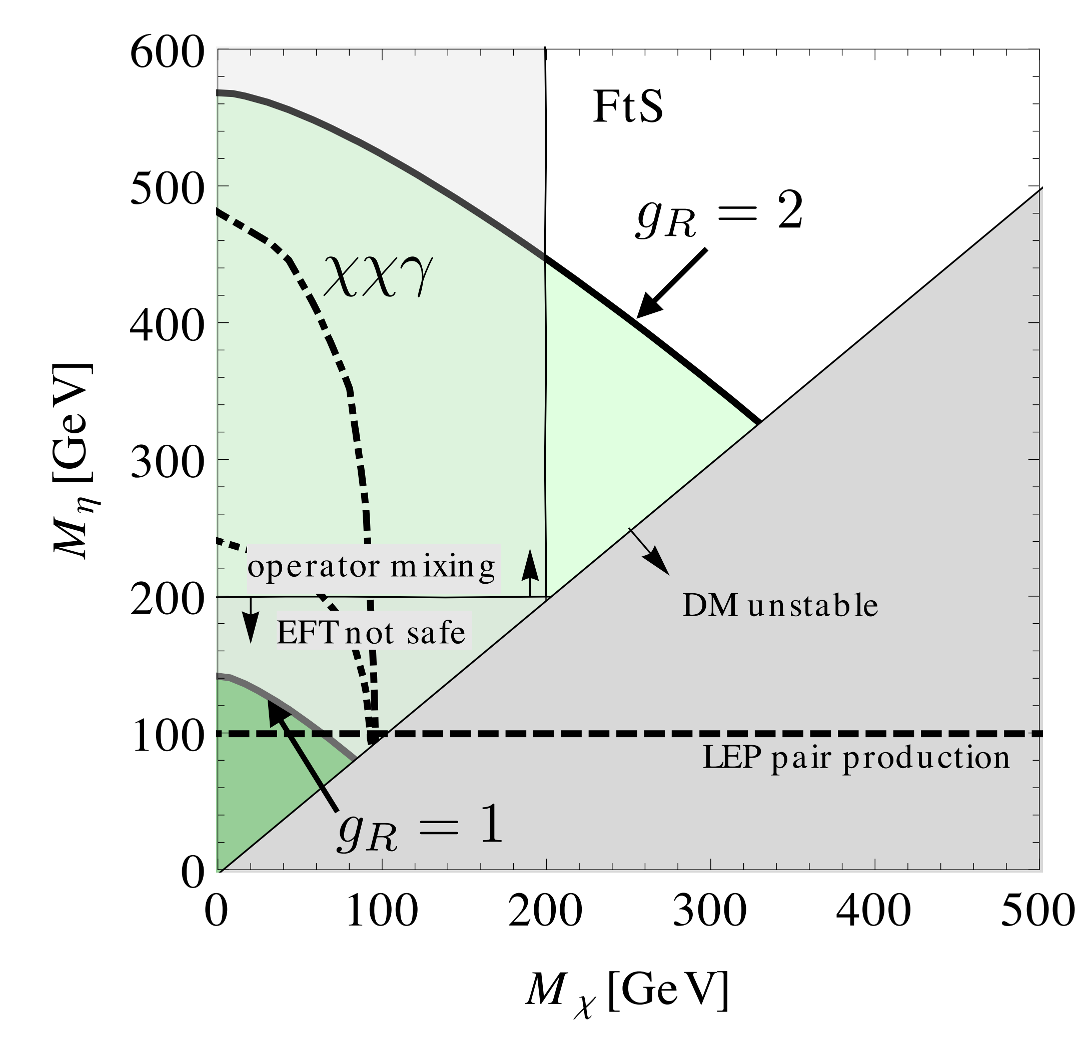
$$\mathcal{O}_{LL} = (\bar{e}\gamma_\mu P_L e)(\bar{\ell}\gamma^\mu P_L \ell) \quad \text{and} \quad \mathcal{O}_{RR} = (\bar{e}\gamma_\mu P_R e)(\bar{\ell}\gamma^\mu P_R \ell)$$

LEP BOUNDS FROM 4-LEPTON INTERACTIONS

s-channel mediation: $g/M_\eta < \mathcal{O}(10^{-4})\ \mathrm{GeV}^{-1}$

Mediators below the terascale are excluded, if $g_\ell = \mathcal{O}(1)$.

t-channel mediation: (here: fermion DM and scalar mediator)



For $g_R \gtrsim 1$,
4-lepton bounds exceed mono-photon searches in
$e^+e^- \to \chi\chi\gamma$

[Dreiner et al., arXiv:1211.2254]

ILC PROJECTIONS

Improved sensitivity due to 1) higher collision energy
2) higher luminosity
3) beam polarization

Upper bound on contact interactions (roughly) scales as

$$|\mathcal{C}_{\mathrm{LL,RR}}|^{\max}_{\mathrm{ILC}} = |\mathcal{C}_{\mathrm{LL,RR}}|^{\max}_{\mathrm{LEP}} \times \left[\frac{s_{\mathrm{ILC}}}{s_{\mathrm{LEP}}} \times \frac{\mathcal{L}_{\mathrm{ILC}}}{\mathcal{L}_{\mathrm{LEP}}}\right]^{-1/2} \times \frac{\sqrt{r_B}}{r_S} \qquad (r_{S,B} = N_{S,B}/N^{\mathrm{unpol}}_{S,B})$$

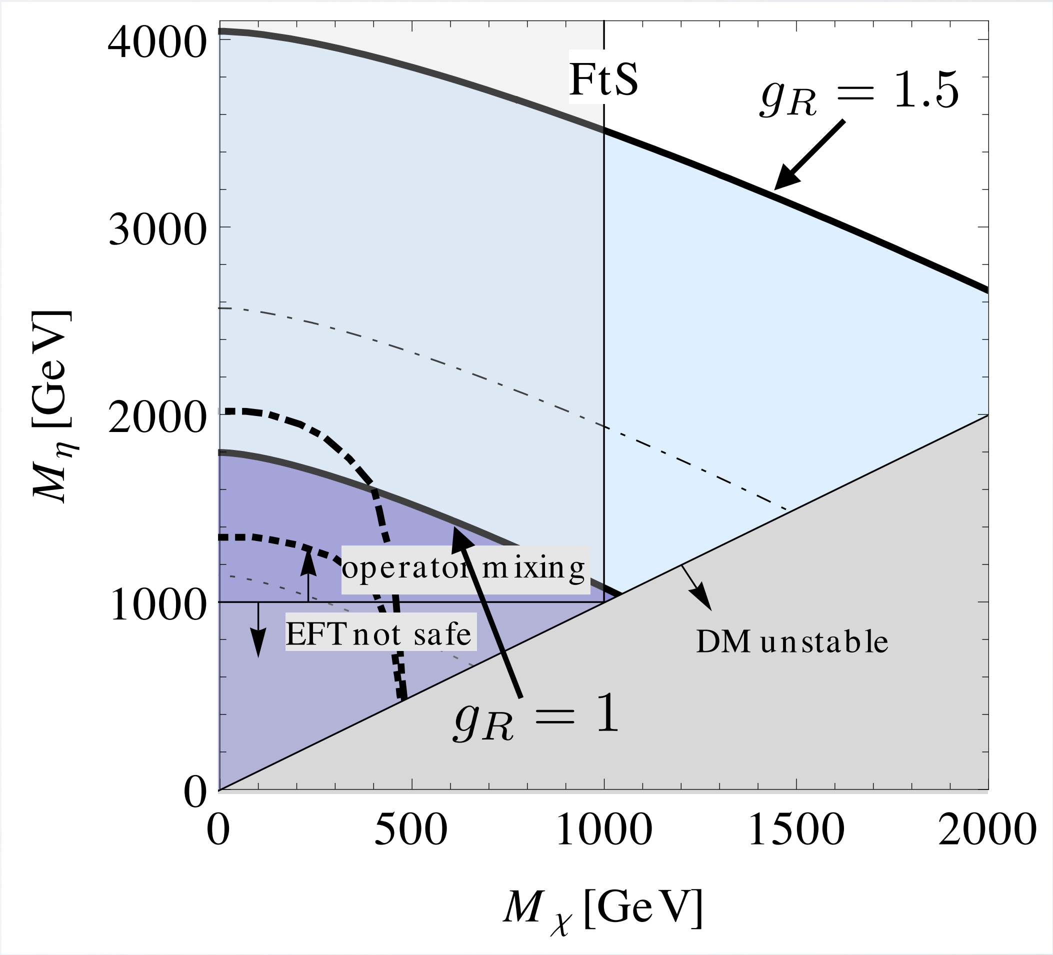
<u>s-channel mediation</u>:

$$g/M_\eta < \mathcal{O}(10^{-5})\,\mathrm{GeV}^{-1}$$

<u>t-channel mediation</u>:

$$\sqrt{s}_{\mathrm{ILC}} = 1\,\mathrm{TeV},\ \ \mathcal{L} = 500\,\mathrm{fb}^{-1}$$

$$r_S = (1+0.8)(1+0.6)$$



SUMMARY LEPTOPHILIC NEW PHYSICS

Combined with LEP bounds, LHC run II will **conclusively test** all of our simplified models for g-2 but mixing fermions.

In case Fermilab and J-PARC find indirect evidence of new particles in g-2, the **LHC might provide the only way to discover them directly**.

Scenarios of leptophilic dark matter are constrained by **four-lepton interactions** at LEP; can be examined more at ILC.

LEP also **excludes large parts** of dark matter scenarios explaining the muon g-2, apart from self-conjugate scalar DM.