TESTING THE MUON G-2 ANOMALY AT THE LHC

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

Susanne Westhoff

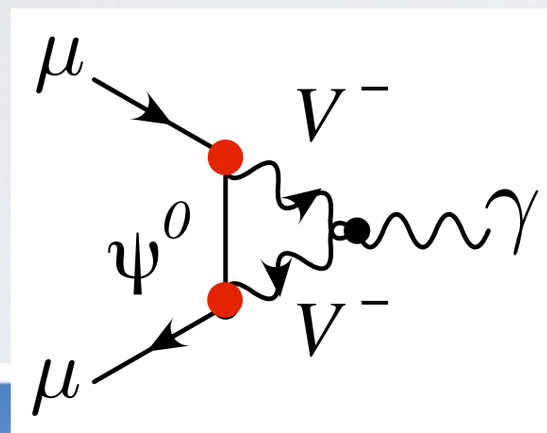
University of Pittsburgh

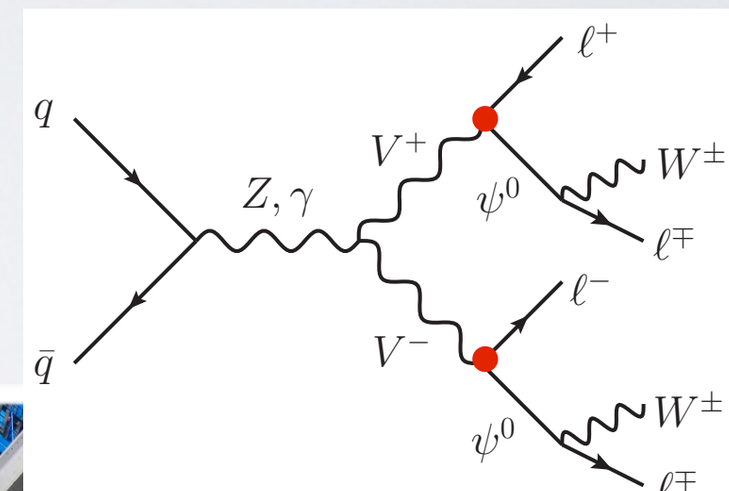
Theory Seminar - April 8, 2015 - Fermilab

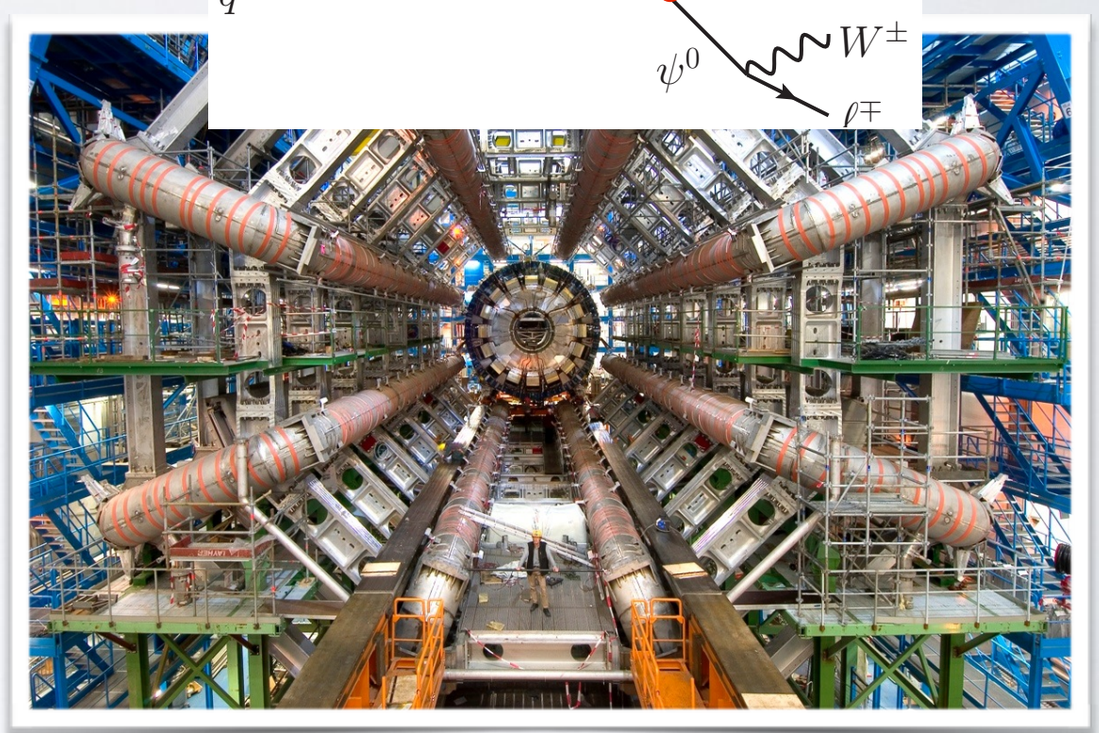
MUON G-2 AND THE LHC

Lepton magnetic moment and its anomalous part:

$$\vec{\mu}_\ell = g_\ell \frac{e}{2m_\ell}\vec{s}, \quad a_\ell = \frac{g_\ell - 2}{2}$$







LEPTON ANOMALOUS MAGNETIC MOMENTS

Electron anomalous magnetic moment measured at Harvard:

$$a_e^{\rm exp} = 1.15965218073(28) \times 10^{-3} \ (0.24\,{\rm ppb})$$

[Hanneke, Fogwell, Gabrielse, PRL 100 (2008) 120801]

SM prediction including electromagn. corrections up to $(\alpha/\pi)^5$:

$$a_e^{\rm SM} = 1.15965218178(77) \times 10^{-3}$$ [Aoyama et al., PRL 109 (2012) 111807]

$\longrightarrow$ fine structure constant $\alpha^{-1} = 137.035999174(35)$

Muon anomalous magnetic moment measured at Brookhaven:

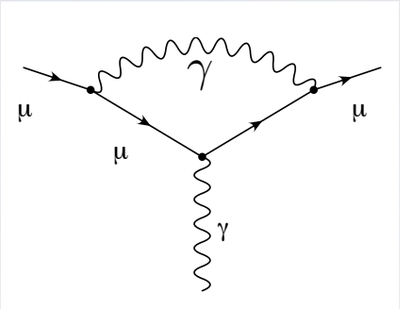
$$a_\mu^{\rm exp} = 1.16592080(54)(33) \times 10^{-3} \ (0.54\,{\rm ppm})$$

[BNL Muon g-2 collaboration, PRD73, 072003 (2006)]

MUON G-2 IN THE STANDARD MODEL

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

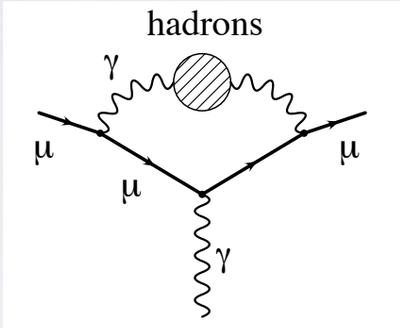
$$a_\mu^{\rm SM} = a_\mu^{\rm QED}$$



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

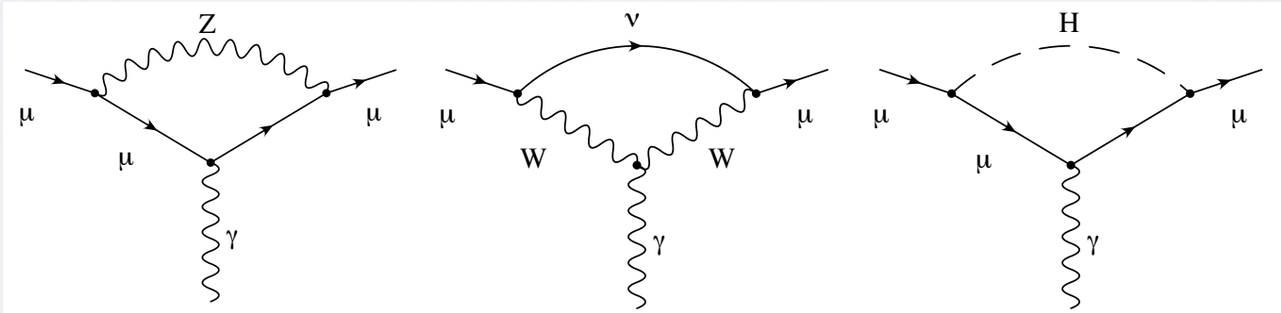
$[10^{-11}]$

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



Leading order:	$6923(42)$
Higher orders:	$-97.9(0.9)$
Light-by-light sctg.:	$105(26)$

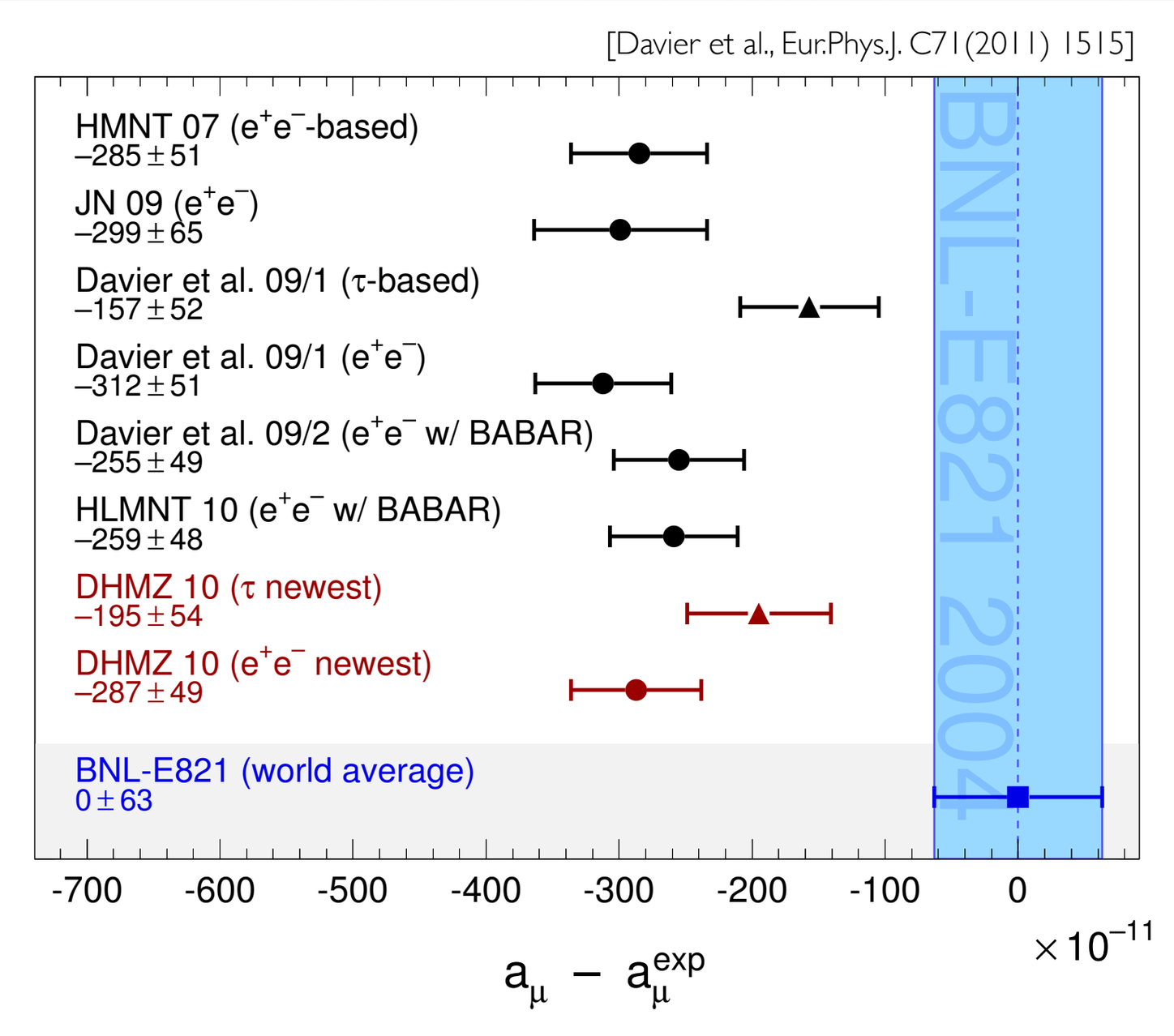
$$+ a_\mu^{\rm EW}$$



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

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

CONFRONTED WITH THE MEASUREMENT



Discrepancy between standard model and experiment $\sim 3\sigma$.

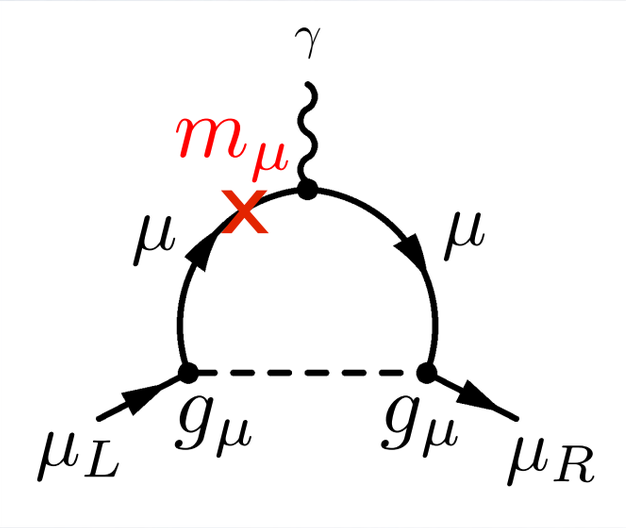
NEW PHYSICS IN G-2

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

[Jegerlehner, Nyffeler, arXiv:0902.3360]

Focus on mass range accessible in direct production at LHC:

$$M_{\rm NP} > 100\,{\rm GeV}$$
$$g_\mu = \mathcal{O}(1)$$



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

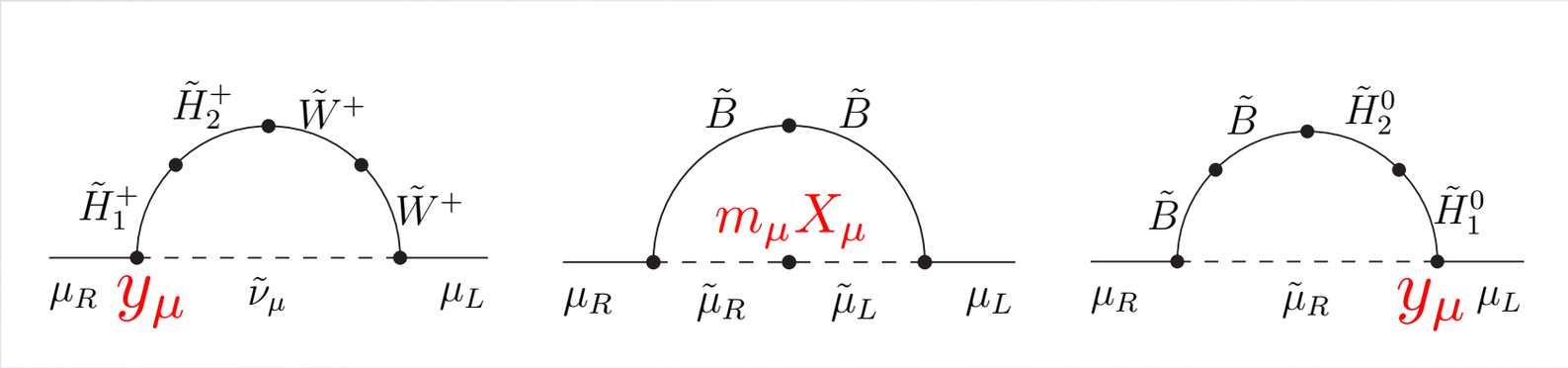
Need chiral symmetry breaking:

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

PROMINENT EXAMPLES

Supersymmetric Standard Model

$\tan\beta$ enhancement from muon Yukawa coupling $y_\mu = \dfrac{m_\mu}{v}\tan\beta$



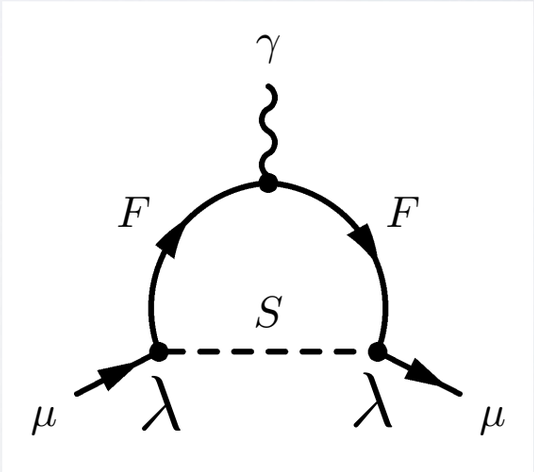
$$a_\mu \sim m_\mu^2 \tan\beta\, \mu\, M$$

[see, for instance, Stöckinger, J.Phys.G34 (2007) R45]

Light dark matter $(M_S \lesssim M_F \sim 1\,\mathrm{GeV})$

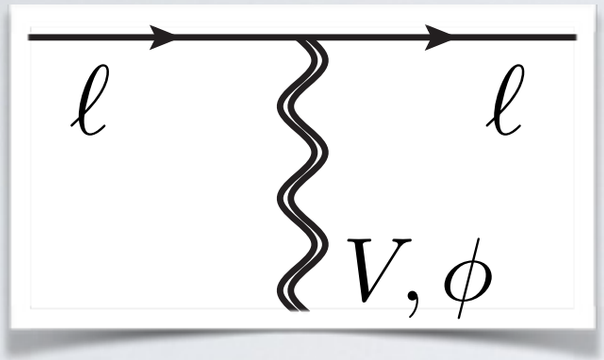
Δa_μ favors $M_F/\lambda \lesssim 100\,\mathrm{GeV}$

Here: dark scalar plus fermion mediator



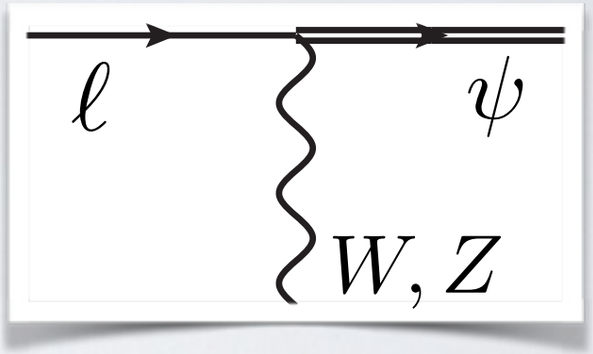
[e.g. Gninenko 2001, Fayet 2007, Pospelov 2008, Agrawal, Chacko, Verhaaren, arXiv:1402.7369]

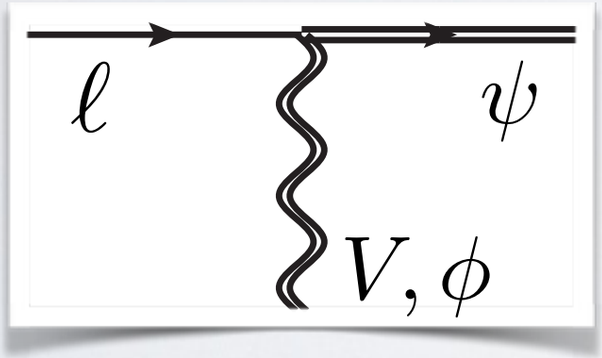
LEPTON INTERACTIONS WITH NEW FIELDS



new boson (scalar/vector)

new fermion





new boson and new fermion

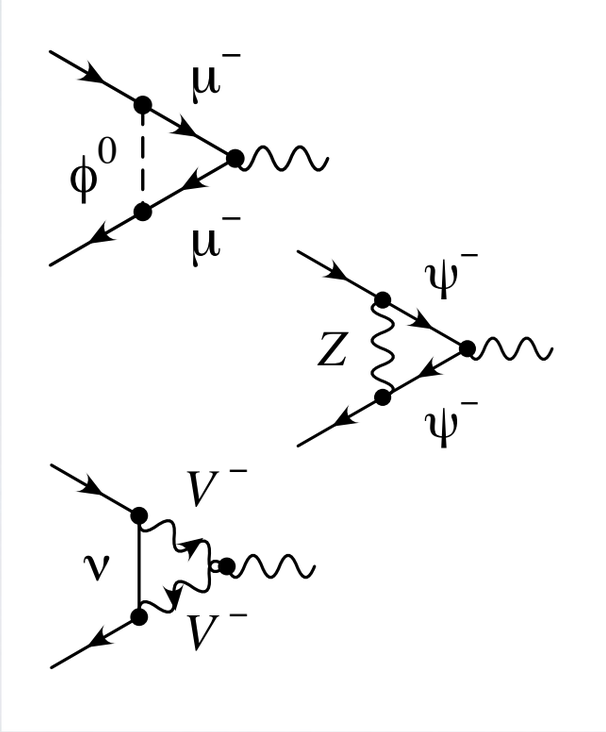
How can we test such g-2 candidates at colliders?

A MODEL-INDEPENDENT APPROACH

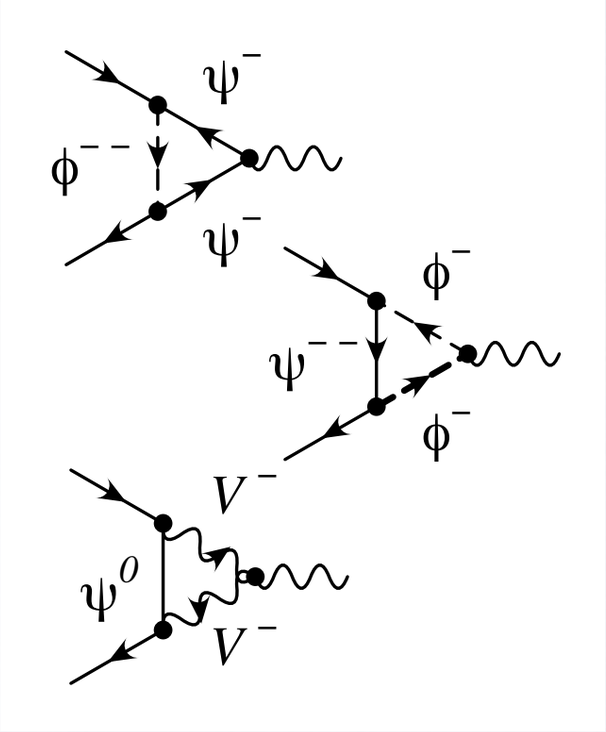
Consider new fields:

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

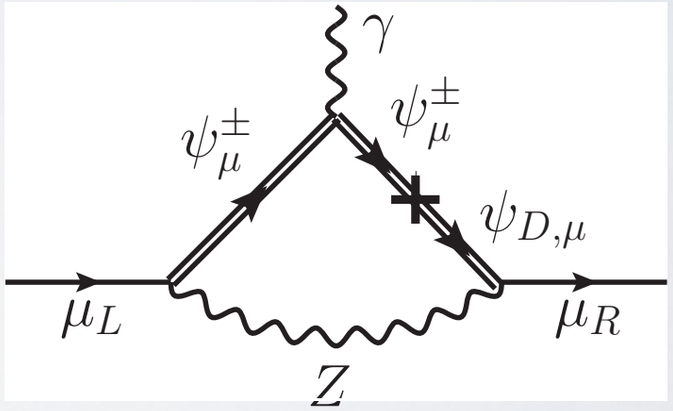
Three classes of one-loop contributions to a_μ :



One new field



Two new fields

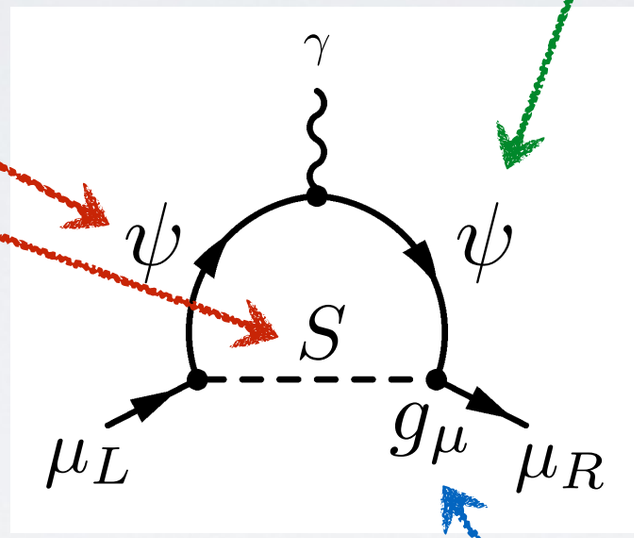


Two mixing fermions

GENERAL PARTICLE FEATURES

New fermions:
vector-like weak interactions.

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

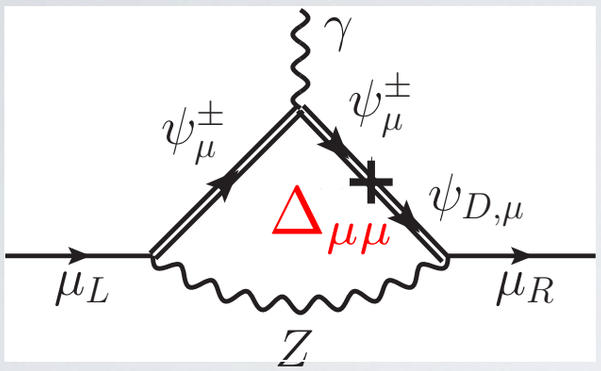


Real, perturbative
couplings to leptons.

Assumption: Interactions are **minimally flavor-violating**.

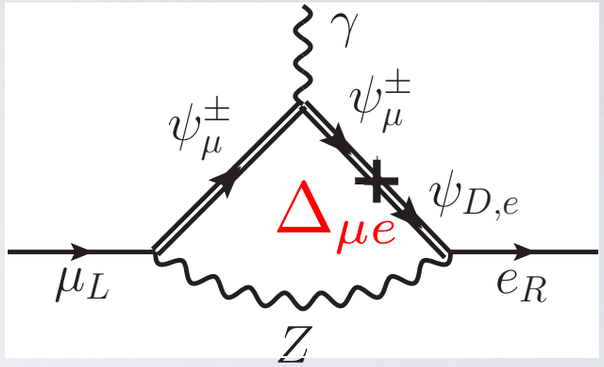
MINIMAL FLAVOR VIOLATION

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 $\sim \Delta_{\mu e}$:

$$\mathcal{B}(\mu \to e\gamma) \approx 6.34 \times 10^{-7} \left(\frac{1\mathrm{TeV}^4}{\Lambda_{\mathrm{FV}}^4} \right) |\Delta_{\mu e}|^2 < 5.7 \times 10^{-13}$$

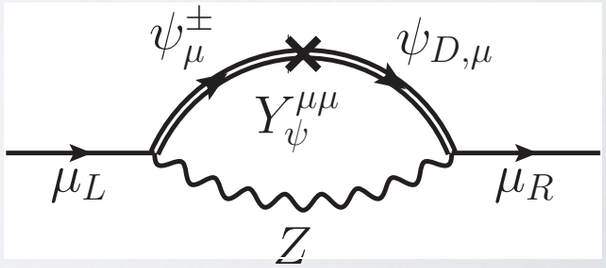
[MEG collaboration, 2013]

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

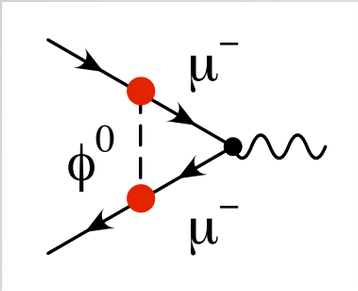
<u>MFV implications for g-2 scenarios:</u>

- 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

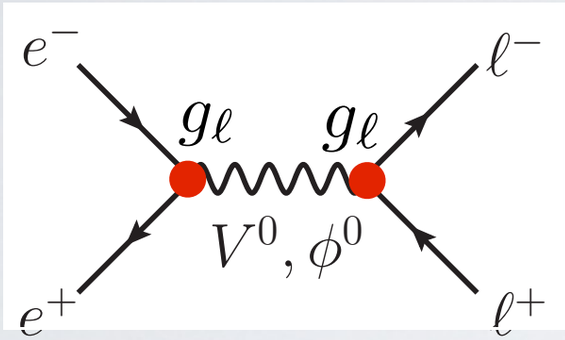


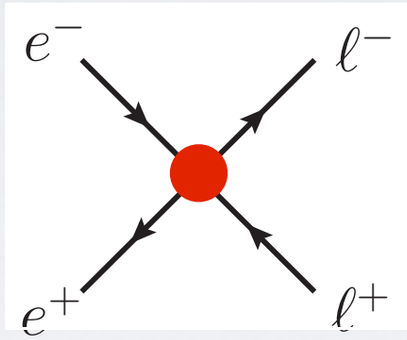
Muon mass protected: $m_\mu = y_\mu v (1 + \delta m_\mu)$



ONE NEW BOSON: LEP BOUNDS

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





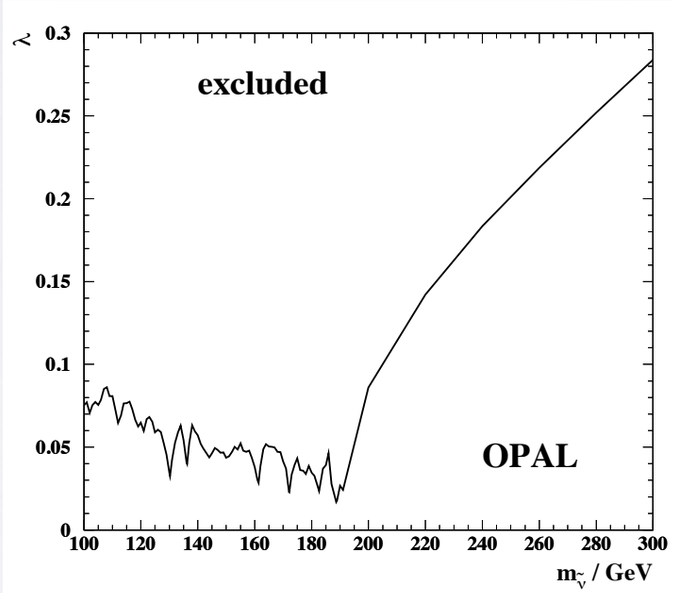
$$\sim \frac{g_\ell^2}{M_{V,\phi}^2} \lesssim (0.0003\,\mathrm{GeV}^{-1})^2$$

[LEP colls., hep-ex/0612034]

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

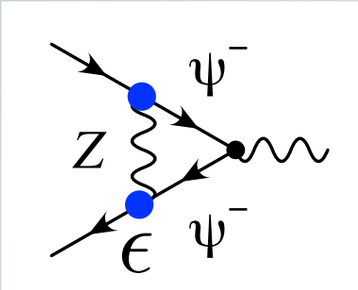
$$e^+e^- \to (V^0, \phi^0)\gamma \to \ell^+\ell^-\gamma$$

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



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

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



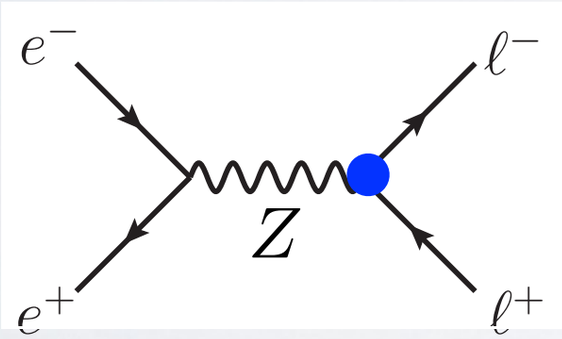
ONE NEW FERMION: LEP BOUNDS

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

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

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

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 $\delta a_\mu < 0$).

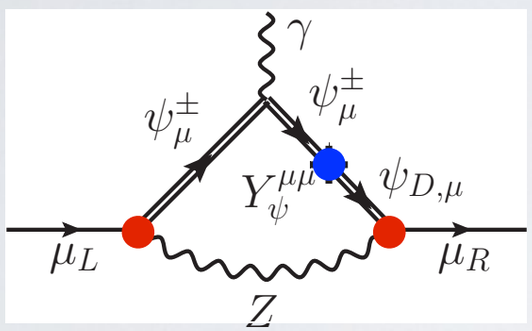
MIXING VECTOR FERMIONS

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

Two viable scenarios of **minimal flavor violation**:

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

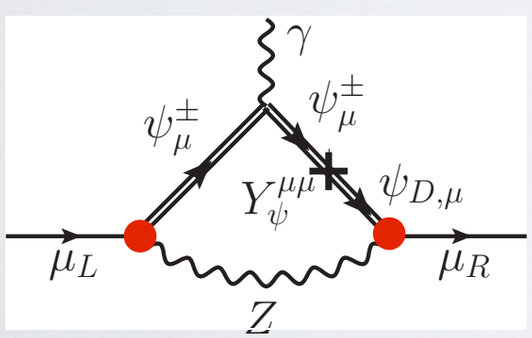
$$\delta a_\mu \sim m_\mu \cdot Y_\psi v \cdot \epsilon_1 \epsilon_2$$



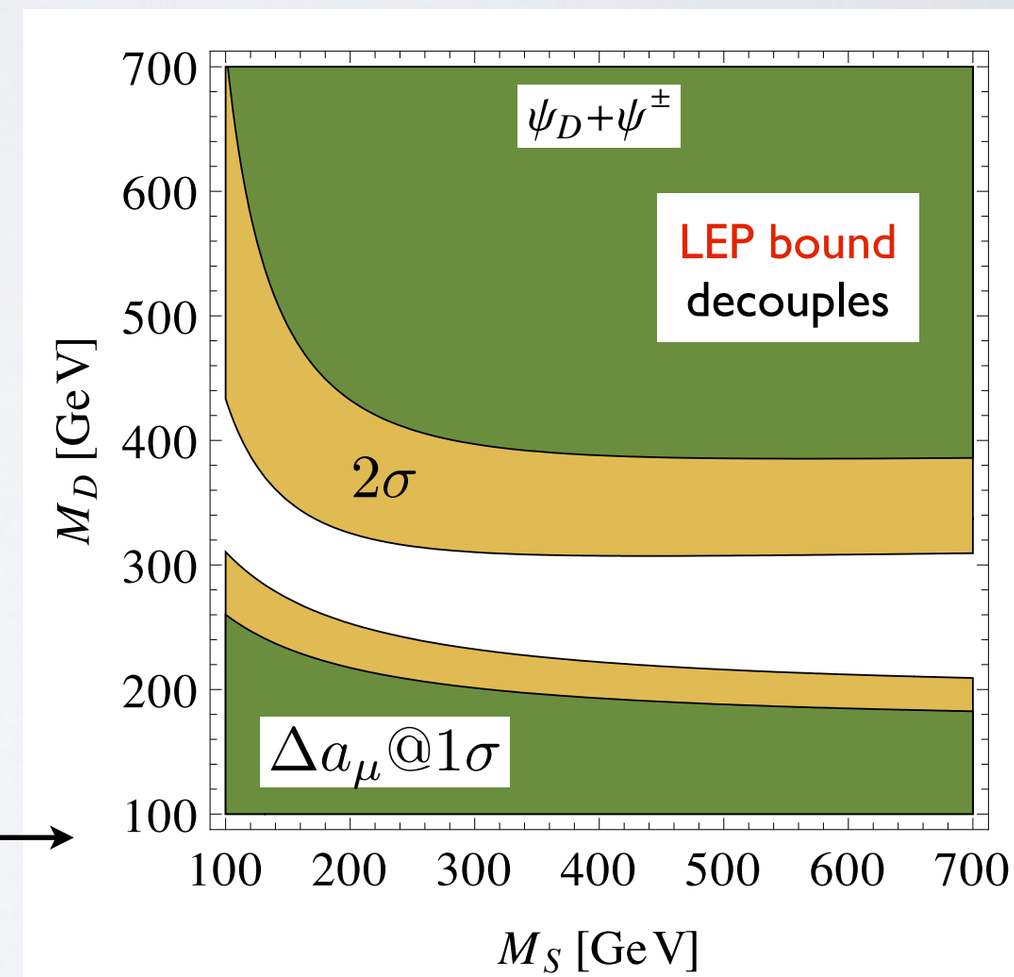
$|Y_\psi| \lesssim 0.2,\ |\epsilon| \lesssim 0.03$

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

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



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

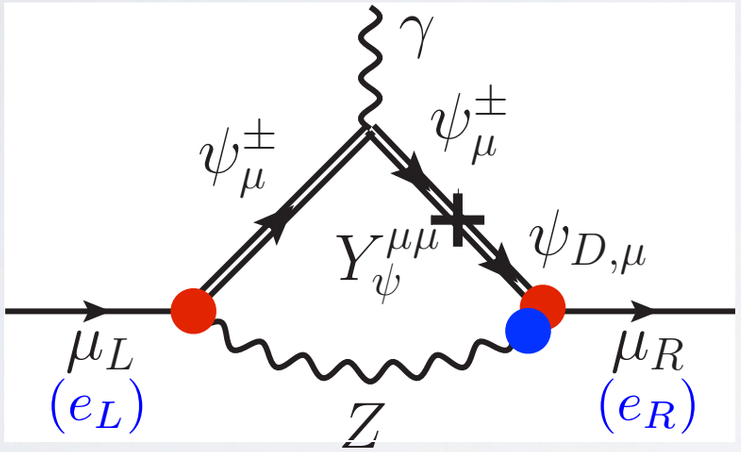


BOUNDS FROM ELECTRON MOMENT

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

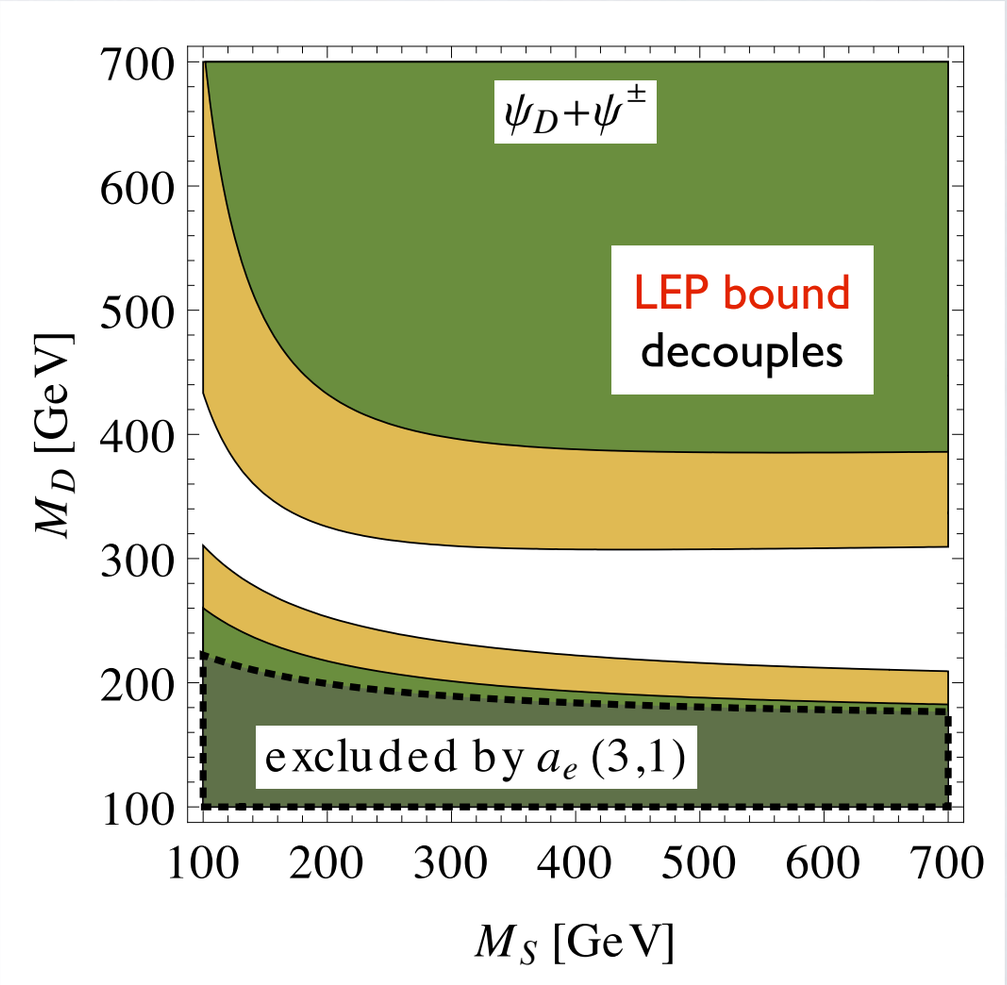
Electron g-2: $a_e^{\rm exp} - a_e^{\rm SM} = (-1.06 \pm 0.82) \times 10^{-12}$ [Aoyama et al., PRL 109 (2012)111807]

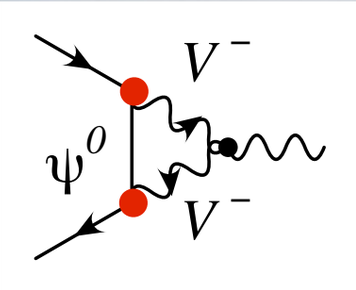
Consider $\psi^\pm = \psi_D = (3,1)$:



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

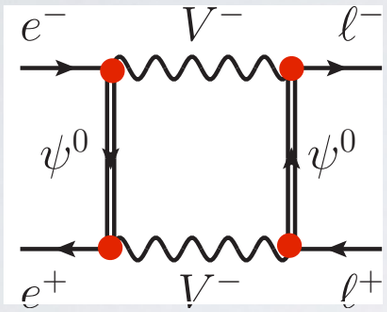
$$= \mathcal{O}(10^{-12}) \text{ for } M_D \lesssim v$$



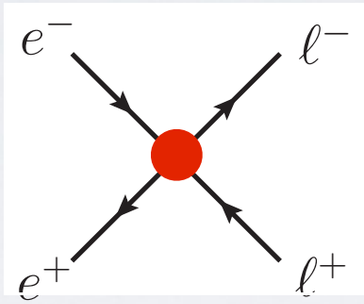


TWO NEW FIELDS: LEP BOUNDS

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



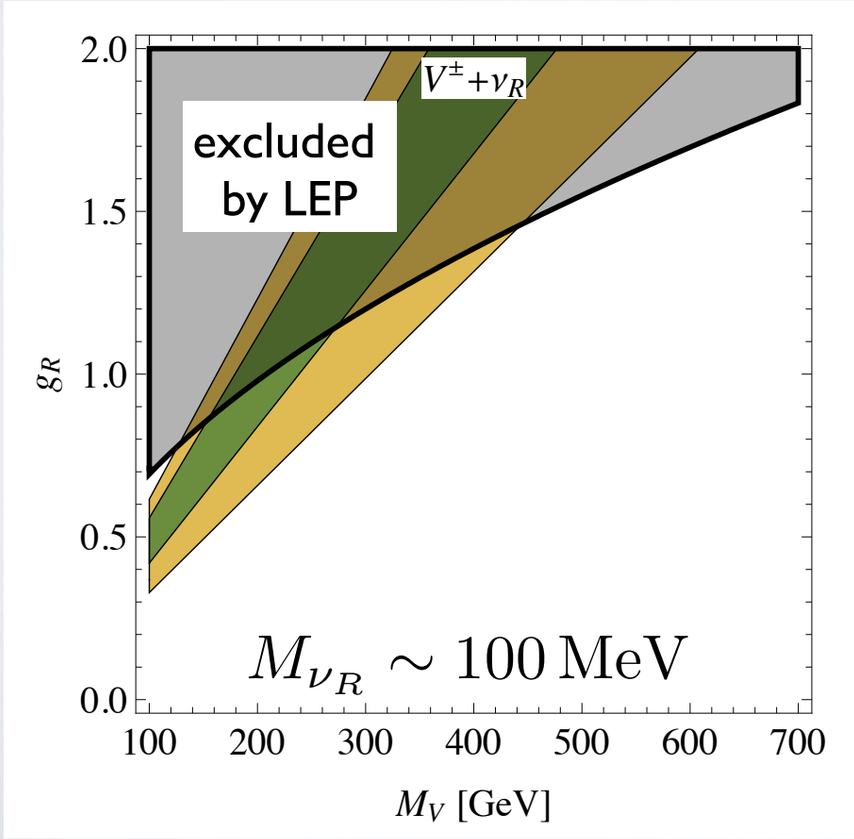
$M \gtrsim \sqrt{s}$ →

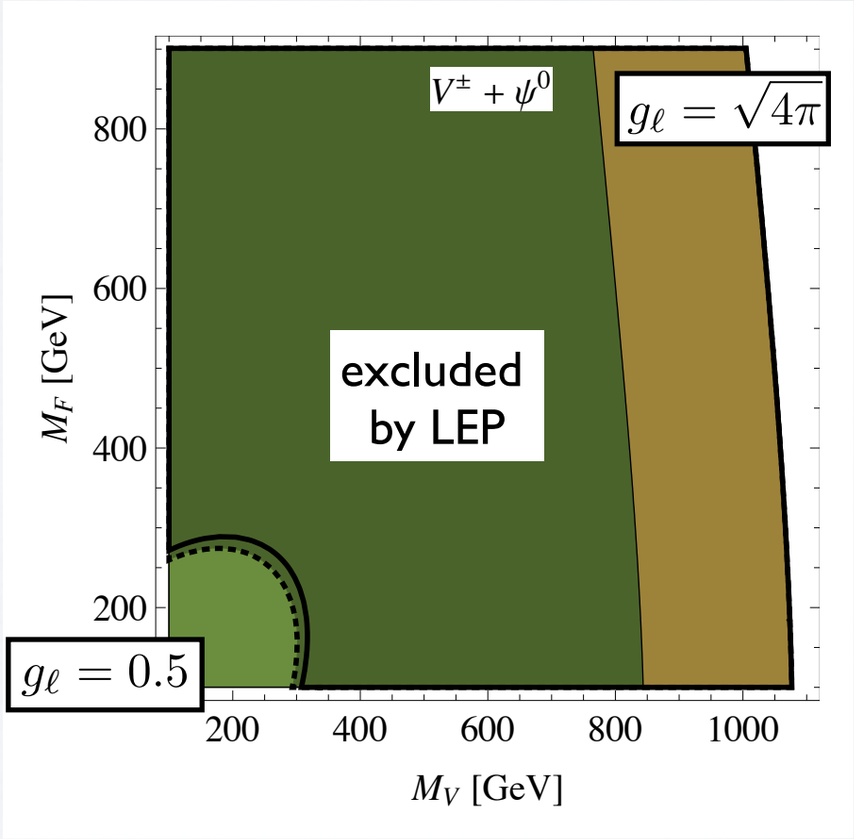


$$\sim \frac{g_\ell^4}{16\pi^2 M_V^2} \lesssim (0.0003\,\mathrm{GeV}^{-1})^2$$

[LEP colls., hep-ex/0612034]

LEP constraints on δa_μ in regions of strong couplings:

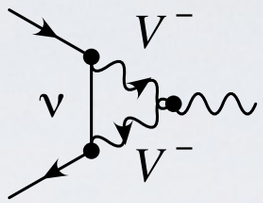




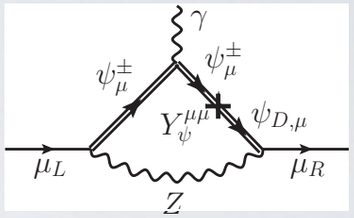
VIABLE G-2 CANDIDATES AFTER LEP

One new field

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

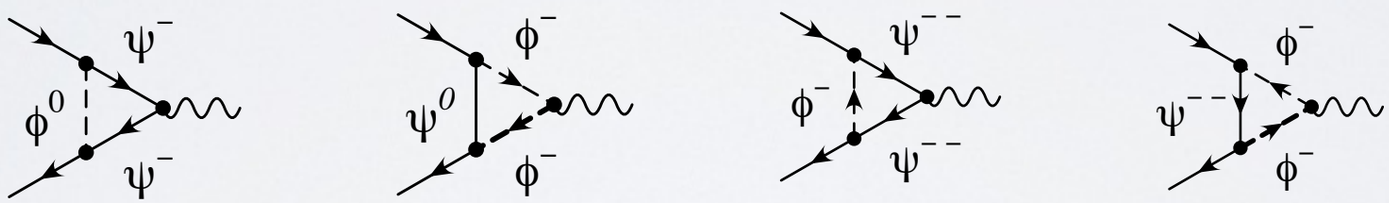


Mixing fermions

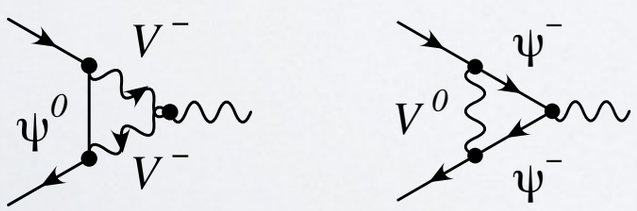


Two new fields

- $\phi^0 + \psi^{\pm}$: 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

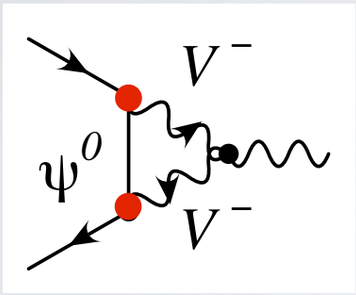


One-loop LEP bounds optional; may be relaxed by tree-level NP.

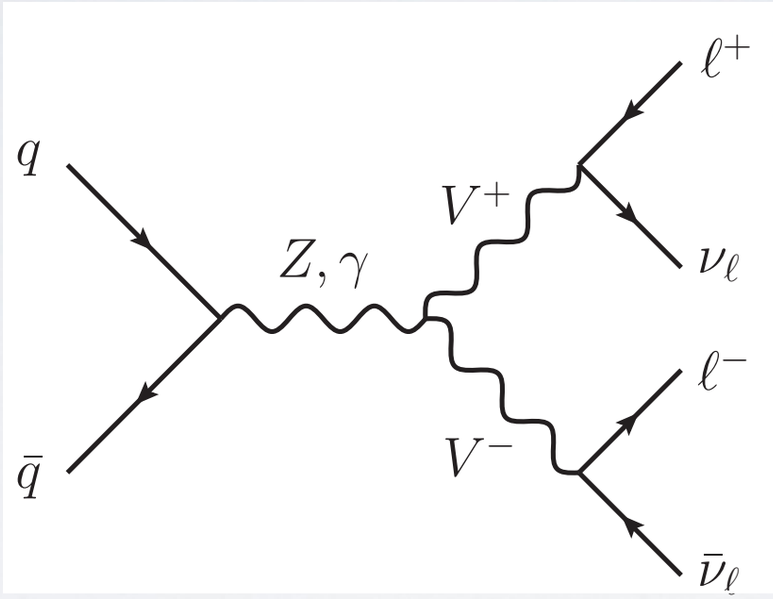
DIRECT TESTS AT THE LHC

(Here: charged vector singlet & neutral fermion singlet)

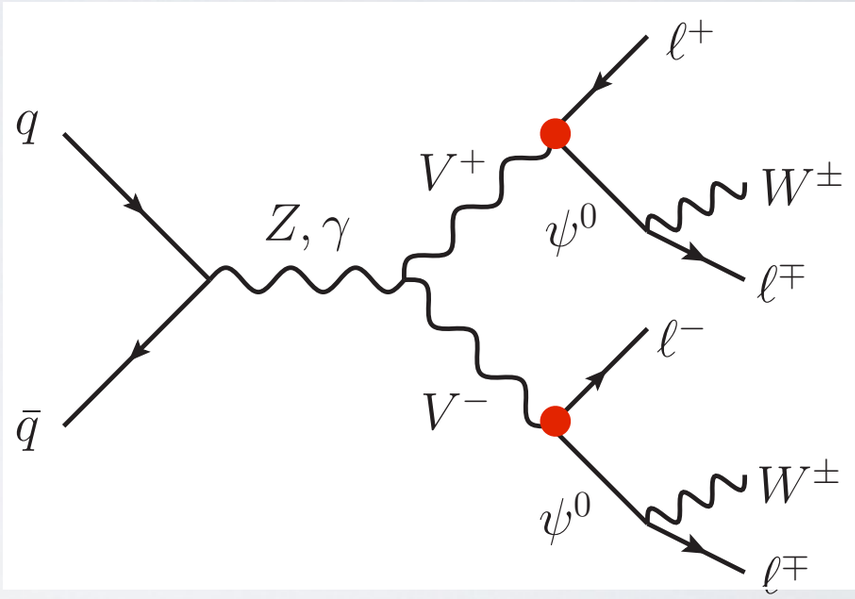
$V^{\pm} + \psi^0$



$M_V < M_\psi$



$M_V > M_\psi$



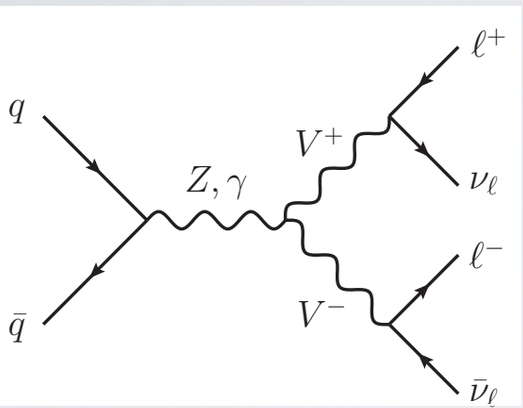
Assumptions

- 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.

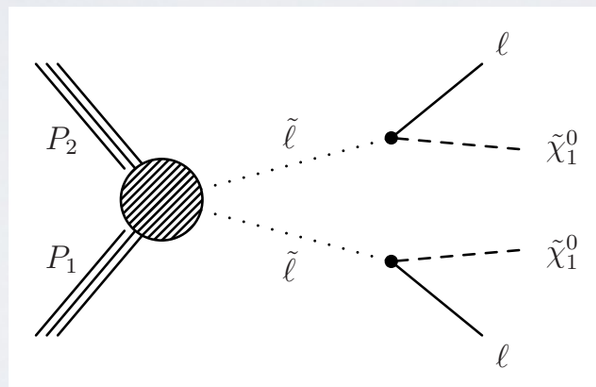
RECAST SEARCHES BY ATLAS & CMS

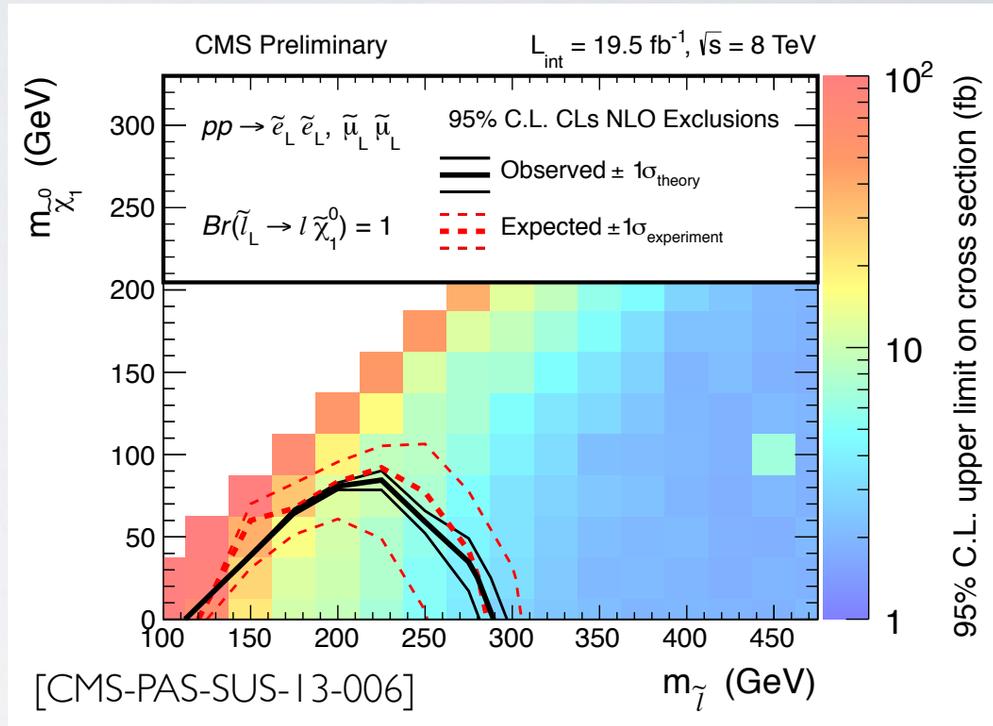
(charged vector singlet & neutral fermion singlet ctd.)

$M_V < M_\psi$: slepton production



$\longleftrightarrow$



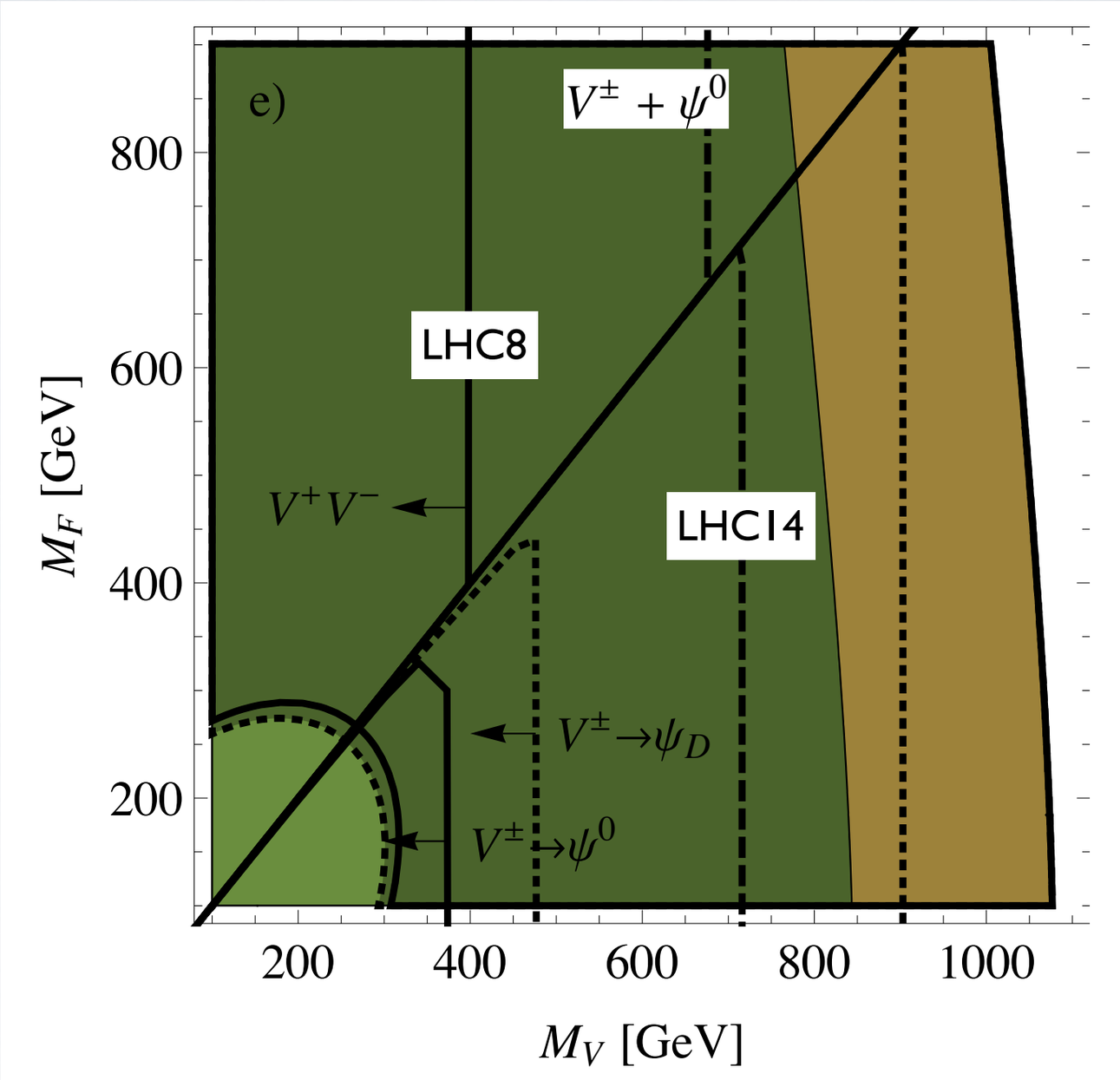


$\longrightarrow \quad M_V > 398\,\mathrm{GeV}$

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

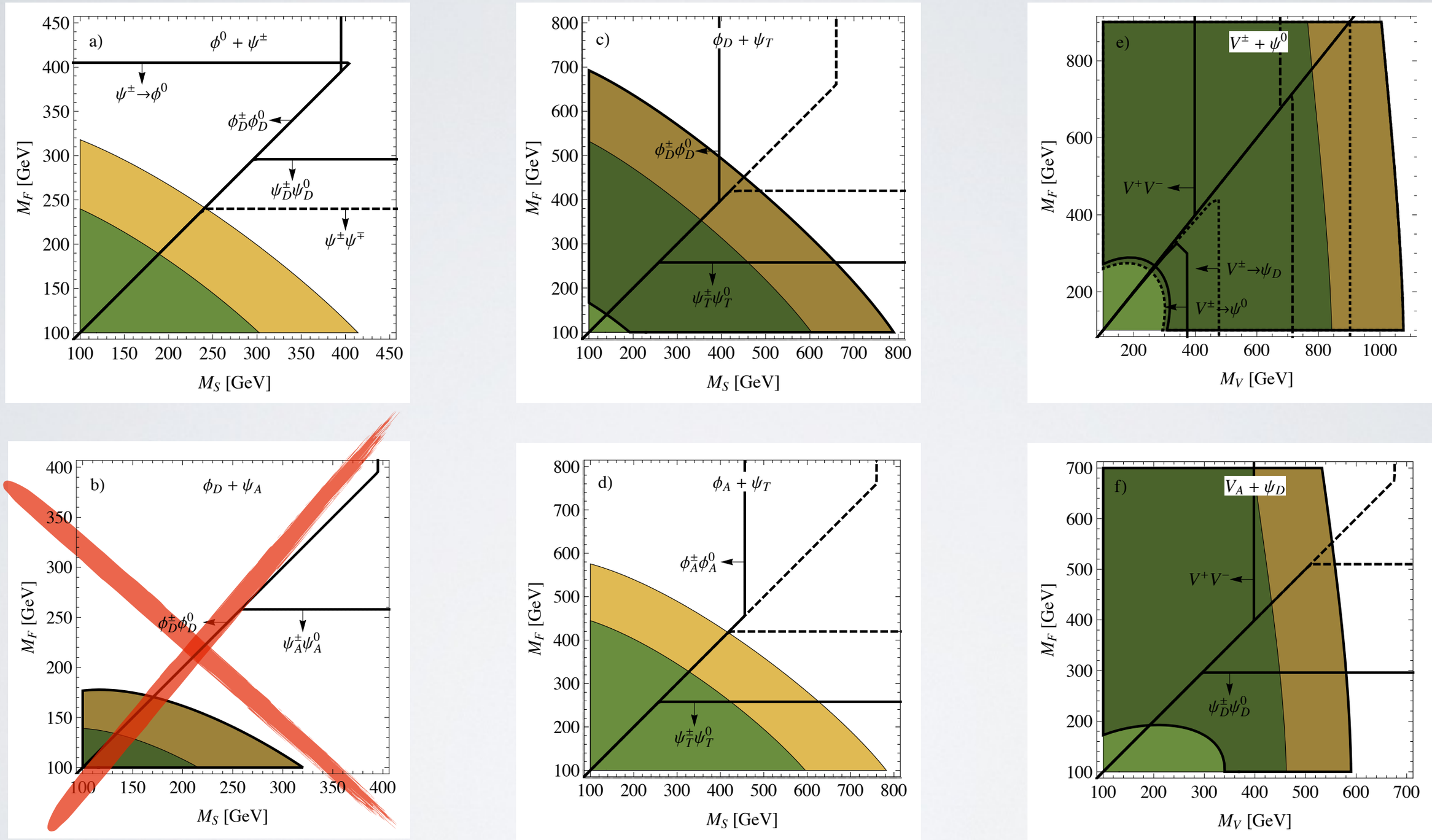
- ψ^0 is weak singlet: $\mathcal{B}(\psi^0 \to W^\pm \ell^\pm) = 1/2$ $\qquad M_V > 373\,\mathrm{GeV}$
- ψ^0 part of weak doublet: $\mathcal{B}(\psi^0 \to W^\pm \ell^\pm) = 1$ $\qquad M_V > 476\,\mathrm{GeV}$

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:

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

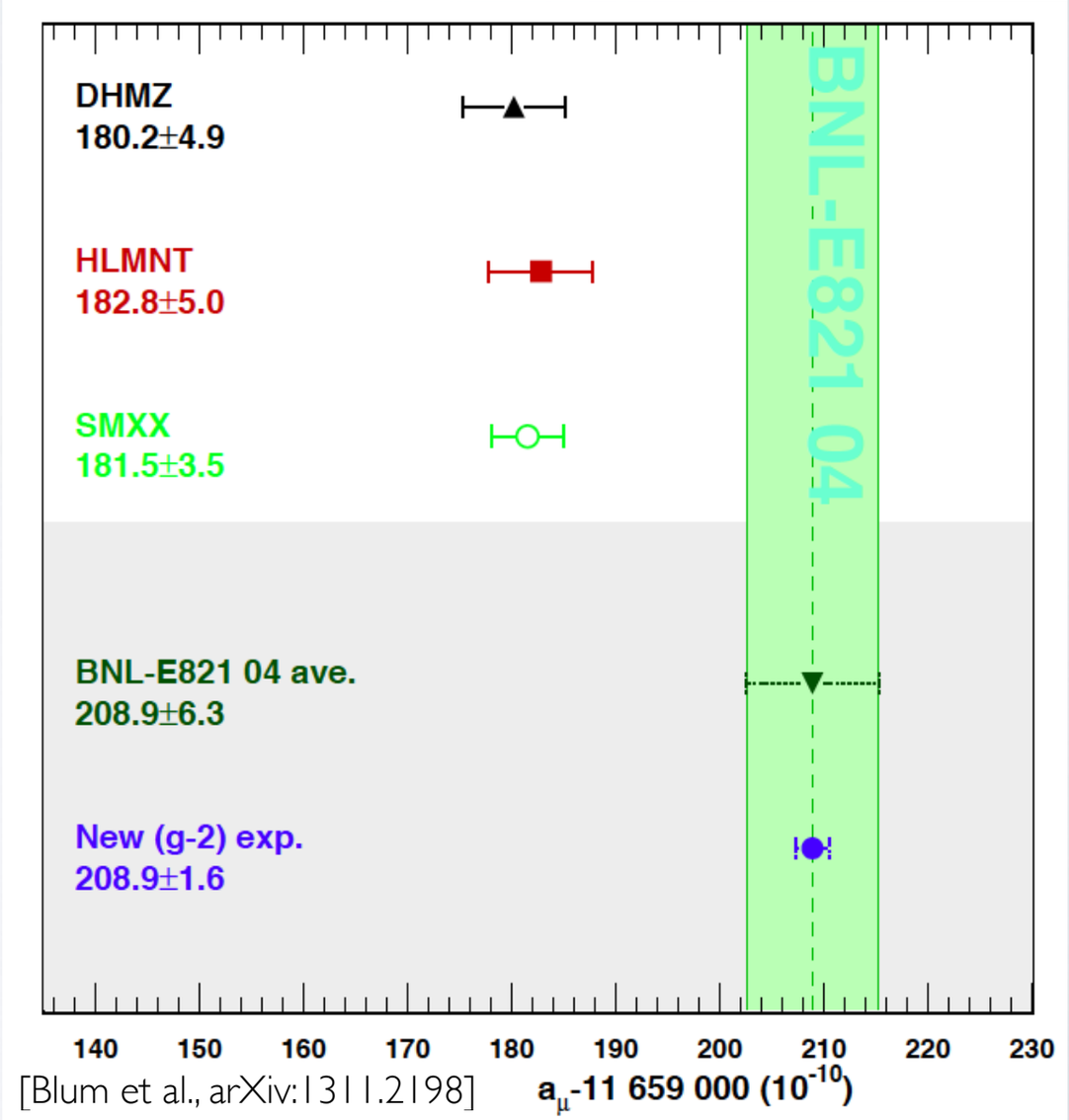
- Fermilab´s E989 and J-PARC:

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

- 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]

SUMMARY

Combined with LEP bounds,
all of our simplified models for g-2 but mixing fermions
can be **conclusively tested at LHC during run II**.

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.