TESTING THE MUON G-2 ANOMALY AT THE LHC

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

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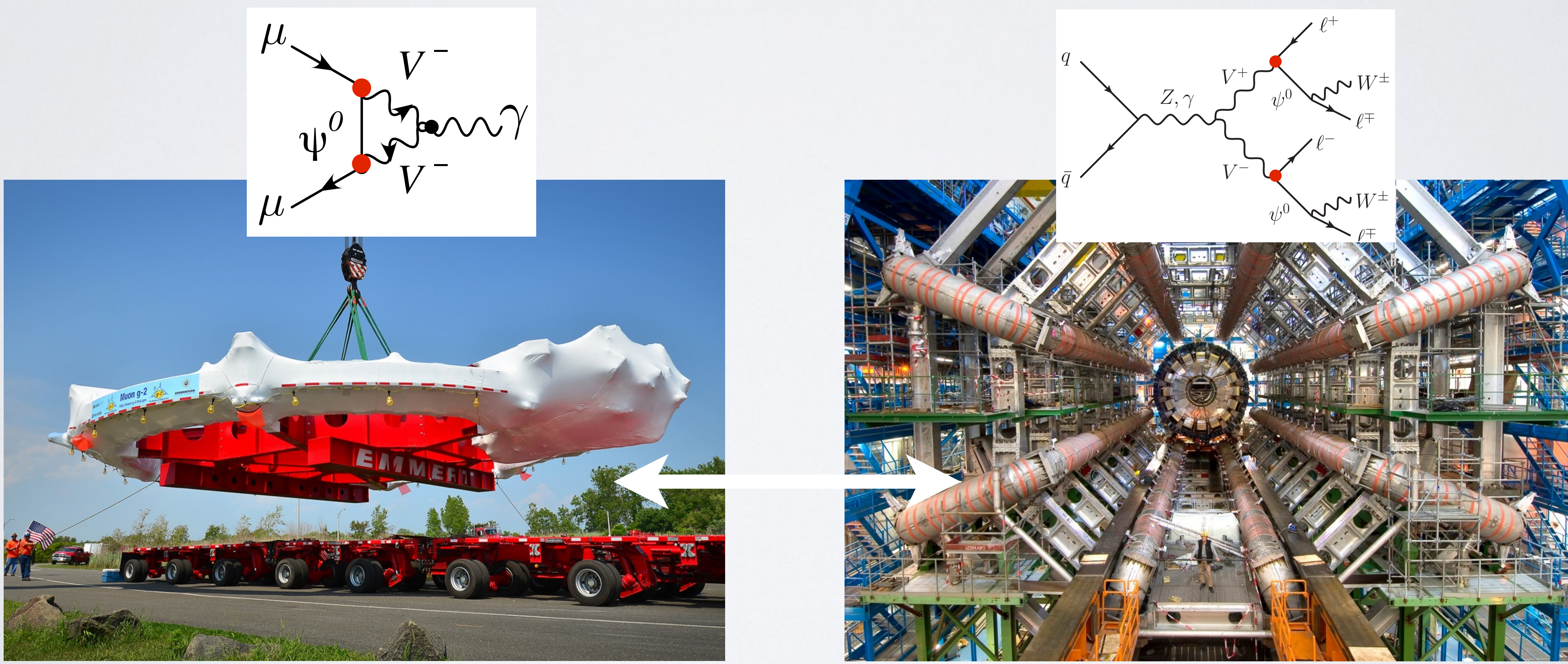
Seminar - June 19, 2014 - LPSC, Grenoble

MUON G-2 AND LHC

Lepton magnetic moment and its anomalous part:

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



LEPTON ANOMALOUS MAGNETIC MOMENTS

Electron anomalous magnetic moment measured at Harvard:

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

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

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

$$a_e^{\mathrm{SM}} = 1.15965218178(77) \times 10^{-3}$$

[Aoyama et al., PRL 109 (2012) 111807]

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

Muon anomalous magnetic moment measured at Brookhaven:

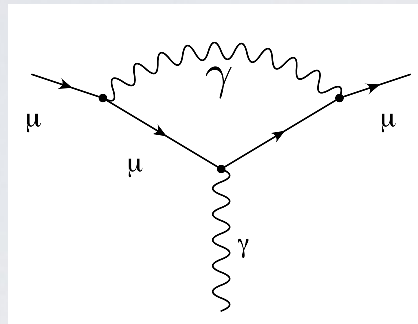
$$a_\mu^{\mathrm{exp}} = 1.16592080(54)(33) \times 10^{-3} \;\; (0.54\,\mathrm{ppm})$$

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

MUON G-2 IN THE STANDARD MODEL

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

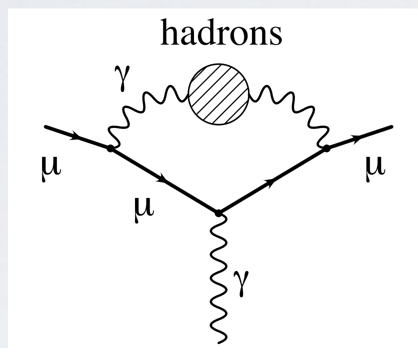
$a_\mu^{\rm SM} = a_\mu^{\rm QED}$



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

$[10^{-11}]$

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

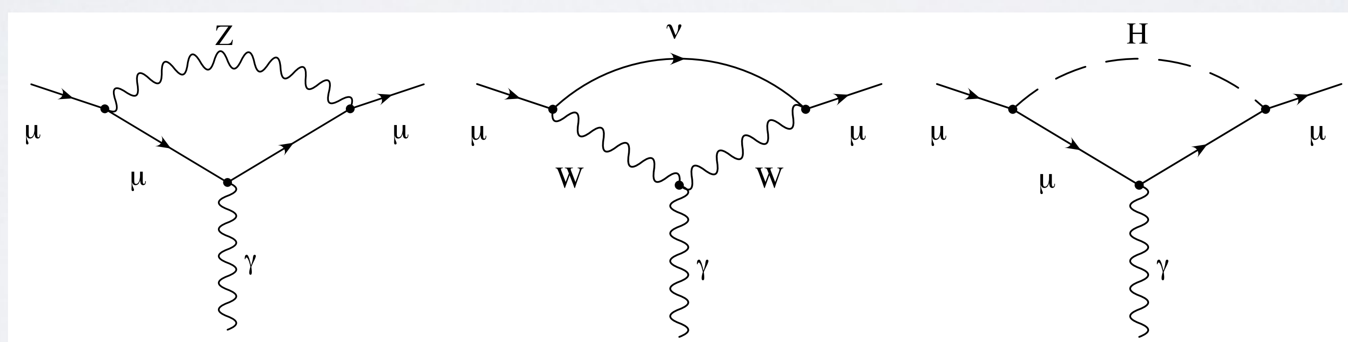


Leading order: $6923(42)$

Higher orders: $-97.9(0.9)$

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

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



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

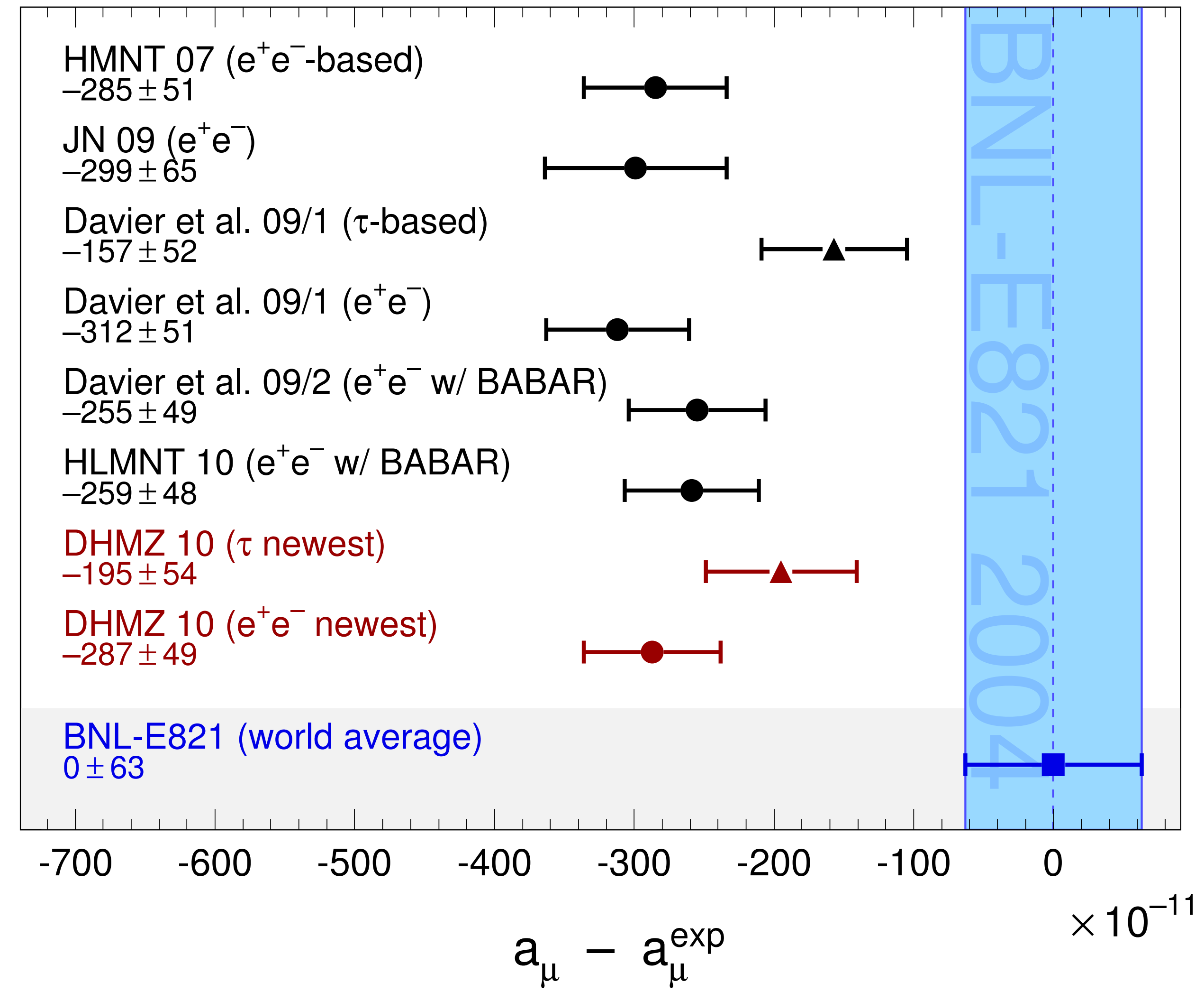
$$\boxed{a_\mu^{\rm SM,tot} = 116591802(49) \times 10^{-11}}$$

THEORY VERSUS BNL MEASUREMENT

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

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

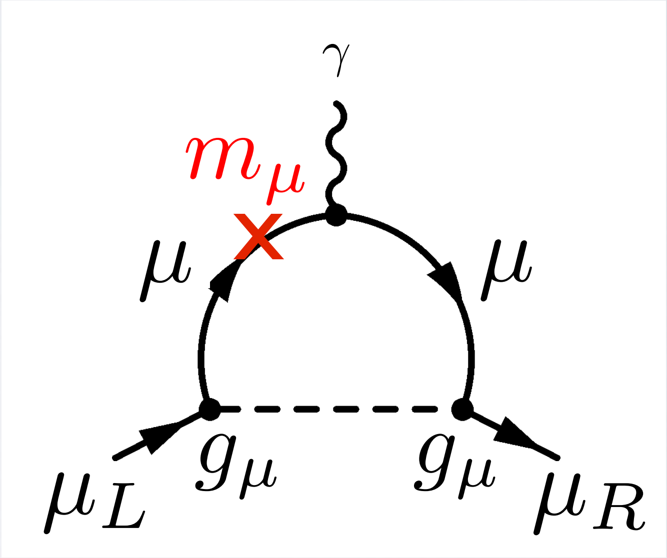
[Davier et al., Eur.Phys.J. C71(2011) 1515]



NEW PHYSICS IN G-2

- $\Delta a_\mu = \mathcal{O}(a_\mu^{\rm EW})$ compatible with new particles at EW scale.

- Need source of chiral symmetry breaking.
  Standard model: $\mathcal{L} \supset -y_\mu \overline{\mu_L} \mu_R h$



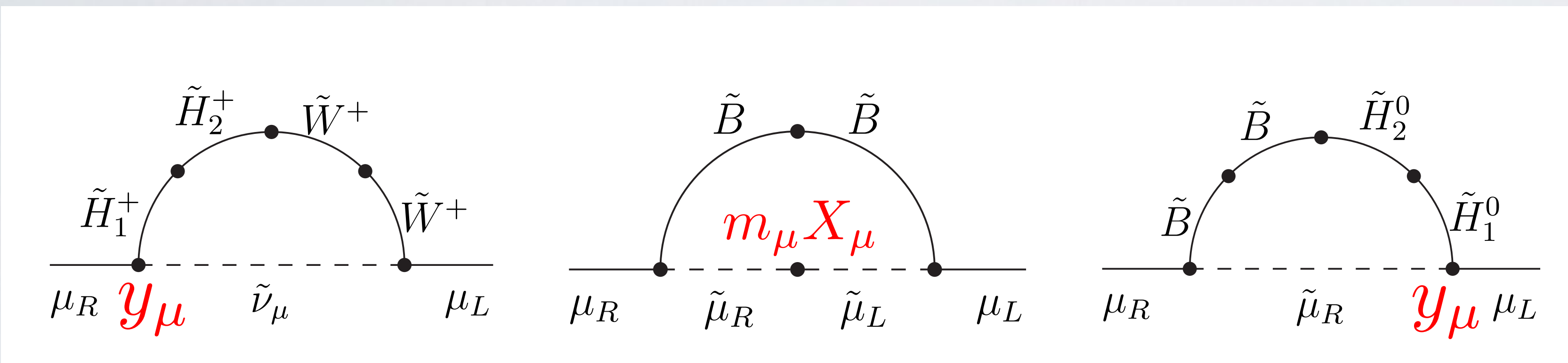
$$a_\mu \sim g_\mu^2 \frac{m_\mu^2}{M^2} \quad \text{and} \quad \frac{a_\mu}{a_e} \sim \frac{m_\mu^2}{m_e^2} \sim 4 \times 10^4$$

- a_μ is more sensitive to NP effects than a_e, despite being less precisely known experimentally.

PROMINENT EXAMPLES

Supersymmetric Standard Model

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



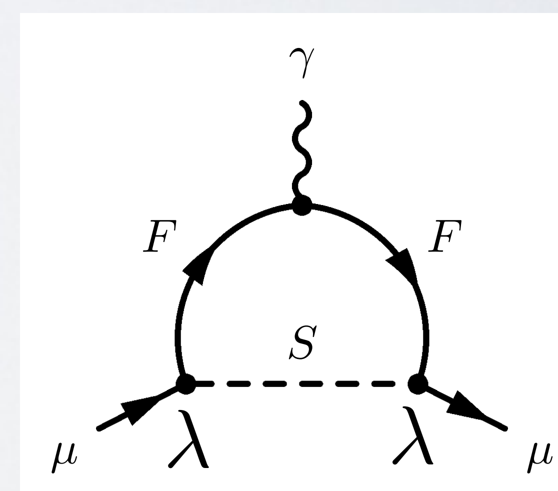
$$a_\mu \sim m_\mu^2 \tan\beta\, \mu\, M$$

[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



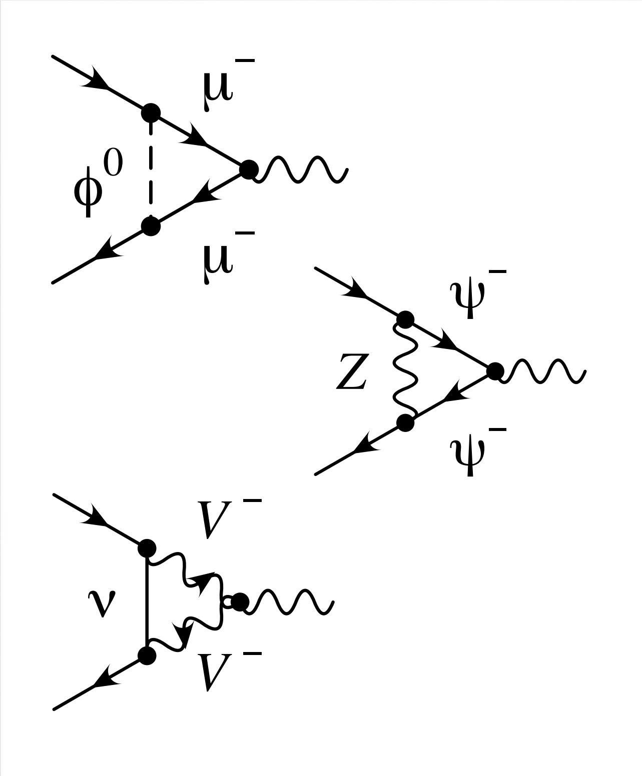
[e.g. Gninenko 2001, Fayet 2007, Pospelov 2008, Agrawal, Chacko, Verhaaren, arXiv:1402.7369]

MODEL-INDEPENDENT APPROACH

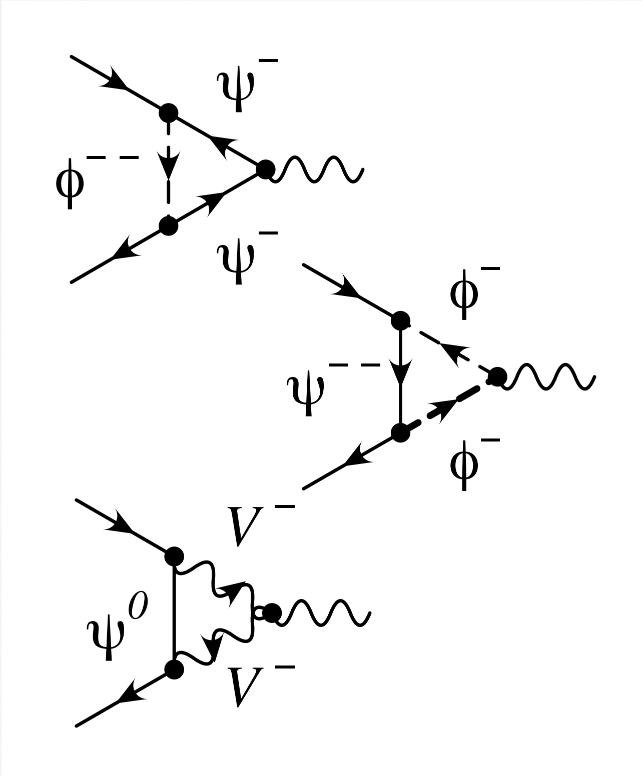
Consider new fields:

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

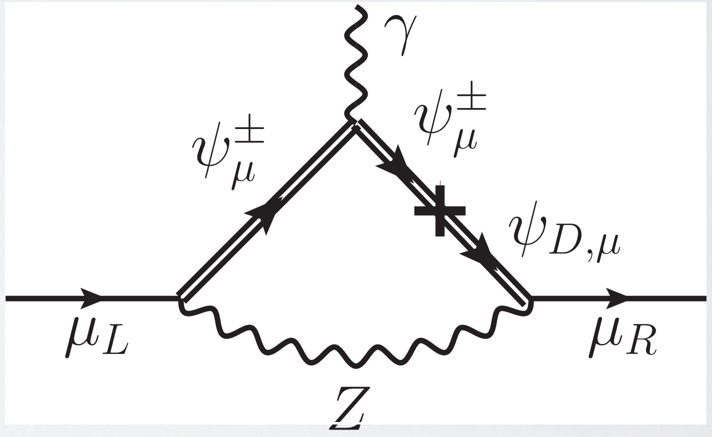
Three classes of one-loop contributions to a_μ :



One new field



Two new fields

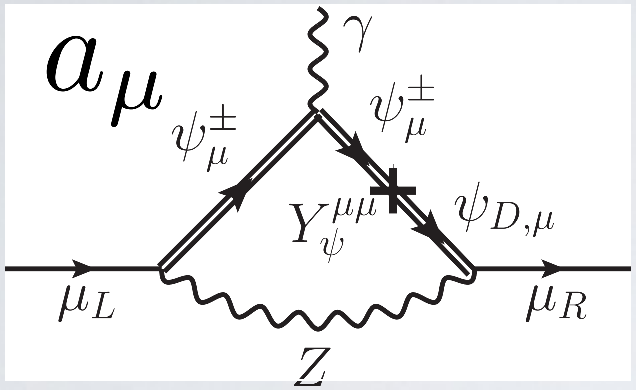


Two mixing fermions

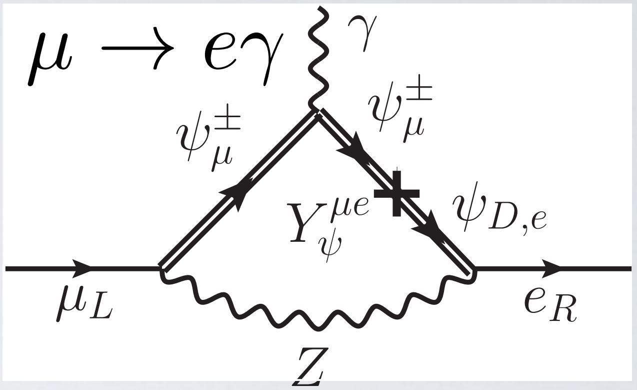
GENERAL PARTICLE FEATURES

- $M > 100\,\mathrm{GeV}$: sizeable couplings → observable at LHC.
- Weak multiplet members are **degenerate in mass**.
- Real, perturbative couplings to leptons.
- New fermions have **vector-like weak interactions**.
- All interactions are **minimally flavor violating**.

MINIMAL FLAVOR VIOLATION



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



Strong exp. constraints on flavor-violating couplings $\sim \Delta_{\mu e}$:

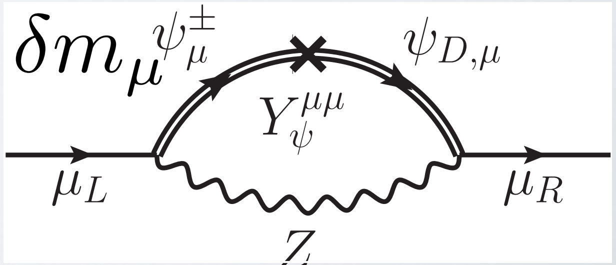
$$\mathcal{B}(\mu \to e\gamma) \approx 6.34 \times 10^{-7} \left(\frac{1\text{TeV}^4}{\Lambda_{\text{FV}}^4} \right) |\Delta_{\mu e}|^2 < 2.4 \times 10^{-12}$$

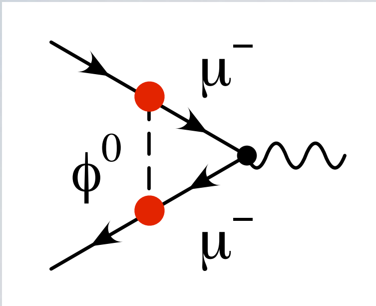
[Cirigliano et al., Nucl.Phys.B728 (2005) 121]

Minimal flavor violation:

- Fermions in **fundamental** repres. of $\mathcal{G}_F = \text{SU}(3)_L \times \text{SU}(3)_e$.
- Three **flavor copies** of new fermions.
- Yukawa mixing $Y_\psi \sim Y_\ell$ or $Y_{\psi\ell} \sim Y_\ell$ ($\Delta_{\mu e} \sim$ neutrino mixing).

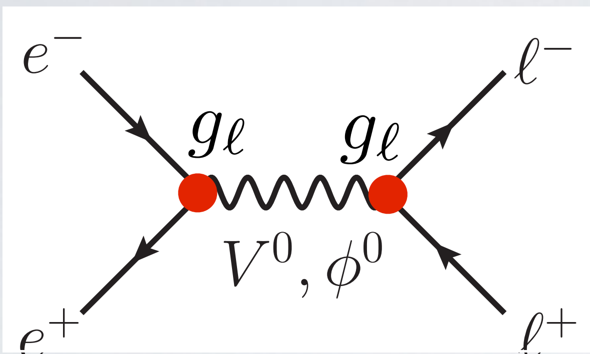
Muon mass protected: $m_\mu = y_\mu v(1 + \delta m_\mu)$





ONE NEW BOSON: LEP BOUNDS

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



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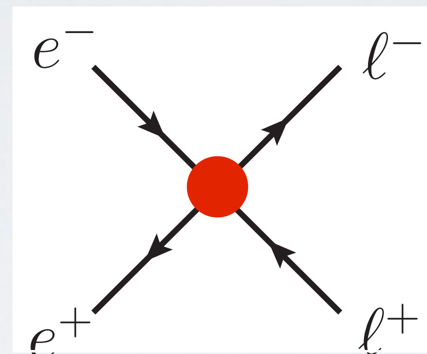


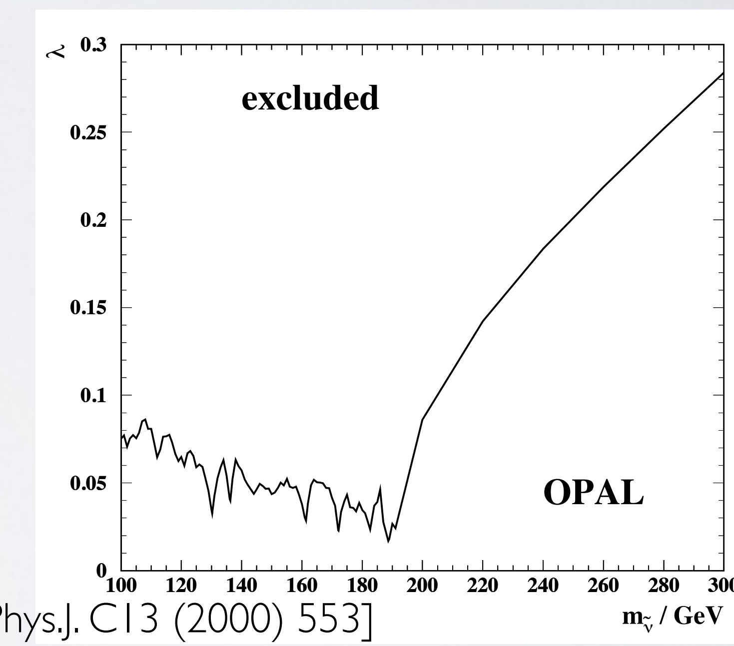
$$\sim \frac{g_\ell^2}{M_{V,\phi}^2} \lesssim (0.0003\,\mathrm{GeV}^{-1})^2$$

[LEP colls., hep-ex/0612034]

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

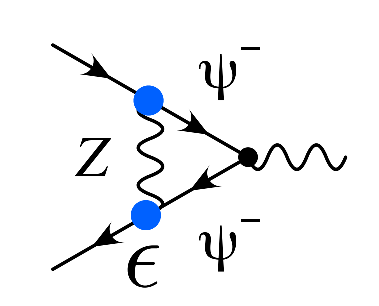
$$e^+e^- \to (V^0, \phi^0)\gamma \to \ell^+\ell^-\gamma$$

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



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

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



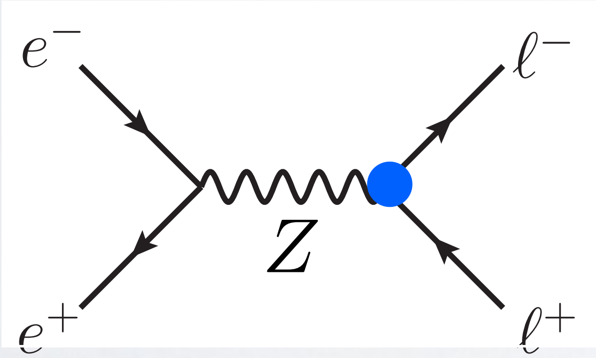
ONE NEW FERMION: LEP BOUNDS

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

$$\mathcal{L} \supset -Y_\ell \overline{\psi_L} H \ell_R + \text{h.c.} \xrightarrow{\langle H \rangle} (1-\epsilon^2/2)\overline{\ell_R}\gamma^\mu \ell_R Z_\mu \qquad \text{(LEP)}$$

$$\text{and} \quad \epsilon\, \overline{\psi_R}\gamma^\mu \ell_R Z_\mu \qquad (a_\mu)$$

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 $\delta a_\mu < 0$).

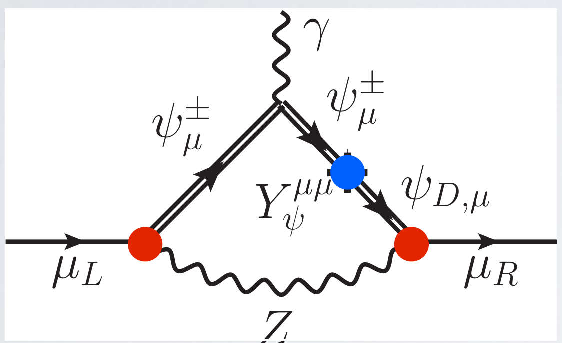
MIXING VECTOR FERMIONS

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

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

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

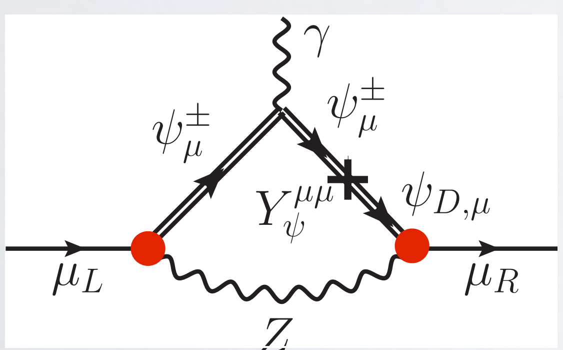
$$\delta a_\mu \sim m_\mu M_\psi \epsilon_1 \epsilon_2 \frac{Y_\psi v}{M_\psi}$$



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

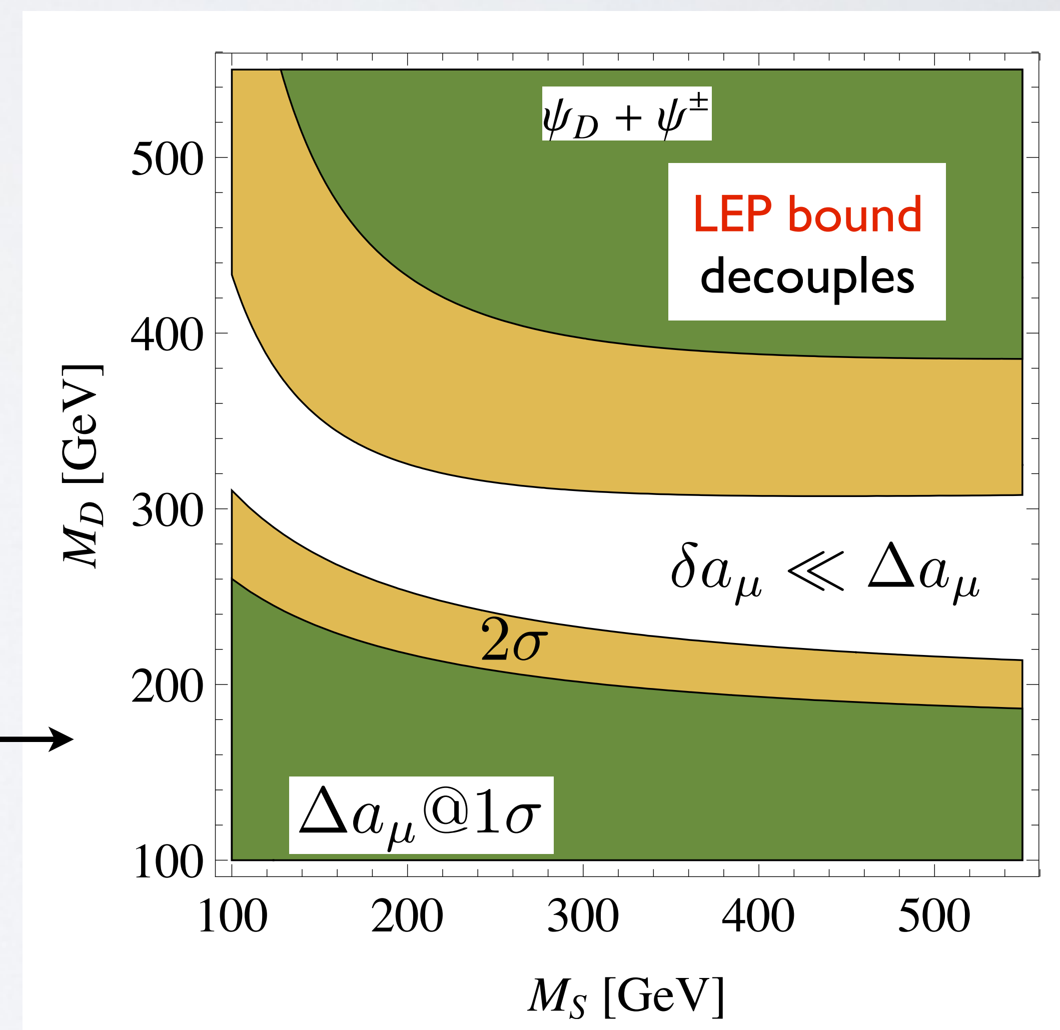
$\longrightarrow \; \delta a_\mu \lesssim \mathcal{O}(10^{-10})$

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



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

$\longrightarrow$



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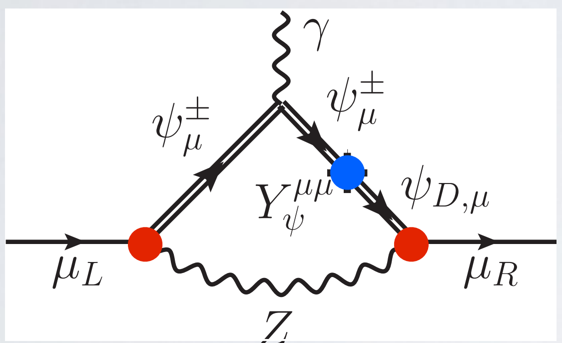
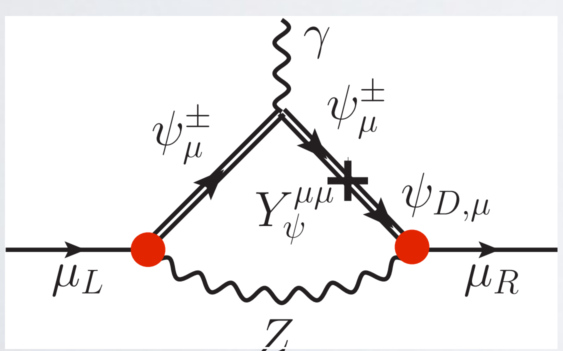


$|Y_\psi| \lesssim 0.2,\ |\epsilon| \lesssim 0.03$

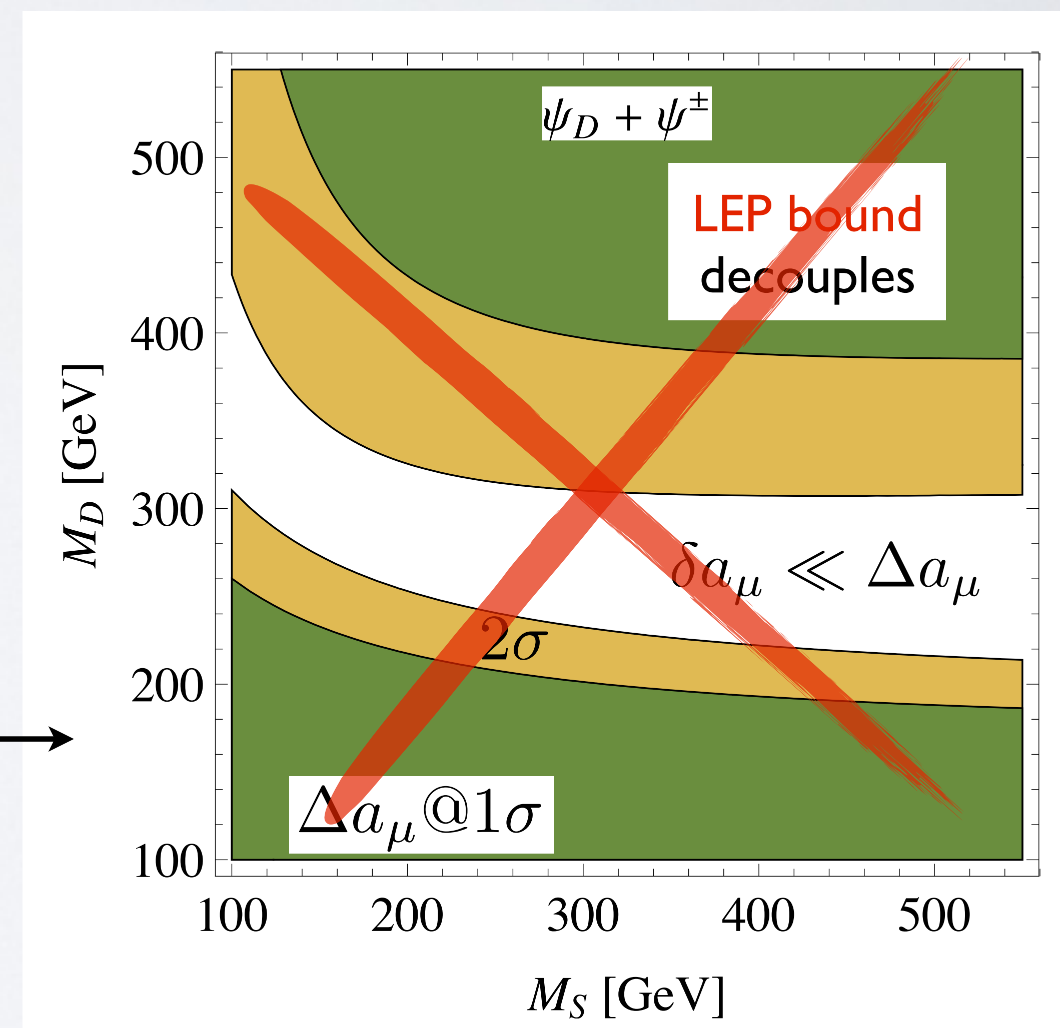
$\longrightarrow\ \delta a_\mu \lesssim \mathcal{O}(10^{-10})$

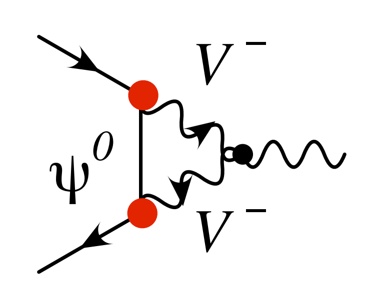
$$\delta a_e = \frac{m_e}{m_\mu}\Delta a_\mu = 1.4\times 10^{-11} \gg a_e^{\rm exp} - a_e^{\rm SM}$$

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



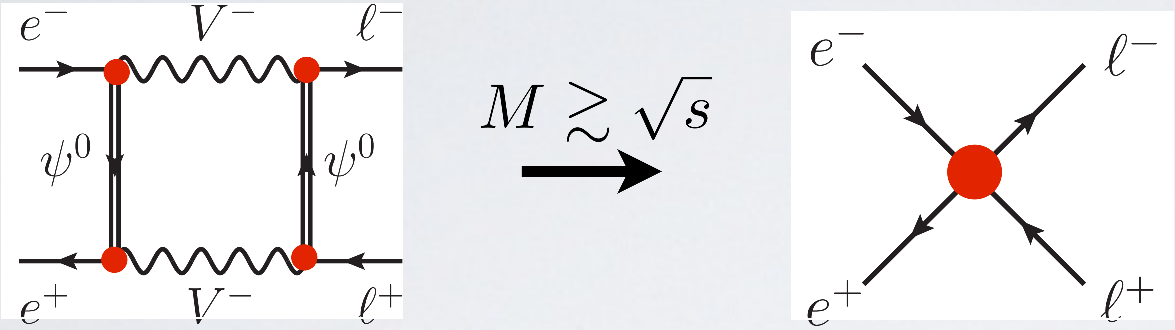
$|Y_\psi| \lesssim \sqrt{4\pi},\ |\epsilon| \lesssim 0.03$





TWO NEW FIELDS: LEP BOUNDS

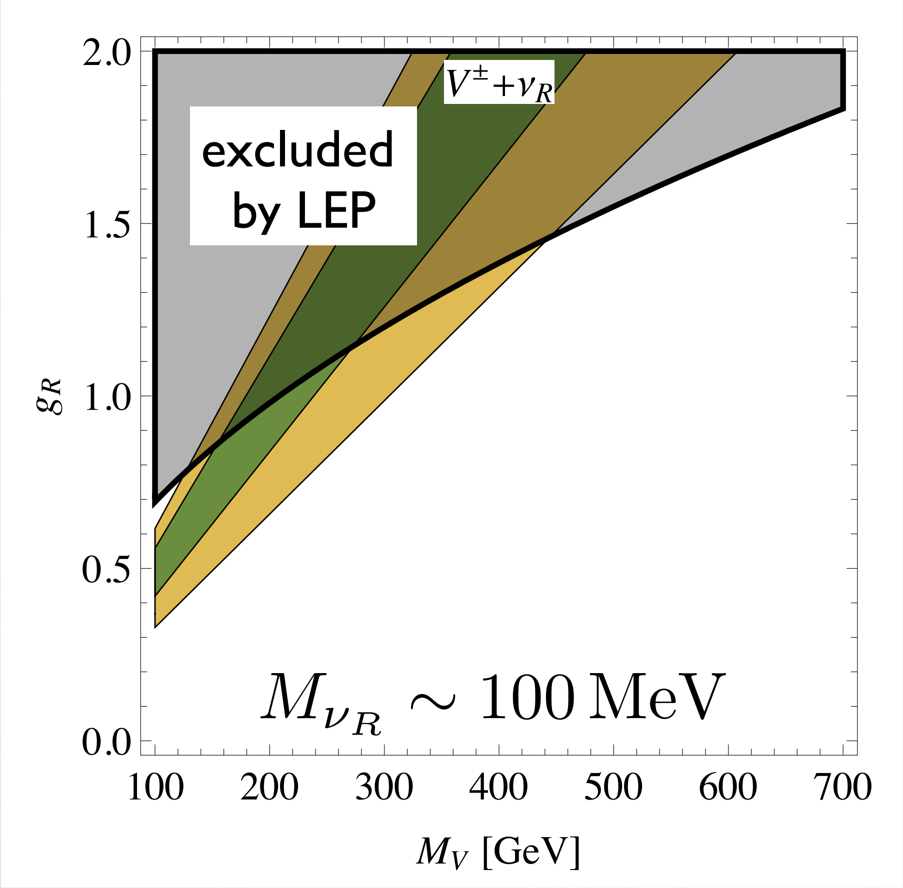
Indirect bound on SM-NP-NP couplings at one-loop level:

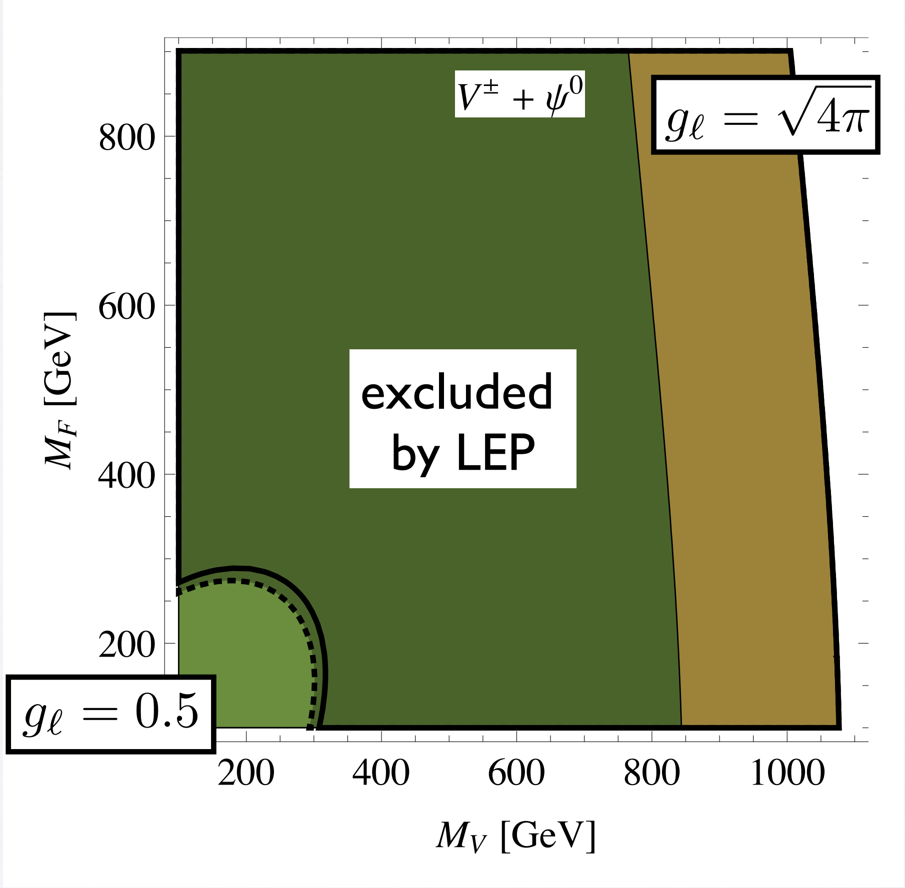


$$\sim \frac{g_\ell^4}{16\pi^2 M_V^2} \lesssim (0.0003\,\mathrm{GeV}^{-1})^2$$

[LEP colls., hep-ex/0612034]

LEP constraints on δa_μ in regions of strong couplings:

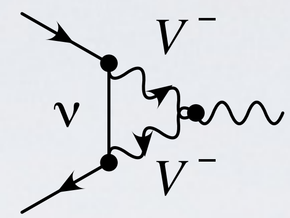




VIABLE G-2 CANDIDATES AFTER LEP

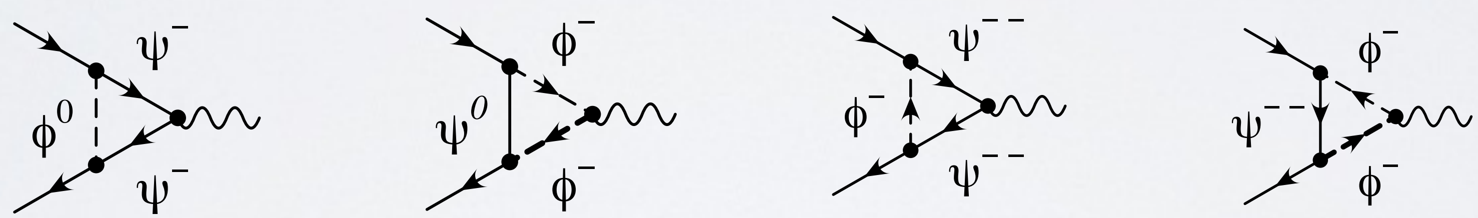
One new field

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

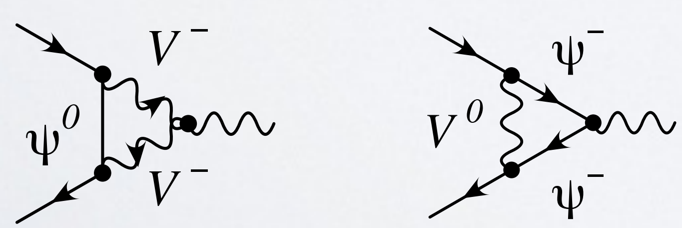


Two new fields

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

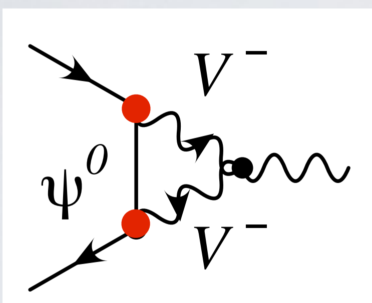


One-loop LEP bounds optional; may be relaxed by tree-level NP.

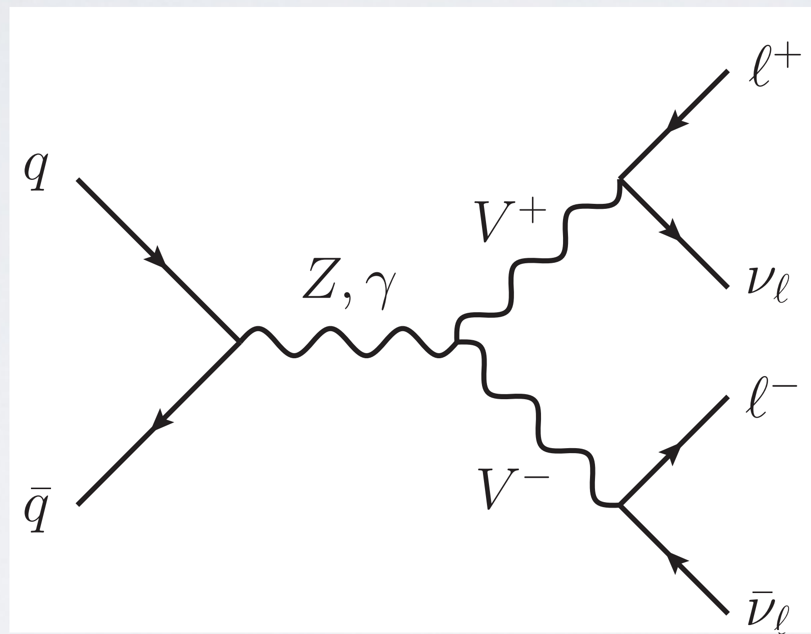
DIRECT TESTS AT THE LHC

(Here: charged vector singlet & neutral fermion singlet)

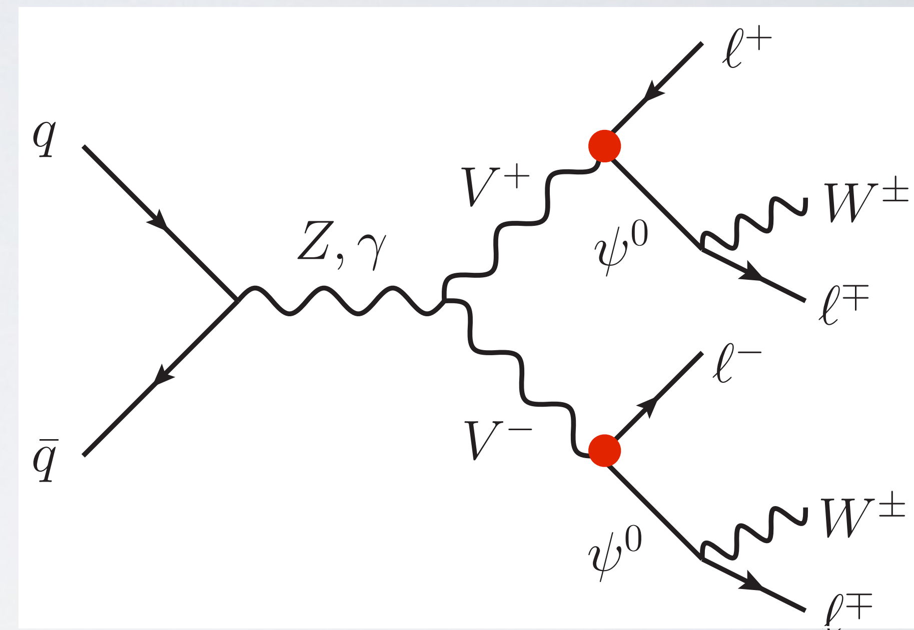
$V^{\pm} + \psi^0$



$M_V < M_\psi$



$M_V > M_\psi$



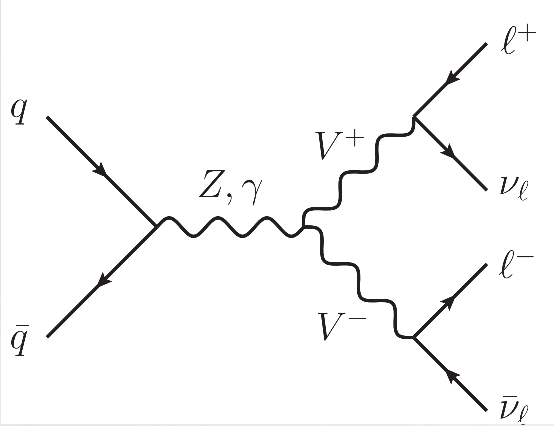
Assumptions

- 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.

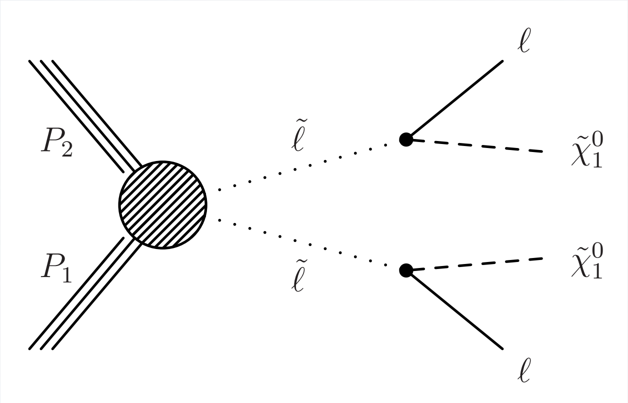
RECAST SEARCHES BY ATLAS & CMS

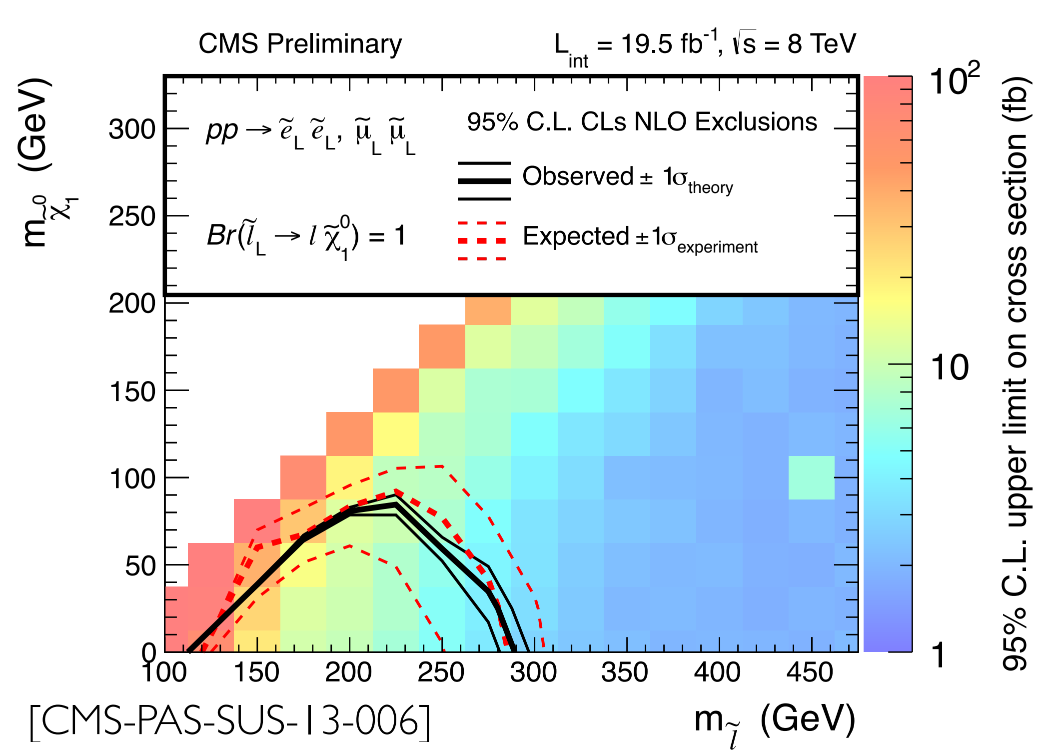
(charged vector singlet & neutral fermion singlet ctd.)

$M_V < M_\psi$: slepton production



$\longleftrightarrow$





[CMS-PAS-SUS-13-006]

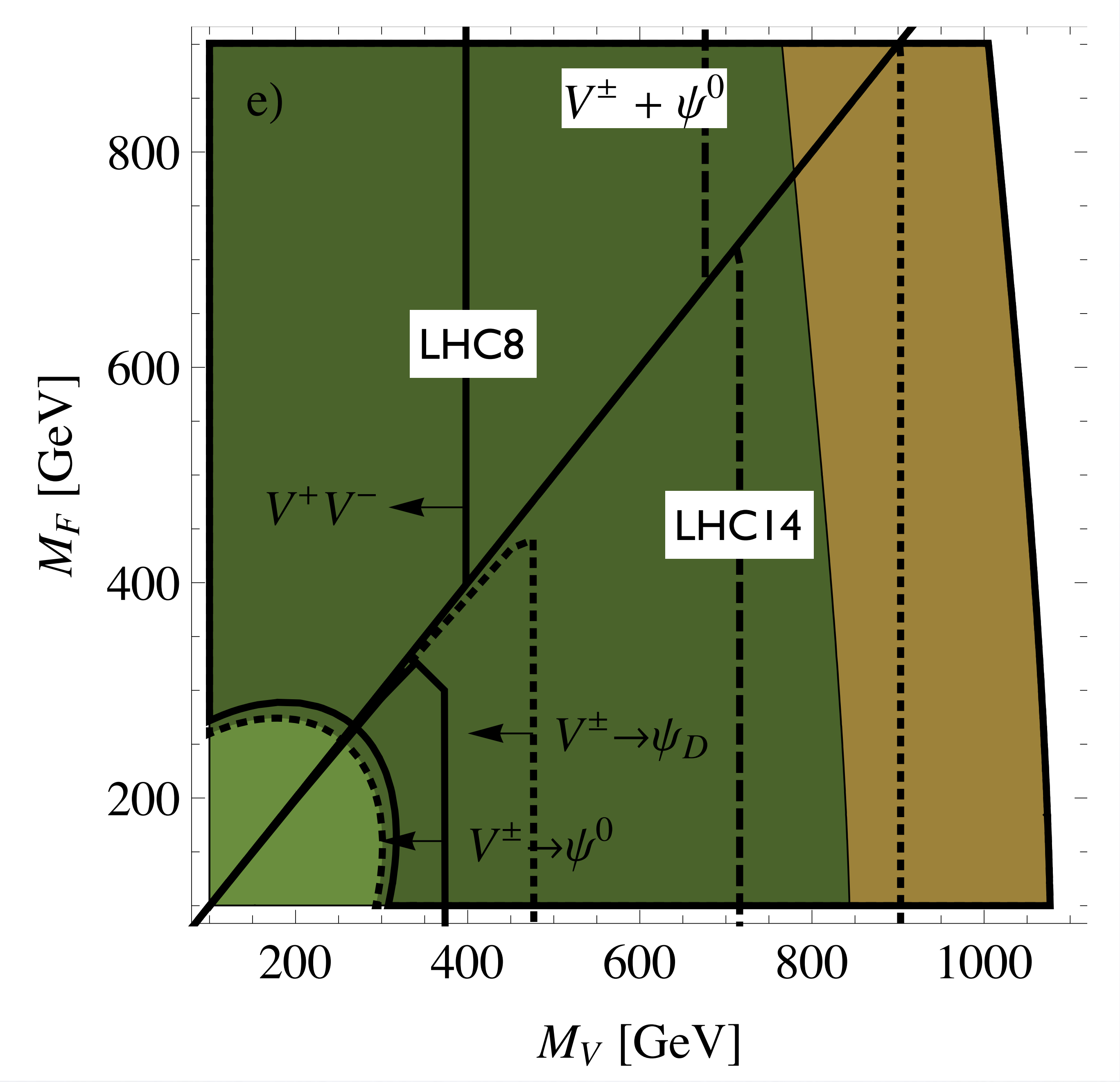
$\longrightarrow \quad M_V > 398\,\mathrm{GeV}$

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

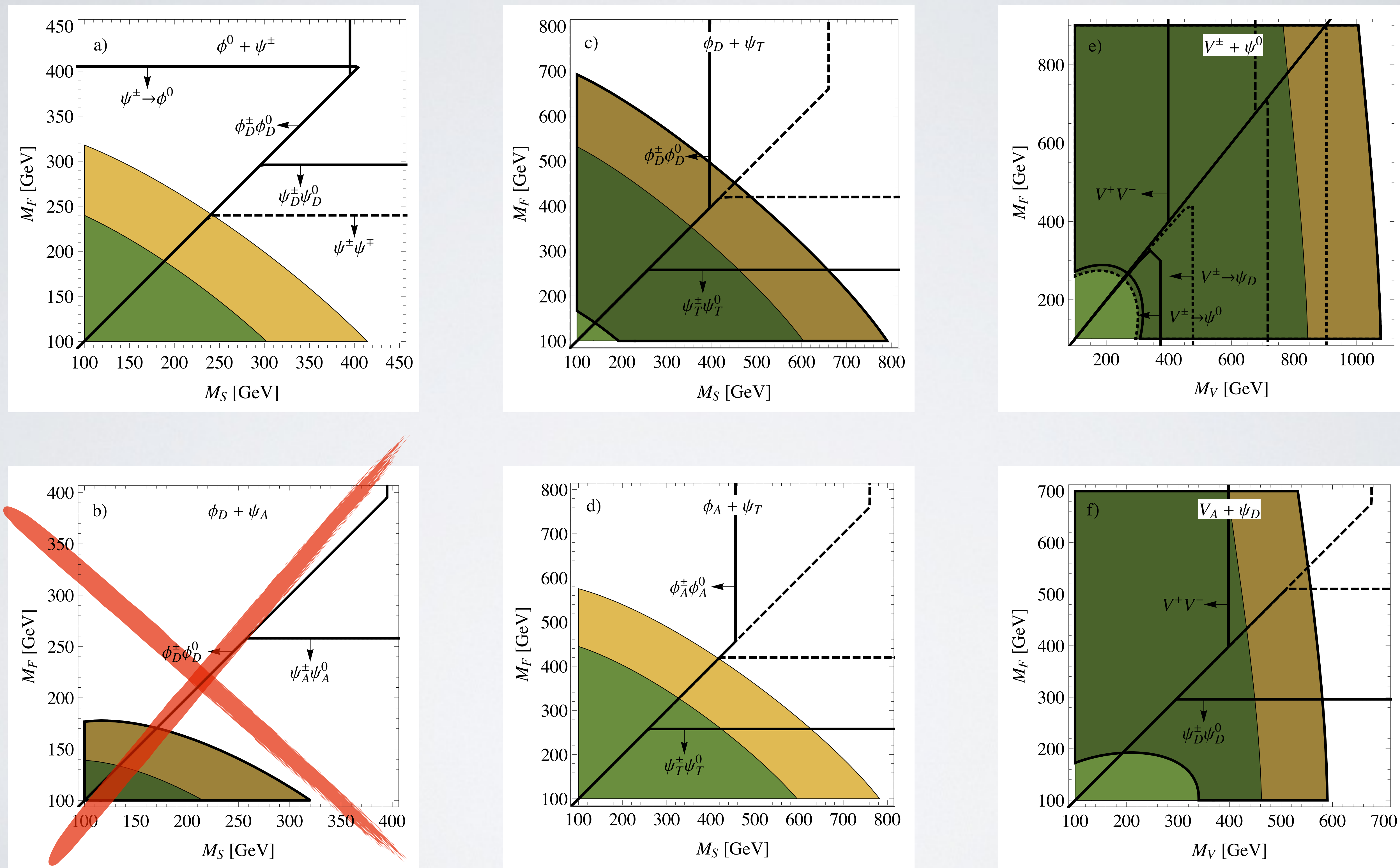
- ψ^0 is weak singlet: $\mathcal{B}(\psi^0 \to W^\pm \ell^\pm) = 1/2$ $\quad M_V > 373\,\mathrm{GeV}$

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

LHC CONSTRAINTS ON G-2



G-2 CANDIDATES AFTER LHC8



G-2 TEST POTENTIAL OF LHC14

- Assuming similar experimental efficiency, rescale event yield

$$N_{14}(300\,\mathrm{fb}^{-1}) = N_8(20\,\mathrm{fb}^{-1})\frac{\sigma(14\,\mathrm{TeV})}{\sigma(8\,\mathrm{TeV})}$$

- LHC14 can test Δa_μ in almost all scenarios at the 2σ level.

- Bounds expected to tighten when searches are optimized to scenarios for Δa_μ.

- Combined with LEP bounds, LHC14 will **conclusively test** all these simplified models.

PROSPECTS: ORIGIN OF G-2 ANOMALY?

- Current g-2 uncertainties:

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

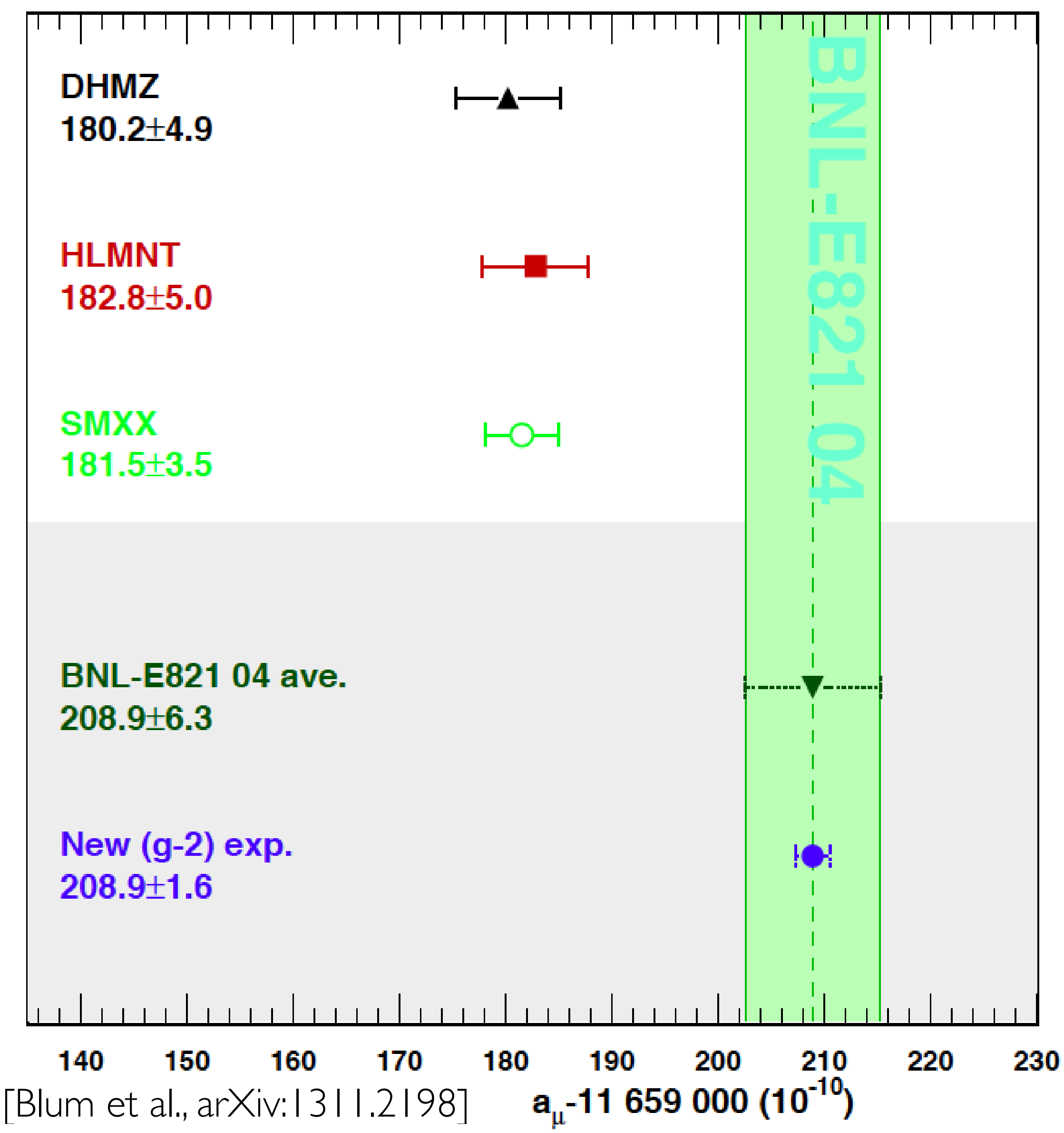
- Fermilab´s E989 and J-PARC:

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

- 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]

BACKUP: LHC CONSTRAINTS ON G-2 SCENARIOS

Scenario	Production	LHC8	LHC14
$V^\pm$	$pp \to V^+V^-$	$M_V > 398$ GeV	$M_V > 676$ GeV
$\phi^0 + \psi^\pm$	$M_\psi < M_\phi$: $pp \to \psi^+\psi^-$	–	$\times$
	$M_\psi > M_\phi$: $pp \to \psi^+\psi^- \to \ell^+\phi^0\,\ell^-\phi^0$	$\times$	$\times$
$\phi^0 + \psi_D$	$M_\psi < M_\phi$: $pp \to \psi^\pm\psi^0$	$\times$	$\times$
	$M_\psi > M_\phi$: $pp \to \psi^+\psi^- \to \ell^+\phi^0\,\ell^-\phi^0$	$\times$	$\times$
$\phi_D + \psi^\pm$	$M_\psi < M_\phi$: $pp \to \psi^+\psi^-$	–	$\times$
	$M_\psi > M_\phi$: $pp \to \phi^\pm\phi^0$	$\times$	$\times$
$\phi_D + \psi_A$	$M_\psi < M_\phi$: $pp \to \psi^\pm\psi^0$	$\times$	$\times$
	$M_\psi > M_\phi$: $pp \to \phi^\pm\phi^0$	$\times$	$\times$
$\phi_D + \psi_T$	$M_\psi < M_\phi$: $pp \to \psi^\pm\psi^0$	$M_\psi > 258$ GeV	$M_\psi > 420$ GeV
	$M_\psi > M_\phi$: $pp \to \phi^\pm\phi^0$	$M_\phi > 380$ GeV	$\times$
$\phi_A + \psi_T$	$M_\psi < M_\phi$: $pp \to \psi^\pm\psi^0$	$M_\psi > 258$ GeV	$\times$
	$M_\psi > M_\phi$: $pp \to \phi^\pm\phi^0$	$\times$	$\times$
$V^\pm + \psi^0$	$M_V < M_\psi$: $pp \to V^+V^-$	$M_V > 398$ GeV	$M_V > 676$ GeV
	$M_V > M_\psi$: $pp \to V^+V^- \to \ell^+\psi^0\,\ell^-\psi^0$	$M_V > 373$ GeV	$M_V > 716$ GeV
$V^\pm + \psi_D$	$M_V < M_\psi$: $pp \to V^+V^-$	$M_V > 398$ GeV	$M_V > 676$ GeV
	$M_V > M_\psi$: $pp \to V^+V^- \to \ell^+\psi^0\,\ell^-\psi^0$	$M_V > 476$ GeV	$M_V > 903$ GeV
$V_A + \psi_D$	$M_V < M_\psi$: $pp \to V^+V^-$	$M_V > 398$ GeV	$\times$
	$M_V > M_\psi$: $pp \to \psi^\pm\psi^0$	$M_\psi > 296$ GeV	$\times$

Decay			
	$\phi^0 \to \ell^+\ell^-$	$V^0 \to \ell^+\ell^-$	$\psi^0 \to \nu Z,\ \nu H,\ \ell^\pm W^\mp$
	$\phi^\pm \to \ell^\pm\nu$	$V^\pm \to \ell^\pm\nu$	$\psi^\pm \to \ell^\pm Z,\ \ell^\pm H,\ \nu W^\pm$