Heavy leptons and the muon anomalous magnetic moment

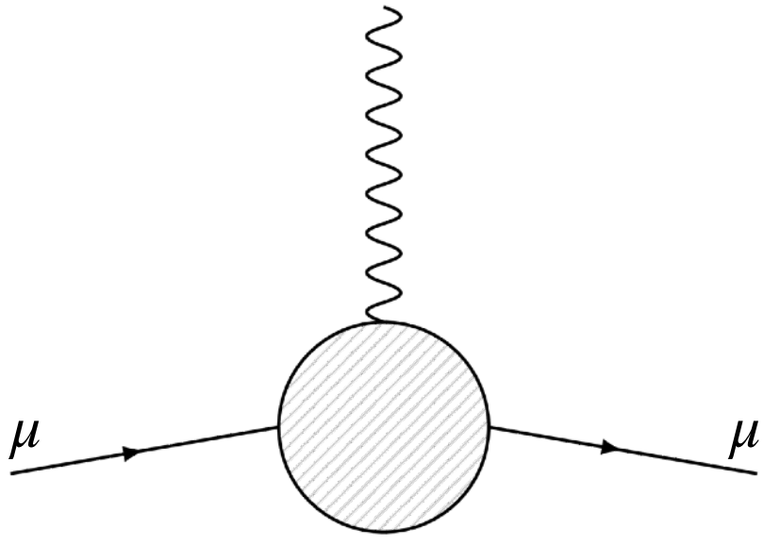
Navin McGinnis

Based on works with R. Dermíšek and K. Hermanek

Phys.Rev.Lett. 126 (2021) 19, 191801
& 2103.05645 [hep-ph]

DPF21 - July 12, 2021

TRIUMF



Featured in Physics | Editors' Suggestion | Open Access

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

B. Abi *et al.* (Muon $g-2$ Collaboration)
Phys. Rev. Lett. **126**, 141801 – Published 7 April 2021

Physics

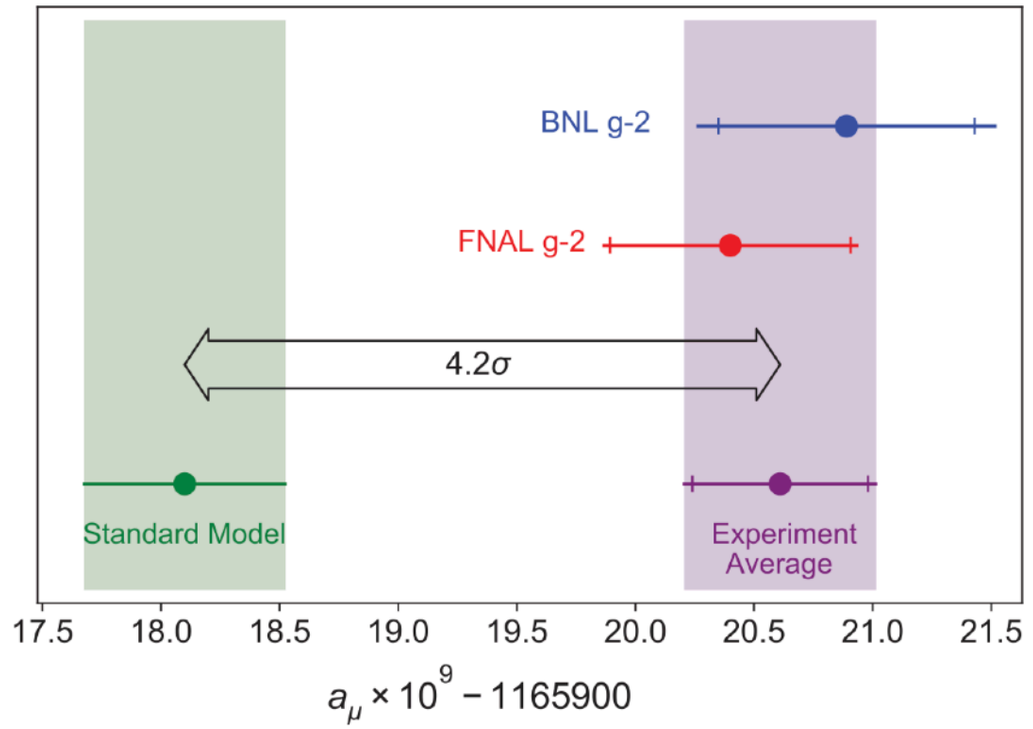
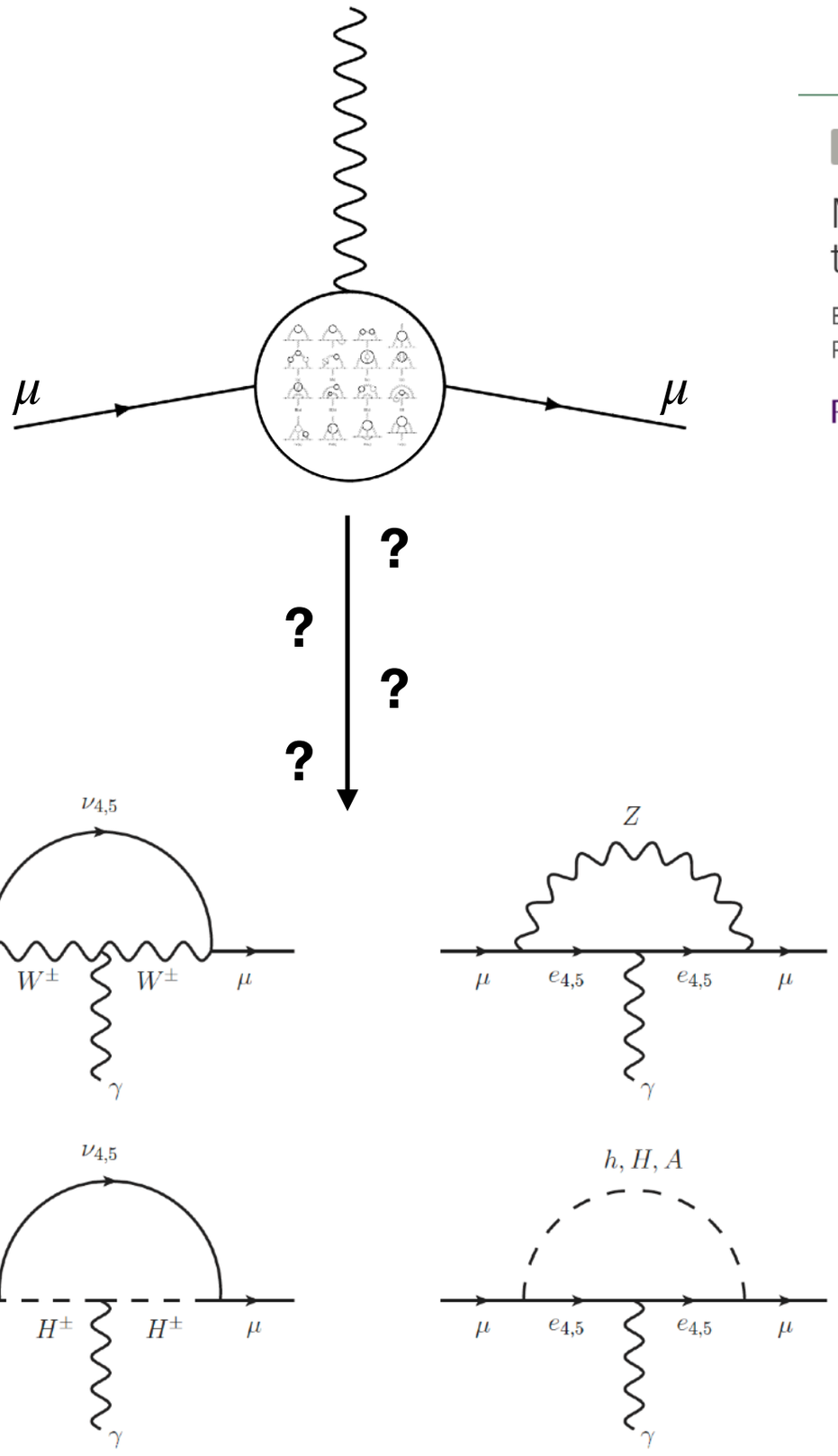


FIG. 4. From top to bottom: experimental values of a_μ from BNL E821, this measurement, and the combined average. The inner tick marks indicate the statistical contribution to the total uncertainties. The Muon $g-2$ Theory Initiative recommended value [13] for the standard model is also shown.



Featured in Physics | Editors' Suggestion | Open Access

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

B. Abi *et al.* (Muon $g-2$ Collaboration)

Phys. Rev. Lett. **126**, 141801 – Published 7 April 2021

Physics

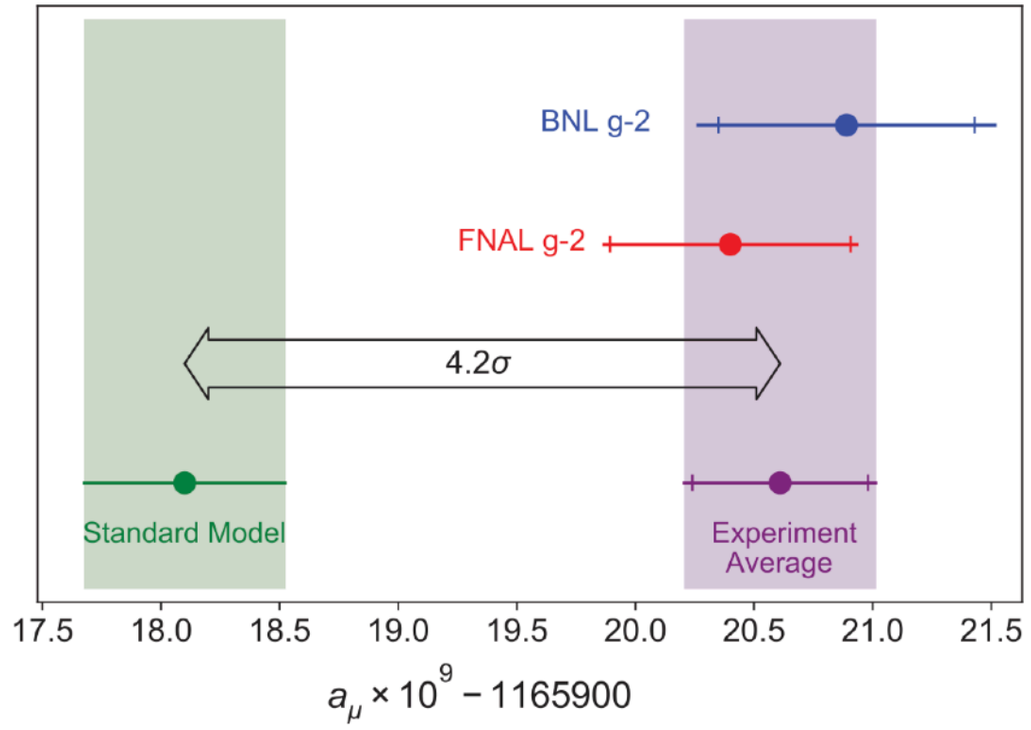


FIG. 4. From top to bottom: experimental values of a_μ from BNL E821, this measurement, and the combined average. The inner tick marks indicate the statistical contribution to the total uncertainties. The Muon $g-2$ Theory Initiative recommended value [13] for the standard model is also shown.

Vectorlike leptons & $(g-2)_\mu$

- VLL appear in many simple extensions of the SM
  - SM + charged/neutral VL matter
    - R. Dermisek & A. Raval: *Phys.Rev.D* 88 (2013) 013017
    - K. Kannike, M. Raidal, D. Straub, & A. Strumia: *JHEP* 02 (2012) 106
    - N. Arkani-Ahmed, & K. Harigaya: 2106.01373 [hep-ph]

- Many models also include additional states (SM + VLL + other stuff)
  - $(g-2)_\mu$ & DM
    - L. Calibbi, R. Ziegler, J. Zupan: *JHEP* 07 (2018) 046
- New physics of $(g-2)_\mu$ and muon colliders
  - R. Capdevilla, D. Curtin, Y. Kahn, G. Krnjaic: *Phys.Rev.D* 103 (2021) 7, 2101.10334 [hep-ph]

Vectorlike leptons & $(g-2)_\mu$

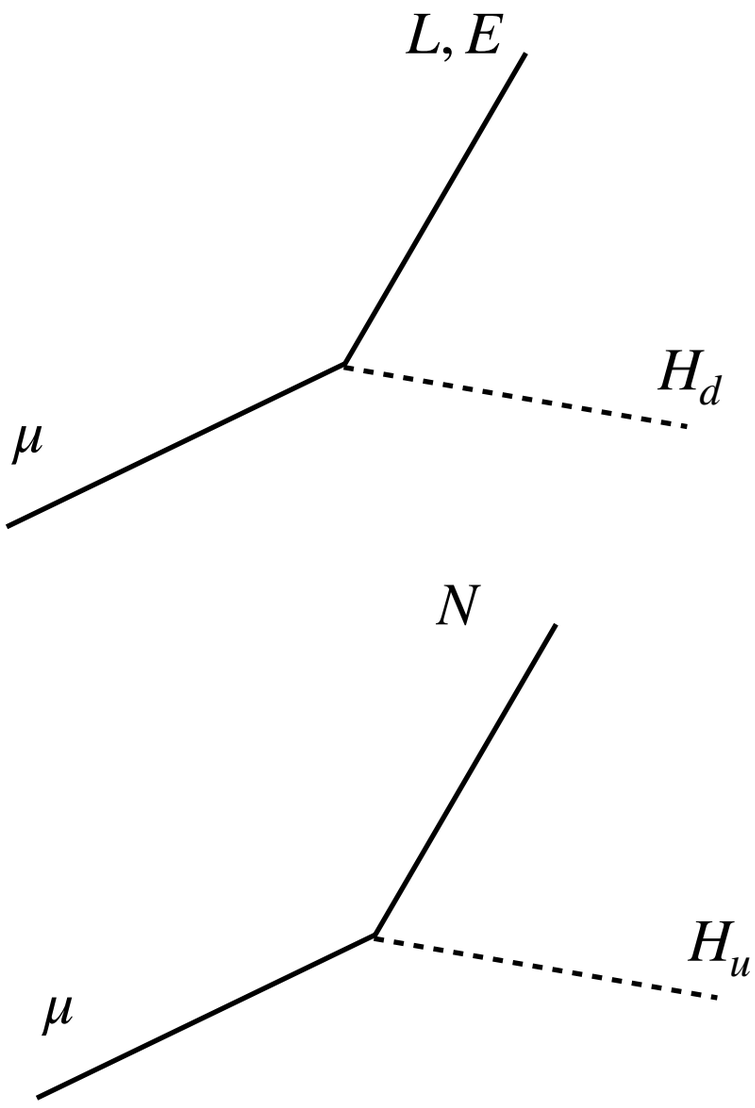
- VLL appear in many simple extensions of the SM
  - SM + charged/neutral VL matter
    - R. Dermisek & A. Raval: *Phys.Rev.D* 88 (2013) 013017
    - K. Kannike, M. Raidal, D. Straub, & A. Strumia: *JHEP* 02 (2012) 106
    - N. Arkani-Ahmed, & K. Harigaya: 2106.01373 [hep-ph]

- Many models also include additional states (SM + VLL + extra bosons)
  - $(g-2)_\mu$ & DM
    - L. Calibbi, R. Ziegler, J. Zupan: *JHEP* 07 (2018) 046
- New physics of $(g-2)_\mu$ and muon colliders
  - R. Capdevilla, D. Curtin, Y. Kahn, G. Krnjaic: *Phys.Rev.D* 103 (2021) 7, 2101.10334 [hep-ph]

My personal motivation:
Possible UV complete models with extended Higgs + matter sectors
2HDM + VLL among simplest avenues

MSSM + vectorlike family gives prediction of seven largest couplings in SM
from RG fixed points, assuming multi-TeV scale for all BSM particles:
R. Dermisek, NM: Phys.Rev.Lett. 122 (2019) 18

Vectorlike leptons & $(g-2)_\mu$

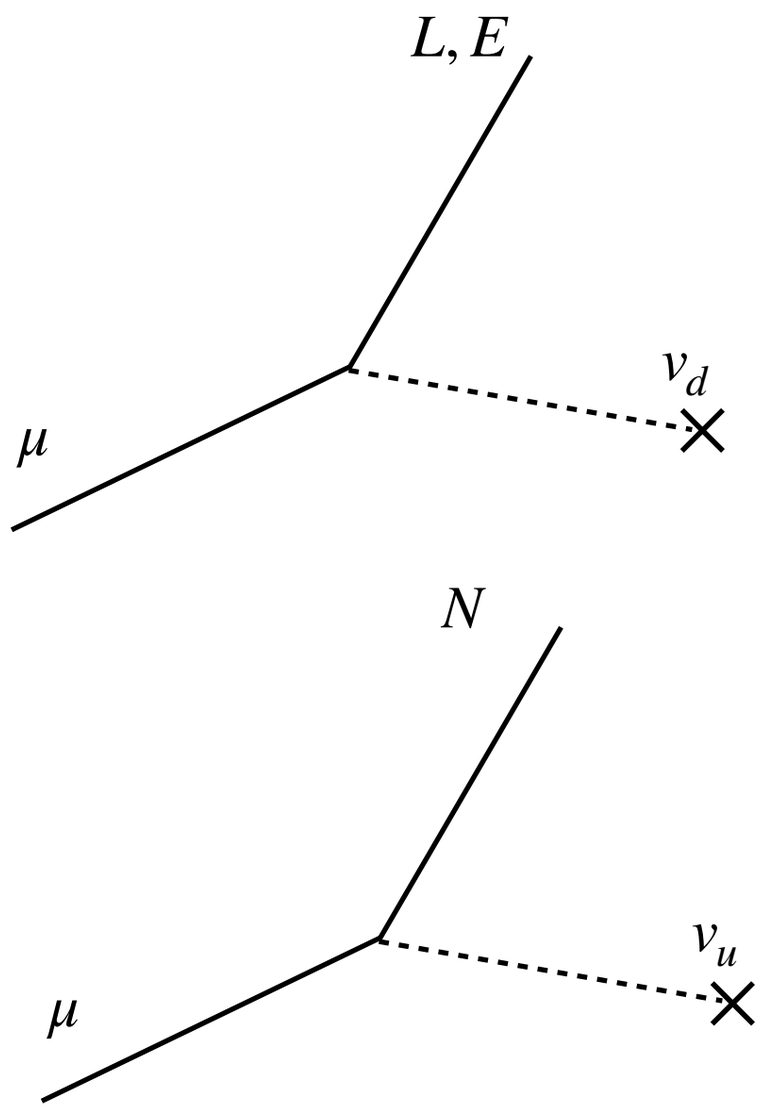


$$L \underset{SU(3)\times SU(2)\times U(1)}{\rightarrow} \mu_L$$

$$E \underset{SU(3)\times SU(2)\times U(1)}{\rightarrow} \mu_R$$

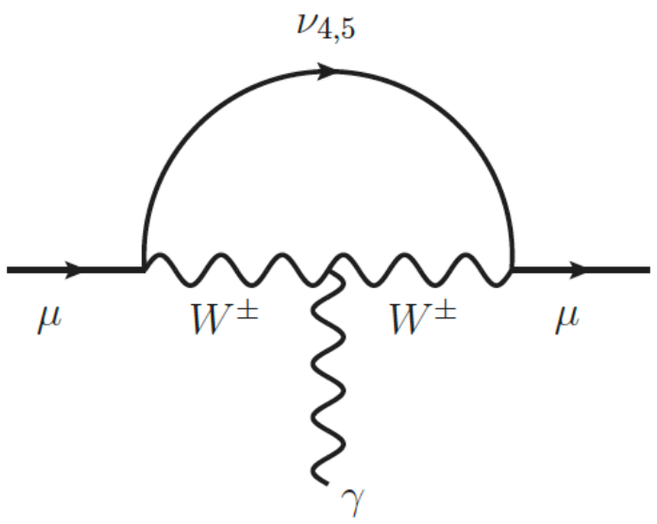
$$N = (1,1,0)$$

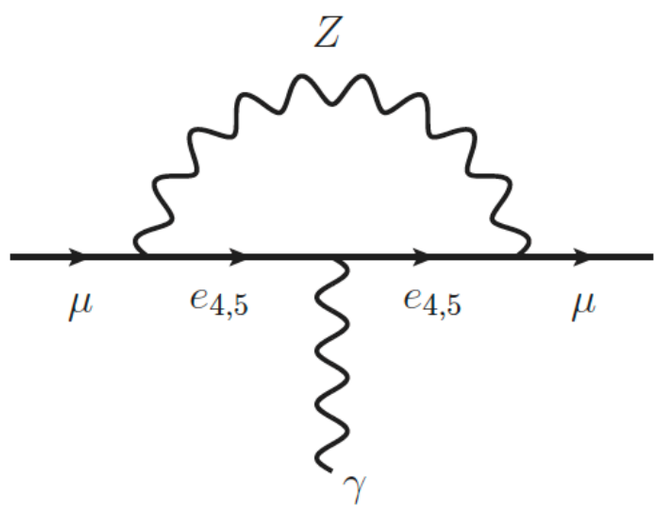
Vectorlike leptons & $(g-2)_\mu$

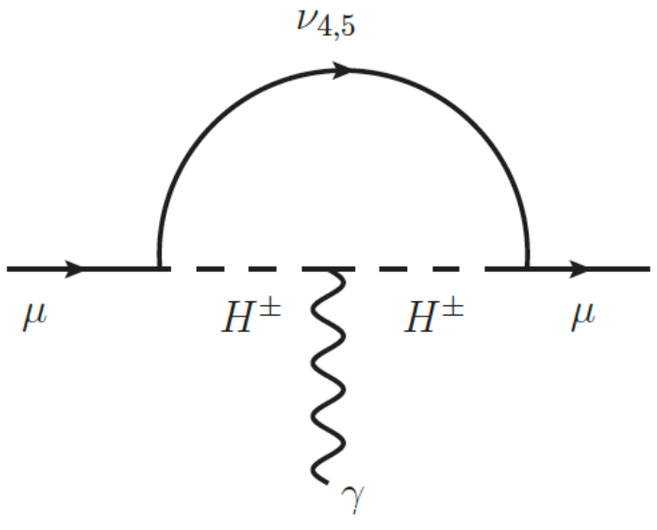


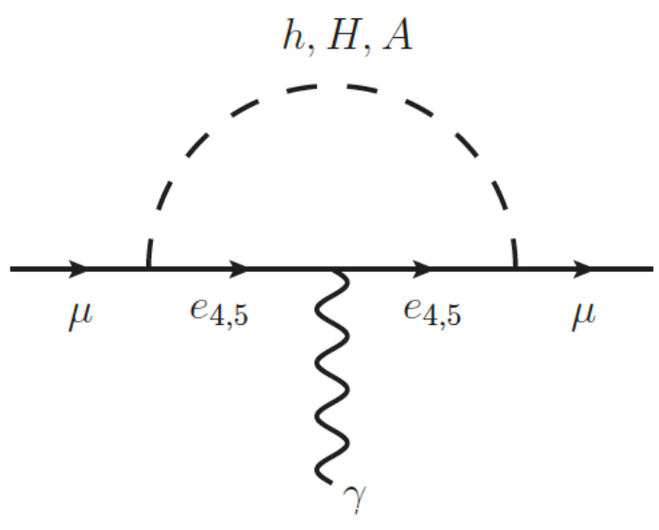
Modifications to couplings of μ to Z,W, h through mass mixing

Vectorlike leptons & $(g-2)_\mu$

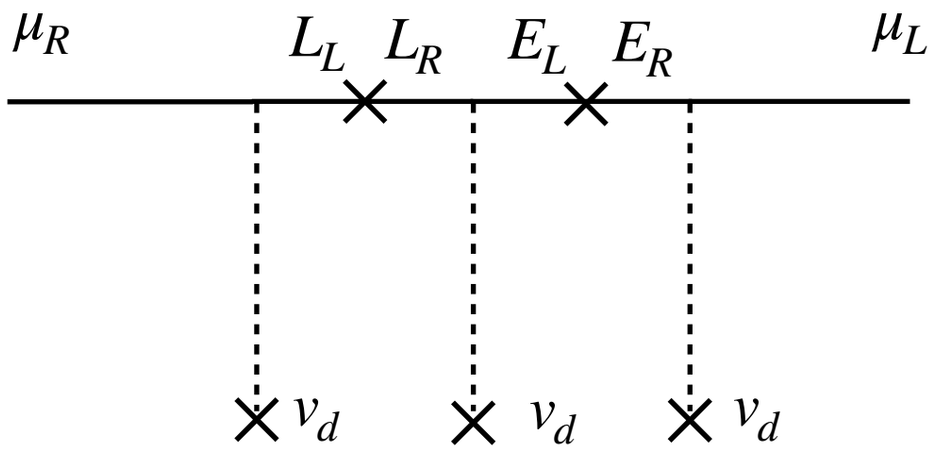








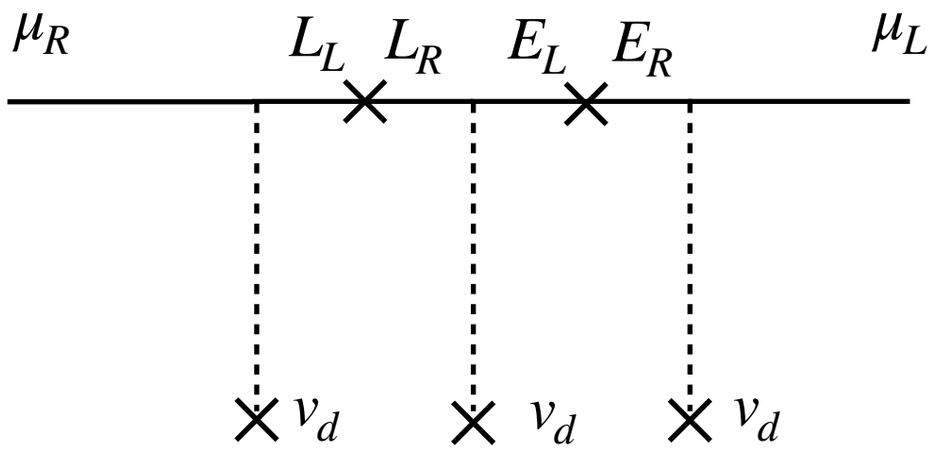
Vectorlike leptons & $(g-2)_\mu$



$$\longrightarrow \quad m_\mu = y_\mu v_d + m_\mu^{LE}$$

$$m_\mu^{LE} \rightarrow \frac{\lambda^3 v_d^3}{M_L M_E}$$

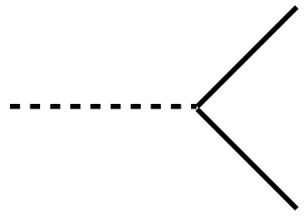
Vectorlike leptons & $(g-2)_\mu$



$$\longrightarrow \quad m_\mu = y_\mu v_d + m_\mu^{LE}$$

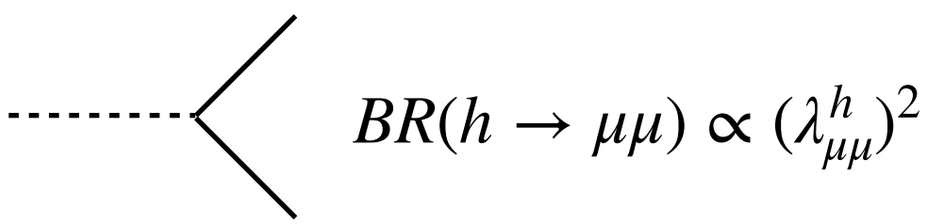
$$m_\mu^{LE} \to \frac{\lambda^3 v_d^3}{M_L M_E}$$

$$\mathscr{L} \supset l_L \left(y_\mu + \frac{m_\mu^{LE}}{v_d^3} H_d^\dagger H_d \right) \mu_R H_d \quad \longrightarrow \quad \lambda^h_{\mu\mu} \simeq \left(m_\mu + 2 m_\mu^{LE} \right) / v$$



Vectorlike leptons & $(g-2)_\mu$

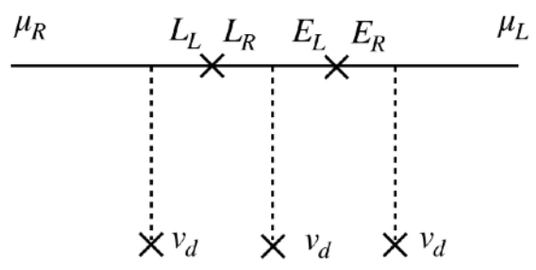
$$\mathscr{L} \supset l_L \left(y_\mu + \frac{m_\mu^{LE}}{v_d^3} H_d^\dagger H_d \right) \mu_R H_d \longrightarrow \lambda_{\mu\mu}^h \simeq \left(m_\mu + 2 m_\mu^{LE} \right) / v$$



$$BR(h \to \mu\mu) \propto (\lambda_{\mu\mu}^h)^2$$

Two possibilities: $m_\mu^{LE} \propto \lambda^3 \to \pm$

- Enhanced BR, quickly ruled out
- $BR \to BR^{SM}$ for $m_\mu^{LE} \to -m_\mu$



Vectorlike leptons & $(g-2)_\mu$

$$\mathscr{L} \sim \mu_L \mu_R h + \mu_L \sigma_{\mu\nu} \mu_R F^{\mu\nu}$$

$$\lambda^h_{\mu\mu} \simeq \left(m_\mu + 2 m^{LE}_\mu \right) / v$$

$$\Delta a^i_\mu \simeq \frac{k^i}{16\pi^2} \frac{m_\mu m^{LE}_\mu}{v^2}$$

Z_2 - 2HDM

$$k^Z = -1/2$$
$$k^W = 1$$
$$k^h = -3/2$$
$$k^H = -(11/12)\tan^2\beta$$
$$k^A = -(5/12)\tan^2\beta$$
$$k^{H^\pm} = (1/3)\tan^2\beta$$

$$v \ll M_{L,E,N} \simeq m_A$$

Vectorlike leptons & $(g-2)_\mu$

$$\mathscr{L} \sim \mu_L \mu_R h + \mu_L \sigma_{\mu\nu} \mu_R F^{\mu\nu}$$

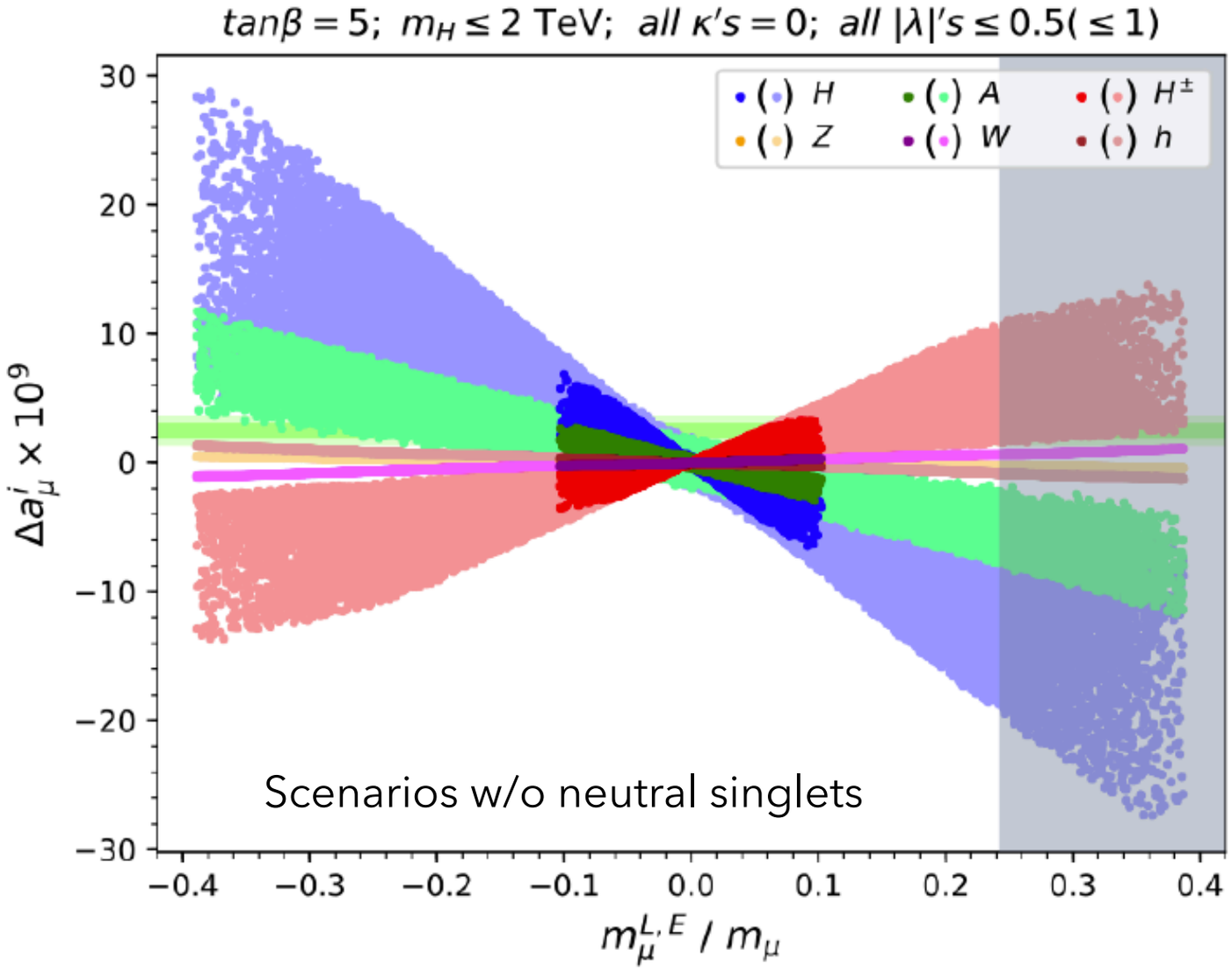
$$\lambda^h_{\mu\mu} \simeq \left(m_\mu + 2 m_\mu^{LE} \right) / v$$

$$\Delta a^i_\mu \simeq \frac{k^i}{16\pi^2} \frac{m_\mu m_\mu^{LE}}{v^2}$$

Z_2 - 2HDM

$k^Z = -1/2$
$k^W = 1$
$k^h = -3/2$
$k^H = -(11/12)\tan^2\beta$
$k^A = -(5/12)\tan^2\beta$
$k^{H^\pm} = (1/3)\tan^2\beta$

$v \ll M_{L,E,N} \simeq m_A$



VL masses/couplings are scanned while satisfying direct searches + EW precision
Heavy Higgs mass scanned to satisfy limits from $H \to \tau\tau / H^\pm \to tb$

Vectorlike leptons & $(g-2)_\mu$

$$\mathscr{L} \sim \mu_L \mu_R h + \mu_L \sigma_{\mu\nu} \mu_R F^{\mu\nu}$$

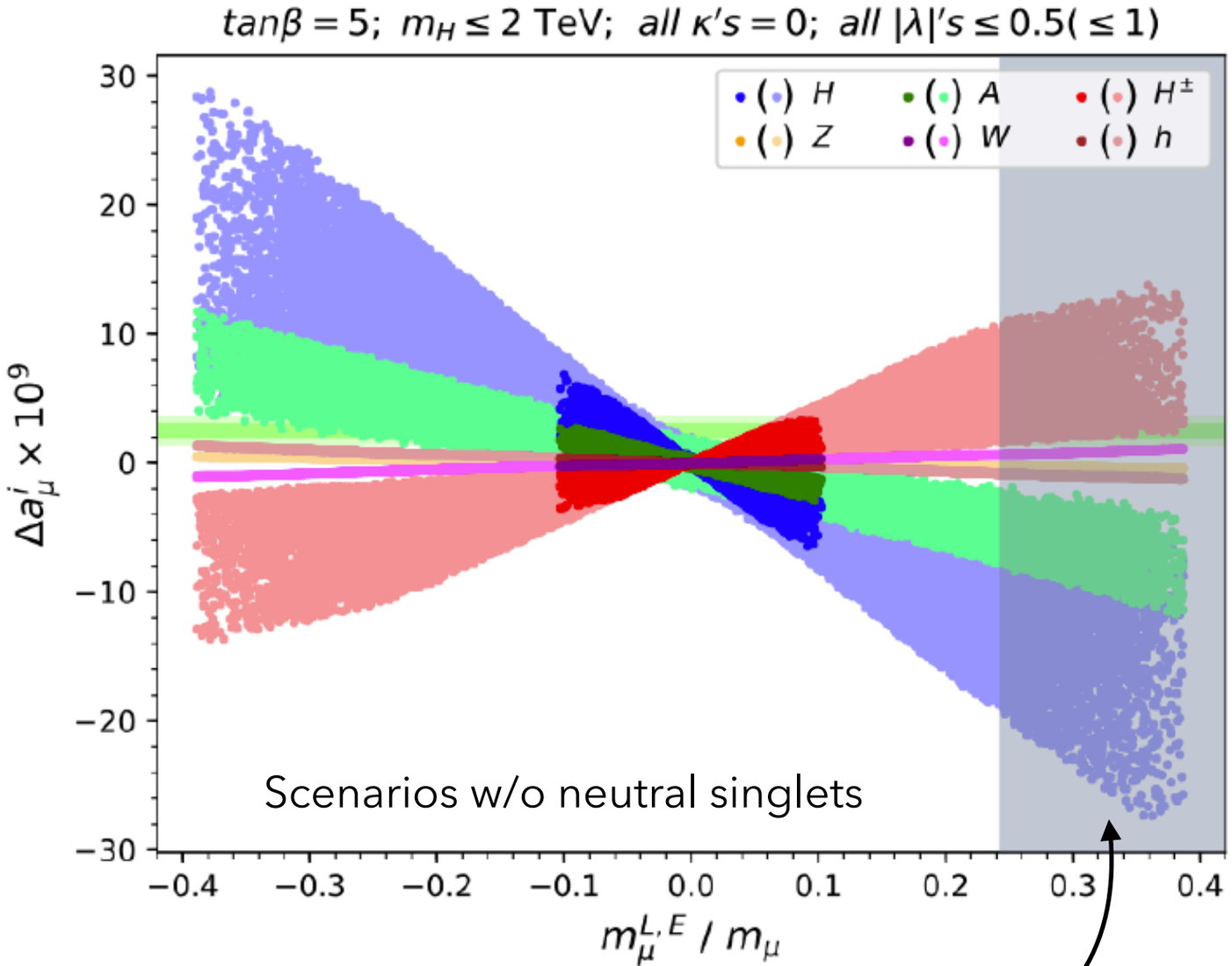
$$\lambda^h_{\mu\mu} \simeq \left(m_\mu + 2 m_\mu^{LE} \right) / v$$

$$\Delta a^i_\mu \simeq \frac{k^i}{16\pi^2} \frac{m_\mu m_\mu^{LE}}{v^2}$$

Z_2 - 2HDM

$k^Z = -1/2$
$k^W = 1$
$k^h = -3/2$
$k^H = -(11/12)\tan^2\beta$
$k^A = -(5/12)\tan^2\beta$
$k^{H^\pm} = (1/3)\tan^2\beta$

$v \ll M_{L,E,N} \simeq m_A$



Vectorlike leptons & $(g-2)_\mu$

$$\mathscr{L} \sim \mu_L \mu_R h + \mu_L \sigma_{\mu\nu} \mu_R F^{\mu\nu}$$

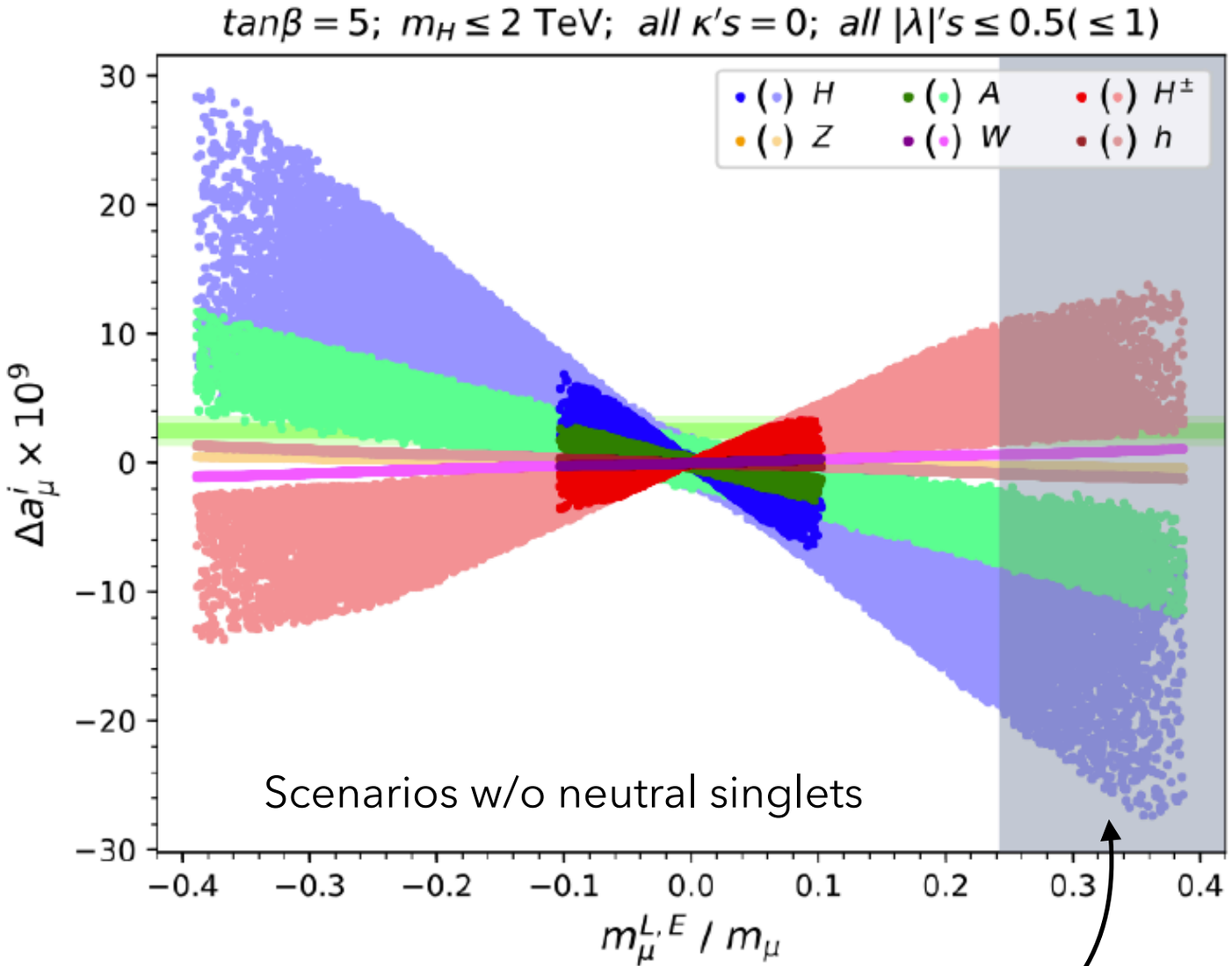
$$\lambda^h_{\mu\mu} \simeq \left(m_\mu + 2 m_\mu^{LE} \right) / v$$

$$\Delta a^i_\mu \simeq \frac{k^i}{16\pi^2} \frac{m_\mu m_\mu^{LE}}{v^2}$$

Z_2 - 2HDM

$k^Z = -1/2$
$k^W = 1$
$k^h = -3/2$
$k^H = -(11/12)\tan^2\beta$
$k^A = -(5/12)\tan^2\beta$
$k^{H^\pm} = (1/3)\tan^2\beta$

$v \ll M_{L,E,N} \simeq m_A$



Ruled out by $h \to \mu\mu$

$m_\mu^{LE} < 0$ necessary to comfortably satisfy $h \to \mu\mu$ AND give correct sign for Δa_μ

Vectorlike leptons & $(g-2)_\mu$

$$\mathscr{L} \sim \mu_L \mu_R h + \mu_L \sigma_{\mu\nu} \mu_R F^{\mu\nu}$$

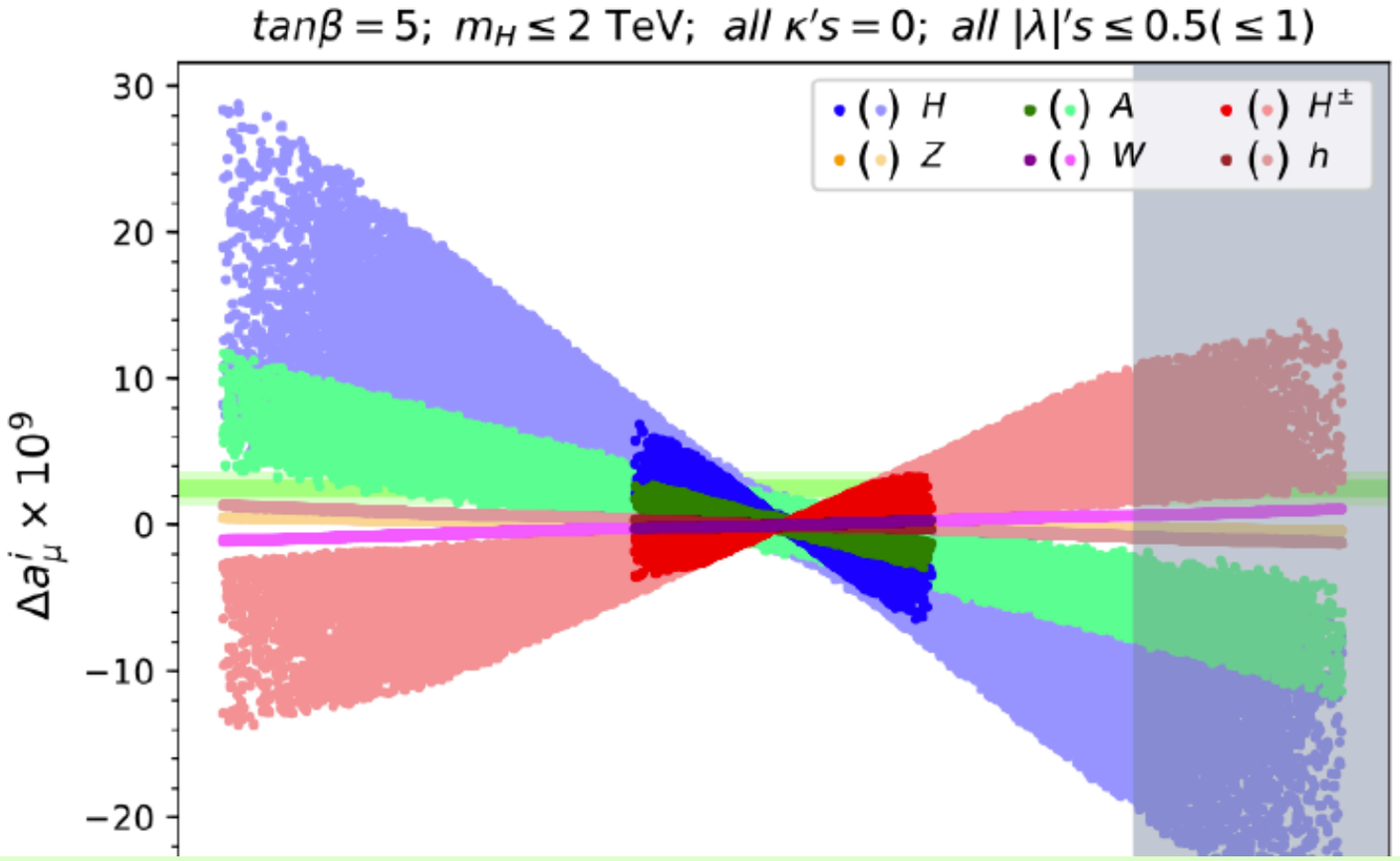
$$\lambda^h_{\mu\mu} \simeq \left(m_\mu + 2 m^{LE}_\mu \right) / v$$

$$\Delta a^i_\mu \simeq \frac{k^i}{16\pi^2} \frac{m_\mu m^{LE}_\mu}{v^2}$$

Z_2 - 2HDM

$$k^Z = -1/2$$
$$k^W = 1$$
$$k^h = -3/2$$
$$k^H = -(11/12)\tan^2\beta$$
$$k^A = -(5/12)\tan^2\beta$$
$$k^{H^\pm} = (1/3)\tan^2\beta$$

$$v \ll M_{L,E,N} \simeq m_A$$

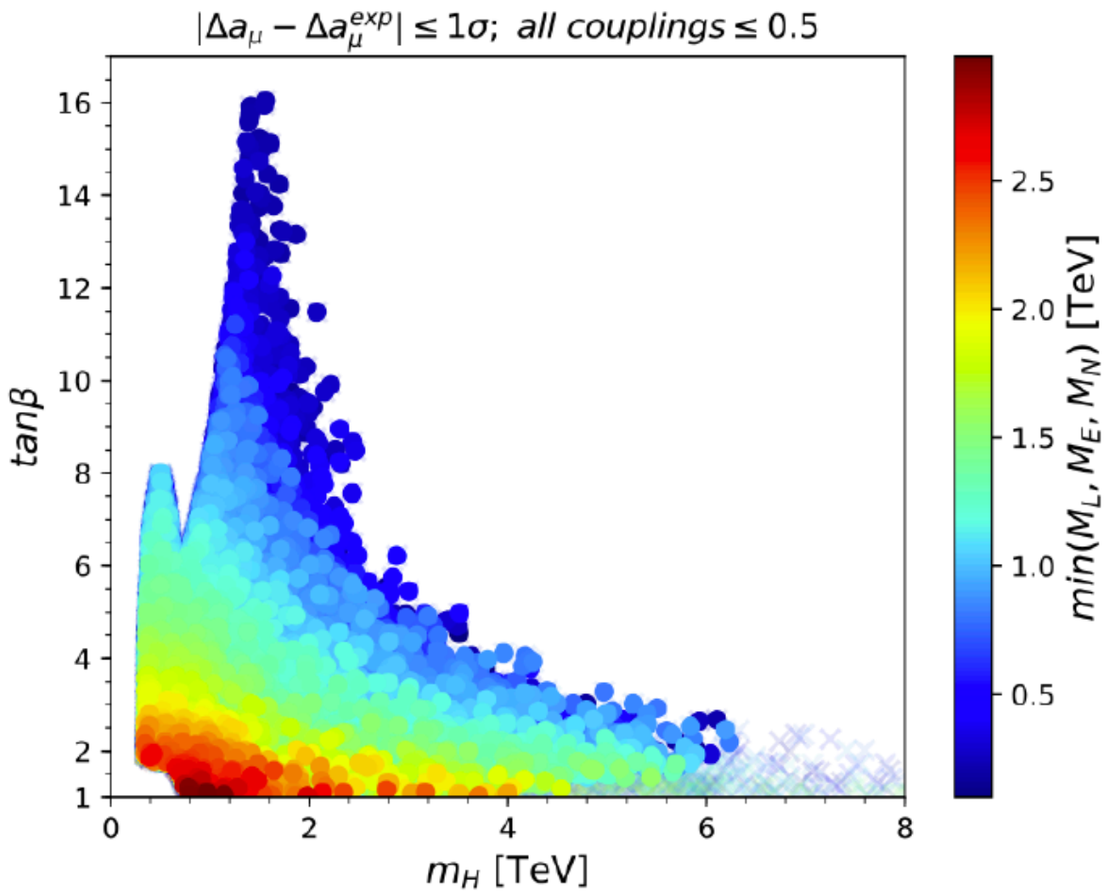


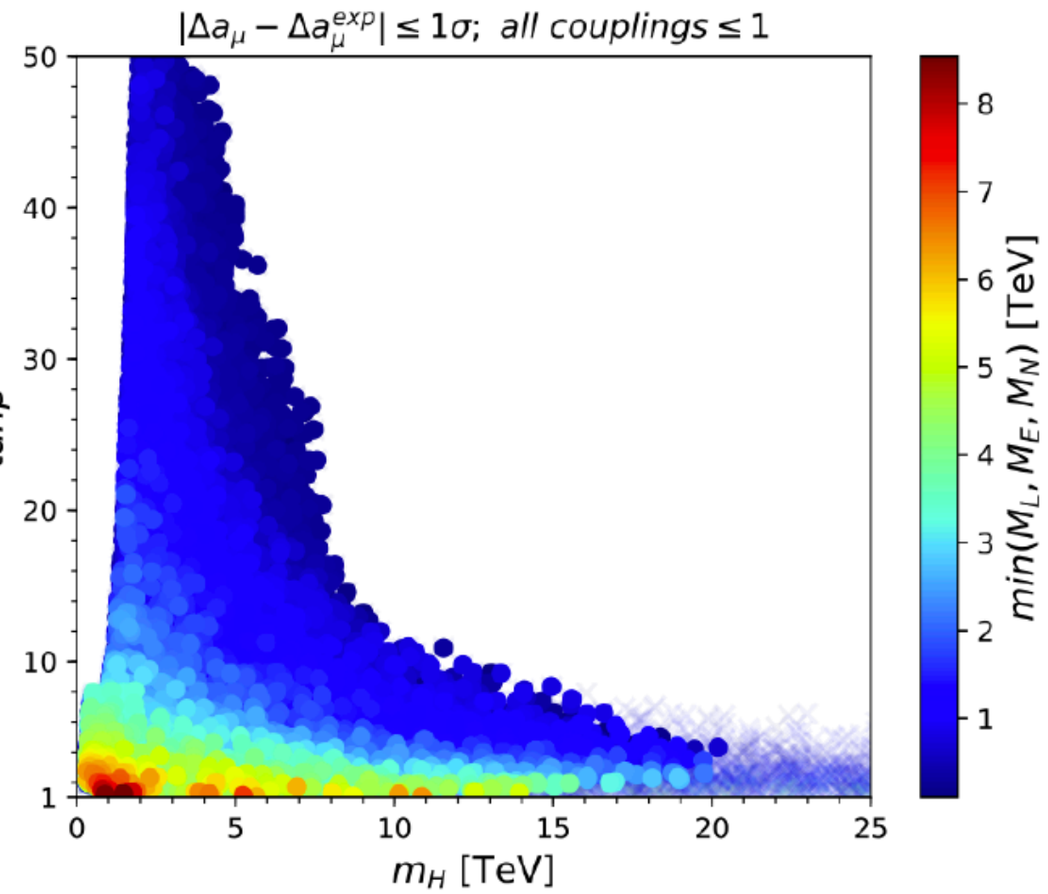
See R. Dermisek, K. Hermanek, NM: 2103.05645 [hep-ph] and N. Arkani-Ahmed & K. Harigaya: 2106.01373 [hep-ph] for scenarions w neutral singlets

Ruled out by $h \to \mu\mu$

$m^{LE}_\mu < 0$ necessary to comfortably satisfy $h \to \mu\mu$ AND give correct sign for Δa_μ

Vectorlike leptons & $(g-2)_\mu$

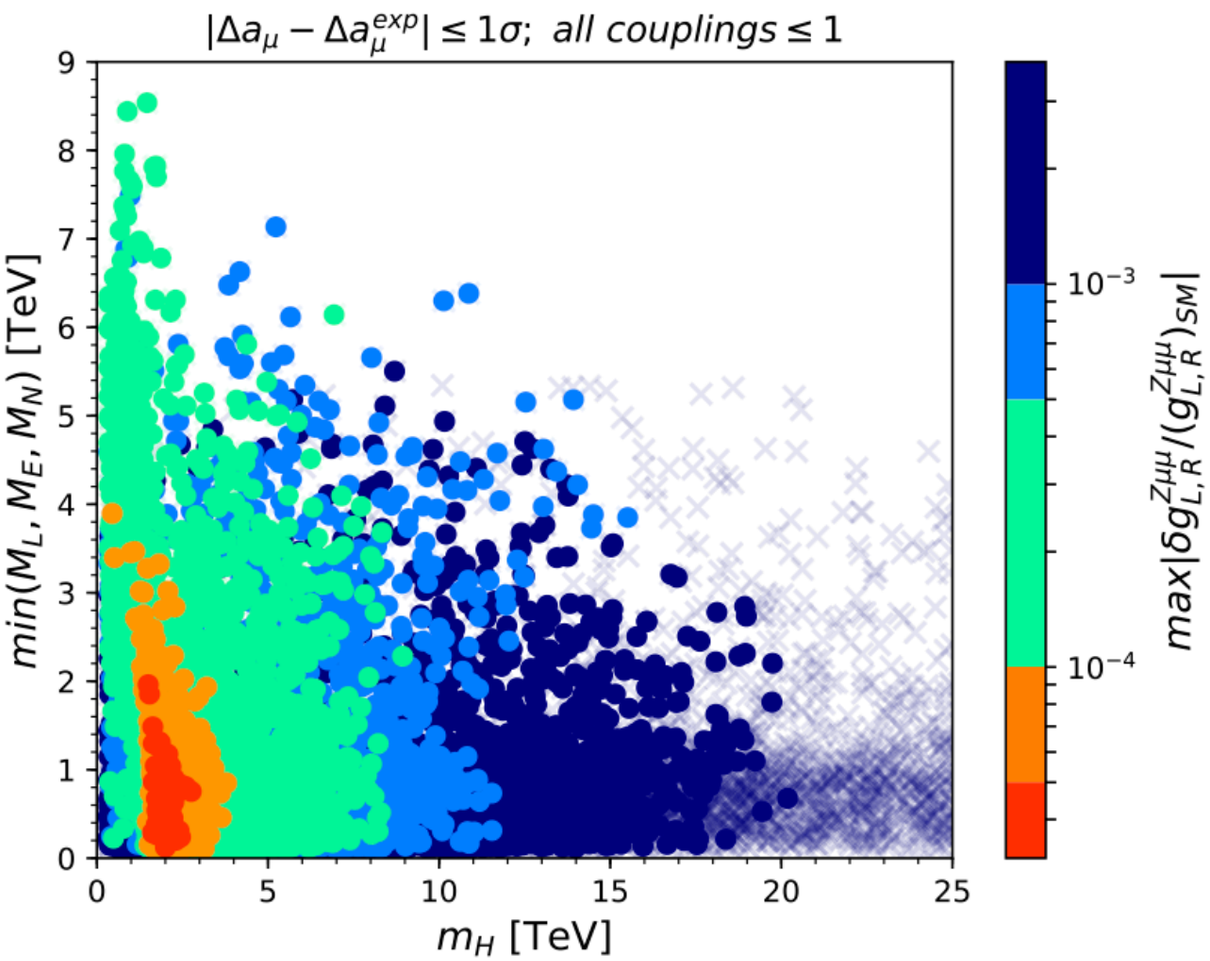


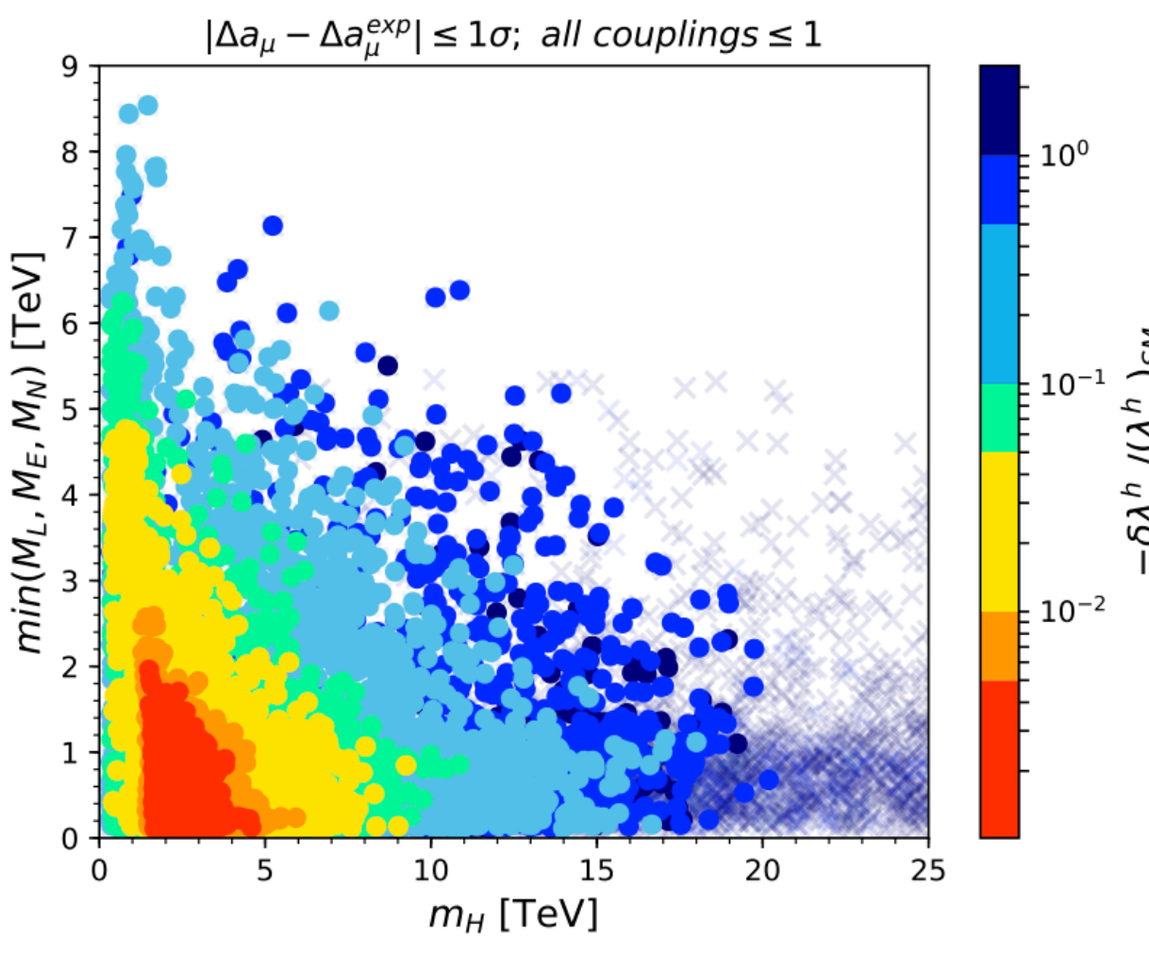


For couplings up to 1, VL masses up to 8 TeV can explain Δa_μ

Far out of reach for expectations of the HL-LHC (1250 GeV), and even FCC-hh projections (6.5 TeV)

Vectorlike leptons & $(g-2)_\mu$



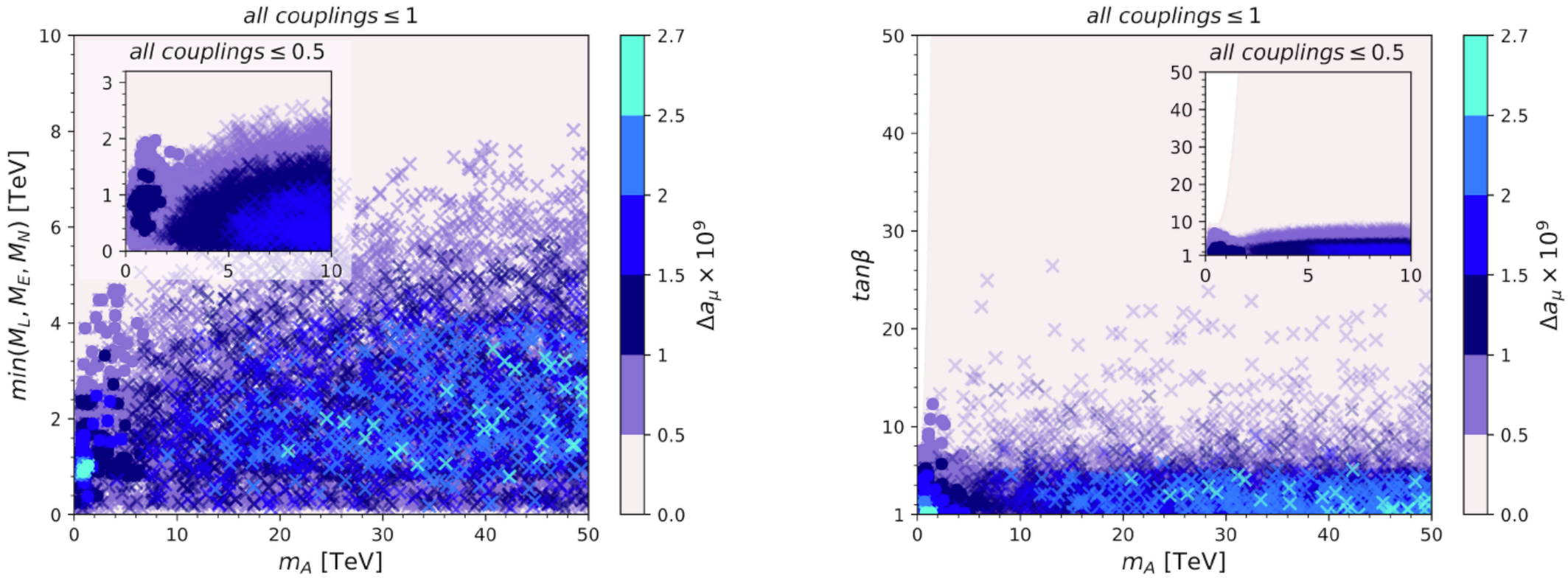


HL-LHC expected to probe $\lambda_{\mu\mu}^h$ to 5% precision (FCC up to 0.5%)

Z couplings to the muon expected to be probed to 0.05% at 250 ILC (0.01% w GigaZ)

Vectorlike leptons & $(g-2)_\mu$

SUSY-2HDM



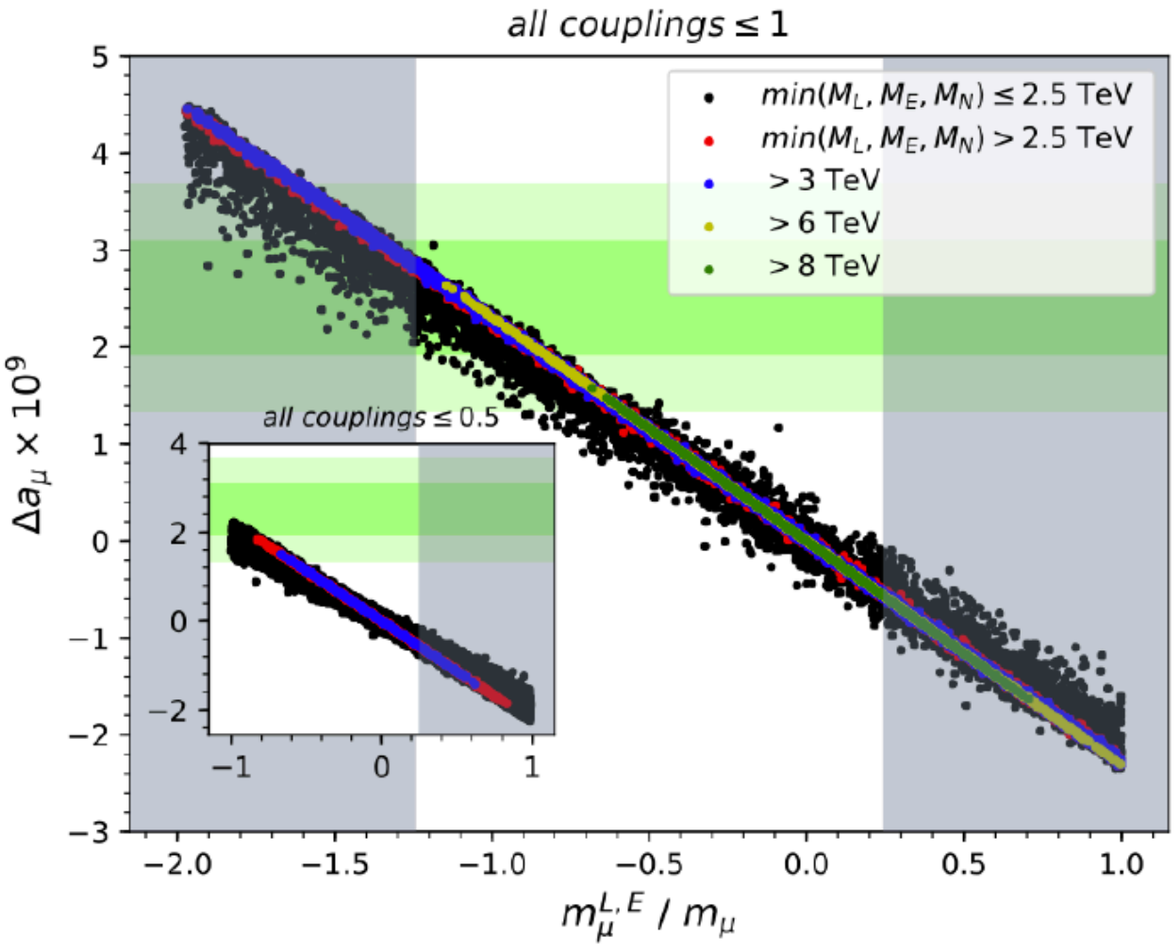
Size of corrections from VLL + heavy Higgses alone can reach ~1σ range

Can simply be added to SUSY contributions

Reach in VL masses lower due to cancellations (difference from Z_2: holomorphic couplings)

Vectorlike leptons & $(g-2)_\mu$

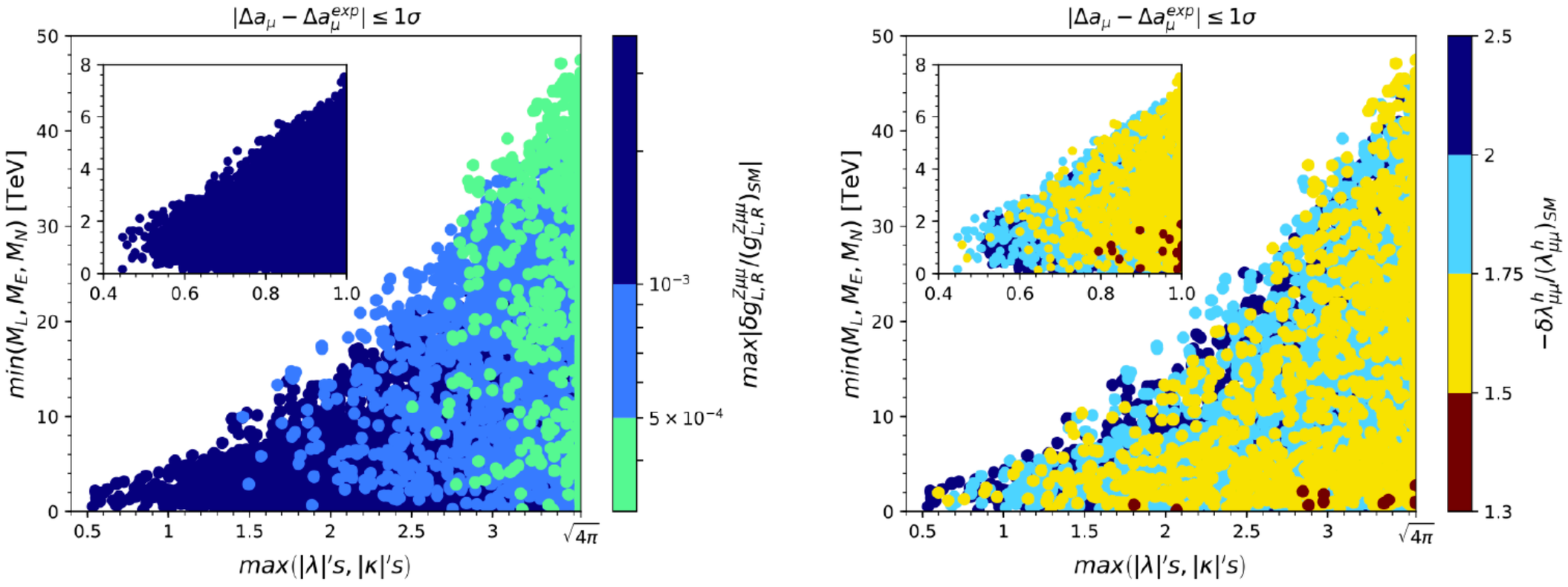
SM+VLL



Similar reach in masses which explain $(g-2)_\mu$ with order 1 couplings, however….

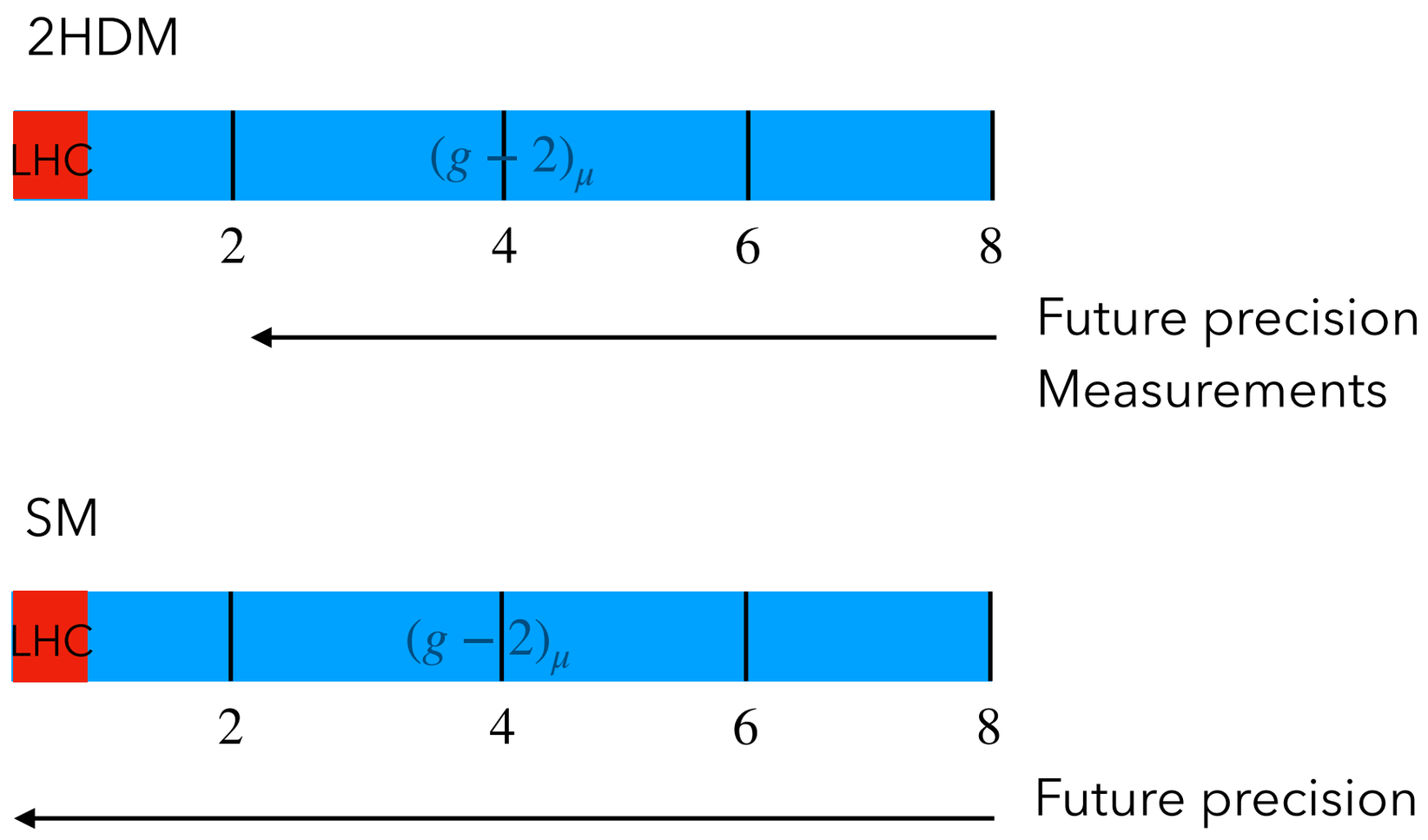
Vectorlike leptons & $(g-2)_\mu$

SM+VLL

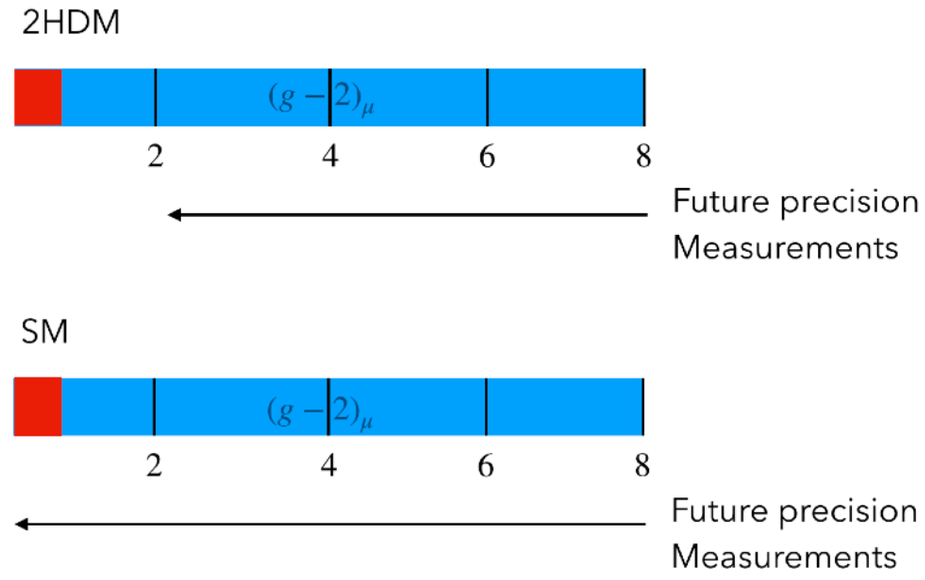


Size of corrections to higgs and Z boson couplings can be fully explored at future machines (up to perturbativity limit)

Vectorlike leptons & $(g-2)_\mu$



Summary

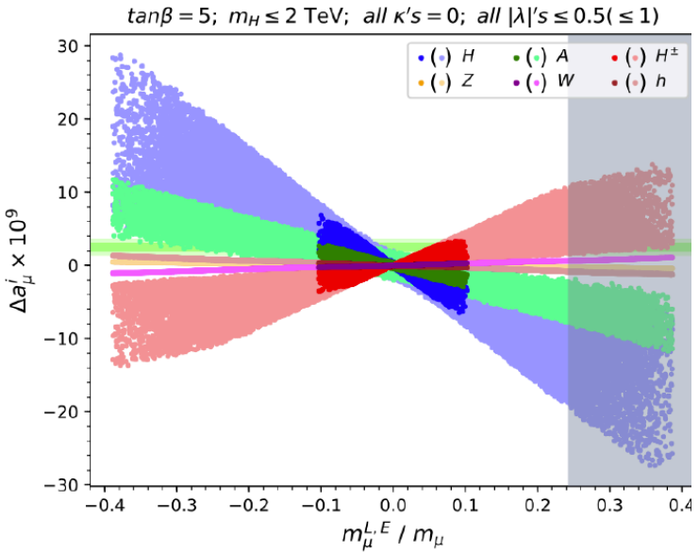


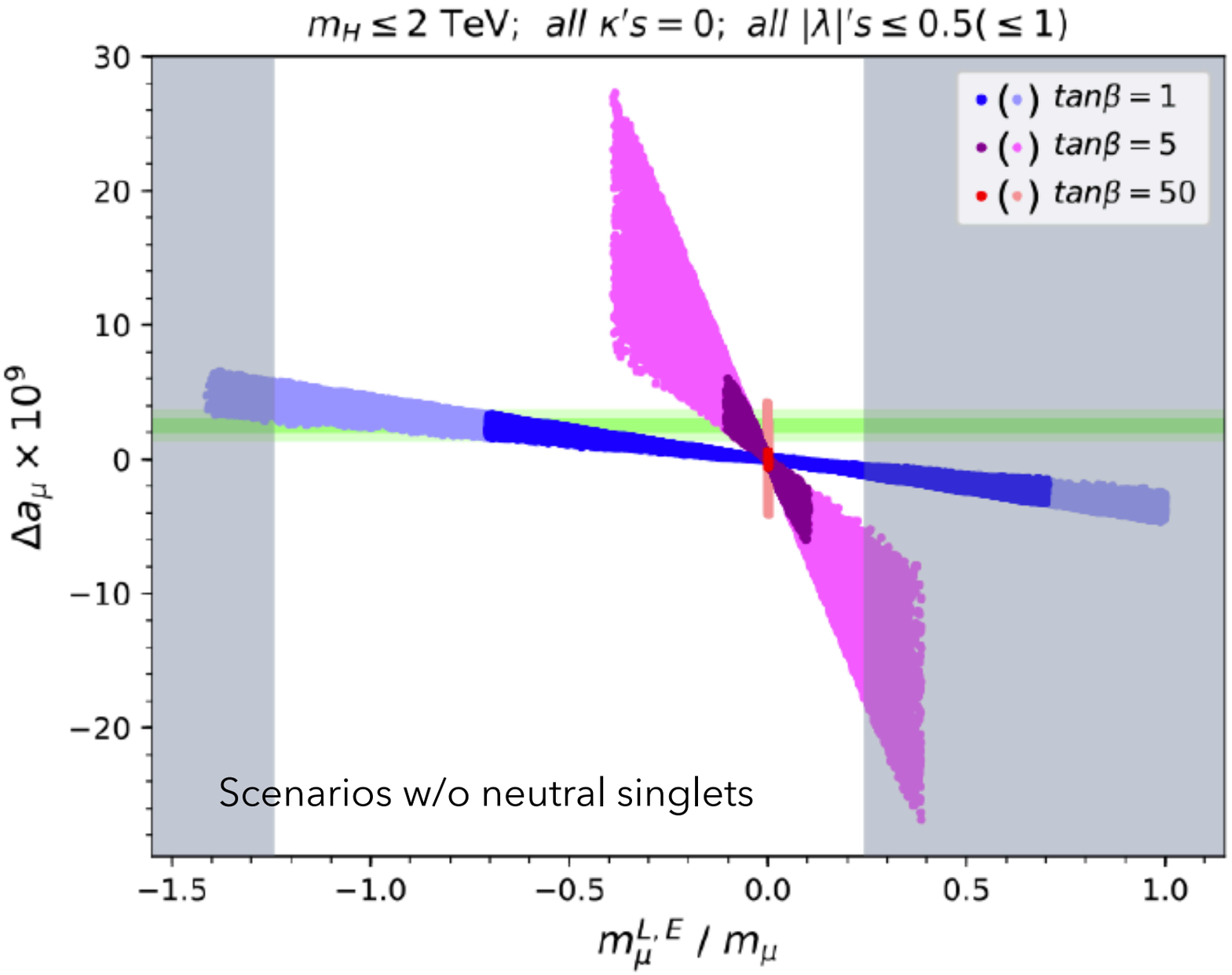
- VLL appear in many simple extensions of the SM and often with extra bosons in more "complete" extended models

- In 2HDM, $(g-2)_\mu$ can be explained with up to 8 TeV leptons with 20 TeV heavy Higgses (assuming order 1 couplings). Similar reach in SM + VLL. Well out of reach of expectations for future colliders

- The correlation of $(g-2)_\mu$ with precision observables at future machines will be crucial to probe and distinguish details of lepton couplings and details of the Higgs sector

Backup



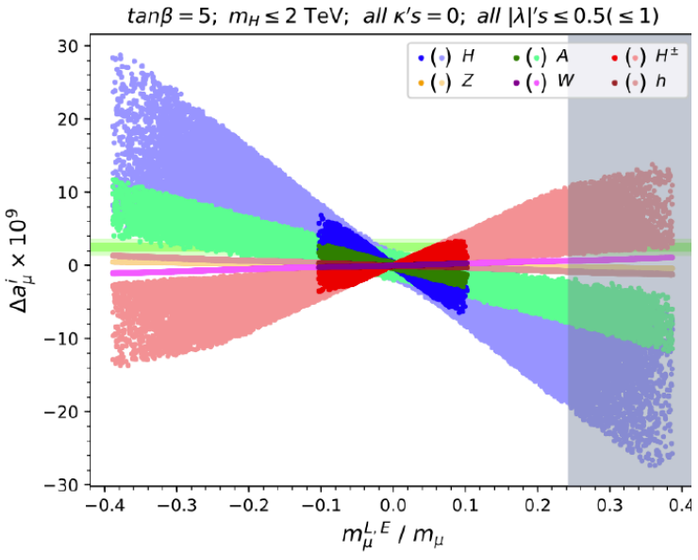


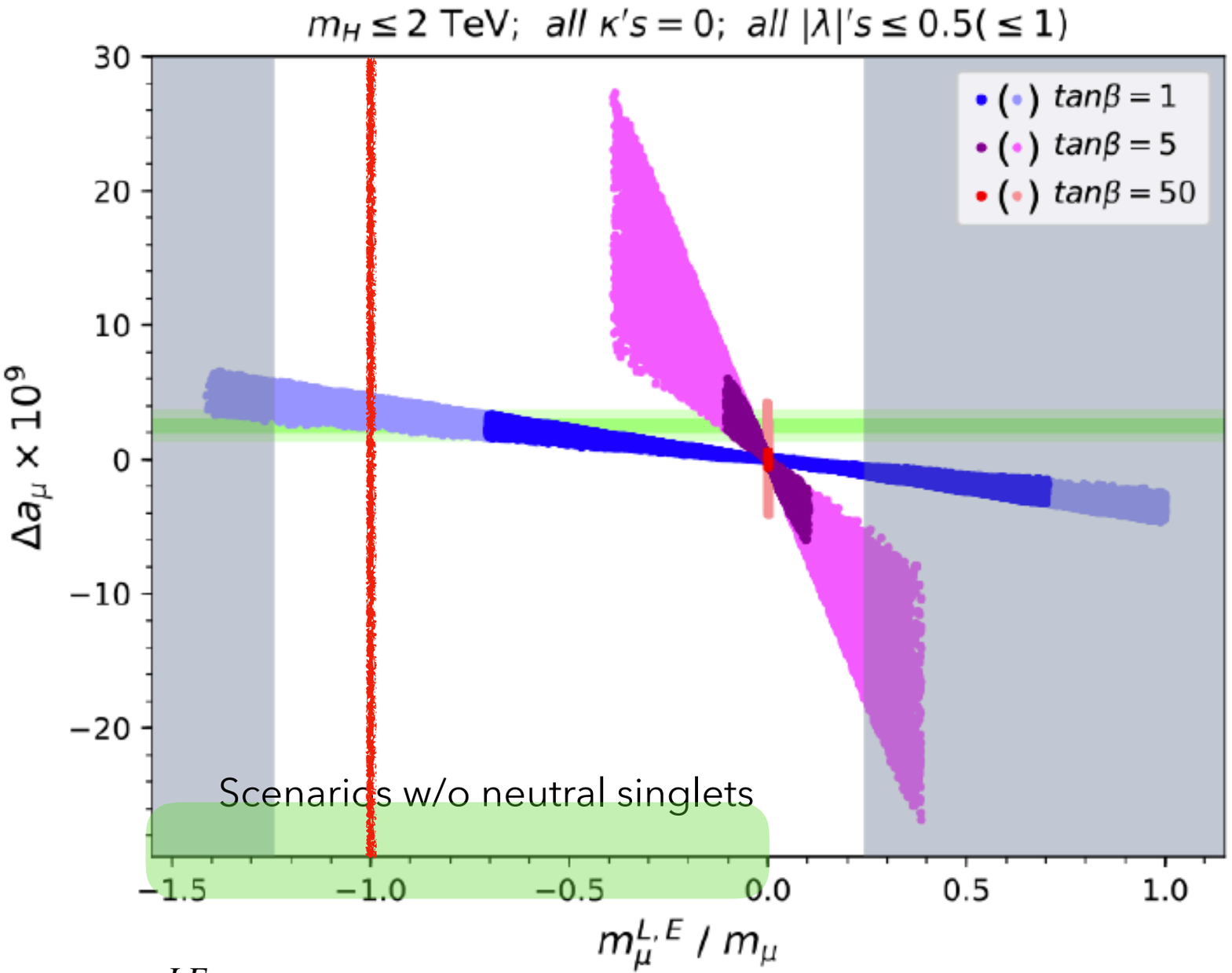
Constraints from Z-couplings

$$\left|\frac{\lambda_E v}{M_E}\cos\beta\right| \leq 0.03$$

$$\left|\frac{\lambda_L v}{M_L}\cos\beta\right| \leq 0.04$$

Backup





Constraints from Z-couplings

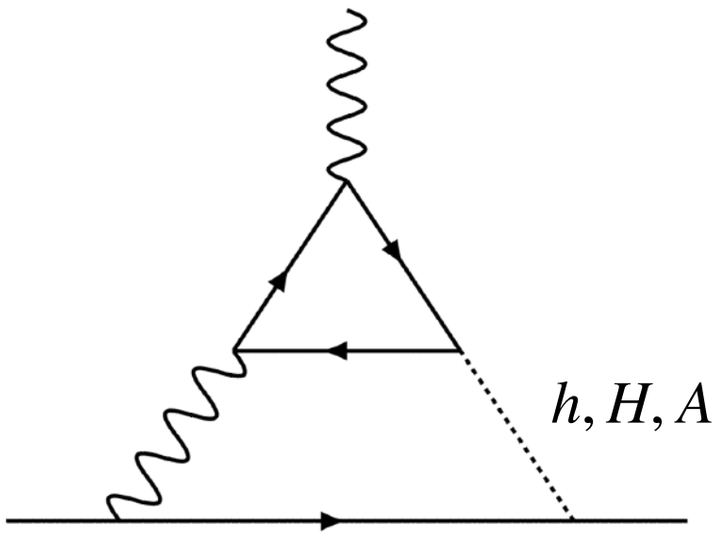
$$\left|\frac{\lambda_E v}{M_E}\cos\beta\right| \leq 0.03$$

$$\left|\frac{\lambda_L v}{M_L}\cos\beta\right| \leq 0.04$$

$m_\mu^{LE} < 0$ necessary to comfortably satisfy $h \to \mu\mu$ AND give correct sign for Δa_μ

Backup

- Comments on Barr-Zee contributions
  - Dominant diagram with photon



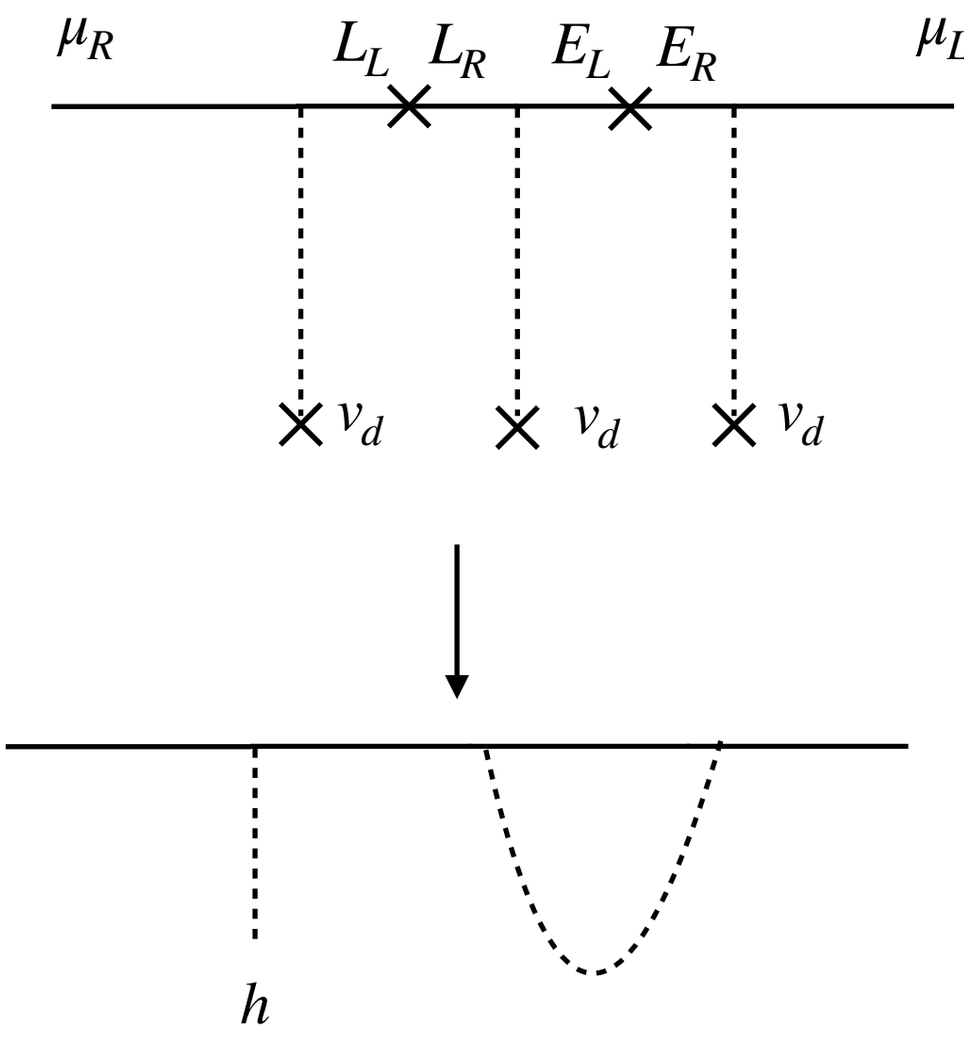
$$\frac{\Delta a_\mu^{h,BZ}}{\Delta a_\mu^h} \simeq \frac{4\alpha}{3\pi}\frac{m_\mu}{v\cos\beta}\ln(x_h^a) \simeq \mathcal{O}(10^{-4}-10^{-5}).$$

For range of parameters where Δa_μ achieved within 1σ at one-loop

$$\frac{\Delta a_\mu^{H,BZ}}{\Delta a_\mu^H} \simeq \frac{4\alpha}{\pi}\frac{m_\mu}{v\cos\beta} \simeq \mathcal{O}(10^{-4}-10^{-5}).$$

Backup

- Corrections to muon Yukawa coupling



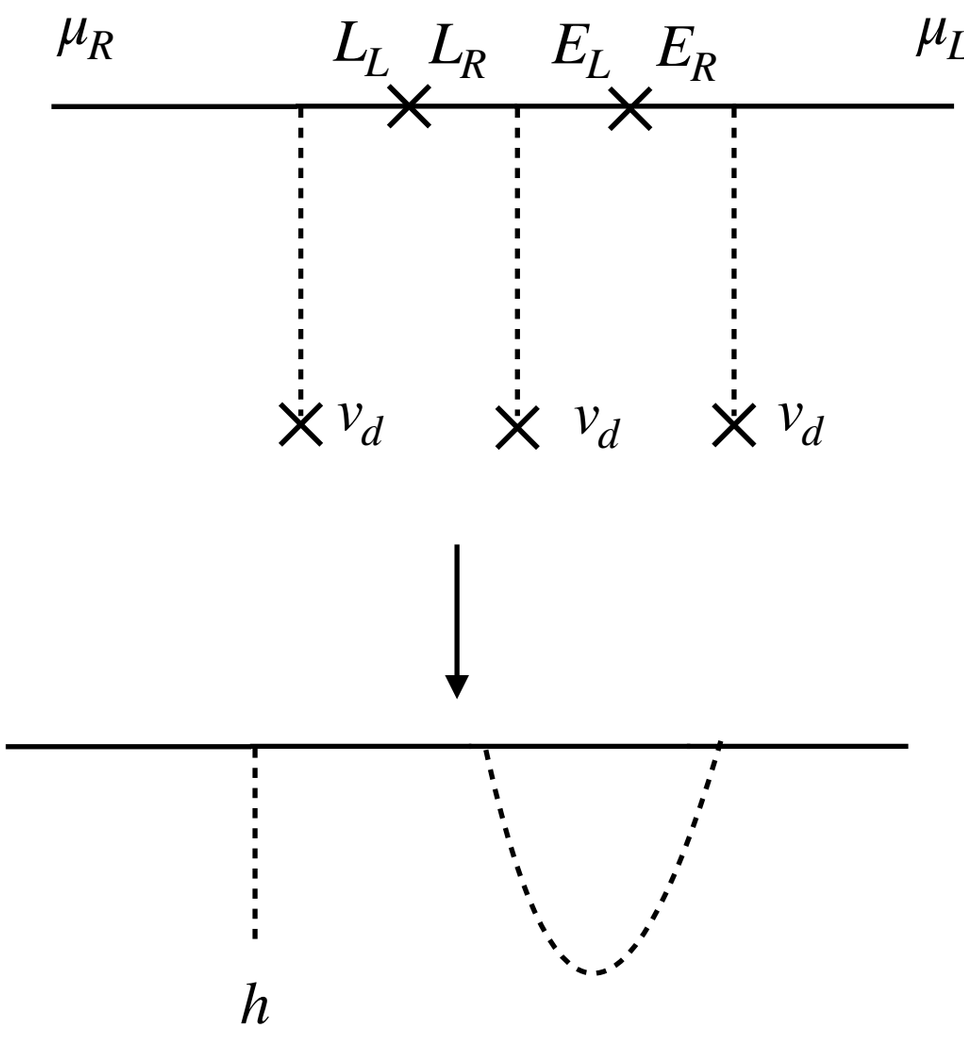
$$m_\mu = y_\mu v_d + m_\mu^{LE}$$

$$y_\mu = y_\mu^{(0)} + y_\mu^{(1)}$$

$$y_\mu^{(1)} \sim \frac{\lambda^3}{16\pi^2}$$

Backup

- Corrections to muon Yukawa coupling



$$m_\mu = y_\mu v_d + m_\mu^{LE}$$

$$y_\mu = y_\mu^{(0)} + y_\mu^{(1)}$$

$$y_\mu^{(1)} \sim \frac{\lambda^3}{16\pi^2} \xrightarrow{\lambda \sim 0.7} \frac{2m_\mu}{v}$$

Typical size of y_μ needed already to obtain correct muon mass