Revisitando o 2HDM em vista do novo resultado para (g-2)

2HDM in view of the new muon (g-2) result

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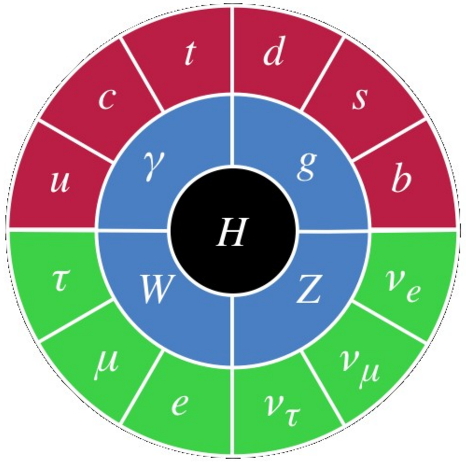
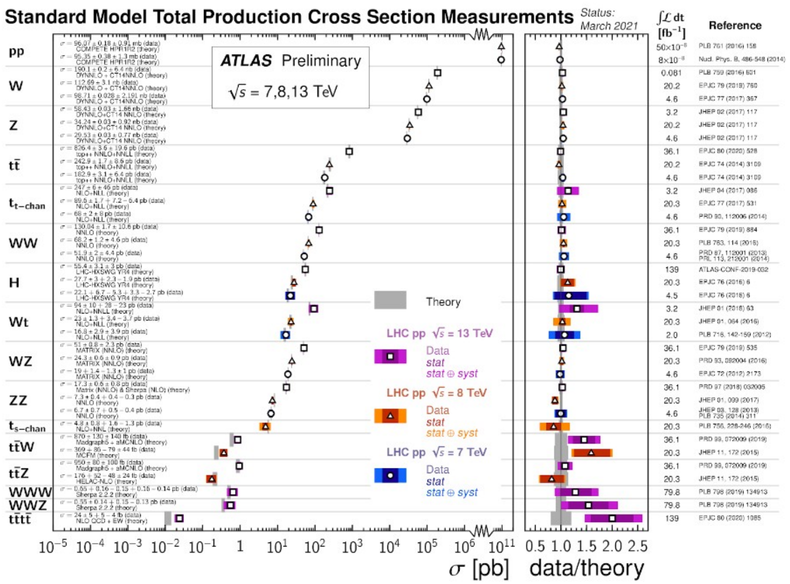
JHEP (2017) 2017: 7; arxiv: 1607.06292
PRD 98, 035001; arxiv: 1711.11567

Standard Model



Particle Fever



https://cds.cern.ch/record/1295244

- Gravitational interaction?
- Dark matter?
- Matter-antimatter asymmetry?
- .....

http://muon-g-2.fnal.gov/

- Experiment

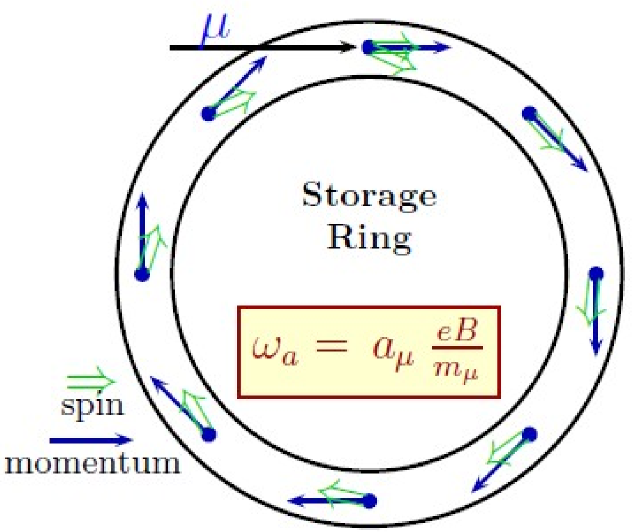
$$H_B = -\vec{\mu}.\vec{B}$$

$$\vec{\mu}_s = g\left(\frac{q}{2m}\right)\vec{s}$$

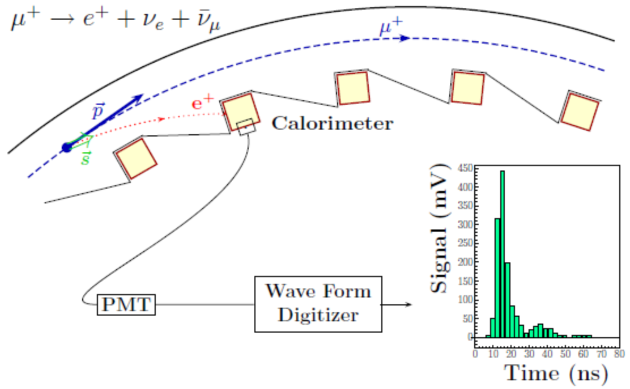
$$a_\mu = \frac{(g-2)_\mu}{2}$$

$$\omega_a = \omega_s - \omega_c.$$

$$\omega_c = \frac{eB}{m_\mu\,\gamma}\,, \quad \omega_s = \frac{eB}{m_\mu\,\gamma} + a_\mu \frac{eB}{m_\mu}\,, \quad \omega_a = a_\mu \frac{eB}{m_\mu}\,,$$

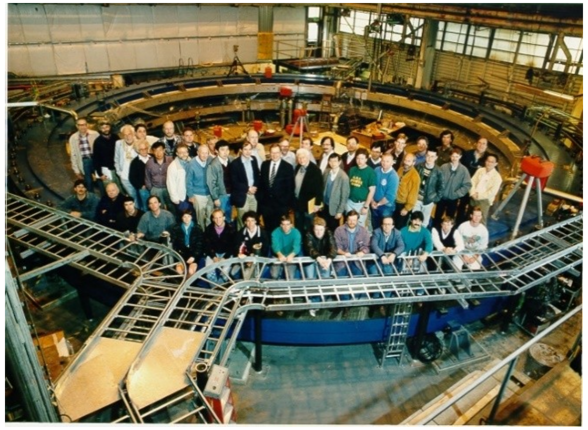


actual precession × 2



Jegerlehner, Nyffeler (09)

- Experiment



http://www.g-2.bnl.gov/

$$a_\mu^{BNL} = (11\,659\,208.9 \pm 6.3)\times 10^{-10}$$

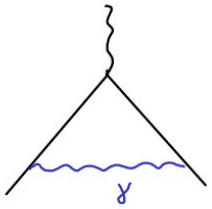
Phys. Rev. Lett. 92, 161802 (2004)

http://muon-g-2.fnal.gov/

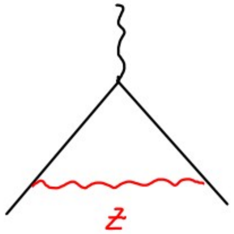
$$a_\mu^{FNAL} = (11\,659\,204.0 \pm 5.4)\times 10^{-10}$$

Phys. Rev. Lett. 126, 141801 (2021)

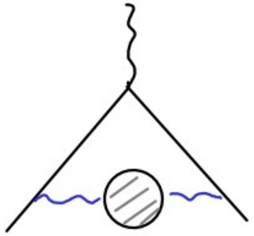
- Theory



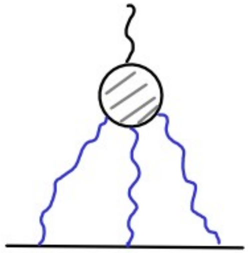
$$a_\mu^{QED} = (11\,658\,471.89 \pm 0.01)\times 10^{-10}$$



$$a_\mu^{weak} = (15.36 \pm 0.1)\times 10^{-10}$$



$$a_\mu^{HVP} = (684.5 \pm 4.0)\times 10^{-10}$$

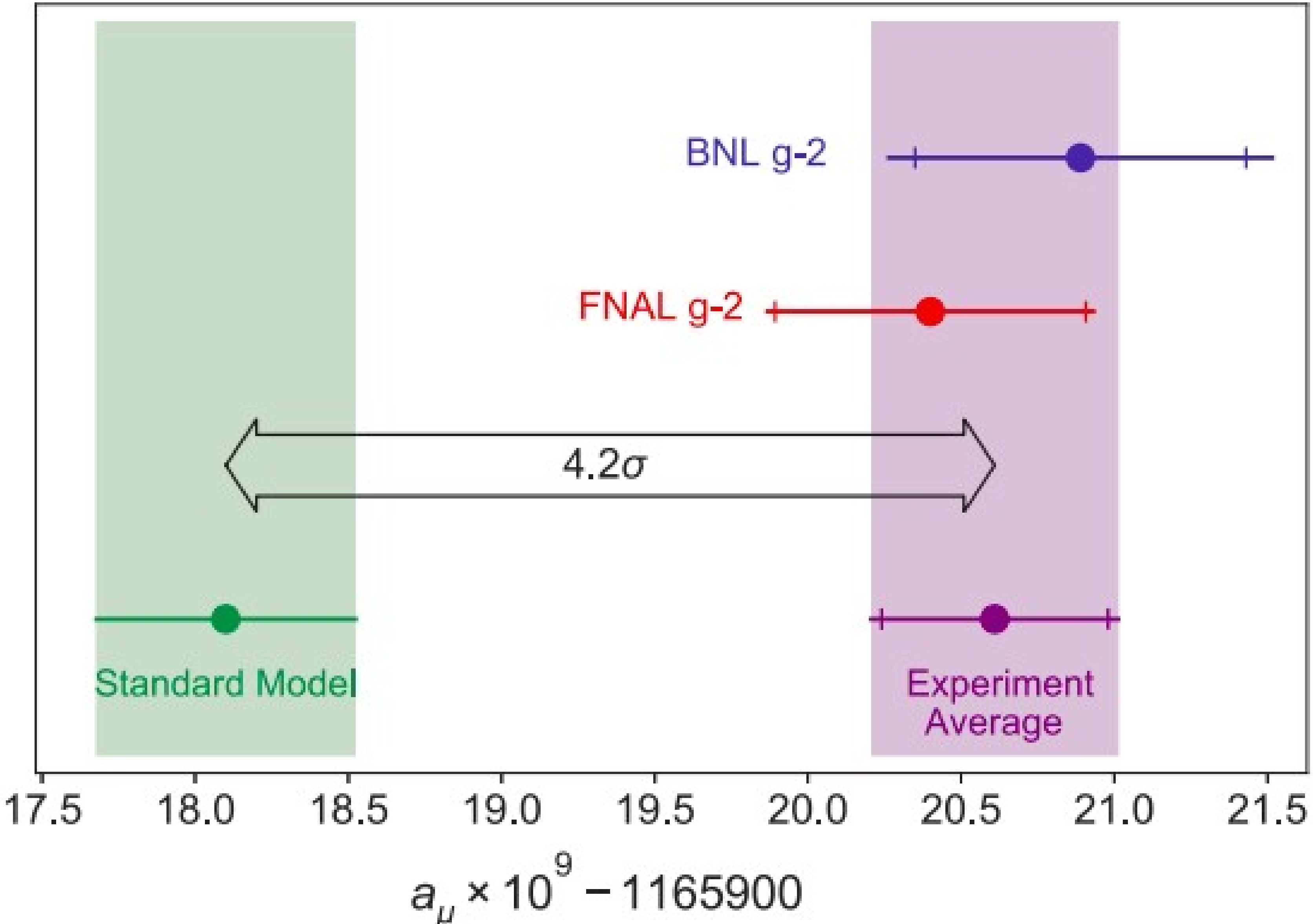


$$a_\mu^{HLL} = (9.2 \pm 1.8)\times 10^{-10}$$

$$a_\mu^{th} = (11\;659\;181.0 \pm 4.3)\times 10^{-10}$$ T. Aoyama et al (20)

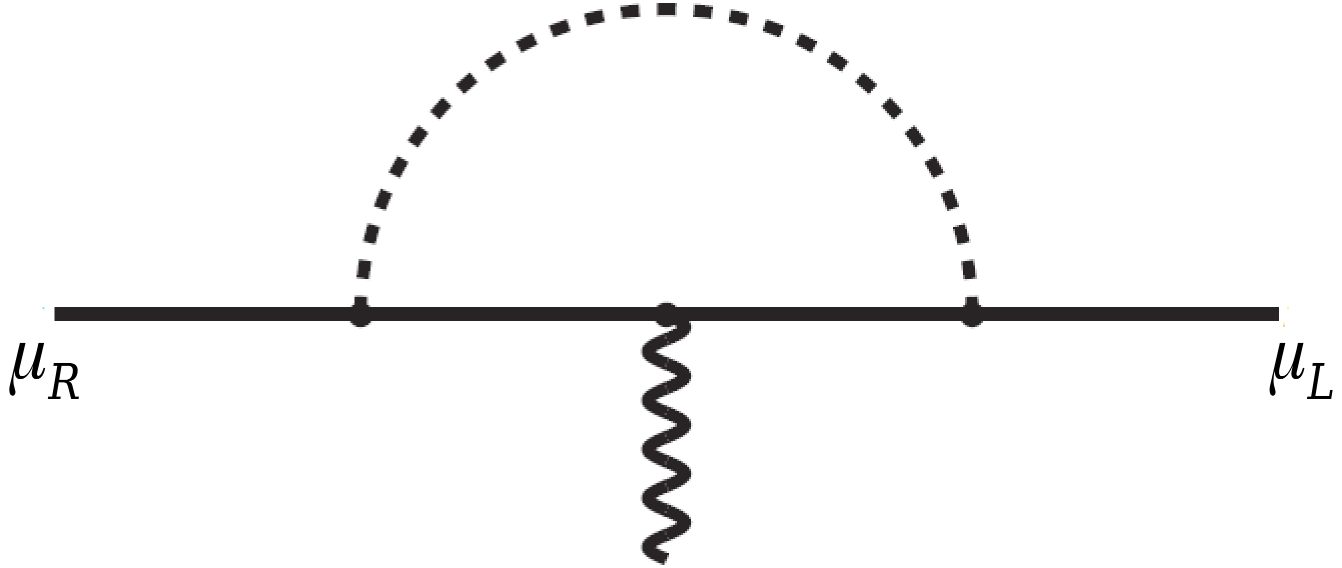
Theory

Experiment



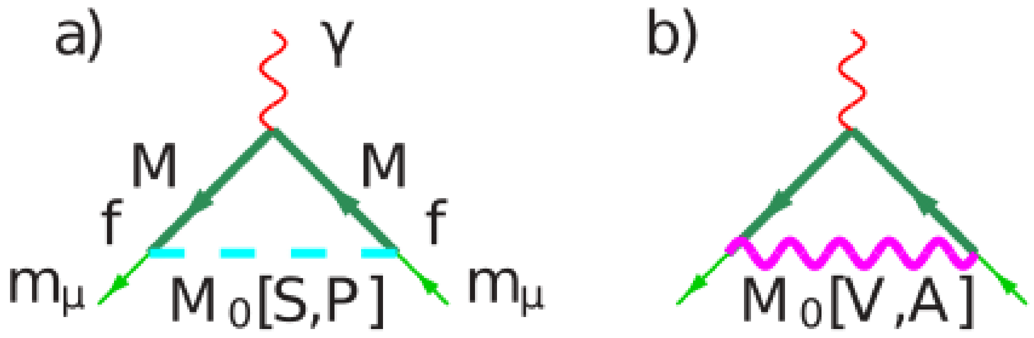
- Beyond Standard Model

$$\mathscr{L}_5 \propto \frac{a_\mu}{m_\mu} \overline{\mu_L} \sigma^{\alpha\beta} F_{\alpha\beta} \mu_R$$



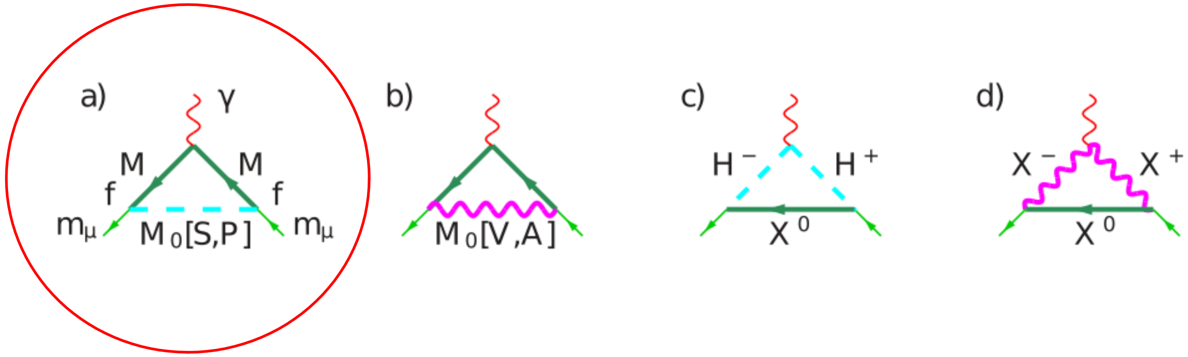
- Chirality flipping
- Loop induced

- Beyond Standard Model



Jegerlehner, Nyffeler
(09)

- 2HDM

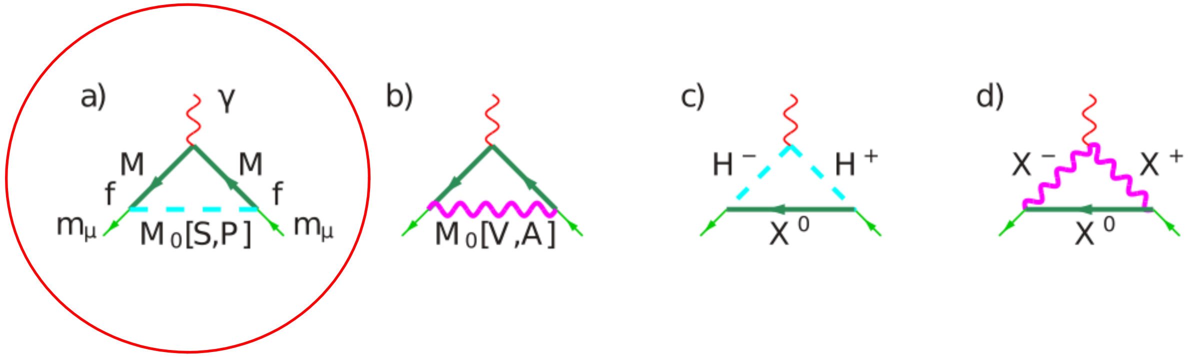


Jegerlehner, Nyffeler (09)

$$a_\mu^S = \frac{G_F m_\mu^2}{4\pi^2\sqrt{2}}\left(\frac{m_\mu^2}{m_S^2}\right)(y_\mu^S)^2 f_S\left(\frac{m_\mu^2}{m_S^2}\right)$$

Haber et al (79)
Dedes, Haber (01)

- 2HDM



Jegerlehner, Nyffeler (09)

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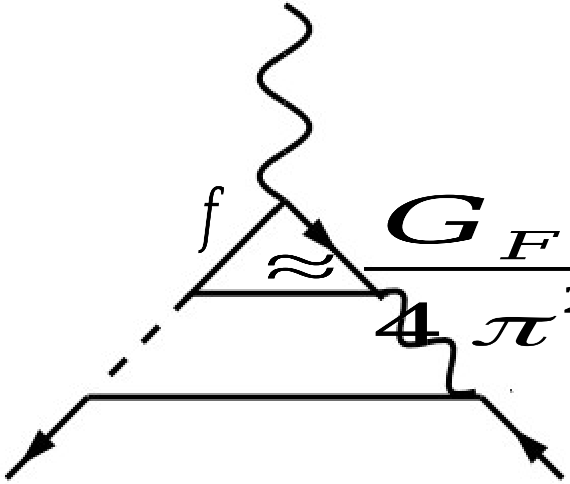
Haber et al (79)
Dedes, Haber (01)

Suppression factor!

- 2HDM

- Two-loop can be more important than one-loop; Chang et al (01)
  Cheung et al (01)



$$\approx \frac{G_F m_\mu^2}{4\pi^2\sqrt{2}} \frac{\alpha}{\pi} \left(\frac{m_f^2}{m_S^2}\right) \left(y_\mu^S y_f^S\right) g_S \left(\frac{m_f^2}{m_S^2}\right)$$

- 2HDM

- Two-loop can be more important than one-loop; Chang et al (01) Cheung et al (01)

$$\approx \frac{G_F m_\mu^2}{4\pi^2\sqrt{2}} \frac{\alpha}{\pi} \left(\frac{m_f^2}{m_S^2}\right) \left(y_\mu^S y_f^S\right) g_S \left(\frac{m_f^2}{m_S^2}\right)$$

$$a_\mu^{1-loop} = \frac{G_F m_\mu^2}{4\pi^2\sqrt{2}} \left(\frac{m_\mu^2}{m_S^2}\right) \left(y_\mu^S\right)^2 f_S \left(\frac{m}{m}\right.$$

- 2HDM

- Two-loop can be more important than one-loop; Chang et al (01) Cheung et al (01)

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- 2HDM

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2HDM

$$\mathcal{L}_S = (D_\mu \phi_1)^\dagger (D^\mu \phi_1) + (D_\mu \phi_2)^\dagger (D^\mu \phi_2) - V(\phi_1, \phi_2)$$

2HDM

Invariant under CP

$$\begin{aligned} V(\phi_1, \phi_2) = {} & m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 - m_{12}^2 \left(\phi_1^\dagger \phi_2 + \phi_2^\dagger \phi_1 \right) \\ & + \frac{\lambda_1}{2} \left(\phi_1^\dagger \phi_1 \right)^2 + \frac{\lambda_2}{2} \left(\phi_2^\dagger \phi_2 \right)^2 + \lambda_3 \phi_1^\dagger \phi_1 \phi_2^\dagger \phi_2 \\ & + \lambda_4 \phi_1^\dagger \phi_2 \phi_2^\dagger \phi_1 + \frac{\lambda_5}{2} \left[\left(\phi_1^\dagger \phi_2 \right)^2 + \left(\phi_2^\dagger \phi_1 \right)^2 \right]. \end{aligned}$$

2HDM

$$\mathcal{L}_S = \left(D_\mu \phi_1\right)^\dagger \left(D^\mu \phi_1\right) + \left(D_\mu \phi_2\right)^\dagger \left(D^\mu \phi_2\right) - V\left(\phi_1, \phi_2\right)$$

2HDM

Invariant under CP

Physical parameters:

Scalar potential parameters:

Flavor aligned 2HDM

$$\mathcal{L}_Y = -\bar{Q}'_L(\Gamma_1\phi_1 + \Gamma_2\phi_2)\, d'_R - \bar{Q}'_L(\Delta_1\tilde{\phi}_1 + \Delta_2\tilde{\phi}_2)\, u'_R$$
$$- \bar{L}'_L(\Pi_1\phi_1 + \Pi_2\phi_2)\, l'_R + \text{h.c.}\,,$$

Pich, Túzon (09)

$$\Gamma_2 = \xi_d\, \mathrm{e}^{-i\theta}\, \Gamma_1\,, \quad \Delta_2 = \xi_u^*\, \mathrm{e}^{i\theta}\, \Delta_1\,, \quad \Pi_2 = \xi_l\, \mathrm{e}^{-i\theta}\, \Pi_1\,. \quad \varsigma_f \equiv \frac{\xi_f - \tan\beta}{1 + \xi_f \tan\beta}\,.$$

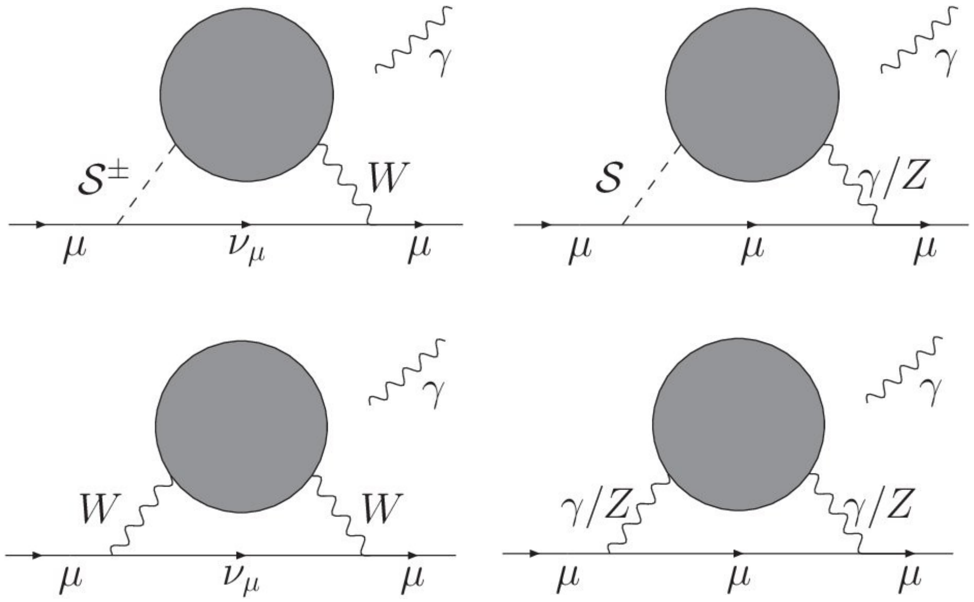
Model	(ξ_d, ξ_u, ξ_l)	ς_d	ς_u	ς_l
Type I	(∞, ∞, ∞)	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$(0, \infty, 0)$	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
Type X	$(\infty, \infty, 0)$	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Y	$(0, \infty, \infty)$	$-\tan\beta$	$\cot\beta$	$\cot\beta$
Inert	$(\tan\beta, \tan\beta, \tan\beta)$	0	0	0

$$Y_f^h = s_{\beta\alpha} + c_{\beta\alpha}\zeta_f,$$
$$Y_f^H = c_{\beta\alpha} - s_{\beta\alpha}\zeta_f,$$
$$Y_{d,l}^A = i\zeta_{d,l},$$
$$Y_u^A = -i\zeta_u.$$

- flavor aligned 2HDM

AC, Kneschke, Stöckinger, Stöckinger-Kim (17)

Complete two-loop prediction



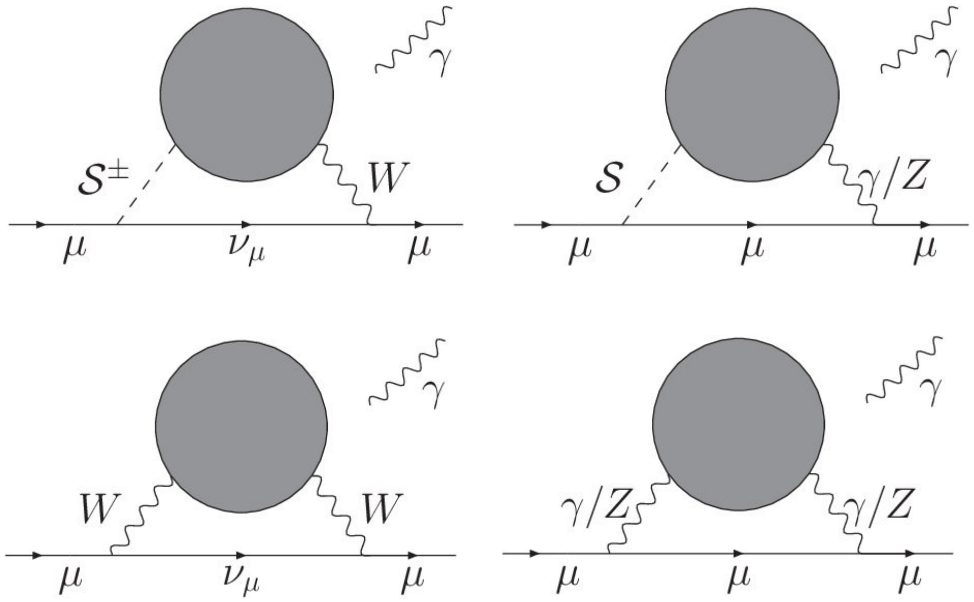
- Results implemented at Gfitter
- Results implemented at HEPfit

The Gfitter Group (18)

The HEPFIT Group (21)

- flavor aligned 2HDM

AC, Kneschke, Stöckinger, Stöckinger-Kim (17)



Given phenomenological constraints,

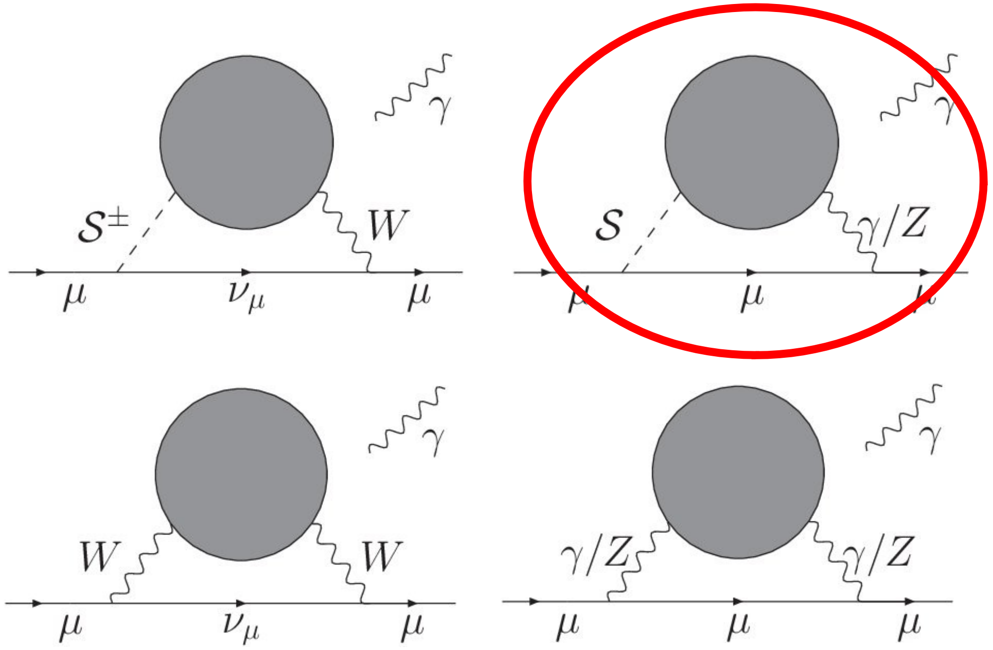
what are the maximum values for ?

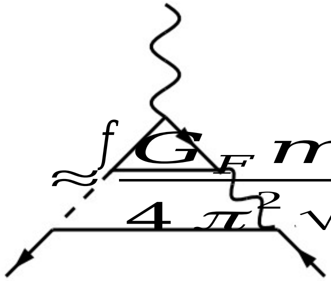
- flavor aligned 2HDM

AC, Kneschke, Stöckinger, Stöckinger-Kim (17)

Given phenomenological constraints,

what are the maximum values for ?



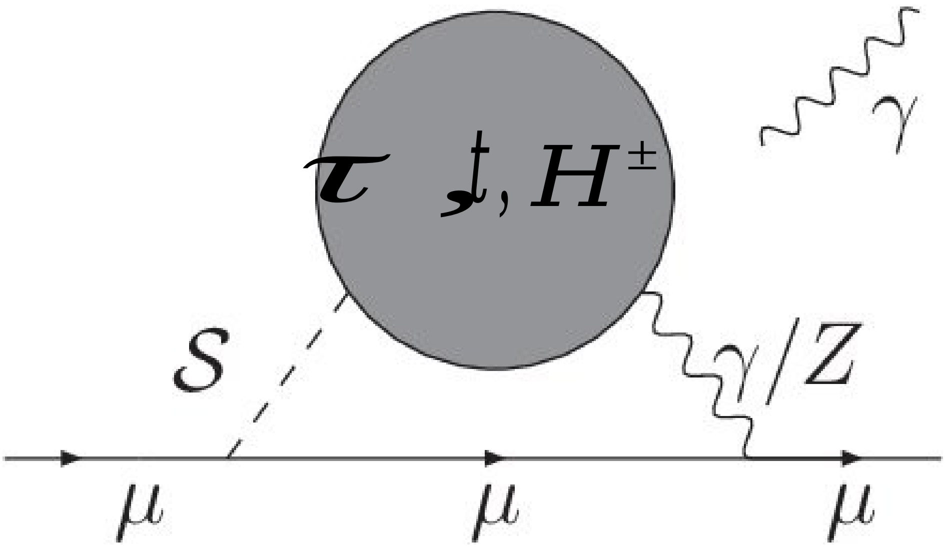


$$\approx \frac{G_F\, m_\mu^2}{4\pi^2\sqrt{2}}\,\frac{\alpha}{\pi}\left(\frac{m_f^2}{m_\mu^2}\right)\left(\frac{m_\mu^2}{m_S^2}\right)\left(y_\mu^S\, y_f^S\right) g_S\!\left(\frac{m_f^2}{m_S^2}\right)$$

One scalar (at least) must be lig

Maximum allowed

AC, Stöckinger, Stöckinger-Kim (18)

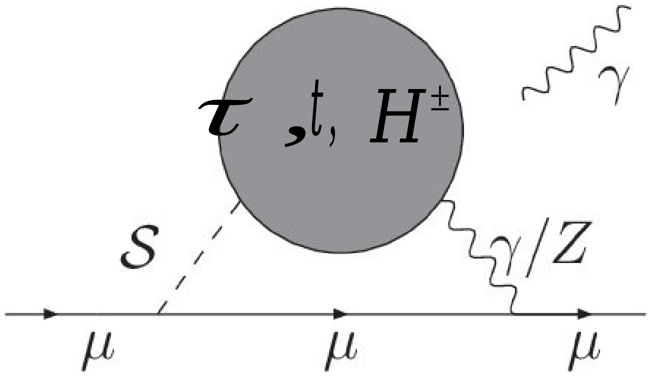


Constraints

- B-physics;
- Tau decay;
- ;
- Collider;
- Theoretical;
- EW parameters.

Maximum allowed

AC, Stöckinger, Stöckinger-Kim (18)



free

Constraints

- B-physics;
- Tau decay;
- ;
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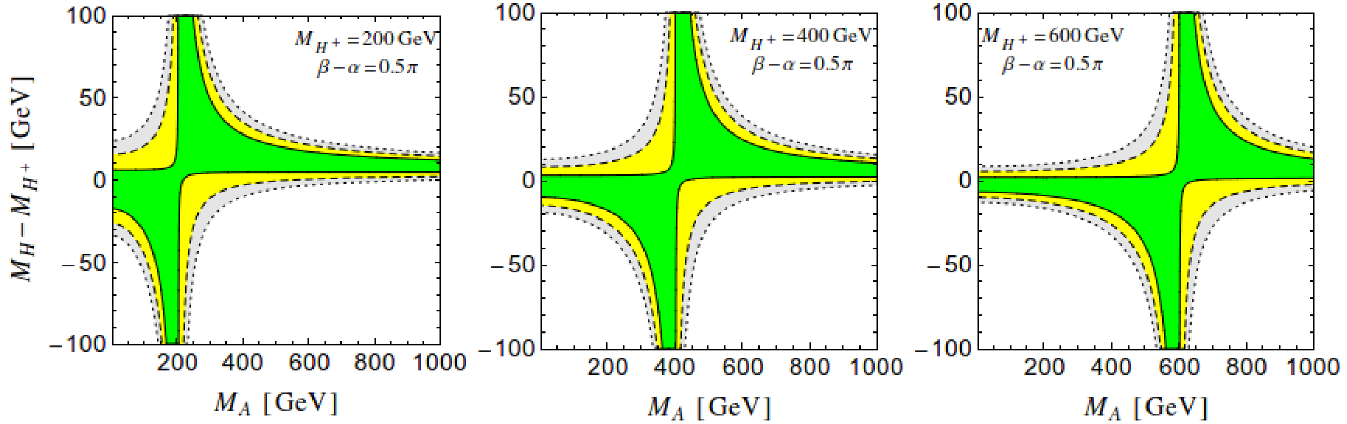
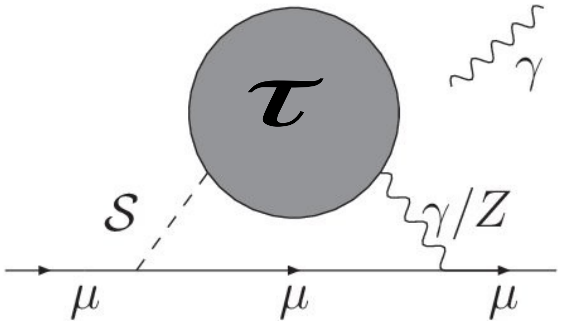
Control splitting between scalar masses.

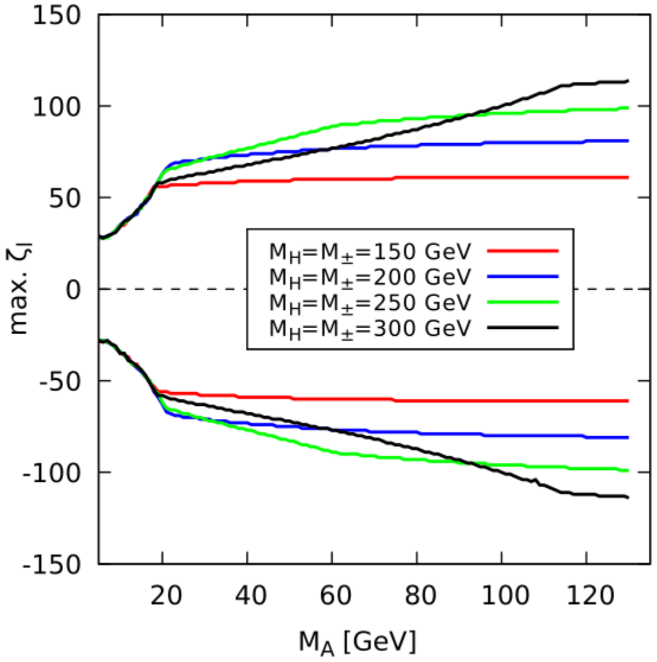


Broggio et al (14)

Maximum allowed

AC, Stöckinger, Stöckinger-Kim (18)





Constraints

- B-physics;
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- ;
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- Theoretical;
- EW parameters.

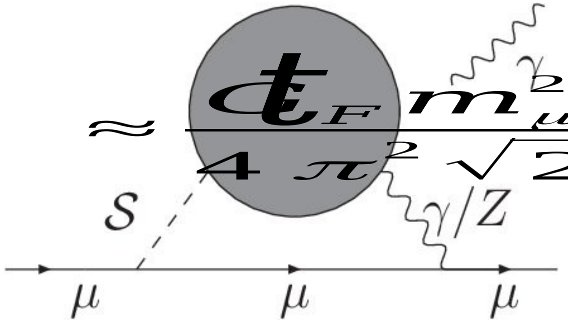
S: *h*, *H*, *A*, *H*±

Flavour-aligned: ,

Only contribution in a lepton-specific scenari

Maximum allowed

AC, Stöckinger, Stöckinger-Kim (18)



$$\approx \frac{G_F\, m_\mu^2}{4\,\pi^2\sqrt{2}}\,\frac{\alpha}{\pi}\left(\frac{m_f^2}{m_S^2}\right)\left(\,y_\mu^S\, y_f^S\,\right) g_S\left(\frac{m_f^2}{m_S^2}\right)$$

Constraints

- B-physics;
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S: *h*, *H*, *A*, *H*$^{\pm}$

Flavour-aligned: ,

Maximum allowed

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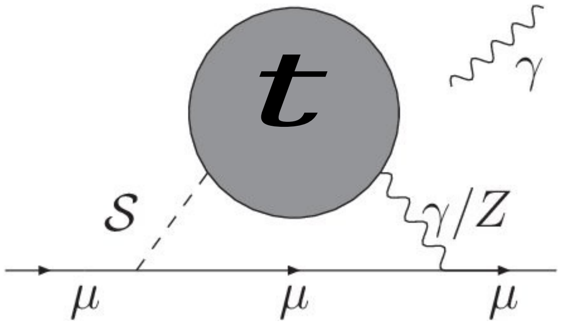

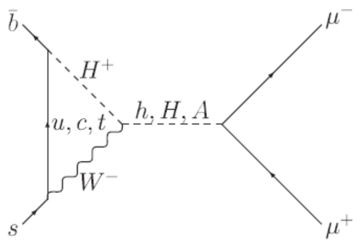

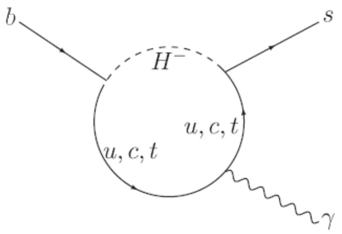

Constraints

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Maximum allowed

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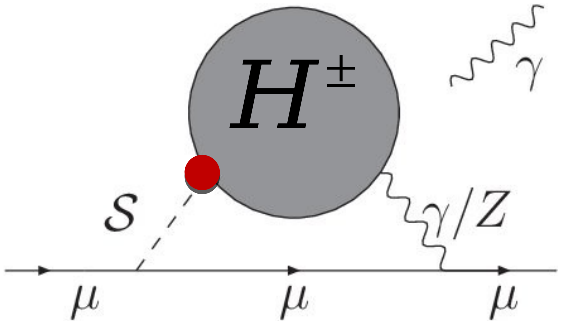

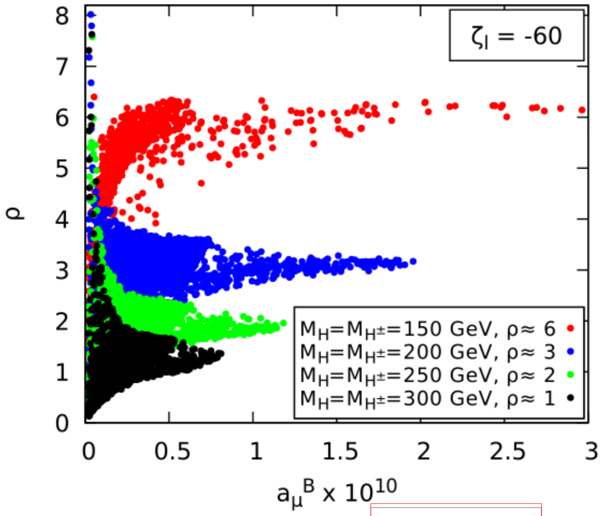

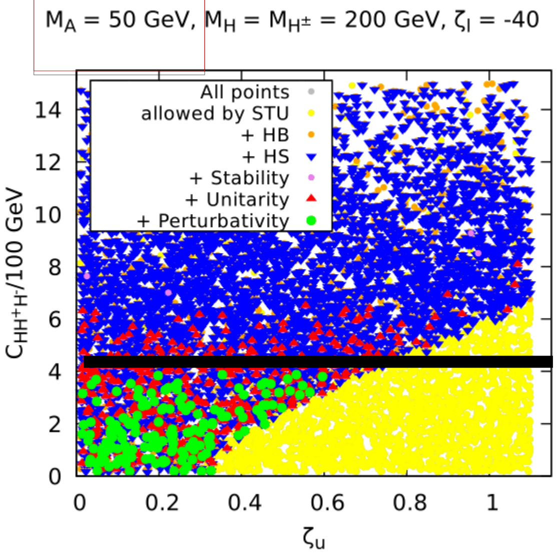

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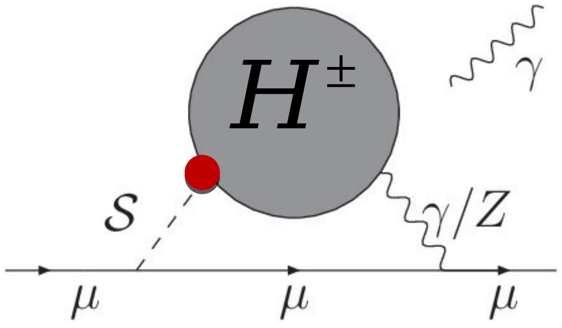

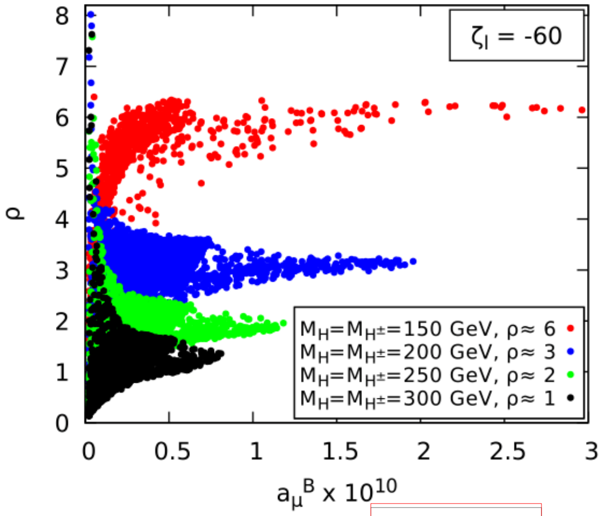

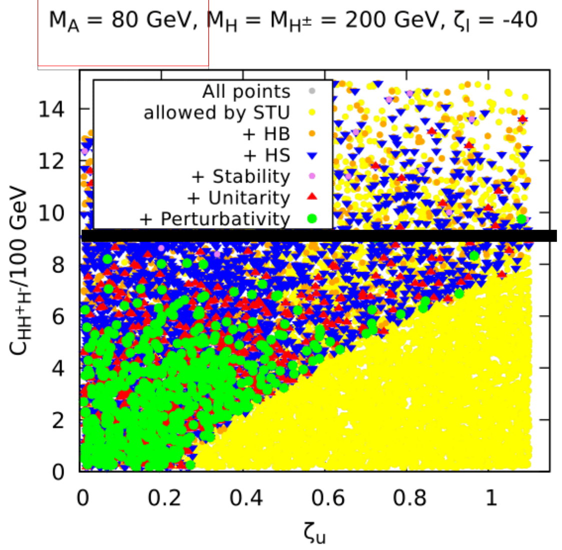

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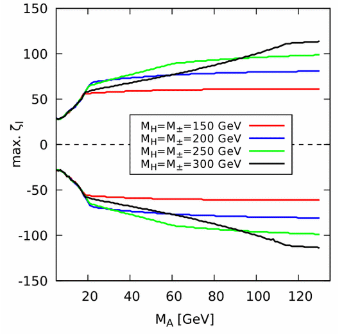
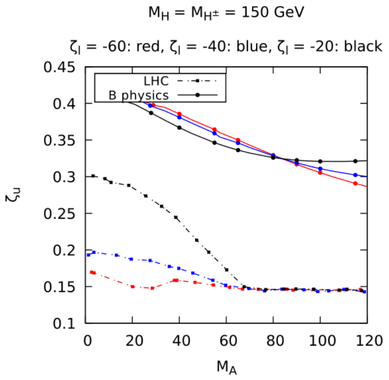
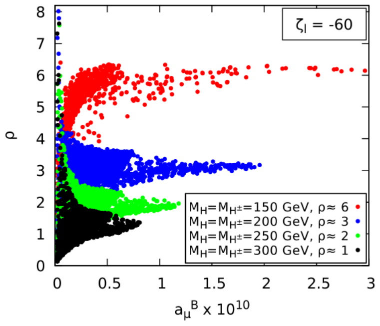
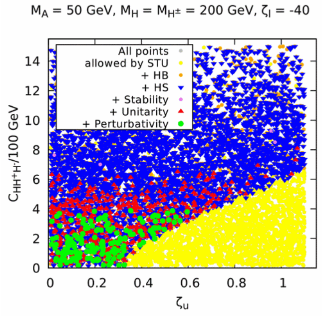
AC, Stöckinger, Stöckinger-Kim (18)



$$\hat{x}_S^2 = \frac{m_S^2}{100\,GeV}$$

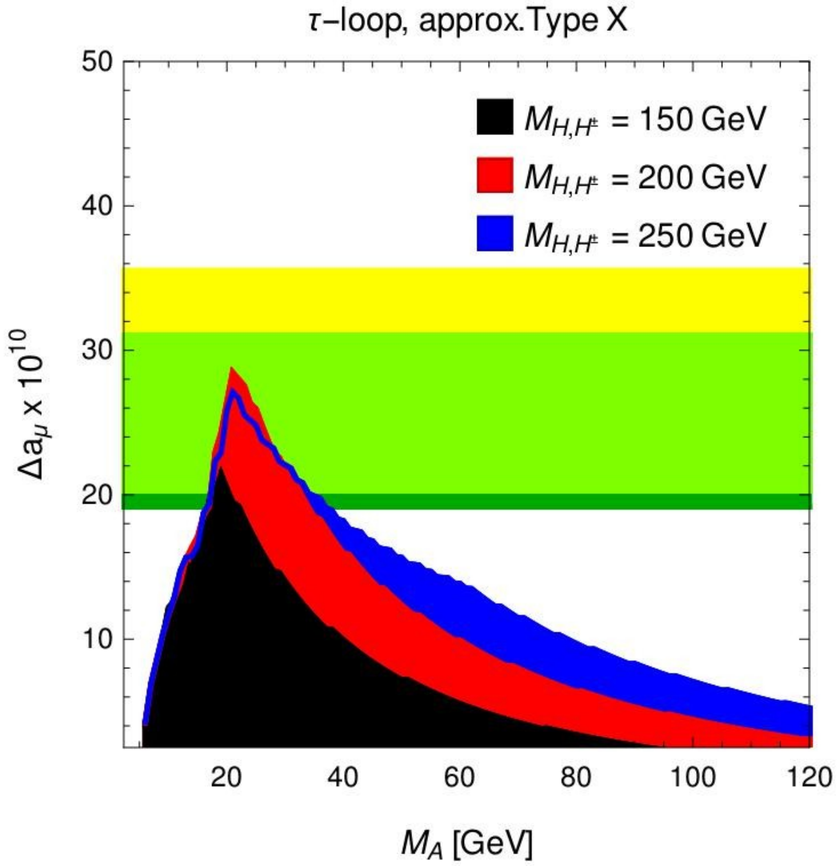


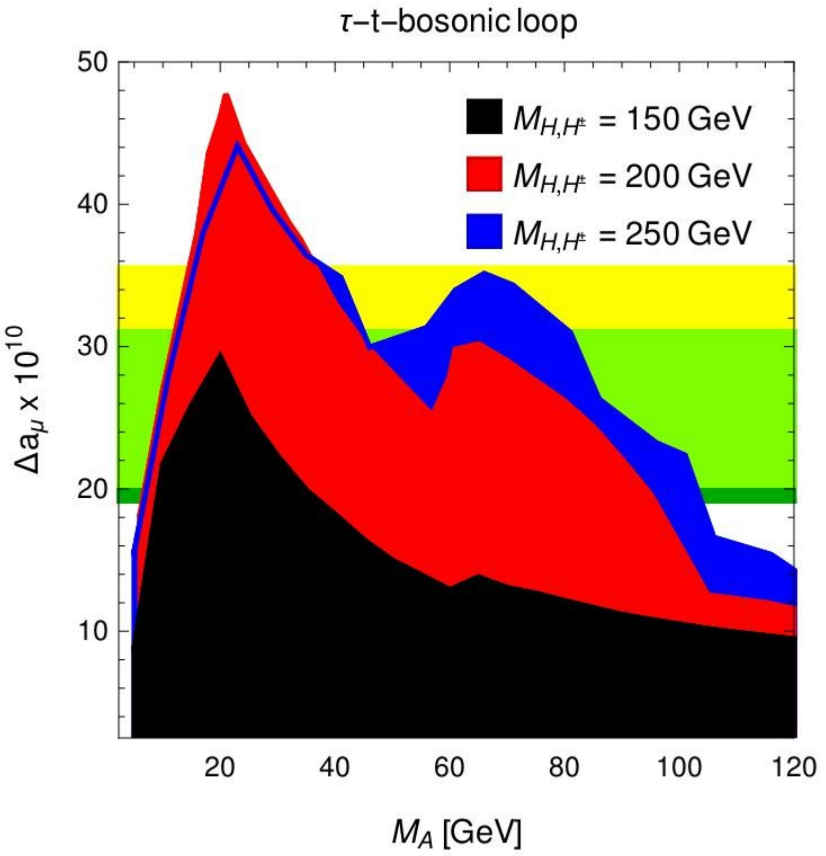




Maximum allowed

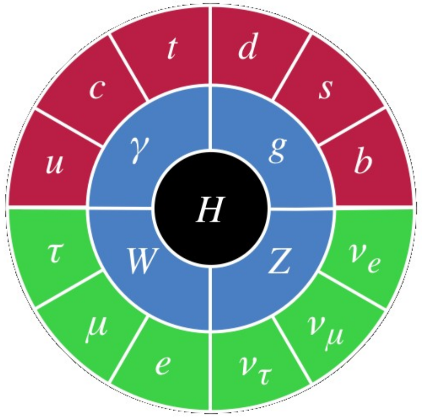
2104.03691





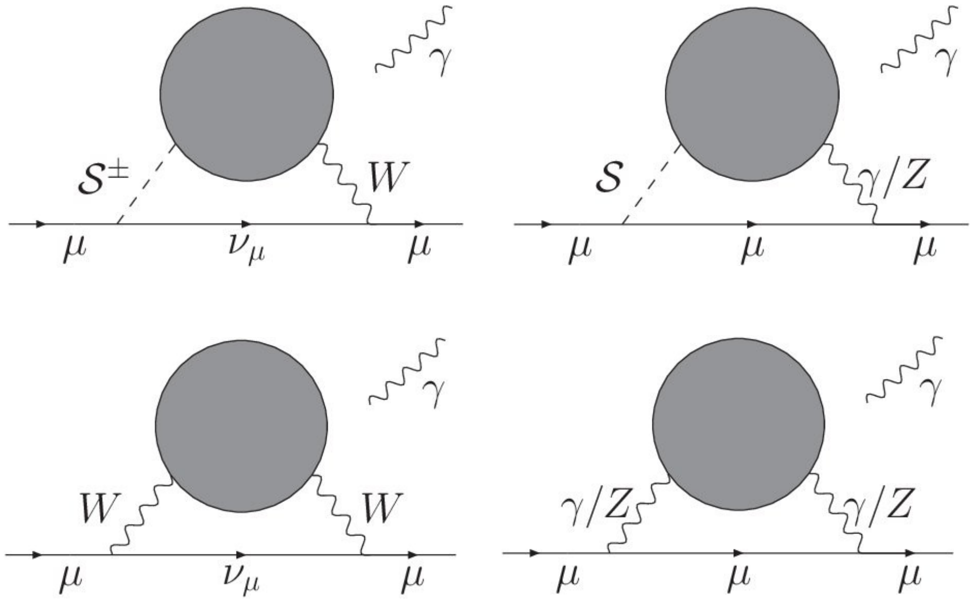
Conclusions

2HDM =



+ 4 scalars

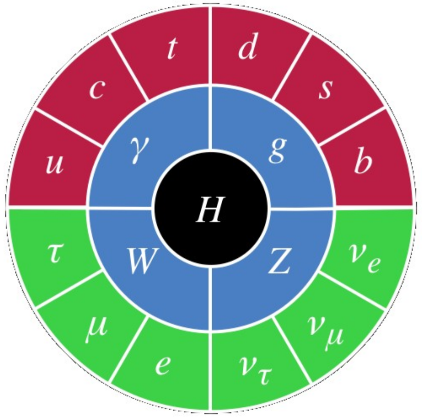
Phenomenology



AC, Kneschke, Stöckinger, Stöckinger-Kim (17)

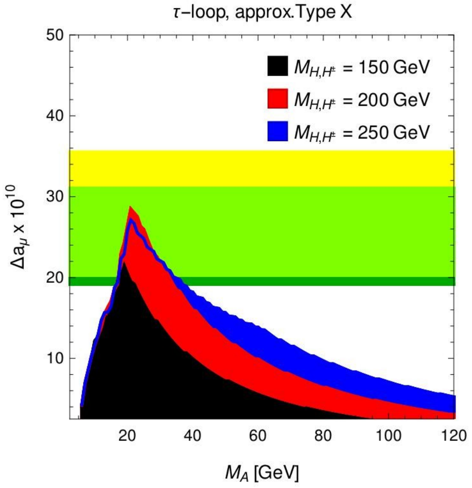
Conclusions

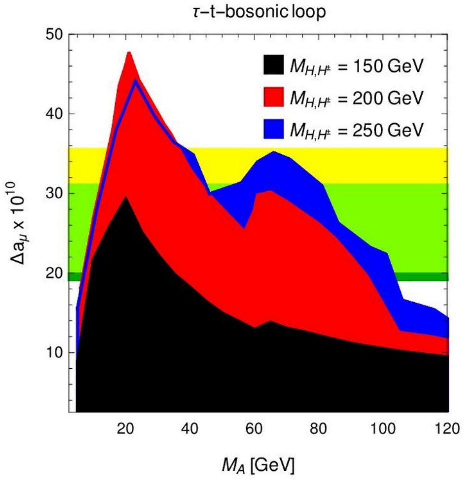
2HDM =



+ 4 scalars

Phenomenology

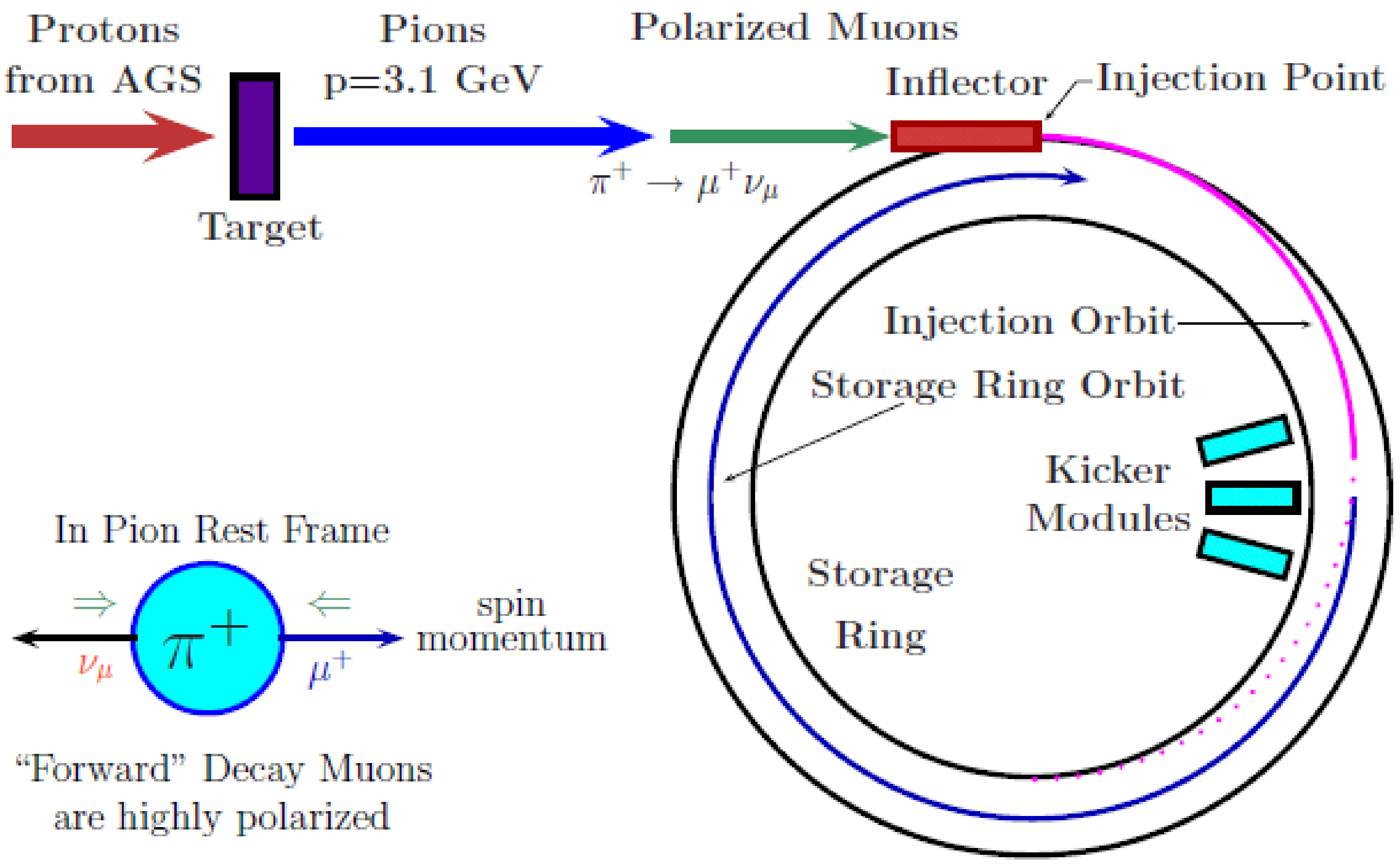




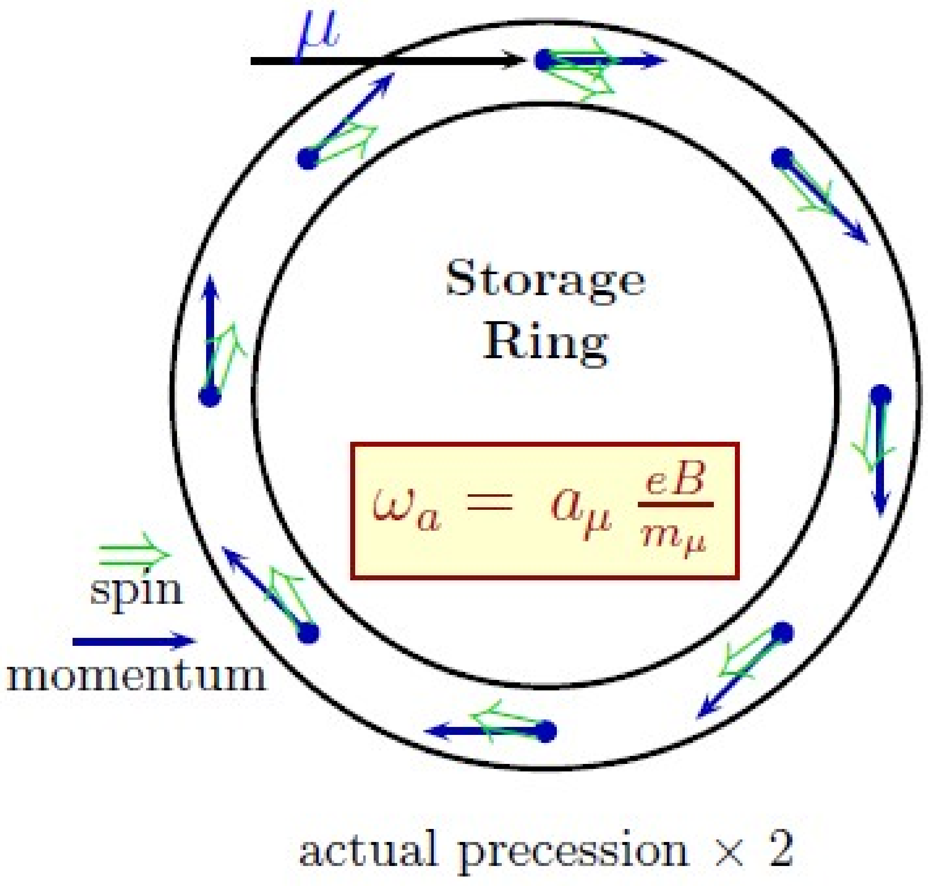
AC, Stöckinger, Stöckinger-Kim (18)

Thanks!

Backup



Jegerlehner, Nyffeler (09)

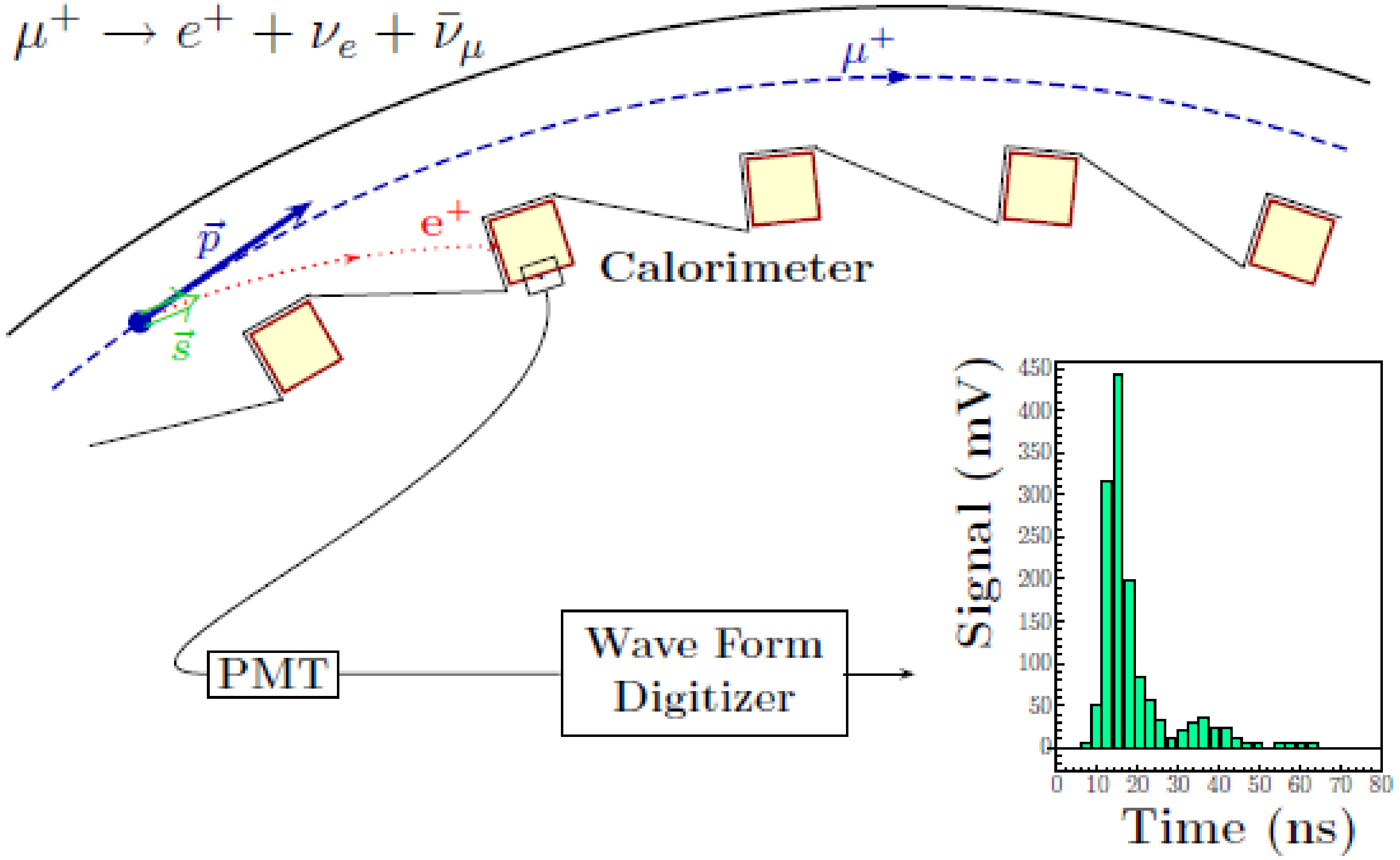


$$\omega_a = \omega_s - \omega_c .$$

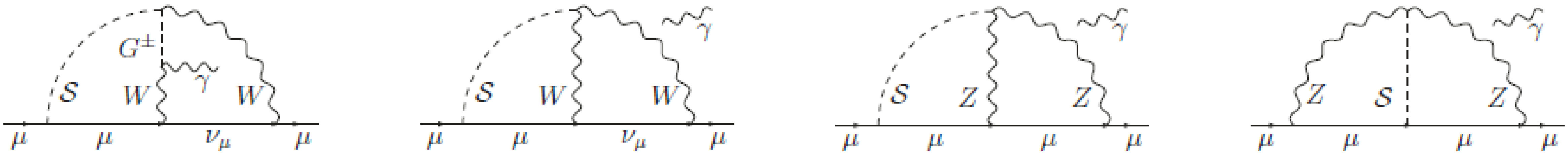
$$\omega_c = \frac{eB}{m_\mu \gamma}\,, \quad \omega_s = \frac{eB}{m_\mu \gamma} + a_\mu \frac{eB}{m_\mu}\,, \quad \omega_a = a_\mu \frac{eB}{m_\mu}\,,$$

ciclotron spin

Jegerlehner, Nyffeler
(09)



Jegerlehner, Nyffeler (09)


$G^{\pm}$
$\mathcal{S}$
W
γ
W
μ
μ
ν_μ
μ
γ
$\mathcal{S}$
W
W
μ
μ
ν_μ
μ
γ
$\mathcal{S}$
Z
Z
μ
μ
μ
μ
γ
Z
$\mathcal{S}$
Z
μ
μ
μ
μ

$$
\begin{aligned}
Y_f^h &= s_{\beta\alpha} + c_{\beta\alpha}\zeta_f, \\
Y_f^H &= c_{\beta\alpha} - s_{\beta\alpha}\zeta_f, \\
Y_{d,l}^A &= i\zeta_{d,l}, \\
Y_u^A &= -i\zeta_u.
\end{aligned}
$$

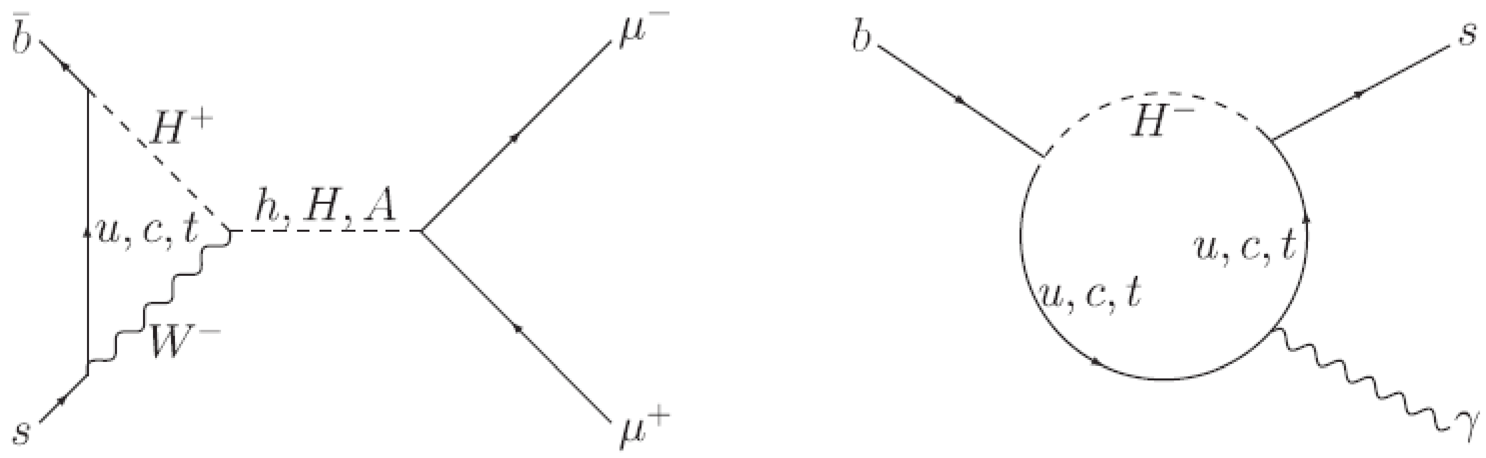
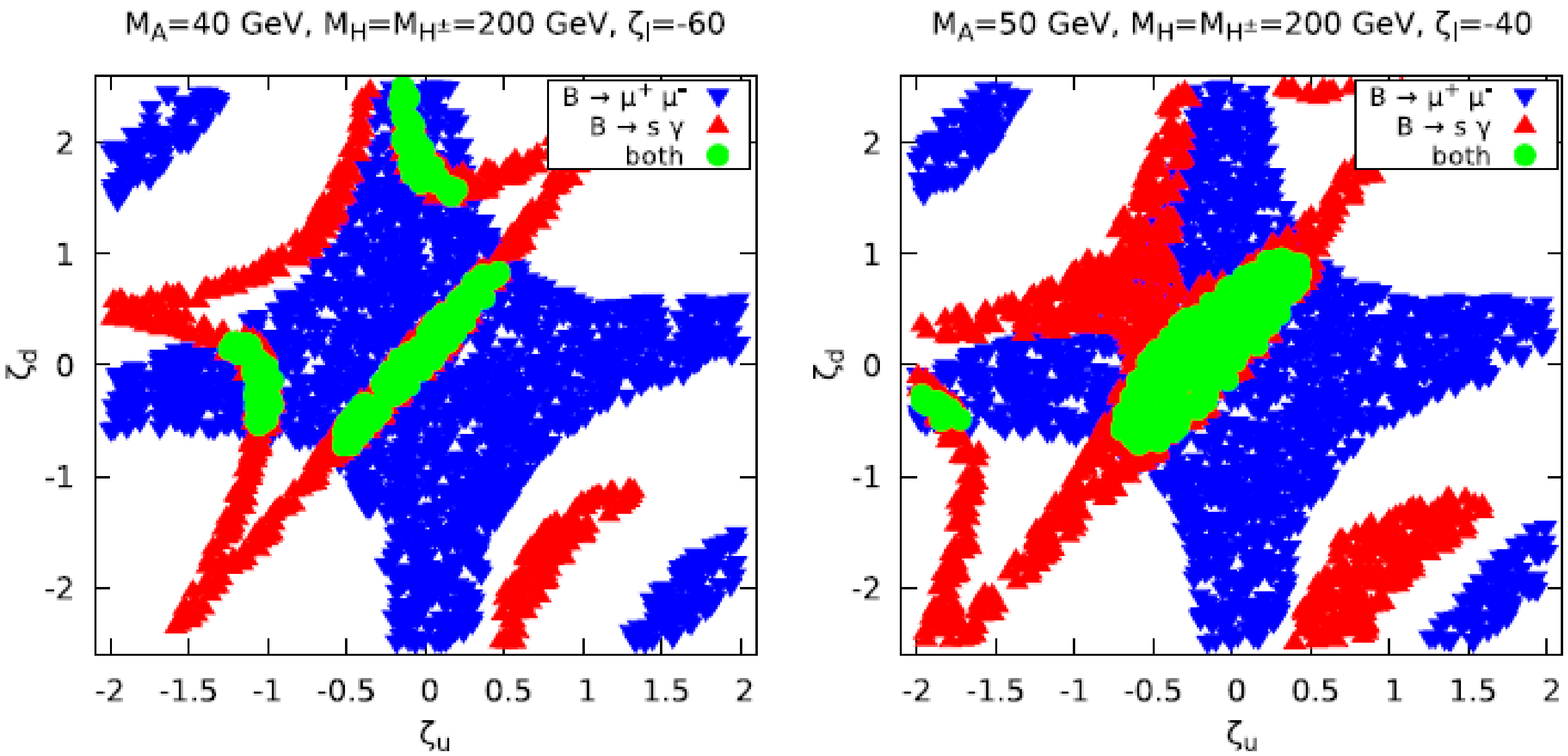


FIG. 2. Sample Feynman diagrams for the processes $B_s \to \mu^+\mu^-$ and $b \to s\gamma$, which depend on the Yukawa couplings of up- and down-type quarks and leptons.



M_A=40 GeV, M_H=$M_{H^\pm}$=200 GeV, ζ_l=-60
M_A=50 GeV, M_H=$M_{H^\pm}$=200 GeV, ζ_l=-40
$B \to \mu^+ \mu^-$
$B \to s\,\gamma$
both
ζ_d
ζ_u