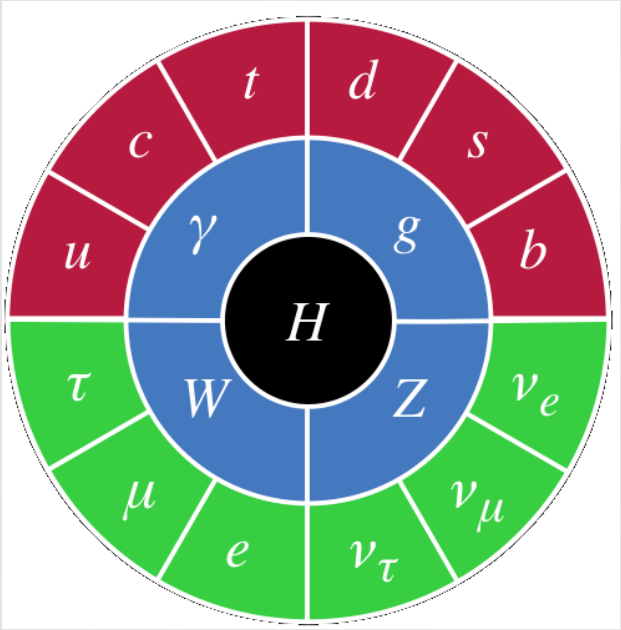
Muon g-2 in the 2HDM: maximum results and detailed phenomenology.

Adriano Cherchiglia, D. Stöckinger, H. Stöckinger-Kim

Latin American Webinars on Physics (W70)

Cherchiglia et al, Phys.Rev. D98 (2018) 035001

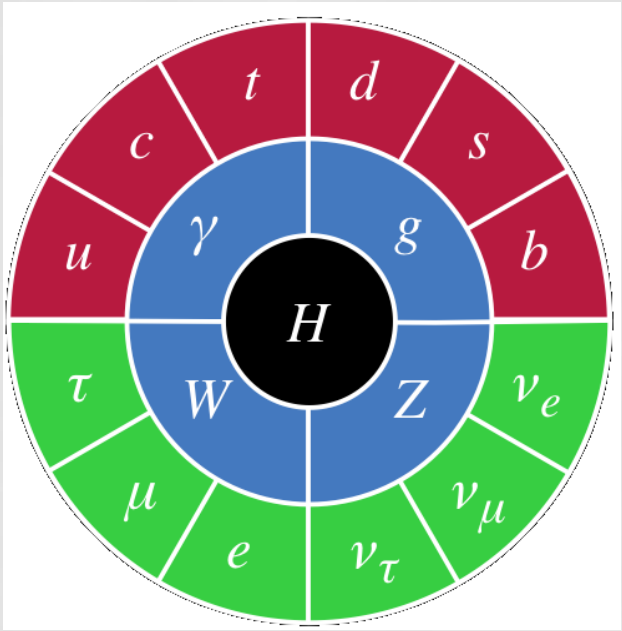
Standard Model



Particle Fever

Cherchiglia et al, Phys.Rev. D98 (2018) 035001

Standard Model



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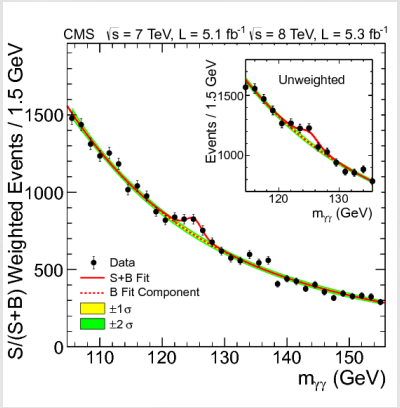
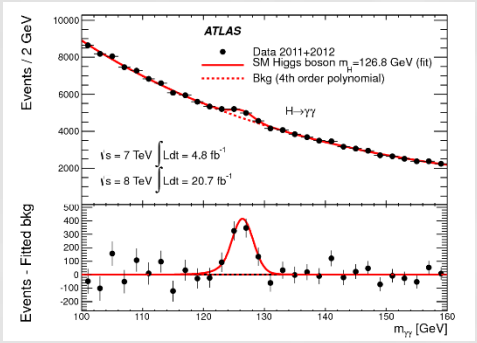


Phys.Lett. B716 (2012) 30-61



Phys.Lett. B716 (2012) 1-29

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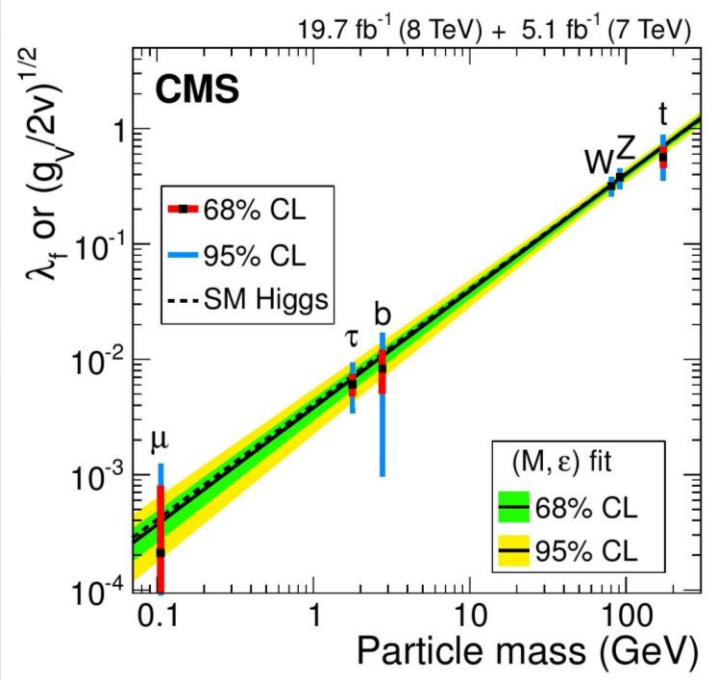
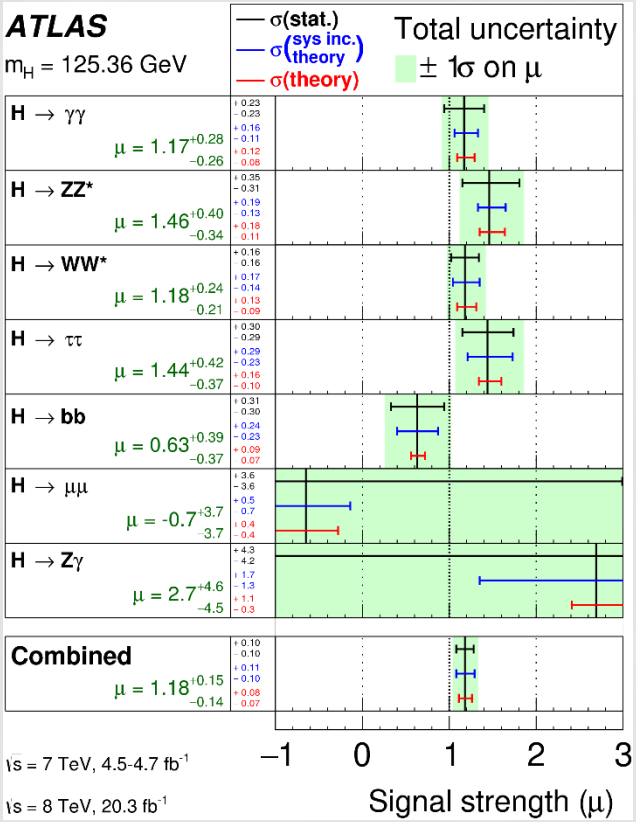
Standard Model

- Scalar sector scrutinized



Eur. Phys. J. C 75 (2015) 212



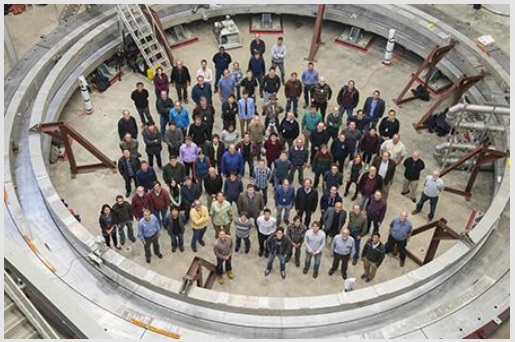
Eur. Phys. J. C76 (2016) 6

In the search for New Physics

- High Energy Physics (colliders)
  - Still no sign of New Physics.

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

- Low-energy observables
  - Muon magnetic moment.



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

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$(g-2)_\mu$

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

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

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

- Dirac: $g = 2$
- Quantum Field Theory: $g = 2 + \cdots$

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

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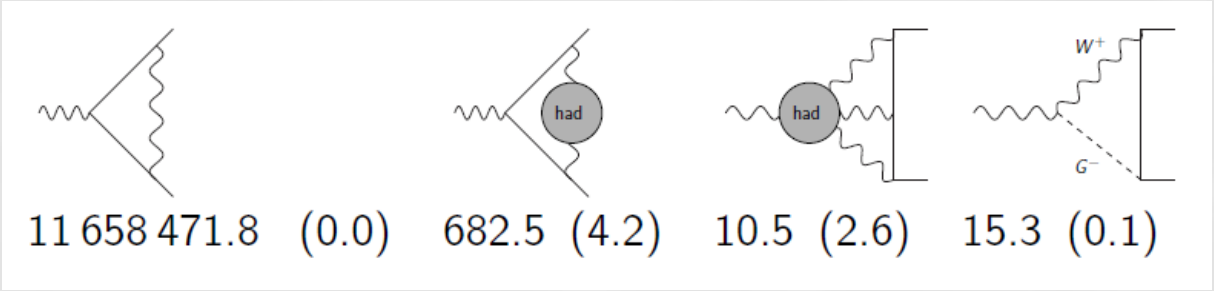
$(g-2)_\mu$ - Theory

- Standard Model



Thanks to D. Stöckinger

$$a_\mu^{th} = \begin{cases} (11\,659\,182.3 \pm 4.3) \times 10^{-10} \\ (11\,659\,182.04 \pm 3.56) \times 10^{-10} \end{cases}$$

Davier et al (17)

Keshavarzi et al (18)

Cherchiglia et al, Phys.Rev. D98 (2018) 035001

$(g-2)_\mu$ - Experiment

- E821 BNL
- Final result in 2004

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

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

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

$(g-2)_\mu$ - Experiment

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

$$a_\mu^{exp} = ????$$

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

Cherchiglia et al, Phys.Rev. D98 (2018) 035001

$(g-2)_\mu$ - Experiment

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

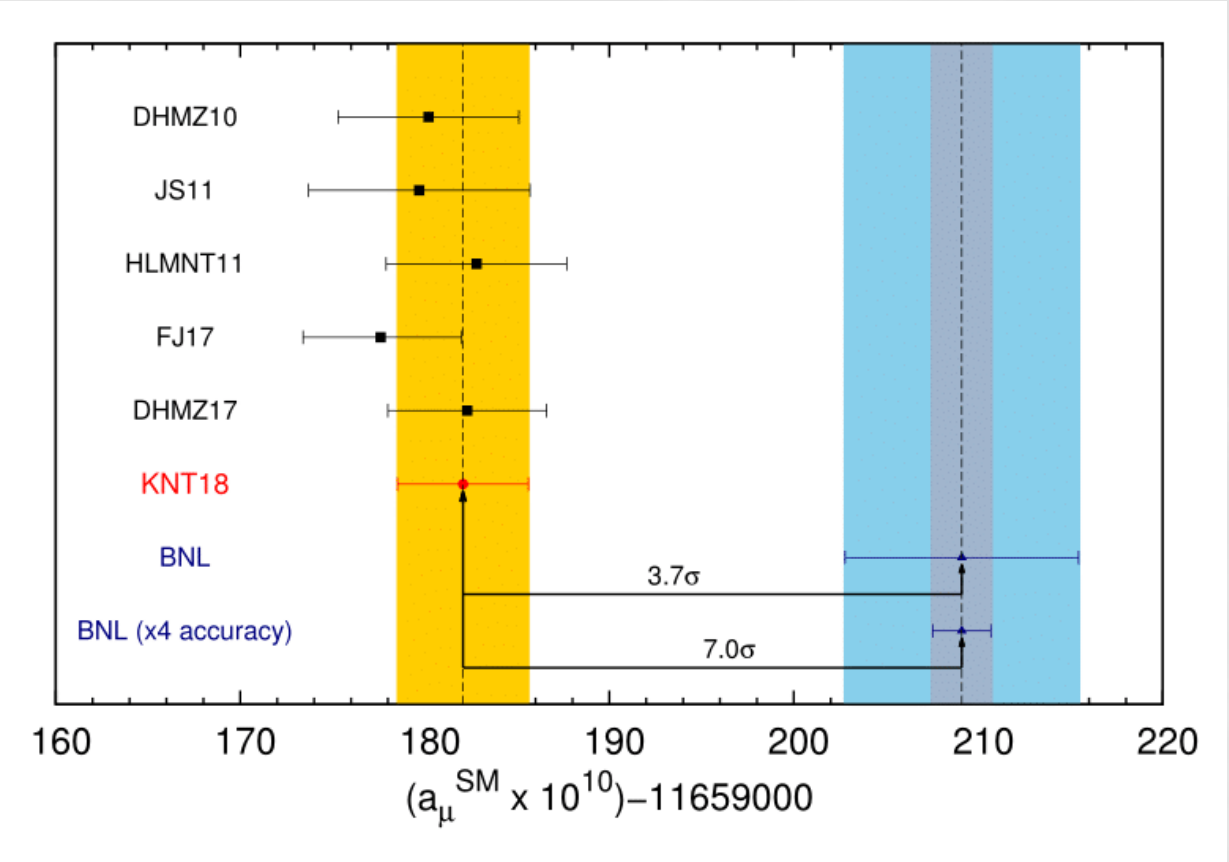
First results by 2019!

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

$$a_\mu^{exp} = ????$$

Cherchiglia et al, Phys.Rev. D98 (2018) 035001

Theory Experiment



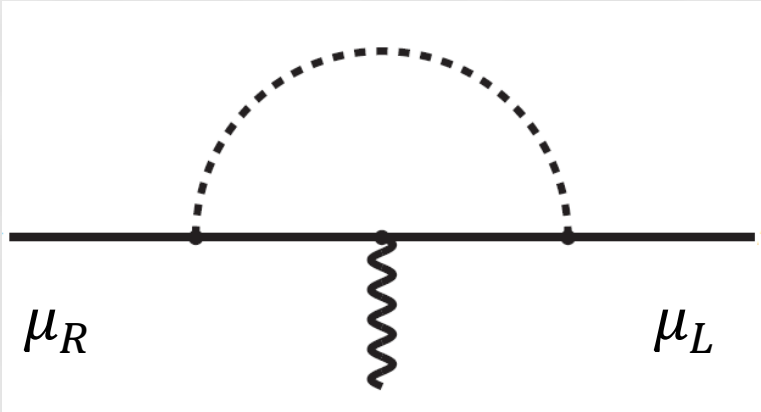
Keshavarzi et al (18)

Cherchiglia et al, Phys.Rev. D98 (2018) 035001

$(g-2)_\mu$ - Beyond Standard Model

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

- Chirality flipping
- Loop induced



Cherchiglia et al, Phys.Rev. D98 (2018) 035001

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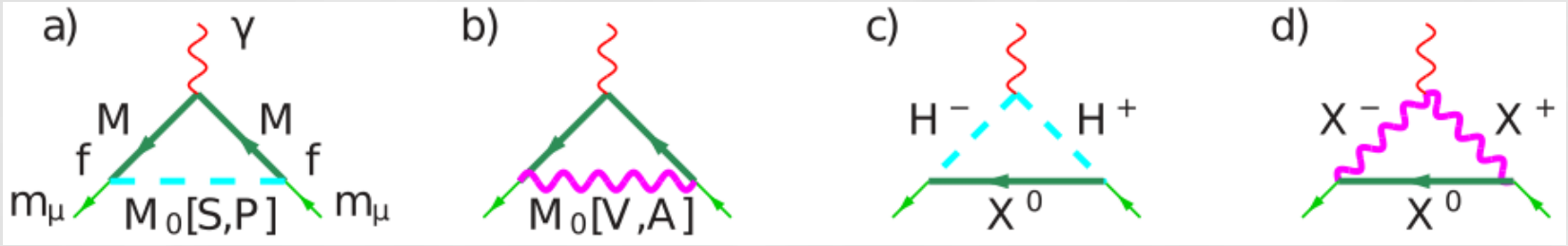

Jegerlehner, Nyffeler (09)

Cherchiglia et al, Phys.Rev. D98 (2018) 035001

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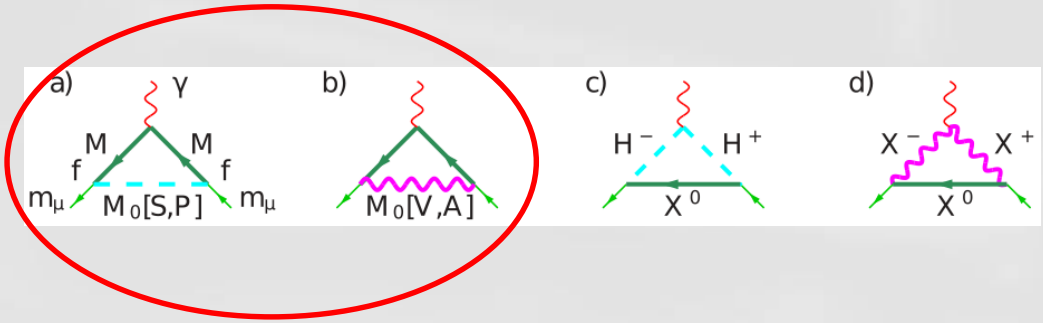
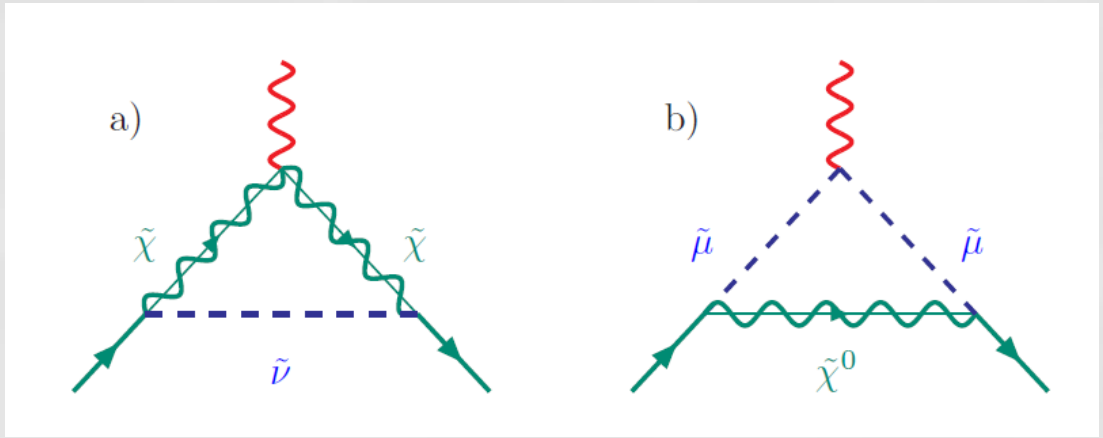


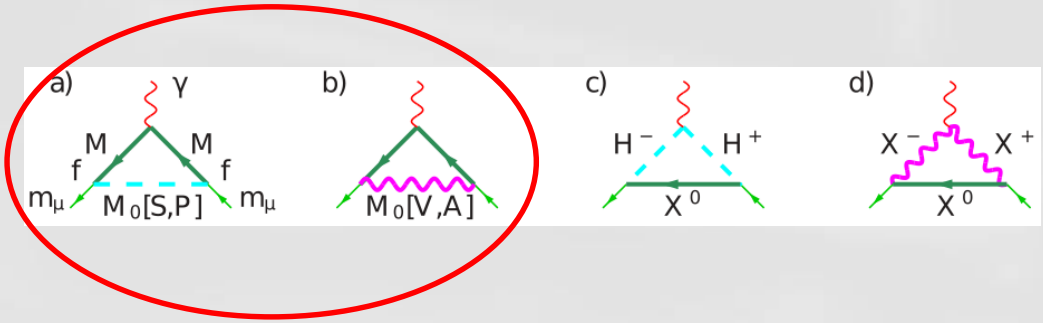
Jegerlehner, Nyffeler (09)

SUSY



Cherchiglia et al, Phys.Rev. D98 (2018) 035001

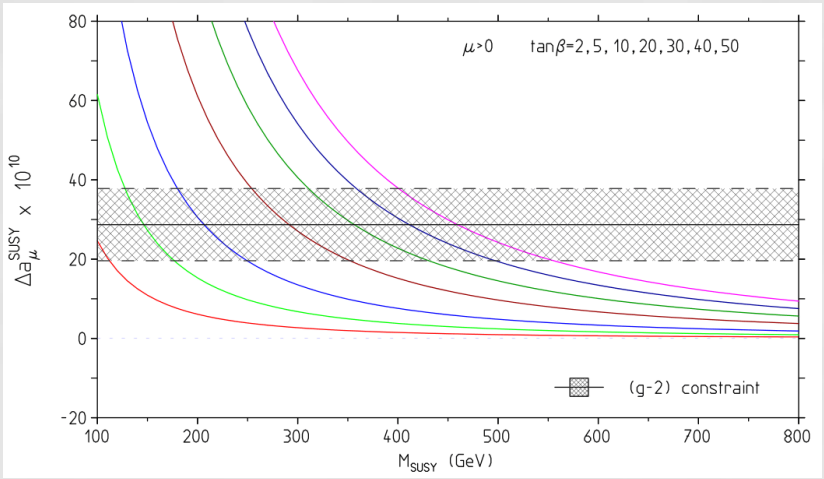
$(g-2)_\mu$ - Beyond Standard Model



Jegerlehner, Nyffeler (09)

SUSY

$$a_\mu(SUSY) \cong 123\times 10^{-11}\left(\frac{100\ GeV}{M_{SUSY}}\right)^2 \tan\beta$$



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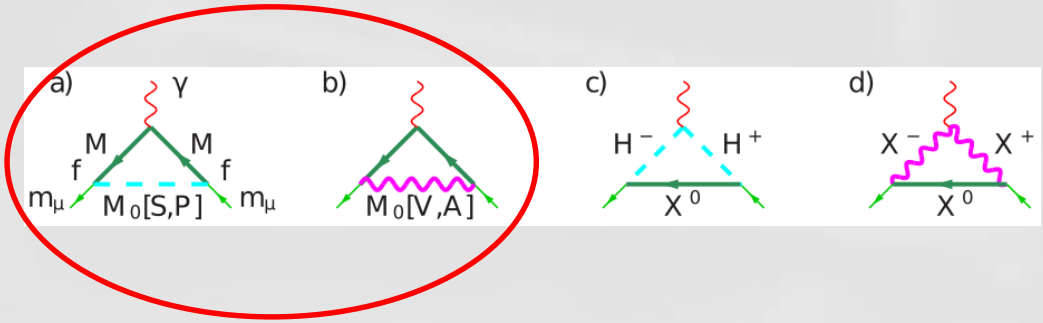

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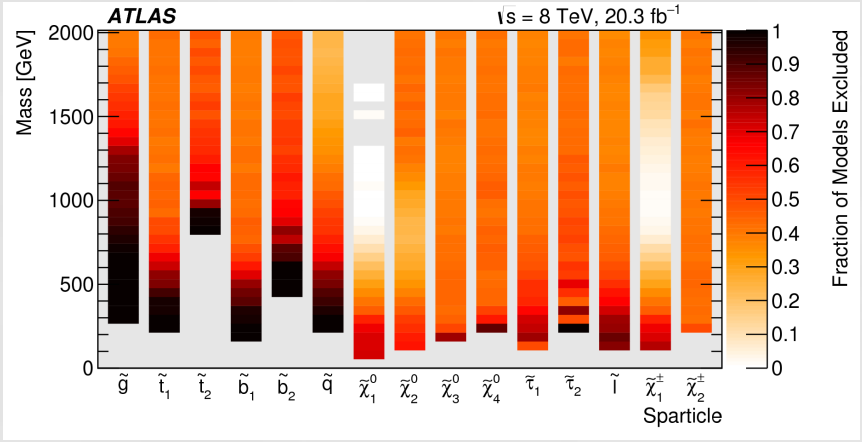
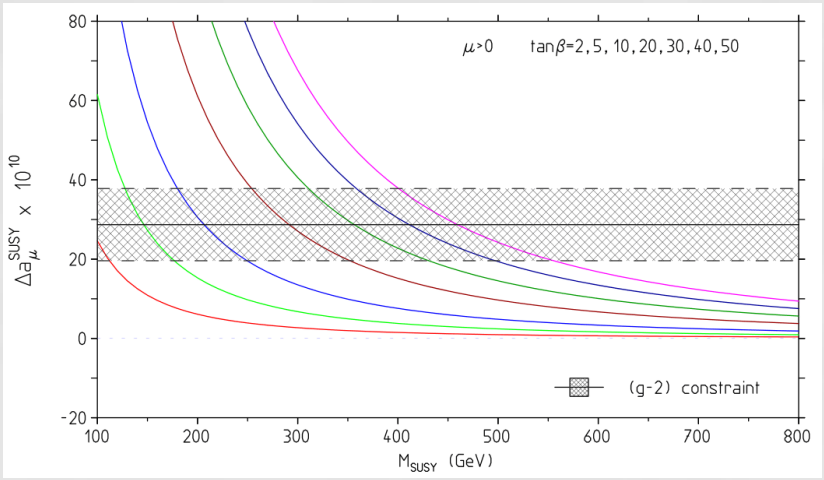


https://atlas.web.cern.ch



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$(g-2)_\mu$ - Beyond Standard Model

- Beyond Standard Model:
  - SUSY

Other scenarios → Ex: extensions to the scalar sector

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

2HDM

Invariant under CP

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Flavor Aligned 2HDM

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

Pich, Túzon, 2009

$$\Gamma_2=\xi_d\,\mathrm{e}^{-i\theta}\,\Gamma_1\,,\quad \Delta_2=\xi_u^*\,\mathrm{e}^{i\theta}\,\Delta_1\,,\quad \Pi_2=\xi_l\,\mathrm{e}^{-i\theta}\,\Pi_1\,.$$

Model	ς_d	ς_u	ς_l
Type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
Type X	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Y	$-\tan\beta$	$\cot\beta$	$\cot\beta$
Inert	0	0	0

$$\varsigma_f\equiv\frac{\xi_f-\tan\beta}{1+\xi_f\tan\beta}\,.$$

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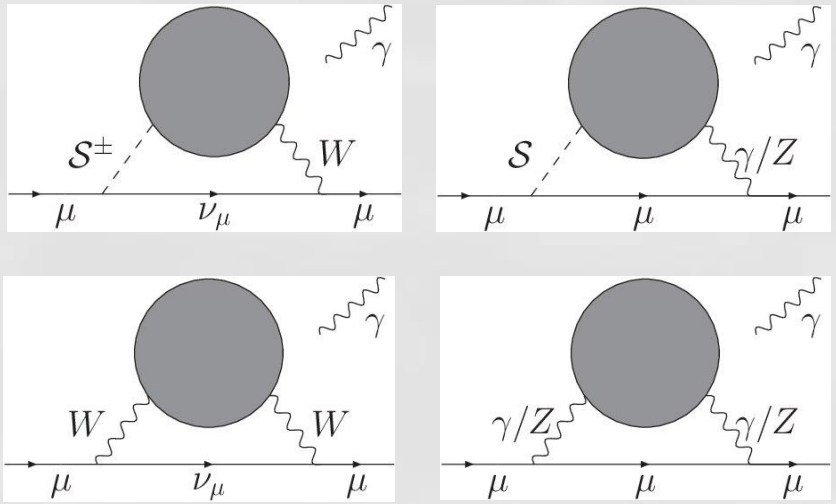
$(g-2)_\mu$ - Flavor Aligned 2HDM

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

Complete two-loop prediction



Theoretical uncertainity under control (below new $(g-2)_\mu$ experiment)

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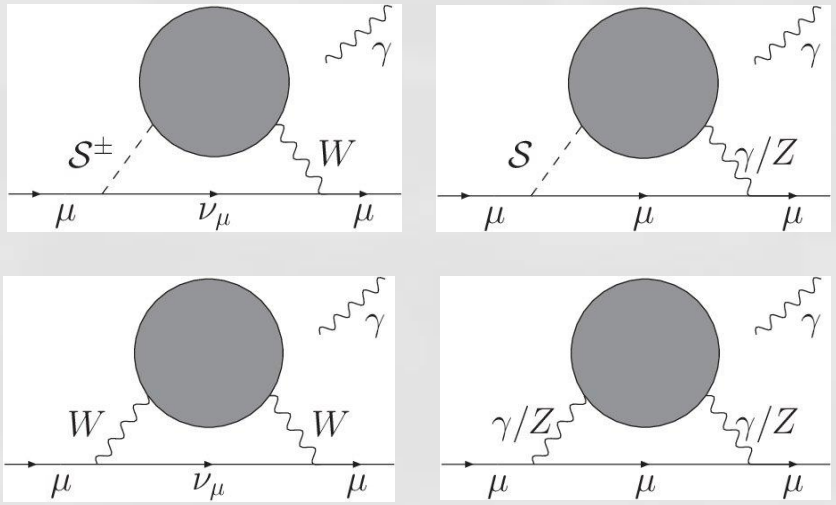
$(g-2)_\mu$ - Flavor Aligned 2HDM

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

Given phenomenological constraints,

what are the maximum values for a_μ ?



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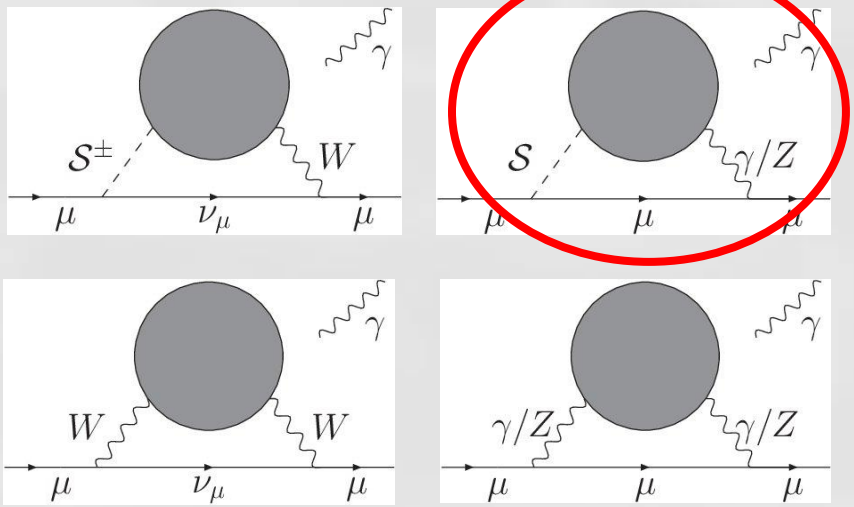

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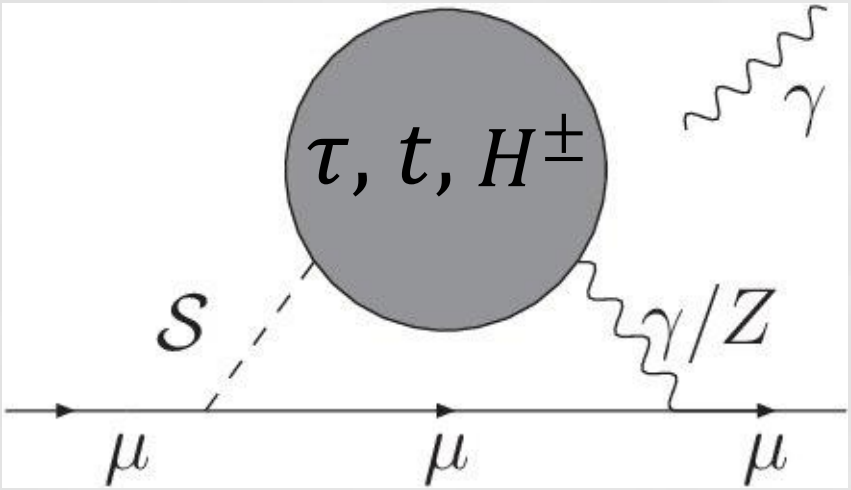
Maximum allowed $(g-2)_\mu$



Constraints

- B-physics;
- Tau decay;
- $Z \to \tau\tau$;
- Collider;
- Theoretical;
- EW parameters.

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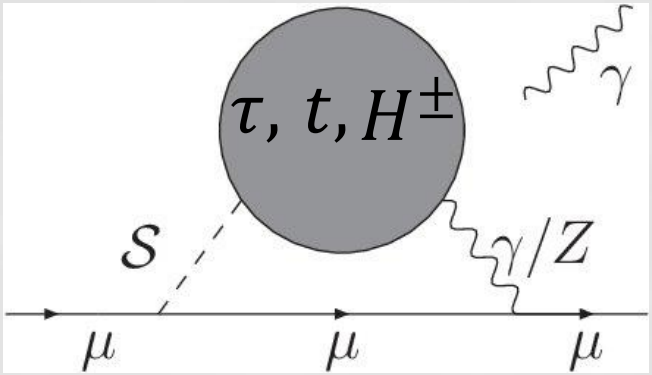

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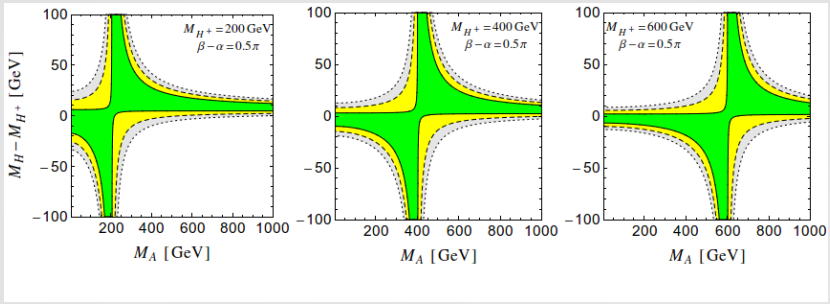
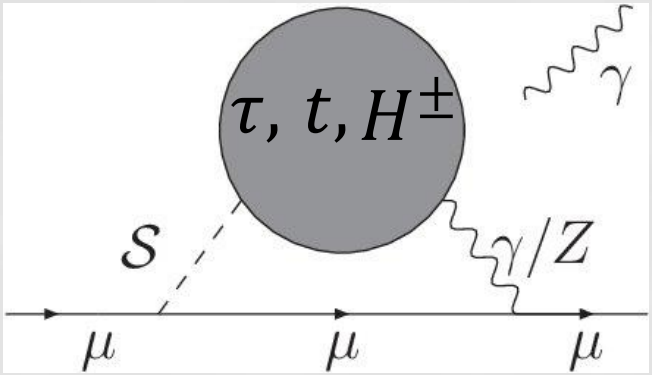


Broggio et al (14)

Control splitting between scalar masses.

Maximum allowed $(g-2)_\mu$



M_A free

$M_H \approx M_{H^{\pm}}$

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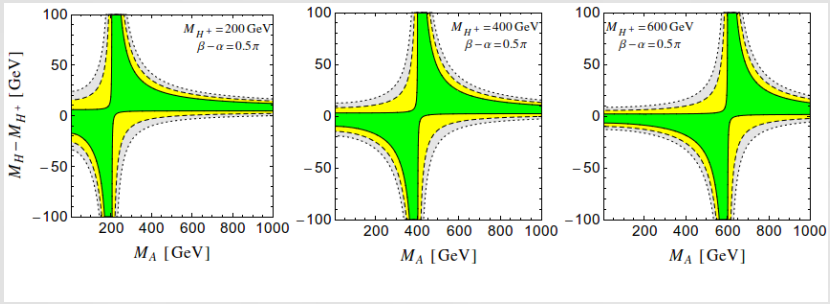

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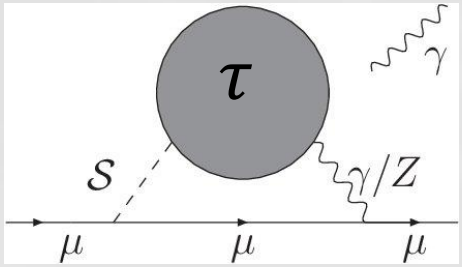

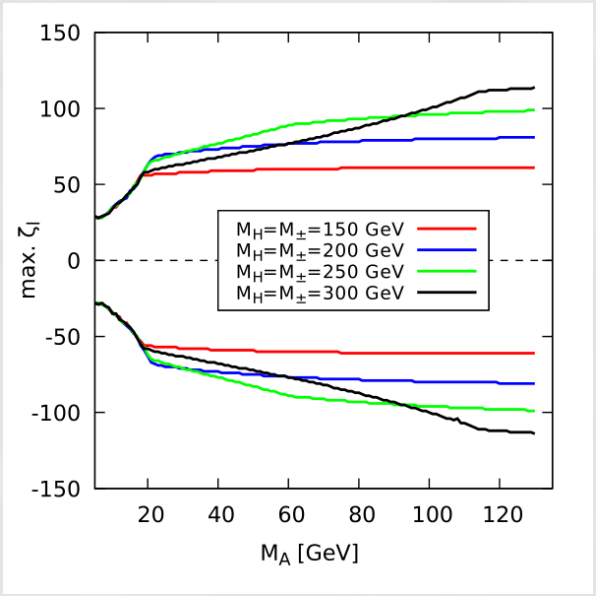

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- Theoretical;
- EW parameters.

***S**: h, H, A, $H^\pm$*

Flavour-aligned: $\varsigma_l, \varsigma_u, \varsigma_d$

Only contribution in a lepton-specific scenario

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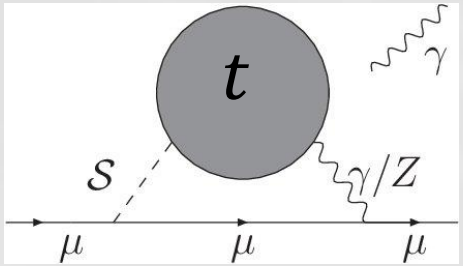
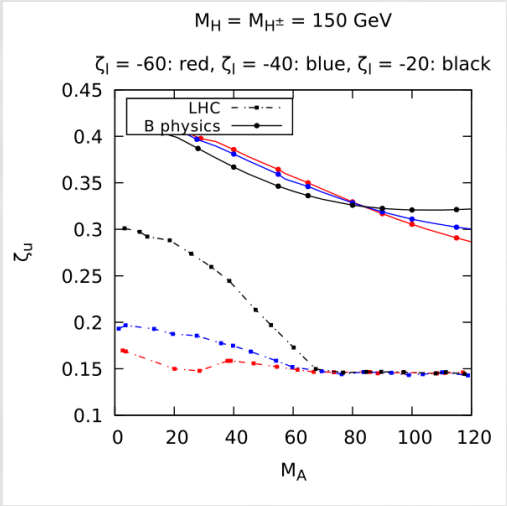
Maximum allowed $(g-2)_\mu$





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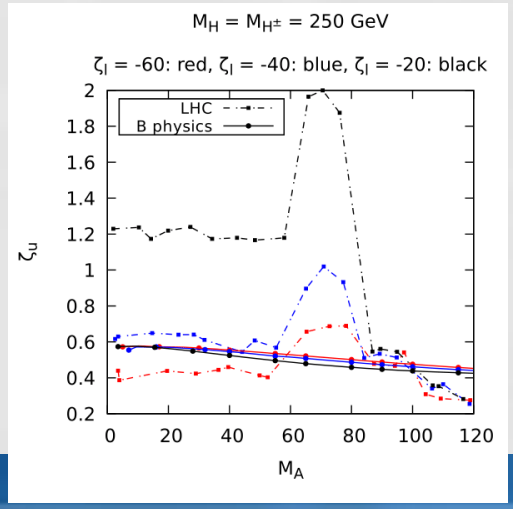

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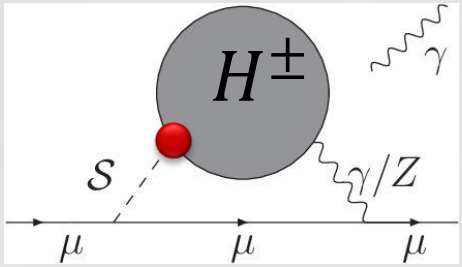
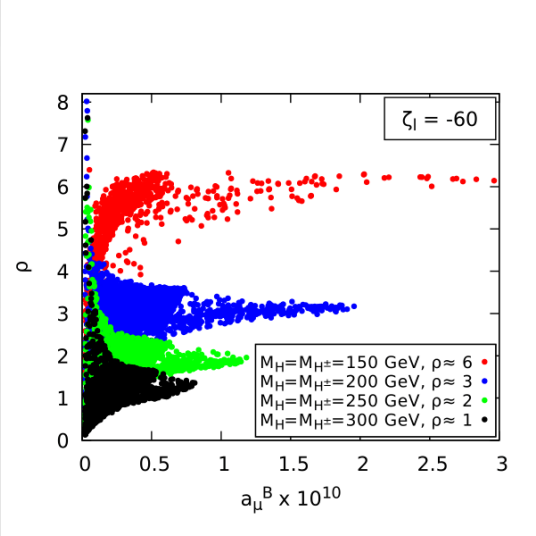
Maximum allowed $(g-2)_\mu$



$$|a_\mu^B| \approx \rho \left|\frac{C_{HH^+H^-}}{\text{GeV}}\right| |\zeta_l| \times 10^{-15}$$



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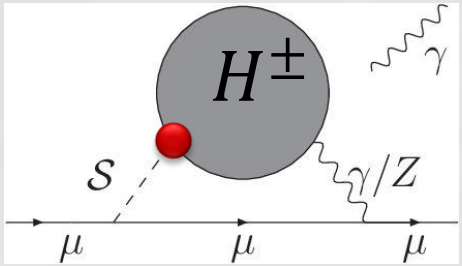

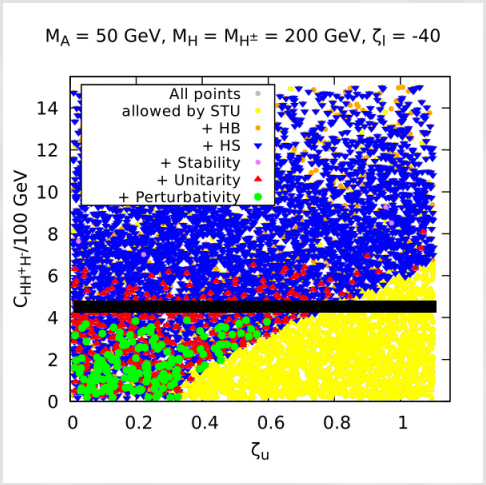

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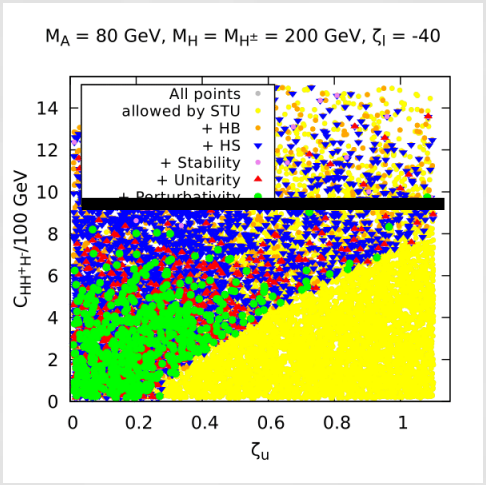

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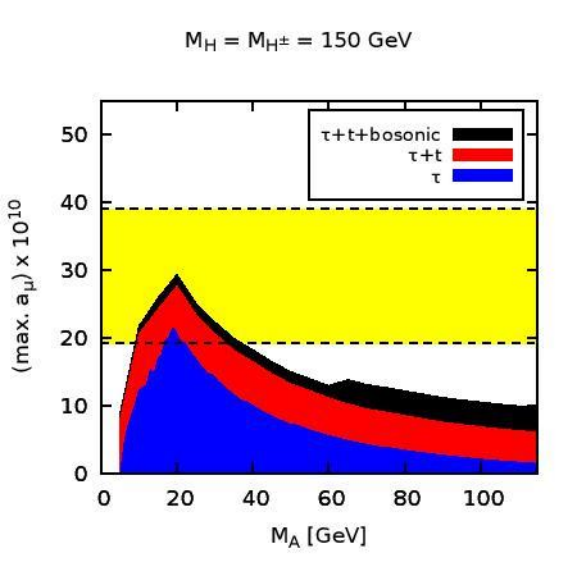

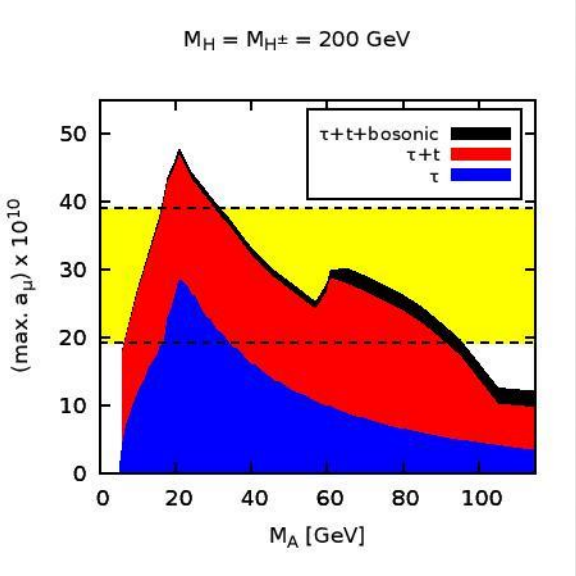

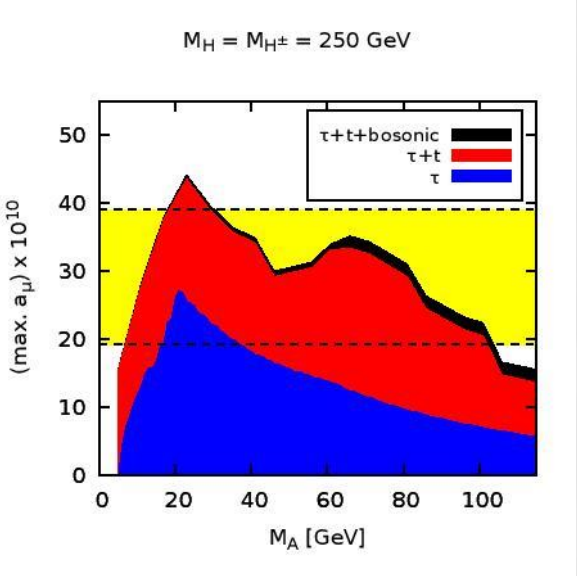

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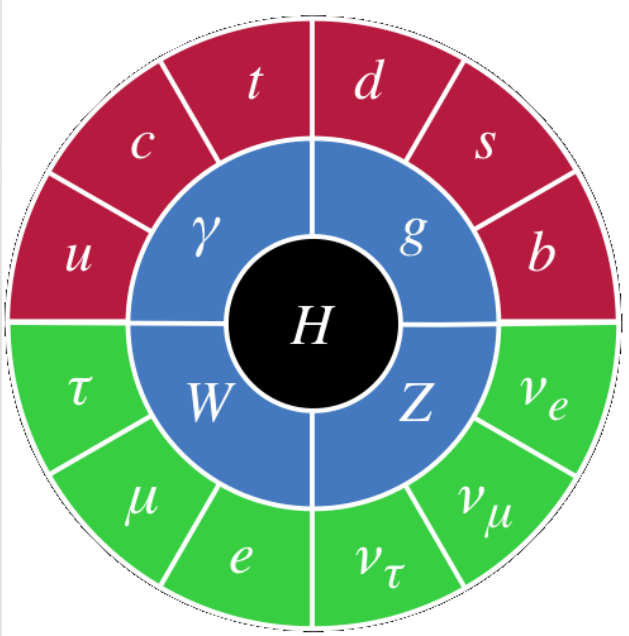
Conclusions



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

Small deviations

THEORY

EXPERIMENT

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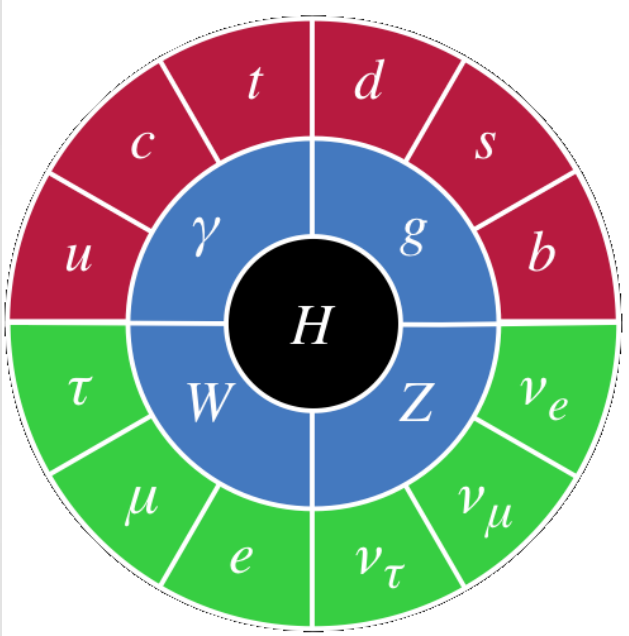
Conclusions



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

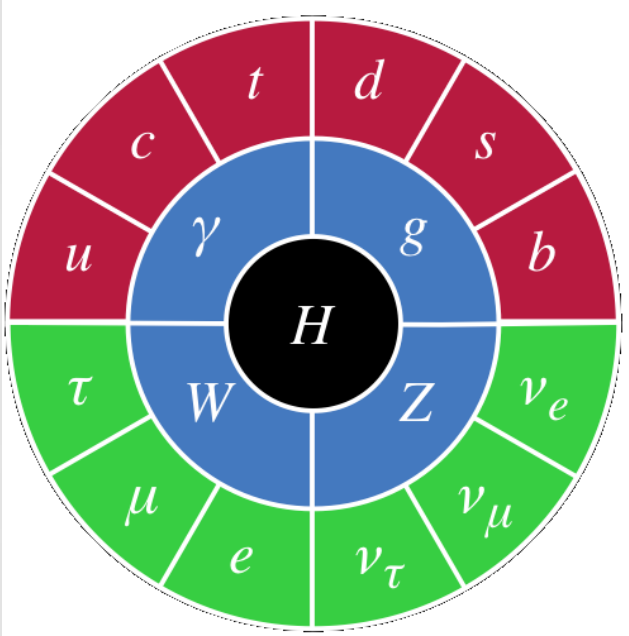
3.7σ deviation

THEORY

EXPERIMENT

Cherchiglia et al, Phys.Rev. D98 (2018) 035001

Conclusions



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

3.7σ deviation

?

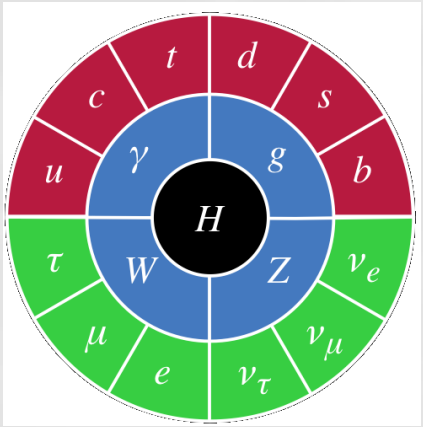
THEORY

EXPERIMENT

Cherchiglia et al, Phys.Rev. D98 (2018) 035001

Conclusions

2HDM =



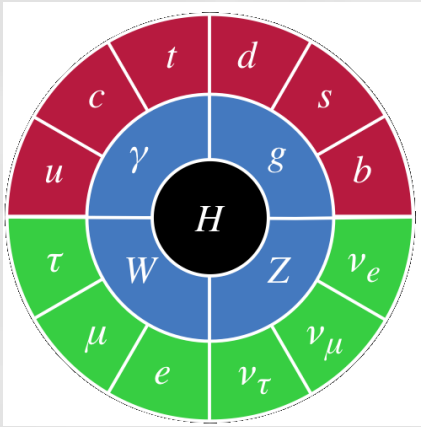
+ 4 scalars

$(g-2)_\mu$
Phenomenology

Cherchiglia et al, Phys.Rev. D98 (2018) 035001

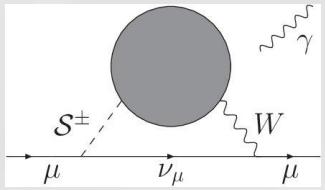
Conclusions

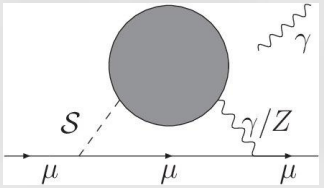
2HDM =

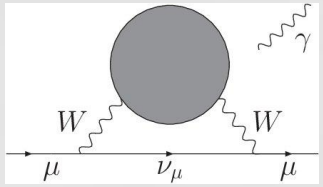


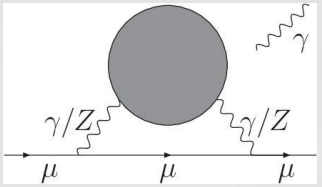
+ 4 scalars

$(g-2)_\mu$
Phenomenology







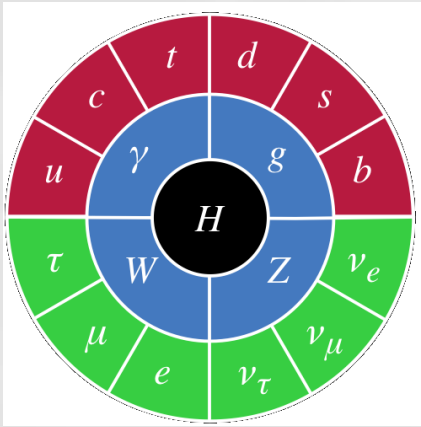


AC, Kneschke, Stöckinger, Stöckinger-Kim (17)

Cherchiglia et al, Phys.Rev. D98 (2018) 035001

Conclusions

2HDM =



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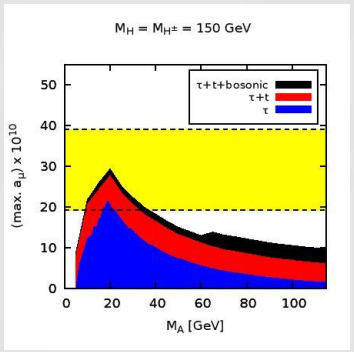
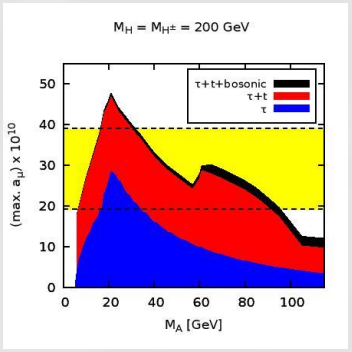
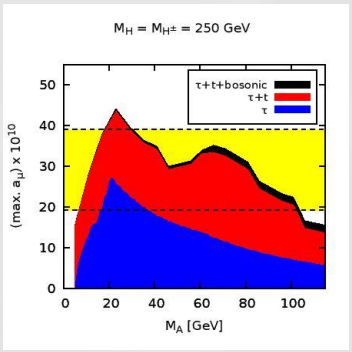
Phenomenology



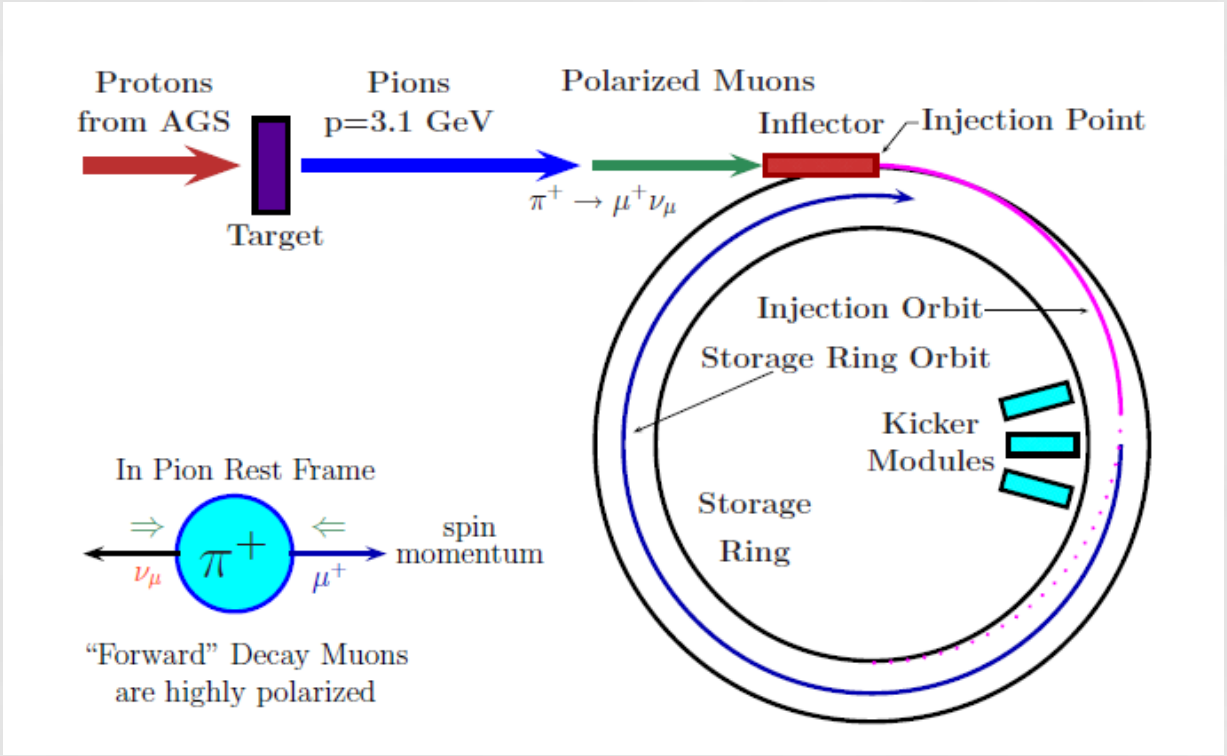




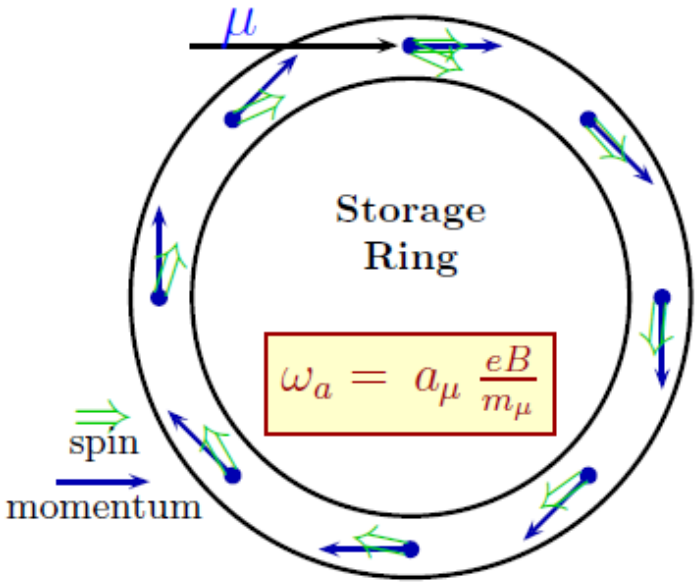
Cherchiglia et al, Phys.Rev. D98 (2018) 035001

Thanks!

Backup



Jegerlehner, Nyffeler (09)



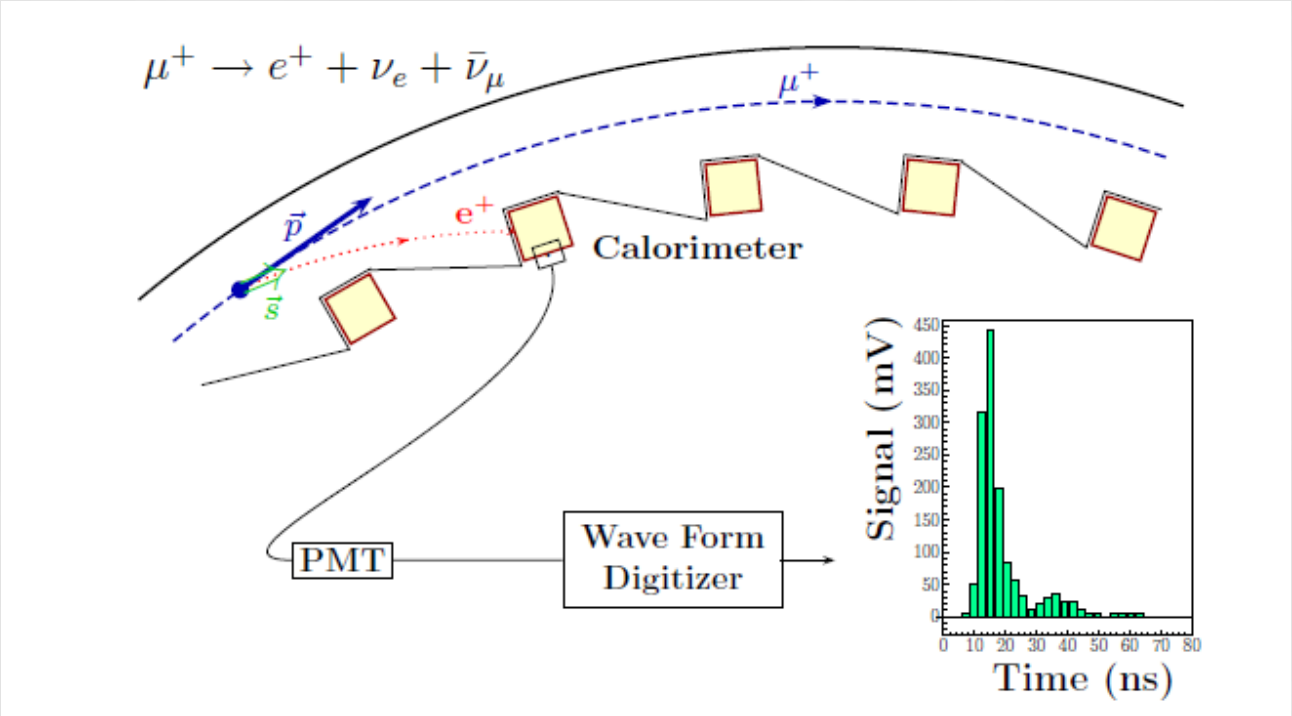
actual precession × 2

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

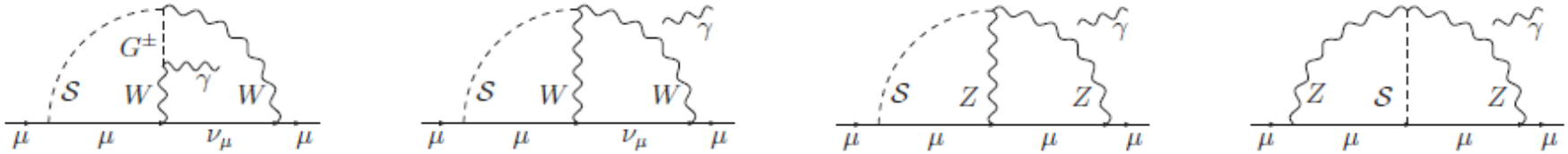
$$\omega_c = \frac{eB}{m_\mu \gamma}, \quad \omega_s = \frac{eB}{m_\mu \gamma} + a_\mu \frac{eB}{m_\mu}, \quad \omega_a = a_\mu \frac{eB}{m_\mu},$$

ciclotron spin

Jegerlehner, Nyffeler (09)



Jegerlehner, Nyffeler (09)


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

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

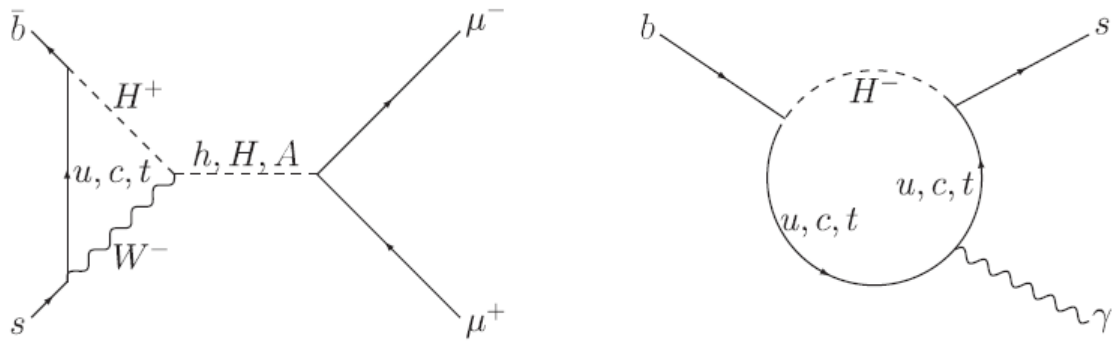
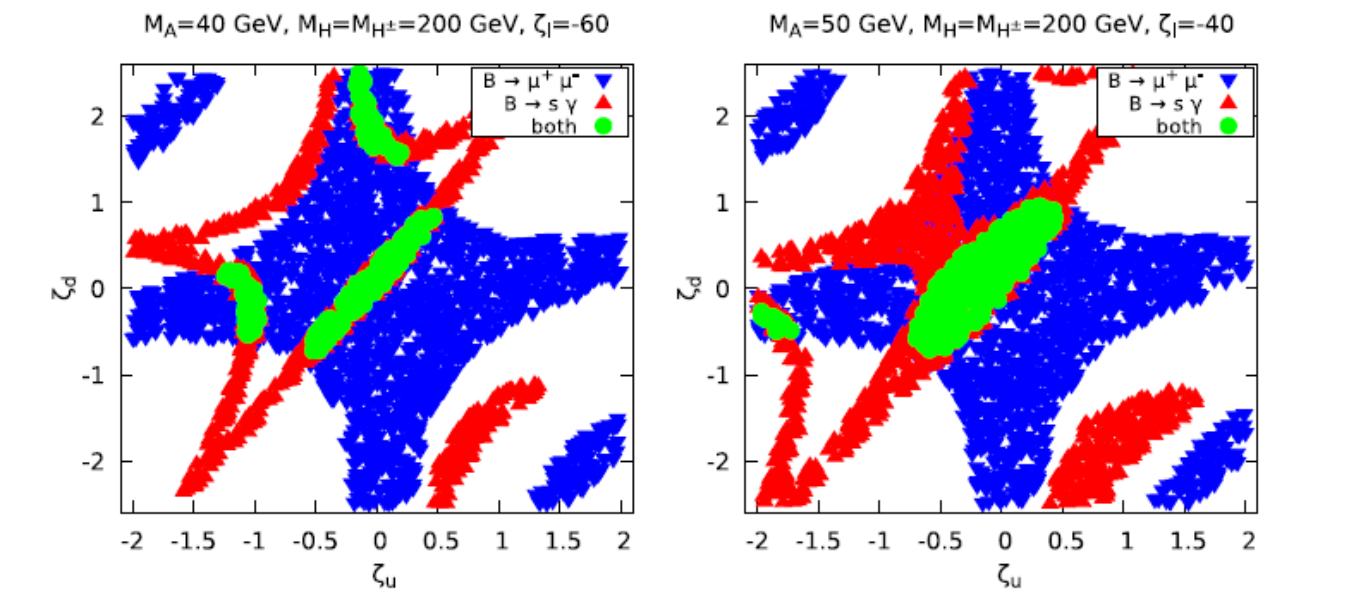


FIG. 2. Sample Feynman diagrams for the processes $B_s \to \mu^+\mu^-$ and $b \to s\gamma$, which depend on the Yukawa couplings of up- and down-type quarks and leptons.


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 → μ⁺ μ⁻
B → s γ
both
ζ_d
ζ_u
2
1
0
-1
-2
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2

Maximum allowed $(g-2)_\mu$

AC, Stöckinger, Stöckinger-Kim (18)

$$a_\mu^{1L} \approx \left(\frac{\zeta_l}{100}\right)^2 \left\{\frac{-3 - 0.5\,\ln(\hat{x}_A)}{\hat{x}_A^2}\right\} \times 10^{-10}$$

$$a_\mu^{F,\tau} \approx \left(\frac{\zeta_l}{100}\right)^2 \left\{\frac{8 + 4\hat{x}_A^2 + 2\,\ln(\hat{x}_A)}{\hat{x}_A^2}\right\} \times 10^{-10}$$

$$a_\mu^{F,t} \approx \left(\frac{-\zeta_l \zeta_u}{100}\right) \{22 - 14\ln(\hat{x}_A) + 32 - 15\ln(\hat{x}_H)\} \times 10^{-10}$$

$$\left|a_\mu^B\right| \approx \rho \left|\frac{C_{HH^+H^-}}{\text{GeV}}\right| |\zeta_l| \times 10^{-15}$$

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

$(g-2)_\mu$

- Beyond Standard Model:
  - Radiative corrections

Phys.Rept. 477 (2009) 1-110

  - Complementary information to direct searches (LHC)

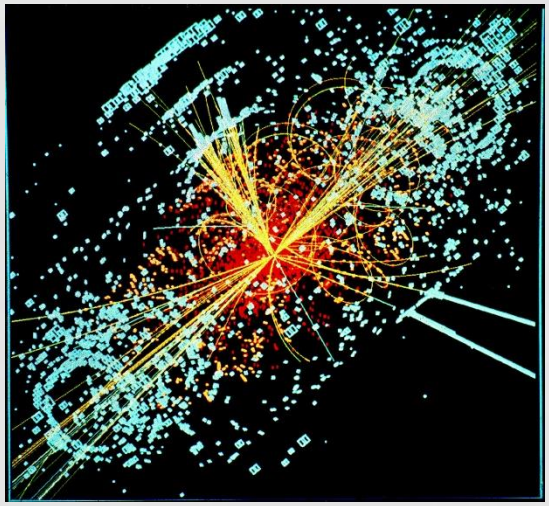
Standard Model

- High Energy Physics (colliders)
  - Small deviations

BSM predictions

Increase precision

- Open questions:
  - No gravitational interactions included;
  - No candidates for Dark Matter;
  - Matter-antimatter assymetry;
  - .....



http://cds.cern.ch/record/628469

Beyond Standard Model

- Two-Higgs-Doublet-Model (2HDM)
  - Minimal extension to scalar sector
  - Four more scalars

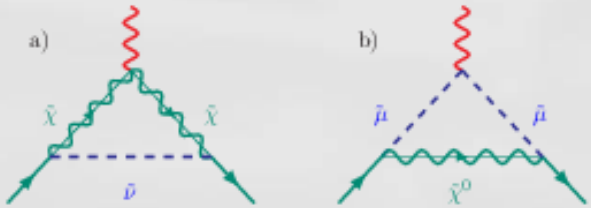
→ Some variants (inert model) have dark matter candidate

- Supersymmetry (SUSY)
  - Correlates bosons and fermions;
  - Has a non-minimal scalar sector (2HDM);
  - Predicts a partner to each particle of SM.

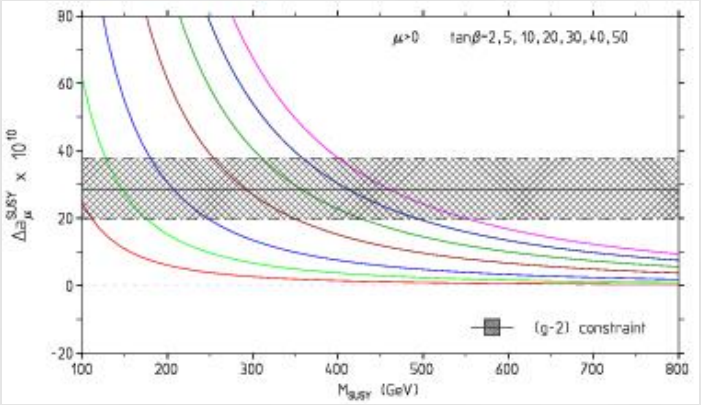
  - Dark matter candidate;
  - Solves naturalness problem.

$(g-2)_\mu$

- Beyond Standard Model:
  - SUSY



$$a_\mu(SUSY) \cong 123\times 10^{-11}\left(\frac{100\ GeV}{M_{SUSY}}\right)^2 \tan\beta$$



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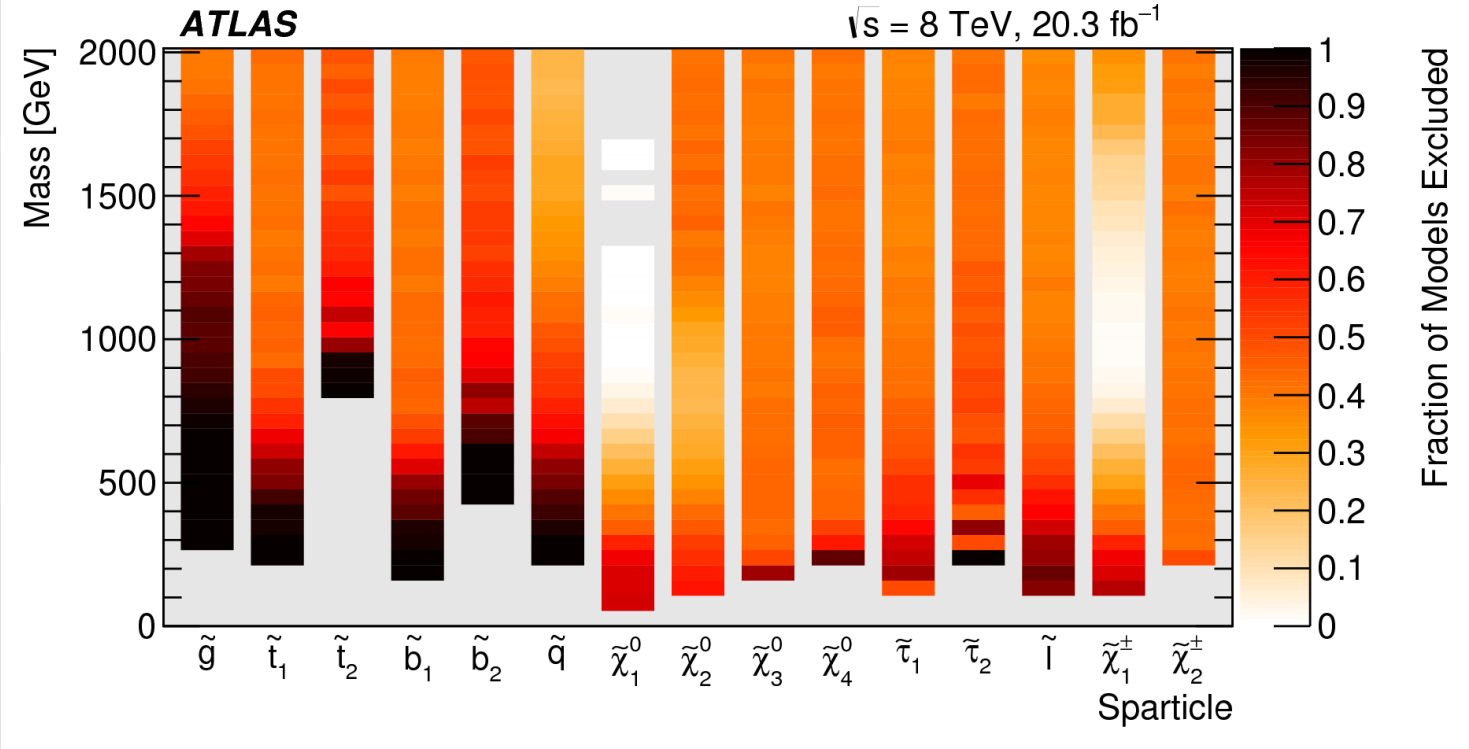
$(g-2)_\mu$

- Beyond Standard Model:
  - SUSY



https://atlas.web.cern.ch