

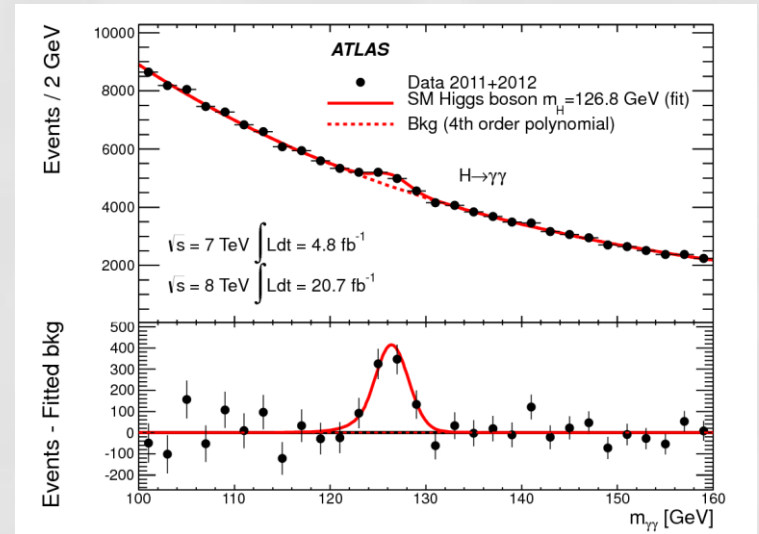
# Muon $g-2$ in the 2HDM: maximum results and detailed phenomenology.

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



# Standard Model

<p>massa → <math>\approx 2.3 \text{ MeV}/c^2</math></p> <p>carga → <math>2/3</math></p> <p>spin → <math>1/2</math></p>	<p><math>\approx 1.275 \text{ GeV}/c^2</math></p> <p><math>2/3</math></p> <p><math>1/2</math></p>	<p><math>\approx 173.07 \text{ GeV}/c^2</math></p> <p><math>2/3</math></p> <p><math>1/2</math></p>	<p>0</p> <p>0</p> <p>1</p>	<p><math>\approx 126 \text{ GeV}/c^2</math></p> <p>0</p> <p>0</p>
u up	c charm	t top	g glúon	H bóson de Higgs
QUARKS	<p><math>\approx 4.8 \text{ MeV}/c^2</math></p> <p><math>-1/3</math></p> <p><math>1/2</math></p>	<p><math>\approx 95 \text{ MeV}/c^2</math></p> <p><math>-1/3</math></p> <p><math>1/2</math></p>	<p><math>\approx 4.18 \text{ GeV}/c^2</math></p> <p><math>-1/3</math></p> <p><math>1/2</math></p>	<p>0</p> <p>0</p> <p>1</p>
d down	s strange	b bottom	$\gamma$ fóton	
<p><math>0.511 \text{ MeV}/c^2</math></p> <p>-1</p> <p><math>1/2</math></p>	<p><math>105.7 \text{ MeV}/c^2</math></p> <p>-1</p> <p><math>1/2</math></p>	<p><math>1.777 \text{ GeV}/c^2</math></p> <p>-1</p> <p><math>1/2</math></p>	<p><math>91.2 \text{ GeV}/c^2</math></p> <p>0</p> <p>1</p>	
e elétron	$\mu$ múon	$\tau$ tau	Z bóson Z	
LÉPTONS	<p><math>&lt; 2.2 \text{ eV}/c^2</math></p> <p>0</p> <p><math>1/2</math></p>	<p><math>&lt; 0.17 \text{ MeV}/c^2</math></p> <p>0</p> <p><math>1/2</math></p>	<p><math>&lt; 15.5 \text{ MeV}/c^2</math></p> <p>0</p> <p><math>1/2</math></p>	<p><math>80.4 \text{ GeV}/c^2</math></p> <p><math>\pm 1</math></p> <p>1</p>
$\nu_e$ neutrino do elétron	$\nu_\mu$ neutrino do múon	$\nu_\tau$ neutrino do tau	W bóson W	BÓSONS DE CALIBRE

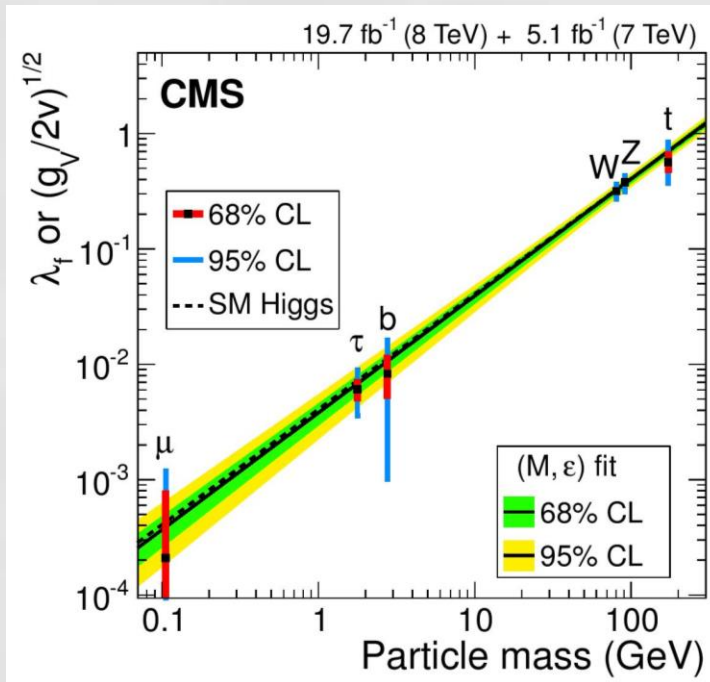


<https://commons.wikimedia.org/w/index.php?curid=49632920>

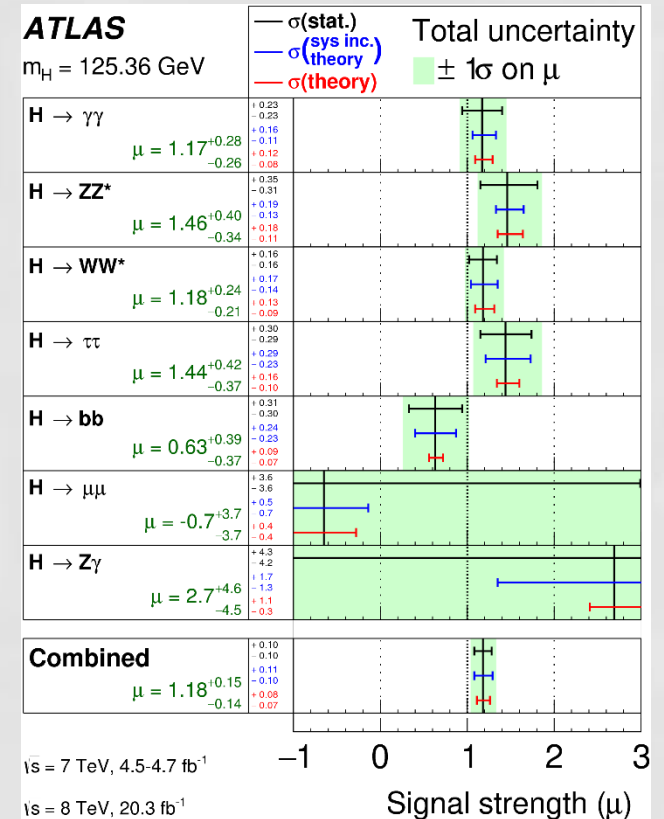
Phys.Lett. B716 (2012) 1-29

# Standard Model

- Scalar sector scrutinized



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



Eur. Phys. J. C76 (2016) 6

# In the search for New Physics

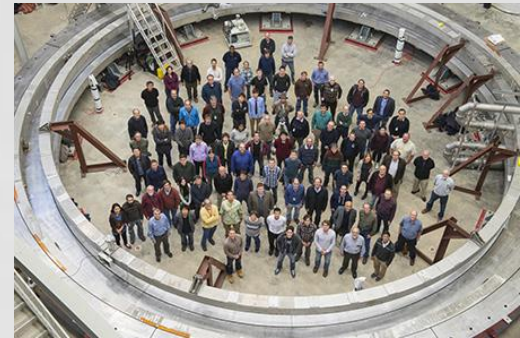
- High Energy Physics (colliders)
  - Still no sign of New Physics.



- Low-energy observables
  - Muon magnetic moment.



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



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

# $(g - 2)_\mu$

- Basic idea

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

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

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

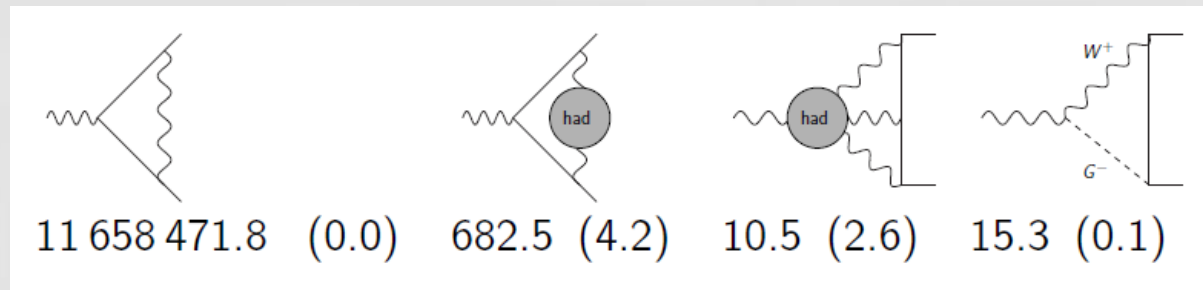


<http://muon-g-2.fnal.gov/>

→ 
$$a_\mu = \frac{(g - 2)}{2}$$

# $(g - 2)_\mu$

- Theory (Standard Model)



Thanks to D. Stöckinger

$$a_\mu^{th} = (11\,659\,180.8 \pm 3.6) \times 10^{-10}$$

“Muon  $g-2$  Theory Initiative”

# $(g - 2)_\mu$

- 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)

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

- Theory X Experiment

$$a_\mu^{th} = (11\,659\,180.8 \pm 3.6) \times 10^{-10}$$

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



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

- Theory X Experiment

$$a_\mu^{exp} - a_\mu^{th} = (28.1 \pm 7.3) \times 10^{-10}$$

3.6  $\sigma$  !



# $(g - 2)_\mu$

- Theory X Experiment

$$a_\mu^{exp} - a_\mu^{th} = (28.1 \pm 7.3) \times 10^{-10}$$



BSM



Increase precision



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

# $(g - 2)_\mu$

- 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



# $(g - 2)_\mu$

- Beyond Standard Model : 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, 2009

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

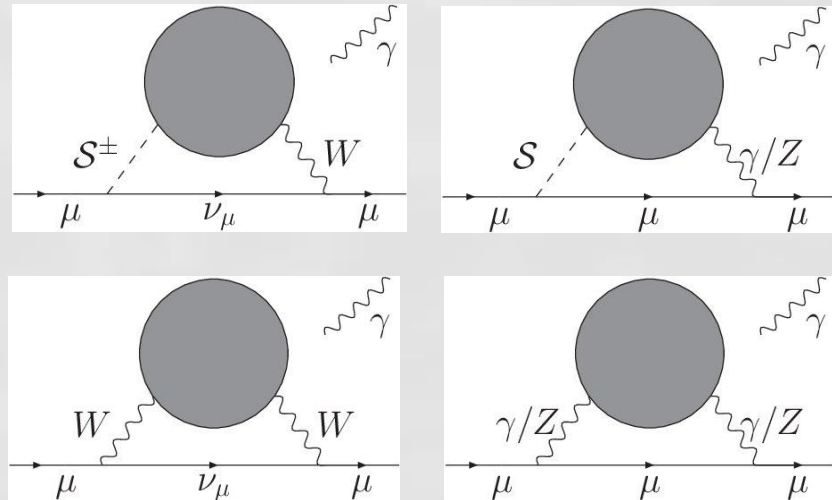
Model	$\varsigma_d$	$\varsigma_u$	$\varsigma_l$
Type I	$\cot \beta$	$\cot \beta$	$\cot \beta$
Type II	$-\tan \beta$	$\cot \beta$	$-\tan \beta$
Type X	$\cot \beta$	$\cot \beta$	$-\tan \beta$
Type Y	$-\tan \beta$	$\cot \beta$	$\cot \beta$
Inert	0	0	0

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

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

- Beyond Standard Model : flavor aligned 2HDM

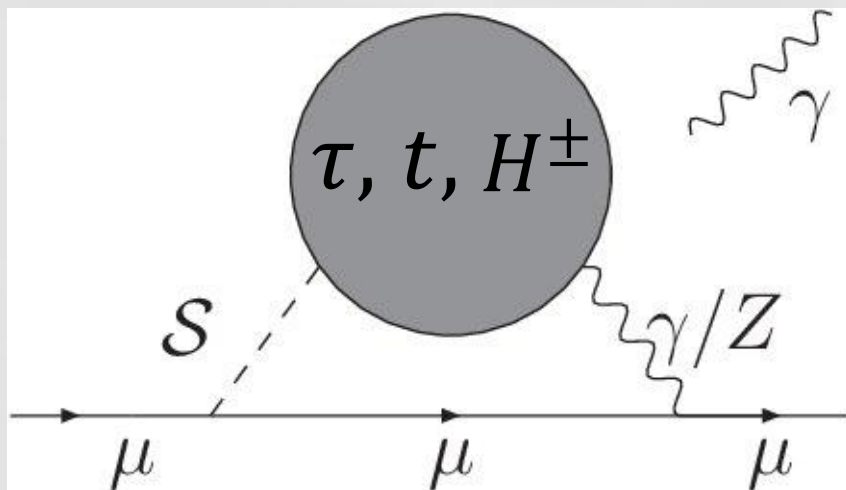
Complete two-loop prediction



Leading order (one-loop suppressed by  $m_\mu^2/m_H^2$ )

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

- Phenomenology:

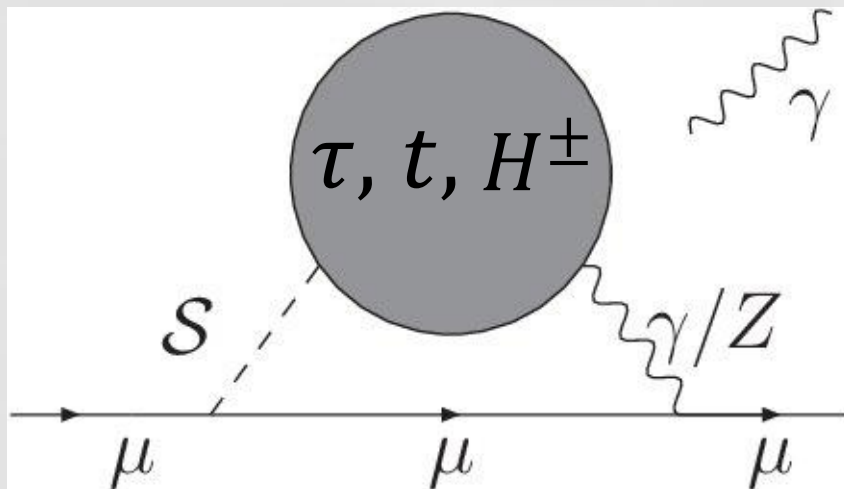


### Constraints

- B-physics;
- Tau decay;
- $Z \rightarrow \tau\tau$ ;
- Collider;
- Theoretical;
- S, T, U parameters.

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

- Phenomenology:



### Constraints

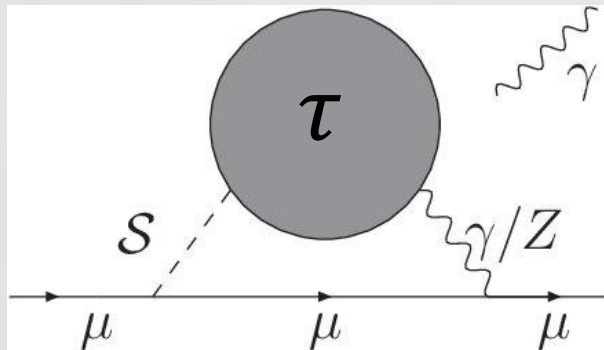
- B-physics;
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- Theoretical;
- S, T, U parameters.



Control splittings between scalar masses.

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

- Phenomenology
  - Tau loop



### Constraints

- B-physics;
- Tau decay;
- $Z \rightarrow \tau\tau$ ;
- Collider;
- Theoretical;
- S, T, U parameters.

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

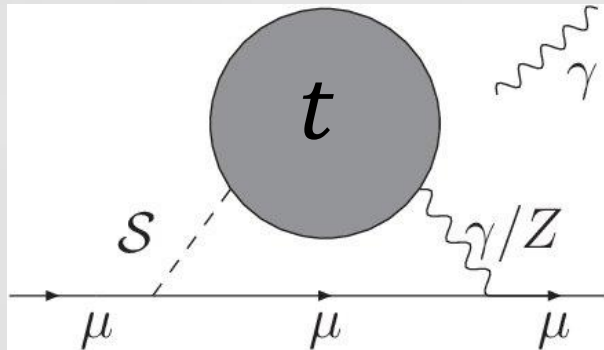
**Flavour-aligned:**  $\epsilon_l, \epsilon_u, \epsilon_d$

Only contribution in a Type X scenario.



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

- Phenomenology
  - Top loop



### Constraints

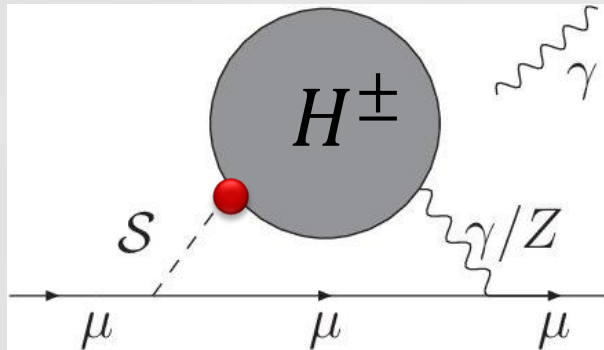
- B-physics;
- Tau decay;
- $Z \rightarrow \tau\tau$ ;
- Collider;
- Theoretical;
- S, T, U parameters.

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

Flavour-aligned:  $\epsilon_l, \epsilon_u, \epsilon_d$

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

- Phenomenology
  - Bosonic



### Constraints

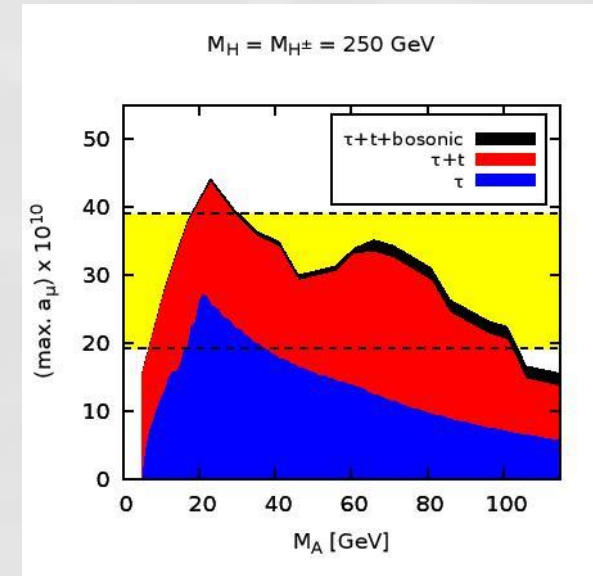
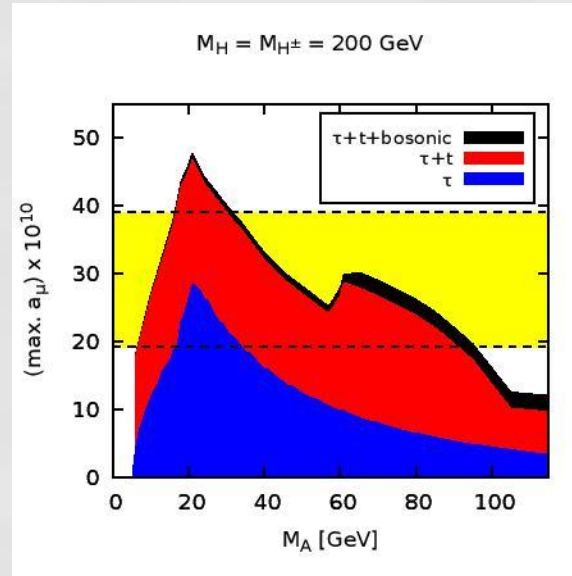
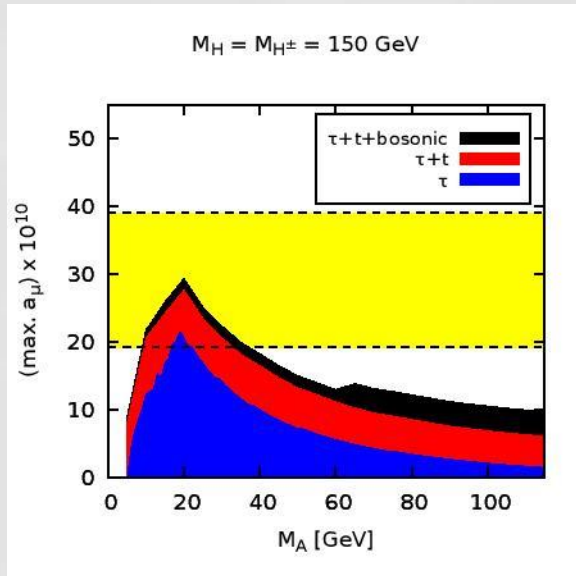
- B-physics;
- Tau decay;
- $Z \rightarrow \tau\tau$ ;
- Collider;
- Theoretical;
- S, T, U parameters.

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

Flavour-aligned:  $\epsilon_l, \epsilon_u, \epsilon_d$

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

- Beyond Standard Model : 2HDM



# Conclusions

## Standard Model

masa → carga → spin →	$\approx 2.3 \text{ MeV}/c^2$ $2/3$ $1/2$ <b>u</b> up	$\approx 1.275 \text{ GeV}/c^2$ $2/3$ $1/2$ <b>c</b> charm	$\approx 173.07 \text{ GeV}/c^2$ $2/3$ $1/2$ <b>t</b> top	0 0 1 <b>g</b> gluon	$\approx 126 \text{ GeV}/c^2$ 0 0 <b>H</b> bóson de Higgs
	$\approx 4.8 \text{ MeV}/c^2$ $-1/3$ $1/2$ <b>d</b> down	$\approx 95 \text{ MeV}/c^2$ $-1/3$ $1/2$ <b>s</b> strange	$\approx 4.18 \text{ GeV}/c^2$ $-1/3$ $1/2$ <b>b</b> bottom	0 0 1 <b>γ</b> fóton	
QUARKS	$0.511 \text{ MeV}/c^2$ $-1$ $1/2$ <b>e</b> elétron	$105.7 \text{ MeV}/c^2$ $-1$ $1/2$ <b>μ</b> muón	$1.777 \text{ GeV}/c^2$ $-1$ $1/2$ <b>τ</b> tau	0 0 1 <b>Z</b> bóson Z	
	$< 2.2 \text{ eV}/c^2$ 0 $1/2$ <b>ν<sub>e</sub></b> neutrino do elétron	$< 0.17 \text{ MeV}/c^2$ 0 $1/2$ <b>ν<sub>μ</sub></b> neutrino do muón	$< 15.5 \text{ MeV}/c^2$ 0 $1/2$ <b>ν<sub>τ</sub></b> neutrino do tau	$80.4 \text{ GeV}/c^2$ $\pm 1$ 1 <b>W</b> bóson W	BÓSONS DE CALIBRE
LÉPTONS					

<https://commons.wikimedia.org/>

THEORY



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

Small deviations

EXPERIMENT

# Conclusions

## Standard Model

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QUARKS	$0.511 \text{ MeV}/c^2$ -1 1/2 <b>e</b> elétron	$105.7 \text{ MeV}/c^2$ -1 1/2 <b><math>\mu</math></b> múon	$1.777 \text{ GeV}/c^2$ -1 1/2 <b><math>\tau</math></b> tau	0 0 1 <b>Z</b> bóson Z	BÓSONS DE CALIBRE
	$\ll 2.2 \text{ eV}/c^2$ 0 1/2 <b><math>\nu_e</math></b> neutrino do elétron	$\ll 0.17 \text{ MeV}/c^2$ 0 1/2 <b><math>\nu_\mu</math></b> neutrino do múon	$\ll 15.5 \text{ MeV}/c^2$ 0 1/2 <b><math>\nu_\tau</math></b> neutrino do tau	$\approx 80.4 \text{ GeV}/c^2$ $\pm 1$ 1 <b>W</b> bóson W	
LÉPTONS					

<https://commons.wikimedia.org/>

THEORY



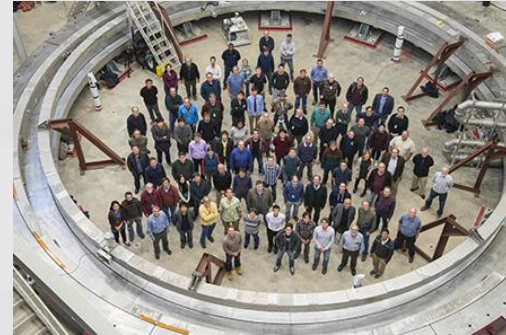
<http://muon-g-2.fnal.gov/>

3.6 $\sigma$  deviation

EXPERIMENT

# Conclusions

Standard Model



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

massa →	≈2.3 MeV/c <sup>2</sup>	≈1.275 GeV/c <sup>2</sup>	≈173.07 GeV/c <sup>2</sup>	0	≈126 GeV/c <sup>2</sup>
carga →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> glúon	<b>H</b> bóson de Higgs
<b>QUARKS</b>					
	≈4.8 MeV/c <sup>2</sup>	≈95 MeV/c <sup>2</sup>	≈4.18 GeV/c <sup>2</sup>	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>γ</b> fóton	
<b>LEPTONS</b>					
	0.511 MeV/c <sup>2</sup>	105.7 MeV/c <sup>2</sup>	1.777 GeV/c <sup>2</sup>	91.2 GeV/c <sup>2</sup>	
	-1	-1	-1	0	
	1/2	1/2	1/2	1	
	<b>e</b> elétron	<b>μ</b> múon	<b>τ</b> tau	<b>Z</b> bóson Z	
	≈2.2 eV/c <sup>2</sup>	≈0.17 MeV/c <sup>2</sup>	≈15.5 MeV/c <sup>2</sup>	80.4 GeV/c <sup>2</sup>	
	0	0	0	±1	
	1/2	1/2	1/2	1	
	<b>ν<sub>e</sub></b> neutrino do elétron	<b>ν<sub>μ</sub></b> neutrino do múon	<b>ν<sub>τ</sub></b> neutrino do tau	<b>W</b> bóson W	
					<b>BÓSONS DE CALIBRE</b>

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THEORY

EXPERIMENT

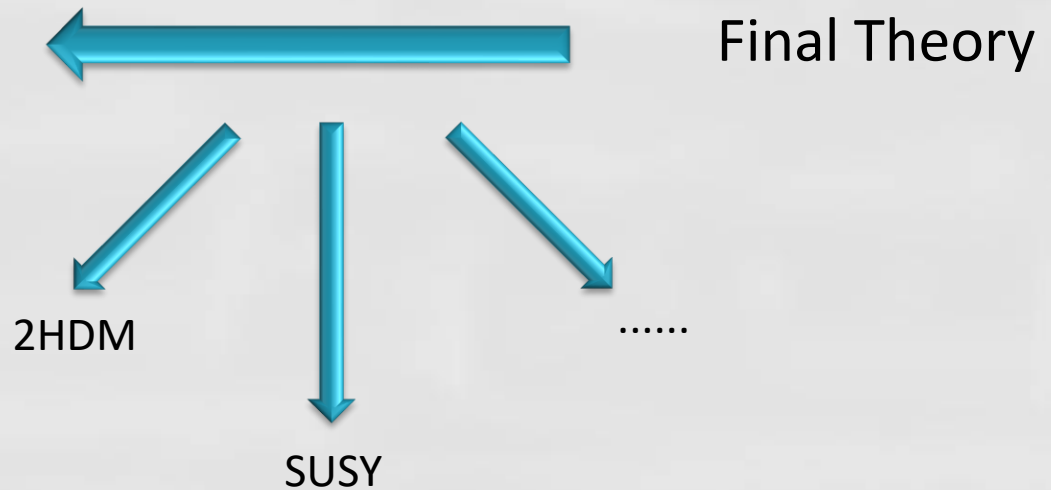
3.6σ deviation

# Conclusions

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carga →	2/3	2/3	2/3	0	0
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	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> glúon	<b>H</b> bóson de Higgs
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>γ</b> fóton	
QUARKS					
	0.511 MeV/c <sup>2</sup>	105.7 MeV/c <sup>2</sup>	1.777 GeV/c <sup>2</sup>	91.2 GeV/c <sup>2</sup>	
	-1	-1	-1	0	
	1/2	1/2	1/2	1	
	<b>e</b> elétron	<b>μ</b> múon	<b>τ</b> tau	<b>Z</b> bóson Z	
	<b>ν<sub>e</sub></b> neutrino do elétron	<b>ν<sub>μ</sub></b> neutrino do múon	<b>ν<sub>τ</sub></b> neutrino do tau	<b>W</b> bóson W	
LÉPTONS					BÓSONS DE CALIBRE

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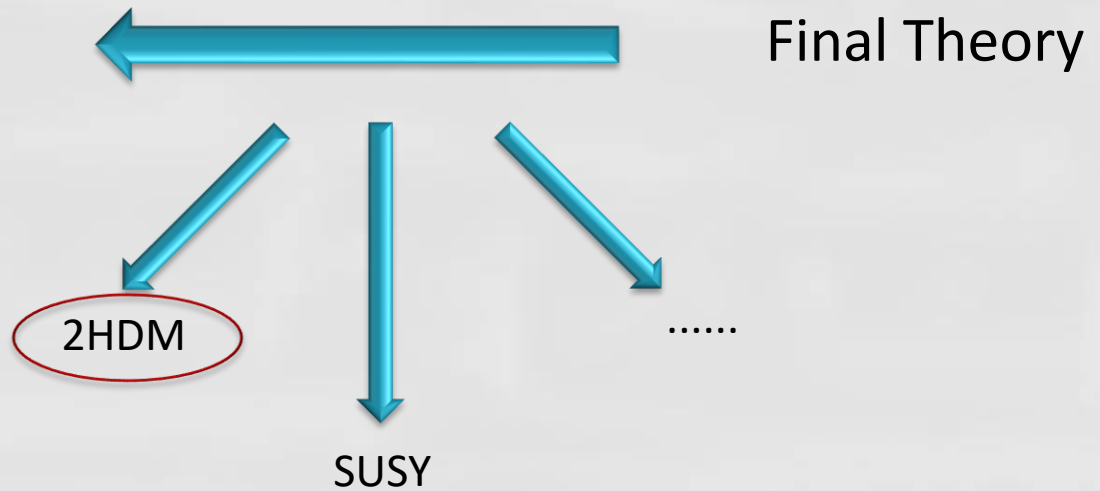
# Conclusions

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spin →	1/2	1/2	1/2	1	0
	<b>u</b>	<b>c</b>	<b>t</b>	<b>g</b>	<b>H</b>
	up	charm	top	glúon	bóson de Higgs
QUARKS					
	≈4.8 MeV/c <sup>2</sup>	≈95 MeV/c <sup>2</sup>	≈4.18 GeV/c <sup>2</sup>	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	<b>d</b>	<b>s</b>	<b>b</b>	<b>γ</b>	
	down	strange	bottom	fóton	
	0.511 MeV/c <sup>2</sup>	105.7 MeV/c <sup>2</sup>	1.777 GeV/c <sup>2</sup>	91.2 GeV/c <sup>2</sup>	
	-1	-1	-1	0	
	1/2	1/2	1/2	1	
	<b>e</b>	<b>μ</b>	<b>τ</b>	<b>Z</b>	
	elétron	múon	tau	bóson Z	
	<2.2 eV/c <sup>2</sup>	<0.17 MeV/c <sup>2</sup>	<15.5 MeV/c <sup>2</sup>	80.4 GeV/c <sup>2</sup>	
	0	0	0	±1	
	1/2	1/2	1/2	1	
	<b>ν<sub>e</sub></b>	<b>ν<sub>μ</sub></b>	<b>ν<sub>τ</sub></b>	<b>W</b>	
	neutrino do elétron	neutrino do múon	neutrino do tau	bóson W	
LÉPTONS				BÓSONS DE CALIBRE	

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Phenomenology  
 $(g - 2)_\mu$





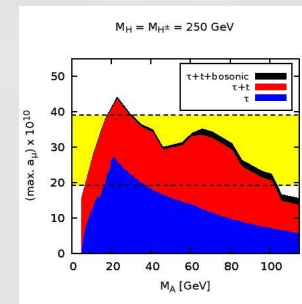
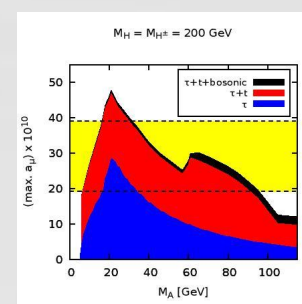
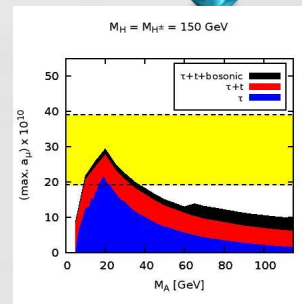
# Conclusions

## Standard Model

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<b>QUARKS</b>	≈4.8 MeV/c <sup>2</sup> -1/3 1/2 <b>d</b> down	≈95 MeV/c <sup>2</sup> -1/3 1/2 <b>s</b> strange	≈4.18 GeV/c <sup>2</sup> -1/3 1/2 <b>b</b> bottom	0 0 1 <b>γ</b> fóton	
	0.511 MeV/c <sup>2</sup> -1 1/2 <b>e</b> elétron	105.7 MeV/c <sup>2</sup> -1 1/2 <b>μ</b> múon	1.777 GeV/c <sup>2</sup> -1 1/2 <b>τ</b> tau	91.2 GeV/c <sup>2</sup> 0 0 <b>Z</b> bóson Z	<b>BÓSONS DE CALIBRE</b>
<b>LÉPTONS</b>	<2.2 eV/c <sup>2</sup> 0 1/2 <b>ν<sub>e</sub></b> neutrino do elétron	<0.17 MeV/c <sup>2</sup> 0 1/2 <b>ν<sub>μ</sub></b> neutrino do múon	<15.5 MeV/c <sup>2</sup> 0 1/2 <b>ν<sub>τ</sub></b> neutrino do tau	80.4 GeV/c <sup>2</sup> ±1 1 <b>W</b> bóson W	

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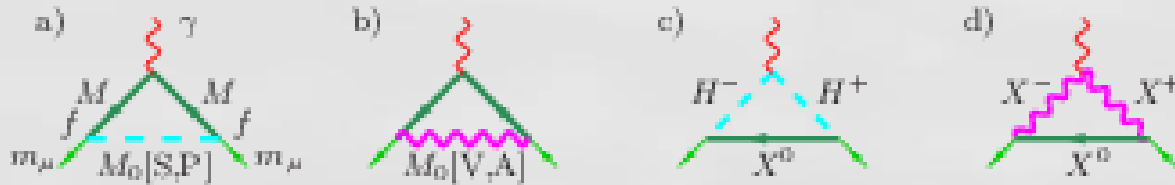
Phenomenology  
 $(g - 2)_\mu$



Thanks!

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

- 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

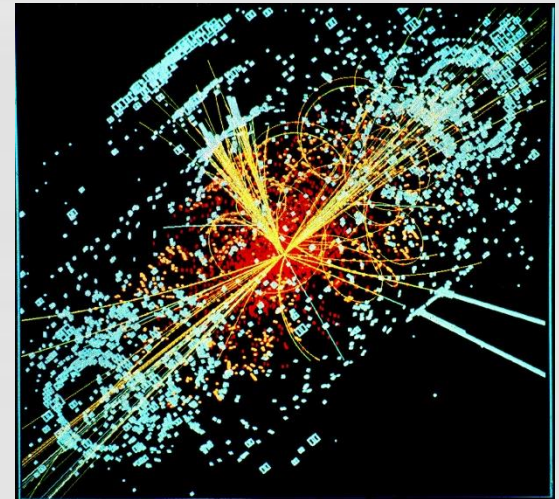


BSM predictions

Increase precision



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



<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)

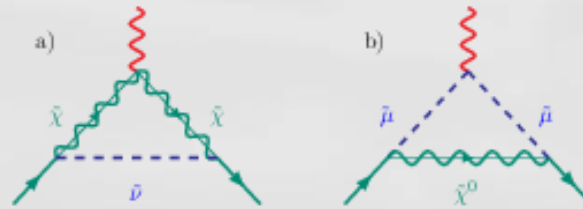
- Correlates bosons and fermions;
- Has a non-minimal scalar sector (2HDM);
- Predicts a partner to each particle of SM.



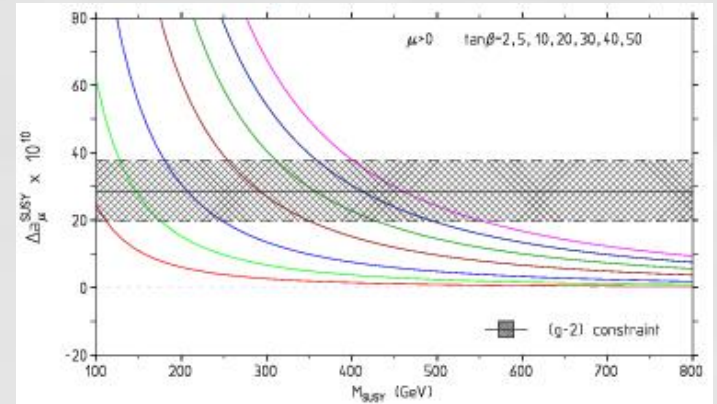
- Dark matter candidate;
- Solves naturalness problem.

# $(g - 2)_\mu$

- Beyond Standard Model:
  - SUSY



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



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

- Beyond Standard Model:
  - SUSY

