
WILL EXPLAIN
HIGGS-BOSON
PARTICLE
FOR
FOOD

# Why the Higgs is not the Standard Model Higgs

*Sven Heinemeyer, IFT/IFCA (CSIC, Madrid/Santander)*

Santander, 02/2020

- The Standard Model and its Higgs
- Why the SM is not enough
- SUSY comes to rescue
- Is SUSY dead?
- Conclusions

# 1. The Standard Model and its Higgs

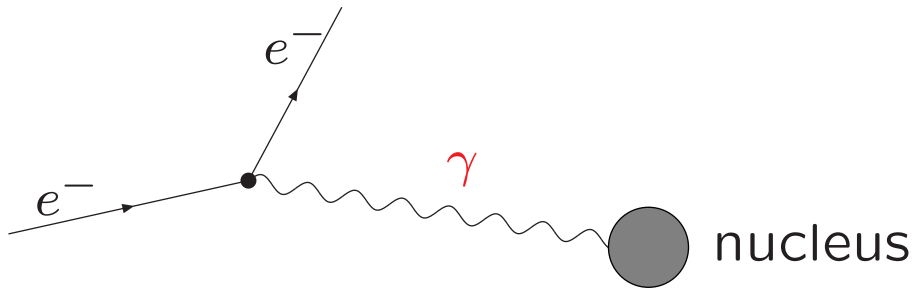
## Standard Model (SM) of the electroweak and strong interaction

SM: Quantum field theory $\Rightarrow$ interaction: exchange of field quanta

Construction principle of the SM: gauge invariance

### Example: Quantum electro-dynamics (QED)

field quanta: photon $A_\mu$



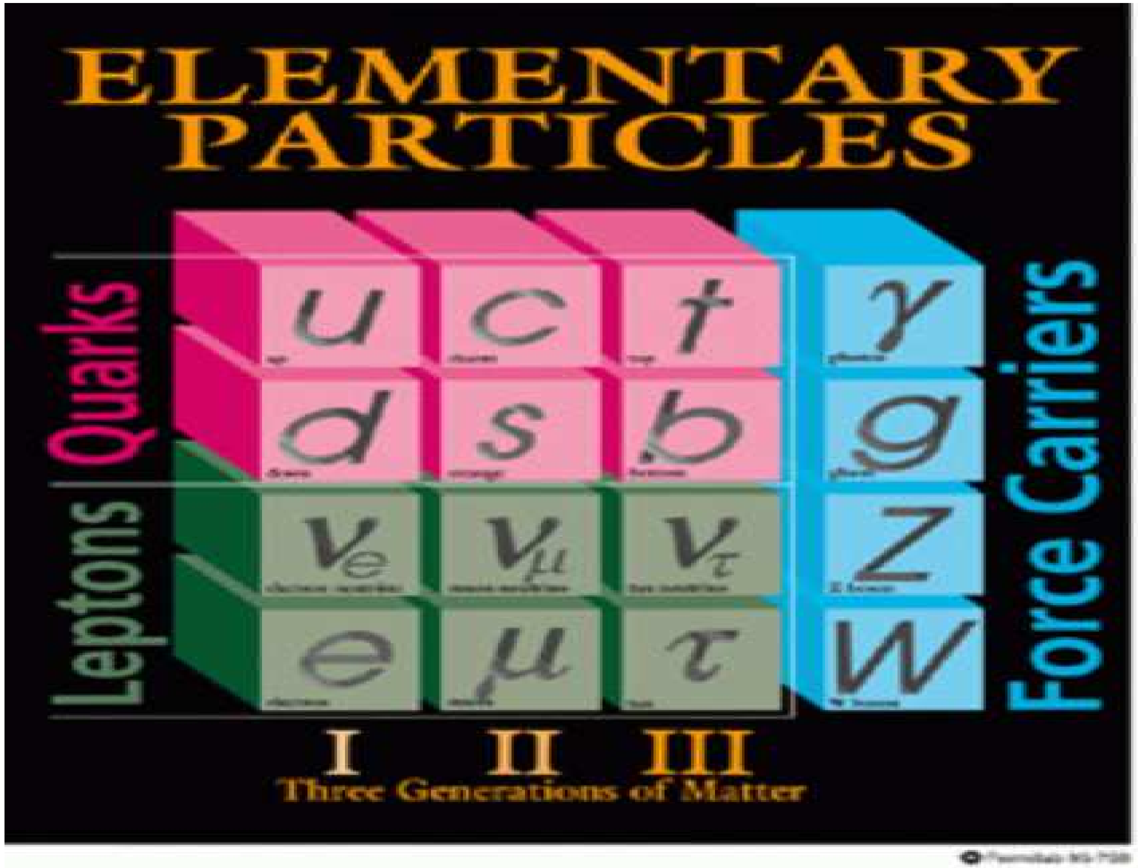

$\mathcal{L}_{\text{QED}}$ invariant under gauge transformation:

$\Psi \to e^{i\,e\,\lambda(x)}\Psi, \; A_\mu \to A_\mu + \partial_\mu \lambda(x)$

mass term for photon: $m^2 A^\mu A_\mu$ not gauge invariant

$\Rightarrow A_\mu$ is massless gauge field

# Current status of knowledge: the Standard Model (SM)




$\Rightarrow$ all particles experimentally seen (as of 2011)

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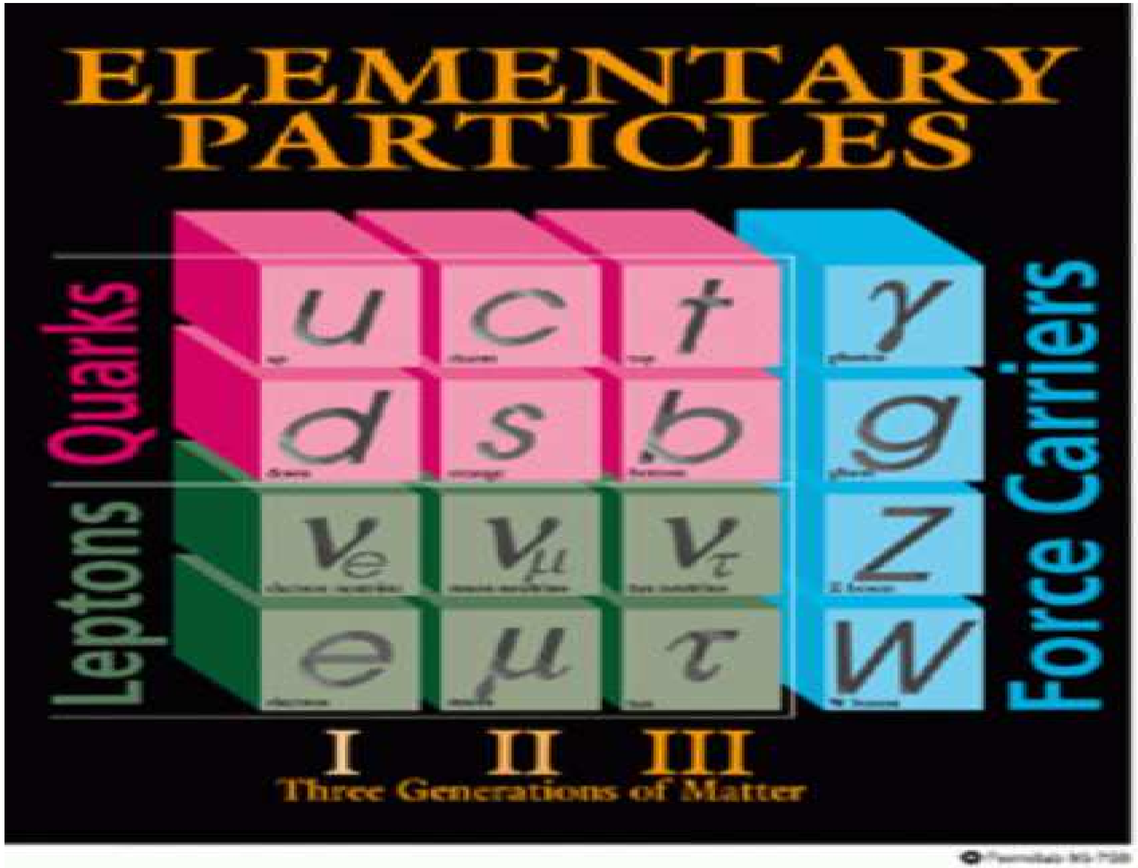



⇒ all particles experimentally seen (as of 2011)

⇒ but it predicts massless gauge bosons . . .

## Problem:

Gauge fields $Z$, $W^+$, $W^-$ are massive

explicite mass terms in the Lagrangian $\Leftrightarrow$ breaking of gauge invariance

## Solution: Higgs mechanism

scalar field postulated, mass terms from coupling to Higgs field

## Higgs sector in the Standard Model:

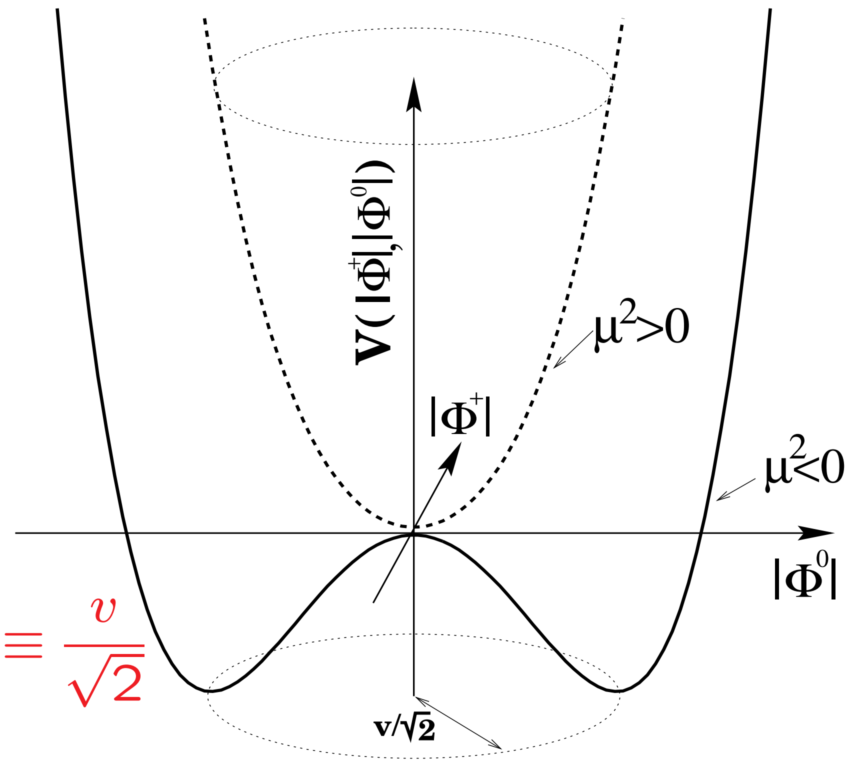
Scalar SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

Higgs potential:

$$V(\phi) = \mu^2 \left|\Phi^\dagger \Phi\right| + \lambda \left|\Phi^\dagger \Phi\right|^2, \quad \lambda > 0$$

$\mu^2 < 0$: Spontaneous symmetry breaking

minimum of potential at $|\langle \Phi_0 \rangle| = \sqrt{\frac{-\mu^2}{2\,\lambda}} \equiv \frac{v}{\sqrt{2}}$



$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \quad \text{(unitary gauge)}$$

$H$: elementary scalar field, Higgs boson

Lagrange density:

$$\begin{aligned} \mathcal{L}_{\text{Higgs}} = \quad & (D_\mu \Phi)^\dagger (D^\mu \Phi) \\ & - g_d \bar{Q}_L \Phi d_R \; - \; g_u \bar{Q}_L \Phi_c u_R \\ & - V(\Phi) \end{aligned}$$

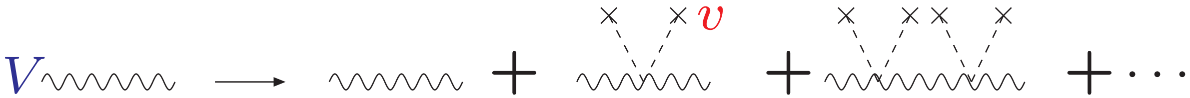
with

$$\begin{aligned} iD_\mu &= i\partial_\mu - g_2 \vec{I} \vec{W}_\mu - g_1 Y B_\mu \\ \Phi_c &= i\sigma_2 \Phi^* \qquad\qquad Q_L \sim \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \; \Phi \sim \begin{pmatrix} 0 \\ v \end{pmatrix}, \; \Phi_c \sim \begin{pmatrix} v \\ 0 \end{pmatrix} \end{aligned}$$

Gauge invariant coupling to gauge fields

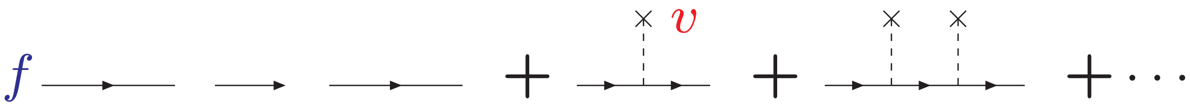
$\Rightarrow$ mass terms for gauge bosons and fermions

## 1.) $VV\Phi\Phi$ coupling:



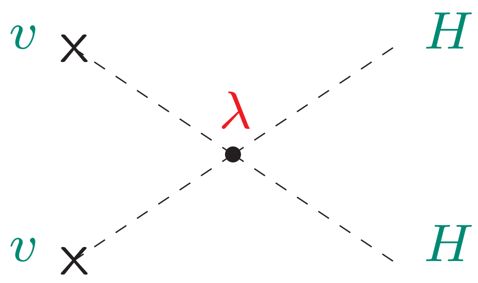

$$\frac{1}{q^2} \to \frac{1}{q^2} + \sum_j \frac{1}{q^2}\left[\left(\frac{gv}{\sqrt{2}}\right)^2 \frac{1}{q^2}\right]^j = \frac{1}{q^2 - M^2} \; : \; M^2 = g^2\frac{v^2}{2} \qquad \Rightarrow M \propto g$$

## 2.) fermion mass terms: Yukawa couplings:




$$\frac{1}{\not{q}} \to \frac{1}{\not{q}} + \sum_j \frac{1}{\not{q}}\left[\frac{g_f v}{\sqrt{2}}\frac{1}{\not{q}}\right]^j = \frac{1}{\not{q} - m_f} \; : \; m_f = g_f\frac{v}{\sqrt{2}} \qquad \Rightarrow m_f \propto g_f$$

# 3.) mass of the Higgs boson: self coupling




. . .

$$\lambda = M_H^2/v^2$$

$M_H = v\sqrt{\lambda}$ free parameter

$\rightarrow$ last unknown (now measured) parameter of the SM

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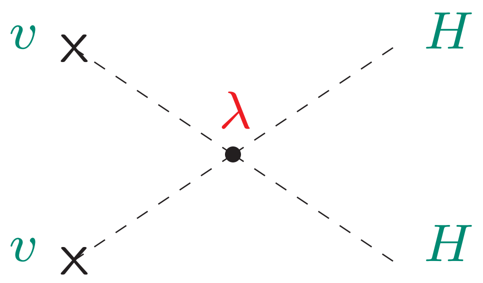


$\dots$

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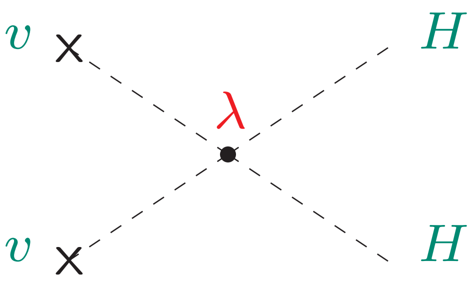


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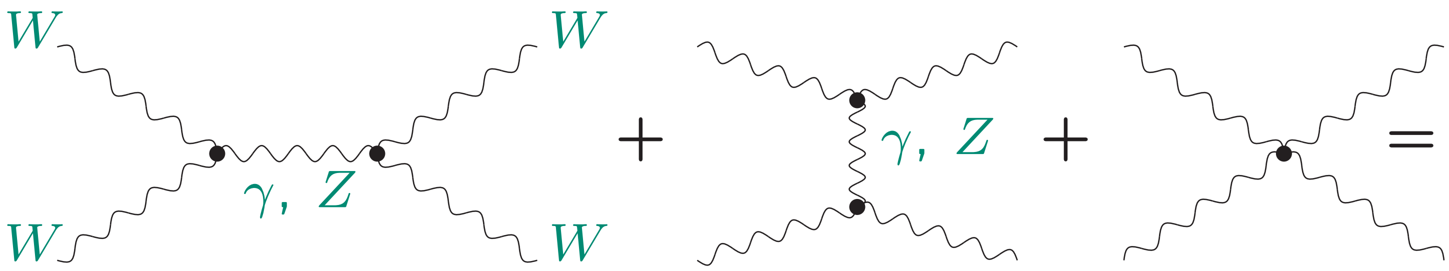
**Q1: Como se puede medir los acoplamientos?**

**Q2: Que mas hay que medir/comprobar?**

Another effect of the Higgs field:

Scattering of longitudinal $W$ bosons: $W_L W_L \to W_L W_L$

$\mathcal{M}_V =$




$= -g^2 \frac{E^2}{M_W^2} + \mathcal{O}(1)$

for $E \to \infty$

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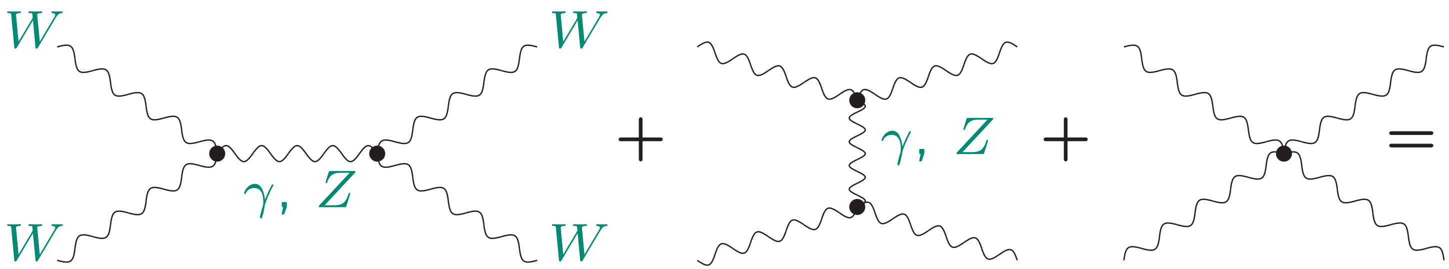


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**Q: porque es eso peligroso?**

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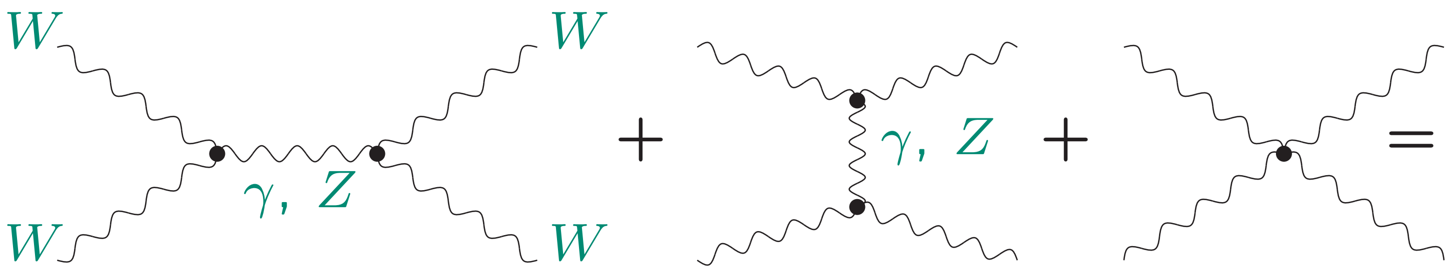


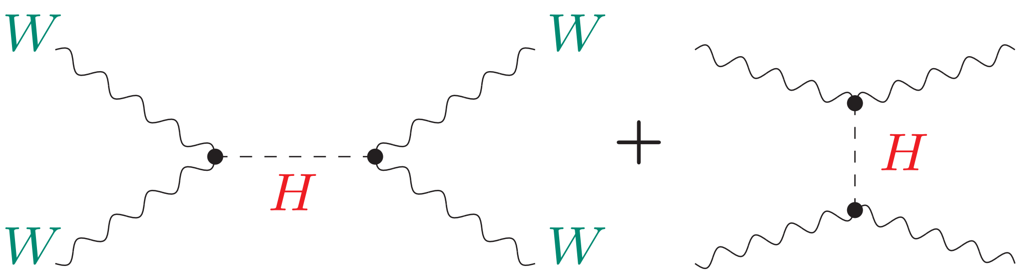

$$= -g^2 \frac{E^2}{M_W^2} + \mathcal{O}(1)$$

for $E \to \infty$

$\Rightarrow$ violation of unitarity

Contribution of a scalar particle with couplings prop. to the mass:

$\mathcal{M}_S =$




$$= g_{WWH}^2 \frac{E^2}{M_W^4} + \mathcal{O}(1)$$

for $E \to \infty$

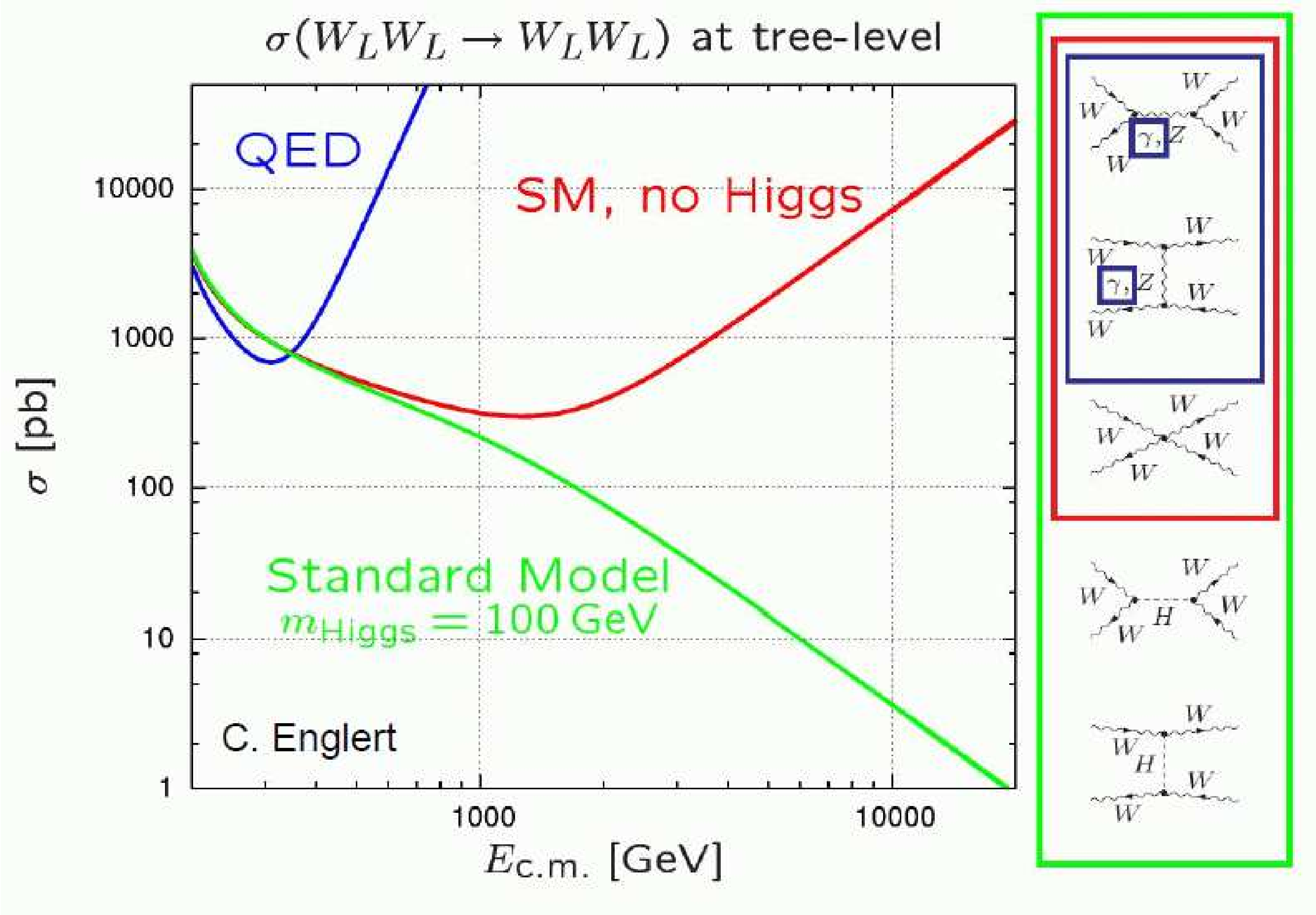
$$\mathcal{M}_{\text{tot}} = \mathcal{M}_V + \mathcal{M}_S = \frac{E^2}{M_W^4} \left( g_{WWH}^2 - g^2 \, M_W^2 \right) + \ldots$$

$\Rightarrow$ compensation of terms with bad high-energy behavior for

$$g_{WWH} = g \, M_W$$

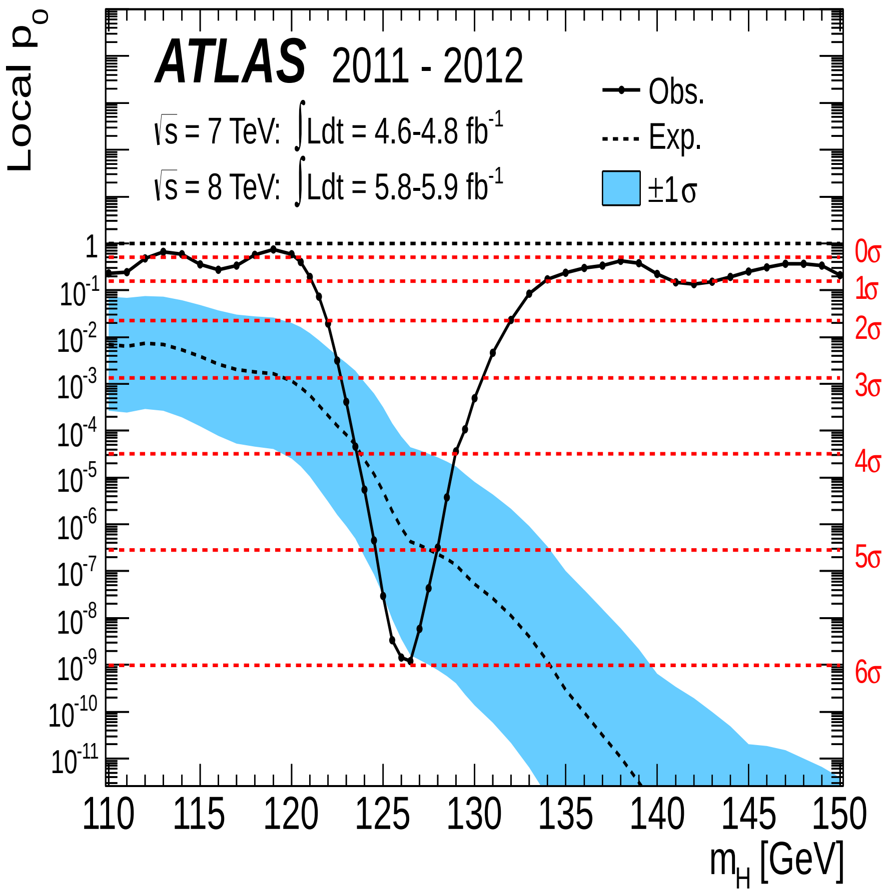
# Cross section with/without the Higgs:

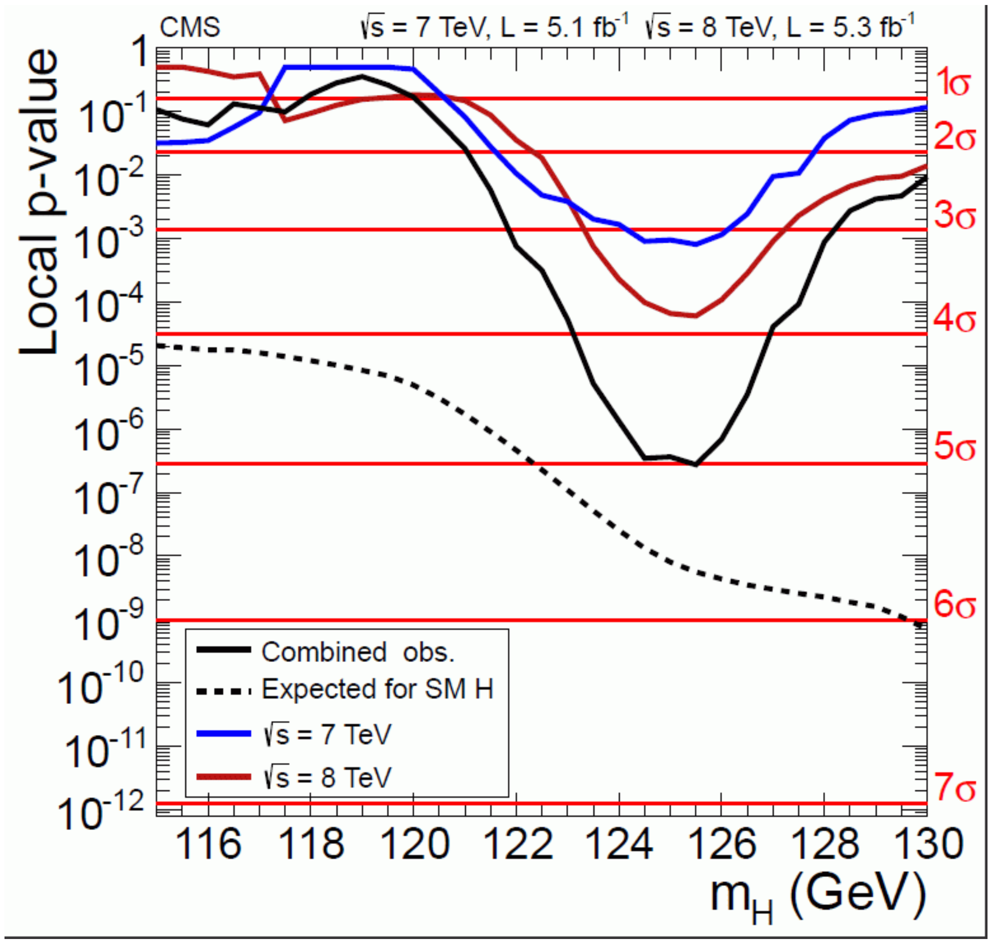
*[taken from M. Schumacher '12 / C. Englert]*



# The physics world changed on 04.07.2012:

## We have a discovery!



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But what is it?

**Q:** Is it a Higgs boson?

**Q:** Is it the Higgs boson (i.e. of the SM)?

**Q:** Is it an MSSM Higgs boson?

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How can we decide?

**A:** Measure all its characteristics

**A:** Compare to the predictions of the various models

**A:** search for additional Higgs bosons above and below 125 GeV

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⇒ Needed: precise predictions for Higgs-Boson properties!

Total width:

sum over all decay widths

$$
\begin{aligned}
\Gamma_{H,\text{tot}} := & \sum_{\text{dd}'} \Gamma(H \to \text{dd}') \\
= & \quad \Gamma(H \to t\bar{t}) + \Gamma(H \to b\bar{b}) + \Gamma(H \to c\bar{c}) + \ldots \\
& + \Gamma(H \to \tau^+\tau^-) + \Gamma(H \to \mu^+\mu^-) + \ldots \\
& + \Gamma(H \to WW^{(*)}) + \Gamma(H \to ZZ^{(*)}) + \Gamma(H \to \gamma\gamma) + \ldots \\
& + \ldots
\end{aligned}
$$

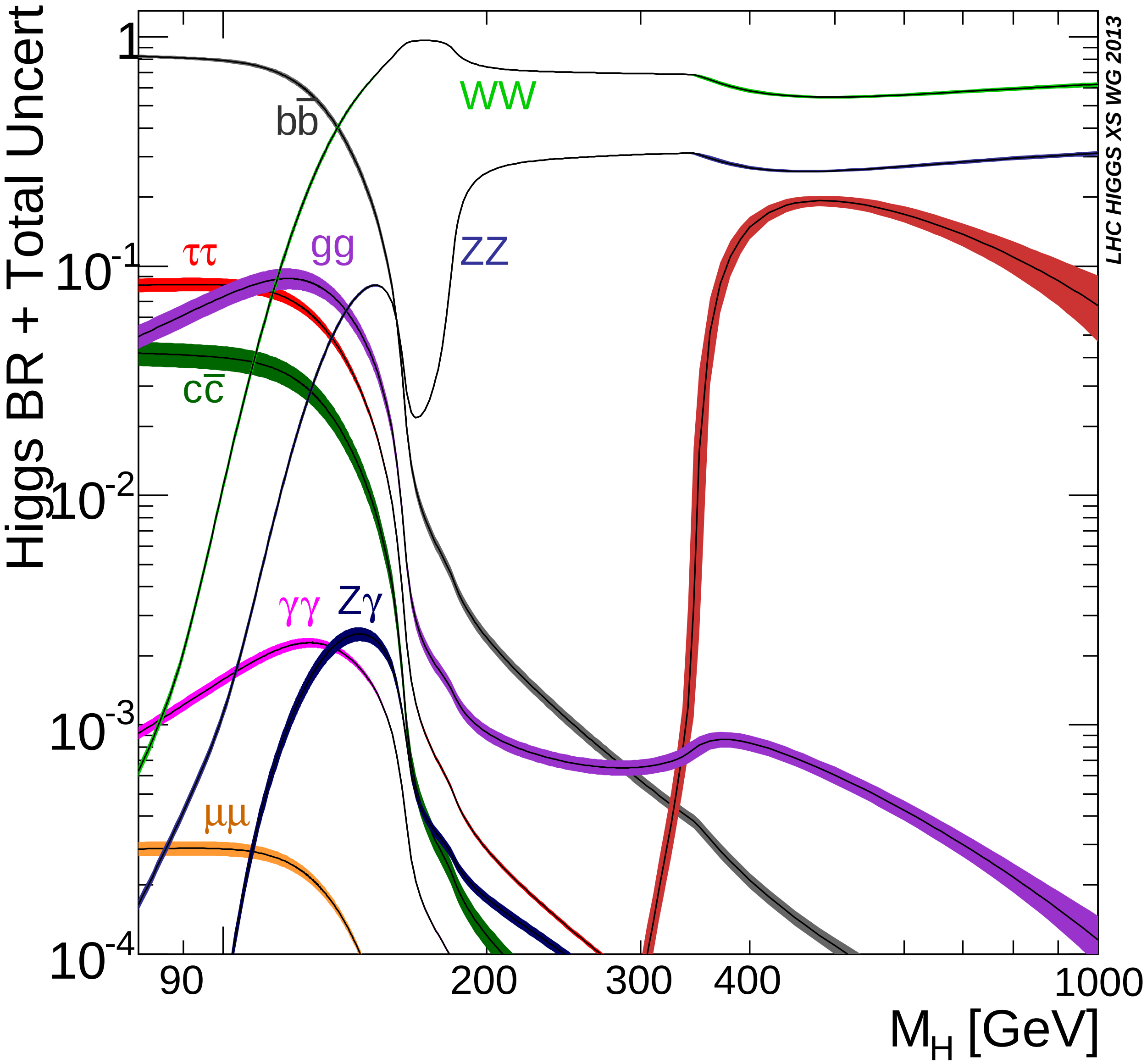
Branching ratio:

probability that a particle decays to a certain final state

$$
\text{BR}(H \to \text{dd}') := \frac{\Gamma(H \to \text{dd}')}{\Gamma_{H,\text{tot}}}
$$

# Latest theory predictions for the SM Higgs: branching ratios

[*LHC Higgs XS WG '13*]



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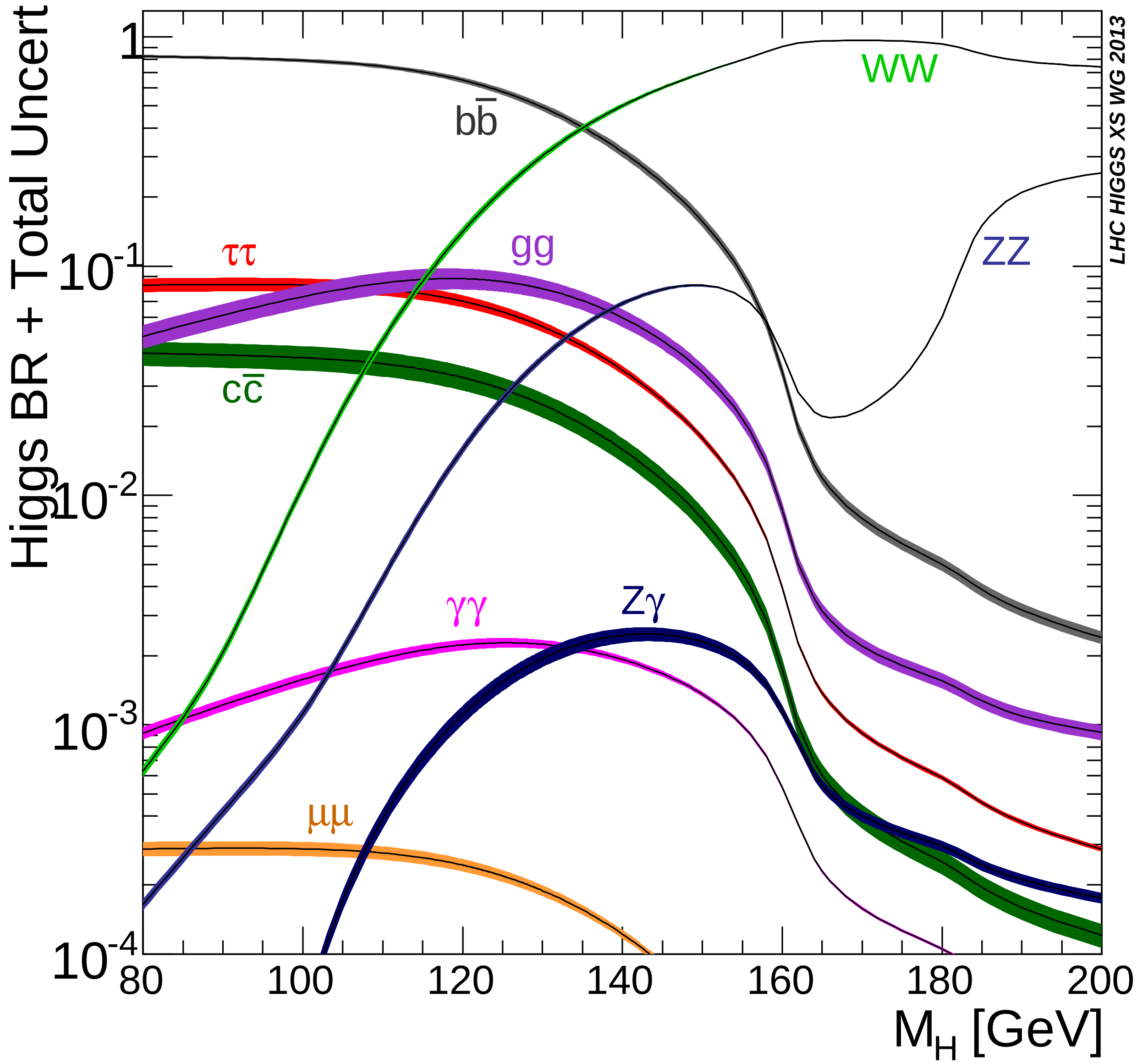
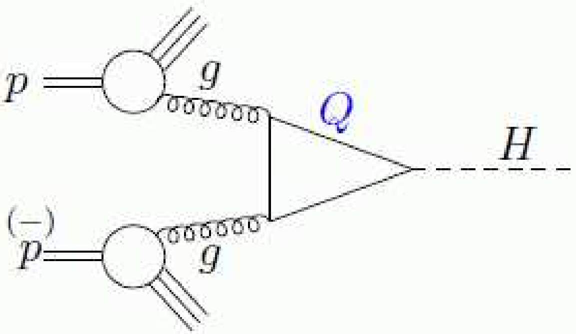


# Higgs production modes at the LHC:

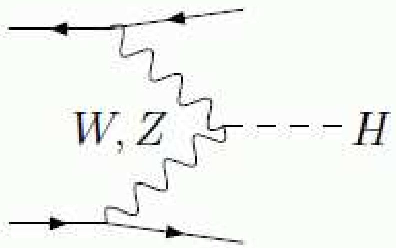
- **Gluon Gluon Fusion**

$pp \to gg \to H$



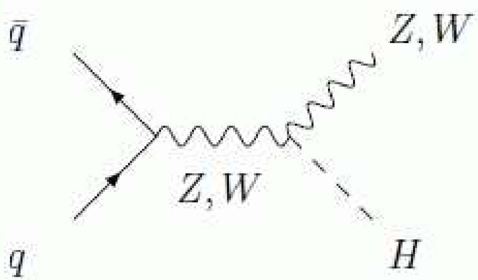

- **$W/Z$ Fusion**

$pp \to qq \to qq + WW/ZZ \to qq + H$




- **Higgs-strahlung**

$pp \to W^*/Z^* \to W/Z + H$



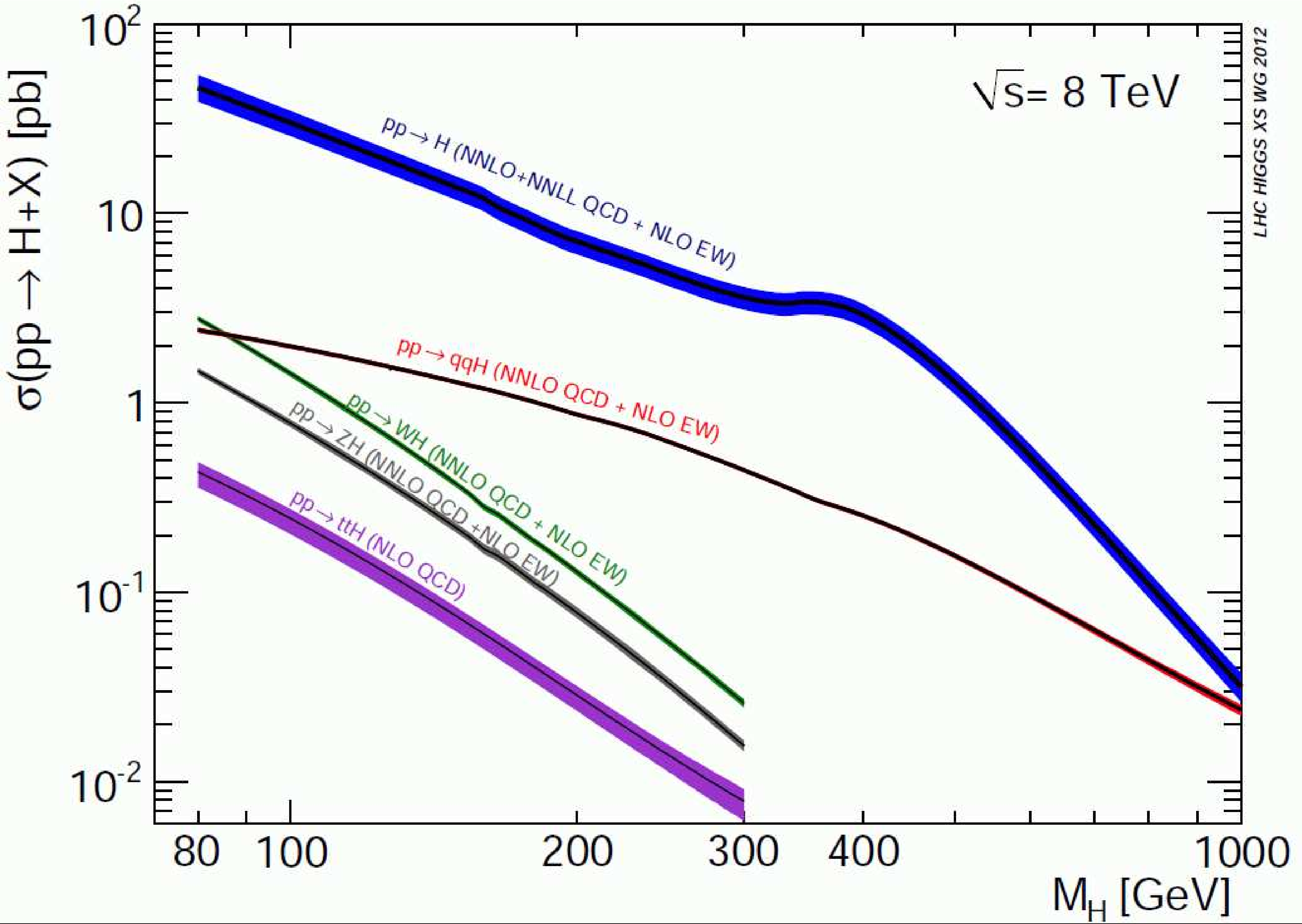

- **Associated production with $t\bar{t}$**

$pp \to t\bar{t} + H$


[*taken from M. Mühlleitner*]

# Latest theory predictions for the SM Higgs: LHC production XS

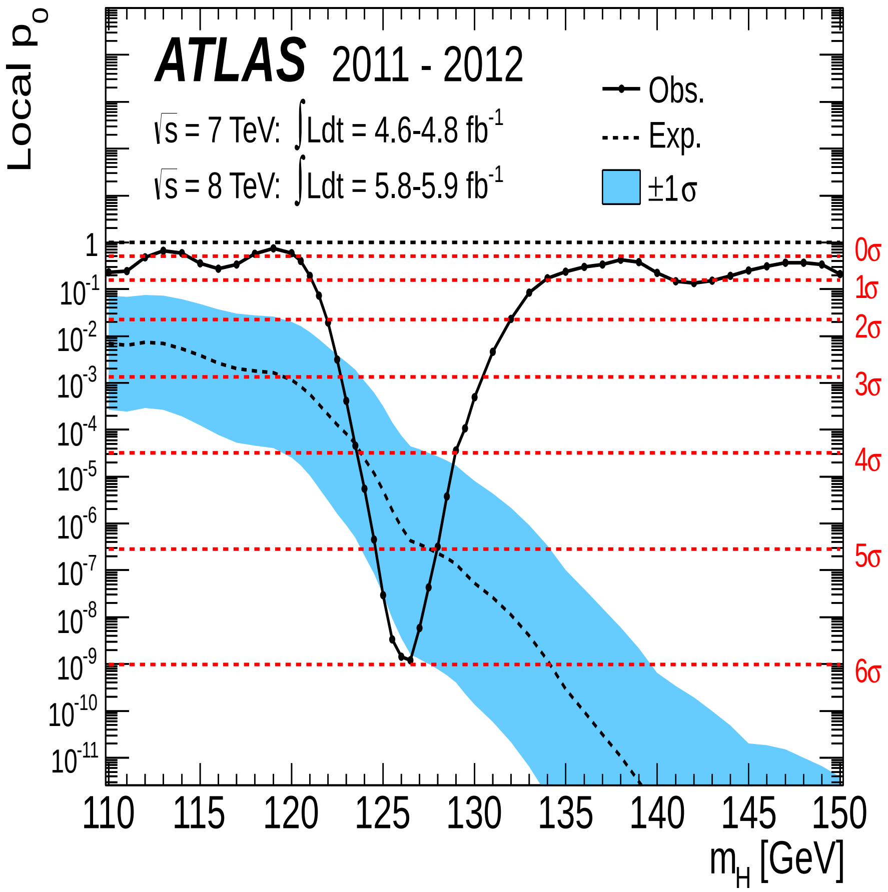
[*LHC Higgs XS WG '12*]

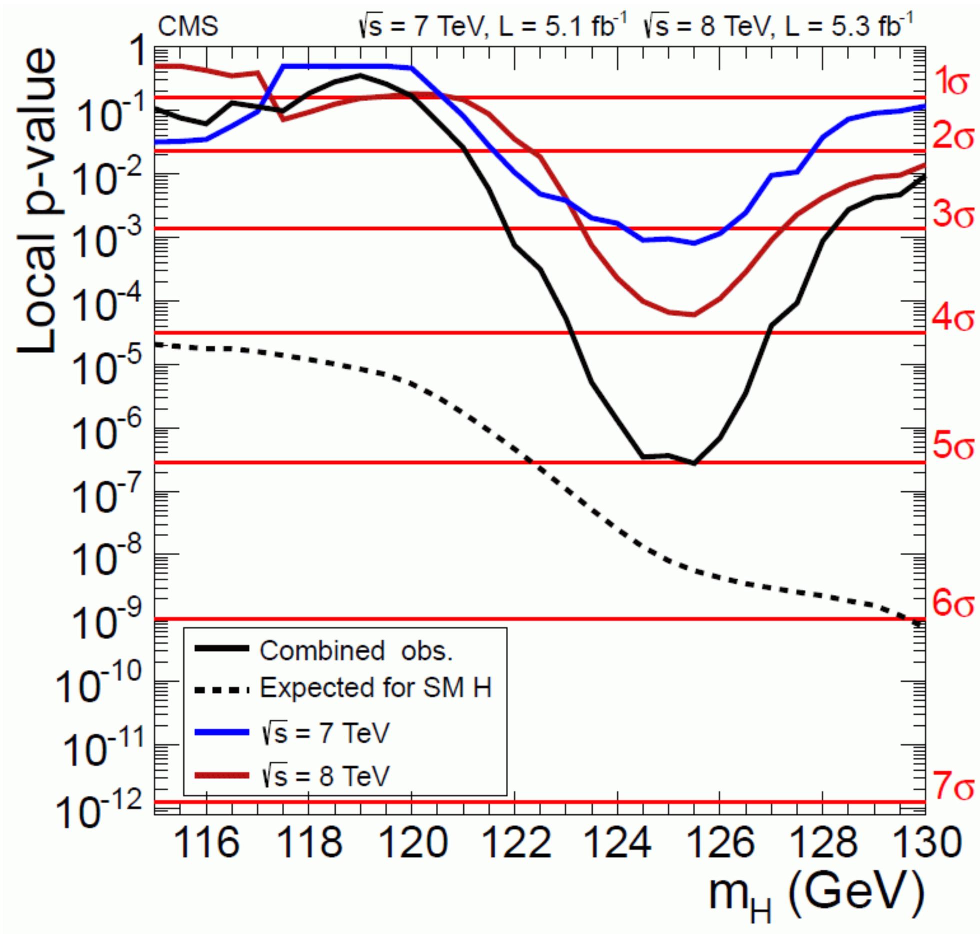


# 2. Why the SM is not Enough

## Fact I:

We have a discovery!

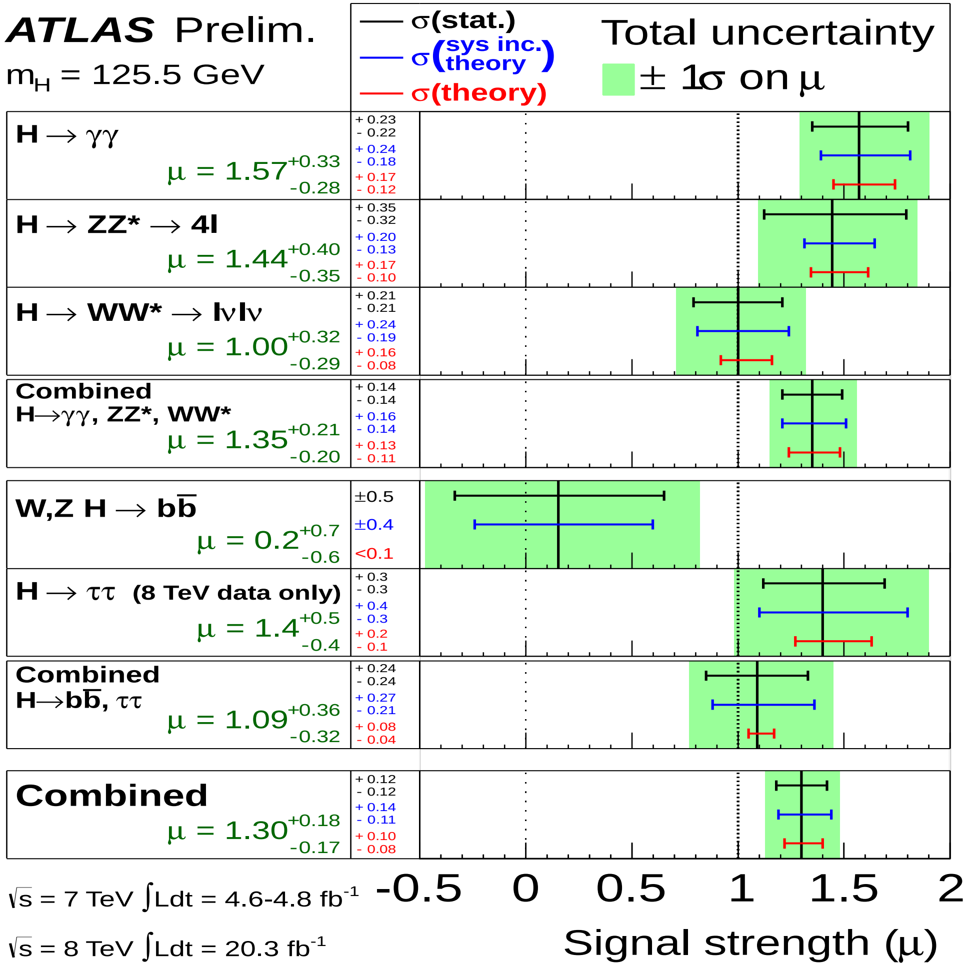


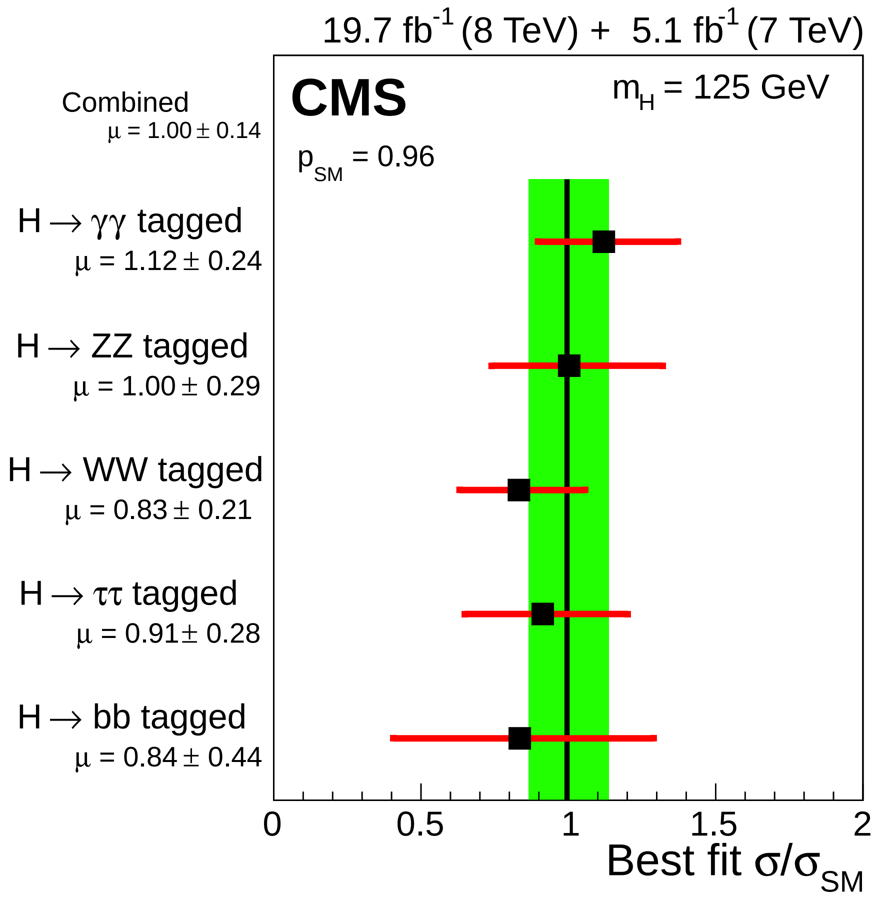



# 2. Why the SM is not Enough

## Fact I:

We have an SM-like discovery!



## Fact II:

**The SM cannot be the ultimate theory!**

Some facts:

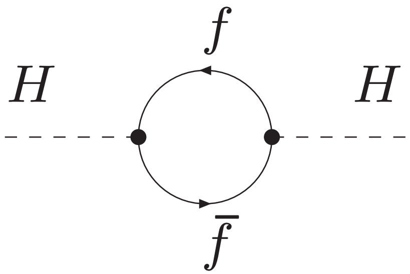
1. gravity is not included
2. the hierarchy problem
3. no unification of the three forces
4. Dark Matter is not included
5. Baryon Asymmetry of the Universe cannot be explained
6. neutrino masses are not included
7. anomalous magnetic moment of the muon shows a $\sim 4\,\sigma$ discrepancy

# Fact 2: the Hierarchy problem

Mass is what determines the properties of the free propagation of a particle

Free propagation: 

inverse propagator: $i(p^2 - M_H^2)$

Loop corrections: 

inverse propagator: $i(p^2 - M_H^2 + \Sigma_H^f)$

QM: integration over all possible loop momenta $k$
dimensional analysis:

$$\Sigma_H^f \sim N_f \, \lambda_f^2 \int d^4k \left( \frac{1}{k^2 - m_f^2} + \frac{2m_f^2}{(k^2 - m_f^2)^2} \right)$$

$$\text{for } \Lambda \to \infty: \quad \Sigma_H^f \sim N_f \, \lambda_f^2 \left( \underbrace{\int \frac{d^4k}{k^2}}_{\sim \Lambda^2} + 2m_f^2 \underbrace{\int \frac{dk}{k}}_{\sim \ln \Lambda} \right)$$

$\Rightarrow$ quadratically divergent!

For $\Lambda = M_{\text{Pl}}$:

$$\Sigma_H^f \approx \delta M_H^2 \sim M_{\text{Pl}}^2 \quad \Rightarrow \quad \delta M_H^2 \approx 10^{30}\, M_H^2$$

(for $M_H \lesssim 1$ TeV)

– no additional symmetry for $M_H = 0$

– no protection against large corrections

$\Rightarrow$ Hierarchy problem is instability of small Higgs mass to large corrections in a theory with a large mass scale in addition to the weak scale

E.g.: Grand Unified Theory (GUT): $\delta M_H^2 \approx M_{\text{GUT}}^2$

Note however: there is another fine-tuning problem in nature, for which we have no clue so far – cosmological constant

# Fact 3: Cold Dark Matter

## Cold Dark Matter exists:

⇒ It all fits together

$$\Omega_{\text{tot}} \approx 1$$

$$\Omega_M h^2 = 0.135^{+0.008}_{-0.009}$$

$$\Omega_B h^2 = 0.0224 \pm 0.0009$$

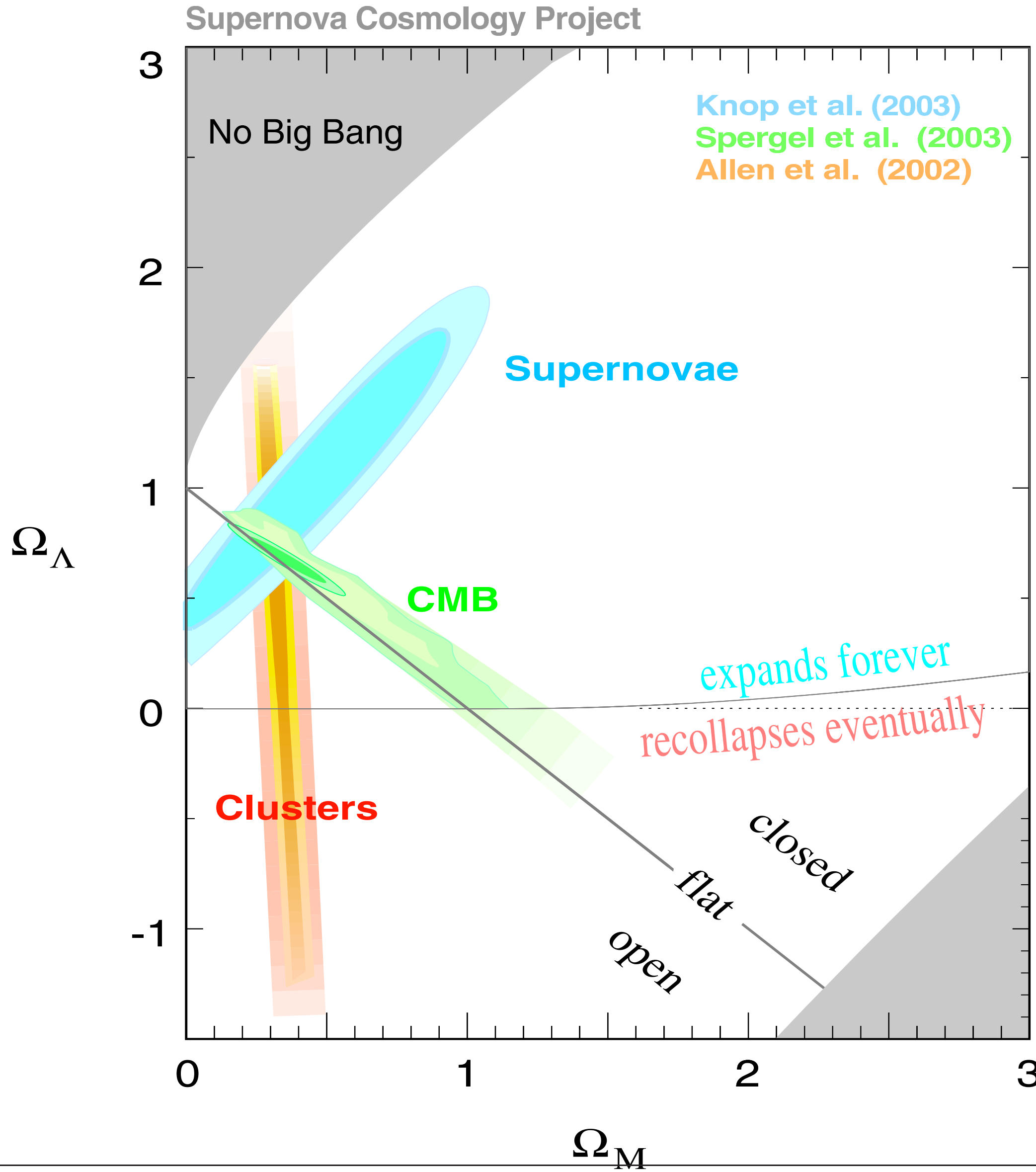
$$\Omega_\chi h^2 = 0.112 \pm 0.018$$

$$\Omega_\Lambda \approx 0.73$$

$\Omega_\chi$ ⇒ dark matter

$\Omega_\Lambda$ ⇒ dark energy . . .

⇒ no SM candidate!

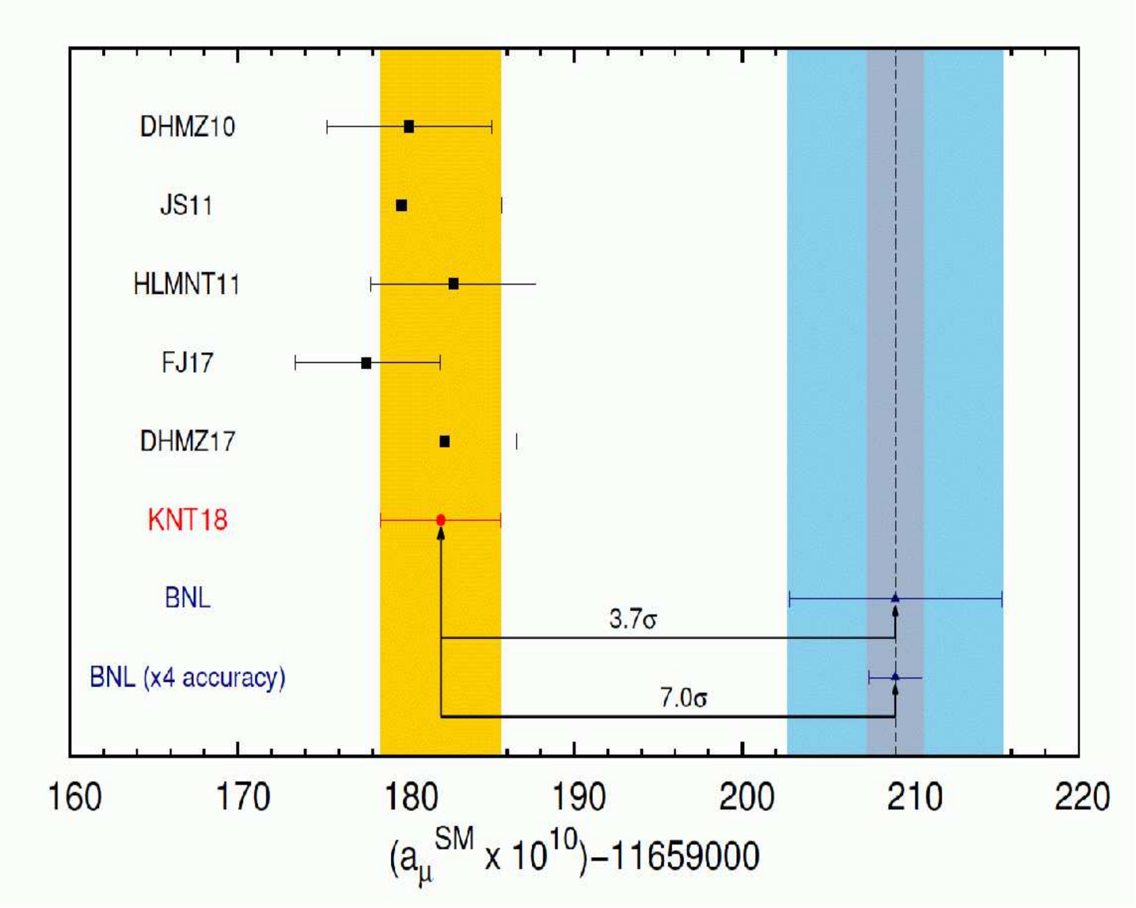


# Fact 6: The anomalous magnetic moment of the muon

$$a_\mu \equiv (g-2)_\mu/2$$

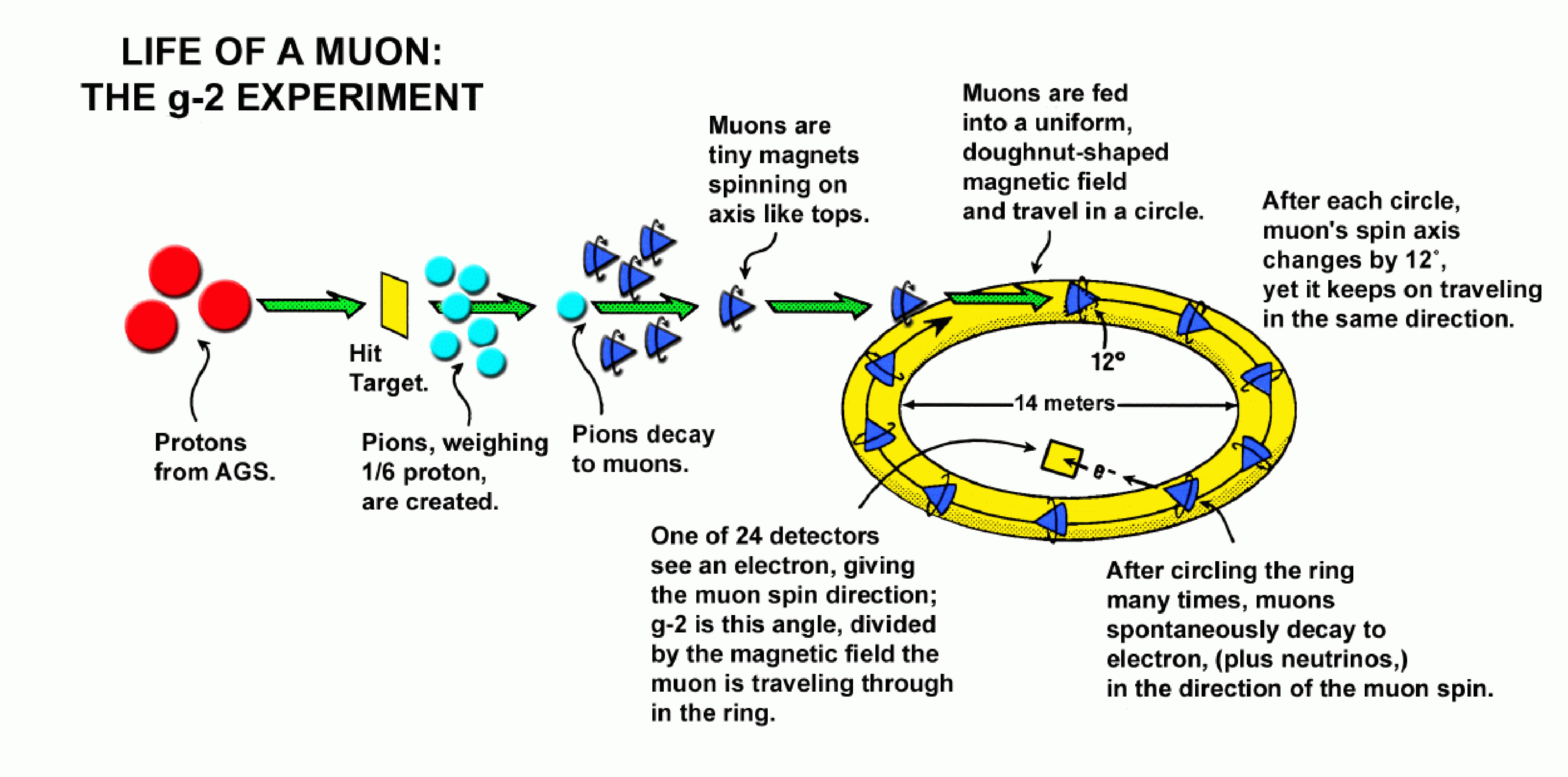
Overview about the current experimental and SM (theory) result:

[*A. Keshavarzia, D. Nomura, T. Teubner '18*]




$$a_\mu^{\rm exp} - a_\mu^{\rm theo,SM} \approx (27.05 \pm 7.26) \times 10^{-10} \quad : \; 3.7\,\sigma$$

The $(g-2)_\mu$ experiment:




Coupling of muon to magnetic field : $\mu - \mu - \gamma$ coupling

$$\bar{u}(p') \left[ \gamma^\mu F_1(q^2) + \frac{i}{2m_\mu} \sigma^{\mu\nu} q_\nu F_2(q^2) \right] u(p) A_\mu \qquad F_2(0) = a_\mu$$

## Current status of $(g-2)_\mu$:

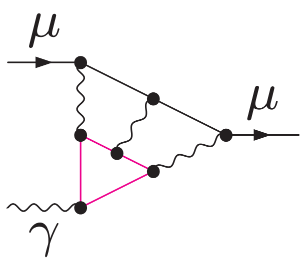
### Experiment:

– 2001 - 2006: very stable development

– final error: $6 \times 10^{-10}$ , still statistically dominated

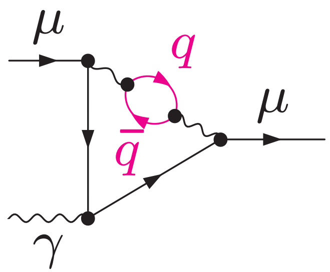
### Theory:

– the light-by-light contribution:




2002: sign error discovered; since then stabilized

– the hadronic vacuum contribution:




problems with the $\tau$ data $\Rightarrow$ hardly used anymore

'direct' $e^+e^-$ data:

from CMD-II, SND, KLOE (radiative return)

$\Rightarrow$ agree quite well (also with old $e^+e^-$ data)

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**A1:** check changed properties

**A2:** check for additional Higgs bosons
**A2':** check for additional Higgs bosons above and below 125 GeV

# Models with extended Higgs sectors:

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**Q: Conoceis un modelo BSM? :-)**

## Models with extended Higgs sectors:

1. SM with addional Higgs singlet

2. Two Higgs Doublet Model (THDM): type I, II, III, IV

3. Minimal Supersymmetric Standard Model (MSSM)

4. MSSM with one extra singlet (NMSSM)

5. MSSM with more extra singlets

6. SM/MSSM with Higgs triplets

7. ...

⇒ BSM models without extended Higgs sectors still have changed Higgs properties (quantum corrections!)

⇒ SM + vector-like fermions, Higgs portal, Higgs-radion mixing, ...

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**$\Rightarrow$ good motivation to look at SUSY! :-)**

# 3. Supersymmetry (SUSY) comes to rescue

$$\text{Bosons} \leftrightarrow \text{Fermions}$$

$$Q\ |\text{Fermion}\rangle \rightarrow |\text{Boson}\rangle$$
$$Q\ |\text{Boson}\rangle \rightarrow |\text{Fermion}\rangle$$

Simplified examples:

$$Q\ |\text{top},\ t\rangle \rightarrow |\text{scalar top},\ \tilde{t}\rangle$$
$$Q\ |\text{gluon},\ g\rangle \rightarrow |\text{gluino},\ \tilde{g}\rangle$$

$\Rightarrow$ each SM multiplet is enlarged to its double size

Unbroken SUSY: All particles in a multiplet have the same mass

Reality: $m_e \neq m_{\tilde{e}} \Rightarrow$ SUSY is broken ...

... via soft SUSY-breaking terms in the Lagrangian (added by hand)

SUSY particles are made heavy: $\boxed{M_{\text{SUSY}} = \mathcal{O}(1\text{ TeV})}$

$\Rightarrow$ each SM multiplet is enlarged to its double size

1. SM spin 0 bosons:

   (spin 0) multiplet $\to$ (spin 0, spin $\frac{1}{2}$) multiplet (→ LH$\chi$SF)
   (left-handed chiral super field)

2. SM spin $\frac{1}{2}$ fermions:

   (spin $\frac{1}{2}$) multiplet $\to$ (spin 0, spin $\frac{1}{2}$) multiplet (→ LH$\chi$SF)

3. SM spin 1 bosons:

   (spin 1) multiplet $\to$ (spin $\frac{1}{2}$, spin 1) multiplet (→ Vector SF)

# The Minimal Supersymmetric Standard Model (MSSM)

## Superpartners for Standard Model particles

$$\left[u, d, c, s, t, b\right]_{L,R} \quad \left[e, \mu, \tau\right]_{L,R} \quad \left[\nu_{e,\mu,\tau}\right]_L \qquad \text{Spin } \tfrac{1}{2}$$

$$\left[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\right]_{L,R} \quad \left[\tilde{e}, \tilde{\mu}, \tilde{\tau}\right]_{L,R} \quad \left[\tilde{\nu}_{e,\mu,\tau}\right]_L \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^{\pm}, H^{\pm}} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin } 1 \text{ / Spin } 0$$

$$\tilde{g} \quad \tilde{\chi}^{\pm}_{1,2} \quad \tilde{\chi}^{0}_{1,2,3,4} \qquad \text{Spin } \frac{1}{2}$$

Enlarged Higgs sector: Two Higgs doublets ⇒ 5 Higgs bosons

⇒ lightest MSSM Higgs-boson is SM-like!

# The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

$$\Big[u, d, c, s, t, b\Big]_{L,R} \quad \Big[e, \mu, \tau\Big]_{L,R} \quad \Big[\nu_{e,\mu,\tau}\Big]_L \qquad \text{Spin } \tfrac{1}{2}$$

$$\Big[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\Big]_{L,R} \quad \Big[\tilde{e}, \tilde{\mu}, \tilde{\tau}\Big]_{L,R} \quad \Big[\tilde{\nu}_{e,\mu,\tau}\Big]_L \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^\pm, H^\pm} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin 1 / Spin 0}$$

$$\tilde{g} \quad \tilde{\chi}^\pm_{1,2} \quad \tilde{\chi}^0_{1,2,3,4} \qquad \text{Spin } \frac{1}{2}$$

Enlarged Higgs sector: Two Higgs doublets ⇒ 5 Higgs bosons

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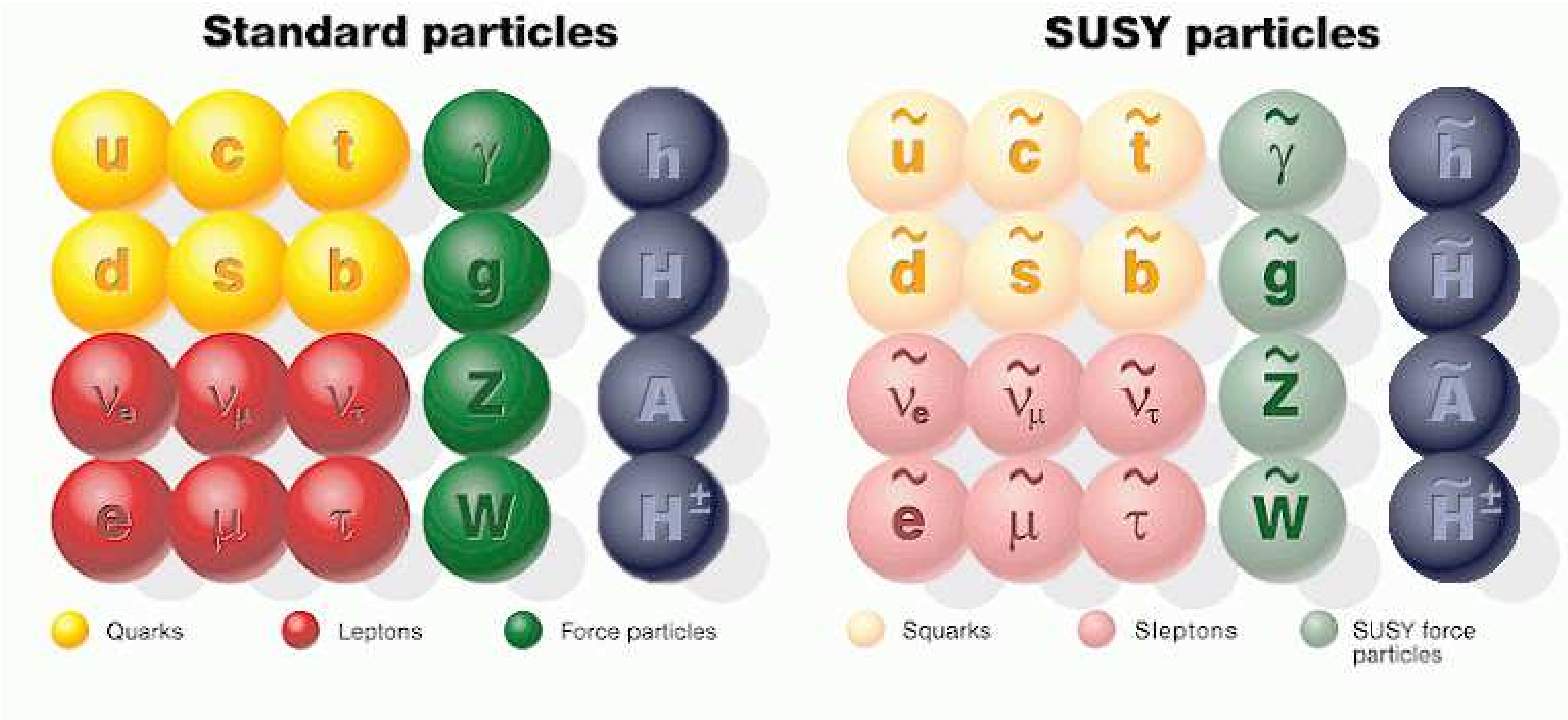
**Q: Porque 5 bosones de Higgs?**

# The Minimal Supersymmetric Standard Model (MSSM)

## Superpartners for Standard Model particles




Problem in the MSSM: more than 100 free parameters

Nobody(?) believes that a model describing nature
has so many free parameters!
⇒ to be discussed later?!

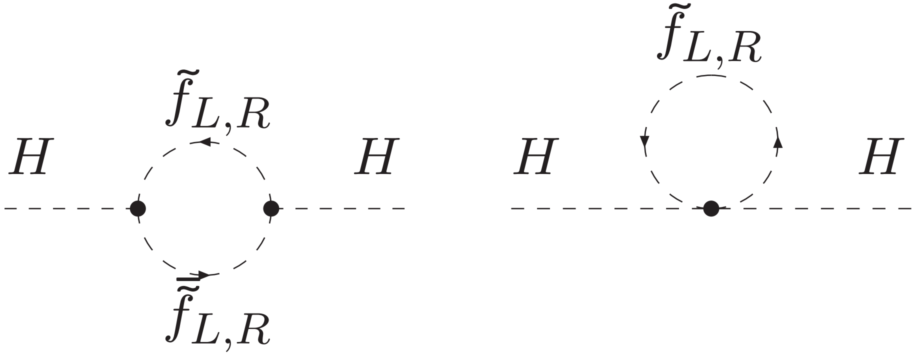
## Fact 2: the hierarchy problem

Symmetry between fermions and bosons

$$Q|\text{boson}\rangle = |\text{fermion}\rangle$$
$$Q|\text{fermion}\rangle = |\text{boson}\rangle$$

Effectively: SM particles have SUSY partners (e.g. $f_{L,R} \to \tilde{f}_{L,R}$)

SUSY: additional contributions from scalar fields:




$$\Sigma_H^{\tilde{f}} \sim N_{\tilde{f}}\, \lambda_{\tilde{f}}^2 \int d^4k \left( \frac{1}{k^2 - m_{\tilde{f}_L}^2} + \frac{1}{k^2 - m_{\tilde{f}_R}^2} \right) + \text{ terms without quadratic div.}$$

for $\Lambda \to \infty$: $\Sigma_H^{\tilde{f}} \sim N_{\tilde{f}}\, \lambda_{\tilde{f}}^2\, \Lambda^2$

⇒ quadratic divergences cancel for

$$N_{\tilde{f}_L} = N_{\tilde{f}_R} = N_f$$
$$\lambda_{\tilde{f}}^2 = \lambda_f^2$$

complete correction vanishes if furthermore

$$m_{\tilde{f}} = m_f$$

Soft SUSY breaking: $m_{\tilde{f}}^2 = m_f^2 + \Delta^2, \quad \lambda_{\tilde{f}}^2 = \lambda_f^2$

$$\Rightarrow \Sigma_H^{f+\tilde{f}} \sim N_f \, \lambda_f^2 \, \Delta^2 + \ldots$$

⇒ correction stays acceptably small if mass splitting is of weak scale

⇒ realized if mass scale of SUSY partners

$$M_{\text{SUSY}} \lesssim \text{few TeV}$$

⇒ SUSY at TeV scale provides attractive solution of hierarchy problem

# Fact 3: Cold Dark Matter: perfect candidate: $\tilde{\chi}_1^0$

Dark Matter in the CMSSM parameter space:

schematic picture

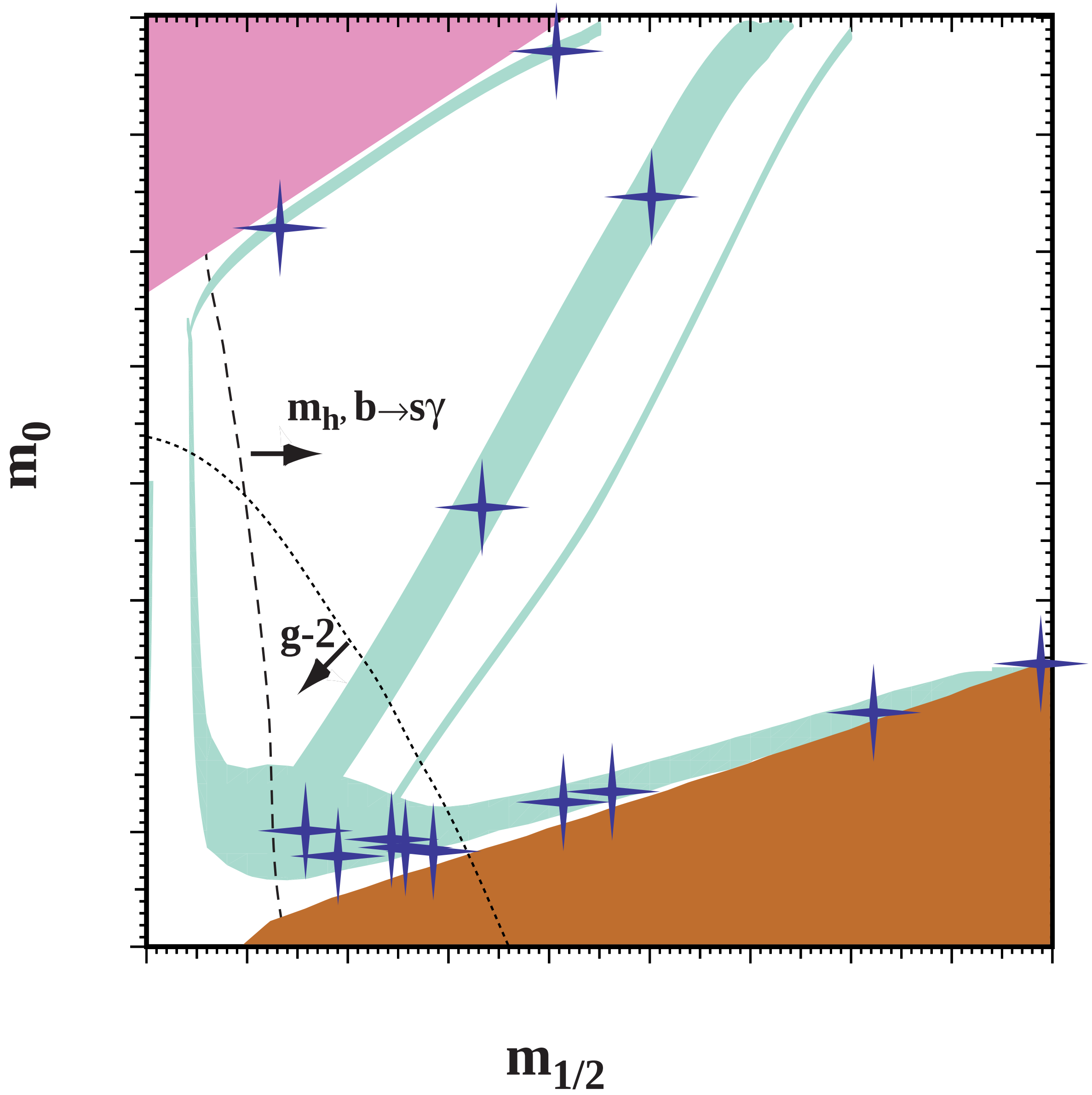
$(0.1 \leq \Omega_\chi h^2 \leq 0.3)$

[*K. Olive et al. '02*]

Despite its simplicity
CMSSM fulfils all experimental bounds

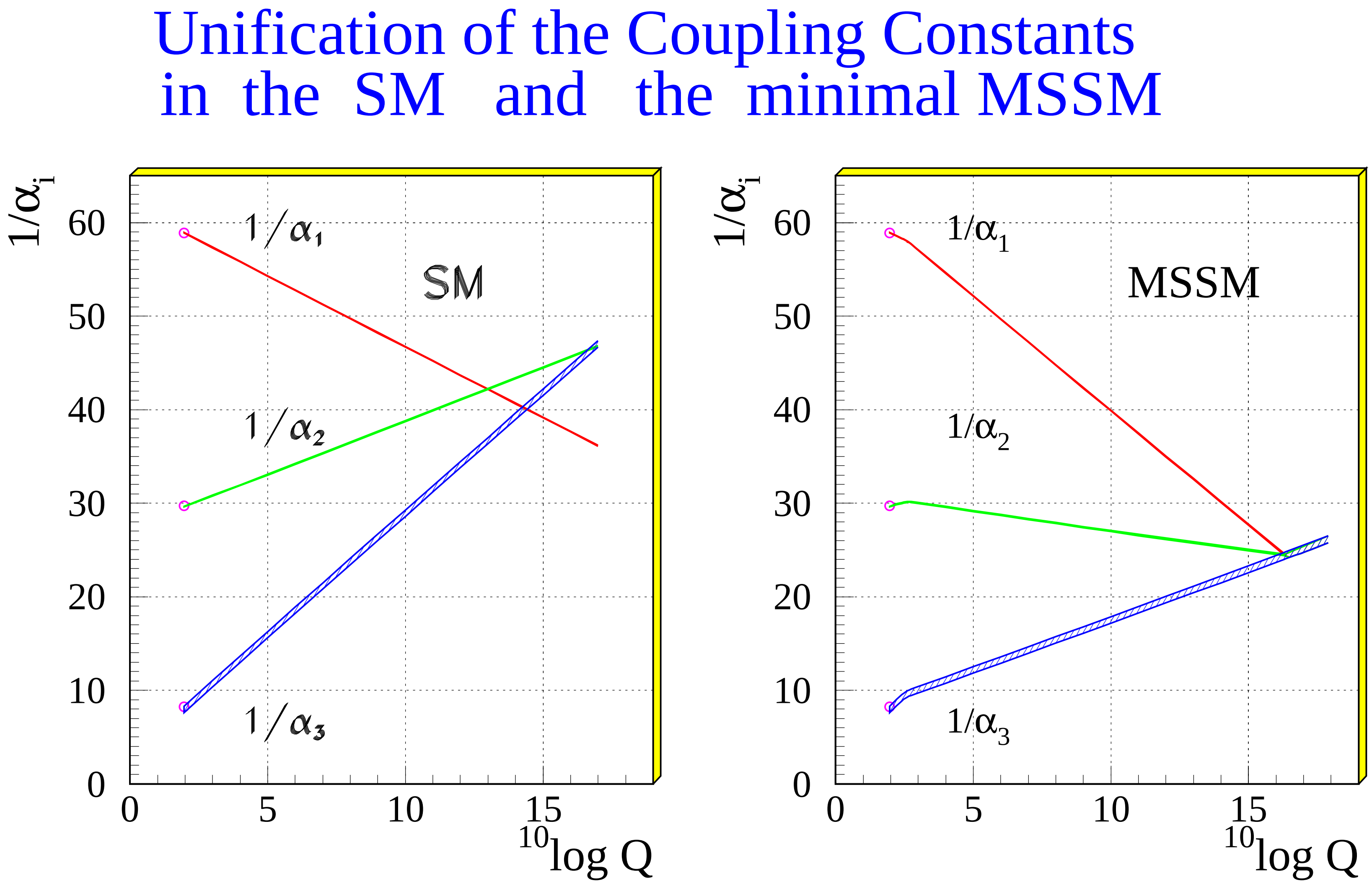
Four mechanisms for "good" $\langle \sigma v \rangle$:

- Bulk
- Stau coannihilation
- Higgs-pole annihilation
- Focus-Point



# Fact 4: Unification of forces

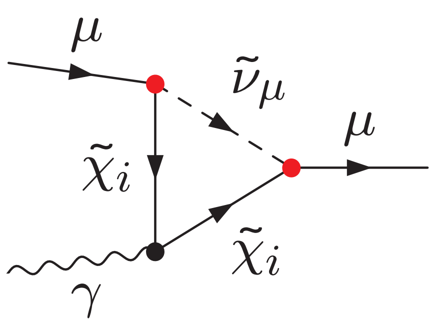
[*Amaldi, de Boer, Fürstenau '92*]

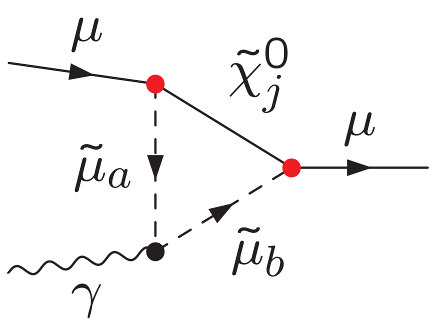


# Fact 6: The anomalous magnetic moment of the muon

SUSY can easily explain the deviation:

Feynman diagrams for MSSM 1L corrections:




– Diagrams with chargino/sneutrino exchange

– Diagrams with neutralino/smuon exchange

Enhancement factor as compared to SM:

$$\mu - \tilde{\chi}_i^\pm - \tilde{\nu}_\mu \quad : \quad \sim m_\mu \tan\beta$$
$$\mu - \tilde{\chi}_j^0 - \tilde{\mu}_a \quad : \quad \sim m_\mu \tan\beta$$

SM, EW 1L: $\frac{\alpha}{\pi} \frac{m_\mu^2}{M_W^2}$

MSSM, 1L: $\frac{\alpha}{\pi} \frac{m_\mu^2}{M_{\text{SUSY}}^2} \times \tan\beta$

## SUSY corrections at 1L:

$$a_\mu^{\text{SUSY,1L}} \approx 13 \times 10^{-10} \left(\frac{100\text{ GeV}}{M_{\text{SUSY}}}\right)^2 \tan\beta\,\text{sign}(\mu)$$

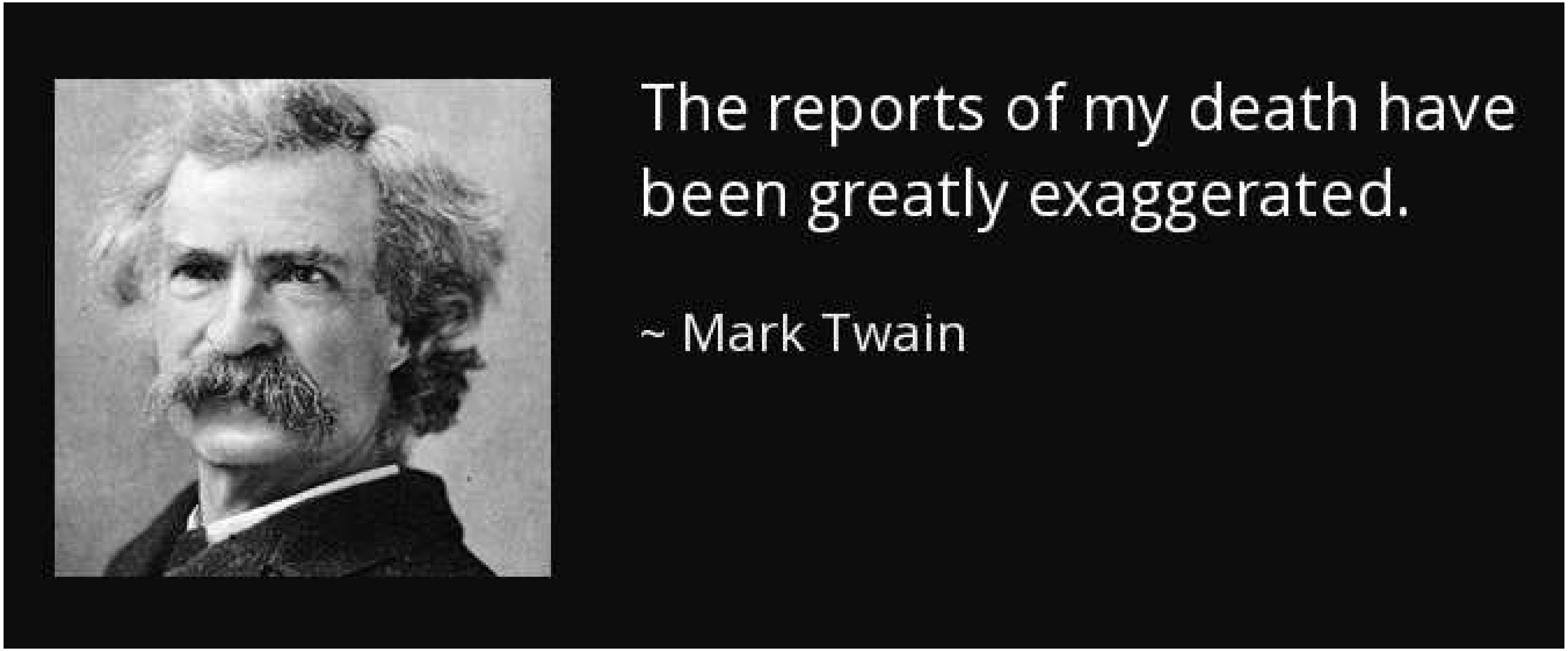
$M_{\text{SUSY}} (= m_{\tilde\mu} = m_{\tilde\nu} = m_{\tilde\chi})$: generic SUSY mass scale

$$\begin{aligned} a_\mu^{\text{SUSY,1L}} &= (-100\ldots+100) \times 10^{-10} \\ a_\mu^{\text{exp}} - a_\mu^{\text{theo,SM}} &\approx (28 \pm 8) \times 10^{-10} \end{aligned}$$

$\Rightarrow$ SUSY could easily explain the "discrepancy"

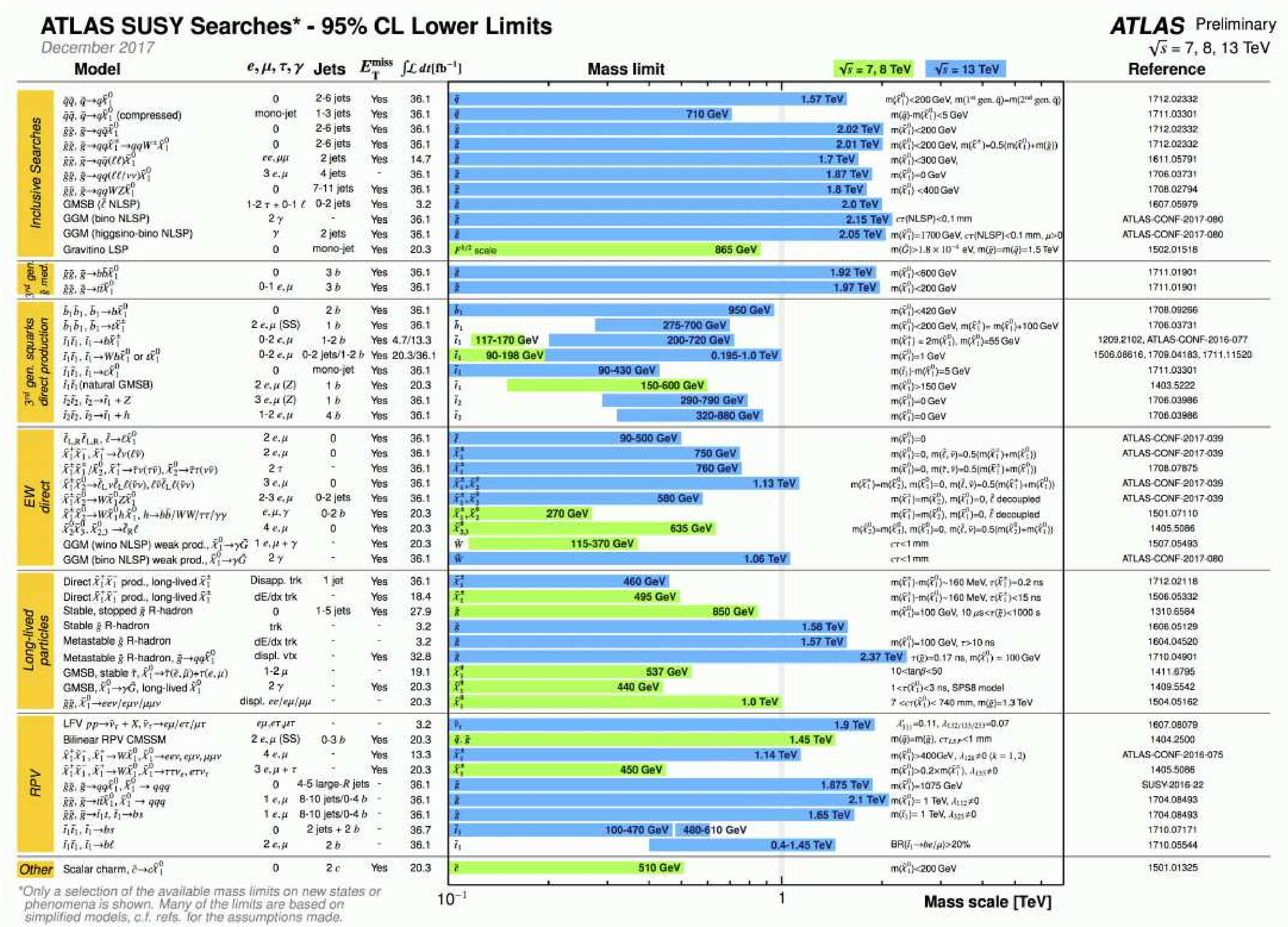
$\Rightarrow$ $a_\mu$ can provide bounds on SUSY parameter space
(by requiering agreement at the 95% C.L.)

# 4. Is SUSY dead?

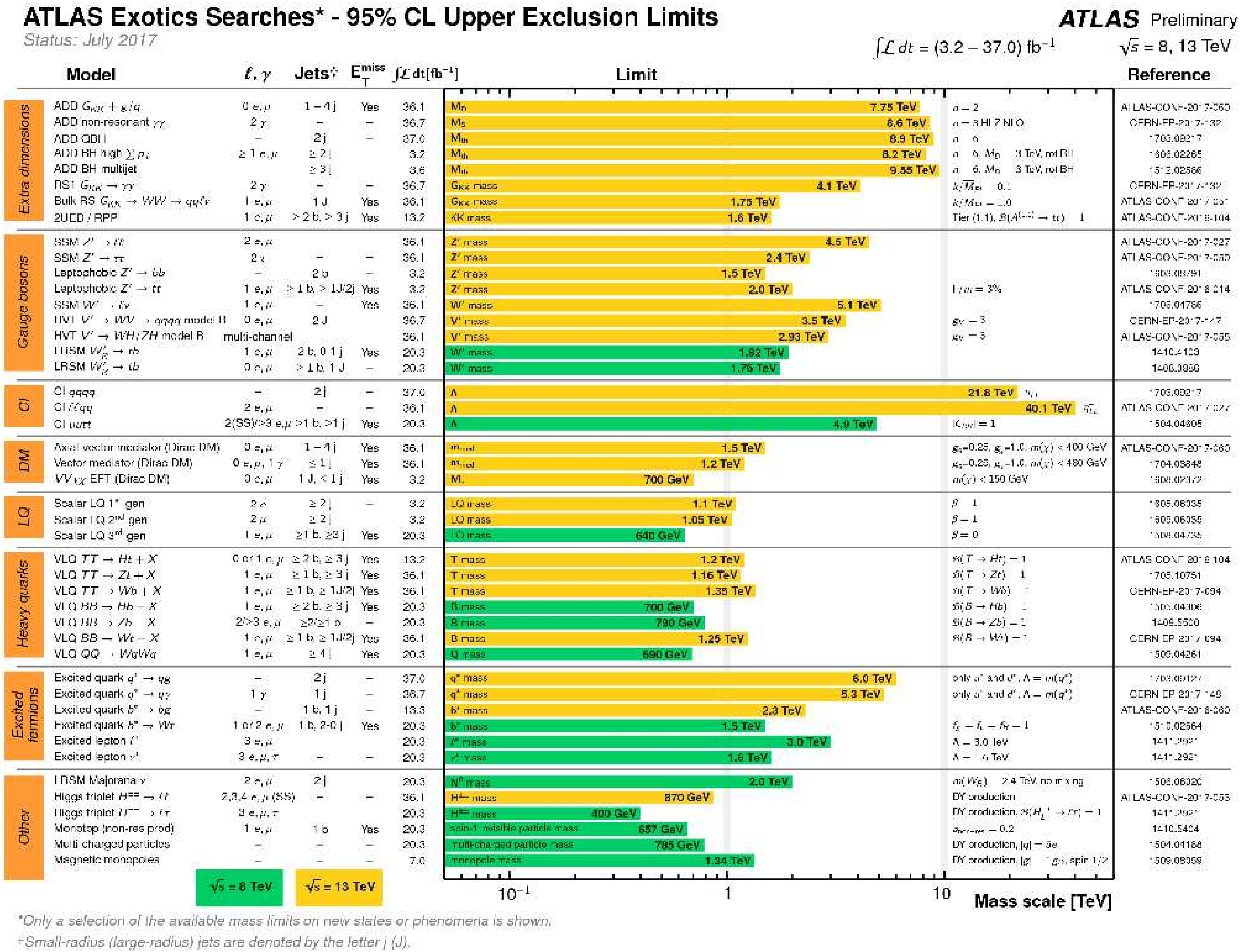



⇒ But what about experimental results?

# Is SUSY dead? When will I give up on SUSY?



# SUSY is as dead (or alive) as ANY OTHER BSM theory



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$\Rightarrow$ **focus on the theoretically most appealing theory!**

## SUSY is as dead (or alive) as ANY OTHER BSM theory

⇒ **focus on the theoretically most appealing theory!**

– It is nearly inconceivable that there is no symmetry between bosons and fermions (at low or high energy?)

– SUSY is the only non-trivial extension of (the SM) gauge symmetries

– SUSY gives you coupling constant unification

– SUSY predicted correctly the top quark mass

– SUSY predicted correctly the Higgs boson mass

– SUSY predicted correctly an SM-like Higgs boson

– SUSY predicted correctly DM properties

# Back to fact 6: The anomalous magnetic moment of the muon

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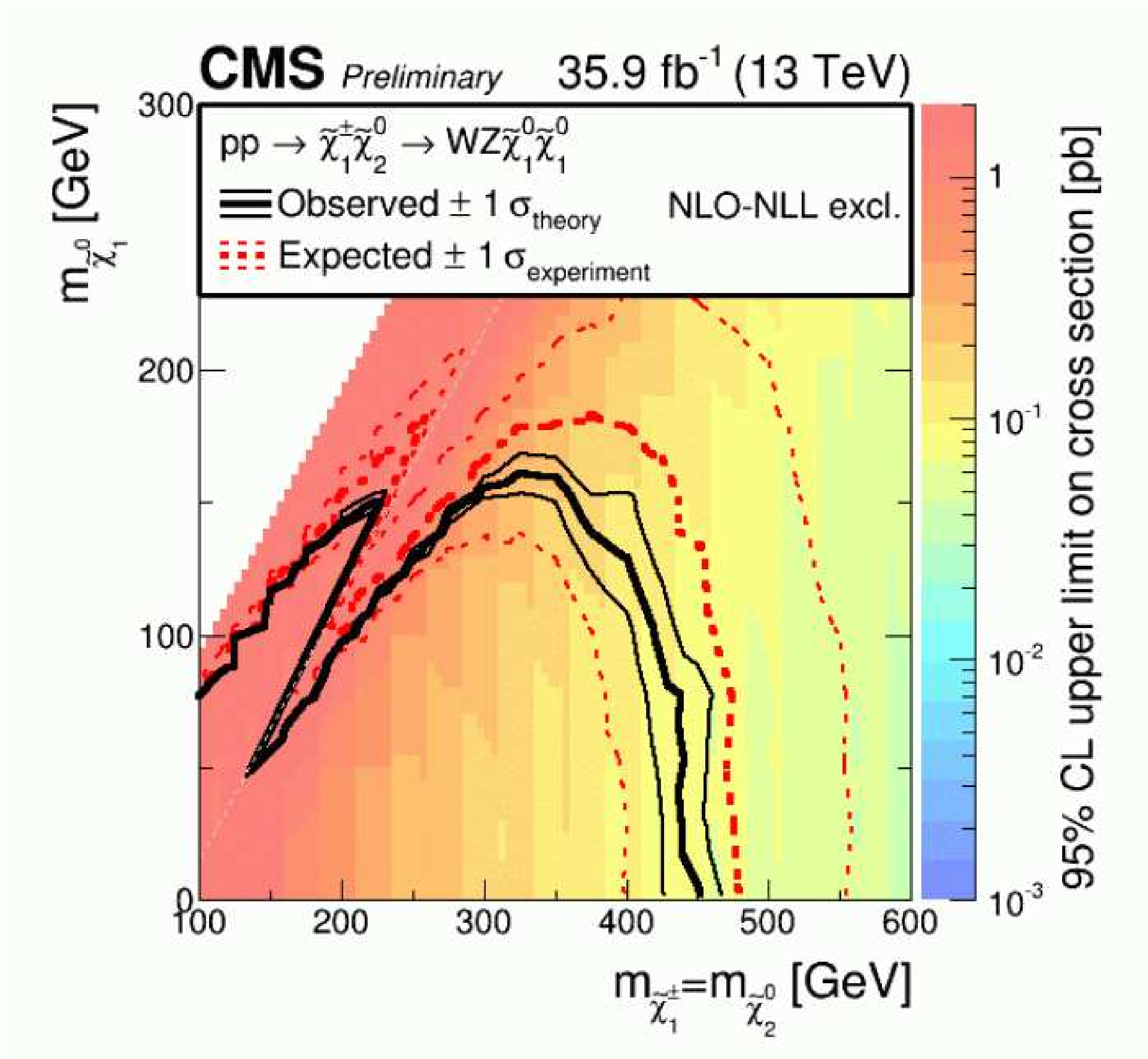
$\Rightarrow$ if SUSY exists, it should explain $(g-2)_\mu$

$\Rightarrow$ light EW SUSY particles must exist!

# Electroweak searches:



# 5. Conclusinos

- The Standard Model is a highly successful theory
- The SM fails to explain: gravity, hierarchy problem, unification of forces, DM, neutrino masses, $(g-2)_\mu$, . . .
- Many BSM models exist!
  $\Rightarrow$ Supersymmetry has the best features
  - paves the way to include gravity (string theory)
  - solves the hierarchy problem
  - unifies the forces
  - natural DM candidate
  - some models naturally include neutrino masses
  - $(g-2)_\mu$ easily explained
- Experimental data: SUSY is as alive (or dead) as any other BSM theory
  $\Rightarrow$ but SUSY is the only theory with all the salient features!
- If SUSY exists, it should explain $(g-2)_\mu$
  $\Rightarrow$ light EW SUSY particles must exist! **This is where to look!**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Theory meets Experiment
28 September - 02 October
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Further Questions?