READi Workshop, DESY Hamburg, April 7$^{th}$, 2014

# Beyond the Standard Model of Particle Physics

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# OUTLINE

1. **Standard Model of Elementary Particle Physics**

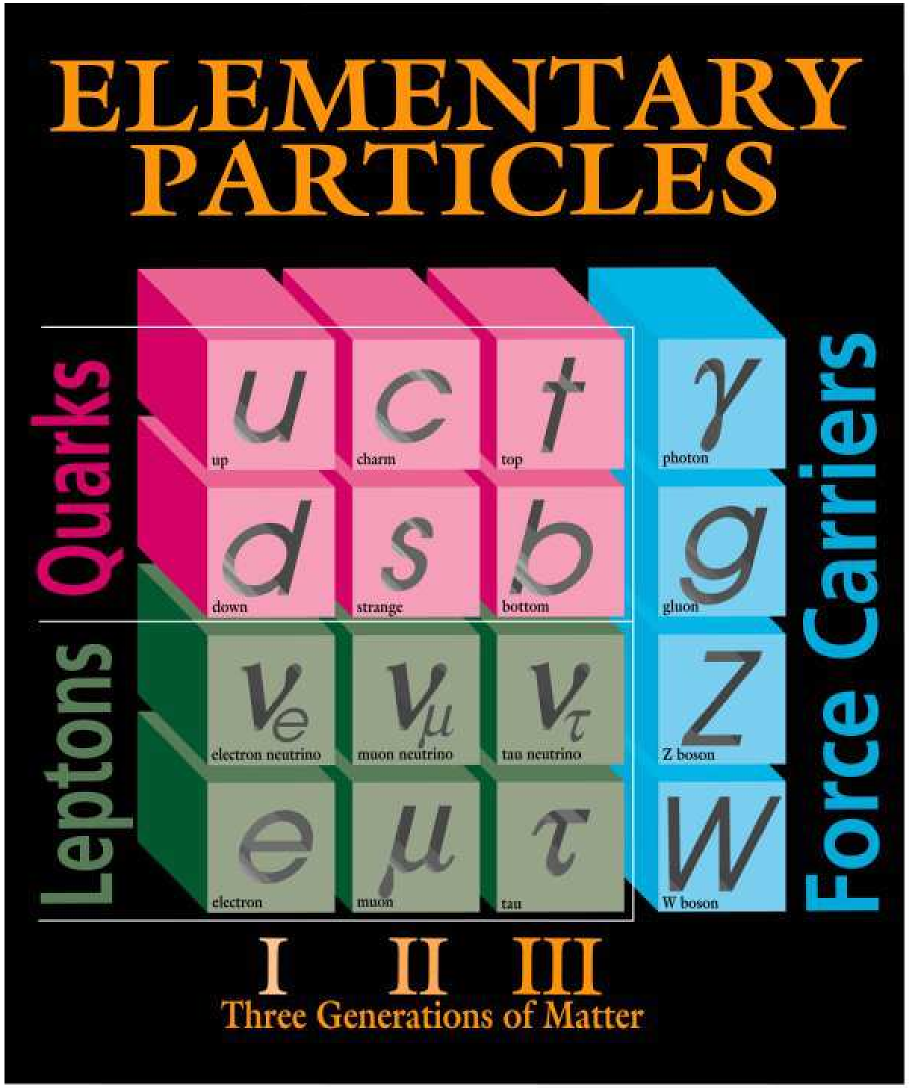
2. **Higgs Boson & Implications**

3. **Open Questions in the Standard Model: Hierarchy Problem**

4. **Supersymmetry**

5. **Conclusions and Outlook**

# Lego blocks of our world, June 2012

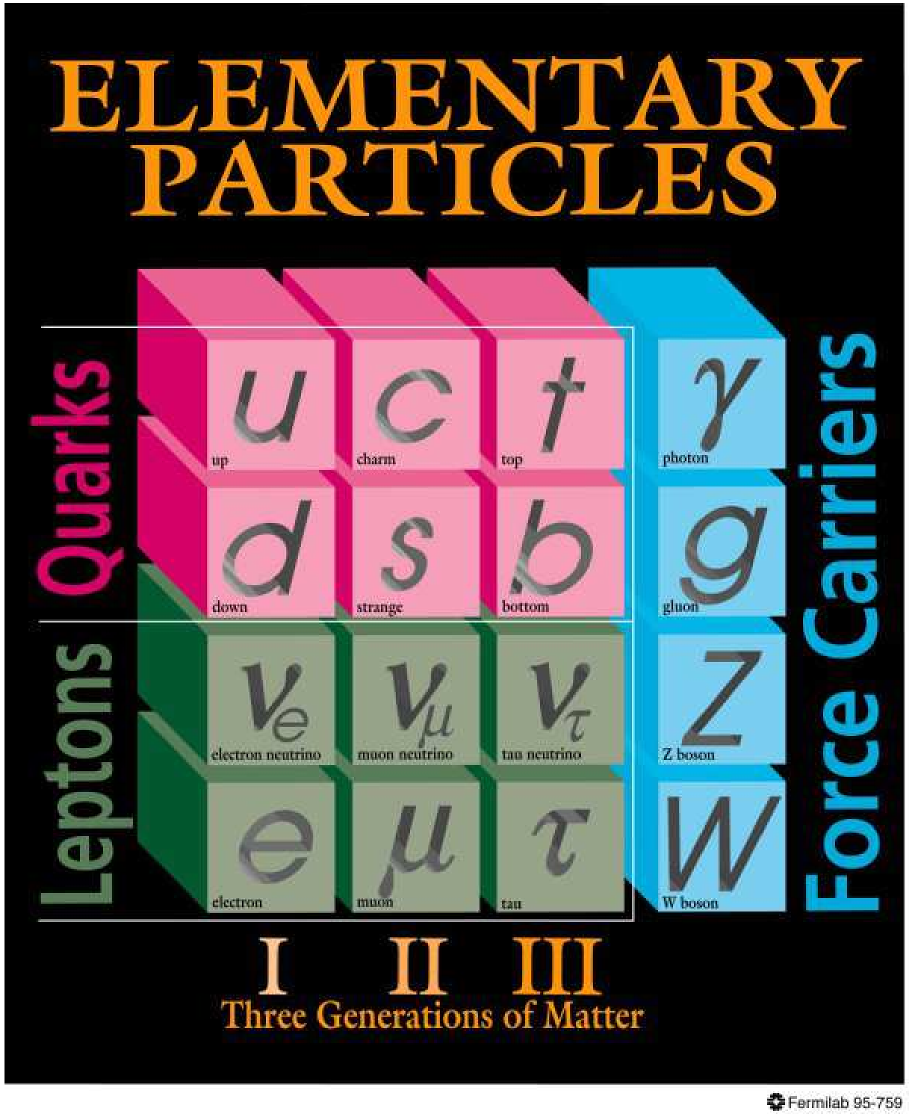



Fermilab 95-759

# July $4^{th}$, 2012, CERN

Discovery of the Higgs Boson!

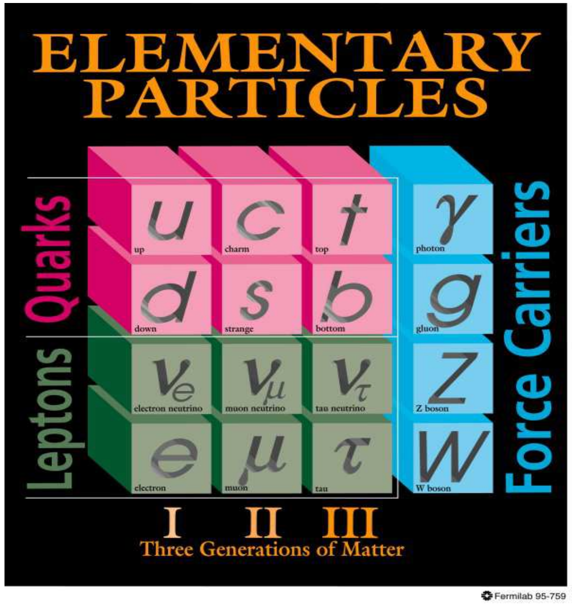
# Lego blocks today




+ **Higgs Boson**

- The Higgs is qualitatively different .... predicted **1964** for internal consistency!

# Step back




- This picture is sloppy

- For one generation we have:

- Leptons: $\begin{pmatrix} \nu \\ e \end{pmatrix}_L; \quad e_R, \quad (\nu_R??)$

- Quarks: $\begin{pmatrix} u \\ d \end{pmatrix}_L; \quad u_R, \quad d_R$

- $e_L$, $e_R$, distinct fields:
  - transform differently under Lorentz group.
  - Have different gauge interactions!

- Same for: $u_{L,R}$, $d_{L,R}$

- Important in constructing supersymmetric Lagrangians

# Historical Interlude

- What was the last SM particle to be observed before the Higgs?
- **Electron** 1897, Thompson
- **Proton** 1917, Rutherford
- **Neutron** 1932, Chadwick
- **Positron** 1932, Anderson
- How about the other (elementary) particles?

# Discovery of Matter Particles

Muon, $\mu$

Electron Neutrino, $\nu_e$

Muon Neutrino, $\nu_\mu$

Light Quarks, $u$, $d$, $s$

Charm Quark, $c$

Bottom Quark, $b$

Tau Lepton, $\tau$

Top Quark, $t$

Tau Neutrino, $\nu_\tau$

# Discovery of Matter Particles

**1934** Muon, $\mu$

**1956** Electron Neutrino, $\nu_e$

**1962** Muon Neutrino, $\nu_\mu$

Light Quarks, $u$, $d$, $s$

Charm Quark, $c$

Bottom Quark, $b$

Tau Lepton, $\tau$

Top Quark, $t$

Tau Neutrino, $\nu_\tau$

# Discovery of Matter Particles

**1934** Muon, $\mu$

**1956** Electron Neutrino, $\nu_e$

**1962** Muon Neutrino, $\nu_\mu$

**1960's** Light Quarks, $u$, $d$, $s$

**1974** Charm Quark, $c$

**1977** Bottom Quark, $b$

Tau Lepton, $\tau$

Top Quark, $t$

Tau Neutrino, $\nu_\tau$

# Discovery of Matter Particles

**1934** Muon, $\mu$

**1956** Electron Neutrino, $\nu_e$

**1962** Muon Neutrino, $\nu_\mu$

**1960's** Light Quarks, $u$, $d$, $s$

**1974** Charm Quark, $c$

**1977** Bottom Quark, $b$

**1977** Tau Lepton, $\tau$

**1995** Top Quark, $t$

**2000** Tau Neutrino, $\nu_\tau$

# ... and the bosons

- Photon, 1905, Hertz, Einstein?
- Gluon, 1979, many, at PETRA at DESY (1978, PLUTO at DORIS?)
- $W^{\pm}$, $Z^0$, 1983 UA1 & UA2 collaborations, CERN

# Higgs Boson, Higgs Mechanism

- Dilemma 1964: • gauge theory – vector boson $M_W = 0$, exactly

  • Weak interaction has a very short range: $M_W \neq 0$

- Add complex scalar SU(2) Higgs doublet to SM: $\Phi = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$

- With Higgs Lagrangian

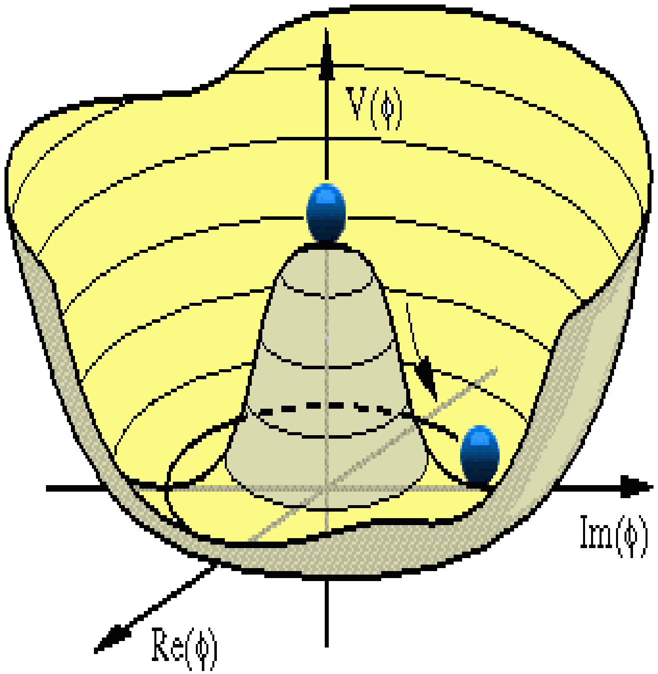
$$\mathscr{L} = (\mathscr{D}_\mu \Phi)^\dagger \mathscr{D}^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2 - Y[\bar{\psi}_R (\Phi^\dagger \psi_L) + (\bar{\psi}_L \Phi) \psi_R]$$

- Gauge covariant derivative: $\mathscr{D}_\mu = \partial_\mu + \frac{ig'}{2} \mathscr{B}_\mu + \frac{ig}{2} \vec{\tau} \cdot \vec{W}_\mu$

# Spontaneous Symmetry Breaking

- Spontaneous symmetry breaking:

$$\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \longrightarrow \mathrm{U}(1)_{\mathrm{EM}}$$




- $\Phi = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \longrightarrow \begin{pmatrix} 0 \\ v \end{pmatrix}$ in vacuum

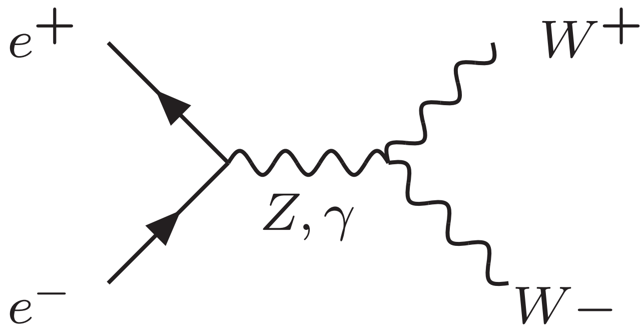
- Only one real scalar remains $h^0$

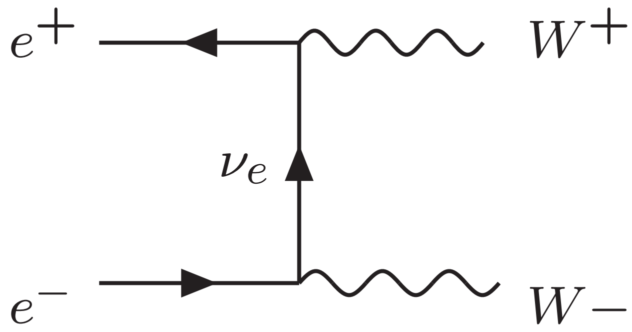
- $M_W \propto gv \neq 0$

- $m_e \propto Yv \neq 0$

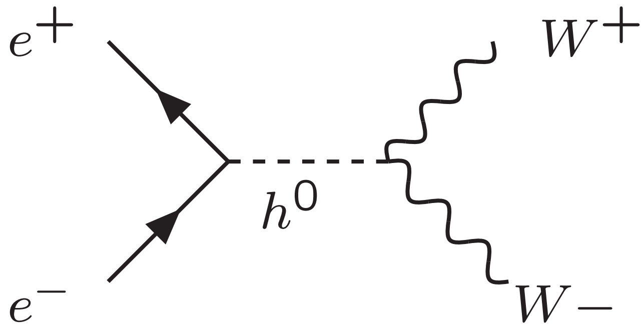
# Unitarity

- Solves extra problem: $e^+e^- \longrightarrow W^+W^-$ (LEP2)



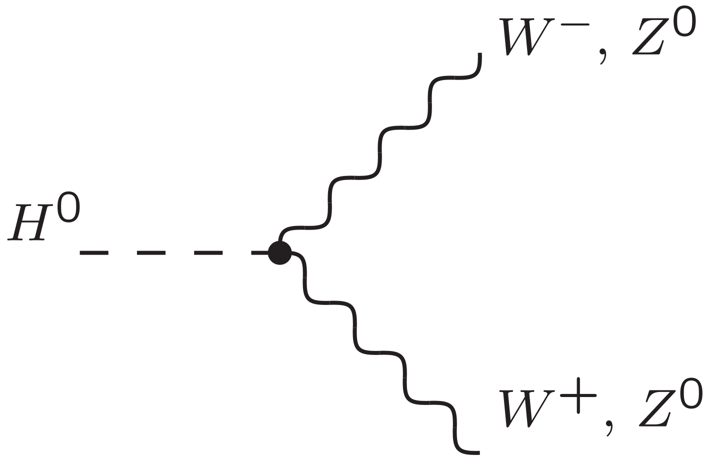

- With Higgs, extra diagram

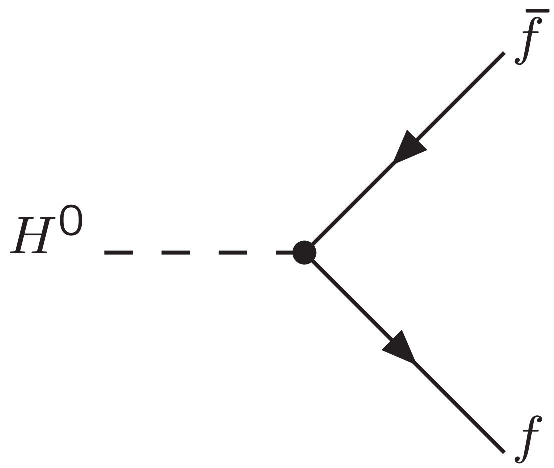



- Cross section obeys unitarity bound

# Higgs Couplings

- Directly from the Lagrangian



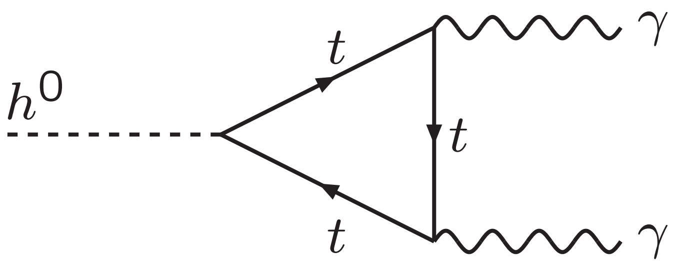

$c = 2M_{W,Z}^2/v$

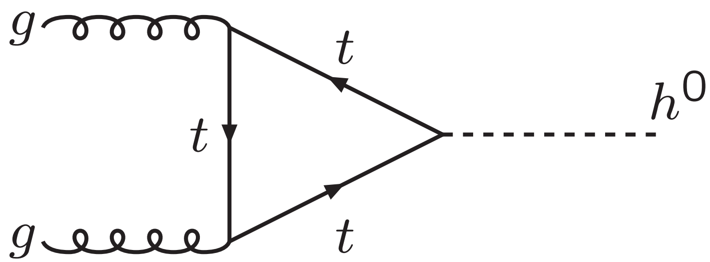
$Y = m_f/v$

- Coupling is proportional to mass!
- Thus also no coupling to gluons or photons.

# Higgs Couplings II

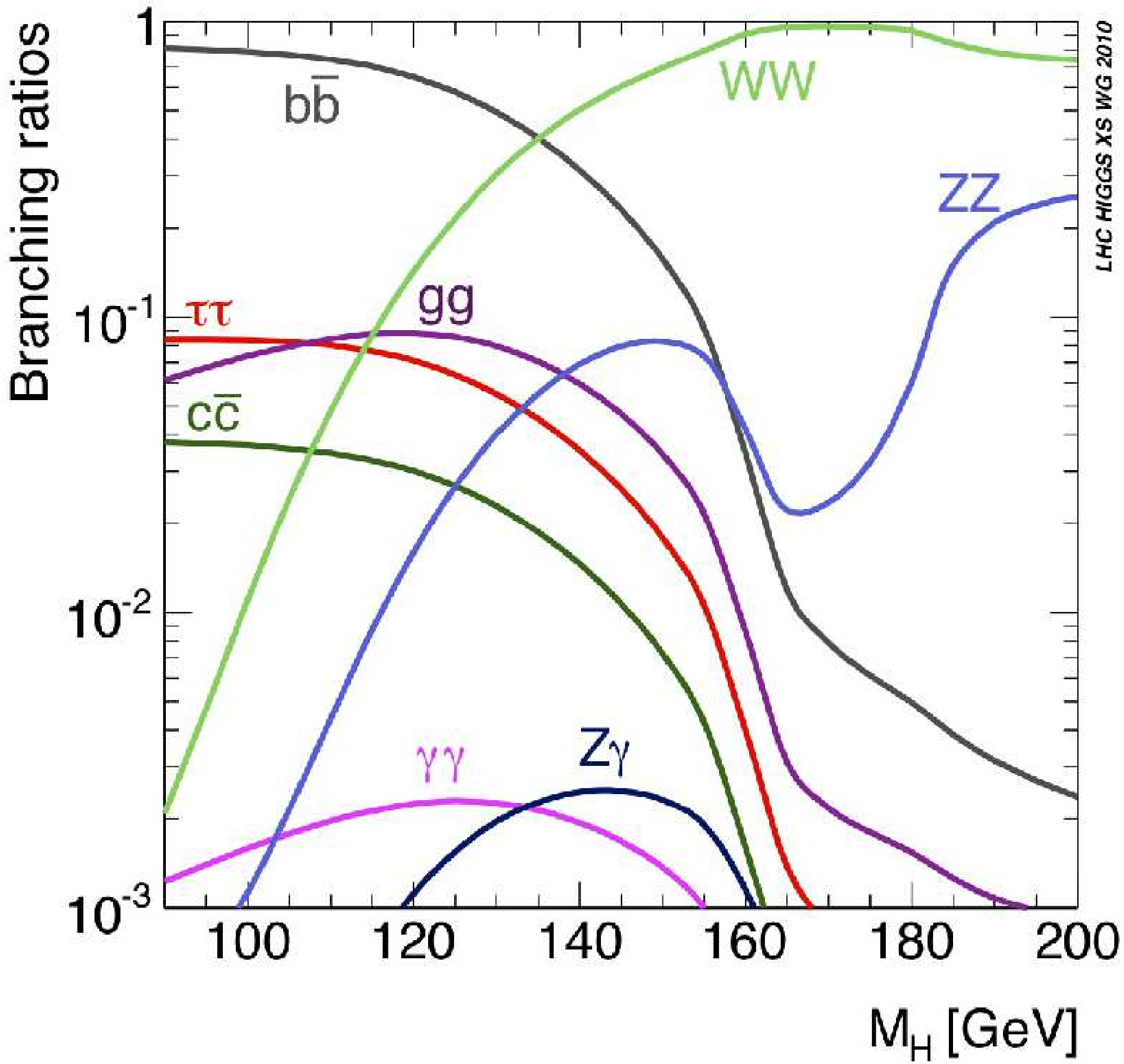
- Quantum Corrections



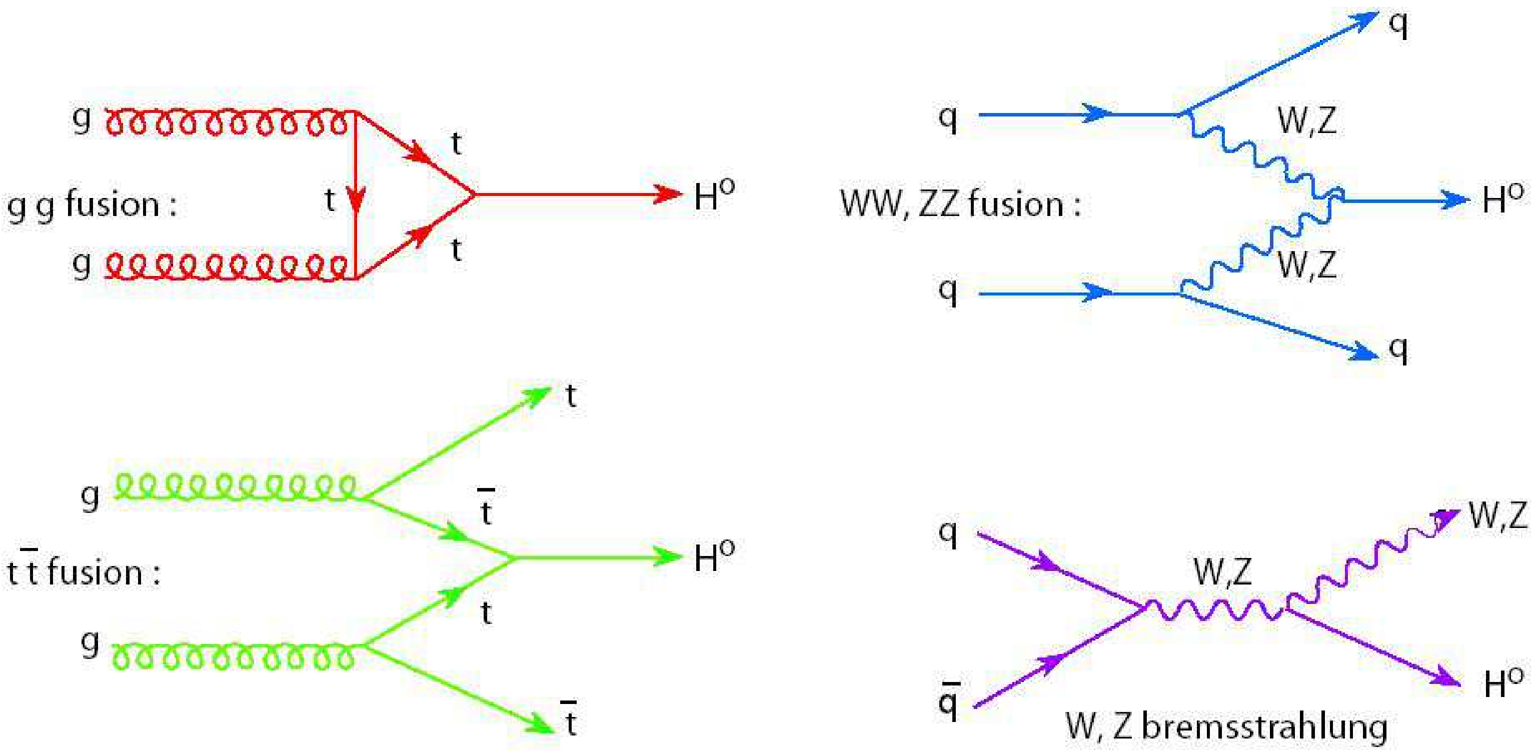

- **Photon**: all charged fermions contribute, plus $W^{\pm}$
- **Gluon**: all quarks contribute
- But top contribution largest
- Loop suppressed, but still essential, can even dominate
- Higher order corrections known (NNLO QCD for prod.: 3-loop!)

# Higgs Decay Branching Ratios

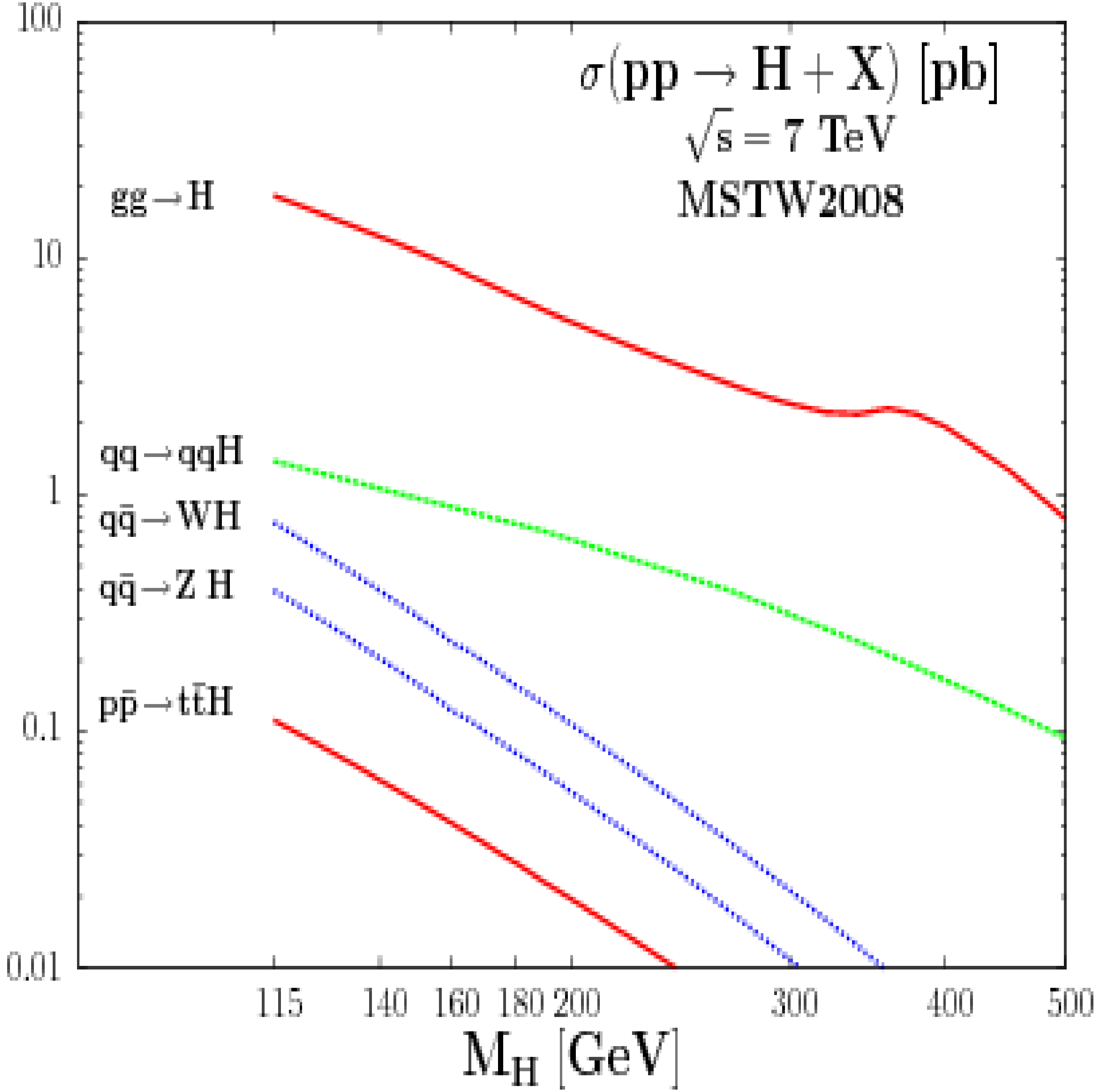



- A lot of theory effort in both this and production cross sections.

# Higgs Production

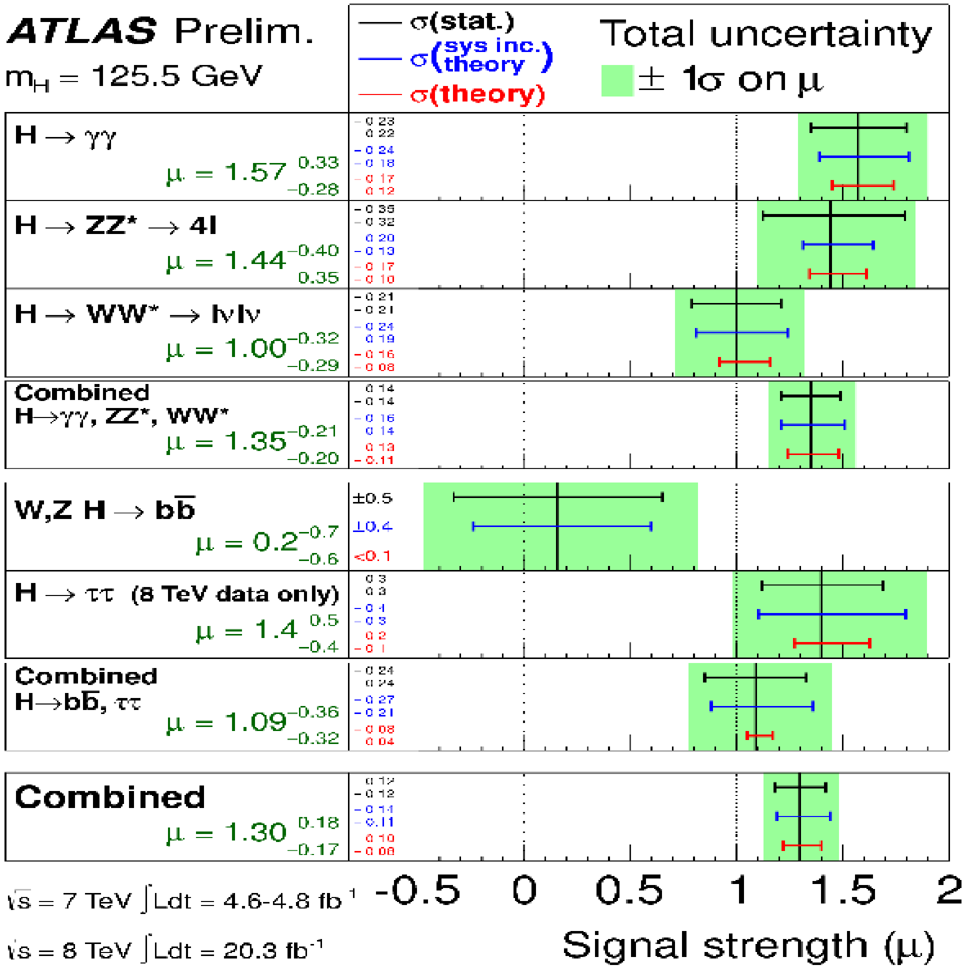


# Higgs Production



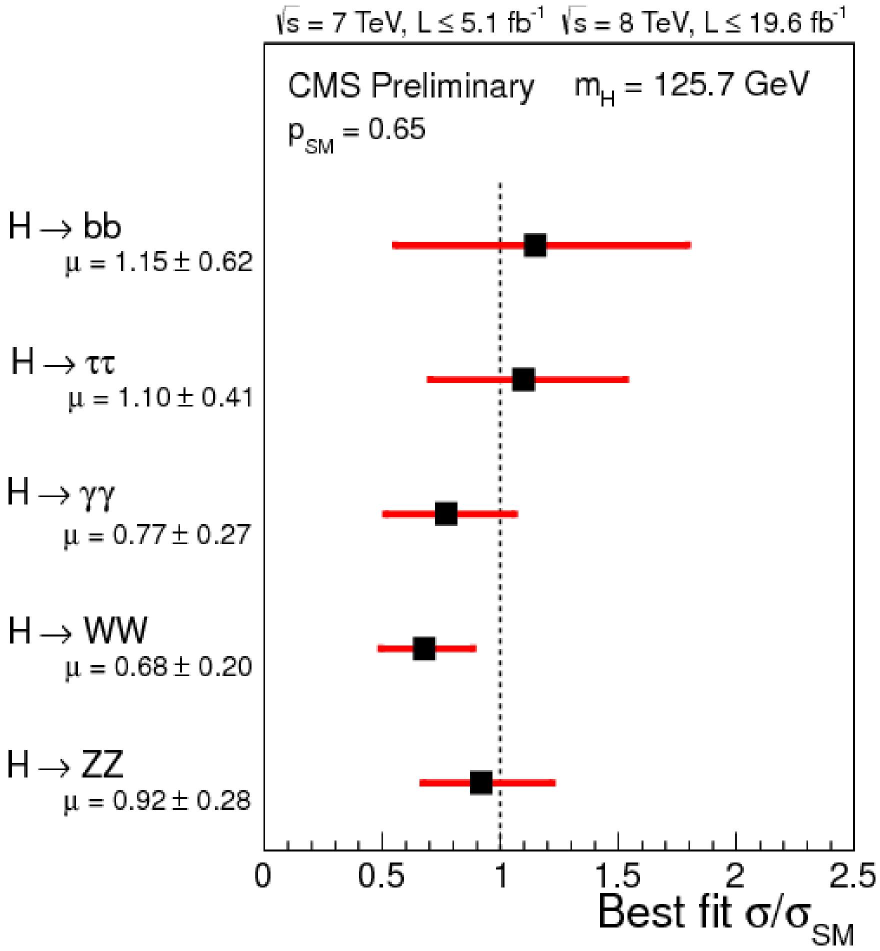
# Higgs Couplings Strengths, ATLAS

- $\mu_i = (\sigma \times BR)_i / (\sigma \times BR)_i^{SM}$



# Higgs Couplings Strengths, CMS

- $\mu_i = (\sigma \times BR)_i / (\sigma \times BR)_i^{SM}$



# Meta Stability

Butazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia

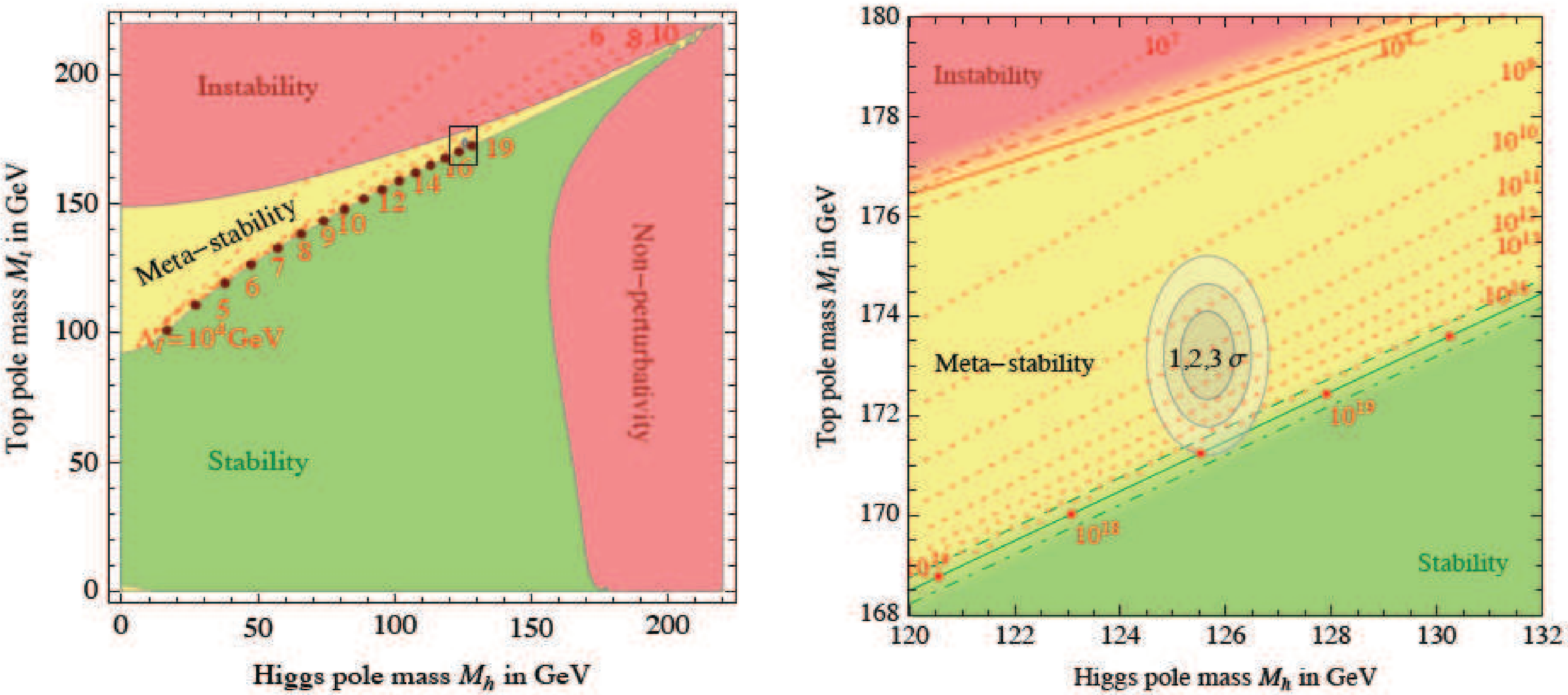



Figure 3: **Left**: *SM phase diagram in terms of Higgs and top pole masses. The plane is divided into regions of absolute stability, meta-stability, instability of the SM vacuum, and non-perturbativity of the Higgs quartic coupling. The top Yukawa coupling becomes non-perturbative for* $M_t > 230$ GeV*. The dotted contour-lines show the instability scale* $\Lambda_I$ *in* GeV *assuming* $\alpha_3(M_Z) = 0.1184$. **Right**: *Zoom in the region of the preferred experimental range of* $M_h$ *and* $M_t$ *(the grey areas denote the allowed region at 1, 2, and* $3\sigma$*). The three boundary lines correspond to 1-*$\sigma$ *variations of* $\alpha_3(M_Z) = 0.1184 \pm 0.0007$*, and the grading of the colours indicates the size of the theoretical error.*

# Higgs Width

Caola, Melnikov, PRL 2013

- $H \to ZZ \to e e \mu\mu$
- $gg \to ZZ \to e e \mu\mu$

FIG. 1: Sample signal (left) and background $gg \to ZZ$ (right) diagrams for the process $pp \to ZZ \to 4l$. The two amplitudes can interfere.

- $\frac{d\sigma_{pp\to H\to ZZ}}{dM^2_{4\ell}} \sim \frac{g^2_{Hgg} g^2_{HZZ}}{(M^2_{4\ell}-m^2_H)^2+m^2_H \Gamma^2_H}$
- Narrow width approximation: $\sigma_{i\to H\to f} \sim \frac{g_i^2 g_f^2}{\Gamma_H}$
- Rescale: $g = \xi g_{SM}$, $\Gamma_H = \xi^4 \Gamma_{H,SM}$
- Dominant contribution at resonance, where $\Gamma_H$ effectively drops out, or is well below detector resolution
- But **off-peak** scaling doesn't cancel. Can bound $\xi$ from off-shell $ZZ$ production rate, including interference!

# Higgs Width II

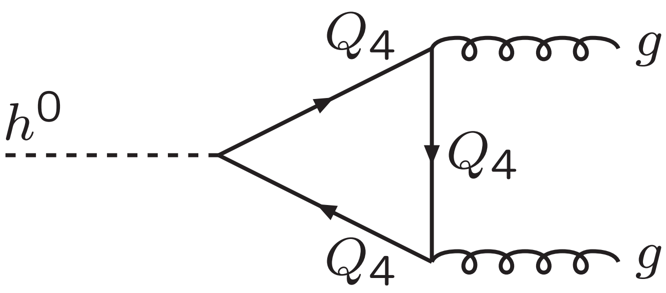
- Caola & Melnikov estimated sensitivity of $\Gamma_{\text{H}} \sim 10 \times \Gamma_{\text{H,SM}}$
- CMS-Experiment, 20.3.2014(!): $\Gamma_{\text{H}} < 4.2 \times \Gamma_{\text{H,SM}}$, @95% C.L.
- With $\Gamma_{\text{H,SM}} = 4.2\,\text{MeV}$
- Also used $2\ell 2\nu$ signature
- If improved, could be important for Higgs invisible width, $h^0 \to \chi_1^0 \chi_1^0$

# Open Questions in Standard Model

1. 3 generations, CP-violation
2. Flavor Problem, 19 Parameters
3. Charge Quantisation, Unification
4. Neutrinos
5. **Hierarchy Problem**
6. Dark Matter
7. Baryo- and Leptogenesis
8. Dark Energy

# Fourth Generation

- A fourth quark generation would contribute significantly to the Higgs production rate, altering the $\mu_i$'s.




- It is excluded by the Higgs data

Eberhardt, Herbert, Lacker, Lenz, Menzel, Nierste, Wiebusch, PRL (2012)

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# FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

**Leptons** spin = 1/2

| Flavor | | Mass GeV/$c^2$ | Electric charge |
|---|---|---|---|
| $\nu_e$ | electron neutrino | $<1\times10^{-8}$ | 0 |
| e | electron | 0.000511 | –1 |
| $\nu_\mu$ | muon neutrino | <0.0002 | 0 |
| $\mu$ | muon | 0.106 | –1 |
| $\nu_\tau$ | tau neutrino | <0.02 | 0 |
| $\tau$ | tau | 1.7771 | –1 |

**Quarks** spin = 1/2

| Flavor | | Approx. Mass GeV/$c^2$ | Electric charge |
|---|---|---|---|
| u | up | 0.003 | 2/3 |
| d | down | 0.006 | –1/3 |
| c | charm | 1.3 | 2/3 |
| s | strange | 0.1 | –1/3 |
| t | top | 175 | 2/3 |
| b | bottom | 4.3 | –1/3 |

- Many ideas, but completely unsolved. Maybe: A. Chamseddine, A Connes JHEP 1311 (2013) 132

- Running out of predictions, as well.

# Flavor Problem

- Predict the Higgs Yukawa couplings: $Y_e \bar{L}_e \Phi e_R$
- Lepton masses $m_{e,\mu,\tau}$; Quark masses: $m_{u,c,t}$, $m_{d,s,b}$. $\rightarrow$ 9 Parameter
- 3 mixing angles, 1 complex phase
- Where do these parameters come from?

# Open Questions in Standard Model

1. 3 generations, CP-violation
2. Flavor Problem, 19 Parameters
3. Charge Quantisation, Unification, **Grand Unified Theories (GUTs)**
4. Neutrinos
5. **Hierarchy Problem**
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# Neutrinos

- Neutrinos are massless in SM
- Observed neutrino oscillations: at least two are massive
- Also: now know 3 mixing angles. Complex phase(s) constrained
- **QUESTIONS**:
- do $\nu_R$ exist?
- Majorana mass? $m\left(L^T i\sigma_2\vec{\sigma}CL\right)\cdot\left(\Phi^T i\sigma_2\vec{\sigma}C\Phi\right)$ (Weinberg operator)
- Dirac mass with $\nu_R$?
- See-saw with heavy $\nu_R$ Majorana mass?
- No-see saw as in one variant of supersymmetry?

# Open Questions in Standard Model

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# Hierarchy Problem

## The Problem:

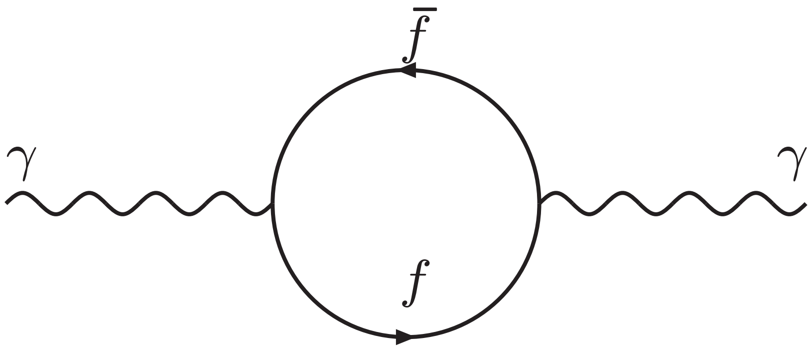
**IF** there is a new, high, scale of physics, $M_X$, due to quantum corr. the natural value of the Higgs mass is $M_{h^0} = \mathcal{O}(M_X)$.

- Only exists if there is a new high scale......like Planck scale of gravity
- If the SM is nature's final answer, and valid to $\infty$ energies, there is **NO** hierarchy problem.
- Why is the Higgs mass special?

— It's a scalar, spin-0, the only in SM

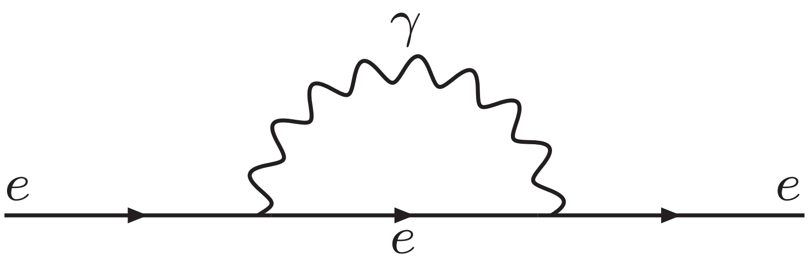
# Quantum Mass Corrections M. Drees, hep-ph/9611409

- **Spin–1, photon**




$\Pi^{\mu\nu}_{\gamma\gamma}(0) = 0$, by gauge symmetry

- **Spin–1/2 electron**




$$\Pi_{ee}(0) = -4e^2 m_e \int^{\Lambda} \frac{d^4k}{(2\pi)^4} \frac{1}{k^2(k^2 - m_e^2)}$$

$$\delta m_e \simeq 2\frac{\alpha_{\text{em}}}{\pi} m_e \log \frac{M_{\text{Pl}}}{m_e} \simeq 0.24 m_e$$

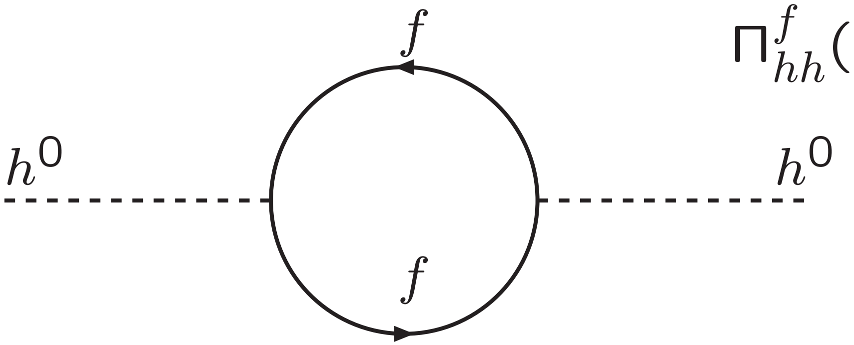
- Proportional to electron mass.

- As $m_e \to 0$ extra symmetry: $\psi_e \to \exp(i\gamma_5\phi)\psi_e$

# Quantum Mass Corrections II

- **Spin-0, Higgs**

$$\Pi^f_{hh}(0) = -2N(f)\lambda_f^2 \int^\Lambda \frac{d^4k}{(2\pi)^4}\left(\frac{1}{k^2-m_f^2} + \frac{2m_f^2}{(k^2-m_f^2)^2}\right)$$




$$\Pi^f_{hh}(0) \simeq \Lambda^2$$

- Correction to $m_h^2$ goes as $\Lambda^2$, thus never small.
- If no higher scale, $\Lambda \to \infty$, $\delta m_h$ absorbed in renormalization of $m_h$
- $\Lambda$ never appears in physical results and all is fine.
- But if extra scale exists need to fine-tune finite corrections at $M_X$ to get $m_h = \mathcal{O}(M_W)$ (drawing)
- Solution $\longrightarrow$ **Supersymmetry**

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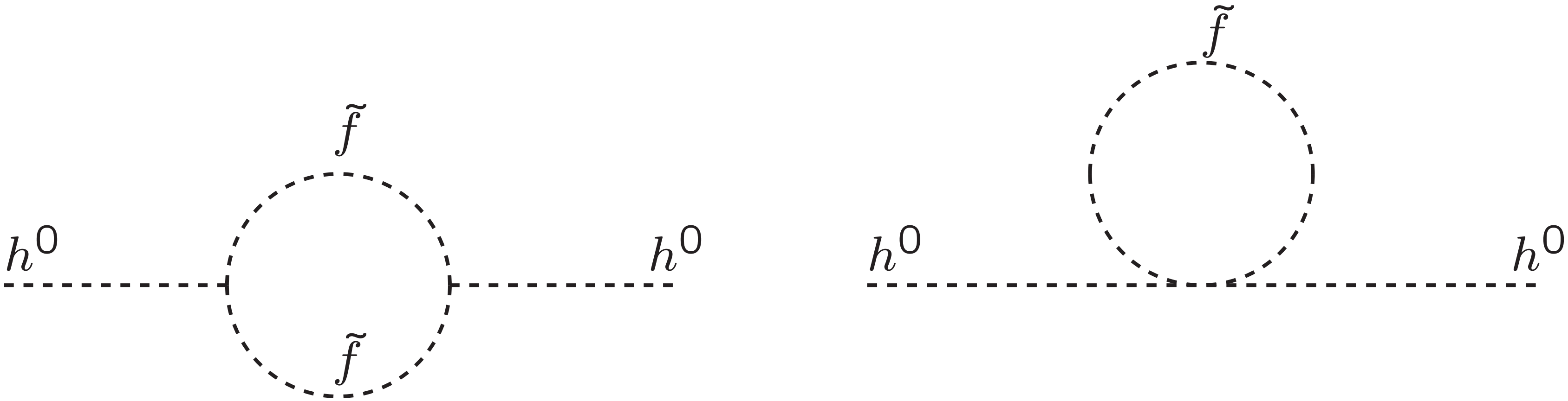
# Supersymmetry

$$\mathscr{L}_{h\tilde{f}} = \frac{1}{2}\tilde{\lambda}_f h^2 \left(|\tilde{f}_L|^2 + |\tilde{f}_R|^2\right) + v\tilde{\lambda}_f h \left(|\tilde{f}_L|^2 + |\tilde{f}_R|^2\right) + \left(\frac{\lambda_f}{\sqrt{2}} A_f h \tilde{f}_L \tilde{f}_R + h.c.\right)$$




- Opposite sign: bosons
- Right diagram cancels $\Lambda^2$ divergence, if: $N(\tilde{f}_L) = N(\tilde{f}_R) = N(f)$

$$\tilde{\lambda} = -\lambda_f^2$$

- Supersymmetry automatically guarantees this

# SUPERSYMMETRY

**BASIC IDEA:** $|\mathbf{FERMION}\rangle \overset{Q}{\longleftrightarrow} |\mathbf{BOSON}\rangle$

**INFINITESIMAL FIELD TRANSFORMATION:**

SCALAR: $\phi \longrightarrow \phi' = \phi + \Delta\phi$

FERMION: $\psi \longrightarrow \psi' = \psi + \Delta\psi$

$$\Delta\phi = \epsilon \cdot |\mathbf{FERMION}\rangle$$

$$\Delta\psi = \epsilon \cdot |\mathbf{BOSON}\rangle$$

$\epsilon$ is a constant spinor in global supersymmetry.

# SUSY SPECTRUM

Standard Model + SUSY $\Longrightarrow$ Double Spectrum (+2 Higgs Doublets)

| | | | |
|---|---|---|---|
| $e^-$ (spin $= \frac{1}{2}$) | $\longleftrightarrow$ | $\tilde{e}$ $(s = 0)$ | scalar electron |
| top $t$ $(s = \frac{1}{2})$ | $\longleftrightarrow$ | $\tilde{t}$ $(s = 0)$ | scalar top |
| $W^\pm$ $(s = 1)$ | $\longleftrightarrow$ | $\tilde{W}^\pm$ $(s = \frac{1}{2})$ | Wino |
| $H^\pm$ $(s = 0)$ | $\longleftrightarrow$ | $\tilde{H}^\pm$ $(s = \frac{1}{2})$ | Higgsino |
| $\gamma$, $Z^0$ $(s = 1)$ | $\longleftrightarrow$ | $\tilde{\gamma}$, $\tilde{Z}^0$ $(s = \frac{1}{2})$ | Photino, Zino |
| $H^0$, $h^0$ $(s = 0)$ | $\longleftrightarrow$ | $\tilde{H}^0$, $\tilde{h}^0$ $(s = \frac{1}{2})$ | Higgsino |
| $g_{a=1,\ldots,8}$ $(s = 1)$ | $\longleftrightarrow$ | $\tilde{g}_a$ $(s = \frac{1}{2})$ | Gluino |

**MIXING:** After $SU(2)_L \times U(1)_Y \longrightarrow U(1)_{EM}$

| | | | |
|---|---|---|---|
| $\tilde{W}^\pm,\ \tilde{H}^\pm$ | $\xrightarrow{\text{MIX}}$ | $\tilde{\chi}^\pm_{i=1,2}$ | Charginos |
| $\tilde{\gamma},\ \tilde{Z}^0,\ \tilde{h}^0,\ \tilde{H}^0$ | $\xrightarrow{\text{MIX}}$ | $\tilde{\chi}^0_{i=1,2,3,4}$ | Neutralinos |

# SUPERFIELDS

- Combine $\psi_e$ and $\phi_{\tilde{e}}$ into chiral superfield

$$\Phi_e \sim \phi_{e_L} + \epsilon\psi_{e_L} = E_L, \qquad \Phi_{u^c} \sim \phi^*_{u_R} + \epsilon\psi^c_{u_R} = U^c$$

Construct function $W(\Phi_i)$, holomorphic (no $\Phi^\dagger$) & gauge invariant

Use chiral SUSY Fields:

$$L = \begin{pmatrix} N \\ E \end{pmatrix}_L \sim \begin{pmatrix} \phi_{\tilde{\nu}} + \epsilon\psi_\nu \\ \phi_{\tilde{e}} + \epsilon\psi_e \end{pmatrix}_L, \qquad E^c \sim \phi^*_{\tilde{e}} + \epsilon\psi^c_{e_R}$$

$$Q = \begin{pmatrix} U \\ D \end{pmatrix}_L \sim \begin{pmatrix} \phi_{\tilde{u}} + \epsilon\psi_u \\ \phi_{\tilde{d}} + \epsilon\psi_d \end{pmatrix}_L, \qquad U^c \sim \phi^*_{\tilde{u}} + \epsilon\psi^c_{u_R}, \qquad D^c \sim \phi^*_{\tilde{d}} + \epsilon\psi^c_{d_R}$$

- Plus Higgs superfields: $H_1$, $H_2$
- Gauge interactions fixed.
- **What is the gauge invariant superpotential?**

# SUPERPOTENTIAL

$$W_{P_6} = (h_e)_{ij}\, L_i H_1 E^c_j + (h_d)_{ij}\, Q_i H_1 D^c_j + (h_u)_{ij}\, Q_i H_2 U^c_j + \mu H_1 H_2$$

- These terms give mass to quarks and leptons. This is not all though!

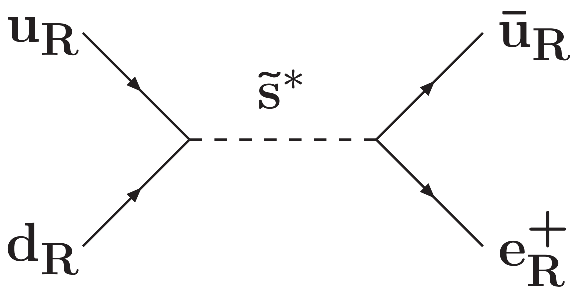
$$W_{\not{P}_6} = \underbrace{\lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \kappa_i L_i H_2}_{\text{Lepton Number Violating}} + \underbrace{\lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k}_{\text{Baryon Num. Viol.}}$$

Lepton Number Violating Baryon Num. Viol.

- Together these lead to rapid proton decay

# PROTON DECAY

- Together LQD and UDD lead to Rapid Proton Decay




- Resulting in the Strict Bound:

$$\boxed{\lambda'_{i1j} \cdot \lambda''_{11j} < 2 \cdot 10^{-27} \left( \frac{M_{\tilde{d}_j}}{100\ \text{GeV}} \right)^2 , \quad i = 1, 2\,,\ j \neq 1\,,}$$

- Therefore the SSM as Defined is Experimentally Excluded

- At least one Coupling must be Zero: Guaranteed by a Symmetry

# Supersymmetry + Extra Symmetry

- **R-parity**: no extra terms, proton stable, dark matter candidate
- **Baryon-Parity**: $LL\bar{E}$, $LQ\bar{D}$, $LH_2$
  - Lepton number violated $\mu \to e\gamma$
  - Neutrino masses with $\nu_L$'s only
  - Dark matter: axino, or gravitino

# Supersymmetry, Basics

- Supersymmetry Generator commutes with mass operator

$$\left[Q_\alpha, \text{Mass}^2\right] = 0$$

- $\Longrightarrow$ $$\text{Mass(e)} = \text{Mass}(\tilde{\text{e}}) \quad \lightning$$

- Supersymmetry must be broken

- No consensus on SUSY breaking mechanism

- SUSY breaking masses, $\text{Mass}(\tilde{\text{e}})$, spoil cancellation of $\Lambda^2$ divergence

- To avoid fine-tuning must have: $\text{Mass}(\tilde{\text{e}})$, $\text{Mass}(\tilde{\text{q}}) < \mathcal{O}(1\,\text{TeV})$,

- Will be tested (conclusively) by next run of LHC

# Fine-tuning in SUSY Models

Kaminska, Ross, Schmidt-Hoberg

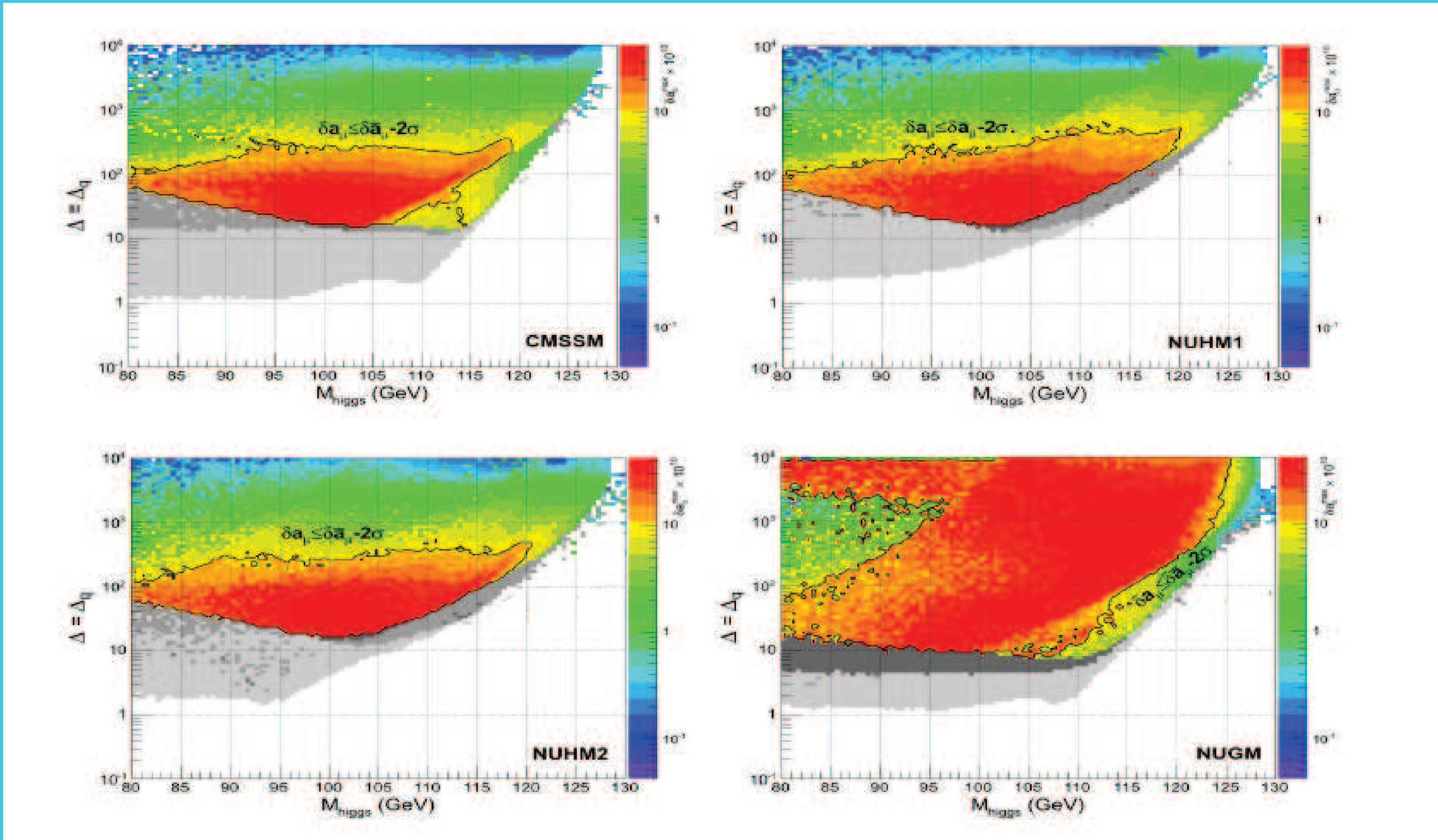
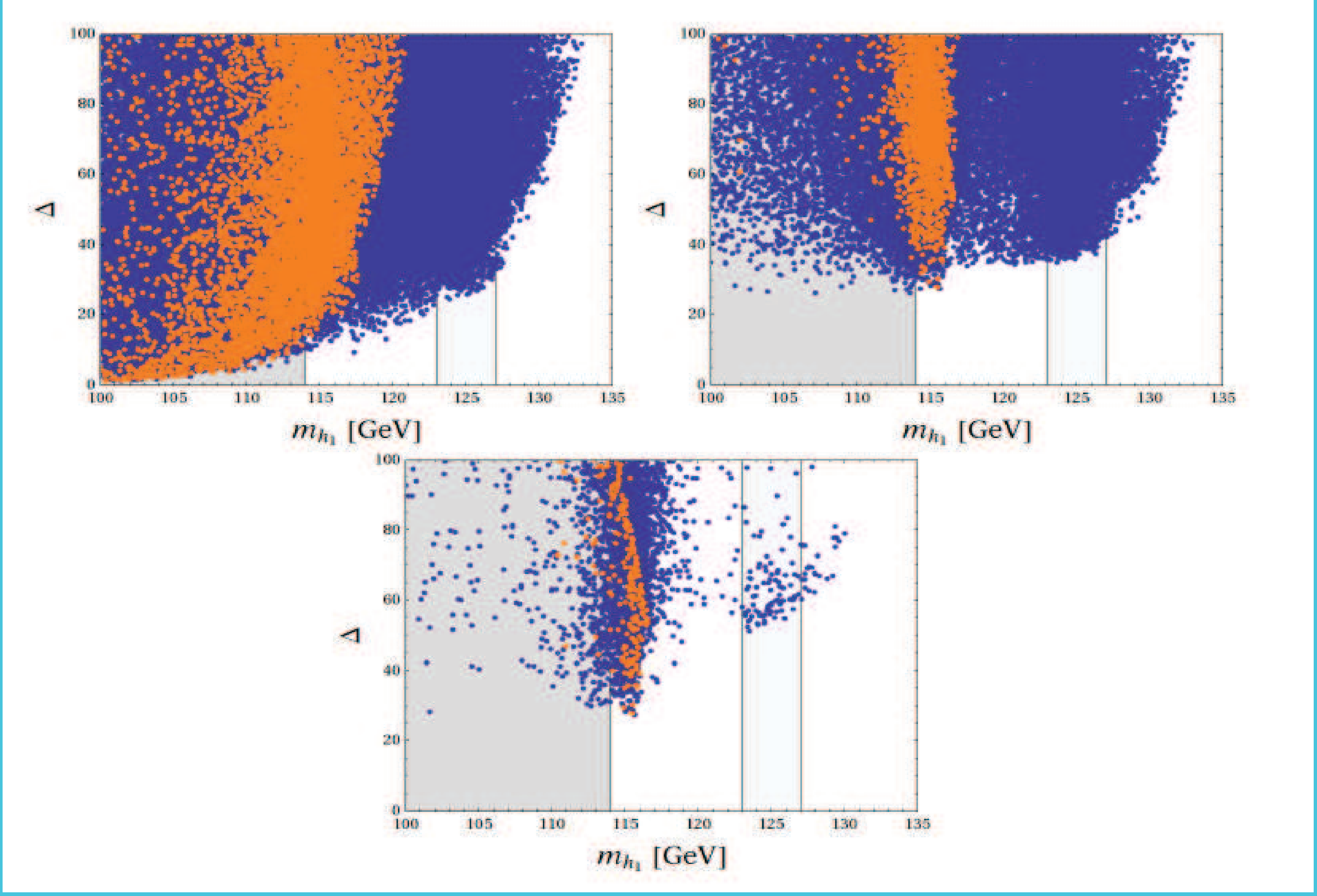


**Figure 1:** $\Delta_q$ versus $M_{higgs}$ in various models, from ref.[2]; lightest grey (0) area: excluded by SUSY mass bounds; darker grey (1): excluded by $b \to s\gamma, B \to \mu^+\mu^-$, $\delta\rho$; dark grey (2): excluded by condition $\delta a_\mu \geq 0$. Area inside the closed contour: allowed by data and with $2\sigma$ deviation of $g-2$: $\delta a_\mu \leq (25.5+2\times 8)10^{-10}$; $\delta a_\mu^{max}$ is shown colour encoded. Area outside closed contour: $\delta a_\mu^{max} \leq (25.5-2\times 8)10^{-10}$ ($2\sigma$). Only in the NUGM is one close to satisfying the $g-2$ constraint within $2\sigma$, not too surprising given its non-universal gaugino masses. In all plots the dark matter relic density was computed [14] and can be fitted within $3\sigma$ [2]. For similar plots in NMSSM or GNMSSM see [15] while for the GNMSSM in the limit of a massive gauge singlet (integrated out) see plots in [16].

# Fine-tuning in SUSY Models
Ross, Schmidt-Hoberg, Staub




• CMSSM, • CGNMSSM

Figure 1: Fine-tuning vs. the lightest Higgs mass in the CGNMSSM case with universal boundary conditions for the CMSSM (orange), and the CGNMSSM (blue). The first plot corresponds to the unconstrained case, the second plot takes into account the LHC bounds on particle masses with a cut on squark and gluino masses of 1.2 TeV and the third plot assumes an additional upper bound on the neutralino relic density.

# The Question of Mass

- Note the Mass of the Proton is NOT due to the Higgs Mechanism

- The proton mass is a dynamical effect in QCD $\longrightarrow$ many Gluons inside Proton

- Therefore our masses are a QCD Effect!

- The Bohr Radius: $R_0 = \dfrac{\hbar}{m_e c \alpha}$

- Higgs mechanism $\longrightarrow m_e$

- Only dimensionful parameter in $R_0$, together with $\alpha$, determines the size of our world

# Summary

- Standard Model of Particle Physics extremely successful (best ever!)
- The Higgs is an amazing breakthrough, giving new insights
- Still very many open questions
- Supersymmetry is a promising solution to the hierarchy problem.
- There are many variants. The simplest are severely under the weather.