# A general perspective on BSM physics

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# Outline

- The Standard Model: reminders and notations
- Model-independent, bottom-up approach to physics BSM
- Composite Higgs and extra-dimensions
- Supersymmetry

# The SM
# as a renormalizable theory

# The (ren) Standard Model lagrangian

| | | |
|---|---|---|
| $$\mathcal{L}_{\rm SM}^{\rm ren} = \bar\Psi_i i\gamma^\mu D_\mu \Psi_i - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu}$$ | gauge | few ‰ |
| $$+\lambda_{ij}\Psi_i\Psi_j H + \text{h.c.}$$ | flavor | few % |
| $$+\|D_\mu H\|^2 - V(H)$$ | symmetry breaking | ? (indirect) |

- An extremely successful synthesis of particle physics
- in compact notations
- i = 1,2,3: family index
- + neutrinos mass operator: LLHH

# The gauge sector

$G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$

$$q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}$$

$$l_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}$$

| | $SU(3)_c$ | $SU(2)_L$ | $U(1)_Y$ |
|---|---|---|---|
| $l_i$ | 1 | 2 | -1/2 |
| $e^c{}_i$ | 1 | 1 | 1 |
| $q_i$ | 3 | 2 | 1/6 |
| $u^c{}_i$ | $3^*$ | 1 | -2/3 |
| $d^c{}_i$ | $3^*$ | 1 | 1/3 |

Y

L-handed
2-component
spinors

i = 1,2,3

# A nice property

- The fermion content is chiral
- I.e. no explicit ($G_{SM}$ symmetric) fermion mass term is allowed
- A puzzle or what expected?
- Extra fermions should be vectorlike
(unless they get mass through EWSB)

# Another nice property

- Anomaly cancellation
- Is $T_{ijk} \equiv \mathrm{Tr}\,(\tau_i\,\{\tau_j, \tau_k\}) = 0$?      $\tau_i = T_A, T_a, Y$

| | |
|---|---|
| $SU(3)^3$ | vectorlike |
| $SU(3)^2 \times SU(2)$ | $\mathrm{Tr}(\sigma_a) = 0$ |
| $SU(3)^2 \times U(1)$ | $2\,Y_q + Y_{u^c} + Y_{d^c} = 0$ |
| $SU(3) \times (\text{not } SU(3))^2$ | $\mathrm{Tr}(\lambda_A) = 0$ |
| $SU(2)^2 \times U(1)$ | $Y_l + 3Y_q$ |
| $U(1)^3$ | $2Y_l^3 + 6Y_q^3 + 3Y_{u^c}^3 + 3Y_{d^c}^3 + Y_{e^c}^3 = 0$ |
| grav. anomaly | $2Y_l + 6Y_q + 3Y_{u^c} + 3Y_{d^c} + Y_{e^c} = 0$ |

(nice, but why??)

# Tree level tests of the gauge sector

- Fermion gauge interactions:

$$\overline{\Psi} i\hat{D}\Psi = \overline{\Psi} i\hat{\partial}\Psi - \left(\frac{g}{\sqrt{2}} j_c^\mu W_\mu^+ + \text{h.c.}\right) - \frac{g}{c_W} j_n^\mu Z_\mu - e j_{\text{em}}^\mu A_\mu - g_s j_s^{\mu A} g_\mu^A$$

$$j_c^\mu = \overline{\nu_{iL}}\gamma^\mu e_{iL} + \overline{u_{iL}}\gamma^\mu d_{iL}, \quad j_n^\mu = \sum \overline{f_X}\gamma^\mu (T^3 - s_W^2 Q) f_X$$

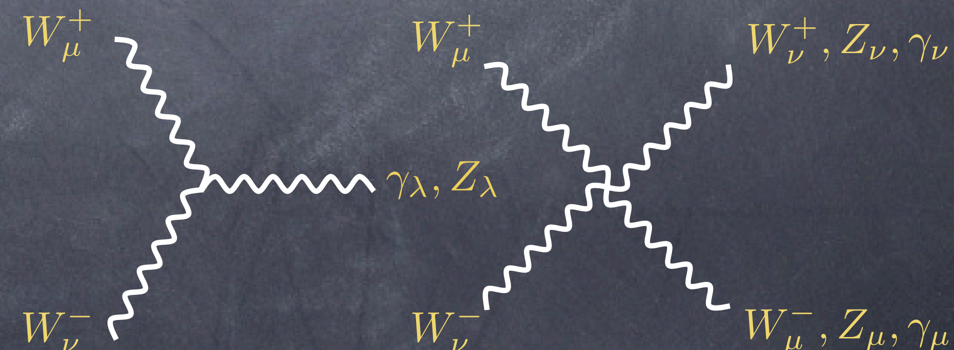
$$(f = \nu_i, e_i, u_i, d_i,\ X = L, R)$$

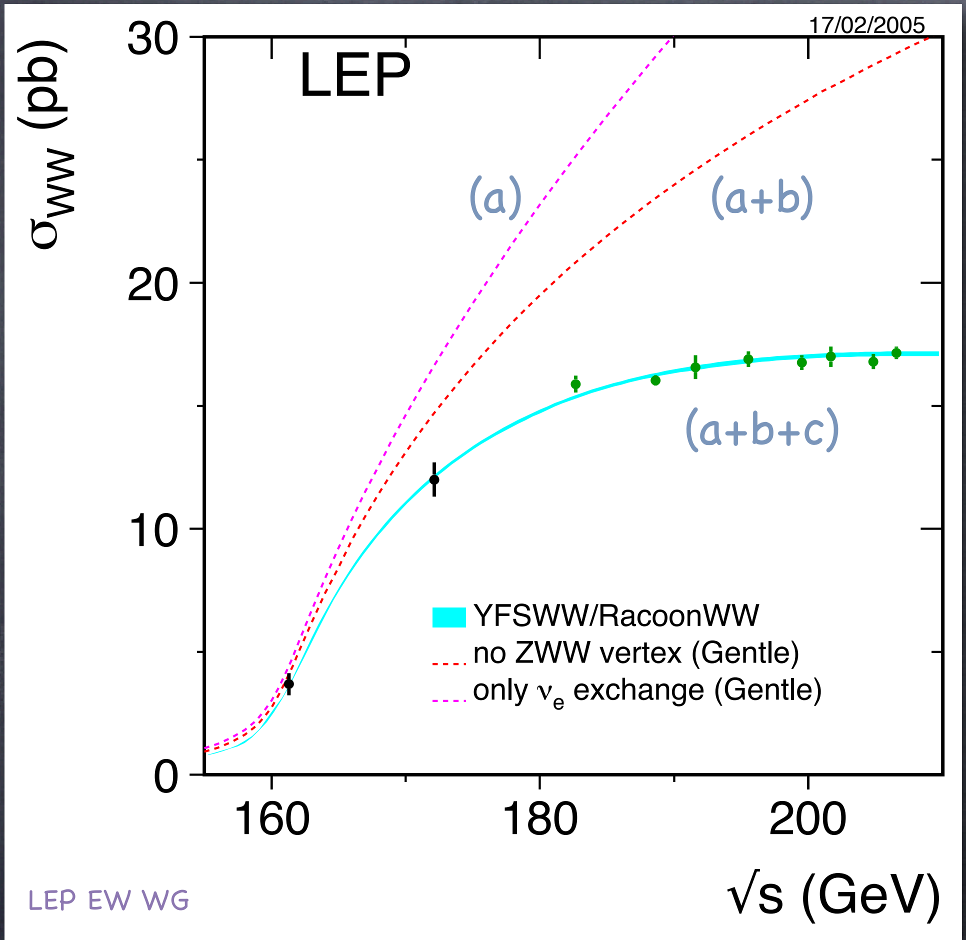
- Gauge boson self-interactions: from $-\frac{1}{4} W_{\mu\nu}^a W^{\mu\nu a}$

$$W_{\mu\nu}^a = \partial_\mu W_\nu^a - \partial_\nu W_\mu^a - g\epsilon_{abc} W_\mu^b W_\nu^c$$

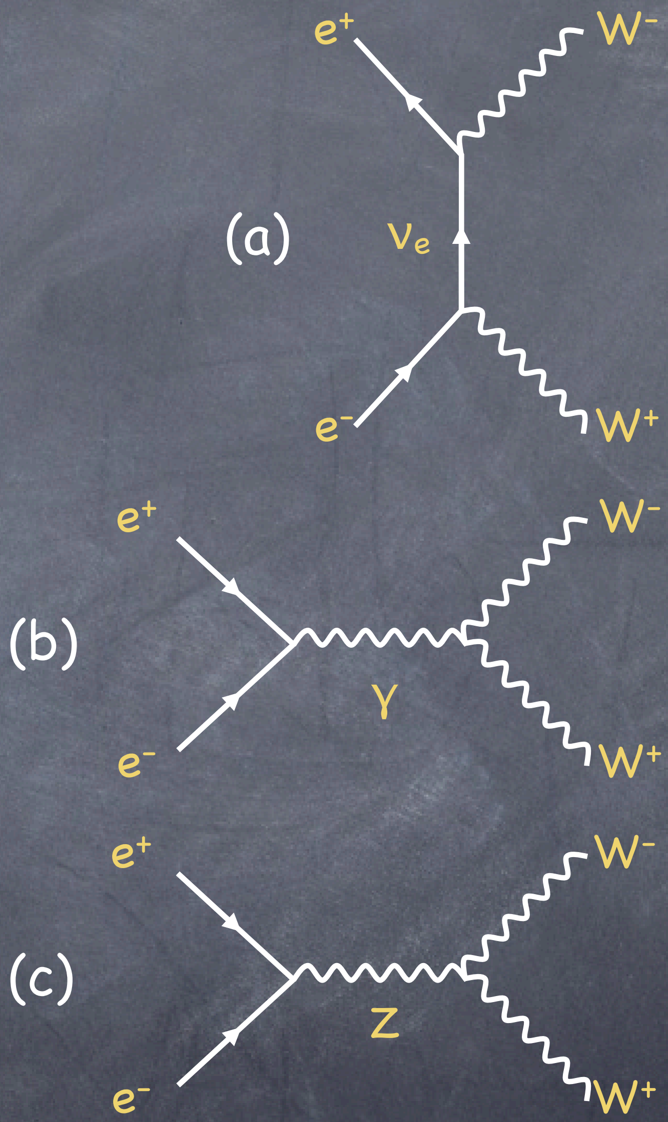
$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

in terms of mass eigenstates:





17/02/2005
LEP
σWW (pb)
(a)
(a+b)
(a+b+c)
YFSWW/RacoonWW
no ZWW vertex (Gentle)
only νe exchange (Gentle)
30
20
10
0
160
180
200
√s (GeV)
LEP EW WG

(a)
e+
W-
νe
e-
W+
(b)
e+
W-
γ
e-
W+
(c)
e+
W-
Z
e-
W+

# The flavour sector

$$\mathcal{L}_{\rm SM}^{\rm ren} = \begin{array}{ll} \bar\Psi_i i\gamma^\mu D_\mu \Psi_i - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} & \text{gauge} \\ +\lambda_{ij}\Psi_i\Psi_j H + \text{h.c.} & \text{flavor} \\ +|D_\mu H|^2 - V(H) & \text{symmetry breaking} \end{array}$$

family number (horizontal) not understood

| | 1 | 2 | 3 |
|---|---|---|---|
| l | $l_1$ | $l_2$ | $l_3$ |
| $e^c$ | $(e^c)_1$ | $(e^c)_2$ | $(e^c)_3$ |
| q | $q_1$ | $q_2$ | $q_3$ |
| $u^c$ | $(u^c)_1$ | $(u^c)_2$ | $(u^c)_3$ |
| $d^c$ | $(d^c)_1$ | $(d^c)_2$ | $(d^c)_3$ |

gauge irreps (vertical) well understood

The flavour sector allows to tell the three families: gauge interactions are $U(3)^5$ symmetric

# U(3)^5

$$\mathcal{L}_{\rm SM}^{\rm ren} = \begin{array}{ll} \bar\Psi_i i\gamma^\mu D_\mu \Psi_i - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} & \text{gauge} \\ +\lambda_{ij}\Psi_i\Psi_j H + \text{h.c.} & \text{flavor} \\ +|D_\mu H|^2 - V(H) & \text{symmetry breaking} \end{array}$$

The flavour (Yukawa) lagrangian is is not U(3)^5 invariant (unless $\lambda_{ij}=0$)

$$U(3)^5: \quad \begin{array}{l} l_i \to U^l_{ij} l_j \\ e^c_i \to U^{e^c}_{ij} e^c_j \\ q_i \to U^q_{ij} q_j \\ u^c_i \to U^{u^c}_{ij} u^c_j \\ d^c_i \to U^{d^c}_{ij} d^c_j \end{array} \quad \Rightarrow \quad \begin{array}{l} \lambda_E \to U^T_{e^c}\lambda_E U_L \\ \lambda_D \to U^T_{d^c}\lambda_D U_Q \\ \lambda_U \to U^T_{u^c}\lambda_U U_Q \end{array} \qquad \begin{array}{l} \mathcal{L}_{\rm SM}^{\rm gauge} \to \mathcal{L}_{\rm SM}^{\rm gauge} \\ \mathcal{L}_{\rm SM}^{\rm SB} \to \mathcal{L}_{\rm SM}^{\rm SB} \\ \langle h \rangle \to \langle h \rangle \end{array}$$

$$\mathcal{L}_{\rm SM}^{\rm flavor} = \lambda^E_{ij} e^c_i l_j H^\dagger + \lambda^D_{ij} d^c_i q_j H^\dagger + \lambda^U_{ij} u^c_i q_j H + \text{h.c.}$$

# Accidental symmetries (ren lagrangian)

- The flavour lagrangian breaks $U(3)^5 \times U(1)_H$ to $U(1)_e \times U(1)_\mu \times U(1)_\tau \times U(1)_B \times U(1)_Y$

- In an appropriate flavour basis (i.e. through $U(5)^5$ transformation)

$$\lambda^E_{ij} e^c_i L_j H^\dagger \to \lambda_{e_i} e^{c\prime}_i L'_i H^\dagger$$
$$\lambda^D_{ij} d^c_i Q_j H^\dagger \to \lambda_{d_i} d^{c\prime}_i Q'_i H^\dagger$$
$$\lambda^U_{ij} u^c_i Q_j H \to \lambda_{u_i} V_{ij} u^{c\prime}_i Q'_i H$$

- $L_e$ $L_\mu$ $L_\tau$: individual lepton numbers

- $L = L_e + L_\mu + L_\tau$: (total) lepton number - arises automatically! (at ren level)

- B: Baryon number - arises automatically! (at ren level)

- (neutrino masses and mixing are a source of LFV; here they are likely to be associated to the NR part of the lagrangian)

# No tree level FCNC

- Fermion masses: $H = \begin{pmatrix} 0 \\ v + \frac{h}{\sqrt{2}} \end{pmatrix}$ (unitarity gauge)

$$\begin{aligned} \mathcal{L}_{\text{SM}}^{\text{flavor}} &= \lambda_{ij}^{E} e_i^c L_j H^\dagger + \lambda_{ij}^{D} d_i^c Q_j H^\dagger + \lambda_{ij}^{U} u_i^c Q_j H + \text{h.c.} \\ &= m_{ij}^{E} e_i^c e_j \quad + m_{ij}^{D} d_i^c d_j \quad + m_{ij}^{U} u_i^c u_j \quad + \text{h.c.} + \ldots \end{aligned}$$

- In terms of mass eigenstates:

$$j^\mu_{\text{c,had}} = \overline{u}_i \sigma^\mu d_i = V_{ij} \overline{u}'_i \sigma^\mu d'_j$$

$$j^\mu_{\text{n,had}} = (j^\mu_{\text{n,had}})'$$

$$j^\mu_{\text{em,had}} = (j^\mu_{\text{em,had}})'$$

$V = U_u U_d^\dagger$ Cabibbo Kobayashi Maskawa (CKM) matrix

# Experimental values

- In an appropriate basis

$$\lambda = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \lambda_{33} \end{pmatrix} + \text{small} \quad (U,\, D,\, E)$$

(the top Yukawa coupling is O(1); the bottom and tau Yukawas are also small but can be large in the MSSM)

- In particular,
  - $\lambda_{1,2} \ll \lambda_3$
  - $V_{CKM} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \text{small}$

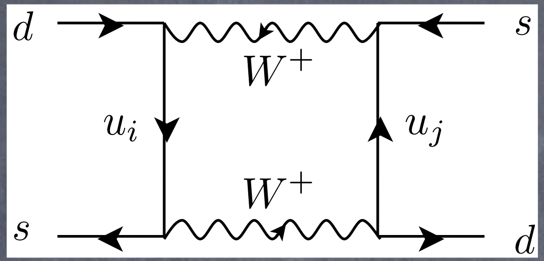
# Approximate flavour symmetry

- The flavour lagrangian is approximately $U(2)^5$ flavour symmetric (exactly symmetric in the limit $\lambda = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \lambda_{33} \end{pmatrix}$ which also implies $V = 1_3$)

- This (or equivalently the smallness of $\lambda_{1,2}$ and $V_{ij}$ $i \neq j$) is the origin of the anomalously small FCNC processes in the SM (and the origin of the flavour problem)

# Anomalously small loop-induced FCNC

- Because of the approximate $U(2)^5$ (GIM)




$K^0$ - $\overline{K}^0$ oscillations

$$\sim \quad \frac{1}{M_W^2} \times \frac{g^4}{(4\pi)^2} \times \epsilon$$

$\epsilon = 0$ in the $U(2)^5$ limit

$\epsilon \sim 10^{-6}$ experiment

- $\left( \epsilon = (V^\dagger_{su_i} V_{u_i d})(V^\dagger_{su_j} V_{u_j d}) f\left(\frac{m^2_{u_i}}{M_W^2}, \frac{m^2_{u_j}}{M_W^2}\right)\right.$
  i = 3: f = O(1), $|V_{td}V_{ts}| \ll 1$
  i = 1,2: $|V_{id}V_{is}|$ = O(1), f $\ll$ 1 )

Challenge for new physics at TeV

- Same for CP-violating effects

# Electroweak symmetry breaking

- Indirect tests, hints from direct tests (but...)
- "Observed" fields:
  - Gauge bosons: $g_\mu^A \quad W_\mu^a \quad B_\mu$
  - Femions: $Q_i \quad u_i^c \quad d_i^c \quad L_i \quad e_i^c$
  - "3/4" of the Higgs field: $G_a$ (long. part of massive gauge bosons, Goldstones of the spontanously broken gauge symmetry)
  - SM masses arise from the symmetry breaking scale v = 174 GeV ($G_a$ decay constant)
- Mission #1 of the LHC: what is the mechanism underlying EWSB? Or where do the $G_a$ and v = 174 GeV come from?
- The Higgs mechanism in the SM:

$$G_a + h \rightarrow H = \begin{pmatrix} G^+ \\ v + \frac{h + iG^0}{\sqrt{2}} \end{pmatrix} \approx (1,2,\tfrac{1}{2})$$

# The Higgs sector

- Most general gauge invariant ren. lagrangian for H:

$$\mathcal{L}_H = (D_\mu H)^\dagger (D^\mu H) - V(H^\dagger H)$$

$$V(H^\dagger H) = \mu^2 H^\dagger H + \frac{\lambda_H}{2}(H^\dagger H)^2$$

- $\lambda_H > 0$
- $\mu^2 < 0 \Rightarrow \langle H \rangle \neq 0 \Rightarrow$ electroweak symmetry breaking
- ($\mu^2 > 0 \Rightarrow$ still electroweak symmetry breaking, but at $\Lambda \approx m_\pi$)

# QED unbroken

- Fix the Higgs quantum numbers from fermion masses. Then the electric charge is automatically conserved

$$\langle H \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}, \; v > 0, \; v^2 = \frac{|\mu^2|}{\lambda_H} \approx (174\,\mathrm{GeV})^2$$

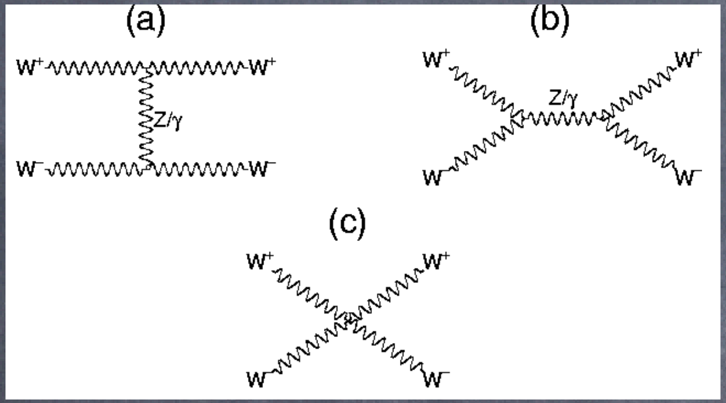
$$T = aY + b_a T_a, \; a, b_a \text{ real}, \; T_a = \frac{\sigma}{2}, \; Y = \frac{\mathbf{1}}{2}$$

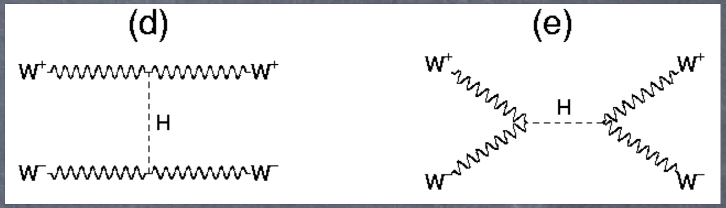
$$0 = T\langle H \rangle = \frac{v}{2} \begin{pmatrix} b_1 - ib_2 \\ a - b_3 \end{pmatrix} \Rightarrow T \propto Q$$

- 3 broken generators ↔ 3 massive vectors ↔ 3 unphysical Goldstone bosons ↔ 1 real physical Higgs particle

# Constraints on the Higgs mass I
# Avoiding the strong coupling regime: $m_H < O(TeV)$

- $A(W_L W_L \to W_L W_L) = \Sigma_l \, a_l \, A_l$, $a_l$ = partial wave amplitude
- Unitarity bound: $|a_0| \leq 1$
- Tree level, no Higgs: $a_0 \sim \frac{s}{16\pi v^2}$, $s = (p_1+p_2)^2$, $v \approx 174$ GeV

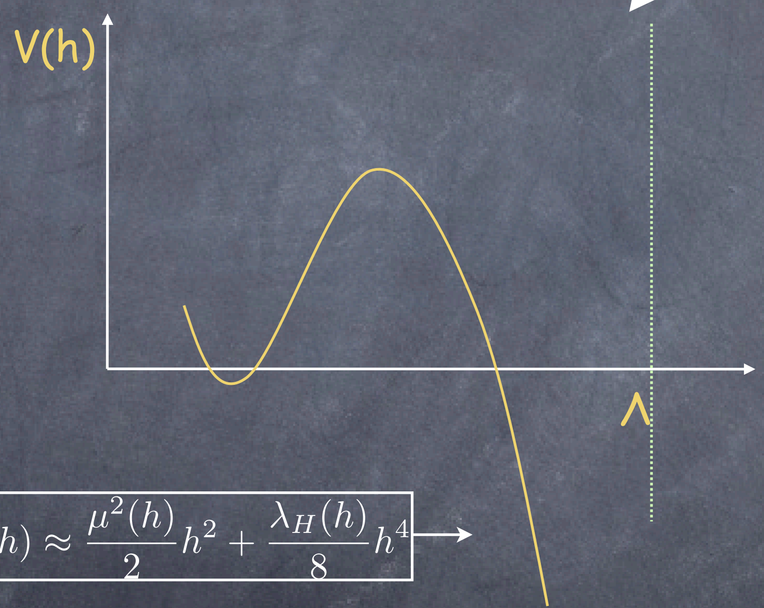


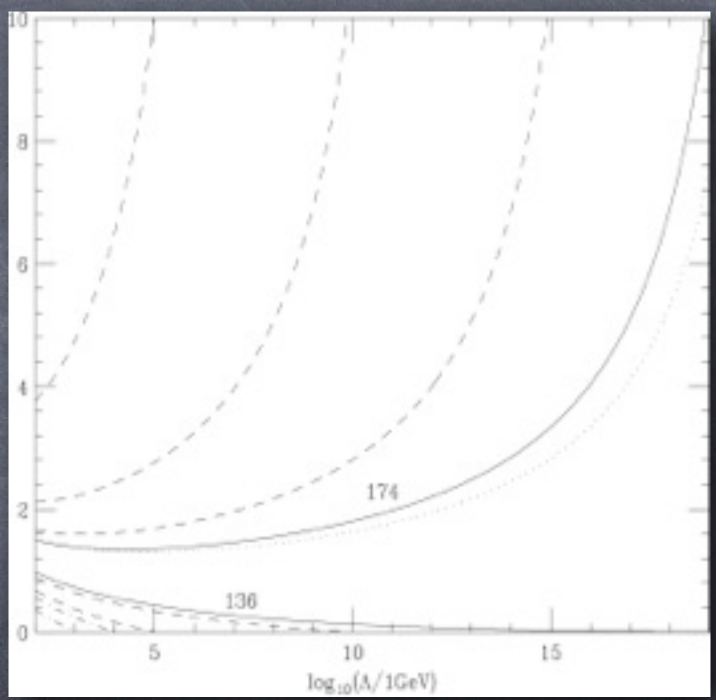

- Unitarity bound saturated at $s \approx (1.2 \text{ TeV})^2$
- Bad behaviour of $a_0$ due to the longitudinal part of the W propagator ~ $p_\mu p_\nu/(M_W)^2$, cancelled by Higgs exchange

# Constraints on the Higgs mass II
## Triviality and stability

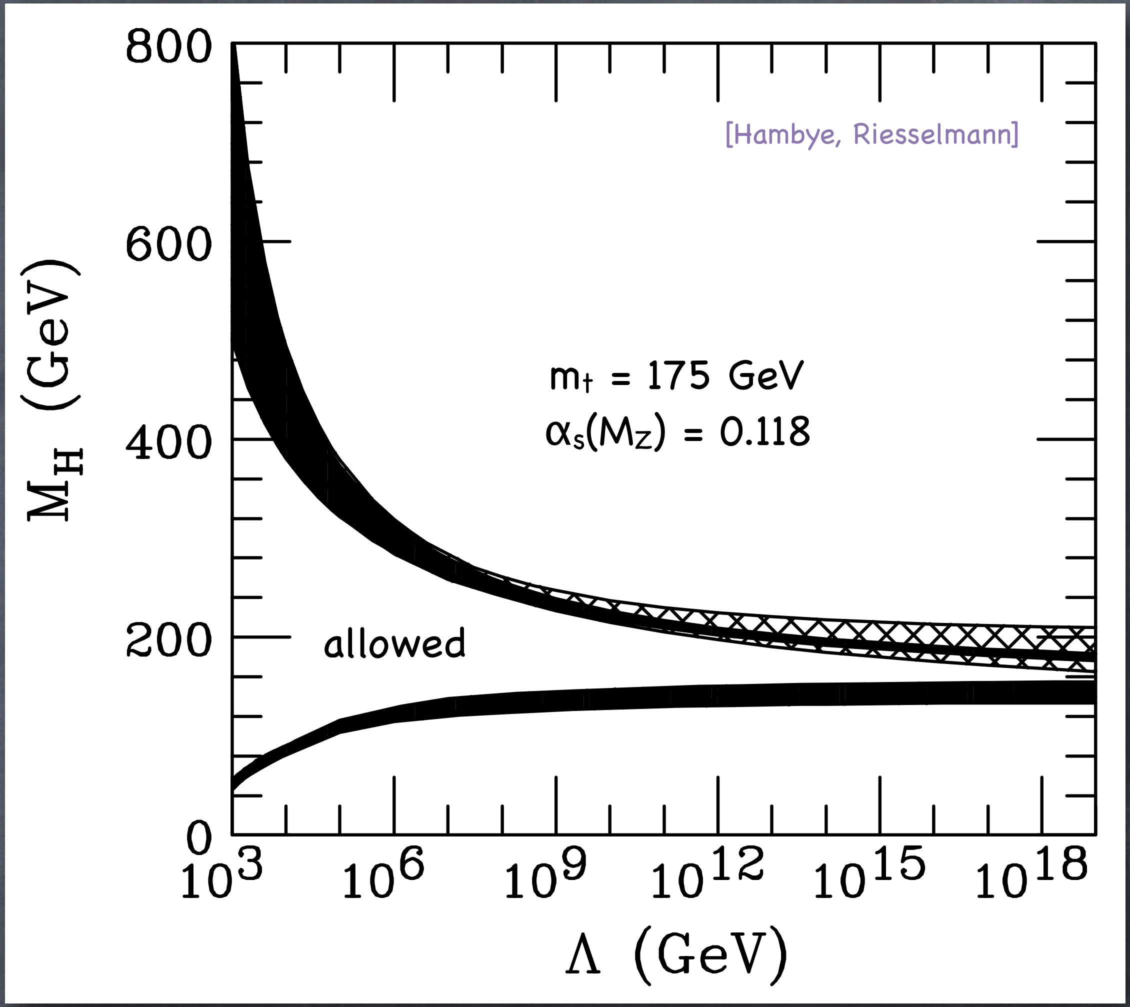
- Assume that the SM holds up to the scale $\Lambda$:
- $\lambda_H(\Lambda)$ finite (perturbative) $\Rightarrow$ upper limit on $m_H$
- $\lambda_H(\Lambda) > 0$ $\Rightarrow$ lower limit on $m_H$




$$V(h) \approx \frac{\mu^2(h)}{2} h^2 + \frac{\lambda_H(h)}{8} h^4$$




- (if $\lambda_H(\Lambda) < 0$, the absolute minimum of the effective potential resides at or above $\Lambda$)

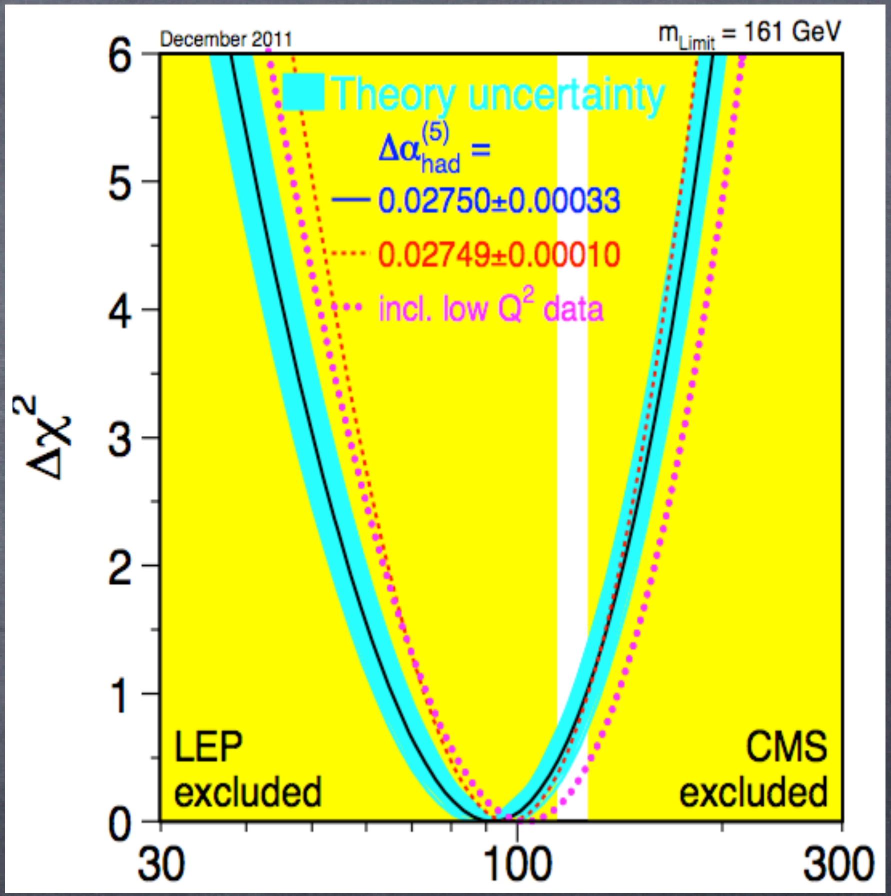



- The lower limit can be relaxed if we live in a metastable vacuum
- $\Lambda \gg v$ introduces a naturalness problem

# Constraints on the Higgs mass III
# Experiment

- Indirect upper limit from EW precision tests (see below):
  161 GeV @ 95% CL (assumes no new physics contributions)

- Direct experimental limit (within SM):
  115.5 GeV < $m_H$ < 127 GeV @ 95% CL
  or $m_H$ > 600 GeV (trivial combination)




$m_H$ (GeV)

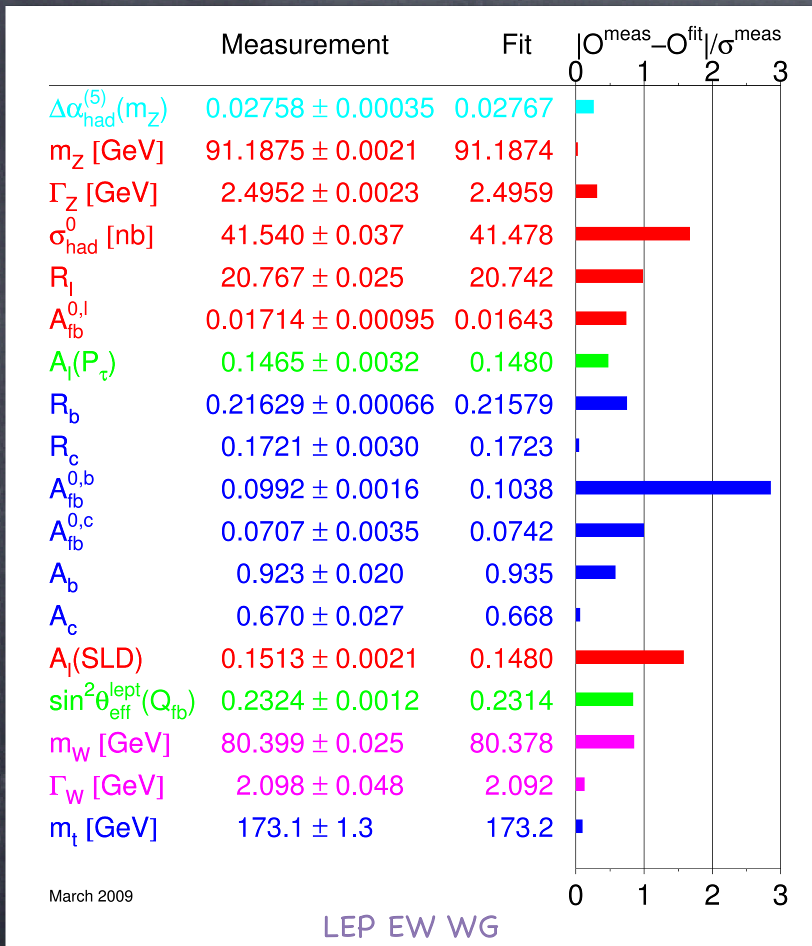
# Tests of the gauge (electroweak) sector

- The gauge sector (fermion gauge interactions) is the best tested part of the SM
  - Wide range of predictions:

    $g, g', v \leftrightarrow (\alpha), s_W, v \leftrightarrow$ QED, W&Z masses, their self-interactions and all fermion gauge interactions (tree level)
  - Measurements at the ‰ level: sensitivity to quantum corrections ($m_t$, $m_H$)
- Good agreement with the experiment

# High energy tests

- At LEP II, LEP I, SLC, Tevatron
- $M_Z$, $\Gamma_Z$,
  - Z resonance in $e+e- \to f\bar{f}$
  - $N_\nu$ = 2.9841±0.0083: 3 light neutrinos + anomaly cancellation = 3 families
- $M_W$, $\Gamma_W$ from $e^+e^- \to W^+ + W^-$ at LEP II
- $\sigma_{h,l}$
- $WW\gamma$, $WWZ$ couplings $\propto$ $e$, $gc_W$
- $$A^f_{LR} = \frac{\Gamma(Z \to f_L \bar{f}_R) - \Gamma(Z \to f_R \bar{f}_L)}{\Gamma(Z \to f_L \bar{f}_R) + \Gamma(Z \to f_R \bar{f}_L)}$$
- $A_{FB}$ ...




- Accuracy in most cases is at the ‰ level → sensitivity to 1-loop corrections, which involve
  - $g$, $g'$, $v$
  - $m_t$, $\alpha_s(M_Z)$, $\Delta\alpha_{had}(M_Z)$
  - $m_h$
- and bring together
  - the gauge sector: $g^2/(4\pi)^2$, $g'^2/(4\pi)^2$
  - the flavour sector: $\lambda^2/(4\pi)^2$
  - the EW-breaking sector: $g^2/(4\pi)^2 \log(m_h/M_W)$
- The agreement works for relatively low values of $m_h$

# Custodial symmetry

- $\rho \equiv \dfrac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1 \text{ (tree level)}$
  - Not guaranteed by gauge invariance nor by the breaking pattern
  - Peculiar of EW breaking by a doublet (triplets ruled out)

- Reminder

$$D_\mu = \partial_\mu + igW_\mu^a \frac{\sigma_a}{2} + i\frac{g'}{2}B_\mu$$

$$W_\mu^+ \equiv \frac{W_\mu^1 - iW_\mu^2}{\sqrt{2}}, \; Z_\mu \equiv c_W W_\mu^3 - s_W B_\mu, \; \begin{cases} c_W \equiv \cos\theta_W = g/\sqrt{g^2+g'^2} \\ s_W \equiv \sin\theta_W = g'/\sqrt{g^2+g'^2} \end{cases}$$

$\theta_W$ = Weinberg angle

# $\rho \approx 1 \leftrightarrow$ custodial SU(2)

- The vector boson masses arise from $(D_\mu\langle H\rangle)^*(D^\mu\langle H\rangle)$

$$D_\mu \langle H\rangle = \frac{iv}{2}\begin{pmatrix} g(W^1_\mu - iW^2_\mu) \\ gW^3_\mu - g' B_\mu \end{pmatrix} = \frac{iv}{2}\begin{pmatrix} \sqrt{2} g W^+_\mu \\ \sqrt{g^2+g'^2} Z_\mu \end{pmatrix}$$

- Same mass term for $W^{1,2,3}$ because of a custodial O(3) ≈ SU(2) symmetry. Which is a remnant of a O(4) ≈ $SU(2)_L \times SU(2)_R$ symmetry, spontaneously broken to the diagonal SU(2) ≈ O(3):

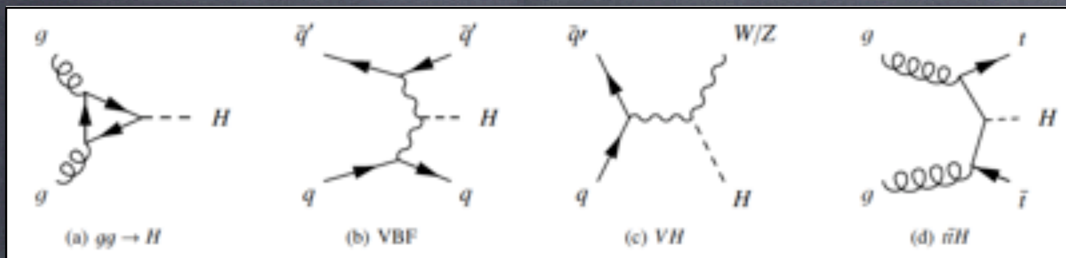
- $|H|^2 = h^2_{1R} + h^2_{1I} + h^2_{2R} + h^2_{2I}$ ⇒ V(H) is symmetric under O(4) ≈ $SU(2)_L \times SU(2)_R$, broken by <H> to the diagonal SU(2)

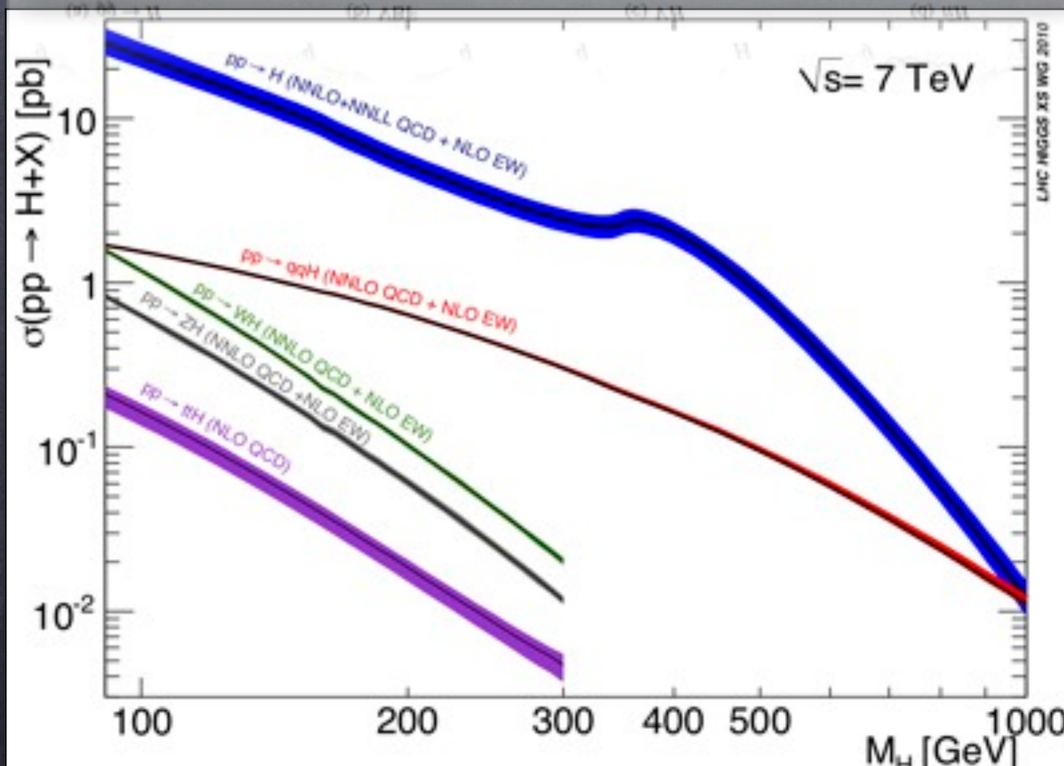
$$\Phi = \left(\epsilon \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}^* \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}\right), \ \Phi \to U_L \Phi U_R^\dagger, \ H^\dagger H = \mathrm{Tr}(\Phi^\dagger \Phi)/2$$

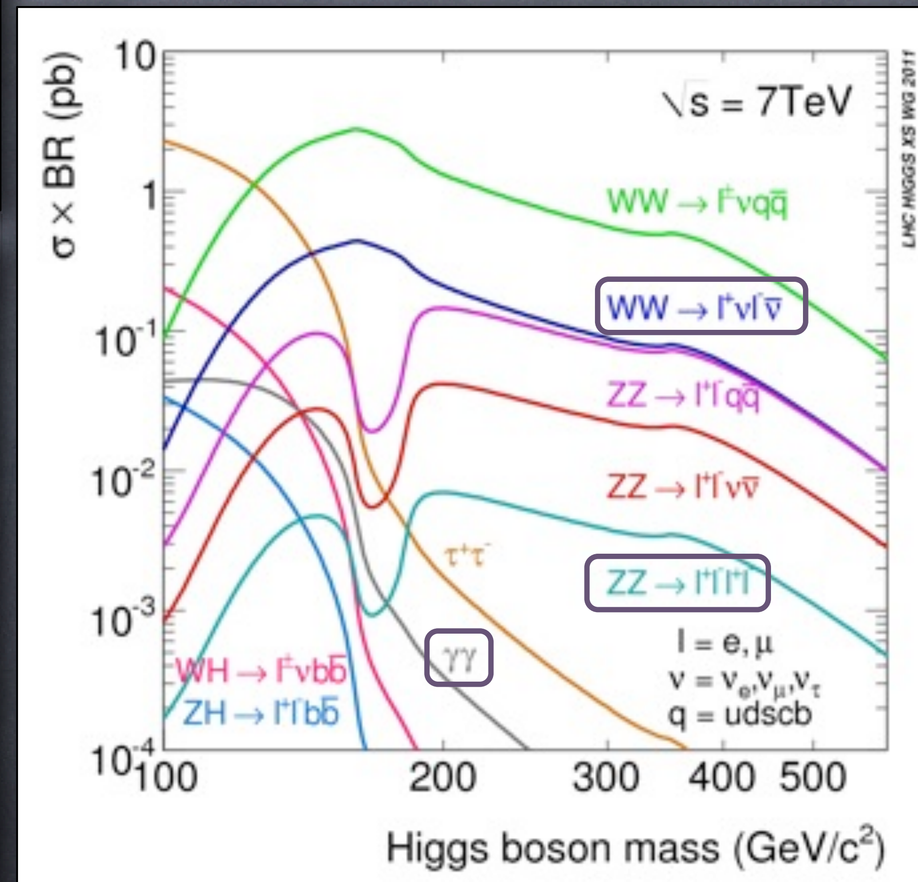
- The symmetry is exact in the limit $g' = 0$, $\lambda_U = \lambda_D$ → loop corrections to $\rho = 1$

- An indication of a fundamental symmetry? ($SU(2)_L \times SU(2)_R$)

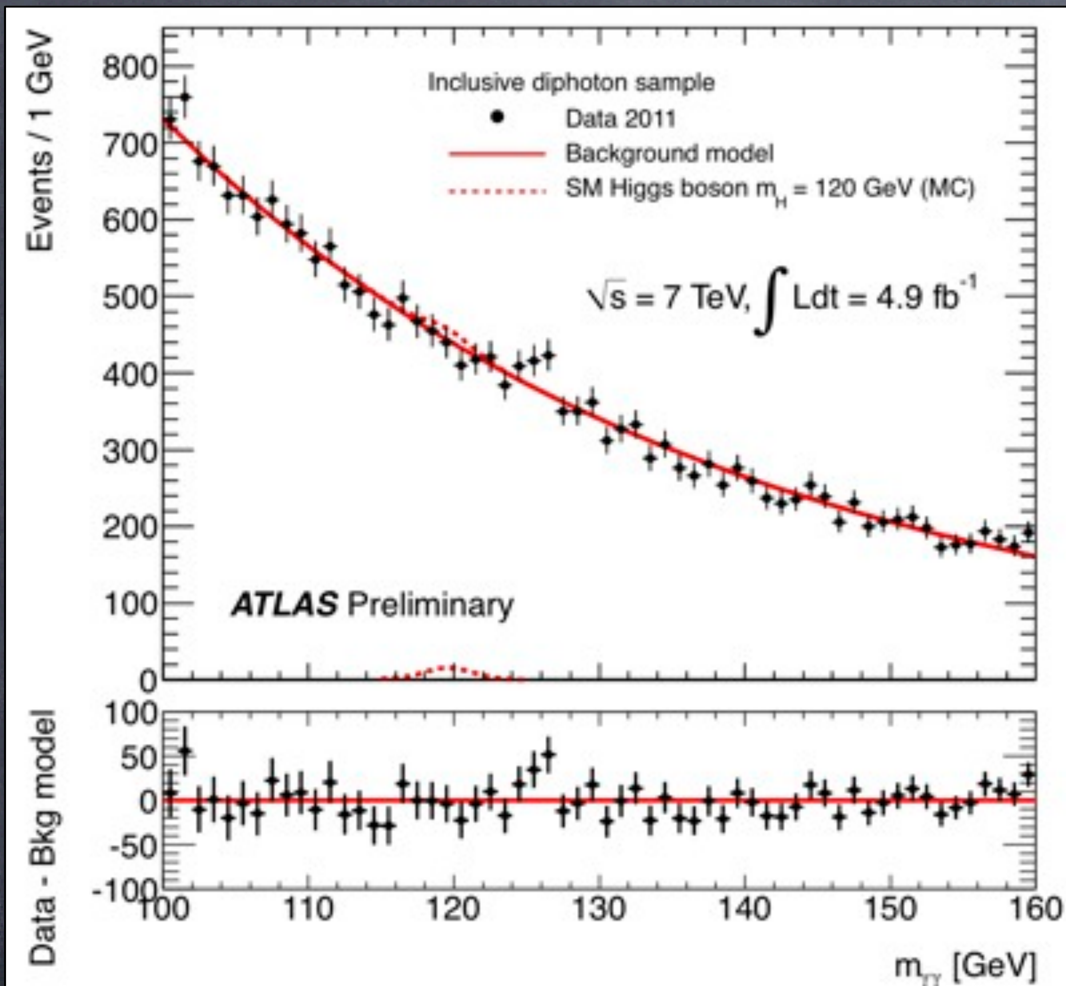
# Direct limits

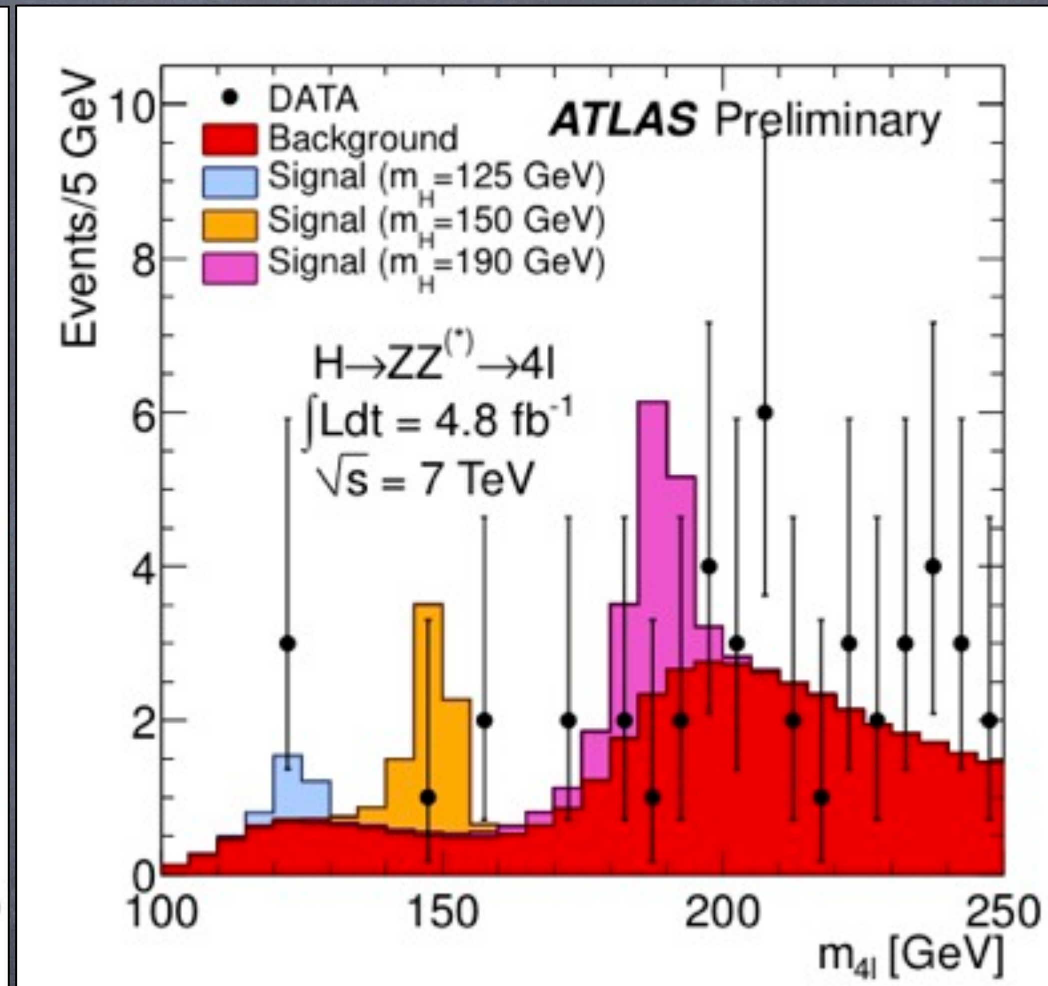


# Atlas (Gianotti 13.12.2011)



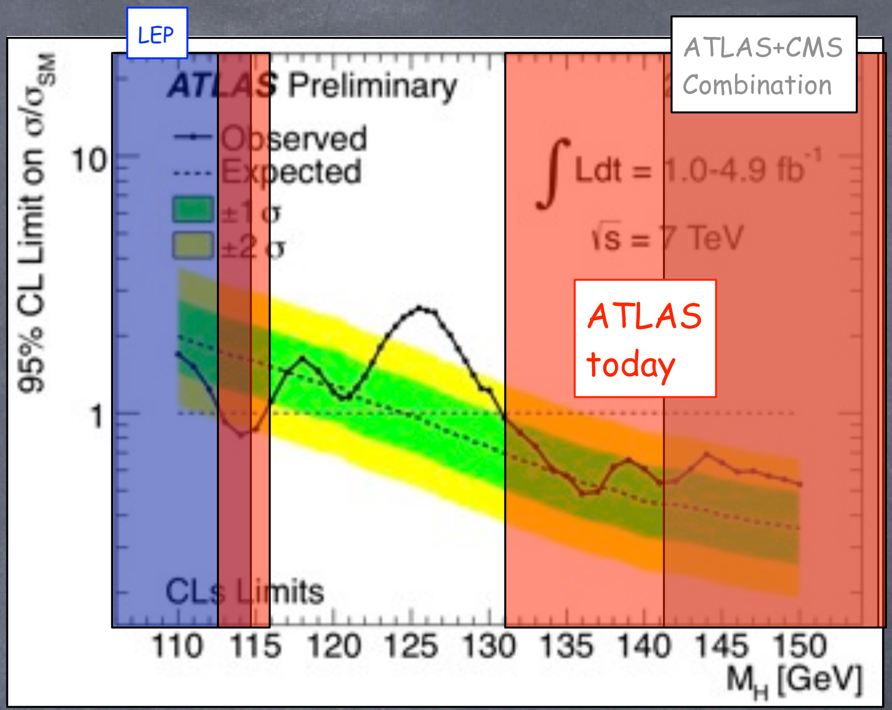




Significance:
$2.8\sigma$ (local)
$1.5\sigma$ (anywhere)

In the region $m_H < 141$ GeV (not excluded at 95% C.L.) 3 events are observed: two 2e2μ events (m=123.6 GeV, m=124.3 GeV) and one 4μ event (m=124.6 GeV)

$H\to\gamma\gamma$, $H\to\tau\tau$
$H\to WW^{(*)}\to l\nu l\nu$
$H\to ZZ^{(*)}\to 4l$, $H\to ZZ\to ll\nu\nu$
$H\to ZZ\to llqq$, $H\to WW\to l\nu qq$
$W/ZH\to lbb+X$ not included

115.5 GeV < $m_H$ < 131 GeV
237 GeV < $m_H$ < 251 GeV allowed 95%
$m_H$ > 453 GeV

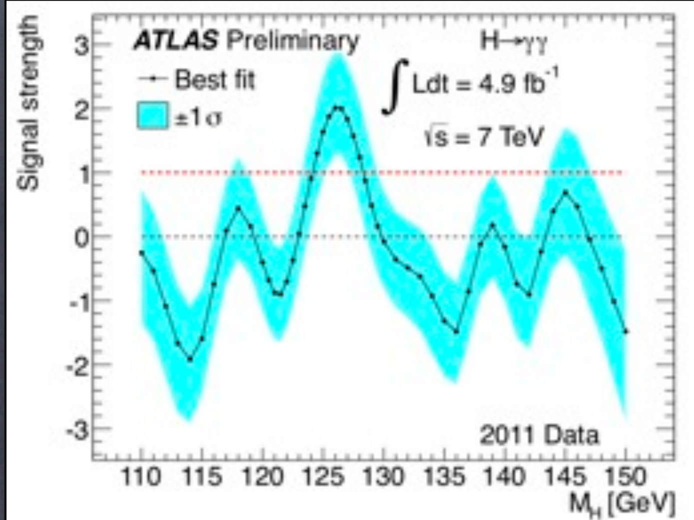


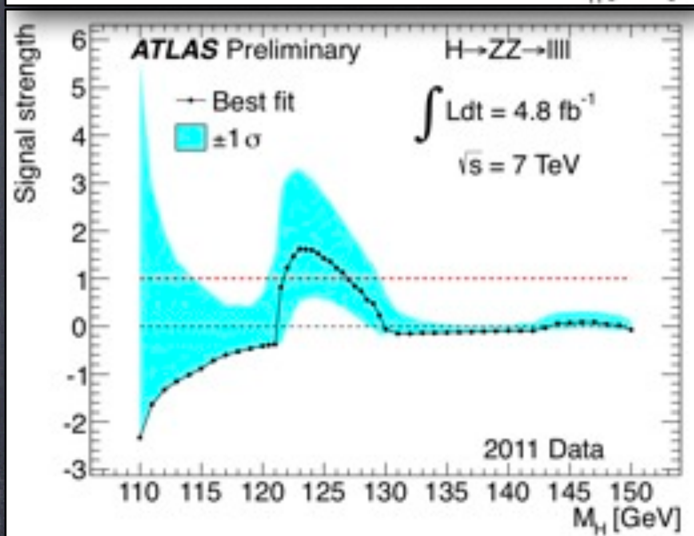

Maximum deviation from background-only expectation observed for $m_H$~126 GeV

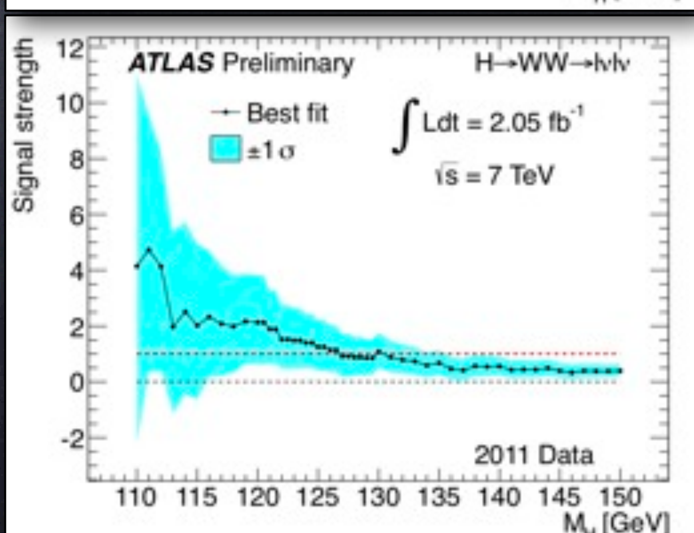
Local $p_0$-value: 1.9 $10^{-4}$
→ local significance of the excess: 3.6σ
~ 2.8σ $H\to\gamma\gamma$, 2.1σ $H\to 4l$, 1.4σ $H\to l\nu l\nu$

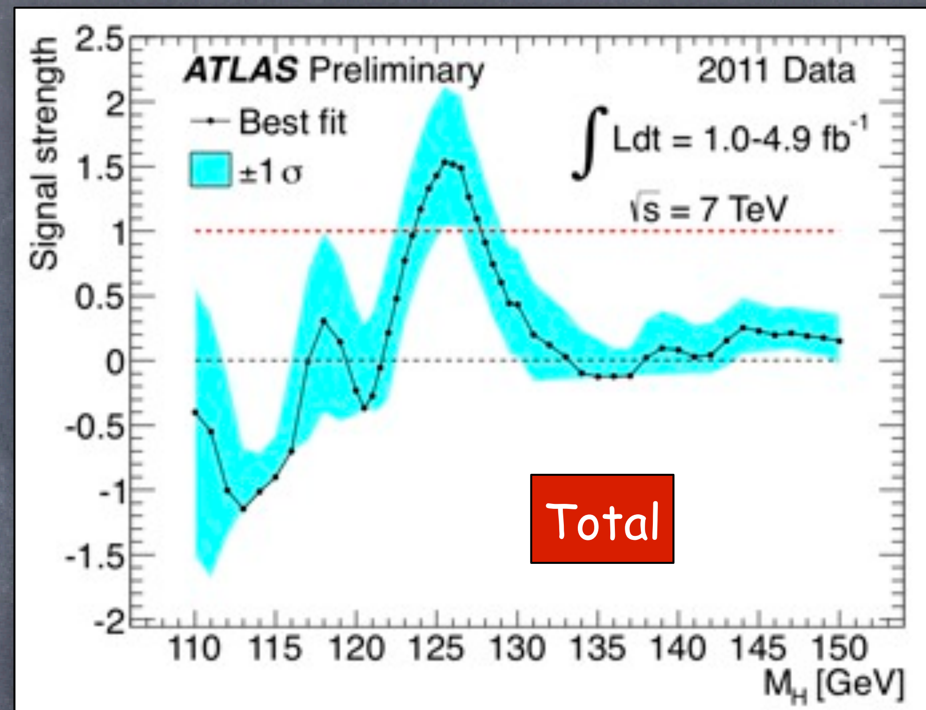
Expected from SM Higgs: ~2.4σ local (~1.4σ per channel)

Global $p_0$-value : 0.6% →2.5σ LEE over 110-146 GeV
Global $p_0$-value : 1.4% →2.2σ LEE over 110-600 GeV

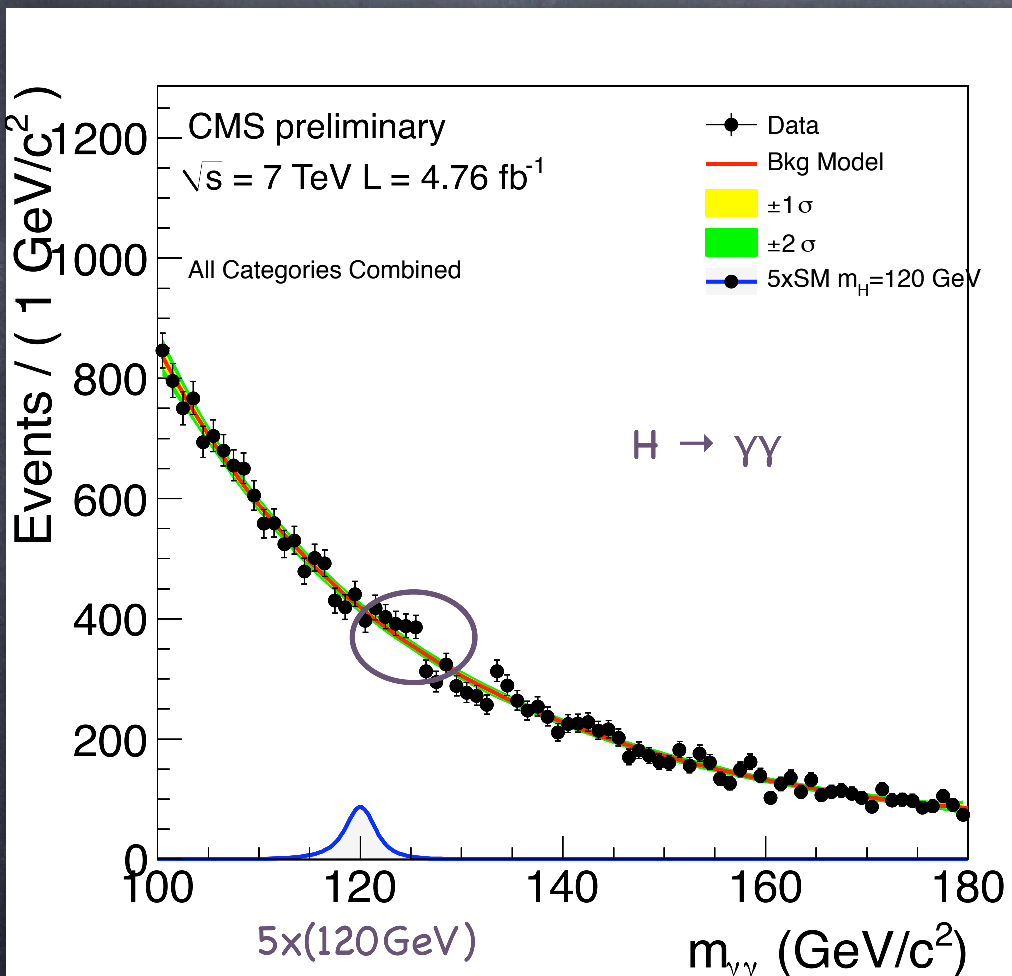

ATLAS Preliminary
H→γγ
Best fit
±1σ
∫Ldt = 4.9 fb⁻¹
√s = 7 TeV
2011 Data
Signal strength
M_H [GeV]

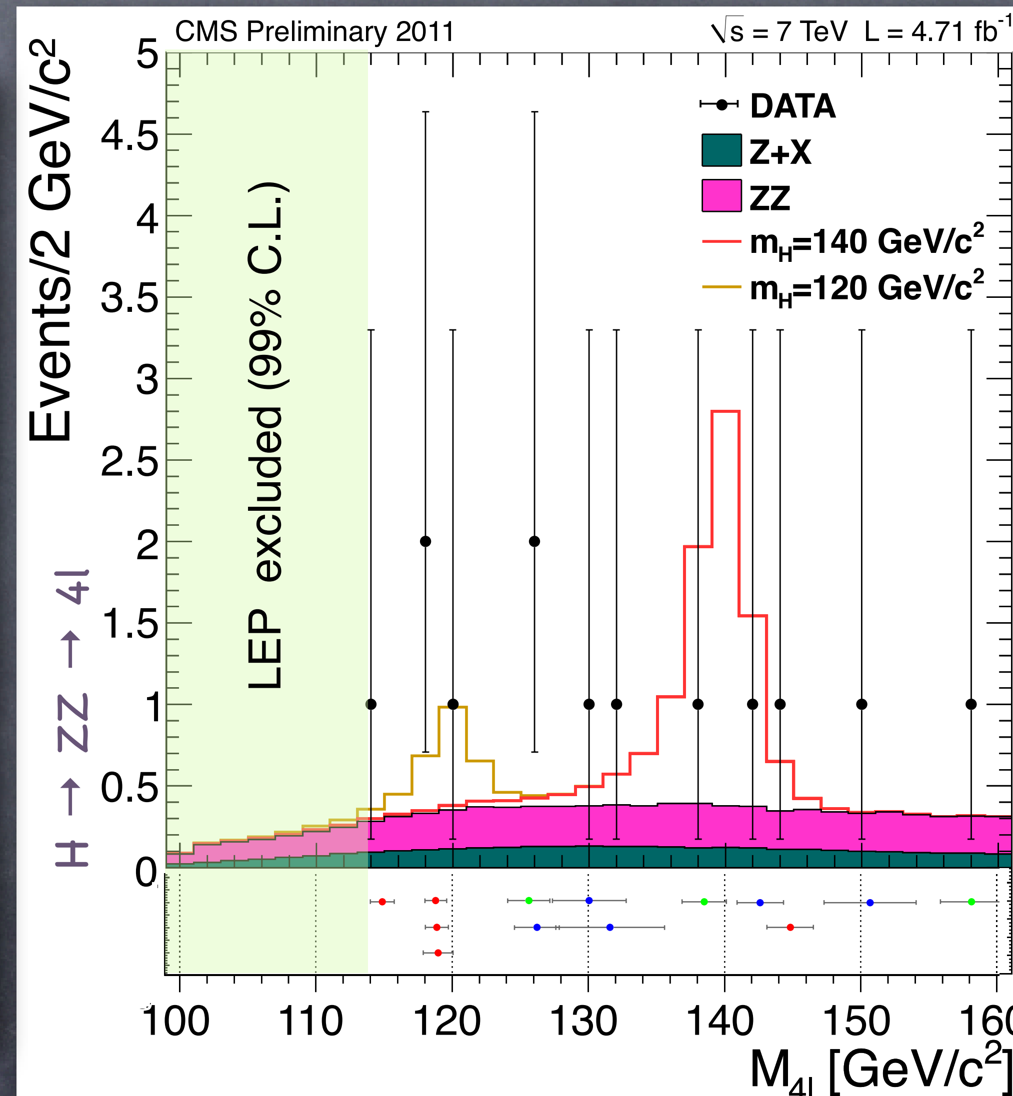

ATLAS Preliminary
H→ZZ→llll
Best fit
±1σ
∫Ldt = 4.8 fb⁻¹
√s = 7 TeV
2011 Data
Signal strength
M_H [GeV]

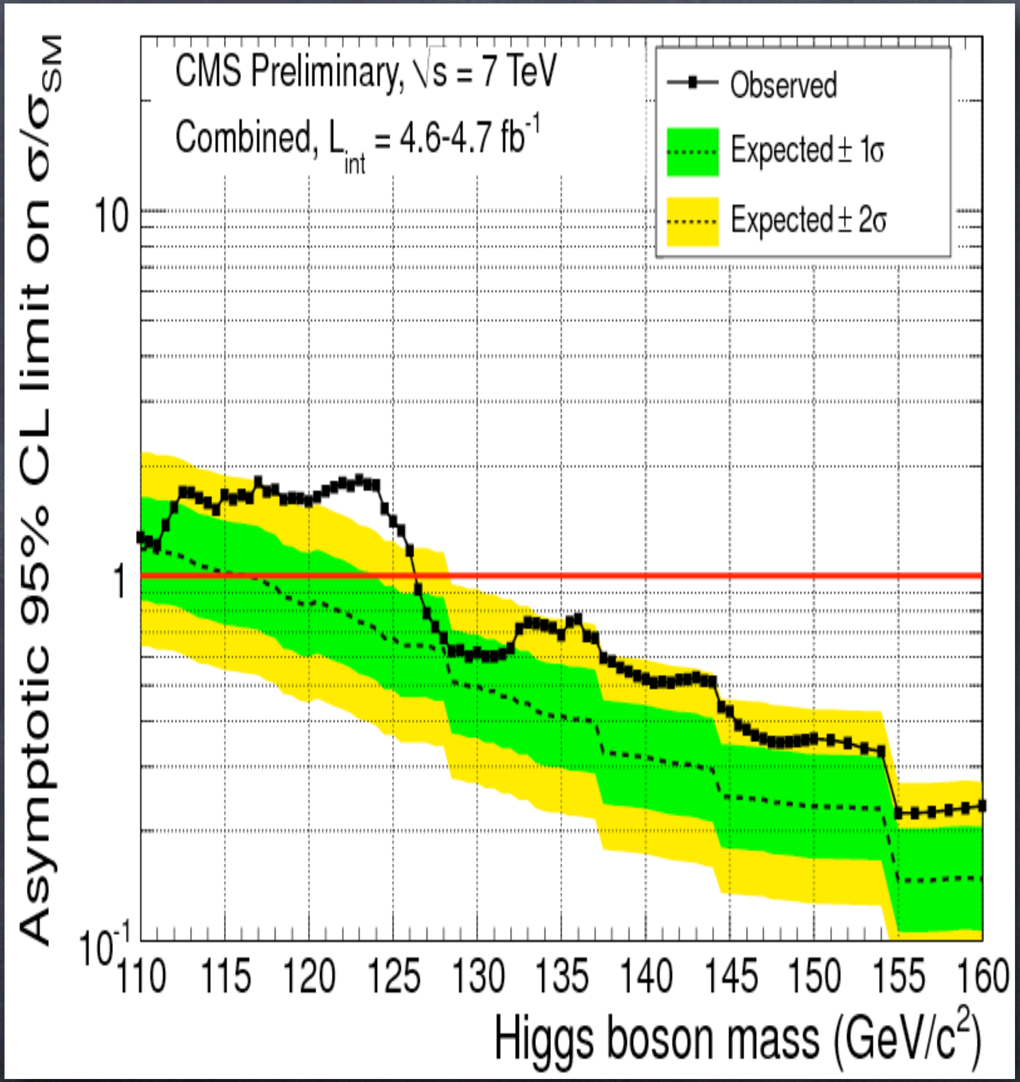

ATLAS Preliminary
H→WW→lνlν
Best fit
±1σ
∫Ldt = 2.05 fb⁻¹
√s = 7 TeV
2011 Data
Signal strength
M_H [GeV]

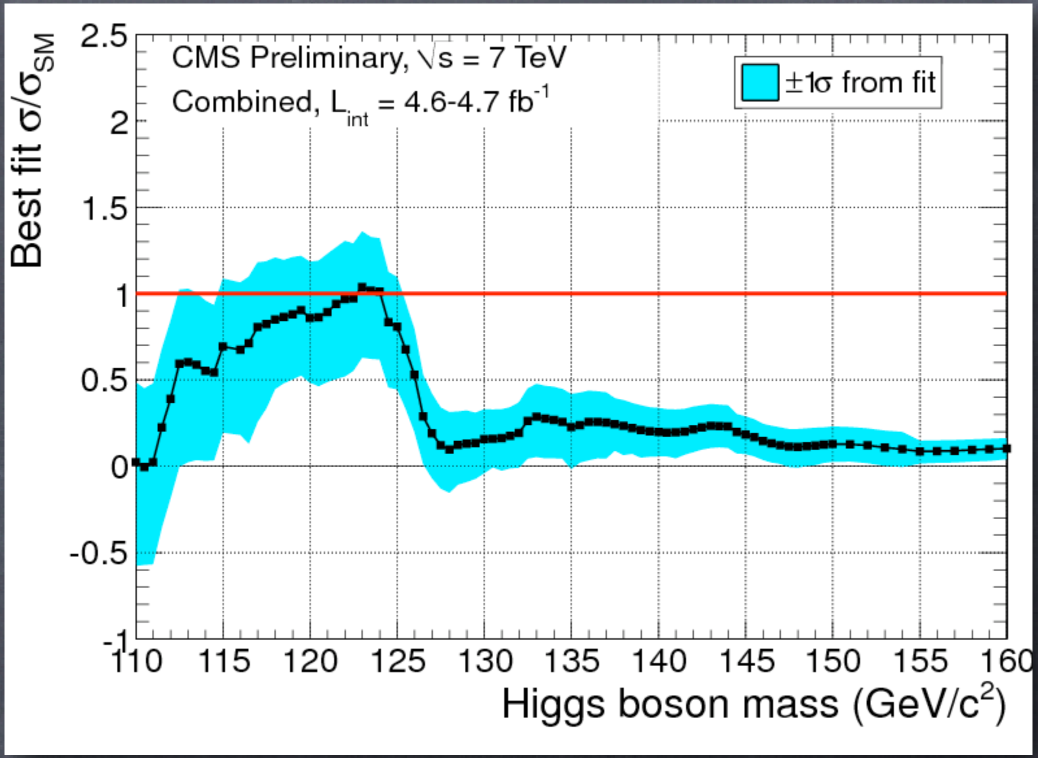

ATLAS Preliminary
2011 Data
Best fit
±1σ
∫Ldt = 1.0-4.9 fb⁻¹
√s = 7 TeV
Signal strength
M_H [GeV]
Total

# CMS (Tonelli 13.12.2011)





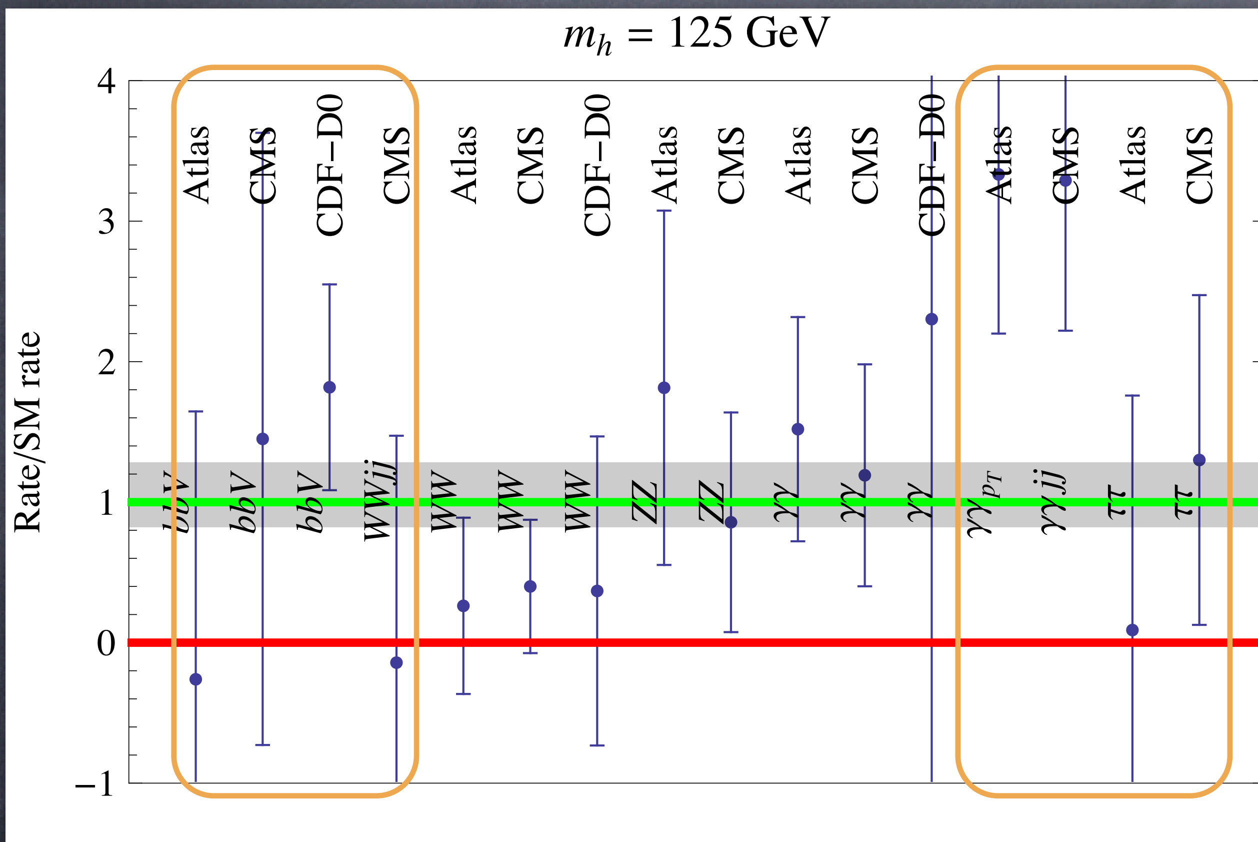

mH < 127 GeV or $m_H$ > 600 GeV @ 95% CL

Maximum local significance **2.6σ.**

LEE-corrected significance (full mass range: 110-600GeV)= **0.6σ**

LEE-corrected significance (low mass range: 110-145GeV)= **1.9σ**

# Preliminary details




$$\frac{\text{observed rate}}{\text{SM rate}} = \begin{cases} 2.0 \pm 0.5 & \text{photons} \\ 0.5 \pm 0.3 & \text{vectors: } W \text{ and } Z \\ 1.3 \pm 0.5 & \text{fermions: } b \text{ and } \tau \end{cases}$$

# Beyond the SM

# Many reasons to go beyond the SM

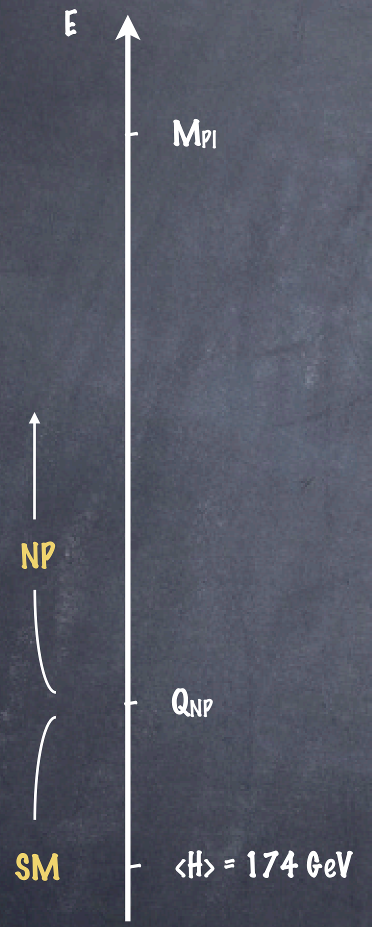
- Experimental "problems" of the SM
  - Gravity
  - Dark matter
  - Baryon asymmetry
- Experimental "hints" of physics beyond the SM
  - Neutrino masses
  - Quantum number unification
- Theoretical puzzles of the SM
  - $\langle H \rangle \ll M_{Pl}$
  - Family replication
  - Small Yukawa couplings, pattern of masses and mixings
  - Gauge group, no anomaly, charge quantization, quantum numbers
- Theoretical problems of the SM
  - Naturalness/unitarity problem
  - Cosmological constant problem
  - Strong CP problem
  - Landau poles

# The unitarity/naturalness argument

Known fields: $g^\mu_A$ $W^\mu_a$ $B^\mu$ $Q_i$ $u^c_i$ $d^c_i$ $L_i$ $e^c_i$ $G_a$

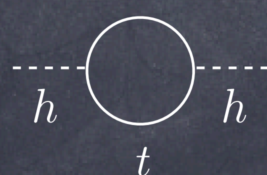
- Claim
  - Either physics becomes strongly interacting (again) at TeV or
  - Physics is weakly interacting up to well beyond the TeV scale in this case the Higgs h exists and $m^2_h \approx (m^2_h)_0 + (115\text{GeV})^2\,(Q_{NP}/0.5\text{TeV})^2$
- In the latter case, $Q_{NP} \gg$ TeV needs delicate cancellations, so that
  - NP @ TeV cuts-off $\delta m^2_h$ and the electroweak scale is “natural”, or
  - the electroweak scale is accidentally smaller than its radiative corrections, or the naturalness argument is not relevant at all

# Naturalness

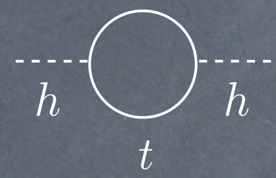



Analogously: contributions from gauge and Higgs self-interaction

$$\delta m_h^2 \sim \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 Q_{\rm NP}^2$$



# More on renormalizability and naturalness

- $\delta m_h^2 \sim \delta m_h^2(\text{top}) \approx$  $= 12\,\lambda_t^2 \int \frac{k^3 dk}{8\pi^2}\frac{1}{k^2} + \ldots \xrightarrow{\text{cut-off}} \frac{3G_{\rm F}}{\sqrt{2}\pi^2} m_t^2 Q^2$

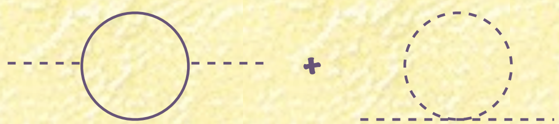

- Renormalization: $(m_h^2)_{\rm phys} \approx (m_h^2)_{\rm tree} + \frac{3G_{\rm F}}{\sqrt{2}\pi^2} m_t^2 Q^2, \quad Q \to \infty$

- The naturalness problem arises if Q corresponds to a physical threshold

# Another caveat: the cosmological constant problem

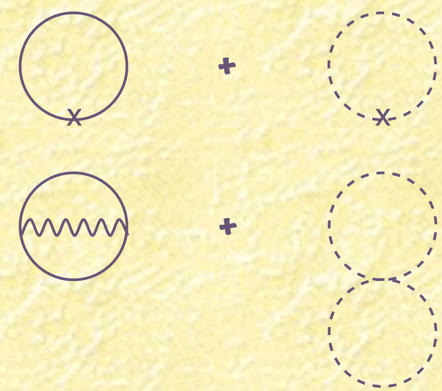
$$\delta m_H^2 \propto Q_{\rm NP}^2 \to Q_{\rm NP} \sim m_H$$

$$\text{SUSY:} \quad \delta m_H^2 \propto \tilde{m}^2 \log \frac{Q_{\rm SUSY}}{\tilde{m}}$$



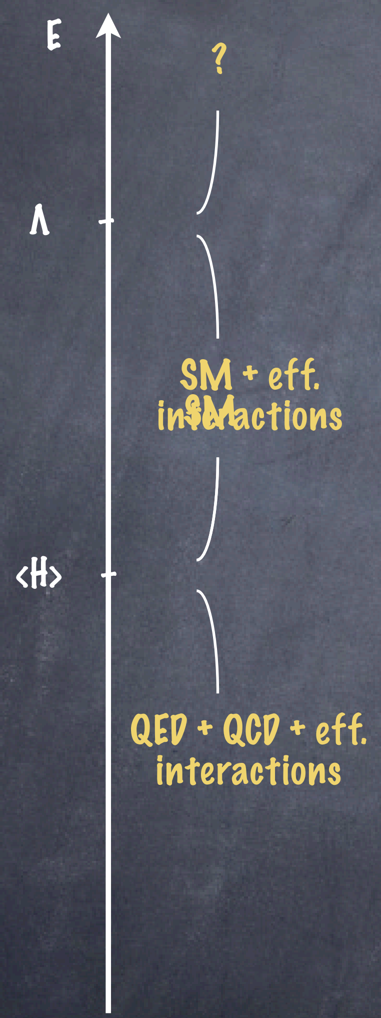
$$\delta\Lambda \propto Q_x^4 \to Q_x \sim 10^{-3}\,\text{eV???}$$

$$\text{SUSY:} \quad \delta\Lambda \propto \tilde{m}^2 Q_{\rm SUSY}^2$$



# The SM
# as an effective theory

# The SM as an effective theory




Analogously..

$$\mathcal{L}^{\rm eff}_{E\ll\Lambda} = \mathcal{L}^{\rm ren}_{\rm SM} + \mathcal{L}^{\rm NR}_{\rm SM}$$

(in the limit $\Lambda \gg M_Z$)

# The SM as an effective theory

$$\mathcal{L}^{\text{eff}}_{E\ll\Lambda} = \mathcal{L}^{\text{ren}}_{\text{SM}} + \sum_n \frac{c_n}{\Lambda^n}\,\mathcal{O}_{4+n}$$

- Consistent renormalization at each order in $(E/\Lambda)$
- Low E effects suppressed by $(E/\Lambda)^n$
  (ren.bility not fundamental in 4D QFT?)
- Allows a general parameterization of any new physics at $\Lambda \gg E$ in terms of light fields only ("indirect effects")
- Identification of $O^{(n)}$ allows to understand the underlying physics (example: from Fermi theory to SM)
- No clear hint of $O^{(n)}$ from the TeV scale (only hint: neutrino masses)

- Best chance for indirect NP effects to emerge is if they violate symmetries $\mathcal{L}_{\rm SM}^{\rm ren}$, also called "accidental symmetries": $L_i$, B

- NP effects can also emerge if are suppressed in the presence of $\mathcal{L}_{\rm SM}^{\rm ren}$ only, e.g. if they contribute to

  - Flavour Changing Neutral Current (FCNC) processes

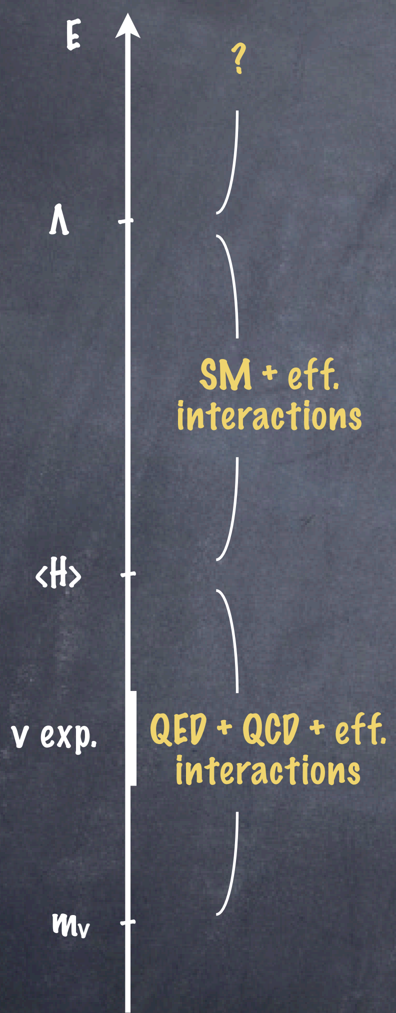
  - CP-violating (CPV) processes

  - Electroweak precision tests (EWPT)

# Hints of NR terms?

- Surprisingly, the most solid hints are associated to scales $\Lambda \gg$ TeV:
  - Neutrino masses
  - Unification

# Neutrino masses




- $\mathcal{L}^{\text{eff}}_{E\ll\Lambda} = \mathcal{L}^{\text{ren}}_{\text{SM}} + \frac{c_{ij}}{2\Lambda}(h\,l_i)(h\,l_j) + \ldots$

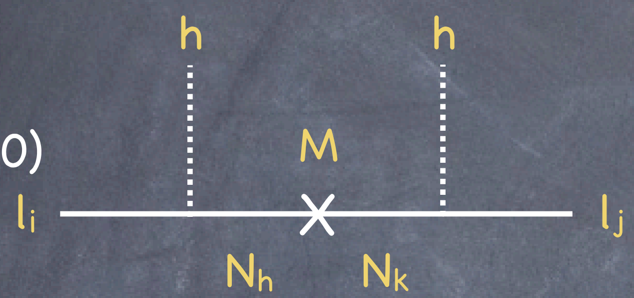
- $m^{E,D,U}_{ij} = \lambda^{E,D,U}_{ij}\, v \quad m^{\nu}_{ij} = c_{ij} v \times \frac{v}{\Lambda}$ (Majorana)

$$\Lambda \sim 0.5 \times 10^{15}\,\text{GeV}\, c \left(\frac{0.05\,\text{eV}}{m_\nu}\right)$$

# Renormalizable origin of neutrino masses

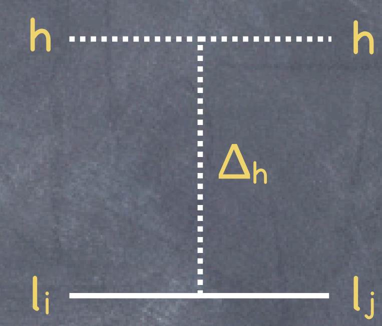
$$\mathcal{L}^{\rm eff}_{E\ll\Lambda} = \mathcal{L}^{\rm ren}_{\rm SM} + \frac{c_{ij}}{2\Lambda}(h\,l_i)(h\,l_j) + \dots$$

$N \approx (1,1,0)$




See-saw type I

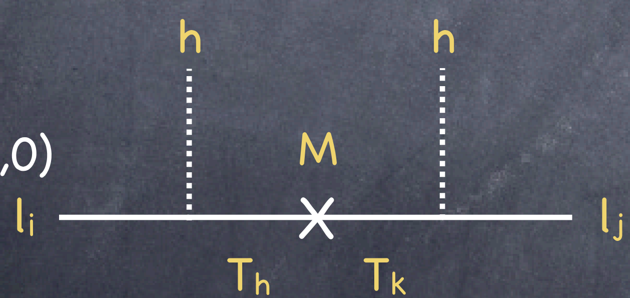
See-saw type II




$\Delta \approx (1,3,1)$

See-saw type III

$T \approx (1,3,0)$

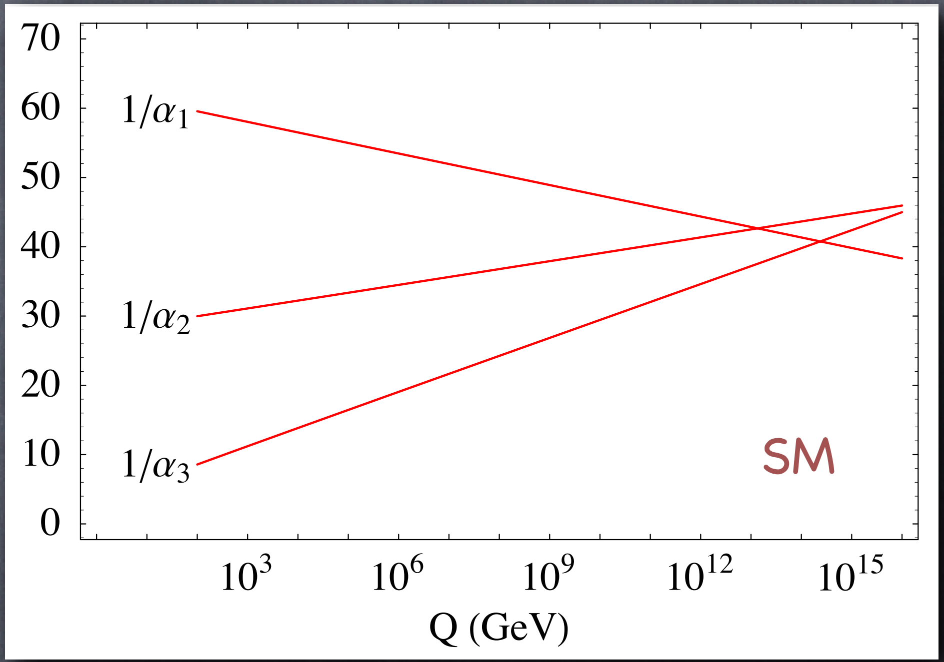



(Any number of $N_h$, $T_h$, $\Delta_h$)

$(SU(3)_c, SU(2)_L, Y)$

# Unification

| | SU(3) | SU(2) | U(1) | | SO(10) |
|---|---|---|---|---|---|
| $L_i$ | 1 | 2 | -1/2 | | |
| $e^c_i$ | 1 | 1 | 1 | | |
| $Q_i$ | 3 | 2 | 1/6 | ⇒ | 16 |
| $u^c_i$ | $3^*$ | 1 | -2/3 | | |
| $d^c_i$ | $3^*$ | 1 | 1/3 | | |
| | | | Y | | |




+ $M_{GUT}$ prediction: $\Lambda_B < M_{GUT} < M_{Pl}$

# Bounds on NR terms

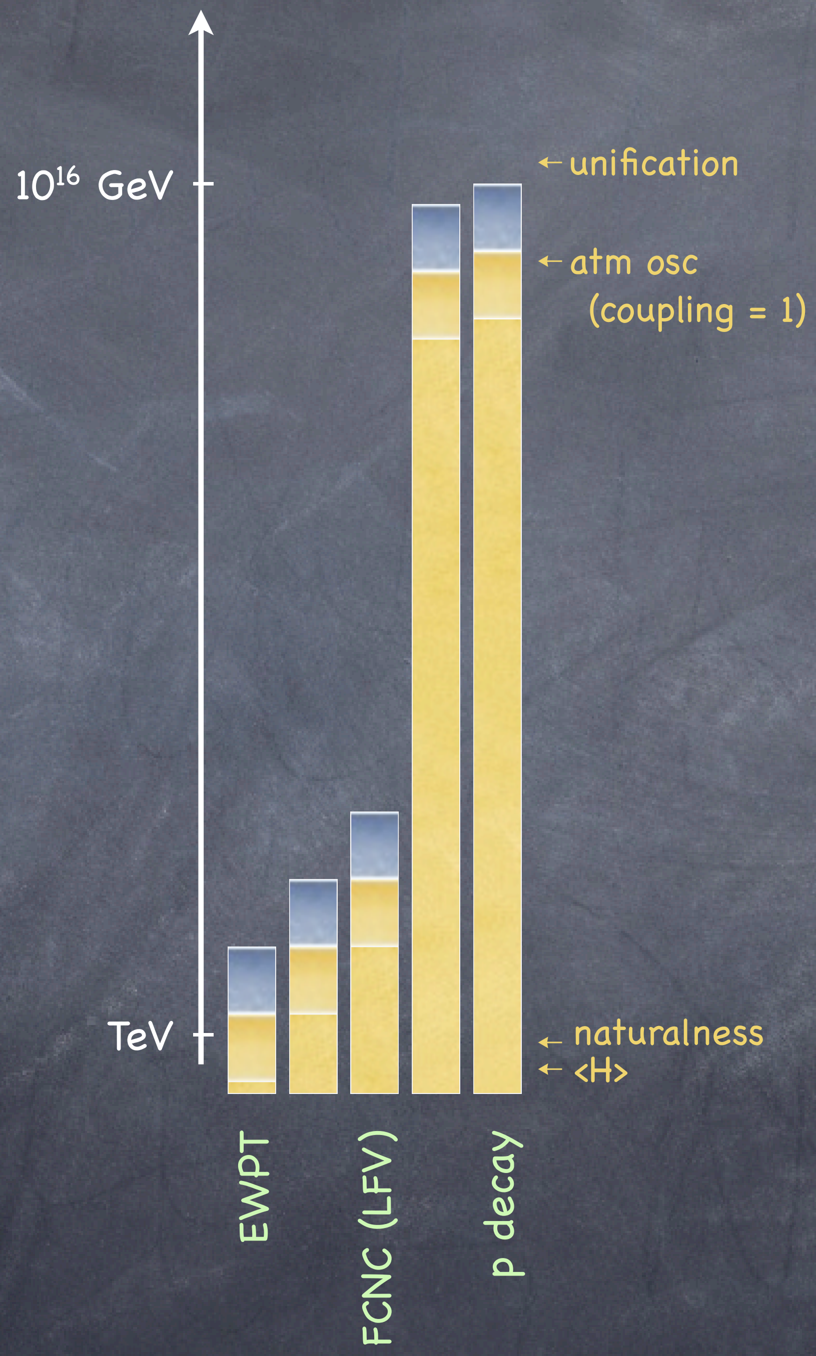
- B number e.g. $\frac{c}{\Lambda^2} qqql$ (proton decay) $\Lambda > c^{1/2}\ 10^{15}$ GeV
- L number e.g. $\frac{c}{\Lambda} llhh$ (neutrino masses) $\Lambda \approx c\ 0.5\ 10^{15}$ GeV
- $L_i$ numbers e.g. $\frac{c}{\Lambda^2} \mu^c \sigma^{\mu\nu} l_e F_{\mu\nu} h$ ($\mu \to e\gamma$) $\Lambda > c^{1/2}\ 10^3$ TeV

(SM accidental symmetries — applies to the three lines above)

- Quark FCNC, CP e.g. $\frac{c}{\Lambda^2} \bar{s}\sigma^\mu d\, \bar{s}\sigma_\mu d$ ($\varepsilon_K$, $\Delta m_K$) $\Lambda > c^{1/2}$ 500 TeV

  $c_{SM} \approx 10^{-8}$ (loop + $U(2)^5$)

- $\frac{c}{\Lambda^2} |h^\dagger D_\mu h|^2$, $\frac{c}{\Lambda^2} \bar{e}\sigma^\mu e\, \bar{e}_i \sigma_\mu e_i$ (EWPTs) $\Lambda > c^{1/2}$ 5 TeV

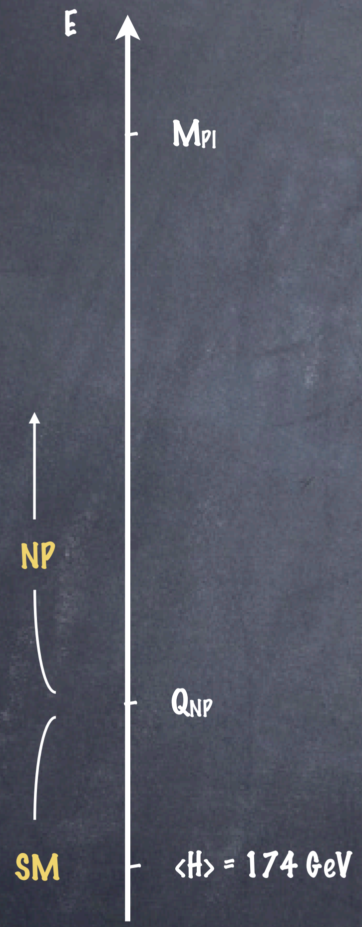


10^16 GeV
TeV
← unification
← atm osc
(coupling = 1)
← naturalness
← <H>
EWPT
FCNC (LFV)
p decay

# The landscape of theory models and its consequences

- Lack of signals, also indirect, from the TeV scale → proliferation of theory models
- Higgsless: TC, ETC, walking-TC, EWSB in 5D or more, etc
- TeV cutoff for $\delta m^2_h$:
  - Fundamental scale (large, TeV, susy, flat, warped, etc)
  - Higgs compositeness (plain, various Little, etc)
  - Supersymmetry breaking scale (MSSM, xMSSM, etc)
- Fine-tuned models (SM, SpS, SuperSpS, etc)
- The experiment provides an interesting perspective
  - the LEP&C heritage: EWPTs and the "little hierarchy" problem
  - quantum number and gauge coupling unification
  - the flavour problem

# The little residual hierarchy




B, L-violating NP: $Q_{NP} > c^{1/2}\, 10^{12}$ TeV

ν's, p-decay, GUTs (4D, 5D)

$B_i$, $L_i$, CP-violating NP: $Q_{NP} > c^{1/2}\, 10^{3}$ TeV

why is TeV flavour violation "small"?

B, L, Fl, CP conserving: $Q_{NP} > c^{1/2}$ 5 TeV

EWPTs, conservative

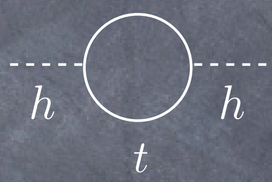
$$\delta m_h^2 \sim \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 Q_{\rm NP}^2 = (115\,{\rm GeV})^2 \left(\frac{Q_{\rm NP}}{0.5\,{\rm TeV}}\right)^2$$

$$Q_{\rm NP} \gtrsim \sqrt{c_i}\cdot 5\,{\rm TeV} \approx \begin{cases} 50\,{\rm TeV} & \text{composite } e \\ 5\,{\rm TeV} & \text{composite } G_a,\ h \\ 0.5\,{\rm TeV} & \text{1-loop perturbative} \end{cases}$$

# MSSM


$$Q_{\rm NP} \gtrsim \sqrt{c_i} \cdot 5\,{\rm TeV} \approx 0.5\,{\rm TeV}$$

$$\delta m_h^2 \sim \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 Q_{\rm NP}^2 \log \frac{M_{\rm Pl}^2}{Q_{\rm NP}^2}$$




$$\delta m_h^2 \sim \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 Q_{\rm NP}^2 = (115\,{\rm GeV})^2 \left(\frac{Q_{\rm NP}}{0.5\,{\rm TeV}}\right)^2$$

# What do we really know about the Higgs sector?

# The "established" SM

- "Observed" fields:
  - Gauge bosons: $g_\mu^A \quad W_\mu^a \quad B_\mu$
  - Femions: $Q_i \quad u_i^c \quad d_i^c \quad L_i \quad e_i^c$
  - "3/4" of the Higgs field: $G_a$ (long. part of massive gauge bosons, Goldstones of $SU(2)_L \times U(1)_Y \to U(1)_{em}$)

# The "established" lagrangian

Callan Coleman Wess Zumino PRD 177 1969

Manohar 9606222
Colangelo Isidori 0101264
Ecker 9501357

Contino 1005.4269

- Most general gauge invariant lagrangian for the observed fields
  - $L_{SM} = L_{EW} + L_{EWSB}$
  - $L_{EW}$ = Gauge bosons, fermions, gauge interactions
  - $L_{EWSB}$ = Goldstone effective lagrangian and interactions

$$\mathcal{L}_0 = -\frac{1}{4}W^a_{\mu\nu}W^{a\,\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G_{\mu\nu}G^{\mu\nu} + \sum_{j=1}^{3} \bar{\Psi}^{(j)} i \not{D} \Psi^{(j)}$$

$$\Sigma(x) = \exp(i\sigma^a \chi^a(x)/v) \qquad \Sigma \to U_L(x)\, \Sigma\, U_Y^\dagger(x)$$

$$\mathcal{L}_{mass} = \frac{v^2}{4}\mathrm{Tr}\left[(D_\mu\Sigma)^\dagger (D^\mu\Sigma)\right] - \frac{v}{\sqrt{2}}\sum_{i,j}\left(\bar{u}_L^{(i)} d_L^{(i)}\right)\Sigma\begin{pmatrix}\lambda^u_{ij}\, u_R^{(j)} \\ \lambda^d_{ij}\, d_R^{(j)}\end{pmatrix} + h.c.$$

$$+\ a_T\, v^2\, \mathrm{Tr}\left[\Sigma^\dagger D_\mu \Sigma\, \sigma^3\right]^2$$

$\rho \approx 1 \Rightarrow a_T \approx 0$

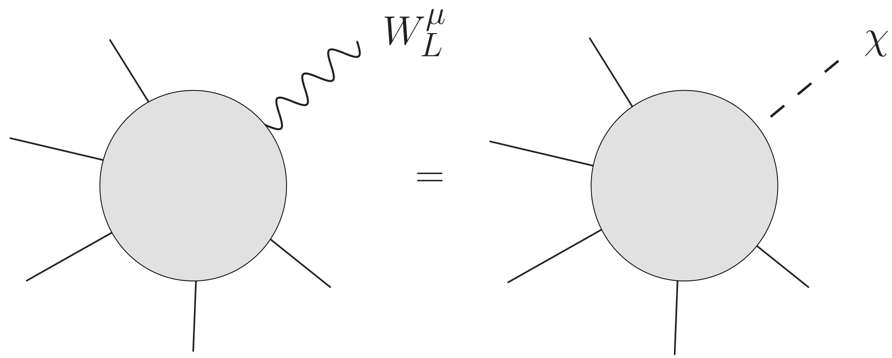
$SU(2)_L \times SU(2)_R$

+ O(p4)

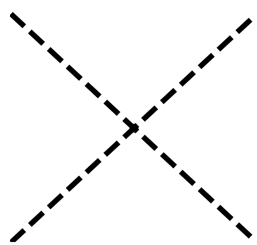
$$\Sigma \to U_L\, \Sigma\, U_R^\dagger$$

# 2 problems:

## 1) The theory is strongly interacting at TeV




$$\times \left(1 + O\left(\frac{m_W^2}{E^2}\right)\right)$$



$$\mathcal{A}(\chi^+\chi^- \to \chi^+\chi^-) = \frac{1}{v^2}(s+t)$$

(while EWPT seem to indicate that strong interactions can appear only above about 5 TeV)

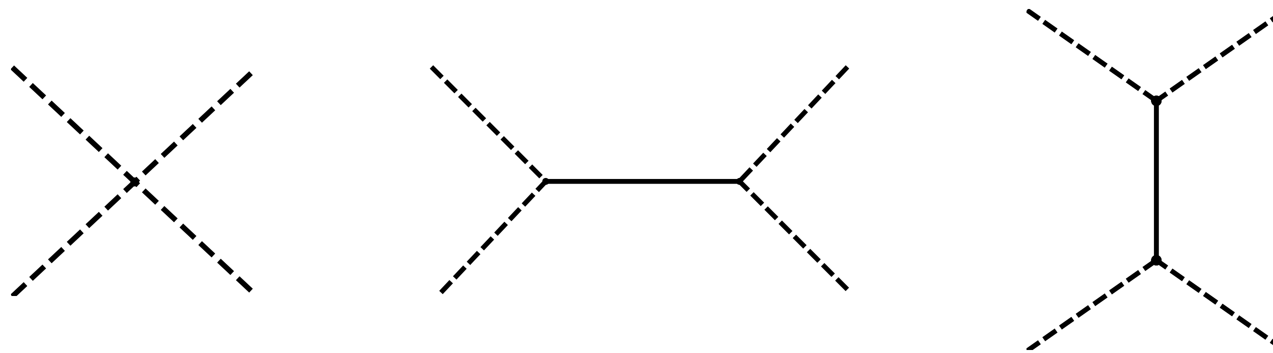
## 2) Hints of a Higgs

# Add scalar h, SU(2)$_L$xSU(2)$_R$ singlet

$$\mathcal{L}_H = \frac{1}{2}\left(\partial_\mu h\right)^2 + V(h) + \frac{v^2}{4}\mathrm{Tr}\left[\left(D_\mu\Sigma\right)^\dagger\left(D_\mu\Sigma\right)\right]\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right)$$

$$-\frac{v}{\sqrt{2}}\sum_{i,j}\left(\bar{u}_L^{(i)} d_L^{(i)}\right)\Sigma\left(1 + c\frac{h}{v} + \cdots\right)\begin{pmatrix}\lambda^u_{ij}\, u_R^{(j)} \\ \lambda^d_{ij}\, d_R^{(j)}\end{pmatrix} + h.c.$$

a ≈ 1



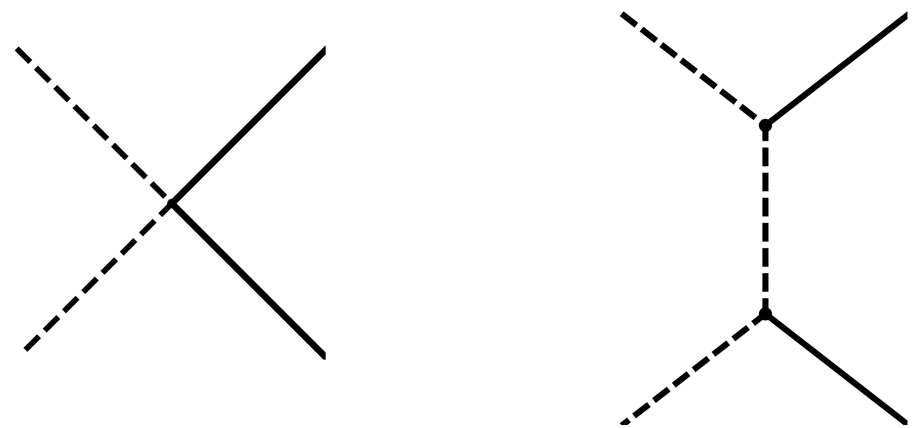
$$\mathcal{A}(\chi^+\chi^- \to \chi^+\chi^-) = \frac{1}{v^2}\left[s - a^2\frac{s^2}{s - m_h^2} + (s \leftrightarrow t)\right]$$

$$= \frac{s+t}{v^2}\left(1 - a^2\right) + O\left(\frac{m_h^2}{E^2}\right) .$$

# Add scalar h, SU(2)$_L$xSU(2)$_R$ singlet

$$\mathcal{L}_H = \frac{1}{2}\left(\partial_\mu h\right)^2 + V(h) + \frac{v^2}{4}\mathrm{Tr}\left[\left(D_\mu\Sigma\right)^\dagger\left(D_\mu\Sigma\right)\right]\left(1 + 2a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + \dots\right)$$
$$- \frac{v}{\sqrt{2}}\sum_{i,j}\left(\bar{u}_L^{(i)} d_L^{(i)}\right)\Sigma\left(1 + c\,\frac{h}{v} + \cdots\right)\begin{pmatrix}\lambda^u_{ij}\,u_R^{(j)}\\ \lambda^d_{ij}\,d_R^{(j)}\end{pmatrix} + h.c.$$

b ≈ 1



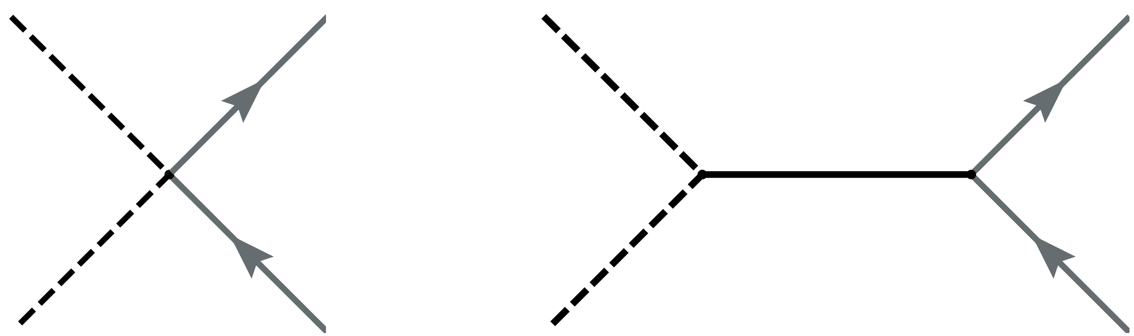
$$\mathcal{A}(\chi^+\chi^- \to hh) = \frac{s}{v^2}\left(b - a^2\right) + O\left(\frac{m_h^2}{E^2}\right)$$

# Add scalar h, $SU(2)_L \times SU(2)_R$ singlet

$$\mathcal{L}_H = \frac{1}{2}\left(\partial_\mu h\right)^2 + V(h) + \frac{v^2}{4}\mathrm{Tr}\left[\left(D_\mu \Sigma\right)^\dagger \left(D_\mu \Sigma\right)\right]\left(1 + 2a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + \dots\right)$$

$$- \frac{v}{\sqrt{2}} \sum_{i,j} \left(\bar{u}_L^{(i)} d_L^{(i)}\right) \Sigma \left(1 + c\,\frac{h}{v} + \cdots\right) \begin{pmatrix} \lambda^u_{ij}\, u_R^{(j)} \\ \lambda^d_{ij}\, d_R^{(j)} \end{pmatrix} + h.c.$$

c ≈ 1



$$\mathcal{A}(\chi^+\chi^- \to \psi\bar{\psi}) = \frac{m_\psi \sqrt{s}}{v^2}\,(1 - ac) + O\left(\frac{m_h^2}{E^2}\right)$$

a = b = c = 1

$$H(x) = \frac{1}{\sqrt{2}}\, e^{i\sigma^a \chi^a(x)/v} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

$L_H$ = SM Higgs + Yukawa lagrangian

# The “established” lagrangian

Callan Coleman Wess
Zumino PRD 177 1969

Manohar 9606222
Colangelo Isidori 0101264
Ecker 9501357

Contino 1005.4269

- The SM Higgs is a special, especially appealing case, with
  - ✓ exact unitarization
  - ✓ agreement with EWPT
  - ✓ understanding of custodial symmetry as accidental symmetry
  - ✗ hierarchy problem

# Higgs as a pseudo-NGB

- $a \neq 1$, $b \neq 1$, $c \neq 1$ are a sign of composite Higgs:
  $\Lambda_{strong}$ just pushed higher than TeV (better for EWPT)

- Composite Higgs welcome as a solution of the hierarchy problem
  (trade-off between HP and EWPT)

- Why $m_H \ll \Lambda_{strong}$?

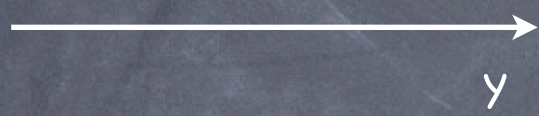
- Perhaps for the same reason why $m_\pi \ll \Lambda_{QCD}$
  H pseudo-NGB of approximate global symmetry
  of strong dynamics at $\Lambda_{strong} \gg m_H$

# Composite Higgs and extra dimensions

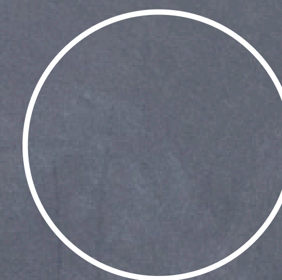
# Realization in Extra Dimensions

Quiros 0302189
Serone 0909.5619
Gherghetta 0601213

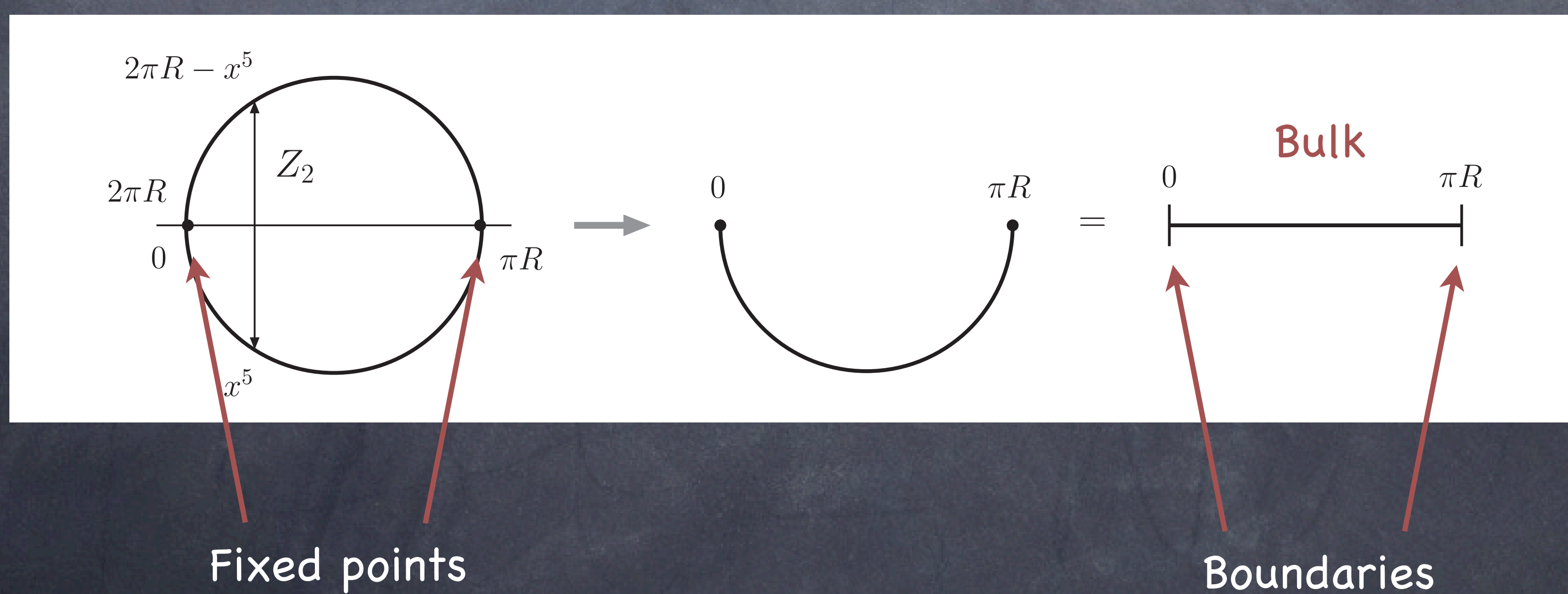
- $S^1$:




$+ \quad y \sim y + 2\pi R$:



- $S^1/Z_2$: $\qquad S^1 + \quad y \sim -y$:



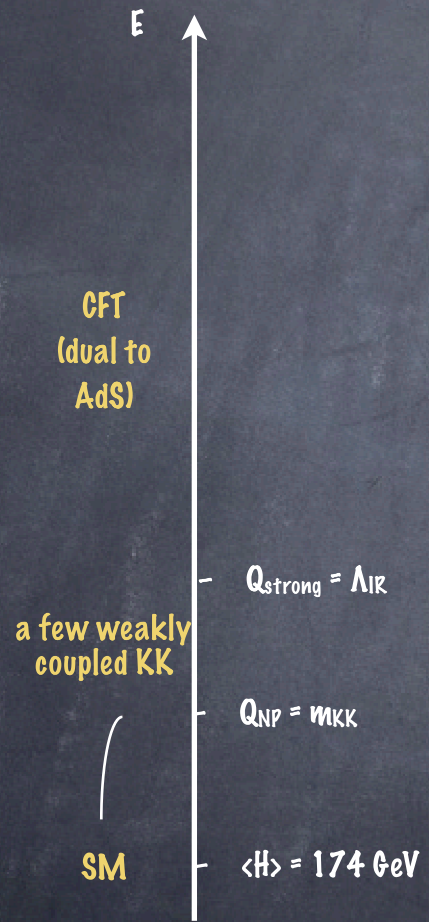
# $Z_2$ parity (boundary conditions)

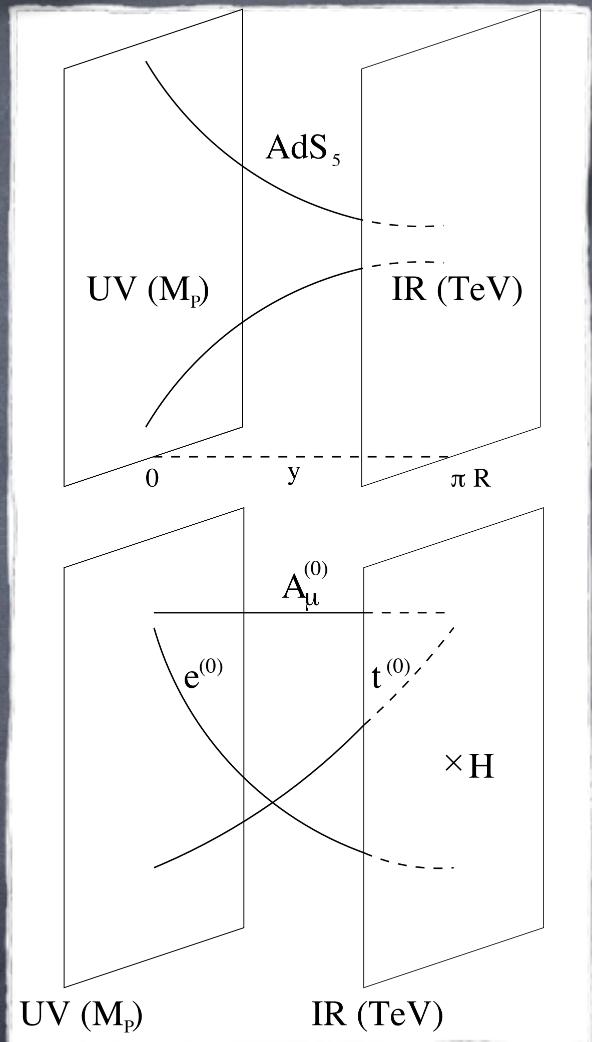
- Can be used to break symmetries in a novel way
- Gauge symmetries can be broken "on the boundaries"
- Boundary conditions for
  - 5D fermions: chirality
  - 5D vectors: massless (tree level) 4D scalars $\leftrightarrow$ broken generators $\leftrightarrow$ pseudo Goldstone bosons

# RS

- $S^1/Z_2$ 5D model with curved 5th dimension: $ds^2 = e^{-2ky} dx^2 + dy^2$
- IR redshift of energies: $y = \pi R$ (IR brane) wrt $y = 0$ (UV brane)
- All scales are $O(M_{Pl})$, including $k, 1/R$, within $O(10)$ factor
- Fields localized near UV see $O(M_{Pl})$, near IR see $O(M_{Pl})e^{-2\pi kR}$
- $kR \approx 12 \rightarrow O(M_{Pl})e^{-2\pi kR} \approx$ TeV
- Solution of hierarchy problem if the graviton is near UV, the Higgs is near IR
- SM in the bulk (instead of on the IR brane as in original RS)
  - eases FCNC problem
  - gives (very) hierarchical fermion masses
- Dual description: fields near IR are mostly composite

# Warping and compositeness



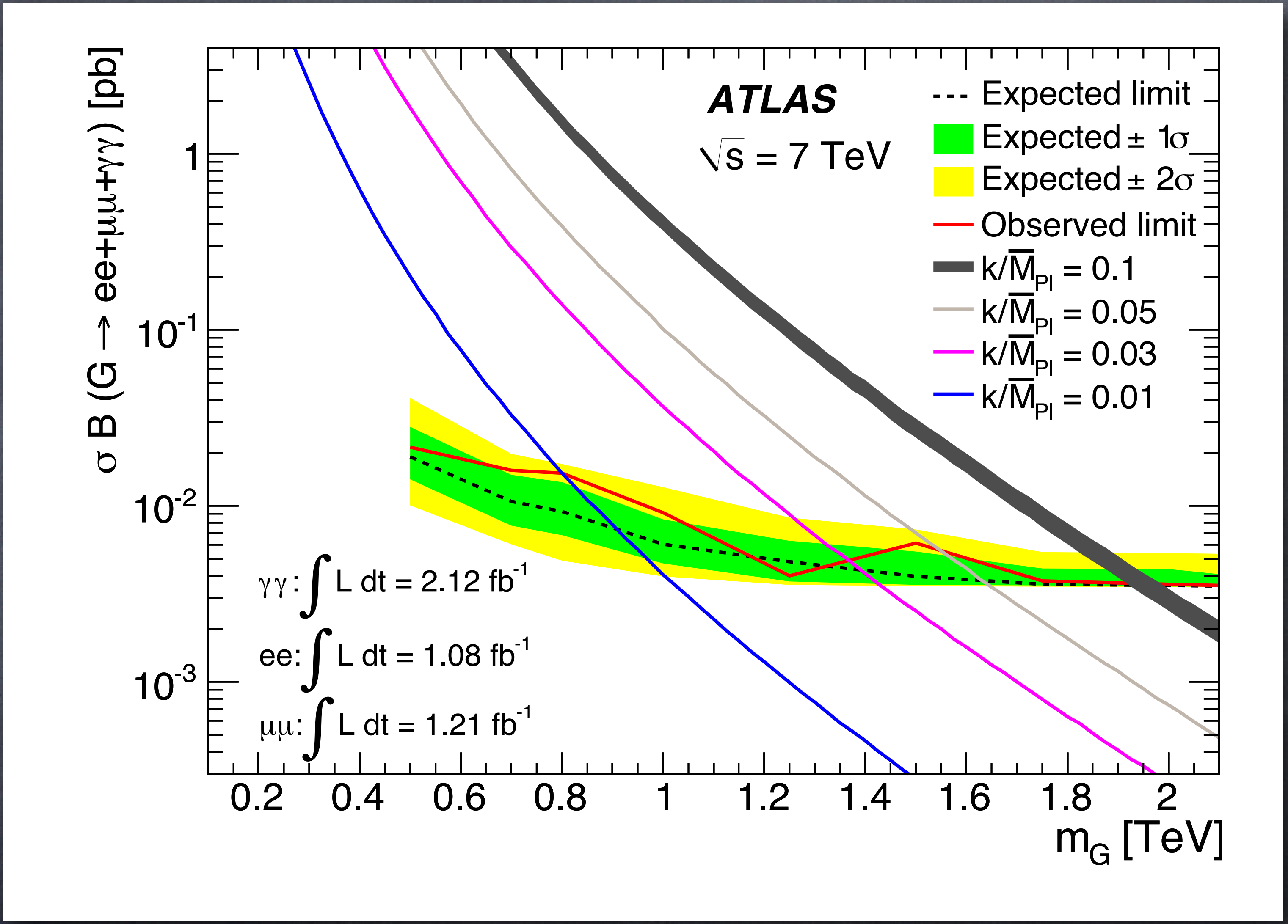

$$m_h \sim M_5 e^{-2\pi k R}$$

$$k = \text{curvature}$$

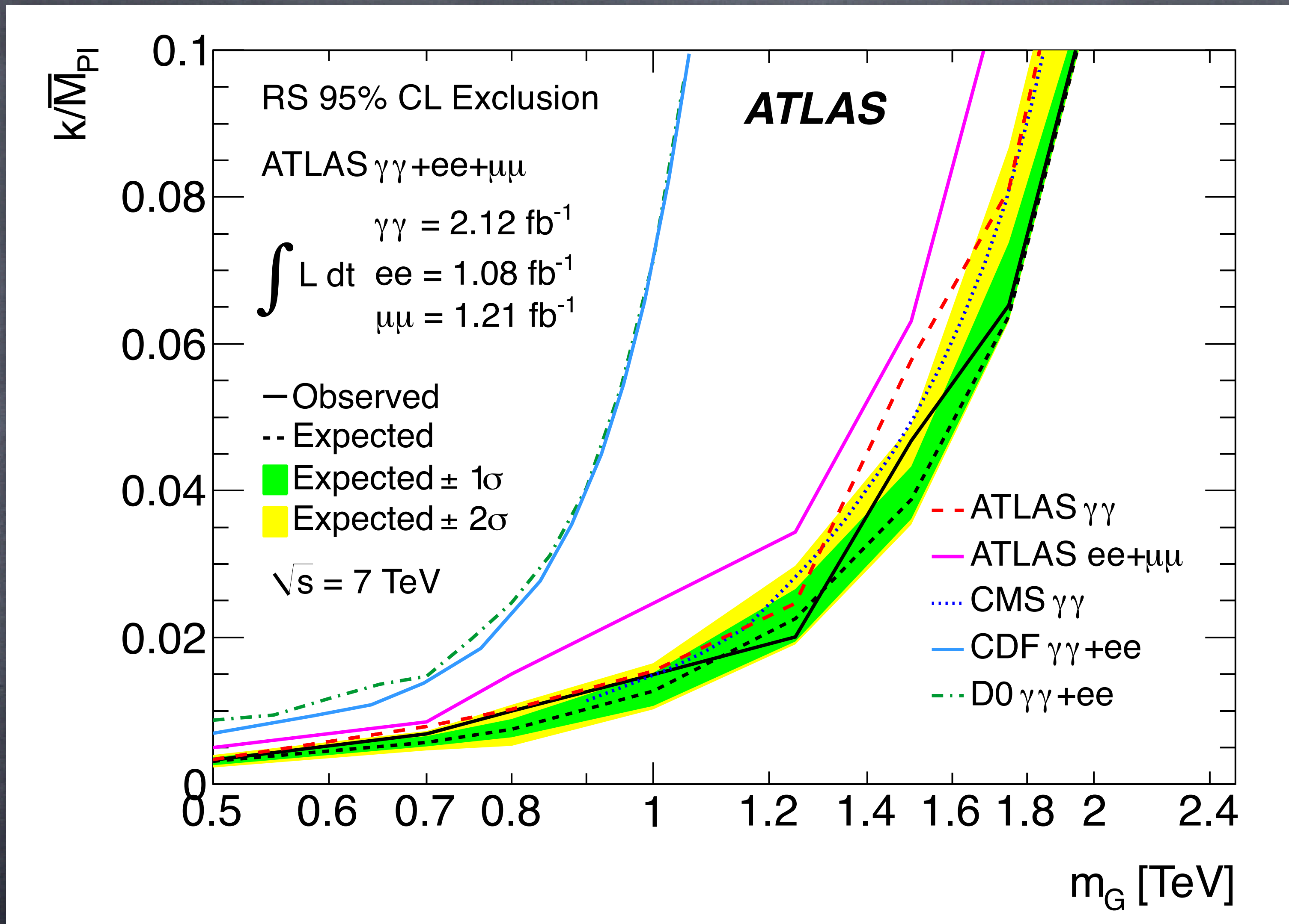
- Extra-dims accessible at LHC and compositeness together with high scale extrapolation
- RS + bulk fermions + H as $(A_5)_0$ + deconstruction = Little Higgs + UV completion
- Flavour, 4D dual
  UV brane: elementary dofs
  IR brane: composite dofs (H, $t_R$)
- $Q_{strong}$ > 5 TeV as usual
  $m_{KK}$ > TeV, watch $Z \to \bar{b}b$
- Gauge coupling unification in a novel way (but limited calculability)

[Contino Nomura Pomarol hep-ph/0306259
Agashe Contino Pomarol hep-ph/0412089
hep-ph/0605341]

$k/M_{Pl} = 0.1$:
$m_G > 1.85$ TeV (γγ only)
$m_G > 1.95$ TeV (combined)

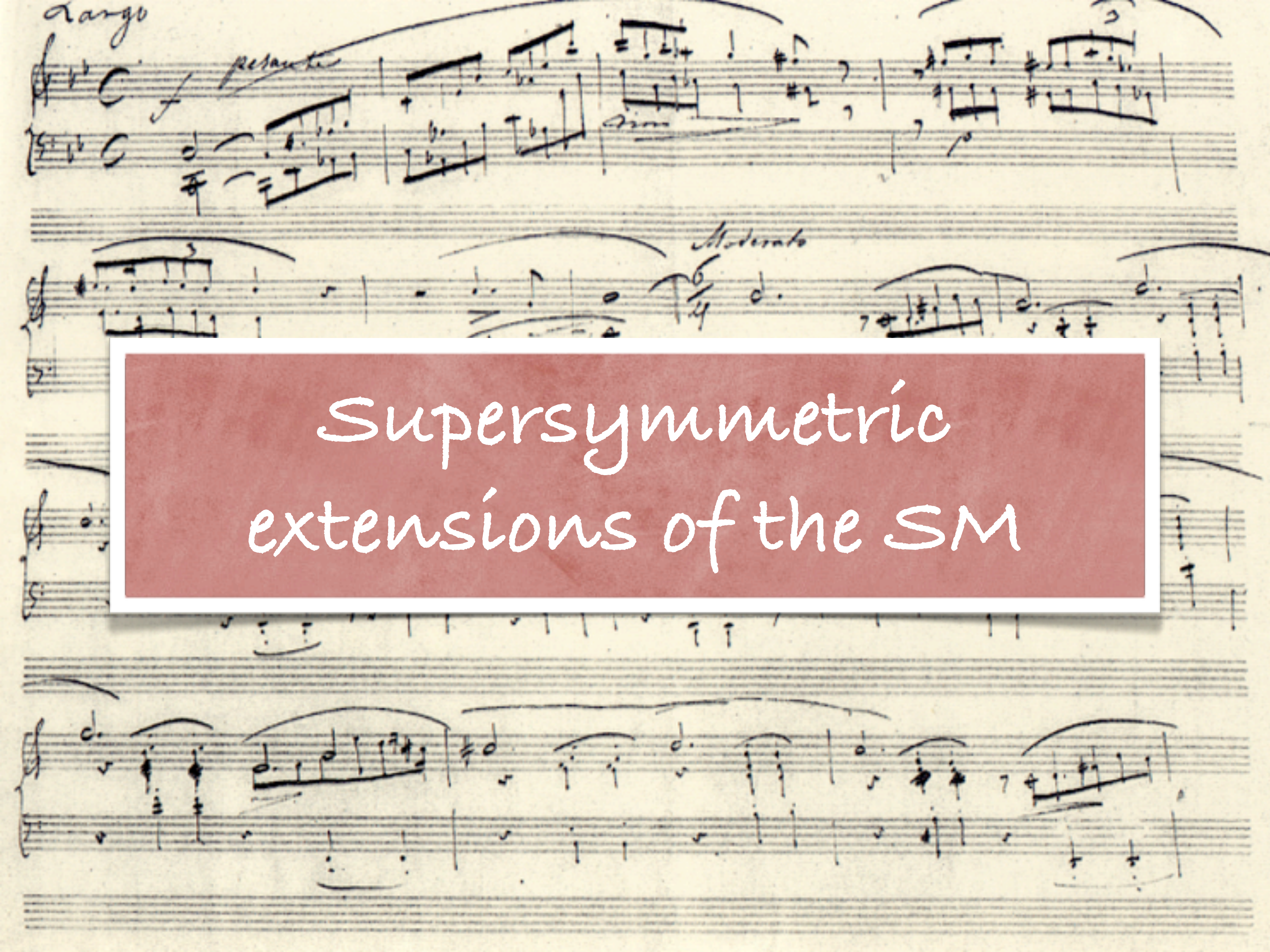



Expected and observed 95% CL limits from the combination of $G_1 \rightarrow \gamma\gamma/ee/\mu\mu$ channels on the product of the RS graviton production cross section and the branching ratio for graviton decay via $G_1 \rightarrow \gamma\gamma/ee/\mu\mu$



RS 95% CL Exclusion
ATLAS
ATLAS γγ+ee+μμ
∫L dt γγ = 2.12 fb-1
ee = 1.08 fb-1
μμ = 1.21 fb-1
Observed
Expected
Expected ± 1σ
Expected ± 2σ
√s = 7 TeV
ATLAS γγ
ATLAS ee+μμ
CMS γγ
CDF γγ+ee
D0 γγ+ee
k/M̄Pl
0.1
0.08
0.06
0.04
0.02
0
0.5
0.6
0.7
0.8
1
1.2
1.4
1.6
1.8
2
2.4
mG [TeV]

# Supersymmetric extensions of the SM



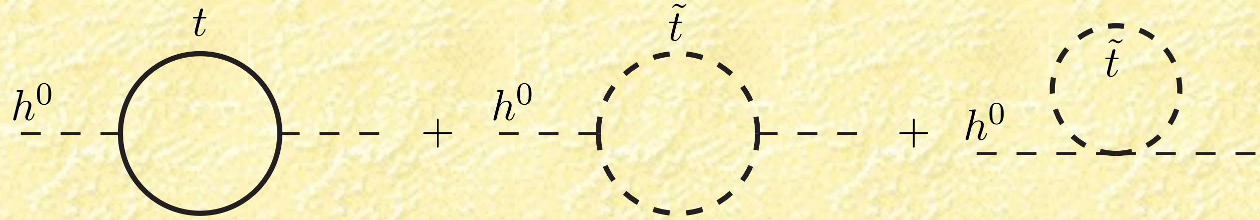
# Motivations

* Phenomenological
  - Solves the naturalness (hierarchy) problem
  - Precisely predicts gauge coupling unification
  - Provides a natural DM candidate (needs $R_P$)
  - See below...
* Theoretical
  - Unification of fermions and bosons
  - Local supersymmetry = supergravity + crucial in string theory
  - Completes the list of possible symmetries of S (under hypotheses)
  - Powerful technical tool

# How supersymmetry solves the hierarchy problem

$$\frac{3}{4\pi^2}\lambda_t^2 Q^2 \qquad\qquad -\frac{3}{4\pi^2}\tilde{\lambda}_t Q^2$$

$\Delta(m_{h^0}^2) =$




$$\lambda_t^2 = \tilde{\lambda}_t$$

* Note that it is crucial that the coupling are exactly equal. Supersymmetry breaking, if it is not to spoil the solution of the hierarchy problem should maintain this equality

# Properties and N=1

* Supersymmetry generators: b ↔ f; #b = #f
* $[P^2, Q_{i\alpha}] = 0 \Rightarrow m_b = m_f$ :  supersymmetry must be broken
* $\langle\Omega|H|\Omega\rangle \propto \Sigma_{i\alpha} (|Q_{i\alpha}\Omega|^2 + |\bar{Q}_{i\alpha}\Omega|^2) \geq 0$ : SSSB ⇔ vacuum energy > 0
* N supersymmetries: massive 1P states contain $j \geq N/2$

  massless 1P states contain $|j| \geq N/4$ (if odd, $N \to N+1$)
* $j \leq 2 \Rightarrow N \leq 8$

  $j \leq 1 \Rightarrow N \leq 4$

  chiral gauge theory ⇒ $N \leq 1$

  (chiral ⇔ not all the fermions can have a gauge invariant mass term

  SM is very chiral ⇒ its extensions must be chiral)

# N=1 supersymmetry algebra

- $\mathcal{G}$ = Poincaré + Internal group generators + $Q_\alpha$, $\bar{Q}_\alpha$
- $Q_\alpha \to L_\alpha{}^\beta\, Q_\beta$ , $[P_\mu, Q_\alpha] = 0$

  $Q_\alpha \to e^\omega\, Q_\alpha$  ("R-symmetry") or invariant under internal symmetries

  $\{Q_\alpha, \bar{Q}_\beta\} = 2\,\sigma^\mu_{\alpha\beta} P_\mu \quad \{Q_\alpha, Q_\beta\} = 0$
- 1 particle supersymmetry multiplets:

m ≠ 0

| j | 1P multiplets | | | |
|---|---|---|---|---|
| 0 | 2 | 1 | | |
| 1/2 | 1 | 2 | 1 | |
| 1 | | 1 | 2 | 1 |
| 3/2 | | | 1 | 2 |
| 2 | | | | 1 |

(j ≥ 1/2)

m = 0

| j | | |
|---|---|---|
| -1 | | 1 |
| -1/2 | 1 | 1 |
| 0 | 2 | |
| 1/2 | 1 | 1 |
| 1 | | 1 |

(|j| ≥ 1/2)

#B = #F

# Field multiplets

* **$(A, \psi)$** "scalar" ("chiral") multiplet

  $A$ scalar, $\psi$ left-handed Weyl spinor

  DOFs: 2B+2F (on shell)

  $[A] = 1$, $[\psi] = 3/2$

* **$(v^\mu, \lambda)$** massless "vector" ("real") multiplet

  $v^\mu$ real vector, $\lambda$ left-handed Weyl spinor

  DOFs: 2B+2F (on shell)

  $[v^\mu] = 1$, $[\lambda] = 3/2$

* **$(v^\mu, \lambda, \chi, C)$** massive vector multiplet

  $\chi$ Weyl, $C$ complex scalar

$m \neq 0$

| j | | |
|---|---|---|
| 0 | 2 | 1 |
| 1/2 | 1 | 2 |
| 1 | | 1 |

$m = 0$

| j | | |
|---|---|---|
| -1 | | 1 |
| -1/2 | 1 | 1 |
| 0 | 2 | |
| 1/2 | 1 | 1 |
| 1 | | 1 |

# Defining a global N=1 renormalizable supersymmetric gauge theory

* Specify the gauge group G

* Specify the chiral superfield content $\Phi_i = (A_i, \psi_i)$ and quantum numbers under G

* Associate a massless vector superfield to each generator of G: $t_A \leftrightarrow (v^A{}_\mu, \lambda^A)$

* Specify a gauge invariant holomorphic function $W(\Phi)$ ("superpotential") $[W] = 3$; renormalizability $\Rightarrow W = (\lambda_{ijk}/3)\Phi_i\Phi_j\Phi_k + (\mu_{ij}/2)\Phi_i\Phi_j + m^2{}_i\, \Phi_i$

# The supersymmetric lagrangian (WZ gauge)

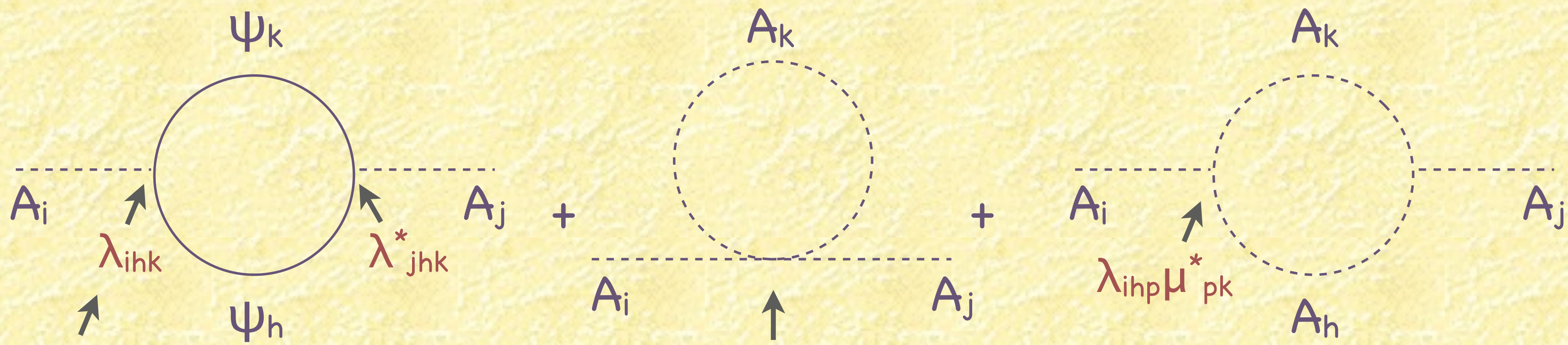
* In terms of $F_i^\dagger = \partial_i W(A) \quad D_A = g_A A_i^\dagger T_A^{ij} A_j$
* Omitting FY and θ term:

$$\mathcal{L}_{\rm susy} = \text{Kinetic} + \text{gauge for } A_i,\, \psi_i,\, v_A^\mu,\, \lambda_A$$
$$- \left( \frac{1}{2} \partial_i \partial_j W(A) \psi_i \psi_j + \sqrt{2} g_A A_i^\dagger T_A^{ij} \lambda^A \psi_j + \text{h.c.} \right) - V(A)$$
$$V(A) = F_i^\dagger F_i + \frac{1}{2} D_A^2 \geq 0$$

* Continuous symmetries (commuting with gauge):
  * commuting with supersymmetry: Q(A) = Q(ψ), Q($v_\mu$) = Q(λ) = 0, **Q(W) = 0**
  * R-symmetries: R(ψ) = R(A)-1, R($v_\mu$) = 0, R(λ) = 1, **R(W) = 2**

# Non renormalization theorem and the solution of the hierarchy problem

- Second line in $L_{susy}$ does not get perturbative radiative corrections
- First line does, but it is (logarithmic) wave function renormalization
- Example: $W \supseteq -\mu_{ij} A_i A_j \Rightarrow V \supseteq (\mu^\dagger \mu)_{ij} A^\dagger_i A_j$, quadratically divergent?




From $-(1/2)\partial_h \partial_k W(A)\ \psi_h \psi_k$

$W(A) \supseteq (\lambda_{ihk}/3) A_i A_h A_k$

$\lambda_{ihk}\ \lambda^*_{jhk}$

From $F^\dagger_h F_h$,

$F^\dagger_h = \partial_h W(A)$

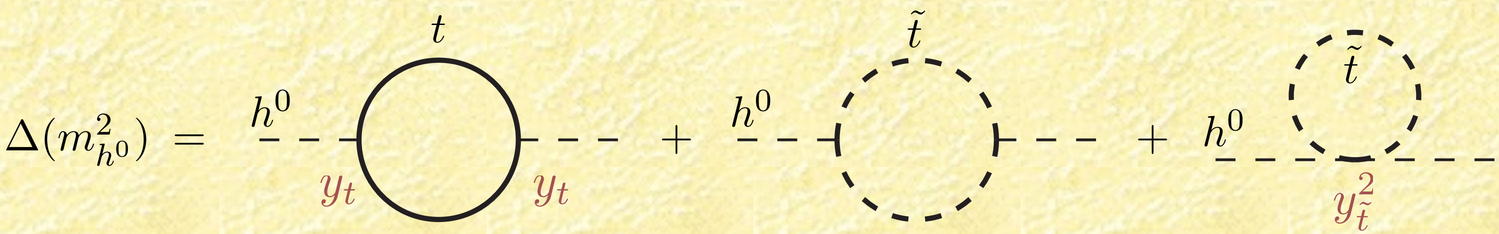
+ gauge contributions

Proof at all orders uses superfields formalism or Seiberg argument (hep-ph/9309335)

- Interpretation: supersymmetry relates scalar masses to fermion masses, which are protected by chiral symmetry

# Explicit (soft) supersymmetry breaking

- $\tilde{m}_e \geq 100$ GeV, not $= 0.5$ MeV
- Most mechanisms of supersymmetry breaking take place at Q » TeV, give rise to effective, explicit, soft supersymmetry breaking terms at Q = TeV
- "Soft" = do not give rise to quadratic divergences



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$$\mathcal{L} = \mathcal{L}_{\text{susy}} + \mathcal{L}_{\text{soft}}$$

$$-\mathcal{L}_{\text{soft}} = m^2_{ij} A_i^\dagger A_j + \left( \frac{M_{AB}}{2} \lambda_A \lambda_B + w(A) + \text{h.c.} \right)$$

[Girardello Grisaru , NPB 194 (1982)]

- w(A) olomorphic, $w = (a_{ijk}/3) A_i A_j A_k + (b^2_{ij}/2) A_i A_j + c^3_i A_i$
- All terms in $\mathcal{L}_{\text{soft}}$ proportional to a (supersymmetry breaking) mass scale
- $(M_{ij})/2\ \psi_i \psi_j$ can be reabsorbed, $w(A, A^\dagger)$, $M_{Ai}\ \lambda_A \psi_i$ give quadratic divergences in the presence of gauge singlets (and very suppressed in explicit models)

Back to $R_P$

# Spontaneous supersymmetry breaking (SSSB)

- SSSB ⇔ V > 0 ⇔ F ≠ 0 or D ≠ 0 $V(A) = F_i^\dagger F_i + \frac{1}{2} D_A^2 \geq 0$

  (if $V_{min}$ = 0, there could still be SSSB in false vacua) $F_i^\dagger = \partial_i W(A)$ $D_A = g_A A_i^\dagger T_A^{ij} A_j$

- SSSB should not couple to the SM fields at the renormalizable + tree level:
  - $Tr(M^2_{s=0}) - 2\,Tr(M^2_{s=1/2}) + 3\,Tr(M^2_{s=1}) = 0$ (tree level, canonical kinetic term)
  - no gaugino masses

[Ferrara Girardello Palumbo, PRD20 (1979)]

- Typically: SSSB in hidden sector at $Q_{SSSB}$ » TeV, communicated to the SM fields by "messengers" at $Q_{mess}$ » $Q_{SSSB}$ (gravity, heavy charged fields, etc)

# The MSSM

# The Minimal Supersymmetric extension of the Standard Model (MSSM)

[Martin, hep-ph/9709356; Drees Godbole Roy, Haber Kane, Phys Rept 117 (1985)]

* "Minimal" = minimal number of fields
* $G = SU(3)_c \times SU(2)_L \times U(1)_Y = G_{SM}$
* Embedding of the SM fields [in $(A,\psi)$ (chiral) or $(v_\mu,\lambda)$ (vector) multiplets]:

| SM | $g_\mu$ | $W_\mu$ | $B_\mu$ | $q_i$ | $u^c_i$ | $d^c_i$ | $l_i$ | $e^c_i$ | $h$ |
|---|---|---|---|---|---|---|---|---|---|
| $SU(3)_c$ | 8 | 1 | 1 | 3 | $\bar{3}$ | $\bar{3}$ | 1 | 1 | 1 |
| $SU(2)_L$ | 1 | 3 | 1 | 2 | 1 | 1 | 2 | 1 | 2 |
| $U(1)_Y$ | 0 | 0 | 0 | 1/6 | -2/3 | 1/3 | -1/2 | 1 | -1/2 |

- Gauge bosons ⊆ vector multiplets (with gauginos)

$$g^A_\mu \to \hat{g}^A \equiv (g^A_\mu, \tilde{g}^A) \qquad \text{(with "gluinos")}$$

$$W^a_\mu \to \hat{W}^a \equiv (W^a_\mu, \tilde{W}^a) \qquad \text{(with "Winos")}$$

$$B_\mu \to \hat{B} \equiv (B_\mu, \tilde{B}) \qquad \text{(with "Binos")}$$

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| $U(1)_Y$ | 0 | 0 | 0 | 1/6 | -2/3 | 1/3 | -1/2 | 1 | -1/2 |

- Fermions ⊆ chiral multiplets (with **s**fermions, **s** for "scalar")

$$l_i \to \hat{l}_i \equiv (\tilde{l}_i, l_i)$$
$$e^c_i \to \hat{e}^c_i \equiv (\tilde{e}^c_i, e^c_i) \quad \text{(with "sleptons")}$$

$$q_i \to \hat{q}_i \equiv (\tilde{q}_i, q_i)$$
$$u^c_i \to \hat{u}^c_i \equiv (\tilde{u}^c_i, u^c_i) \quad \text{(with "squarks")}$$
$$d^c_i \to \hat{d}^c_i \equiv (\tilde{d}^c_i, d^c_i)$$

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[Martin, hep-ph/9709356; Drees Godbole Roy]

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|---|---|---|---|---|---|---|---|---|---|
| $SU(3)_c$ | 8 | 1 | 1 | 3 | $\bar{3}$ | $\bar{3}$ | 1 | 1 | 1 |
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| $U(1)_Y$ | 0 | 0 | 0 | 1/6 | -2/3 | 1/3 | -1/2 | 1 | -1/2 |

- Higgs ⊆ chiral multiplets (with Higgsi**nos**)
  lepton number conservation: $h \neq \tilde{l}_i$
  anomaly cancellation + fermion masses: $h \to \hat{h}_u \equiv (h_u, \tilde{h}_u) + \hat{h}_d \equiv (h_d, \tilde{h}_d)$

$$\lambda_U u^c q\, h^* + \lambda_D d^c q\, h \to \lambda_U u^c q\, h_u + \lambda_D d^c q\, h_d$$

# The MSSM superfield content

| MSSM | $\hat{g}_\mu$ | $\hat{W}_\mu$ | $\hat{B}_\mu$ | $\hat{q}_i$ | $\hat{u}^c{}_i$ | $\hat{d}^c{}_i$ | $\hat{l}_i$ | $\hat{e}^c{}_i$ | $\hat{h}_u$ | $\hat{h}_d$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $SU(3)_c$ | 8 | 1 | 1 | 3 | $\bar{3}$ | $\bar{3}$ | 1 | 1 | 1 | 1 |
| $SU(2)_L$ | 1 | 3 | 1 | 2 | 1 | 1 | 2 | 1 | 2 | 2 |
| $U(1)_Y$ | 0 | 0 | 0 | 1/6 | -2/3 | 1/3 | -1/2 | 1 | 1/2 | -1/2 |
| | vector | | | chiral | | | | | | |

SM field content + gauginos, sfermions, Higgsinos (and 1 extra Higgs doublet)

"**s**particles" , **s** for "supersymmetric"

Gauge rep not (fully) chiral, unlike in the SM → $\mu$ problem

- SUSY: fermion ↔ scalars; SUSY partners much heavier

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $u$ | $c$ | $t$ | $\gamma$ | $\tilde{u}$ | $\tilde{c}$ | $\tilde{t}$ | $\tilde{\gamma}$ |
| $d$ | $s$ | $b$ | $g$ | $\tilde{d}$ | $\tilde{s}$ | $\tilde{b}$ | $\tilde{g}$ |
| $e$ | $\mu$ | $\tau$ | $W$ | $\tilde{e}$ | $\tilde{\mu}$ | $\tilde{\tau}$ | $\tilde{W}$ |
| $\nu_1$ | $\nu_2$ | $\nu_3$ | $Z$ | $\tilde{\nu}_1$ | $\tilde{\nu}_2$ | $\tilde{\nu}_3$ | $\tilde{Z}$ |
| | $H_1$ | $H_2$ | | | $\tilde{H}_1$ | $\tilde{H}_2$ | |

# The SM Yukawas and the superpotential

* Must identify the SM Yukawa interactions, e.g. $\lambda\, u^c q\, h$

* Candidate Yukawa interactions:

$$\mathcal{L}_{\rm susy} = \text{Kinetic} + \text{gauge for } A_i,\ \psi_i,\ v^\mu_A,\ \lambda_A$$
$$- \left(\frac{1}{2}\partial_i\partial_j W(A)\psi_i\psi_j + \sqrt{2}g_A A_i^\dagger T_A^{ij}\lambda^A\psi_j + \text{h.c.}\right) - V(A)$$
$$V(A) = F_i^\dagger F_i + \frac{1}{2}D_A^2 \geq 0$$

* The SM Yukawa interactions must come from superpotential terms

$$W \supseteq \lambda^U_{ij}\hat{u}^c_i\hat{q}_j\hat{h}_u + \lambda^D_{ij}\hat{d}^c_i\hat{q}_j\hat{h}_d + \lambda^U_{ij}\hat{e}^c_i\hat{l}_j\hat{h}_d$$

# R-parity

* The most general renormalizable gauge invariant superpotential:

$$W = \lambda^U_{ij}\hat{u}^c_i\hat{q}_j\hat{h}_u + \lambda^D_{ij}\hat{d}^c_i\hat{q}_j\hat{h}_d + \lambda^E_{ij}\hat{e}^c_i\hat{l}_j\hat{h}_d + \mu\,\hat{h}_u\hat{h}_d$$

→ SM Yukawas
+ Higgs and Higgsino mass
+ more interactions

$$+\lambda_{[ij]k}\hat{l}_i\hat{l}_j\hat{e}^c_k + \lambda'_{kji}\hat{l}_i\hat{q}_j\hat{d}^c_k + \lambda''_{i[jk]}\hat{u}^c_i\hat{d}^c_j\hat{d}^c_k + \mu'_i\hat{l}_i\hat{h}_u$$

→ L and B violation:
proton decay,
neutrino masses

* In the SM: L, B accidentally conserved (welcome)
* In the MSSM: L, B accidentally conserved once matter parity ($P_M$) or equivalently R-parity ($P_R$ or $R_P$) is imposed
* $P_M = +1$ on $\hat{h}_u$, $\hat{h}_d$ (scalar component $\in$ SM)

  $P_M = -1$ on $\hat{q}$, $\hat{u}^c$, $\hat{d}^c$, $\hat{l}$, $\hat{e}^c$ (fermion component $\in$ SM)

  $P_M = (-1)^{3(B-L)}$ (remnant of B-L gauge symmetry?), commutes with SUSY
* $R_P = +1$ on $q$, $u^c$, $d^c$, $l$, $e^c$, $h_u$, $h_d$ (SM fields + additional Higgs)

  $R_P = -1$ on $\tilde{q}$, $\tilde{u}^c$, $\tilde{d}^c$, $\tilde{l}$, $\tilde{e}^c$, $\tilde{h}_u$, $\tilde{h}_d$ (supersymmetric partners)

  $R_P = (-1)^{3(B-L)+2s}$, discrete R-symmetry

# Consequences of $R_P$

* Constrains the form of W, $\mathcal{L}_{\rm soft}$ (B, L accidentally conserved)

$$W = \lambda^U_{ij}\hat{u}^c_i\hat{q}_j\hat{h}_u + \lambda^D_{ij}\hat{d}^c_i\hat{q}_j\hat{h}_d + \lambda^E_{ij}\hat{e}^c_i\hat{l}_j\hat{h}_d + \mu\,\hat{h}_u\hat{h}_d$$

$$-\mathcal{L}_{\rm soft} = A^U_{ij}\tilde{u}^c_i\tilde{q}_j h_u + A^D_{ij}\tilde{d}^c_i\tilde{q}_j h_d + A^E_{ij}\tilde{e}^c_i\tilde{l}_j h_d + m^2_{ud}h_u h_d + \text{h.c.}$$
$$+ (\tilde{m}^2_q)_{ij}\tilde{q}^\dagger_i\tilde{q}_j + (\tilde{m}^2_{u^c})_{ij}(\tilde{u}^c_i)^\dagger\tilde{u}^c_j + (\tilde{m}^2_{d^c})_{ij}(\tilde{d}^c_i)^\dagger\tilde{d}^c_j + (\tilde{m}^2_l)_{ij}\tilde{l}^\dagger_i\tilde{l}_j$$
$$+ (\tilde{m}^2_{e^c})_{ij}(\tilde{e}^c_i)^\dagger\tilde{e}^c_j + m^2_{h_u}h^\dagger_u h_u + m^2_{h_d}h^\dagger_d h_d$$
$$+ \frac{M_3}{2}\tilde{g}_A\tilde{g}_A + \frac{M_2}{2}\tilde{W}_a\tilde{W}_a + \frac{M_1}{2}\tilde{B}\tilde{B} + \text{h.c.}$$

→

* **MSSM** ≡ $G_{SM}$ + field content above + most general $R_P$-invariant W, $\mathcal{L}_{\rm soft}$
* Sparticles are produced in pairs
* The Lightest Supersymmetric Particle (LSP) is stable
* Processes with SM external states only get susy corrections through loops

# Parameter counting

* 3 gauge couplings, quantum numbers, $\theta_{QCD}$

* $\mathcal{L}_{SUSY}$: (3x18+2) - (9x5+2-5) = 14 = 9 fermion masses + 4 CKM parameters + 1 Higgs/ino mass = SM - 1 (Higgs coupling predicted)

* $\mathcal{L}_{SUSY} + \mathcal{L}_{soft}$: [3x18+2 (W) + 3x2 (gaugino masses) + 3x18+2 (w) + 5x9+2 (scalar masses)] - [9x5+2 ($U(3)^5 \times U(1)^2$) + 1 (R-symmetry) - 3 (B, L, Y)] = 120 = SM + 105 = 14 + 3 gaugino masses + 3x6+3 sfermion masses + v, tanβ, $m_A$ + 79 mixing and phases

* Too large FCNC and CPV processes in most of the parameter space

# Flavour violation

* $\mathcal{L}_{\text{SUSY}}$

- The only sources of $U(3)^5$ breaking are the Yukawa matrices in W: $\lambda_U$, $\lambda_D$, $\lambda_E$ (as in the SM)

- New flavour-violating interactions but controlled by the same parameters ("Mimimal Flavour Violation" MFV). Expect new effects but of the same order of magnitude as in the SM

- $U(2)^5$ still approximate symmetry (exact in the limit $\lambda = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \lambda_{33} \end{pmatrix}$)

# Flavour violation

* $\mathcal{L}_{\text{SUSY}} + \mathcal{L}_{\text{soft}}$

- New sources of U(3)$^5$ violation:

$$A^U_{ij}, A^D_{ij}, A^E_{ij}$$
$$(\tilde{m}^2_q)_{ij}, (\tilde{m}^2_{u^c})_{ij}, (\tilde{m}^2_{d^c})_{ij}, (\tilde{m}^2_l)_{ij}, (\tilde{m}^2_{e^c})_{ij}$$

- Under a U(3)$^5$ transformation

$$A_U \to U^T_{u^c} A_U U_q, \ldots$$
$$\tilde{m}^2_q \to U^\dagger_q \tilde{m}^2_q U_q \ldots$$

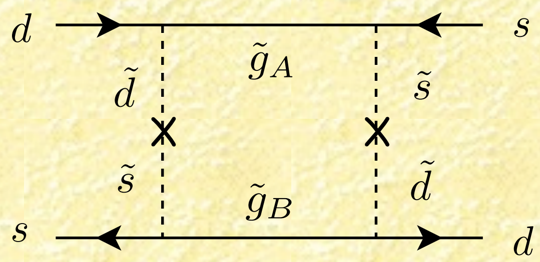
- New effects controlled by new parameters unrelated to SM Yukawas: potentially unsuppressed: $\varepsilon \approx 10^{-6} \to O(1)$

- Unless the soft terms are also approximately U(2)$^5$ symmetric:

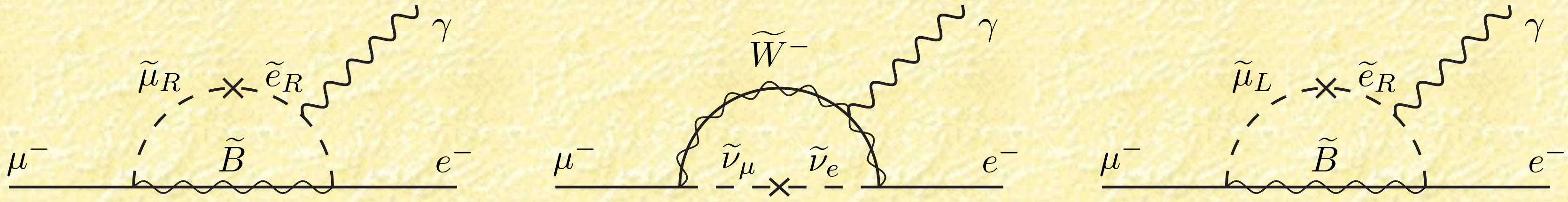
$$A = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & A_{33} \end{pmatrix} + \text{“small”} \qquad \tilde{m}^2 = \begin{pmatrix} m^2 & 0 & 0 \\ 0 & m^2 & 0 \\ 0 & 0 & m^2_3 \end{pmatrix} + \text{“small”}$$

# Flavour violation: examples

- $K^0(d\bar{s})$ - $\bar{K}^0(\bar{d}s)$ oscillations (adds to the SM)




- $\mu \to e\,\gamma$ (negligible in the SM even adding neutrino masses)



# The Constrained MSSM (CMSSM)

* Assume that at some scale $M_0 \gg$ TeV the soft term satisfy (tree level):
  * $M_1 = M_2 = M_3 \equiv M_{1/2}$ (universal gaugino masses)
  * $A_{U,D,E} = A_0\, \lambda_{U,D,E}$ (A-term proportionality)
  * $(\tilde{m}^2_q)_{ij} = (\tilde{m}^2_u)_{ij} = (\tilde{m}^2_d)_{ij} = (\tilde{m}^2_l)_{ij} = (\tilde{m}^2_e)_{ij} = m^2_0\, \delta_{ij}$ $\quad m^2_{hu} = m^2_{hd} = m^2_0$ (universality of scalar masses)
* Motivation:
  * Benchmark model with few parameters and FCNCs under control
  * Minimal supergravity (msugra) gives the CMSSM (with model-dependent $A_0$–$B_0$ relation)
* Parameter counting: 106 → 4 dimensionful pars + 2 phases (no new mixing pars, all mixing can be expressed in terms of CKM: an example of Minimal Flavour violation)

# Phase convention

| Complex parameters: | $\mu$ | $M_{1/2}$ | $A_0$ | $m^2_{ud}$ |
|---|---|---|---|---|
| R-symmetry: | $\mu$ | $M_{1/2}\ e^{2i\omega}$ | $A_0\ e^{2i\omega}$ | $m^2_{ud}$ |
| Peccei-Quinn symmetry | $\mu\ e^{2i\alpha}$ | $M_{1/2}$ | $A_0$ | $m^2_{ud}\ e^{2i\alpha}$ |

- R-symmetry: $\mathcal{L}_{susy}$ invariant, $R[\lambda\lambda] = 2$, $R[W] = 2 \Rightarrow R[w] = 2$
- Peccey-Quinn: $\hat{h}_{u,d} \to \hat{h}_{u,d}\ e^{i\alpha}$, $PQ(u^c q h_u) = PQ(d^c q h_d) = PQ(e^c l h_d) = 0$
- Standard phase convention: $M_{1/2} > 0$, $m^2_{ud} > 0$, phases in $\mu$, $A_0$ also used in the MSSM (provided that the gaugino phases differ by $\pi$)
- Constraints from EDMs: $|\sin\varphi_\mu|$, $|\sin\varphi_A| \lesssim 10^{-2}$ (supersymmetric CP "problem")

# CP-conserving CMSSM

- Physical parameters (besides gauge, fermion masses and mixings)

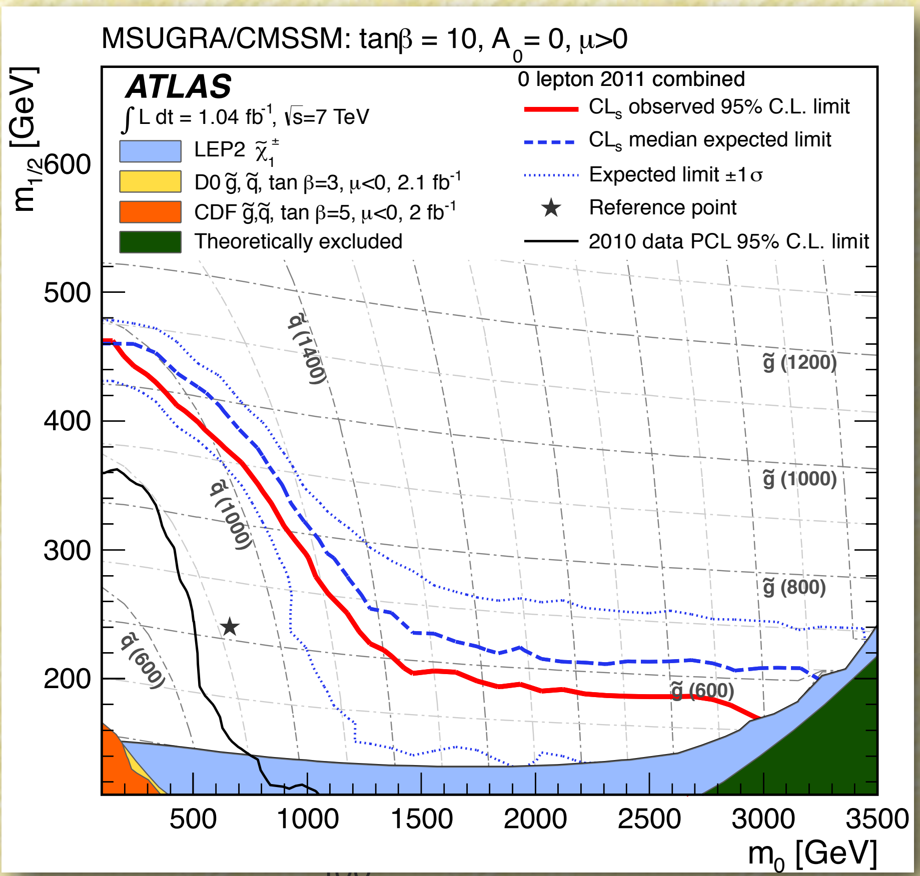
  $-\infty < m^2_0 < \infty$, $-\infty < A_0 < \infty$, $|\mu| > 0$, $M_{1/2} > 0$, $m^2_{ud} > 0$, $\text{sign}(\mu) = \pm 1$

- Trade $|\mu|$ for $M_Z$, $m^2_{ud}$ for $\tan\beta$ (see below):

  $-\infty < m^2_0 < \infty$, $-\infty < A_0 < \infty$, $M_{1/2} > 0$, $0 \leq \beta \leq \pi/2$, $\text{sign}(\mu) = \pm 1$

- Plots often in $m_0$-$M_{1/2}$ plane for fixed $\beta$, $A_0$, $\text{sign}(\mu)$

Example:
Atlas exclusion



# Analysis of the MSSM

# Analysis of the MSSM

1. Find the minimum of the potential (symmetry breaking) $\phi_0$ and express the lagrangian in terms of $\delta\phi = \phi - \phi_0$ [lagrangian terms linear in the fields]

2. Collect the mass terms, find the mass eigenstates, express the original fields in terms of the mass eigenstates [terms quadratic in the fields]

3. Write the interactions in terms of the mass eigenstates [terms at least trilinear in the fields]

# Electroweak symmetry breaking

$$V = V_{\text{susy}} + V_{\text{soft}} = V(h_u, h_d, \tilde{q}_i, \tilde{u}^c_i, \tilde{d}^c_i, \tilde{l}_i, \tilde{e}^c_i)$$

* Issues:
  1. V bounded from below? ("UFB" directions)
  2. $\langle\tilde{q}_i\rangle = \langle\tilde{u}^c_i\rangle = \langle\tilde{d}^c_i\rangle = \langle\tilde{l}_i\rangle = \langle\tilde{e}^c_i\rangle = 0$? ("CCB" (and L breaking) minima)
  3. $\langle h_u\rangle$, $\langle h_d\rangle$ preserve $U(1)_{em}$ ?

$$m_u^2 \equiv m_{h_u}^2 + |\mu|^2$$
$$m_d^2 \equiv m_{h_d}^2 + |\mu|^2$$

1. Not guaranteed. E.g. along $\langle h_u\rangle = \begin{pmatrix} 0 \\ w \end{pmatrix}$, $\langle h_d\rangle = \begin{pmatrix} w \\ 0 \end{pmatrix}$, $\left\langle \tilde{f} \right\rangle = 0$

   $V = (m_u^2 + m_d^2 - m_{ud}^2)\, w^2$ is unbounded from below unless $m_u^2 + m_d^2 > m_{ud}^2$

2. Not guaranteed. E.g. along $\langle h_d\rangle = \begin{pmatrix} w \\ 0 \end{pmatrix}$, $\left\langle \tilde{l}_i \right\rangle = \begin{pmatrix} 0 \\ w \end{pmatrix}$, $\langle \tilde{e}^c_i\rangle = -we^{-\phi(A^E_{ii})}$, $\langle \text{else}\rangle = 0$

   V(w) has a (deep) ~~U(1)~~$_{em}$ minimum unless $|A^E_{ii}|^2 < 3\lambda^2_{e_i}\left[(\tilde{m}^2_l)_{ii} + (\tilde{m}^2_{e^c})_{ii} + m_d^2\right]$

   Analogously: $|A^D_{ii}|^2 < 3\lambda^2_{d_i}\left[(\tilde{m}^2_q)_{ii} + (\tilde{m}^2_{d^c})_{ii} + m_d^2\right]$

   Also: check positivity of mass eigenvalues $|A^U_{ii}|^2 < 3\lambda^2_{u_i}\left[(\tilde{m}^2_q)_{ii} + (\tilde{m}^2_{u^c})_{ii} + m_u^2\right]$

   Note: $|A| \lesssim \lambda\, \tilde{m}$, $A \equiv \lambda \hat{A}$

3. Guaranteed (provided that 1. and 2. are fine)

* Assume <q̃ᵢ> = <ũᶜᵢ> = <d̃ᶜᵢ> = <l̃ᵢ> = <ẽᶜᵢ> = 0. Then

$$V = \frac{g^2+g'^2}{8}\left(h_u^\dagger h_u - h_d^\dagger h_d\right)^2 + \frac{g^2}{2}\left|h_u^\dagger h_d\right|^2 + |\mu|^2\left(h_u^\dagger h_u + h_d^\dagger h_d\right) \quad \text{from } \mathcal{L}_{\text{susy}}$$

$$+ m_{h_u}^2 h_u^\dagger h_u + m_{h_d}^2 h_d^\dagger h_d + m_{ud}^2 (h_u h_d + \text{h.c.}) \quad \text{from } \mathcal{L}_{\text{soft}}$$

* Up to a gauge transformation: $h_u = v_u \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \; h_d = v_d e^{i\phi} \begin{pmatrix} \cos\chi \\ \sin\chi \end{pmatrix}$ $\quad v_{u,d} > 0$, $\; 0 \le \chi \le \pi/2$

* $\chi \neq 0 \Leftrightarrow U(1)_{em}$ spontaneously broken

  $e^{i\phi} \neq \pm 1 \Leftrightarrow$ CP spontaneously broken

* V minimum at $\chi = 0$, $e^{i\phi} = 1$ (for given $v_{u,d}$)

* $h_u = v_u \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \; h_d = v_d \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ $\quad v_u = v\sin\beta$, $\; v_d = v\cos\beta$, $\quad v \simeq 174\,\text{GeV}$, $\; 0 \le \beta \le \pi/2$

* $V(v_u,v_d) = \frac{g^2+g'^2}{8}\left(v_u^2 - v_d^2\right)^2 + m_u^2 v_u^2 + m_d^2 v_d^2 - 2m_{ud}^2 v_u v_d$

$$m_u^2 \equiv m_{h_u}^2 + |\mu|^2$$
$$m_d^2 \equiv m_{h_d}^2 + |\mu|^2$$

* Quartic term dominates at large v, except for tanβ = 1 ($v_u = v_d = v/\sqrt{2}$), in which case: $V(v/\sqrt{2}, v/\sqrt{2}) = (m_u^2 + m_d^2 - 2m_{ud}^2)\, v^2/2$. V bounded from below iff

$$m_u^2 + m_d^2 \geq 2m_{ud}^2 (\geq 0)$$

* Local extrema:
  - v = 0, V = 0
  - v ≠ 0: iff $m_u^2 m_d^2 \leq (m_{ud}^2)^2$ from $\begin{matrix} v_d\partial_d V - v_u \partial_u V \\ v_d \partial_u V + v_u \partial_d V \end{matrix}$ : $V = -\frac{4}{g^2+g'^2}\left(m_u^2 s_\beta^2 - m_d^2 c_\beta^2\right)^2$

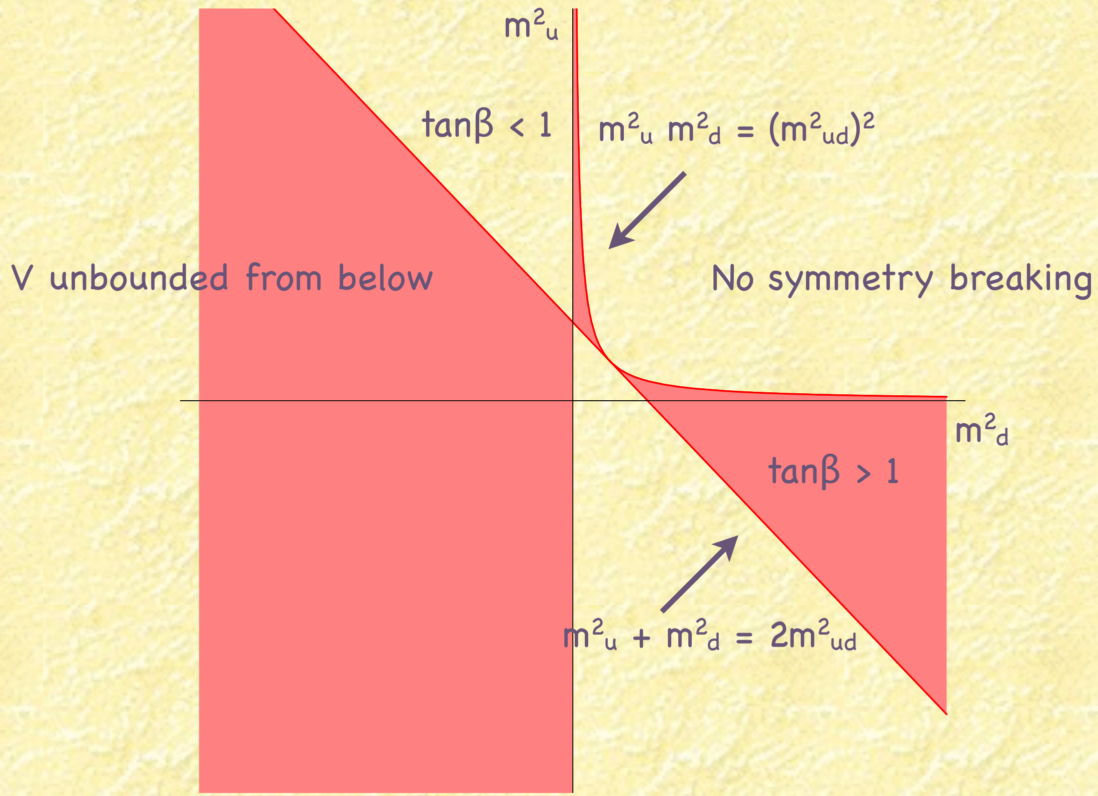
$$\frac{g^2+g'^2}{4} v^2 = -\frac{m_u^2 \tan^2\beta - m_d^2}{\tan\beta^2 - 1} = \frac{M_Z^2}{2}$$

$$\sin 2\beta = \frac{2m_{ud}^2}{m_u^2 + m_d^2}$$

β is given by the solution with tanβ ≷ 1 if $m^2_d$ ≷ $m^2_u$

* Bounds on β:
  - $\lambda_t$ Landau pole beyond $M_{Pl}$: tanβ ≳ 1 (see below)
  - Higgs mass bound: tanβ ≳ 2 (see below)
  - B-physics: tanβ ≲ 60

Radiative corrections lower $m^2_u$ more than $m^2_d$




We typically need $m^2_{hu} < 0$

while $m^2_{hd}, \tilde{m}^2_f > 0$:

an accident?

# Radiative EWSB

* Soft terms generated at $M_0$ » TeV    e.g. in sugra $M_0 = M_{Pl}$
* Rad corrs to soft terms enhanced by large logs: $t = \frac{1}{(4\pi)^2} \log \frac{M_{\rm Pl}^2}{Q^2} \simeq 0.5$
* RGEs:

$$\frac{d}{dt}\tilde{m}^2_{q_3} = \frac{16}{3} g_3^2 M_3^2 + 3 g_2^2 M_2^2 + \frac{1}{15} g_1^2 M_1^2 - \lambda_t^2 \left( \tilde{m}^2_{q_3} + \tilde{m}^2_{t^c} + \tilde{m}^2_{h_u} + |\hat{A}_t|^2 \right)$$

$$\frac{d}{dt}\tilde{m}^2_{t^c} = \frac{16}{3} g_3^2 M_3^2 + \frac{4}{15} g_1^2 M_1^2 - 2\lambda_t^2 \left( \tilde{m}^2_{q_3} + \tilde{m}^2_{t^c} + \tilde{m}^2_{h_u} + |\hat{A}_t|^2 \right)$$

$$\frac{d}{dt} m^2_{h_u} = \quad \times \quad 3 g_2^2 M_2^2 + \frac{3}{5} g_1^2 M_1^2 - 3\lambda_t^2 \left( \tilde{m}^2_{q_3} + \tilde{m}^2_{t^c} + \tilde{m}^2_{h_u} + |\hat{A}_t|^2 \right)$$

$$\frac{d}{dt} m^2_{\rm others} = \text{only gauge terms}$$

[Martin Vaughn, PRD50 (1994)
Barger Berger Ohmann, PRD49 (1994)]

* BTW: $\frac{d}{dt} g_i^2 = -b_i g_i^4, \ \frac{d}{dt} M_i = -b_i g_i^2 M_i \Rightarrow \frac{M_i(Q_1)}{M_i(Q_2)} = \frac{g_i^2(Q_1)}{g_i^2(Q_2)}$

$M_1 = M_2 = M_3$ , $g_1 = g_2 = g_3$ @ $M_{GUT}$ ⇒ $M_1 : M_2 : M_3 = g^2_1 = g^2_2 = g^2_3$

$M_1 : M_2 : M_3 \approx 1 : 2 : 7$

$m_0 = 80$ GeV, $m_{1/2} = 250$ GeV, $A_0 = -500$ GeV, $\tan\beta = 10$

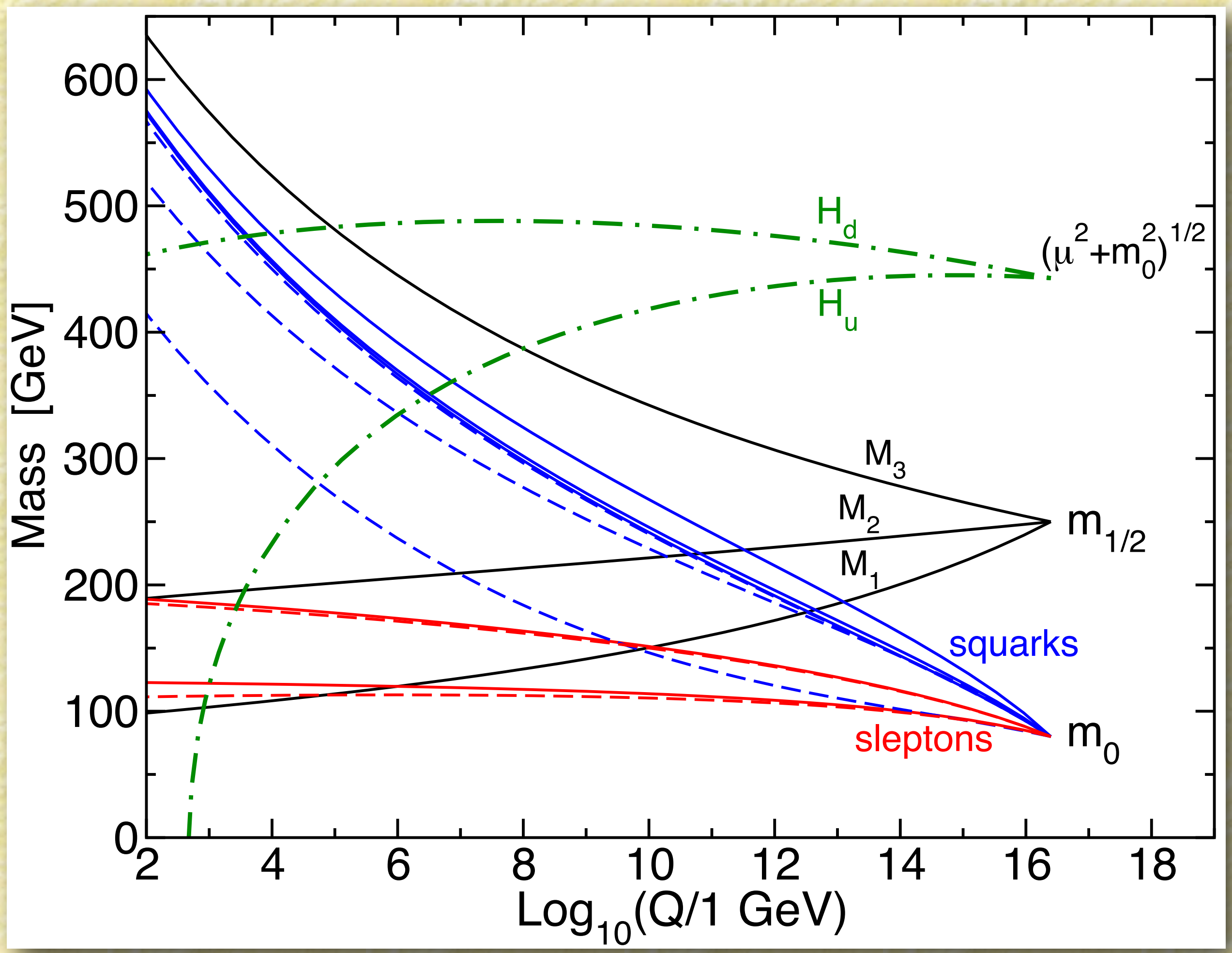



Figure 7.4: RG evolution of scalar and gaugino mass parameters in the MSSM with typical minimal supergravity-inspired boundary conditions imposed at $Q_0 = 2.5 \times 10^{16}$ GeV. The parameter $\mu^2 + m^2_{H_u}$ runs negative, provoking electroweak symmetry breaking.

Martin hep-ph/9709356

# Spectrum

MSSM fields:

$$g_\mu \; W_\mu \; B_\mu \quad \tilde{g} \; \tilde{W} \; \tilde{B} \quad q_i \; u_i^c \; d_i^c \; l_i \; e_i^c \; \tilde{h}_u \; \tilde{h}_d \quad \tilde{q}_i \; \tilde{u}_i^c \; \tilde{d}_i^c \; \tilde{l}_i \; \tilde{e}_i^c \; h_u \; h_d$$

Mass matrices → masses + expressions in terms of mass eigenstates

Conserved quantum numbers: spin, color, charge, $R_P$

# Gauge bosons

$g^A_\mu$ $W^a_\mu$ $B_\mu$

$$M_W^2 = \frac{g^2}{2} v^2$$

$$M_Z^2 = \frac{g^2 + g'^2}{2} v^2$$

$$g_s g_\mu^A T_A + g W_\mu^a T_a + g' B_\mu Y$$
$$= g_s g_\mu^A T_A + \frac{g}{\sqrt{2}} (W_\mu^+ T_+ + W_\mu^- T_-) + \frac{g}{c_W} Z_\mu (T_3 - s_W^2 Q) + e A_\mu Q$$

Same as in the SM, with $v^2 = v^2_u + v^2_d$

# $R_P = 1$ (SM) fermions

* $q_i \quad u^c_i \quad d^c_i \quad l_i \quad e^c_i$

* $-\mathcal{L} \supseteq \lambda^U_{ij} u^c_i q_j h_u + \lambda^D_{ij} d^c_i q_j h_d + \lambda^E_{ij} e^c_i l_j h_d \quad \rightarrow \quad \begin{aligned} m_U &= \lambda_U v \sin\beta \\ m_D &= \lambda_D v \cos\beta \\ m_E &= \lambda_E v \cos\beta \end{aligned}$

* $\frac{m_t}{m_b} = \frac{\lambda_t}{\lambda_b} \tan\beta$ : $m_b \ll m_t$ either because $\lambda_b \ll \lambda_t$ (as in the SM)
  or because $\tan\beta \gg 1$
  (allows $\lambda_b \sim \lambda_t$, relevant for rad corrs, Yukawa unification)

* $\lambda_t = \frac{m_t}{v \sin\beta}$ : $\lambda_t(M_{GUT}) < \infty \Rightarrow \tan\beta \gtrsim 1$ (depending on what goes on from $M_Z$ to $M_{GUT}$)

# $R_P = -1$ fermions (gauginos and Higgsinos)

* $\tilde{g}_A$ $\tilde{W}_a$ $\tilde{B}$ $\tilde{h}_u$ $\tilde{h}_d$

* $\tilde{h}_u = \begin{pmatrix} \tilde{h}_u^+ \\ \tilde{h}_u^0 \end{pmatrix} \quad \tilde{h}_d = \begin{pmatrix} \tilde{h}_d^0 \\ \tilde{h}_d^- \end{pmatrix} \quad \tilde{W}^\pm = \frac{\tilde{W}_1 \mp i\tilde{W}_2}{\sqrt{2}} \quad \tilde{W}^0 = \tilde{W}^3$

* $\tilde{g}_A$ have mass $M_3$

* $\tilde{h}^+_u$ $\tilde{W}^+$ / $\tilde{h}^-_d$ $\tilde{W}^-$ can mix ("charginos")

* $\tilde{h}^0_u$ $\tilde{h}^0_d$ $\tilde{W}^0$ $\tilde{B}$ can mix ("neutralinos")

* Charginos: $-\mathcal{L} \supseteq \left(\tilde{W}^- \ \tilde{h}_d^-\right) M_C \begin{pmatrix} \tilde{W}^+ \\ \tilde{h}_u^+ \end{pmatrix} + \text{h.c.}$

$$M_C = \begin{pmatrix} M_2 & \sqrt{2} M_Z c_W s_\beta \\ \sqrt{2} M_Z c_W c_\beta & |\mu| e^{i\phi_\mu} \end{pmatrix}$$

e.g. $\sqrt{2} M_Z c_W c_\beta$ from $\sqrt{2} h_u^\dagger (g \frac{\sigma_a}{2} \tilde{W}_a + g' \frac{1}{2} \tilde{B}) \tilde{h}_u + \sqrt{2} h_d^\dagger (g \frac{\sigma_a}{2} \tilde{W}_a - g' \frac{1}{2} \tilde{B}) \tilde{h}_d$

* Neutralinos: $-\mathcal{L} \supseteq \frac{1}{2} \left(\tilde{B} \ \tilde{W}^3 \ \tilde{h}_d^0 \ \tilde{h}_u^0\right) M_N \begin{pmatrix} \tilde{B} \\ \tilde{W}^3 \\ \tilde{h}_d^0 \\ \tilde{h}_u^0 \end{pmatrix} + \text{h.c.}$

$$M_N = \begin{pmatrix} M_1 & 0 & -\sqrt{2} M_Z s_W c_\beta & \sqrt{2} M_Z s_W s_\beta \\ 0 & M_2 & \sqrt{2} M_Z c_W c_\beta & -\sqrt{2} M_Z c_W s_\beta \\ -\sqrt{2} M_Z s_W c_\beta & \sqrt{2} M_Z c_W c_\beta & 0 & -|\mu| e^{i\phi_\mu} \\ \sqrt{2} M_Z s_W s_\beta & -\sqrt{2} M_Z c_W s_\beta & -|\mu| e^{i\phi_\mu} & 0 \end{pmatrix}$$

* The LSP can easily be a neutralino

# $R_P$ = 1 scalars (Higgs sector)

- $h_u$ $h_d$ 8 real dofs: 2x(Q=1) + 2x(Q=-1) + 2x(Q=0,CP+) + 2x(Q=0,CP-)

$V(h_u, h_d)$ breaks $SU(2)_W \times U(1)_Y$, preserves $U(1)_{em}$, CP

(barring $\phi_{\mu,A}$ effects through loop corrections, neglecting $\delta_{CKM}$)

- 3 massless Goldstones $G^+$ $G^-$ $G^0$ (CP-)

- 5 physical dofs: $H^+$ $H^-$ A (CP-) $\phi_u$ $\phi_d$ (CP+)

$$h_u = \begin{pmatrix} c_\beta H^+ + i s_\beta G^+ \\ v s_\beta + \dfrac{\phi_u - i(s_\beta G^0 + c_\beta A)}{\sqrt{2}} \end{pmatrix} \qquad h_d = \begin{pmatrix} v c_\beta + \dfrac{\phi_d + i(c_\beta G^0 - s_\beta A)}{\sqrt{2}} \\ s_\beta H^- + i c_\beta G^- \end{pmatrix}$$

* Masses: the 8x8 mass matrix decomposes into
    - a vanishing 3x3 block corresponding to the Goldstones $G^+$ $G^-$ $G^0$
    - a mass term for $H^+H^-$: $m^2_{H^\pm} = \frac{\partial^2 V_\pm}{\partial H^+ \partial H^-}\Big|_{H^\pm=0}$ $\quad V_\pm = V\left(\begin{pmatrix} c_\beta H^+ \\ v s_\beta \end{pmatrix}, \begin{pmatrix} v c_\beta \\ s_\beta H^- \end{pmatrix}\right)$
    - a mass term for A: $m^2_A = \frac{\partial^2 V_A}{\partial A^2}\Big|_{A=0}$
    - a 2x2 mass matrix for $\phi_u$ $\phi_d$: $-\mathcal{L} \supseteq -\frac{1}{2}(\phi_u\ \phi_d)\, M^2_\phi \begin{pmatrix} \phi_u \\ \phi_d \end{pmatrix}$

$$M^2_\phi = R(\alpha)\begin{pmatrix} m^2_H & \\ & m^2_h \end{pmatrix} R(\alpha)^{-1} \quad m^2_h < m^2_H \quad R(\alpha) = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix}$$

$$\boxed{\begin{aligned} \phi_d &= c_\alpha H - s_\alpha h \\ \phi_u &= c_\alpha h + s_\alpha H \end{aligned}}$$

* Decoupling limit: $m_A \gg v \Leftrightarrow m_{H\pm} \gg v \Leftrightarrow m_H \gg v$ $(m_h \sim v)$ $\alpha \approx \beta-\pi/2$

# In the MSSM

* $m^2_h \quad m^2_H \quad m^2_{H\pm} \quad m^2_A \quad \alpha \quad \beta \leftrightarrow$ MSSM parameters

$$m^2_A = m^2_u + m^2_d = m^2_{h_u} + m^2_{h_d} + 2|\mu|^2$$
$$m^2_{H^\pm} = m^2_A + M^2_W$$

$$M^2_\phi = \begin{pmatrix} m^2_A s^2_\beta + M^2_Z c^2_\beta & -s_\beta c_\beta (m^2_A + M^2_Z) \\ -s_\beta c_\beta (m^2_A + M^2_Z) & m^2_A c^2_\beta + M^2_Z s^2_\beta \end{pmatrix}$$

* Decoupling limit: $m^2_h \approx M^2_Z \cos^2 2\beta$
* In general: $m^2_{h,H} = \frac{1}{2}\left[M^2_Z + m^2_A \pm \sqrt{(M^2_Z + m^2_A)^2 - 4M^2_Z m^2_A \cos^2 2\beta}\right]$

$$\tan 2\alpha = \frac{m^2_A + M^2_Z}{m^2_A - M^2_Z} \tan 2\beta$$

$$\left(\begin{aligned} \cos 2\alpha &= \frac{M^2_Z - m^2_A}{m^2_H - m^2_h} \cos 2\beta \\ \sin 2\alpha &= -\frac{M^2_Z + m^2_A}{m^2_H - m^2_h} \sin 2\beta \end{aligned}\right)$$

* $m^2_h \le M^2_Z \cos^2 2\beta \quad \text{(tree level)}$

[Ellis Ridolfi Zwirner]

* 1-loop corrections (very basic approx): $m^2_h \lesssim M^2_Z \cos^2 2\beta + \frac{3}{4\pi^2} h^2_t m^2_t \log \frac{\tilde{m}^2_t}{m^2_t} \lesssim 130\,\text{GeV}$
  - Lower limit on $m^2_h$ → lower limit on $\tilde{m}_t$ → lower limit on FT — for $\tilde{m}_t \lesssim$ 1-2 TeV
  - lower tanβ requires a larger correction (upper limit on $m_t$ → lower limit on tanβ)
  - $m^2_h$ > 115 GeV (≈125 GeV?) can be evaded in the MSSM but requires even more FT

# Radiative corrections to $m_h$

* Full 1-loop computation: Coleman-Weinberg potential + self-energy
* Moderate tanβ: corrections dominated by top-stop sector
* The stop mixing ($A_t$ + μcotβ) has a significant impact on the results
* $\log(\tilde{m}_t^2/m_t^2)$-enhanced contributions:
    - consider the limit $\tilde{m}_t^2 \gg m_t^2$
    - match the MSSM at Q > m̃ with the SM at Q < m̃:

$$\begin{cases} \lambda_h(\tilde{m}_t) = \dfrac{g^2+g'^2}{4}\cos^2 2\beta + 6\dfrac{h_t^2}{(4\pi)^2}\dfrac{X_t^2}{\tilde{m}_t^2}\left(1-\dfrac{X_t^2}{12\tilde{m}_t^2}\right) \\ h_t = \lambda_t \sin\beta = m_t/v \end{cases} \qquad X_t = A_t - \mu\cot\beta$$

    - compute leading-log corrections to the SM Higgs coupling

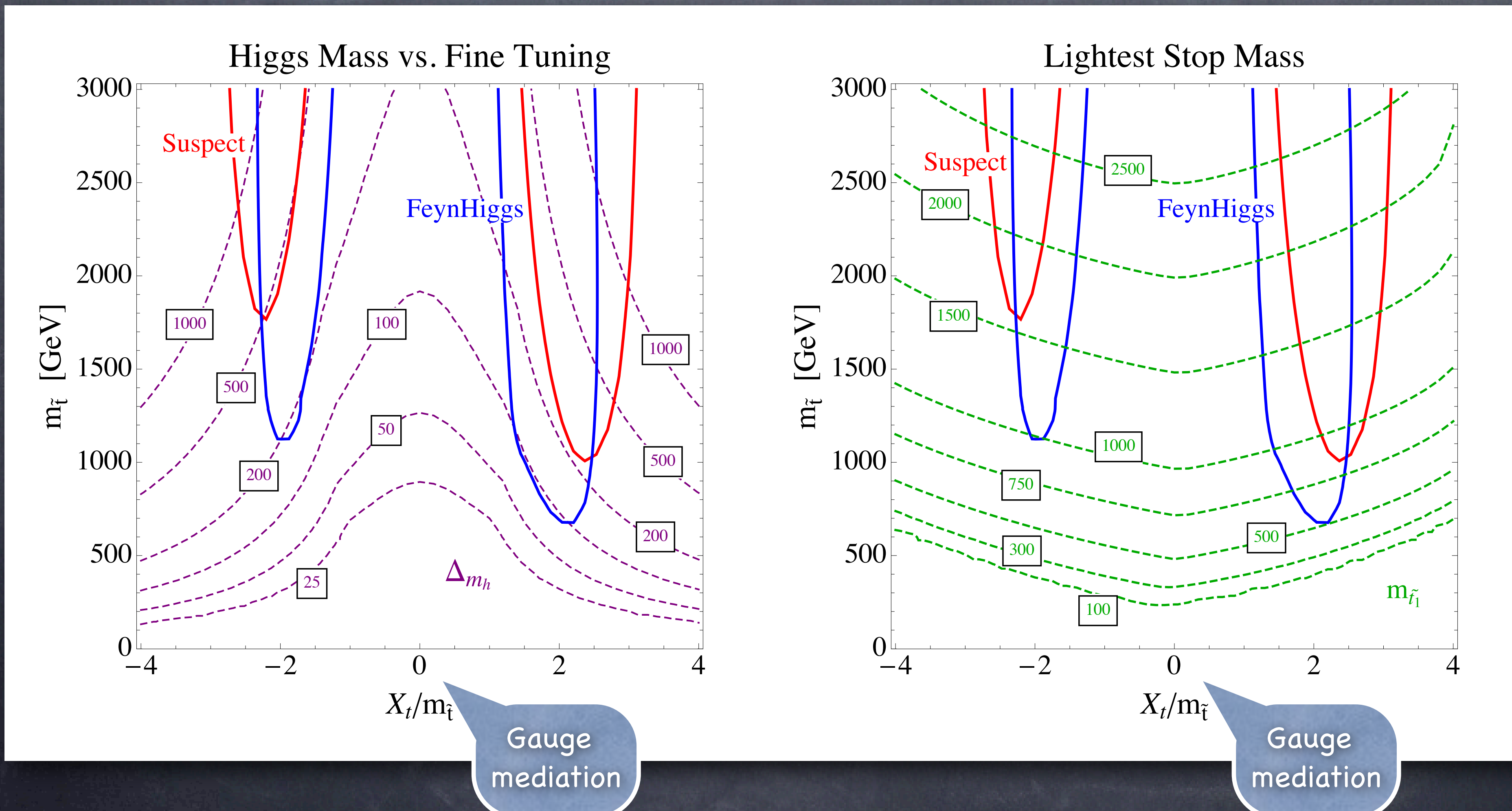
$$\lambda_h(m_t) = \lambda_h(\tilde{m}_t) + 6\frac{h_t^2}{(4\pi)^2}\log\frac{\tilde{m}_t^2}{m_t^2}$$

    - $m_h^2 = 2\lambda_h(m_t)v^2 = M_Z^2\cos^2 2\beta + 12\dfrac{h_t^2 m_t^2}{(4\pi)^2}\left[\log\dfrac{\tilde{m}_t^2}{m_t^2} + \dfrac{X_t^2}{\tilde{m}_t^2}\left(1-\dfrac{X_t^2}{12\tilde{m}_t^2}\right)\right]$

# Indirect bounds on stop mass in the MSSM for $m_H \approx 125$ GeV

- Assuming degenerate stop masses, maximal $X_t$, $\tan\beta = 20$: $m_{stop} \gtrsim$ TeV, FT $\gtrsim$ 200, possibly larger because of large A-terms
- Either stops or A-term are multi-TeV

Hall Pinner Rudeman 1112.2703



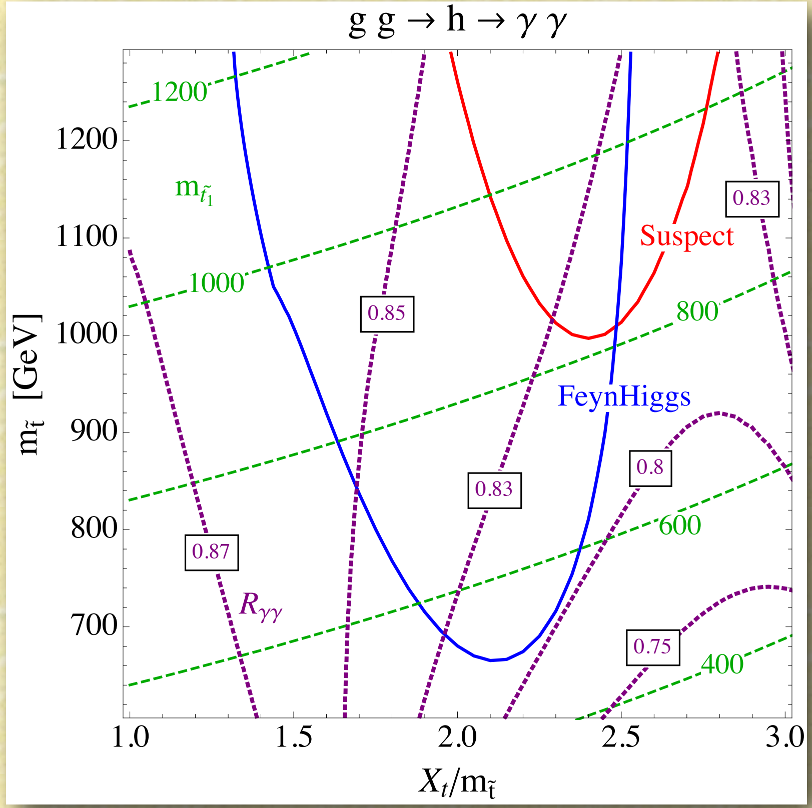
# Beyond MSSM: xMSSM

- Minimal extension: $\lambda S H_u H_d$ (symmetries forbid $\mu H_u H_d$)
    - harmless (unification OK)
    - welcome ($\mu = \lambda\langle S\rangle \approx$ susy scale)
- Spectrum: h H → $h_1$ $h_2$ $h_3$, A → $a_1$ $a_2$, $N_1 \ldots N_4$ → $N_0$ $N_1 \ldots N_4$
- Help with FT from Higgs bound:
    - $m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \text{loops}$ gain limited by poles

      $\lambda$(10 TeV) < 3 (EWPTs) best, $\lambda(M_{GUT})$ < 3 (unification) OK
    - light but hidden Higgs: h → aa → 4X ($m_a$ protected by PQ, R)
- Persistent FT from
    - direct bounds on SUSY partners
    - arranging the invisible decay [Shuster Toro hep-ph/0512189]

# Light Higgs detection

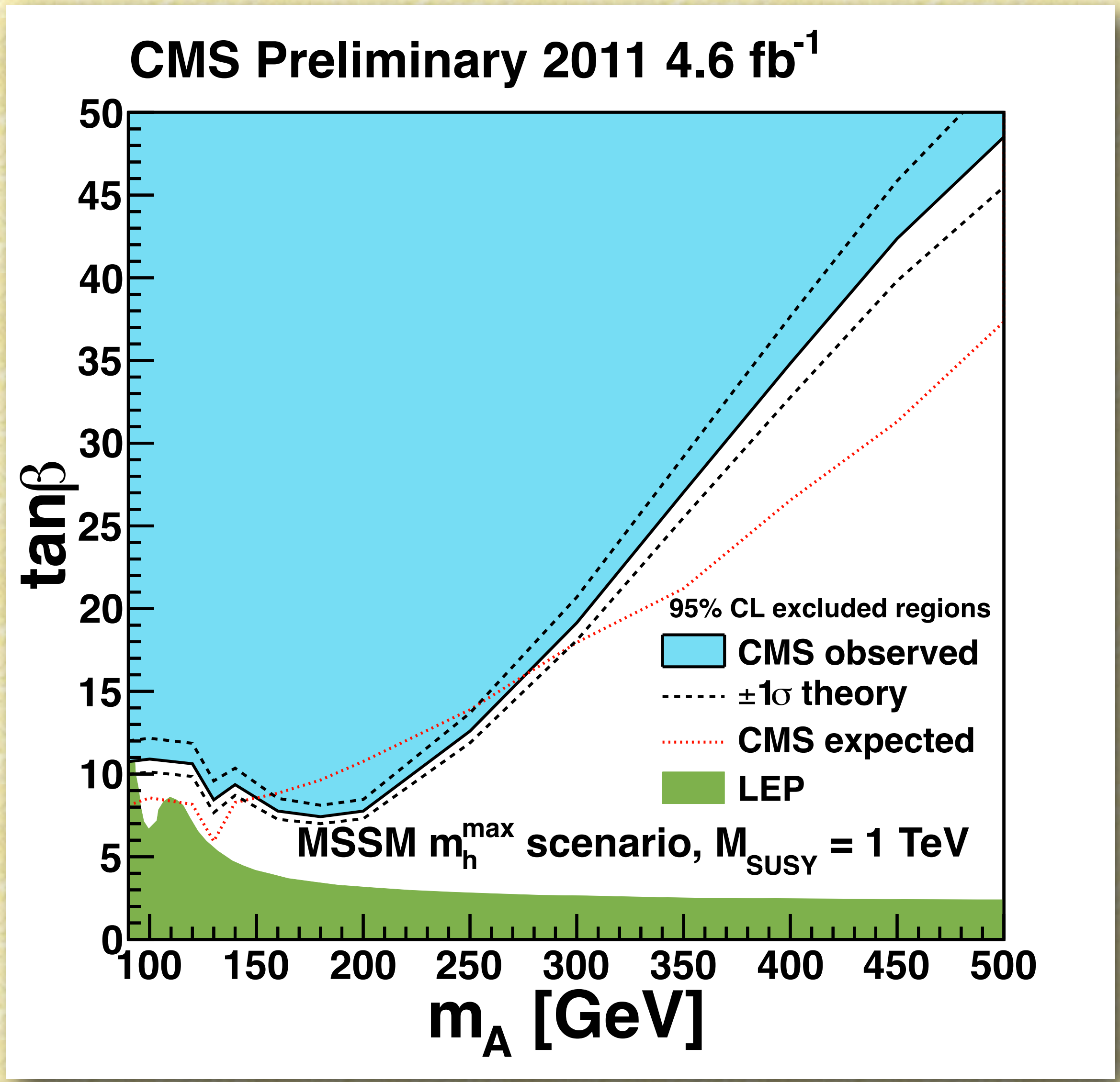
$$\frac{\sigma(gg\to h)}{\sigma_{SM}(gg\to h)} \approx \left[1+\frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2}+\frac{m_t^2}{m_{\tilde{t}_2}^2}-\frac{m_t^2(A_t+\mu/\tan\beta)(A_t-\mu\tan\alpha)}{m_{\tilde{t}_1}^2\, m_{\tilde{t}_2}^2}\right)\right]^2$$



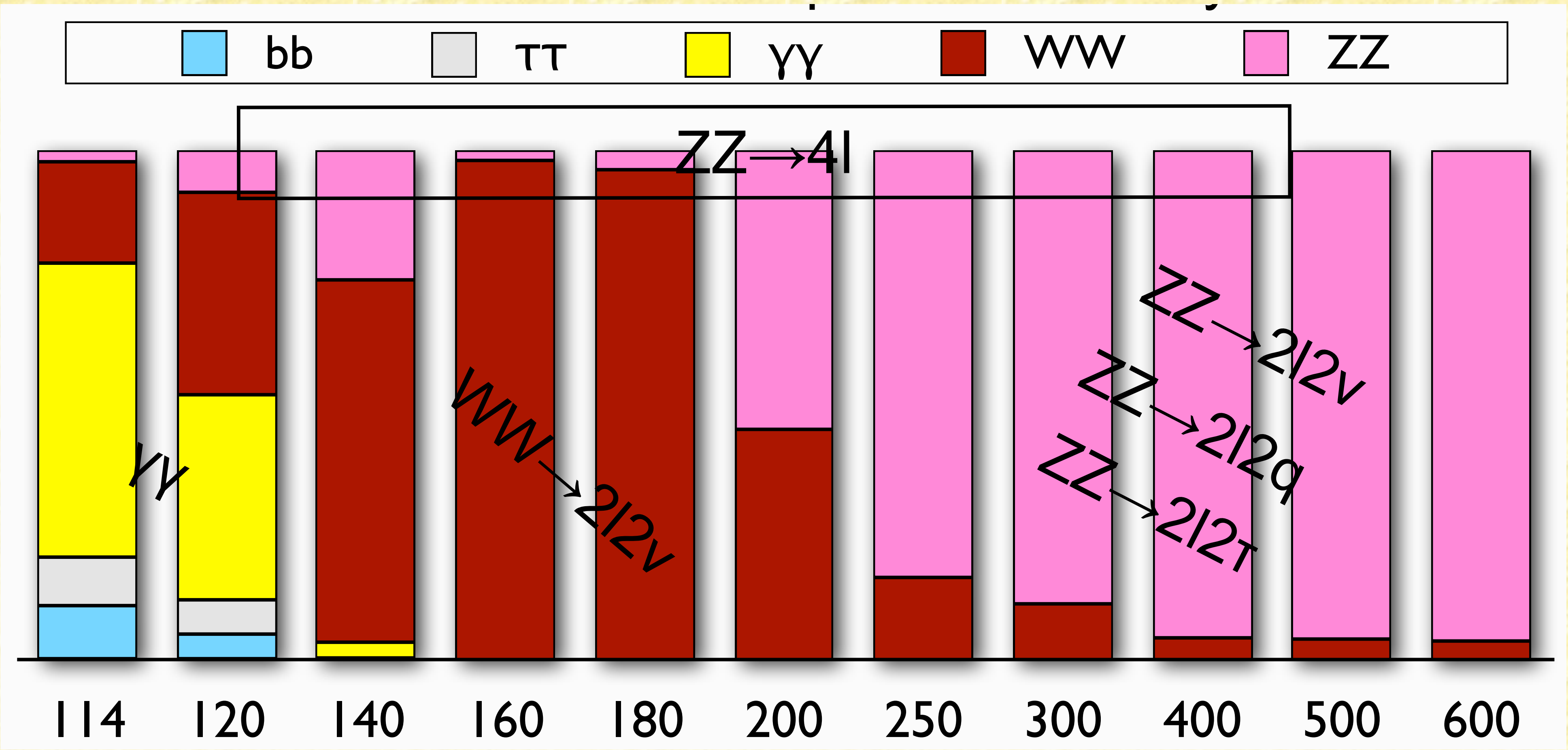

$$\frac{\delta y_b}{y_b} = -\frac{\sin\alpha}{\cos\beta} - 1 \approx \frac{2\,\frac{m_Z^2}{m_A^2}}{1-\frac{m_Z^2}{m_A^2}},$$

$$\frac{\delta g_{VV}}{g_{VV}} = \sin(\beta-\alpha) - 1 \approx \frac{1}{\tan^2\beta}\,\frac{2\,\frac{m_Z^4}{m_A^4}}{\left(1-\frac{m_Z^2}{m_A^2}\right)^2}$$

# Bounds on $m_A$ and tanβ from heavier Higgs decays



# Weight of the individual channels




Gigi Rolandi HCP 2011

# $R_P$ = -1 scalars (squarks and sleptons)

* $\tilde{q}_i = \begin{pmatrix} \tilde{u}_i \\ \tilde{d}_i \end{pmatrix} \quad \begin{matrix} \tilde{u}_i^c \\ \tilde{d}_i^c \end{matrix} \quad \tilde{l}_i = \begin{pmatrix} \tilde{\nu}_i \\ \tilde{e}_i \end{pmatrix} \quad \tilde{e}_i^c \quad \tilde{q}_i^* = \begin{pmatrix} \tilde{u}_i^* \\ \tilde{d}_i^* \end{pmatrix} \quad \begin{matrix} \tilde{u}_i^{c*} \\ \tilde{d}_i^{c*} \end{matrix} \quad \tilde{l}_i^* = \begin{pmatrix} \tilde{\nu}_i^* \\ \tilde{e}_i^* \end{pmatrix} \quad \tilde{e}_i^{c*}$

* Possible mixing between

  - $SU(3)_c$ triplets, Q=2/3 (up squarks): $\tilde{u}_i$ $\tilde{u}^c{}_i{}^*$

  - $SU(3)_c$ triplets, Q=-1/3 (down squarks): $\tilde{d}_i$ $\tilde{d}^c{}_i{}^*$

  - $SU(3)_c$ singlets, Q=-1 (charged sleptons): $\tilde{e}_i$ $\tilde{e}^c{}_i{}^*$

  - $SU(3)_c$ singlets, Q=0 (sneutrinos): $\tilde{\nu}_i$

$$-\mathcal{L} = (\tilde{u}^* \ \tilde{u}^c)\mathcal{M}_U^2 \begin{pmatrix} \tilde{u} \\ \tilde{u}^{c*} \end{pmatrix} + (\tilde{d}^* \ \tilde{d}^c)\mathcal{M}_D^2 \begin{pmatrix} \tilde{d}_i \\ \tilde{d}_i^{c*} \end{pmatrix} + (\tilde{e}^* \ \tilde{e}^c)\mathcal{M}_E^2 \begin{pmatrix} \tilde{e} \\ \tilde{e}^{c*} \end{pmatrix} + \tilde{\nu}^* M_\nu^2 \tilde{\nu}$$

$$\mathcal{M}_U^2 = \begin{pmatrix} \tilde{m}_q^2 + M_U^\dagger M_U + M_Z^2 z_u c_{2\beta}\mathbf{1} & -(\hat{A}_U^\dagger + \mu\cot\beta)M_U^\dagger \\ -M_U(\hat{A}_U + \mu^*\cot\beta) & \tilde{m}_{u_R}^2 + M_U M_U^\dagger + M_Z^2 z_{u_c} c_{2\beta}\mathbf{1} \end{pmatrix} = \begin{pmatrix} \mathrm{LL} & \mathrm{LR} \\ \mathrm{RL} & \mathrm{RR} \end{pmatrix}$$

$$\mathcal{M}_D^2 = \begin{pmatrix} \tilde{m}_q^2 + M_D^\dagger M_D + M_Z^2 z_d c_{2\beta}\mathbf{1} & -(\hat{A}_D^\dagger + \mu\tan\beta)M_D^\dagger \\ -M_D(\hat{A}_D + \mu^*\tan\beta) & \tilde{m}_{d_R}^2 + M_D M_D^\dagger + M_Z^2 z_{d_c} c_{2\beta}\mathbf{1} \end{pmatrix}$$

$$\mathcal{M}_E^2 = \begin{pmatrix} \tilde{m}_l^2 + M_E^\dagger M_E + M_Z^2 z_e c_{2\beta}\mathbf{1} & -(\hat{A}_E^\dagger + \mu\tan\beta)M_E^\dagger \\ -M_E(\hat{A}_E + \mu^*\tan\beta) & \tilde{m}_{e_R}^2 + M_E M_E^\dagger + M_Z^2 z_{e_c} c_{2\beta}\mathbf{1} \end{pmatrix}$$

$$M_\nu^2 = \tilde{m}_l^2 + M_Z^2 z_\nu c_{2\beta}\mathbf{1} \qquad A_{U,D,E} \equiv \lambda_{U,D,E}\hat{A}_{U,D,E} \quad m_R^2 \equiv (m_c^2)^*$$

$$z_A \equiv t_3(A) - \sin^2\theta_W q(A)$$

- Super-CKM basis: write the scalar mass matrices in the basis in flavour space in which the corresponding fermions are diagonal (U **or** D)

* FCNC/sugra-inspired ansatz for colliders: (neglecting small off-diagonal entries, $V_{cb,ub}$)

$$(\tilde{m}^2_{ij}) = \begin{pmatrix} \tilde{m}^2 & & \\ & \tilde{m}^2 & \\ & & \tilde{m}^2_3 \end{pmatrix}$$

* I and II families up squarks:

$$\tilde{m}^2_{u_{1,2}} = \tilde{m}^2_q + z_u c_{2\beta} M_Z^2$$
$$\tilde{m}^2_{u^c_{1,2}} = \tilde{m}^2_{u^c} + z_{u^c} c_{2\beta} M_Z^2$$

* III family (stops):

$$\begin{pmatrix} \tilde{m}^2_{q_3} + m_t^2 + z_u c_{2\beta} M_Z^2 & -m_t(A_t + \mu \cot\beta) \\ -m_t(A_t + \mu\cot\beta) & \tilde{m}^2_{u^c_3} + m_t^2 + z_{u^c} c_{2\beta} M_Z^2 \end{pmatrix}$$

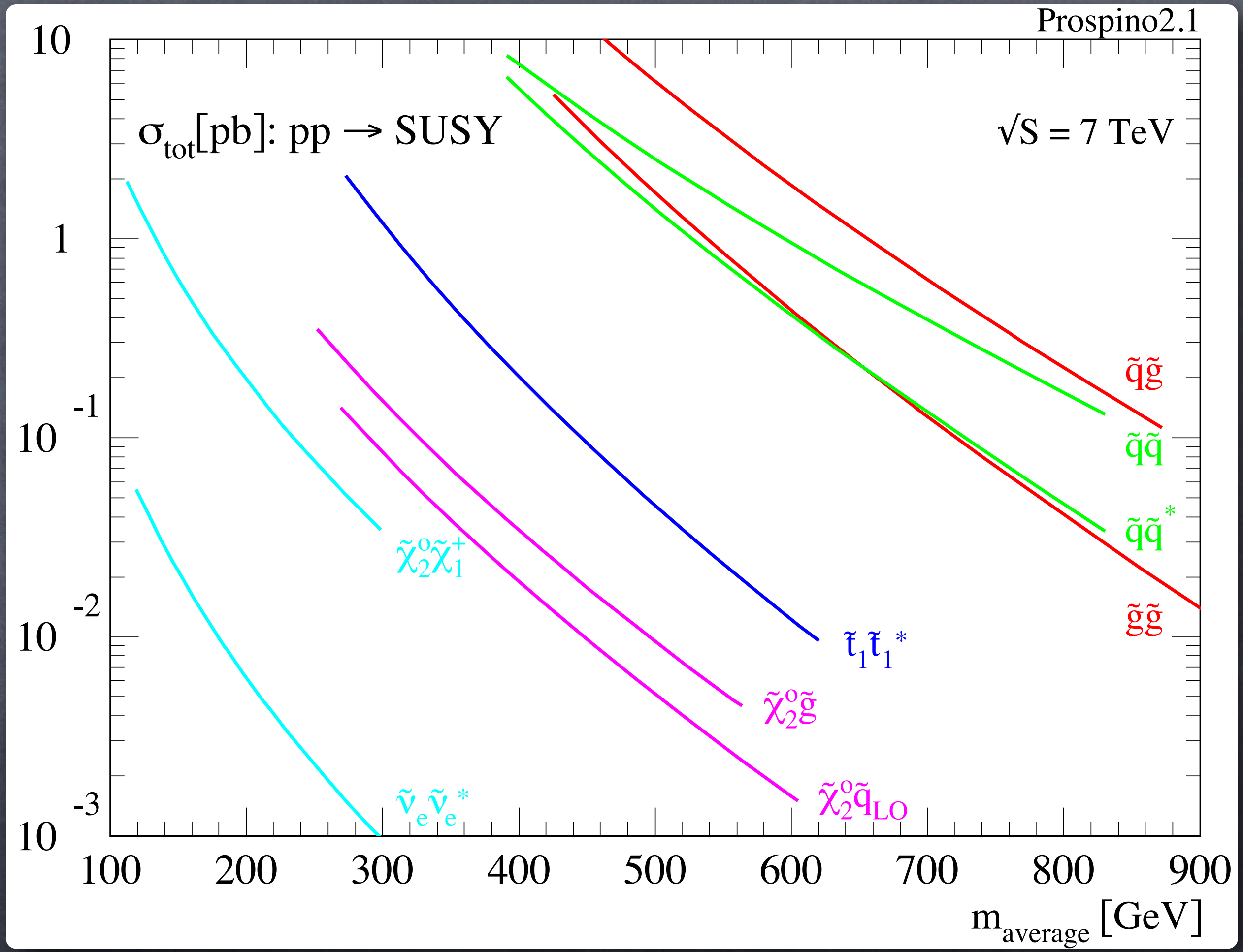
$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} \qquad 0 \le \theta \le \pi, \quad \tilde{m}_{t_1} < \tilde{m}_{t_2}$$

* Analogously in the D, E sectors. Relevant LR mixing in the third family only for large $\tan\beta$

# Experimental signatures

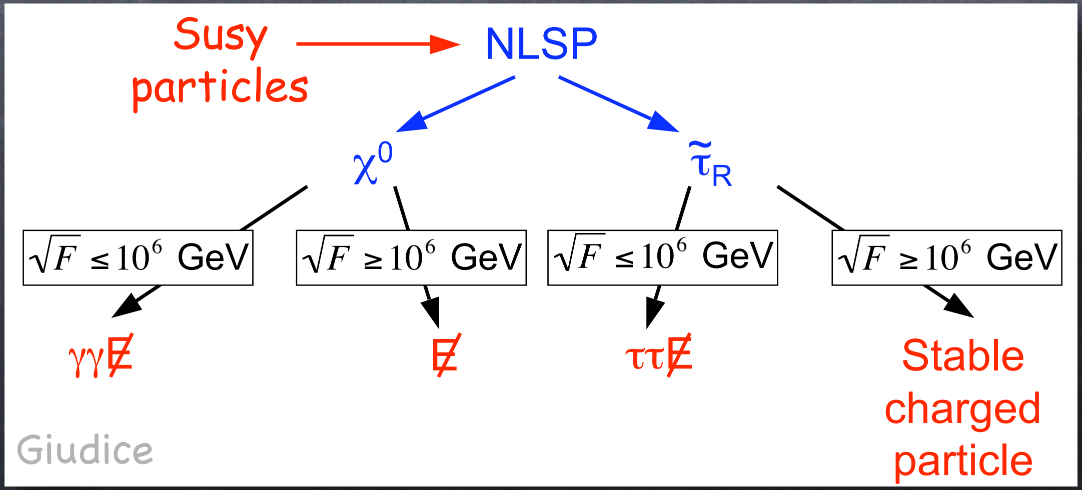
# Sparticle production

- At LHC: mainly coloured particles (but stops suppressed)



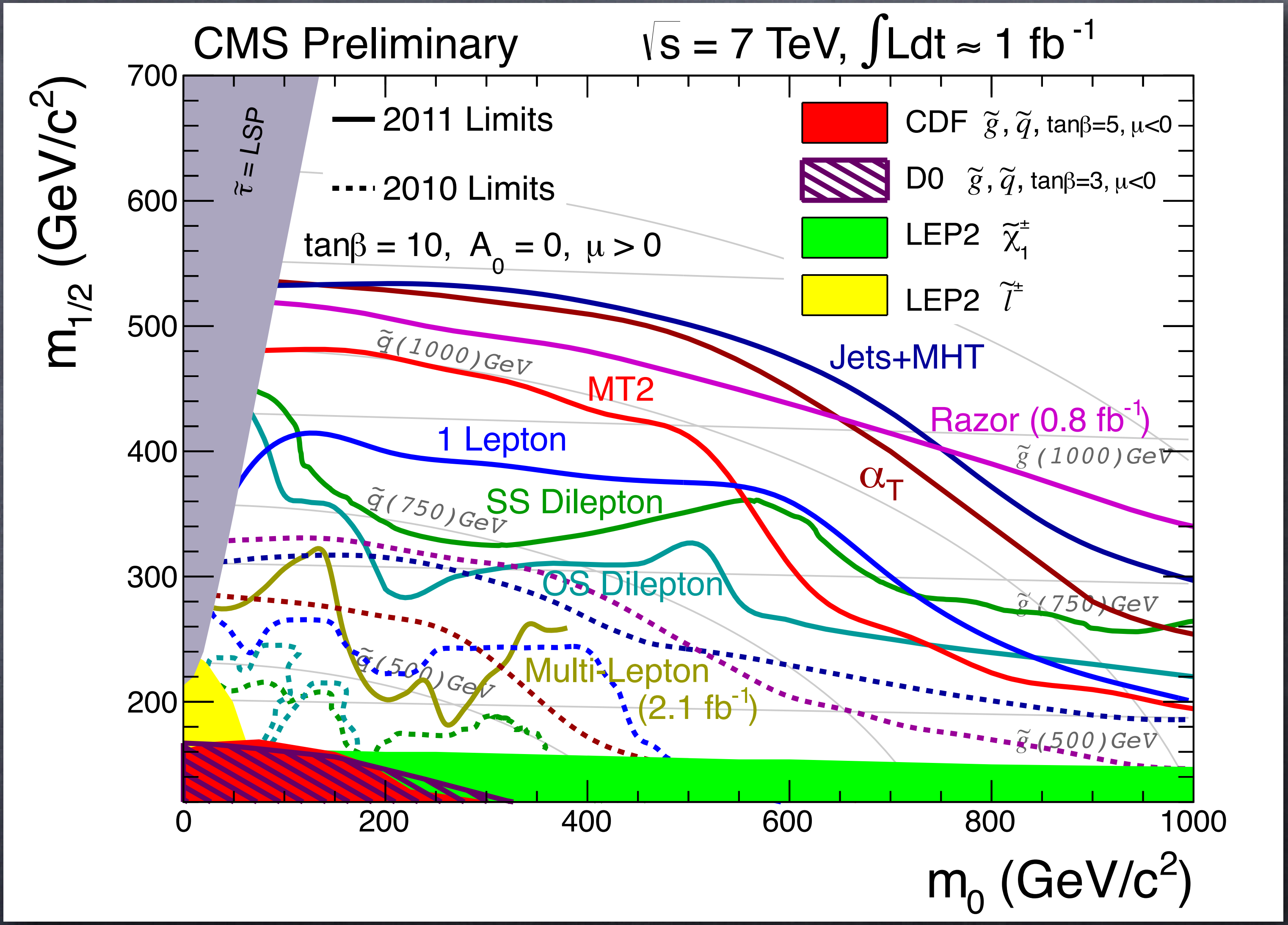
# Sparticle decay

- $R_P$ conserved: decay always contains LSP (neutralino, gravitino)
- Gravitino mass: $\tilde{m} = c\,\frac{F}{M} \quad \Rightarrow \quad m_{3/2} = \frac{F}{M_{\rm Pl}} = \tilde{m}\left(\frac{M}{c\,M_{\rm Pl}}\right)$
- Gravity mediation: LSP = neutralino: missing $E_T$
- (L,T) gauge mediation: LSP = gravitino

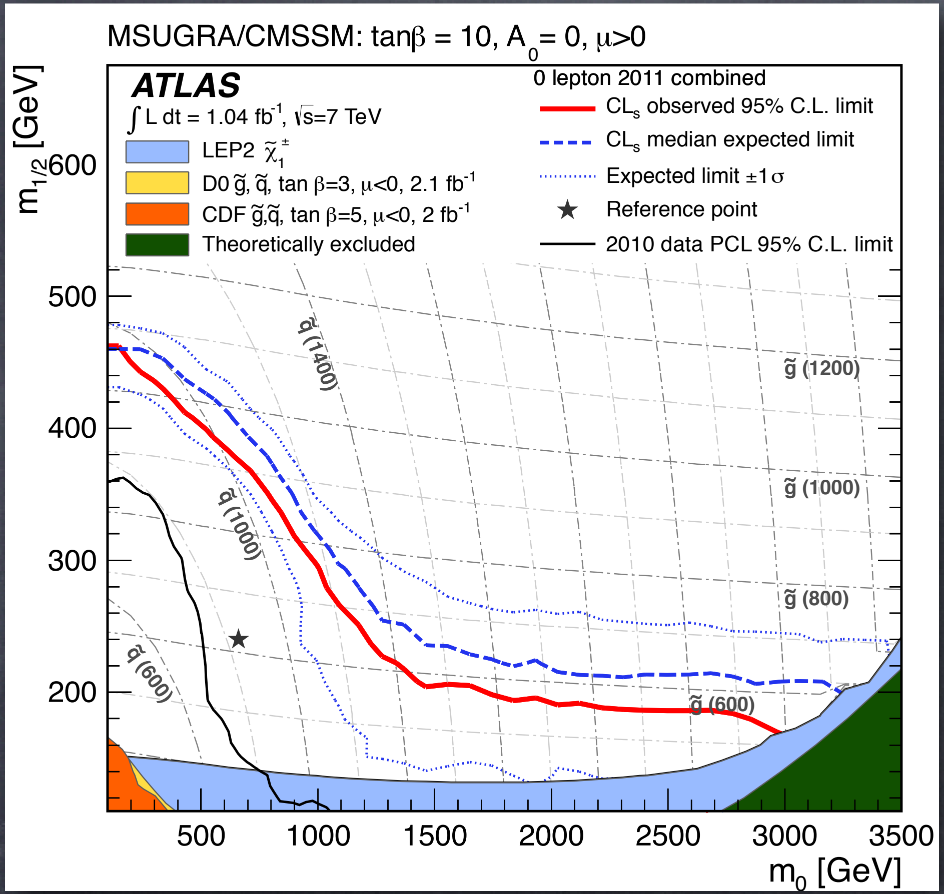


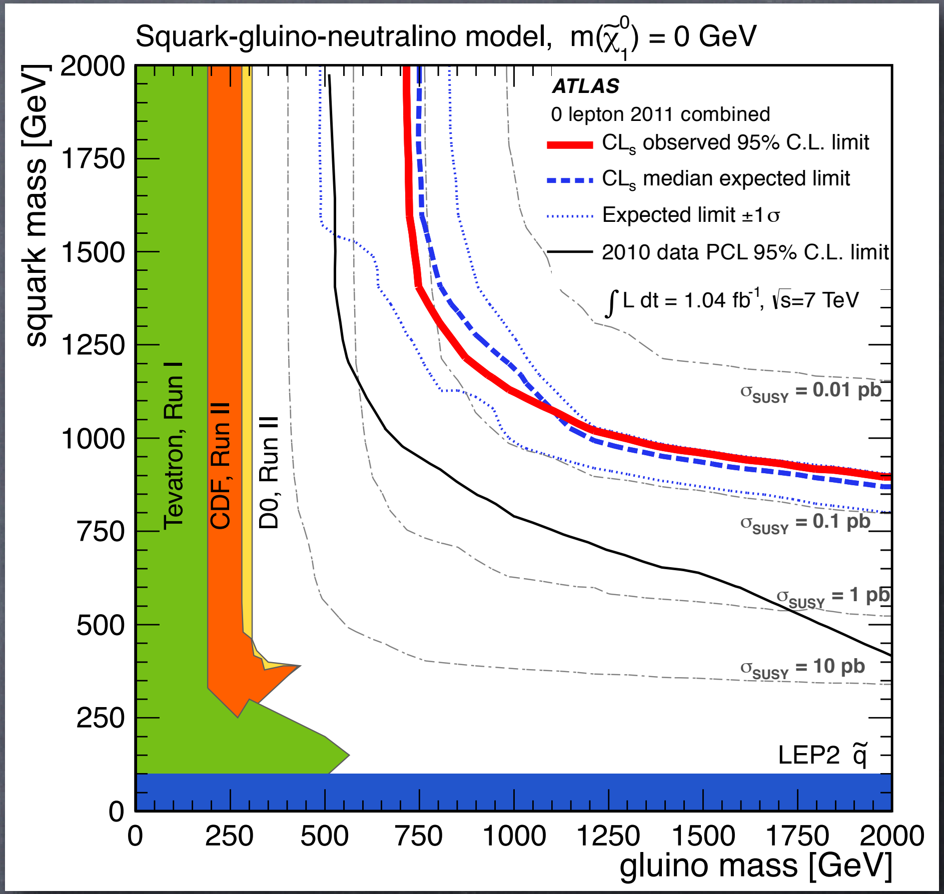
# Example of signals (MSSM LSP)

- 0 leptons: jets + missing $E_T$
  - Reduces the SM W decay background
  - Effective if the dominant susy decay is with no leptons
- 2 same-sign leptons + jets + missing $E_T$
  - Does not take place in the SM
  - From 2 gluinos, with gluino → q + chargino → q + ($l^\pm$ + ν + LSP) (twice)
    Each gluino decays into $l^+$ or $l^-$ with equal probability
- 3 leptons + missing $E_T$ + (possibly) jets
  - $\chi^+\chi^0$, $\chi^+ \to l^+ \nu$ LSP, $\chi^0 \to l^+ l^-$ LSP (2-body decay better be forbidden)
- 1 lepton + missing $E_T$
  - large background from SM W decay (but relevant in some par space)



CMS Preliminary
√s = 7 TeV, ∫Ldt ≈ 1 fb⁻¹
2011 Limits
2010 Limits
tanβ = 10, A0 = 0, μ > 0
CDF g̃, q̃, tanβ=5, μ<0
D0 g̃, q̃, tanβ=3, μ<0
LEP2 χ̃±1
LEP2 l̃±
τ̃ = LSP
Jets+MHT
MT2
Razor (0.8 fb⁻¹)
αT
1 Lepton
SS Dilepton
OS Dilepton
Multi-Lepton
(2.1 fb⁻¹)
q̃(1000)GeV
q̃(750)GeV
q̃(500)GeV
g̃(1000)GeV
g̃(750)GeV
g̃(500)GeV
m1/2 (GeV/c²)
m0 (GeV/c²)



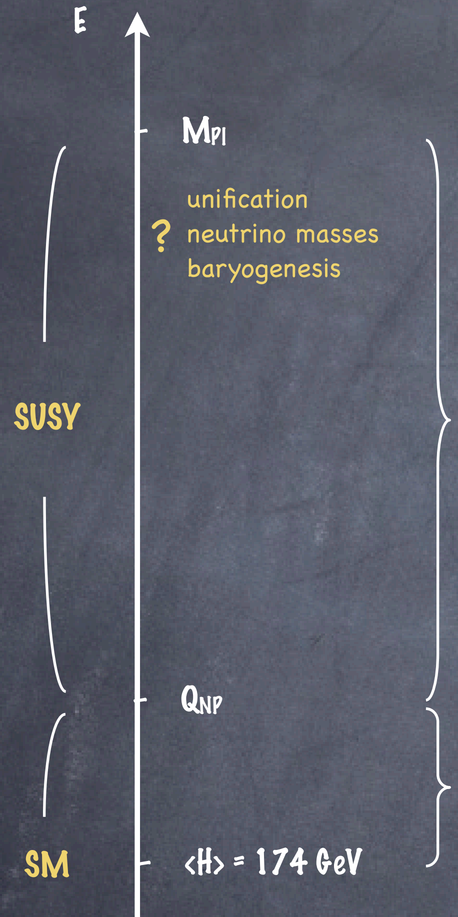




**mSUGRA/CMSSM** with $\tan\beta = 0, A=0, m>0$
**$m(\tilde{g}) = m(\tilde{q}) > 950$ GeV**

**Simplified model** with a gluino, first two generation squarks, and massless neutralino
**$m(\tilde{g}) > 700$ GeV $\quad m(\tilde{q}) > 875$ GeV**
**$m(\tilde{g}) = m(\tilde{q}) > 1075$ GeV**

# Fine-Tuning

# Fine-tuning in the MSSM




$$\delta m_h^2 \sim \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 Q_{\rm NP}^2 \log \frac{M_{\rm Pl}^2}{Q_{\rm NP}^2}$$

$$\delta m_h^2 \sim \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 Q_{\rm NP}^2 = (115\,{\rm GeV})^2 \left(\frac{Q_{\rm NP}}{0.5\,{\rm TeV}}\right)^2$$

- $$M_Z^2 = -2\frac{m_{h_u}^2 \tan^2\beta - m_{h_d}^2}{\tan^2\beta - 1} - 2|\mu|^2 \approx -2m_{h_u}^2 - 2|\mu|^2 \quad (\text{large } \tan\beta)$$
$$\approx -2\left(m_{h_u}^2(M_0) + |\mu|^2\right) + 2\,\delta m_{h_u}^2$$
- Large logs + color factors + lower bounds on gluinos and squarks: $\delta m_{h_u}^2 \gg M_Z^2$
A certain (at least %) fine-tuning is required to obtain $M_Z$ = 91 GeV

# Sources of Fine-Tuning

- Assuming soft terms generated at the GUT scale:

$$M_Z^2 \approx (91\,\mathrm{GeV})^2 \left[ \frac{\tilde{m}_t^2}{(70\,\mathrm{GeV})^2} - \frac{\tilde{m}_h^2}{(80\,\mathrm{GeV})^2} + \frac{M_{1/2}^2}{(40\,\mathrm{GeV})^2} - \frac{\mu^2}{(70\,\mathrm{GeV})^2} \right]_{M_0}$$

- Unavoidable source of FT: $M_3 \gtrsim 800$ GeV $\Rightarrow M_{1/2} \gtrsim 300$ GeV $\Rightarrow$ FT $\gtrsim 60$

- Bounds on stop mass
  - direct: weak because of small production cross section and detection efficiency corresponding FT; can be avoided by taking $m_3 < m_{1,2}$
  - indirect: from Higgs mass measurement - in the MSSM

$$(115.5\,\mathrm{GeV})^2 < m_h^2 < M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} h_t^2 m_t^2 \left[ \log \frac{\tilde{m}_t^2}{m_t^2} + \frac{X_t^2}{\tilde{m}_t^2} \left( 1 - \frac{X_t^2}{12\tilde{m}_t^2} \right) \right]$$

$X_t = A_t - \mu \cot\beta$ Maximal for $X_t = \sqrt{6}\,\tilde{m}_t$ $m_H \approx 125$ GeV?

# Indirect bounds on stop mass in the MSSM for $m_H \approx 125$ GeV

- Assuming degenerate stop masses, maximal $X_t$, $\tan\beta = 20$: $m_{stop} \gtrsim$ TeV, FT $\gtrsim$ 200, possibly larger because of large A-terms
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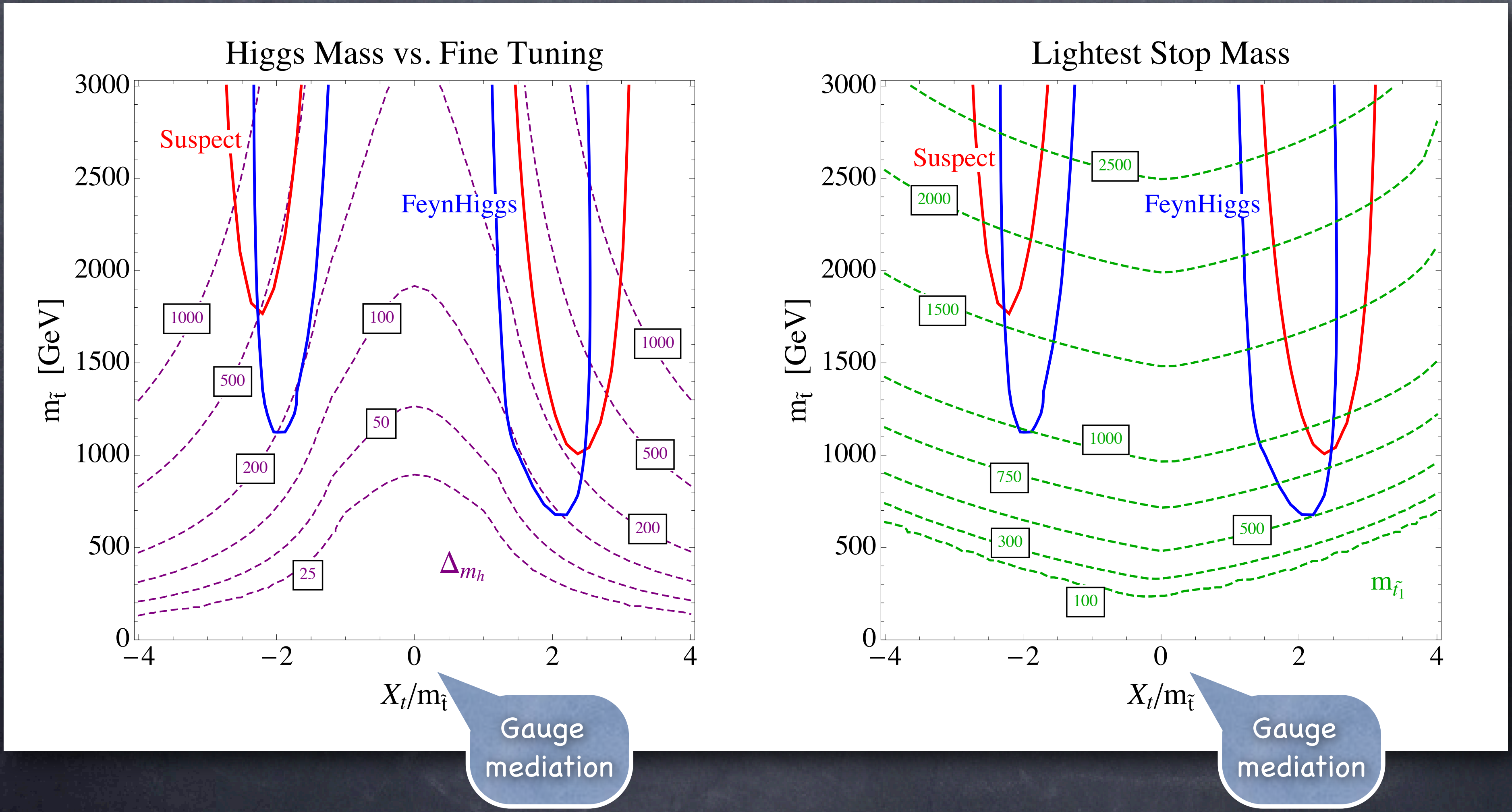
Hall Pinner Rudeman 1112.2703



# Beyond MSSM: xMSSM

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  - welcome ($\mu = \lambda \langle S \rangle \approx$ susy scale)
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- Help with FT from Higgs bound:
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    $\lambda$(10 TeV) < 3 (EWPTs) best, $\lambda(M_{GUT})$ < 3 (unification) OK
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- Persistent FT from
  - direct bounds on SUSY partners
  - arranging the invisible decay [Shuster Toro hep-ph/0512189]

- Invisible Higgs decays: $h \to aa \to 4X$ [No loose? Ellwanger Gunion Hugonie Moretti hep-ph/0401228, ...]
- 3leptons → multileptons from additional steps in chargino/neutralino decays
  - $C_1+N_2$ and then
  - $N_2 \to N_1+2l \to N_0+4l$ (if $N_0$ is lightest and mainly singlino)
  - $C_1 \to N_0+l+\nu$ (5l overall) or even $C_1 \to N_1+l+\nu \to N_0+3l+\nu$ (7l overall)
- Deviation from MSSM coupling relations: VVh = VHA = $\sin^2(\alpha-\beta)$, VVH = VhA = $\cos^2(\alpha-\beta)$ (optimistic)
- Z′ if μ is protected by a gauge symmetry

# Is fine-tuning really relevant?

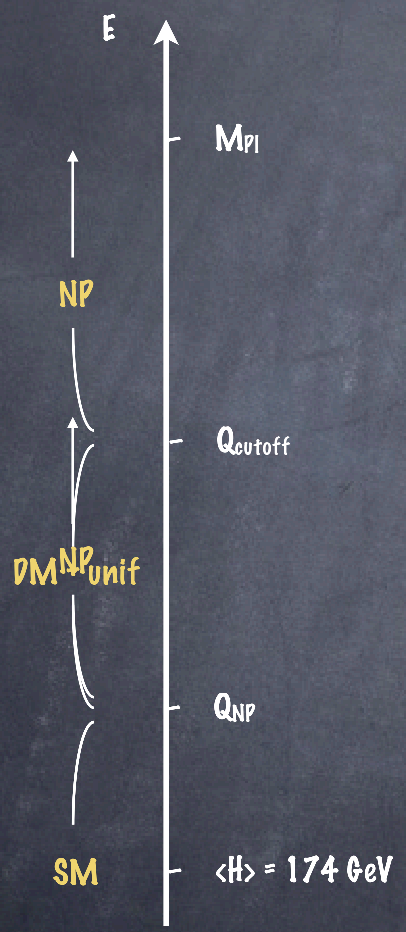
* Issues
  - Potentially > 100 parameters (CMSSM)
  - FCNCs and CP-violation in particular EDMs (SUSY breaking mechanism, symmetries)
  - Proton decay from dimension 5 operators (non minimal models)
  - Gravitino and moduli problem (low reheating T)
  - Fine-tuning (NMSSM)

  } scalars

* Successes of the MSSM
  - Gauge coupling unification
  - Natural dark matter candidate (with R-parity)

  } fermions

# Fine-tuned models

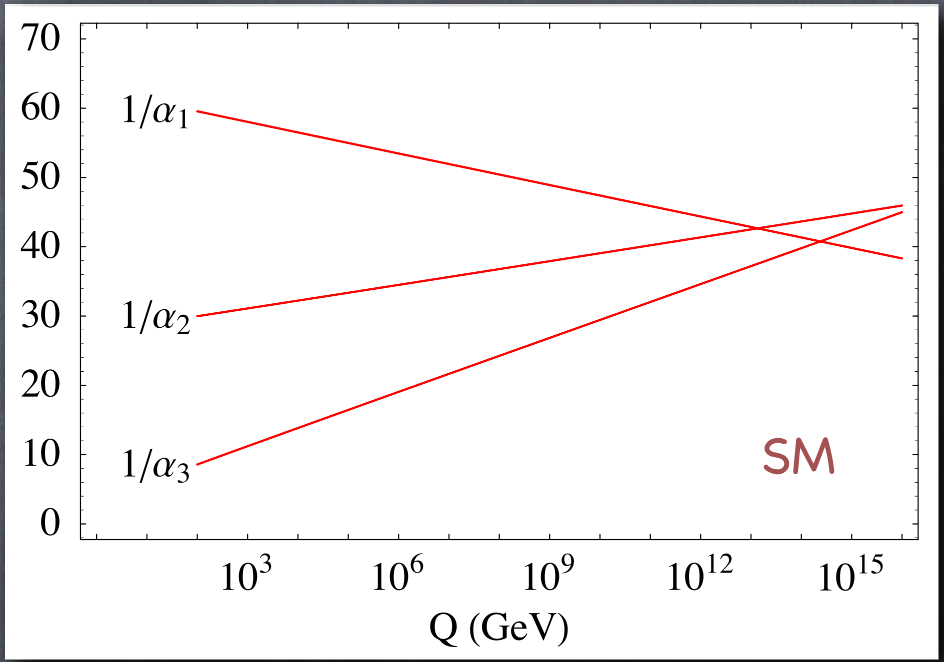



- $\delta m^2_h \gg m^2_h$
  $m_h$ is accidentally small or because of unspeakable reasons (connection with the cosmological constant problem)
- Note: often models (even MSSM benchmarks) are fine-tuned
- Still, dark matter and unification may save the day
  - by keeping (at least part) of new physics near TeV
  - giving rise to predictive models with characteristic signatures at LHC and other experiments

[Arkani-Hamed Dimopoulos 04, Giudice R 04, Arkani-Hamed Dimopoulos Giudice R 04]

# Unification

| | SU(3) | SU(2) | U(1) | SO(10) |
|---|---|---|---|---|
| $L_i$ | 1 | 2 | -1/2 | |
| $e^c_i$ | 1 | 1 | 1 | |
| $Q_i$ | 3 | 2 | 1/6 | 16 |
| $u^c_i$ | $3^*$ | 1 | -2/3 | |
| $d^c_i$ | $3^*$ | 1 | 1/3 | |
| | | | Y | |

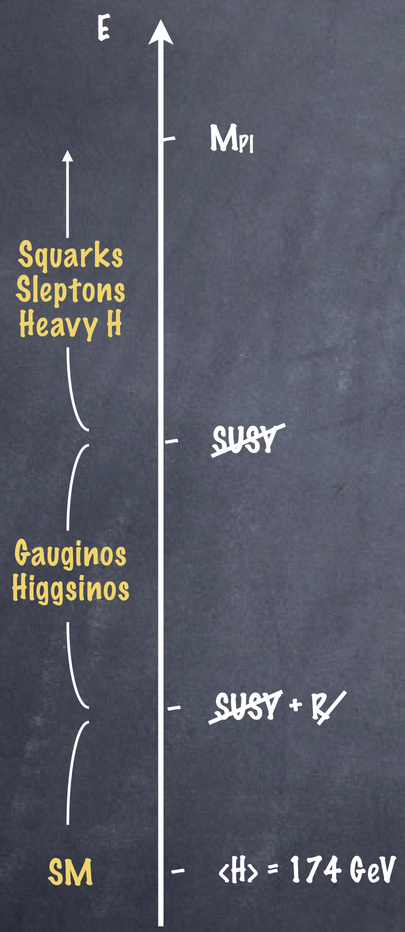



+ $M_{GUT}$ prediction: $\Lambda_B < M_{GUT} < M_{Pl}$

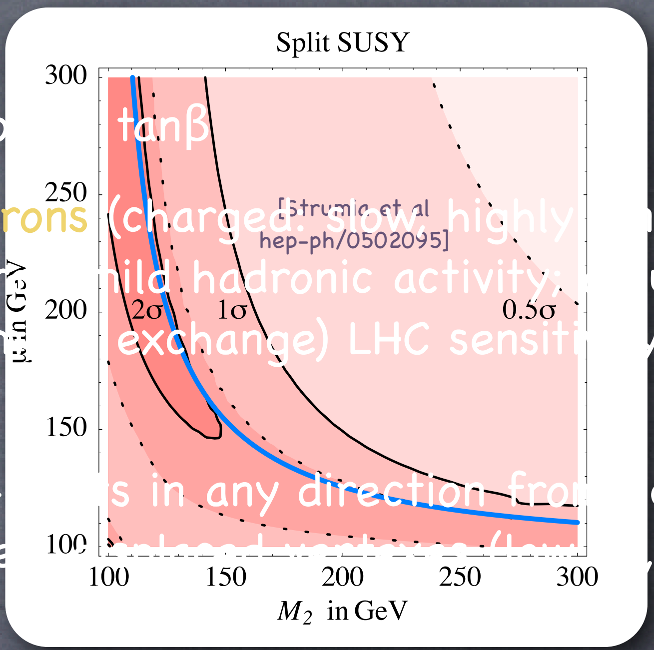
# Dark Matter

$$\Omega_\chi h^2 = \frac{688\pi^{5/2} T_\gamma^3 x_f}{99\sqrt{5g_*}(H_0/h)^2 M_{\rm Pl}^3 \sigma} = 0.1\,\frac{\rm pb}{\sigma}$$

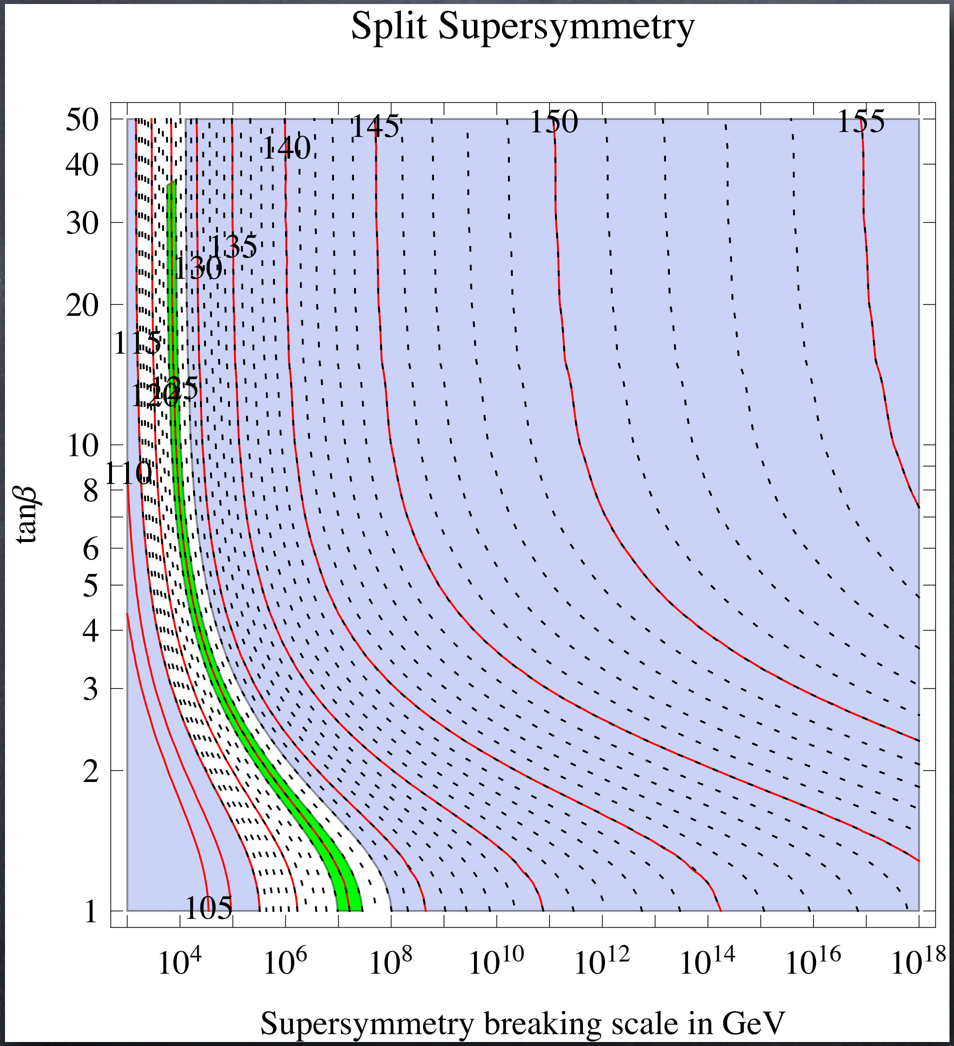
# Split Supersymmetry

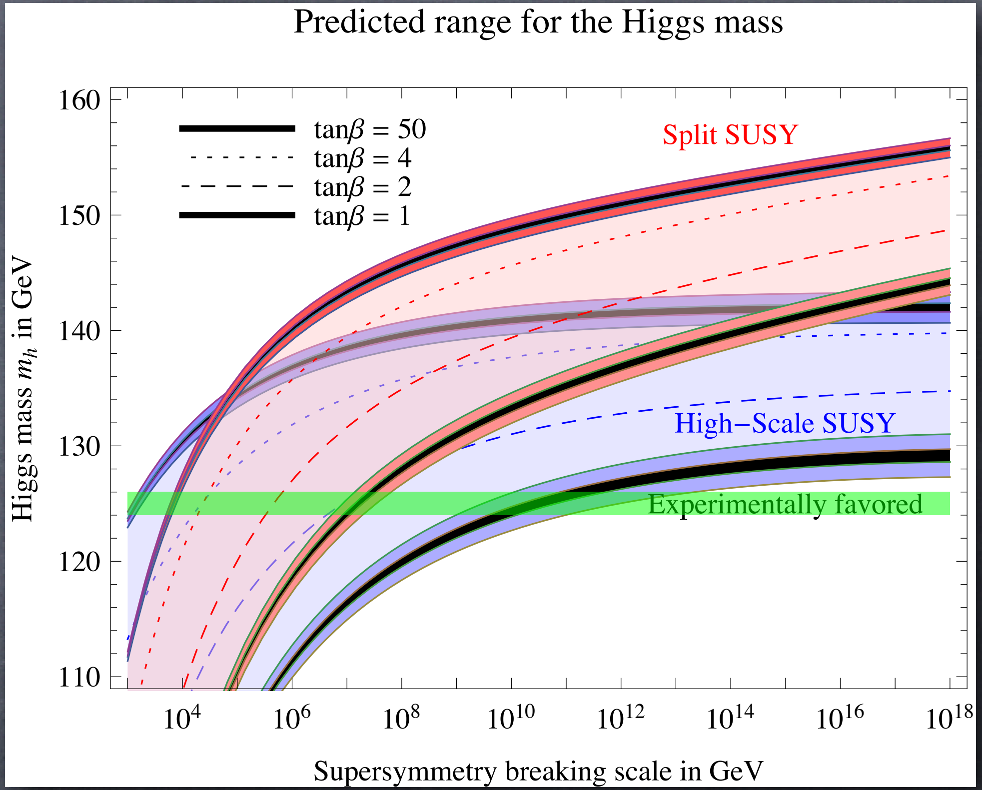



- DM: μ < 1.2 TeV ($M_1$ < $M_2$), mostly Bino favourable for LHC
- No bounds from EWPTs
- $m_H$ < 170 GeV, in terms of c… tanβ
- Long-live the gluino: R-hadrons (charged: slow, highly …izing track; neutral: missing ener… …ild hadronic activity; …ually: Energy, charge, Baryon-num… exchange) LHC sensiti… up to (1-2.5) TeV
- Wilder: stopping gluinos (1-… …s in any direction from …enser parts of the detector + m.e… …, charge flips



# Higgs mass and Split Supersymmetry




Giudice Strumia 1108.6077