$\mathcal{S}$USY $\mathcal{P}$hysics and ($\mathcal{C}$omposite) $\mathcal{H}$iggs at the $\mathcal{L}$HC

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CALC 2012, Dubna, July/August 2012

CALC 2012 - Outline

I SUSY at the LHC

– Motivation for beyond the SM (BSM) physics
– Introduction Supersymmetry
– MSSM
– SUSY GUT
– SUSY Breaking
– SUSY Particle Production
– SUSY Searches

II SM Higgs Physics and Beyond

– Introduction Higgs mechanism
– SM Higgs Sector
– Experimental Searches
– MSSM Higgs Sector (Brief)
– Composite Higgs Sector

$\mathcal{S}$USY $\mathcal{P}$hysics at the $\mathcal{L}$HC

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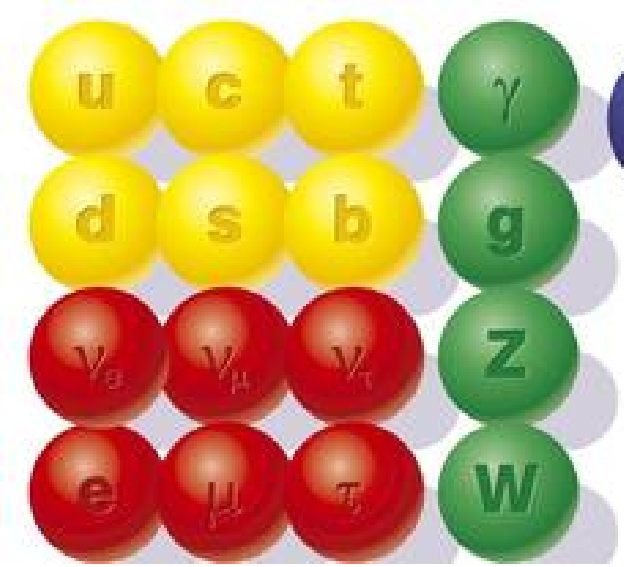
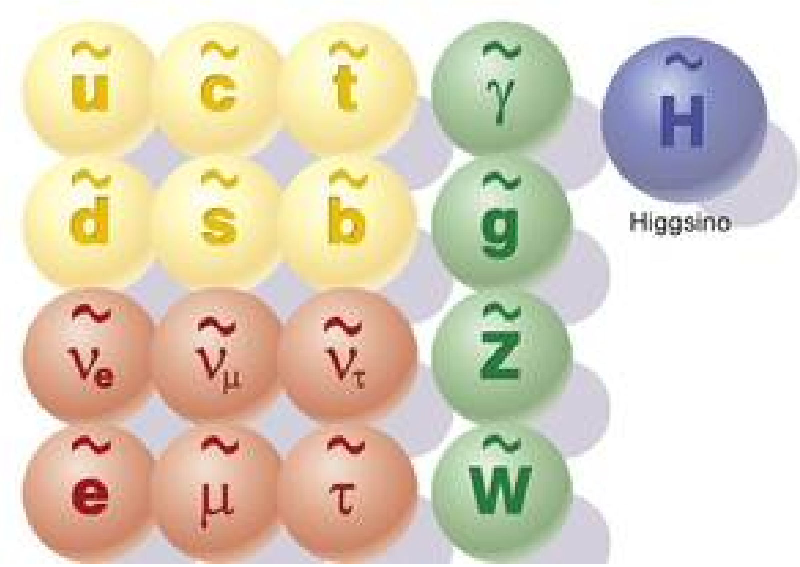
(KIT)

CALC 2012, Dubna, July/August 2012





$\mathcal{L}$iterature

- D.V. Volkov, V.P. Alkulov, Phys. Lett. **B46** (1973) 109.
- J. Wess and B. Zumino, Nucl. Phys. **B70** (1974) 39.
- H.P. Nilles, Phys. Rep. **110** (1984) 1.
- H.E. Haber and G.L. Kane, Phys. Rep. **117** (1985) 75.
- Wess & Bagger, *Supersymmetry and Supergravity*, Princeton University Press.
- S. Martin, *A Supersymmetry Primer*, hep-ph/9709356.
- S. Dawson, *The MSSM and why it works*, hep-ph/9712464.
- S. Dawson, J.F. Gunion, H.E. Haber and G. Kane, *The Higgs Hunter's Guide*, Frontiers in Physics.
- M. Drees, R.M. Godbole and P. Roy, *Theory and Phenomenology of Sparticles*, World Scientific.
- H. Baer and X. Tata, *Weak Scale Supersymmetry*, Cambridge University Press.
- H. Kalka und G. Soff, *Supersymmetrie*, Teubner Studienbücher 1997. (For notation, SUSY algebra etc.)
- ATLAS, CMS Webpages

(I) Motivation

Why Beyond Standard Model (BSM) Physics?

Standard Model: incomplete picture of the universe

- Standard Model (SM) has 19 free parameters:
  - 3 gauge couplings: g_1, g_2, g_3
  - 6 quark and 3 lepton masses
  - Higgs mass M_H, the vacuum expectation value (VEV)
  - 3 mixing angles and 1 phase in the CKM matrix
  - the θ parameter of QCD

- What are the values of these parameters?
  - Why is the top quark so heavy compared to the other fermions?
  - Why is the θ parameter so small?
  - Enough CP violation to explain matter-antimatter asymmetry?

$\mathcal{W}$hy $\mathcal{B}$eyond $\mathcal{S}$tandard $\mathcal{M}$odel ($\mathcal{BSM}$) $\mathcal{P}$hysics?

Standard Model: incomplete picture of the universe

- Standard Model (SM) has 19 free parameters:
- What are the values of these parameters?
- Common origin of all three forces of the SM?
- How to incorporte gravity?
- Candidate for Dark Matter (DM)? ...

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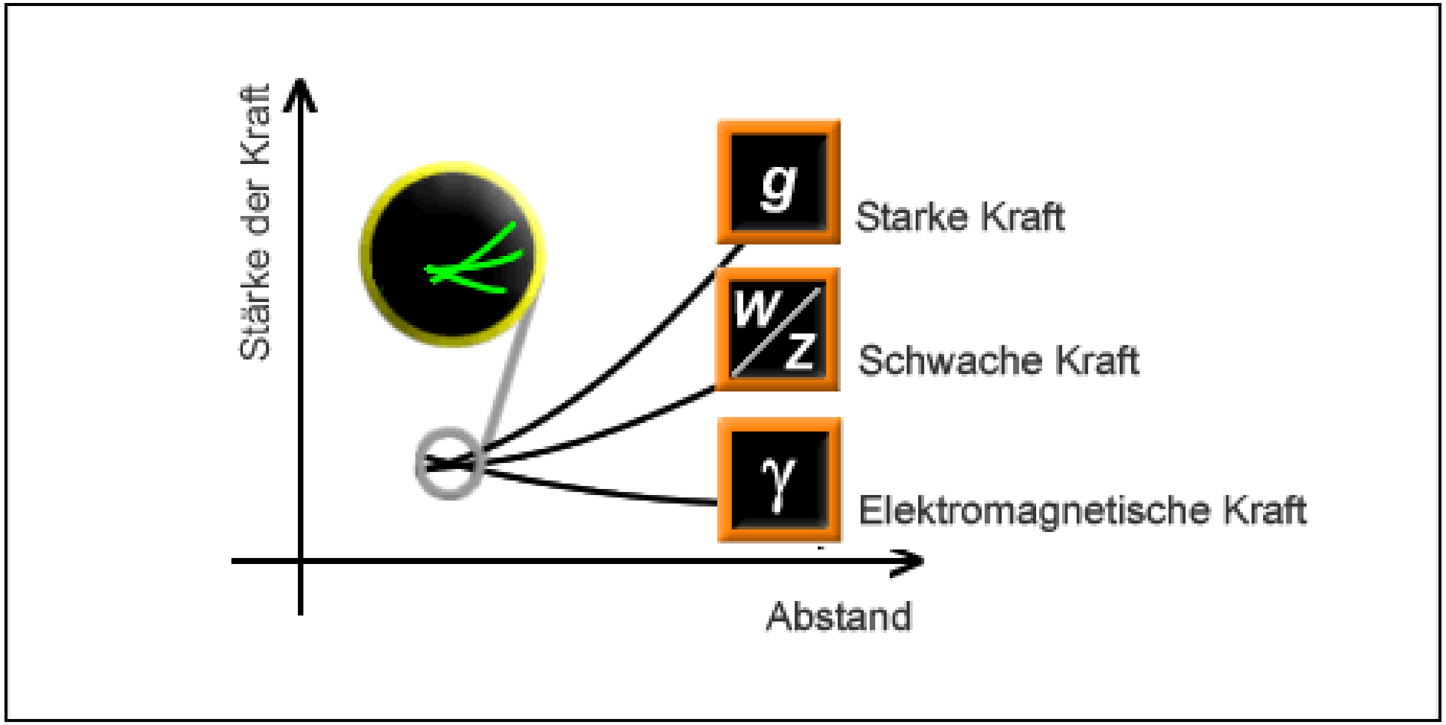

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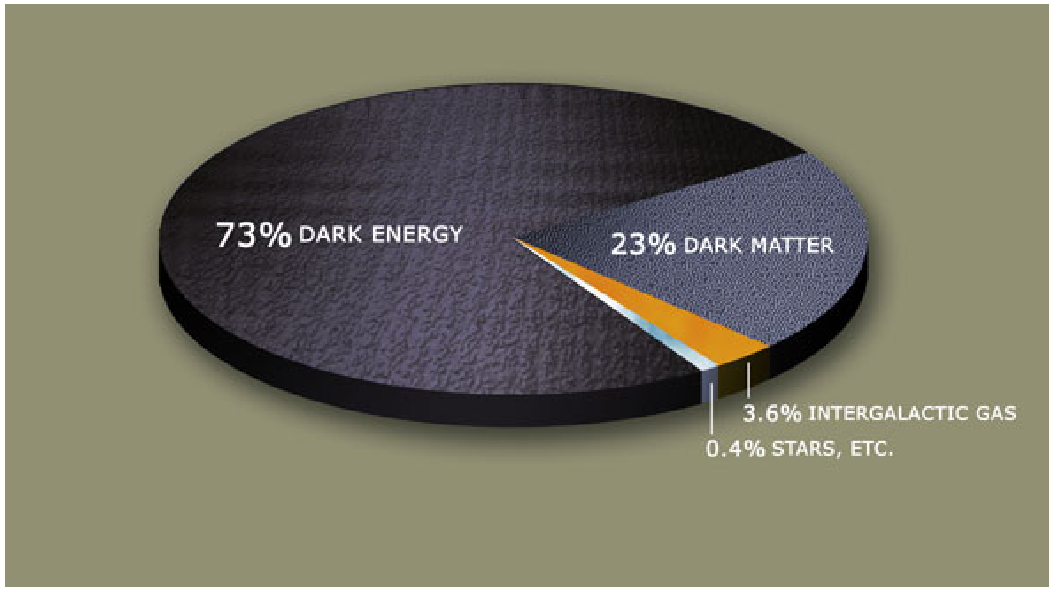
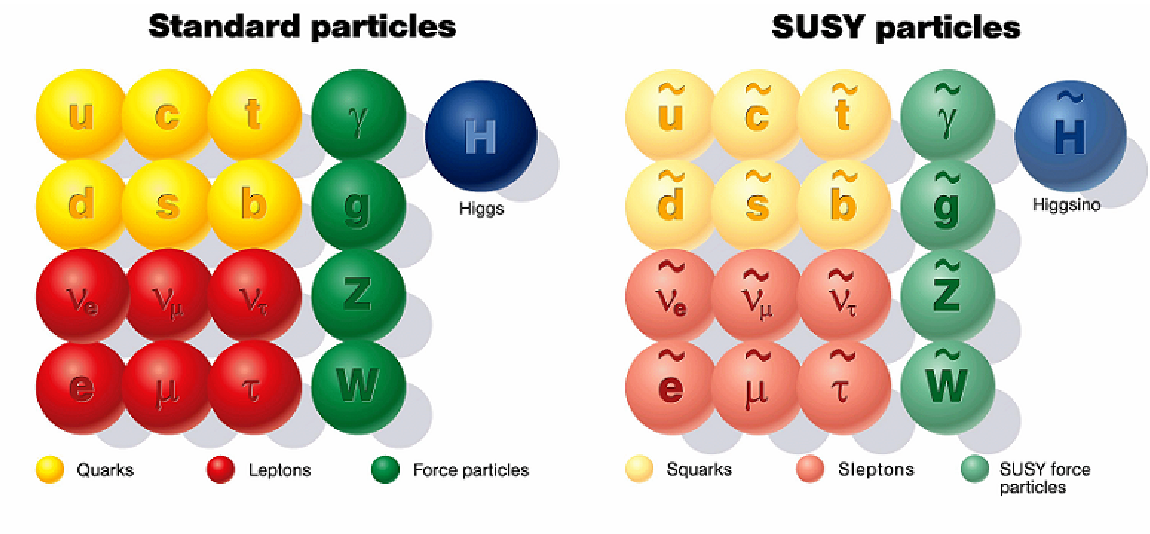


Possible answers from: Supersymmetry

Fermions ↔ Bosons

Price: doubling of the particle spectrum



$\mathcal{S}$upersymmetry - $\mathcal{M}$otivation

(i) Relates bosons $\leftrightarrow$ fermions:

$$\left.\begin{array}{l} Q|F>=|B> \\ Q|B>=|F> \end{array}\right\} \text{1 multiplet}$$

(ii) Maximal symmetry of the $\mathcal{S}$-matrix:

Coleman-Mandula theorem: Bosonic operators cannot extend the Poincaré algebra.

Fermionic operators: $Q \sim$ spin $\frac{1}{2} \Rightarrow$ graded Lie-algebra

(iii) Hierarchy problem:

Standard Model:
Relevant low-energy scale: electroweak scale $v \sim 10^2$ GeV ($\rightarrow$ Higgs mass M_H)
Up to which scale is the SM valid? E.g. the GUT scale $M_{GUT} \sim 10^{16}$ GeV
Hierarchy problem: M_H unstable w.r.t. the quantum corrections: $\delta M_H^2 \sim \Lambda^2$

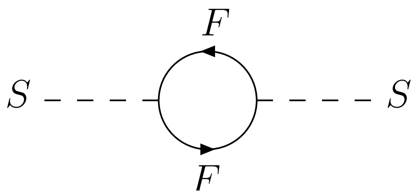
$\mathcal{H}$ierarchy $\mathcal{P}$roblem

Boson masses unstable w.r.t. quantum corrections:

$$\mathcal{L}_1 = \bar{\psi}(i\partial\!\!\!/ - m_F)\psi + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \frac{\lambda_F}{2}\bar{\psi}\psi S$$

Free propagator: S - - - - - - - - - S inverse propagator: $i(p^2 - m_S^2)$

Loop corrections:



inverse propagator: $i(p^2 - m_S^2 + \underbrace{\Sigma_S^F}_{\Delta m_S^2})$

We find for the integration over all possible loop momenta k by dimensional analysis

$$\Delta m_S^2 \sim \lambda_F^2 \int d^4k \Big(\frac{1}{k^2 - m_F^2} + \frac{2m_F^2}{(k^2 - m_F^2)^2} \Big)$$

$$\Lambda \to \infty : \qquad \Delta m_S^2 \sim \lambda_F^2 \Big(\underbrace{\int \frac{d^4k}{k^2}}_{\sim \Lambda^2} + 2m_f^2 \underbrace{\int \frac{dk}{k}}_{\sim \ln \Lambda} \Big)$$

$\Rightarrow$ quadratically divergent

$\mathcal{H}$ierarchy $\mathcal{P}$roblem

- For $\Lambda = M_{GUT} = 10^{16}$ GeV:

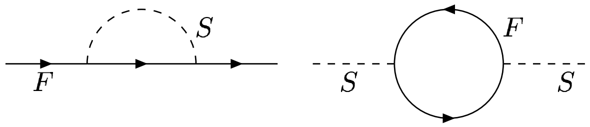
$$\Delta m_S^2 \sim M_{GUT}^2 \quad \Rightarrow \quad \Delta m_S^2 \approx 10^{28} m_S^2$$

for $m_S \sim \mathcal{O}(10^2 \text{ GeV})$. Hence

$$m_{S_R}^2 = m_S^2 + \Delta m_S^2 + \text{ counterterm} = (1 + 10^{28}) m_S^2 + \text{ counterterm} \stackrel{!}{=} (10^2 \text{ GeV})^2$$

$\Rightarrow$ Counterterm must be extremely finetuned

- Comparison of corrections to fermion masses and scalar masses:



$$\delta m_F = -\frac{3\lambda_F^2 m_F}{64\pi^2} \log \frac{\Lambda^2}{m_F^2} + \ldots$$

$$\delta m_S^2 = -\frac{\lambda_F^2}{8\pi^2} \left[\Lambda^2 - m_F^2 \log \frac{\Lambda^2}{m_F^2} \right] + \ldots$$

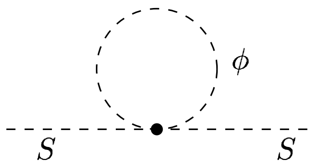
F : mild log. divergence $\sim m_F \log \Lambda \to 0$ for $m_F \to 0$ ($m_F \to 0 \to \gamma_5$-symmetry)

B : quadratic divergence $\sim \Lambda^2 \to$ cancelled only by fine-tuning of the bare mass term.
Bosonic masses cannot be kept small in a natural way within the presence of high-energy scales

$\mathcal{H}$ierarchy $\mathcal{P}$roblem

- Solution: Bosonic masses can be kept small in a natural way if bosons are related to fermions.

$$\mathcal{L}_2 = |\partial_\mu \phi_1|^2 + |\partial_\mu \phi_2|^2 + \frac{\lambda_S}{2} S^2(|\phi_1|^2 + |\phi_2|^2) - m_\phi^2(|\phi_1|^2 + |\phi_2|^2) \quad [\psi \leftrightarrow \phi_1, \phi_2]$$



$$\delta m_S'^2 = +\frac{\lambda_S^2}{8\pi^2}\left[\Lambda^2 - m_\phi^2 \log\frac{\Lambda^2}{m_\phi^2}\right] + \ldots \qquad (\pm\text{Pauli principle})$$

$$\delta m_S^2 = -\frac{\lambda_F^2}{8\pi^2}\left[\Lambda^2 - m_F^2 \log\frac{\Lambda^2}{m_F^2}\right] + \ldots$$

SUSY: degree of freedoms : 4 fermionic $\leftrightarrow$ 4 bosonic; $\lambda_F = \lambda_S$ $\Big\}$ $\delta m_S^2 \sim \frac{\lambda^2}{8\pi^2}(m_F^2 - m_\phi^2)\log\Lambda^2$

$\mathcal{H}$ierarchy $\mathcal{P}$roblem

SUSY: $\left.\begin{array}{l}\text{degree of freedoms : 4 fermionic} \leftrightarrow \text{ 4 bosonic} \\ \lambda_F = \lambda_S\end{array}\right\} \quad \delta m_S^2 \sim \frac{\lambda^2}{8\pi^2}(m_F^2 - m_\phi^2)\log\Lambda^2$

- Exact cancellation for $m_F = m_\phi \Rightarrow$
  exact supersymmetry between bosonic and fermionic degrees of freedom
- No SUSY particles discovered yet $\Rightarrow$ SUSY must be broken
- Soft SUSY breaking: $m_{SUSY} \neq m_{SM}$, but $\lambda_{SUSY} = \lambda_{SM}$
- Corrections remain small enough not to reintroduce finetuning if $m_{SUSY} \lesssim 1$ TeV

TeV scale Supersymmetry:
solution to hierarchy problem

$\mathcal{S}$upersymmetry - $\mathcal{M}$otivation

(iv) Higgs mechanism generated via radiative corrections (for $m_t \sim 100...200$ GeV) $\rightarrow$ T

(v) Unification of ELM + weak + strong couplings $\rightarrow$ T

$$\frac{1}{\alpha_i(Q^2)} = \frac{1}{\alpha_i} - \frac{b_i}{2\pi} \log Q^2 \quad \text{for} \quad i = U(1), SU(2), SU(3)$$

SM: No single crossing point: order of magnitude deficit.

SUSY: Unification of couplings $\delta\alpha/\alpha \approx 1.5\%$. Depends solely on quantum numbers, independent of mass spectrum beyond ~ 1 TeV.

(vi) Cold Dark Matter (CDM) If SUSY particles assigned conserved multiplicative quantum number,

R-parity $= +1$ SM, $= -1$ SUSY, then

SUSY particles prod. pairwise in SM collisions   lightest SUSY particle stable: CDM candidate

(vii) Local SUSY: enforces gravity

$\mathcal{S}$upersymmetry - $\mathcal{M}$otivation

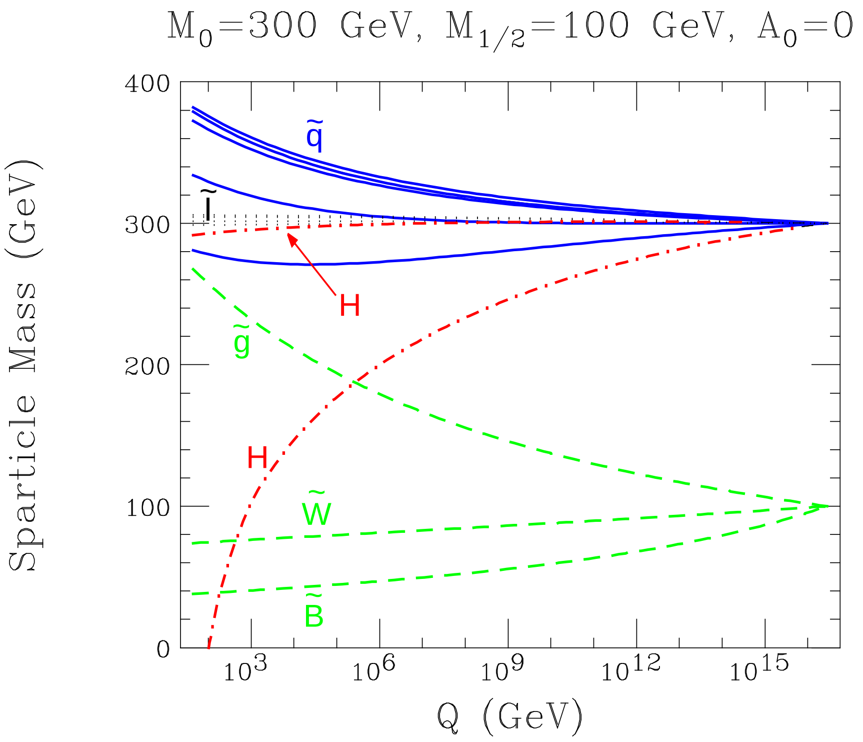
Evolution: $M^2_{H_2}(Q^2) \approx M_0^2 + \mu^2 - \frac{3g_t^2}{8\pi^2}(3M_0^2+\mu^2)\log\frac{M_{GUT}}{Q}$

Bagger

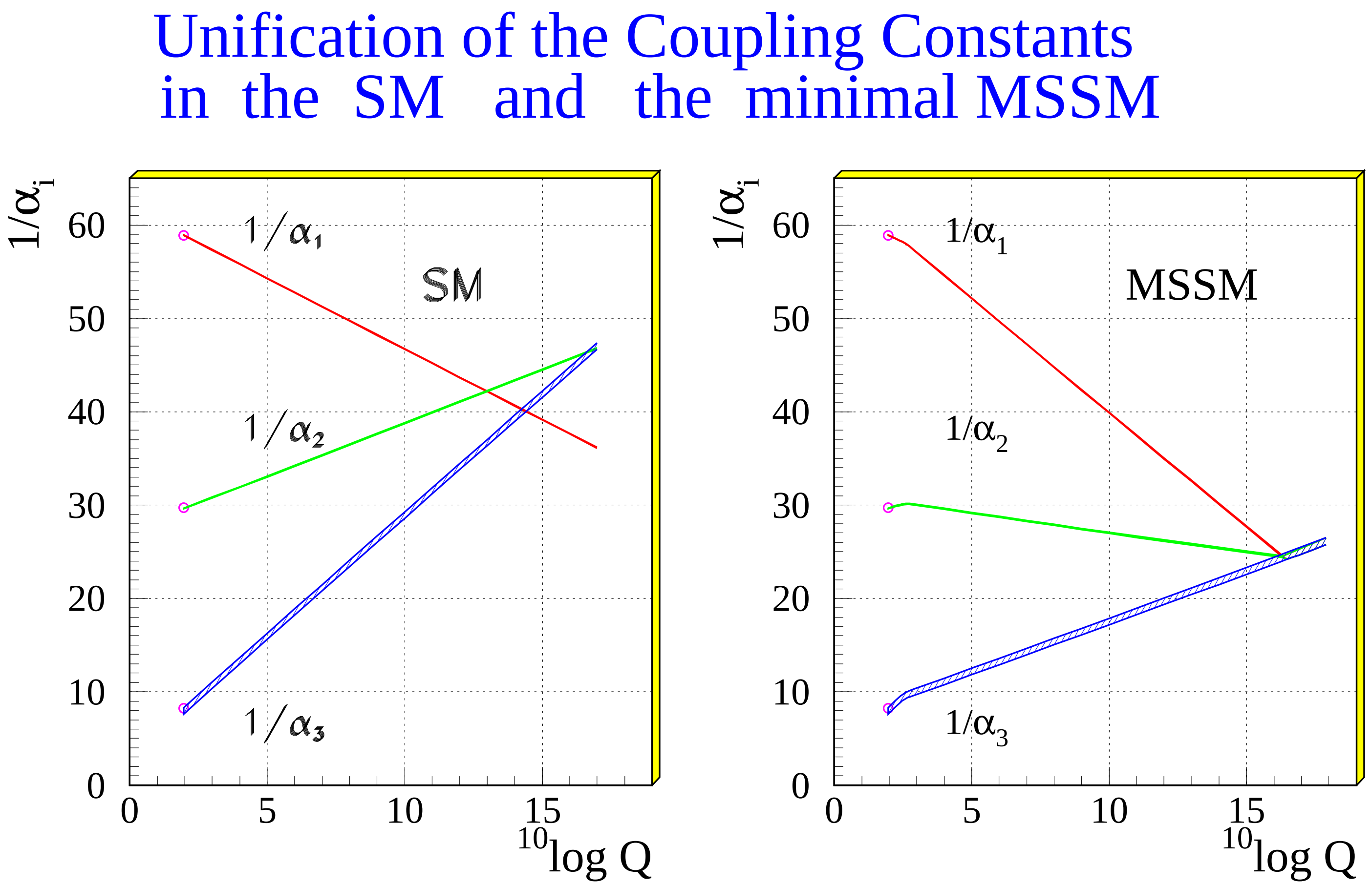
$M^2_{H_2}(M_Z^2) < 0$ possible for $m_t \sim 100 - 200$ GeV

$\longrightarrow$ radiative symmetry breaking

$SU_3 \times SU_2 \times U_1 \rightarrow SU_3 \times U_1^{em}$



Amaldi,de Boer,Fürstenau



(II) Supersymmetry Introduction

(II) $\mathcal{S}$upersymmetry $\mathcal{I}$ntroduction

a) Symmetries

Lagrangian called symmetric if invariant under a certain group of transformations.
Generators of the group fulfill an algebra.
Continuous symmetry of the Lagrangian related to existence of a conserved quantity $Q \rightarrow$ Noethertheorem.

Examples

(i) Invariance under 3-dim rotations ($\leftarrow$ isotropy of space): $\psi \rightarrow \psi e^{i\theta^a L_a}$
generators: angular momenta L_a; algebra $[L_a, L_b] = i\epsilon_{abc}L_c$
quantum numbers: angular momentum (also spin) $|\vec{L}|^2, L_3$

(ii) Internal symmetries, e.g. Standard Model invariant under $SU(2)_L \times U(1)_Y \times SU(3)_C$
gauge symmetries of the electroweak and strong forces
e.g. $SU(3)_C$ generators T_a with the algebra $[T_a, T_b] = if_{abc}T_c$
quantum numbers: weak isospin, hypercharge, colour

(iii) Poincaré symmetry - describes structure of our space-time:
Lorentz transformations Λ^μ_ν (rotations & boosts) and translations P^μ
quantum numbers: mass, spin of particles

Weyl spinors: Two-component spinors; all other spinors are built from Weyl spinors

* Left- and right-handed Weyl spinors Ψ_L and Ψ_R transform under the left and right fundamental respresentation of the special Lorentz group

$$A_L := \Lambda^{(\frac{1}{2},0)} = \exp\Big\{-\frac{i}{2}(\vec{\varphi} - i\vec{\nu})\cdot\vec{\sigma}\Big\}$$

$$A_R := \Lambda^{(0,\frac{1}{2})} = \exp\Big\{-\frac{i}{2}(\vec{\varphi} + i\vec{\nu})\cdot\vec{\sigma}\Big\}$$

(rapidity $\vec{\nu}$, Pauli matrices σ_i, i=1,2,3) as

$$\psi'_L = A_L\psi_L \qquad \text{and} \qquad \psi'_R = A_R\psi_R$$

* Complex 2×2 matrix $A \in SL(2,\mathbb{C})$: 4 representations

selbst representation:	$D(A) = A$		
duale self representation:	$D(A) = A^{-1T}$	}	equivalent
conjugate representation:	$D(A) = A^{-1\dagger}$	}	equivalent .
duale conjugate representation:	$D(A) = A^{*}$		

* Ψ_L transforms under the $(\frac{1}{2},0)$ fundamental representation
  Ψ_R transforms under the $(0,\frac{1}{2})$ fundamental (conjugate) representation

∗ Notation: fundamental and dual respresenation: lower ↔ higher indices (co- and contravariant)
conjugate representation: dotted indices

$$\Psi_L = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} \qquad \text{and} \qquad \Psi_R^\dagger = (\psi^1, \psi^2) \ ,$$

$$\Psi_R = \begin{pmatrix} \bar{\psi}^{\dot{1}} \\ \bar{\psi}^{\dot{2}} \end{pmatrix} \qquad \text{and} \qquad \Psi_L^\dagger = (\bar{\psi}_{\dot{1}}, \bar{\psi}_{\dot{2}}) \ .$$

∗ Bispinor: Direct sum of the fundamental reprs. $(\frac{1}{2}, 0) \oplus (0, \frac{1}{2}) \rightsquigarrow$ bispinor with 4 spinor comps.

∗ Dirac spinor (chiral representation)

$$\text{Dirac spinor:} \qquad \Psi = \begin{pmatrix} \psi_L \\ \phi_R \end{pmatrix}$$

transforms according to

$$\Psi \longrightarrow \Psi' = S\Psi \qquad \text{with} \qquad S := \Lambda^{(\frac{1}{2},0)\oplus(0,\frac{1}{2})} = \begin{pmatrix} A_L & 0 \\ 0 & A_R \end{pmatrix}$$

∗ Majorana spinor: half degrees of freedom of Dirac spinor

$$\text{Majorana spinor:} \qquad \Psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

- **Standard Model** described by
  - ▷ internal symmetry: T^a
  - ▷ Poincaré symmetry: $\Lambda^{\mu\nu}, P^\rho$

Internal symmetry is a trivial extension of the Poincaré symmetry:

$$[\Lambda^{\mu\nu}, T^a] = 0 \, , \qquad [P^\rho, T^a] = 0$$

⇒ direct product: (Poincaré group) $\bigotimes$ (internal symmetry)

Particles characterized by maximal set of commuting observables:

$$\underbrace{m, s; \vec{p}, s_3}_{\text{space-time}} ; \underbrace{Q, I, I_3, Y, ...}_{\text{internal}}$$

quantum numbers

- **Question: Can we extend the Standard Model (SM)?**

c) The Coleman Mandula Theorem (1967) - No go theorem

Every quantum field theory satisfying certain assumptions about its S matrix and which has non-trivial interactions can only have:

a symmetry Lie algebra which is always
a direct product of the Poincaré group and an internal group

beyond $P_\mu, M_{\mu\nu}$ (generators of the Lorentz rotations) no more conserved bosonic observables

- New group G with generators R^α and

$$[\Lambda^{\mu\nu}, R^\alpha] \neq 0 \ , \qquad [P^\alpha, R^\alpha] \neq 0$$

impossible

- New symmetry must predict new particles with the same mass and spin as in the SM

Experimentally excluded

c) Way out: SUSY algebra

Uniqueness of SUSY extension: beyond $P_\mu, M_{\mu\nu}$ no more conserved bosonic observables.

HOWEVER: fermionic transformations are not forbidden $\Rightarrow$
(Q_α = left-handed Weyl spinor: $\gamma_5 Q = -Q$; $[A,B] \equiv AB - BA; \{A,B\} \equiv AB + BA$)

Poincaré algebra:

$$
\begin{aligned}
[P_\mu, P_\nu] &= 0 \\
[P_\mu, M_{\rho\sigma}] &= i(g_{\mu\rho}P_\sigma - g_{\mu\sigma}P_\rho) \\
[M_{\mu\nu}, M_{\rho\sigma}] &= i(-g_{\mu\rho}M_{\nu\sigma} + g_{\mu\sigma}M_{\nu\rho} + g_{\nu\rho}M_{\mu\sigma} - g_{\nu\sigma}M_{\mu\rho})
\end{aligned}
$$

$\oplus$ SUSY algebra: of fermionic Q's

$$
\begin{aligned}
\{Q_\alpha, Q_\beta\} &= \{\bar{Q}_{\dot{\alpha}}, \bar{Q}_{\dot{\beta}}\} = 0 \\
\{Q_\alpha, \bar{Q}_{\dot{\beta}}\} &= 2\sigma^\mu_{\alpha\dot{\beta}}P_\mu \\
[Q_\alpha, P_\mu] &= [\bar{Q}_{\dot{\alpha}}, P_\mu] = 0 \\
[Q_\alpha, M_{\mu\nu}] &= \tfrac{1}{2}(\sigma_{\mu\nu})_{\alpha\beta}Q_\beta
\end{aligned}
$$

SUSY multiplets combine fermions with bosons spectrum: $M_{12} = J_3$, $\sigma_{12} = \sigma_3$

$J_3\bar{Q}_{\dot{1},\dot{2}} = \bar{Q}_{\dot{1},\dot{2}}\left(J_3 \pm \frac{1}{2}\right) \Rightarrow \bar{Q}_{\dot{1}(\dot{2})}$ generates (destroys), $Q_{1(2)}$ destroys (generates) spin $\frac{1}{2}$

multiplet structure: particle multiplet $|\lambda>, |\lambda + \frac{1}{2}>$

antiparticle multiplet $|-\lambda>, |-\lambda - \frac{1}{2}>$

Generalization: $Q^{i=1,2,\dots,N}_{\alpha=1,2}$: $\{Q^i_\alpha, Q^j_\beta\} = \{\bar{Q}^i_{\dot\alpha}, \bar{Q}^j_{\dot\beta}\} = 0, \quad \{Q^i_\alpha, \bar{Q}^j_{\dot\beta}\} = 2\delta_{ij}\sigma^\mu_{\alpha\dot\beta}P_\mu$

Maximum: $|-\lambda_{max}> \dots | -\lambda_{max} + \frac{N}{2} >= |\lambda_{max}>$ consistent field theory: $\lambda_{max} = 2 \Rightarrow \boxed{N \leq 8}$

d) Implications

Same number of fermions and bosons in one multiplet

Witten Index: $\Delta = \text{Tr}(-1)^{N_F}$, with N_F the particle number operator for fermions

$$\Delta|B>=|B> \qquad \text{and} \qquad \Delta|F>=-|F>$$

We have $\{Q, \bar{Q}\} = 2\sigma_\mu P^\mu \quad \Rightarrow$

$\Delta\{Q, \bar{Q}\} = \Delta 2\sigma_\mu P^\mu$ LHS: $\text{Tr} < (-1)^{N_F} Q\bar{Q} > \quad + \text{Tr} < (-1)^{N_F}\bar{Q}Q >$

$= \quad \sim \quad + \text{Tr} < Q(-1)^{N_F}\bar{Q} >$

$= \quad \sim \quad - \text{Tr} < (-1)^{N_F} Q\bar{Q} >= 0$

RHS: $2\sigma^\mu \text{Tr}[(-1)^{N_F} P_\mu] = 0 \qquad \Rightarrow \Delta = \text{Tr}(-1)^{N_F} = 0$

Witten index = difference in number of bosonic and fermionic states: $\Delta = 0 \Rightarrow$

number of bosons = number of fermions

Masses of fermions and bosons are equal

We have $[P_\mu, Q] = [P_\mu, \bar{Q}] = 0$. Hence for $P_0 = H$:

$$[P_0, Q] = [P_0, \bar{Q}] = 0 \qquad \begin{aligned} H|B> &= m_B|B> \\ QH|B> &= HQ|B> = H|F> \quad \Rightarrow \\ m_B|F> &= m_F|F> \end{aligned}$$

$$\boxed{m_B = m_F}$$

Experimentally: no SUSY partners to SM particles with identical mass observed $\Rightarrow$

If SUSY is realized in nature, it must be broken.

e) Superfields

Superfield: combination of fields belonging to the same multiplet into one single field.

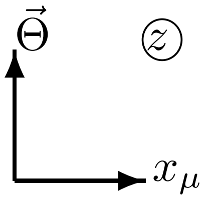
pairings:

fermion f	$\sim$	sfermion $\tilde{f}$	[spin $\frac{1}{2}$ - spin 0]
gauge field W	$\sim$	gaugino $\tilde{W}$	[spin 1 - spin $\frac{1}{2}$]
Higgs H	$\sim$	Higgsino $\tilde{H}$	[spin 0 - spin$\frac{1}{2}$]

combined to superfields defined in superspace.

Superspace:

- Translation transformation P_μ; parameter: x_μ
- SUSY transformation: $Q_\alpha, \bar{Q}_{\dot{\alpha}}$; parameter: $\theta, \bar{\theta}$



$z = [x_\mu; \theta, \bar{\theta}]$ $\quad x_\mu =$ space-time, $\theta_{1,2}, \bar{\theta}_{\dot{1},\dot{2}}$ fermionic coordinates

Reminder Grassmann numbers:

▷ Without spinor index $\{\theta, \theta\} = 0 \qquad \Rightarrow \qquad \theta\theta = 0$

▷ With two-component spinor index:

Metric: $\theta_\alpha, \bar{\theta}_{\dot{\alpha}}$ $(\alpha = 1, 2)$ $(\epsilon^{12} = -\epsilon^{21} = 1)$

$$\begin{aligned} \theta^2 &= \theta_\alpha \theta^\alpha = \epsilon^{\alpha\beta}\theta_\alpha\theta_\beta = 2\theta_1\theta_2 \\ &= -\theta^1\theta_1 - \theta^2\theta_2 = \theta_1\theta^1 + \theta_2\theta^2 \end{aligned}$$

$\theta^2 \neq 0$, but $\theta^\alpha\theta^\beta\theta^\gamma = 0$ $(\alpha, \beta, \gamma = 1, 2)$

Taylor expansion ends after $\theta\theta$: $\phi(\theta) = a + \theta\psi + \theta\theta f$

Integration: $\int d\theta = 0$, $\int d\theta\theta = 1$ and $d^2\theta = \frac{1}{2} d\theta_1 d\theta_2$

$$\Rightarrow \int d^2\theta \phi(\theta) = \int d^2\theta (a + \theta\psi + \theta\theta f) = f$$

e) Translations in superspace

◇ 14 generators $\{P^\mu, M^{\mu\nu}, Q, \bar{Q}\}$ $\Rightarrow$ group of symmetry transformations

Translation: $\exp\{-iy^\mu P_\mu\}$

SUSY-Translation: $\exp\{i(\xi Q + \bar{\xi}\bar{Q})\}$

SUSY generators lead to translations in super-space by the spinoriel parameters $\xi, \bar{\xi}$

◇ Element of the Poincaré supergroup

$$S(y, \xi, \bar{\xi}) = \exp\{i(\xi Q + \bar{\xi}\bar{Q} - y^\mu P_\mu - \frac{1}{2}\omega^{\mu\nu} M_{\mu\nu})\}$$

In the following only SUSY translations (w/o rotations)

◇ SUSY translations form a group; $\xi, \bar{\xi}$ independent of y^μ: global SUSY transformation

◇ Transformation of a superfield, $S(y, \xi, \bar{\xi})\phi(x, \theta, \bar{\theta})$:

$$S(y, \xi, \bar{\xi})\phi(x, \theta, \bar{\theta}) = \phi(x^\mu + y^\mu - i\xi\sigma^\mu\bar{\theta} + i\theta\sigma^\mu\bar{\xi}, \xi + \theta, \bar{\xi} + \bar{\theta})$$

◇ Representations of the generators ($\partial_\alpha = \partial/\partial\theta^\alpha, \bar{\partial}_{\dot{\alpha}} = \partial/\partial\bar{\theta}^{\dot{\alpha}}$, $\overset{(\sim)}{\sigma}_\mu = (1, \pm\vec{\sigma})$, σ_i Pauli Matrices)

$$P_\mu = -i\partial_\mu \; , \quad Q_\alpha = -i\partial_\alpha - (\sigma^\mu\bar{\theta})_\alpha\partial_\mu \; , \quad \bar{Q}_{\dot{\alpha}} = -i\bar{\partial}_{\dot{\alpha}} - (\tilde{\sigma}^\mu\theta)_{\dot{\alpha}}\partial_\mu$$

◇ Definition of covariant derivatives

$$D_\alpha = \partial_\alpha + i(\sigma^\mu\bar{\theta})_\alpha\partial_\mu \; , \quad \bar{D}_{\dot{\alpha}} = -\bar{\partial}_{\dot{\alpha}} + i(\tilde{\sigma}^\mu\theta)_{\dot{\alpha}}\partial_\mu$$

f) General superfield in component form

$*$ Most general superfield $\mathcal{F}(x,\theta,\bar\theta)$ dependent on $x,\theta,\bar\theta$

$$\begin{aligned}\mathcal{F}(x,\theta,\bar\theta) &= f(x)+\theta\phi(x)+\bar\theta\bar\chi(x)+(\theta\theta)M(x)+(\bar\theta\bar\theta)N(x)+\theta\sigma^\mu\bar\theta A_\mu(x)\\ &+ (\theta\theta)\bar\theta\bar\lambda(x)+(\bar\theta\bar\theta)\theta\alpha(x)+(\theta\theta)(\bar\theta\bar\theta)d(x)\end{aligned}$$

$*$ Component fields (16 real bosonic and 16 real fermionic, boson-fermion rule $\surd$)

4 complex scalar fields:	$f(x), M(x), N(x), d(x)$
2 left-handed Weyl spinor fields:	$\phi(x), \alpha(x)$
2 right-handed Weyl spinor fields:	$\bar\chi(x), \bar\lambda(x)$
1 complex vector fields:	$A_\mu(x)$

$*$ Superfields: linear but reducibel representation of the SUSY algebra $\Rightarrow$

g) Constraint superfields

$*$ SUSY-invariant conditions on superfield $\rightsquigarrow$ constraint superfield

$\bar D_{\dot A}\mathcal{F}=0$	$\Rightarrow$	chiral (scalar) superfield $\Phi(x,\theta,\bar\theta)$
$D_A\mathcal{F}=0$	$\Rightarrow$	antichiral (scalar) superfield $\Phi^\dagger(x,\theta,\bar\theta)$
$\mathcal{F}=\mathcal{F}^\dagger$	$\Rightarrow$	vector superfield $V(x,\theta,\bar\theta)$

Chiral Superfield

Defined by covariant condition

Chiral Superfield: $\bar{D}\Phi_- = 0$

with $\bar{D} = \frac{\partial}{\partial\bar{\theta}} + i\theta\sigma\partial$: SUSY-invariant $[\bar{D}, Q] = ... = 0$

antichiral superfield: $D\Phi_+ = 0 \quad D = \frac{\partial}{\partial\theta} + i\sigma\bar{\theta}\partial$

Solution: $\Phi_- = \Phi_-(x + i\theta\sigma\bar{\theta}; \theta, 0) \equiv \Phi_-(y;\theta)$ is general chiral superfield

$$\bar{D}\Phi_- = -i\theta\sigma\partial\Phi + i\theta\sigma\partial\Phi = 0$$

$* \ \Phi(y,\theta) = \varphi(y) + \sqrt{2}\theta\psi(y) + (\theta\theta)F(y)$

Taylor expansion $[y = x + i\theta\sigma\bar{\theta}] \rightsquigarrow$ chiral superfield in component fields

$$\begin{aligned}\Phi(x,\theta,\bar{\theta}) \quad &= \quad \varphi + \sqrt{2}\theta\psi + (\theta\theta)F + i(\theta\sigma^\mu\bar{\theta})\partial_\mu\varphi \\ &\quad -\frac{i}{\sqrt{2}}(\theta\theta)\partial_\mu(\psi\sigma^\mu\bar{\theta}) - \frac{1}{4}(\theta\theta)(\bar{\theta}\bar{\theta})\Box\varphi\end{aligned}$$

Φ :

- φ = 1 complex scalar field for the description of sleptons and squarks
- ψ = 1 left-handed Weyl spinor field for the description of leptons and quarks
- F = 1 non-propagating auxiliary field

Gauge Superfield

Defined by:

$$V = V^\dagger \text{ hermitesch}$$

$*$ gauge trafo: $V \rightarrow V + \chi + \chi^\dagger \rightarrow$ minimal field content: Wess-Zumino gauge

$$V = -\theta\sigma_\mu\bar\theta A^\mu(x) + i\theta^2\bar\theta\bar\lambda(x) - i\bar\theta^2\theta\lambda(x) + \theta^2\bar\theta^2 d(x)$$

$$\hat V : \begin{array}{lcl} A_\mu & = & \text{real vector field} \\ \lambda & = & \text{spin } \frac{1}{2} \text{ vectorino field} \\ d & = & \text{non-propagating auxiliary field} \end{array}$$

$*$ Supersymmetric field strength W_α

$$W_\alpha = -\frac{1}{4}(\bar D \bar D) D_\alpha V(x, \theta, \bar\theta)$$

$*$ Components of W_α

$$W_\alpha = i\lambda_\alpha - 2d\theta_\alpha - (\sigma^{\mu\nu}\theta)_\alpha F_{\mu\nu} - (\theta\theta)(\sigma^\mu\partial_\mu\bar\lambda)_\alpha$$

Fields $\lambda, d, F_{\mu\nu}, = \partial_\mu A_\nu - \partial_\nu A_\mu$ are gauge invariant

h) Behaviour under SUSY transformations

∗ Highest components of superfields transform as total derivative:

Chiral superfield: $\delta F = i\sqrt{2}\partial_\mu(\bar{\xi}\tilde{\sigma}^\mu\psi)$

Vector superfield: $\delta d = \frac{i}{2}\partial_\mu(\xi\sigma^\mu\bar{\lambda})$

i) Construction of SUSY Lagrangians

∗ Action must be invariant under SUSY transformations:

$$\delta S = \delta \int d^4x\,\mathcal{L} = 0$$

Satisfied if $\mathcal{L} \to \mathcal{L} +$ total derivative

∗ d ($\theta\theta\bar{\theta}\bar{\theta}$ component) and F ($\theta\theta$ component) terms transform as total derivative

∗ SUSY Lagrangian given by highest component of products of superfields

$$\mathcal{L} = \text{(superfields)}|_{\theta\theta\bar{\theta}\bar{\theta}} + \text{(chiral superfields)}|_{\theta\theta y\to x} + h.c.$$

∗ Superfield products:

Products of chiral superfields are chiral superfields

j) Lagrangian of chiral superfields consists of kinetic, mass and interaction term

$$\mathcal{L} = \mathcal{L}_{kin} + \mathcal{L}_m + \mathcal{L}_{int}$$

with (m - mass, g - coupling constant)

$$\begin{aligned}
\mathcal{L}_{kin} &= \Phi^\dagger(x,\theta,\bar\theta)\Phi(x,\theta,\bar\theta)|_{\theta\theta\bar\theta\bar\theta} \\
\mathcal{L}_m &= -\frac{m}{2}\Phi^2(y,\theta)|_{\theta\theta\, y\to x} + h.c. \\
\mathcal{L}_{int} &= -\frac{g}{3}\Phi^3(y,\theta)|_{\theta\theta\, y\to x} + h.c.
\end{aligned}$$

leads to

$$\mathcal{L}_{kin} = (\partial_\mu\varphi^*)(\partial^\mu\varphi) - \frac{i}{2}(\bar\psi\tilde\sigma^\mu\partial_\mu\psi + \psi\sigma^\mu\partial_\mu\bar\psi) + F^*F$$

- **In terms of the superpotential**

$$\mathcal{L} = \mathcal{L}_{kin} - [U(\Phi)|_{\theta\theta y\to x} + h.c.]$$

with the potential

$$U(\Phi) = \frac{m}{2}\Phi^2 + \frac{g}{3}\Phi^3$$

Potential is a super function with the Taylor expansion ($\Phi_S = \sqrt{2}\theta\psi + (\theta\theta)F$)

$$U(\Phi) = U(\varphi + \Phi_S) = U(\varphi) + \frac{dU(\varphi)}{d\varphi}\Phi_S + \frac{1}{2}\frac{d^2U(\varphi)}{d\varphi^2}\Phi_S^2$$

- **Lagrangian without auxiliary fields**

Use Euler-Lagrange equation to eliminate the auxiliary field $F \rightsquigarrow F = m\varphi^* + g\varphi^{*2} \Rightarrow$

$$\begin{aligned}\mathcal{L} \;=\; & (\partial_\mu\varphi^*)(\partial^\mu\varphi) - m^2|\varphi|^2 \\ & -\frac{i}{2}(\bar\psi\tilde\sigma^\mu\partial_\mu\psi + \psi\sigma^\mu\partial_\mu\bar\psi) + \frac{m}{2}(\psi\psi + \bar\psi\bar\psi) \\ & +g(\varphi\psi\psi + \varphi^*\bar\psi\bar\psi) - mg|\varphi|^2(\varphi + \varphi^*) - g^2|\varphi|^4\end{aligned}$$

◇ First line: free equation of motion of the bosonic field $\varphi(x)$ with mass m

◇ Middle line: free motion of fermionic field $\psi(x)$ with the same mass m

◇ The particles described by φ, ψ are the superpartners of the chiral supermultiplet:

$\psi(x)$: lepton, quark

$\varphi(x)$: slepton, squark or Higgs boson

◇ Last line: interaction terms Yukawa term: $g(\varphi\psi\psi + \varphi^*\bar\psi\bar\psi)$

Last two terms: self-interaction of the bosonic field

Strength of interaction given by g

k) Lagrangian for vector superfields

Use field strength tensor $W_\alpha \rightsquigarrow$

$$\mathcal{L} = \frac{1}{4} W^\alpha W_\alpha|_{\theta\theta\; y\to x} + h.c.$$

The Lagrangian of the vector superfield finally reads (fields $\lambda, F^{\mu\nu}, d$ are gauge invariant)

$$\mathcal{L} = -\frac{i}{2}(\lambda\sigma^\mu\partial_\mu\bar{\lambda} + \bar{\lambda}\tilde{\sigma}^\mu\partial_\mu\lambda) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + 2d^2$$

l) Supersymmetric gauge theory

With the gauge transfomation (q charge, Λ chiral superfield)

$$\Phi' = e^{-iq\Lambda(x)}\Phi$$

the gauge invariant kinetic part of the chiral Lagrangian reads ($V' = V + i[\Lambda - \Lambda^\dagger]$)

$$\bar{\mathcal{L}}_{kin} = \Phi^\dagger e^{qV}\Phi|_{\theta\theta\bar{\theta}\bar{\theta}}$$

In terms of the component fields we find

$$\begin{aligned}\bar{\mathcal{L}}_{kin} &= (D_\mu\varphi)^*(D^\mu\varphi) - \frac{i}{2}(\bar{\psi}\tilde{\sigma}^\mu D_\mu\psi + \psi\sigma^\mu D_\mu^*\bar{\psi}) \\ &\quad + |F|^2 + \frac{i}{\sqrt{2}}q[\varphi^*(\psi\lambda) - \varphi(\bar{\psi}\bar{\lambda})] + qd|\varphi|^2\end{aligned}$$

$D_\mu = \partial_\mu - \frac{i}{2} q A_\mu$

$$\bar{\mathcal{L}}_{kin} = (D_\mu \varphi)^* (D^\mu \varphi) - \frac{i}{2}(\bar{\psi}\tilde{\sigma}^\mu D_\mu \psi + \psi \sigma^\mu D^*_\mu \bar{\psi}) + |F|^2 + \frac{i}{\sqrt{2}} q[\varphi^*(\psi\lambda) - \varphi(\bar{\psi}\bar{\lambda})] + qd|\varphi|^2$$

* Contains photon - 2 sfermions interaction

$$\frac{i}{2} q A^\mu \varphi^* \partial_\mu \varphi + h.c.$$

* The 2 photons - 2 sfermions interaction

$$\frac{q^2}{4} A_\mu A^\mu |\varphi|^2$$

* The photon - 2 fermions interaction

$$q A_\mu (\psi \sigma^\mu \bar{\psi})$$

* The gaugino - fermion - sfermion interaction

$$\frac{iq}{\sqrt{2}} \varphi^* (\psi\lambda) + h.c.$$

Supersymmetry $\rightsquigarrow$ all interaction terms are described by the same coupling strength q

• **Minimal coupling in the Lagrangion of the vector superfields**

∗ Non-Abelian gauge theory

$$i\partial_\mu \to iD_\mu = i\partial_\mu - g_S G^a_\mu \frac{\lambda^a}{2} - g W^b_\mu \frac{\sigma^b}{2} - g' B_\mu \frac{Y}{2}$$

m) Complete Lagrangian

Built up by kinetic Lagrangian

$$\begin{aligned}\bar{\mathcal{L}}_{kin} &= (D_\mu\varphi)^*(D^\mu\varphi) - \frac{i}{2}(\bar{\psi}\tilde{\sigma}^\mu D_\mu\psi + \psi\sigma^\mu D^*_\mu\bar{\psi}) \\ &+|F|^2 + \frac{i}{\sqrt{2}}q[\varphi^*(\psi\lambda) - \varphi(\bar{\psi}\bar{\lambda})] + qd|\varphi|^2\end{aligned}$$

the part $\mathcal{L}_U$ coming from the superpotential

$$U(\Phi)|_{\theta\theta} + h.c. = (m\varphi + g\varphi^2)F - \frac{1}{2}(m + 2g\varphi)(\psi\psi)$$

hence

$$\begin{aligned}\mathcal{L}_U &= \frac{m}{2}(\psi\psi + \bar{\psi}\bar{\psi}) + g(\varphi\psi\psi + \varphi^*\bar{\psi}\bar{\psi}) \\ &-(m\varphi + g\varphi^2)F - (m\varphi^* + g\varphi^{*2})F^*\end{aligned}$$

and the vector superfield Lagrangian with minimal coupling

$$\mathcal{L}_V = -\frac{i}{2}(\lambda\sigma^\mu D_\mu\bar{\lambda} + \bar{\lambda}\tilde{\sigma}^\mu D_\mu\lambda) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + 2d^2$$

⋆ Exploiting the Euler Lagrange equation the parts of the Lagrangian containing the auxiliary fields F, d can be replaced by the potential V

$$V = 2d^2 + |F|^2$$

where for non-Abelian gauge theories
(t^a generators of the respetive gauge group with the coupling constants q_a)

$$\begin{aligned} |F|^2 &= \left|\frac{dU}{d\varphi}\right|^2 \\ d^2 &= \frac{1}{16}\sum_a |q_a \varphi t^a \varphi|^2 \end{aligned}$$

Note: scalar quartic coupling generated by SUSY gauge interactions
$\Rightarrow$ Higgs mass small [quartic Higgs couping $\sim g^2$]

⋆ Definition of the superpotential depending on several chiral superfields

$$W(\varphi, \varphi^*) := \sum_{i=1}^{n} |F_i|^2 = \sum_{i=1}^{n} \left|\frac{\partial U}{\partial \varphi_i}\right|^2$$

and analoguously (with the redefinition $D \equiv 2d$)

$$\begin{aligned} V_D &= \frac{1}{2}\sum_A D^A D^A \\ D^A &= -g_A \sum_i \varphi_i T^A_{ij} \varphi_i \end{aligned}$$

n) Supersymmetry Breaking General supersymmetric system:

same number of fermions and bosons in one multiplet

masses of fermions and bosons are equal

Supersymmetric ground state has vanishing energy Algebra: $\{Q_\alpha, \bar{Q}_\beta\} = 2\sigma^\mu_{\alpha\beta} P_\mu \Rightarrow$

$$H = \frac{1}{4}\sum_\alpha [Q_\alpha Q^\dagger_\alpha + Q^\dagger_\alpha Q_\alpha] \rightsquigarrow < 0|H|0 >= \frac{1}{4}\sum_\alpha \left[||Q^\dagger_\alpha|0>||^2 + ||Q_\alpha|0>||^2\right] \Rightarrow$$

$$< H > \geq 0$$

SUSY ground state $< 0|H|0 >= 0 \Leftrightarrow Q_\alpha|0>= 0, Q^\dagger_\alpha|0>= 0$ for all $Q_\alpha, Q^\dagger_\alpha$

$\langle H \rangle \neq 0$: SUSY sponanteously broken, i.e. $Q_\alpha|0\rangle \neq 0 \Rightarrow \langle H \rangle = E_{\mathsf{vac}} \neq 0$

SUSY broken: $V = \frac{1}{2}D^2 + |F|^2$: $D \neq 0$ D breaking: Fayet-Iliopoulos

$F \neq 0$ F breaking: O'Raifeartaigh

$\rightarrow$ Ferrara-Girardello-Palumbo mass sum rule

$< H >= 0$ in SUSY: $\Lambda_{cosmo} = 0$

Scheme cannot be realized by spontaneous symmetry breaking in visible eigenworld:

Ferrara-Girardello-Palumbo sum rule: $\sum(-1)^{2J}(2J+1)m^2_J = 0$ supermultiplet

Example: $m^2_{\tilde{e}_L} + m^2_{\tilde{e}_R} - 2m^2_e = 0$ not compatible with observation $\Rightarrow$

Possible solution: RHS $\neq 0$ through supergravitation sector $\sim m^2_{3/2} \rightarrow$ soft, i.e. renormalizable SUSY breaking in Standard sector (through explicit mass terms)

Breaking in hidden sector communicated by gravity/gauge/messengers to eigenworld

hidden SUSY	gravity, gauge,... $\Longrightarrow$	SUSY eigenworld

Soft SUSY breaking Define SUSY breaking operators such that no new quadratic divergences are generated

Realisation:

- spontaneous SUSY breaking in "hidden sector"
- mediated in eigen-world through gravitation etc.
- apparent explicit SUSY breaking in eigen-world
  - identity between Yukawa/gauge couplings preserved
  - SUSY masses $\neq$ SM masses

SUSY breaking Lagrangian [Grisaru,Girardello]

$$\begin{aligned}\mathcal{L}_{break} &= -\tfrac{1}{2}M_i\bar{\lambda}_i\lambda_i && \text{for gauginos}\\ &- m^2_{\tilde{f}}|\tilde{f}|^2 + \dots && \text{for sfermions,Higgs}\\ &- W_2(\phi) - W_3(\phi) && \text{superpotential}\end{aligned}$$

(III) The Minimal Supersymmetry Model

(III) $\mathcal{M}$inimal $\mathcal{S}$upersymmetry $\mathcal{M}$odel - $\mathcal{MSSM}$

The SM alone cannot be formulated as SUSY theory $(N \leq 8) \Rightarrow$

SUSY-Standard Model $= SM \otimes SUSY(N = 1)$

minimal particle content

$\longrightarrow$ Doubling of the particle spectrum: SM+SUSY partner

Minimal Supersymmetric Standard Model (MSSM)

benchmark model, compatible with experiment, for exploiting phenomenology of SUSY models

Vector multiplets

$J = 1$	$J = \frac{1}{2}$
Gluon g	Gluino $\tilde{g}$
$W^\pm, W^3$	Wino $\tilde{W}^\pm, \tilde{W}^3$
B	Bino $\tilde{B}$

Chiral multiplets

$J = \frac{1}{2}$	$J = 0$
Quarks q_L, q_R	Squarks $\tilde{q}_L, \tilde{q}_R$
Leptons l_L, l_R	Sleptons $\tilde{l}_L, \tilde{l}_R$
Higgsinos $\tilde{H}_1, \tilde{H}_2$	Higgs H_1, H_2

Interactions

Gauge field and matter Lagrangians adapted to $SU(3) \times SU(2) \times U(1)$ from previous basis

The Lagrangian

$$\mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}_{matter} + \mathcal{L}_D + \mathcal{L}_W + \mathcal{L}_{soft}$$

∗ Lagrangian for the gauge fields

$$\mathcal{L}_{gauge} = -\frac{1}{4}G^{a\mu\nu}G^a_{\mu\nu} - \frac{1}{4}W^{a\mu\nu}W^a_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} + Tr[\bar{\tilde{g}} i \not{D} \tilde{g}] + Tr[\bar{\tilde{W}} i \not{D} \tilde{W}] + \frac{1}{2}\bar{\tilde{B}} i \not{\partial} \tilde{B}$$

covariant derivative $iD_\mu = i\partial_\mu - gV_\mu$ (minimal substraction)
field strength tensor $V_{\mu\nu} = \partial_\nu V_\mu - \partial_\mu V_\nu - ig[V_\mu, V_\nu]$ and the vector potential $V_\mu = V^a_\mu T^a$
T^a group generators, $[T^a, T^b] = if_{abc}T^c$
$SU(2) : T^a = \frac{\sigma^a}{2}$ Pauli matrices, $SU(3) : T^a = \frac{\lambda^a}{2}$ Gell-Mann matrices

∗ Lagrangian for the matter fields

$$\mathcal{L}_{matter} = \sum_{\psi=f,\tilde{H}_i} \bar{\psi} i \not{D} \psi + \sum_{\tilde{f},H_i} |D_\mu \phi|^2 + i \sum_{\psi,\phi,V} \frac{g_V}{\sqrt{2}} [\overline{\psi_L} T^a \tilde{V}^a \phi - \tilde{V}^a T^a \psi_L \phi^*]$$

∗ Lagrangian of the help fields

$$\mathcal{L}_D = -\frac{1}{2}\sum_{a,V} |D^V_a|^2$$

with $D^V_a = -g_V \phi^*_i T^a_{ij} \phi_j$

$$\mathcal{L}_W = -\sum_i \left|\frac{\partial W}{\partial \phi_i}\right|^2 - \frac{1}{2}\sum_{ij}\overline{\psi^c_{iL}}\frac{\partial^2 W}{\partial\phi_i\partial\phi_j}\psi_{jL} + h.c.$$

with

$$\begin{aligned} W &= W_R + W_{\not R} \\ W_R &= -\epsilon_{ij}\mu H_1^i H_2^j + \epsilon_{ij}[\lambda_L H_1^i \tilde{L}_j \tilde{E}^c + \lambda_D H_1^i \tilde{Q}_j \tilde{D}^c + \lambda_U H_2^i \tilde{Q}_j \tilde{U}^c] \\ W_{\not R} &= \epsilon_{ij}[\lambda \tilde{L}_i \tilde{L}_j \tilde{E}^c + \lambda' \tilde{L}_i \tilde{Q}_j \tilde{D}^c] + \lambda'' \tilde{U}^c \tilde{D}^c \tilde{D}^c \end{aligned}$$

$R -$ parity violating

with $\epsilon_{12} = -\epsilon_{21} = 1, \epsilon_{11} = \epsilon_{22} = 0$

$*$ **Remark: Multiplicative quantum number R-parity**

$R -$ parity	$=$	$+1$	for SM particles	$\overset{\text{if conserved}}{\Longrightarrow}$	• SUSY particle production in pairs
	$=$	-1	for SUSY partners		• lightest SUSY particle LSP stable

$*$ **R-parity violating superpotential** $\quad \sim \epsilon_{ij}[\lambda \tilde{L}_i \tilde{L}_j \tilde{E}^c + \lambda' \tilde{L}_i \tilde{Q}_j \tilde{D}^c] + \lambda'' \tilde{U}^c \tilde{D}^c \tilde{D}^c$

potentially leading to proton decay: $\quad \lambda''\lambda' \sim \begin{matrix} ud \\ u \end{matrix} \rightarrow d^c \rightarrow \begin{matrix} u^c e^+ \\ u \end{matrix}$

$$P \rightarrow \pi^0 e^+$$

$\lambda''\lambda' \sim 0$ necessarily, <u>MSSM:</u> $\lambda = \lambda' = \lambda'' = 0$

$*$ The soft SUSY breaking Lagrangian

$$\begin{aligned}\mathcal{L}_{soft} &= -\tfrac{1}{2}\sum_{i=1}^{3} M_i\bar{\lambda}_i^a\lambda_i^a - m_1^2|H_1|^2 - m_2^2|H_2|^2 + B\mu\epsilon_{ij}(H_1^iH_2^j + h.c.)\\ &\quad -M_{\tilde{Q}}^2(\tilde{u}_L^\dagger\tilde{u}_L + \tilde{d}_L^\dagger\tilde{d}_L) - M_{\tilde{U}}^2\tilde{u}_R^\dagger\tilde{u}_R - M_{\tilde{D}}^2\tilde{d}_R^\dagger\tilde{d}_R + (\tilde{l})\\ &\quad +\frac{g}{\sqrt{2}M_W}\epsilon_{ij}\left[\frac{M_d}{\cos\beta}A_dH_1^i\tilde{Q}^j\tilde{d}_R^\dagger + (\tilde{u}) + (\tilde{l})\right]\end{aligned}$$

a) Higgs sector

(i) mass generation of SM particles via Higgs mechanism

(ii) two independent Higgs fields H_1, H_2 to provide mass to down- and up-type particles in holomorphic superpotential of SUSY theories

$$\begin{array}{llll}\underline{\mathrm{SM:}} & \mathcal{L}_d \sim \bar{Q}_L\phi d_R & \phi_0 = [0, \frac{v}{\sqrt{2}}] & \Rightarrow\ m_d\bar{d}_Ld_R + h.c.\\ & \mathcal{L}_u \sim \bar{Q}_L\phi^c u_R & \phi^c = i\tau_2\phi^*,\ \phi_0^c = [\frac{v}{\sqrt{2}}, 0] & \Rightarrow\ m_u\bar{u}_Lu_R + h.c.\end{array}$$

$\underline{\mathrm{SUSY:}}$ $\phi^c \sim \phi^*$ not allowed in holomorphic function next to ϕ

(iii) Higgs potential:

$$
\begin{aligned}
V_{Higgs} &= V_F + V_D + V_{soft} \\
V_F &= |F|^2 = \sum_{i=1,2} \left|\frac{\partial W}{\partial H_i}\right|^2 = \mu^2(|H_1|^2 + |H_2|^2) \\
V_D &= \tfrac{1}{2}D^2 = \tfrac{1}{2}\sum_{a,V} |-g_V H_i^* T^a_{ij} H_j|^2 = \tfrac{g^2+g'^2}{8}[|H_1|^2 - |H_2|^2]^2 + \tfrac{g^2}{2}|H_1^\dagger H_2|^2 \\
V_{soft} &= m_1^2|H_1|^2 + m_2^2|H_2|^2 - B\mu\epsilon_{ij}(H_1^i H_2^j + h.c.)
\end{aligned}
$$

$$
\begin{aligned}
V_{Higgs} = {} & (m_1^2 + \mu^2)|H_1|^2 + (m_2^2 + \mu^2)|H_2|^2 - B\mu\epsilon_{ij}(H_1^i H_2^j + h.c.) \\
& + \tfrac{g^2+g'^2}{8}[|H_1|^2 - |H_2|^2]^2 + \tfrac{g^2}{2}|H_1^\dagger H_2|^2
\end{aligned}
$$

with $H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} \phi_1^{0*} \\ -\phi_1^- \end{pmatrix} \qquad H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$

quartic couplings $\sim$ gauge couplings

spontaneous symmetry breaking: minV_{Higgs} for $< H_{1,2} >_0 \neq 0$:

$$
H_1 = \begin{pmatrix} \phi_1^{0*} + \frac{v_1}{\sqrt{2}} \\ -\phi_1^- \end{pmatrix} \qquad H_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 + \frac{v_2}{\sqrt{2}} \end{pmatrix}
$$

8 degrees of freedom: 3 zero-mass states: Goldstone bosons absorbed by elw gauge bosons

5 physical states:

diagonalisation:

$$
\begin{aligned}
H_1^1 &= \tfrac{1}{\sqrt{2}}(v_1 + H^0\cos\alpha - h^0\sin\alpha + iA^0\sin\beta - iG^0\cos\beta)\\
H_1^2 &= H^-\sin\beta - G^-\cos\beta\\
H_2^1 &= H^+\cos\beta + G^+\sin\beta\\
H_2^2 &= \tfrac{1}{\sqrt{2}}(v_2 + H^0\sin\alpha + h^0\cos\alpha + iA^0\cos\beta + iG^0\sin\beta)
\end{aligned}
$$

$G^\pm, G^0 \Rightarrow$ Goldstone bosons

parameters:

$$
\begin{aligned}
M_Z^2 &= \tfrac{g^2+g'^2}{4}(v_1^2+v_2^2) & M_A^2 &= B\mu\tfrac{v_1^2+v_2^2}{v_1 v_2}\\
\tan\beta &= \tfrac{v_2}{v_1} & &\\
m_1^2+\mu^2 &= M_A^2\sin^2\beta - \tfrac{M_Z^2}{2}\cos 2\beta & m_2^2+\mu^2 &= M_A^2\cos^2\beta + \tfrac{M_Z^2}{2}\cos 2\beta
\end{aligned}
$$

5 physical states:

- charged: $M_{H^\pm}^2 = M_A^2 + M_W^2$
- pseudoscalar: M_A^2 $\mathcal{CP}_o$
- scalar: $M_{h,H}^2 = \frac{1}{2}\{M_A^2 + M_Z^2 \mp \sqrt{(M_A^2+M_Z^2)^2 - 4M_A^2M_Z^2\cos^2 2\beta}\}$ $\mathcal{CP}_e$

$$\tan 2\alpha = \tan 2\beta\frac{M_A^2+M_Z^2}{M_A^2-M_Z^2} \qquad -\frac{\pi}{2} < \alpha < 0$$

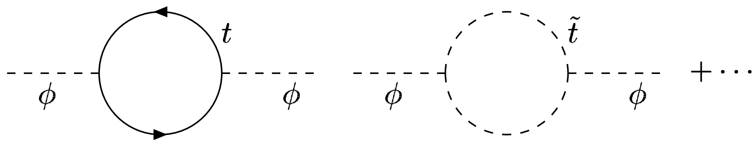
Higgs system parameterized by (at LO): M_A and $\tan\beta$

$M_A \sim M_H \sim M_{H^\pm} \gg v$ decoupling limit: $h \to$ SM-like

Inequalities:

$$M_h < M_Z, M_A$$
$$M_H > M_Z, M_A$$
$$M_{H^\pm} > M_A, M_W$$

modified through radiative corrections



$$\epsilon = \frac{3 G_F m_t^4}{\sqrt{2}\pi^2 \sin^2\beta} \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} + \text{stop mixing } [\mu, A_t] \Rightarrow$$

$$M_h \lesssim 140 \text{ GeV}$$
$$M_{H,A,H^\pm} = \mathcal{O}(v) \ldots 1 \text{ TeV}$$

b) Gluino, Charginos/Neutralinos

- Gluino mass: $M_3 \leftarrow$ soft mass term

- Chargino masses: Charginos are mixings of charged Winos $\tilde{W}^\pm$ and Higgsinos $\tilde{H}^\pm \Rightarrow$
  2 charginos $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$

$$\mathcal{L}_C = -\frac{1}{2}\psi_\pm^T \mathcal{M}_C \psi_\pm + h.c. \quad \text{with} \quad \psi_\pm = \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}_u^+ \\ \tilde{W}^- \\ \tilde{H}_d^- \end{pmatrix} \quad \text{and} \quad \mathcal{M}_C = \begin{pmatrix} 0 & X^T \\ X & 0 \end{pmatrix}$$

where

$$X = \begin{pmatrix} M_2 & \sqrt{2}M_W \sin\beta \\ \sqrt{2}M_W \cos\beta & \mu \end{pmatrix}$$

M_2 :	from $\mathcal{L}_{soft}$				
μ :	from $W(\Phi)$	$\rightarrow$	$-\frac{1}{2}\sum_{ij}\overline{\psi_{iL}^c}\frac{\partial^2 W}{\partial\phi_i\partial\phi_j}\psi_{jL}$	$\rightarrow$	higgsino term μ
non-diag:	from $\mathcal{L}_{matter}^{\lambda H\psi}$	$\rightarrow$	mixing term $\sim \tilde{W}\tilde{H}$	$\rightarrow$	$M_W\sqrt{2}\cos\beta(\sin\beta)$

diagonalisation $\rightarrow$ mass eigenstates $\tilde{\chi}_{1,2}^\pm$ with

$$m^2_{\tilde{\chi}^\pm_{1,2}} = \frac{1}{2}\{M_2^2 + \mu^2 + 2M_W^2 \mp \sqrt{(M_2^2-\mu^2)^2 + 4M_W^2(M_2^2+\mu^2+2M_2\mu\sin 2\beta + M_W^2\cos^2 2\beta)}\}$$

Limits: $\mu, M_2 \gg M_W$

$$m_{\tilde\chi^\pm_{1,2}} = M_2 - \frac{M_W^2(M_2+\mu\sin 2\beta)}{\mu^2-M_2^2}$$
$$m_{\tilde\chi^\pm_{2,1}} = |\mu| + \frac{M_W^2(|\mu|+\epsilon M_2\sin 2\beta)}{\mu^2-M_2^2} \qquad \epsilon = \text{sign}(\mu)$$

- $|\mu| \gg M_2$: $\tilde\chi^\pm_1$ gaugino-like, $\tilde\chi^\pm_2$ Higgsino-like
- $|\mu| \ll M_2$: $\tilde\chi^\pm_1$ Higgsino-like, $\tilde\chi^\pm_2$ gaugino-like
- $\mu \sim -M_2, \tan\beta \sim 1$: $m_{\tilde\chi^\pm_{1,2}} \sim \sqrt{M_2^2 + M_W^2}$ degenerate

- Neutralino masses: Neutralinos are mixings of $\tilde B$, $\tilde W^3$, $\tilde H_u^0$, $\tilde H_d^0$ $\Rightarrow$ 4 neutralinos $\tilde\chi^0_{1,2,3,4}$

$$\mathcal{L}_0 = -\frac{1}{2}\psi_0^T \mathcal{M}_0 \psi_0 + h.c. \quad \text{with} \quad \psi_0 = \begin{pmatrix} \tilde B \\ \tilde W^3 \\ \tilde H_d^0 \\ \tilde H_u^0 \end{pmatrix}$$

where

$$\mathcal{M}_0 = \begin{pmatrix} M_1 & 0 & -M_Z\sin\theta_W\cos\beta & M_Z\sin\theta_W\sin\beta \\ 0 & M_2 & M_Z\cos\theta_W\cos\beta & -M_Z\cos\theta_W\sin\beta \\ -M_Z\sin\theta_W\cos\beta & M_Z\cos\theta_W\cos\beta & 0 & -\mu \\ M_Z\sin\theta_W\sin\beta & -M_Z\cos\theta_W\sin\beta & -\mu & 0 \end{pmatrix}$$

Diagonalisation $\rightarrow$ mass eigenstates $\tilde\chi^0_{1,2,3,4}$

Limits: $\mu, M_1, M_2 \gg M_Z$

$$
\begin{aligned}
m_{\tilde\chi_1^0} &= M_1 - \frac{M_Z^2 s_W^2 (M_1+\mu s_\beta)}{\mu^2 - M_1^2} \\
m_{\tilde\chi_2^0} &= M_2 - \frac{M_Z^2 c_W^2 (M_1+\mu s_\beta)}{\mu^2 - M_2^2} \\
m_{\tilde\chi_3^0} &= |\mu| + \frac{M_Z^2 (1-\epsilon s_{2\beta})(|\mu|+M_1 c_W^2 + M_2 s_W^2)}{2(|\mu|+M_1)(|\mu|+M_2)} \\
m_{\tilde\chi_4^0} &= |\mu| + \frac{M_Z^2 (1+\epsilon s_{2\beta})(|\mu|-M_1 c_W^2 - M_2 s_W^2)}{2(|\mu|-M_1)(|\mu|-M_2)}
\end{aligned}
$$

$$\Rightarrow \tilde\chi_1^0 \sim \tilde B^0, \tilde\chi_2^0 \sim \tilde W^3, \tilde\chi_{3,4}^0 \sim \frac{\tilde H_d^0 \pm \tilde H_u^0}{\sqrt{2}}, m_{\tilde\chi_2^0} \sim m_{\tilde\chi_1^\pm}$$

- $|\mu| \gg M_1, M_2$: LSP gaugino-like
- $|\mu| \ll M_1, M_2$: LSP Higgsino-like; $m_{\tilde\chi_1^0} \sim m_{\tilde\chi_2^0} \sim m_{\tilde\chi_1^\pm}$

c) Slepton/Squark masses

L and R states for fermions and sfermions independent degrees of freedom

LR mass matrix:

$$\mathcal{L}_{\tilde f} = -\tilde f^\dagger \mathcal{M}_{\tilde f}^2 \tilde f \qquad \text{with } \tilde f = \begin{pmatrix} \tilde f_L \\ \tilde f_R \end{pmatrix} \qquad \text{and}$$

$$\mathcal{M}^2_{\tilde{f}} = \begin{pmatrix} M^2_{\tilde{f}_L} + m^2_f + \overbrace{M^2_Z(I_{3L} - e_f \sin^2\theta_W)\cos 2\beta}^{D-term} & m_f(A_f - \mu r_f) \\ m_f(A_f - \mu r_f) & M^2_{\tilde{f}_R} + m^2_f - M^2_Z(I_{3R} - e_f \sin^2\theta_W)\cos 2\beta \end{pmatrix}$$

$$r_f = \begin{cases} \cot\beta & \text{for} \quad f = \text{up-type} \\ \tan\beta & \text{for} \quad f = \text{down-type} \end{cases}$$

$M^2_{\tilde{f}_{L/R}}$: from $\mathcal{L}_{soft}$

m^2_f : from $\mathcal{L}_W \sim \left|\frac{\partial W}{\partial \phi}\right|^2$

$D - term$: from $\mathcal{L}_D$

mixing $m_f \mu r_f$: from $\mathcal{L}_W \sim \left|\frac{\partial W}{\partial \phi}\right|^2$

Mixing large only for 3rd generation: $L, R \to 1, 2$

$$m^2_{\tilde{f}_{1,2}} = m^2_f + \frac{1}{2}\left\{M^2_{\tilde{f}_L} + M^2_{\tilde{f}_R} \mp \sqrt{(M^2_{\tilde{f}_L} - M^2_{\tilde{f}_R})^2 + 4m^2_f(A_f - \mu r_f)^2}\right\} \qquad \text{(without } D - term\text{)}$$

Diagonalisation:

$$\begin{pmatrix} \tilde{f}_1 \\ \tilde{f}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_f & \sin\theta_f \\ -\sin\theta_f & \cos\theta_f \end{pmatrix} \begin{pmatrix} \tilde{f}_L \\ \tilde{f}_R \end{pmatrix}$$

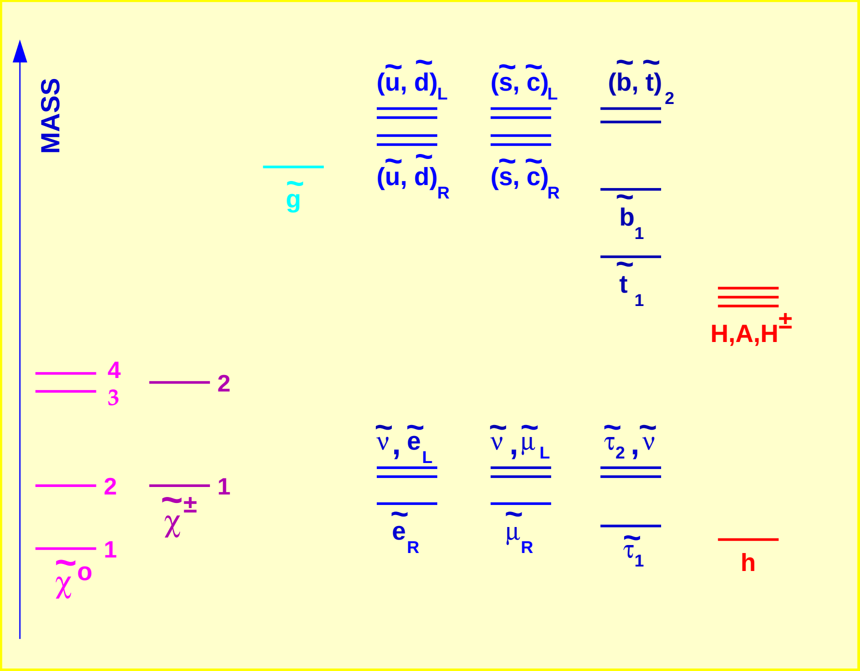
$$\sin 2\theta_f = \frac{2m_f(A_f - \mu r_f)}{m^2_{\tilde{f}_1} - m^2_{\tilde{f}_2}}$$

$$\cos 2\theta_f = \frac{M^2_{\tilde{f}_L} - M^2_{\tilde{f}_R}}{m^2_{\tilde{f}_1} - m^2_{\tilde{f}_2}}$$

- Splitting is largest for the heaviest fermions $\Rightarrow$ $\tilde{t}_1$ can be the lightest squark
  $\tilde{\tau}_1$ can be the lightest slepton
- large $\tan\beta$: splitting $\tilde{b}_1 \leftrightarrow \tilde{b}_2$ large $\Rightarrow$ there are regions where $\tilde{b}_1$ is the lightest squark

Example of SUSY Spectrum

Schematic Sparticle Spectrum in MSSM



(IV) SUSY-GUT

(IV) SUSY-GUT

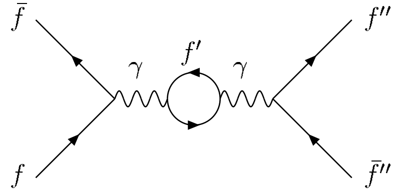
SUSY physically motivated by GUT: stability of the radiative corrections to W, Z, H masses.
Aim: resonstruction of the fundamental SUSY theory at the GUT/PLANCK scale.

MSSM: 124 free parameters $\rightsquigarrow$ constrained by unification at the GUT scale

(a) Unification of the gauge couplings

SM: $SU_3 \times SU_2 \times U_1 \overset{GUT}{\longrightarrow} SU_5 \quad g_3 \;\; g_2 \;\; g_1 \to g_5 : \sin^2\theta_W = \frac{3}{8}$ at GUT

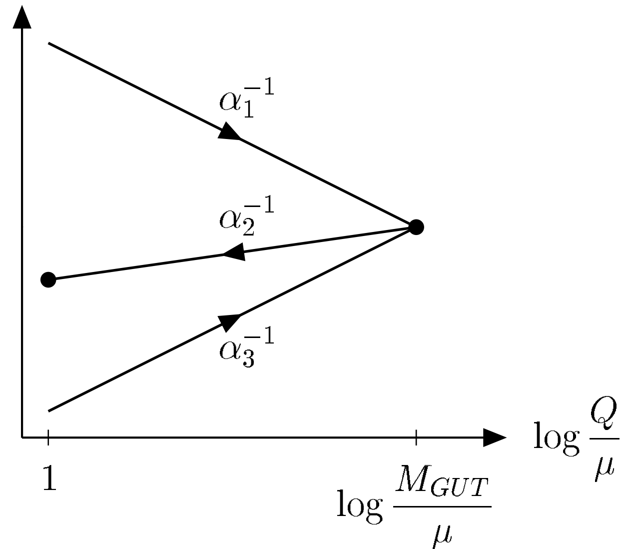
Running couplings:



$$\frac{\partial \alpha_i}{\partial \log \mu^2} = -\frac{b_i}{4\pi}\alpha_i^2 + \mathcal{O}(\alpha_i^3)$$

$$\text{SM:} \quad b_i = \left|\begin{array}{c} 0 \\ \frac{22}{3} \\ 11 \end{array}\right| - N_G \left|\begin{array}{c} \frac{4}{3} \\ \frac{4}{3} \\ \frac{4}{3} \end{array}\right| - N_H \left|\begin{array}{c} \frac{1}{10} \\ \frac{1}{6} \\ 0 \end{array}\right|$$

$$\text{SUSY:} \quad b_i = \left|\begin{array}{c} 0 \\ 6 \\ 9 \end{array}\right| - N_G \left|\begin{array}{c} 2 \\ 2 \\ 2 \end{array}\right| - N_H \left|\begin{array}{c} \frac{3}{10} \\ \frac{1}{2} \\ 0 \end{array}\right|$$



$\underline{\sin^2\theta_W(M_Z^2)}$:

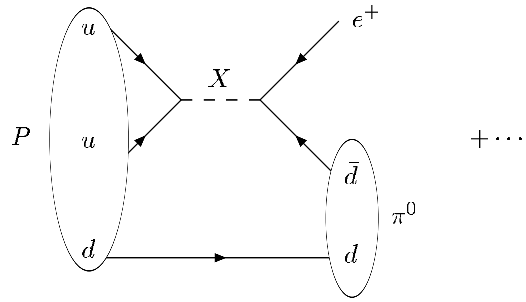
	SM:	0.2100 ± 0.0026
	MSSM:	0.2335 ± 0.0017
	exp:	0.2316 ± 0.0002

- SM couplings cannot be unified. SUSY couplings can
- SUSY predictions of $\sin^2\theta_W$ within 2 permille. Independent of details of the $\tilde{M} \sim 1$ TeV spectrum, only sensitive to particle spectrum.

(b) Proton decay:

SM-SU(5): gauge interactions between leptons and quarks:

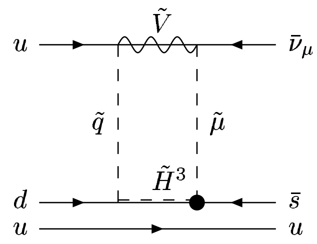
$$\tau(P \to \pi^0 + e^+) \sim \frac{M_X^4}{\alpha_5^2 M_P^5}$$



SM: $M_X \sim 10^{15}$ GeV: $\sim 10^{30}$ a   SUSY: $M_X > 10^{16}$ GeV: $\gtrsim 10^{35}$ a (exp: $> 10^{33}$ a)

However: additional dim 5 contribution

$$\tau(P \to K^+\bar{\nu}_\mu) \sim \left(\frac{16\pi^2}{\lambda^2 g^2}\right)^2 \frac{m_{\tilde{H}^3}^2 \tilde{m}^2}{M_P^5}$$ near experimental limit



(c) Radiative symmetry breaking:

universal sGUT masses (mSUGRA): Gauginos: $M_1, M_2, M_3 = M_{1/2}$

Scalars: $M_H^2 - \mu^2 = m_{\tilde{l}}^2 = m_{\tilde{q}}^2 = M_0^2$

RGE: GUT $\rightarrow$ ELW

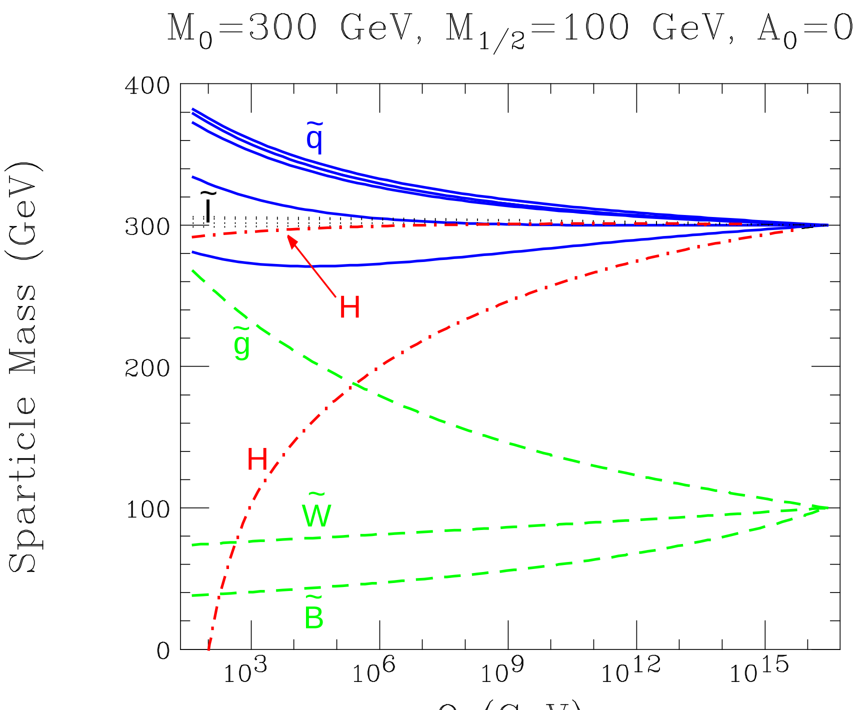
$$\frac{\partial}{\partial \log Q} \begin{pmatrix} M_{H_2}^2 \\ m_{\tilde{t}_R}^2 \\ m_{\tilde{t}_L}^2 \end{pmatrix} = \frac{g_t^2}{8\pi^2} \begin{pmatrix} 3 & 3 & 3 \\ 2 & 2 & 2 \\ 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} M_{H_2}^2 \\ m_{\tilde{t}_R}^2 \\ m_{\tilde{t}_L}^2 \end{pmatrix} + \frac{g_t^2 A_t^2}{8\pi^2} \begin{pmatrix} 3 \\ 2 \\ 1 \end{pmatrix}$$

Evolution: $M_{H_2}^2(Q^2) \approx M_0^2 + \mu^2 - \frac{3g_t^2}{8\pi^2}(3M_0^2 + \mu^2) \log \frac{M_{GUT}}{Q}$ Bagger

$M_{H_2}^2(M_Z^2) < 0$ possible for $m_t \sim 100 - 200$ GeV

$\rightarrow$ radiative symmetry breaking

$SU_3 \times SU_2 \times U_1 \rightarrow SU_3 \times U_1^{em}$



(V) SUSY Breaking

(V) SUSY Breaking Mechanisms

Ferrara sum rule: no spontaneous symmetry breaking in eigenworld: $\sum(-1)^{2J}(2J+1)M_J^2 \neq 0$.

Mechanisms:		
	Supergravitation	mSUGRA
	Gauge-mediated SUSY breaking	GMSB
	Anomaly-mediated SUSY breaking	AMSB
	Scherk-Schwarz SUSY breaking	SSSB ...

Minimal SUPERGRAVITATION:

Hidden sector
SUSY: $\langle\bar{\lambda}\lambda\rangle \neq 0$ $\rightsquigarrow$ *GRAV.* $\rightsquigarrow$ Eigenworld $\Rightarrow$ $M_{SUSY\,break} \sim 10^{11}$ GeV

Soft parameters "universal": 5 parameters: $M_0, M_{1/2}, A_0, \tan\beta, \mathrm{sgn}\mu$

Evolution: GUT $\rightarrow$ ELW:

$$\frac{\partial M_i}{\partial \log \mu^2} = -\frac{b_i}{4\pi}\alpha_i M_i$$

$$\frac{\partial \alpha_i}{\partial \log \mu^2} = -\frac{b_i}{4\pi}\alpha_i^2$$

$$\Rightarrow \frac{M_i}{\alpha_i} = \text{const}$$

Gaugino masses run like gauge couplings $\Rightarrow$

$$M_1 = M_2 \frac{5}{3} \cdot \tan^2\theta_W \sim \frac{1}{2} M_2 \qquad (M_i(M_{GUT}) = M_{1/2})$$

$$\frac{M_3}{M_2} = \frac{\alpha_3}{\alpha_2} \gg 1 \Rightarrow \qquad m_{\tilde{g}} \gg m_{\tilde{\chi}}$$

Reconstruction of the fundamental theory at GUT/Planck scale:

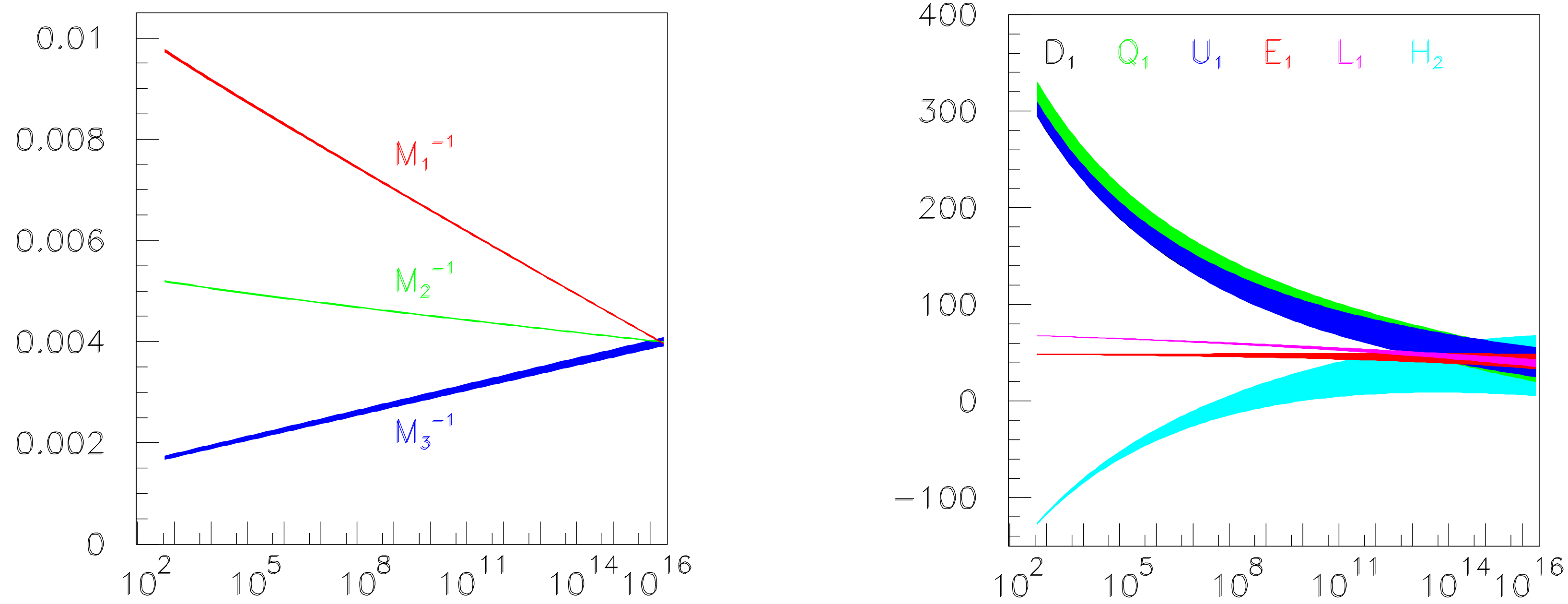
high-precision measurements of low-energy Lagrangian parameters (LHC+ILC)

⇒ extrapolate to high scale: - symmetries/universal behaviour?
- impact of high-scale physics?

Evolution: RG equations

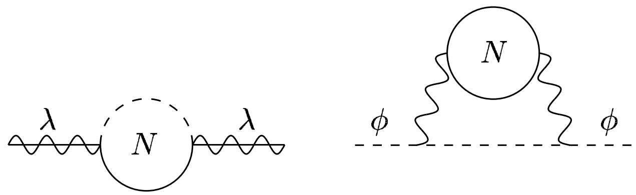
Evolution: gaugino and scalar mass parameters

Blair,Porod,Zerwas

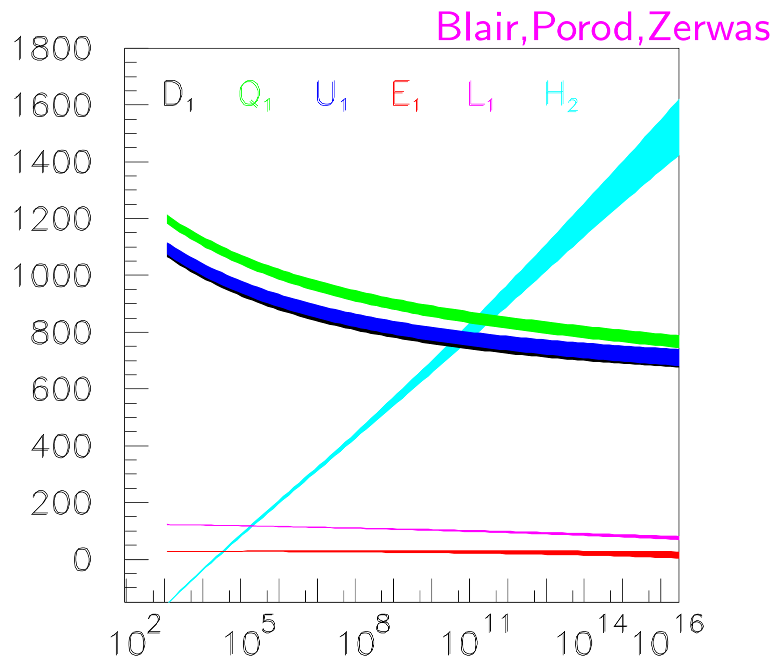


Gauge-mediated SUSY breaking (GMSB):

- flavor-blind SUSY-breaking mediating interactions are ordinary EW and QCD gauge interactions
- MSSM soft terms come from loop diagrams involving messenger particles
- messengers are new chiral supermultiplets coupling to a SUSY breaking VEV (F) and also have $SU(3)_C \times SU(2)_L \times U(1)_Y$ interactions providing the necessary connection to the MSSM



- gaugino masses evolve like in mSUGRA but without unification
- scalar masses significantly different, determined by F, the messenger mass M_{mess} and the number N of messenger fields
- 5 parameters: $F, M_{mess}, N, \tan\beta, \text{sgn}\mu$
- $m_{\tilde{e}_L} = M_{H_u}$ at $\mu = \sqrt{F}$ → exp. reconstr. of $\sqrt{F} = M_{SUSY\,break}$
- lower limit to M_{mess}, SUSY masses $\Rightarrow \sqrt{F} \gtrsim 10^5$ GeV
- Gravitino is LSP, $m_{\tilde{G}} \sim \frac{<F>}{M_{Planck}} \ll M_{weak}$
- NLSP: (i) N small → neutralino
  (ii) N large → slepton



(VI) SUSY Particle Production

Scattering processes at hadron colliders

- Connect incoming quarks, gluons with colliding protons
  outgoing particles with observed hadronic jets

- Scattering processes at high-energy hadron colliders: $\rightarrow$ hard $\longleftarrow$ QCD
  $\rightarrow$ soft

- Hard processes (e.g. Higgs boson or high-p_T jet production): perturbation theory

- Soft processes (e.g. total cross section, underlying event etc.)
  non-perturbative QCD effects

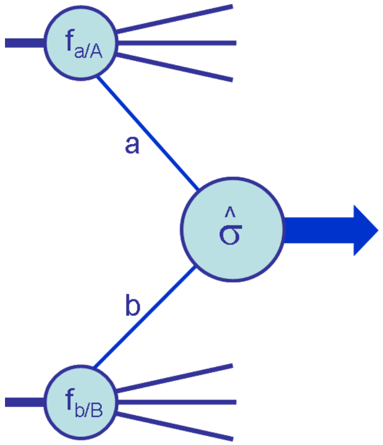
Factorisation theorem of the QCD

Partonic cross sections have collinear divergences in the hadronic initial state, which factorise universally (i.e. independent of the process) from the hard scattering process and can be absorbed in the renormalized parton densities of the initial state. These renormalized parton densities are solutions of the Altarelli-Parisi equations.

Master Formula

- **Master Formula $pp \longrightarrow X$: QCD factorization**

$$\sigma_{AB} = \sum_{ab} \int dx_1 dx_2\, f_{a/A}(x_1, \mu_F^2)\;\; f_{b/B}(x_2, \mu_F^2)\;\; \hat{\sigma}_{ab \to X}$$



$A = B = p$ und $a = b = q/g$

- **Partonic cross section $\hat{\sigma}$:**

▷ Partons of the incoming hadrons interact at short distance
Example Drell-Yan process: $\hat{\sigma}(q\bar{q} \to l^+ l^-)$

- **Parton distribution functions (pdf)** $f_{a/A}(x_1, \mu_F^2),\; f_{b/B}(x_2, \mu_F^2)$

▷ $x_1 = 2E_a/\sqrt{S}, x_2 = 2E_b/\sqrt{S}$ momentum fraction carried by the incoming quarks,gluons

▷ μ_F^2 factorization scale (separates short- and long-distance physics)

pdf's extracted from deep-inelastic scattering

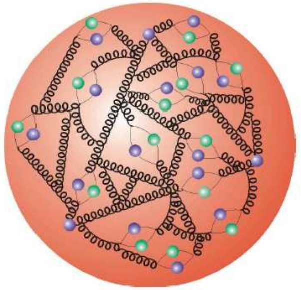
Scattering processes at hadron colliders

- **General process $\sigma(pp \to X)$**

$$\sigma_{pp\to X} = \sum_{a,b,k} f_{a/p}(\mu_F^2) \otimes f_{b/p}(\mu_F^2) \otimes \hat{\sigma}_{ab\to k}(\alpha_s(\mu_R^2), \mu_R^2) \otimes D_{k\to X}(\mu_F^2)$$

- **Partonic cross section $\hat{\sigma}_{ab\to k}$**
  calculable with perturbation theory in powers of α_s
  $\hat{\sigma}_{ab\to k} = [\hat{\sigma}_0 + \alpha_s(\mu_R^2)\hat{\sigma}_1 + \alpha_s^2(\mu_R^2)\hat{\sigma}_2 + ...]_{ab\to k}$

- **Parton luminosity $f_{a/p}(\mu_F^2) \otimes f_{b/p}(\mu_F^2)$**
  proton: very complicated multi-particle bound state



- **Final state X:** hadrons, mesons, jets, ...
  - ▷ fragmentation function $D_{k\to X}(\mu_F^2)$ or jet algorithm
  - ▷ interface with showering-algorithms (Monte Carlo)

$\mathcal{SUSY}$ $\mathcal{P}$article $\mathcal{P}$roduction

R-Parity: multiplicative quantum numbers (prevents proton decay)

$$R = (-1)^{3B+L+2S} = \begin{cases} +1 & \text{SM particle} \\ -1 & \text{SUSY partner} \end{cases}$$

$$\begin{aligned} R-\text{parity} &= +1 \quad \text{for SM particles} \\ &= -1 \quad \text{for SUSY partners} \end{aligned} \quad \Rightarrow$$

- SUSY particle production in pairs
- lightest SUSY particle LSP stable

Assume R-parity conservation in the following

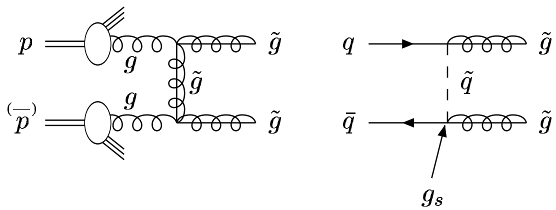
Hadron Collider

Large production cross sections for moderate squark/gluino masses through strong interactions in $pp/p\bar{p}$ collisions

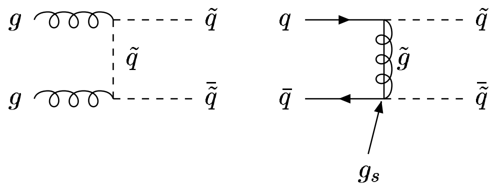
Through cascade decays + 3 classes of SUSY pair production processes:

(i) Strongly interacting particle pairs

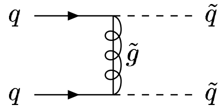
$$p\overset{(-)}{p} \longrightarrow \tilde{g}\tilde{g}$$



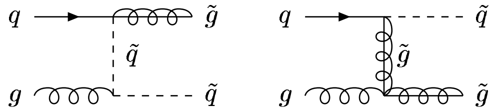
$$p\overset{(-)}{p} \longrightarrow \tilde{q}\bar{\tilde{q}}$$



$$p\overset{(-)}{p} \longrightarrow \tilde{q}\tilde{q}$$



$$p\overset{(-)}{p} \longrightarrow \tilde{q}\tilde{g}$$



$\mathcal{SUSY}$ $\mathcal{P}$article $\mathcal{P}$roduction

$$\sigma_{gg} = \int_{\tau_0}^1 dx_1 \int_{\tau_0/x_1}^1 dx_2\, g(x_1,\mu_F^2) g(x_2,\mu_F^2)\, \hat{\sigma}_{gg}(\hat{s} = x_1 x_2 s)$$

with $\tau_0 = 4m^2/s$ $[m = (m_1+m_2)/2]$ and

$$\hat{\sigma}_{gg}(\hat{s} = x_1 x_2 s) = \alpha_s^2(\mu_R) f_0(\hat{s} = x_1 x_2 s)$$

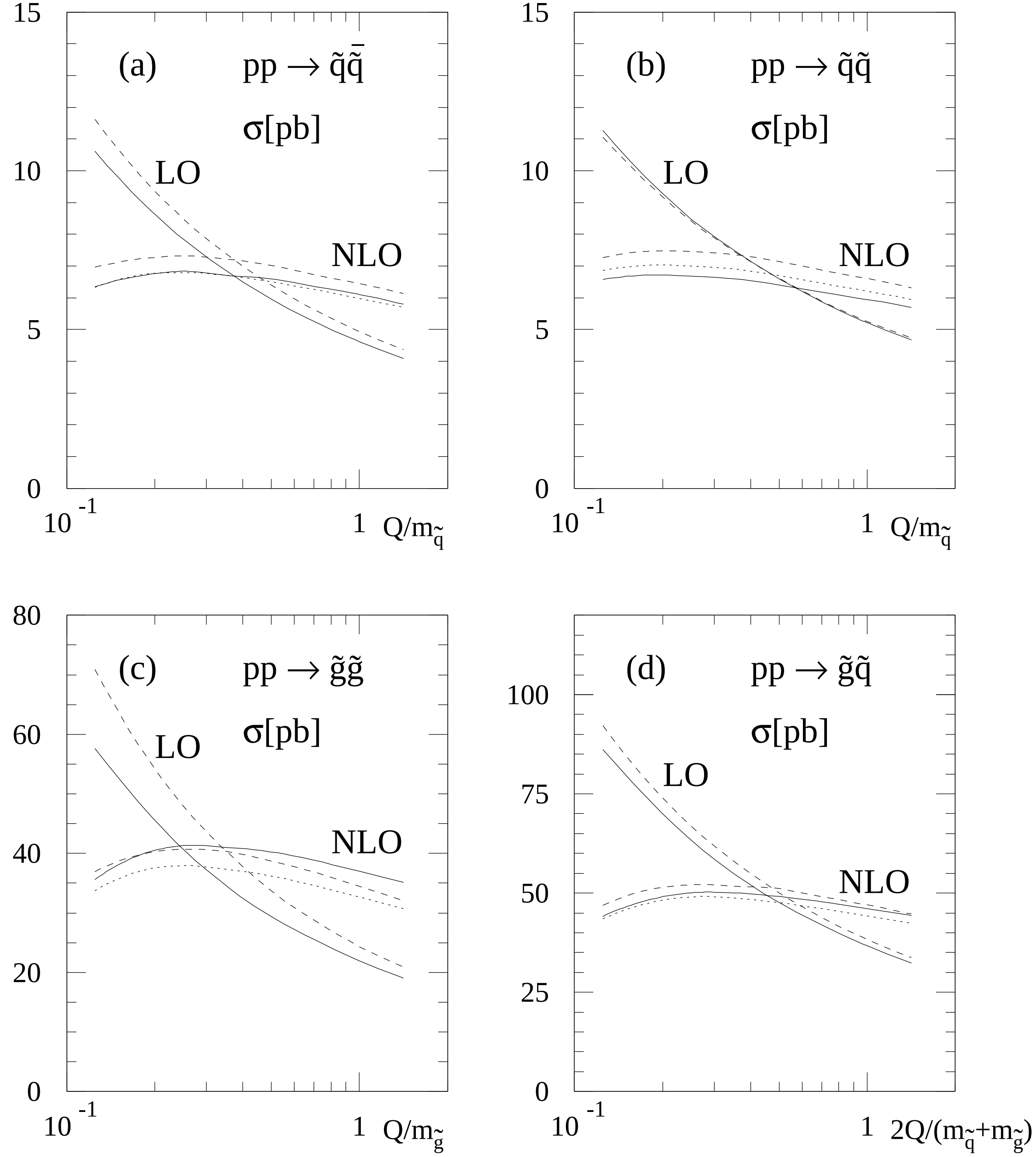
- leading order: large theoretical uncertainties (due to undefined renormalization scale μ_R, factorisation scale μ_F)
- natural scale: $\mu_R = \mu_F = m$; scale variation $\rightarrow$ estimate of theoretical uncertainties with respect to scale choice (large logarithms in higher order):

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1+\frac{33-2N_F}{12}\frac{\alpha_s(\mu^2)}{\pi}\log\frac{Q^2}{\mu^2}} = \alpha_s(\mu^2)\left[1 - \frac{33-2N_F}{12}\frac{\alpha_s}{\pi}\log\frac{Q^2}{\mu^2} + \mathcal{O}(\alpha_s^2)\right]$$

[parton densities in analogy]

$$\frac{1}{2}m < \mu_R = \mu_F < 2m : \delta\sigma \sim \pm 50\ \%$$

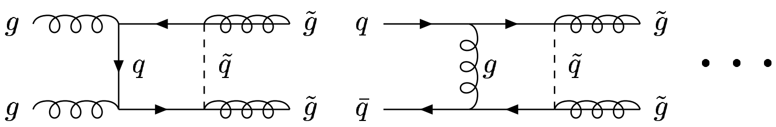
LHC



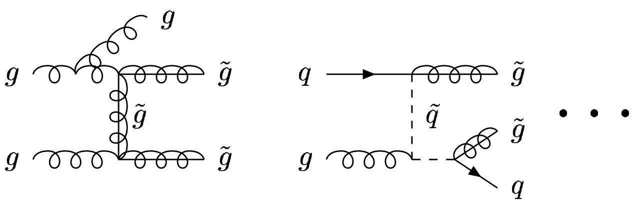
Beenakker, Höpker, Spira, Zerwas

Effect reduced through SUSY QCD corrections:

- virtual 1-loop contributions



- real contributions through gluon radiation/crossing



$$\hat{\sigma}_{gg} = \alpha_s^2(\mu_R) \left\{ f_0 + f_0 \frac{33-3N_F}{6} \frac{\alpha_s}{\pi} \log \frac{\mu_R^2}{m^2} + \frac{\alpha_s}{\pi} f_1 \right\}$$
$$= \alpha_s^2(m^2) \left\{ f_0 + \frac{\alpha_s}{\pi} f_1 + \mathcal{O}(\alpha_s^2) \right\}$$

[parton densities in analogy]

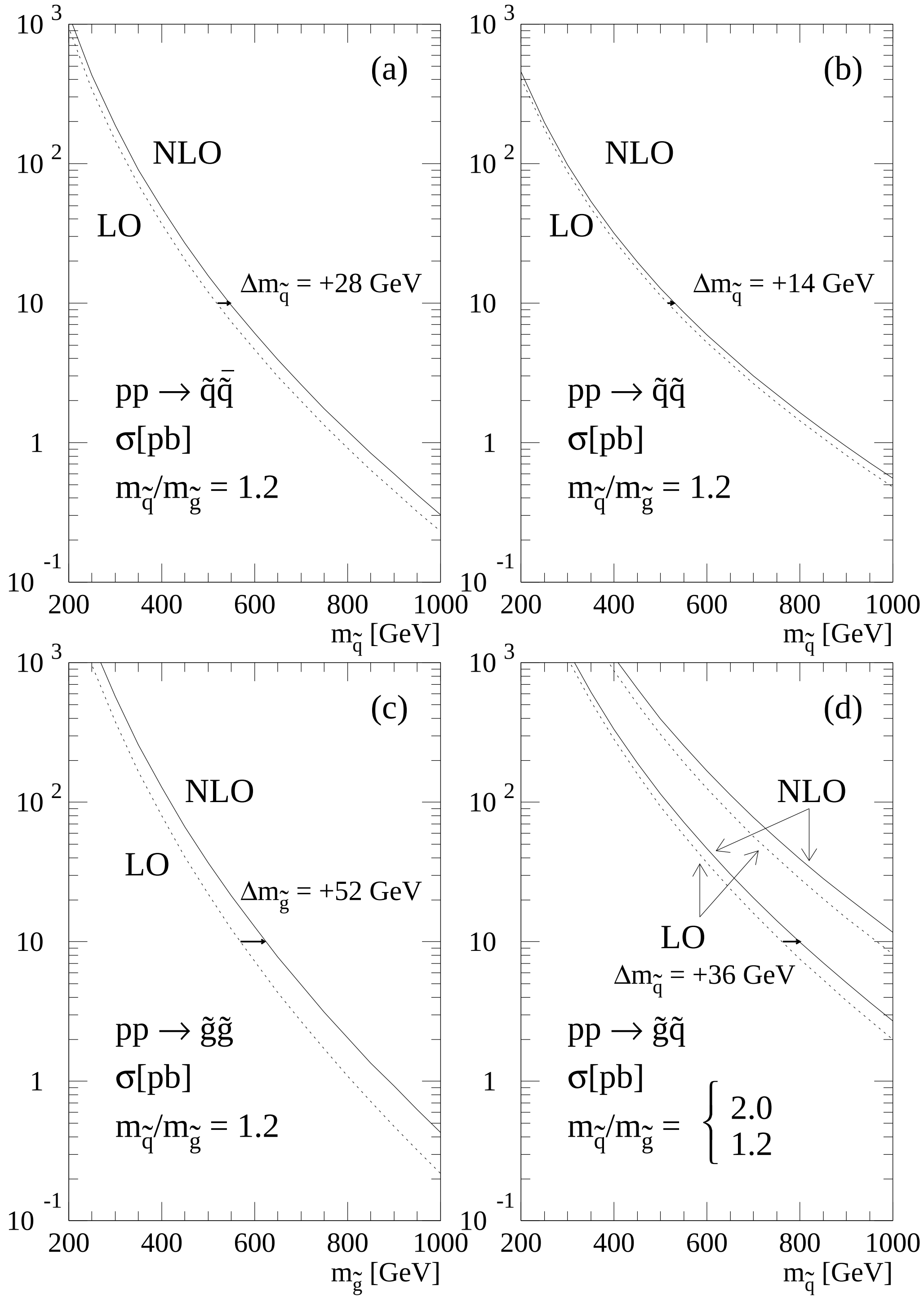
$$\frac{1}{2}m < \mu_R = \mu_F < 2m : \delta\sigma \sim \pm 10\ \%$$

$\Rightarrow$ NLO corrections provide reliable predictions of cross sections at hadron colliders

central scale: $K = \frac{\sigma_{NLO}}{\sigma_{LO}} \sim 1.1 - 2.0$

LHC

Beenakker,Höpker,Spira,Zerwas



Implications for exp. searches:

(i) Renorm./factor. scale dep. reduced by $\sim 2.5-4 \rightsquigarrow$ stable theor. predictions for σ

(ii) NLO corrs. large & positive $\rightsquigarrow$ to be included in analyses ($\rightarrow$ masses)

(iii) p_T and y distributions hardly affected by NLO

(iv) NLO $\rightsquigarrow$ raise of TeV lower $\tilde{q}$, $\tilde{g}$ mass bounds by +10–30 GeV

$\mathcal{S}$ignatures

Classical signatures (R-parity conserving SUSY, i.e. pair production/LSP stable):

- gluino > squark: $$\tilde{g} \rightarrow q\tilde{\chi}_1^0 = q + E_T^{miss}$$ $$\tilde{g} \rightarrow q\tilde{q} \rightarrow qq\tilde{\chi}_1^0 = qq + E_T^{miss}$$
- squark > gluino: $$\tilde{g} \rightarrow q\tilde{q}_{virt} \rightarrow qq\tilde{\chi}_1^0 = qqE_T^{miss}$$ $$\tilde{q} \rightarrow q\tilde{g} \rightarrow qqq\tilde{\chi}_1^0 = qqq + E_T^{miss}$$

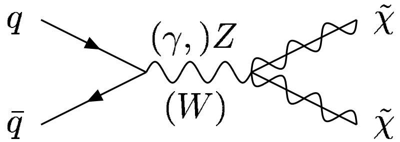
$$pp \rightarrow n\ jets + E_T^{miss}$$

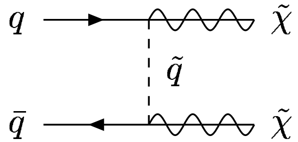
Discovery range:

Tevatron	$\lesssim$	500 GeV
LHC	$\lesssim$	$2.5...3$ TeV

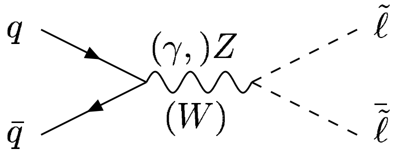
(ii) Weakly interacting particle pairs

$p\overset{(-)}{p} \rightarrow \tilde{\chi}\tilde{\chi}$





$p\overset{(-)}{p} \rightarrow \tilde{l}\bar{\tilde{l}}$



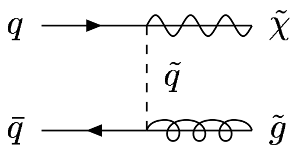
Signatures

$$\tilde{l} \quad \rightarrow \quad l\tilde{\chi}_1^0 \; : \qquad pp \rightarrow l^+l^- + E_T^{miss}$$

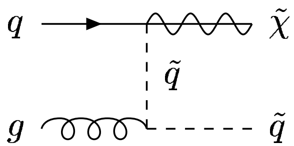
$$\tilde{\chi}_2^0 \quad \rightarrow \quad l^+l^-\tilde{\chi}_1^0 \quad \text{etc.} \; : \quad pp \rightarrow l^+l^+l^-l^- + E_T^{miss} \quad \text{etc.}$$

(iii) Associated production

$p\overset{(-)}{p} \rightarrow \tilde{g}\tilde{\chi}$



$p\overset{(-)}{p} \rightarrow \tilde{q}\tilde{\chi}$

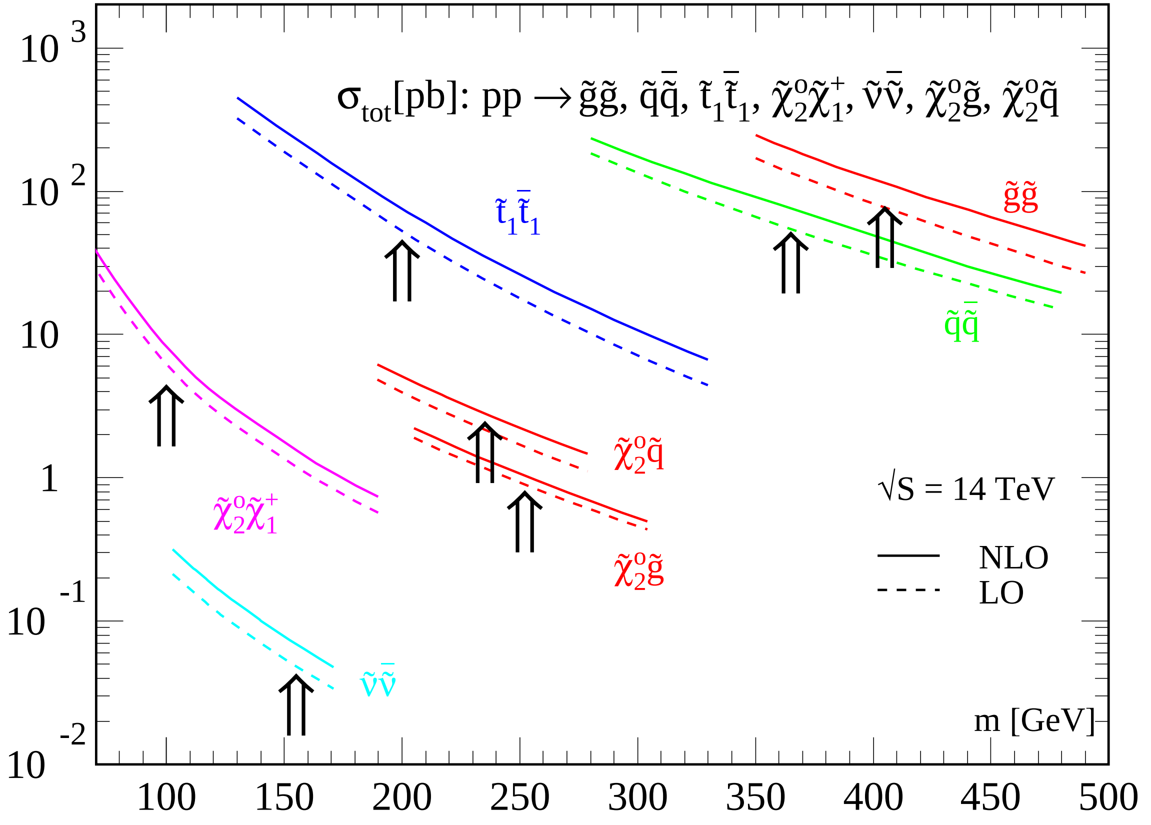


SUSY Particle Production at the LHC

NLO SUSY-QCD corrections for SUSY particle production at hadron colliders

Public code PROSPINO

Beenakker,Höpker,Krämer,Plehn,Spira,Zerwas



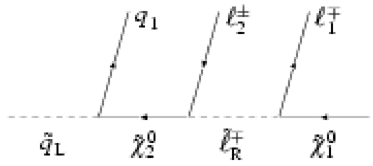
Cascade decays

gluino/squark decays = rich source for non-colored (supersymmetric) particles

Mass determination: kinematic endpoint technique

Contruct lepton/quark upper/lower endpoints and relate them to the masses in the decay chain

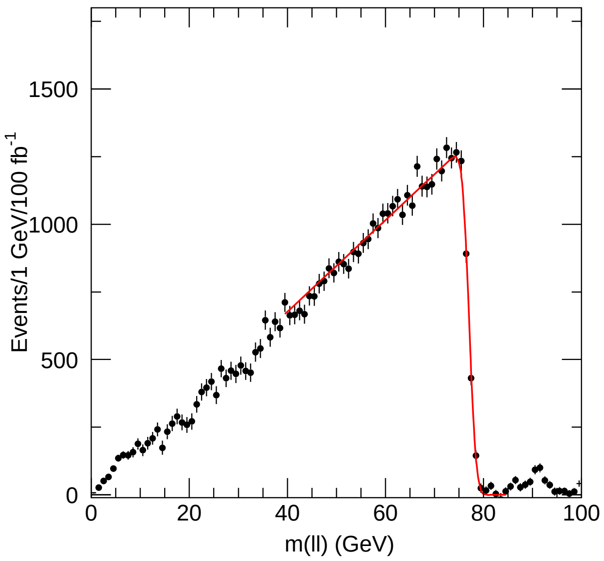
E.g.: $\tilde{q} \to \tilde{\chi}_2^0 q \to \tilde{l}^{\pm} l^{\mp} q \to \tilde{\chi}_1^0 l^+ l^- q = j + l^+ + l^- + E_T^{miss}$

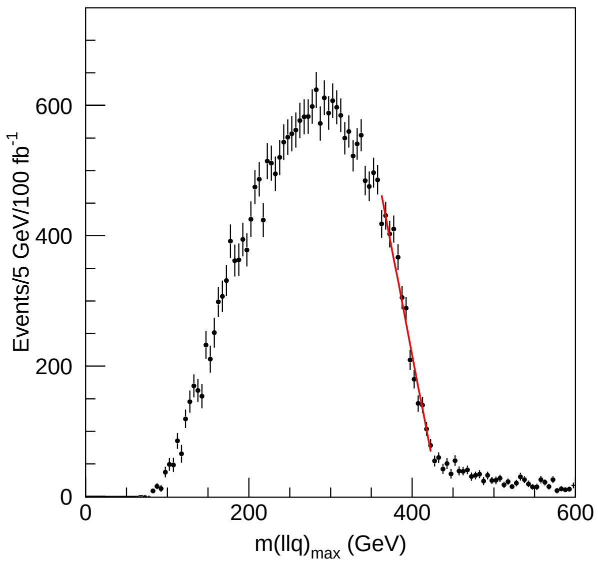


- 4 unknown masses: $M_{\tilde{q}}, M_{\tilde{\chi}_2^0}, M_{\tilde{l}}, M_{\tilde{\chi}_1^0}$
- 4 endpoints: $M(ll)^{max}, M(l_1 q)^{max}, M(l_2 q)^{max}, M(llq)^{max}$

$\Rightarrow$ all masses can be determined

$$\max M^2(ll) = M^2_{\tilde{\chi}_2^0}\left[1 - \frac{M^2_{\tilde{l}}}{M^2_{\tilde{\chi}_2^0}}\right]\left[1 - \frac{M^2_{\tilde{\chi}_1^0}}{M^2_{\tilde{l}}}\right] \qquad \max M^2(llq) = M^2_{\tilde{q}}\left[1 - \frac{M^2_{\tilde{\chi}_2^0}}{M^2_{\tilde{q}}}\right]\left[1 - \frac{M^2_{\tilde{\chi}_1^0}}{M^2_{\tilde{\chi}_2^0}}\right]$$





Spin:

particle chain in SUSY equivalent to UED

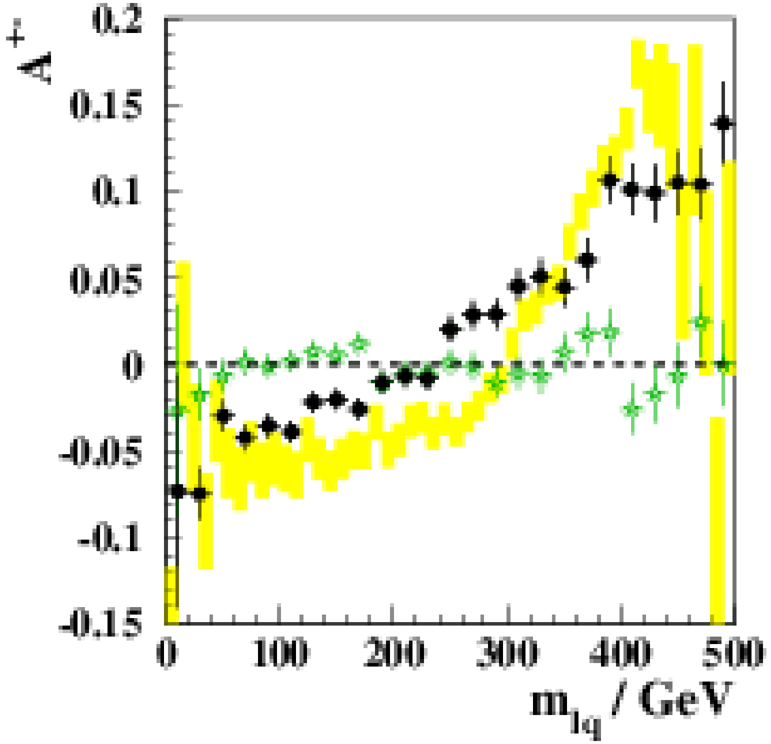
SUSY: $\tilde{q}_L \to q + \tilde{\chi}_2^0 \to q + (\tilde{l}l) \to q + ll + \tilde{\chi}_1^0$

UED: $q_1 \to q + Z_1 \to q + (l_1 l) \to q + ll + \gamma_1$

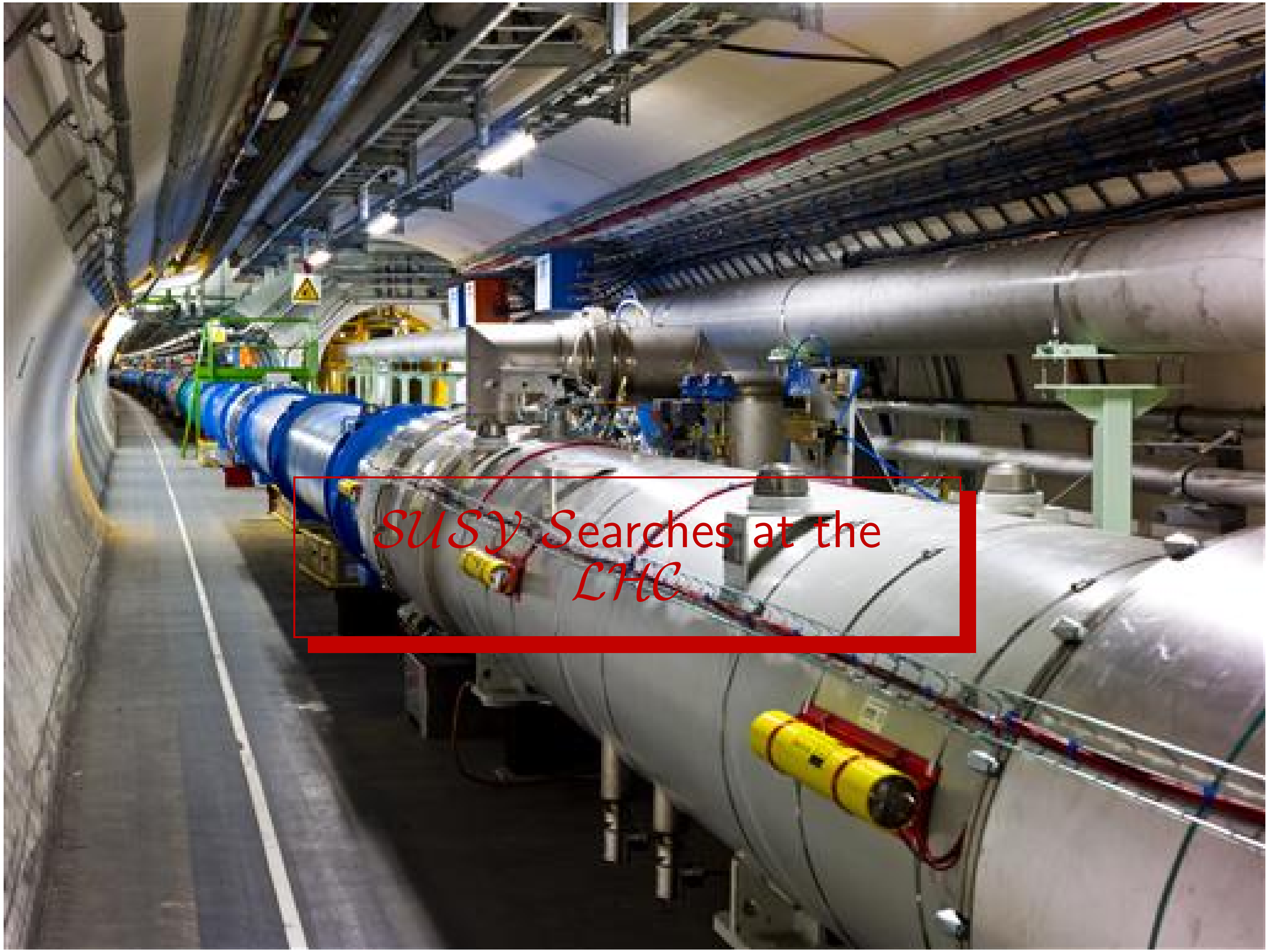
distinction by spin: $\sim$ angular distributions / invariant masses

charge asymmetry in $[ql^+]$ vs $[ql^-]$:

difficult analysis $\to$ A.J.Barr, hep-ph/0405052.



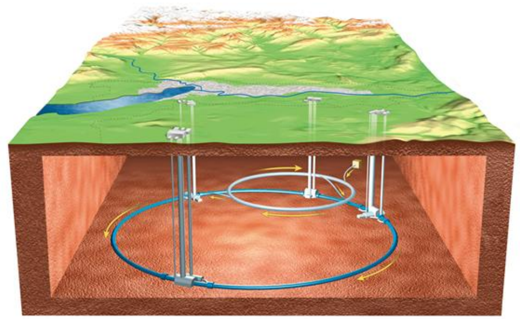
(VII) LHC Search for SUSY Particles



$\mathcal{SUSY}$ $\mathcal{S}$earches at the $\mathcal{LHC}$

Large Hadron Collider LHC

Circular collider for hadrons at CERN, LHC is a discovery machine

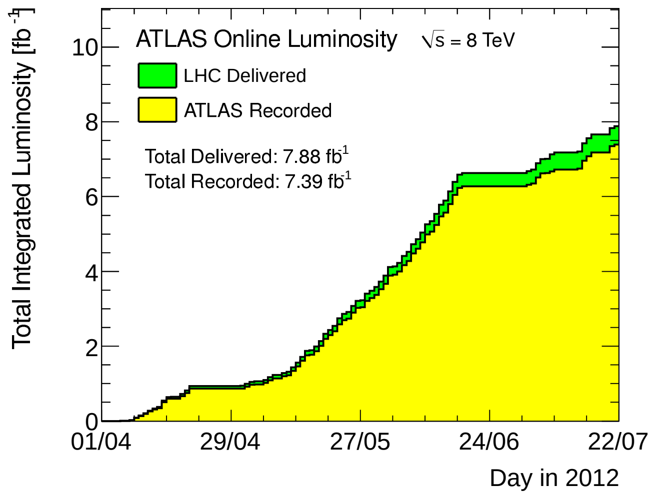


Most important parameters

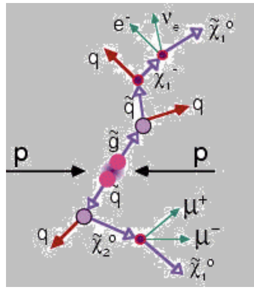
Circumference	26,659 km
Colliding particles	Protons and heavy ions
Design $\sqrt{s}$	14 TeV/Protons
4 biggest experiments	
* ALICE	gen. purpose detector: heavy ion collisions
* ATLAS	general purpose detector: pp collisions
* CMS	general purpose detector: pp collisions
* LHCb	pp collisions: B-physics

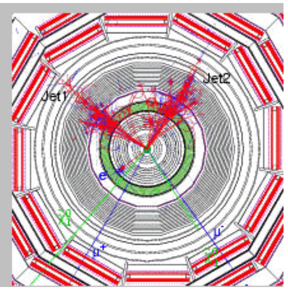
Outstanding performance 2011/12: $\sqrt{s} = 7$TeV, $\int \mathcal{L} = 5.6$ fb^{-1}

Run 2012: $\sqrt{s} = 8$ TeV, by end of 2012: $\int \mathcal{L} = 15$ fb^{-1}



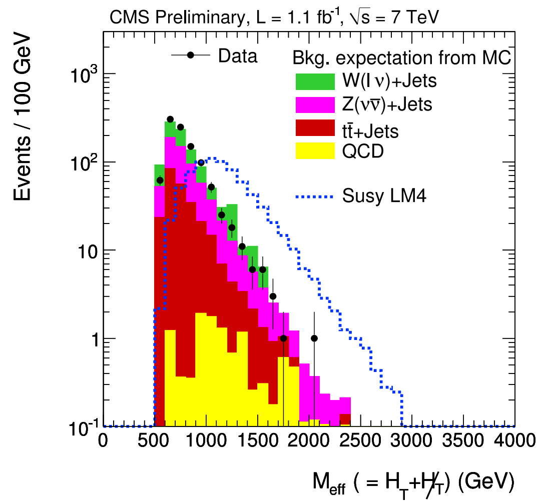
$\mathcal{SUSY}$ $\mathcal{S}$earch at the $\mathcal{LHC}$





- **SUSY particle production:** assume R-parity conservation $\rightsquigarrow$
  - ◇ SUSY particles are pair-produced
  - ◇ dominantly coloured particles $\tilde{q}, \tilde{g}$ due to strong interactions
  - ◇ sparticles cascade decay into stable LSP ($\tilde{\chi}_1^0$ or $\tilde{G}$): escapes detection
- **Signatures**
  - ▷ events with E_T^{miss} and multiple high-p_T jets (and leptons)
  - ▷ final states distinguished through additional particles (0,1,2... leptons, 2 γ's,..,b-jets)
- **Signal & background**
  - ∗ LSP escapes detection $\rightsquigarrow$ no mass peak, smooth excess at large energies $\Rightarrow$
  - ∗ background control is crucial:
    - SM background extracted from control region
    - irreducible background from Monte Carlo simulations

CMS PAS-SUS-11-004



$\mathcal{I}$nterpretation of the $\mathcal{R}$esults

- **If no excess in signal regions** $\rightsquigarrow$ derive exclusion limits

- experiment: limits on number of signal events, limits on visible cross section

- **Interpretation**
  - ∗ Plethora of models, large number of parameters $\Rightarrow$
  - ∗ Impossible to test all models and the full parameter space
  - ∗ Interpretation in the framework of specific models
    - reduce number of parameters, predict mass spectrum
    - models e.g. mSUGRA, CMSSM
  - ∗ Benchmark scenarios: capture different and characteristic features of a specific model
  - ∗ Compute model-independent cross section limits, translate these to model-dependent results. $\rightsquigarrow$
  - ∗ Simplified models
    - reduce particle content and number of couplings
    - reproduce a given topological signature
    - test different mass combinations, give limit on σ_{prod}

$\mathcal{E}$xclusion $\mathcal{L}$imits in $\mathcal{M}$issing p_T and $\mathcal{J}$ets

Simplified Model

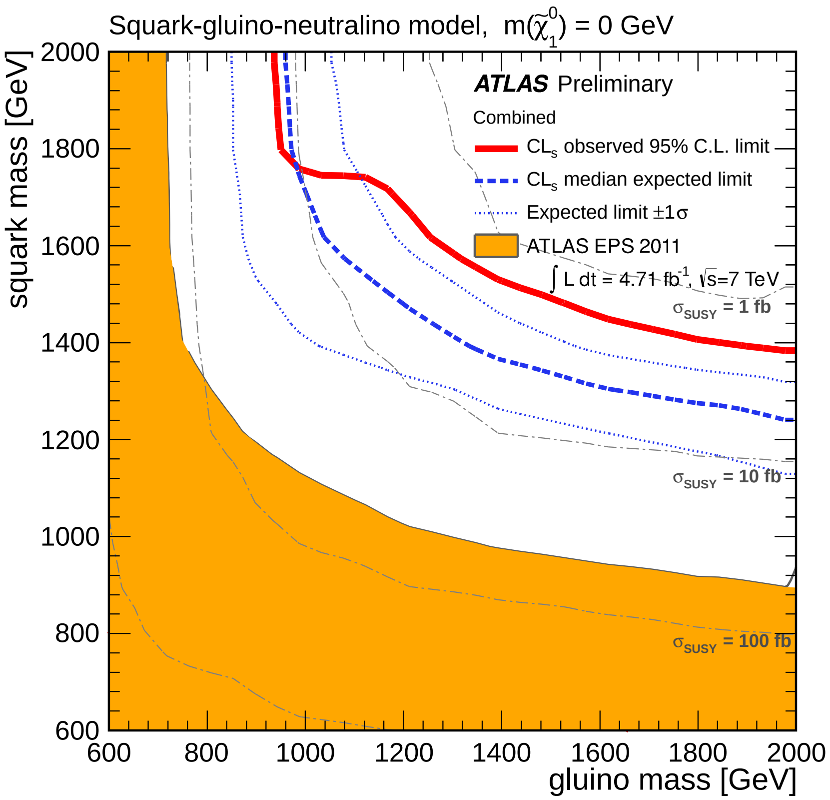
- limits on $\tilde{g}$ and $\tilde{q}$ of 1st and 2nd generation
- massless $m_{\tilde{\chi}_1^0}$
- all other SUSY particles assumed to be very heavy

mSUGRA/CMSSM

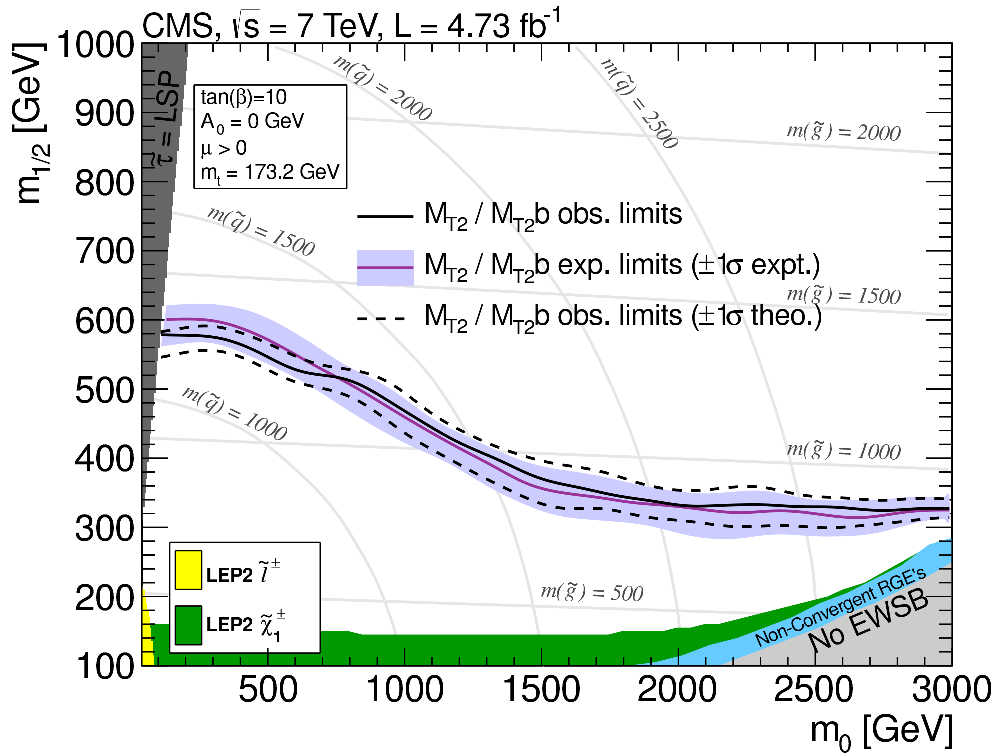
assume mSUGRA SUSY breaking mechanism

few parameters: $M_0, M_{1/2}, A_0, \tan\beta$, sgn$\mu$

ATLAS-CONF-2012-033



CMS PAS-SUS-12-002



$\mathcal{B}$eyond $\mathcal{S}$quark/$\mathcal{G}$luino $\mathcal{S}$earches

- **First searches: squark-gluino mediated SUSY production**
  - ▷ large σ_{prod}
  - ▷ rich final state phenomenology

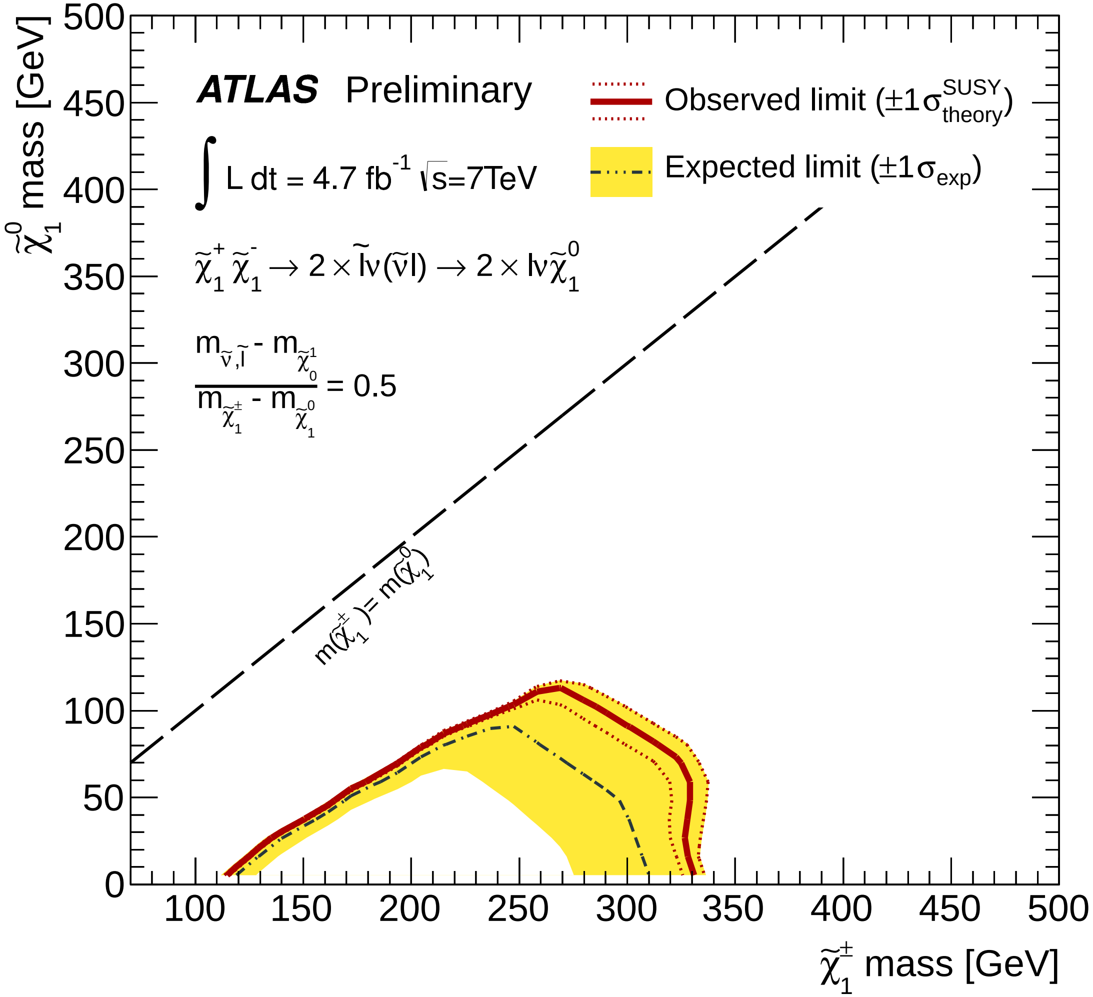
- **More $\int \mathcal{L} \rightsquigarrow$ sensitivity to more exclusive production modes**
  - ▷ electroweak chargino/neutralino production
  - ▷ direct sbottom and stop production

$\mathcal{E}$lectroweak $\mathcal{M}$ultilepton $\mathcal{P}$roduction

Slepton or chargino pair production

Example chargino pair production: $pp \to \tilde{\chi}^{\mp}\tilde{\chi}^{\pm} \to 2 \times \tilde{l}\nu(\tilde{\nu}l) \to 2 \times l\nu\tilde{\chi}_1^0$

ATLAS CONF-2012-076



$\mathcal{S}$quarks of $\mathcal{T}$hird $\mathcal{G}$eneration - $\mathcal{S}$bottom

- **Squarks of third generation are special:**
  - ▷ should be light for SUSY naturalness
  - ▷ mixing can make stops, sbottoms, staus much lighter than squarks of 1st, 2nd generation
    $\longrightarrow$ dedicated experimental searches for third generation squarks

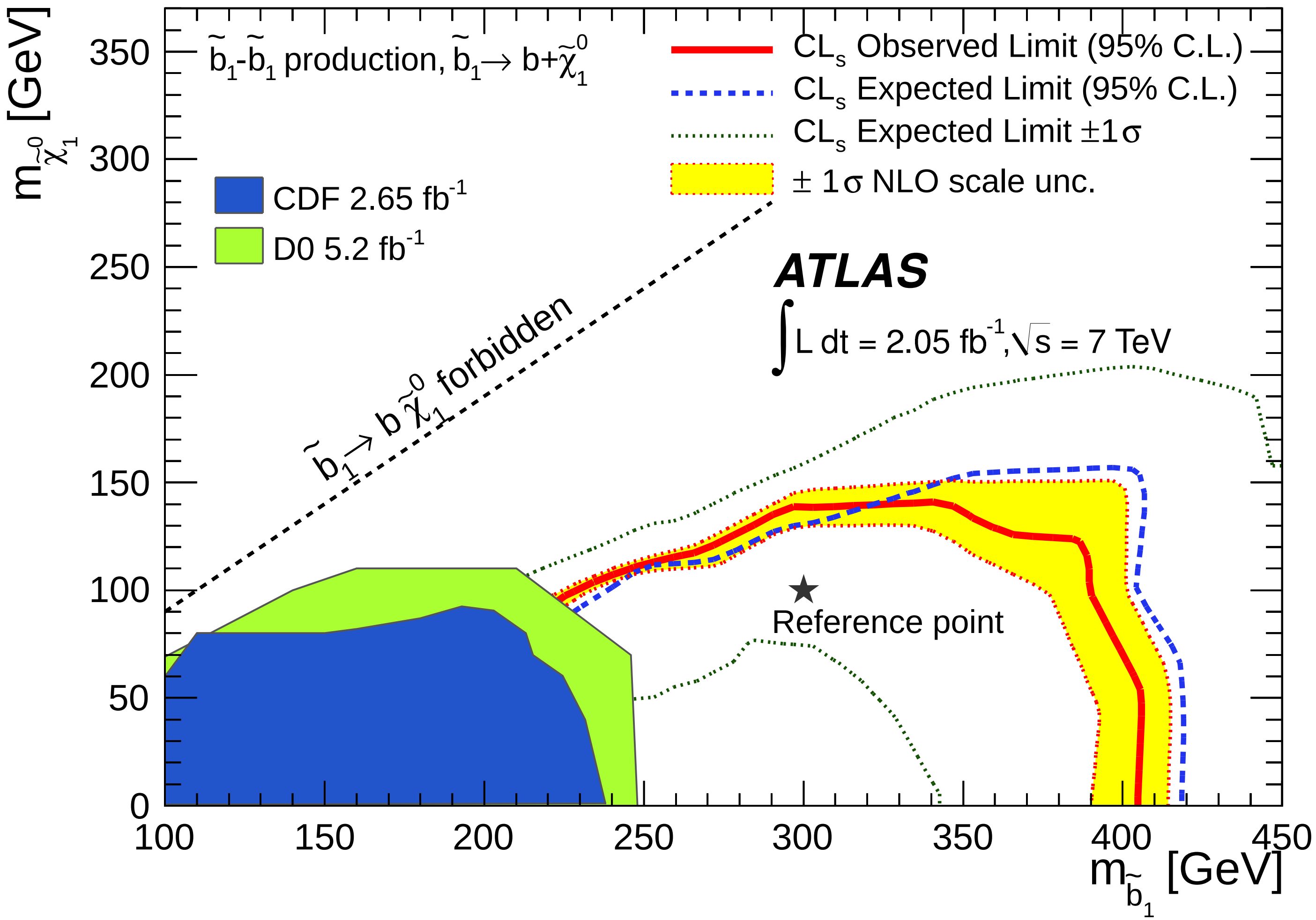
- **Example: sbottom production**
  - from gluino decays: $pp \to \tilde{g}\tilde{g} \to (b\tilde{b}_1)(b\tilde{b}_1) \to (bb\tilde{\chi}_1^0)(bb\tilde{\chi}_1^0)$
  - direct production: $pp \to \tilde{b}_1^*\tilde{b}_1 \to (\tilde{\chi}_1^0 b)(\tilde{\chi}_1^0 \bar{b})$

- **Simplified 'gluino-sbottom' model (0-lepton)** $\longrightarrow$ T
  - $\tilde{b}_1$ lightest squark, all other squarks heavier than $\tilde{g}$
  - $m_{\tilde{g}} > m_{\tilde{b}_1} > m_{\tilde{\chi}_1^0} \rightsquigarrow BR(\tilde{g} \to \tilde{b}_1 b) = 1$
  - sbottom production via $\tilde{g}\tilde{g}$ and $\tilde{b}_1\tilde{b}_1$ and $BR(\tilde{b}_1 \to b\tilde{\chi}_1^0) = 1$

$\mathcal{S}$quarks of $\mathcal{T}$hird $\mathcal{G}$eneration - $\mathcal{S}$bottom

Simplified 'gluino-sbottom model'

ATLAS arXiv:1112.3832



$\mathcal{S}$quarks of $\mathcal{T}$hird $\mathcal{G}$eneration - $\mathcal{S}$top

- **Exclusion limits on Squarks of 3rd generation are much weaker**

- **Light Stop $\tilde{t}_1$**
  - $\ast$ arises naturally from renormalization-group running
  - $\ast$ large top Yukawa coupling $\rightsquigarrow$ large mass splitting $\rightsquigarrow$ light $\tilde{t}_1$
  - $\ast$ provides natural solution to finetuning problem
  - $\ast$ light stop favoured by Baryogenesis — Carena eal; de Carlos, Espinosa; Huet, Nelson; Delepine eal; Losada; Cirigliano eal

- **Production** in $\tilde{g}$ decays or direct $\tilde{t}\tilde{t}$ production

$\mathcal{S}$top $\mathcal{P}$roduction at the $\mathcal{LHC}$

- **Example: Stop production**

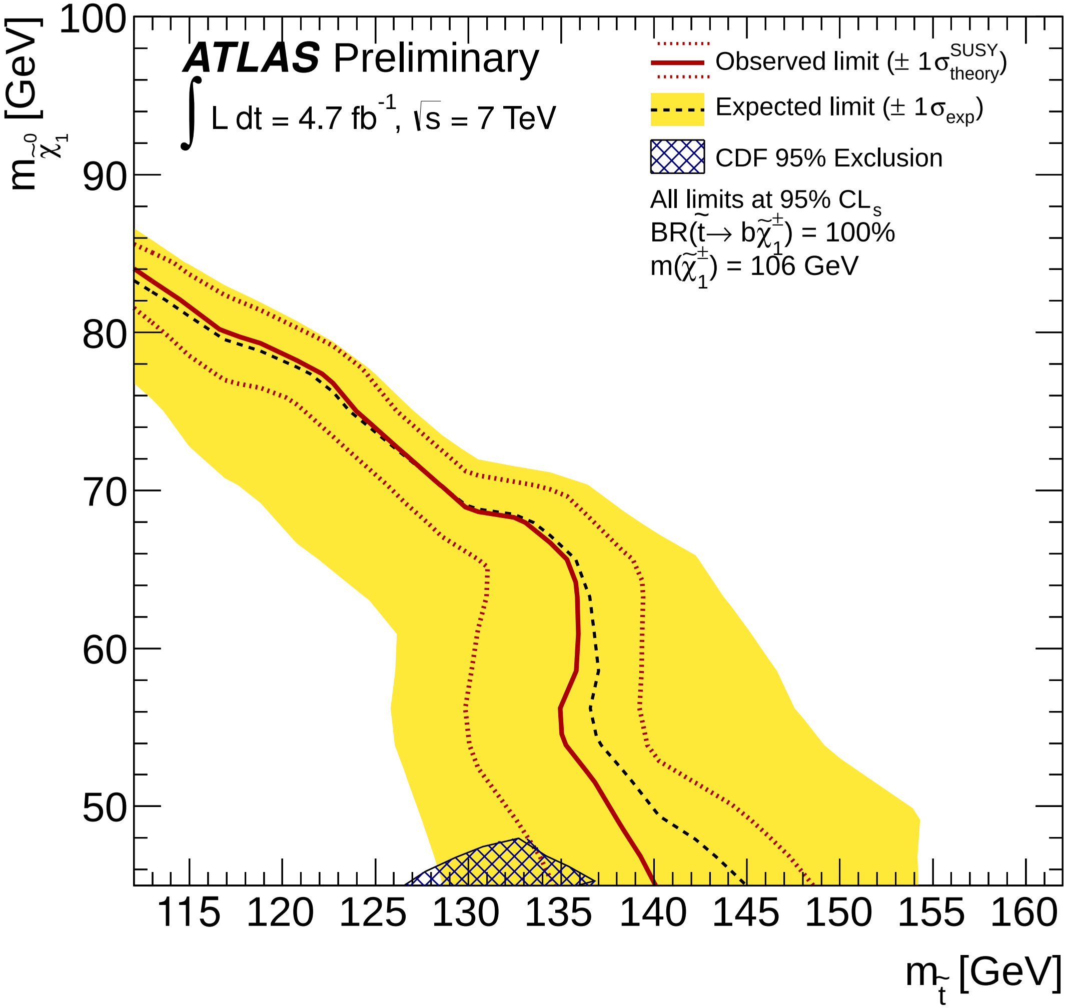
- **Model assumptions (dilepton final state)** $\longrightarrow$ T

  - $\tilde{t}_1$ lightest squark, all other squarks heavier than 2 TeV
  - direct stop pair production via $\tilde{t}_1\tilde{t}_1$ and $BR(\tilde{t}_1 \to b\tilde{\chi}_1^\pm) = 1$
  - $m_{\tilde{\chi}_1^0} > 45$ GeV and $m_{\tilde{\chi}_1^\pm} = 106$ GeV
  - $BR(\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 l^\pm \nu) = 0.11$

- **Production in this model:**

  - direct production:
    $pp \to \tilde{t}_1\tilde{t}_1 \to (\tilde{\chi}_1^- \bar{b})(\tilde{\chi}_1^+ b) \to (W^{-(*)}\tilde{\chi}_1^0\bar{b})(W^{+(*)}\tilde{\chi}_1^0 b) \to (l^-\nu\tilde{\chi}_1^0\bar{b})(l^+\nu\tilde{\chi}_1^0 b)$

ATLAS CONF-2012-059



Exclusion of $m_{\tilde{t}_1} \lesssim 130$ GeV for $m_{\tilde{\chi}^0_1} \lesssim 65$ GeV

$\mathcal{N}$o $\mathcal{S}$ign of $\mathcal{SUSY}$

Altarelli: *'The situation is depressing but not desperate.'*

Experimentalists: *'SUSY is simply not just around the corner.'*

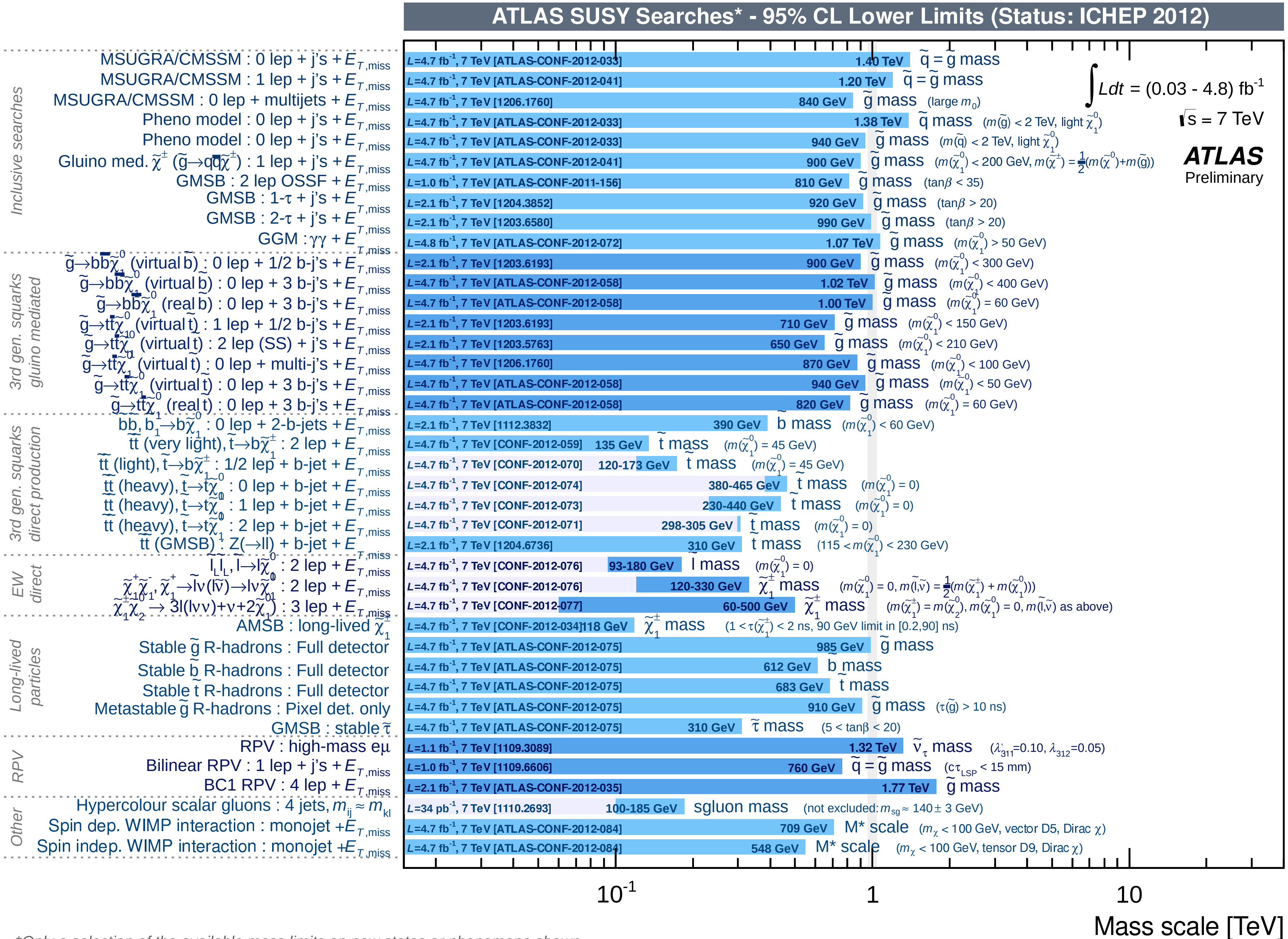
Think of e.g.

- Compressed SUSY: supressed $\tilde{g}, \tilde{q}$ masses *i.e.* $m_{\tilde{\chi}_1^0} \approx m_{\tilde{g}} \approx m_{\tilde{q}} \rightsquigarrow \tilde{q}, \tilde{g}$ difficult to detect $\rightsquigarrow$ limits on $\tilde{q}, \tilde{g}$ much weaker S.P.Martin'07
- Split SUSY: only light particles are $\tilde{g}, \tilde{\chi}_i^0, \tilde{\chi}_j^\pm$ and $\tilde{q}, \tilde{l}$ are very heavy; $\tilde{\chi}_i^0, \tilde{\chi}_j^\pm$ difficult to access at the LHC, $\tilde{g}$ is long-lived Wells;Arkani-Hamed,Dimopoulos;Giudice,Romanino
- Long-lived SUSY ($\rightarrow$ R-parity violation): slowly moving particles, decays outside the detectors
- Invisible SUSY: only $\tilde{\chi}_1^0$ accessible at LHC $\rightsquigarrow$ monojet events

SUSY may hide very well!

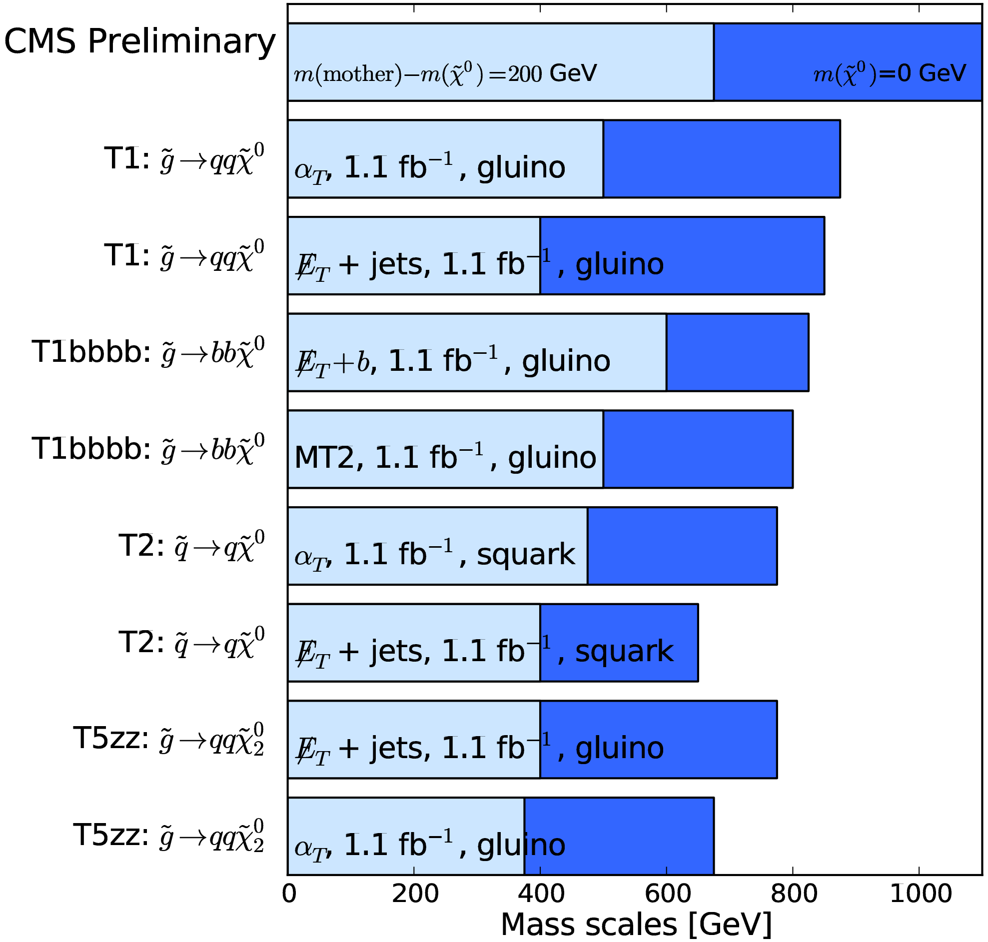
- Still plenty of room for SUSY to hide.
- 2012 will provide more data.
- Experimentalists will turn around every stone!

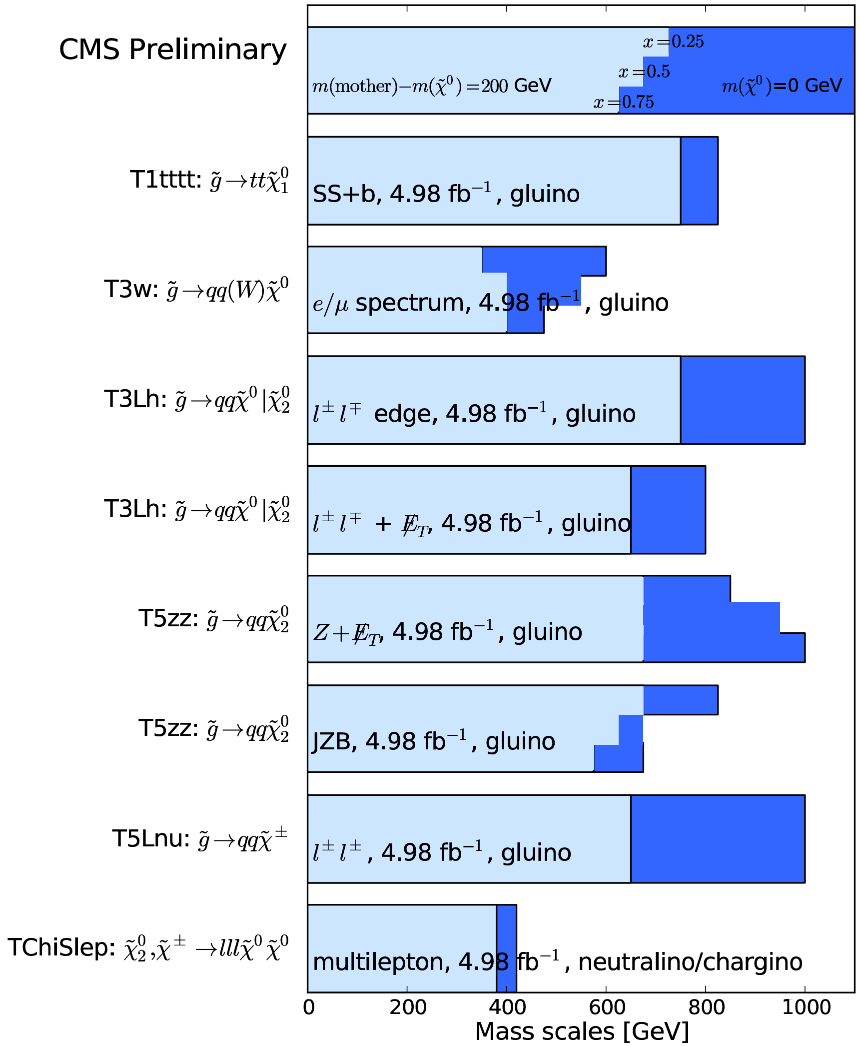
Summary SUSY Searches - ATLAS



*Only a selection of the available mass limits on new states or phenomena shown

$\mathcal{S}$ummary $\mathcal{SUSY}$ $\mathcal{S}$earches - $\mathcal{CMS}$

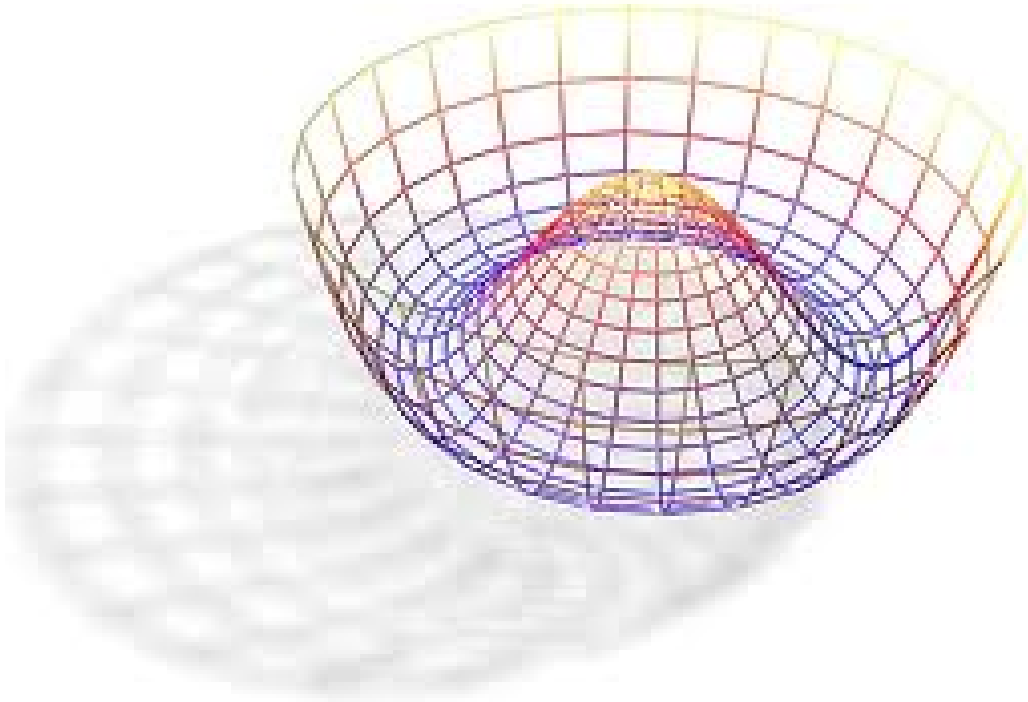


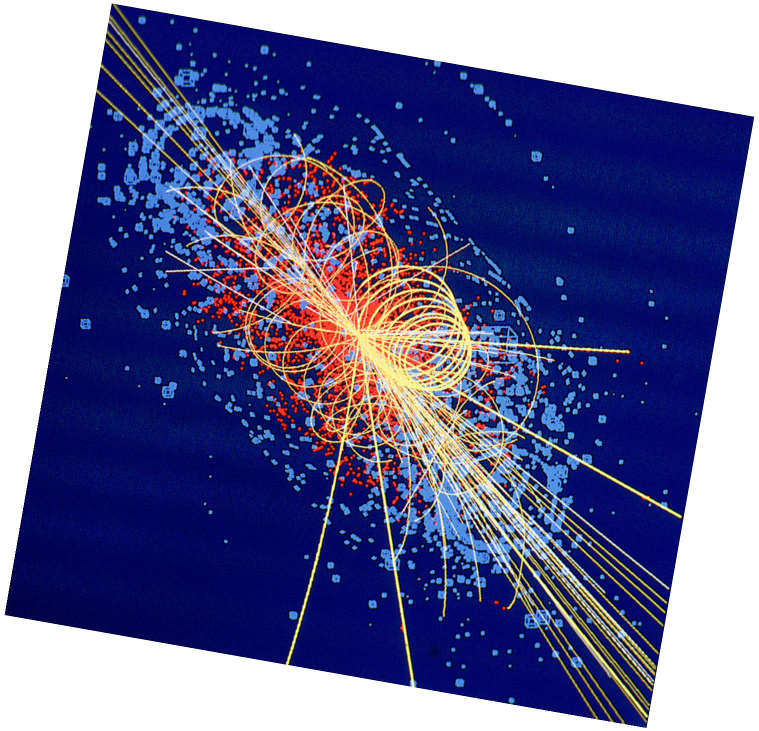


Electroweak Symmetry Breaking (EWSB) and LHC

Margarete Mühlleitner
(KIT)

CALC 2012, Dubna, July/August 2012





Outline

- Introduction Higgs mechanism
  Standard Model Higgs Sector
- Experimental Verification of the Higgs Mechanism
  First Step: Higgs Searches
- MSSM Higgs Sector (Brief)
- Composite Higgs Sector
- Model-independent fits to SM Higgs Search Results

(I) Introduction Higgs Mechanism and Standard Model Higgs Sector

$\mathcal{E}$lectroweak $\mathcal{S}$ymmetry $\mathcal{B}$reaking ($\mathcal{EWSB}$)

Why? explain existence of massive particles consistently with the underlying symmetries of the SM

How? Higgs mechanism [SM, SUSY, ...]
strong EW symmetry breaking [LH, "Higgsless", extra Dims., ...]

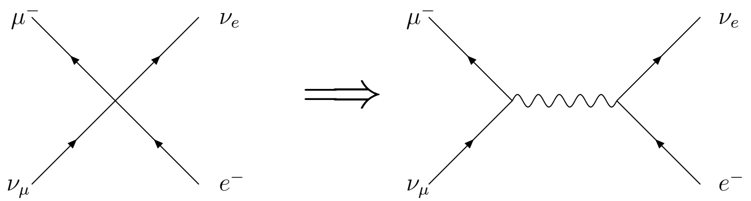
- **Fermi theory:** describes weak interaction with an effective Lagrangian

  E.g. μ decay: $\quad \mu^- \to e^- \bar{\nu}_e \nu_\mu$

  $\mathcal{L} = \frac{G_F}{\sqrt{2}} [\bar{\nu}_\mu \gamma_\lambda (1-\gamma_5)\mu][\bar{e}\gamma^\lambda(1-\gamma_5)\nu_e]$

  $G_F \approx 1.17 \times 10^{-5}$ GeV^{-2} (Fermi coupling)

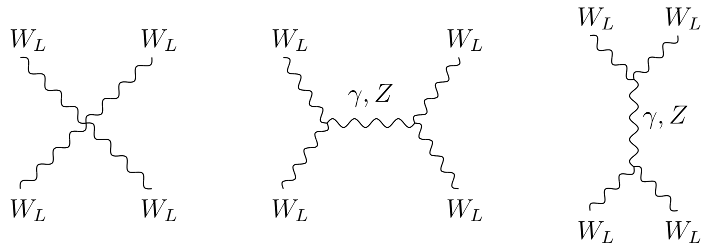
- **Fermi theory at high energies:** $\mathcal{M}[\nu_\mu e^- \to \mu^- \nu_e] \sim \frac{G_F}{2\sqrt{2}\pi} s \Rightarrow$ violates unitarity



$\mathcal{M}[\nu_\mu e^- \to \mu^- \nu_e] \to \frac{G_F s}{2\sqrt{2}\pi} \frac{M_W^2}{M_W^2 - s} \quad$ (with $M_W \approx 100$ GeV)

$\mathcal{T}$he $\mathcal{H}$iggs $\mathcal{P}$article as $\mathcal{UV}$ $\mathcal{R}$egulator

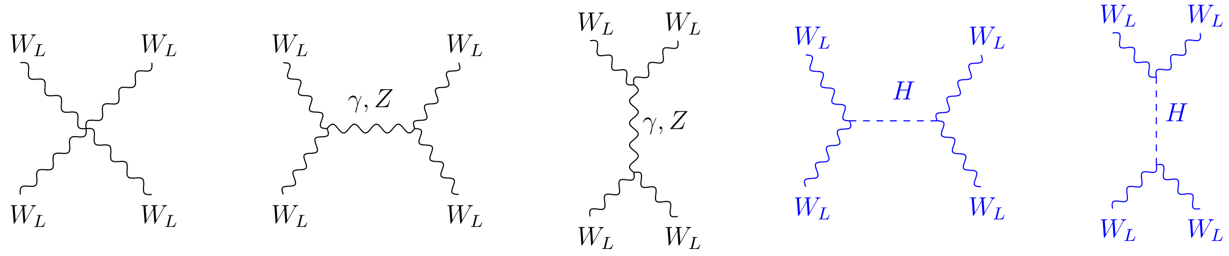
- **Scattering of longitudinally polarized W bosons**



$$\mathcal{A} = \frac{G_F s}{8\pi\sqrt{2}}$$

$\mathcal{T}$he $\mathcal{H}$iggs $\mathcal{P}$article as $\mathcal{UV}$ $\mathcal{R}$egulator

- **Scattering of longitudinally polarized W bosons**



$$\mathcal{A} = \frac{G_F M_H^2}{4\sqrt{2}\pi}$$

Higgs particle guarantees unitarity of the W scattering
(if its mass $\lesssim 1$ TeV, $g_{XXH} \sim$ particle mass M_X; also unitarity in $WW \to hh$, $WW \to ff$)

A theory with massive gauge bosons and fermions, which is weakly coupled up to very high energies, requires, because of the demand for unitarity, the existence of a Higgs particle.
The Higgs particle is a scalar 0^+ particle, which couples to other particles with a coupling proportional to the mass of the particle.

$\mathcal{E}$lectroweak $\mathcal{S}$ymmetry $\mathcal{B}$reaking ($\mathcal{EWSB}$)

Goal: generate W and Z boson masses without violating gauge invariance. Toy model:

▷ Local $U(1)$ gauge theory with single spin-1 gauge field A_μ

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad \text{where} \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$\longrightarrow$ mass term $\sim m^2 A^\mu A_\mu$ not gauge invariant $\rightsquigarrow$ massless gauge boson A

▷ Possible solution: add complex scalar field ϕ $\quad (D_\mu = \partial_\mu - ieA_\mu)$

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + |D_\mu\phi|^2 - V(\phi) \quad \text{where} \quad V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$$

if $\mu^2 > 0$: unique minimum at $\phi = 0 \longrightarrow$ QED with $M_A = 0$ and $M_\phi = \mu$

▷ Reverse sign of μ^2 so that $V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$

$\longrightarrow$ minimum of the potential at $\sqrt{-\frac{\mu^2}{2\lambda}} \equiv \frac{v}{\sqrt{2}}$

▷ Expand ϕ around the vacuum expectation value v: $\phi = \frac{1}{\sqrt{2}}(v + H + i\chi) \Rightarrow$

$\mathcal{E}$lectroweak $\mathcal{S}$ymmetry $\mathcal{B}$reaking ($\mathcal{EWSB}$)

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\partial_\mu H \partial^\mu H + \frac{1}{2}\partial_\mu \chi \partial^\mu \chi + \frac{1}{2}e^2 v^2 A_\mu A^\mu + ev A^\mu \partial_\mu \chi$$
$$-eA^\mu(\chi\partial_\mu H - H\partial_\mu \chi) + \frac{1}{2}e^2 A_\mu A^\mu (H^2+\chi^2) - \underbrace{(-\mu^2)}_{\frac{1}{2}m_H^2} H^2 + \text{interaction}(H^3, H^4)$$

▷ The theory has now

- a photon of mass $M_A = ev$
- a scalar field H with $M_H^2 = -2\mu^2 > 0$
- a massless scalar field χ (Goldstone boson)

▷ Mixed $A-\chi$ propagator: can be removed by a gauge transformation

$A_\mu \to A_\mu - \frac{1}{ev}\partial_\mu \chi$ and $\phi \to e^{-i\frac{\chi}{v}}\phi$ (unitary gauge)

$\rightsquigarrow$ the χ field has been absorbed by a redefinition of A
(jargon: χ has been "eaten"to give the photon mass)

▷ Degrees of freedom:

before symmetry breaking:	massles gauge boson (2 dof) and complex scalar field (2 dof)
after symmetry breaking:	massive gauge boson (3 dof) and physical scalar (1 dof)

$\mathcal{T}$he $\mathcal{SM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

- **Add complex Higgs doublet to $\mathcal{L}$**

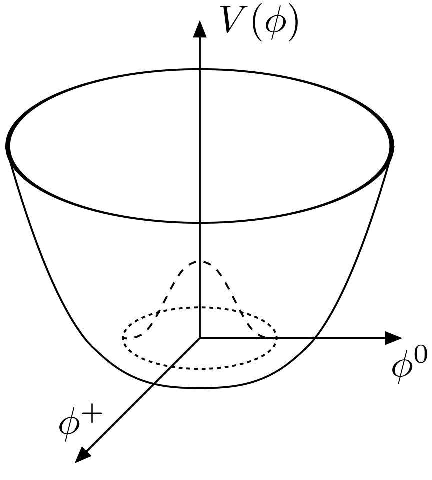
$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad \text{with} \quad <\Phi>=\frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \quad \text{and} \quad v = 246 \text{ GeV}$$

- **Lagrangian of the Higgs doublet**

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

- **The Higgs potential:**

$$V(\Phi) = \lambda[\Phi^\dagger \Phi - \frac{v^2}{2}]^2$$



The minimum of the potential is at $v = 246$ GeV

$\rightsquigarrow$ spontaneous symmetry breaking (SSB)

$\mathcal{T}$he $\mathcal{SM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

- **Higgs field in the unitary gauge**

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix} \Rightarrow$$

$$V(H) = \frac{1}{2}M_H^2 H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$$

- **$\Rightarrow$ Higgs mass and self-couplings:**

$\mathcal{H}$iggs boson mass	$M_H = \sqrt{2\lambda} v$
$\mathcal{T}$rilinear coupling [units $\lambda_0 = 33.8$ GeV]	$\lambda_{HHH} = 3\frac{M_H^2}{M_Z^2}$
$\mathcal{Q}$artic coupling [units λ_0^2]	$\lambda_{HHHH} = 3\frac{M_H^2}{M_Z^4}$

Higgs self-couplings in the SM uniquely determined by the Higgs mass!

(II) Experimental Verification of the Higgs Mechanism
First Step: Higgs Searches

$\mathcal{E}$lectroweak $\mathcal{S}$ymmetry $\mathcal{B}$reaking ($\mathcal{EWSB}$)

Why? explain existence of massive particles consistently with the underlying symmetries of the SM

How? Higgs mechanism [SM, SUSY, ...]
strong EW symmetry breaking [LH, "Higgsless", extra dims., ...]

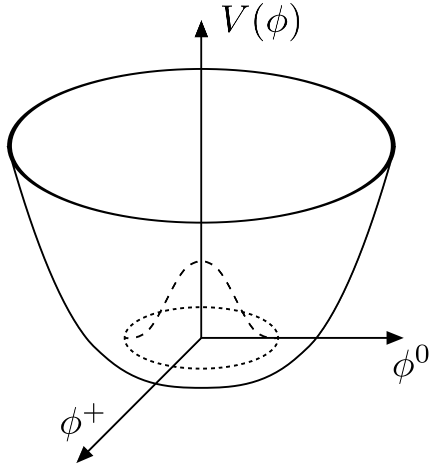
Higgs mechanism

Symmetry of the Lagrangian

$SU(2)_L \times U(1)_Y$

Higgs doublet

$$\Phi = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$



$$V(\Phi) = \lambda[\Phi^\dagger\Phi - \frac{v^2}{2}]^2$$

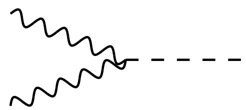
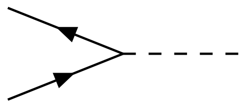
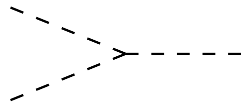
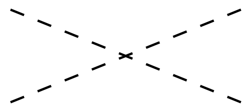
Symmetry of the vacuum

$U(1)_{em}$

vacuum expectation value

$$< \Phi >= \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$

$v = 246$ GeV

Higgs boson mass	$M_H = \sqrt{2\lambda}v$	
Gauge couplings	$g_{VVH} = \frac{2M_V^2}{v}$	
Yukawa couplings	$g_{ffH} = \frac{m_f}{v}$	
Trilinear coupling [units $\lambda_0 = 33.8$ GeV]	$\lambda_{HHH} = 3\frac{M_H^2}{M_Z^2}$	
Quartic coupling [units λ_0^2]	$\lambda_{HHHH} = 3\frac{M_H^2}{M_Z^4}$	

Only unknown parameter in the SM is the Higgs boson mass!

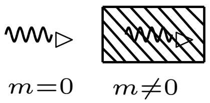
$\mathcal{N}$ext $\mathcal{S}$teps in $\mathcal{E}$xperimental $\mathcal{V}$erification of the $\mathcal{H}$iggs $\mathcal{M}$echanism

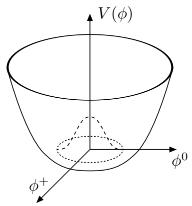
Higgs mechanism:

Creation of particle masses without violating gauge symmetries

Test of the Higgs mechanism

- Discovery – m
- Interaction with a scalar Higgs with $v = 246$ GeV$\neq 0$ $\rightsquigarrow$ $g_{HXX} \sim m_X$
- Spin and parity quantum numbers – J^{PC}
- EWSB requires Higgs potential – $\lambda_{HHH}, \lambda_{HHHH}$





$\mathcal{W}$ould require another lecture!

Higgs mechanism:

Creation of particle masses without violating gauge symmetries

Test of the Higgs mechanism

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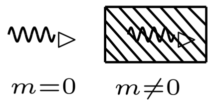

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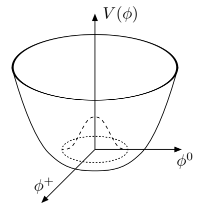
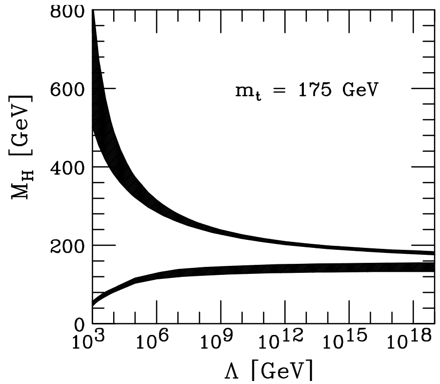


$\mathcal{SM}$ $\mathcal{H}$iggs $\mathcal{M}$ass $\mathcal{L}$imits

- Triviality → upper limit
  Vacuum stability → lower limit

Cabibbo,...;Sher; Lindner;Hasenfratz,...; Lüscher, Weisz; Hambye,...;...

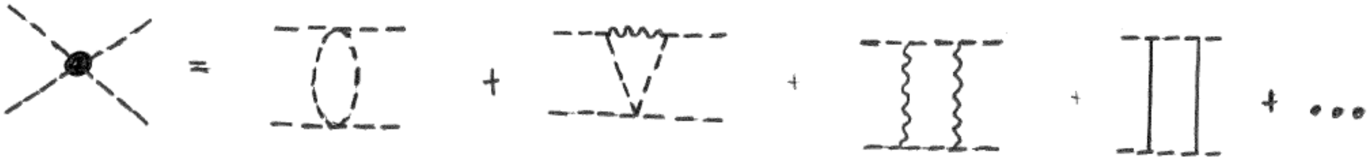
Hambye,Riesselmann



$\Lambda = 1$ TeV : 55 GeV $\lesssim M_H \lesssim$ 700 GeV
$\Lambda_{GUT} = 10^{16}$ GeV: 130 GeV $\lesssim M_H \lesssim$ 190 GeV

$\mathcal{T}$riviality $\mathcal{B}$ound

- **Quantum corrections to the Higgs potential:** $V(\Phi) = \lambda[\Phi^\dagger\Phi - \frac{v^2}{2}]^2$
- **Corrections to coupling λ**



- **Large mass** $\rightsquigarrow$ λ dominated renormalisation group equation (RGE):

$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2 \qquad \Longrightarrow \qquad \lambda(Q) = \frac{M_H^2}{2v^2 - \frac{3}{2\pi^2} M_H^2 \ln(Q/v)}$$

λ increases with Q

- **Landau pole**

$$\Lambda \le v e^{4\pi^2 v^2/3M_H^2}$$

New Physics must appear before this point to restore stability

$\Longrightarrow$ For Λ fixed upper bound on M_H

- **Triviality** No quantum theory for $\Lambda \to \infty$: trivial theory $\lambda = 0$.

$\mathcal{T}$riviality $\mathcal{B}$ound

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- **Corrections to coupling λ**

$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2 - (3g'^2 + 9g^2 - 12y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2g^2 + \frac{9}{8}g^4 - 6y_t^4 + \text{higher order}$$

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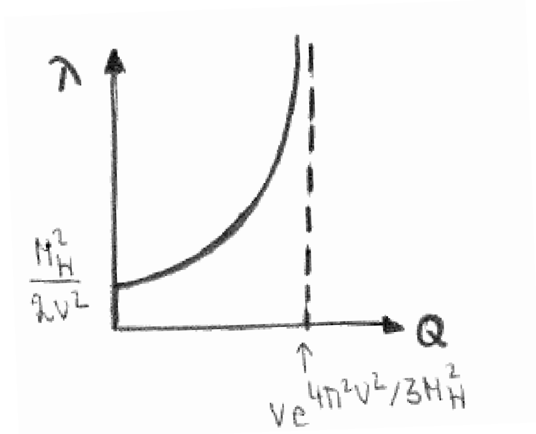


- **Triviality** No quantum theory for $\Lambda \to \infty$: trivial theory $\lambda = 0$.

$\mathcal{V}$acuum $\mathcal{S}$tability

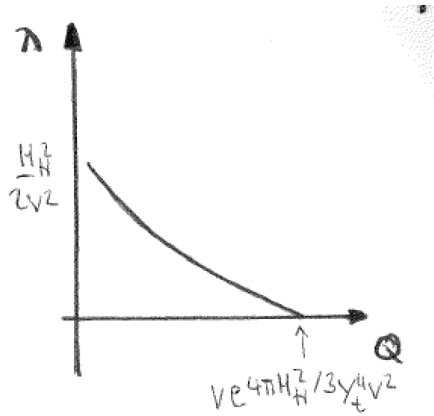
- **Corrections to coupling λ**

$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2 - (3g'^2 + 9g^2 - 12y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - 6y_t^4 + \text{higher order}$$

- **Small mass** $\rightsquigarrow$ y_t dominated RGE:

$$16\pi^2 \frac{d\lambda}{d\ln Q} = -6y_t^4 \qquad \Longrightarrow \qquad \lambda(Q) = \lambda_0 - \frac{\frac{3}{8\pi^2} y_0^4 \ln\frac{Q}{Q_0}}{1 - \frac{9}{16\pi^2} y_0^2 \ln\frac{Q}{Q_0}}$$

λ decreases with Q; $\lambda < 0 \rightsquigarrow$ potential unbounded from below
$\lambda = 0$ for $\lambda_0 \approx \frac{3}{8\pi^2}\, y_0^4 \ln\frac{Q}{Q_0}$



- **Vacuum stability**

$$\Lambda \leq v e^{4\pi^2 M_H^2 / 3 y_t^4 v^2}$$

New Physics must appear before this point to ensure vacuum stability

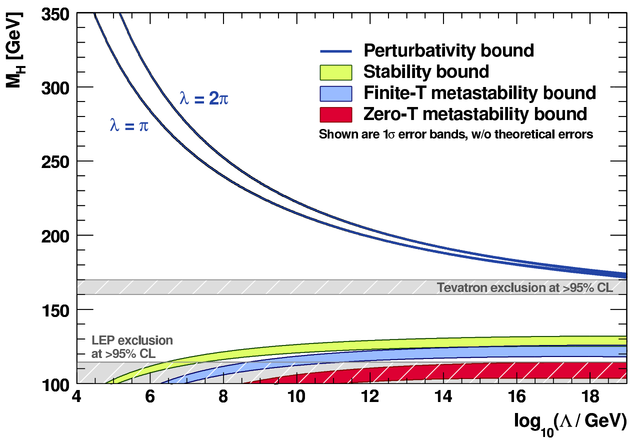
$\Longrightarrow$ For Λ fixed lower bound on M_H

SM Higgs Mass Constraints

- Triviality → upper bound
  Vacuum stability → lower bound

Cabibbo,...;Sher; Lindner;Hasenfratz,...; Lüscher, Weisz; Hambye,...;...

Ellis,Espinosa,Giudice,Hoecker,Riotto



$\Lambda = 1$ TeV : 55 GeV $\lesssim M_H \lesssim$ 700 GeV

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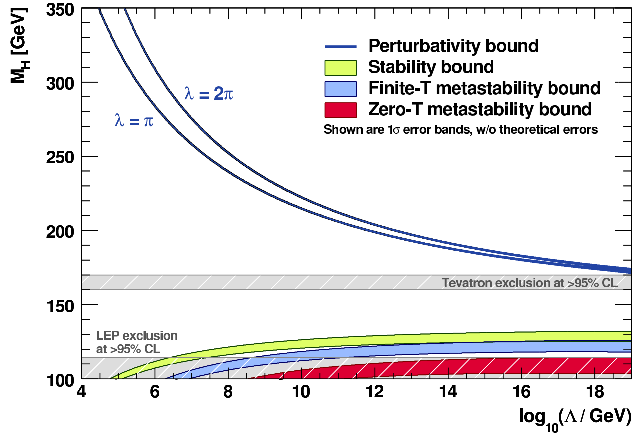

$\Lambda = 1$ TeV : 55 GeV $\lesssim M_H \lesssim$ 700 GeV
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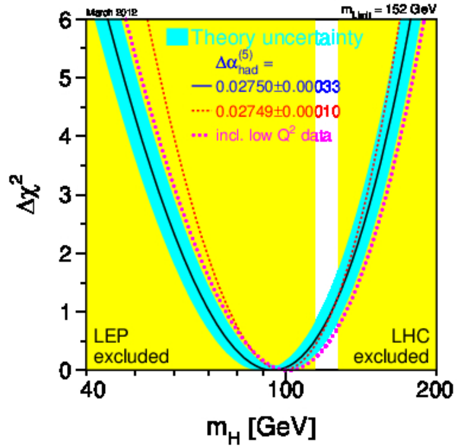
- Fits to electroweak precision data



EP Coll.

EWWG

$M_H = 94^{+29}_{-24}$ GeV, $M_H \lesssim 171$ GeV @ 95% CL

$\mathcal{P}$recision $\mathcal{T}$ests of the $\mathcal{S}$tandard $\mathcal{M}$odel

- **Precision electroweak measurements, in particular at**

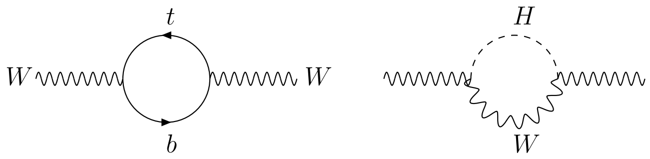
  LEP (Large Electron-Positron storage ring at CERN, $M_Z \lesssim \sqrt{s} \lesssim 200$ GeV) and
  SLC (Stanford Linear Collider, $\sqrt{s} = M_Z$)

  allow to test the SM at very high accuracy!

  $\longrightarrow$ quantum corrections must be included
  $\longrightarrow$ sensitive to energy scales beyond direct reach

  - indirect search for the Higgs

- **Quantum corrections to precision observables** give access to high mass scales:



Calculate M_W from M_Z and G_F including quantum corrections

$$\frac{M_W^2}{M_Z^2}\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F M_Z^2(1-\Delta r)}$$

where the quantum correction Δr is composed of

$$\Delta r=\Delta\alpha-\cot\theta_W\Delta\rho^{top}+\Delta r^{Higgs}+...$$

The leading top contribution is quadratic in m_{top}

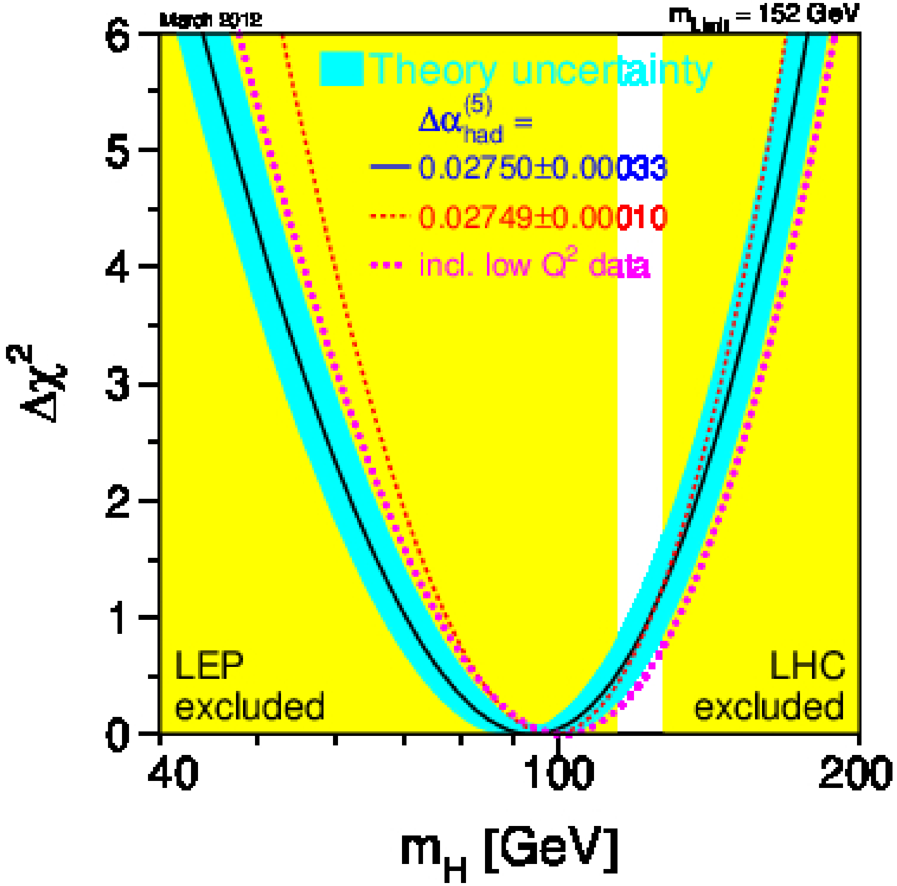
$$\Delta\rho^{top}=\frac{3G_F m_{top}^2}{8\pi^2\sqrt{2}}+...$$

The Higgs contribution is screened, depending only logarithmically on M_H

$$\Delta r^{Higgs}=\frac{G_F M_W^2}{8\pi^2\sqrt{2}}\frac{1+9\sin^2\theta_W}{3\cos^2\theta_W}\ln\left(\frac{M_H^2}{M_W^2}\right)+...$$

$\mathcal{H}$iggs $\mathcal{M}$ass from $\mathcal{C}$ombined $\mathcal{F}$it to $\mathcal{EWPD}$

LEPEWWG



Minimum at: $M_H = 94\,^{+29}_{-24}$ GeV, $M_H \lesssim 171$ GeV @ 95% CL

$\mathcal{SM}$ $\mathcal{H}$iggs $\mathcal{M}$ass Constraints

- Triviality → upper bound
  Vacuum stability → lower bound

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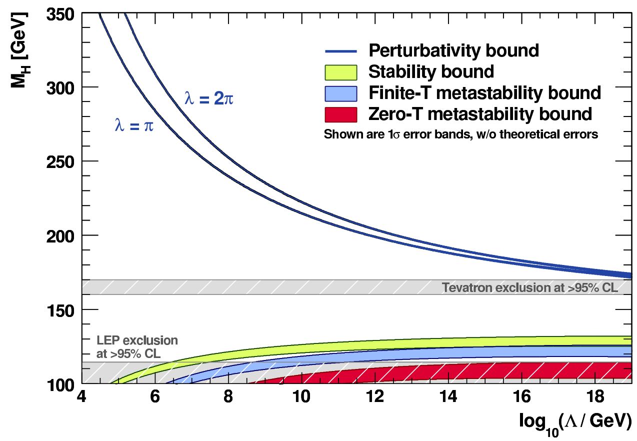
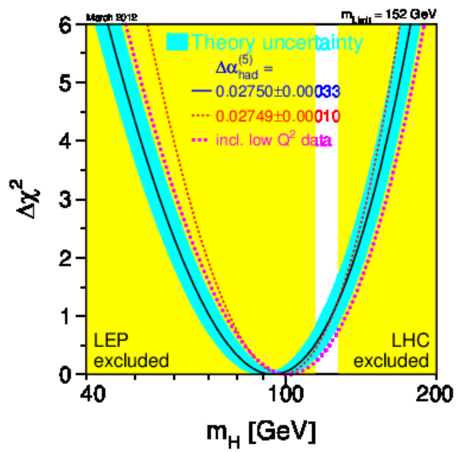


$$\Lambda = 1 \text{ TeV}: \quad 55 \text{ GeV} \lesssim M_H \lesssim 700 \text{ GeV}$$
$$\Lambda_{GUT} = 10^{16} \text{ GeV}: \quad 130 \text{ GeV} \lesssim M_H \lesssim 190 \text{ GeV}$$

- Fits to electroweak precision data



LEP Coll.

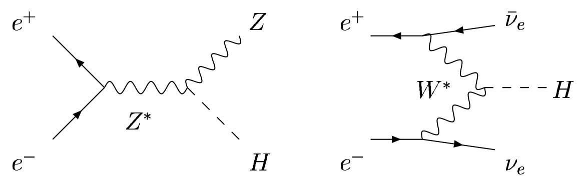
EWWG

$$M_H = 94^{+29}_{-24} \text{ GeV}, \; M_H \lesssim 171 \text{ GeV @ } 95\% \text{ CL}$$

- Direct search @ LEP: $[M_H = 115.3 \text{ GeV}]$

$$M_H > 114.4 \text{ GeV @ } 95\% \text{ CL}$$

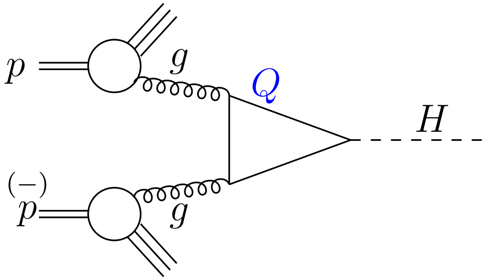
LEP Coll.



Higgs boson production in the SM

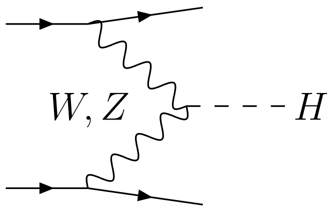
- **Gluon Fusion**

  $pp \to gg \to H$



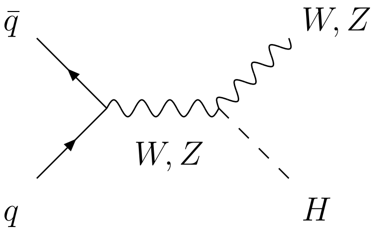
- **W/Z Fusion**

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



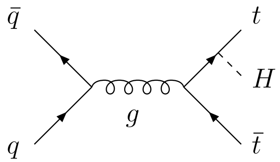
- **Higgs-strahlung**

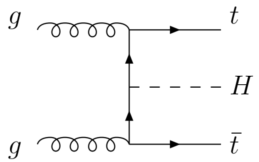
  $pp \to W^*/Z^* \to W/Z + H$



- **Associated Production**

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





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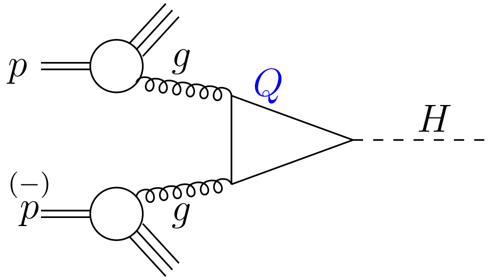
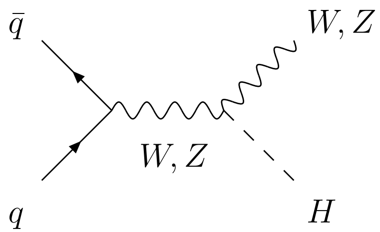


- **LHC**

$gg \to \phi$ dominant

- **Higgs-strahlung**

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



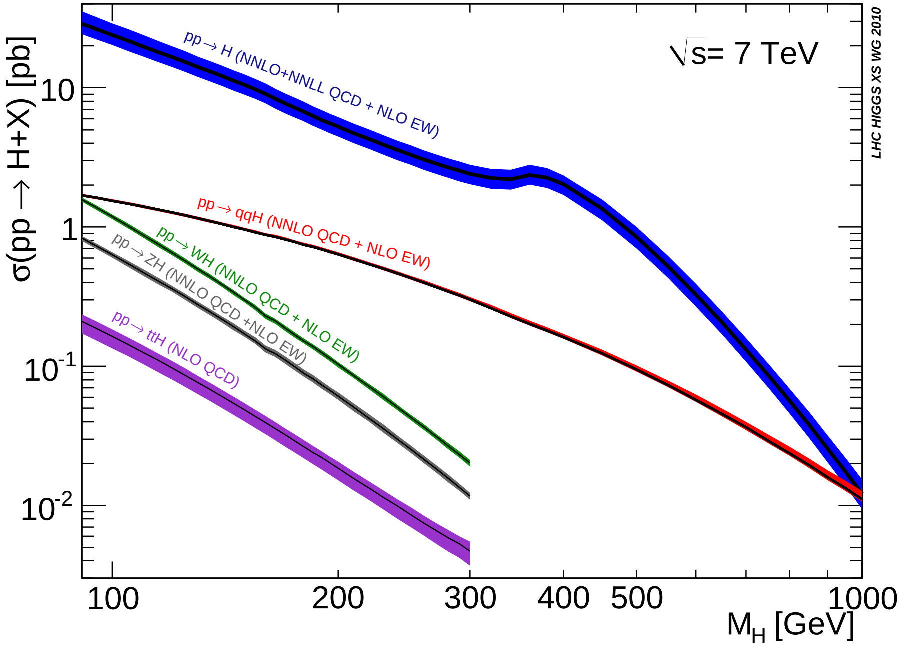
- **Tevatron**

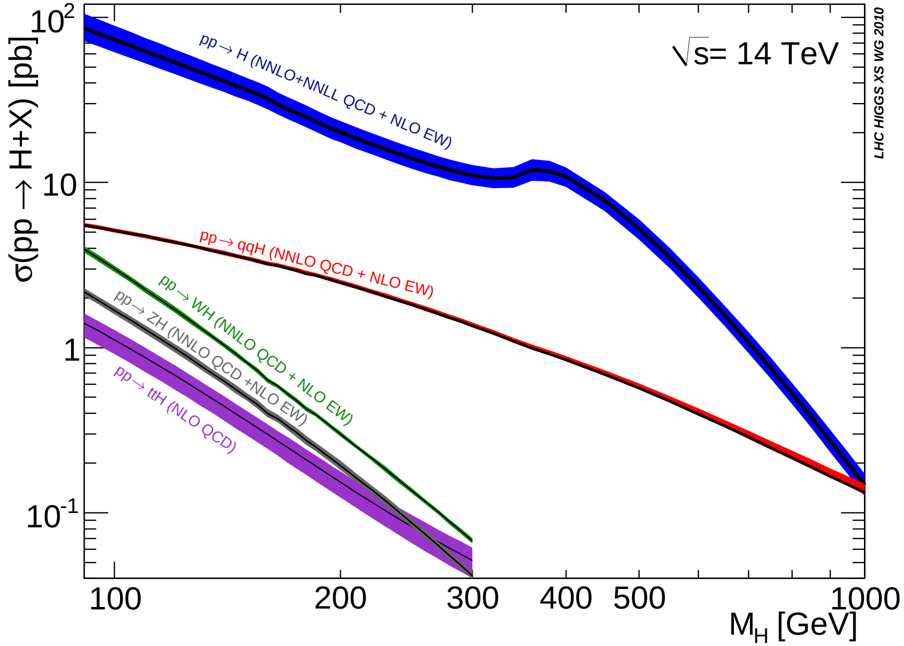
$gg \to \phi$ dominant

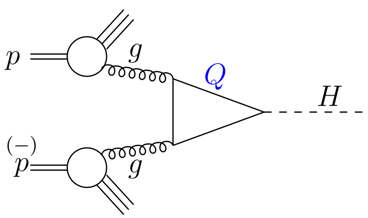
$q\bar{q}' \to \phi W$ most important

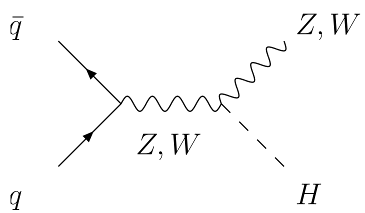
$\mathcal{SM}$ $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{P}$roduction at the $\mathcal{LHC}$

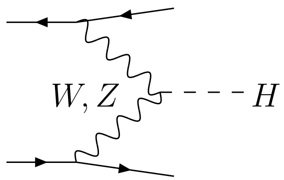
LHC Higgs XS WG, arXiv:1101.0593

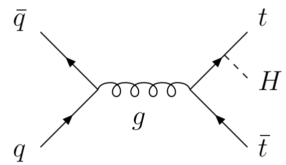












$\mathcal{H}$igher $\mathcal{O}$rder $\mathcal{C}$orrections

Precision calculations needed for signal and background processes

- ◇ Higgs discovery in WW decay $\leftarrow$ no reconstruction of the mass peak possible
- ◇ reliable extraction of the discovery/exclusion significances
- ◇ precise measurement of the Higgs couplings
- ◇ ...

$\Rightarrow$

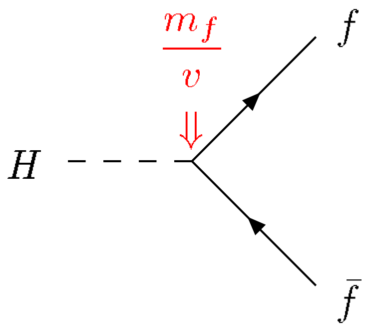
- ▷ test of the Higgs mechanism
- ▷ discrimination between SM and SM extensions (e.g. SUSY)

$\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{D}$ecays

- **Higgs boson coupling $\sim$ particle mass** $\rightsquigarrow$ most important decays: into heavy particles

Fermions

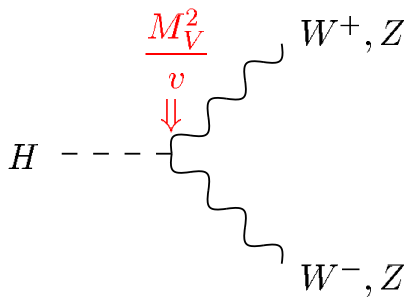
$BR(H \to b\bar{b})$	$\lesssim$	85%
$BR(H \to \tau^+\tau^-)$	$\lesssim$	8%
$BR(H \to c\bar{c})$	$\lesssim$	4%
$BR(H \to t\bar{t})$	$\lesssim$	20%



large QCD corrections, up to -50%

Gauge bosons

$BR(H \to W^+W^-)$	$\lesssim$	$60 - 95\%$
$BR(H \to ZZ)$	$\lesssim$	30%



EW corrections $\mathcal{O}(5 - 20\%)$

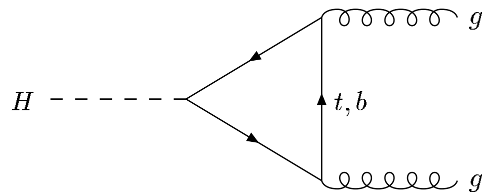
$\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{D}$ecays

<u>Gluons</u>

$$BR(H \to gg) \quad \lesssim \quad 6\%$$

Loop-mediated decays, dominant contribution from top loops

large QCD corrections, up to $+70\%$

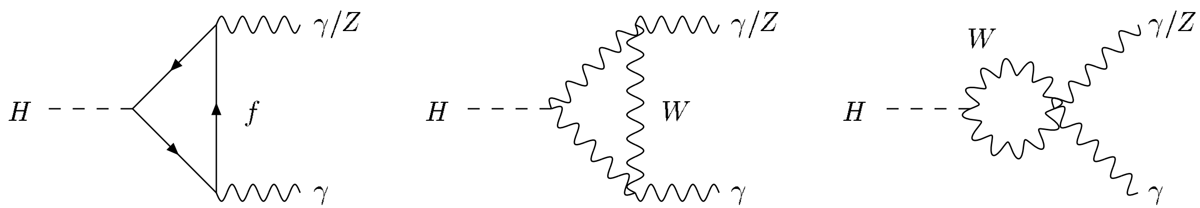


<u>$\gamma\gamma$ and $Z\gamma$</u>

$$BR(H \to \gamma\gamma, Z\gamma) \quad \lesssim \quad 2 \times 10^{-3}$$

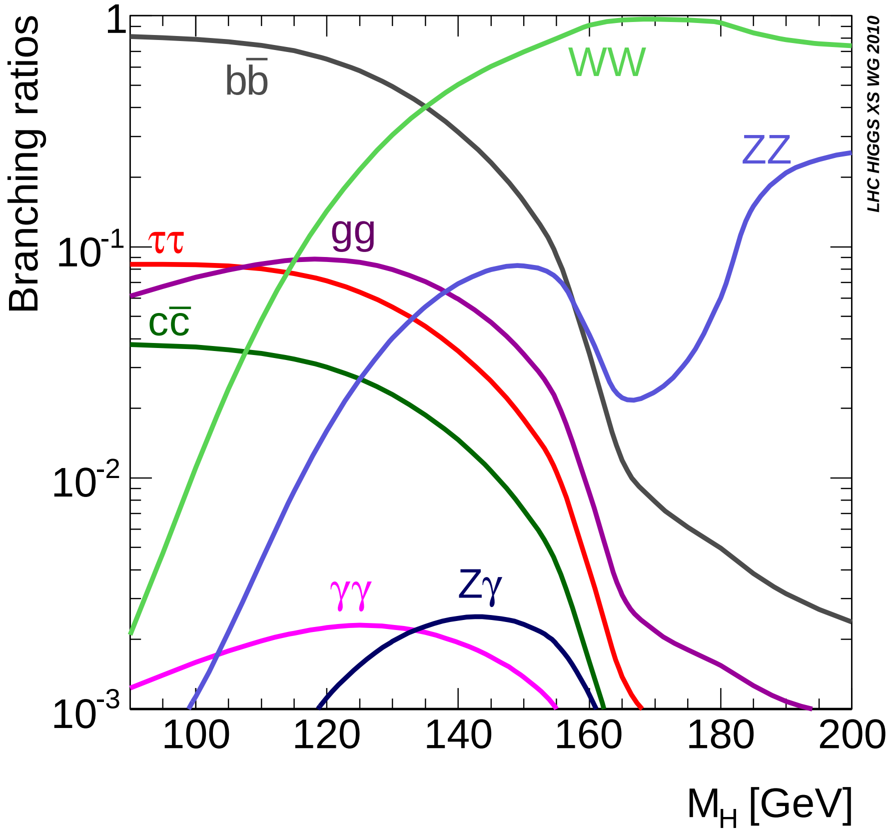
Loop-mediated decay via charged fermions and W bosons

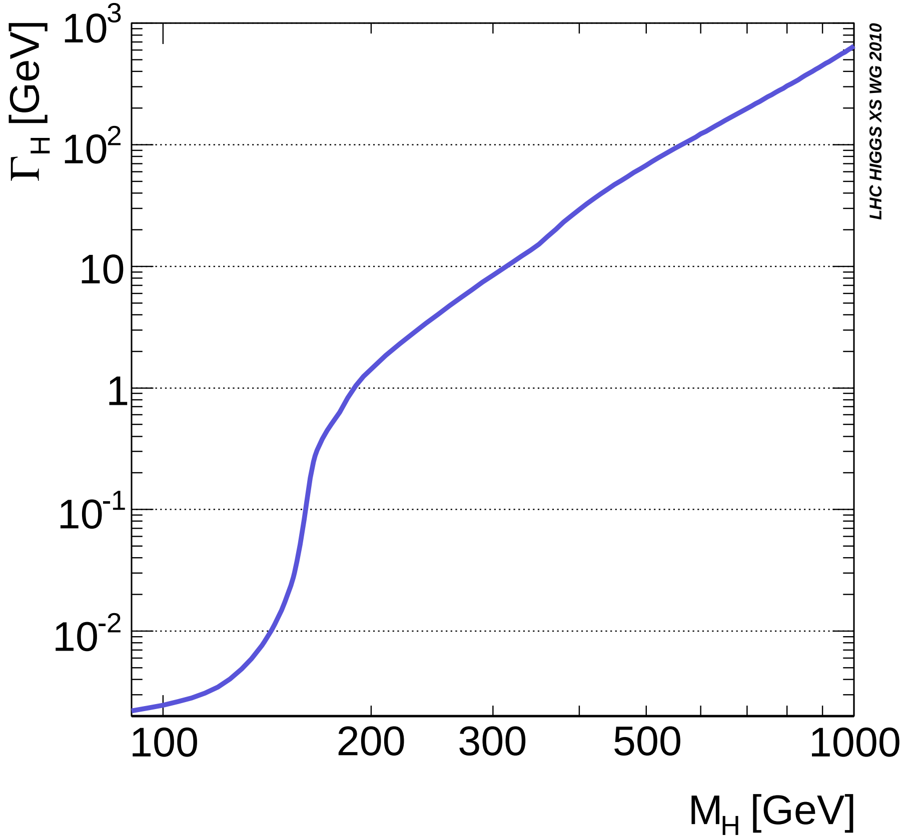
QCD corrections small



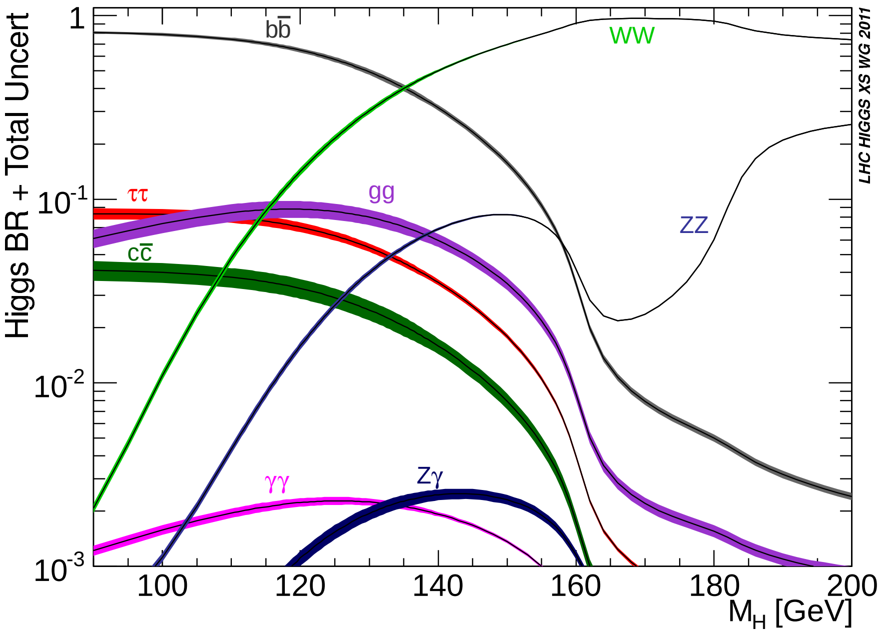
$\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{D}$ecays

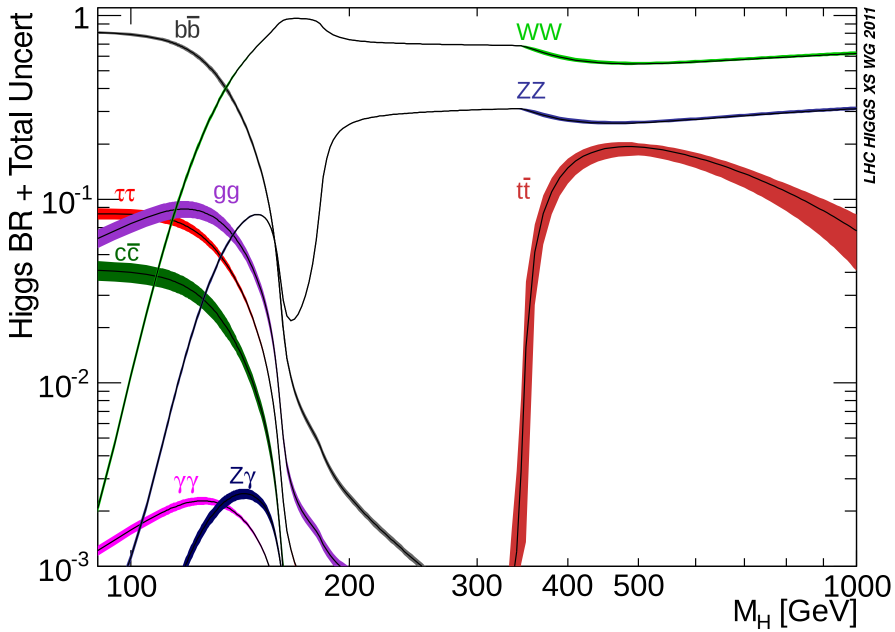
Higgs cxn working group



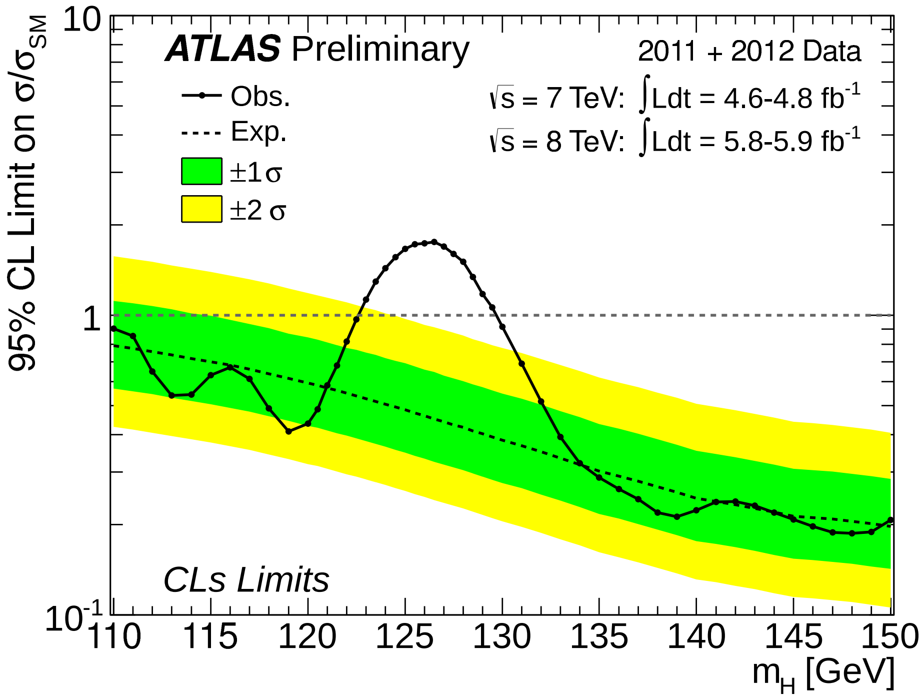


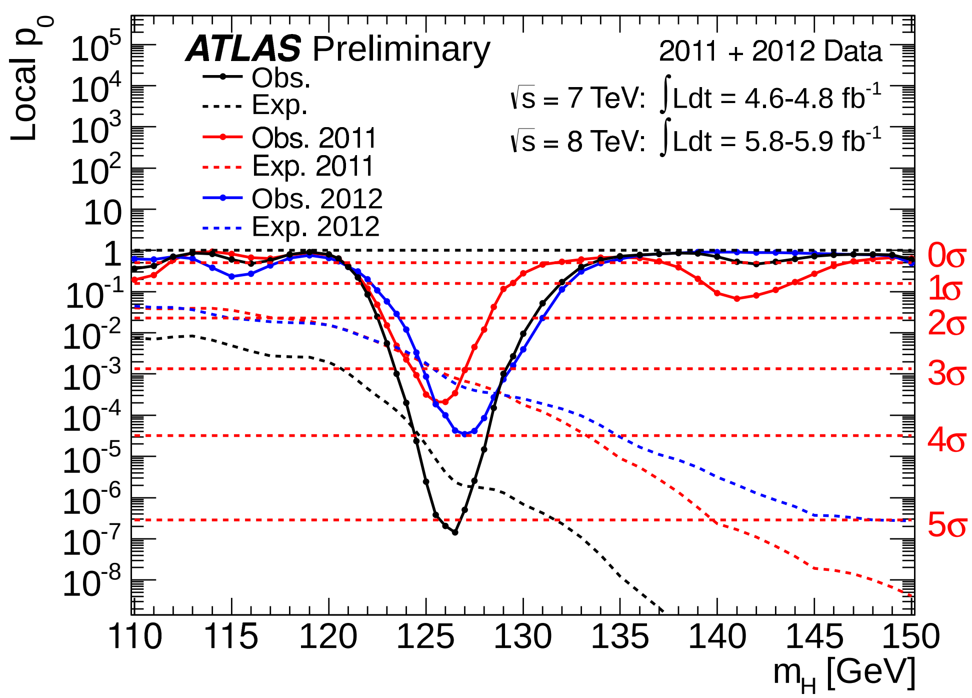
Higgs cxn working group





LHC Higgs Search Results - ATLAS 4th July 2012

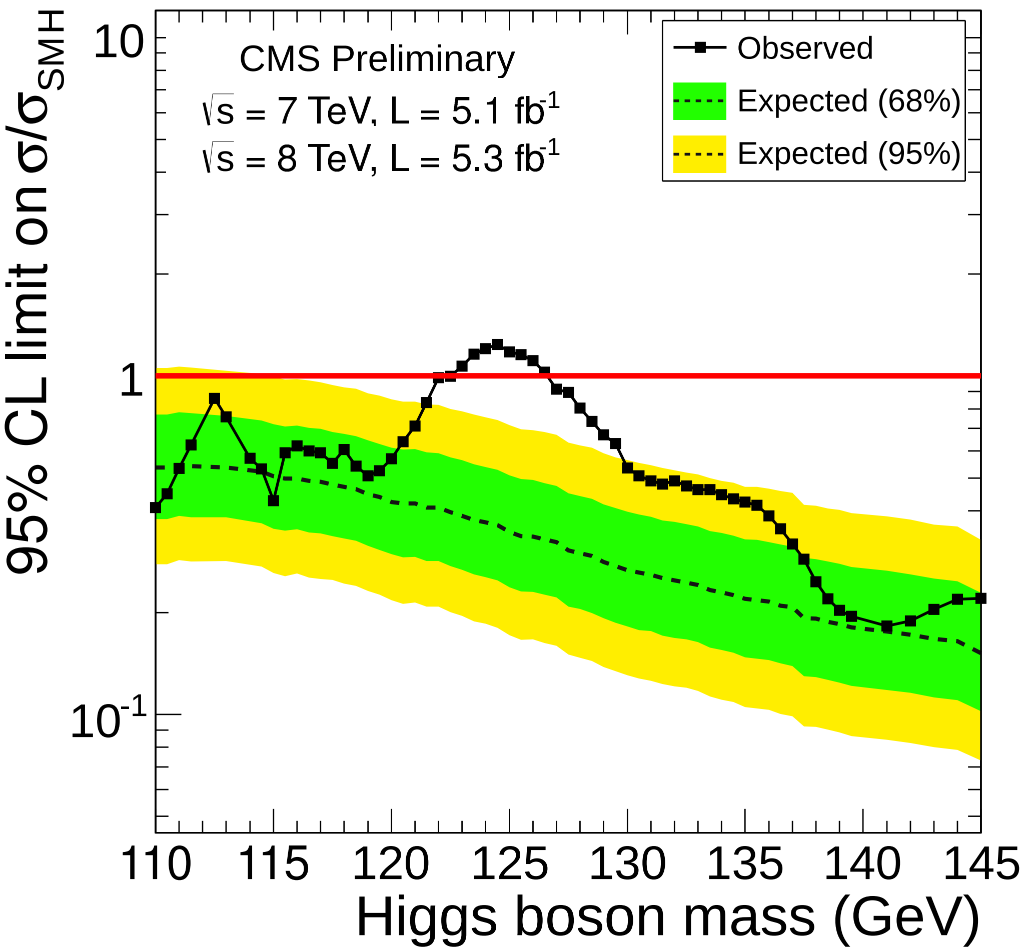


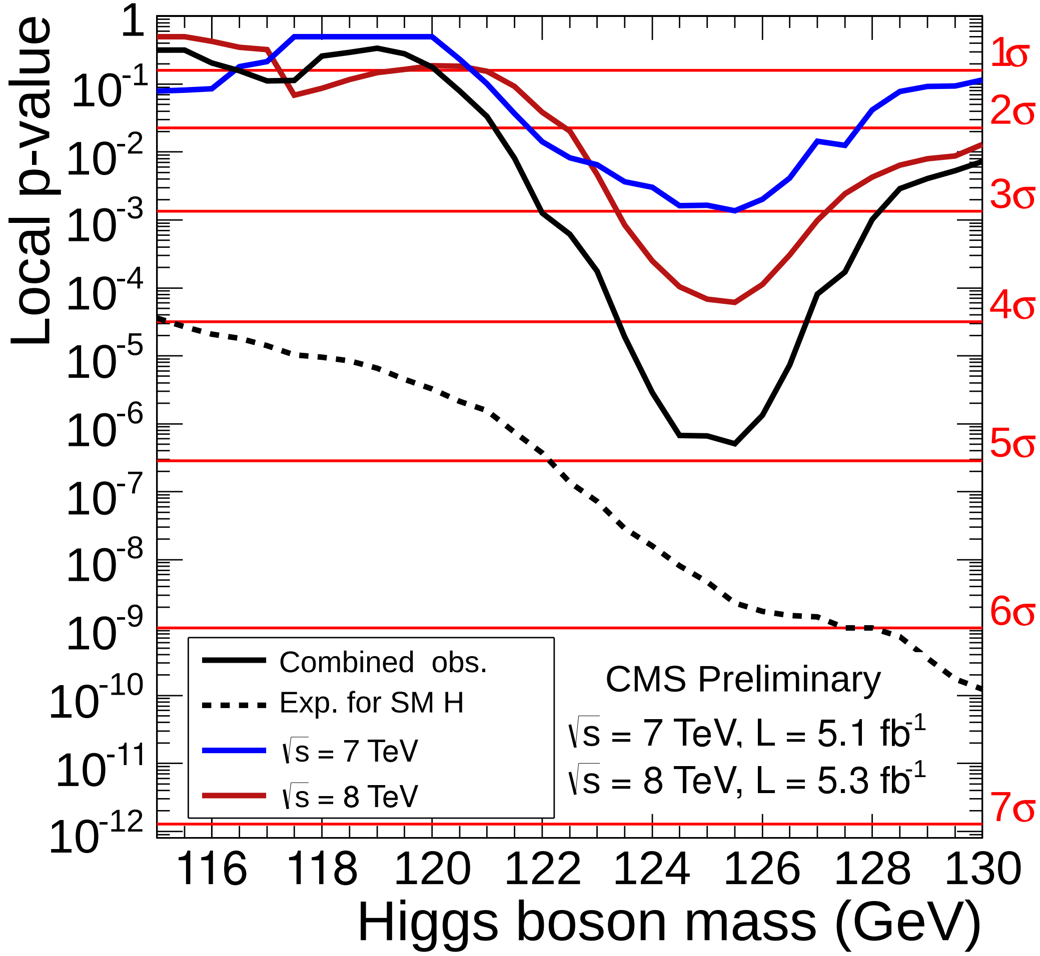


Observed exclusion at 95% CL: 110-122.6, 129.7-558 GeV

Local significance of excess compatible with Higgs mass hypothesis near 126.5 GeV: 5σ

$\mathcal{LHC}$ $\mathcal{H}$iggs $\mathcal{S}$earch $\mathcal{R}$esults - $\mathcal{CMS}$ 4th $\mathcal{J}$uly 2012





Observed exclusion at 95% CL: 110-122.5, 127-600 GeV

Local significance of excess compatible with Higgs mass hypothesis near 125 GeV: 4.9σ

BSM Higgs Sectors

The MSSM Higgs Sector

MSSM Higgs sector – supersymmetry & anomaly free theory $\Rightarrow$ 2 complex Higgs doublets

$\stackrel{\text{EWSB}}{\longrightarrow}$ neutral, CP-even h, H | neutral, CP-odd A | charged H^+, H^-

Higgs masses

$$M_h \lesssim 140 \text{ GeV}$$
$$M_{A,H,H^\pm} \sim \mathcal{O}(v)...1 \text{ TeV}$$

Ellis et al;Okada et al;Haber,Hempfling;
Hoang et al;Carena et al;Heinemeyer et al;
Zhang et al;Brignole et al;Harlander et al
Degrassi et al;Kant et al;...

Decoupling limit:

$M_A \sim M_H \sim M_{H^\pm} \gtrsim v$

$M_h \rightarrow$ max. value, $\tan\beta$ fixed; h becomes SM-like

Modified couplings with respect to the SM: (decoupling limit Gunion,Haber)

Φ	$g_{\Phi u\bar{u}}$	$g_{\phi d\bar{d}}$	$g_{\Phi VV}$
h	$c_\alpha/s_\beta \rightarrow 1$	$-s_\alpha/c_\beta \rightarrow 1$	$s_{\beta-\alpha} \rightarrow 1$
H	$s_\alpha/s_\beta \rightarrow 1/\text{tg}\beta$	$c_\alpha/c_\beta \rightarrow \text{tg}\beta$	$c_{\beta-\alpha} \rightarrow 0$
A	$1/\text{tg}\beta$	$\text{tg}\beta$	0

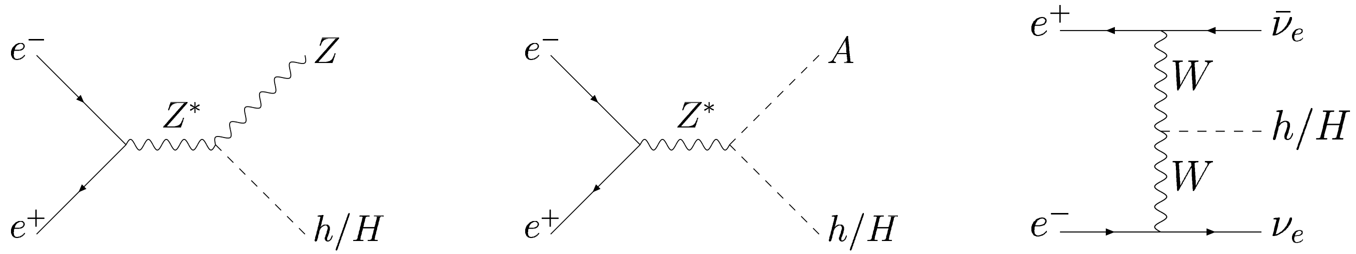
$\tan\beta \uparrow \Rightarrow g_{\Phi uu} \downarrow$

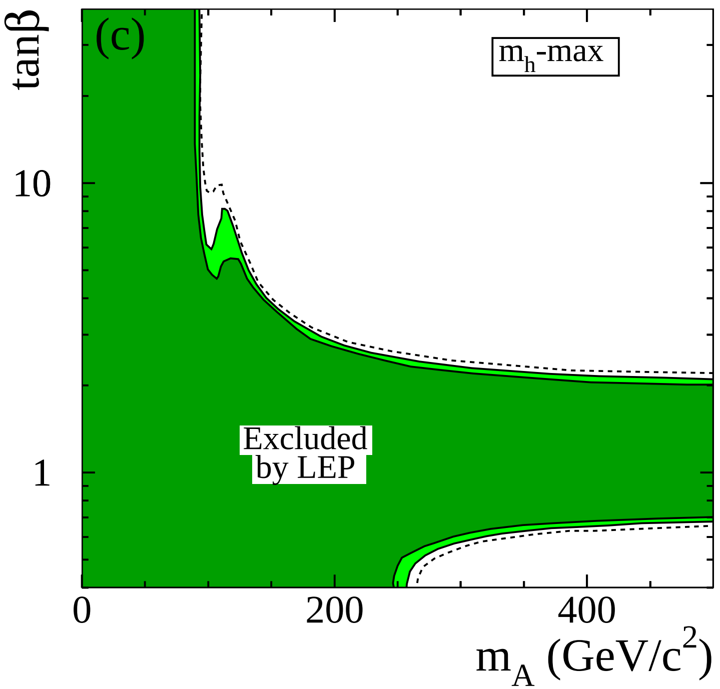
$g_{\Phi dd} \uparrow$

$g^{MSSM}_{\Phi VV} \lesssim g^{SM}_{\Phi VV}$

Pre-LHC MSSM Higgs Mass Limits

▷ Direct Search at LEP $e^+e^- \to Z + h/H,\ A + h/H,\ \nu_e\bar{\nu}_e + h/H$





$M_{h/H} \gtrsim 92.6$ GeV

$M_A \gtrsim 93.4$ GeV

$M_{H^\pm} > 78.6$ GeV

$0.6 < \tan\beta < 2.5$ excluded

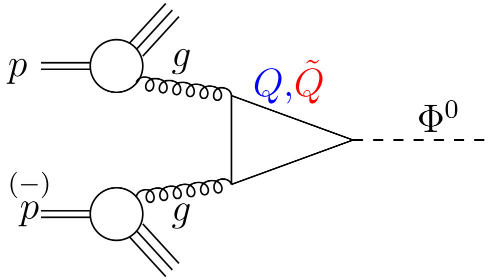
(only in this scenario, $m_t = 174.3$ GeV!)

$\mathcal{H}$iggs $\mathcal{S}$earch at the $\mathcal{LHC}$

Higgs boson production in the MSSM

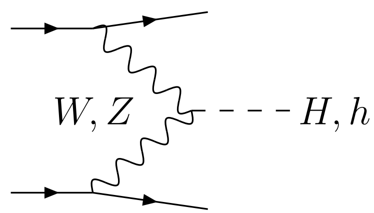
- **Gluon Fusion**

  $pp \to gg \to h, H, A$



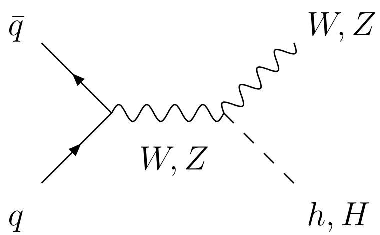
- **W/Z Fusion**

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



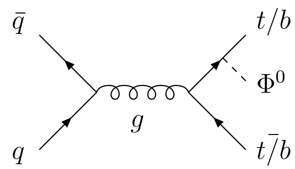
- **Higgs-strahlung**

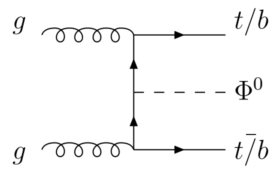
  $pp \to W^*/Z^* \to W/Z + h, H$



- **Associated Production**

  $pp \to t\bar{t}/b\bar{b} + h, H, A$



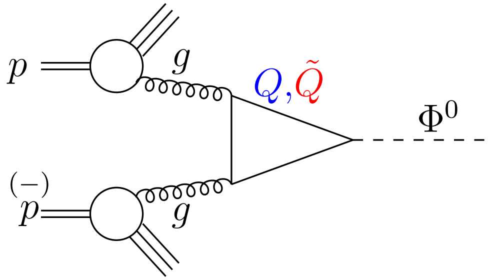


dominant

Higgs boson production in the MSSM

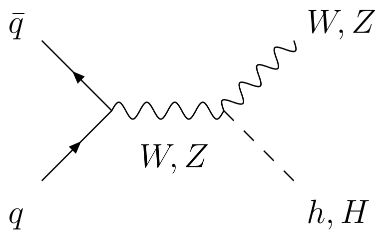
- **Gluon Fusion**

  $pp \to gg \to h, H, A$



- **Higgs-strahlung**

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



- **LHC**

  $gg \to \phi$ dominant for $\tan\beta \lesssim 10$

  $gg \to \phi b\bar{b}$ dominant for $\tan\beta \gtrsim 10$

- **Tevatron**

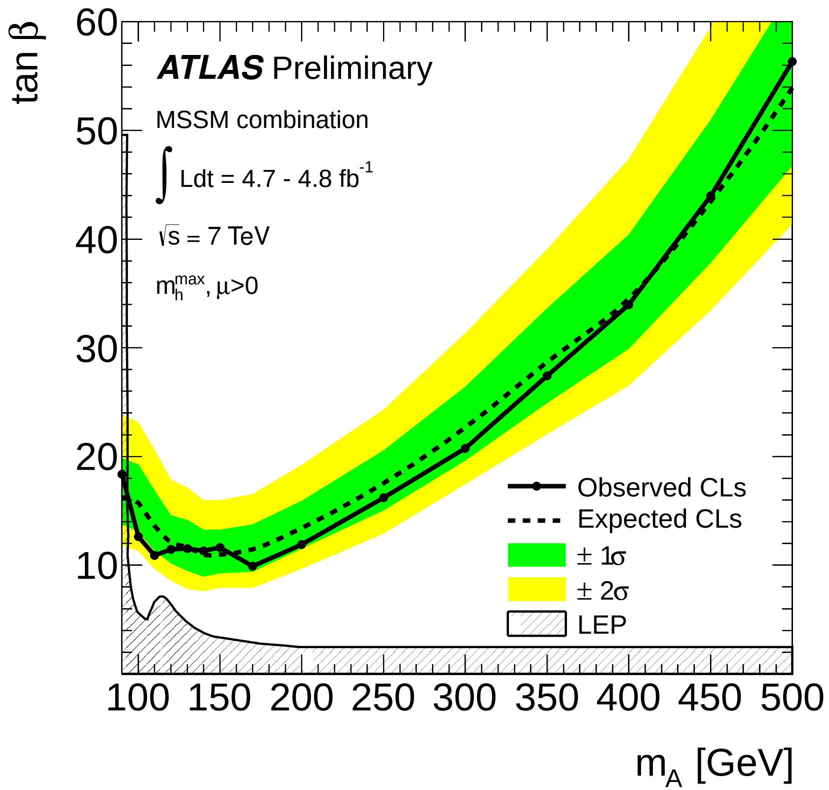
  $gg \to \phi$ dominant, for large $\tan\beta$: $\phi b\bar{b}$

  $q\bar{q}' \to \phi W$ most important

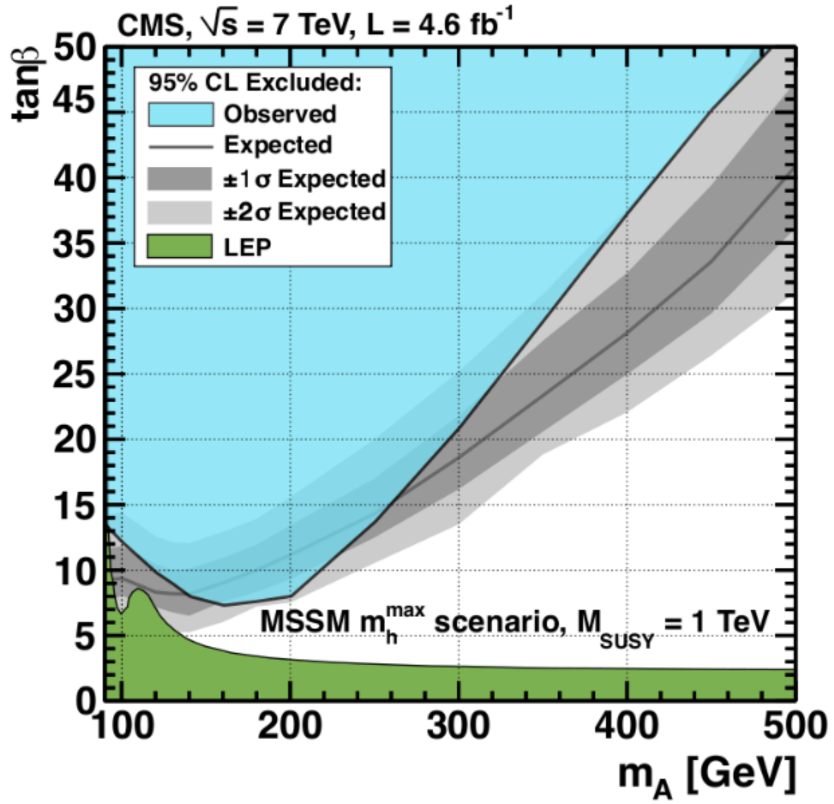
Search for MSSM Higgs Bosons at the LHC

$$gg \to b\bar{b}\phi^0,\ gg \to \phi^0, \qquad \phi^0 \to \mu^+\mu^-,\ \tau^+\tau^-$$

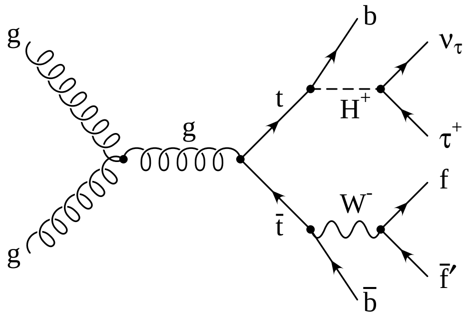
ATLAS-CONF-2012-094



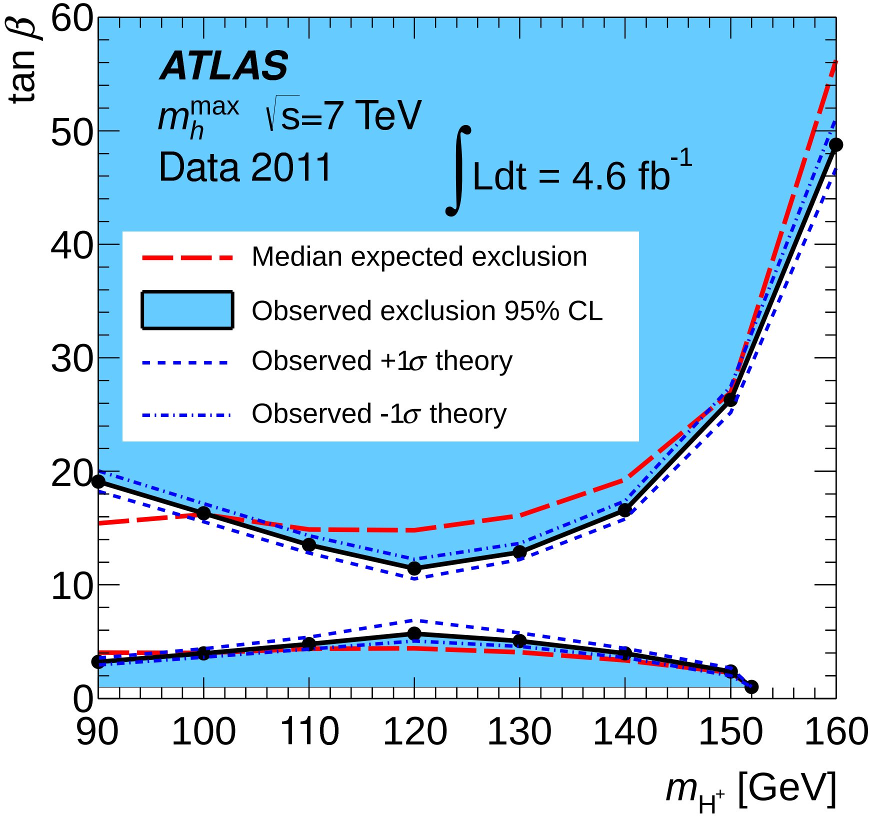
CMS 1202.4083



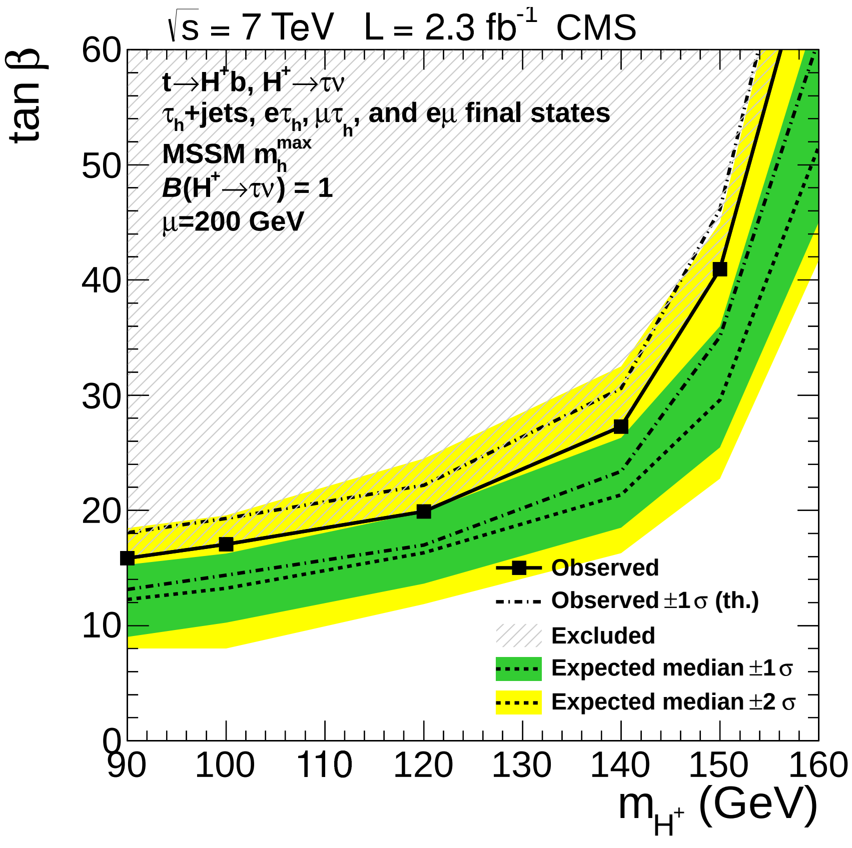
Search for MSSM Higgs Bosons at the LHC



ATLAS arXiv:1204.2760



CMS arXiv:1205.5736



$\mathcal{MSSM}$ $\mathcal{H}$iggs $\mathcal{M}$ass in $\mathcal{V}$iew of the $\mathcal{LHC}$ $\mathcal{R}$esults

- **Vast literature on MSSM Higgs of $\sim 122...128$ GeV**

  Arbey eal; Li eal; Feng eal; Baer eal; Hall eal; Albornoz Vasquez eal; Heinemeyer eal; Desai et al.; Draper eal; Carena eal; Cao eal; Christensen eal; Kadastik eal; Buchmuller eal; Arvanitaki eal; Ellis eal; Curtin eal; ...

- **MSSM Higgs mass corrections**

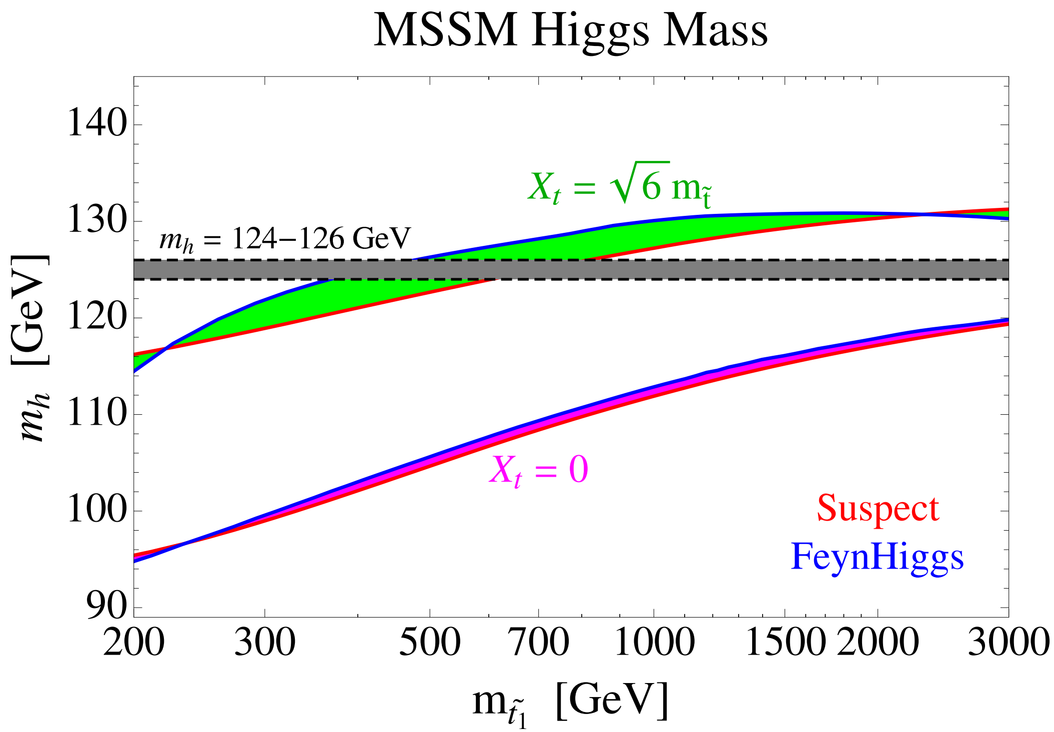
$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \Delta m_h^2$$

$\Rightarrow M_H \approx 125$ GeV requires

$\Delta m_h \approx 85$ GeV ($\tan\beta$ large) $\Rightarrow$ large corrections $\rightsquigarrow$ finetuning

$\mathcal{MSSM}$ $\mathcal{H}$iggs $\mathcal{M}$ass in $\mathcal{V}$iew of the $\mathcal{LHC}$ $\mathcal{R}$esults

Hall,Pinner,Ruderman 1112.2703



Maximal stop mixing:
$m_{\tilde{t}_1} \overset{!}{\gtrsim}$ 500 GeV

- **Further remarks:**
  - next-lightest Higgs can be SM-like 122-128 GeV Higgs (low M_A, moderate $\tan\beta$) lightest Higgs below LEP limit see e.g. Heinemeyer eal '11
  - enhanced diphoton rate can be achieved within MSSM w/ light staus Carena eal '11
  - $\gamma\gamma$ excess, but no WW excess requires New Physics beyond MSSM Christensen eal '12

Which Higgs Boson?

UnHiggs

Private Higgs

Little Higgs

Gaugephobic Higgs

Intermediate Higgs

Littlest Higgs

Slim Higgs

Composite Higgs

Fat Higgs

Higgsless

Portal Higgs

Gauge Higgs

Twin Higgs

Lone Higgs

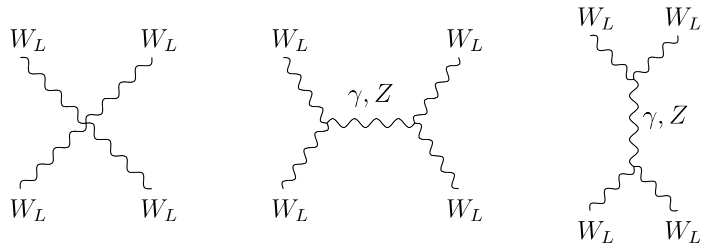
Simplest Higgs

Phantom Higgs

Composite Higgs Boson

$\mathcal{W}$hat is the $\mathcal{SM}$ and what the $\mathcal{C}$omposite $\mathcal{H}$iggs $\mathcal{B}$oson?

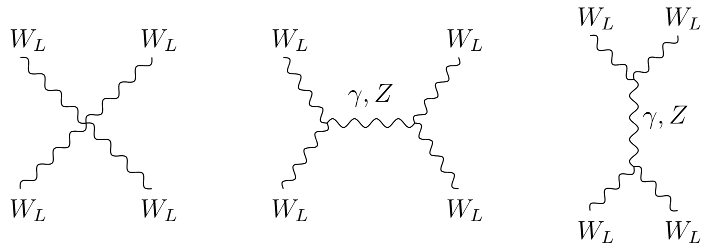
- **Higgs boson: creation of particle masses**



$$\mathcal{A} = \frac{s}{v^2}$$

What is the SM and what the Composite Higgs Boson?

- **Higgs boson: creation of particle masses**



$$\mathcal{A} = \frac{s}{v^2}$$

- **Electroweak symmetry breaking $\mathcal{L}$** Cornwall eal; Contino,Grojean,Moretti,Piccinini,Rattazzi

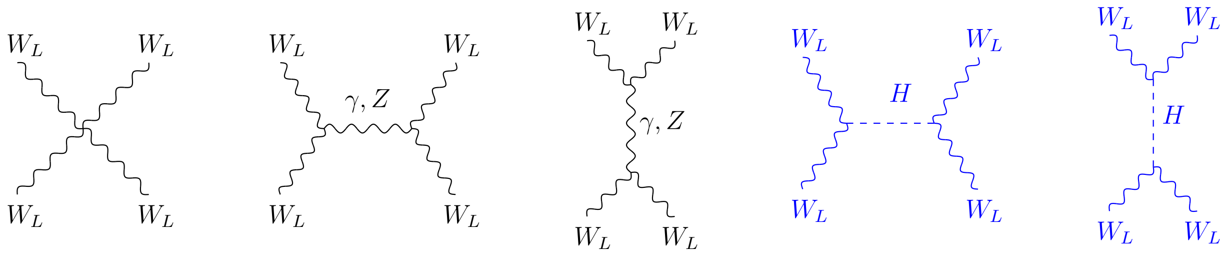
  custodial symmetry and minimal flavour violation (MFV) built-in

$$\mathcal{L}_{\text{EWSB}} = \frac{v^2}{4}\mathrm{Tr}(D_\mu \Sigma^\dagger\, D^\mu \Sigma)\left(1 + 2\,a\,\frac{h}{v} + b\,\frac{h^2}{v^2}\right) - \lambda \bar{\psi}_L \Sigma\, \psi_R \left(1 + c\,\frac{h}{v}\right)$$

$\Sigma = e^{i\sigma^a \pi^a / v}$ Goldstone of $SU(2)_L \times SU(2)_R / SU(2)_V$

$\mathcal{W}$hat is the $\mathcal{SM}$ and what the $\mathcal{C}$omposite $\mathcal{H}$iggs $\mathcal{B}$oson?

- **Higgs boson: creation of particle masses**



$$\mathcal{A} = \frac{1}{v^2}\left(s - \frac{a^2 s^2}{s - m_h^2}\right)$$

- **Electroweak symmetry breaking $\mathcal{L}$** Cornwall eal; Contino,Grojean,Moretti,Piccinini,Rattazzi
  custodial symmetry and minimal flavour violation (MFV) built-in

$$\mathcal{L}_{\text{EWSB}} = \frac{v^2}{4}\mathrm{Tr}(D_\mu \Sigma^\dagger D^\mu \Sigma)\left(1 + 2\,a\,\frac{h}{v} + b\,\frac{h^2}{v^2}\right) - \lambda \bar{\psi}_L \Sigma\, \psi_R \left(1 + c\,\frac{h}{v}\right)$$

$\Sigma = e^{i\sigma^a \pi^a / v}$ Goldstone of $SU(2)_L \times SU(2)_R / SU(2)_V$

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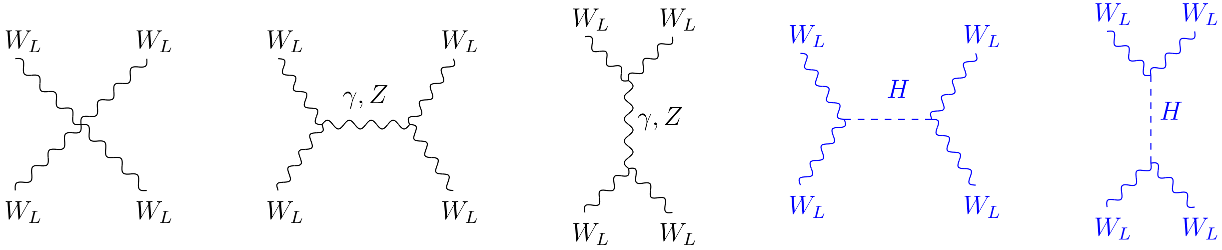
- **Higgs boson: creation of particle masses**



$$\mathcal{A} = \frac{1}{v^2}\left(s - \frac{a^2 s^2}{s - m_h^2}\right)$$

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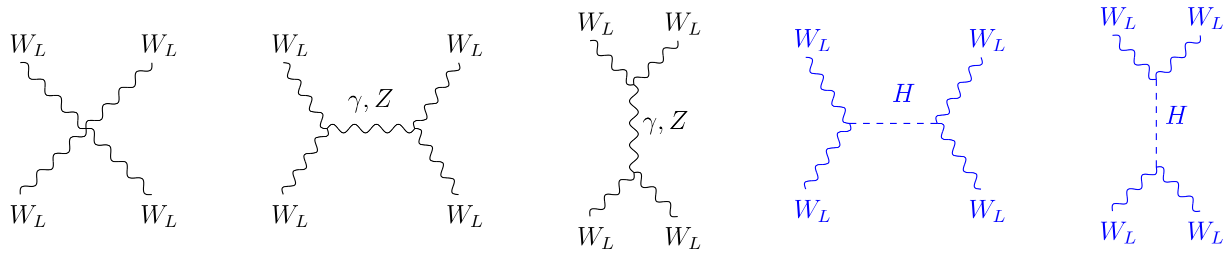
$a = 1$ perturbative unitarity in $WW \to WW$

$b = a^2$ perturbative unitarity in $WW \to hh$

$ac = 1$ perturbative unitarity in $WW \to \psi\psi$

$\mathcal{W}$hat is the $\mathcal{SM}$ and what the $\mathcal{C}$omposite $\mathcal{H}$iggs $\mathcal{B}$oson?

- **Higgs boson: creation of particle masses and UV regulator**



$$\mathcal{A} = \frac{m_h^2}{v^2}$$

- **Electroweak symmetry breaking $\mathcal{L}$** Cornwall eal; Contino,Grojean,Moretti,Piccinini,Rattazzi

custodial symmetry and minimal flavour violation (MFV) built-in

$$\mathcal{L}_{\text{EWSB}} = \frac{v^2}{4}\text{Tr}(D_\mu\Sigma^\dagger D^\mu\Sigma)\left(1 + 2\,a\,\frac{h}{v} + b\,\frac{h^2}{v^2}\right) - \lambda\bar{\psi}_L\Sigma\,\psi_R\left(1 + c\,\frac{h}{v}\right)$$

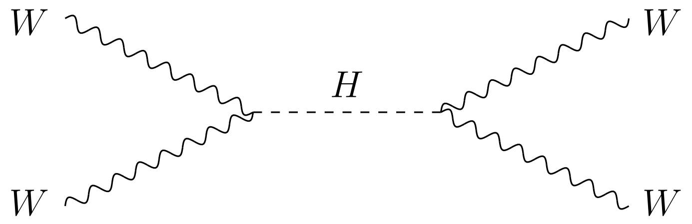
$a = 1$	perturbative unitarity in $WW \to WW$
$b = a^2$	perturbative unitarity in $WW \to hh$
$ac = 1$	perturbative unitarity in $WW \to \psi\psi$

SM Higgs boson: $a = b = c = 1$
Composite Higgs boson: $a, b, c \neq 1$

$\mathcal{C}$omposite $\mathcal{H}$iggs

What guarantees the unitarity of the WW scattering amplitude?

Weakly coupled models

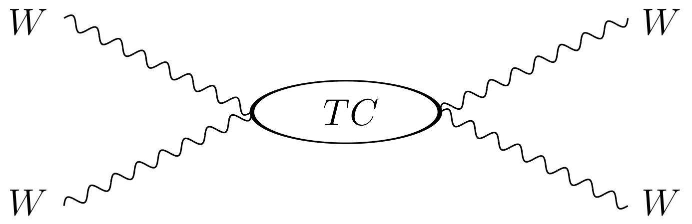


$\mathcal{S}$USY, ...

SUSY Partner ~ 100 GeV

New particles necessary to stabilise the Higgs mass

Strongly coupled models



$\mathcal{T}$echnicolor

rho meson ~ 1 TeV

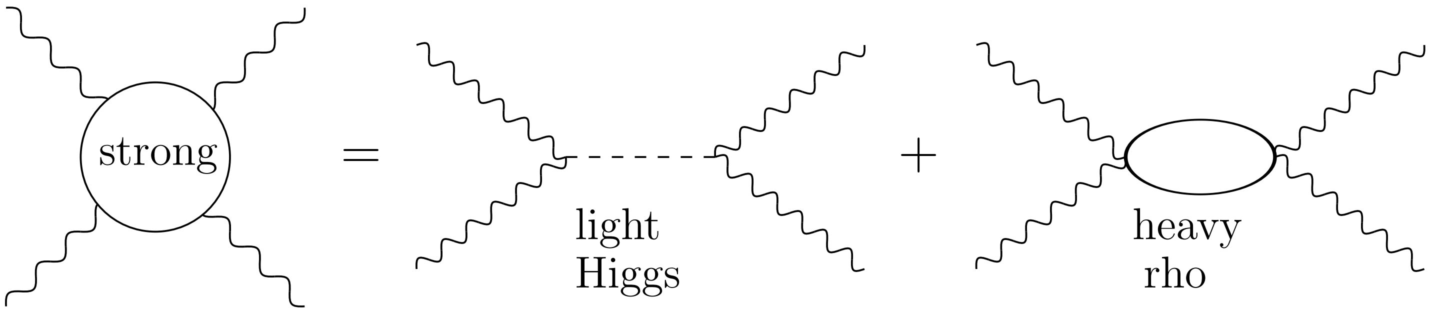
Resonances for unitarity generate EW corrections

$\mathcal{C}$omposite $\mathcal{H}$iggs

$\mathcal{C}$omposite $\mathcal{H}$iggs

Georgi,Kaplan

Higgs = Composite Object couplings deviate from pointlike scalar;
pseudo-Goldstone boson of strong sector



Unitarity restored half-way between weak and strong unitarity

- $\neq$ SUSY: composite particle $\rightsquigarrow$ no naturalness problem $\rightsquigarrow$ no new particles necessary for this
- $\neq$ Technicolor: amplitude partly cancelled by Higgs $\rightsquigarrow$ ρ heavier $\rightsquigarrow$ smaller corrections to S, T-parameter

Composite Higgs Boson

- **How can we obtain a light composite Higgs?**

Higgs: Pseudo-Goldstone boson of strongly interacting sector

$$\text{Global symmetry of strong sector } G \xrightarrow[]{\text{spontaneously broken at } f} \text{subgroup } H$$

G/H: 4th Nambu-Goldstone Boson: Higgs boson

- **Possible symmetry patterns**

$*$ H must contain SM gauge group

$*$ G must contain an $SU(2) \times SU(2) \sim SO(4)$ symmetry $\rightsquigarrow$ PGB is a Higgs doublet

Examples:

- $SO(5)/SO(4) \rightsquigarrow$ PGB: one doublet
- $SO(6)/SO(5) \rightsquigarrow$ PGB: one doublet + singlet
- ...

$\mathcal{C}$omposite $\mathcal{H}$iggs $\mathcal{B}$oson - $\mathcal{P}$hysics

- **SILH effective Lagrangian** Giudice,Grojean,Pomarol,Rattazzi
  (SILH=strongly interacting light Higgs)

- **Genuine strong operators** (sensitive to the scale f)

$$\frac{c_H}{2f^2}(\partial_\mu(|H|^2))^2 + \frac{c_T}{2f^2}(H^\dagger \overleftrightarrow{D^\mu})^2 + \left(\frac{c_y y_f}{f^2}|H|^2 \bar{f}_L H f_R + h.c.\right) + \frac{c_6 \lambda}{f^2}|H|^6$$

- **Form factor operators** (sensitive to the scale m_ρ)

$$\frac{ic_w g}{2m_\rho^2}(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H)(D^\nu W_{\mu\nu})^i + \frac{ic_B g'}{2m_\rho^2}(H^\dagger \overleftrightarrow{D^\mu} H)(\partial^\nu B_{\mu\nu}) + \ldots$$

$c_H, c_T, \ldots$: $\mathcal{O}(1)$, MFV built in (no FCNC)

- **Contribution to Higgs kinetic term:** $\frac{c_H}{2f^2}(\partial_\mu(|H|^2))^2$

  Rescale Higgs field $\rightsquigarrow$ $g_{Hf\bar{f}} = g^{SM}_{Hf\bar{f}}\left(1 - (c_y + c_H/2)\frac{v^2}{f^2}\right)$ $g_{HWW} = g^{SM}_{HWW}\left(1 - c_H\frac{v^2}{f^2}\right)$

Higgs Anomalous Couplings

- **SILH effective Lagrangian** — Giudice,Grojean,Pomarol,Rattazzi
- **Large ξ** 5D MCHM provides completion for large $\frac{v}{f}$ $(SO(5)/SO(4))$ — Contino eal; Agashe eal

- **Fermion couplings** depend on embedding into representations of the bulk symmetry

spinorial representations of $SO(5)$	fundamental representations of $SO(5)$
MCHM4	MCHM5

MCHM4	MCHM5
$g_{HVV} = g^{SM}_{HVV}\sqrt{1-\xi}$ $g_{Hff} = g^{SM}_{Hff}\sqrt{1-\xi}$	$g_{HVV} = g^{SM}_{HVV}\sqrt{1-\xi}$ $g_{Hff} = g^{SM}_{Hff}\frac{(1-2\xi)}{\sqrt{1-\xi}}$
universal factor $\rightsquigarrow$ BRs unchanged	g_{Hff} coupling vanishes for $\xi = 0.5$

In the following: $\xi = 0.2, 0.5, 0.8$

- **Impact on** BR's, Γ_{tot}, production cross sections, Higgs search significances

Constraints

- **EW precision observables:** constrain only a
  - $*$ $\hat{T} = c_T \frac{v^2}{f^2} \Rightarrow |c_T \frac{v^2}{f^2}| < 2 \times 10^{-3}$ removed by custodial symmetry
  - $*$ $\hat{S} = (c_W + c_B) \frac{m_W^2}{m_\rho^2}$ $m_\rho \geq (c_W + c_B)^{1/2} 2.5$ TeV
  - $\star$ 1-loop IR effects Barbieri eal

    $\Delta\epsilon_{1,3} = -c_{1,3}(1-a^2)\log(m_\rho^2/m_h^2)$ constrains a

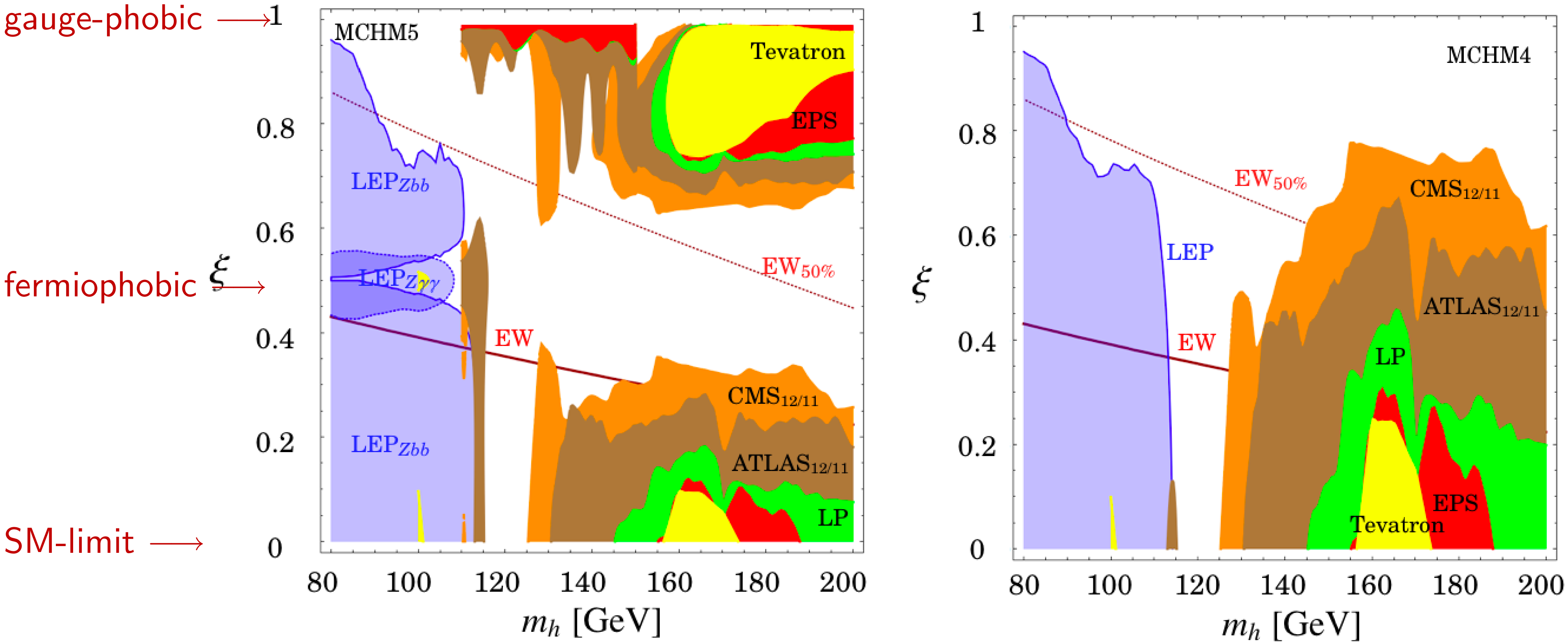
- **Flavor constraints**
  - $*$ no tree-level FCNC c is flavor universal $\rightarrow$ MFV built in

- **Direct searches LEP, Tevatron, LHC:** constrain a and c

  [rescale σ_{prod} and Γ_{decay}, add channels in quadrature]

$\mathcal{C}$onstraints from EWPT, LEP, Tevatron, LHC - $\mathcal{P}$re-$\mathcal{M}$oriond '12

Espinosa,Grojean,MMM



CMS 12/11 ATLAS 12/11 Lepton-Photon 11

LEP EPS-HEP 11 Tevatron

$\mathcal{H}$ow to test $\mathcal{C}$omposite $\mathcal{N}$ature of the $\mathcal{H}$iggs $\mathcal{B}$oson?

- **Resonances**

  Production of heavy resonances m_ρ

- **Coupling modifications:**

  ◇ modification of production and decay rates*

  LHC/300 fb^{-1}: $\delta g \approx 20 - 40\%$ Dührssen eal. $\rightsquigarrow$ probe $4\pi f = 5 - 7$ TeV

  ILC/500 GeV $\rightsquigarrow$ probe $4\pi f \sim 30$ TeV, $\delta\lambda_{HHH} \sim 10 - 20\%$ Barger eal

  CLIC/3 TeV $\rightsquigarrow$ improve sensitivity by factor 2

  Composite Higgs model: accuracy of couplings 20-30% (30 fb^{-1}) Bock eal

  ◇ strong WW scattering: $W_L W_L \to W_L W_L$

  difficult: disentangle L from T polarization Giudice eal; Han eal

  ◇ strong HH production: $W_L W_L \to HH$

  SLHC/5 ab^{-1}: $3l$ final state: rather clean signal $\xi > 0.5$ Contino eal

  * no direct probe of strong sector at origin of EWSB

- **Impact on Higgs boson searches at the LHC** Espinosa,Grojean,Mühlleitner

$\mathcal{I}$s it the $\mathcal{SM}$ $\mathcal{H}$iggs $\mathcal{B}$oson?

- **Effective Lagrangian** valid at $E \sim m_t$
  - $*$ consider effective $\mathcal{L}$ w/ a light scalar resonance and Goldstone bosons associated with EWSB and the SM field content
  - $*$ minimal description: effective chiral $\mathcal{L}$ w/ a nonlinear realisation of $SU(2) \times U(1)_Y$

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}(D_\mu \Sigma^\dagger D^\mu \Sigma)\left[1 + 2\,a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + b_3\,\frac{h^3}{v^3} + \cdots\right],$$

$$-\frac{v}{\sqrt{2}}\,(\bar{u}^i_L \bar{d}^i_L)\,\Sigma\,\left[1 + c\,\frac{h}{v} + c_2\,\frac{h^2}{v^2} + \cdots\right]\begin{pmatrix} y^u_{ij}\,u^j_R \\ y^d_{ij}\,d^j_R \end{pmatrix} + h.c., \quad \text{with}$$

$$V(h) = \frac{1}{2}\,m_h^2\,h^2 + \frac{d_3}{6}\left(\frac{3\,m_h^2}{v}\right)h^3 + \frac{d_4}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \cdots$$

a characterises deviation from SM Higgs coupling to the gauge bosons (SM: a=1)
c characterises deviation from SM Higgs coupling to the fermions (SM: c=1)

- Incorporates $SU(2)_L \times U(1)_Y \to U(1)_{em}$ symmetry breaking
- $+$ custodial symmetry
- $y^{u,d}_{ij} \to y^{u,d}\delta_{ij}$: no tree-level FCNC from h exchange

Model-Independent Fit to (Moriond) LHC Data

Effective theory assuming: custodial symmetry & MFV

Espinosa, Grojean, MMM, Trott '12

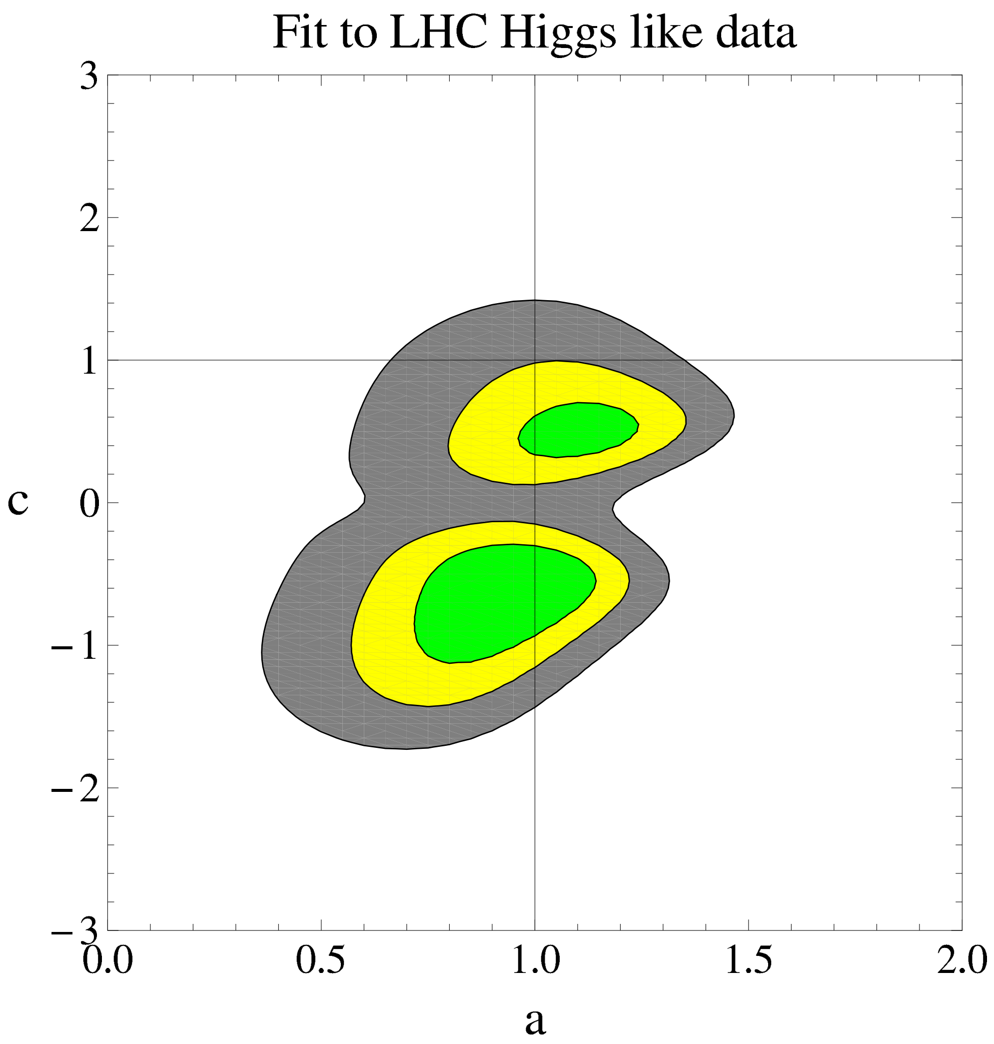
(green/yellow/gray)
(65/90/99% CL)

SM 88%CL away
from best fit point

Two minima:

$(a, c) = (1.18, 0.55)$
$\chi^2 = 7.5$

$(a, c) = (0.99, -0.64)$
$\chi^2 = 6.3$



Note: a fermiophobic Higgs is disfavoured by data

for similar analyses, see also

Azatov, Contino, Galloway '12
Carmi, Falkowski, Kuflik, Volansky '12
Ellis, You '12; Giardino eal '12

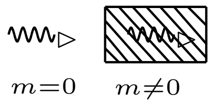
$\mathcal{N}$ext $\mathcal{S}$teps in $\mathcal{E}$xperimental $\mathcal{V}$erification of the $\mathcal{H}$iggs $\mathcal{M}$echanism

Higgs mechanism:

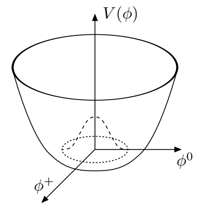
Creation of particle masses without violating gauge symmetries

Test of the Higgs mechanism

- Discovery – m
- Interaction with a scalar Higgs with $v = 246$ GeV$\neq 0$ $\rightsquigarrow$ $g_{HXX} \sim m_X$



- Spin and parity quantum numbers – J^{PC}
- EWSB requires Higgs potential – $\lambda_{HHH}, \lambda_{HHHH}$



$\mathcal{W}$ould require another lecture!

Thank you for your attention!