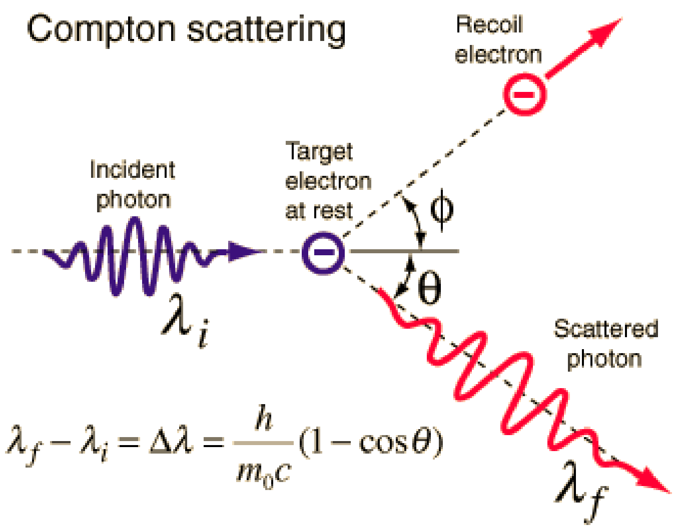
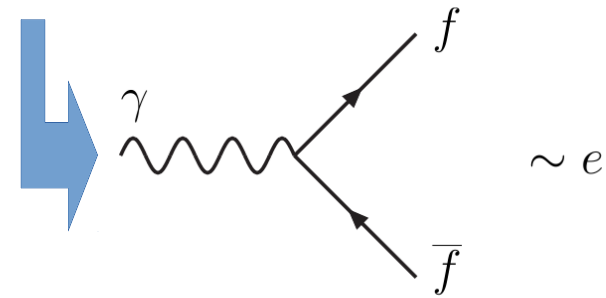
Higgs Boson(s) and Supersymmetry

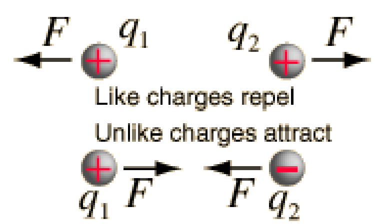
Quantum Electrodynamics

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \overline{\psi}_e \left[i\gamma^\mu (\partial_\mu - ieA_\mu) - m_e \right] \psi_e$$



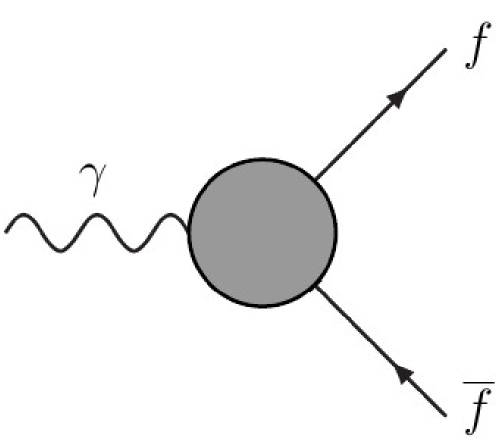
- Mass for the photon forbidden (gauge invariance).
- Mass for the electron allowed.





$$F = \frac{kq_1q_2}{r^2} = \frac{q_1q_2}{4\pi\varepsilon_0 r^2}$$ Coulomb's Law

Anomalous magnetic moment of the electron:



$$\frac{g_e - 2}{2} = F_2(0) = 0.00115965218076 \pm 0.00000000000027$$

D. Hanneke et.al. (2011)

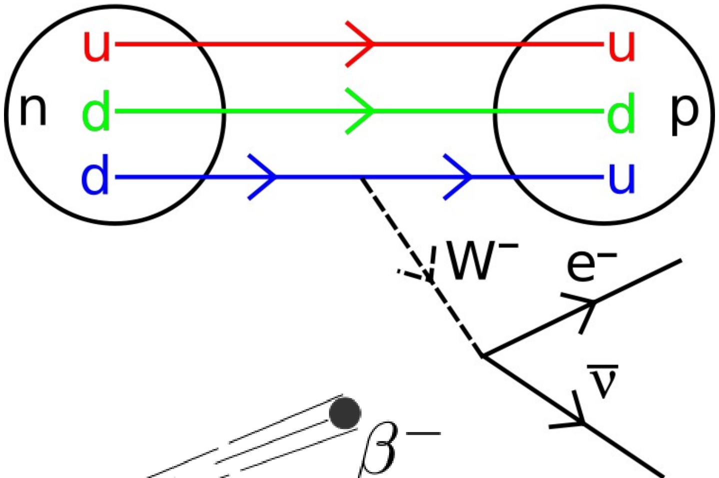
$$\sim \Gamma^\mu(q) = F_1(q^2)\gamma^\mu + \frac{F_2(q^2)}{2m_e} i\sigma^{\mu\nu} q_\nu$$

$$\left.\frac{g_e - 2}{2}\right|_{th} = 0.00115965218007 \pm 0.00000000000078$$

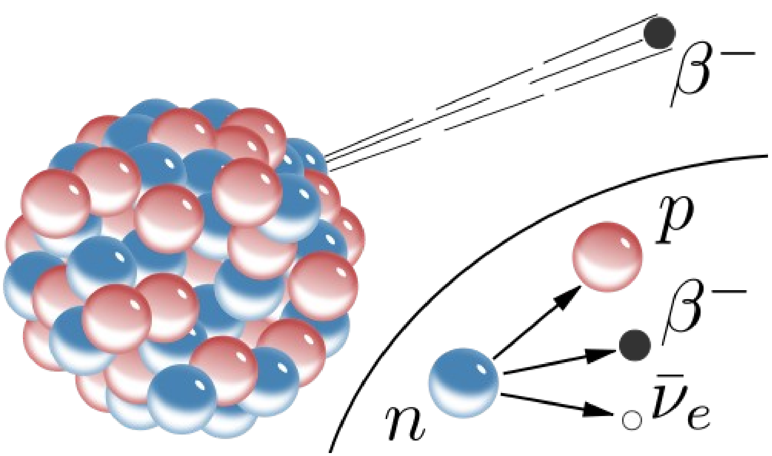
M. Hayakawa

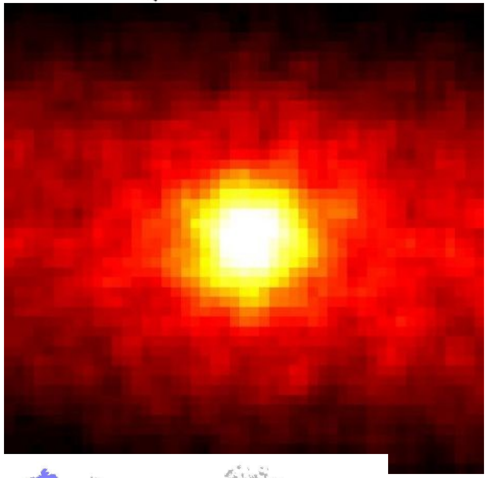
Weak Interactions

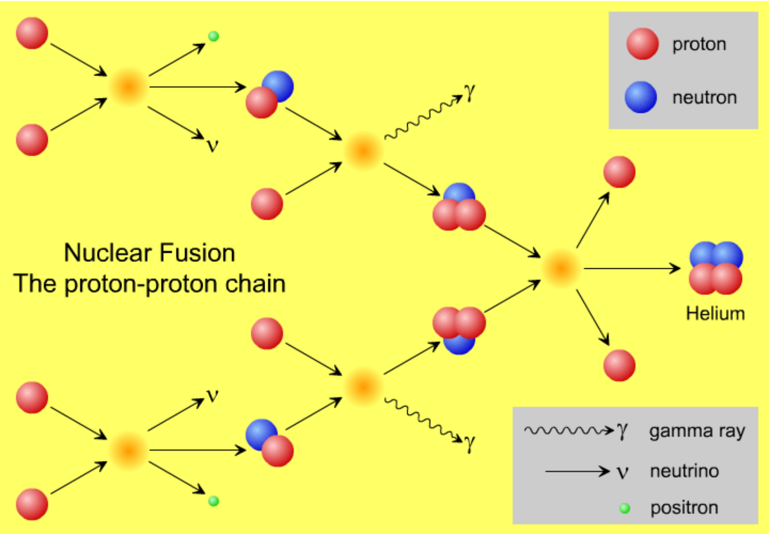
$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (\overline{\nu}_L\,\overline{e}_L)\,i\gamma^\mu\left(\partial_\mu - \frac{i}{2}g_1B_\mu\right)\begin{pmatrix}\nu_L\\ e_L\end{pmatrix} + \overline{e}_R i\gamma^\mu(\partial_\mu - ig_1B_\mu)e_R$$



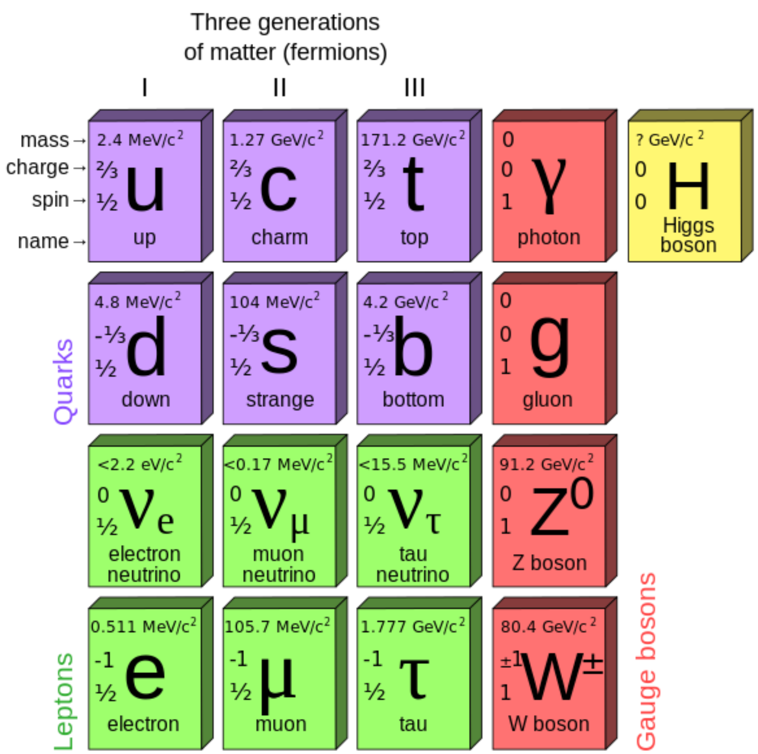
- Still cannot give mass to the gauge boson B, thus, neither to the Z gauge boson!
- Cannot write a mass term for the electron neither, due to the splitting between the left and right component.
- Need Brout-Englert-Higgs mechanism.

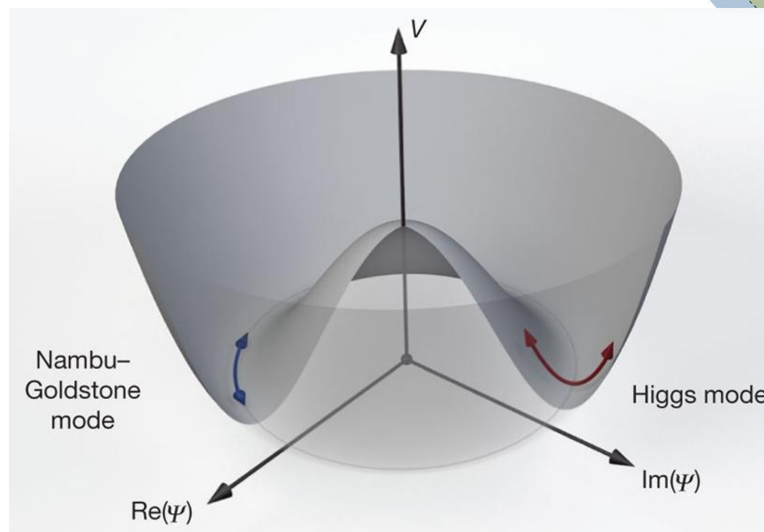


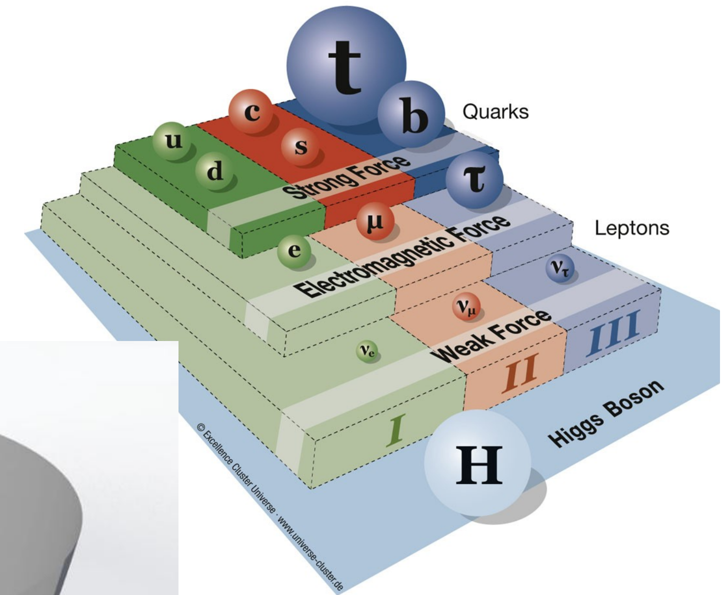




Higgs Mechanism

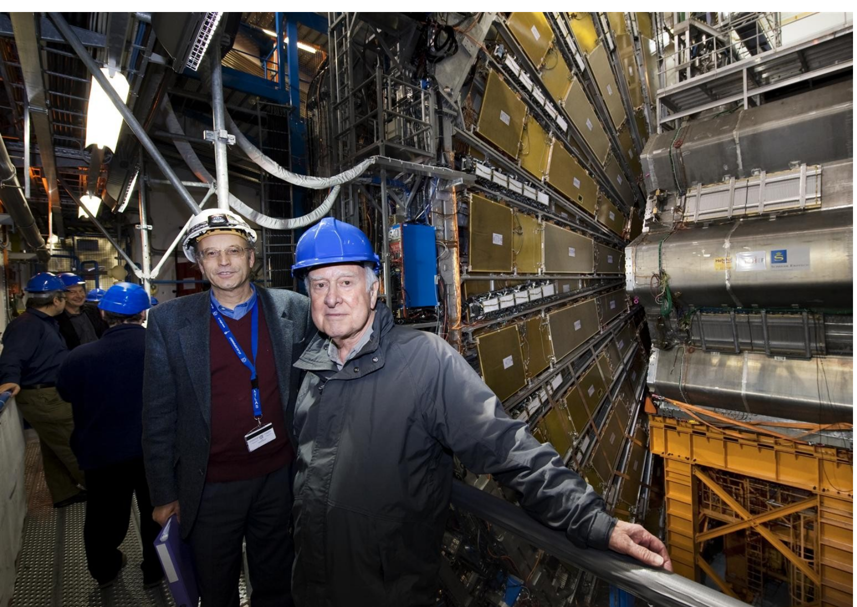






It does not explain why the masses are so different.

Simultaneous work: Englert y Brout.



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BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

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Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

In a recent note[1] it was shown that the Goldstone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if the conserved currents associated with the internal group are coupled to gauge fields. The purpose of the present note is to report that, as a consequence of this coupling, the spin-one quanta of some of the gauge fields acquire mass; the longitudinal degrees of freedom of these par-

about the "vacuum" solution $\varphi_1(x)=0$, $\varphi_2(x)=\varphi_0$:

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1)-e\varphi_0A_\mu\}=0, \tag{2a}$$

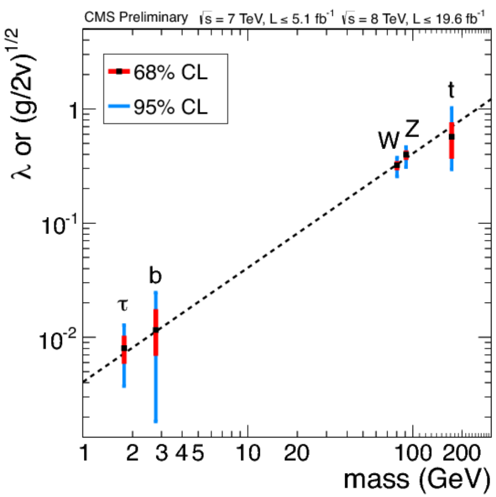
$$\{\partial^2-4\varphi_0^2V''(\varphi_0^2)\}(\Delta\varphi_2)=0, \tag{2b}$$

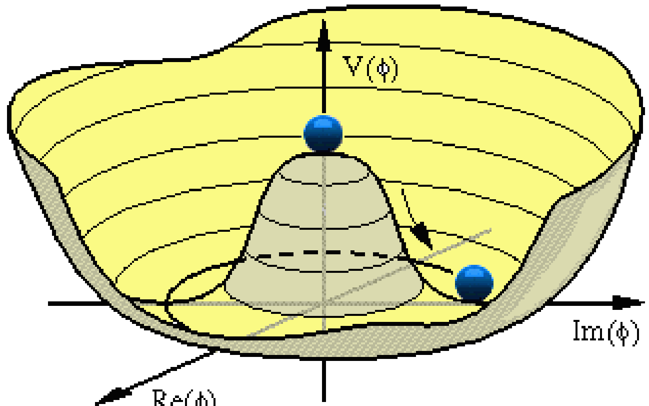
$$\partial_\nu F^{\mu\nu}=e\varphi_0\{\partial^\mu(\Delta\varphi_1)-e\varphi_0A_\mu\}. \tag{2c}$$

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0^2)\}^{1/2}$; Eqs. (2a) and (2c)

Higgs Potential

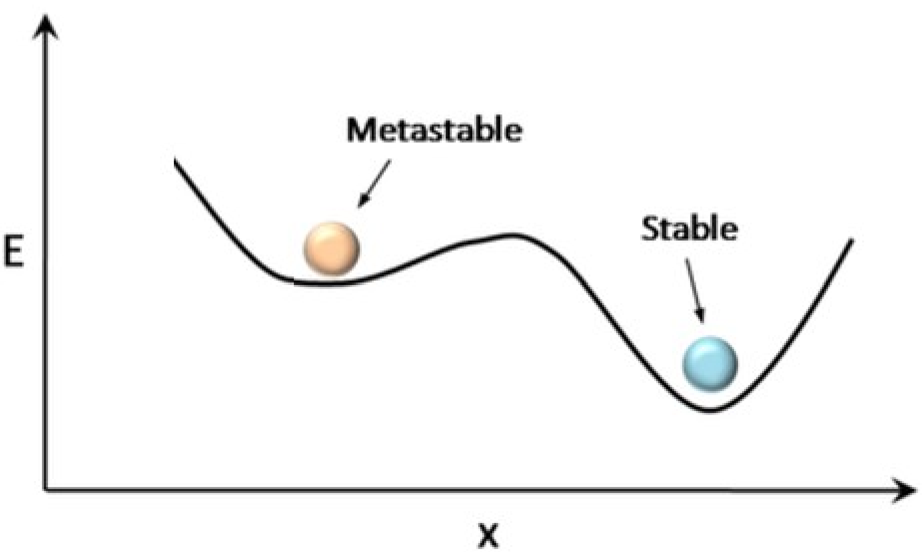
$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\left|(\partial_\mu + iyB_\mu)\phi\right|^2 + \frac{1}{2}\mu^2(\phi^\dagger\phi) - \frac{1}{4}(\phi^\dagger\phi)^2$$



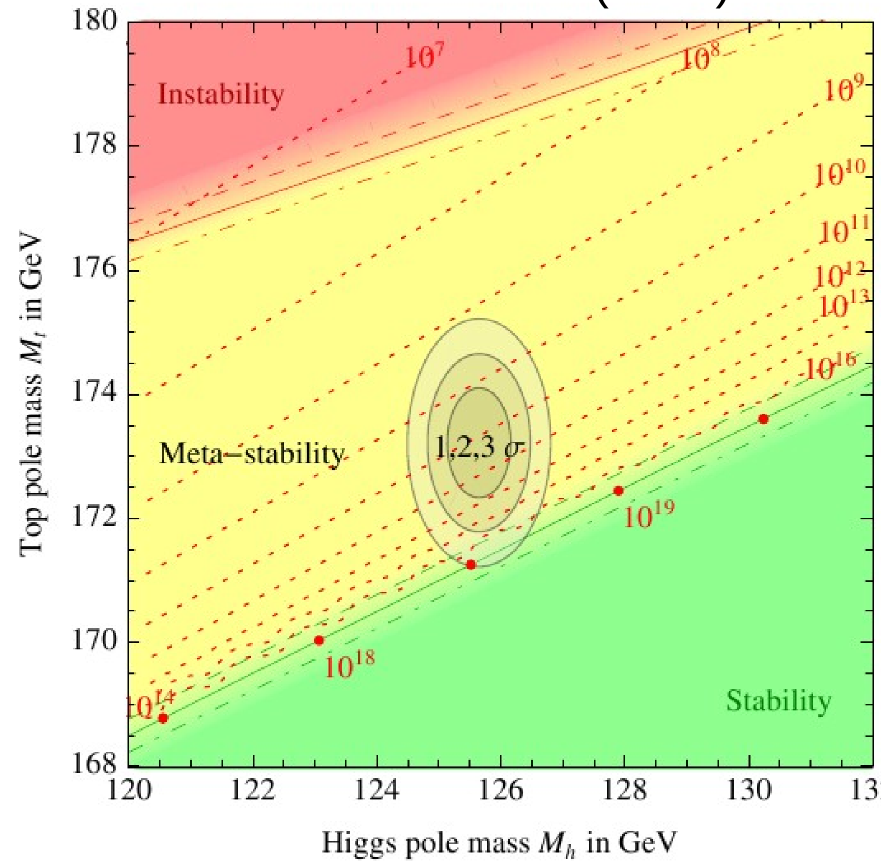


The field must have spin 0, and a non-zero vacuum expectation value.

$$\mathcal{L} = -f_e\psi_L^\dagger\phi\psi_R$$

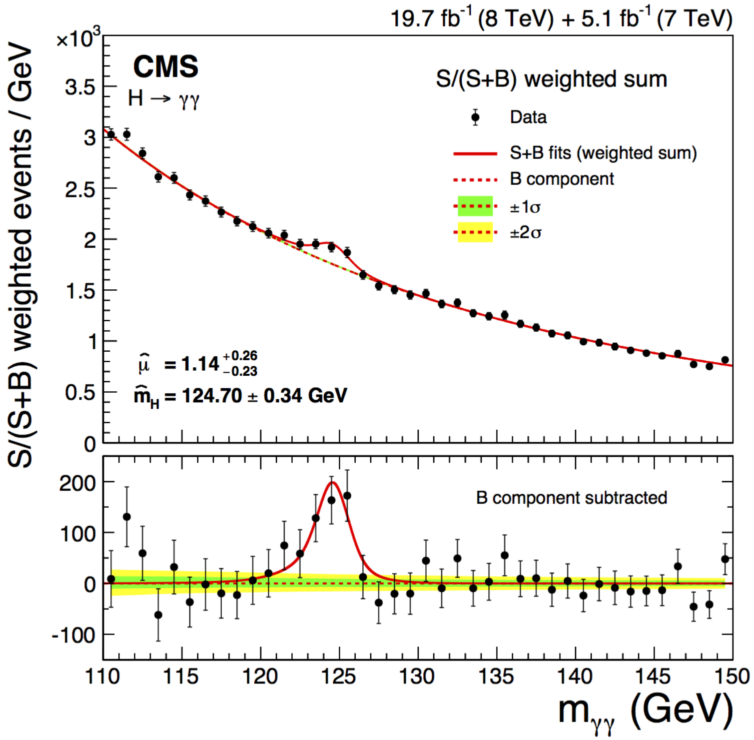


Buttazzo et.al. (2013)

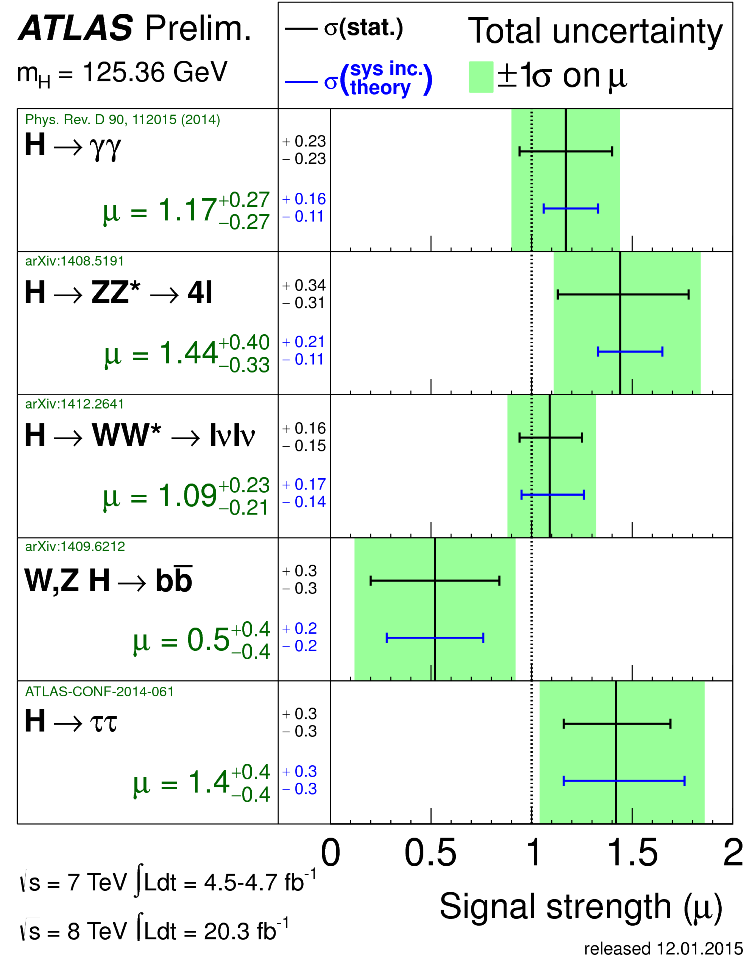


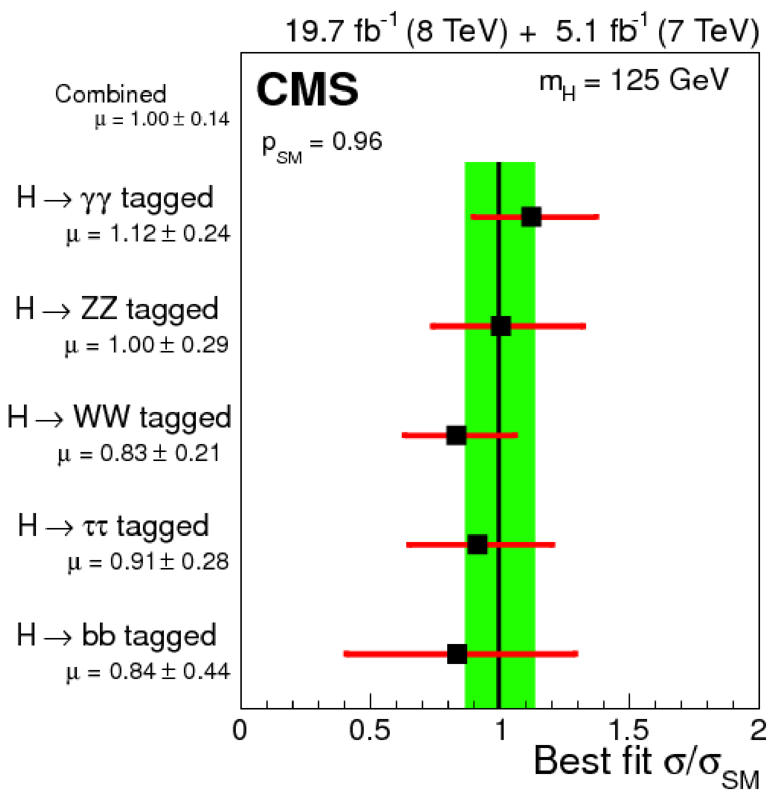
But, lifetime of meta-stable vacuum is very large!

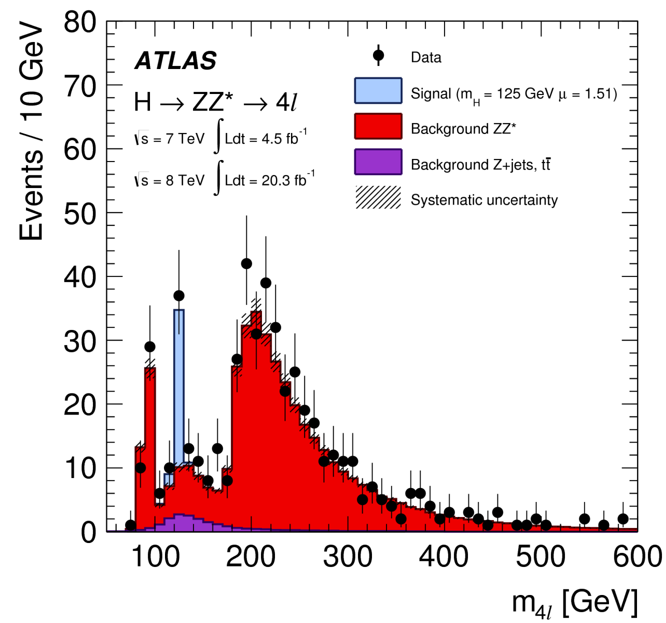
Higgs Boson



It is well established the existence of a scalar with Standard Model couplings and a mass ≈ 125 GeV.

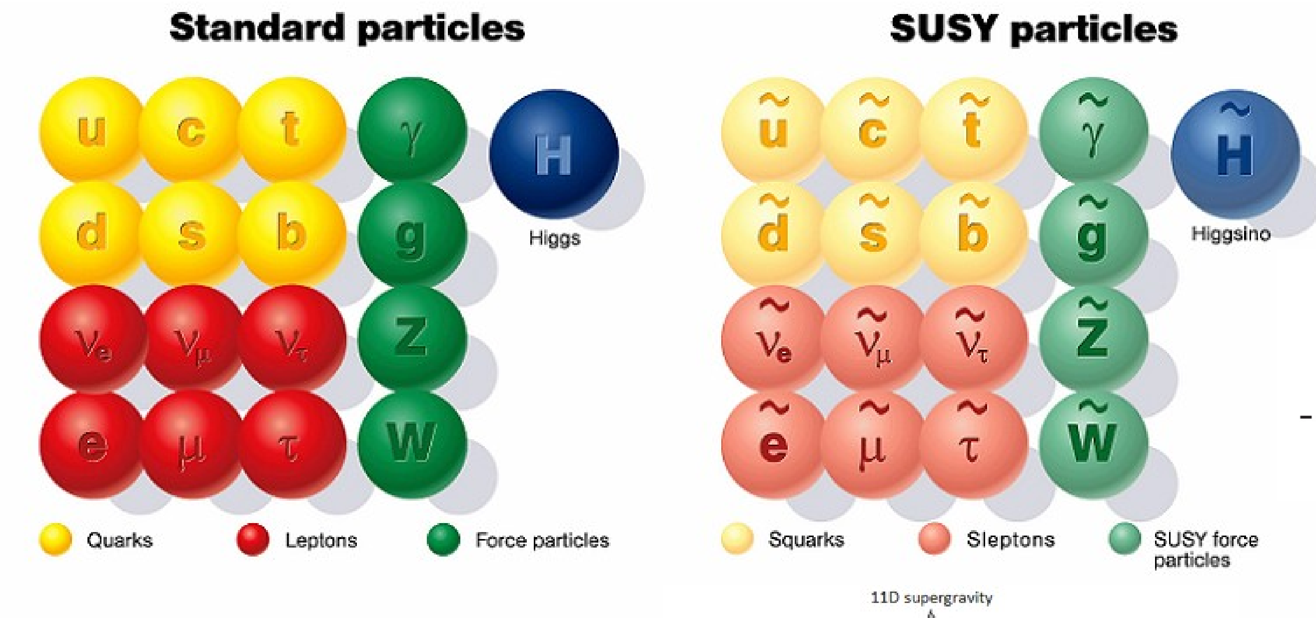


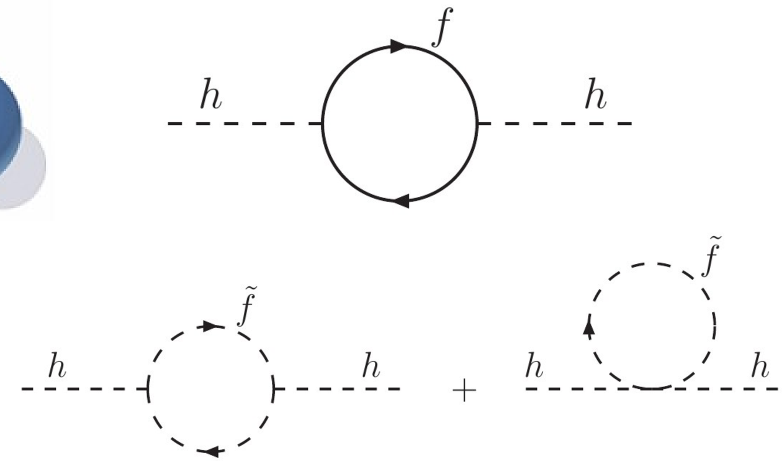




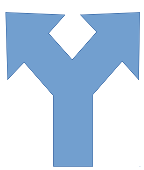
Evidence points to spin cero and couplings to fermions as well as gauge bosons.

Supersymmetry

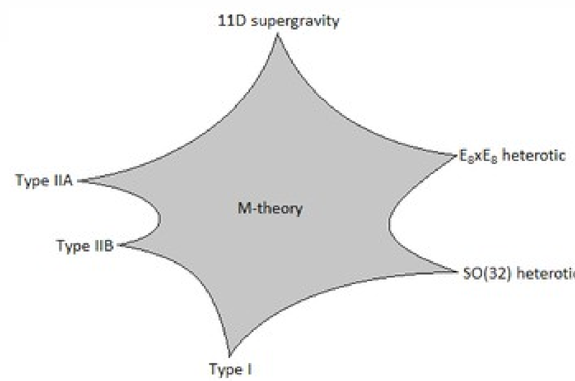


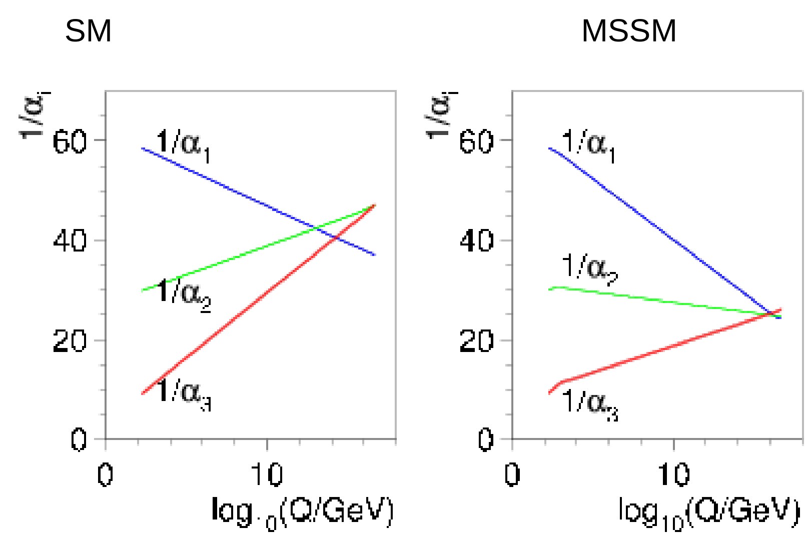


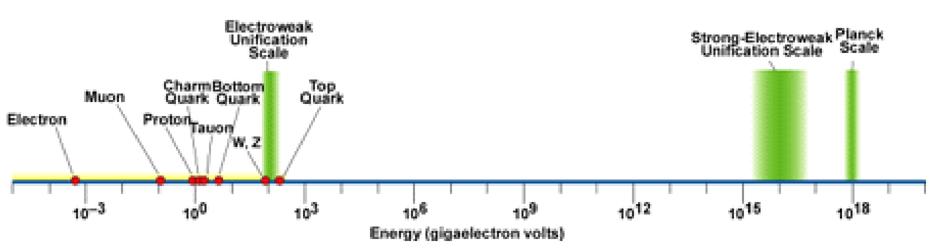
Neutralino Gravitino

Rp Conserving  Rp Violating

Dark Matter



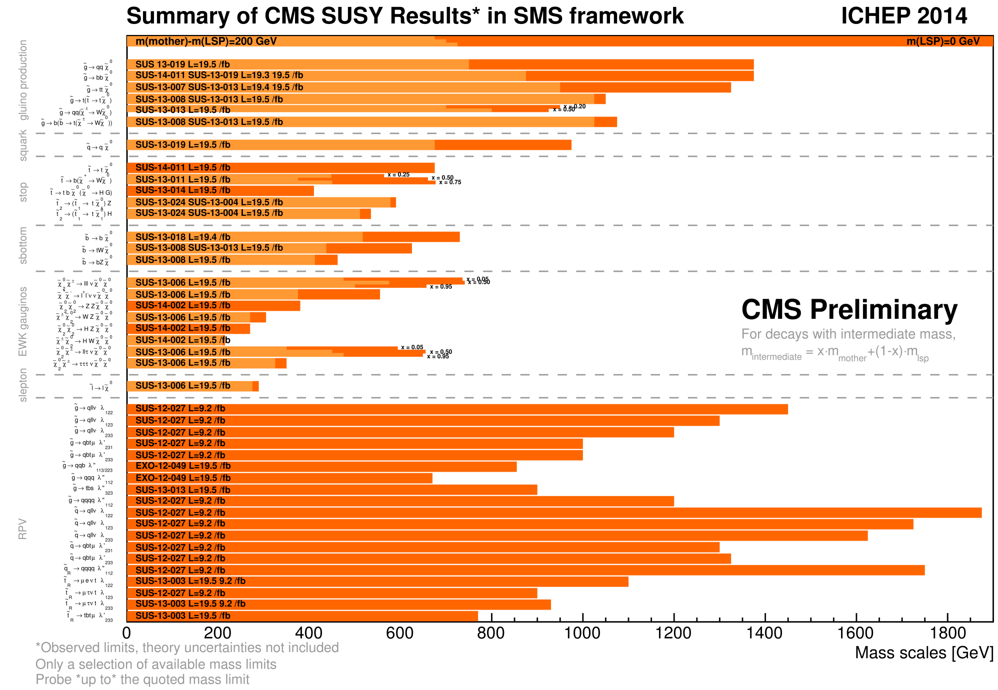


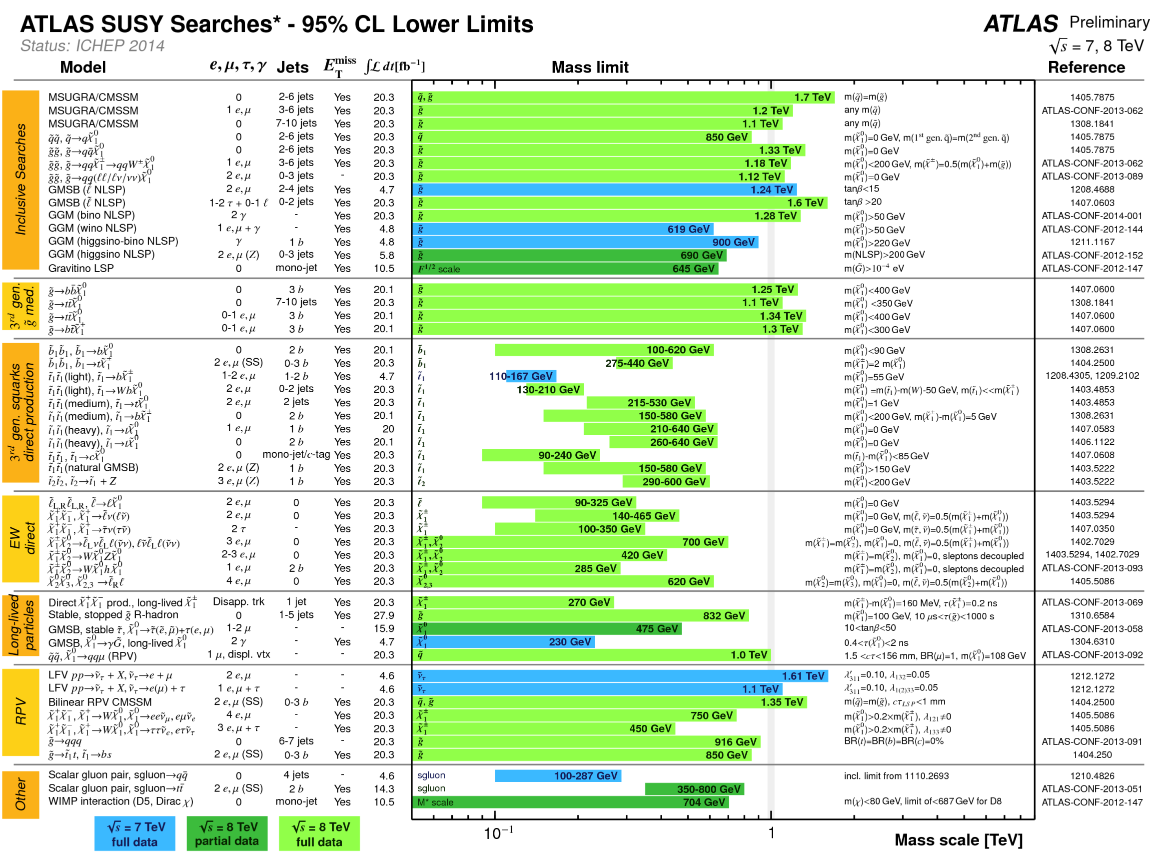


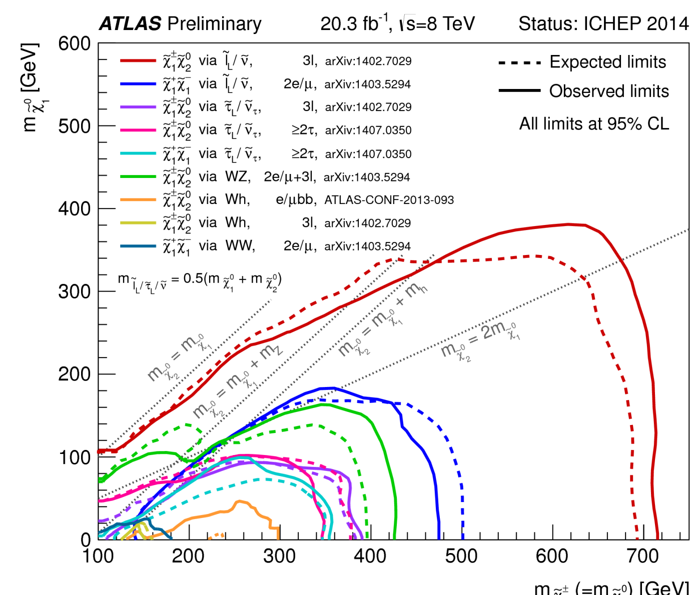
De Boer et.al. (2004)

Supersymmetric Searches

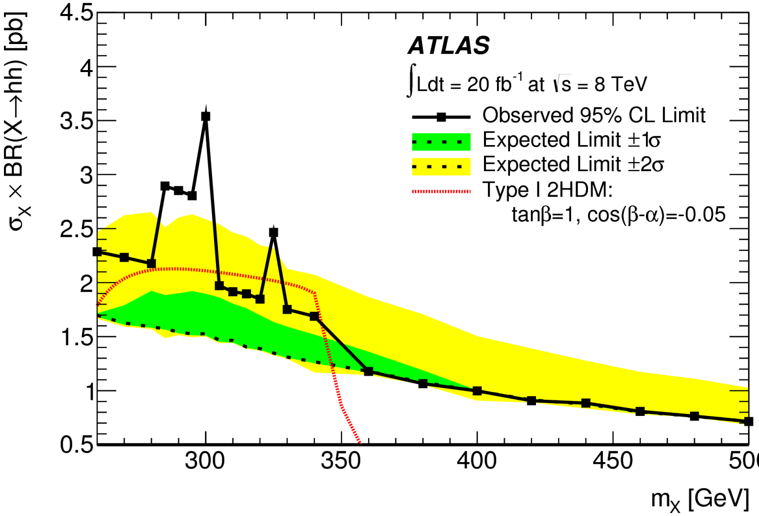
Squarks, sleptons, and gluinos seem to be heavier than ~1 TeV.





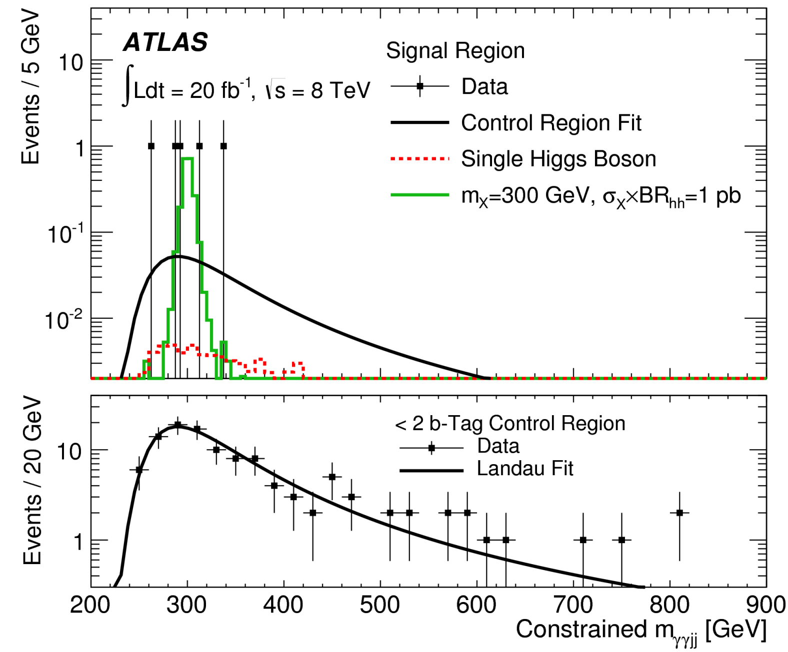


Mysteries

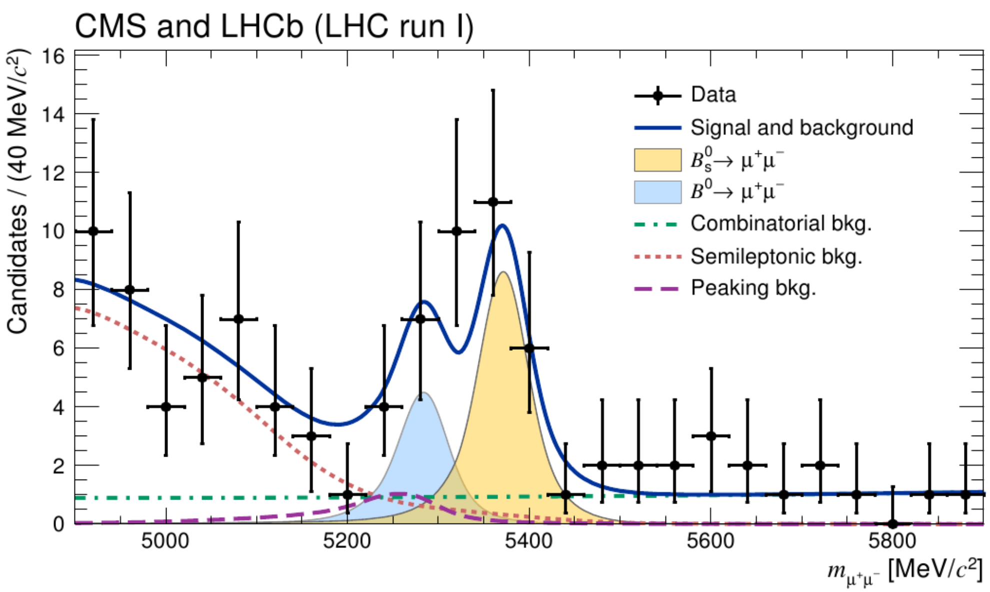


Triple Higgs coupling:

- $\gamma\gamma$bb-bar channel.
- hhh in SM is too low to be seen by the LHC.
- Hhh in 2HDM may be seen (excess?).
- arXiv:1406.5053



CMS and LHCb observe the rare decay Bs to mu mu (arXiv:1411.4413).

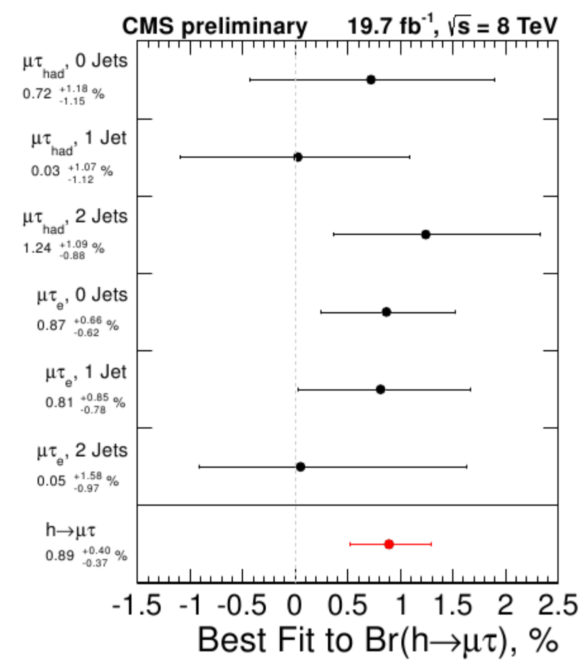


B(B→μμ) / B(Bs→μμ) too large!

Heavy squarks and gluinos
and low tan(β) (arXiv:1501.02044)?

$$B(H \to \mu\tau) = 0.0089 \pm 0.0040$$

~2.5 σ (CMS PAS HIG-14-005)

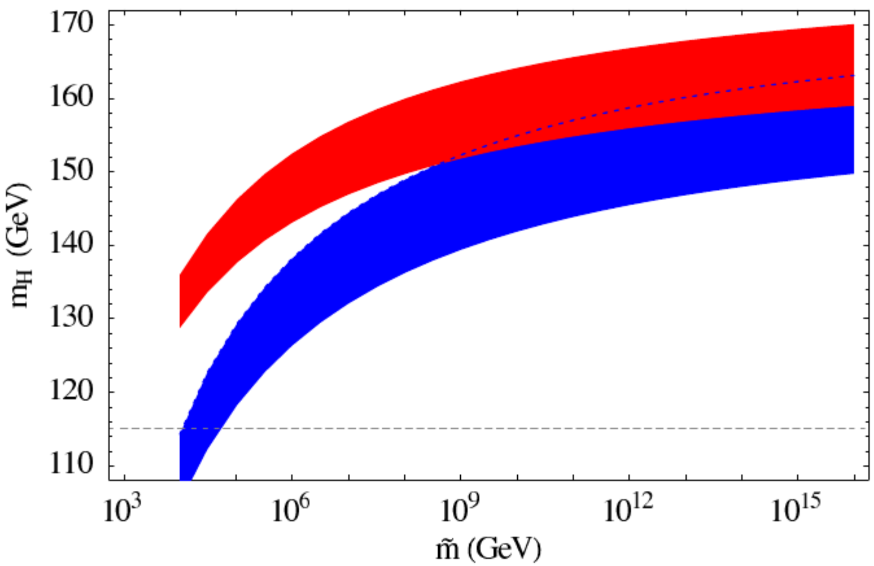


Heavy Supersymmetry

Split Supersymmetry

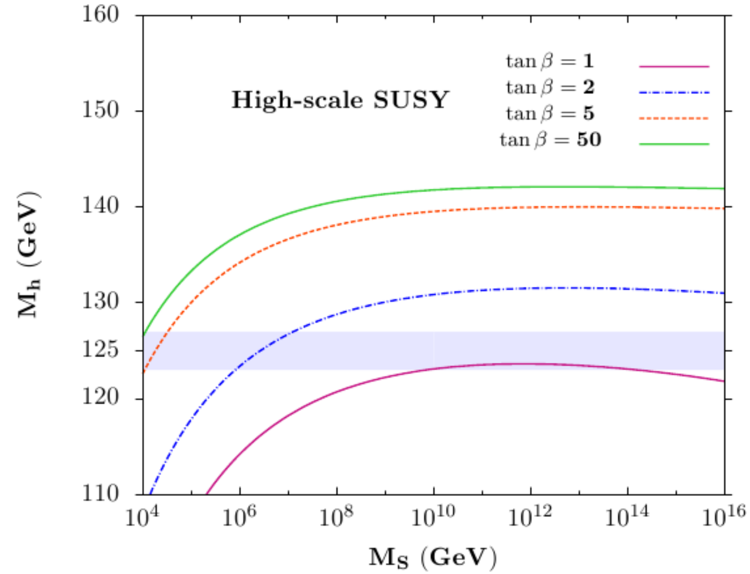
hep-th/0405159, hep-ph/0406088

- Gauge coupling unification
- Higgs boson SM-like
- Partial Split Susy: also neutrino masses from RpV (hep-ph/0605285).



High Scale Supersymmetry

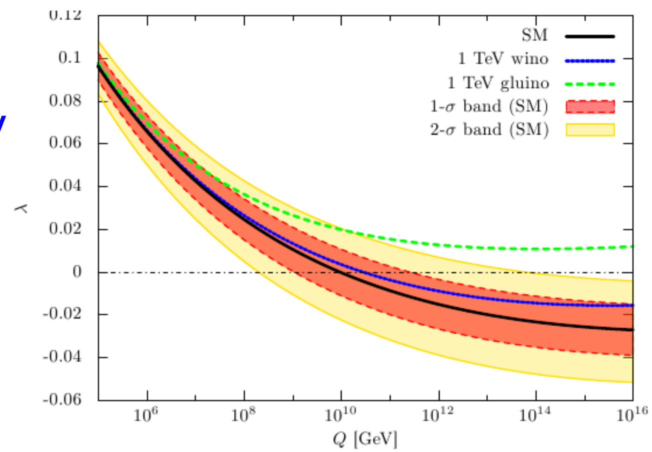
- All supersymetry partners are heavy.
- Plot taken from arXiv:1112.3028



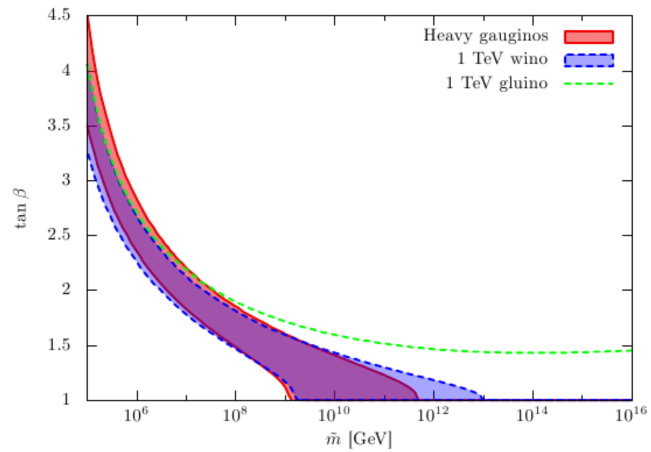
Intermediate Scale Supersymmetry

Hall et.al.

- Quartic Higgs coupling tends to zero at high scales.
- Gauge coupling unification.
- tan(beta) near unity.



(a) Higgs quartic coupling λ



(b) 1-σ band of tan β

Conclusions

- Discovered particle in 2012 looks like the Standard Model Higgs boson.
- Mysteries and unexplained excesses are seen. Next data will tell.
- Heavy Supersymmetry is a way to explain many shortcomings of the SM. Next data also will tell.