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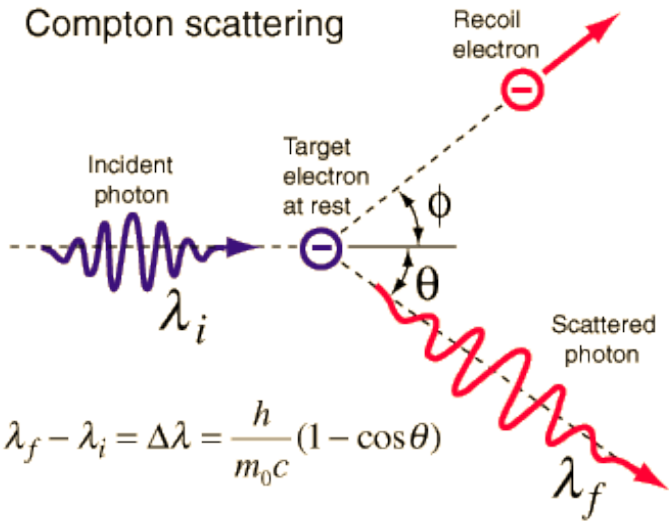


Higgs Boson(s) and Supersymmetry

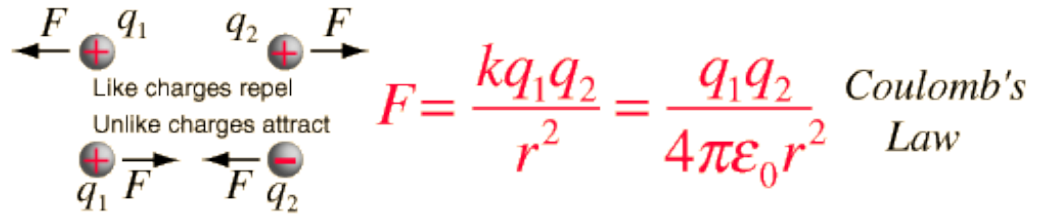
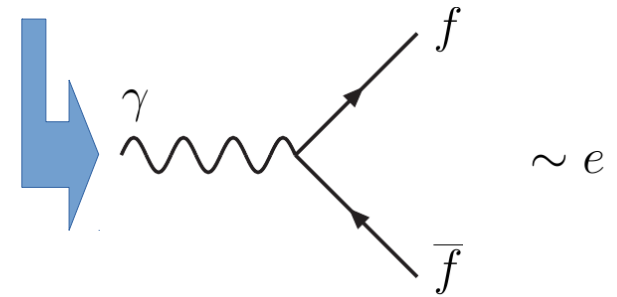


Quantum Electrodynamics

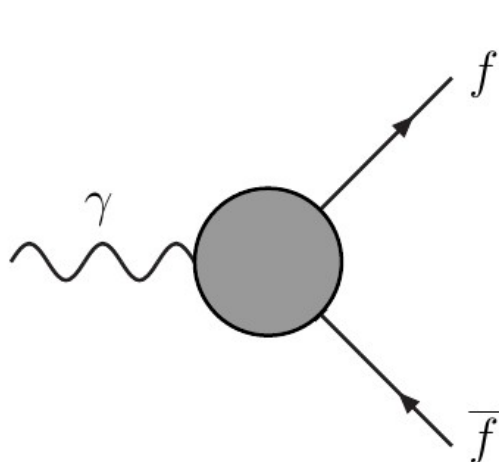
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}_e [i\gamma^\mu(\partial_\mu - ieA_\mu) - m_e] \psi_e$$



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



Anomalous magnetic moment of the electron:



$$\frac{g_e - 2}{2} = F_2(0) = 0.00115965218076 \pm 0.000000000000027$$

D. Hanneke et.al. (2011)

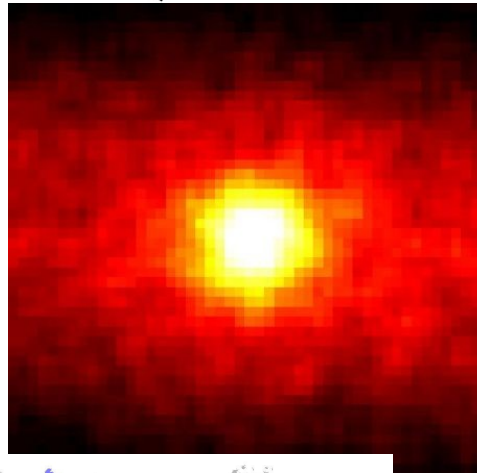
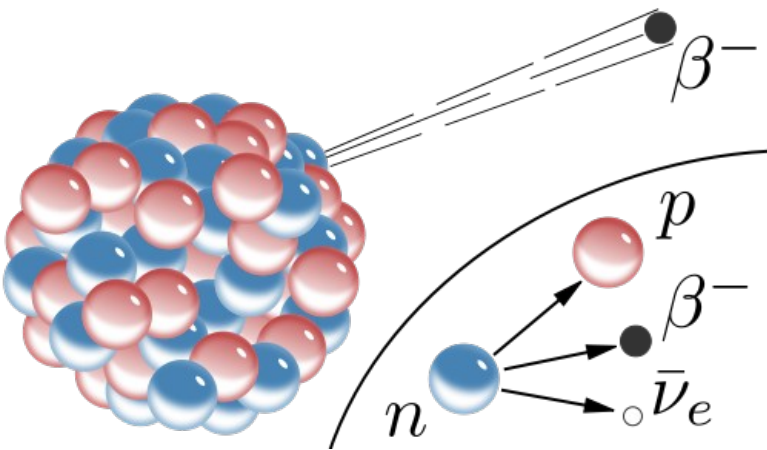
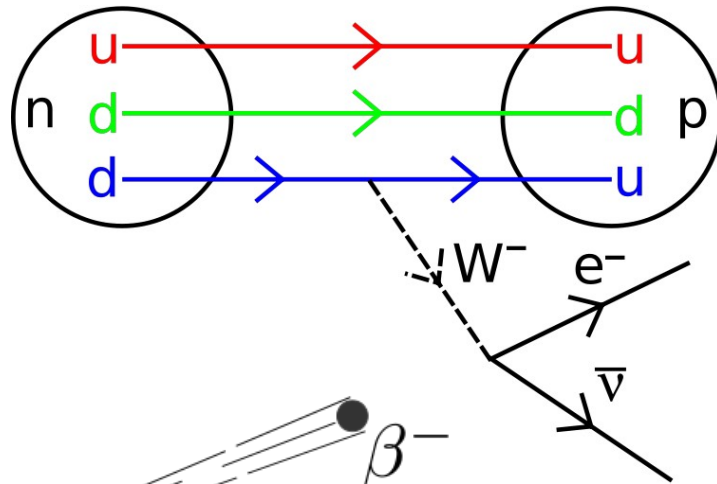
$$\sim \Gamma^\mu(q) = F_1(q^2)\gamma^\mu + \frac{F_2(q^2)}{2m_e} i\sigma^{\mu\nu} q_\nu$$

$$\left. \frac{g_e - 2}{2} \right|_{th} = 0.00115965218007 \pm 0.000000000000078$$

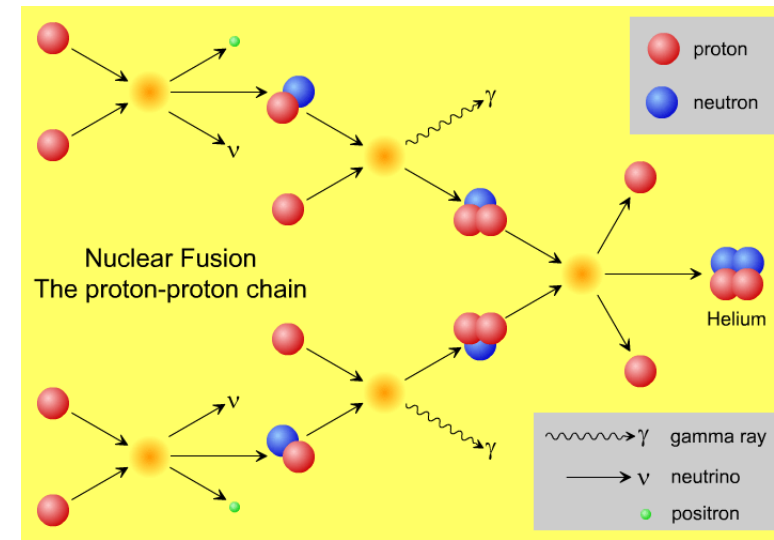
M. Hayakawa

Weak Interactions

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (\bar{\nu}_L \bar{e}_L) i\gamma^\mu \left(\partial_\mu - \frac{i}{2}g_1 B_\mu \right) \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R i\gamma^\mu (\partial_\mu - ig_1 B_\mu) e_R$$

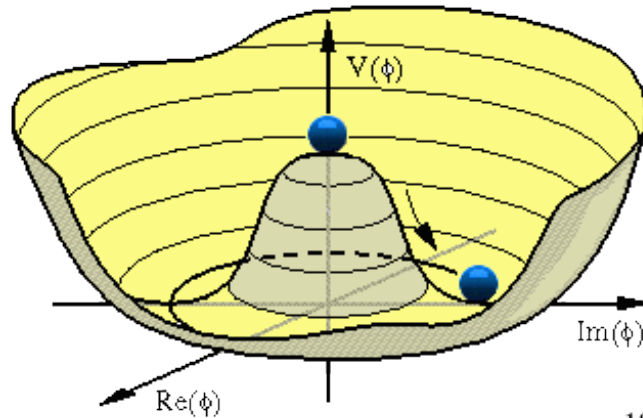
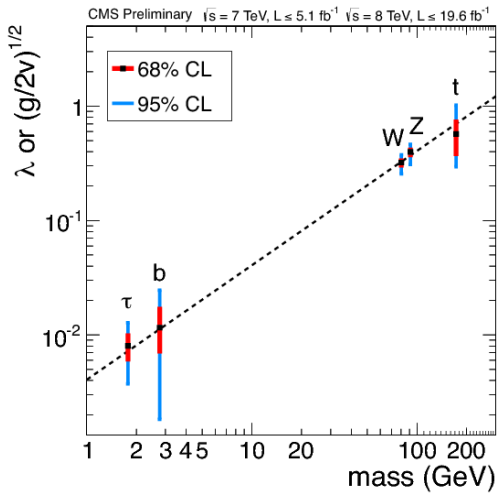


- Still cannot give mass to the gauge boson B, thus, neither to the Z gauge boson!
- Cannot write a mass term for the electron neither, due to the splitting between the left and right component.
- Need Brout-Englert-Higgs mechanism.



Higgs Potential

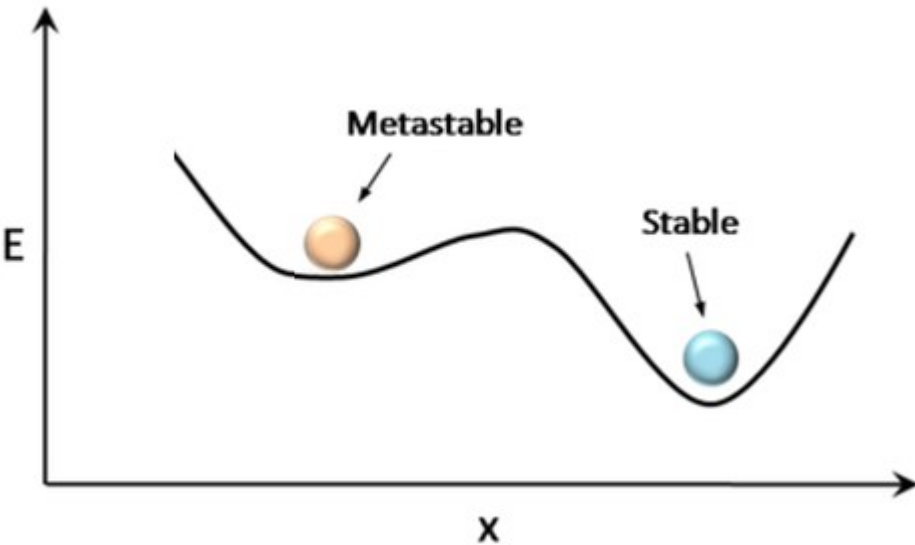
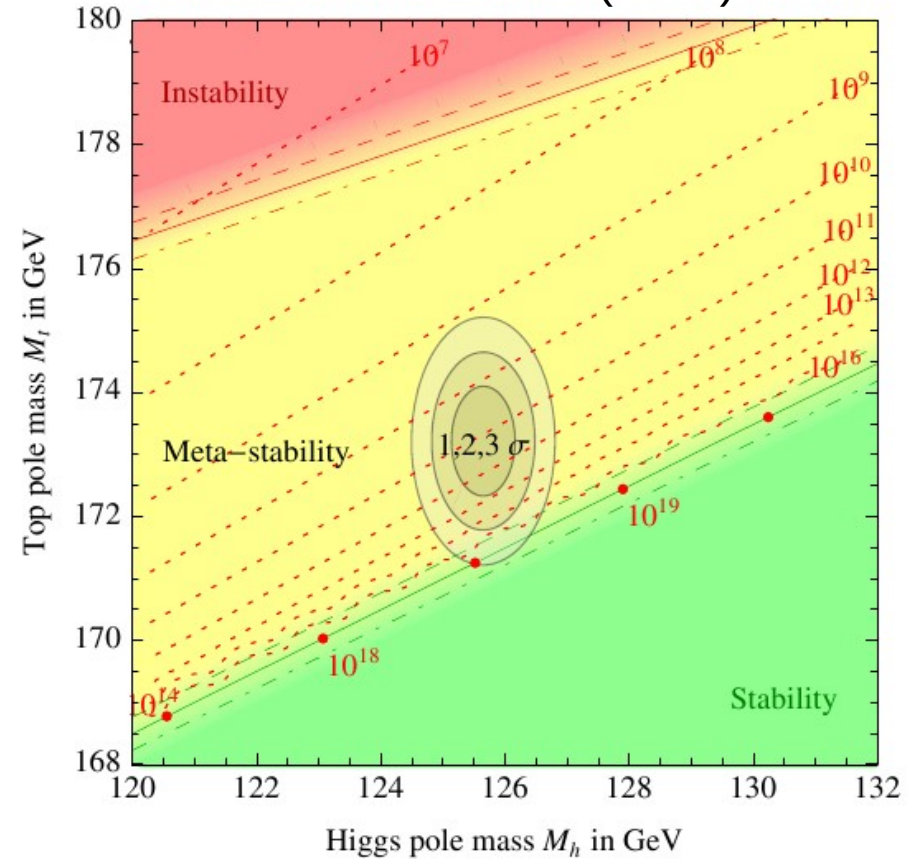
$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\left|(\partial_\mu + iyB_\mu)\phi\right|^2 + \frac{1}{2}\mu^2(\phi^\dagger\phi) - \frac{1}{4}(\phi^\dagger\phi)^2$$



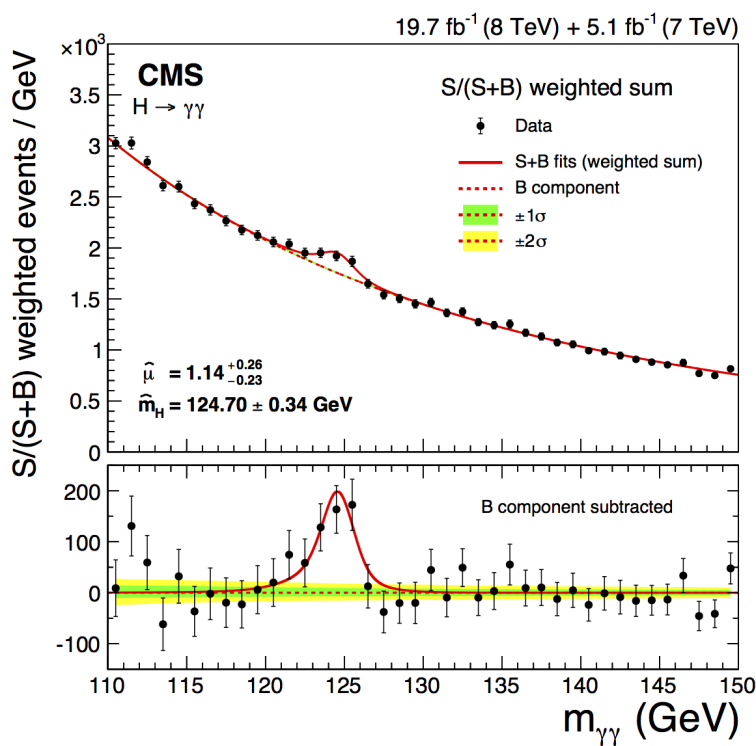
The field must have spin 0, and a non-zero vacuum expectation value.

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

Buttazzo et.al. (2013)

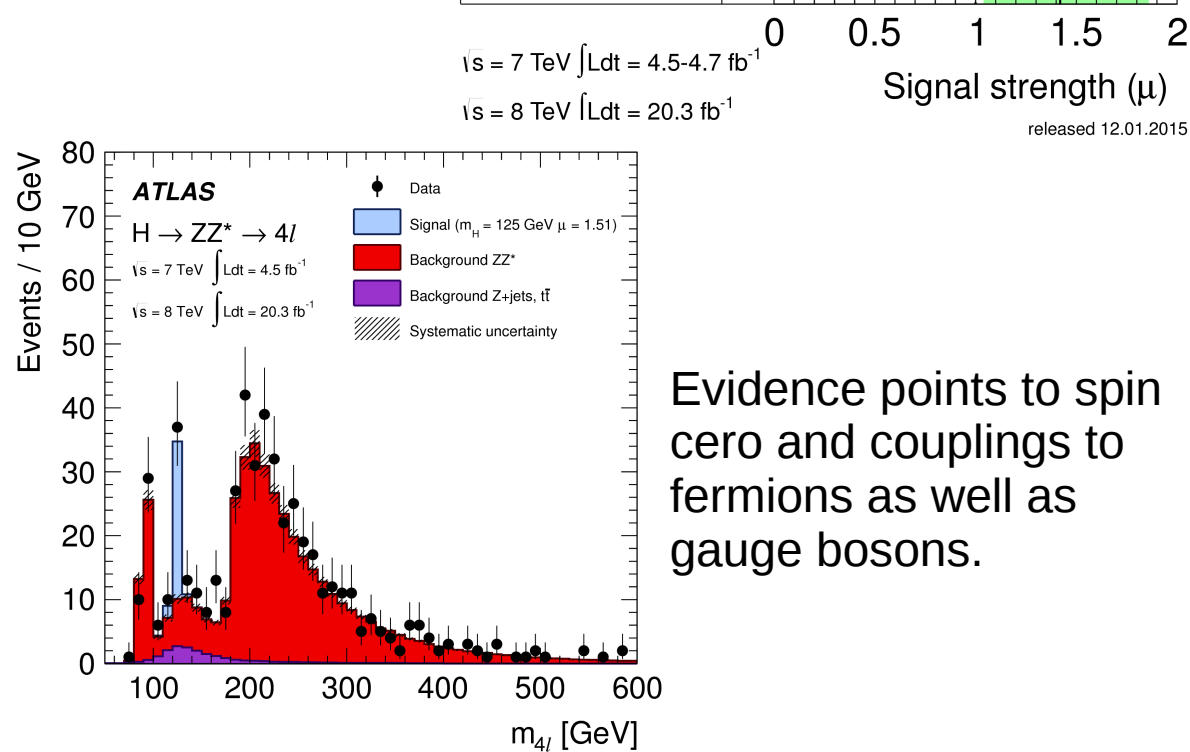
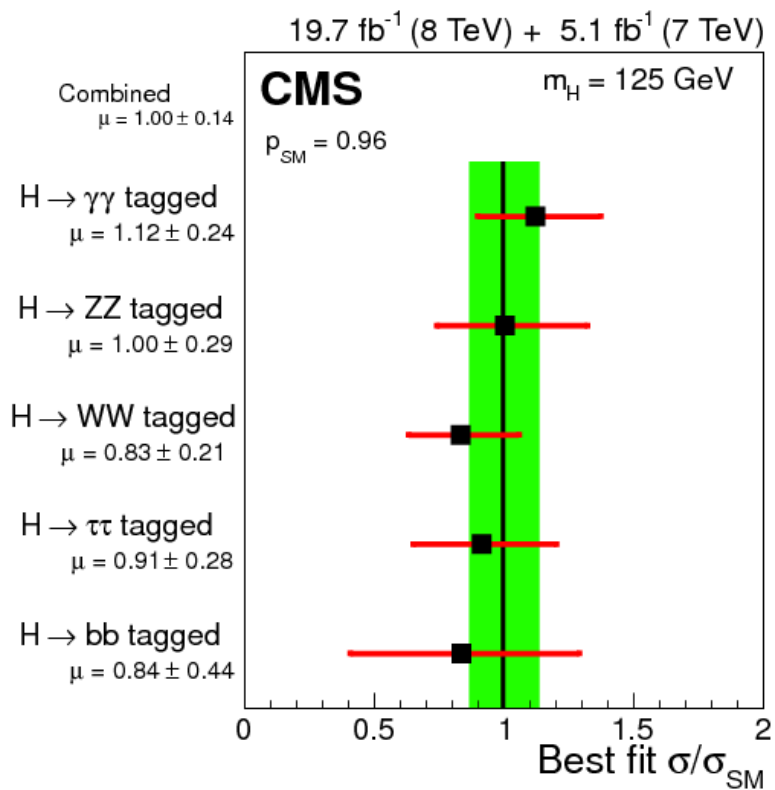
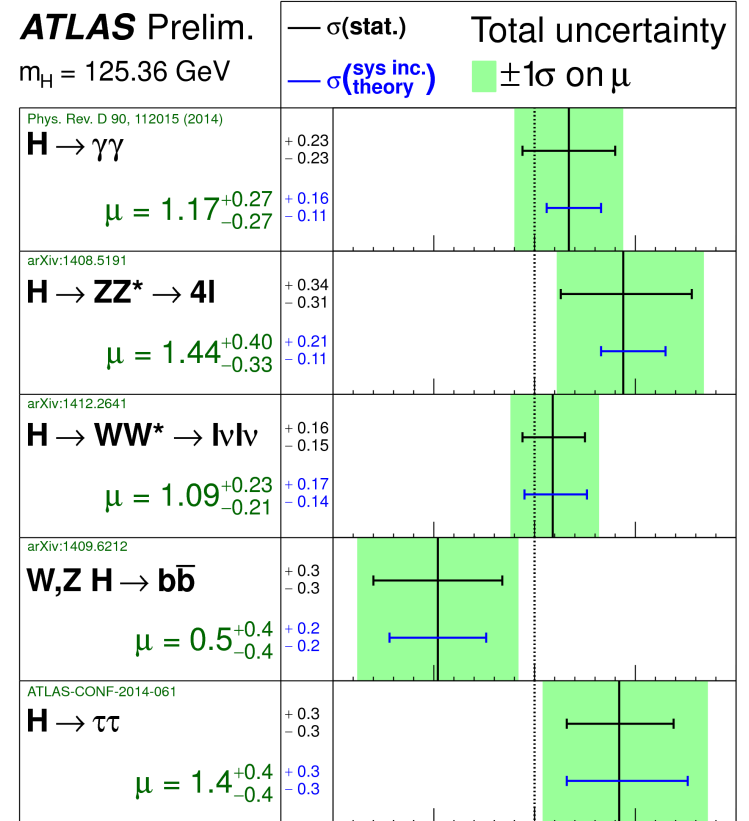


But, lifetime of meta-stable vacuum is very large!



Higgs Boson

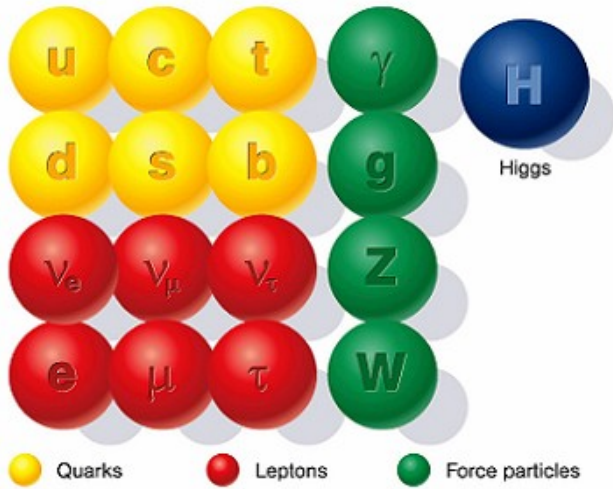
It is well established the existence of a scalar with Standard Model couplings and a mass $\approx 125 \text{ GeV}$.



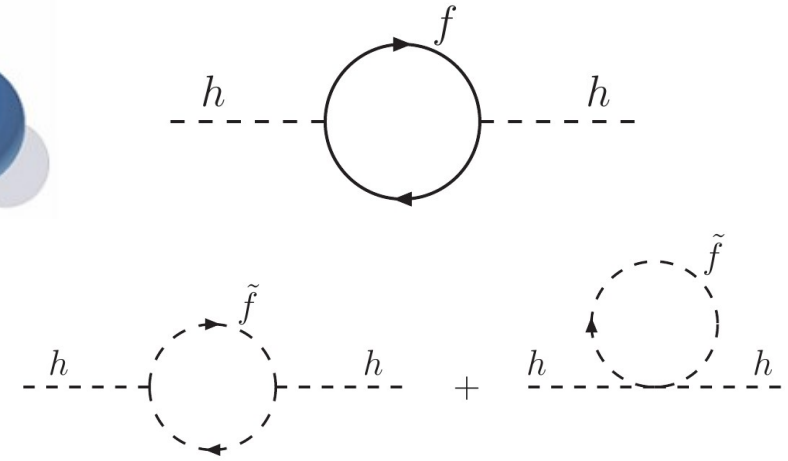
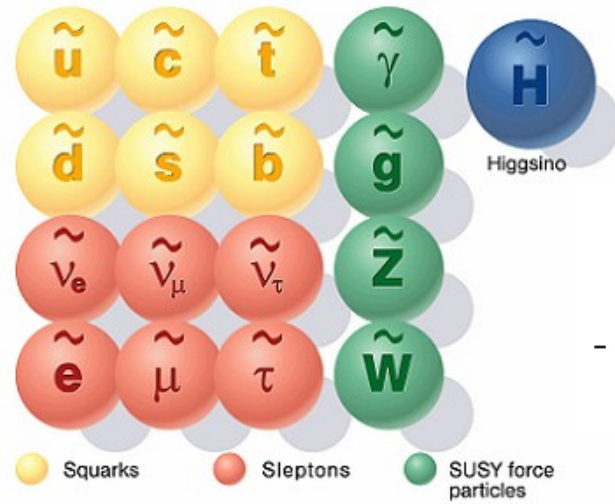
Evidence points to spin zero and couplings to fermions as well as gauge bosons.

Supersymmetry

Standard particles



SUSY particles



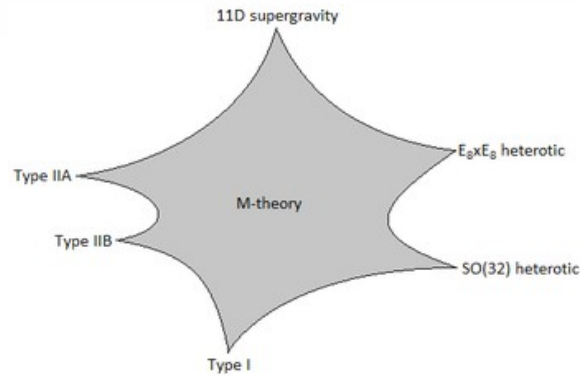
Neutralino Gravitino



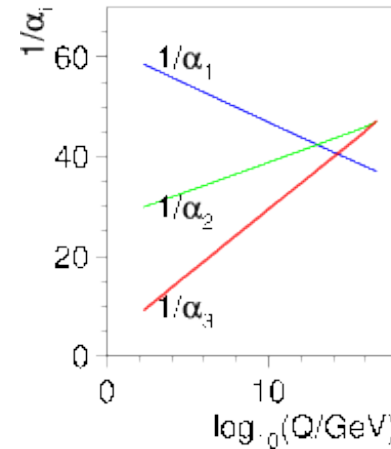
Rp Conserving

Rp Violating

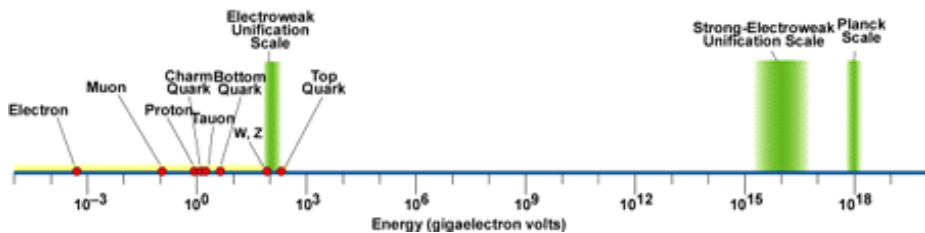
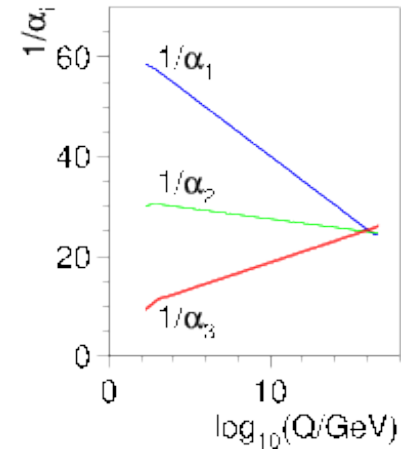
Dark Matter



SM

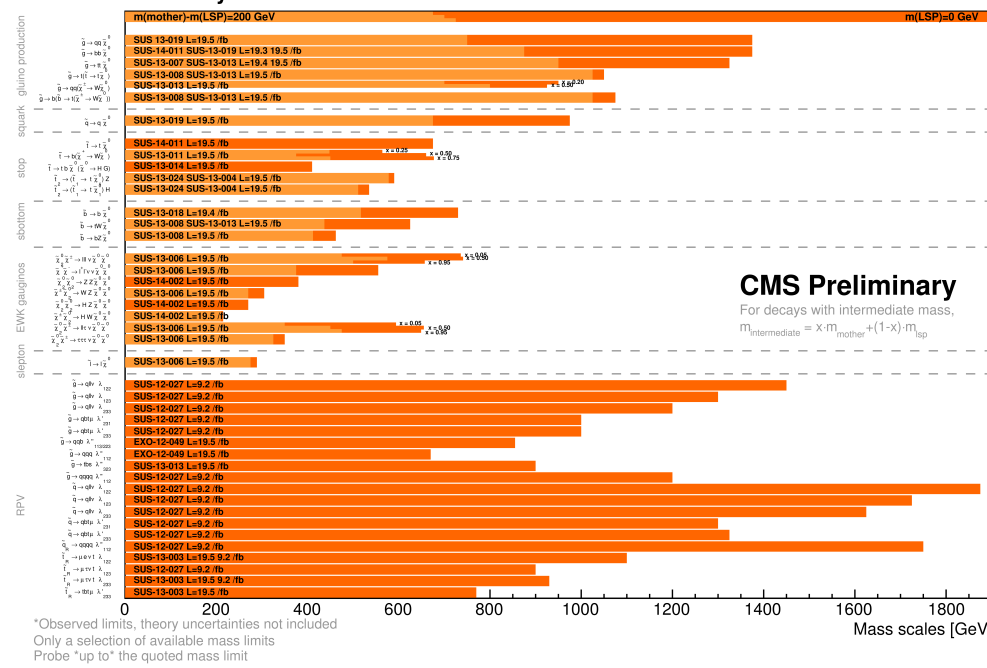


MSSM



Supersymmetric Searches

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



*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe 'up to' the quoted mass limit

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

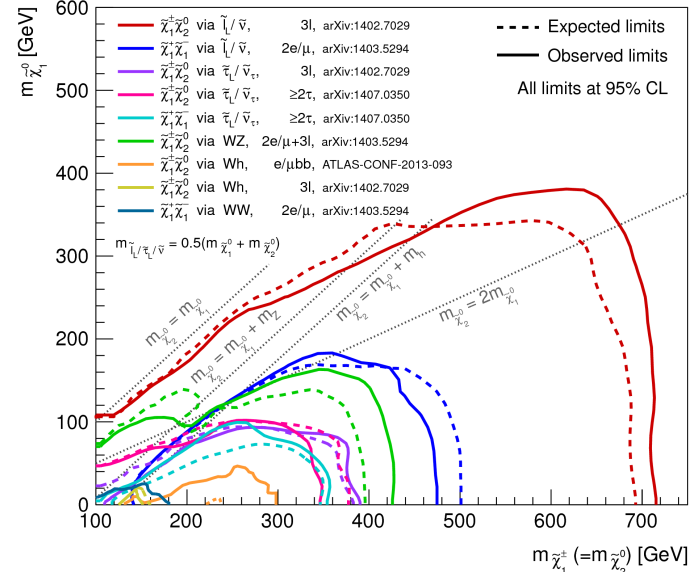
Model	$\epsilon, \mu, \tau, \gamma$	Jets	E_{miss}^T	$\int \mathcal{L} d\mathcal{L}(\text{fb}^{-1})$	Mass limit	Reference
Inclusive Searches						
MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	1.7 TeV	1405.7875
MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	1.2 TeV	ATLAS-CONF-2013-062
MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	1.1 TeV	1308.1841
$g\bar{g}, \bar{q}q \rightarrow g\bar{g}$	0	2-6 jets	Yes	20.3	850 GeV	1405.7875
$\bar{g}\bar{g}, \bar{q}q \rightarrow g\bar{g}$	0	2-6 jets	Yes	20.3	1.33 TeV	1405.7875
$\bar{g}\bar{g}, \bar{q}q \rightarrow g\bar{g} + \text{gluino}$	1 e, μ	3-6 jets	Yes	20.3	1.18 TeV	ATLAS-CONF-2013-062
$\bar{g}\bar{g}, \bar{q}q \rightarrow g\bar{g} + \text{gluino}$	2 e, μ	0-3 jets	Yes	20.3	1.12 TeV	ATLAS-CONF-2013-089
GMSB (\tilde{g} NLSP)	2 e, μ	2-4 jets	Yes	4.7	1.24 TeV	1208.4588
GMSB (\tilde{t} NLSP)	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	20.3	1.6 TeV	1407.0603
GGM (bino NLSP)	2 γ	-	Yes	20.3	1.28 TeV	ATLAS-CONF-2014-001
GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	619 GeV	ATLAS-CONF-2012-144
GGM (higgsino-bino NLSP)	2 γ	1 b	Yes	4.8	900 GeV	1211.1167
GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	690 GeV	ATLAS-CONF-2012-152
Gravitino LSP	0	mono-jet	Yes	10.5	645 GeV	ATLAS-CONF-2012-147
3rd gen. \tilde{g} and \tilde{t}						
$\tilde{g} \rightarrow b\bar{b}$	0	3 b	Yes	20.1	1.25 TeV	1407.0600
$\tilde{g} \rightarrow t\bar{t}$	0	7-10 jets	Yes	20.3	1.1 TeV	1407.0600
$\tilde{g} \rightarrow t\bar{t}$	0-1 e, μ	3 b	Yes	20.1	1.3 TeV	1407.0600
$\tilde{g} \rightarrow b\bar{b}$	0-1 e, μ	3 b	Yes	20.1	1.3 TeV	1407.0600
3rd gen. squarks direct production						
$\tilde{b}_1 \tilde{b}_1$	0	2 b	Yes	20.1	100-620 GeV	1308.2631
$\tilde{b}_1 \tilde{b}_1$ (SS)	2 e, μ	0-3 b	Yes	20.3	140-465 GeV	1404.2500
$\tilde{t}_1 \tilde{t}_1$ (light)	1-2 e, μ	1-2 b	Yes	4.7	110-167 GeV	1208.4935, 1209.2102
$\tilde{t}_1 \tilde{t}_1$ (medium)	2 e, μ	0-2 jets	Yes	20.3	130-210 GeV	1403.4853
$\tilde{t}_1 \tilde{t}_1$ (heavy)	2 e, μ	2 jets	Yes	20.3	215-530 GeV	1403.4853
$\tilde{t}_1 \tilde{t}_1$ (heavy)	0	2 b	Yes	20.1	190-580 GeV	1308.2631
$\tilde{t}_1 \tilde{t}_1$ (heavy)	1 e, μ	1 b	Yes	20.1	210-640 GeV	1407.0583
$\tilde{t}_1 \tilde{t}_1$ (heavy)	0	2 b	Yes	20.1	260-640 GeV	1406.1122
$\tilde{t}_1 \tilde{t}_1$ (heavy)	0	mono-jet/c-tag	Yes	20.3	90-240 GeV	1407.0608
$\tilde{t}_1 \tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	150-580 GeV	1403.5222
$\tilde{t}_1 \tilde{t}_1$ (natural GMSB)	3 e, μ (Z)	1 b	Yes	20.3	290-600 GeV	1403.5222
EW direct						
$\tilde{t}_1 \tilde{t}_1$	2 e, μ	0	Yes	20.3	90-325 GeV	1403.5294
$\tilde{t}_1 \tilde{t}_1$	2 e, μ	0	Yes	20.3	140-465 GeV	1403.5294
$\tilde{t}_1 \tilde{t}_1$	2 τ	-	Yes	20.3	100-350 GeV	1407.0350
$\tilde{t}_1 \tilde{t}_1$	3 e, μ	0	Yes	20.3	700 GeV	1402.7029
$\tilde{t}_1 \tilde{t}_1$	2 e, μ	0	Yes	20.3	420 GeV	1403.5294, 1402.7029
$\tilde{t}_1 \tilde{t}_1$	1 e, μ	2 b	Yes	20.3	285 GeV	ATLAS-CONF-2013-093
$\tilde{t}_1 \tilde{t}_1$	4 e, μ	0	Yes	20.3	620 GeV	1405.5086
Long-lived particles						
Direct $\tilde{t}_1 \tilde{t}_1$ prod. long-lived \tilde{t}_1	Disapp. trk	1 jet	Yes	20.3	270 GeV	ATLAS-CONF-2013-069
Stable, stopped \tilde{t}_1 R-hadron	0	1-5 jets	Yes	27.9	832 GeV	1310.6584
GMSB, stable \tilde{t}_1	1-2 μ	-	Yes	15.9	475 GeV	ATLAS-CONF-2013-058
GMSB, $\tilde{t}_1 \rightarrow \gamma$	2 γ	-	Yes	4.7	230 GeV	1304.6310
$g\bar{g}, \bar{q}q \rightarrow g\bar{g}$ (RPV)	1 μ , displ. vtx	-	Yes	20.3	1.0 TeV	ATLAS-CONF-2013-092
RPV						
LFV $pp \rightarrow \tau + X, \bar{\nu}_\tau \rightarrow e + \mu$	2 e, μ	-	-	4.6	1.61 TeV	1212.1272
BFV $pp \rightarrow \tau + X, \bar{\nu}_\tau \rightarrow e + \mu + \tau$	1 $e, \mu + \tau$	-	-	4.6	1.1 TeV	1212.1272
Linear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	1.35 TeV	1404.2500
$\tilde{t}_1 \tilde{t}_1$	4 e, μ	-	Yes	20.3	750 GeV	1405.5086
$\tilde{t}_1 \tilde{t}_1$	3 $e, \mu + \tau$	-	Yes	20.3	450 GeV	1405.5086
$\tilde{t}_1 \tilde{t}_1$	0	6-7 jets	-	20.3	916 GeV	ATLAS-CONF-2013-091
$\tilde{t}_1 \tilde{t}_1$	2 e, μ (SS)	0-3 b	Yes	20.3	850 GeV	1404.2500
Other						
Scalar gluon pair, sgluon $\rightarrow g\bar{g}$	0	4 jets	-	4.6	100-287 GeV	1210.4826
Scalar gluon pair, sgluon $\rightarrow t\bar{t}$	2 e, μ (SS)	2 b	Yes	14.3	350-800 GeV	ATLAS-CONF-2013-051
WIMP interaction (DS, Dirac χ)	0	mono-jet	Yes	10.5	704 GeV	ATLAS-CONF-2012-147

ATLAS Preliminary

$\sqrt{s} = 7, 8$ TeV

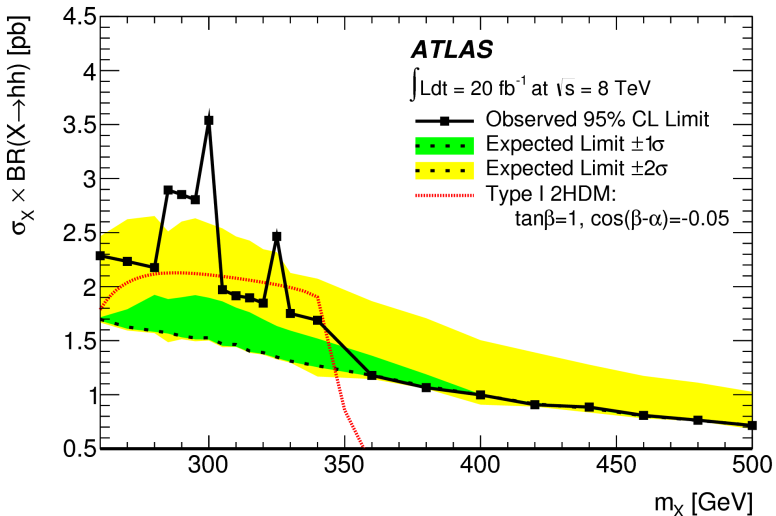
Reference

ATLAS Preliminary 20.3 fb⁻¹, $\sqrt{s}=8$ TeV Status: ICHEP 2014

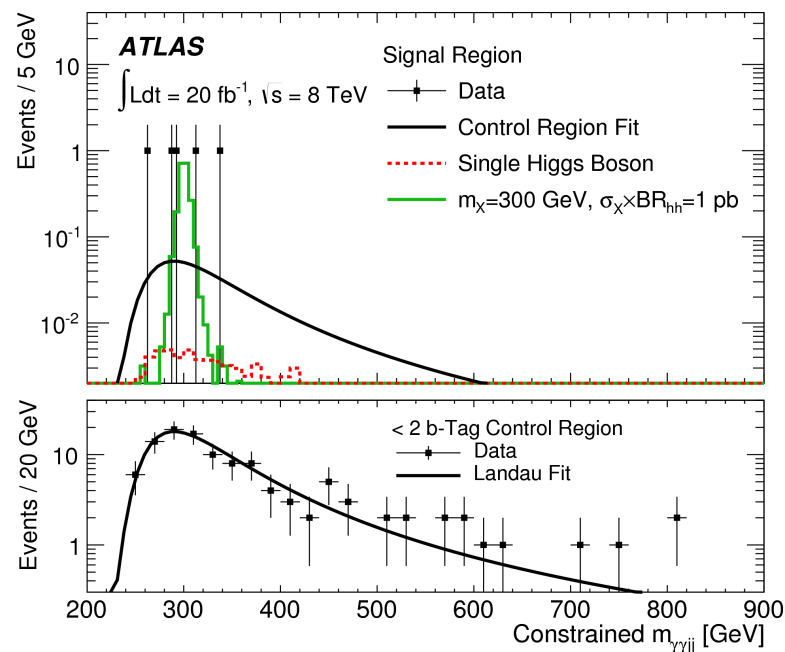


*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 σ theoretical signal cross section uncertainty.

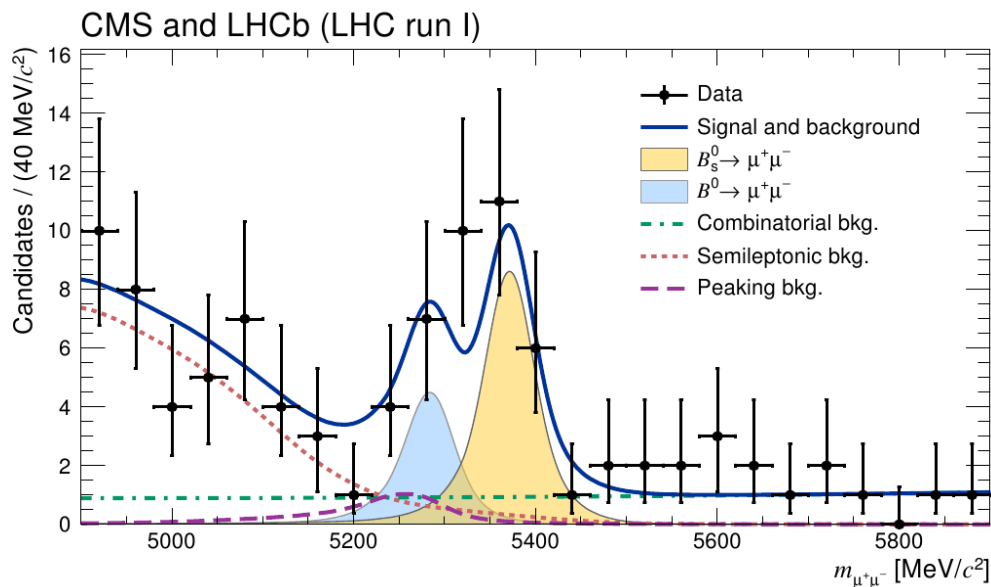
Mysteries



- Triple Higgs coupling:
- $\gamma\gamma bb\text{-bar}$ 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 B_s to $\mu\mu$ (arXiv:1411.4413).

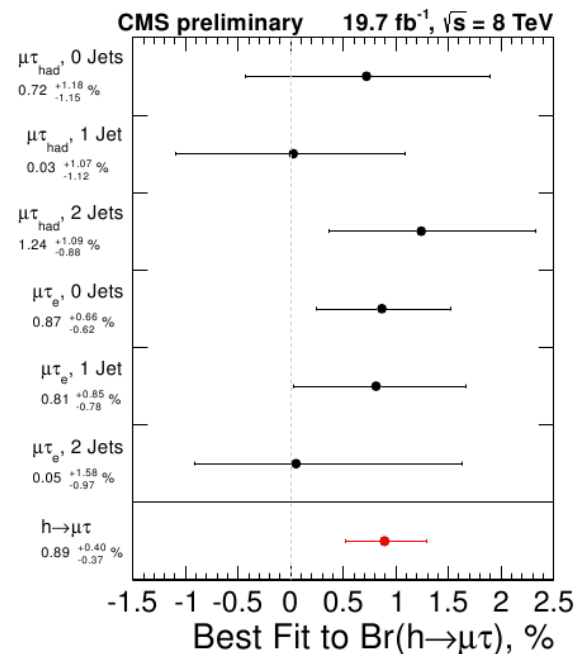


$B(B \rightarrow \mu\mu) / B(B_s \rightarrow \mu\mu)$ too large!

Heavy squarks and gluinos and low $\tan(\beta)$ (arXiv:1501.02044)?

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

$$\sim 2.5 \sigma \text{ (CMS PAS HIG-14-005)}$$

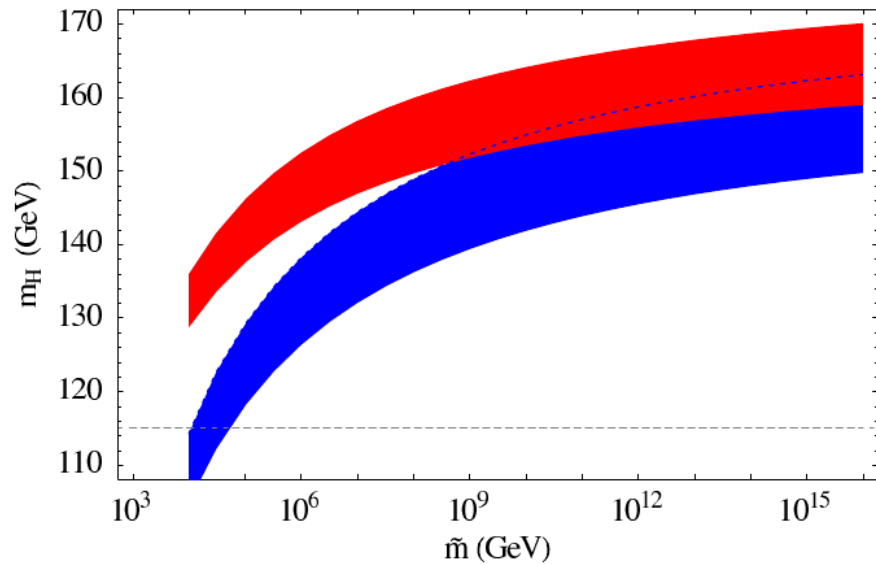


Heavy Supersymmetry

Split Supersymmetry

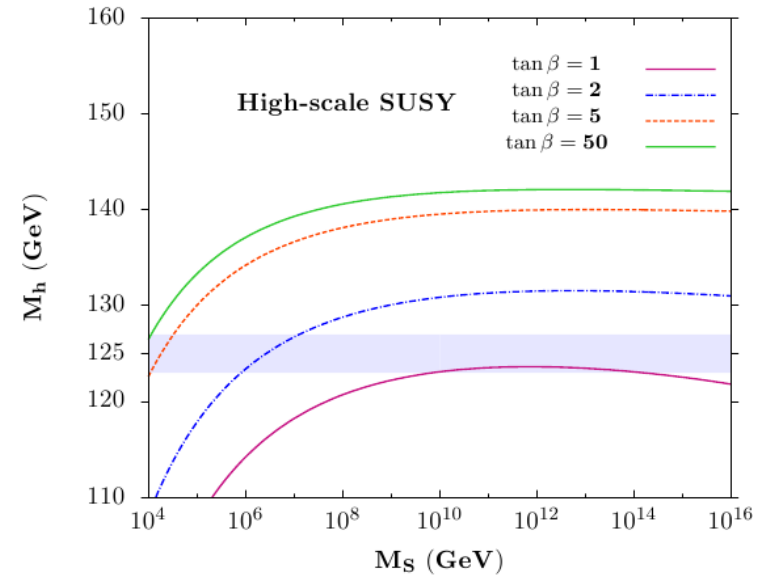
hep-th/0405159, hep-ph/0406088

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



High Scale Supersymmetry

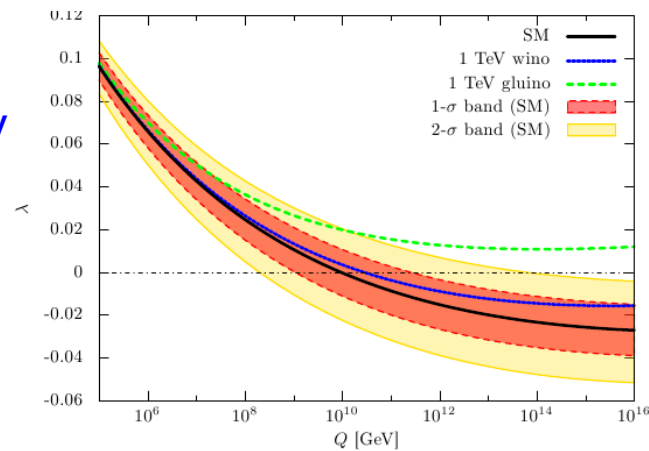
- All supersymmetry partners are heavy.
- Plot taken from arXiv:1112.3028



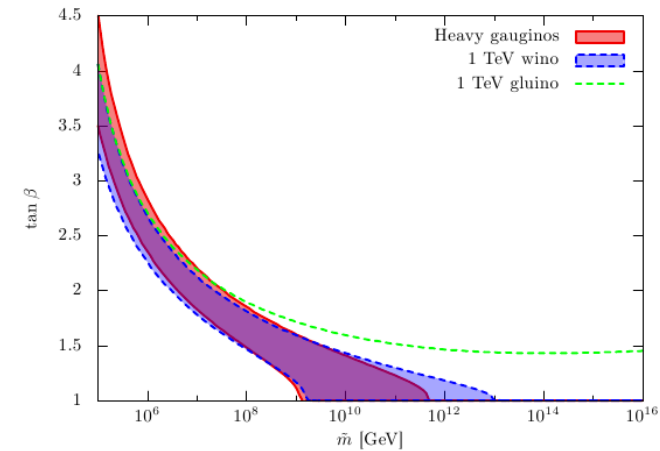
Intermediate Scale Supersymmetry

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 $\tan \beta$



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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.

