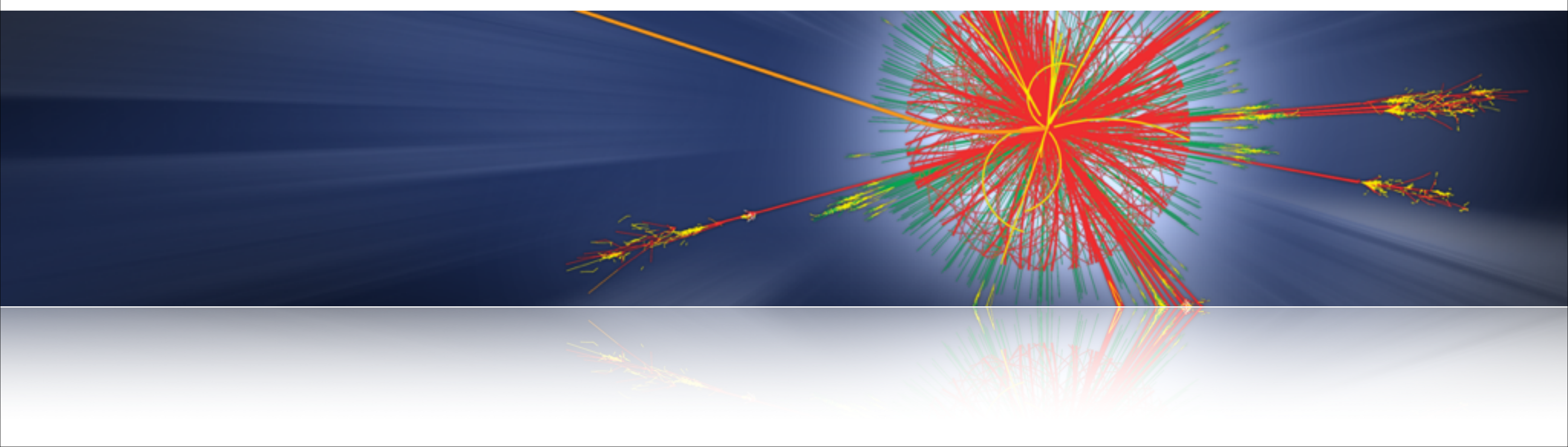
BSM Higgs Searches

Experimental view …



Theoretical Problems and Open Questions

Standard model cannot be valid
up to large energy scales Λ ...

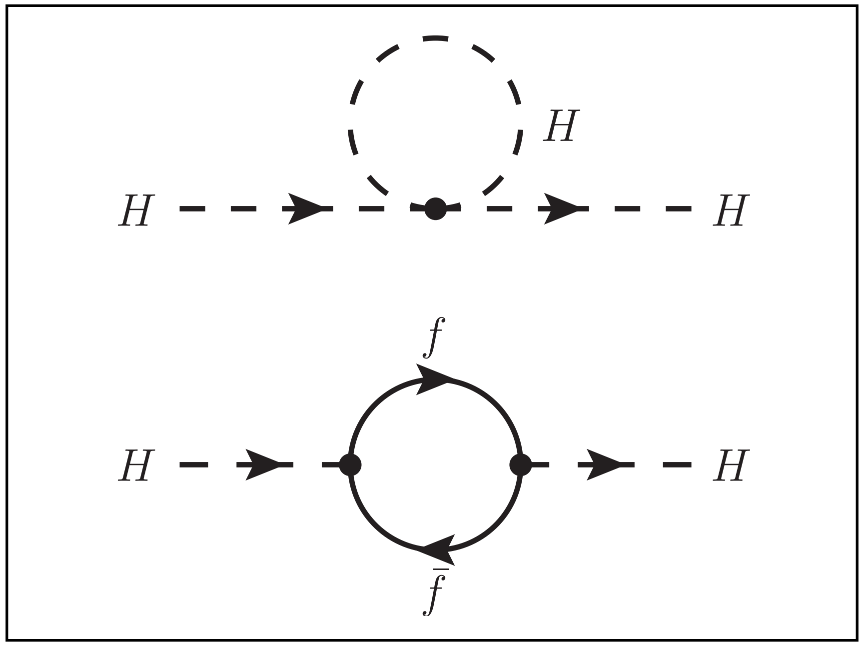
Problem: Higgs self-energy [$\Delta m_H^2 \sim \Lambda^2$]

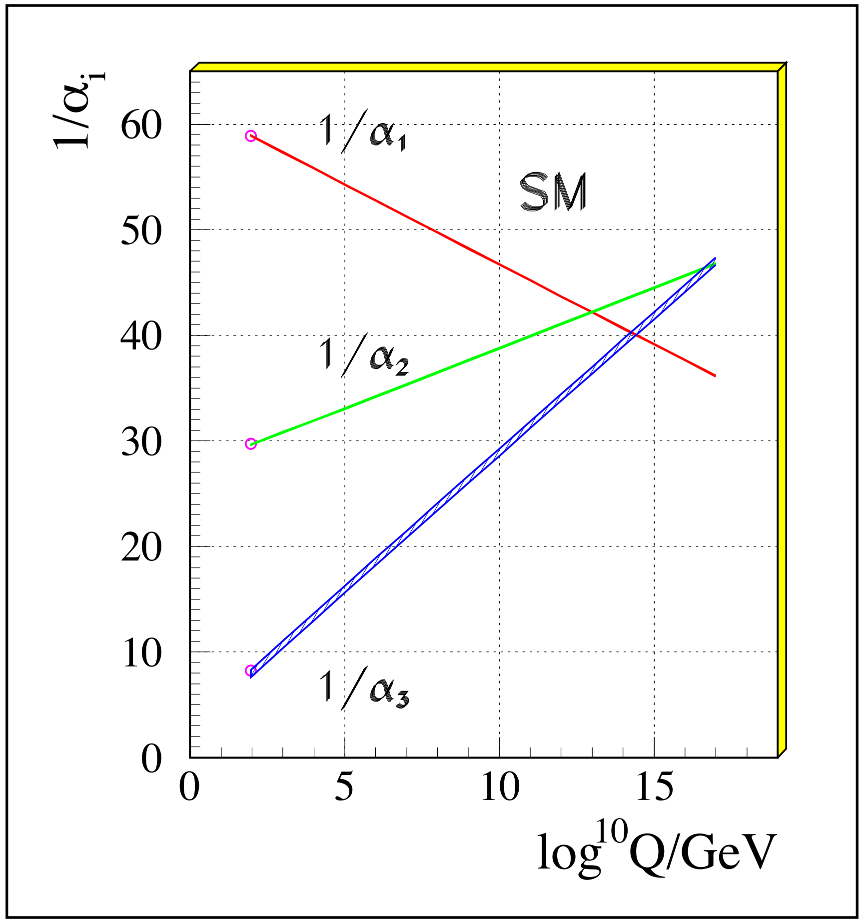
- Quadratically divergent
- Only stable if $m_H \approx \Lambda$ ["natural" Higgs mass]
- Typical value $\Lambda = 10^{15}$ GeV,
  scale of new grand unified theory (GUT)
  [➛ fine tuning problem: keep $m_H \ll \Lambda$]

Unification of SM forces
at GUT scale

- RGE evolutions of coupling constants
  do not meet in one point

$$\alpha_1 \equiv \frac{5}{3}\frac{\alpha}{\cos^2\theta_W}, \quad \alpha_2 \equiv \frac{\alpha}{\sin^2\theta_W}, \quad \alpha_3 \equiv \alpha_S$$





[Amaldi et al., Phys. Lett. B260 (1991) 447]

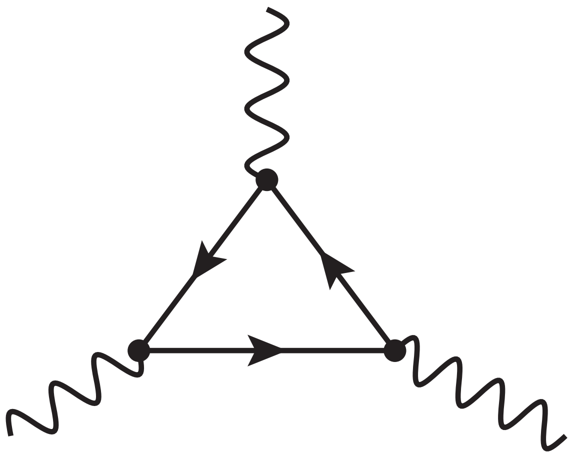
Theoretical Problems and Open Questions

Cancellation of chiral anomaly requires “conspiracy” between QCD and electroweak theory ...

SM: fulfilled “by accident”; deeper reason?

$$N_C(Q_u + Q_d) = - Q_e$$

colors — quark charges — electron charges



Gravity not included in Standard Model ...

Gravity much weaker than all other forces ...
Hierarchy problem, i.e. ...

why is the Planck scale (10^{19} GeV) much larger than EW scale (250 GeV)?

SM = gauge theories of quantum fields in space-time,
but general relativity = non-quantized geometrical field theory ...

No renormalizable quantum theory of gravity so far ...

Theoretical Problems and Open Questions

How can we solve the mystery of dark energy?

How did the universe come to be?

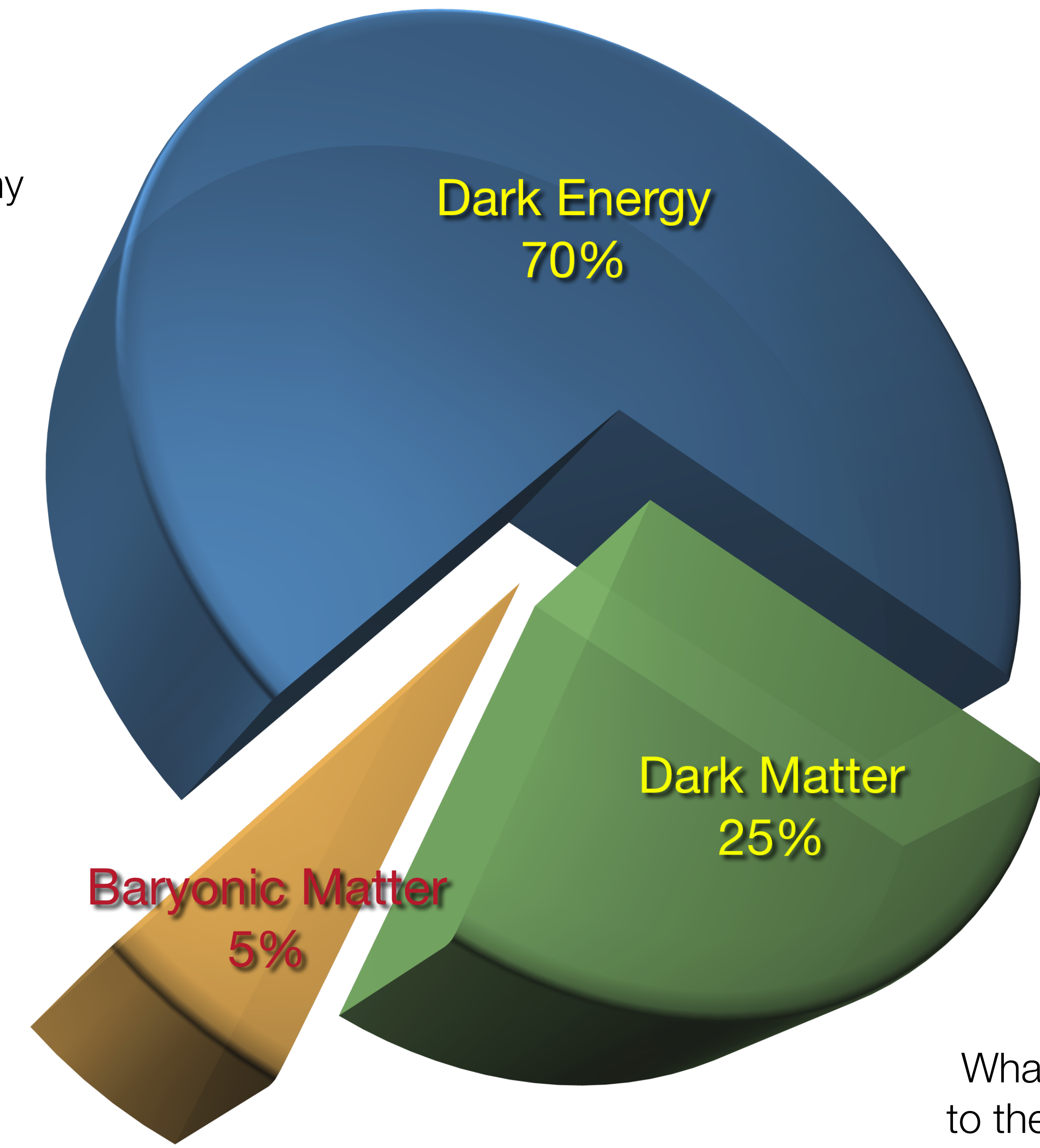
Are there extra dimensions of space?

Why are there so many kinds of particles?

Are there undiscovered principles of nature?

Do all forces become one?

Can we make dark matter in the laboratory?



What are neutrinos telling us?

What is dark matter?

What happened to the antimatter?

What Theorists Think About ...

There exists a large number of models which predict new physics at the TeV scale accessible @ LHC ...

- Grand Unified Theories (SU(5), O(10), E6, …)
  embed SM gauge group in larger symmetry
- Supersymmetry (SUSY - around since a long time)
- Extended Higgs sector
  e.g. in SUSY models
- Leptoquarks
- New heavy gauge bosons
- Technicolour
- Compositeness
- Extra dimensions

Any of this is what the LHC still hopes for ...

... in addition to the Higgs

LHC BSM Higgs Searches

BSM Scenarios:

[see e.g. PDG: Status of Higgs Boson Physics]

Supersymmetric Extensions …

One neutral Higgs with close to SM properties (h); two extra neutral Higgs bosons (H,A);
two charged Higgs bosons ($H^{\pm}$); potential departures from SM Higgs decay rates (e.g. h ➛ bb) …

Two Higgs-Doublet Models (2-HDMs)…

Simple extension with 7 free parameters; different types, distinguished based on coupling to fermions …
Type-I: only one doublet couples to fermions; Type-II (SUSY): ϕ_1/ϕ_2 couples to up/down-type fermions …

Composite Higgs Scenarios …

Idea: Higgs is composite bound state; e.g. Little Higgs Models; partial compositeness …
Extra particles at the TeV scale (Z′, W′, …); extra Higgs bosons; charged and doubly charged Higgs bosons …

Higgs Triplet Models …

Add electroweak triplet scalar to SM; motivation: neutrinos acquire Majorana mass …
Extra Higgs bosons, in particular doubly charged Higgs ($H^{\pm\pm}$); fermiophobic Higgs (also for 2HDM) …

Search Categories …

Three main subgroups:

1. Neutral Higgs with SM-like properties …
   [m ≠ 125 GeV; using the SM as a benchmark …]
2. Neutral Higgs with non-SM properties
   [additional Higgs @ m≠125 GeV; BSM properties of Higgs @ m=125 GeV]
3. Charged Higgs Bosons …
   [Single and doubly charged …]

Signatures:

Hadronic decay channels, decays into gauge bosons
leptonic decay channels, invisible Higgs …

Public Results – ATLAS [CONF Notes]

CONF-2013-090	Search for charged Higgs bosons in the τ+jets final state with pp collision data recorded at $\sqrt{s}$=8 TeV with the ATLAS experiment
CONF-2013-067	Search for a high-mass Higgs boson in the H->WW->lvlv decay channel with the ATLAS detector using 21 fb^{-1} of proton-proton collision data
CONF-2013-027	Search for Higgs bosons in Two-Higgs-Doublet models in the $H \to WW \to e\nu\mu\nu$ channel with the ATLAS detector
CONF-2013-011	Search for invisible decays of a Higgs boson produced in association with a Z boson in ATLAS
CONF-2012-079	Search for a Higgs boson decaying to four photons through light CP-odd scalar coupling using 4.9 fb^{-1} of 7 TeV pp collision data taken with ATLAS detector
CONF-2011-135	Higgs in SM with 4^{th} fermion generation [in "Update of the Combination of Higgs Boson Searches in 1.0 to 2.3 fb^{-1} …"]
CONF-2011-020	A search for a light CP-Odd Higgs boson decaying to $\mu^+\mu^-$ in ATLAS

… very similar for CMS

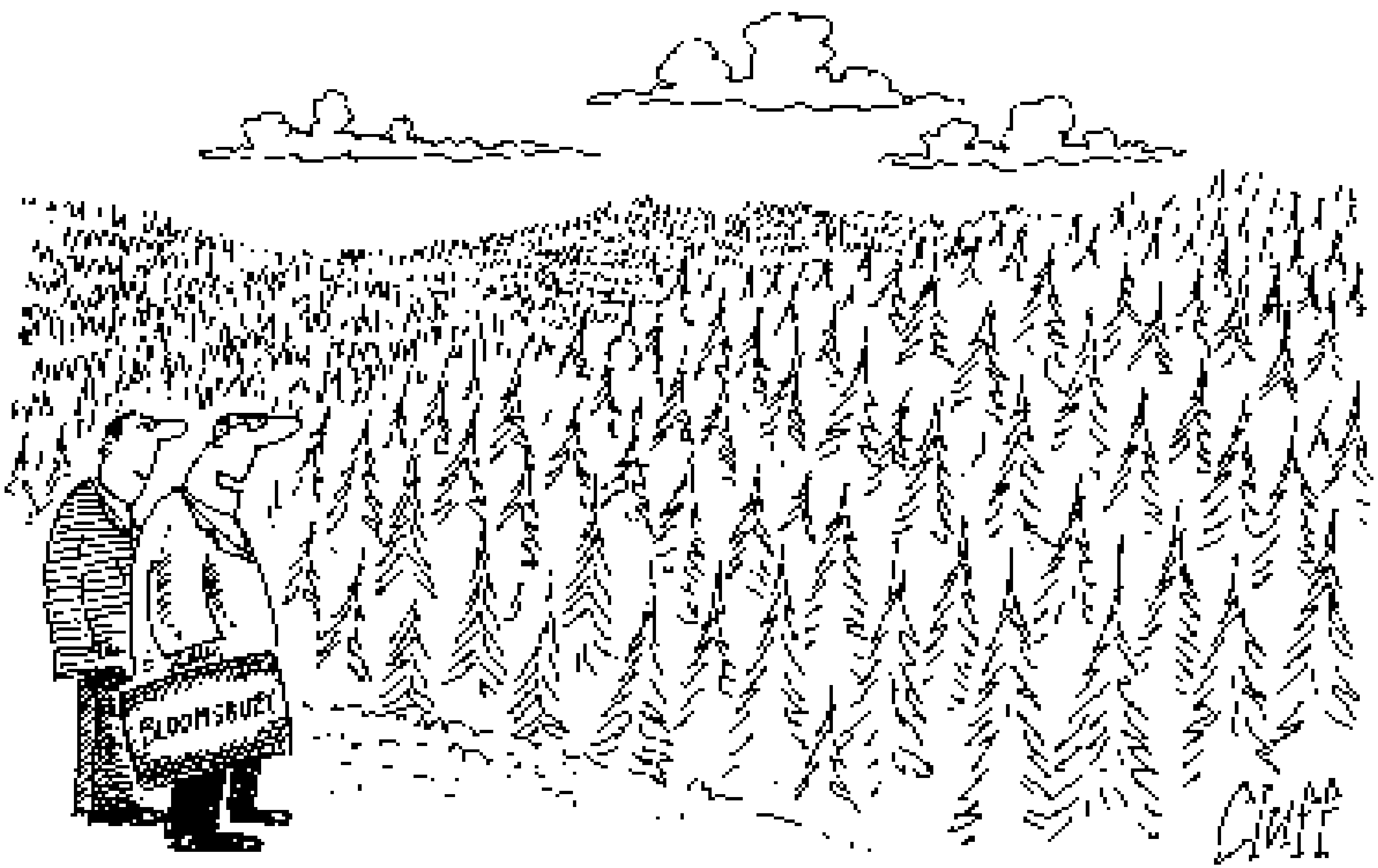
Public Results – ATLAS [Papers]

PH-EP-2012-347	Search for charged Higgs bosons through the violation of lepton universality in tt events using pp collision data at $\sqrt{s}$ = 7 TeV with the ATLAS experiment
PH-EP-2012-338	Search for a light charged Higgs boson in the decay channel $H^+ \rightarrow cs$ in tt events using pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector
PH-EP-2012-323	Search for the neutral Higgs bosons of the Minimal Supersymmetric Standard Model in pp collisions at s = $\sqrt{7}$ TeV with the ATLAS detector
PH-EP-2012-105	Search for a fermiophobic Higgs boson in the diphoton decay channel with the ATLAS detector
PH-EP-2012-083	Search for charged Higgs bosons decaying via $H^\pm \rightarrow \tau\nu$ in tt events using pp collision data at s = $\sqrt{7}$ TeV with the ATLAS detector

… very similar for CMS

Higgs Searches

Supersymmetry

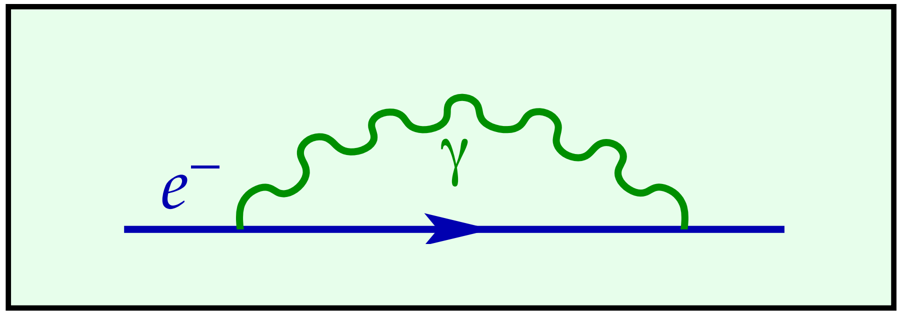


"One day, all of these will be supersymmetric phenomenology papers."

Motivation

Electrons in classical Electrodynamics

[Murayama, arXiv:0709.3041]



QED: Photon exchange ⇔ Coulomb law

Electromagnetic self-energy:

$$\Delta E_C = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r_e}$$

Self-energy must be part of electron mass:

$$(m_e c^2)_{observed} = (m_e c^2)_{bare} + \Delta E_C$$

Experiment: $r_e < 10^{-17}$ cm ➛ $\Delta E_C > 10$ GeV

$m_e = 511$ keV $= 0.511$ MeV

"fine-tuning problem"

$$(m_e c^2)_{bare} = (m_e c^2)_{observed} - \Delta E_C$$

$$= 0.511\ \text{MeV} - 10000\ \text{MeV}$$

$$= -9999.489\ \text{MeV}$$

Classical Electrodynamic
not valid for $\Delta E_C > m_e c^2$, i.e. for $d < 2.8 \cdot 10^{-13}$ cm
[from $d < e^2/4\pi\varepsilon_0\, m_e c^2$]

Motivation
Electrons in classical Electrodynamics

[Murayama, arXiv:0709.3041]

Description of self-energy in Quantum Electrodynamics via photon exchange.

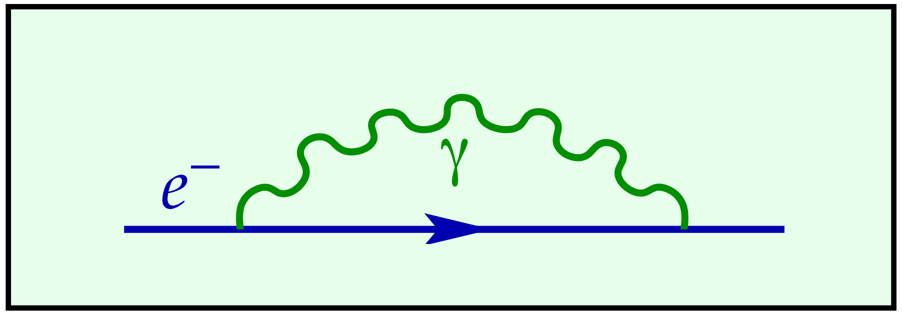
Introduction of positron ...
cure of “fine-tuning problem” via vacuum fluctuations.

Modify physics at

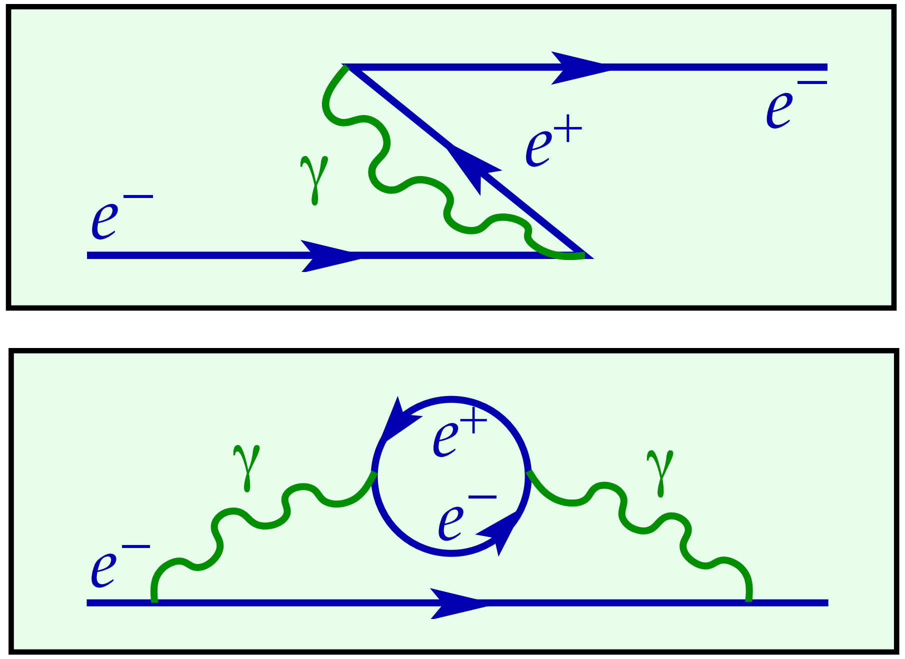
$d \sim c \cdot \Delta t \sim 200 \cdot 10^{-13}$ cm

with $\Delta t \sim \hbar/\Delta E \sim \hbar/2m_e c^2$

$$\rightarrow \quad \Delta E_{Pair} = -\frac{1}{4\pi\epsilon_0}\frac{e^2}{r_e} + \dots$$



QED: Photon exchange ⇔ Coulomb law



Vacuum fluctuations: e^+e^--pair production

$$\Delta E = \Delta E_C + \Delta E_{Pair} = \frac{3\alpha}{4\pi} m_e c^2 \log\frac{\hbar}{m_e c r_e}$$

smaller self-energy !

Motivation

Electrons in classical Electrodynamics

[Murayama, arXiv:0709.3041]

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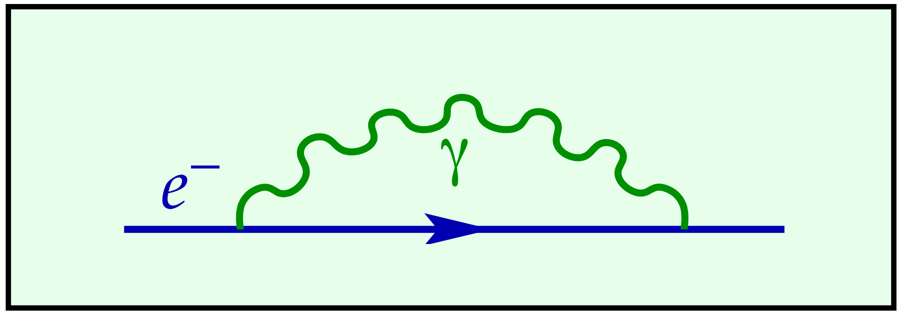

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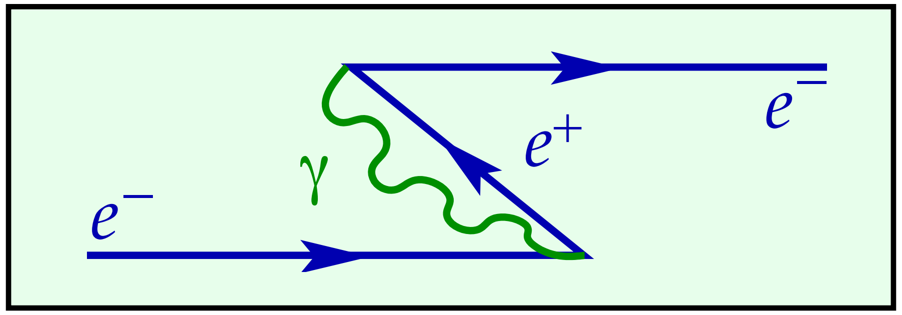
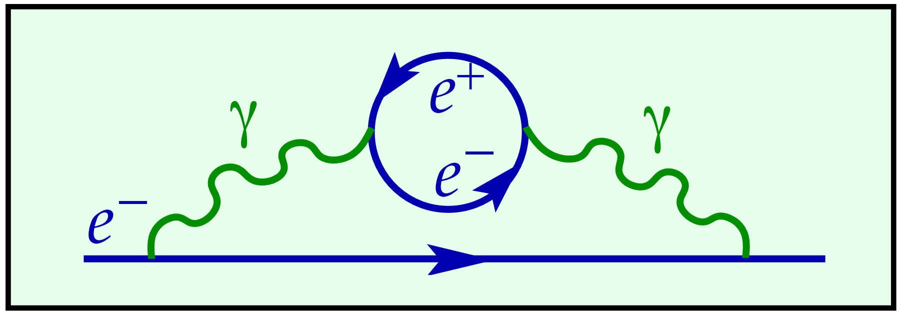


Modify physics at

$d \sim c\cdot\Delta t \sim 200\cdot 10^{-13}$ cm

with $\Delta t \sim \hbar/\Delta E \sim \hbar/2m_e c^2$



Vacuum fluctuations: e^+e^--pair production

Doubling d.o.f. & symmetry result in divergence cancellation.

➛ “Naturally” small mass correction.

$$(m_e c^2)_{observed} = (m_e c^2)_{bare}\left[1 + \frac{3\alpha}{4\pi}\log\frac{\hbar}{m_e c r_e}\right]$$

max. 9%
even @ $r_e = 1/M_P$

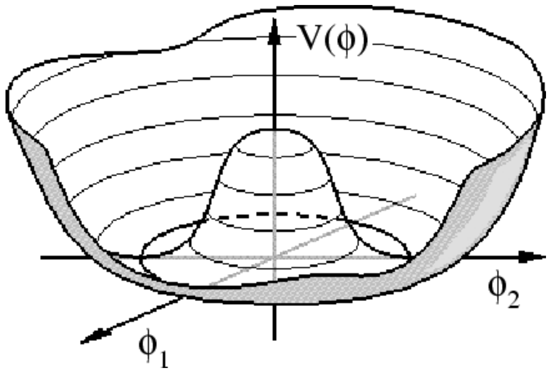
Motivation

Supersymmetry and the Higgs self-energy

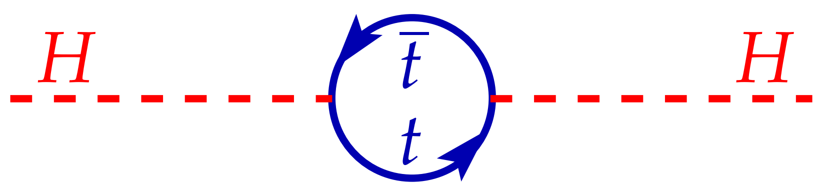
[Murayama, arXiv:0709.3041]

Higgs self-energy: $$V = -\mu^2|H|^2 + \lambda|H|^4$$

$$M_H = \sqrt{2}\mu$$



Self-energy correction through top-loops:



$$\Delta\mu^2_{\rm top} = -6\frac{h_t^2}{4\pi^2 r_H^2} + \ldots$$

Higgs-Top coupling

"Higgs radius"

➛ Standard Model not applicable for d < 10^{-17} cm;
i.e. above a scale Λ > 2 TeV ...

Solution: double d.o.f. introducing boson partners for each fermion;

$$\Delta\mu^2_{\rm stop} = +6\frac{h_t^2}{4\pi^2 r_H^2} + \ldots$$

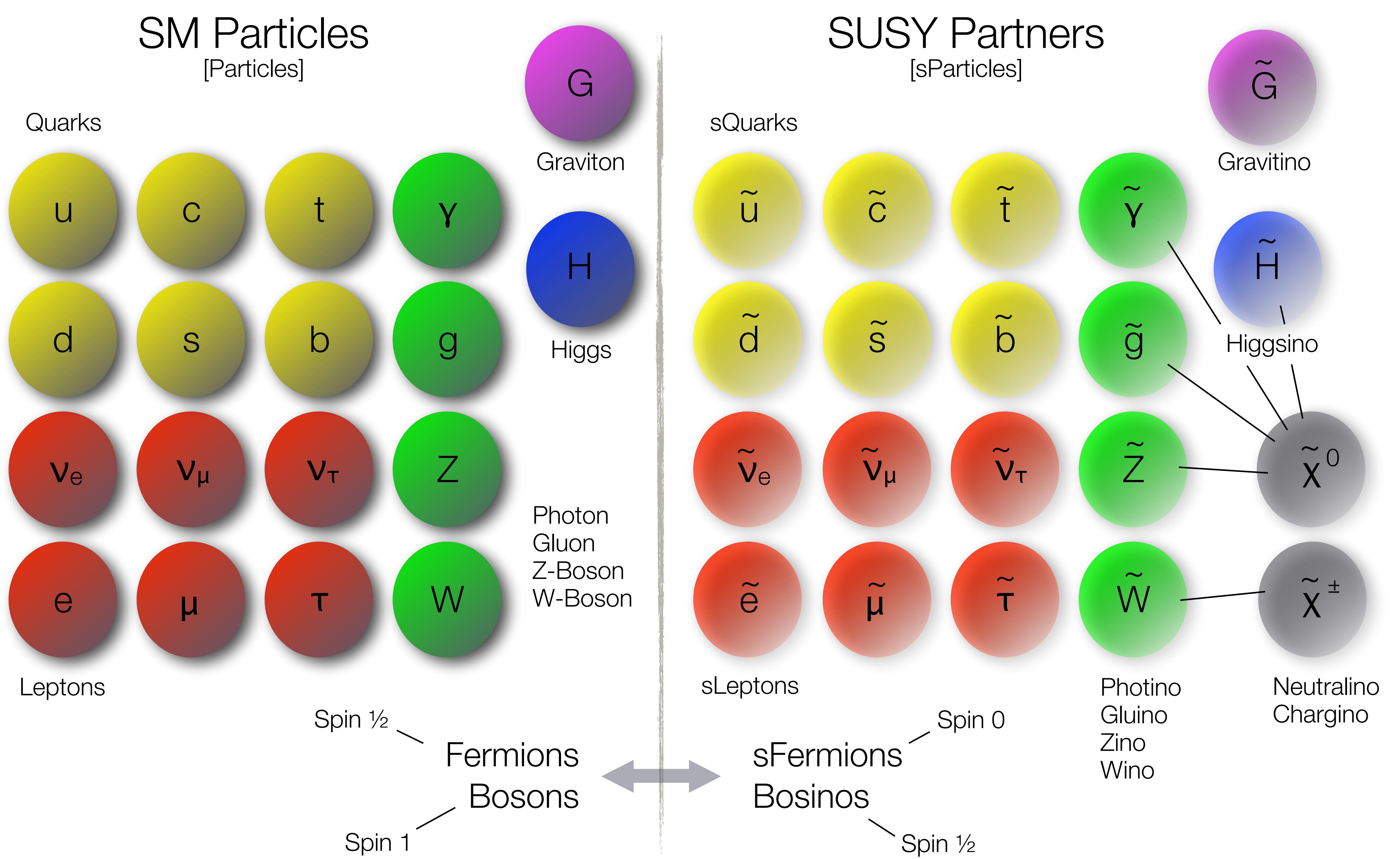
results in loop corrections with opposite sign.

Remaining correction:

$$\Delta\mu^2_{\rm top} + \Delta\mu^2_{\rm stop} = -6\frac{h_t^2}{4\pi^2}(m^2_{\tilde{t}} - m^2_t)\log\frac{1}{r_h^2 m^2_{\tilde{t}}}$$

➛ "Naturalness" argument: $m_{\tilde{t}}$ not much larger than m_t, i.e. $m_{\tilde{t}}$ in TeV range.

Supersymmetric Particle Spectrum



SUSY Higgs Sector

Higgs sector
extended in SUSY:

SM: simplest mechanism to generate gauge boson and fermion masses

➛ single SU(2) doublet

$$\phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

Minimal model compatible with
SUSY: two Higgs doublet models [2HDM]

➛ separate fields coupling to down-type and up-type quarks
[SM: $\tilde{\phi} = i\tau_2\phi^*$ for up-type]

$$\phi_u = \begin{pmatrix} \phi_u^+ \\ \phi_u^0 \end{pmatrix}, \quad \phi_d = \begin{pmatrix} \phi_d^0 \\ \phi_d^- \end{pmatrix}$$

Higgs bosons in 2HDM:

8 degrees of freedom:
3 massive vector bosons,
5 physical Higgs bosons

2 charged Higgs $H^\pm$

1 CP-odd neutral Higgs [A]

2 CP-even neutral Higgs
[H ("heavy") and h ("light")]

Key parameter: tan β

Ratio of vacuum expectation values of ϕ_u and ϕ_d

$$\tan\beta = \frac{v_u}{v_d}, \quad v_u^2 + v_d^2 = v_{SM}^2$$

Minimal Supersymmetric Models

Extension of the Standard Model

Supersymmetric partner for each SM particle

2 Higgs doublets

Minimal structure to guarantee cancellations of anomalies

Two Higgs field needed to give masses to 'up' and 'down' type quarks in a consistent way

New quantum number: R-parity R_p

Particles: $R_p = +1$

S-Particles: $R_p = -1$

$$R_p = (-1)^{B+L+2S}$$

R_p-conservation circumvents proton decay; conservation of B-L

Motivation of SUSY

Avoid divergent quantum corrections to Higgs mass

Allows for unification of gauge couplings

Existence of lightest supersymmetric particle (LSP); candidate for dark matter

Minimal Supersymmetric Models

Supersymmetry is not an exact symmetry

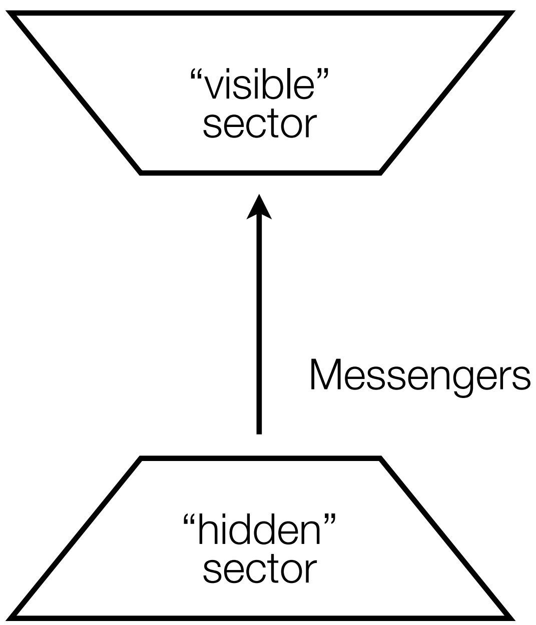
... as SUSY particles are not observed at low masses

Needs model(s) for (soft) symmetry breaking

Most models assume "hidden" sector ...

Hidden sector: particles neutral to SM gauge group

Visible sector: MSSM particle spectrum



completely neutral with respect to SM gauge group

SUSY breaking occurs in the hidden sector

Transmitted to MSSM by specific mechanism:

Gravity Mediated Supersymmetry Breaking (mSUGRA, cMSSM) — LSP: Neutralino

Gauge Mediated Supersymmetry Breaking (GMSB) — LSP: Gravitino

Anomaly Mediated Supersymmetry Breaking (AMSB)

SUSY breaking leads to extra parameters

Unconstrained models: 105 parameters (Masses, couplings, phases)

Constrained models: 4 or 5 parameters, assuming SUSY breaking scheme

Examples: mSugra, cMSSM ...

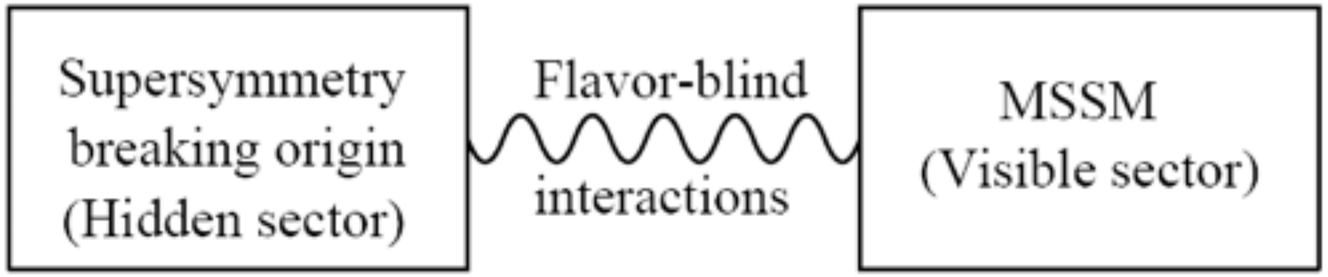
mSUGRA – A Constrained Model

Unification assumption

Assume universal masses for all bosons and
fermions at the GUT (Grand Unification Theory) scale

Symmetry breaking assumption

Model where breaking is
mediated by gravity

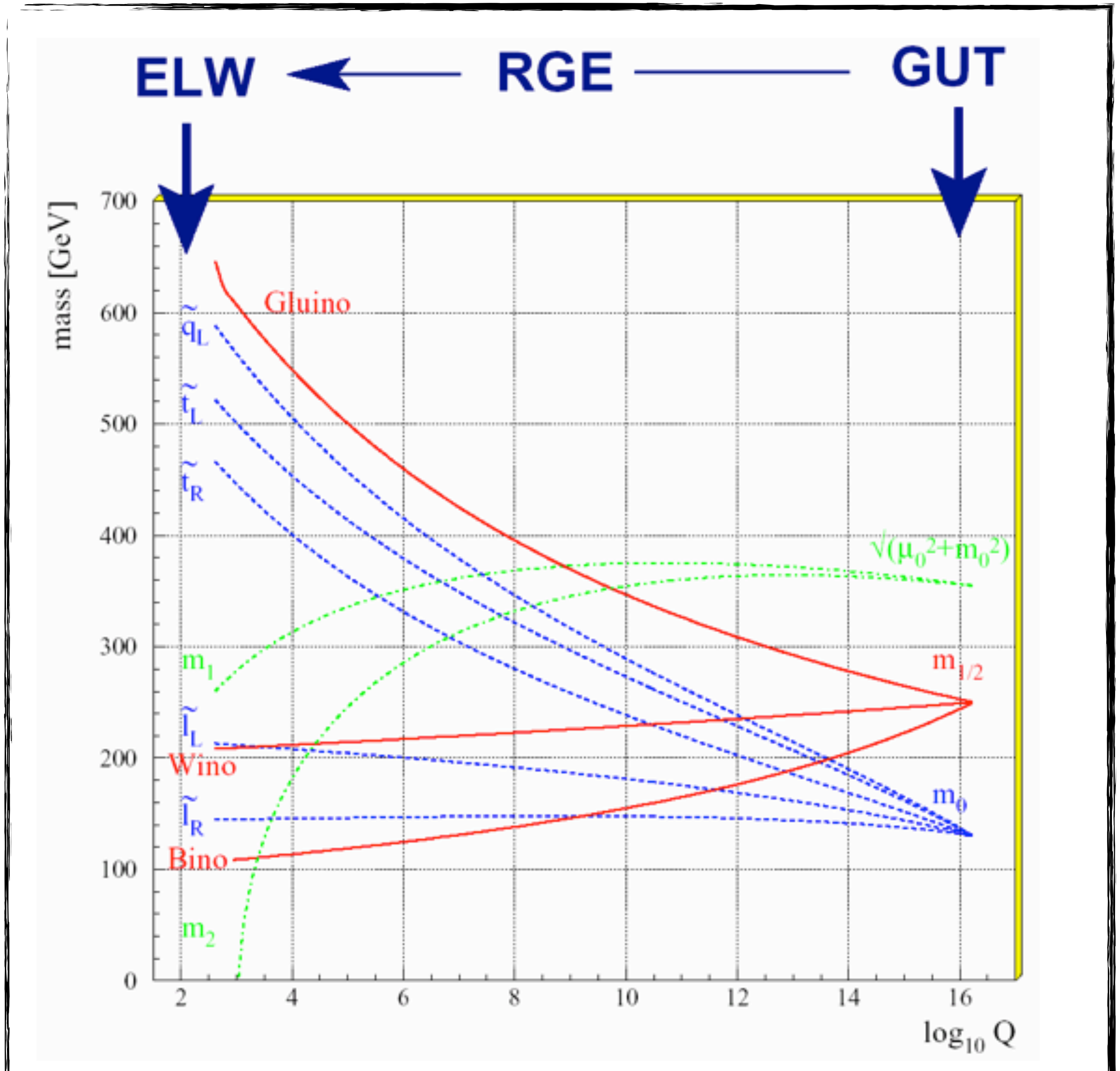


Results in

5 remaining parameters

m_0:	universal boson (scalar) mass
$m_{½}$:	universal gaugino mass
A_0:	universal trilinear coupling
$\tan\beta$:	ratio of the two Higgs VEVs (vacuum expectation values)
sgn(μ):	sign of the higgsino mass parameter

mSUGRA Mass Spectrum

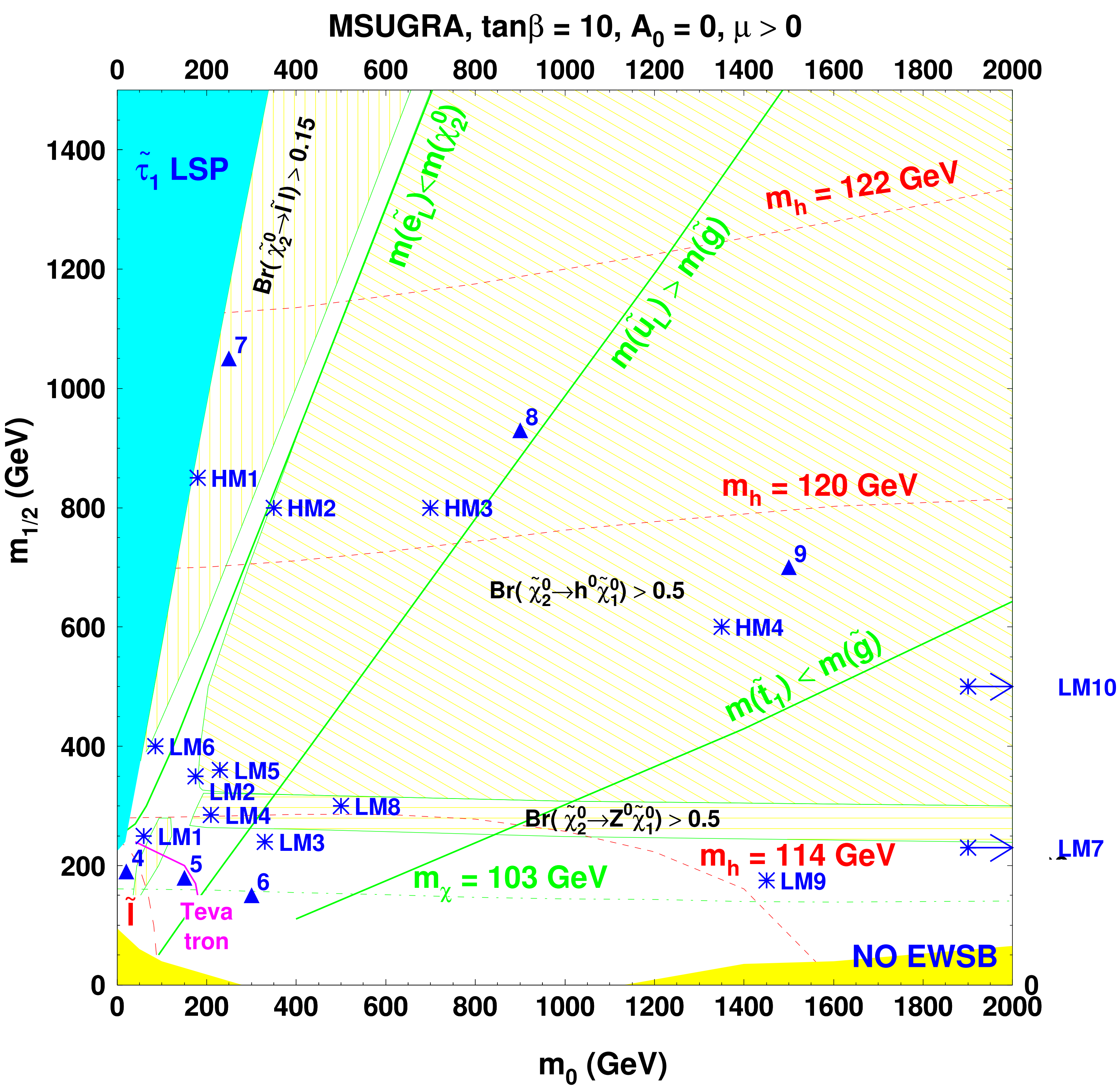


Running masses:

Universal masses at GUT scale lead to sparticle masses at EW scale via RGE evolution

from 2006

mSUGRA Parameter Space



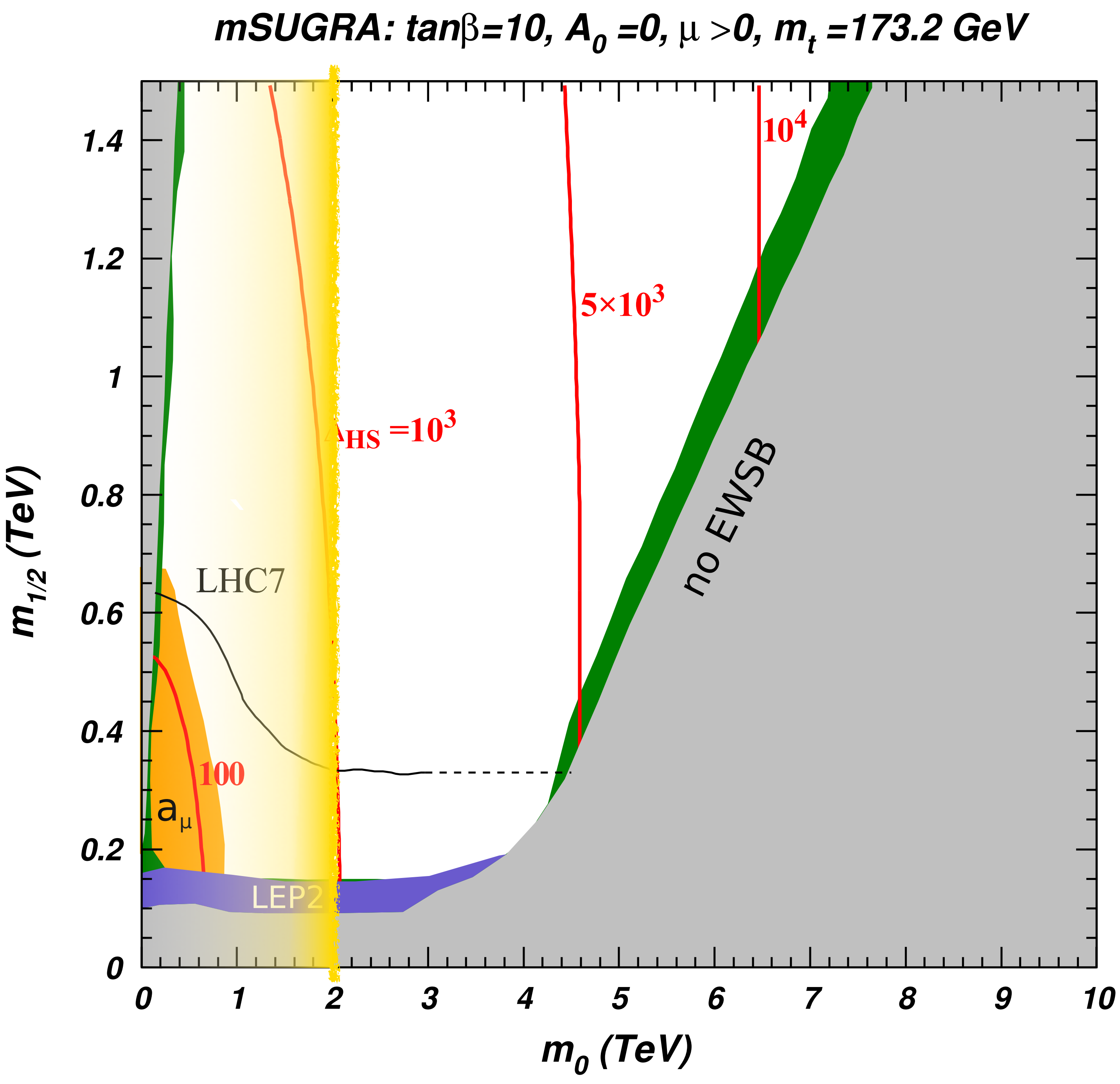
Map of mSUGRA parameter space

[CMS, LHCC-2006-021]

Position of the test points in the m_0 versus $m_{1/2}$ plane. The lines in this plane correspond to the assumptions that tan β = 10, A_0 = 0 and μ > 0. The shaded regions are excluded because either the stau1 would be the LSP or because there is not radiative electroweak symmetry breaking. The regions excluded by the LEP limit on the h_0 or the chargino masses are delineated by dashed lines. The CMS test points are indicated by stars and the points used in the CMS DAQ TDR by triangles.

from 2013

mSUGRA Parameter Space



Map of mSUGRA parameter space

[Bear et al., Phys Rev. D87, 2013]

Contours of Δ_{HS} in the mSUGRA model with A0 = 0 and tanβ = 10. We take μ > 0 and m_t = 173.2 GeV. The grey region on the left is excluded either because the stau is too light or becomes tachyonic, the grey region at the bottom is excluded by LEP1 constraints, while in the region on the right we do not get the correct pattern of EWSB, since either μ^2 or m_A^2 become negative. The region labeled LEP2 is excluded by constraints on the chargino mass. The region labeled a_μ is allowed at the 3σ level by the E821 experiment while in the dark-shaded (green-shaded) region, the thermal neutralino relic density is at or below the WMAP measurement of the cold dark matter density. The region below black contour labeled LHC7 is excluded by SUSY searches. The lighter Higgs boson mass m_h < 123 GeV throughout this parameter plane.

from 2006

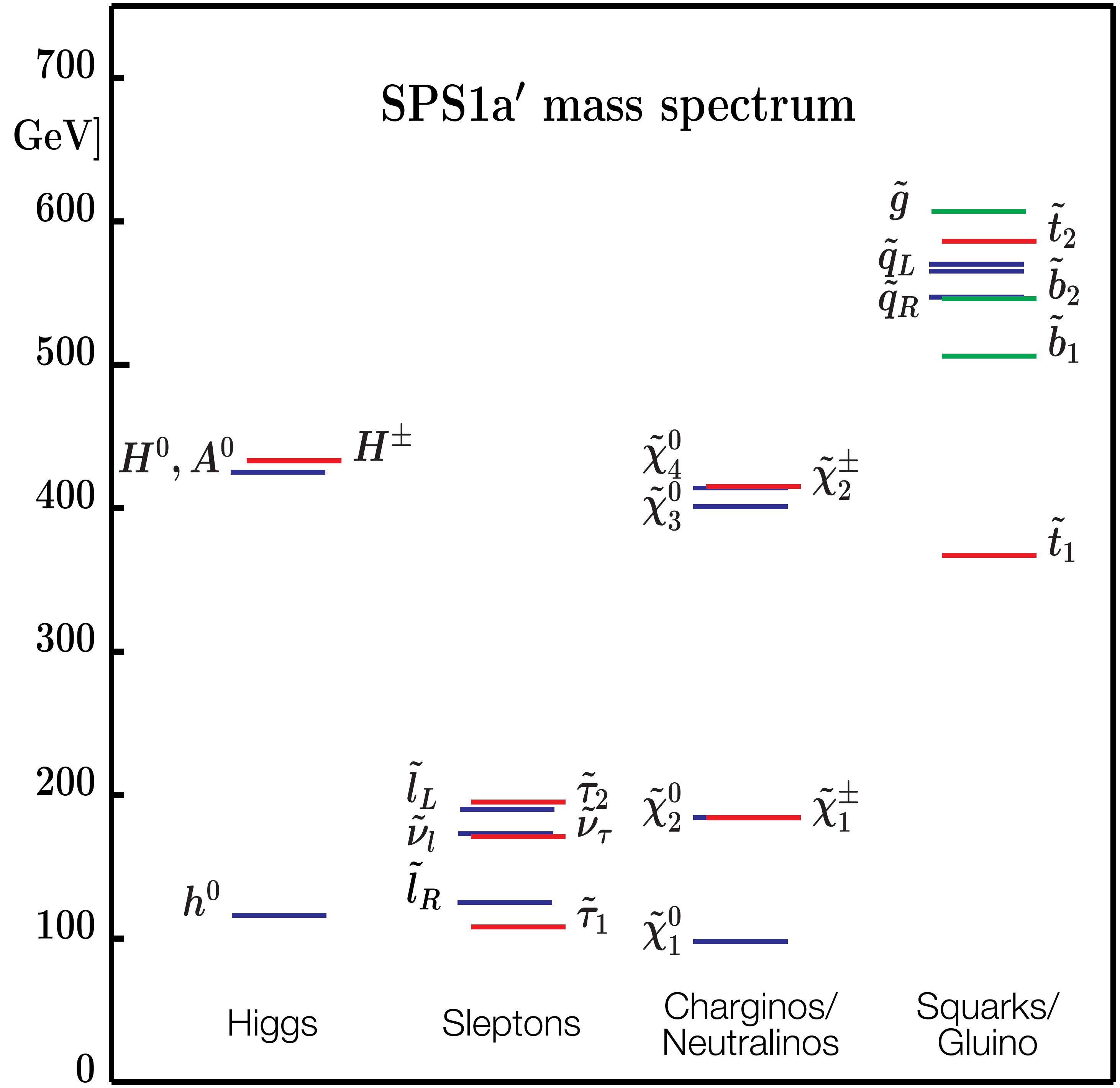
mSUGRA Particle Spectrum

SUSY parameter space too large ...

Define
Benchmark points ...

Example: SPS1a'

tanβ	=	10
$m_{1/2}$	=	250 GeV
m_0	=	70 GeV
A	=	– 300 GeV
sign(μ)	=	+ 1



[J.A. Aguillar-Saavedra et al., Eur Phys. J C46 (2006) 43]

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

$\int \mathcal{L}\, dt = (4.6 - 22.9)\ \mathrm{fb}^{-1}$ $\sqrt{s}$ = 7, 8 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^{\pm})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	$\tan\beta$<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	$\tan\beta$ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	4.8	$\tilde{g}$ 1.07 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	$m(\tilde{H})$>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde{g})>10^{-4}$ eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.2 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2013-061
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$ 275-430 GeV	$m(\tilde{\chi}_1^{\pm})=2\ m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-220 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{t}_1)-m(W)$-50 GeV, $m(\tilde{t}_1)<<m(\tilde{\chi}_1^{\pm})$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$ 225-525 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-065
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20.7	$\tilde{t}_1$ 200-610 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$ 320-660 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-200 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$ 500 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$ 271-520 GeV	$m(\tilde{t}_1)=m(\tilde{\chi}_1^0)$+180 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 85-315 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 125-450 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}_1^{\pm}$ 180-330 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.7	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 600 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	3 e,μ	0	Yes	20.7	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 315 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 285 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-093
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 270 GeV	$m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	10<$\tan\beta$<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{q}\tilde{q}, \tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e,μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$ 1.2 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.7	$\tilde{\chi}_1^{\pm}$ 760 GeV	$m(\tilde{\chi}_1^0)$>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.7	$\tilde{\chi}_1^{\pm}$ 350 GeV	$m(\tilde{\chi}_1^0)$>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$ 880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e,μ (SS)	1 b	Yes	14.3	sgluon 800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

10^{-1} 1 **Mass scale [TeV]**

$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

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

from 2013

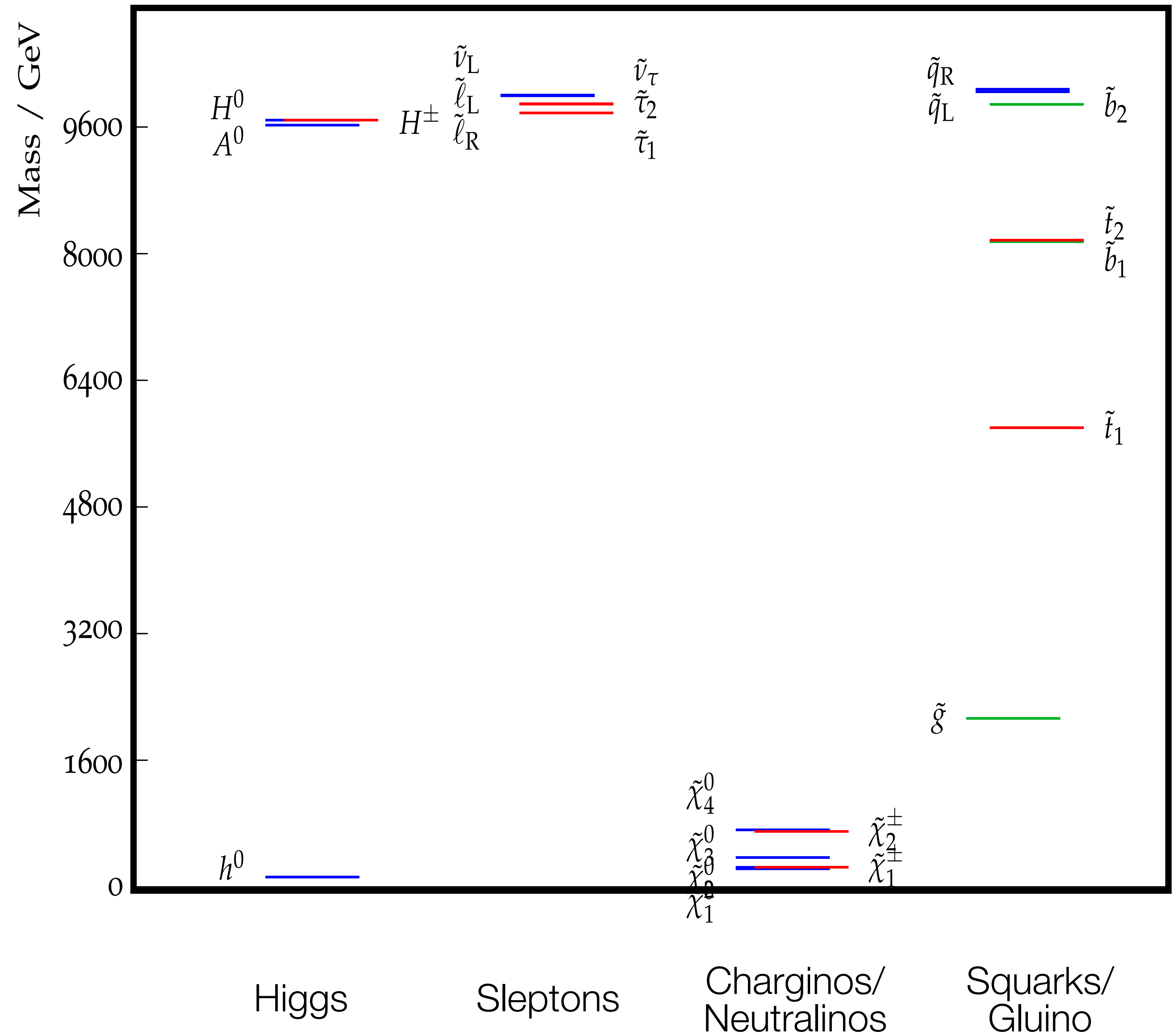
mSUGRA Particle Spectrum

SUSY parameter space too large ...

Define
Benchmark points ...

Example: Post-LHC8

tanβ	=	15
$m_{1/2}$	=	800 GeV
m_0	=	10 TeV
A	=	– 5.45 TeV
sign(μ)	=	+ 1



[Bear et al., Phys. Rev. D88, 055004, 2013]

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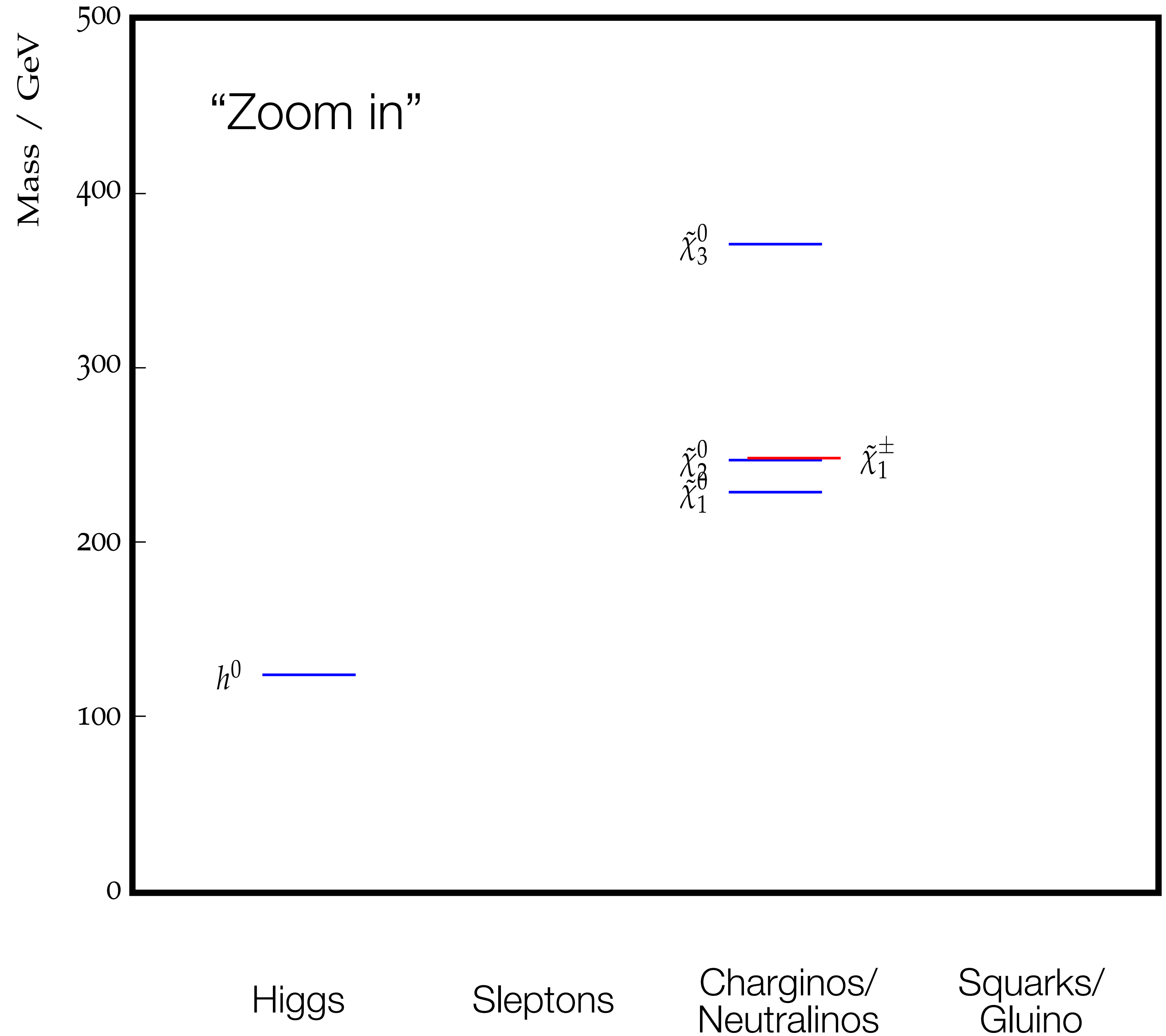


[Bear et al., Phys. Rev. D88, 055004, 2013]

from 2013

NUMH2 Particle Spectrum

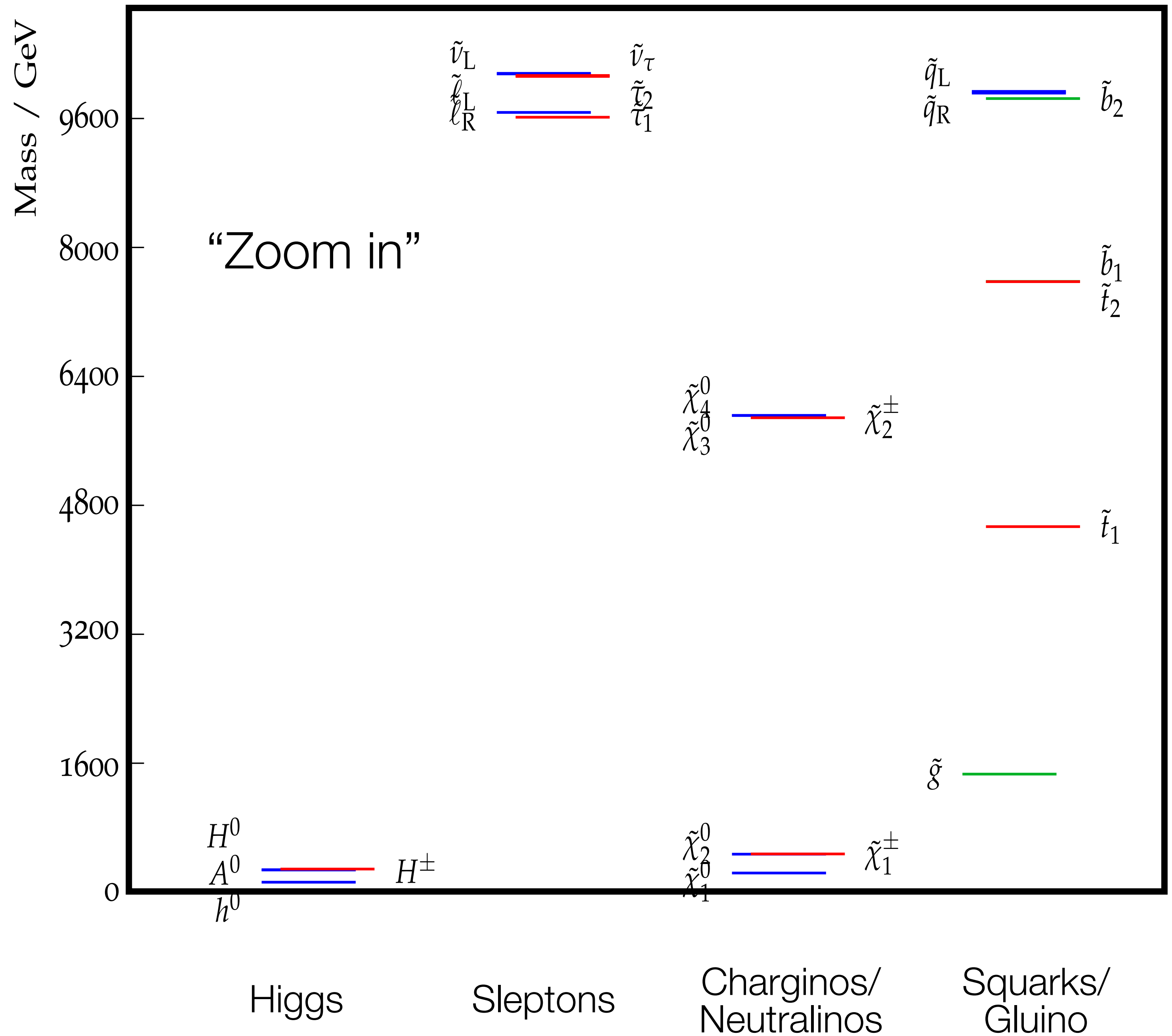
[]NUMH2: 2-parameter non-universal Higgs model]

SUSY parameter space too large ...

Define
Benchmark points ...

Example: Post-LHC8

$\tan\beta$ = 7
$m_{1/2}$ = 500 GeV
m_0 = 10 TeV
A = – 16 TeV
μ = 6 TeV



[Bear et al., Phys. Rev. D88, 055004, 2013]

from 2013

NUMH2 Particle Spectrum

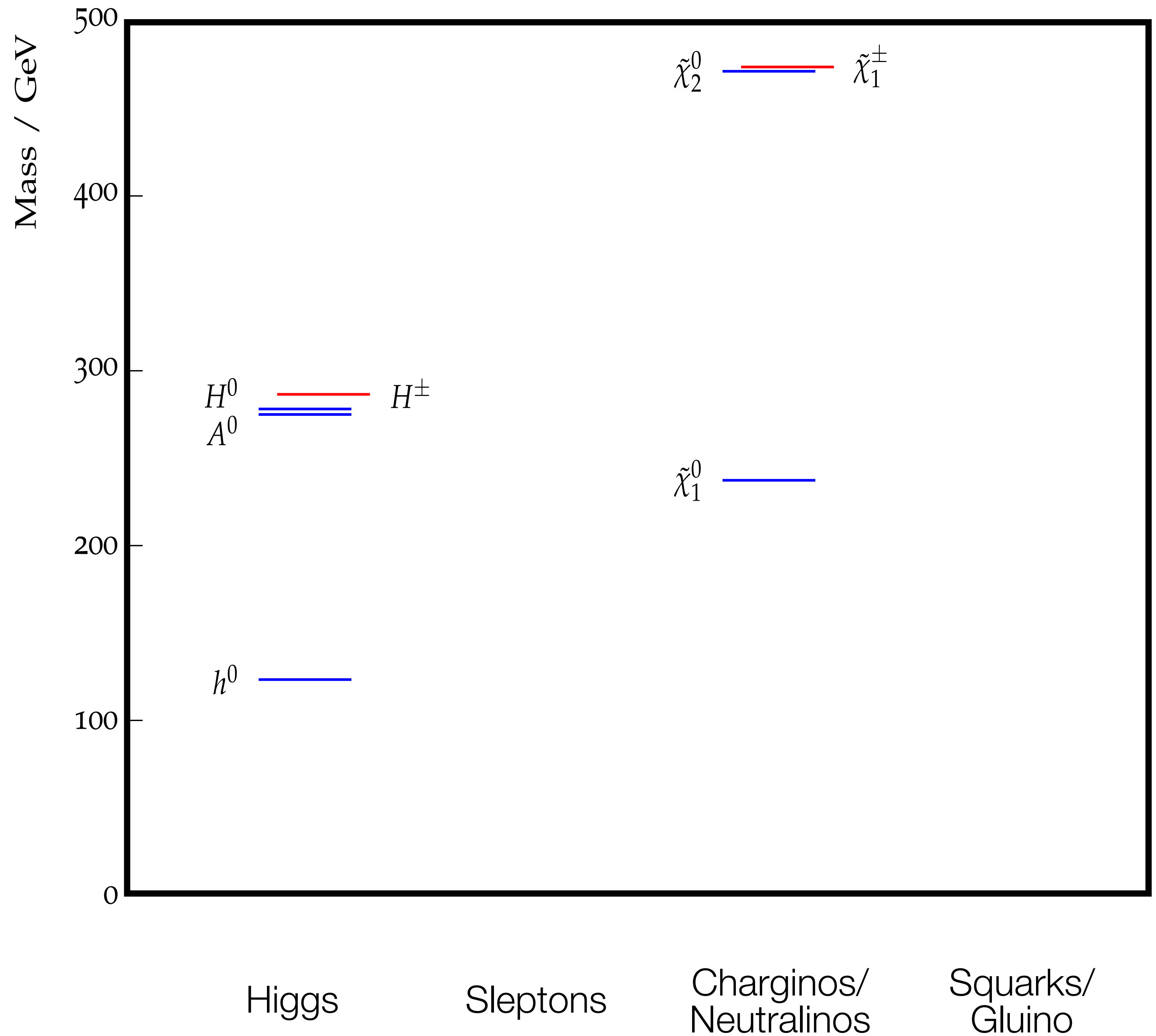
[]NUMH2: 2-parameter non-universal Higgs model]

SUSY parameter space too large ...

Define
Benchmark points …

Example: Post-LHC8

tanβ	=	7
$m_{½}$	=	500 GeV
m_0	=	10 TeV
A	=	– 16 TeV
μ	=	6 TeV



[Bear et al., Phys. Rev. D88, 055004, 2013]

MSSM Higgs Sector

Consider MSSM Higgs:

Two Higgs doublets ➛ 5 physical Higgs bosons: h, H, A, $H^{\pm}$ …

Enhanced coupling to 3rd generation …
Strong coupling to down-type fermions …
[at large tanβ get strong enhancements to h/H/A production rates]

Couplings: $g_{MSSM} = \xi \cdot g_{SM}$

ξ	t	b/τ	W/Z
h	cosα/sinβ	- sinα/cosβ	sin(α-β)
H	sinα/sinβ	cosα/cosβ	cos(α-β)
A	cotβ	tanβ	–

Mixing angels: α,β

α: Mixing of CP even Higgs H_u,H_d ➛ h,H
β: Mixing of charged fields $\phi^{\pm}_{1,2}$
[also: $\tan\beta = v_u/v_d$]

usually vanishing
[decoupling limit; $M_A \gg M_Z$]

Large tanβ:
Enhancement of Higgs couplings to b,τ …
[and decreased coupling to top …]

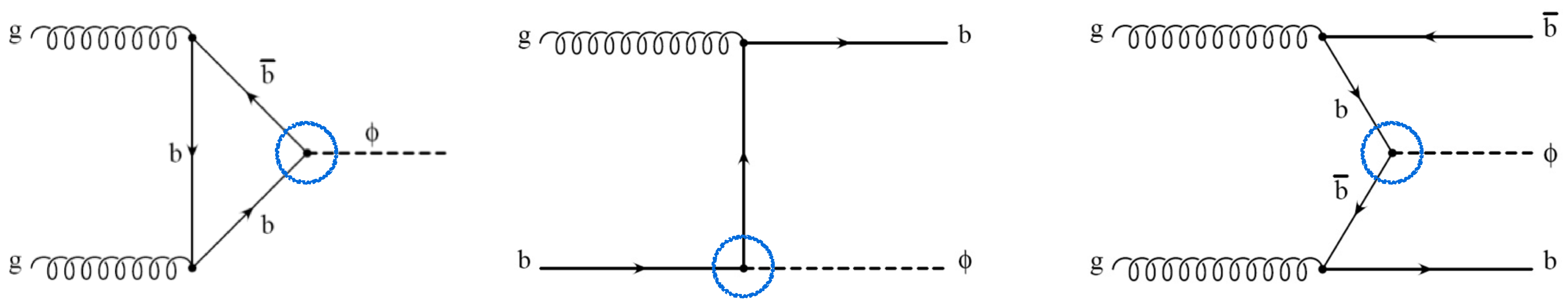
MSSM Higgs Sector

Consider MSSM Higgs:

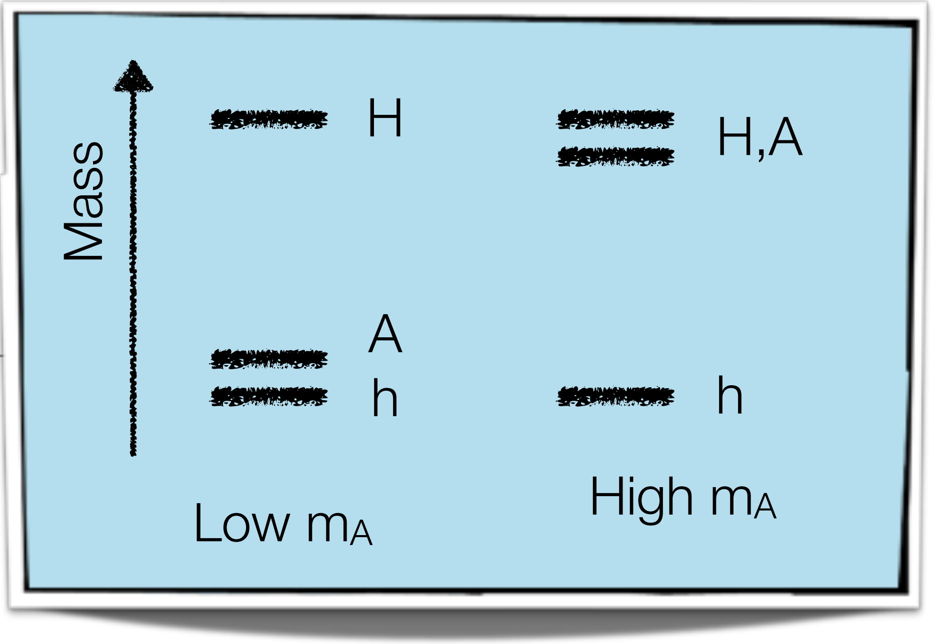
Two Higgs doublets ➛ 5 physical Higgs bosons: h, H, A, $H^{\pm}$ …

Enhanced coupling to 3rd generation …
Strong coupling to down-type fermions …
[at large tanβ get strong enhancements to h/H/A production rates]

Enhanced bbϕ diagrams [ϕ = h,H,A]
[Examples]



MSSM Higgs Sector



Consider MSSM Higgs:

Masses of Higgs bosons h,H,A
parametrized by two parameters: tanβ, m_A …

$$m^2_{\mathrm{h,H}} = \frac{1}{2}\left(m^2_{\mathrm{A}} + m^2_{\mathrm{Z}} \mp \sqrt{(m^2_{\mathrm{A}} - m^2_{\mathrm{Z}})^2 + 4m^2_{\mathrm{A}} m^2_{\mathrm{Z}} \sin^2(2\beta)}\right)$$

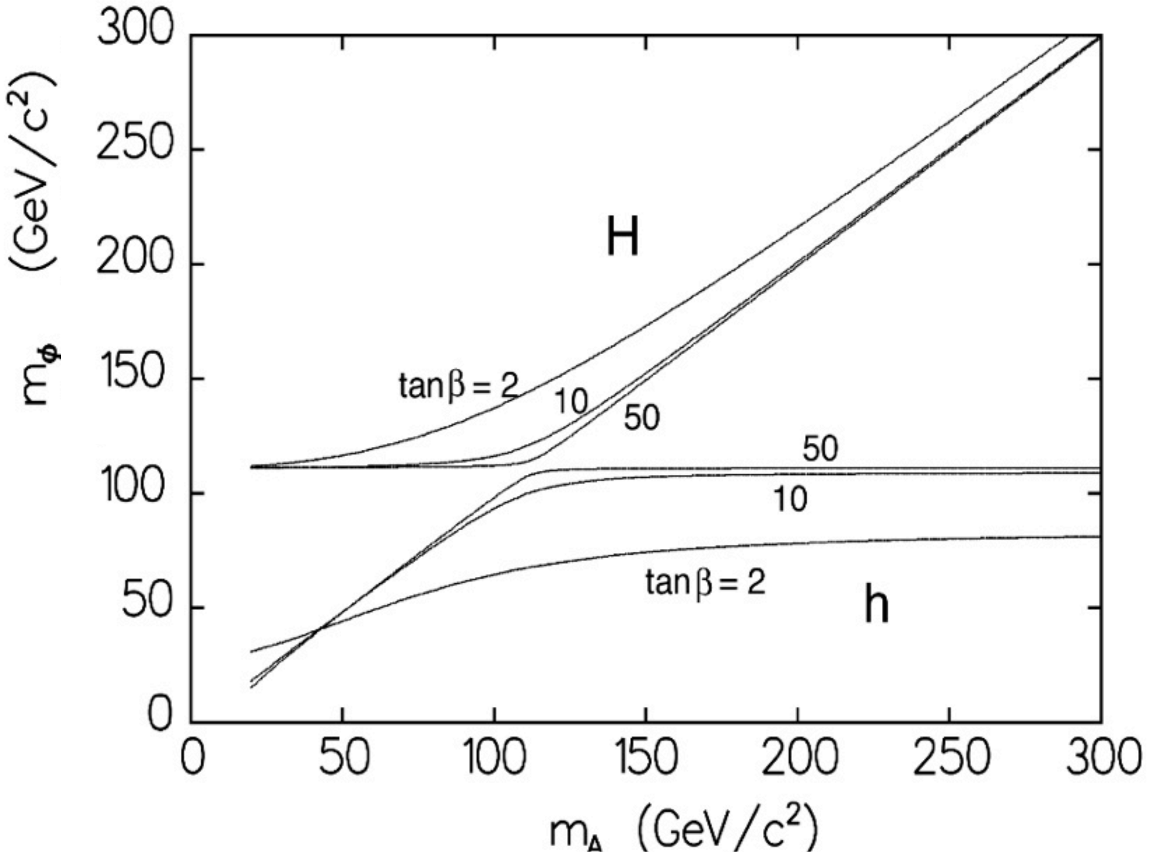
$$m^2_{\mathrm{A}} = 2b/\sin(2\beta)$$

Decoupling limit …
i.e. m_A large …

$m_H \approx m_A$, $m_h \approx m_Z|\cos 2\beta|$
[needs radiative corrections to allow m_h = 125 GeV]

Low m_A …

$m_h \approx m_A|\cos 2\beta|$
$m_H \approx m_Z$



Searching for the MSSM Higgs

A popular and well-studied extension …

Mass of light CP-even Higgs $m_h < 135$ GeV

For large parts of the parameter space
H ➛ bb and H ➛ ττ decays dominate
[and also $H^{\pm}$ ➛ $\tau^{\pm}\nu$; see later]

WW/ZZ decays are suppressed
for heavier CP-even Higgs H …
[decoupling limit]

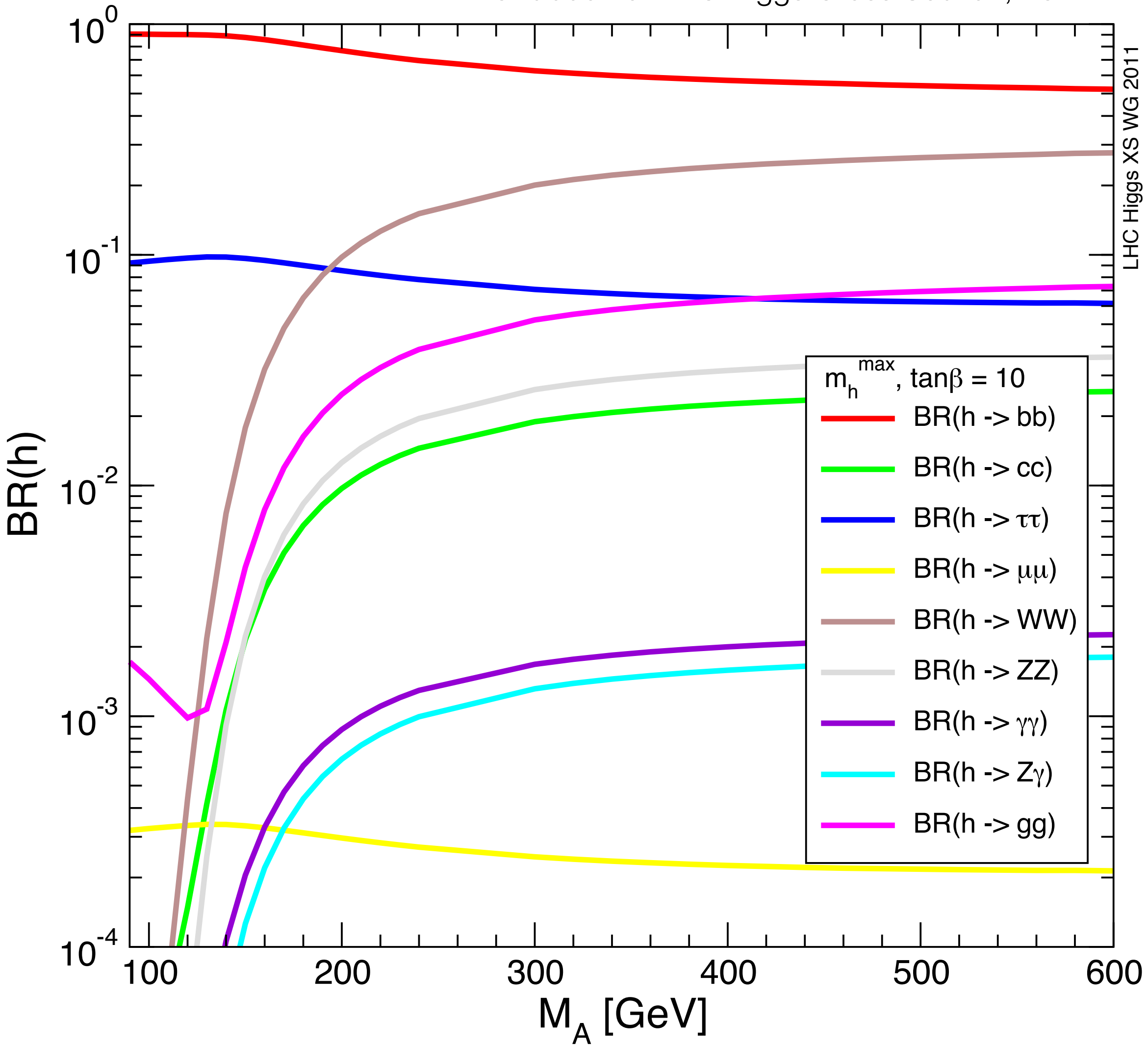
Use m_h^{max} Scenario …

[Carena et al.]

MSSM parameters chosen
to maximize m_h for given m_A, tanβ …

➛ $M_A < 130$ GeV: $m_h \approx m_A$, $m_H \approx 130$ GeV
$M_A > 130$ GeV: $m_h \approx m_H$, $m_h \approx 130$ GeV

[arXiv:1201.3084]
Handbook of LHC Higgs Cross Section, Part II



MSSM Higgs Production