UNIVERSITY OF Southampton
School of Physics and Astronomy

Steve King

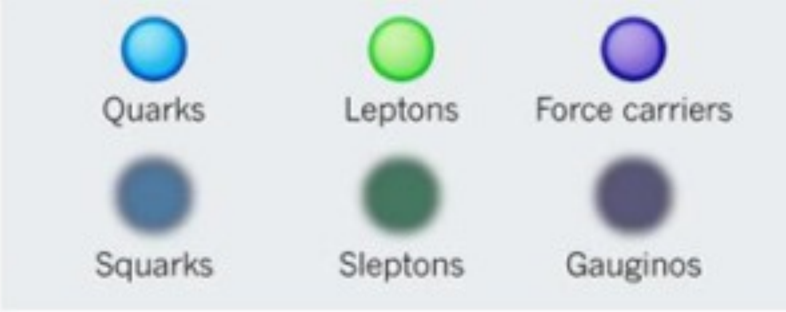
Introduction to SUperSymmetrY and current status of MSSM

S.P. Martin, “SUSY Primer”, hep-ph/9709356
Chung et al, “Soft SUSY Breaking Lagrangian”, hep-ph/0312374

Supersymmetry

Corfu Summer Institute

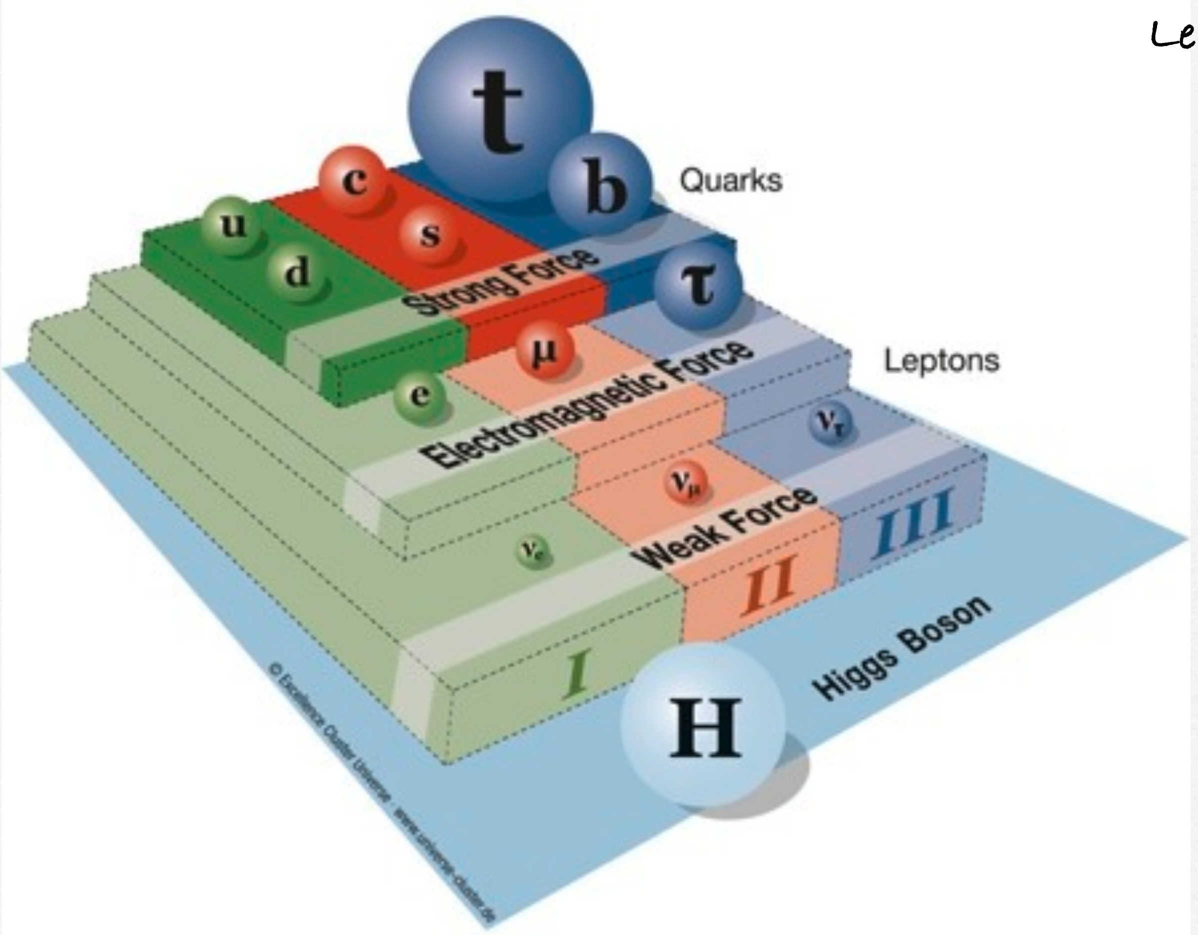
SUSY



SUSY'S MID-LIFE CRISIS

1970–74	Several theorists independently develop SUSY
1981	Supersymmetric version of the standard model proposed
1983	SUSY used to explain dark matter
1990	SUSY suggested as a way to unify electroweak and strong forces
2000	Large Electron Positron collider (the LHC's predecessor) fails to find evidence of SUSY particles called sleptons
2008	Tevatron sets mass limits on supersymmetric quarks (squarks)
2011	LHC tightens limits on SUSY masses

The Standard Model



Lectures by Hollik, Pittau

With the discovery of the "Higgs" it now seems to be complete... so why the continued interest in SUSY after LHC8?

Standard Model Puzzles

1. The origin of mass - the origin of the weak scale, its stability under radiative corrections, and the solution to the hierarchy problem

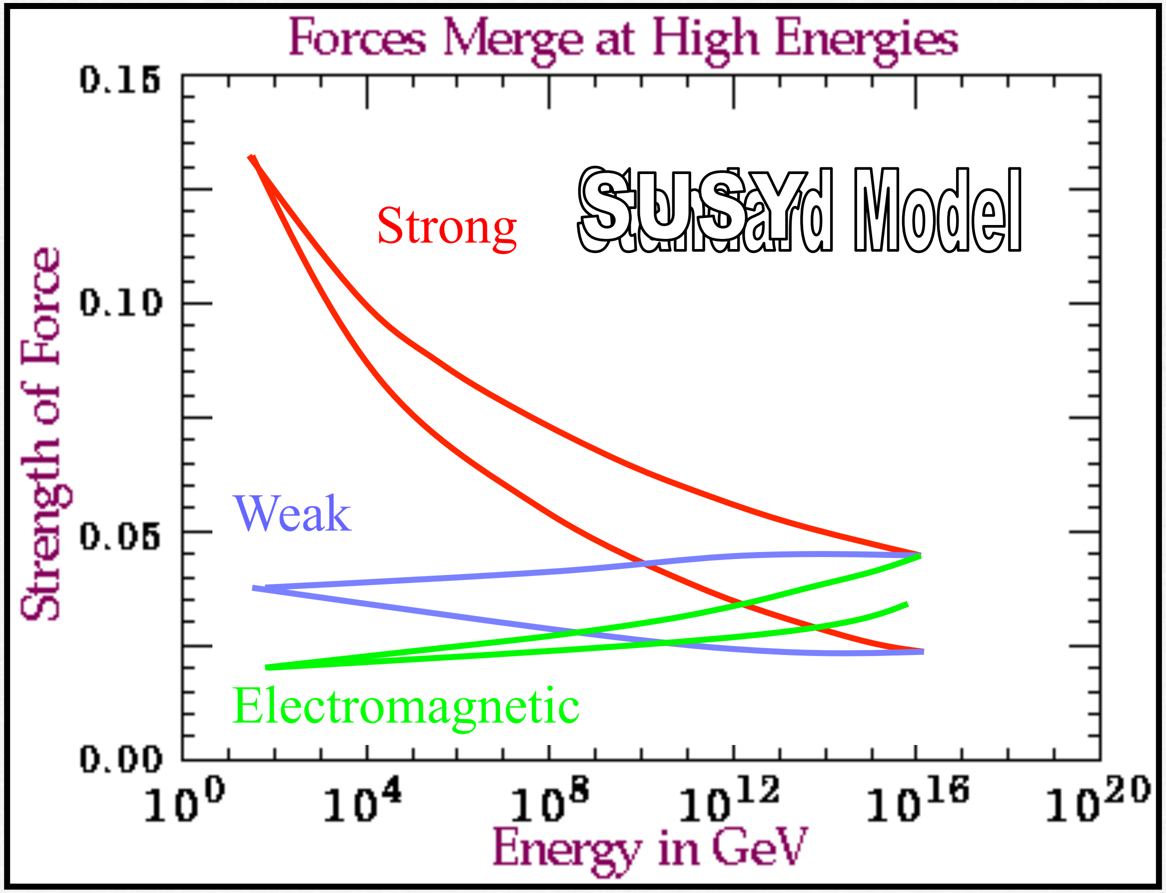
2. The quest for unification - the question of whether the three known forces of the standard model may be related into a grand unified theory, and whether such a theory could also include a unification with gravity.

3. The problem of flavour - the problem of the undetermined fermion masses and mixing angles (including neutrino masses and mixing angles) together with the CP violating phases, in conjunction with the observed smallness of flavour changing neutral currents and very small strong CP violation.

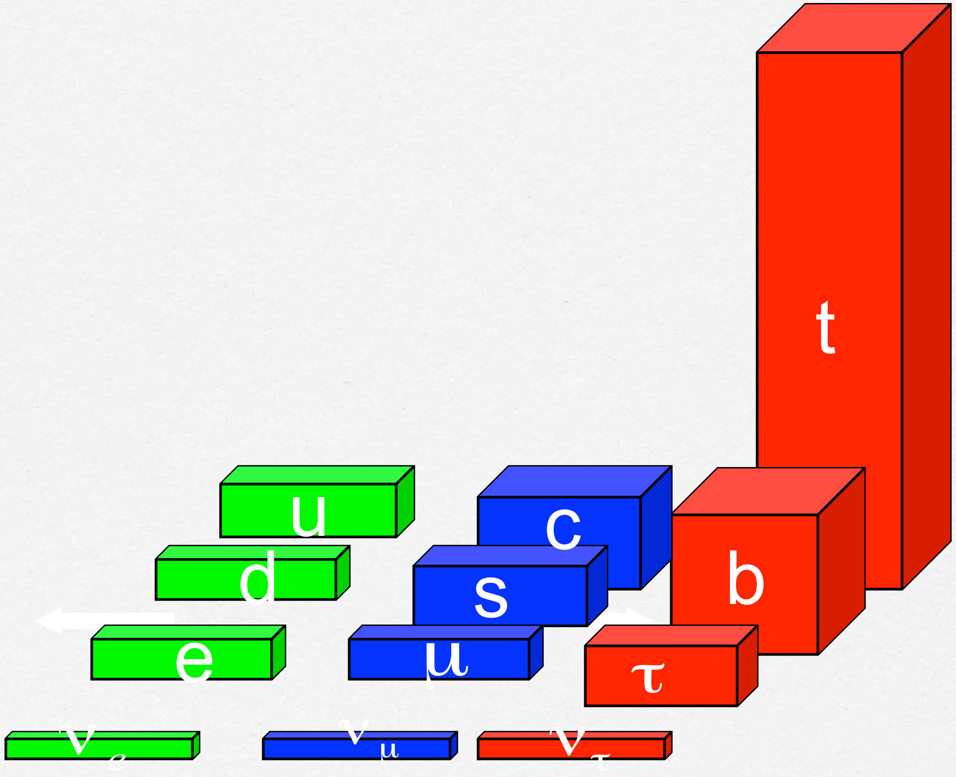
Cosmological Puzzles

1. The origin of dark matter and dark energy: the embarrassing fact that 95% of the mass-energy of the Universe is in a form that is presently unknown, including 27% dark matter and 68% dark energy
2. The problem of matter-antimatter asymmetry: the problem of why there is a tiny excess of matter over antimatter in the Universe, at a level of one part in a billion, without which there would be no stars, planets or life
3. The question of the size, age, flatness and smoothness of the Universe: the question of why the Universe is much larger and older than the Planck size and time, and why it has a globally flat geometry with a very smooth cosmic microwave background radiation containing just enough fluctuations to seed the observed galaxy structures

SUSY facilitates GUTs



GUTs and Flavour Models are typically Supersymmetric

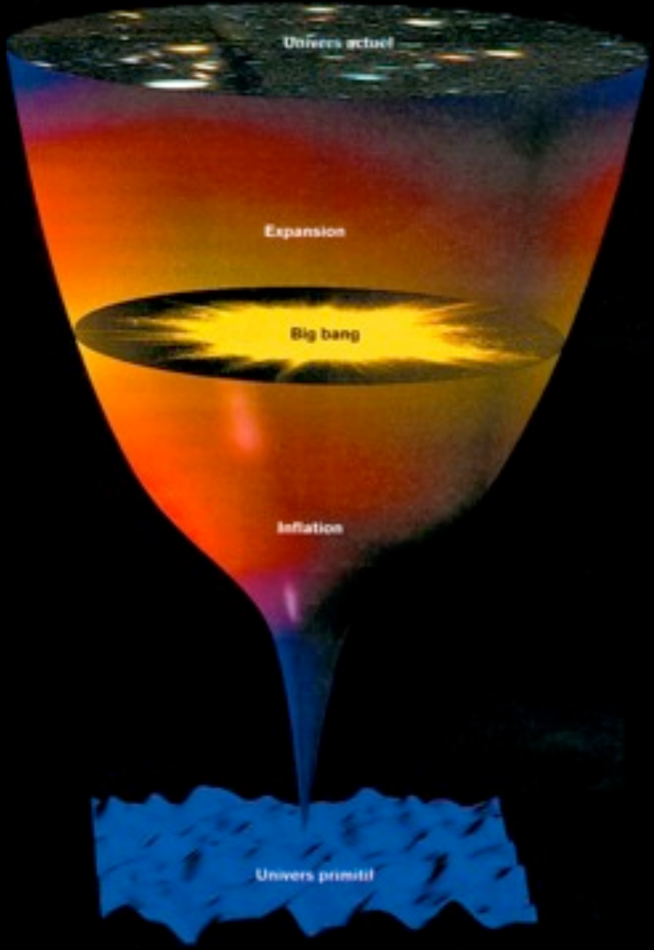


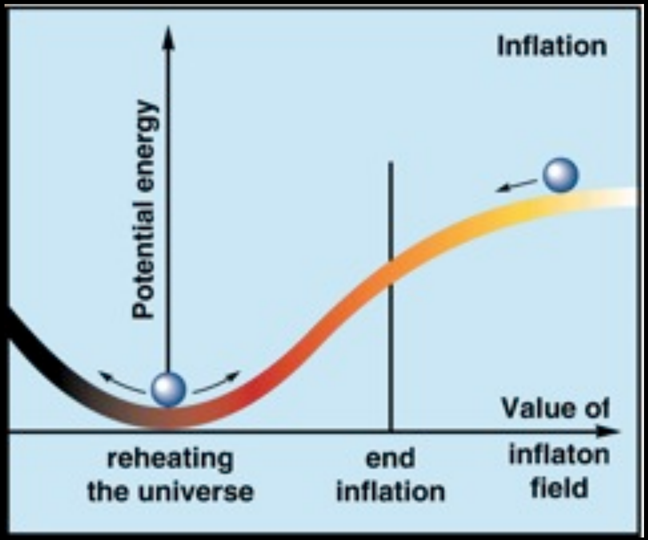
Many inflation models are supersymmetric

Why is the Universe so big and flat?

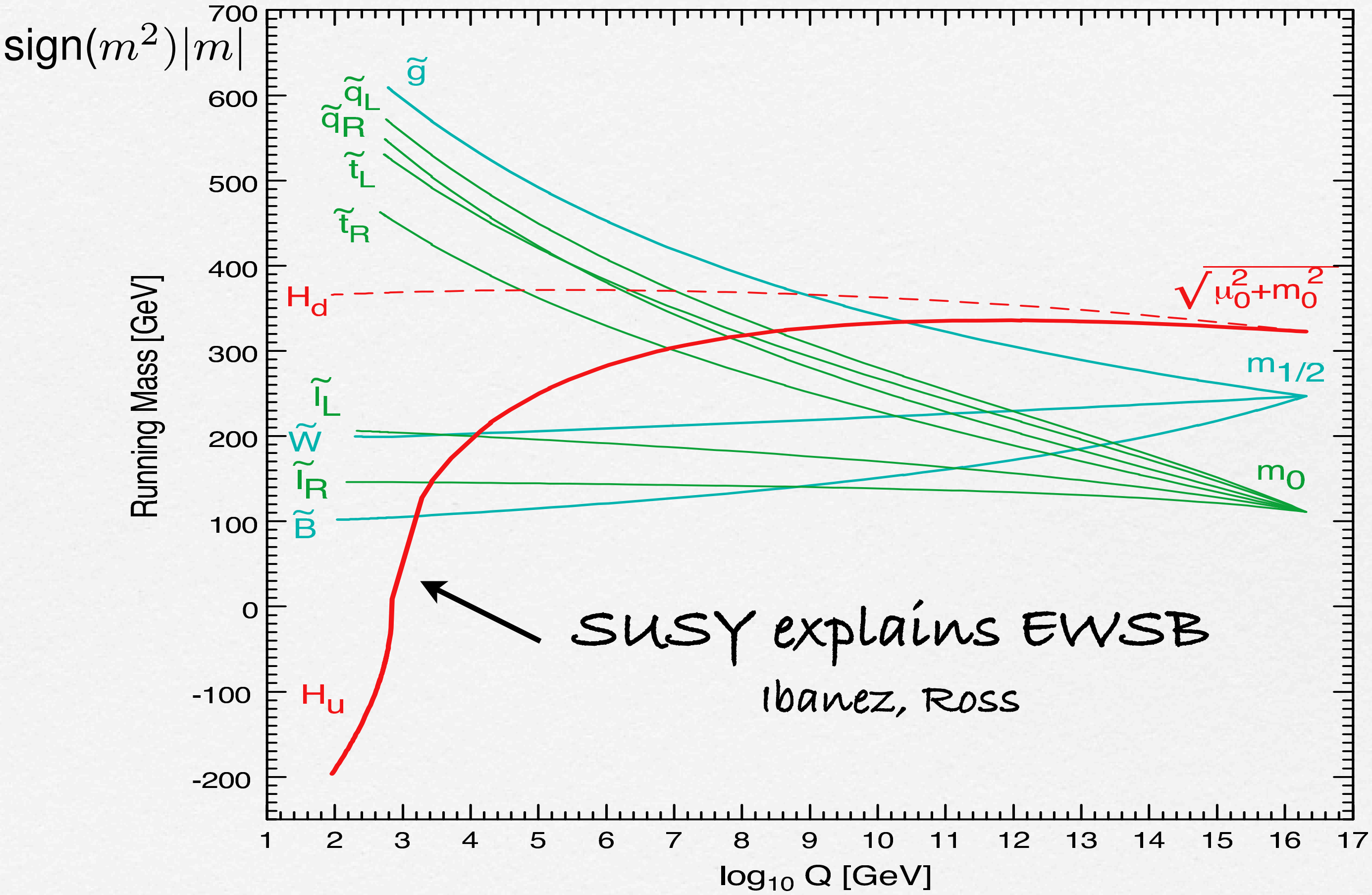
What seeds the density perturbations?

-- Inflation!





- ”Why does electroweak symmetry break?” or ”Why is $\mu^2 < 0$ in the SM?”

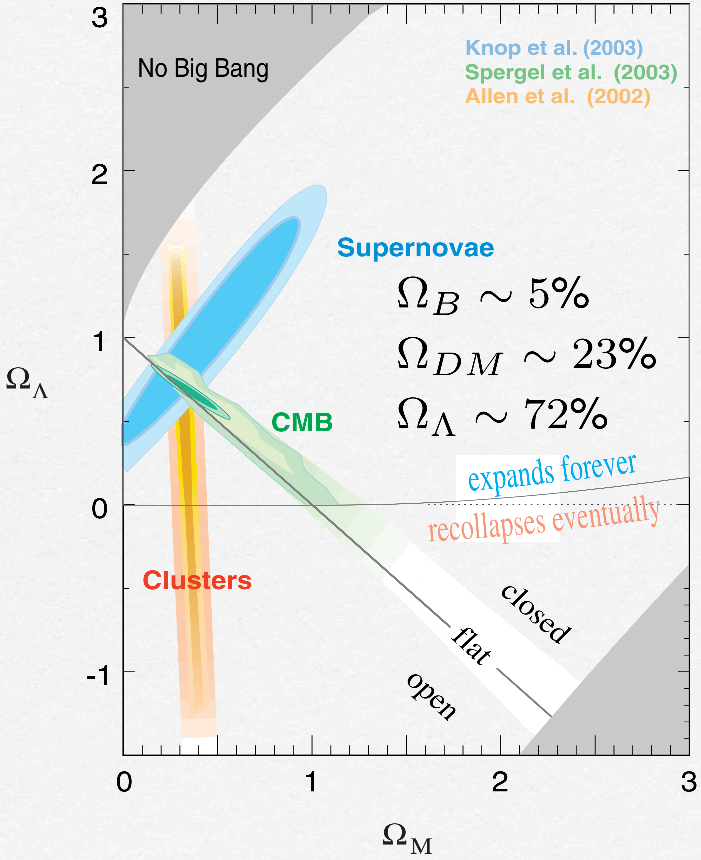


SUSY explains EWSB

Ibanez, Ross

G. Kane, C. Kolda, L. Roszkowski, J. Wells, PRD 1994

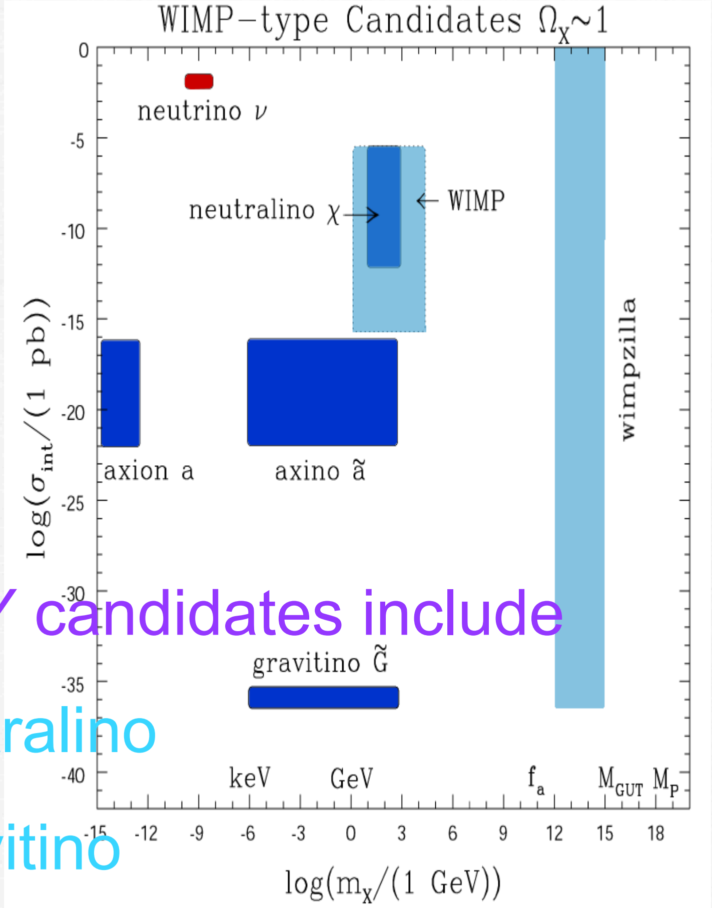
- What is the nature of dark matter ?



$$\Omega_B \sim 5\%$$

$$\Omega_{DM} \sim 23\%$$

$$\Omega_\Lambda \sim 72\%$$



SUSY candidates include

- Neutralino
- Gravitino

R.A. Knopp et al., Astrophys. J. **598** (2003) 102

L. Roszkowski, astro-ph/0404052

Once upon a time, there was a naturalness problem...

Murayama

- At the end of 19th century: a "crisis" about electron
  - Like charges repel: hard to keep electric charge in a small pack
  - Electron is point-like
  - At least smaller than 10^{-17}cm
- Need a lot of energy to keep it small!

$$\Delta m_e c^2 \sim \frac{e^2}{r_e} \sim \mathrm{GeV}\frac{10^{-17}\mathrm{cm}}{r_e}$$

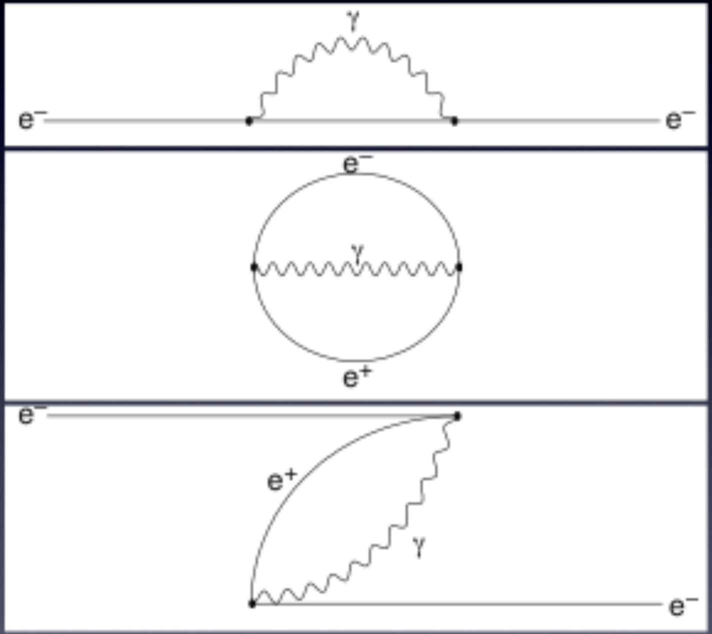
- Correction $\Delta m_e c^2 > m_e c^2$ for $r_e < 10^{-13}$cm
- Breakdown of theory of electromagnetism

$\Rightarrow$ Can't discuss physics below 10^{-13}cm

Anti-Matter Comes to Rescue by Doubling of #Particles

- Electron creates a force to repel itself
- Vacuum bubble of matter anti-matter creation/annihilation
- Electron annihilates the positron in the bubble

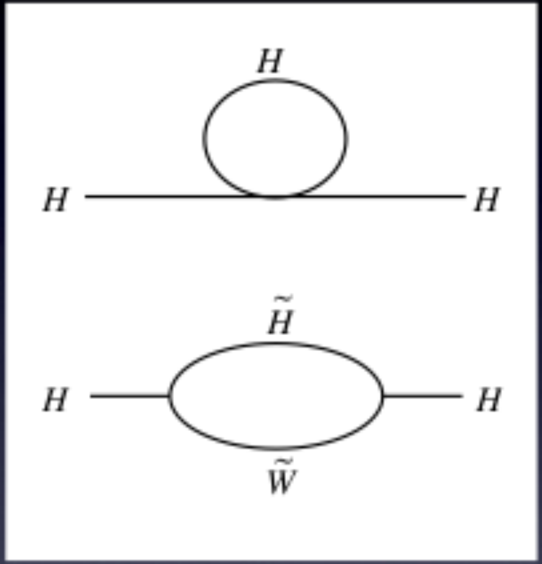
⇒ only 10% of mass even for Planck-size $r_e \sim 10^{-33}$cm



$$\Delta m_e \sim m_e \frac{\alpha}{4\pi} \log(m_e r_e)$$

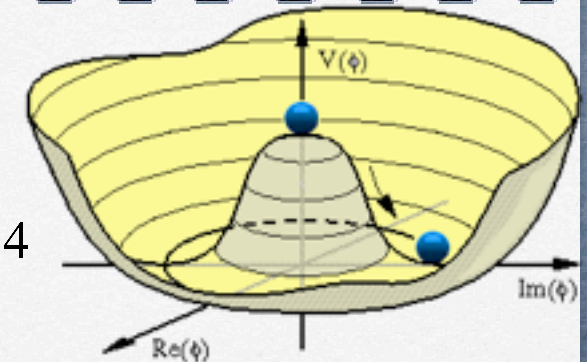
History repeats itself?

- Higgs also repels itself
- Double #particles again
  ⇒ superpartners
- “Vacuum bubbles” of superpartners cancel the energy required to contain Higgs boson in itself
- Standard Model made consistent with whatever physics at shorter distances



$$\Delta m_H^2 \sim \frac{\alpha}{4\pi} m_{SUSY}^2 \log(m_H r_H)$$

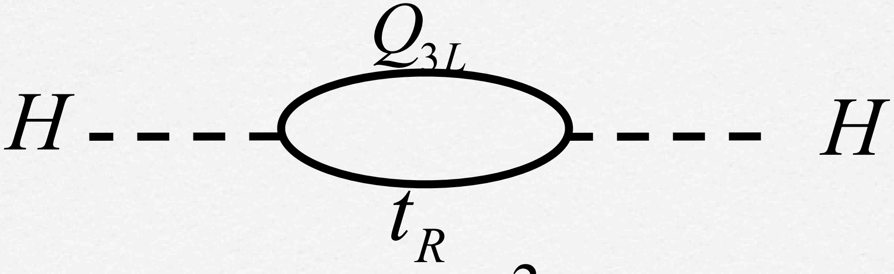
Higgs Theory in SM



Higgs potential $V = m_H^2 \left|H\right|^2 + \frac{1}{2}\lambda \left|H\right|^4$

Tree-level min cond $m_H^2 = -\lambda v^2 = -\lambda \left(246\,GeV\right)^2$

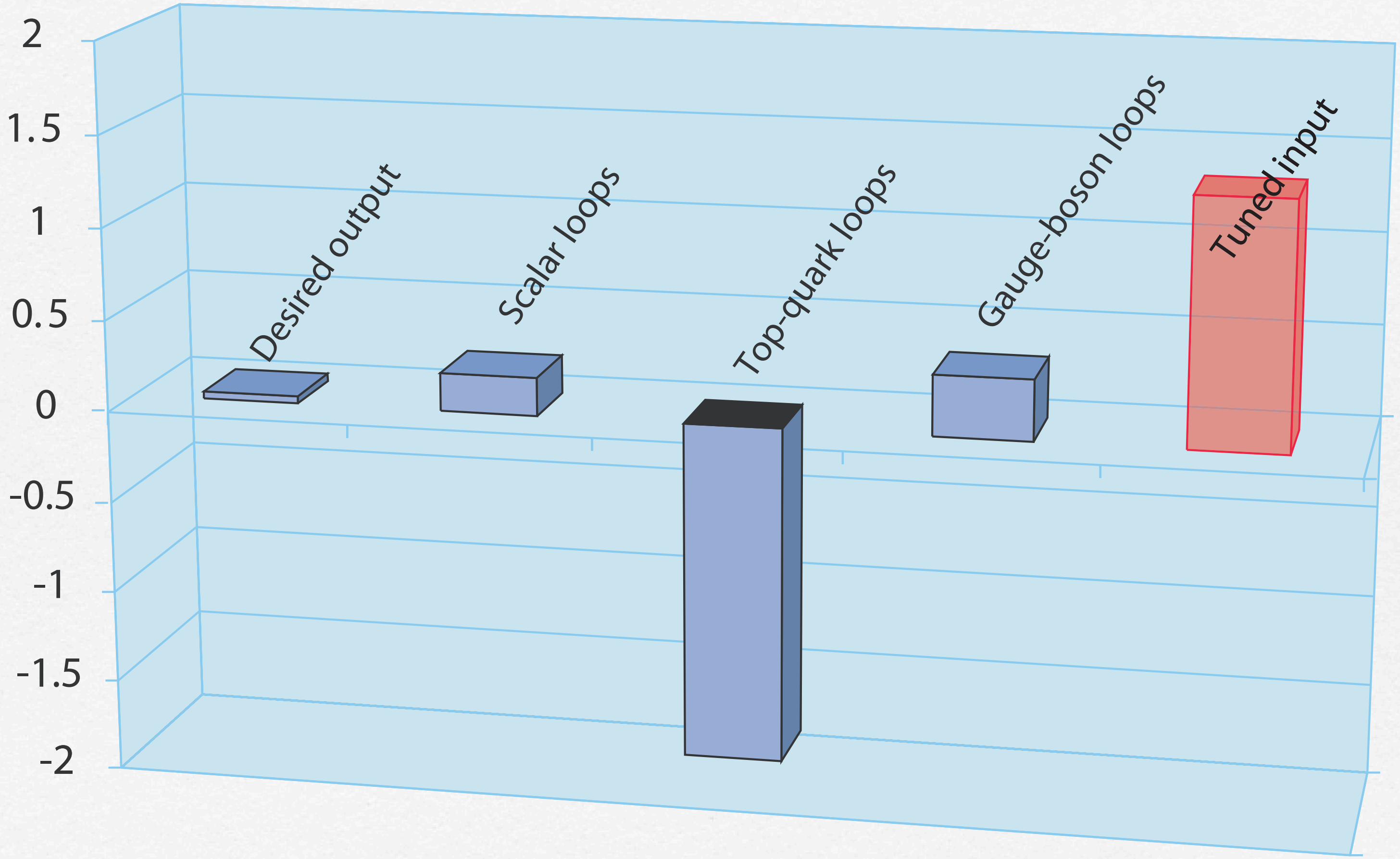
Including rad corr $m_H^2 + \delta m_H^2 = -\lambda \left(246\,GeV\right)^2$



$$\delta m_H^2(top\,loop) = -\frac{3}{\sqrt{2}\pi^2} G_F m_t^2 \Lambda^2 = -\left(100\,GeV\right)^2 \left(\frac{\Lambda}{1\,TeV}\right)^2$$

Fine-tuning is required if the cut-off $\Lambda \gg 1\,TeV$

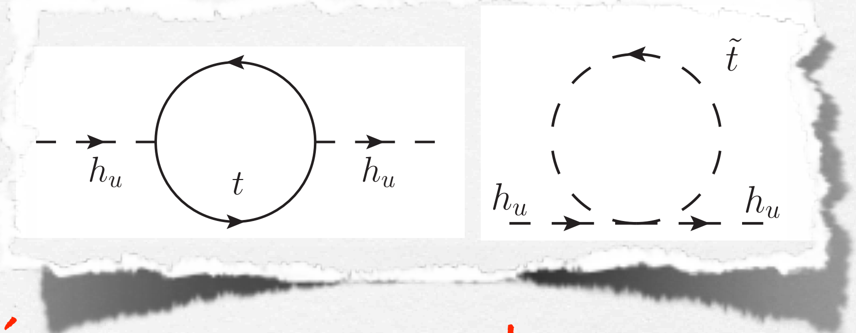
Relative contributions to ΔM_H^2 for $\Lambda = 5$ TeV



Quigg 0704.2232

In SUSY, stop loops dominate Higgs mass parameter correction

$$\delta m_H^2(stop\ loop)$$

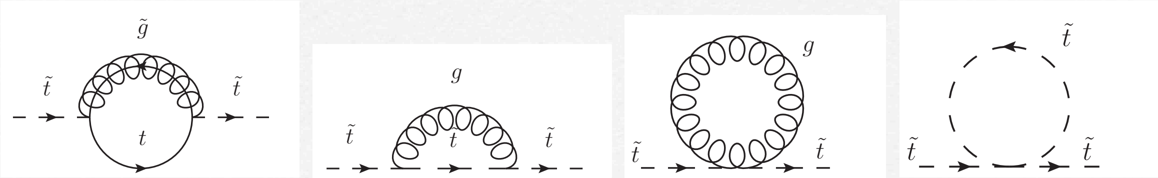


Leading quadratic divergence cancels

$$\delta m_{h_u}^2 = -\frac{3y_t^2}{4\pi^2} m_{\tilde{t}}^2 \ln\left(\frac{\Lambda_{UV}}{m_{\tilde{t}}}\right)$$

To avoid tuning need $m_{\tilde{t}} \lesssim 400\text{GeV}.$

Gluino corrections to stop

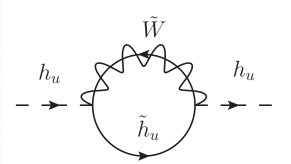


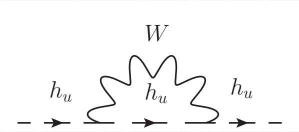
$$\delta m_{\tilde{t}}^2 = \frac{2g_s^2}{3\pi^2} m_{\tilde{g}}^2 \ln \frac{\Lambda_{UV}}{m_{\tilde{g}}}.$$

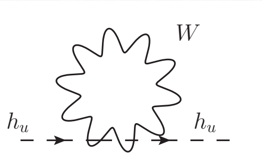
To avoid
tuning need

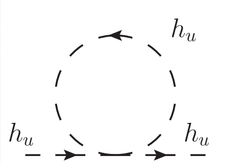
$$m_{\tilde{g}} \lesssim 2m_{\tilde{t}}.$$

Other important loops







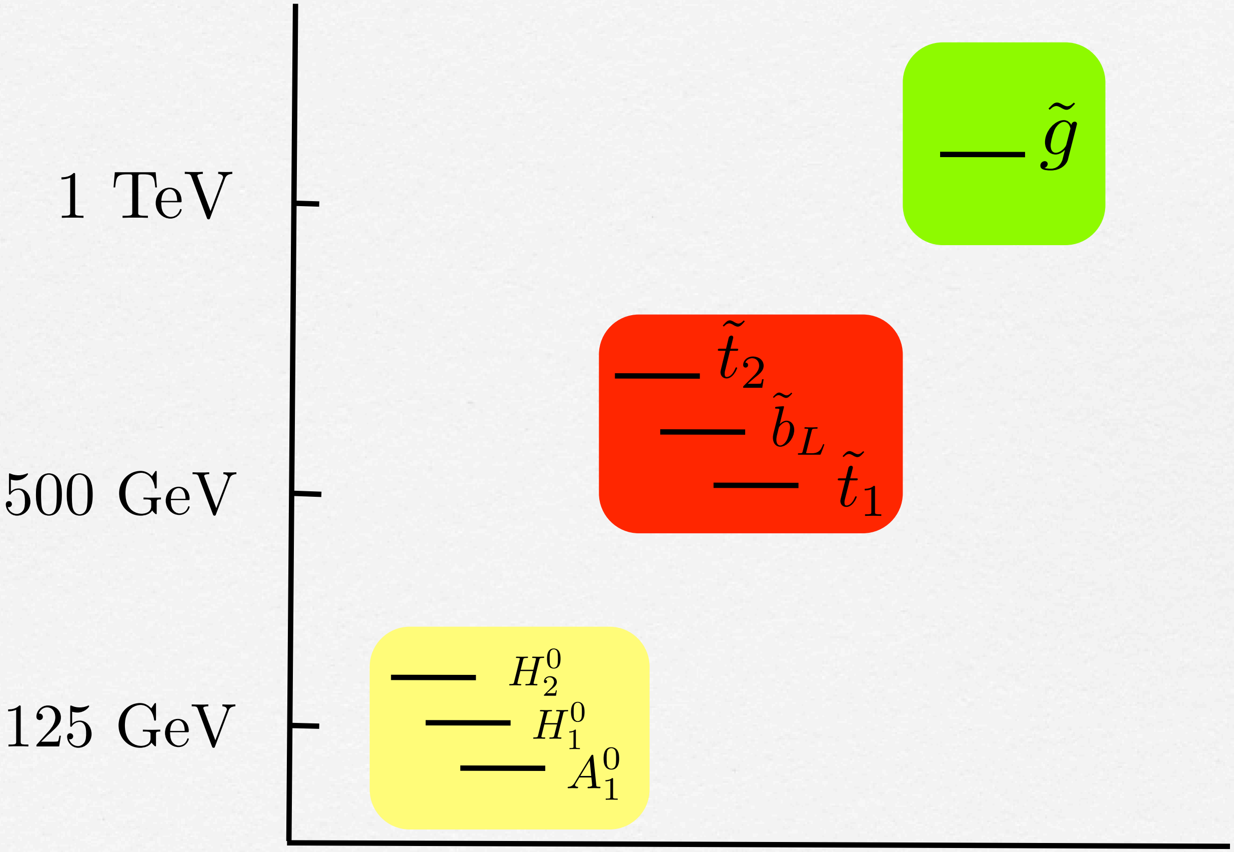


$$\delta m_{h_u}^2 = \frac{3g^2}{8\pi^2}(m_{\tilde{W}}^2 + m_{\tilde{h}}^2)\ln\frac{\Lambda_{UV}}{m_{\tilde{W}}}.$$

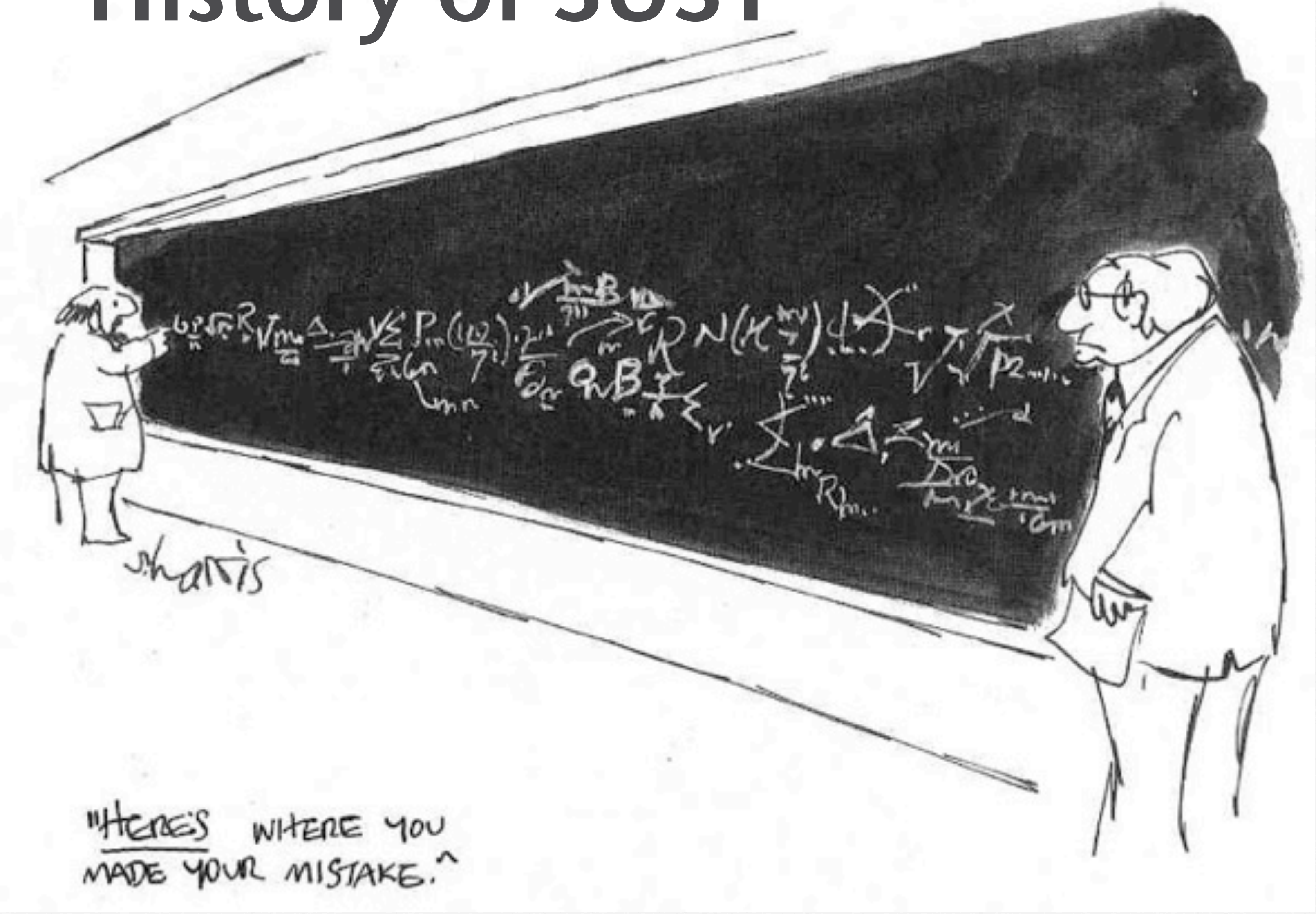
To avoid
tuning need

$$m_{\tilde{W}} \lesssim \text{TeV}.$$

Natural SUSY



History of SUSY



"Here's where you made your mistake."

History of SUSY

Porod

Coleman and Mandula, Phys. Rev. **159** (1967) 1251

Possible symmetries of the S-matrix

- Poincaré invariance, the semi-direct product of translations and Lorentz rotations, with generators P_μ, $M_{\mu\nu}$.
- So-called "internal" global symmetries, related to conserved quantum numbers such as electric charge and isospin. The symmetry generators are Lorentz scalars and generate a Lie algebra,

  $$[B_\ell, B_k] = iC^j_{\ell k} B_j$$

  where the $C^j_{\ell k}$ are structure constants.
- Discrete symmetries: C, P, and T

However:

- above theorem assumes commutator only
- allowing anticommuting generators as well as commuting generators leads to the possibility of supersymmetry (SUSY)

N=1 SUSY algebra

introduce anticommuting symmetry generators which transform in the $(\frac{1}{2},0)$ and $(0,\frac{1}{2})$ (i.e. spinor) representations of the Lorentz group.

Q_α $\overline{Q}_{\dot\alpha}$

bar and dot notation means right-handed

Fundamental SUSY anti-commutator (with P_μ the four-momentum):

$$\begin{aligned} \{Q_\alpha, \overline{Q}_{\dot\alpha}\} &= 2\sigma^\mu_{\alpha\dot\alpha} P_\mu \\ \{Q_\alpha, Q_\beta\} &= 0 = \{\overline{Q}_{\dot\alpha}, \overline{Q}_{\dot\beta}\} \end{aligned}$$

Pauli-matrices:

$$\sigma^\mu_{\alpha\dot\alpha} = (\mathbb{1}_2, \sigma^i) \ , \ \bar\sigma^{\mu\alpha\dot\alpha} = (\mathbb{1}_2, -\sigma^i)$$

$$\sigma^1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \ , \ \sigma^2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \ , \ \sigma^3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

SUSY is an internal symmetry

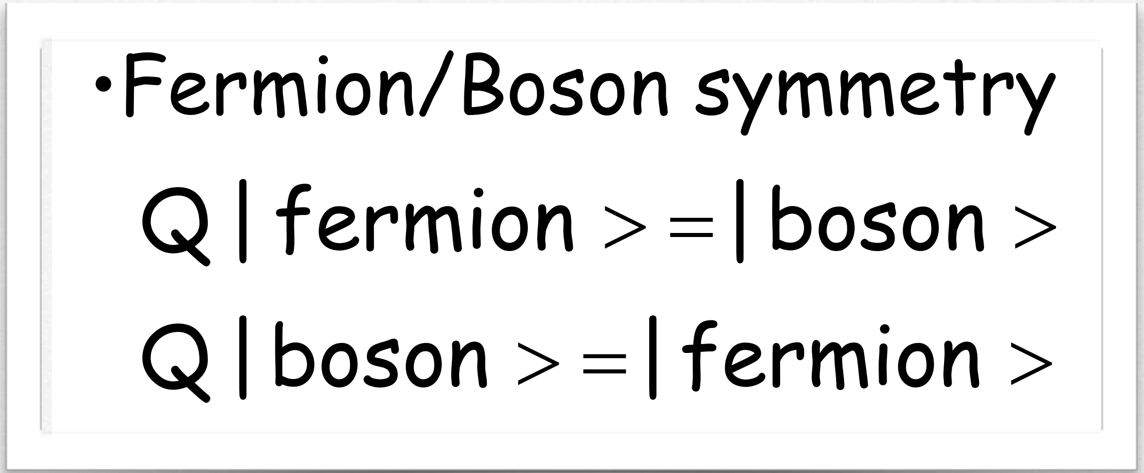
$$[P_\mu, Q_\alpha] = [P_\mu, \overline{Q}_{\dot\alpha}] = 0$$

It is useful to keep track of 'SUSY-ness' by the R-symmetry generator R:

$$[Q_\alpha, R] = Q_\alpha \;\;,\;\; [\overline{Q}_{\dot\alpha}, R] = -\overline{Q}_{\dot\alpha}$$

In short: Q_α decreases the R-quantum number by 1, while $\overline{Q}_{\dot\alpha}$ increases
The SUSY generator is a spacetime spinor so due to the spin-statistics theorem its action turns fermions into bosons, and vice versa:

where



- Fermion/Boson symmetry

$$Q\,|\,\text{fermion}> = |\,\text{boson}>$$

$$Q\,|\,\text{boson}> = |\,\text{fermion}>$$

SUSY Multiplets

Consequences

- members of a SUSY-multiplet have the same masses as $[P_\mu, Q_\alpha] = 0 = [P^2, Q_\alpha]$

- # fermions = # bosons in a multiplet

The massive 'chiral' multiplet ($s = 0$):

state	s_3	
$\vert\Omega_s\rangle$	0	squark
$\overline{Q}_{\dot{1}}\vert\Omega_s\rangle, \overline{Q}_{\dot{2}}\vert\Omega_s\rangle$	$\pm\frac{1}{2}$	quark
$\overline{Q}_{\dot{1}}\overline{Q}_{\dot{2}}\vert\Omega_s\rangle$	0	squark

contains: complex scalar and 2-component fermion (Majorana fermion)

SUSY Multiplets cont’d

Massless vector multiplet

starts wie $\lambda = \frac{1}{2}$

	state	helicity
gluino	$\vert\Omega_{\frac{1}{2}}\rangle$	$\frac{1}{2}$
gluon	$\overline{Q}_{\dot{1}}\vert\Omega_{\frac{1}{2}}\rangle$	1

$+$

state	helicity	
$\vert\Omega_{-1}\rangle$	-1	gluon
$\overline{Q}_{\dot{1}}\vert\Omega_{-1}\rangle$	$-\frac{1}{2}$	gluino

consits of a vector particle and a Weyl fermion

Superfields for SUSY multiplets

chiral
(left-handed)

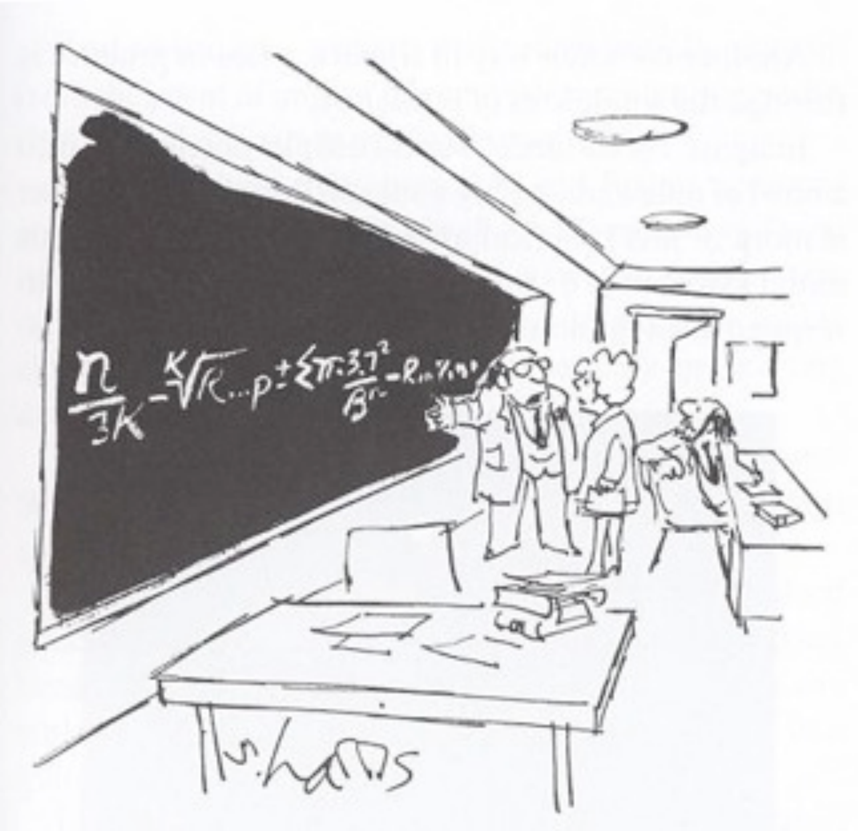
$$\Phi(y,\theta) = \underset{\substack{\uparrow\\ \text{squark}}}{\phi(y)} + \sqrt{2}\theta\underset{\substack{\uparrow\\ \text{quark}}}{\psi(y)} + \theta^2 \underset{\substack{\uparrow\\ \text{auxiliary field}}}{F(y)}$$

$$y^\mu = \underset{\substack{\uparrow\\ \text{space-time}}}{x^\mu} - i\underset{\substack{\uparrow\\ \text{super-space}\\ \text{coordinates}}}{\theta}\sigma^\mu\underset{\uparrow}{\bar\theta}$$

vector
(Wess-Zumino)

$$V_{WZ}(x,\theta,\bar\theta) = \theta\sigma^\mu\bar\theta\underset{\substack{\uparrow\\ \text{gluon}}}{V_\mu(x)} - i\bar\theta\bar\theta\theta\underset{\substack{\nwarrow\\ \text{gluino}}}{\lambda(x)} + i\theta\theta\bar\theta\underset{\nearrow}{\bar\lambda(x)} + \theta\theta\bar\theta\bar\theta\underset{\substack{\nearrow\\ \text{auxiliary field}}}{D(x)}$$

SUSY Lagrangians



"BUT THIS IS THE SIMPLIFIED VERSION FOR THE GENERAL PUBLIC."

SUSY Lagrangians

General Form is F-terms + D-terms:

$$\int d^2\theta \mathscr{L}_F + \int d^2\theta d^2\overline{\theta} \mathscr{L}_D$$

$$d^2\theta = -\frac{1}{4} d\theta^\alpha d\theta^\beta \varepsilon_{\alpha\beta}, \qquad d^2\overline{\theta} = -\frac{1}{4} d\bar{\theta}_{\dot{\alpha}} d\bar{\theta}_{\dot{\beta}} \varepsilon^{\dot{\alpha}\dot{\beta}}$$

$$\int d\theta_\alpha = 0, \qquad \int \theta_\alpha d\theta_\alpha = 1 \qquad \int d^2\theta(\theta\theta) = 1,$$ integration acts like differentiation

$$\Phi(y,\theta) \quad = \quad \phi(y) + \sqrt{2}\theta\psi(y) + \theta^2 F(y)$$

$$\int d^2\theta\Phi = F$$ integrating a superfield over $d^2\theta$ picks out the $\theta\theta$ term F

similarly integrating over $d^2\theta d^2\overline{\theta}$ picks out D-term

SUSY Lagrangians cont'd

Superpotential: $W(\Phi_i) = \frac{1}{2}M^{ij}\Phi_i\Phi_j + \frac{1}{6}y^{ijk}\Phi_i\Phi_j\Phi_k$

↑ No $\Phi^\dagger$ (holomorhic)

$$\int d^2\theta W = [W]_F$$

$$\Phi_{i,L} = \phi_i + \sqrt{2}\theta\psi_i + \theta\theta F_i$$

$$\int d^2\theta\Phi_{1,L}\Phi_{2,L} = \phi_1 F_2 + \phi_2 F_1 - \psi_1\psi_2$$

Mass terms

Yukawa terms

$$\int d^2\theta\Phi_{1,L}\Phi_{2,L}\Phi_{3,L} = \phi_1\phi_2 F_3 + \phi_1 F_2\phi_3 + F_1\phi_2\phi_3 - \psi_1\phi_2\psi_3 - \phi_1\psi_2\psi_3 - \psi_1\psi_2\phi_3$$

$$\int d^2\theta d^2\overline{\theta}\Phi_L\Phi_L^\dagger = FF^* - \phi\partial_\mu\partial^\mu\phi^* - i\overline{\psi}\sigma_\mu\partial^\mu\psi$$

Kinetic terms and Scalar interactions

Eliminate F_i using equations of motion $\frac{\partial\mathcal{L}}{\partial F_i} = 0 \longrightarrow F_i = -\left[\frac{\partial W(\phi_j)}{\partial\phi_i}\right]^*$

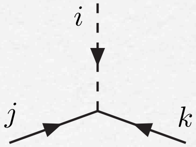
Gauge terms $\frac{1}{32g^2}W_\alpha W^\alpha = -\frac{1}{4}F^a_{\mu\nu}F_a^{\mu\nu} + \frac{1}{2}D_a D^a + \left(-\frac{i}{2}\lambda^a\sigma_\mu\partial^\mu\overline{\lambda}_a + \frac{g}{2}\lambda_a\sigma_\mu A^\mu_b\overline{\lambda}_c + \text{h.c.}\right)$

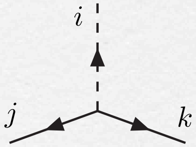
SUSY Lagrangians cont'd

Superpotential: $W(\Phi_i) = \frac{1}{2}M^{ij}\Phi_i\Phi_j + \frac{1}{6}y^{ijk}\Phi_i\Phi_j\Phi_k$

Lagrangian (excluding gauge terms):

$$\begin{aligned}\mathcal{L} \quad &= \quad -\partial^\mu\phi^{*i}\partial_\mu\phi_i - V(\phi,\phi^*) + i\psi^{\dagger i}\overline{\sigma}^\mu\partial_\mu\psi_i - \frac{1}{2}M^{ij}\psi_i\psi_j - \frac{1}{2}M^*_{ij}\psi^{\dagger i}\psi^{\dagger j} \\ &\quad -\frac{1}{2}y^{ijk}\phi_i\psi_j\psi_k - \frac{1}{2}y^*_{ijk}\phi^{*i}\psi^{\dagger j}\psi^{\dagger k}.\end{aligned}$$



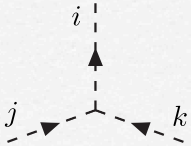


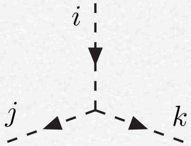
Potential: $V(\phi_i) = |F_i|^2 + \frac{1}{2}D^aD^a$

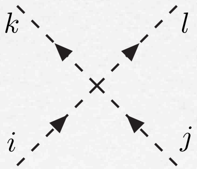
$$FF^* = M^*_{ik}M^{kj}\phi^{*i}\phi_j + \frac{1}{2}M^{in}y^*_{jkn}\phi_i\phi^{*j}\phi^{*k} + \frac{1}{2}M^*_{in}y^{jkn}\phi^{*i}\phi_j\phi_k + \frac{1}{4}y^{ijn}y^*_{kln}\phi_i\phi_j\phi^{*k}\phi^{*l}$$

$$\frac{1}{2}D^aD^a = \frac{1}{2}\sum_a g_a^2(\phi^*T^a\phi)^2.$$

$$D^a \quad = \quad -g(\phi_i^*T^a_{ij}\phi_j)$$







SUSY Lagrangians cont'd

Lagrangian (gauge terms):

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}F^a_{\mu\nu}F^{\mu\nu a} + i\lambda^{\dagger a}\overline{\sigma}^\mu \nabla_\mu \lambda^a + \frac{1}{2}D^a D^a$$

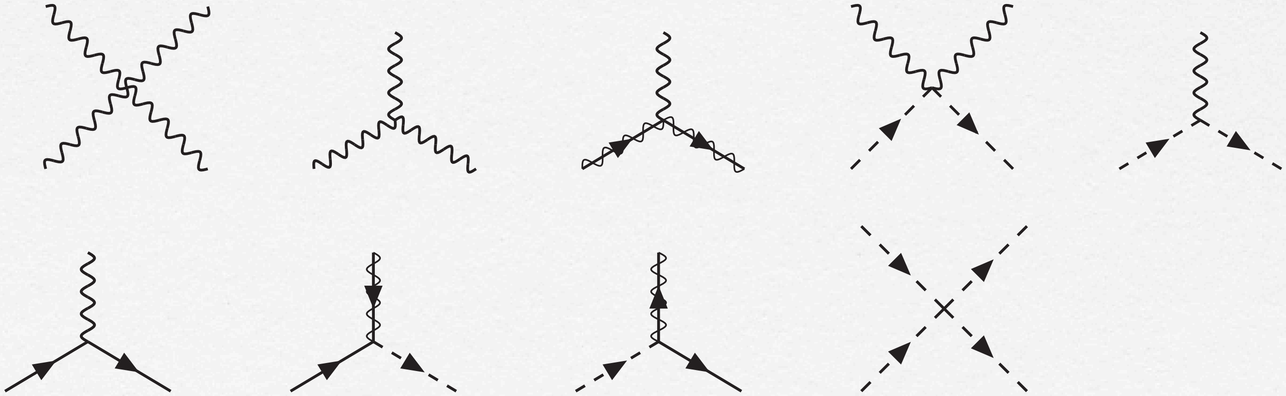
$$\nabla_\mu \lambda^a = \partial_\mu \lambda^a + g f^{abc} A^b_\mu \lambda^c$$

Covariant derivatives →

$$\left\{ \begin{array}{rcl} \nabla_\mu \phi_i & = & \partial_\mu \phi_i - igA^a_\mu (T^a\phi)_i \\ \nabla_\mu \phi^{*i} & = & \partial_\mu \phi^{*i} + igA^a_\mu (\phi^* T^a)^i \\ \nabla_\mu \psi_i & = & \partial_\mu \psi_i - igA^a_\mu (T^a\psi)_i . \end{array} \right.$$

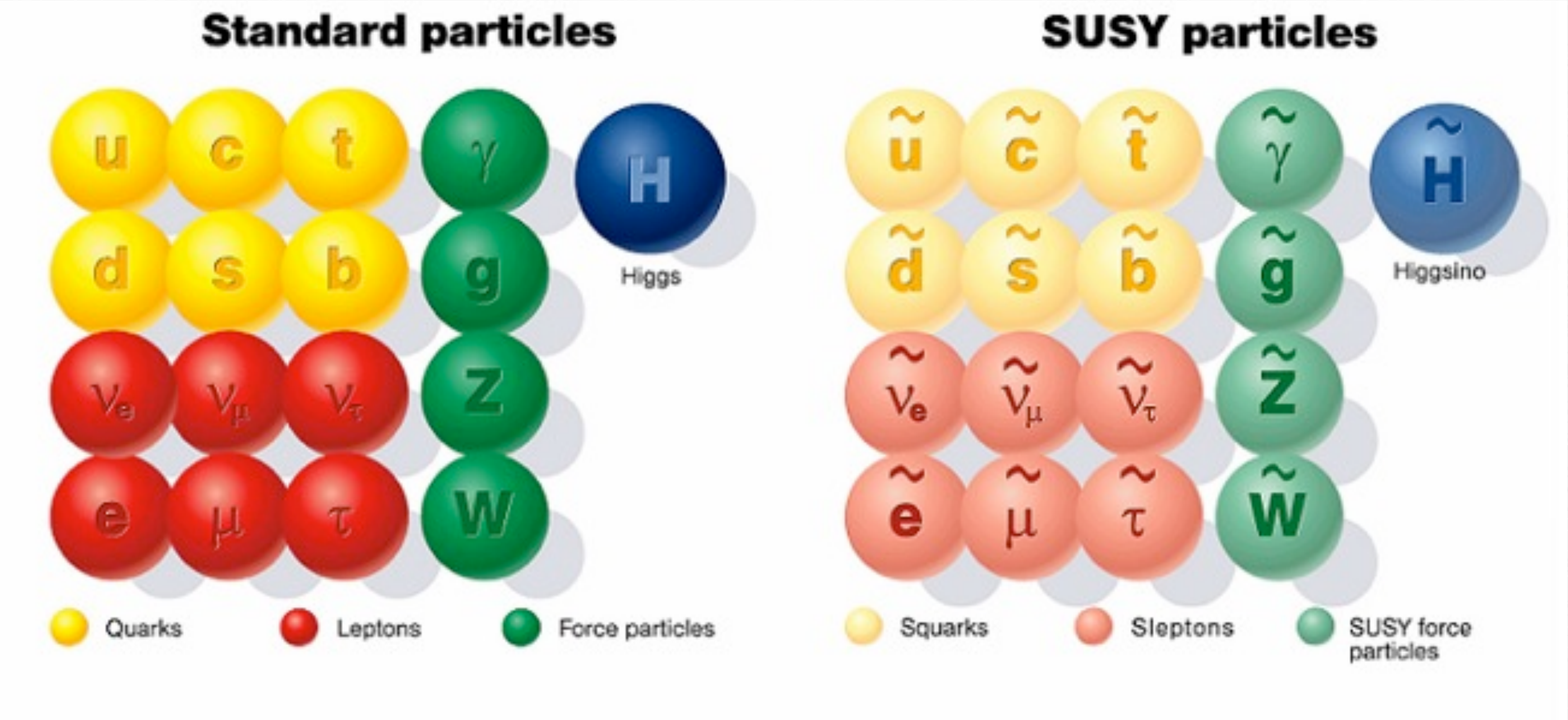
Gauge interaction terms:

$$\left[\Phi^{*i}(e^{2T^a\widehat{V}^a})_i{}^j\Phi_j\right]_D \longrightarrow -\sqrt{2}g(\phi^* T^a\psi)\lambda^a - \sqrt{2}g\lambda^{\dagger a}(\psi^\dagger T^a \phi) + g(\phi^* T^a \phi)D^a$$



Rule: take any SM diagram and replace any two lines by SUSY particles (preserving mass dimensions)

Minimal Supersymmetric Standard Model (MSSM) at a glance



Minimal Supersymmetric Standard Model (MSSM)

Superfield	Bosons	Fermions	SU(3)$_C$	SU(2)$_L$	U(1)$_Y$
Gauge Multiplets					
$\widehat{G}$	g	$\widetilde{g}$	8	1	0
$\widehat{V}$	W^a	$\widetilde{W}^a$	1	3	0
$\widehat{V}'$	B	$\widetilde{B}$	1	1	0
Matter Multiplets					
$\widehat{L}$	$(\tilde{\nu}, \tilde{e}^-_L)$	(ν, e^-_L)	1	2	-1/2
$\widehat{E}^C$	$\tilde{e}^+_R$	e^c_R	1	1	1
$\widehat{Q}$	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)	3	2	1/6
$\widehat{U}^C$	$\tilde{u}^*_R$	u^c_L	3^*	1	-2/3
$\widehat{D}^C$	$\tilde{d}^*_R$	d^c_L	3^*	1	1/3
Higgs Multiplets					
$\widehat{H}_d$	(H^0_d, H^-_d)	$(\tilde{H}^0_d, \tilde{H}^-_d)$	1	2	-1/2
$\widehat{H}_u$	(H^+_u, H^0_u)	$(\tilde{H}^+_u, \tilde{H}^0_u)$	1	2	1/2

Two Higgs doublets
required for anomaly
cancellation (and
holomorphicity of W)

Mass Spectrum in MSSM

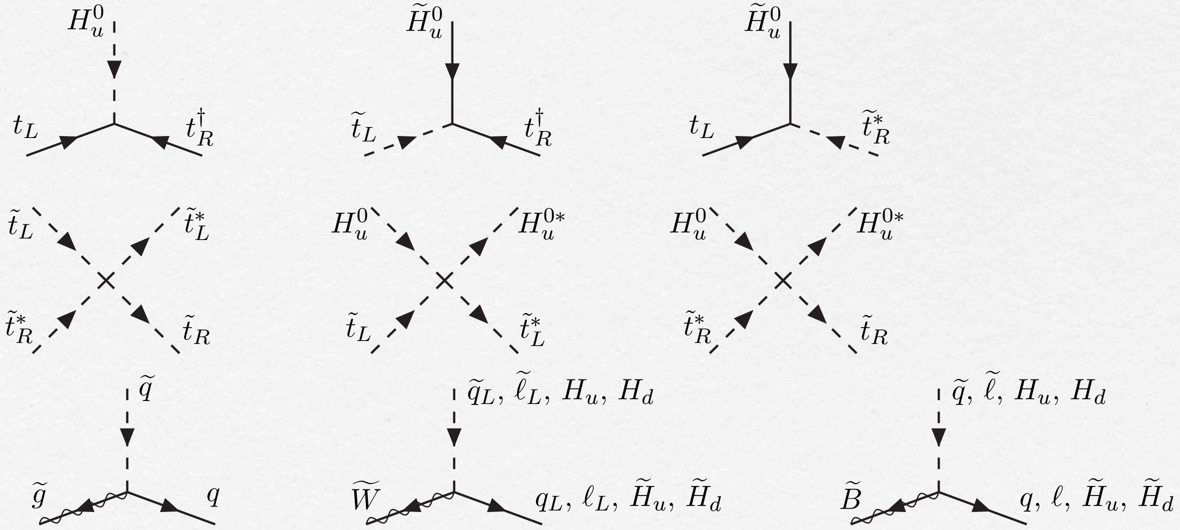
LHC Higgs?

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	$+1$	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	-1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$ $\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$ $\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	(same) (same) $\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	-1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$ $\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$ $\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	(same) (same) $\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralinos	1/2	-1	$\tilde{B}^0\ \ \widetilde{W}^0\ \ \tilde{H}_u^0\ \ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
charginos	1/2	-1	$\widetilde{W}^\pm\ \ \tilde{H}_u^+\ \ \tilde{H}_d^-$	$\tilde{C}_1^\pm\ \ \tilde{C}_2^\pm$
gluino	1/2	-1	$\tilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	-1	$\tilde{G}$	(same)

Minimal Supersymmetric Standard Model (MSSM)

Superpotential: Yukawa couplings and SUSY masses

$$W = \epsilon_{\alpha\beta}[-\hat{H}_u^\alpha \hat{Q}_i^\beta Y_{u_{ij}} \hat{U}_j^c + \hat{H}_d^\alpha \hat{Q}_i^\beta Y_{d_{ij}} \hat{D}_j^c + \hat{H}_d^\alpha \hat{L}_i^\beta Y_{e_{ij}} \hat{E}_j^c - \mu \hat{H}_d^\alpha \hat{H}_u^\beta].$$



Yukawa couplings

Potential couplings

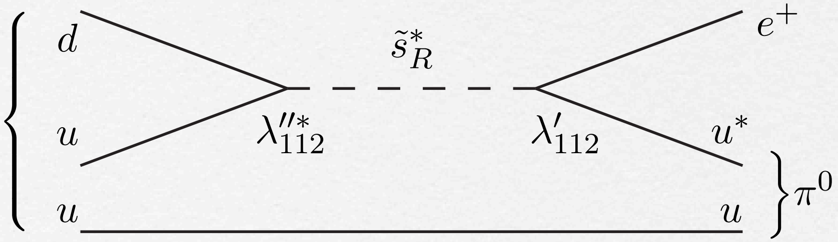
Gauge couplings

Proton decay from extra terms

What about the gauge invariant terms:

$$
\begin{aligned}
W_{\Delta\mathrm{L}=1} &= \frac{1}{2}\lambda^{ijk} L_i L_j \overline{e}_k + \lambda'^{ijk} L_i Q_j \overline{d}_k + \mu'^{i} L_i H_u \\
W_{\Delta\mathrm{B}=1} &= \frac{1}{2}\lambda''^{ijk} \overline{u}_i \overline{d}_j \overline{d}_k
\end{aligned}
$$

Both these terms together would allow proton decay



$$\Gamma_{p\to e^+\pi^0} \sim m^5_{\mathrm{proton}} \sum_{i=2,3} |\lambda'^{11i}\lambda''^{11i}|^2/m^4_{\tilde{d}_i}$$

If couplings of order unity then proton lifetime would be a fraction of a second!

How to forbid the extra terms

$$W_{\Delta \mathrm{L}=1} = \frac{1}{2}\lambda^{ijk}L_iL_j\overline{e}_k + \lambda'^{ijk}L_iQ_j\overline{d}_k + \mu'^{i}L_iH_u$$
$$W_{\Delta \mathrm{B}=1} = \frac{1}{2}\lambda''^{ijk}\overline{u}_i\overline{d}_j\overline{d}_k$$

Both terms forbidden in MSSM

Both terms forbidden by Matter Parity

$$P_M = (-1)^{3(\mathrm{B}-\mathrm{L})}$$

Matter superfields = -1,
Higgs superfields = +1,
Gauge superfields = +1

Equivalent effect to R-Parity

$$P_R = (-1)^{3(\mathrm{B}-\mathrm{L})+\overset{\nearrow}{\underset{\text{spin}}{2s}}}$$

SM particles = 1,
SUSY particles = -1

- LSP with P_R=-1 is absolutely stable (WIMP dark matter candidate)
- Each sparticle must decay eventually into an odd number of LSPs
- Sparticles must be produced in pairs at the LHC

R-parity violating theories preserve either lepton number or baryon number but not both

Non-renormalisable operators

Matter parity Z^M_2 allowed: $\frac{1}{M}(QQQL + LLH_uH_u)$

To satisfy proton decay need $M > 10^{25}$ GeV !

Forbidden by baryon parity Z^B_3:

$Q=1$, $D=H_u=\alpha$, $L=E=U=H_d=\alpha^2$ which allows:

$\frac{1}{M}(QUEH_d + LLH_uH_u)$ RPV LSP unstable

Proton hexality applies both $Z^M_2 \times Z^B_3$ $\frac{1}{M}(LLH_uH_u)$

R-symmetry in the MSSM

Do not confuse R-parity with continuous U(1) R-symmetry

$$\theta \rightarrow e^{i\alpha}\theta, \qquad \theta^\dagger \rightarrow e^{-i\alpha}\theta^\dagger$$

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

Superfield assigned R-charge r_Φ:

$$\phi \rightarrow e^{ir_\Phi\alpha}\phi, \qquad \psi \rightarrow e^{i(r_\Phi-1)\alpha}\psi, \qquad F \rightarrow e^{i(r_\Phi-2)\alpha}F.$$

$$A^\mu \rightarrow A^\mu, \qquad \lambda \rightarrow e^{i\alpha}\lambda, \qquad D \rightarrow D.$$

Superpotential has R=2 since Lagrangian must have R=0 and is given by

$$\int d^2\theta W = [W]_F$$

$$U(1)_R \rightarrow Z_n^R$$

Discrete subgroups e.g. for n=4 have been proposed as an alternative to R-parity

Respects GUTs

Lee, Raby, Ratz, Ross, Schieren, Schmidt-Hoberg, Vaudrevange

Soft SUSY breaking mass terms

Soft means does not spoil the cancellation of quadratic divergences

- Soft *trilinear scalar* interactions: $\frac{1}{3!}\widetilde{A}_{ijk}\phi_i\phi_j\phi_k + \text{h.c.}$.
- Soft *bilinear scalar* interactions: $\frac{1}{2}b_{ij}\phi_i\phi_j + \text{h.c.}$.
- Soft *scalar mass-squares:* $m_{ij}^2\phi_i^\dagger\phi_j$.
- Soft *gaugino masses:* $\frac{1}{2}M_a\lambda^a\lambda^a + \text{h.c.}$.

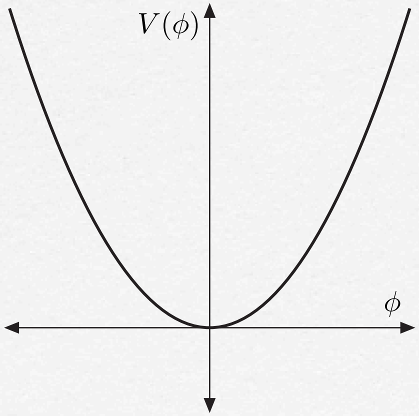
What is the origin of the soft SUSY breaking Lagrangian?

Global SUSY breaking

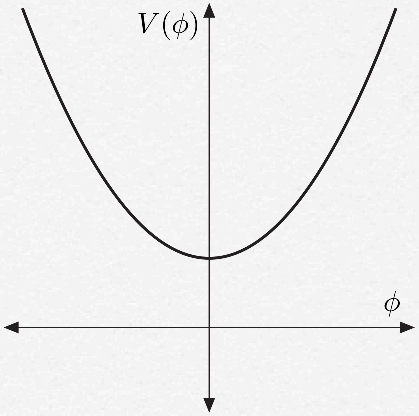
If global SUSY is preserved the vacuum has zero energy
If global SUSY is broken the vacuum has positive energy

$$H = P^0 = \frac{1}{4}(Q_1 Q_1^\dagger + Q_1^\dagger Q_1 + Q_2 Q_2^\dagger + Q_2^\dagger Q_2) \qquad Q_\alpha|0\rangle \neq 0 \text{ and } Q_{\dot\alpha}^\dagger|0\rangle \neq 0$$

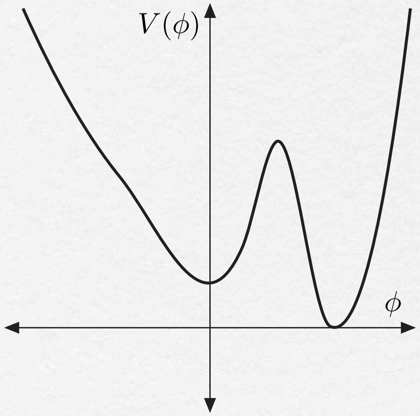
SUSY unbroken



SUSY spontaneously broken



Metastable SUSY breaking



$$V(\phi_i) = |F_i|^2 + \frac{1}{2}D^a D^a$$

to break SUSY need F or D non-zero

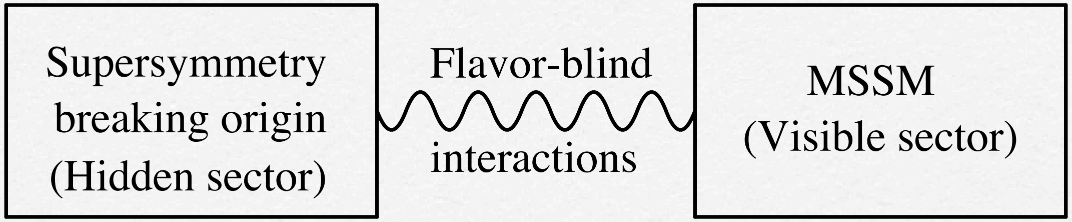
But sum rule for each charge sector

$$\sum m^2_{J=0} - 2\sum m^2_{J=\frac{1}{2}} + 3\sum m^2_{J=1} = 0.$$

Hard to satisfy

$$m^2_{\tilde{e}_1} + m^2_{\tilde{e}_2} = 2m^2_e;$$

Hidden Sector SUSY Breaking



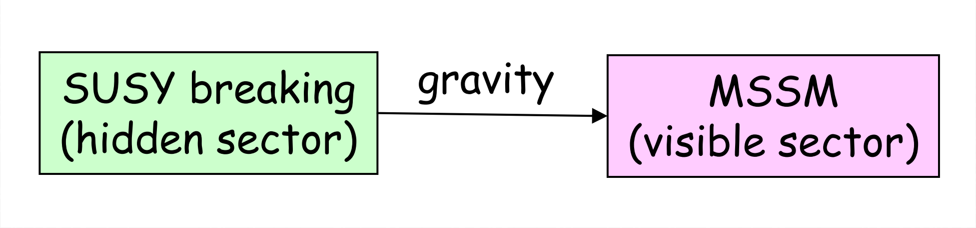
Supersymmetry breaking origin (Hidden sector)

Flavor-blind interactions

MSSM (Visible sector)

Idea is that the sum rules apply in some hidden sector and not in our visible sector

e.g.



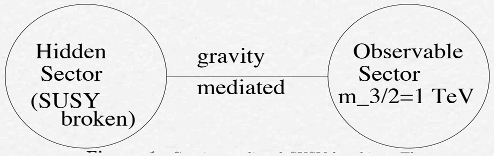
SUSY breaking (hidden sector)

gravity

MSSM (visible sector)

Hidden Sector SUSY Breaking

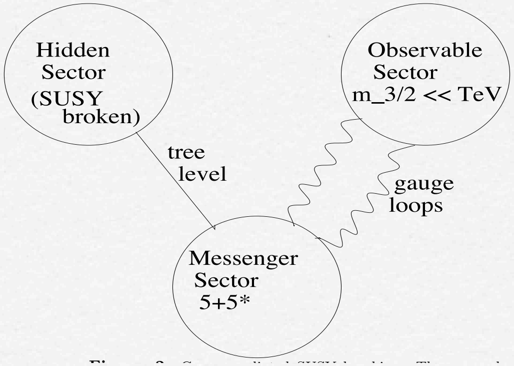
Gravity Mediated



$$m_{\rm soft} \sim \langle F\rangle/M_{\rm P}$$

$$\sqrt{\langle F\rangle} \sim 10^{10} \text{ or } 10^{11} \text{ GeV.}$$

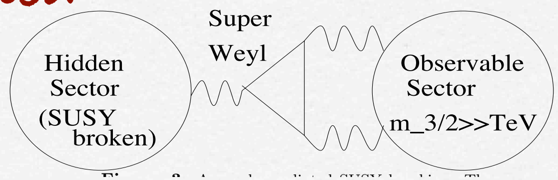
Gauge Mediated



$$m_{\rm soft} \sim \frac{\alpha_a}{4\pi}\frac{\langle F\rangle}{M_{\rm mess}}$$

$$\sqrt{\langle F\rangle} \sim 10^4 \text{ GeV}$$

Anomaly Mediated

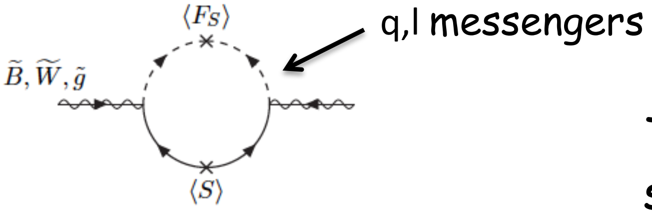


$$m_{\rm soft} \sim \langle F\rangle/16\pi^2 M_P$$

$$\sqrt{\langle F\rangle} \sim 10^6 GeV$$

“Gauge” mediation

Ross



$$\boxed{M_a = \frac{\alpha_a}{4\pi}\Lambda,}$$

Typical hierarchy bertween strongly/weakly interacting particles:

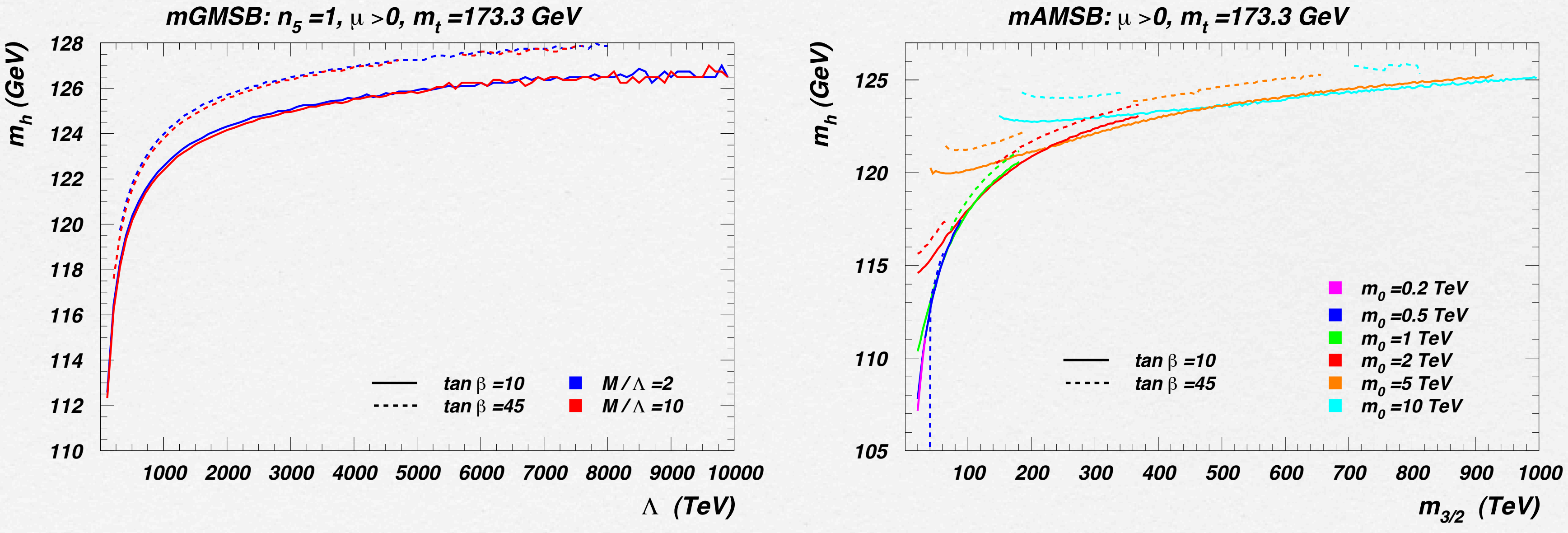
$$\alpha_3 : \alpha_2 : \alpha_1$$

+...

$$\boxed{m^2_{\phi_i} = 2\Lambda^2 \left[\left(\frac{\alpha_3}{4\pi}\right)^2 C_3(i) + \left(\frac{\alpha_2}{4\pi}\right)^2 C_2(i) + \left(\frac{\alpha_1}{4\pi}\right)^2 C_1(i) \right]}$$

Higgs mass challenges mGMSB and mAMSB

Baer and List 1307.0782



Lightest SUSY particles must be >5 TeV

Supergravity

Lectures by Nilles

$$W = W_{hid} + W_{obs}$$
$$K = K_{hid} + K_{obs}$$

$$G = K/M_P^2 + \ln |W/M_P^3|^2$$
$$m_{3/2}^2 = \frac{1}{3M_P^2} < K_j^i F_i F^{*j} >= M_P^2 e^{<G>}$$ gravitino mass

$$V_F = M_P^4 e^G [G^i (G^{-1})_i^j G_j - 3]$$ SUGRA potential can be negative

$$K = K_{hid} + \tilde{Q}^{*i}\tilde{Q}^i + \ldots \longrightarrow V_{soft} = m_0^2(\tilde{Q}^{*i}\tilde{Q}^i + \ldots)$$

mSUGRA

universal soft masses

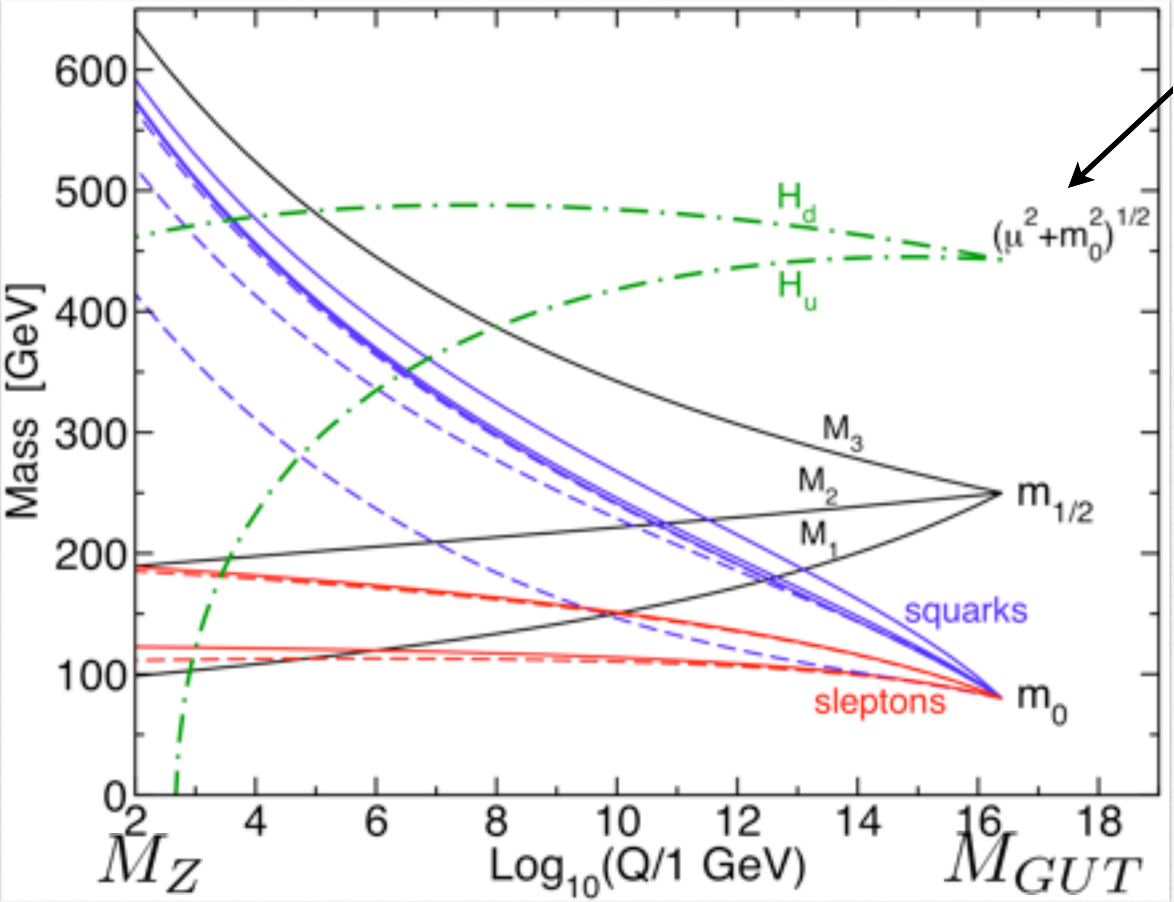
- a common gaugino mass $m_{1/2}$
- a common soft scalar mass m_0
- a common soft trilinear parameter A_0 $(\widetilde{A}_{ij} = A_0 Y_{ij})$
- a bilinear term b_0

Gravitino problems:
1. Over-production of dark matter
2. Late (>1s) decaying gravitinos

Gravitino solutions:
1. Low reheat $T_R < 10^5$ GeV
2. Heavy gravitinos > 5 TeV

Constrained MSSM/mSUGRA

$$m_H^2 = \mu^2 + m_0^2$$



m_0: common scalar mass at GUT

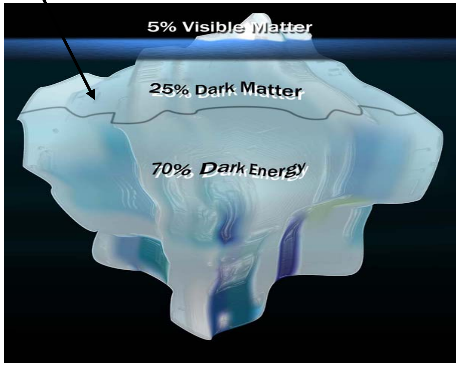
$m_{1/2}$: the common gaugino mass at GUT

tanβ: <HU>/<HD>

A_0: common (scalar)^3 coupling

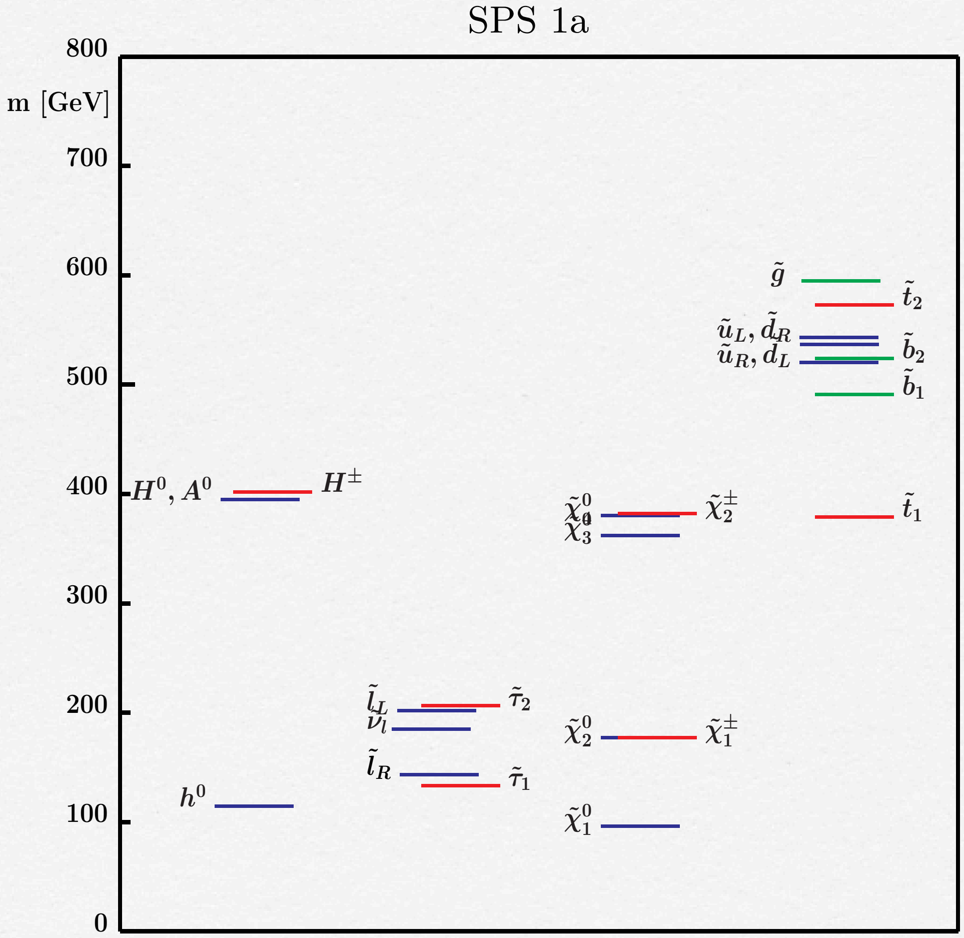
Sign(μ): Higgs mass term

1. Squarks and Gluinos are heavy
2. mixing of third generation leads to light stop/sbottom and stau
3. χ_1^0 will be the LSP (stable if R_P conserved)



CMSSM Benchmark SPS 1a

$$m_0 = 100\,\text{GeV}, \quad m_{1/2} = 250\,\text{GeV}, \quad A_0 = -100\,\text{GeV}, \quad \tan\beta = 10, \quad \mu > 0.$$

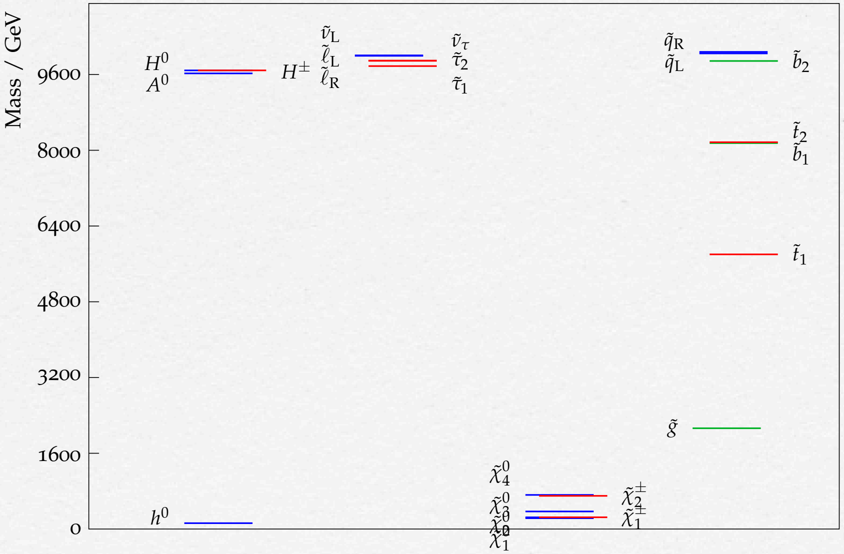


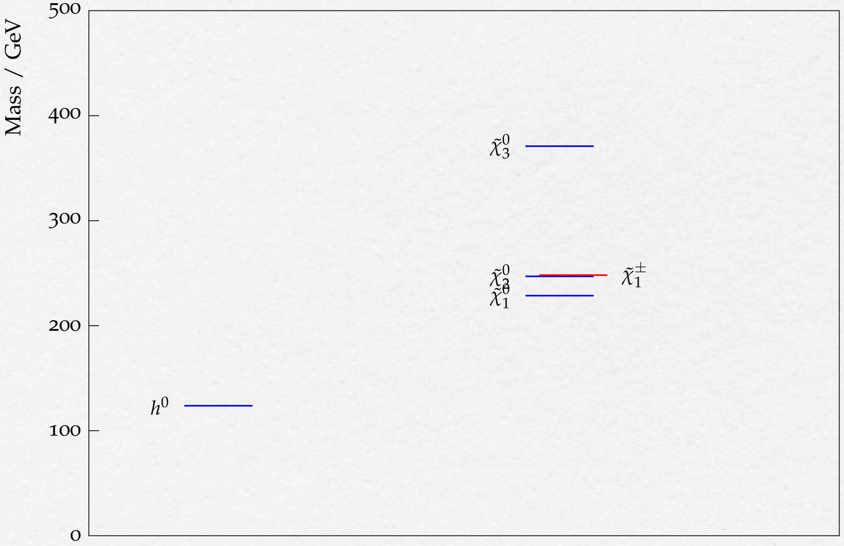
Excluded by LHC8

CMSSM Benchmark post LHC8

Baer and List 1307.0782

$$m_0 = 10\ \text{TeV},\ \ m_{1/2} = 0.8\ \text{TeV},\ \ A_0 = -5.45\ \text{TeV},\ \ \tan\beta = 15,\ \ \mu > 0$$





$$pp \to \tilde{\chi}_1^+ \tilde{\chi}_2^0 \to W^* h^* + E_T^{\text{miss}}$$

SSI 2012
SLAC SUMMER INSTITUTE

The WIMP ‘Miracle’

Hewett,
Sarkar Lectures

(1) Assume a new (heavy) particle χ is initially in thermal equilibrium:

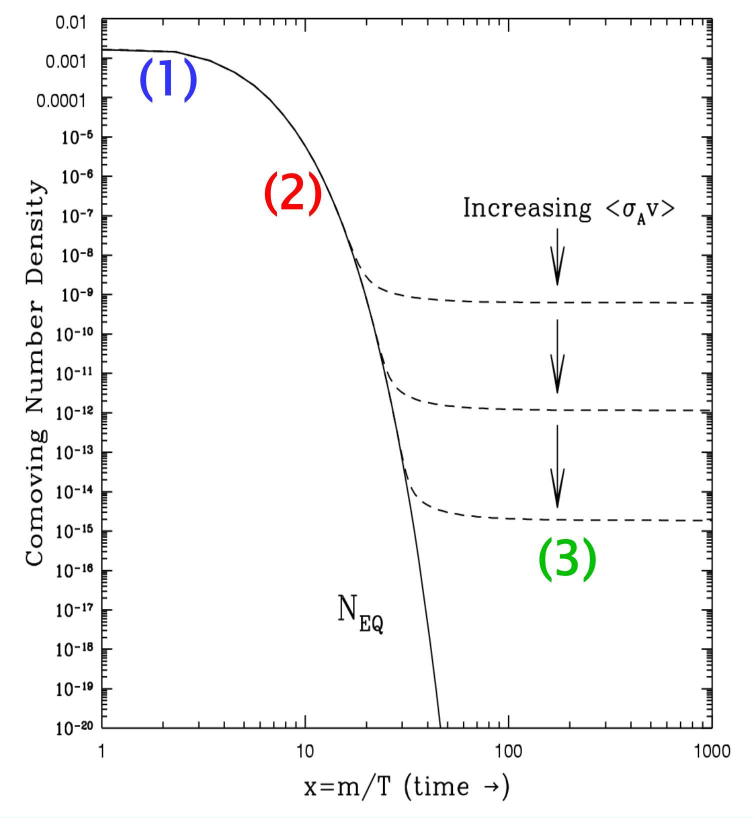
$$\chi\chi \leftrightarrow f f$$

(2) **Universe cools**:

$$\chi\chi \substack{\rightarrow \\ \not\leftarrow} f f$$

(3) χ s **“freeze out”**:

$$\chi\chi \substack{\not\rightarrow \\ \not\leftarrow} f f$$



Zeldovich et al. (1960s)

CMSSM Dark Matter

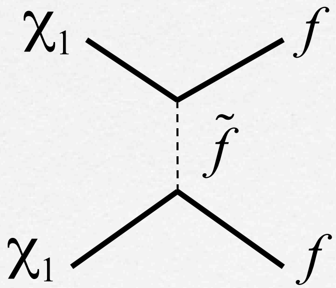
Neutralino mass matrix

$$\begin{array}{c} \begin{array}{cccc} \tilde{B} & \tilde{W}_3 & \tilde{H}_d & \tilde{H}_u \end{array} \\ \begin{pmatrix} M_1 & & & \\ & M_2 & & \\ & & 0 & -\mu \\ & & -\mu & 0 \end{pmatrix} \end{array}$$

$$\chi_1 = N_1\tilde{B} + N_2\tilde{W} + N_3\tilde{H}_d + N_4\tilde{H}_u$$

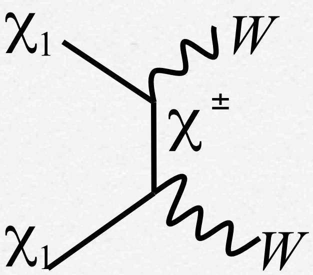
WIMP = Lightest neutralino

$$\Omega_{DM}h^2 = C\frac{T_0^3}{M_P^2}\frac{1}{\langle\sigma v\rangle}$$



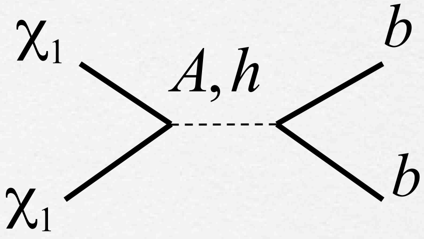
Bulk

$$m_{\tilde{f}} \approx m_{\chi_1}$$



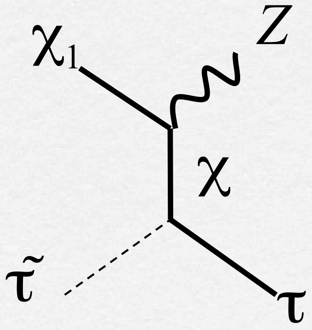
Focus

Higgsino LSP



Funnel

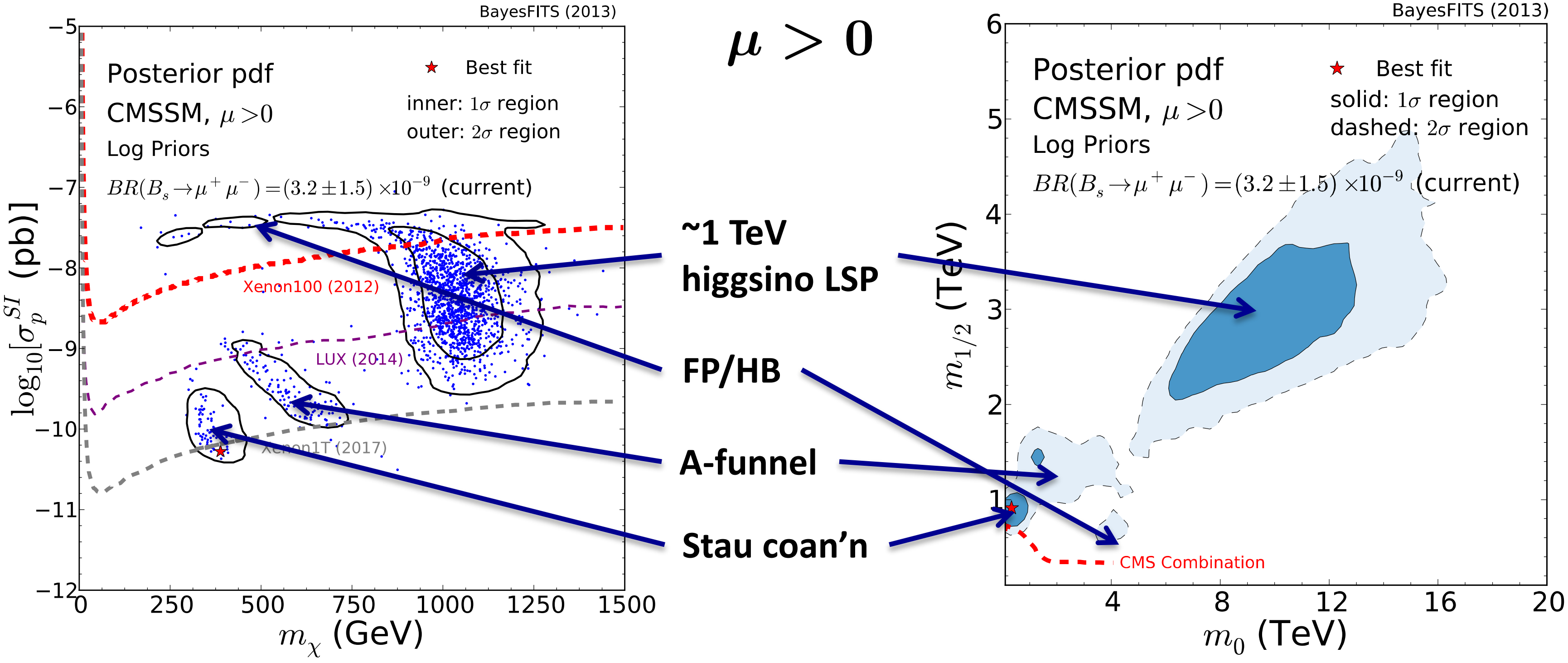
$$m_{A,h} \approx 2m_{\chi_1}$$



Co-annihilation

$$m_{\tilde{\tau}} \approx m_{\chi_1}$$

$\mu > 0$



~1 TeV higgsino LSP

FP/HB

A-funnel

Stau coan'n

1-tonne DM detectors to cover most of CMSSM predictions

Constrained SUSY – still alive?

The constrained MSSM (CMSSM) paradigm is "hardly tenable"

At Open Symposium of the European Strategy Preparatory Group, Krakow, Poland, 10-12 Sept. 2012

Constrained SUSY is in coma

A. Masiero, PLANCK-13

Really?

SUSY cannot be experimentally ruled out.

It can only be discovered.

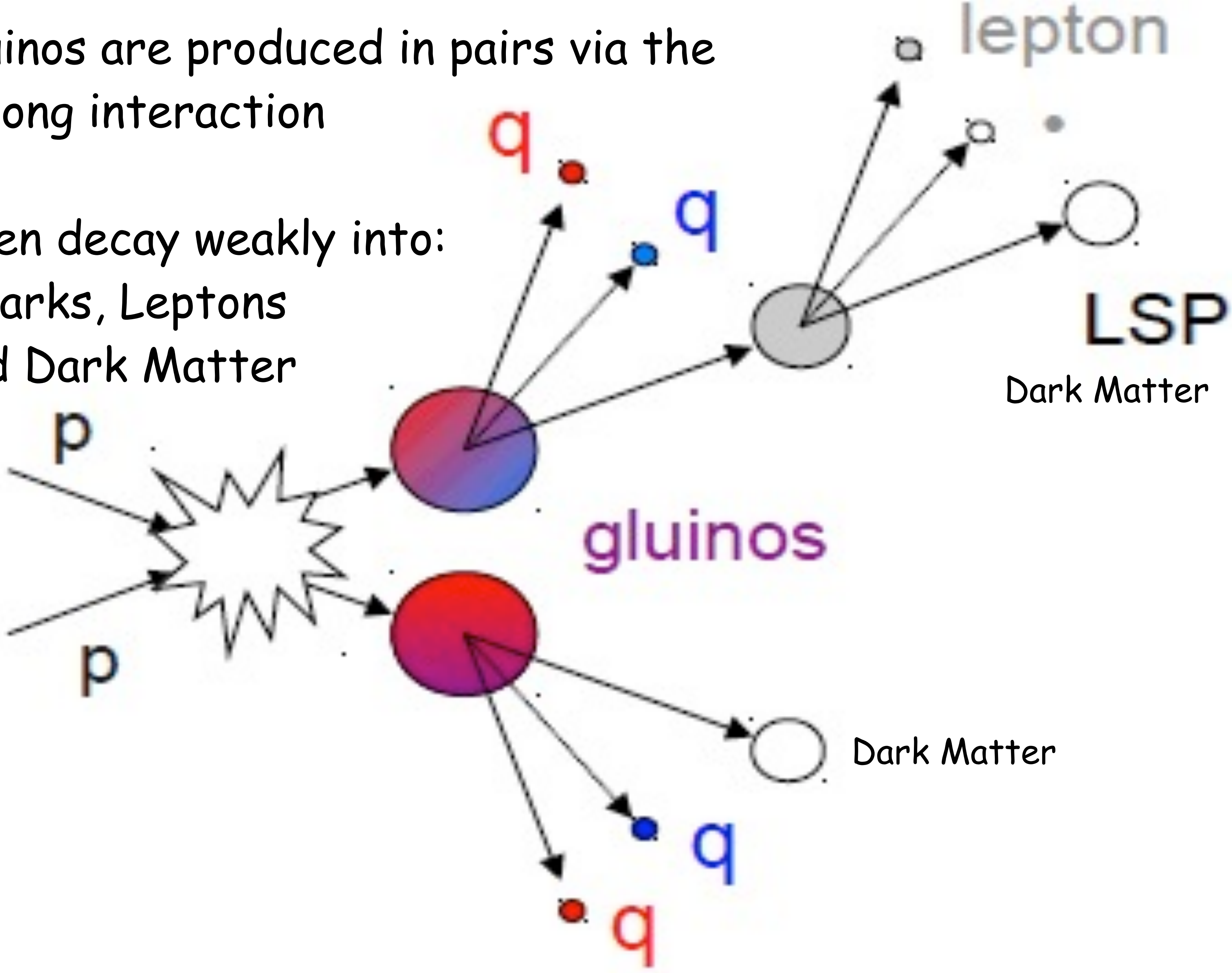
Or else abandoned.

Leszek Roszkowski

How to discover SUSY @ LHC?

Gluinos are produced in pairs via the strong interaction

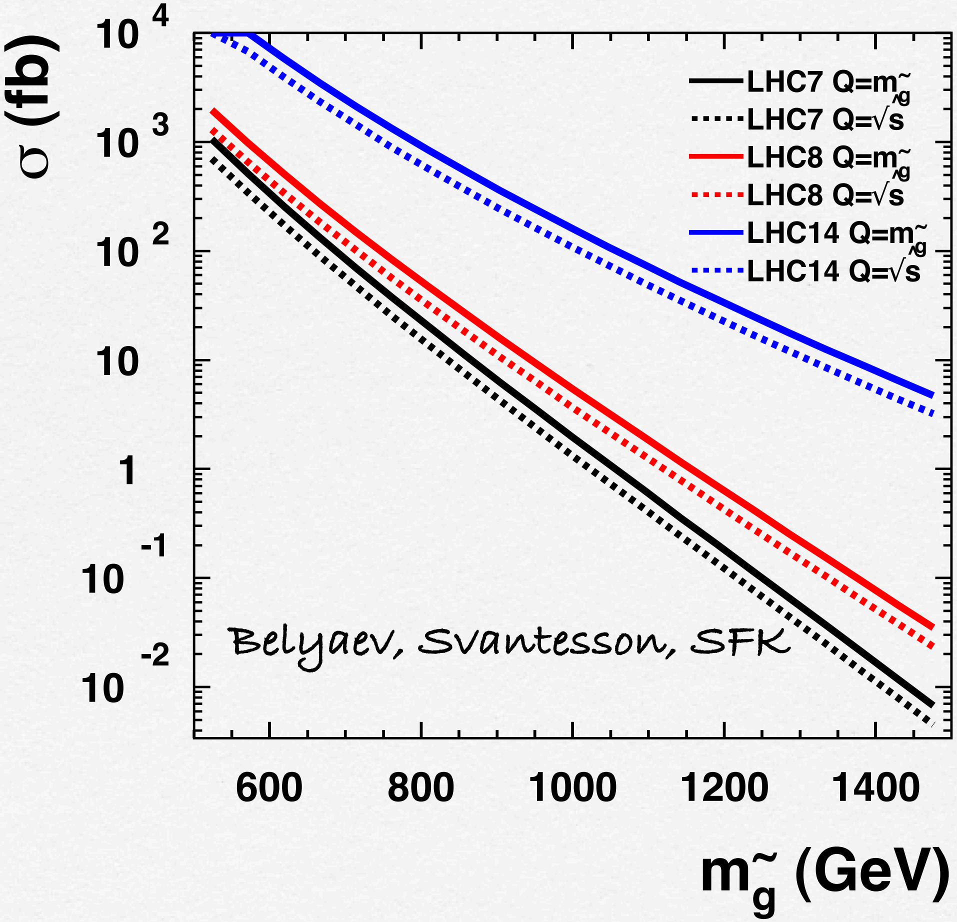
Then decay weakly into:
Quarks, Leptons
and Dark Matter



Dark Matter

Dark Matter

Gluino pair production



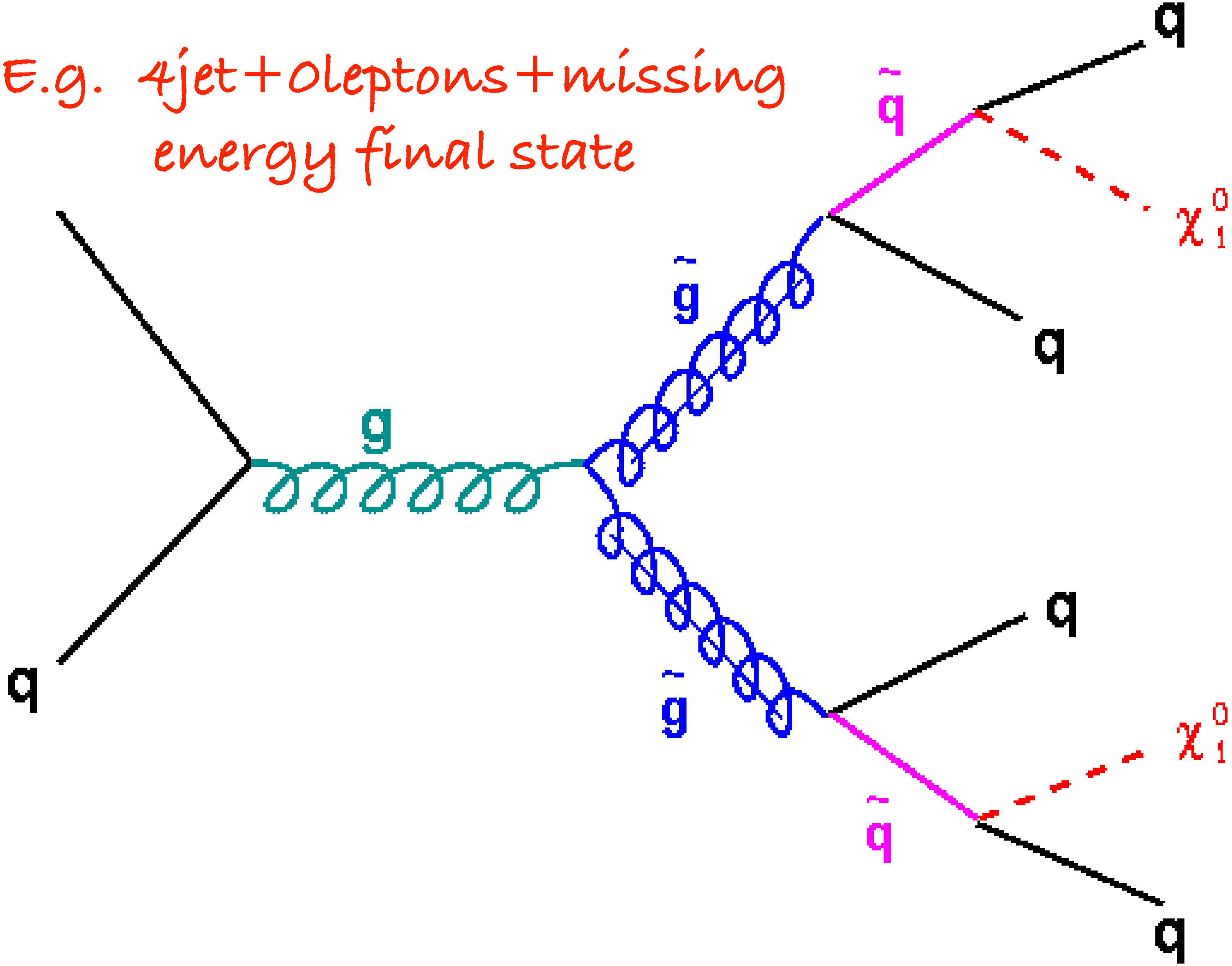
$$N_{\text{events}} = \sigma \times \int Ldt$$

$$= \sigma \times 20fb^{-1}$$

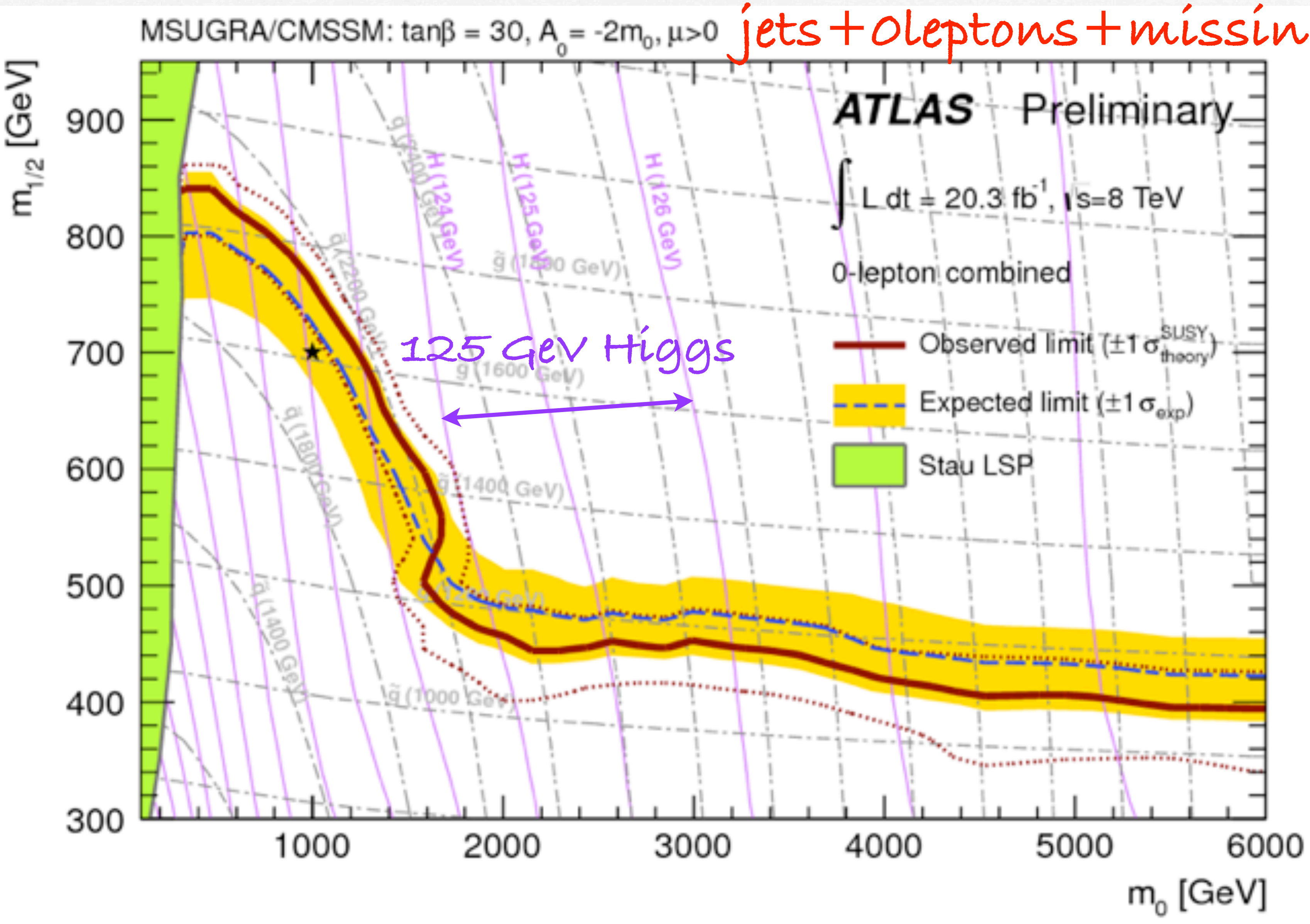
$$\sqrt{s} = 8\text{TeV}$$

Need to consider branching ratios into observable final states, efficiency, backgrounds...not so easy...

E.g. 4jet+0leptons+missing energy final state

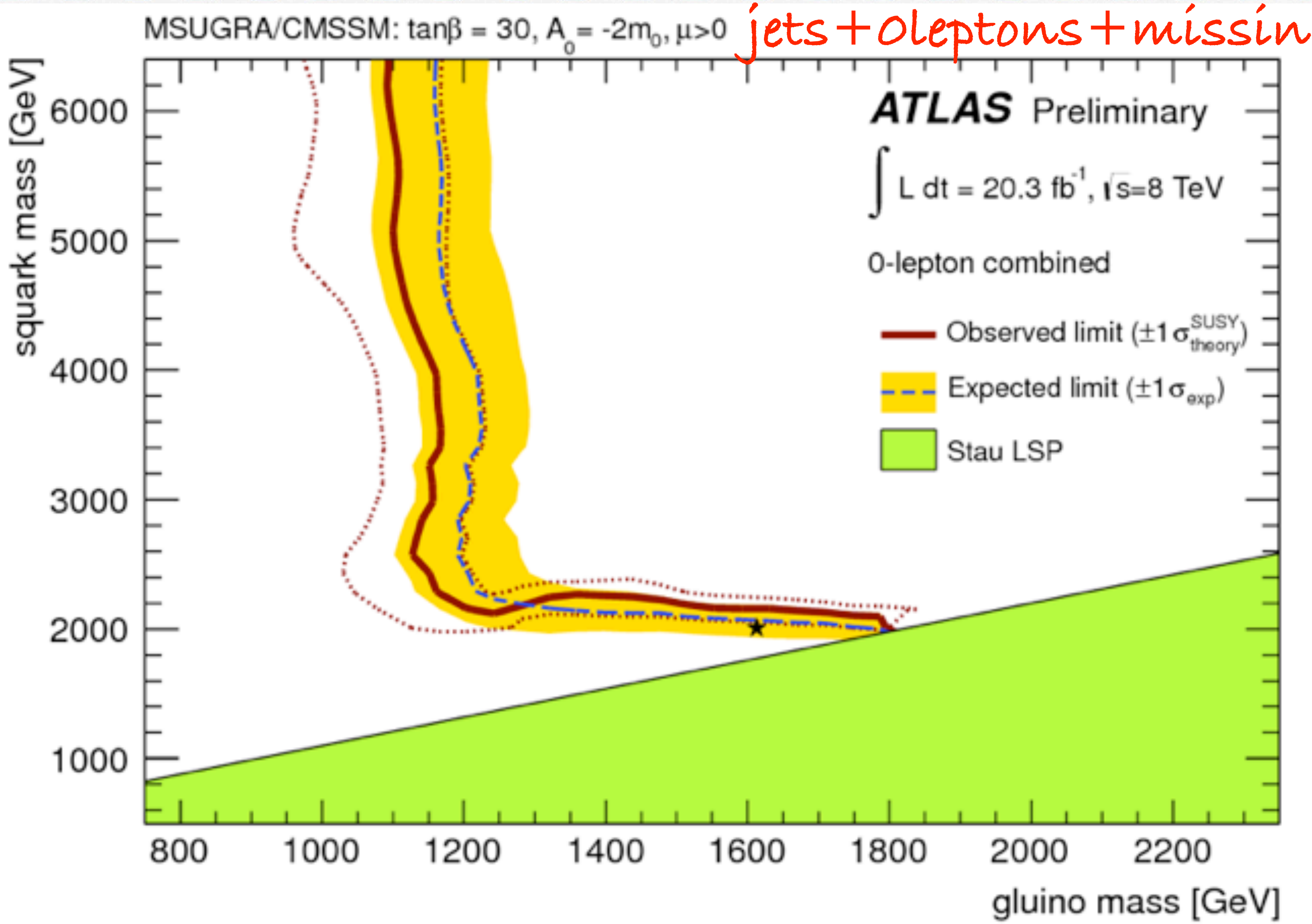


jets+0leptons+missing

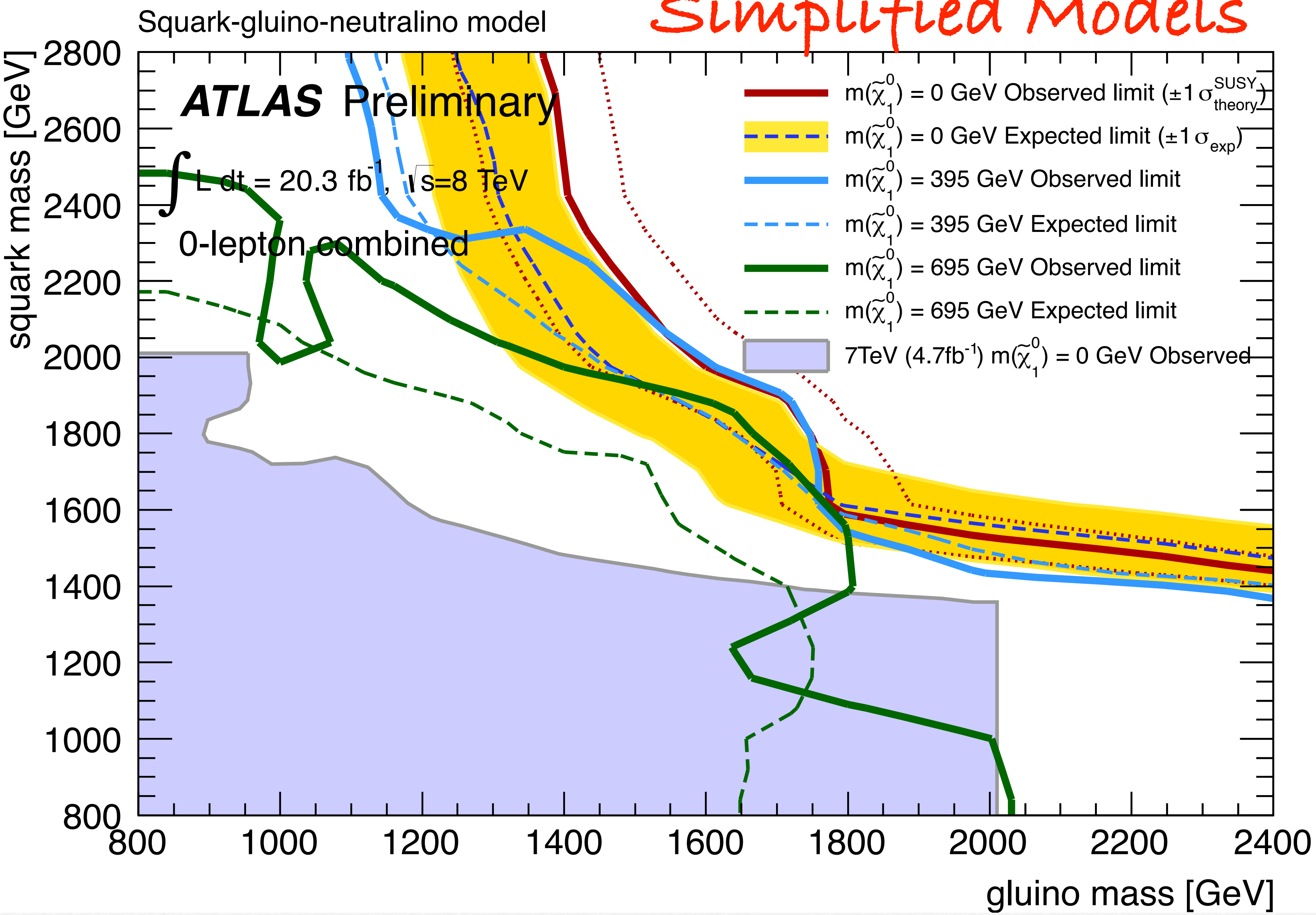


125 GeV Higgs

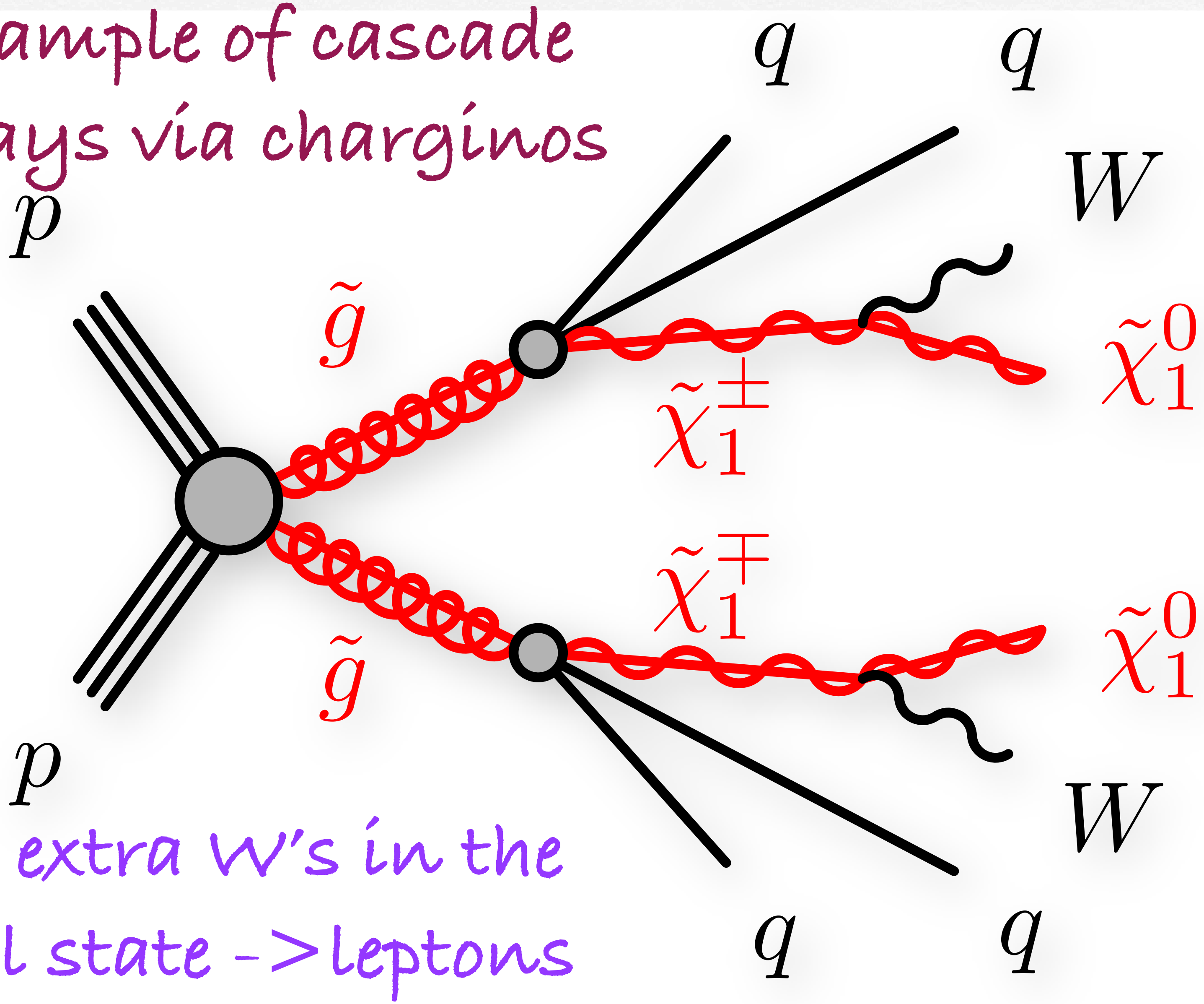
jets + 0leptons + missing



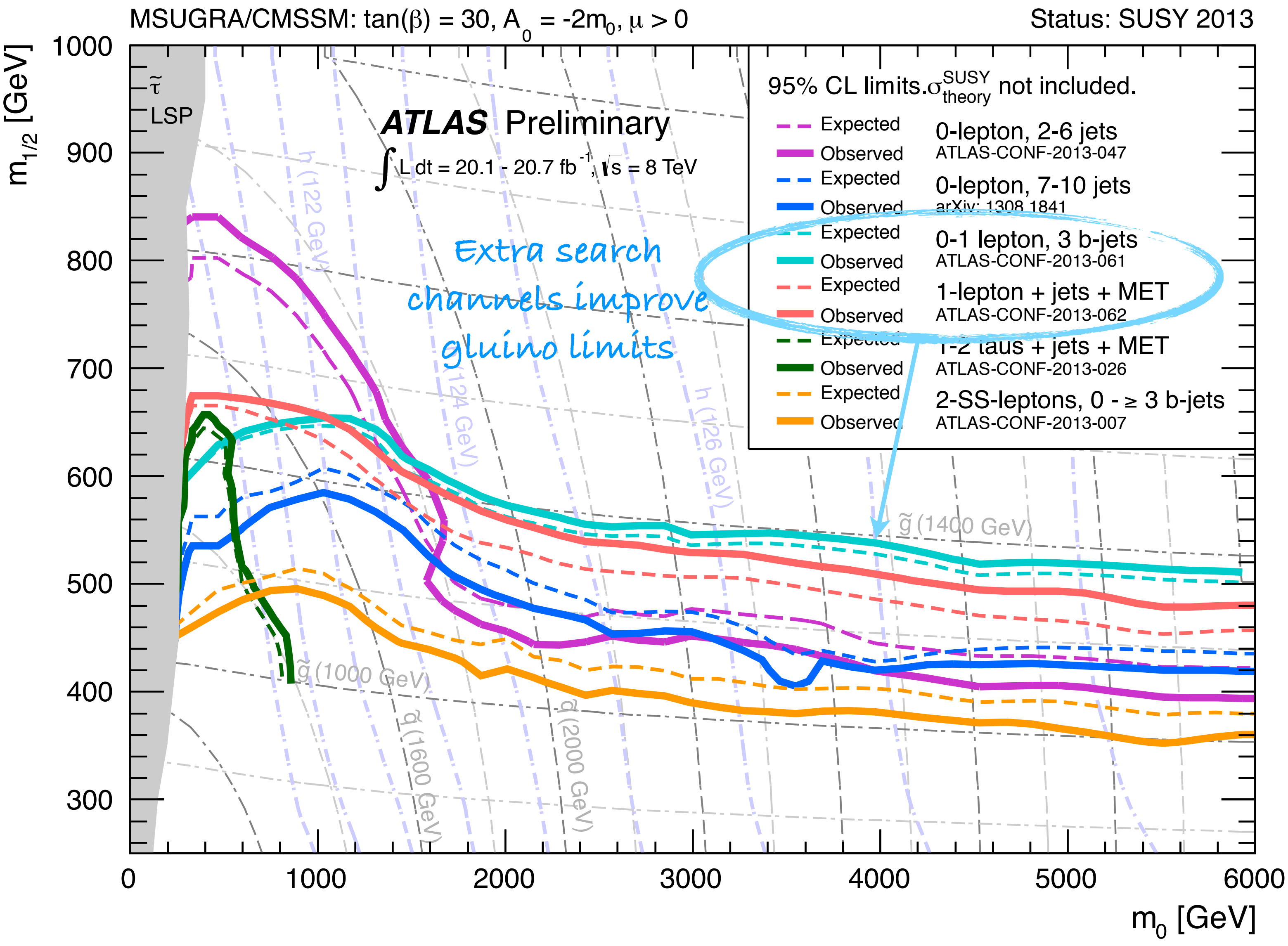
Simplified Models



Example of cascade decays via charginos



Two extra W's in the final state ->leptons

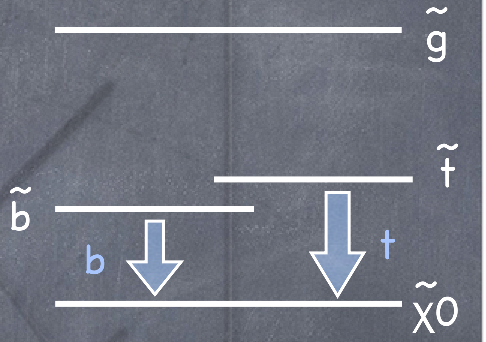


Extra search channels improve gluino limits

Searches with 8 TeV data
Stop and Sbottom

- Direct squark searches

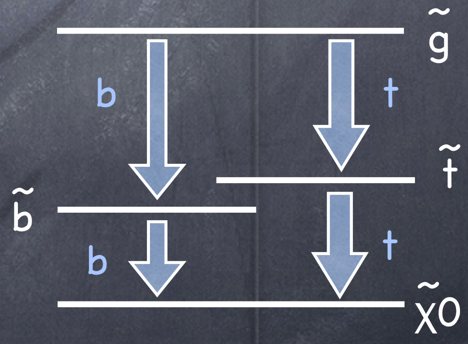
  Smaller cross section
  Final state similar to tt in the bulk of the parameter space
  Reduced bkg discrimination power
  Only handle if gluino heavy



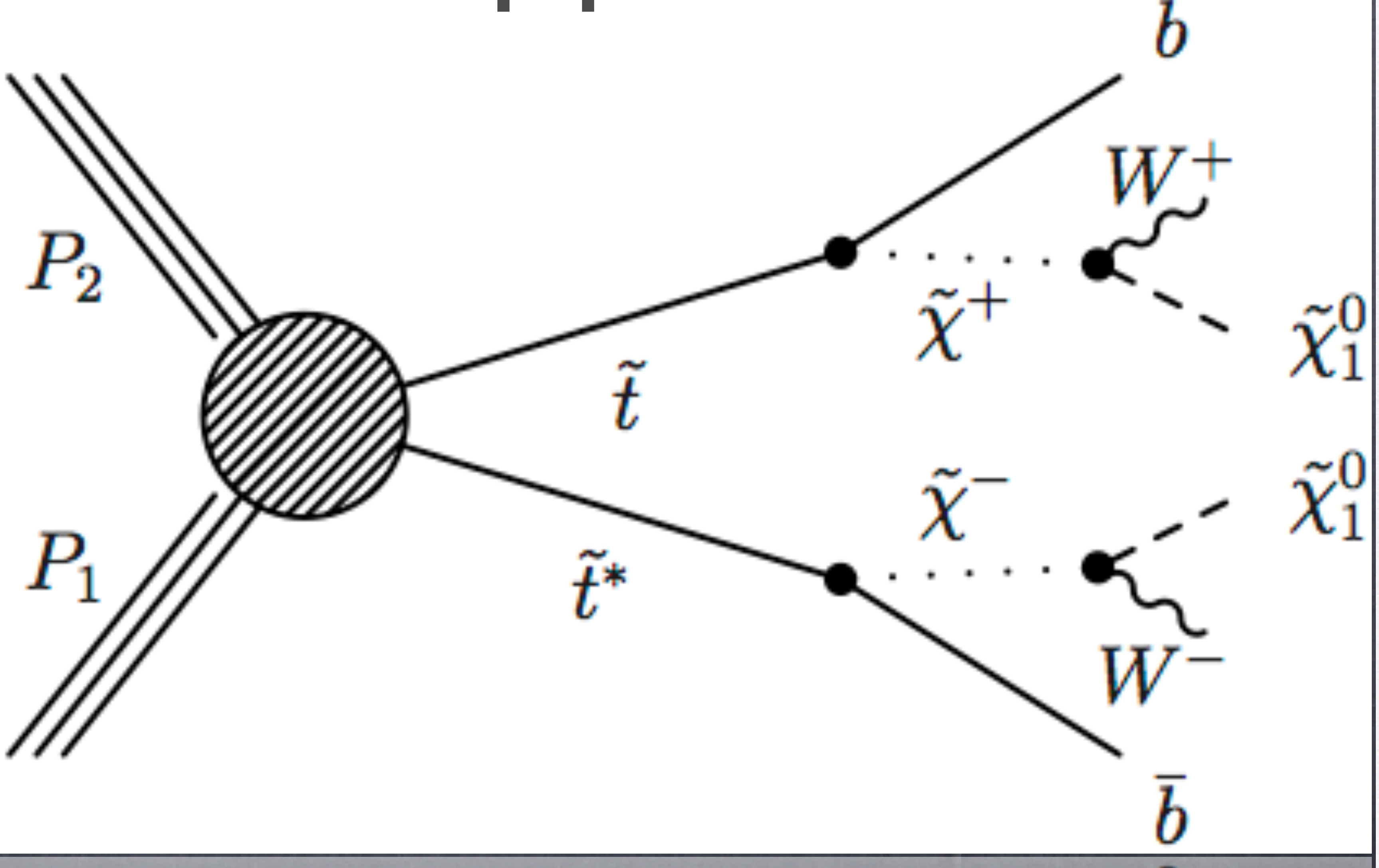
Maurizio Pierini

- Gluino-mediated searches

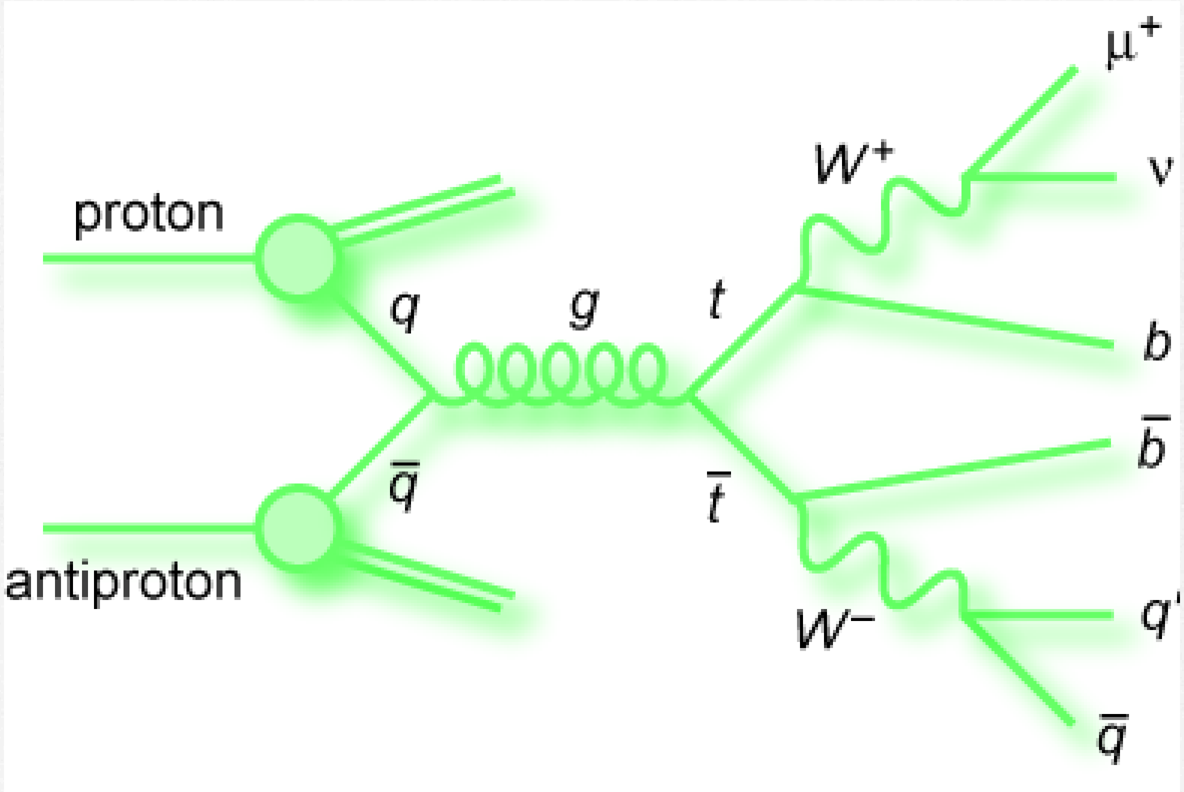
  Larger cross section
  4b quarks in the final state, with or w/o leptons
  More handles for bkg discrimination
  Gluinos might be too heavy for these searches to be effective



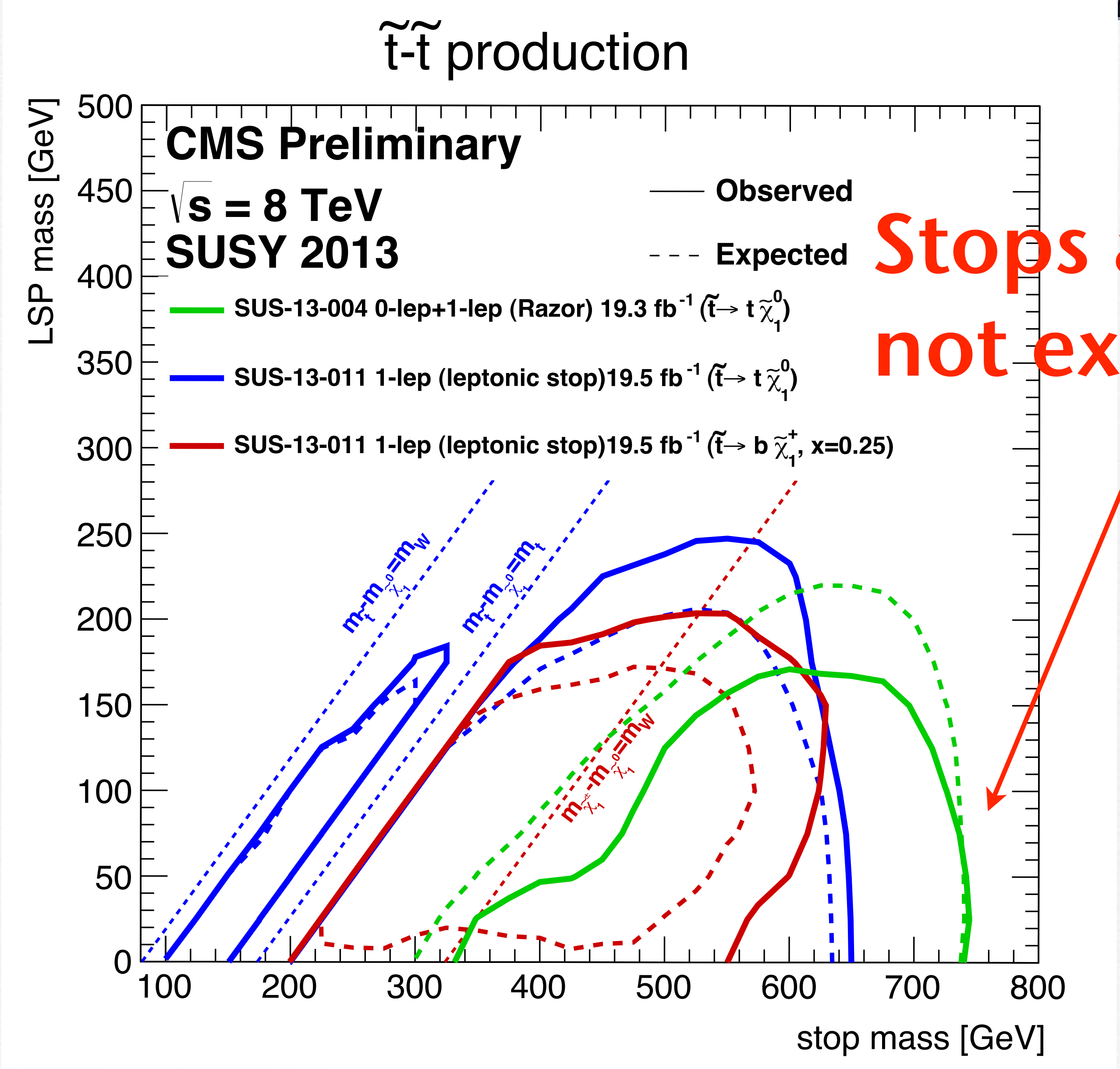
Direct stop production



Top production background

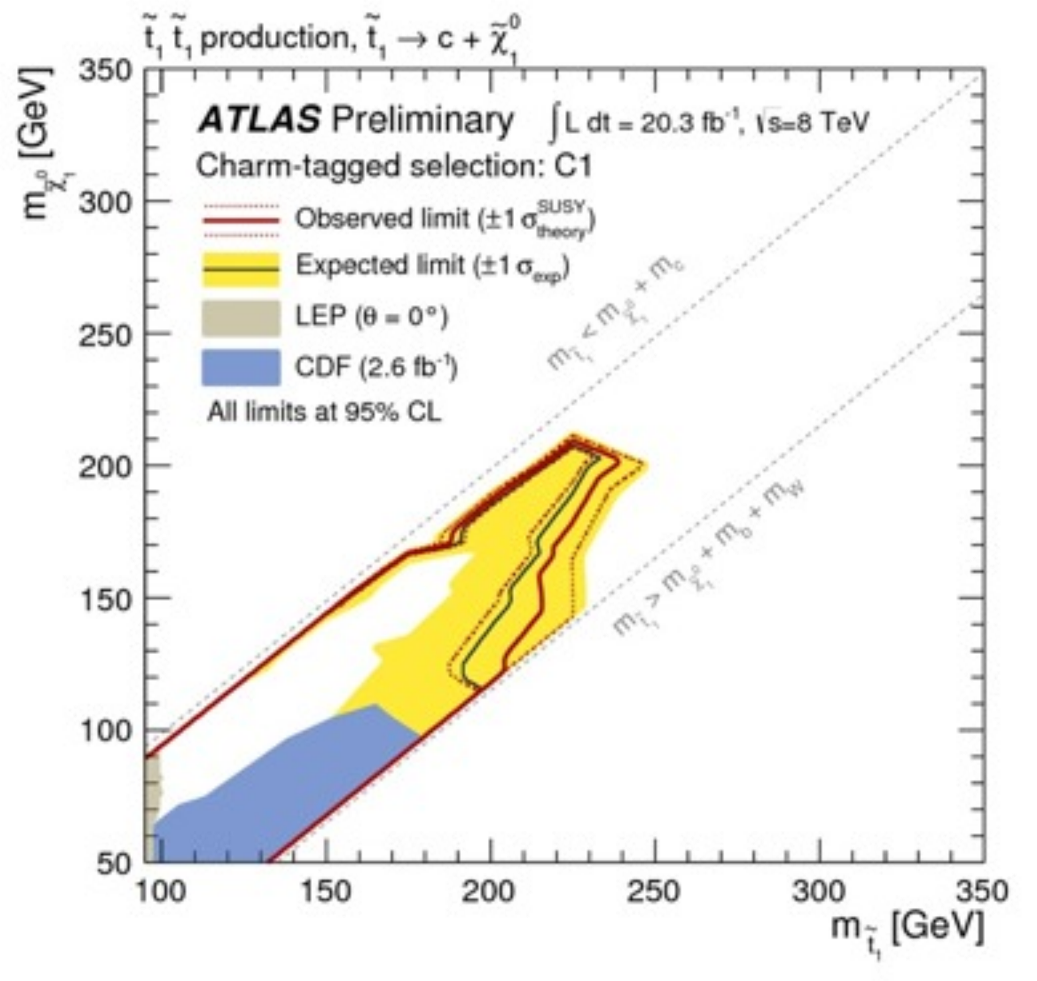


Copious source of leptons + jets + missing energy



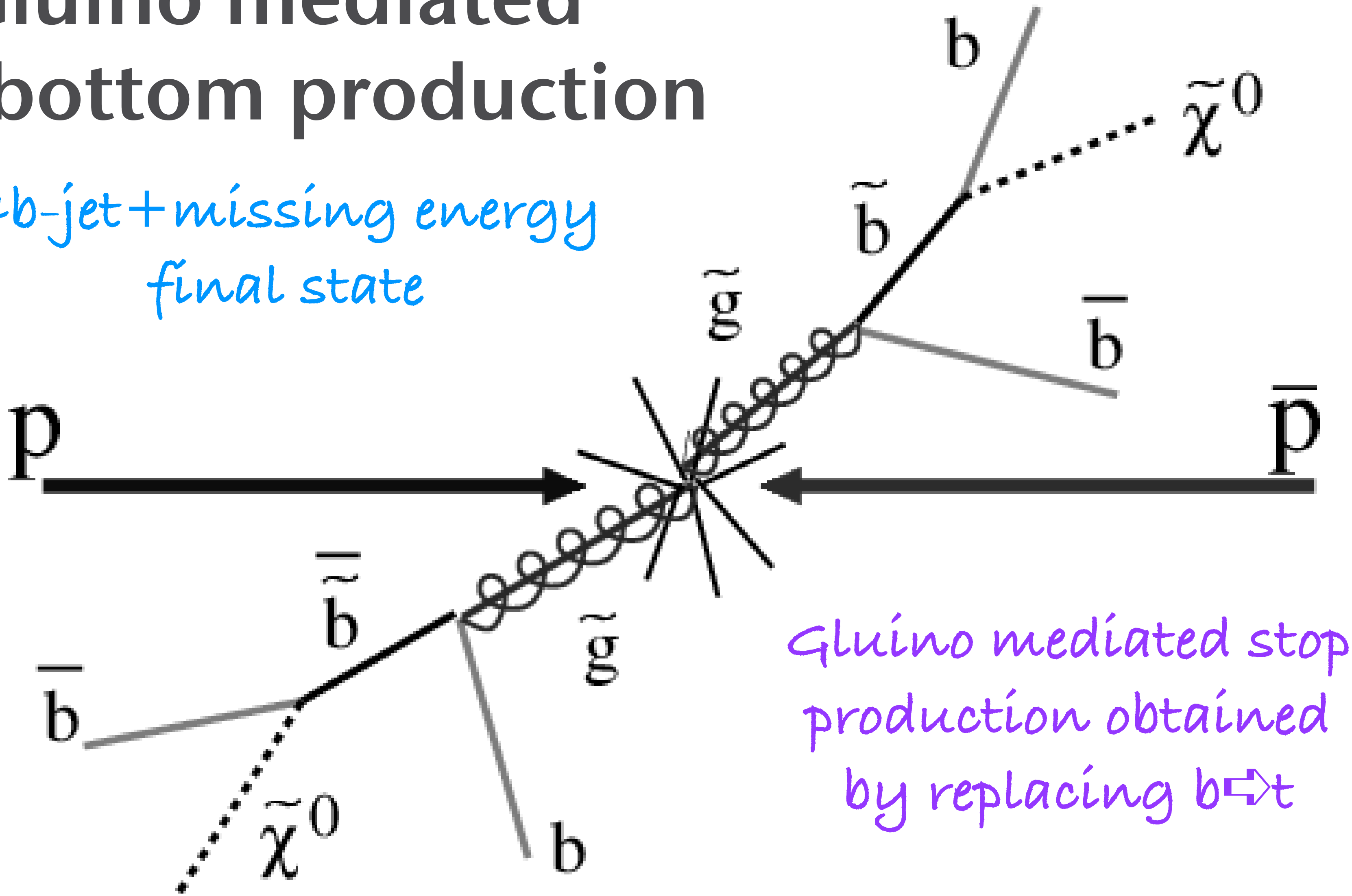
Stops at 750 GeV not excluded

Closing the charm window



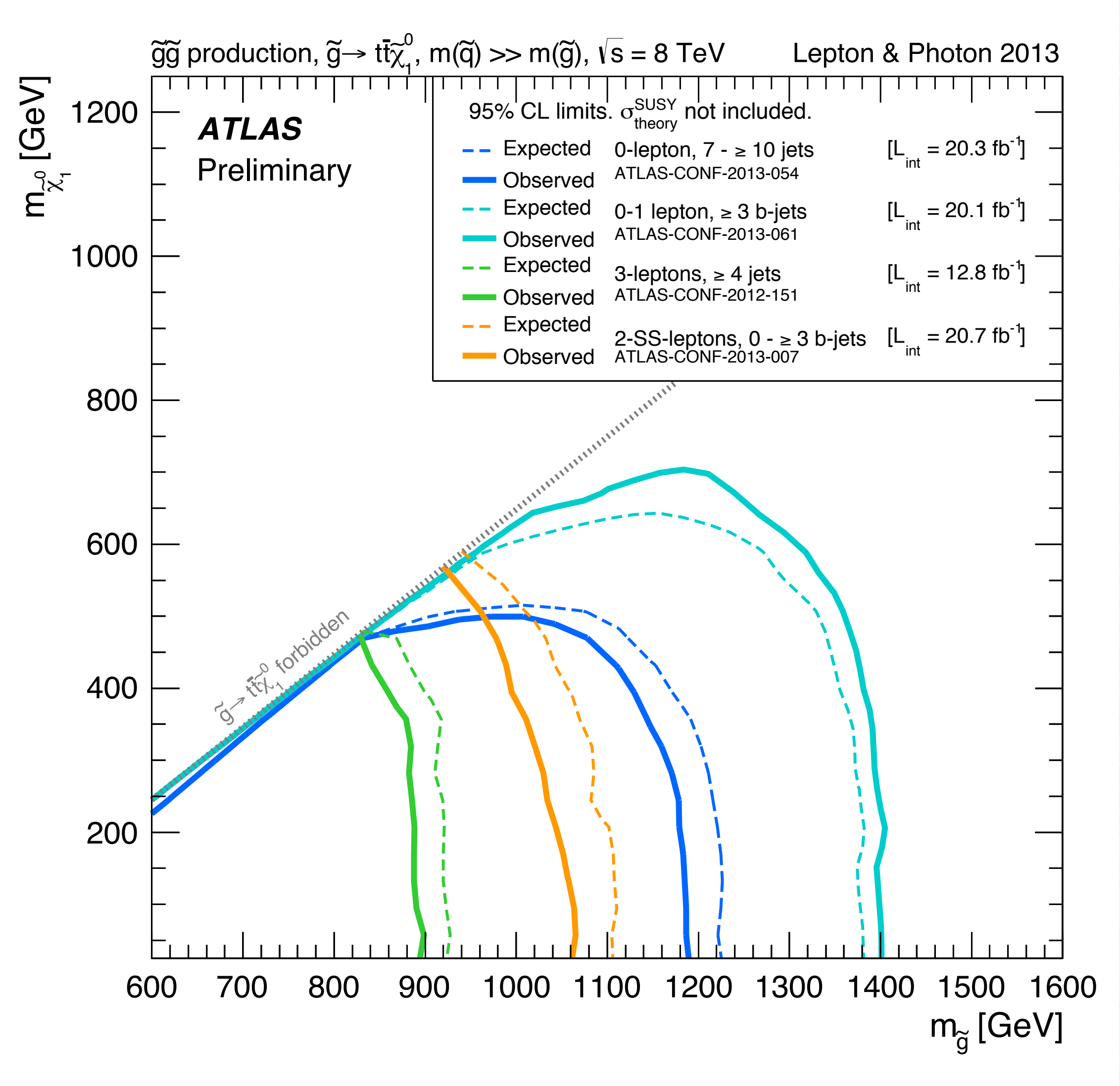
Gluino mediated sbottom production

4b-jet+missing energy final state



Gluino mediated stop production obtained by replacing b⇨t

Gluinos at 1450 GeV not excluded



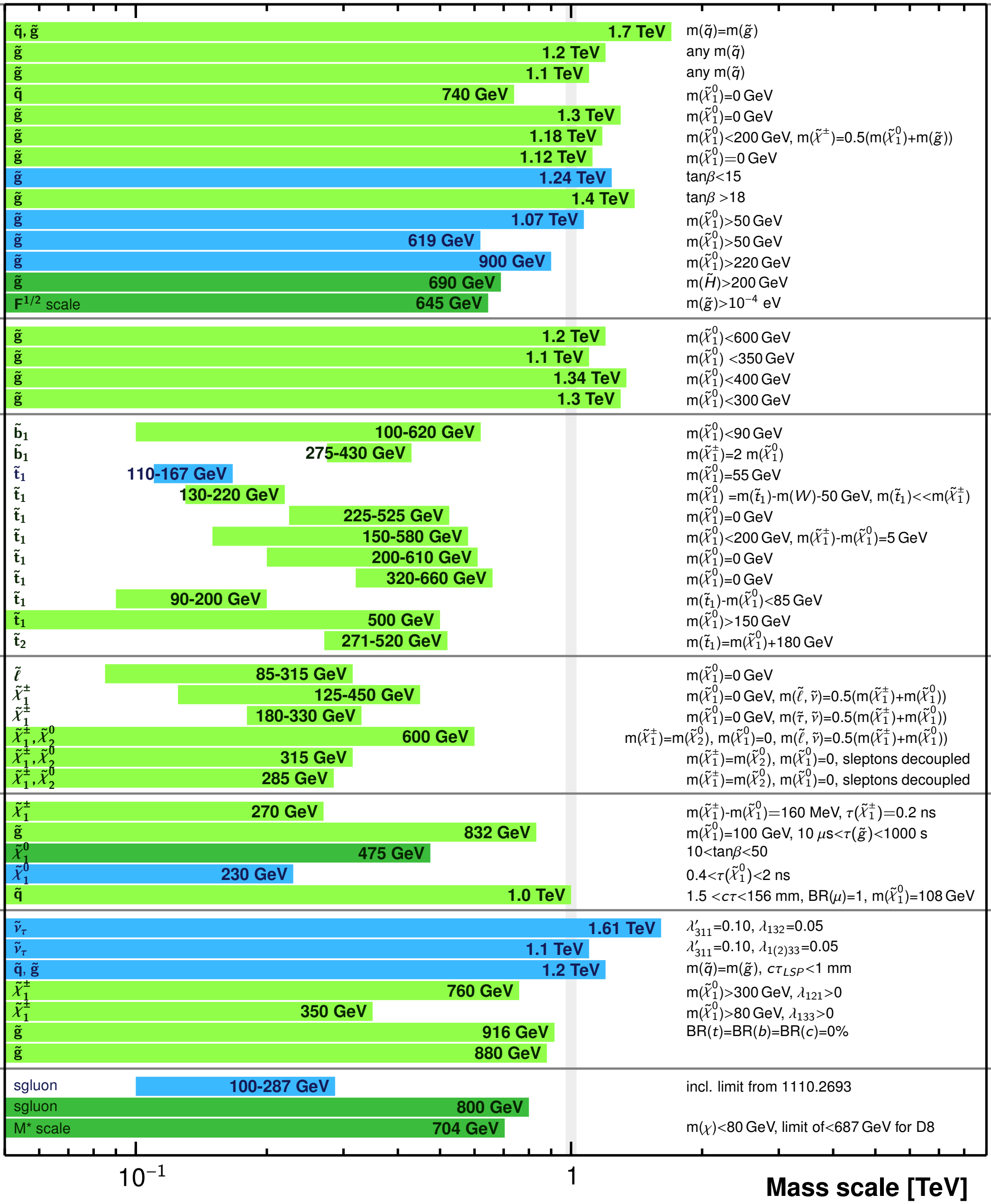
4t+missing
final state

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

$\int \mathcal{L}\,dt$ = (4.6 - 22.9) 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	tanβ<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$	1.4 TeV	tanβ >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
3^{rd} 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
3^{rd} 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<tanβ<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

$\sqrt{s}$ = 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.

Muon g-2: the only hint for SUSY

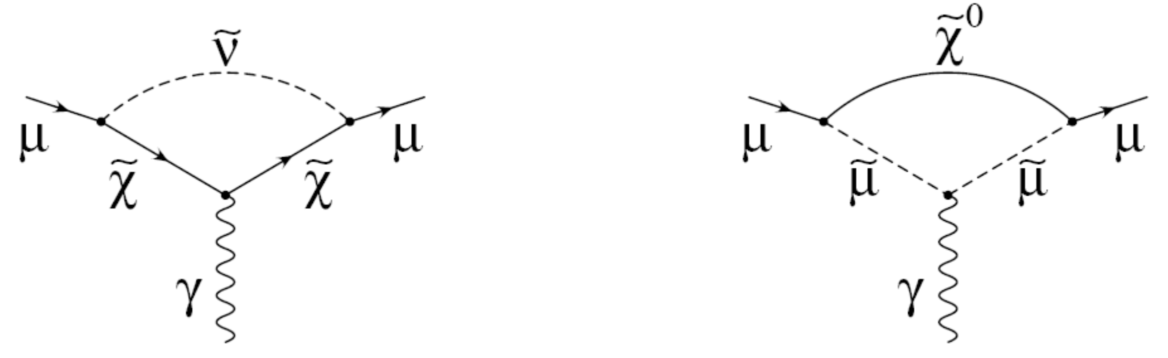
$a_\mu = (g_\mu - 2)/2$

$a_\mu(\text{Expt}) = 116592089(54)(33) \times 10^{-11}$ (BNL 821)

$a_\mu(\text{SM}) = 116591802(42)(26)(02) \times 10^{-11}$

$\Delta a_\mu = 287(80) \times 10^{-11}$ 3.6σ discrepancy!!

Supersymmetric Contributions



Needs light smuons

$$|a_\mu(\text{SUSY})| \simeq 130 \times 10^{-11} \left(\frac{100\text{ GeV}}{\tilde{m}}\right)^2 \tan\beta$$

SUSY Flavour

The down squark mass matrix

In the diagonal down quark basis (Super CKM basis)

$$\begin{pmatrix} m^2_{\tilde d_L} & m_d(A_d-\mu\tan\beta) & (\Delta^d_{12})_{LL} & (\Delta^d_{12})_{LR} & (\Delta^d_{13})_{LL} & (\Delta^d_{13})_{LR} \\ & m^2_{\tilde d_R} & (\Delta^d_{12})_{RL} & (\Delta^d_{12})_{RR} & (\Delta^d_{13})_{RL} & (\Delta^d_{13})_{RR} \\ & & m^2_{\tilde s_L} & m_s(A_s-\mu\tan\beta) & (\Delta^d_{23})_{LL} & (\Delta^d_{23})_{LR} \\ & & & m^2_{\tilde s_R} & (\Delta^d_{23})_{RL} & (\Delta^d_{23})_{RR} \\ & & & & m^2_{\tilde b_L} & m_b(A_b-\mu\tan\beta) \\ & & & & & m^2_{\tilde b_R} \end{pmatrix}$$

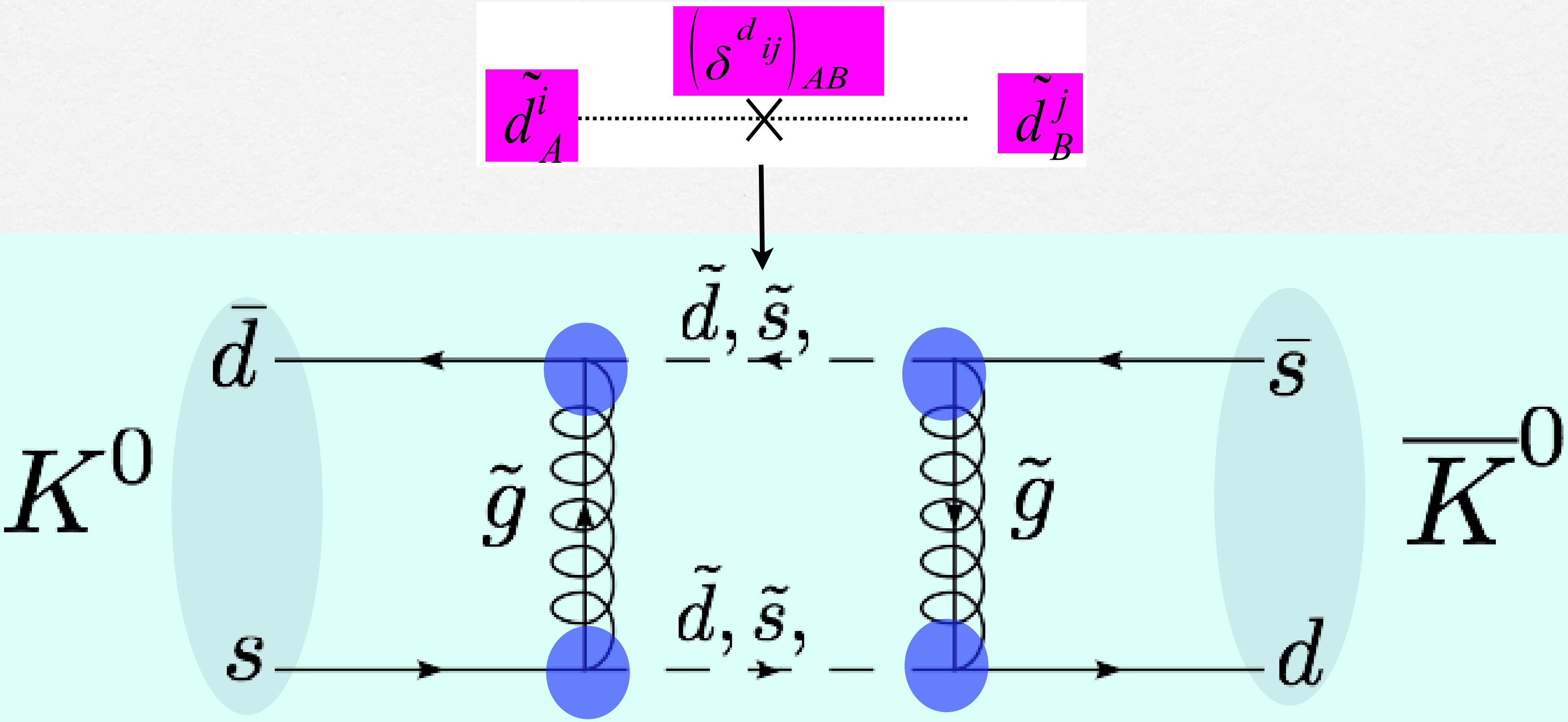
LHC direct measurement/limits

Matrix is diagonal corresponds to "minimal flavour violation"
we say that SUSY is "flavour blind"

Constrain off-diagonal elements from rare/FC processes

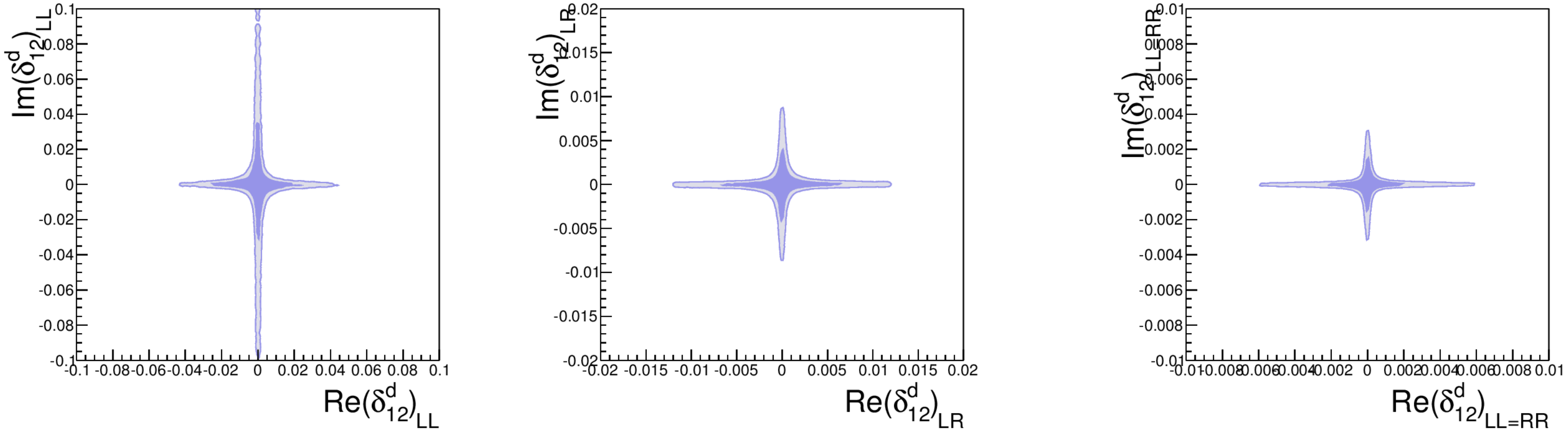
$$(\delta^d_{ij})_{LL}=\frac{(\Delta^d_{ij})_{LL}}{m_{\tilde d_{i\,L}}m_{\tilde d_{j\,L}}} \qquad (\delta^d_{ij})_{RR}=\frac{(\Delta^d_{ij})_{RR}}{m_{\tilde d_{i\,R}}m_{\tilde d_{j\,R}}} \qquad (\delta^d_{ij})_{LR}=\frac{(\Delta^d_{ij})_{LR}}{m_{\tilde d_{i\,L}}m_{\tilde d_{j\,R}}}$$

Mass insertion approximation



Silvestrini

KAON MIXING



	$\sqrt{\left\|\mathrm{Re}\left[(\delta^d_{12})_{LL}\right]^2\right\|}$	$\sqrt{\left\|\mathrm{Re}\left[(\delta^d_{12})_{LR}\right]^2\right\|}$	$\sqrt{\left\|\mathrm{Re}\left[(\delta^d_{12})_{LL=RR}\right]^2\right\|}$
bound on δ ($\tilde{m} = 1$ TeV)	$1 \cdot 10^{-1}$	$1 \cdot 10^{-2}$	$6 \cdot 10^{-3}$
bound on $\tilde{m}$ (TeV) for $\delta_{\mathrm{LL,RR}} = 1$	10	$--$	170
	$\sqrt{\left\|\mathrm{Im}\left[(\delta^d_{12})_{LL}\right]^2\right\|}$	$\sqrt{\left\|\mathrm{Im}\left[(\delta^d_{12})_{LR}\right]^2\right\|}$	$\sqrt{\left\|\mathrm{Im}\left[(\delta^d_{12})_{LL=RR}\right]^2\right\|}$
bound on δ ($\tilde{m} = 1$ TeV)	$8 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	$6 \cdot 10^{-4}$
bound on $\tilde{m}$ (TeV) for $\delta_{\mathrm{LL,RR}} = 1$	100	$--$	1700

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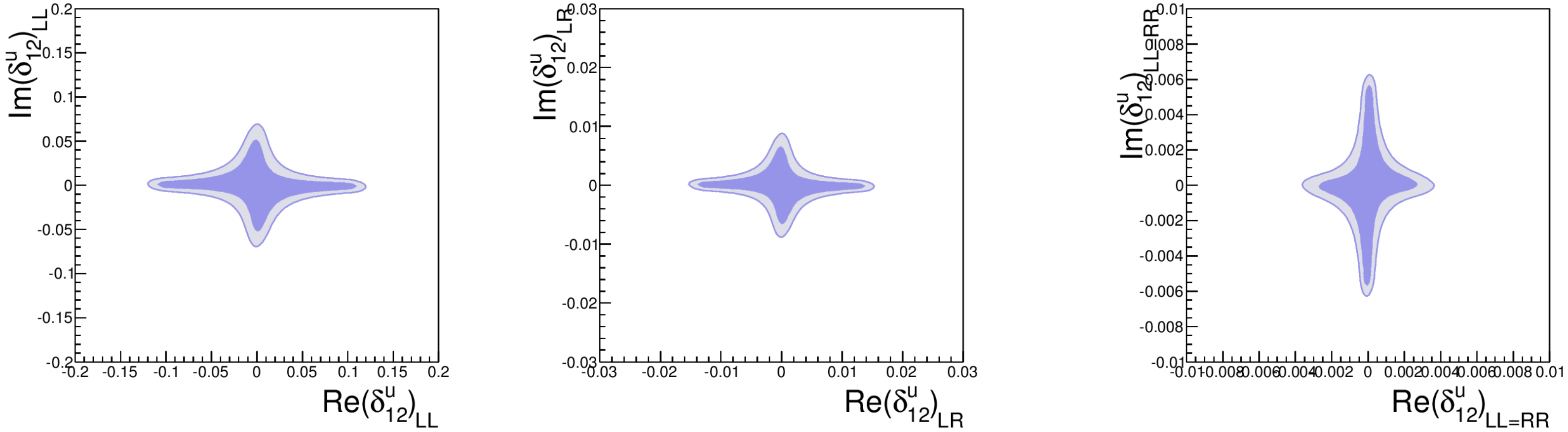
D MIXING



bound on δ ($\tilde{m} = 1$ TeV) bound on $\tilde{m}$ (TeV) for $\delta_{\mathrm{LL,RR}} = 1$	$\sqrt{\left\|\mathrm{Re}\left[(\delta^u_{12})_{LL}\right]^2\right\|}$ $1 \cdot 10^{-1}$ 10	$\sqrt{\left\|\mathrm{Re}\left[(\delta^u_{12})_{LR}\right]^2\right\|}$ $1 \cdot 10^{-2}$ $--$	$\sqrt{\left\|\mathrm{Re}\left[(\delta^u_{12})_{LL=RR}\right]^2\right\|}$ $6 \cdot 10^{-3}$ 170
bound on δ ($\tilde{m} = 1$ TeV) bound on $\tilde{m}$ (TeV) for $\delta_{\mathrm{LL,RR}} = 1$	$\sqrt{\left\|\mathrm{Im}\left[(\delta^u_{12})_{LL}\right]^2\right\|}$ $3 \cdot 10^{-2}$ 30	$\sqrt{\left\|\mathrm{Im}\left[(\delta^u_{12})_{LR}\right]^2\right\|}$ $4 \cdot 10^{-3}$ $--$	$\sqrt{\left\|\mathrm{Im}\left[(\delta^u_{12})_{LL=RR}\right]^2\right\|}$ $2 \cdot 10^{-3}$ 500

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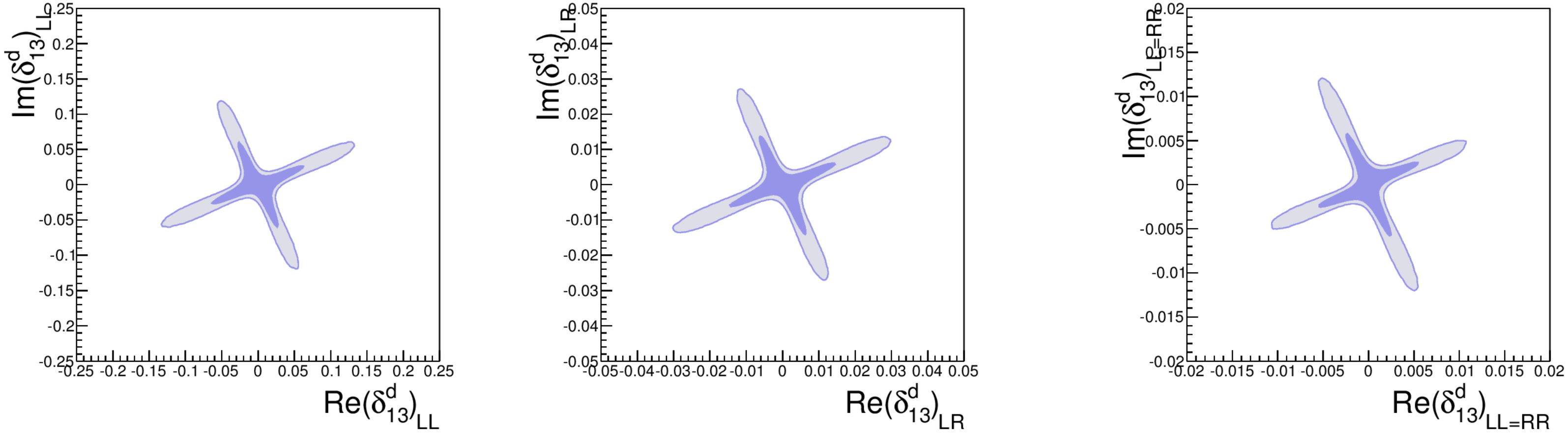
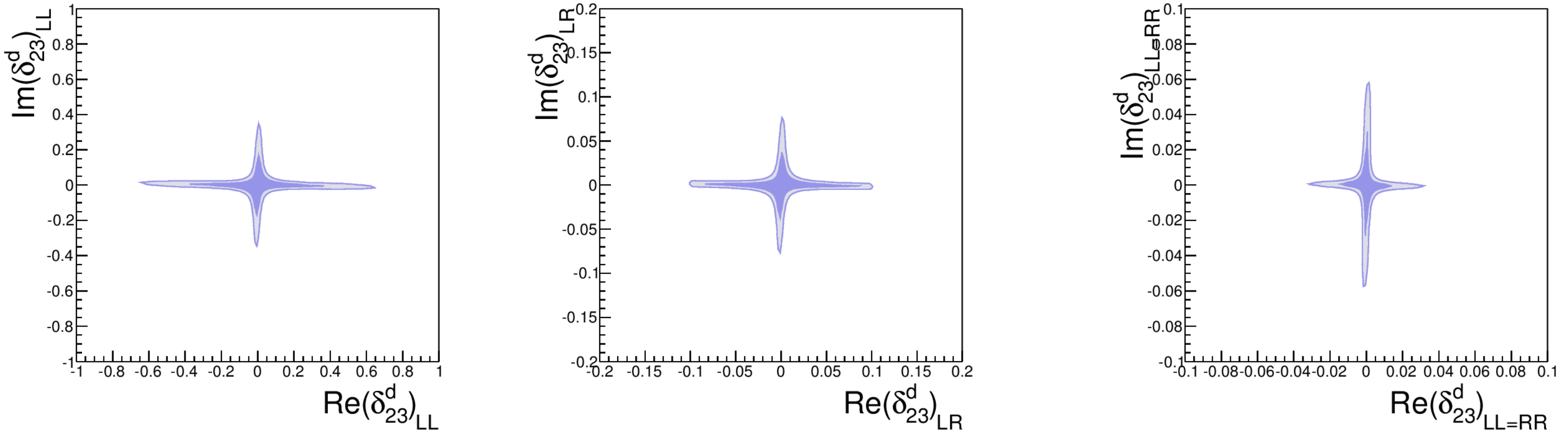
B_d MIXING



	$\sqrt{\lvert \mathrm{Re}\left[(\delta^d_{13})_{LL}\right]^2 \rvert}$	$\sqrt{\lvert \mathrm{Re}\left[(\delta^d_{13})_{LR}\right]^2 \rvert}$	$\sqrt{\lvert \mathrm{Re}\left[(\delta^d_{13})_{LL=RR}\right]^2 \rvert}$
bound on δ ($\tilde{m} = 1$ TeV)	$9 \cdot 10^{-2}$	$2 \cdot 10^{-2}$	$8 \cdot 10^{-3}$
bound on $\tilde{m}$ (TeV) for $\delta_{\mathrm{LL,RR}} = 1$	10	$--$	125
	$\sqrt{\lvert \mathrm{Im}\left[(\delta^d_{13})_{LL}\right]^2 \rvert}$	$\sqrt{\lvert \mathrm{Im}\left[(\delta^d_{13})_{LR}\right]^2 \rvert}$	$\sqrt{\lvert \mathrm{Im}\left[(\delta^d_{13})_{LL=RR}\right]^2 \rvert}$
bound on δ ($\tilde{m} = 1$ TeV)	$1 \cdot 10^{-1}$	$2 \cdot 10^{-2}$	$9 \cdot 10^{-3}$
bound on $\tilde{m}$ (TeV) for $\delta_{\mathrm{LL,RR}} = 1$	10	$--$	110

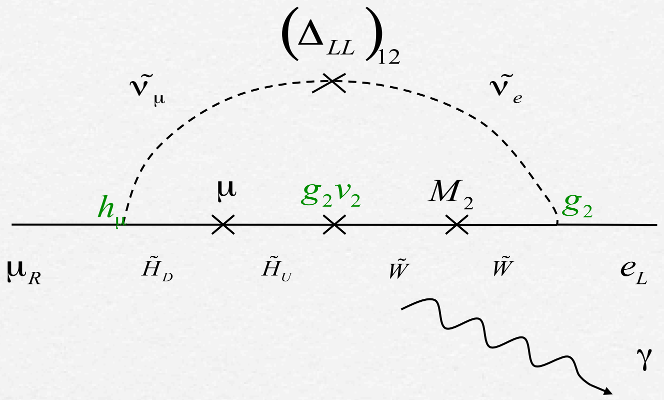
B_s MIXING

Silvestrini



	$\sqrt{\lvert \mathrm{Re}\left[(\delta^d_{23})_{LL}\right]^2 \rvert}$	$\sqrt{\lvert \mathrm{Re}\left[(\delta^d_{23})_{LR}\right]^2 \rvert}$	$\sqrt{\lvert \mathrm{Re}\left[(\delta^d_{23})_{LL=RR}\right]^2 \rvert}$
bound on δ ($\tilde{m} = 1$ TeV)	$6 \cdot 10^{-1}$	$1 \cdot 10^{-1}$	$5 \cdot 10^{-2}$
bound on $\tilde{m}$ (TeV) for $\delta_{\mathrm{LL,RR}} = 1$	1.7	$--$	20
	$\sqrt{\lvert \mathrm{Im}\left[(\delta^d_{23})_{LL}\right]^2 \rvert}$	$\sqrt{\lvert \mathrm{Im}\left[(\delta^d_{23})_{LR}\right]^2 \rvert}$	$\sqrt{\lvert \mathrm{Im}\left[(\delta^d_{23})_{LL=RR}\right]^2 \rvert}$
bound on δ ($\tilde{m} = 1$ TeV)	$1 \cdot 10^{-1}$	$2 \cdot 10^{-2}$	$1 \cdot 10^{-2}$
bound on $\tilde{m}$ (TeV) for $\delta_{\mathrm{LL,RR}} = 1$	10	$--$	100

LFV



Observable	MSSM Flavor Content
$\mu \to e\gamma$	$(\delta_{AB})_{12}$
$\tau \to \mu\gamma$	$(\delta_{AB})_{23}$
$\tau \to e\gamma$	$(\delta_{AB})_{13}$

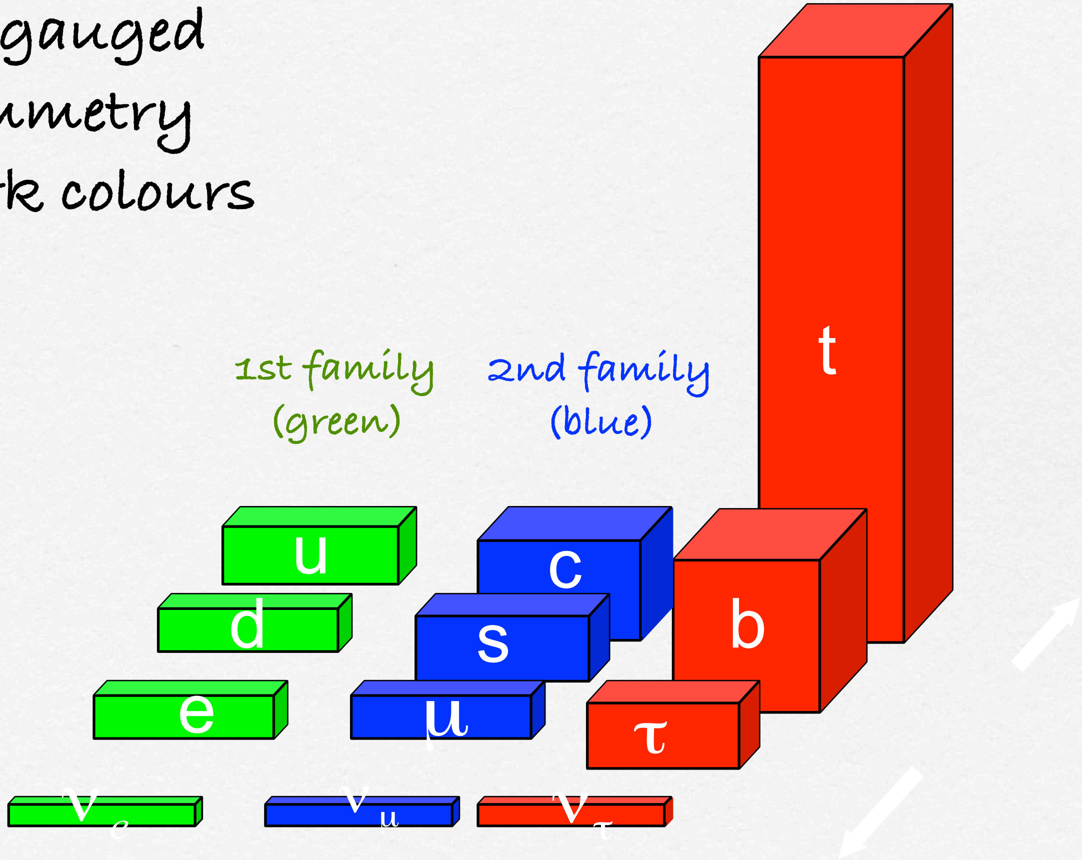
Observable	SM Prediction	MSSM Flavor Content
Δm_K	$\sim (V_{cs}^* V_{cd})^2$	$(\delta_{AB})_{12}$
ϵ	$\sim \mathrm{Im}(V_{ts}^* V_{td})\mathrm{Re}(V_{cs}^* V_{cd})$	$(\delta_{AB})_{12}$
$\epsilon^{'}/\epsilon$	$\sim \mathrm{Im}(V_{ts}^* V_{td})$	$(\delta_{AB})_{12}$
$b \to s\gamma$	$\sim V_{tb} V_{ts}^*$	$(\delta_{AB})_{23}$
$A_{CP}(b \to \ s\gamma)$	$\sim \alpha_s(m_b)\frac{V_{ub}}{V_{cb}}\frac{m_c^2}{m_b^2}$	$(\delta_{AB})_{23}$
Δm_{B_d}	$\sim (V_{td}^* V_{tb})^2$	$(\delta_{AB})_{13}$
Δm_{B_s}	$\sim (V_{ts}^* V_{tb})^2$	$(\delta_{AB})_{23}$
$A_{CP}(B \to \ \psi K_S)$	$= \sin 2\beta$	$(\delta_{AB})_{13}$
$A_{CP}(B \to \ \phi K_S)$	$= \sin 2\beta$	$(\delta_{AB})_{23}$

Why are the off-diagonal squark masses so small?

- Maybe not small - just very heavy squarks (first and second family)
- Some alignment mechanism as in GMSB or AMSB
- mSUGRA ? But not well motivated...
- In general SUGRA need a theory of flavour to understand this - involving a family symmetry

Family Symmetry

E.g. SU(3) gauged
family symmetry
c.f. QCD quark colours


3rd family
(red)

1st family
(green)

2nd family
(blue)

SU(3) Family Symmetry and Soft Masses

$\psi_i \in (Q_i, L_i) \sim \mathbf{3}$ Flavons $\phi \sim \bar{3}$

SFK,Ross; Ross,Velasco-Sevilla,Vives
Antusch, SFK, Malinsky

Yukawas

$$\frac{b_3}{M^2}\phi_3^i\psi_i\phi_3^j\psi_j H + \frac{b_{23}}{M^2}\phi_{23}^i\psi_i\phi_{23}^j\psi_j H + \ldots$$

Soft masses

$$m^2 = m_0^2\left(\delta_{ij} + c_3\frac{\phi_3^*\phi_3}{M'^2} + c_{23}\frac{\phi_{23}^*\phi_{23}}{M'^2} + \ldots\right)$$

- Leading order universal due to $SU(3)_{fam}$
- Sub-leading mainly (2,3) flavour violation controlled by flavons

$$m^2 \sim \begin{pmatrix}1 & & \\ & 1 & \\ & & 1\end{pmatrix} m_0^2 + \begin{pmatrix}0 & & \\ & 0 & \\ & & \varepsilon_3^2\end{pmatrix} m_3^3 + \begin{pmatrix}0 & & \\ & \varepsilon_{23}^2 & \varepsilon_{23}^2 \\ & \varepsilon_{23}^2 & \varepsilon_{23}^2\end{pmatrix} m_{23}^3 + \ldots$$

The SUSY CP Problem

Abel, Khalil,Lebedev;

Ross,Vives;

Antusch, SFK, Malinsky, Ross

- SUSY neutron EDM $d_n \sim \left(\frac{300\ \mathrm{GeV}}{M}\right)^2 \sin\phi \times 10^{-24} e\ \mathrm{cm}$

$\phi_\mu \sim \phi_A \equiv \phi \ll 1,\ \tan\beta \sim 3 \quad \rightarrow \phi < 10^{-2}$

Why are SUSY phases so small?

- Postulate CP conservation (e.g. $\mu H_u H_d$ real) with CP is spontaneously broken by flavon vevs
- Trilinear soft

$$\tilde{A}_{ij} = A_0\left(a_3\frac{\phi_3^i\phi_3^j}{M^2} + a_{23}\frac{\phi_{23}^i\phi_{23}^j}{M^2} + \ldots\right)$$

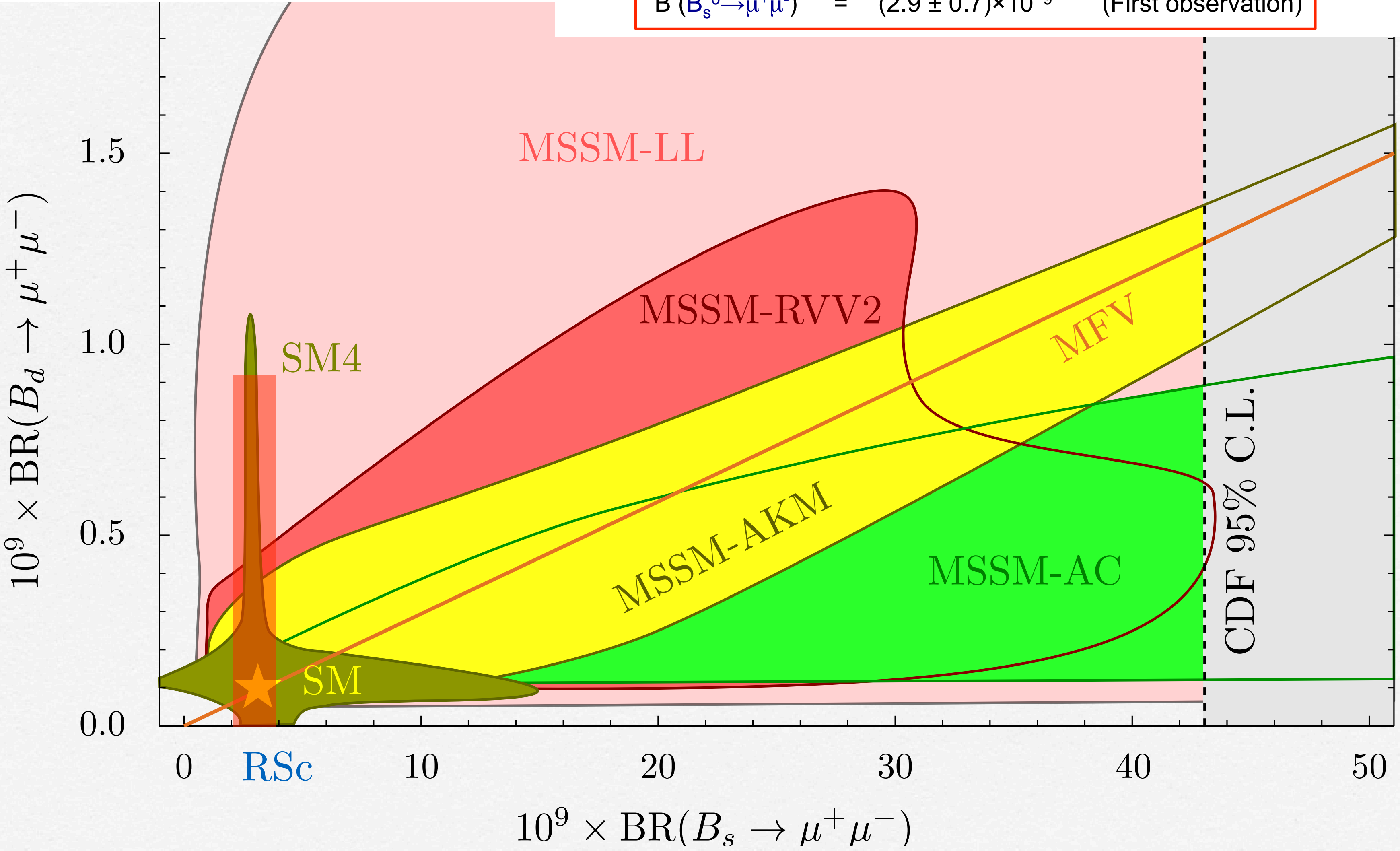
A_0 , a_3 , a_{23} , real gives real soft masses times complex Yukawa elements → no soft phases at leading order

$\mathcal{B}(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10}$ @ 95% CL

- The LHCb and CMS results have been combined

[LHCb-CONF-2013-012]
[CMS-PAS-BPH-13-007]

$B\,(B_s^0 \to \mu^+\mu^-) \quad = \quad (2.9 \pm 0.7) \times 10^{-9}$ (First observation)



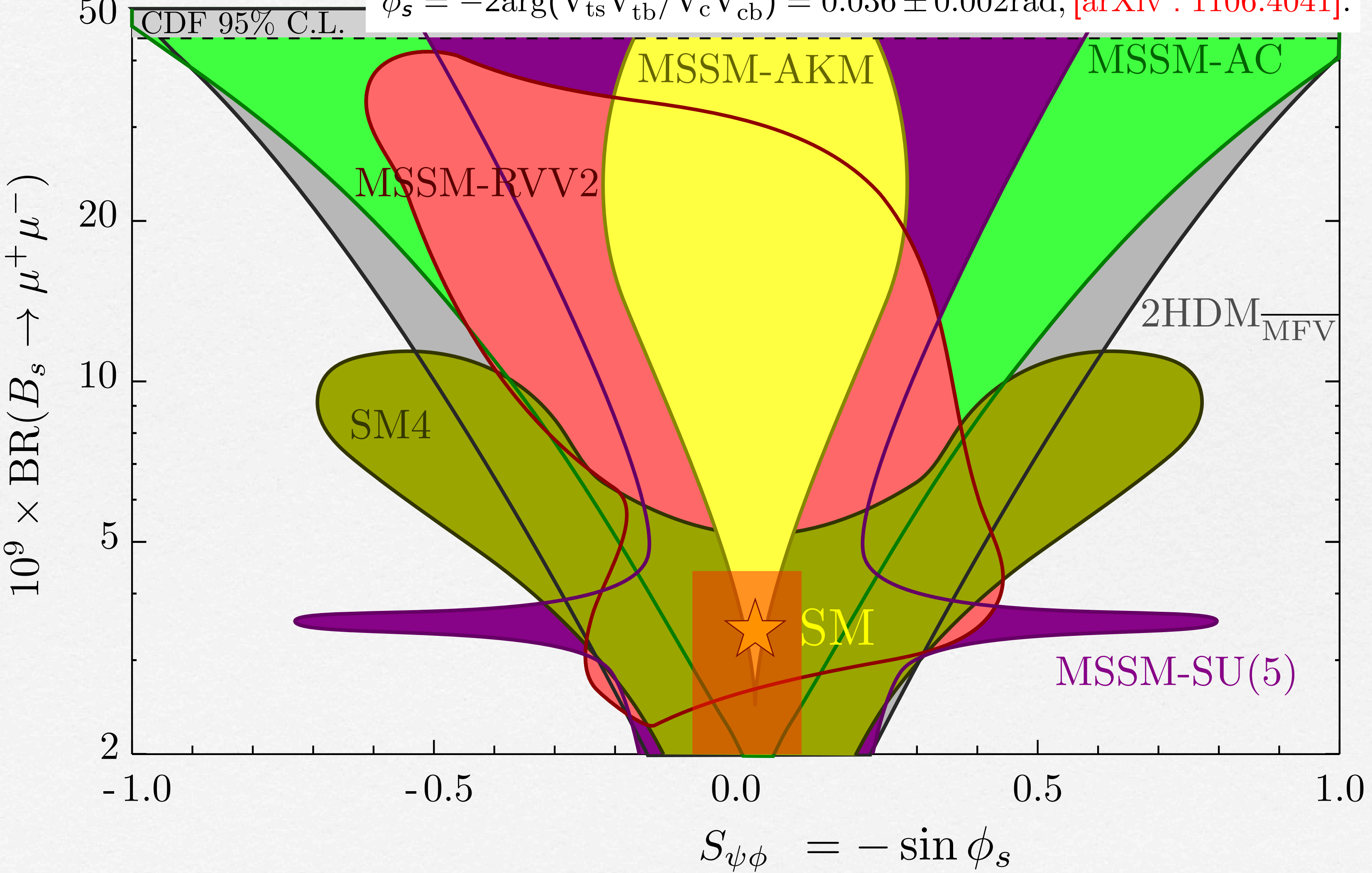
Combined results with $B_s^0 \to J/\psi \pi^+\pi^-$ [arXiv:1304.2600]:

$$\phi_s = 0.01 \pm 0.07 \pm 0.01 \text{ rad}$$

exp't

$\phi_s = -2\arg(\mathrm{V_{ts}V_{tb}^*/V_cV_{cb}^*}) = 0.036 \pm 0.002\mathrm{rad}$, [arXiv : 1106.4041].

SM



SUSY Higgs

Higgs in MSSM

A special two Higgs doublet model

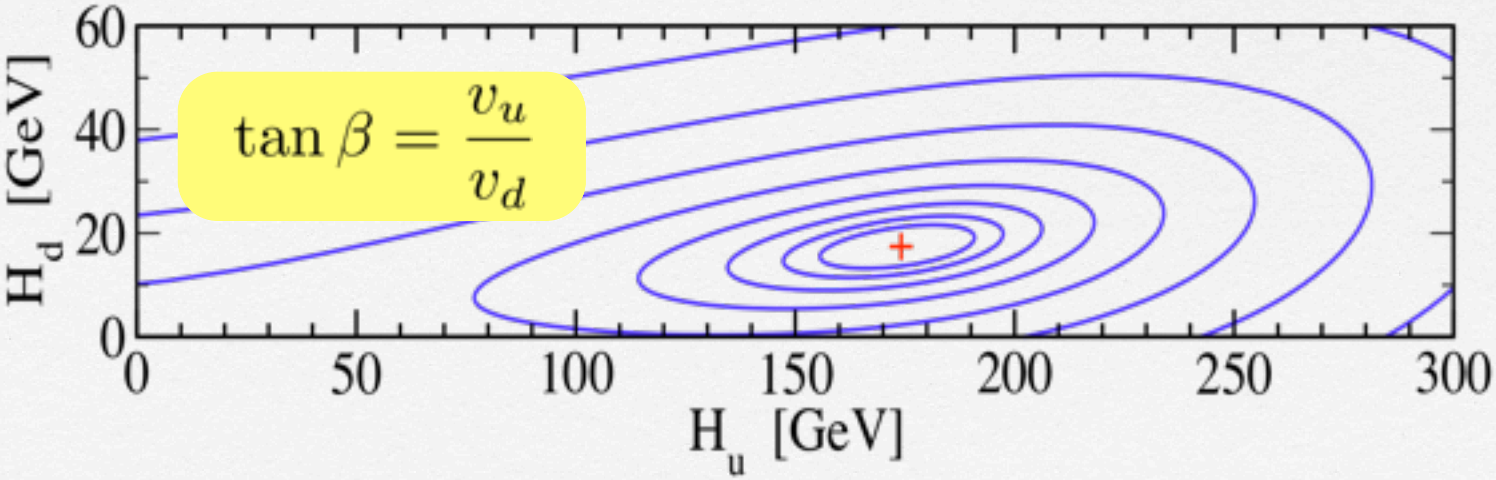
$$H_u = (H_u^+,\ H_u^0)$$
$$H_d = (H_d^0,\ H_d^-)$$

Mahmoudi lectures

Superpotential $\mathcal{W} = \mu \widehat{H}_u \widehat{H}_d$

Potential $V = |F|^2 + (D)^2 + V_{soft}$

$$\begin{aligned} V &= (|\mu|^2 + m^2_{H_u})|H_u^0|^2 + (|\mu|^2 + m^2_{H_d})|H_d^0|^2 - (b\, H_u^0 H_d^0 + \text{c.c.}) \\ &\quad + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2. \end{aligned}$$



$$\tan\beta = \frac{v_u}{v_d}$$

MSSM Higgs decoupling limit

CP even Higgs mass matrix

$$\mathcal{M}_0^2 = \begin{pmatrix} m_A^2 \sin^2\beta + m_Z^2 \cos^2\beta & -(m_A^2 + m_Z^2)\sin\beta\cos\beta \\ -(m_A^2 + m_Z^2)\sin\beta\cos\beta & m_A^2\cos^2\beta + m_Z^2\sin^2\beta \end{pmatrix}$$

CP even Higgs masses

$$m_{H,h}^2 = \frac{1}{2}\left(m_A^2 + m_Z^2 \pm \sqrt{(m_A^2 + m_Z^2)^2 - 4m_Z^2 m_A^2 \cos^2 2\beta}\right)$$

Tree-level mass bound

$$m_h \le m_Z |\cos 2\beta| \le m_Z$$

ϕ		$g_{\phi\bar{t}t}$	$g_{\phi\bar{b}b}$	$g_{\phi VV}$
SM	H	1	1	1
MSSM	h^o	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$
	H^o	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$
	A^o	$1/\tan\beta$	$\tan\beta$	0

Decoupling limit

$$M_A \gg M_Z$$

$$\frac{\cos\alpha}{\sin\beta} \simeq 1 + \mathcal{O}(M_Z^2/M_A^2)\,, \quad -\frac{\sin\alpha}{\cos\beta} \simeq 1 + \mathcal{O}(M_Z^2/M_A^2)$$

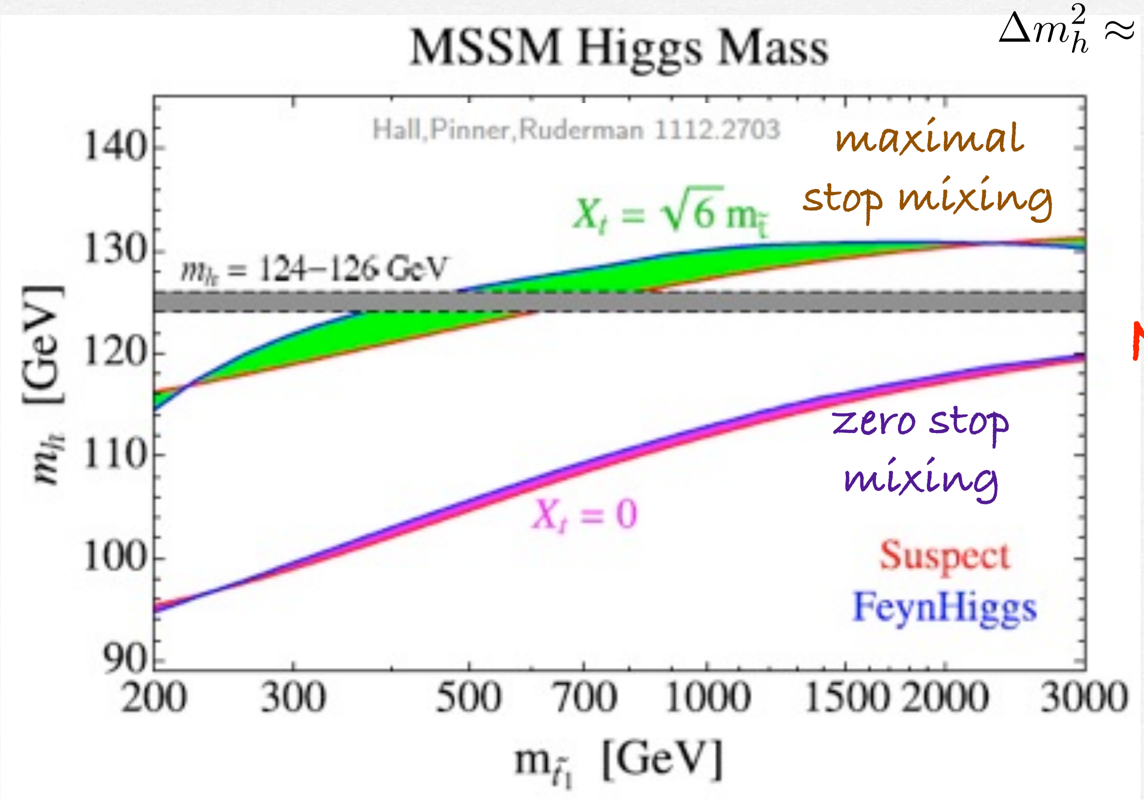
$$\sin(\beta-\alpha) \simeq 1 + \mathcal{O}(M_Z^4/M_A^4).$$

Higgs h Mass in MSSM

$$\mathcal{W} = \mu \widehat{H}_u \widehat{H}_d$$

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

$$\Delta m_h^2 \approx \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1-\frac{X_t^2}{12m_{\tilde{t}}^2}\right)\right]$$



$$m_{\tilde{t}}^2 = m_{\tilde{Q}_3} m_{\tilde{t}_R} \qquad X_t = A_t - \mu \cot\beta.$$

Need $\Delta m_h \approx M_Z$

Must have heavy stops

Large Fine Tuning!

The mu problem(s) of MSSM

Min cond'n:

$$\mathcal{W} = \mu \widehat{H}_u \widehat{H}_d \xrightarrow{\qquad} \mu^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \frac{1}{2} m_Z^2 .$$

Clearly to avoid tuning need mu ~ M_Z

mu problem 1 (big hierarchy problem) :
mu ~ M_{GUT} is not forbidden in the MSSM

mu problem 2 (little hierarchy problem):
Experimentally mu must be larger than M_Z
(typically due to radiative breaking w/heavy stops)

Next-to-Minimal SUSY SM (NMSSM)

Model gives dynamical origin of μ term via complex singlet S:

$\mu H_u H_d \rightarrow S H_u H_d$ where singlet $\langle S \rangle \sim \mu \sim$ TeV

Danger from weak scale axion due to global U(1) symmetry

Need to avoid axion somehow

In NMSSM we add S^3 to break U(1) to Z_3

$$\mathcal{W} = \lambda \widehat{S} \widehat{H}_u \widehat{H}_d + \frac{\kappa}{3} \widehat{S}^3$$

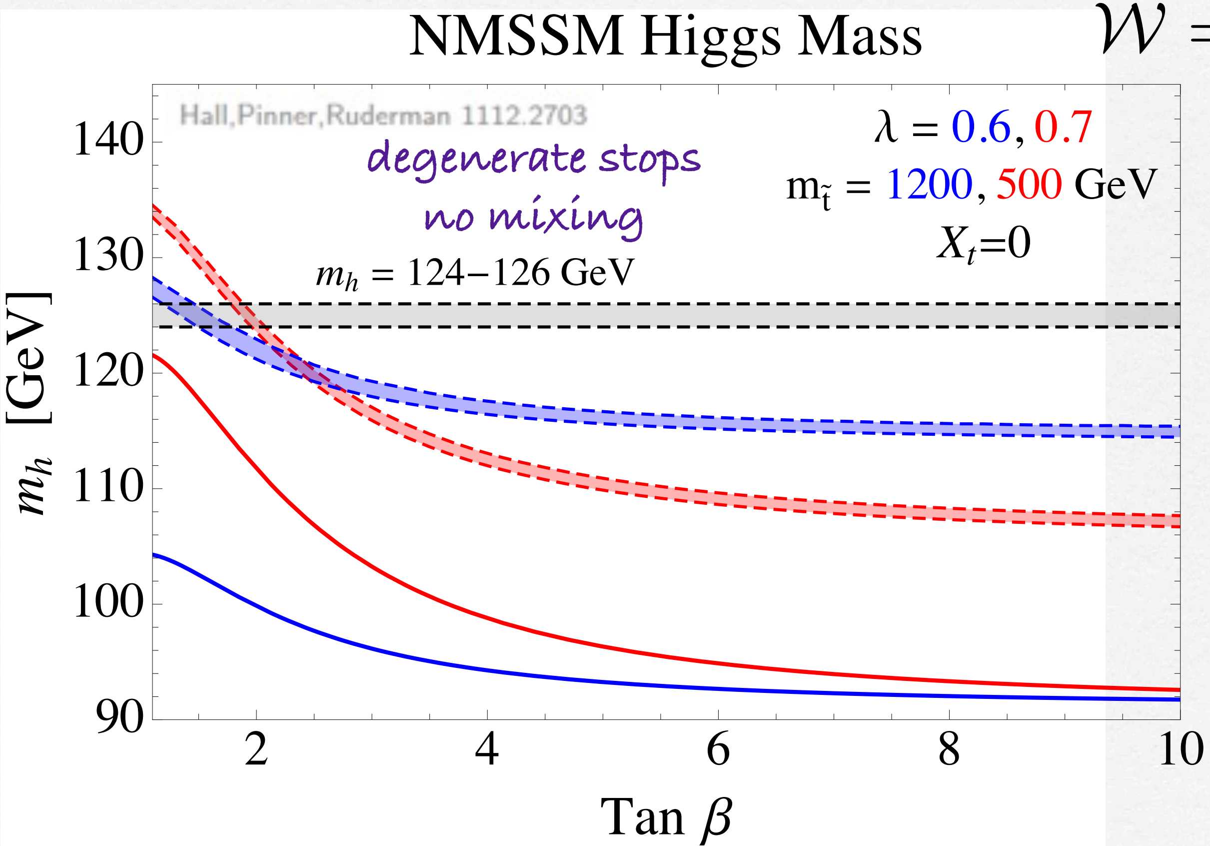
Extra tree-level contribution to Higgs mass reduces fine-tuning

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \boxed{\lambda^2 v^2 \sin^2 2\beta} + \Delta m_h^2$$

Want λ as large as possible but avoiding Landau pole

Higgs h Mass in NMSSM

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \Delta m_h^2$$



$$\mathcal{W} = \lambda \widehat{S} \widehat{H}_u \widehat{H}_d + \frac{\kappa}{3} \widehat{S}^3$$

Light stops w/zero mixing allowed for large λ

small κ

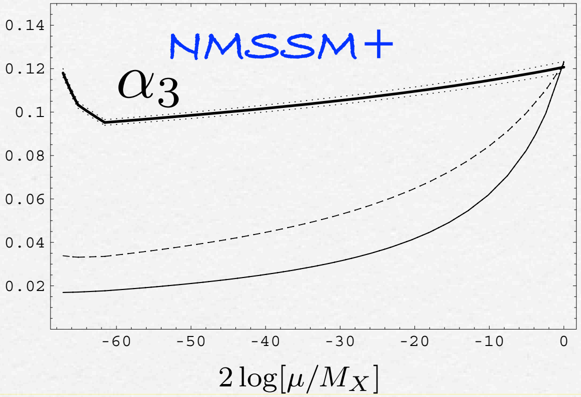
NMSSM+

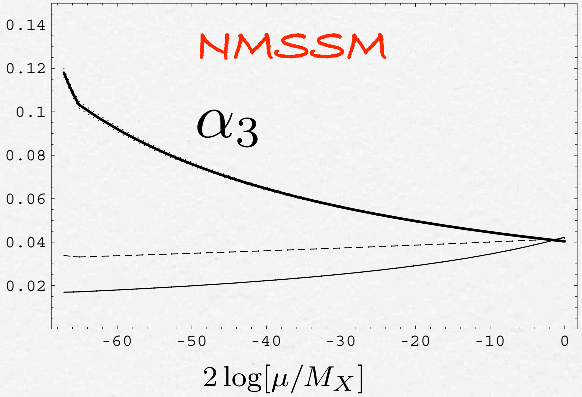
$$W^{\rm NMSSM+} \in 3(27) \text{ of } E_6$$

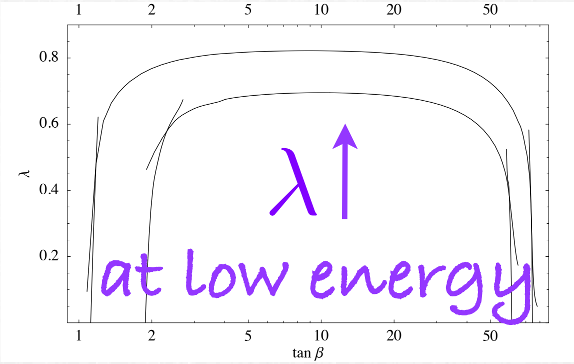
$$W^{\rm extra} \in 3(5+\bar{5}) \text{ of } SU(5)$$

King, Hall 1209.4657

Masip, Munoz-Tapia,
Pomarol hep-ph/9801437







$$8\pi^2\frac{\partial\lambda}{\partial t} = (2\lambda^2 + k^2 + \frac{3}{2}h_t^2 - \frac{3}{2}g_2^2 - \frac{1}{2}g_1^2)\lambda$$

$$8\pi^2\frac{\partial k}{\partial t} = (3\lambda^2 + 3k^2)k$$

$$8\pi^2\frac{\partial h_t}{\partial t} = (\frac{1}{2}\lambda^2 + 3h_t^2 - \frac{8}{3}g_3^2 - \frac{3}{2}g_2^2 - \frac{13}{18}g_1^2)h_t$$

Why add extra stuff ?

$\alpha_3\uparrow$ at high energy

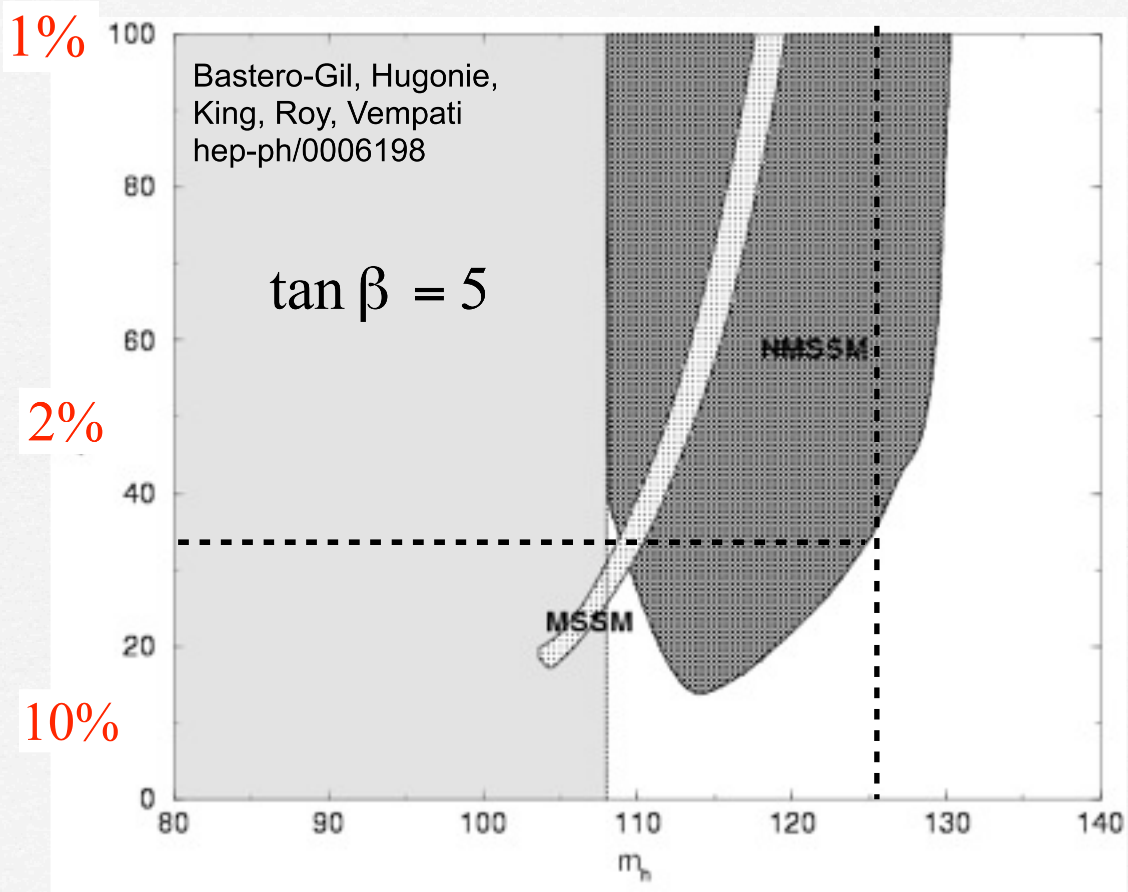
$h_t\downarrow$ at high energy

$\lambda\downarrow$ at high energy

Allows λ ~0.8 at low energy avoiding Landau Pole

Fine Tuning in NMSSM

Fine tuning



Bastero-Gil, Hugonie, King, Roy, Vempati hep-ph/0006198

For 125 GeV Higgs the MSSM fine tuning is much worse than in NMSSM

Recent analyses:
Ross et al;
Ellwanger et al

LEP favours NMSSM over MSSM (13 years ago)

LHC with Higgs @ 125 GeV strengthens conclusion

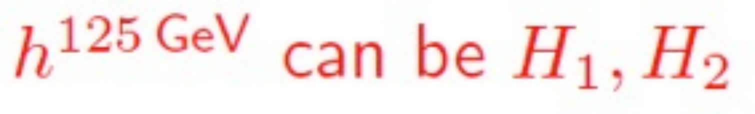
NMSSM Higgs Mixing

Spectrum has an extra complex singlet S giving an extra CP even H plus extra CP odd A compared to MSSM

CP even mass eigenstates

$$\begin{aligned} H_1 &= S_{1,d}\, H_d + S_{1,u}\, H_u + S_{1,s}\, S\ , \\ H_2 &= S_{2,d}\, H_d + S_{2,u}\, H_u + S_{2,s}\, S\ , \\ H_3 &= S_{3,d}\, H_d + S_{3,u}\, H_u + S_{3,s}\, S\ . \end{aligned}$$

H_1 or H_2 have reduced couplings due to the singlet component



$h^{125\text{ GeV}}$ can be H_1, H_2

CP odd mass eigenstates

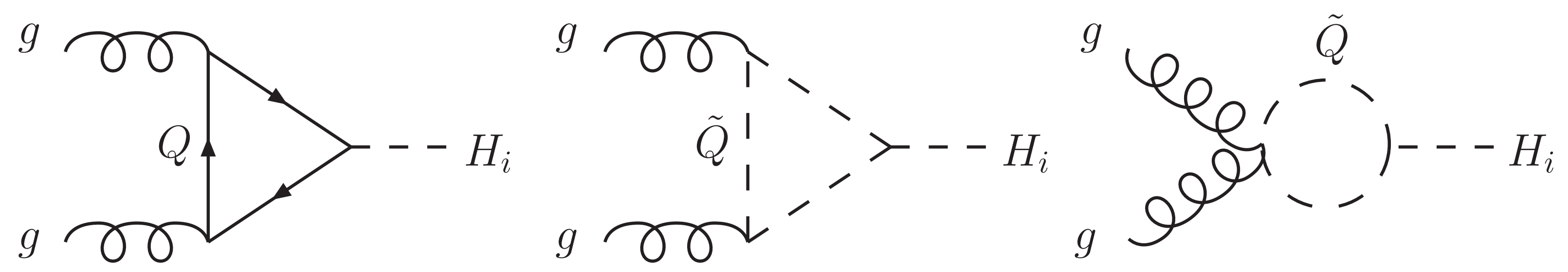
$$\begin{aligned} A_1^{\text{mass}} &= P'_{11} A + P'_{12} S_I\ , \\ A_2^{\text{mass}} &= P'_{21} A + P'_{22} S_I\ . \end{aligned}$$

$$A = \cos\beta\, H_{uI} + \sin\beta\, H_{dI}$$

NMSSM Higgs Phenomenology

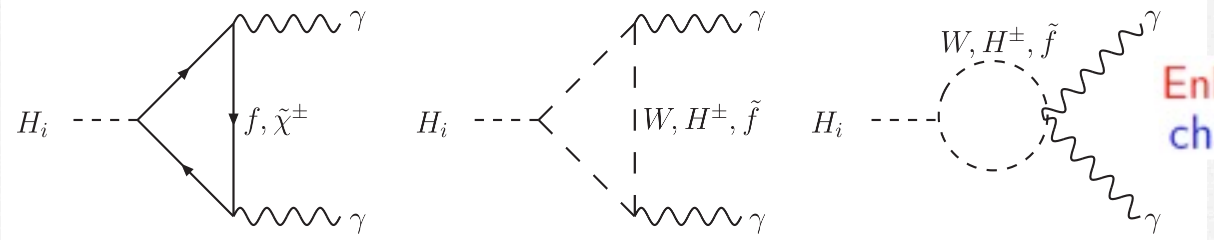
Enhanced gluon fusion production

Stop and sbottom loop contributions in $gg \to H_i$



$$BR(h^{125\,\text{GeV}} \to \gamma\gamma) = \frac{\Gamma(h^{125\,\text{GeV}} \to \gamma\gamma)}{(\Gamma_{b\bar{b}} + \Gamma_{WW} + \Gamma_{ZZ} + ...)[h^{125\,\text{GeV}}]}$$

Suppression of $\Gamma(h^{125\,\text{GeV}} \to b\bar{b})$ due to strong singlet-doublet mixing



Enhanced $\Gamma(h^{125\,\text{GeV}} \to \gamma\gamma)$ due to chargino loop contributions

Definitions

Production $R_{\sigma_{incl}}(H_i) \equiv \frac{\sigma_{incl}(H_i)}{\sigma_{incl}(H^{\rm SM})} \approx R_{\sigma_{gg}}(H_i)$ $\quad R_{\sigma_{gg}}(H_i) \equiv \frac{\sigma(gg \to H_i)}{\sigma(gg \to H^{\rm SM})}$

$$R_{\Gamma_{XX}}(H_i) \equiv \frac{\Gamma(H_i \to XX)}{\Gamma(H^{\rm SM} \to XX)}$$

Decay $R^{BR}_{XX}(H_i) \equiv \frac{BR(H_i \to XX)}{BR(H^{\rm SM} \to XX)} = \frac{R_{\Gamma_{XX}}(H_i)}{R_{\Gamma_{tot}}(H_i)}$

$$R_{\Gamma_{tot}}(H_i) \equiv \frac{\Gamma_{tot}(H_i)}{\Gamma_{tot}(H^{\rm SM})}$$

$$R_{\gamma\gamma}(H_i) \equiv R_{\sigma_{incl}}(H_i) R^{BR}_{\gamma\gamma}(H_i) \qquad R_{b\bar{b}}(H_i) \equiv R_{\sigma_{incl}}(H_i) R^{BR}_{b\bar{b}}(H_i)$$

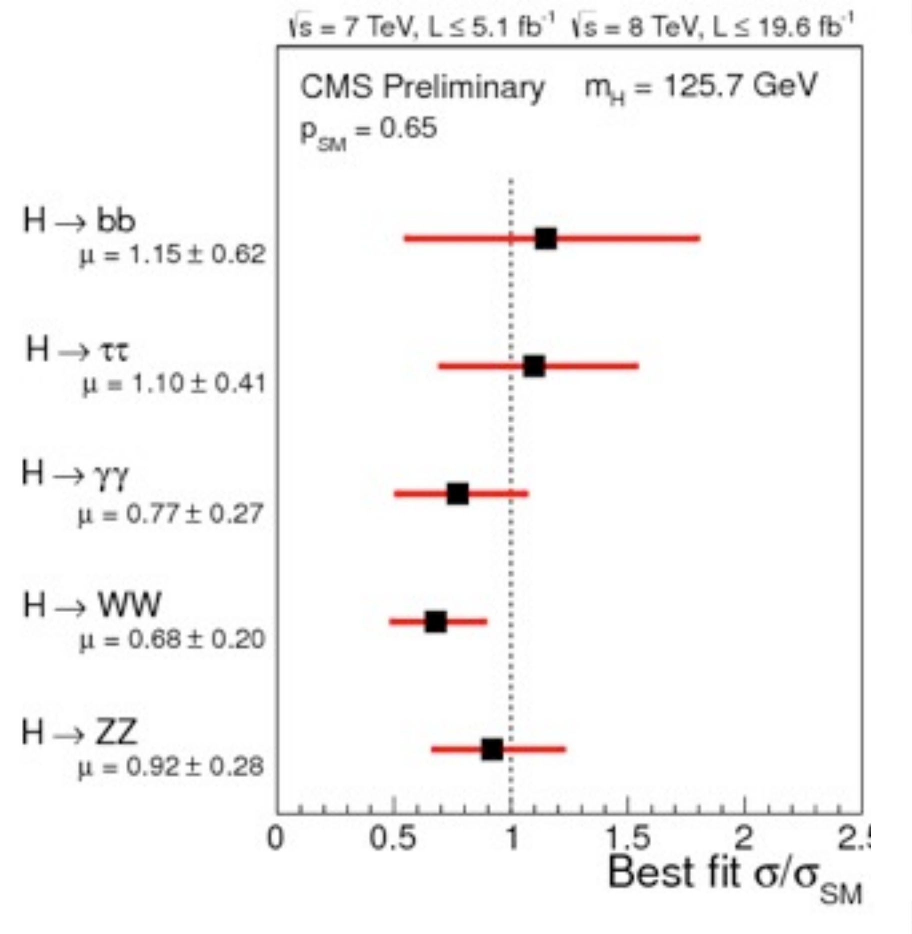
$$R_{VV}(H_i) \equiv R_{\sigma_{incl}}(H_i) R^{BR}_{VV}(H_i) \qquad R_{\tau\bar{\tau}} \equiv R_{\sigma_{incl}}(H_i) R^{BR}_{\tau\bar{\tau}}(H_i)$$

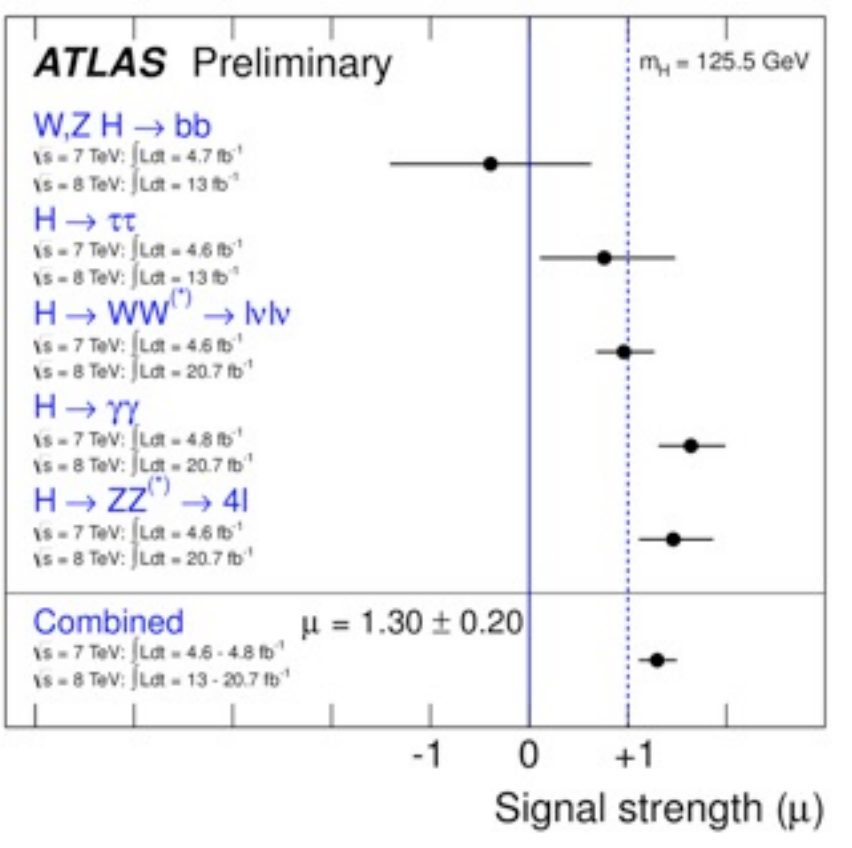
$$\mu_{XX}(h) \equiv R_\sigma(h) R^{BR}_{XX}(h) + \sum_{\substack{\Phi \neq h \\ |M_\Phi - M_h| \leq \delta}} R_\sigma(\Phi) R^{BR}_{XX}(\Phi) F(M_h, M_\Phi, d_{XX})$$

Gaussian weighting function

NMSSM Tools

LHC Data


√s = 7 TeV, L ≤ 5.1 fb⁻¹ √s = 8 TeV, L ≤ 19.6 fb⁻¹
CMS Preliminary m_H = 125.7 GeV
p_SM = 0.65
H → bb
μ = 1.15 ± 0.62
H → ττ
μ = 1.10 ± 0.41
H → γγ
μ = 0.77 ± 0.27
H → WW
μ = 0.68 ± 0.20
H → ZZ
μ = 0.92 ± 0.28
0
0.5
1
1.5
2
2.
Best fit σ/σ_SM


ATLAS Preliminary
m_H = 125.5 GeV
W,Z H → bb
√s = 7 TeV: ∫Ldt = 4.7 fb⁻¹
√s = 8 TeV: ∫Ldt = 13 fb⁻¹
H → ττ
√s = 7 TeV: ∫Ldt = 4.6 fb⁻¹
√s = 8 TeV: ∫Ldt = 13 fb⁻¹
H → WW(*) → lνlν
√s = 7 TeV: ∫Ldt = 4.6 fb⁻¹
√s = 8 TeV: ∫Ldt = 20.7 fb⁻¹
H → γγ
√s = 7 TeV: ∫Ldt = 4.8 fb⁻¹
√s = 8 TeV: ∫Ldt = 20.7 fb⁻¹
H → ZZ(*) → 4l
√s = 7 TeV: ∫Ldt = 4.6 fb⁻¹
√s = 8 TeV: ∫Ldt = 20.7 fb⁻¹
Combined
μ = 1.30 ± 0.20
√s = 7 TeV: ∫Ldt = 4.6 - 4.8 fb⁻¹
√s = 8 TeV: ∫Ldt = 13 - 20.7 fb⁻¹
-1
0
+1
Signal strength (μ)

Natural NMSSM Higgs Bosons

King, Muhlleitner, Nevzorov, Walz 1211.5074

- ☐ We perform a scan over parameter space in the low fine-tuning region

$$100 \text{ GeV} \le \mu_{\text{eff}} \le 200 \text{ GeV}$$

$$0.55 \le \lambda \le 0.8 \quad \text{and} \quad 10^{-4} \le \kappa \le 0.4$$

$$-500 \text{ GeV} \le A_\kappa \le 0 \text{ GeV} \quad \text{and} \quad 200 \text{ GeV} \le A_\lambda \le 800 \text{ GeV}$$

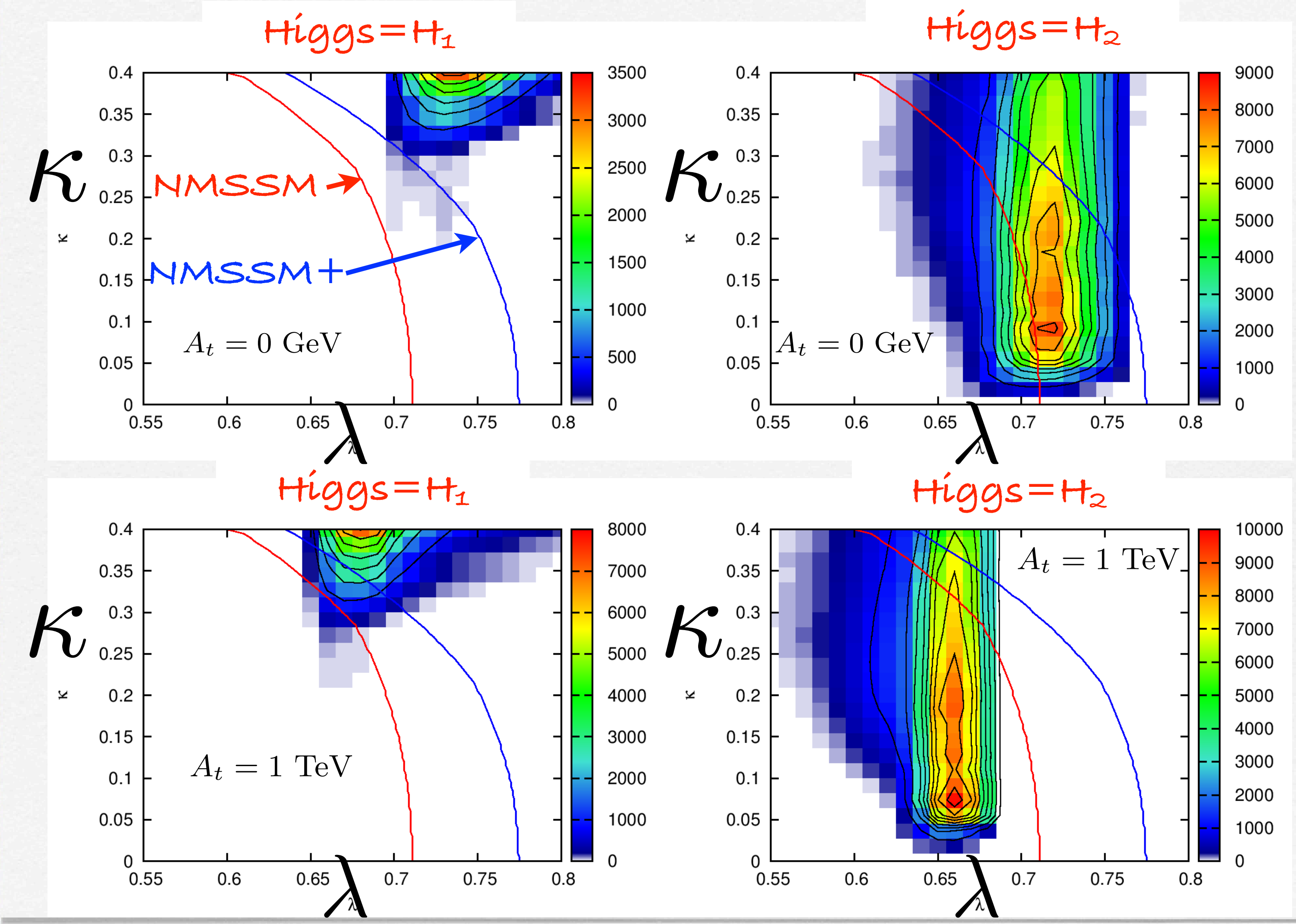
$$500 \text{ GeV} \le M_{\tilde{Q}_3} = M_{\tilde{t}_R} \le 800 \text{ GeV} \qquad A_U = 0 \text{ GeV} \quad \text{and} \quad 1 \text{ TeV}$$

$$m_{\tilde{t}_1} \;=\; 400 - 820 \text{ GeV}\,, \quad m_{\tilde{t}_2} = 530 - 890 \text{ GeV}\,, \qquad \tan\beta = 2$$

$$M_{H^\pm} \;=\; 200 - 500 \text{ GeV}\,, \quad M_{\tilde{\chi}_1^\pm} = 105 - 165 \text{ GeV}\,, \quad M_{\tilde{\chi}_2^\pm} = 345 - 360 \text{ GeV}$$

$$M_{\tilde{u}_R} = M_{\tilde{c}_R} = M_{\tilde{D}_R} = M_{\tilde{Q}_{1,2}} = M_{\tilde{e}_R} = M_{\tilde{\mu}_R} = M_{\tilde{L}_{1,2}} = 2.5 \text{ TeV},$$
$$M_{\tilde{\tau}_R} = M_{\tilde{L}_3} = 300 \text{ GeV}\,, \quad A_D = A_E = 1 \text{ TeV}\,. \quad M_3 = 1 \text{ TeV}$$

λ - κ in NMSSM and NMSSM+



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Nevzorov, Walz
1211.5074

Colour coding is number of points in scan

Higgs spectrum in NMSSM

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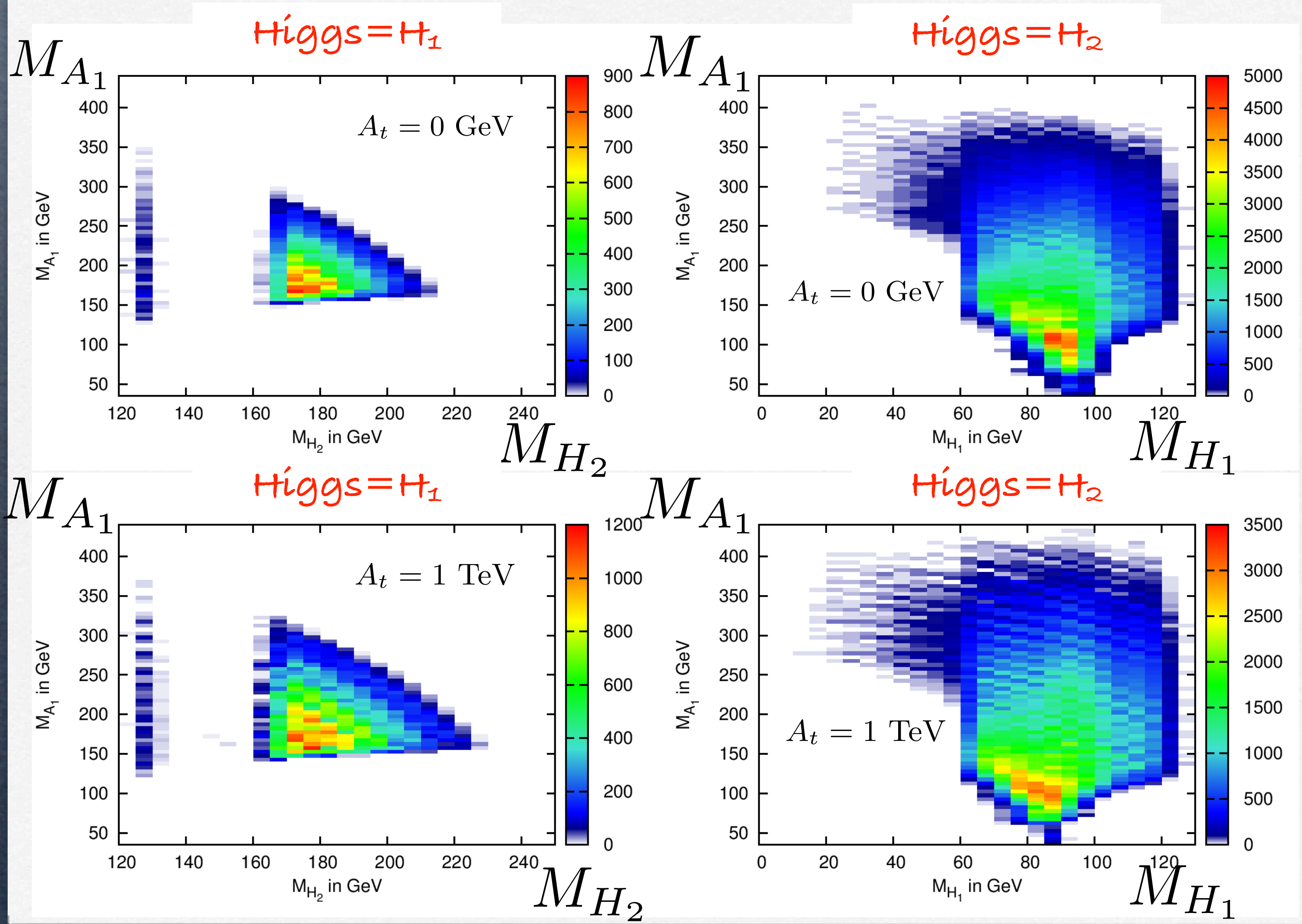
Nevzorov, Walz
1211.5074



Colour coding is number of points

Higgs →diphotons in NMSSM

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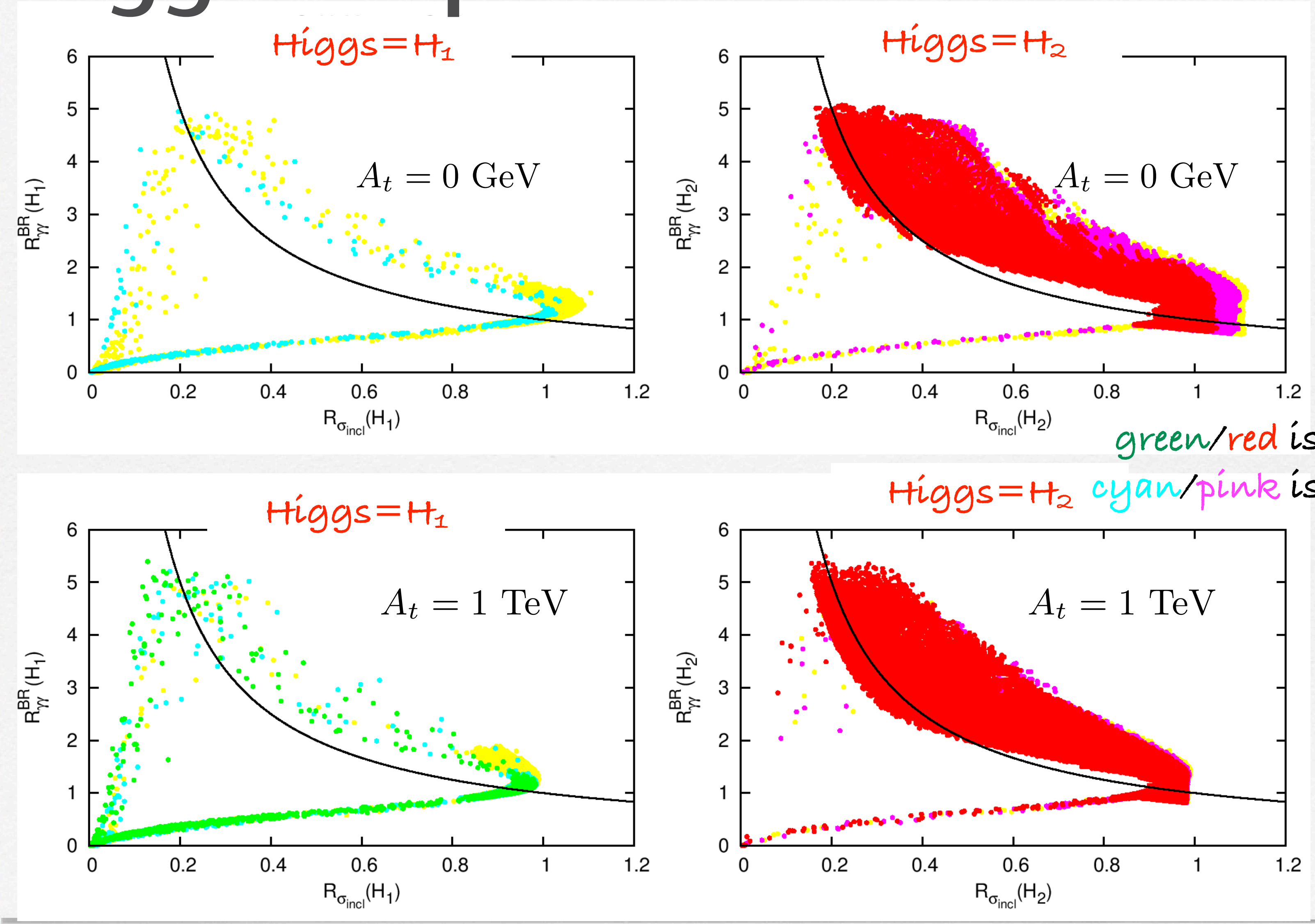
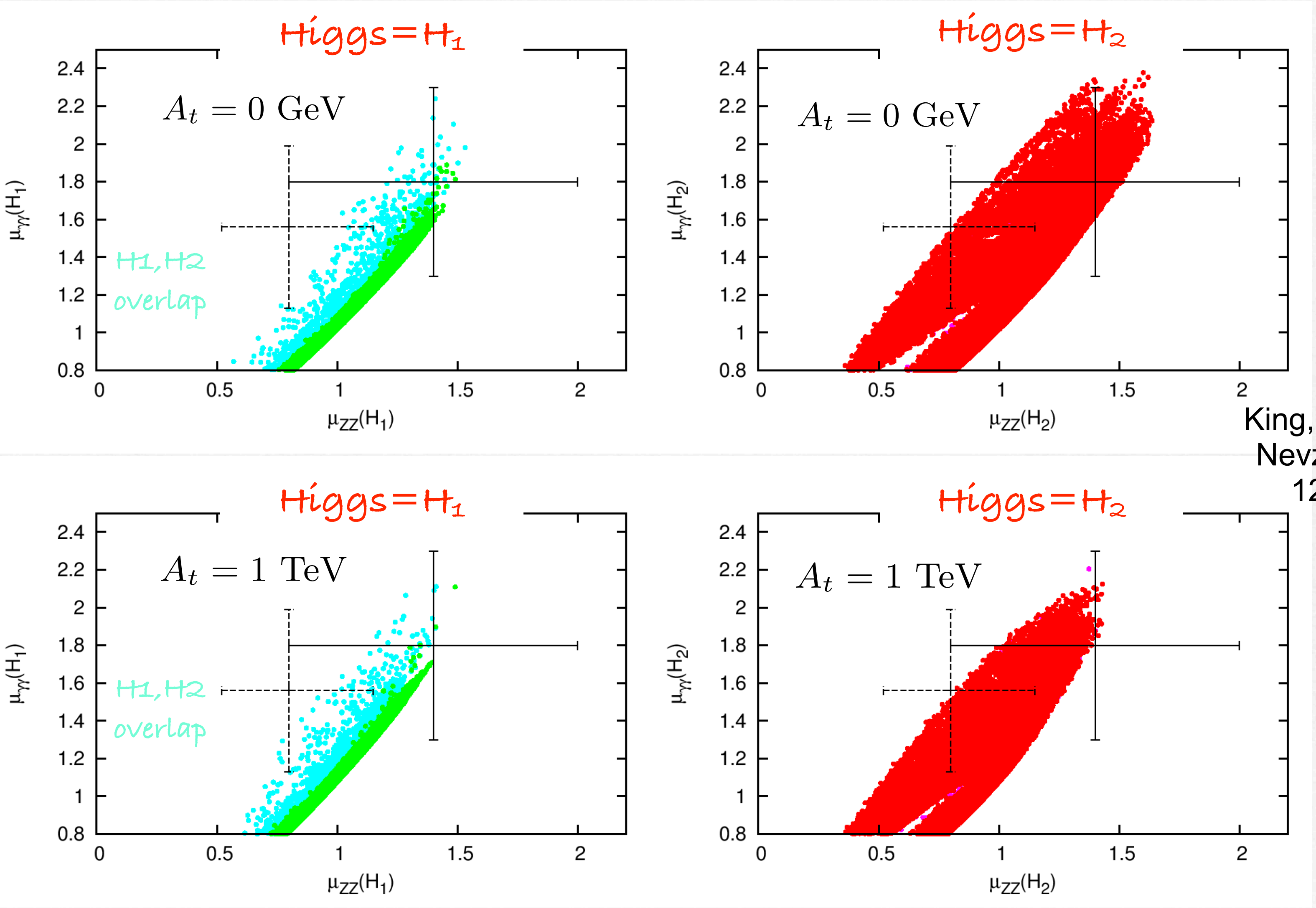
Nevzorov, Walz
1211.5074



green/red is NMSSM

cyan/pink is NMSSM+

Diphoton vs. ZZ decays in NMSSM



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1211.5074

Diphoton vs. WW decays

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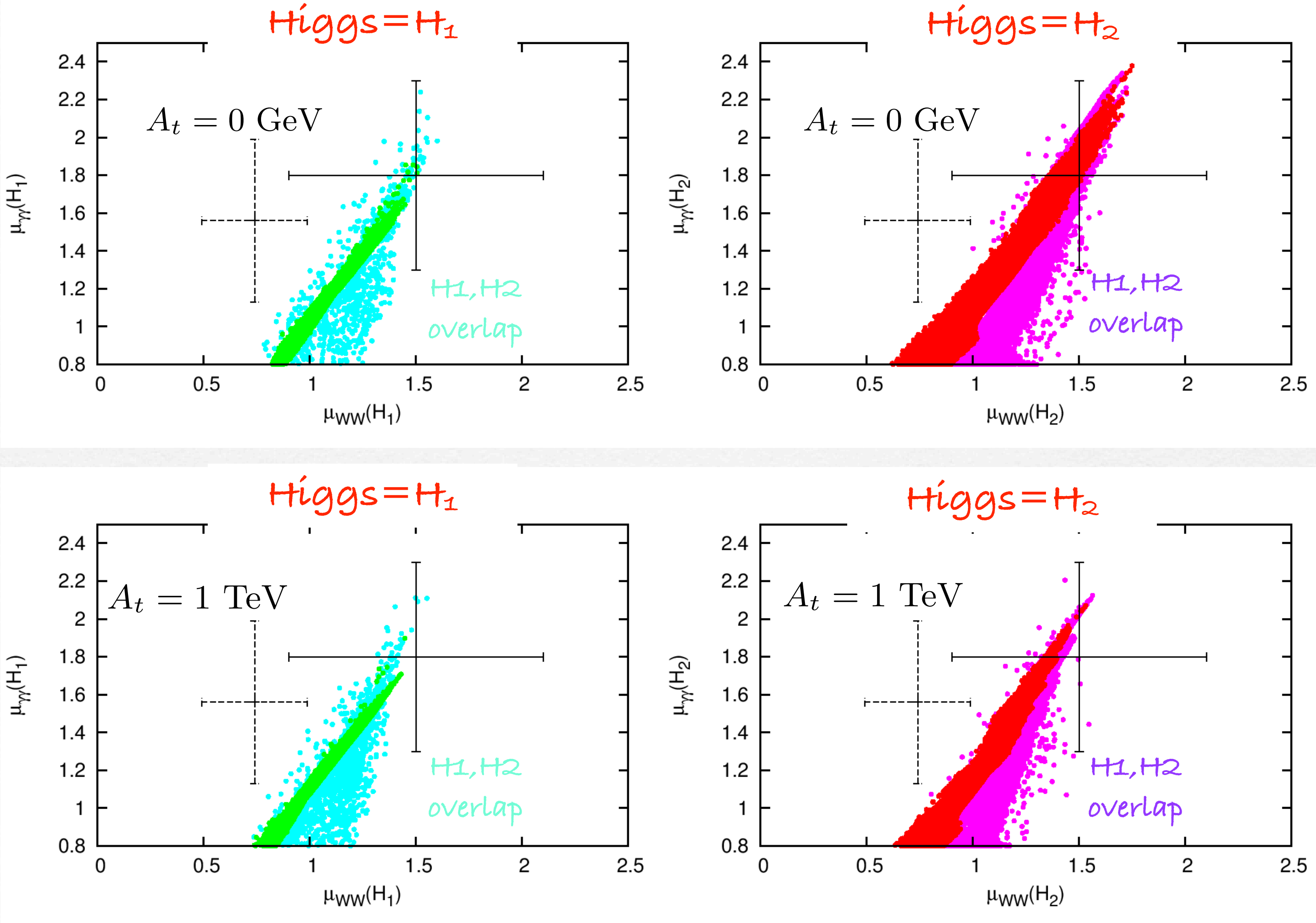
Nevzorov, Walz
1211.5074



Diphoton vs. bb decays

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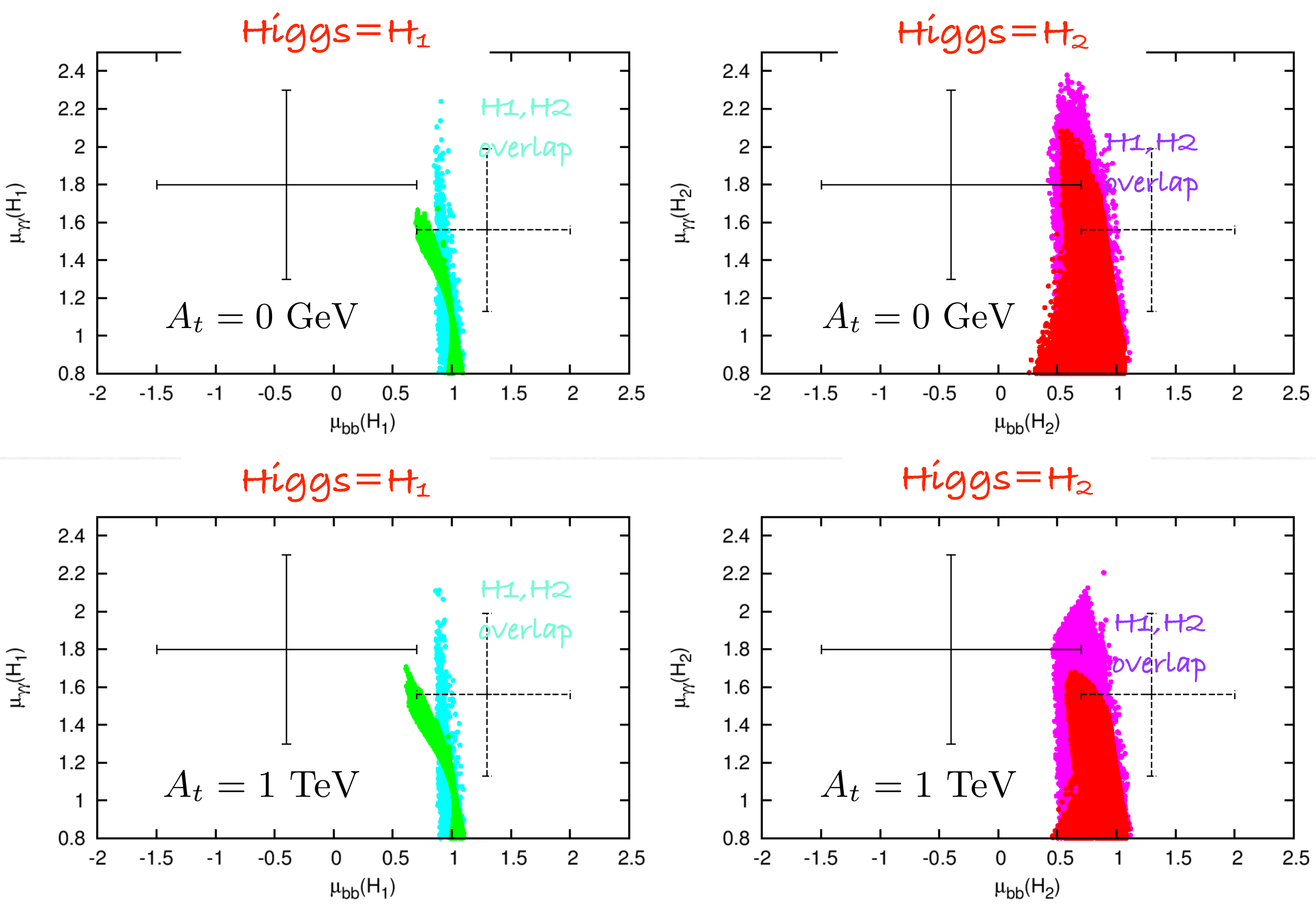
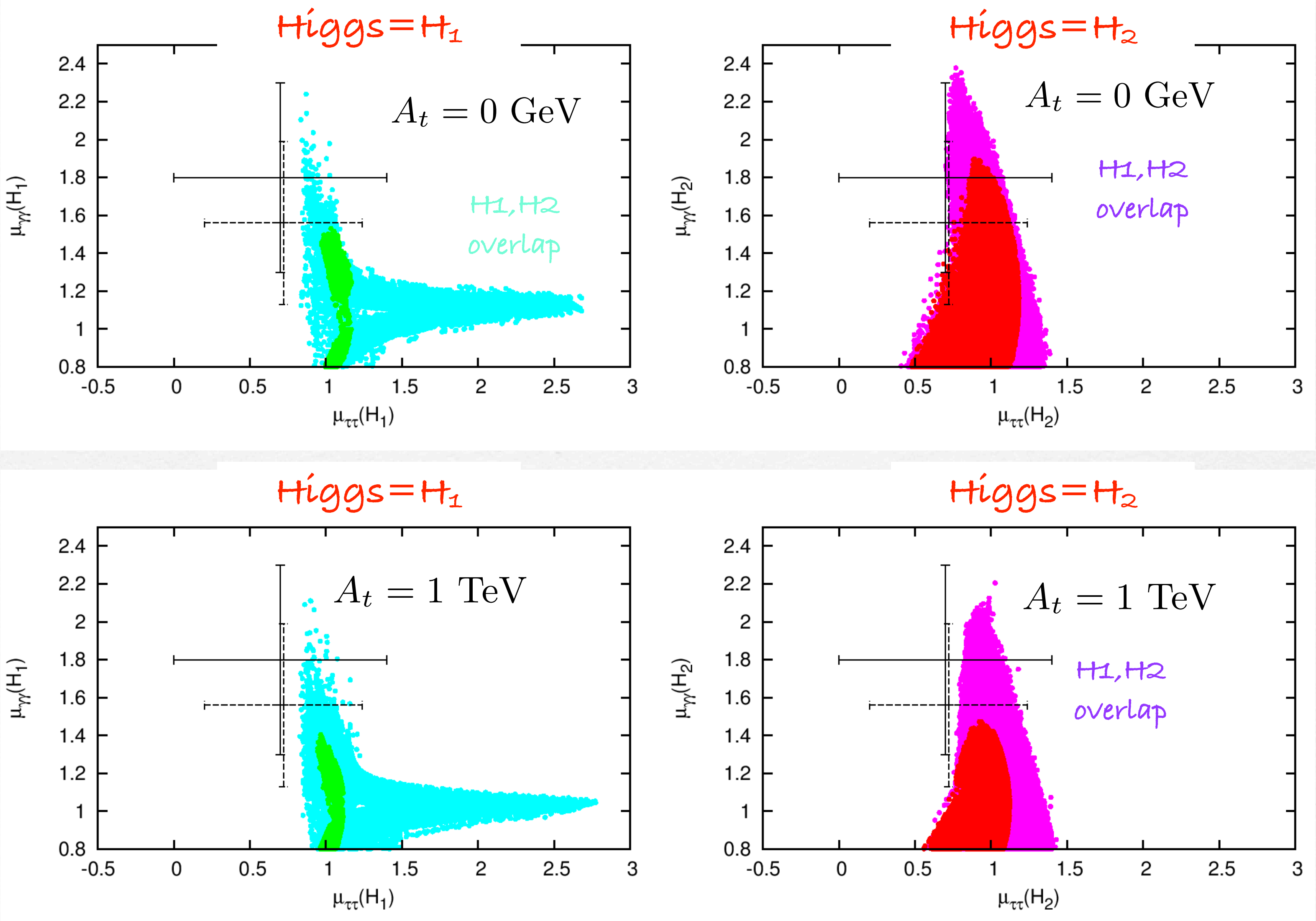
Nevzorov, Walz
1211.5074



Diphoton vs. tau decays

King, Muhlleitner,
Nevzorov, Walz
1211.5074



Two Smoking Barrels of NMSSM

King, Muhlleitner,
Nevzorov, Walz
1211.5074

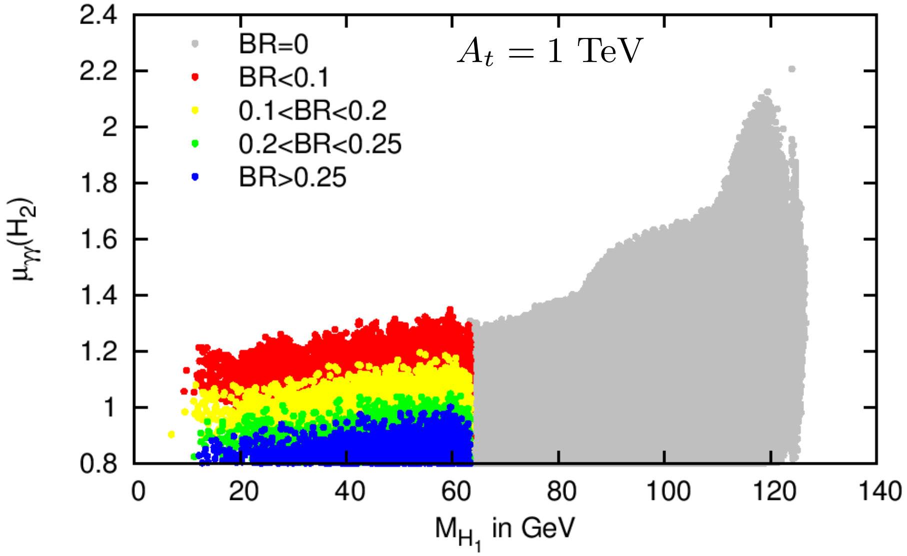
$$H_2 \rightarrow H_1 H_1$$

$$\rightarrow bbbb, bb\tau\tau, \tau\tau\tau\tau$$

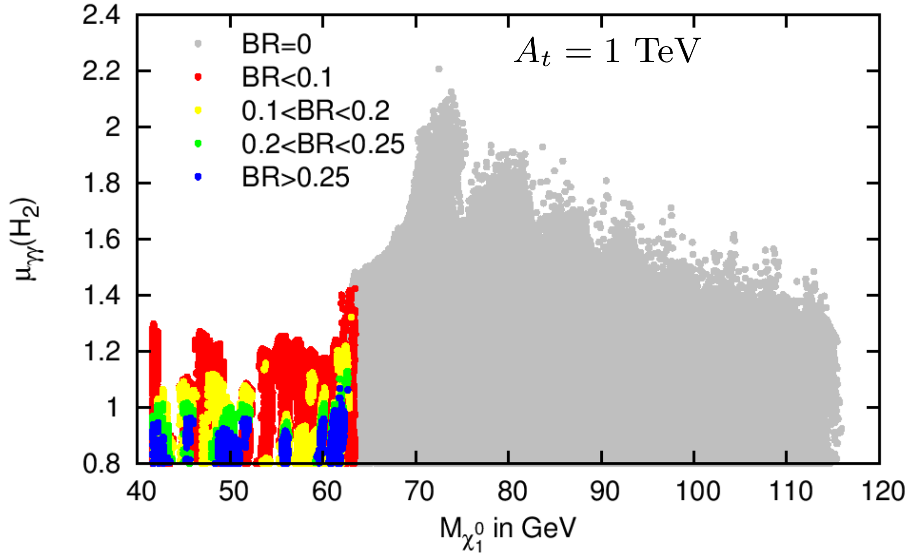
$$H_2 \rightarrow \chi_1^0 \chi_1^0$$

invisible Higgs decays

Higgs=H_2



Higgs=H_2



$$BR_{H_2}^{\max}(H_1 H_1) \approx 0.36 \text{ and } BR_{H_2}^{\max}(\tilde{\chi}_1^0 \tilde{\chi}_1^0) \approx 0.43$$

Beyond the (N)MSSM

More general SUSY models

Focus on models which provide a dynamical origin of μ term:

SH_uH_d where singlet $<S> \sim \mu \sim$ TeV

Danger from weak scale axion due to global U(1) symmetry

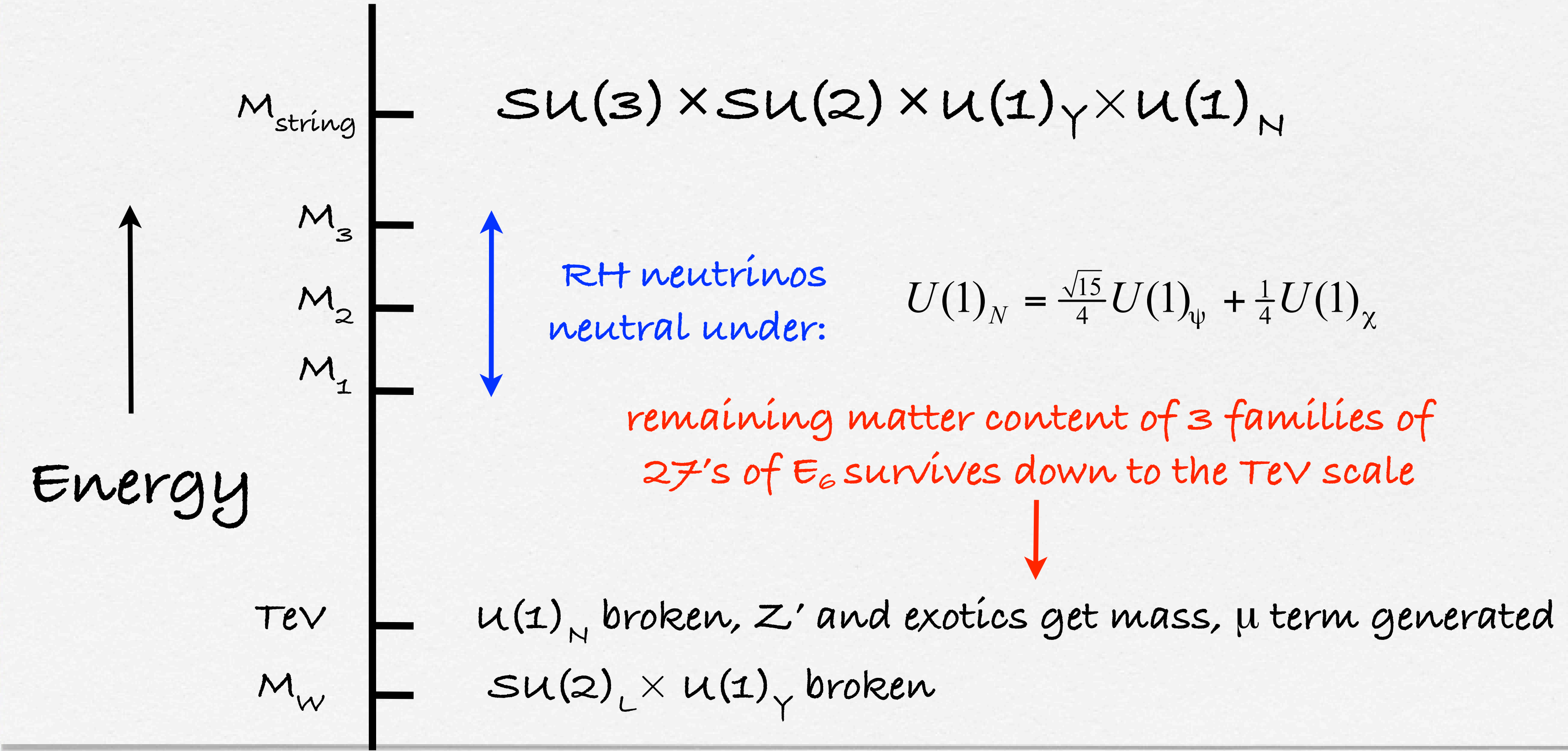
Need to avoid axion somehow

- In NMSSM we add S^3 to break U(1) to Z_3 – but this results in cosmological domain walls (μS^2, $\mu^2 S$ reintroduces μ problem)
- In E_6SSM we gauge the U(1) symmetry to eat the axion resulting in a massive Z' gauge boson - anomalies are cancelled by three complete 27's of E_6 at the TeV scale with $U(1) \in E_6$

King, Moretti, Nevzorov

Exceptional SUSY SM (E$_6$SSM)

$$E_6 \to SO(10) \times U(1)_\psi \qquad SO(10) \to SU(5) \times U(1)_\chi$$



$SU(3)\times SU(2)\times U(1)_Y\times U(1)_N$

RH neutrinos neutral under: $U(1)_N = \frac{\sqrt{15}}{4}U(1)_\psi + \frac{1}{4}U(1)_\chi$

remaining matter content of 3 families of 27's of E$_6$ survives down to the TeV scale

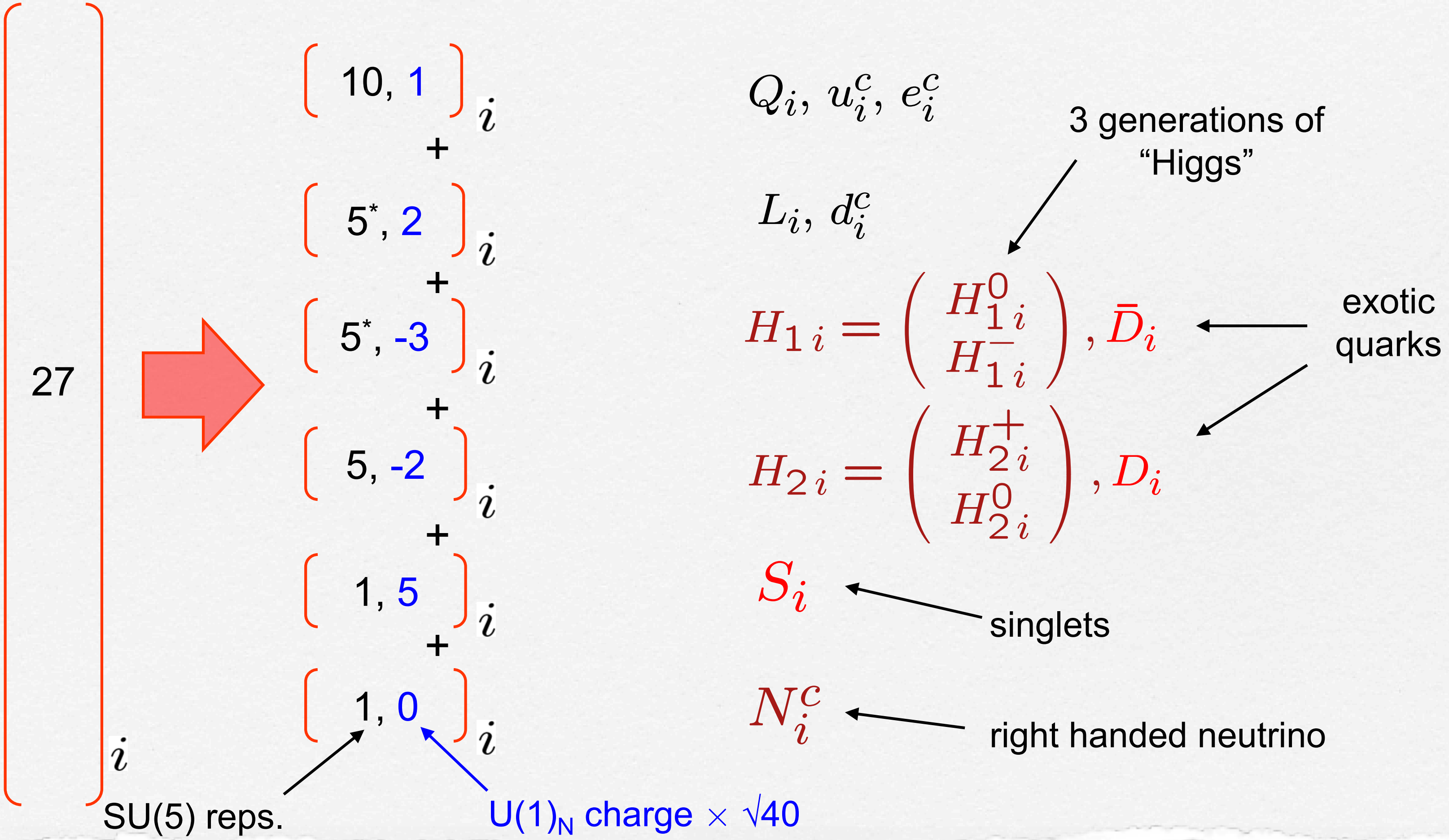
$U(1)_N$ broken, Z′ and exotics get mass, μ term generated

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

Matter Content of 27’s of E_6

Miller

All the SM matter fields are contained in one 27-plet of E_6 per generation.



$$\left(27\right)_i \Rightarrow \left(10, 1\right)_i + \left(5^*, 2\right)_i + \left(5^*, -3\right)_i + \left(5, -2\right)_i + \left(1, 5\right)_i + \left(1, 0\right)_i$$

$$Q_i,\ u_i^c,\ e_i^c$$

$$L_i,\ d_i^c$$

$$H_{1\,i} = \begin{pmatrix} H_{1\,i}^0 \\ H_{1\,i}^- \end{pmatrix},\ \bar{D}_i$$

$$H_{2\,i} = \begin{pmatrix} H_{2\,i}^+ \\ H_{2\,i}^0 \end{pmatrix},\ D_i$$

$$S_i$$

$$N_i^c$$

3 generations of “Higgs”

exotic quarks

singlets

right handed neutrino

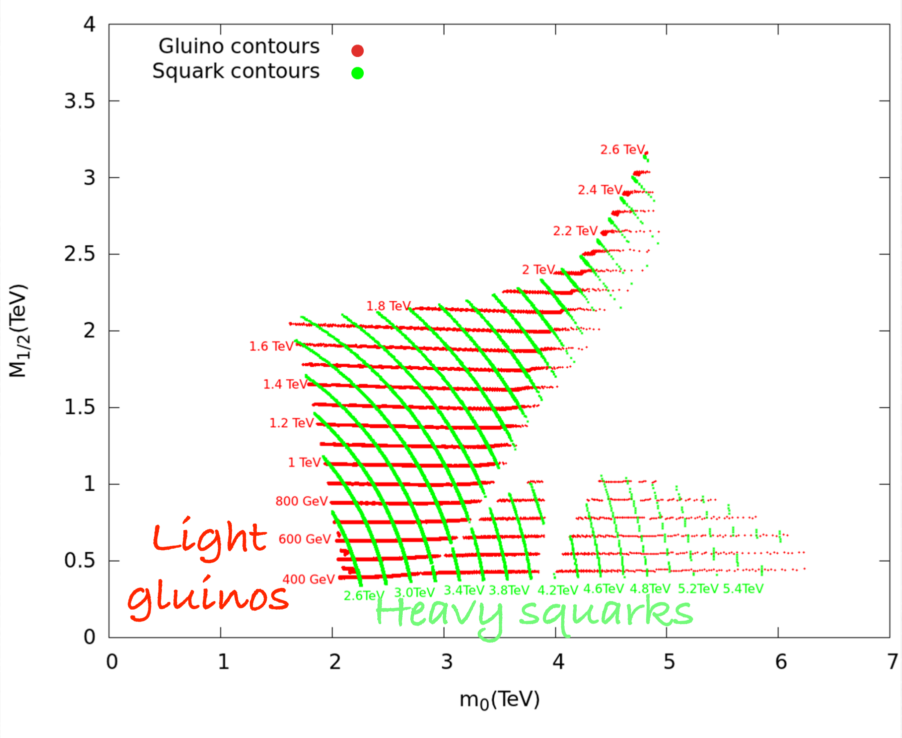
SU(5) reps.

$U(1)_N$ charge × √40

The Constrained E6SSM

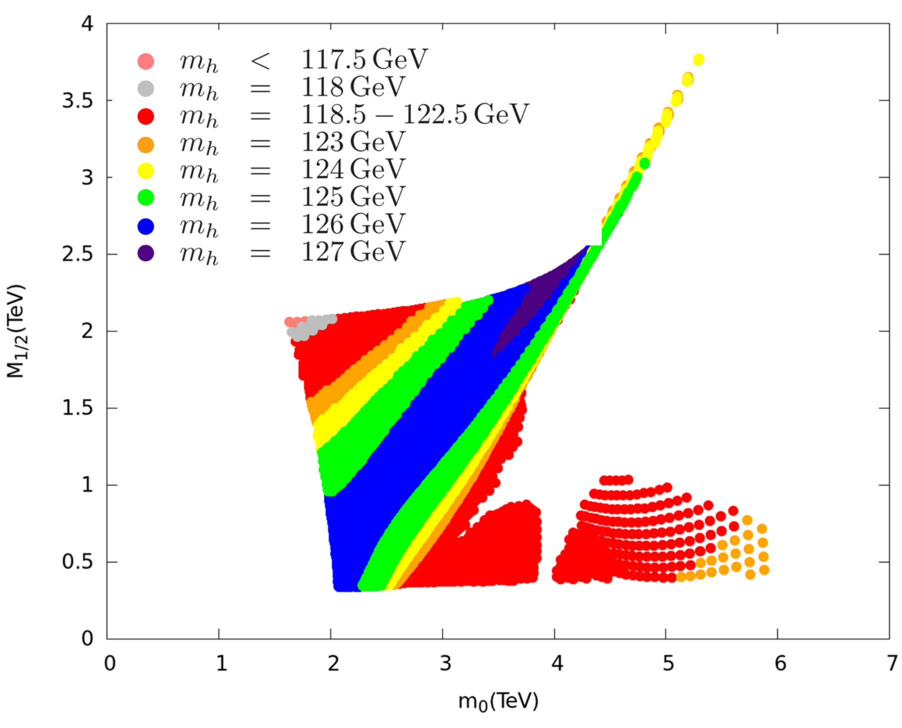
Athron, King, Miller, Moretti, Nevzorov

$$\tan\beta = 10,\ \lambda_{12} = 0.1,\ s = 10\ \mathrm{TeV},$$



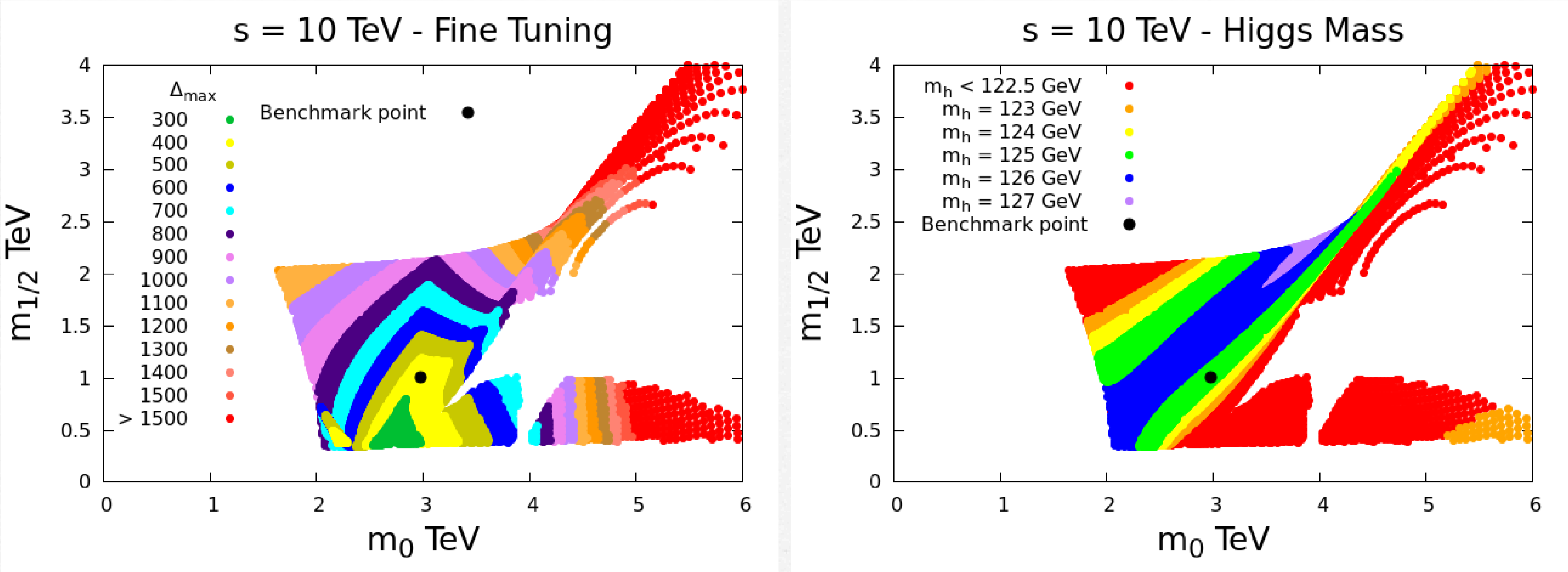
Light gluinos

Heavy squarks



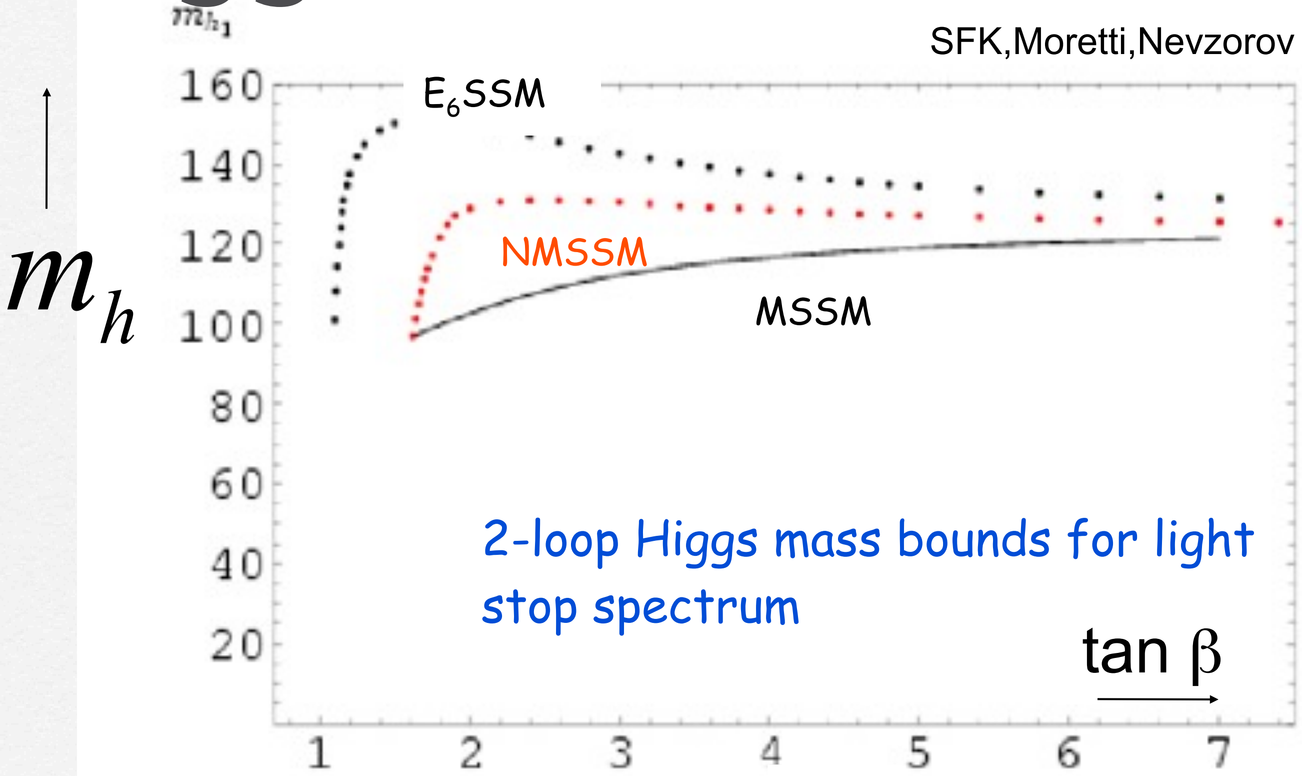
Fine-tuning in the cE6SSM

$\tan\beta = 10,\ \lambda_{12} = 0.1,\ s = 10\ \text{TeV},$ Athron, Binjonaid, King



Lower fine-tuning than cMSSM

Higgs mass bounds in SSM's



SFK,Moretti,Nevzorov hep-ph/0510419

2-loop Higgs mass bounds for light stop spectrum

$$m_h^2 \approx \underbrace{\underbrace{\underbrace{M_Z^2\cos^2 2\beta}_{MSSM} + \frac{\lambda^2}{2}v^2\sin^2 2\beta}_{NMSSM} + \frac{M_Z^2}{4}\left(1+\frac{1}{4}\cos 2\beta\right)^2}_{E_6SSM} + \Delta m_h^2$$

Extra terms in non-minimal models allow

$$\Delta m_h < M_Z$$

Hence allow lighter stops and lower fine-tuning

LHC phenomenology of E_6SSM

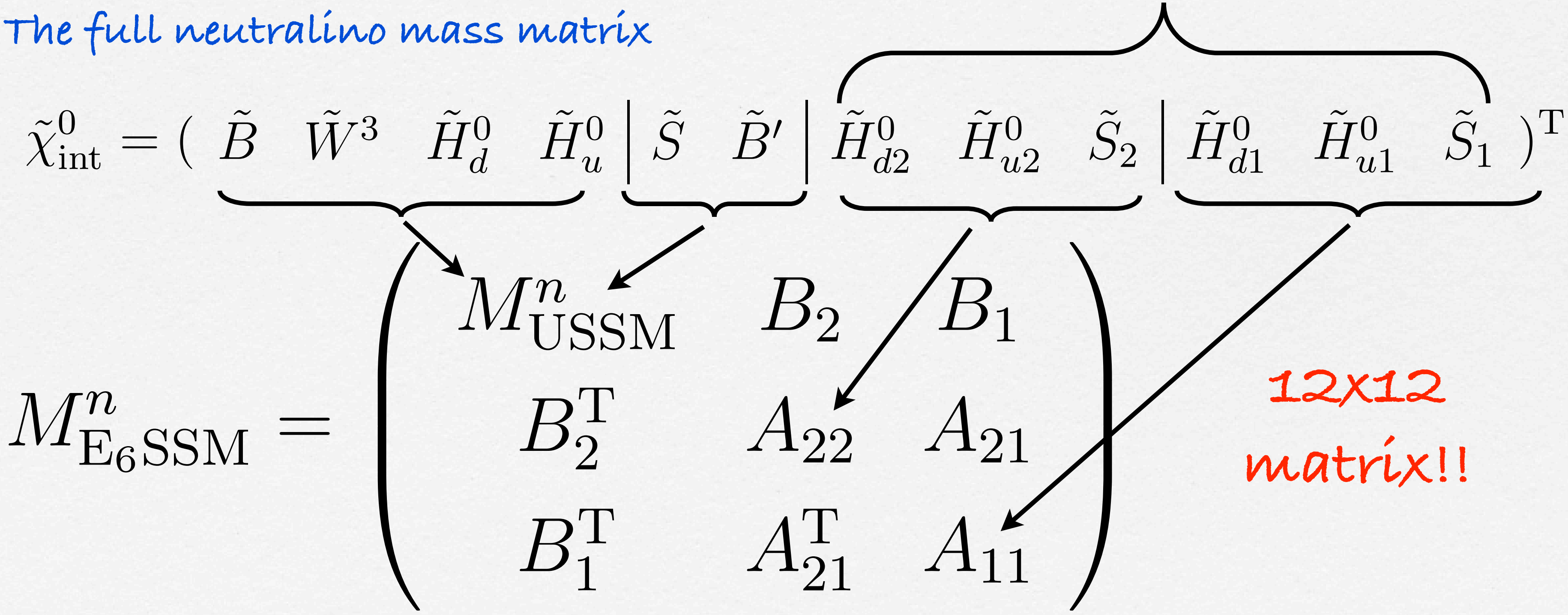
- SUSY - typical spectrum has heavier squarks and lighter gluinos, with gluinos having longer decay chains than MSSM, due to extra neutralinos and charginos, giving less missing energy and more soft leptons and jets
- Higgs - Richer Higgs spectrum than MSSM or NMSSM (incl. inert Higgs)
- Exotics - Z', D-leptoquarks/diquarks

Neutralinos in E_6SSM

Hall, King

- ☐ 3 Higgs families = 1 MSSM family H_u H_d + 2 inert families H_{u1} H_{d1} H_{u2} H_{d2}
- ☐ 3 families of Singlets = 1 NMSSM singlet S + 2 inert singlets S_1 S_2

The full neutralino mass matrix



$$\tilde{\chi}^0_{\rm int} = (\underbrace{\tilde{B} \quad \tilde{W}^3 \quad \tilde{H}^0_d \quad \tilde{H}^0_u} \,|\, \underbrace{\tilde{S} \quad \tilde{B}'} \,|\, \overbrace{\underbrace{\tilde{H}^0_{d2} \quad \tilde{H}^0_{u2} \quad \tilde{S}_2} \,|\, \underbrace{\tilde{H}^0_{d1} \quad \tilde{H}^0_{u1} \quad \tilde{S}_1}})^{\rm T}$$

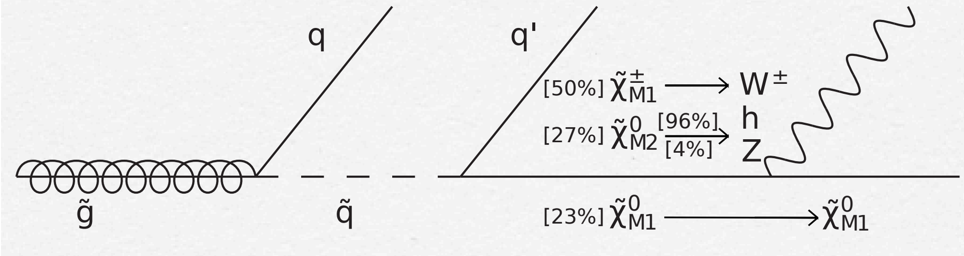
$$M^n_{\rm E_6SSM} = \begin{pmatrix} M^n_{\rm USSM} & B_2 & B_1 \\ B_2^{\rm T} & A_{22} & A_{21} \\ B_1^{\rm T} & A_{21}^{\rm T} & A_{11} \end{pmatrix}$$

12x12 matrix!!

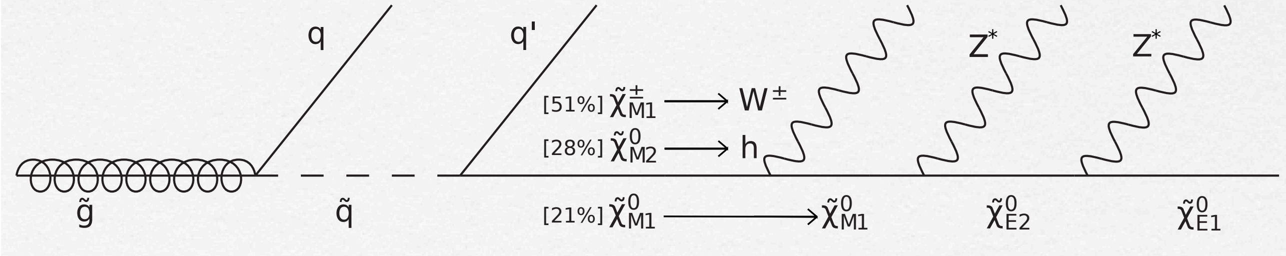
Belyaev, Hall,
King, Svantesson

Longer decay chains

MSSM:



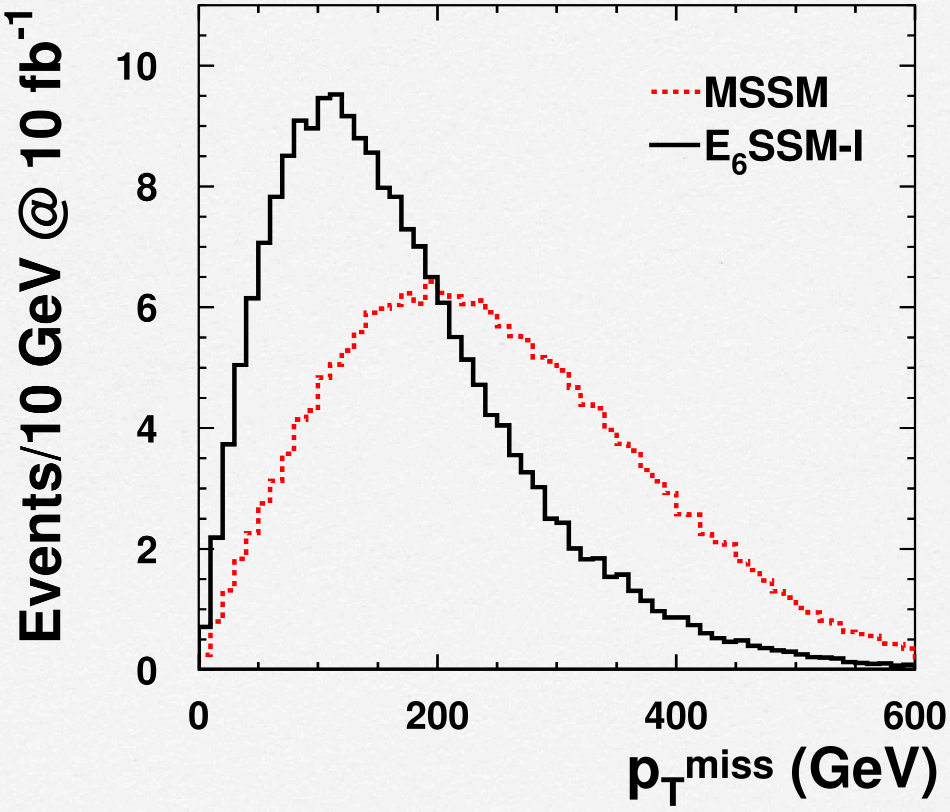
E_6SSM:



Bino can decay into inert neutralinos

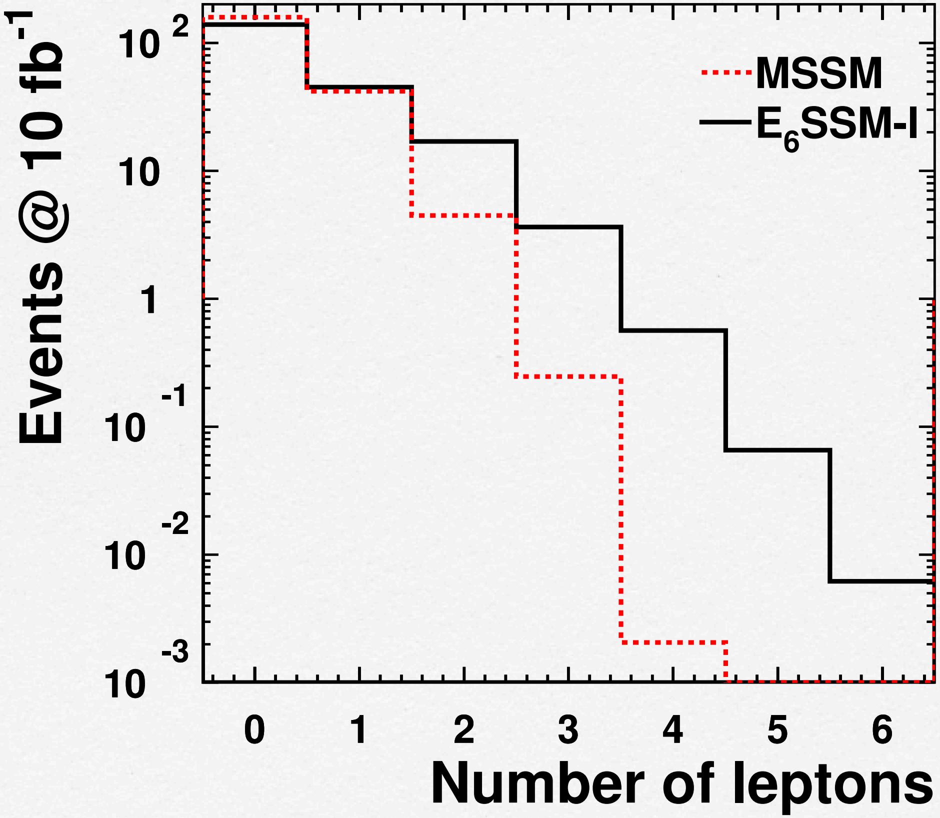
Belyaev, Hall,
King, Svantesson

Less missing p_T



Belyaev, Hall,
King, Svantesson

More leptons



Hall, King

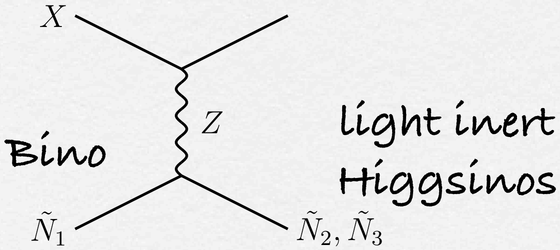
Maybe inert singlinos decoupled

$$\tilde{N}_{\rm int} = \left(\begin{array}{cccccc|cc} \tilde{B} & \tilde{W}^3 & \tilde{H}^0_{d3} & \tilde{H}^0_{u3} & \tilde{S}_3 & \tilde{B}' & \tilde{H}^0_{d\alpha} & \tilde{H}^0_{u\beta} \end{array} \right)^T$$

$$\left(\begin{array}{cccccc|cc}
M_1 & 0 & -\frac{1}{2}g'v_d & \frac{1}{2}g'v_u & & & & \\
0 & M_2 & \frac{1}{2}gv_d & -\frac{1}{2}gv_u & & & & \\
-\frac{1}{2}g'v_d & \frac{1}{2}gv_d & 0 & -\mu & -\frac{\lambda_{333}v_u}{\sqrt{2}} & Q_d g'_1 v_d & 0 & -\frac{\lambda_{33\beta}s}{\sqrt{2}} \\
\frac{1}{2}g'v_u & -\frac{1}{2}gv_u & -\mu & 0 & -\frac{\lambda_{333}v_d}{\sqrt{2}} & Q_u g'_1 v_u & -\frac{\lambda_{3\alpha 3}s}{\sqrt{2}} & 0 \\
 & & -\frac{\lambda_{333}v_u}{\sqrt{2}} & -\frac{\lambda_{333}v_d}{\sqrt{2}} & 0 & Q_S g'_1 s & -\frac{\lambda_{3\alpha 3}v_u}{\sqrt{2}} & -\frac{\lambda_{33\beta}v_d}{\sqrt{2}} \\
 & & Q_d g'_1 v_d & Q_u g'_1 v_u & Q_S g'_1 s & M'_1 & & \\
\hline
 & & 0 & -\frac{\lambda_{3\alpha 3}s}{\sqrt{2}} & -\frac{\lambda_{3\alpha 3}v_u}{\sqrt{2}} & & 0 & -\frac{\lambda_{3\alpha\beta}s}{\sqrt{2}} \\
 & & -\frac{\lambda_{33\beta}s}{\sqrt{2}} & 0 & -\frac{\lambda_{33\beta}v_d}{\sqrt{2}} & & -\frac{\lambda_{3\alpha\beta}s}{\sqrt{2}} & 0
\end{array} \right)$$

⇨ Bino dark matter

correct relic abundance



low DD cross-section

$\sigma_{\rm SI} \sim$ few $\times 10^{-11}$pb

massless $\tilde{S}_{1,2}$ ⇨ dark radiation

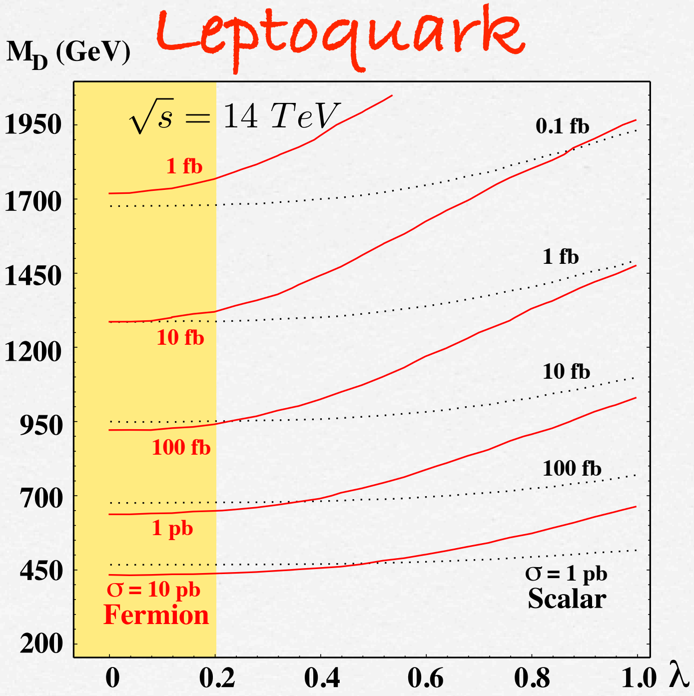
$N_{eff} \approx 3.2$ c.f. $N_{\rm eff}^{\rm Planck} = 3.36 \pm 0.34$

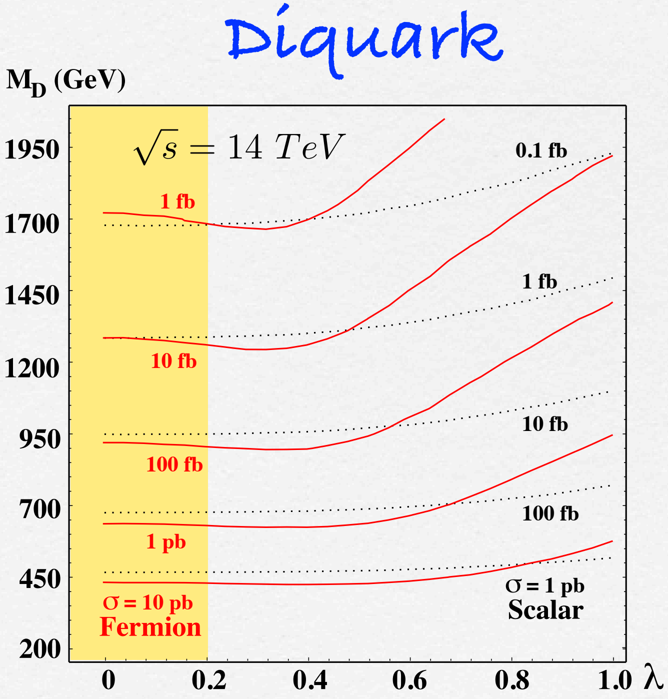
Exotic D-particles

Kang, Langacker, Nelson

D-particles are coloured and may be pair produced at LHC

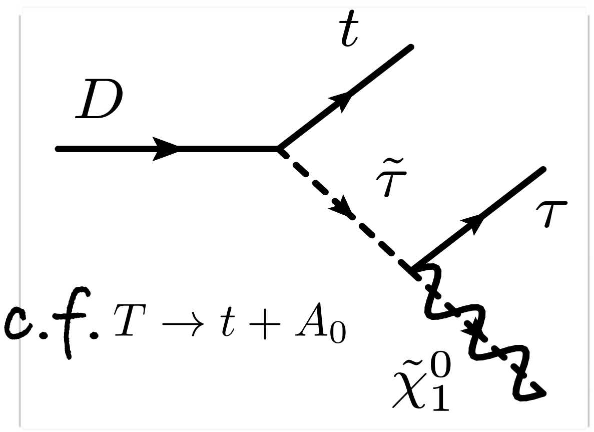
D-particles may be Leptoquarks D→LQ or Diquarks D→QQ


Leptoquark


Diquark

D-fermion decays

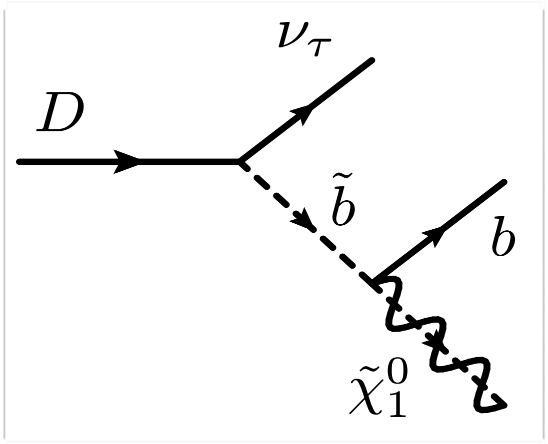
Leptoquark



c.f. $T \to t + A_0$

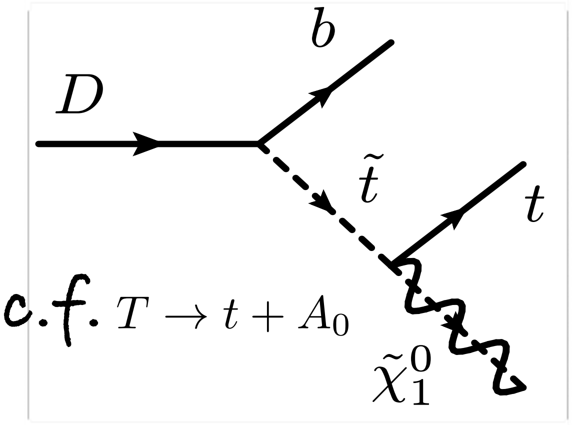
$$pp \to t\bar{t}\tau^+\tau^- + E_T^{miss} + X$$

Leptoquark



$$pp \to b\bar{b} + E_T^{miss} + X$$

Diquark

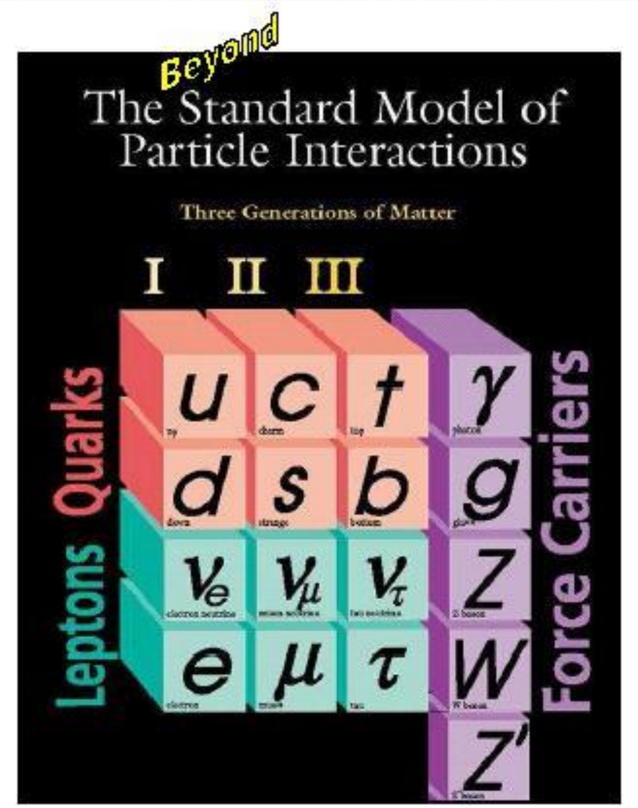


c.f. $T \to t + A_0$

$$pp \to t\bar{t}b\bar{b} + E_T^{miss} + X$$

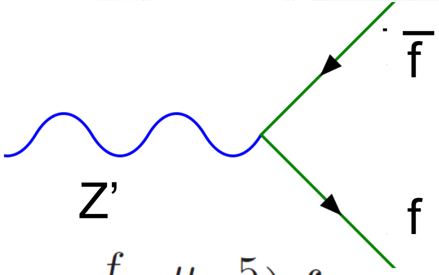
spectacular signals!

Z' physics



Spin-1 Z'

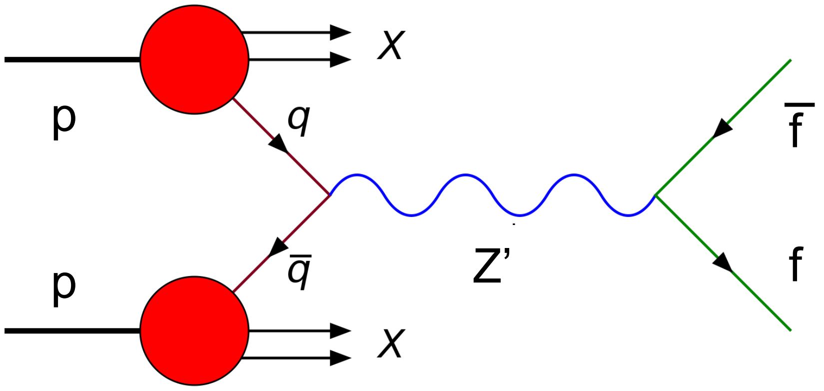
Feynman rule



Z' coupling to SM fermions f

$$\frac{g'}{2} Z'_\mu \overline{f}(g_V^f \gamma^\mu - g_A^f \gamma^\mu \gamma^5) f$$

Drell-Yan production cross-section



$$\sigma_{f\overline{f}} \equiv \sigma(pp \to Z'X \to f\overline{f}X)$$

Narrow width approximation

$$\sigma_{f\bar{f}} = \int_{(M_{Z'}-\Delta)^2}^{(M_{Z'}+\Delta)^2} \frac{d\sigma}{dM^2}(pp \to Z' \to f\bar{f}X)dM^2 \approx \left(\frac{1}{3}\sum_{q=u,d}\left(\frac{dL_{q\bar{q}}}{dM^2_{Z'}}\right)\hat{\sigma}(q\bar{q} \to Z')\right) \times Br(Z' \to f\bar{f})$$

Simple structure

$$\boxed{\sigma_{l^+l^-} \approx \frac{\pi}{48s}\left[c_u w_u(s, M^2_{Z'}) + c_d w_d(s, M^2_{Z'})\right]}$$

Carena, Daleo, Dobrescu, Tait

Model dependent

$$\left\{\begin{array}{l} c_u \propto \hat{\sigma}(u\bar{u} \to Z') \times Br(Z' \to l^+l^-) \\ c_d \propto \hat{\sigma}(d\bar{d} \to Z') \times Br(Z' \to l^+l^-) \end{array}\right\}$$

depend on g' and $g_{V,A}^{f}$

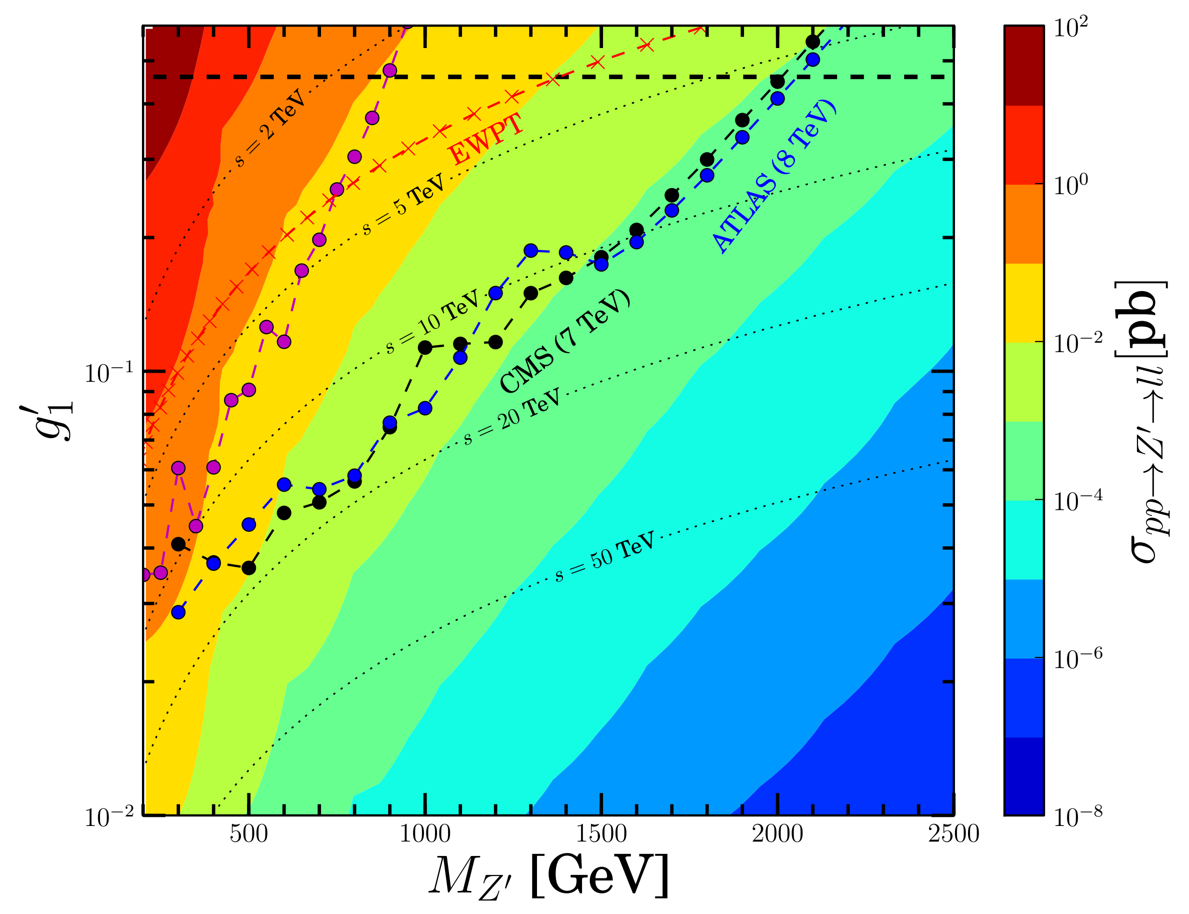
Model independent

$$\left. w_u \propto \frac{dL_{u\bar{u}}}{dM^2_{Z'}} \qquad w_d \propto \frac{dL_{d\bar{d}}}{dM^2_{Z'}} \right\}$$

depend on s and $M_{Z'}$

Belyaev, King, Svantesson

Little Z' models



Mass limit may be weakened by reducing the gauge coupling (F-theory motivation)

Conclusion

Where we stand with SUSY

☐ Gauge hierarchy problem solved by TeV scale SUSY

☐ But Natural SUSY is under threat from LHC (if not excluded) so we are faced with a Little Hierarchy Problem: some degree of tuning is apparently required

☐ How much? It is very model and measure dependent

☐ Remember that SUSY is not just MSSM!

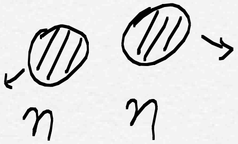
- If we use naturalness as a guiding principle then we are led to SUSY models without a mu term but with a singlet (S)

- These models (prototype NMSSM) solve both mu problems: forbid explicit mu term and allow effective mu term to be smaller due to lighter stop masses (since Higgs mass is larger at tree-level)

- However eventually stops around TeV scale must be discovered otherwise NMSSM type models also become unnatural..but is 1% tuning that bad?

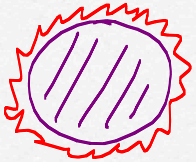
There are many ~1% level "accidents"

Arkani-Hamed
SUSY 2033



Two neutrons
<u>not</u> bound by
60 keV!

Low Quadrupole
of CMB power



Moon
eclipsing the
sun

Adding "EWSB" to this list from
L.H.C would be fascinating, but not KNOCKOUT
(for SUSY)

How will we Know?

Arkani-Hamed
SUSY 2033

- Higher Energy!!
  - * Find Something! → End of discussion!
  - * Find Nothing → Tuning $\propto E^2_{\text{machine}}$
- Rare processes
- Precision measurements

} Indirect, Linear gain in tuning

Arkani-Hamed
SUSY 2033

- Tuning probe $\propto E_{CM}^{2}$

- Higgs + nothing else @ 100 TeV

$\Longrightarrow \sim 10^{-4}$ tuning!

- Never seen this level of tuning in particle physics - Dramatically new

Let us be patient … Ellis

- If you have a problem, postulate a new particle:
  - QM and Special Relativity: Antimatter
  - Nuclear spectra: Neutron
  - Continuous spectrum in β decay: Neutrino
  - Nucleon-nucleon interactions: Pion
  - Absence of lepton number violation: Second neutrino
  - Flavour SU(3): Ω^-
  - Flavour SU(3): Quarks
  - FCNC: Charm
  - CP violation: Third generation
  - Strong dynamics: Gluons
  - Weak interactions: $W^\pm$, Z^0
  - Renormalizability: H (48 years)
  - Naturalness: Supersymmetry? (40 years)

SUSY cannot be experimentally ruled out.

It can only be discovered.

Or else abandoned.

Leszek Roszkowski