UNIVERSITY OF
Southampton
School of Physics
and Astronomy

SUperSymmetrY

Steve King

NExT PhD Workshop at QMUL

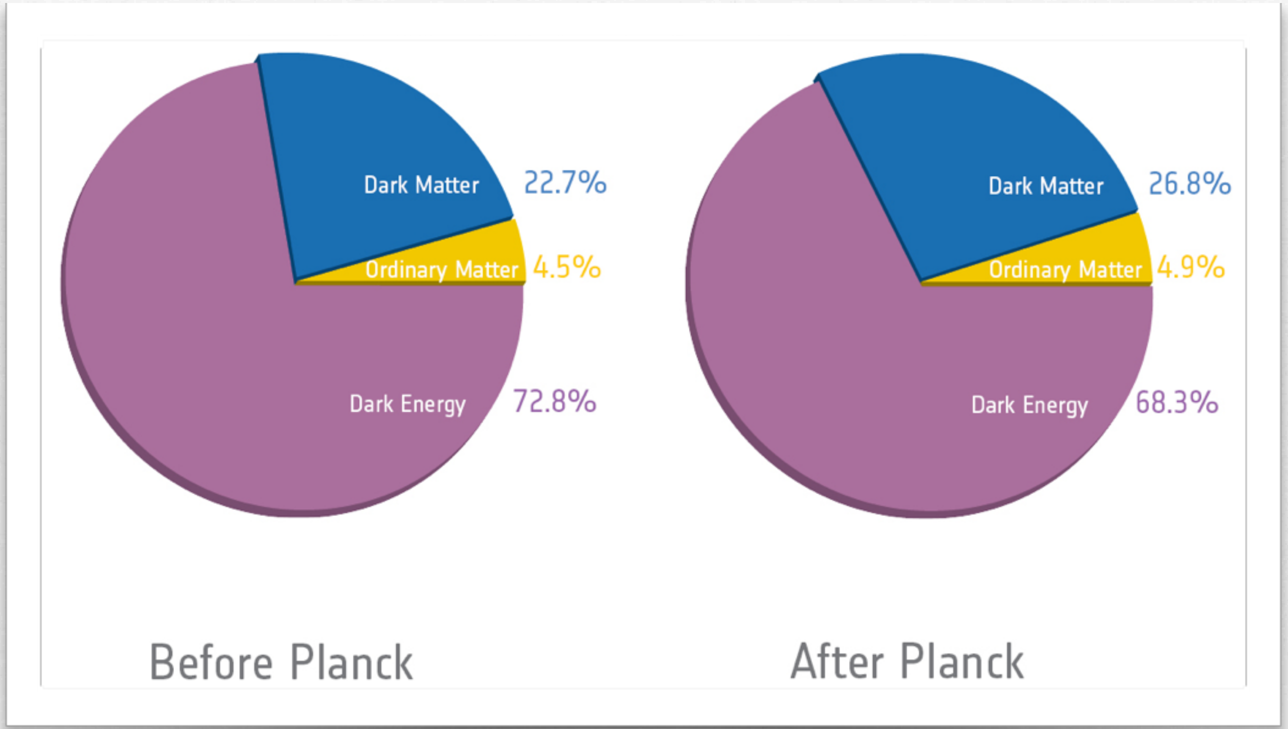
At the Frontier of our Knowledge

17th June – 19th June 2013

NExT PhD Workshop at QMUL

ΛCDM Model

Lectures by Alessandro Melchiorri



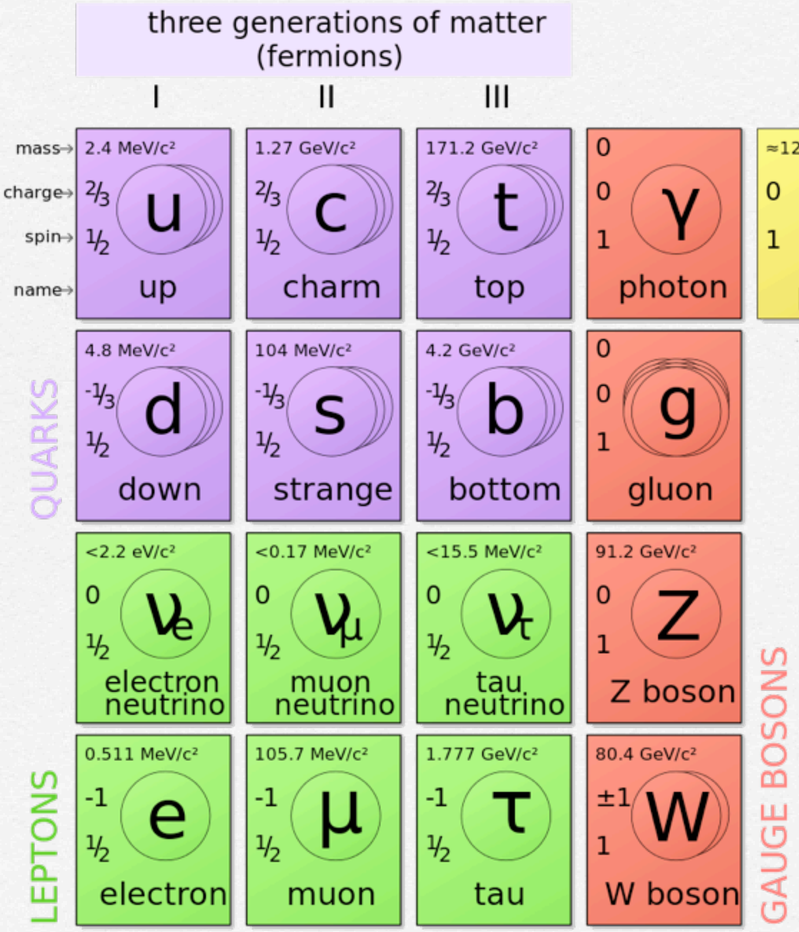
Following Planck it is in good shape... but it leaves some puzzles

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

Standard Model

Lectures by Jeppe Andersen



three generations of matter (fermions)

	I	II	III		
mass→ charge→ spin→ name→	2.4 MeV/c^2 ⅔ ½ u up	1.27 GeV/c^2 ⅔ ½ c charm	171.2 GeV/c^2 ⅔ ½ t top	0 0 1 γ photon	≈126 GeV/c^2 0 1 H Higgs boson
QUARKS	4.8 MeV/c^2 -⅓ ½ d down	104 MeV/c^2 -⅓ ½ s strange	4.2 GeV/c^2 -⅓ ½ b bottom	0 0 1 g gluon	
	<2.2 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<15.5 MeV/c^2 0 ½ ν_τ tau neutrino	91.2 GeV/c^2 0 1 Z Z boson	
LEPTONS	0.511 MeV/c^2 -1 ½ e electron	105.7 MeV/c^2 -1 ½ μ muon	1.777 GeV/c^2 -1 ½ τ tau	80.4 GeV/c^2 ±1 1 W W boson	

GAUGE BOSONS

With the discovery of the "Higgs" it now seems to be complete... but it leaves some puzzles in its wake

Standard Model Puzzles

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

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.

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.

Neutrino Mass and Mixing

Lectures by Michele Maltoni

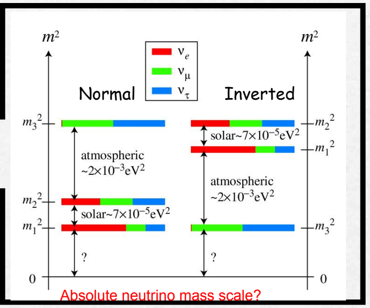
Standard Model states

$$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L \quad \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L \quad \begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}_L$$

PMNS matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Neutrino mass states



Absolute neutrino mass scale?

Pontecorvo
Maki
Nakagawa
Sakata

$$U_{PMNS} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}e^{i\alpha_1/2} & 0 & 0\\ 0 & e^{i\alpha_2/2} & 0\\ 0 & 0 & 1\end{pmatrix}$$

$s_{ij} = \sin\theta_{ij}$
$c_{ij} = \cos\theta_{ij}$

Atmospheric | Reactor | Solar | Majorana

Oscillation phase δ

Majorana phases α_1, α_2

3 masses + 3 angles + 1 (or 3) phase(s) =
7 (or 9) new parameters for SM

Implications for PP and cosmology

☐ Origin of tiny neutrino mass

Extra dimensions, See-saw mechanism, RPV SUSY

☐ Unification of matter, forces and flavour

SUSY, GUTs, Family Symmetry,...

Particle Physics

☐ Did neutrinos play a role in our existence?

Leptogenesis

☐ Did neutrinos play a role in forming galaxies?

Hot/Warm Dark matter component

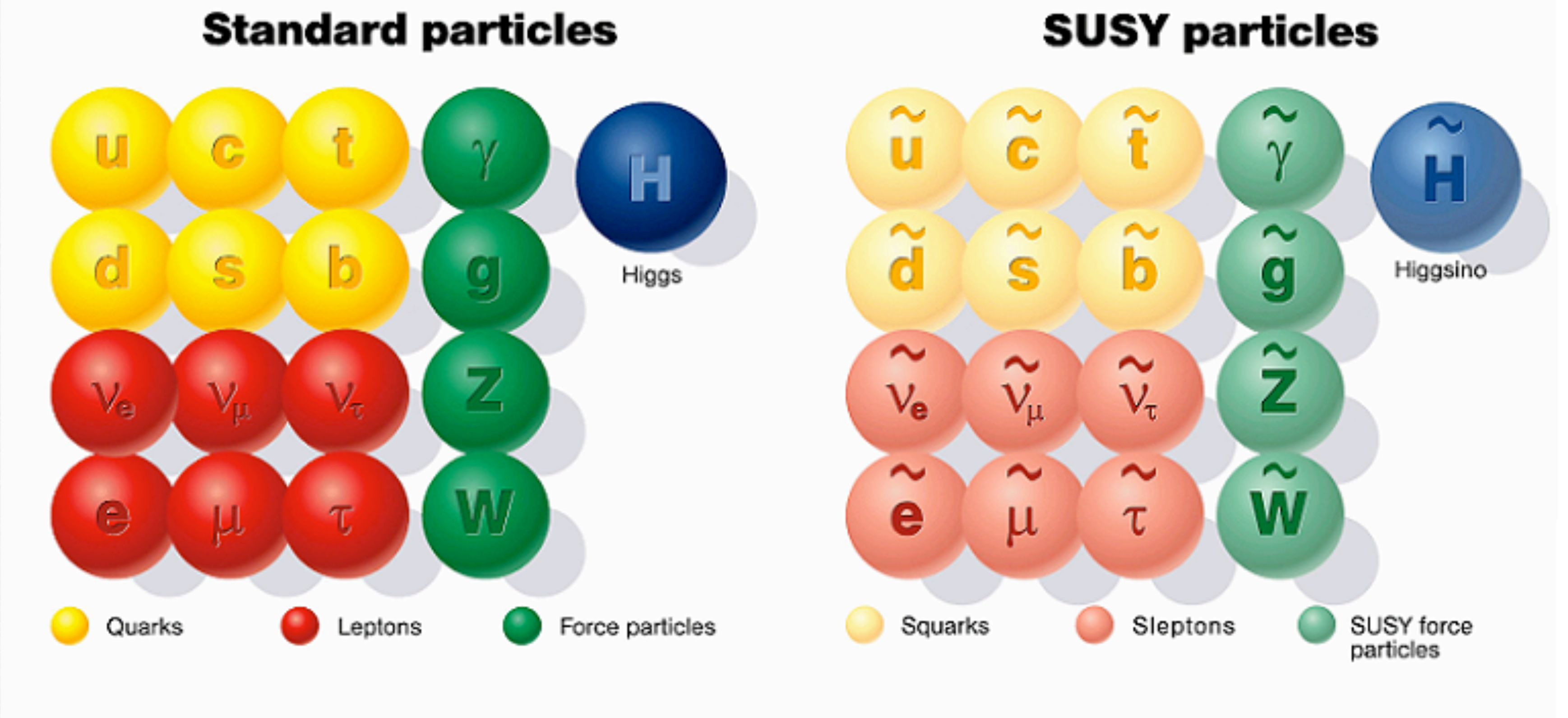
☐ Did neutrinos play a role in birth of the universe?

Sneutrino inflation

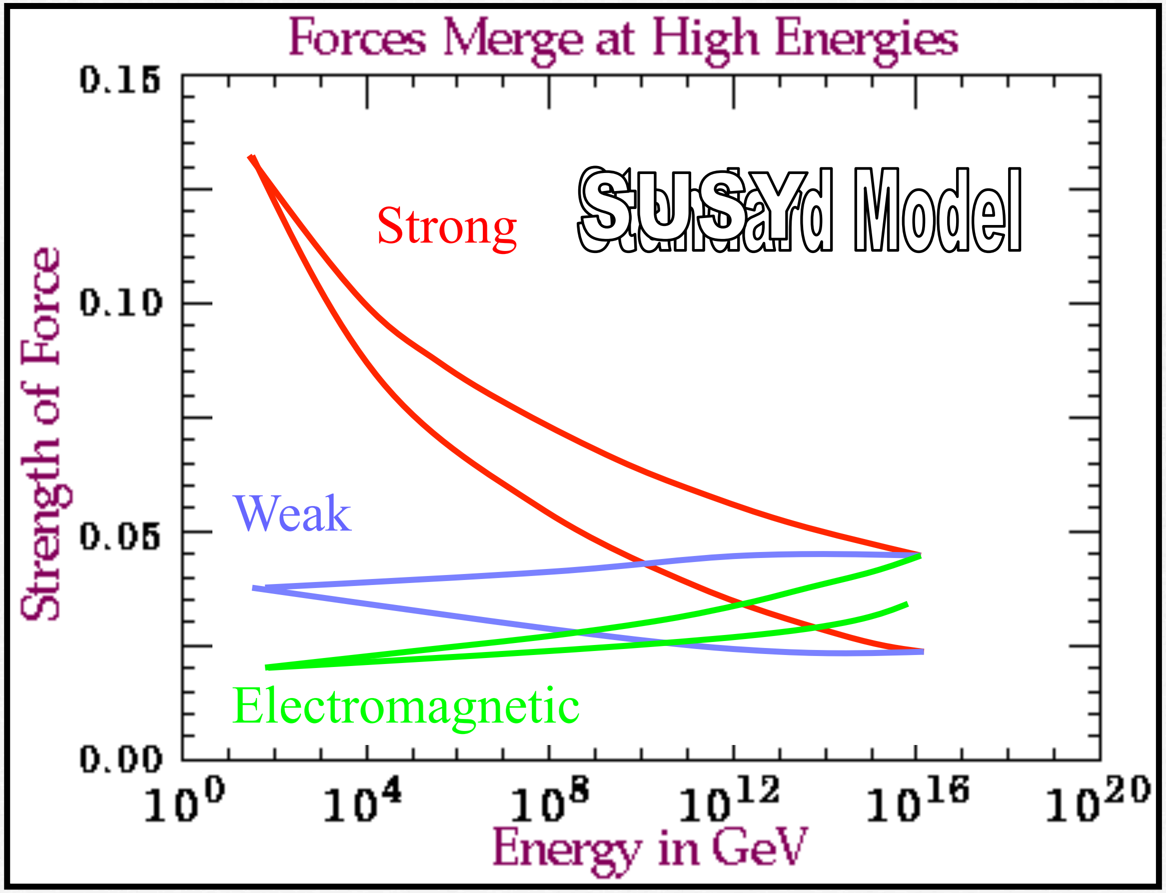
☐ Can neutrinos shed light on dark energy? $\Lambda \sim m_\nu^4$

Cosmology

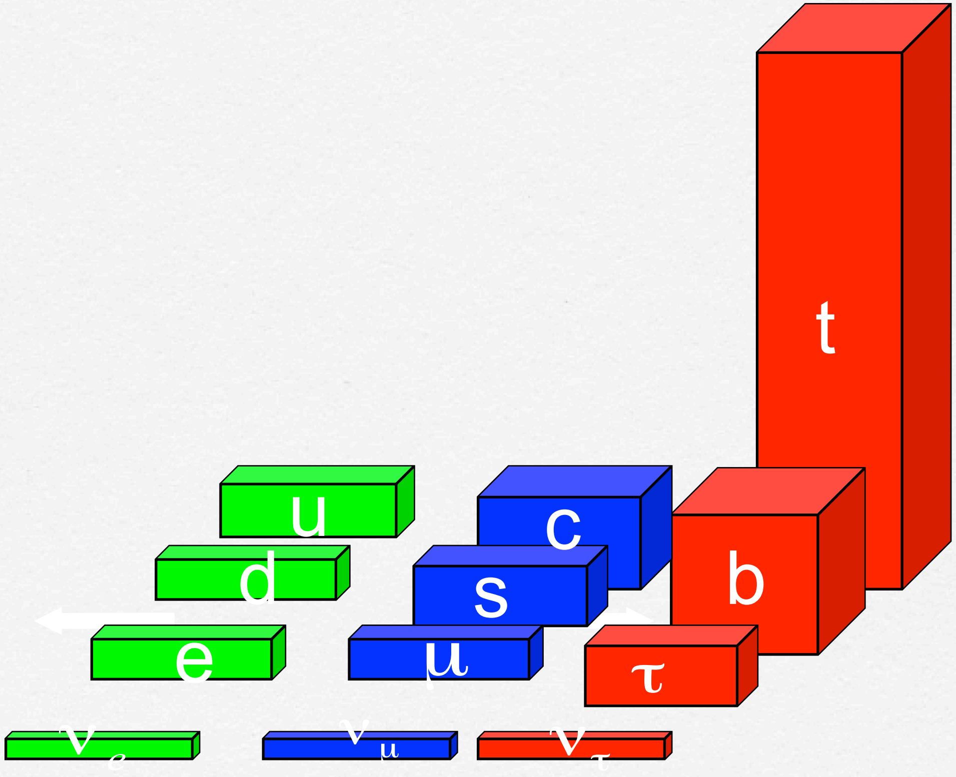
How can SUSY help with any of this?



SUSY facilitates GUTs



GUTs and Flavour Models are typically Supersymmetric

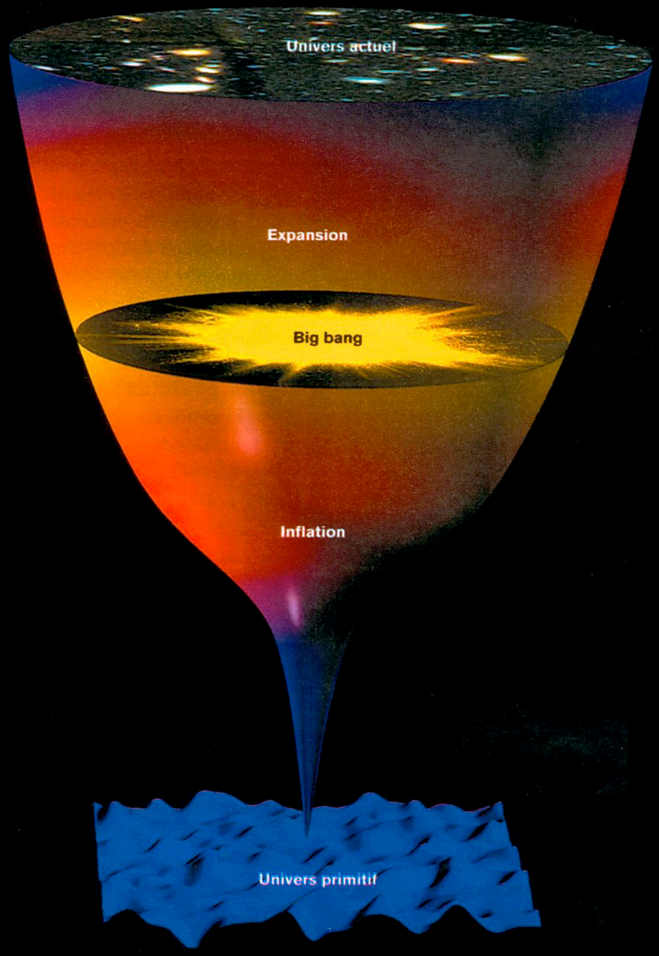


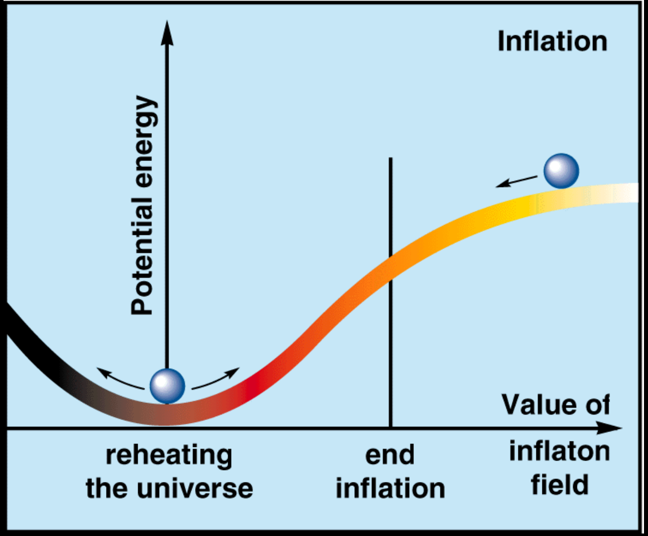
Many inflation models are supersymmetric

Why is the Universe so big and flat?

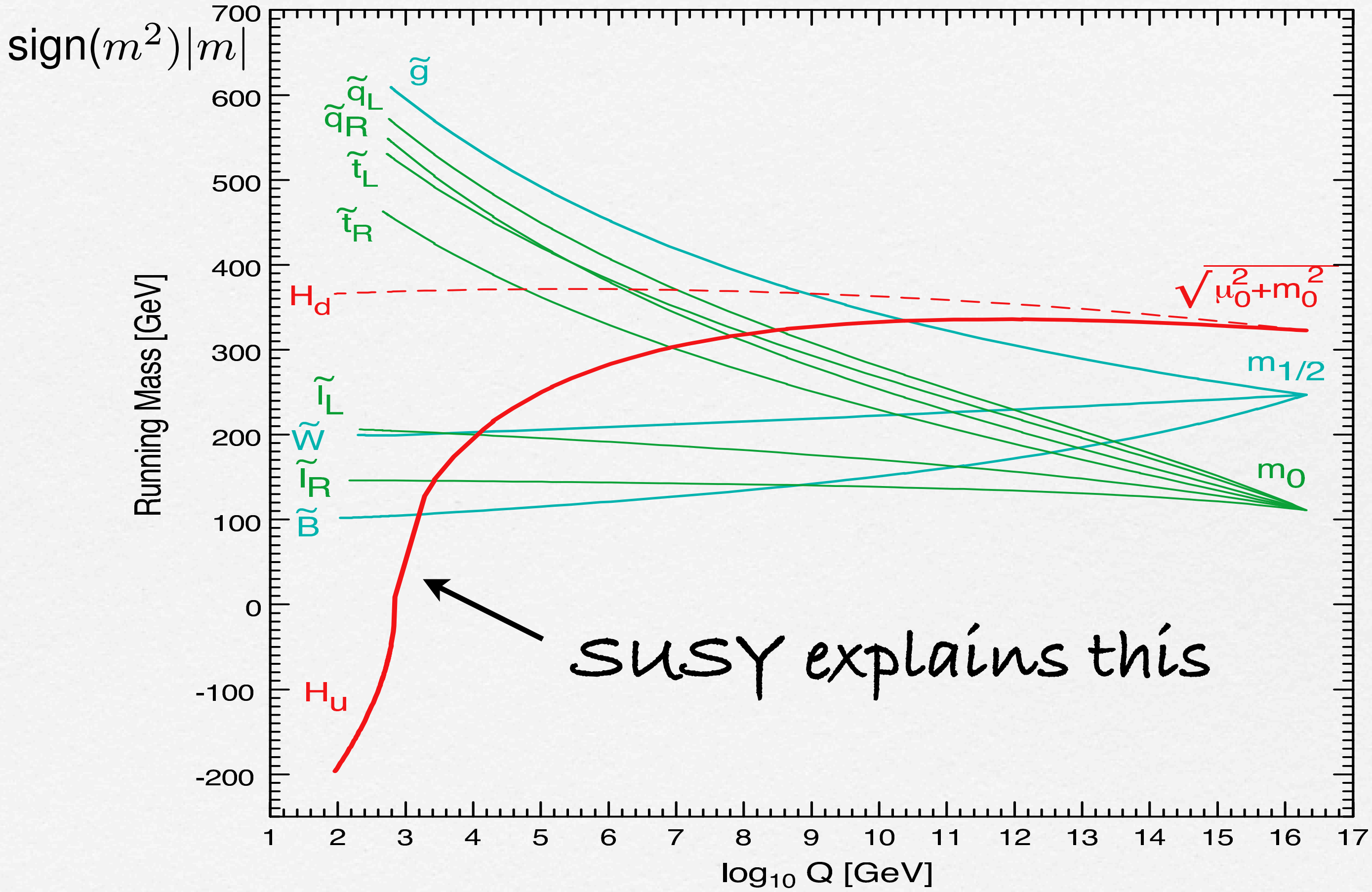
What seeds the density perturbations?

-- Inflation!





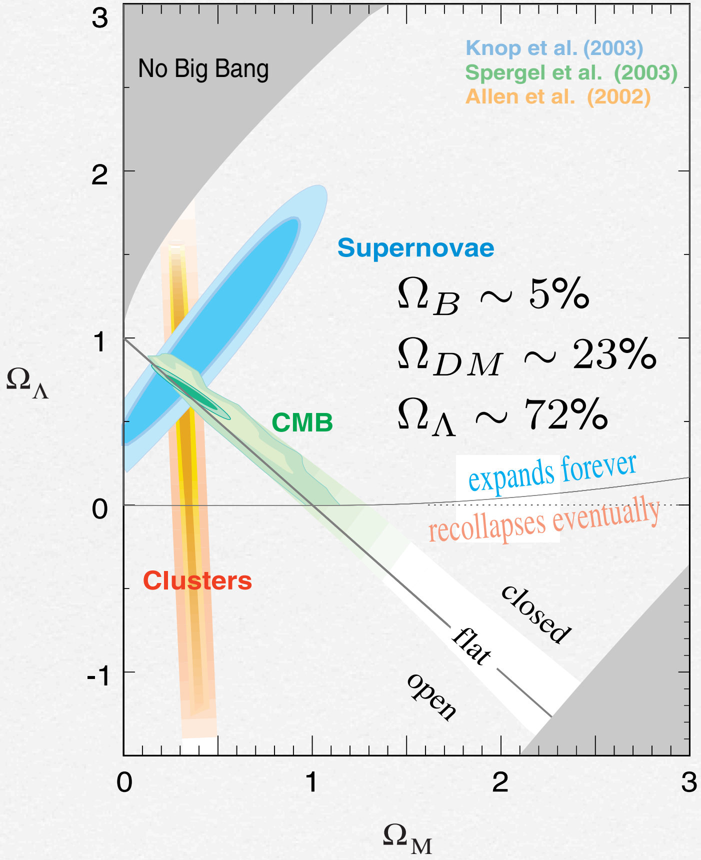
- "Why does electroweak symmetry break?" or "Why is $\mu^2 < 0$ in the SM?"



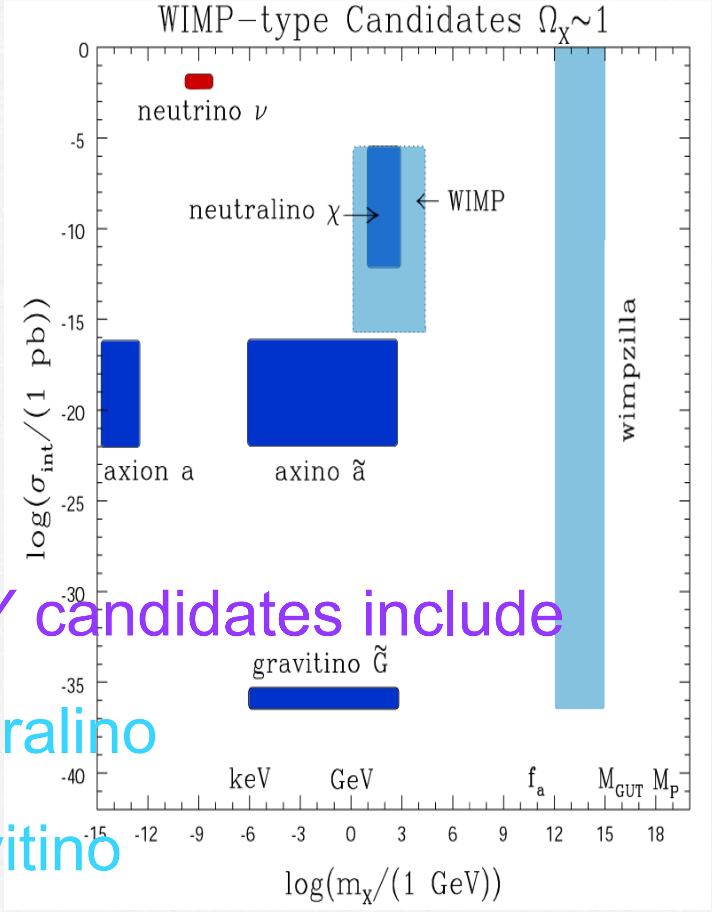
SUSY explains this

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 $10^{-17}\mathrm{cm}$
- Need a lot of energy to keep it small!

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

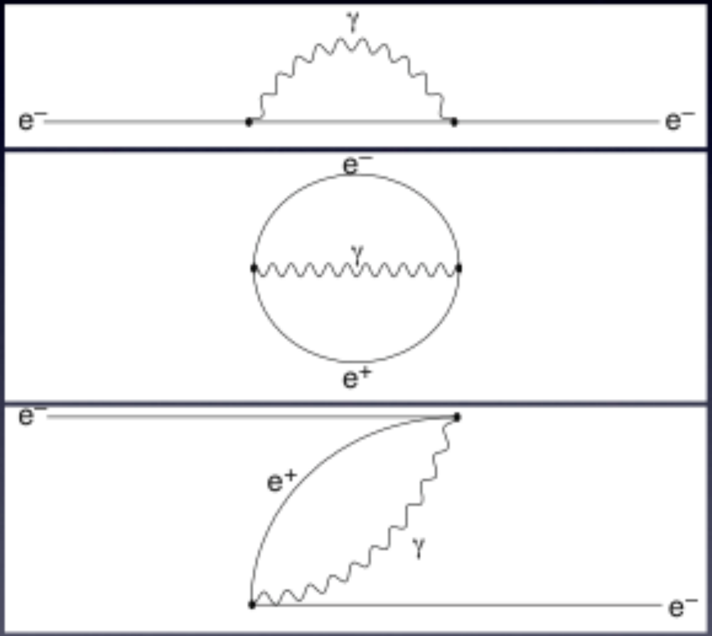
- Correction $\Delta m_e c^2 > m_e c^2$ for $r_e < 10^{-13}\mathrm{cm}$
- Breakdown of theory of electromagnetism

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

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

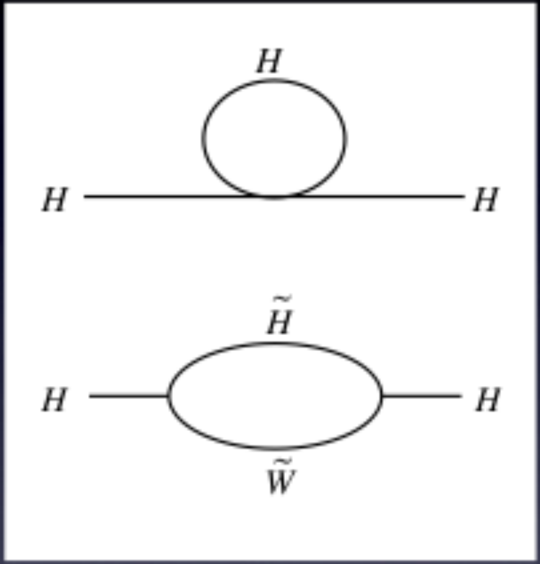
⇒ only 10% of mass even for Planck-size $r_e \sim 10^{-33}$cm



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

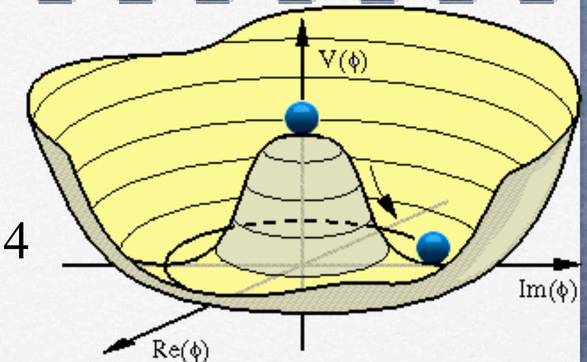
History repeats itself?

- 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



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

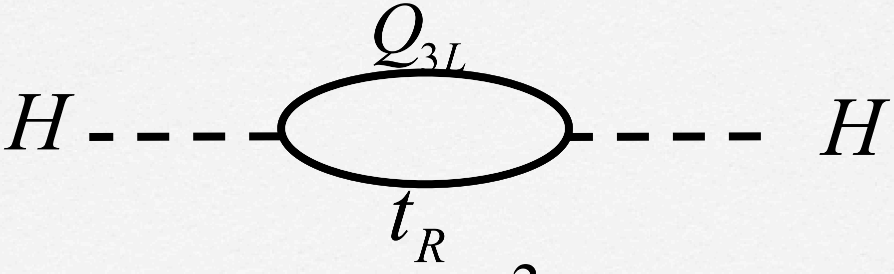
Higgs Theory in SM



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

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

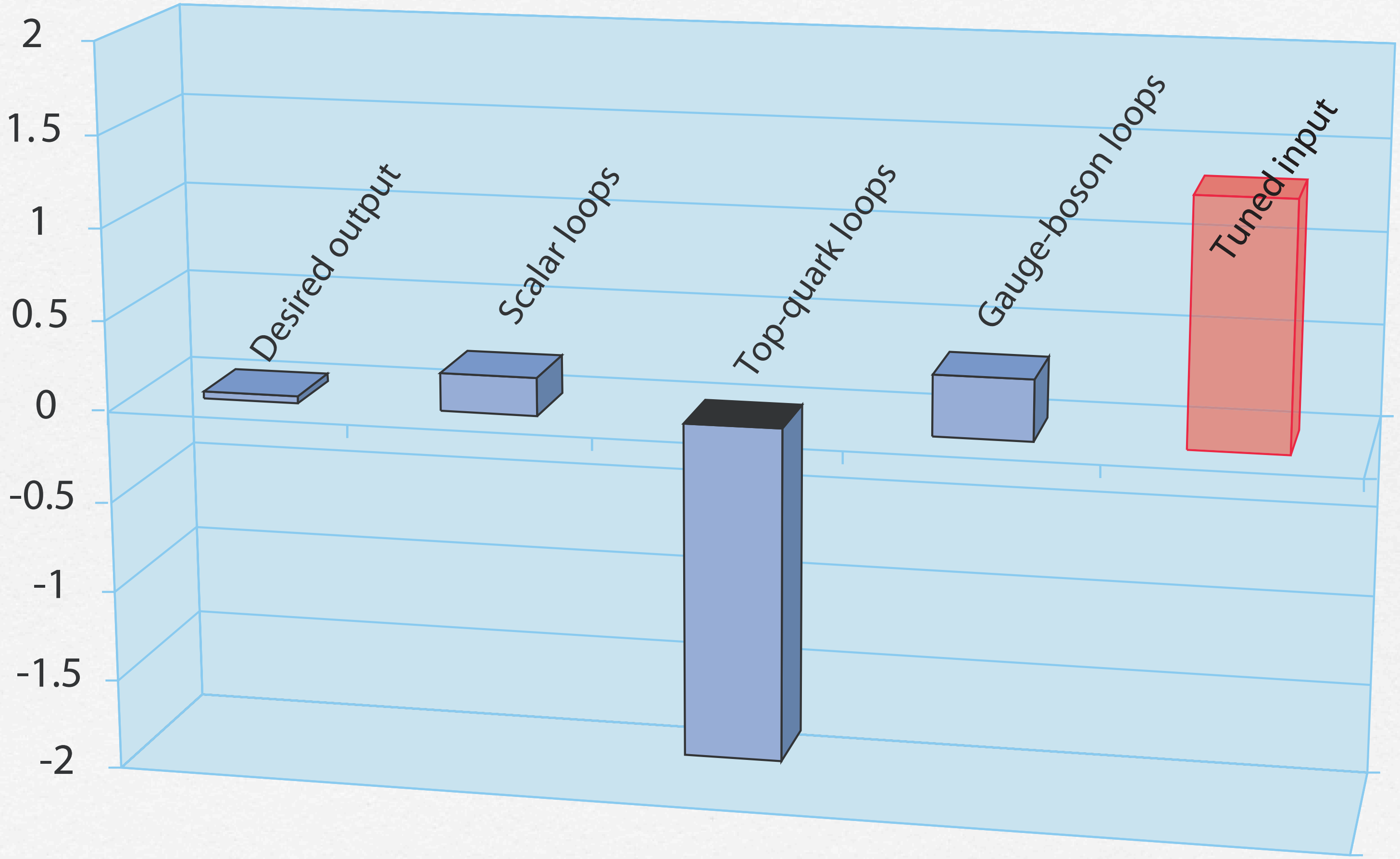
Including rad corr $m_H^2 + \delta m_H^2 = -\lambda \left(246\,GeV\right)^2$



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

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

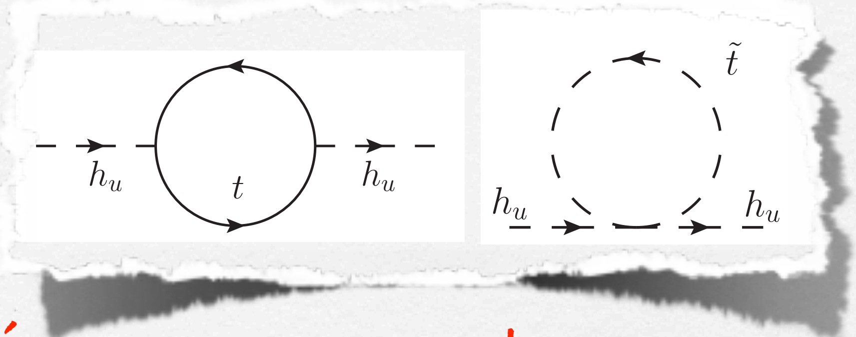
Relative contributions to ΔM_H^2 for $\Lambda = 5$ TeV



Quigg 0704.2232

In SUSY, stop loops dominate Higgs mass parameter correction

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



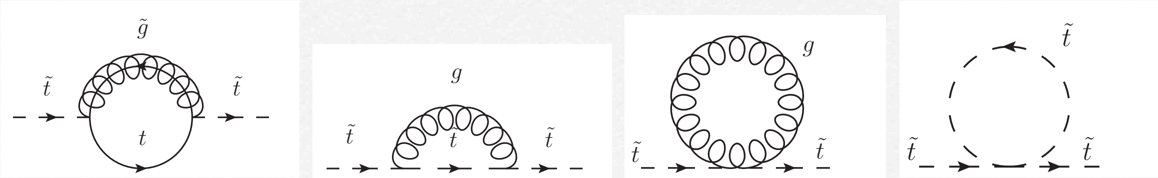
Leading quadratic divergence cancels

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

To avoid tuning need

$$m_{\tilde{t}} \lesssim 400 \mathrm{GeV}.$$

Gluino corrections to stop

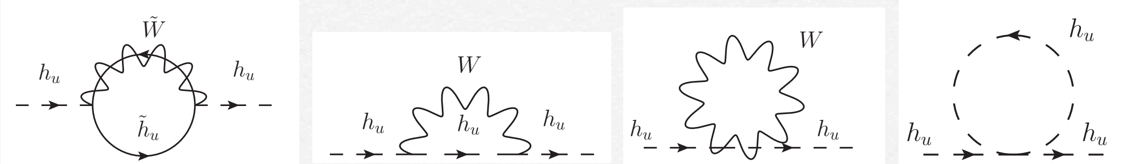


$$\delta m_{\tilde{t}}^2 = \frac{2g_s^2}{3\pi^2} m_{\tilde{g}}^2 \ln \frac{\Lambda_{UV}}{m_{\tilde{g}}}.$$

To avoid tuning need

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

Other important loops

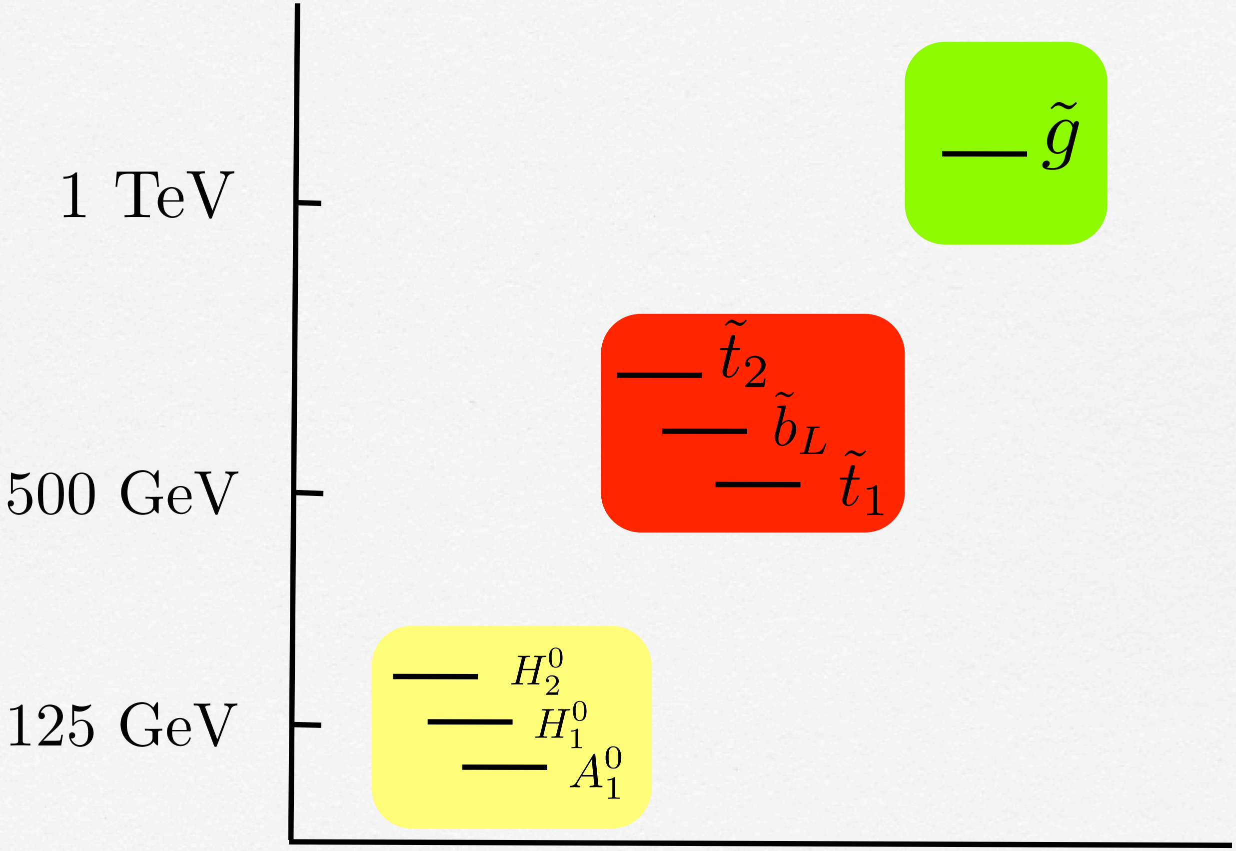


$$\delta m_{h_u}^2 = \frac{3g^2}{8\pi^2}(m_{\tilde{W}}^2 + m_{\tilde{h}}^2)\ln\frac{\Lambda_{UV}}{m_{\tilde{W}}}.$$

To avoid tuning need

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

Natural SUSY



History of SUSY

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,

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

  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 $\qquad$ $\overline{Q}_{\dot\alpha}$

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

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

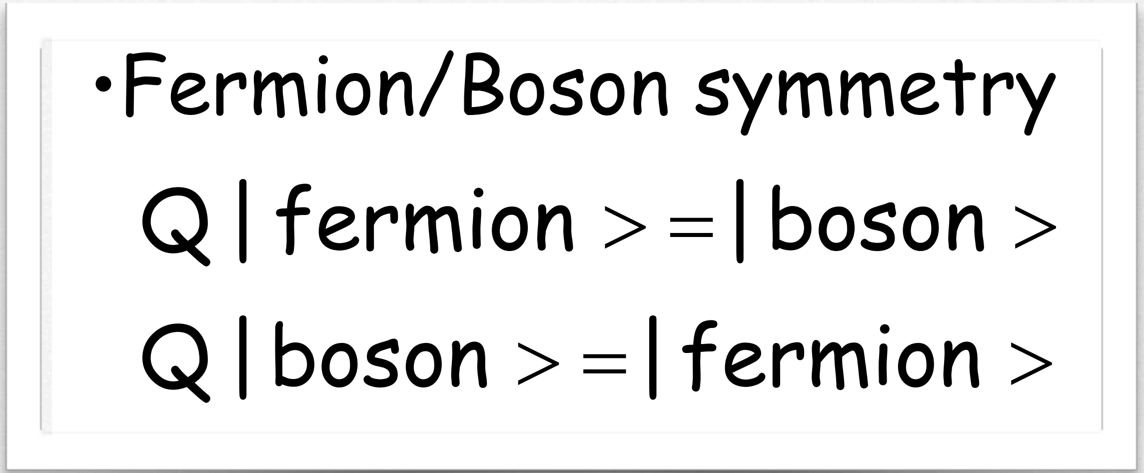
It is useful to keep track of 'SUSY-ness' by the R-symmetry generator R:

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

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)

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

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

super-space
coordinates

vector
(Wess-Zumino)

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

gluino

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_R^c	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_L^c	3^*	1	-2/3
$\widehat{D}^C$	$\tilde{d}_R^*$	d_L^c	3^*	1	1/3
Higgs Multiplets					
$\widehat{H}_d$	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$	1	2	-1/2
$\widehat{H}_u$	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$	1	2	1/2

R-parity

SM Particle = +

SUSY particle = -

Superpotential: Yukawa couplings and SUSY masses

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

Potential: F-terms $|F|^2$ D-terms $(D)^2$

$$V(\phi) \supset \sum_i \left| \frac{\partial W(\phi_i)}{\partial \phi_i} \right|^2$$

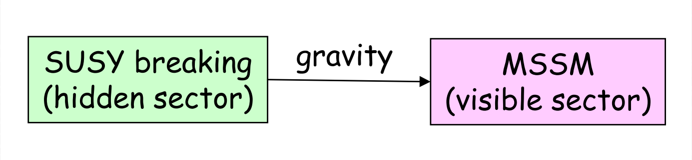
$$V(\phi) \supset \tfrac{1}{2} \sum_a (g_a \, \phi_i^\dagger T_{ij}^a \phi_j + k^a)^2$$

*Soft Lagrangian: SUSY breaking mass terms

- 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:* $\frac{1}{2} M_a \lambda^a \lambda^a + \text{h.c.}$.

*soft means does not spoil the cancellation of quadratic divergences

Possible origin of soft Lagrangian



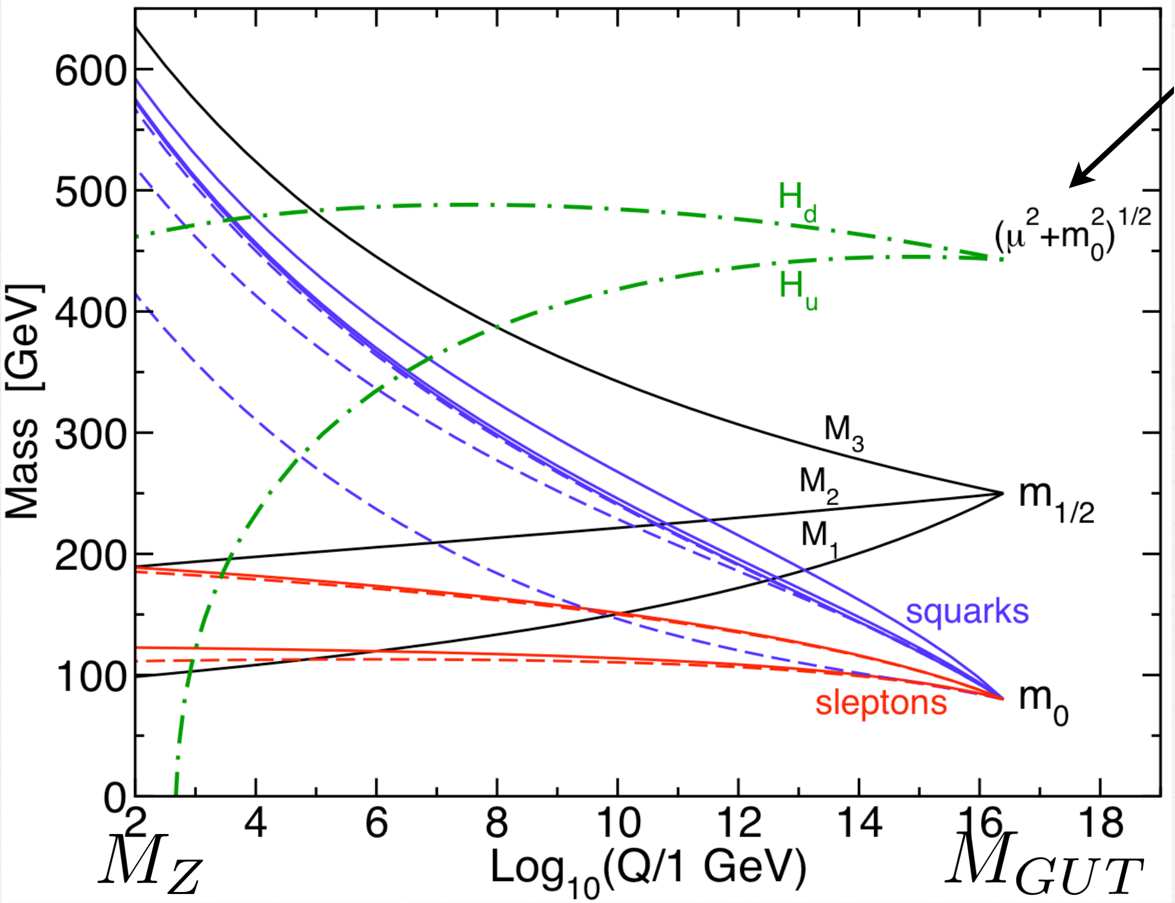
Mass Spectrum in MSSM

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	$\widetilde{u}_L \; \widetilde{u}_R \; \widetilde{d}_L \; \widetilde{d}_R$ $\widetilde{s}_L \; \widetilde{s}_R \; \widetilde{c}_L \; \widetilde{c}_R$ $\widetilde{t}_L \; \widetilde{t}_R \; \widetilde{b}_L \; \widetilde{b}_R$	(same) (same) $\widetilde{t}_1 \; \widetilde{t}_2 \; \widetilde{b}_1 \; \widetilde{b}_2$
sleptons	0	-1	$\widetilde{e}_L \; \widetilde{e}_R \; \widetilde{\nu}_e$ $\widetilde{\mu}_L \; \widetilde{\mu}_R \; \widetilde{\nu}_\mu$ $\widetilde{\tau}_L \; \widetilde{\tau}_R \; \widetilde{\nu}_\tau$	(same) (same) $\widetilde{\tau}_1 \; \widetilde{\tau}_2 \; \widetilde{\nu}_\tau$
neutralinos	1/2	-1	$\widetilde{B}^0 \; \widetilde{W}^0 \; \widetilde{H}_u^0 \; \widetilde{H}_d^0$	$\widetilde{N}_1 \; \widetilde{N}_2 \; \widetilde{N}_3 \; \widetilde{N}_4$
charginos	1/2	-1	$\widetilde{W}^\pm \; \widetilde{H}_u^+ \; \widetilde{H}_d^-$	$\widetilde{C}_1^\pm \; \widetilde{C}_2^\pm$
gluino	1/2	-1	$\widetilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	-1	$\widetilde{G}$	(same)

Constrained MSSM

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



m_0: common scalar mass at GUT

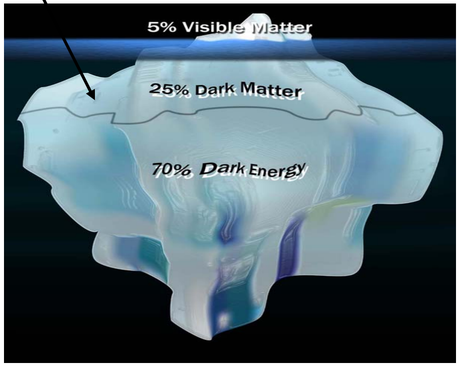
$m_{1/2}$: the common gaugino mass at GUT

tanβ: <H$_U$>/<H$_D$>

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)



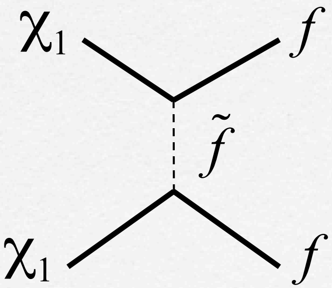
CMSSM Dark Matter

Neutralino mass matrix

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

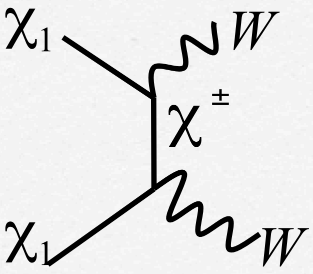
$$\chi_1 = N_1\tilde{B} + N_2\tilde{W} + N_3\tilde{H}_d + N_4\tilde{H}_u$$

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



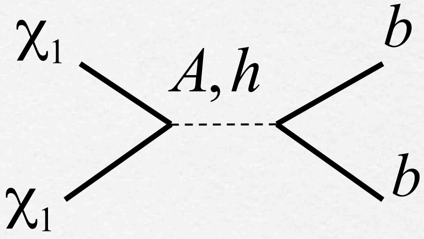
Bulk

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



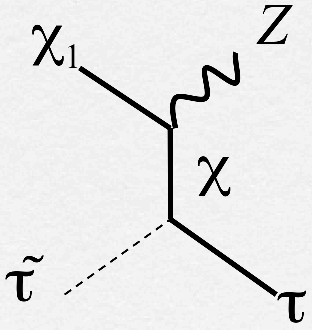
Focus

Higgsino LSP



Funnel

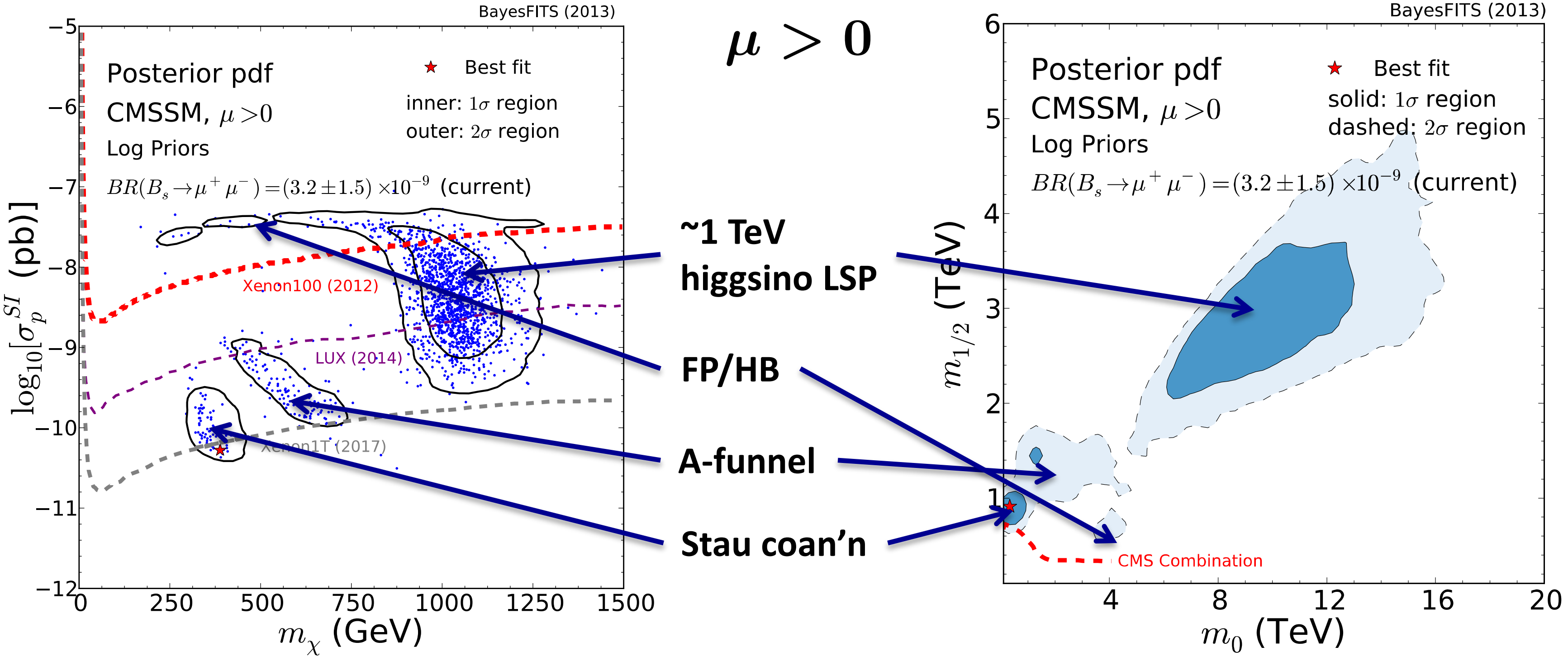
$$m_{A,h} \approx 2m_{\chi_1}$$



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

Where is SUSY?

After LHC(7/8TeV):

We know better now where SUSY is not.

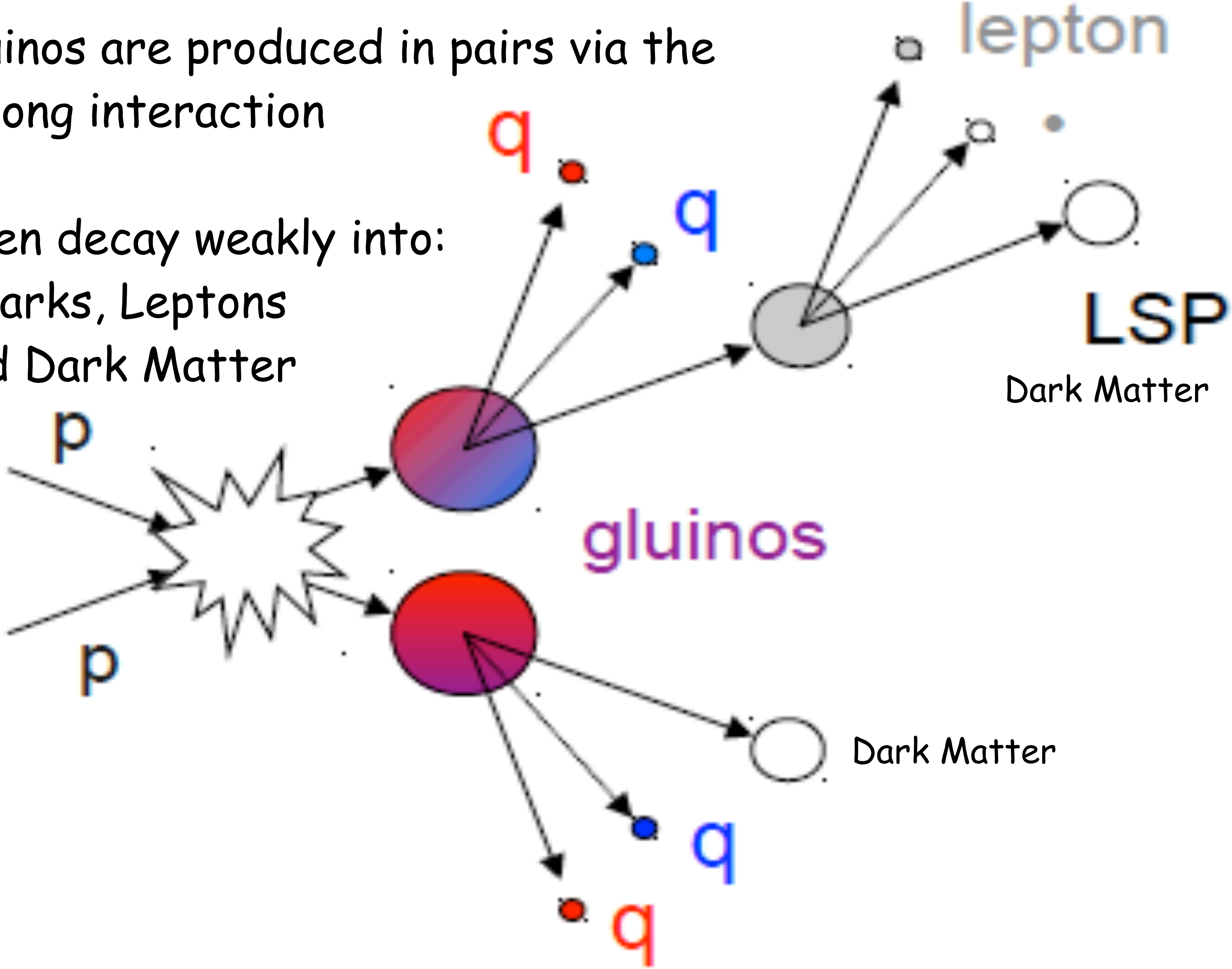
Hints where SUSY may actually be.

© Ron Leishman * www.ClipartOf.com/1047187

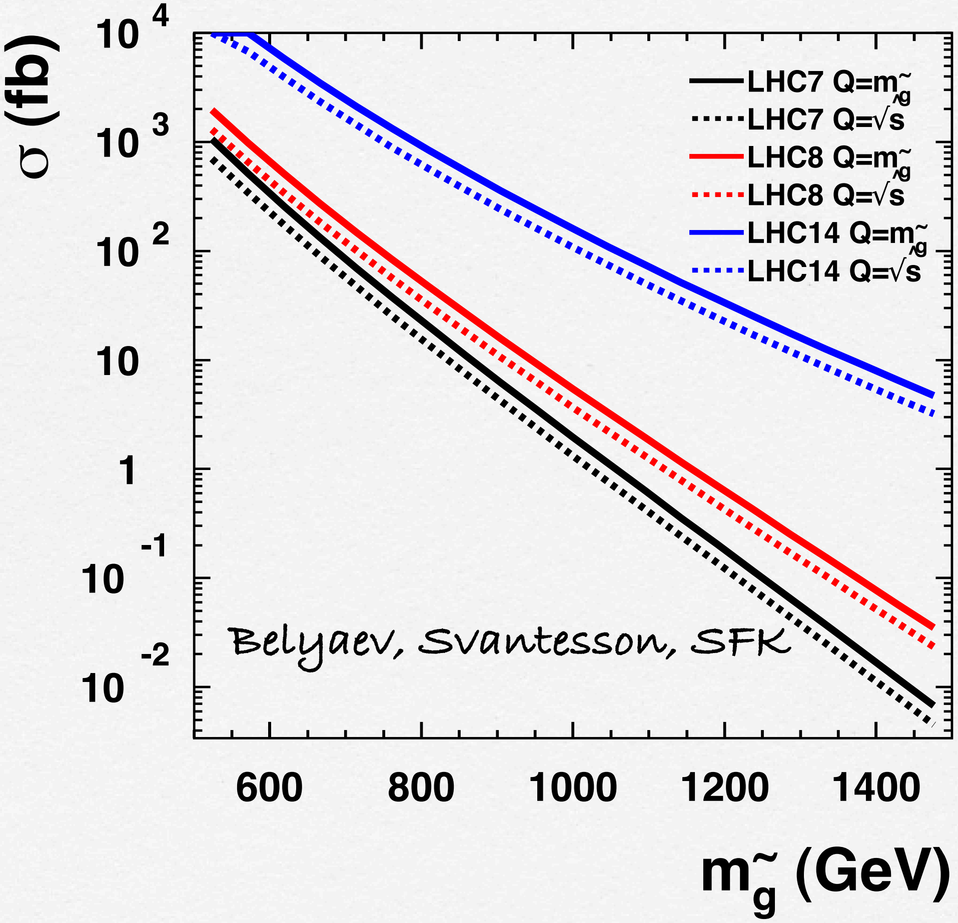
How to discover SUSY @ LHC?

Gluinos are produced in pairs via the strong interaction

Then decay weakly into:
Quarks, Leptons
and Dark Matter



Gluino pair production



Belyaev, Svantesson, SFK

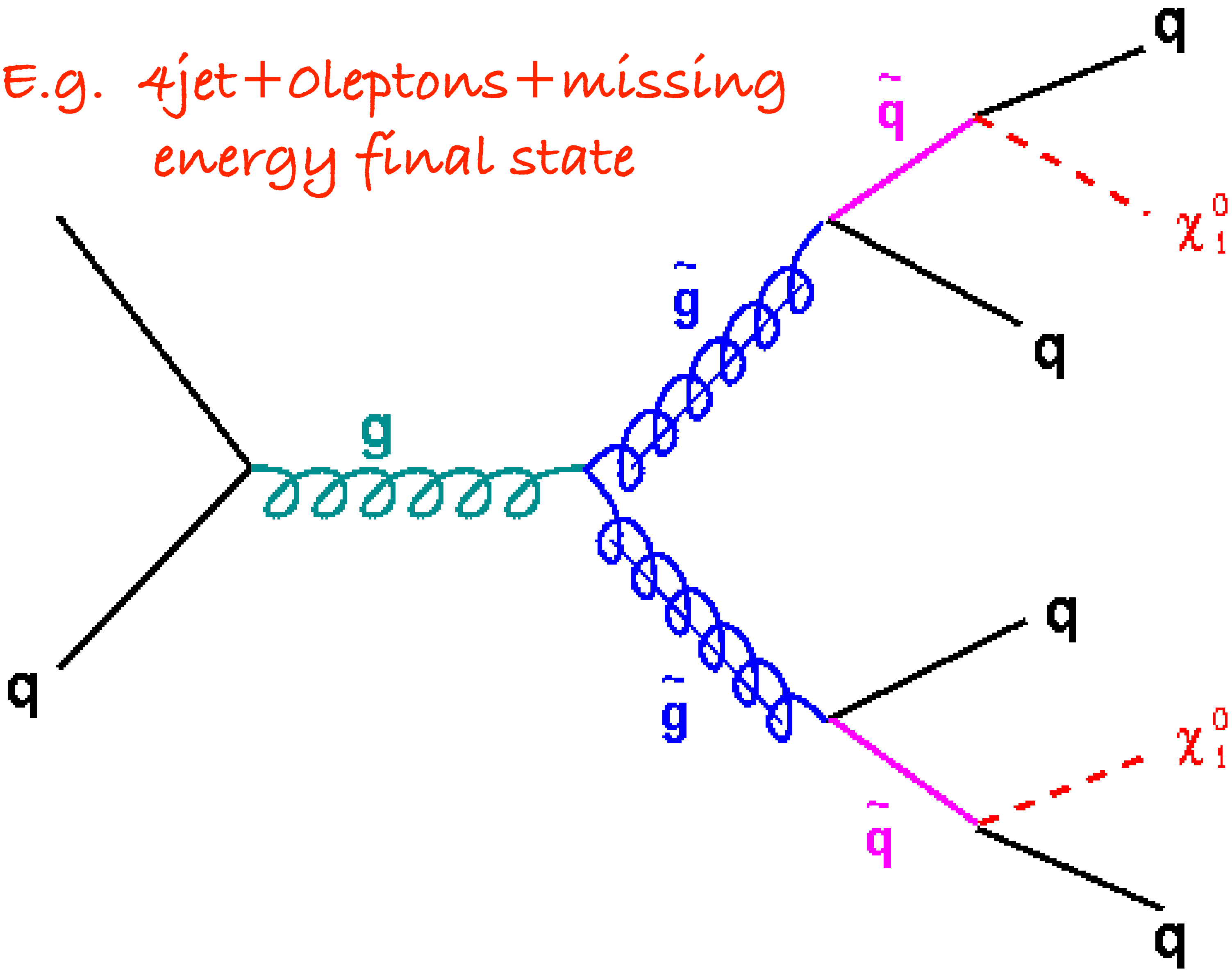
$$N_{\text{events}} = \sigma \times \int L dt$$

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

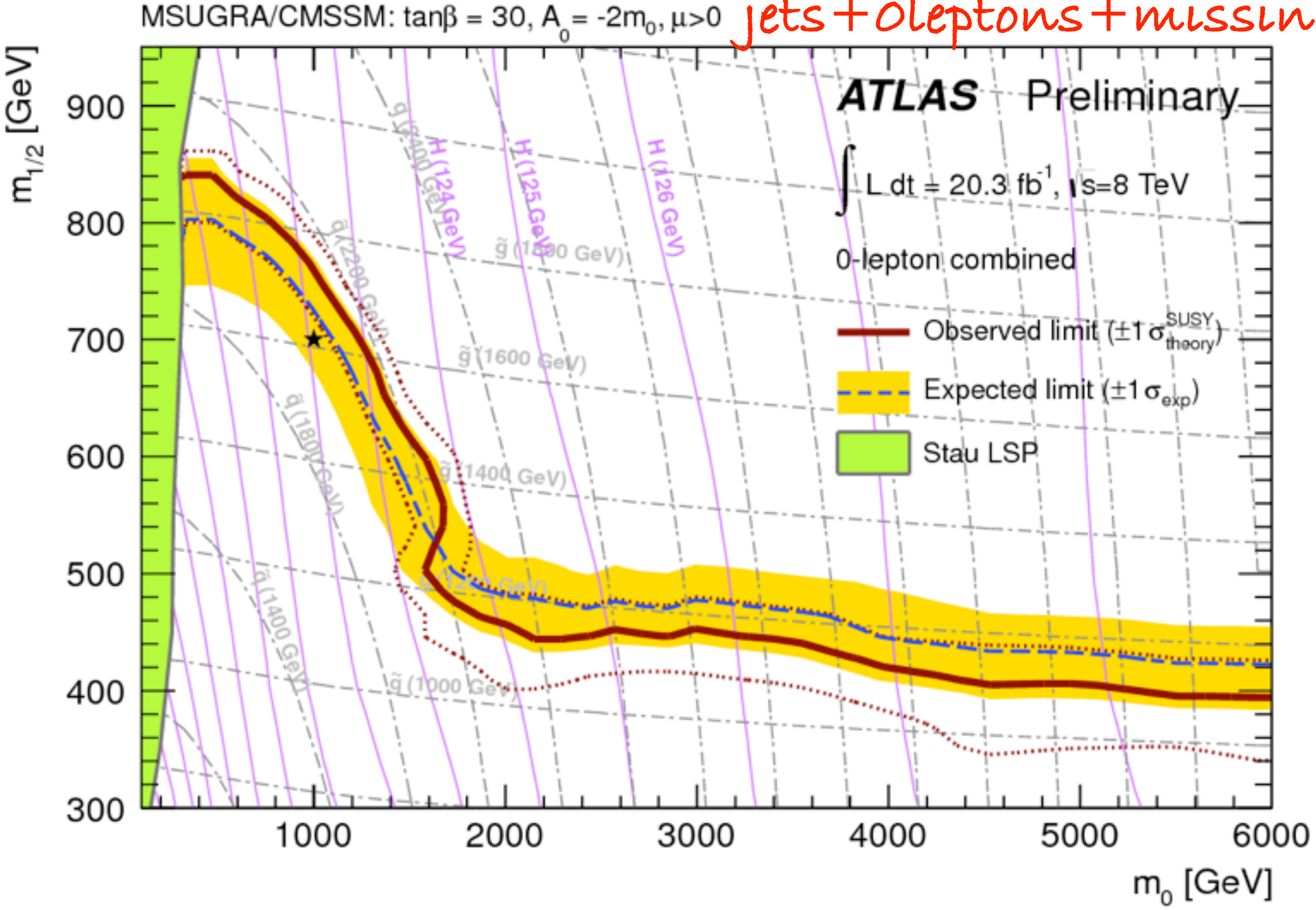
$$\sqrt{s} = 8\text{TeV}$$

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

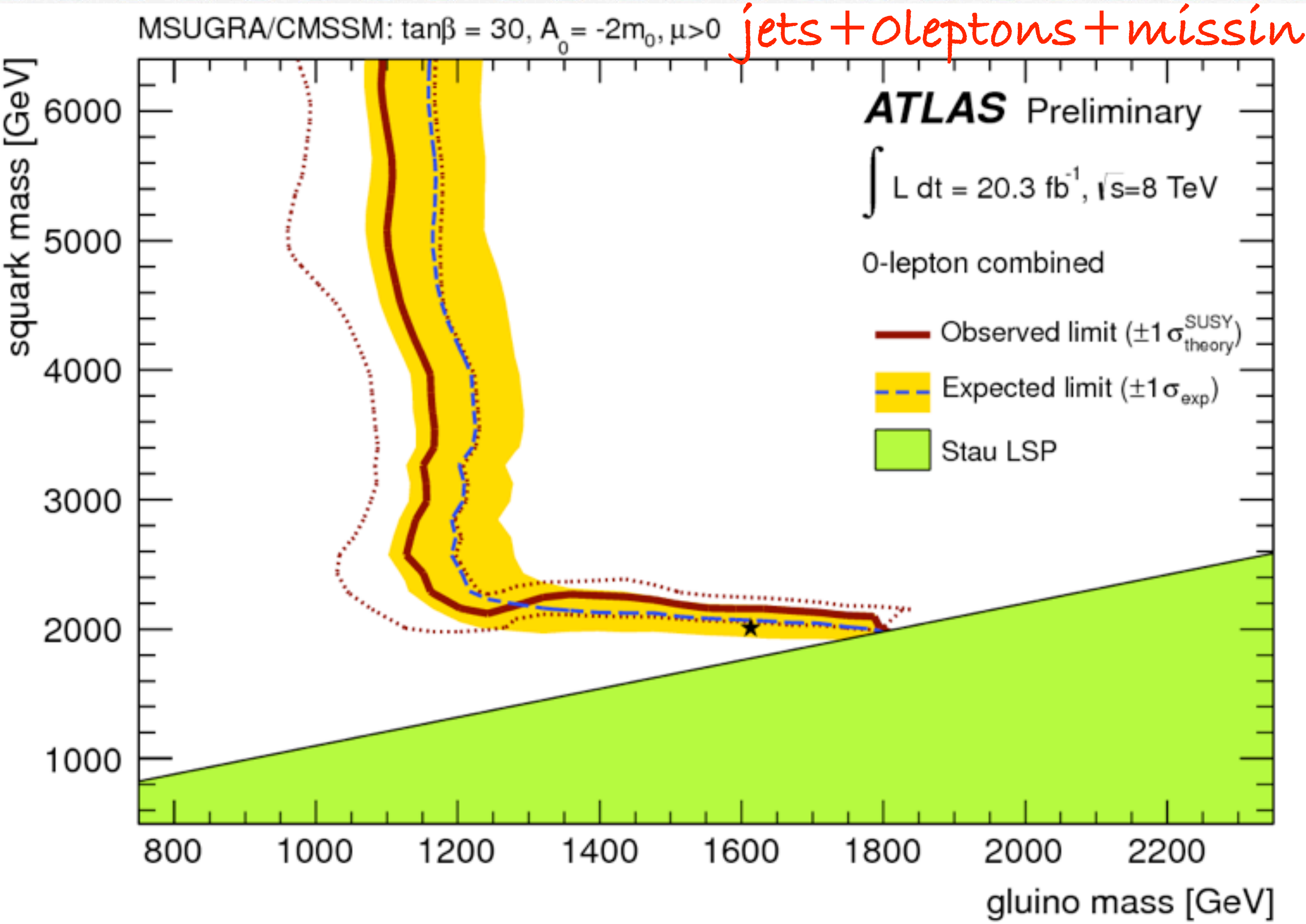
E.g. 4jet+0leptons+missing energy final state



jets + 0leptons + missing



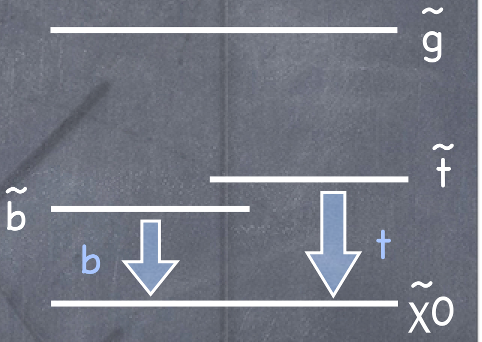
jets + 0leptons + missing



Searches with 8 TeV data
Stop and Sbottom

- Direct squark searches

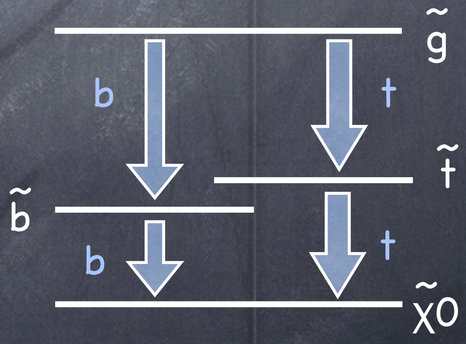
  Smaller cross section
  Final state similar to tt in the bulk of the parameter space
  Reduced bkg discrimination power
  Only handle if gluino heavy



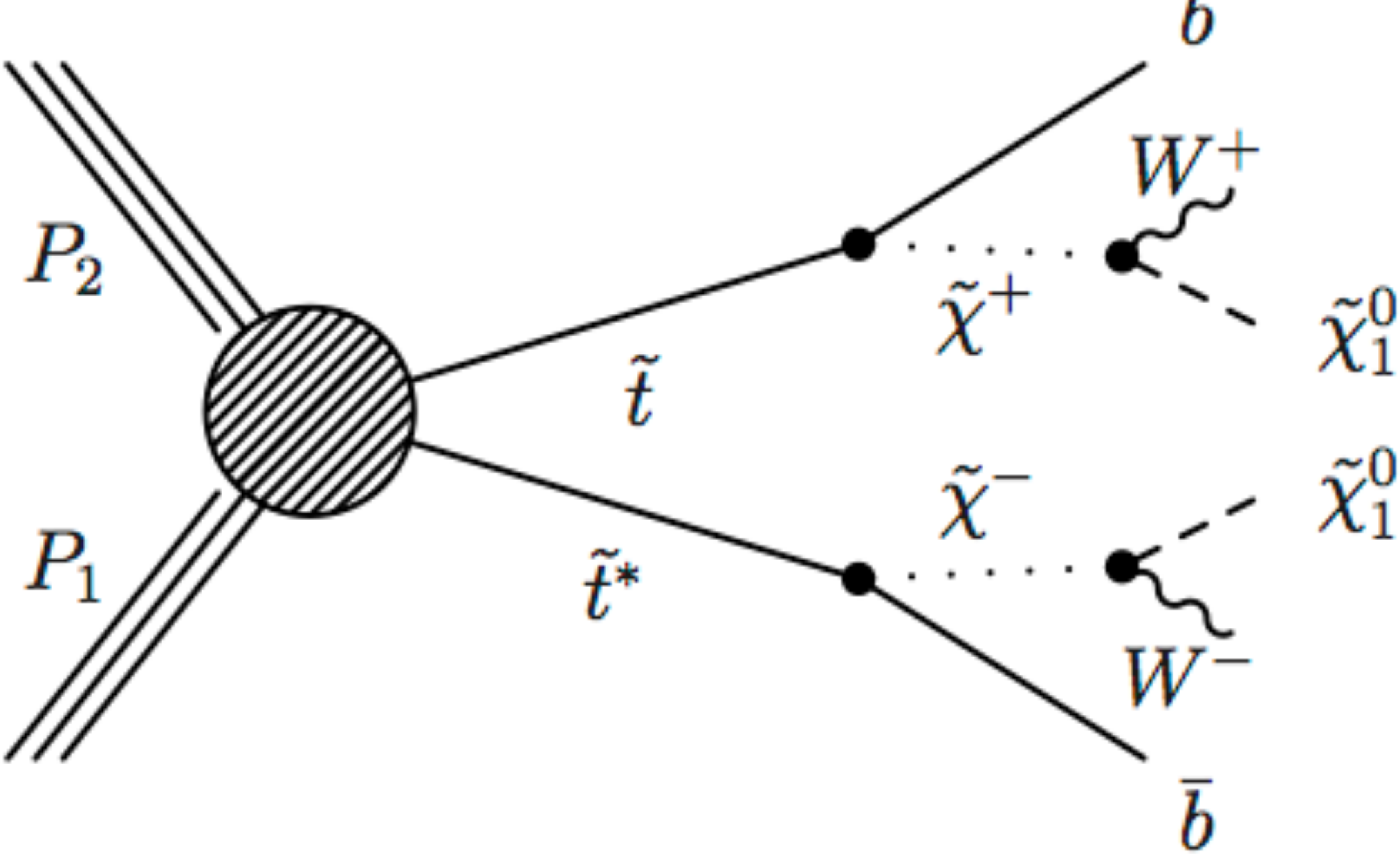
Maurizio Pierini

- Gluino-mediated searches

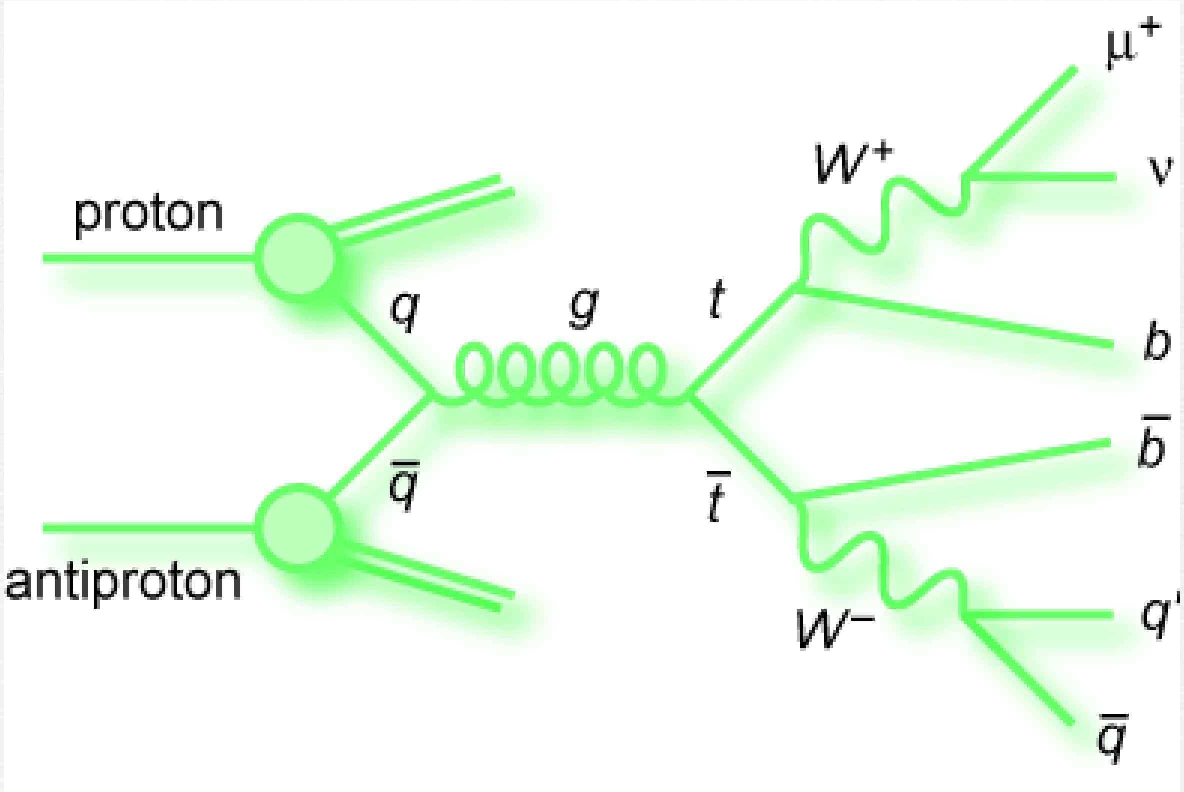
  Larger cross section
  4b quarks in the final state, with or w/o leptons
  More handles for bkg discrimination
  Gluinos might be too heavy for these searches to be effective



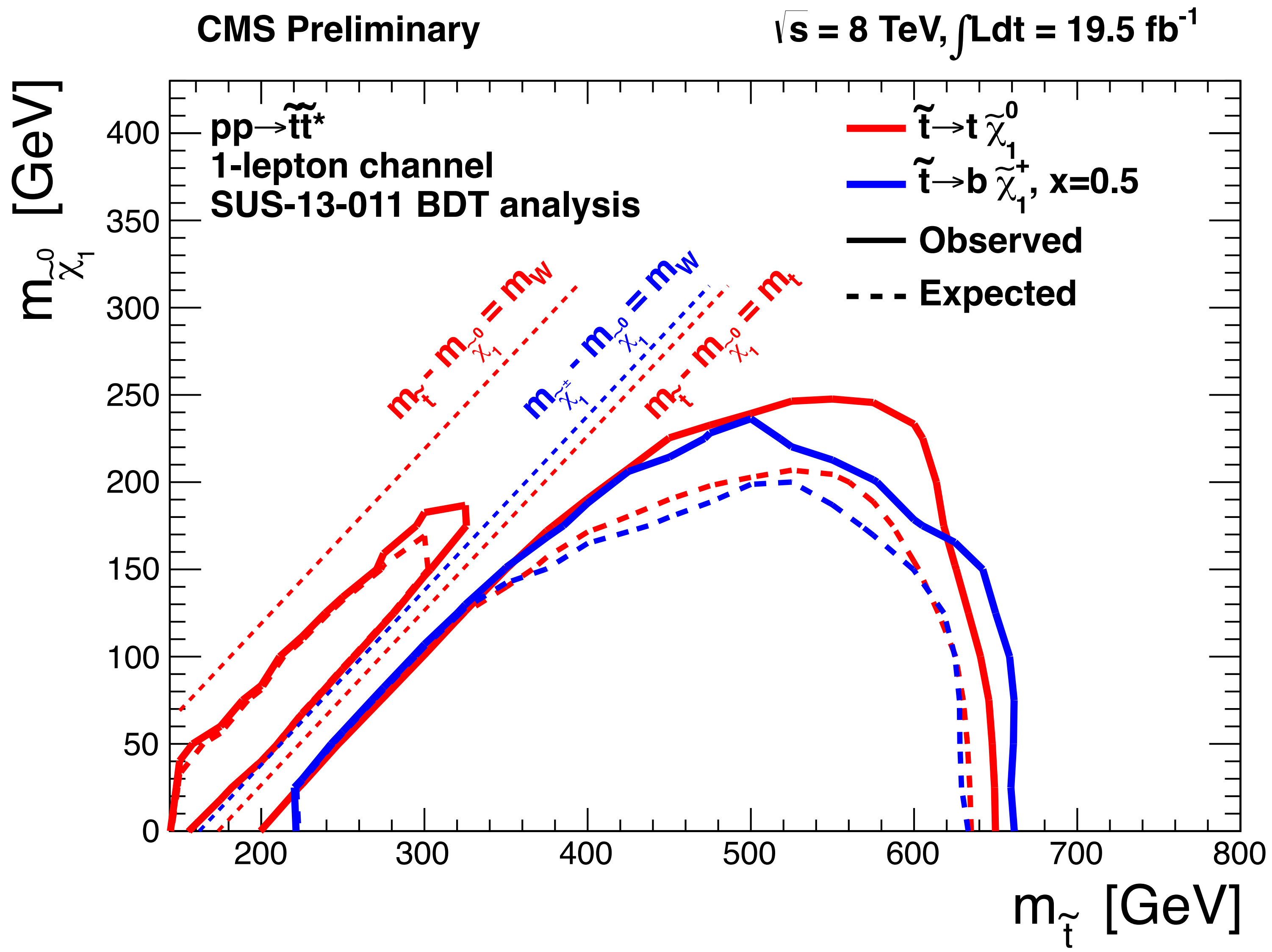
Direct stop production



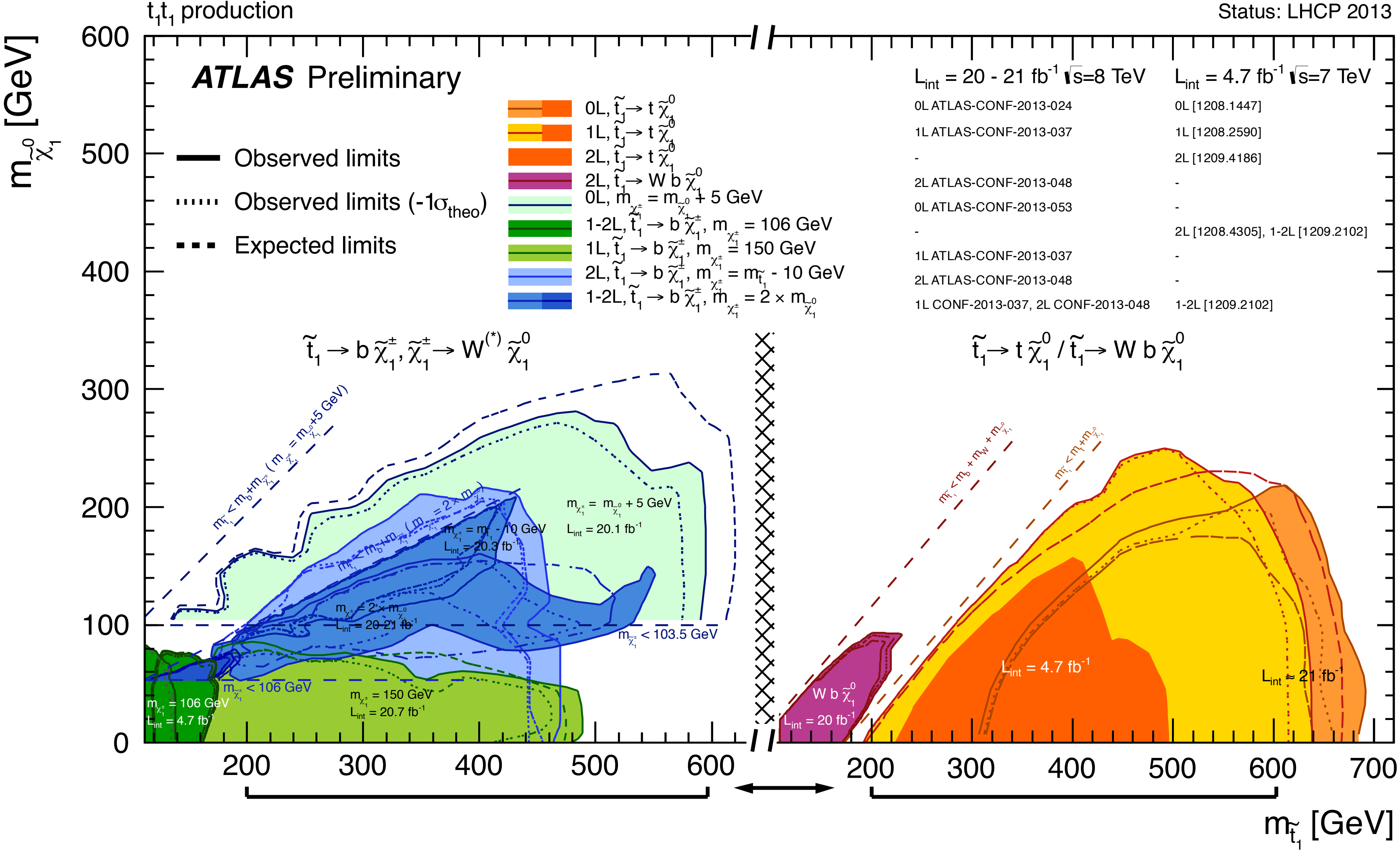
Top production background



Copious source of leptons + jets + missing energy

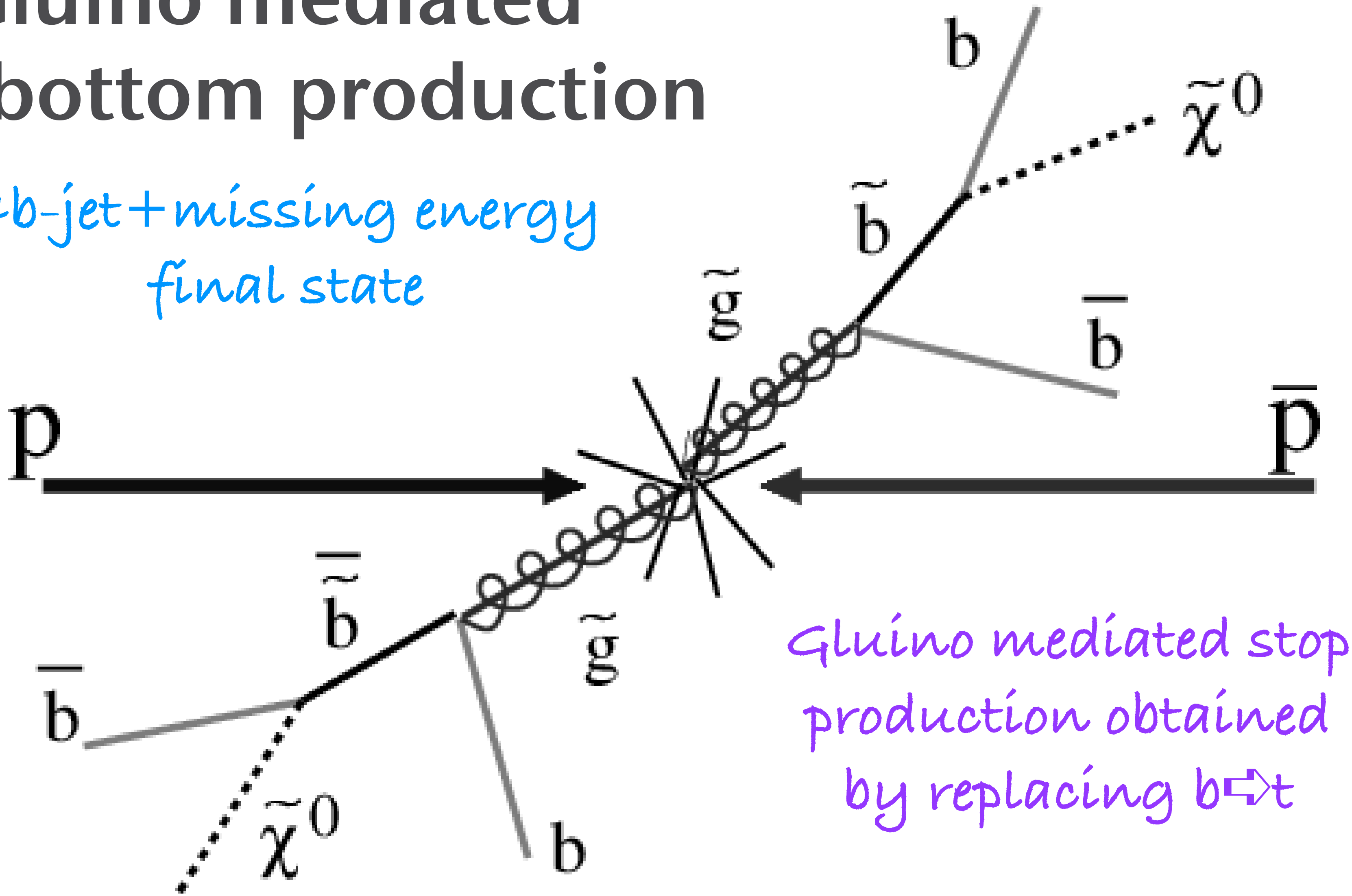

CMS Preliminary
$\sqrt{s}$ = 8 TeV, $\int$Ldt = 19.5 fb^{-1}
pp→$\tilde{t}\tilde{t}$*
1-lepton channel
SUS-13-011 BDT analysis
$\tilde{t}\rightarrow t\,\tilde{\chi}^0_1$
$\tilde{t}\rightarrow b\,\tilde{\chi}^+_1$, x=0.5
Observed
Expected
$m_{\tilde{t}} - m_{\tilde{\chi}^0_1} = m_W$
$m_{\tilde{\chi}^\pm_1} - m_{\tilde{\chi}^0_1} = m_W$
$m_{\tilde{t}} - m_{\tilde{\chi}^0_1} = m_t$
$m_{\tilde{\chi}^0_1}$ [GeV]
0
50
100
150
200
250
300
350
400
200
300
400
500
600
700
800
$m_{\tilde{t}}$ [GeV]

Stops at 700 GeV not excluded



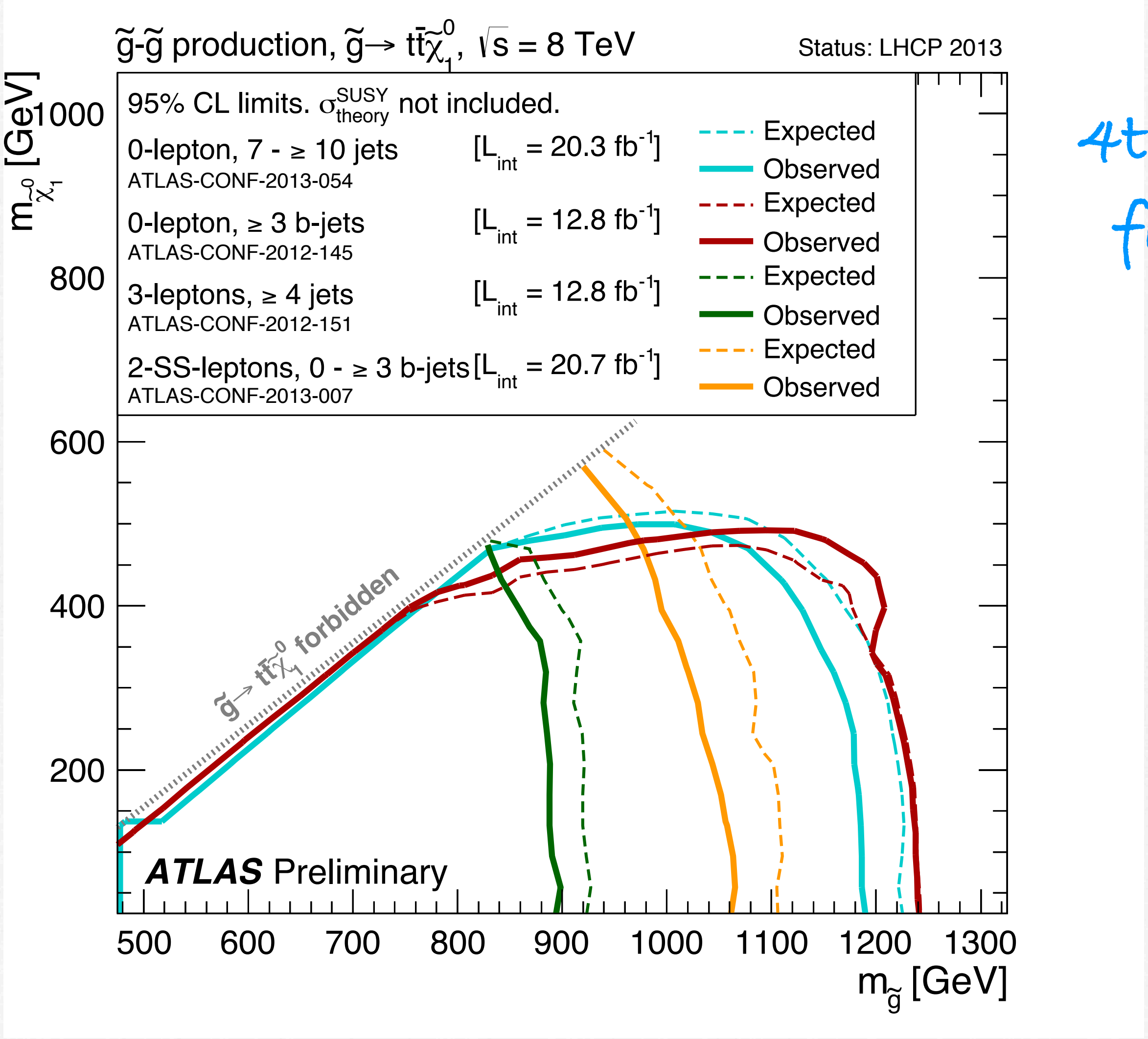
Gluino mediated sbottom production

4b-jet+missing energy final state



Gluino mediated stop production obtained by replacing b⇨t

Gluinos at 1250 GeV not excluded



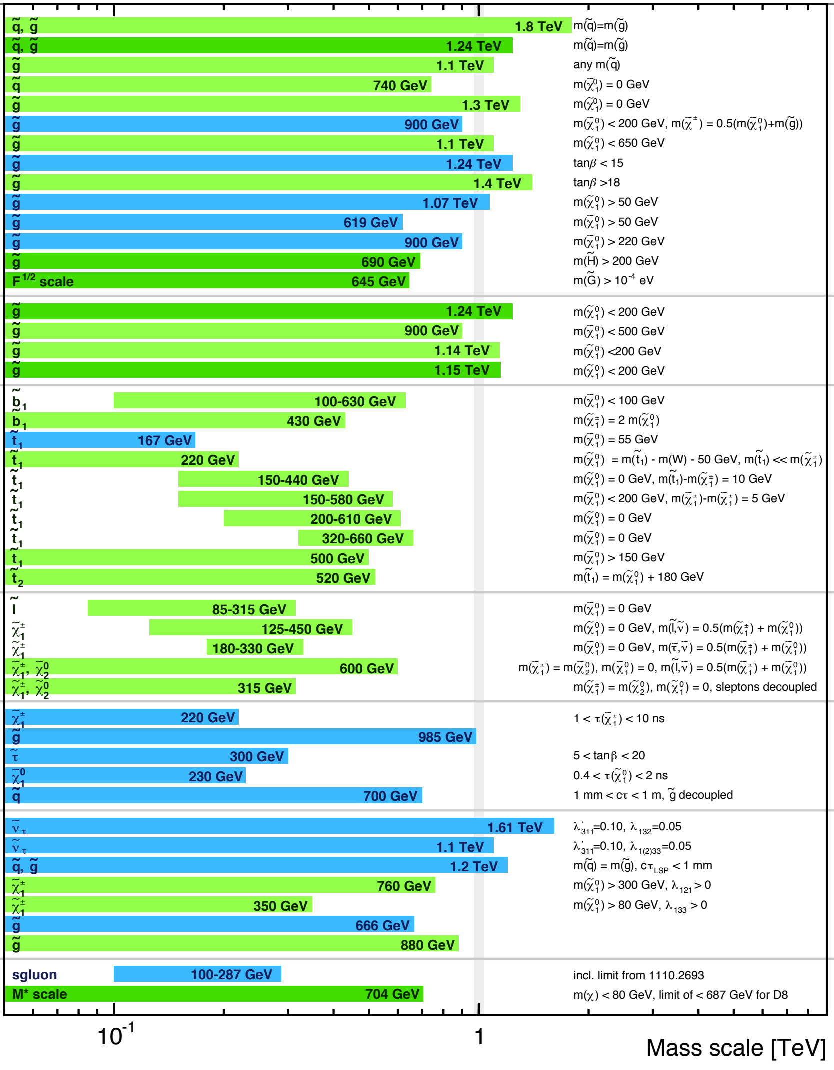
4t+missing final state

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: LHCP 2013

ATLAS Preliminary

$\int L dt = (4.4 - 20.7)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV



	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int L dt$ [fb^{-1}]	Mass limit			Reference
Inclusive searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$	1.8 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e, μ	4 jets	Yes	5.8	$\tilde{q}, \tilde{g}$	1.24 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2012-104
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-054
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	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
	Gluino med. $\tilde{\chi}^\pm$ ($\tilde{g}\to q\bar{q}\tilde{\chi}^\pm$)	1 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$	900 GeV	$m(\tilde{\chi}_1^0) < 200$ GeV, $m(\tilde{\chi}^\pm) = 0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	1208.4688
	$\tilde{g}\tilde{g}\to qqqqll(ll)\tilde{\chi}_1^0\tilde{\chi}_1^0$	2 e, μ (SS)	3 jets	Yes	20.7	$\tilde{g}$	1.1 TeV	$m(\tilde{\chi}_1^0) < 650$ GeV	ATLAS-CONF-2013-007
	GMSB ($\tilde{l}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	$\tan\beta < 15$	1208.4688
	GMSB ($\tilde{l}$ 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	0	Yes	4.8	$\tilde{g}$	1.07 TeV	$m(\tilde{\chi}_1^0) > 50$ GeV	1209.0753
	GGM (wino NLSP)	1 e, μ + γ	0	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	12.8	$\tilde{g}$	1.24 TeV	$m(\tilde{\chi}_1^0) < 200$ GeV	ATLAS-CONF-2012-145
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	2 e, μ (SS)	0-3 b	No	20.7	$\tilde{g}$	900 GeV	$m(\tilde{\chi}_1^0) < 500$ GeV	ATLAS-CONF-2013-007
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.14 TeV	$m(\tilde{\chi}_1^0) <200$ GeV	ATLAS-CONF-2013-054
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	3 b	Yes	12.8	$\tilde{g}$	1.15 TeV	$m(\tilde{\chi}_1^0) < 200$ GeV	ATLAS-CONF-2012-145
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	$\tilde{b}_1$	100-630 GeV	$m(\tilde{\chi}_1^0) < 100$ GeV	ATLAS-CONF-2013-053
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$	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	$\tilde{t}_1$	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	$\tilde{t}_1$	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), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	150-440 GeV	$m(\tilde{\chi}_1^0) = 0$ GeV, $m(\tilde{t}_1)-m(\tilde{\chi}_1^\pm) = 10$ GeV	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$ (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, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^\pm) = 5$ GeV	ATLAS-CONF-2013-053
	$\tilde{t}_1\tilde{t}_1$ (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
	$\tilde{t}_1\tilde{t}_1$ (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	$\tilde{t}_2$	520 GeV	$m(\tilde{t}_1) = m(\tilde{\chi}_1^0) + 180$ GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{l}_{L,R}\tilde{l}_{L,R}, \tilde{l}\to l\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{l}$	85-315 GeV	$m(\tilde{\chi}_1^0) = 0$ GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{l}\nu\,(l\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$	125-450 GeV	$m(\tilde{\chi}_1^0) = 0$ GeV, $m(\tilde{l},\tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu\,(\tau\tilde{\nu})$	2 τ	0	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
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \to \tilde{l}_L\nu\tilde{l}_L l(\tilde{\nu}\nu), l\tilde{\nu}\tilde{l}_L l(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	600 GeV	$m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0) = 0$, $m(\tilde{l},\tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$	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
Long-lived particles	Direct $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ prod., long-lived $\tilde{\chi}_1^\pm$	0	1 jet	Yes	4.7	$\tilde{\chi}_1^\pm$	220 GeV	$1 < \tau(\tilde{\chi}_1^\pm) < 10$ ns	1210.2852
	Stable $\tilde{g}$, R-hadrons	0-2 e, μ	0	Yes	4.7	$\tilde{g}$	985 GeV		1211.1597
	GMSB, stable $\tilde{\tau}$, low β	2 e, μ	0	Yes	4.7	$\tilde{\tau}$	300 GeV	$5 < \tan\beta < 20$	1211.1597
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	0	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	$0.4 < \tau(\tilde{\chi}_1^0) < 2$ ns	1304.6310
	$\tilde{\chi}_1^0 \to qq\mu$ (RPV)	1 e, μ	0	Yes	4.4	$\tilde{q}$	700 GeV	1 mm < cτ < 1 m, $\tilde{g}$ decoupled	1210.7451
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e+\mu$	2 e, μ	0	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	$\lambda'_{311}=0.10$, $\lambda_{132}=0.05$	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e(\mu)+\tau$	1 e,μ + τ	0	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	$\lambda'_{311}=0.10$, $\lambda_{1(2)33}=0.05$	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
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\nu_\mu, e\mu\nu_e$	4 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm$	760 GeV	$m(\tilde{\chi}_1^0) > 300$ GeV, $\lambda_{121} > 0$	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$	3 e, μ + τ	0	Yes	20.7	$\tilde{\chi}_1^\pm$	350 GeV	$m(\tilde{\chi}_1^0) > 80$ GeV, $\lambda_{133} > 0$	ATLAS-CONF-2013-036
	$\tilde{g} \to qqq$	0	6 jets	-	4.6	$\tilde{g}$	666 GeV		1210.4813
	$\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$	880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	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

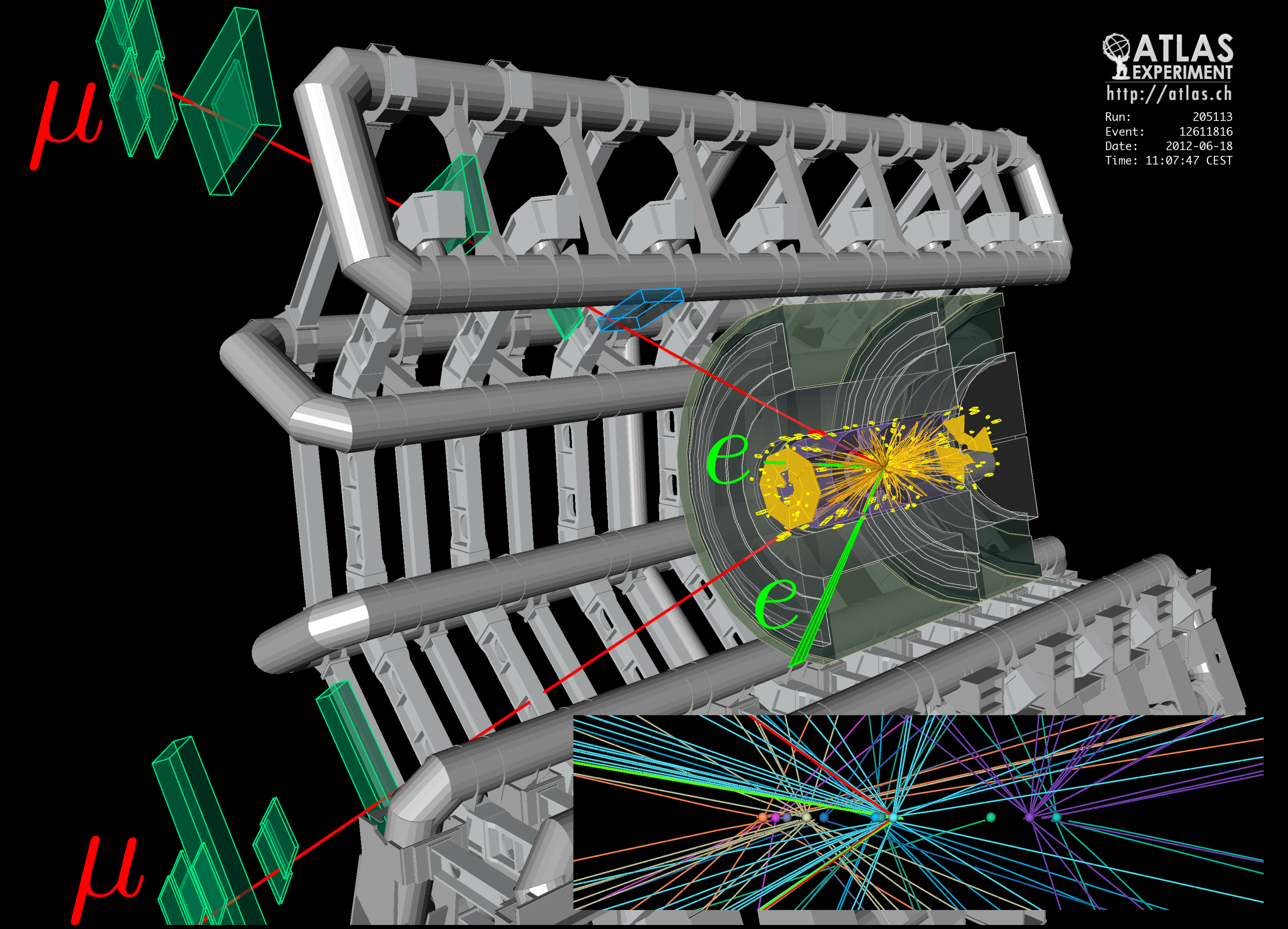
$\sqrt{s}$ = 7 TeV full data

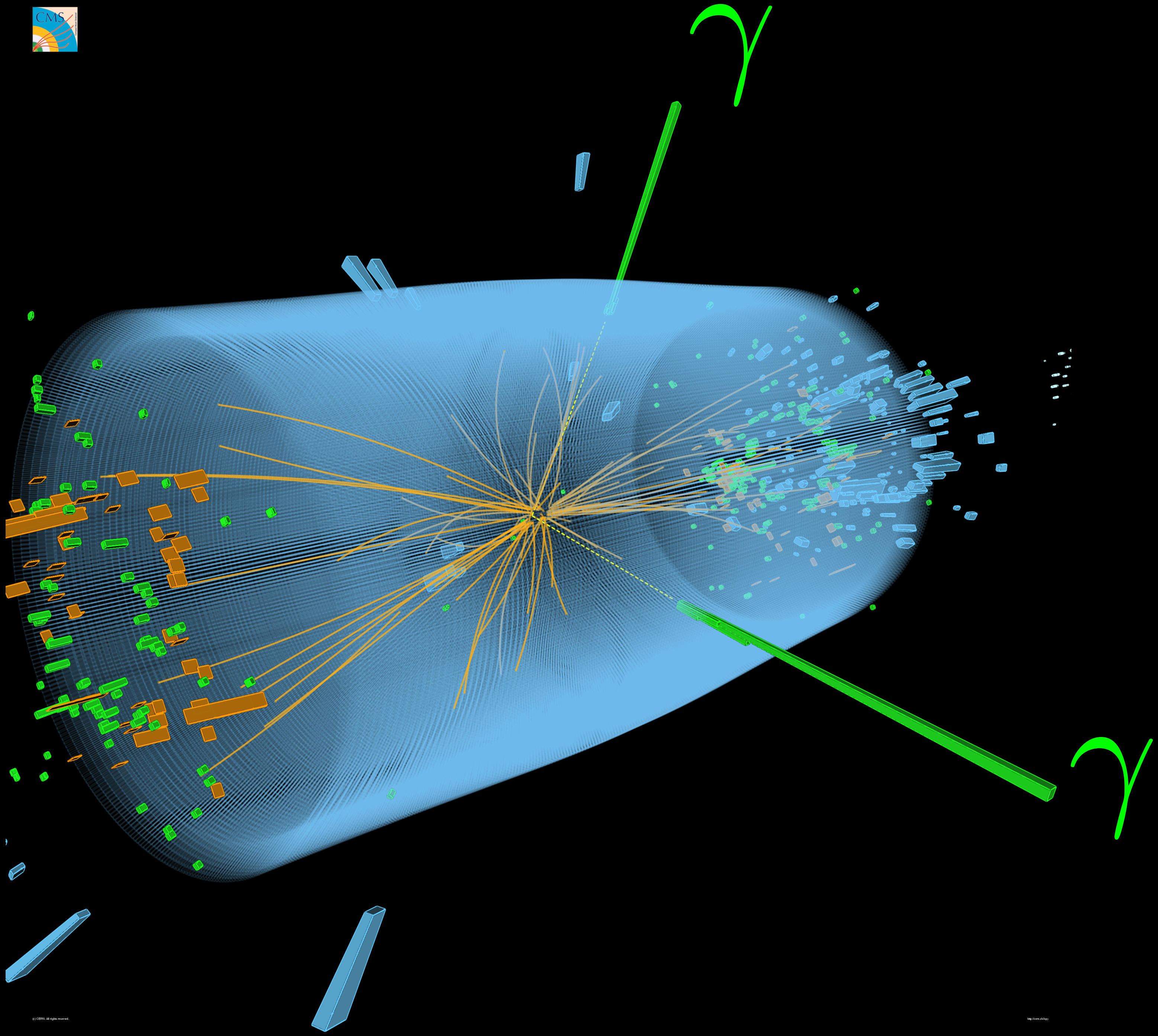
$\sqrt{s}$ = 8 TeV partial data

$\sqrt{s}$ = 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.*

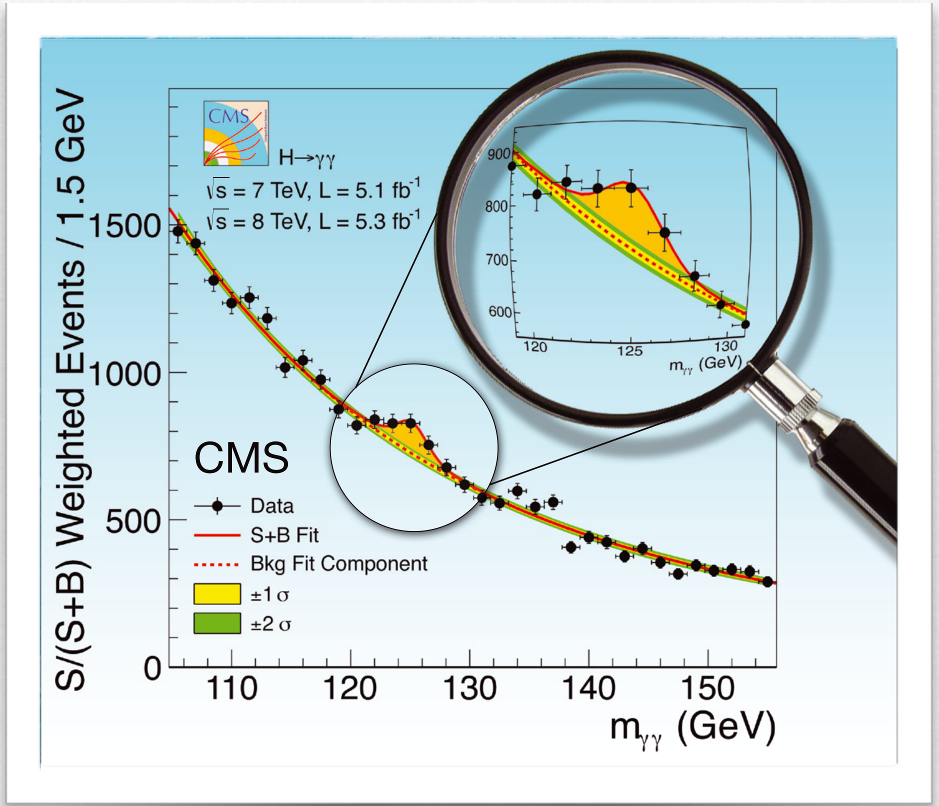
SUSY Higgs


ATLAS EXPERIMENT
http://atlas.ch
Run: 205113
Event: 12611816
Date: 2012-06-18
Time: 11:07:47 CEST
μ
e
e
μ



CMS
γ
γ
http://cern.ch/ispy

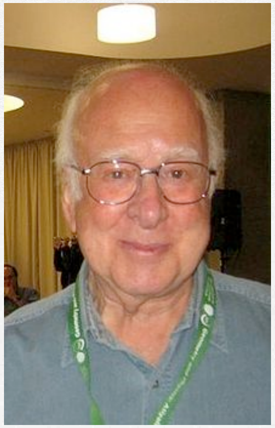
LHC has discovered a new particle



Congratulations to both
Atlas and CMS Collaborations
and to the builders of the LHC
on a magnificent achievement!

Peter Higgs

30 August 2012

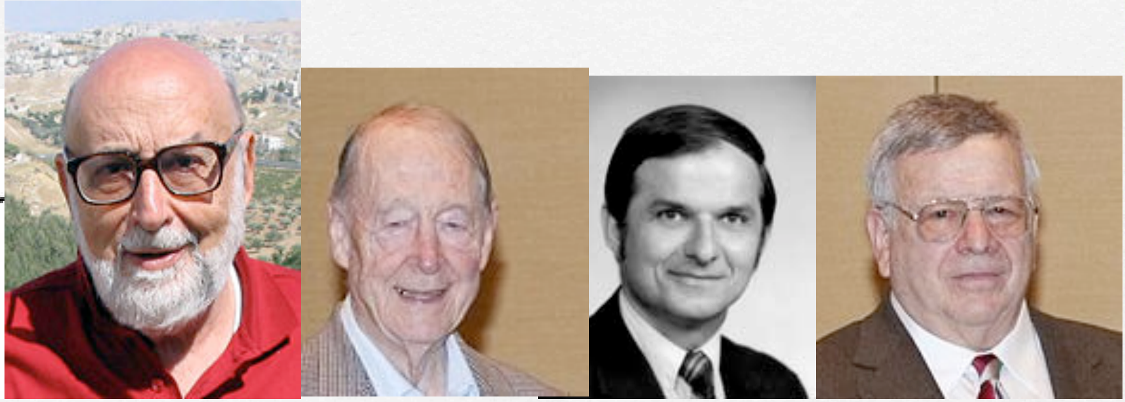


" … The decay to two photons indicates that the new particle is a boson with spin different from one. The results presented here are consistent, … with expectations for a standard model Higgs boson."

\- CMS Collaboration

Not only does the discovery yield the missing link to the present Standard Model theory of elementary particles, but a detailed analysis of the decays, in particular of the decay of the Scalar to two photons which is sensitive to loops of intermediated charged particles, will possibly yield information about the spectrum beyond the Standard Model.

Prof. François Englert



It is great to know that the famous boson almost certainly exists, and we are eagerly waiting for detailed measurement of its properties.

Prof. Tom Kibble

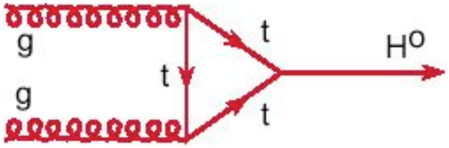
Tom Kibble

Prof. Carl R. Hagen

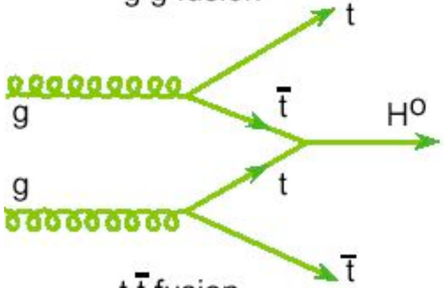
Carl R Hagen

Prof. Gerald Guralnik

- Higgs production mechanisms and cross sections

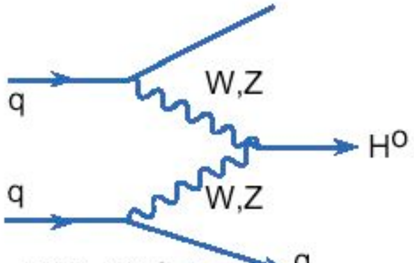


g g fusion

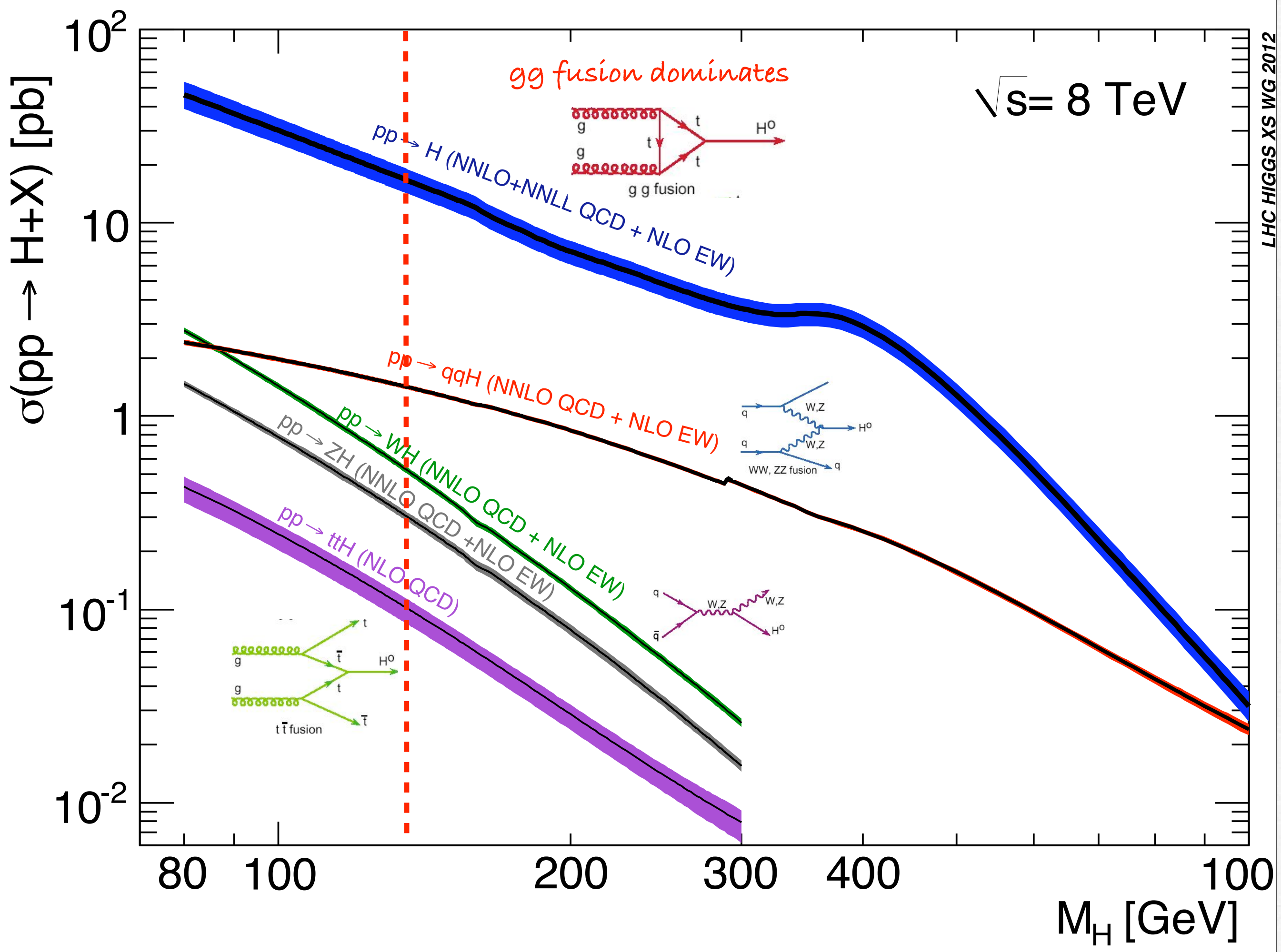


$t\,\bar{t}$ fusion

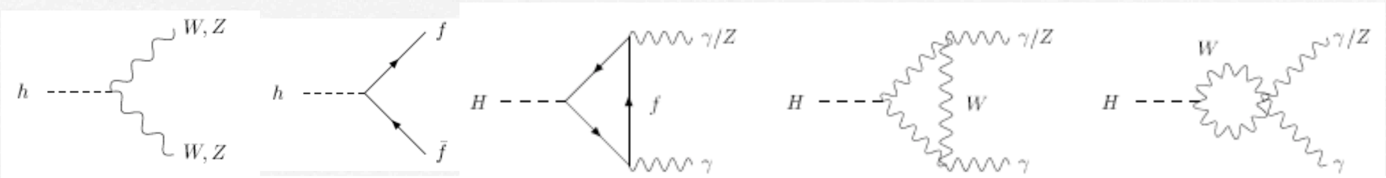
W, Z bremsstrahlung



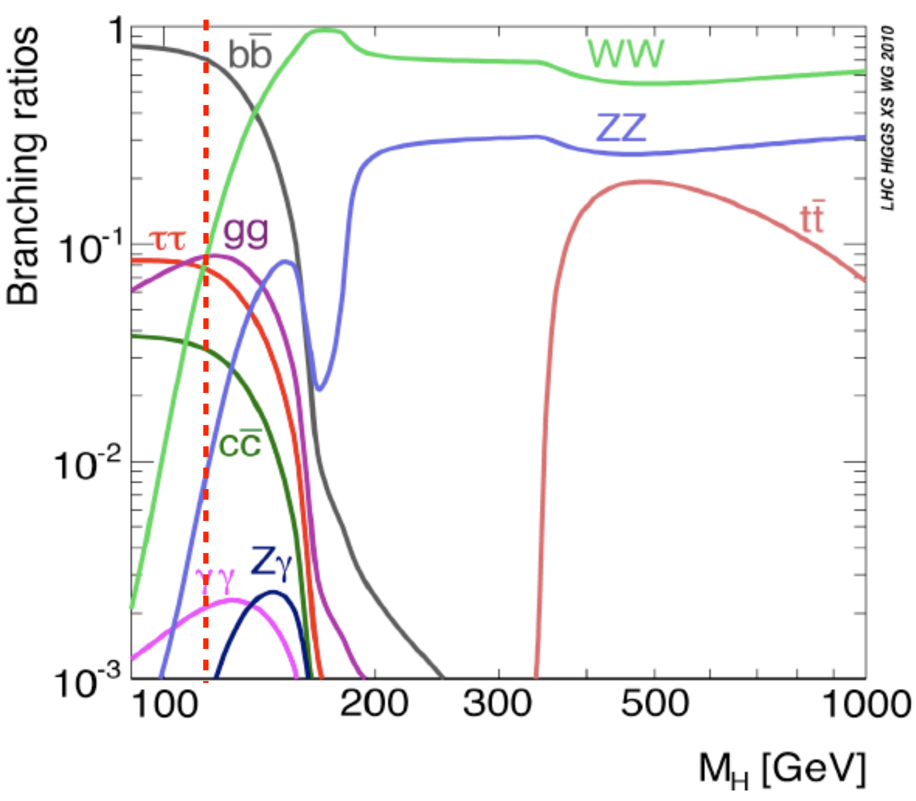
WW, ZZ fusion

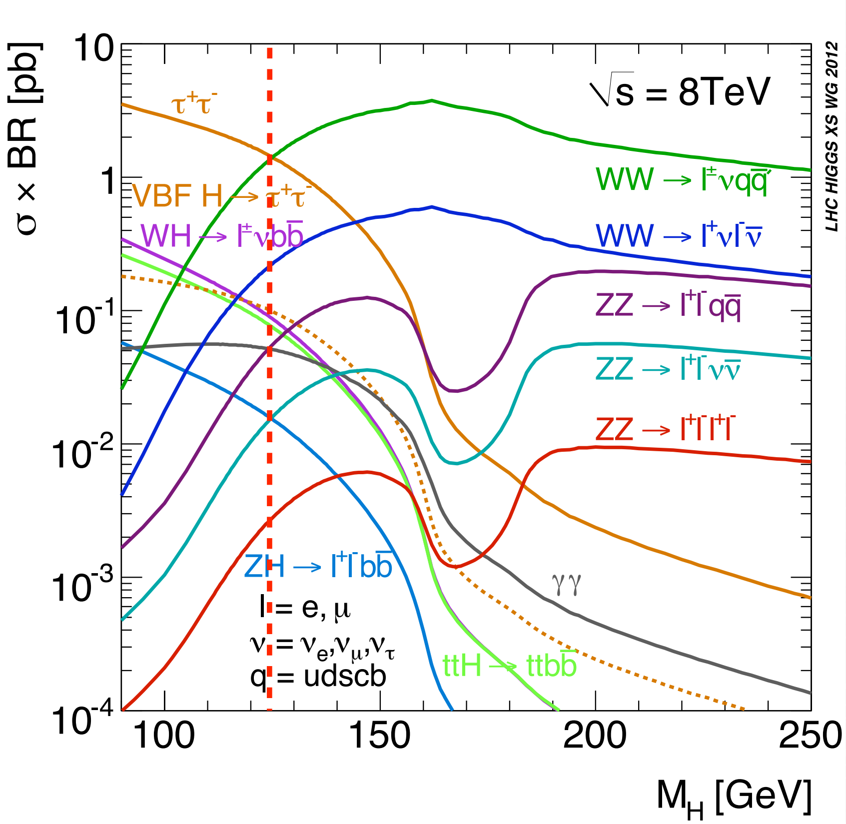


Higgs Decays



LHC search channels





Higgs in MSSM

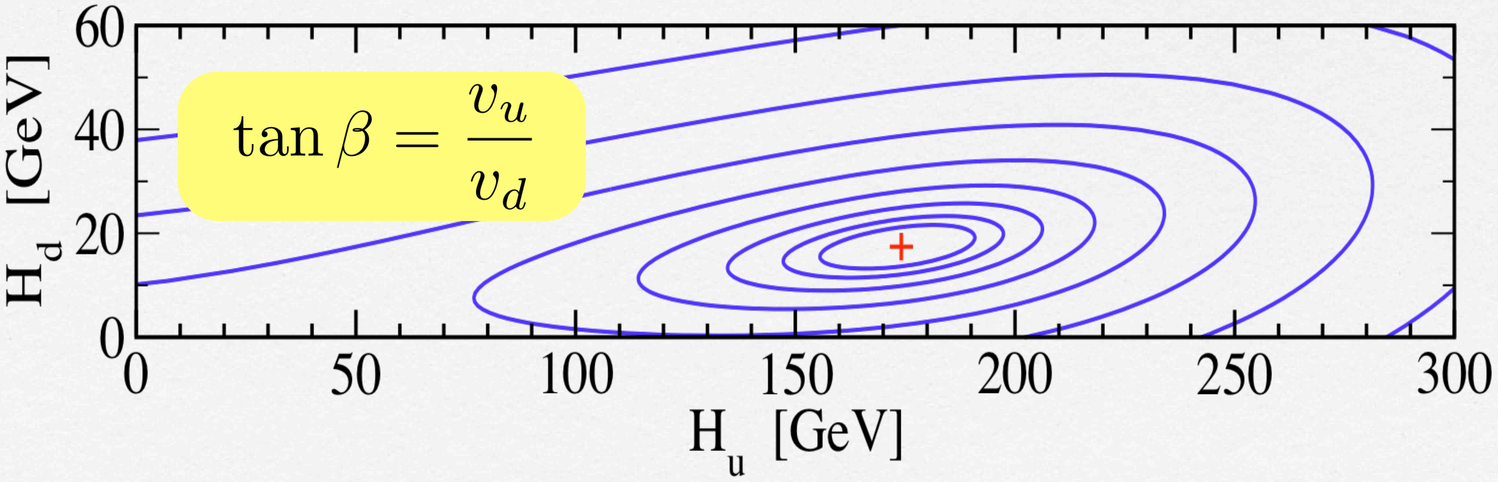
A special two Higgs doublet model

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

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

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

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



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

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

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

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

$$M_A \gg M_Z$$

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

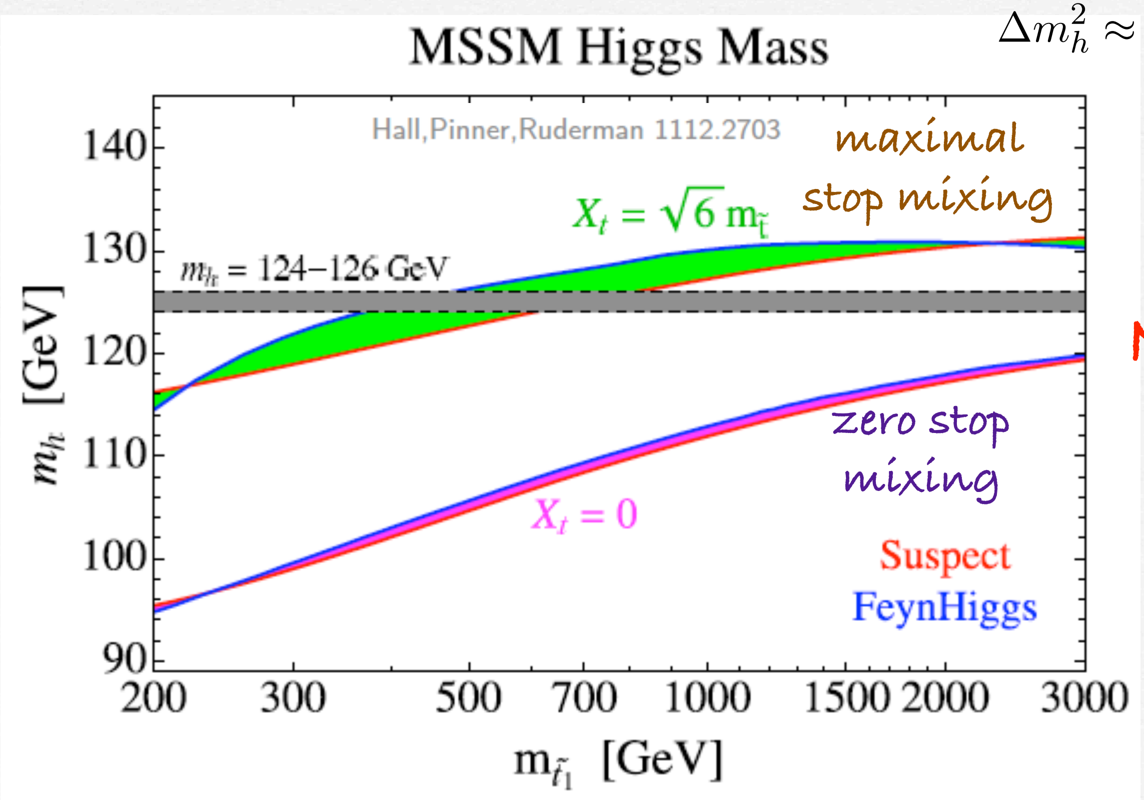
$$\sin(\beta-\alpha) \simeq 1 + \mathcal{O}(M_Z^4/M_A^4).$$

Higgs h Mass in MSSM

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

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

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



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

Need $\Delta m_h \approx M_Z$

Must have heavy stops

Large Fine Tuning!

Next-to-Minimal SUSY SM (NMSSM)

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

SH_uH_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

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

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

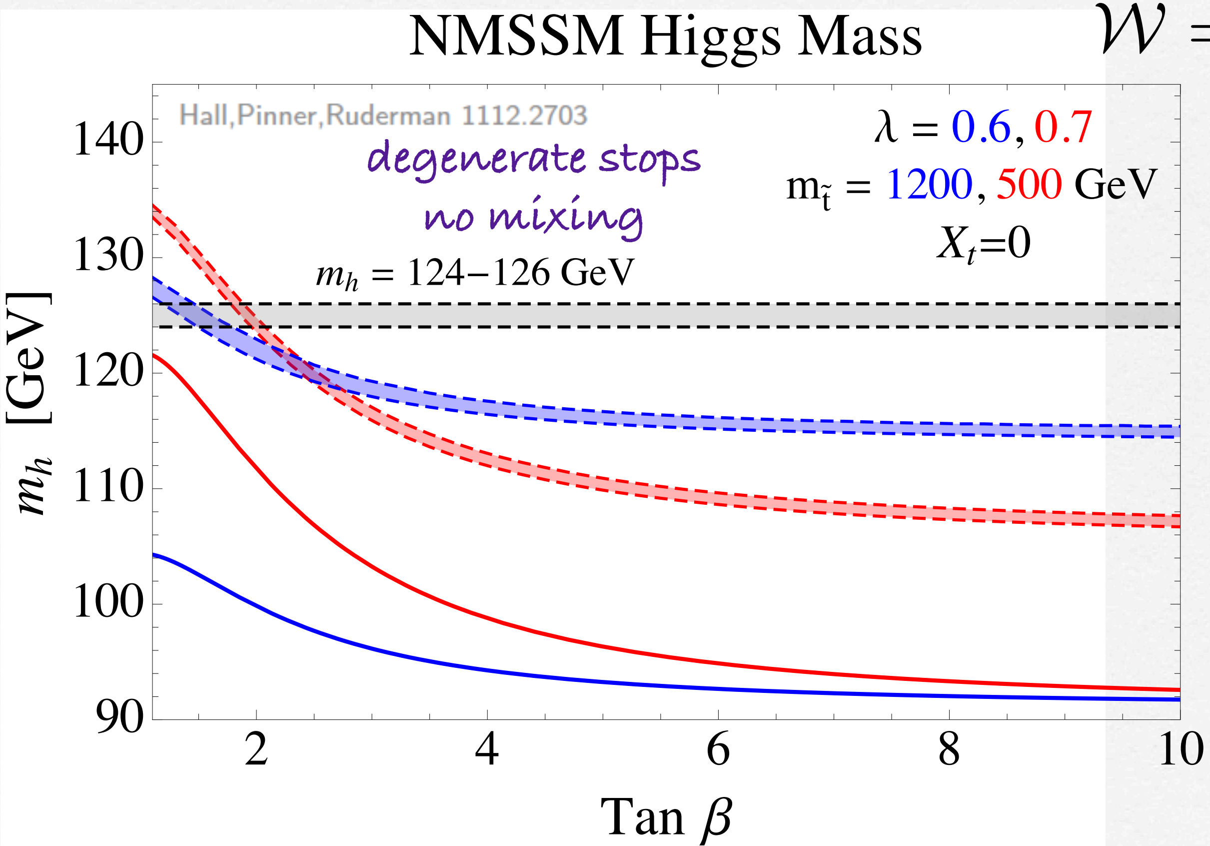
$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \Delta m_h^2$$

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

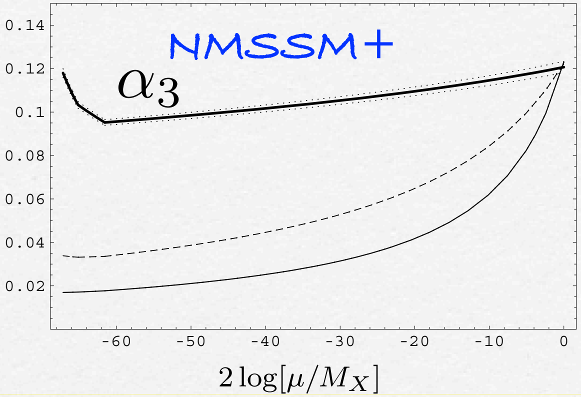
NMSSM+

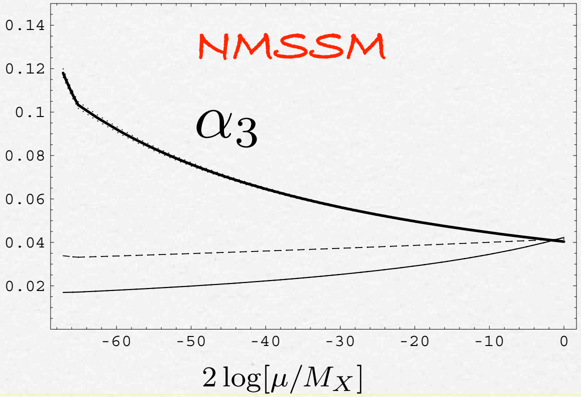
$$W^{\text{NMSSM+}} \in 3(27) \text{ of } E_6$$

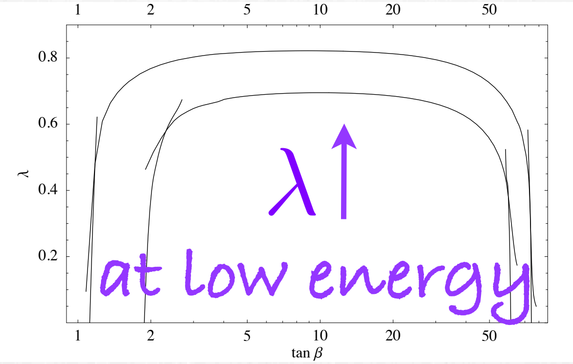
$$W^{\text{extra}} \in 3(5+\bar{5}) \text{ of } SU(5)$$

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

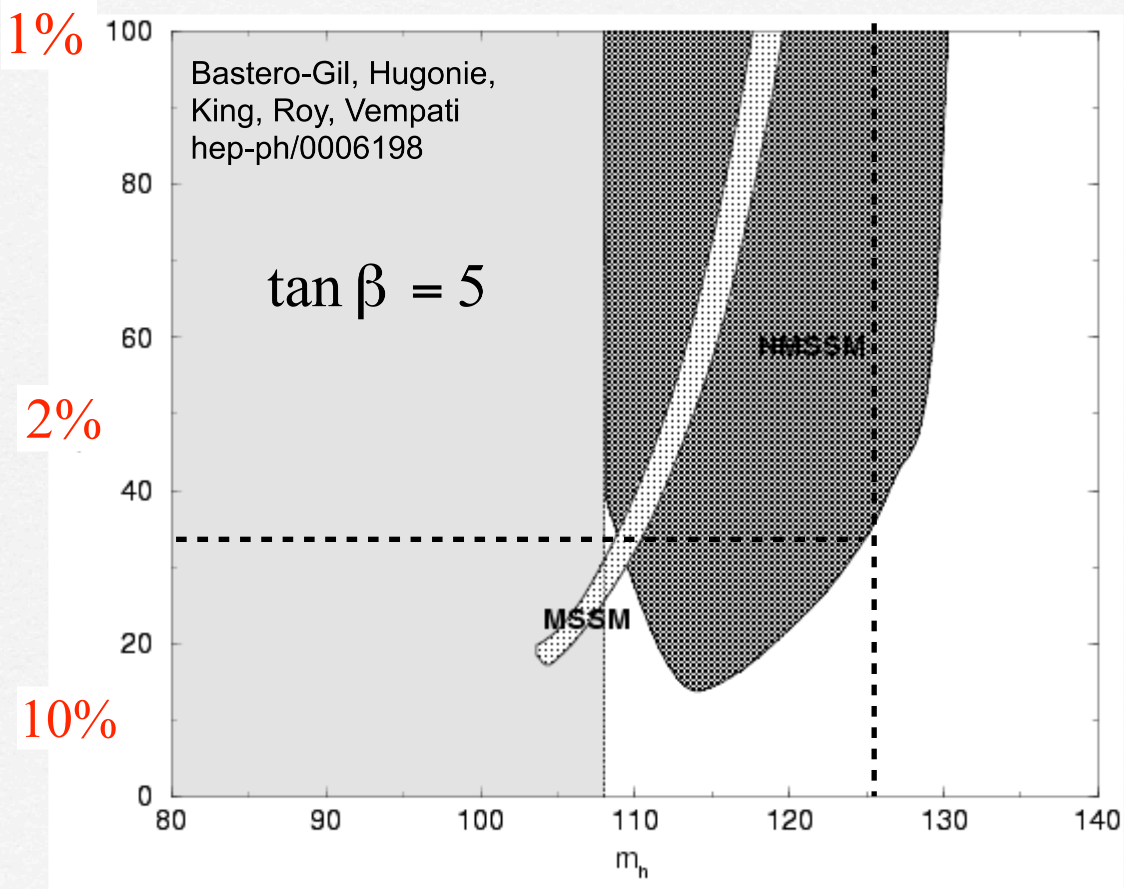
$h_t\downarrow$ at high energy

$\lambda\downarrow$ at high energy

Allows $\lambda \sim 0.8$ 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

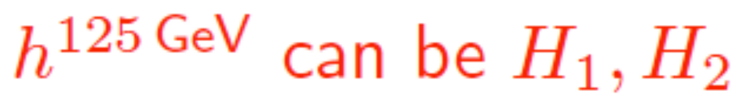
NMSSM Higgs Mixing

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



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

CP odd mass eigenstates

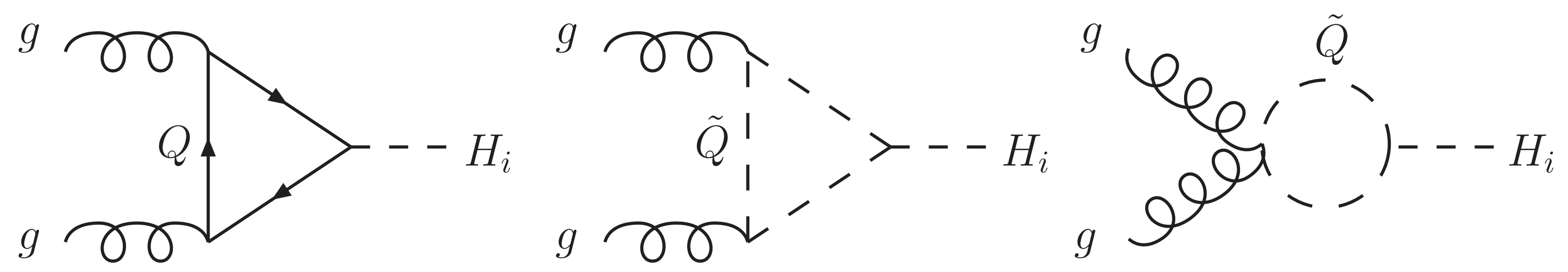
$$
\begin{aligned}
A_1^{\mathrm{mass}} &= P'_{11} A + P'_{12} S_I\ , \\
A_2^{\mathrm{mass}} &= P'_{21} A + P'_{22} S_I\ .
\end{aligned}
$$

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

NMSSM Higgs Phenomenology

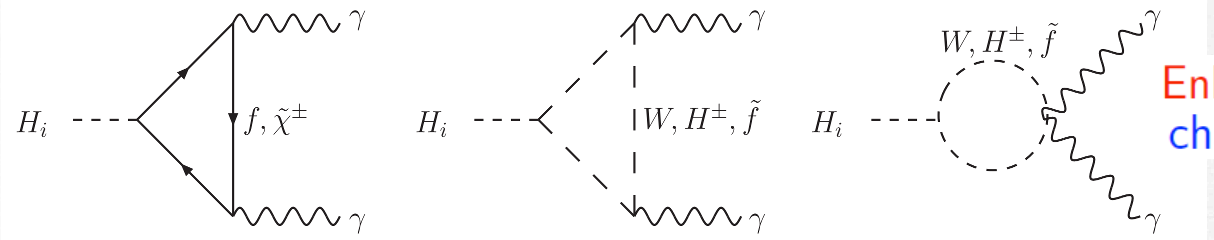
Enhanced gluon fusion production

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



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

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



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

Definitions

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

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

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

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

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

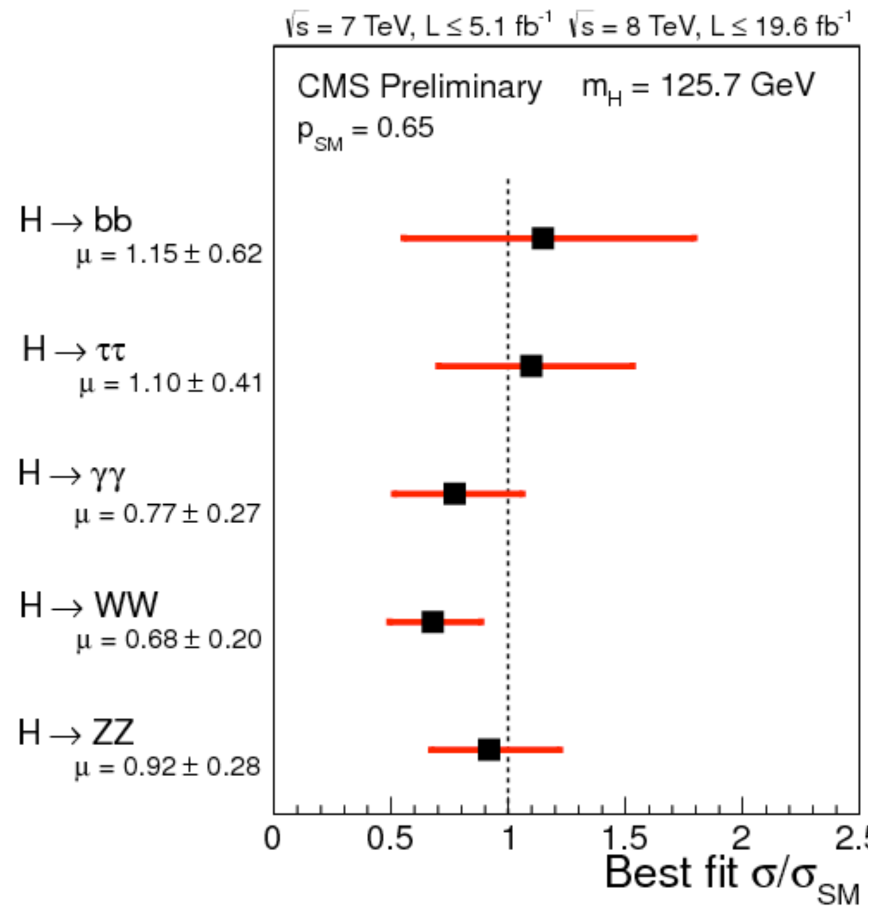
$$R_{VV}(H_i) \equiv R_{\sigma_{incl}}(H_i) R^{BR}_{VV}(H_i) \qquad R_{\tau\bar{\tau}} \equiv R_{\sigma_{incl}}(H_i) R^{BR}_{\tau\bar{\tau}}(H_i)$$

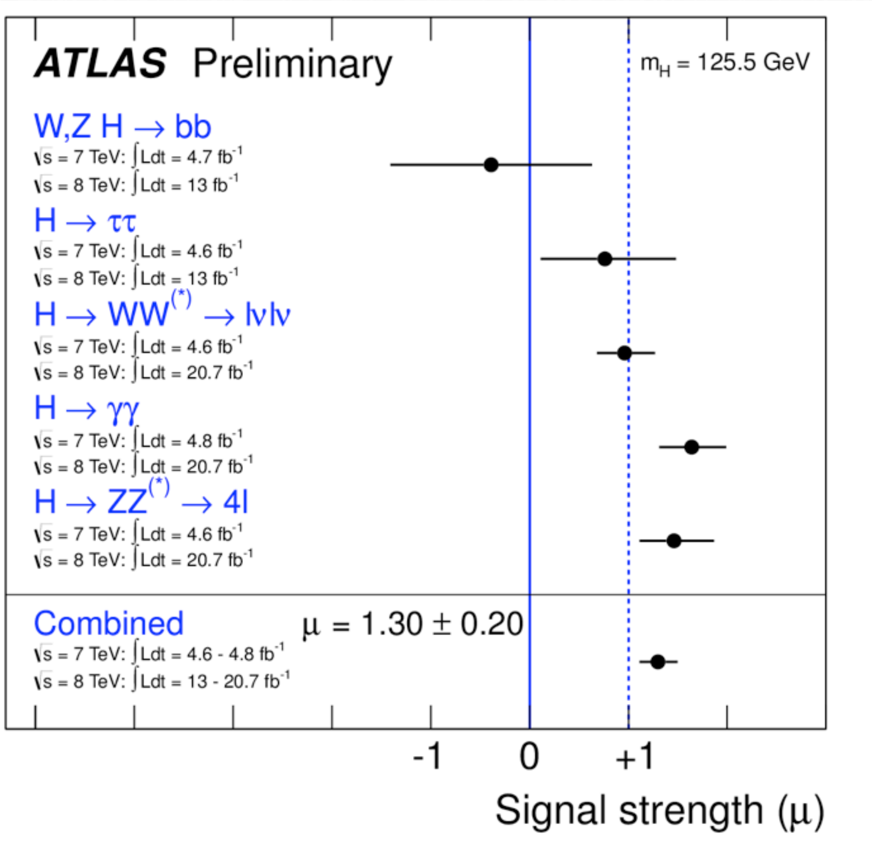
$$\mu_{XX}(h) \equiv R_{\sigma}(h) R^{BR}_{XX}(h) + \sum_{\substack{\Phi \neq h \\ |M_\Phi - M_h| \leq \delta}} R_{\sigma}(\Phi) R^{BR}_{XX}(\Phi) F(M_h, M_\Phi, d_{XX})$$

Gaussian weighting function

NMSSM Tools

LHC Data


$\sqrt{s}$ = 7 TeV, L ≤ 5.1 fb^{-1} $\sqrt{s}$ = 8 TeV, L ≤ 19.6 fb^{-1}
CMS Preliminary
m_H = 125.7 GeV
p_{SM} = 0.65
$H \to bb$
$\mu = 1.15 \pm 0.62$
$H \to \tau\tau$
$\mu = 1.10 \pm 0.41$
$H \to \gamma\gamma$
$\mu = 0.77 \pm 0.27$
$H \to WW$
$\mu = 0.68 \pm 0.20$
$H \to ZZ$
$\mu = 0.92 \pm 0.28$
0
0.5
1
1.5
2
2.
Best fit σ/σ_{SM}


ATLAS Preliminary
m_H = 125.5 GeV
W,Z H → bb
$\sqrt{s}$ = 7 TeV: $\int Ldt$ = 4.7 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 13 fb^{-1}
$H \to \tau\tau$
$\sqrt{s}$ = 7 TeV: $\int Ldt$ = 4.6 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 13 fb^{-1}
$H \to WW^{(*)} \to l\nu l\nu$
$\sqrt{s}$ = 7 TeV: $\int Ldt$ = 4.6 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 20.7 fb^{-1}
$H \to \gamma\gamma$
$\sqrt{s}$ = 7 TeV: $\int Ldt$ = 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 20.7 fb^{-1}
$H \to ZZ^{(*)} \to 4l$
$\sqrt{s}$ = 7 TeV: $\int Ldt$ = 4.6 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 20.7 fb^{-1}
Combined
$\mu = 1.30 \pm 0.20$
$\sqrt{s}$ = 7 TeV: $\int Ldt$ = 4.6 - 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 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

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

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

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

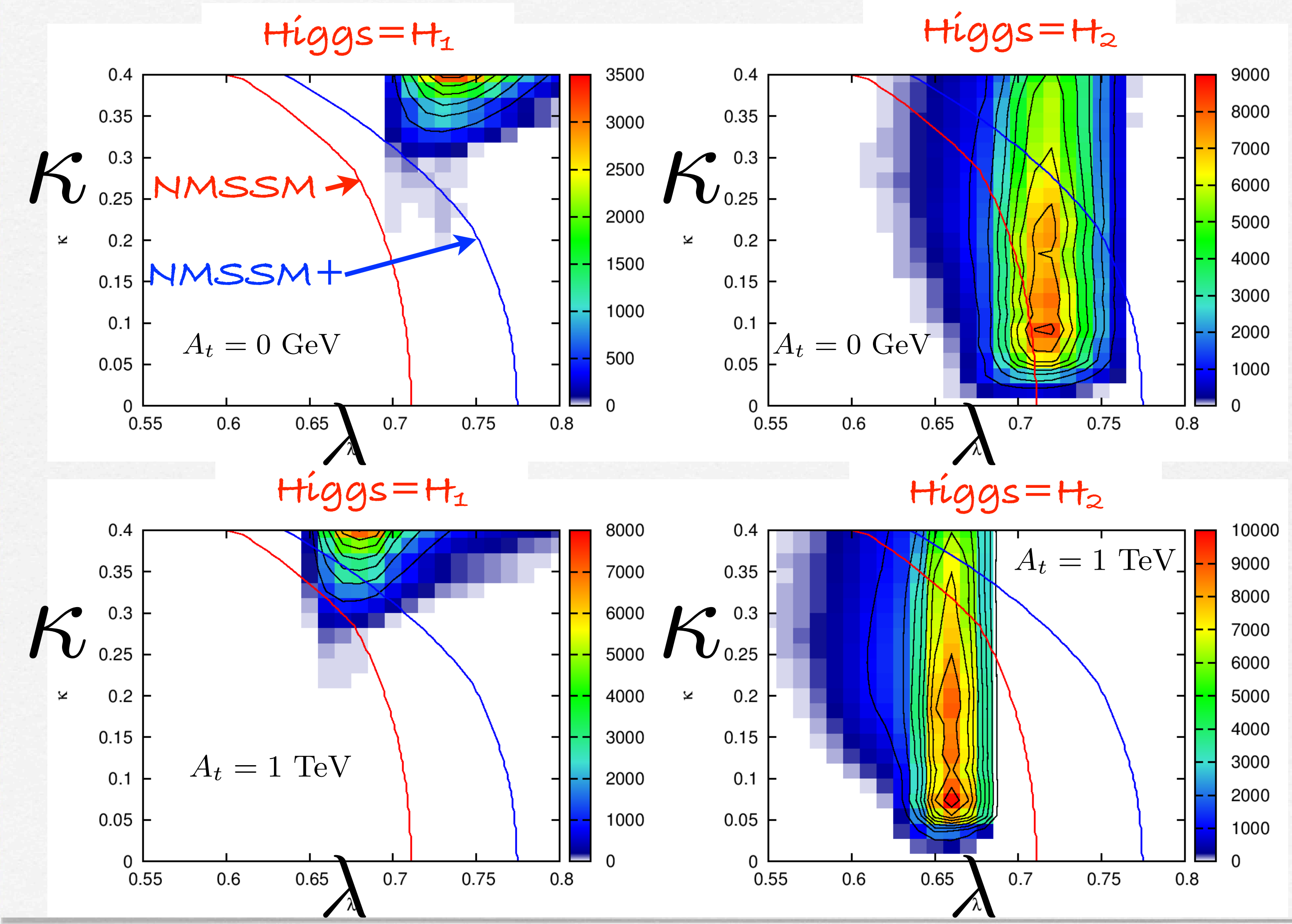
$$500\ \mathrm{GeV} \le M_{\tilde{Q}_3} = M_{\tilde{t}_R} \le 800\ \mathrm{GeV} \qquad A_U = 0\ \mathrm{GeV} \quad \text{and} \quad 1\ \mathrm{TeV}$$

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

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

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

λ - κ in NMSSM and NMSSM+



King, Muhlleitner,
Nevzorov, Walz
1211.5074

Colour coding
is number of
points in scan

Higgs spectrum in NMSSM

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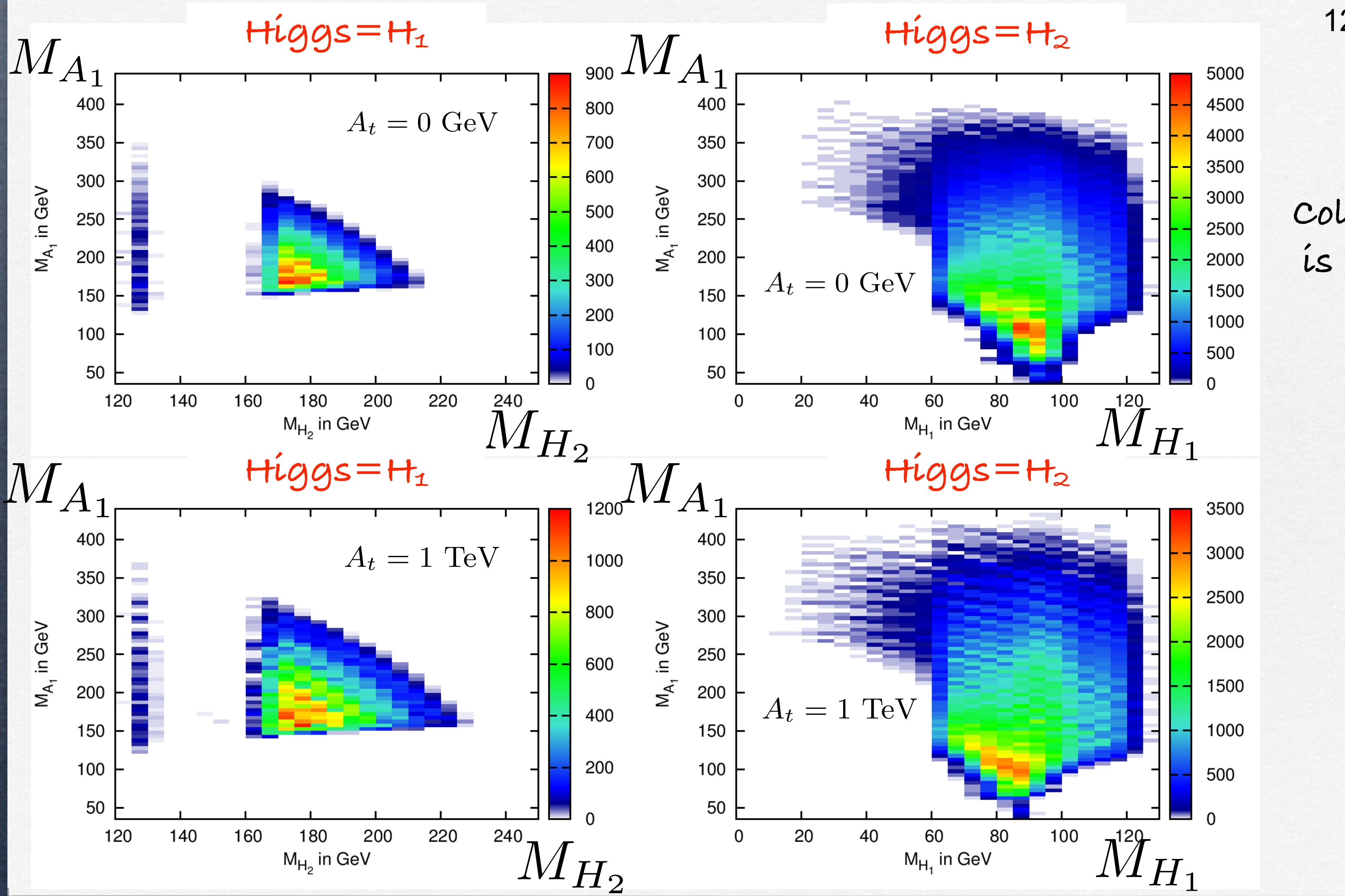
Nevzorov, Walz
1211.5074



Colour coding is number of points

Higgs →diphotons in NMSSM

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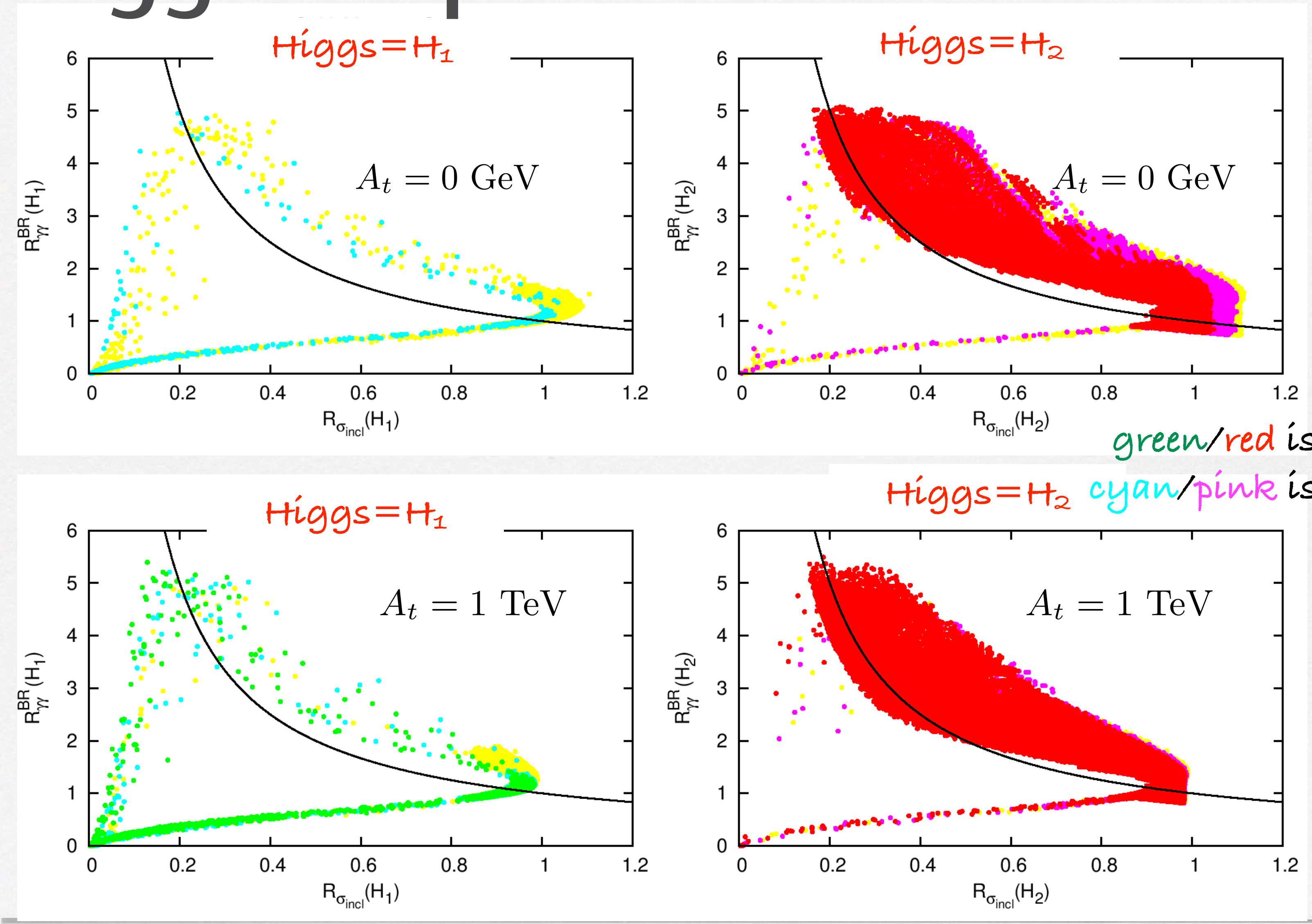
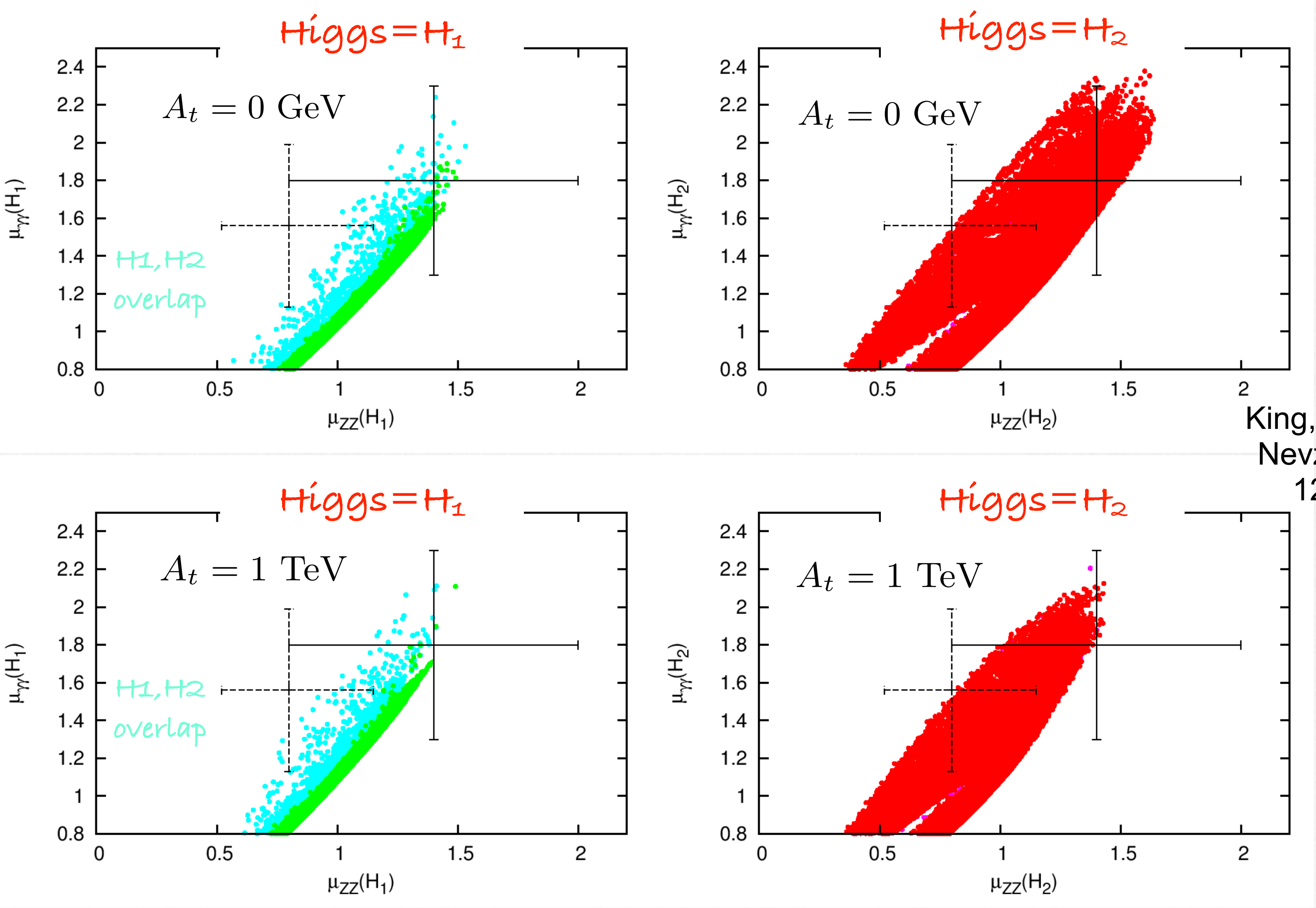


green/red is NMSSM
cyan/pink is NMSSM+

Diphoton vs. ZZ decays in NMSSM



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Diphoton vs. WW decays

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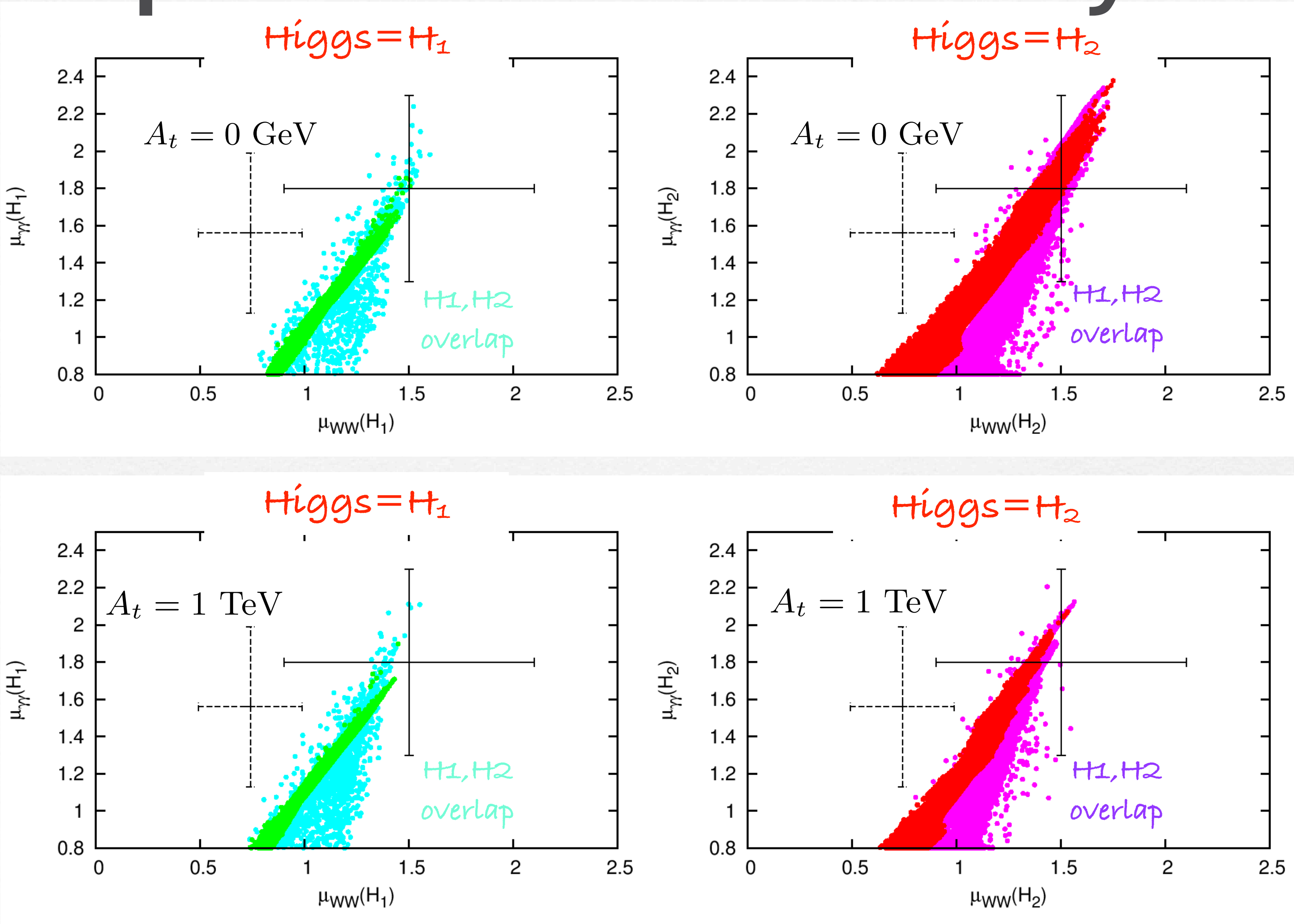

Diphoton vs. bb decays

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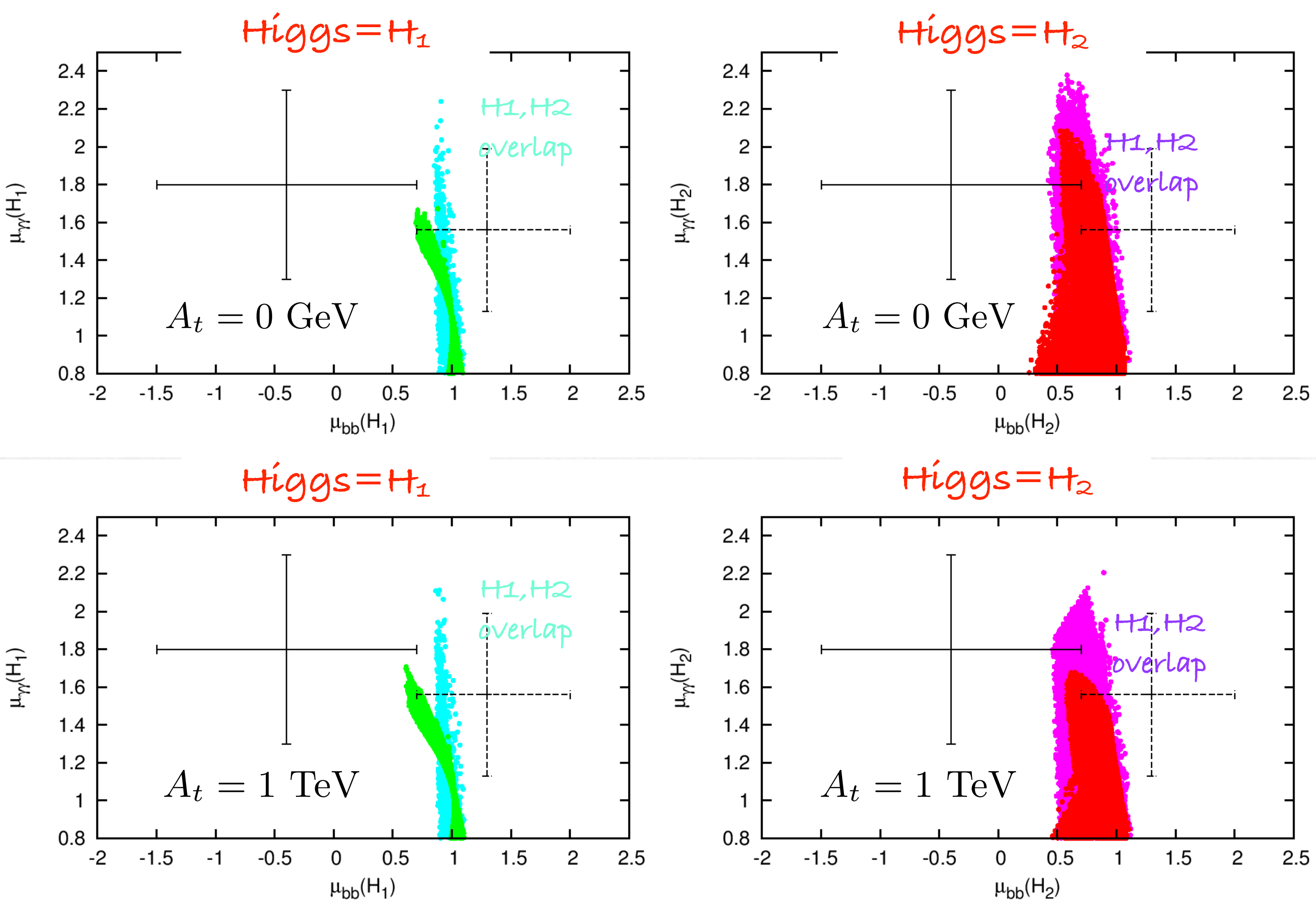
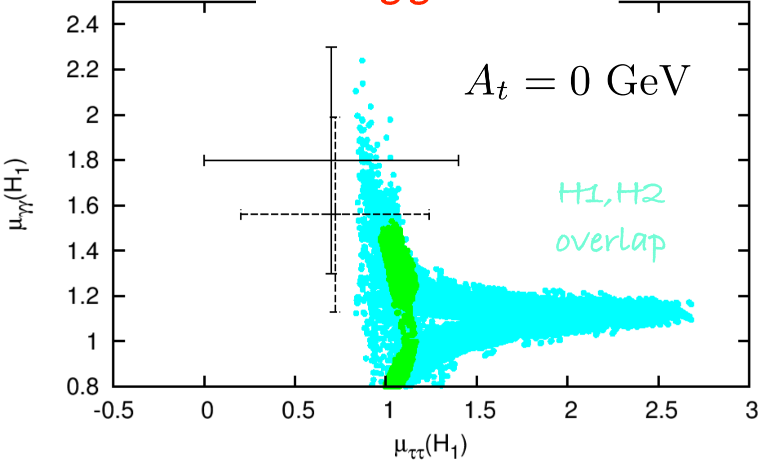


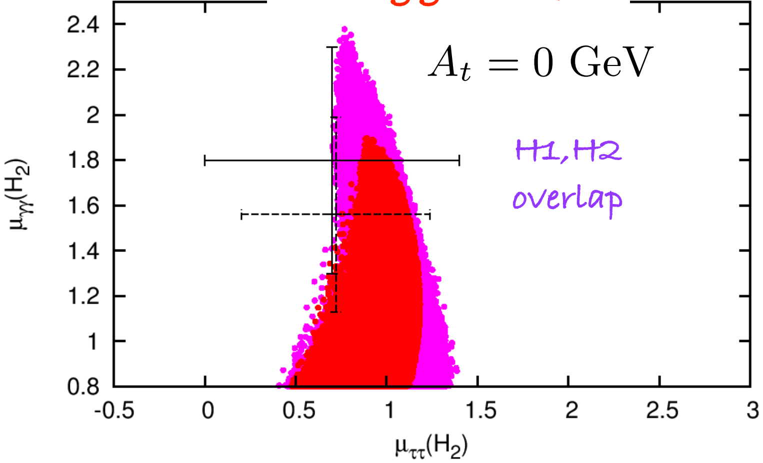
Diphoton vs. tau decays

King, Muhlleitner,
Nevzorov, Walz
1211.5074

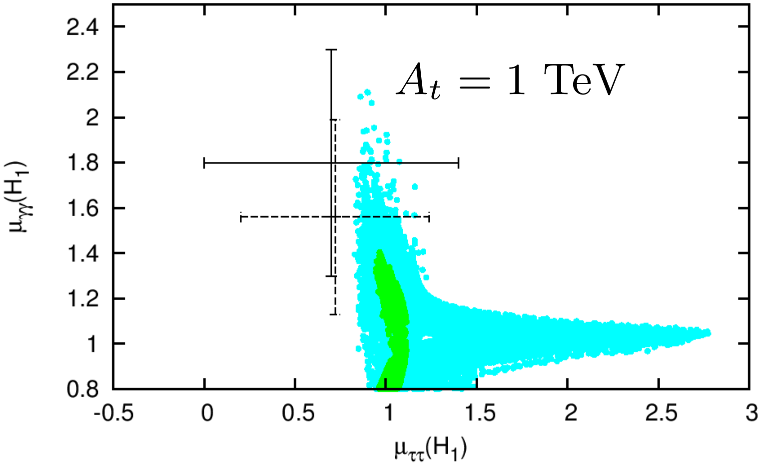
Higgs=H_1



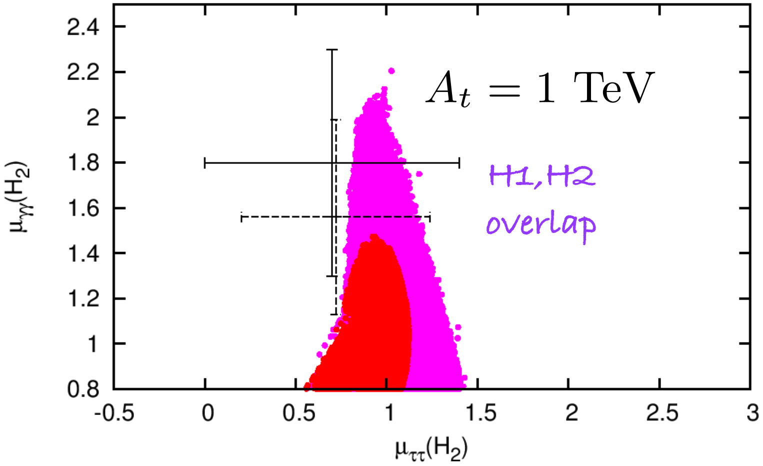
Higgs=H_2



Higgs=H_1



Higgs=H_2



Two Smoking Barrels of NMSSM

King, Muhlleitner,
Nevzorov, Walz
1211.5074

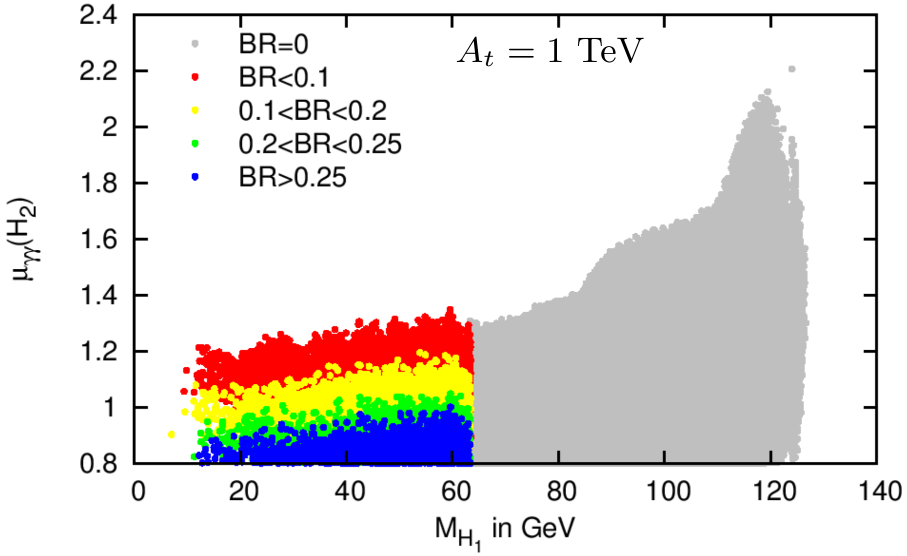
$$H_2 \to H_1 H_1$$

$$\to bbbb, bb\tau\tau, \tau\tau\tau\tau$$

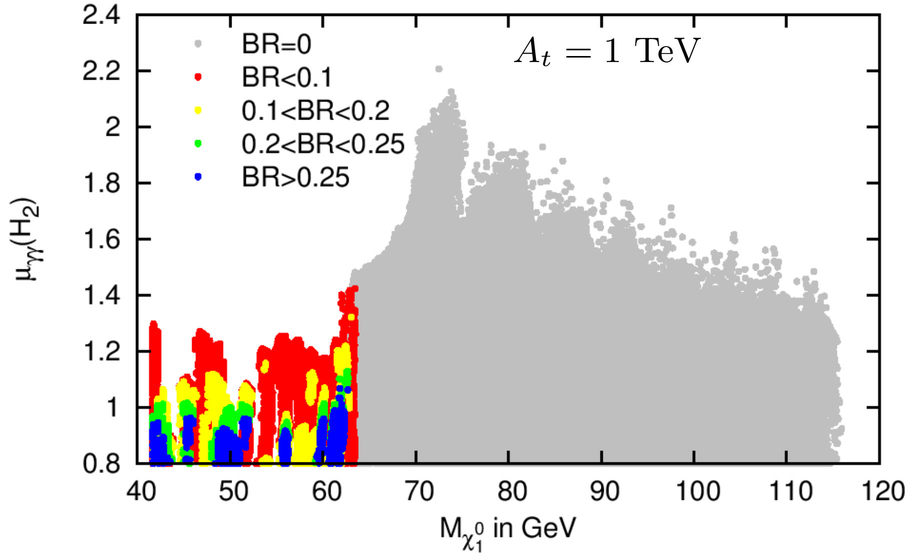
$$H_2 \to \chi_1^0 \chi_1^0$$

invisible Higgs decays

Higgs=H_2



Higgs=H_2



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

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

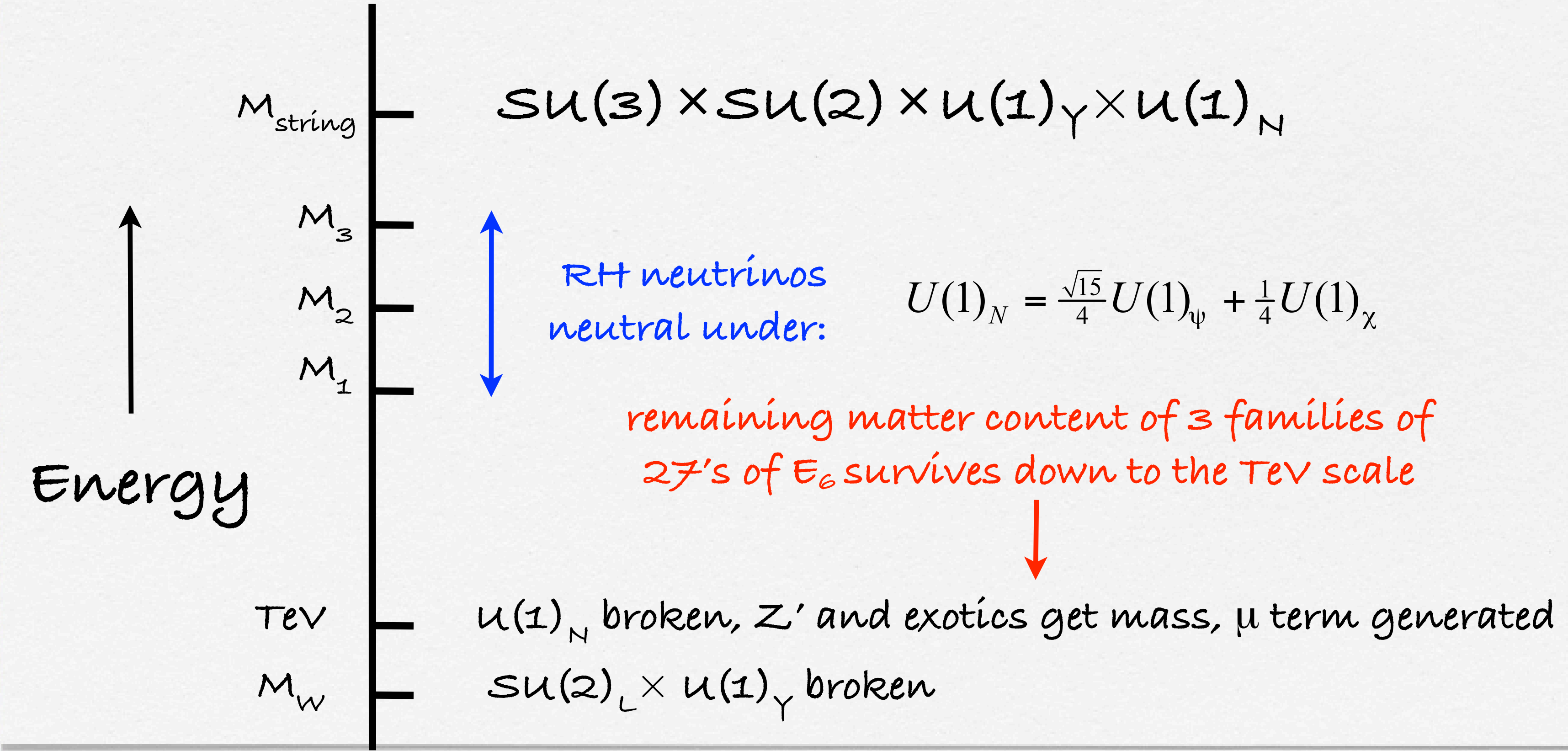
Need to avoid axion somehow

- 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 (E₆SSM)

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



M_{string} $\quad SU(3) \times SU(2) \times U(1)_Y \times U(1)_N$

M_3

M_2

M_1

Energy

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

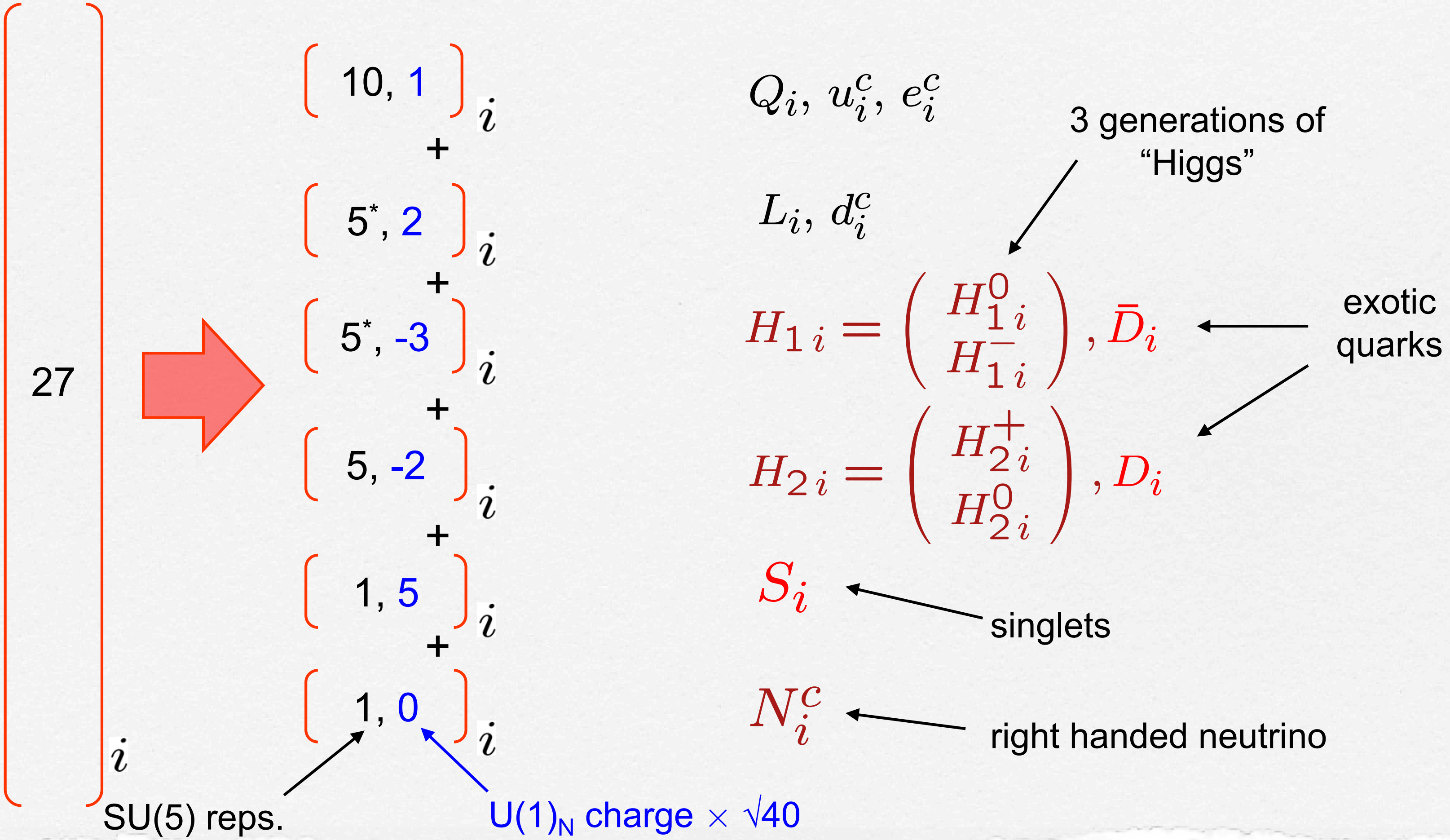
TeV $\quad U(1)_N$ broken, Z′ and exotics get mass, μ term generated

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

Matter Content of 27’s of E$_6$

All the SM matter fields are contained in one 27-plet of E$_6$ per generation.

Miller



$$[27]_i \Rightarrow [10, 1]_i + [5^*, 2]_i + [5^*, -3]_i + [5, -2]_i + [1, 5]_i + [1, 0]_i$$

$Q_i,\ u^c_i,\ e^c_i$

$L_i,\ d^c_i$

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

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

S_i

N^c_i

3 generations of “Higgs”

exotic quarks

singlets

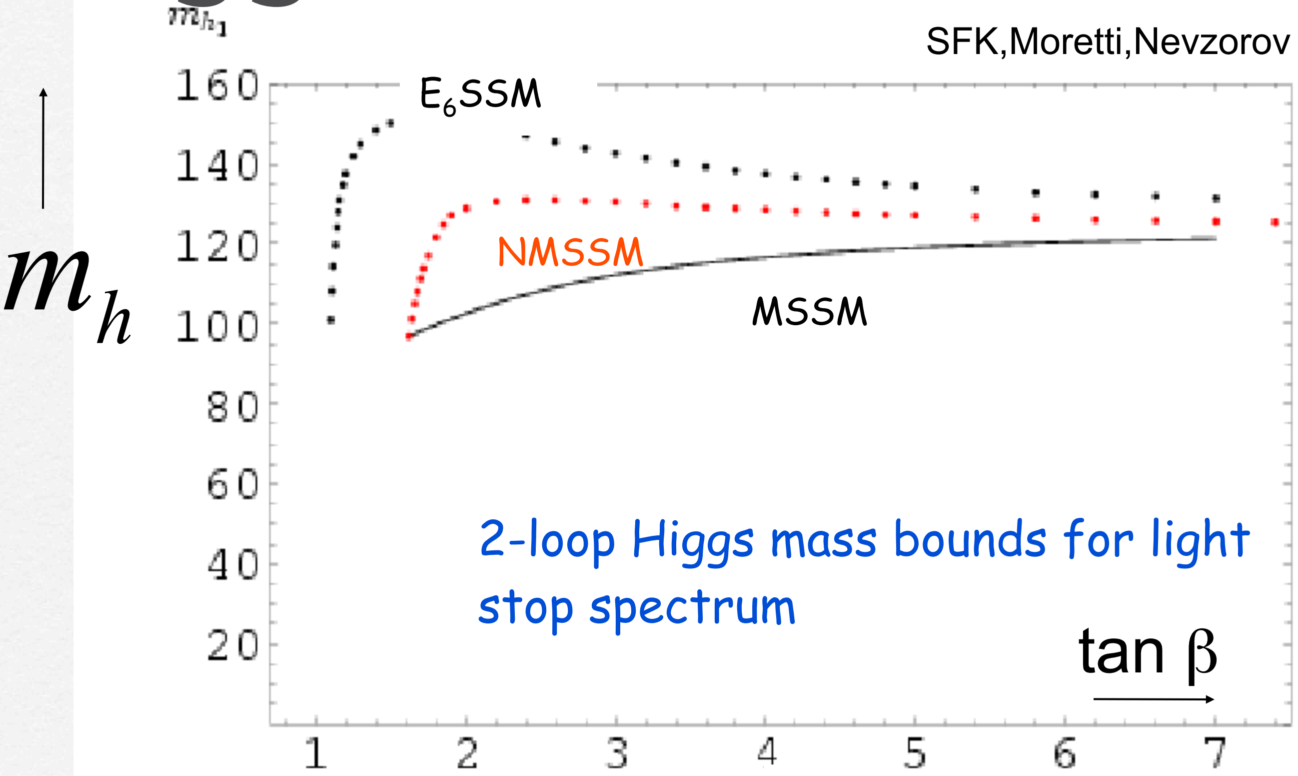
right handed neutrino

SU(5) reps.

U(1)$_N$ charge × √40

Higgs mass bounds in SSM’s

SFK,Moretti,Nevzorov hep-ph/0510419



2-loop Higgs mass bounds for light stop spectrum

Extra terms in non-minimal models allow

$$\Delta m_h < M_Z$$

Hence allow lighter stops and lower fine-tuning

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

E6SSM Couplings

$S \subset S_i,$ $D \subset D_i, \bar{D}_i,$

$H \subset H_i^u, H_i^d$ $F \subset Q_i, L_i, U_i^c, D_i^c, E_i^c, N_i^c$

$$W = SHH + SDD + HFF + DFF$$

Singlet-Higgs-Higgs couplings includes effective μ term

Singlet-D-D couplings includes effective D mass terms

Yukawa couplings but extra Higgs give FCNCs

DQQ, DQL allows D decay but also proton decay. Need to:
– either forbid one of DQQ or DQL
- or allow both with Yukawas $\sim 10^{-12}$

LHC phenomenology of E$_6$SSM

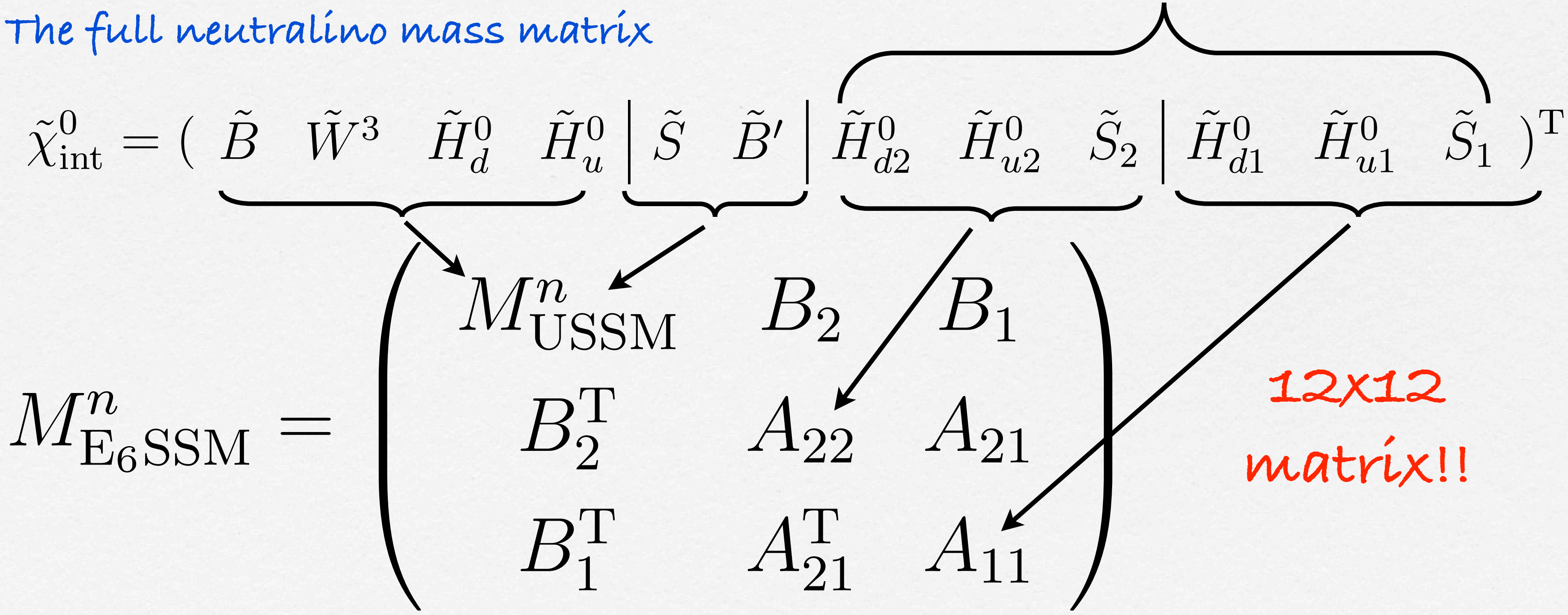
- SUSY - typical spectrum has heavier squarks and lighter gluinos, with gluinos having longer decay chains than MSSM, due to extra neutralinos and charginos, giving less missing energy and more soft leptons and jets
- Higgs - Richer Higgs spectrum than MSSM or NMSSM (incl. inert Higgs)
- Exotics - Z',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



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

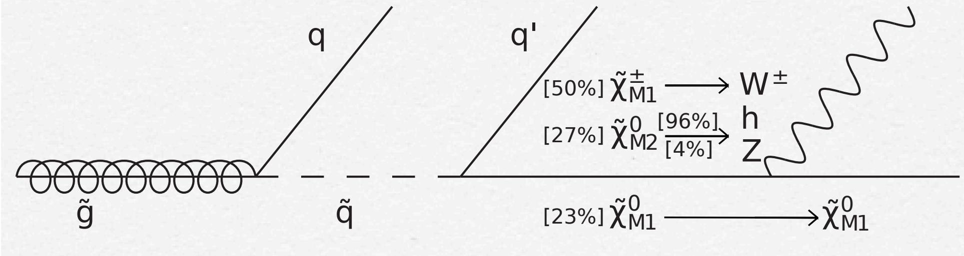
$$M^n_{\mathrm{E_6SSM}} = \begin{pmatrix} M^n_{\mathrm{USSM}} & B_2 & B_1 \\ B_2^{\mathrm{T}} & A_{22} & A_{21} \\ B_1^{\mathrm{T}} & A_{21}^{\mathrm{T}} & A_{11} \end{pmatrix}$$

12x12 matrix!!

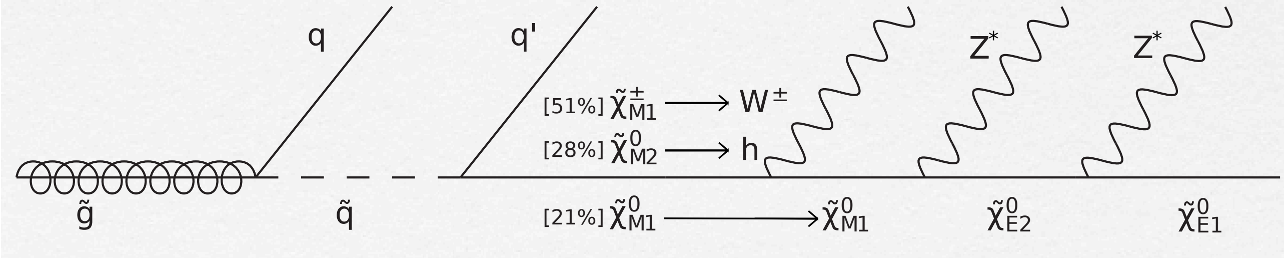
Belyaev, Hall,
King, Svantesson

Longer decay chains

MSSM:



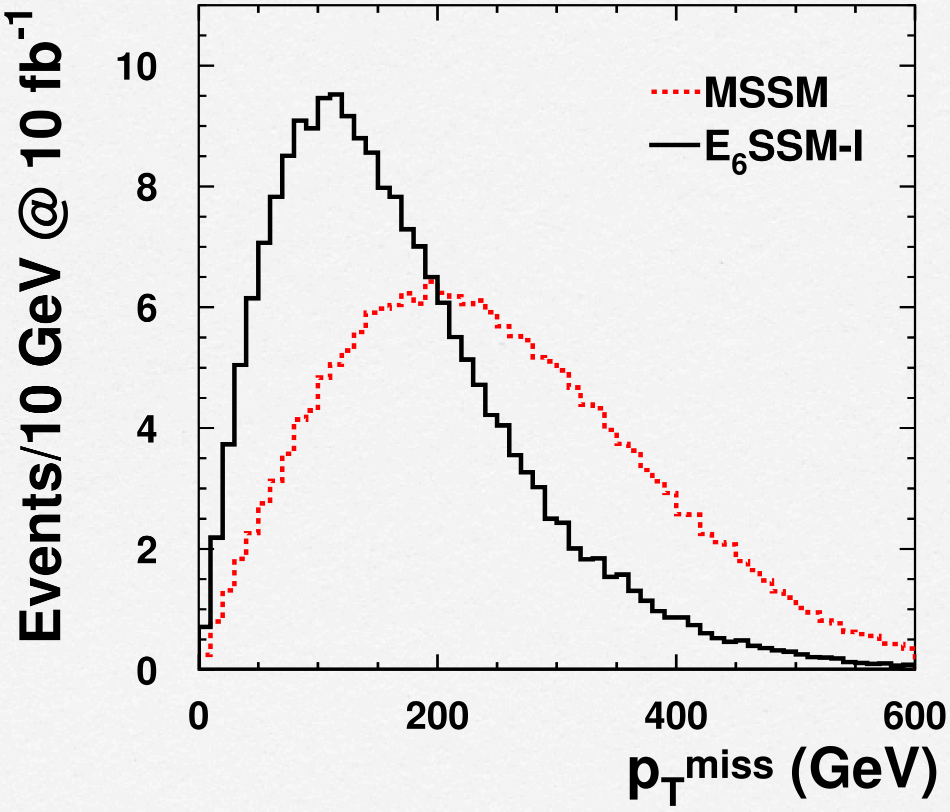
E_6SSM:



Bino can decay into inert neutralinos

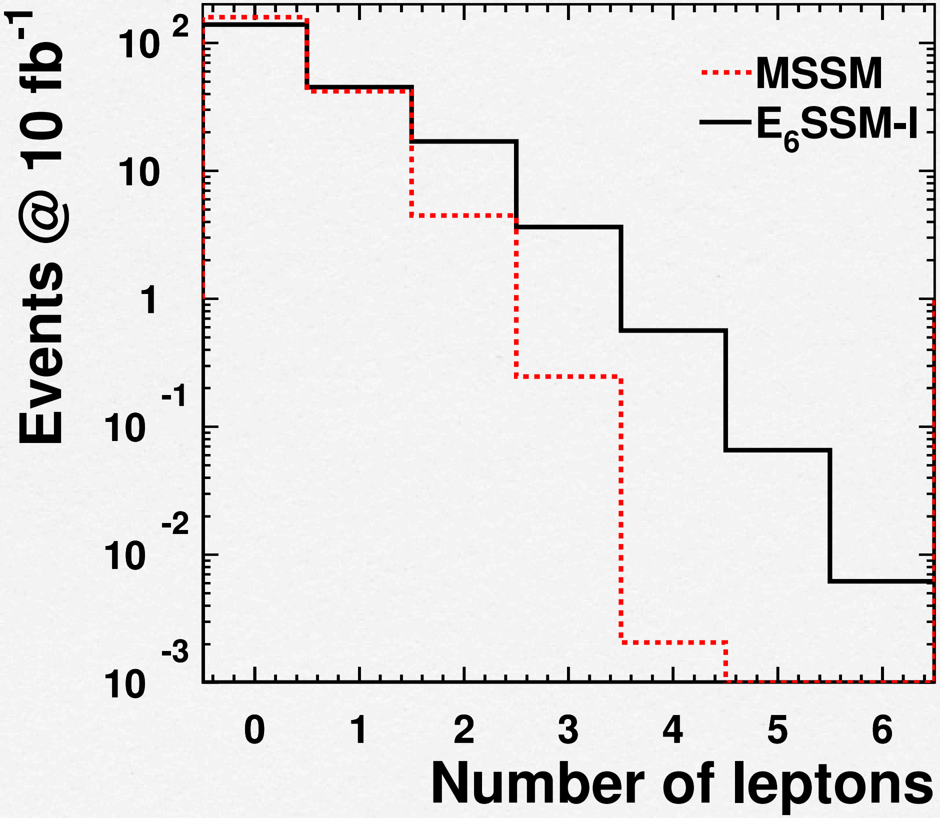
Belyaev, Hall,
King, Svantesson

Less missing p_T



Belyaev, Hall,
King, Svantesson

More leptons



Hall, King

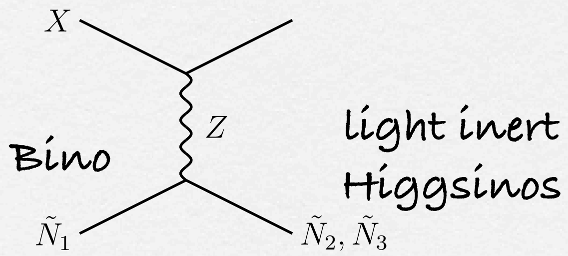
Maybe inert singlinos decoupled

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

$$\left(\begin{array}{cccccc|cc}
M_1 & 0 & -\frac{1}{2}g'v_d & \frac{1}{2}g'v_u & & & & \\
0 & M_2 & \frac{1}{2}gv_d & -\frac{1}{2}gv_u & & & & \\
-\frac{1}{2}g'v_d & \frac{1}{2}gv_d & 0 & -\mu & -\frac{\lambda_{333}v_u}{\sqrt{2}} & Q_d g_1' v_d & 0 & -\frac{\lambda_{33\beta}s}{\sqrt{2}} \\
\frac{1}{2}g'v_u & -\frac{1}{2}gv_u & -\mu & 0 & -\frac{\lambda_{333}v_d}{\sqrt{2}} & Q_u g_1' v_u & -\frac{\lambda_{3\alpha3}s}{\sqrt{2}} & 0 \\
 & & -\frac{\lambda_{333}v_u}{\sqrt{2}} & -\frac{\lambda_{333}v_d}{\sqrt{2}} & 0 & Q_S g_1' s & -\frac{\lambda_{3\alpha3}v_u}{\sqrt{2}} & -\frac{\lambda_{33\beta}v_d}{\sqrt{2}} \\
 & & Q_d g_1' v_d & Q_u g_1' v_u & Q_S g_1' s & M_1' & & \\
\hline
 & & 0 & -\frac{\lambda_{3\alpha3}s}{\sqrt{2}} & -\frac{\lambda_{3\alpha3}v_u}{\sqrt{2}} & & 0 & -\frac{\lambda_{3\alpha\beta}s}{\sqrt{2}} \\
 & & -\frac{\lambda_{33\beta}s}{\sqrt{2}} & 0 & -\frac{\lambda_{33\beta}v_d}{\sqrt{2}} & & -\frac{\lambda_{3\alpha\beta}s}{\sqrt{2}} & 0
\end{array} \right)$$

⇨ Bino dark matter

correct relic abundance



low DD cross-section

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

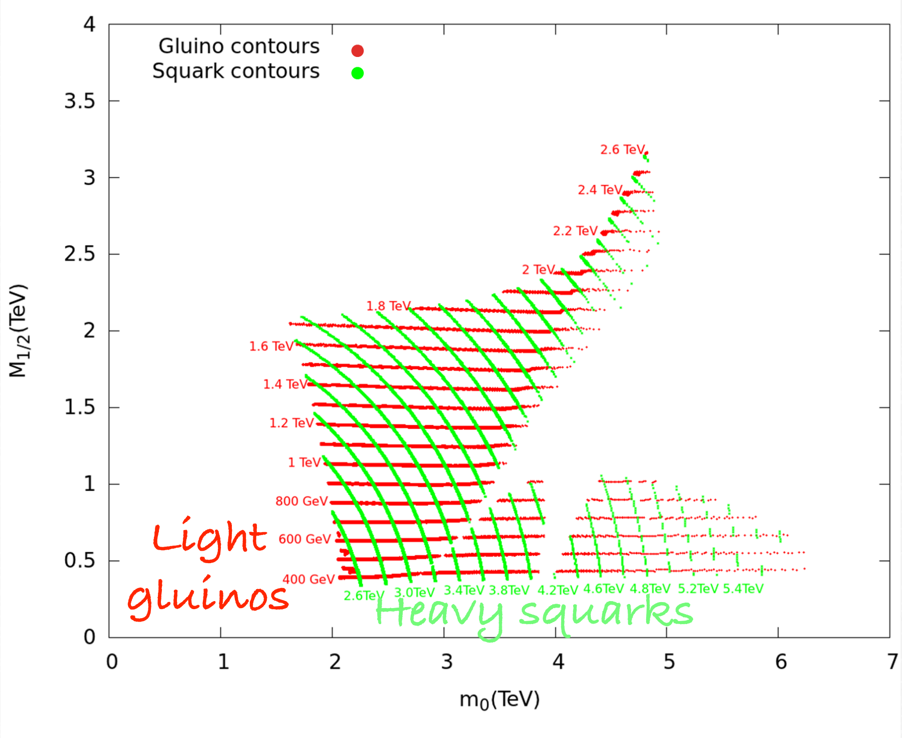
massless $\tilde{S}_{1,2}$ ⇨ dark radiation

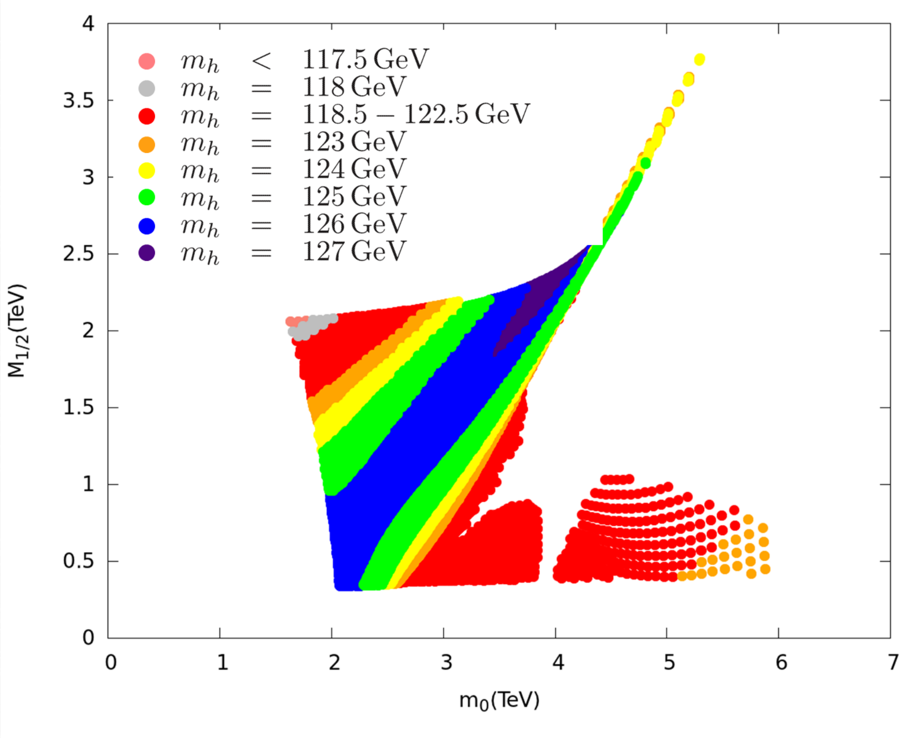
$N_{eff} \approx 3.2$ c.f. $N_{\rm eff}^{\rm Planck} = 3.36 \pm 0.34$

The Constrained E6SSM

Athron, King, Miller, Moretti, Nevzorov

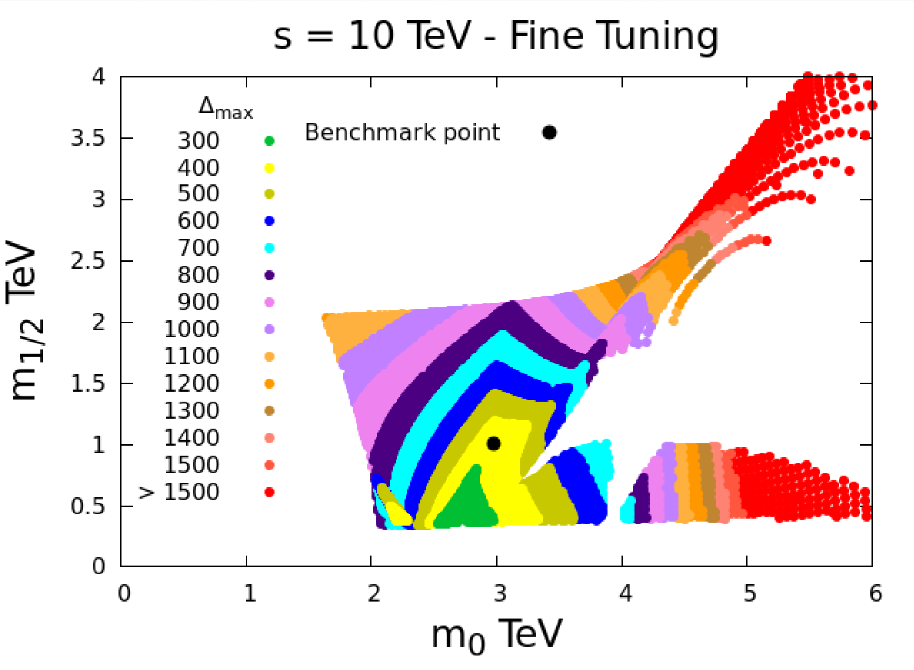
$$\tan\beta = 10,\ \lambda_{12} = 0.1,\ s = 10\ \mathrm{TeV},$$

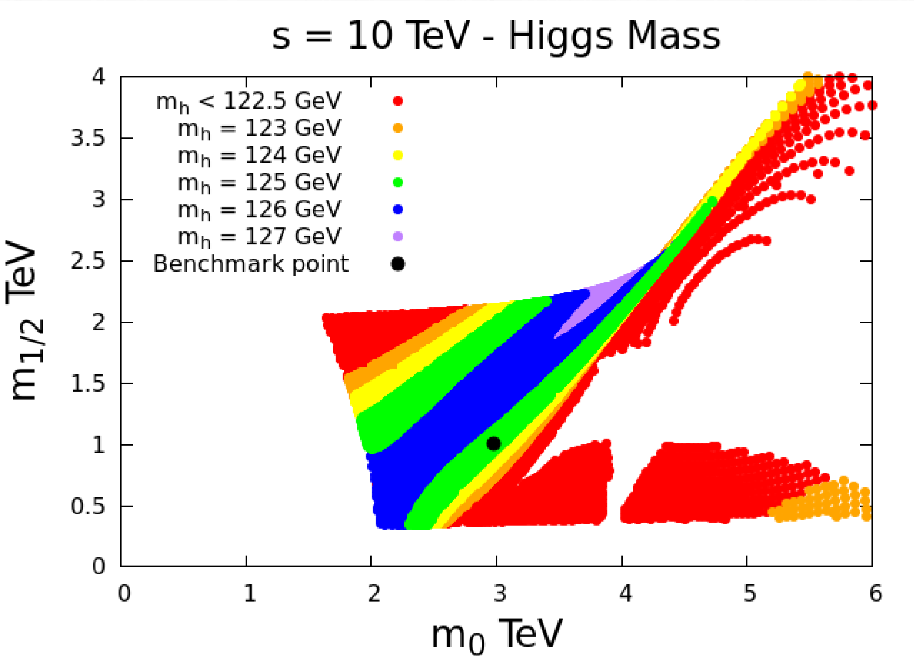




Fine-tuning in the cE6SSM

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





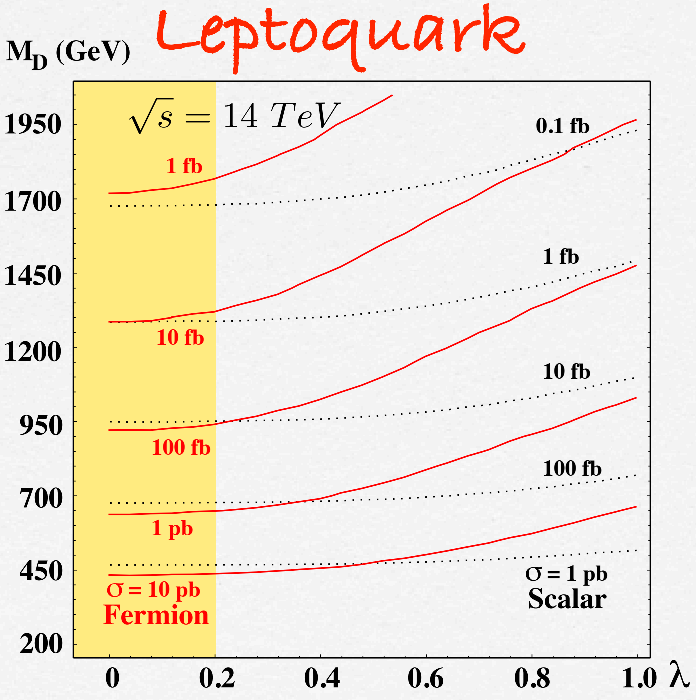
Lower fine-tuning than cMSSM

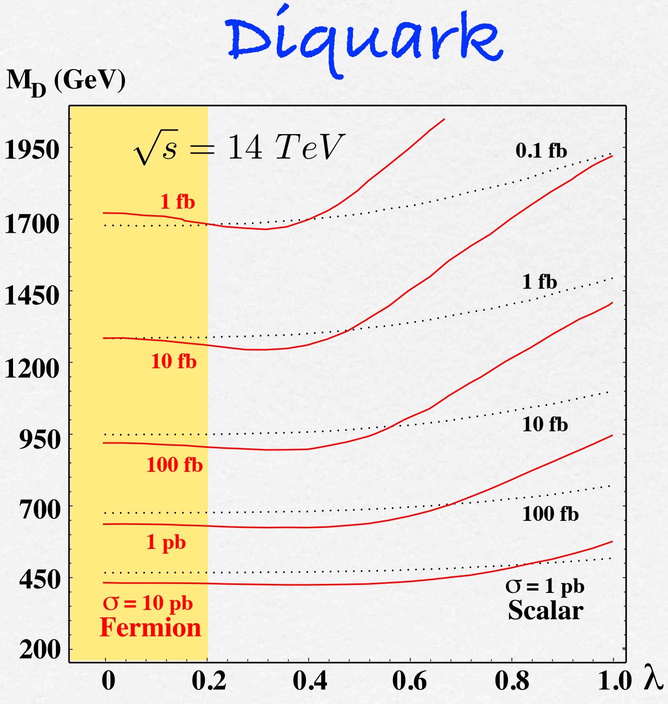
Exotic D-particles

Kang, Langacker, Nelson

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

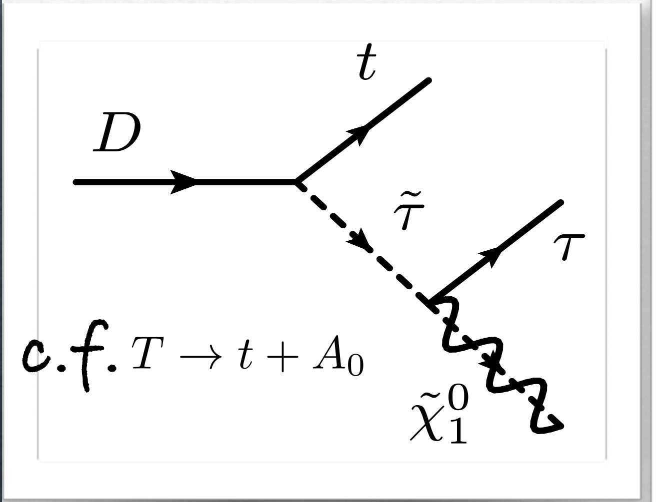
D-particles may be Leptoquarks D→LQ or Diquarks D→QQ


Leptoquark


Diquark

D-fermion decays

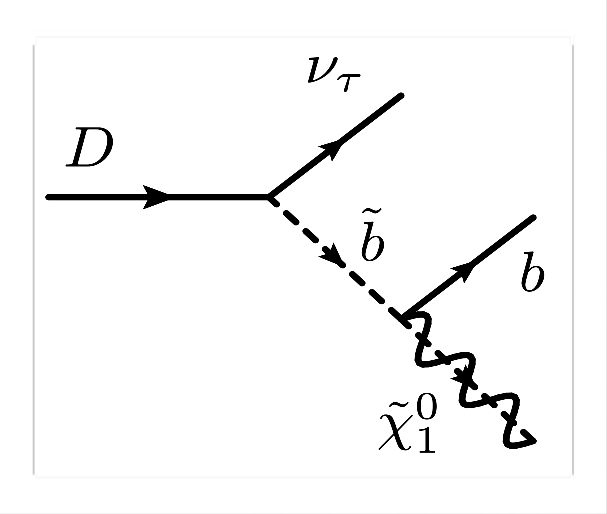
Leptoquark



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

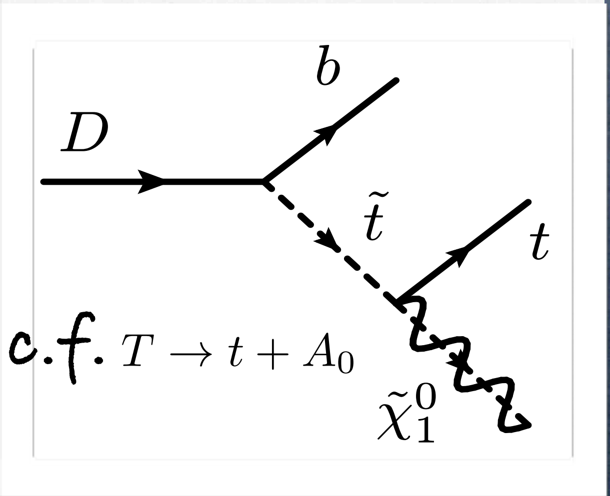
$$pp \rightarrow t\bar{t}\tau^+\tau^- + E_T^{miss} + X$$

Leptoquark



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

Diquark

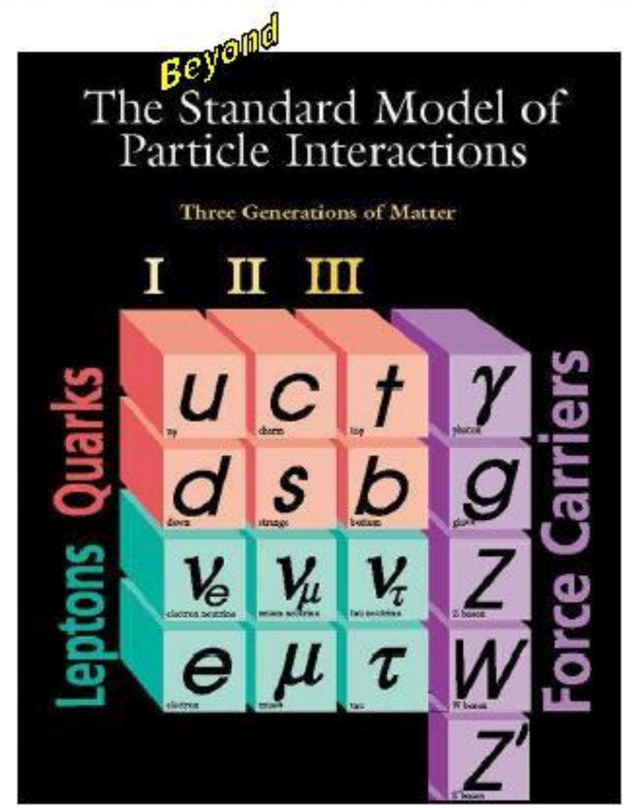


c.f. $T \rightarrow t + A_0$

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

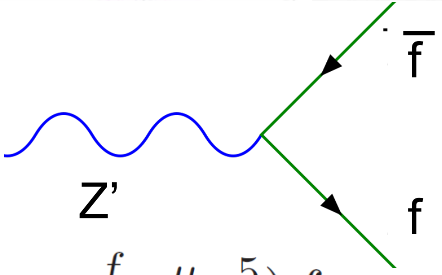
spectacular signals!

Z’ physics



Spin-1 Z’

Feynman rule

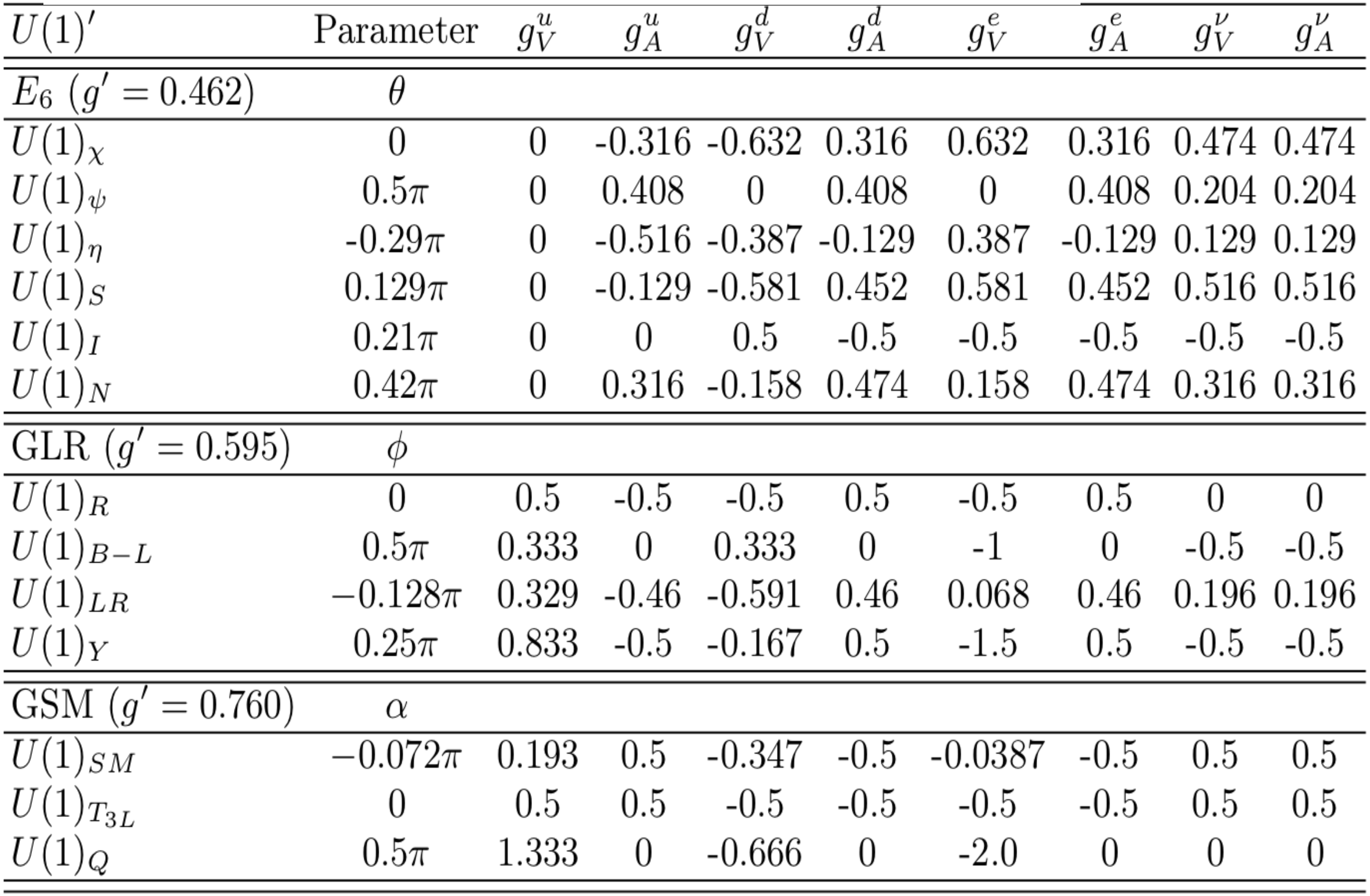


Z’ coupling to SM fermions f

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

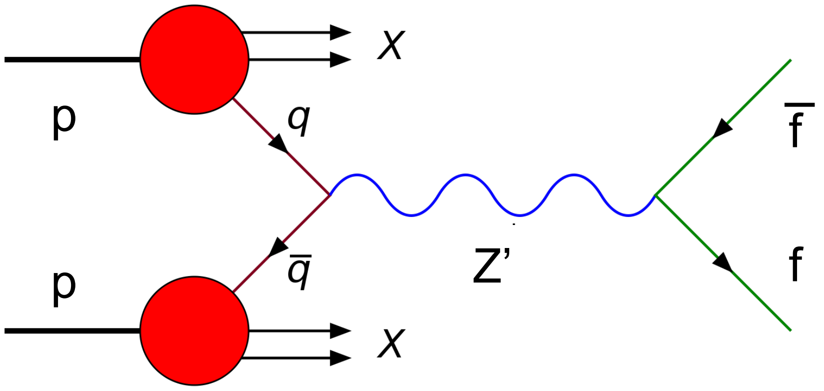
General U(1)’ gauge models: couplings

[Accomando, Belyaev, King, Fedeli, Shepherd-Themistocleous, 2011]



$U(1)'$	Parameter	g_V^u	g_A^u	g_V^d	g_A^d	g_V^e	g_A^e	g_V^ν	g_A^ν
E_6 $(g' = 0.462)$	θ								
$U(1)_\chi$	0	0	-0.316	-0.632	0.316	0.632	0.316	0.474	0.474
$U(1)_\psi$	0.5π	0	0.408	0	0.408	0	0.408	0.204	0.204
$U(1)_\eta$	-0.29π	0	-0.516	-0.387	-0.129	0.387	-0.129	0.129	0.129
$U(1)_S$	0.129π	0	-0.129	-0.581	0.452	0.581	0.452	0.516	0.516
$U(1)_I$	0.21π	0	0	0.5	-0.5	-0.5	-0.5	-0.5	-0.5
$U(1)_N$	0.42π	0	0.316	-0.158	0.474	0.158	0.474	0.316	0.316
GLR $(g' = 0.595)$	ϕ								
$U(1)_R$	0	0.5	-0.5	-0.5	0.5	-0.5	0.5	0	0
$U(1)_{B-L}$	0.5π	0.333	0	0.333	0	-1	0	-0.5	-0.5
$U(1)_{LR}$	-0.128π	0.329	-0.46	-0.591	0.46	0.068	0.46	0.196	0.196
$U(1)_Y$	0.25π	0.833	-0.5	-0.167	0.5	-1.5	0.5	-0.5	-0.5
GSM $(g' = 0.760)$	α								
$U(1)_{SM}$	-0.072π	0.193	0.5	-0.347	-0.5	-0.0387	-0.5	0.5	0.5
$U(1)_{T3L}$	0	0.5	0.5	-0.5	-0.5	-0.5	-0.5	0.5	0.5
$U(1)_Q$	0.5π	1.333	0	-0.666	0	-2.0	0	0	0

Drell-Yan production cross-section



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

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

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

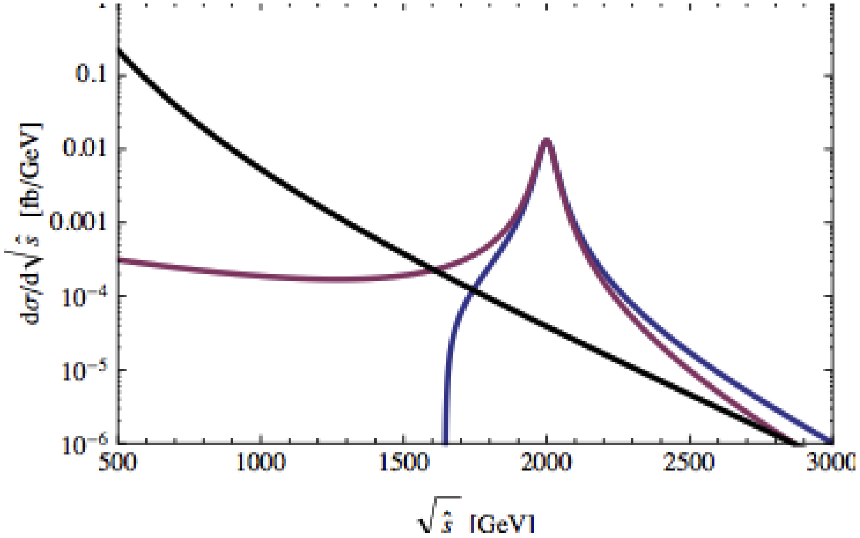
depend on s and $M_{Z'}$

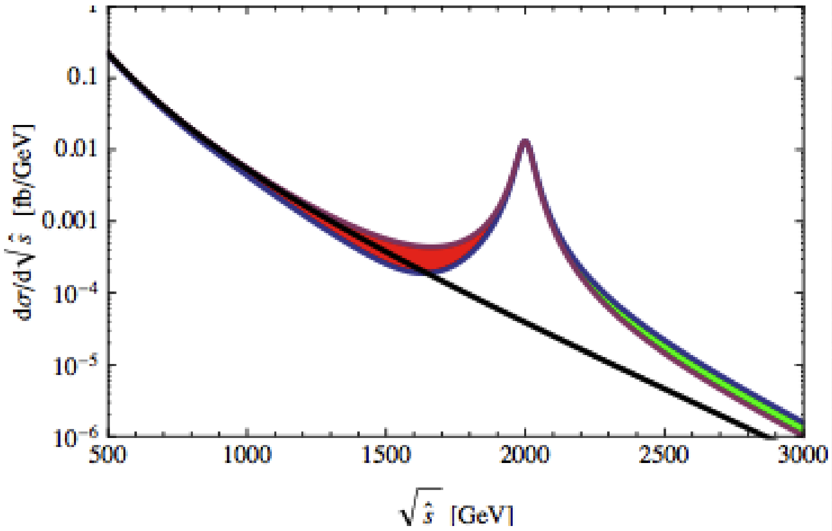
SSM Z' Drell-Yan production @ the LHC

Non-interferred model vs complete SSM

Moretti

[Accomando, Becciolini, Belyaev, SM, Shepherd-Themistocleous, arXiv:1304.6700]





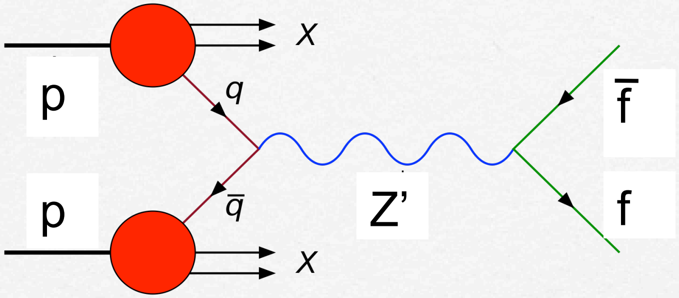
Interference effects are sizeable and model-dependent:

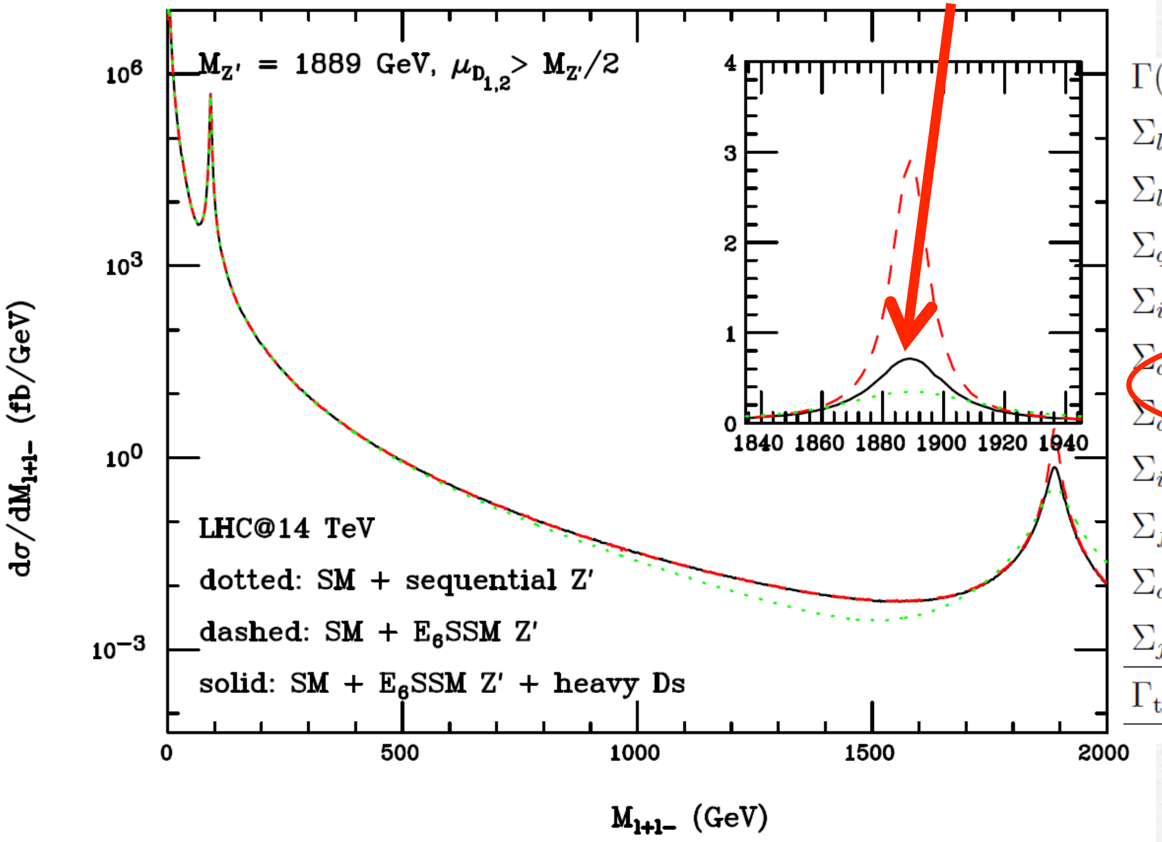
up to O(200%) in the SSM

Athron, SFK, Miller, Moretti, Nevzorov

Z'_N

Latest CMS limit is
$M_{Z'} \gtrsim 2.08$ TeV
but exotic decays
makes Z’ peak smaller
and harder to discover

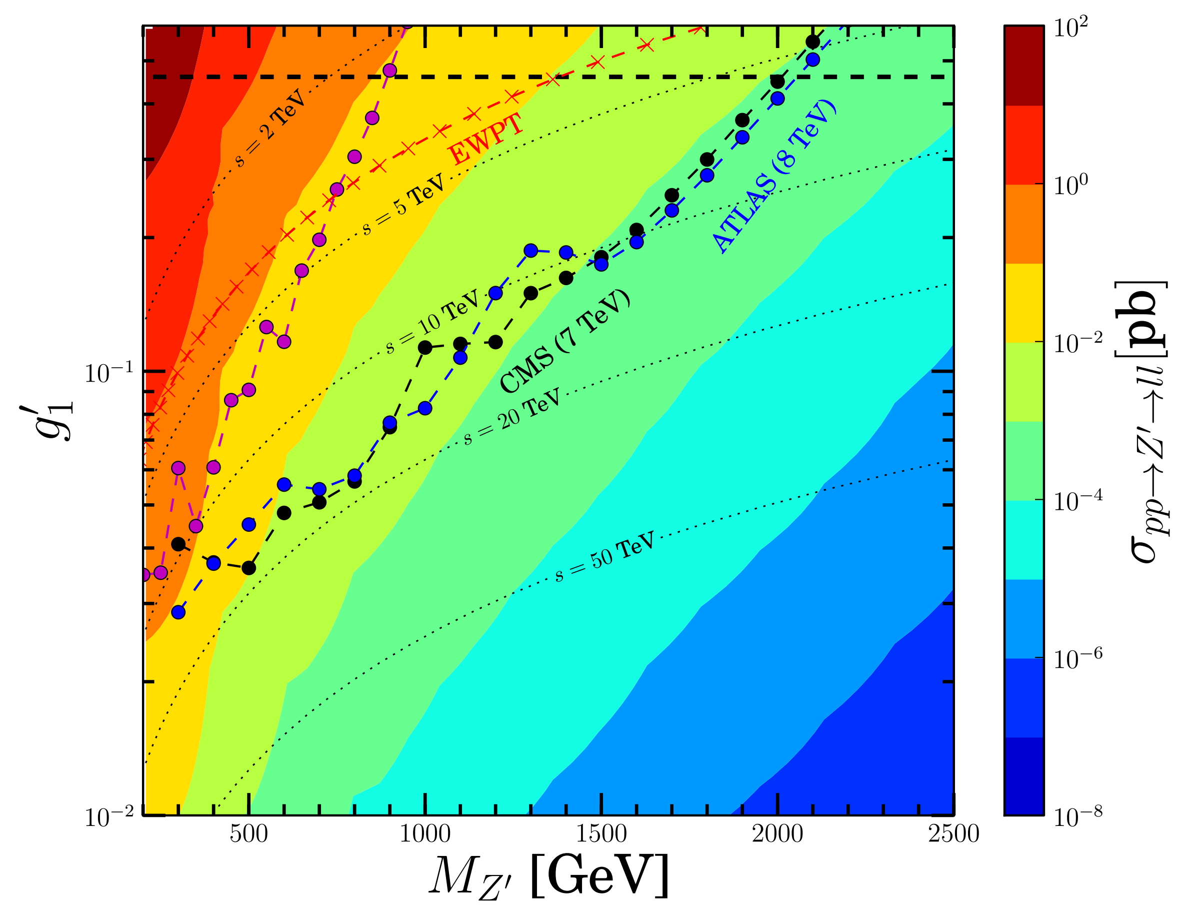




$\Gamma(Z'_N \to l^+l^-)$ ($l = e, \mu$ or τ)	0.77
$\Sigma_l\Gamma(Z'_N \to \nu_l\bar{\nu}_l)$ (all neutrinos)	1.64
$\Sigma_l\Gamma(Z'_N \to l^+l^-, \nu_l\bar{\nu}_l)$ (all leptons)	3.96
$\Sigma_q\Gamma(Z'_N \to q\bar{q})$ (all quarks)	10.08
$\Sigma_i\Gamma(Z'_N \to D_i\bar{D}_i)$ (exotic fermions)	0.00
$\Sigma_\alpha\Gamma(Z'_N \to \tilde{H}_\alpha\tilde{H}_\alpha)$ (inert Higgsinos	5.19
$\Sigma_\alpha\Gamma(Z'_N \to \tilde{S}_\alpha\tilde{S}_\alpha)$ (singlinos)	7.63
$\Sigma_i\Gamma(Z'_N \to D_iD_i)$ (exotic scalars)	0.19
$\Sigma_f\Gamma(Z'_N \to \tilde{f}\tilde{f})$ (sfermions)	0.010
$\Sigma_\alpha\Gamma(Z'_N \to H_\alpha H_\alpha)$ (inert Higgses)	0.39
$\Sigma_j\Gamma(Z'_N \to \tilde{\chi}_j\tilde{\chi}_j)$ (gauginos)	7.92×10^{-5}
$\Gamma_{\rm tot}$ (all)	27.45

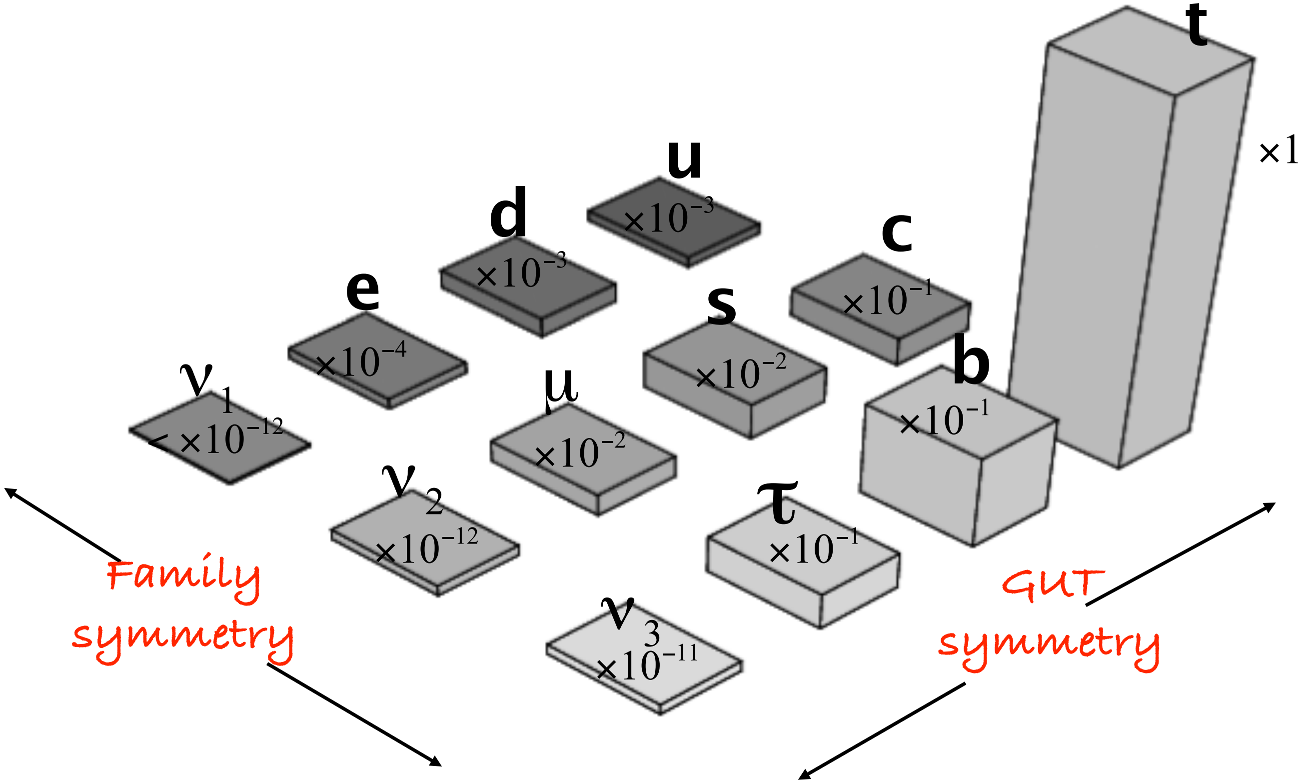
Little Z’ models

Belyaev, King,
Svantesson



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

Family Symmetry × GUTs



Grand Unified Theories (GUTs)

Basic idea is to embed the SM gauge group into a simple gauge group G with a single coupling constant, broken at a high energy scale

$$G \longrightarrow SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

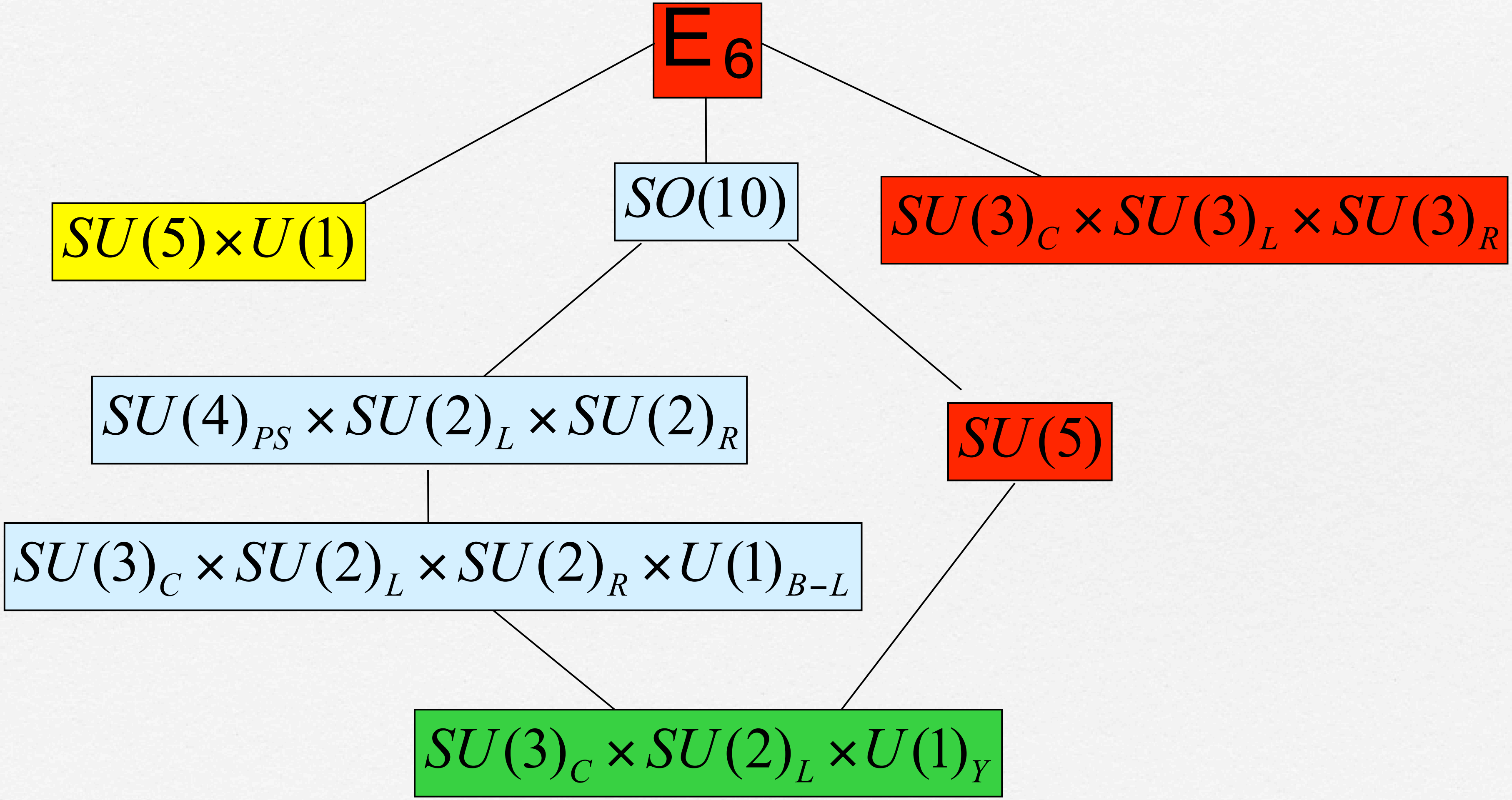
$$u_i^c = (\bar{3},\, 1,\, -\tfrac{2}{3}), \quad d_i^c = (\bar{3},\, 1,\, \tfrac{1}{3}), \quad e^c = (1,\, 1,\, 1),$$

$$Q^{\alpha\, i} = (u^i,\, d^i) = (3,\, 2,\, \tfrac{1}{6}), \qquad L^\alpha = (\nu,\, e) = (1,\, 2,\, -\tfrac{1}{2}),$$

Motivations

1. Continuation of process of unification of physics starting with Maxwell
2. Remarkable fit of SM multiplets into Pati-Salam, SU(5), SO(10), E_6…
3. Unification of gauge couplings at high energy scale M_{GUT}
4. Charge quantization: equality of electron and proton charges
5. High energy fermion mass relations e.g. $m_b=m_\tau$

Paths to Unification



E_6

$SU(5) \times U(1)$

$SO(10)$

$SU(3)_C \times SU(3)_L \times SU(3)_R$

$SU(4)_{PS} \times SU(2)_L \times SU(2)_R$

$SU(5)$

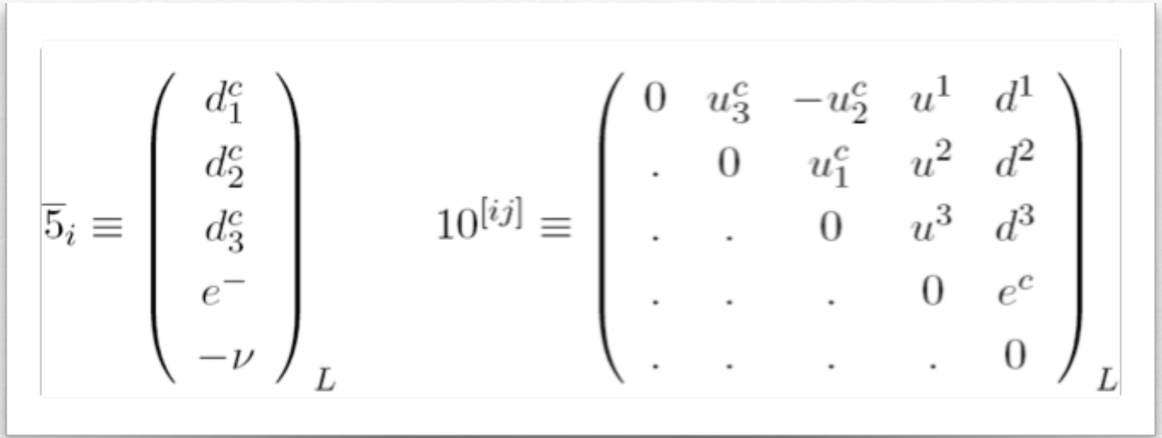
$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$SU(3)_C \times SU(2)_L \times U(1)_Y$

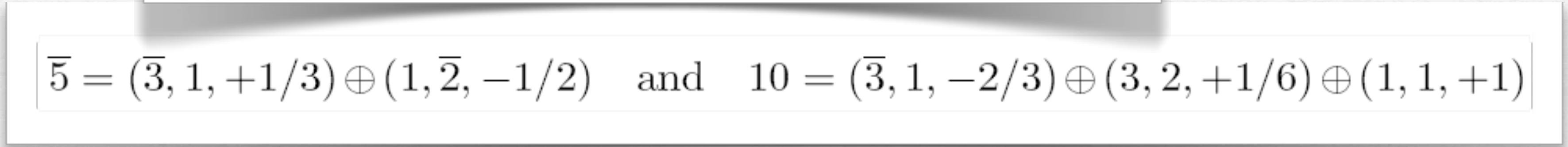
SU(5) GUT

Georgi, Glashow

Each family fits nicely into the SU(5) multiplets



$$\overline{5}_i \equiv \begin{pmatrix} d^c_1 \\ d^c_2 \\ d^c_3 \\ e^- \\ -\nu \end{pmatrix}_L \qquad 10^{[ij]} \equiv \begin{pmatrix} 0 & u^c_3 & -u^c_2 & u^1 & d^1 \\ . & 0 & u^c_1 & u^2 & d^2 \\ . & . & 0 & u^3 & d^3 \\ . & . & . & 0 & e^c \\ . & . & . & . & 0 \end{pmatrix}_L$$



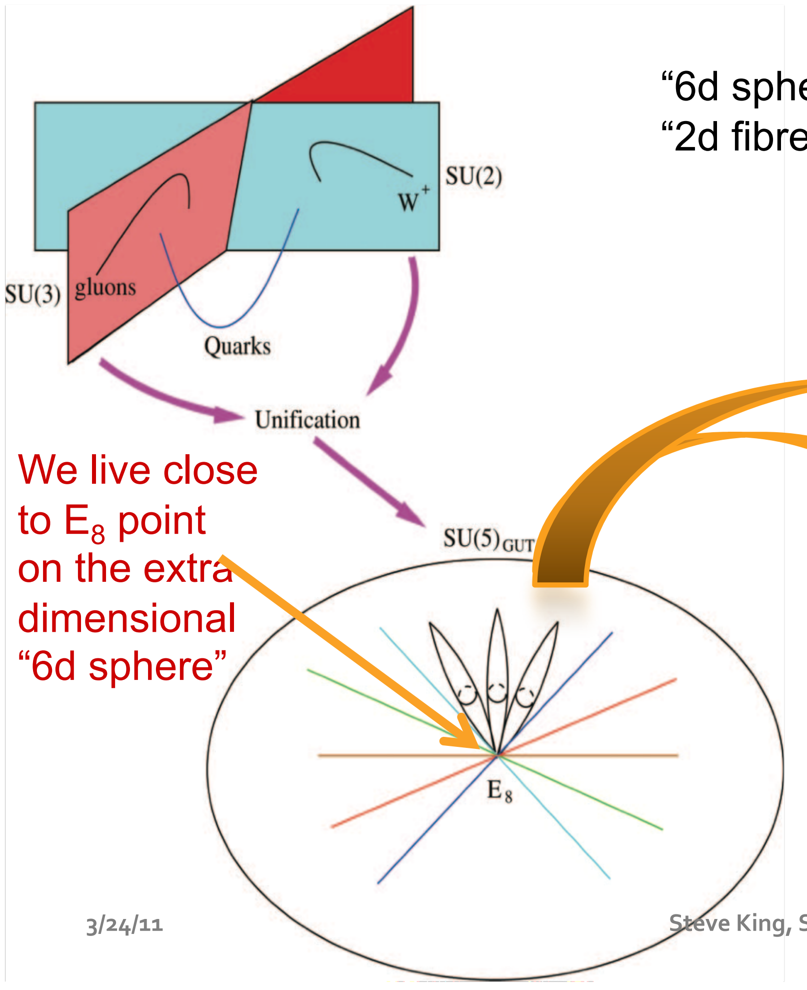
$$\overline{5} = (\overline{3}, 1, +1/3) \oplus (1, \overline{2}, -1/2) \quad \text{and} \quad 10 = (\overline{3}, 1, -2/3) \oplus (3, 2, +1/6) \oplus (1, 1, +1)$$

N.B in minimal SU(5) neutrino masses are zero.

Right-handed neutrinos may be added to give neutrino masses but they are not predicted.

F-Theory GUTs: a 12d string theory

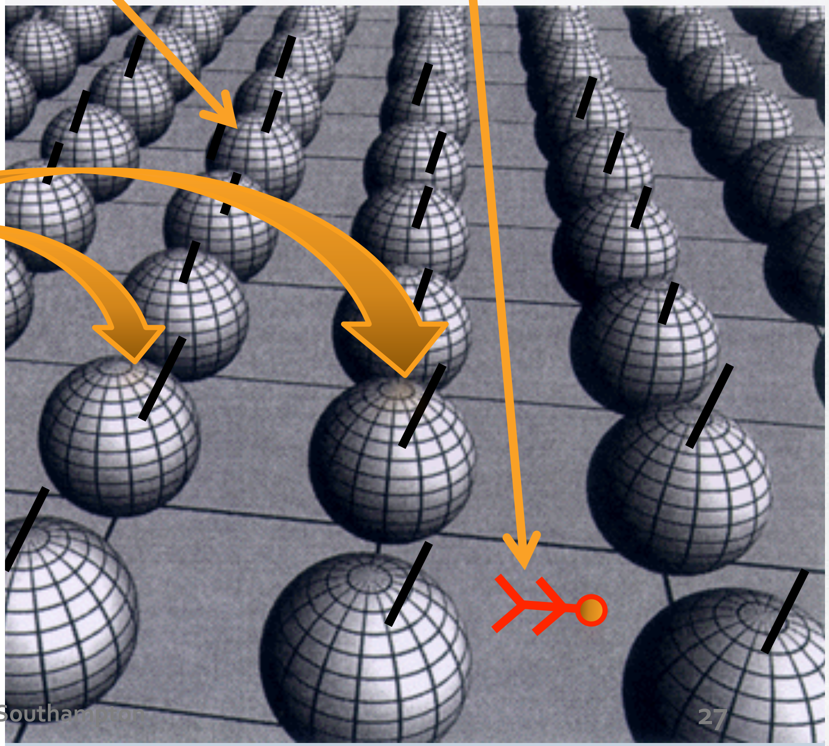
Heckman and Vafa



We live close to E_8 point on the extra dimensional “6d sphere”

“6d spheres” with “2d fibres”

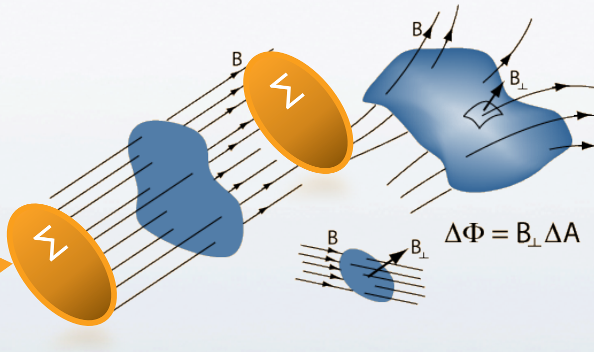
“4d Flatlander”



GUT breaking is achieved not with Higgs but with Hypercharge Flux

$$SU(5) \supset SU(3)_C \times SU(2)_L \times U(1)_Y$$

$$5 \to (1,2)_{1/2} + (3,1)_{-1/3}.$$



Think of magnetic flux PHYS2001

2-d Matter curve Σ

Index theorem gives number of chiral doublets and triplets (think of Gauss's law):

$$(1,2)_{1/2} : n_L - n_R = 3\int_\Sigma F_{U(1)_Y} + q\int_\Sigma F_{U(1)_\perp}$$

$$(3,1)_{-1/3} : n_L - n_R = -2\int_\Sigma F_{U(1)_Y} + q\int_\Sigma F_{U(1)_\perp}$$

Doublet-triplet Higgs splitting requires:

$$\text{Higgs:} \int_\Sigma F_{U(1)_Y} \neq 0$$

$$\text{Matter:} \int_\Sigma F_{U(1)_Y} = 0.$$

Typically predicts exotics

Callaghan, King

E6SSM from F-theory

E_6	$SO(10)$	$SU(5)$	Weight vector	Q_N	N_Y	$M_{U(1)}$	SM particle content	Low energy spectrum
$27_{t_1'}$	16	$\overline{5}_3$	t_1+t_5	$\frac{1}{\sqrt{10}}$	1	4	$4d^c+5L$	$3d^c+3L$
$27_{t_1'}$	16	10_M	t_1	$\frac{1}{2\sqrt{10}}$	-1	4	$4Q+5u^c+3e^c$	$3Q+3u^c+3e^c$
$27_{t_1'}$	16	θ_{15}	t_1-t_5	0	0	n_{15}	$3\nu^c$	-
$27_{t_1'}$	10	5_1	$-t_1-t_3$	$-\frac{1}{\sqrt{10}}$	-1	3	$3D+2H_u$	$3D+2H_u$
$27_{t_1'}$	10	$\overline{5}_2$	t_1+t_4	$-\frac{3}{2\sqrt{10}}$	1	3	$3\overline{D}+4H_d$	$3\overline{D}+3H_d$
$27_{t_1'}$	1	θ_{14}	t_1-t_4	$\frac{5}{2\sqrt{10}}$	0	n_{14}	θ_{14}	θ_{14}
$27_{t_3'}$	16	$\overline{5}_5$	t_3+t_5	$\frac{1}{\sqrt{10}}$	-1	-1	$\overline{d^c}+2\overline{L}$	-
$27_{t_3'}$	16	10_2	t_3	$\frac{1}{2\sqrt{10}}$	1	-1	$\overline{Q}+2\overline{u^c}$	-
$27_{t_3'}$	16	θ_{35}	t_3-t_5	0	0	n_{35}	$-$	-
$27_{t_3'}$	10	5_{H_u}	$-2t_1$	$-\frac{1}{2\sqrt{10}}$	1	0	H_u	H_u
$27_{t_3'}$	10	$\overline{5}_4$	t_3+t_4	$-\frac{3}{2\sqrt{10}}$	-1	0	$\overline{H_d}$	-
$27_{t_3'}$	1	θ_{34}	t_3-t_4	$\frac{5}{2\sqrt{10}}$	0	n_{34}	θ_{34}	θ_{34}
-	1	θ_{31}	t_3-t_1	0	0	n_{31}	θ_{31}	-
-	1	θ_{53}	t_5-t_3	0	0	n_{53}	θ_{53}	-
-	1	θ_{54}	t_5-t_4	$\frac{5}{2\sqrt{10}}$	0	n_{54}	θ_{54}	-
-	1	θ_{45}	t_4-t_5	$-\frac{5}{2\sqrt{10}}$	0	n_{45}	θ_{45}	-

F-theory model predicts incomplete multiplets with matter content of 3 copies of 27s of E6

SUSY models from F-theory

Model Features	F-MSSM	F-E6SSM	F-NMSSM+
$\langle\theta_{53}\rangle$, $\langle\theta_{31}\rangle$	$\sim M_X$	$\sim M_X$	$\sim M_X$
$\langle\theta_{34}\rangle$	$\sim M_X$	~ 1 TeV	~ 1 TeV
$\langle\theta_{14}\rangle$	0	~ 1 TeV	~ 1 TeV
$U(1)_N$ breaking	Flux $\sim M_X$	$\langle\theta_{34}\rangle \sim 1$TeV	Flux $\sim M_X$
Non perturbative μ term	$\mu^{N.P} H_u H_d$	-	-
Effective μ term	-	$\theta_{14} H_u H_d$	$\theta_{14} H_u H_d$
Non perturbative singlet masses	-	-	$m_s\theta_{14}^2$, $m_s^2\theta_{14}$

1. If the additional Abelian gauge group is unbroken then it can have weaker gauge coupling than in the E6SSM.

2. If Abelian gauge group is broken then non-perturbative effects can violate scale invariance of NMSSM+ leading to a generalised model.

3. Unification is achieved not at the field theory level but at the F-theory level since the gauge couplings are split by flux effects, negating the need for any additional doublet states which are usually required.

4. Proton decay is suppressed by the geometric coupling suppression of a singlet state,which is possible in F-theory, which effectively suppresses the coupling of the exotic charge −1/3 colour triplet state D to quarks and leptons.

5. The D couples to left-handed leptoquarks providing characteristic and striking signatures at the LHC.