SUSY and Exotics

- Standard Model and the Origin of Mass
- Puzzles of Standard Model and Cosmology
- Bottom-up and top-down motivation
- Extra dimensions
- Supersymmetry

- MSSM
- NMSSM
- E_6SSM and its exotics

UK HEP Forum"From the Tevatron to the LHC, Cosener's House, May 2009

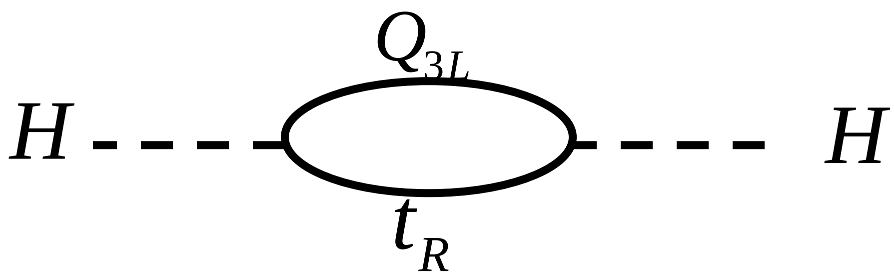
UNIVERSITY OF Southampton
School of Physics and Astronomy

Origin of mass in SM

$$V = m_H^2 |H|^2 + \tfrac{1}{2}\lambda |H|^4$$

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

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



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

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

Hierarchy problem → new physics at $\Lambda \sim$ TeV

Standard Model Puzzles

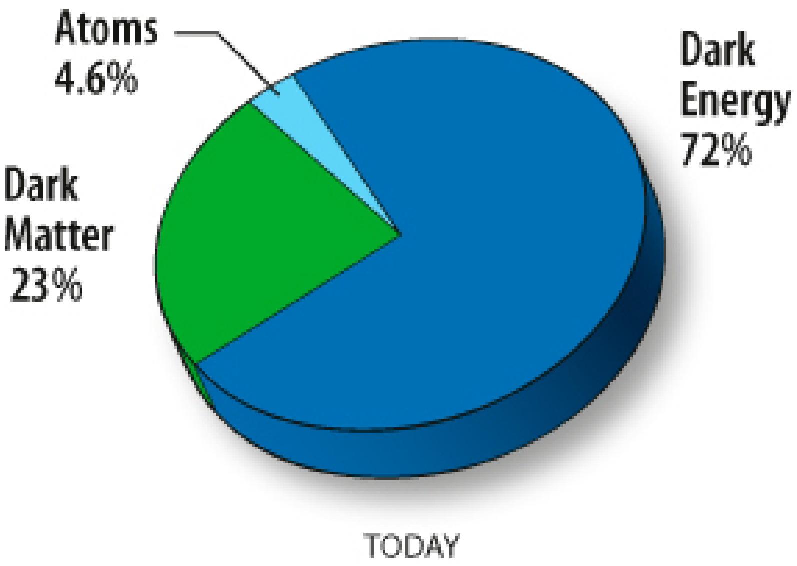
1. *The origin of mass* - the origin of the weak scale, its stability under radiative corrections, and the solution to the hierarchy problem (most urgent problem of LHC)

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.

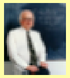
3. *The problem of flavour* - the problem of the undetermined fermion masses and mixing angles (including neutrino masses and mixing angles) together with the CP violating phases, in conjunction with the observed smallness of flavour changing neutral currents and very small strong CP violation.

Cosmology provide further motivation for new physics BSM:

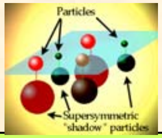
- Origin of dark energy?
- Origin of dark matter?
- Origin of atoms?
- Origin of the Universe?



Hierarchy problem provides a bottom-up motivation for new physics BSM

Little Higgs  models

Technicolour



Supersymmetry

TeV

Extra dimensions 

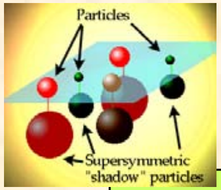
Mz

The Hierarchy Problem 

String Unification provides a top-down motivation for new physics BSM

String Unification

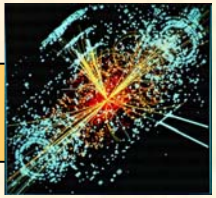
M*



Supersymmetry

Extra dimensions

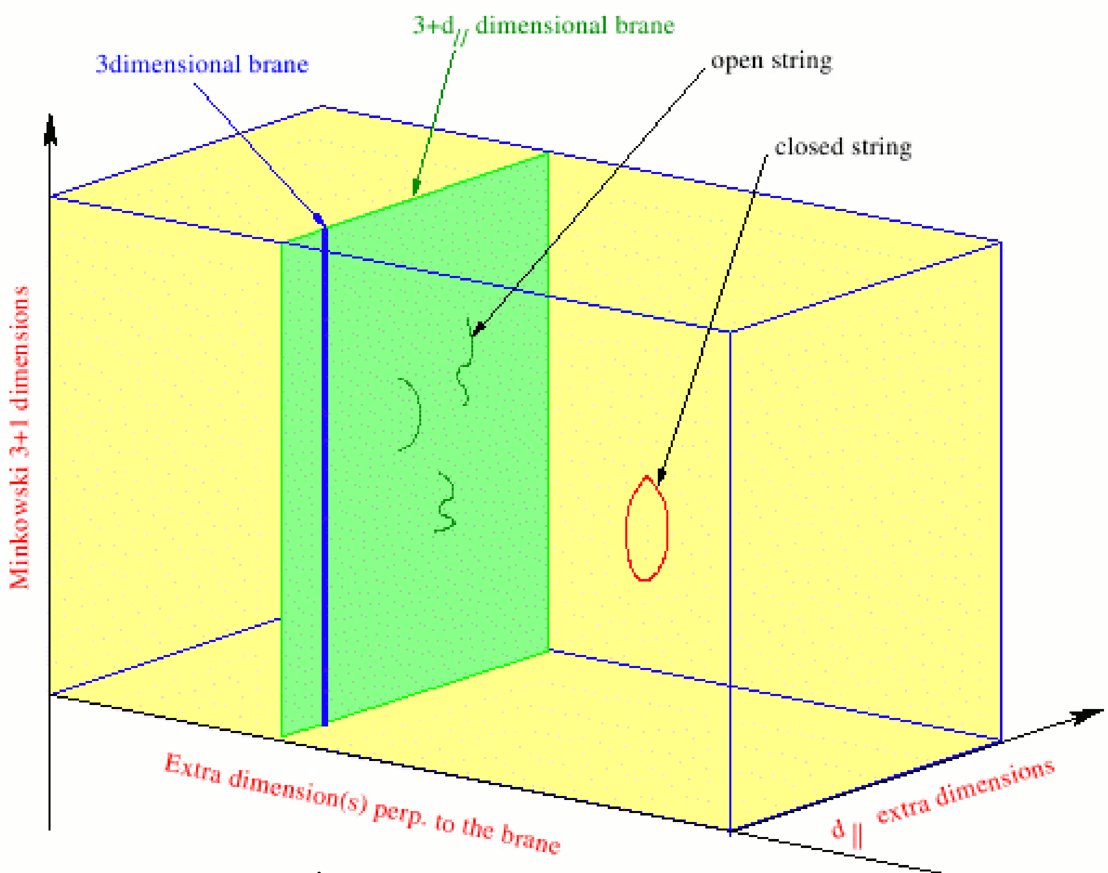
New TeV scale physics

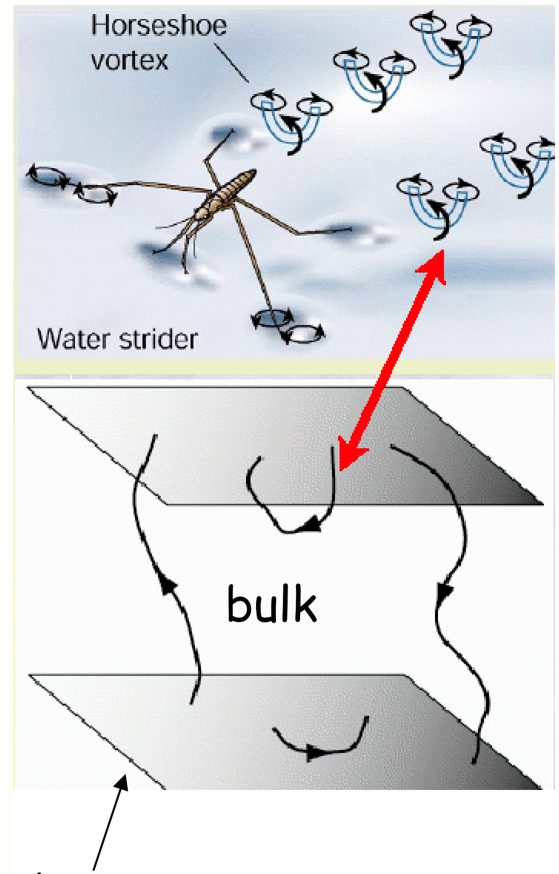


Extra dimensions

An entomological analogy

Typical string/D-brane set-up involves extra dimensions

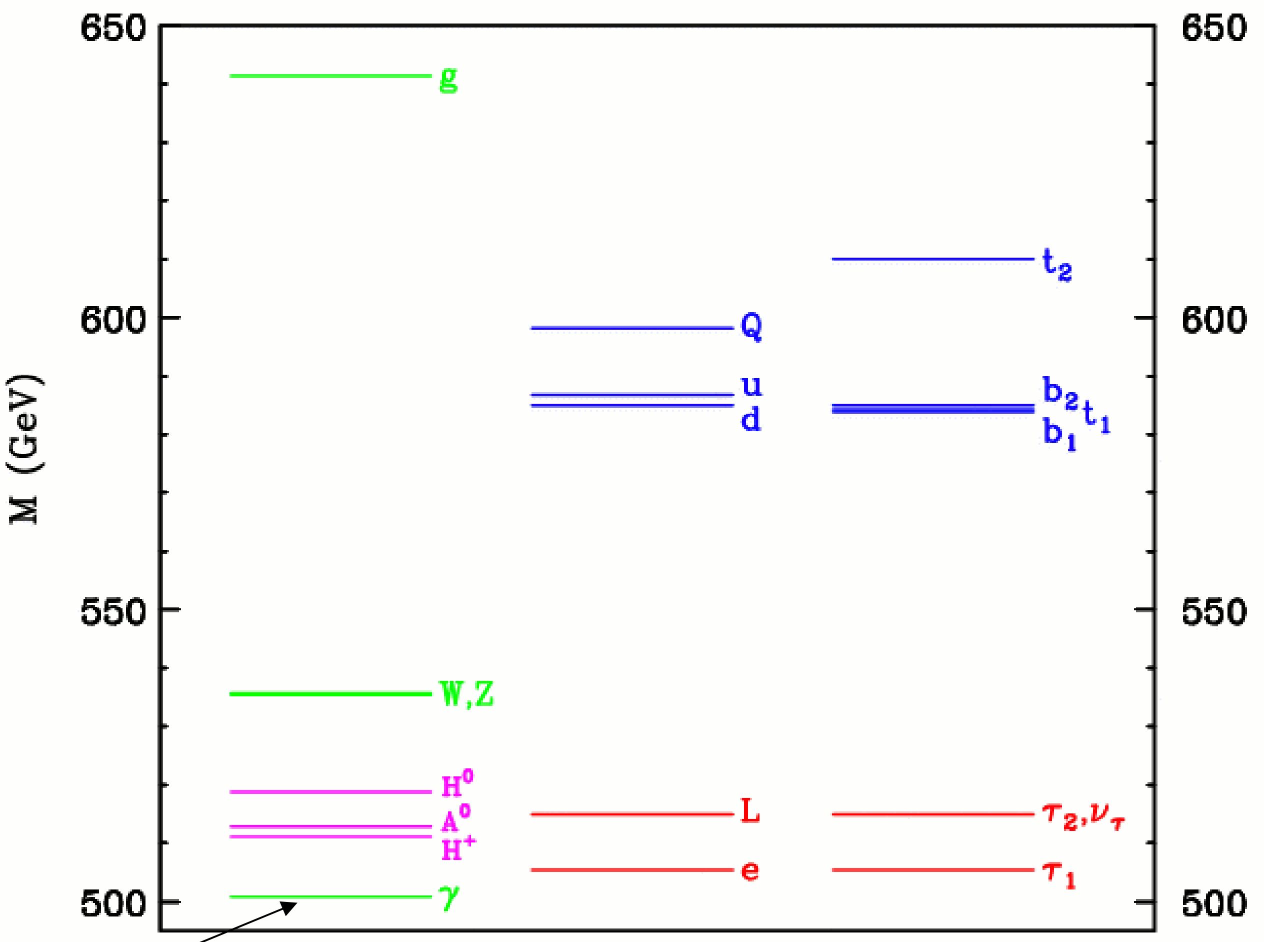




Antoniadis

brane

UED: flat extra dimensions with everything in the bulk gives KK excitations of everything

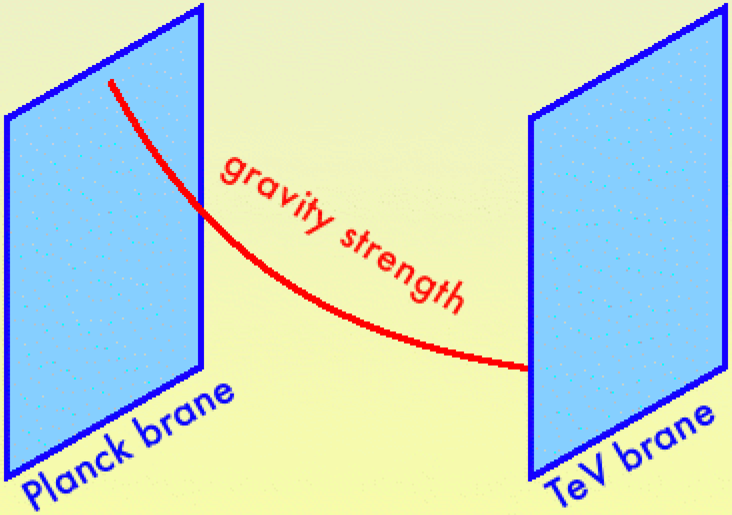


LKP stable
WIMP

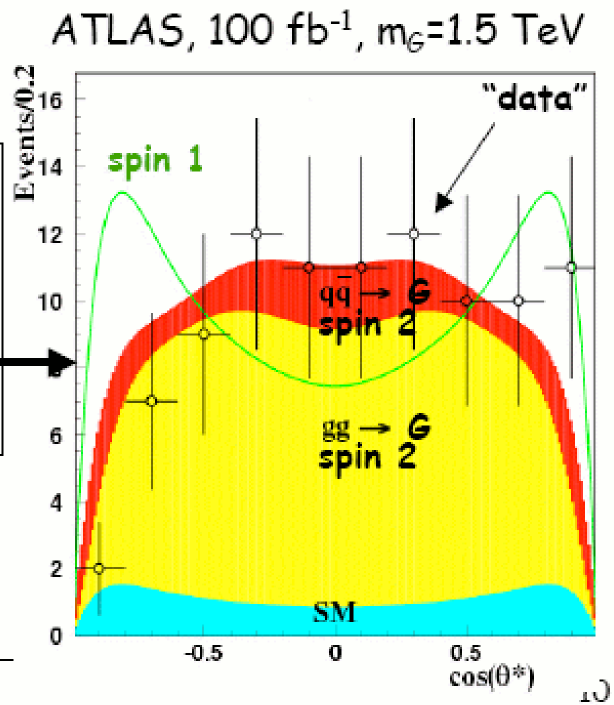
Cheng, Matchev,Schmaltz

RS: warped extra dimensions with gravity only in the bulk

- RS1: "warped" XD, with second (EW or TeV) brane, where gravity exp. suppressed
  - TeV resonances on EW brane ⇔ KK modes .

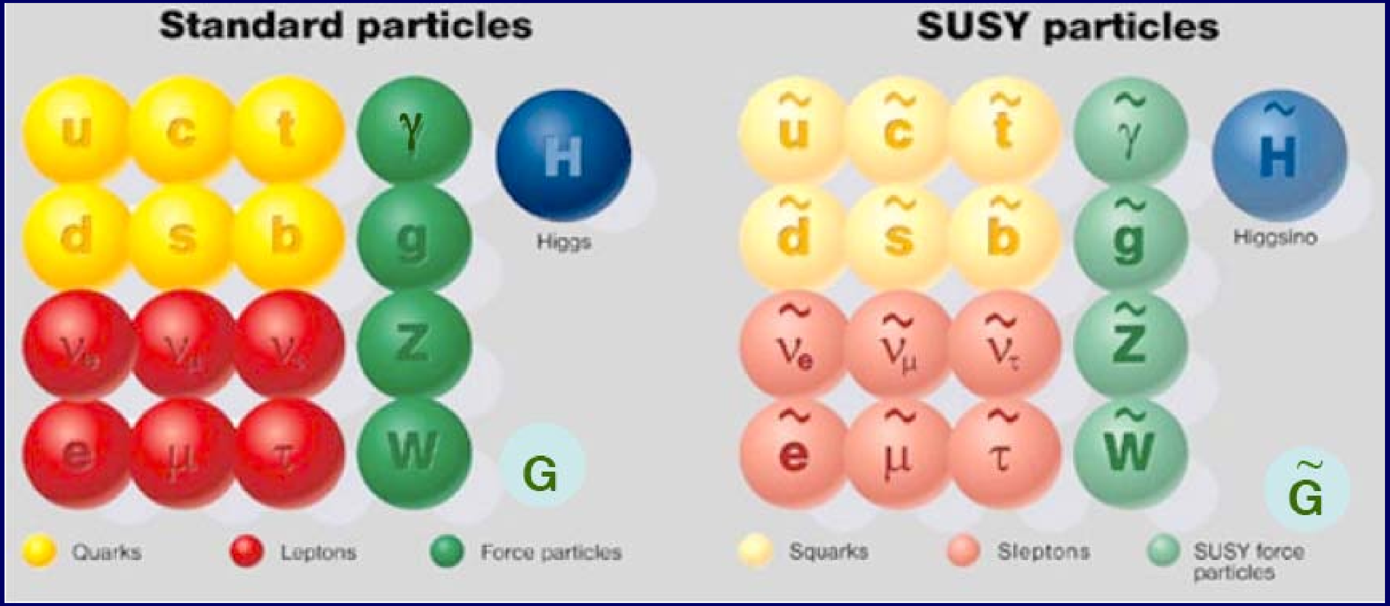


Graviton (s=2) or Z' (s=1) ? → look at $e^{\pm}$ angular distributions



- Warped XD provide calculable substitutes for strongly coupled 4D theories (eg technicolor)

Supersymmetry



FERMIONS $\Leftrightarrow$ SUSY $\Leftrightarrow$ BOSONS

BOSONS $\Leftrightarrow$ SUSY $\Leftrightarrow$ FERMIONS

What has SUSY ever done for us?

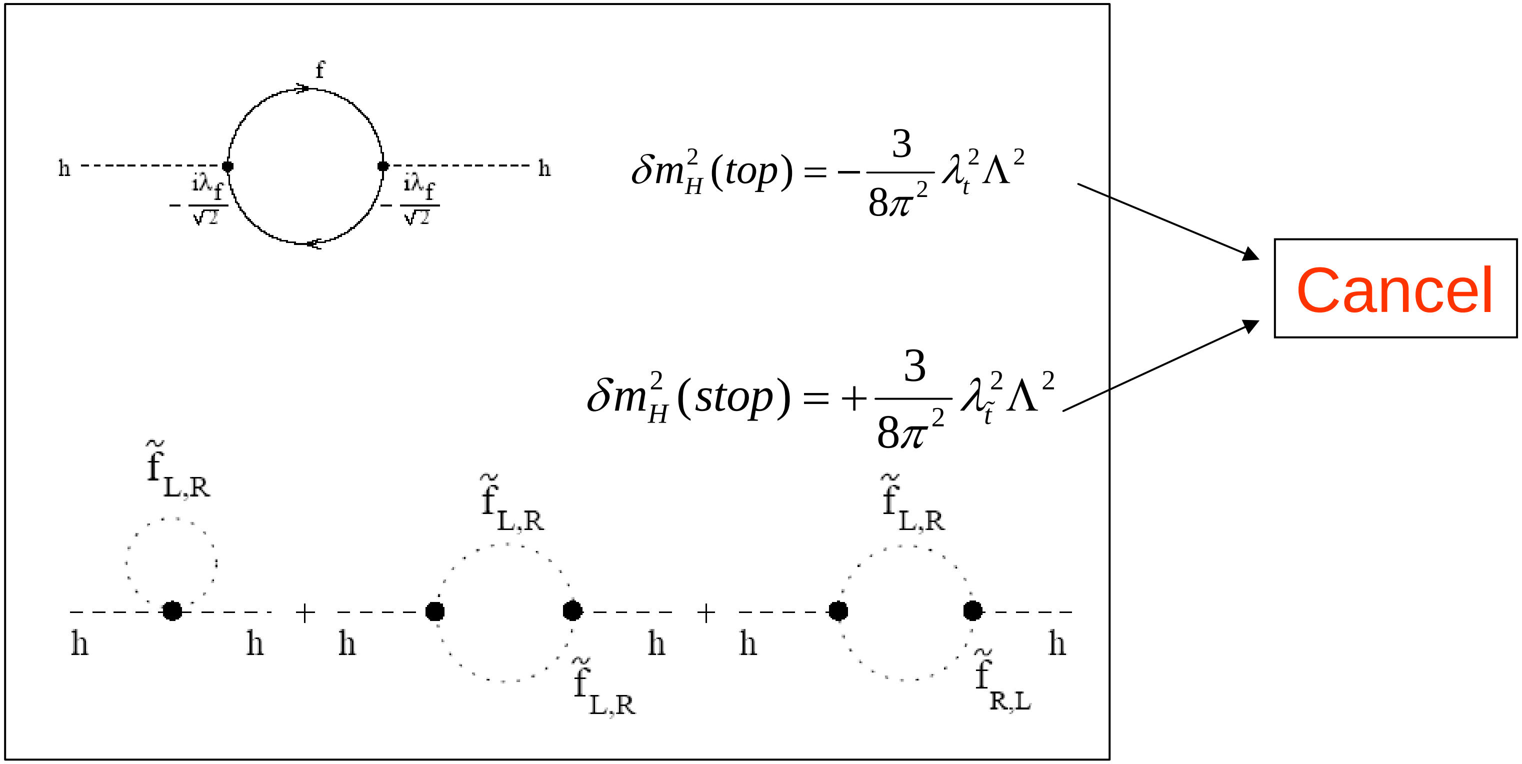
- Solve hierarchy problem (origin of mass)
- Facilitates unification (quest for unification)
- Provides WIMPs (origin of dark matter)
- Helps inflation (origin of universe)
- Enables baryogenesis (origin of atoms)

What SUSY doesn't help with:

- Cosmological constant (origin of dark energy)
- Quark and lepton spectrum (flavour problem)

In fact SUSY makes the flavour problem worse due to squarks and sleptons (sflavour problem)

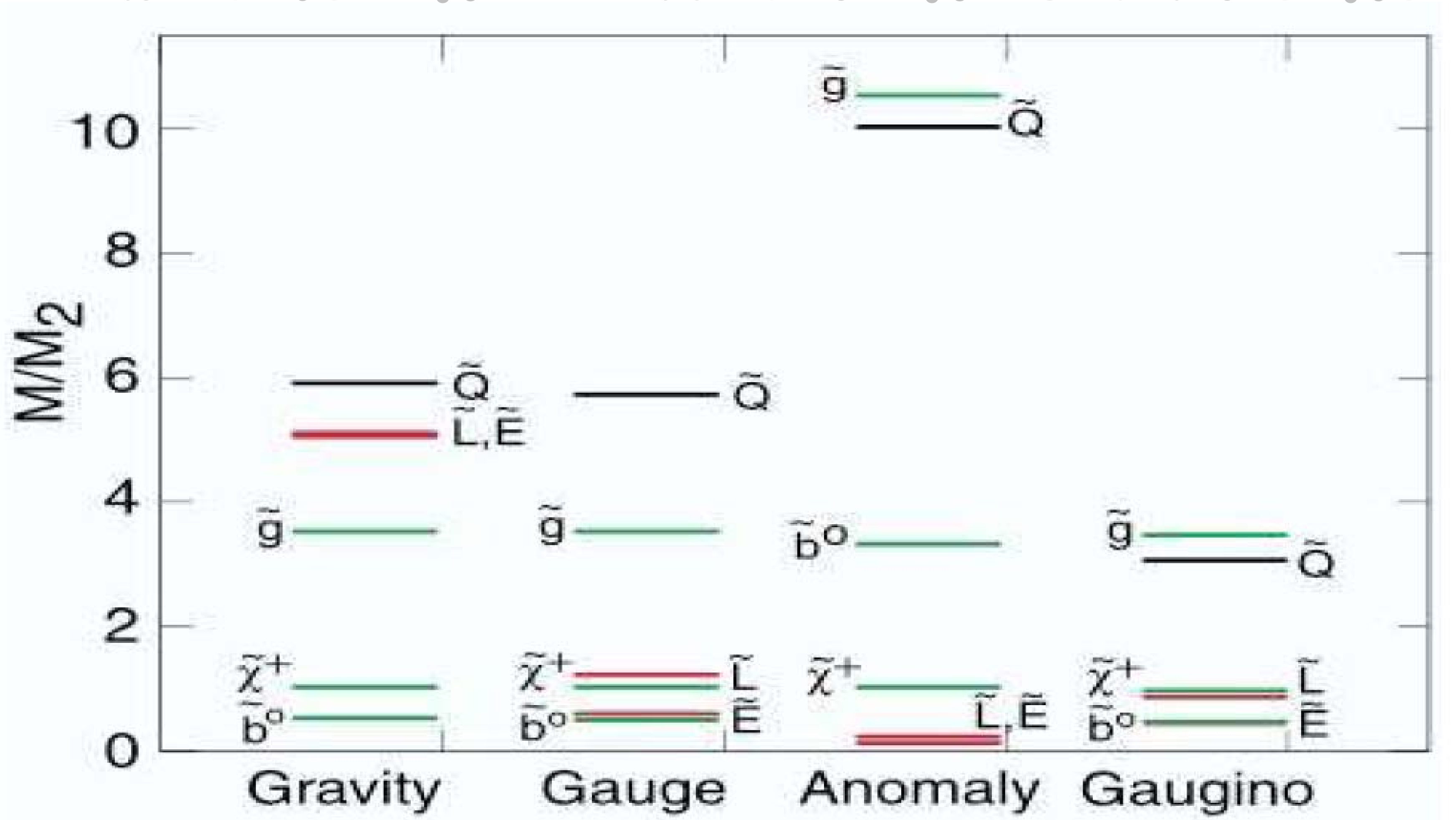
Stabilising the Hierarchy in SUSY



Quadratic divergence cancels leaving $\delta m_H^2 \approx -\frac{9}{8\pi^2}\lambda_t^2 m_{\tilde{t}}^2 \ln\frac{\Lambda}{m_{\tilde{t}}}$

SUSY stabilises the hierarchy providing $m_{\tilde{t}} < 1 TeV$

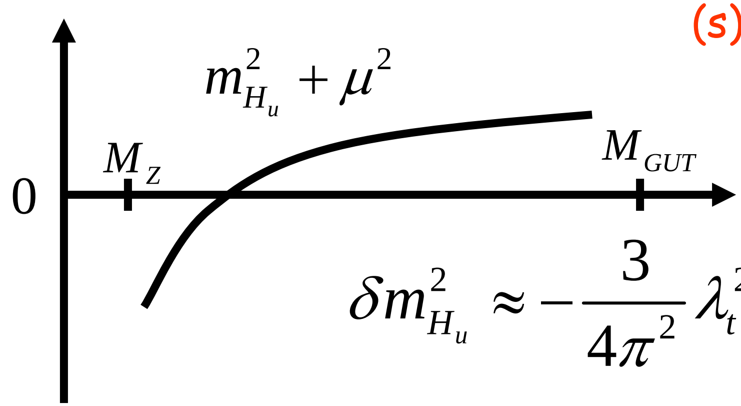
MSSM sparticle spectra for various mediation mechanisms



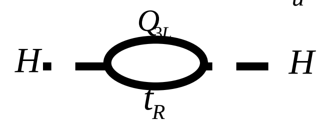
MSSM EWSB

$$W = \mu H_u H_d \qquad H_u = \begin{pmatrix} H_u^{\ +} \\ H_u^{\ 0} \end{pmatrix} \quad H_d = \begin{pmatrix} H_d^{\ 0} \\ H_d^{\ -} \end{pmatrix}$$

A nice feature of MSSM is radiative EWSB Ibanez-Ross



(s)top loops drive $m_{H_u}^2$ negative



$$\delta m_{H_u}^2 \approx -\frac{3}{4\pi^2}\lambda_t^2 m_{stop}^2 \ln\frac{M_{GUT}}{Q} \sim -O(1)m_{stop}^2$$

Min conds at low energy → $\dfrac{M_Z^2}{2} \approx -\left(\mu^2 + m_{H_u}^2 + \delta m_{H_u}^2\right)$

Naturalness requirement is $M_Z \sim \delta m_{H_u} \sim m_{stop}$

But $M_Z \ll m_{stop}$ → Two per cent fine tuning

Also no reason why $\mu \sim 1$ TeV (μ problem)

→ **Motivates non-minimal SUSY models**

Non-Minimal SUSY Models

To solve the μ problem and reduce fine tuning consider:

$W = \lambda S H_u H_d$ where singlet $\langle S \rangle \sim \mu$

But leads to weak scale axion due to global U(1) PQ symmetry

Need to remove axion somehow

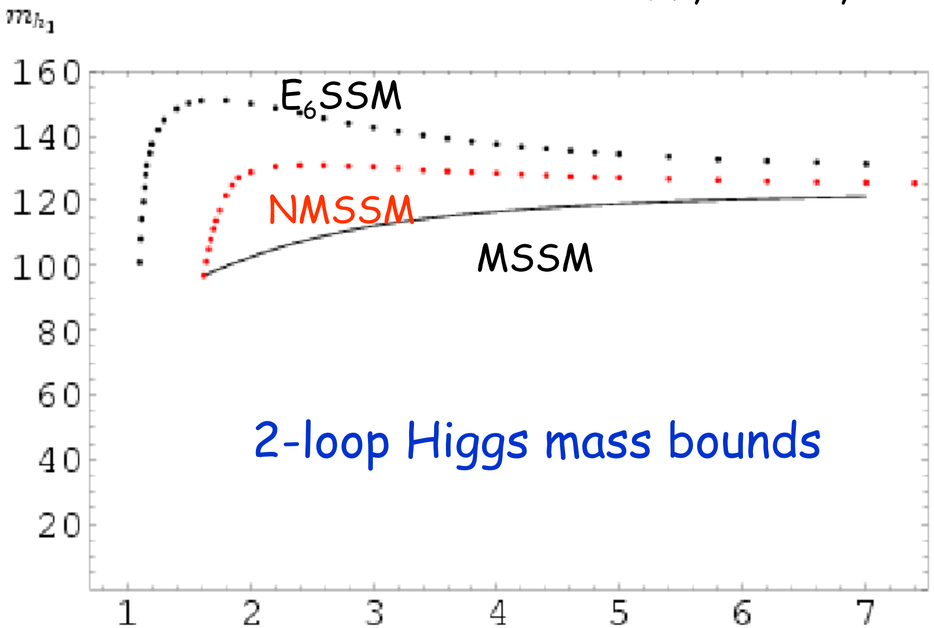
In NMSSM we add S^3 to break U(1) PQ to Z_3 – but this results in cosmological domain walls (or tadpoles if broken)

In E_6SSM we gauge the U(1) PQ 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 gauged $U(1)_N$ from E_6

Higgs mass bounds in SUSY Models

SFK,Moretti,Nevzorov

Higgs mass bound



tan β

$$m_h^2 \leq \frac{\lambda^2}{2} v^2 \sin^2 2\beta + M_Z^2 \cos^2 2\beta$$

NMSSM MSSM

In E_6SSM, λ can be larger than in the NMSSM

NMSSM benchmarks

Djouadi et al '08

Point	P1	P2	P3	P4	P5
GUT/input parameters					
sign($\mu_{\rm eff}$)	+	+	+	−	+
$\tan\beta$	10	10	10	2.6	6
m_0 (GeV)	174	174	174	775	1500
$M_{1/2}$ (GeV)	500	500	500	760	175
A_0	-1500	-1500	-1500	-2300	-2468
A_λ	-1500	-1500	-1500	-2300	-800
A_κ	-33.9	-33.4	-628.56	-1170	60
NUHM: M_{H_d} (GeV)	-	-	-	880	-311
NUHM: M_{H_u} (GeV)	-	-	-	2195	1910
Parameters at the SUSY scale					
λ (input parameter)	0.1	0.1	0.4	0.53	0.016
κ	0.11	0.11	0.31	0.12	-0.0029
A_λ (GeV)	-982	-982	-629	-510	45.8
A_κ (GeV)	-1.63	-1.14	-11.4	220	60.2
M_2 (GeV)	392	392	393	603	140
$\mu_{\rm eff}$ (GeV)	968	968	936	-193	303
CP even Higgs bosons					
$m_{h_1^0}$ (GeV)	120.2	120.2	89.9	32.3	90.7
R_1	1.00	1.00	0.998	0.034	-0.314
t_1	1.00	1.00	0.999	0.082	-0.305
b_1	1.018	1.018	0.975	-0.291	-0.644
BR($h_1^0 \to bb$)	0.072	0.056	7×10^{-4}	0.918	0.895
BR($h_1^0 \to \tau^+\tau^-$)	0.008	0.006	7×10^{-5}	0.073	0.088
BR($h_1^0 \to a_1^0 a_1^0$)	0.897	0.921	0.999	0.0	0.0

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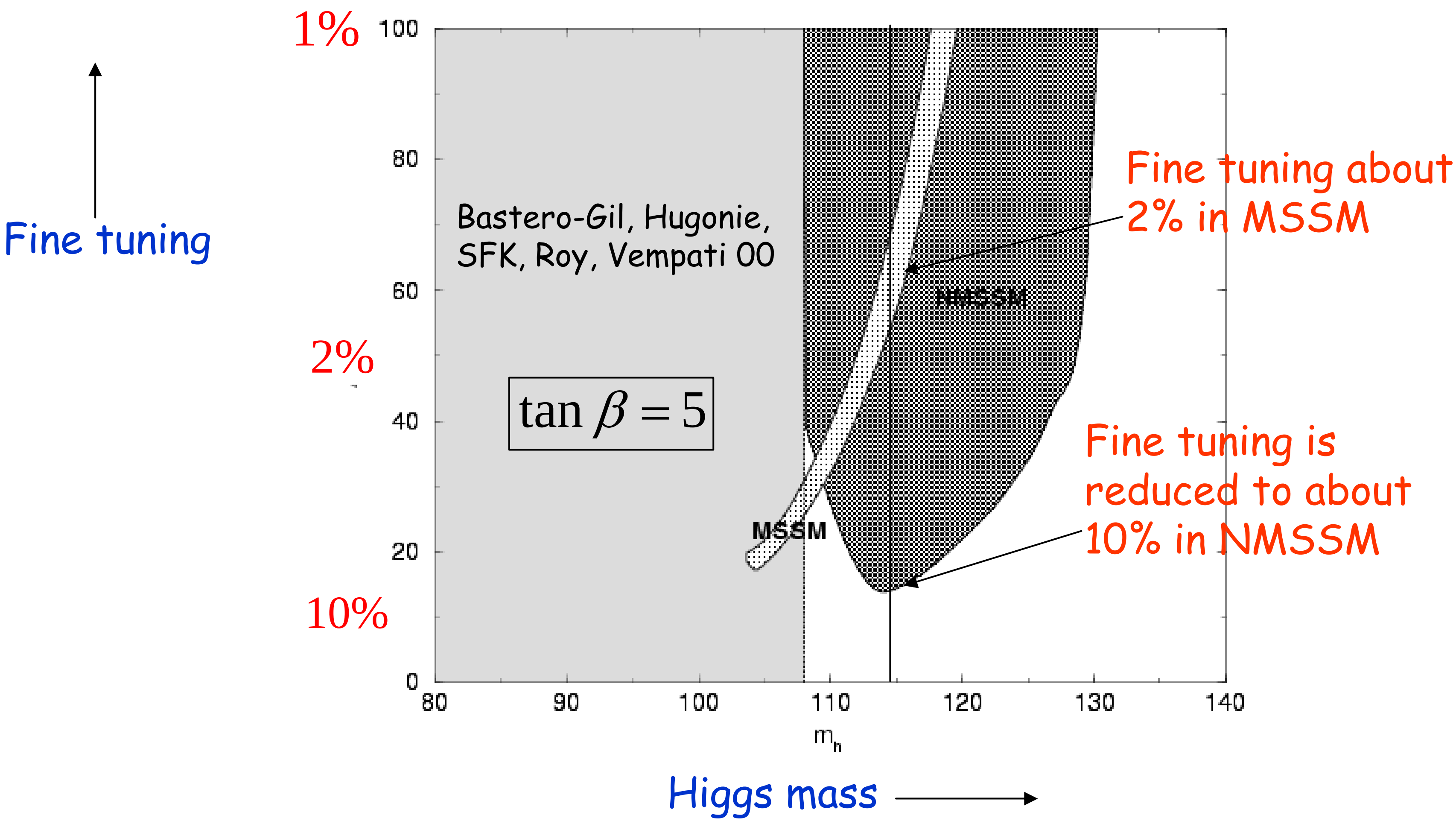
CP odd Higgs bosons					
$m_{a_1^0}$ (GeV)	40.5	9.1	9.1	185	99.6
t_1'	0.0053	0.0053	0.0142	0.0513	-0.00438
b_1'	0.529	0.528	1.425	0.347	-0.158
$\mathrm{BR}(a_1^0 \to bb)$	0.91	0.	0.	0.62	0.91
$\mathrm{BR}(a_1^0 \to \tau^+\tau^-)$	0.085	0.88	0.88	0.070	0.090

h→aa may dominate, with a→bb or τ τ

Fine tuning in NMSSM vs MSSM



E_6SSM

SFK, Moretti, Nevzorov

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

E_6 broken via SU(5) chain

Right handed neutrinos are neutral under: $U(1)_N = \frac{\sqrt{15}}{4}U(1)_\psi + \frac{1}{4}U(1)_\chi \longrightarrow Z'(N)$

M_{GUT} — $E_6 \to SU(5)\times U(1)_N \to SM \times U(1)_N$

$$\boxed{27_i \to (10,1)_i + (5^*,2)_i + (5^*,-3)_i + (5,-2)_i + (1,5)_i + (1,0)_i} \qquad \boxed{27', \overline{27}'}$$

Quarks, leptons | Triplets and Higgs | Singlets and RHν s | H',H'-bar

RH ν masses: M_3, M_2, M_1

To achieve GUT scale unification we add non-Higgs

TeV — $U(1)_N$ broken, Z'(N) & triplets get mass, μ term generated

M_W — $SU(2)_L\times U(1)_Y$ broken

Matter content of E_6SSM at TeV

Quarks and Leptons

EXOTIC D,D-bar

$$27_i \longrightarrow 3\left[(Q_i,\, u^c_i,\, d^c_i,\, L_i,\, e^c_i)\right] + 3(D_i,\, \overline{D}_i) + $$
$$+ 3(H_{2i}) + 3(H_{1i}) + 3(S_i) + 3(N^c_i) + H' + \overline{H}'.$$

Three families of Higgs
(Six Higgs doublets!)

Singlets

Right-handed
neutrinos
(superheavy)

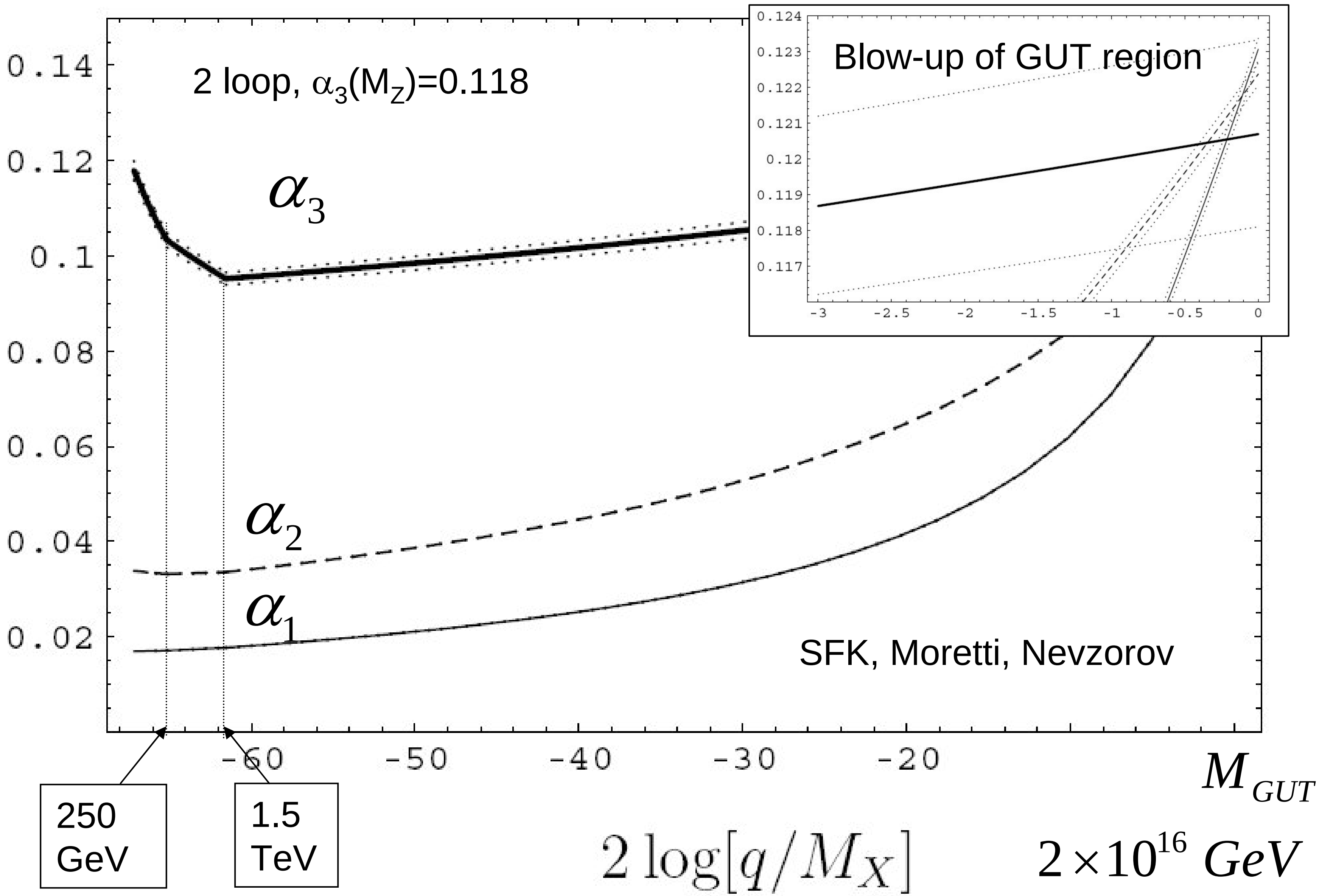
EXOTIC
Vector leptons

Plus a TeV scale Z'(N)

Plus all their SUSY superpartners

Message: E_6SSM predicts SUSY+ EXOTICS at LHC

Unification in E_6SSM



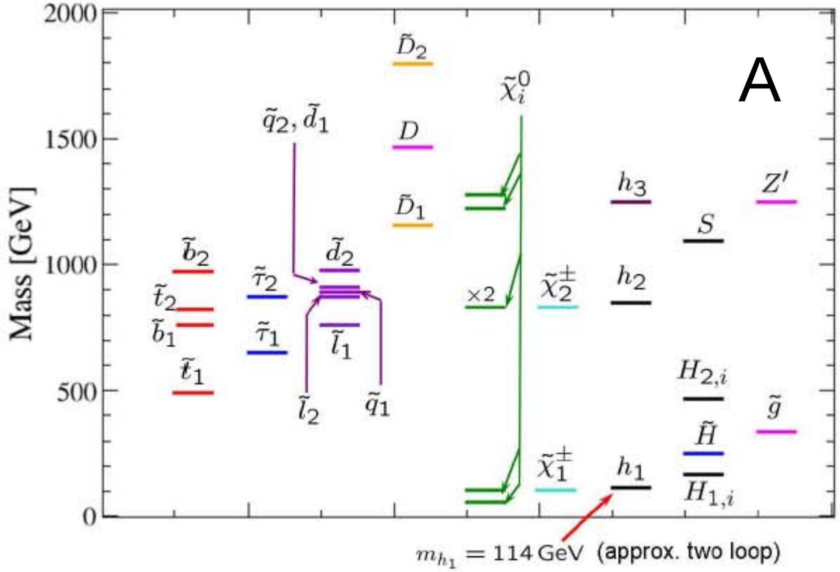
Athron, SFK, Miller, Moretti, Nevzorov

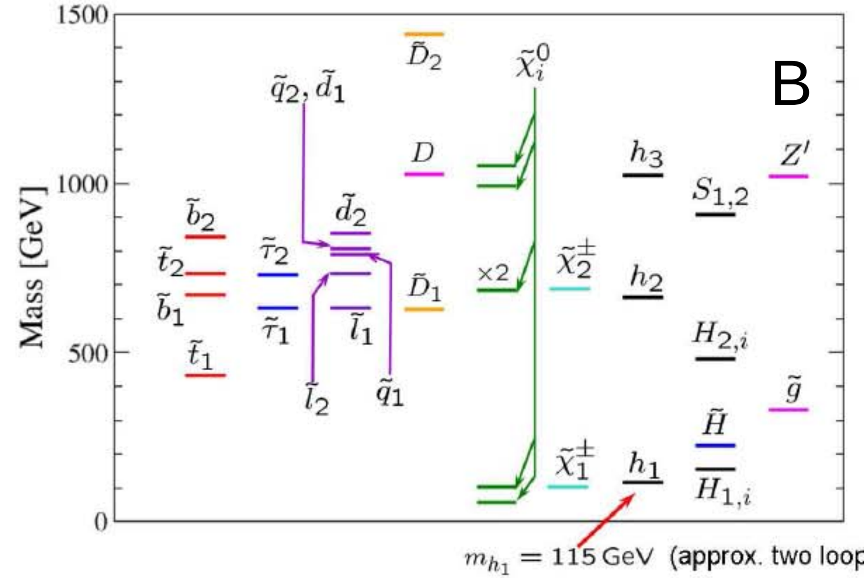
The Constrained E_6SSM

$$W \approx \lambda_i S H_{u,i} H_{d,i} + \kappa_i S D_i \bar{D}_i$$

EWSB, LEP, 2-loop RGE

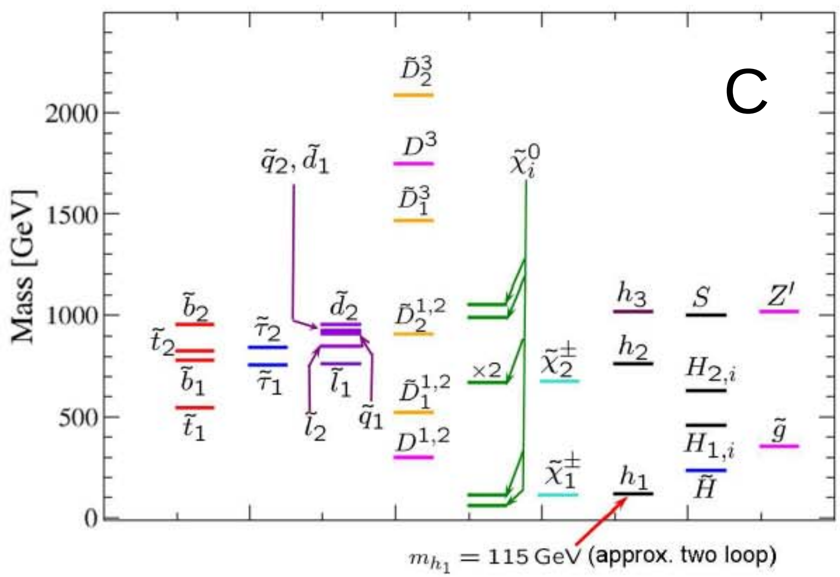
Low Mass Benchmark Points	A	B	C	D
$\tan\beta$	3	10	10	10
$\lambda_3(M_X)$	-0.465	-0.37	-0.378	-0.395
$\lambda_{1,2}(M_X)$	0.1	0.1	0.1	0.1
$\kappa_3(M_X)$	0.3	0.2	0.42	0.43
$\kappa_{1,2}(M_X)$	0.3	0.2	0.06	0.08
s[TeV]	3.3	2.7	2.7	2.7
$M_{1/2}$[GeV]	365	363	388	358
m_0 [GeV]	640	537	681	623
A_0[GeV]	798	711	645	757

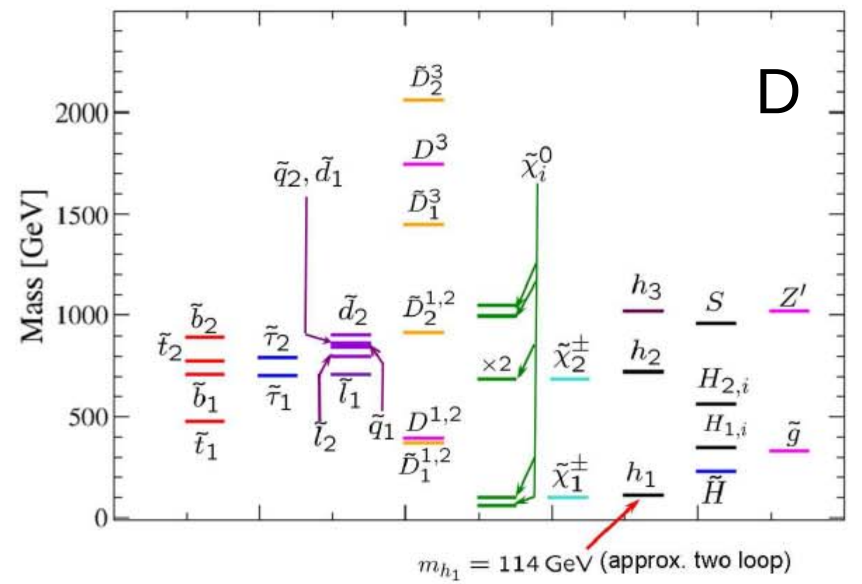




CE$_6$SSM Low Mass Benchmarks

Athron, SFK, Miller, Moretti, Nevzorov





Light gauginos are a general prediction of CE$_6$SSM

$$M_3 \sim 0.7\, M_{1/2}$$ —— $\tilde{g}$ Gluino

$$M_2 \sim 0.25 M_{1/2}$$ —— $\chi_2^0, \chi_1^\pm$ ~ Wino

$$M_1 \sim 0.15 M_{1/2}$$ —— χ_1^0 ~ Bino

Since $$M_i = \frac{\alpha_i}{\alpha_{GUT}} M_{1/2}$$ with $\alpha_3 \sim 0.7\ \alpha_{GUT}$ in E$_6$SSM

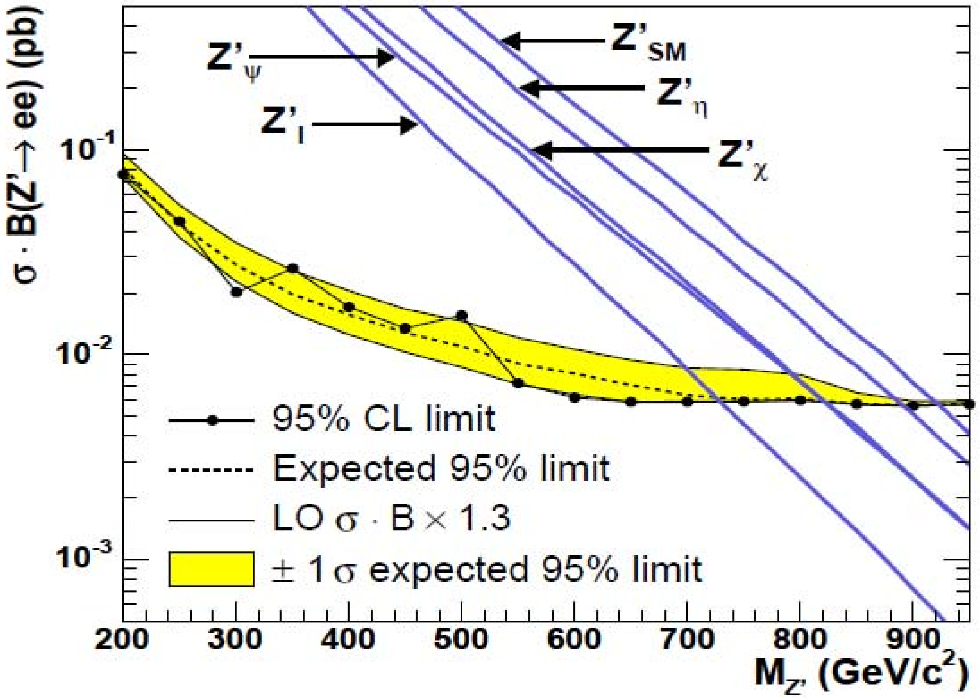
c.f. MSSM $$M_3 \sim 2.7 M_{1/2},\ M_2 \sim 0.8 M_{1/2},\ M_1 \sim 0.4 M_{1/2}$$

Z' (E_6) limits

CDF II preliminary L = 2.3 fb^{-1}

Model	Mass Limits, 95% CL (GeV/c^2)
Z' (SM)	1030
Z' (η)	975
Z' (χ)	892
Z' (ψ)	878
Z' (N)	861
Z' (ι)	789
Z' (sq)	754

CDF FERMILAB-PUB-07-367-E

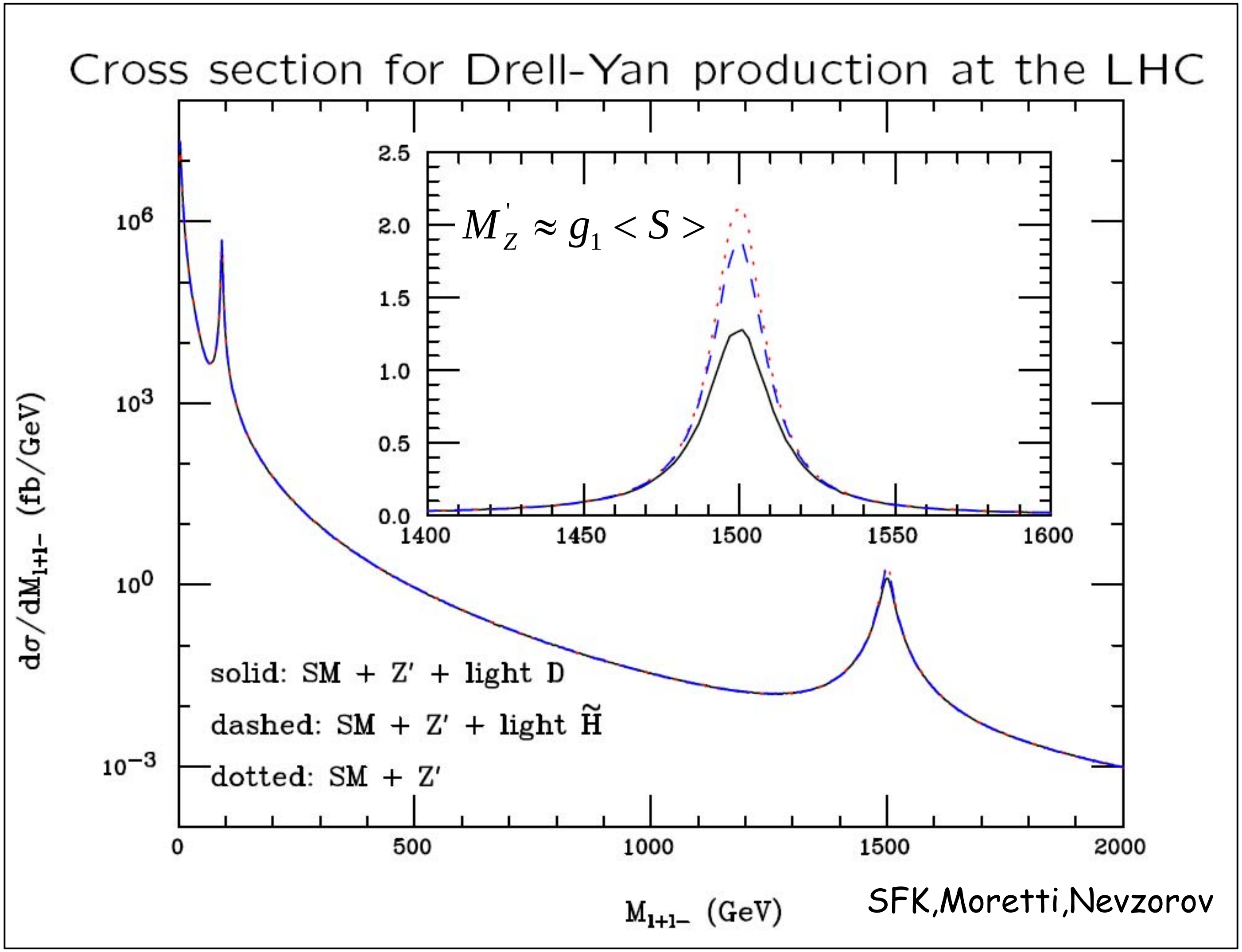


Chris Hays et al

http://www-cdf.fnal.gov/physics/exotic/r2a/20080710.dimuon_resonance/

$SO(10)$	$SU(5)$	$2\sqrt{10}Q_\chi$	$2\sqrt{6}Q_\psi$	$2\sqrt{15}Q_\eta$	$2Q_I$	$2\sqrt{10}Q_N$	$2\sqrt{15}Q_S$
16	$10\ (u,d,u^c,e^+)$	-1	1	-2	0	1	$-1/2$
	$5^*\ (d^c,\nu,e^-)$	3	1	1	-1	2	4
	ν^c	-5	1	-5	1	0	-5
10	$5\ (D,H_u)$	2	-2	4	0	-2	1
	$5^*\ (D^c,H_d)$	-2	-2	1	1	-3	$-7/2$
1	$1\ S$	0	4	-5	-1	5	$5/2$

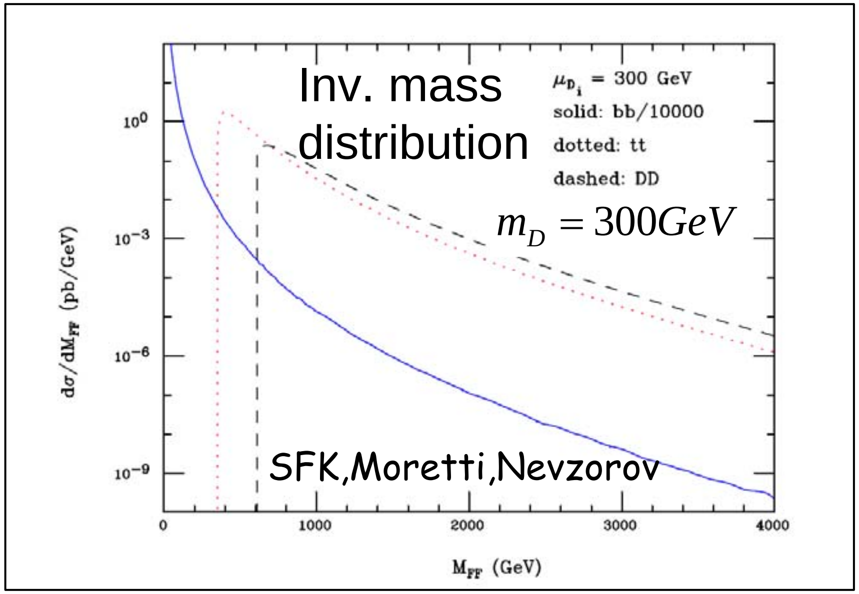
Z'(N)

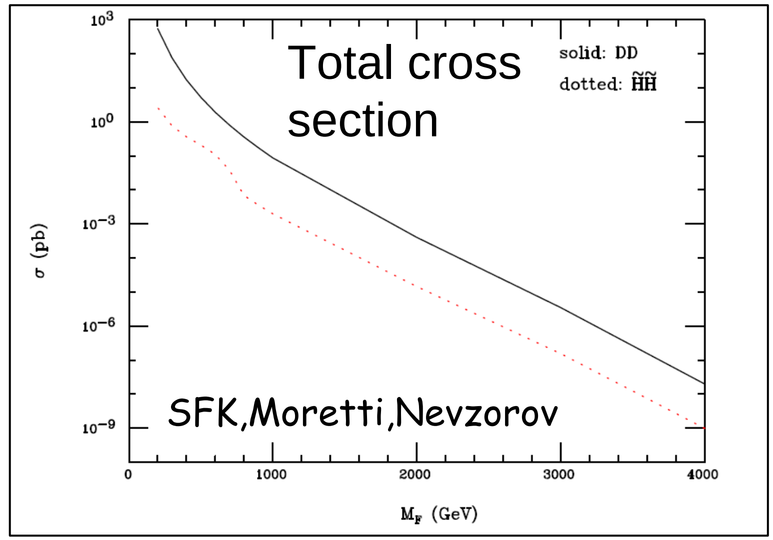


Cross section for Drell-Yan production at the LHC
$M_Z^{'} \approx g_1 < S >$
2.5
2.0
1.5
1.0
0.5
0.0
1400
1450
1500
1550
1600
10^6
10^3
10^0
10^{-3}
$d\sigma/dM_{l+l-}$ (fb/GeV)
solid: SM + Z′ + light D
dashed: SM + Z′ + light $\tilde{H}$
dotted: SM + Z′
0
500
1000
1500
2000
M_{l+l-} (GeV)
SFK,Moretti,Nevzorov

D fermions

Usual case is of scalar leptoquarks, here we have novel case of D being fermionic diquarks or fermionic leptoquarks





Fermionic diquarks D→ $\tilde{t}b,\ t\tilde{b},\ \bar{\tilde{t}}\bar{b},\ \bar{t}\bar{\tilde{b}}$ $\quad \left\{\ pp \to t\bar{t}b\bar{b} + E_T^{\rm miss} + X\right.$

Fermionic leptoquarks D→ $\tilde{t}\tau,\ t\tilde{\tau},\ \tilde{b}\nu_\tau,\ b\tilde{\nu}_\tau$ $\quad \left\{\begin{array}{l} pp \to t\bar{t}\tau\bar{\tau} + E_T^{\rm miss} + X \\ pp \to b\bar{b} + E_T^{\rm miss} + X \end{array}\right.$

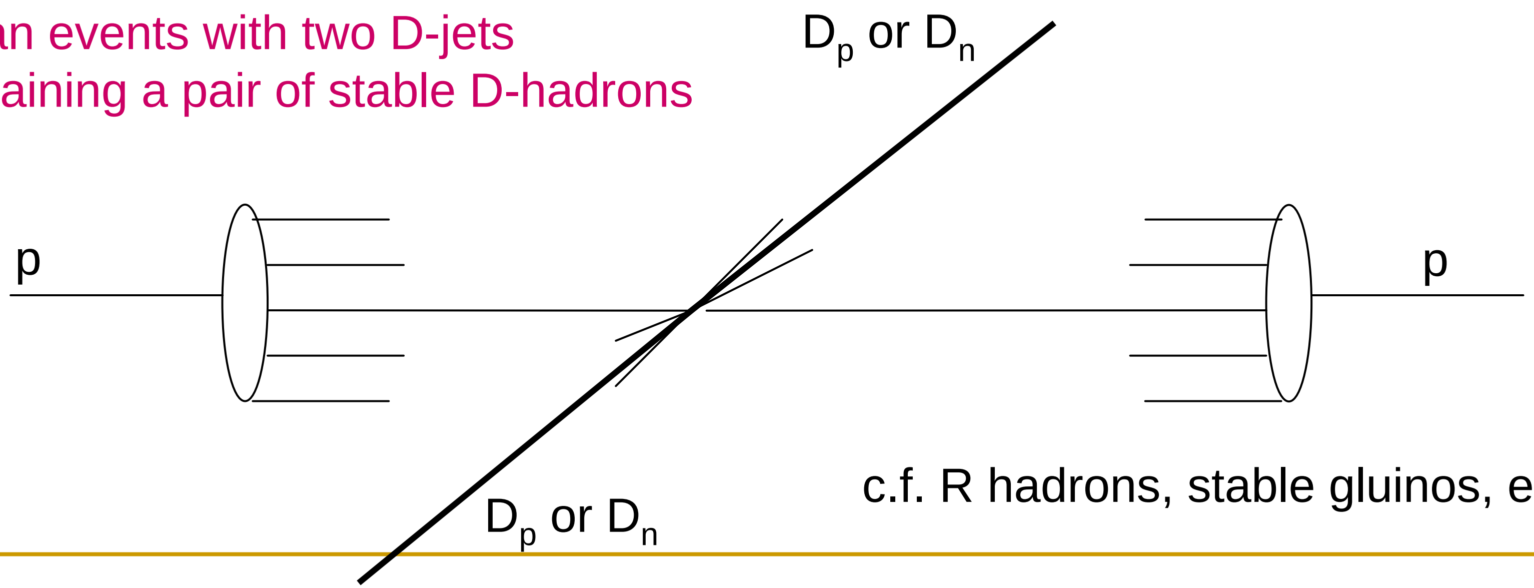
D hadrons

It is possible that D fermions are very long lived (lifetime up to 1 sec) giving jets containing heavy long lived D-hadron

D-hadrons resemble protons or neutrons but with mass >300 GeV:

$$D_p = \bar{D}u,\ D_n = \bar{D}d$$

Clean events with two D-jets
containing a pair of stable D-hadrons



c.f. R hadrons, stable gluinos, etc..

SFK, Hall

Dark Matter from Inert Higgsinos

3 families of Higgs = 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

SUSY partners to inert Higgsinos are good dark matter candidates, which may be almost decouped from the usual MSSM neutralinos and lighter

$$\tilde{\chi}^0_{\rm int} = \begin{pmatrix} \tilde{H}^0_{d1} & \tilde{H}^0_{u1} & \tilde{S}_1 \end{pmatrix}$$

LSP is naturally light

$$\frac{1}{\sqrt{2}}\begin{pmatrix} 0 & \lambda' s & f_u v\sin(\beta) \\ \lambda' s & 0 & f_d v\cos(\beta) \\ f_u v\sin(\beta) & f_d v\cos(\beta) & 0 \end{pmatrix} \longrightarrow m_1 = \frac{1}{\sqrt{2}}\frac{f_d f_u}{\lambda'}\frac{v^2}{s}\sin(2\beta)$$

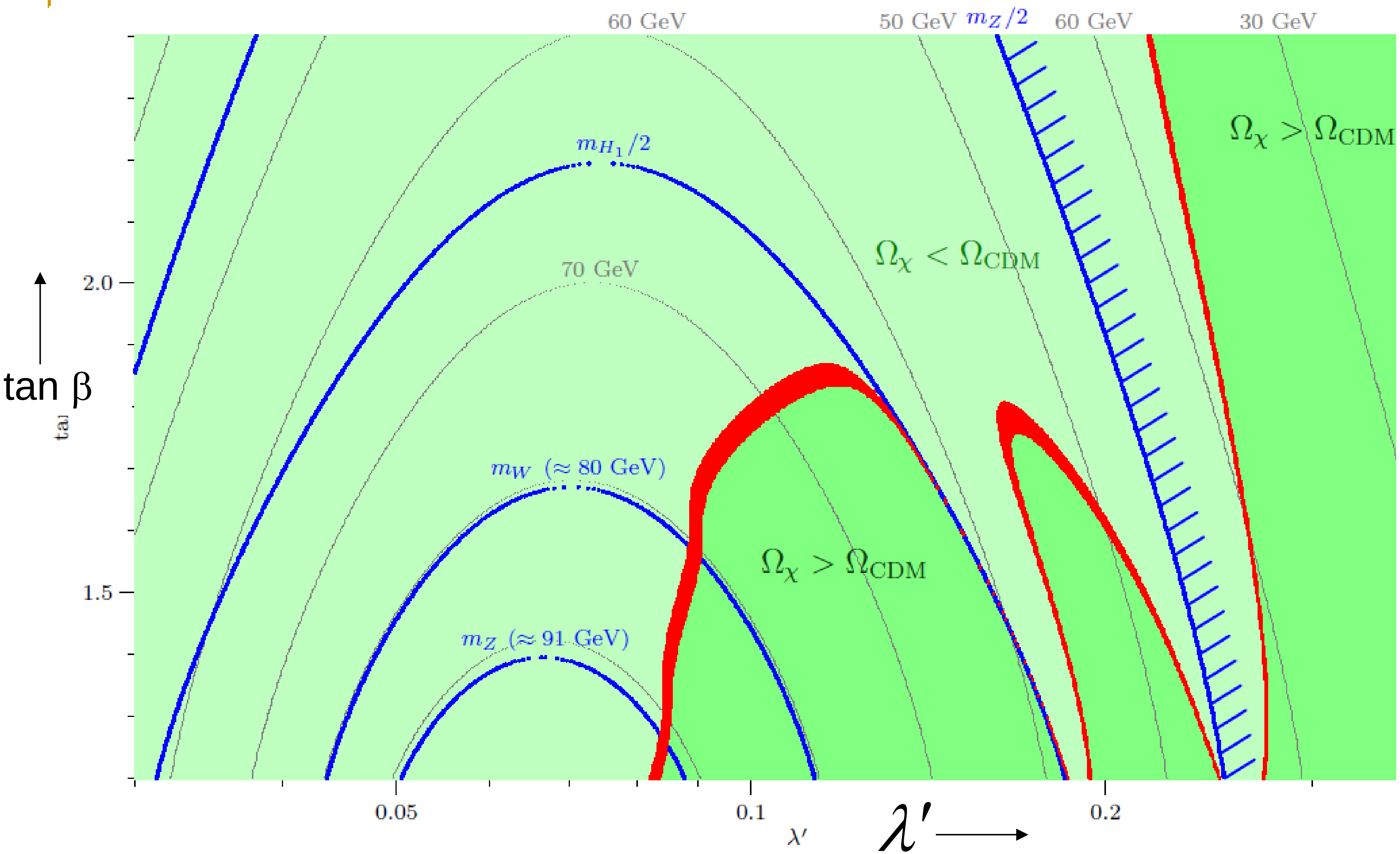
LSP is mainly inert singlino

$$\tilde{\chi}^0_1 = N^1_1 \tilde{H}^0_{d1} + N^2_1 \tilde{H}^0_{u1} + N^3_1 \tilde{S}_1$$

$$-\frac{f_d v}{\lambda' s}\cos(\beta) \qquad -\frac{f_u v}{\lambda' s}\sin(\beta) \qquad 1 - \frac{1}{2}\left(\frac{v}{\lambda' s}\right)^2\left[f_d^2\cos^2(\beta) + f_u^2\sin^2(\beta)\right]$$

Contours of Ω and LSP mass

SFK, Hall



Conclusion

- **Good motivations for BSM physics**
- **Many possibilities: Extra dimensions, TC, SUSY...**
- **MSSM problems→ NMSSM, E6SSM (light/heavy higgs)**
- **NMSSM: higgs phenomenology changed e.g. h→aa**
- **E_6SSM has light gaugino spectrum and predicts lots of exotics: Z', D-fermions, inert Higgs/higgsinos**
- **Neutralino Dark Matter could originate from an almost decoupled sector of inert Higgsinos → relaxes parameter space of SUSY models**
- **SUSY promises the most but CC and sflavour/CP?**
- **Sflavour/CP problem may be addressed by a theory of flavour that describes the quark and lepton spectrum e.g. SU(3) family symmetry** **(Antusch, SFK, Malinsky, Ross)**