The Constrained E_6SSM
and its signatures at the LHC

Work with Moretti and Nevzorov; Howl;
Athron, Miller, Moretti, Nevzorov

Related work:

Demir, Kane, T.Wang; Langacker, Nelson; Morrissey, Wells;
Bourjaily; Cvetic, Demir, Espinosa, Everett, Langacker; J.Wang;
Keith, Ma; Daikoku, Suematsu; Demir, Everett; Hewett, Rizzo;
Barger, Langacker, Lee, Shaughnessy, many others (apologies)

The μ problem

- MSSM solves “technical hierarchy problem” (loops)
- But no reason why Higgs/Higgsino mass $\mu \sim m_{soft}$ → the “μ problem”.
- In the NMSSM μ=0 but singlet allows SHuHd → <S> Hu Hd where <S>$\sim \mu$
- S^3 term required to avoid a massless axion due to global U(1) PQ symmetry
- S^3 breaks PQ to Z_3 resulting in cosmo domain walls (or tadpoles if broken)
- One solution is to forbid S^3 and gauge U(1) PQ symmetry so that the dangerous axion is eaten to form a massive Z’ gauge boson → U(1)’ model
- Anomaly cancellation in low energy gauged U(1)’ models implies either extra low energy exotic matter or family-nonuniversal U(1)’ charges
- For example can have an E_6 model with three complete 27’s at the TeV scale to cancel anomalies with a U(1)’ broken by singlets which solve the μ problem
- This is an example of a model where Higgs triplets are not split from doublets

Howl, SFK

Minimal E_6SSM: Unification at M_P

$$E_6 \to SO(10) \times U(1)_\psi$$

$$SO(10) \to SU(4)_{PS} \times SU(2)_L \times SU(2)_R$$

E_6 broken via Pati-Salam chain

Extra $U(1)_X$ survives to TeV scale

M_{Planck} — $E_6 \to SU(4)_{PS} \times SU(2)_L \times SU(2)_R \times U(1)_\psi$

M_{GUT} — $SU(4)_{PS} \times SU(2)_L \times SU(2)_R \times U(1)_\psi \to SM \times U(1)_X$

$$\underbrace{(4,2,1)+(\bar{4},1,2)}_{\text{Quarks, leptons}}+\underbrace{(6,1,1)+(1,2,2)}_{\text{Triplets and Higgs}}+\underbrace{(1,1,1)}_{\text{Singlet}}=27$$

RH ν masses: M_3, M_2, M_1

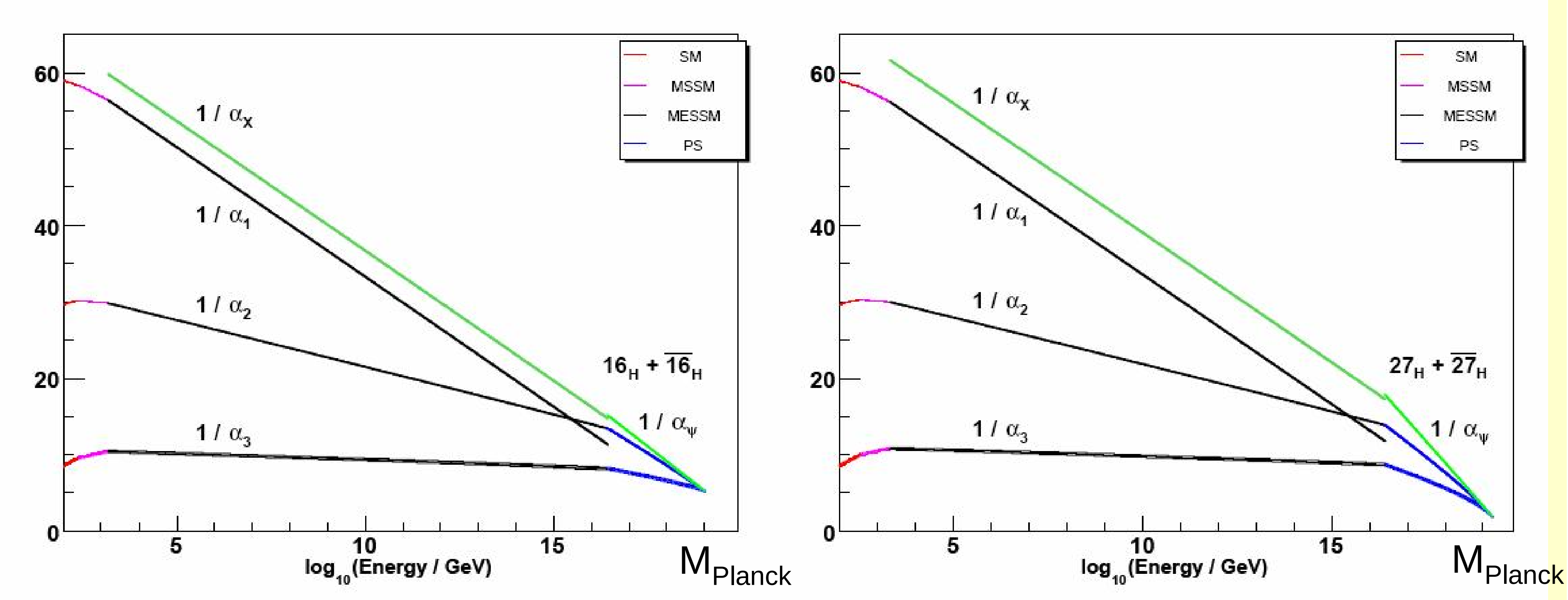
Three families of 27's survive to low energy (minus the RH ν's)

TeV — $U(1)_X$ broken, Z' and triplets get mass, μ term generated

M_W — $SU(2)_L \times U(1)_Y$ broken

Howl, SFK

Unification at M_P in Minimal E_6SSM



Low energy (below M_{GUT})
three complete families of 27's of E_6

High energy (above $M_{GUT} \sim 10^{16}$ GeV) this is embedded into a left-right symmetric Pati-Salam model and additional heavy Higgs are added.

SFK, Moretti, Nevzorov

E_6SSM: Unification at M_{GUT}

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

E_6 broken via SU(5) chain

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

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

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

- $(10,1)_i + (5^*,2)_i$: Quarks, leptons
- $(5^*,-3)_i + (5,-2)_i$: Triplets and Higgs
- $(1,5)_i + (1,0)_i$: Singlets and RHν s
- $27', \overline{27}'$: H',H'-bar

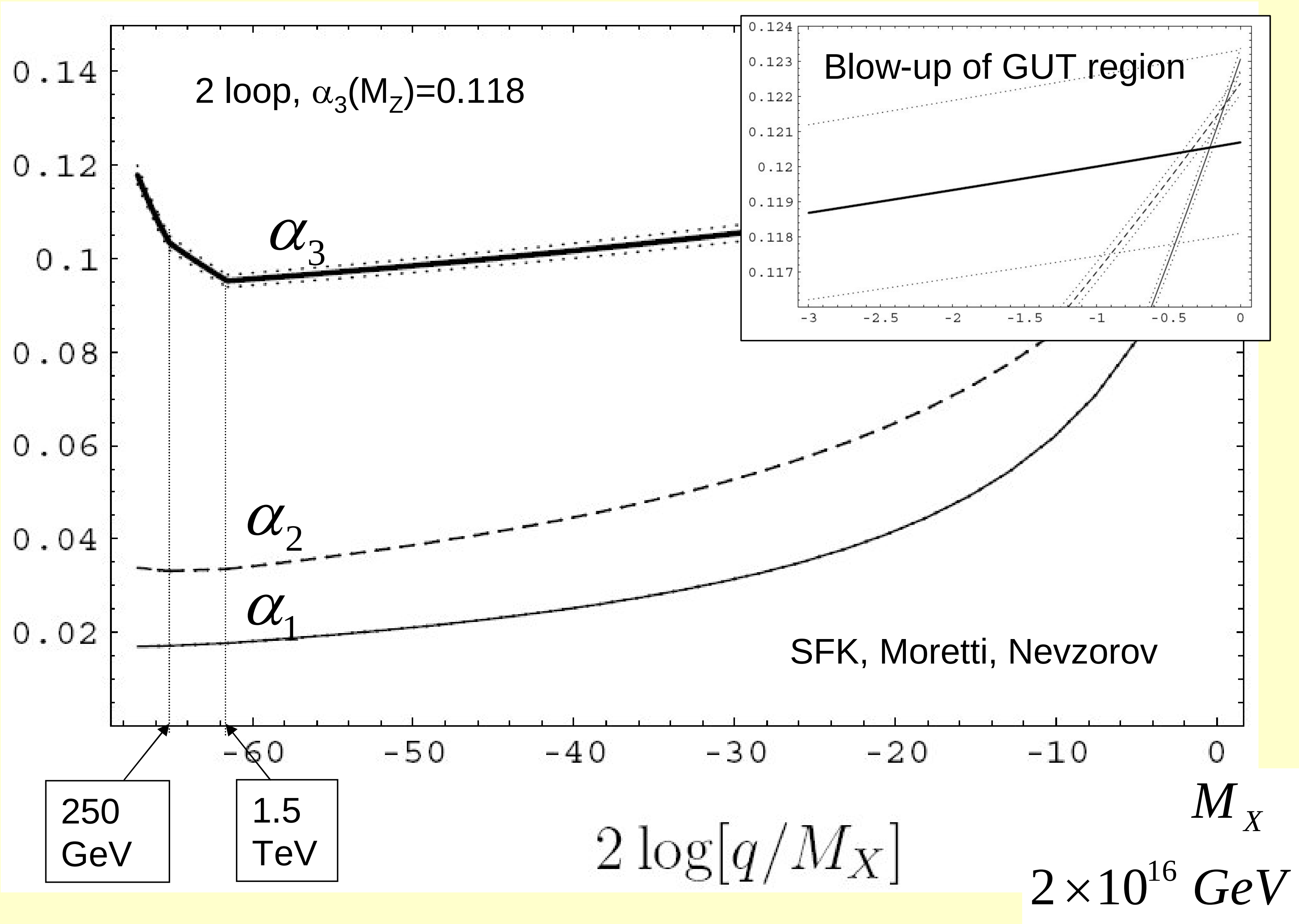
RH ν masses: M_3, M_2, M_1

To achieve GUT scale unification we add non-Higgs

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

M_W — $SU(2)_L \times U(1)_Y$ broken

Unification at M_{GUT} in E_6SSM



Low energy matter content of E_6SSM's

Quarks and Leptons

Exotic D,D-bar

$$27_i \rightarrow 3\left[(Q_i,\, u_i^c,\, d_i^c,\, L_i,\, e_i^c)\right] + 3(D_i,\, \overline{D}_i) + \\ + 3(H_{2i}) + 3(H_{1i}) + 3(S_i) + 3(N_i^c) + H' + \overline{H}'$$

Three families of Higgs

Singlets

Right-handed neutrinos

Optional non-Higgs from incomplete reps 27'+27'-bar → μ' and doublet-triplet problems (absent in minimal E_6SSM)

E_6SSM couplings

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

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

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

- SHH: Singlet-Higgs-Higgs couplings includes effective μ term
- SDD: Singlet-D-D couplings includes effective D mass terms
- HFF: Yukawa couplings but extra Higgs give FCNCs
- DFF: DQQ, DQL allows D decay but also proton decay

Two potential problems: rapid proton decay + FCNCs

• FCNC problem may be tamed by introducing a Z_2 under which third family Higgs and singlet are even all else odd → only allows Yukawa couplings involving third family Higgs and singlet H_u , H_d , S

• Z_2 also forbids all DFF and hence forbids D decay (and p decay)
→ Z_2 cannot be an exact symmetry!
How do we reconcile D decay with p decay?
Two strategies: extra exact discrete symmetries or small D Yukawas

• In E_6SSM can have extra discrete symmetries, two possibilities:

I. Z_2^L under which L are odd → forbids DQL, allows DQQ → exotic D are diquarks

II. Z_2^B with L & D odd → forbids DQQ, allows DQL → exotic D are leptoquarks

• Small DFF couplings $<10^{-8}$ will suppress p decay sufficiently
but couplings $>10^{-12}$ will allow D decay with lifetime <0.1 s (nucleosynth)
N.B. $\Gamma_D \propto g^2$, $\Gamma_p \propto g^4$ (this is the only possibility in the minimal E_6SSM)

Henceforth assume problems solved by one of these approaches

Athron, SFK, Miller, Moretti, Nevzorov

The Constrained E_6SSM

$$W \approx \lambda_i S H_{u,i} H_{d,i} + \kappa_i S D_i \bar{D}_i$$
$$+ f_{\alpha j} S_\alpha H_{u,\beta} H_d + h_{\alpha\beta} S_\alpha H_u H_{d,\beta}$$
$$+ h_t Q H_u t + h_b Q H_d b + h_\tau L H_d \tau$$

The Z_2 allowed couplings

H_u, H_d, S without indices are third family Higgs and singlet, $H_{u,\alpha}$, $H_{d,\beta}$, S_α are non-Higgs

Assume universal soft masses m_0, A, $M_{1/2}$ at M_{GUT}

In practice, input SUSY and exotic threshold scale μ_S then select tan β and singlet VEV <S>=s and run up third family Yukawas from μ_S to M_{GUT}

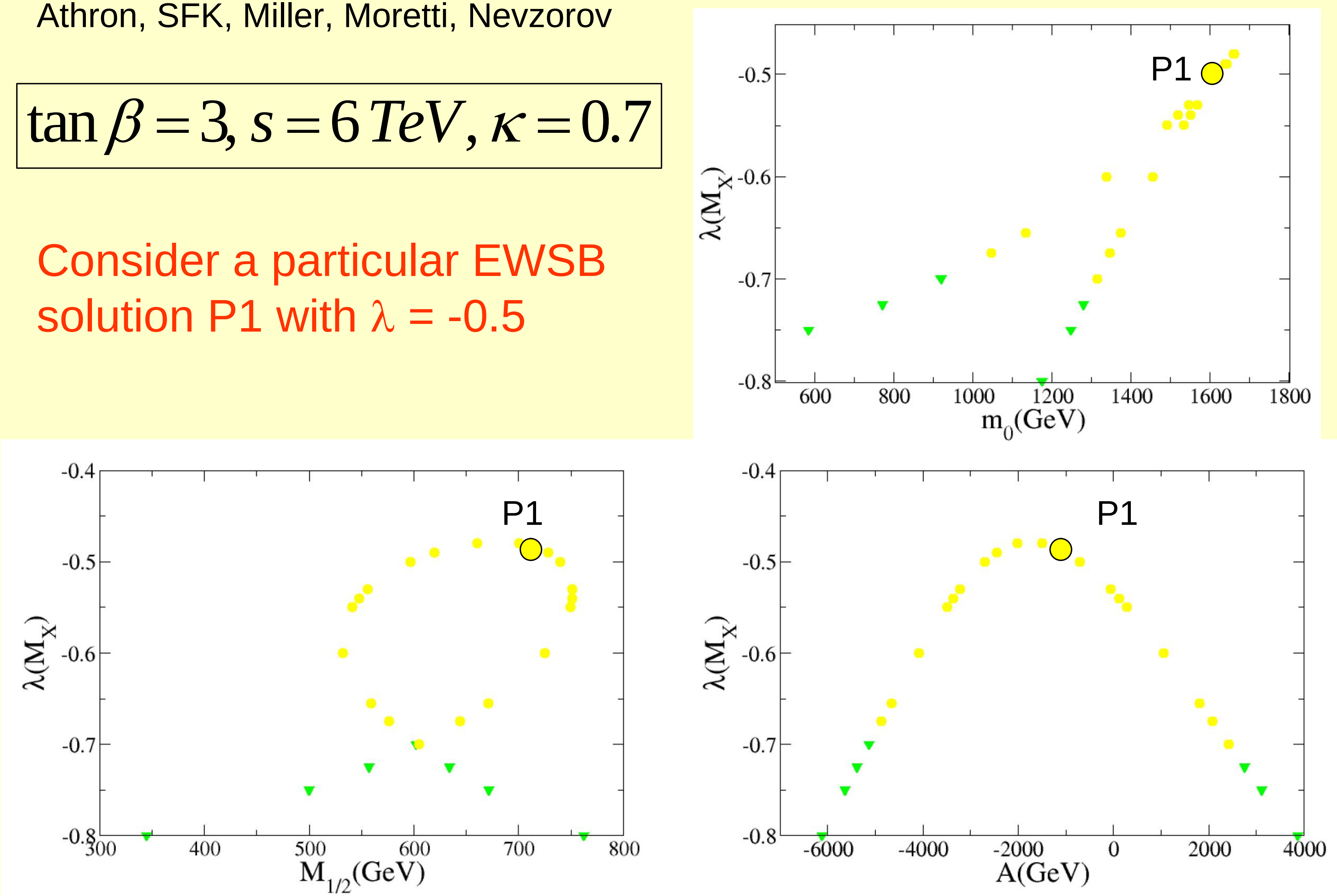
Then choose m_0, A, $M_{1/2}$ at M_{GUT} and run down gauge couplings, Yukawas and soft masses to low energy and minimise Higgs potential for the 3 Higgs fields S, H_u, H_d (even under Z_2)

EWSB is not guaranteed, but remarkably there is always a solution for sufficiently large κ to drive $m_S^2 < 0$ (c.f. large h_t to drive $m_H^2 < 0$)

Athron, SFK, Miller, Moretti, Nevzorov

$$\tan\beta = 3, s = 6\,TeV, \kappa = 0.7$$

Consider a particular EWSB solution P1 with λ = -0.5



Spectrum for P1

Athron, SFK, Miller, Moretti, Nevzorov

$$\tan\beta = 3,\ s = 6\,TeV,\ \ \kappa = 0.7,\ \lambda = -0.5$$

$$M_{1/2} = 700\,GeV,\ m_0 = 1.6\,TeV,\ A = -1\,TeV$$

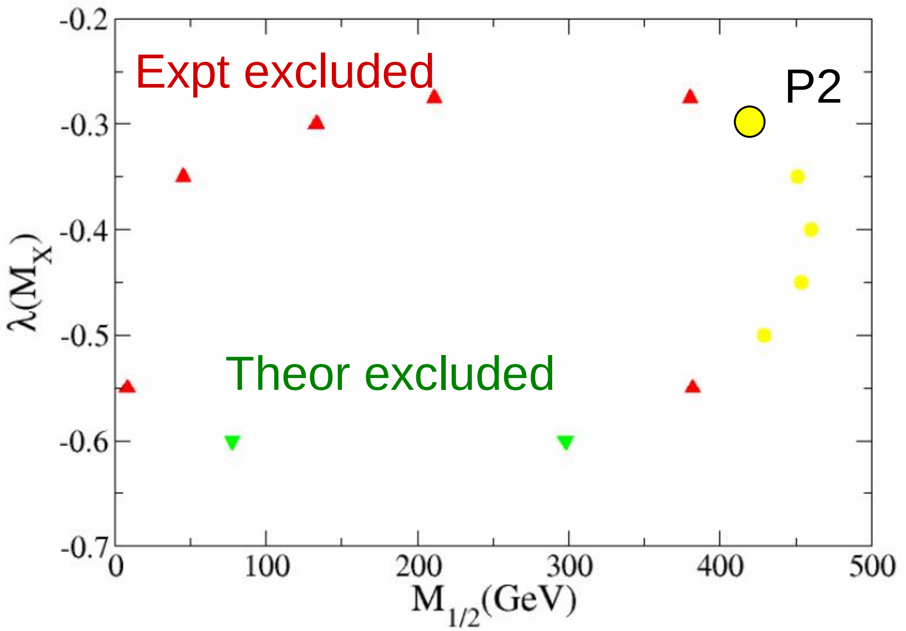
$2.2TeV$	$\chi^0_{5,6}, h^0_3, Z'$
$1.8TeV$	$H^{\pm}, h^0_2, A$
$1.4TeV$	$\chi^0_{3,4}, \chi^{\pm}_2$
$460GeV$	$\tilde{g}$
$174GeV$	$\chi^0_2, \chi^{\pm}_1$
$120GeV$	h^0_1
$97GeV$	χ^0_1

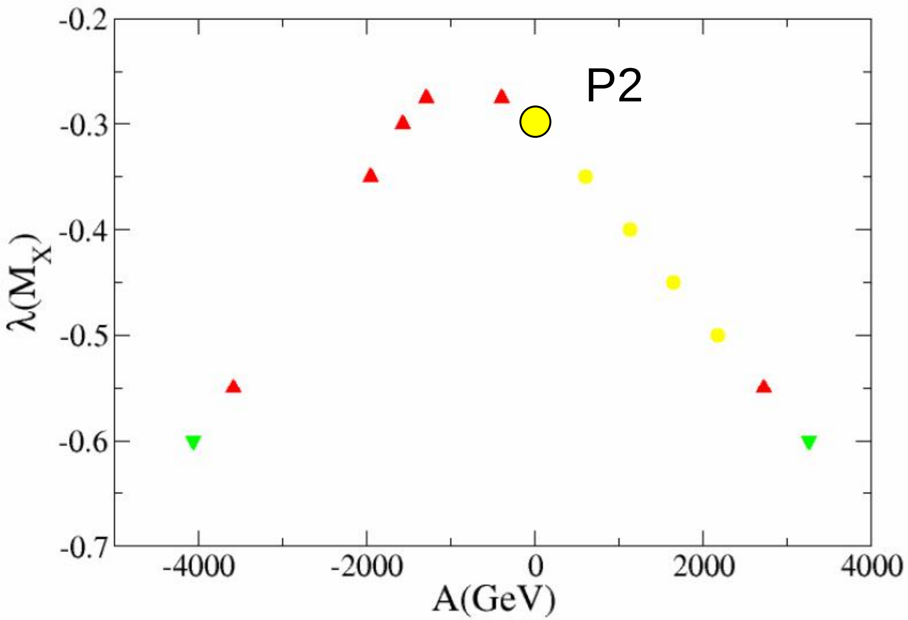
$5TeV$	$\tilde{D}_3$
$4.7TeV$	D_3
$>1.5TeV$	$\tilde{D}_{1,2}$
$1.8TeV$	$\tilde{Q}, \tilde{t}_2, \tilde{b}, \tilde{L}$
$1.7TeV$	non-Higgs
$1.4TeV$	$\tilde{t}_1$
$>300GeV$	$D_{1,2}$
$??\,GeV$	non-Higgsinos

Athron, SFK, Miller, Moretti, Nevzorov

$$\tan\beta = 10,\, s = 6\,TeV,\;\; \kappa = 0.7$$

Consider a particular EWSB solution P2 with λ = -0.3





Spectrum for P2

Athron, SFK, Miller, Moretti, Nevzorov

$$\tan\beta = 10,\ s = 6\,TeV,\ \ \kappa = 0.7,\ \lambda = -0.3$$

$$M_{1/2} = 420GeV,\ m_0 = 2\,TeV,\ A = 20GeV$$

$4.9TeV$ — $\tilde{D}_3$

$4.6TeV$ — D_3

$>1.5TeV$ — $\tilde{D}_{1,2}$

$2.2TeV$ — $\chi^0_{5,6}, h^0_3, Z'$

$2.0TeV$ — $\tilde{Q}, \tilde{t}_2, \tilde{b}, \tilde{L}$ non-Higgs

$1.8TeV$ — $H^{\pm}, h^0_2, A$

$1.5TeV$ — $\tilde{t}_1$

$1.0TeV$ — $\chi^0_{3,4}, \chi^{\pm}_2$

$300GeV$ — $\tilde{g}$

$>300GeV$ — $D_{1,2}$

$125GeV$ — h^0_1

$116GeV$ — $\chi^0_2, \chi^{\pm}_1$

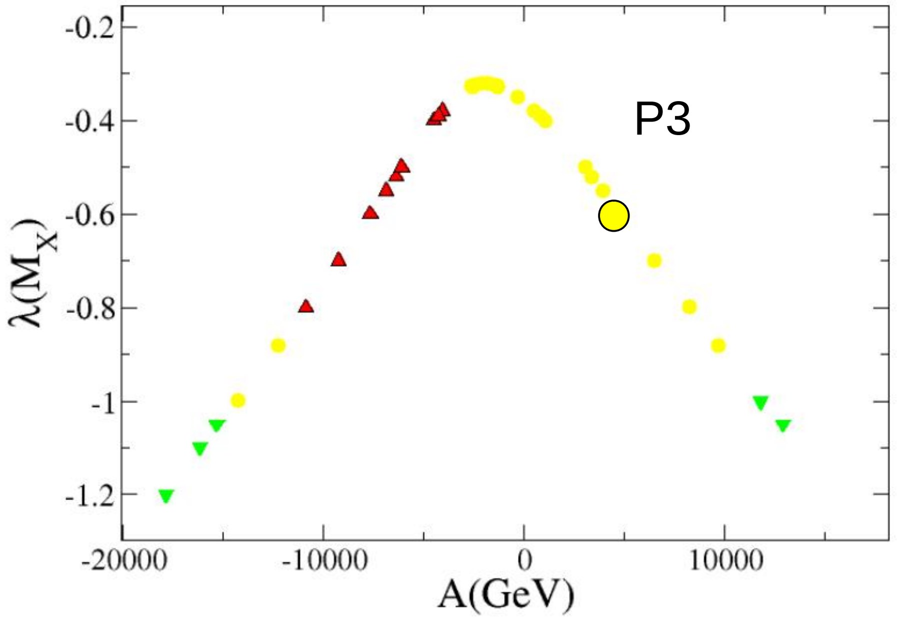
$??\,GeV$ — non-Higgsinos

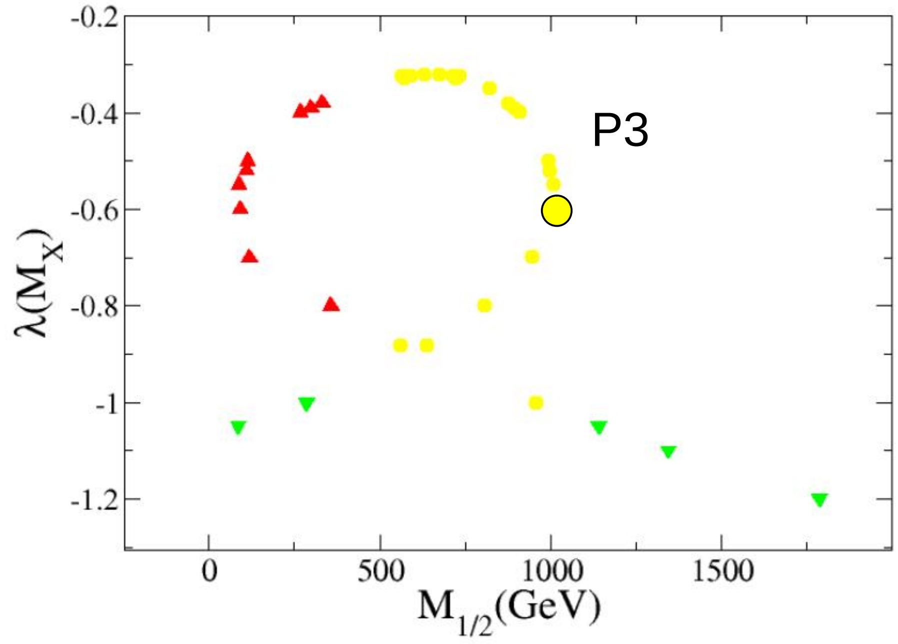
$65GeV$ — χ^0_1

Athron, SFK, Miller, Moretti, Nevzorov

$$\tan\beta = 10,\ s = 20\ TeV,\ \ \kappa = 1.8$$

Consider a particular EWSB solution P3 with λ = -0.6





Spectrum for P3

Athron, SFK, Miller, Moretti, Nevzorov

$$\tan\beta = 10,\ s = 20TeV,\ \ \kappa = 1.8,\ \lambda = -0.6$$

$$M_{1/2} = 1TeV,\ m_0 = 5.5TeV,\ A = 4.6TeV$$

$7.5TeV$ —— $\chi^0_{5,6}, h^0_3, Z'$

$4.9TeV$ —— $H^{\pm}, h^0_2, A$

$3.5TeV$ —— $\chi^0_{3,4}, \chi^{\pm}_2$

$650GeV$ —— $\tilde{g}$

$230GeV$ —— $\chi^0_2, \chi^{\pm}_1$

$130GeV$ —— χ^0_1, h^0_1

$17TeV$ —— $\tilde{D}_3, D_3$

$> 4TeV$ —— $\tilde{D}_{1,2}$

$5.5TeV$ —— $\tilde{Q}, \tilde{t}_2, \tilde{b}, \tilde{L}$ non-Higgs

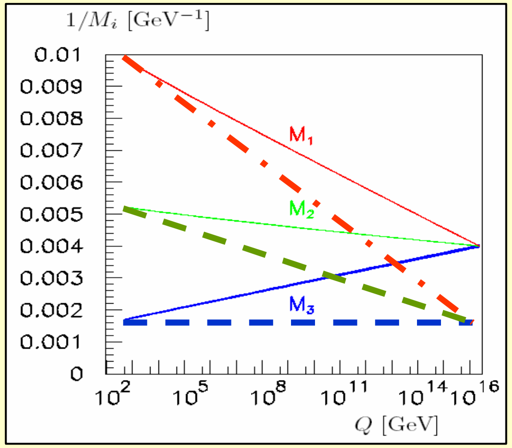
$4TeV$ —— $\tilde{t}_1$

$> 300GeV$ —— $D_{1,2}$

$??\,GeV$ —— non-Higgsinos

Note the characteristic spectrum

For a given low energy M_1, M_2, M_3 need a larger $M_{1/2}$ than in the MSSM



Lightest states are h_1^0 and gauginos:

$$m_{\chi_1^0} \simeq M_1 \,, \qquad m_{\chi_2^0} \simeq m_{\chi_1^\pm} \simeq M_2 \,, \qquad m_{\tilde{g}} \simeq M_3$$

Remaining gauginos, Higgs and Z' are much heavier (ignoring non-Higgs and non-Higgsinos)

$$m_{\chi_2^\pm} \simeq m_{\chi_{3,4}^0} \simeq \mu = \frac{\lambda}{\sqrt{2}} s$$

$$|m_{\chi_5^0}| \simeq |m_{\chi_6^0}| \simeq m_{h_3^0} \simeq M_{Z'}$$

$$m_{H^\pm} \simeq m_{h_2^0} \simeq m_A$$

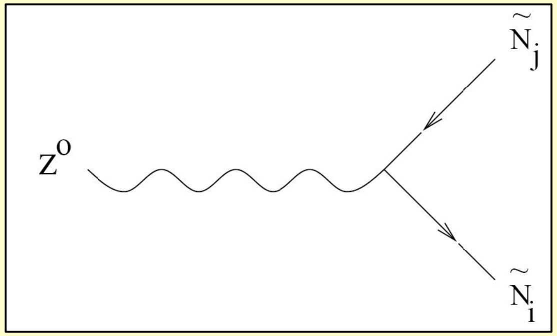
Generally $m_0 > M_{1/2}$ →heavy squarks,sleptons with $\frac{m_0}{M_{1/2}} \propto \tan\beta$

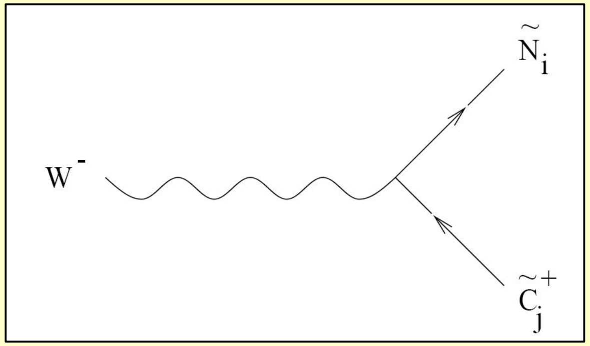
Consider the lightest gaugino states

Gluino	$M_3 \sim 0.7\, M_{1/2}$	————	$\tilde{g}$
~ Wino	$M_2 \sim 0.25 M_{1/2}$	————	$N_2 = \chi_2^0, \quad C_1 = \chi_1^{\pm}$
~ Bino	$M_1 \sim 0.15 M_{1/2}$	————	$N_1 = \chi_1^0$

$$M_{1/2} = 400 - 1000 GeV$$

Chargino and neutralino production and decay

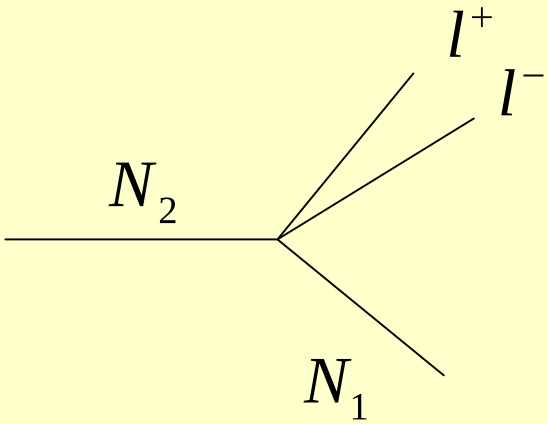


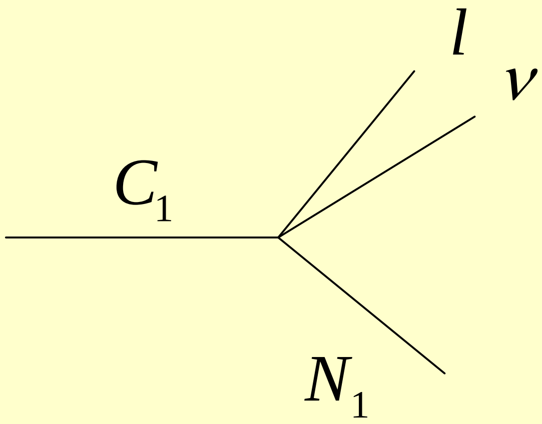


N.B. Wino production only is allowed (no Bino production via W,Z)

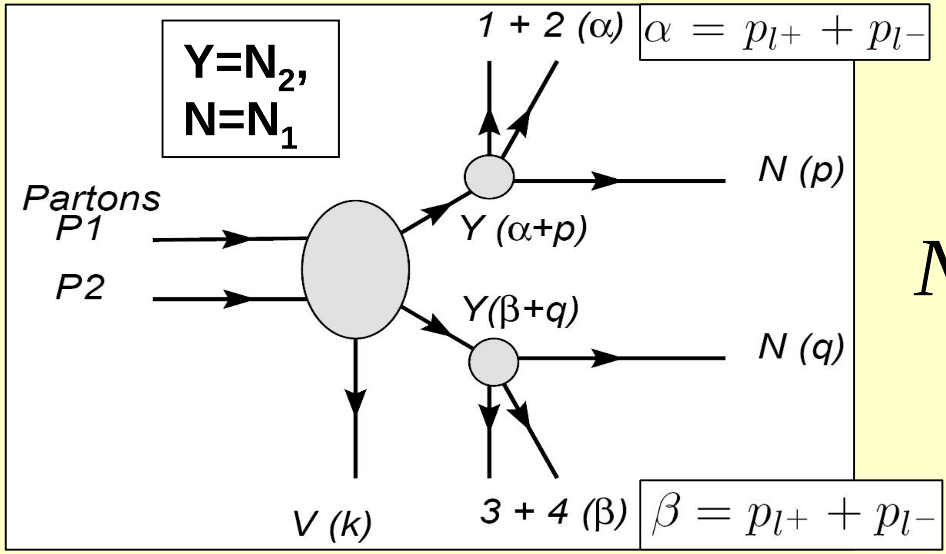
→ Expect N_2N_2 , N_2C_1 , C_1C_1 pair production (not involving the $N_1 \sim$ Bino)

However the decays must involve N_1





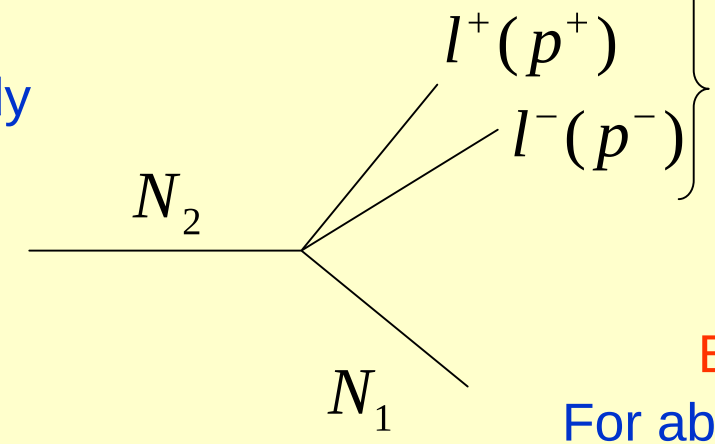
e.g. N_2N_2 production and decay



$$pp \to N_2 N_2 + V$$

$$N_2 N_2 \to l^+ l^- l^+ l^- + E_T^{miss}$$

Three body decays
Δ M < M_Z



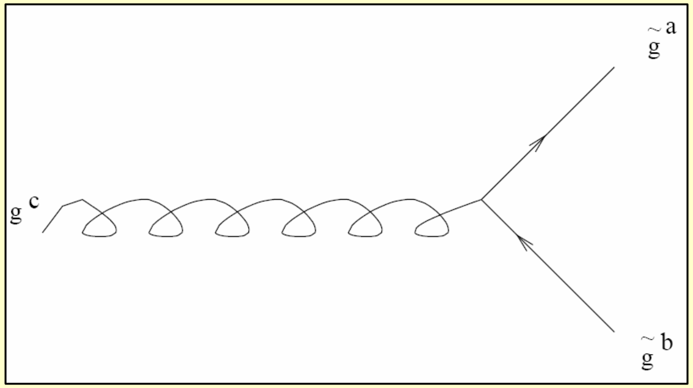
$$m_{ll}^2 = \left(p^+ + p^-\right)^2$$

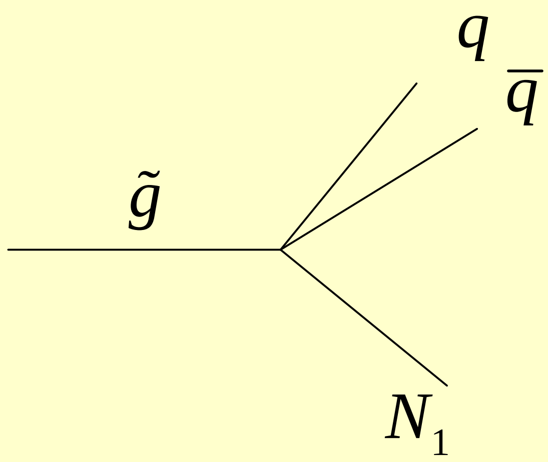
$$\max m_{ll} = \Delta M = M_{N_2} - M_{N_1}$$

End point gives mass difference

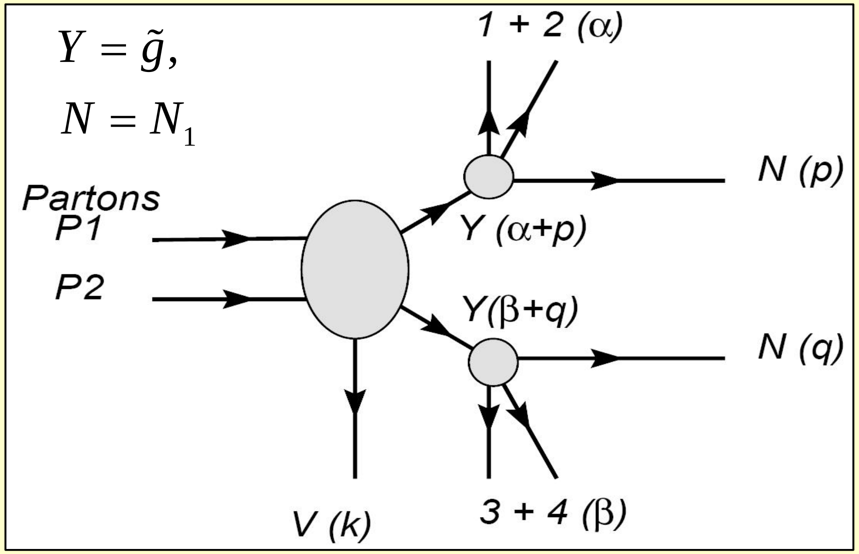
For absolute masses see Choi, Kim talks

Gluinos are light < 1 TeV and easily produced





$$\Gamma \propto \frac{m_{\tilde{g}}^5}{m_{\tilde{q}}^4}$$

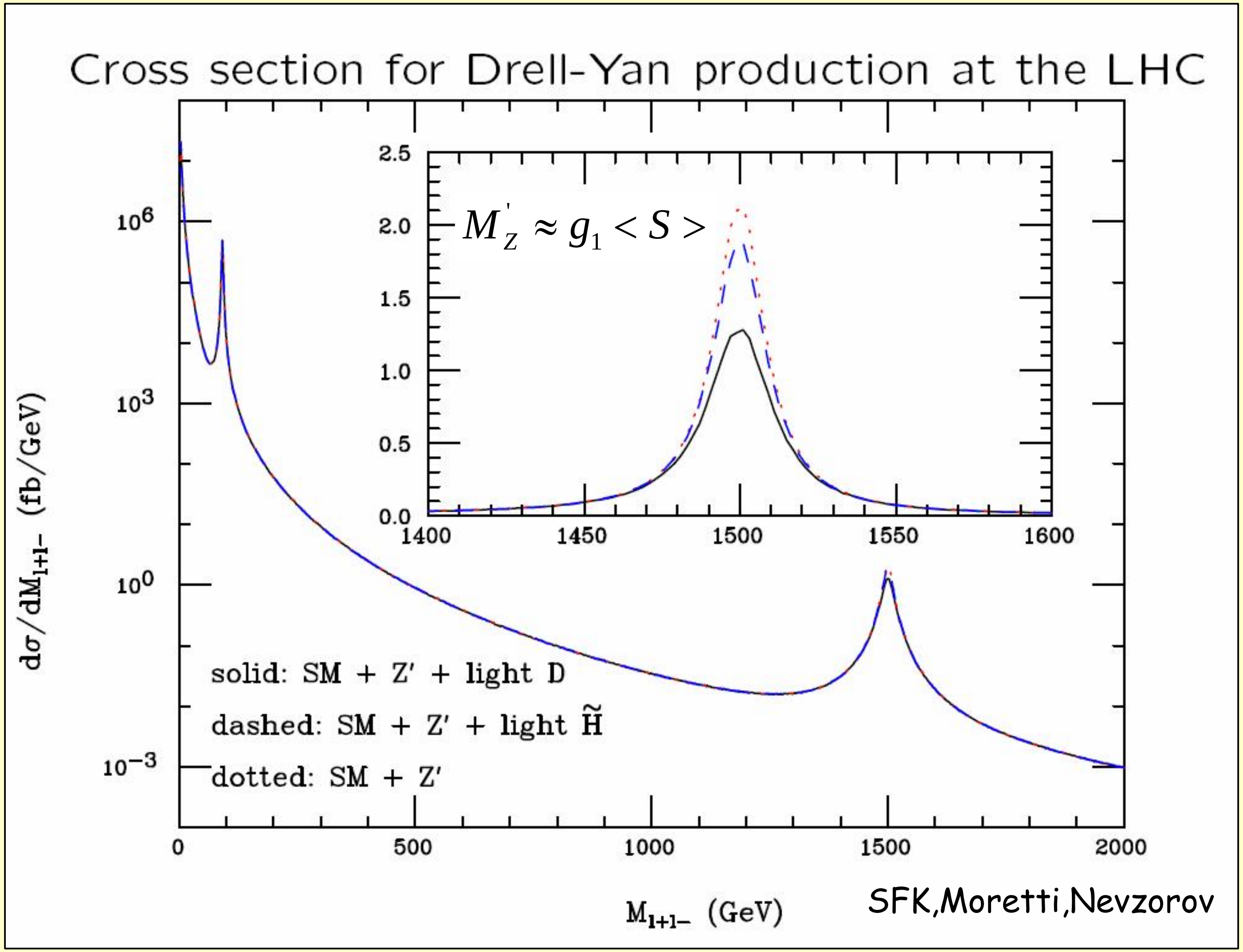


$$pp \to \tilde{g}\tilde{g} + V$$

$$\tilde{g}\tilde{g} \to q\overline{q}q\overline{q} + E_T^{miss}$$

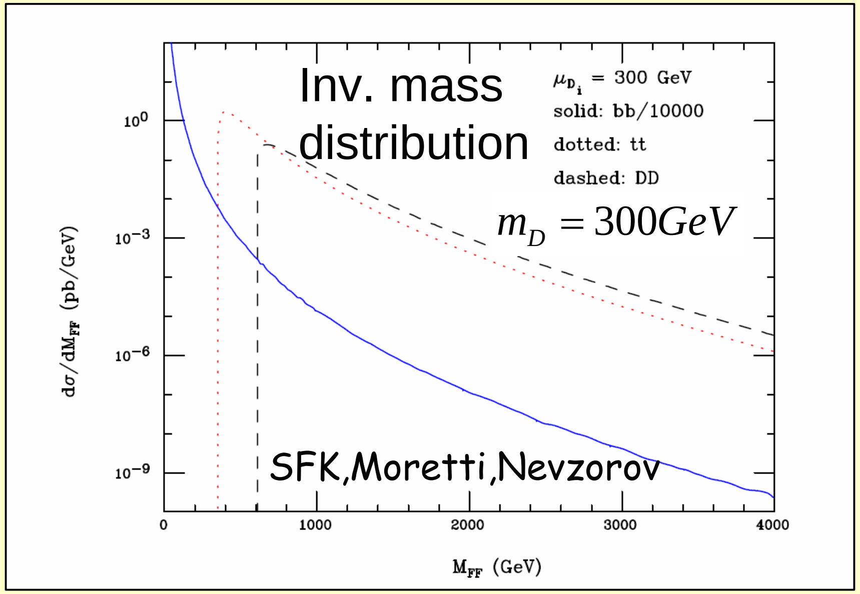
For gluino mass see Choi, Kim talks

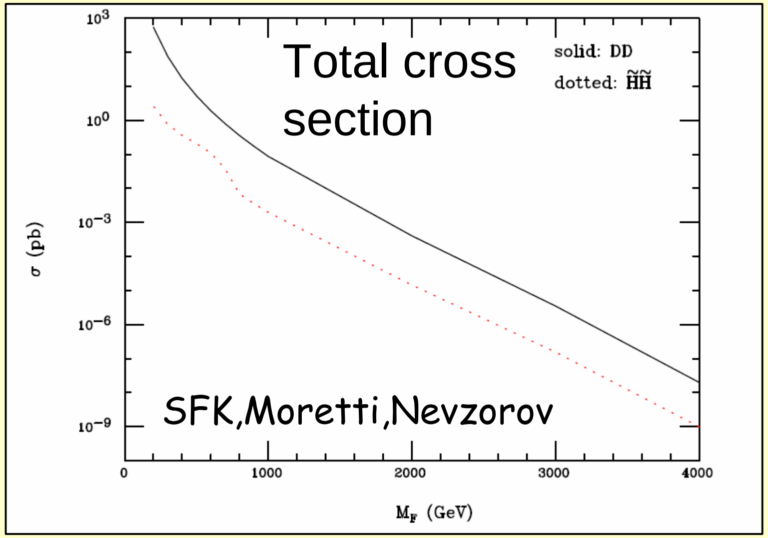
Z' < 5 TeV can be discovered



Exotic D-quarks in E_6SSM

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





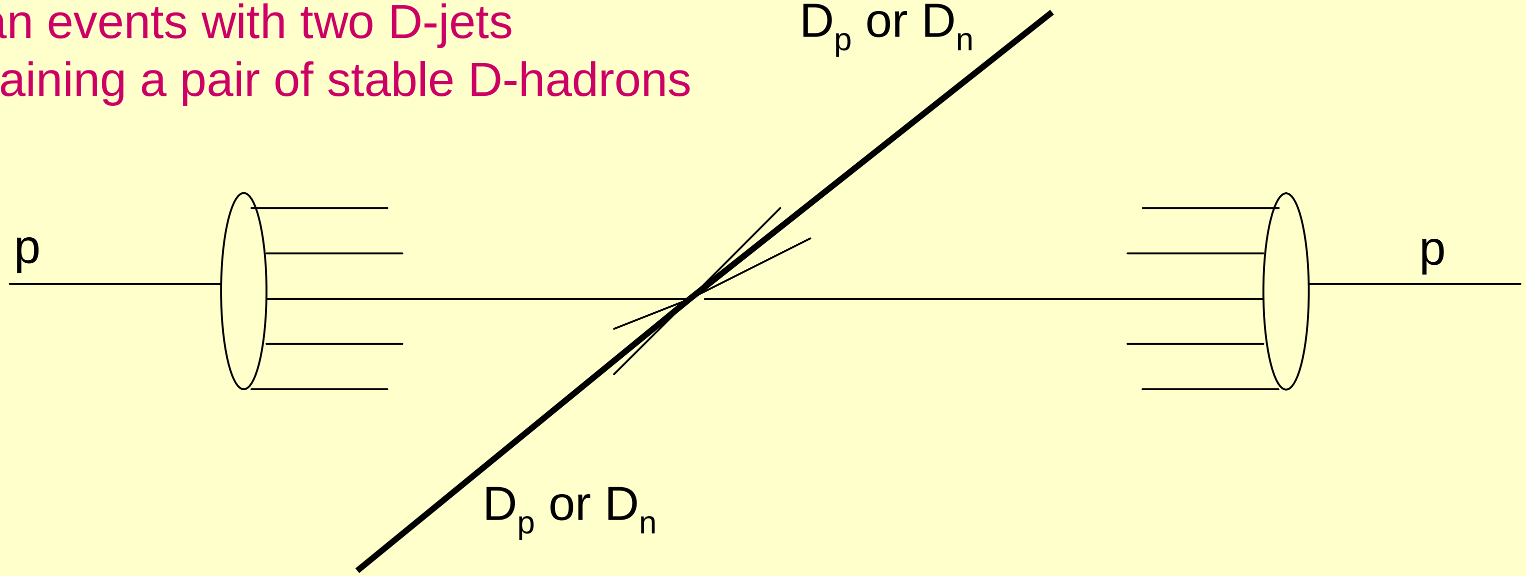
Novel signatures of D quarks

In E_6SSM it is possible that the D fermions decay rapidly as leptoquarks or diquarks giving missing energy in the final state (Brent Nelson's talk)

However it is also possible that DFF couplings are highly suppressed giving rise to long lived D quarks 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



Conclusions

E_6 SSM's are well motivated from string theory

Generally lead to lower fine tuning

Unification at GUT scale or Planck scale (ME_6SSM)

ME_6SSM solves μ problem without doublet-triplet splitting

CE_6SSM has successful EWSB and leads to a characteristic SUSY spectrum with light gauginos, and heavy Z'

D quarks can either decay promptly as fermionic leptoquarks or diquarks, or can be long lived → spectacular LHC signals

Some details about E_6SSM's

	Q	u^c	d^c	L	e^c	N^c	S	H_2	H_1	D	$\overline{D}$	H'	$\overline{H'}$
$\sqrt{\frac{5}{3}}Q_i^Y$	$\frac{1}{6}$	$-\frac{2}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	1	0	0	$\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	$\frac{1}{2}$
$\sqrt{40}Q_i^N$	1	1	2	2	1	0	5	-2	-3	-2	-3	2	-2

Hypercharge

Extra $U(1)_N$ surviving to TeV scale

RH ν chargeless

Optional non-Higgs

Most general E_6 allowed couplings from 27^3:

$$W_{E_6} = W_0 + W_1 + W_2 \,,$$

$$W_0 = \lambda_{ijk} S_i (H_{1j} H_{2k}) + \kappa_{ijk} S_i (D_j \overline{D}_k) + h^N_{ijk} N_i^c (H_{2j} L_k) + h^U_{ijk} u_i^c (H_{2j} Q_k) + h^D_{ijk} d_i^c (H_{1j} Q_k) + h^E_{ijk} e_i^c (H_{1j} L_k) \,,$$

$$W_1 = g^Q_{ijk} D_i (Q_j Q_k) + g^q_{ijk} \overline{D}_i d_j^c u_k^c \,,$$

$$W_2 = g^N_{ijk} N_i^c D_j d_k^c + g^E_{ijk} e_i^c D_j u_k^c + g^D_{ijk} (Q_i L_j) \overline{D}_k \,.$$

SHH terms

SDD terms

Yukawas of quarks, leptons

DFF terms (F=Q,L)

FCNC's from extra Higgs

Allows p and D decay

EWSB minimisation conditions

$$\begin{aligned}
\frac{\partial V}{\partial s} &= m_S^2 s - \frac{\lambda A_\lambda}{\sqrt{2}} v_1 v_2 + \frac{\lambda^2}{2}(v_1^2+v_2^2)s + \\
&+ \frac{g_1^{'2}}{2}\left(\tilde{Q}_1 v_1^2 + \tilde{Q}_2 v_2^2 + \tilde{Q}_S s^2\right)\tilde{Q}_S s + \frac{\partial \Delta V}{\partial s} = 0\,, \\
\frac{\partial V}{\partial v_1} &= m_1^2 v_1 - \frac{\lambda A_\lambda}{\sqrt{2}} s v_2 + \frac{\lambda^2}{2}(v_2^2+s^2)v_1 + \frac{\bar{g}^2}{8}\left(v_1^2 - v_2^2)\right)v_1 + \\
&+ \frac{g_1^{'2}}{2}\left(\tilde{Q}_1 v_1^2 + \tilde{Q}_2 v_2^2 + \tilde{Q}_S s^2\right)\tilde{Q}_1 v_1 + \frac{\partial \Delta V}{\partial v_1} = 0\,, \\
\frac{\partial V}{\partial v_2} &= m_2^2 v_2 - \frac{\lambda A_\lambda}{\sqrt{2}} s v_1 + \frac{\lambda^2}{2}(v_1^2+s^2)v_2 + \frac{\bar{g}^2}{8}\left(v_2^2 - v_1^2\right)v_2 + \\
&+ \frac{g_1^{'2}}{2}\left(\tilde{Q}_1 v_1^2 + \tilde{Q}_2 v_2^2 + \tilde{Q}_S s^2\right)\tilde{Q}_2 v_2 + \frac{\partial \Delta V}{\partial v_2} = 0\,,
\end{aligned}$$

With λ , κ , s , v_1 , v_2 fixed these fix m_1 , m_2 and m_s which are given by

$$\begin{aligned}
m_S^2(\mu_S) &= -0.649\, m_0^2 - 1.680\, M_{1/2}^2 - 0.076\, A^2 - 0.226\, A M_{1/2}, \\
m_{H_u}^2(\mu_S) &= -0.0296\, m_0^2 - 1.353\, M_{1/2}^2 - 0.116\, A^2 - 0.470\, A M_{1/2}, \\
m_{H_d}^2(\mu_S) &= 0.893\, m_0^2 + 0.360\, M_{1/2}^2 - 0.0113\, A^2 + 0.0123\, A M_{1/2},
\end{aligned}$$

Leading to quadratic equations for m_0 , $M_{1/2}$, A with two solutions