Beyond the Standard Model:
from neutrinos to neutralinos

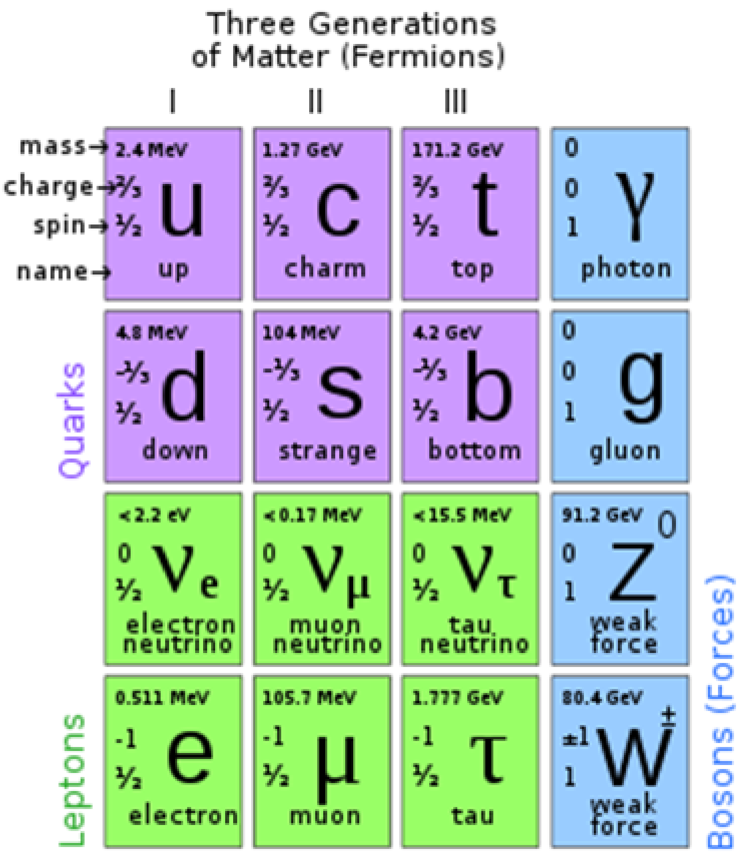
- The Standard Model and Beyond
- Neutrino mass and mixing
- Supersymmetry and neutralino dark matter

IOP Institute of Physics

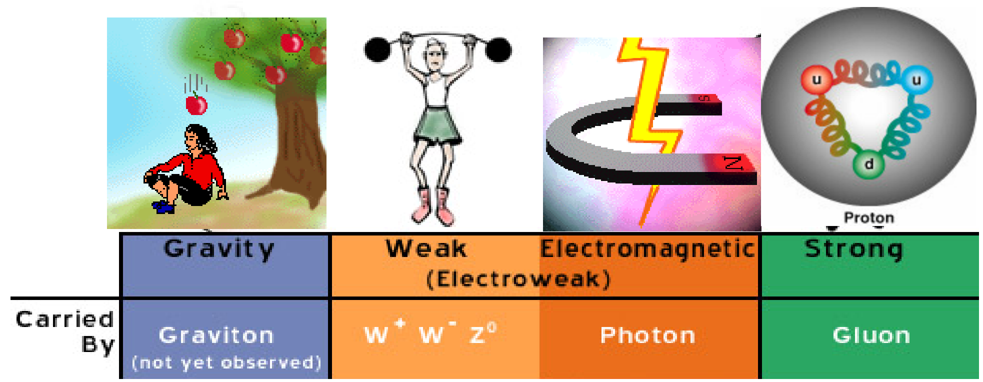
Annual conference of the High Energy Particle Physics group, Oxford, 2009

UNIVERSITY OF Southampton School of Physics and Astronomy

Standard Model



Matter (Fermions)



Forces (Bosons)

Higgs?

Gravity?

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.

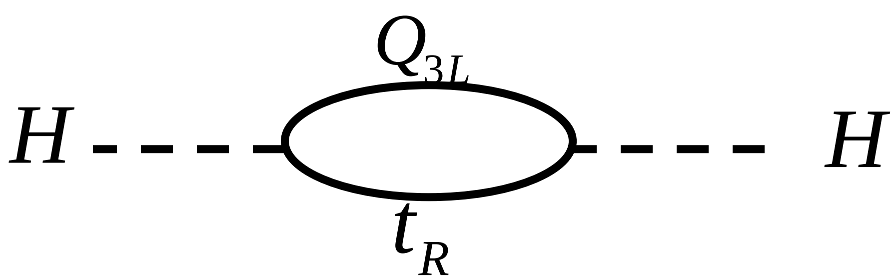
3. *The problem of flavour* - the problem of the undetermined fermion masses and mixing angles (including neutrino masses and mixing angles) together with the CP violating phases, in conjunction with the observed smallness of flavour changing neutral currents and very small strong CP violation.

Origin of mass in SM

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

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

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

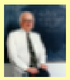


$$\delta m_H^2(top\,loop) = -\frac{3}{\sqrt{2}\pi^2} G_F m_t^2 \Lambda^2 = -\left(100\,GeV\right)^2 \left(\frac{\Lambda}{1TeV}\right)^2$$

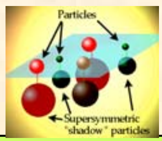
Fine-tuning is required if the cut-off $\Lambda \gg 1TeV$

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

Bottom-up motivation for new physics BSM

Little Higgs  models

Technicolour 



Supersymmetry

TeV

Extra dimensions 

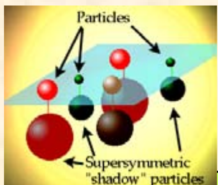
Mz

The Hierarchy Problem

Top-down motivation for new physics BSM

String Unification

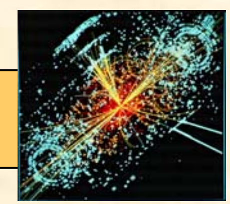
M*



Supersymmetry

Extra dimensions

New TeV scale physics



Neutrinos in the Standard Model

1. There are no right-handed neutrinos ν_R
2. There are only Higgs doublets of $SU(2)_L$
3. There are only renormalizable terms

In the Standard Model these conditions all apply so neutrinos are massless, with ν_e , ν_μ , ν_τ distinguished by separate lepton numbers L_e, L_μ, L_τ

Neutrinos and anti-neutrinos are distinguished by the total conserved lepton number $L=L_e+L_\mu+L_\tau$

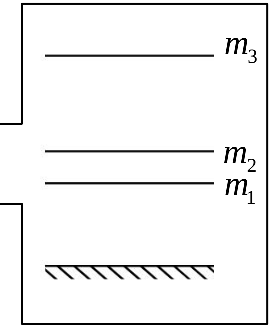
To generate neutrino mass we must relax 1 and/or 2 and/or 3 i.e. we need to go beyond the Standard Model (no choice!)

Three neutrino mass and mixing

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

Standard Model states

Neutrino mass states



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

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

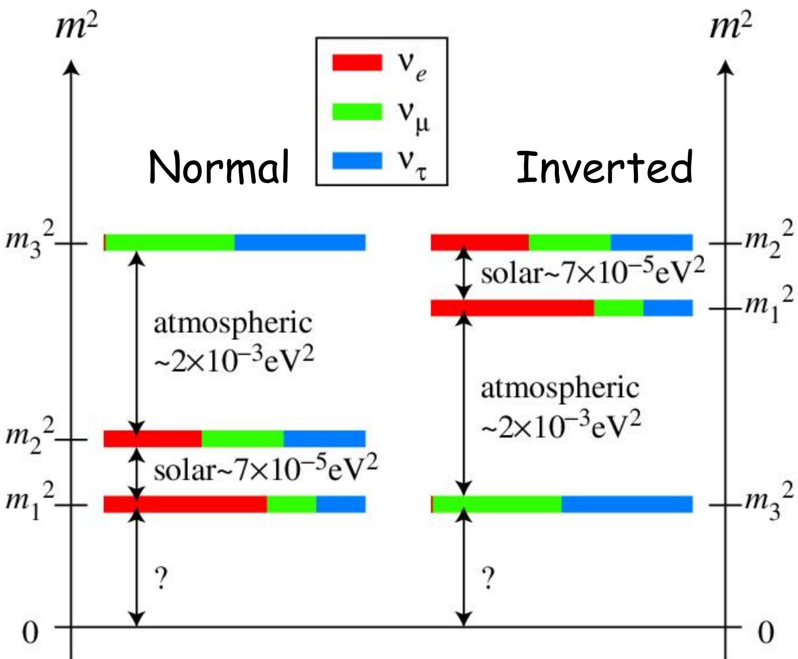
Atmospheric | Reactor | Solar | Majorana

Oscillation phase δ

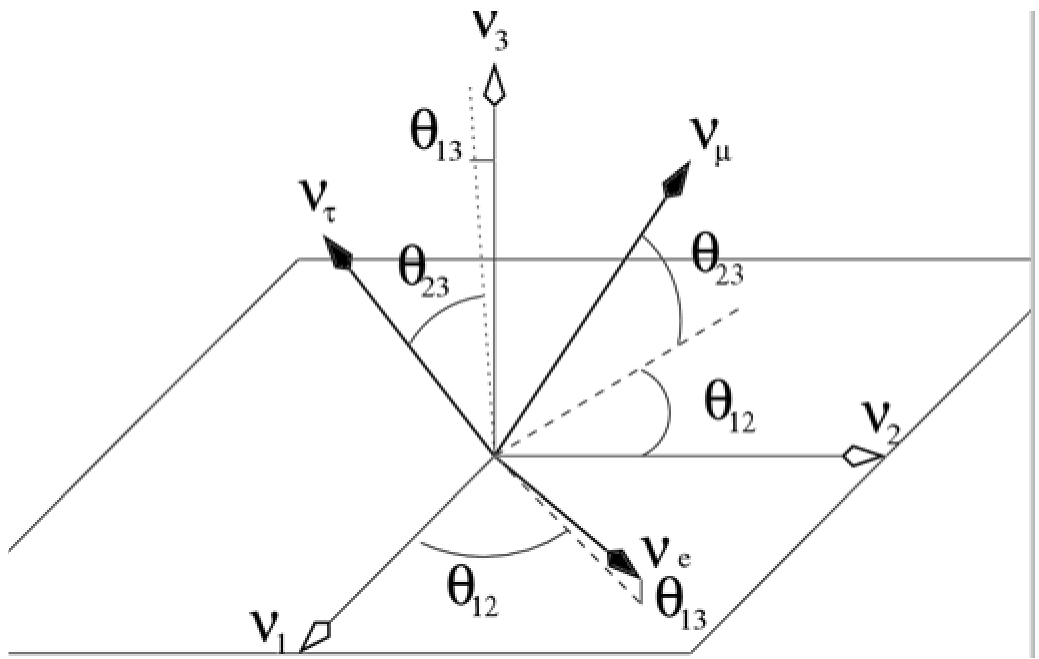
Majorana phases α_1, α_2

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

Neutrino mass squared splittings and angles

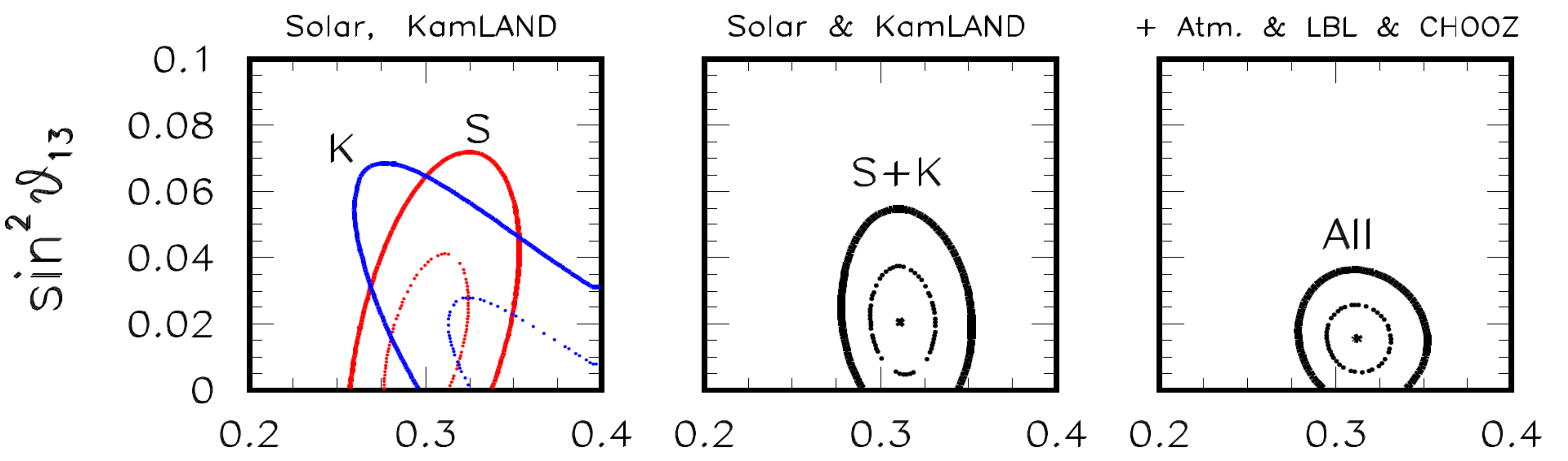


Absolute neutrino mass scale?



$$\theta_{12} = 34.5^o \pm 1.4^o, \quad \theta_{23} = 43.1^{o}{}^{+4.4^o}_{-3.5^o}$$

There is a 2σ hint for θ_{13} being non-zero



$$\sin^2\theta_{13} = 0.016 \pm 0.010$$ Fogli et al '08

$$\sin^2\theta_{13} = 0.02 \pm 0.01$$ Fogli et al '09

The 2009 estimate includes the preliminary MINOS results which show a 1σ excess of events in the electron appearance channel

Tri-bimaximal (TB) mixing

Harrison, Perkins, Scott

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\theta_{12} = 35^\circ, \qquad \theta_{23} = 45^\circ, \qquad \theta_{13} = 0^\circ.$$

c.f. data $\theta_{12} = 34.5^\circ \pm 1.4^\circ, \theta_{23} = 43.1^\circ \pm 4^o, \ \theta_{13} = 8^\circ \pm 2^o$

- Current data is consistent with TB mixing apart from the 2σ hint for θ_{13}

It is useful to consider the following parametrization of the PMNS mixing matrix in terms of deviations from TBM

$$s_{13} = \frac{r}{\sqrt{2}}, \quad s_{12} = \frac{1}{\sqrt{3}}(1+s), \quad s_{23} = \frac{1}{\sqrt{2}}(1+a)$$

SFK '07

$$0.14 < r < 0.24, \;\; -0.05 < s < 0.02, \;\; -0.04 < a < 0.10$$

r = reactor

s = solar

a = atmospheric

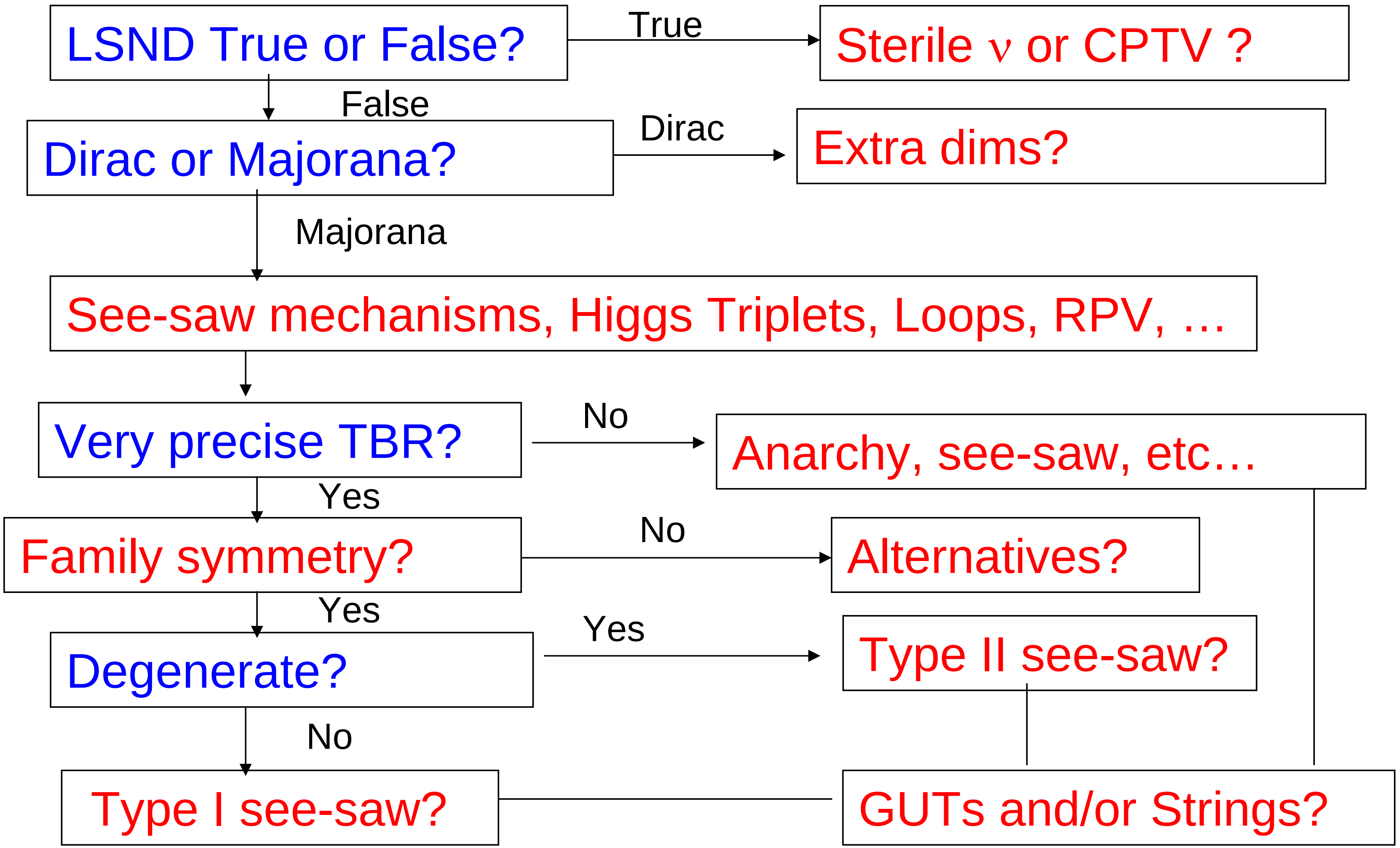
Assuming s=a=0 but r≠ 0 leads to **tri-bimaximal-reactor (TBR) mixing**

$$U_{TBR} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} r e^{-i\delta} \\ -\frac{1}{\sqrt{6}}(1+re^{i\delta}) & \frac{1}{\sqrt{3}}(1-\frac{1}{2}re^{i\delta}) & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}}(1-re^{i\delta}) & -\frac{1}{\sqrt{3}}(1+\frac{1}{2}re^{i\delta}) & \frac{1}{\sqrt{2}} \end{pmatrix}$$

SFK '09

Central value is r ≈ 0.2

Neutrino mass models decision tree



Dirac or Majorana?

Majorana masses

CP conjugate

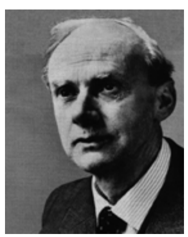
$$m_{LL}\overline{\nu}_L\nu_L^c$$

$$M_{RR}\overline{\nu}_R\nu_R^c$$

Violates L

Violates L_e, L_μ, L_τ

Neutrino=antineutrino



$$m_{LR}\overline{\nu}_L\nu_R$$

Conserves L

Violates L_e, L_μ, L_τ

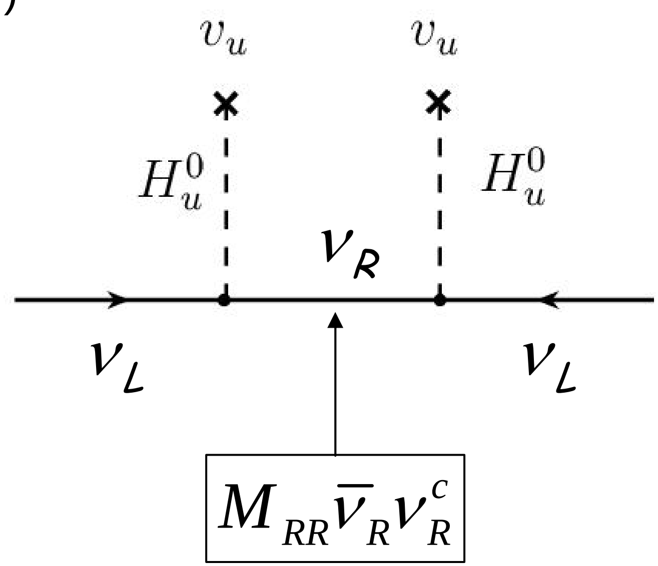
Neutrino $\neq$ antineutrino

Dirac mass

Majorana suggests a see-saw mechanism

Type I see-saw mechanism

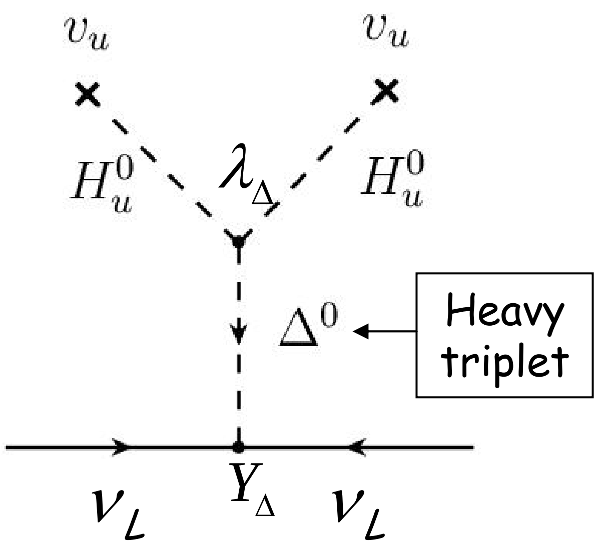
Minkowski (1977)



$$m_{LL}^{I} \approx -m_{LR} M_{RR}^{-1} m_{LR}^{T}$$

Type II see-saw mechanism

Lazarides, Magg, Mohapatra, Senjanovic, Shafi, Wetterich (1981)



$$m_{LL}^{II} \approx \lambda_\Delta Y_\Delta \frac{v_u^2}{M_\Delta}$$

Deriving TBR mixing from see-saw mechanism

SFK

Diagonal RH nu basis

$$M_{RR} = \begin{pmatrix} X & 0 & 0 \\ 0 & Y & 0 \\ 0 & 0 & Z \end{pmatrix}$$

columns

$$Y^{\nu}_{LR} = \begin{pmatrix} A & B & C \end{pmatrix}$$

See-saw I ⇨

$$m^{\nu}_{LL} = \frac{AA^T}{X} + \frac{BB^T}{Y} + \frac{CC^T}{Z}$$

Sequential dominance ⇨ Dominant m_3, Subdominant m_2, Decoupled m_1

$$\left|A_1\right| = \varepsilon\left|A_2\right|$$

$$\left.\begin{aligned} |A_2| &= |A_3|, \\ |B_1| &= |B_2| = |B_3|, \end{aligned}\right\}$$

⇨

$$m^{\nu}_{LL} = \frac{m_3}{2}\begin{pmatrix} 0 & \varepsilon & \varepsilon \\ \varepsilon & 1 & 1 \\ \varepsilon & 1 & 1 \end{pmatrix} + \frac{m_2}{3}\begin{pmatrix} 1 & 1 & -1 \\ 1 & 1 & -1 \\ -1 & -1 & 1 \end{pmatrix}$$

Partially Constrained SD

TBR mass matrix (∼ 2RHN)

This requires a non-Abelian family symmetry

Need

$$Y^{\nu}_{LR} = \begin{pmatrix} A_1 & B_1 & - \\ A_2 & B_2 & - \\ A_3 & B_3 & - \end{pmatrix}$$

with

$$\left.\begin{array}{l} |A_1| = \varepsilon |A_2| \\ |A_2| = |A_3|, \\ |B_1| = |B_2| = |B_3|, \end{array}\right\}$$

Partially Constrained SD

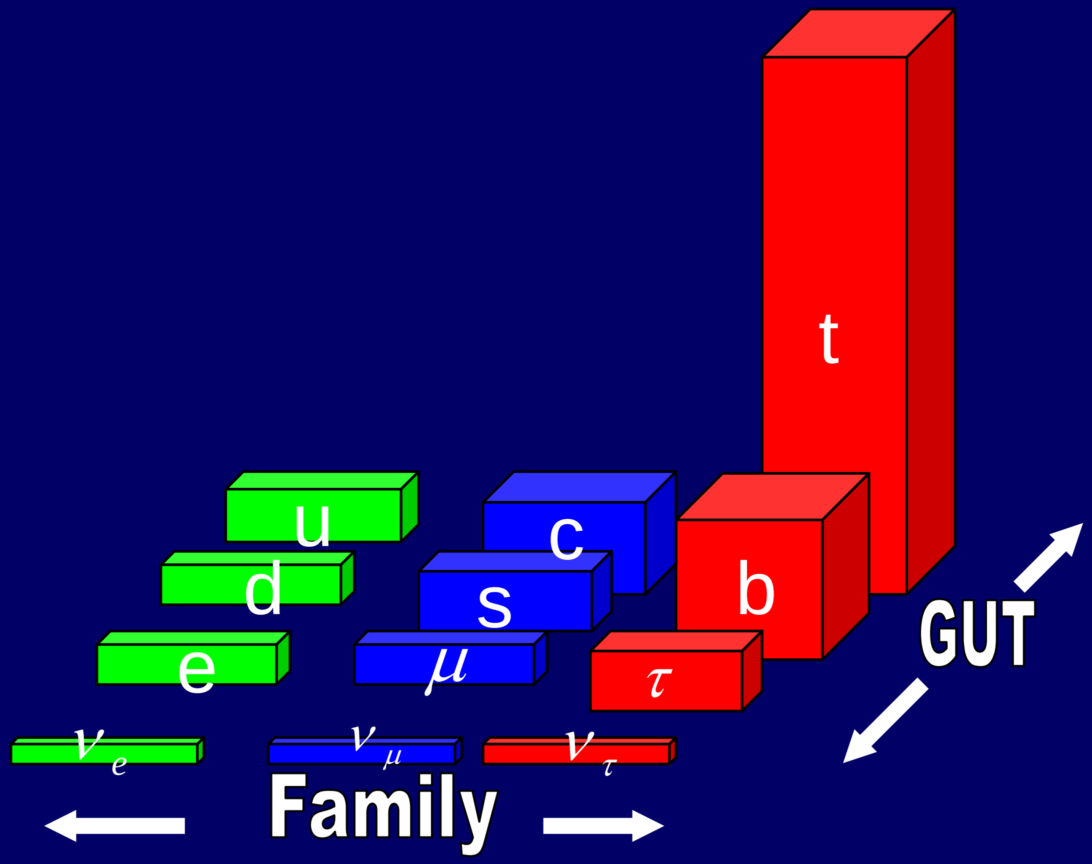
$2 \leftrightarrow 3$ symmetry (from maximal atmospheric mixing)

$1 \leftrightarrow 2 \leftrightarrow 3$ symmetry (from tri-maximal solar mixing)

Several examples of suitable non-Abelian Family Symmetries:

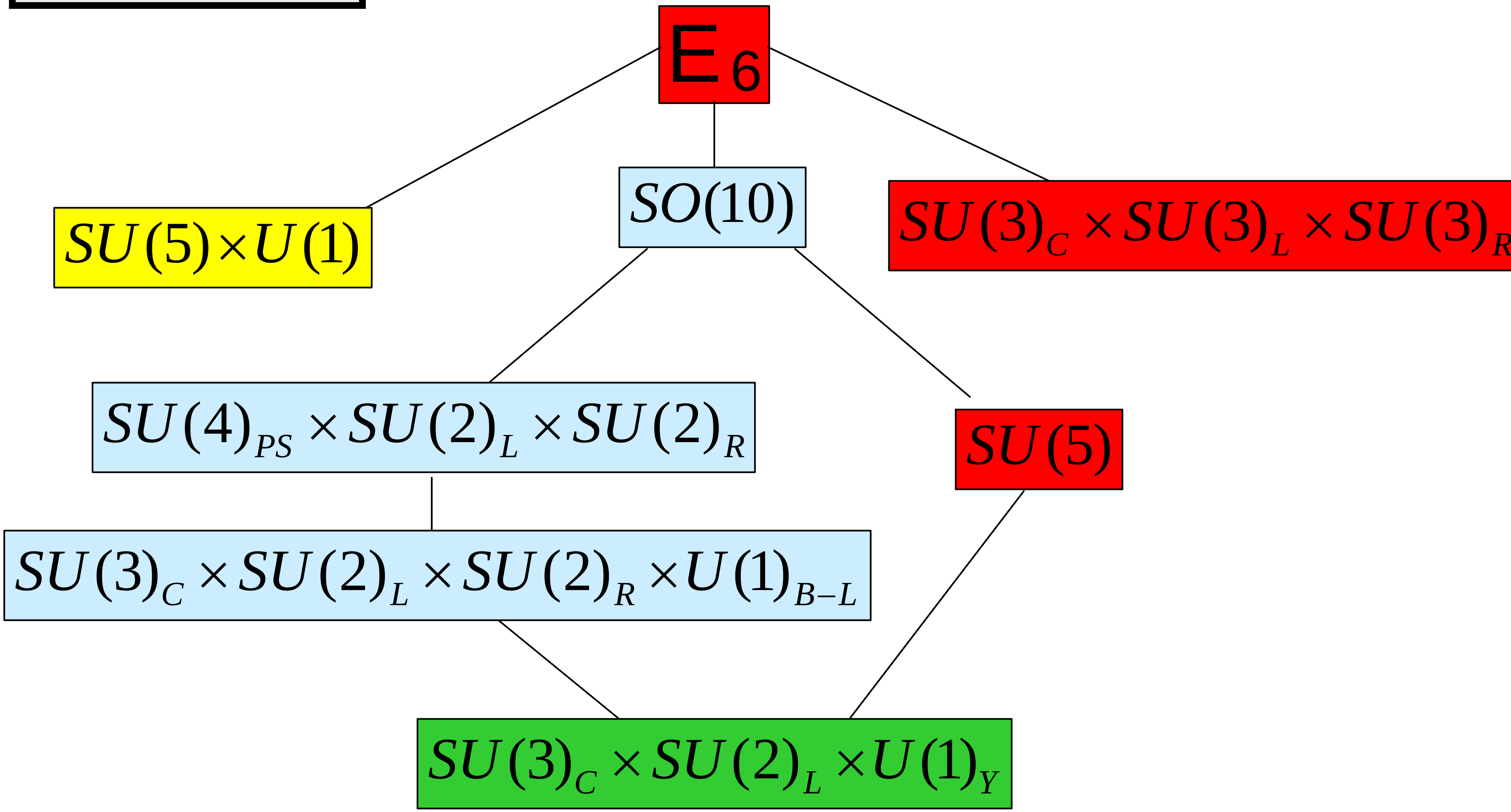
SFK, Ross; Velasco-Sevilla; Varzelias	$SU(3)$	Δ_{27}	Discrete subgroups preferred by vacuum alignment
SFK, Malinsky	$SO(3)$	A_4	

GUTs and Family Symmetry



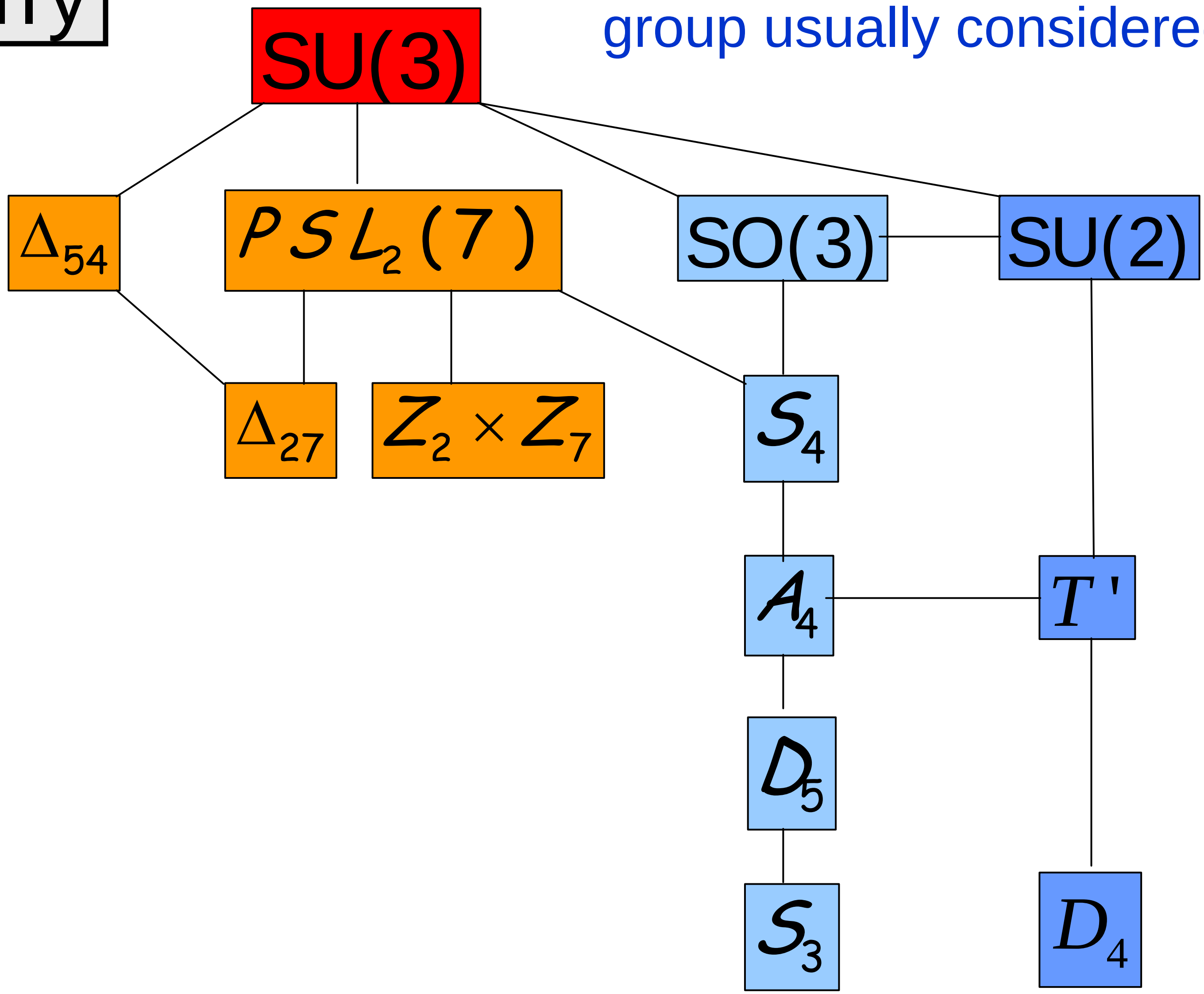
The basic idea of family symmetry is to distinguish each family by a new type of charge c.f. quark colour

G_{GUT}

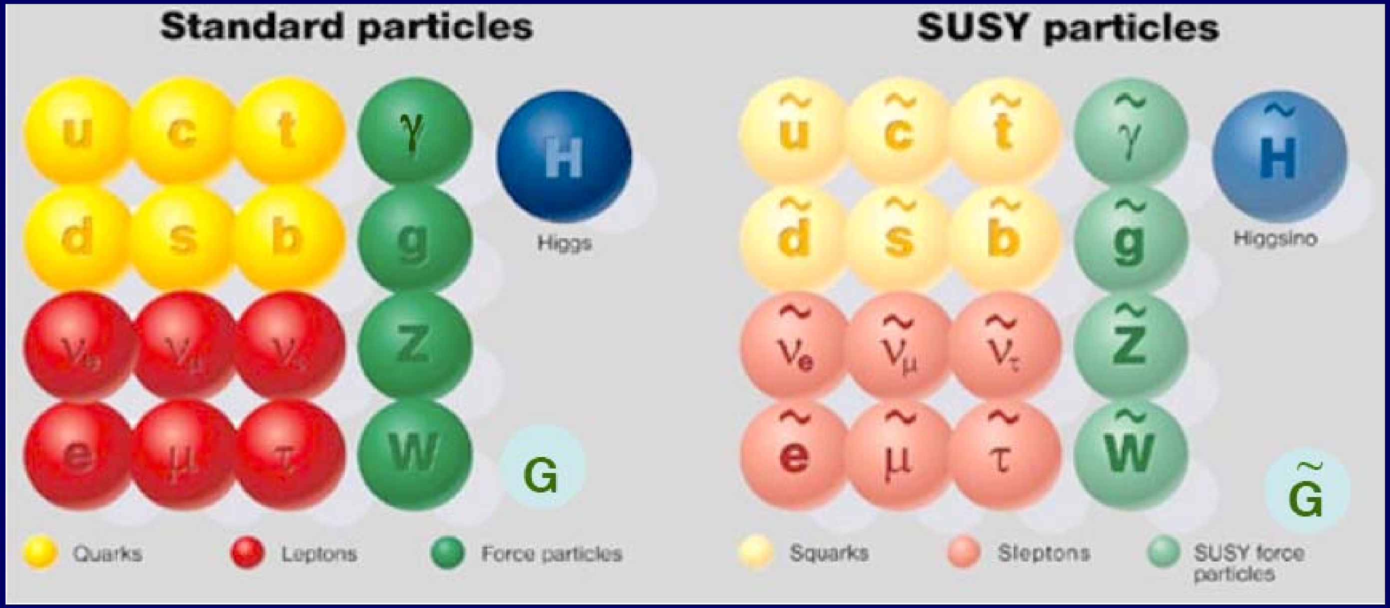

E_6
$SU(5)\times U(1)$
$SO(10)$
$SU(3)_C\times SU(3)_L\times SU(3)_R$
$SU(4)_{PS}\times SU(2)_L\times SU(2)_R$
$SU(5)$
$SU(3)_C\times SU(2)_L\times SU(2)_R\times U(1)_{B-L}$
$SU(3)_C\times SU(2)_L\times U(1)_Y$

G_{Family}

SU(3) is the largest family group usually considered



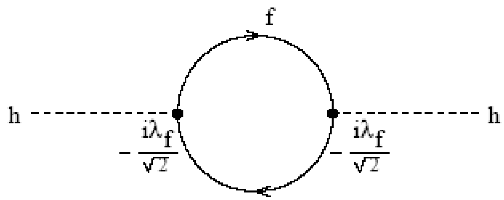
Hierarchies suggest SUSY



FERMIONS ⟺ SUSY ⟺ BOSONS

BOSONS ⟺ SUSY ⟺ FERMIONS

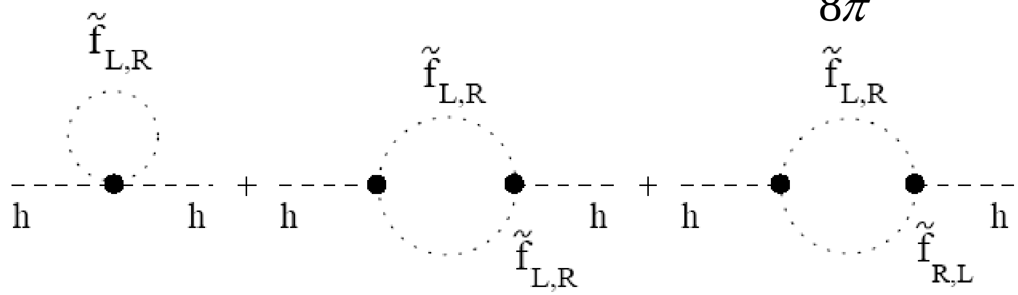
Stabilising the Hierarchy in SUSY



$$\delta m_H^2(top) = -\frac{3}{8\pi^2}\lambda_t^2\Lambda^2$$

$$\delta m_H^2(stop) = +\frac{3}{8\pi^2}\lambda_{\tilde{t}}^2\Lambda^2$$

Cancel



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

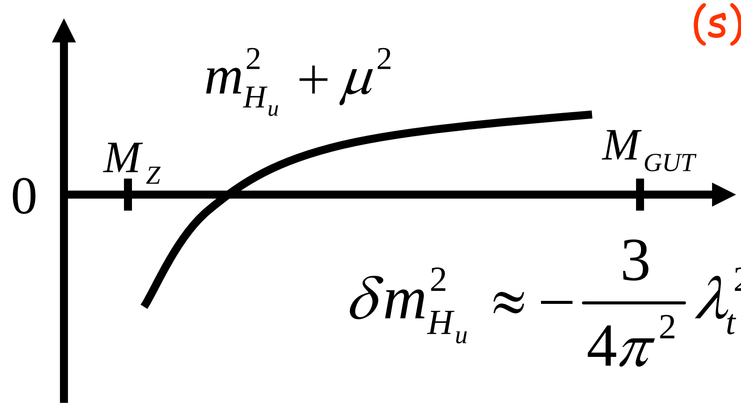
SUSY stabilises the hierarchy providing $m_{\tilde{t}} < 1TeV$

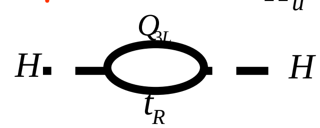
MSSM

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

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 $M_Z \sim \delta m_{Hu} \sim m_{stop}$

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

Also no reason why μ should be any particular value (μ problem)

Singlet 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

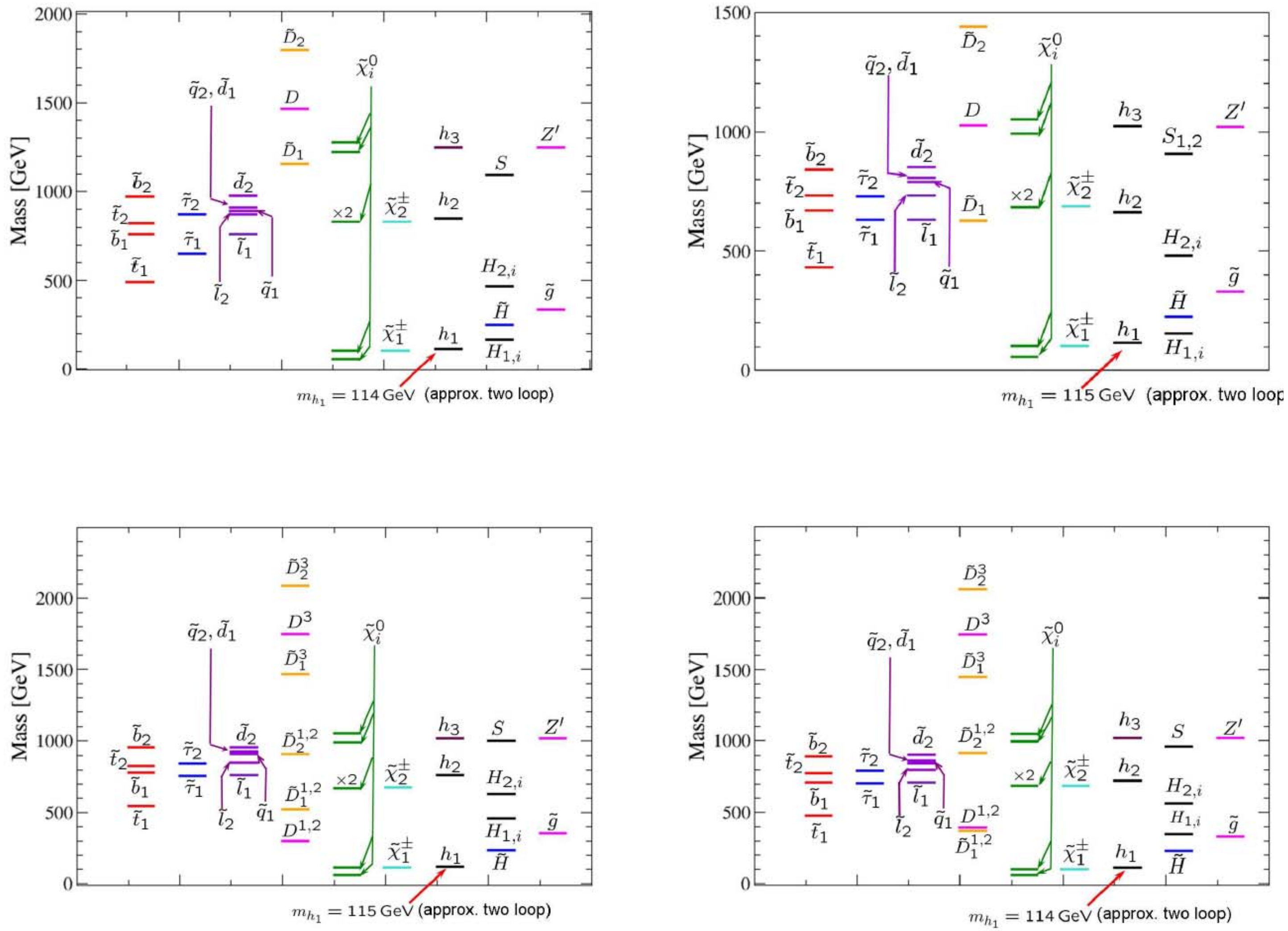
In NMSSM we add S^3 to break U(1) PQ to Z_3 – but this results in cosmological domain walls (or tadpoles if broken)

In USSM we gauge the U(1) PQ symmetry to eat the axion resulting in a massive Z' gauge boson – but not anomaly free

In E_6SSM the anomalies of the USSM are cancelled by three complete 27's of E_6 at the TeV scale with U(1) PQ $\in E_6$

Athron, SFK, Miller, Moretti, Nevzorov

The E$_6$SSM Predicts a Bonanza at LHC



Jungman, Kamionkowski, Griest, hep-ph/9506380
Muñoz, hep-ph/0309346
Bertone, Hooper and Silk, hep-ph/0404175

MSSM Neutralino Dark Matter

Neutralino mass matrix

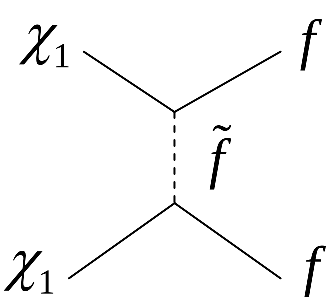
$$W_{MSSM} = \mu H_u H_d + W_{Yuk}$$

$$\begin{array}{cccc} \tilde{B} & \tilde{W}_3 & \tilde{H}_d & \tilde{H}_u \end{array}$$

$$\begin{pmatrix} M_1 & & & \\ & M_2 & & \\ & & 0 & -\mu \\ & & -\mu & 0 \end{pmatrix}$$

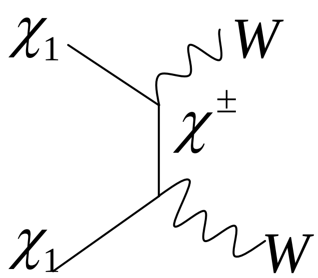
$$\chi_1 = N_1 \tilde{B} + N_2 \tilde{W} + N_3 \tilde{H}_d + N_4 \tilde{H}_u$$

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



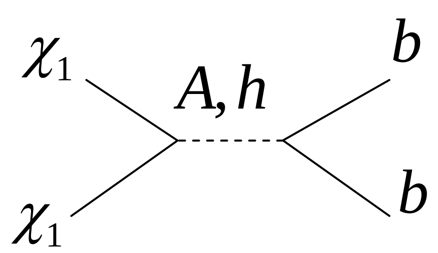
Bulk

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



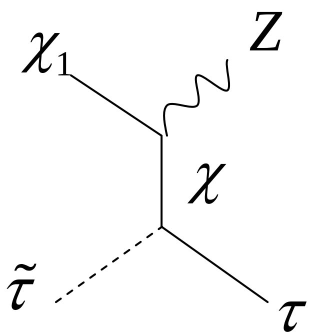
Focus

Higgsino LSP



Funnel

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



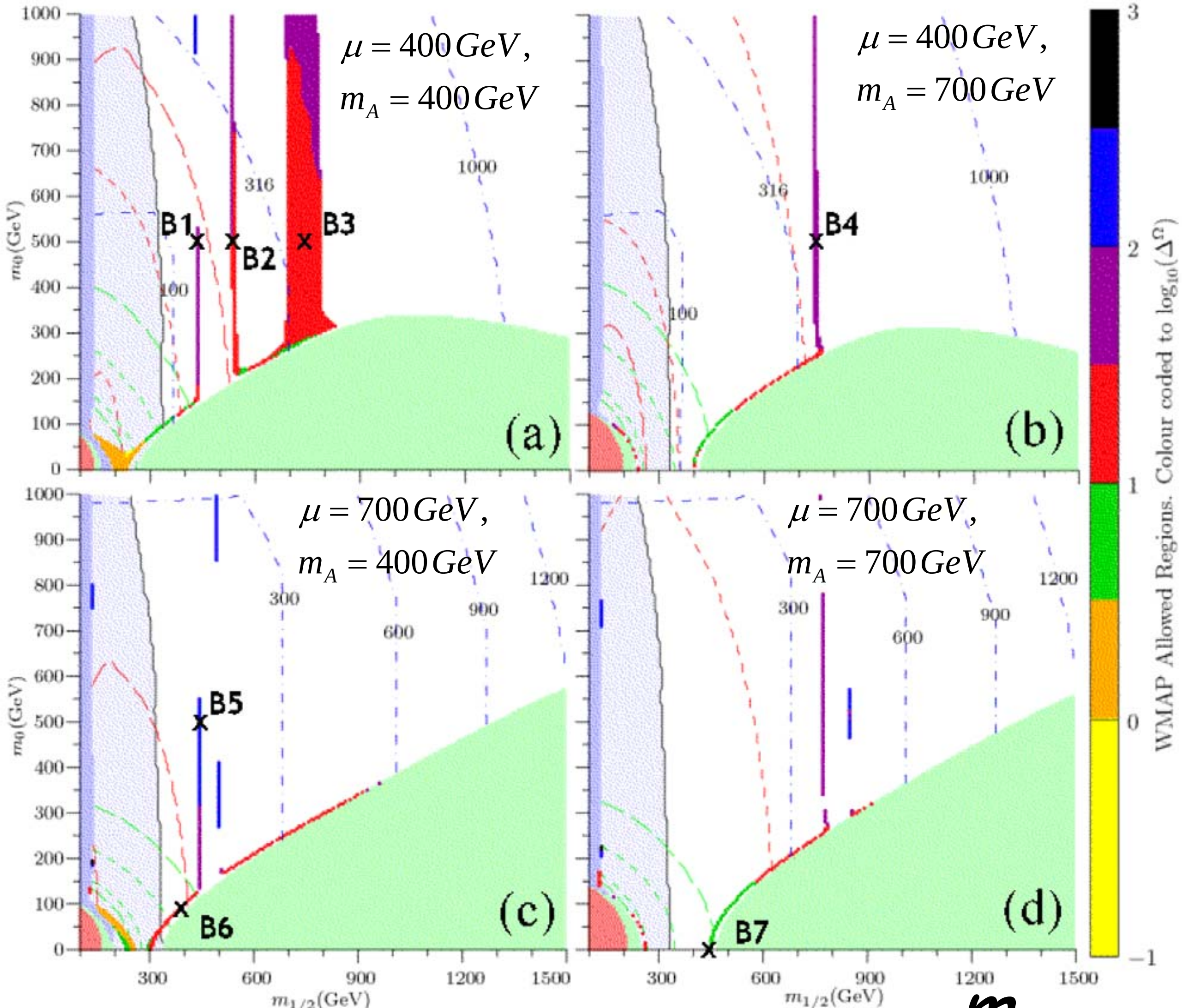
Co-annihilation

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

NUHM $a_{NUHM} = \{m_0,\ m_{H_1},\ m_{H_2},\ m_{1/2},\ A_0,\ \tan\beta,\ \text{sign}(\mu)\}$

Ellis, SFK, Roberts

m_0



m_0

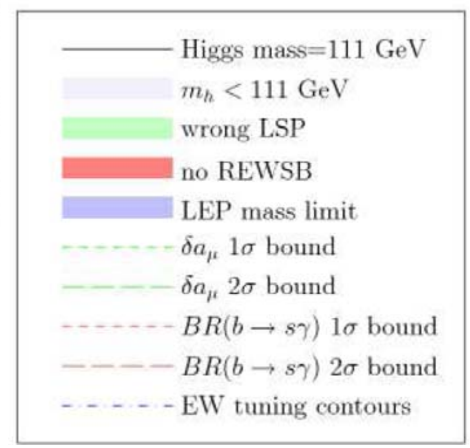
$m_{1/2}$ $m_{1/2}$

$A_0 = 0, \quad \tan\beta = 10,$
$\text{sgn}(\mu) = +$

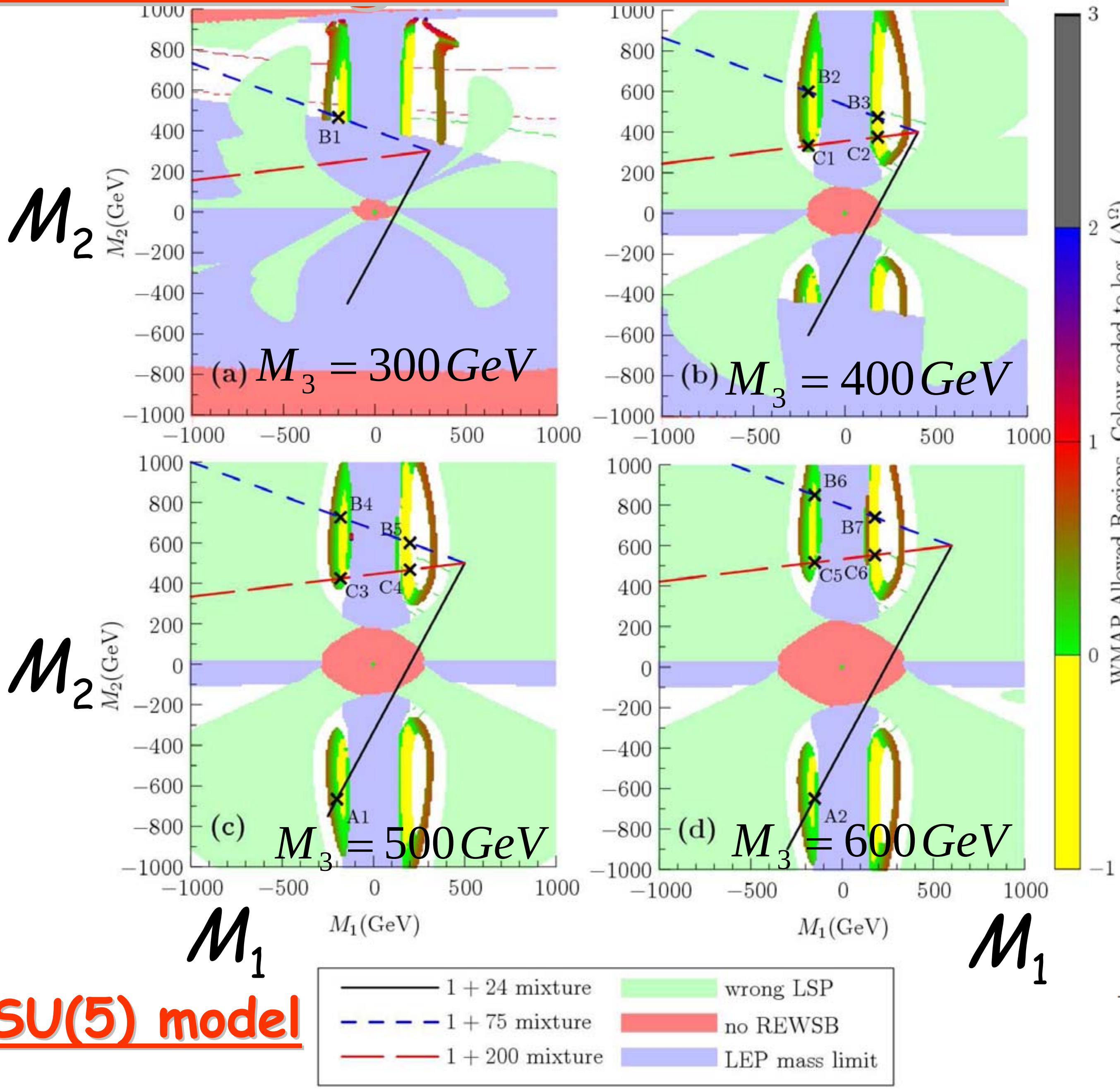
CPodd Higgs funnel: B1,2,4,5

Bino-Higgsino LSP: B3

Stau co-ann: B6,7



NU Gauginos in SU(5)



SFK, Roberts, Roy

$A_0 = 0, \quad \tan\beta = 10,$
$m_0 = 70\,GeV$

All points A,B,C are for the bulk region with very low sensitivity "supernatural dark matter"

SU(5) 1+24: A1,2

SU(5) 1+75: B1-7

SU(5) 1+200: C1,2,3

SU(5) model

$$L = \frac{< F_\Phi >_{ij}}{M_{Planck}} \lambda_i \lambda_j$$

de Carlos, Espinosa, Cvetic, Demir, Everett, Langacker; Barger, Lewis, McCaskey, Shaughnessy, Yencho, Kalinowski, SFK, Roberts

USSM Neutralino Dark Matter

$$W_{USSM} = \lambda S H_u H_d + W_{Yuk} + U(1)'_{gauge} \rightarrow MSSM\ \ states + S + Z'$$

Solves μ problem of MSSM

Plus extra states for anomaly cancellation

$$\begin{array}{cccccc} \tilde{B} & \tilde{W}_3 & \tilde{H}_d & \tilde{H}_u & \tilde{S} & \tilde{B}' \end{array}$$

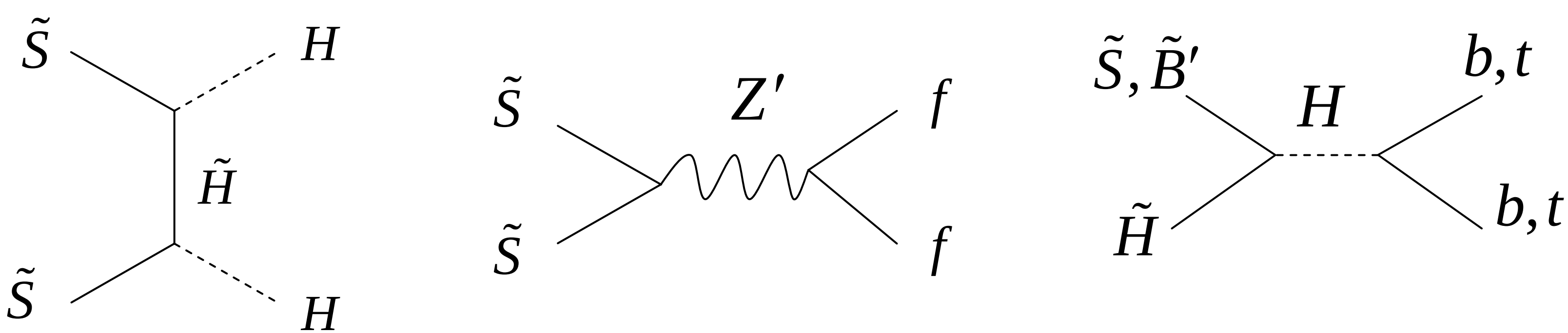
$$\begin{pmatrix} M_1 & & & & & \\ & M_2 & & & & \\ & & 0 & -\lambda s & & \\ & & -\lambda s & 0 & & \\ & & & & 0 & \sim M_{Z'} \\ & & & & \sim M_{Z'} & M_1' \end{pmatrix}$$

$$\chi_1 = N_1\tilde{B} + N_2\tilde{W} + N_3\tilde{H}_d + N_4\tilde{H}_u + \underbrace{N_5\tilde{S} + N_6\tilde{B}'}_{\text{New}}$$

$$M_1' \rightarrow \infty \quad \longrightarrow \quad M_{\tilde{S}} \approx \frac{M_{Z'}^2}{M_1'} \rightarrow 0$$

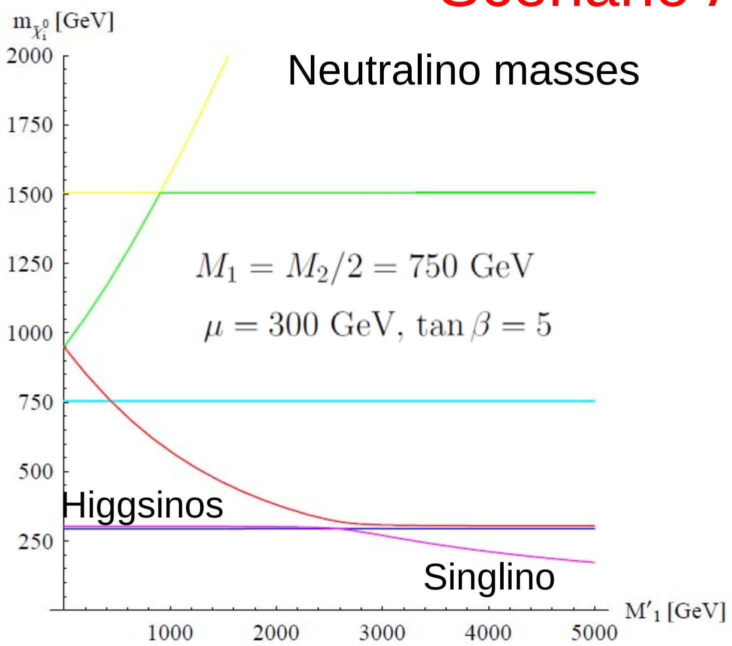
mini-see-saw gives singlino LSP as $M_1' \rightarrow \infty$

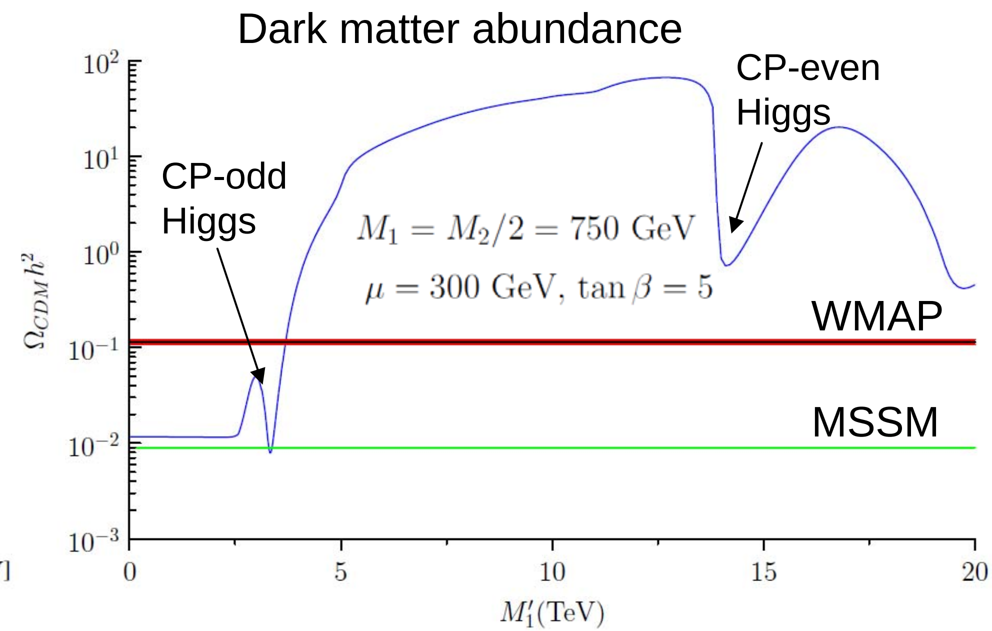
How can a singlino LSP annihilate? Via λSHH and Z' couplings

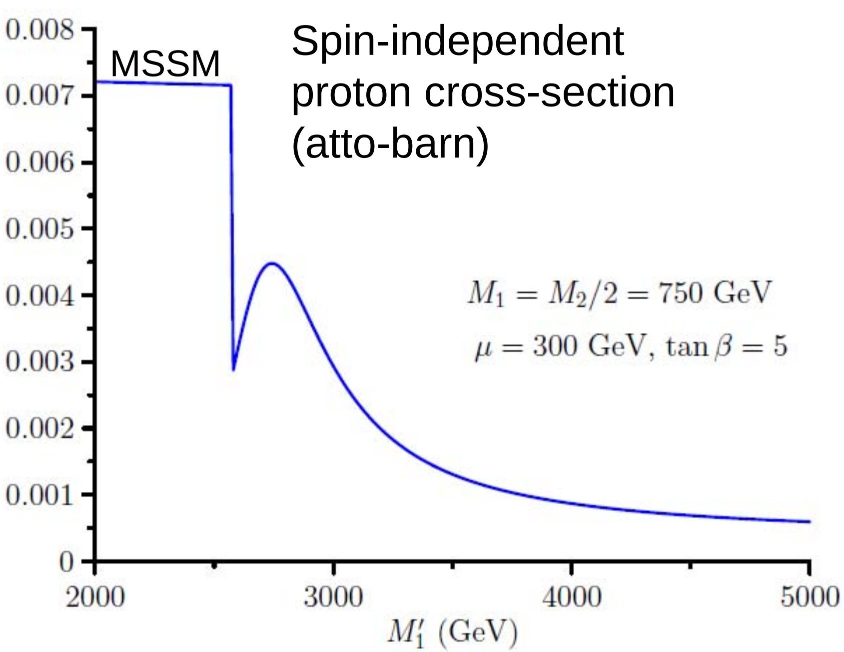


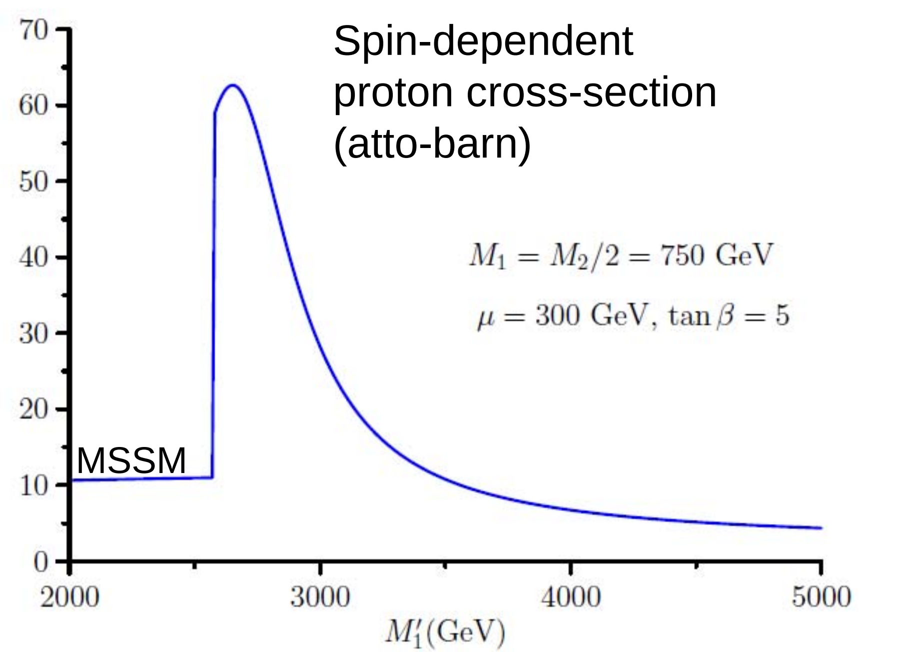
Scenario A: $M_1' \neq M_1$

Kalinowski, SFK, Roberts



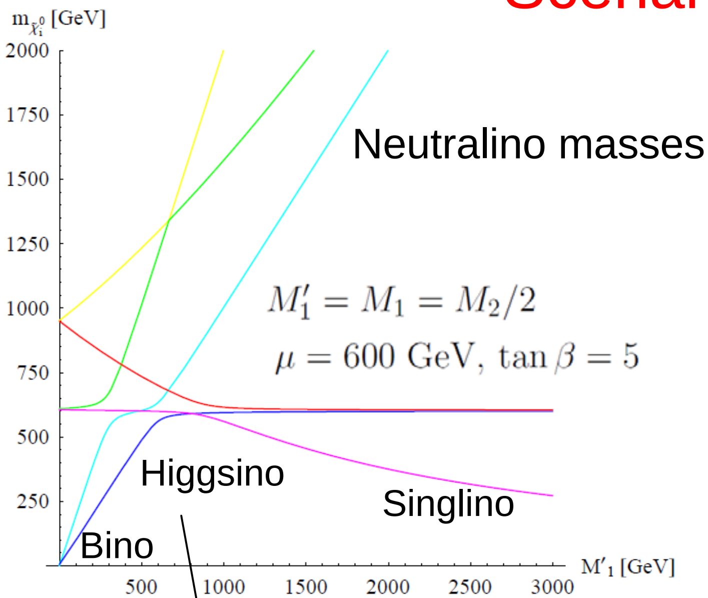


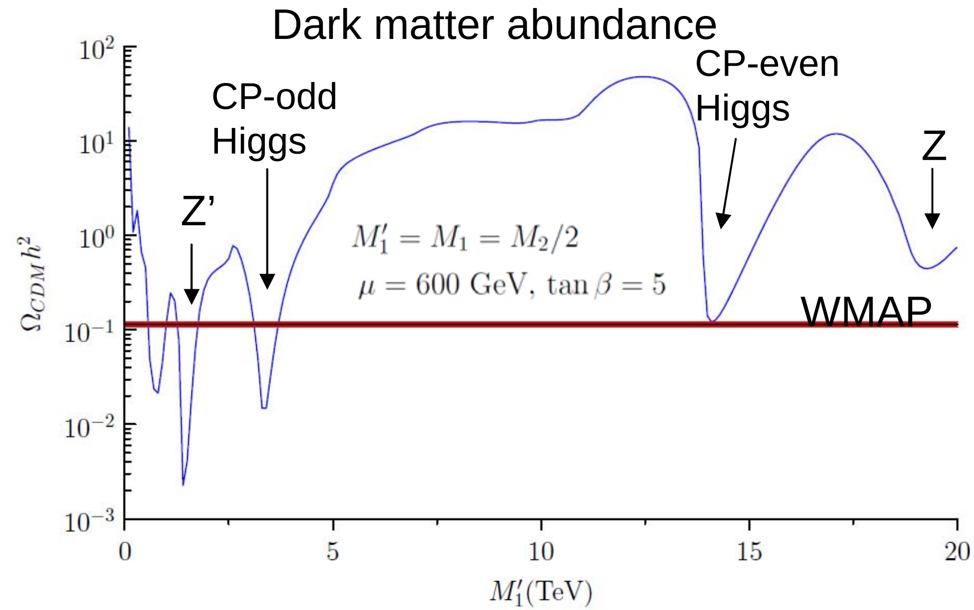


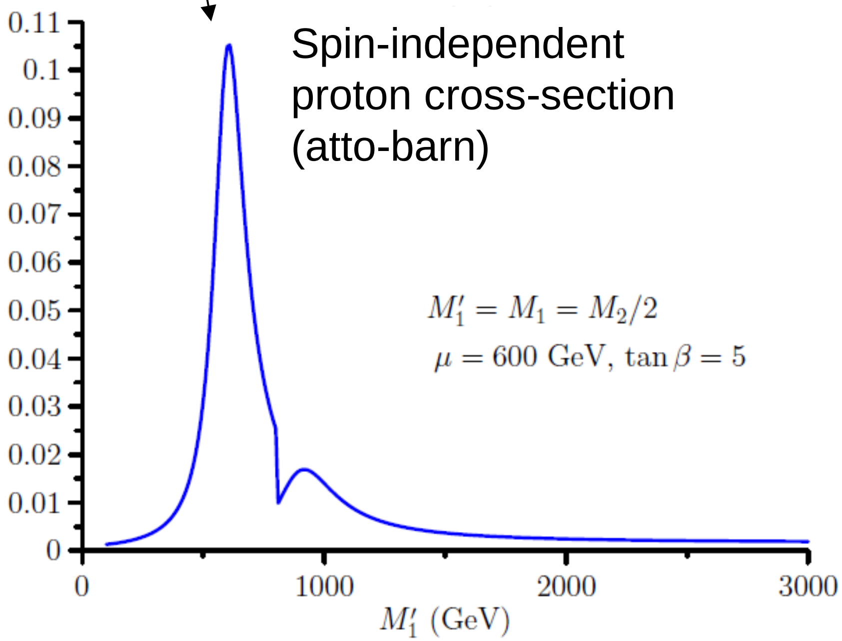


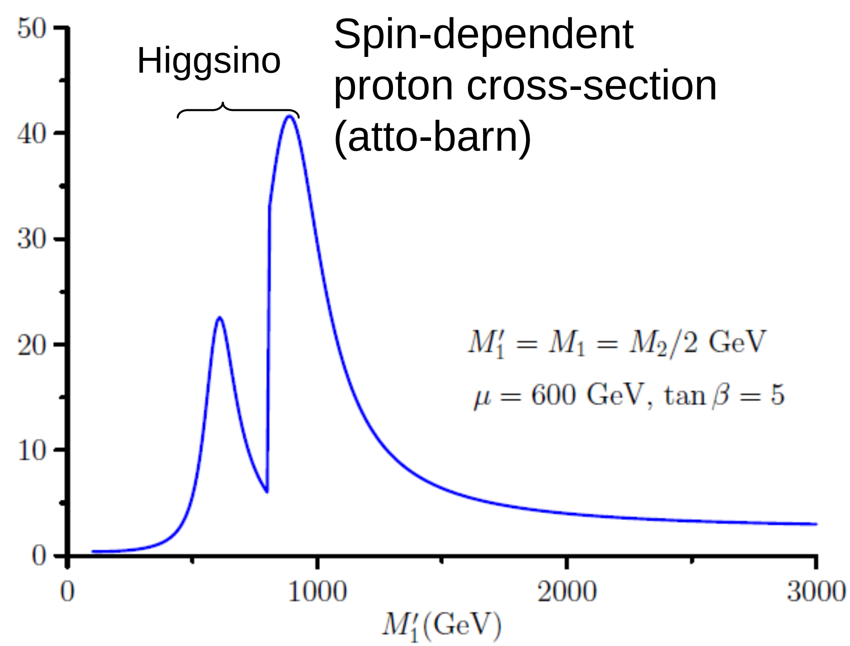
Scenario B: $M_1' = M_1$

Kalinowski, SFK, Roberts









Conclusion

- **Good motivations for BSM physics**
- **Neutrino mass and mixing requires new physics BSM**
- **If TBR is accurately realised this may imply a new symmetry of nature: family symmetry**
- **GUTs $\times$ family symmetry with see-saw is very attractive framework for TBR mixing**
- **Such large hierarchies as in GUTs suggest SUSY**
- **SUSY models include MSSM, NMSSM, USSM, E6SSM**
- **Neutralino Dark Matter can arise from any SUSY Model with conserved R-parity (not just the MSSM)**
- **The first decade of the 21st Century has been the decade of the neutrino**
- **Could the second decade belong to the neutralino (and the other SUSY particles, Higgs, Z’, etc…)?**