Yukawa Coupling Ratios in SU(5) GUTs

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Based on collaborations with:
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FLASY 2014

Outline

- Introduction
- Yukawa Coupling Ratios
  - Theoretical Considerations
  - Comparison to Data & Applications
  - GUT Breaking
- Summary and Conclusions

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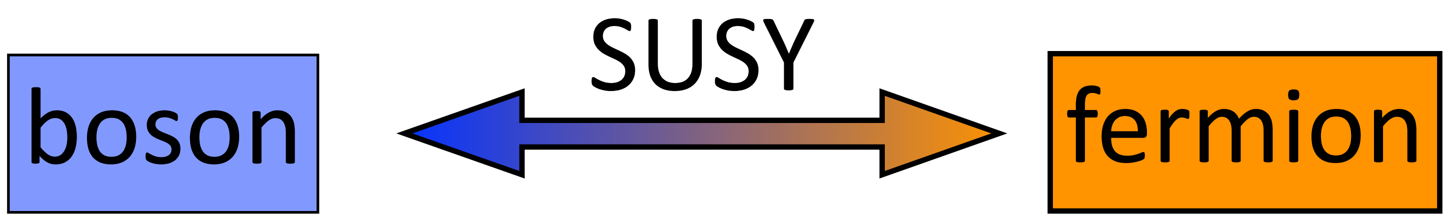
Why Grand Unification?

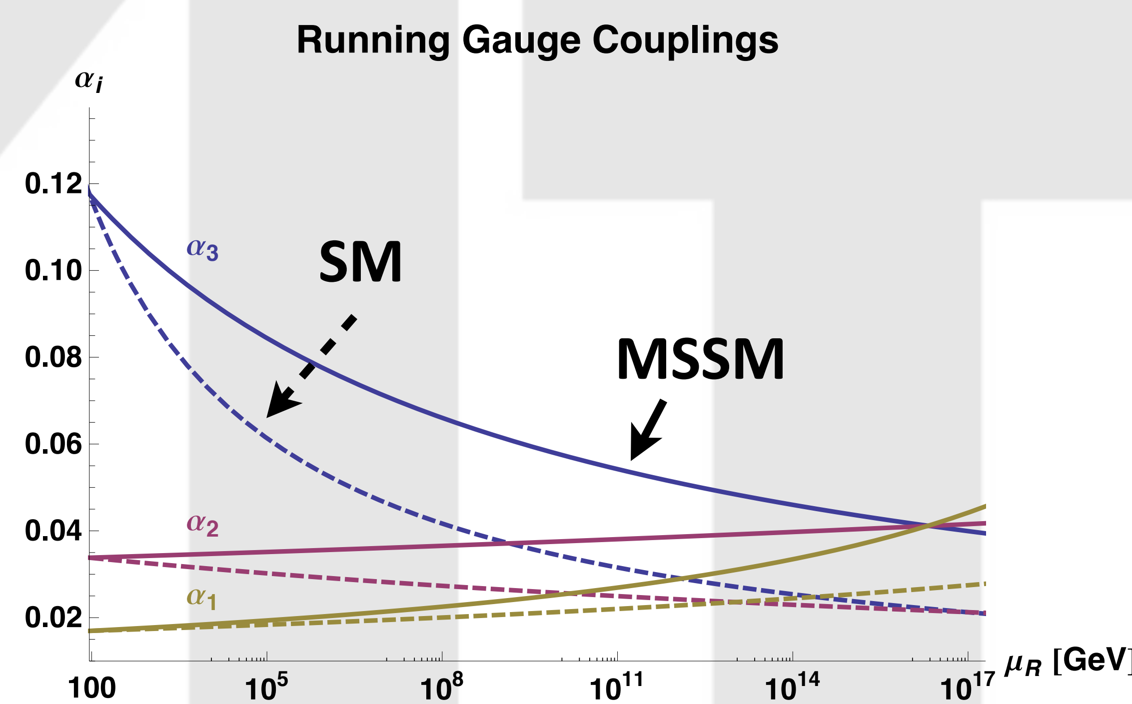
- Simplification (unify $SU(3)_C \times SU(2)_L \times U(1)_Y$)
- Solves one naturalness problem
  - ➡ The cancellation of the electron and proton charge in H
- Relates fermion masses (Yukawa couplings)
- Small neutrino masses due to the seesaw

Why SUSY GUTs?

- What is SUSY?



- What is SUSY good for?
  - Gives dark matter candidate
  - Solves the hierarchy problem
  - Gauge coupling unification



Why this talk?

- What do GUTs tell us about relations among fermion masses?
- Are these relations realistic?
- Can we learn more from that?
- Implications from/for GUT breaking?

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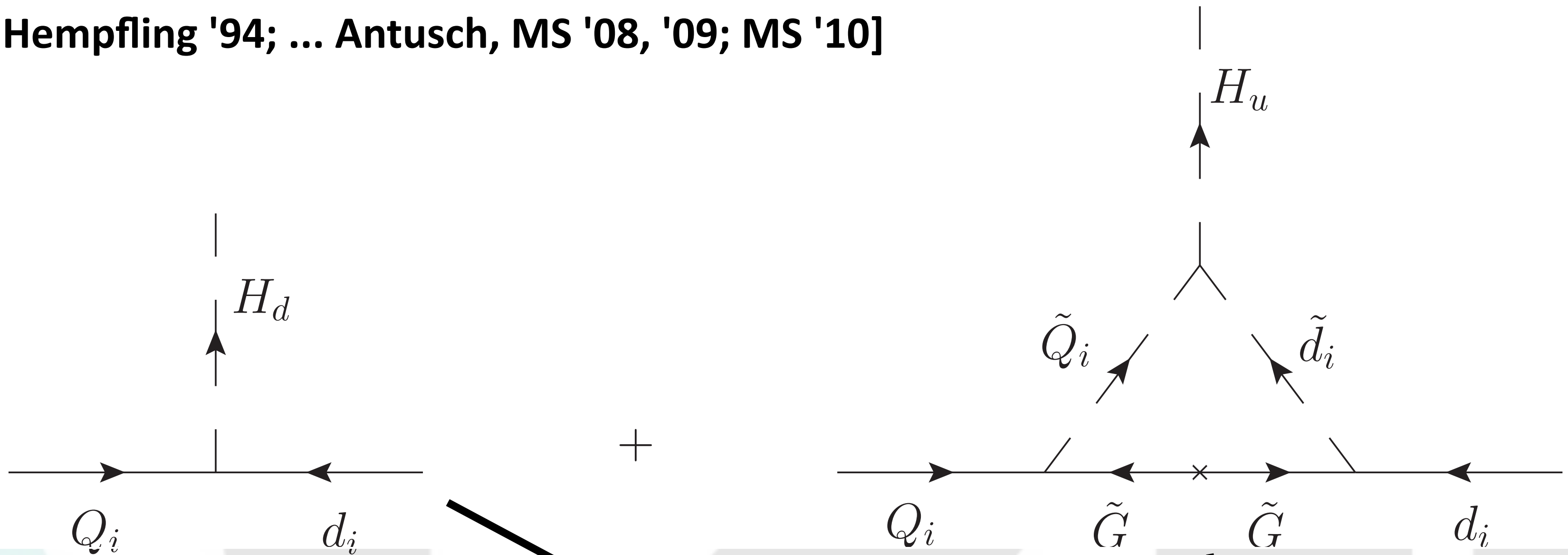
SUSY Threshold Corrections I

[Hall, Rattazzi, Sarid '94; Blazek, Raby, Pokorski '95; Carena, Olechowski, Pokorski, Wagner '94; Hempfling '94; ... Antusch, MS '08, '09; MS '10]



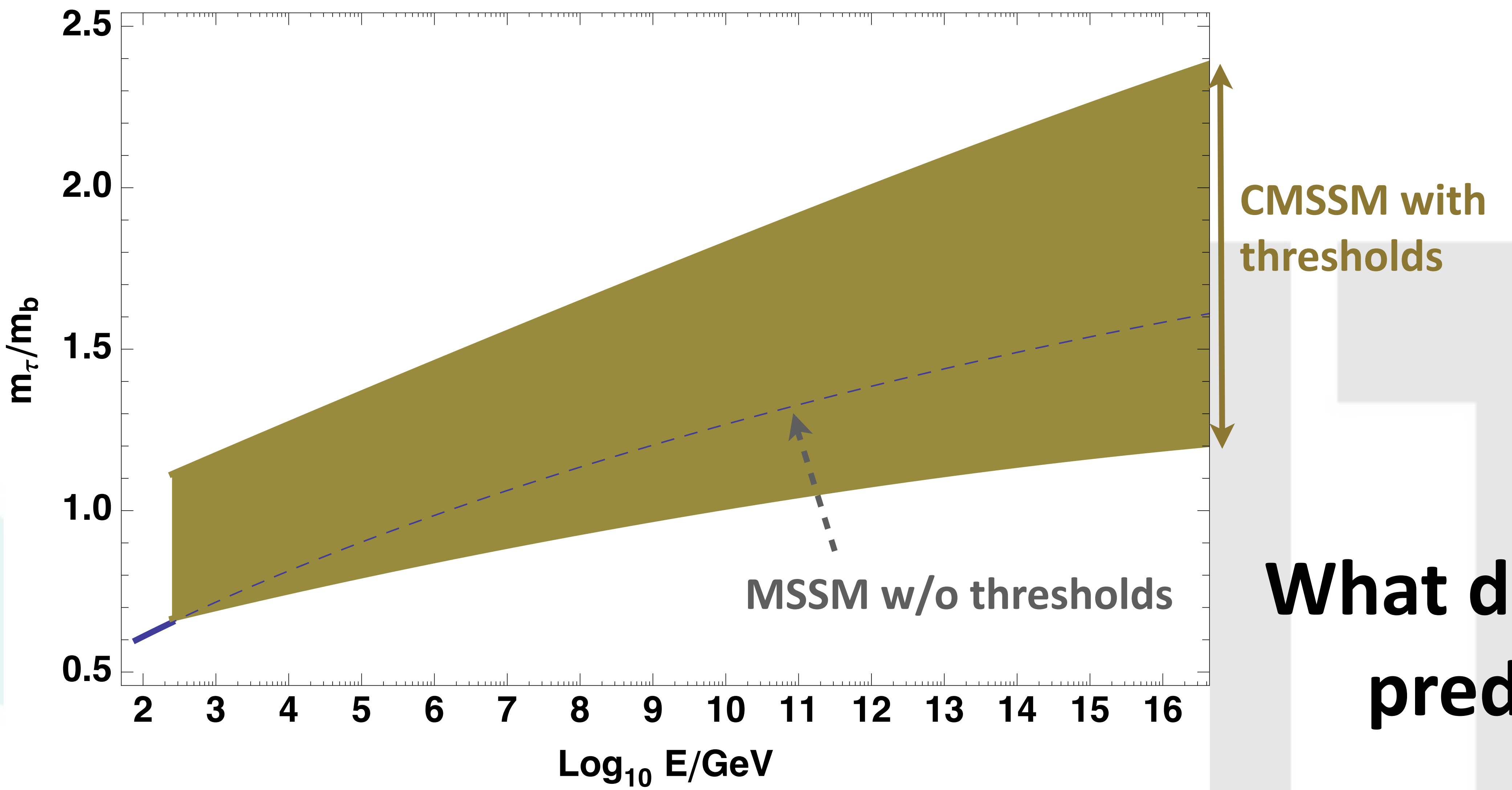
Matching: $\mathcal{L}_{\text{eff}}^{\text{MSSM}} = -y_b^{\text{MSSM}} \left(\bar{b}_R Q_L H_d + \varepsilon_b \bar{b}_R Q_L H_u^c \right) + \text{H.c.}$

to: $\mathcal{L}^{\text{SM}} = -y_b^{\text{SM}} \bar{b}_R Q_L \epsilon H + \text{H.c.}$

gives: $y_b^{\text{SM}} = y_b^{\text{MSSM}} \cos\beta \,(1 + \varepsilon_b \tan\beta)$

tan β enhanced!!!

SUSY Threshold Corrections II



What do GUTs predict?

Alternative Ratios I

Consider first the most minimal case:

$$F_3 T_3 \langle \overline{H}_5 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} b^c_R \\ b^c_B \\ b^c_G \\ \tau \\ -\nu_\tau \end{pmatrix} \begin{pmatrix} 0 & -t^c_G & t^c_B & -t_R & -b_R \\ t^c_G & 0 & -t^c_R & -t_B & -b_B \\ -t^c_B & t^c_R & 0 & -t_G & -b_G \\ t_R & t_B & t_G & 0 & -\tau^c \\ b_R & b_B & b_G & \tau^c & 0 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ v \end{pmatrix}$$

$$\stackrel{SSB}{\longrightarrow} -\frac{v}{\sqrt{2}} \left(\bar{b} b + \bar{\tau} \tau \right) \longrightarrow y_\tau / y_b = 1$$

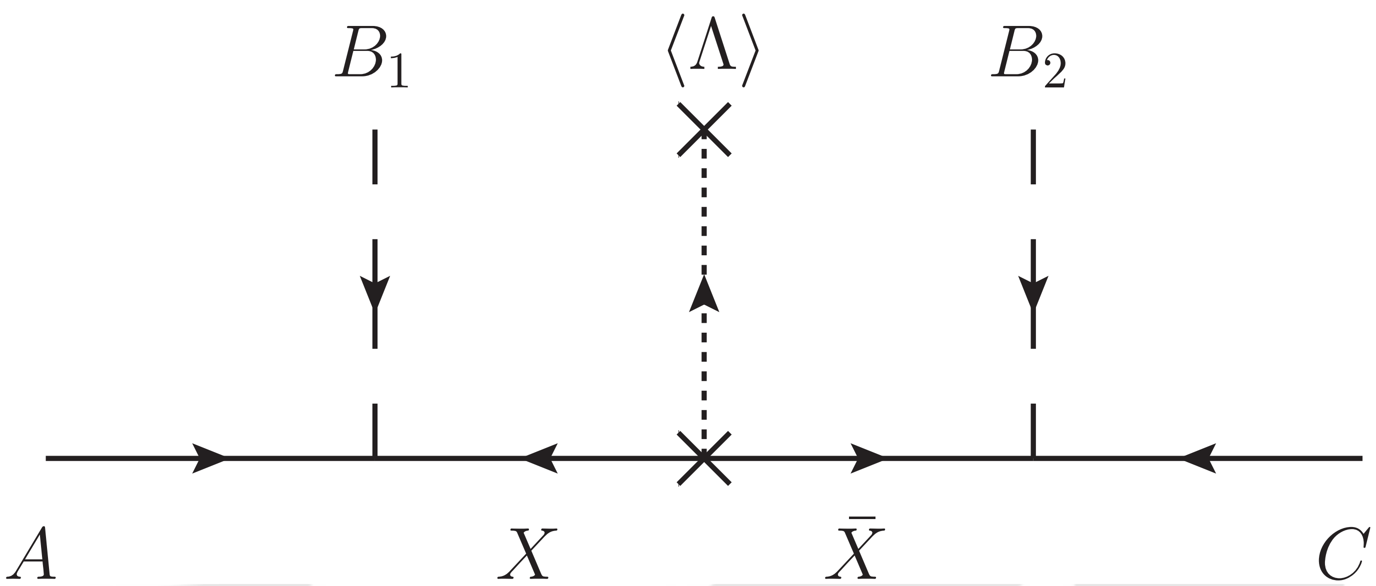
[Georgi, Glashow ’74, see also talk by Q. Shafi]

Using a 45-dim. Higgs gives a ratio of -3

[Georgi, Jarlskog '79]

Alternative Ratios II

[Antusch, MS '09; MS '10; Antusch, King, MS '13]



- Take A = F_2, B_1 = H_{24}, B_2 = H_{45}, C = T_2, X = 5, Λ = 1
- From <H_{24}>: y_μ/y_s = -3/2
- From <H_{45}>: y_μ/y_s = -3
- From both combined: y_μ/y_s = 9/2

Alternative Ratios III

[Antusch, MS '09; MS '10; Antusch, King, MS '13;
dim. 6 SU(5) operators Antusch *et al.* '14]

Operator Dimension	$(Y_e)_{ji}/(Y_d)_{ij}$
4	1
	-3
5	1/6
	-1/2
	-2/3
	1
	±3/2
	-3
	9/2
	6
	-18

[Antusch, King, MS '13]

[Antusch, MS '09; MS '10]

Summary of possible predictions from SU(5)

Operator Dimension	$((Y_e)_{ij}/(Y_d)_{ij}, (Y_u)_{ij}/(Y_d)_{ij})$
4	(1, 1)
	(-3, 1)
5	(0, ±1)
	(-1/3, ±1)
	(1, ±1)
	(3/2, ±1)
	(-3, ±1)
	(9, ±1)

[Antusch, King, MS '13]

[Antusch, MS '09; MS '10]

Summary of possible predictions from Pati-Salam

Which ratios are realistic?

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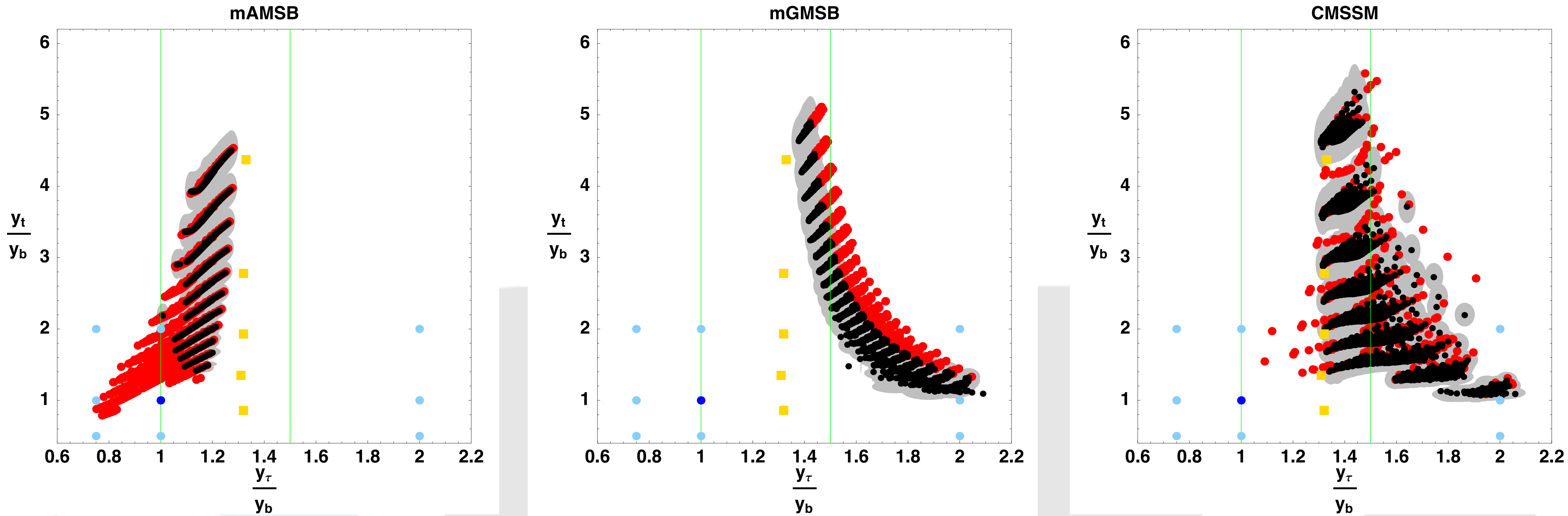
Used Data in the 2009 study

- Direct LEP searches
- Electroweak precision observables
- B-physics:
  - $BR(b \to s\gamma) = (3.55 \pm 0.36) \times 10^{-4}$
  - $BR(B_s \to \mu\mu) \leq 5.8 \times 10^{-8}$
- Anomalous magnetic moment of the muon

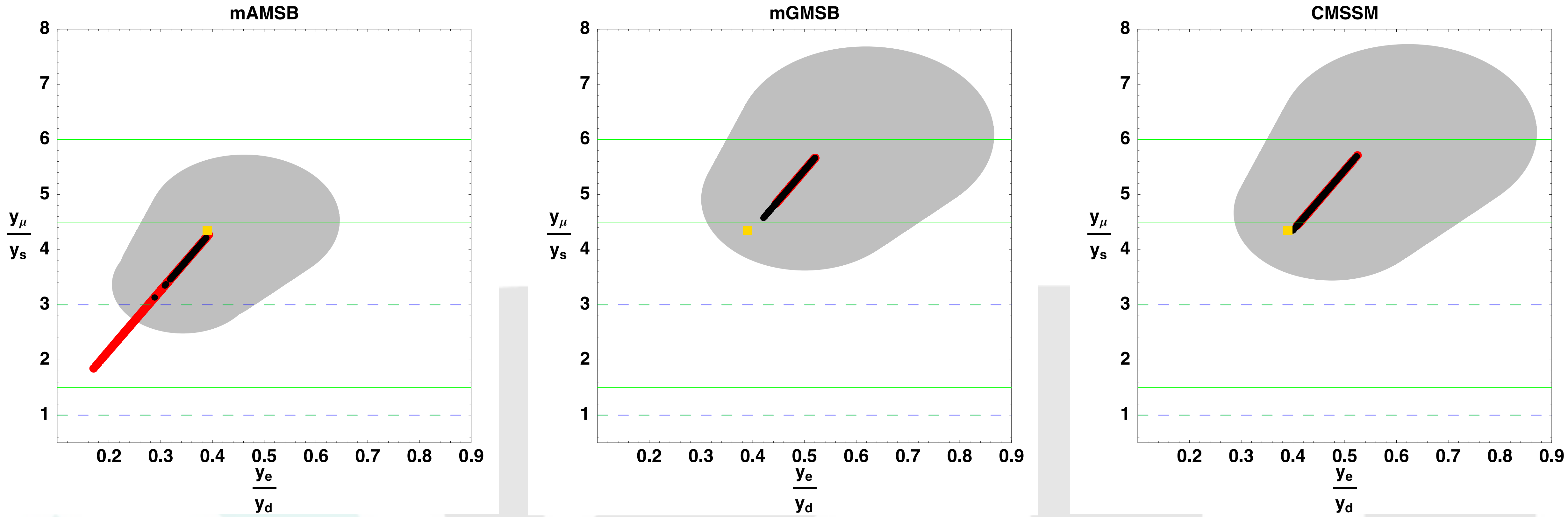
Pre-LHC data

Results for the 3rd generation



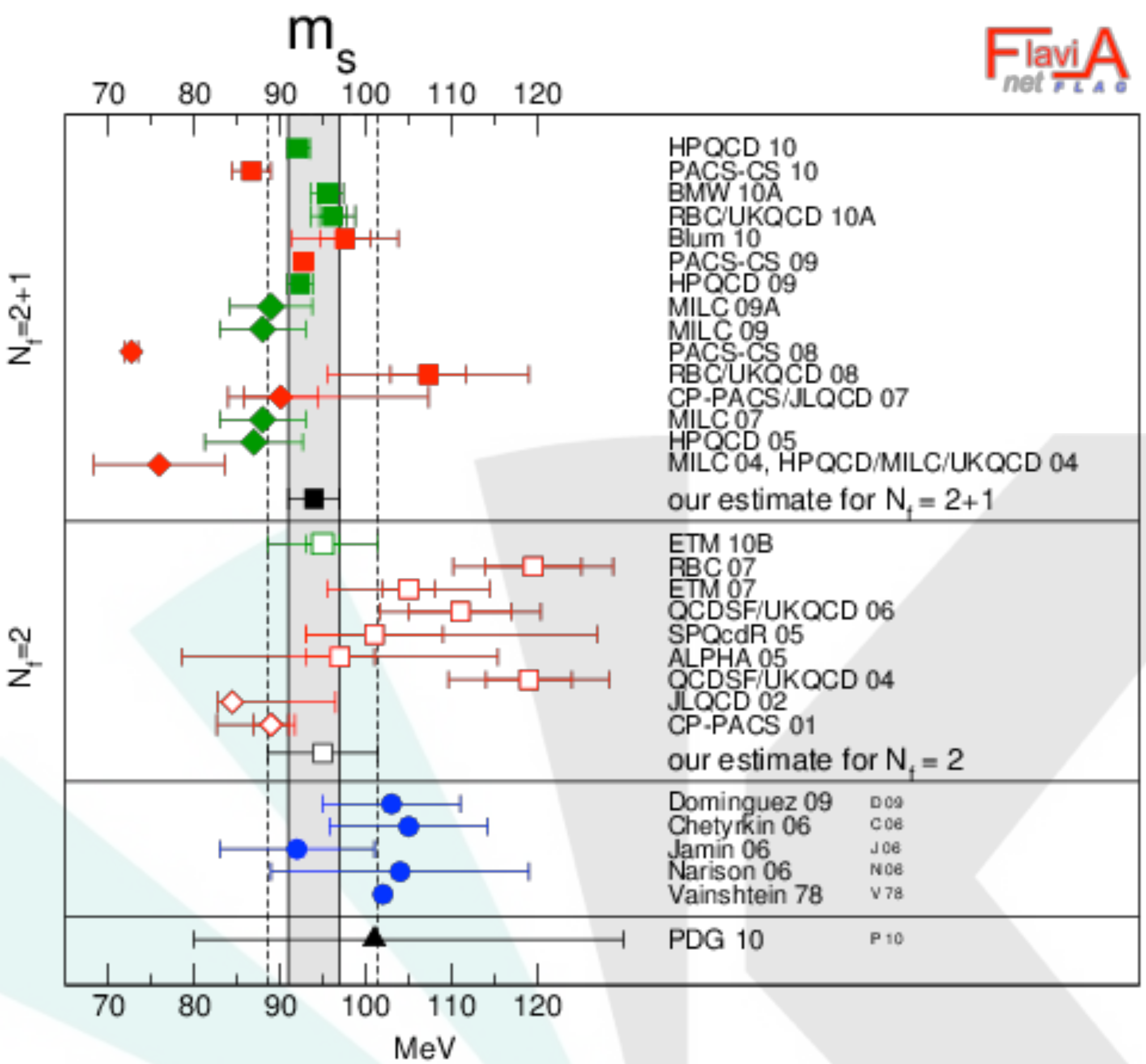
exp. allowed (2009) | exp. disfavored (2009)
mass uncertainties | w/o thresholds
SU(5) predictions | Pati-Salam predictions

Results for the 1st and 2nd generation



exp. allowed (2009) | exp. disfavored (2009)
mass uncertainties | w/o thresholds
SU(5) predictions | Pati-Salam predictions

Regarding mass uncertainties...

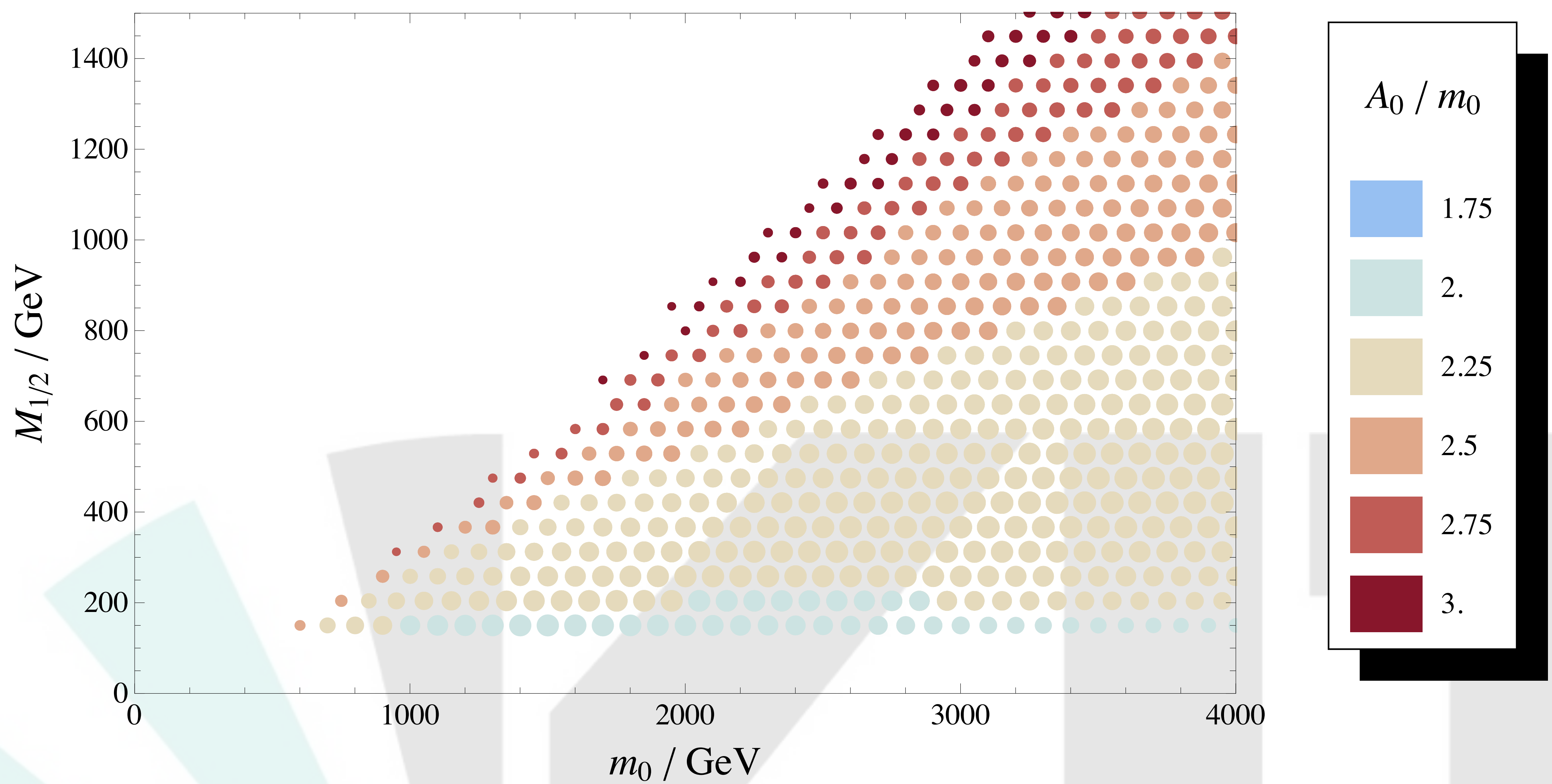


we took this number in '09

[taken from http://itpwiki.unibe.ch/flag/index.php/Quark_masses on 14/01/13]

Implications for SUSY Spectrum

[Antusch, Calibbi, Maurer, MS '11]

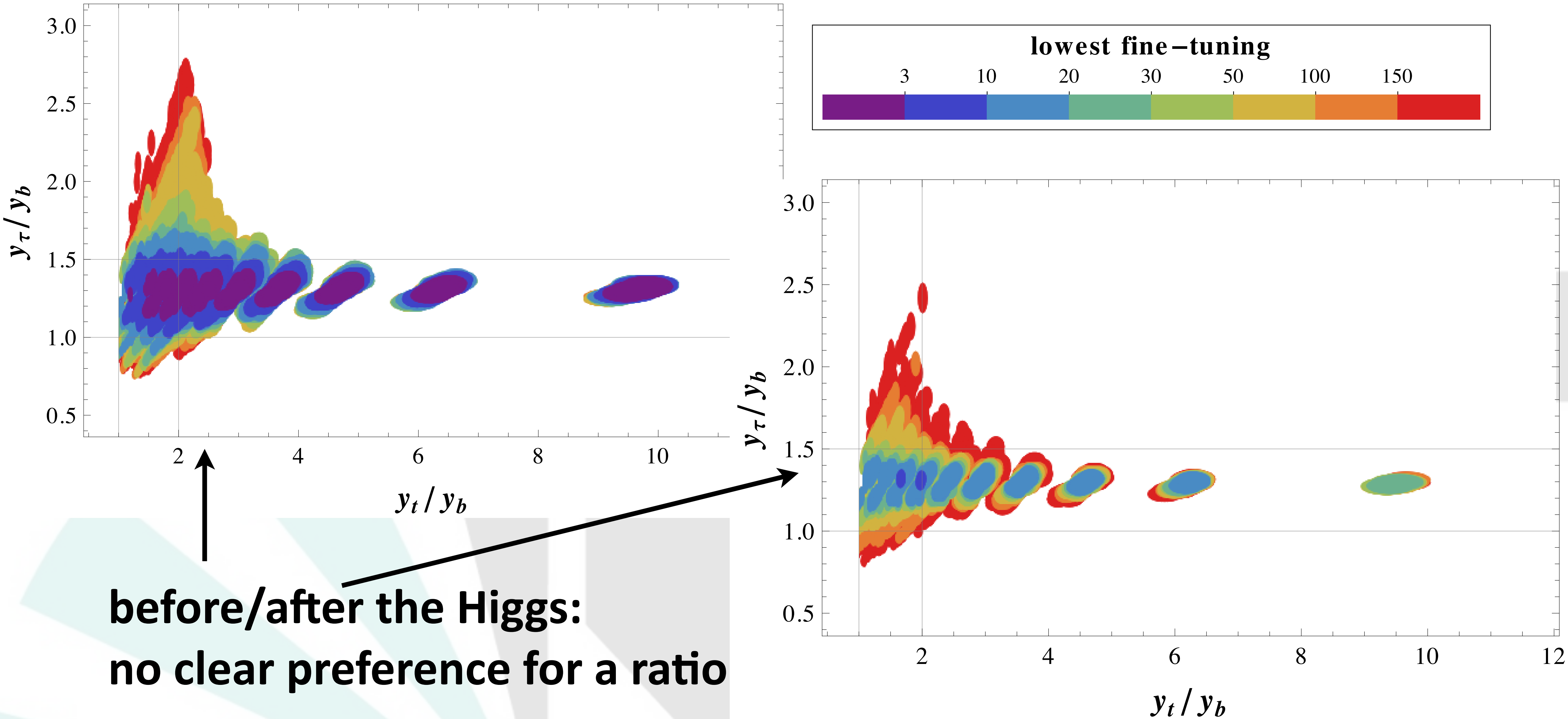


Constrained Spectrum from a CMSSM scan

(y_τ/y_b = -3/2, y_μ/y_s = 6, tan β = 30)

Naturalness of Fermion Mass Ratios

[Antusch, Calibbi, Maurer, Monaco, MS '12]



before/after the Higgs:
no clear preference for a ratio

The θ_{13} study - Setup

[Marzocca *et al*. '11, see also Antusch, Maurer '11]

- Assume SU (5) relations:

$$\hat{\lambda}^{D}_{[12]} = \begin{pmatrix} a & b' \\ b & c \end{pmatrix} \qquad \hat{\lambda}^{E}_{[12]} = \begin{pmatrix} \alpha a & \beta b \\ \beta' b' & \gamma c \end{pmatrix}$$

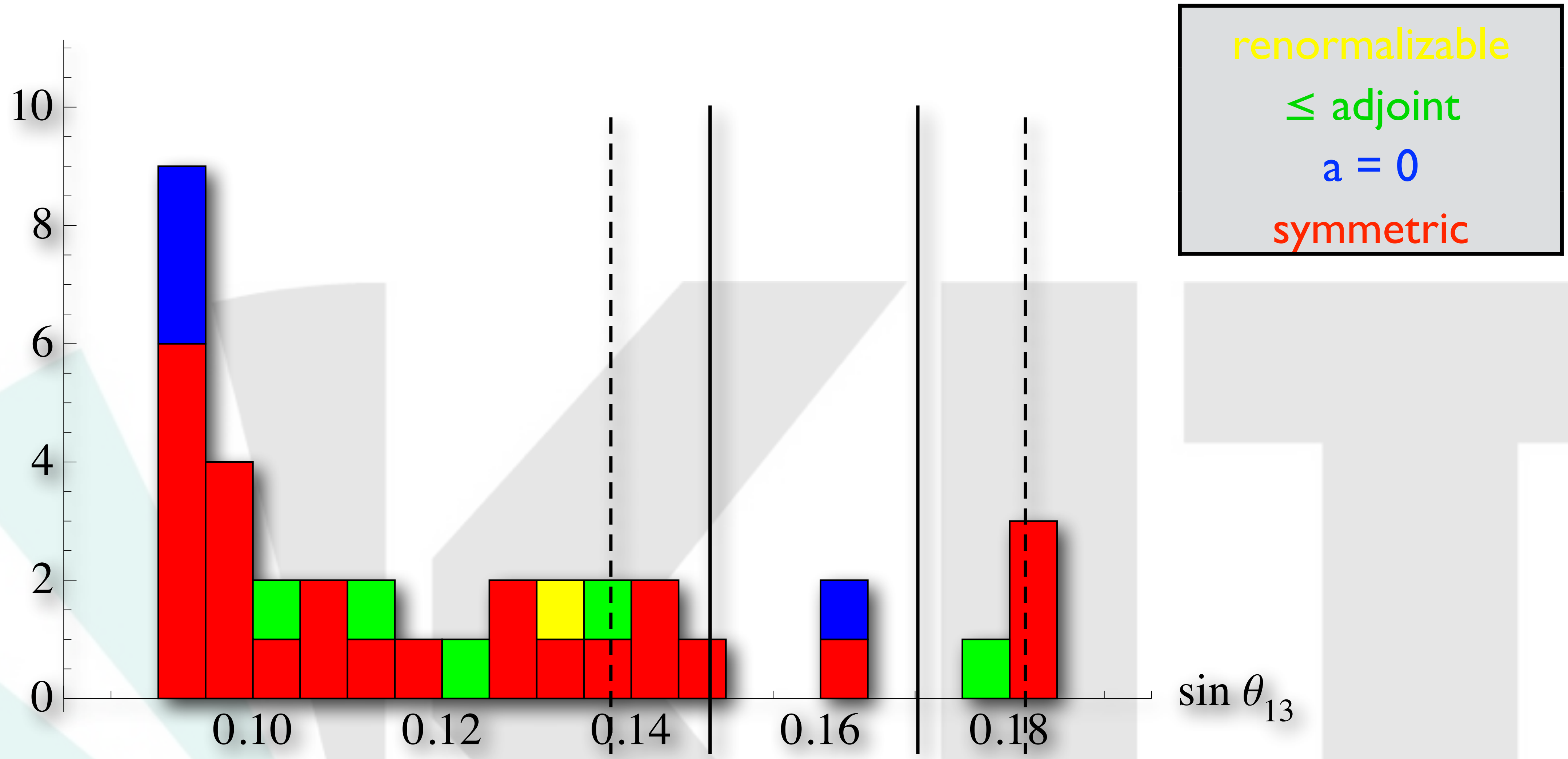
- No 1-3 mixing in the neutrino and only 1-2 mixing in the charged lepton sector:

$$\sin\theta_{13} \approx \sin\theta^{e}_{12} \sin\theta^{\nu}_{23} \approx \frac{1}{\sqrt{2}} \frac{\beta'}{\gamma} \frac{b'}{c}$$

- α, β, β', γ are SU(5) Clebsch-Gordan coefficients (1, -3/2, -3 , 9/2, 6, ...)

[for lists see Antusch, MS '09; Antusch, King, MS '13; Antusch *et al.* '14]

Scan results with free θ_{13} (May '12)



[Based on the global fit by Forero, Tortola, Valle '12, Thanks to D. Marzocca for providing this plot]

The Good Cases

- The Georgi-Jarlskog structure would predict

$$\sin\theta_{13} \approx \frac{1}{3\sqrt{2}}\theta_C \approx 3^\circ$$

- The good cases feature instead

$$\sin\theta_{13} \approx \frac{1}{\sqrt{2}}\theta_C \approx 9^\circ$$

- Successful models realised

[1205.5241 (SISSA); 1305.6612, 1306.3984 (Basel)]

- Can improve as well on

$$\left|\frac{y_\mu}{y_s}\frac{y_d}{y_e}\right| = 10.7^{+1.8}_{-0.8}$$

[Antusch, Maurer '13]

Corrections to other Mixing Angles

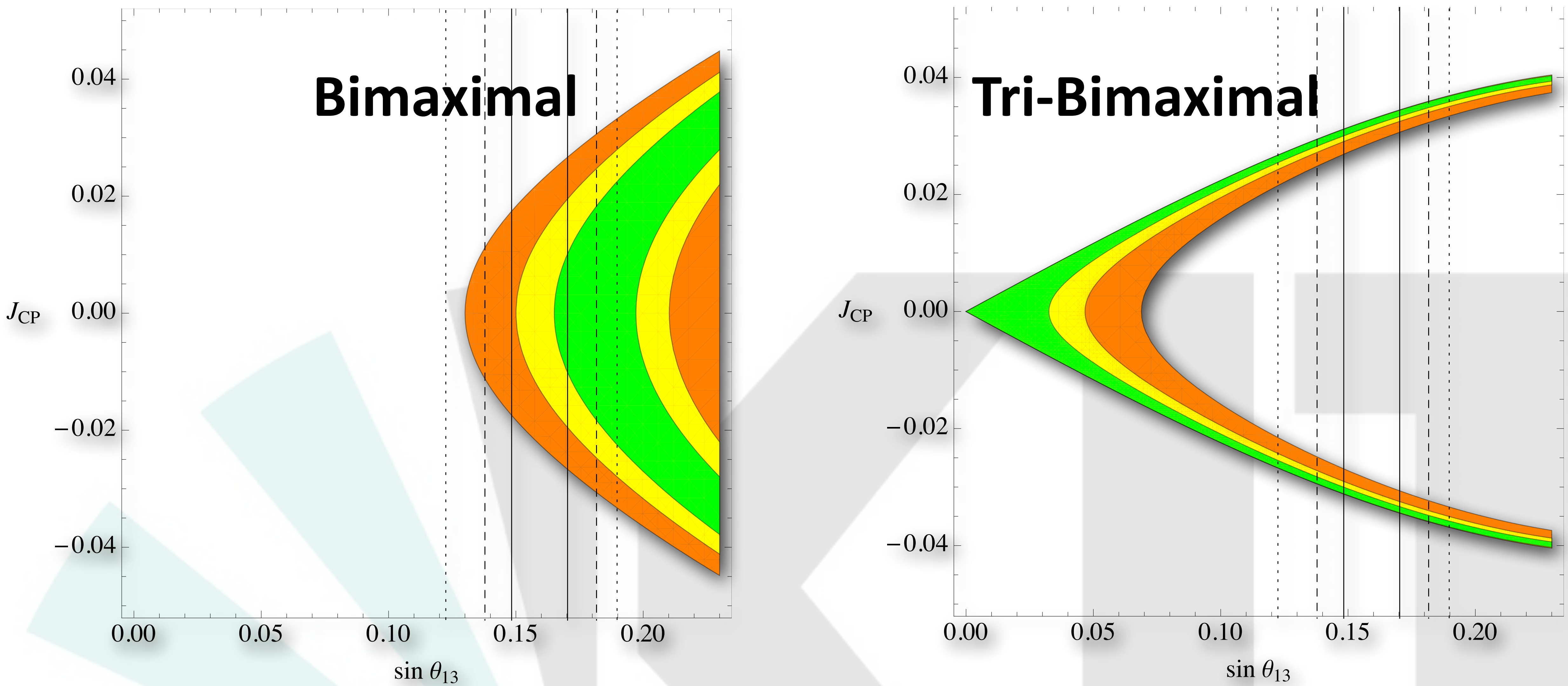
- For Bimaximal mixing:

$$\sin^2\theta_{12} \approx \frac{1}{2} + \sin\theta_{13}\cos\delta$$

- For Tri-Bimaximal mixing:

$$\sin^2\theta_{12} \approx \frac{1}{3} + \frac{2\sqrt{2}}{3}\sin\theta_{13}\cos\delta$$

Implications for J_{CP} (May '12)



[Based on the global fit by Forero, Tortola, Valle '12, Thanks to D. Marzocca for providing this update]

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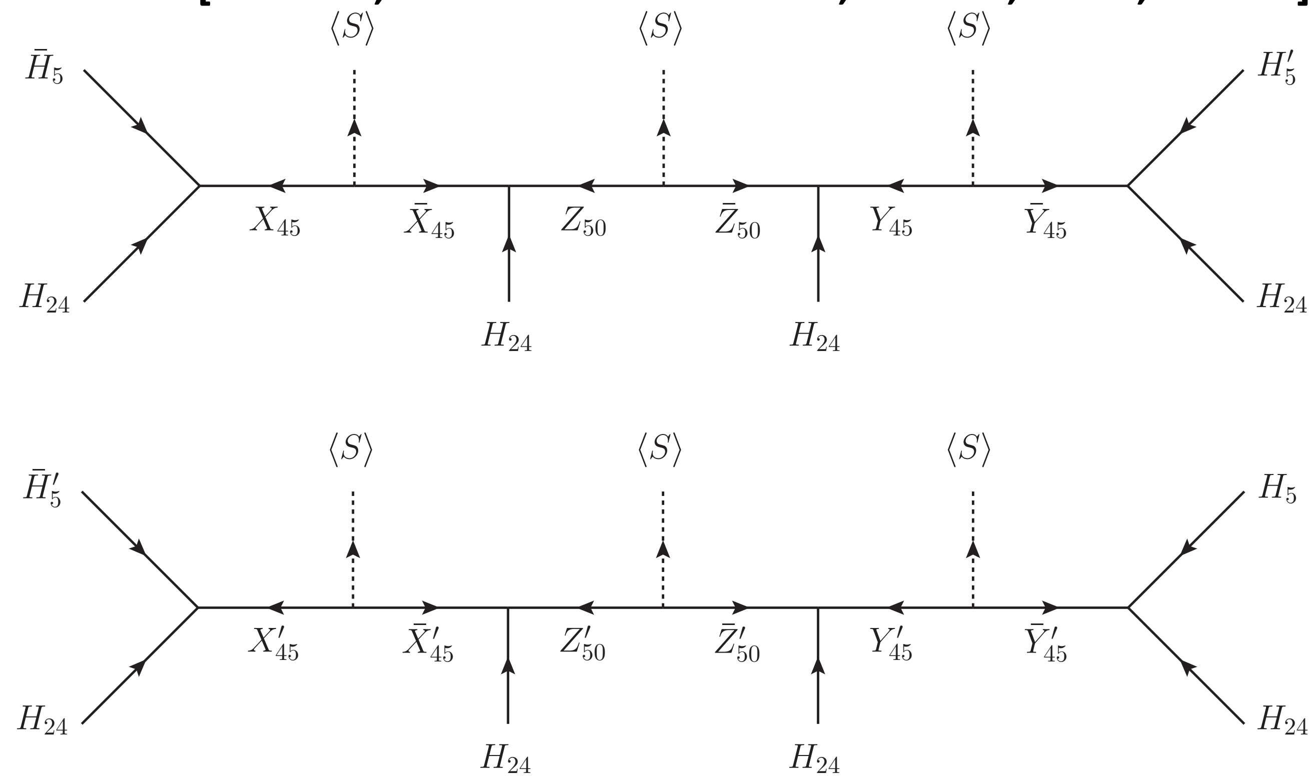
Two Questions

1. Can the doublet-triplet-splitting problem be solved in this models?

2. How does the potential for the adjoints look like?

Double Missing Partner Mechanism

[Antusch, de Medeiros-Varzielas, Maurer, Sluka, MS '14]



- Coloured triplets projected out by missing partners in **50** (MPM)

[Masiero, Nanopoulos, Namvakis, Yanagida '82; Grinstein '82]

- The DMPM keeps gauge couplings perturbative up to the Planck scale

[Hisano, Moroi, Tobe, Yanagida '95]

- We replaced the **75** with two **24**'s to allow charges for **24**'s

GUT breaking Potentials

[Antusch, de Medeiros-Varzielas, Maurer, Sluka, MS '14]

- Four different superpotentials:

(a) $W = M_{24}\ \mathrm{tr}\, H_{24}^2 + M'_{24}\,\mathrm{tr}\, H'^2_{24} + \kappa'\ \mathrm{tr}\, H_{24} H'^2_{24} + \lambda\ \mathrm{tr}\, H_{24}^3$, with $\mathbb{Z}_2$

(b) $W = \tilde{M}_{24}\ \mathrm{tr}\, H_{24} H'_{24} + \lambda\ \mathrm{tr}\, H_{24}^3 + \lambda'\ \mathrm{tr}\, H'^3_{24}$, with $\mathbb{Z}_3$

(c) $W = \tilde{M}_{24}\ \mathrm{tr}\, H_{24} H'_{24} + \lambda\ \mathrm{tr}\, H_{24}^3 + \kappa'\ \mathrm{tr}\, H_{24} H'^2_{24}$, with $\mathbb{Z}_4^R$

(d) no symmetry

- Different GUT scales and effective triplet masses (p decay sufficiently suppressed)

➡ Talk of Vinzenz Maurer on wednesday (session IIB)

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Summary and Conclusions

- There are interesting GUT ratios beyond the standard ones, e.g.
  - y_μ/y_s = 9/2, 6 and y_τ/y_b = -3/2
- Low energy data constrains GUT models, e.g.
  - LHC constrains the SUSY spectrum
  - Information even from neutrinos
- Viable GUT breaking Higgs potentials