Predictive SUSY flavour GUTs & the precision analysis tool SusyTC

Stefan Antusch

University of Basel
Department of Physics

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

USM Valparaiso, Chile; September 2016

Amo, Valparaiso, cuanto encierras
y cuanto irradias, novia del océano,
hasta más lejos que tu nimbo sordo....
Pablo Neruda

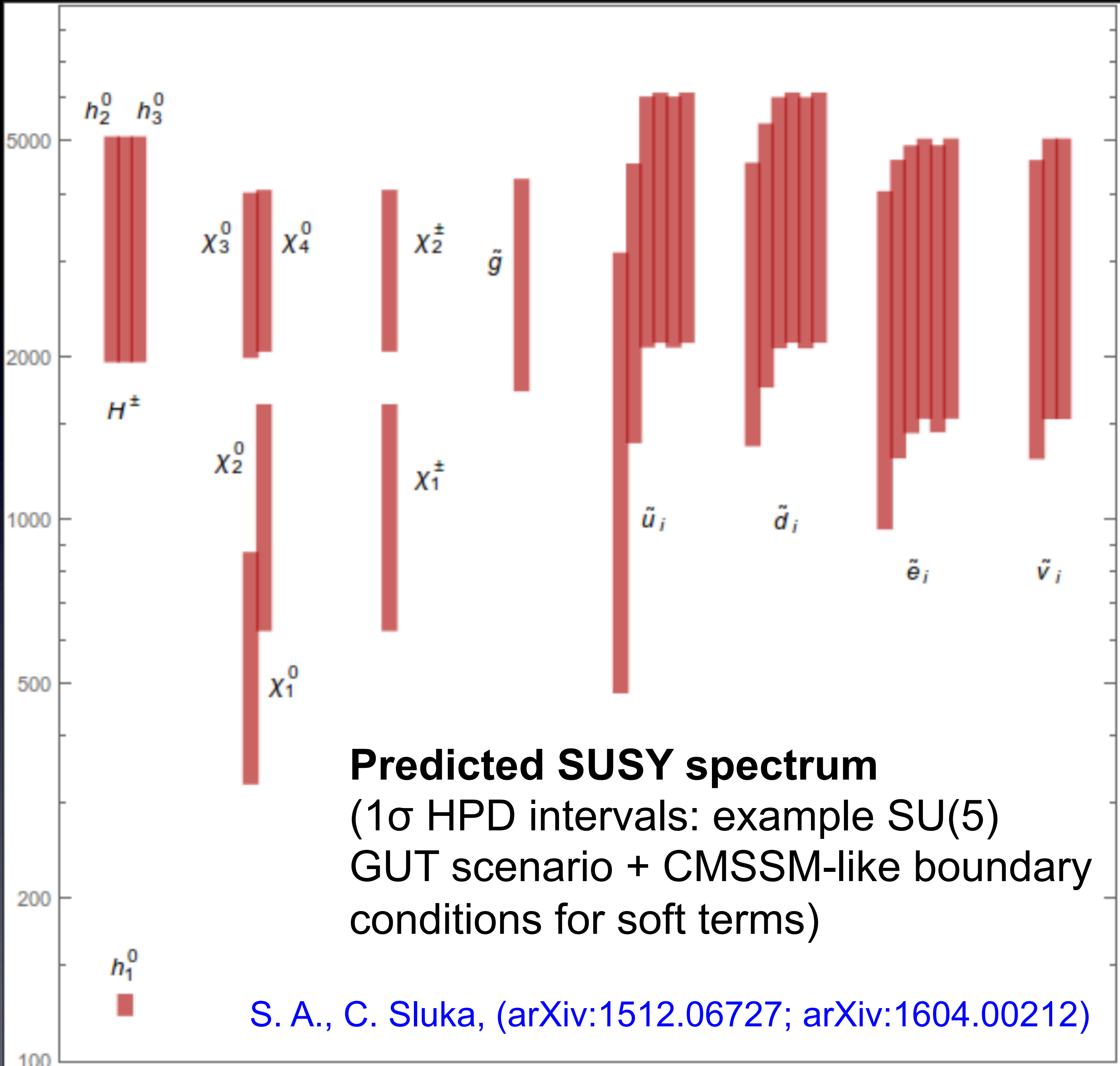
FLASY 2016: 6th Workshop on Flavour Symmetries and Consequences in Accelerators and Cosmology

Motivation: Interesting question which came up at Flasy 2013 in Niigata …

Which predictions do SUSY flavour GUT models make for the SUSY particle spectrum?

… we finally have an answer (for the class of SU(5) GUT models we presented @ Flasy2013)

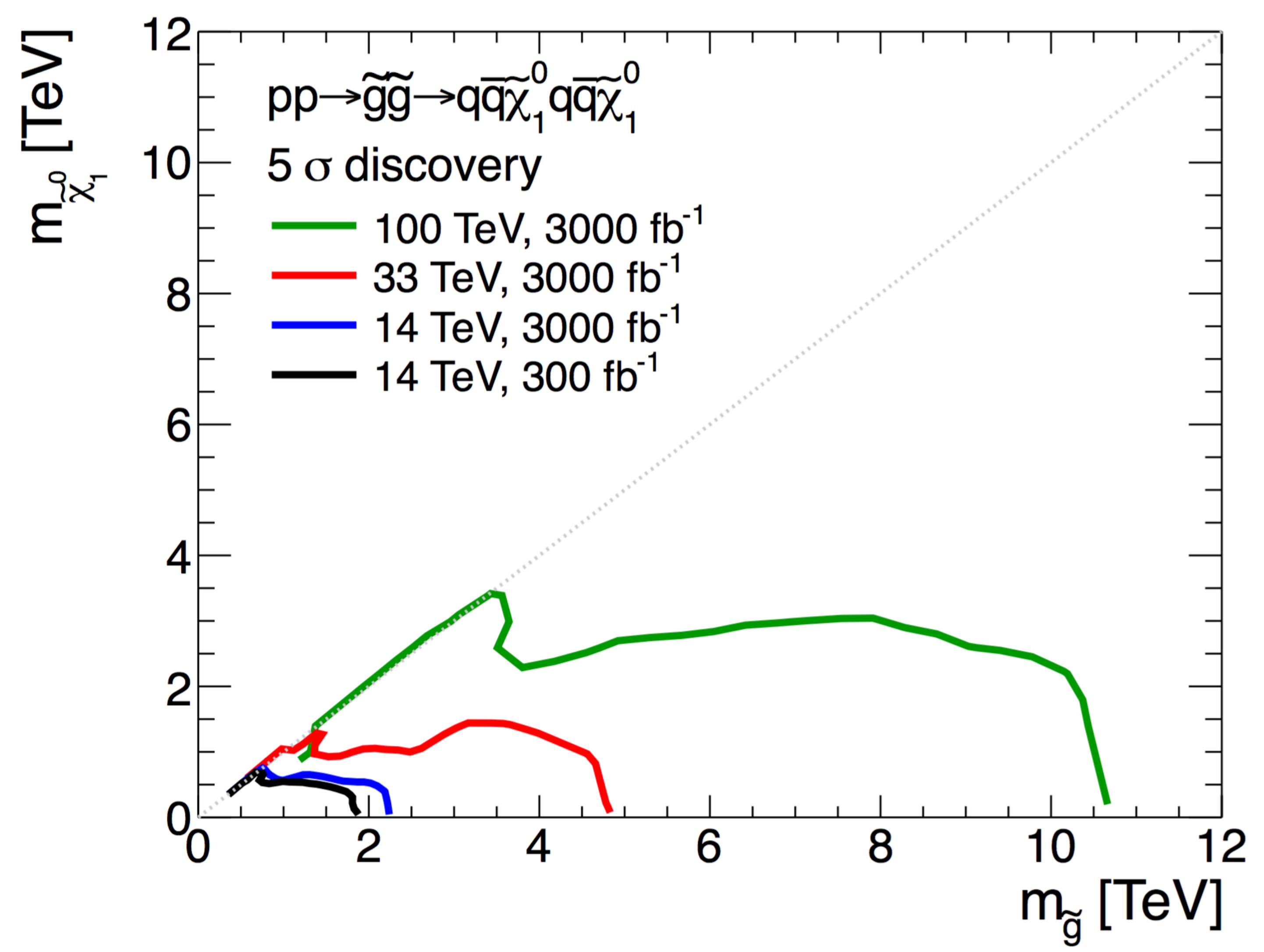
… and we made our software tool SusyTC public for you to check the predictions of your favourite GUT model



Predicted SUSY spectrum
(1σ HPD intervals: example SU(5) GUT scenario + CMSSM-like boundary conditions for soft terms)

S. A., C. Sluka, (arXiv:1512.06727; arXiv:1604.00212)

Interesting: Too heavy for LHC (run 1) but testable at a future 100 TeV pp collider (e.g. FCC-hh)



Plot from: Cohen, Golling, Hance, Henrichs, Howe, Loyal, Padhi, Wacker (arXiv:1311.6480)

Content of my talk

Predictions from (supersymmetric) GUT-flavour models:

- Interesting type of predictions: Quark-lepton mass ratios from GUTs
- SUSY loop threshold corrections: The link to the SUSY spectrum
- An example model …

Model analysis & predictions for the SUSY spectrum from GUTs:

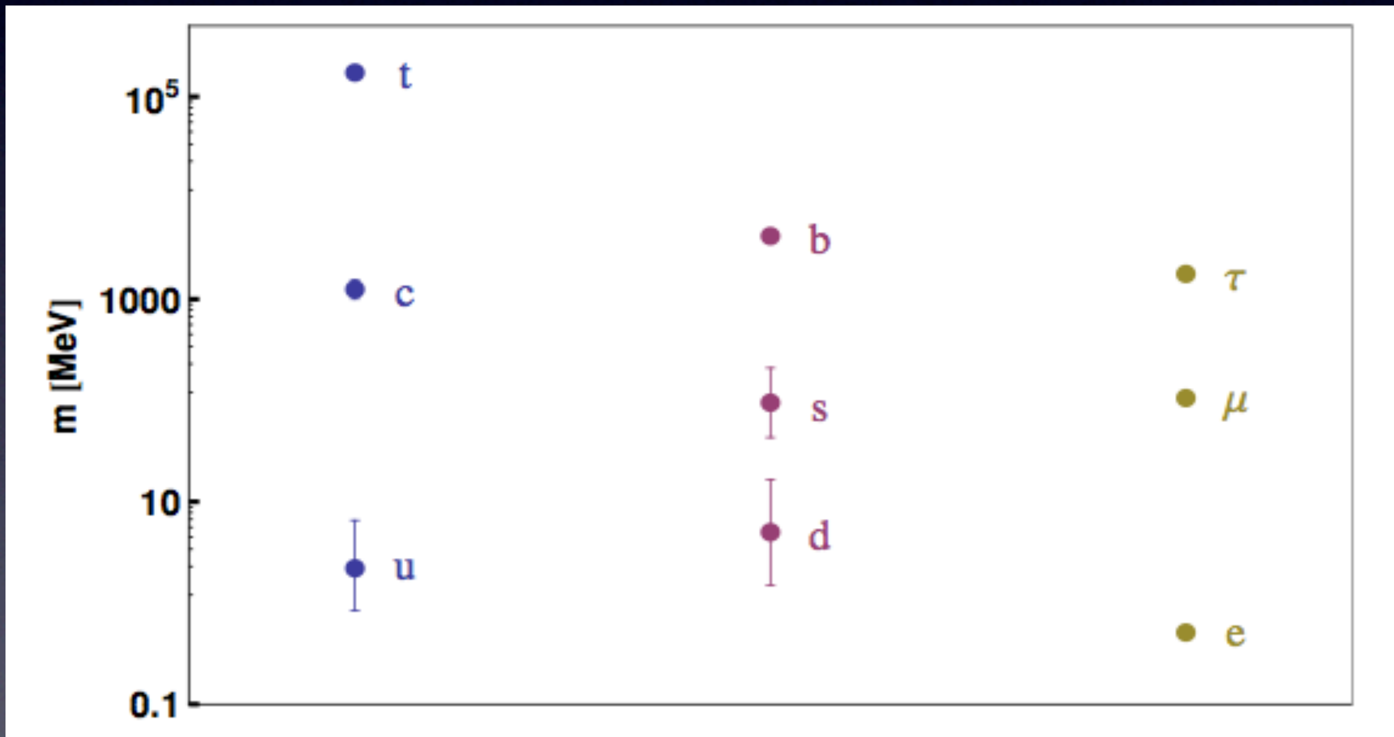
- SusyTC: a REAP extension for soft SUSY running + threshold corrections
- Predictions for the SUSY spectrum from fermion mass relations in GUTs

S. A., C. Sluka, (arXiv:1512.06727)

Quark-lepton mass ratios from GUTs

Fermion mass ratios from GUTs?

- Why are the observed masses of each family of down-type quarks and charged leptons "similar" (but not equal).



$m_b \leftrightarrow m_\tau$?

$m_s \leftrightarrow m_\mu$?

(running masses at the top-mass scale; errors are 3 times the 1σ errors ...)

GUT predictions for mass ratios

- Simplest example: In SU(5) GUTs

  → m_b and m_τ from one fundamental operator

$$y_{33}\, \bar{\mathbf{5}}_3\, \mathbf{10}_3\, \langle \bar{H}_5 \rangle$$

MSSM Higgs H_d in GUT representation $\bar{H}_5$

$$\langle \bar{H}_5 \rangle = \begin{pmatrix} 0 & 0 & 0 & 0 & v_\mathrm{d} \end{pmatrix}$$

$$\mathbf{10}_i = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & -u_R^{cG} & u_R^{cB} & -u_L^R & -d_L^R \\ u_R^{cG} & 0 & -u_R^{cR} & -u_L^B & -d_L^B \\ -u_R^{cB} & u_R^{cR} & 0 & -u_L^G & -d_L^G \\ u_L^R & u_L^B & u_L^G & 0 & -e_R^c \\ d_L^R & d_L^B & d_L^G & e_R^c & 0 \end{pmatrix}_i$$

$$\bar{\mathbf{5}}_i = \begin{pmatrix} d_R^{cR} & d_R^{cB} & d_R^{cG} & e_L & -\nu_L \end{pmatrix}_i$$

GUT predictions for mass ratios

- Simplest example: In SU(5) GUTs

  → m_b and m_τ from one fundamental operator

$$y_{33}\ \bar{\mathbf{5}}_3\, \mathbf{10}_3\, \langle \bar{H}_5 \rangle \ \Rightarrow\ \boxed{\left.\frac{m_\tau}{m_b}\right|_{M_{GUT}} = 1}$$

"b-τ unification"

Remark: In this talk "mass ratio" = "Yukawa coupling ratio"

GUT predictions for mass ratios

- GUT predictions from fundamental operators in SU(5)
  - → 3rd family masses from

$$y_{33}\ \bar{\mathbf{5}}_3\,\mathbf{10}_3\,\langle \bar{H}_5\rangle \Rightarrow \frac{m_\tau}{m_b}\Big|_{M_{GUT}} = 1$$

"b-τ unification"

  - → 2nd family masses from

MSSM Higgs H_d in representation $\bar{H}_{45}$

$$y_{22}\ \bar{\mathbf{5}}_2\,\mathbf{10}_2\,\langle \bar{H}_{45}\rangle \Rightarrow \frac{m_\mu}{m_s}\Big|_{M_{GUT}} = 3$$

Georgi, Jarlskog ('79)

GUT predictions for mass ratios

- GUT predictions from fundamental operators in SU(5)

Remark:
In models aiming at explaining the fermion mass hierarchies,
the masses << m_t are typically generated by effective operators!
Froggatt, Nielsen ('79)

→ With effective operators new interesting GUT predictions for m_τ/m_b and m_μ/m_s can arise!

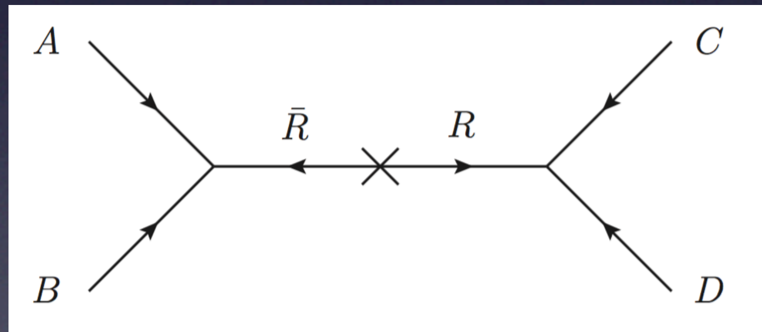
S. A., Spinrath ('09)

GUT predictions for mass ratios

- New GUT predictions from effective operators, for example:
  - → For the 3rd family relation m_τ / m_b :

$$y_{33}\ \bar{\mathbf{5}}_3 \frac{\langle H_{24} \rangle}{\Lambda} \mathbf{10}_3 \ \langle \bar{H}_5 \rangle$$

The vev of the GUT-Higgs H_{24} breaks SU(5) to the SM gauge symmetry by $\langle H_{24} \rangle \sim v_{GUT}$ diag(2 , 2 , 2, -3 , -3)



$A\,B$	$C\,D$	R	$(Y_e)_{ji}/(Y_d)_{ij}$
$H_{24}\,\mathcal{F}$	$\mathcal{T}\,\bar{H}_5$	$\bar{\mathbf{5}}$	$-\frac{3}{2}$

S. A., Spinrath (arXiv:0902.4644)

GUT predictions for mass ratios

- New GUT predictions from effective operators, for example:
  - → For the 3rd family relation m_τ / m_b :

$$y_{33}\ \bar{\mathbf{5}}_3 \frac{\langle H_{24} \rangle}{\Lambda} \mathbf{10}_3 \langle \bar{H}_5 \rangle \Rightarrow \left. \frac{m_\tau}{m_b} \right|_{M_{GUT}} = \frac{3}{2}$$

The vev of the GUT-Higgs H_{24} breaks SU(5) to the SM gauge symmetry by $\langle H_{24} \rangle \sim v_{GUT}$ diag(2 , 2 , 2, -3 , -3)

S. A., Spinrath (arXiv:0902.4644)

GUT predictions for mass ratios

- New GUT predictions from effective operators, for example:
  - → For the 3rd family relation m_τ/m_b :

$$y_{33}\ \bar{\mathbf{5}}_3 \frac{\langle H_{24}\rangle}{\Lambda} \mathbf{10}_3 \langle \bar{H}_5\rangle \ \Rightarrow\ \boxed{\left.\frac{m_\tau}{m_b}\right|_{M_{GUT}} = \frac{3}{2}}$$

  - → For the 2nd family relation m_μ/m_s:

$$y_{22}\ \bar{\mathbf{5}}_2 \frac{\langle H_{24}\rangle}{\Lambda} \mathbf{10}_2 \langle \bar{H}_{45}\rangle \ \Rightarrow\ \boxed{\left.\frac{m_\mu}{m_s}\right|_{M_{GUT}} = \frac{9}{2}}$$

$$y_{22}\ \bar{\mathbf{5}}_2 \langle \overline{H}_5\rangle \mathbf{10}_2 \frac{\langle H_{24}\rangle}{\Lambda} \ \Rightarrow\ \boxed{\left.\frac{m_\mu}{m_s}\right|_{M_{GUT}} = 6}$$

S. A., Spinrath (arXiv:0902.4644)

Which GUT scale predictions are compatible with the experimental data?

- Procedure: RG running from high to low energies

GUT scale (M_{GUT} ~ 10^{16} GeV) → **SUSY scale (sparticle masses)** → **Exp. Data (E ~ O(v_{EW}))**

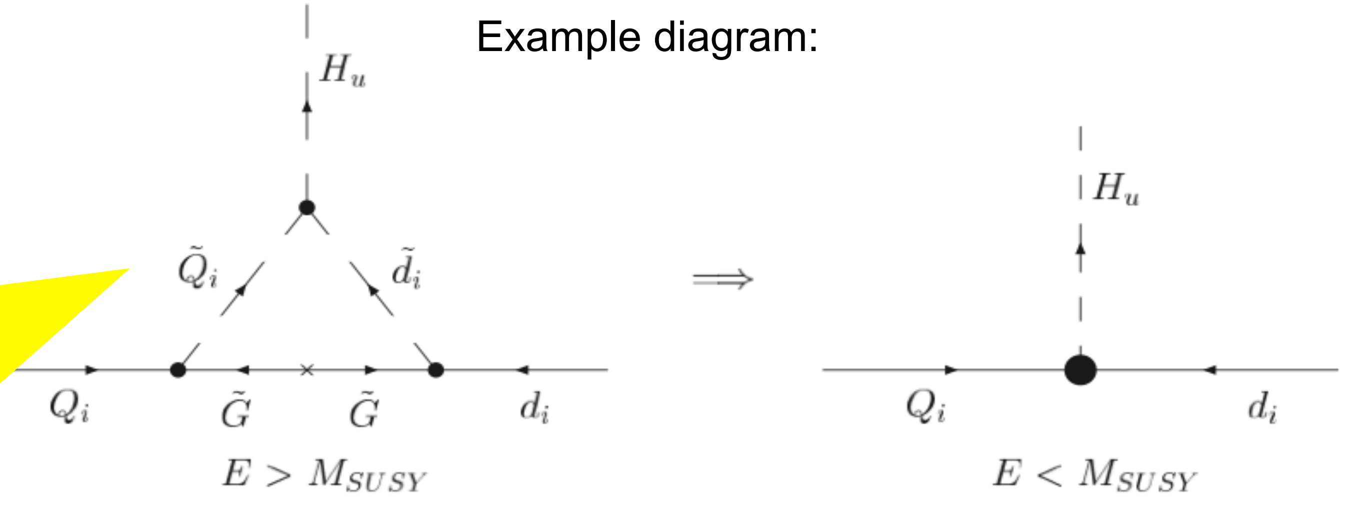
Running masses at μ = M_Z:
S. A., Maurer, (arXiv:1306.6879)

SUSY loop threshold corrections: Link to the SUSY spectrum

At the SUSY scale: Matching of the MSSM to the SM @ loop level

Hall, Rattazzi, Sarid ('93),
Carena et al ('94), Blazek et al ('95),
S.A., Spinrath ('08); S.A., Sluka, ('15)

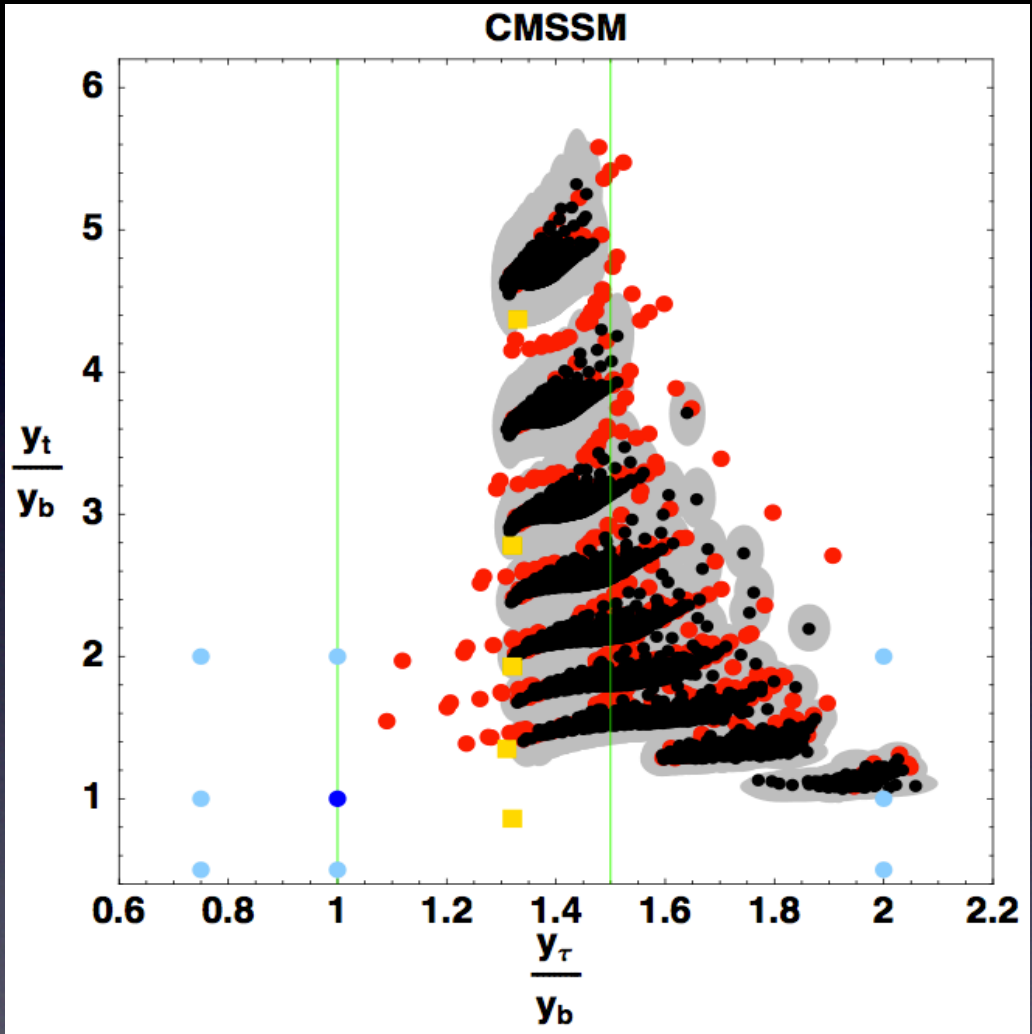
Example diagram:



SUSY threshold effects at M_{SUSY} <u>depend on the SUSY parameters</u>, i.e. on the spectrum, tan β, ... and can strongly affect the low scale results for the quark and lepton masses!

- Example: Yukawa coupling ratios at the GUT scale for the 3rd family, CMSSM (with μ > 0)

S. A., Spinrath (arXiv:0902.4644)

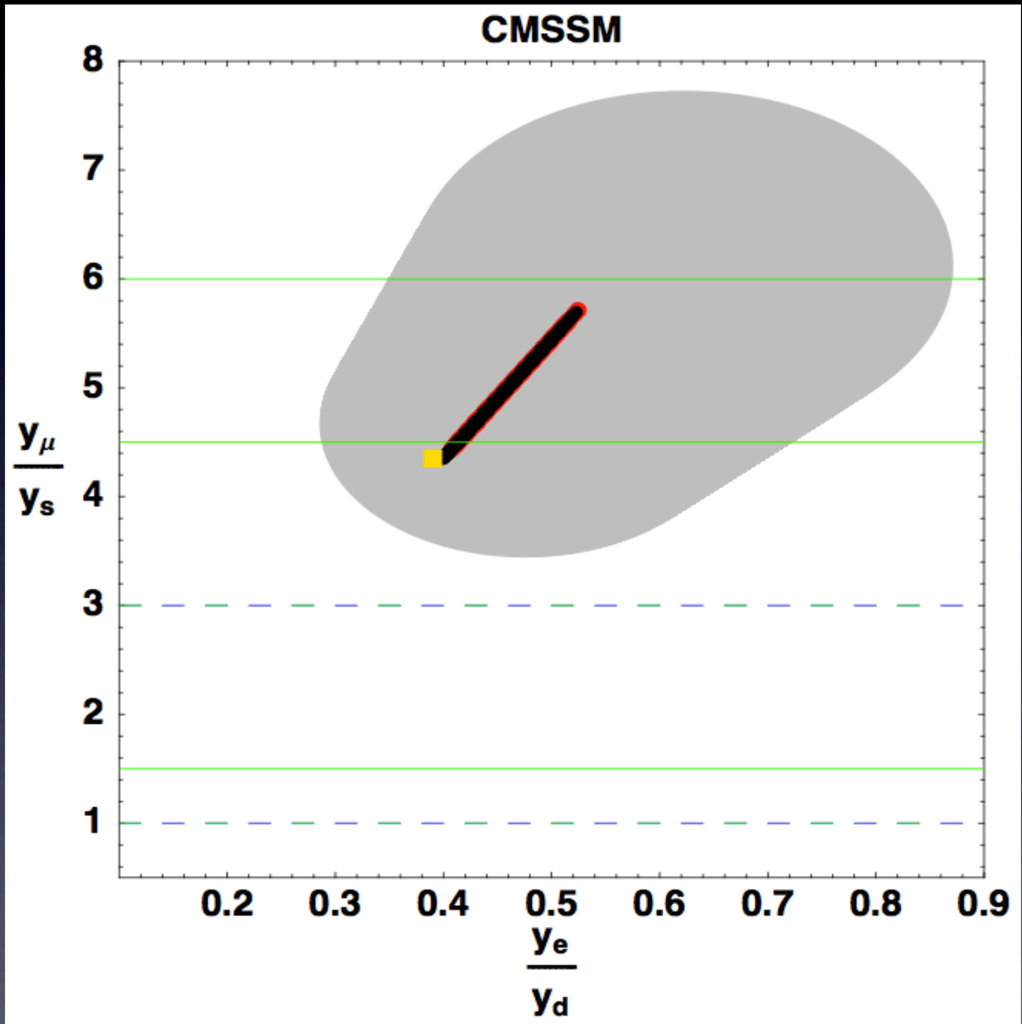


Colours:

- Black: exp. allowed
- Red: exp. disfavoured
- Yellow: no threshold effects
- Grey: exp. uncertainty

- Example: Yukawa coupling ratios at the GUT scale for the 2nd family, CMSSM (with μ > 0)

S. A., Spinrath (arXiv:0902.4644)



Colours:

- Black: exp. allowed
- Red: exp. disfavoured
- Yellow: no threshold effects
- Grey: exp. uncertainty

Brief: An example GUT flavour model …

Example for a supersymmetric SU(5) GUT flavour model

S. A., C. Gross, V. Maurer, C. Sluka (arXiv:1305.6612)

Symmetries: SU(5) x A_4 x “shaping symmetries”

Charged lepton sector: GUT relations for masses & mixings

$$Y_d = \begin{pmatrix} 0 & \tilde{\epsilon}_2 & 0 \\ \tilde{\epsilon}_{ab} c_{ab} & i\tilde{\epsilon}_{ab} s_{ab} & 0 \\ 0 & \omega^2 \hat{\epsilon}_\chi & \tilde{\epsilon}_3 \end{pmatrix}, \; Y_e = \begin{pmatrix} 0 & 6\tilde{\epsilon}_{ab} c_{ab} & 0 \\ -\frac{1}{2}\tilde{\epsilon}_2 & i6\tilde{\epsilon}_{ab} s_{ab} & 6\omega^2 \hat{\epsilon}_\chi \\ 0 & 0 & -\frac{3}{2}\tilde{\epsilon}_3 \end{pmatrix}, \; Y_u = \begin{pmatrix} \epsilon_2^4 & \epsilon_{12}^5 & 0 \\ \epsilon_{12}^5 & \epsilon_{ab}^2 & \epsilon_{23} \\ 0 & \epsilon_{23} & y_t \end{pmatrix}$$

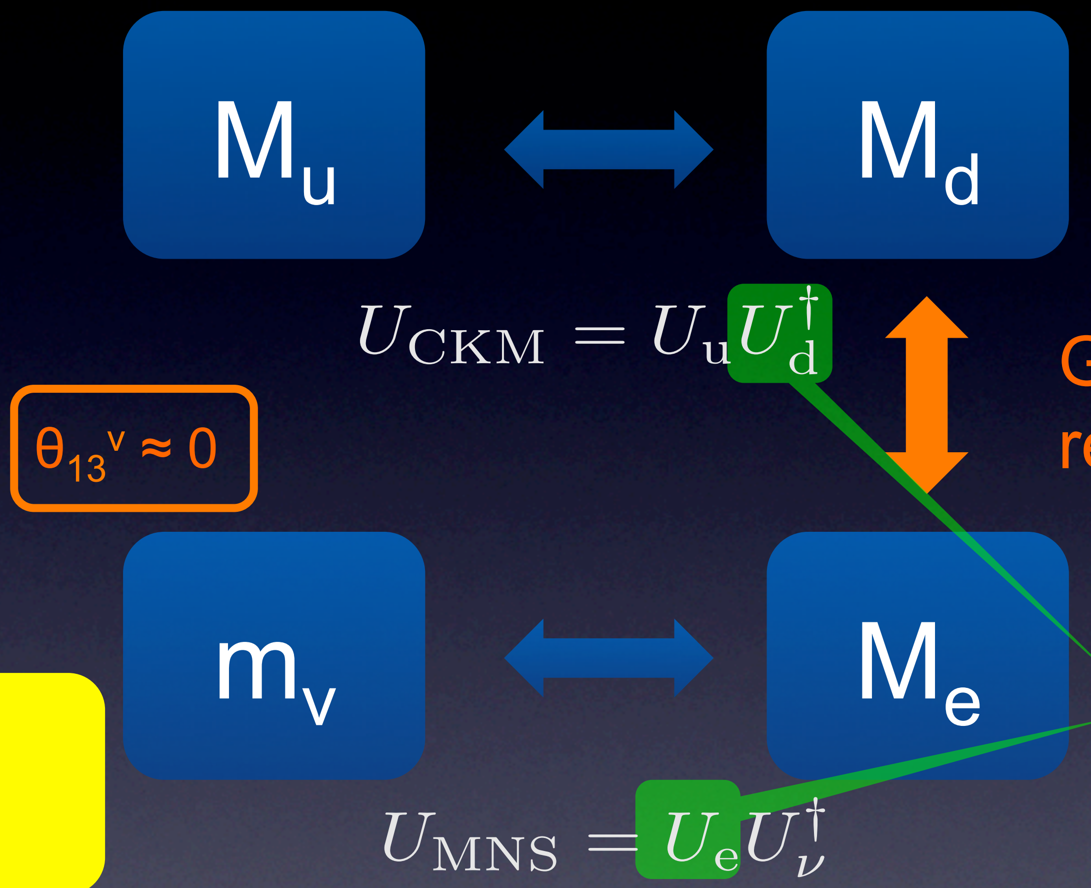
Neutrino sector: TB neutrino mixing (+ charged lepton mixing contr.)

$$Y_\nu = \begin{pmatrix} 0 & \epsilon_{N_2} \\ \epsilon_{N_1} & \epsilon_{N_2} \\ -\epsilon_{N_1} & \epsilon_{N_2} \end{pmatrix}, \quad M_R = \begin{pmatrix} M_{R_1} & 0 \\ 0 & M_{R_2} \end{pmatrix}$$

➔ Normal neutrino mass hierarchy

→ Overview of predictions:

S. A., C. Gross, V. Maurer, C. Sluka (arXiv:1305.6612)



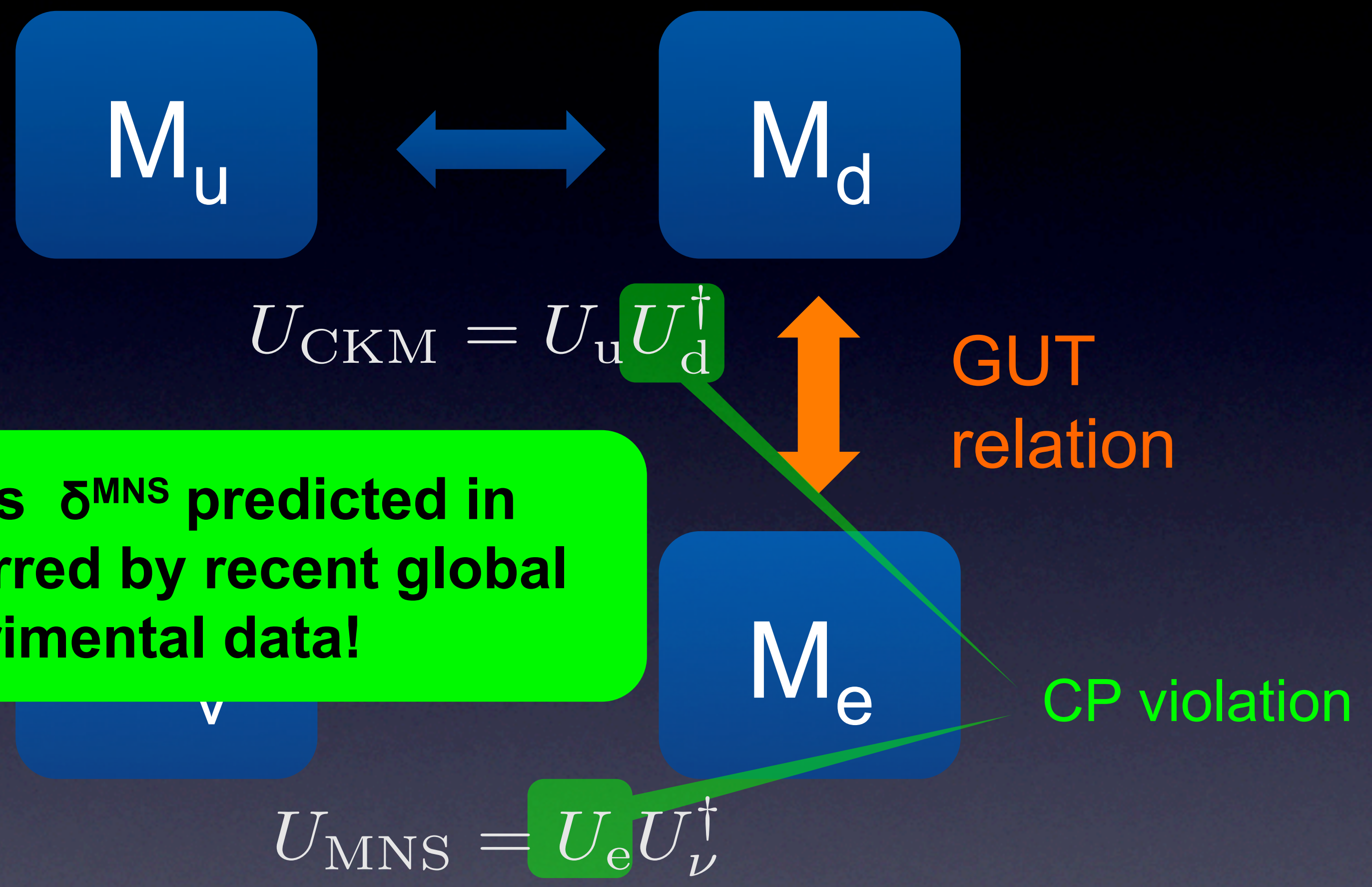
Best fit point:
χ^2/d.o.f. = 2.0

The models predict $\theta_{23}^{PMNS} \approx 40°$ (in any case < 45°)

✓ Excellent fit to the 2013 exp. data: 6 predictions, e.g.: $\theta_{13}^{PMNS} \approx s_{23}^{PMNS}\, \theta_C$
$\delta^{PMNS} \sim 270°$, ... , (plus: constraints on SUSY spectrum)

→ Overview of predictions:

S. A., C. Gross, V. Maurer, C. Sluka (arXiv:1305.6612)

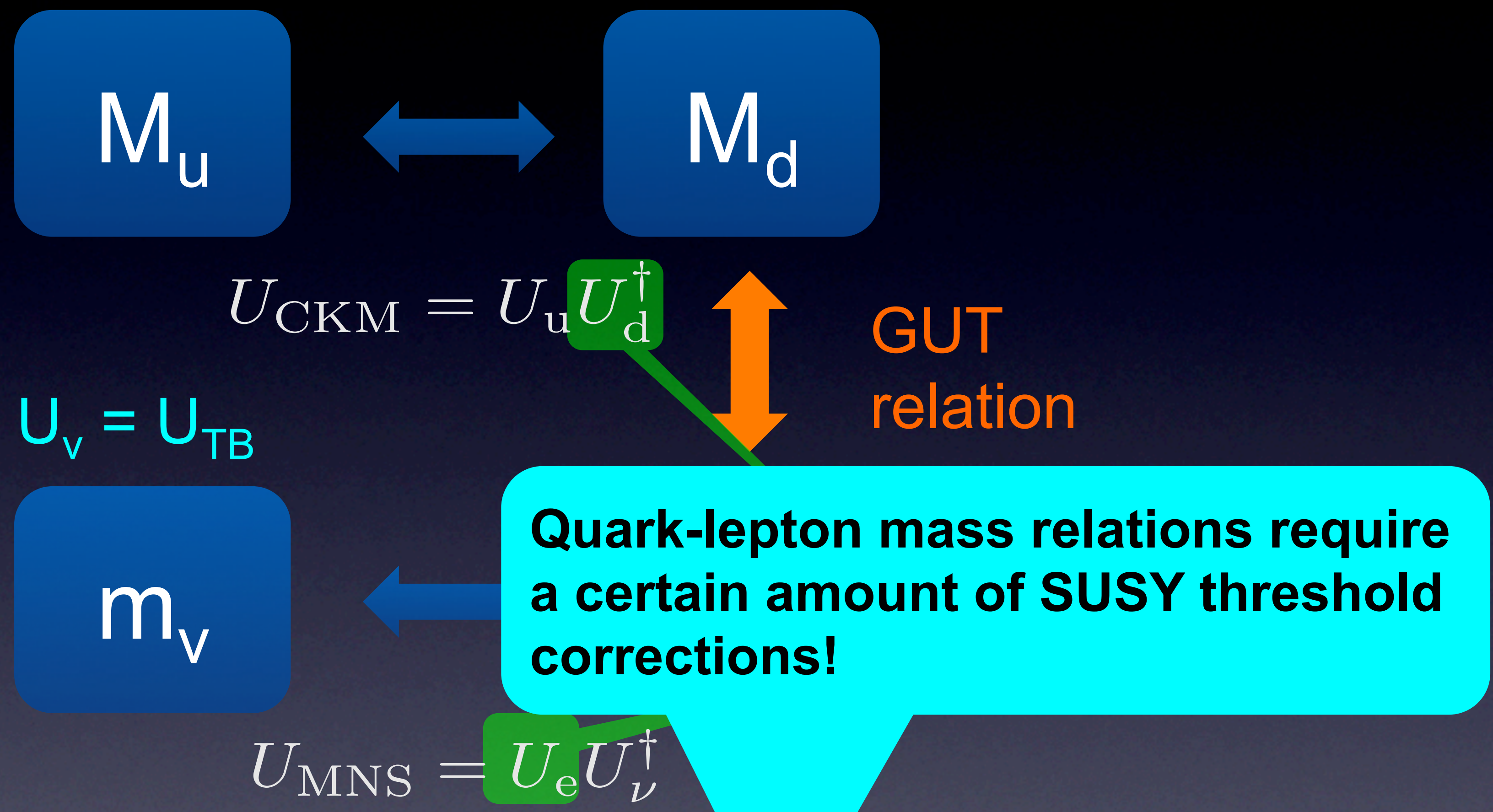


Dirac CP phases δ^{MNS} predicted in the range preferred by recent global fits to the experimental data!

✓ Excellent fit to the 2013 exp. data: 6 predictions, e.g.: $\theta_{13}^{PMNS} \approx s_{23}^{PMNS}\, \theta_C$, $\delta^{PMNS} \sim 270°$, ... , (plus: constraints on SUSY spectrum)

→ Overview of predictions:

S. A., C. Gross, V. Maurer, C. Sluka (arXiv:1305.6612)



✓ Excellent fit to the 2013 exp. data: 6 predictions, e.g.: $\theta_{13}^{PMNS} \approx s_{23}^{PMNS} \theta_C$, $\delta^{PMNS} \sim 270°$, ... , (plus: constraints on SUSY spectrum)

➢ 14 parameters vs 18 measurements + additional predictions (e.g. δ^{PMNS})

Simplified treatment of SUSY threshold corrections

(similar to S. A., V. Maurer; arXiv:1306.6879)

Parameters:

Parameter		Best fit value	Uncertainty
$\tilde{\epsilon}_2$	in 10^{-4}	6.83	$^{+0.10}_{-0.07}$
$\tilde{\epsilon}_3$	in 10^{-1}	2.16	± 0.04
$\tilde{\epsilon}_{ab}$	in 10^{-3}	-3.09	$^{+0.03}_{-0.04}$
θ_{ab}		1.319	$^{+0.005}_{-0.003}$
$\hat{\epsilon}_\chi$	in 10^{-2}	-1.27	$^{+0.21}_{-0.26}$
$\eta_{Q_{12}}$	in 10^{-1}	3.31	$^{+1.45}_{-3.50}$
η_{Q_3}	in 10^{-1}	1.93	$^{+0.49}_{-0.38}$
ϵ_2	in 10^{-2}	{5.27; 6.07}	{$^{+0.34}_{-0.36}$; $^{+0.17}_{-0.26}$}
ϵ_{ab}	in 10^{-2}	4.46	$^{+0.75}_{-0.19}$
ϵ_{12}	in 10^{-1}	-1.65	± 0.05
ϵ_{23}	in 10^{-2}	1.78	$^{+0.73}_{-0.22}$
y_t	in 10^{-1}	5.29	$^{+0.29}_{-0.25}$
ϵ_{N_1}	in 10^{-3}	2.91	± 0.05
ϵ_{N_2}	in 10^{-3}	3.12	± 0.06

➔

Observables:

Observable		Value at m_t		Best fit result	Uncertainty
m_u	in MeV	1.22	$^{+0.48}_{-0.40}$	1.22	$^{+0.49}_{-0.40}$
m_c	in GeV	0.59	± 0.08	0.59	± 0.08
m_t	in GeV	162.9	± 2.8	162.89	$^{+2.62}_{-2.36}$
m_d	in MeV	2.76	$^{+1.19}_{-1.14}$	2.73	$^{+0.30}_{-0.70}$
m_s	in MeV	52	± 15	51.66	$^{+5.60}_{-13.68}$
m_b	in GeV	2.75	± 0.09	2.75	± 0.09
m_e	in MeV	0.485	$\pm 1\%$	0.483	± 0.005
m_μ	in MeV	102.46	$\pm 1\%$	102.83	$^{+1.01}_{-0.98}$
m_τ	in MeV	1742	$\pm 1\%$	1741.75	$^{+17.38}_{-17.10}$
$\sin\theta_C$		0.2254	± 0.0007	0.2255	± 0.0007
$\sin\theta_{23}^{CKM}$		0.0421	± 0.0006	0.0422	± 0.0006
$\sin\theta_{13}^{CKM}$		0.0036	± 0.0001	0.0036	± 0.0001
δ^{CKM}	in °	69.2	± 3.1	65.65	$^{+1.78}_{-0.53}$
$\sin^2\theta_{12}^{PMNS}$		0.306	± 0.012	0.317	± 0.006
$\sin^2\theta_{23}^{PMNS}$		0.437	$^{+0.061}_{-0.031}$	0.387	$^{+0.017}_{-0.023}$
$\sin^2\theta_{13}^{PMNS}$		0.0231	$^{+0.0023}_{-0.0022}$	0.0269	$^{+0.0011}_{-0.0015}$
δ^{PMNS}	in °		-	268.79	$^{+1.32}_{-1.72}$
φ_2^{PMNS}	in °		-	297.34	$^{+8.66}_{-10.01}$
Δm^2_{sol}	in 10^{-5} eV^2	7.45	$^{+0.19}_{-0.16}$	7.45	$^{+0.18}_{-0.17}$
Δm^2_{atm}	in 10^{-3} eV^2	2.421	$^{+0.022}_{-0.023}$	2.421	$^{+0.022}_{-0.023}$

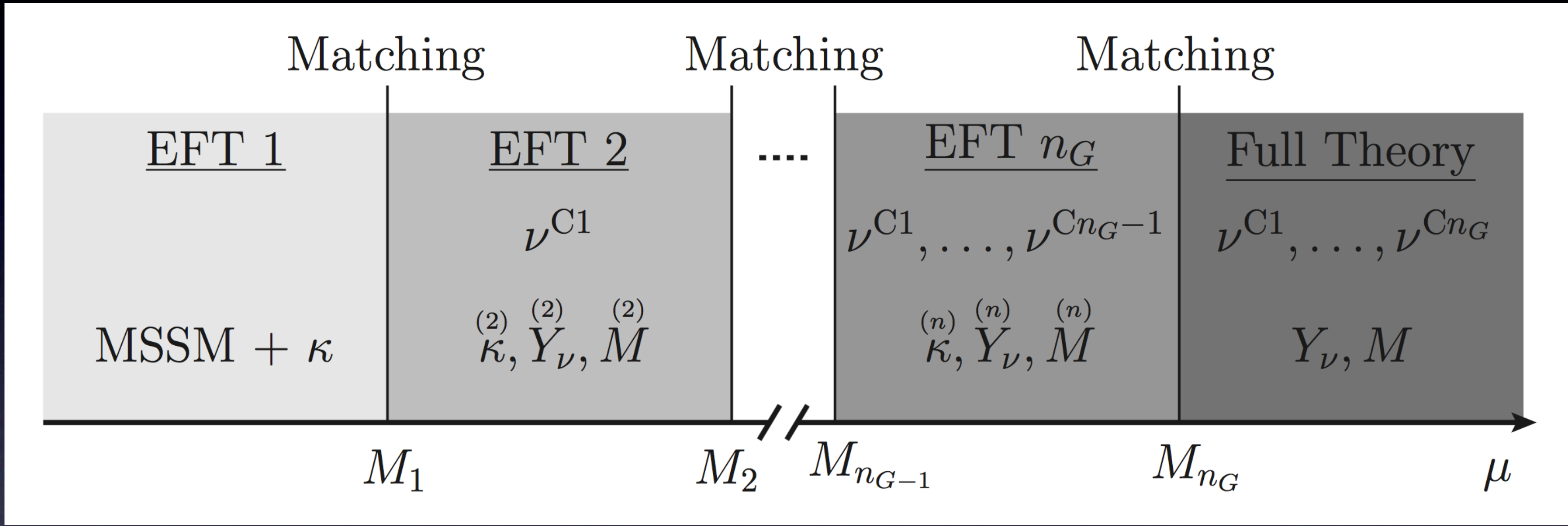
NH: S. A., C. Gross, V. Maurer, C. Sluka (arXiv:1305.6612)

SusyTC: ***A new tool (REAP extension) for including the SUSY sector in the analysis***

S. A., C. Sluka (arXiv:1512.06727)

REAP: A Mathematica software package for RG running in seesaw scenarios

REAP: S. A., J. Kersten, M. Lindner, M. Ratz, M. A. Schmidt (hep-ph/0501272)



- RG running of all SM + seesaw parameters (Options: SUSY (2-loop) & Non-SUSY)
- Integrates out the RH neutrinos successively at their mass thresholds (@ tree-level)
- 1-loop RN ν thres. corr. (cf. S.A., E. Cazzato; arXiv:1509.05604) can be implemented
- Option for simplified treatment of SUSY threshold corrections at M_{SUSY}

New REAP extension: SusyTC

S. A., C. Sluka, arXiv:1512.06727

Features:

- Full 2-loop running of MSSM soft SUSY breaking parameters
- Automatic calculation of μ (@ 1-loop) and m_{SUSY}
- Calculation of sparticle spectrum at m_{SUSY} (@ tree-level)
- Calculation of <u>all</u> SUSY threshold corrections for quarks and charged leptons
- Automatic matching to the SM
- Allows for real and complex soft breaking parameters
- Calculates m_A (CP-odd Higgs mass) for real MSSM or m_{H+} for complex MSSM @ 1-loop (necessary input for e.g. FeynHiggs to calculate m_h)
- Checks (in simplified way) for charge and color-breaking minima and field directions which are ‘unbounded from below’
- Option for input/output in SLHA conventions (useful for linking to external codes)

Example application: GUT model constraints on CMSSM parameters

S. A., C. Sluka, arXiv:1512.06727

- We consider predictions for the quark lepton mass ratios as in the example flavour GUT model (after diagonalization), i.e. m_τ/m_b,= 3/2, $m_\mu/m_s \approx 6$, $m_e/m_d \approx ½$

Approximate, in the mass basis of Y_d and Y_e: (CKM mixing now from Y_u)

$$Y_d = \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix}, \; Y_e = \begin{pmatrix} -\frac{1}{2}y_d & 0 & 0 \\ 0 & 6y_s & 0 \\ 0 & 0 & -\frac{3}{2}y_b \end{pmatrix}, \; Y_u = \begin{pmatrix} y_{11} & y_{12} & y_{13} \\ y_{12} & y_{22} & y_{23} \\ y_{13} & y_{23} & y_{33} \end{pmatrix}$$

- We consider CMSSM boundary conditions from the soft terms at the GUT scale
- Using REAP with SusyTC 1.0, we fit the parameters to the experimental data on quark and lepton masses as well as on the mass m_h of the SM-like Higgs boson (using *FeynHiggs 2.11.2*)

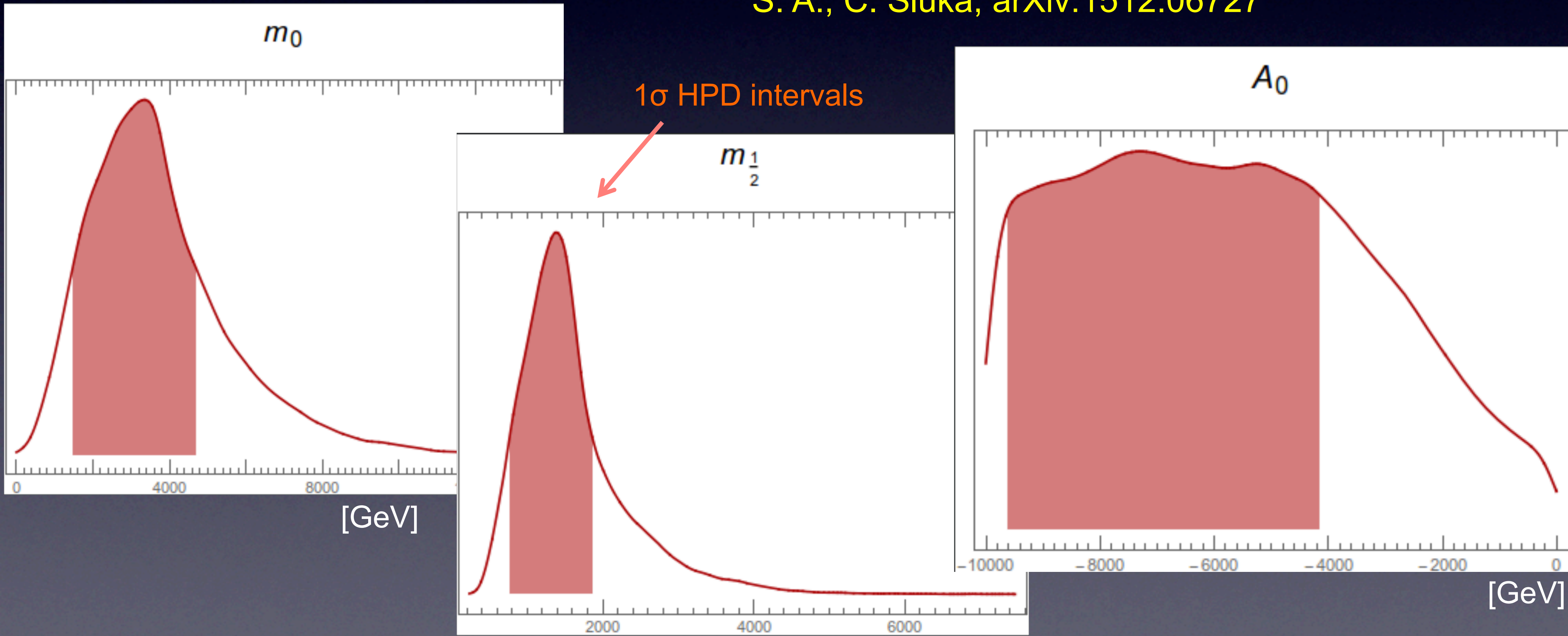
FeynHiggs: Heinemeyer, Hahn, Rzehak, Weiglein, Hollik

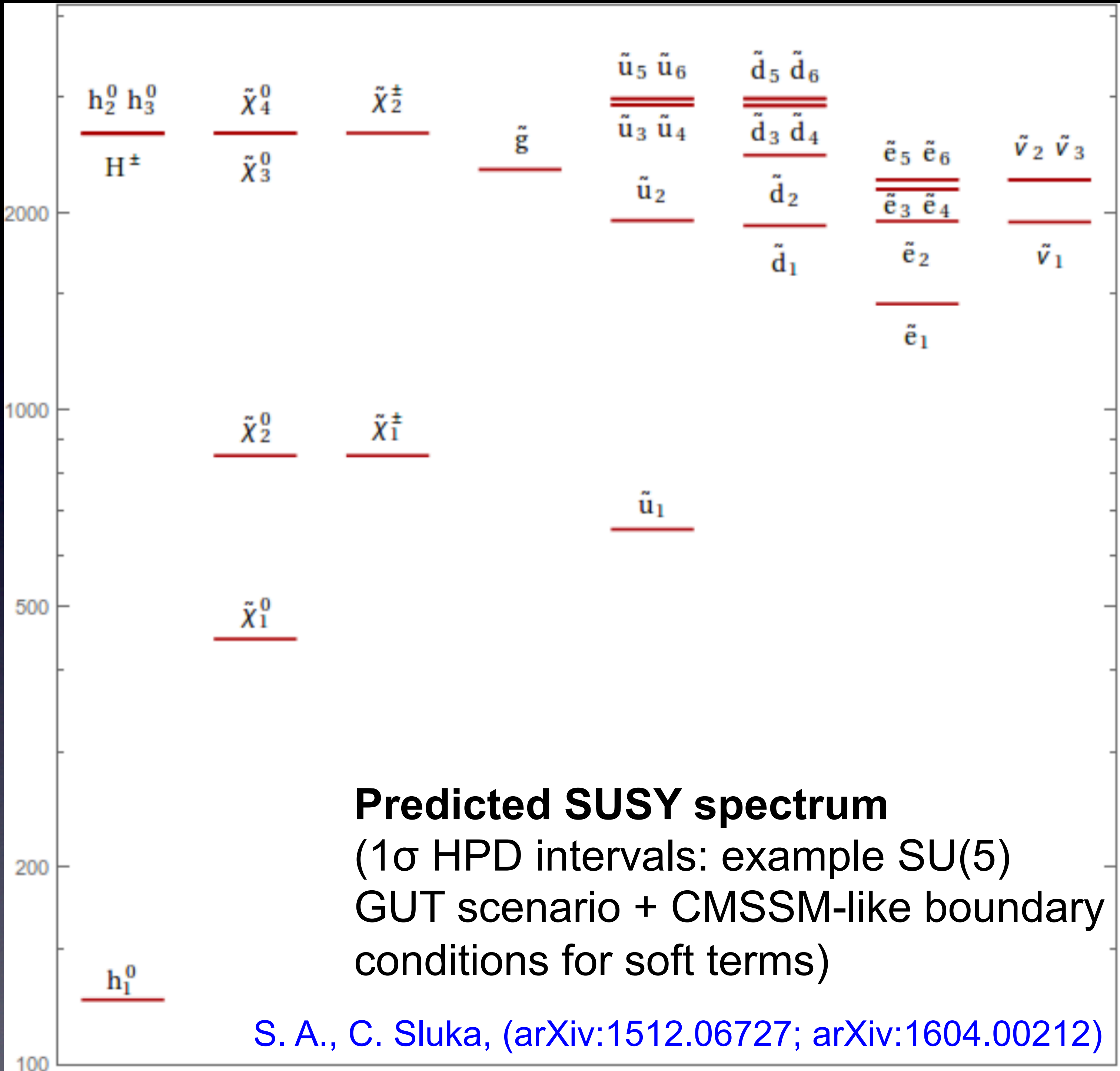
GUT model constraints on CMSSM parameters using SusyTC: MC Monte Carlo Fit

Parameter	m_0	A_0	$m_{1/2}$
Best fit value	2119 GeV	-5822 GeV	1008 GeV

Fixed tan β = 30 (optimal value), μ>0

S. A., C. Sluka, arXiv:1512.06727

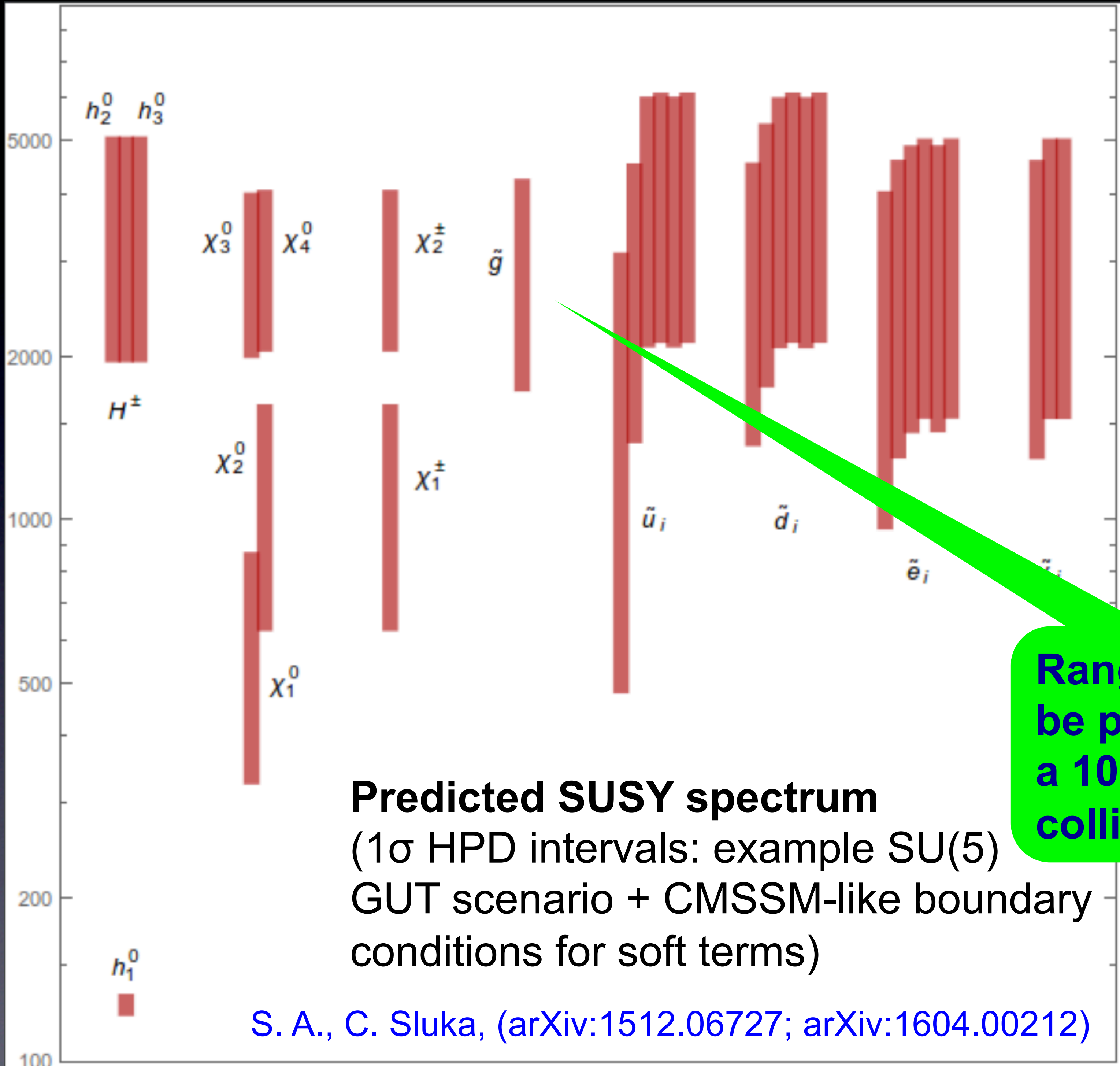




Predicted SUSY spectrum

(1σ HPD intervals: example SU(5) GUT scenario + CMSSM-like boundary conditions for soft terms)

S. A., C. Sluka, (arXiv:1512.06727; arXiv:1604.00212)



Predicted SUSY spectrum
(1σ HPD intervals: example SU(5) GUT scenario + CMSSM-like boundary conditions for soft terms)

S. A., C. Sluka, (arXiv:1512.06727; arXiv:1604.00212)

Range can be probed at a 100 TeV pp collider

General argument: SUSY spectra from predictive GUTs

- GUT predictions for quark-lepton mass ratios require some amount of SUSY loop threshold corrections for each generation.

  This implies that SUSY spectrum cannot be "too split". More specifically, the ratios of trilinear couplings, gaugino masses, μ and sfermion masses get constrained. Also tan β cannot be too small.

  In a CMSSM-like scenario ➔ ratios between m_0, $m_{1/2}$ and A_0 are constrained

- With the above-described constraints, obtaining the measured value of the mass m_h of the SM-like Higgs fixes the overall SUSY scale!

  The combination of the two effects can result in a predicted sparticle spectrum from GUT models!

S. A., C. Sluka, (arXiv:1512.06727; 1604.00212)

From GUT-flavour perspective: No surprise SUSY was not found yet - “climb up” some more in energy to see SUSY …

Thanks for your attention!