Predicting the SUSY spectrum with the REAP extension SusyTC

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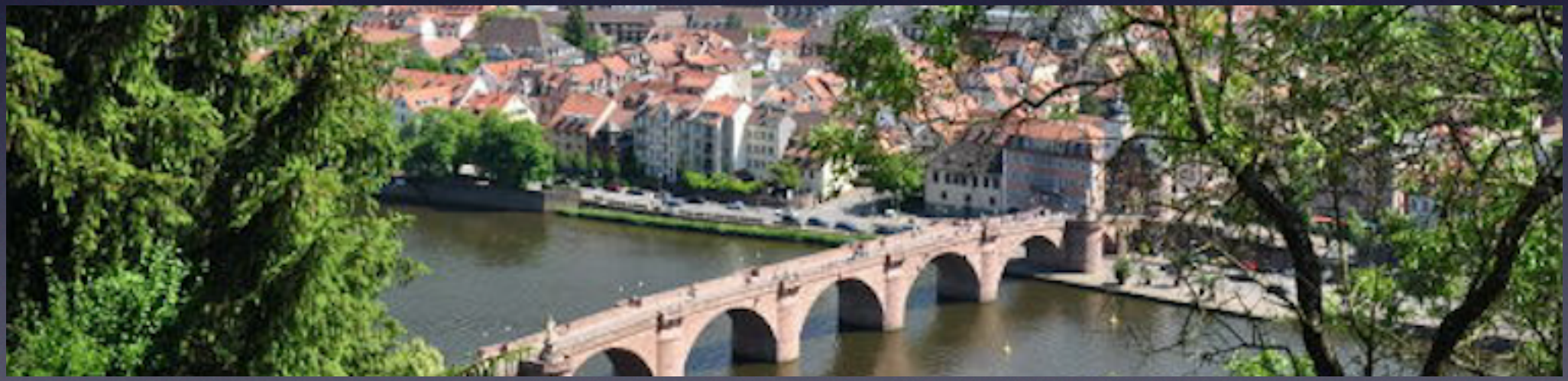


Launch17 & Manfred‘s 60th Birthday, MPIK Heidelberg 15.9.2017

Going back to year 2001 ...

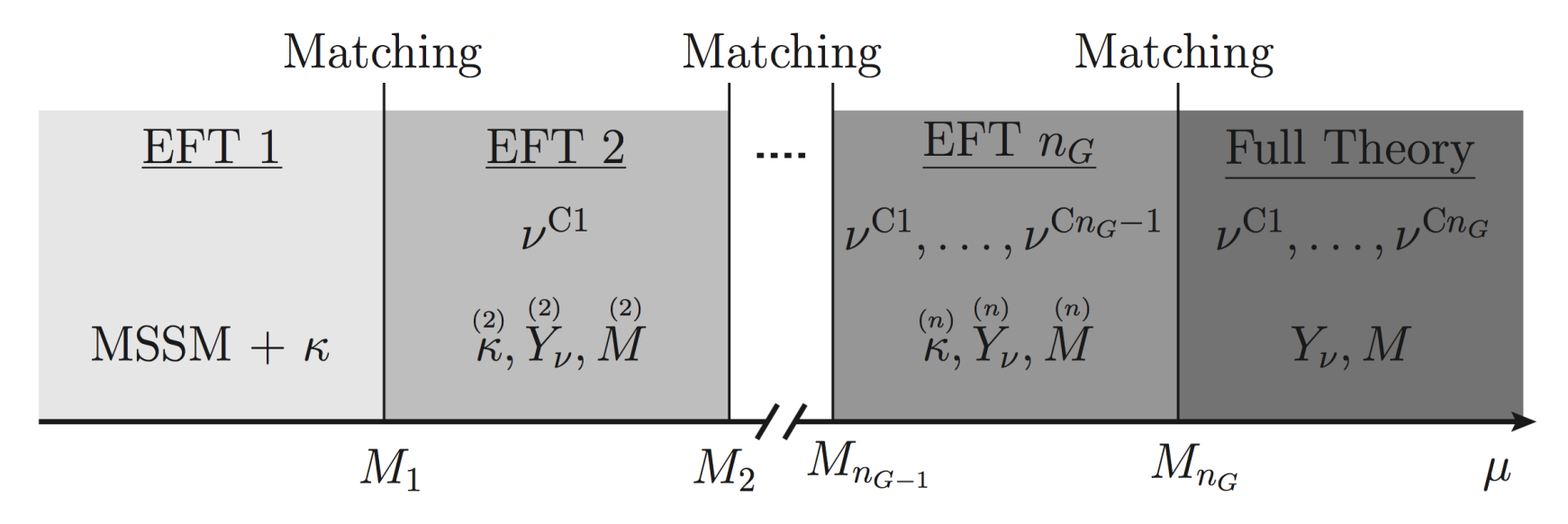
... we had a great time discussing various fascinating physics questions!

One of them was:

Towards answering this question, we calculated the required RGEs ... and, together with Manfred, Jörn Kersten, Michael Ratz and Michael Schmidt, we released the software tool REAP!

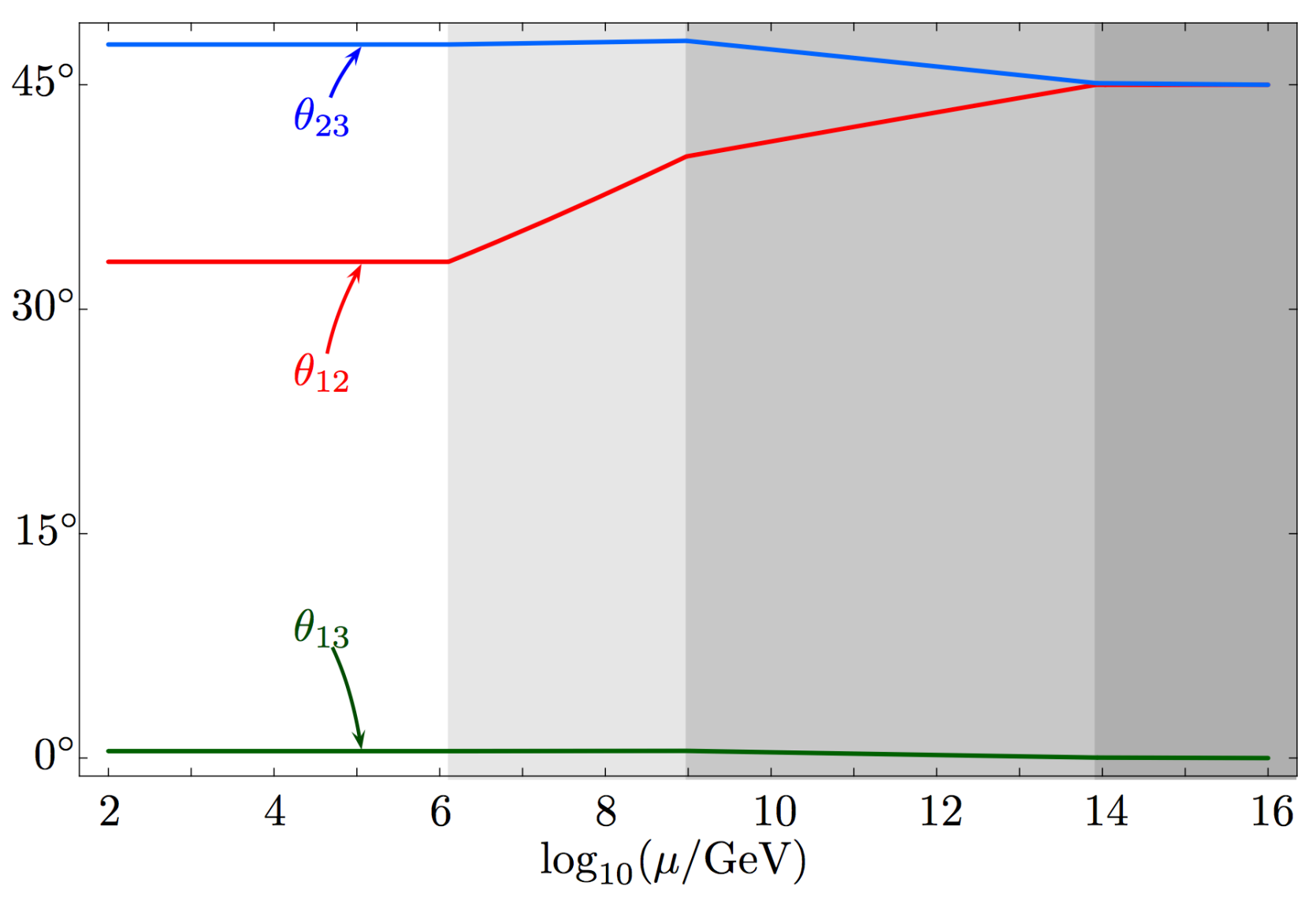
REAP: A Mathematica software package for RG running in seesaw scenarios

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



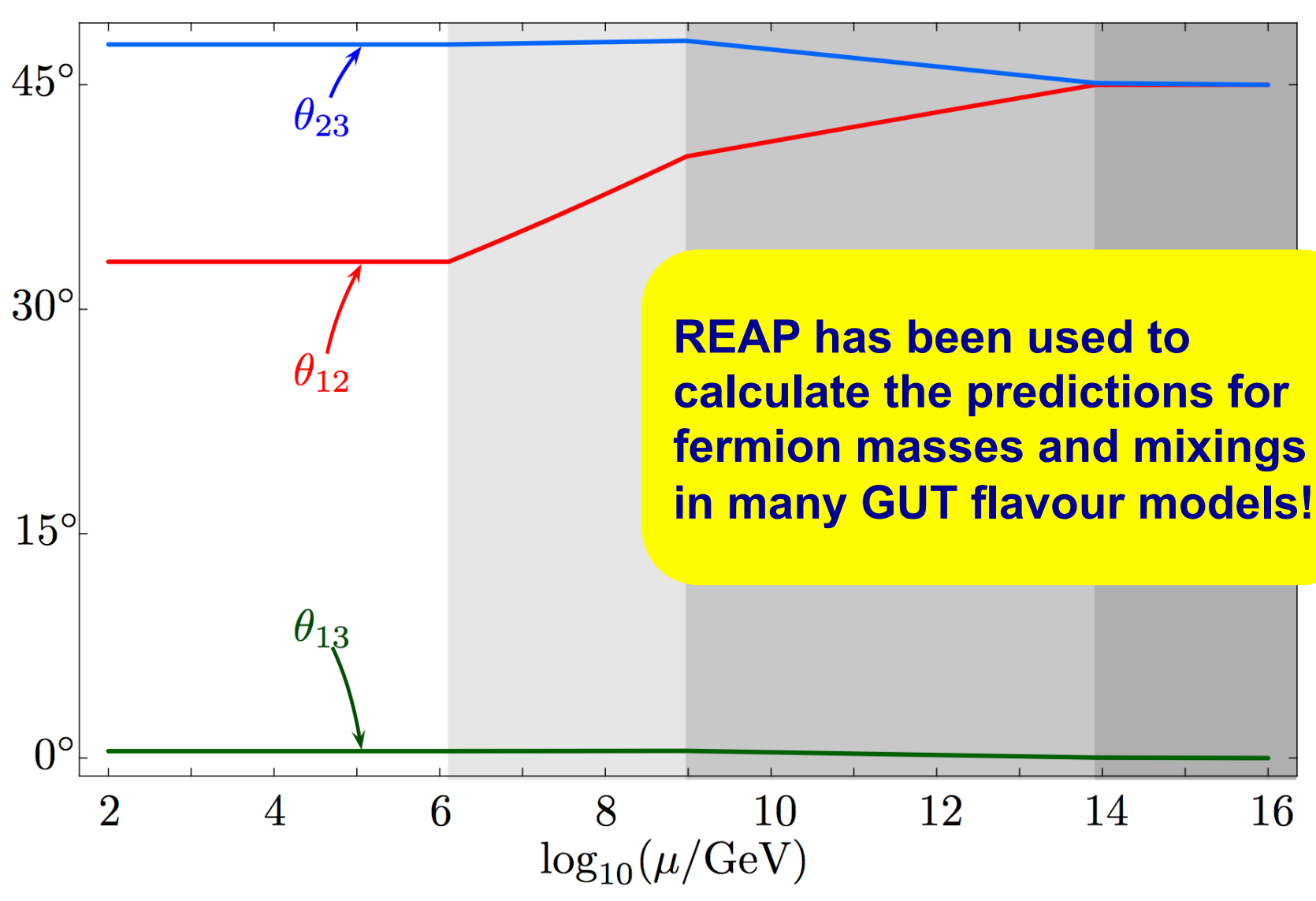
- RG running of all SM + seesaw parameters (Options: SUSY (2-loop) & Non-SUSY)
- Integrates out the RH neutrinos successively at their mass thresholds (@ tree-level)
- 1-loop RN v thres. corr. (cf. S.A., E. Cazzato; arXiv:1509.05604) can be implemented
- Option for simplified treatment of SUSY threshold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

Example: Large effects in running of neutrino mixing angles (from 2005)



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

Example: Large effects in the running of the lepton mixing angles (from 2005)



REAP has been used to calculate the predictions for fermion masses and mixings in many GUT flavour models!

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

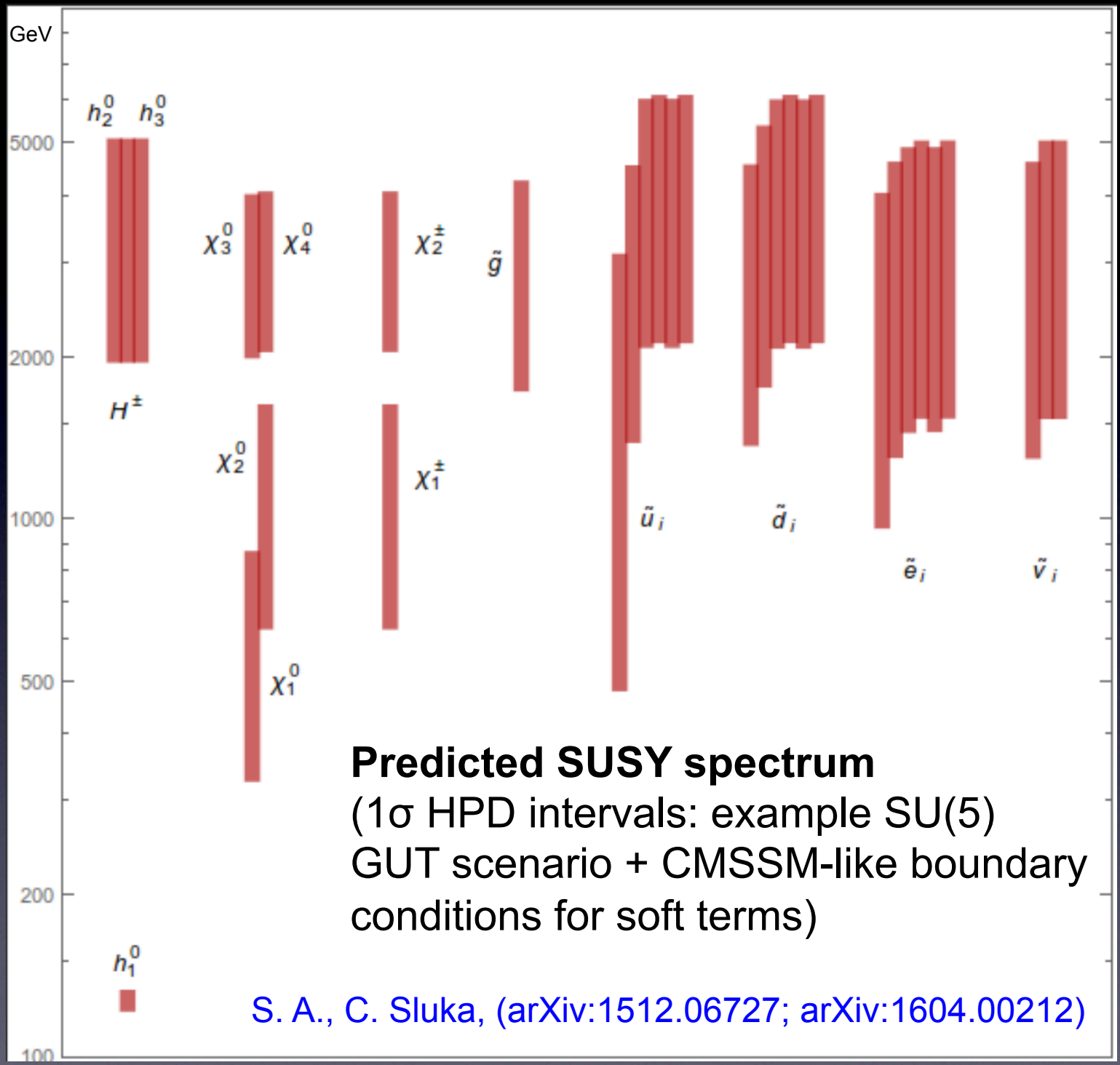
In addition to predictions for fermion masses and mixings we found recently that:

SUSY GUT flavour models can be so predictive that also the (allowed ranges for the) masses of the SUSY particles are predicted!

… and we released the REAP extension SusyTC, which allows to calculate the predictions of your favourite GUT model for the SUSY spectrum!

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

Teaser:

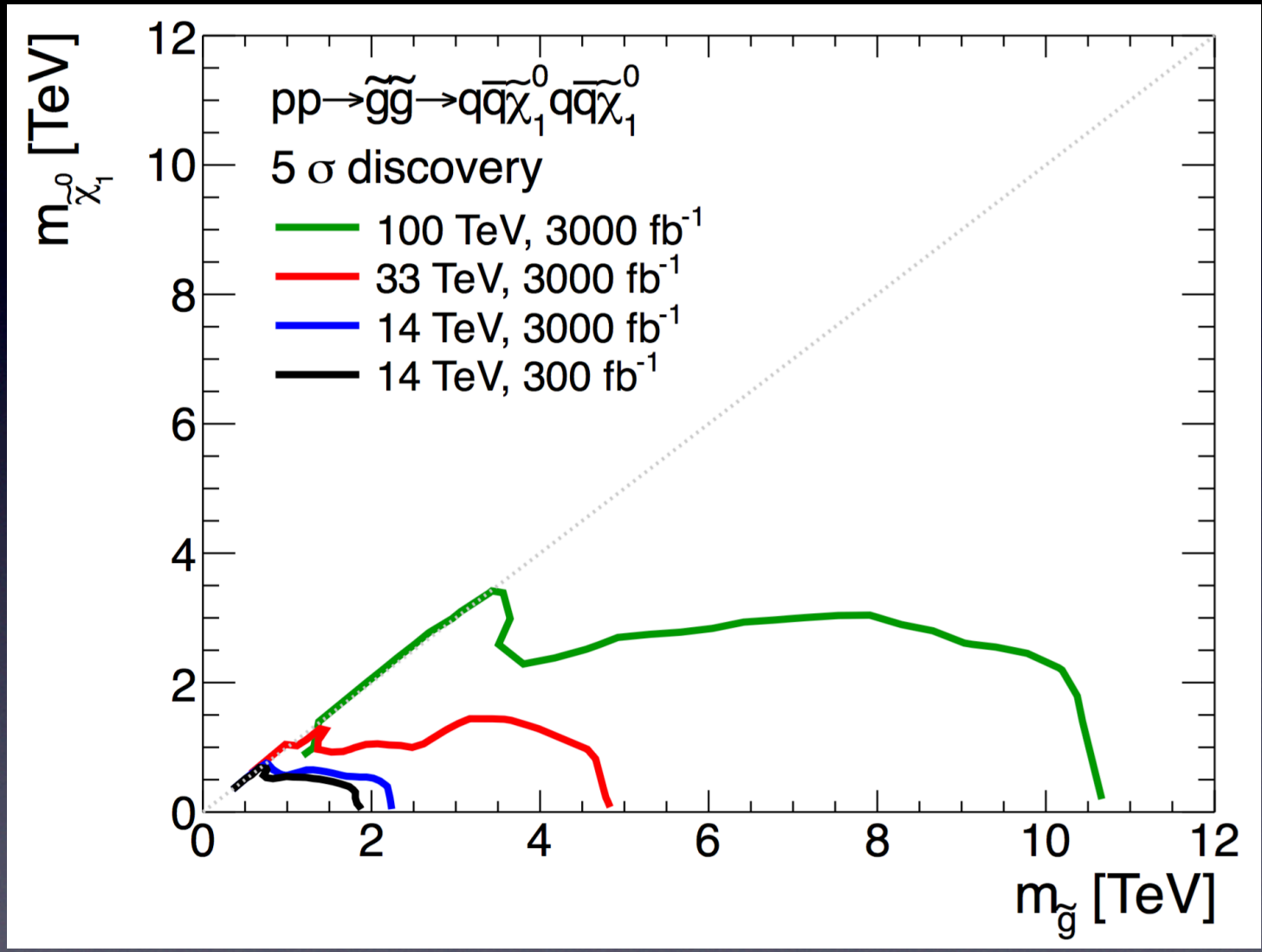


Predicted SUSY spectrum
(1σ HPD intervals: example SU(5) GUT scenario + CMSSM-like boundary conditions for soft terms)

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

Note: No LHC bounds from SUSY searches used here, pure GUT scenario prediction!

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

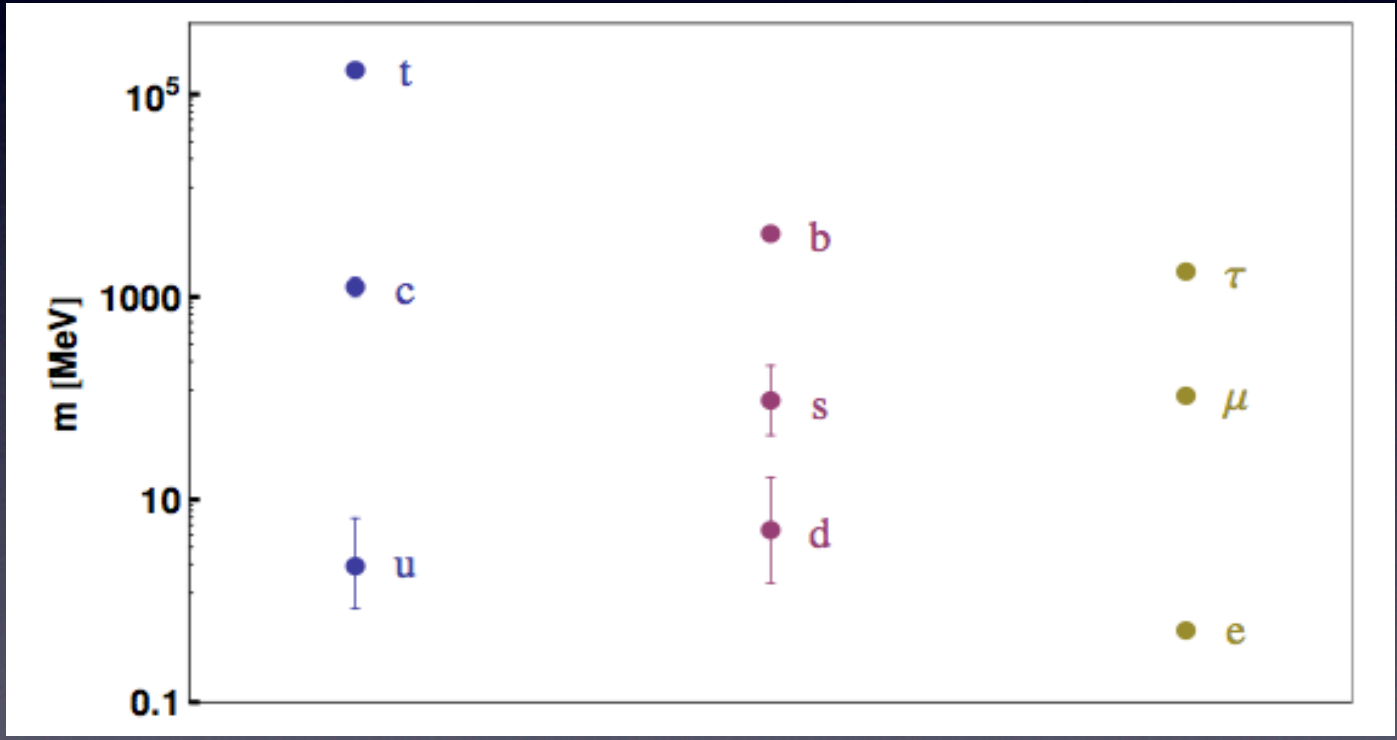


Plot from: Cohen, Golling, Hance, Henrichs, Howe, Loyal, Padhi, Wacker (arXiv:1311.6480)

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 ...)

Which GUT scale predictions are compatible with the experimental data?

- Procedure: RG running between high and low energies

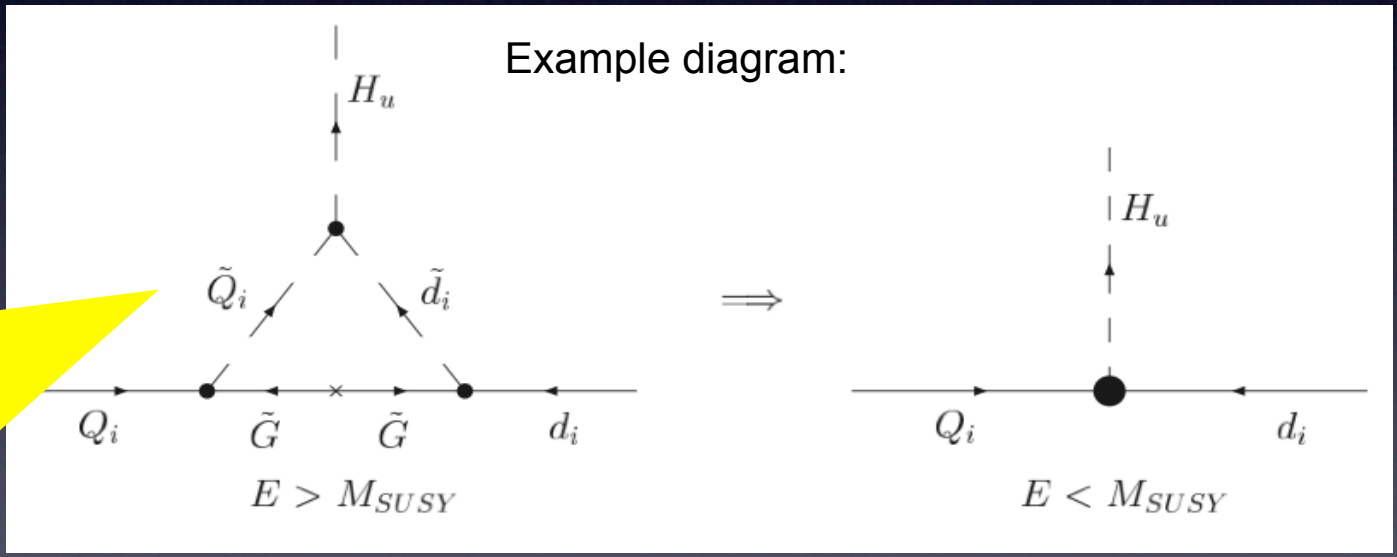
Running masses at $\mu = M_Z$:
S. A., Maurer, (arXiv:1306.6879)

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)

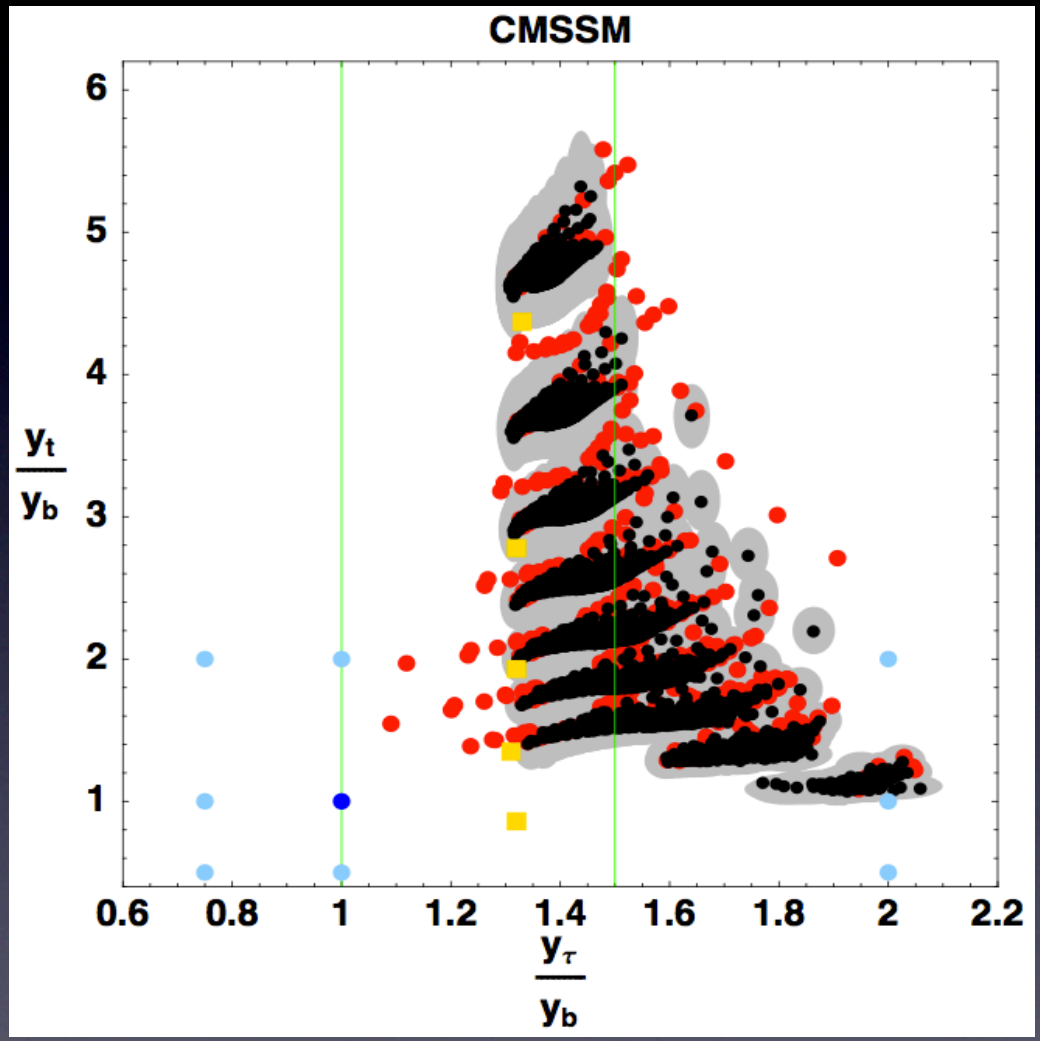
Example diagram:



SUSY threshold effects at M_{SUSY} depend on the SUSY parameters, 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

SU(5) GUT predictions for mass ratios (3rd family)

- Example: b-tau unification (from fundamental GUT operator)

  → 3rd family masses from

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

"b-τ unification"

Georgi, Jarlskog ('79)

- New GUT predictions from effective operators, for example:

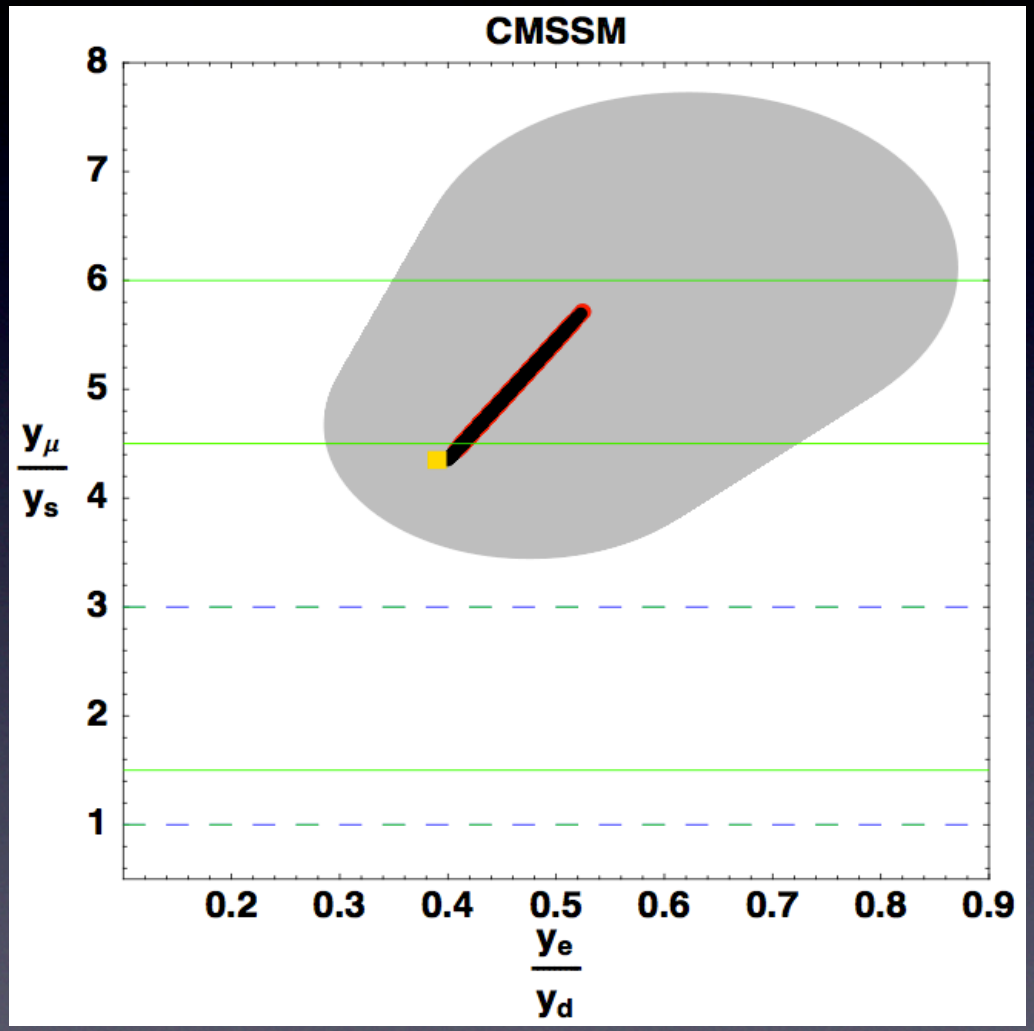
  → For the 3rd family relation m_τ / m_b :

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

S. A., Spinrath (arXiv:0902.4644)

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

S. A., Spinrath (arXiv:0902.4644)



Colours:

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- Yellow: no threshold effects
- Grey: exp. uncertainty

SU(5) GUT predictions for mass ratios (2nd family)

- Often used in GUT models: Clebsch factor 3 for the 2nd family

  → 2nd family masses from

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

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

Georgi, Jarlskog ('79)

- New GUT predictions from effective operators, for example:

  → For the 2nd family relation m_μ / m_s:

S. A., Spinrath (arXiv:0902.4644)

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

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

Main point: The SUSY 1-loop threshold corrections link the GUT mass ratio predictions to the SUSY spectrum ···

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

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

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 all 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)

Toy example application:

Predicted SUSY spectrum from GUT mass ratio predictions

Example: SUSY spectrum prediction from GUT scenario with $m_\tau/m_b = 3/2$, $m_\mu/m_s = 6$, $m_e/m_d = ½$

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

- We consider GUT mass ratio predictions as e.g. in arXiv:1305.6612 (after diagonalization), i.e. Yukawa matrices at M_{GUT} of the form:

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

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

- In addition, we consider CMSSM boundary conditions (m_0, $m_{1/2}$, A_0, tan β) for the soft SUSY breaking 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*)

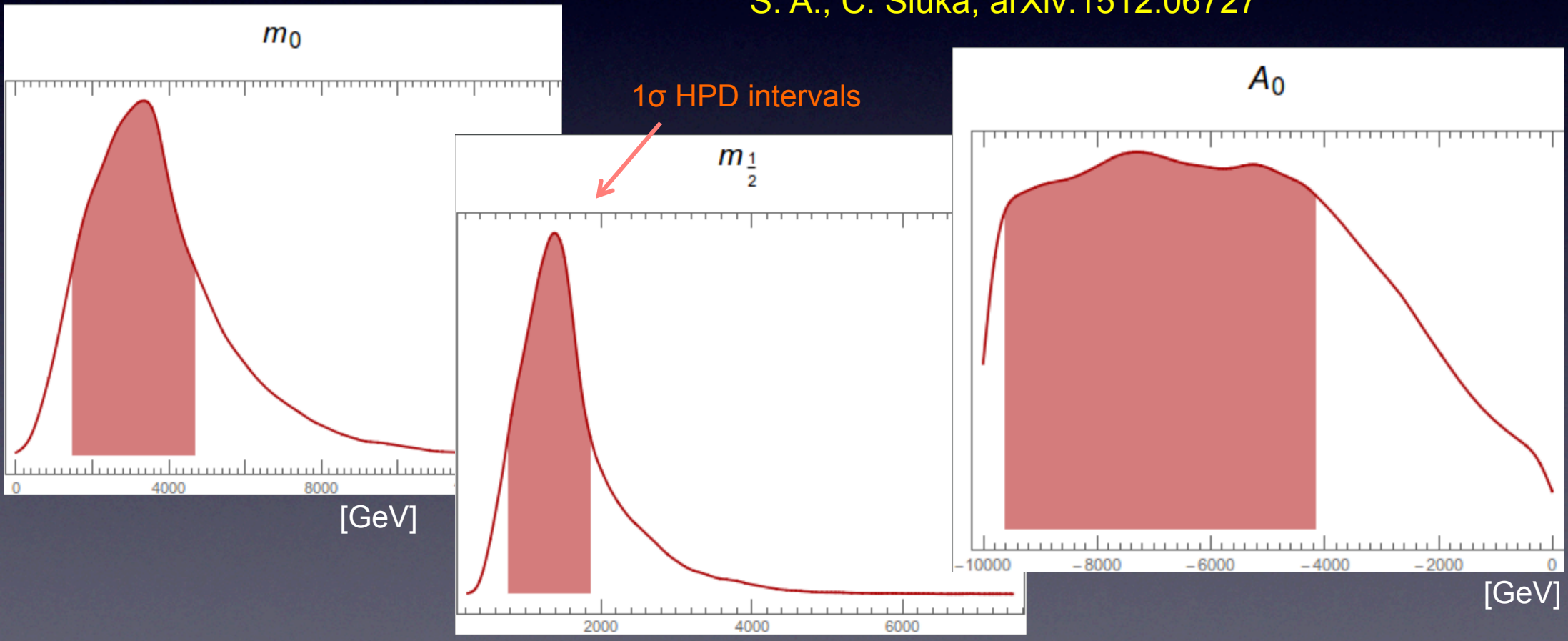
FeynHiggs: Heinemeyer, Hahn, Rzehak, Weiglein, Hollik

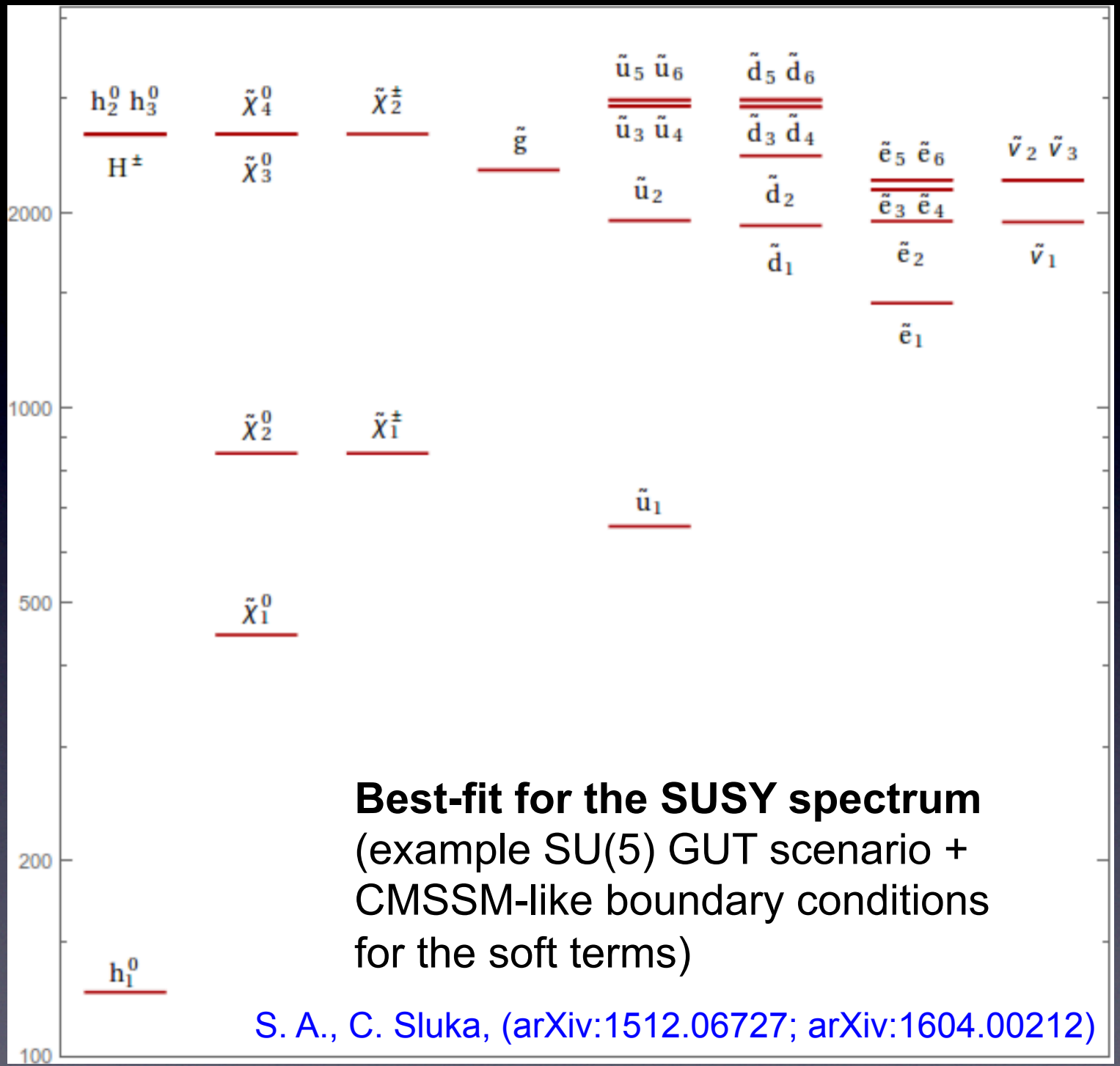
GUT model constraints on CMSSM parameters using SusyTC: MC Monte Carlo Fit

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

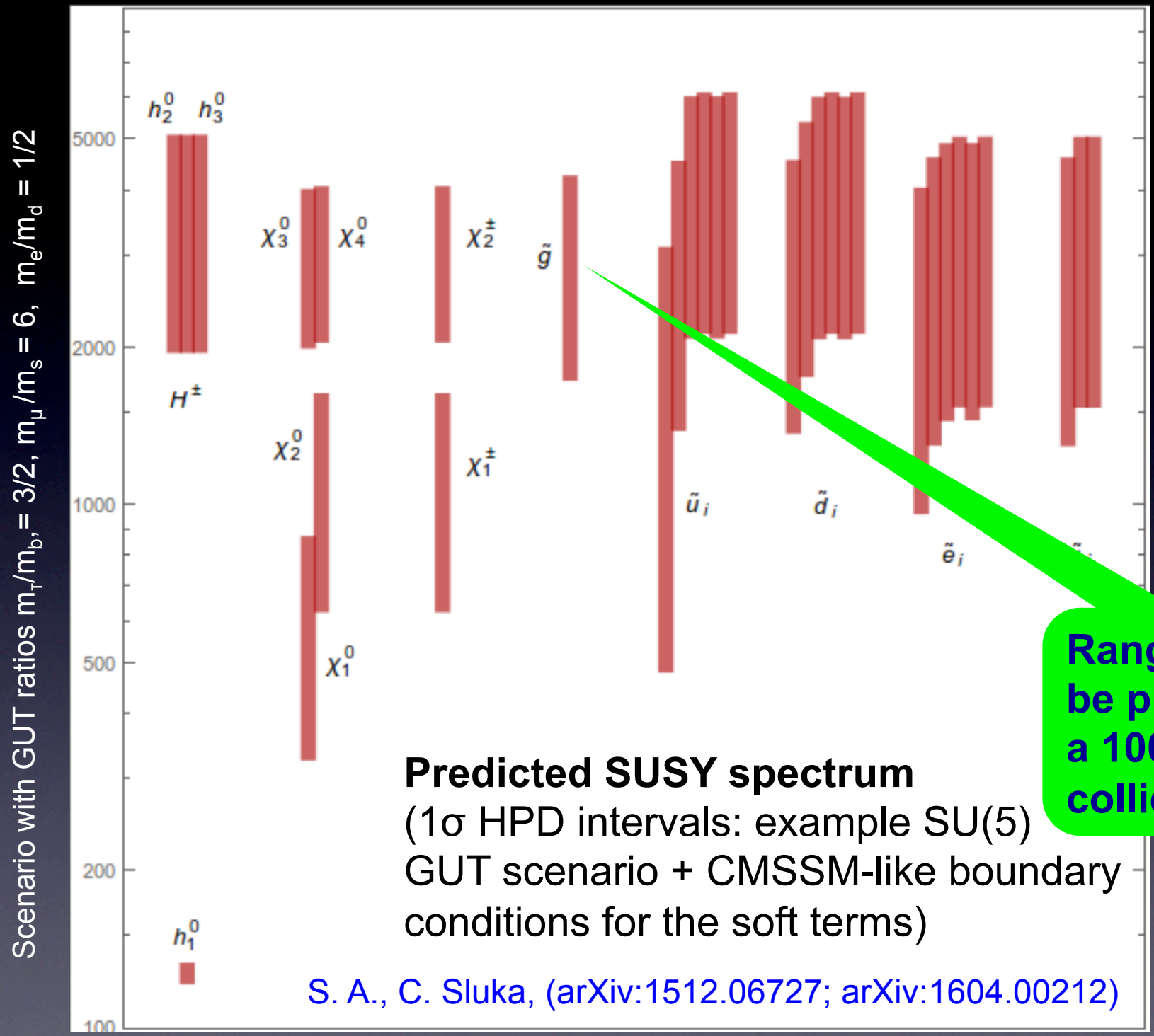
S. A., C. Sluka, arXiv:1512.06727





Best-fit for the SUSY spectrum
(example SU(5) GUT scenario + CMSSM-like boundary conditions for the soft terms)

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

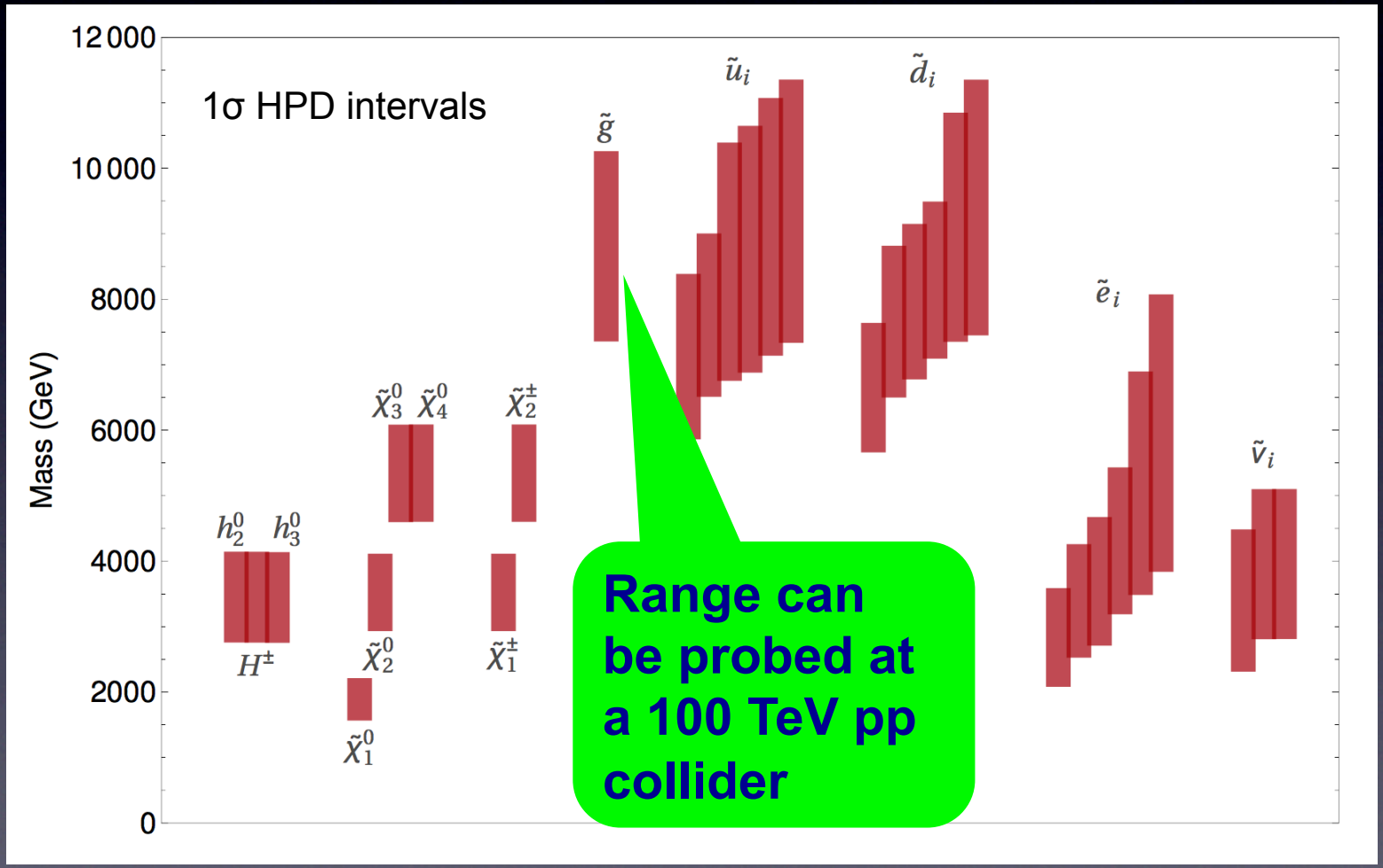

Scenario with GUT ratios m_τ/m_b,= 3/2, m_μ/m_s = 6, m_e/m_d = 1/2
5000
2000
1000
500
200
100
h_2^0 h_3^0
$H^\pm$
h_1^0
χ_3^0 χ_4^0
χ_2^0
χ_1^0
$\chi_2^\pm$
$\chi_1^\pm$
$\tilde{g}$
$\tilde{u}_i$
$\tilde{d}_i$
$\tilde{e}_i$
Predicted SUSY spectrum
(1σ HPD intervals: example SU(5) GUT scenario + CMSSM-like boundary conditions for the soft terms)
S. A., C. Sluka, (arXiv:1512.06727; arXiv:1604.00212)
Range can be probed at a 100 TeV pp collider

Note: In my talk I have shown the predicted spectrum from a toy model. For the predicted SUSY spectrum from a worked out SUSY SU(5) flavour GUT model with SUSY breaking (and with different GUT predictions m_τ / m_b,= 1, $m_\mu / m_s = 3$, $m_e / m_d = 1/3$ for the fermion mass ratios), see: S.A., C. Hohl, arXiv:1706.04274

Predictions from a worked out SU(5)xA$_4$ SUSY GUT flavour model

- Examples: Sparticle spectrum

S.A., C. Hohl, arXiv:1706.04274

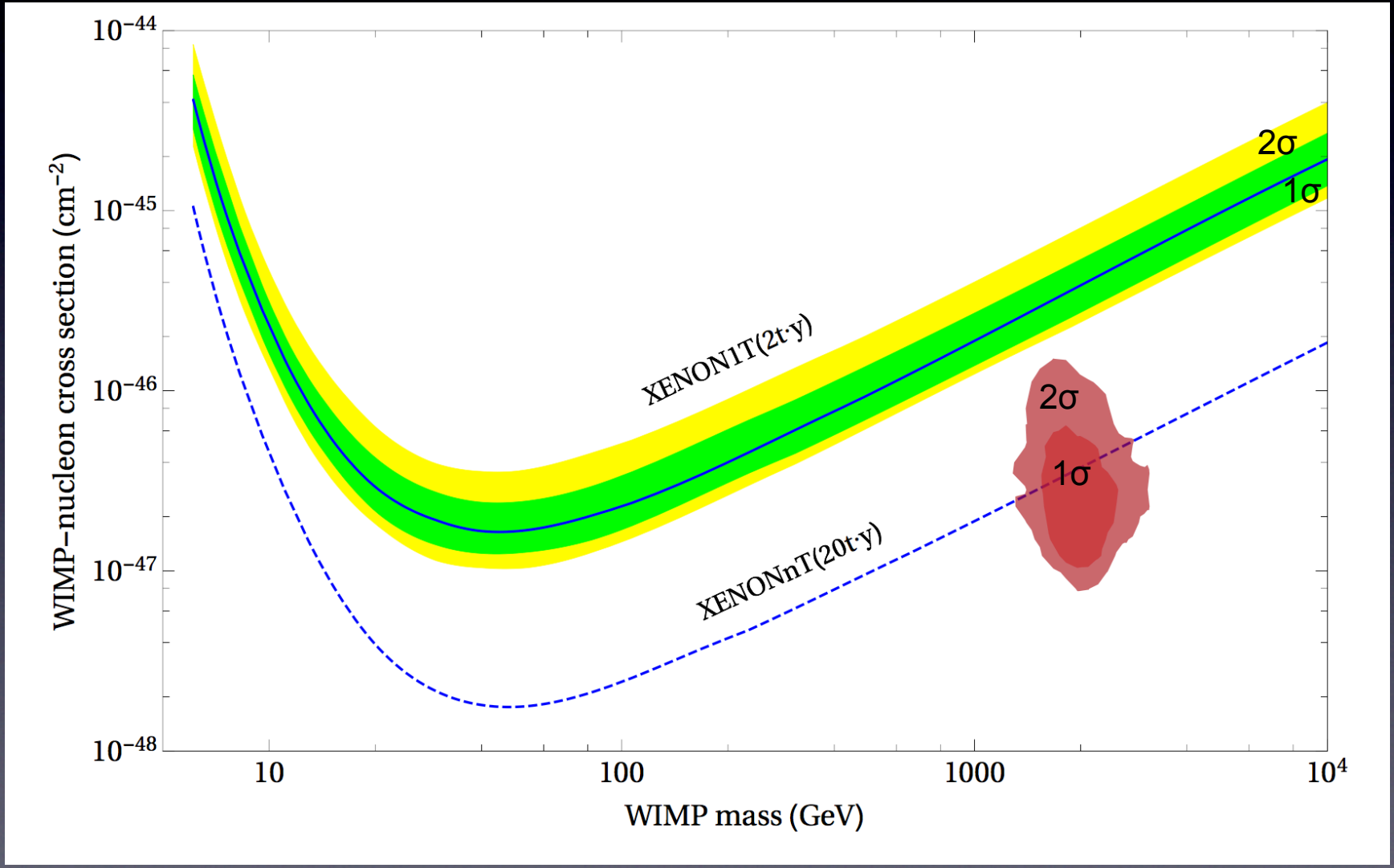


Analysis using REAP with SusyTC

Predictions from a worked out SU(5)xA_4 SUSY GUT flavour model

- Examples: WIMP DM properties

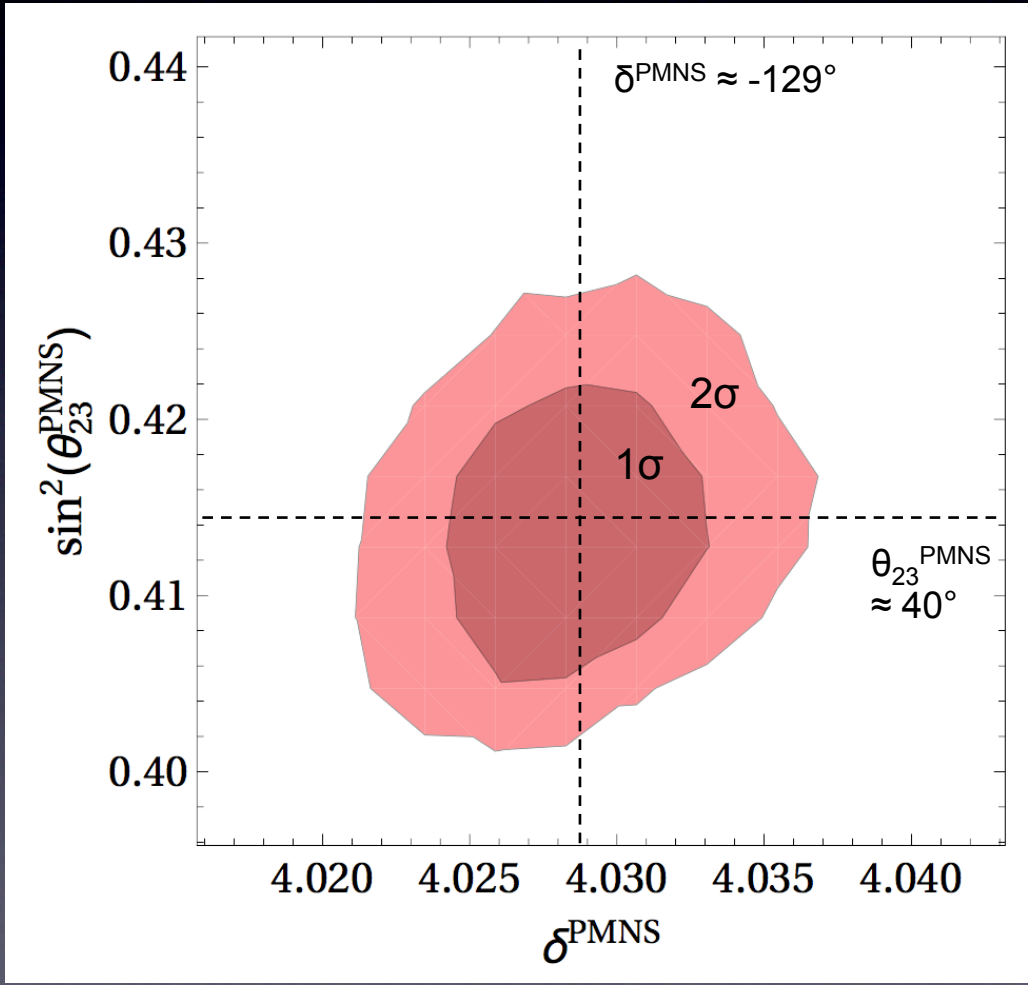
S.A., C. Hohl, arXiv:1706.04274



Predictions from a worked out SU(5)xA_4 SUSY GUT flavour model

S.A., C. Hohl, arXiv:1706.04274

- Examples: Lepton mixing θ_{23}^{PMNS} and Dirac CP phase δ^{PMNS}



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 …

Summary

- To make progress in GUT flavour model building an accurate RG running analysis, including matching and threshold corrections, is required to determine the model predictions
- REAP is an easy-to-use Mathematica software package, desigend for this purpose.
- The new REAP extension SusyTC allows to also include the SUSY sector in the analysis (including in particular the full loop SUSY threshold corrections)
- Predictive SUSY GUT flavour models can also predict the (ranges of the) masses of the SUSY particles!

Happy Birthday Manfred!

Thanks to everybody for your attention!