At which scale are the sparticle masses - a GUT model perspective

Stefan Antusch

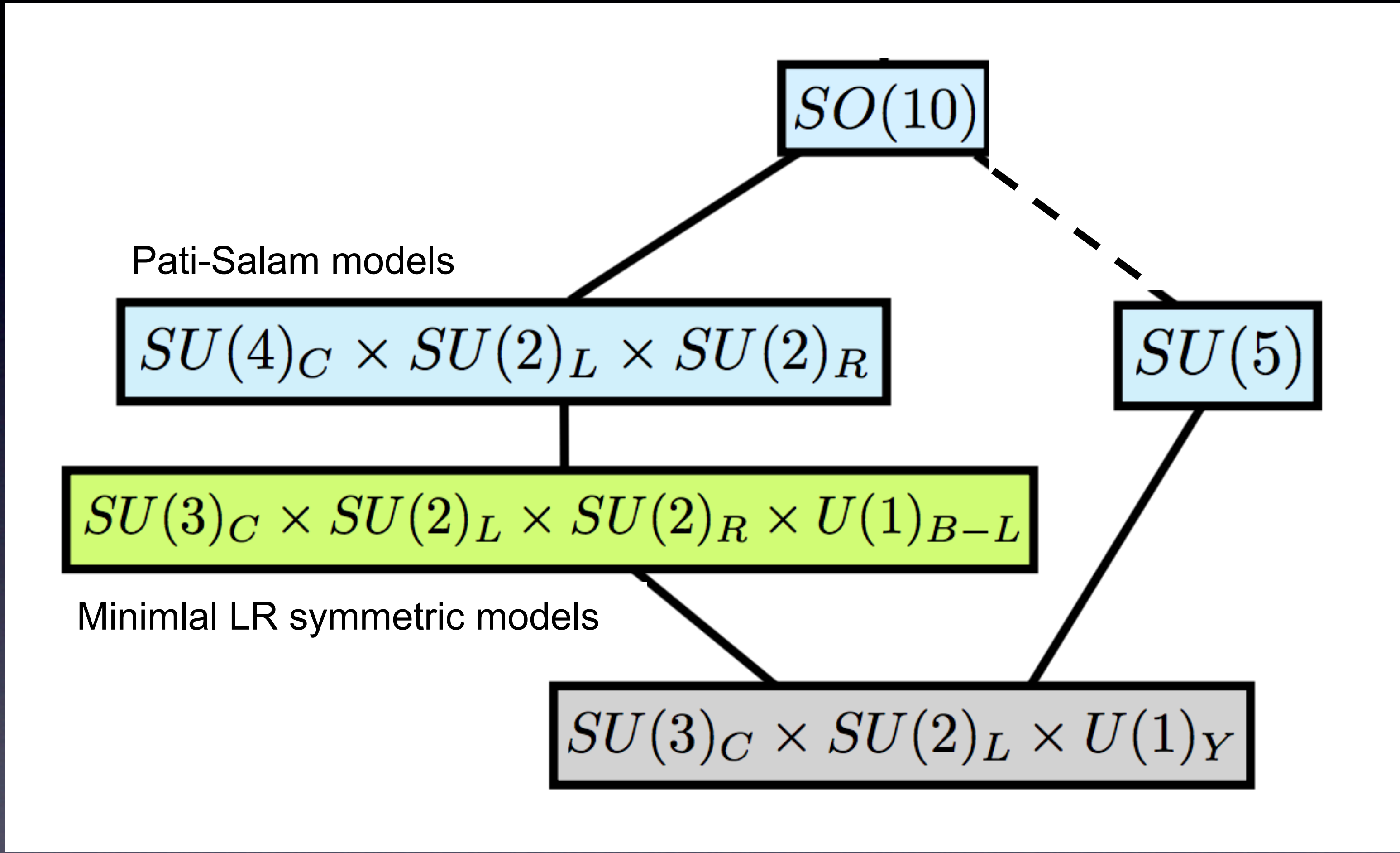
University of Basel, Department of Physics

Workshop “The Future of Particle Physics .. “,
KIT, Karlsruhe

October 2nd, 2018

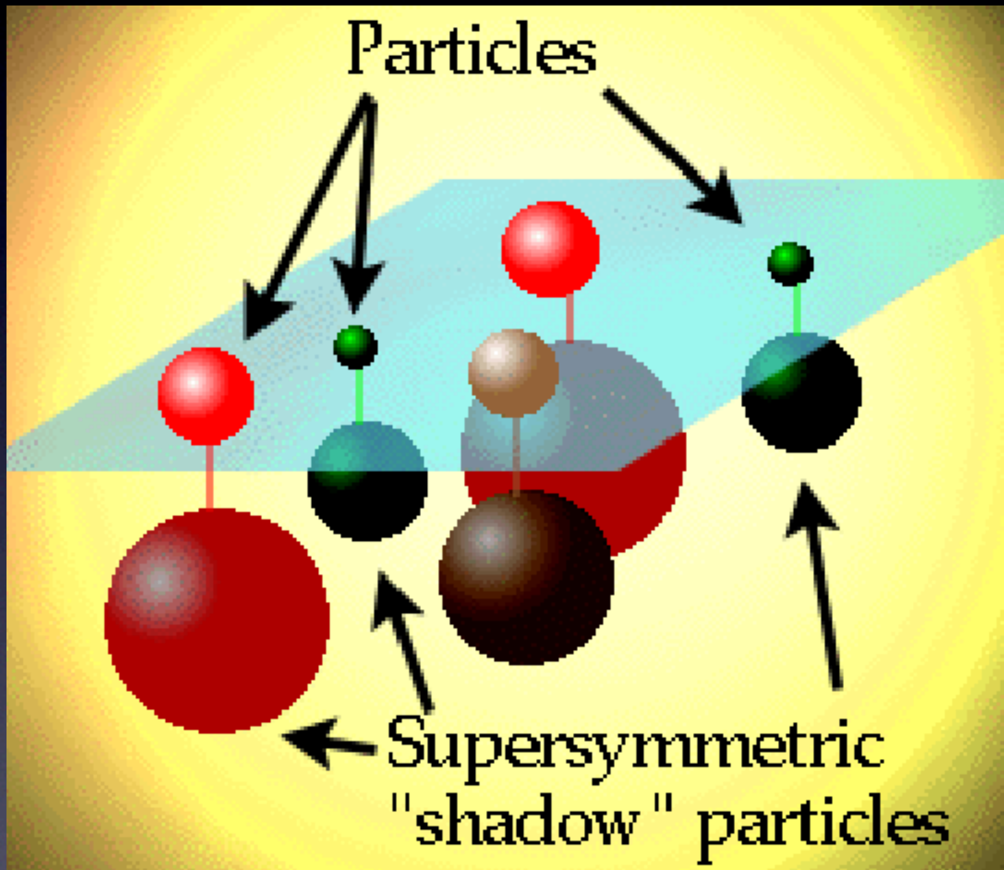
Grand Unified Theories (GUTs): Unification of forces and of matter

Attractive route towards a more fundamental particle theory ...



- **Gauge forces of the SM emerge from one unified gauge group (e.g. SO(10), SU(5))**
- **"Quark-lepton unification": quarks and leptons in joint GUT representations**

Supersymmetry: Stabilizes the hierarchy between the EW and the GUT scale



- **Also: Running gauge couplings (in GUT normalization) meet (at $M_{GUT} \sim 10^{16}$ GeV) already in simple/minimal models; DM candidate (neutralino) , …**

The Future of Particle Physics: A Quest for Guiding Principles

The motivation to build particle colliders like LEP, Tevatron, and LHC was given by the search for the Higgs boson and the hope to find Supersymmetry. In the meantime the Higgs boson was found as predicted by the SM. Lessons learned from these experiments make it clear that it is timely to consider the future of particle physics.

Unfortunately, without conclusive BSM findings from the LHC, no clear guiding principle for a future collider project exists at present. Nevertheless, three options are being discussed by the particle physics community: The Future Circular Collider study at CERN (including also the High-Energy LHC and electron-hadron collisions with the LHC [the LHeC]), the International Linear Collider in Japan, and the Circular electron positron Collider and Super proton proton Collider in China.

The scale of these projects presents a number of problems that demand a thorough, global discussion: the large amounts of resources that are necessary implies a strong competition of the projects with each other, and also with other large scale projects. There is no guarantee that major new fundamental insights into nature can be obtained, however, deciding against a new large scale experiment might bring the end of particle physics as we know it.

In this workshop, the major question of 'how to proceed in the post-LHC era in terms of experimental efforts' is to be discussed by a broad spectrum of experienced scientists, covering the subjects of future colliders as well as beam dump, neutrino oscillation, and astrophysical experiments.

[from workshop webpage]

The Future of Particle Physics: A Quest for Guiding Principles

The motivation to build particle colliders like LEP, Tevatron, and LHC was given by the search for the Higgs boson and the hope to find Supersymmetry. In the meantime the Higgs boson was found as predicted by the SM. Lessons learned from these experiments make it clear that it is timely to consider the future of particle physics.

Unfortunately, without conclusive BSM findin
collider project exists at present. Nevertheless, t
physics community: The Future Circular Collider
and electron-hadron collisions with the LHC [the
and the Circular electron positron Collider and S

Main argument that SUSY should be found quickly at LHC: "Naturalness" … otherwise "finetuning" would be too "large" (→ "Little Hierarchy Problem")

The scale of these projects presents a number of problems that demand a thorough, global discussion: the large amounts of resources that are necessary implies a strong competition of the projects with each other, and also with other large scale projects. There is no guarantee that major new fundamental insights into nature can be obtained, however, deciding against a new large scale experiment might bring the end of particle physics as we know it.

In this workshop, the major question of 'how to proceed in the post-LHC era in terms of experimental efforts' is to be discussed by a broad spectrum of experienced scientists, covering the subjects of future colliders as well as beam dump, neutrino oscillation, and astrophysical experiments.

[from workshop webpage]

The Future of Particle Physics: A Quest for Guiding Principles

The motivation to build particle colliders like LEP, Tevatron, and LHC was given by the search for the Higgs boson and the hope to find Supersymmetry. In the meantime the Higgs boson was found as predicted by the SM. Lessons learned from these experiments make it clear that it is timely to consider the future of particle physics.

Unfortunately, without conclusive BSM findin
collider project exists at present. Nevertheless, t
physics community: The Future Circular Collider
and electron-hadron collisions with the LHC [the
and the Circular electron positron Collider and S

The scale of these projects presents a number of problems that demand a thorough, global
discussion: the large amounts of resou
projects with each other, and also with
new fundamental insights into nature c
experiment might bring the end of par

In this workshop, the major question c
efforts' is to be discussed by a broad s
future colliders as well as beam dump

ge]

Main argument that SUSY should be found quickly at LHC: "Naturalness" … otherwise "finetuning" would be too "large" (→ "Little Hierarchy Problem")

<u>However:</u> There is <u>no physically meaningful measure for quantifying "finetuning"</u> (recall that all our theories are effective theories, i.e. we do not know what the truly fundamental parameters are)! Measure depends on parameterisation (e.g. "tuning" in x vs. "tuning" in y=exp(x) or …)!

The Future of Particle Physics: A Quest for Guiding Principles

The motivation to build particle colliders like LEP, Tevatron, and LHC was given by the search for the Higgs boson and the hope to find Supersymmetry. In the meantime the Higgs boson was found as predicted by the SM. Lessons learned from these experiments make it clear that it is timely to consider the future of particle physics.

Unfortunately, without conclusive BSM findin

collider project exists at present. Nevertheless,

cular Collider

he LHC [the

llider and S

a number of problems that demand a thorough, global

future colliders as well as beam dump

ge]

Main argument that SUSY should be found quickly at LHC: “Naturalness” … otherwise “finetuning” would be too “large” (→ “Little Hierarchy Problem”)

While a stabilisation mechanism for the huge hierarchy between M_{EW} and M_{GUT} is a benefit for GUT models (at least to me) some “finetuning numbers” are not an appropriate means to determine the SUSY scale …

<u>However:</u> There is <u>no physically meaningful measure for quantifying “finetuning”</u> (recall that all our theories are effective theories, i.e. we do not know what the truly fundamental parameters are)! Measure depends on parameterisation (e.g. “tuning” in x vs. “tuning” in y=exp(x) or …)!

The Future of Particle Physics: A Quest for Guiding Principles

The motivation to build particle colliders like LEP, Tevatron, and LHC was given by the search for the Higgs boson and the hope to find Supersymmetry. In the meantime the Higgs boson was found as predicted by the SM. Lessons learned from these experiments make it clear that it is timely to consider the future of particle physics.

Unfortunately, without conclusive BSM findings fro ... for a future collider project exists at present. Nevertheless, th ... article physics community: The Future Circular Collider ... nergy LHC and electron-hadron collisions with the LHC [the ... n Japan, and the Circular electron positron Collider and Su ...

The scale of these projects presents a number of ... l discussion: the large amounts of resources that a ... n of the projects with each other, and also with other large ... that major new fundamental insights into nature can be obtained, however, deciding against a new large scale experiment might bring the end of particle physics as we know it.

In this workshop, the major question of 'how to proceed in the post-LHC era in terms of experimental efforts' is to be discussed by a broad spectrum of experienced scientists, covering the subjects of future colliders as well as beam dump, neutrino oscillation, and astrophysical experiments.

This talk: GUT model perspective

→ <u>No surprise that SUSY has not been found yet …</u>

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

[from workshop webpage]

Main message:

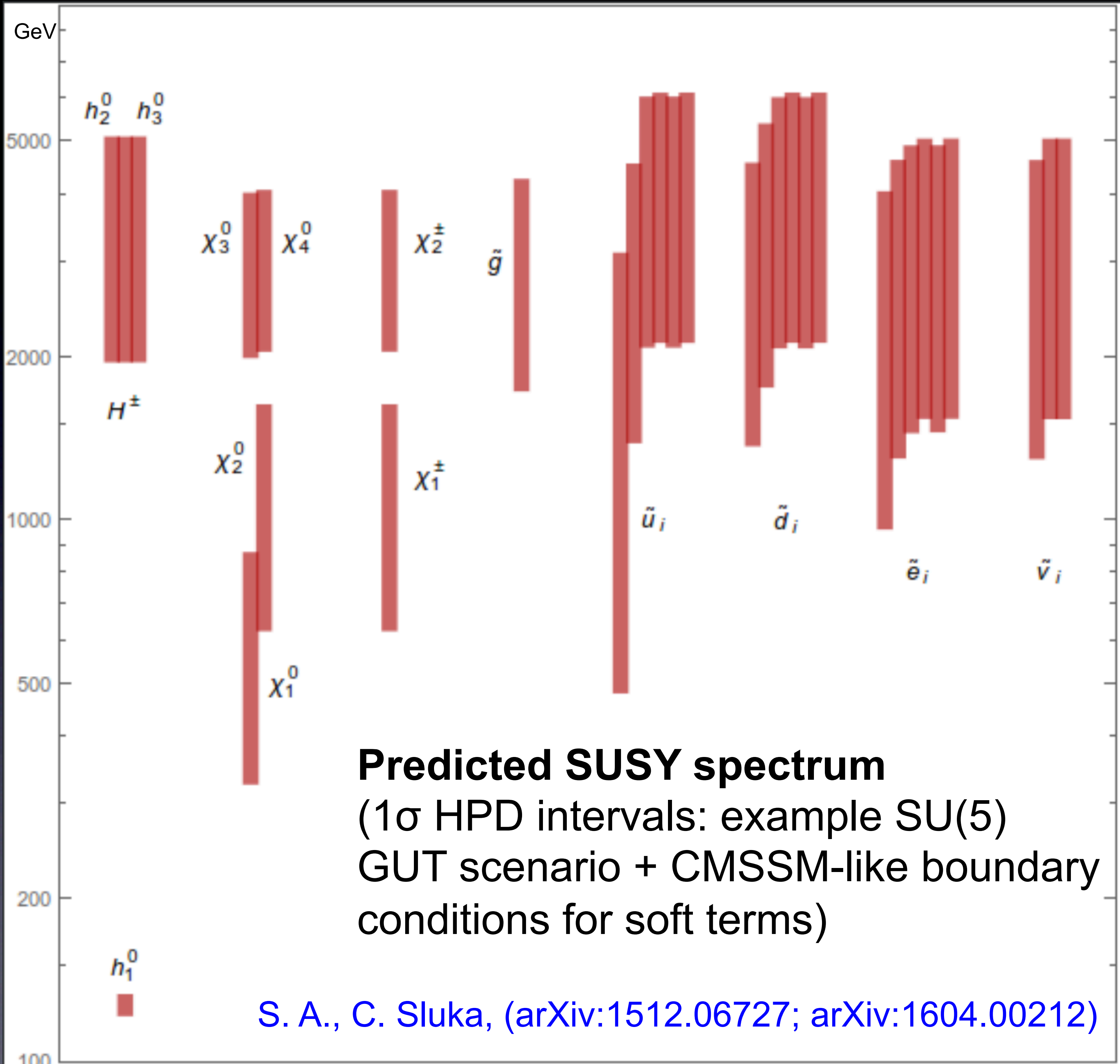
Predictive GUT models, which fix the ratios between quark and lepton Yukawa couplings (@ M_{GUT}), also imply a predicted sparticle spectrum ...

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

... and the predicted range for the sparticles is above the LHC (run 1) reach, but could be fully covered by e.g. an FCC-hh!

Teaser:

Scenario with GUT ratios $m_\tau/m_b = 3/2$, $m_\mu/m_s = 6$, $m_e/m_d = 1/2$

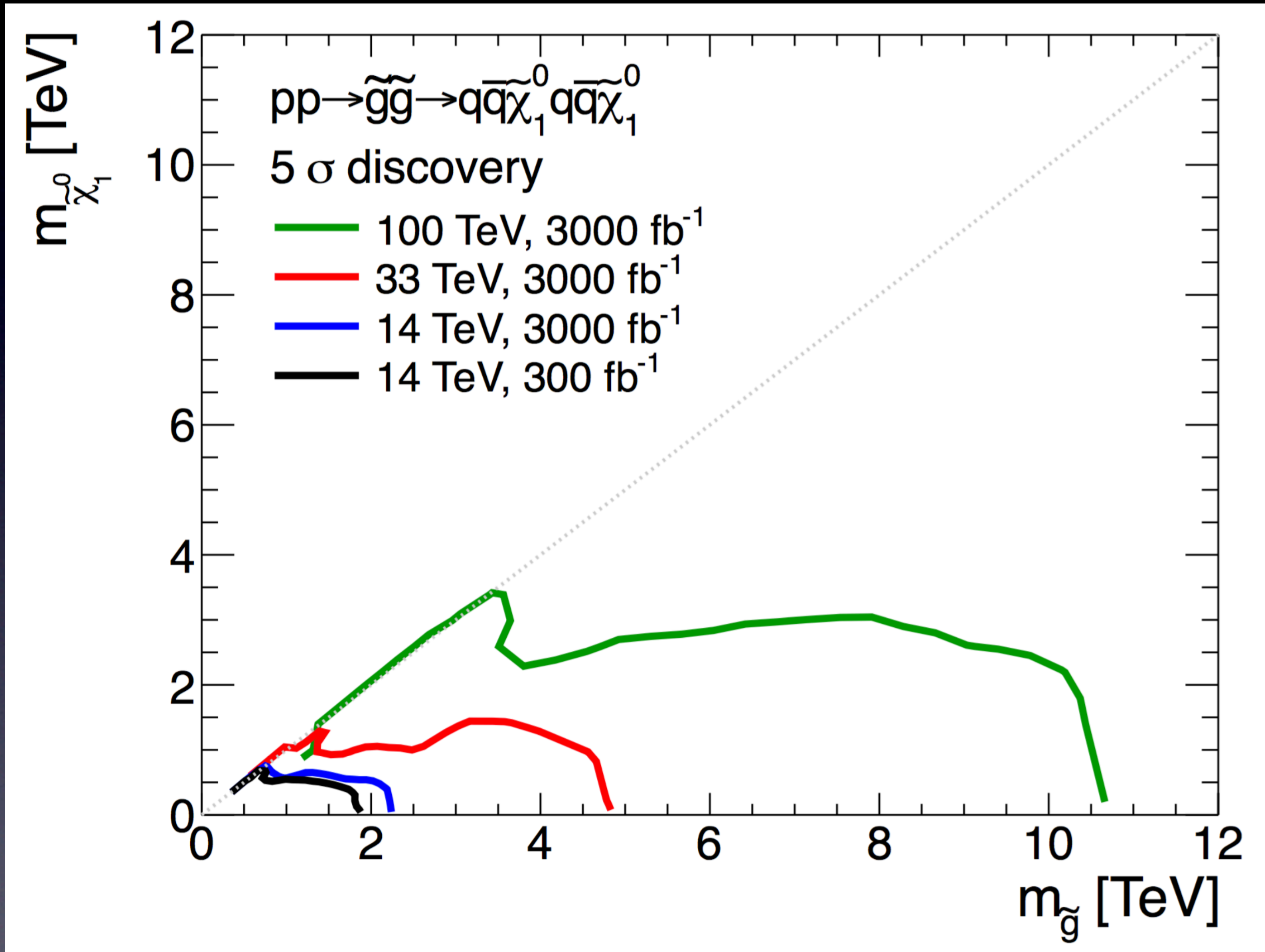


Predicted SUSY spectrum
(1σ HPD intervals: example SU(5) GUT scenario + CMSSM-like boundary conditions for soft terms)

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

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

Remark: 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)

Where is the prediction for the SUSY spectrum coming from?

→ Quark-lepton mass relations from GUTs (example: SU(5)-GUTs)

→ SUSY loop threshold corrections (link the quark-lepton mass relations to the SUSY spectrum)

SM fermions (partially) unified in SU(5) GUT representations

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

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

Consequence:

In SU(5) GUTs:
$Y_d \sim Y_e^T$

Towards SO(10) GUTs:
→ **$16_i = 10_i + \overline{5}_i + 1_i$** (RH neutrino)

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

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

  → 3rd family masses from

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

"b-τ unification"

Georgi, Jarlskog ('79)

- New GUT predictions from effective operators, for example:

  → For the 3rd family relation m_τ / m_b :

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

S. A., Spinrath (arXiv:0902.4644)

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:

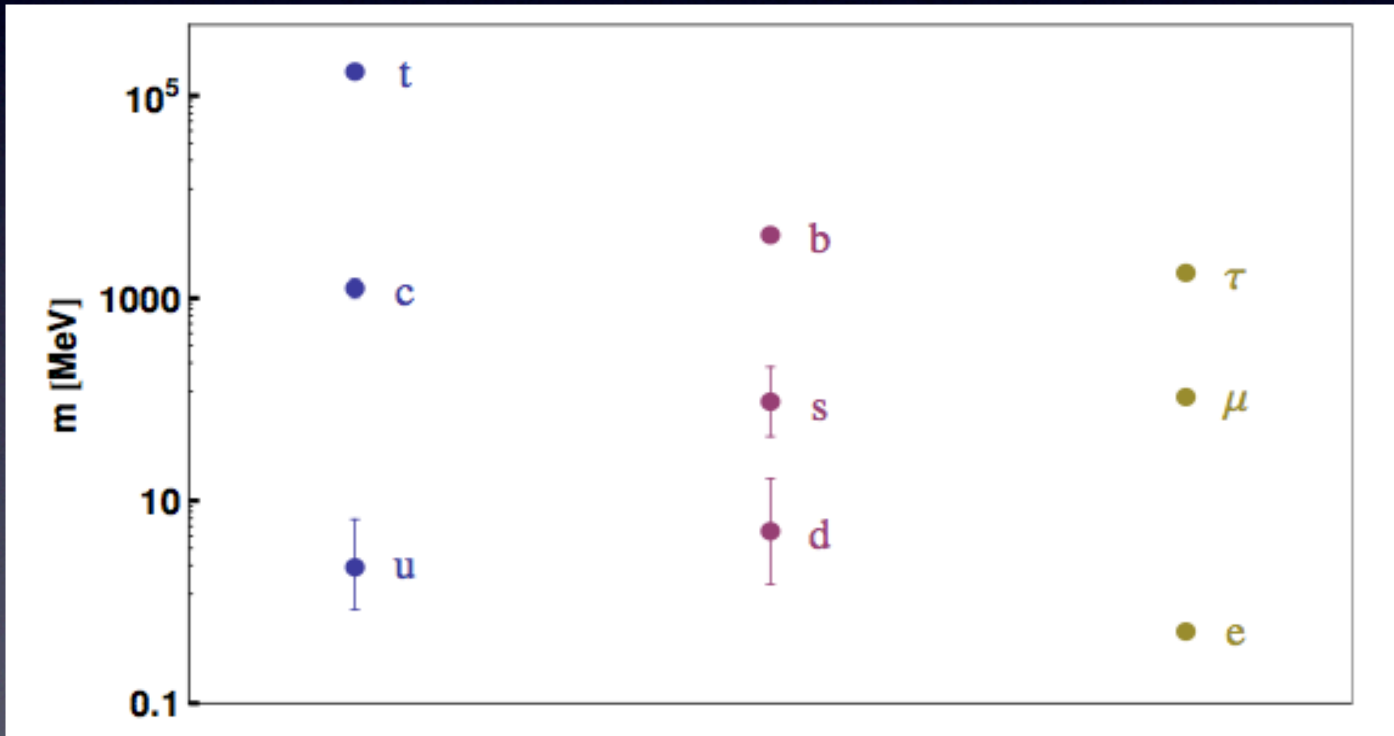
S. A., Spinrath (arXiv:0902.4644)

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

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

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

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

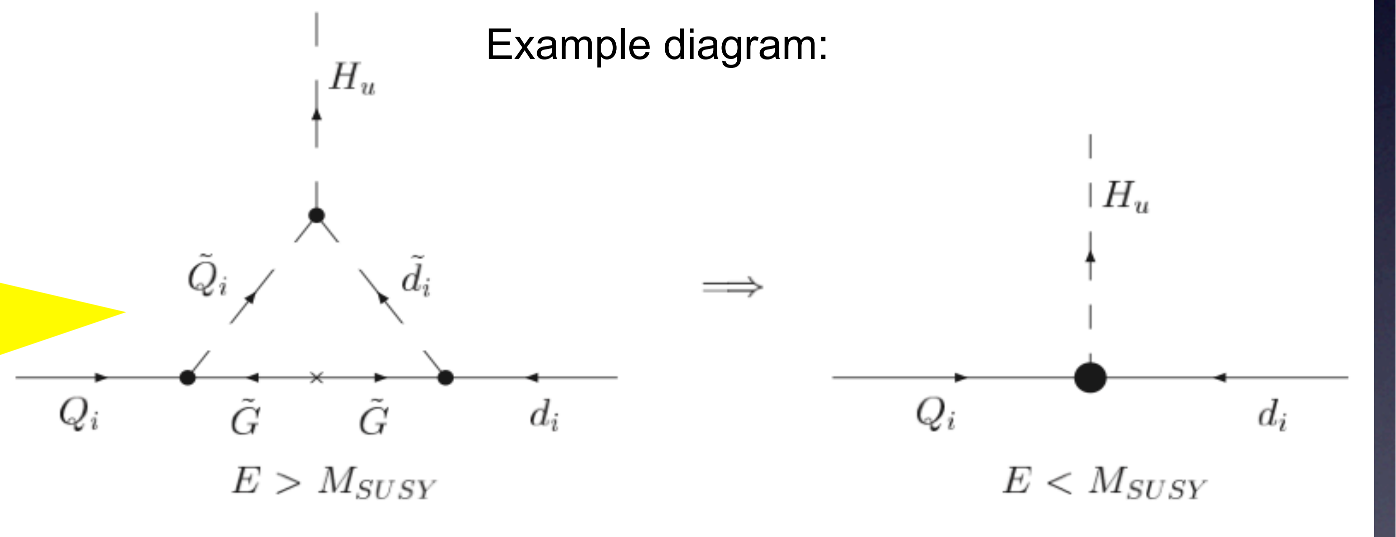
e.g. running masses at $\mu = M_Z$:
S. A., Maurer, (arXiv:1306.6879)

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:

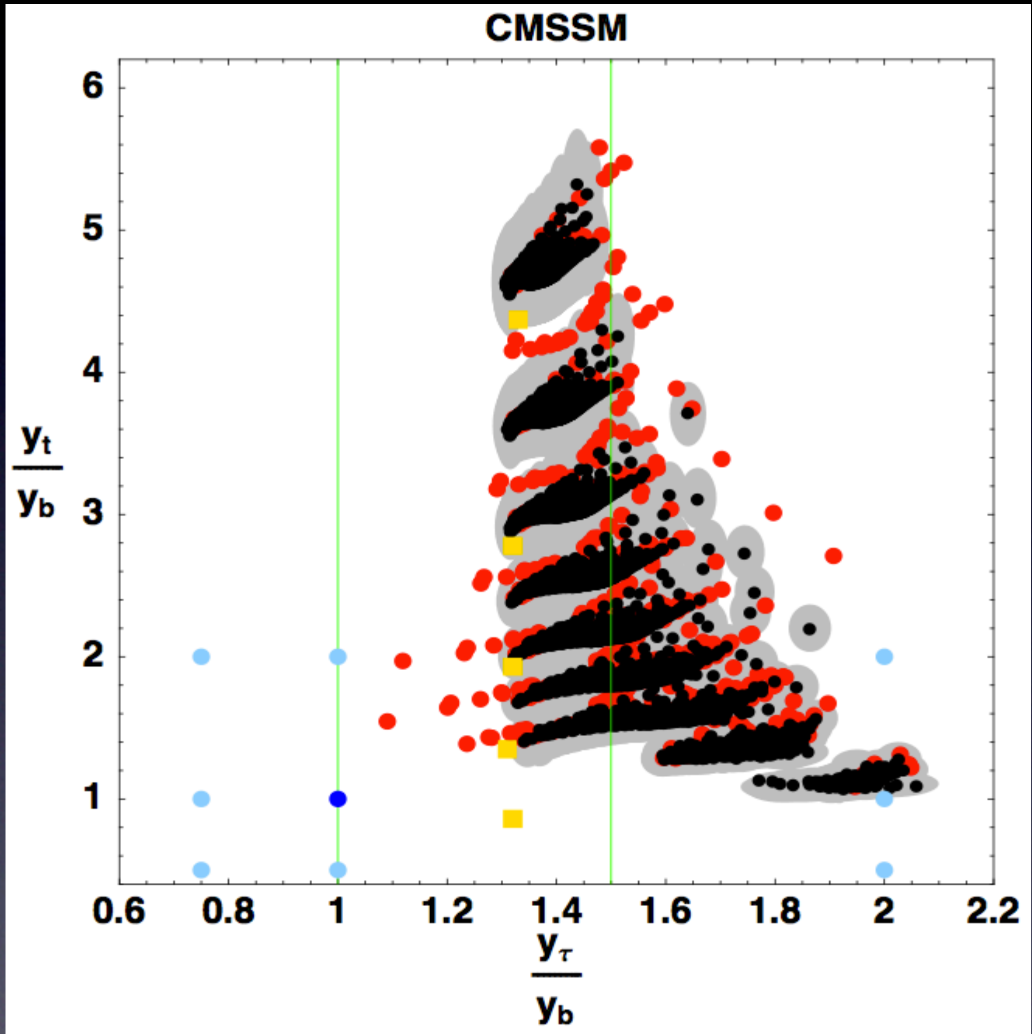


SUSY threshold effects at M_{SUSY} depend on the SUSY parameters, i.e. on the spectrum, tan β, ...

Can be tan β enhanded! → SUSY threshold corrections 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, scan over CMSSM parameters (with μ > 0)

S. A., Spinrath (arXiv:0902.4644)



Colours:

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

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

Analysis tool available:

➔ *SusyTC: A new tool (REAP extension) for including the SUSY sector in the analysis with full inclusion of 1-loop SUSY threshold corrections for all families (newest version 1.2)*

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

Simple example analysis: We confronted SUSY GUT scenarios with predicted ratios y_τ/y_b,= 3/2, y_μ/y_s = 6, y_e/y_d = ½ (@ M_{GUT})

and CMSSM parameters: m_0, $m_{1/2}$, A_0, tan β

with

the measurements for m_τ/m_b,= 3/2, m_μ/m_s = 6, m_e/m_d = ½ and also m_h ~125 GeV

→ CMSSM parameters get determined (= sparticle masses determined)

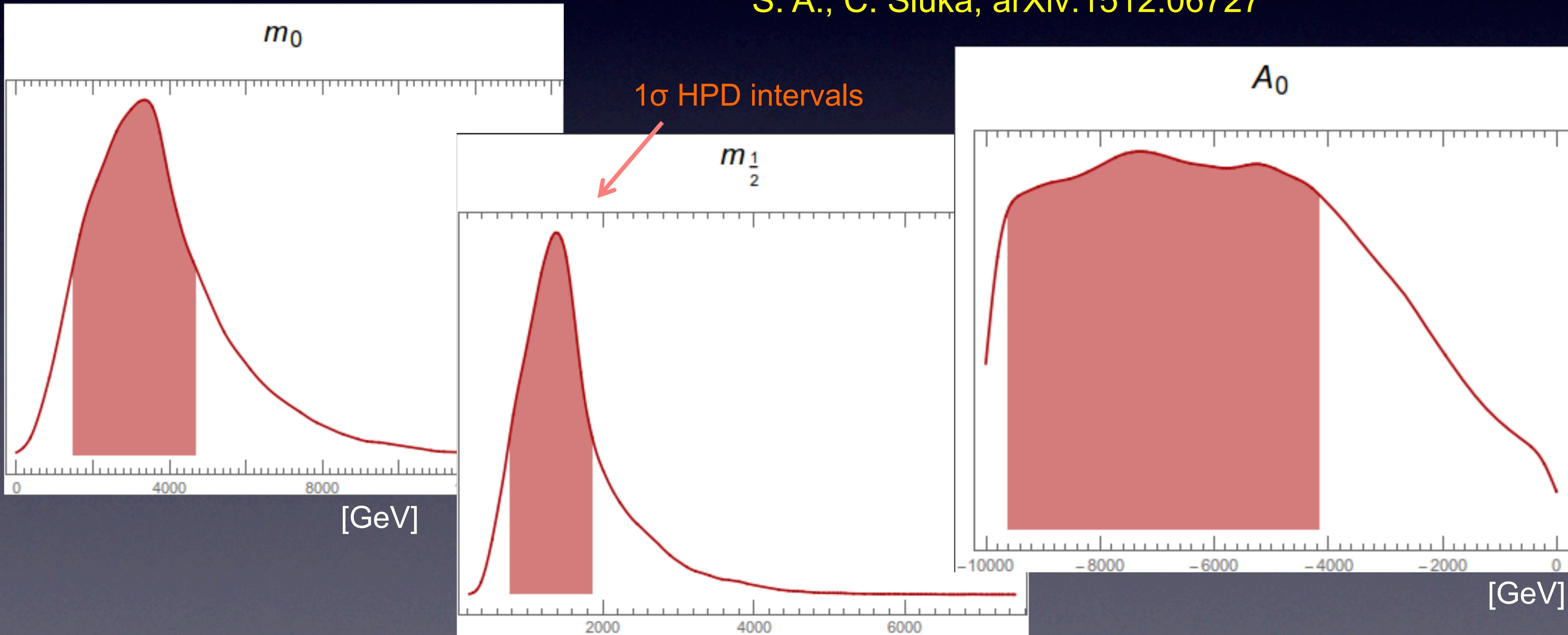
Using REAP with SusyTC and *FeynHiggs 2.11.2* for the calculation of m_h at 2-loop.

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

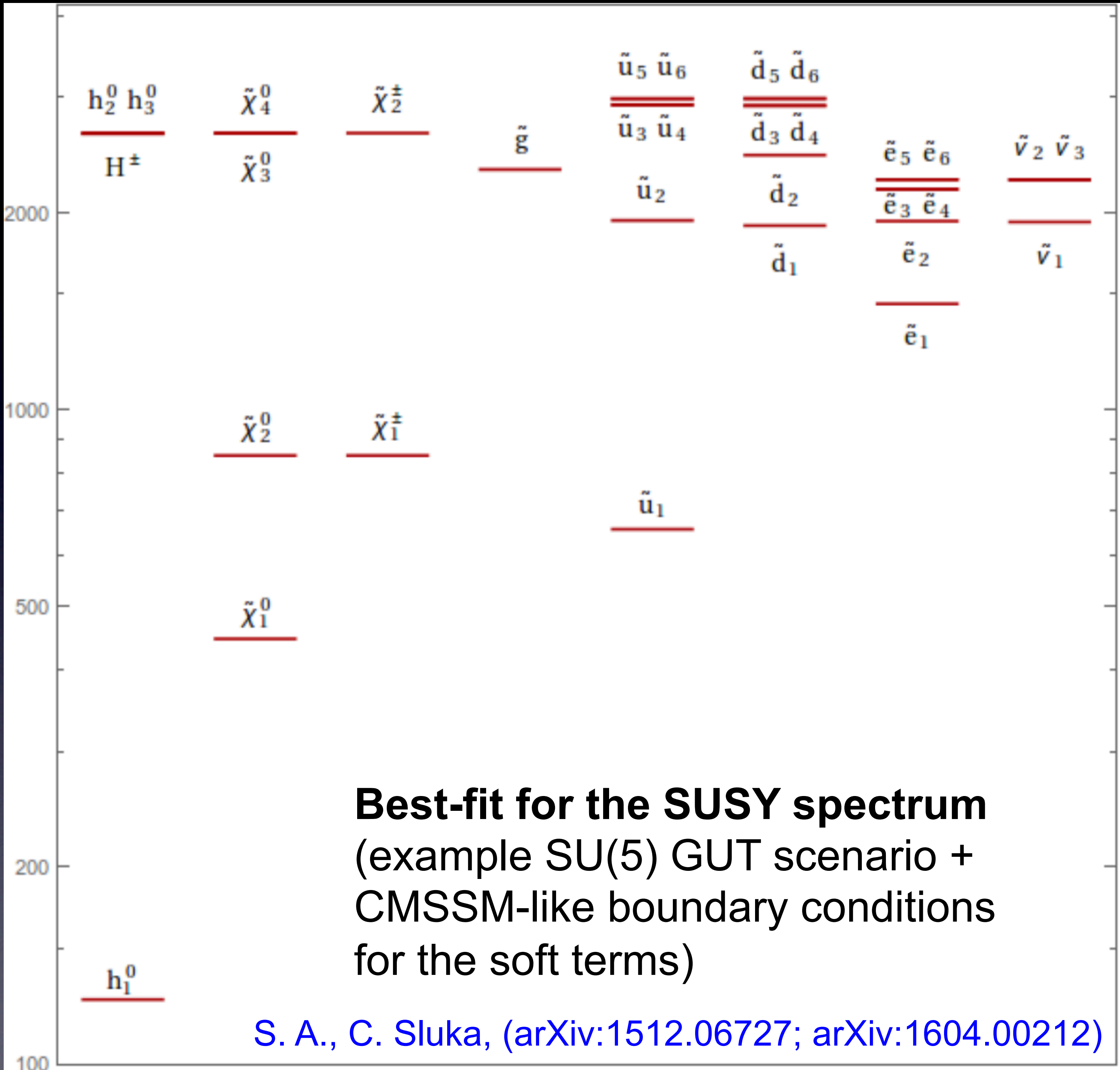
Parameter	m_0	A_0	$m_{1/2}$
Best fit value	2119 GeV	-5822 GeV	1008 GeV

and (fixed) tan β = 30, (optimal value), μ>0

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



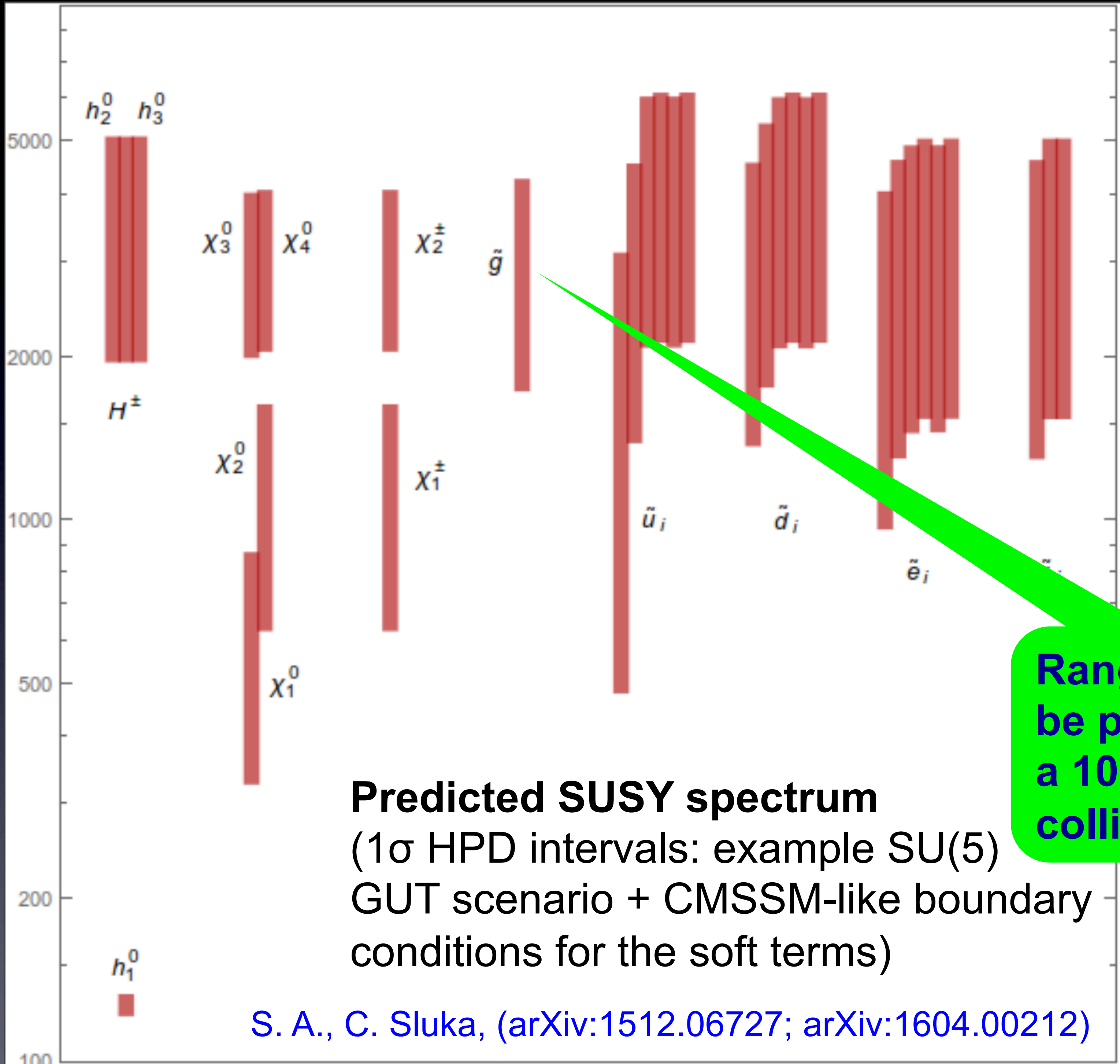
Scenario with GUT ratios $m_\tau/m_b = 3/2$, $m_\mu/m_s = 6$, $m_e/m_d = 1/2$



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 $m_\tau/m_b = 3/2$, $m_\mu/m_s = 6$, $m_e/m_d = 1/2$



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

Range can be probed at a 100 TeV pp collider

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

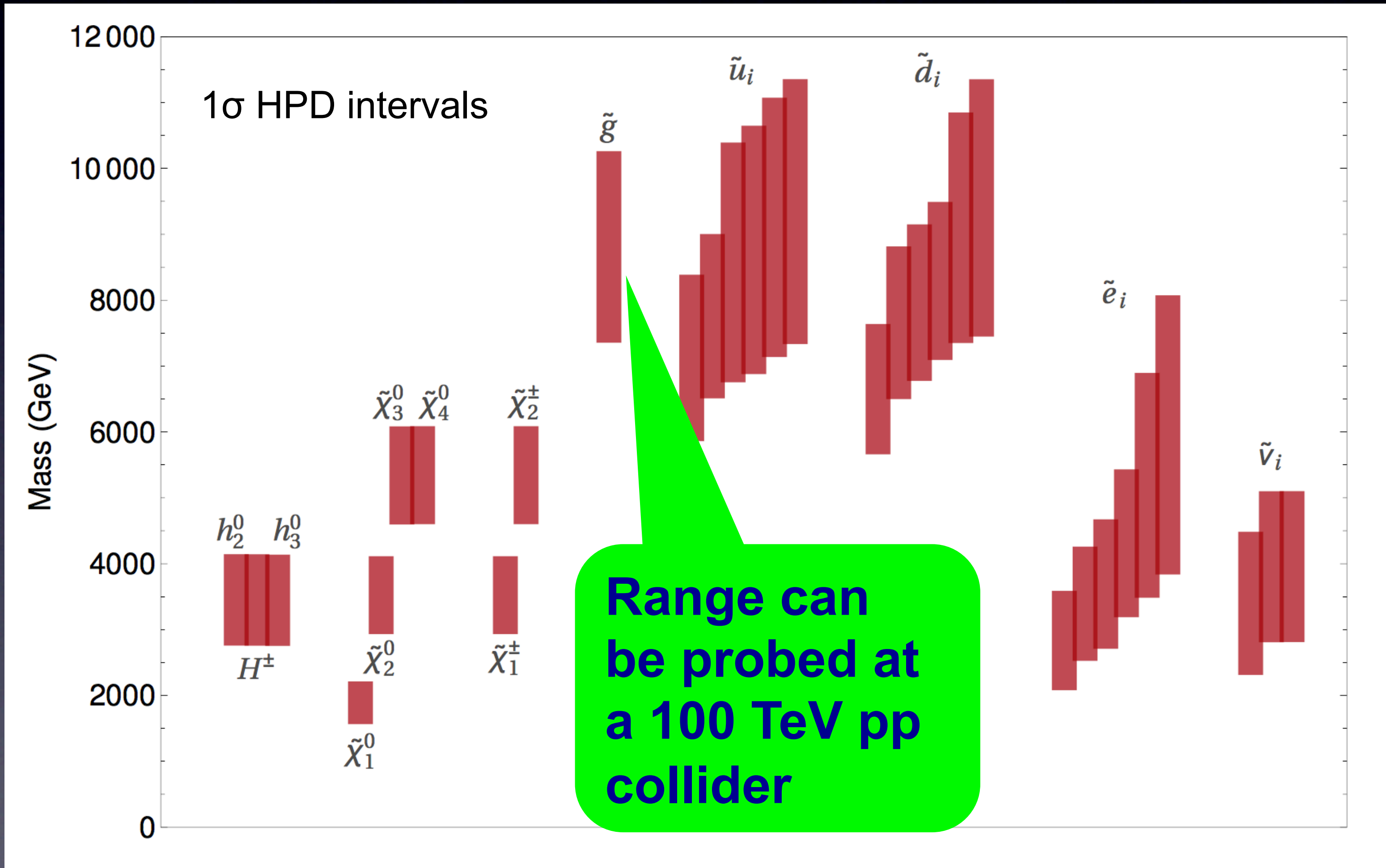
Note: In my talk I have shown the predicted spectrum from a “toy model”. For the predicted SUSY spectrum from a worked out SUSY SU(5) flavour GUT model with SUSY breaking (and with different GUT predictions $m_\tau/m_b = 1$, $m_\mu/m_s = 3$, $m_e/m_d = 1/3$ for the fermion mass ratios), see: S.A., C.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

Model with GUT ratios
$m_\tau/m_b = 1$, $m_\mu/m_s = 3$, $m_e/m_d = 1/3$

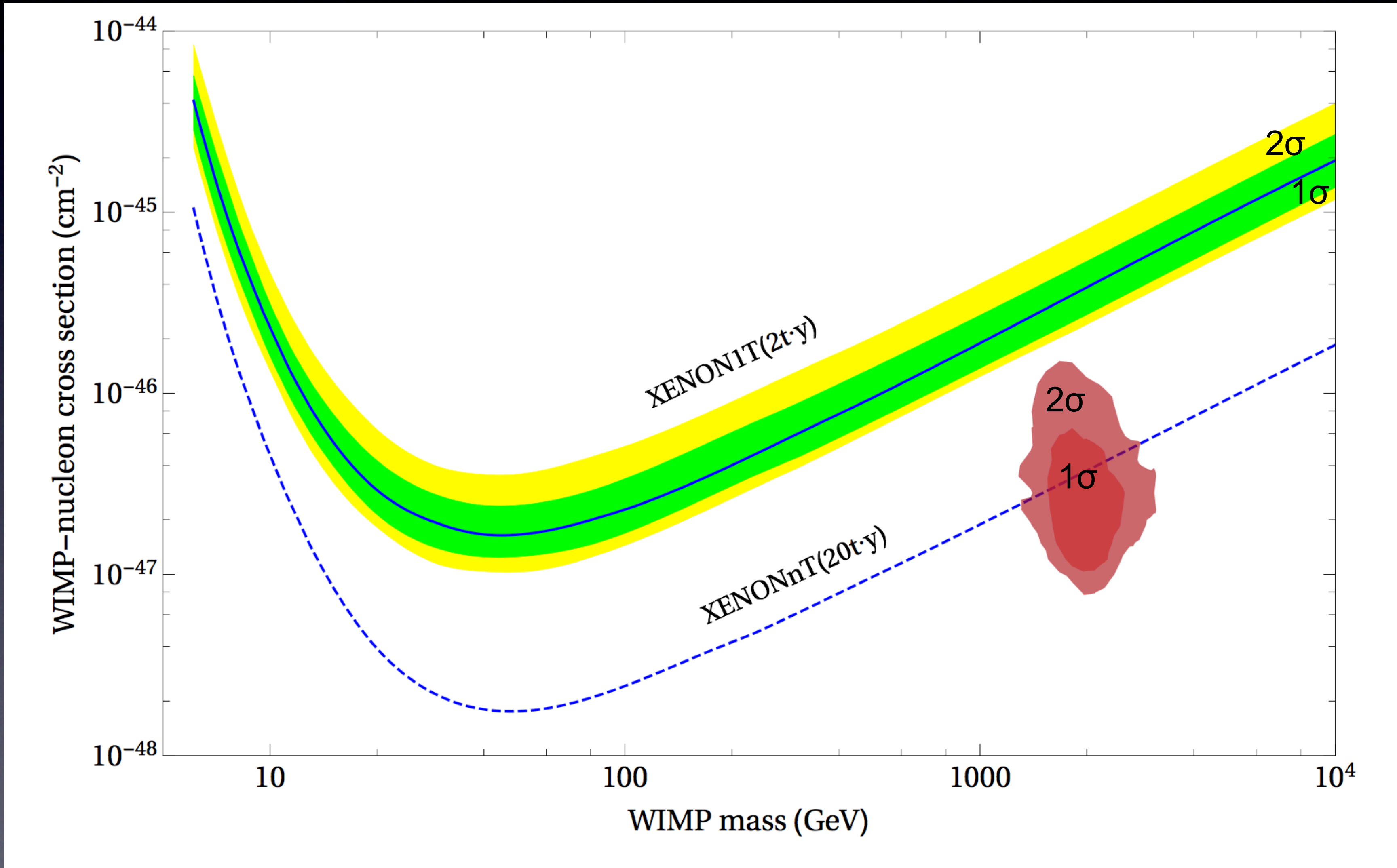


Analysis using REAP with SusyTC

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

- Examples: WIMP DM properties

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



Summary: From GUT-model perspective - No surprise SUSY was not found yet - "climb up" some more in energy to see SUSY … ?

Thanks for your attention!