General Gauge Mediation @ the EW scale

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Montpellier, France
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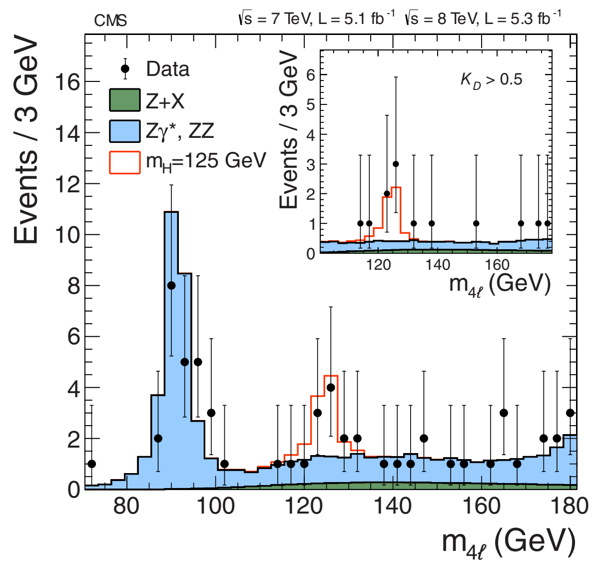
based on **1507.04364** & to appear work with

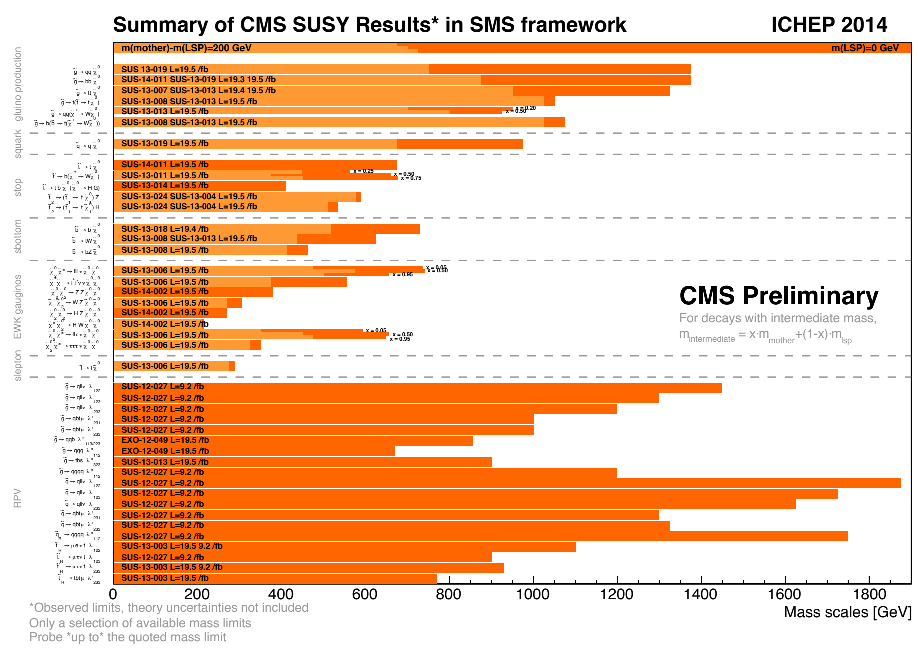
S. Knapen and D.Shih

2+1 problems for BSM physics



Why is the Higgs @ 125 GeV?

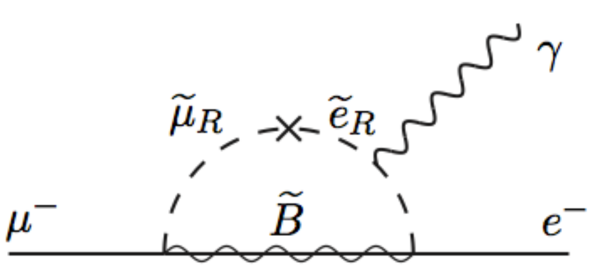
Is the EW scale natural at all?



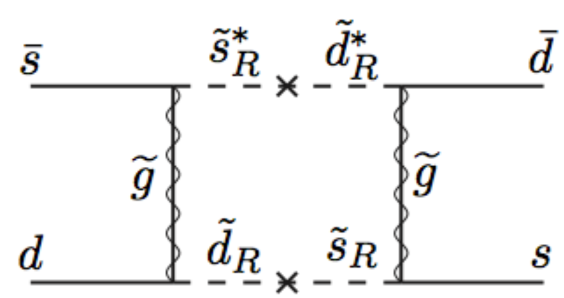
Where is everybody?

SM & nothing else or

BSM around the corner?



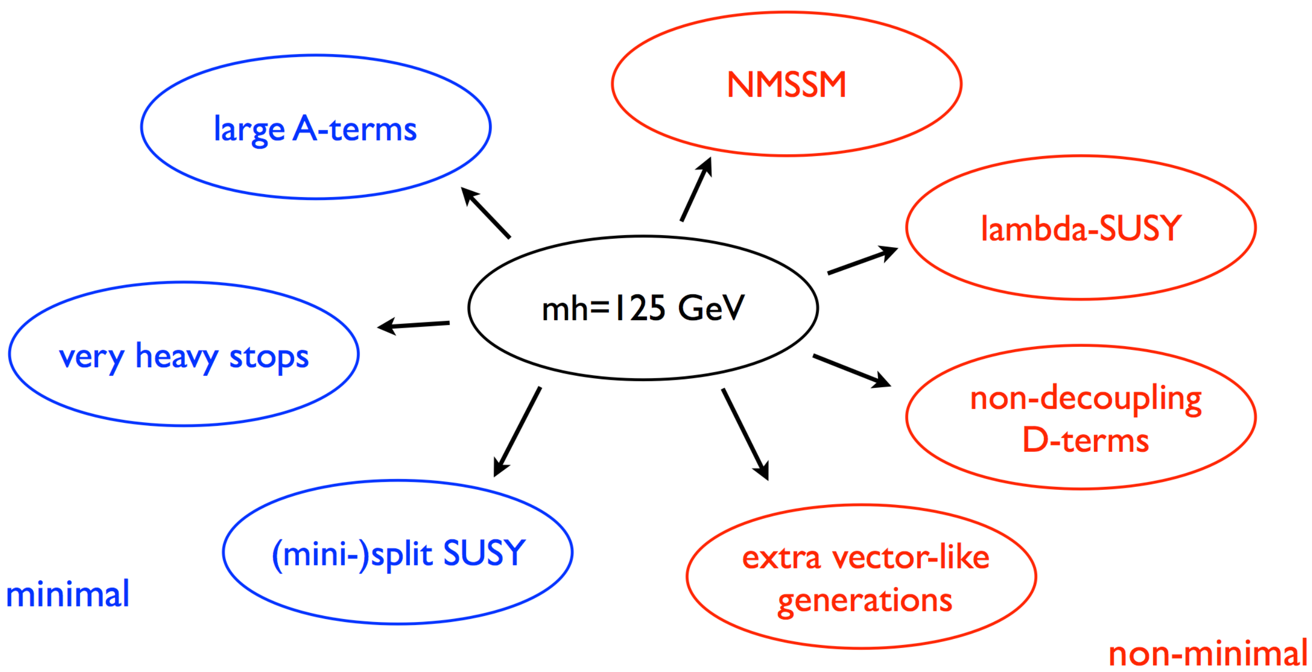
$$\mathrm{Br}(\mu \to e\gamma)_{exp} < 1.2 \times 10^{-11}$$



$$(\Delta m_K)_{exp} = (3.483 \pm 0.006) \times 10^{-12}\ \mathrm{MeV}$$

BSM physics vs strong bounds from flavor observables

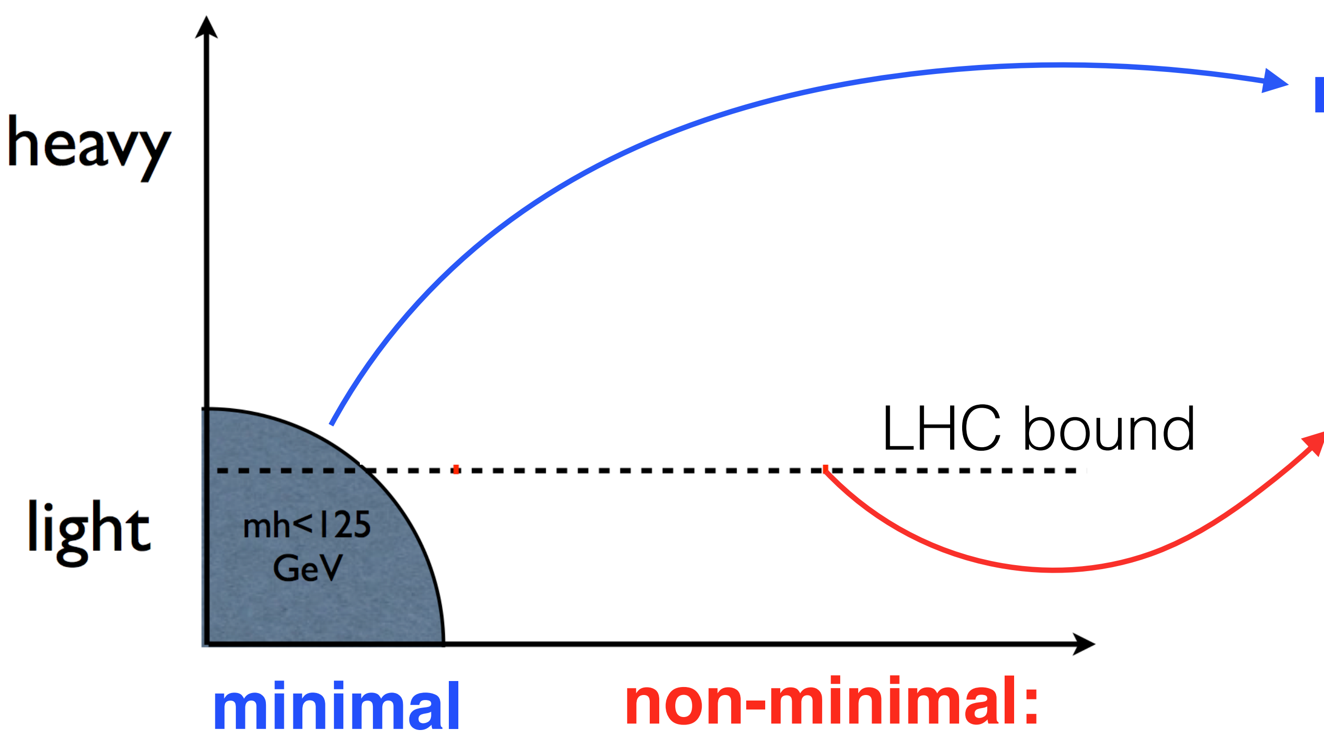
$m_h = 125\ \mathrm{GeV}$ has far reaching implications for SUSY



minimal: *consistent UV completions BUT issues with fine-tuning*

non-minimal: *hard UV completions BUT better fine-tuning*

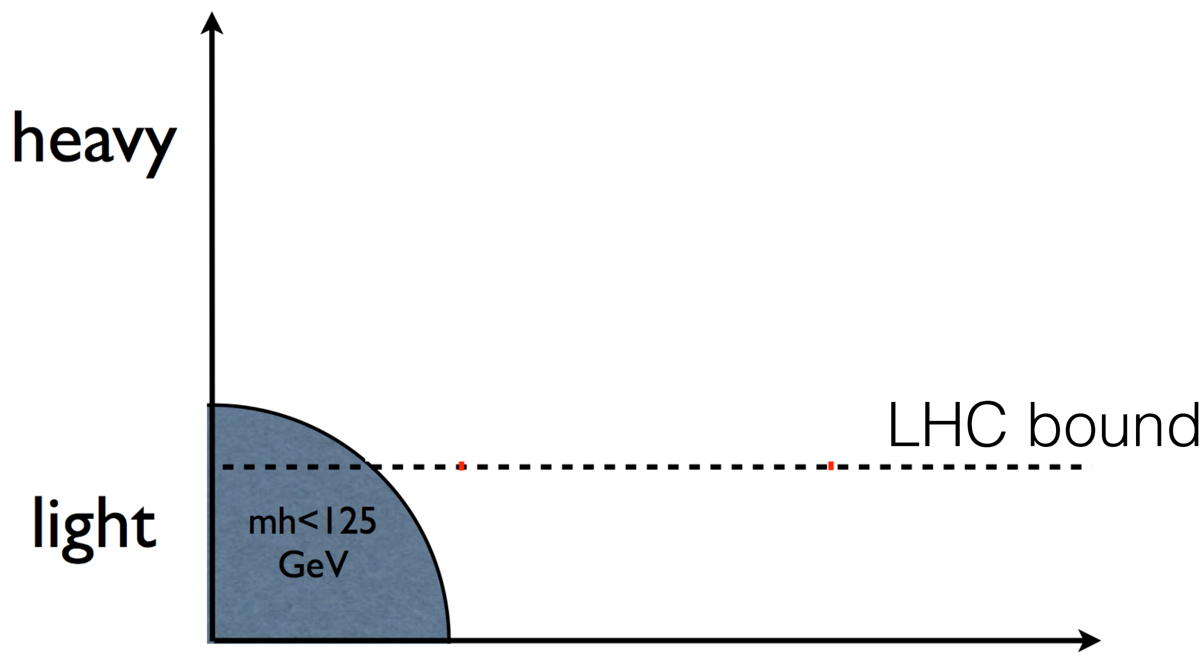
Run I hints at an heavier scale for SUSY states



minimal: no light states at Run I are expected once the Higgs mass is imposed

non-minimal: LHC bounds are dominating the tuning

Maybe in minimal SUSY the Higgs mass is already telling us that SUSY was not expected at Run I?



What about Run II?

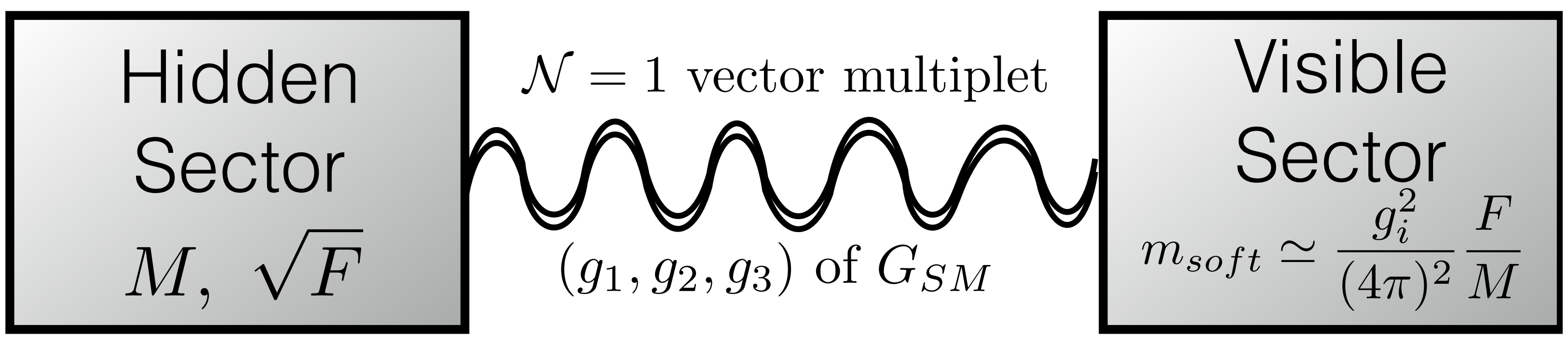
Have we learned everything we can from Run I?

We will try to answer these questions for ALL the possible gauge mediation models with the MSSM @ low energy

Why gauge mediation?

In the MSSM,
SUSY-breaking terms
are problematic for flavor

Gauge mediation
automatically gives
flavor bind SUSY-breaking



SM gauge interactions are flavor blind!

It also provides a COMPLETE theory of SUSY breaking

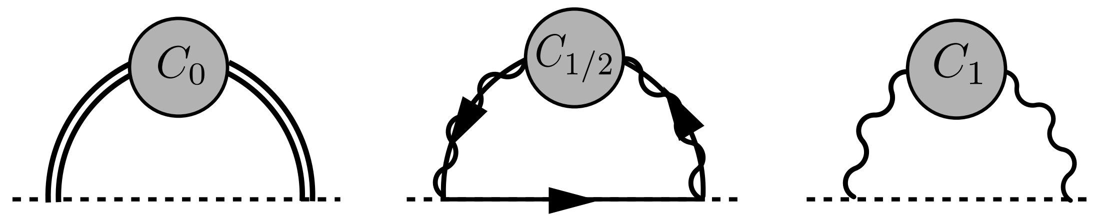
It is consistent up to the Planck scale

It accommodates unification of gauge couplings

General Gauge Mediation (GGM)

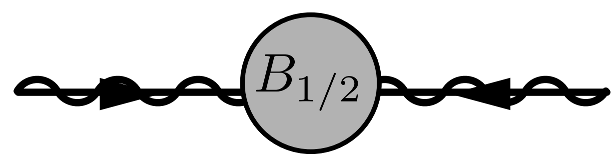
gives a model independent definition of "pure" gauge mediation *(Meade, Seiberg, Shih 2008)*

sfermion masses:



$\{m_Q^2\ ,\ m_U^2\ ,\ m_L^2\}$ +

gaugino masses:



$\{M_1\ ,\ M_2\ ,\ M_3\}$ +

μ
"by-hand" +

M_{mess}

All the other (non-zero) soft masses are fixed by UV sum-rules/flavor universality

ex: $m_{H_u}^2 = m_{H_d}^2 = m_L^2$

$$m_E^2 = \frac{3}{2}\left(m_U^2 - m_Q^2 + m_L^2\right)$$

8 PARAMETERS

CALCULABLE parameter space:
i.e. realizable in terms of *weakly* coupled models
(Buican, Meade, Seiberg, Shih 2008)

$B_\mu \approx 0$

A-terms ≈ 0

CAVEAT: extensions of the pure GGM will destroy the sum-rules and in some cases even flavor universality:

Ex: ***D-tadpoles, MSSM-messenger-messenger, MSSM-MSSM-messenger couplings…***

The low energy theory for GGM is the MSSM:

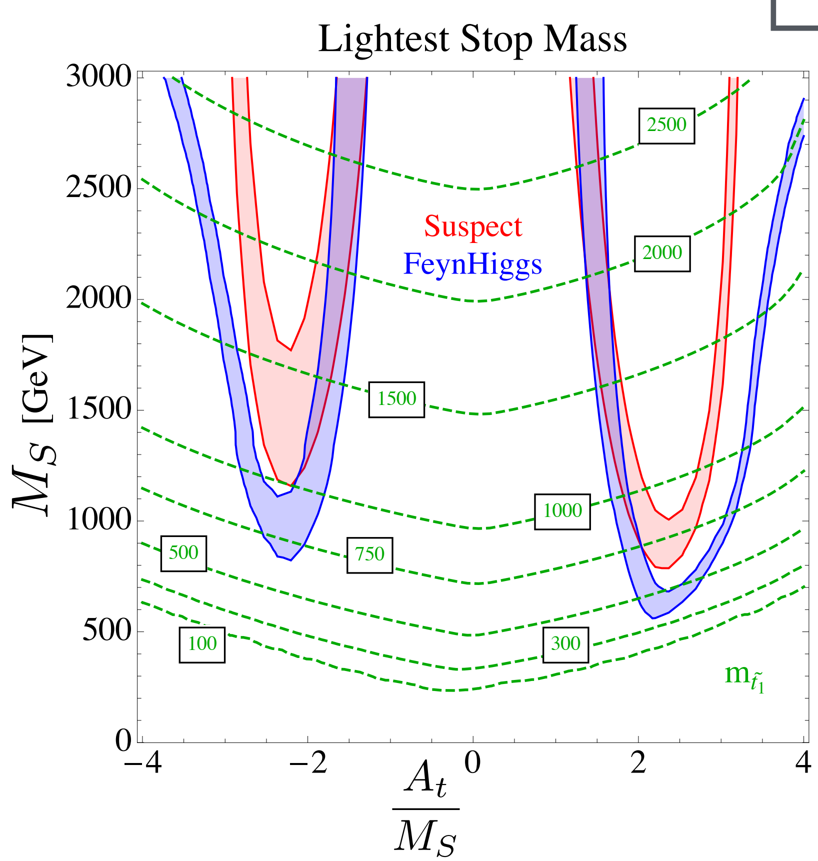
$$m_h^{\text{tree}} \leq m_Z$$

How do we get $m_h = 125 \text{ GeV}$?

m_h^2 is radiatively sensitive to **3 soft parameters**

$$-\mathcal{L}_{\text{soft}} \supset m_{Q_3}^2 |\tilde{Q}_3|^2 + m_{U_3}^2 |\tilde{U}_3|^2 + (A_t H_u \tilde{Q}_3 \tilde{U}_3 + c.c.)$$

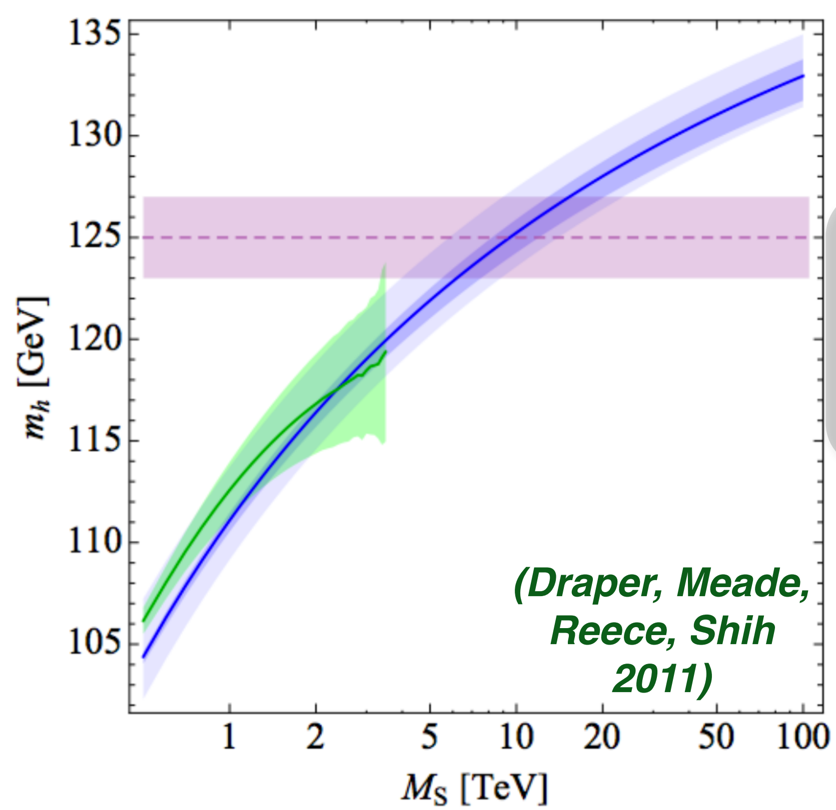
$m_{Q_3} \approx m_{U_3}$ to keep it simple



multi-TeV A-terms

(Hall, Pinner, Ruderman, 2011)

Maximal Mixing delivers light stops
(possibly accessible at LHC)



(Draper, Meade, Reece, Shih 2011)

zero A-terms

Heavy stops: High-scale SUSY, Split-SUSY

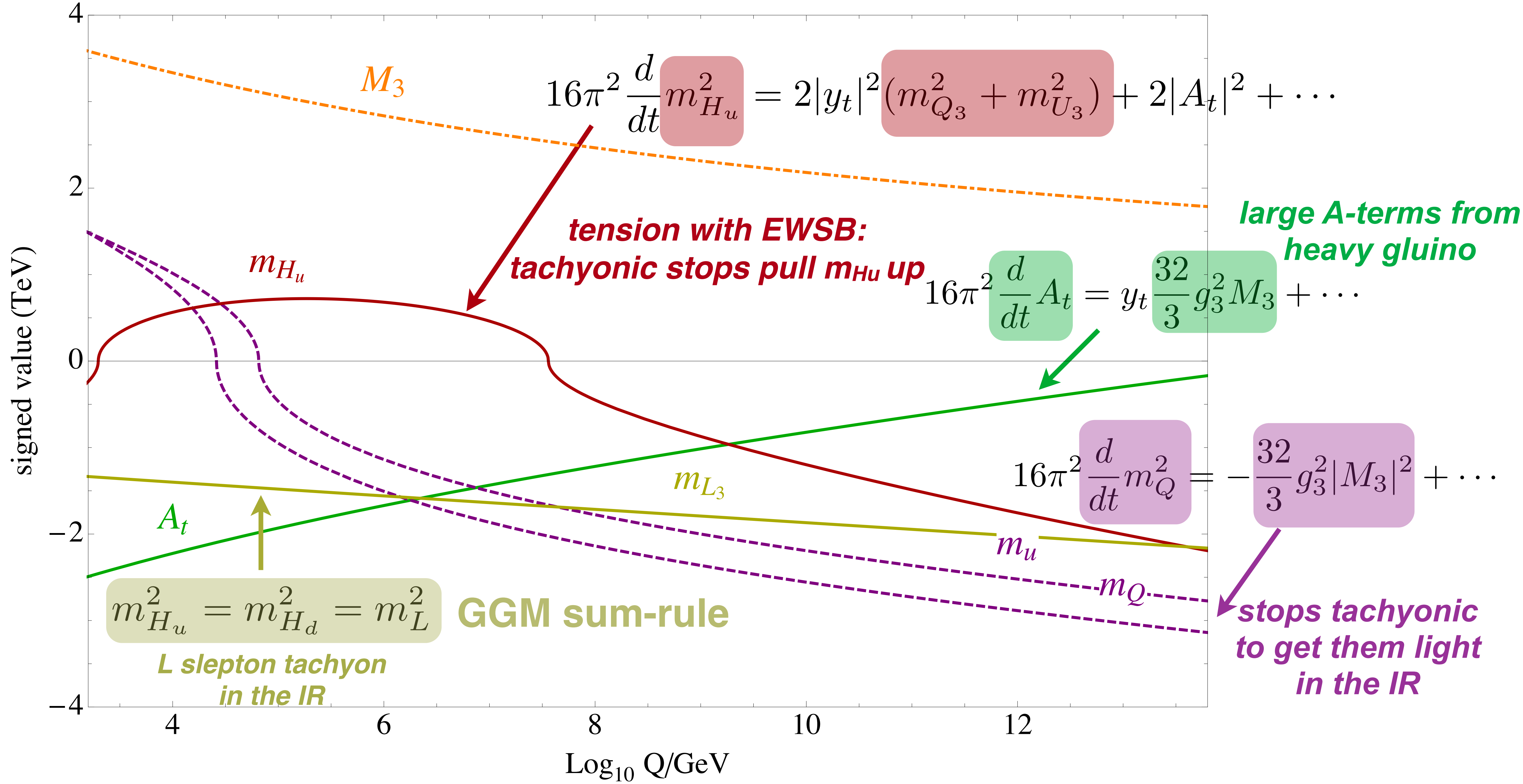
$A_t = 0$ in (pure) GGM

extensions of the pure GGM can generate large UV A-terms but destroy sum-rules/flavor universality

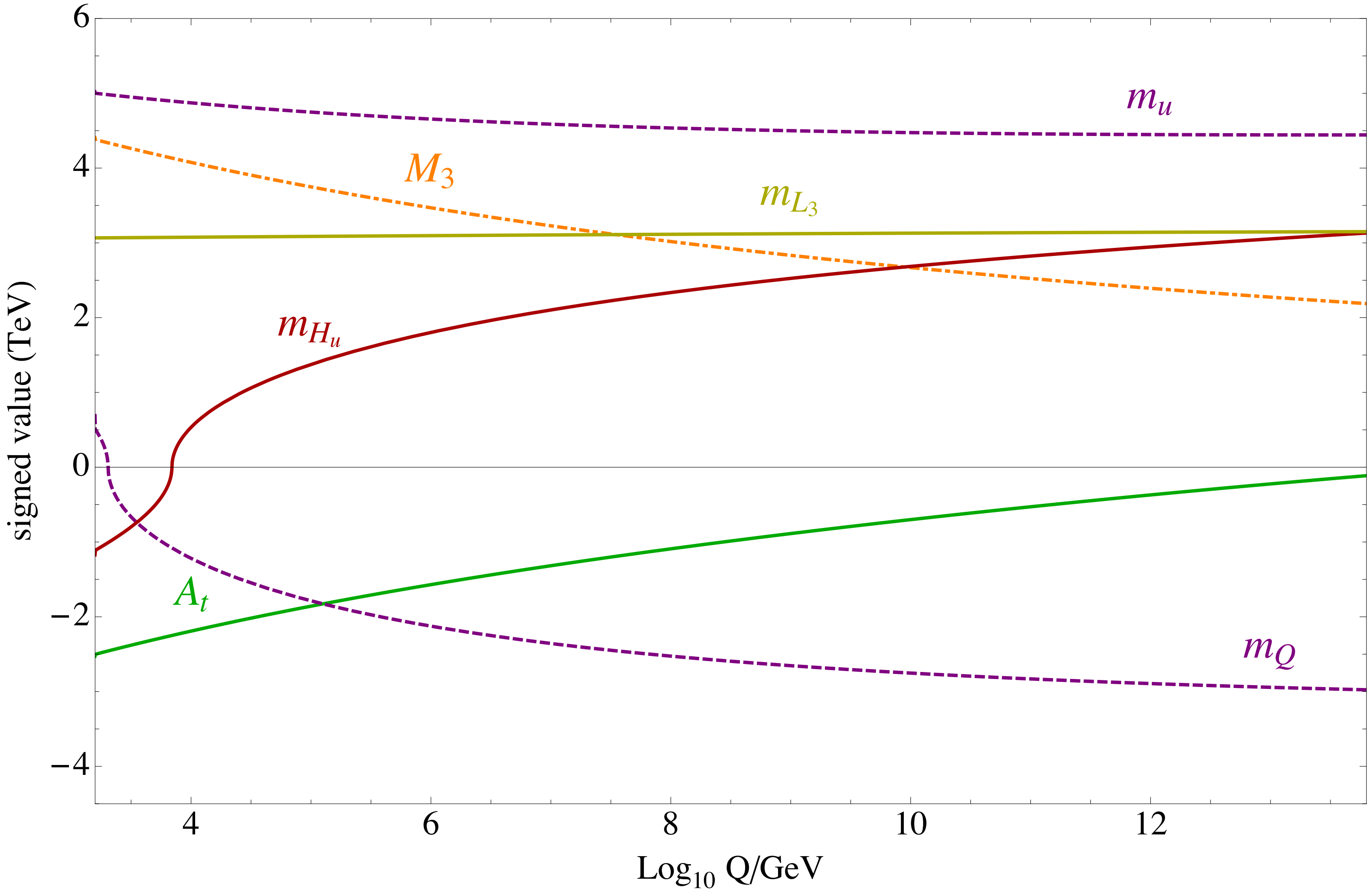
Can we generate large A-terms in pure GGM?

What is the min stop mass after $m_h = 125\ \mathrm{GeV}$ is imposed?

An intuitive picture I: $m_Q \approx m_U$

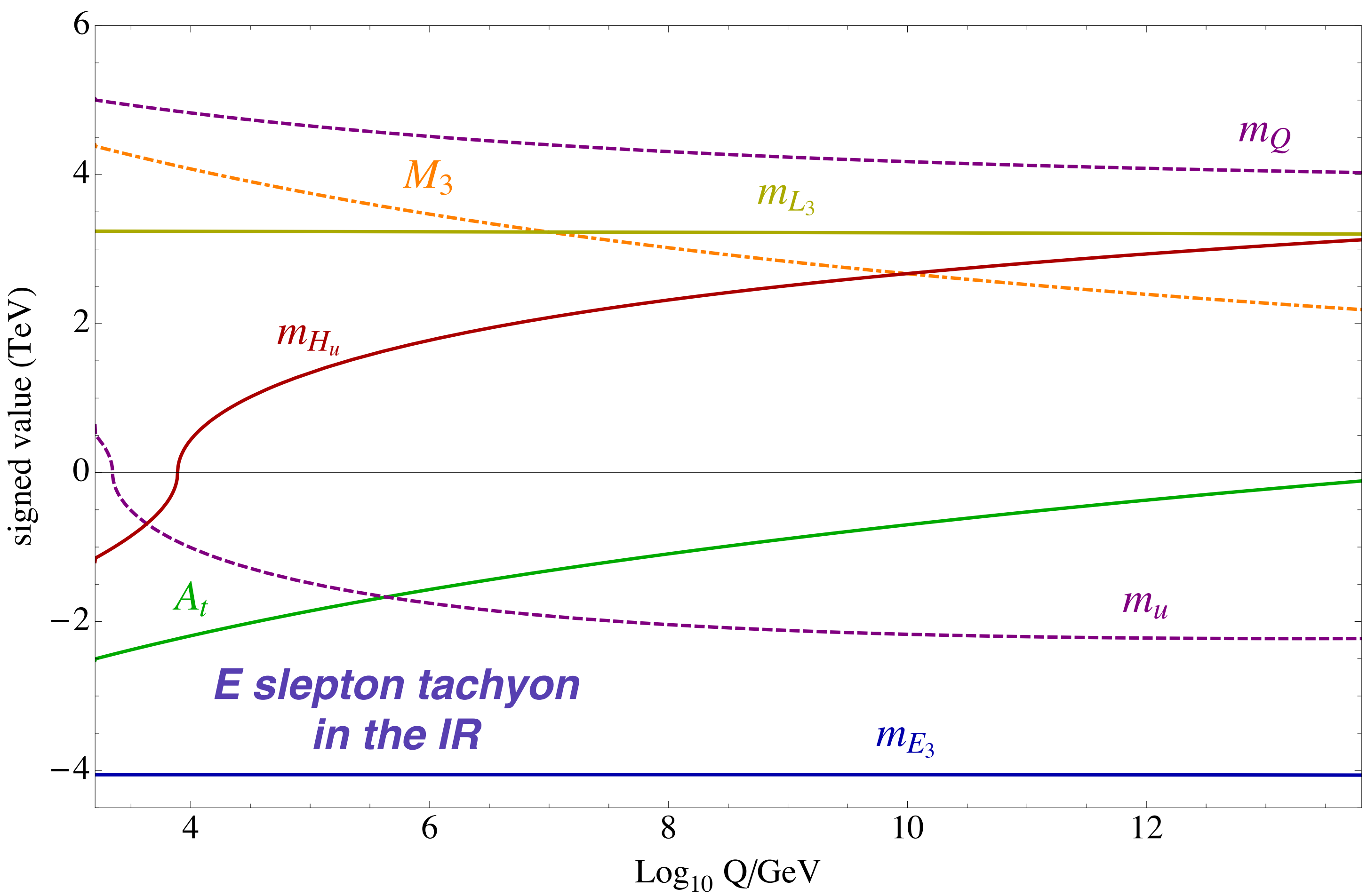


Splitting the stops soft masses



$$m_U \gg m_Q$$

light
left-handed stop



$$m_U \ll m_Q$$

light
right-handed stop

GGM sum-rule

$$m_E^2 = \frac{3}{2}\left(m_U^2 - m_Q^2 + m_L^2\right)$$

We expect boundaries @ low stop masses
to be produced by the convergence of the tensions discussed

The main technical difficulty to get a complete picture is that

- *EWSB+Higgs constraints are imposed @ EW scale*
- *GGM boundary conditions are defined @* M_{mess}

A systematic approach:

We completely characterize GGM with $m_h = 125\ \mathrm{GeV}$

We understand its features in a simple analytical approximation

We can use these results to study the LHC coverage on GGM after Higgs

Similar techniques can possibly be used in other frameworks

Key ingredient to handle the RG evolution

Transfer matrix (TM) method: RGE's are bilinear in soft masses

$$\vec{A}_{IR} = T\vec{A}_{UV}$$ *(common in high-scale scenarios)*

$$\vec{m}^2_{IR} = \vec{A}_{UV}\vec{T'}\vec{A}_{UV} + T''\vec{m}^2_{UV}$$

$$\vec{A} = \begin{pmatrix} \mu \\ A_t \\ \vdots \\ M_3 \\ \vdots \end{pmatrix} \quad \vec{m}^2 = \begin{pmatrix} B_\mu \\ m^2_{H_u} \\ m^2_{H_d} \\ m^2_{Q_3} \\ \vdots \end{pmatrix}$$

$T \;\; T' \;\; T''$ depend on M_{mess} , M_S , $\tan\beta$ ONLY

We trade UV parameters for IR ones once and for all!

From GGM UV b.c.
we get relations among IR quantities

Ex: $A_t(M_{mess}) = 0 \longrightarrow M_3 \approx p' A_t + q' M_2$

parameter counting

GGM in the IR : $M_1, \ M_2, \ A_t, \ m^2_{Q_3}, \ m^2_{U_3}, \ m^2_{L_3}, \ \mu$ and M_{mess}

all the rest of the spectrum is fixed by
IR relations @ the weak scale

8 parameters

$M_{mess} = 10^{15}, \ 10^{11}, \ 10^7 \ \mathrm{GeV}$ "high", "medium", "low"

$M_1 = 1 \ \mathrm{TeV}$ has little impact on the RGEs $\sim g_1^2$

-2 parameters

IR constraints:

2 EWSB conditions
$(\tan\beta = 20)$

$$\begin{cases} m_Z^2 = -2(m^2_{H_u} + |\mu|^2) + \cdots \\ \sin 2\beta = \dfrac{2B_\mu}{2|\mu|^2 + m^2_{H_u} + m^2_{H_d}} + \cdots \end{cases}$$

$m_h = 123 \ \mathrm{GeV}$ *(accounting conservatively for theory error Allanach & co. 2004)*

-3 parameters

---

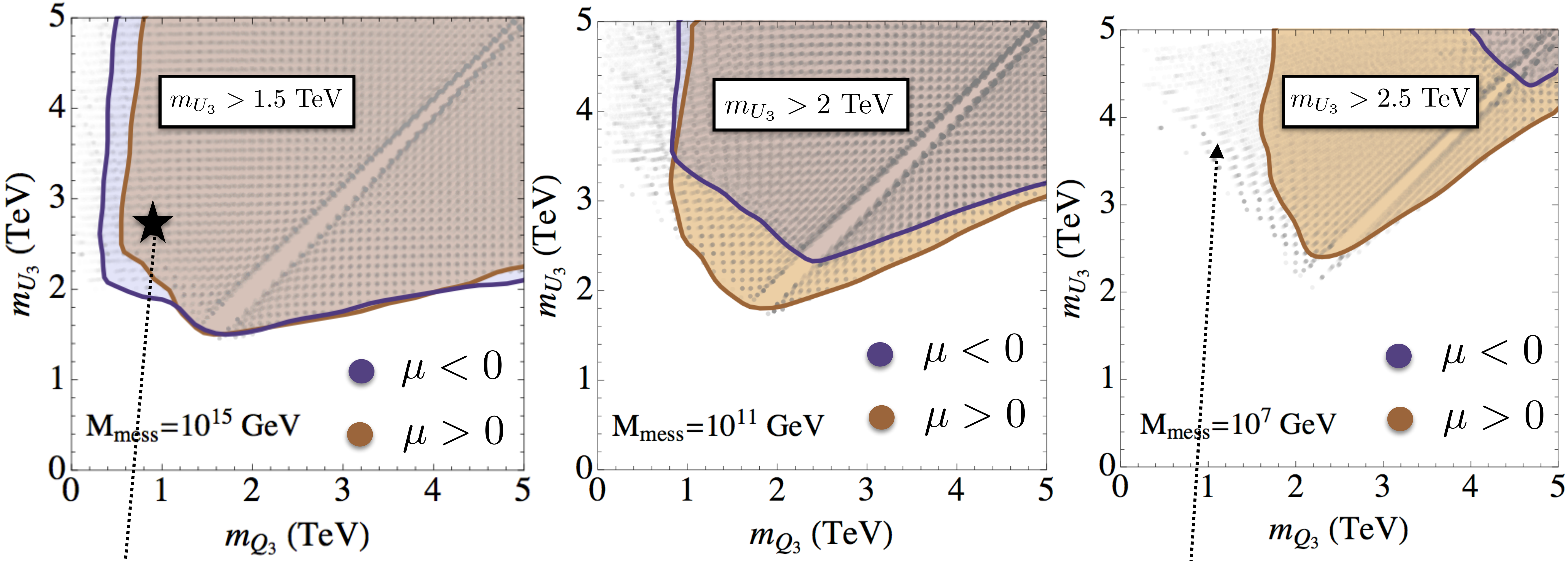
3 parameters

$m^2_{Q_3}, \ m^2_{U_3}, \ M_2$
$+ \ \mathrm{sign}\mu$

A bird's-eye view of the results from the scan:

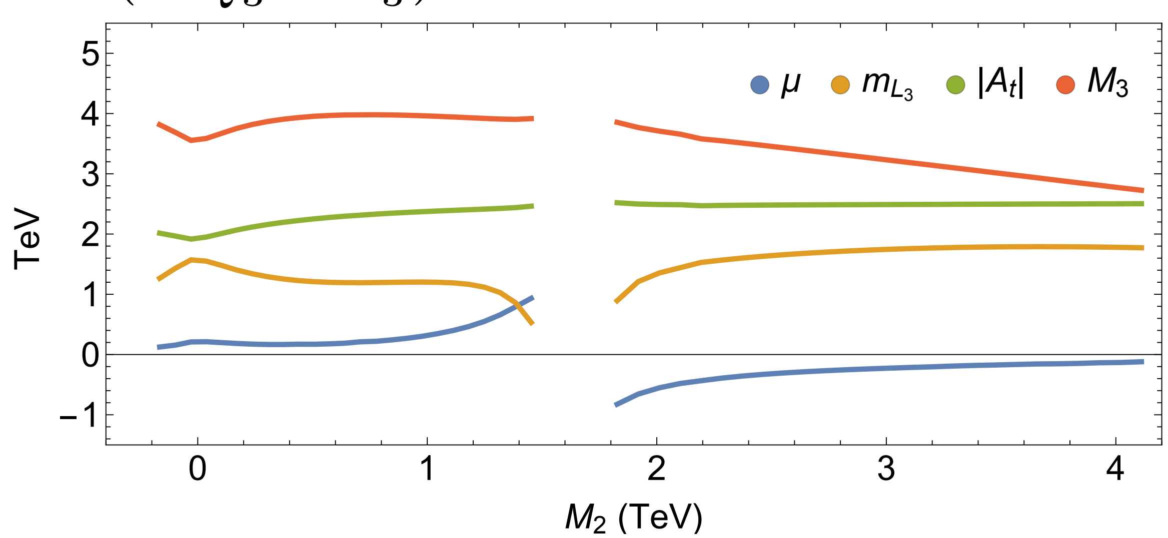
(TM to trade UV & IR)

(EWSB conditions + Higgs mass computed by SoftSUSY)



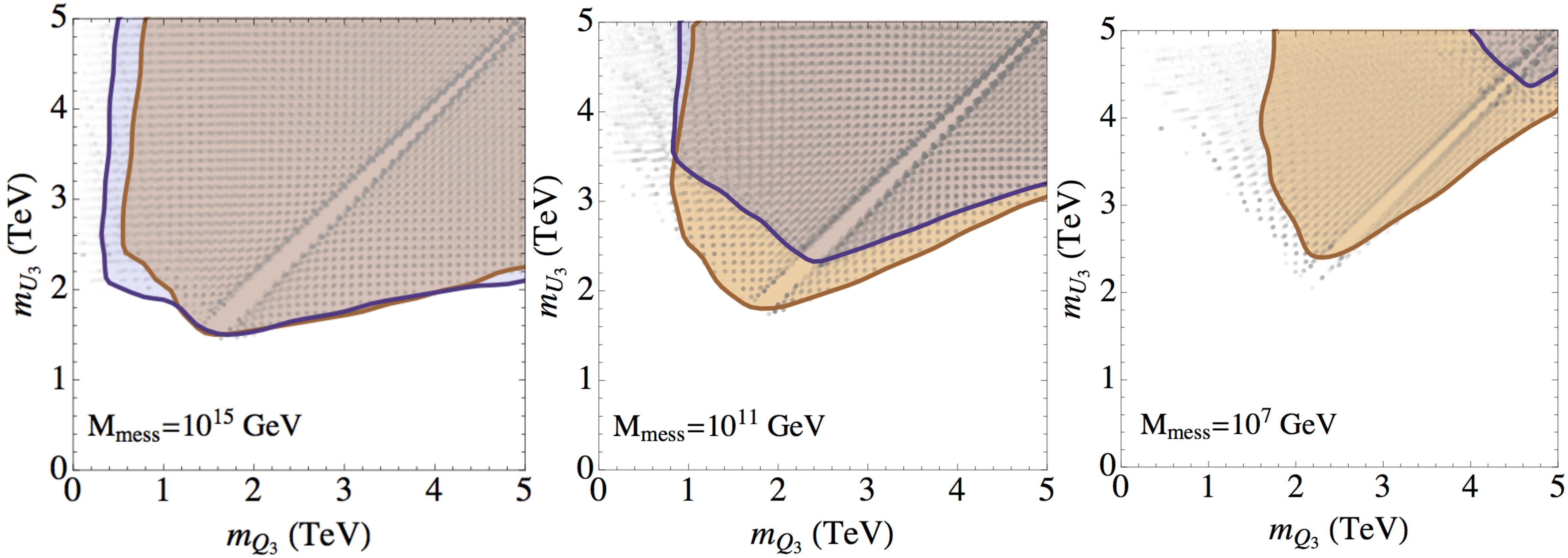
$(m_{Q_3}\, m_{U_3})$ fixed

The gray dots are physical stop masses (including 1-loop thresholds)



the M_2 interval is divided in two disconnected segments with different $\mathrm{sign}\mu$

The plan of the TALK is to explain a number of features of these plots…



1) How the Higgs mass constraint acts on the stop mass plane?

2) What is the role of M_{mess}?

3) How boundaries of the M_2-interval arise?

4) How the lower bound on m_{U_3} is produced?

5) How the physics depend on the stop mass plane?

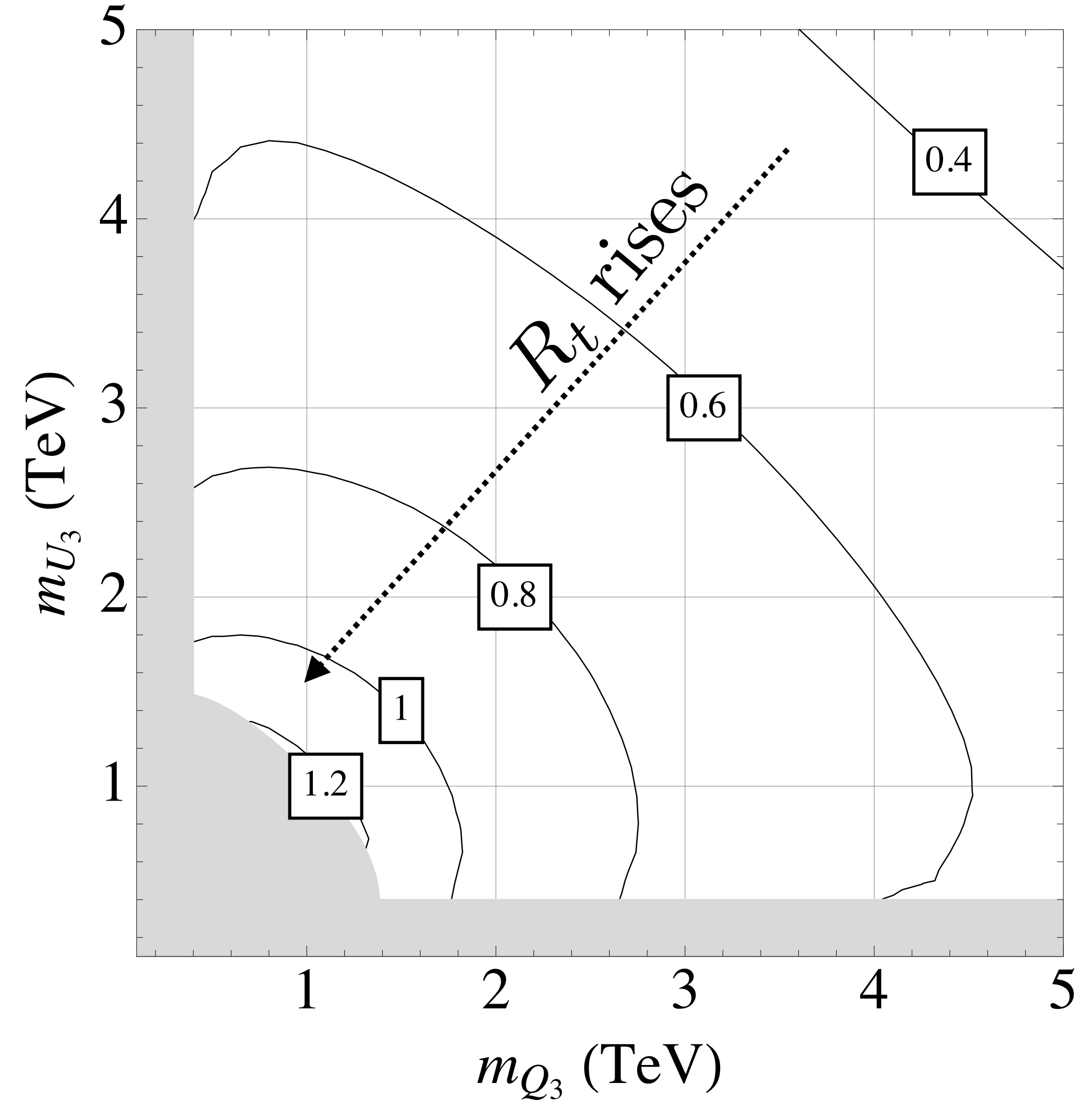
6) What is the role of $\mathrm{sign}\mu$?

The role of the Higgs constraint

Approximations:

- 1-loop RGEs
- neglecting $y_b, \; y_\tau, \; g_1$ effects
- tree-level EWSB
- leading order in $\tan\beta \to \infty$

$$R_t \equiv \frac{|A_t|}{\sqrt{m_{Q_3}^2 + m_{U_3}^2}}$$



One of the EWSB conditions in GGM

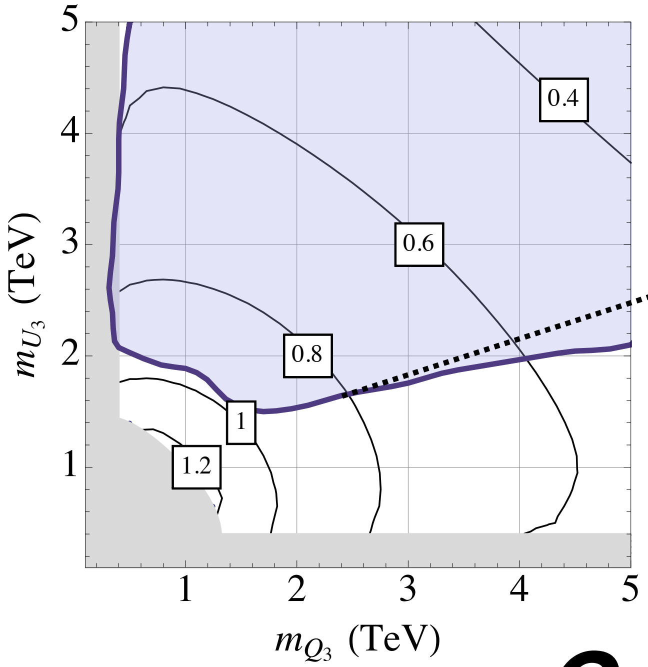
$$e\,(\delta M_2 + d\,A_t)^2 + a\,m_{L_3}^2 + \mu^2 \approx m_0^2$$

where $m_0^2 \equiv b\,(m_{Q_3}^2 + m_{U_3}^2) - c\,A_t^2$

$m_0^2 > 0$ *implies* $R_t^2 < b/c$

M_{mess}	15	11	7
$\sqrt{b/c}$	1.01	0.85	0.69

the bounds gets more strict for low M_{mess}



Extra boundaries in GGM

no-tachyon constraints

Can we understand them in general?

$$m^2_{Q_{1,2}} \approx m^2_{Q_3} + \frac{1}{3}(m^2_{L_3} - m^2_{H_u})$$
$$m^2_{U_{1,2}} \approx m^2_{U_3} + \frac{2}{3}(m^2_{L_3} - m^2_{H_u})$$
$$m^2_{L_{1,2}} \approx m^2_{L_3}$$

ONLY 3rd generations matter

$$m^2_{D_{1,2,3}} \approx \frac{1}{2}(m^2_{Q_3} + m^2_{U_3}) - \frac{1}{2}m^2_{H_u}$$

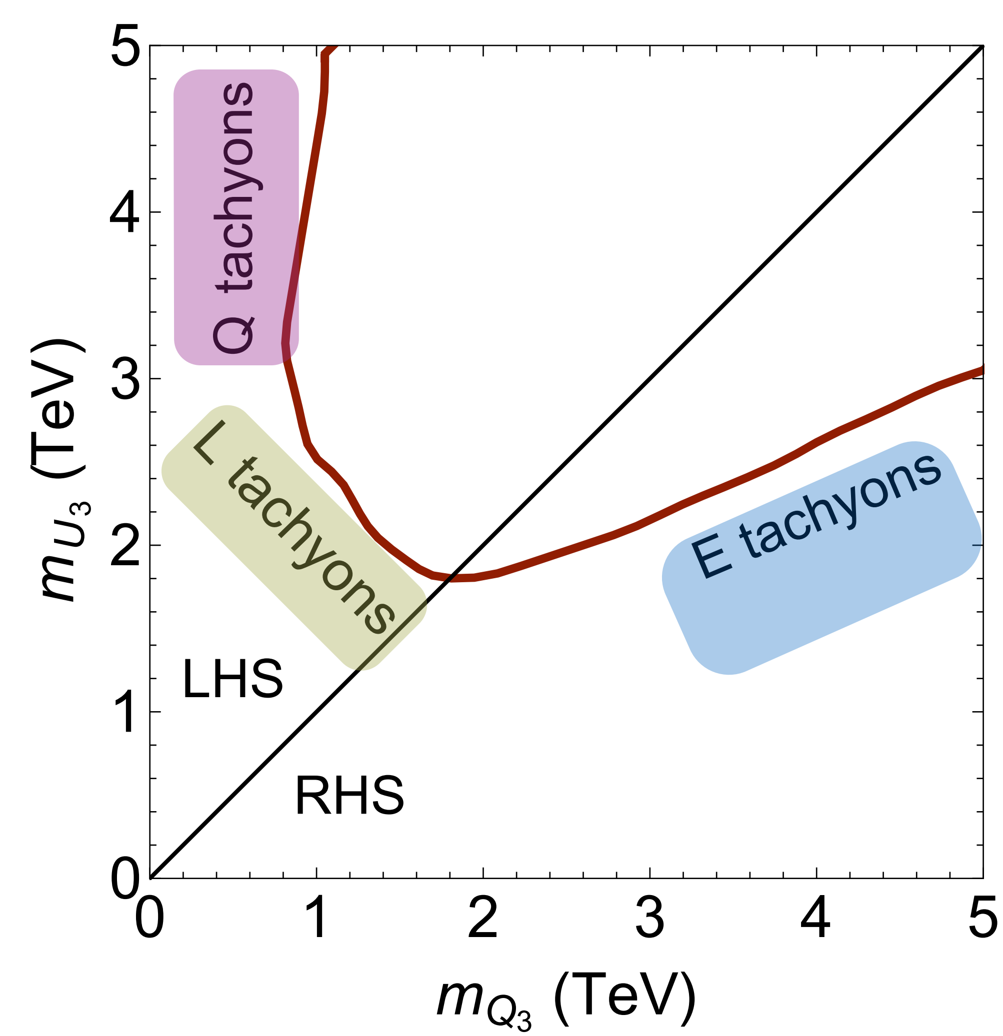
D quarks don't matter

$$m^2_{E_{1,2,3}} \approx 2m^2_{L_3} - \frac{1}{2}m^2_{H_u} + \frac{3}{2}(m^2_{U_3} - m^2_{Q_3})$$

$$m^2_{E_3} < \left(\frac{3}{2} + \frac{2b}{a}\right) m^2_{U_3} - \left(\frac{3}{2} - \frac{2b}{a}\right) m^2_{Q_3} - \frac{2c}{a} A_t^2 \,.$$

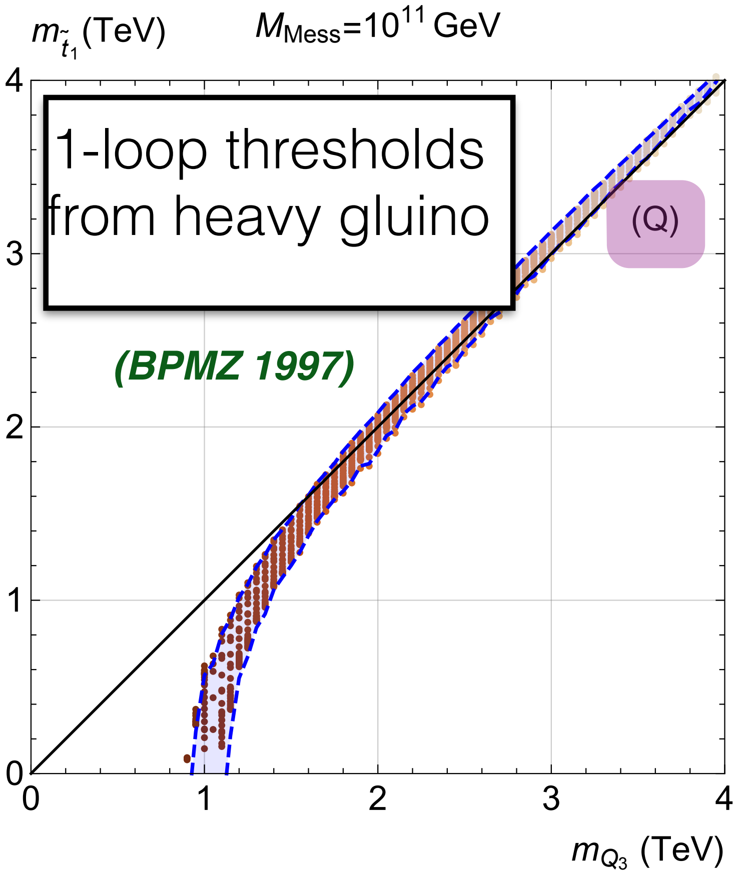
$$m^2_A = m^2_{L_3} + \mu^2$$

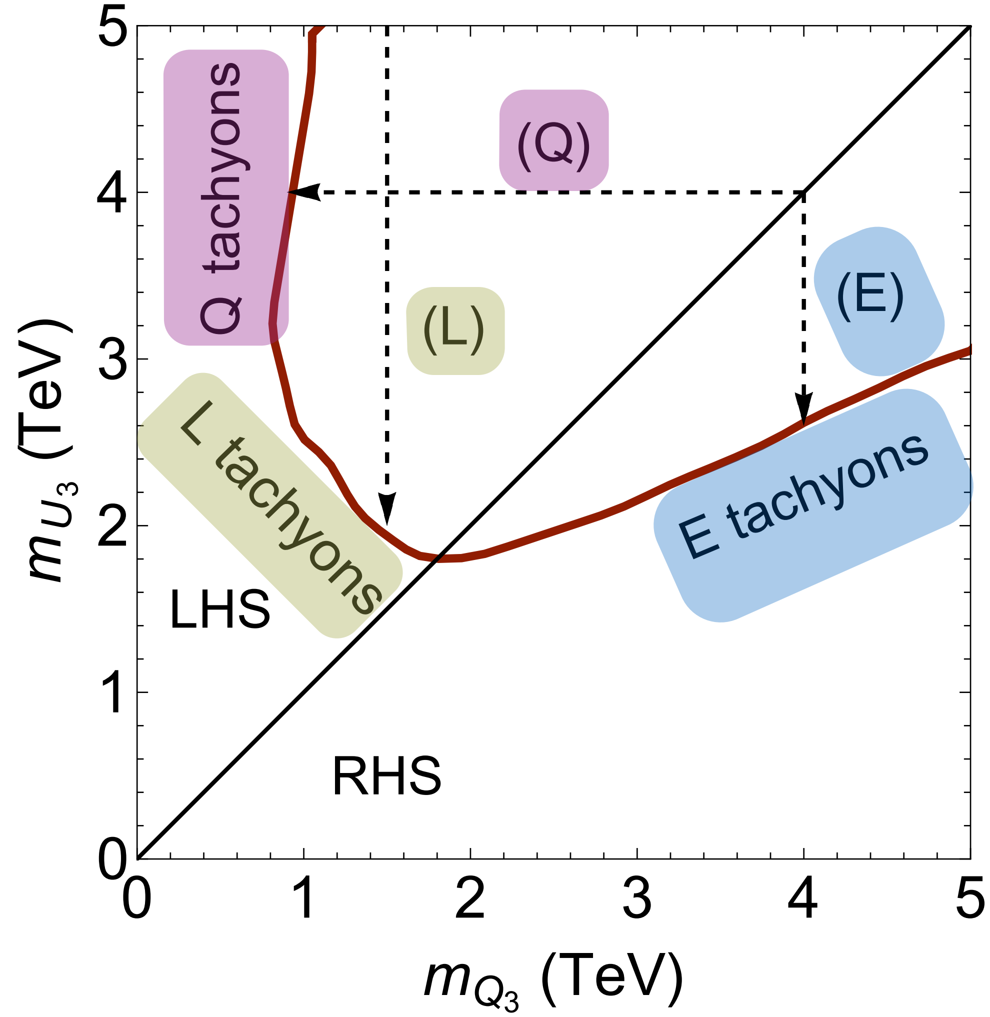
CP-odd Higgs doesn't matter

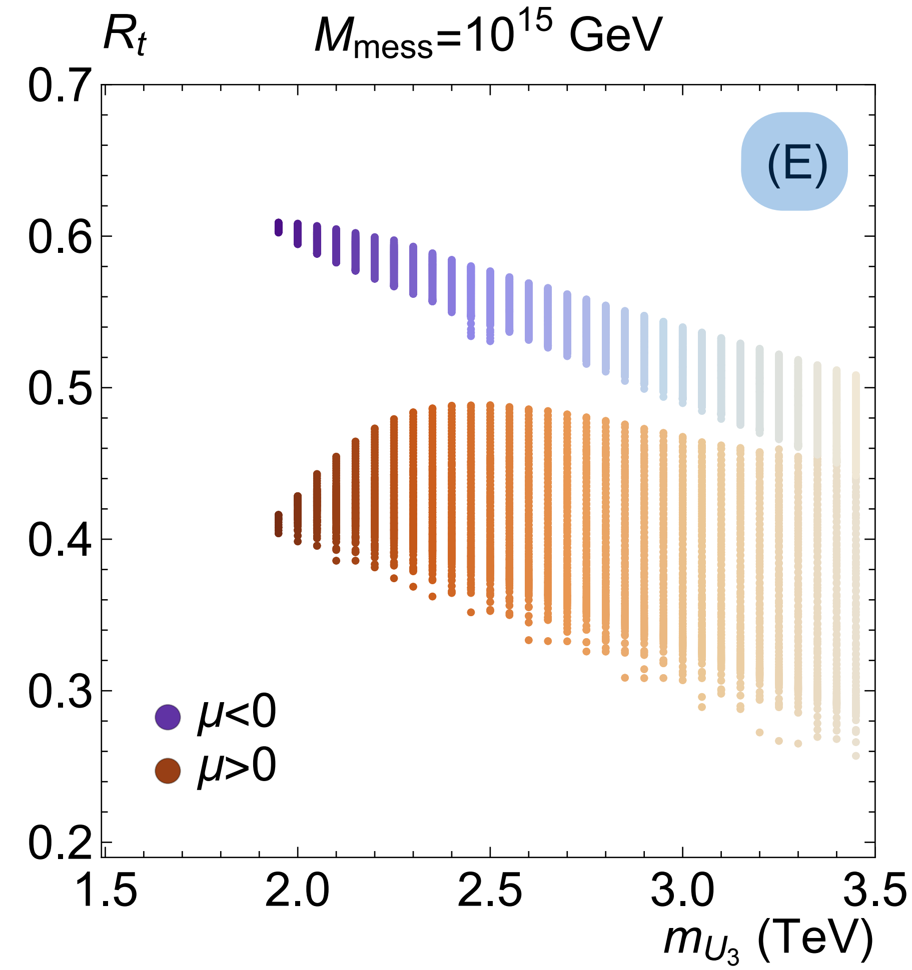


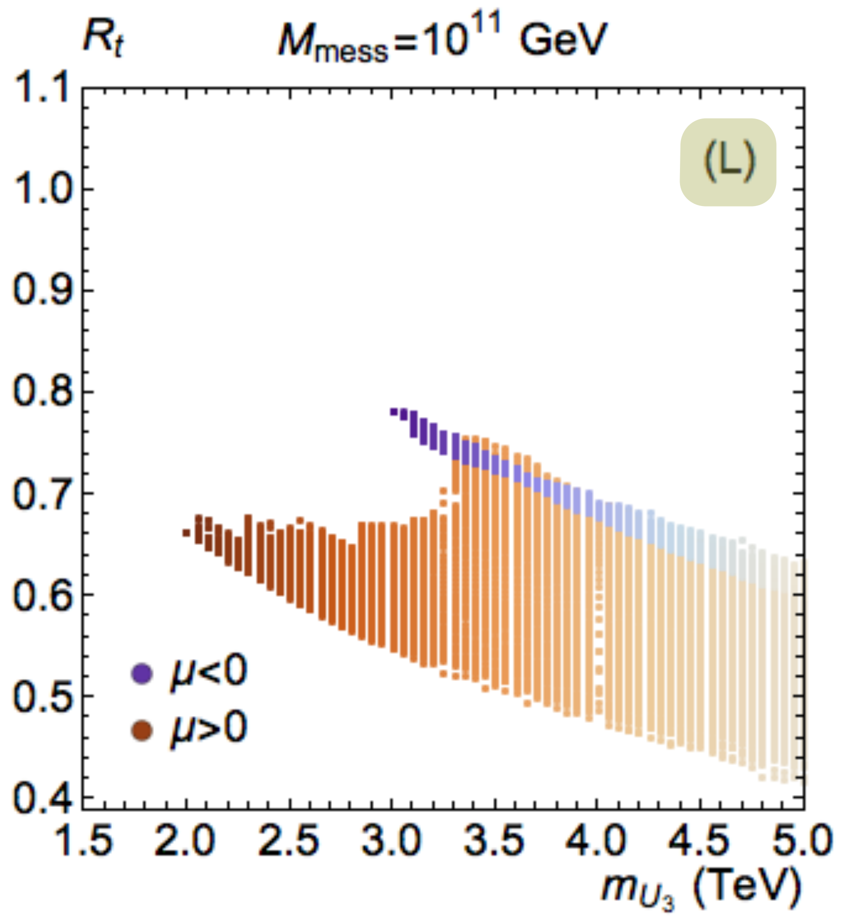
$m^2_{E_3}$, $m^2_{L_3}$, $m^2_{Q_3}$ **ARE THE ONLY RELEVANT TACHYONS**

Each tachyon characterizes a boundary









L-R COMMON FEATURES:

the allowed range of R_t (in the M_2-interval) shrinks to a point

R_t almost constant for $\mu < 0$ varies a lot for $\mu > 0$

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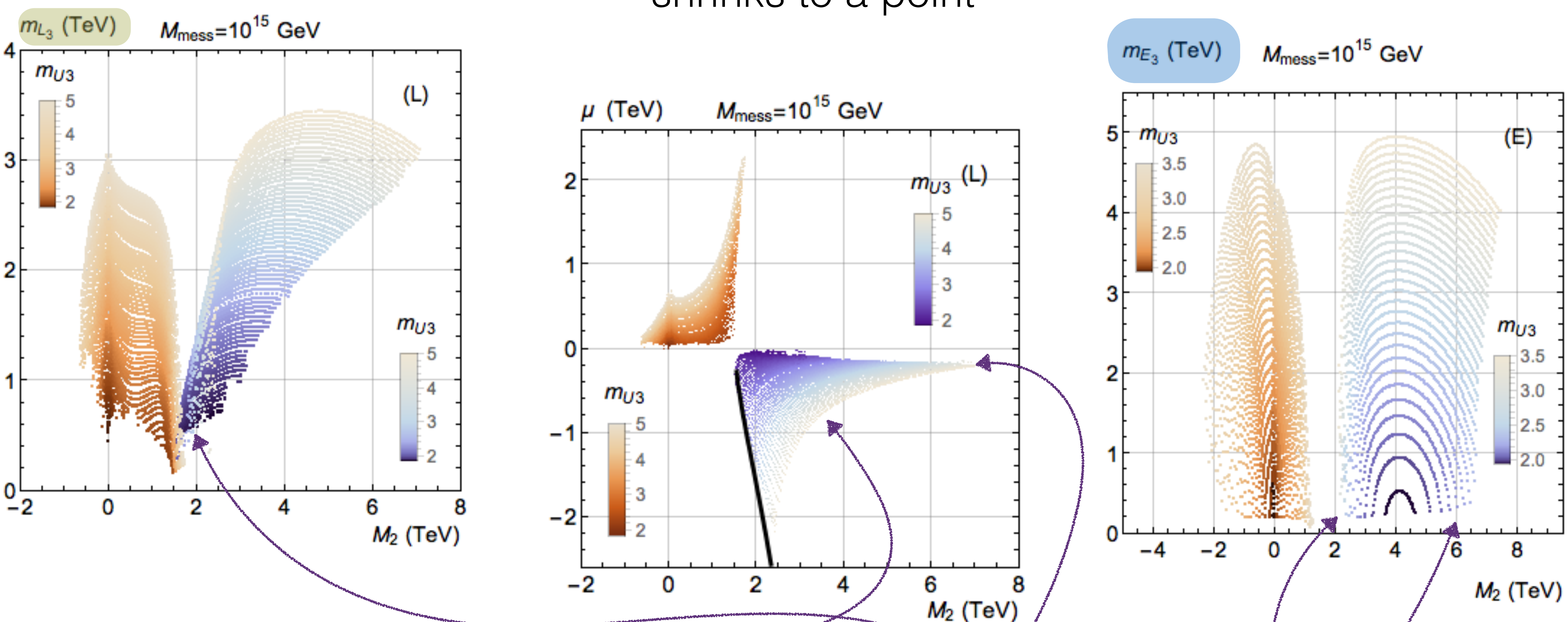
the allowed range of R_t (in the M_2-interval) shrinks to a point



$\mu < 0$ is a monotonic function of M_2

The upper end of M_2-interval is bounded by $\mu \to 0$

The lower end of M_2-interval is bounded by $m_{L_3} \to 0$ / $m_{E_3} \to 0$ (it is true also for the upper end)

The lower end can be understood analytically! (black line)

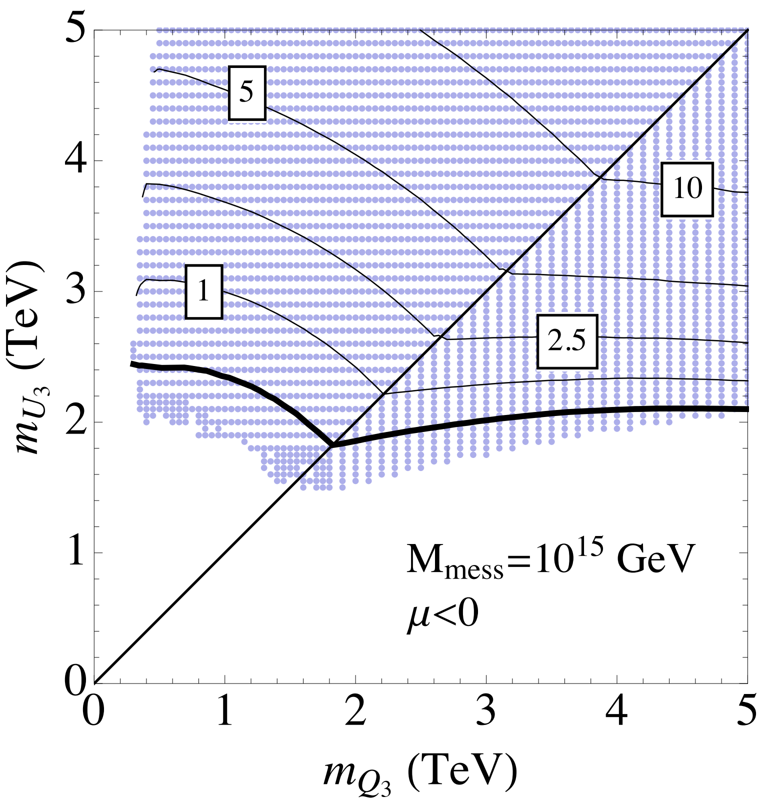
We can get a complete description of the GGM boundary analytically for $\mu < 0$

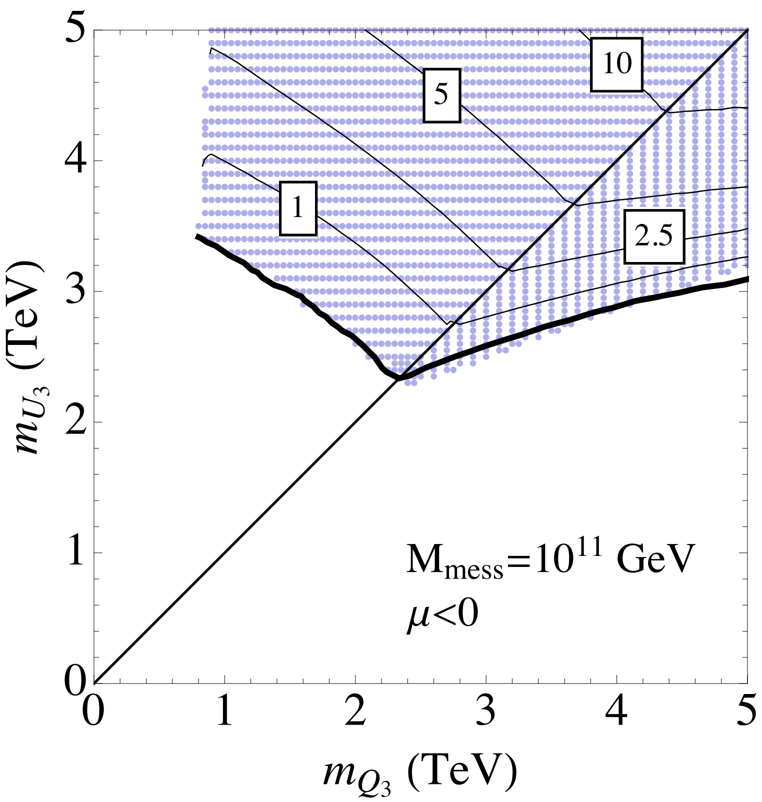
We define: $m^2 \equiv m_0^2 - \frac{3}{4} a (m_{Q_3}^2 - m_{U_3}^2)\theta(m_{Q_3}^2 - m_{U_3}^2)$

In terms of this quantity we get from EWSB

$m_{L_3} \to 0$ $\quad \mu = -\sqrt{m^2 - e\,d^2 A_t^2}$ $\qquad$ $m_{E_3} \to 0$ $\quad \mu = -\sqrt{\frac{m^2 - e\,d^2 A_t^2}{a'}}$

$m^2 = ed^2 A_t$ describes the boundary quite well!





A new feature for $\mu < 0$

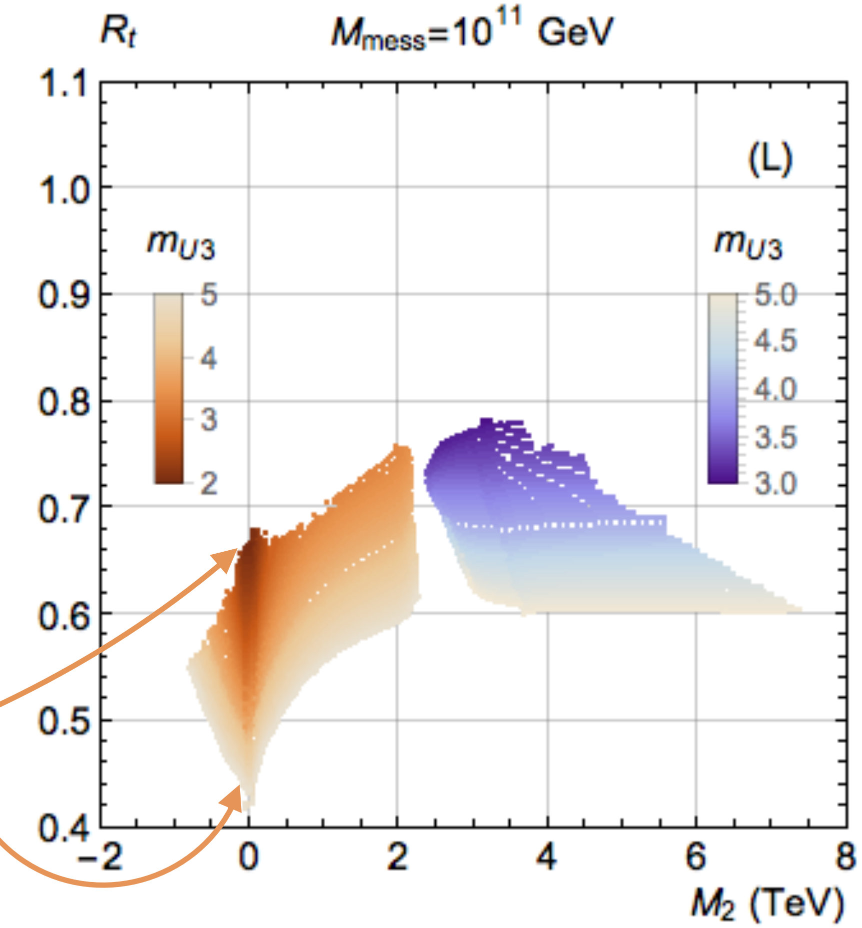
R_t almost constant for $\mu < 0$ varies a lot for $\mu > 0$

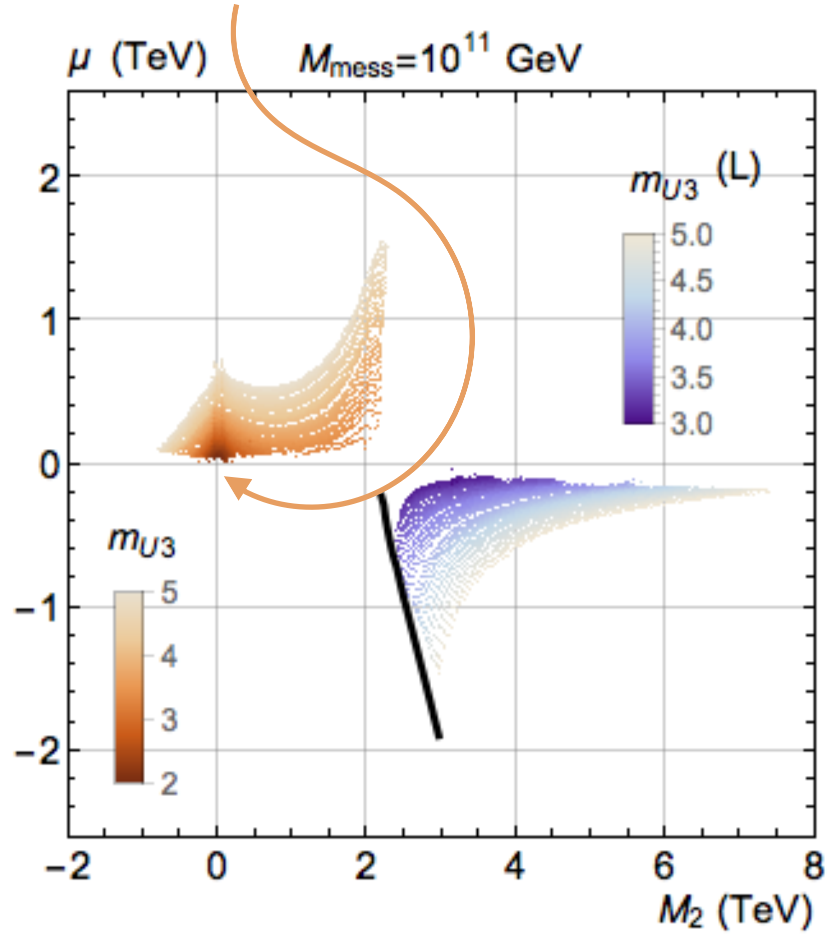
$M_2 \approx 0$ has a large effect

R_t drops

$\min[m_Q]$ has $M_2 \approx 0$

$\min[m_Q]$ has $\mu \approx 0$





From EWSB:

$$-g\,\delta M_2\,\mu\tan\beta \approx m_{L_3}^2 + \mu^2$$

$$\delta M_2 \equiv M_2 + f\,A_t$$

$\text{sign}\mu$ and $\text{sign}\delta M_2$ are correlated!

Only for $\mu > 0$ $M_2 = 0$ is allowed

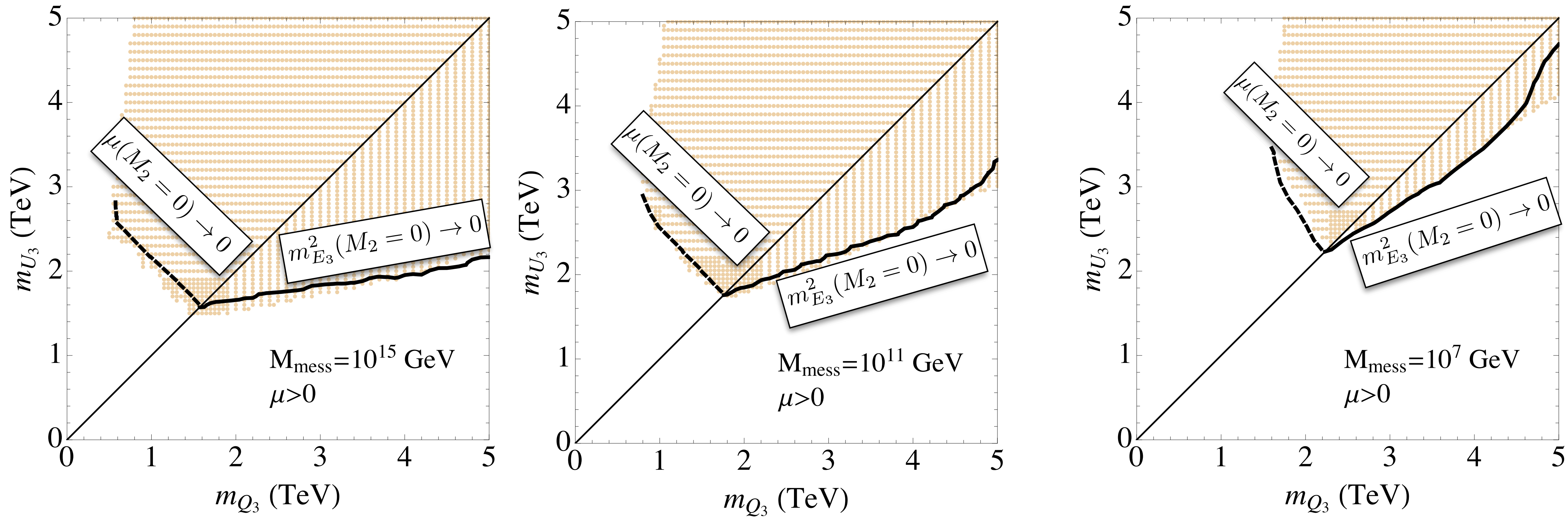
What happens for $\mu \approx M_2 \approx 0$?

There is a 1-loop threshold correction from Winos-Higgsinos enhancing the Higgs mass (see backup)

Boundary well described by taking $M_2 \approx 0$

$$\mu(M_2 = 0) = \frac{m_0^2 - e(d+f)^2 A_t^2}{agf(-A_t)\tan\beta} + \dots \text{ (dashed)}$$

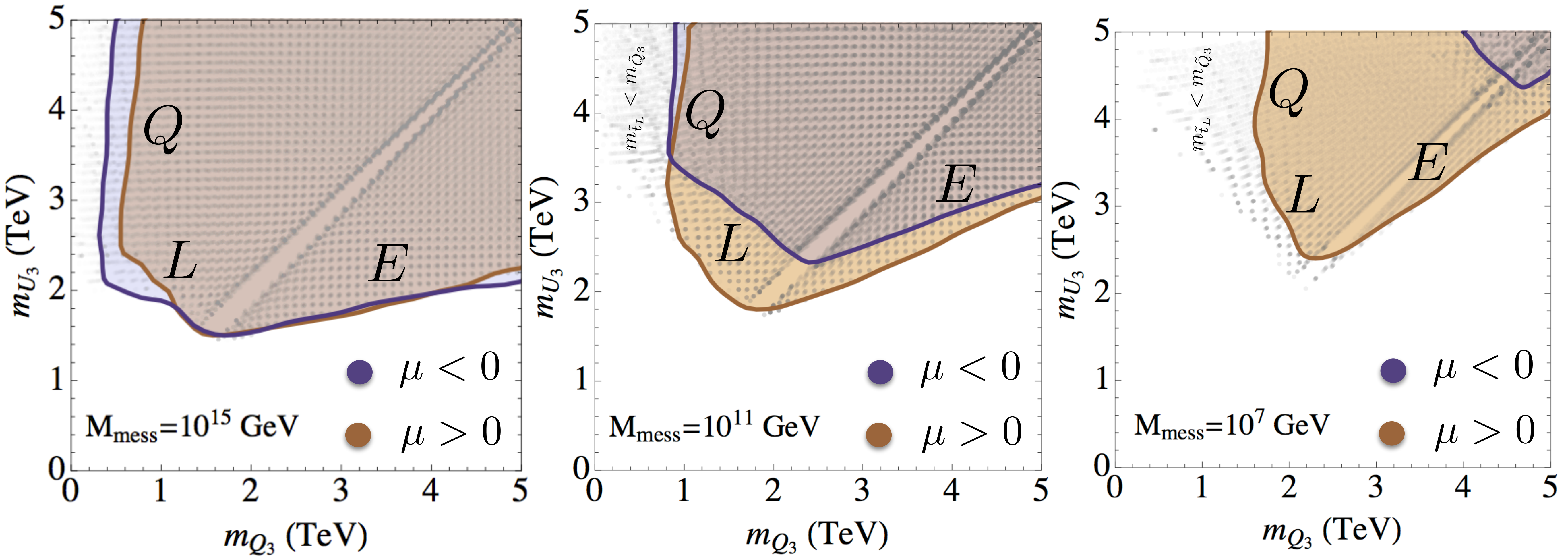
$$m_{E_3}^2(M_2 = 0) = 2\frac{m_0^2 - e(d+f)^2 A_t^2 - \frac{3}{4}a(m_{Q_3}^2 - m_{U_3}^2)}{a} + \dots \text{ (solid)}$$



This effect becomes crucial to get $m_h = 123$ GeV

at low messenger scale (for $M_{mess} = 10^7$ GeV $\mu < 0$ $m_{Q_3/U_3} > 4$ TeV)

SUMMARY



Absolute lower bound on m_{U_3} (stronger for lower M_{mess})

$m_{Q_3} \sim m_{U_3} \sim |A_t|/\sqrt{6}$ ruled out

$m^2_{Q_3}$, $m^2_{L_3}$, $m^2_{E_3}$ tachyons determines the boundary

$\tilde{t}_L , \tilde{b}_L$ arbitrarily light (driven lighter by large gluino thresholds)

$\mu > 0$ threshold from light wino-higgsino (crucial for lower M_{mess})

SKETCHES OF LHC Phenomenology

(a detailed study is work in progress…)

We have a full dataset of allowed points with m_h imposed

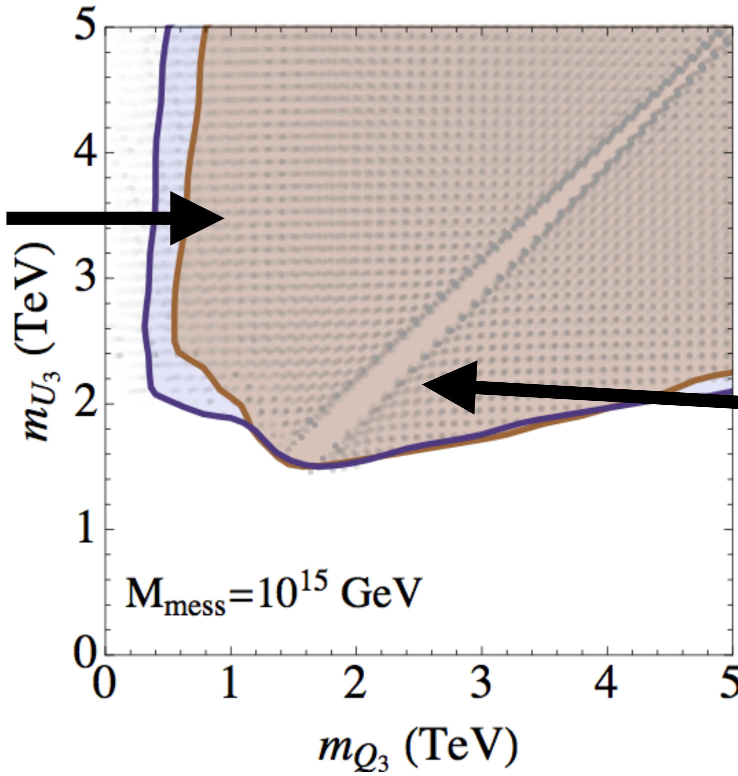
$(m_{Q_3}\, m_{U_3})$ fixed the behavior of the M_2 interval

tells which particle can be light

NLSP types & production channels in the stop mass plane

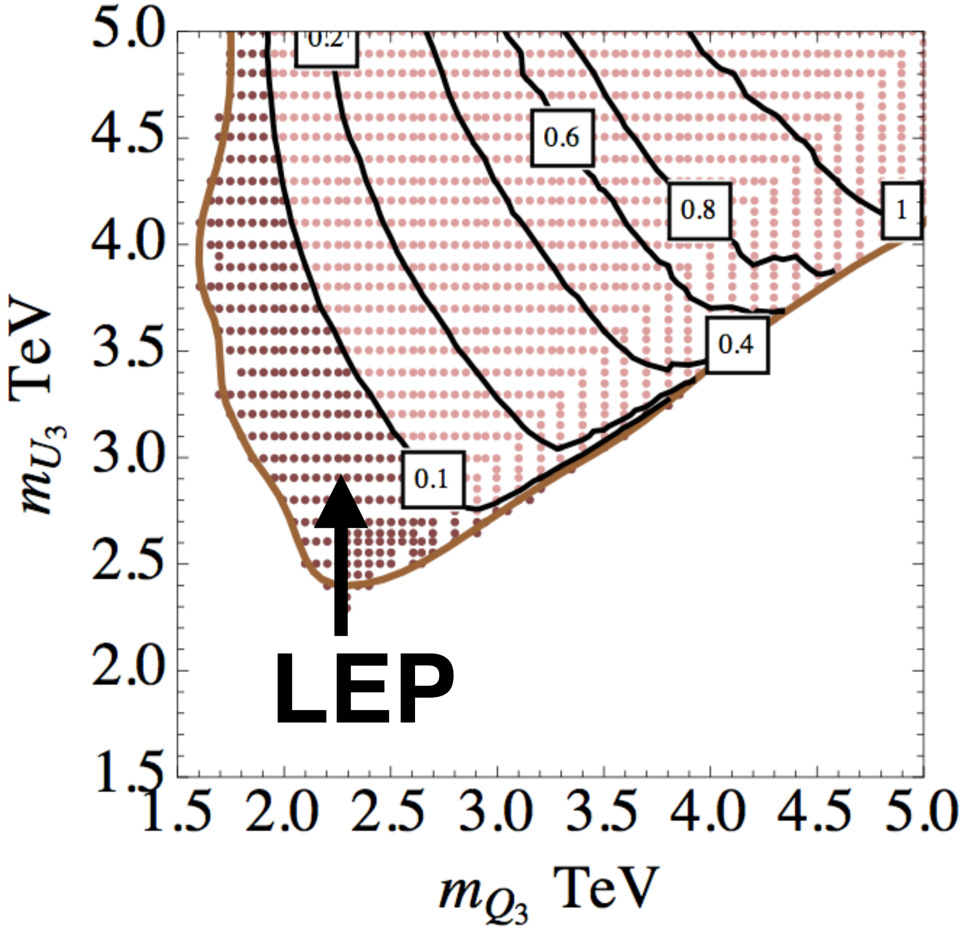
Which are the most relevant simplified models to probe GGM at Run II?

COLORED xsec:
l.h squarks & stop/bottom
from the L.H.S



EW xsec:
Higgsinos & Winos $(\mu > 0)$
from the bottom

An interesting example:



@ LOW SCALE:
most of the parameter space
can be probed with
Wino-Higgsino simplified model!

What is next?

Are there extra constraints?

Vacuum metastability (tachyons along the flow) *(Riotto & Roulet 1995)*
previous studies show that these constraints are mild

Gravitino overabundance
Dangerous effects of NLSP decays on BBN *(Giudice & Rattazzi review 1998)*
need of a very low reheating temperature

Doing better with the Higgs mass computation

ex: EFT for $m_{Q_3} \ll m_{U_3} < M_3$

(Espinosa & Navarro 2001)

Beyond pure GGM?

No results presented can be extrapolated
Similar techniques can be useful

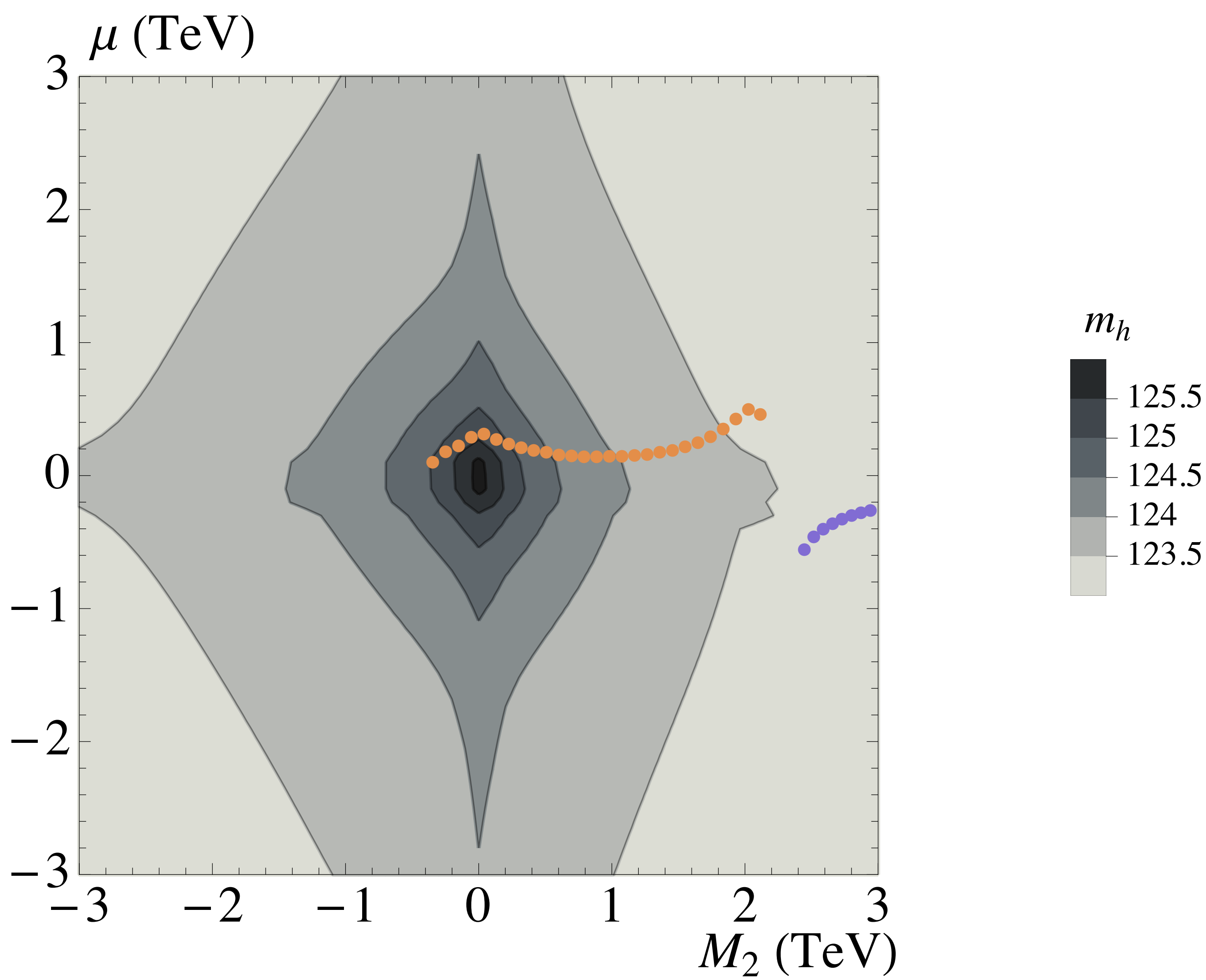
(extensive class of models...)

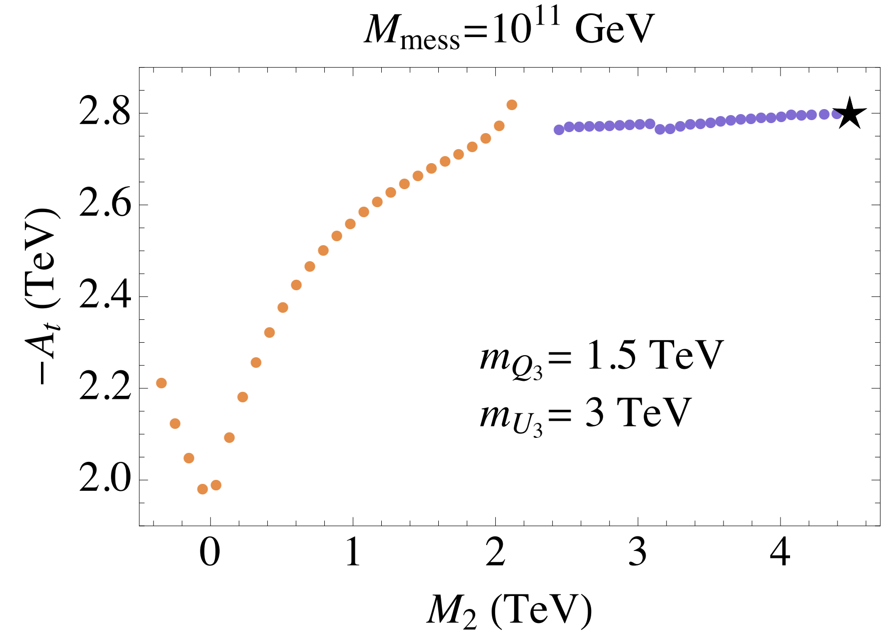
Thanks for your attention

BACKUP SLIDES I

Higgsino-Wino threshold corrections

(already noticed of course see for example Vega & Villadoro 2015)





we get a shift of around 2.5 GeV when

$$\mu \approx M_2 \approx 0$$

this corresponds to an almost 1 TeV shift in A_t

Are there other “forgotten” thresholds like this one in the MSSM?

BACKUP SLIDES II

More details on the scan

M_{mess}	M_1	m_{Q_3}, m_{U_3}, M_2	A_t	$m_{L_3},\ \mu$
$10^7, 10^{11}, 10^{15}$ GeV	1 TeV	fine scan	$m_h = 123$ GeV	EWSB conditions

Because of SoftSUSY there is a particular ordering we are forced to solve constraints

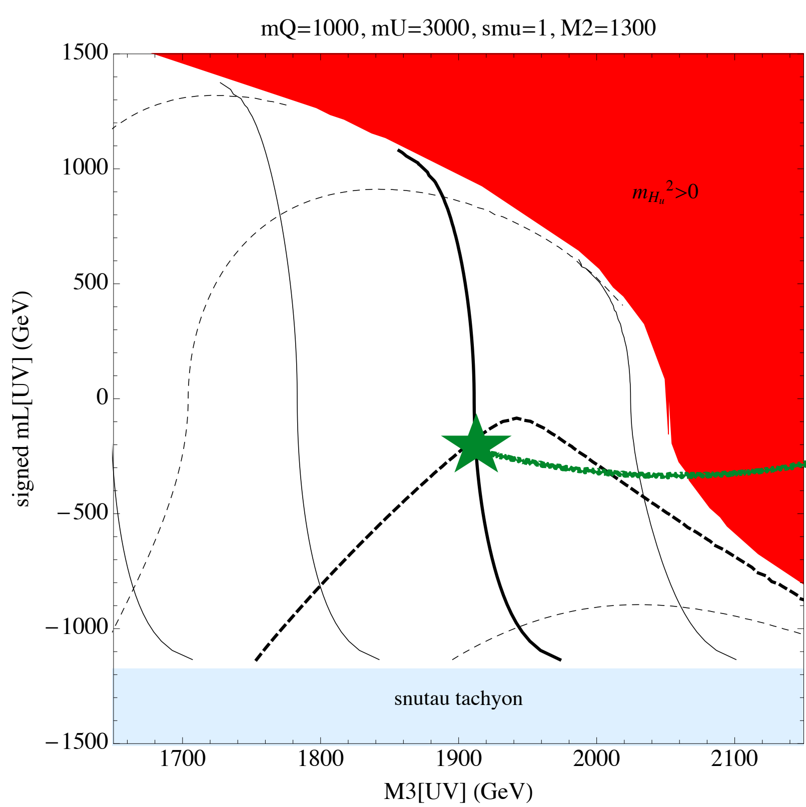
SoftSUSY: $m_{H_u}\ ,\ m_{H_d}$ ⟷ $\mu\ ,\ B_\mu\ ,\ m_h$

$m_{Q_3}\ ,\ m_{U_3}\ ,\ M_2$ ⟷

μ given

$A_t\ ,\ m_{L_3}$ scan $m_h = 123$ GeV

$B_\mu(M_{mess}) = 0$



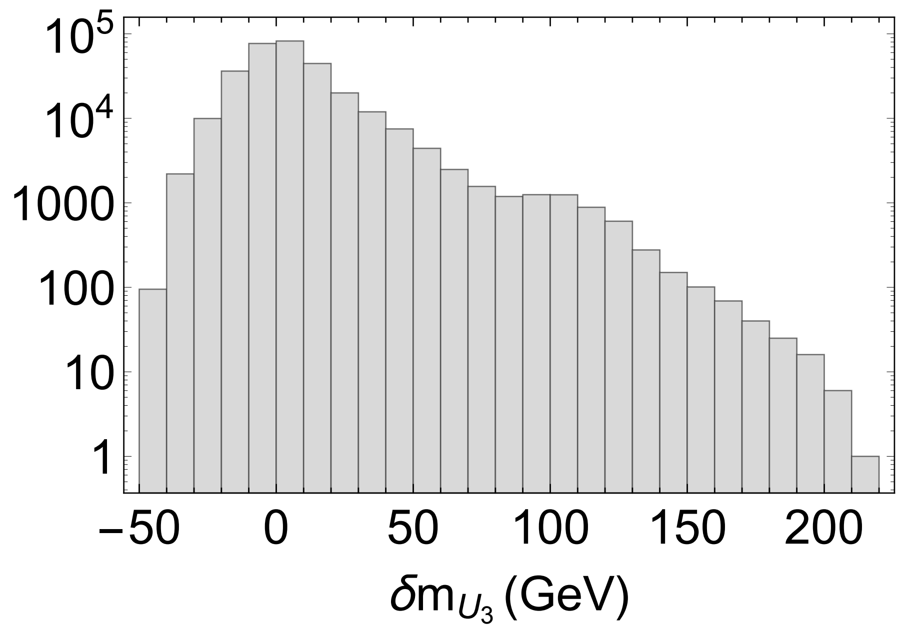
cannot do a flat scan!

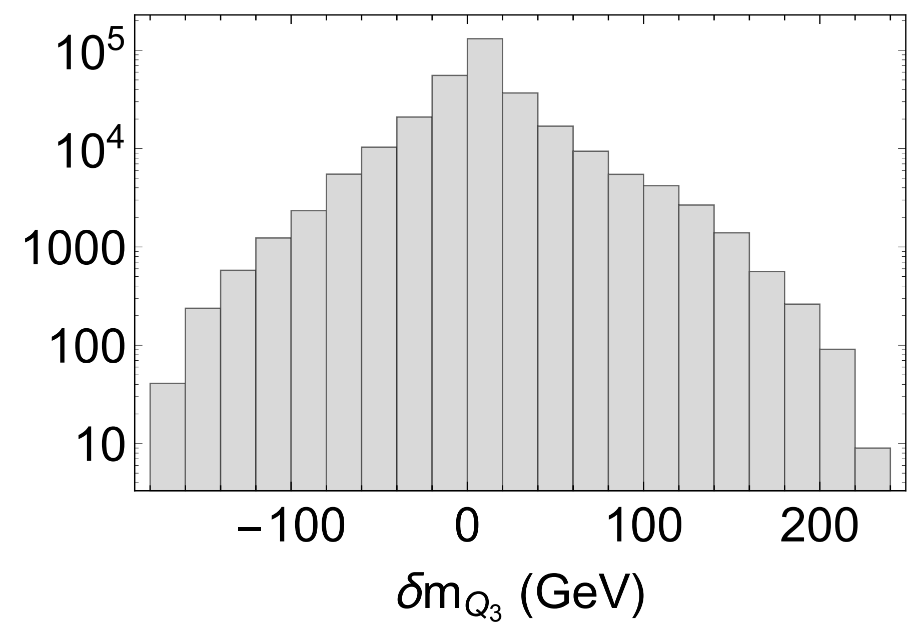
iterative method around a seed guess

it is crucial to get a good initial guess!

Algorithm convergence

Accuracy of transfer matrix in getting the stop masses
vs
SoftSUSY





TM does not capture

IR thresholds to
gauge & yukawa couplings

iterative determination
of M_S

Accuracy of the seeding algorithm