New particles' masses from transverse mass kinks: The case of Yukawa-unified SUSY GUTs

Diego Guadagnoli
LPT Orsay, Université Paris-Sud XI

Short Outline

- **SUSY GUTs with YU:** status and expected SUSY spectrum
- **M_{T2}:** why it is suitable for that spectrum
- **M_{T2}:** application (highlights)

Based on:

Choi, DG, Im, Park (JHEP 10)

DG, Raby, Straub (JHEP 09)

Altmannshofer, DG, Raby, Straub (PLB 08)

Introductory remarks

Exp. determined
SM gauge couplings
+
SM becomes supersymmetric
above O(1 TeV)

→

Couplings numerically unify
(w/ remarkable accuracy)
at a high scale $M_G \approx O(10^{16}$ GeV)

- ☐ a (remarkable) coincidence
- ☐ first hint to a larger group embedding the SM one

This observed gauge coupling unification

- ✓ is very weakly dependent on the details of the SUSY spectrum assumed
- ✓ happens at just the "right" scale M_G:
  - M_G > scale where unacceptably large proton decay is generic
  - M_G < Planck scale, where the calculation wouldn't be trustworthy

GUT groups

SO(10):

Simplest simple group where all (15) SM matter fields of generation *k* nicely fit into a single matter representation: $\mathbf{16}_k$

The 16th entry accommodates the right-handed neutrino: $(\nu_R)_k$

→

The appealing see-saw mechanism can be "built-in" automatically

The presence of SUSY guarantees stability of the ratios:

$$\frac{M_{\mathrm{GUT}}}{M_{\mathrm{EW}}}, \frac{M_{\mathrm{see-saw}}}{M_{\mathrm{EW}}} \gg 1$$

Looking for further SUSY GUT tests

Generic predictions (besides coupling unification)**:**

- ☞ **proton decay** [See *e.g.*: Dermisek, Mafi, Raby]
- ☞ **SUSY between the Fermi and the GUT scale,** hence, presumably, TeV-scale sparticles

However, in both cases detailed predictions require further model assumptions.

Are "robust" tests possible?

Looking for further SUSY GUT tests

Generic predictions (besides coupling unification)**:**

- **proton decay** [See *e.g.*: Dermisek, Mafi, Raby]

- **SUSY between the Fermi and the GUT scale,** hence, presumably, TeV-scale sparticles

Predicted pattern of SUSY masses needs specification of

- *the mechanism of SUSY breaking*
- *the form Yukawa couplings have at the high scale*

However, in both cases detailed predictions require further model assumptions.

Are "robust" tests possible?

Looking for further SUSY GUT tests

Generic predictions (besides coupling unification):

- **proton decay** [See *e.g.*: Dermisek, Mafi, Raby]
- **SUSY between the Fermi and the GUT scale,** hence, presumably, TeV-scale sparticles

However, in both cases detailed predictions require further model assumptions.

Are "robust" tests possible?

Predicted pattern of SUSY masses needs specification of

- *the mechanism of SUSY breaking*
- *the form Yukawa couplings have at the high scale*

Hypothesis:

Yukawa coupling unification (across each matter multiplet)

- Generically also model-dependent (e.g. threshold corrections, role of higher-dim operators)
- However, for the 3rd generation: $Y_t \simeq Y_b \simeq Y_\tau \simeq Y_\nu$ it remains an appealing possibility

Note:

Yukawa interactions have dim 4.

It's not unlikely that they preserve info about the symmetries of the UV theory

3^{rd} generation Yukawa unification (YU)

YU depends:

– on $\tan\beta$ being large, O(50).

– on the details of the SUSY spectrum, since m_b receives EW-scale threshold corrections, growing with growing $\tan\beta$

Hall, Rattazzi, Sarid

How to test YU, if the exact value of m_b depends on the details of the SUSY spectrum?

3rd generation Yukawa unification (YU)

YU depends:

– on $\tan\beta$ being large, O(50).

– on the details of the SUSY spectrum, since m_b receives EW-scale threshold corrections, growing with growing $\tan\beta$

Hall, Rattazzi, Sarid

How to test YU, if the exact value of m_b depends on the details of the SUSY spectrum?

Turn the argument around

Blazek, Dermisek, Raby

☑ Assume exact YU

☑ Impose the constraints from the *observed* top, bottom and tau masses

Learn about the implied GUT-scale parameter space

Assuming universal GUT-scale mass terms for sfermions (m_{16}, A_0) and for gauginos ($m_{1/2}$), one preferred region emerges:

$$A_0 \approx -2\, m_{16}, \qquad \mu\,,\, m_{1/2} \ll m_{16}$$

These relations automatically lead to Inverted Scalar Mass Hierarchy

3rd generation Yukawa unification (YU)

YU depends:

– on tanβ being large, O(50).

– on the details of the SUSY spectrum, since m_b receives EW-scale threshold corrections, growing with growing tanβ

Hall, Rattazzi, Sarid

How to test YU, if the exact value of m_b depends on the details of the SUSY spectrum?

Turn the argument around

Blazek, Dermisek, Raby

☑ Assume exact YU

☑ Impose the constraints from the *observed* top, bottom and tau masses

[*Learn about the implied GUT-scale parameter space*]

Assuming universal GUT-scale mass terms for sfermions (m_{16}, A_0) and for gauginos ($m_{1/2}$), one preferred region emerges:

$$A_0 \approx -2\, m_{16}, \qquad \mu\,, m_{1/2} \ll m_{16}$$

These relations automatically lead to Inverted Scalar Mass Hierarchy

Concrete example

Dermisek+Raby SO(10) SUSY GUT with a D_3 family symmetry

☑ Successfully describes EWPO, quark and lepton masses, CKM, PMNS.

Can one perform a deeper test of the model?

Since YU is sensitive to the whole SUSY spectrum,
to really test YU one needs additional observables, able to constrain the spectrum itself

Testing YU

Albrecht, Altmannshofer, Buras, D.G., Straub

Aim: *test YU beyond 3rd generation fermion masses*

Look at the observable consequences of the implied SUSY spectrum

Use info from FCNCs!

FCNCs: loop-suppressed observables highly sensitive to the details of the SUSY spectrum

Strategy: perform a global fit to the SO(10) GUT model parameters *including* FCNCs among the observables *directly in a fit*.

Testing YU

Albrecht, Altmannshofer, Buras, D.G., Straub

Aim: *test YU beyond 3rd generation fermion masses*

Look at the observable consequences of the implied SUSY spectrum

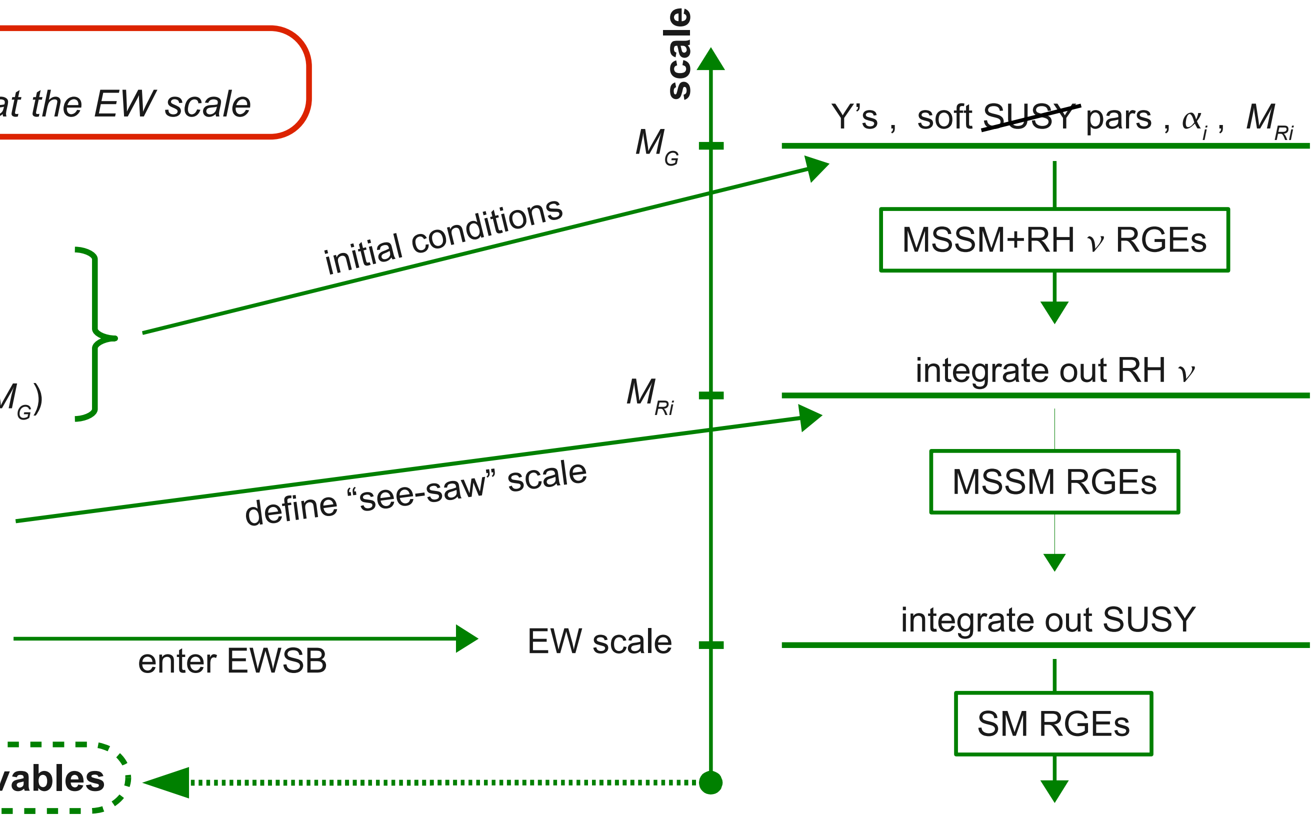
Use info from FCNCs!

FCNCs: loop-suppressed observables highly sensitive to the details of the SUSY spectrum

Strategy: perform a global fit to the SO(10) GUT model parameters *including* FCNCs among the observables *directly in a fit*.

One step back:
how a GUT-scale model is tested at the EW scale

- unified coupling and scale: α_G , M_G
- soft SUSY-breaking params at M_G
- (textures entering the Yukawa's at M_G)
- right-handed neutrino masses M_{Ri}
- μ-term and tanβ at the EW scale



Compute observables

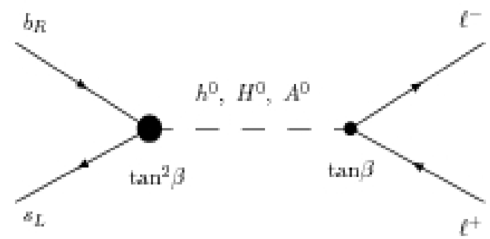
The two crucial FCNCs: $B_s \to \mu^+\mu^-$ and $B \to X_s \gamma$

A generic expectation in YU is large tanβ

$\Rightarrow$ All the FCNCs need to be computed in the MSSM with large tanβ

☑ $BR[B_s \to \mu^+\mu^-]$

For large tanβ (and sizable A_t), dominated by double penguins with neutral Higgses



Enhancement going as:

$$\mathrm{BR}[B_s \to \mu^+ \mu^-] \propto A_t^2 \frac{\tan^6\beta}{M_A^4}$$

Upper bound from CDF

$$\mathrm{BR}[B_s \to \mu^+ \mu^-]_{\mathrm{exp}} < 5.8 \times 10^{-8}$$

(at the time of our work)

M_A > 500 GeV

Generic bound valid for all the heavy Higgs masses in our class of models

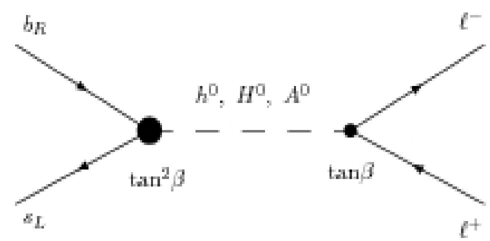
The two crucial FCNCs: $B_s \to \mu^+\mu^-$ and $B \to X_s \gamma$

A generic expectation in YU is large tanβ

$\Rightarrow$ All the FCNCs need to be computed in the MSSM with large tanβ

☑ $BR[B_s \to \mu^+\mu^-]$

For large tanβ (and sizable A_t), dominated by double penguins with neutral Higgses



Enhancement going as:

$$\mathrm{BR}[B_s \to \mu^+ \mu^-] \propto A_t^2 \frac{\tan^6 \beta}{M_A^4}$$

Upper bound from CDF

$$\mathrm{BR}[B_s \to \mu^+ \mu^-]_{\mathrm{exp}} < 5.8 \times 10^{-8}$$

(at the time of our work)

M_A > 500 GeV

Generic bound valid for all the heavy Higgs masses in our class of models

☑ $BR[B \to X_s \gamma]$

$$\mathrm{BR}[B \to X_s \gamma]^{\mathrm{exp}}_{E_\gamma > 1.6\mathrm{GeV}} < (3.52 \pm 0.25) \times 10^{-4}$$ { HFAG average }

$$\mathrm{BR}[B \to X_s \gamma]^{\mathrm{SM}}_{E_\gamma > 1.6\mathrm{GeV}} < (3.15 \pm 0.23) \times 10^{-4}$$ { Misiak *et al.*, PRL '07 }

The theory prediction for $B \to X_s \gamma$ must be "SM-like"

☑ $\mathrm{BR}[B \to X_s \gamma]$ [continued]

Very rough formula

$$\Gamma[B \to X_s \gamma] \approx \frac{G_F^2 \alpha_{\mathrm{e.m.}}}{32\pi^4} |V_{ts}^* V_{tb}|^2 m_b^5 \left(|C_7^{\mathrm{eff}}(\mu_b)|^2 + \ldots \right)$$

with $C_7^{\mathrm{eff}}(\mu_b) = C_{7,\mathrm{SM}}^{\mathrm{eff}}(\mu_b) + C_{7,\mathrm{NP}}(\mu_b)$

New contributions come mainly from charginos and Higgses. Gluinos play here a minor role

$$C_{7,\mathrm{NP}}(\mu_b) \simeq C_7^{\tilde{\chi}^+}(\mu_b) + C_7^{H^+}(\mu_b)$$

☑ $\mathrm{BR}[B \to X_s \gamma]$ [continued]

Very rough formula

$$\Gamma[B \to X_s \gamma] \approx \frac{G_F^2 \alpha_{\mathrm{e.m.}}}{32\pi^4} |V_{ts}^* V_{tb}|^2 m_b^5 \left(|C_7^{\mathrm{eff}}(\mu_b)|^2 + \ldots \right)$$

with $C_7^{\mathrm{eff}}(\mu_b) = C_{7,\mathrm{SM}}^{\mathrm{eff}}(\mu_b) + C_{7,\mathrm{NP}}(\mu_b)$

New contributions come mainly from charginos and Higgses. Gluinos play here a minor role

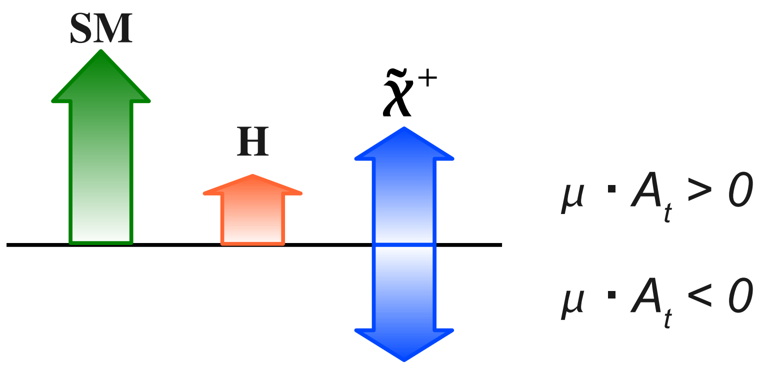
$$C_{7,\mathrm{NP}}(\mu_b) \simeq C_7^{\tilde{\chi}^+}(\mu_b) + C_7^{H^+}(\mu_b)$$

Main features

- Contributions from charginos are the dominant ones, and behave like

$$C_7^{\tilde{\chi}^+} \propto +\mu A_t \tan\beta \times \mathrm{sign}(C_7^{\mathrm{SM}})$$

In our case, $\mu \cdot A_t < 0$ ⇨ *large, negative, chargino contribs.*



☑ BR$[B \to X_s \gamma]$ [continued]

Very rough formula

$$\Gamma[B \to X_s \gamma] \approx \frac{G_F^2 \alpha_{\rm e.m.}}{32\pi^4} |V_{ts}^* V_{tb}|^2 m_b^5 \left(|C_7^{\rm eff}(\mu_b)|^2 + \ldots \right)$$

with $C_7^{\rm eff}(\mu_b) = C_{7,\rm SM}^{\rm eff}(\mu_b) + C_{7,\rm NP}(\mu_b)$

New contributions come mainly from charginos and Higgses. Gluinos play here a minor role

$$C_{7,\rm NP}(\mu_b) \simeq C_7^{\tilde{\chi}^+}(\mu_b) + C_7^{H^+}(\mu_b)$$

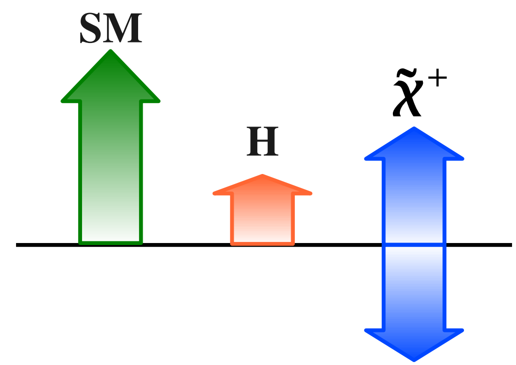
Main features

- Contributions from charginos are the dominant ones, and behave like

$$C_7^{\tilde{\chi}^+} \propto +\mu A_t \tan\beta \times {\rm sign}(C_7^{\rm SM})$$

In our case, $\mu \cdot A_t < 0$ ⇨ *large, negative, chargino contribs.*

- Higgs contrib's *add up* to the SM ones. However, Higgs contrib's are made small by the *lower bound on* M_A placed by $B_s \to \mu^+ \mu^-$



$\mu \cdot A_t > 0$

$\mu \cdot A_t < 0$

Higgs contribs are too small to cancel the chargino ones.

To make chargino contribs small, one has to invoke decoupling in up-type scalars.

☑ **The technique discussed** – a global fit to 3rd generation masses, EW observables *and FCNCs* – **can be used to test <u>different realizations</u> of Yukawa-unified SUSY GUTs**

☞ **Different realizations =**
different choices for the pattern of soft SUSY-breaking terms at the GUT scale.

☑ **The technique discussed** – a global fit to 3rd generation masses, EW observables *and FCNCs* – **can be used to test <u>different realizations</u> of Yukawa-unified SUSY GUTs**

☞ **Different realizations =**
different choices for the pattern of soft SUSY-breaking terms at the GUT scale.

☑ **We focussed on two main scenarios:**

❶ *universal GUT-scale soft terms*

❷ *GUT-scale soft terms inheriting from the Yukawa couplings (Minimal Flavor Violating).*
In particular: split trilinear soft terms

Both scenarios are relatively simple to handle in a fitting procedure, and the second scenario is also quite plausible.

Scenarios considered ❶ *SUSY GUTs with YU and universal GUT-scale soft terms*

Assumptions here: *Soft terms consist of a universal bilinear (m_{16}), a universal trilinear (A_0), a universal gaugino mass ($m_{1/2}$) and split soft terms for the Higgses (m_{Hu} , m_{Hd})*

Scenarios considered ➊ *SUSY GUTs with YU and universal GUT-scale soft terms*

Assumptions here: *Soft terms consist of a universal bilinear (m_{16}), a universal trilinear (A_0), a universal gaugino mass ($m_{1/2}$) and split soft terms for the Higgses (m_{Hu} , m_{Hd})*

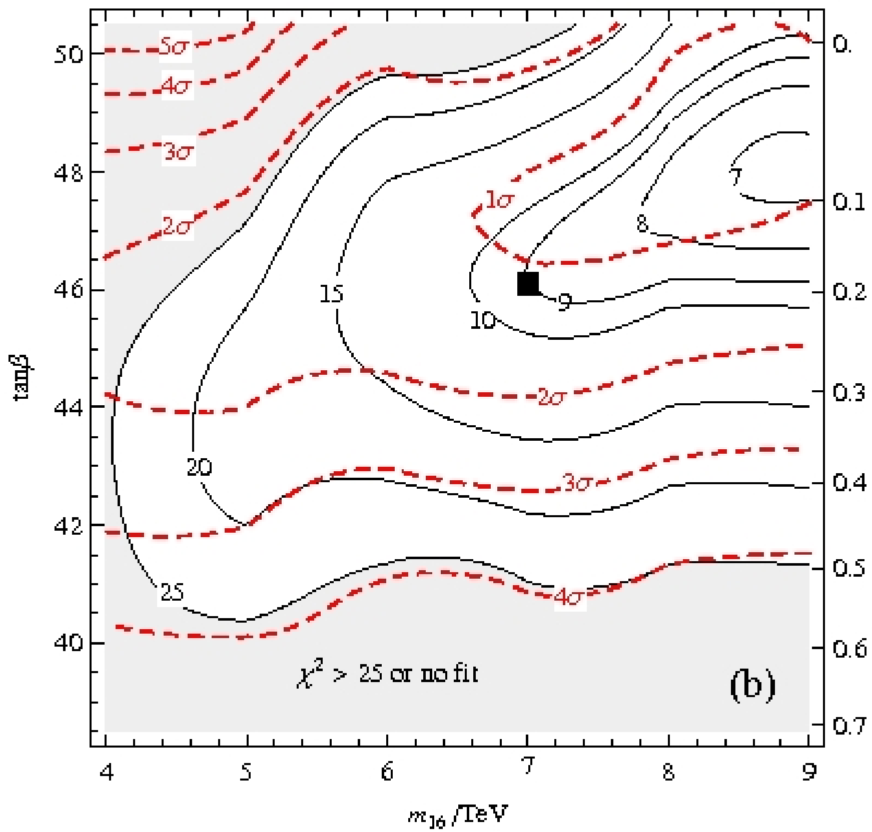
Features/Issues

The combined **info from FCNCs** (in particular $B \to X_s \gamma$ and $B_s \to \mu^+ \mu^-$) **favors values of tanβ lower than O(50)**

Conversely, it is known that $\boldsymbol{m_b}$ **prefers tanβ O(50)** (or else, tanβ close to 1, excluded by LEP)

Scenario 1 is viable only by advocating ***partial decoupling of the sfermion spectrum,*** *the lightest mass exceeding 1 TeV*

Altmannshofer, DG, Raby, Straub ('08)



Scenarios considered ❶ *SUSY GUTs with YU and universal GUT-scale soft terms*

Assumptions here: *Soft terms consist of a universal bilinear (m_{16}), a universal trilinear (A_0), a universal gaugino mass ($m_{1/2}$) and split soft terms for the Higgses (m_{Hu} , m_{Hd})*

Features/Issues

- The combined **info from FCNCs** (in particular $B \to X_s \gamma$ and $B_s \to \mu^+ \mu^-$) **favors values of tanβ lower than O(50)**

  Conversely, it is known that **m_b prefers tanβ O(50)** (or else, tanβ close to 1, excluded by LEP)

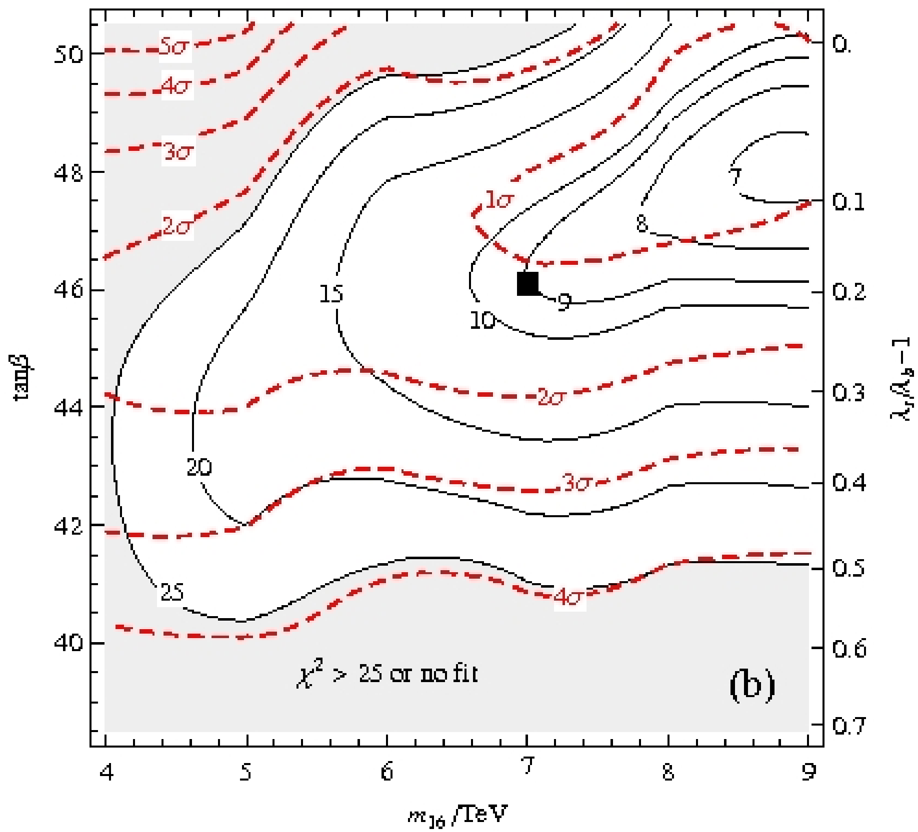
→ *Scenario 1 is viable only by advocating* ***partial decoupling of the sfermion spectrum,*** *the lightest mass exceeding 1 TeV*

- **Spectrum predictions are robust**, because of the cross-fire among the constraints:

$$m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\chi}_2^0}/2 \simeq m_{\tilde{\chi}_1^\pm} \simeq 60 \text{ GeV}$$

$$m_{\tilde{g}} \simeq 500 \text{ GeV} \qquad m_{\text{scalars}} \geq 1 \text{ TeV}$$

Altmannshofer, DG, Raby, Straub ('08)



Let us turn to the 2nd scenario: soft terms non-universalities.

Two simple such scenarios of non universalities emerge:

- non-universal gaugino masses — widely studied, see e.g. Baer *et al.*, Balazs, Dermisek
- non-universal soft terms of "minimal flavor violating" (MFV) form, i.e. inheriting from the Yukawa couplings present in the SM — **our focus**

Let us turn to the 2nd scenario: soft terms non-universalities.

Two simple such scenarios of non universalities emerge:

- non-universal gaugino masses — widely studied, see e.g. Baer *et al.*, Balazs, Dermisek
- non-universal soft terms of "minimal flavor violating" (MFV) form, i.e. inheriting from the Yukawa couplings present in the SM — **our focus**

Soft terms are functions of the Yukawa couplings:
Yukawa's are the only spurions of the broken flavor symmetry

$$m_Q^2 = \overline{m}_Q^2(1_{3\times 3} + c_Q^u Y_U Y_U^+ + c_Q^d Y_D Y_D^+ + O(Y_{U,D}^4))$$

$$m_U^2 = \overline{m}_U^2(1_{3\times 3} + c_U^u Y_U^+ Y_U + O(Y_U^4))$$

$$m_D^2 = \overline{m}_D^2(1_{3\times 3} + c_D^d Y_D^+ Y_D + O(Y_D^4))$$

$$A_U = \overline{A}_U Y_U(1_{3\times 3} + O(Y_D^2))$$

$$A_D = \overline{A}_D Y_D(1_{3\times 3} + O(Y_U^2))$$

The YU hypothesis and the hierarchical structure of the Yukawa couplings allow to drastically simplify the previous expansions.

Soft terms in the previous expansions are in fact easily seen to fulfill the approximate patterns

$$m^2_{Q,U,D} \simeq \begin{pmatrix} \overline{m}^2_{Q,U,D} & 0 & 0 \\ 0 & \overline{m}^2_{Q,U,D} & 0 \\ 0 & 0 & \overline{m}^2_{Q,U,D} + \Delta m^2_{Q,U,D} \end{pmatrix}, \quad A_{U(D)} \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_{t(b)} \overline{A}_{U(D)} \end{pmatrix}$$

valid up to terms of order $(Y^2_{U(D)})_{ij} / y^2_{33}$

The YU hypothesis and the hierarchical structure of the Yukawa couplings allow to drastically simplify the previous expansions.

Soft terms in the previous expansions are in fact easily seen to fulfill the approximate patterns

$$m^2_{Q,U,D} \simeq \begin{pmatrix} \overline{m}^2_{Q,U,D} & 0 & 0 \\ 0 & \overline{m}^2_{Q,U,D} & 0 \\ 0 & 0 & \overline{m}^2_{Q,U,D} + \Delta m^2_{Q,U,D} \end{pmatrix}, \quad A_{U(D)} \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_{t(b)} \overline{A}_{U(D)} \end{pmatrix}$$

valid up to terms of order $(Y^2_{U(D)})_{ij} / y^2_{33}$

We will focus on the case of <u>trilinear splittings</u>

- bilinear splittings have already been (partly) explored, and look only partly promising
- our initial χ^2 explorations – with all the splittings allowed – pointed mostly to trilinear splittings

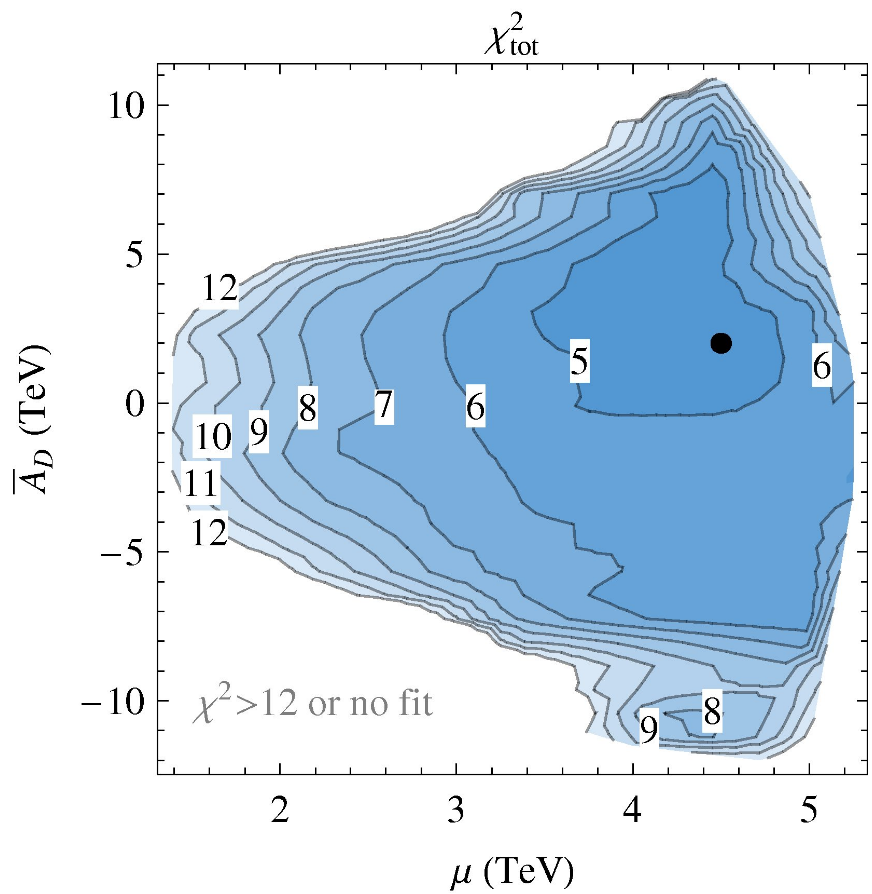
Scenarios considered ❷ *SUSY GUTs with YU and split trilinear soft terms at the GUT scale*

Assumptions here: *With respect to scenario 1, trilinears are allowed to be split: A_U ,A_D*
(In principle also bilinears, e.g. between the Q, U, D multiplets, but fits indicate a marginal impact)

Features/Issues

- Agreement with data clearly selects the region with large $\mu = O(m_{16})$ and sizable $A_U - A_D$ splitting

DG, Raby, Straub ('09)



Scenarios considered ❷ *SUSY GUTs with YU and split trilinear soft terms at the GUT scale*

Assumptions here: *With respect to scenario 1, trilinears are allowed to be split: A_U ,A_D*
(In principle also bilinears, e.g. between the Q, U, D multiplets, but fits indicate a marginal impact)

Features/Issues

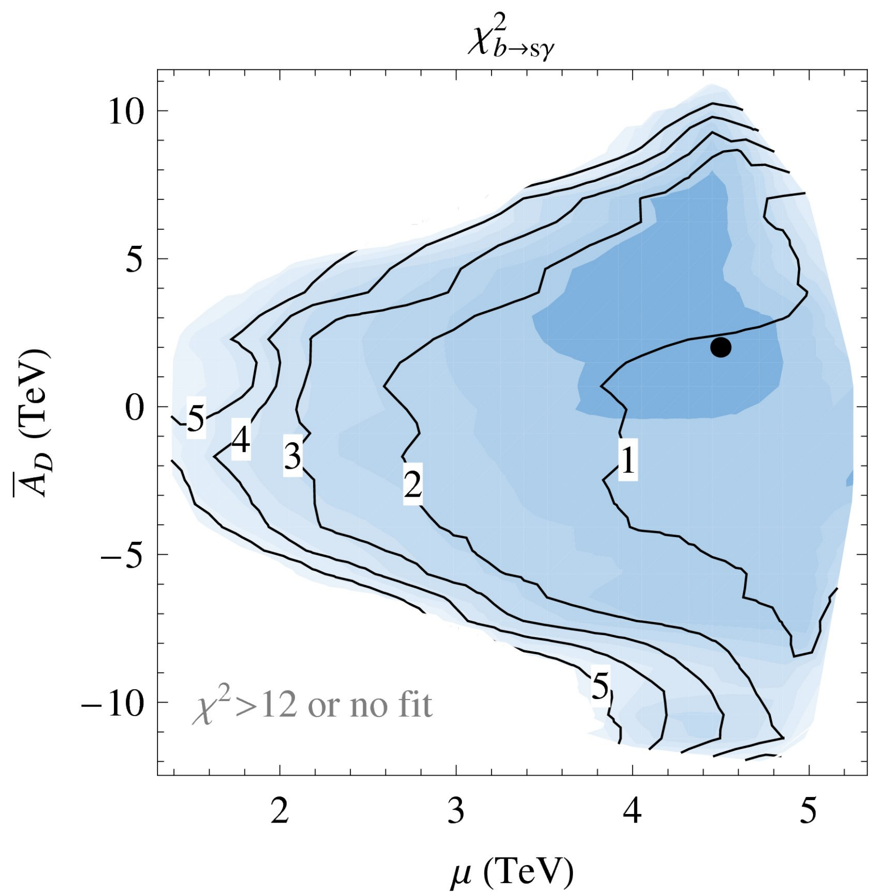
- Agreement with data clearly selects the region with large μ = O(m_{16}) and sizable $A_U - A_D$ splitting

In this region:

*The **lightest (RH) stop** (and the gluino) are required to be very close to their exp bounds, i.e. **are veeeery light**.*

All the FCNC tensions are relieved.

DG, Raby, Straub ('09)



Scenarios considered ❷ *SUSY GUTs with YU and split trilinear soft terms at the GUT scale*

Assumptions here: *With respect to scenario 1, trilinears are allowed to be split: A_U ,A_D*
(In principle also bilinears, e.g. between the Q, U, D multiplets, but fits indicate a marginal impact)

Features/Issues

- Agreement with data clearly selects the region with large $\mu = O(m_{16})$ and sizable $A_U - A_D$ splitting

In this region:

The ***lightest (RH) stop*** *(and the gluino) are required to be very close to their exp bounds, i.e.* ***are veeeery light****.*

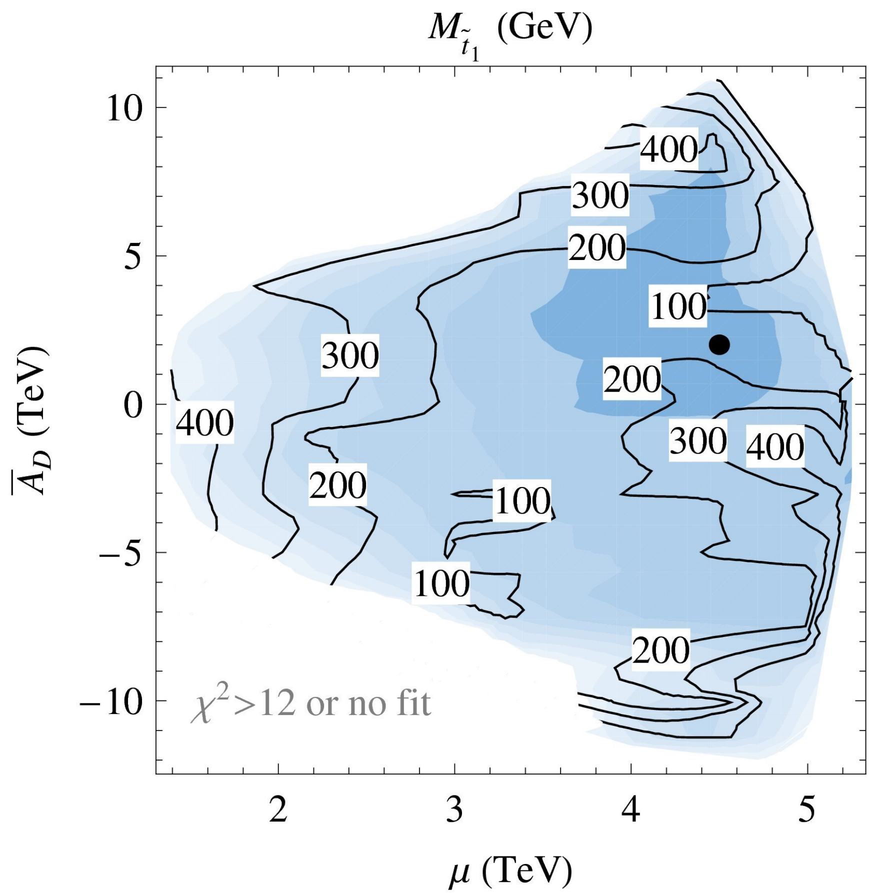
All the FCNC tensions are relieved.

- So, *substantial improvement on the fine tuning on the above quantities*.

Price: achieving EWSB with precisely the right value of M_Z does require increased fine tuning, because of the large μ

- Again, spectrum predictions are robust

DG, Raby, Straub ('09)



The above scenarios at the LHC

“ Upon discovery of new particles, the first fundamental question to ask is what is the mass of these particles ”

Spectrum predictions

scenario 1		scenario 2	
M_{h^0}	121	M_{h^0}	126
M_{H^0}	585	M_{H^0}	1109
M_A	586	M_A	1114
M_{H^+}	599	M_{H^+}	1115
$m_{\tilde{t}_1}$	783	$M_{\tilde{t}_1}$	192
$m_{\tilde{t}_2}$	1728	$m_{\tilde{t}_2}$	2656
$m_{\tilde{b}_1}$	1695	$m_{\tilde{b}_1}$	2634
$m_{\tilde{b}_2}$	2378	$m_{\tilde{b}_2}$	3759
$m_{\tilde{\tau}_1}$	3297	$m_{\tilde{\tau}_1}$	3489
$m_{\tilde{\chi}_1^0}$	59	$m_{\tilde{\chi}_1^0}$	53
$m_{\tilde{\chi}_2^0}$	118	$m_{\tilde{\chi}_2^0}$	104
$m_{\tilde{\chi}_1^+}$	117	$m_{\tilde{\chi}_1^+}$	104
$M_{\tilde{g}}$	470	$M_{\tilde{g}}$	399

- Main difference: a stop respectively lighter and heavier than the gluino

The above scenarios at the LHC

" Upon discovery of new particles, the first fundamental question to ask is what is the mass of these particles "

Spectrum predictions

scenario 1		scenario 2	
M_{h^0}	121	M_{h^0}	126
M_{H^0}	585	M_{H^0}	1109
M_A	586	M_A	1114
M_{H^+}	599	M_{H^+}	1115
$m_{\tilde{t}_1}$	783	$M_{\tilde{t}_1}$	192
$m_{\tilde{t}_2}$	1728	$m_{\tilde{t}_2}$	2656
$m_{\tilde{b}_1}$	1695	$m_{\tilde{b}_1}$	2634
$m_{\tilde{b}_2}$	2378	$m_{\tilde{b}_2}$	3759
$m_{\tilde{\tau}_1}$	3297	$m_{\tilde{\tau}_1}$	3489
$m_{\tilde{\chi}_1^0}$	59	$m_{\tilde{\chi}_1^0}$	53
$m_{\tilde{\chi}_2^0}$	118	$m_{\tilde{\chi}_2^0}$	104
$m_{\tilde{\chi}_1^+}$	117	$m_{\tilde{\chi}_1^+}$	104
$M_{\tilde{g}}$	470	$M_{\tilde{g}}$	399

- Main difference: a stop respectively lighter and heavier than the gluino
- For neutralino1,2 and chargino1 and basically also the gluino, predictions are the same.

The above scenarios at the LHC

" Upon discovery of new particles,
the first fundamental question to ask
is what is the mass of these particles "

Spectrum predictions

scenario 1		scenario 2	
M_{h^0}	121	M_{h^0}	126
M_{H^0}	585	M_{H^0}	1109
M_A	586	M_A	1114
M_{H^+}	599	M_{H^+}	1115
$m_{\tilde{t}_1}$	783	$M_{\tilde{t}_1}$	192
$m_{\tilde{t}_2}$	1728	$m_{\tilde{t}_2}$	2656
$m_{\tilde{b}_1}$	1695	$m_{\tilde{b}_1}$	2634
$m_{\tilde{b}_2}$	2378	$m_{\tilde{b}_2}$	3759
$m_{\tilde{\tau}_1}$	3297	$m_{\tilde{\tau}_1}$	3489
$m_{\tilde{\chi}_1^0}$	59	$m_{\tilde{\chi}_1^0}$	53
$m_{\tilde{\chi}_2^0}$	118	$m_{\tilde{\chi}_2^0}$	104
$m_{\tilde{\chi}_1^+}$	117	$m_{\tilde{\chi}_1^+}$	104
$M_{\tilde{g}}$	470	$M_{\tilde{g}}$	399

- Main difference: a stop respectively lighter and heavier than the gluino
- For neutralino1,2 and chargino1 and basically also the gluino, predictions are the same.

- **gluino-gluino** production is substantial in both scenarios (60 vs. 40%)
- **stop1 – stop1** production is also large (40% !) in scenario 2 (and basically zero in the other)
- **chargino1 – neutralino2** associated production is also interesting in both scenarios (25 vs. 10%)

The above scenarios at the LHC

" Upon discovery of new particles, the first fundamental question to ask is what is the mass of these particles "

Spectrum predictions

scenario 1		scenario 2	
M_{h^0}	121	M_{h^0}	126
M_{H^0}	585	M_{H^0}	1109
M_A	586	M_A	1114
M_{H^+}	599	M_{H^+}	1115
$m_{\tilde{t}_1}$	783	$M_{\tilde{t}_1}$	192
$m_{\tilde{t}_2}$	1728	$m_{\tilde{t}_2}$	2656
$m_{\tilde{b}_1}$	1695	$m_{\tilde{b}_1}$	2634
$m_{\tilde{b}_2}$	2378	$m_{\tilde{b}_2}$	3759
$m_{\tilde{\tau}_1}$	3297	$m_{\tilde{\tau}_1}$	3489
$m_{\tilde{\chi}_1^0}$	59	$m_{\tilde{\chi}_1^0}$	53
$m_{\tilde{\chi}_2^0}$	118	$m_{\tilde{\chi}_2^0}$	104
$m_{\tilde{\chi}_1^+}$	117	$m_{\tilde{\chi}_1^+}$	104
$M_{\tilde{g}}$	470	$M_{\tilde{g}}$	399

- Main difference: a stop respectively lighter and heavier than the gluino
- For neutralino1,2 and chargino1 and basically also the gluino, predictions are the same.

- **gluino-gluino** production is substantial in both scenarios (60 vs. 40%)
- **stop1 – stop1** production is also large (40% !) in scenario 2 (and basically zero in the other)
- **chargino1 – neutralino2** associated production is also interesting in both scenarios (25 vs. 10%)

☑ A suitable mass-determination strategy should be able to determine the masses of all the light gauginos and, for scenario 2, of the stop1 as well.

Can one construct such a strategy ? *Would it realistically work on LHC data ?*

☑ **Note:** gluino and (for scenario 2) stop1 are light, hence one can expect 2- or 3-steps decay chains: *short decay chains*

The M_{T2} event variable

Precursor: the M_T variable

At UA1, one could measure the W mass from $W \to \ell\, \nu$, by forming the variable

$$M_T^2 \;=\; 2(E_T^\ell E_T^\nu - \vec{p}_T^{\,\ell} \cdot \vec{p}_T^{\,\nu})$$

Barger-Martin-Phillips, 1983

Note that:

$$\begin{aligned} m_W^2 &= (p_\ell + p_\nu)^2 \\ &= m_\ell^2 + m_\nu^2 + 2(E_T^\ell E_T^\nu \cosh(\eta_\ell - \eta_\nu) - \vec{p}_T^{\,\ell} \cdot \vec{p}_T^{\,\nu}) \geq M_T^2 \end{aligned}$$

Therefore M_T provides, event by event, a lower bound on the m_W mass.

The M_{T2} event variable

Precursor: the M_T variable

- *At UA1, one could measure the W mass from $W \to \ell\, \nu$, by forming the variable*

$$M_T^2 = 2(E_T^\ell E_T^\nu - \vec{p}_T^{\,\ell} \cdot \vec{p}_T^{\,\nu})$$

Barger-Martin-Phillips, 1983

- *Note that:*

$$\begin{aligned} m_W^2 &= (p_\ell + p_\nu)^2 \\ &= m_\ell^2 + m_\nu^2 + 2(E_T^\ell E_T^\nu \cosh(\eta_\ell - \eta_\nu) - \vec{p}_T^{\,\ell} \cdot \vec{p}_T^{\,\nu}) \geq M_T^2 \end{aligned}$$

Therefore M_T provides, event by event, a lower bound on the m_W mass.

Lester-Summers, 1999

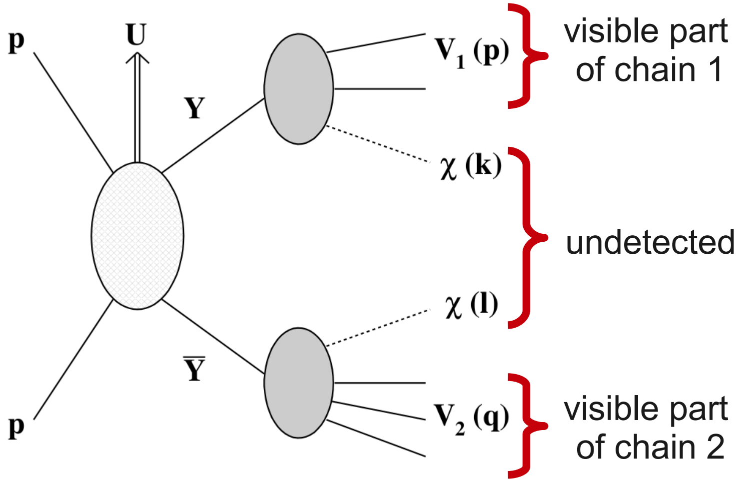
M_{T2} is the two-decay-chains generalization of M_T

- **Two decay chains, each with a final particle escaping detection**, is an event topology actually very useful for many SM extensions (e.g. all those with a conserved Z_2 symmetry)
- The **inclusion of only transverse momentum components** makes M_{T2} very suitable for hadron colliders, where the boost along the beam axis is unknown

The M_{T2} event variable: continued

Lester-Summers, 1999

Event topology relevant for M_{T2}



- Suppose both V_1 and V_2 are entirely reconstructible (mass and transverse boost)

  One could then construct two M_T variables:

  M_T(chain 1) & M_T(chain 2)

- **However,** the missing p_T's of the two chains are **not** determined separately. One only knows that:

  $$\vec{k}_T + \vec{l}_T = \text{total missing } \vec{p}_T$$

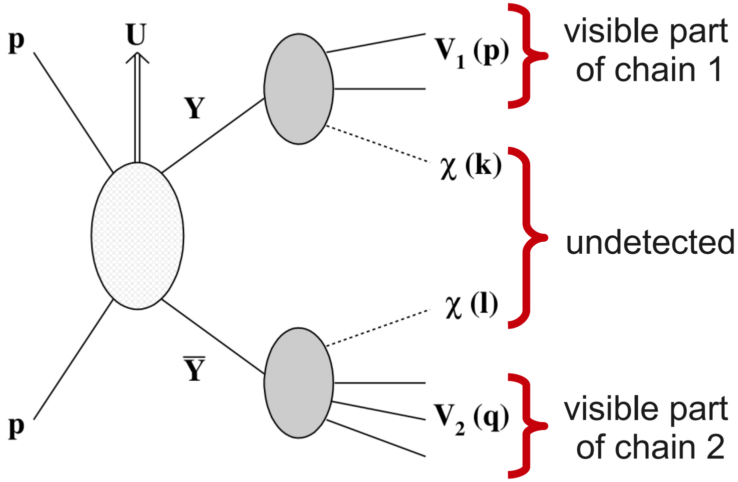
Hence, event by event, the best one can say is:

$$M_{T2}^2 = \min_{\vec{k}_T + \vec{l}_T = \text{tot miss } \vec{p}_T} \left\{ \max\left[M_T^2(\text{chain 1}), M_T^2(\text{chain 2}) \right] \right\} \leq m_Y^2$$

The M_{T2} event variable: continued

Lester-Summers, 1999

Event topology relevant for M_{T2}



- Suppose both V_1 and V_2 are entirely reconstructible (mass and transverse boost)

  One could then construct two M_T variables:

  M_T(chain 1) & **M_T(chain 2)**

- **However,** the missing p_T's of the two chains are **not** determined separately. One only knows that:

$$\vec{k}_T + \vec{l}_T = \text{total missing } \vec{p}_T$$

Hence, event by event, the best one can say is:

$$M_{T2}^2 = \min_{\vec{k}_T + \vec{l}_T = \text{tot miss } \vec{p}_T} \left\{ \max\left[M_T^2(\text{chain } 1), M_T^2(\text{chain } 2) \right] \right\} \leq m_Y^2$$

Cho-Choi-Kim-Park, 2007

☑ **Additional issue:** in $W \to \ell\, \nu$ the missing-particle mass was zero.
Here, in general, it is non-zero, and it is unknown.

☑ **The functional dependence $M_{T2}\,(m_\chi)$ can actually be turned into an advantage:**

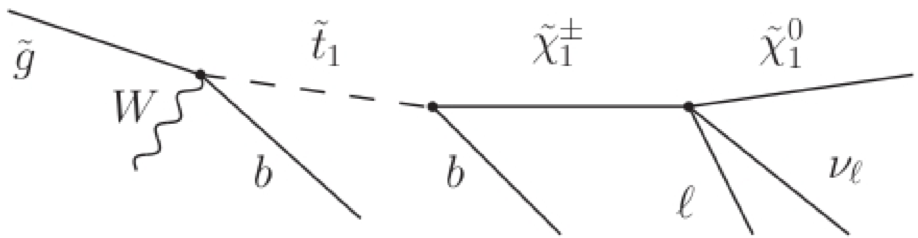
In fact, the maximum over the events of $M_{T2}\,(m_\chi)$ has a "kink" (1st derivative jump) at $\{m_Y^{phys}, m_\chi^{phys}\}$.
Hence the kink location permits a simultaneous measurement of both masses!

Application example: *determination of the gluino, chargino1, neutralino1,2 and stop1 masses within scenario 2*

from **Choi, DG, Im, Park, 2010**

Step ①

Construct M_{T2} for $\tilde{g} - \tilde{g}$ production followed by the decay



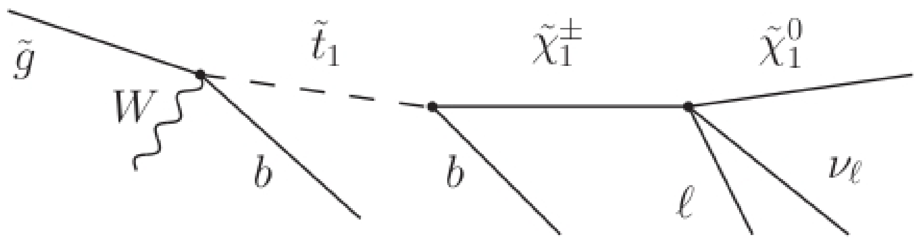
- In about 100/fb of data, one expects around 1.1 million such events
- The alternative channel with $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0\, q\, q'$ (where namely only the $\tilde{\chi}_1^0$ is invisible) is affected by a much larger combinatoric error

Application example: *determination of the gluino, chargino1, neutralino1,2 and stop1 masses within scenario 2*

from **Choi, DG, Im, Park, 2010**

Step ①

Construct M_{T2} for $\tilde{g}-\tilde{g}$ production followed by the decay



- In about 100/fb of data, one expects around 1.1 million such events
- The alternative channel with $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0\, q\, q'$ (where namely only the $\tilde{\chi}_1^0$ is invisible) is affected by a much larger combinatoric error

☑ Trigger on 2 W + 4 b + 2 ℓ + missing p_T

☑ Apply suitable kinematical cuts on the event sample

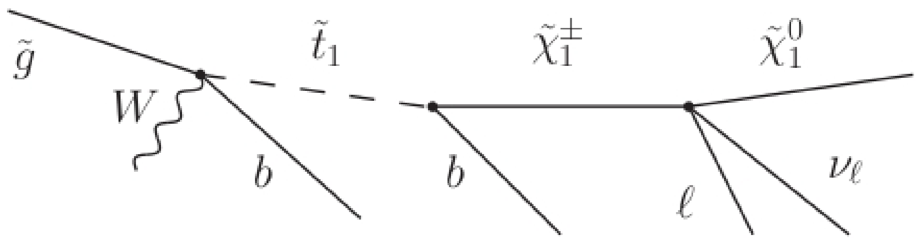
☑ In the construction of M_{T2}, include the whole $\tilde{\chi}_1^{\pm}$ initiated decay chain in the missing p_T

Application example: *determination of the gluino, chargino1, neutralino1,2 and stop1 masses within scenario 2*

from **Choi, DG, Im, Park, 2010**

Step ①

Construct M_{T2} for $\tilde{g} - \tilde{g}$ production followed by the decay



- In about 100/fb of data, one expects around 1.1 million such events
- The alternative channel with $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0\, q\, q'$ (where namely only the $\tilde{\chi}_1^0$ is invisible) is affected by a much larger combinatoric error

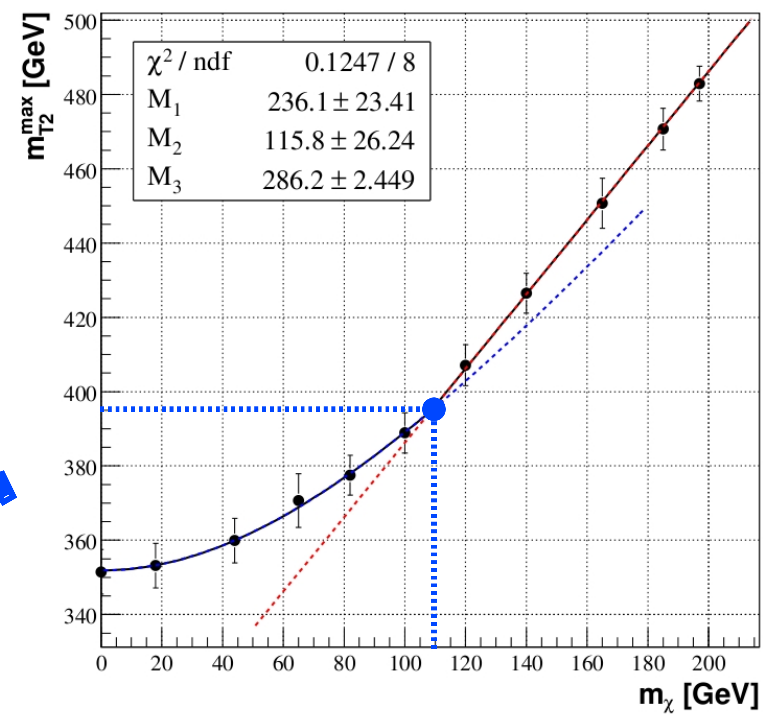
☑ Trigger on 2 W + 4 b + 2 ℓ + missing p_T

☑ Apply suitable kinematical cuts on the event sample

☑ In the construction of M_{T2}, include the whole $\tilde{\chi}_1^\pm$ initiated decay chain in the missing p_T

The kink location allows to determine simultaneously the gluino and chargino1 masses:

$$m_{\tilde{g}} = 395(16)\ \text{GeV}\,, \quad m_{\tilde{\chi}_1^\pm} = 109(17)\ \text{GeV}$$

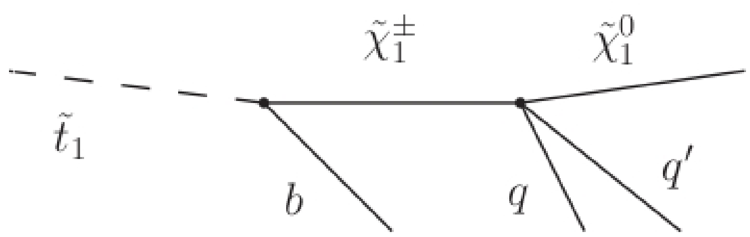


D. Guadagnoli, Sparticle masses from transverse mass kinks

Application example: continued

Step ②

Consider $\tilde{t}_1 - \tilde{t}_1$ production, followed by the decay



Trigger on 2 *b* + 4 *q* + missing p_T

- ☑ Construct the M_T distributions for the *b-q-q'* and for the *q-q'* systems.
- ☑ The *endpoints* of these distributions are such that:

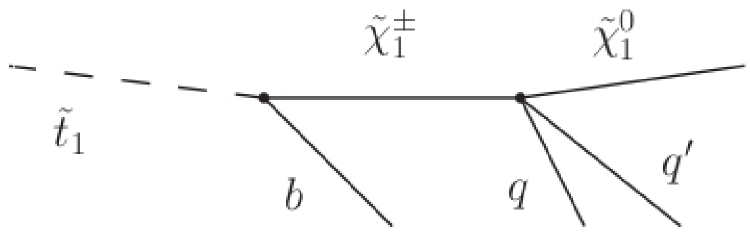
$$M_{T,bqq'}(\text{endpoint}) = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} = 149(3)\ \text{GeV}$$

$$M_{T,qq'}(\text{endpoint}) = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} = 52(2)\ \text{GeV}$$

Application example: continued

Step ②

Consider $\tilde{t}_1 - \tilde{t}_1$ production, followed by the decay



Trigger on 2 b + 4 q + missing p_T

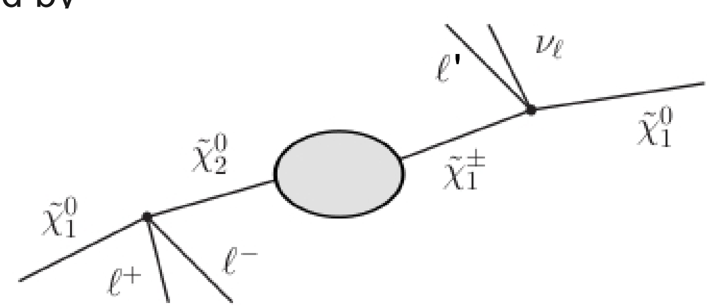
- ☑ Construct the M_T distributions for the *b*-*q*-*q'* and for the *q*-*q'* systems.
- ☑ The *endpoints* of these distributions are such that:

$$M_{T,bqq'}(\text{endpoint}) = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} = 149(3)\ \text{GeV}$$

$$M_{T,qq'}(\text{endpoint}) = m_{\tilde{\chi}_1^{\pm}} - m_{\tilde{\chi}_1^0} = 52(2)\ \text{GeV}$$

Step ③

Finally, consider $\tilde{\chi}_2^0 - \tilde{\chi}_1^{\pm}$ associated production, followed by



Trigger on 2 $\ell^{\pm}$ + 1 ℓ' + missing p_T

- ☑ Different flavor between ℓ and ℓ'
- ☑ Veto on hadronically decaying taus
- ☑ The *endpoint* of the $\ell^+\ell^-$ distribution is such that

$$m_{\ell\ell}(\text{endpoint}) = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 50(5)\ \text{GeV}$$

Conclusions

- ☑ Within SUSY GUTs with Yukawa unification, we have considered **two representative scenarios** – both experimentally viable, but with important **differences in the SUSY spectrum and decay modes**.

- ☑ For these scenarios, we have addressed the question to which extent is it possible to **determine the lightest part of the SUSY spectrum at the LHC**.

Conclusions

- ☑ Within SUSY GUTs with Yukawa unification, we have considered **two representative scenarios** – both experimentally viable, but with important **differences in the SUSY spectrum and decay modes**.

- ☑ For these scenarios, we have addressed the question to which extent is it possible to **determine the lightest part of the SUSY spectrum at the LHC**.

- ☑ The event topologies of interest are characterized by **short decay chains. This suggests M_{T2} variables** as the most promising quantities for our problem.

- ☑ **We have elaborated a stategy based on M_{T2}** and studied it on 100/fb of data of 14 TeV LHC collisions. We included hadronization / detector-level effect with Pythia / PGS.

- ☑ We showed this strategy to be able to **determine, within about 20 GeV, the masses of all the light gauginos** (neutralino1,2, chargino1, gluino) and also **the mass of the lightest stop (for the scenario where it is below the gluino)**.

Spare Slides

Why A-term splitting helps YU

Recall: *to suppress gluino contributions (positive) to* m_b*,*

one needs a large trilinear term for the stop (to enhance chargino contributions)

AND

a $m_{stops} \ll m_{sbottoms}$ *hierarchy*

the latter is greatly helped by $|\bar{A}_D| \ll |\bar{A}_U|$

$$(m_Q^2)_{33} \approx 0.51\, m_{16}^2 - 0.12\, m_{H_u}^2 - 0.09\, m_{H_d}^2 - 0.02\, \overline{A}_U^2 - 0.02\, \overline{A}_D^2$$

$$(m_U^2)_{33} \approx 0.49\, m_{16}^2 - 0.22\, m_{H_u}^2 - 0.01\, m_{H_d}^2 - 0.06\, \overline{A}_U^2 + 0.01\, \overline{A}_D^2$$

$$(m_D^2)_{33} \approx 0.55\, m_{16}^2 + 0.01\, m_{H_u}^2 - 0.21\, m_{H_d}^2 + 0.01\, \overline{A}_U^2 - 0.05\, \overline{A}_D^2$$

ruling $m_{\tilde{t}_2} \approx m_{\tilde{b}_1}$ (first line)

ruling $m_{\tilde{t}_1}$ (second line)

ruling $m_{\tilde{b}_2}$ (third line)

Note:
m^2_U goes down if
$\bar{A}_D$ is smaller

Hence $|\bar{A}_D| \ll |\bar{A}_U|$ ***helps the hierarchy*** $(m_U^2)_{33} \ll (m_Q^2)_{33} < (m_D^2)_{33}$

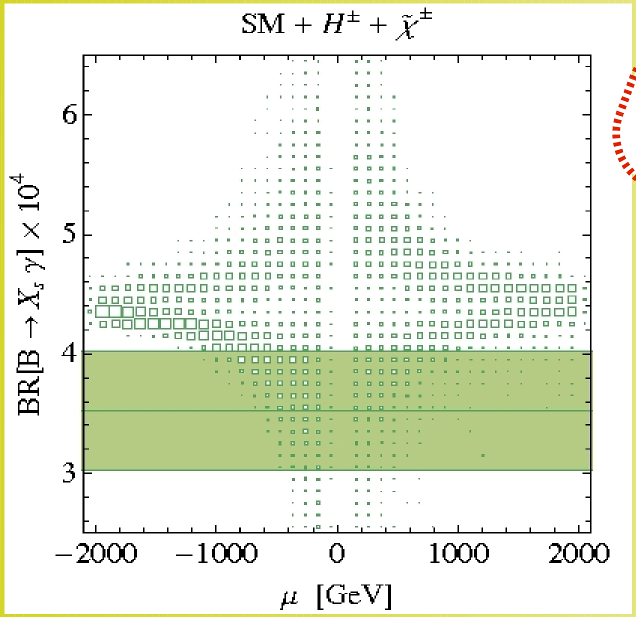
$$\Rightarrow \quad m_{\tilde{t}_R} \ll m_{\tilde{t}_L} \approx m_{\tilde{b}_L} < m_{\tilde{b}_R}$$

Why large μ

Recall: $\Delta m_b = \Delta_{\text{gluino}} + \Delta_{\text{chargino}} < 0$ *thanks to the trilinear-splitting mechanism*

Since both corrections are proportional to μ,
large μ *triggers the* *right size* *for the total correction* Δm_b

In addition: *large* μ *suppresses the chargino contributions to* $b \to s\, \gamma$,
thus preventing a large destructive interference with the SM contribution



Plot and discussion in **Wick, Altmannshofer, SUSY08 procs.**

Note also: *for too large* μ, *the negative correction to* m_b *becomes too large in magnitude, so that the mechanism has to be tamed somehow.*