

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

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Excellence Cluster Universe &
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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 (arXiv:1005.0618)

DG, Raby, Straub (JHEP 09)

Altmannshofer, DG, Raby, Straub (PLB 08)

On SUSY GUTs with Yukawa unification

**1993: Hall-
Rattazzi-Sarid**

see also:
Carena et al.

Use YU to predict the top mass, with input from the (measured!) bottom and tau masses

It was realized that, when $\tan \beta$ is large, the bottom and tau masses get large EW-scale threshold corrections, due to loops proportional to the “wrong” vev.

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

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Interestingly, the very same relations among soft terms emerge as fixed-point solution of the RGEs (under the assumption of GUT-scale YU).

This solution gives rise to inverted scalar mass hierarchy, namely light 3rd generation and heavy 1st and 2nd generation squarks.

The reason is the O(1) 33-entry in the Yukawa matrix.

On SUSY GUTs with YU: continued

 **More recent studies** appraise the above scenario in the light of low-energy data.


Different approaches pursued on:

Many refs:

Tobe+Wells; Auto *et al.* (x 2);
Balazs+Dermisek; Baer *et al.* (x 6);
Albrecht *et al.*; Altmannshofer *et al.*;
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- ① data considered (fermion masses, EWPO, FCNCs)
- ② boundary conditions for the soft terms
- ③ techniques to explore the parameter space

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Our approach

Technique

- a. Construct a χ^2 function with all the best known low-energy observables, including:
 - EW observables (M_W , M_Z , G_F , $\alpha_{e.m.}$, α_s) and 3rd generation quark masses
 - quark FCNCs: $\Delta M_s / \Delta M_d$, $B \rightarrow X_s \gamma$, $B \rightarrow X_s \ell^+ \ell^-$, $B \rightarrow \tau \nu$
- b. Minimize this χ^2 function upon variation of the model parameters.
One can thus **enforce exact YU**.

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Pros

- ☑ Provides a global assessment of the model in a reparameterization-invariant way (what matters is the χ^2 minimum)
- ☑ “Exploits” the errors on the low-energy param's, to which the high-energy param's carry very strong sensitivity [see discussion in Tobe-Wells, 2003]

Scenarios considered

① *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_{H_u}, m_{H_d})*

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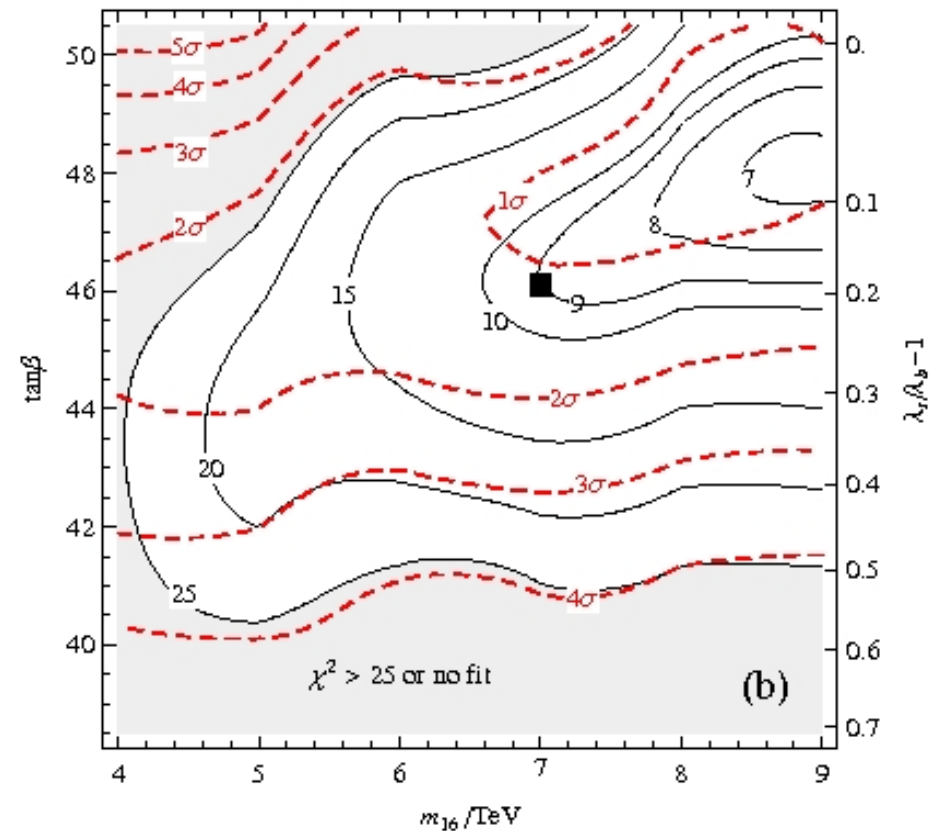
Features/Issues

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

Conversely, it is known that m_b prefers $\tan\beta$ **$O(50)$**
(or else, $\tan\beta$ 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,
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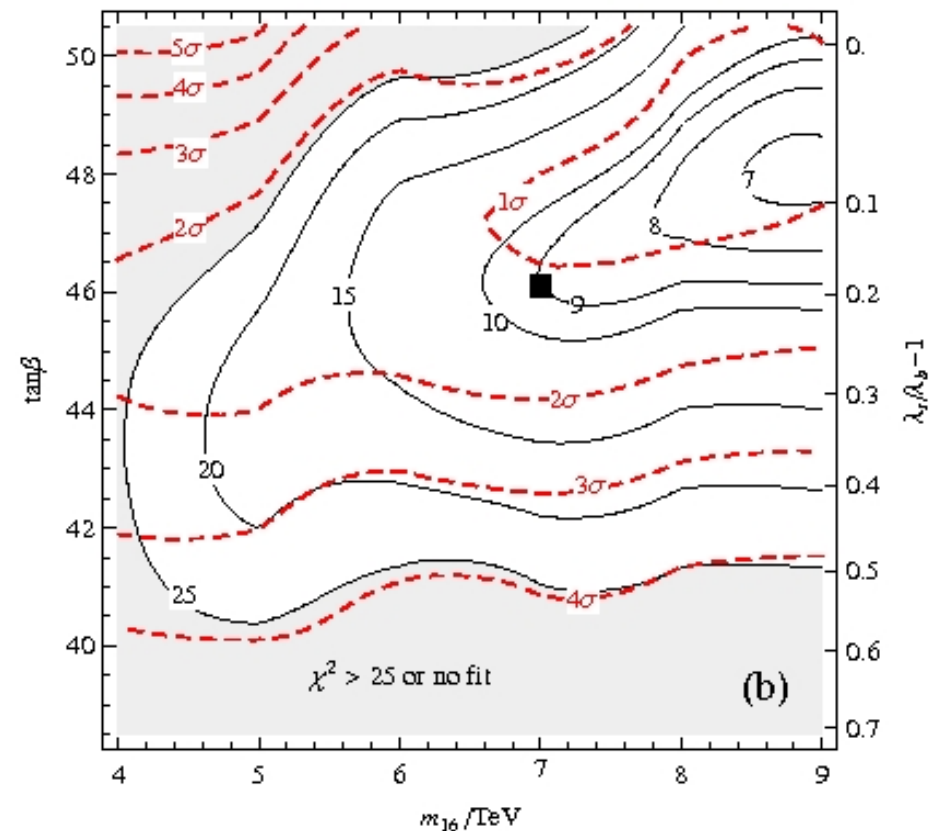
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👉 Pheno viability can be recovered without decoupling, by **relaxing $t - b - \tau$ YU to just $b - \tau$ unification**:
Compromise between the FCNC and m_b constraints

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

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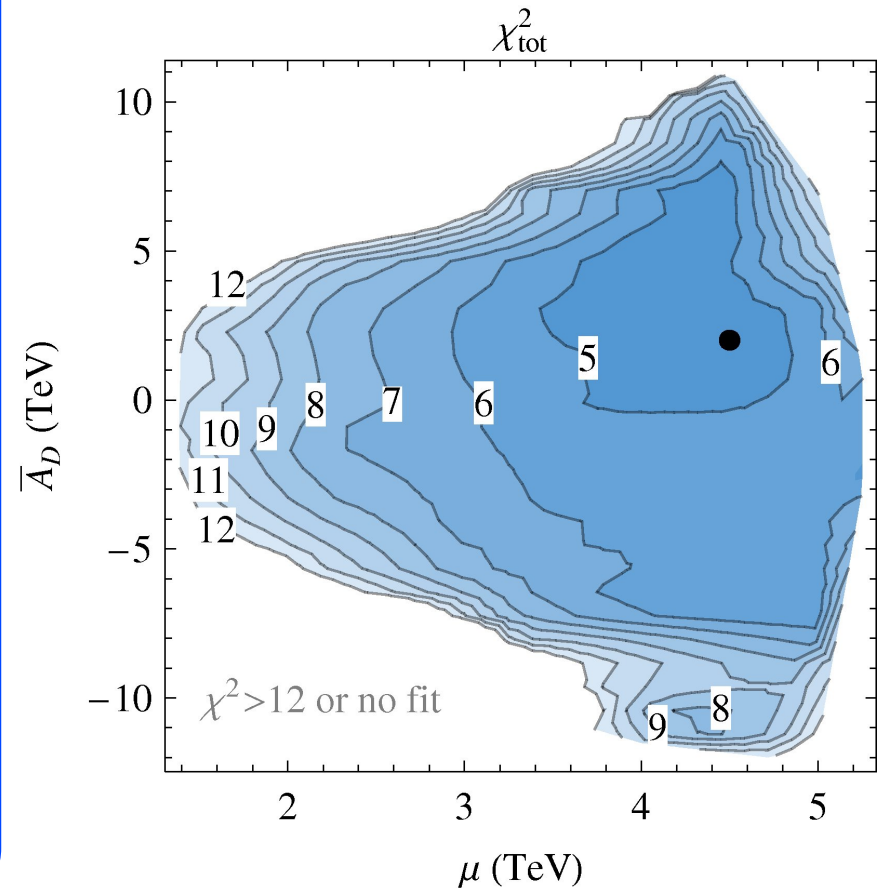
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 Agreement with data clearly selects the region with large $\mu = O(m_{16})$ and sizable $A_U - A_D$ splitting

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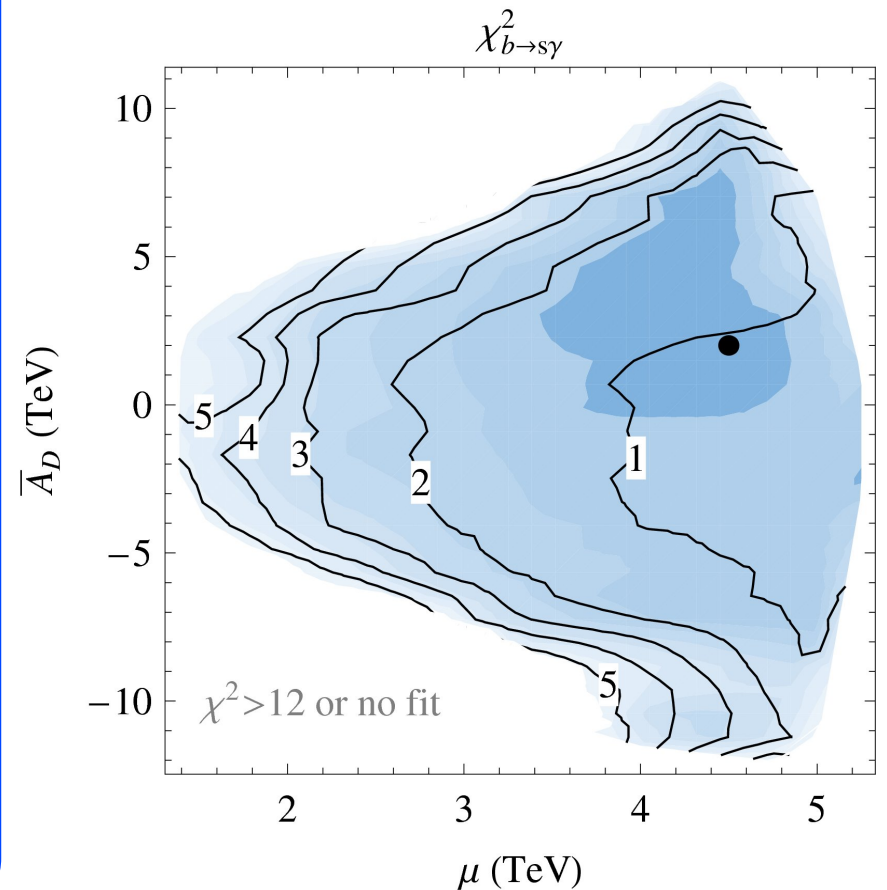
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*The **lightest (RH) stop** (and the gluino) are required to be very close to their exp bounds, i.e. are **veeeery light**.*

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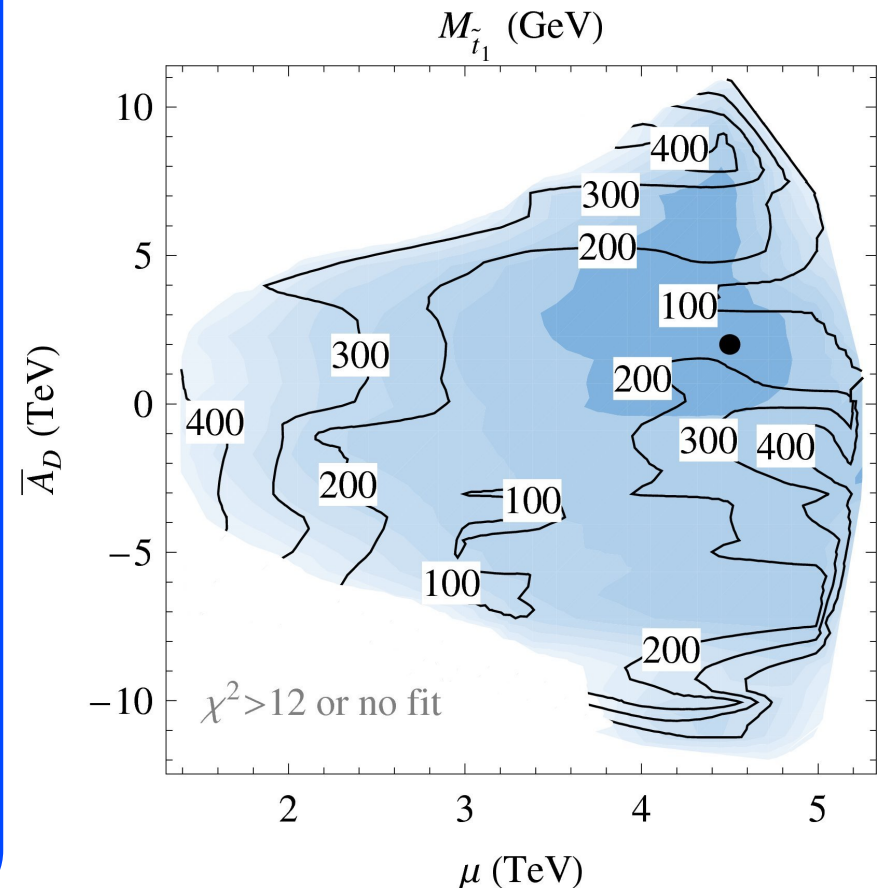
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 So, *substantial improvement on the fine tuning on the above quantities.*

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,
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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^\pm}	599	M_{H^\pm}	1115
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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.

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- ✓ 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 $W \rightarrow \ell \nu$, 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:

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

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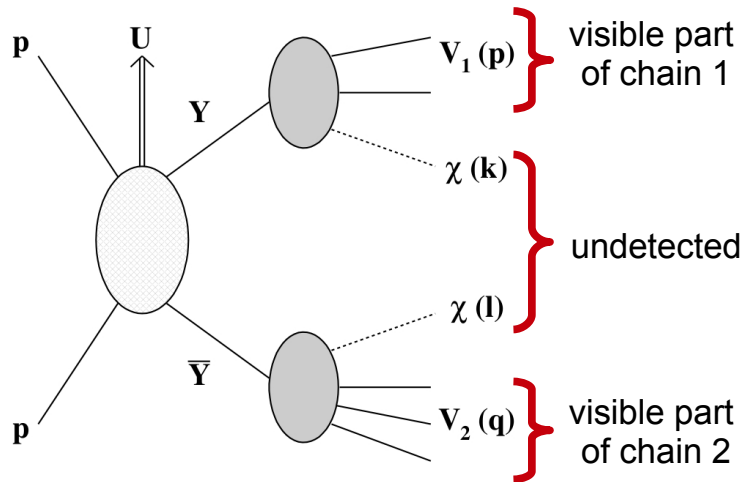
M_{T2} is the two-decay-chains generalization of M_T

- ✓ **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 topology: continued

Lester-Summers, 1999

Event topology relevant for M_{T2}



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

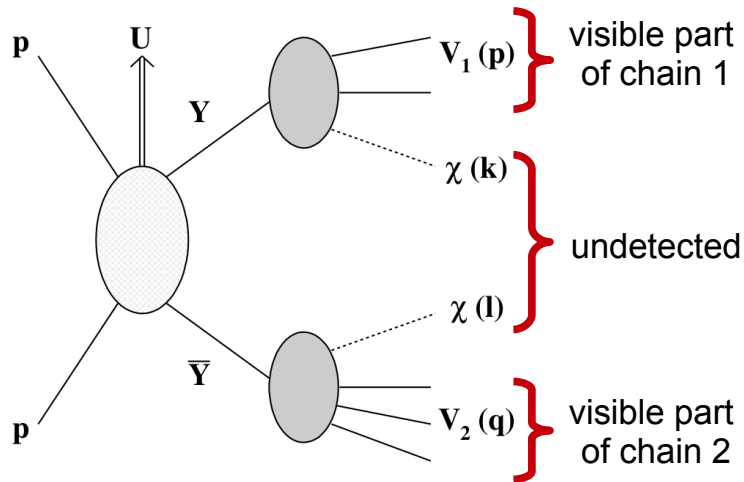
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$$M_T(\text{chain 1}) \quad \& \quad M_T(\text{chain 2})$$

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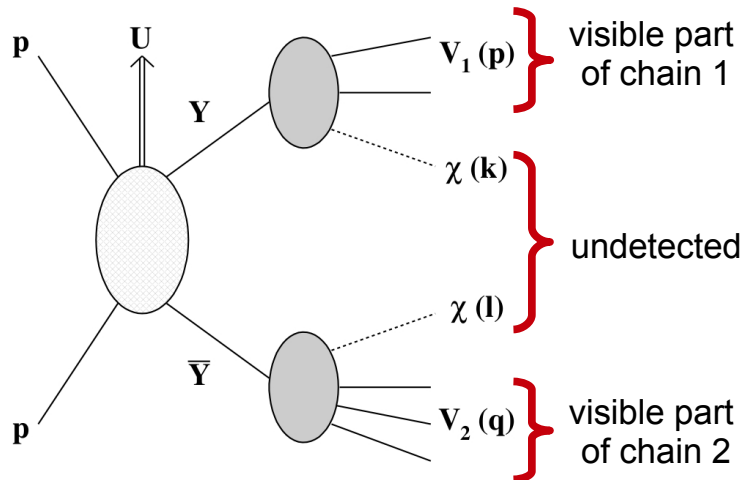
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- Additional issue: in $W \rightarrow \ell \nu$ the missing-particle mass was zero.

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 $\{m_Y^{\text{phys}}, m_\chi^{\text{phys}}\}$.

Hence the kink location permits a simultaneous measurement of both masses!

Cho-Choi-Kim-Park, 2007

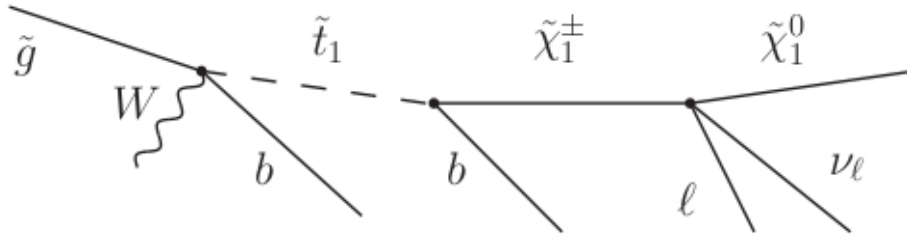
Application example:

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 $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 q q'$ (where namely only the $\tilde{\chi}_1^0$ is invisible) is affected by a much larger combinatoric error

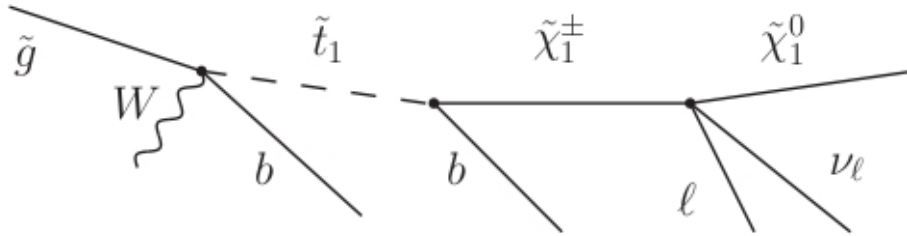
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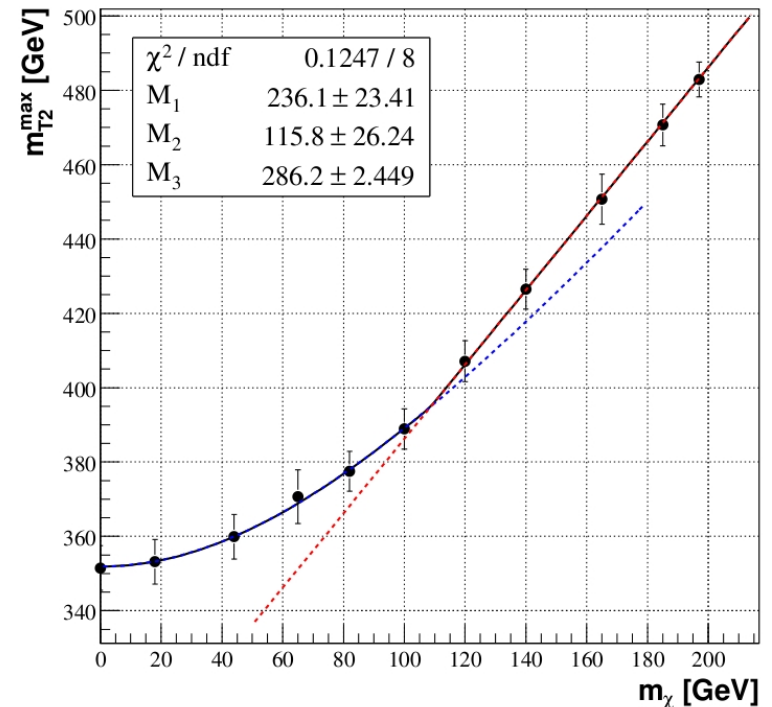
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- ✓ Trigger on 2 W + 4 b + 2 ℓ + missing p_T
- ✓ Apply suitable kinematical cuts on the event sample
- ✓ In the construction of M_{T2} , include the whole $\tilde{\chi}_1^\pm$ initiated decay chain in the missing p_T



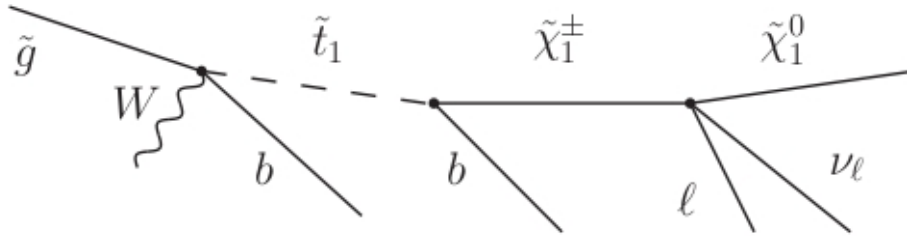
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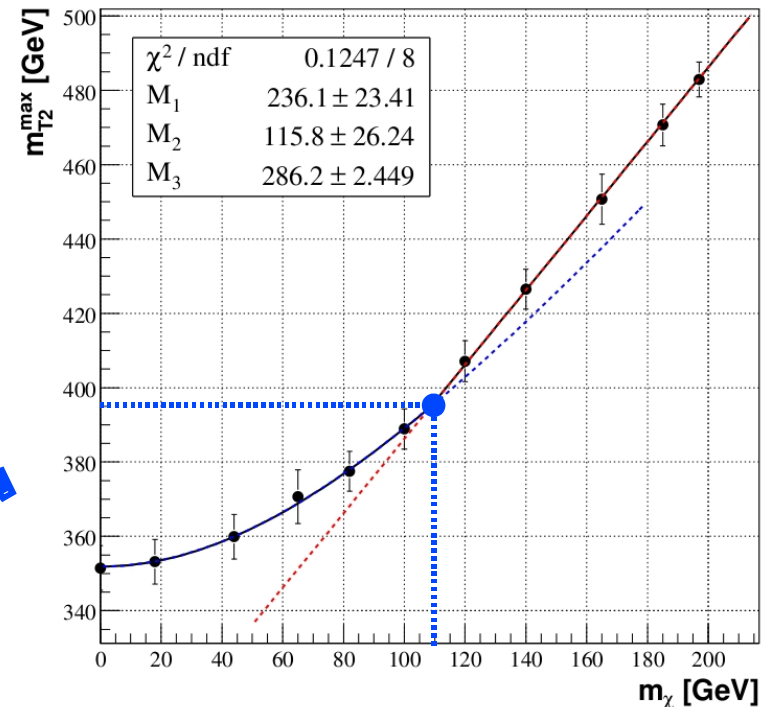


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The kink location allows to determine simultaneously the gluino and chargino1 masses:

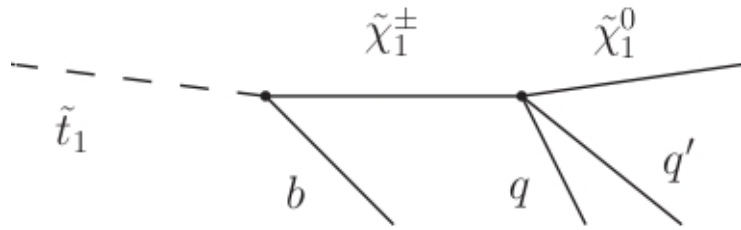
$$m_{\tilde{g}} = 395(16) \text{ GeV}, \quad m_{\tilde{\chi}_1^\pm} = 109(17) \text{ GeV}$$



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:

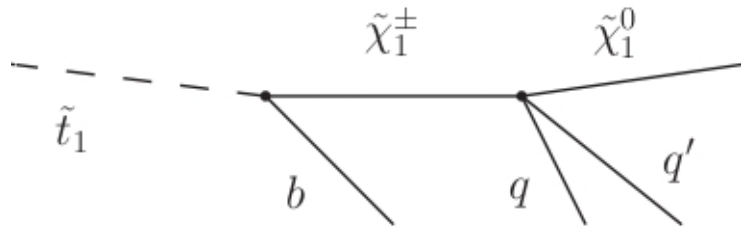
$$M_{T,bqq'}(\text{endpoint}) = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} = 149(3) \text{ GeV}$$

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

Application example: continued

Step ②

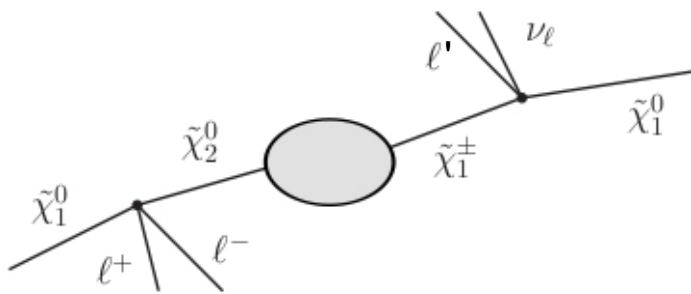
Consider $\tilde{t}_1 - \tilde{t}_1$ production, followed by the decay



(Trigger on 2 b + 4 q + missing p_T)

Step ③

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



(Trigger on 2 ℓ^\pm + 1 ℓ' + 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:

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

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

✓ 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**.

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- ✓ 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 strategy 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.

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- ✓ 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)**.