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

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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 β 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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2001: Blazek-Dermisek-Raby

Rather than using YU to predict the top mass, use its measured value to make predictions for the SUSY spectrum.

Assuming GUT-scale soft-terms universalities, one preferred region emerges:

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

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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:

① data considered (fermion masses, EWPO, FCNCs)

② boundary conditions for the soft terms

③ techniques to explore the parameter space

Many refs:
Tobe+Wells; Auto *et al.* (x 2); Balazs+Dermisek; Baer *et al.* (x 6); Albrecht *et al.*; Altmannshofer *et al.*; D.G. *et al.*; Antusch+Spinrath (x 2); Gogoladze *et al.*

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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: ΔM_s / ΔM_d , $B \to X_s \gamma$, $B \to X_s \ell^+ \ell^-$, $B \to \tau \nu$

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 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})*

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Features/Issues

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

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*

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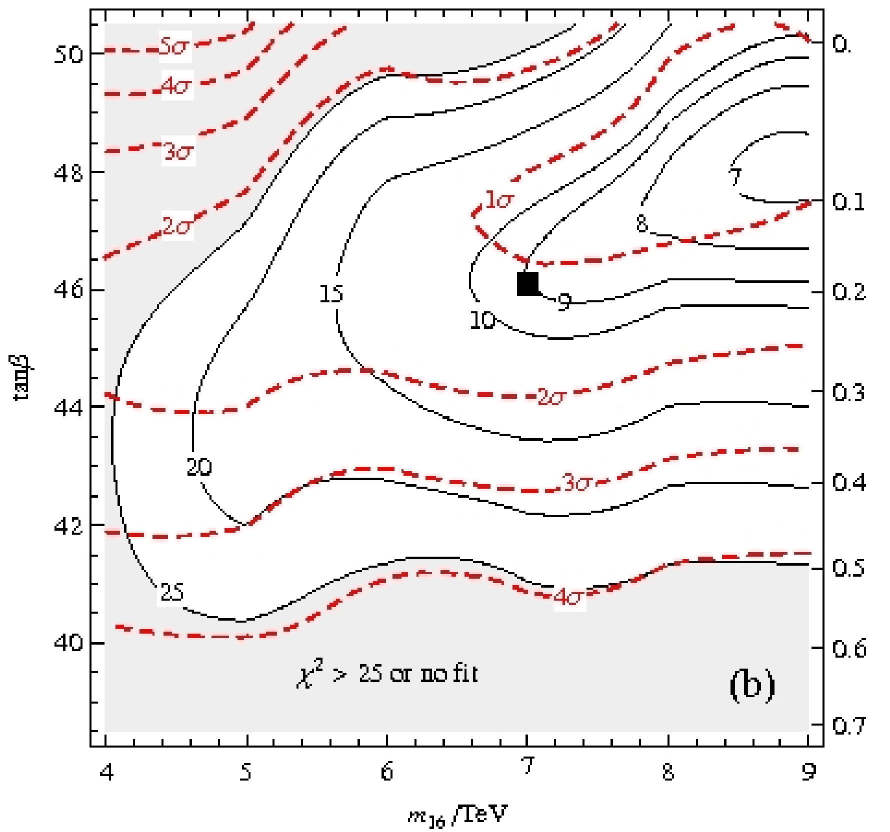

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- Pheno viability can be recovered without decoupling, by **relaxing $t - b - \tau$ YU to just $b - \tau$ unification:** Compromise between the FCNC and m_b constraints

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

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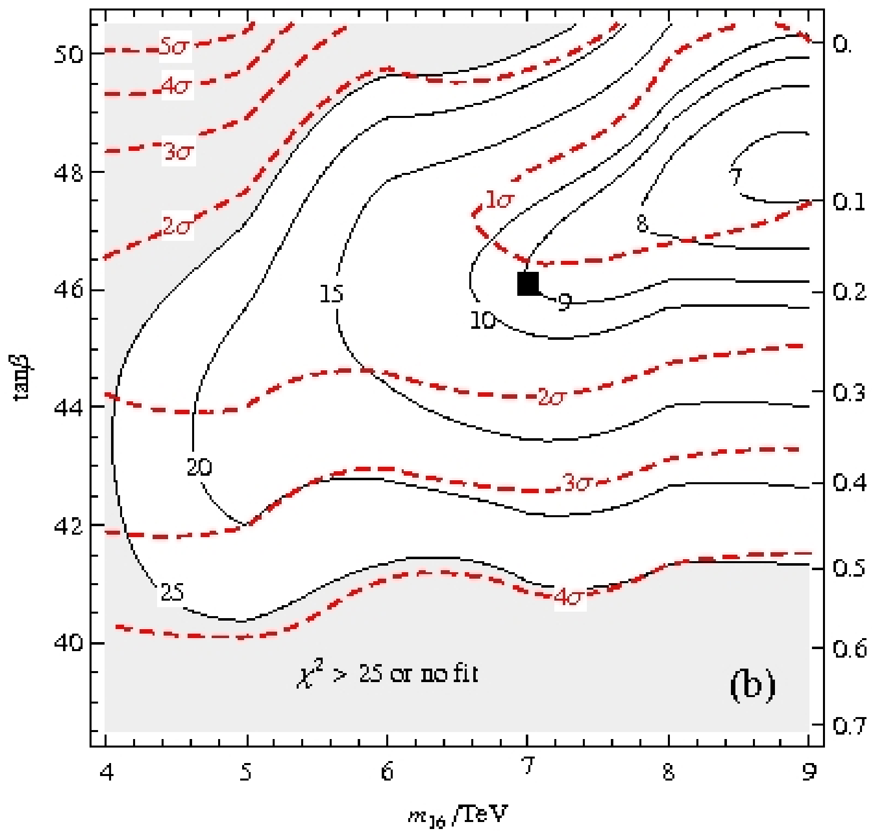

D. Guadagnoli, Sparticle masses from transverse mass kinks

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(In principle also bilinears, e.g. between the Q, U, D multiplets, but fits indicate a marginal impact)

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

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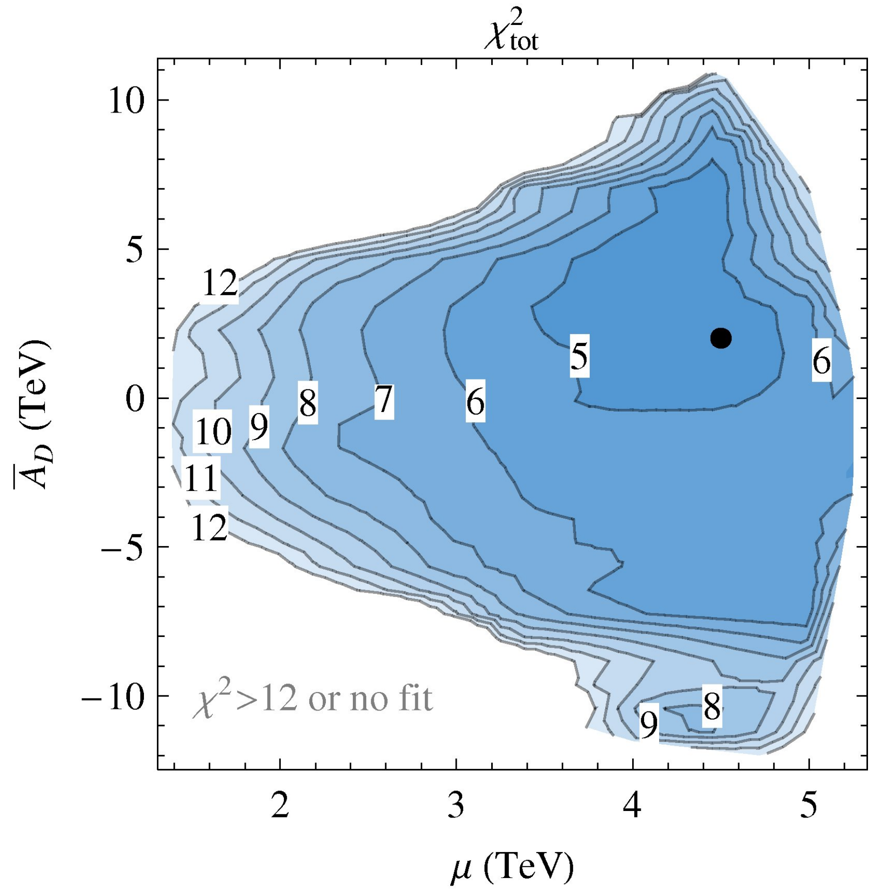

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All the FCNC tensions are relieved.

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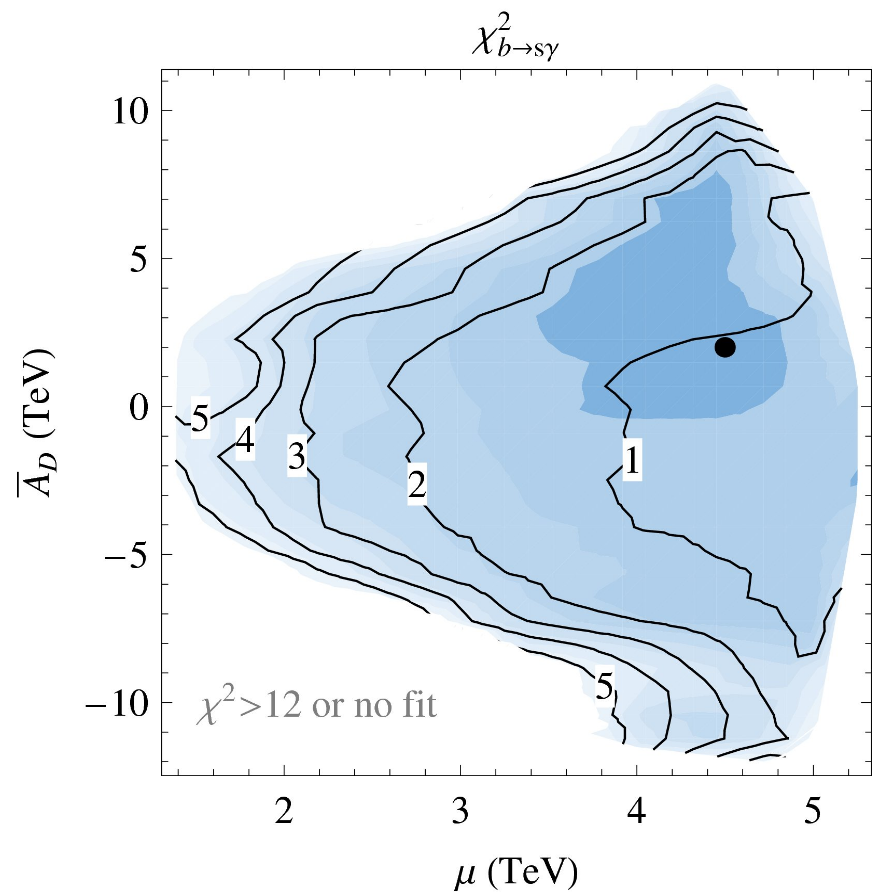

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- So, *substantial improvement on the fine tuning on the above quantities*.

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

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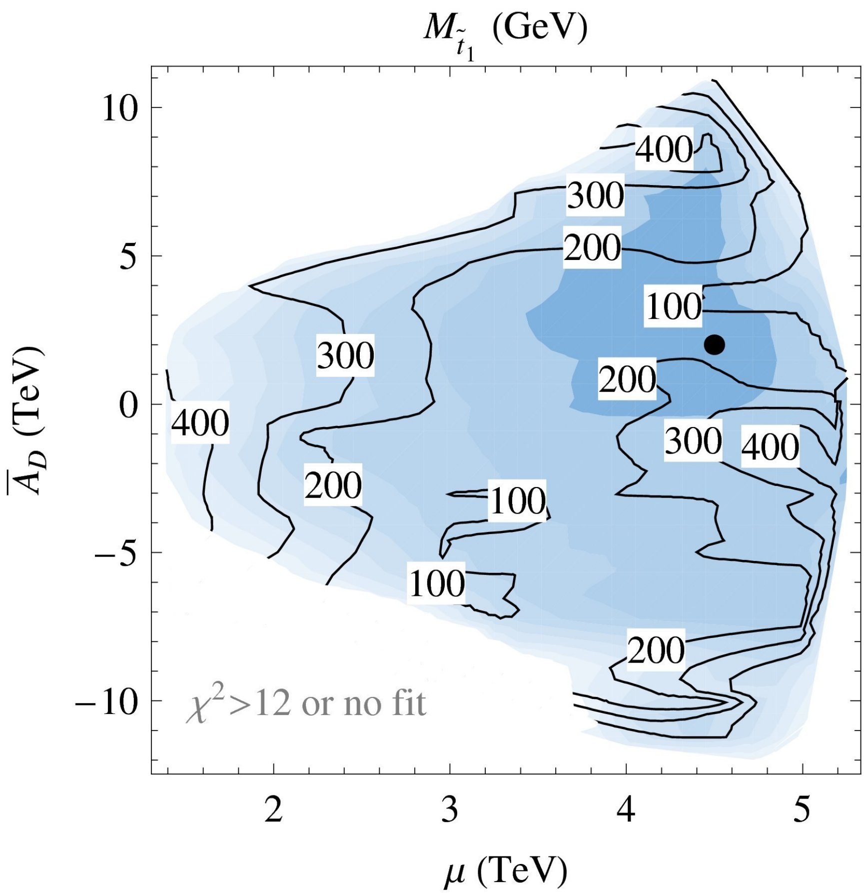

The above scenarios at the LHC

" 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^+}	599	M_{H^+}	1115
$m_{\tilde{t}_1}$	783	$M_{\tilde{t}_1}$	192
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- 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 $W \to \ell\, \nu$, 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:*

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

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Lester-Summers, 1999

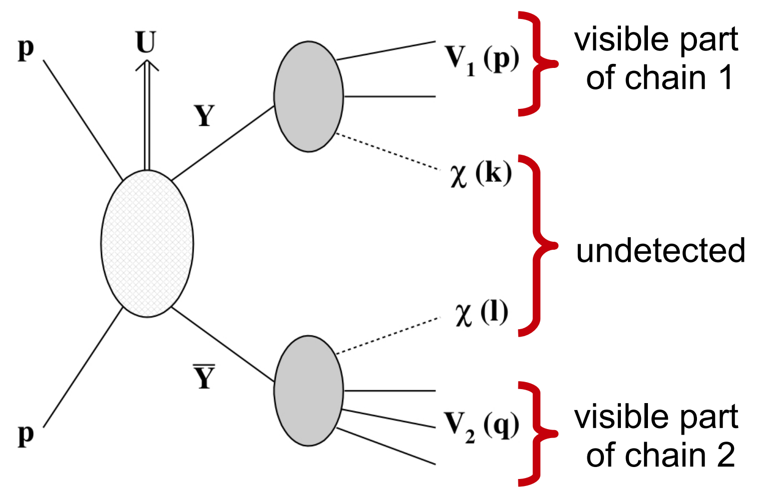
M_{T2} is the two-decay-chains generalization of M_T

- **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}



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  One could then construct two M_T variables:

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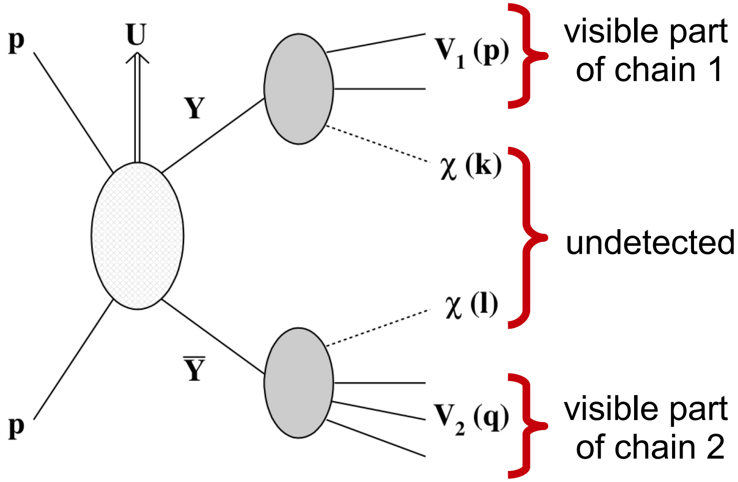

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- **However,** the missing p_T's of the two chains are **not** determined separately. One only knows that:

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

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

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

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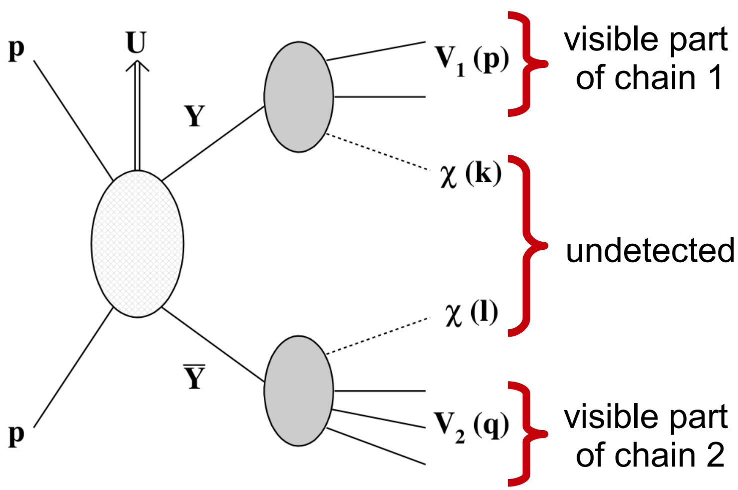

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Cho-Choi-Kim-Park, 2007

☑ **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:**

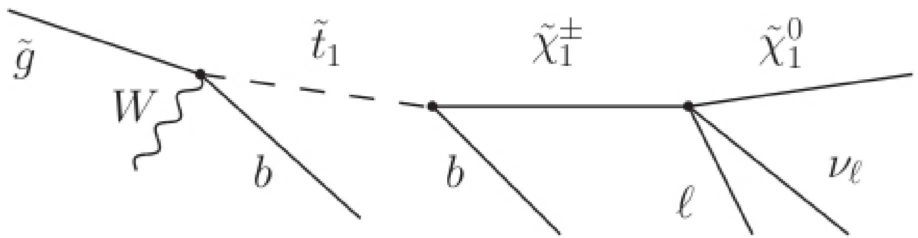
In fact, the maximum over the events of $M_{T2}\,(m_\chi)$ has a “kink” (1st derivative jump) at $\{m_Y^{phys}, m_\chi^{phys}\}$.
Hence the kink location permits a simultaneous measurement of both masses!

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

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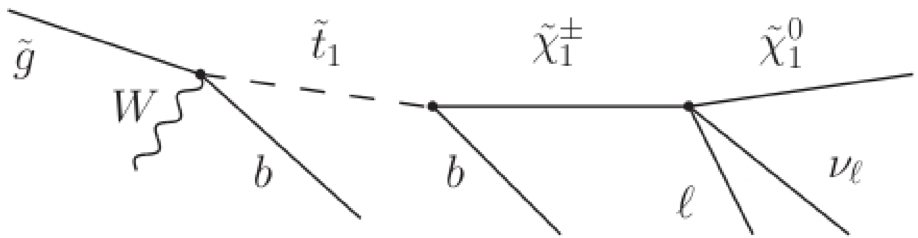

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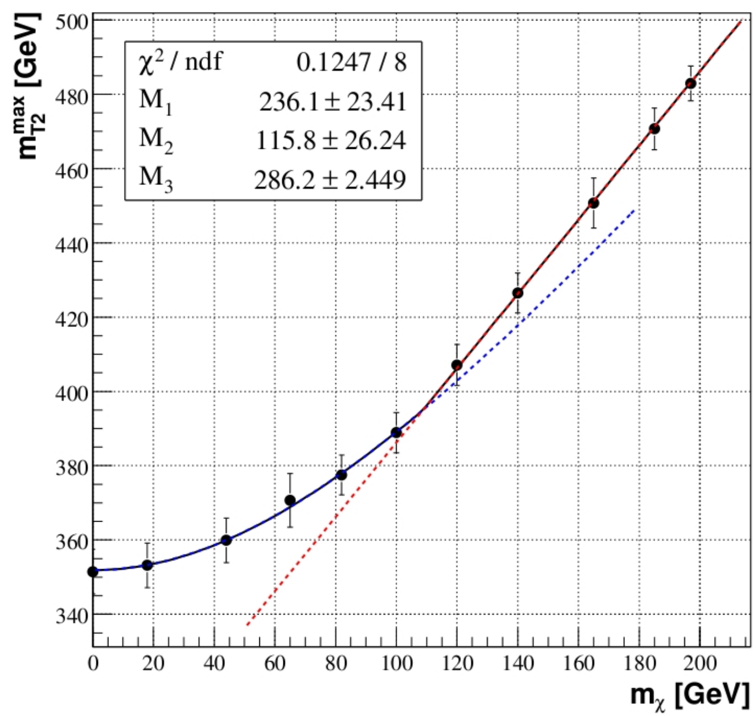
☑ Trigger on 2 W + 4 b + 2 ℓ + missing p_T

☑ 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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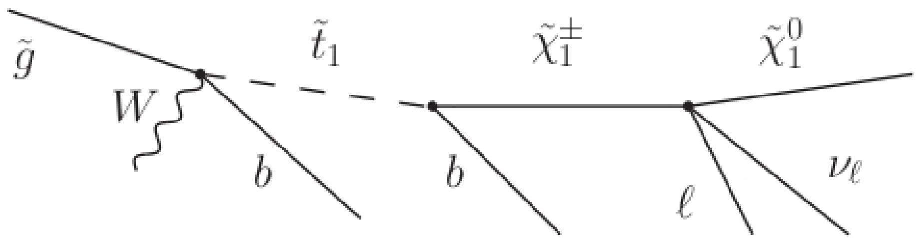

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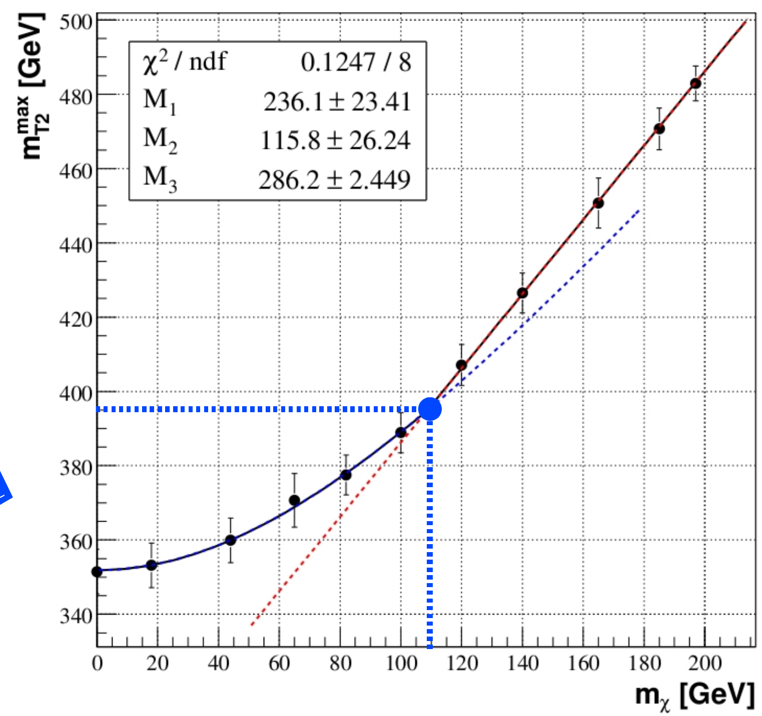
The kink location allows to determine simultaneously the gluino and chargino1 masses:

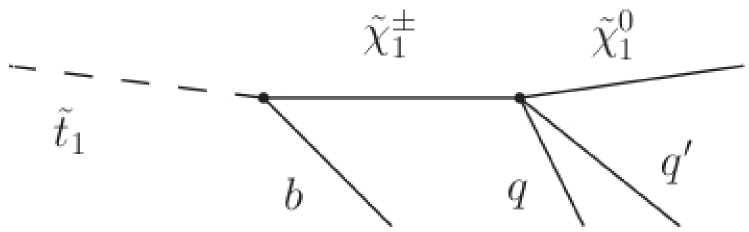
$$m_{\tilde{g}} = 395(16)\ \text{GeV}\,, \quad m_{\tilde{\chi}_1^{\pm}} = 109(17)\ \text{GeV}$$



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:

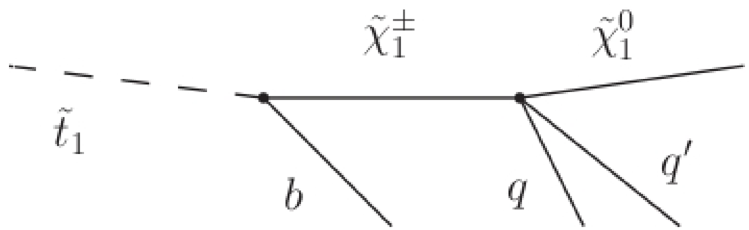
$$M_{T,bqq'}(\text{endpoint}) = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} = 149(3)\ \text{GeV}$$

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

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

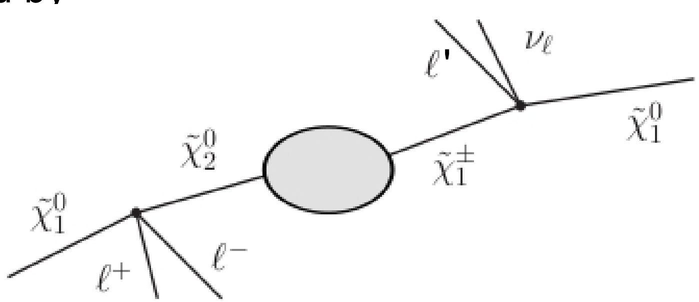
- ☑ Construct the M_T distributions for the *b-q-q'* and for the *q-q'* systems.
- ☑ The *endpoints* of these distributions are such that:

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

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

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**.

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- **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.

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- We showed this strategy to be able to **determine, within about 20 GeV, themasses 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)**.