New particles' mass measurements at the LHC: the collider variable M_{T2}

Diego Guadagnoli
LPT Orsay, Université Paris-Sud XI

Short Outline

☑ **Statement of the problem:** *determining new particles' masses at the LHC*

☑ **The event variable M_{T2}** : *properties and application example*

Based on:

Choi, DG, Im, Park (JHEP 10)

DG, Raby, Straub (JHEP 09)

Altmannshofer, DG, Raby, Straub (PLB 08)

Problem at hand: identifying new particles from collider events

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☑ Each event consists therefore of a list of measurements that includes :

- the 4-momenta of the objects listed in (a) above;
- E_{miss} and the total $\overline{\mathbf{p}}_{T,\, miss}$ as in (b) above.

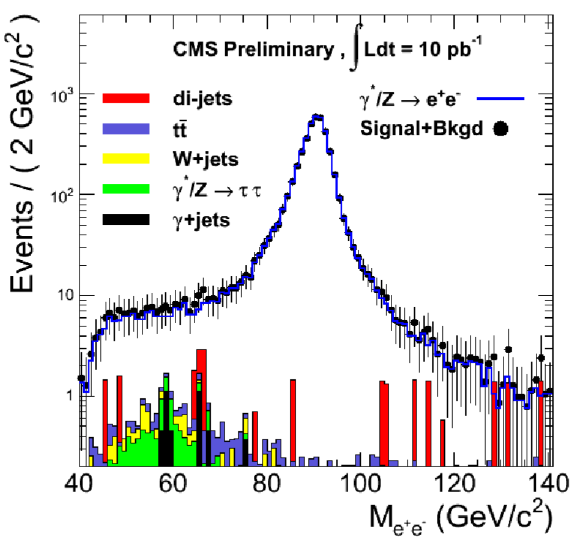
} ☞ *The presence, and the mass scale, of possible new particles, is inferred from this “event kinematics”*

Identification of new particles / new mass scales: 1

☑ The simplest identification method is, in general, to find a peak in the invariant-mass distribution of the decay products of the particle of interest.

Example: $Z \rightarrow e^+ e^-$

Look for a peak in the invariant mass of the lepton pair



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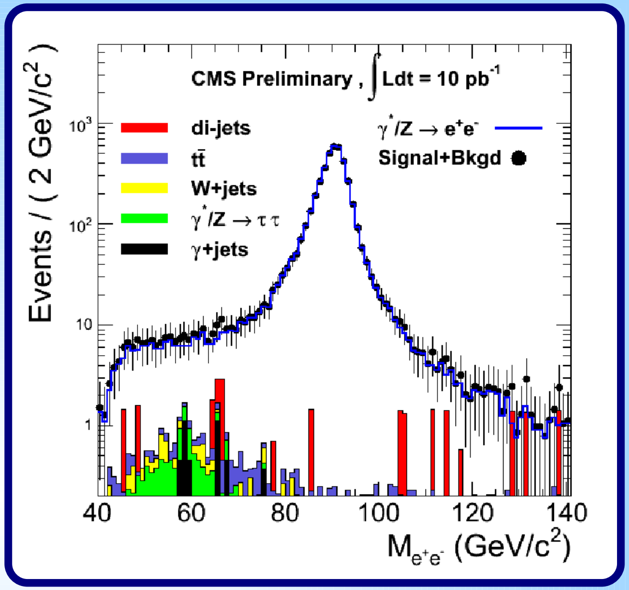

☑ This is however inapplicable if the event of interest includes components that escape detection.

The latter is actually a typical case in new-physics models, e.g.:

- SUSY with R-parity: the lightest SUSY particle is stable, and doesn't interact in the detectors
- Any other model predicting TeV-scale Dark Matter, that, by definition, will exit the detectors without interaction

Identification of new particles / new mass scales: 2

☑ **"Global searches"**

In searches that do not involve a specific scenario, one uses global event variables, in order to optimize in the signal discriminating power.

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Hence one can construct a global variable, able to capture such total transverse activity. E.g. the effective mass M_{eff} :

$$M_{\text{eff}} = \sum_{i=1}^{4} p_T^{\text{jet},i} + \sum_i p_T^{\text{lep},i} + E_T^{\text{miss}}$$

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☑ **The information we get**

Quantitatively, observables like M_{eff} are able to determine a "new-physics mass scale", and not more than that.

In particular, if this new-physics scale has anything to do with the hierarchy problem, i.e. with explaining the electroweak scale $M_{\text{Fermi}} \approx$ 250 GeV, then M_{eff} will be related to M_{Fermi} itself.

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While the above information is – no doubt – absolutely crucial, one needs more than that when it comes to discriminating models from one another.

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Mass-determination methods for the LHC

As mentioned, we focus on decay topologies that include undetected components – such as the SUSY LSP.

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Many such methods exist. The most known and used include:

- the "endpoint" method

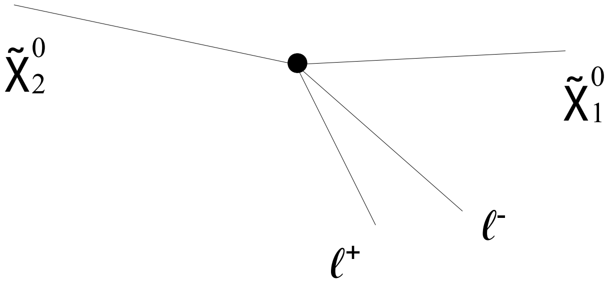
See, e.g.: Hinchliffe, Paige, Shapiro, Soderqvist, Yao (96); Bachachou *et al.* (99); Hinchliffe, Paige (99); Allanach, Lester, Parker, Webber (00); Gjelstein, Miller, Osland, Raklev (04, 05, 06); Weiglein *et al.* (04), Lester, Parker, White (06), **...**

- the "mass-relation" method

See e.g.: Nojiri, Polesello, Tovey (03, 08); Kawagoe, Nojiri, Polesello (04); Cheng, Gunion, Han, Marandella, McElrath (07); Cheng, Engelhardt, Gunion, Han, McElrath (08), **...**

The endpoint method, in short

☑ **A prototype example**



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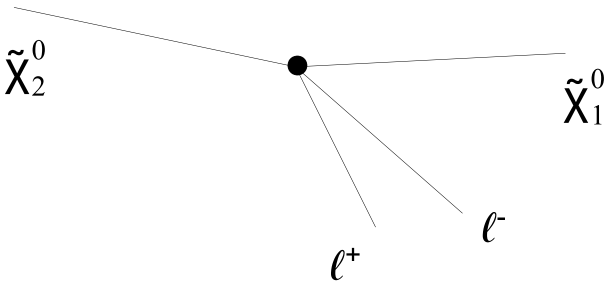

Look at the distribution of values for the invariant mass of the two-leptons system.

Its maximum allowed value (= endpoint) is:

$$\max[m_{l^+l^-}] = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$$

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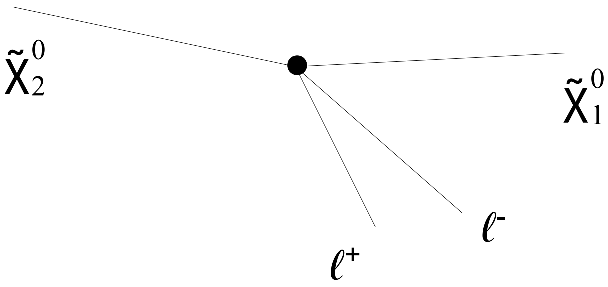

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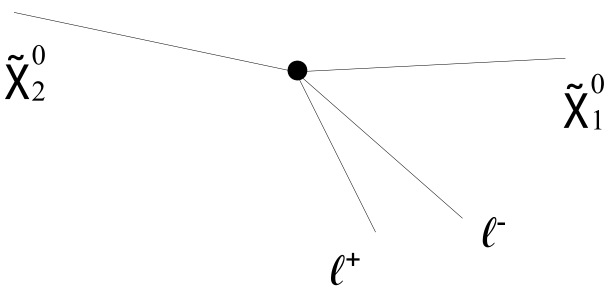

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“In a given decay chain, the endpoint values of the invariant-mass distributions constructed for visible decay products depend on the masses of the invisible particles as well.”

Note however, that by this method, one typically determines mass combinations (not single masses), e.g. the mass difference of the above example.

In order for all the new particles' masses of a given decay chain to be – even in principle – separately reconstructible, one needs long enough decay chains (≥ 3 branchings)

See: Burns, Kong, Matchev, Park (08)

The mass-relation method, in short

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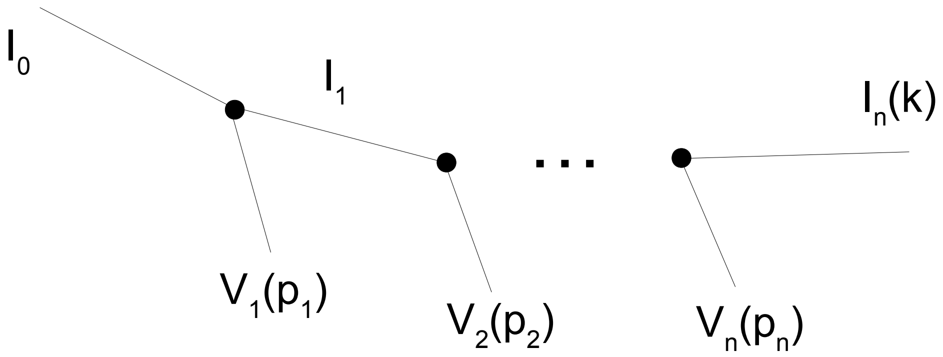

- The V_i particles are “visible”, i.e. their momenta p_i are supposed to be completely reconstructible
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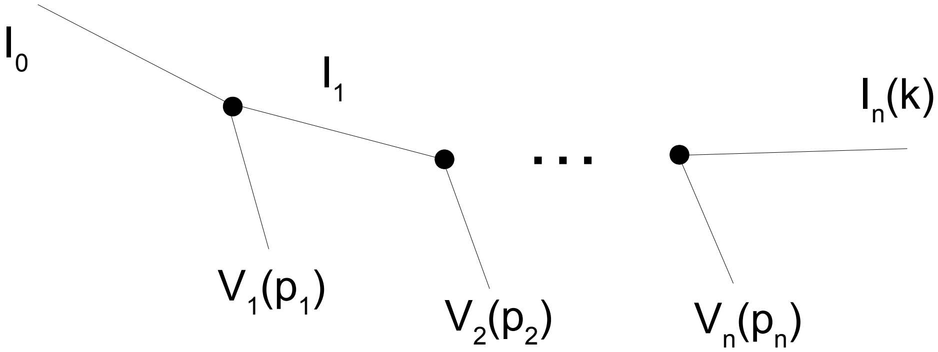

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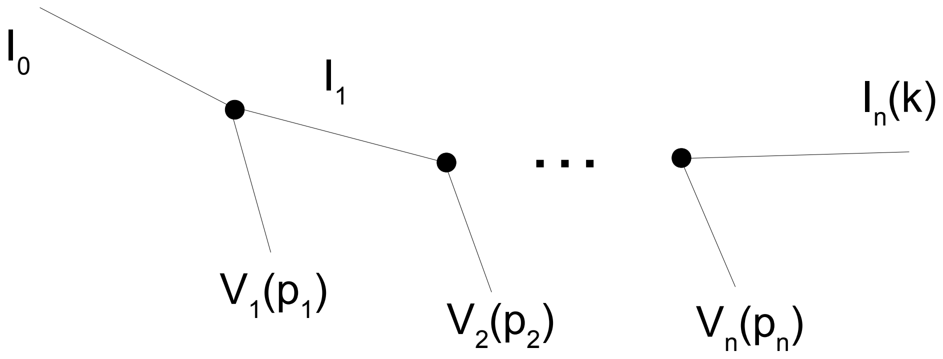

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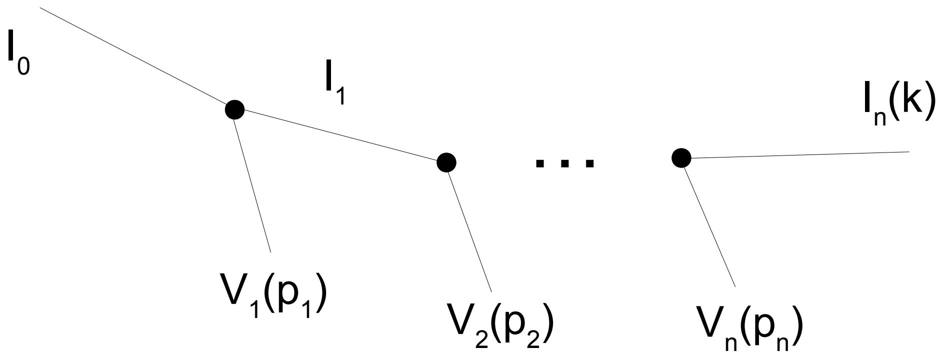

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Conclusion:

Suppose to have a large number of events, N → ∞.

Then, for the number of constraints to exceed or equal the number of unknowns, one needs n ≥ 4.

Namely, again, one can solve for all the masses only <u>for long enough decay chains.</u>

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Devising a strategy to solve for all the masses of the new particles, not mass combinations

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All these considerations led us to focus on M_{T2} *,*
that does not pose restrictions on the chain length in order to be applicable.

The M_{T2} event variable

Precursor: the M_T variable

☑ *At UA1, one could measure the W mass from W → ℓ ν, by forming the variable*

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

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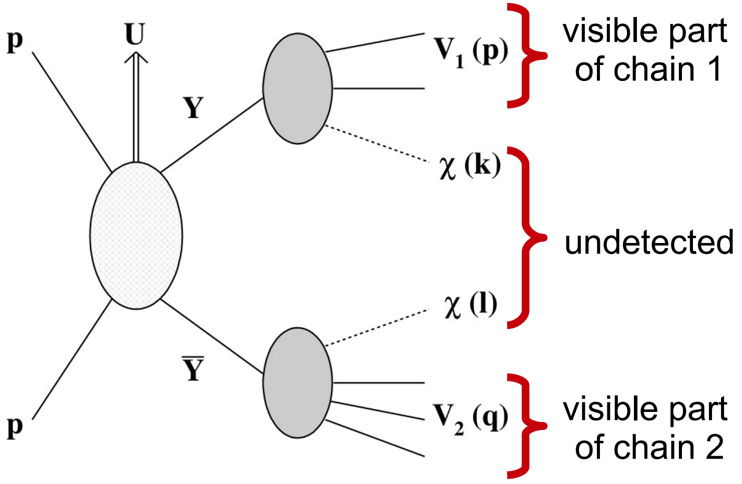
☑ The **inclusion of only transverse momentum components** makes M_{T2} very suitable for hadron colliders, where the boost along the beam axis is unknown

The M_{T2} event variable: main formula

Event topology relevant for M_{T2}



visible part of chain 1

undetected

visible part of chain 2

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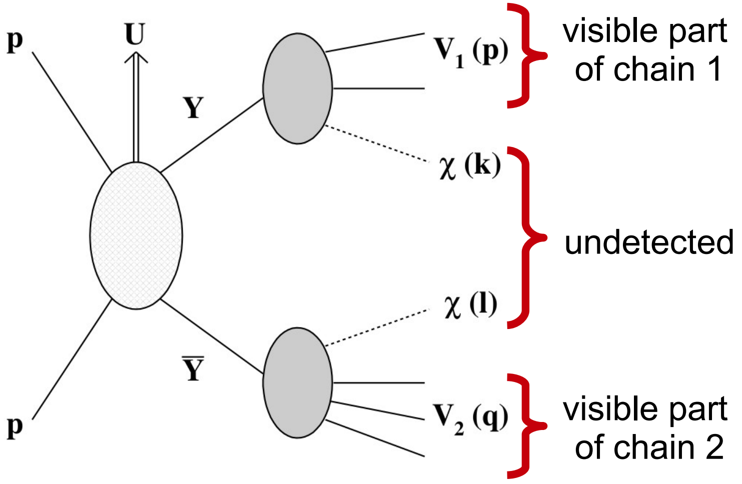

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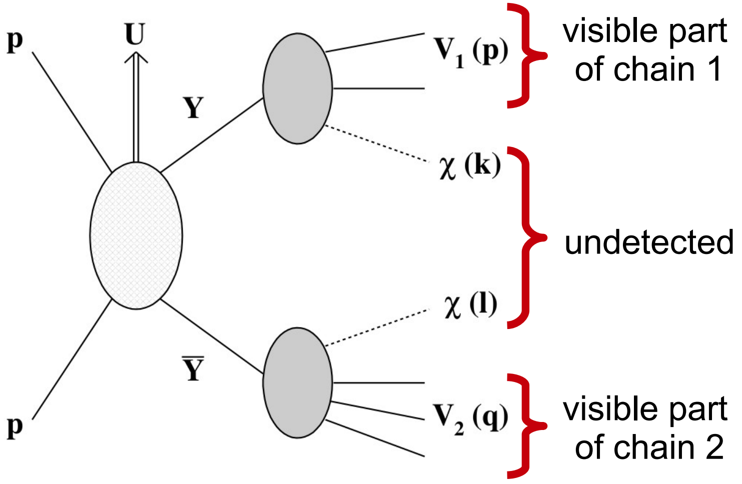

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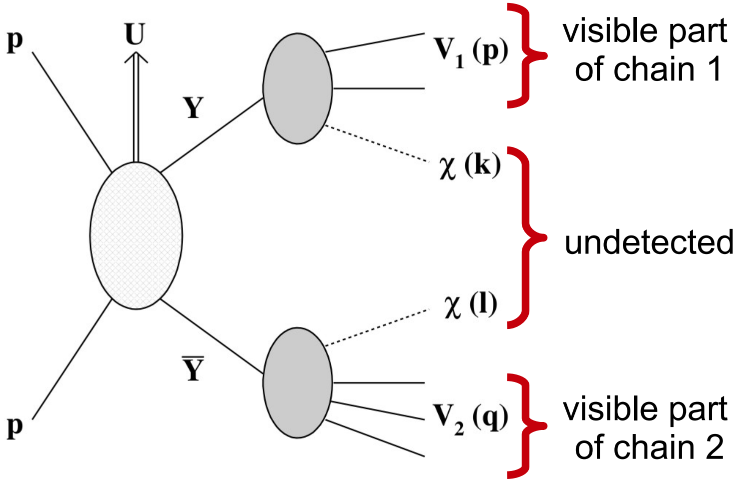

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Hence, event by event, the best one can say is:

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

The M_{T2} event variable: kink feature

Cho-Choi-Kim-Park, 2007

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

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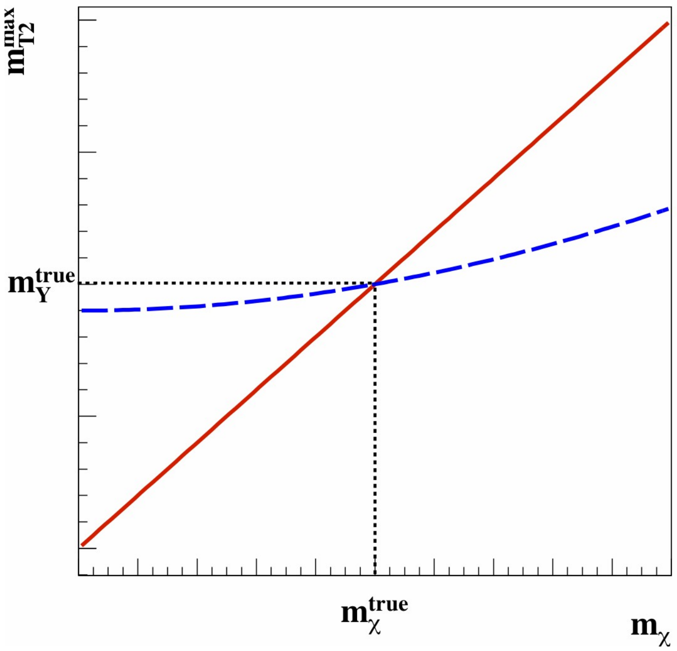
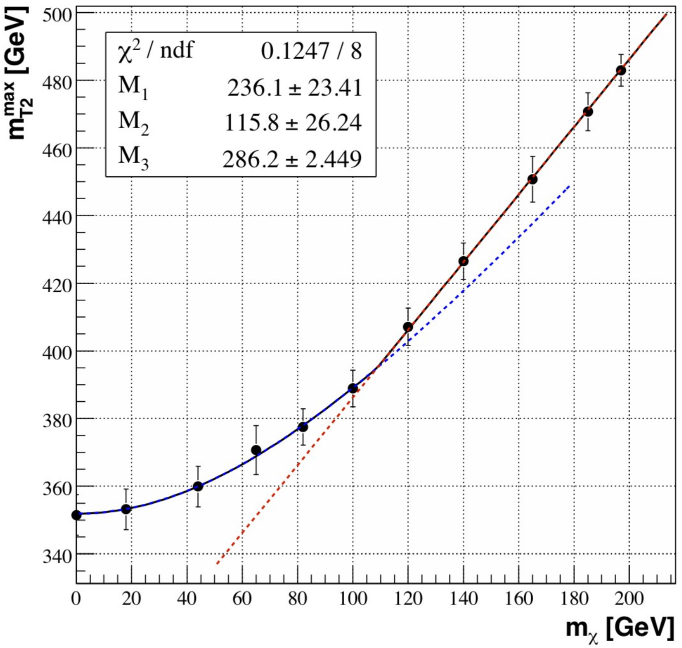
M_{T2} kink: ideal case

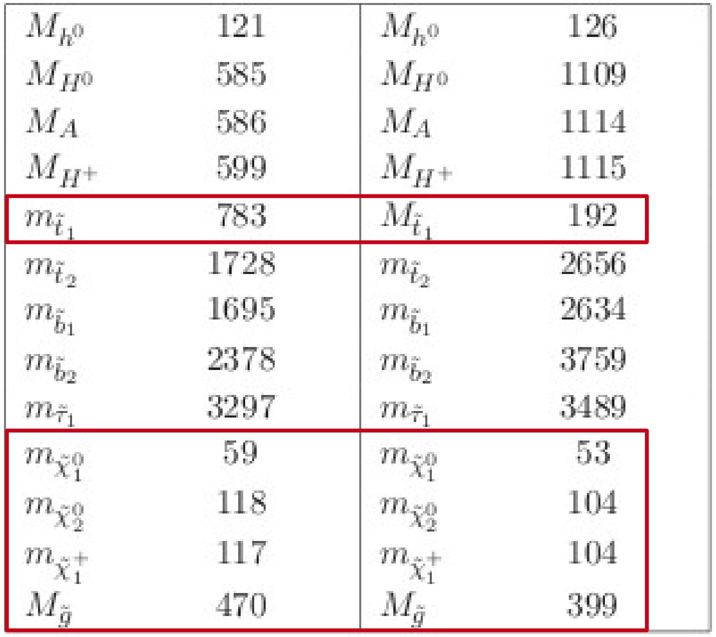


M_{T2} kink: real-life case (see next)



Example of application:
SUSY GUTs with Yukawa unifications

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

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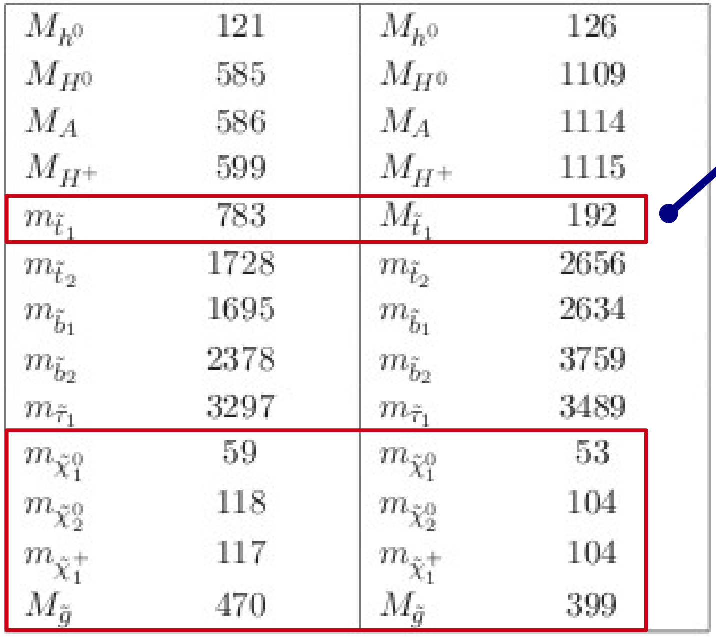
Choi, DG, Im, Park, 2010

Spectrum predictions



scenario 1		scenario 2	
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- Main difference: a stop respectively lighter and heavier than the gluino

Example of application:
SUSY GUTs with Yukawa unifications

from
Choi, DG, Im, Park, 2010

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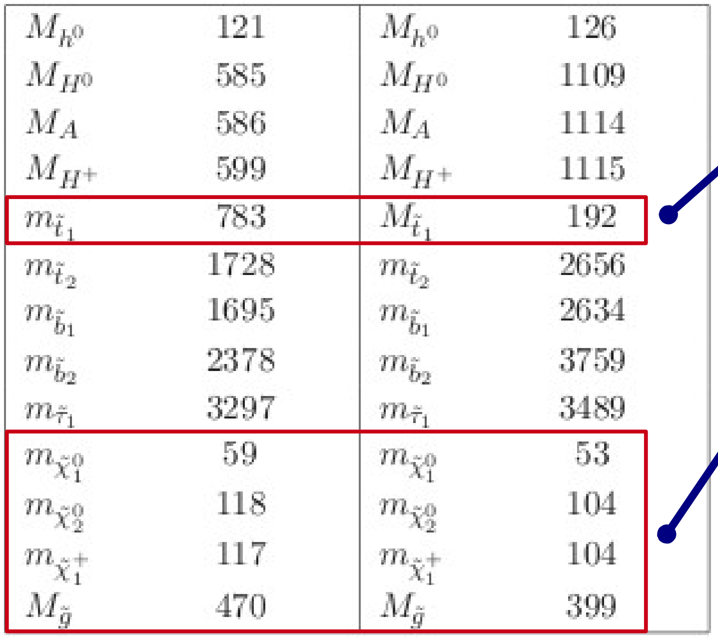

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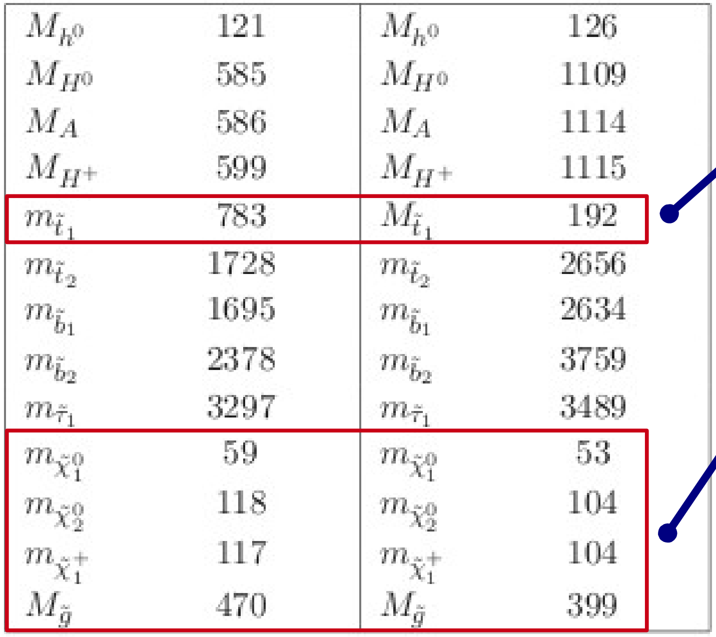

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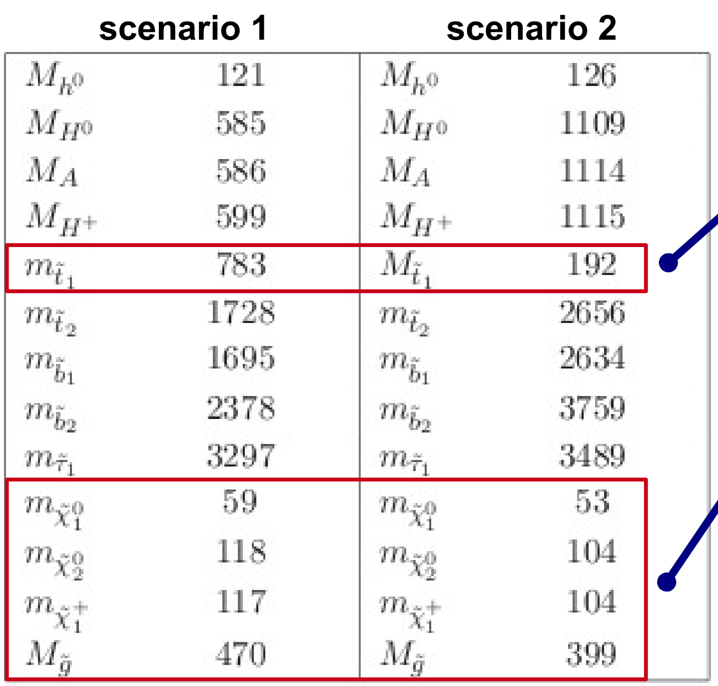

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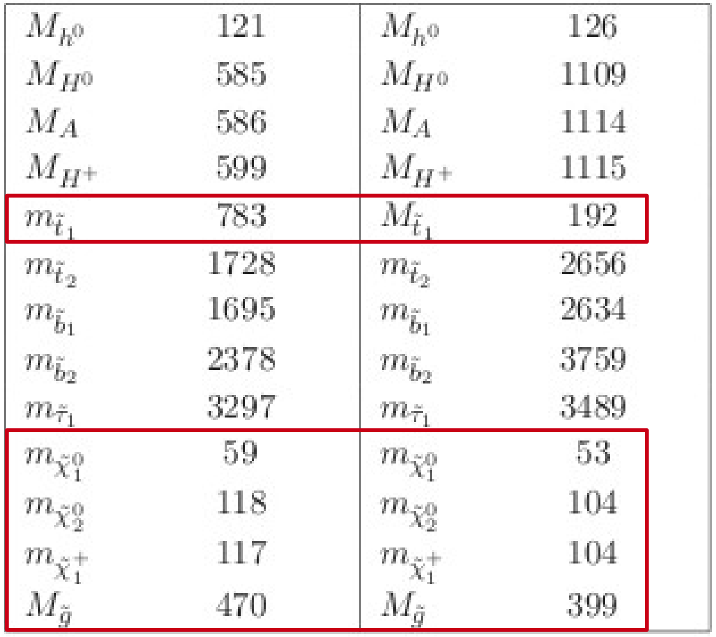
☑ A suitable mass-determination strategy should be able to determine the masses of all the light gauginos and, for scenario 2, of the stop1 as well.

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*

Example of application:
SUSY GUTs with Yukawa unifications

Spectrum predictions



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Main messages

☑ We devised a strategy able to "discover"
all of the sub-TeV SUSY spectrum in either scenario,
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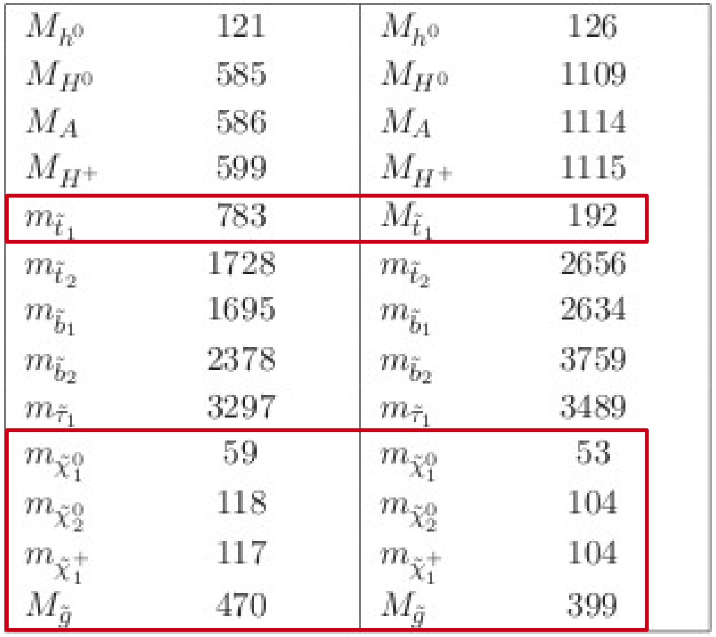
Example of application:

SUSY GUTs with Yukawa unifications

Spectrum predictions



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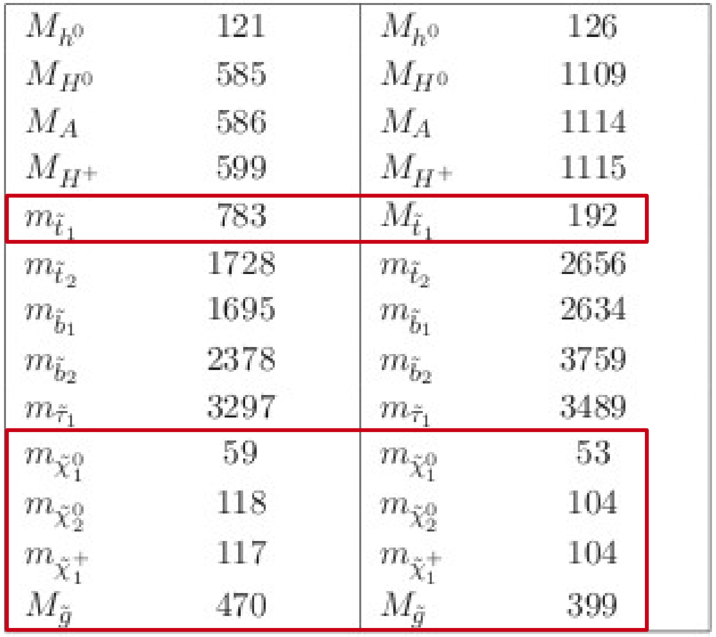
The adoption of the M_{T2} variable was crucial for the above result. The fact that the M_{T2} kink can determine two masses simultaneously allows to “unlock” the system of unknown masses.

Once two masses, in either scenario, are determined through M_{T2} , the rest of the masses can be determined via usual endpoint methods.

Example of application:
SUSY GUTs with Yukawa unifications

Spectrum predictions

scenario 1 **scenario 2**



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The adoption of the M_{T2} variable was crucial for the above result. The fact that the M_{T2} kink can determine two masses simultaneously allows to “unlock” the system of unknown masses.

Once two masses, in either scenario, are determined through M_{T2} , the rest of the masses can be determined via usual endpoint methods.

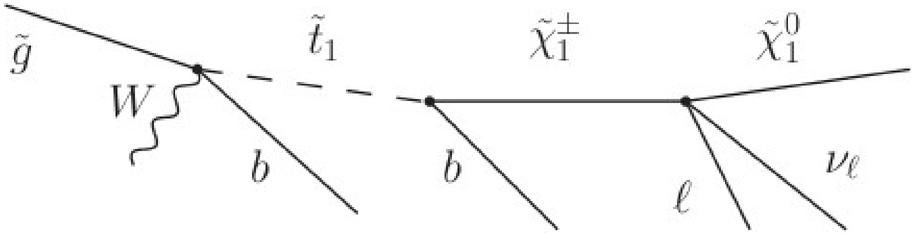
☑ Therefore, by determining the spectra in the two scenarios, our M_{T2} strategy allows to discriminate among these scenarios, already from LHC data.

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 gluino – gluino 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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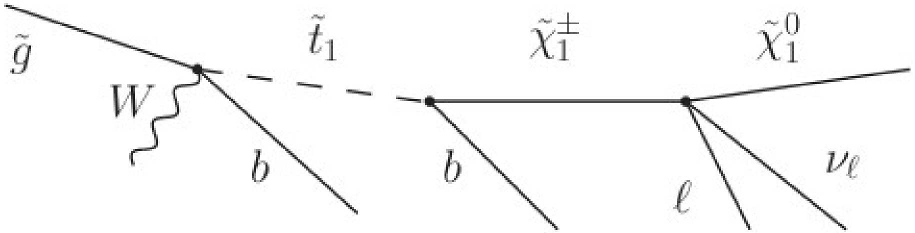

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☑ Trigger on 2 W + 4 b + 2 ℓ + missing p_T

☑ 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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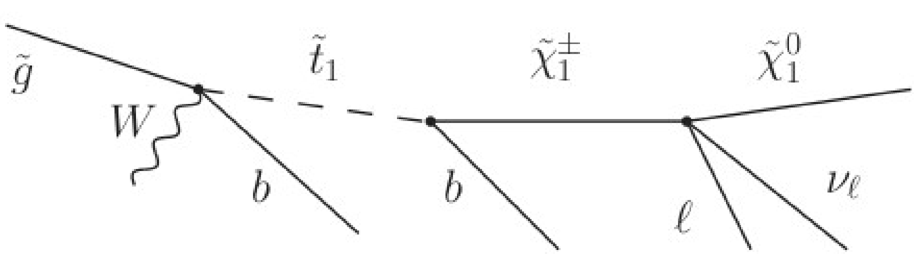

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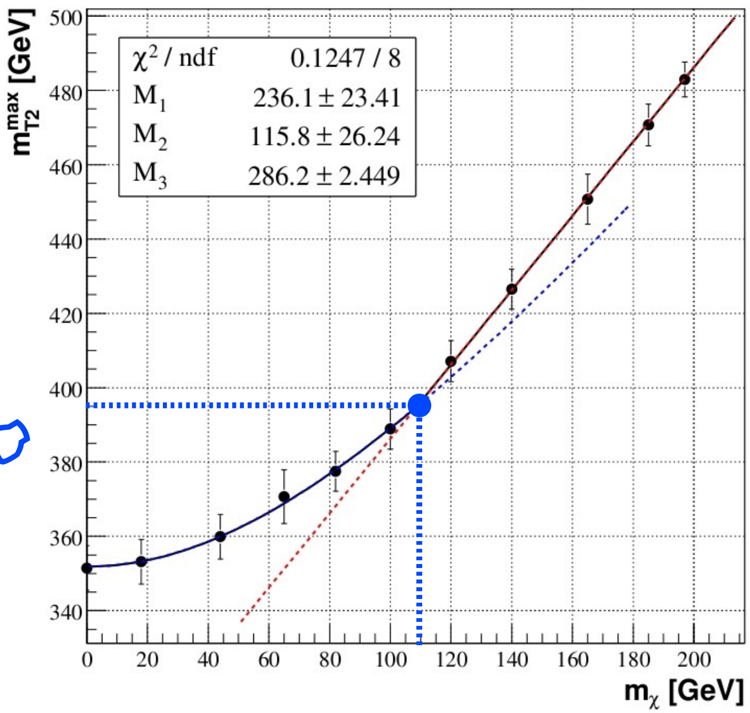
The kink location allows to determine simultaneously the gluino and chargino1 masses:

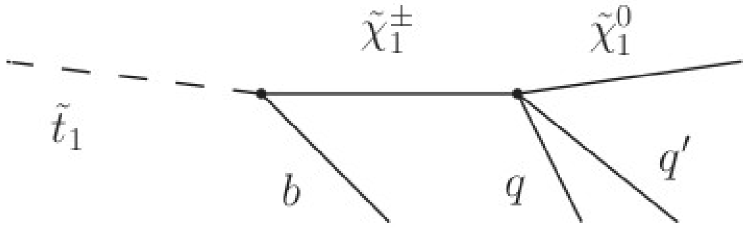
$$m_{\tilde{g}} = 395(16)\ \mathrm{GeV}\,, \quad m_{\tilde{\chi}_1^{\pm}} = 109(17)\ \mathrm{GeV}$$



Application example: continued

Step ②

Consider stop1 – stop1 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:

$$
\begin{aligned}
M_{T,bqq'}(\text{endpoint}) &= \\
m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} &= 149(3)\ \text{GeV} \\
M_{T,qq'}(\text{endpoint}) &= \\
m_{\tilde{\chi}_1^{\pm}} - m_{\tilde{\chi}_1^0} &= 52(2)\ \text{GeV}
\end{aligned}
$$

Application example: continued

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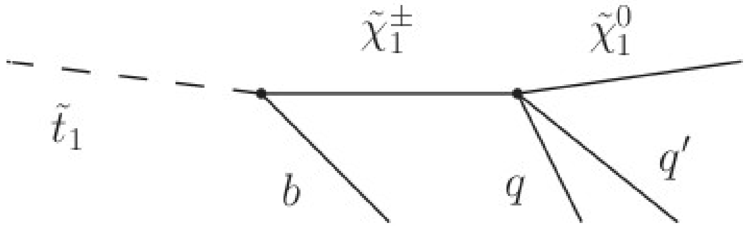

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- ☑ The *endpoints* of these distributions are such that:

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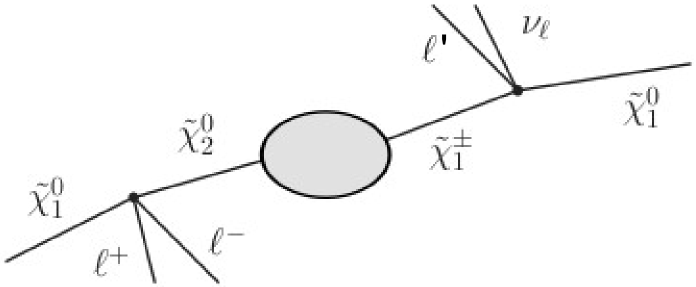
$$M_{T,qq'}(\text{endpoint}) = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} = 52(2)\ \text{GeV}$$

Step ③

Finally, consider neutralino2 – chargino1 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

☑ Our starting point was the question:
“Is it possible, from LHC data, to determine new particles' masses, rather than mass combinations or a “mass scale” for new physics ? If yes, with what accuracy ?”

☑ We focused on events characterized by **short decay chains (≤ 3 branchings), suitable for the use of M_{T2} variables.**

The M_{T2} “kink” allows to determine two masses at a time, which makes it very promising for our purposes.

☑ As a concrete playground, we have considered representative scenarios for SUSY GUTs with Yukawa Unification.
We have then elaborated a strategy, based on M_{T2}, and aimed at the determination of the sub-TeV part of the spectra.

We have studied this strategy on 100 fb^{-1} of data of LHC collisions (14 TeV), including hadronization / detector-level effect with Pythia / PGS.

☑ We have shown this strategy to be able to **determine, with about 20 GeV accuracy, 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)**.

☑ **Luminosity for discovery:** a rough extrapolation of our results indicates that about 10 fb^{-1} would be sufficient for the discovery of either channel.