Understanding and improving the Effective Mass for LHC searches

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[arXiv:1207.0435]

Outline

Introduction

- The LHC is working with impressive performance.
- Is there any signal of New Physics? In a positive case, Which New Physics is it?
- Supersymmetry $\rightarrow$ multijets and large missing energy.
- Kinematic variables.
- In ATLAS analyses the Effective Mass variable ($M_{\rm eff}$) plays a very important role. [arXiv:0901.0512, arXiv:1102.5290, arXiv:1109.6572]

Outline

The Effective Mass

Defined as,

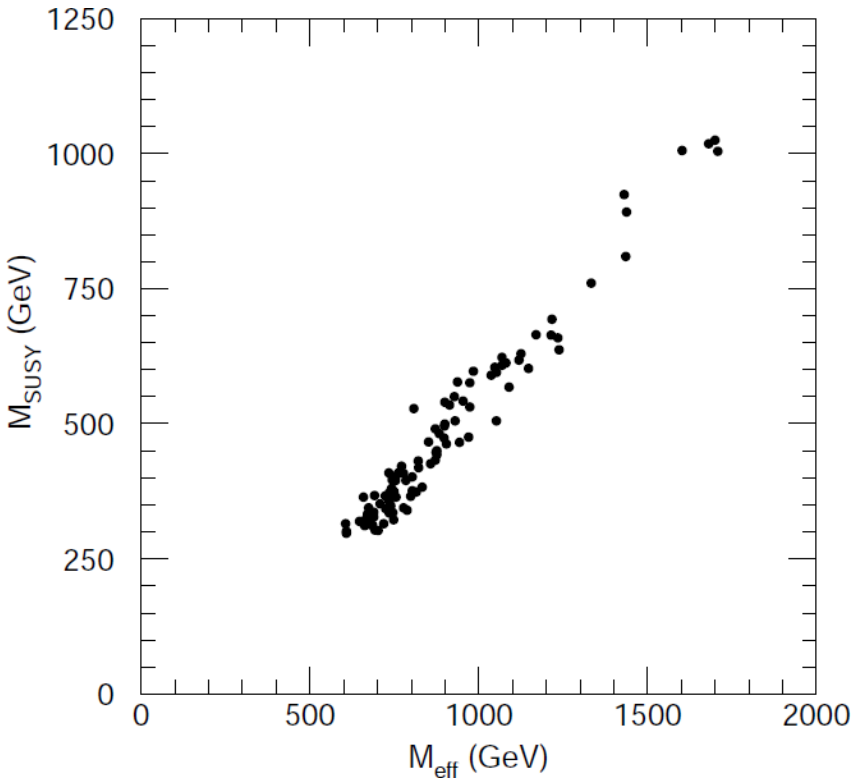
$$M_{\rm eff}^{(4)} = \sum_{j=1}^{4} |p_T^j| + |p_T^{\rm miss}|,$$

where j denote the four hardest jets.

There is a correlation between $M_{\rm eff}^{(4)}|_{\rm max}$ and the SUSY mass $M_{\rm susy}$ defined as,

$$M_{\rm susy} = \min\{m_{\tilde{q}}, m_{\tilde{g}}\}.$$

I. Hinchliffe, et. al [hep-ph/9610544]



Systematically $M_{\rm eff}^{(4)}|_{\rm max} \simeq 1.9\ M_{\rm susy}^{(\rm HPSSY)}$ for a large collection of **CMSSM** models

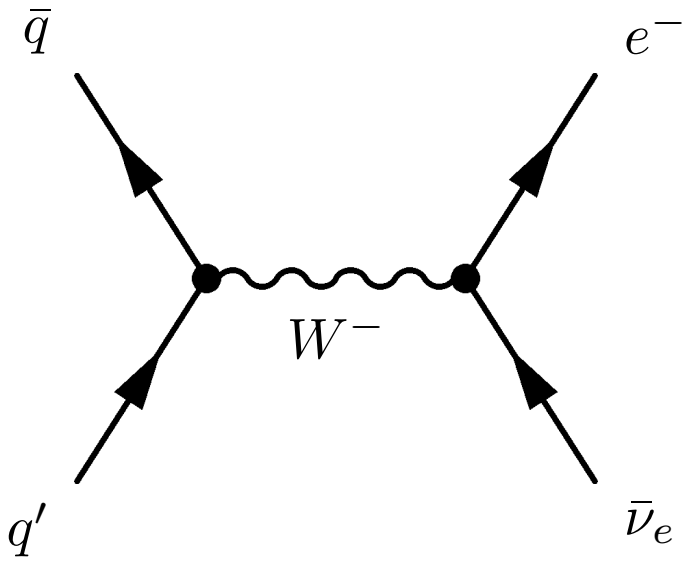
- The definition of $M_{\rm susy}$ is rather arbitrary.
- So far, there is no theoretical explanation for the strong correlation found between the effective mass and the supersymmetric mass.
- For more generic **MSSM** models (beyond the **CMSSM**) such correlation fails in many instances. [Tovey, hep-ph/0006276]

Let's try to understand the behavior of the Effective Mass.

Outline

Kinematic Analysis: W boson production

The simplest case involving visible and invisible particles



Transverse Energy

$$(E_T^a)^2 = m_a^2 + (p_T^a)^2 = (E^a)^2 - (p_z^a)^2$$

Rapidity

$$y^a = \frac{1}{2} \ln \left(\frac{E^a + p_z^a}{E^a - p_z^a} \right) .$$

Invariant Mass : $M_{\rm inv}^2 = m_e^2 + m_\nu^2 + 2\,[\, E_T^e\, E_T^\nu \cosh(y^e - y^\nu) - \vec{p}_T^{\,e} \cdot \vec{p}_T^{\,\nu}\,].$

Kinematic Analysis: W boson production

The differential cross: $d\sigma \propto d^2\Omega$

$$d^2\Omega = d\cos\theta d\phi \;=\; \frac{d\cos\theta}{dp_T^e} dp_T^e \; d\phi,$$

where θ, ϕ are the polar and azimuthal angles.

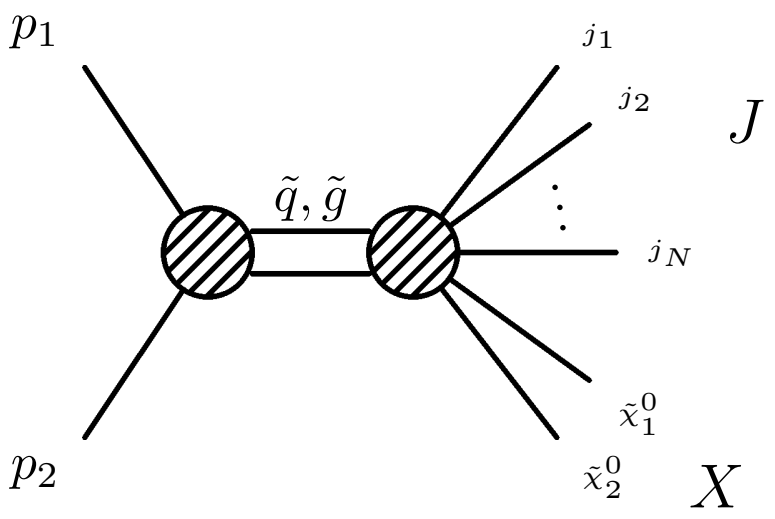
The Jacobian factor of the production of an $e - \nu$ pair at CM frame

$$\frac{d\cos\theta}{dp_T^e} = \frac{-p_T^e|\vec{p_e}|}{\sqrt{|\vec{p_e}|^2 - (p_T^e)^2}} \rightarrow \frac{-M_w p_T^e}{\sqrt{M_w^2 - 4(p_T^e)^2}}$$

A pole in $p_T^e = \frac{1}{2}M_w$

Kinematic Analysis: Production of SUSY particles

Considering two pseudo-particles **J** and **X**



Visible $\rightarrow$ $(E_T^J)^2 = (p_T^J)^2 + m_J^2 \;=\; (E^J)^2 - (p_z^J)^2$

Invisible $\rightarrow$ $(E_T^X)^2 = (p_T^X)^2 + m_X^2 \;=\; (E^X)^2 - (p_z^X)^2$

Kinematic Analysis: Pair production of SUSY

In analogy with the **W boson** case

$$\frac{d\sigma}{dp_T^J} \propto \frac{1}{\sqrt{E^2 - (E_T^J + E_T^X)^2}}$$

with E denoting the total energy in the CM.
We define a global "transverse energy" as

$$\mathcal{E}_T = E_T^J + E_T^X \ .$$

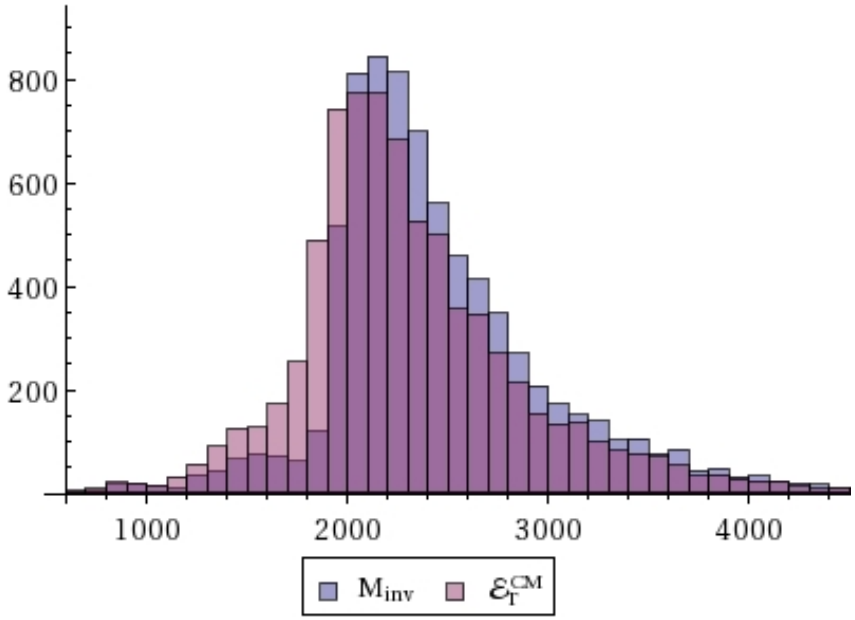
The differential cross section ($d\sigma/d\mathcal{E}$) shows a pole at

$$\mathcal{E}_T|_{\rm pole} = E = M_{\rm inv} \simeq m_1 + m_2 \ .$$

Kinematic Analysis: Pair production of SUSY

At CM frame

A histogram in the $\mathcal{E}_T$ must show a peak at $\mathcal{E}_T = M_{\rm inv}$



The two histograms are pretty similar, exhibiting a peak at the expected value.

Outline

Understanding the correlation $M_{\rm susy} - M_{\rm eff}$

A more convenient definition of $M_{\rm susy}$

$$M_{\rm susy} = \frac{\sum_{a,b} \sigma_{ab} \left(m_a + m_b\right)}{\sum_{a,b} \sigma_{ab}},$$

- Weighting the masses with their cross section, [Tovey, hep-ph/0006276].
- Works fine when the dominant productions have similar masses.

Understanding the correlation $M_{\rm susy} - M_{\rm eff}$

Remember that definitions

$$M_{\rm eff} = M_{\rm eff}^J + |p_T^{\rm miss}| \ , \qquad \mathcal{E}_T = E_T^J + E_T^X$$

where $M_{\rm eff}^J \equiv \sum_j |p_T^j|$.

A connection between $\mathcal{E}_T$ and $M_{\rm eff}$

- Massless jets
- All jets with the same rapidity

- Massless LSP
- Both LSP's in same direction

$$E_T^J = M_{\rm eff}^J$$

$$E_T^X = p_T^{\rm miss}$$

Understanding the correlation $M_{\rm susy} - M_{\rm eff}$

In the peak of the histogram satisfy $E_T^J = E^J = \sum_j E^j \simeq \sum_j |\vec{p}^{\,j}|$ then,

$$\frac{M_{\rm eff}^J}{E_T^J} \simeq \frac{\sum_j |p_T^j|}{\sum_j |\vec{p}^{\,j}|} \ .$$

Then the differential probability that a jet occurs at a particular θ is $\sin\theta d\theta$. In average

$$\langle p_T^j \rangle = |\vec{p}^{\,j}| \int d\theta \sin^2\theta = (\pi/4)|\vec{p}^{\,j}|$$

at the peak of the histogram

$$\frac{< M_{\rm eff}^J >}{E_T^J} \simeq \frac{\pi}{4} = 78.5\% \ .$$

Outline

Proposal of new kinematic variable

But E_T^X is not measurable.

It turns out that if

m_X are fairly smaller than their momenta

then

$$\langle E_T^X \rangle \simeq 2|p_T^{\rm miss}|.$$

We propose a kinematic variable,

$$\mathcal{E}_T^{\rm eff} = E_T^J + 2|p_T^{\rm miss}| \ ,$$

The extension of this variables to other scenarios of new physics is straightforward.

The simulation

We will simulate LHC signals at 14 TeV center-of-mass energy using SOFTSUSY and PYTHIA version 6.419

1. At least three jets with $p_T > 50$ GeV.
2. The hardest jet with $p_T > 100$ GeV and $|\eta| < 1.7$.
3. $p_T^{\rm miss} > 100$ GeV.
4. $\Delta\phi(\text{jet}_1 - p_T^{\rm miss}) > 0.2$, $\Delta\phi(\text{jet}_2 - p_T^{\rm miss}) > 0.2$, $\Delta\phi(\text{jet}_3 - p_T^{\rm miss}) > 0.2$.

For the construction of the jets we will use FASTJET.

Supersymmetry

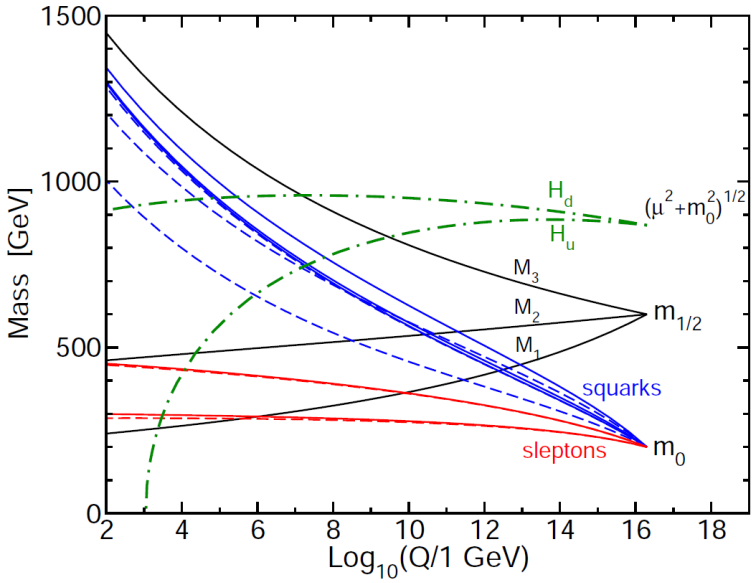
CMSSM

$$\{\theta_i\} \;=\; \{m, M, A, B, \mu\}\ .$$

m, M, A and B: soft parameters

μ: Higgs mass term in the superpotential,

S. P. Martin, [arXiv:hep-ph/9709356]



$\Rightarrow$ Two Higgs doublets H_u, H_d

$$v^2 = 2(v_u^2 + v_d^2)$$

where $\tan\beta \equiv v_u/v_d$

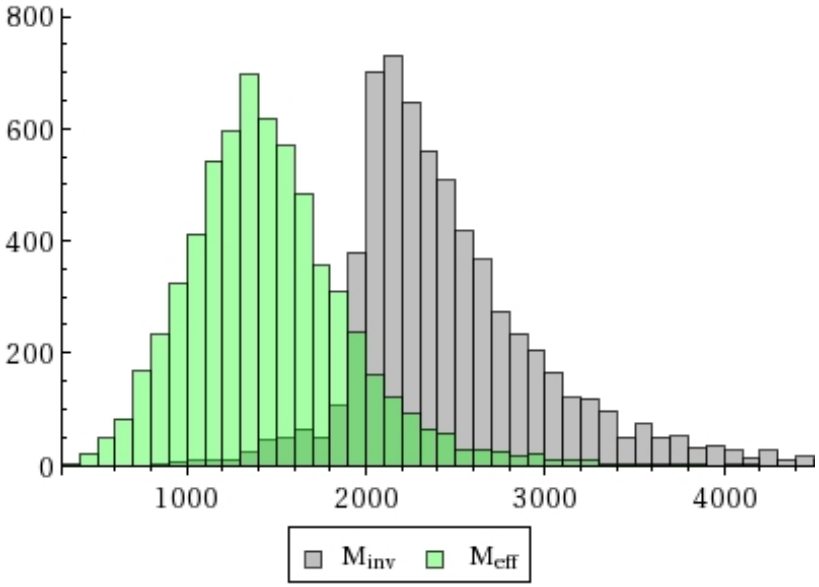
$$m_u \sim y_u v_u = y_u v \sin\beta$$
$$m_d \sim y_d v_d = y_d v \cos\beta$$

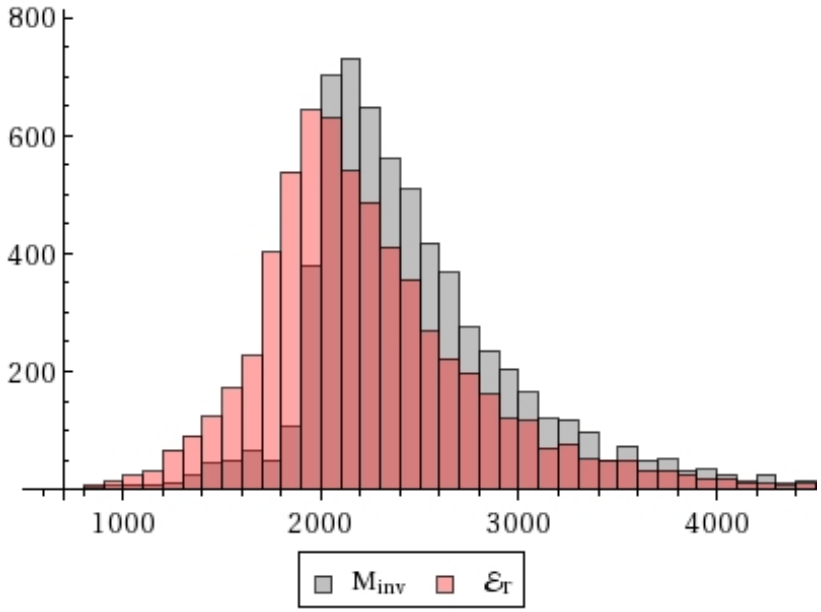
Supersymmetry: The CMSSM

Benchmark point SU9

$m = 300$ GeV, $M_{1/2} = 425$ GeV, $A = 20$ GeV, $\tan\beta = 20$, $\mu > 0$

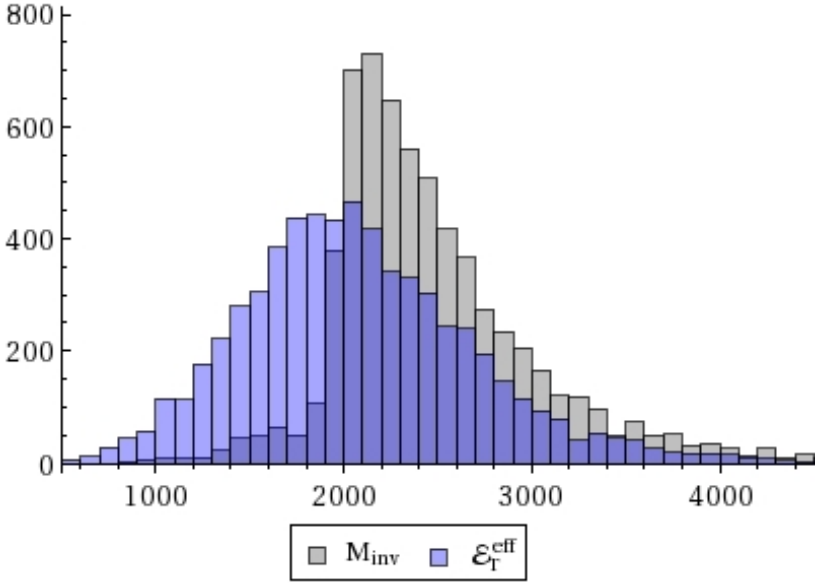
$M_{\rm susy} = 1898$ GeV

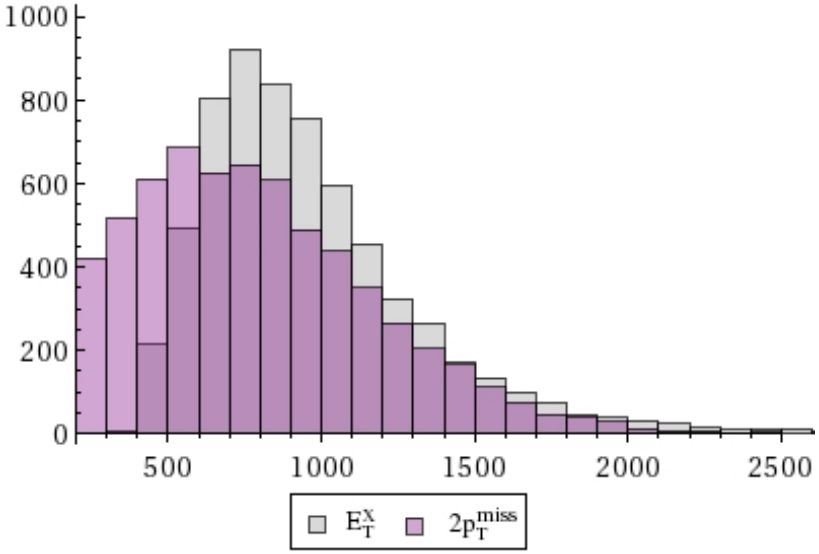




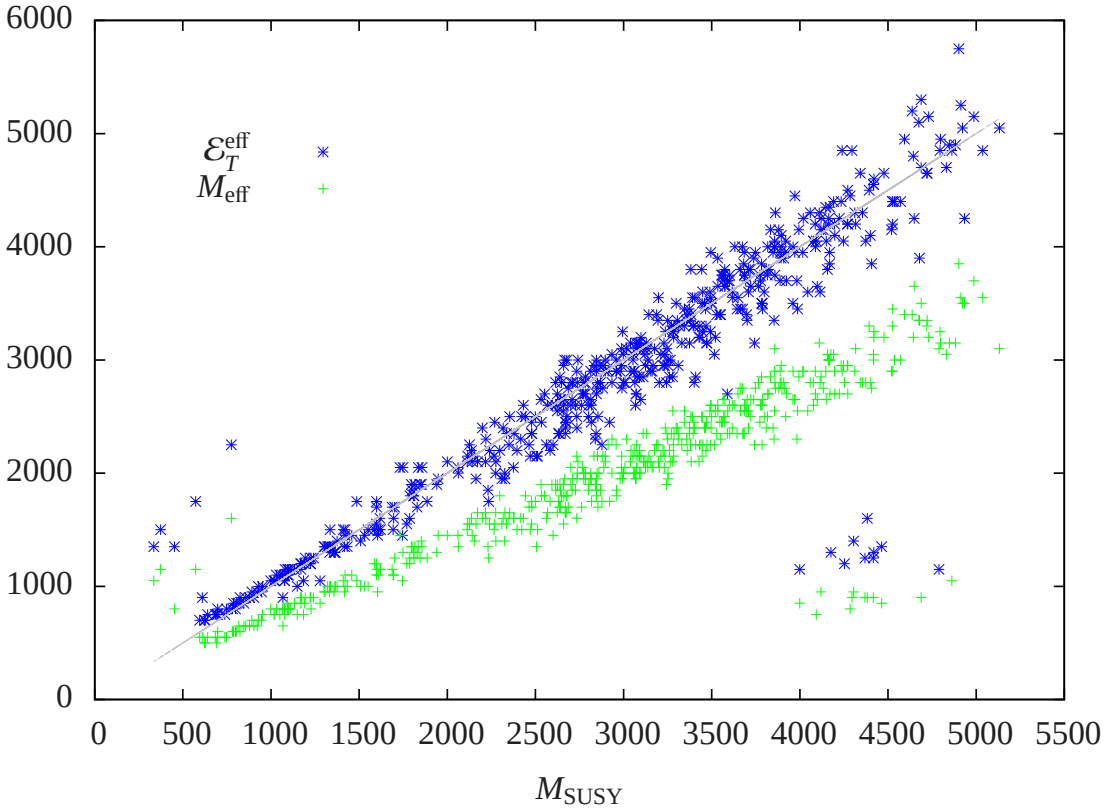
Supersymmetry: The CMSSM

How do $\mathcal{E}_T^{\rm eff}$ behaves?





Testing $\mathcal{E}_T^{\rm eff}$: The CMSSM



A remarkable correlation between $\mathcal{E}_T^{\rm eff}$ at the maximum of the histogram and $M_{\rm susy}$!

Supersymmetry

MSSM

Allowing non-universal soft parameters at the M_X scale

M_1, M_2, M_3: gaugino masses

A_t, A_b, A_τ: trilinear couplings

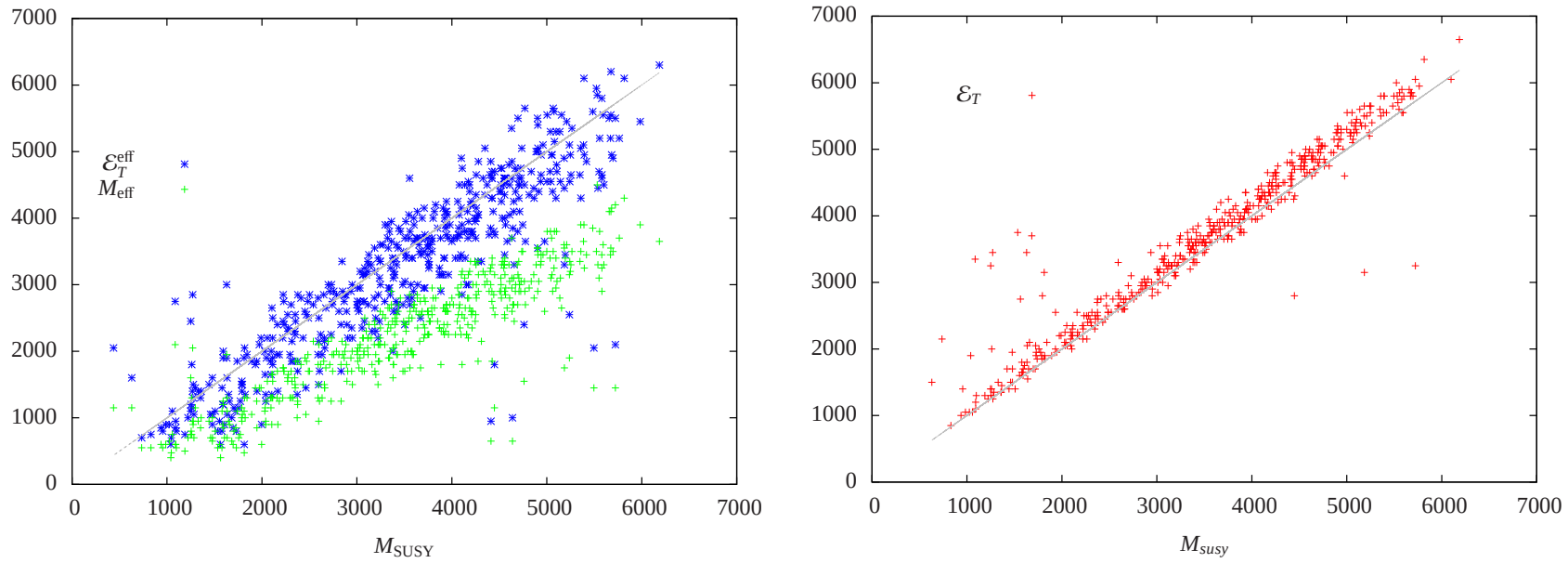
$m_{\tilde{q}_L,\tilde{q}_R}, m_{\tilde{t}_L,\tilde{b}_L}, m_{\tilde{t}_R}, m_{\tilde{b}_R}$: squark masses,

$m_{\tilde{l}_L,\tilde{l}_R}, m_{\tilde{\tau}_L,\tilde{\nu}_{\tau L}}, m_{\tilde{\tau}_R}$: slepton masses,

m_{H_u,H_d}: Higgs masses

$\tan\beta$.

Testing $\mathcal{E}_T^{\rm eff}$: The MSSM



→ Neglecting the neutralino mass one is missing a potential important piece.

Testing $\mathcal{E}_T^{\rm eff}$

One need a better estimation of E_T^X,

$$\langle E_T^X \rangle \simeq \sqrt{4(p_T^X)^2 + 4m_\chi^2} \simeq 2p_T^X + 2m_\chi^2/E_T^X$$

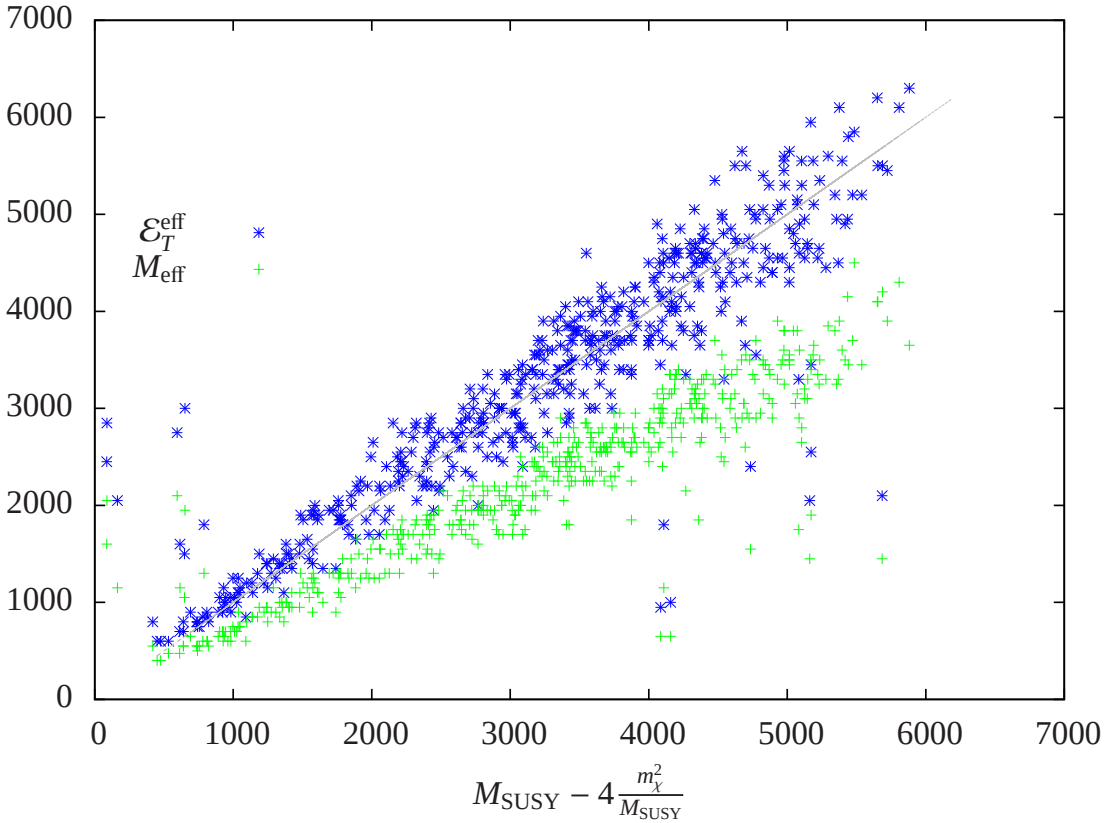
A conservative correction

$$2m_\chi^2/E_T^X \sim 4m_\chi^2/M_{\rm susy}$$

then, the maximum of the histogram must be around

$$M_{\rm susy} \quad \rightarrow \quad M_{\rm susy} - 4\frac{m_\chi^2}{M_{\rm susy}}$$

Testing $\mathcal{E}_T^{\rm eff}$: The MSSM



The correlation is there for a more general MSSM models ! !

Outline

Conclusions

- We have found an explanation for the correlation

$$M_{\rm eff}|_{\rm max} \simeq 80\% \; M_{\rm susy} \; ,$$

- This understanding has allowed us to propose a new kinematic variable

$$\mathcal{E}_T^{\rm eff} = E_T^J + 2|p_T^{\rm miss}|.$$

- We have examine the correlation of $\mathcal{E}_T^{\rm eff}$ in the CMSSM and a more general MSSM showing that it is a simple kinematic variable to determine the characteristic SUSY masses.

- $\mathcal{E}_T^{\rm eff}$ and $M_{\rm eff}$ are complementary variables, rather than competitors.