In the search for Supersymmetry

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Outline

Introduction

- The discovery of a SM-like Higgs boson

$$m_h = 126.0 \pm 0.4\ (\mathrm{stat})\ \pm 0.4\ (\mathrm{sys})\ \mathrm{GeV}\ \ (\mathrm{ATLAS})$$
$$m_h = 125.7 \pm\ 0.4\ (\mathrm{stat})\ \pm 0.4\ (\mathrm{sys})\ \mathrm{GeV}\ \ (\mathrm{CMS})$$

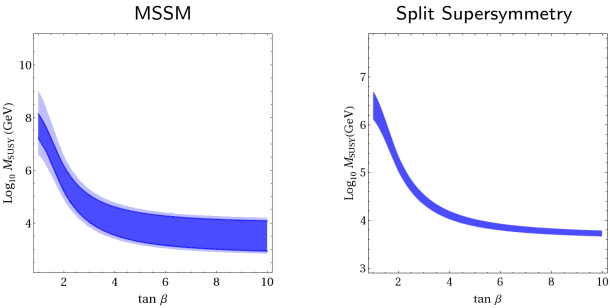
- LHC bounds on supersymmetric particles.
- XENON100 constraints on fermionic Dark Matter
- The health of Supersymmetry

Implication of a higgs of 125GeV

The higgs mass,

$$m_h^2 \simeq M_Z^2 \cos 2\beta + \frac{3m_t^4}{2\pi^2 v^2}\left[\log\frac{M_{\mathrm{SUSY}}^2}{m_t^2} + \frac{X_t^2}{M_{\mathrm{SUSY}}^2}\left(1 - \frac{X_t^2}{12M_{\mathrm{SUSY}}^2}\right)\right]$$

M_{SUSY} : Geometrical average of stop masses
X_t : Mixing parameter



Implication of a higgs of 125GeV

Large squarks

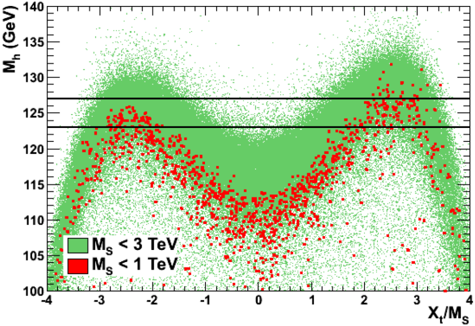
$m_{\tilde{t}} \gtrsim 3$ TeV

unless

Maximal mixing

$X_t \simeq \sqrt{6} m_{\tilde{t}}$

Arbey et al [arXiv:1112.3028 [hep-ph]]



A higgs mass of 126 are not very good news for MSSM.

The health of Supersymmetry

Naturalness and Supersymmetry

From **the minimization of the tree-level form of the scalar potential**

$$M_Z^2 \quad = \quad 2\,\frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - 2\mu_{low}^2 \quad .$$

Barbieri-Giudice fine-tuning parameters

$$c_i = \left|\frac{\partial \ln M_Z^2}{\partial \ln p_i}\right|,$$

The global measure of the fine-tuning is taken as $c \equiv \max\{c_i\}$ or $c \equiv \sqrt{\sum c_i^2}$.

Naturalness and Supersymmetry

Since naturalness arguments are deep down statistical arguments,

$$\begin{aligned} \mathcal{L} &= N_Z \; e^{-\frac{1}{2}\left(\frac{M_Z - M_Z^{\rm exp}}{\sigma_Z}\right)^2} \mathcal{L}_{\rm rest} \\ &\simeq \delta(M_Z - M_Z^{\rm exp}) \; \mathcal{L}_{\rm rest} \end{aligned}$$

Use M_Z to marginalize μ

$$p(s, m, M, A, B | \;{\rm data}) \sim \left[\frac{d\mu}{dM_Z}\right]_{\mu_0} \mathcal{L}_{\rm rest} \; p(s, m, M, A, B, \mu_0)$$

then,

$$p(s, m, M, A, B | \;{\rm data}) \;=\; 2\frac{\mu_0}{M_Z} \; \frac{1}{c_\mu} \; \mathcal{L}_{\rm rest} \; p(s, m, M, A, B, \mu_0) \;\; !$$

An effective penalization of fine-tunings arises from the Bayesian analysis itself.

Constrained SUSY scenarios

CMSSM

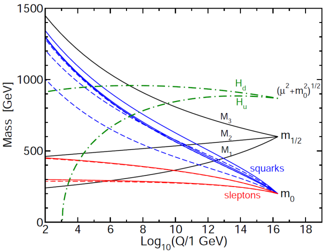
$$\{\theta_i\} = \{m_0, m_{1/2}, A, B, \mu, s\} ,$$

NUHM

$$\{\theta_i\} = \{m_0, m_H, m_{1/2}, A, B, \mu, s\} .$$

m_0, m_H, M, A and B: soft parameters
μ: Higgs mass term in the superpotential,
s: SM-like parameters.

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 $\tan\beta \equiv v_u/v_d$

Neutralinos

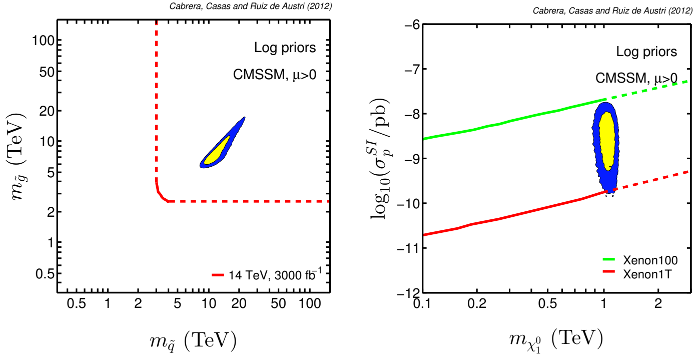
$\tilde{B}$, $\tilde{W}$, $\tilde{H}_u$, $\tilde{H}_d$

$\Downarrow$

$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$

Supersymmetry: The CMSSM

Single-component CDM

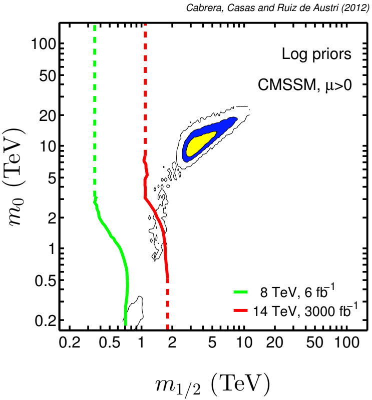


The contours enclose the 68% (yellow) and 95% (blue) of integrated probability.

`SuperBayeS: SoftSusy, FeynHiggs, SuperIso, SusyBSG, MicrOMEGAs, DarkSusy`

Comparison with previous literature

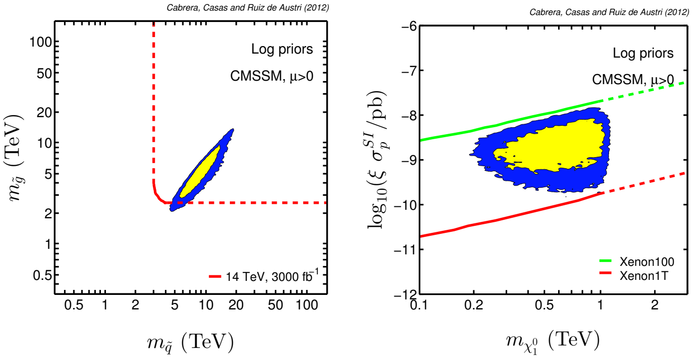
Balazs et al [1205.1568], Fowlie et al. [1206.0264], Akula et al. [1207.1839], Buchmueller et al. [1207.7315], Strege et al [1212.2636]



The contours enclose the 68% (yellow), 95% (blue) and 99.9% (black) of integrated probability.

Supersymmetry: The CMSSM

Multi-component CDM



Where $\xi \equiv \Omega_{LSP}/\Omega_{DM}$.

Supersymmetry: The MSSM

In constrained scenarios:

$m_h = 125$ GeV $\longrightarrow$ large sfermion masses

XENON100 bounds $\longrightarrow$ excludes higgsino-bino LSP

The neutralino is essentially a **Higgsino**, with a mass of ~ 1 **TeV**.

To which extent the problems of the CMSSM remains in the MSSM?

Breaking universality

- Light third generation and maximal mixing
- Compressed spectrum

Supersymmetry: The MSSM

Regarding CDM:

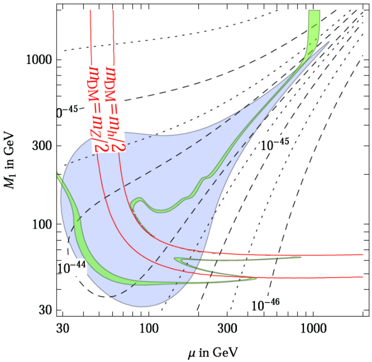
(a) Almost purely higgsino ($\simeq$ 1TeV) or wino ($\simeq$ 2.5 TeV) like $\tilde{\chi}_1^0$

(b) Bino/Wino $\tilde{\chi}_1^0$ ($M_1 \simeq M_2$)

(c) Higgs funnel region

(d) Coannihilation with light sleptons (sfermions)

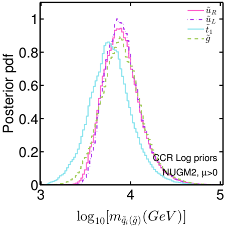
Farina et al [arXiv:1104.3572 [hep-ph]]

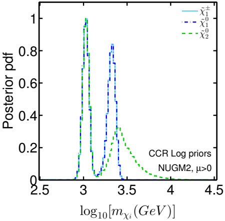


(a), **(b)** and **(c)** appear when breaking gaugino masses unification at GUT scale

Supersymmetry: NUGM + NUHM

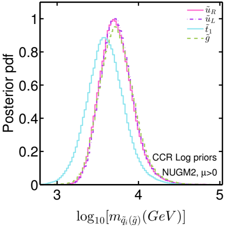
Single-component CDM

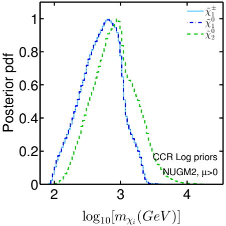




- Prior independent
- $\tilde{\chi}_1^0 \simeq 1$ TeV (higgsino)
- $\tilde{\chi}_1^0 \simeq 2.5$ TeV (Wino)
- $m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\chi}_1^\pm}$

Multi-component CDM





- Prior dependence
- $\tilde{\chi}_1^0$ higgsino-like
- $\tilde{\chi}_1^0$ wino-like
- $m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\chi}_1^\pm}$

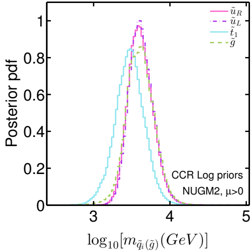
Work in progress...

Supersymmetry: NUGM + NUHM

"Low energy" Supersymmetry: the region accessible to LHC

Imposing the conditions:

Observable	Condition
$m_{\tilde{q}}$	$\lesssim$ 3 TeV
$m_{\tilde{g}}$	$\lesssim$ 3 TeV
$m_{\tilde{t}_1}$	$\lesssim$ 1.5 TeV
$m_{\chi^0_{2(3)}}$	$\lesssim$ 1.0 TeV

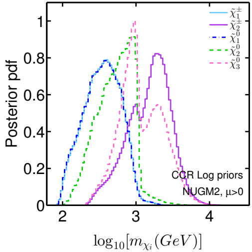


Prior dependence, but

* split susy like scenarios

* It is easier to get light neutralinos and charginos rather that light gluinos and stops

* Neutralino-chargino production !



Work in progress...

"Low energy" Supersymmetry

Collider signatures: Neutralinos and Charginos

- Long live $\tilde{\chi}_1^{\pm}$ (wino-like)
- $\tilde{\chi}_1^{\pm}$ ($\tilde{\chi}_2^0$) soft decay

$$\text{If } \tilde{\chi}_1^0 \text{ wino-like} \quad \rightarrow \quad m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\chi}_1^{\pm}}$$
$$\text{If } \tilde{\chi}_1^0 \text{ higgsino-like} \quad \rightarrow \quad m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\chi}_2^0} \simeq m_{\tilde{\chi}_1^{\pm}}$$

  Effectively, $\tilde{\chi}_1^{\pm}$ ($\tilde{\chi}_2^0$) are invisible particles

- Production:

  * $\tilde{\chi}_1^0\ \tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^{\pm}\ \tilde{\chi}_1^{\pm}$ will produce "invisible" final state (monojets ?)
  * One heavy ($\tilde{\chi}_{2,3}^0$, $\tilde{\chi}_2^{\pm}$) and one light ($\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_{1(2)}^0$) state.
  * Production of heavy states $\tilde{\chi}_{2(3)}^0\ \tilde{\chi}_2^{\pm}$: three leptons plus missing energy.

Work in progress...

"Low energy" Supersymmetry

Multijet final states

Gluinos	Light stop
$\tilde{g} \rightarrow t\ \bar{t}\ \tilde{\chi}^0_{1(2)}$	$\tilde{t}_1 \rightarrow t\ \tilde{\chi}^0_{1(2)}$
$\tilde{g} \rightarrow t\ \bar{b}\ \tilde{\chi}^{\pm}_1$	$\tilde{t}_1 \rightarrow b\ \tilde{\chi}^{+}_1$
$\tilde{g} \rightarrow q\ \bar{q}\ \tilde{\chi}^0_1$	
$\tilde{g} \rightarrow q'\ \bar{q}\ \tilde{\chi}^{\pm}_1$	

What about light sleptons?

Efficient CDM annihilation channel: $\tilde{\chi}^0_1$ with light sleptons

Neutralinos and charginos will decay throw sleptons.

$$p\ p \rightarrow \chi^0_i\ \chi^{\pm}_j, \quad \chi^0_i \rightarrow \tilde{l^{\pm}}\ l^{\mp} \rightarrow l^{\pm}\ l^{\mp}\ \tilde{\chi}^0_1, \quad \chi^{\pm}_j \rightarrow \tilde{l^{\pm}}\ \nu, \rightarrow l^{\pm}\ \nu\ \tilde{\chi}^0_1$$

Three lepton + missing momentum final state

Going beyond: The PMSSM

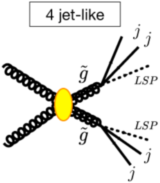
Outline

Supersymmetry searches

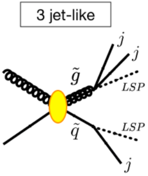
- LHC is working with impressive performance
- CMSSM was a starting point to optimize SUSY searches.
- Are the CMSSM strategies optimal to the MSSM searches?
- The PMSSM and Simplified models

Supersymmetry searches: The CMSSM

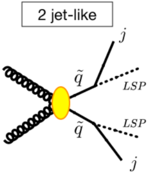
The golden channel: **multijets, 0 leptons and missing energy**



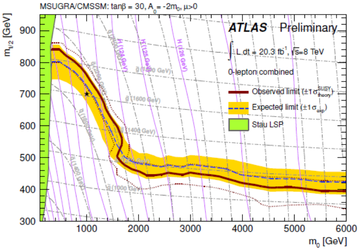
Dominant when
$m_{squark} >> m_{gluino}$

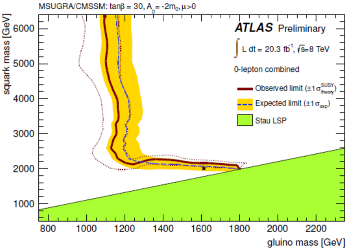


Dominant when
$m_{squark} \sim m_{gluino}$



Dominant when
$m_{gluino} >> m_{squark}$





Supersymmetry searches: The PMSSM

Boundary conditions at EW breaking scale

Gauginos	$M_1,\ M_2,\ M_3$
Squarks 1st, 2nd	$m_{\tilde{u}_L} = m_{\tilde{d}_L},\ m_{\tilde{u}_R},\ m_{\tilde{d}_R}$
Squarks 3rd	$m_{\tilde{t}_L} = m_{\tilde{b}_L},\ m_{\tilde{t}_R},\ m_{\tilde{b}_R}$
Sleptons 1st, 2nd	$m_{\tilde{e}_L} = m_{\tilde{\nu}_L},\ m_{\tilde{e}_R}$
Sleptons 3rd	$m_{\tilde{\tau}_L},\ m_{\tilde{\tau}_R}$
Higgs masses	$m_{H_u},\ m_{H_d}$
μ parameter	sign of μ
Higgs vev's ratio	$\tan\beta$
Trilinears parameters	$A_t,\ A_b,\ A_\tau$

Many possible hierarchy masses:

* Compressed spectrum
* Light stops and sbottoms
* Light sleptons.
* Different hierarchy between sleptons and squarks.

Supersymmetry searches: Simplified Models

How to test the PMSSM?

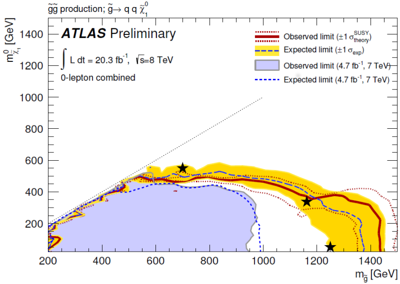
Focusing on specific final state and picking the relevant parameter to build a **simplified model**

Gluino production

$$pp \to \tilde{g}\ \tilde{g} \to q\ \bar{q}\ q'\ \bar{q}'\tilde{\chi}_1^0\ \tilde{\chi}_1^0,$$

The model:

$$m_{\tilde{g}},\ m_{\tilde{\chi}_1^0}$$



- A simple way of testing MSSM and beyond!
- Assumptions are needed to make the model simple
- A challenge: to capture all the possibilities.

Supersymmetry searches: Colored particles

Gluinos and squarks

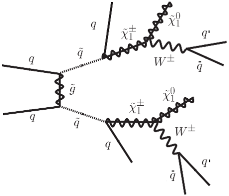
Multijets, 0 leptons and missing energy

Production,

$$
\begin{array}{lcl}
p\ p & \to & \tilde{g}\ \tilde{g} \\
p\ p & \to & \tilde{g}\ \tilde{q} \\
p\ p & \to & \tilde{q}\ \tilde{q}
\end{array}
$$

Decay

$$
\begin{array}{lcl}
\tilde{g} & \to & q\ \bar{q}\ \tilde{\chi}_i^0 \\
\tilde{g} & \to & q'\ \bar{q}\ \tilde{\chi}_i^\pm \\
\tilde{q} & \to & q\ \bar{\chi}_i^0 \\
\tilde{q} & \to & q'\ \bar{\chi}_i^\pm
\end{array}
$$



- The most important channel for 1st and 2nd generation of squarks
  Unless: higgssino-lsp and light sleptons,...

- Third generation: stops and sbottoms

$$
\begin{array}{lcl}
\tilde{t} & \to & t\ \tilde{\chi}_i^0 \\
\tilde{t} & \to & b\ \tilde{\chi}_i^\pm \\
\tilde{b} & \to & b\bar{\chi}_i^0
\end{array}
$$

Supersymmetry searches: Colored particles

Extracting information from multijets final states:

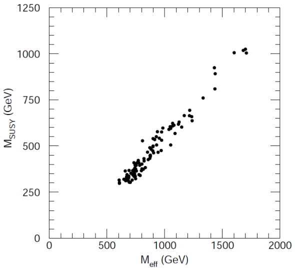
- Large systematic uncertainties
- Final parton $\neq$ Identified jet

The Effective Mass ($M_{\rm eff}$)

$$M_{\rm eff} = \sum_i^{\rm jets} |p_T^i| + \not{p}_T$$

$$M_{\rm SUSY} = \min\{m_{\tilde{u}_R}, m_{\tilde{g}}\}$$

Good correlation between $M_{\rm eff} \simeq 1.8 M_{\rm susy}$

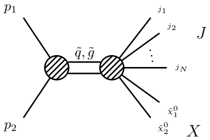


Hinchliffe et al [hep-ph/9610544]

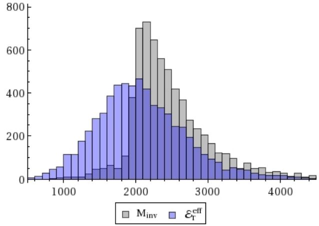
Supersymmetry searches: Colored particles

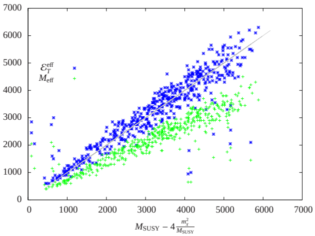
$\mathcal{E}_T^{\rm eff}$ [Cabrera et al 2012]

$$\mathcal{E}_T^{\rm eff} = E_T^J + 2\not{p}_T^2 \quad \text{where} \quad (E_T^J)^2 = \sum_i^{\rm jets} (E_T^i)^2 - (P_Z^i)^2$$



Improving $M_{\rm eff}$



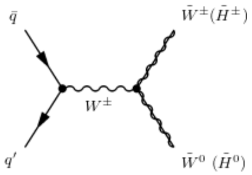


See also $\sqrt{\hat{s}}_{\rm min}$. **Matchev et al** arXiv:0812.1042 [hep-ph]

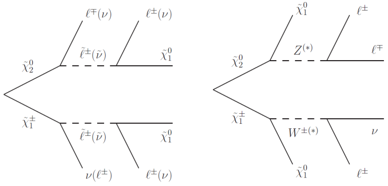
Supersymmetry searches: Neutralinos, Charginos

Charginos and Neutralinos

Multileptons and missing energy



$\longrightarrow$

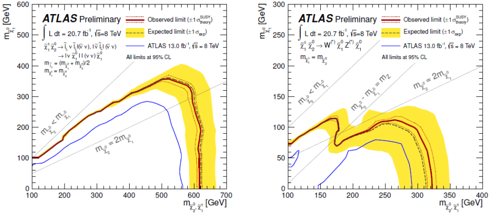


(a) via sleptons (b) via gauge bosons

Simplified Model:

$$m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^{\pm}}$$

$$m_{\tilde{l}} = 2m_{\tilde{\chi}_1^0}$$



(a) Decay via sleptons (b) Decay via gauge bosons

Supersymmetry searches: Neutralinos, Charginos

Regarding the 3 leptons + $\not{p}_T$ simplified model:

- *Even when exclusion limits assume a specific relation between $m_{\tilde{l}}$ and $m_{\tilde{\chi}_1^0}$, the analysis is optimized for the two configurations*

Is this the "golden" channel for neutralino-chargino production?

* If χ_1^0 is Bino like, YES

* What about higgsino or wino χ_1^0?

- 3 leptons + $\not{p}_T$ corresponds to the production of heavy states: $\chi_2^{\pm}$, $\chi_{2(3)}^0$
- $\chi_{1(2)}^0$, $\chi_1^{\pm}$ soft decays.
- $p\ p > \chi_i^0\ \chi_j^{\pm}$, $\chi_i^0\ \chi_j^0$, $\chi_i^{\pm}\ \chi_j^{\pm}$ become relevant

The nature of the lsp plays a very important roll.

Supersymmetry searches: Neutralinos, Charginos

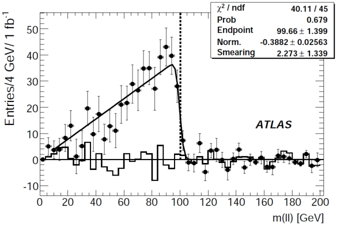
Kinematics

Leptons are "clean" final states:

* Precise energy and momentum measurements,
* Ability to distinguish between flavor.
* Allows to separate decay chains.

The case of $\tilde{\chi}_2^0 \to \tilde{l}^{\pm} l^{\mp} \to l^{\pm} l^{\mp} \tilde{\chi}_1^0$

$$M_{ll}^{edge} = m_{\tilde{\chi}_2^0}^2 \sqrt{1 - \frac{m_{\tilde{l}}^2}{m_{\tilde{\chi}_2^0}^2}} \sqrt{1 - \frac{m_{\tilde{\chi}_1^0}^2}{m_{\tilde{l}}^2}}$$



Supersymmetry searches: Neutralinos, Charginos

The case of $\tilde{\chi}_2^0 \rightarrow Z\ \tilde{\chi}_1^0 \rightarrow l^{\pm}\ l^{\mp}\ \tilde{\chi}_1^0$

A complementarity strategy

Whatever the χ_2^0 is decaying through, in the rest-frame of χ_2^0, the transverse energy

$$\mathcal{E}_T = E_T^v + E_T^{\chi}$$

with

$$(E_T^v)^2 = M_v^2 + (p_T^v)^2 \quad , \qquad (E_T^{\chi})^2 = M_{\chi}^2 + (p_T^{\chi})^2$$

This translate into a pole in the visible transverse energy

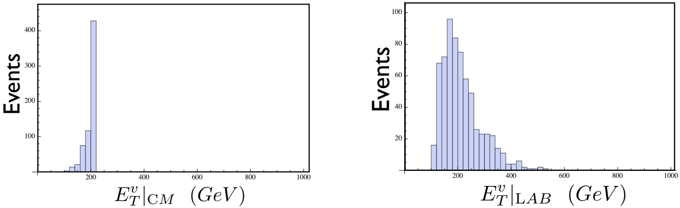
$$\mathcal{E}_T|_{\rm pole} = E_{{\rm CM}\chi} = M_{\tilde{\chi}_2}$$

which can be rewritten as,

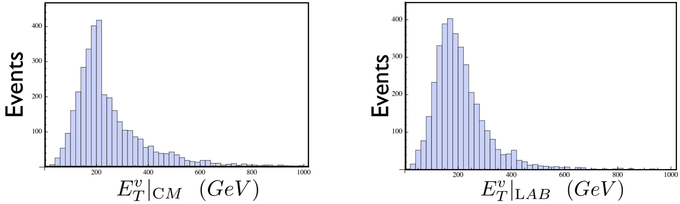
$$E_T^v = \frac{m_{\tilde{\chi}_2^0}^2 + M_v^2 - M_{\chi_1^0}^2}{2M_{\chi_2^0}}$$

Supersymmetry searches: E_T^v

$\tilde{\chi}_2^0 \rightarrow \tau^{\pm}\ \tau^{\mp}\ \tilde{\chi}_1^0$



$\tilde{\chi}_2^0 \rightarrow j\ j\ \tilde{\chi}_1^0$

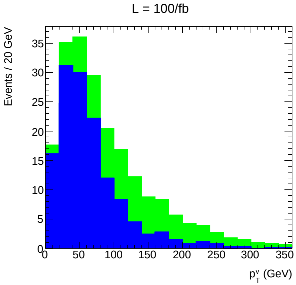


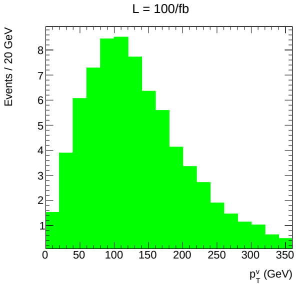
Supersymmetry searches: E_T^ν

An Example

$$M_1 = 47 \text{ GeV} \ , \quad M_2 = 244 \text{ GeV} \ , \mu = -515 \text{ GeV} \ , \tan\beta = 19$$

$$m_{\tilde{\chi}_1^0} = 53 \text{ GeV} \ , \quad m_{\tilde{\chi}_2^0} = 273 \text{ GeV} \ , \quad m_{\tilde{\chi}_1^\pm} = 273 \text{ GeV}$$

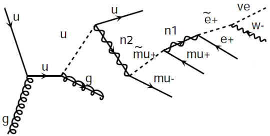




Supersymmetry searches: Beyond the MSSM

- MSSM + seesaw

  $\tilde{\nu}$ LSP $\longrightarrow$ many leptons at final state



[On going project]

- NMSSM

- R parity violation

Conclusions

- SUSY (MSSM) is in trouble but still alive and attractive.
- An attractive possibility: light charginos and neutralinos.
- New challenges to optimize the LHC discovery potential.
- MSSM-like models can be consistent with DM and provide testable signals at LHC and direct-detection experiments.
- An alternative/complementary experimental strategy to identify/interpret the signal of $\tilde{\chi}^{\pm}\ \tilde{\chi}^{0}$.