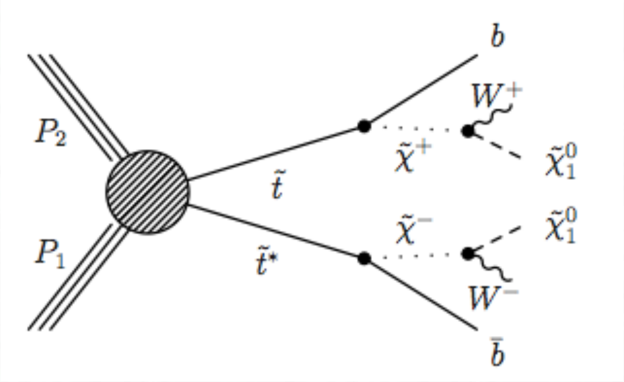
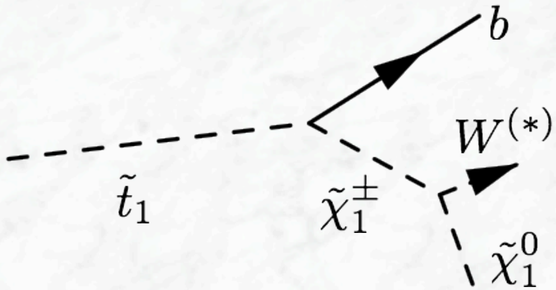
$$\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$$

- With respect to $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$, the mass of the chargino is one additional degree of freedom

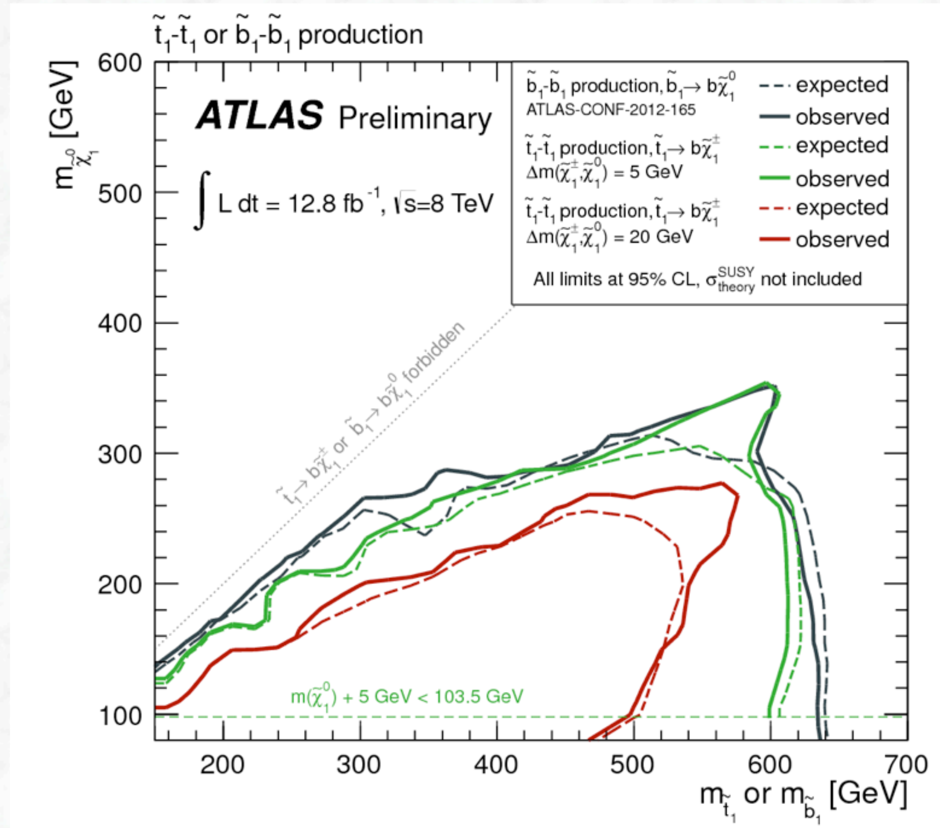
Hypothesis	Targeted signature (3 players at 8 TeV)
gaugino universality: $m_{\chi^\pm} \sim 2m_{\chi^0}$	2-leptons - large leptons M_{T2} 1-lepton (dedicated SR)
stop-chargino mass degeneracy $m_{\chi^\pm} \sim m_{t1}$ - 10 GeV	2-leptons - large leptons MT2
neutralino-chargino mass degeneracy (favoured if $\tilde{\chi}_1^0, \tilde{\chi}_1^\pm$ higgsino-like): $m_{\chi^\pm} \sim m_{\chi^0}$	2 b-jets + MET; 0-lepton
Fixed chargino mass at 150 GeV	2-leptons - large leptons M_{T2} 1-lepton (dedicated SR)



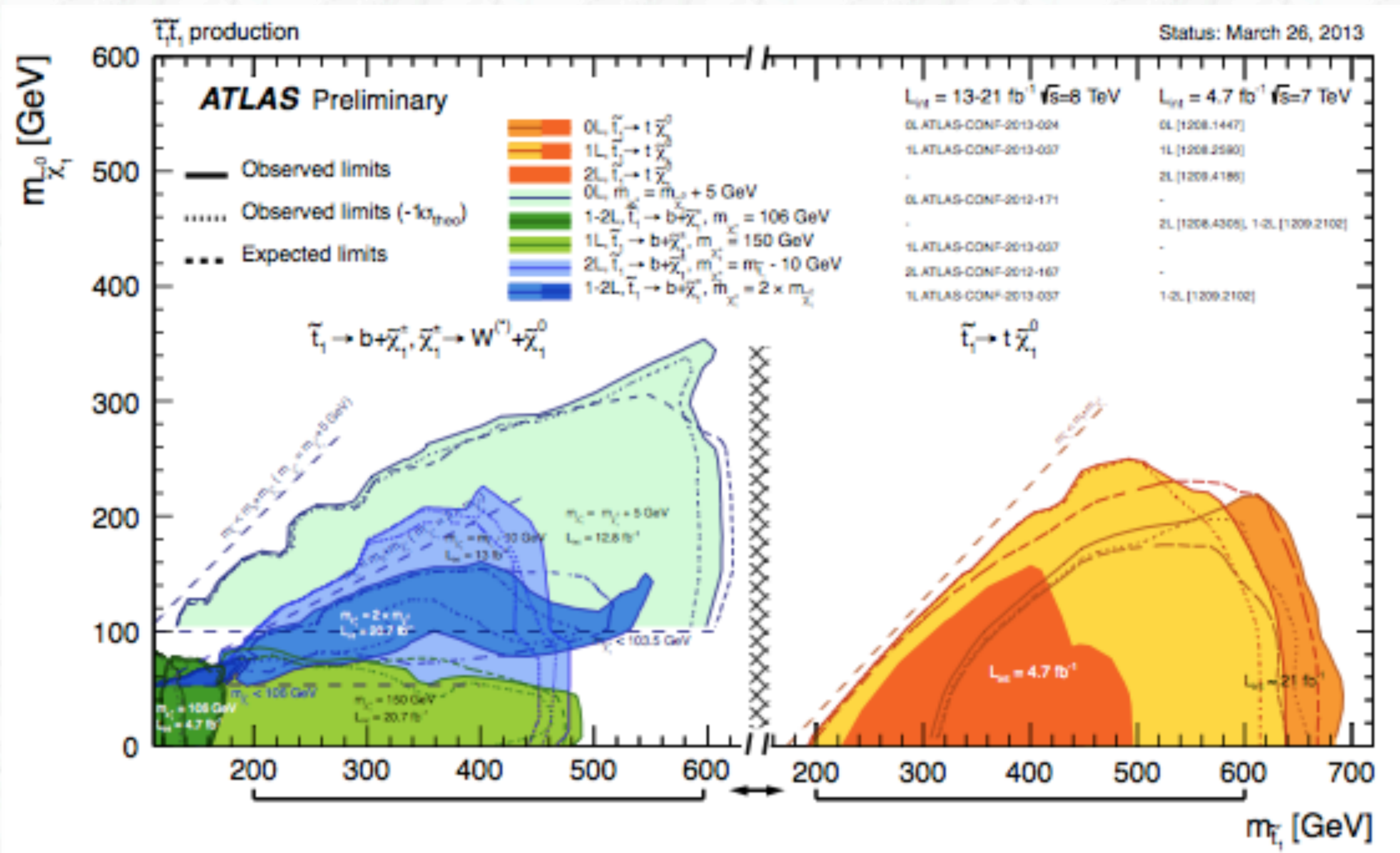
$$\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$$



- 2 b + E_T^{miss} analysis already discussed
- **Same signal regions** as for direct sbottom sensitive to **$\tilde{t}_1 \rightarrow b\tilde{X}_1^{\pm}$ for small $\Delta\tilde{m}(X_1^{\pm},X_1^0)$**
- Loss of acceptance due to lepton and jet veto

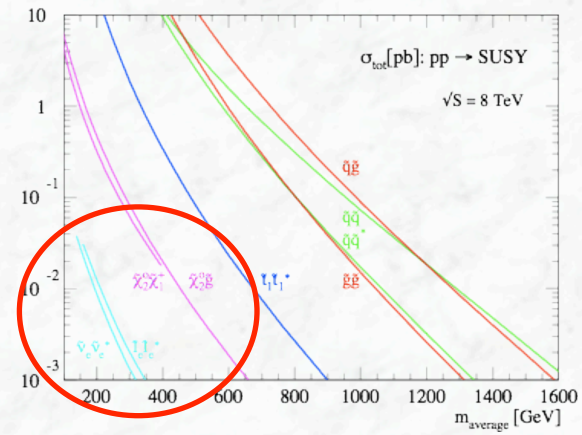


Stop summary

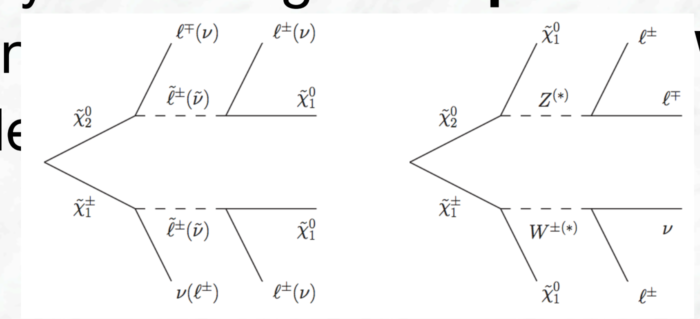


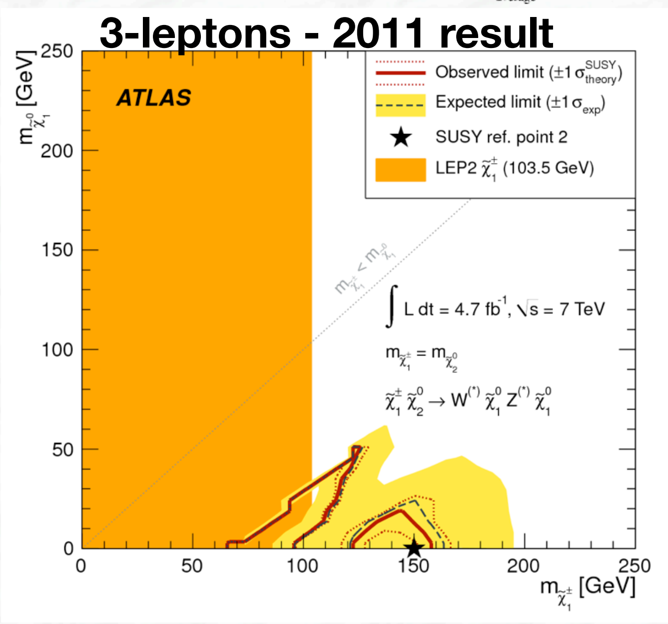
Electroweak $\tilde{\chi}^0$, $\tilde{\chi}^\pm$ production

- Neutralinos and chargino masses of **few hundreds GeV** expected in natural SUSY models
- LHC has sensitivity to the **EW coupling-suppressed cross sections**



- Give rise to **multi-lepton final states**
  - Very **low SM background** expected
  - Decays through **sleptons** (BR to leptor … **WZ-like** (challe…

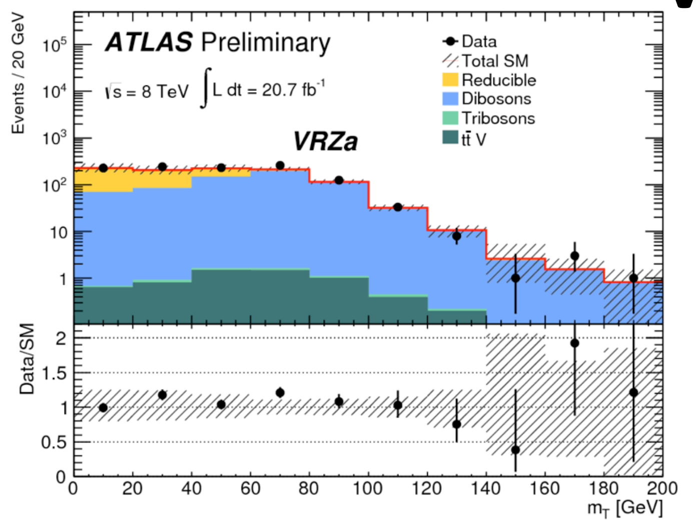


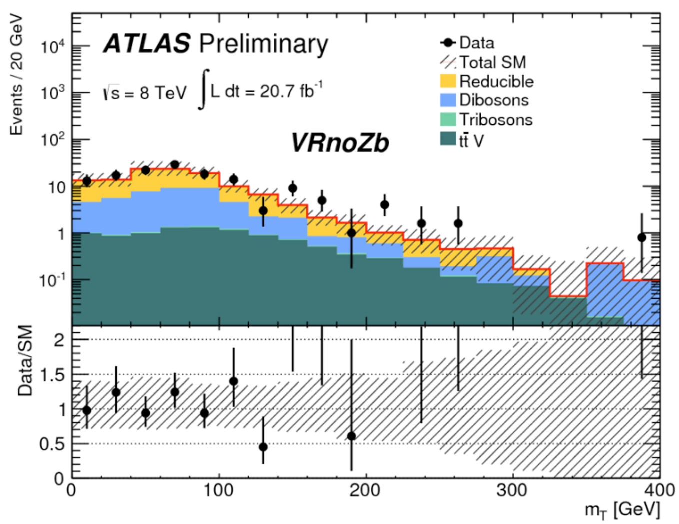


Electroweak $\tilde{\chi}^0$, $\tilde{\chi}^\pm$ production

Production channel	Analysis
chargino pair production	**2-leptons**
$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production	**2-leptons**, **3-leptons**
$\tilde{\chi}_2^0 \tilde{\chi}_3^0$ production	**4-leptons**

3-leptons background prediction validation



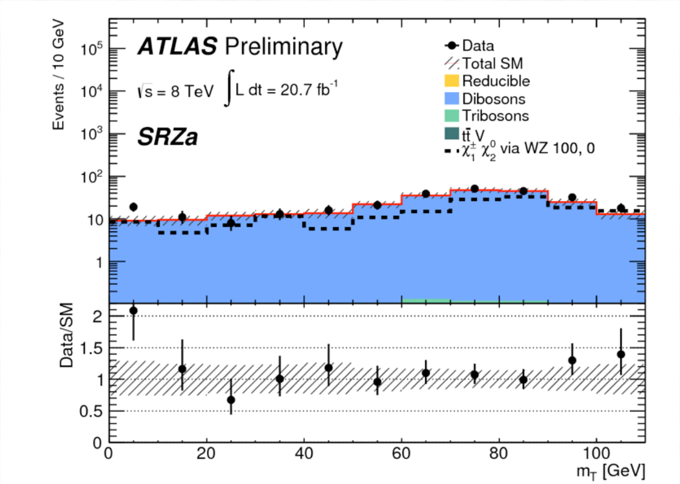


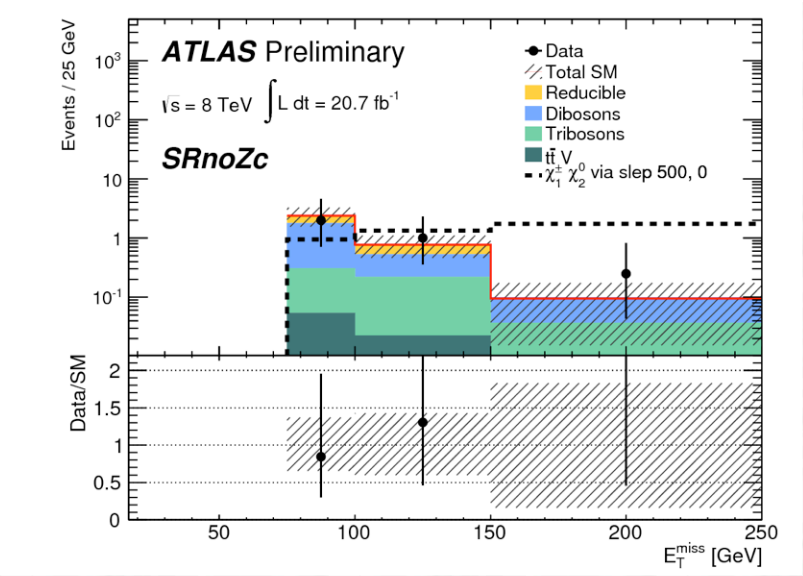
- Background prediction **validated** in dedicated regions with **different**

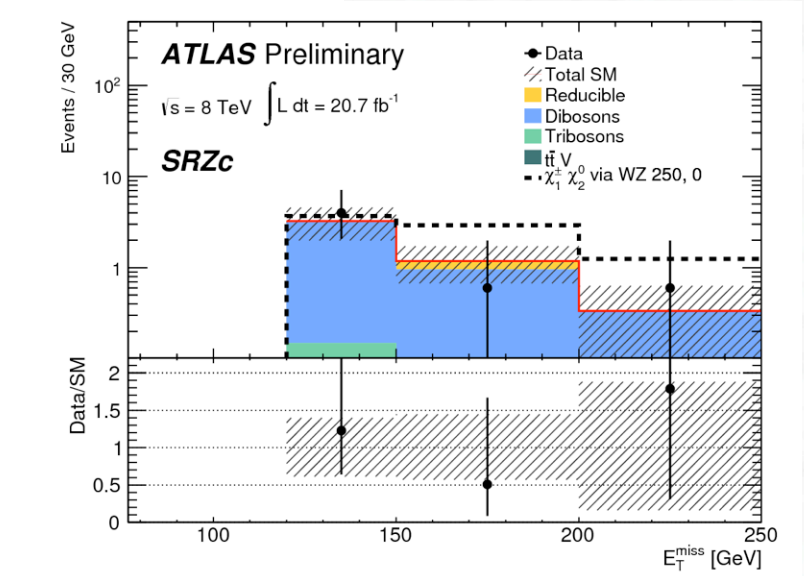
Selection	VRnoZa	VRnoZb	VRZa	VRZb
m_{SFOS} [GeV]	<81.2 or >101.2	<81.2 or >101.2	81.2–101.2	81.2–101.2
b-jet	veto	request	veto	request
E_T^{miss} [GeV]	35–50	>50	30–50	>50
Dominant process	WZ^*, Z^*Z^*, Z^*+jets	$t\bar{t}$	WZ, Z+jets	WZ

Selection	VRnoZa	VRnoZb	VRZa	VRZb
Tri-boson	1.4 ± 1.4	0.5 ± 0.5	0.6 ± 0.6	0.26 ± 0.26
ZZ	$(1.3 \pm 0.9) \times 10^2$	4.5 ± 2.8	108 ± 23	6.9 ± 2.2
$t\bar{t}V$	2.9 ± 1.2	21 ± 7	7.4 ± 2.6	26 ± 8
WZ	110 ± 21	34 ± 15	$(5.5 \pm 0.9) \times 10^2$	$(1.4 \pm 0.4) \times 10^2$
Σ SM irreducible	$(2.4 \pm 0.9) \times 10^2$	60 ± 16	$(6.6 \pm 0.9) \times 10^2$	$(1.7 \pm 0.4) \times 10^2$
SM reducible	$(1.5 \pm 0.6) \times 10^2$	$(0.7 \pm 0.4) \times 10^2$	$(3.8 \pm 1.4) \times 10^2$	27 ± 13
Σ SM	$(3.9 \pm 1.1) \times 10^2$	$(1.3 \pm 0.5) \times 10^2$	$(10.4 \pm 1.7) \times 10^2$	$(2.0 \pm 0.4) \times 10^2$
Data	463	141	1131	171

3-leptons results

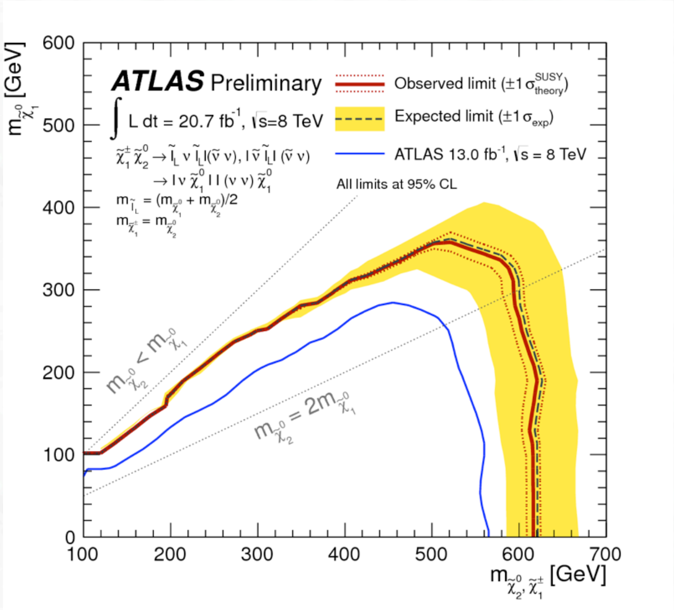


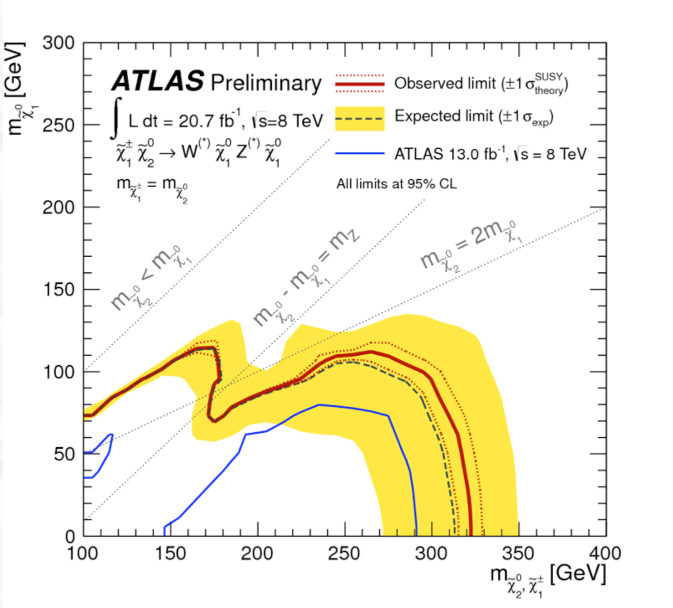




3-leptons interpretation

- **Signal interpretation** (simplified models) assumes **wino-like $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^{\pm}$, bino-like $\tilde{\chi}_1^0$: $m(\tilde{\chi}_2^0) = m(\tilde{\chi}_1^{\pm})$**
- **Degenerate neutralino-chargino mass** excluded **up to 610 GeV** if **decay via sleptons** is assumed
- masses **up to 310 GeV excluded** even for the **decay through W/Z bosons**





Further reading, available on the web:

- S. Martin, “A Supersymmetry Primer”, hep-ph/97093
  http://arxiv.org/abs/hep-ph/9709356

- D.I. Kazakov, „Beyond the Standard Model“, CERN school 2004
  http://doc.cern.ch/yellowrep/2006/2006-003/p169.pdf

- J. Ellis, Supersymmetry for Alp Hikers

  http://arxiv.org/abs/hep-ph/0203114

Lehrbücher:

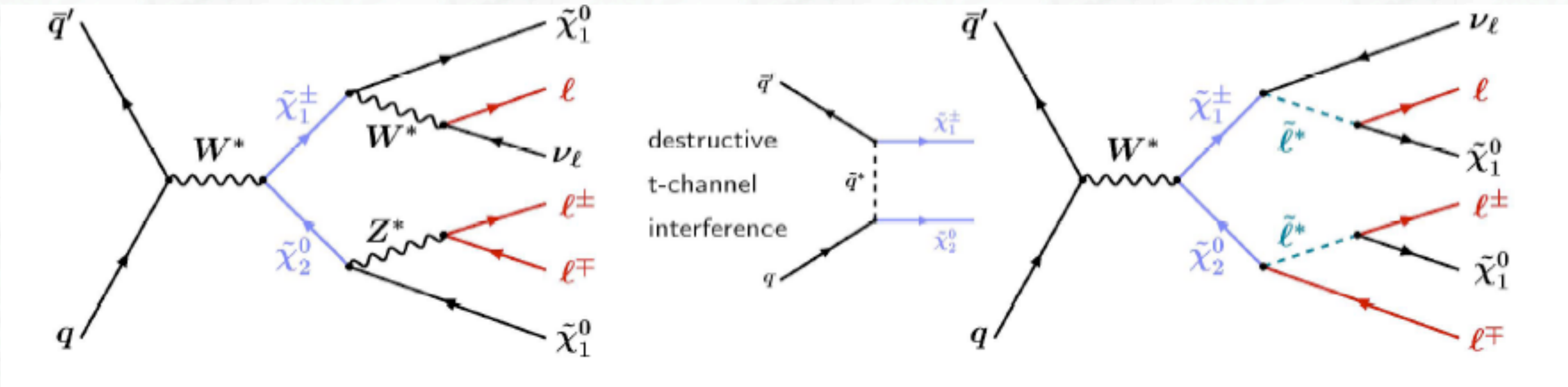
- H.Baer, X. Tata, „Weak Scale Supersymmetry“, 2006

- Drees, Godbole, Roy, „Theory and Phenomenology of Sparticles“, 2004

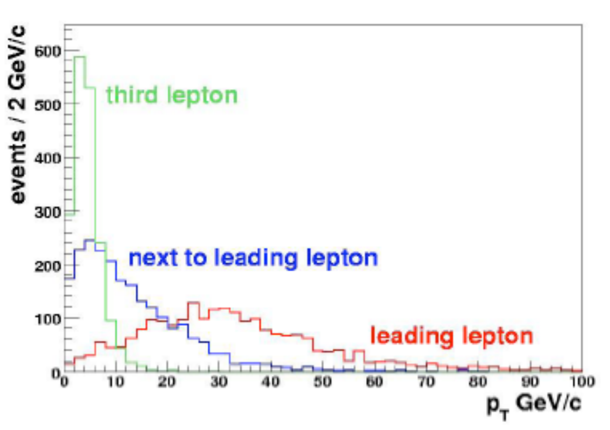
BACKUP

Search for Charginos and Neutralinos
- the tri-lepton channel-

- Gaugino pair production via electroweak processes
  (small cross sections, ~0.1 – 0.5 pb, however, small expected background)



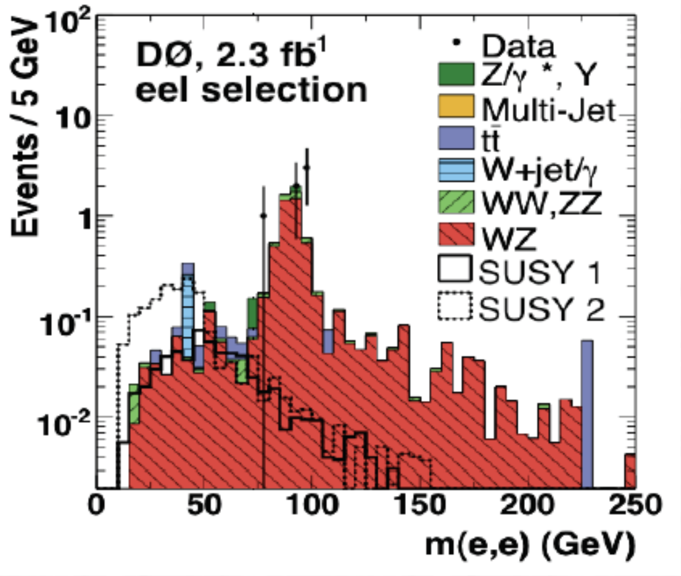
- For small gaugino masses (~100 GeV/c^2) one needs to be sensitive to low P_T leptons

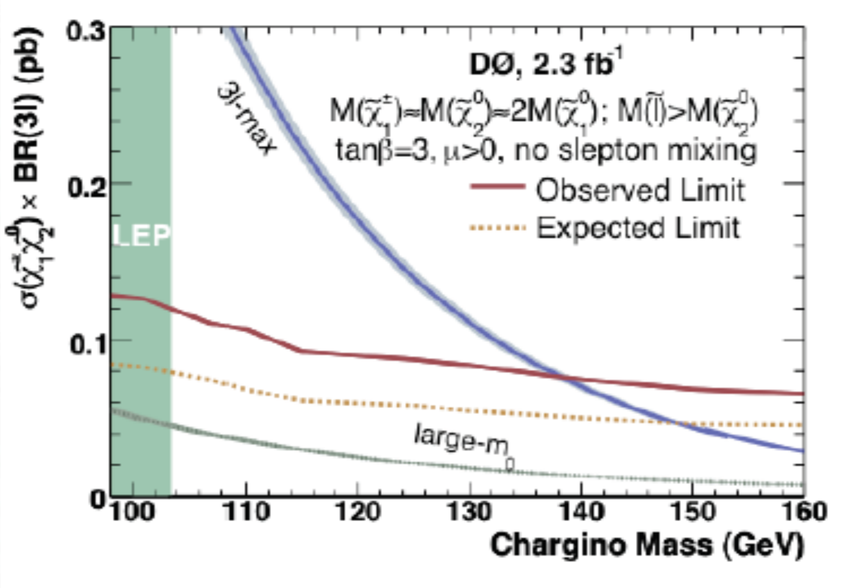


Analysis:

- Search for different (ℓℓℓ) + like-sign μμ final states with missing transverse momentum
- In order to gain efficiency, no lepton identification is required for the 3rd lepton, select: two identified leptons + a track with $p_T > 4$ GeV/c

mSUGRA interpretation





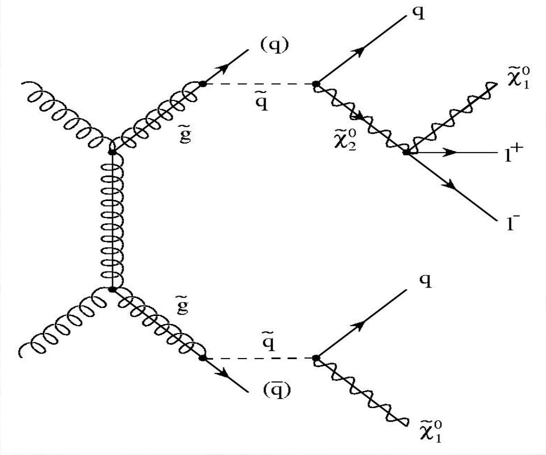
For specific scenarios: sensitivity / limits above LEP limits;
e.g., $M(\chi^{\pm}) > 140$ GeV/c^2 for the 3l-max scenario

9.5 Search for Supersymmetry at the LHC

• If SUSY exists at the electroweak scale, a discovery at the LHC should be easy

• Squarks and Gluinos are strongly produced

They decay through cascades to the lightest SUSY particle (LSP)



$\Longrightarrow$ combination of Jets, Leptons, E_T^{miss}

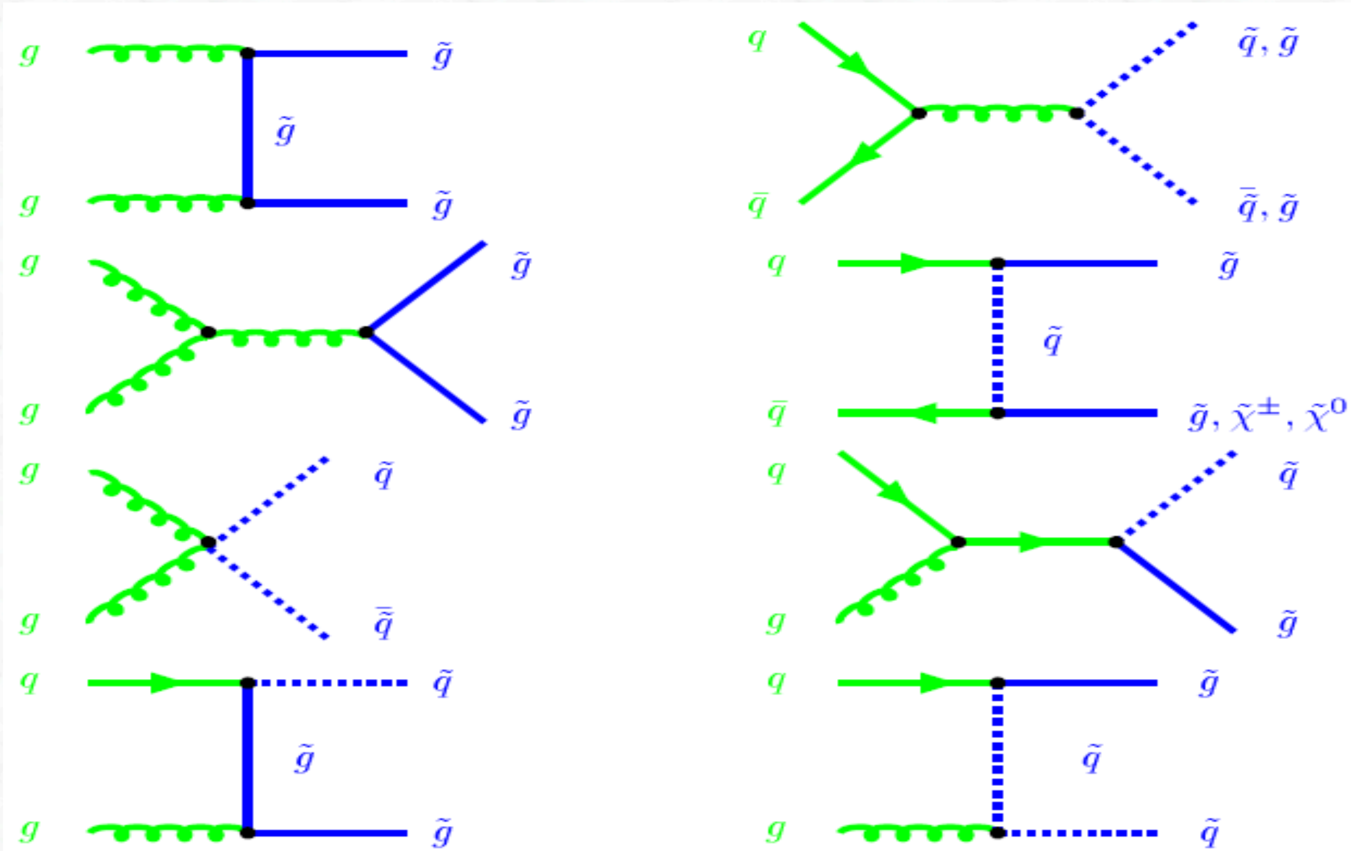
1. Step: Look for deviations from the Standard Model
   Example: Multijet + E_T^{miss} signature

2. Step: Establish the SUSY mass scale use inclusive variables, e.g. effective mass distribution

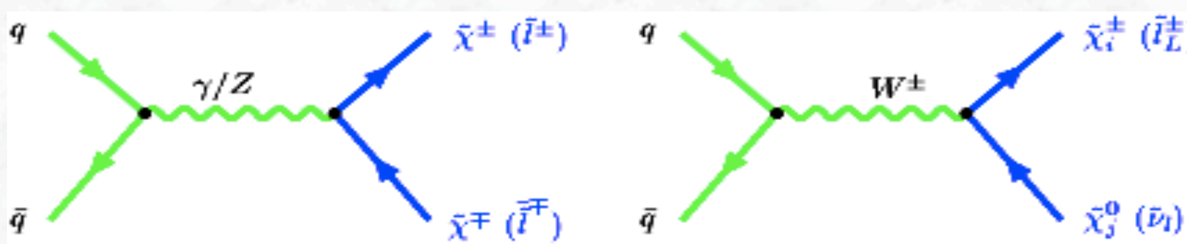
3. Step: Determine model parameters (difficult)
   Strategy: select particular decay chains and use kinematics to determine mass combinations

Sparticle production at the LHC

Quark-gluon fusion

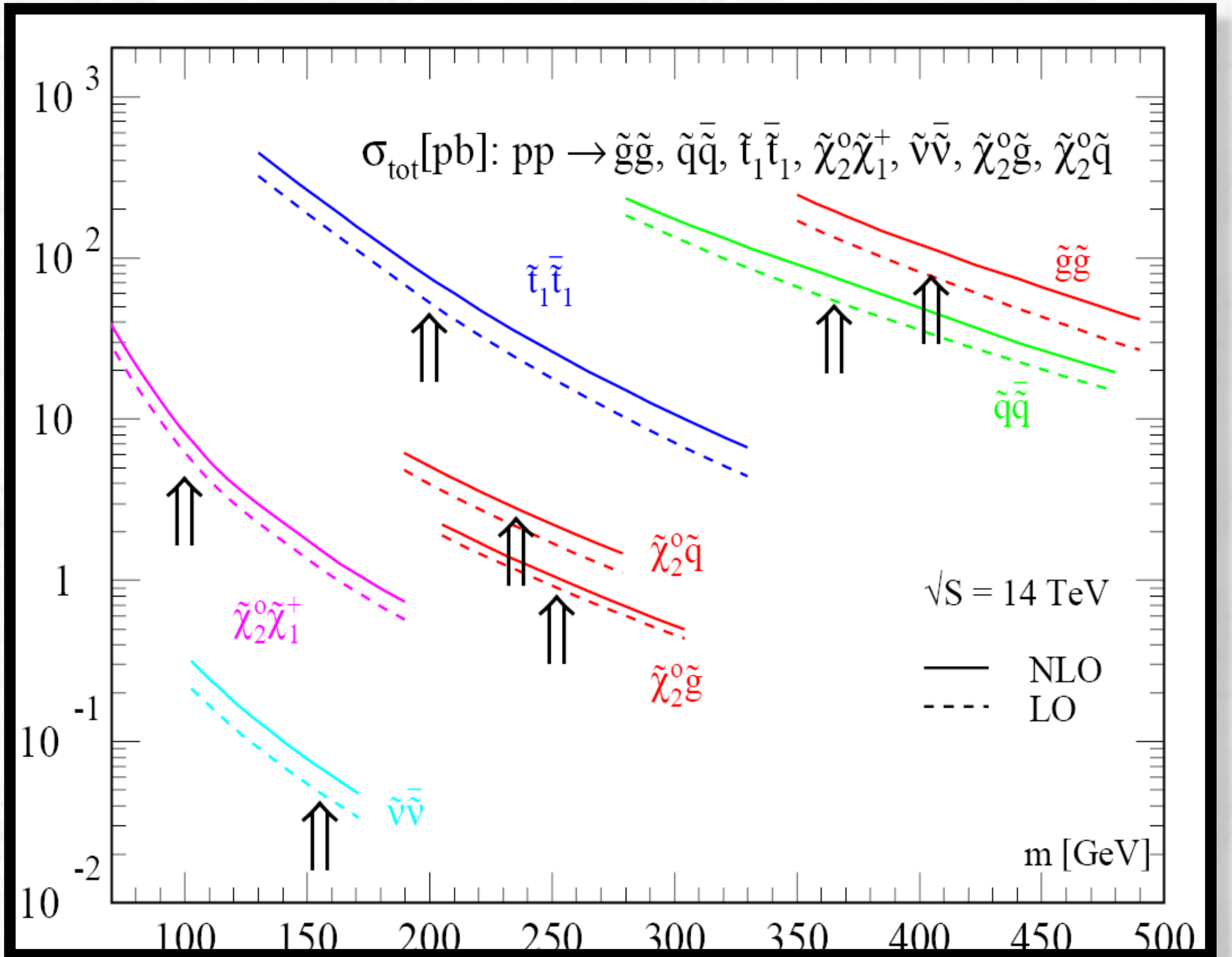


Quark annihilation



Cross sections for SUSY production processes

σ (pb)



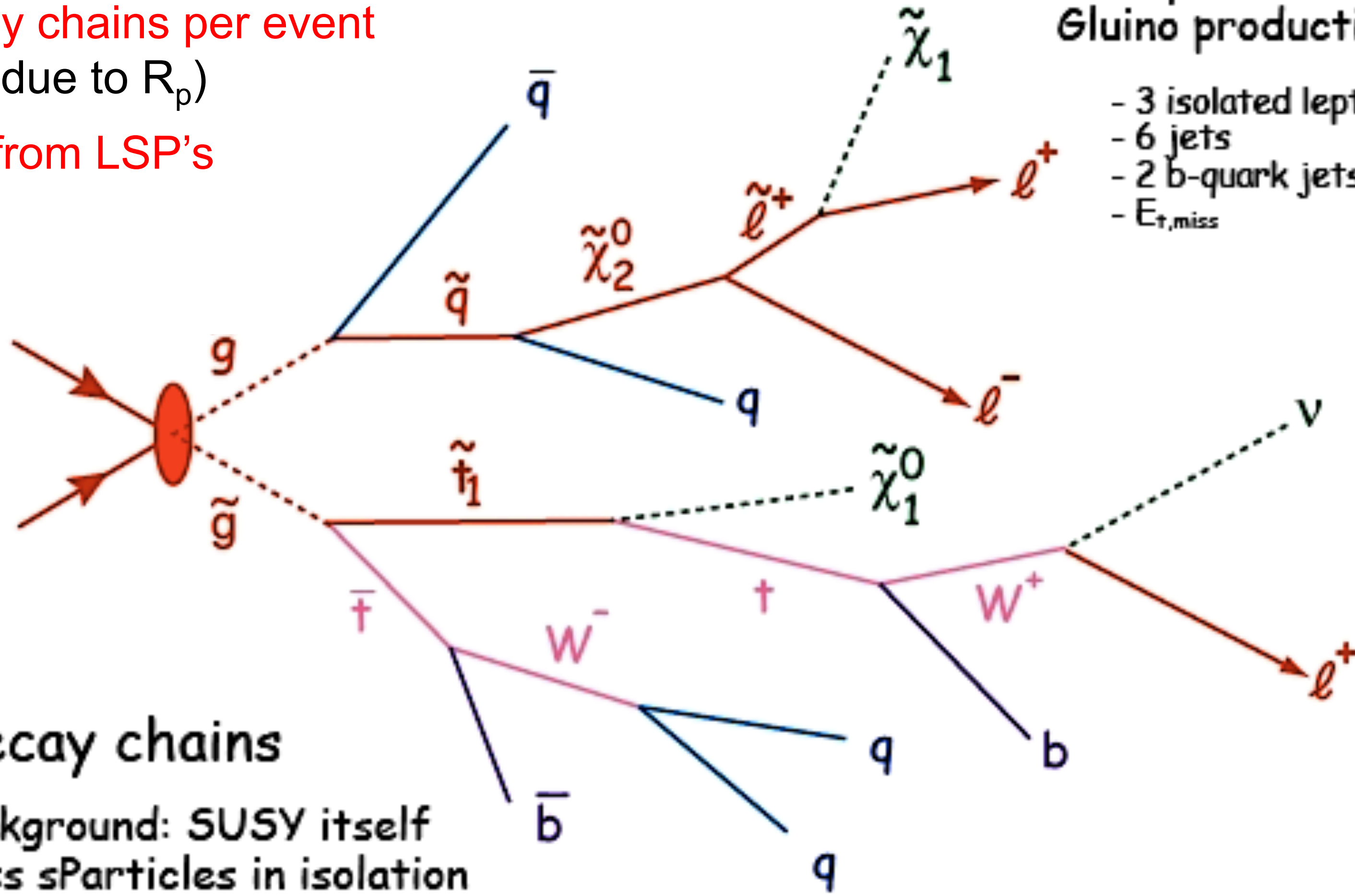
M (GeV)

Examples of SUSY decay chains at the LHC:

- Long, complex decay chains (at the end: SM particles and LSP's)
- Two SUSY decay chains per event
  (pair production due to R_p)
- Missing energy from LSP's

Example:
Gluino production

- 3 isolated leptons
- 6 jets
- 2 b-quark jets
- $E_{t,miss}$



But: Long decay chains

- dominant background: SUSY itself
- cannot discuss sParticles in isolation
- use consistent model for simulation

Typical final states: jets + E_T^{miss} (+ leptons)

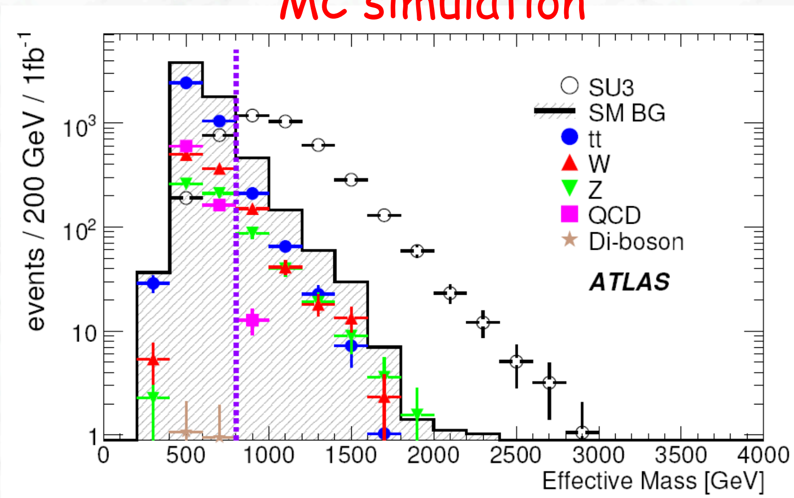
A typical search for squark and gluino production

- If R-parity conserved, cascade decays produce distinctive events: multiple jets, leptons, and E_T^{miss}

- Typical selection: $N_{jet} > 4$, $E_T > 100, 50, 50, 50$ GeV, $E_T^{miss} > 100$ GeV

- Define: $M_{eff} = E_T^{miss} + P_T^1 + P_T^2 + P_T^3 + P_T^4$ (effective mass)

MC simulation



example: mSUGRA, point SU3 (bulk region)
m_0 = 100 GeV, $m_{1/2}$ = 300 GeV
$\tan\beta$ = 6, A_0 = -300 GeV, $\mu > 0$

Expectations from simulations:

LHC reach for squark- and gluino masses:

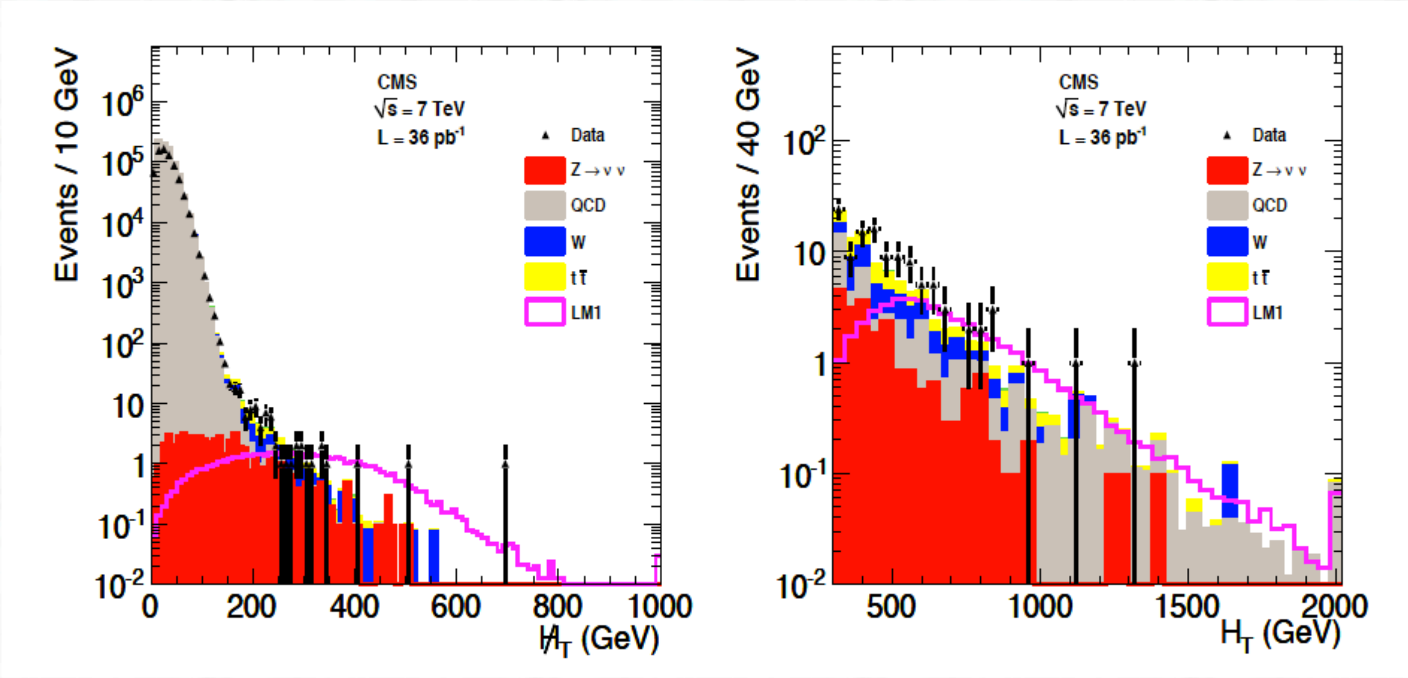
0.1 fb^{-1}	$\Rightarrow$	M ~ 750 GeV
1 fb^{-1}	$\Rightarrow$	M ~ 1350 GeV
10 fb^{-1}	$\Rightarrow$	M ~ 1800 GeV

Deviations from the Standard Model due to SUSY at the TeV scale can be detected fast !

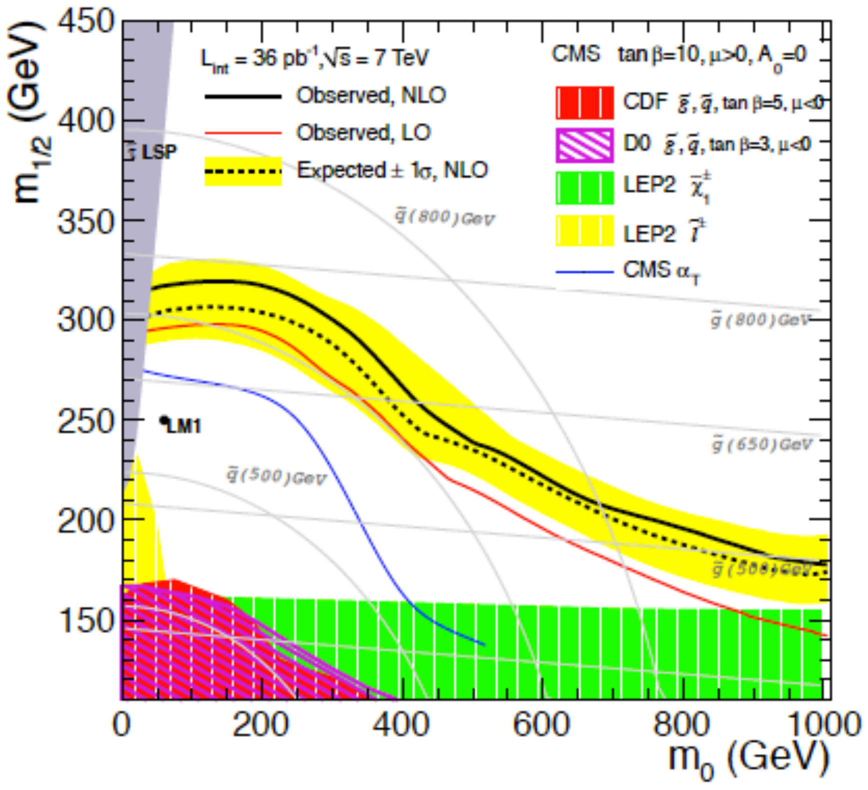
First results on the search for Etmiss + jets, no leptons (2010 data)

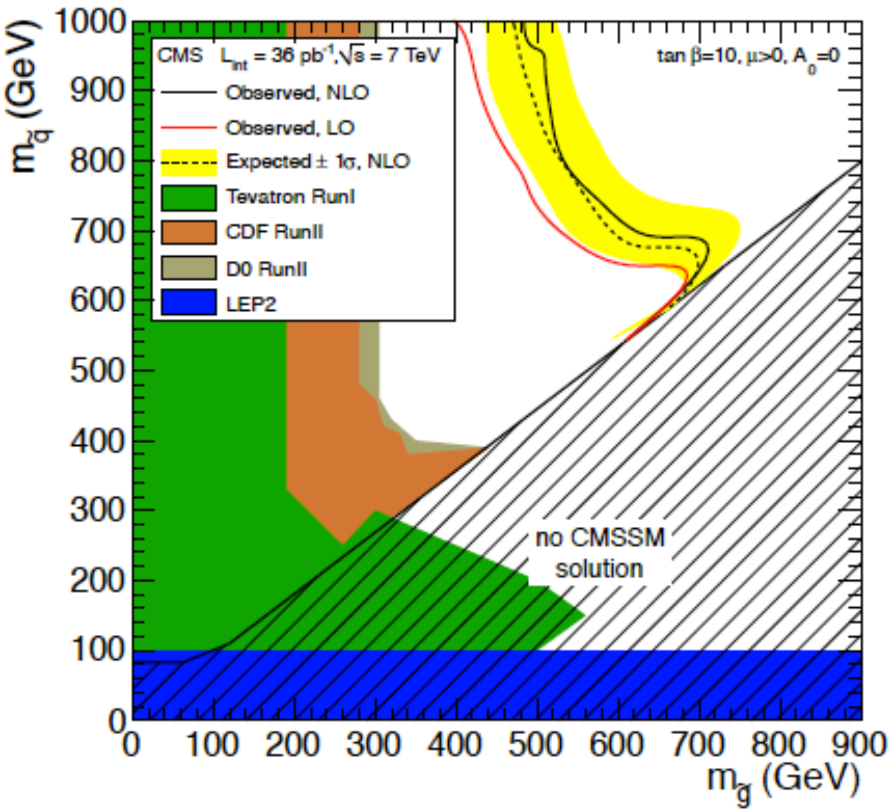
Simple selection:

- 3 jets with p_T > 50 GeV , η < 2.5
- H_T > 300 GeV (scalar sum of jets with p_T > 50 and η < 2.5)
- H_T^{miss} > 150 GeV (modulus of vector sum of jets with p_T > 30 GeV and η < 5)



- Good agreement between data and expectations from Standard Model processes
- No evidence for an excess → limits in SUSY parameter space





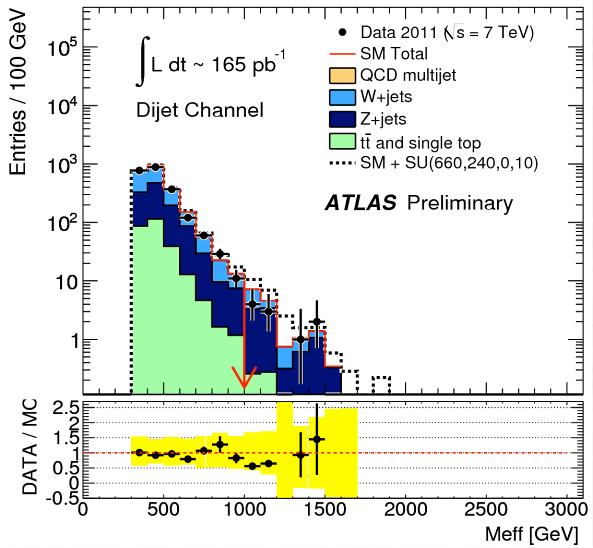
- Significant extension of exclusion contours in the squark-gluino mass plane
- Gluinos below 500 GeV are excluded for m(squarks) < 1000 GeV

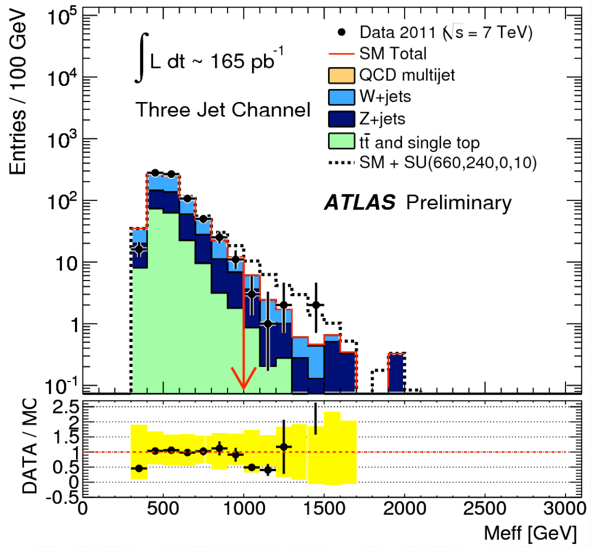
First results on the search for E_T^{miss} + jets (165 pb^{-1})

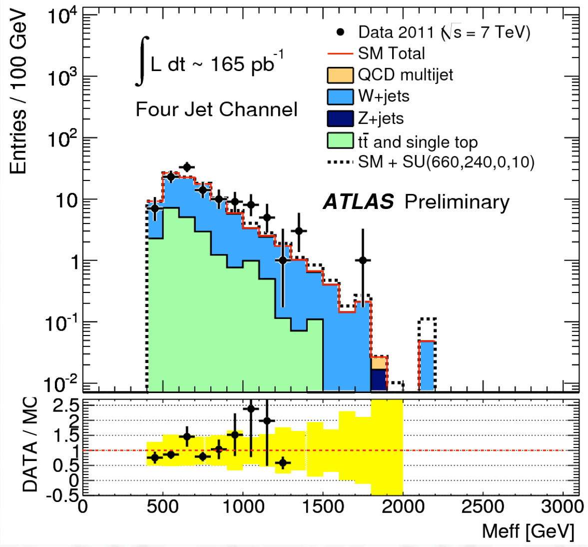
(part of 2011 data already included)

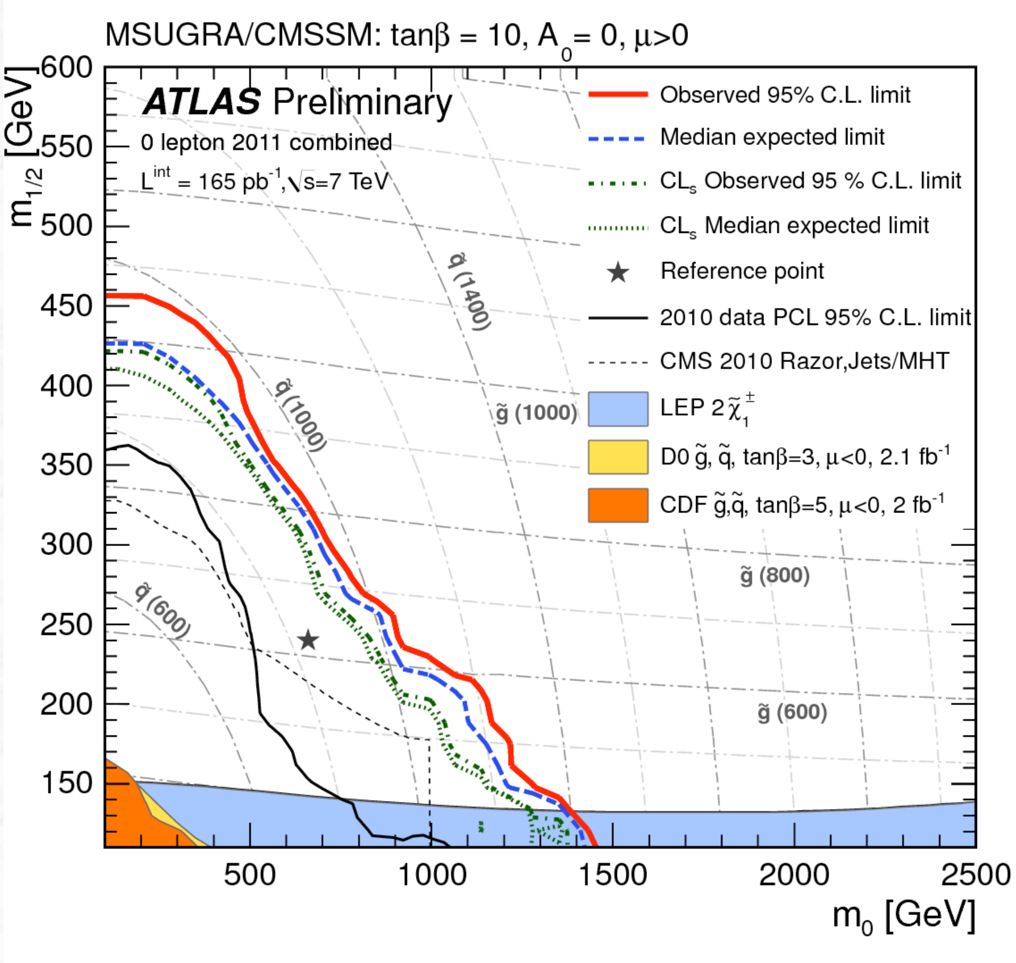
Selection of events with E_T^{miss} + jets

Split the analysis according to jet multiplicities: 2,3 and 4 jets
(different sensitivity for different squark/gluino mass combinations,
i.e. in different regions of SUSY parameter space)



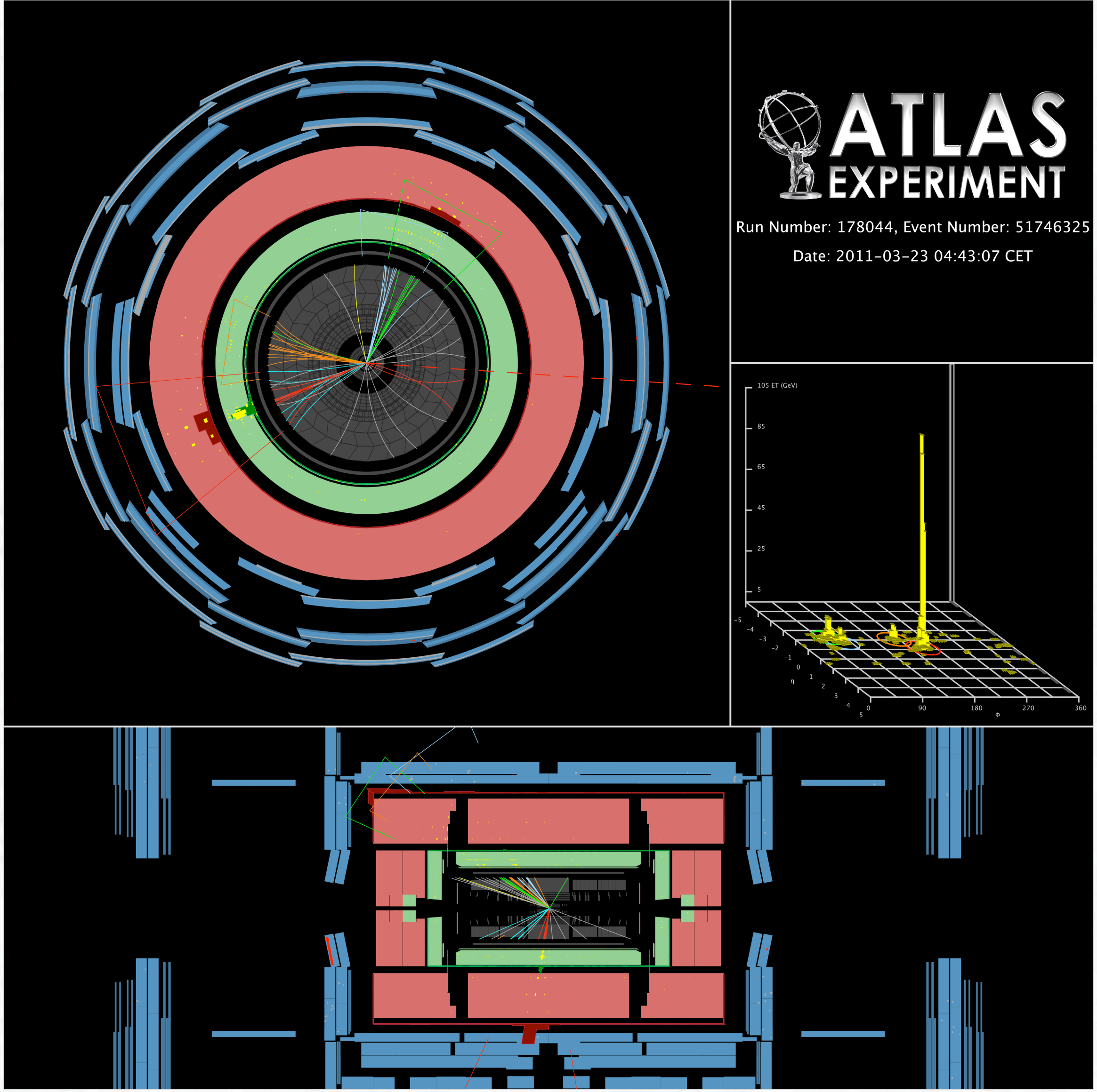






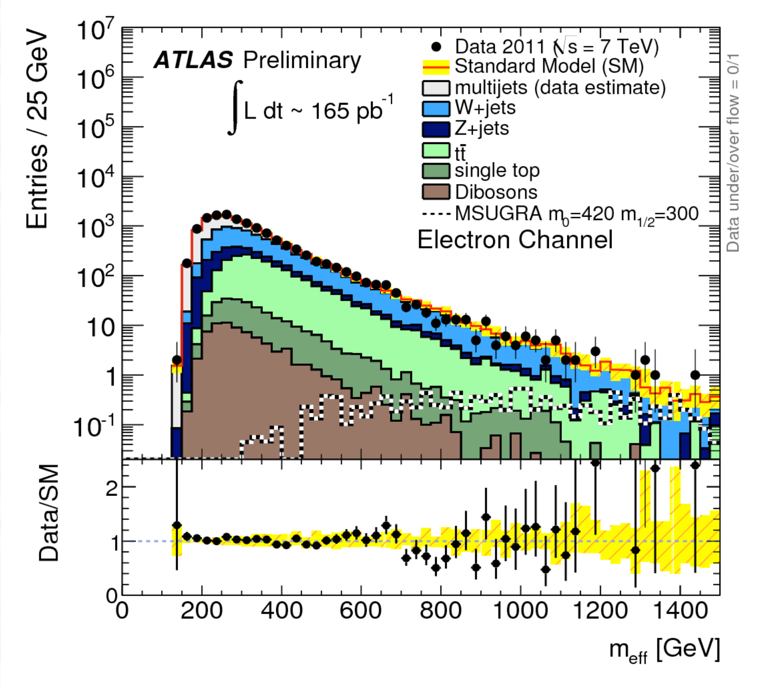
MSSM/cMSSM interpretation (for equal squark and gluino masses):

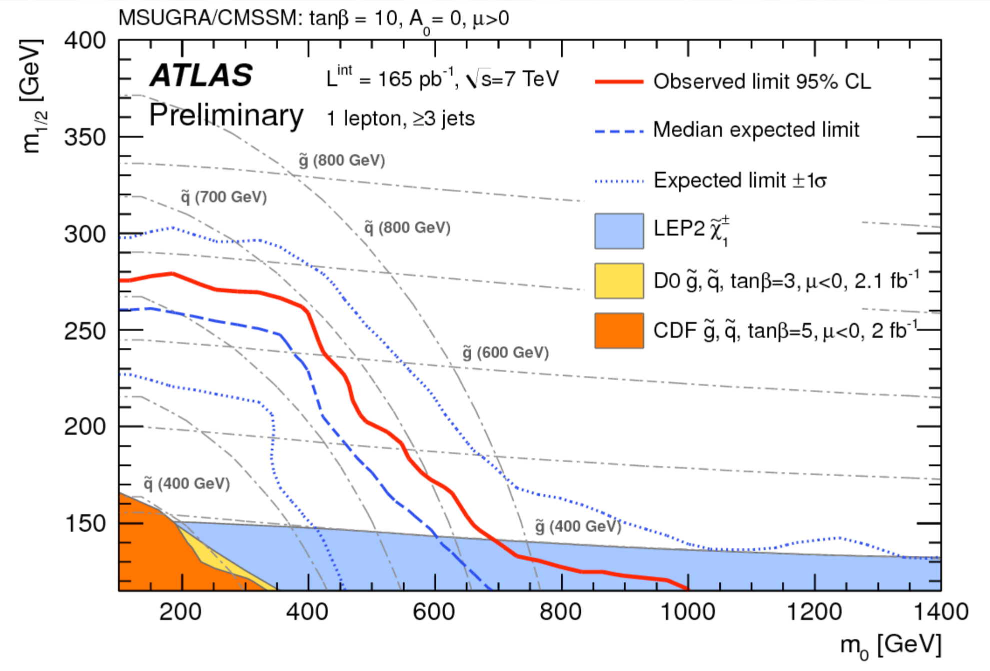
L = 165 pb^{-1}: m(squark), m(gluino) > 950 GeV



A display of the reconstructed event with the highest m_{eff} (1548 GeV) found in the ATLAS data sample. This event possesses four jets with $p_T > 40$ GeV (p_T = 636, 189, 96 and 81 GeV respectively) and E_T^{miss} = 547 GeV.

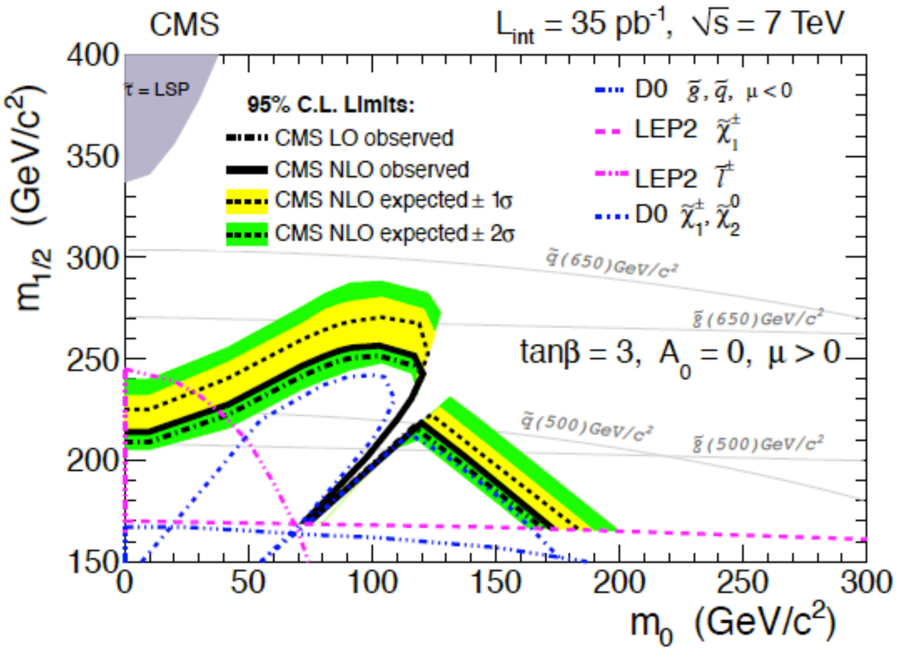
…additional potential: inclusive searches with leptons
i.e. E_T^{miss}, jets + leptons

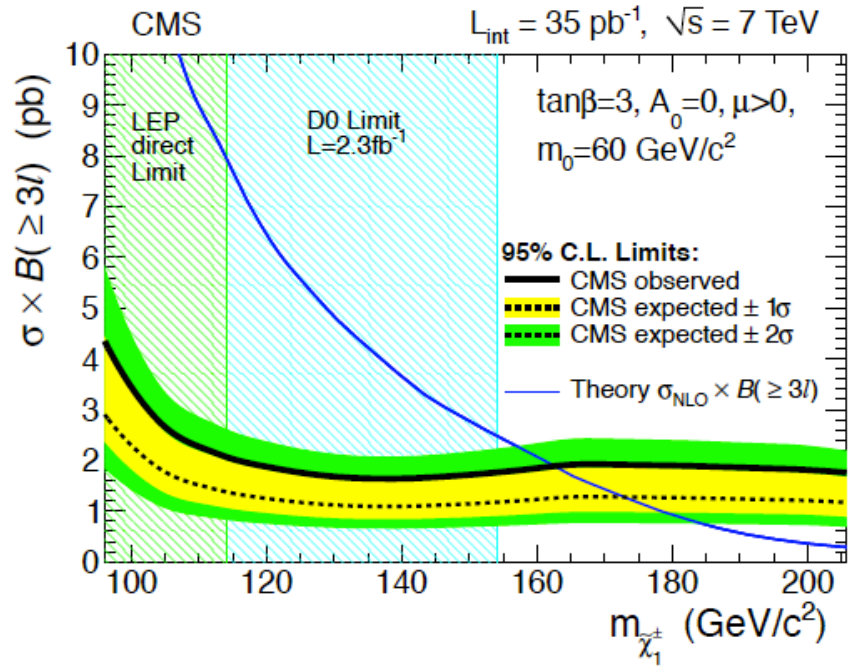




- Smaller signal rates, but different background composition
- Again: data are well described by contributions from Standard Model processes
- Similar exclusions in the MSSM models

Multi-lepton search in CMS





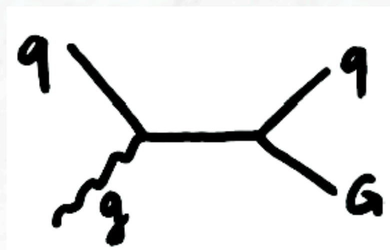
- Multi-leptons are produced via associated production of charginos and neutralinos (like at Tevatron, see above)
- Limits extracted are already beyond the Tevatron

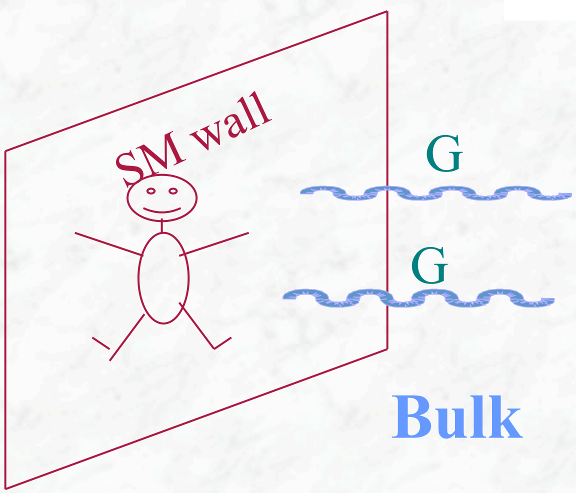
9.6 How can the parameter of the SUSY model be constrained ?

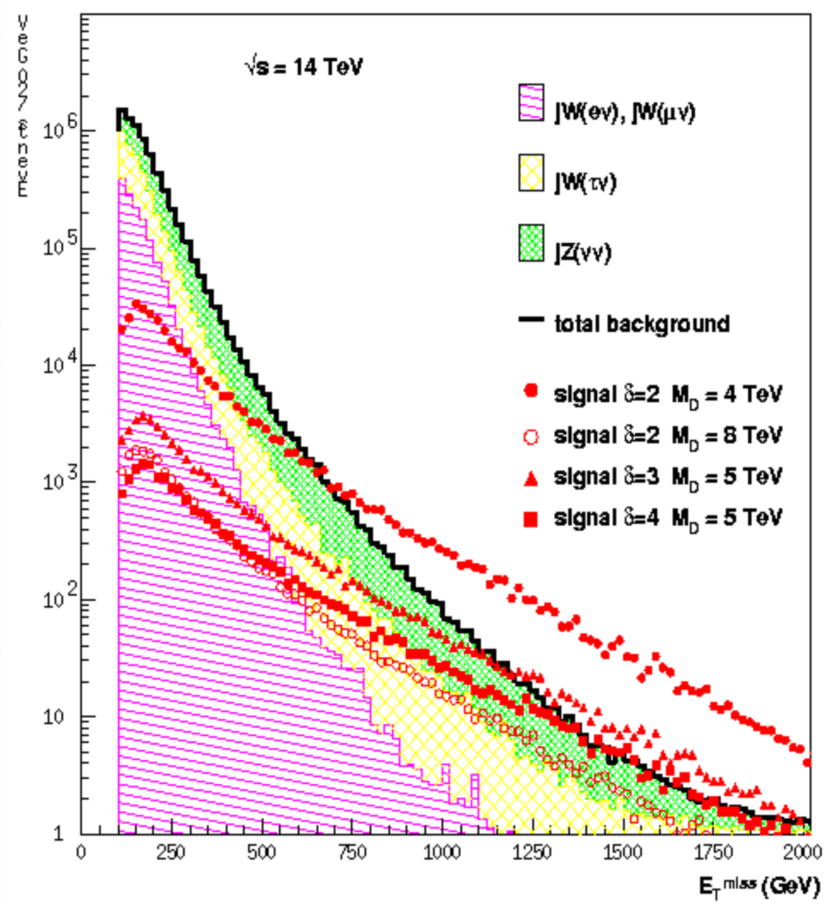
- Not easy !!
- Other possible scenarios for Physics Beyond the Standard Model could lead to similar final state signatures
  e.g. search for direct graviton production in extra dimension models

$gg \rightarrow gG,\ qg \rightarrow qG,\ q\bar{q} \rightarrow Gg$

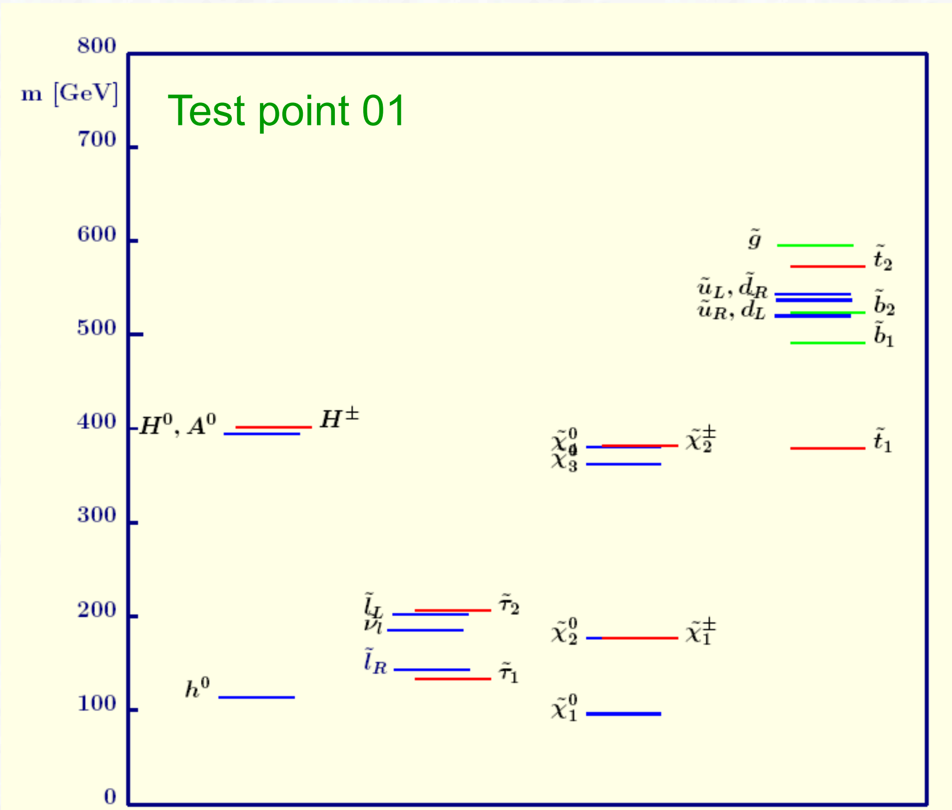
$q\bar{q} \rightarrow G\gamma$

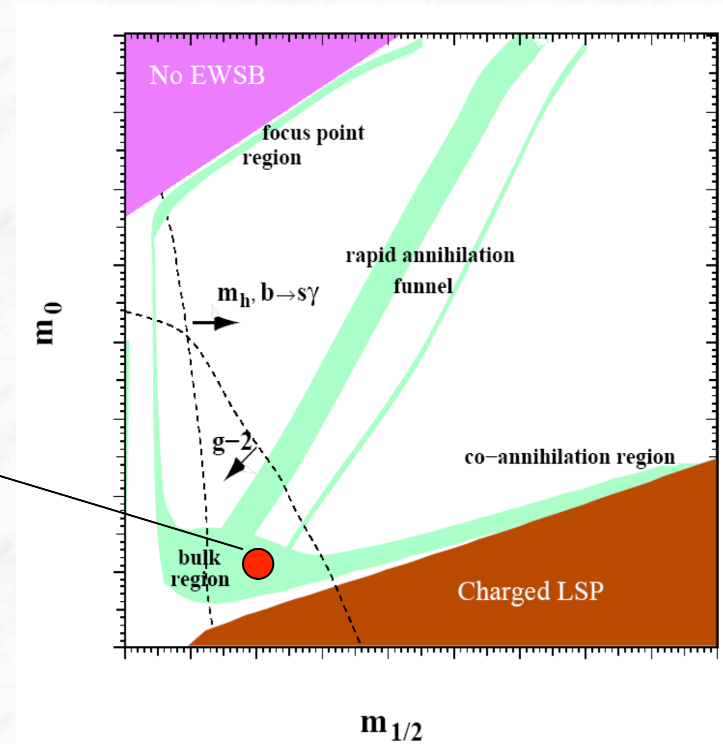






Measurement of the SUSY spectrum → Parameter of the theory



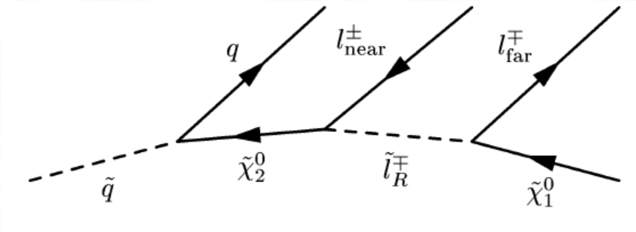


LHC: strongly interacting squarks and gluinos

ILC / CLIC: precise investigation of electroweak SUSY partners

LHC Strategy: End point spectra of cascade decays

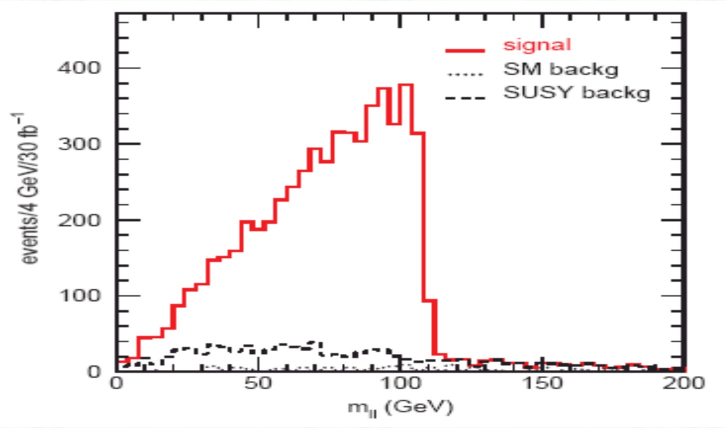
Example: $\tilde{q} \to q\tilde{\chi}_2^0 \to q\tilde{\ell}^{\pm}\ell^{\mp} \to q\ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$



$$M^{max}_{\ell^+\ell^-} = \frac{\sqrt{(m^2_{\chi^0_2} - m^2_{\tilde{\ell}})(m^2_{\tilde{\ell}} - m^2_{\chi^0_1})}}{m_{\tilde{\ell}}}$$

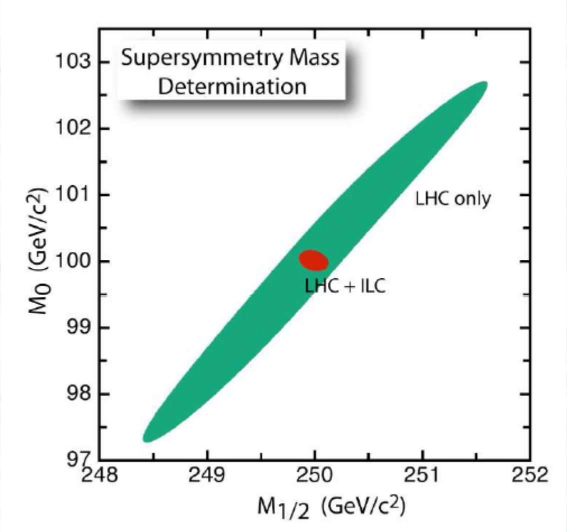
$$M^{max}_{\ell_1 q} = \frac{\sqrt{(m^2_{\chi^0_2} - m^2_{\tilde{\ell}})(m^2_{\tilde{q}} - m^2_{\chi^0_2})}}{m_{\chi^0_2}}$$

Results for point 01:

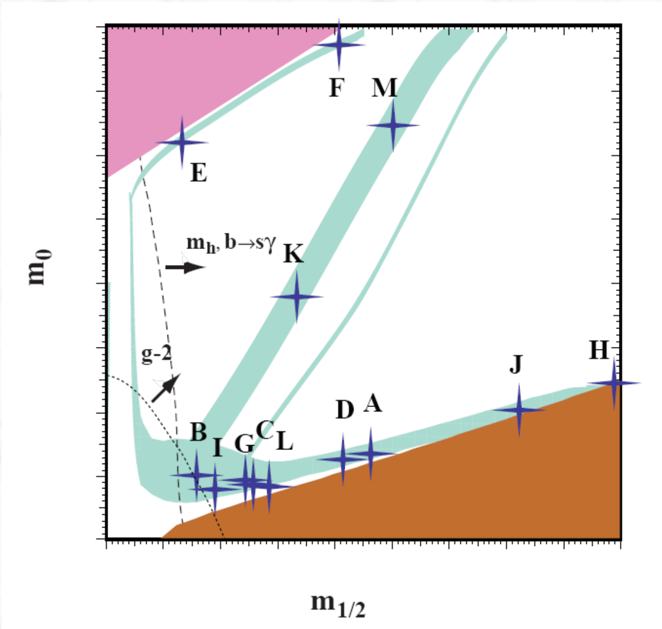


	LHC	LHC⊕ILC
$\Delta m_{\tilde{\chi}_1^0}$	4.8	0.05 (input)
$\Delta m_{\tilde{l}_R}$	4.8	0.05 (input)
$\Delta m_{\tilde{\chi}_2^0}$	4.7	0.08
$\Delta m_{\tilde{q}_L}$	8.7	4.9
$\Delta m_{\tilde{q}_R}$	11.8	10.9
$\Delta m_{\tilde{g}}$	8.0	6.4
$\Delta m_{\tilde{b}_1}$	7.5	5.7
$\Delta m_{\tilde{b}_2}$	7.9	6.2
$\Delta m_{\tilde{l}_L}$	5.0	0.2 (input)
$\Delta m_{\tilde{\chi}_4^0}$	5.1	2.23

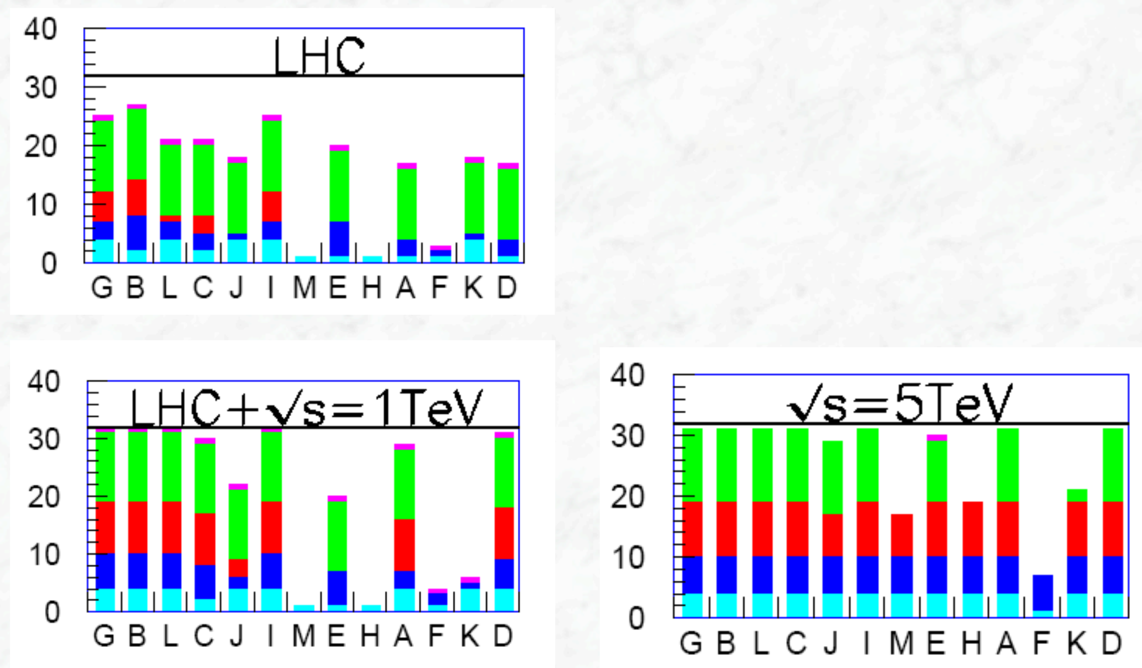
$L = 300\ \mathrm{fb}^{-1}$



The LHC and the ILC (International Linear Collider, in study/planning phase) are complementary in SUSY searches



Number of observable SUSY particles:



)* Study by J. Ellis et al., hep-ph/0202110

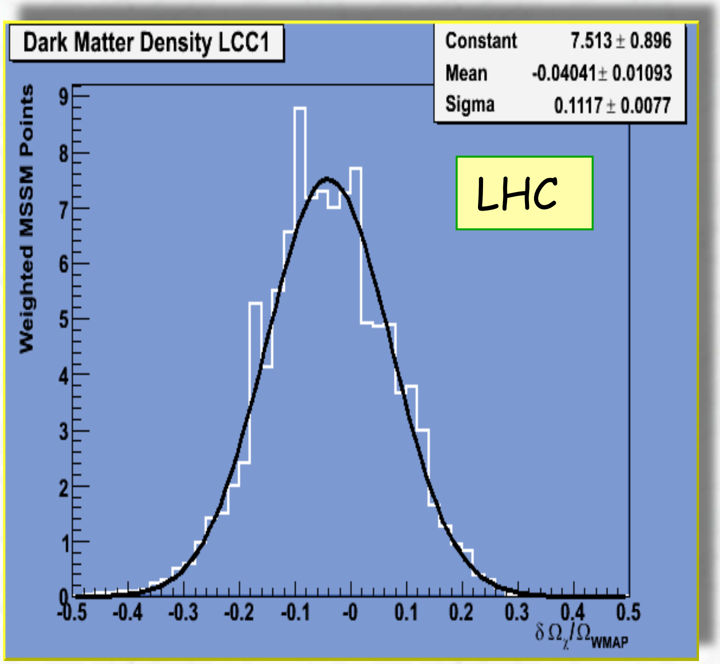
Strategy in SUSY Searches at the LHC:

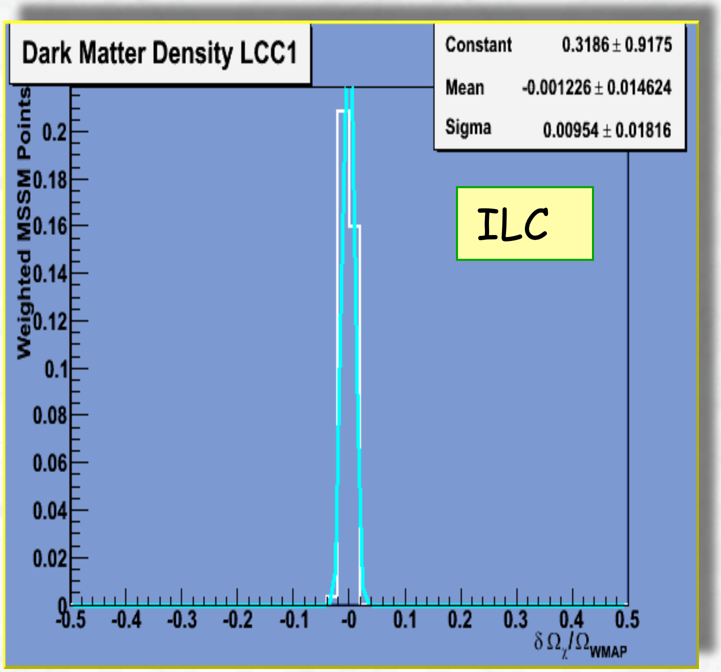
- Search for multijet + E_T^{miss} excess
- If found, select SUSY sample (simple cuts)
- Look for special features (γ's , long lived sleptons)
- Look for $\ell^\pm$, $\ell^+ \ell^-$, $\ell^\pm \ell^\pm$, b-jets, τ's
- End point analyses, global fit $\rightarrow$ SUSY model parameters

Dark Matter at Accelerators ?

Parameter of the SUSY-Model $\Rightarrow$ Predictions for the relic density of Dark Matter

$$\rho_\chi \sim m_\chi n_\chi \,, \quad n_\chi \sim \frac{1}{\sigma_{ann}(\chi\chi \to \ldots)}$$





Battaglia et al.

L = 300 fb^{-1} $\delta\Omega / \Omega \sim 11\%$

L = 1000 fb^{-1} $\delta\Omega / \Omega \sim 1\%$

Importance for the interplay between direct and indirect Dark Matter searches

- Following a discovery of New Physics at the LHC (deviation from the Standard Model) the LHC will aim to test the Dark Matter hypothesis
- Estimation of relic density in a simple model-dependent scenario will be the first goal
- Less model-dependent scenarios will follow, detailed studies probably require the ILC
- Conclusive result is only possible in conjunction with astroparticle physics experiments
- Ultimate goal: observation of LSP at the LHC, confirmed by a signal in a direct dark matter experiment with predicted mass and cross-section