SUSY AT LHC

IFAE 2008 Bologna, 26-28 marzo 2008

Umberto De Sanctis, Università di Milano & INFN

Outline

- Searches for Supersymmetry at LHC
  - Search strategies for mSUGRA models
  - Commissioning of the detector
  - Measurement and control of backgrounds
- After discovery
  - Measurement of masses and other properties

SUPERSYMMETRY REMINDER

Adds to each SM **fermion** (**boson**) a **bosonic** (**fermionic**) partner.

SM Particles	SUSY Particles			
quarks: q	q	squarks: $\tilde{q}$		
leptons: l	l	sleptons: $\tilde{l}$		
gluons: g	g	gluino: $\tilde{g}$		
charged weak boson: $W^{\pm}$	$W^{\pm}$	Wino: $\tilde{W}^{\pm}$	$\tilde{\chi}^{\pm}_{1,2}$	chargino
Higgs: H^0	$H^{\pm}$	charged higgsino: $\tilde{H}^{\pm}$		
	h^0, A^0, H^0	neutral higgsino: $\tilde{h}^0, \tilde{A}^0$,	$\tilde{\chi}^{0}_{1,2,3,4}$	neutralino
neutral weak boson: Z^0	Z^0	Zino: $\tilde{Z}^0$		
photon: γ	γ	photino: $\tilde{\gamma}$		

- **R-parity** $R = (-1)^{3(B-L)+2S}$ can be conserved (**RPC**) or violated (**RPV**)
- **RPC** implies:
  - SUSY particles produced in pairs
  - stable and neutral lightest SUSY particle (**LSP**)
  - no proton decay
- **LSP** is a good candidate for cold **Dark Matter**

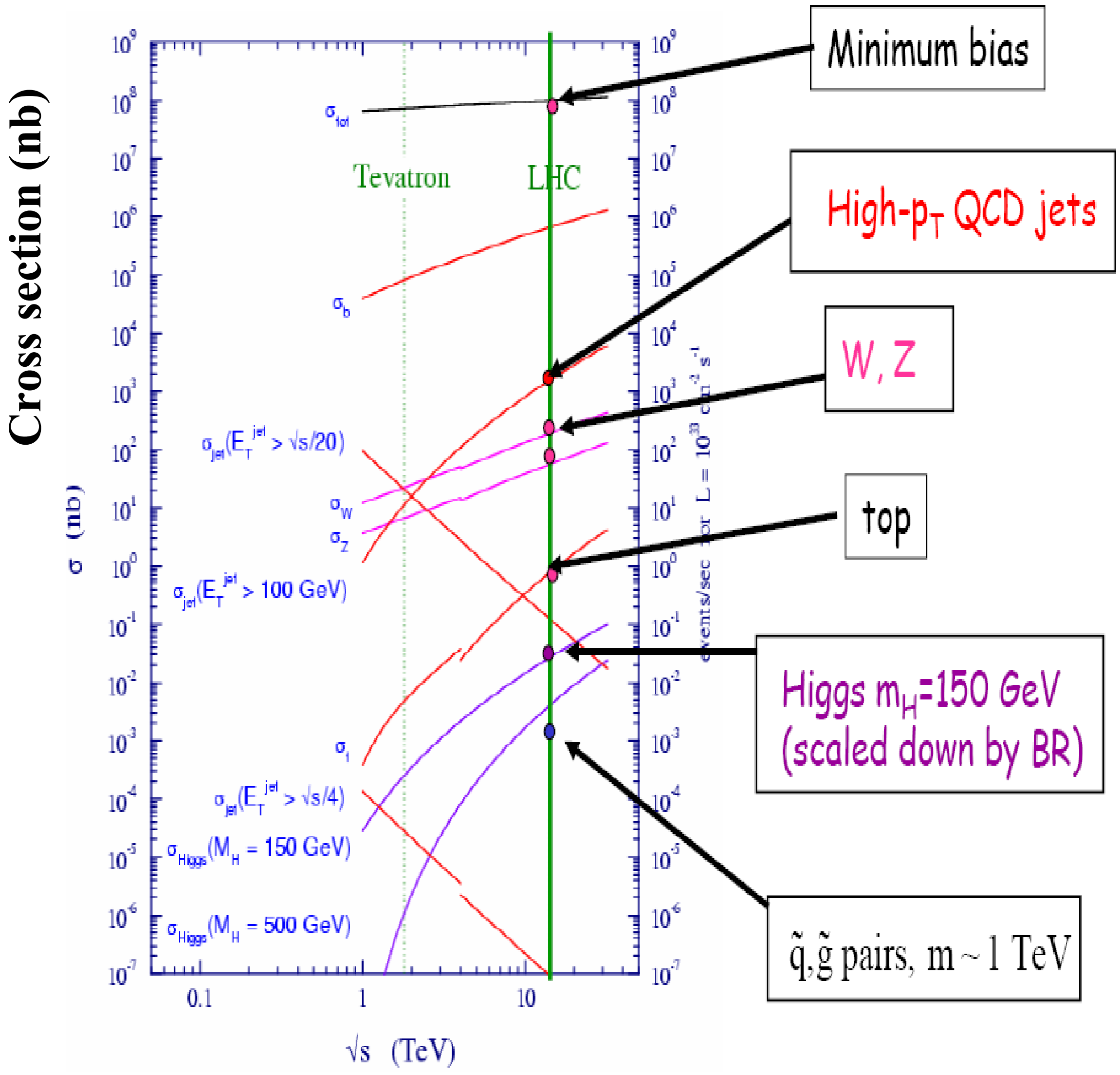
MSSM Lagrangian depends on 105 parameters

mSUGRA requires only 5 parameters

- Also other SUSY models exist: **GMSB**, **AMSB**, …

Par.	Description
m_0	Common scalar mass
$m_{1/2}$	Common gaugino mass
A_0	Common trilinear term
$\tan\beta$	Ratio of Higgs vev
sign(μ)	μ from Higgs sector

A needle in an hay stack



Only one event (i.e. pp collision) in **one bilion** may contain an Higgs boson or a squark….

Need **high luminosity**

Need an **efficient online selection** (trigger) to select interesting events: cannot register everything electronically for further processing

What do we do when we get the data?

Before we can claim discovery of "New Physics" we have to do some homework…

- Understand and calibrate detector and trigger in situ using well-known physics samples: $Z/W\rightarrow$leptons, semileptionic tt
- Understand basic SM physics at 14 TeV: first measurements and publications
  - jets and W, Z cross-section top mass and cross-section
  - Event features: Min. bias, jet distributions, PDF constraints
- Understand tails of SM processes as backgrounds (tt, W/Z + jets), go for discovery: Z', SUSY, Higgs

But let's have a look at our main SUSY discovery strategy, to understand what we need to understand to get there…

mSUGRA benchmark points

SUSY benchmark points chosen in the **(m_0, $m_{1/2}$)** plane for different **tan**β values:

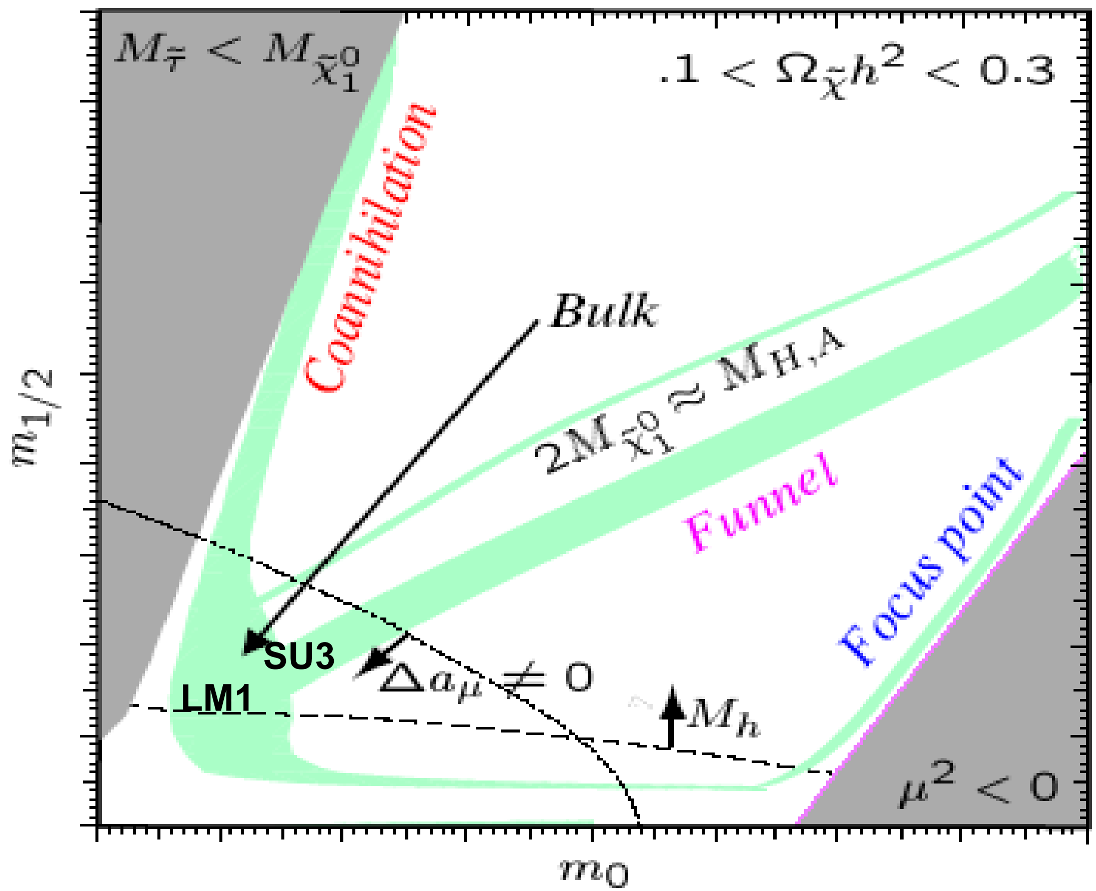
- ✓ Systematically exploring phenomenological signatures
- ✓ Scanning the parameter phase space constrained by latest experimental data

Coannihilation: Light $\tilde{\tau}_1$ in equilibrium with $\tilde{\chi}_1^0$, so annihilate via $\tilde{\chi}_1^0 \tilde{\tau}_1 \to \gamma\tau$.

Bulk: bino $\tilde{\chi}_1^0$; light $\tilde{\ell}_R$ enhances annihilation.

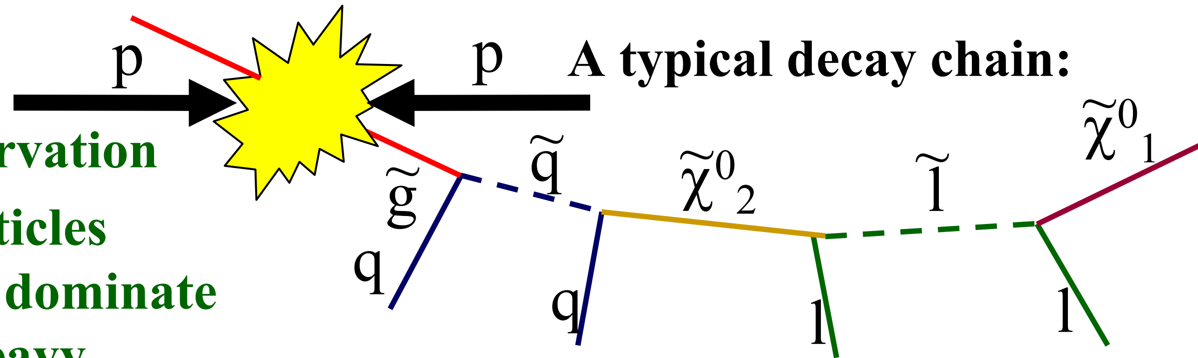
Funnel: H,A poles enhance annihilation for $\tan\beta \gg 1$.

Focus point: Small μ^2, so Higgsino $\tilde{\chi}_1^0$ annihilate. Heavy s-fermions, so small FCNC.



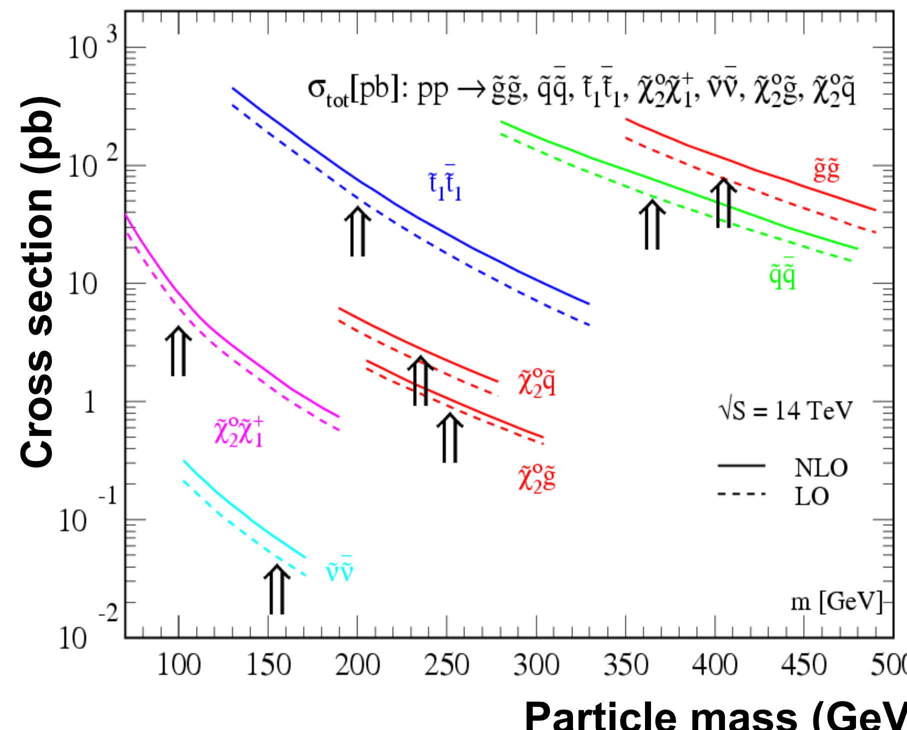
SUSY signatures at an hadronic collider

A typical decay chain:



- **Assuming R-parity conservation**
- **Strongly interacting sparticles (squarks, gluinos) should dominate production unless very heavy.**
- **Cascade decays to the stable, weakly interacting lightest neutralino follows.**
- **Event topology:**
  - **high p_T jets (from squark/gluino decay)**
  - **Large E_T^{miss} signature (from LSP)**
  - **High p_T leptons, b-jets, τ-jets (depending on model parameters).**

Several other possibilities exist (even if not mentioned in this talk), but our effort has to be as more "model independent" as possible.



Event topologies and baseline selection

Early searches try to cover a broad range of experimental signatures, but they are classified based on the event topology:

Large E_T^{miss} +

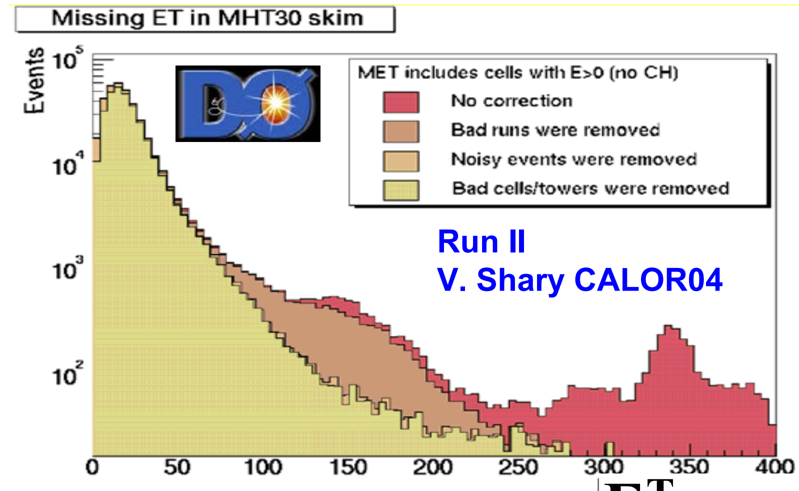
Jet multiplicity	Additional signature	SUSY scenario	Backgrounds
≥ 4	No lepton	mSUGRA, AMSB, split SUSY, heavy squark	QCD, ttbar, W/Z
	One lepton (e,μ)	mSUGRA, AMSB, split SUSY, heavy squark	ttbar, W
	di-lepton	mSUGRA, AMSB, GMSB	ttbar
	di-tau	GMSB, large tan β	ttbar, W
	$\gamma\gamma$	GMSB	free
~2		light squark	Z

<u>Baseline selection (to be optimized)</u>

- Jet multiplicity ≥ 4, $p_T^{1st} > 100$GeV, $p_T^{others} > 50$GeV
- $E_T^{miss} > \max(100\text{GeV}, 0.2\text{x}M_{eff})$
- Transverse sphericity > 0.2
- Additional cuts depending on signature: Transverse mass > 100GeV , $p_T^{lepton} > 20$GeV (for one-lepton mode) , harder cuts on M_{eff} …

E^T_{MISS} Commissioning

- Biggest challenge fake E^T_{MISS}: Tevatron experience shows can be hard to control
  - Machine backgrounds, calorimeter problems, jet mis-measurement …
  - Devote much effort to event-cleaning
  - Focus on channels where minimised until understood (e.g. leptons)



- Key input: understanding of E^T_{MISS} Gaussian response:
  - min bias events, dijet P_T balance, m_T(W→lν), Z→ll, Z→ττ etc.
- Beyond this: non-Gaussian tails absolutely crucial
  - Event cleaning/rejection
  - Estimation

After this:

- Validation of MC with control sample (Z-→ℓℓ, tt→bqqbℓν);
- Estimation of W/Z+jets and tt backgrounds from $m_T(\ell, E^T_{MISS})$ or Z-→ℓℓ control sample;
- Optimization of inclusive search event selection with major backgrounds estimates (MC or data driven) normalized to data;

SUSY search strategies: No lepton mode

Most promising search strategy:
jets + E_T^{miss} + n-leptons

- **Real missing energy from SM processes with hard neutrino (tt, W+jets, Z+jets, bb*, cc*)**

* ν from semileptonic B/D decay

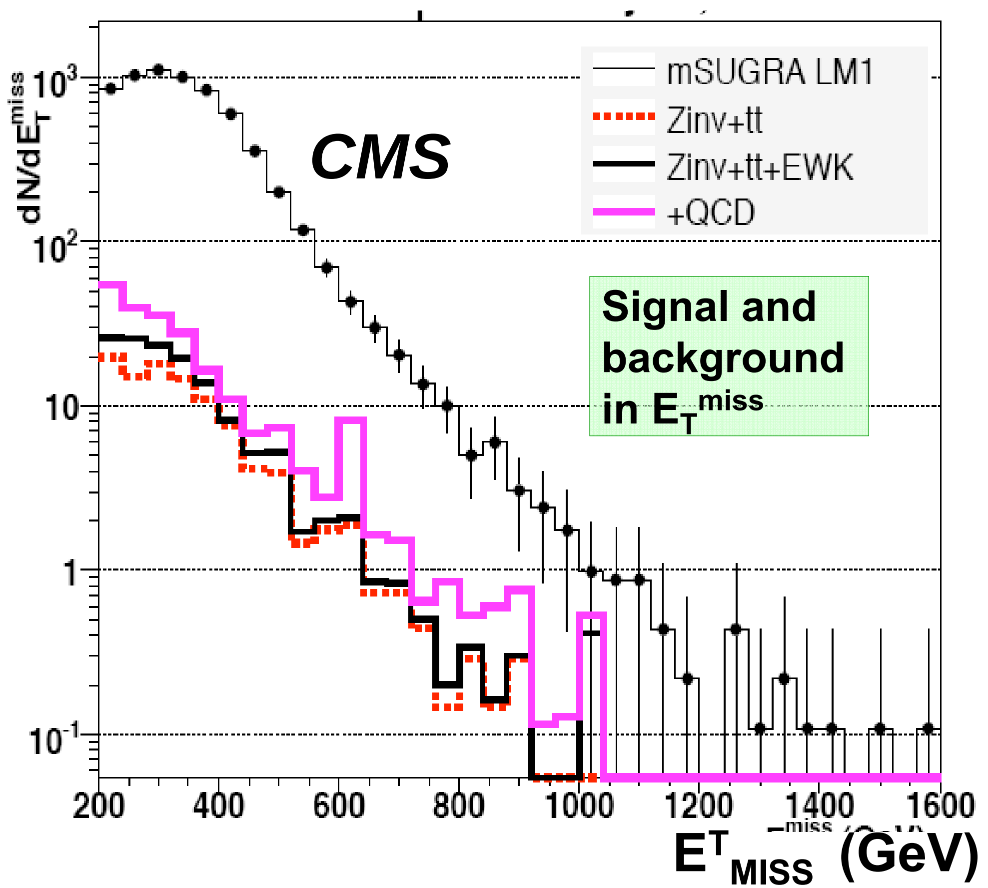
- **Fake missing energy from detector**

Jet energy resolution (expecially non-gaussian tails) critical

A good understanding of both SM physics and detector (missing energy expecially) critical to claim excess over SM predictions

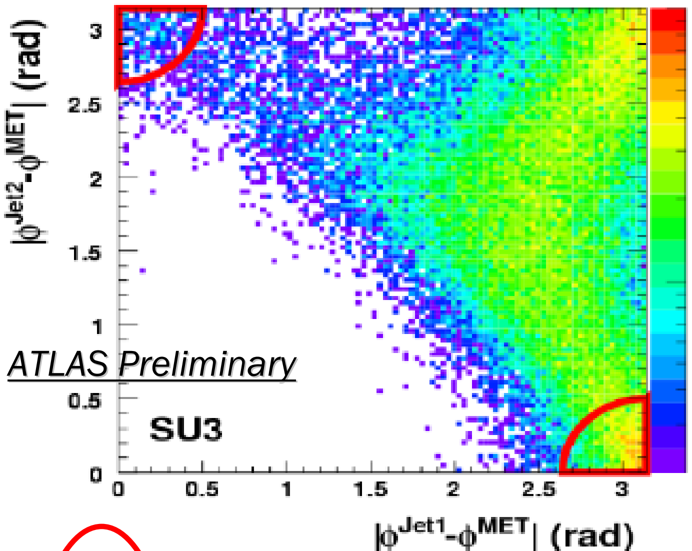
1 fb-1

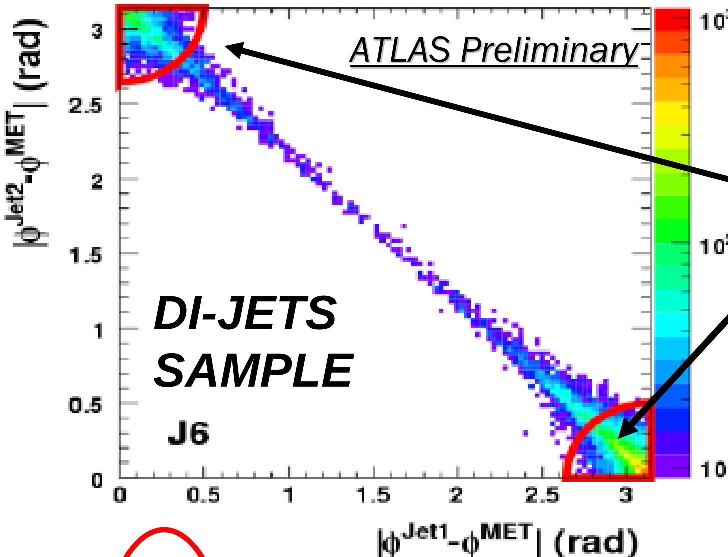
E^T_{MISS} + Jets + 0 lepton



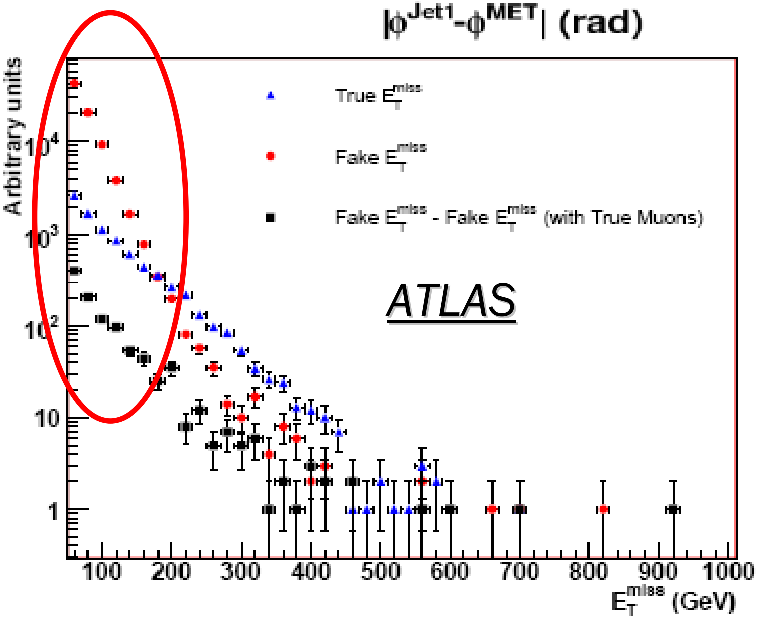
E_T^{MISS} & QCD (1)

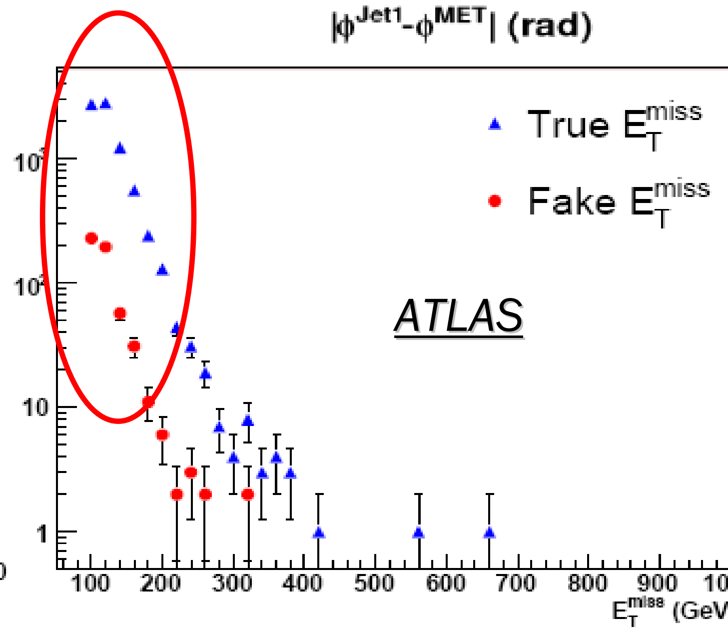
Azimuthal difference of 2 leading jets w.r.t. MET vector





Avoiding these regions…..

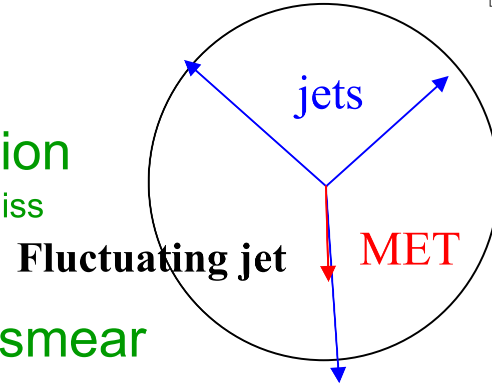


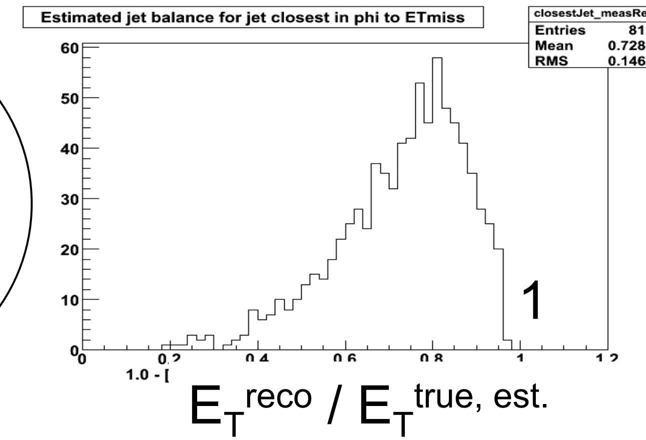


….. **QCD contribution to fake MET** is strongly lowered, especially for MET<200 GeV (red circles).

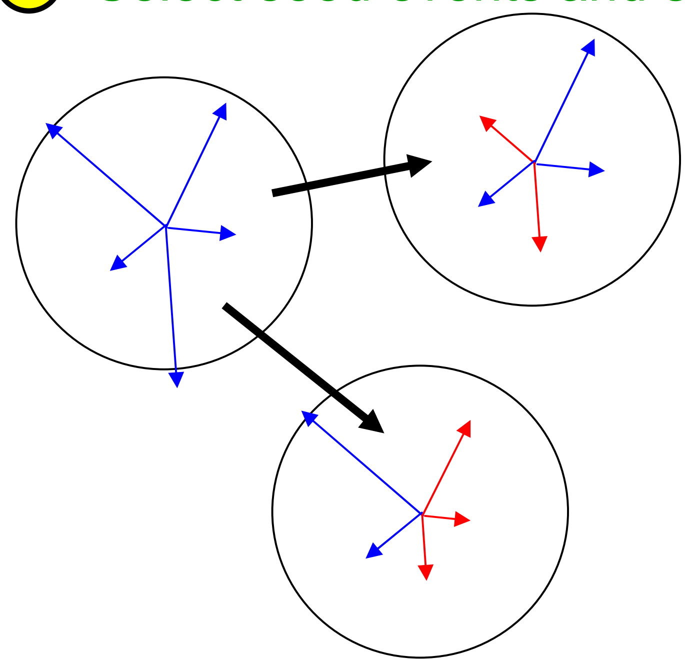
E_T^{MISS} & QCD (2)

1 Measure smearing function in events with large E_T^{miss}

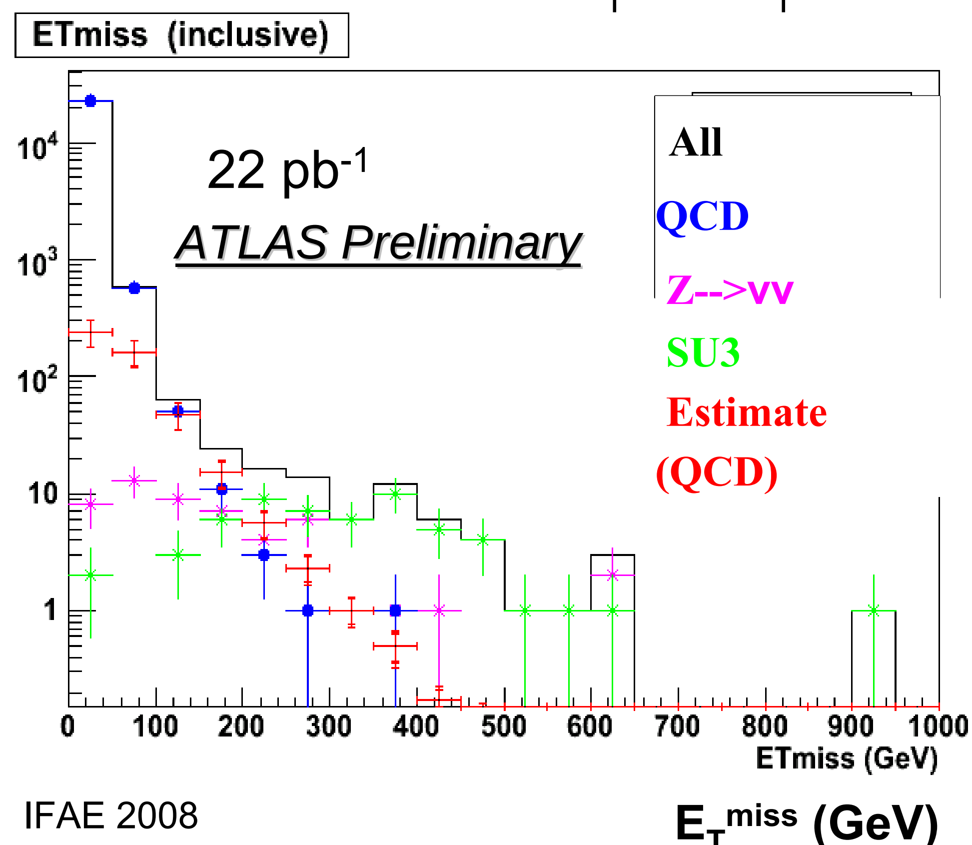




2 Select seed events and smear



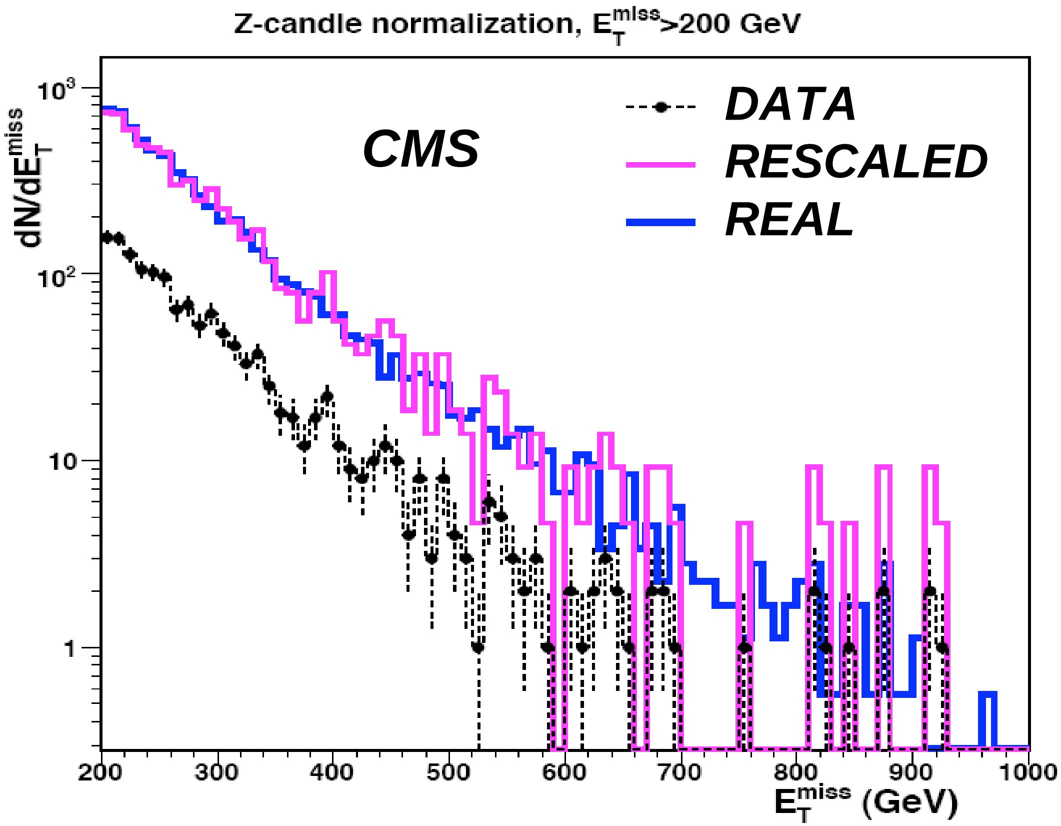
Seed events: low $E_T^{miss}/ \Sigma E_T$

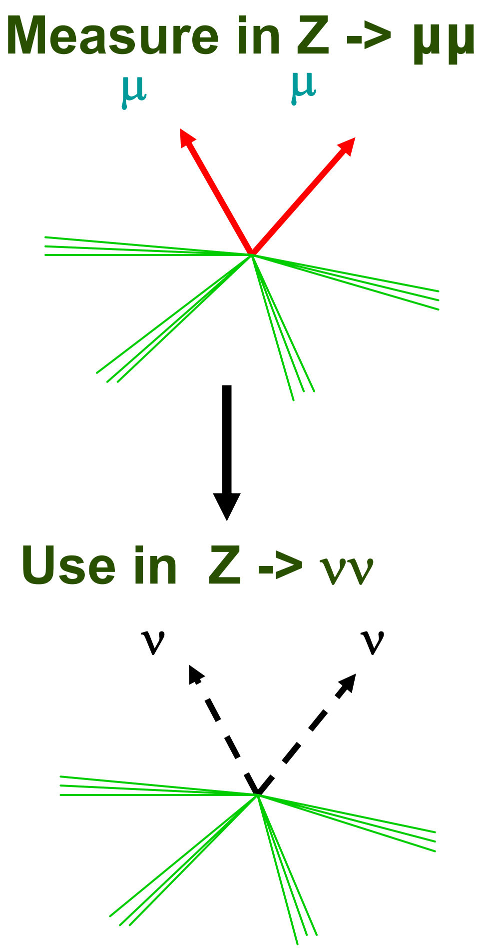


3 Normalize estimate to data

Z+ jets background

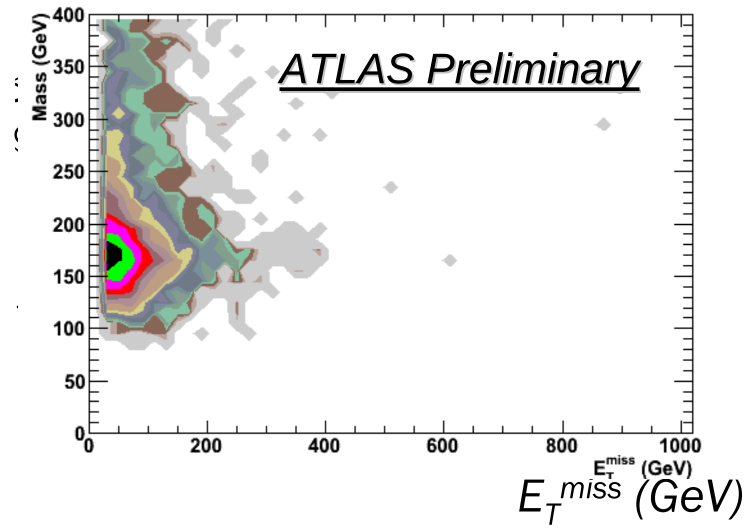
- Data-driven estimation of **Z→νν** bkg **E_T^{miss}** shape and normalization using Z→μμ sample and replacing μ with ν

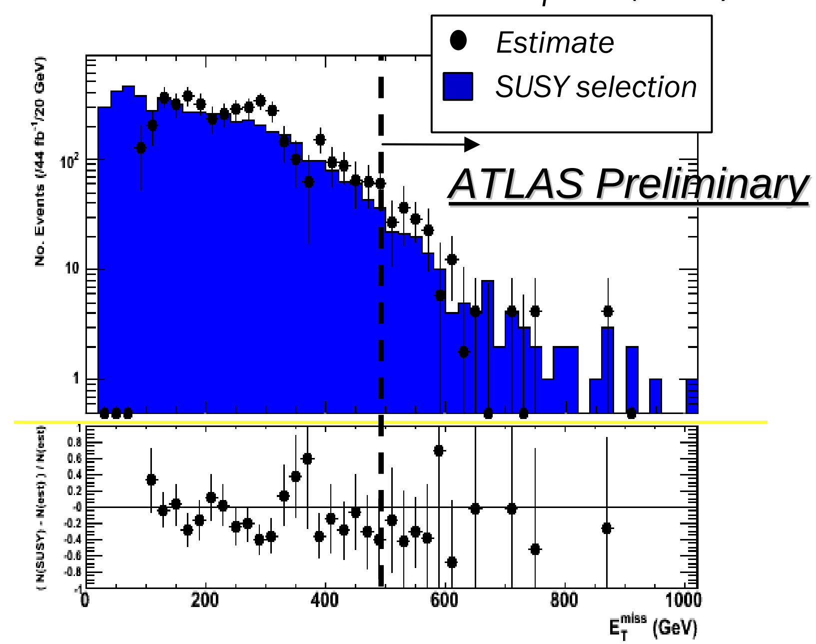




ttbar background

1. Top mass is largely uncorrelated with E_T^{miss}
   - used as a calibration variable
2. Select semi-leptonic top candidates
   - mass window: 140-200 GeV
3. Contributions of combinatorial BG to top mass are estimated from the side-band events (200GeV<m_{top}<260GeV)
4. Normalize the E_T^{miss} distribution in low E_T^{miss} region where SUSY signal contamination is small.
5. Extrapolate it to high E_T^{MISS} region and estimate the background with SUSY signal selection.

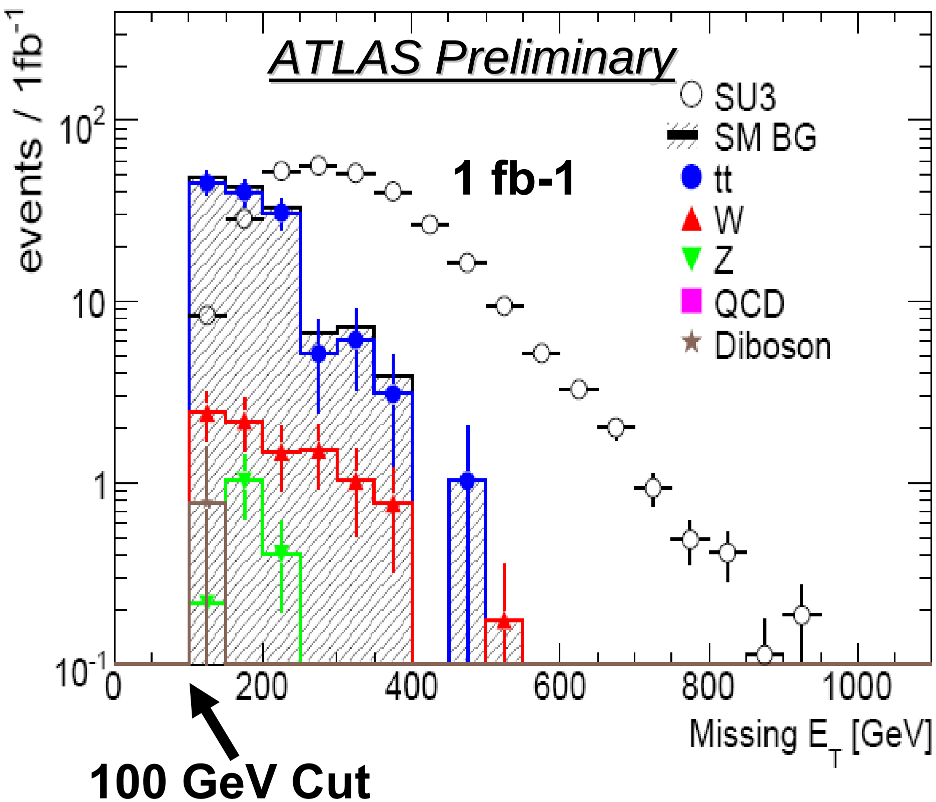


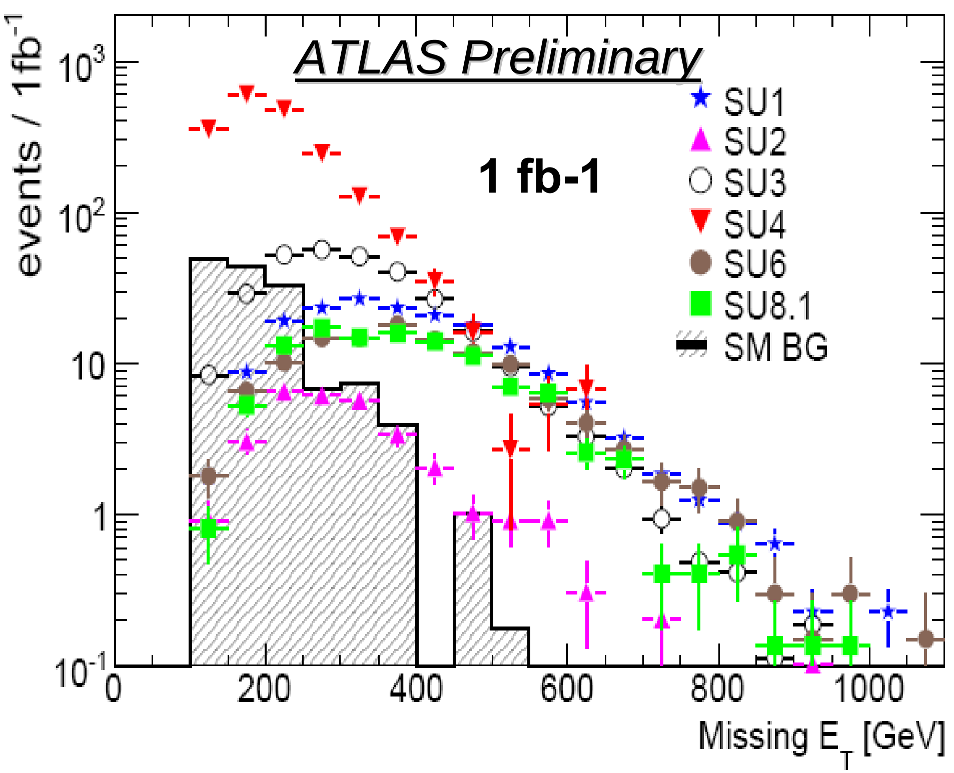


Several other techniques also under investigation

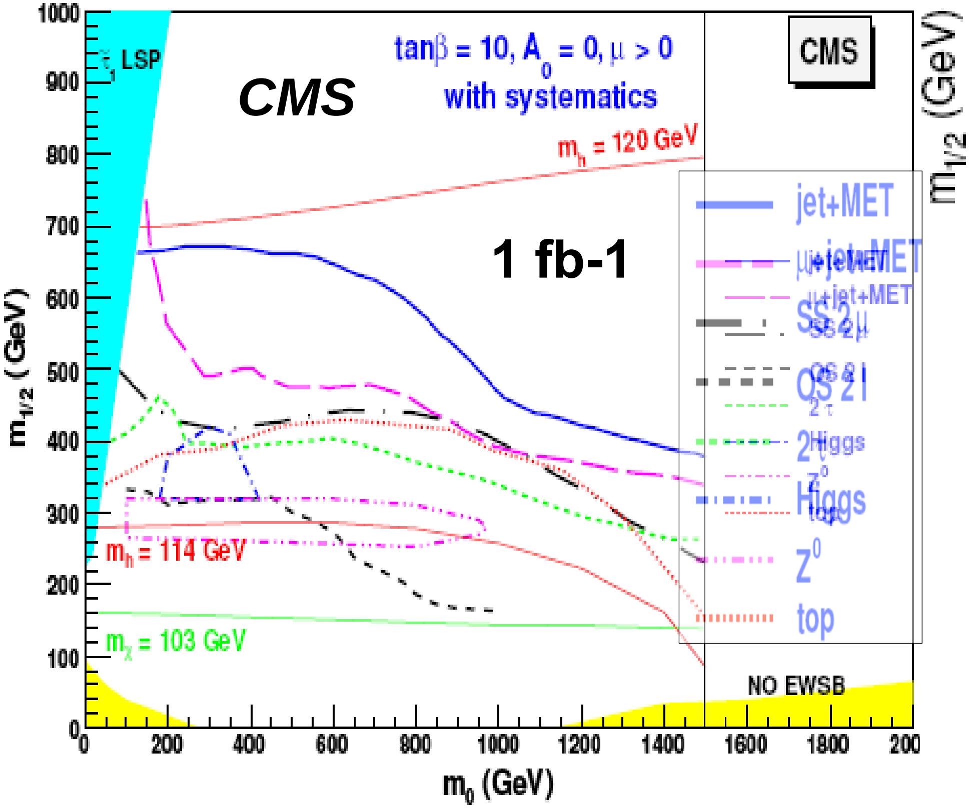
Other strategy: 1-lepton channel

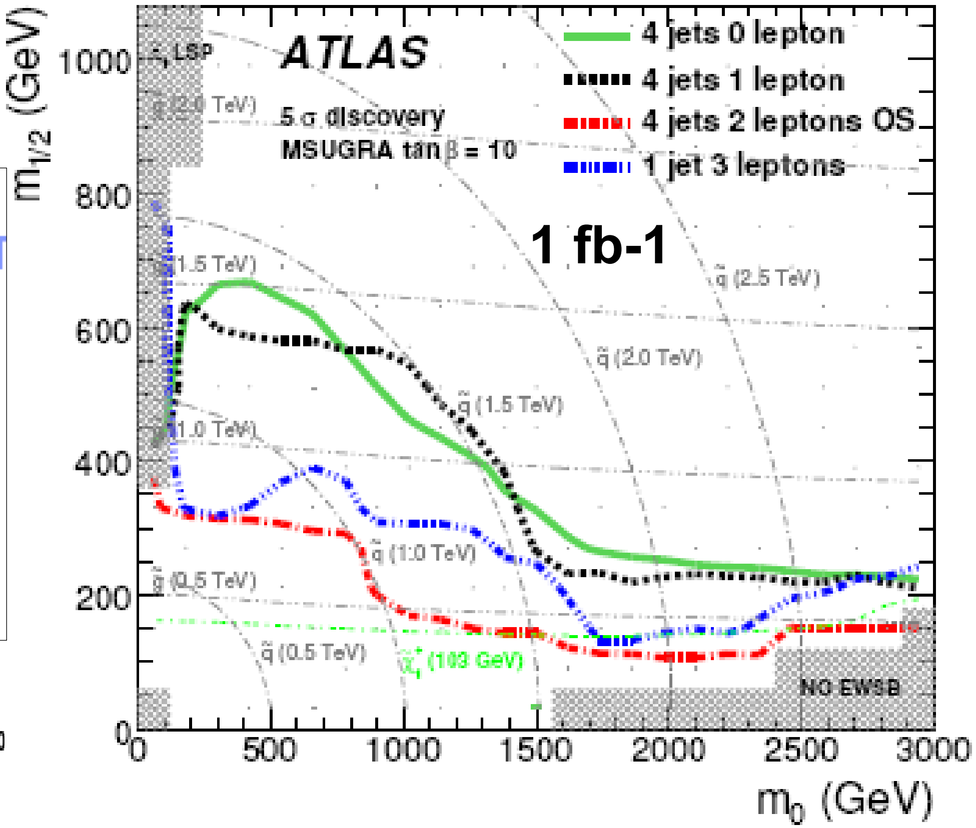
- Removing the lepton-veto: 1 lepton + Jets + E^T_{MISS} channel
  - Lepton can usually come from chargino/neutralino decays into LSP
  - Heavily suppression of the QCD background (difficult to estimate from data and also with MC) requiring 1 isolated lepton with $P_T > 20$ GeV/c.
  - Dominant background are the same as the 0-lepton channel (except QCD) : top seems to be the dominant one, but W + jets is not negligible.





Back to SUSY discovery



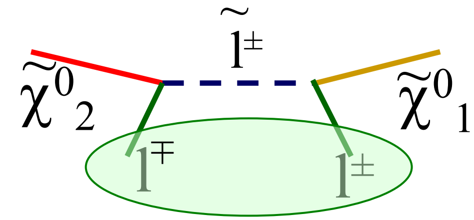


5σ discovery potential on m1/2-m0 (mgluino-msquark) space for 1 fb-1

1 fb^{-1} of **ATLAS/CMS** data should be **enough** to discover **SUSY** if squark/gluino mass **lower than 1.5÷2 TeV**.

Di-Lepton Edge mass measurement (1)

- In case of a discovery of SUSY, **particle properties** can be measured to verify that they are indeed SUSY partners



- Edge(s) of **di-lepton invariant mass** correlated with slepton and neutralino masses

$$\tilde{\chi}^0{}_2 \rightarrow \tilde{l}\, l \rightarrow \tilde{\chi}^0{}_1\ l^+ l^-$$

- Impossible to reconstruct peaks because $\chi^0{}_1$ (LSP) escapes detection, more complicated relations between masses of particles involved.

$$M_{ll}^{\max} = M(\tilde{\chi}_2^0)\sqrt{1-\frac{M^2(\tilde{l}_R)}{M^2(\tilde{\chi}_2^0)}}\sqrt{1-\frac{M^2(\tilde{\chi}_1^0)}{M^2(\tilde{l}_R)}}$$

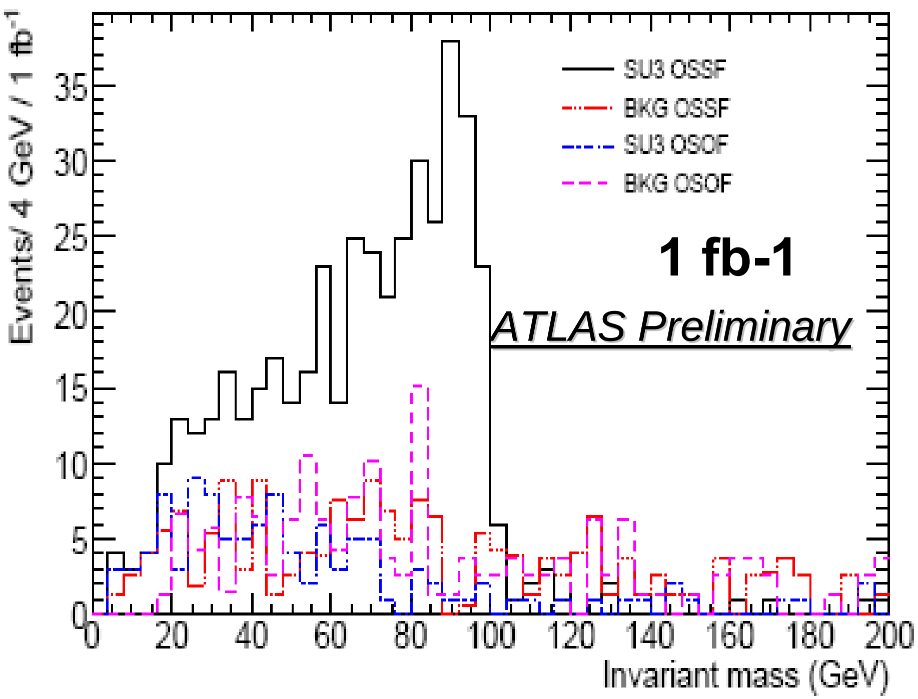
✓ Uncorrelated (SUSY+SM) background (two leptons from independent chains) **removed** by **flavour subtraction**:

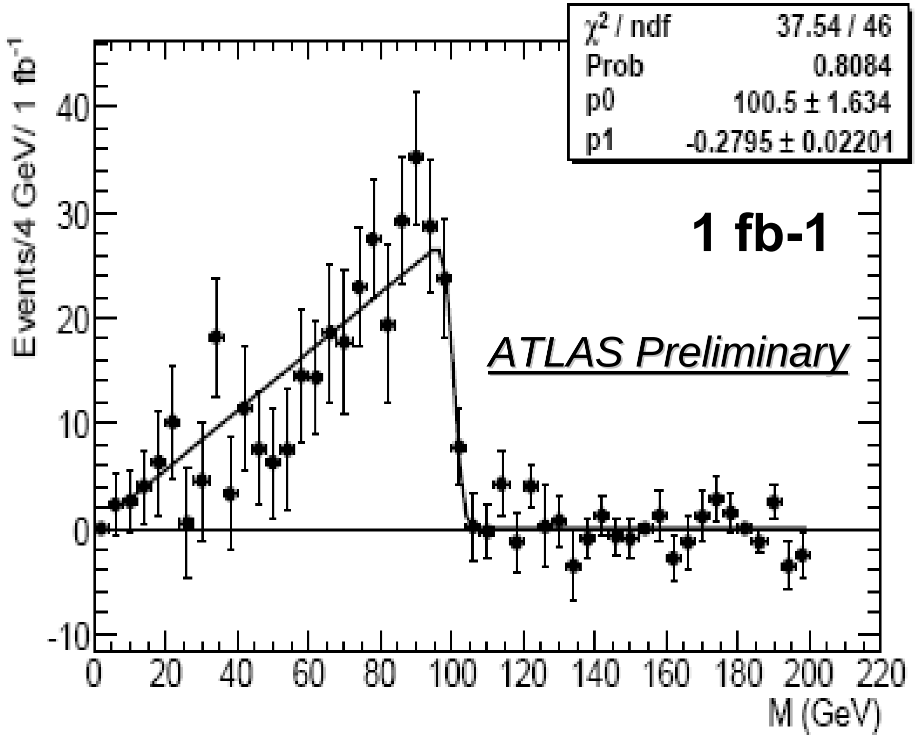
$$e^+e^- + \beta^2\,\mu^+\mu^- - \beta\,(e^+\mu^- - e^-\mu^+)\ ,\ \beta = \varepsilon_e/\varepsilon_\mu$$

✓ Leptons can also be combined with jets of the full decay chain to look for other **kinematical edges** (M_{llj} or M_{lj})

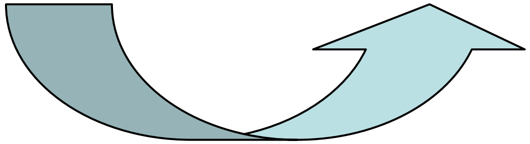
Di-Lepton Edge mass measurement (2)

Flavour subtraction at work….





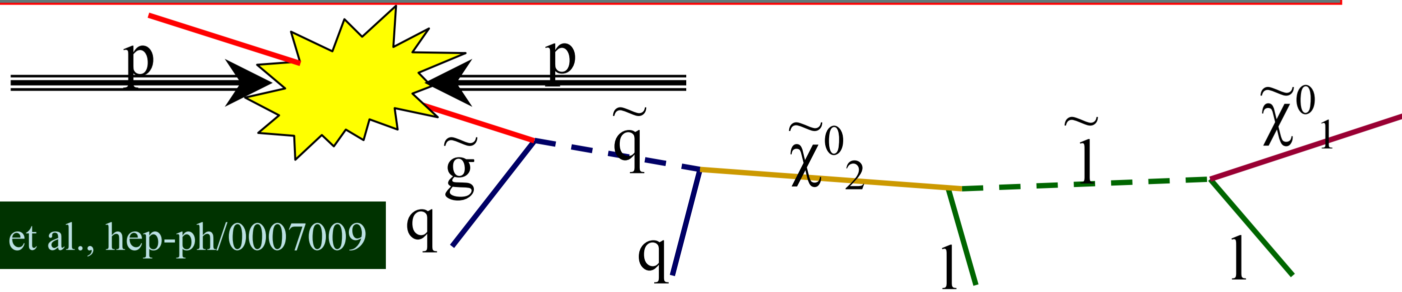
SU3, 1 fb^{-1}
Edge: (100.5±1.6) GeV
Truth: 100.2 GeV



Flavour Subtraction

Fitting function:
Triangle smeared with a Gaussian with $\sigma = 2$ GeV (to take into account experimental resolution)

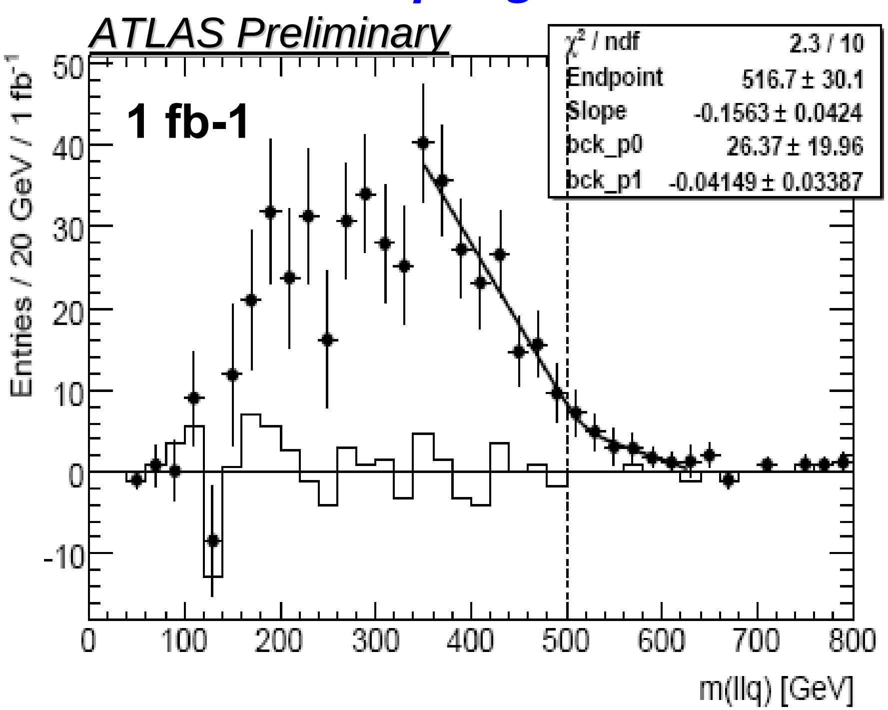
Lepton+jets combination



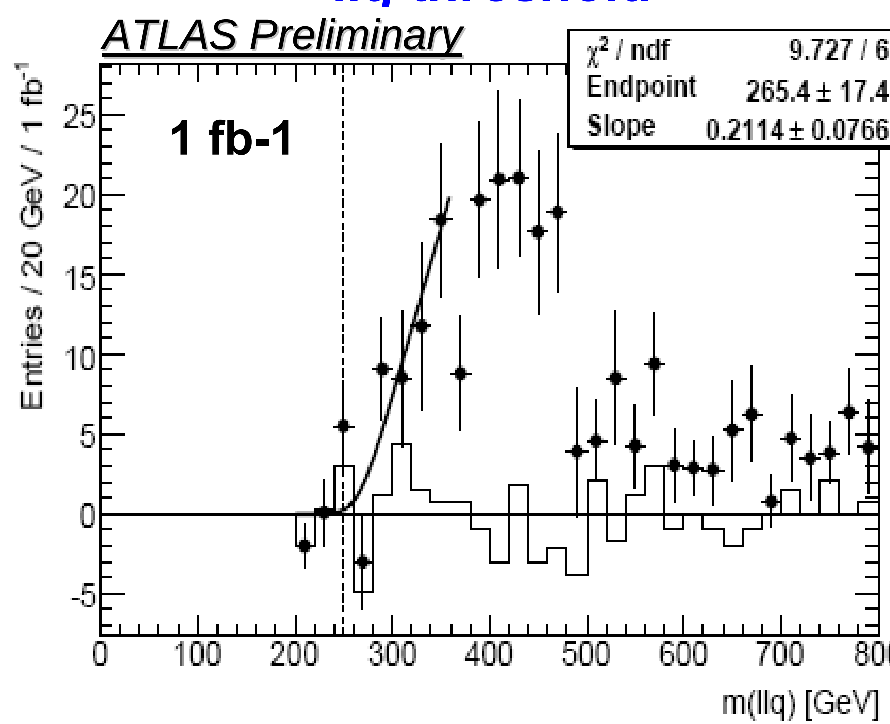
Formulas in Allanach et al., hep-ph/0007009

The invariant mass of each combination has a minimum or a maximum which provides one constraint on the masses of $\tilde{\chi}^0_1$ $\tilde{\chi}^0_2$ $\tilde{l}$ $\tilde{q}$

llq edge



llq threshold



Conclusions

- A brief review of the search strategies for SUSY in ATLAS & CMS has been presented;
  - New discoveries possible with early LHC data (O(100)pb^{-1})
- Accurate knowledge of SM physics and of detector performance needed for any new discovery
  - **First data** taking period devoted to understanding of detector
- Any claim of new physics requires check of trigger refinements and data-driven estimates of syst./background
  - First, focus on less systematic-affected analyses (e.g. striking signatures and resonances)
- Larger statistics needed for full scan over SUSY parameters space and **discrimination** between different models.

BACKUP SLIDES

Detector calibration and alignment

The jet energy scale affects directly SUSY discovery plots trough the cut on the presence of hard jets.

Also, E_T^{miss} depends on the correct reconstruction of the energies of jets, photons, electrons, and muons!

- We will start from the knowledge obtained from test-beam data, electronics calibrations, survey measurements during installation of the tracking detectors, and cosmics data.
- We will then use well-known SM processes (standard candles) to improve

Examples: leptonic decays of Z, W mass in semileptonic top events

	Expected performance day-1	Physics samples to improve (examples)
ECAL uniformity	1-2% (~0.5% locally)	Isolated electrons, $Z \to ee$
e/γ E-scale	~ 2 %	$Z \to ee$
HCAL uniformity	~ 3 %	Single pions, QCD jets
Jet E-scale	< 10%	γ/Z + 1j, $W \to jj$ in $t\bar{t}$ events
Tracking alignment	10-200 μm in $R\phi$ Pixels/SCT ?	Generic tracks, isolated μ, $Z \to \mu\mu$

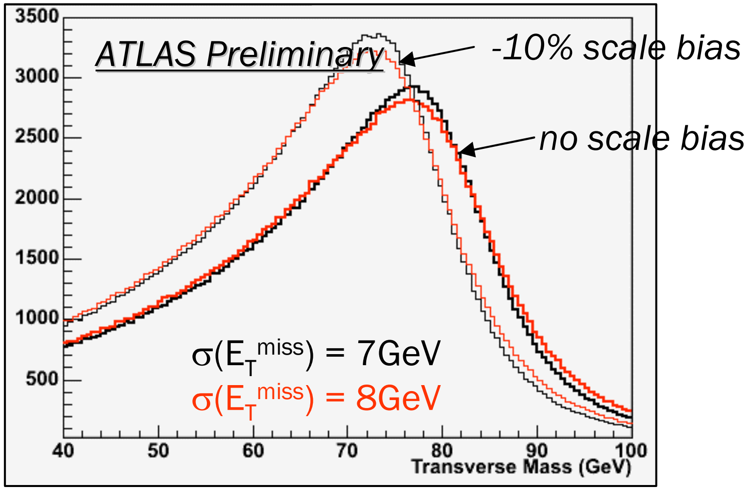
Process	$\sigma \times BR$	***Eff.***	Events selected for 100 pb^{-1}
$W \to \ell\nu$	20 nb	$\sim 20\%$	~ 400000
$Z \to \mu\mu$	2 nb	$\sim 20\%$	~ 40000
$\bar{t}t$ (semileptonic)	370 pb	$\sim 1.5\%$	< 1000

Available statistics, with conservative estimates of reconstruction efficiencies

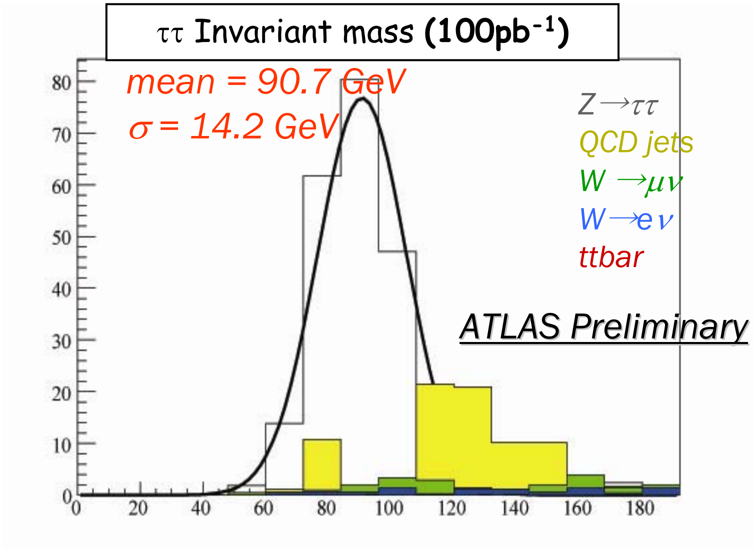
E_T^{MISS} Commissioning (2)

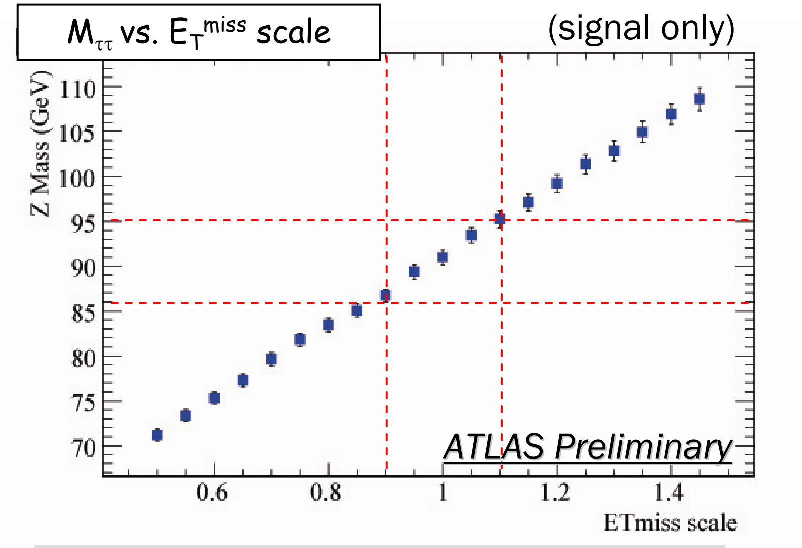
Just two examples, several other physics process can be used: minimum bias, Z(ll), ttbar, …

W(lν) sample: Shape of transverse mass distribution depends on E_T^{miss} scale and resolution.



Z(ττ) sample: Z mass can be reconstructed with collinear approximation (since the τ are boosted, ν are along visible τ energy). Can be used to calibrate E_T^{miss} scale.

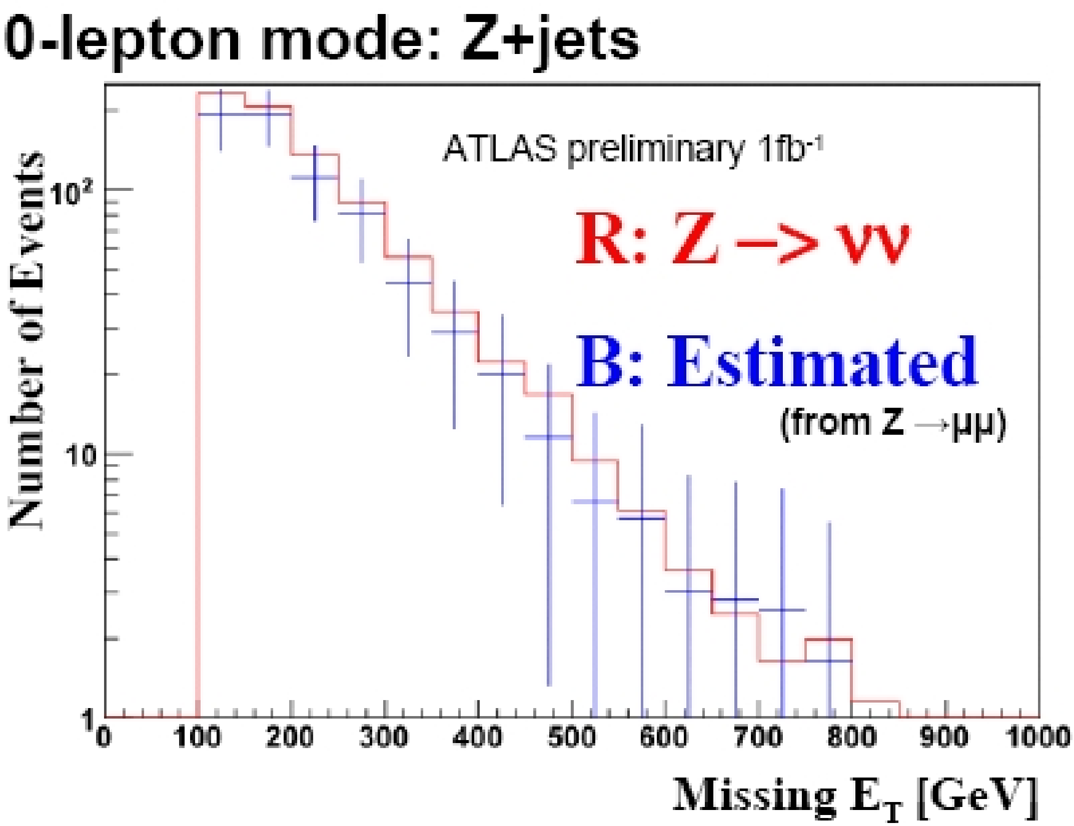




10% in E_T^{miss} scale ⇔ 3% shift in Z mass

Z and W background

Estimate $Z \to \nu\nu$ from $Z \to \ell^+\ell^-$

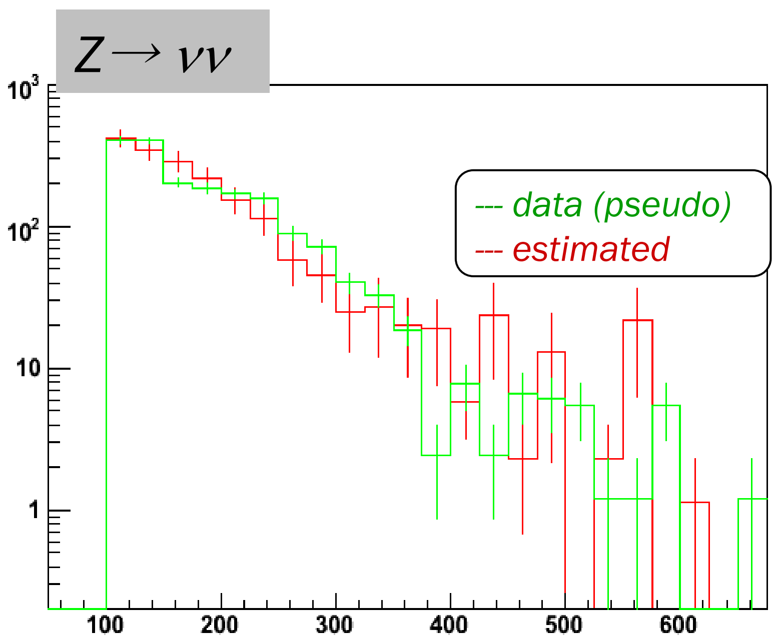


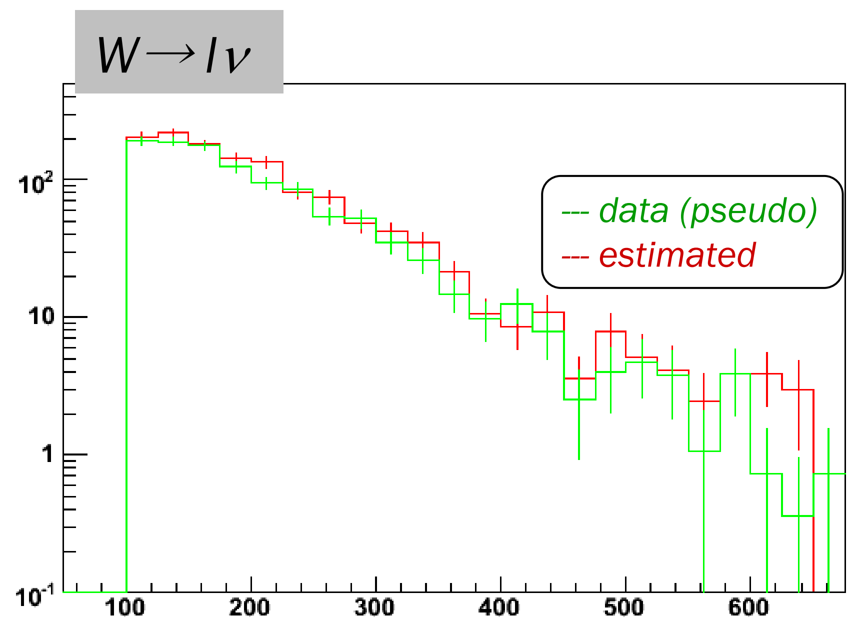
Similarly we can use the Z distribution to estimate the $W \to \ell\nu$ background

$Z \to \nu\nu$ and $W \to l\nu$ can be estimated from $Z \to \ell^+\ell^-$

Either **replace** the two leptons with neutrinos correcting for acceptance and efficiency

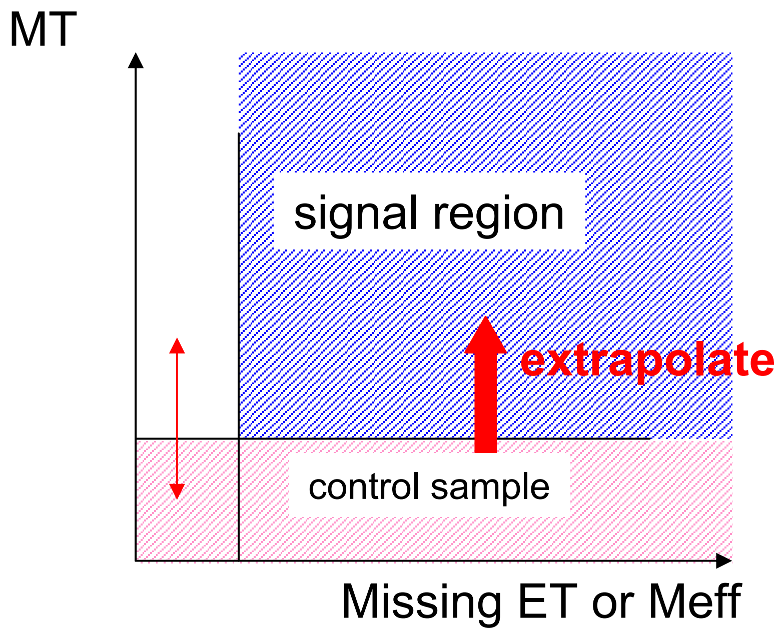
Or determine the **MC normalization** from Z(ll) and apply it to normalize the MC distribution of $Z(\nu\nu)$ and $W(l\nu)$ (almost same production mechanism)

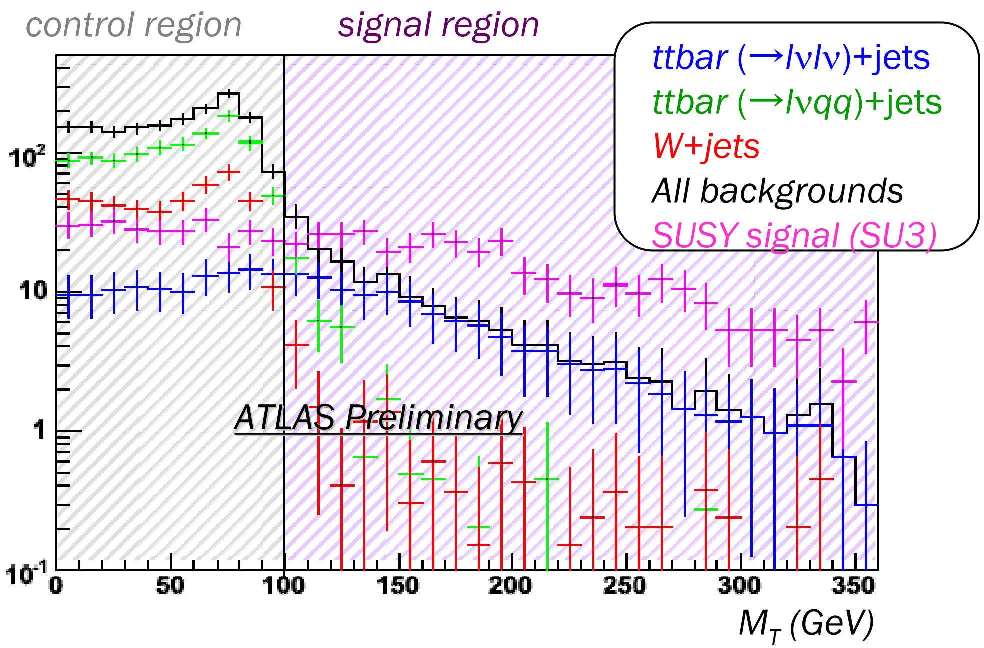




ATLAS Preliminary E^T_{MISS} (GeV) *ATLAS Preliminary* E^T_{MISS} (GeV)

Transverse mass method



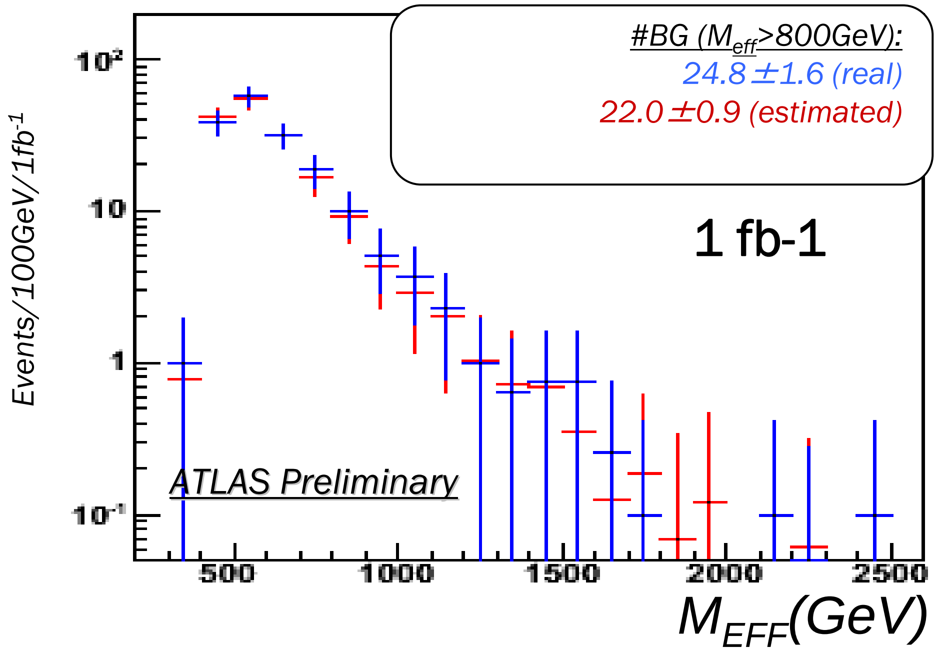


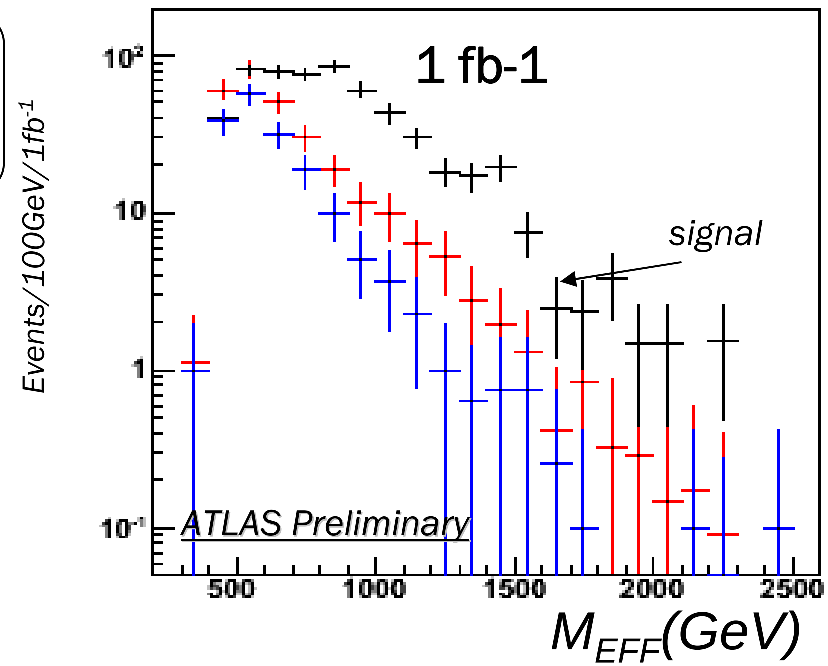
1. Define control sample with transverse mass <100GeV
2. Estimate the E_T^{miss}/M_{eff} shapes of background processes using control sample
3. Determine the normalization of backgrounds with low E_T^{miss} regions of control and signal samples.

Can be used for both W and top backgrounds in 0-lepton, 1-lepton and 2 lepton channels (results shown here for 1-lepton)

Transverse mass method

Including SUSY signal (SU3)



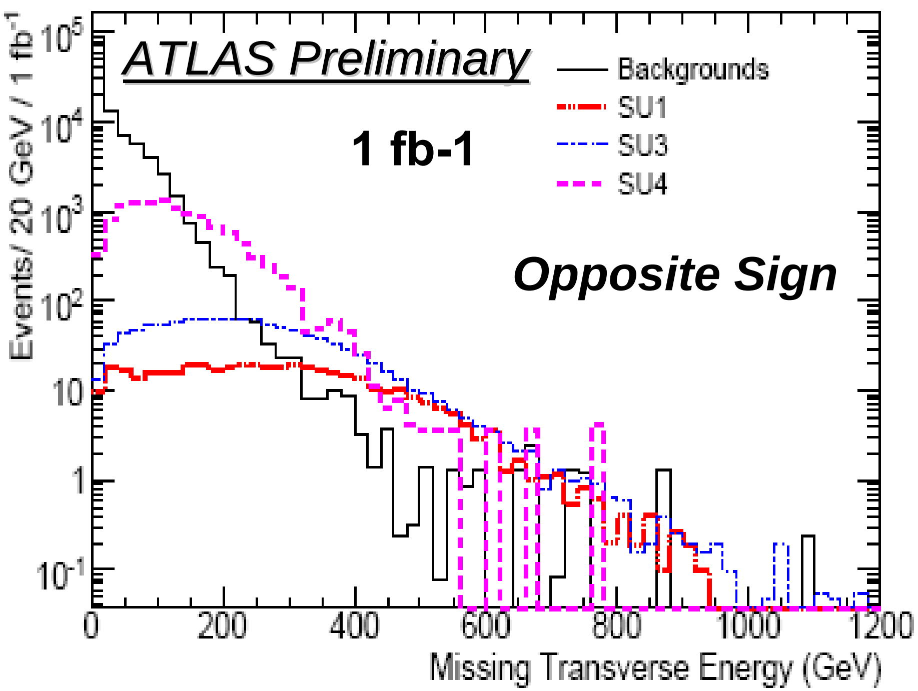


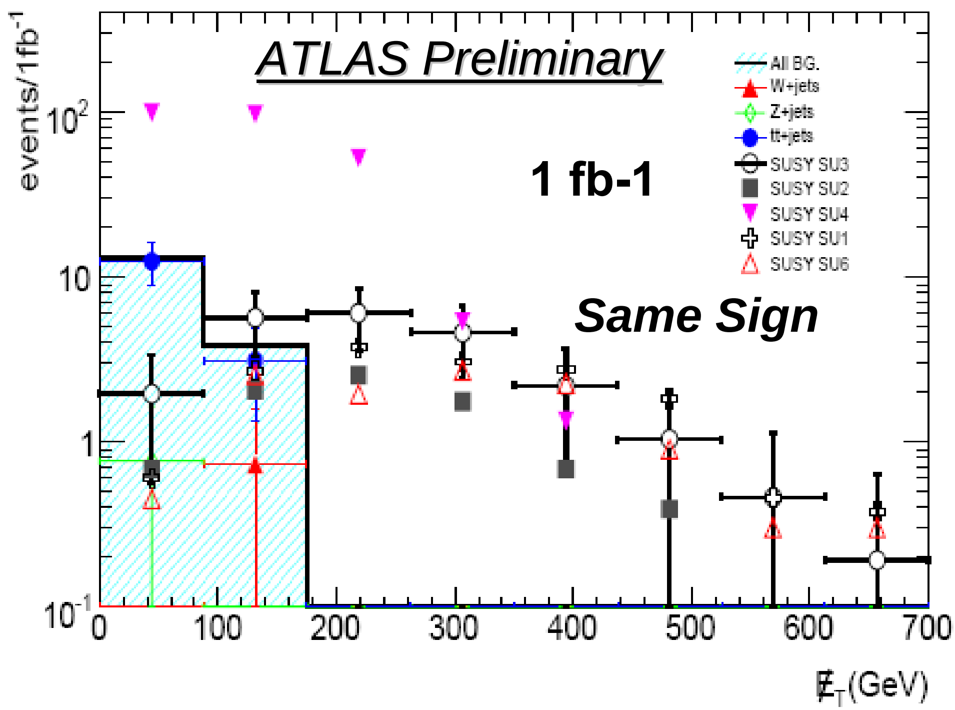
- *Satisfying performances with the M_T discrimination technique.*
- *However, taking account of SUSY signal contamination in the control sample, this estimate appears to be over the mark (by a factor of 2.5 for SU3).*

It would not prevent discovery.

Other strategy: 2-lepton channel

- Increasing the number of leptons
  - Reduces the signal because of (model dependent) leptonic BRs
  - Heavily suppresses the background
  - Statistical significance is smaller but S/B ratio larger. Top is dominant background
  - The Same Sign channel has the best S/B ratio – but limited by signal rate



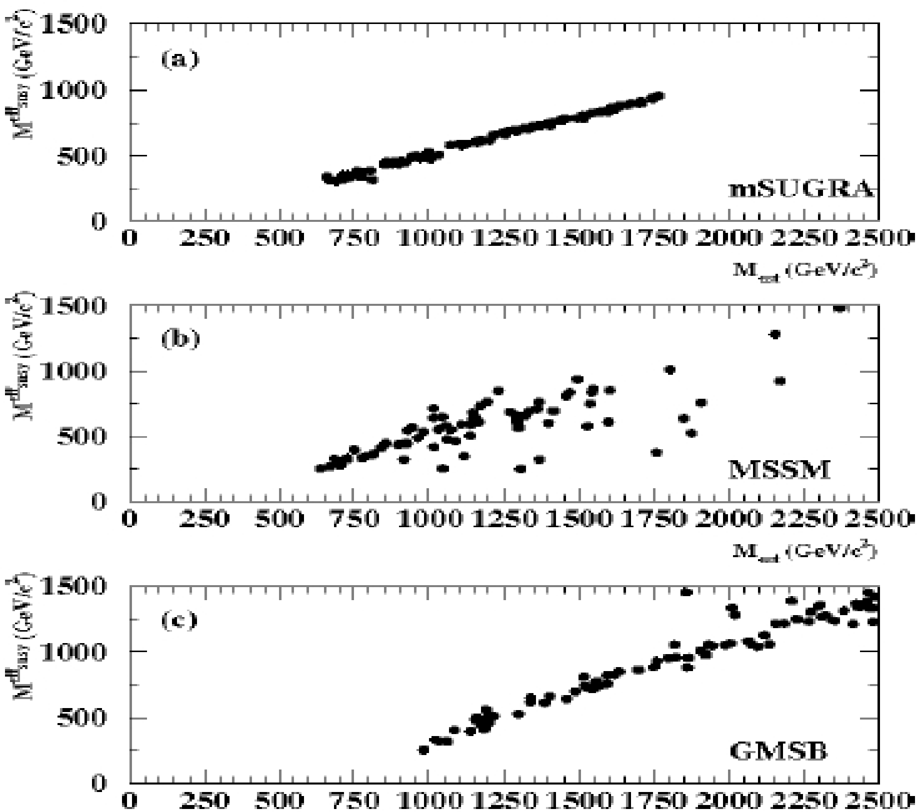


What next ?

"Observation of an excess of events in multijet+MET events in pp collisions at 14 TeV with the ATLAS detector"

Is it SUSY?

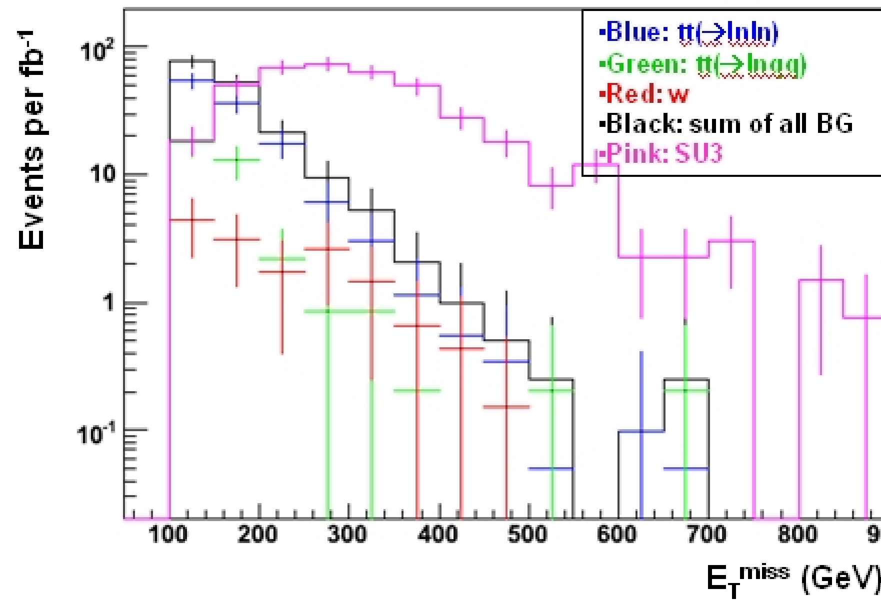
If yes, what are the model parameters?



[Tovey 01]

M_{Eff} (GeV)

Large (>100GeV) Missing ET events: Smoking gun of Supersymmetry



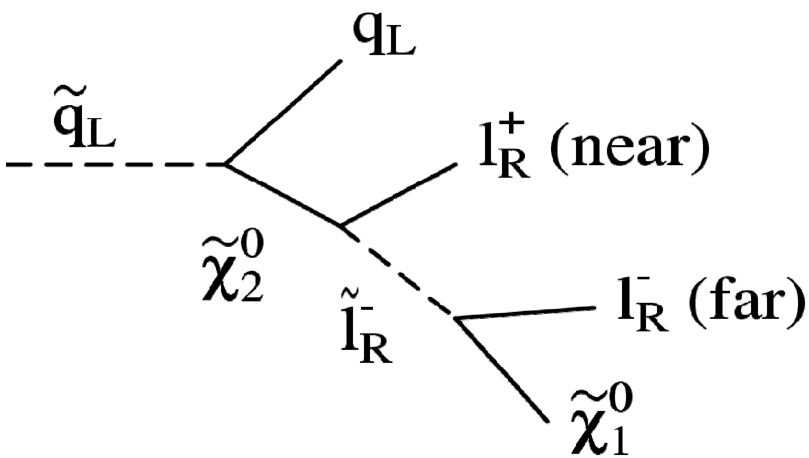
Measurement of the "effective mass" peak correlates with the SUSY mass scale (average squark, gluino mass)

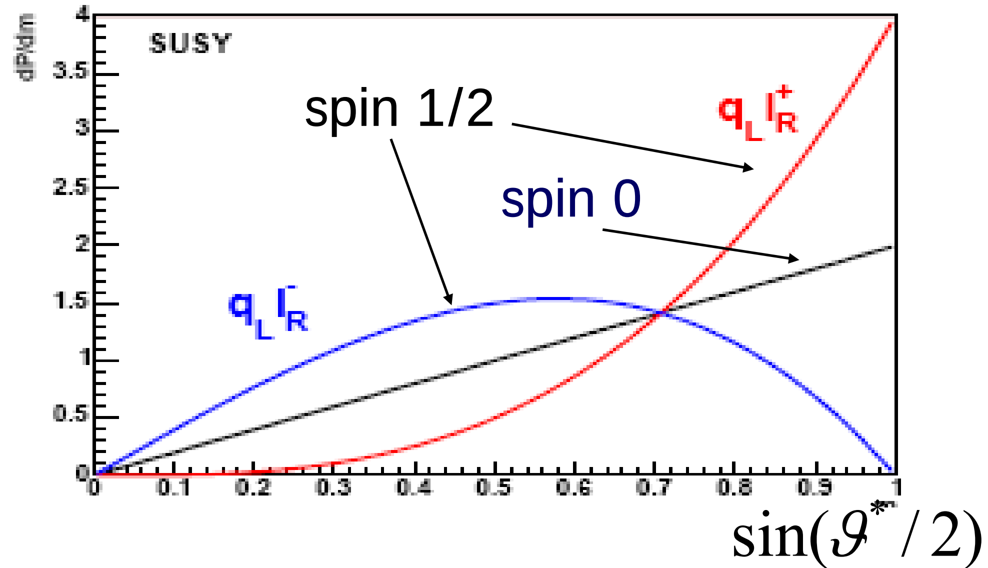
Meff = MET+PT,1+PT,2+PT,3+PT,4

15% (40%) precision on M(SUSY) with 10fb^{-1} for mSUGRA (MSSM)

Measurement of neutralino spin (1)

Important to measure the spin of new particles: it's the fundamental check to ensure that what we have discovered is SUSY!!





The charge asymmetry is **diluted** because:

1. Usually it is not possible to discriminate the *near* and *far* leptons: we sum $m(ql^{far})$ and $m(ql^{near})$ invariant masses
2. The charge conjugated cascade decay (from the anti-squark) gives the opposite asymmetry. However, cancelation is not exact because at LHC a larger number of squarks than anti-squarks is produced (pp collider)

Measurement of neutralino spin (2)

SU1 point: 7.8 pb x 1.6%

Ratio squarks/anti-squarks ~3.5

$$\tilde{q}_L \rightarrow q\ \tilde{\chi}_2^0 \rightarrow q\ \tilde{l}_L\ l \rightarrow q l^{\pm} l^{\mp} + \tilde{\chi}_1^0$$

264 | 255 soft | hard 137

$$\tilde{q}_L \rightarrow q\ \tilde{\chi}_2^0 \rightarrow q\ \tilde{l}_R\ l \rightarrow q l^{\pm} l^{\mp} + \tilde{\chi}_1^0$$

264 | 154 hard | soft 137

SU3 point: 19.3 pb x 3.8%

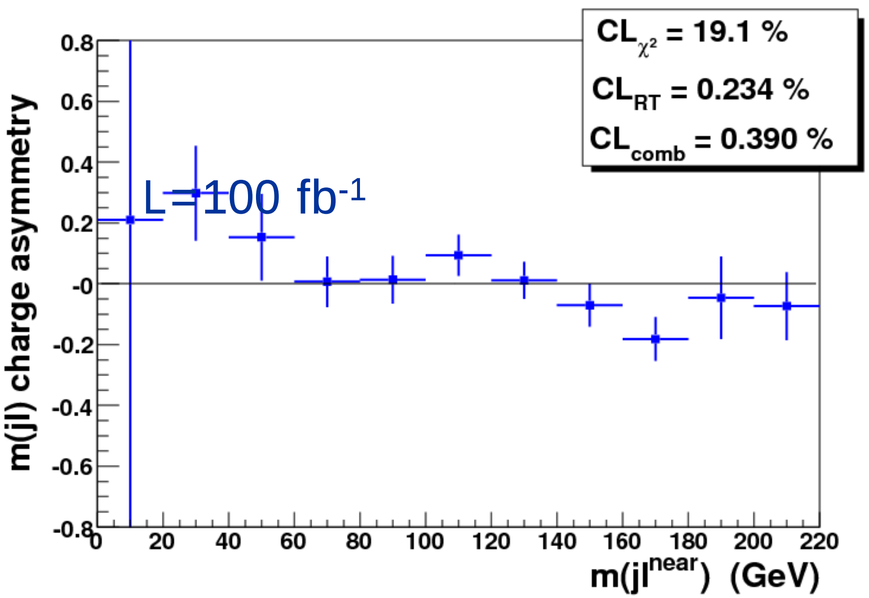
Ratio squarks/anti-squarks ~3

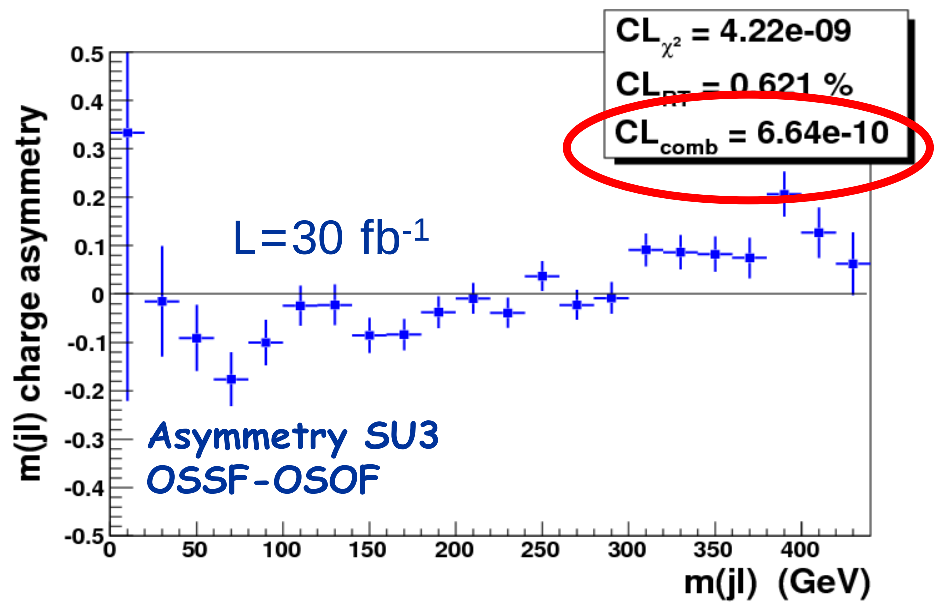
$$\tilde{q}_L \rightarrow q\ \tilde{\chi}_2^0 \rightarrow q\ \tilde{l}_R\ l^{\pm} \rightarrow q l^{\pm} l^{\mp} + \tilde{\chi}_1^0$$

219 | 155 | 118

- Cuts on missing energy and jet pt to reject SM background
- 2 Opposite Sign, Same Flavour (OSSF) electrons or muons.
- Subtract background from independent decay chains with the combination $\mu^+\mu^- + e^+e^- - \mu^{\pm}e^{\mp}$

In **SU3** point, **5÷10 fb^{-1}** are **already enough** to exclude charge symmetry





Other SUSY scenarios

Across the MSSM, there is a rich variation in the SUSY phenomenology.
The signatures expected at the LHC can be very different from the "mainstream' scenario discussed so far.

- **GMSB:** the lightest SUSY particle is the gravitino. The next-to-lightest particle (NLSP) decay only trough gravitational interactions and may live longer than the time-of-flight across the detector.
- **Split SUSY:** scalars are much heavier than the electroweak scale. The gluino decays trough virtual squarks, and may live longer than the time of flight across the detector.
- **R-parity violation:** the neutralino decays. Less missing energy and more jets or other particles.
- **Light stop models:** a scalar top with 120-150 GeV mass is still allowed.

Each scenario is covered by dedicated search strategies. I will discuss the GMSB scenario here…

GMSB Model (1)

- Gauge Mediated Supersymmetry Breaking.
  Models for SUSY breaking, alternative to **mSUGRA**
- SUSY breaking transmitted from Hidden sector to visible sector via gauge interactions ("messengers")
- Why interesting?
  - more natural suppression of FCNC
  - not huge σ but clear signature to claim early discovery or exclusion
    - $\sigma \sim 0.1 \div 1$ pb (model dependent)

Par.	Description
Λ	SUSY breaking scale
M_m	Messenger mass scale
$\tan\beta$	Ratio of Higgs vev
N_m	Number of SU(5) messenger multiplets
sign(μ)	μ from Higgs sector
C_{grav}	Sets NLSP lifetime

- LSP is the **Gravitino** ($m \leq$ keV)
  - light, stable and weakly interacting
  - possible candidate for Dark Matter

Present limits: Tevatron, $\Lambda > 80$ TeV,
m(*neutralino,chargino*) > 108, 195 GeV

GMSB Model (2)

Phenomenology depends on nature and lifetime of the second lightest state (NLSP):

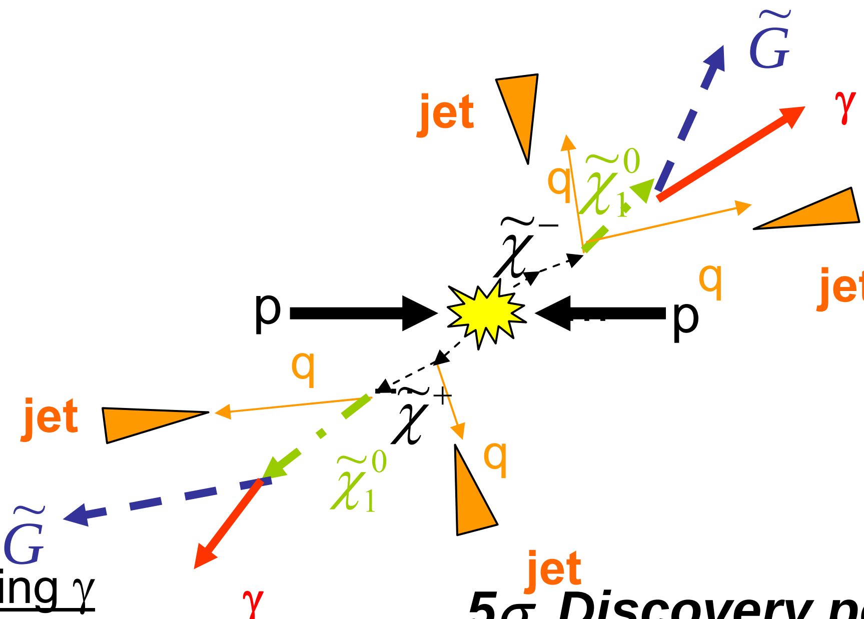
	$\tilde{\tau}$ or $\tilde{l}$ is NLSP	$\tilde{\chi}_1$ is NLSP
cτ >> L	**Like an heavy μ**	**Like mSUGRA**
cτ ≈ L	**NLSP decays in the detector, lifetimes measurements.**	
cτ << L	Decays into 2 τ	Decays into 2 γ

- **τ trigger and reconstruction** in early data not trivial
- **Decay into 2γ promising** (good ECAL performance early enough?)
- **Lifetime measurements**: need to understand **vertexing** in early data
  - For longer lifetimes, need to understand **background:**
    - Hard radiation from high-p_T cosmic muons
    - Delayed hadronic showers (K^0_L and neutrons)

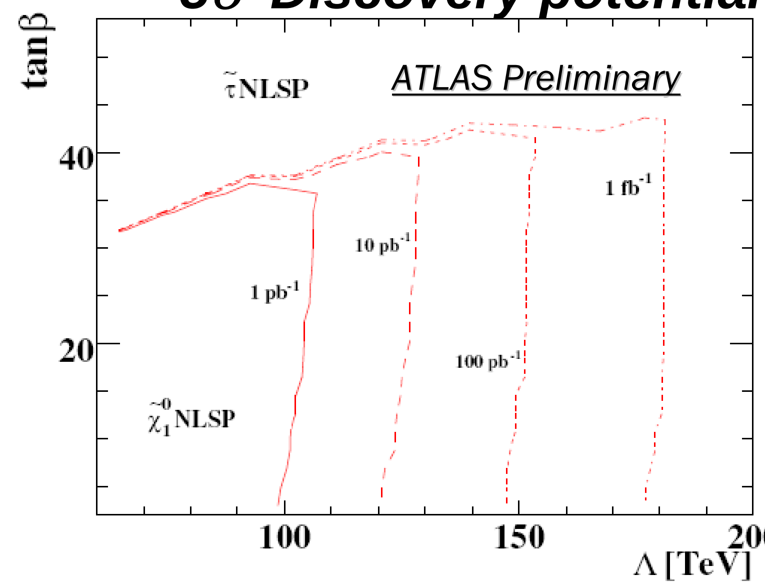
MET
+ photons

GMSB Model: Performances (1)

- If NLSP is **neutralino** $\Rightarrow$ 2γ in event
- Selection
  - γ, isolation, $P_T > 80$ GeV
  - High MET, $N_{jets} > 3$
- Main backgrounds
  - γ+jets
  - W+jets
- If lifetime(χ) $\neq$ 0 $\Rightarrow$ non-pointing γ $\Rightarrow$ possible to extract **lifetime**



5σ Discovery potential

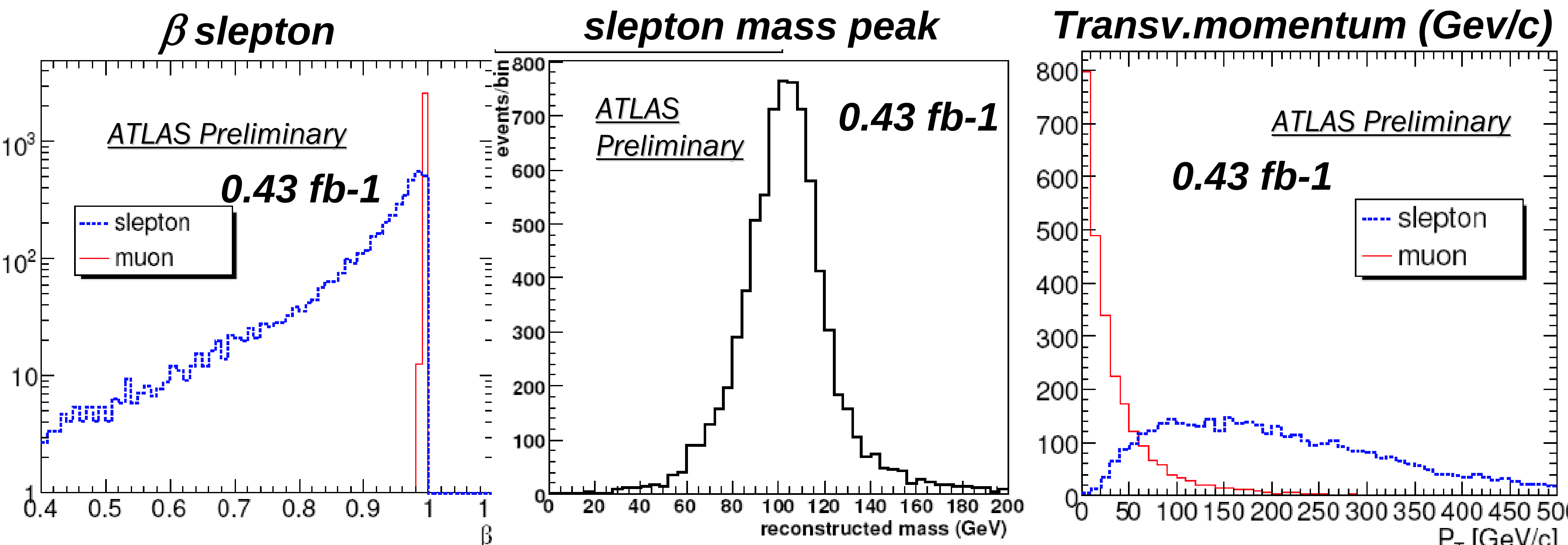


MET tails critical for early discoveries

- Trigger efficiency (combining jet, MET and photon triggers) seems not a problem at 10^33 luminosity menus.
- Possible bias in lifetime measure from identification and reconstruction cuts for photons.

GMSB Model: Performances (2)

- Heavy slow "stable" leptons can be tagged with Time-Of-Flight measurements in muon drift tubes.
- Large calorimetric E^{T}_{MISS} due to quasi-stable leptons, like in mSUGRA.
- Timing/triggering issues most critical (association to the correct BCID problematic if $\beta < 0.7$, recoverable with MDT but specific algorithm for long-lived heavy particles will be useful).

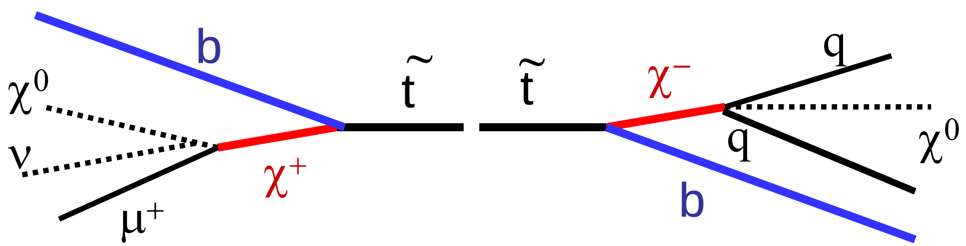


$$\Lambda = 30TeV, M_m = 250TeV, N_m = 3, \tan\beta = 5, sign(\mu) = +, C_{grav} = 4$$

$$m(q,g) \approx 700GeV \quad m(\chi) \approx 114\ GeV \quad m(l) \approx 102\ GeV \quad \sigma = 23\ pb$$

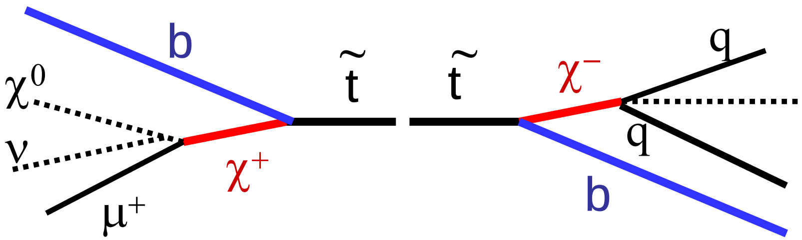
Light stop scenario

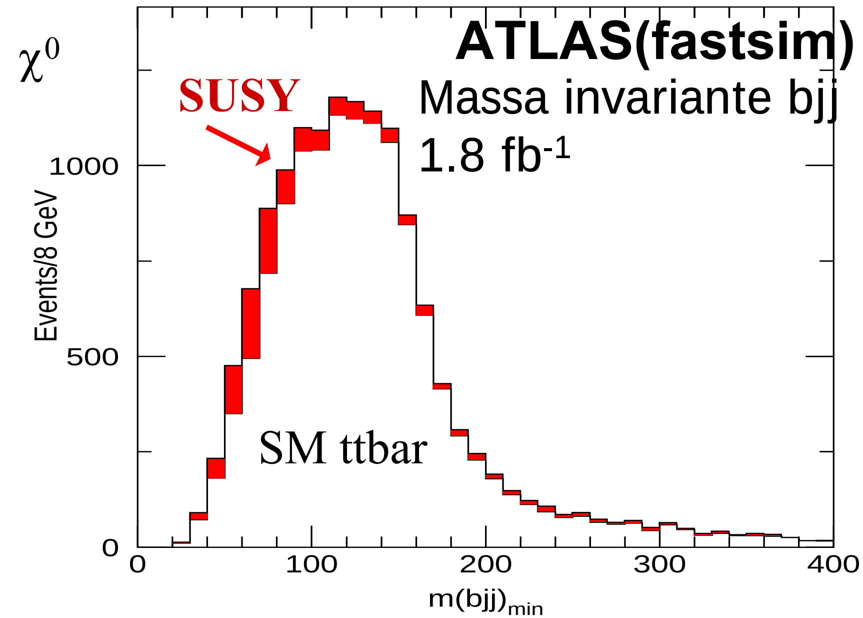
- Direct limits allows the scalar top to be lighter than top
- There are models which explain baryogenesis (the generation of matter-antimatter asymmetryof the Universe) and Dark Matter at once using SUSY
  - Give up SUGRA-like unification of SUSY masses
  - Require a very light stop
  - … and of course CP violation
- Consider direct production stop pairs:



- Looks a lot like top pair production
  - Cross section is comparable (400 pb for a 140 GeV stop)
  - Same final state, but "wrong" invariant mass combination (no W, top peak)
  - Still two unobserved neutralinos: no mass peak!
  - Softer leptons, jets and missing energy than in ttbar
  - Biggest problem is ttbar background

Search for light stop (I)





Event selection:

4 jets with $p_T > 25$ GeV

$E_T^{miss} > 20$ GeV

1 elec. or muon with pt>20 GeV

M(jj) < 60 GeV (veto on W → jj)

Distribution of interest: M(jjb), M(lb)

The signal is "visible" on top of the SM background if we assume we know (from Montecarlo predictions) how many SM events (and the shape of distribution) pass event selection on average.

Since we may not trust the MC prediction to this level of accuracy, we developed a technique to estimate the shape of the SM contribution to the distribution.

Once we know the shape, we can fix the normalization of the background using the events at large invariant mass, where no SUSY contribution is expected.

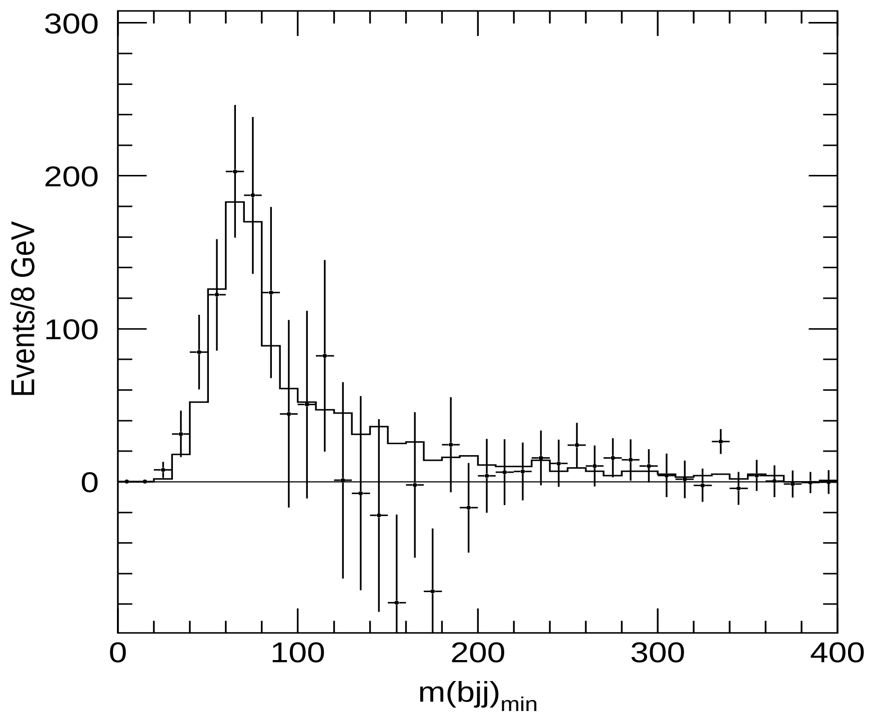
Search for light stop (II)

We developed a technique to estimate the ttbar bckg from data:

Control sample 1: tight extra cuts on hadronic side [M(jjb) = m(top), M(jj)=M(W)] select ttbar
- Used to measure shape of M(bl) in ttbar events

Control sample 2: tight cuts on leptonic side [M(lb,xEt) = M(top)] to select ttbar
-Used to measure shape of M(bjj) in ttbar events

Signal visible after background subtraction with ~1 fb^{-1}



Solid line: SUSY events among those passing event selection
Points: Measured distribution, after subtracting the SM contribution estimated with control samples
It works!

mSUGRA models

- **A random choice of the 105 MSSM parameters violates limits** from B/D/K physics, electric dipole moments, FCNC, …
- **Need** some **assumption** on the structure **of SUSY breaking lagrangian**. In **mSUGRA** (5 free parameters, most studied by ATLAS and CMS):
  - **Conserved R-parity**
  - **Common mass** m_0 for susy scalars, $m_{1/2}$ for fermions (at GUT scale).
  - **Common value** A_0 for the trilinear coupling of the s-fermions with the 2 Higgs doublets.

Then 5 free parameters: $m_0, \; m_{1/2}, \; A_0, \; \tan\beta, \; \mathrm{sgn}\,\mu$

Further constraints if it is required that the Big Bang has produced the right amount of stable neutralinos to explain observed Dark Matter density

May be too constrained. Experiments at colliders are interested mostly in identify signatures to develop and study search strategies

Supersymmetry: what is?

Supersymmetry (SUSY) in a nutshell

Standard particles	***Superpartners***
Quarks, leptons, neutrinos (spin 1/2)	Squarks, sleptons, sneutrinos (spin-0)
W, Z, gluino (spin-1)	Wino, zino, gluino (spin 1/2)
Higgs (spin-0)	Higgsino (spin ½)

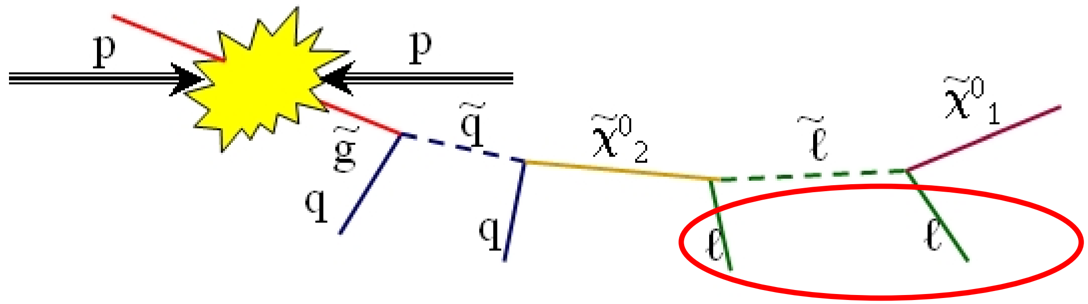
At least two Higgs doublets are needed → **five Higgs bosons**
Wino, Zino, Higgsino mix → 4 charged (chargino) and 4 neutral (neutralino) states

SUSY particles not observed yet → must be heavy → **symmetry is broken**

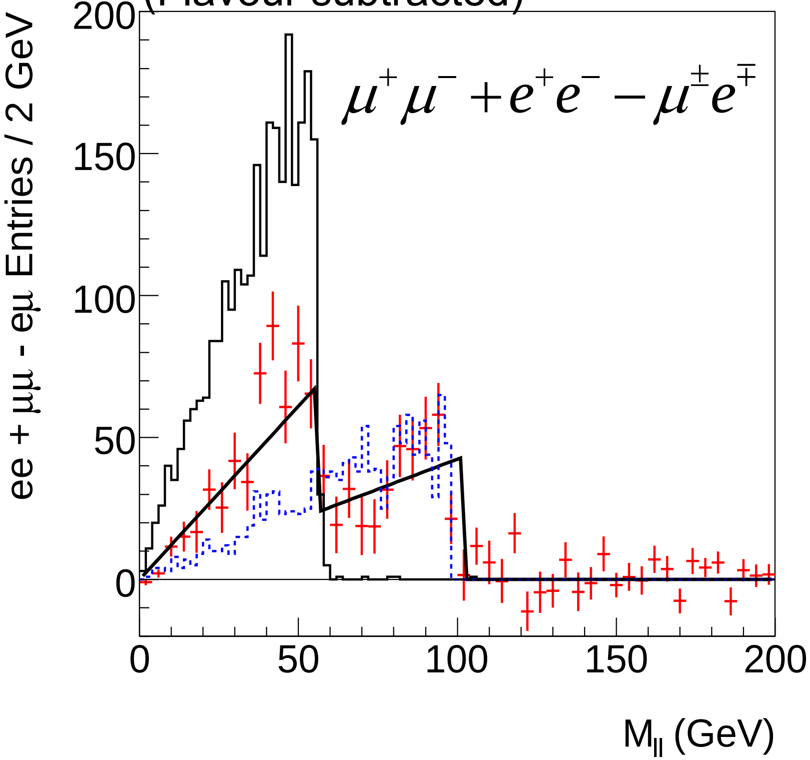
It is possible to put directly SUSY mass terms in the lagrangian. This gives about **100 free parameters** with the minimal field content above (MSSM model)

Constrained models (with assumptions on the structure of SUSY breaking) have only a few parameters – but assumptions may be wrong.

Kinematical structures



Same-Flavour Other-sign
Lepton combinations.
(Flavour subtracted)



The invariant mass of the two leptons has a kinematical endpoint which measures:

$$M_{ll}^{\max} = M(\tilde{\chi}_2^0)\sqrt{1-\frac{M^2(\tilde{l}_R)}{M^2(\tilde{\chi}_2^0)}}\sqrt{1-\frac{M^2(\tilde{\chi}_1^0)}{M^2(\tilde{l}_R)}}$$

It may be possible to observe two edges, if both decays are open:

$$\chi_2^0 \rightarrow l\tilde{l}_L \rightarrow ll\chi_1^0$$
$$\chi_2^0 \rightarrow l\tilde{l}_R \rightarrow ll\chi_1^0$$

The SM and SUSY combinatorial backgrounds have two leptons from independent decay chains. The background cancel in the flavour subtraction

Getting mass peaks

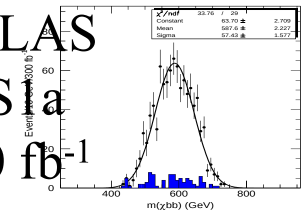
- The 4-momentum of the χ^0_2 can be reconstructed from the approximate relation

$$p(\chi^0_2) = (\, 1 - m(\chi^0_1)/m(ll)\,)\, p_{ll}$$

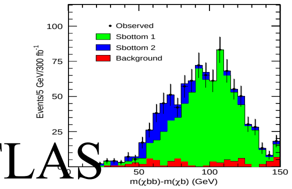
valid when m(ll) near the edge.

- The χ^0_2 can be combined with b-jets to reconstruct the gluino and sbottom mass peaks from $\tilde{g} \rightarrow b\tilde{b} \rightarrow bb\chi^0_2$

ATLAS
SPS1a
300 fb^{-1}



m(χbb) (GeV)



ATLAS
SPS1a
300 fb^{-1}

m(χbb)-m(χb) (GeV)

SPS1a, 300 fb^{-1}, stat. errors only:

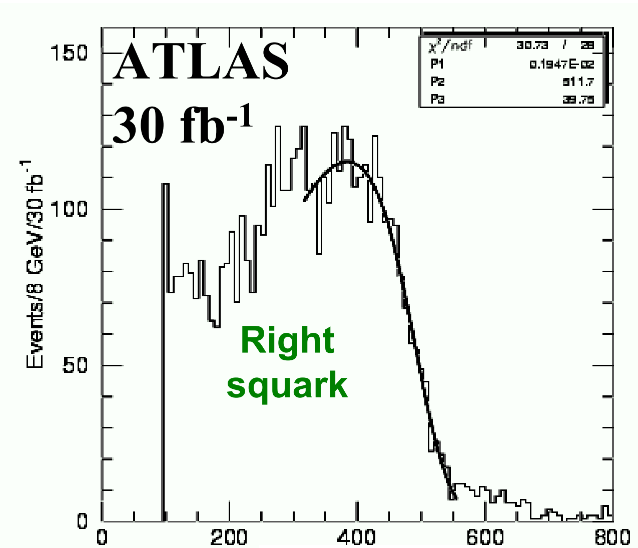
$m(\tilde{g}) - 0.99\, m(\chi^0_1) = (500.0 \pm 6.4)$ GeV

$m(\tilde{g}) - m(\tilde{b}_1) = (103.3 \pm 1.8)$ GeV

$m(\tilde{g}) - m(\tilde{b}_2) = (70.6 \pm 2.6)$ GeV

Other mass measurements

$q_R \rightarrow \chi^0_1 q$



MT2 (GeV)

2 hard jets and lots of E_T^{miss}.

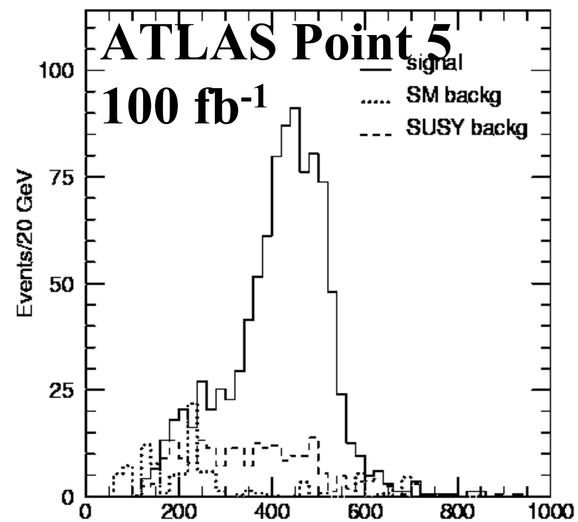
Reconstruct with

$$M_{T2}^2 = \min_{\not p_1 + \not p_2 = \not p_T} \left[\max \left\{ m_T^2(p_T^{\ell_1}, \not p_1), m_T^2(p_T^{\ell_2}, \not p_2) \right\} \right]$$

$m(\tilde{q}_R) - m(\chi^0_1) = (424.2 \pm 10.9)$ GeV

Also works for sleptons.

$q_L \rightarrow \chi^0_2 q \rightarrow \chi^0_1 hq \rightarrow \chi^0_1 bbq$



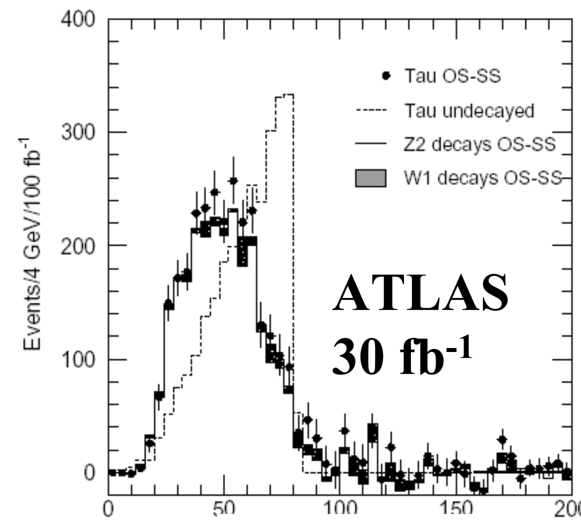
M(bbq) (GeV)

Two body decay of χ^0_2 to higgs and χ^0_1.

Reconstruct higgs mass (2 b-jets) and combine with hard jet.

Get additional mass constraint.

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



M(ττ) (GeV)

Tau decay dominates neutralino BR at large tanβ.

No sharp edge because of ν, but end-point can still be measured.

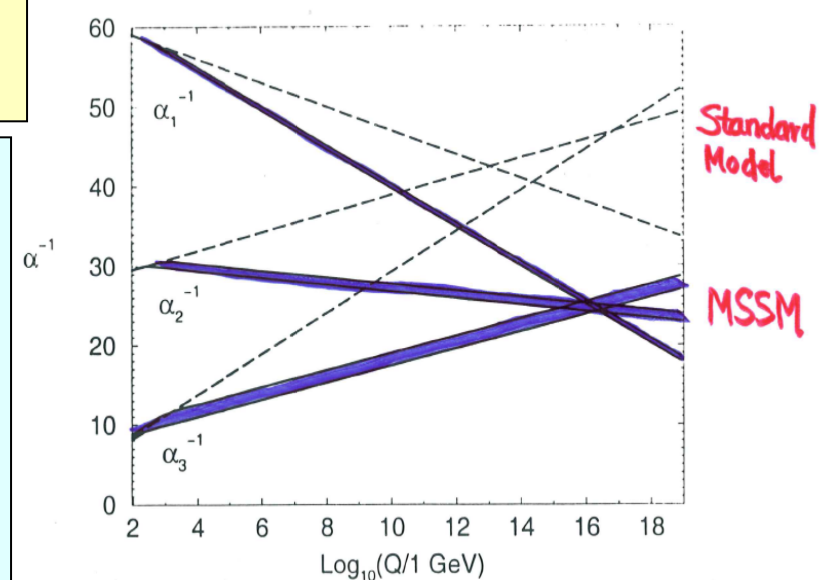
Supersymmetry: why?

Supersymmetry can solve several problems of the Standard Model at once

Hierarchy problem:
- Fermions and bosons contribute with opposite sign to the Higgs mass
- $\delta m_H \sim m_{SUSY}$ [SUSY mass scale]
- Hierarchy ok if SUSY masses near the Higgs scale (**accessible to a TeV-scale collider)**

True also for other SM extensions addressing hierarchy.
The TeV-scale new physics and the Higgs are the main motivations for the Large Hadron Collider

Unification of forces:
Better convergence of interaction strength as a function of energy



Dark Matter
Need a conserved quantum number to avoid proton decay: R = +1 for SM particles, R = - 1 for SUSY particles. Consequences:
- **SUSY particles are produced in pairs**
- The **lightest SUSY particle is stable**. If weakly interacting, it's a good candidate for Dark Matter

HT2 method

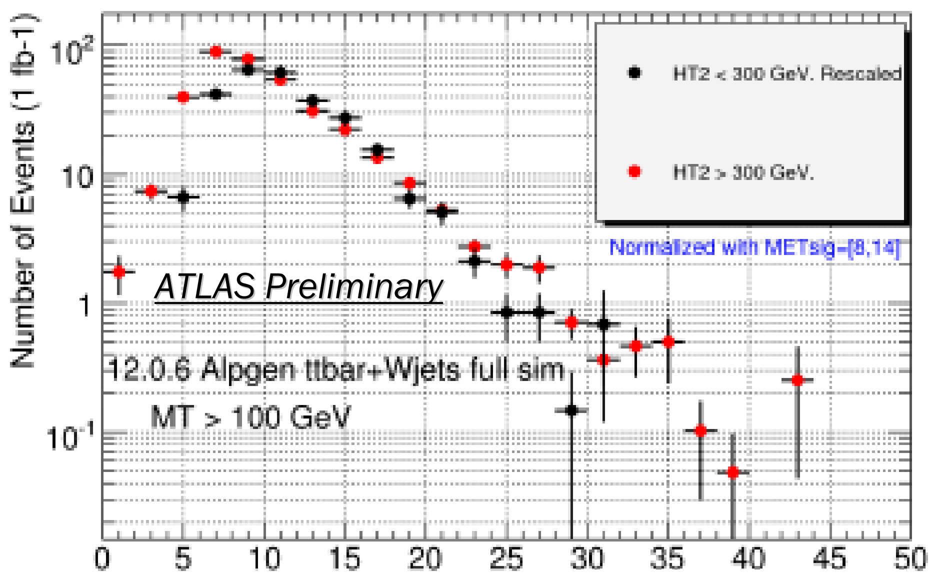
An other variable which has small correlation with MET is

$$HT2 \equiv \sum(\text{pt jets } 2,3,4) + \sum(\text{pt } e,\mu)$$

- leading jet is not included in order to avoid correlation with MET
- use MET significance rather than MET to reduce correlation

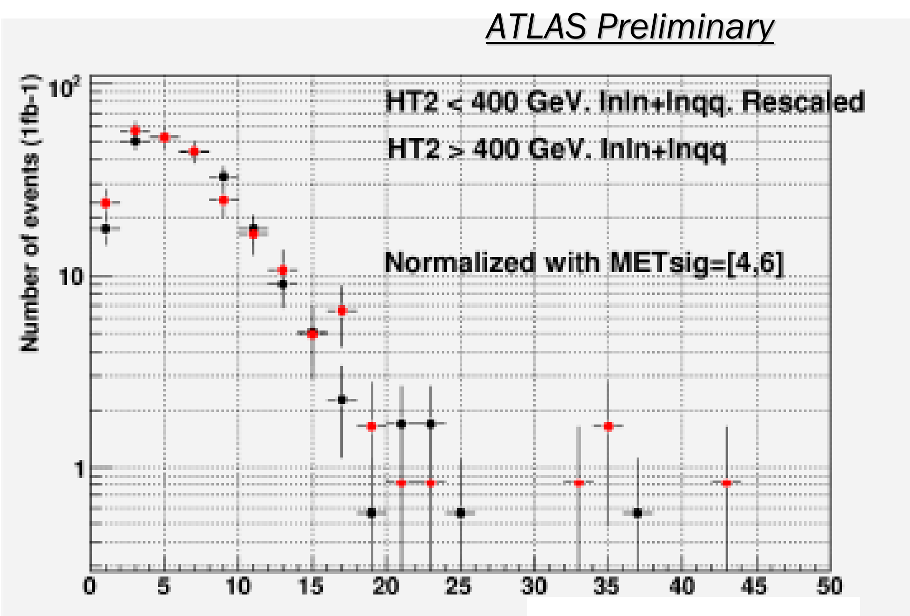
one lepton mode

ttbar (ℓνℓν and ℓνqq), W(eν)+jets, W(μν)+jets



$MET/0.49\sqrt{\sum E_T}$

also works for **OS di-lepton mode**

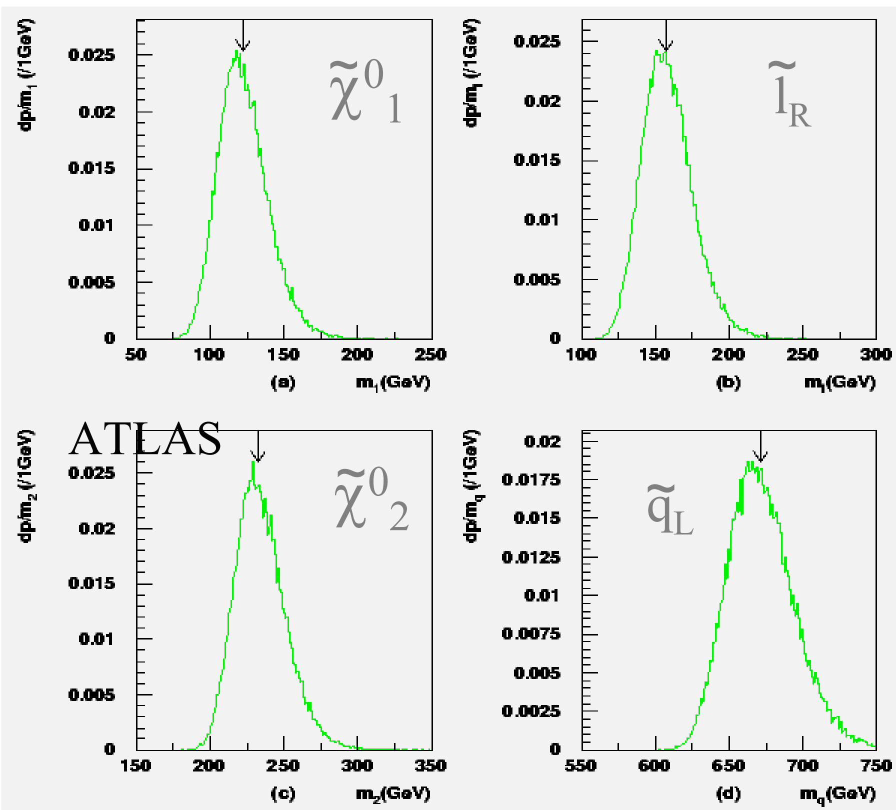


$MET/0.49\sqrt{\sum E_T}$

MET/0.49sqrt(etsum)

Getting SUSY particle masses

- Combine measurements from edges of different jet/lepton combinations to obtain ‘model-independent’ mass measurements.
- LSP mass uncertainty large, all other masses strongly correlated with it. A future Linear Collider measurement of χ^0_1 mass would improve the precision on all masses.



masses (GeV)	LHCC5	SPS1a
$m(\tilde{\chi}^0_1)$	122	96
$m(\tilde{l}_R)$	157	143
$m(\tilde{\chi}^0_2)$	233	177
$m(\tilde{q}_L)$	687-690	537-543

Sparticle	Expected precision (100 fb^{-1})
$\tilde{q}_L$	± 3%
$\tilde{\chi}^0_2$	± 6%
$\tilde{l}_R$	± 9%
$\tilde{\chi}^0_1$	± 12%

From masses to model parameters

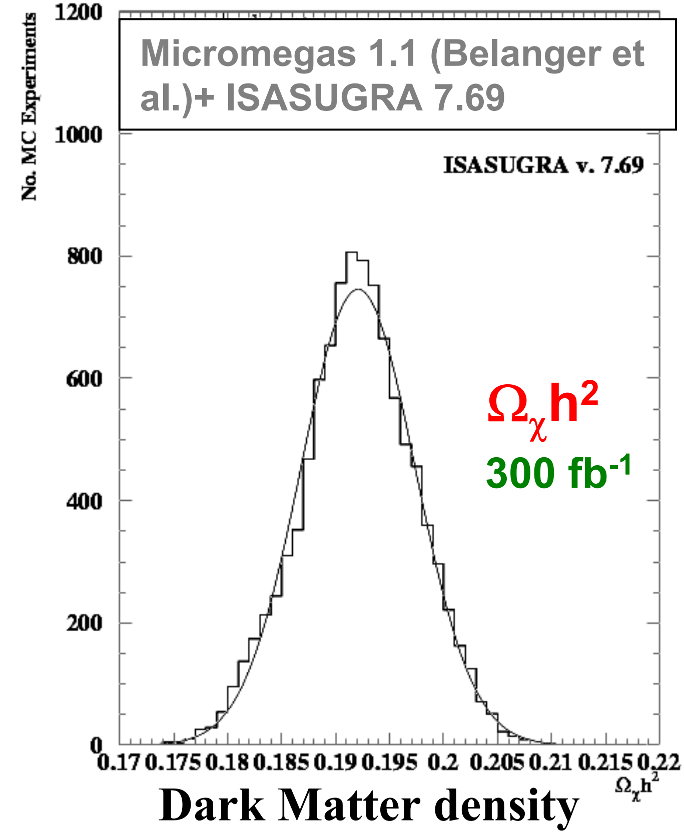
From a given set of measurements one scans the **parameter space** and finds the points compatible with data. These points are fed to relic density calculators to get constraints on **neutralino dark matter abundance**

Variable	Value (GeV)	Errors Stat. (GeV)	Scale (GeV)	Total
$m_{\ell\ell}^{max}$	77.07	0.03	0.08	0.08
$m_{\ell\ell q}^{max}$	428.5	1.4	4.3	4.5
$m_{\ell q}^{low}$	300.3	0.9	3.0	3.1
$m_{\ell q}^{high}$	378.0	1.0	3.8	3.9
$m_{\ell\ell q}^{min}$	201.9	1.6	2.0	2.6
$m_{\ell\ell b}^{min}$	183.1	3.6	1.8	4.1
$m(\ell_L) - m(\tilde{\chi}_1^0)$	106.1	1.6	0.1	1.6
$m_{\ell\ell}^{max}(\tilde{\chi}_4^0)$	280.9	2.3	0.3	2.3
$m_{\tau\tau}^{max}$	80.6	5.0	0.8	5.1
$m(\tilde{g}) - 0.99 \times m(\tilde{\chi}_1^0)$	500.0	2.3	6.0	6.4
$m(\tilde{q}_R) - m(\tilde{\chi}_1^0)$	424.2	10.0	4.2	10.9
$m(\tilde{g}) - m(\tilde{b}_1)$	103.3	1.5	1.0	1.8
$m(\tilde{g}) - m(\tilde{b}_2)$	70.6	2.5	0.7	2.6

$\Omega_\chi h^2 = 0.1921 \pm 0.0053$

$\log_{10}(\sigma_{\chi p}/pb) = -8.17 \pm 0.04$

Parameter	Expected precision (300 fb^{-1})
m_0	± 2%
$m_{1/2}$	± 0.6%
$\tan(\beta)$	± 9%
A_0	± 16%



How much data will we need?

Statistical reach with 100 pb^{-1} is in the TeV region, well beyond Tevatron limits (~400 GeV) BUT

- **only in a few cases SUSY has distinctive kinematical features**
- **main selection tool at both trigger and analysis level is to select event with large missing Et, difficult to muster experimentally**

More luminosity (for control samples) and/or time may be needed to understand backgrounds

Let's go back to detector commissioning and SM background studies…