Lecture 1: Discovering SUSY

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Introduction:LHC and new physics

With LHC open the TeV scale to experimentation

From theoretical speculations expect to find signals for physics beyond SM

In the past years many studies of possible extensions of SM

For many models studied, large production cross-section, expect enough statistics for discovery in few weeks of data taking

In the initial phase long time and large amount of work in order to:

- Master the performance of very complex detectors
- Understand and Control Standard Model backgrounds

I will illustrate these issues applied to SUSY, leading new physics candidate

Introduce the topic with a quick overview of the startup strategy developed to make optimal use of early data, followed by a reminder of main features of SUSY

Experimental start-up strategy

- Last few years: extensive test-beam activities with final detector components to achieve basic calibration. e.g. ATLAS combined test-beam of full detector slice
- Now, extending up to most of 2007: Cosmics data taking. Detector timing and alignment
- From first injections: beam-halo and beam-gas interactions. More specialised alignment work
- First interactions:
  - Understand and calibrate detector and trigger in situ using well-known physics samples:
    - $Z \to ee, \mu\mu$: tracker, ECAL, muons system
    - $tt \to b\ell\nu bjj$: Jets scale, b-tag performance, $\not{E}_T$
  - Understand basic SM physics at 14 TeV: first checks of MonteCarlo
    - jets and W, Z cross-section/ratios top mass and cross-section
    - Event features: Min. bias, jet distributions, PDF constraints
  - Prepare road to discovery: background to discovery from tt, W/Z + jets.

Mandatory to demonstrate that we understand LHC physics through SM measurements before going for discovery physics

Why physics beyond the Standard Model?

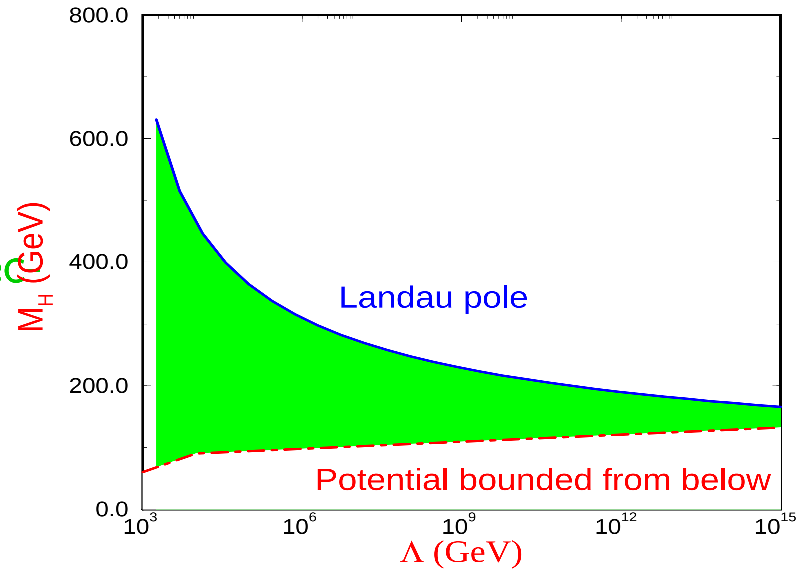
- Gravity is not yet incorporated in the Standard Model
- Hierarchy/Naturalness problem

Standard Model only valid up to scale $\Lambda < M_{pl}$

(ex: M_H =115 GeV $\Rightarrow \Lambda < 10^6$ GeV)

Higgs mass becomes unstable to quantum corrections: from sfermion loops,

$$\delta m_H^2 \propto \lambda_f^2 \Lambda^2$$

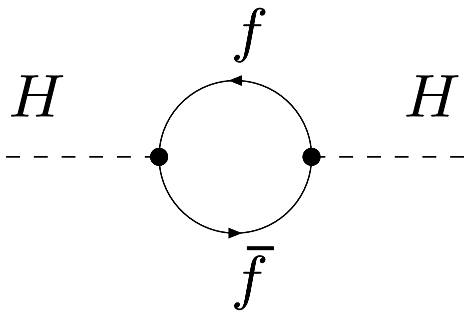


- Additional problems: Unification of couplings, Flavour/family problem

Need a more fundamental theory of which SM is low-E approximation

Naturalness problem and SUSY

Problem: correction to higgs mass from fermion loop (coupling -$\lambda_f H \bar{f} f$):



$$\Delta m_H^2 \sim \frac{\lambda_f^2}{4\pi^2}(\Lambda^2 + m_f^2) + ...$$

Where Λ is high-energy cutoff to regulate loop integral.

If $\Lambda \sim M_{Planck} \sim 10^{18}$ GeV radiative corrections explode

Correction from scalar $\tilde{f}$, loop with coupling $-\lambda_{\tilde{f}}^2 H^2 \tilde{f}^2$, is

$$\Delta m_H^2 \sim -\frac{\lambda_{\tilde{f}}^2}{4\pi^2}(\Lambda^2 + m_{\tilde{f}}^2) + ...$$

Corrections have opposite sign, and cancel each other

Full cancellation of divergences if for N_f fermionic degrees of freedom one has $N_{\tilde{f}}$ scalars such that: $\lambda_{\tilde{f}}^2 = \lambda_f^2$ and $m_{\tilde{f}} = m_f$

Achieved in theory where lagrangian is invariant under transformation Q:

$$Q|\text{boson}\rangle = |\text{fermion}\rangle \qquad Q|\text{fermion}\rangle = |\text{boson}\rangle \qquad \Rightarrow \text{SUSY}$$

General class of theories, specialise studies to minimal model: MSSM

Minimal Supersymmetric Standard Model (MSSM)

Minimal particle content:

- A spin $\Delta J = \pm 1/2$ superpartner for each Standard Model particle
- Two higgs doublets with v.e.v's v_1 and v_2 and superpartners. After EW symmetry breaking: 5 Higgs bosons: $h,\ H,\ A,\ H^\pm$

If SUSY is unbroken, same mass for ordinary particles and superpartners

No superpartner observed to date

SUSY explicitly broken by inserting in the lagrangian all "soft" breaking terms

The model has 105 free parameters (!)

Additional ingredient: R-parity conservation: $R = (-1)^{3(B-L)+2S}$:

- Sparticles are produced in pairs
- The Lightest SUSY Particle (LSP) is stable

Impose phenomenological constraints (e.g FCNC suppression) to reduce SUSY breaking parameters. End up with 15-20 parameters

Soft parameters are three gaugino masses (M_1, M_2, M_3), higgsino mass (μ), $\tan\beta \equiv v_1/v_2$, sfermion masses, tri-linear couplings A.

Resulting physical spectrum:

quarks	$\longrightarrow$	squarks	$\tilde{q}_L$, $\tilde{q}_R$	
leptons	$\longrightarrow$	sleptons	$\tilde{\ell}_L$ $\tilde{\ell}_R$	
$W^\pm$	$\longrightarrow$	winos	$\tilde{\chi}^\pm_{1,2}$	charginos
$H^\pm$	$\longrightarrow$	charged higgsinos	$\tilde{\chi}^\pm_{1,2}$	charginos
γ	$\longrightarrow$	photino	$\tilde{\chi}^0_{1,2,3,4}$	neutralinos
Z	$\longrightarrow$	zino	$\tilde{\chi}^0_{1,2,3,4}$	neutralinos
g	$\longrightarrow$	gluino	$\tilde{g}$	

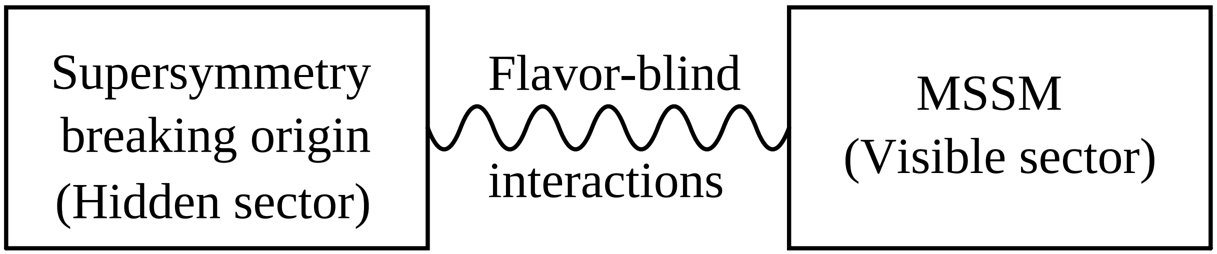
For each fermion f two partners $\tilde{f}_L$ and $\tilde{f}_R$ corresponding to the two helicity states

Charginos and neutralinos result from the mixing of gauginos and higgsinos

Need to measure masses of all neutralinos/charginos to reconstruct soft breaking parameters

Models of SUSY breaking

Spontaneous breaking not possible in MSSM, need to postulate hidden sector



Phenomenological predictions determined by messenger field:

Three main proposals, sparticle masses and couplings function of few parameters

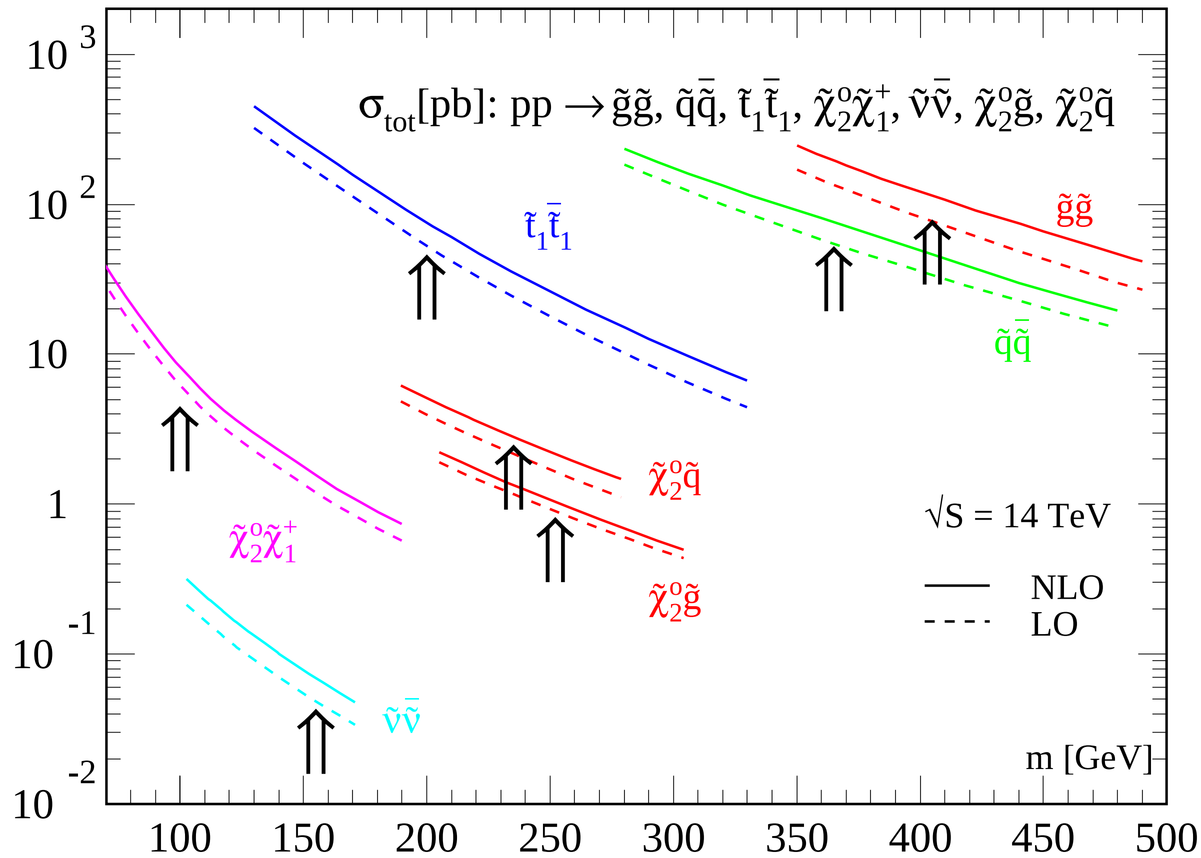
- Gravity: mSUGRA. Parameters: $m_0,\ m_{1/2},\ A_0,\ \tan\beta,$ sgn μ
- Gauge interactions: GMSB. Parameters: $\Lambda = F_m/M_m$, M_m, N_5 (number of messenger fields) $\tan\beta$, $sgn(\mu)$, C_{grav}
- Anomalies: AMSB. Parameters: $m_0,\ m_{3/2},\ \tan\beta,\ sign(\mu)$

Main task of experimental work: measure soft breaking parameters, from observed pattern of parameters constrain the possible SUSY breaking mechanisms

SUSY at the LHC: general features

Sparticles have same couplings of SM partners $\Rightarrow$ production dominated by colored sparticles: squarks and gluinos if light enough

Squark and gluino production cross-section $\sim$ only function of squark and gluino mass



Production cross-section $\sim$ independent from details of model:

- $\sigma_{SUSY} \sim 50$ pb for $m_{\tilde{q},\tilde{g}} \sim 500$ GeV
- $\sigma_{SUSY} \sim 1$ pb for $m_{\tilde{q},\tilde{g}} \sim 1000$ GeV

Features of SUSY events at the LHC

Broad band parton beam: all processes on at the same time: different from e^+e^- colliders where one can scan in energy progressively producing heavier particles

Bulk of SUSY production is given by squarks and gluinos, which are typically the heaviest sparticles

$\Rightarrow$ If R_p conserved, complex cascades to undetected LSP, with large multiplicities of jets and lepton produced in the decay.

Both negative and positive consequences:

- Many handles for the discovery of deviations from SM, and rich and diverse phenomenology to study
- Unraveling of model characteristics will mostly rely on identification of specific decay chains: difficult to isolate from the rest of SUSY events

SUSY is background to SUSY!

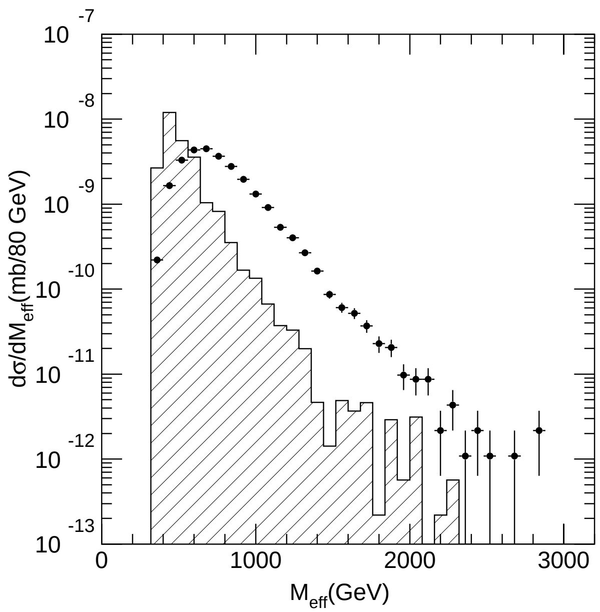
First step on inclusive SUSY: triggering

ATLAS inclusive approach: $\not{E}_T + 1$ jet and multi-jet triggers

Keep lowest threshold compatible with affordable rate.

- high signal efficiency
- possibility of more detailed background studies

Ex. $\not{E}_T > 70$ GeV, 1 Jet with $E_T > 70$ GeV. Rate ~20 Hz at 2×10^{33} cm^{-2}s^{-1}.



Example:Point with m($\tilde{q}$, $\tilde{g}$)=400 GeV

Require $\not{E}_T > 80$ GeV, 1 Jet $E_T > 80$ GeV

Plot:

$$M_{\text{eff}} \equiv \sum_i |p_{T(i)}| + E_T^{\text{miss}}$$

With higher cuts the signal turn on would not be observable

In addition: flexible array of trigger selections helps to cover with high efficiency wealth of SUSY signatures

Trigger menu table

Object	Physics coverage	Object name
electrons	Higgs, new gauge bosons, extra dim., SUSY, W/Z, top	e25i, 2e15i, e60
Photons	Higgs, SUSY, extra dim.	γ60, 2γ20i
Muons	Higgs, new gauge bosons, extra dim., SUSY, W/Z, top	μ20i, 2μ10
Jets	SUSY,compositness,resonances	j400, 3j165, 4j110
Jets+missEt	SUSY, leptoquarks	j70+xE70
Tau+missEt	Extended Higgs models (e.g. MSSM), SUSY	τ35i+xE45

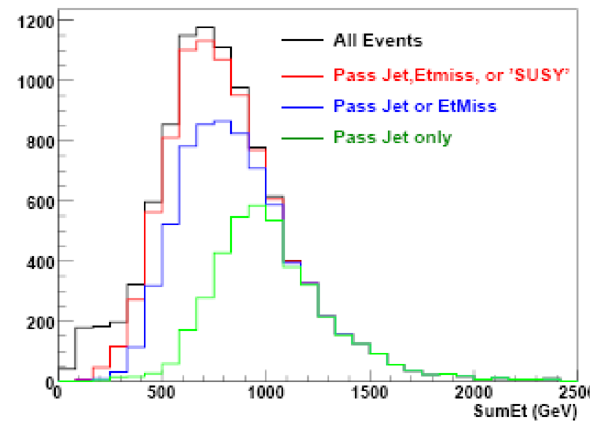
SUSY events are complex with many physics objects. triggered by many items

Example: efficiency for specific SUSY model

Focus on mSUGRA point with $m(\tilde{g}) \sim m(\tilde{q}) \sim 600$ GeV

Evaluate efficiency for different components of jet trigger menu (K. Cramner)

trigger	Efficiency (%)
J400	34
2J350	12
3J165	13
4J110	7
xE200	63
SUSY xE70+J70	90
Only jets	43
Jet or xE	73
Anything	92



Using only jet triggers gives low efficiency

missEt and 'SUSY' trigger do most of the job!

No lepton/tau trigger included in this study.

SUSY discovery:basic strategy

SUSY covers very broad range of phenomenologies. Go for simple signatures which address general class of models

Basic assumption: discovery from squark/gluinos cascading to undetectable LSP

Most important features of SUSY events used for discovery:

- $\not\!\!E_T$: from LSP escaping detection
- High E_T jets: variables: N_{jets}, $P_T(jet_1)$, $P_T(jet_2)$ $\Sigma_i |p_{T(i)}|$ $\Delta\phi(jet - \not\!\!E_T)$

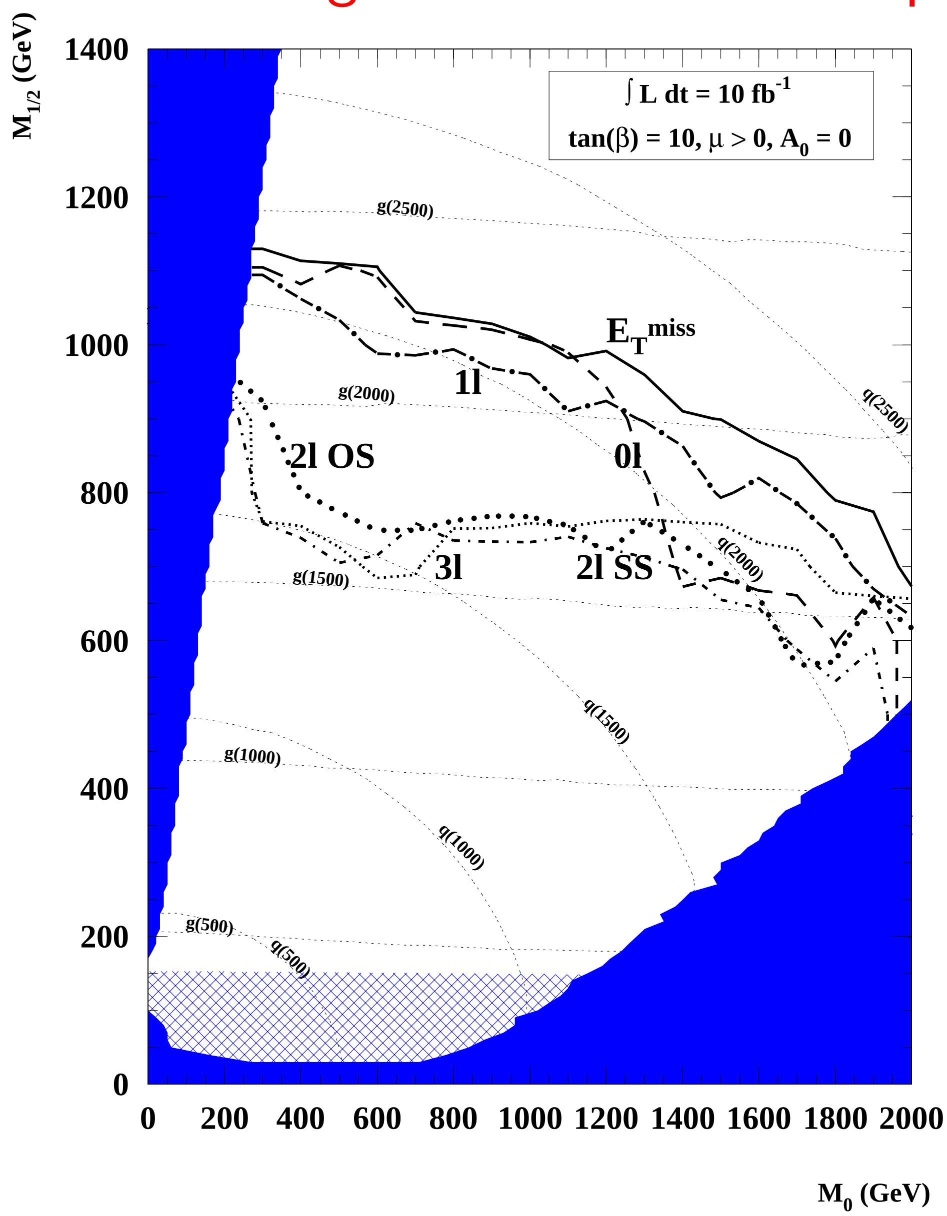
  guaranteed if squarks/gluinos not too degenerate with gauginos, e.g. if unification of gaugino masses assumed. Variables:
- Spherical events: variable S_T

  From Tevatron limits squarks/gluinos must be heavy ($\gtrsim$ 400 GeV).
- Multiple leptons: from decays of Charginos/neutralinos typically present in cascade

Define criteria on sets of basic inclusive signatures for RPC SUSY with $\tilde{\chi}_1^0$ LSP

Alternative options have often final states with additional leptons, photons, CHAMPS, easier to select.

Inclusive signatures in mSUGRA parameter space

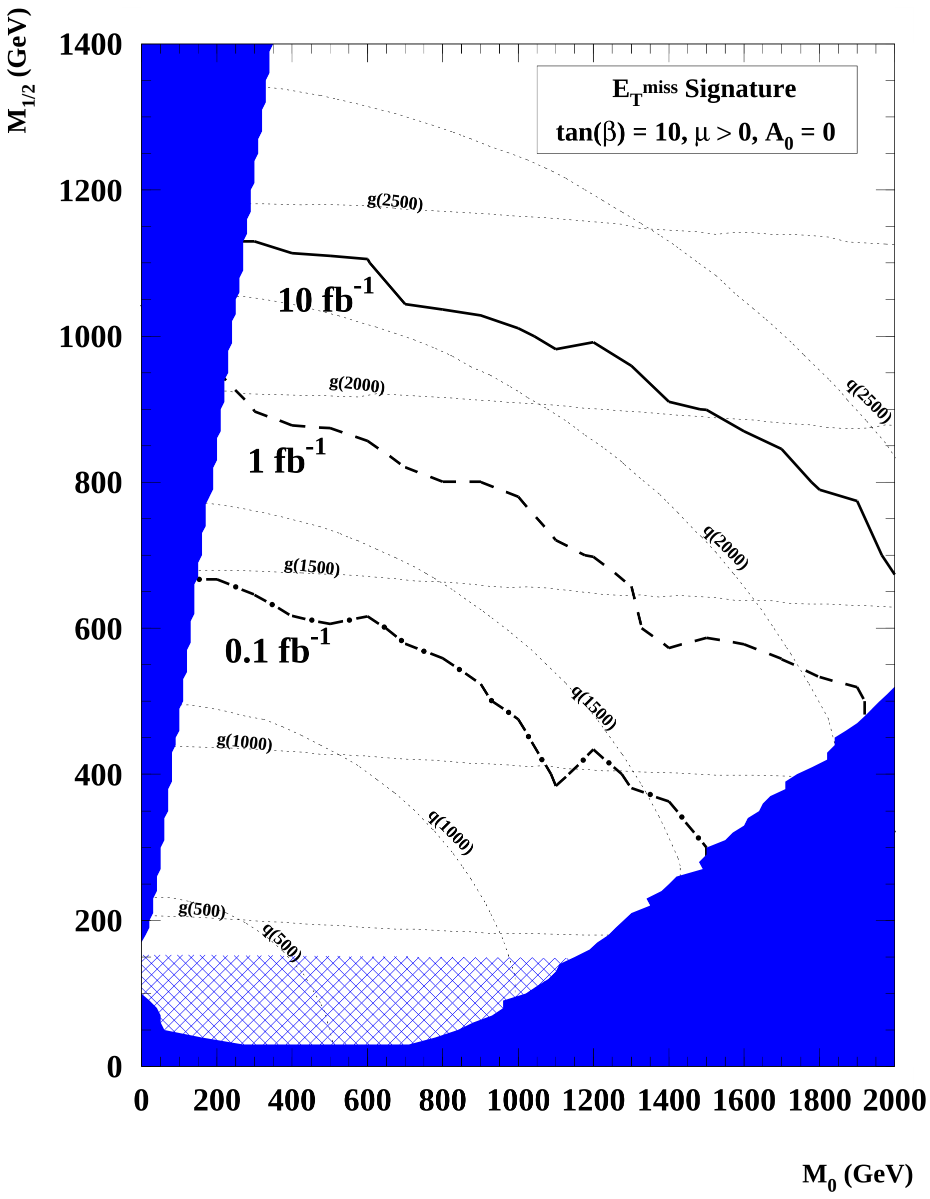


Multiple signatures on most of parameter space

- $\not\!\!E_T$ ⇐ Dominant signature
- $\not\!\!E_T$ with lepton veto
- One lepton
- Two leptons Same Sign (SS)
- Two leptons Opposite Sign (OS)

When first signal observed with a signature, look for it also in other channels

Discovery reach as a function of luminosity



- ~1300 GeV in 100 pb^{-1}
- ~1800 GeV in 1 fb^{-1}
- ~2200 GeV in 10 fb^{-1}

Fast discovery from signal statistics

Time for discovery determined by:

- Time to understand detector performance ($\not{E}_T$ tails, lepton id, jet scale)
- Time to collect sufficient statistics of SM control samples: W, Z+jets, $\bar{t}t$

Two main background classes:

- Instrumental $\not{E}_T$
- Real $\not{E}_T$ from neutrinos

Backgrounds to $\not\!\!E_T +$ jets analysis

Instrumental $\not\!\!E_T$ from mismeasured multi-jet events:

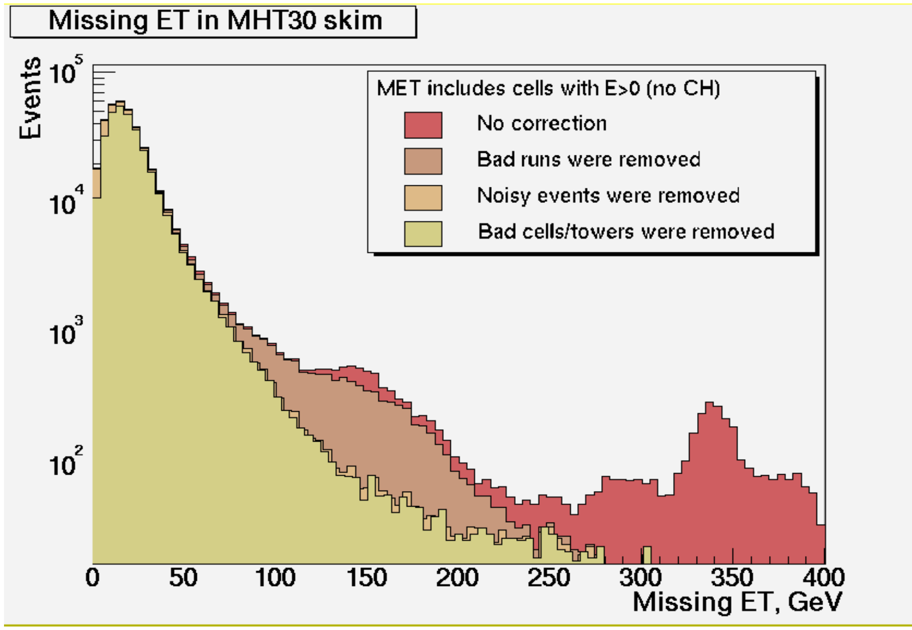
Many sources: gaps in acceptance, dead/hot cells, non-gaussian tails, etc.

Require detailed understanding of tails of detector performance.

Reject events where fake $\not\!\!E_T$ likely.

- beam-gas and machine backgrounds
- displaced vertexes
- hot cells
- $\not\!\!E_T$ pointing along jets
- jets in regions of poor response

See effect of $\not\!\!E_T$ cleaning in D0



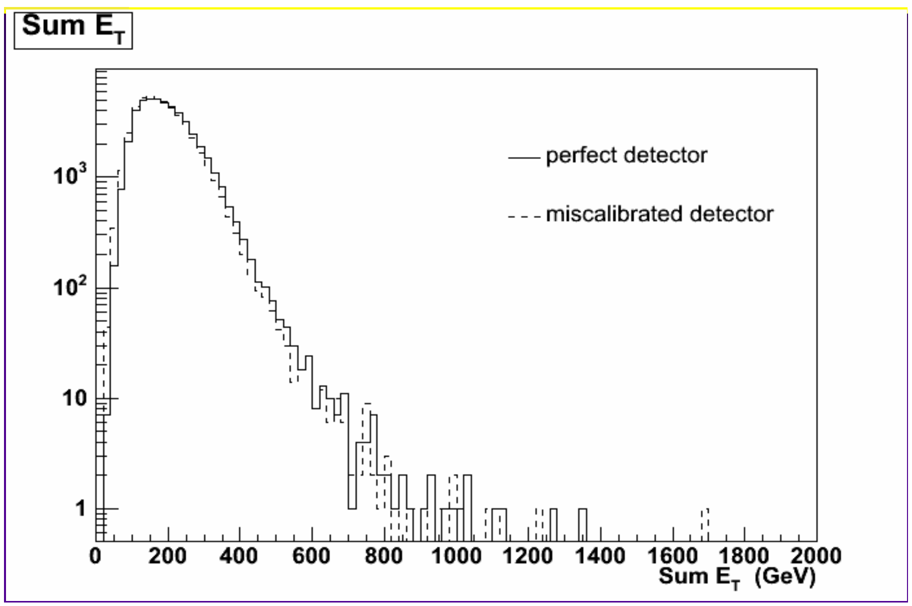
All detector and machine garbage will end up in $\not\!\!E_T$ trigger Long and painstaking work before all the sources of instrumental $\not\!\!E_T$ are correctly identified

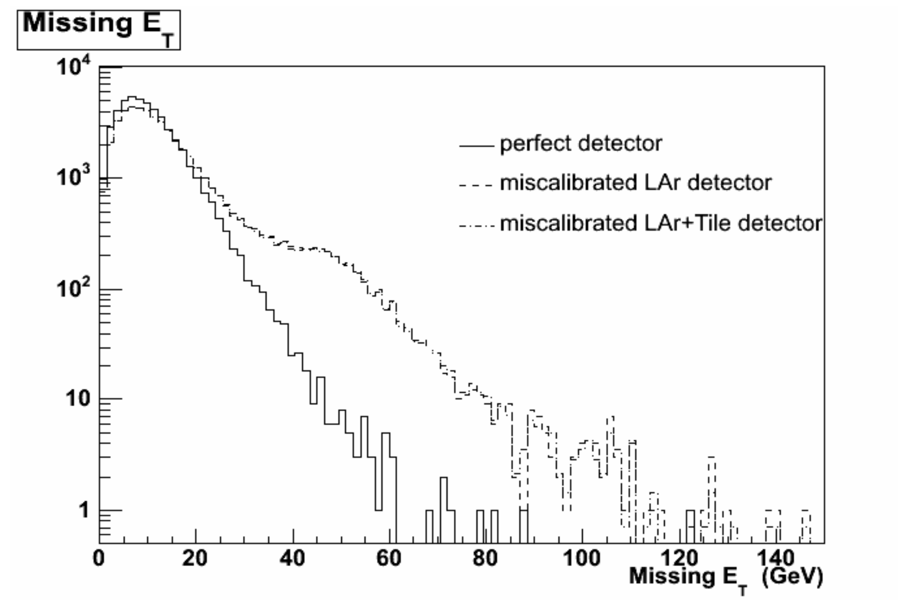
Example of LHC study: effect of dead cells

Preliminary ATLAS study (R. Mc.Pherson, K. Voss)

Assume readout of a certain number of calo cells not working. Evaluate effect on $\not{E}_T$

Apply to $Z \rightarrow ee$ sample





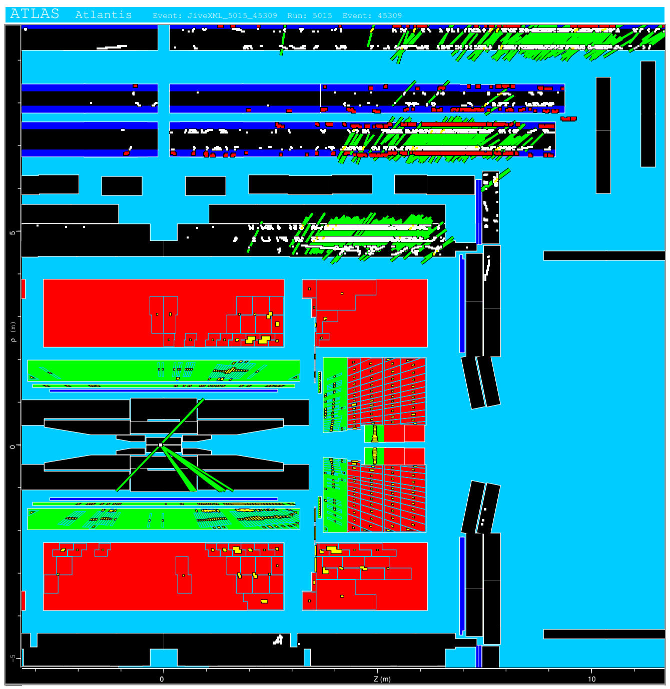
Aim of the exercise: evaluate sensitivity of $Z \rightarrow \ell\ell$ as a diagnostic of detector imperfections affecting $\not{E}_T$ studies

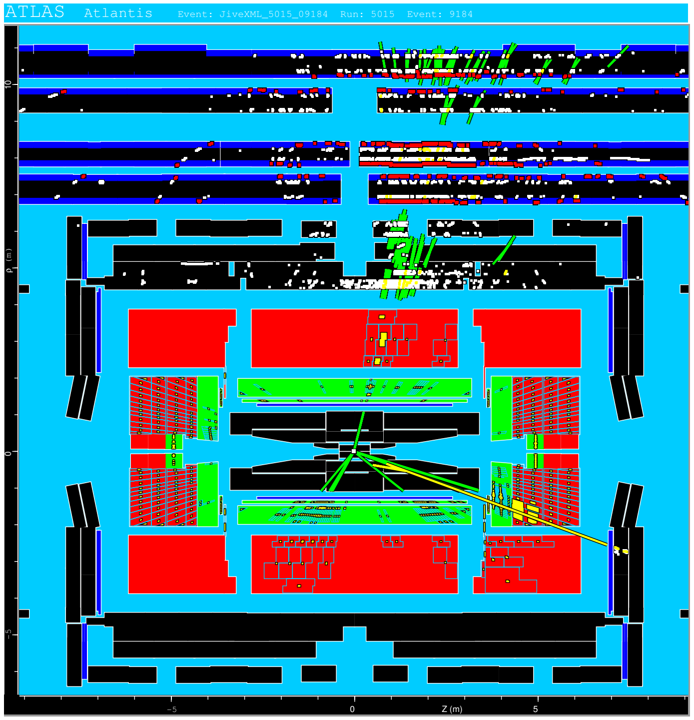
Evaluate the possibility of applying event-by-event corrections

Another example: scan of $\not\!\!E_T$ tails

Scan fully simulated jet events in ATLAS ($P_T(jet) \gtrsim 500$ GeV) with $\Delta \not\!\!E_T > 250$ GeV (F. Paige, S. Willocq)

$\not\!\!E_T$ from: Jet leakage from cracks, Fake muons from cracks, Jet punch-through





Problematic events characterised by large occupancy in muon chambers

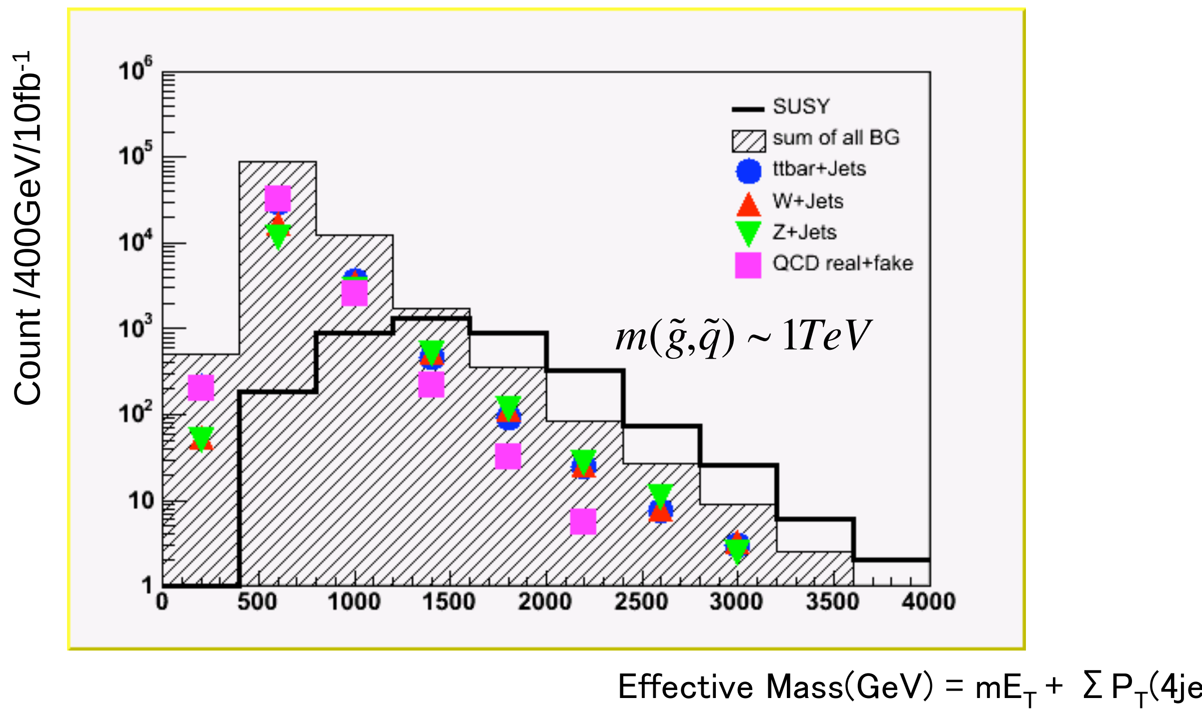
Control of $\not\!\!E_T$ from Standard Model processes

Real $\not\!\!E_T$ from ν production in SM:

(S. Asai et al.)

SUSY selection:

- $\not\!\!E_T > 100$ GeV
- At least 1 jet with $p_T > 100$ GeV
- At least 4 jets with $p_T > 50$ GeV



Plot $M_{\rm eff} = \Sigma_{i=1}^{4} |p_{T(jet_i)}| + E_T^{\rm miss}$

Comparable contributions from: • $\bar{t}t$+jets • W+jets • Z+jets

Counting experiment: need precise estimate of background processes in signal region

Complex multi-body final states: can not rely on MonteCarlo alone. Need both data and MonteCarlo

SM backgrounds: Monte Carlo issues

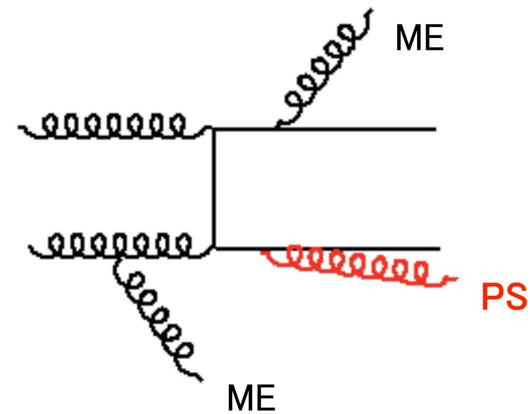
SUSY processes: high multiplicity of final state jets from cascade decays

Require high jet multiplicity to reject backgrounds: ~ 4 jets

Additional jets in $\bar{t}t, W, Z$, production from QCD radiation

Two possible way of generating additional jets:

- Parton showering (PS): good in collinear region, but underestimates emission of high-p_T jets
- Matrix Element (ME): requires cuts at generation to regularize collinear and infrared divergences



Optimal description of events with both ME and PS switched on

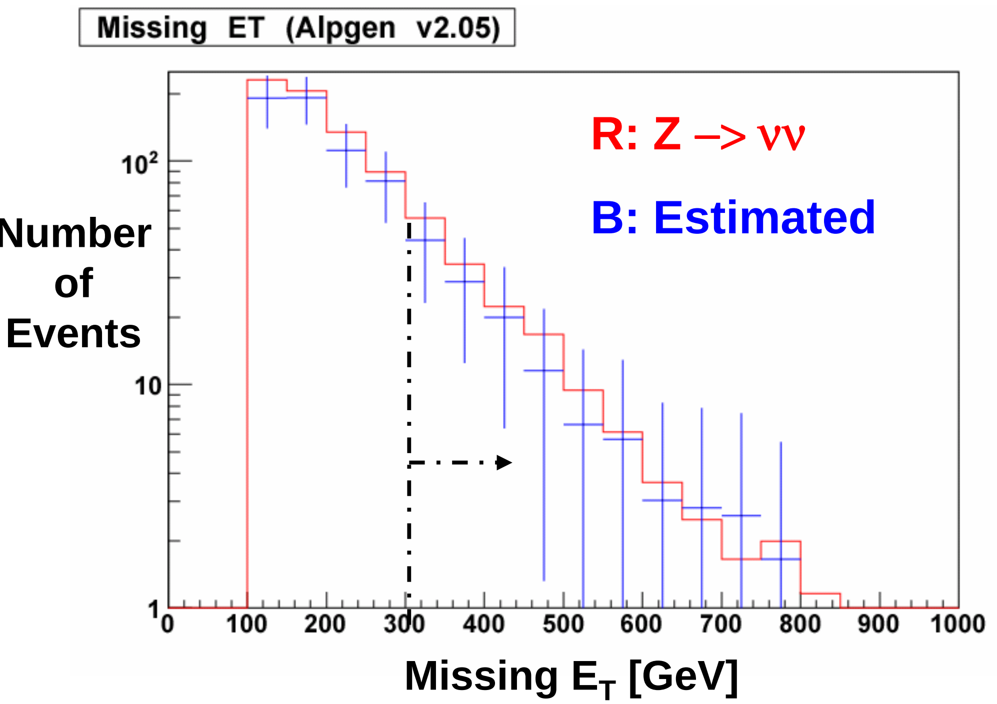
Prescription developed (CKKW, MLM) to avoid double counting, i.e. kinematic configurations produced by both techniques. Very active field of theoretical work

The simplest case: $Z \to \nu\nu +$ jets

Preliminary ATLAS fast simulation study of Y. Okawa et al.

Select a sample of $Z \to \mu\mu$+multijets from data using $Z \to \mu\mu$

Same cuts as for SUSY analysis (4 jets+Etmiss), throw away μ's and calculate $\not{p}_T$ of events from μ momenta (normalized to 1 fb^{-1})



Main problem is correct normalisation and shape distortion from $Z \to \mu\mu$ selection

Need to correct for:

- Efficiency for μ (experimental)
- Acceptance of $\mu^+\mu^-$ pairs (MonteCarlo)

Again, combination of data and MonteCarlo needed for firm estimate

Good prediction of background shape, but statistically limited: $\sim 30\%$ for 1 fb^{-1}

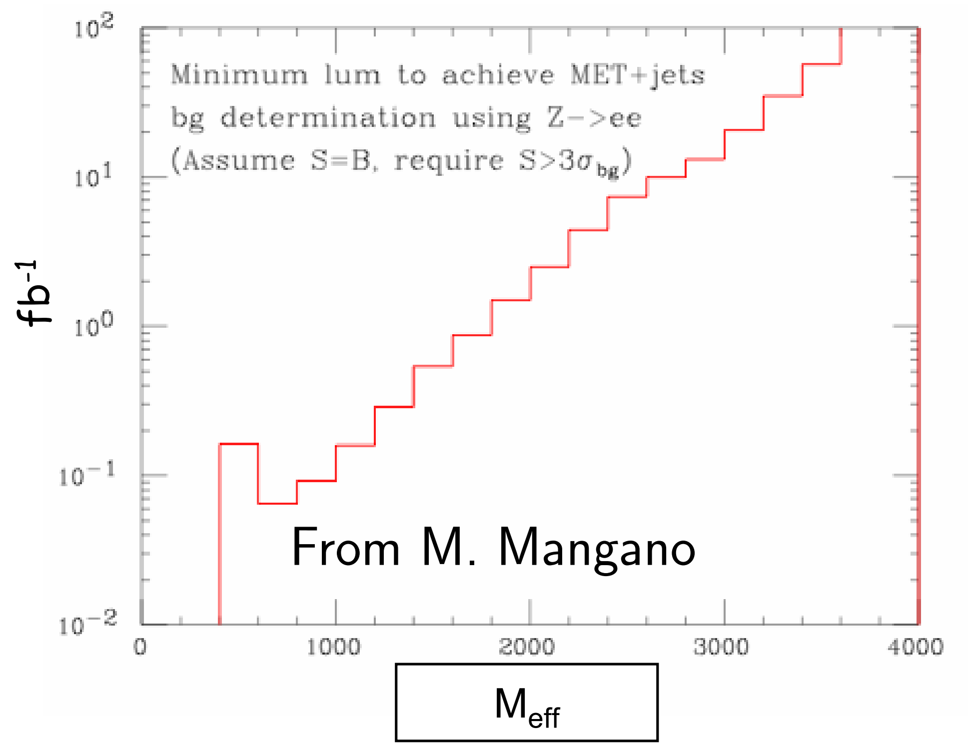
Normalisation needs to be multiplied by $BR(Z \to \nu\nu)/BR(Z \to ee) \sim 6$

Assuming SUSY signal $\sim Z \to \nu\nu$ bg, evaluate luminosity necessary for having $N_{SUSY} > 3 \times \sigma_{bg}$

Stat error on background:

$$\sigma_{bg} = \sqrt{N(Z \to ee)} \times \frac{BR(Z \to \nu\nu)}{BR(Z \to ee)}$$

For each bin where normalisation required, need ~ 10 reconstructed $Z \to \ell\ell$ events. Need to consider acceptance/efficiency factors as well



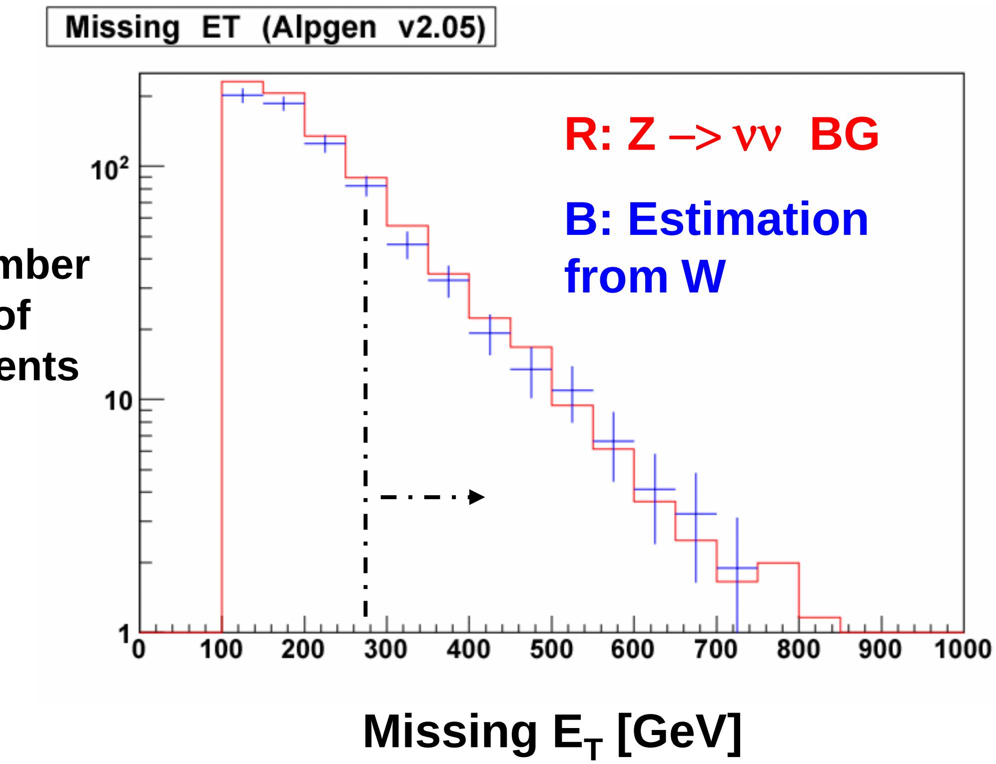
Several hundred pb^{-1} required. Sufficient if we believe in shape, and only need normalisation. Much more needed to perform bin-by-bin normalisation

Improve statistics: use $W \rightarrow \mu\nu$

Try to simulate $Z \rightarrow \nu\nu$+jets using $W \rightarrow \mu\nu$+jets

Select events with SUSY cuts, estimate $\not{E}_T$ from P_T of $\mu\nu$ system

10 times more statistics than using $Z \rightarrow \mu\mu$



Error on signal and background equivalent

Good reproduction of shape

Promising approach, need to understand effect of difference between W and Z production mechanism on estimate

Additional inclusive signatures

$\not\!\!E_T$+jets signature is most powerful and least model-dependent

SM and instrumental backgrounds might require long time before convincing signal can be claimed

With most recent evaluation of SM backgrounds, shoulder in M_{eff} distribution disappears

Need to optimize search strategy by tackling in parallel all of the inclusive discovery channels

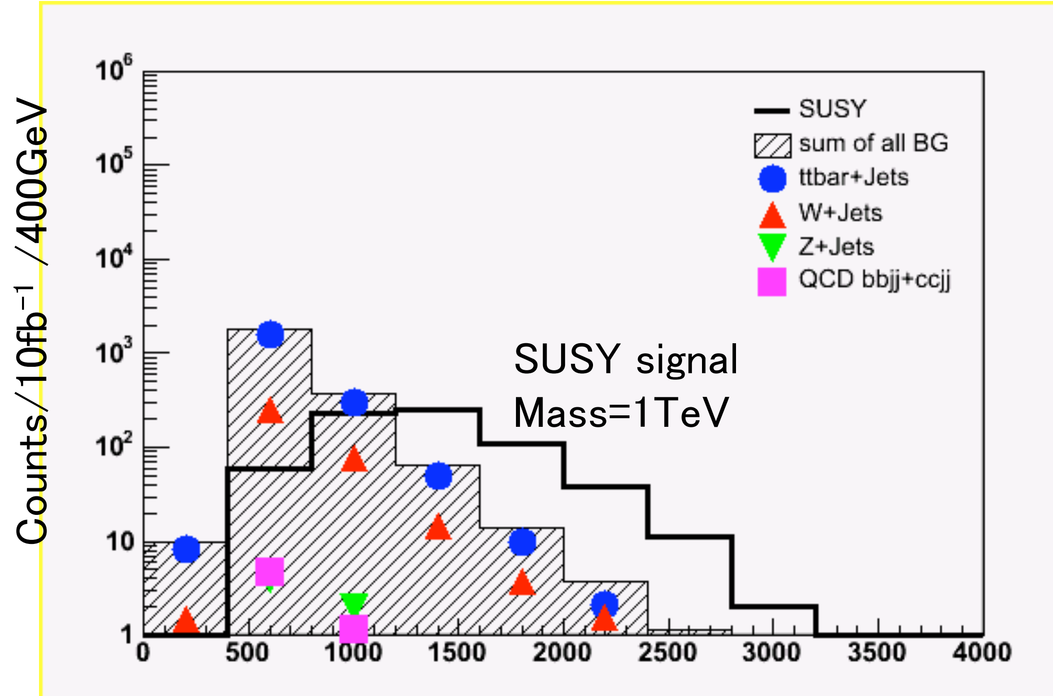
Example: single lepton + jets + $\not\!\!E_T$

Smaller number of backgrounds:

$\bar{t}t$ dominant,easier to control

Shoulder might be observable

Main experimental difficulty: correct estimate of contribution from fake leptons



1-lepton inclusive analysis. Control of top background

Try to develop method to use top data to understand top background

Preliminary ATLAS exercise (Dan Tovey)

Standard semileptonic top analysis:

- $P_t(lep) > 20$ GeV, $\not{E}_T > 20$ GeV
- ≥ 4 jets with $P_T > 40$ GeV
- ≥ 2 b-tagged jets

Very similar to cuts for SUSY analysis with looser $\not{E}_T$ requirement

If harden $\not{E}_T$ cuts, sample contaminated with SUSY

Possible approach:

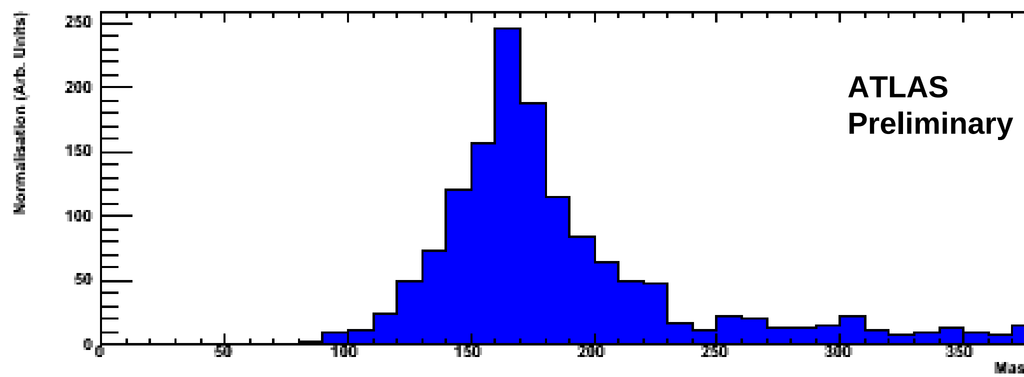
- Select semi-leptonic top candidates (standard cuts: what b-tag available?)
- Fully reconstruct top events from $\not{E}_T$ and W mass constraint

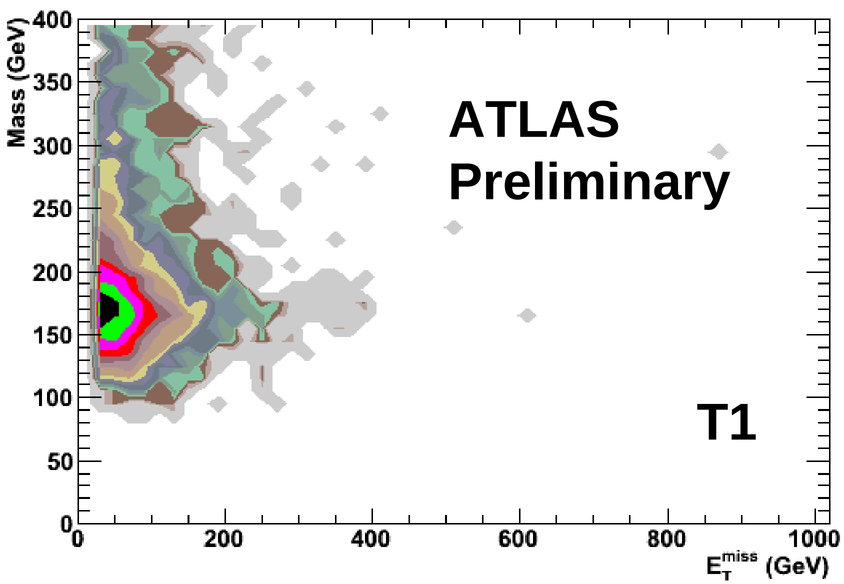
$\Rightarrow$ obtain pure top sample with no SUSY contamination

- Apply SUSY selection criteria to pure top sample, and plot $\not{E}_T$ distribution
- normalize pure top sample to data at low $\not{E}_T$
- obtain prediction of amount of top background at high $\not{E}_T$

Top mass reconstruction

- Reconstruct semi-leptonic top mass from lepton + $\not{E}_T$ and W mass constraint
- Reduce jet combinatorics by selecting highest p_T candidate





$\not{E}_T$ and reconstructed top mass reasonably uncorrelated $\rightarrow \sim$ no bias on $\not{E}_T$ distribution from selection on m(top)

Subtract W+4 jets background under top peak using side-band

Analysis based on two MC samples: $T1$ (inclusive), $T2$ ($P_T^{top} > 500$ GeV)

Normalising the estimate

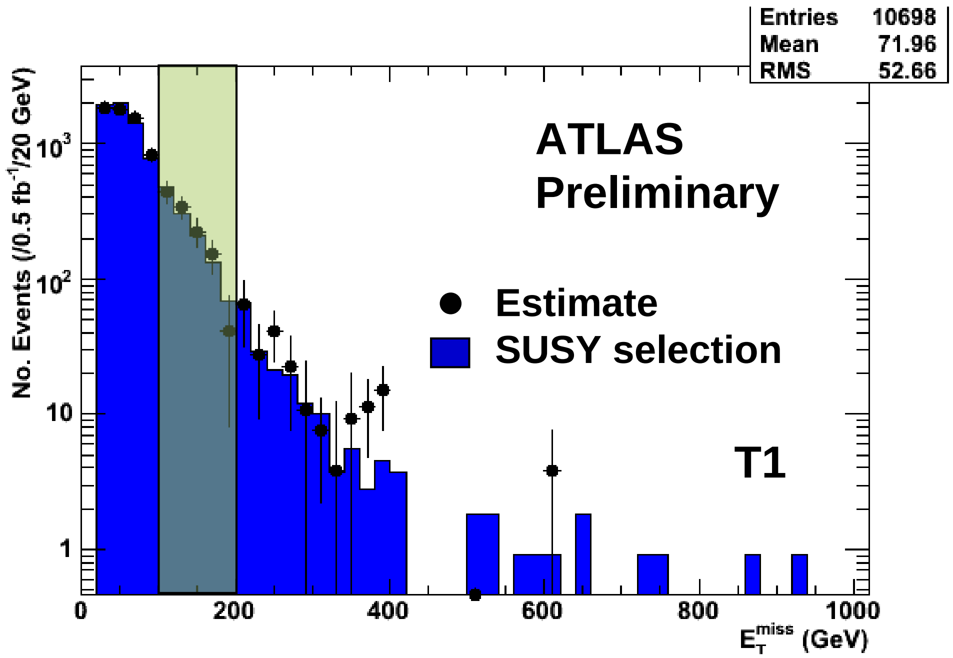
"Estimate": fully reconstructed top sample after side-band subtraction

Normalise estimate to "SUSY selection" sample, to account for relative efficiency of top selection

Reminder: "SUSY Selection" sample:

tt events with no top mass constraint

- $\not{E}_T > 20$ GeV (to be hardened later)
- At least 4 GeV with $p_T > 40$ GeV
- Exactly 1 lepton with $p_T > 20$ GeV



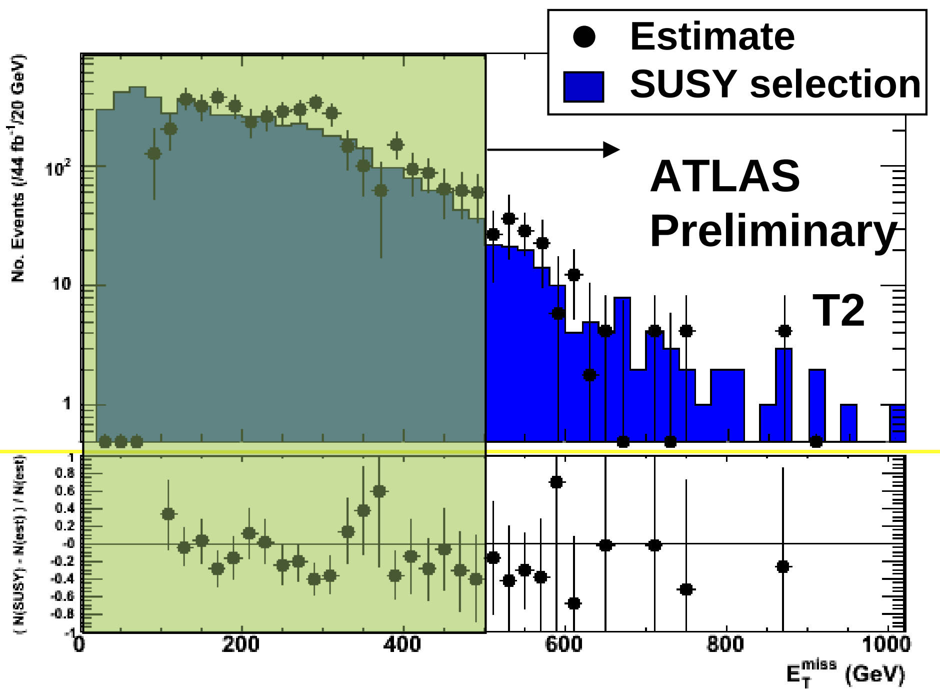
In low $\not{E}_T$ region (100 GeV-200 GeV): SUSY signal expected to be small

Assume low available statistics (0.5 fb^{-1}) of fully simulated top

Obtain scaling factor of ~ 4

Background estimates

Verify if method works on sample T_2 ($P_T(top) > 500$ GeV) Compare number of events with $\not{E}_T > 500$ GeV in "SUSY selection" sample to background estimate



With 44 fb^{-1}:

- Found 174 ± 13 Ev (stat)
- Expected 198 ± 38 (stat) $\rightarrow$ 20%

Statistical error mainly from sideband subtraction

Negligible contribution from normalisation

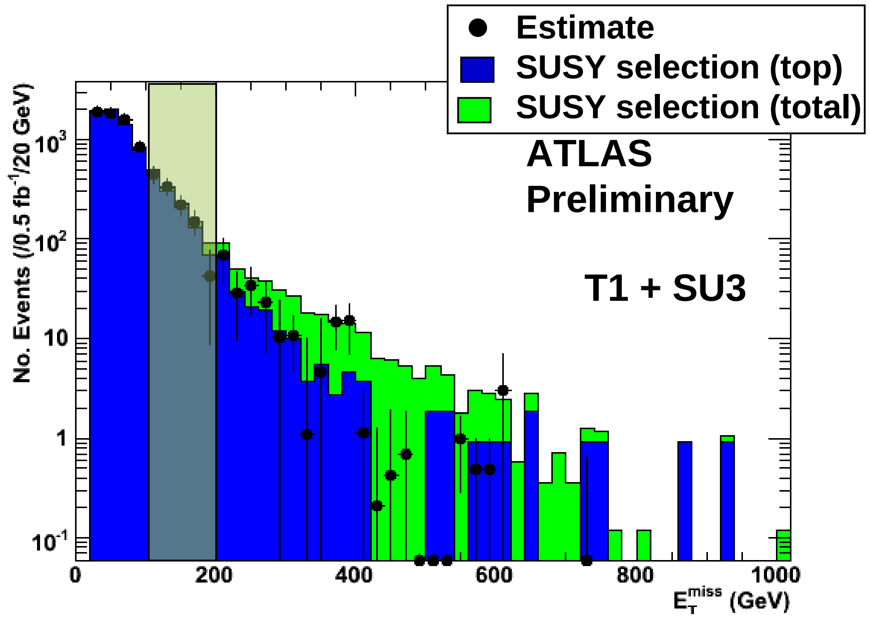
SUSY

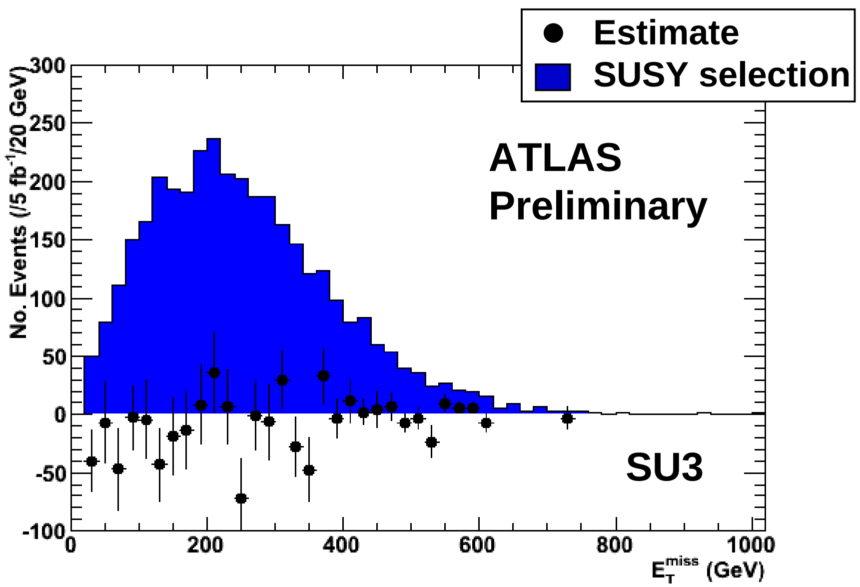
What happens if SUSY signal present?

Study effect by mixing inclusive top sample and SUSY SU3 sample:

Squark-gluino mass scale ~ 600 GeV.

Repeat previous steps





Normalisation procedure OK for SU3 and 100-200 GeV window

Sideband subtraction seems to work

Example of possible approach, work in progress

2-leptons + $\not{E}_T$ + jets inclusive search

Significantly lower reach than other channels, but also lower backgrounds

Various different topologies, corresponding to different configuration of SM backgrounds

- Opposite-Sign Same-Flavour (OSSF)
- Opposite-Sign Opposite-Flavour (OSOF)
- Same-Sign Same-flavour (SSSF)
- Same-sign Opposite-Flavour (SSOF)

Interesting possibility: flavour-correlated signal. Example:

$$\tilde{q}_L \longrightarrow \tilde{\chi}_2^0 \quad q$$
$$\hookrightarrow \tilde{\ell}_R^{\pm} \quad \ell^{\mp}$$
$$\hookrightarrow \tilde{\chi}_1^0 \quad \ell^{\pm}$$

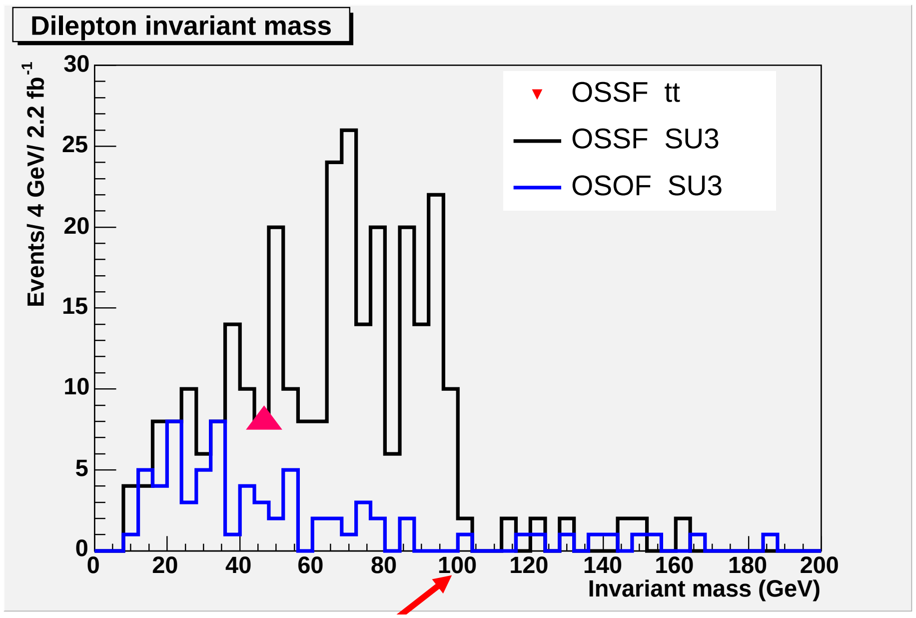
Only $Z/\gamma \to e^+e^-, \mu^+\mu^-$ has correlated flavours

All backgrounds except Z can be exactly subtracted (modulo lepton efficiencies)

2-lepton invariant mass

Events with two leptons selected: build the invariant mass of the two leptons

Plot $m(\ell\ell)$ for OSSF and OSOF samples (U.de Sanctis et al.) for ATLAS sample point SU3, light sleptons, SUSY scale $\sim$600 GeV



Statistics in plot is 2.2 fb^{-1}

Top background negligible

Observe clear structure, strong evidence for new physics

If we are lucky first and clearest evidence from this channel

This kind of structure will be main handle to SUSY parameter measurement: tomorrow's lecture

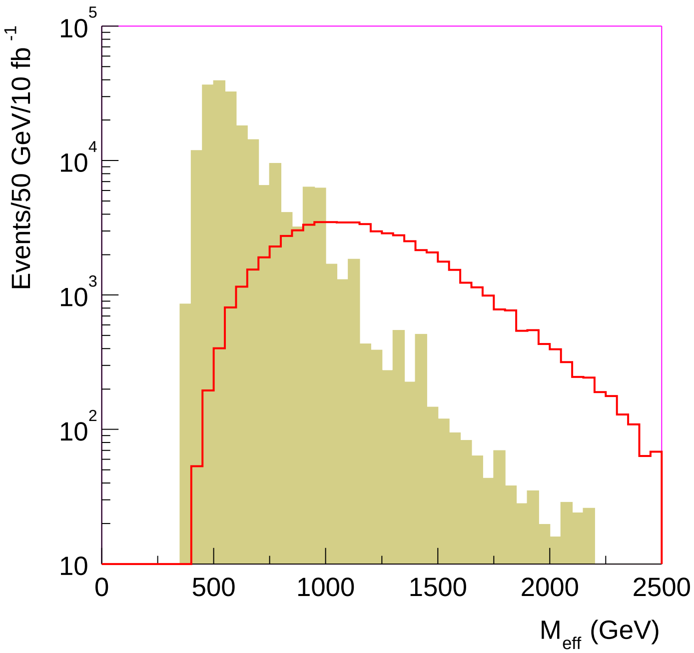
SUSY mass scale from inclusive analysis

Start from multijet + $\not{E}_T$ signature.

Simple variable sensitive to sparticle mass scale:

$$M_{\text{eff}} = \sum_i |p_{T(i)}| + E_T^{\text{miss}}$$

where $p_{T(i)}$ is the transverse momentum of jet i



M_{eff} distribution for signal (red) and background (brown)

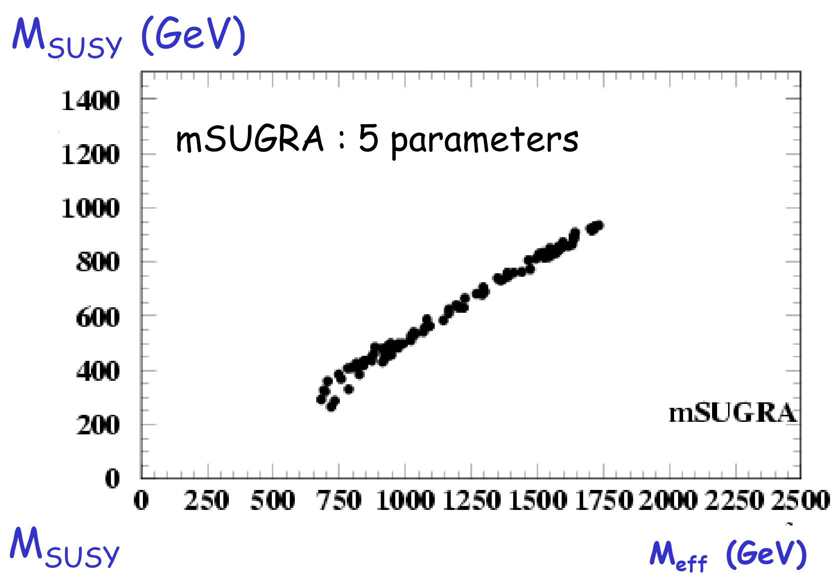
(mSUGRA $m_0 = 100$ GeV, $m_1/2 = 300$ GeV, $\tan\beta = 10$, $A = 0$, $\mu > 0$)

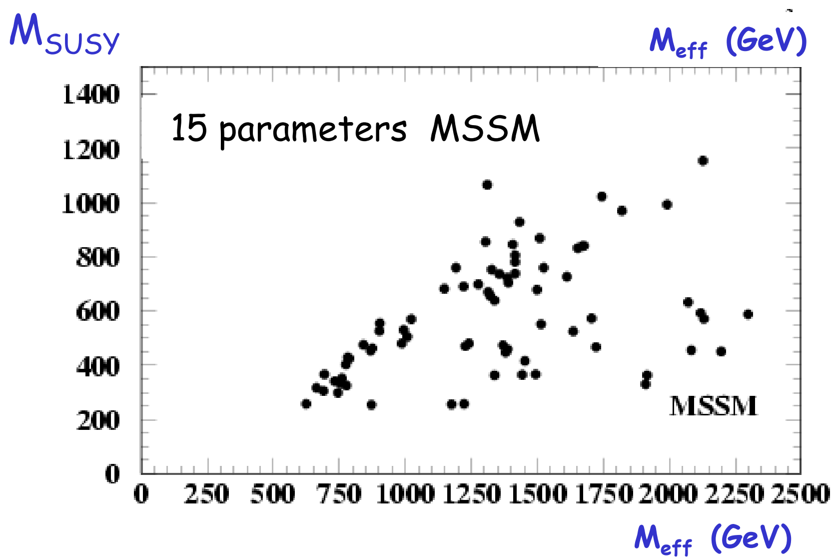
A cut on M_{eff} allows to separate the signal from SM background

The M_{eff} distribution shows a peak which moves with the SUSY mass scale.

Define the SUSY mass scale as:

$$M_{\rm susy}^{\rm eff} = \left(M_{\rm susy} - \frac{M_\chi^2}{M_{\rm susy}} \right), \text{ with } M_{\sf SUSY} \equiv \frac{\Sigma_i M_i \sigma_i}{\Sigma_i \sigma_i}$$





Estimate peak in $M_{\sf eff}$ by a gaussian fit to the background-subtracted signal distributions

Test the correlation of $M_{\sf eff}$ with $M_{\rm susy}^{\rm eff}$ on a random set of models: mSUGRA and MSSM

Excellent correlation in mSUGRA, acceptable for MSSM

Expect $\sim$ 10% precision on SUSY mass scale for one year at high luminosity

What might we know after inclusive analyses?

Assume we have a MSSM-like SUSY model with $m_{\tilde{q}} \sim m_{tg} \sim 600$ GeV

Observe excesses in $\not{E}_T + jets$ inclusive, $+1$ lepton, $+2$ leptons

- Undetectable particles in the final state $\not{E}_T$
- Production of particles with mass∼600 GeV (M_{eff} study) and with couplings of ∼QCD strength (X-section)
- Some of the produced particles are coloured (jets in the final state)
- Some of the new particles are Majorana (excess of same-sign lepton pairs)
- Lepton flavour $\sim$ conserved in first two generations (same number of leptons and muons)
- Decays of neutral particle into two particles with lepton quantum numbers (excess of Opposite-Sign/Same-Flavour (OS-SF) leptons)
- ....

Some sparse pieces of a giant jigsaw puzzle. Proceed to try exclusive analyses to fill in some of the gaps