Part 3: SUSY discovery

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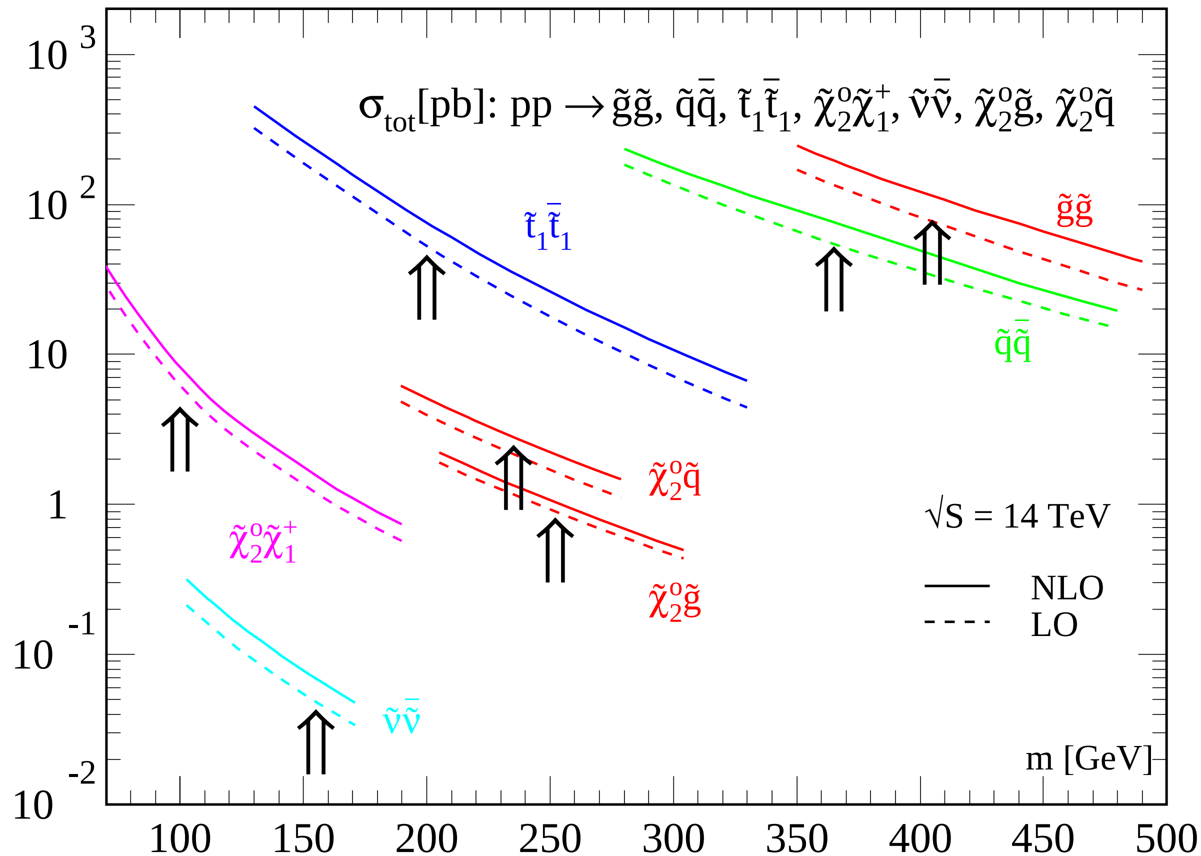
SUSY at the LHC: general features

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
- Unravelling 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!

Triggering on SUSY

Model independent SUSY signature: multi-jet + Etmiss

Huge QCD rate, trigger rate to tape limited by HLT computing power

CMS trigger study

Example points at the limit of Tevatron discovery range

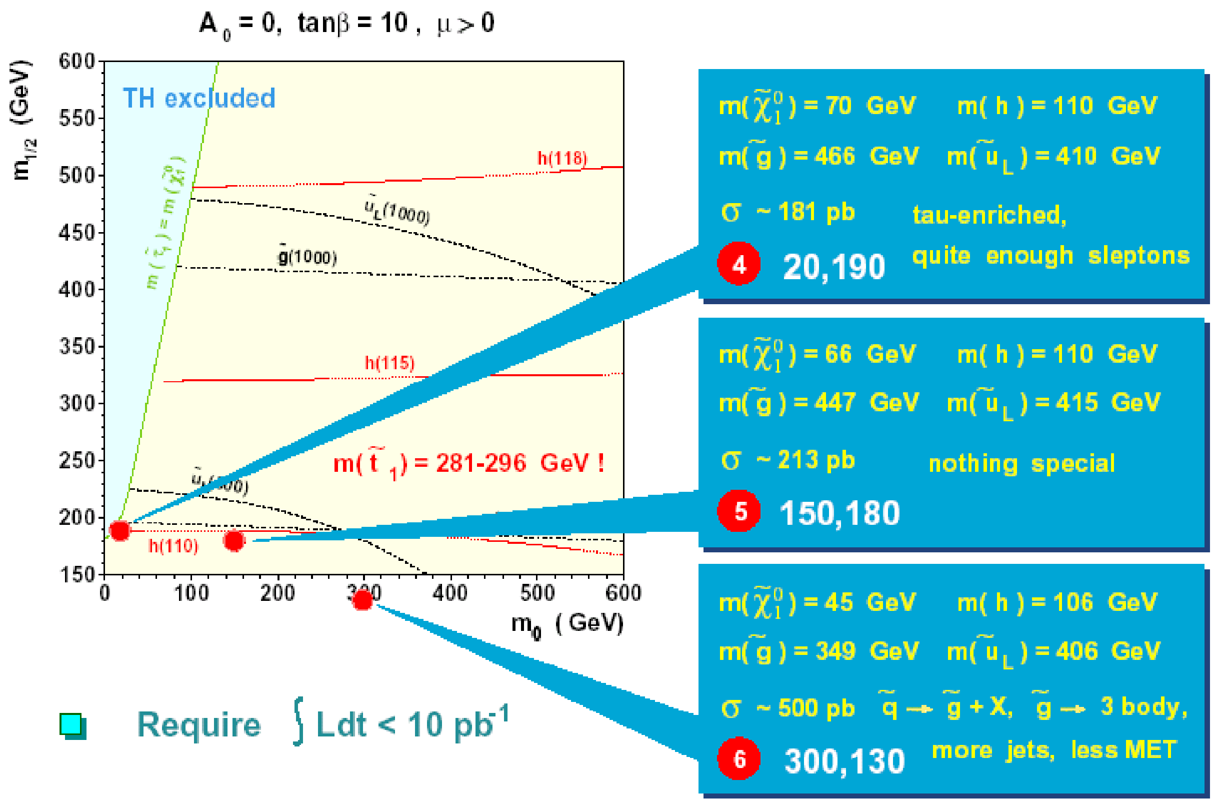
Both R-conserving and R-violating case

Optimize efficiency for a few Hz rate by varying selection cuts

Possible scheme (at 2×10^{33} cm^{-2}s^{-1}):

$\not{E}_T > 123$ GeV, 1 Jet $E_T > 180$ GeV

4 jets with $E_T > 113$ GeV



Achieve 60-70% (25-45%) efficiency % for all R_P conserving (violating) cases

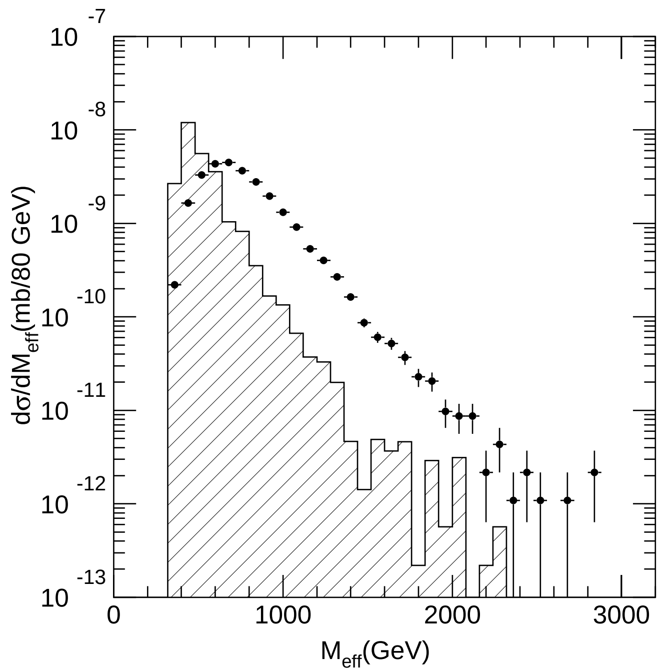
ATLAS strategy:

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

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

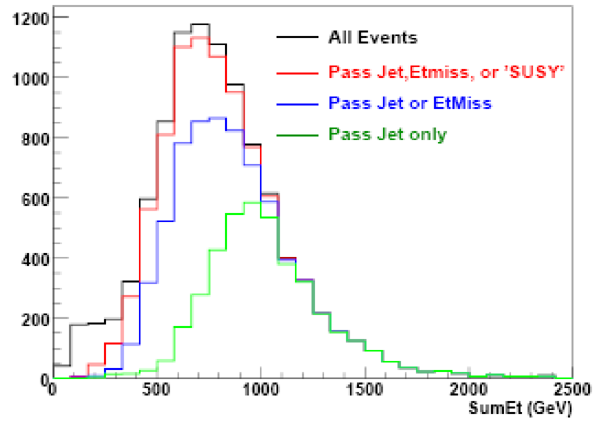
SUSY events are complex with many physics objects. triggered by many items

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

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

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 unification of gaugino masses assumed, otherwise can devise degenerate models where jets are very soft. Variables:
- Spherical events: variable S_T

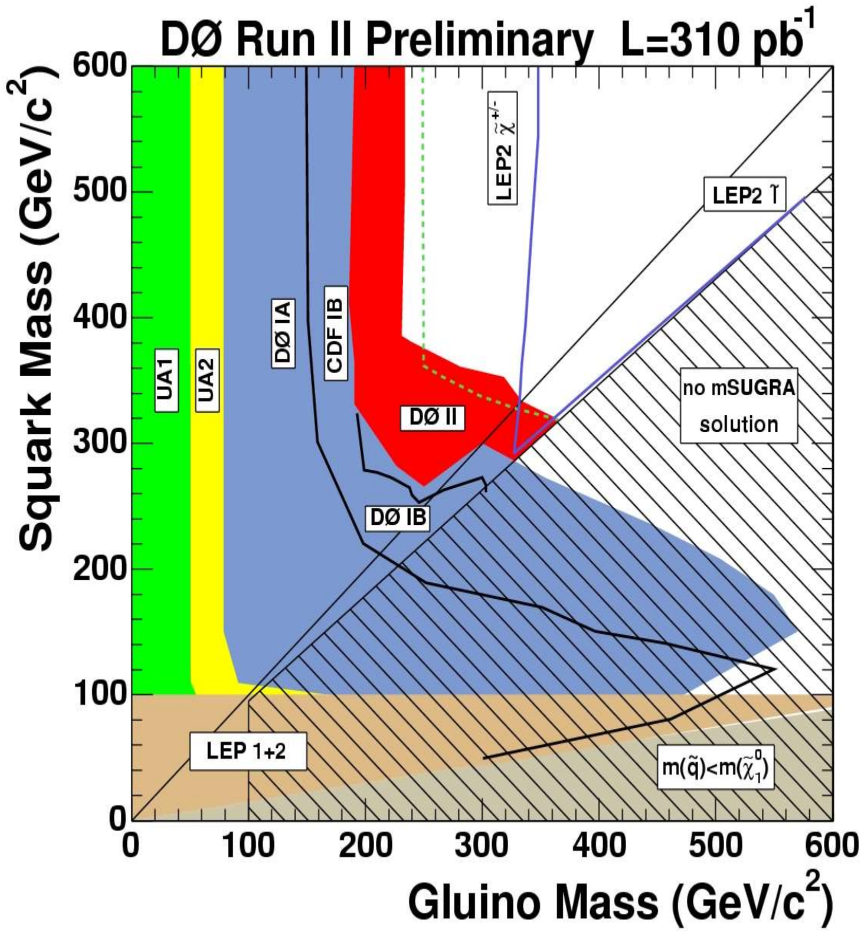
  From Tevatron limits squarks/gluinos must be heavy ($\gtrsim$ 400 GeV).
- Multiple leptons: from decays of Charginos/neutralinos typically present in cascade

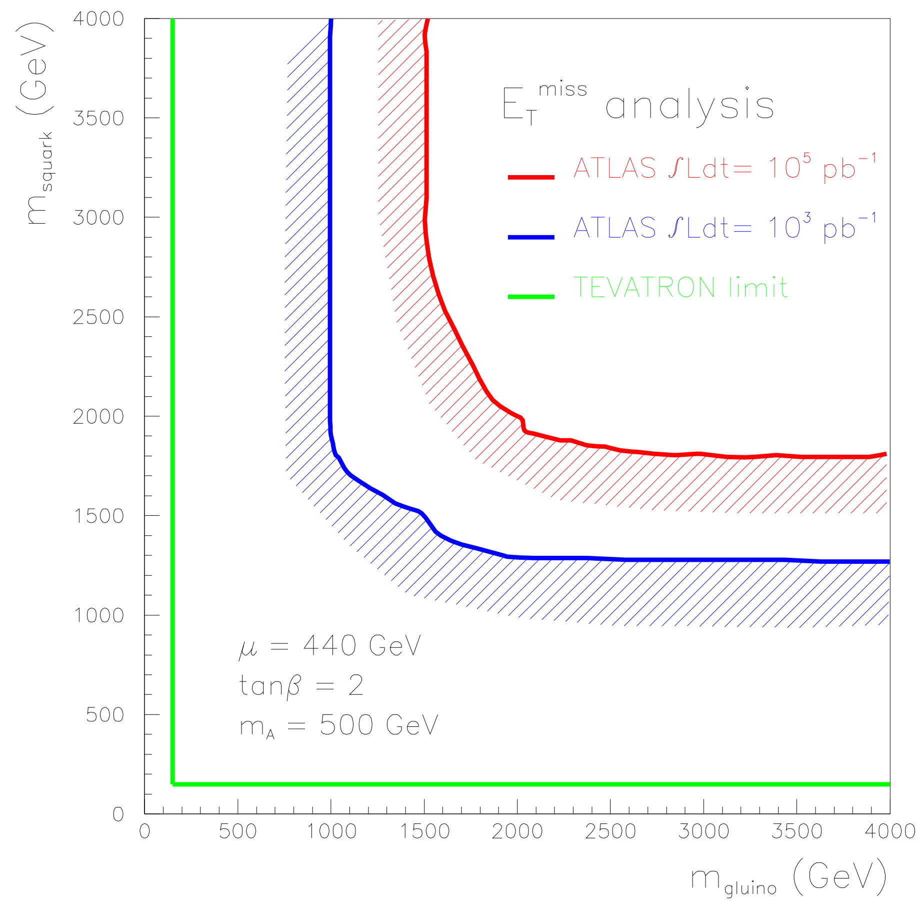
Analysis method: study a grid of points in SUSY parameter space, for each point optimize cut on variables for different basic signatures:

($\not{E}_T$+jets, 1 lepton, 2 leptons OS, 2 leptons SS)

Call within reach points for which $S/\sqrt{B} > 5$ and $S > 10$ Events after cuts

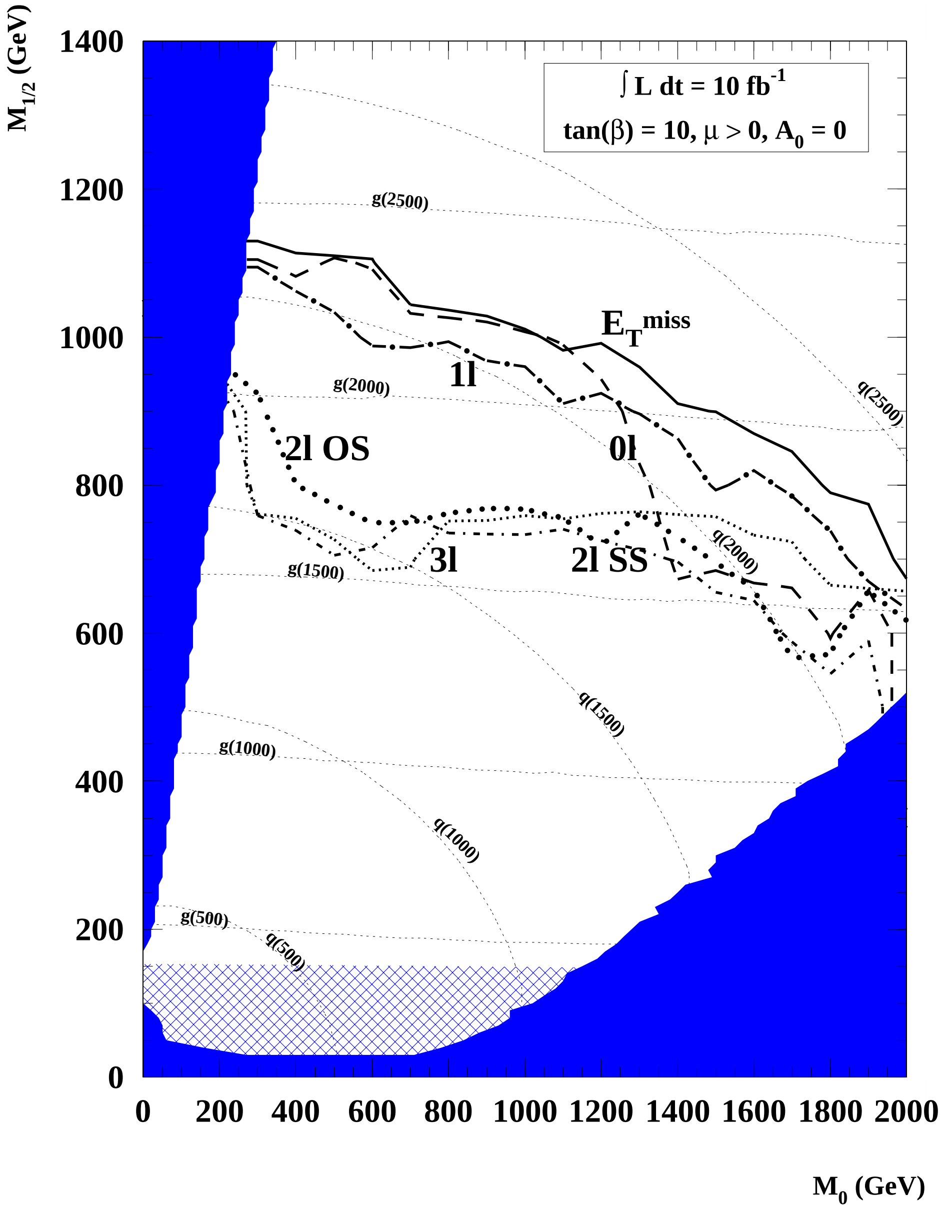
Study in $m_{\tilde{q}} - m_{\tilde{g}}$ parameter space: Tevatron and LHC





Very old ATLAS study, generic analysis cuts not optimised for different phase-space regions

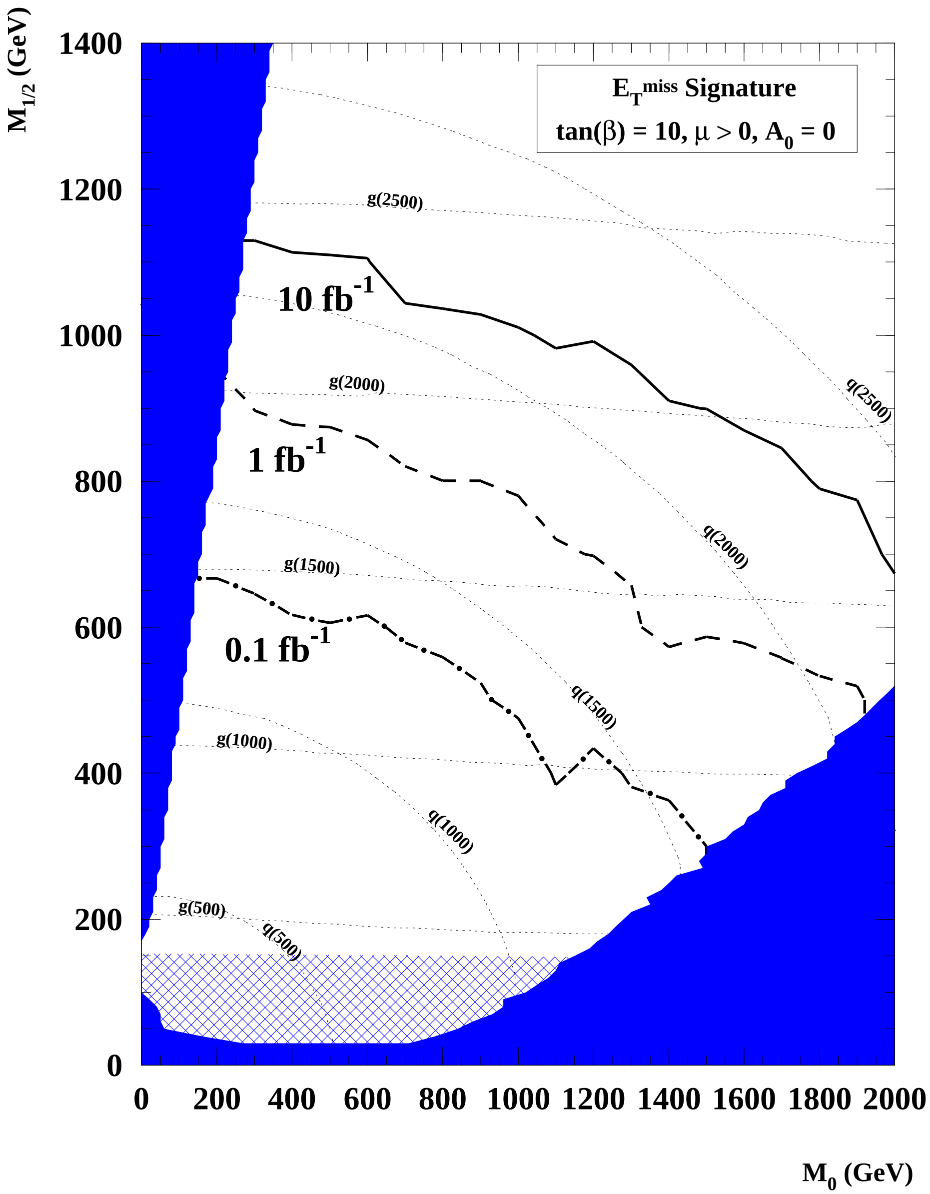
Inclusive reach in mSUGRA parameter space



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)

Significant reach from $\not{E}_T$ signature from earliest phases of the experiment



Assume 10^{33} cm^{-2}s^{-1}:

- ~1300 GeV in "one week"
- ~1800 GeV in "one month"
- ~2200 GeV in one year

Main time limitation not from signal statistics, but from understanding the detector performance.

Need large amounts of $W, Z, \bar{t}t$ data for firm background evaluation

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

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

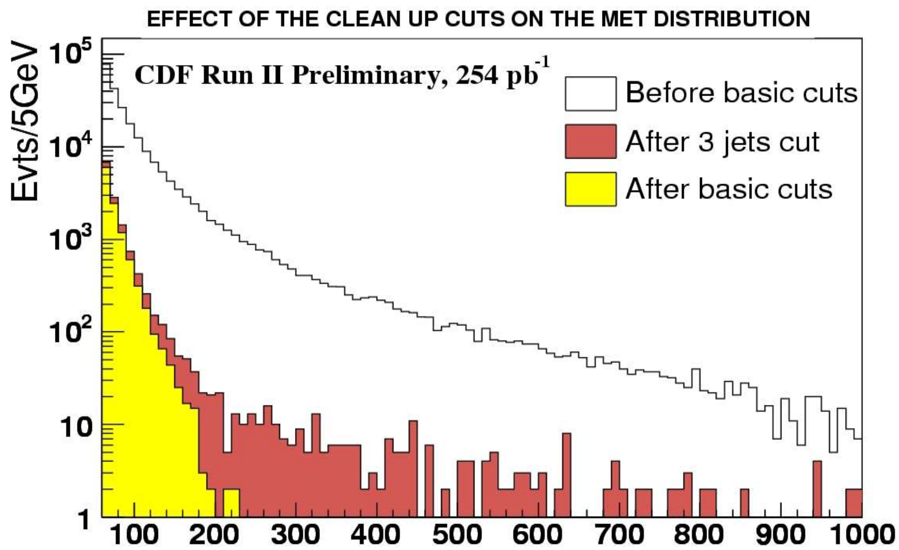
Many sources: gaps in acceptance, dead/hot cells, non-gaussian tails, etc.

Require detailed understanding of tails of detector performance.

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

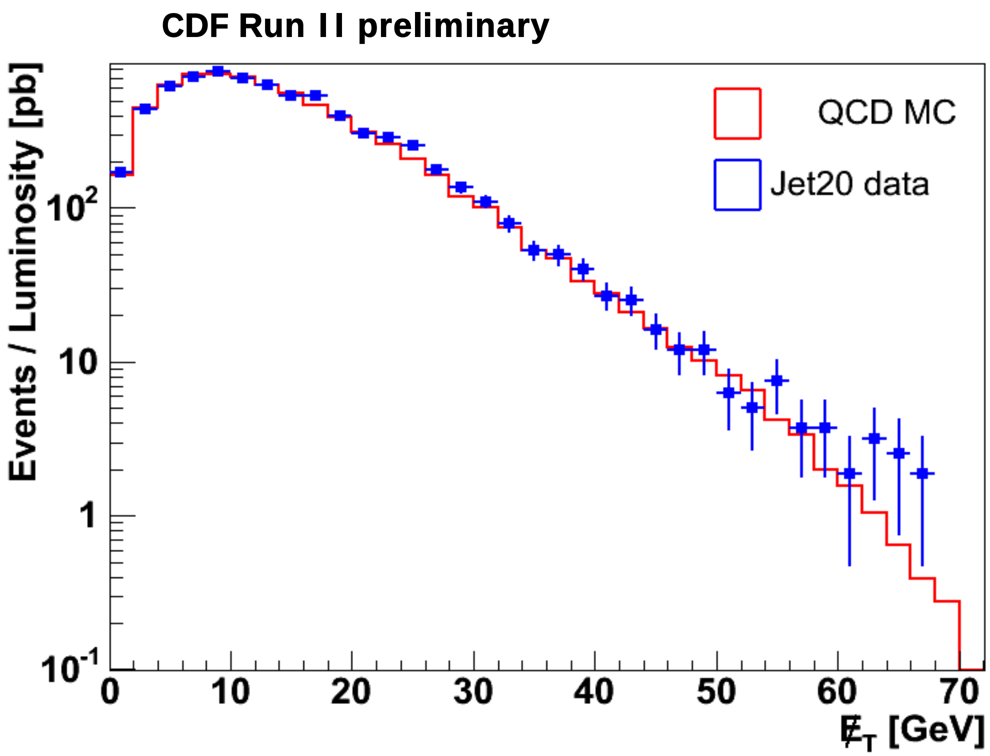
- beam-gas and machine backgrounds
- displaced vertexes
- hot cells
- $\not\!\!E_T$ pointing along jets
- jets in regions of poor response

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



All detector and machine garbage will end up in $\not\!\!E_T$ trigger

Need fast Monte Carlo with good reproduction of detector response: normalise MC to data at low $\not{E}_T$ and use it to predict high $\not{E}_T$ background in "signal" region



Again example from CDF:

Select region where $\not{E}_T$ has low significance, no signal expected

MonteCarlo reproduces nicely data distribution

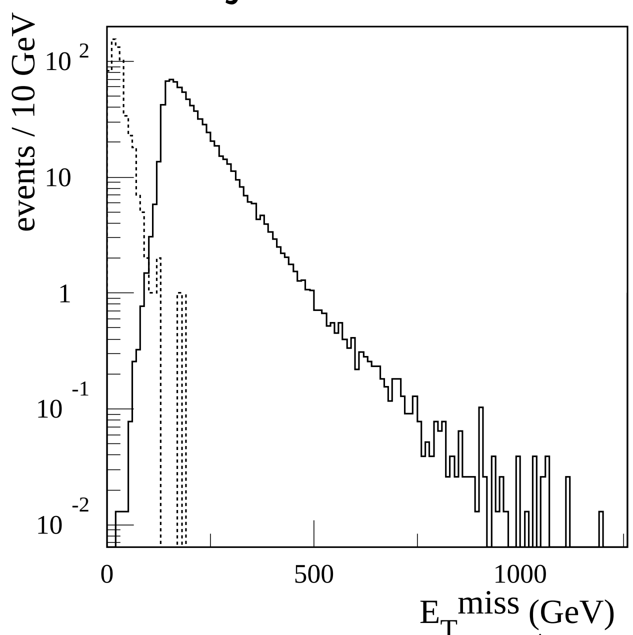
Very high priority for LHC collaborations is reaching this level of detector understanding

Example: control of instrumental $\not{E}_T$ (ATLAS TDR)

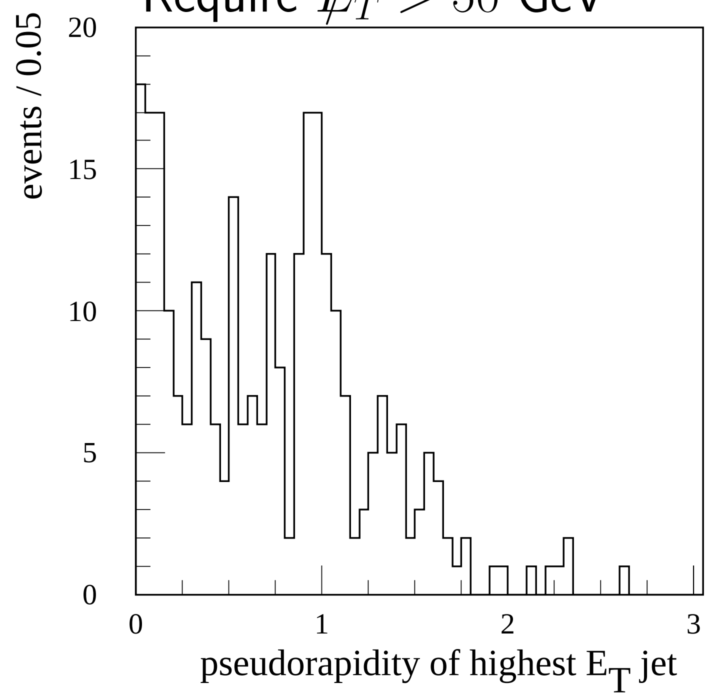
ATLAS study: event balance in fully simulated $Z \to \mu\mu$ with $p_T(Z) > 200$ GeV

Dotted: measured $\not{E}_T$

Full: jet undetected



Require $\not{E}_T > 50$ GeV



Two events with high $\not{E}_T$: real ν

Left plot: reducible background from Z+jets a factor ~1000 smaller than irreducible $Z \to \nu\nu$

Control of $\not{E}_T$ from Standard Model processes

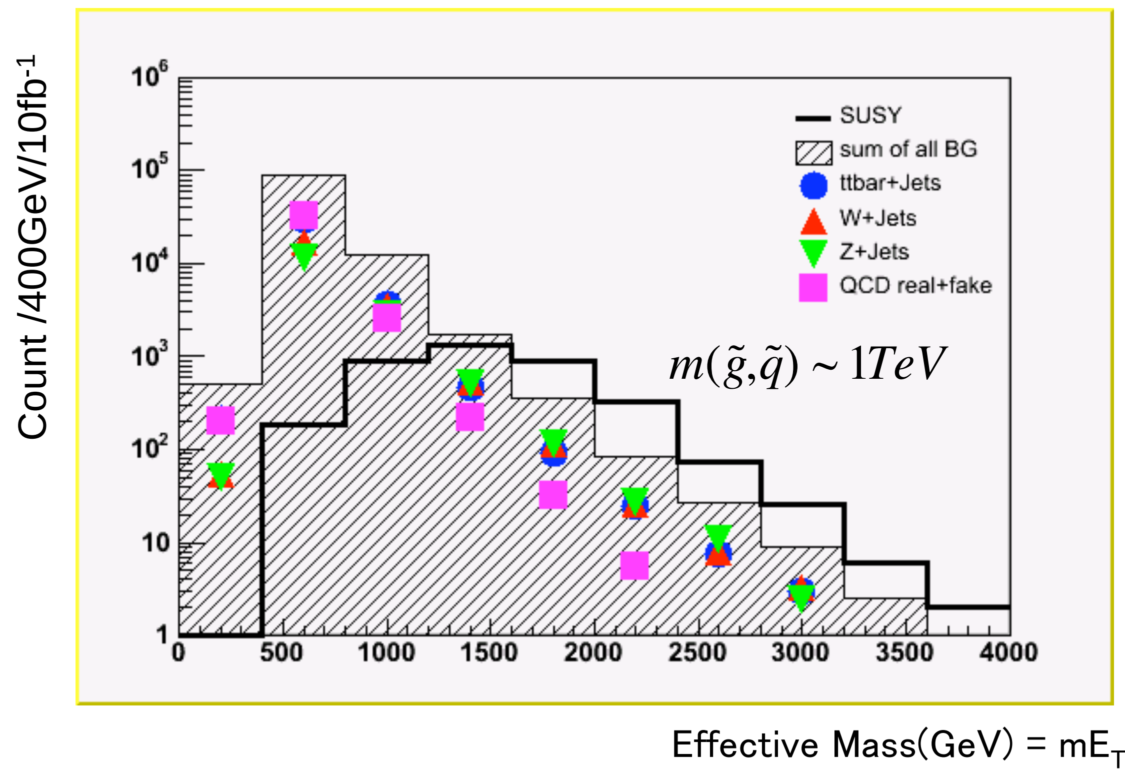
Real $\not{E}_T$ from ν production in SM events:

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

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



Comparable contributions from three processes:

- $\bar{t}t$+jets
- W+jets
- Z+jets

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

SM backgrounds: Monte Carlo issues

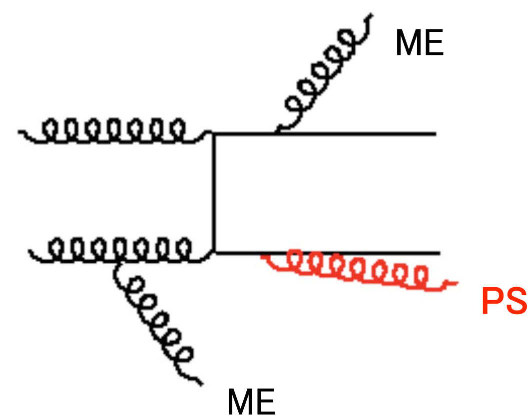
SUSY processes: high multiplicity of final state jets from cascade decays

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:

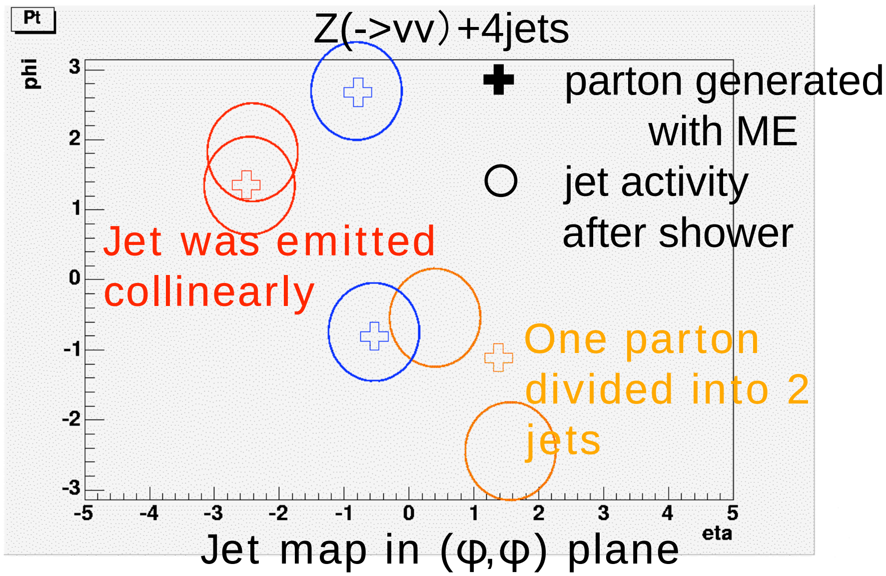
- Parton showering (PS): good in collinear region, but underestimates emission of high-p_T jets
- Matrix Element (ME): requires cuts at generation to regularize collinear and infrared divegencies



Optimal description of events with both ME and PS switched on

Need prescription to avoid double counting, i.e. kinematic configurations produced by both techniques

Final number of jets in event complicated convolution of ME, PS, and experimental definition of jets



Contributions from Z+1,2,3,4,5.. jets to experimental 4-jet sample

Prescriptions available (MLM, CKKW) to obtain MC predictions for experimental $Z + 4$ jets sample as a combination of all the exclusivve $Z+$ n jets sample

Very active field, experimental effort to see how well different prescriptions match Tevatron data

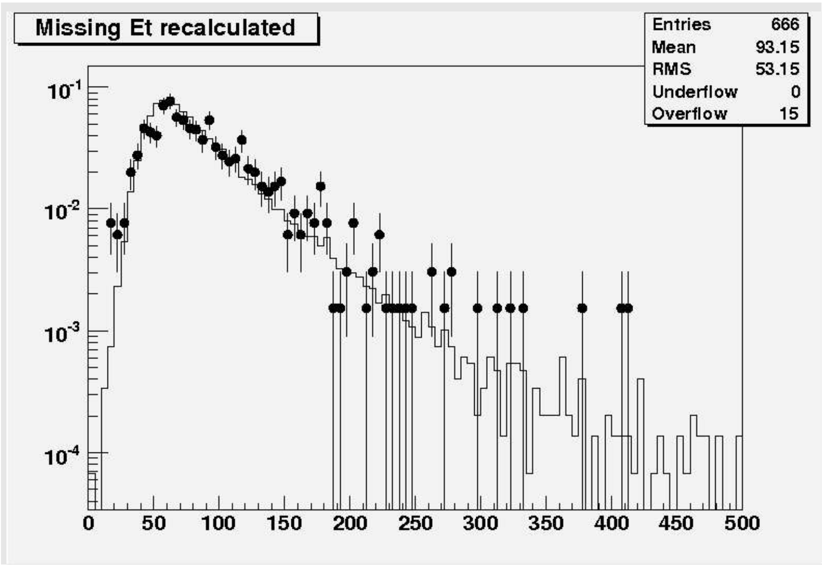
BUT, tuning of matching valid for Tevatron might not be valid in LHC regime

At the LHC Develop strategies based on the combined use of MC and data to correctly predict the backgrounds

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

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

Apply same cuts as for SUSY analysis, throw away electrons and calculate $\not{p}_T$ of events



Select $Z \to ee$ events with low $\not{E}_T$

Normalisation taking equal areas, calculation of normalisation form data still to be done

In order to have correct normalisation and shape correct for:

- Efficiency for electrons (experimental)
- $\not{E}_T$ distorsion from subtracting electrons from calo
- Acceptance of e^+e^- pairs (MonteCarlo)

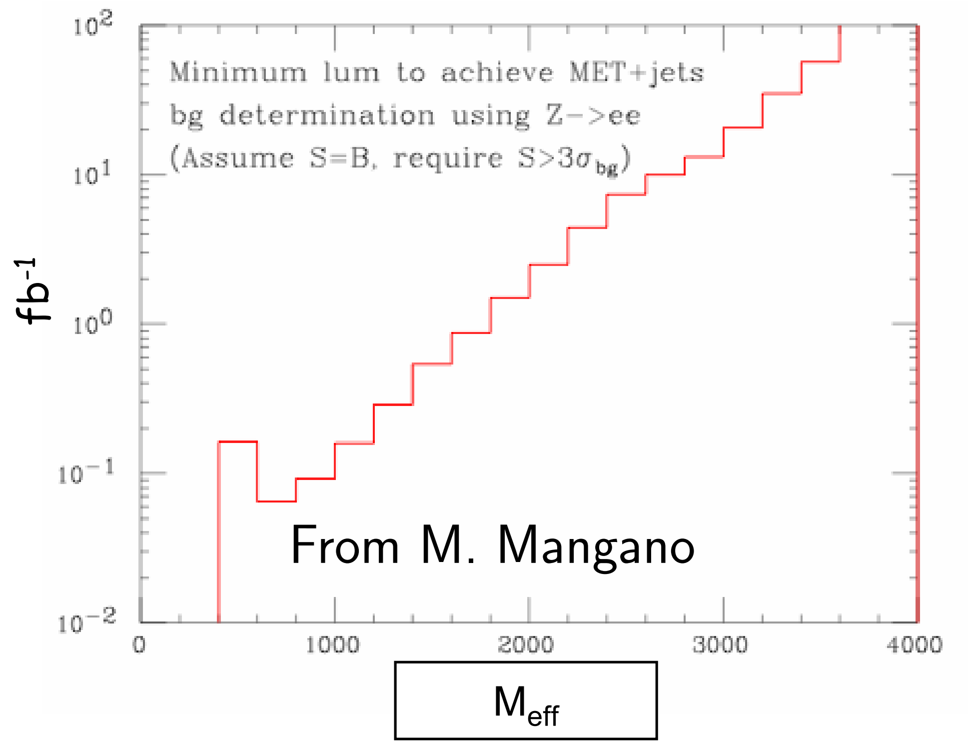
Need to evaluate systematic error from these corrections

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

$N_{SUSY} > 3 \times \sigma_{bg}$

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



Several hundred pb^{-1} required. Sufficient if we believe in MC shape, and only need normalisation. Much more needed to keep search completely MC independent

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

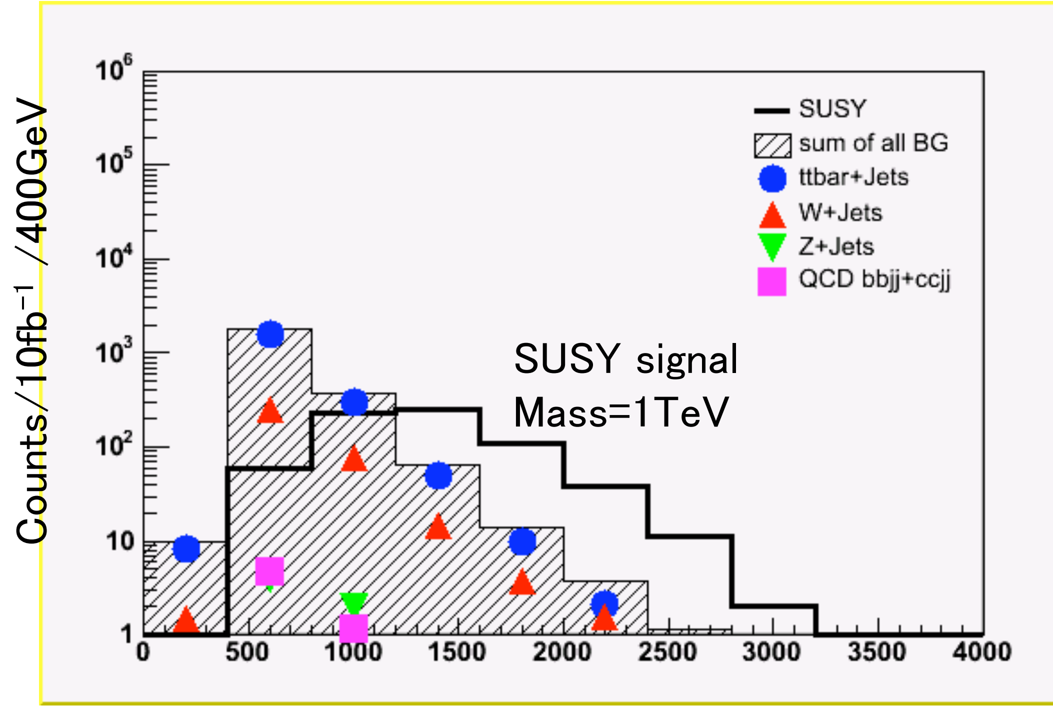
Need to optimize search strategy by tackling in parallel all of the inclusive discovery channels

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 is 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:

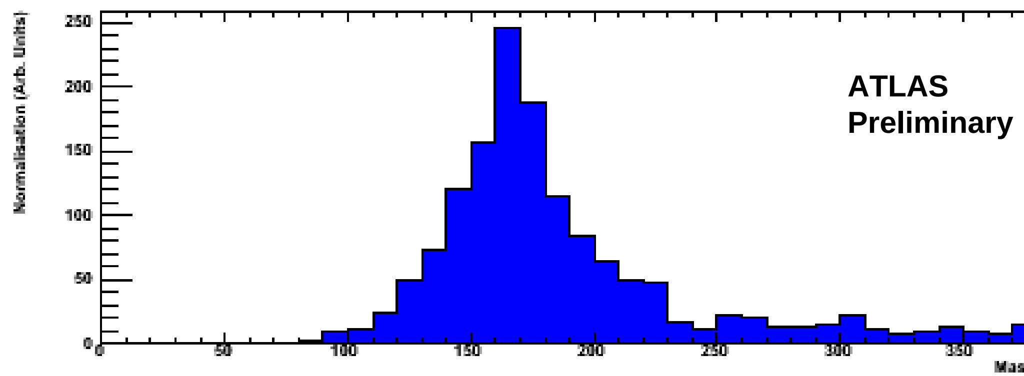
- Select semi-leptonic top candidates (standard cuts: what b-tag available?)
- Fully reconstruct top events from $\not{E}_T$ and W mass constraint

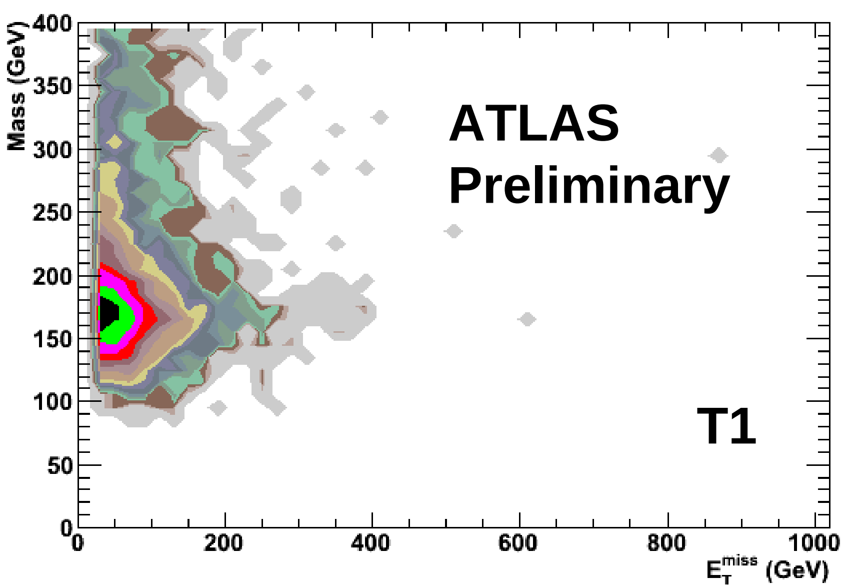
$\Rightarrow$ Reject (SUSY) background via reconstructed m(top)

- Estimate background at high $\not{E}_T$ with events in top mass peak
- normalize to data at low $\not{E}_T$

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 $\rightarrow$ selecting a sample around $m(top)$ sould not bias $\not\!\!E_T$ distribution

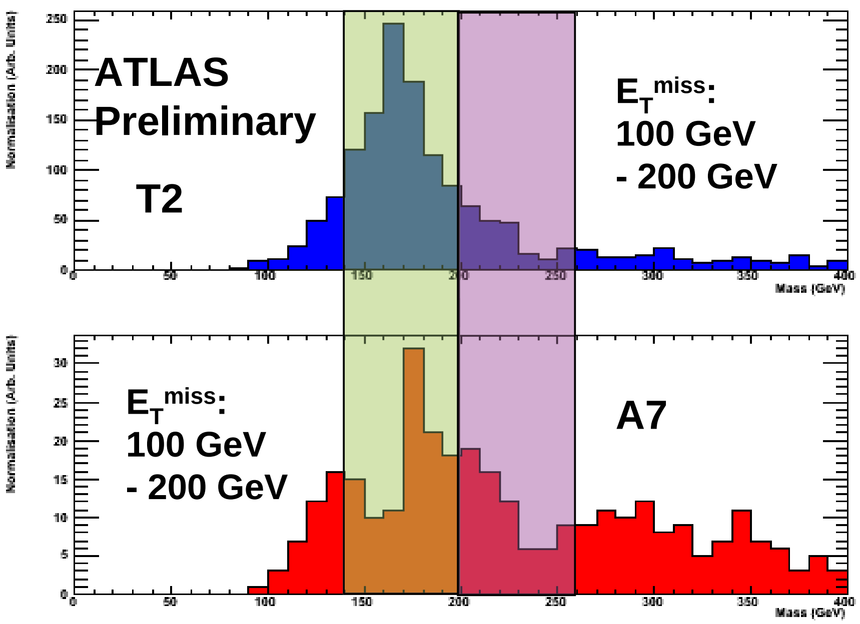
Use standard ATLAS top samples:

$T1$ (inclusive) $T2$ ($P_T^{top} > 500$ GeV)

Side-band subtraction

Select low $\not{E}_T$ top sample: $100 < \not{E}_T < 200$ GeV

Combinatorial from W+4 jets: compare to MonteCarlo W+4 jets sample (A7) to estimate contribution



Define:

- Signal band: 140-200 GeV
- Side band: 200-260 GeV

Sideband needs to be scaled by factor 1.57 to account for combinatorial under $m(top)$

Assume this factor can be calculated with MonteCarlo

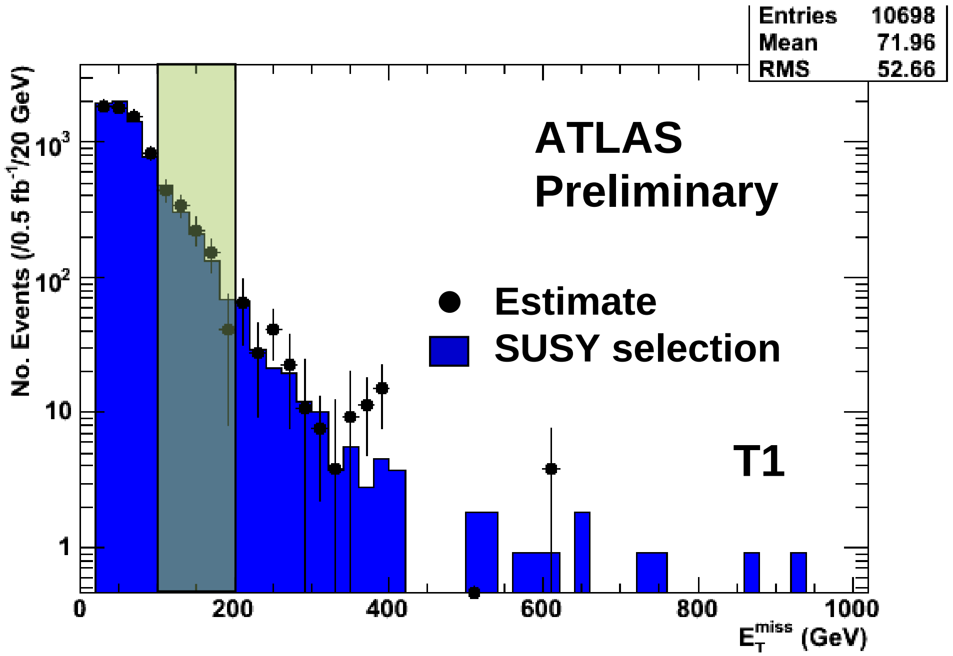
Normalising the estimate

Use signal band-sideband $\not\!\!E_T$ distribution for background estimate

Normalise to SUSY selection, to account for relative efficiency of top selection

Reminder: SUSY Selection:

- $\not\!\!E_T > 20$ GeV (to be hardened later)
- At least 4 GeV with $p_T > 40$ GeV
- Exactly 1 lepton with $p_T > 20$ GeV



Normalise to low $\not\!\!E_T$ region (100 GeV-200 GeV): SUSY signal expected to be small

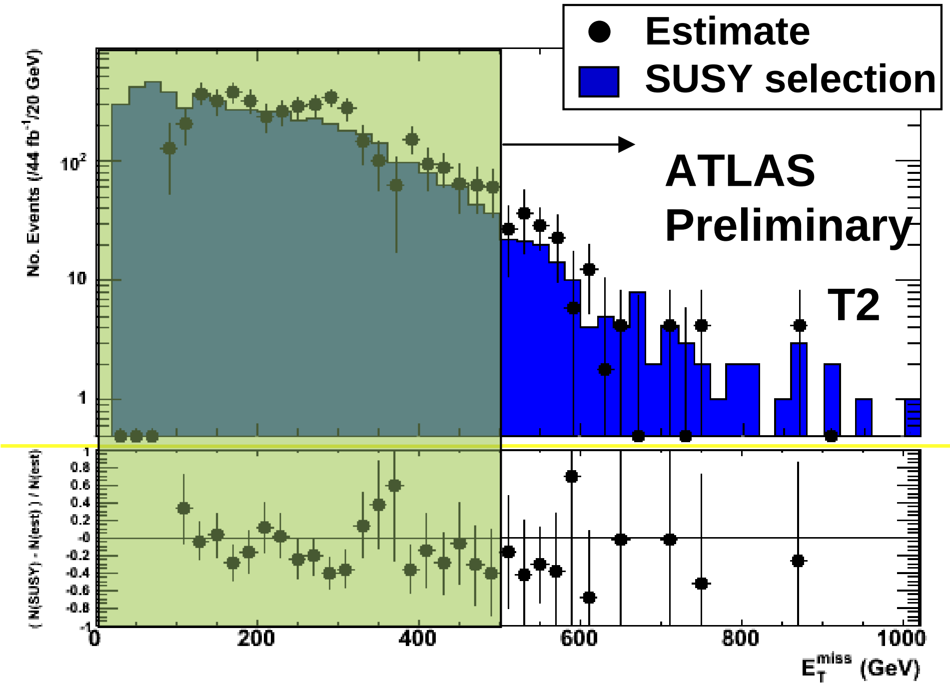
Assume low statistics (0.5 fb^{-1}) and use inclusive top sample

Obtain scaling factor of sim 4

Background estimates

Use sample T_2 ($P_T(top) > 500$ GeV to estimate precision

Count events with $\not{E}_T > 500$ GeV in SUSY selection and 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

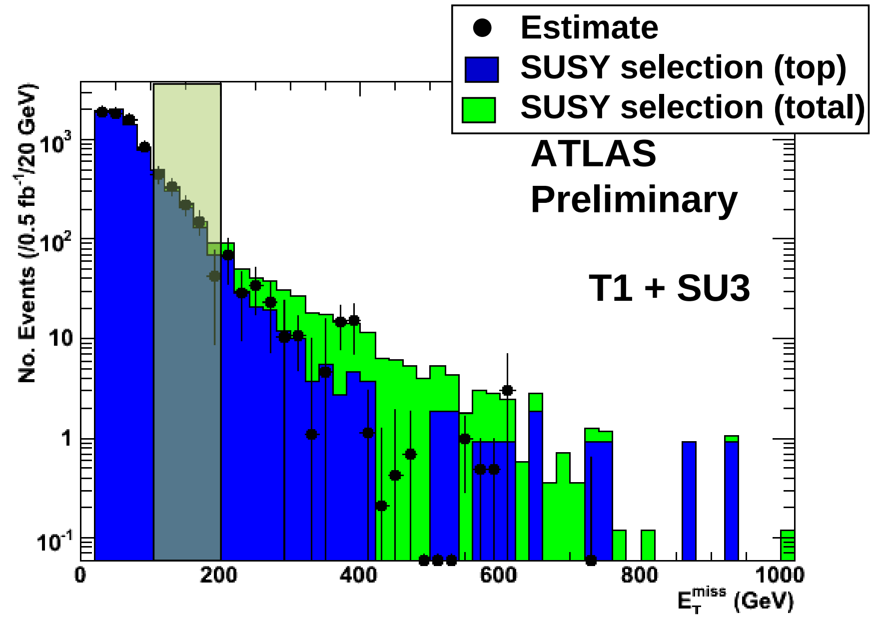
SUSY

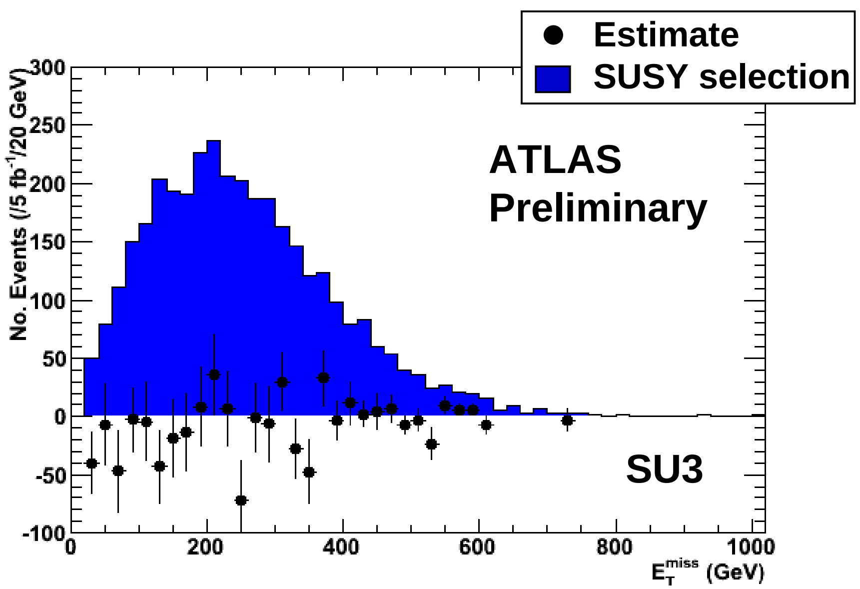
What happens if SUSY signal present?

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

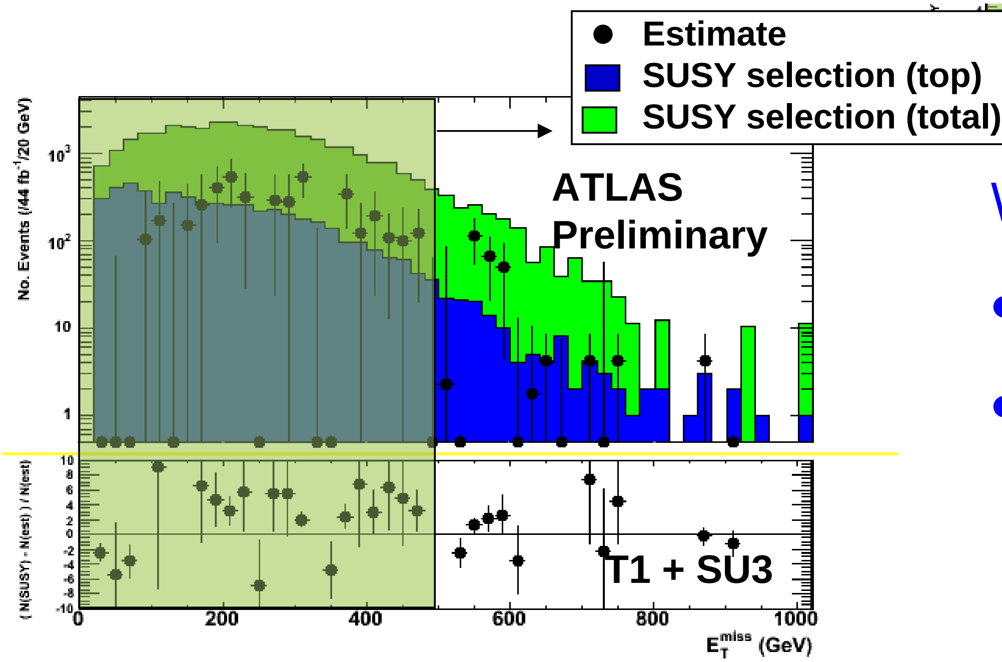
Sideband subtraction seems to work

Estimates with signal

Perform SUSY analysis using T_2 background sample

Background extrimates affected by increased sideband due to SUSY signal

Events after subtraction of expected top background:



With 44 fb^{-1}:

- SUSY signal+BG: 2146 ± 46
- BG only: -15 ± 75

Only an example, work ongoing for developing comparable strategies for main SM background sources

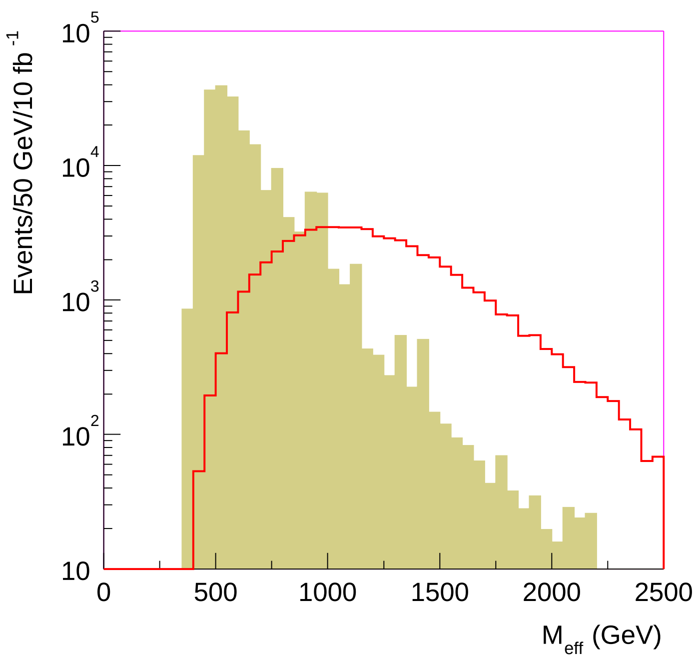
SUSY mass scale from inclusive analysis

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)

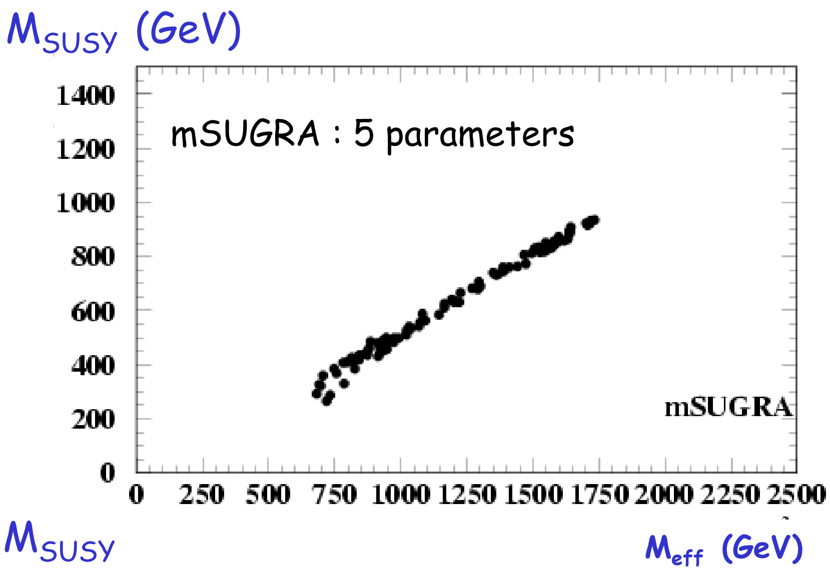
(mSUGRA $m_0 = 100$ GeV, $m_1/2 = 300$ GeV, $\tan\beta = 10$, $A = 0$, $\mu > 0$)

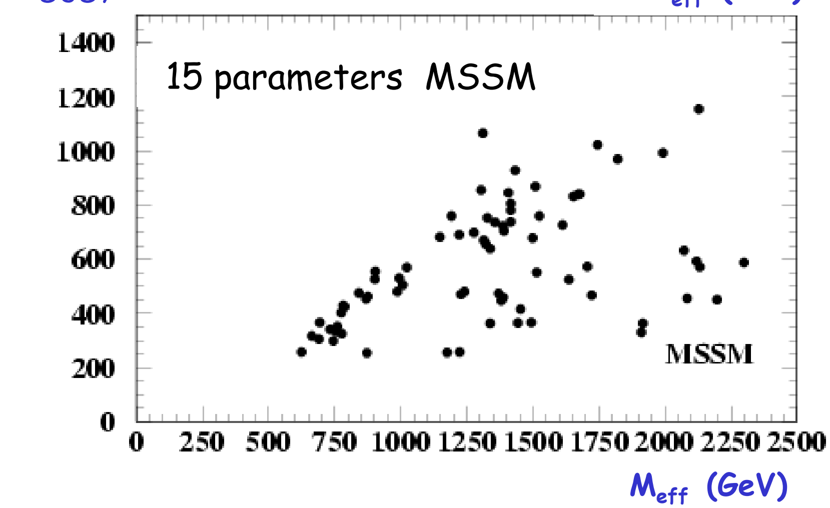
A cut on M_{eff} allows to separate the signal from SM background

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

Define the SUSY mass scale as:

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

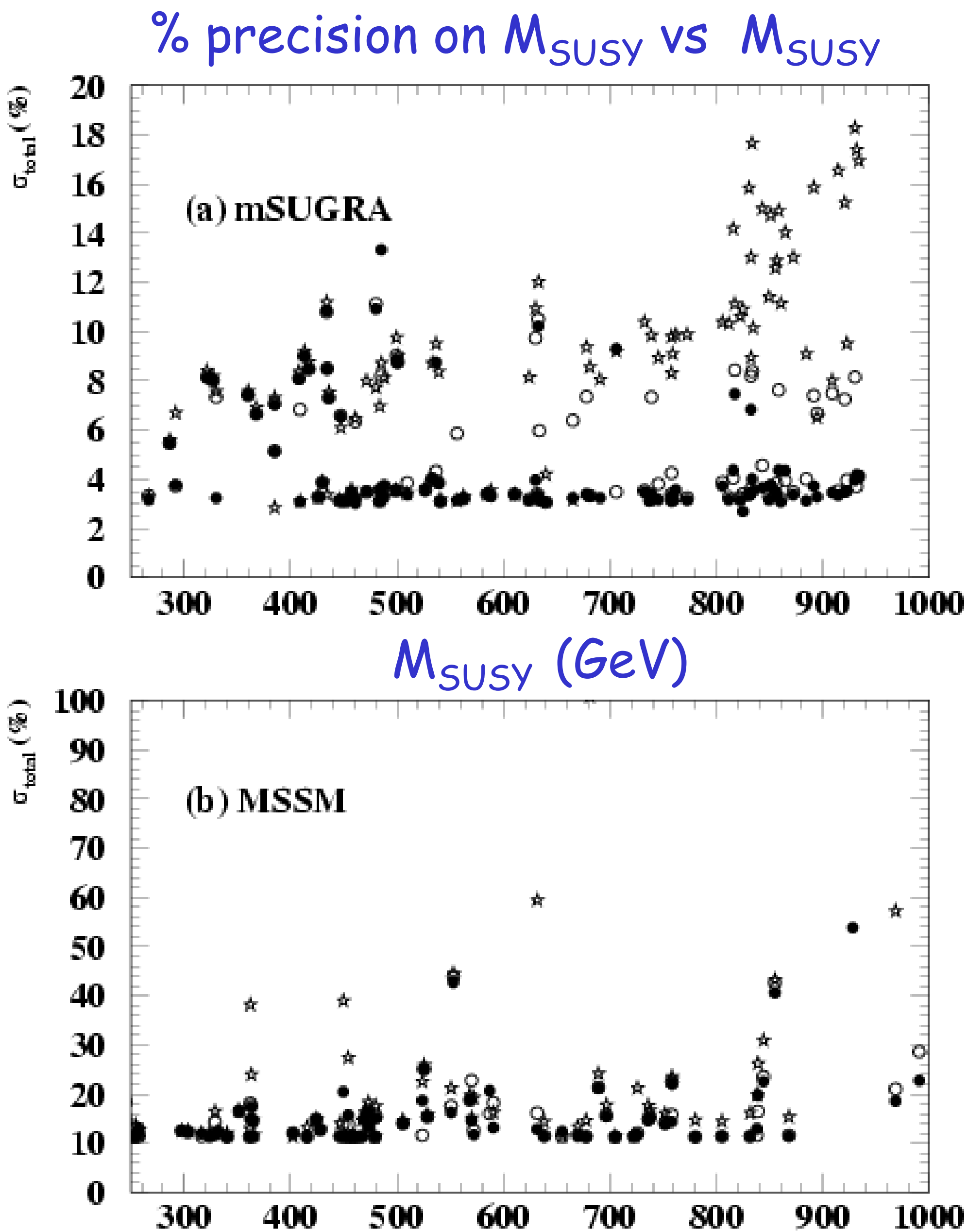




Estimate peak in $M_{\rm eff}$ by a gaussian fit to the background-subtracted signal distributions

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

Excellent correlation in mSUGRA, acceptable for MSSM



Evaluate uncertainty in mass scale from spread in correlation plots.

- 10 fb^{-1} - stars
- 100 fb^{-1} - open circles
- 1000 fb^{-1} - filled circles

$\sim 10\%$ 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 ∼ 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