Lecture2

SUSY searches at the LHC

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The LHC machine

Energy: $\sqrt{s}$=14 TeV

LEP tunnel: 27 Km circumference

1232 Superconducting dipoles, field 8.33 T

Luminosity:

- peak$\sim 10^{33}$ cm^{-2}s^{-1} - initial "low luminosity"

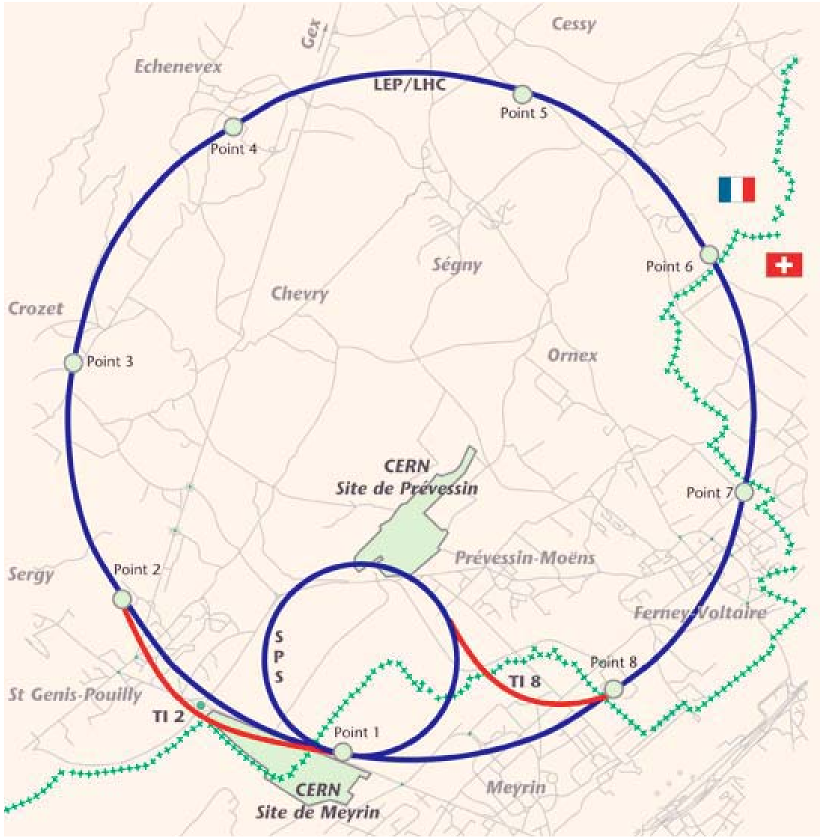
$$\int \mathcal{L}\mathrm{dt} = 10\ \mathrm{f}b^{-1}\ \text{per year}$$

- peak$\sim 10^{34}$ cm^{-2}s^{-1} - design "high luminosity"

$$\int \mathcal{L}\mathrm{dt} = 100\ \mathrm{f}b^{-1}\ \text{per year}$$

2808 bunches, 1.15×10^{11} protons per bunch

Inter-bunch space: 25 ns $\Rightarrow\sim 23$ inelastic interactions per crossing at full luminosity



Eight sectors

Point 1: ATLAS General purpose

Point 2: ALICE Heavy ions

Point 5: CMS General purpose

Point 8: LHCb B-physics

ATLAS detector

EM Calorimeters, $\sigma/E \approx 10\%/\sqrt{E(\text{GeV})} \oplus 0.7\%$

excellent electron/photon identification

Good *E* resolution (e.g., $H \to \gamma\gamma$)

Precision Muon Spectrometer,

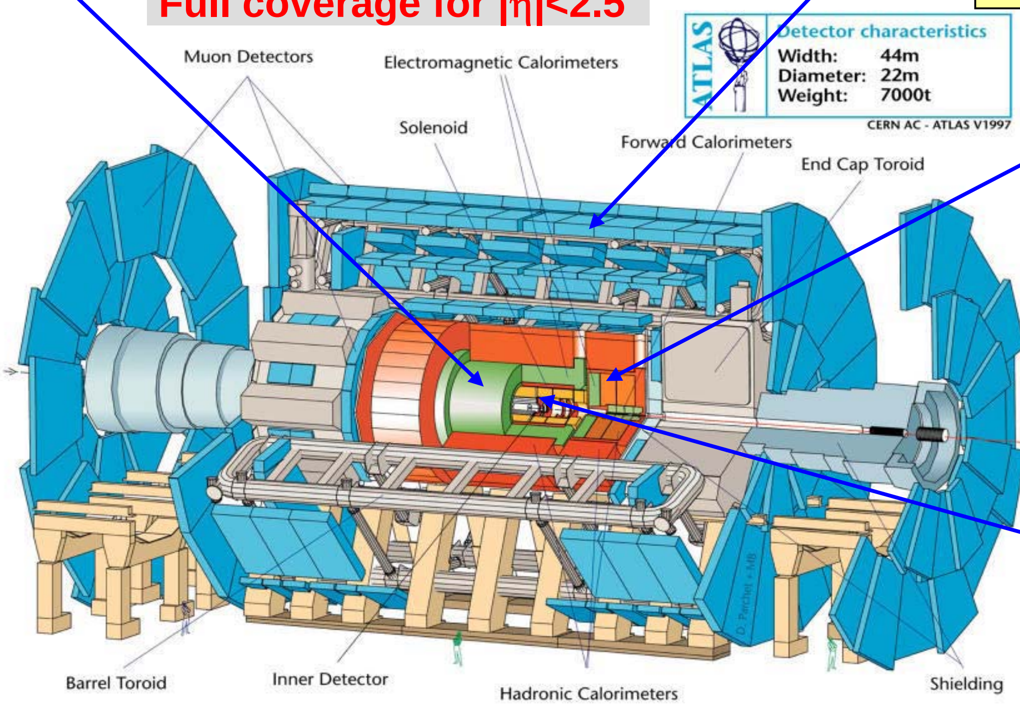
$\sigma/p_T \approx 10\%$ at 1 TeV/c

Fast response for trigger

Good *p* resolution

(e.g., $A/Z' \to \mu\mu$, $H \to 4\mu$)

Full coverage for $|\eta|<2.5$



Hadron Calorimeters,

$\sigma/E \approx 50\% / \sqrt{E(\text{GeV})} \oplus 3\%$

Good jet and E_T miss performance

(e.g., $H \to \tau\tau$)

Inner Detector:

Si Pixel and strips (SCT) &

Transition radiation tracker (TRT)

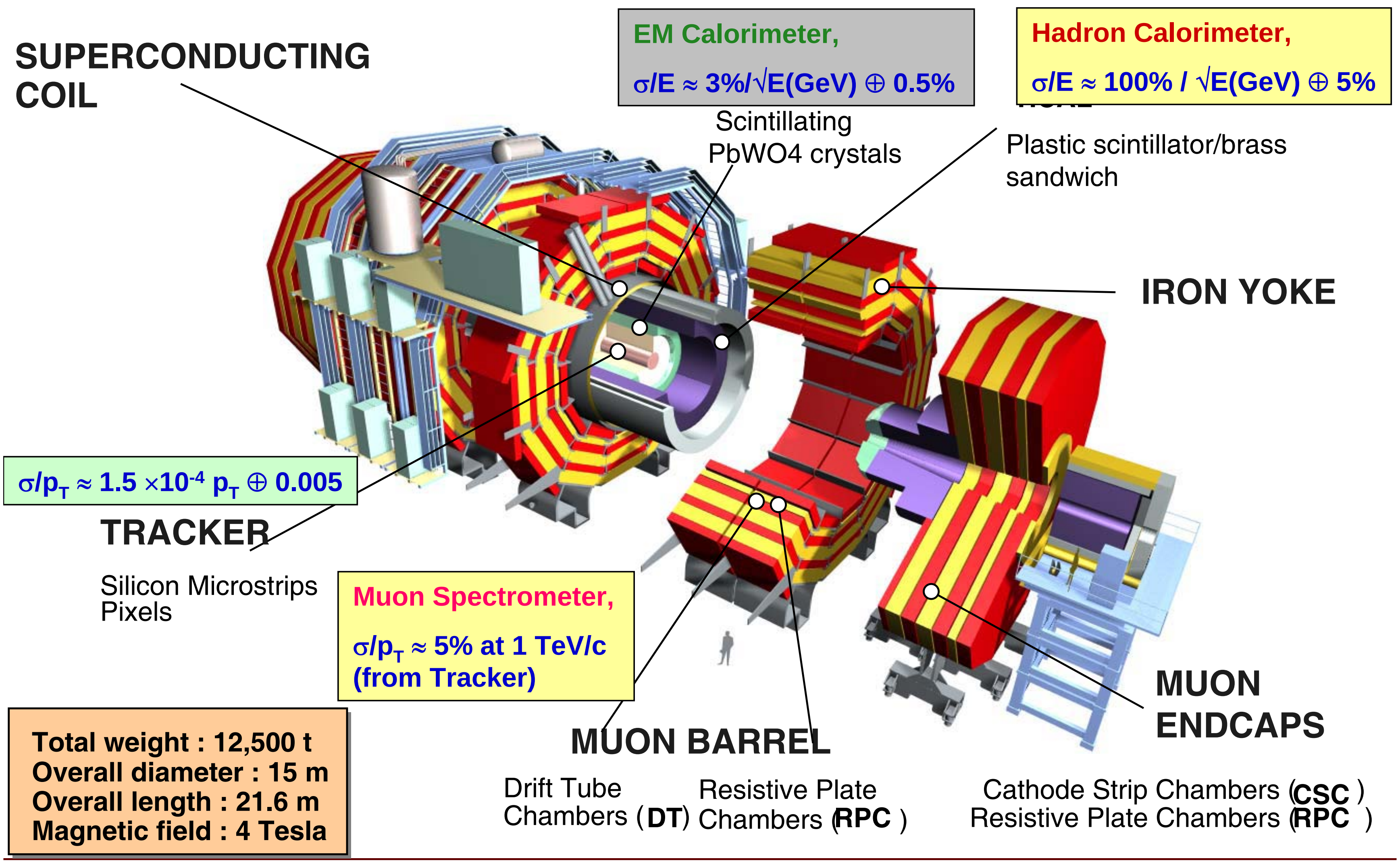
$\sigma/p_T \approx 5 \times 10^{-4}\, p_T \oplus 0.001$

Good impact parameter res.

$\sigma(d_0)=15\mu m@20GeV$ (e.g. $H \to bb$)

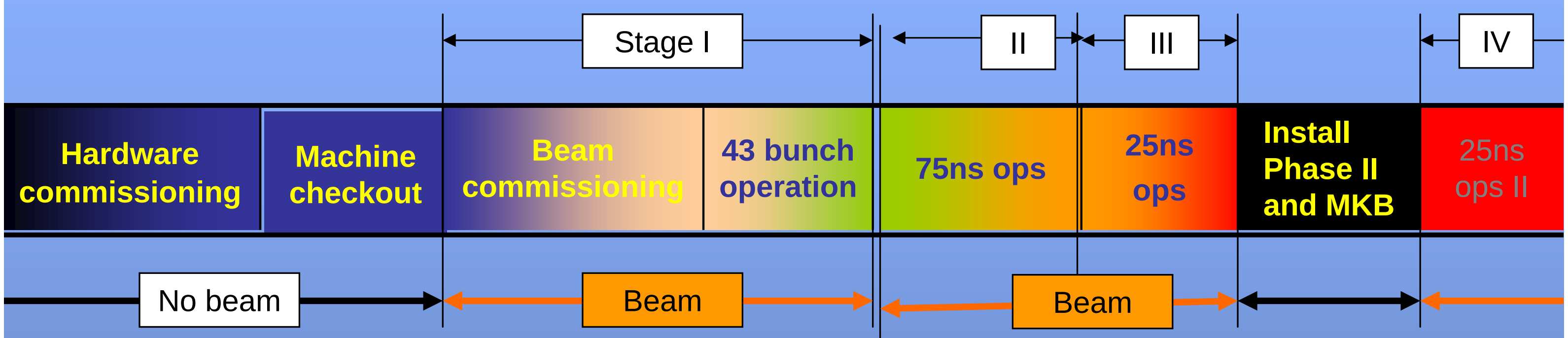
Magnets: solenoid (Inner Detector) 2T, air-core toroids (Muon Spectrometer) ~0.5T

CMS detector



What luminosity profile at the start?

Staged commissioning plan for protons



I. Pilot physics run
   - **First collisions**
   - **43 bunches, no crossing angle, no squeeze, moderate intensities**
   - **Push performance (156 bunches, partial squeeze in 1 and 5, push intensity)**

II. 75ns operation
   - **Establish multi-bunch operation, moderate intensities**
   - **Relaxed machine parameters (squeeze and crossing angle)**
   - **Push squeeze and crossing angle**

III. 25ns operation I
   - **Nominal crossing angle**
   - **Push squeeze**
   - **Increase intensity to 50% nominal**

IV. 25ns operation II
   - **Push towards nominal performance**

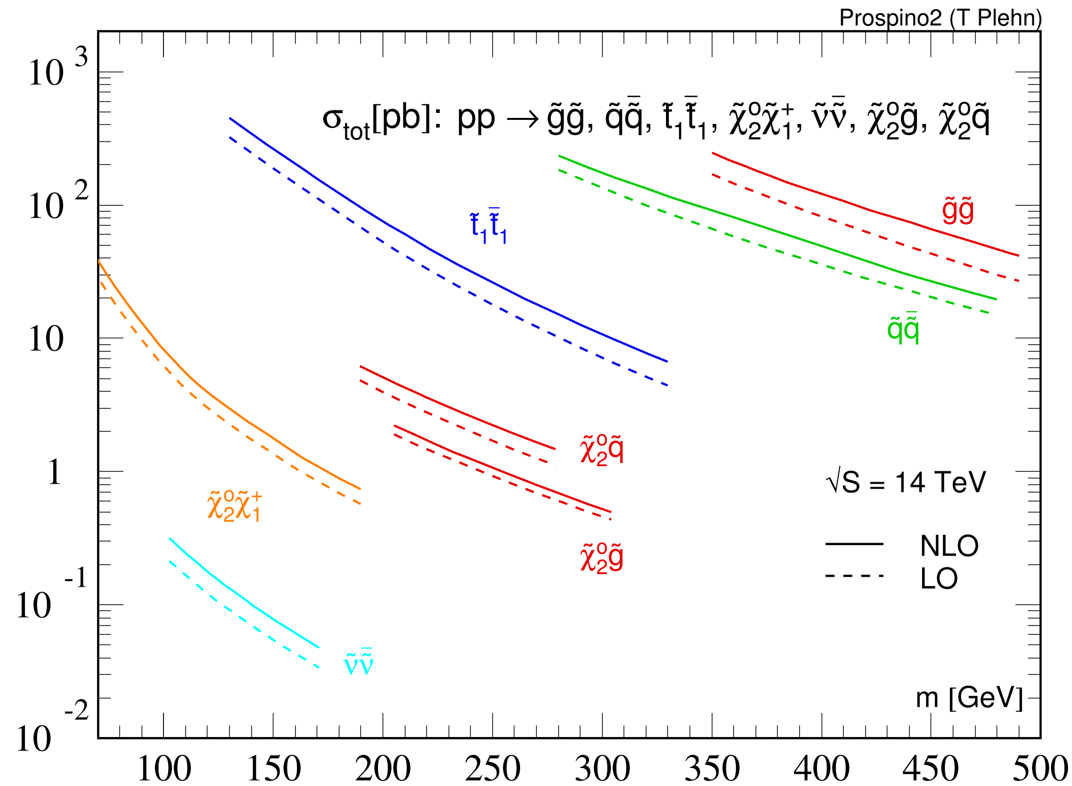
The beam commissioning at 7 TeV might take around 2 months. (M. Lamont)

First collisions late summer? Hope for 1 fb^{-1} by end 2008?

SUSY at the LHC: general features

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

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

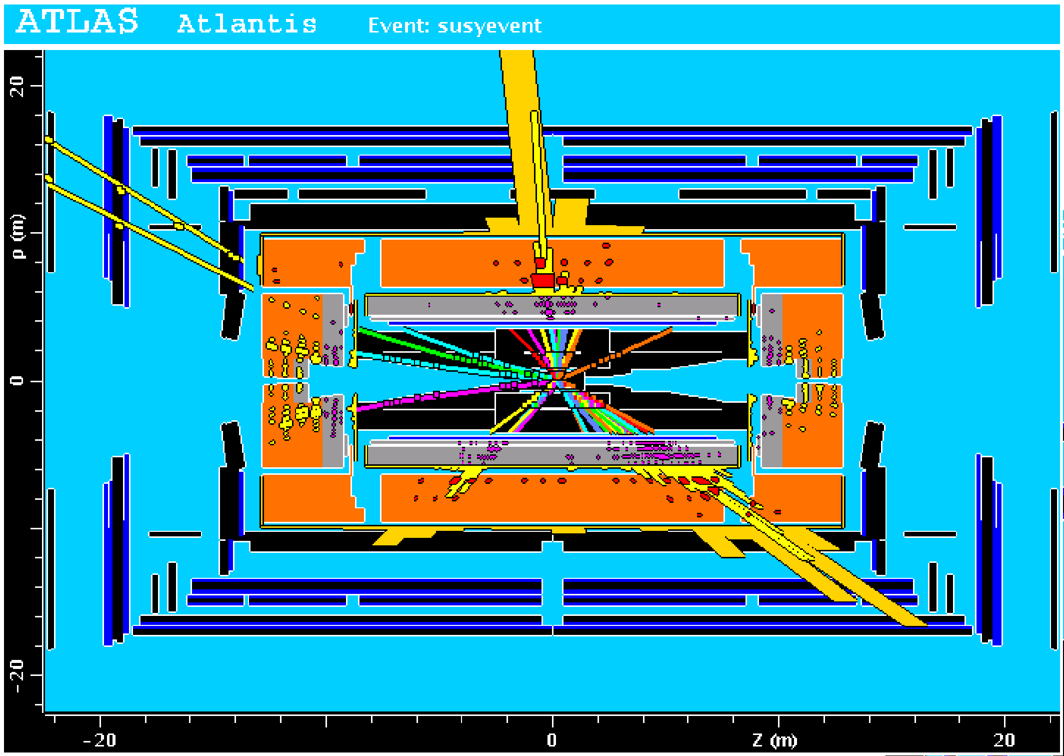
$\Rightarrow$ If R_p conserved, complex cascades to undetected LSP, with large multiplicities of jets and leptons produced in the decay.

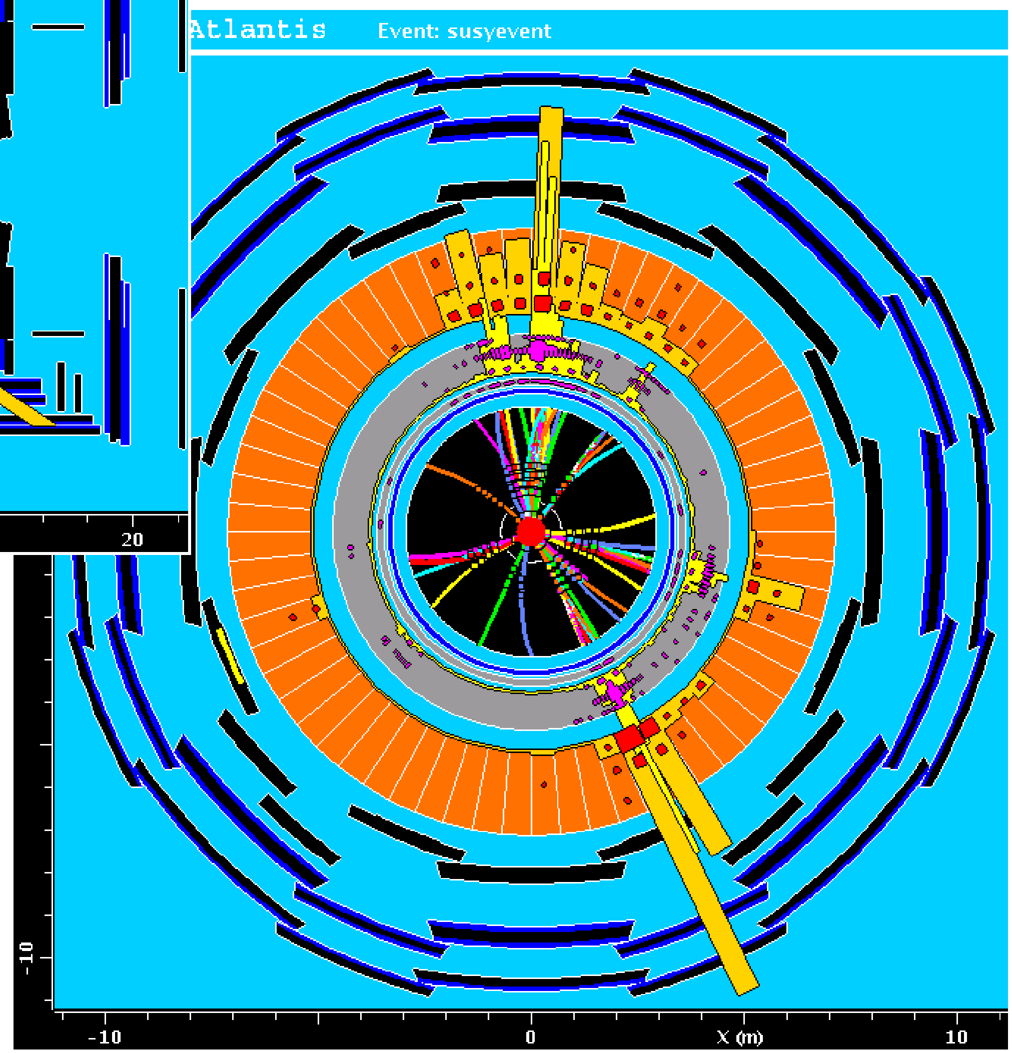
Both negative and positive consequences:

- 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!

A SUSY event in ATLAS





Multi-jet event in
Bulk Region

- 6 jets
- 2 high-pt muons
- Large missing E_T

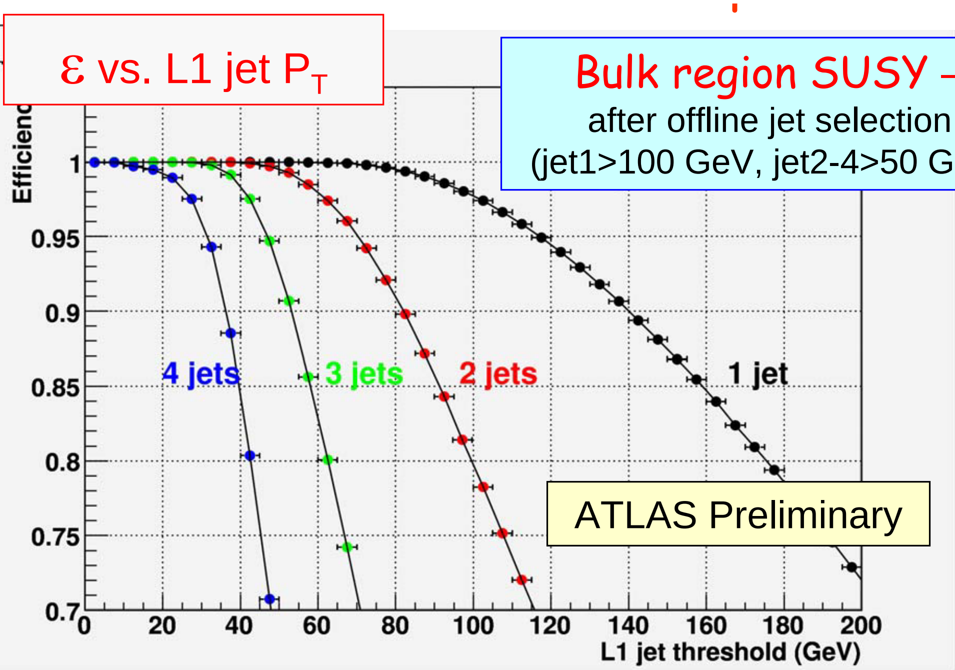
Triggering on SUSY

We do not know how SUSY will appear, use very simple, inclusive triggers

The main features for RPC SUSY will be: high multiplicity of high P_T jets, $\not{E}_T$+jets

$\not{E}_T$ might require time to be understood: in early running (10^{31} cm^{-2}s^{-1}) select SUSY with low-threshold multijet triggers

Very useful to collect control samples with unbiased $\not{E}_T$



Example: SUSY point $m(\tilde{q}/\tilde{g}) \sim 600$ GeV

Require four jets with LVL1 Threshold > 25 GeV

Efficiency close to one w.r.t to the offline selection.

Absolute efficiency on signal $\sim 50 - 60\%$, rate ~ 10 Hz (preliminary)

Single jet trigger, to catch low multiplicity decays

LVL1 Thresh:115 GeV, $\epsilon \sim 90\%$, Rate ~ 6 Hz

Examples under discussion, need to match them with overall ATLAS trigger strategy

E_T^{miss} trigger

$\not\!\!E_T$ single cut with largest rejection power for SUSY

Run the lowest $\not\!\!E_T$ threshold compatible with budgeted rate

Needed to achieve high efficiency for lowest mass points, and to put on tape control samples necessary for background evaluation

At 10^{31} cm^{-2}s^{-1} for LVL1 $\not\!\!E_T > 50$ GeV rate $\sim$20 Hz (ATLAS)

Validate $\not\!\!E_T$ trigger by requiring additional high E_T jet.

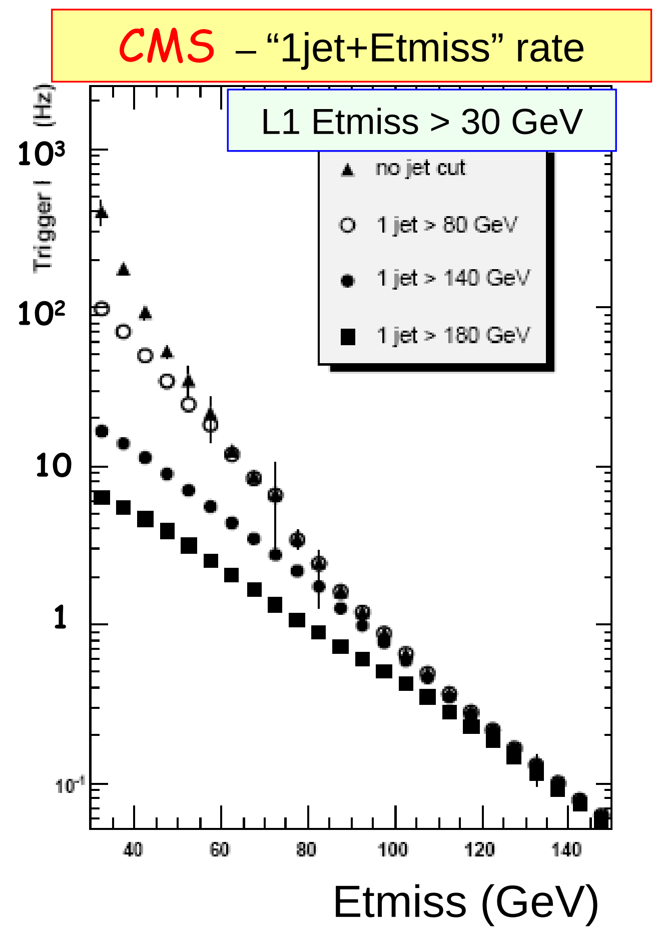
Rejects instrumental and machine background

CMS plot for 10^{32} cm^{-2}s^{-1}:

evolution of $\not\!\!E_T$+jet rate for increasing value of jet E_T

ATLAS: $\not\!\!E_T > 70$ GeV, 1 Jet with $E_T > 70$ GeV.

Rate $\sim$20 Hz at 2×10^{33} cm^{-2}s^{-1}.



ATLAS standard trigger menu for 10^{33} cm^{-2}s^{-1}

Trigger menu table

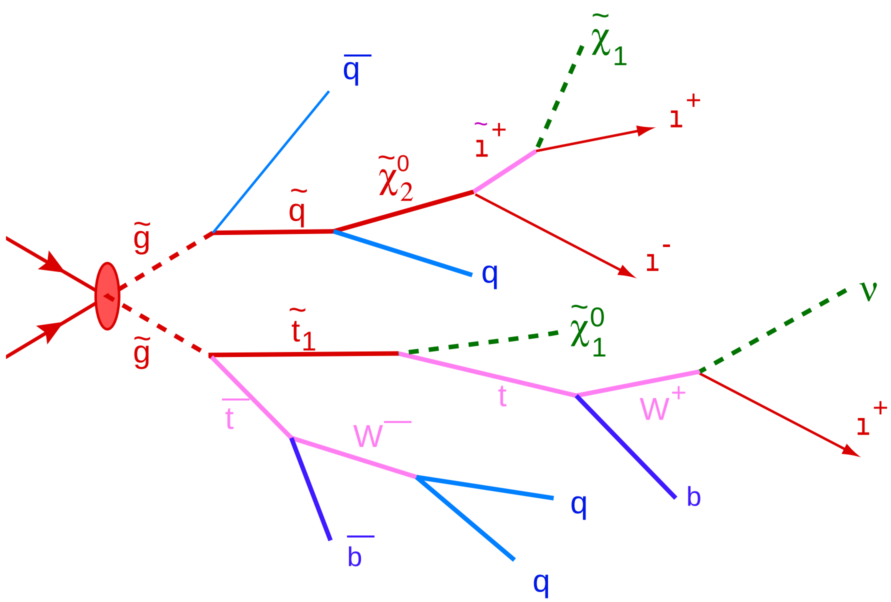
Object	Physics coverage	Object name
electrons	Higgs, new gauge bosons, extra dim., SUSY, W/Z, top	e25i, 2e15i, e60
Photons	Higgs, SUSY, extra dim.	γ60, 2γ20i
Muons	Higgs, new gauge bosons, extra dim., SUSY, W/Z, top	μ20i, 2μ10
Jets	SUSY,compositness,resonances	j400, 3j165, 4j110
Jets+missEt	SUSY, leptoquarks	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

SUSY discovery: basic strategy

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

Details of cascade decays are a function of model parameters. Focus on robust signatures covering large classes of models and large rejection of SM backgrounds



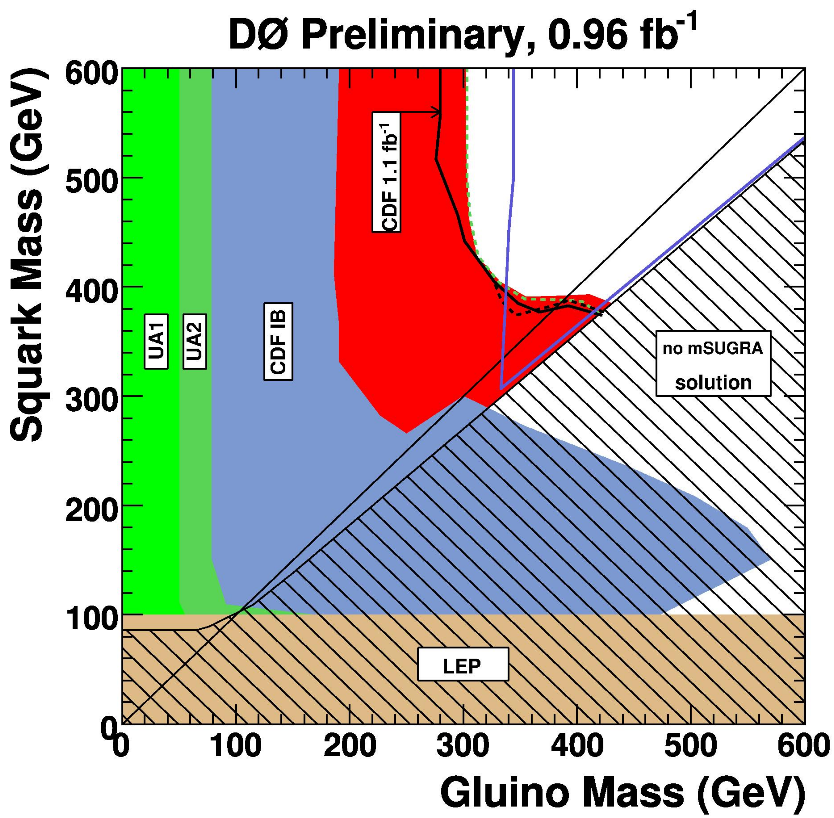
- $\not\!\!E_T$: from LSP escaping detection
- High E_T jets: guaranteed if squarks/gluinos if unification of gaugino masses assumed.
- Multiple leptons (Z): from decays of Charginos/neutralinos in cascade
- Multiple τ-jets or b-jets (h): Often abundant production of third generation sparticles

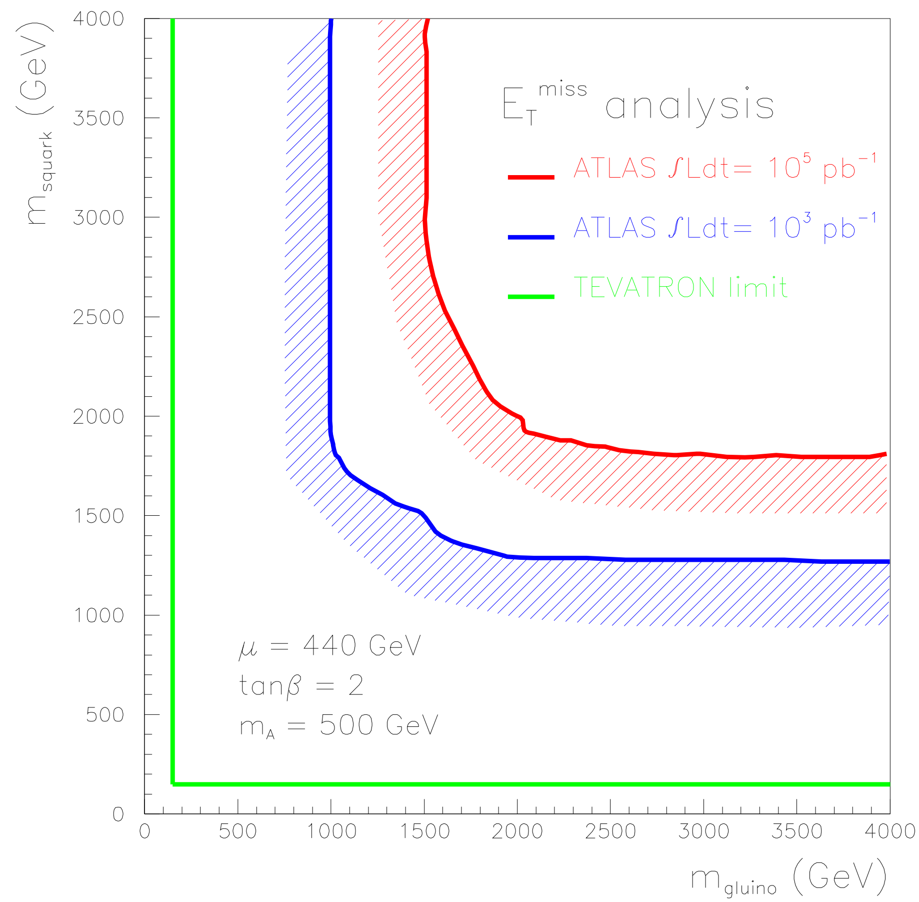
Define basic selection criteria on these variables for RPC SUSY with $\tilde{\chi}_1^0$ LSP

Optimisation of criteria on parameter space ongoing, will define set of topologies, and for each define sets of cuts aimed respectively at high and low SUSY masses

Alternative LSP options with different signatures also under study

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

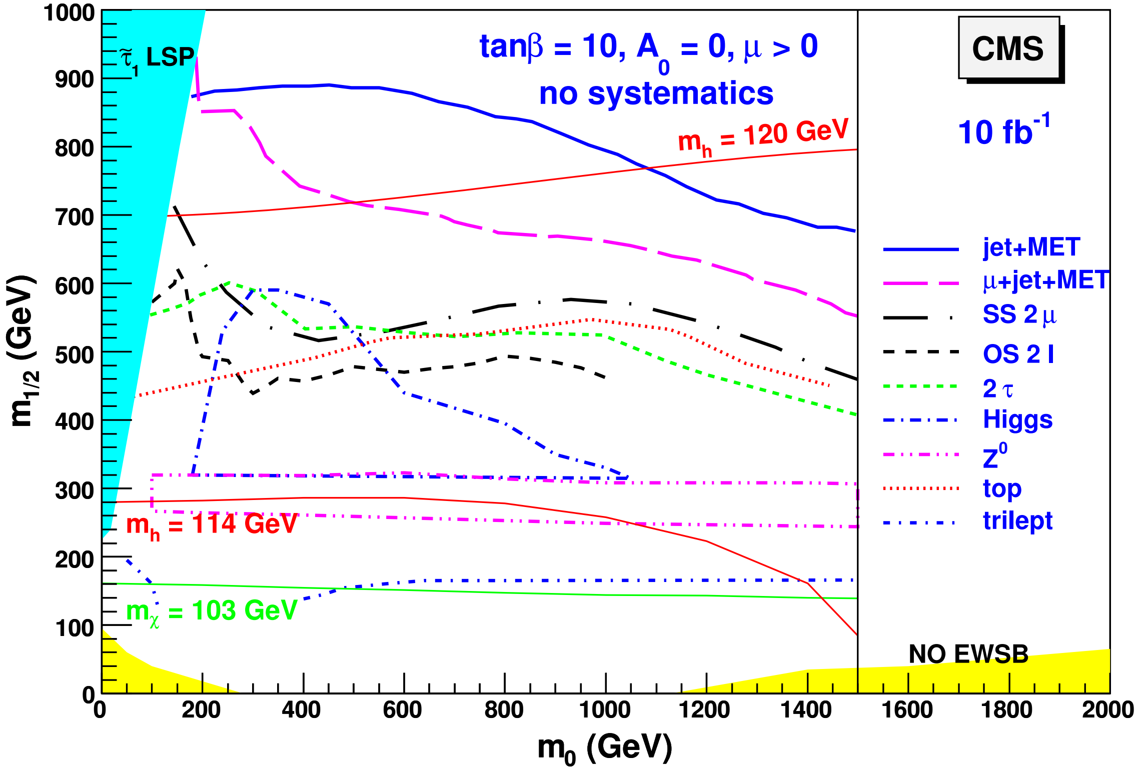




Large increase in mass reach for the LHC

Very old ATLAS study (early 90's), generic analysis cuts not optimised for different phase-space regions

Inclusive signatures in mSUGRA parameter space



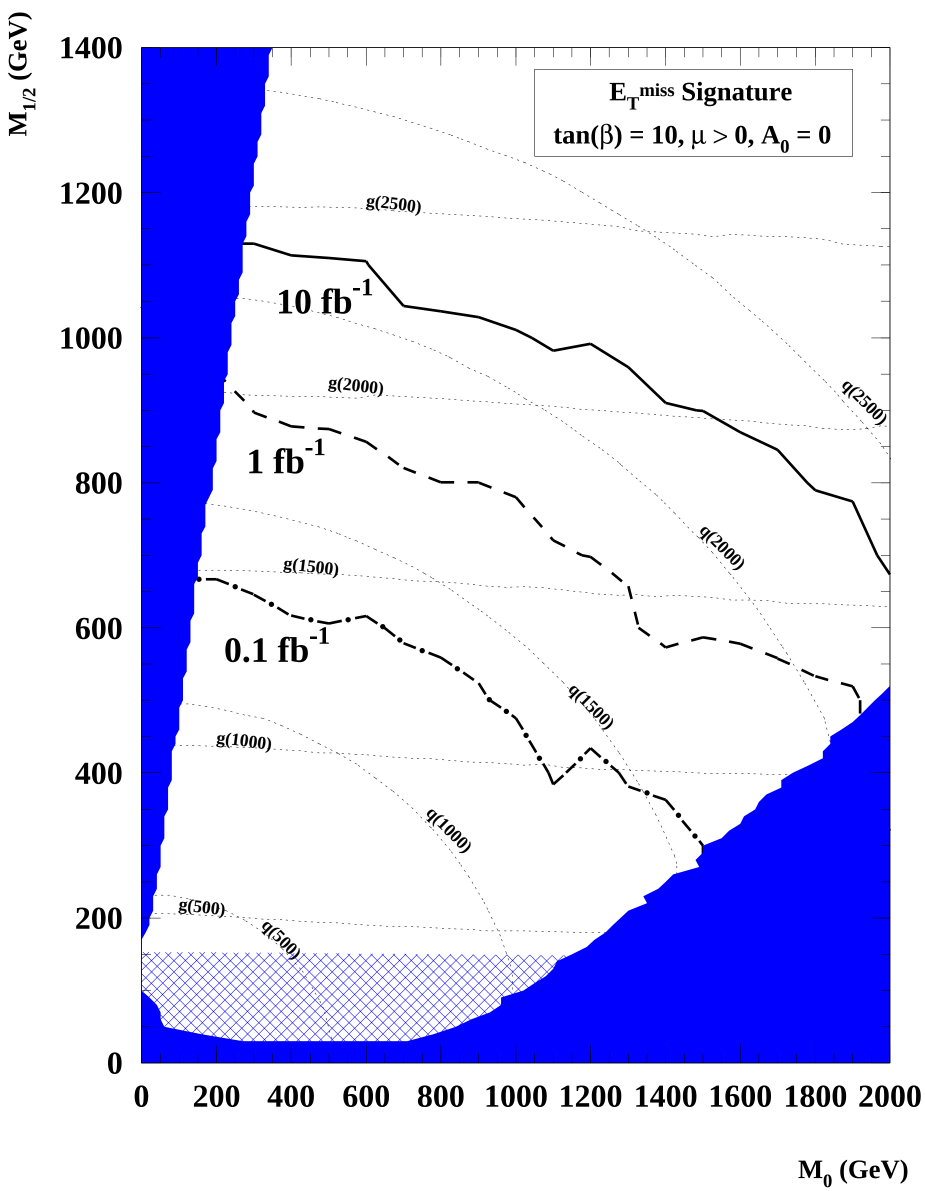
Multiple signatures over most of parameter space

Dominated by $\not\!\!E_T$+jets

Robust search, if signal observed in a channel, can look for confirmation in other channels

ATLAS (preliminary) tried also scan in model with non universal higgs masses, with in principle different decay patterns, and result are very similar

Discovery reach as a function of luminosity



$\sim$100 pb^{-1}: few days of running

$\sim$1 fb^{-1}: first run (1-2 months)

$\sim$10 fb^{-1}: first year at 10^{33}cm^{-2}s^{-1}

Fast discovery from signal statistics, *BUT*

Before we discover SUSY we need to:

- Understand early detector performance:

  $\not\!\!E_T$ tails, lepton id, jet scale

- 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

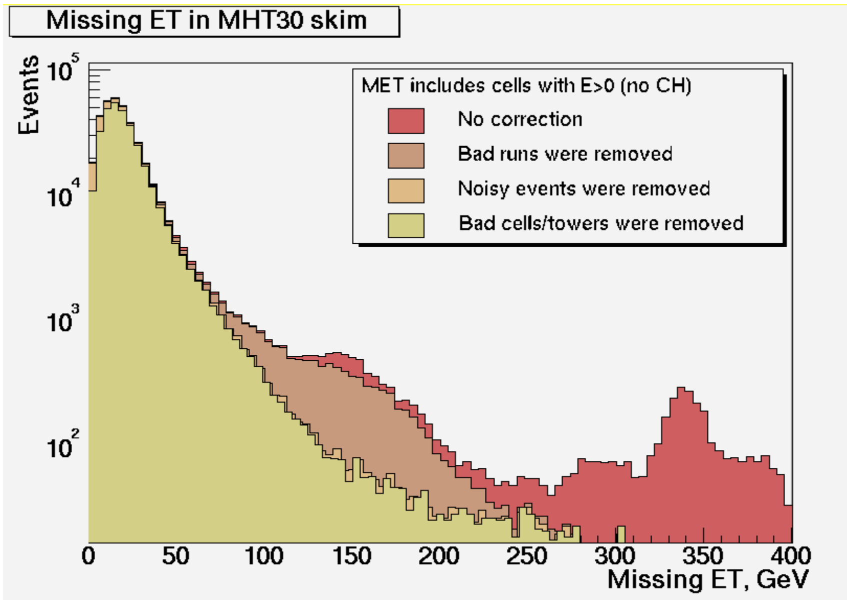
Instrumental backgrounds to $\not{E}_T +$ jets analysis

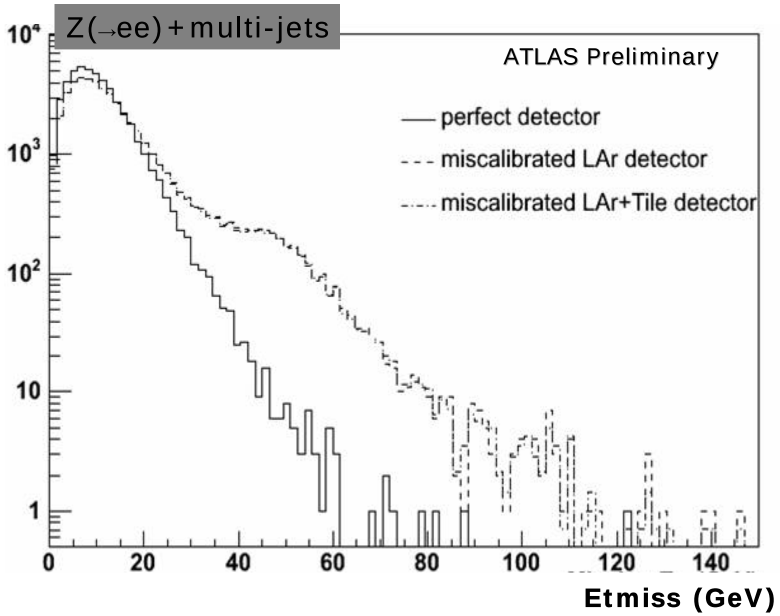
$\not{E}_T$ from mismeasured multi-jet events:

Populated by detector and machine problems

Example of $\not{E}_T$ cleaning in D0

- Reject runs with detector malfunctioning
- Reject events with noise in the detector
- Remove bad cells





ATLAS example: assume a few HV channels dead in calorimeters

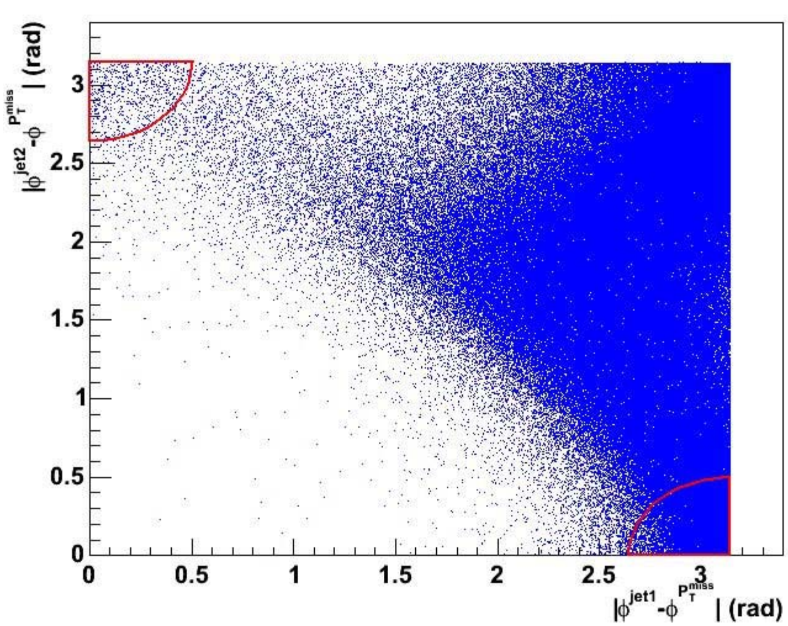
Tools being prepared to monitor and correct event-by-event

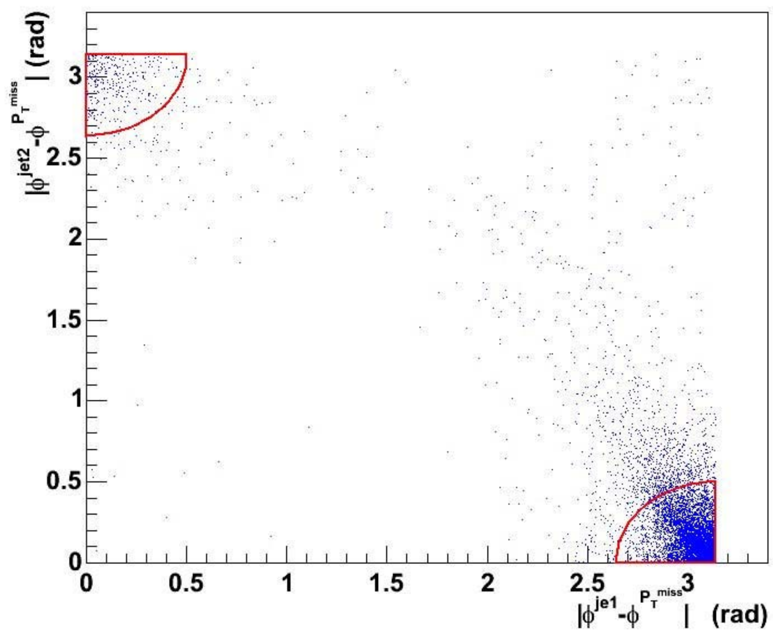
Instrumental background: Cleaning the sample 1

Next step is rejection of topologies which likely to yield instrumental $\not{E}_T$

One jet is undermeasured, expect that $\not{E}_T$ be aligned with its p_T. If two-jet events, this will be measured as the second jet in the event

If one jet overmeasured jet energy measurement: $\not{E}_T$ back to back with respect to it





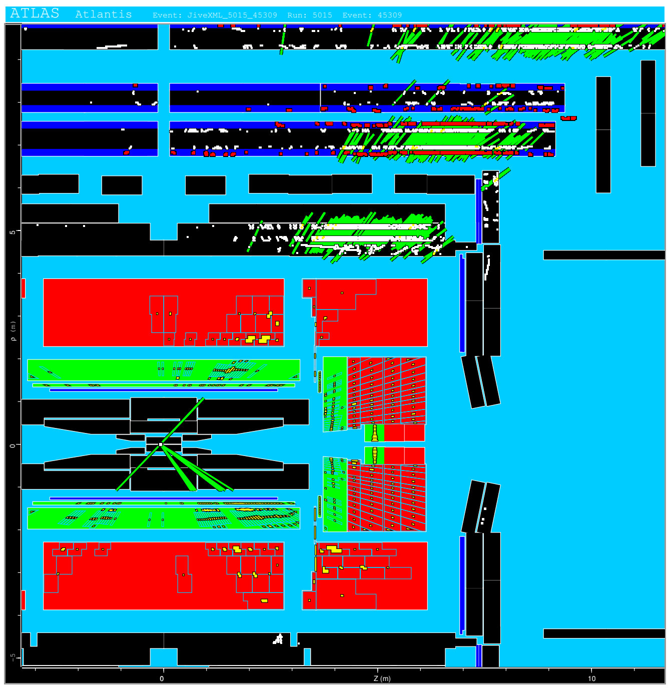
From CMS TDR: $|\phi^{jet2} - \phi^{\not{E}_T}|$ vs. $|\phi^{jet1} - \phi^{\not{E}_T}|$

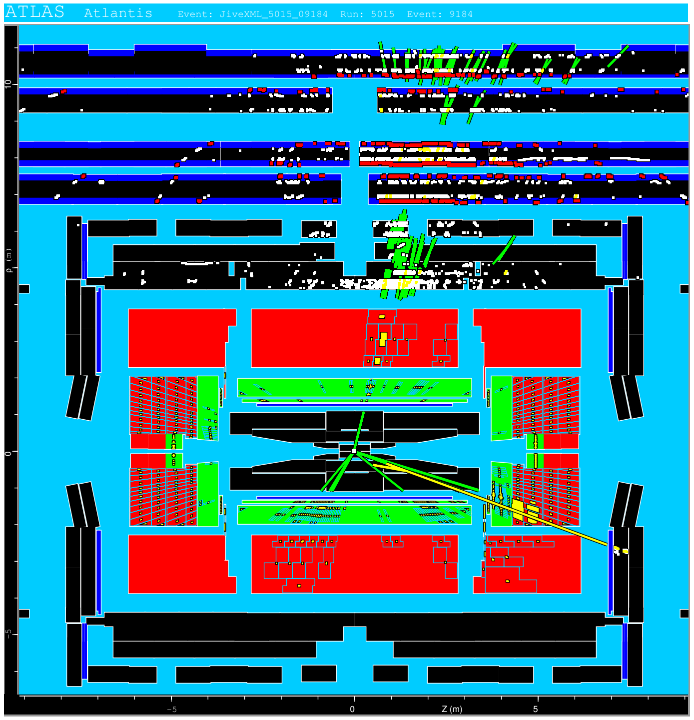
Left plot: Signal Right plot: QCD

Instrumental background: cleaning the sample 2

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.

Use this variable to clean the sample

Instrumental backgrounds: data-driven estimate

MonteCarlo estimate of QCD background hard

Requires complete understanding of detector

$\Rightarrow$ Develop data-driven estimate (ATLAS preliminary)

1: Measure jet smearing function:

- Select events with:

$\not\!\!E_T > 60$ GeV, $\Delta\phi(\not\!\!E_T, jet) < 0.1$

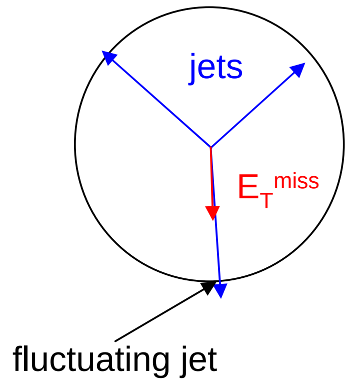
- Estimate true E_T of jet closest to $\not\!\!E_T$ as:

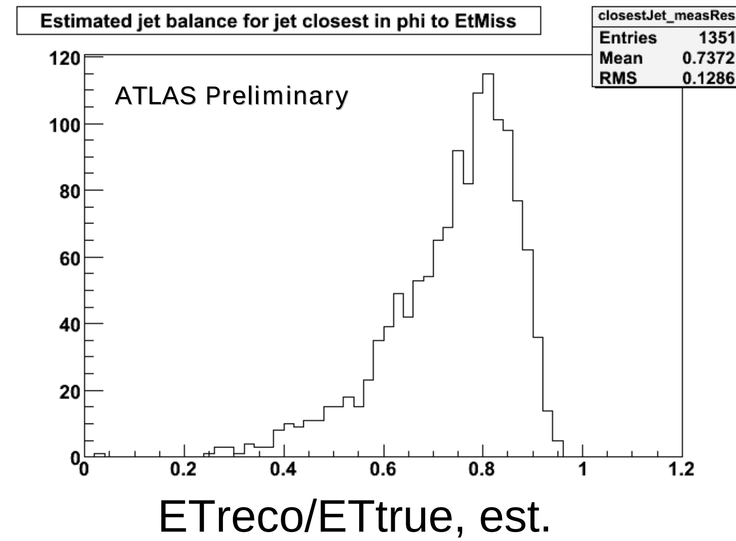
$E_T^{true} = p_T^{reco} + \not\!\!E_T$

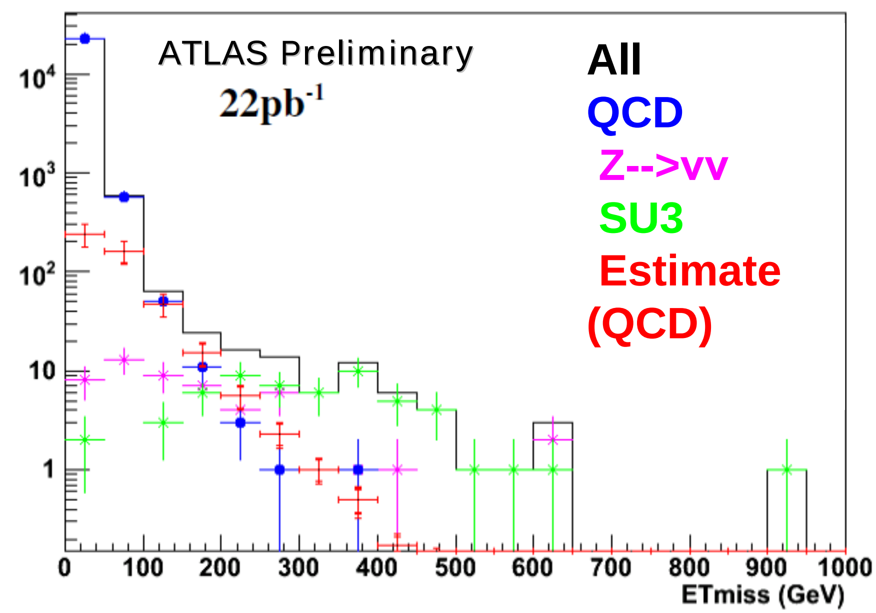
2: Take low $\not\!\!E_T$ jet events and smear jets with measured smearing function

3: Normalize to data

QCD $\not\!\!E_T$ tail nicely reproduced







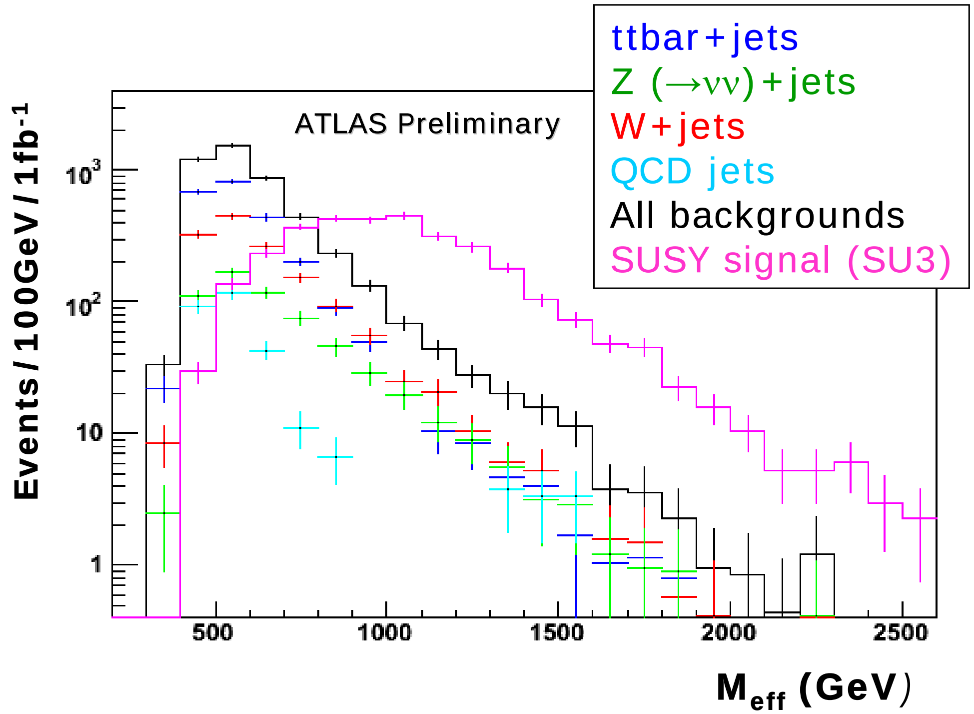
Control of $\not\!\!E_T$ from Standard Model processes

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

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



SU3 benchmark Point: $m_0 = 100$ GeV, $m_{1/2} = 300$ GeV, $\tan\beta = 6$, $A = -300$ GeV, $\mu > 0$

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

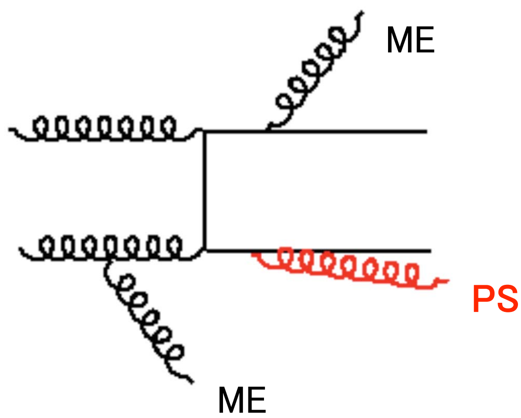
SM backgrounds: Monte Carlo issues

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:



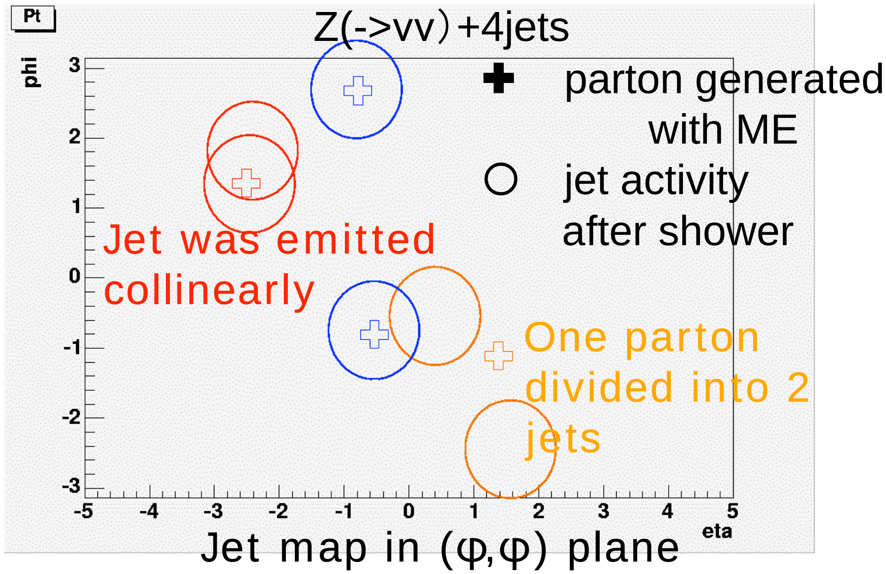
- Parton showering (PS): good in collinear region, but underestimates emission of high-p_T jets
- Matrix Element (ME): requires cuts at generation to regularize collinear and infrared divergences

Optimal description of events with both ME and PS switched on

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

Additional issue: normalisation (no NLO calculation possible)

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 exclusive $Z+$ n jets sample

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

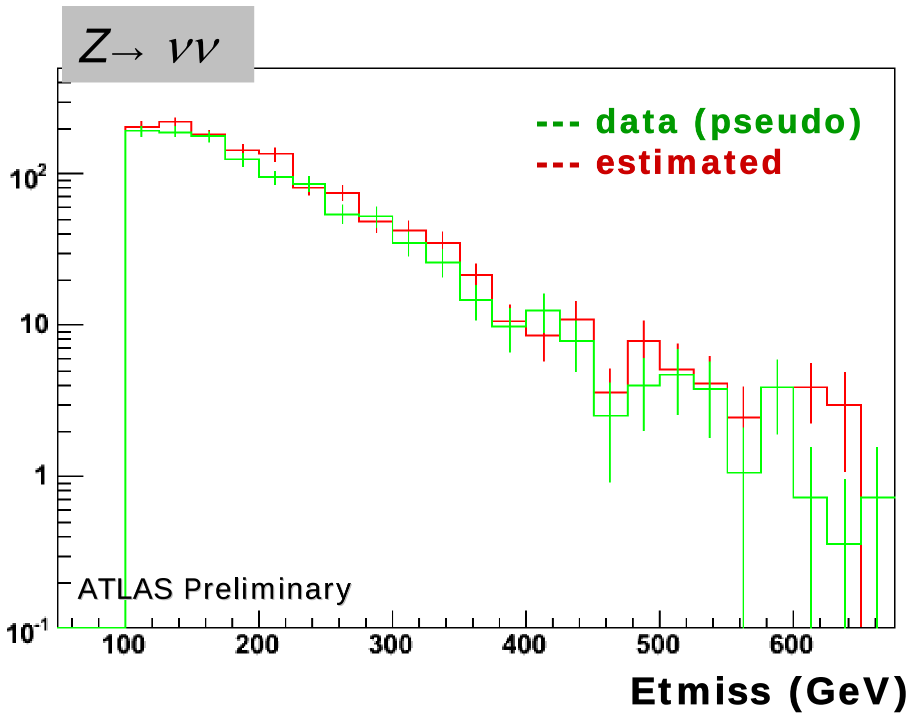
BUT, tuning of matching valid for Tevatron might not be valid in LHC regime. A detailed comparison of W/Z+jets MonteCarlos with LHC data is necessary prerequisite for SUSY searches

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

Data driven estimates: $Z \to \nu\nu+$ jets

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

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})



By comparing $Z \to \mu\mu$ sample from data and MC, calculate normalisation factor to apply to MC $Z \to \nu\nu$ sample

Combination of data and MonteCarlo needed for estimate

Good absolute prediction of background

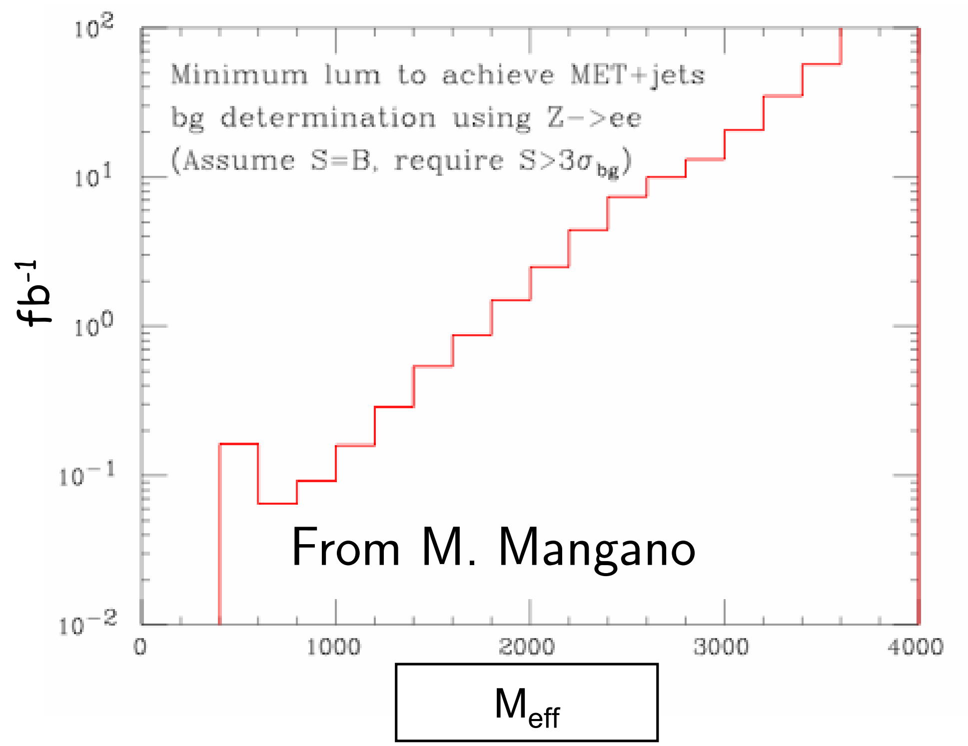
Normalisation needs to be multiplied by $BR(Z \to \nu\nu)/BR(Z \to ee) \sim 6$

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

Additional inclusive signatures

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

BUT control of SM and instrumental backgrounds might require long time before discovery

Optimize search strategy by tackling in parallel all of the inclusive discovery channels

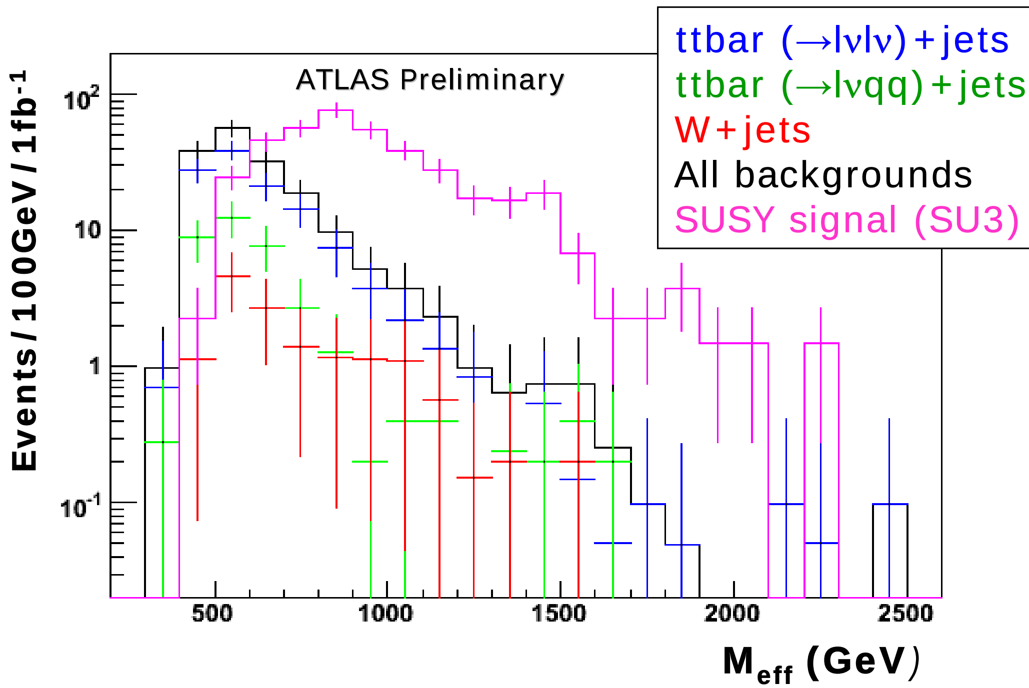
Example: single lepton + jets + $\not\!\!E_T$

Smaller number of backgrounds:

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

Shoulder m M_{eff} might be observable

If adequate lepton ID achieved, background dominated by SM events with neutrinos: $\bar{t}t$, W+jets



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:

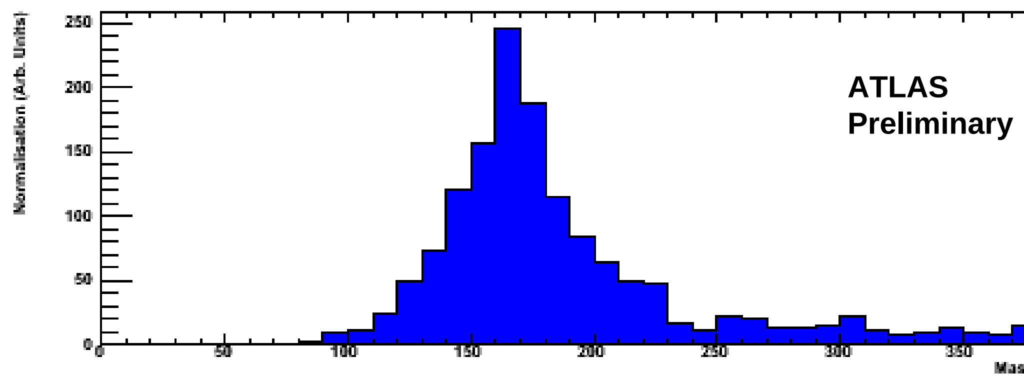
- Select semi-leptonic top candidates (standard cuts: what b-tag available?)
- Fully reconstruct top events from $\not{E}_T$ and W mass constraint

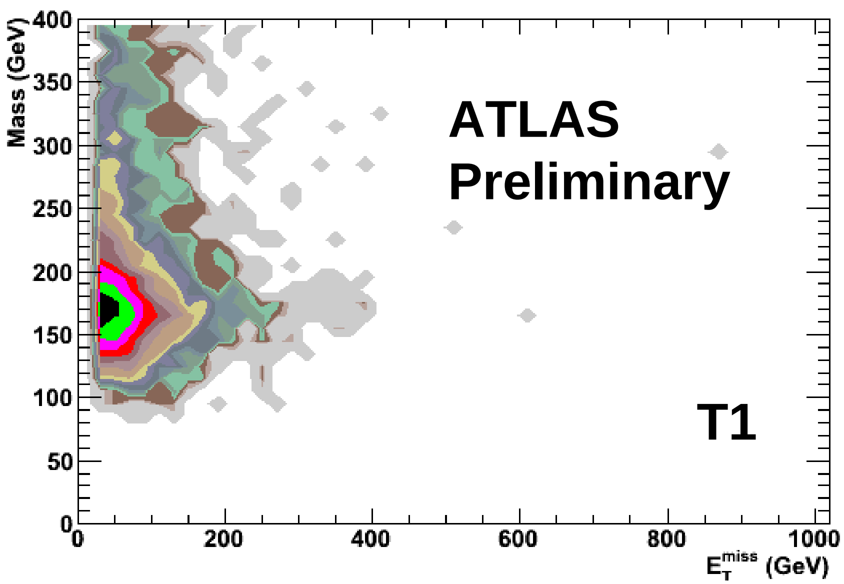
$\Rightarrow$ obtain pure top sample with no SUSY contamination

- 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

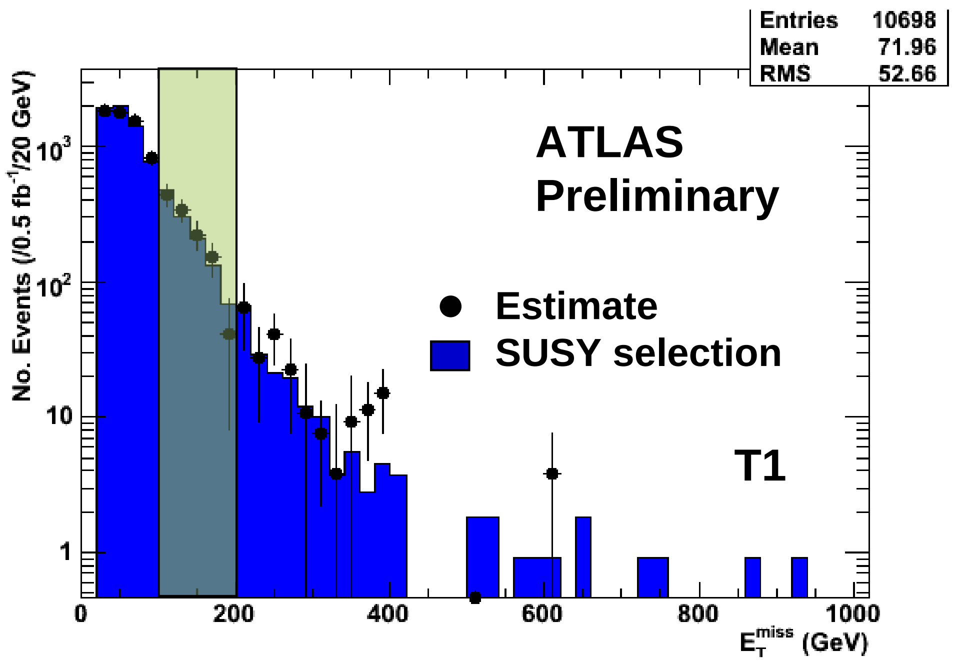
"Estimate": fully reconstructed top sample after side-band subtraction

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



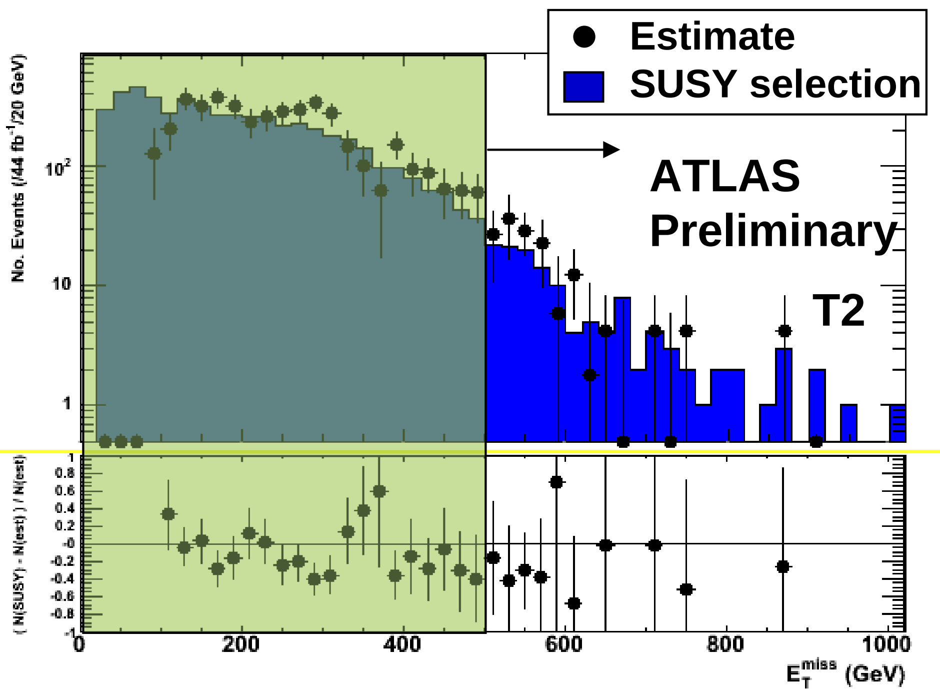
In low $\not\!\!E_T$ region (100 GeV-200 GeV): SUSY signal expected to be small

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

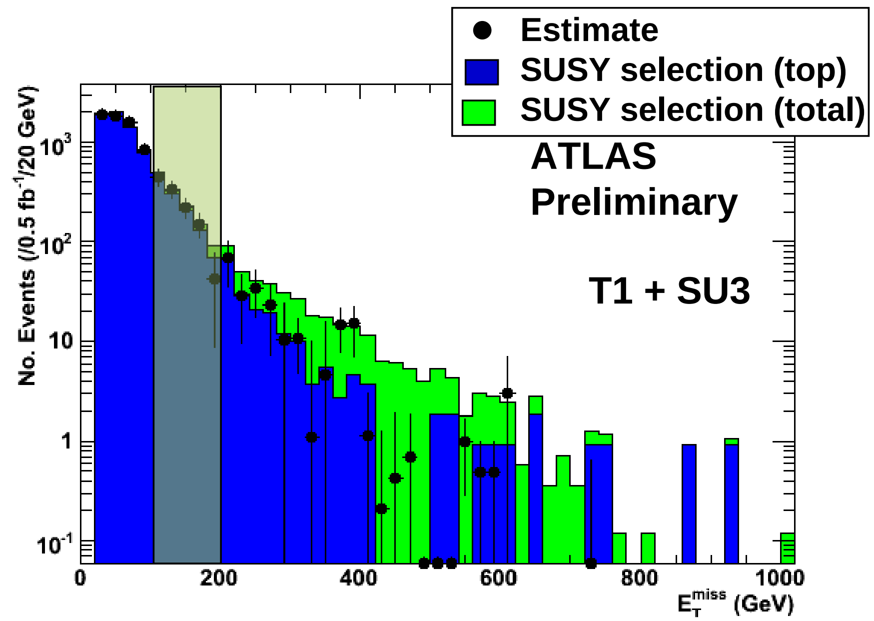
SUSY

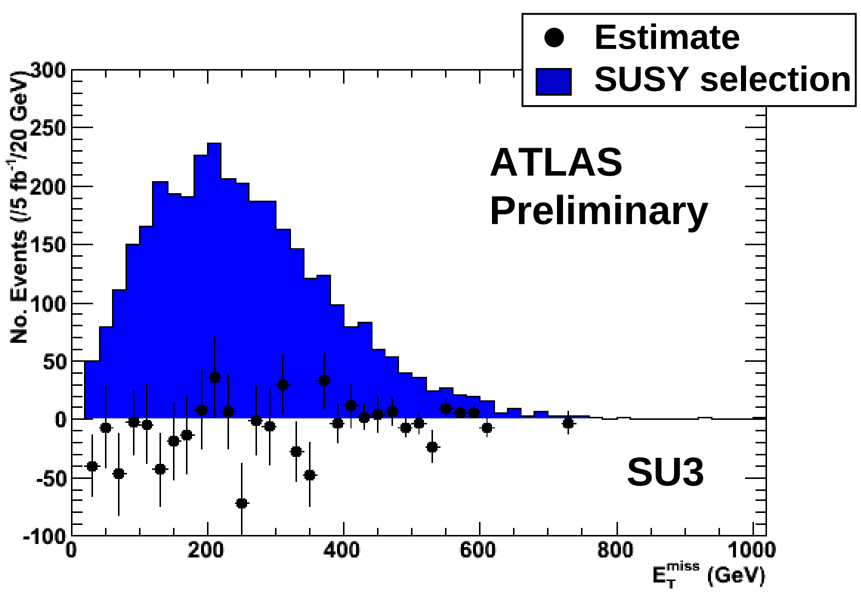
What happens if SUSY signal present?

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

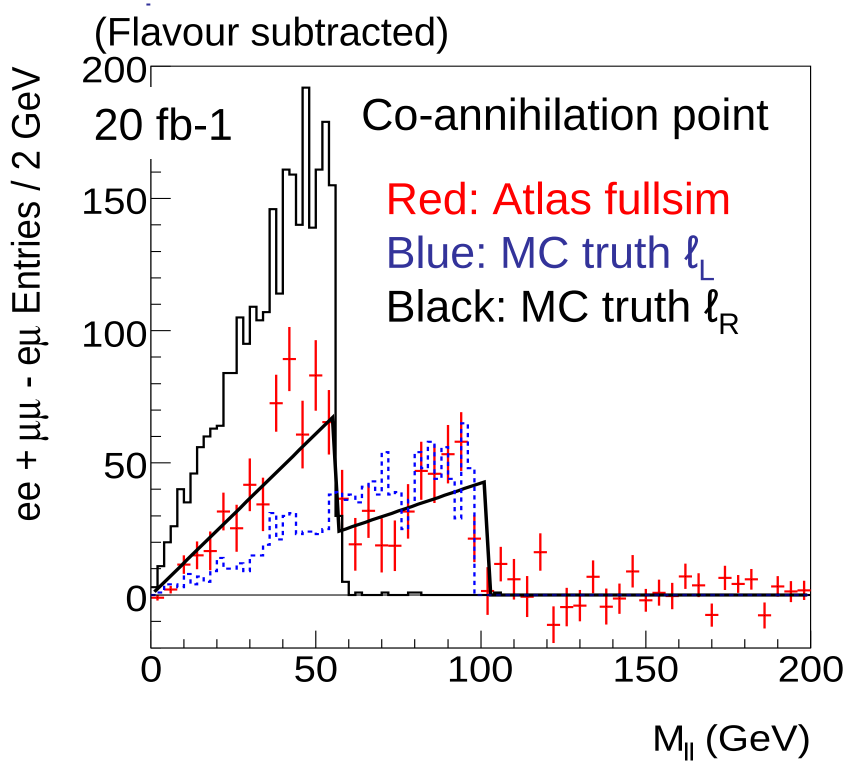
Significantly lower reach than other channels, but also lower backgrounds

Different topologies, corresponding to different SM background sources

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

OS-OF can show flavour-correlated signal.

$$\tilde{q}_L \rightarrow \tilde{\chi}_2^0 \; q$$
$$\quad \hookrightarrow \tilde{\ell}^{\pm}_{R(L)} \; \ell^{\mp}$$
$$\quad\quad \hookrightarrow \tilde{\chi}_1^0 \; \ell^{\pm}$$



Only $Z/\gamma \rightarrow e^+e^-, \mu^+\mu^-$ has same-flavour leptons, strongly reduced by $\not\!\!E_T$+jets requirement

Background dominated by $\bar{t}t$, can be exactly flavour-subtracted

Clear kinematic signature: if we are lucky best chance for early discovery

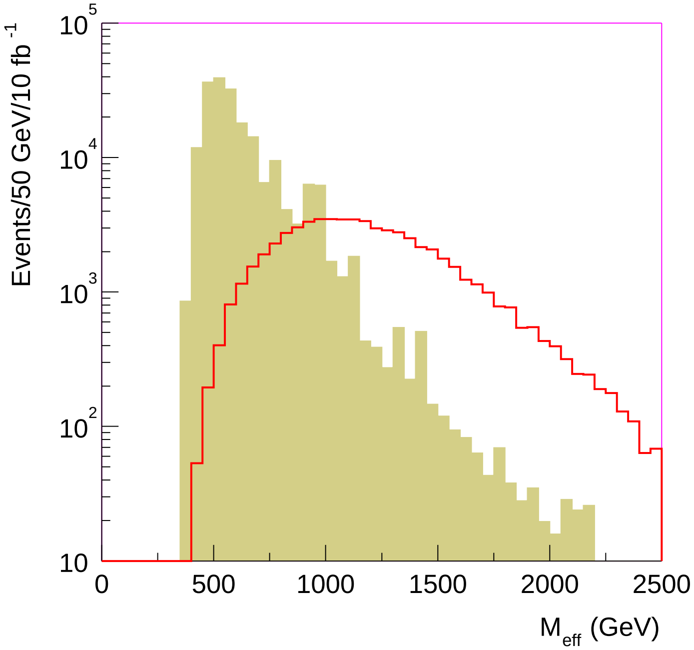
SUSY mass scale from inclusive analysis

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)

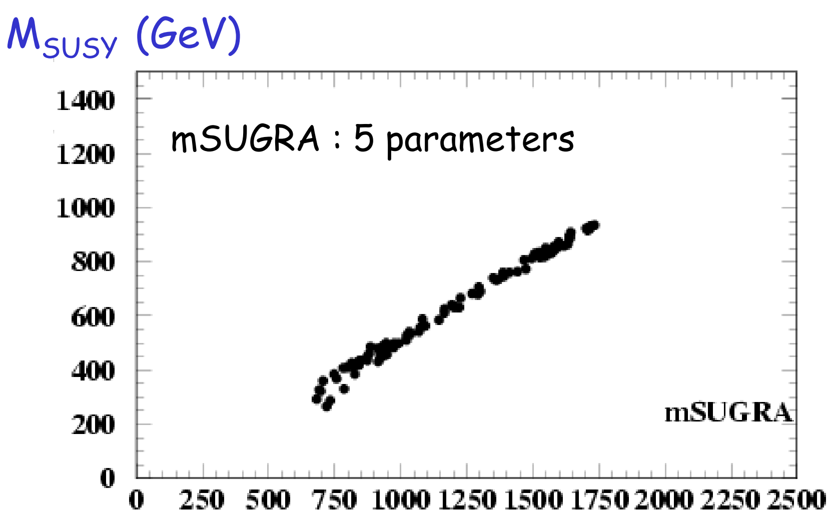
(mSUGRA $m_0 = 100$ GeV, $m_1/2 = 300$ GeV, $\tan\beta = 10$, $A = 0$, $\mu > 0$)

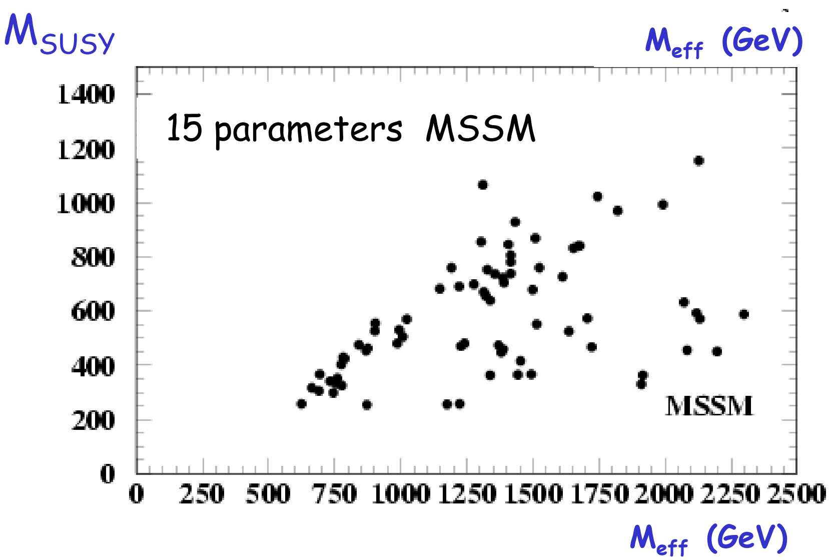
A cut on M_{eff} allows to separate the signal from SM background

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

Define the SUSY mass scale as:

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

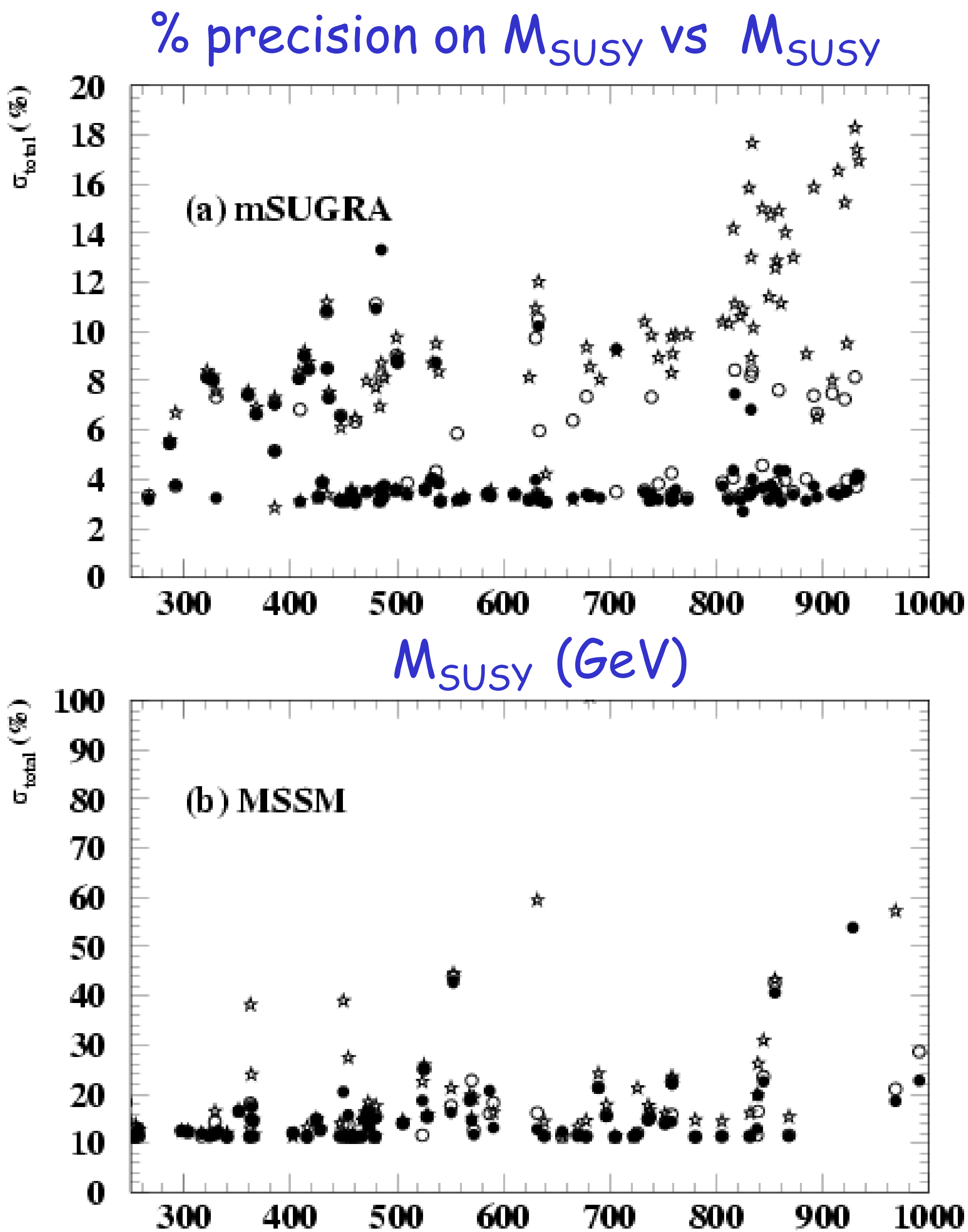




Estimate peak in M_{eff} by a gaussian fit to the background-subtracted signal distributions

Test the correlation of M_{eff} with $M^{\text{eff}}_{\text{susy}}$ 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 $m_{\tilde{q}} \sim m_{\tilde{g}} \sim 600$ GeV

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

- Undetectable particles in the final state $\not{E}_T$
- Particles with mass$\sim$600 GeV (M_{eff} study) and with couplings of $\sim$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 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