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"

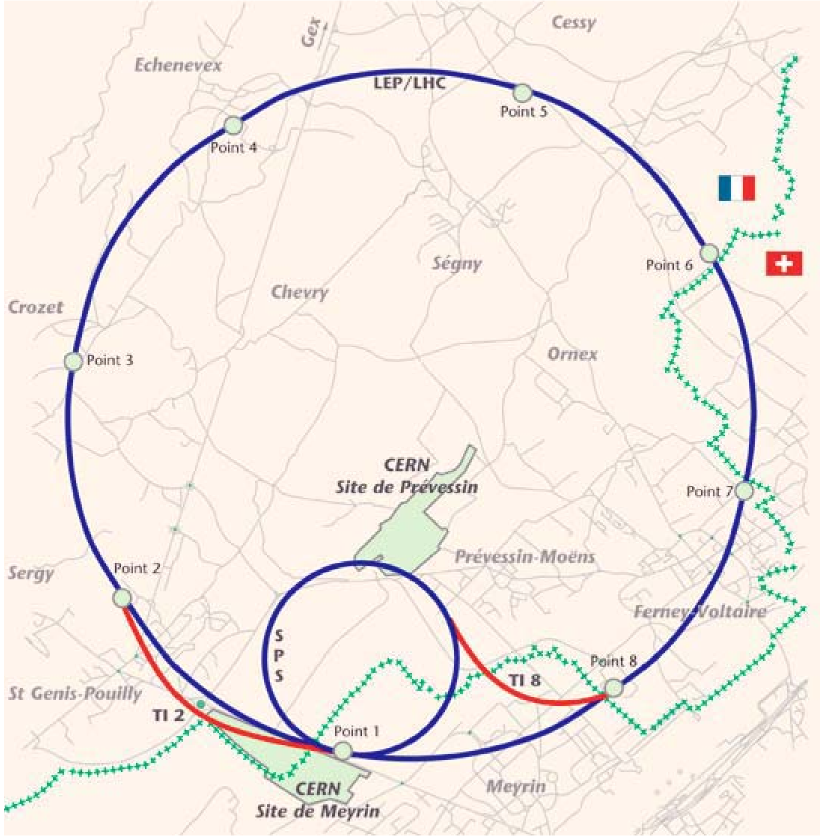
$$\int \mathcal{L}\mathrm{dt} = 10\ \mathrm{f}b^{-1}\ \mathrm{per\ year}$$

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

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

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

Inter-bunch space: 25 ns ⇒~ 23 inelastic interactions per crossing at full luminosity



Eight sectors

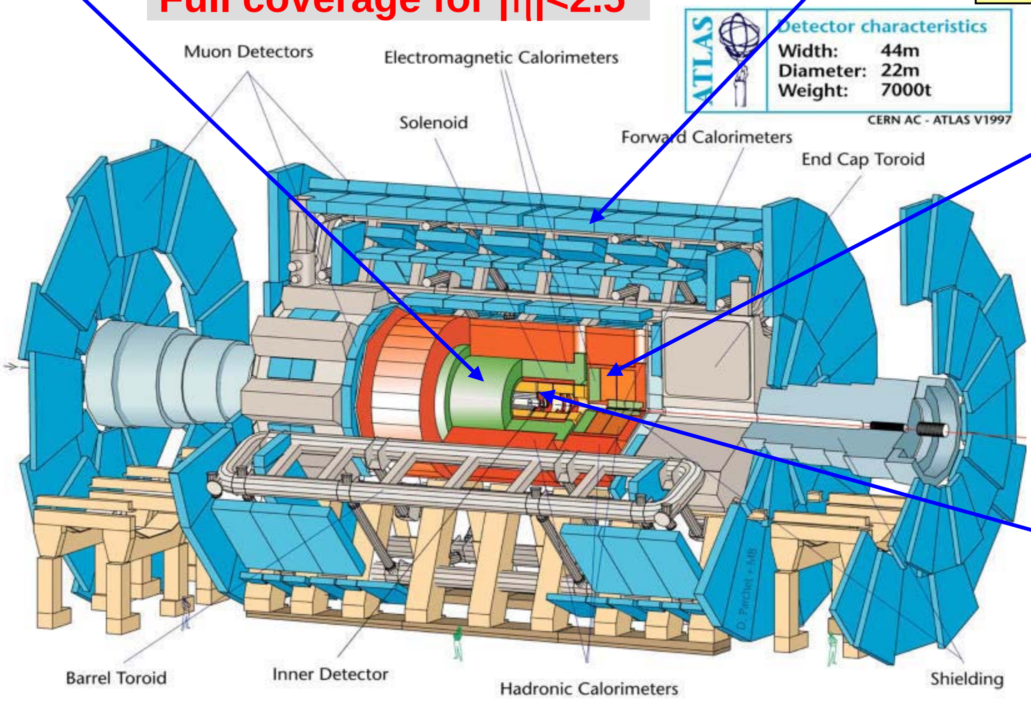
Point 1: ATLAS General purpose

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., $H \to \gamma\gamma$)

Full coverage for $|\eta|<2.5$

Precision Muon Spectrometer,

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

Fast response for trigger

Good *p* resolution

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

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)

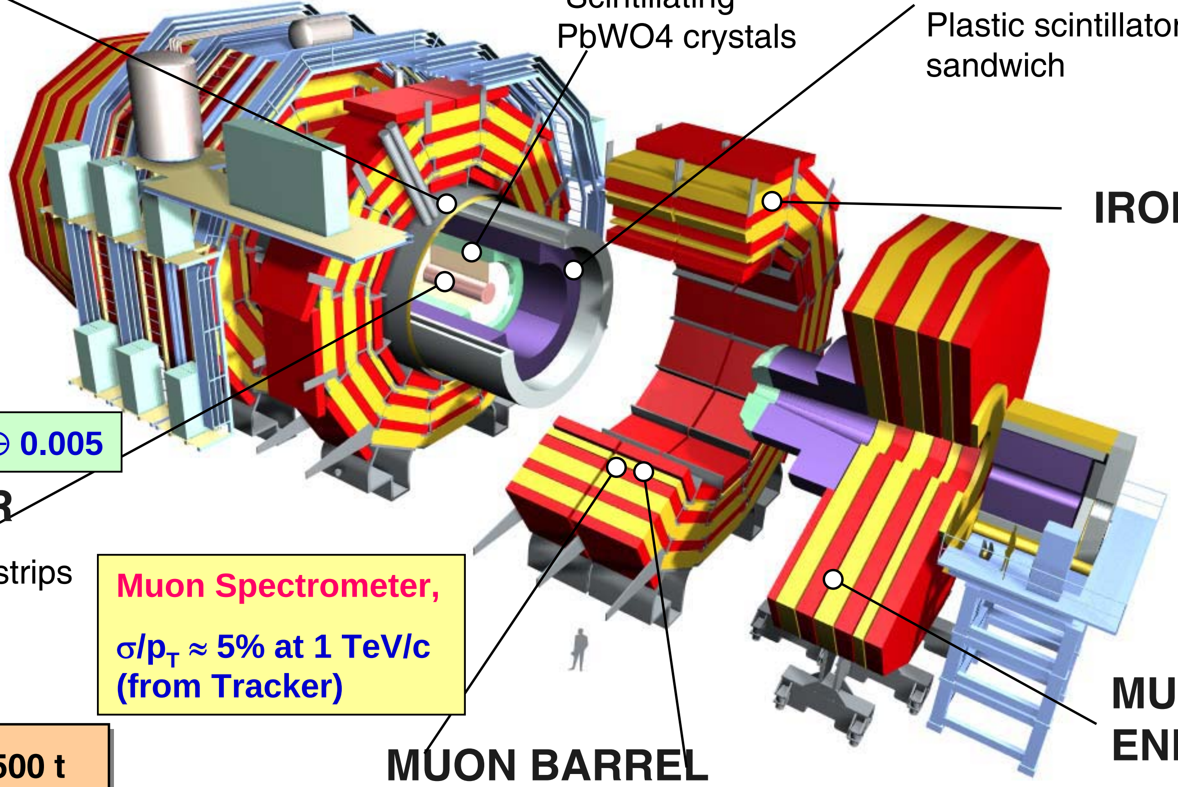
$\sigma/p_T \approx 5 \times 10^{-4}\, p_T \oplus 0.001$

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



SUPERCONDUCTING COIL

EM Calorimeter,

$\sigma/E \approx 3\%/\sqrt{E(\mathrm{GeV})} \oplus 0.5\%$

Scintillating PbWO4 crystals

Hadron Calorimeter,

$\sigma/E \approx 100\% / \sqrt{E(\mathrm{GeV})} \oplus 5\%$

Plastic scintillator/brass sandwich

IRON YOKE

$\sigma/p_T \approx 1.5 \times 10^{-4}\, p_T \oplus 0.005$

TRACKER

Silicon Microstrips
Pixels

Muon Spectrometer,

$\sigma/p_T \approx 5\%$ at 1 TeV/c (from Tracker)

MUON ENDCAPS

MUON BARREL

Drift Tube Chambers (**DT**)

Resistive Plate Chambers (**RPC**)

Cathode Strip Chambers (**CSC**)
Resistive Plate Chambers (**RPC**)

Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

Introduction:LHC and new physics

With LHC open the TeV scale to experimentation

From theoretical speculations expect to find signals for physics beyond 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.

We take here SUSY as a template theory with:

- Rich spectrum of new particles
- High production cross-section
- Complex decay chains with invisible particles in final state

Experimentally most challenging scenario, does not cover all SUSY possibilites

Also other models (UED, Little Higgs with T-parity) give a similar scenario

To do before going for discovery

- 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 2008: 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?

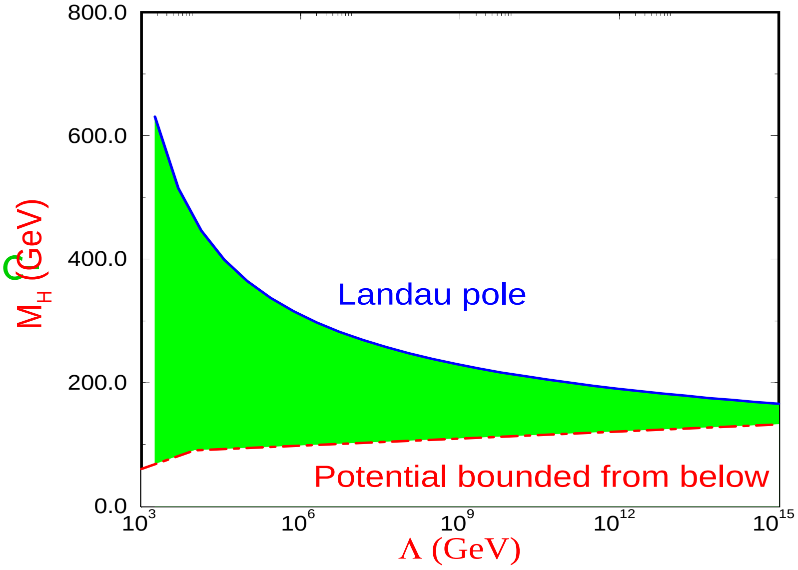
- Gravity is not yet incorporated in the Standard Model
- Hierarchy/Naturalness problem

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,

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

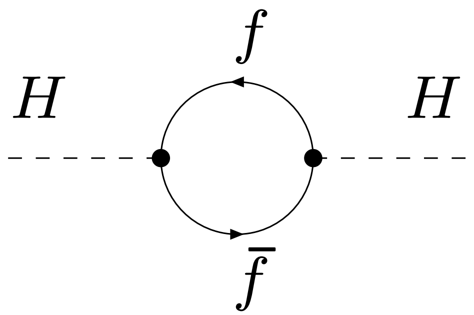


- Additional problems: Unification of couplings, Flavour/family problem

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:

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

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

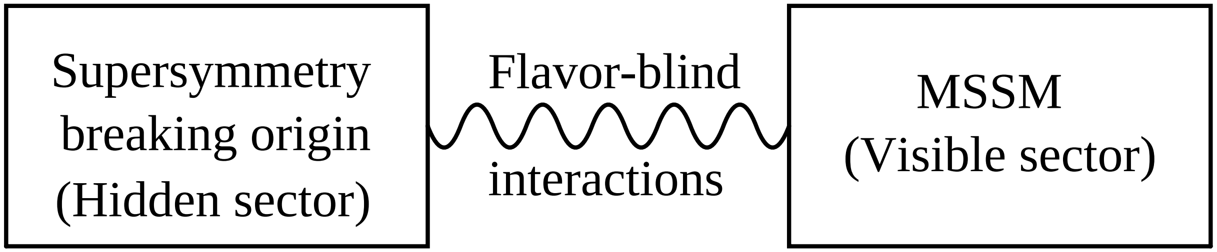
For each fermion f two partners $\tilde{f}_L$ and $\tilde{f}_R$ for the two helicity states

Charginos and neutralinos from the mixing of gauginos and higgsinos

Measure masses of all neutralinos/charginos to reconstruct gaugino soft breaking parameters

Models of SUSY breaking

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



Supersymmetry breaking origin (Hidden sector)

Flavor-blind interactions

MSSM (Visible sector)

Phenomenological predictions determined by messenger field:

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

- Gravity: mSUGRA. Parameters: $m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{sgn}\,\mu$

  Variations:

  - Decouple Higgs bosons from sfermions (NUHM). Add 2 parameters: $m(A), \mu$
  - Give up gaugino mass unification. $m_{1/2} \Rightarrow m_1, m_2, m_3$

- 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: $m_0,\ m_{3/2},\ \tan\beta,\ sign(\mu)$

SUSY breaking structure

SUSY breaking communicated to visible sector at some high scale

$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{sgn}\,\mu$ (mSUGRA)

Evolve down to EW scale through Renormalization Group Equations (RGE)

$M_1,\ M_2,\ M_3,\ m(\tilde{f}_R),\ m(\tilde{f}_L),\ A_t,\ A_b,\ A_\tau,\ m(A),\ \tan\beta, \mu$

From 'soft' terms derive mass eigenstates and sparticle couplings.

$m(\tilde{\chi}^0_j),\ m(\tilde{\chi}^\pm_j),\ m(\tilde{q}_R),\ m(\tilde{q}_L),\ m(\tilde{b}_1),\ m(\tilde{b}_2),\ m(\tilde{t}_1),\ m(\tilde{t}_2)......$

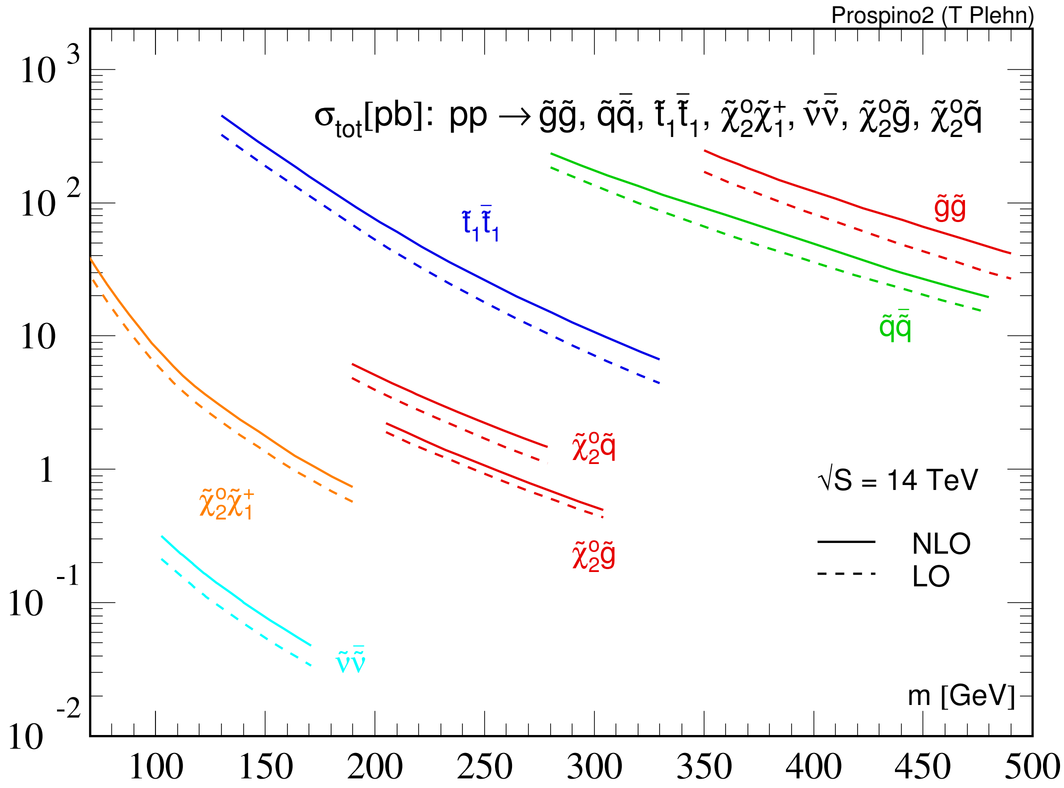
Structure enshrined in Monte Carlo generators (e.g ISAJET)

Task of experimental SUSY searches is to go up the chain, i.e. to measure enough sparticles and branching ratios to infer information on the SUSY breaking mechanism

SUSY at the LHC: general features

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

Squark and gluino production cross-section ∼ only function of squark and gluino mass



Production cross-section ∼ 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

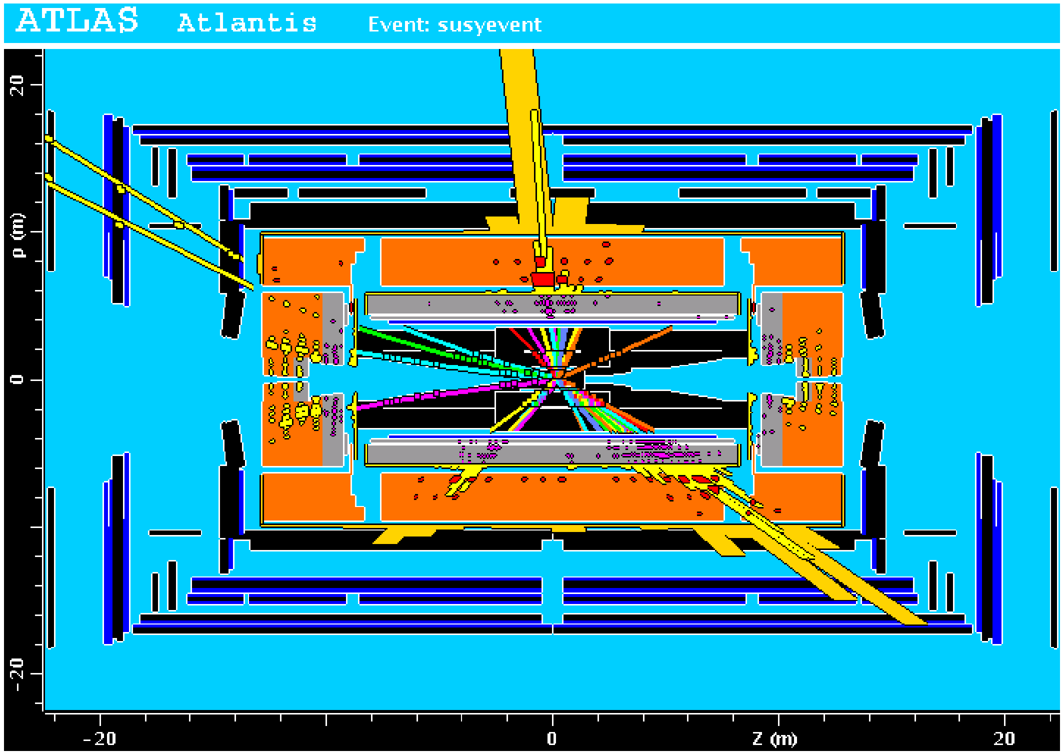
⇒ If R_p conserved, complex cascades to undetected LSP, with large multiplicities of jets and leptons produced in the decay.

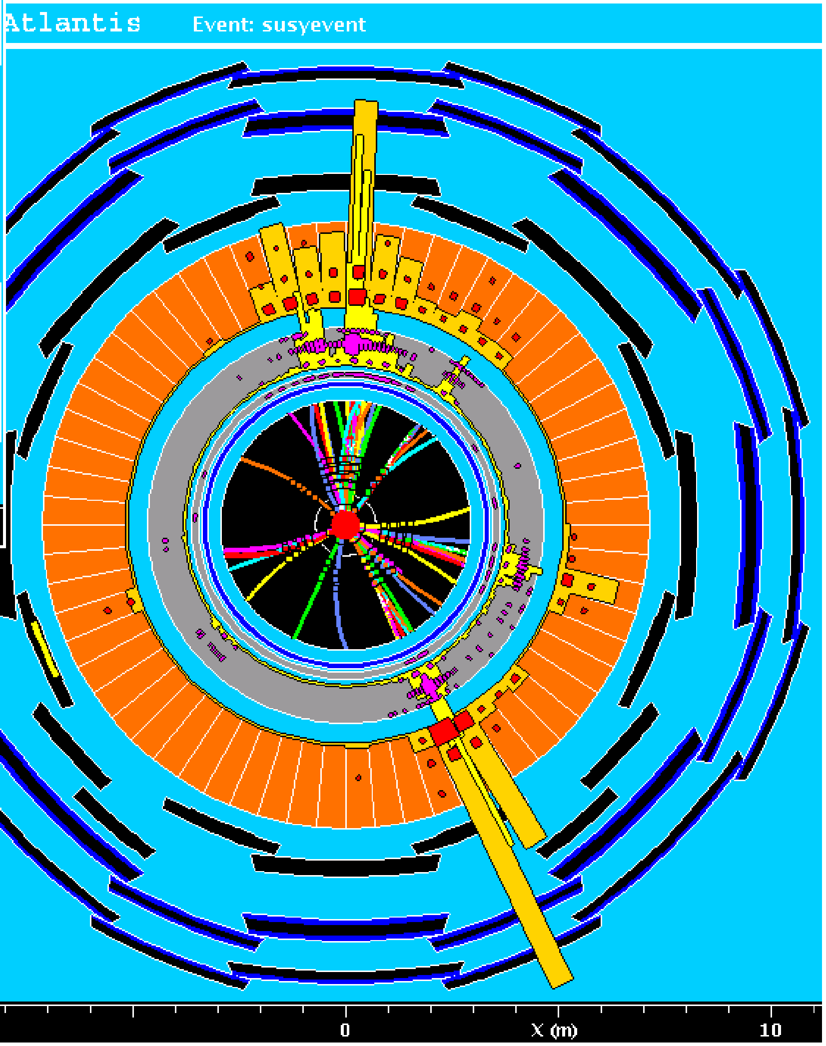
Both negative and positive consequences:

- 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

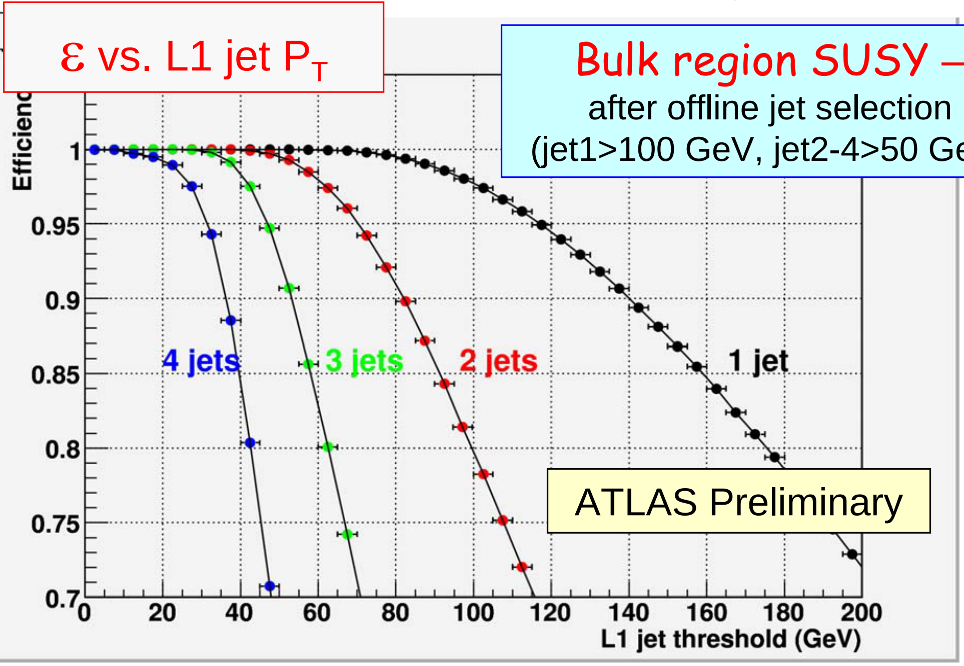
Triggering on SUSY

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 $\not{E}_T$



ε vs. L1 jet P_T

Bulk region SUSY –
after offline jet selection
(jet1>100 GeV, jet2-4>50 GeV)

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 ∼20 Hz (ATLAS)

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

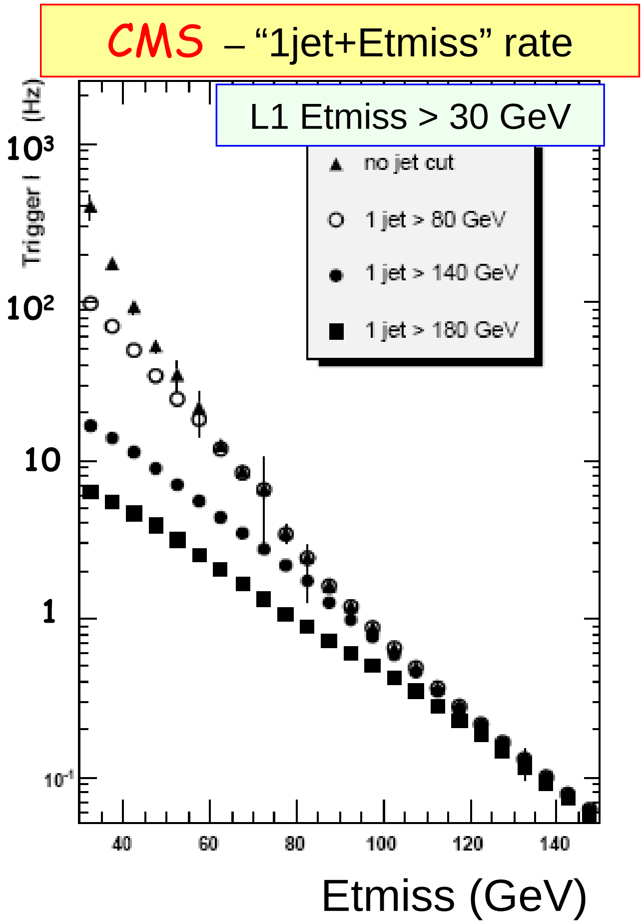
Rejects instrumental and machine background

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.

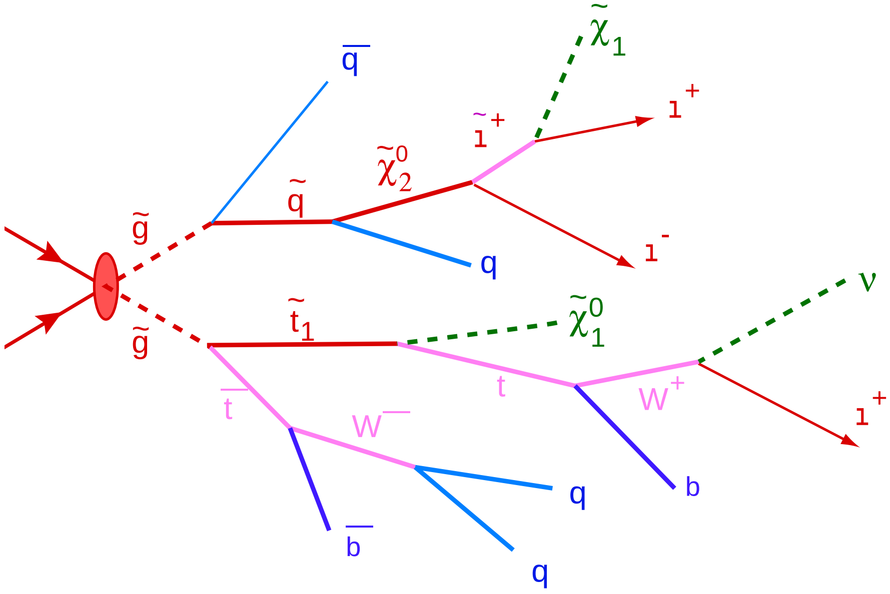
Rate ∼20 Hz at 2×10^{33} cm^{-2}s^{-1}.



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



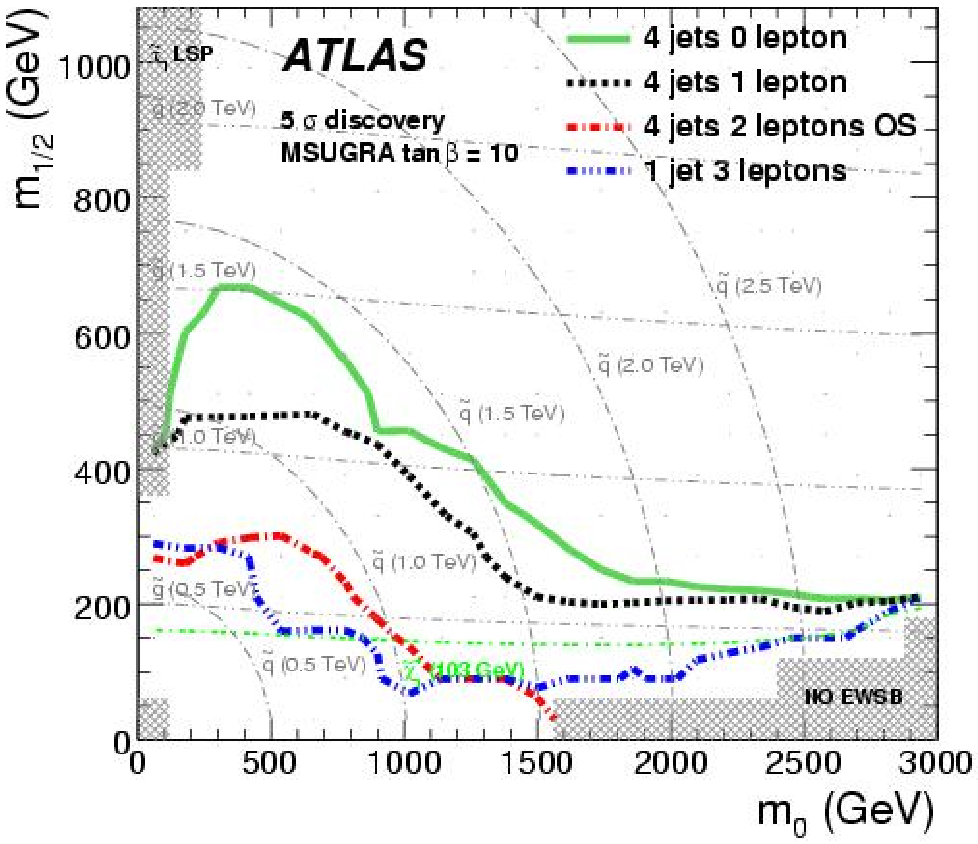
- $\not\!\!E_T$: from LSP escaping detection
- High E_T jets: guaranteed if squarks/gluinos if unification of gaugino masses assumed.
- Multiple leptons (Z): from decays of Charginos/neutralinos in cascade
- Multiple τ-jets or b-jets (h): Often abundant production of third generation sparticles

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

Inclusive reach in mSUGRA parameter space



ATLAS Reach for 1 fb^{-1}

Includes expected uncertainties on SM backgrounds after 1 fb^{-1} of data:

- 50% on QCD backgrounds
- 20% on $\bar{t}t$, W, Z+jets

Multiple signatures over most of space

Dominated by $\not{E}_T$+jets

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

ATLAS scanned model with non universal higgs masses, with in principle different decay patterns, and result are very similar

How fast can the discovery be?

Recent ATLAS analyses consistently carried out assuming 1 fb-1 both for background determination and for signal search

Reach in 0-lep channel for 1 fb^{-1}, assuming $m(\tilde{q}) = m(\tilde{g})$ is ~ 1300 GeV

Assuming the same level of background control, reach for ∼100 pb^{-1} is ~ 800 GeV

Probably not realistic, worse control of backgrounds at 100 pb^{-1} than at 1 fb^{-1}

Ingredients of background estimate:

- Understanding of early detector performance: $\not{E}_T$ tails, lepton id, jet scale
- Understanding SM at 14 TeV: : Set X-section scales, MC Tuning,..
- Collecting sufficient statistics of SM control samples:

  QCD jets in appropriate configurations (trigger!), W, Z+jets, $\bar{t}t$

Going through some of the main exclusive analyses, look at techniques for:

- Preliminary cleaning of $\not{E}_T$ sample
- Controlling Instrumental $\not{E}_T$ in QCD events
- Controlling real $\not{E}_T$ from SM processes with neutrinos

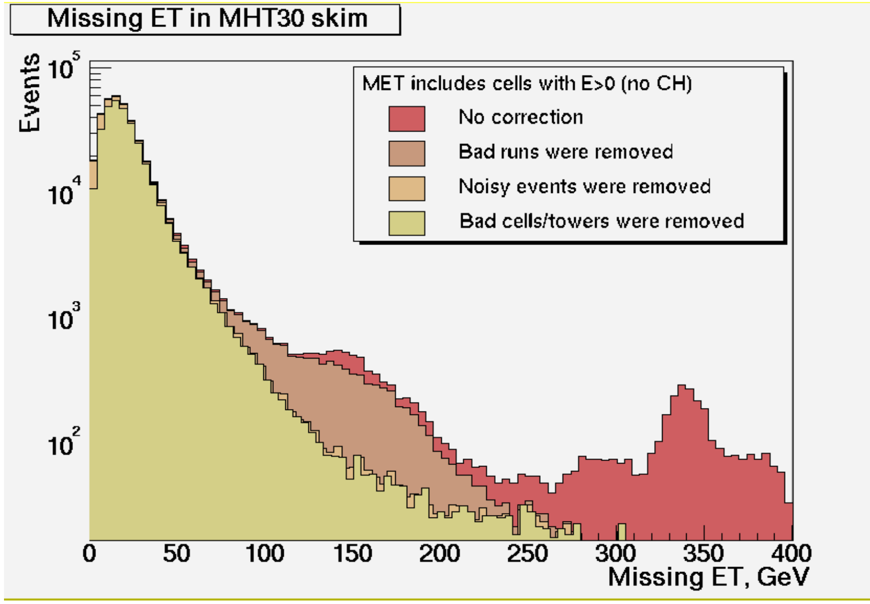
Cleaning of $\not{E}_T$ sample

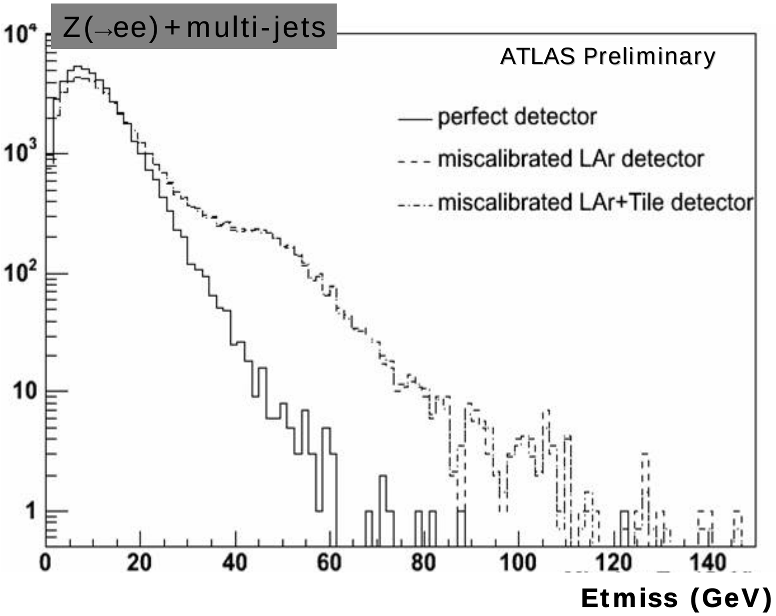
$\not{E}_T$ from mismeasured multi-jet events:

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





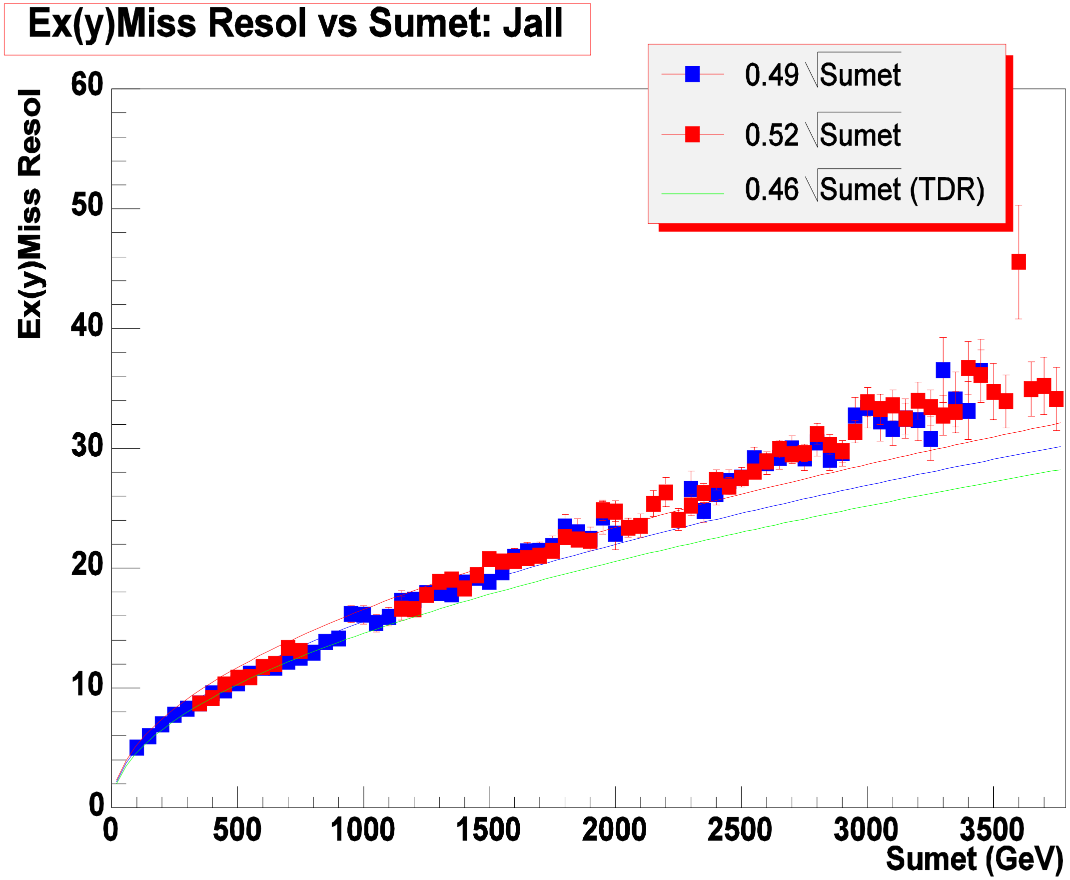
ATLAS example: assume a few HV channels dead in calorimeters

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

$\not{E}_T$ significance

Once detector malfunctioning and external source ubderstotd, $\not{E}_T$ comes from fluctuations in calorimeter response

MonteCarlo study: take events with no real $\not{E}_T$, build distribution of $x(y)$ component of $\not{E}_T$, and take σ



Preliminary ATLAS plot

$\not{E}_T$ resolution can be parametrised as a function of the sum of the E_T deposition in the calorimeter

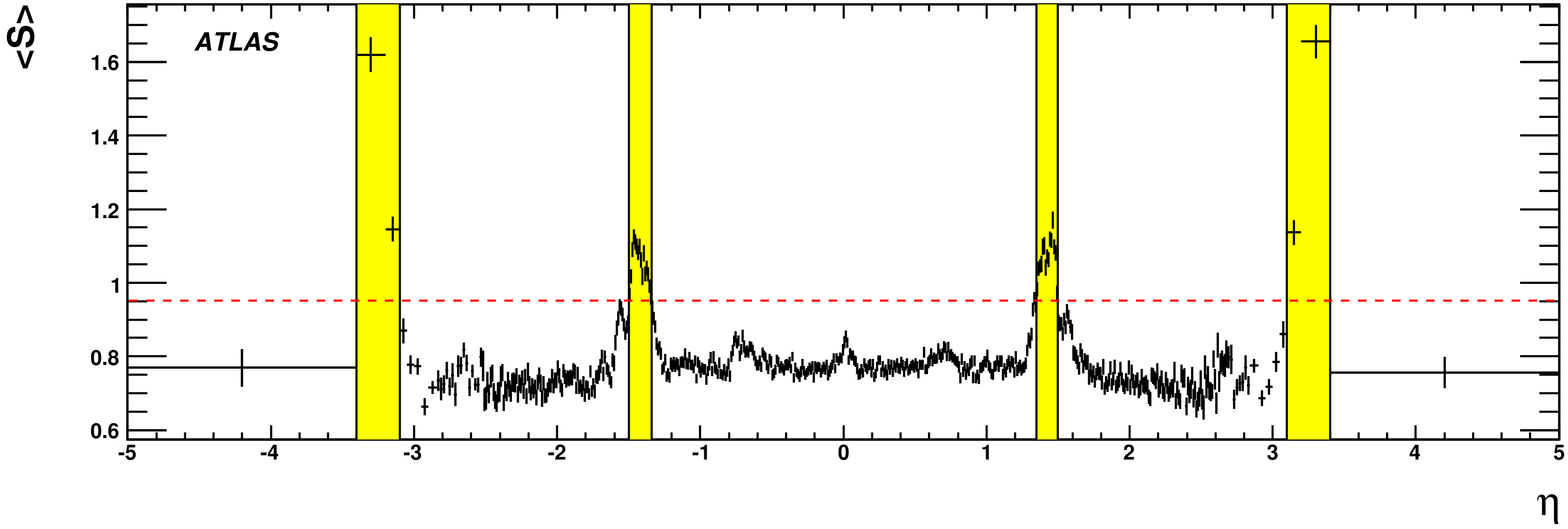
For each event can evaluate significance of measured $\not{E}_T$

Can use this variable to map the response of the detector

Instrumental background: definition of fiducial region for jets

Use a sample of 2-jet events ($p_T > 280$ GeV), apply basic cuts to reject events containing neutrinos

- For each event calculate $S = \not{E}_T / \sqrt{\Sigma\, E_T}$
- For each jet in the event, take $\eta(jet)$, and fill one entry in the plot
- For each bin in η calculate the average value of S



Observe clear degradation at interface between calorimeters

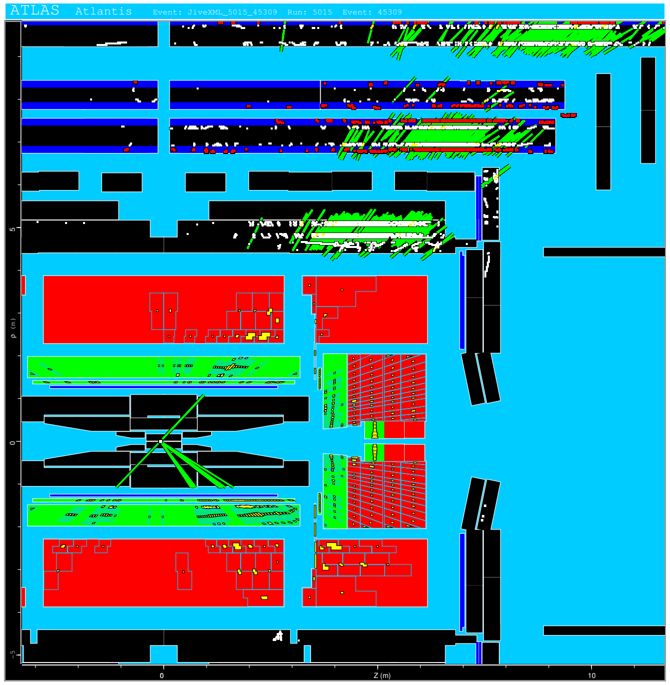
Reject high $\not{E}_T$ events with a jet falling in yellow regions

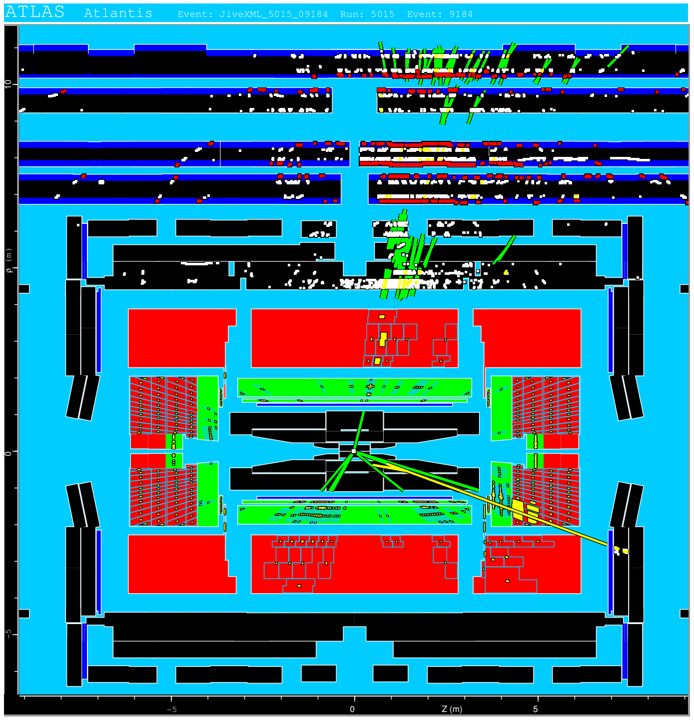
Instrumental background: beyond fiducial cuts

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.

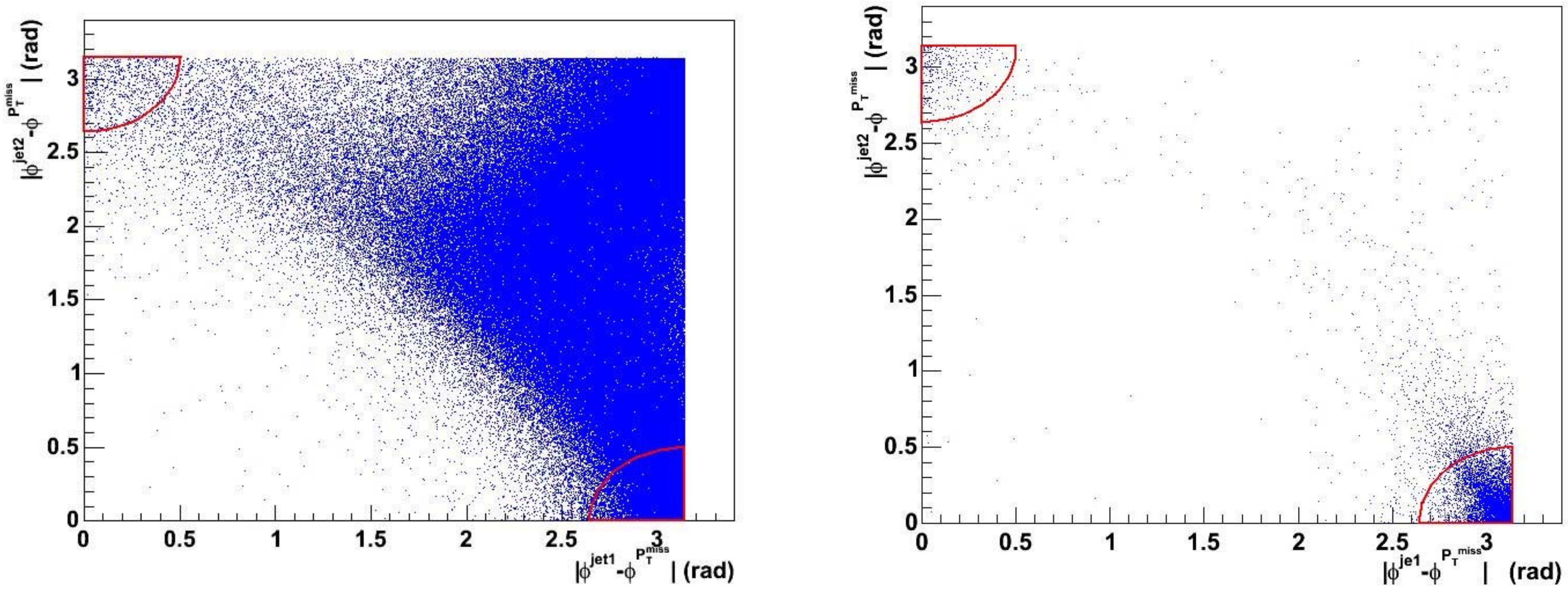
Can develop criteria based on the muon chambers to further reduce tails

Instrumental background: Rejecting specific topologies

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

At this point, we are entering the domain of analysis cuts

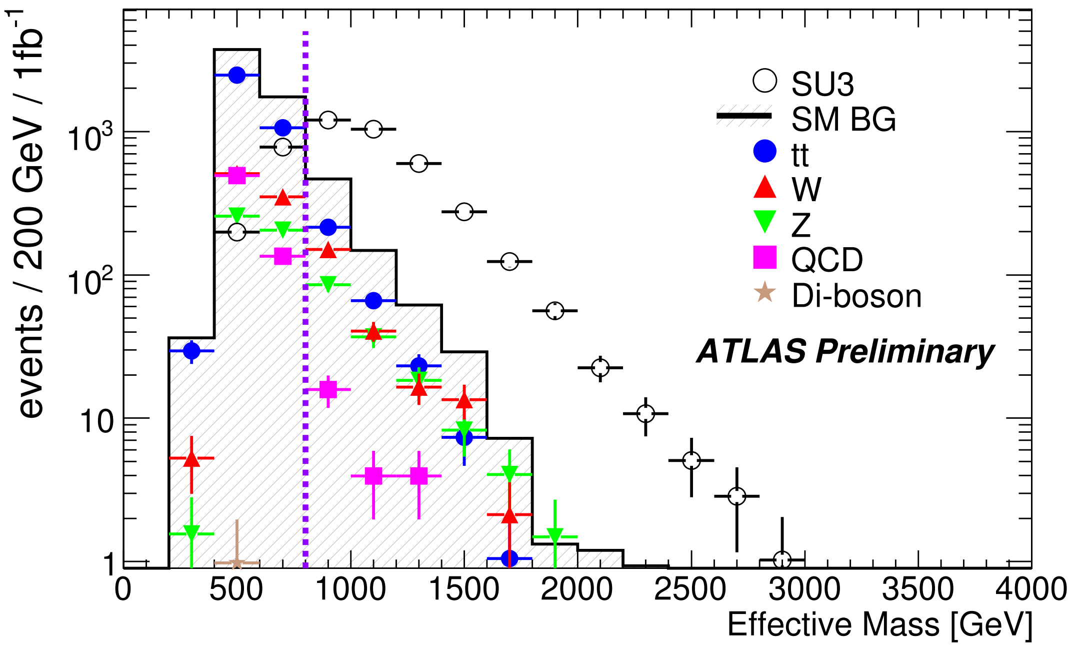
Inclusive signature for zero leptons

SUSY selection:

- 4 jets ($P_T < 100, 50, 50, 50$) GeV)
- $\not\!\!E_T > 100$ GeV and $\not\!\!E_T > 0.2 M_{\text{eff}}$
- $\Delta\phi(j, \not\!\!E_T) > 0.2$
- Transverse sphericity> 0.2

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

Typical cut: $M_{\text{eff}} > 800$ GeV



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

QCD background reduced to $\lesssim 5\%$ after all cuts, but with large uncertainites!

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.

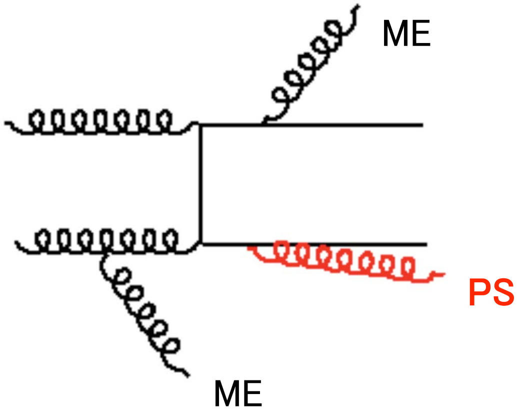
SM backgrounds: Monte Carlo issues

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

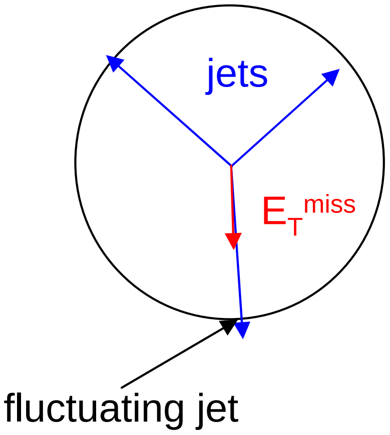
Additional issue: normalisation (no NLO calculation possible)

Instrumental backgrounds: data-driven estimate

MonteCarlo estimate of QCD background hard. It requires:

- Good MonteCarlo simulation of QCD multijets
- Excellent understanding of detector incorporated in simulation
- $\not\!\!E_T$ is from tails of response: need to simulate huge number of events

⇒ Develop multi-step data-driven estimate



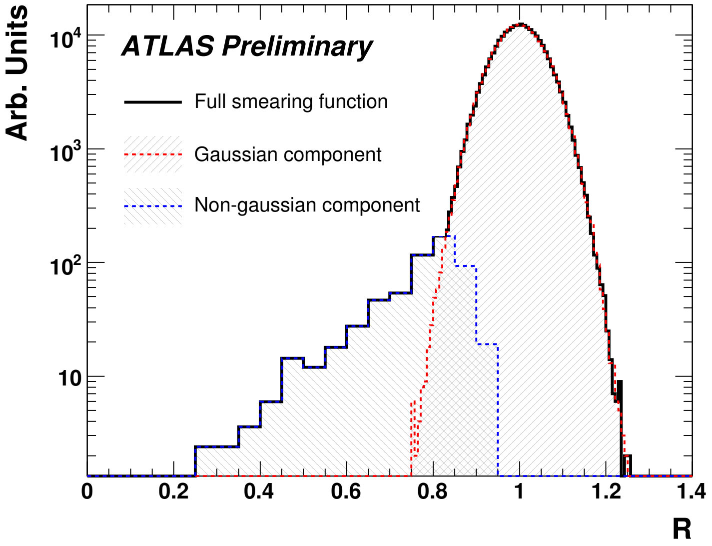
Step 1: Measure the gaussian part of response with balance of γ+jet events

Step 2: Measure the non-gaussian part of response and combine it with the gaussian part

- Require: 3 jets, $p_T(J) > 250, 50, 25$ GeV, $\not\!\!E_T > 60$ GeV
- One and only one jet parallel to the $\not\!\!E_T$ vector
- Define the true $P_T(J)$ as: $\vec{p}_T(J, \text{true}) \simeq \vec{p}_T(J) + \vec{\not\!\!E}_T$

Plot:

$$R_2 = \frac{\vec{p}_T(J) \cdot \vec{p}_T(J, \text{true})}{|\vec{p}_T(J, \text{true})|^2}$$



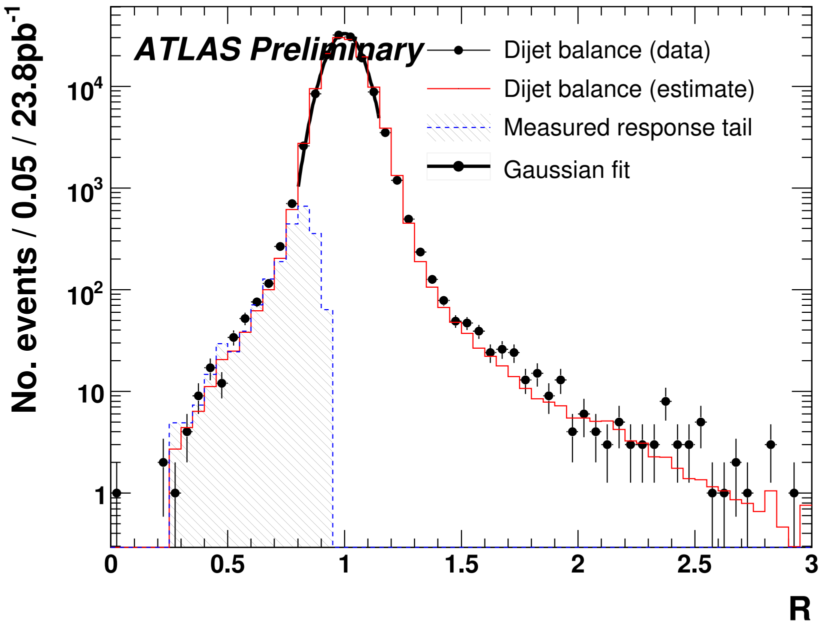
Finally normalize the two estimates from the balance of a sample of 2-jet events

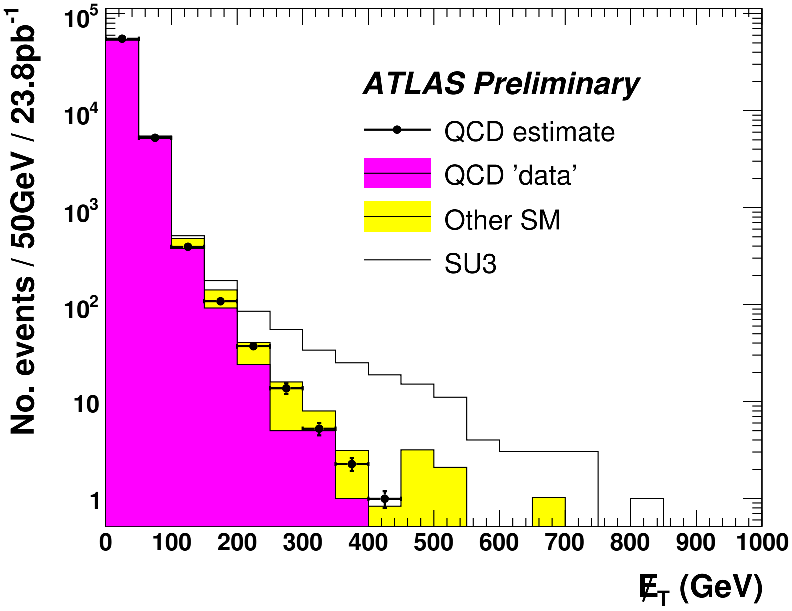
Closure test: compare estimated response curve with 'data' from balance of a sample of two-jet events. Plot for each jet:

$$R_3(j) = 1 + \frac{\vec{\not{E}}_T \cdot \vec{p}_T(j')}{|\vec{p}_T(j')|^2}$$

Step 3: Seed event selection and jet p_T smearing:

Smear according to measured function jet P_T in multi-jet events with low $\not{E}_T$ ('seed events')





Plot the $\not{E}_T$ distribution for the smeared 'seed'events is plotted, normalised to simulated QCD events with $\not{E}_T < 50$ GeV

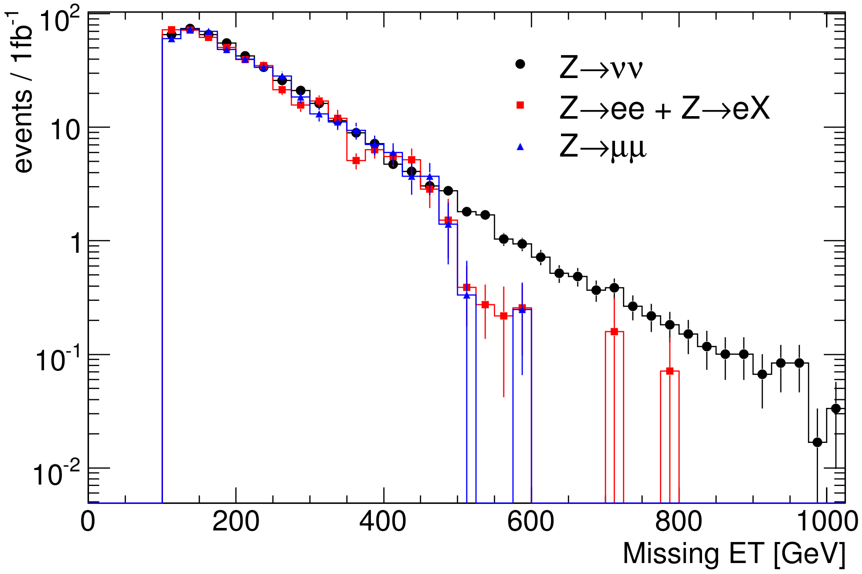
Good agreement between the estimated and 'data' distributions

Dominant systematic errors are the P_T bias in event selection and the statistical error on 'Mercedes' events.

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

Select samples of $Z \rightarrow \mu\mu(ee, eX)$+multijets from data

Apply same cuts as for SUSY analysis (4 jets+Etmiss), remove leptons and calculate $\not{p}_T$ of events from the vector sum of their momenta (normalized to 1 fb^{-1})



Number of $N_{Z\rightarrow\nu\nu}$ per $\not{E}_T$ bin calculated from $N_{Z\rightarrow\ell\ell}$ applying corrections for:

- Fiducial for leptons (P_T and η cuts)
- Kinematic cuts to select pure Z sample
- Lepton id efficiency
- $BR(Z \rightarrow \nu\nu)/BR(Z \rightarrow \ell\ell)$

First two from MC, last one from data

Low statistics at high $\not{E}_T$, improve precision through fit of the shape

Main uncertainites from:

• MC used for corrections ($\sim 6\%$) • $\not{E}_T$ scale ($\sim 5\%$) • Statistics of control sample ($\sim 13\%$)

Method under study using shapes from MC and normalisation from data.

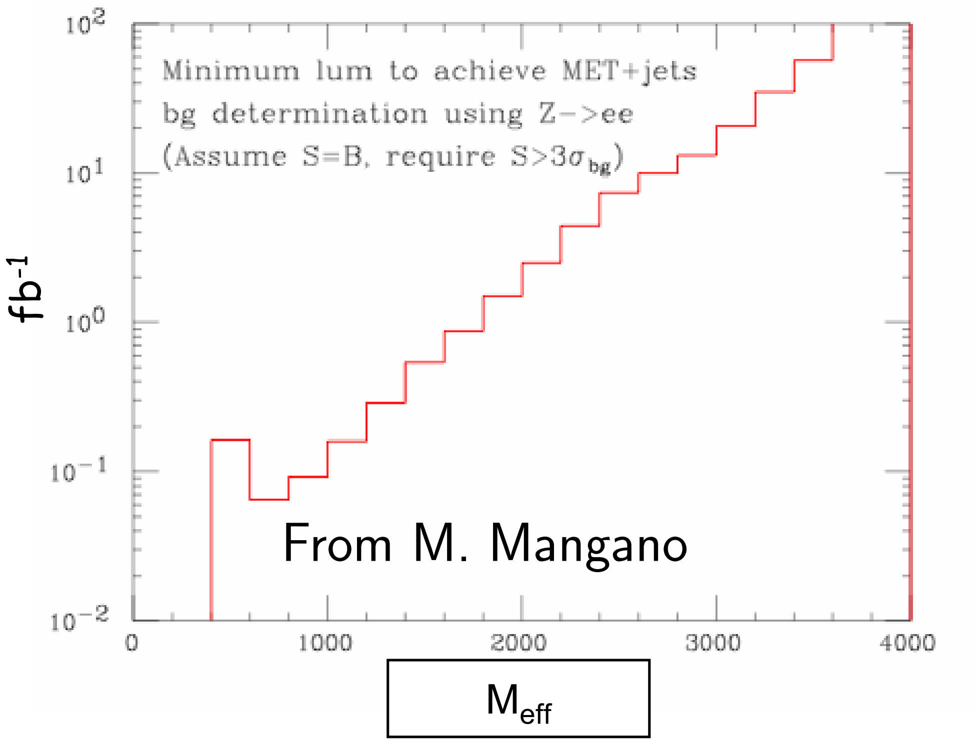
Normalisation needs to be multiplied by $BR(Z \rightarrow \nu\nu)/BR(Z \rightarrow ee) \sim 6$

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

Stat error on background:

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

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



From M. Mangano

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

Inclusive signature with one lepton

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

BUT control of SM and instrumental backgrounds might require long time

The channel single lepton + jets + $\not\!\!E_T$ has somewhat smaller parameter space coverage, but might be easier to control

Same kinematic cuts as for 0 lep+jets

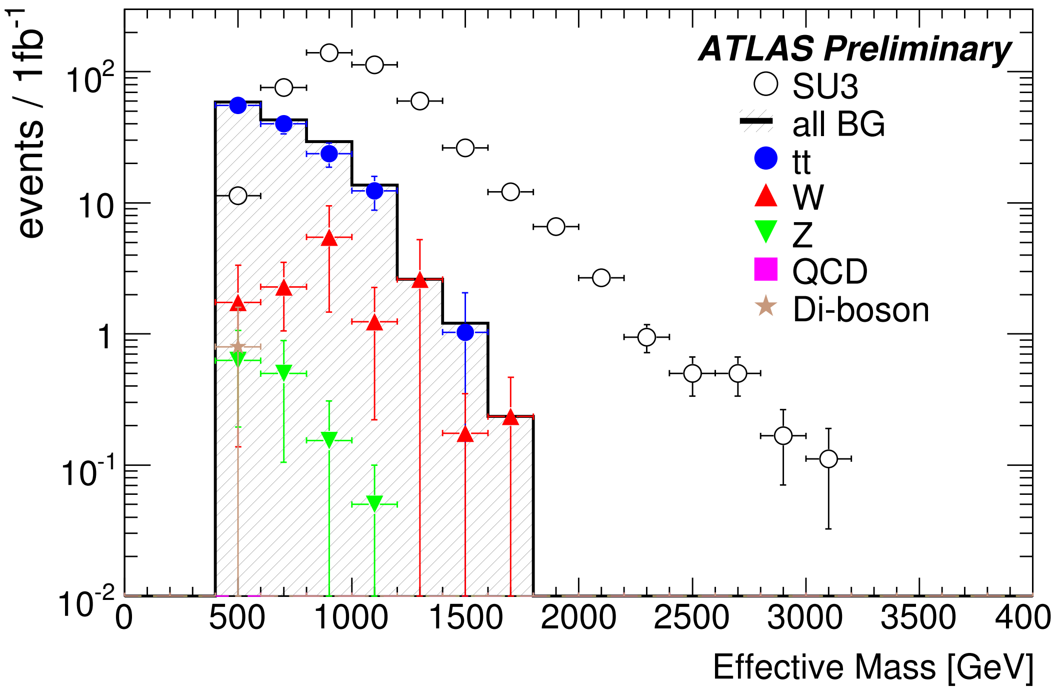
In addition require one lepton

Cut on M_T, transverse mass of the lepton and $\not\!\!E_T$

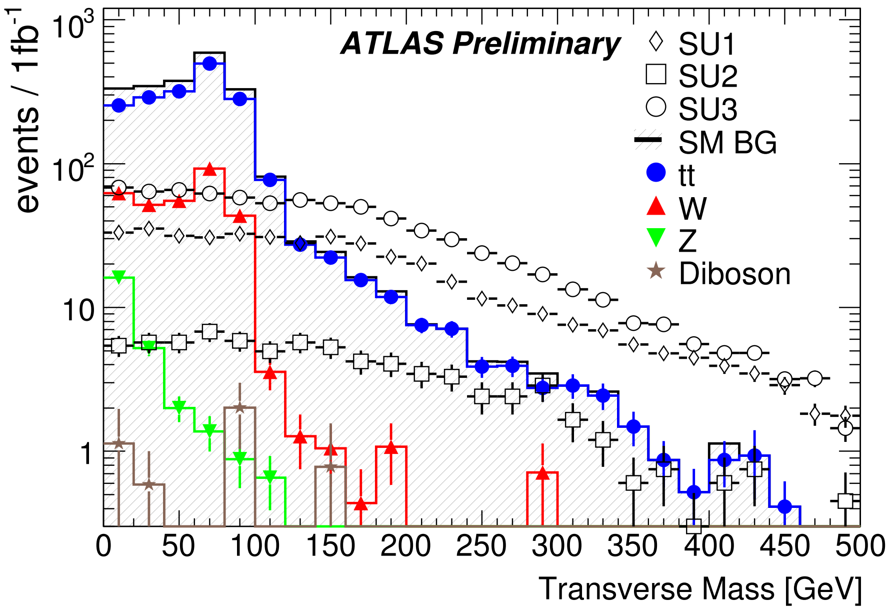
$\bar{t}t$ dominant, $W+$ jets becomes important for higher $\not\!\!E_T$, QCD negligeable

Need data-driven evaluation of single lepton backgrounds from $\bar{t}t$ and W

Use M_T evaluation as illustrative example



One lepton background evaluation with M_T method



M_T variable gives excellent discrimination against $\bar{t}t$, $W+$ jets

Main discriminant value together with $\not{E}_T$

Invert the M_T cut to evaluate background?

Basic Principle:

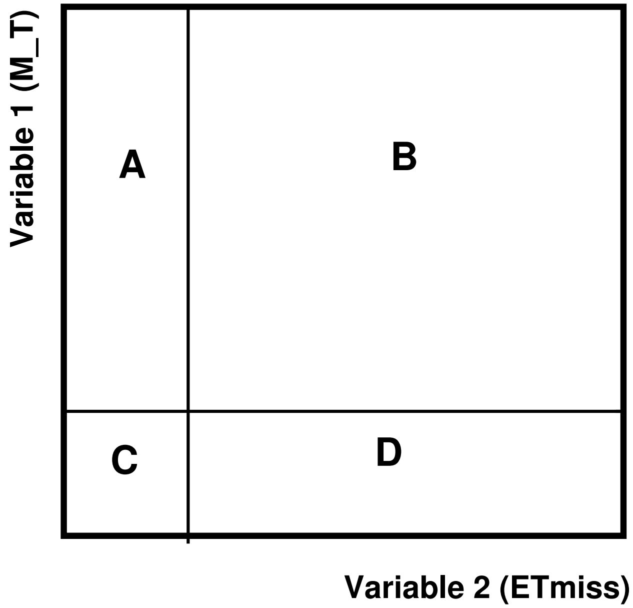
B is *signal region*, ∼no signal in A,C,D

D is *control region*

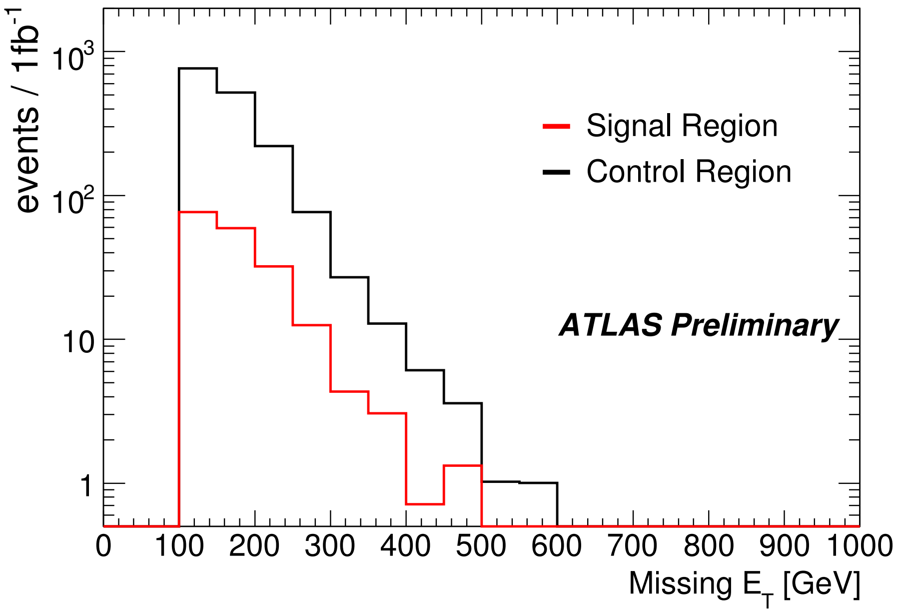
If shape of $\not{E}_T$ the same in (A+B) and (C+D):

$$N(B) = N(D) \times \frac{N(A)}{N(C)}$$

Where $N(X)$ is BG in region X



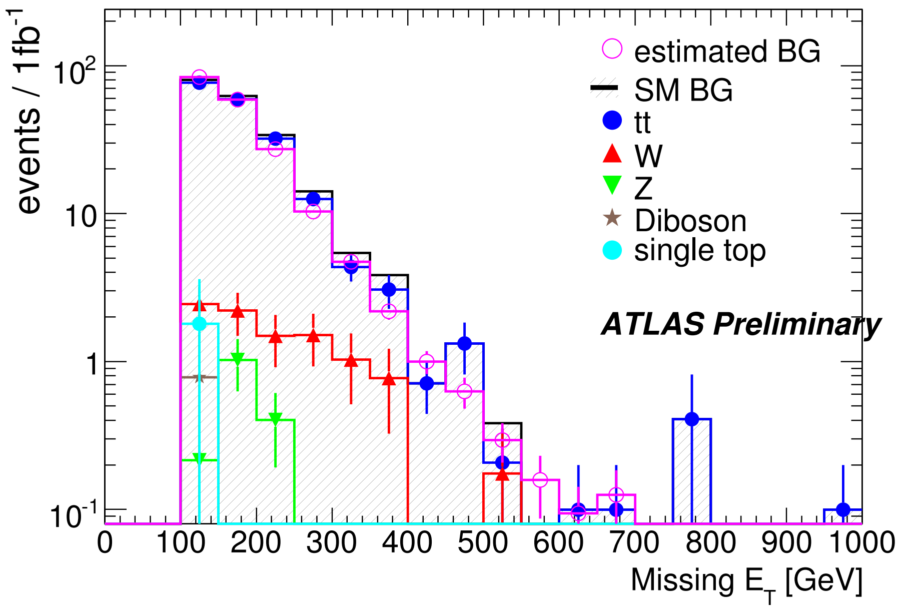
M_T method: results without signal



$\not\!\!E_T$ distributions in signal and control region approximately consistent

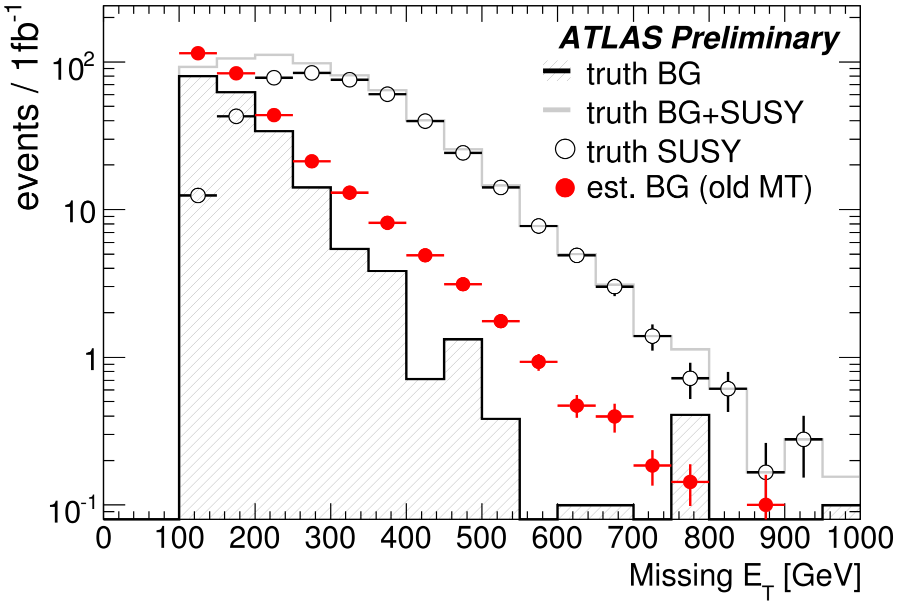
Estimate background in absence of signal:

	$\not\!\!E_T > 100$ GeV	$\not\!\!E_T > 300$ GeV
True BG	203 ± 6	12.4 ± 1.6
Estimated BG	190 ± 8	9.4 ± 0.7
Ratio(Est./True)	0.93 ± 0.05	0.76 ± 0.11



Good estimate of background

What if there is signal?



Example: assume SU3 signal.

	$\not{E}_T > 100$ GeV	$\not{E}_T > 300$ GeV
True BG	203 ± 6	12.4 ± 1.6
Estimated BG	296 ± 10	33.3 ± 1.4
True BG+SUSY	653 ± 8	245 ± 4

Clear overestimate of background, dependent on amount of signal

Work in progress to master the issue of signal contamination, two directions of exploration:

- Iteration procedure: if excess observed, use properties of excess to correct for estimate.

  Example in M_T method: assume that all events observed in signal region are from signal, and with some ansatz on signal shape, extrapolate back in control region

- Combined fit determining the composition of control sample allowing for SUSY contribution

Only preliminary work, very active field of investigation

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

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

Gluino Majorana particle, in gluino decay same probability for positive and negative lepton

Very little SM background, dominated by $\bar{t}t$, very sensitive to lepton isolation

- Opposite-Sign Same-Flavour (OSSF)
- Opposite-Sign Opposite-Flavour (OSOF)

In OS-SF pair two leptons may come from decay of same gaugino ⇒

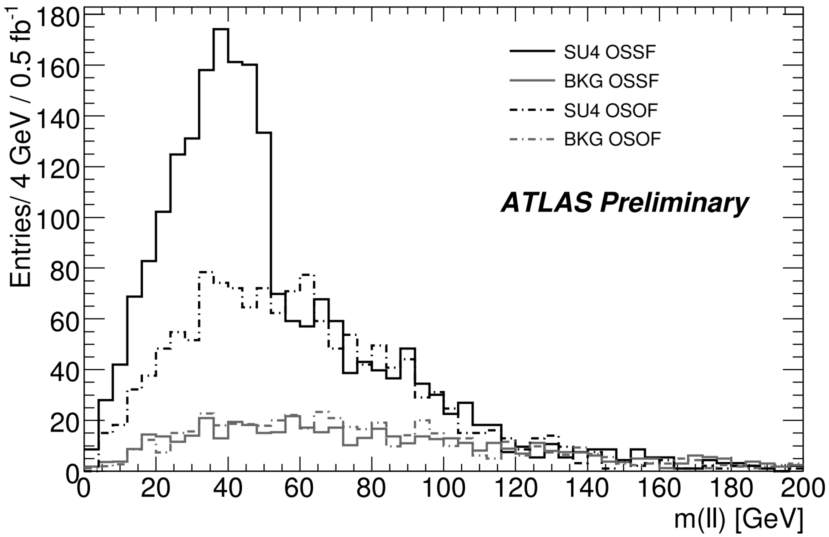
OS-SF invariant mass distribution may exhibit structure, not present in OS-OF pairs

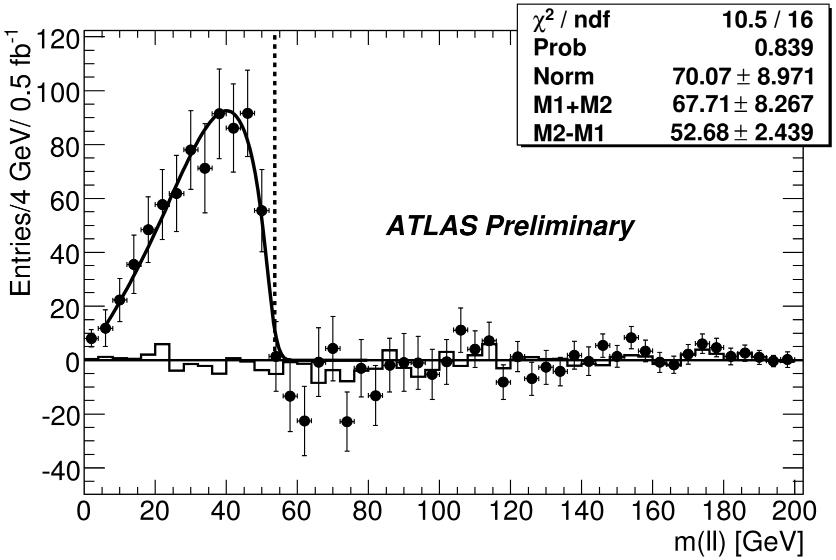
$$\begin{array}{l} \tilde{q}_L \longrightarrow \tilde{\chi}_2^0 \quad q \\ \qquad\quad \hookrightarrow \tilde{\ell}^{\pm}_{R(L)} \quad \ell^{\mp} \\ \qquad\qquad\qquad \hookrightarrow \tilde{\chi}_1^0 \quad \ell^{\pm} \end{array}$$

$$\begin{array}{l} \tilde{q}_L \longrightarrow \tilde{\chi}_2^0 \quad q \\ \qquad\quad \hookrightarrow (Z^*) \quad \tilde{\chi}_1^0 \\ \qquad\qquad\qquad \hookrightarrow \ell^+ \quad \ell^- \end{array}$$

$$\begin{array}{l} \tilde{q}_L \longrightarrow \tilde{\chi}_2^+ \quad q' \\ \qquad\quad \hookrightarrow \tilde{\nu}_\ell \quad \ell^{\pm} \\ \qquad\qquad\qquad \hookrightarrow \tilde{\chi}_1^{\pm} \quad \ell^{\mp} \end{array}$$

Flavour subtraction method





For $\bar{t}t$ and SUSY backgrounds same number of $e^+\mu-$, μ^+e^-, e^+e^-, $\mu^+\mu^-$ pairs

Only $Z/\gamma \to e^+e^-, \mu^+\mu^-$ has same-flavour leptons, strongly reduced by $\not{E}_T$+jets requirement

Fully subtract backgrounds by plotting for each $m(\ell\ell)$ bin: $N(e^+e^-)/\beta + \beta N(\mu^+\mu^-) - N(e^\pm\mu^\mp)$

With $\beta \sim 0.86$ ratio of electron and muon reconstruction efficiencies

Bulk of background uncertainty included in statistical error of subtracted distribution:

$$S \equiv (N(OSSF) - N(OSOF))/\sqrt{N(OSSF) - N(OSOF)}$$

Main additional systematic comes from uncertainty on β, order 10% with 1 fb^{-1}

For the appropriate parameter values, this might be the fastest discovery channel

Inclusive analysis: critical reassessment

I have shown how LHC experiment will try to discover RP conserving SUSY

A certain number of generic assumptions:

- Detection through discovery of squark and gluino production
- Squark and gluino decay to jets + some kind of $SU(2) \times U(1)$ gaugino/higgsino
- Mass difference between squark/gluino and gauginos with dominant BR such as to yield high p_T jets. More or less guaranteed in case of gluino accessible and gaugino mass unification
- Gauginos will decay into "something" and finally into an invisible LSP

Searches are therefore: 2 to 4 jets, depending on relation between gluino and squark masses + $\not{E}_T$ + "something"

Examples of "something": nothing, 1,2,3 leptons (e, μ) τ (hadronic), b-jets, Z , h

Generic variables: P_T/η of ingredients + estimator of mass of system. Canonically:

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

How generic?

Typically reach shown on mSUGRA plane (to fix the “something”), but shown to cover other $\tilde{\chi}_1^0$ LSP scenarios e.g NUHM

Will also e.g. cover most cases in GMSB (gravitino LSP)

- NLSP is $\tilde{\chi}_1^0$. If long lived: phenomenology as for mSUGRA If short lived: add photons to the “something” If medium lived (decay inside the detector), discovery OK, need care to figure out photons
- NLSP is slepton/stau. If short lived OK, additional leptons in the “something”.
  If long-lived need detector-specific studies

Specific searches for cases where assumption of accessible squarks/gluino breaks:

- light stops
- direct gaugino/higgsino search in 3-lepton channel
- long lived heavy particles (staus or R-hadrons)

Also cases with very degenerate spectra need attention

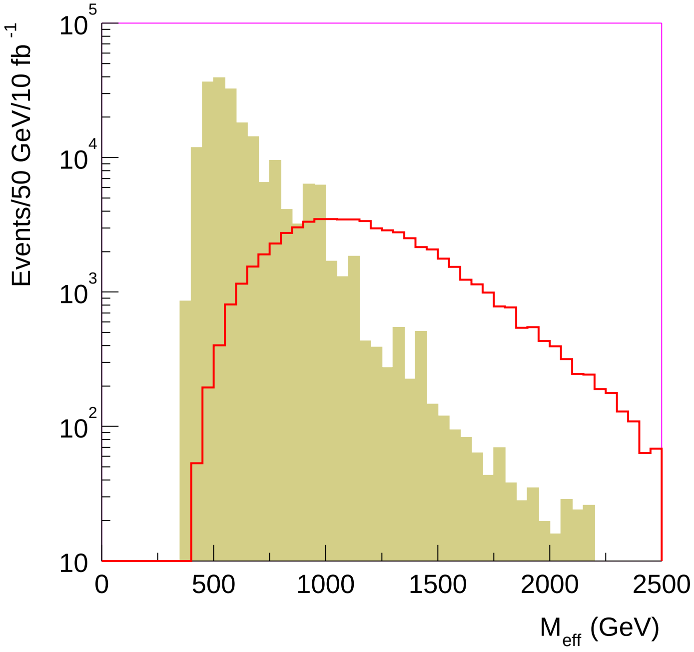
SUSY mass scale from inclusive analysis

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

Simple variable sensitive to sparticle mass scale:

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

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



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

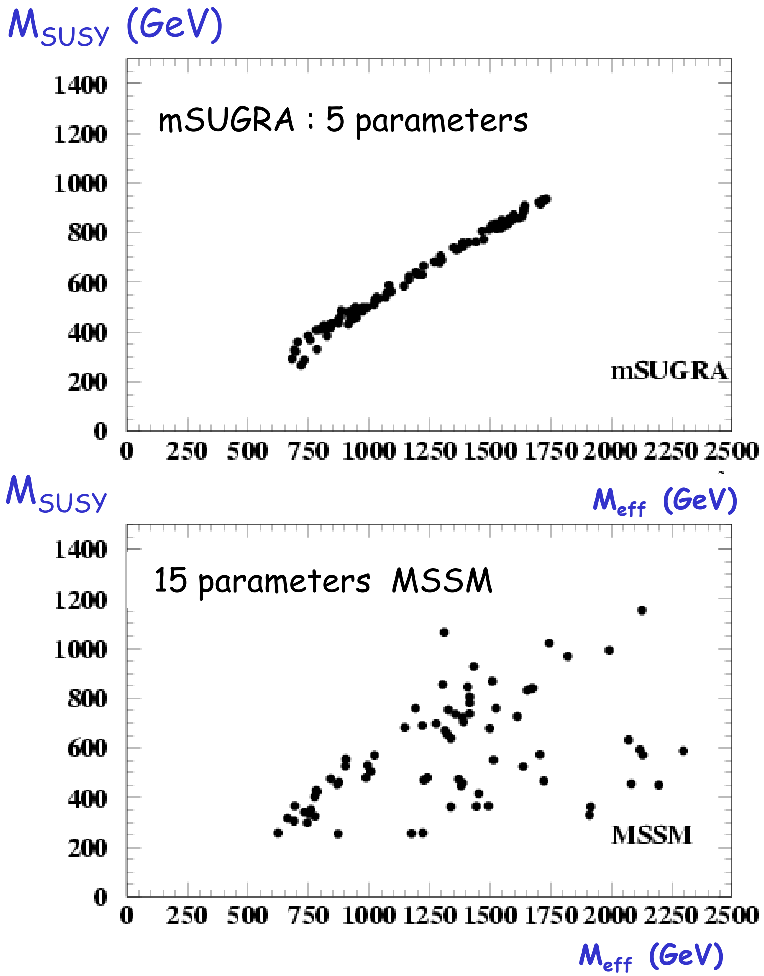
(mSUGRA $m_0 = 100$ GeV, $m_1/2 = 300$ GeV, $\tan\beta = 10$, $A = 0$, $\mu > 0$)

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

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

Define the SUSY mass scale as:

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



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

Test the correlation of M_{eff} with $M_{\text{susy}}^{\text{eff}}$ on random sets: mSUGRA and MSSM

Excellent correlation in mSUGRA, less good for MSSM

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

Old work, to update with new backgrounds

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, and in some of the $\not{E}_T + jets +$ "something" channels. Null results in specialised searches

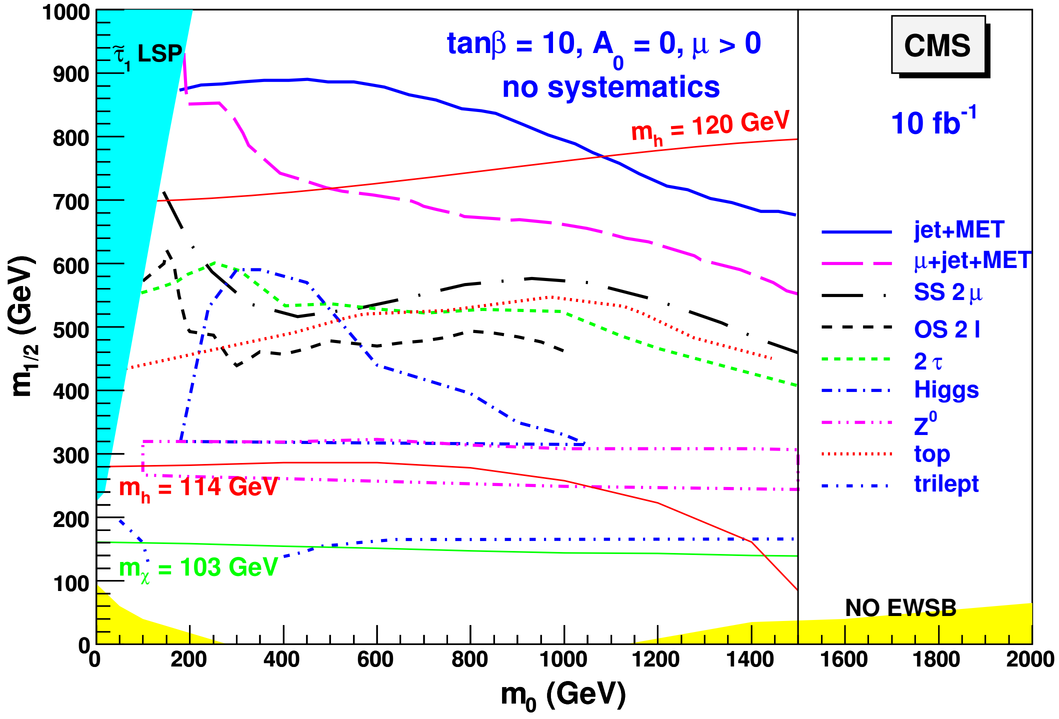
- Undetectable particles in the final state: $\not{E}_T$. Stable or ling-lived?
- Primary particles with mass∼600 GeV (M_{eff} study)
- Assigning spin hypotheses to produced sparticles can get an idea of couplings (exp. difficulty: need some assumption on gaugino spectrum to evaluate selection efficiency)
- Many more things depending on the excesses observed for the different "something". Examples:
  - Excess of of same-sign lepton pairs: some of the primary particles are Majorana
  - See same number of leptons and muons: lepton flavour ∼ conserved in first two generations
  - ....

How can we use it?

Too little information to zoom into a model

Probably with guess the composition of the produced primary particles

One can exclude detailed implementations of model



Ex. in mSUGRA for each point one has different inclusive signatures, and one can compare observed and predicted relative rates

Already quite a few theoretical attempts in this direction, e.g. LHC Olympics

However, more detailed info can be extracted from the data

What kind of info for establishing SUSY?

Long lists of requests. Need to demonstrate that:

- Every particle has a superpartner
- Their spin differ by $1/2$
- Their gauge quantum numbers are the same
- Their couplings are identical
- Mass relations predicted by SUSY hold

Available observables:

- Sparticle masses,
- Production cross-sections,
- BR's of cascade decays
- Angular decay distributions

Measurements of observables depends on detail of model and requires development of ad-hoc techniques. Over last ten years strategy based on detailed MC study of reasonable candidate models

Did we focus too much on a too restricted class of models?

What path from the observables to the model?

The problem is the presence of a very complex spectroscopy due to long decay chains, with crowded final states.

Many concurrent signatures obscuring each other

General strategy:

- Select signatures identifying well defined decay chains
- Extract constraints on masses, couplings, spin from decay kinematics/rates
- Try to match emerging pattern to template models, SUSY or anything else
- Having adjusted template models to measurements, try to find additional signatures to discriminate different options

Most of work done on sparticle mass measurement

Briefly introduce the most basic mass measurement technique

Conclusions

No statistical problem for the quick discovery of SUSY at the LHC if $m(SUSY) \sim 1-2$ TeV

Clear but difficult signatures, long work on understanding detector performance and estimate Standard Model backgrounds. Main focus of ATLAS and CMS work

Can typically confirm signal through multiple signatures

Once convincing signal claimed, try to pin down what kind of SM extension generated deviation

A few benchmark models studied, and some general techniques developed for mass and spin measurements of SUSY particles

Lots of work to learn how to make use of all the experimental information

If indeed we do observe a signal, many years of excitement ahead of us

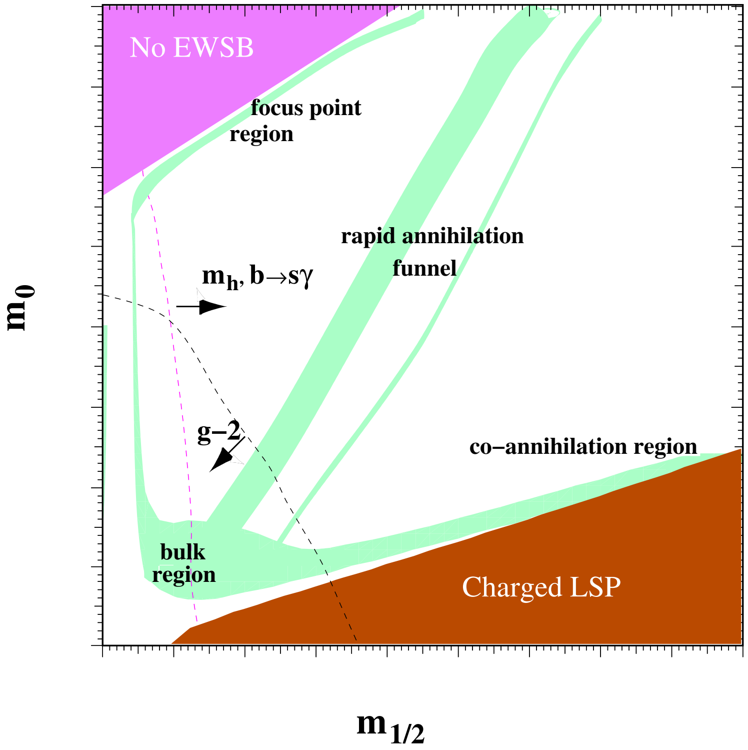
Backup

ATLAS Benchmarks

Large annihilation sross-section required by WMAP data

Boost annihilation via quasi-degeneracy of a sparticle with $\tilde{\chi}_1^0$, or large higgsino content of $\tilde{\chi}_1^0$

Regions in mSUGRA $(m_{1/2}, m_0)$ plane with acceptable $\tilde{\chi}_1^0$ relic density (e.g. Ellis et al.):



- SU3: Bulk region. Annihilation dominated by slepton exchange, easy LHC signatures fom $\tilde{\chi}_2^0 \to \tilde{\ell}\ell$
- SU1: Coannihilation region. Small $m(\tilde{\chi}_1^0) - m(\tilde{\tau})$ (1-10 Gev). Dominant processes $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tau\tau$, $\tilde{\chi}_1^0\tilde{\tau} \to \tau\gamma$ Similar to bulk, but softer leptons!
- SU6: Funnel region. $m(\tilde{\chi}_1^0) \simeq m(H/A)/2$ at high $\tan\beta$ Annihilation through resonant heavy Higgs exchange. Heavy higgs at the LHC observable up to ∼800 GeV
- SU2: Focus Point high m_0, large higgsino content, annihilation through coupling to W/Z Sfermions outside LHC reach, study gluino decays.
- SU4: Light point. Not inspired by cosmology. Mass scale ~ 400 GeV, at limit of Tevatron reach

Parameters and cross-sections of benchmark Points

SU1: $m_0 = 70\,\mathrm{GeV},\ m_{1/2} = 350\,\mathrm{GeV},\ A_0 = 0,\ \tan\beta = 10,\ \mu > 0.$

SU2: $m_0 = 3550\,\mathrm{GeV},\ m_{1/2} = 300\,\mathrm{GeV},\ A_0 = 0,\ \tan\beta = 10,\ \mu > 0.$

SU3: $m_0 = 100\,\mathrm{GeV},\ m_{1/2} = 300\,\mathrm{GeV},\ A_0 = -300\,\mathrm{GeV},\ \tan\beta = 6,\ \mu > 0.$

SU4: $m_0 = 200\,\mathrm{GeV},\ m_{1/2} = 160\,\mathrm{GeV},\ A_0 = -400\,\mathrm{GeV},\ \tan\beta = 10,\ \mu > 0.$

SU6: $m_0 = 320\,\mathrm{GeV},\ m_{1/2} = 375\,\mathrm{GeV},\ A_0 = 0,\ \tan\beta = 50,\ \mu > 0.$

Signal	σ^{LO} (pb)	σ^{NLO} (pb)	N
SU1	8.15	10.86	200 K
SU2	5.17	7.18	50 K
SU3	20.85	27.68	500 K
SU4	294.46	402.19	200 K
SU6	4.47	6.07	30 K

Particle	SU1	SU2	SU3	SU4	SU6
$\tilde{u}_L$	760.42	3563.24	631.51	412.25	866.84
$\tilde{b}_1$	697.90	2924.80	575.23	358.49	716.83
$\tilde{t}_1$	572.96	2131.11	424.12	206.04	641.61
$\tilde{u}_R$	735.41	3574.18	611.81	404.92	842.16
$\tilde{b}_2$	722.87	3500.55	610.73	399.18	779.42
$\tilde{t}_2$	749.46	2935.36	650.50	445.00	797.99
$\tilde{e}_L$	255.13	3547.50	230.45	231.94	411.89
$\tilde{\nu}_e$	238.31	3546.32	216.96	217.92	401.89
$\tilde{\tau}_1$	146.50	3519.62	149.99	200.50	181.31
$\tilde{\nu}_\tau$	237.56	3532.27	216.29	215.53	358.26
$\tilde{e}_R$	154.06	3547.46	155.45	212.88	351.10
$\tilde{\tau}_2$	256.98	3533.69	232.17	236.04	392.58
$\tilde{g}$	832.33	856.59	717.46	413.37	894.70
$\tilde{\chi}_1^0$	136.98	103.35	117.91	59.84	149.57
$\tilde{\chi}_2^0$	263.64	160.37	218.60	113.48	287.97
$\tilde{\chi}_3^0$	466.44	179.76	463.99	308.94	477.23
$\tilde{\chi}_4^0$	483.30	294.90	480.59	327.76	492.23
$\tilde{\chi}_1^+$	262.06	149.42	218.33	113.22	288.29
$\tilde{\chi}_2^+$	483.62	286.81	480.16	326.59	492.42