Prospects for Supersymmetry with early ATLAS data

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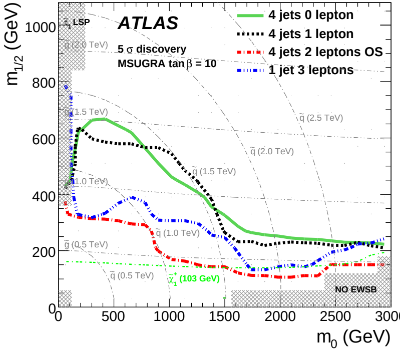
Introduction

A large region of the SUSY parameter space can be explored at the LHC, even after a few month of running ($\mathcal{L} \approx 1\ \text{fb}^{-1}$)

- SUSY discovery may depend on how quickly we understand the detector rathert than the LHC luminosity profile
- I will concentrate in this talk on the physics we can study with early data (1fb^{-1})
- See Alan Barr talk (this morning) for the long term LHC reach and an introduction to SUSY at the LHC

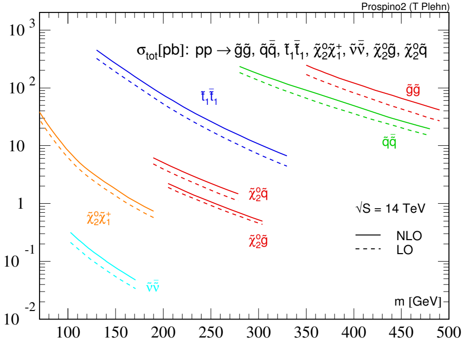


For comparison. Tevatron reach at the bottom-left corner

Outline

- ATLAS and Supersymmetry
- A selection of experimental challenges
- Supersymmetry searches in channels with no leptons
- Supersymmetry with one final state lepton
- SUSY measurements with 1fb^{-1} of data (next year)

SUSY cross sections at the LHC



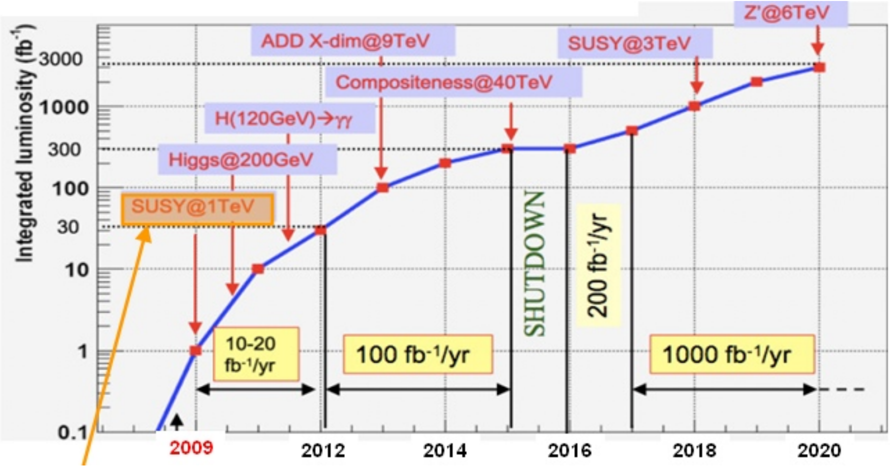
Sparticles have same couplings of SM partners ⇒ production dominated by colored sparticles: squarks and gluinos

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

Timeline for discovery



Discover SUSY in 2009 and spend the next 10 years measuring it!

The ATLAS Detector

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

excellent electron/photon identification

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

Precision Muon Spectrometer,

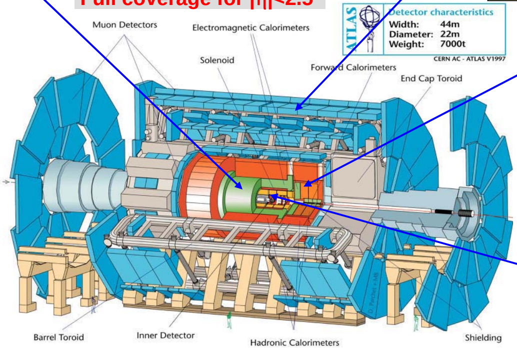
$\sigma/p_T \approx 10\%$ at 1 TeV/c

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,

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

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.

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

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

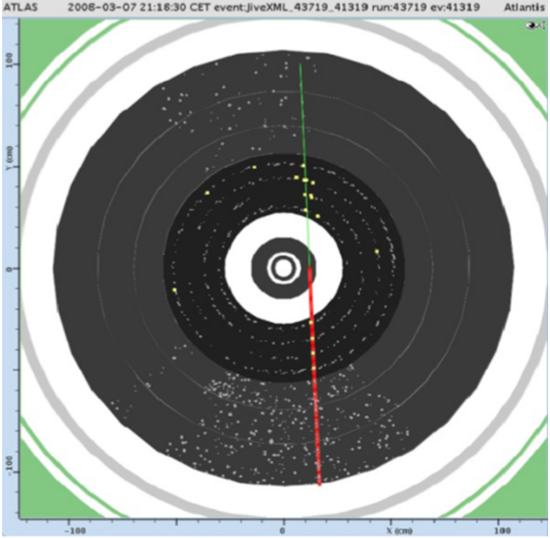
Before we get there...

- Past: Use test beams to study the response of detectors, tune simulation etc
- Present: Commission the detector with cosmic rays and beam gas.
- Future: Study Standard Model processes (eg QCD, W, Z, top) as a learning experience
- Not-too-far-Future: Start looking for new physics. Note that 10TeV center-of-mass energy offers great opportunities

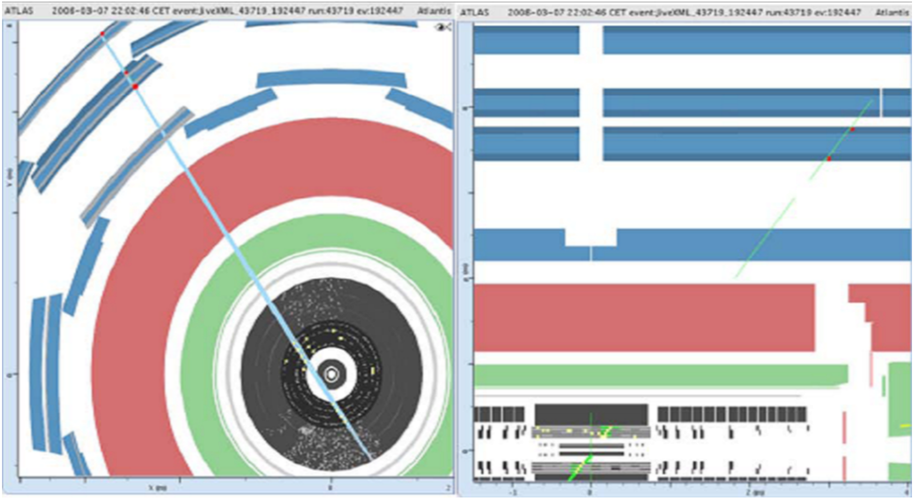
ATLAS first data

Milestone Run 6 (M6) in March 2008:

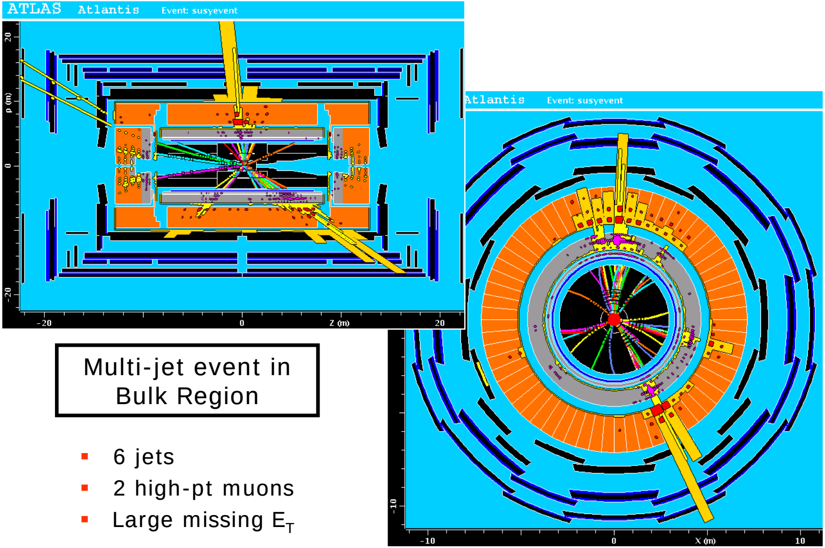
- Successfully took cosmics data with SCT and TRT sectors
- Only part of TRT was turned on (clearly visible from noise hits)
- Timing and alignment checks successful



Matching Inner Detector and Muons



A SUSY event in ATLAS



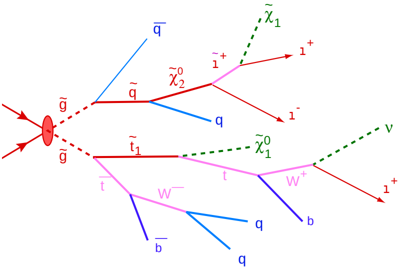
Multi-jet event in Bulk Region

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

SUSY discovery: basic strategy

Discovery from quarks/gluinos cascading to undetectable LSP

Details of the decay process are model specific. Focus on signatures that cover large classes of models



- $\not{E}_T$: from LSP escaping detection
- High p_T jets: from squark and gluino decays
- Charged leptons: from chargino and neutralino decays
- Multiple τ or b-jets: Often abundant production of third generation sparticles

Discuss searches for R-Parity conserving models with $\tilde{\chi}_1^0$ LSP

Other models investigated. Long-lived particles, R-hadrons later in this workshop

A comment on SUSY models

Don't believe in any one model... However

- Using a model gives a self consistent picture
- Ensures that claims are tenable

Limits are (will) be very difficult in model independent way

Very large model and parameter space at the moment:

- Situation will be easier once we get data as some models will be ruled out

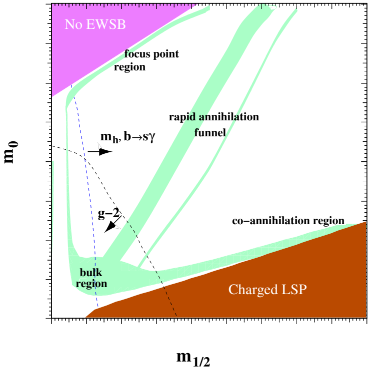
I will show examples from mSUGRA (mostly bulk SU3-point) in this talk:

- More ATLAS studies in different contexts
- "Nordic" talks on R-hadrons and long-lived stable particles

ATLAS Benchmark points

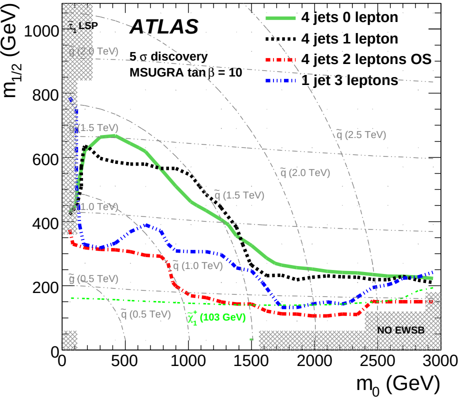
Select a few benchmark points to highlight specific signatures

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



- SU3: Bulk region. Annihilation dominated by slepton exchange, easy LHC signatures from $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}\ell$
- SU4: Low mass. At limit of Tevatron reach
- SU1: Coannihilation region. Small $m(\tilde{\chi}_1^0) - m(\tilde{\tau})$, soft leptons!
- SU6: Funnel region. $m(\tilde{\chi}_1^0) \approx m(H/A)/2$ at high $\tan\beta$. Annihilation through resonant heavy Higgs exchange.
- SU2: Focus Point high m_0, large higgsino content, annihilation through coupling to W/Z. Sfermions outside LHC reach, study gluino decays.

Inclusive reach in mSUGRA parameter space



ATLAS reach for 1fb^{-1}

Includes expected uncertainties on SM backgrounds:

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

Multiple signatures over most of the parameter space

Dominated by channels with $\not{E}_T$

Robust discovery strategy

For low values of m_0 and $m_{1/2}$ is limited by how quickly we can understand the detector

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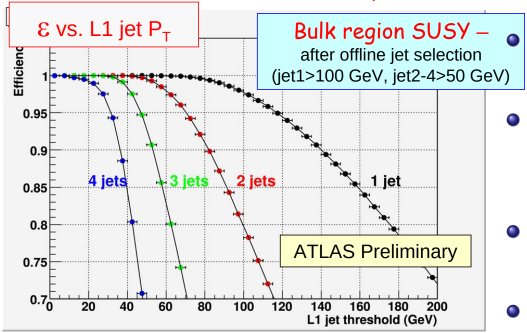
Triggering on SUSY

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

The main feature: high multiplicity of high P_T jets, $\not{E}_T$

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



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

- Require four jets with LVL1 Threshold > 25 GeV
- Absolute efficiency on signal $\approx 50 - 60\%$, rate ≈ 10 Hz (preliminary)
- Single jet trigger, to catch low multiplicity decays
- LVL1 Thresh:115 GeV, $\epsilon \approx 90\%$, Rate ≈ 6 Hz

SUSY Trigger efficiency

No Trigger, No Signal

LHC trigger menu will evolve rapidly with data

Trigger efficiency must be measured

Combining triggers is non-trivial

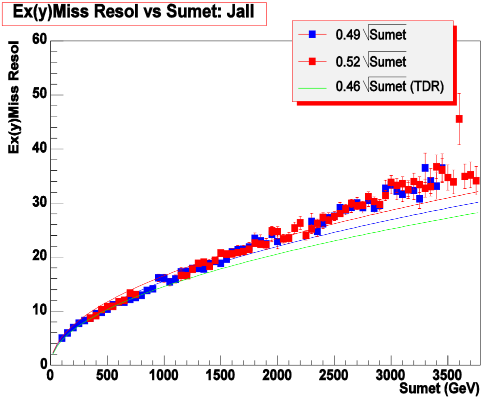
Best if one trigger is highly efficient

Trigger	SU1	SU2	SU3	SU4
	0-lepton, 4-jet			
JETS	44.6	51.0	33.8	7.7
XE120	96.9	90.1	94.0	68.8
J70_XE70	99.7	98.7	99.5	97.2
	0-lepton, 3-jet			
Trigger	SU1	SU2	SU3	SU4
JETS	64.9	71.1	54.9	34.3
XE120	100.	99.0	99.8	98.8
J70_XE70	100.	99.8	100.	99.9
	0-lepton, 2-jet			
JETS	44.1	39.9	30.1	8.8
XE120	99.8	97.5	99.5	96.5
J70_XE70	100.	100.	100.	99.9
	1-lepton			
JETS	41.8	50.5	31.7	8.1
XE120	96.6	91.1	93.0	69.5
J70_XE70	99.6	99.0	98.9	95.6
1LEP (MU20 OR EM25I)	81.2	81.0	79.9	80.3
	OS 2-lepton			
JETS	36.7	47.3	34.0	6.7
XE120	95.8	92.7	92.9	64.9
J70_XE70	99.2	100.0	98.9	94.3
1LEP (MU20 OR EM25I)	87.0	90.0	87.5	84.8
2LEP (2MU10 OR 2E15I)	20.5	35.5	27.0	18.0
	SS 2-lepton			
JETS	39.9	48.8	29.2	1.6
XE120	94.8	97.6	94.5	63.5
J70_XE70	99.3	100.0	98.9	84.1
1LEP (MU20 OR EM25I)	94.2	92.7	95.9	95.2
2LEP (2MU10 OR 2E15I)	32.6	41.5	32.2	25.4

Measuring Missing E_T

Once detector malfunctioning and external source understood, $\not{E}_T$ 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

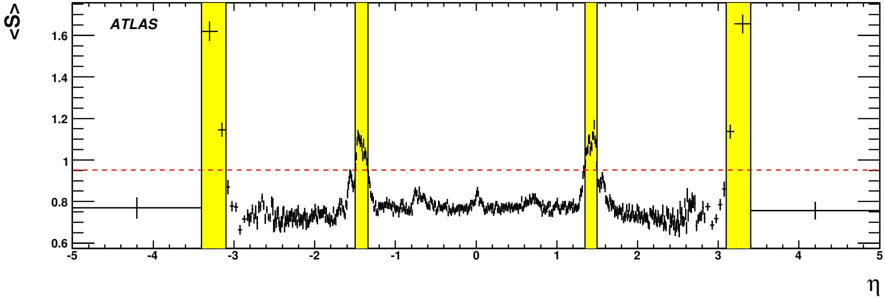


- $\not{E}_T$ resolution parametrised as a function of $\sum E_T$
- for each event evaluate significance as $S = \not{E}_T / \sqrt{\sum E_T}$
- Use variable S to monitor detector response

Fiducial regions for jets

Use a sample of 2-jet events ($p_T > 280$ GeV):

- For each event calculate $S = \not{E}_T / \sqrt{\sum E_T}$
- 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



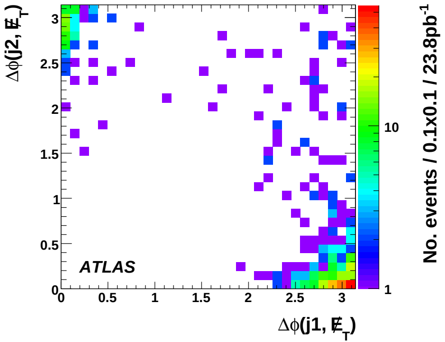
Observe clear degradation at interface between calorimeters

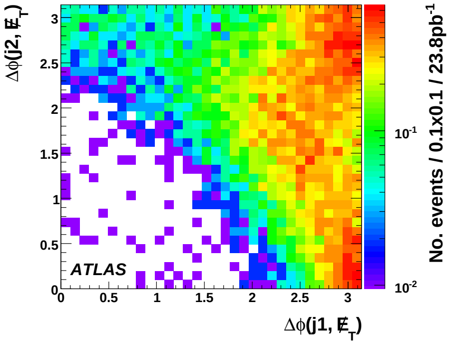
Reject high $\not{E}_T$ events with a jet falling in yellow regions

Rejecting specific topologies

Next step is rejection of topologies which yield to instrumental $\not\!\!E_T$

If one jet is undermeasured, expect that $\not\!\!E_T$ be aligned with its p_T .





Reject events with:

$\Delta\phi_{\rm min} = \min(\Delta\phi(j_1, \not\!\!E_T), \Delta\phi(j_2, \not\!\!E_T), \Delta\phi(j_3, \not\!\!E_T)) < 0.2$

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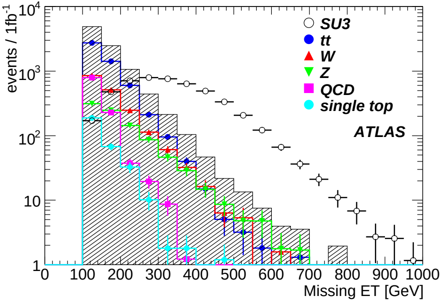
Inclusive signature for zero leptons

SUSY selection:

- 4 jets ($P_T < 100, 50, 50, 50$) GeV)
- $\not{E}_T > 100$ GeV and $\not{E}_T > 0.2 M_{\mathrm{eff}}$
- $\Delta\phi(j, \not{E}_T) > 0.2$
- Transverse sphericity> 0.2
- No leptons ($e^{\pm}$ or $\mu^{\pm}$) with $p_T >$20GeV



$$M_{\mathrm{eff}} = \sum_1^4 E^i_{T,J} + \not{E}_T$$

QCD background reduced to $\approx 5\%$ but with large uncertainites!

Comparable contributions from:

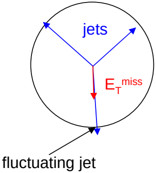
- $\bar{t}t$+jets
- W+jets
- Z+jets

Counting experiment: need precise estimate of background processes

QCD background. Data driven estimate

MonteCarlo estimate of QCD background hard. It requires:

- Good MonteCarlo simulation of QCD multijets
- Excellent modeling of detector response
- $\not\!\!E_T$ is from tails of response

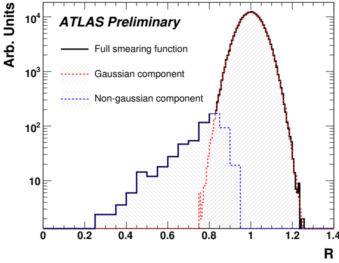


$\Rightarrow$ Develop multi-step data-driven estimate

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

Step 2: Measure the non-gaussian part:

- 3 jets, $p_T(J) > 250, 50, 25$ GeV, $\not\!\!E_T > 60$ GeV
- Only one jet parallel to the $\not\!\!E_T$ vector
- Define: $\vec{p}_T(J, \text{true}) \simeq \vec{p}_T(J) + \vec{\not\!\!E}_T$
- Plot: $R_2 = \frac{\vec{p}_T(J) \cdot \vec{p}_T(J,\text{true})}{|\vec{p}_T(J,\text{true})|^2}$



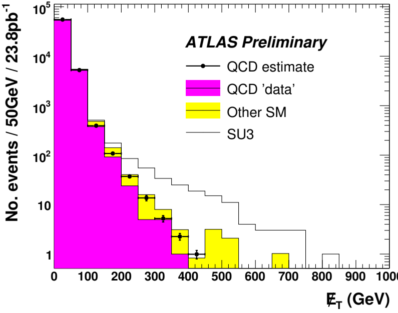
QCD background. Data driven estimate

Step 3: Normalise the gaussian and non-gaussian components using a sample of di-jet events. The measured response function can be used to smear events with low $\not{E}_T$ ('seed events')

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

Good agreement between the estimated and "data" distributions

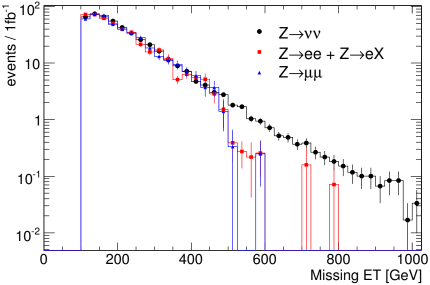
Dominant systematic errors are the p_T bias in event selection and the statistical error on "Mercedes" events.



$Z \to \nu\nu$+jets. Data driven estimate

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

Apply same cuts as for SUSY analysis (4 jets+Etmiss), remove leptons and calculate $\not\!\!E_T$ of events from the vector sum of their momenta



Number of $N_{Z\to\nu\nu}$ per $\not\!\!E_T$ bin calculated from $N_{Z\to\ell\ell}$ applying corrections for:

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

First two from MC, third one from data. Main uncertainites from:

- MC used for corrections ($\sim 6\%$)
- $\not\!\!E_T$ scale ($\sim 5\%$)
- Statistics of control sample ($\sim 13\%$)

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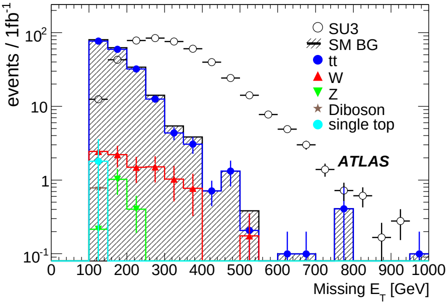
Inclusive signature with one lepton

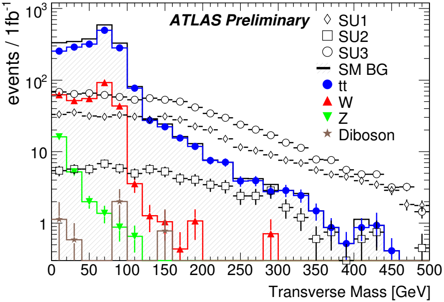
$\not\!\!E_T$+jets signature is most powerful and least model-dependent
BUT control of SM and instrumental backgrounds might require long time
The channel single lepton + jets + $\not\!\!E_T$ has somewhat smaller parameter space coverage, but might be easier to control

- Same kinematic cuts as for 0 lep+jets
- One lepton p_T >20GeV
- Cut on M_T , transverse mass of the lepton and $\not\!\!E_T$

$t\bar{t}$ dominant, W+jets becomes important for higher $\not\!\!E_T$, QCD negligible
Need data-driven evaluation of single lepton backgrounds from $t\bar{t}$ and W



One lepton Background evaluation: M_T method

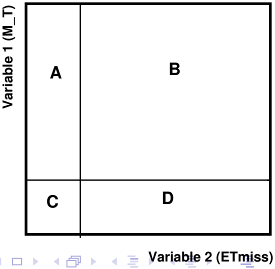


- M_T variable gives excellent discrimination against $t\bar{t}$ and W+jets
- Main discriminant value together with $\not{E}_T$
- Invert the M_T cut to evaluate background

Basic Principle:

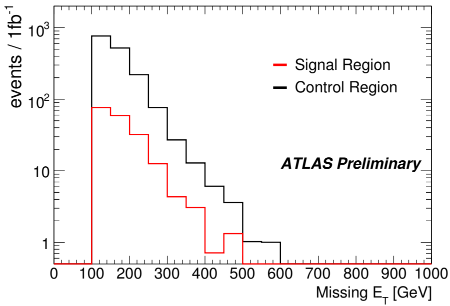
B is *signal region*, ≈no signal in A,C,D
D is *control region*
If shape of $\not{E}_T$ the same in (A+B) and (C+D):

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



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

M_T method: Resuls if there is no SUSY

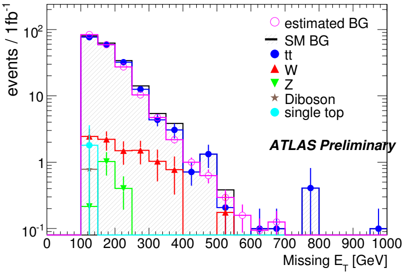


$\not{E}_T$ distributions in signal and control region approximately consistent

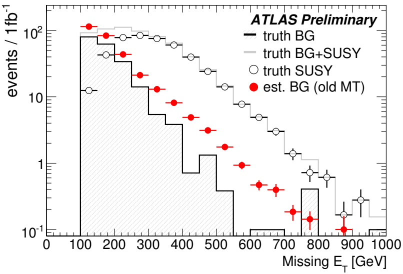
Background in absence of signal:

	$\not{E}_T > 100$ 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

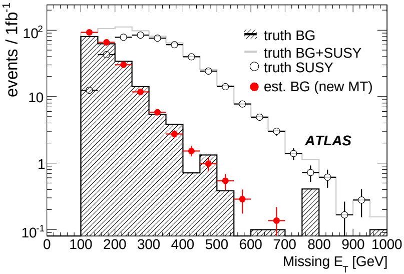


Background estimate in presence of SUSY



Background is overestimated due to signal "contamination" in the control region

- Iteration procedure. If excess observed, use property of excess to correct estimate.
- Assume that all events in the signal region are from signal and extrapolate back into the control region



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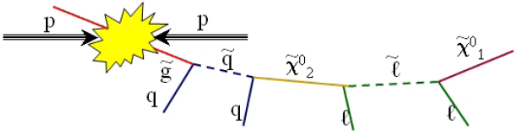
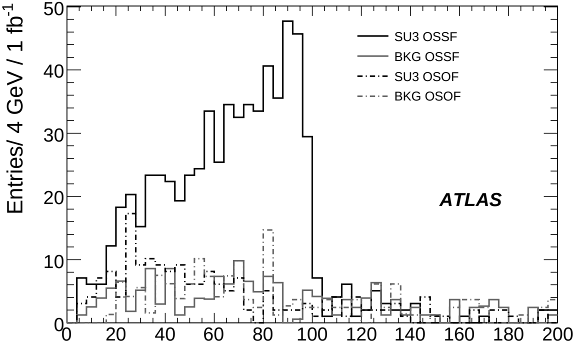
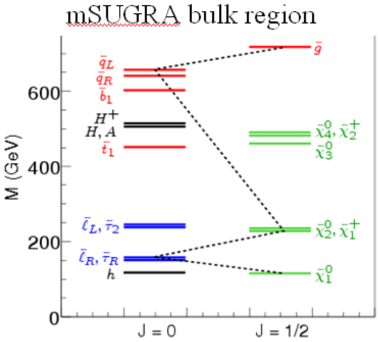
Sparticle mass measurements. Dilepton edges in SU3

Study decay chains:
$\tilde{\chi}_2^0 \rightarrow \tilde{\ell}\ell \rightarrow \tilde{\chi}_1^0 \ell\ell$



$$m_{edge} = m_{\tilde{\chi}_2^0} \sqrt{1 - \left(\frac{m_{\tilde{\ell}}}{m_{\tilde{\chi}_2^0}}\right)^2} \sqrt{1 - \left(\frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{\ell}}}\right)^2}$$

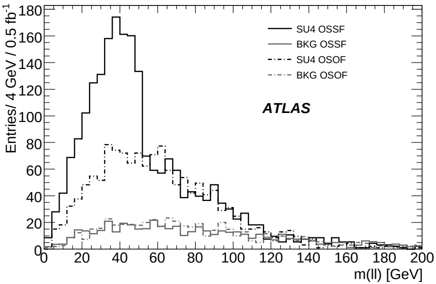




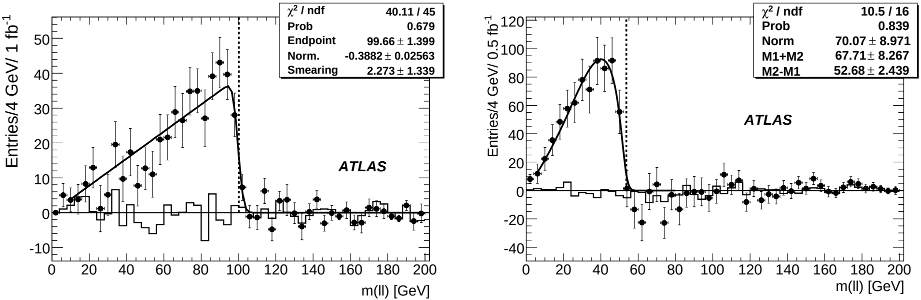
Sparticle mass measurements. Dilepton edges in SU4

Study decay chains: $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell\ell$
(sleptons are heavier than $\tilde{\chi}^0$)

$$m_{edge} = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$$



Flavour subtracted histograms



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

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

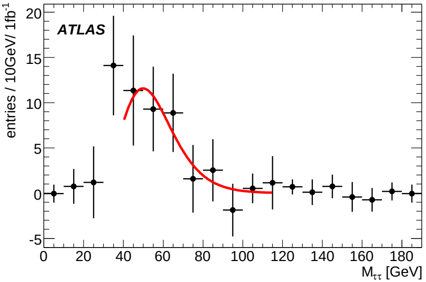
With 0.86 ratio of electron and muon reconstruction efficiencies

Tau-Tau mass edges

Normally large BR for $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \tau^+ \tau^-$. However:

- τ decay and are not measured directly. Part of its energy is invisible
- Large backgrounds from e.g. QCD
- Mass edge washed out due to invisible energy

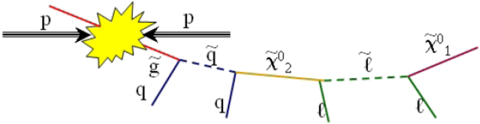
Shown here: visible $\tau\tau$ invariant mass for SU3 point See talk later in this workshop

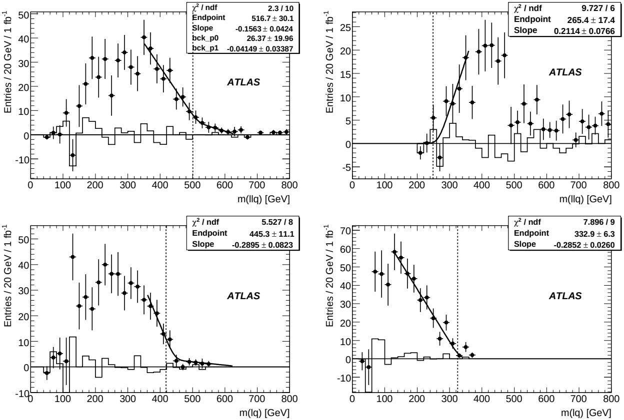


- Fit distribution
- Measure inflection point
- Use MC parametrisation to derive end point:

$$m_{EP} = (102 \pm 17^{\mathrm{stat}} \pm 5.5^{\mathrm{syst}})\mathrm{GeV}$$

Combine two leptons with a jet





- Edges in $m(\ell\ell q)$ and $m(\ell q)$
- Use the two leading jets for combinations
- Fit the endpoint with two straight lines convoluted with a Gaussian

Mass measurement with first data

Invert equations for edge positions to determine sparticle masses:

- Fit assumes we know mass hierarchy, eg from di-lepton edge shape
- Otherwise model independent
- Not precise for mass determination with 1fb^{-1}
- Sensitive to mass difference

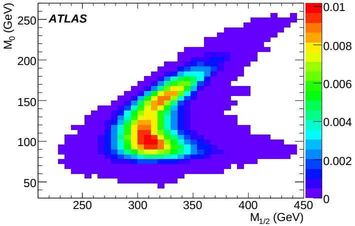
Observable	SU3 m_{meas} [GeV/c^2]	SU3 m_{MC} [GeV/c^2]	SU4 m_{meas} [GeV/c^2]	SU4 m_{MC} [GeV/c^2]
$m_{\tilde{\chi}_1^0}$	$88 \pm 60 \mp 2$	118	$62 \pm 126 \mp 0.4$	60
$m_{\tilde{\chi}_2^0}$	$189 \pm 60 \mp 2$	219	$115 \pm 126 \mp 0.4$	114
$m_{\tilde{q}}$	$614 \pm 91 \pm 11$	634	$406 \pm 180 \pm 9$	416
$m_{\tilde{\ell}}$	$122 \pm 61 \mp 2$	155		
Observable	SU3 Δm_{meas} [GeV/c^2]	SU3 Δm_{MC} [GeV/c^2]	SU4 Δm_{meas} [GeV/c^2]	SU4 Δm_{MC} [GeV/c^2]
$m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$	$100.6 \pm 1.9 \mp 0.0$	100.7	$52.7 \pm 2.4 \mp 0.0$	53.6
$m_{\tilde{q}} - m_{\tilde{\chi}_1^0}$	$526 \pm 34 \pm 13$	516.0	$344 \pm 53 \pm 9$	356
$m_{\tilde{\ell}} - m_{\tilde{\chi}_1^0}$	$34.2 \pm 3.8 \mp 0.1$	37.6		

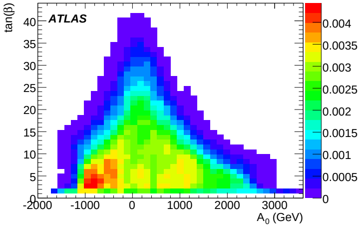
Parameter measurement with first data

Use measured edges as input to a global fit to the model parameters (assume mSUGRA).

Parameter	SU3 value	fitted value	exp. unc.	theo. + exp. unc.
		$\mathrm{sign}(\mu) = +1$		
$\tan\beta$	6	7.4	4.6	–
M_0	100 GeV	98.5 GeV	$\pm$9.3 GeV	$\pm$9.5 GeV
$M_{1/2}$	300 GeV	317.7 GeV	$\pm$6.9 GeV	$\pm$7.8 GeV
A_0	$-$300 GeV	445 GeV	$\pm$408 GeV	–
		$\mathrm{sign}(\mu) = -1$		
$\tan\beta$		13.9	$\pm$2.8	–
M_0		104 GeV	$\pm$18 GeV	–
$M_{1/2}$		309.6 GeV	$\pm$5.9 GeV	–
A_0		489 GeV	$\pm$189 GeV	–

- Scan of mSUGRA parameter space
- Pseudo experiments
- A_0 not well constrained
- μ ambiguity



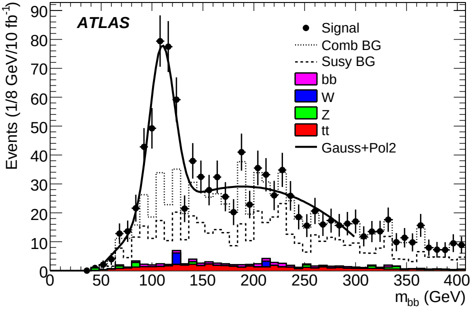


Higgs in SUSY events

Higgs boson can be produced in SUSY decay chains with the process: $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h$, if $m(\tilde{\chi}_2^0) > m(\tilde{\chi}_2^0) + m(h)$

Main background is SUSY combinatorics, *b*-jets produced by other sparticle decays

Ad-hoc SUSY point with enhanced Higgs production



Selection cuts:

- $\not{E}_T > 300$ GeV;
- two light-flavoured jets with $p_T > 100$ GeV;
- two *b*-jets with $p_T > 50$ GeV;
- no leptons with $p_T > 10$ GeV.

If Higgs exists it will be discovered as a SUSY decay!

See talk later in this workshop

Conclusions

- A huge experimental challenge is still ahead of us
- The ATLAS detector is going to be completed in a few weeks
- The LHC is starting to deliver *pp* collisions (at 10TeV center of mass) later this year
- SUSY could be hiding next door...
- Expect the unexpected!