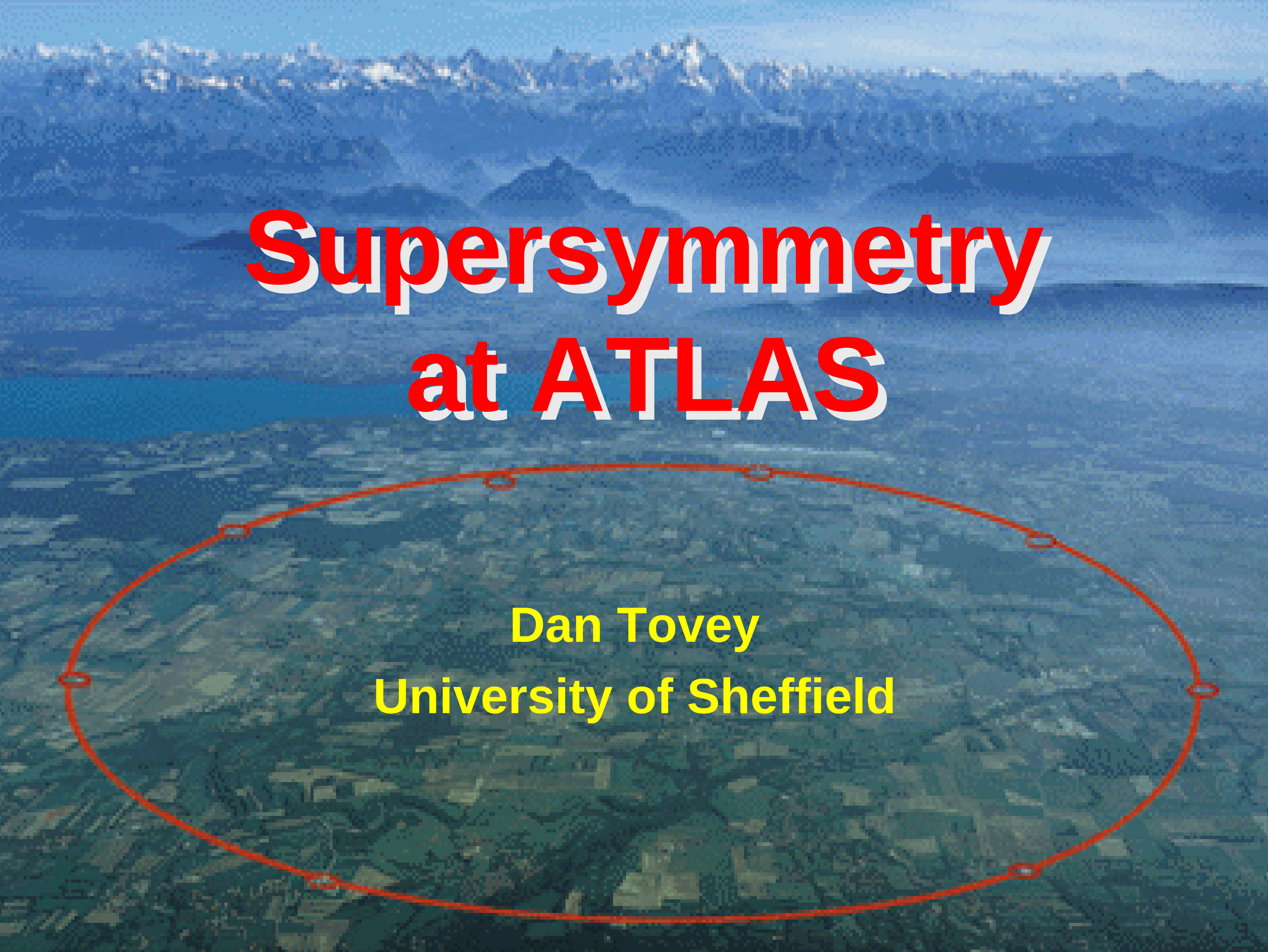


Supersymmetry at ATLAS

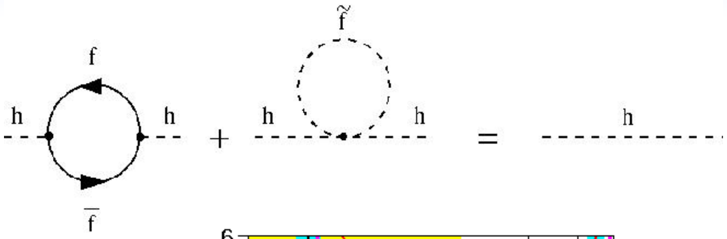
Dan Tovey
University of Sheffield

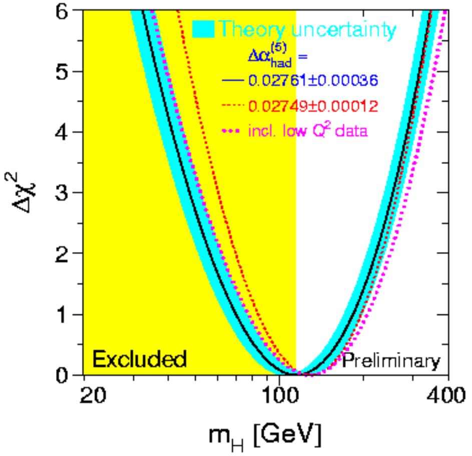
Supersymmetry

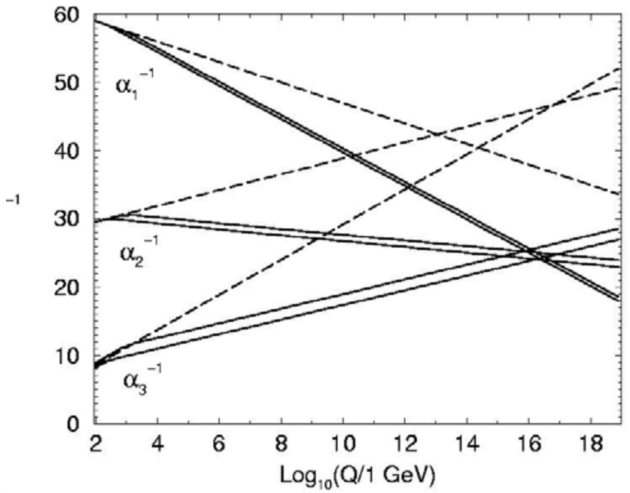
- Supersymmetry (SUSY) fundamental continuous symmetry connecting fermions and bosons

$$Q_\alpha|F\rangle = |B\rangle, \qquad Q_\alpha|B\rangle = |F\rangle$$

- $\{Q_\alpha, Q_\beta\} = -2\gamma^\mu_{\alpha\beta} p_\mu$: generators of SUSY ~ 'square-root' of translations
  - Connection to space-time symmetry
- SUSY stabilises Higgs mass against loop corrections (gauge hierarchy/fine-tuning problem)
  - Leads to Higgs mass ≤ 135 GeV
  - Good agreement with LEP constraints from EW global fits
- SUSY modifies running of SM gauge couplings 'just enough' to give Grand Unification at single scale.







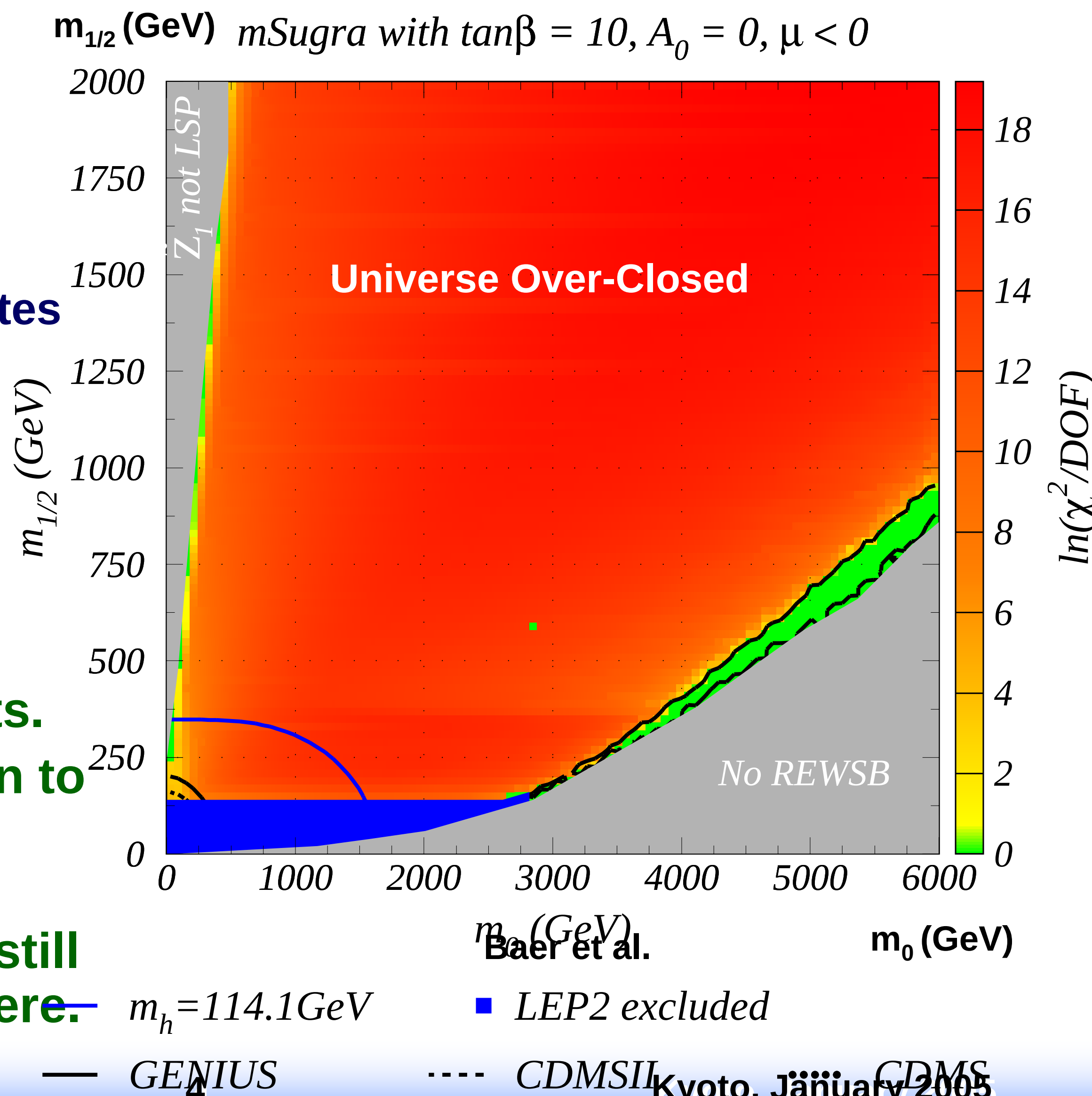
SUSY Spectrum

- **SUSY gives rise to partners of SM states with opposite spin-statistics but otherwise same Quantum Numbers.**
- **Expect SUSY partners to have same masses as SM states**
  - **Not observed (despite best efforts!)**
  - **SUSY must be a broken symmetry at low energy**
- **Higgs sector also expanded**

Standard Model Particles		SUSY Partners		
Particles	States	Sparticles	States	Mixtures
quarks (q) (spin-$\frac{1}{2}$)	$\binom{u}{d}_L$, u_R, d_R $\binom{c}{s}_L$, c_R, s_R $\binom{t}{b}_L$, t_R, b_R	squarks ($\tilde{q}$) (spin-0)	$\binom{\tilde{u}}{\tilde{d}}_L$, $\tilde{u}_R$, $\tilde{d}_R$ $\binom{\tilde{c}}{\tilde{s}}_L$, $\tilde{c}_R$, $\tilde{s}_R$ $\binom{\tilde{t}}{\tilde{b}}_L$, $\tilde{t}_R$, $\tilde{b}_R$	$\tilde{t}_{1,2}$, $\tilde{b}_{1,2}$
leptons (l) (spin-$\frac{1}{2}$)	$\binom{e}{\nu_e}_L$, e_R $\binom{\mu}{\nu_\mu}_L$, μ_R $\binom{\tau}{\nu_\tau}_L$, τ_R	sleptons ($\tilde{l}$) (spin-0)	$\binom{\tilde{e}}{\tilde{\nu}_e}_L$, $\tilde{e}_R$ $\binom{\tilde{\mu}}{\tilde{\nu}_\mu}_L$, $\tilde{\mu}_R$ $\binom{\tilde{\tau}}{\tilde{\nu}_\tau}_L$, $\tilde{\tau}_R$	$\tilde{\tau}_{1,2}$
gauge/Higgs bosons (spin-1, spin-0)	g, Z, γ, h, H, A $W^\pm$, $H^\pm$	gauginos/Higgsinos (spin-$\frac{1}{2}$)	$\tilde{g}$, $\tilde{Z}$, $\tilde{\gamma}$, $\tilde{H}^0_{1,2}$ $\tilde{W}^\pm$, $\tilde{H}^\pm$	$\tilde{\chi}^0_{1,2,3,4}$ $\tilde{\chi}^\pm_{1,2}$
graviton (spin-2)	G	gravitino (spin-$\frac{3}{2}$)	$\tilde{G}$	

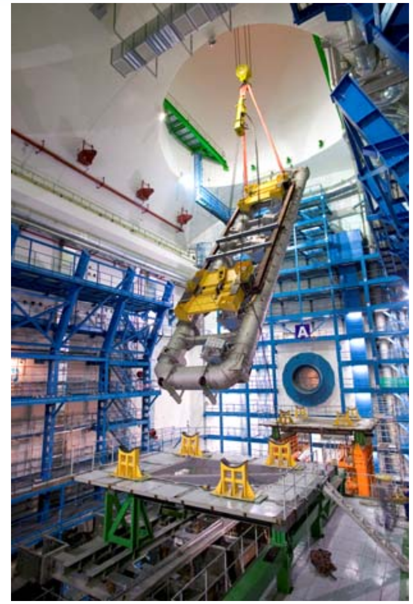
SUSY & Dark Matter

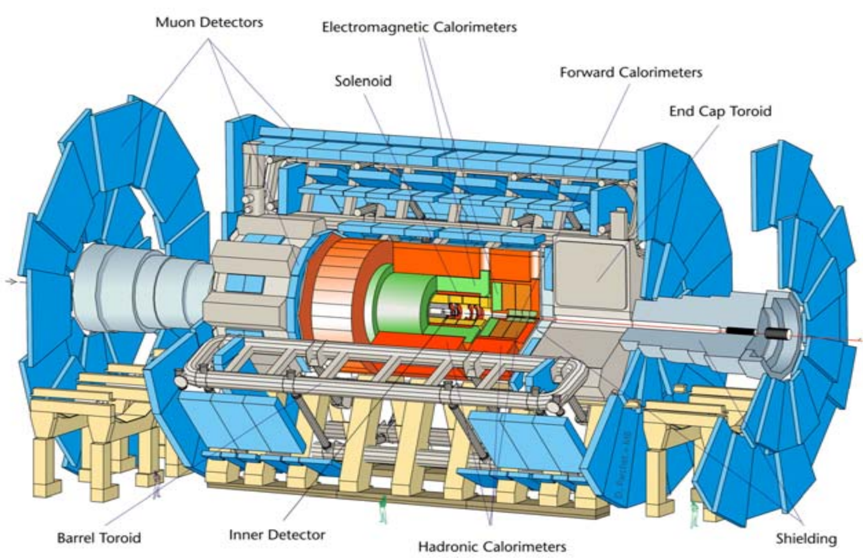
- R-Parity $R_p = (-1)^{3B+2S+L}$
- Conservation of R_p (motivated e.g. by string models) attractive
  - e.g. protects proton from rapid decay via SUSY states
- Causes Lightest SUSY Particle (LSP) to be absolutely stable
- LSP neutral/weakly interacting to escape astroparticle bounds on anomalous heavy elements.
- Naturally provides solution to dark matter problem of astrophysics / cosmology
- R-Parity violating models still possible ➔ not covered here.



SUSY @ ATLAS

- **LHC will be a 14 TeV proton-proton collider located inside the LEP tunnel at CERN.**
- **Luminosity goals:**
  - **10 fb^{-1} / year (first 3 years)**
  - **100 fb^{-1}/year (subsequently).**
- **First data in 2007.**
- **Higgs & SUSY main goals.**

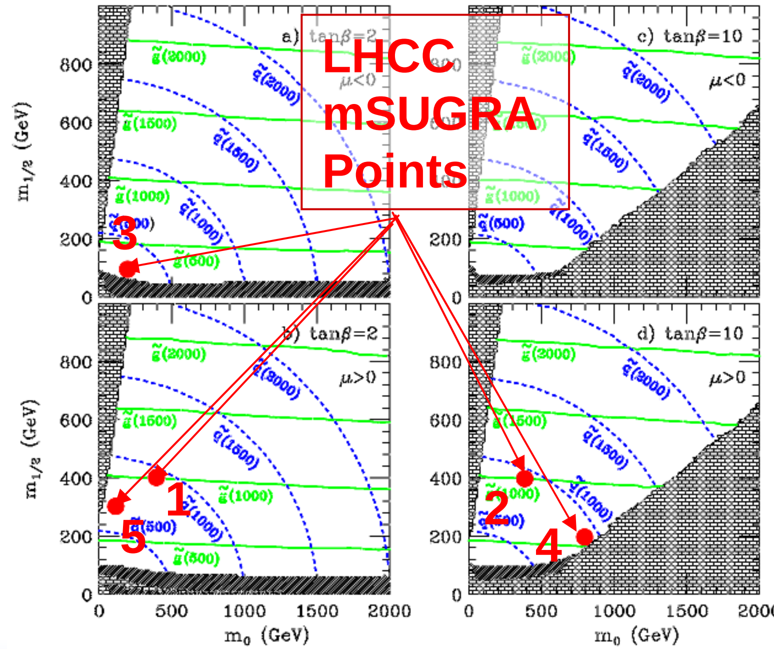




- **Much preparatory work carried out historically by ATLAS**
  - **Summarised in Detector and Physics Performance TDR (1998/9).**
- **Work continuing to ensure ready to test new ideas in 2007.**
- **Concentrate here on more recent work.**

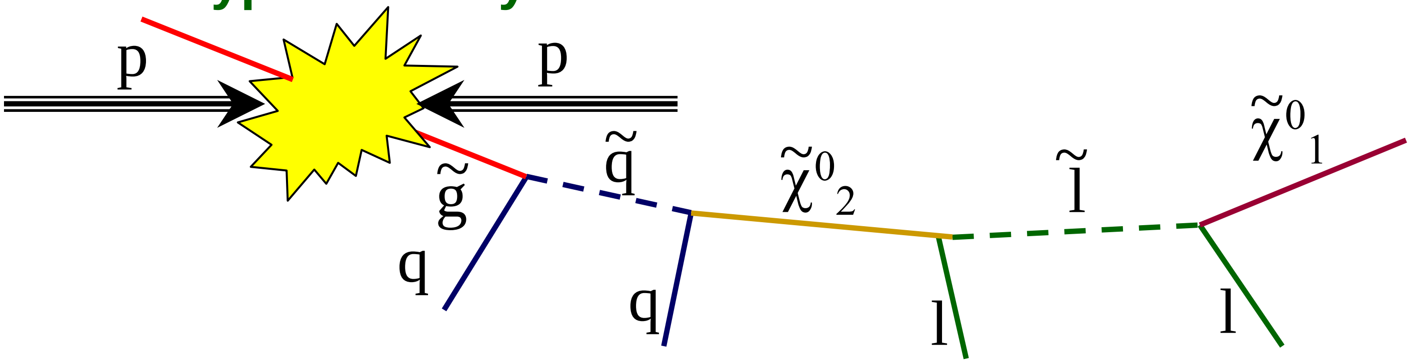
Model Framework

- Minimal Supersymmetric Extension of the Standard Model (MSSM) contains > 105 free parameters, NMSSM etc. has more → difficult to map complete parameter space!
- Assume specific well-motivated model framework in which generic signatures can be studied.
- Often assume SUSY broken by gravitational interactions → mSUGRA/CMSSM framework : unified masses and couplings at the GUT scale → 5 free parameters
  (m_0, $m_{1/2}$, A_0, tan(β), sgn(μ)).
- R-Parity assumed to be conserved.
- Exclusive studies use benchmark points in mSUGRA parameter space:
  - LHCC Points 1-6;
  - Post-LEP benchmarks (Battaglia et al.);
  - Snowmass Points and Slopes (SPS);
  - etc…



SUSY Signatures

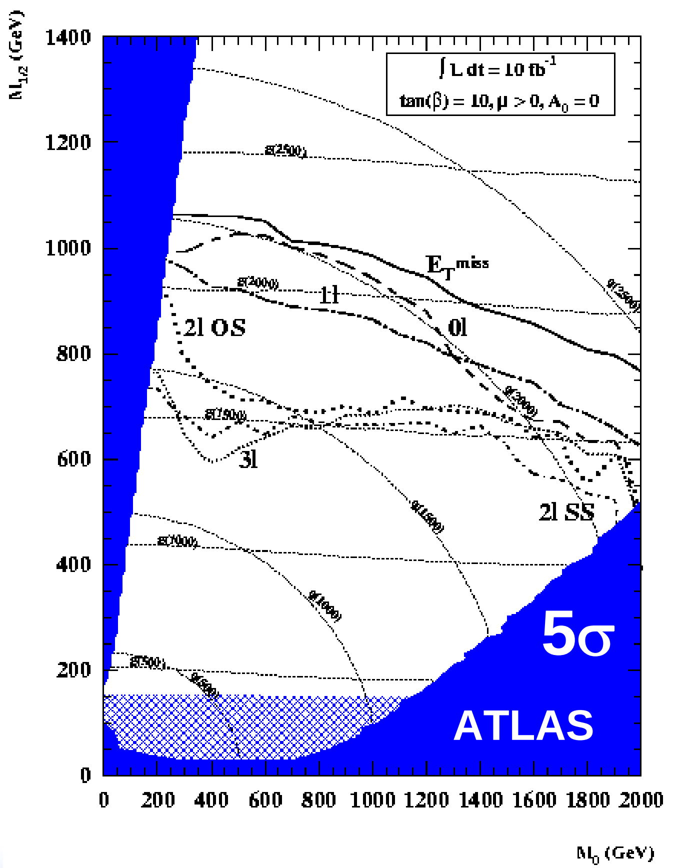
- Q: What do we expect SUSY events @ LHC to look like?
- A: Look at typical decay chain:

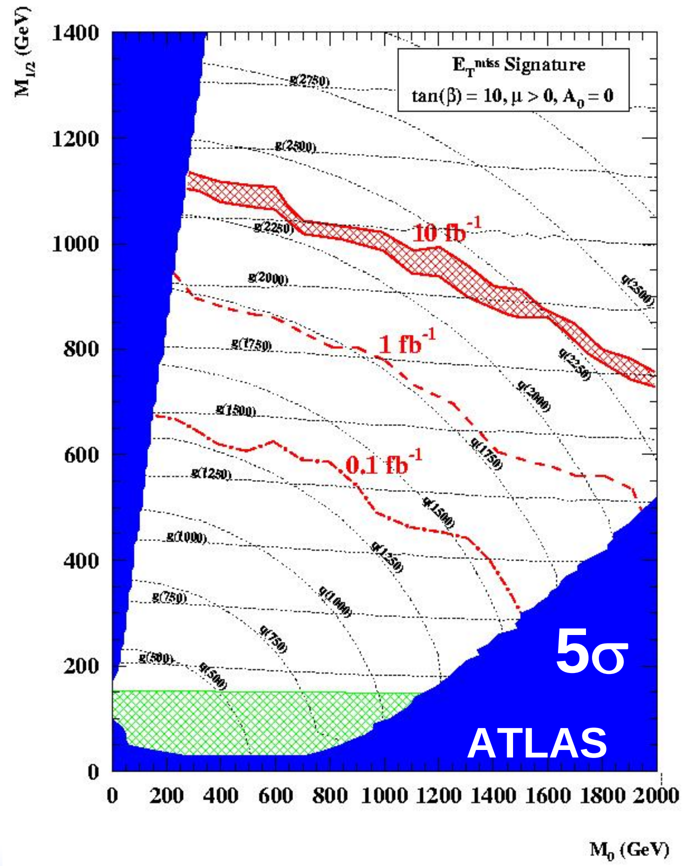


- Strongly interacting sparticles (squarks, gluinos) dominate production.
- Heavier than sleptons, gauginos etc. → cascade decays to LSP.
- Long decay chains and large mass differences between SUSY states
  - Many high p_T objects observed (leptons, jets, b-jets).
- If R-Parity conserved LSP (lightest neutralino in mSUGRA) stable and sparticles pair produced.
  - Large E_T^{miss} signature (c.f. $W \rightarrow l\nu$).
- Closest equivalent SM signature $t \rightarrow Wb$.

Inclusive Searches

- Use 'golden' Jets + n leptons + E_T^{miss} discovery channel.
- Map statistical discovery reach in mSUGRA m_0-$m_{1/2}$ parameter space.
- Sensitivity only weakly dependent on A_0, $\tan(\beta)$ and sign(μ).
- Syst.+ stat. reach harder to assess: focus of current & future work.



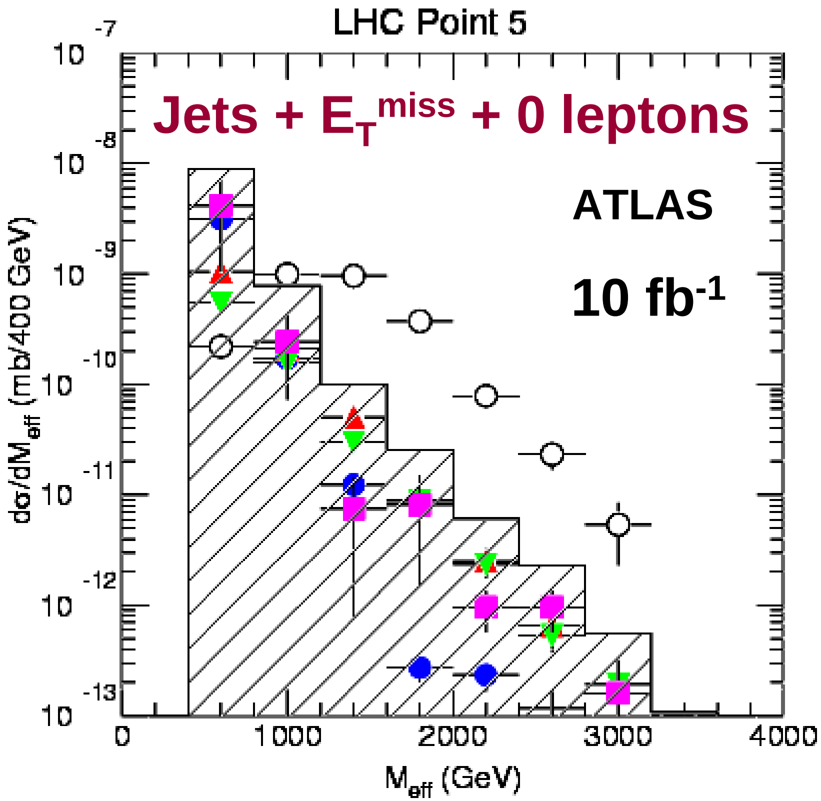


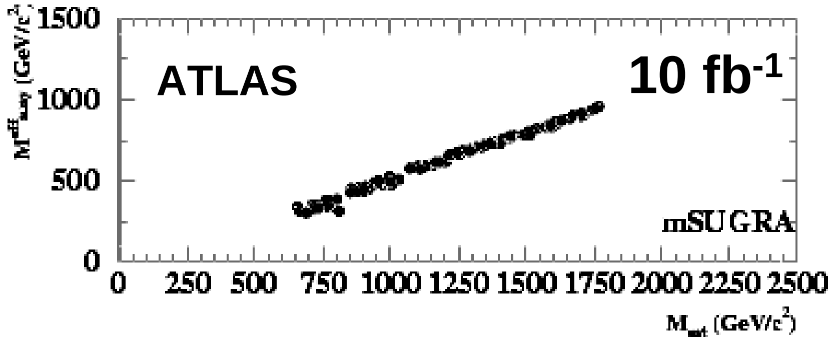
SUSY Mass Scale

- First measured SUSY parameter likely to be mass scale:
  - Defined as weighted mean of masses of initial sparticles.
- Calculate distribution of 'effective mass' variable defined as scalar sum of masses of all jets (or four hardest) and E_T^{miss}:

$$M_{eff}=\Sigma|p_T^i| + E_T^{miss}.$$

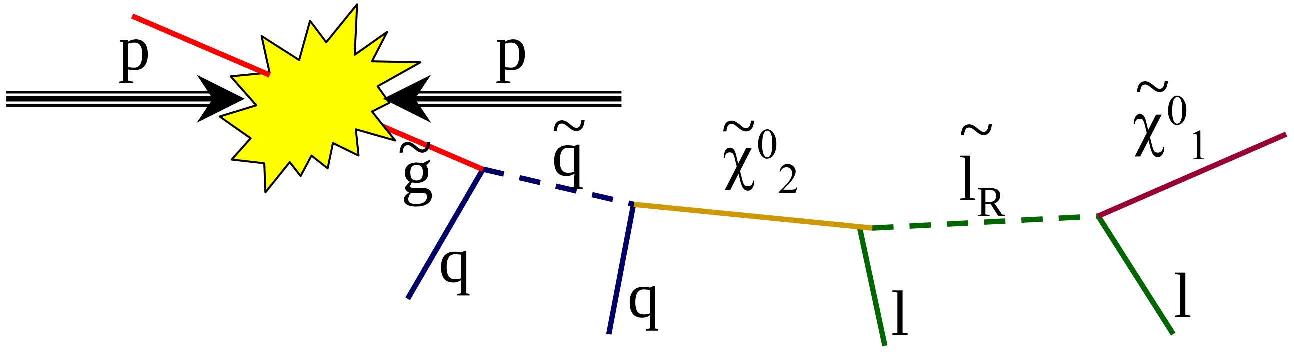
- Distribution peaked at ~ twice SUSY mass scale for signal events.
- Pseudo 'model-independent' measurement.
- Typical measurement error (syst+stat) ~10% for mSUGRA models for 10 fb^{-1}.





Exclusive Studies

- With more data will attempt to measure weak scale SUSY parameters (masses etc.) using exclusive channels.
- Different philosophy to TeV Run II (better S/B, longer decay chains) → aim to use model-independent measures.



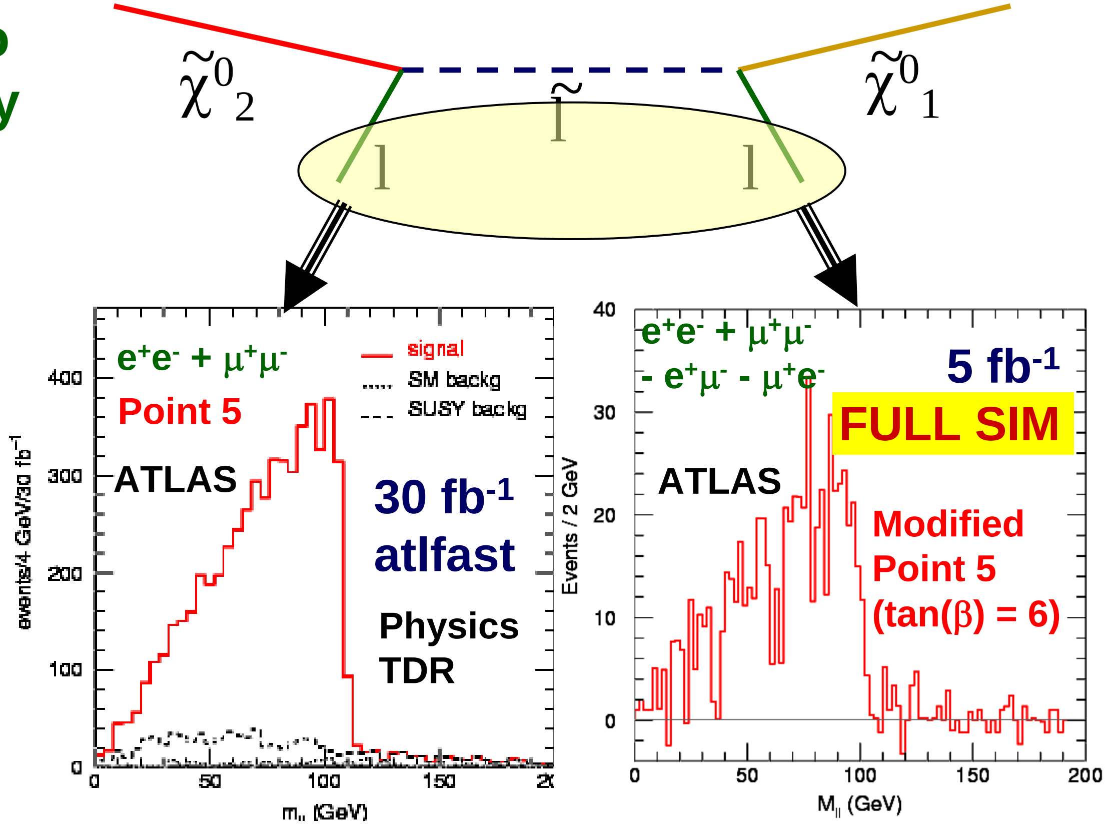
- Two neutral LSPs escape from each event
  - Impossible to measure mass of each sparticle using one channel alone
- Use kinematic end-points to measure combinations of masses.
- Old technique used many times before (ν mass from β decay spectrum, W (transverse) mass in W→lν).
- Difference here is we don't know mass of neutral final state particles.

Dilepton Edge Measurements

- When kinematically accessible $\tilde{\chi}^0_2$ can undergo sequential two-body decay to $\tilde{\chi}^0_1$ via a right-slepton (e.g. LHC Point 5).
- Results in sharp OS SF dilepton invariant mass edge sensitive to combination of masses of sparticles.
- Can perform SM & SUSY background subtraction using OF distribution

  $e^+e^- + \mu^+\mu^- - e^+\mu^- - \mu^+e^-$

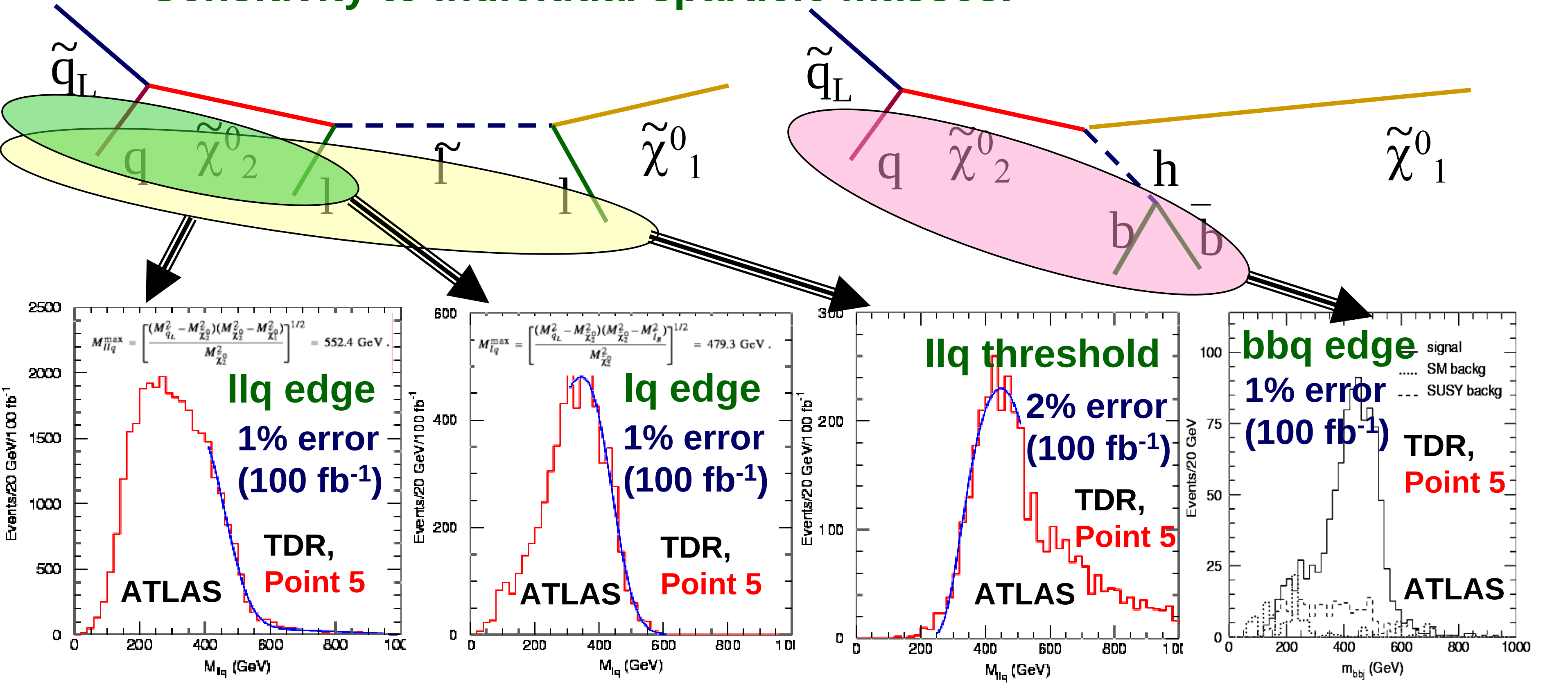
- Position of edge measured with **precision ~ 0.5%** (30 fb^{-1}).



$$M_{ll}^{max} = M(\tilde{\chi}_2^0)\sqrt{1-\frac{M^2(\tilde{l}_R)}{M^2(\tilde{\chi}_2^0)}}\sqrt{1-\frac{M^2(\tilde{\chi}_1^0)}{M^2(\tilde{l}_R)}} = 108.93 \text{ GeV}$$

Measurements With Squarks

- Dilepton edge starting point for reconstruction of decay chain.
- Make invariant mass combinations of leptons and jets.
- Gives multiple constraints on combinations of four masses.
- Sensitivity to individual sparticle masses.

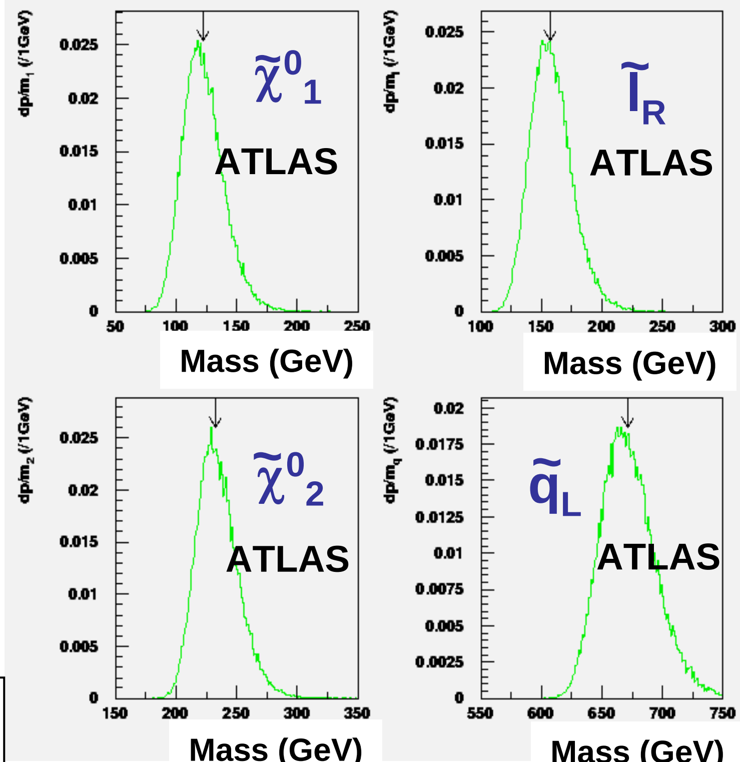


‘Model-Independent’ Masses

- **Combine measurements from edges from different jet/lepton combinations to obtain ‘model-independent’ mass measurements.**

Related edge	Kinematic endpoint
l^+l^- edge	$(m_{ll}^{max})^2 = (\tilde{\xi} - \tilde{l})(\tilde{l} - \tilde{\chi})/\tilde{l}$
l^+l^-q edge	$(m_{llq}^{max})^2 = \begin{cases} \max\left[\frac{(\tilde{q}-\tilde{\xi})(\tilde{\xi}-\tilde{\chi})}{\tilde{\xi}}, \frac{(\tilde{q}-\tilde{l})(\tilde{l}-\tilde{\chi})}{\tilde{l}}, \frac{(\tilde{q}\tilde{l}-\tilde{\xi}\tilde{\chi})(\tilde{\xi}-\tilde{l})}{\tilde{\xi}\tilde{l}}\right] \\ \text{except for the special case in which } \tilde{l}^2 < \tilde{q}\tilde{\chi} < \tilde{\xi}^2 \text{ and} \\ \tilde{\xi}^2\tilde{\chi} < \tilde{q}\tilde{l}^2 \text{ where one must use } (m_{\tilde{q}} - m_{\tilde{\chi}_1^0})^2. \end{cases}$
Xq edge	$(m_{Xq}^{max})^2 = X + (\tilde{q} - \tilde{\xi})\left[\tilde{\xi} + X - \tilde{\chi} + \sqrt{(\tilde{\xi} - X - \tilde{\chi})^2 - 4X\tilde{\chi}}\right]/(2\tilde{\xi})$
l^+l^-q threshold	$(m_{llq}^{min})^2 = \begin{cases} [\; 2\tilde{l}(\tilde{q} - \tilde{\xi})(\tilde{\xi} - \tilde{\chi}) + (\tilde{q} + \tilde{\xi})(\tilde{\xi} - \tilde{l})(\tilde{l} - \tilde{\chi}) \\ \; -(\tilde{q} - \tilde{\xi})\sqrt{(\tilde{\xi} + \tilde{l})^2(\tilde{l} + \tilde{\chi})^2 - 16\tilde{\xi}\tilde{l}^2\tilde{\chi}} \;]/(4\tilde{l}\tilde{\xi}) \end{cases}$
$l^{\pm}_{near}q$ edge	$(m_{l_{near}q}^{max})^2 = (\tilde{q} - \tilde{\xi})(\tilde{\xi} - \tilde{l})/\tilde{\xi}$
$l^{\pm}_{far}q$ edge	$(m_{l_{far}q}^{max})^2 = (\tilde{q} - \tilde{\xi})(\tilde{l} - \tilde{\chi})/\tilde{l}$
$l^{\pm}q$ high-edge	$(m_{lq(high)}^{max})^2 = \max\left[(m_{l_{near}q}^{max})^2, (m_{l_{far}q}^{max})^2\right]$
$l^{\pm}q$ low-edge	$(m_{lq(low)}^{max})^2 = \min\left[(m_{l_{near}q}^{max})^2, (\tilde{q} - \tilde{\xi})(\tilde{l} - \tilde{\chi})/(2\tilde{l} - \tilde{\chi})\right]$
M_{T2} edge	$\Delta M = m_{\tilde{l}} - m_{\tilde{\chi}_1^0}$

Table 4: The absolute kinematic endpoints of invariant mass quantities formed from decay chains of the types mentioned in the text for known particle masses. The following shorthand notation has been used: $\tilde{\chi} = m^2_{\tilde{\chi}_1^0}$, $\tilde{l} = m^2_{\tilde{l}_R}$, $\tilde{\xi} = m^2_{\tilde{\chi}_2^0}$, $\tilde{q} = m^2_{\tilde{q}}$ and X is $m^2_{\tilde{\chi}}$ or $m^2_{\tilde{q}}$ depending on which particle participates in the "branched" decay.

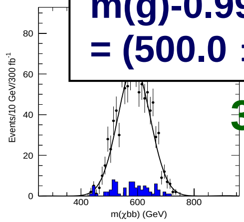


LHCC Point 5

Sparticle	Expected precision (100 fb^{-1})
$\tilde{q}_L$	$\pm$ 3%
$\tilde{\chi}^0_2$	$\pm$ 6%
$\tilde{l}_R$	$\pm$ 9%
$\tilde{\chi}^0_1$	$\pm$ 12%

Sbottom/Gluino Mass

- Following measurement of squark, slepton and neutralino masses move up decay chain and study alternative chains.
- One possibility: require b-tagged jet in addition to dileptons.
- Give sensitivity to sbottom mass (actually two peaks) and gluino mass.
- Problem with large error on input $\tilde{\chi}^0_1$ mass remains → reconstruct difference of gluino and sbottom masses.
- Allows separation of $\tilde{b}_1$ and $\tilde{b}_2$ with 300 fb^{-1}.



$m(\tilde{g})-0.99m(\tilde{\chi}^0_1) = (500.0 \pm 6.4)$ GeV

300 fb^{-1}

ATLAS

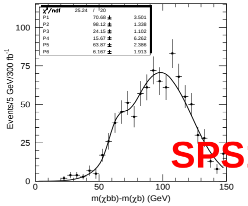
SPS1a

$m(\tilde{g})-m(\tilde{b}_1) = (103.3 \pm 1.8)$ GeV

ATLAS

$m(\tilde{g})-m(\tilde{b}_2) = (70.6 \pm 2.6)$ GeV

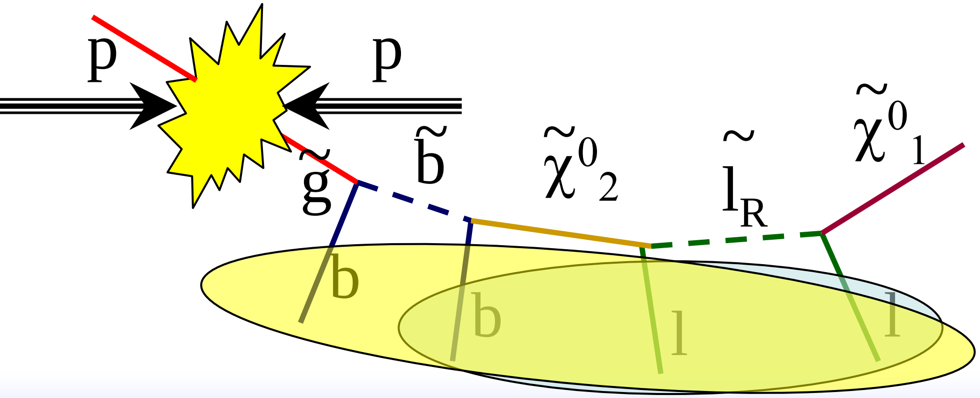
300 fb^{-1}



SPS1a

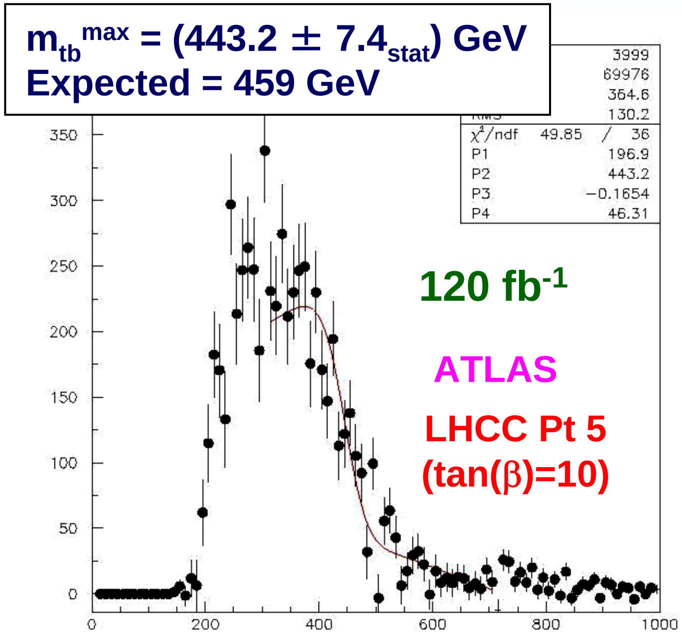
Figure 8: Distribution of $m(\tilde{\chi}^0_2 bb) - m(\tilde{\chi}^0_2 b)$ for an integrated luminosity of 300 fb^{-1}. Superimposed is the fit performed assuming the sum of two gaussian distributions.

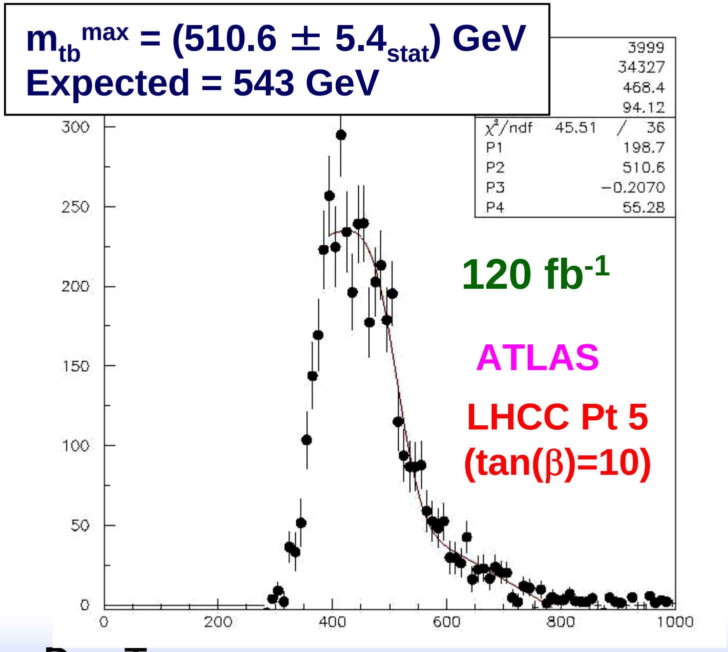
10



Stop Mass

- **Look at edge in tb mass distribution.**
- **Contains contributions from**
  - $\tilde{g} \rightarrow t\tilde{t}_1 \rightarrow tb\tilde{\chi}^+_1$
  - $\tilde{g} \rightarrow b\tilde{b}_1 \rightarrow bt\tilde{\chi}^+_1$
  - **SUSY backgrounds**
- **Measures weighted mean of end-points**
- **Require m(jj) ~ m(W), m(jjb) ~ m(t)**





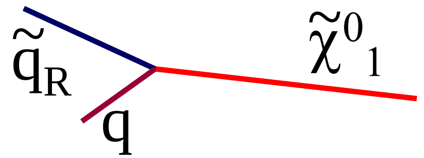
- **Subtract sidebands from m(jj) distribution**
- **Can use similar approach with** $\tilde{g} \rightarrow t\tilde{t}_1 \rightarrow tt\tilde{\chi}^0_i$
  - **Di-top selection with sideband subtraction**
- **Also use 'standard' bbll analyses (previous slide)**

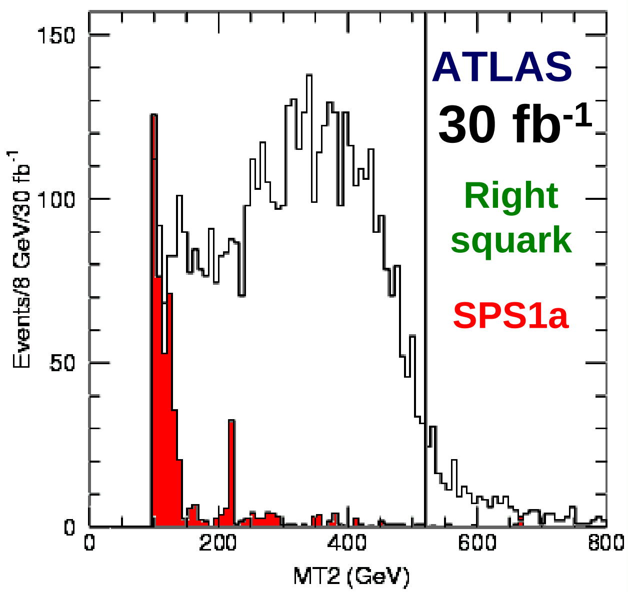
RH Squark Mass

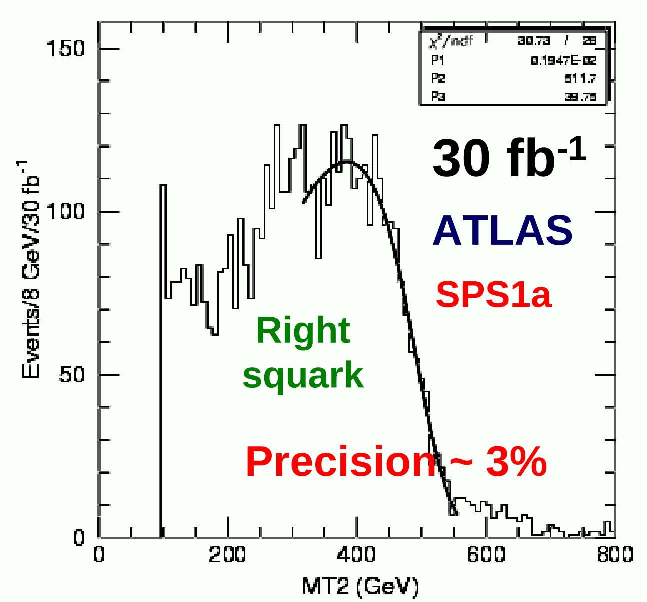
- **Right handed squarks difficult as rarely decay via 'standard' $\tilde{\chi}^0_2$ chain**
  - **Typically BR ($\tilde{q}_R \rightarrow \tilde{\chi}^0_1 q$) > 99%.**
- **Instead search for events with 2 hard jets and lots of E_T^{miss}.**
- **Reconstruct mass using 'stransverse mass' (Allanach et al.):**

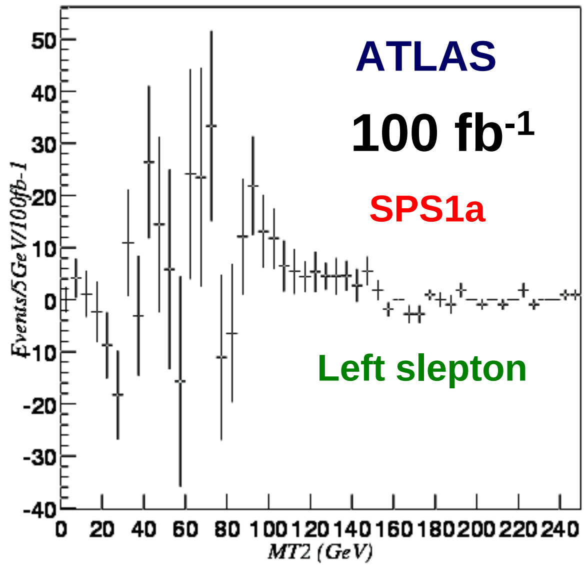
$$m_{T2}^2 = \min_{q_T^{\chi(1)}+q_T^{\chi(2)}=E_T^{miss}} \left[\max\{m_T^2(p_T^{j(1)},q_T^{\chi(1)};m_\chi),m_T^2(p_T^{j(2)},q_T^{\chi(2)};m_\chi)\}\right]$$

- **Needs $\tilde{\chi}^0_1$ mass measurement as input.**
- **Also works for sleptons.**





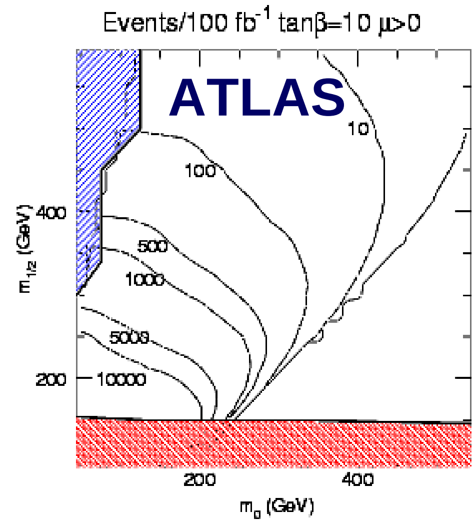


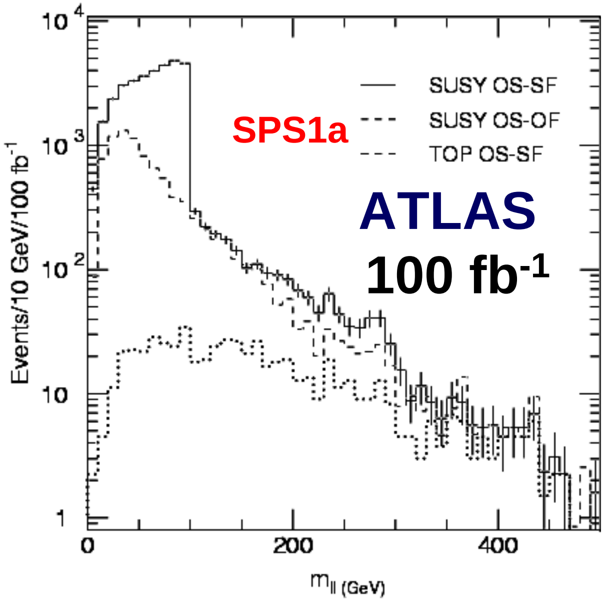


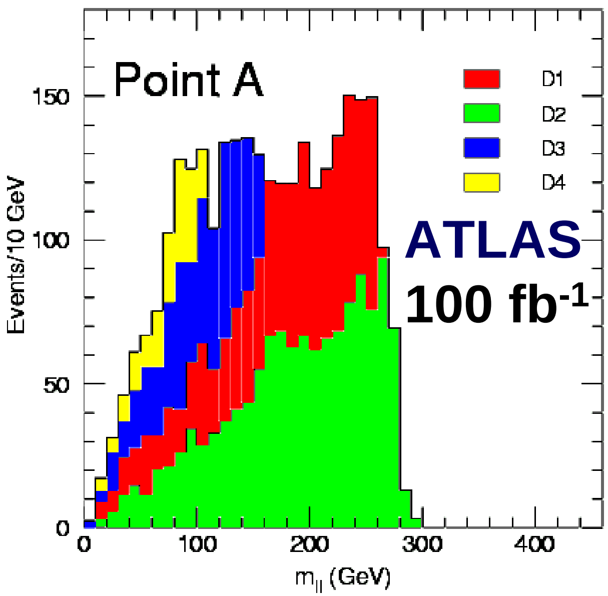
Heavy Gaugino Measurements

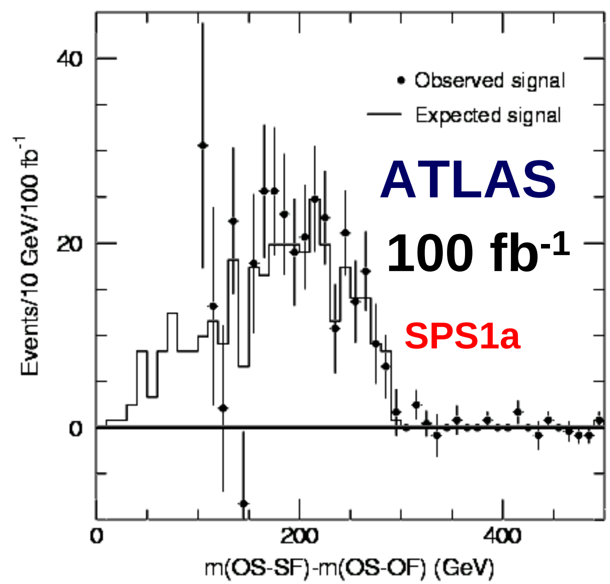
- Also possible to identify dilepton edges from decays of heavy gauginos.
- Requires high stats.
- Crucial input to reconstruction of MSSM neutralino mass matrix (independent of SUSY breaking scenario).

$\tilde{\chi}_4^0$



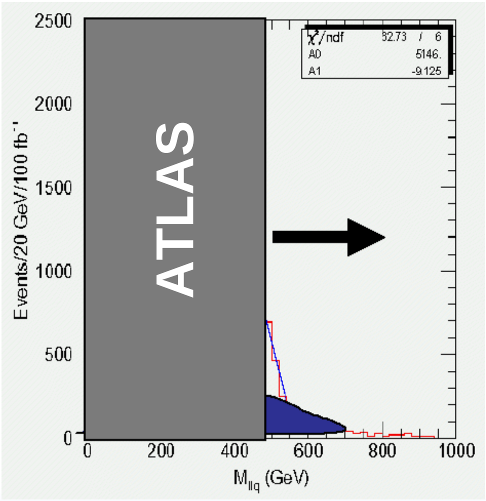


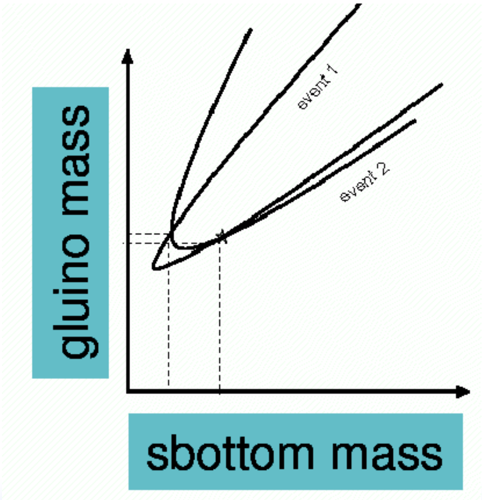


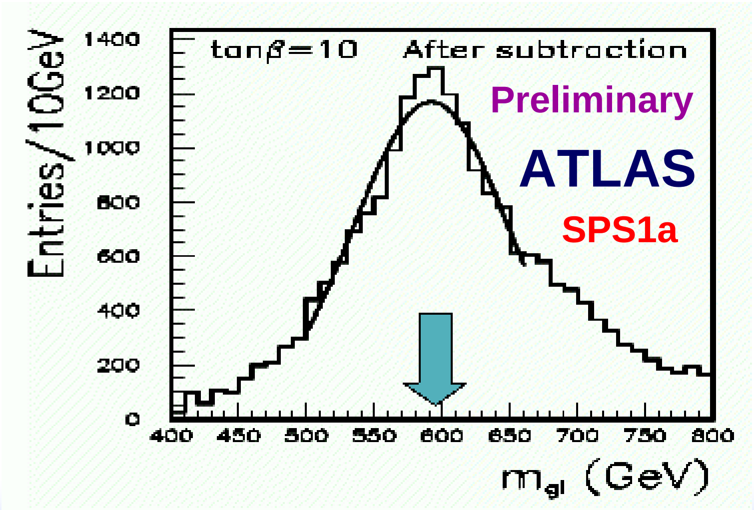


Mass Relation Method

- New idea for reconstructing SUSY masses!
- 'Impossible to measure mass of each sparticle using one channel alone' (Slide 10).
  - Should have added caveat: Only if done event-by-event!
- Assume in each decay chain 5 inv. mass constraints for 6 unknowns (4 $\tilde{\chi}^0_1$ momenta + gluino mass + sbottom mass).
- Remove ambiguities by combining different events analytically → 'mass relation method' (Nojiri et al.).
- Also allows all events to be used, not just those passing hard cuts (useful if background small, buts stats limited – e.g. high scale SUSY).

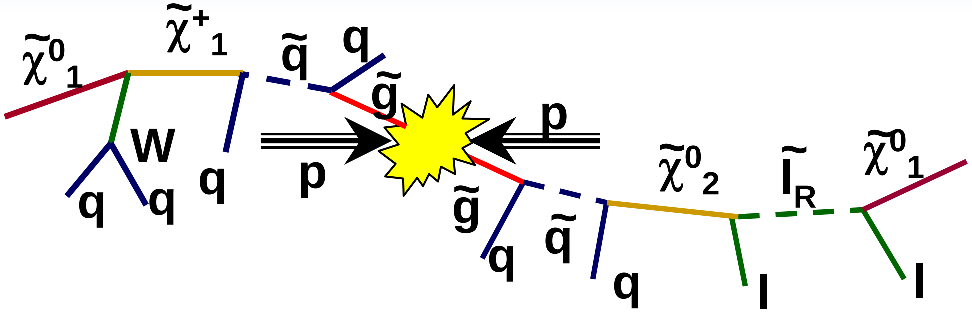


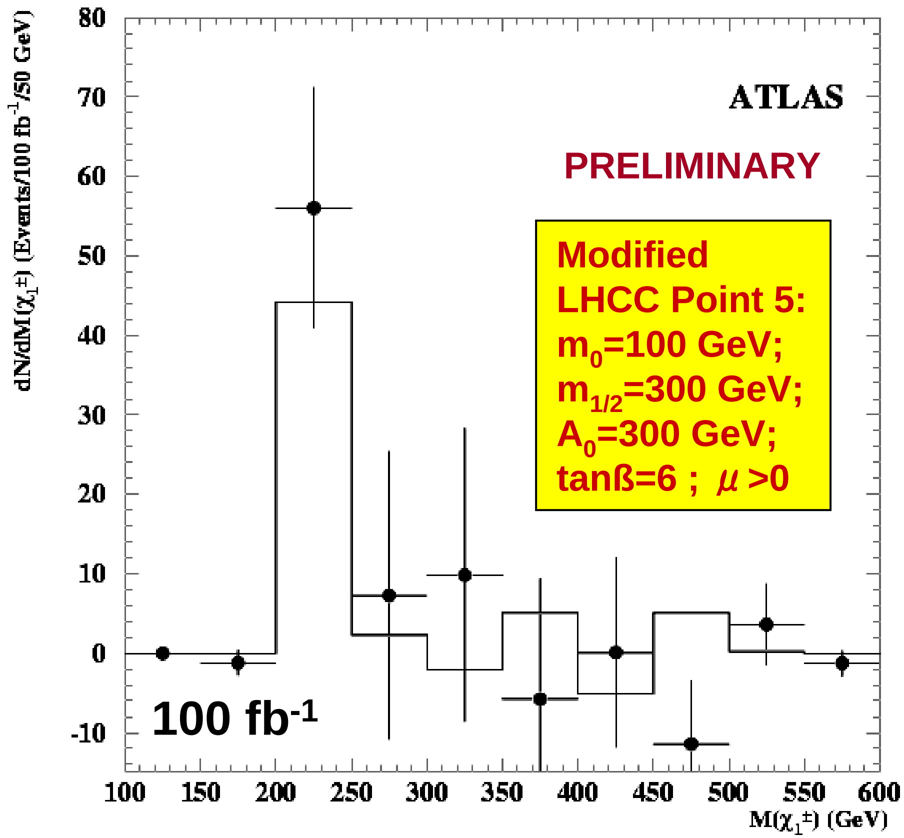




Chargino Mass Measurement

- Mass of lightest chargino very difficult to measure as does not participate in standard dilepton SUSY decay chain.
- Decay process via ν+slepton gives too many extra degrees of freedom - concentrate instead on decay $\tilde{\chi}^{+}_{1} \rightarrow W \tilde{\chi}^{0}_{1}$.
- Require dilepton $\tilde{\chi}^{0}_{2}$ decay chain on other 'leg' of event and use kinematics to calculate chargino mass analytically.
- Using sideband subtraction technique obtain clear peak at true chargino mass (218 GeV).
- **~ 3 σ significance for 100 fb^{-1}.**





Measuring Model Parameters

- **Alternative use for SUSY observables (invariant mass end-points, thresholds etc.).**
- **Here assume mSUGRA/CMSSM model and perform global fit of model parameters to observables**
  - **So far mostly private codes but e.g. SFITTER, FITTINO now on the market;**
  - **c.f. global EW fits at LEP, ZFITTER, TOPAZ0 etc.**

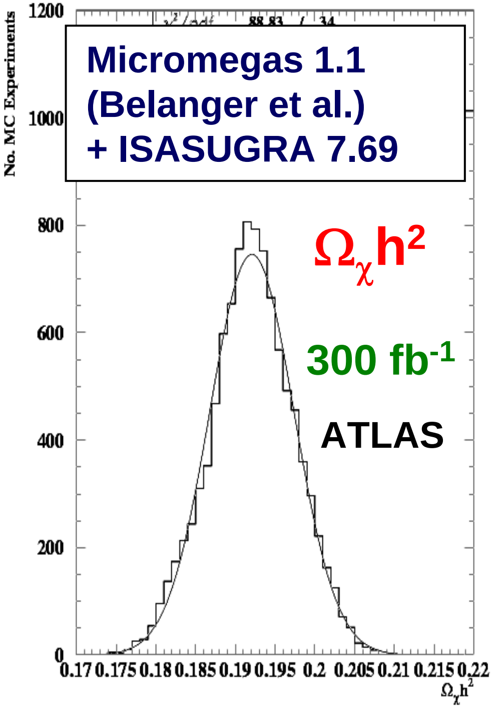
Point	m_0	$m_{1/2}$	A_0	$\tan(\beta)$	sign(μ)
LHC Point 5	100	300	300	2	+1
SPS1a	100	250	-100	10	+1

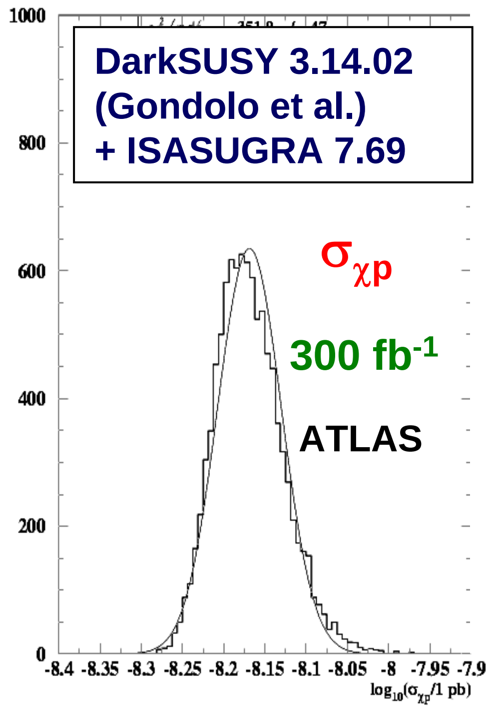
Variable	Value (GeV)	Errors Stat. (GeV)	Errors Scale (GeV)	Errors Total
$m_{\ell\ell}^{max}$	77.07	0.03	0.08	0.08
$m_{\ell\ell q}^{max}$	428.5	1.4	4.3	4.5
$m_{\ell q}^{low}$	300.3	0.9	3.0	3.1
$m_{\ell q}^{high}$	378.0	1.0	3.8	3.9
$m_{\ell\ell q}^{min}$	201.9	1.6	2.0	2.6
$m_{\ell\ell b}^{min}$	183.1	3.6	1.8	4.1
$m(\ell_L) - m(\tilde{\chi}_1^0)$	106.1	1.6	0.1	1.6
$m_{\ell\ell}^{max}(\tilde{\chi}_4^0)$	280.9	2.3	0.3	2.3
$m_{\tau\tau}^{max}$	80.6	5.0	0.8	5.1
$m(\tilde{g}) - 0.99 \times m(\tilde{\chi}_1^0)$	500.0	2.3	6.0	6.4
$m(\tilde{q}_R) - m(\tilde{\chi}_1^0)$	424.2	10.0	4.2	10.9
$m(\tilde{g}) - m(\tilde{b}_1)$	103.3	1.5	1.0	1.8
$m(\tilde{g}) - m(\tilde{b}_2)$	70.6	2.5	0.7	2.6

Parameter	Expected precision (300 fb^{-1})
m_0	$\pm$ 2%
$m_{1/2}$	$\pm$ 0.6%
$\tan(\beta)$	$\pm$ 9%
A_0	$\pm$ 16%

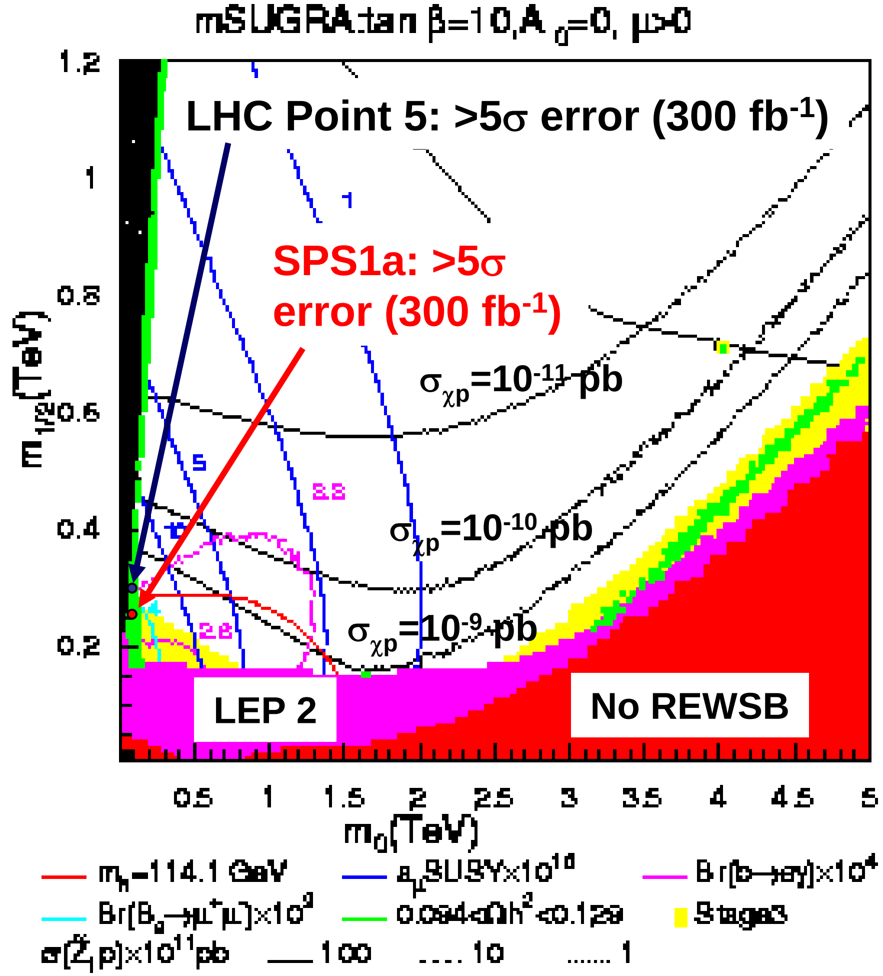
SUSY Dark Matter

- **Can use parameter measurements for many purposes, e.g. estimate LSP Dark Matter properties (e.g. for 300 fb^{-1}, SPS1a)**
  - $\Omega_\chi h^2 = 0.1921 \pm 0.0053$
  - $\log_{10}(\sigma_{\chi p}/pb) = -8.17 \pm 0.04$





Baer et al. hep-ph/0305191



SUSY Dark Matter

- SUSY (e.g. mSUGRA) parameter space strongly constrained by cosmology (e.g. WMAP satellite) data.

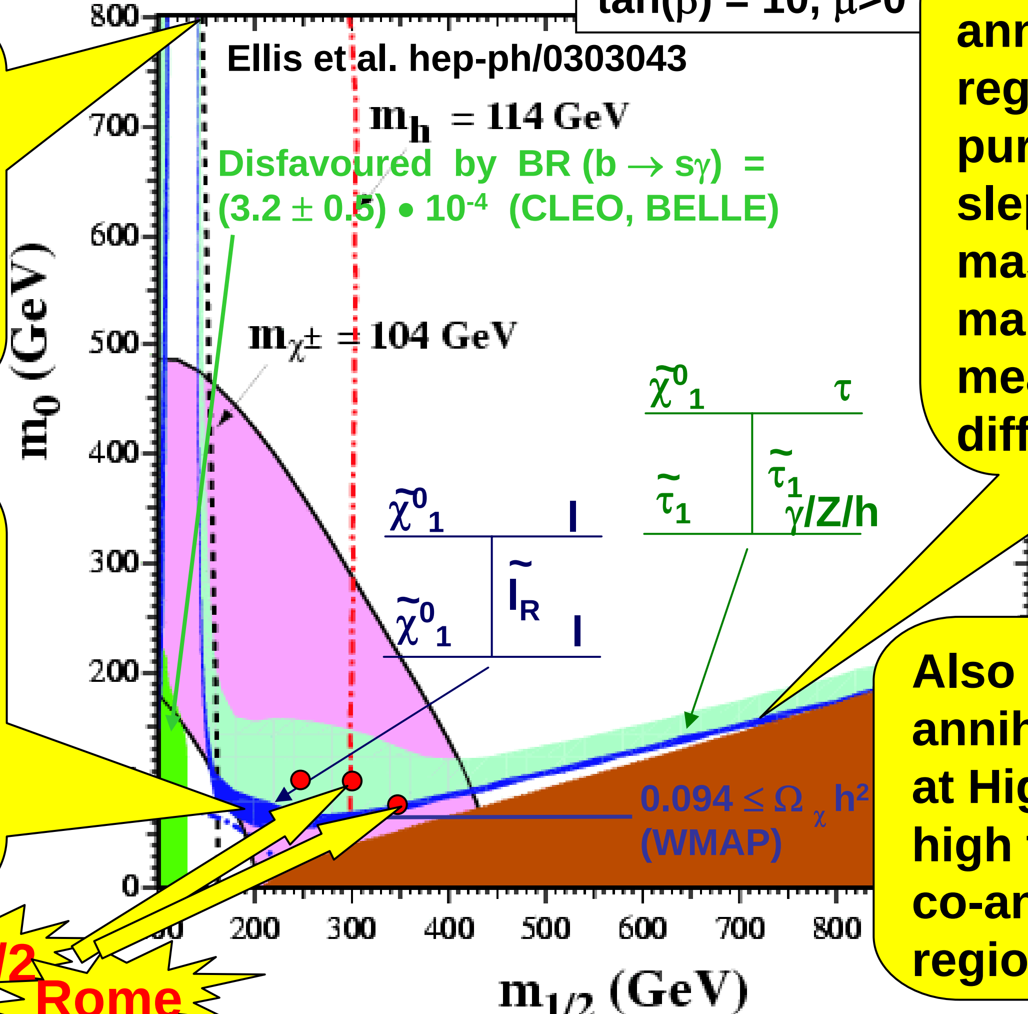
mSUGRA A_0=0, tan(β) = 10, μ>0

'Focus point' region: significant h̃ component to LSP enhances annihilation to gauge bosons

'Bulk' region: t-channel slepton exchange - LSP mostly Bino. 'Bread and Butter' region for LHC Expts.

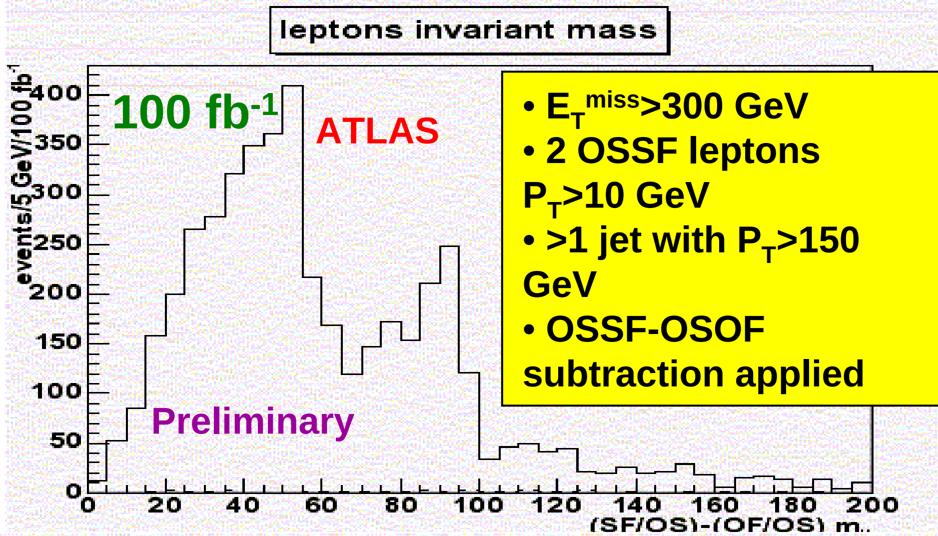
Slepton Co-annihilation region: LSP ~ pure Bino. Small slepton-LSP mass difference makes measurements difficult.

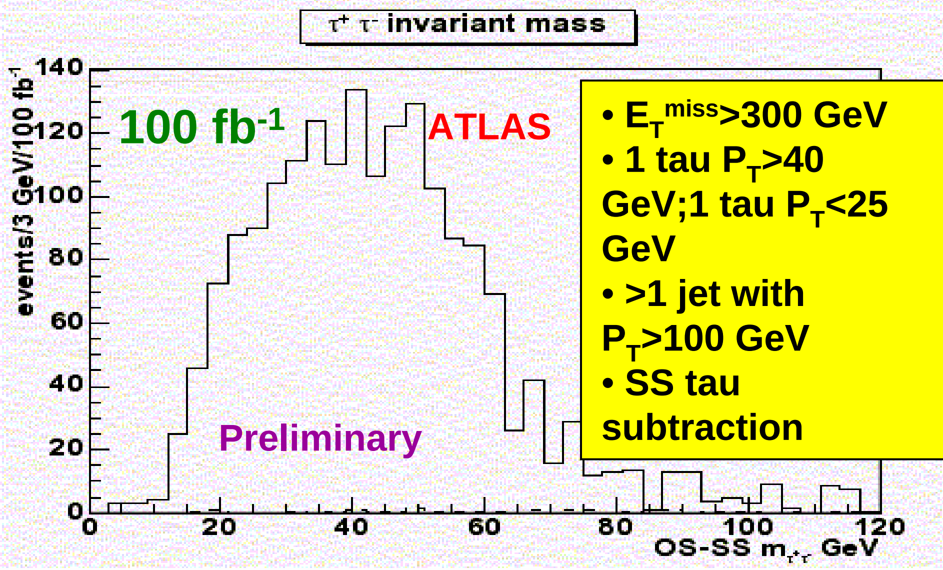
Also 'rapid annihilation funnel' at Higgs pole at high tan(β), stop co-annihilation region at large A_0



Coannihilation Signatures

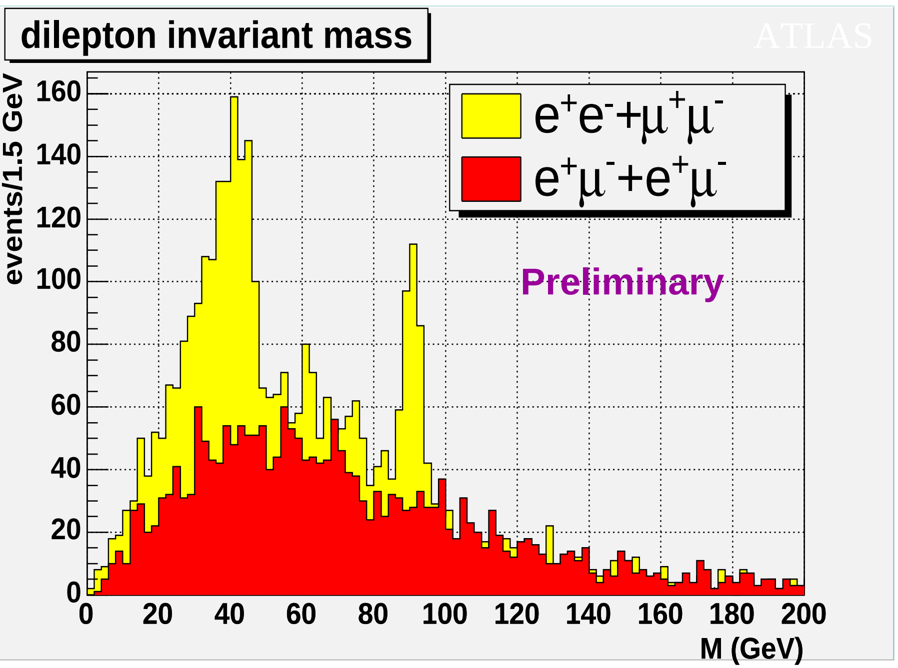
- **Small slepton-neutralino mass difference gives soft leptons**
  - Low electron/muon/tau energy thresholds crucial.
- **Study point chosen within region:**
  - m_0=70 GeV; $m_{1/2}$=350 GeV; A_0=0; tanß=10 ; μ >0;
  - Same model used for DC2 study.
- **Decays of $\tilde{\chi}^0_2$ to both $\tilde{l}_L$ and $\tilde{l}_R$ kinematically allowed.**
  - Double dilepton invariant mass edge structure;
  - Edges expected at 57 / 101 GeV
- **Stau channels enhanced (tanβ)**
  - Soft tau signatures;
  - Edge expected at 79 GeV;
  - Less clear due to poor tau visible energy resolution.

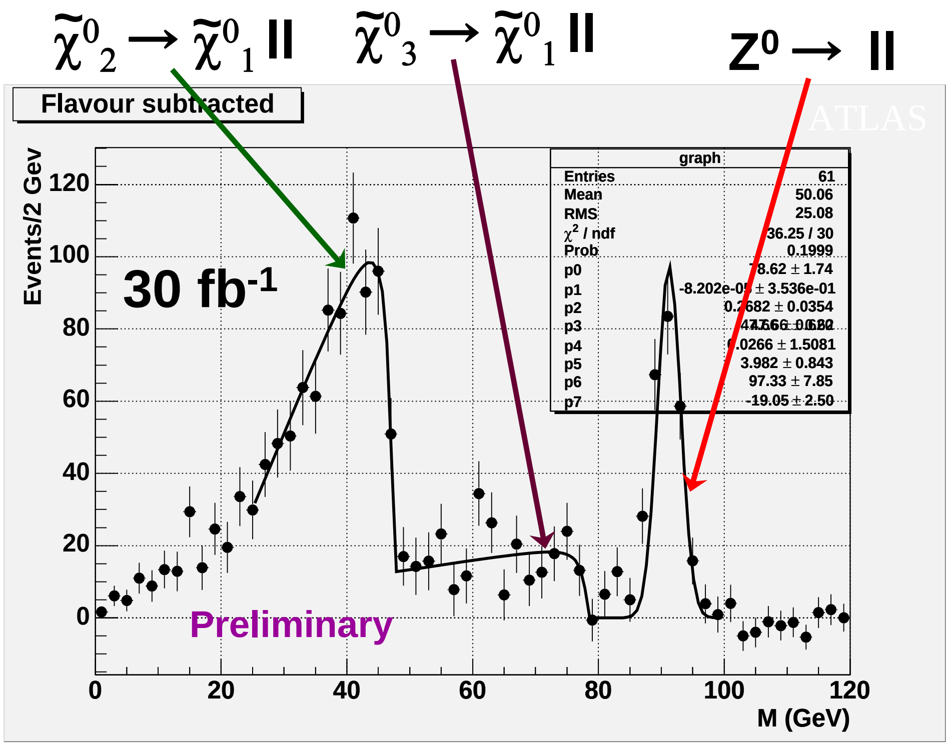




Focus Point Models

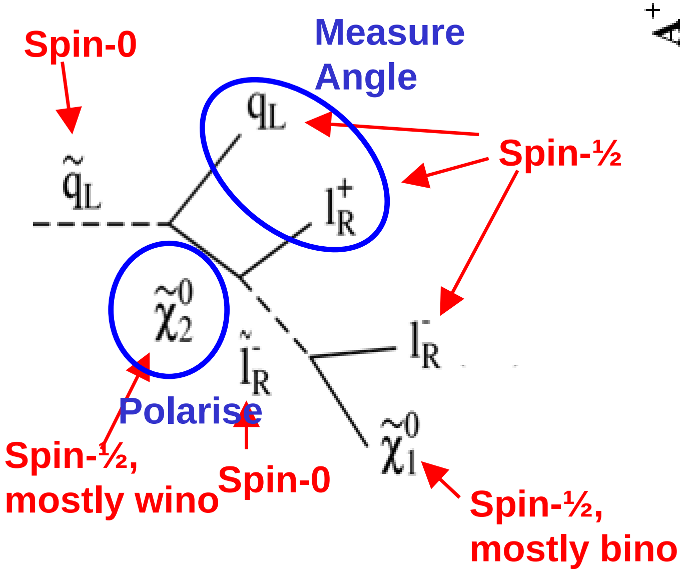
- Large m_0 ➔ sfermions are heavy
- Most useful signatures from heavy neutralino decay
- Study point chosen within focus point region :
  - m_0=3000 GeV; $m_{1/2}$=215 GeV; A_0=0; tanß=10 ; μ >0
- Direct three-body decays $\tilde{\chi}^0_n \rightarrow \tilde{\chi}^0_1$ ll
- Edges give $m(\tilde{\chi}^0_n)-m(\tilde{\chi}^0_1)$

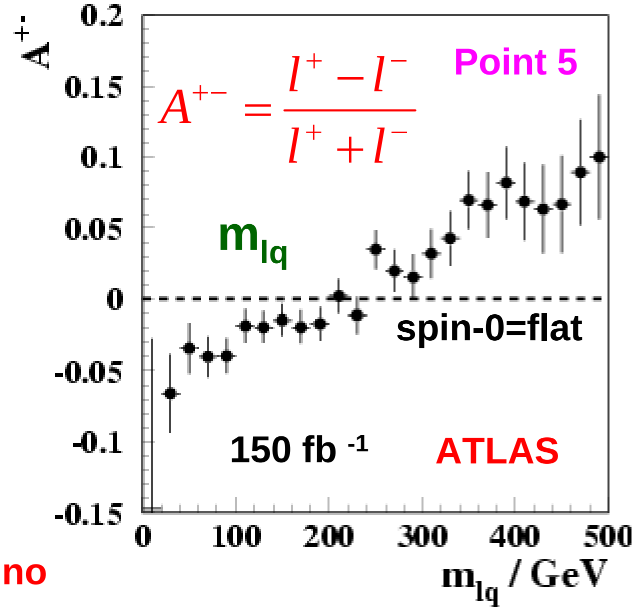


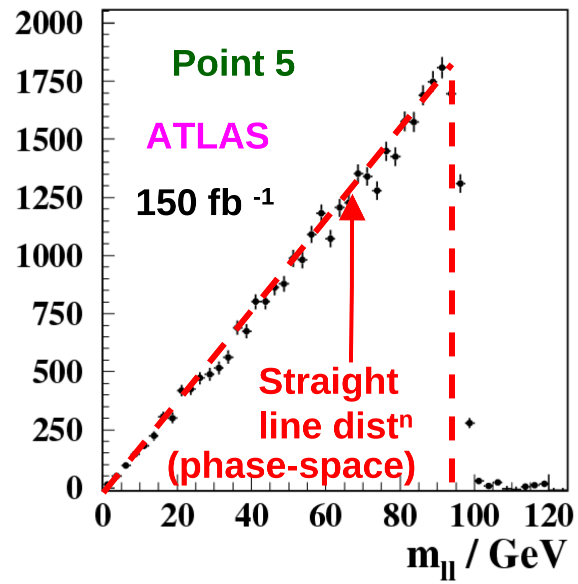


SUSY Spin Measurement

- Q: How do we know that a SUSY signal is really due to SUSY?
  - Other models (e.g. UED) can mimic SUSY mass spectrum
- A: Measure spin of new particles.
- One proposal – use 'standard' two-body slepton decay chain
  - charge asymmetry of lq pairs measures spin of $\tilde{\chi}^0_2$
  - relies on valence quark contribution to pdf of proton (C asymmetry)
  - shape of dilepton invariant mass spectrum measures slepton spin

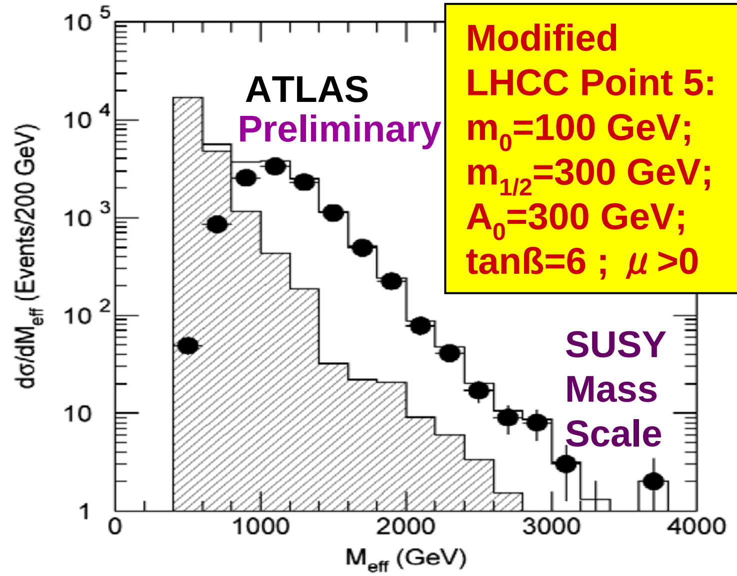


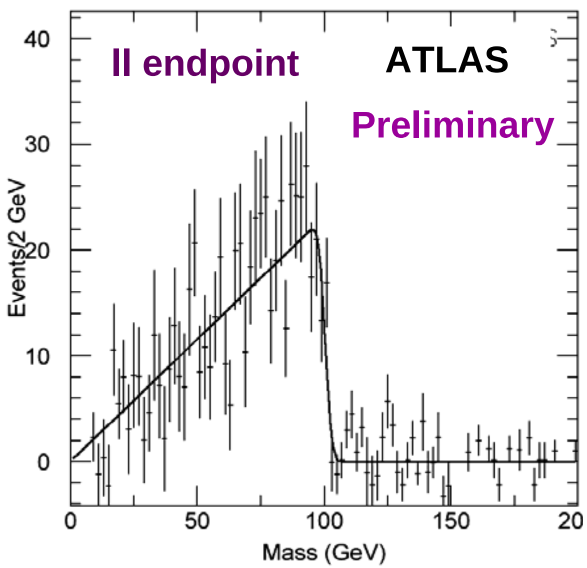


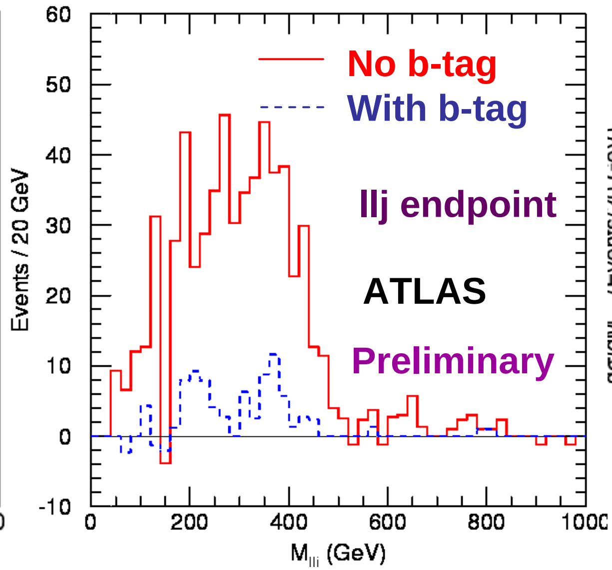


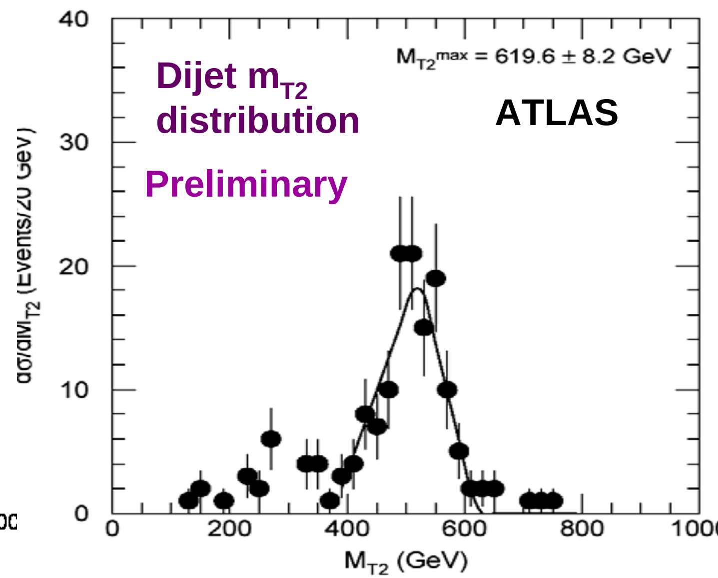
DC1 SUSY Challenge

- First attempt at large-scale simulation of SUSY signals in ATLAS (100 000 events: ~5 fb^{-1}) in early 2003.
- Tested Geant3 simulation and ATHENA (C++) reconstruction software framework thoroughly.



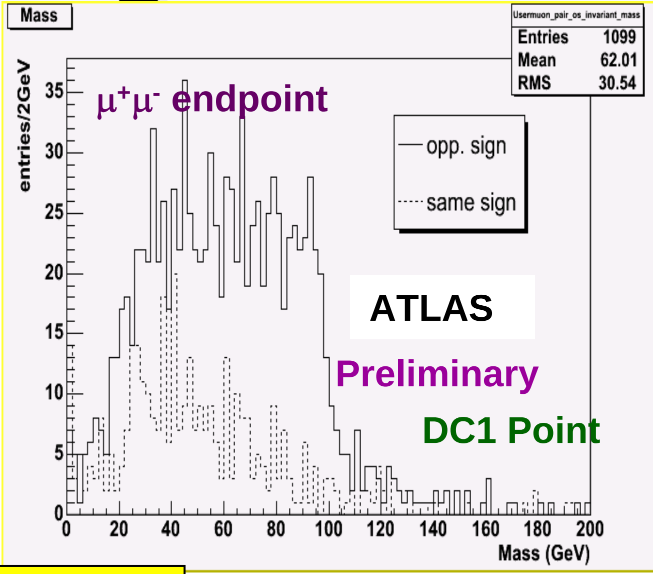


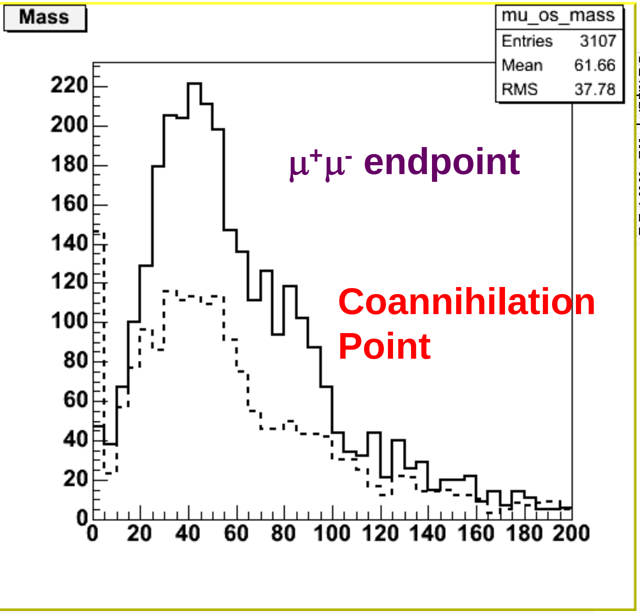




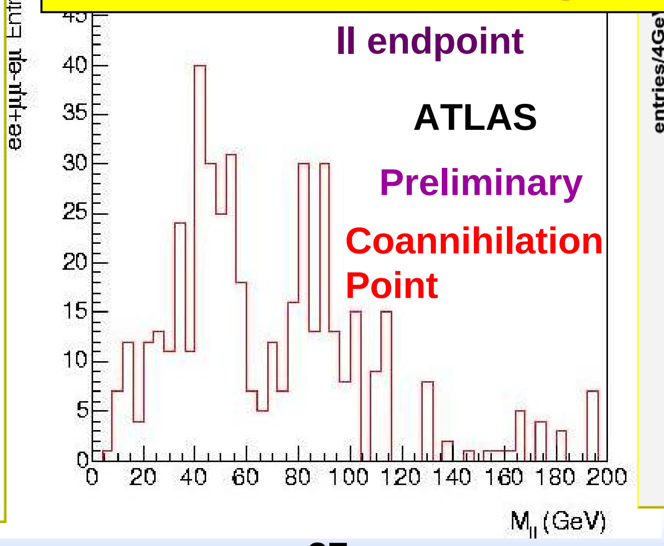
DC2 SUSY Challenge

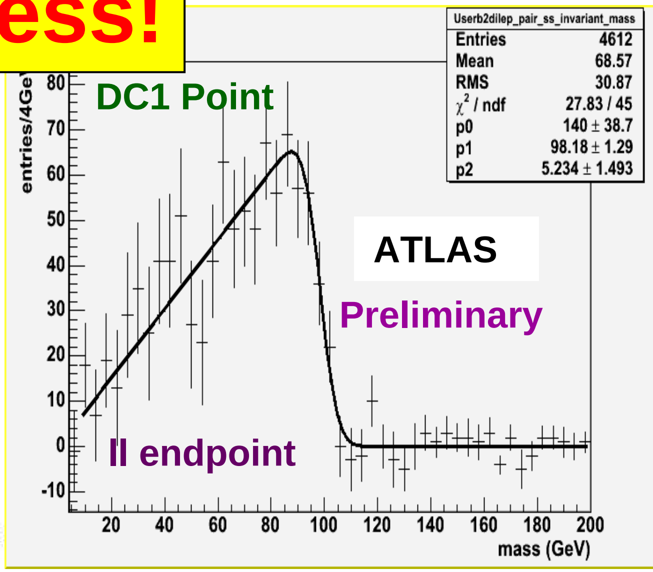
- DC2 testing new G4 simulation and reconstruction.
- Points studied:
  - DC1 bulk region point (test G4)
  - Stau coannihilation point (rich in signatures - test reconstruction)
- Further studies planned in run up to Rome Physics Workshop (Focus Point model etc.)





Work in Progress!



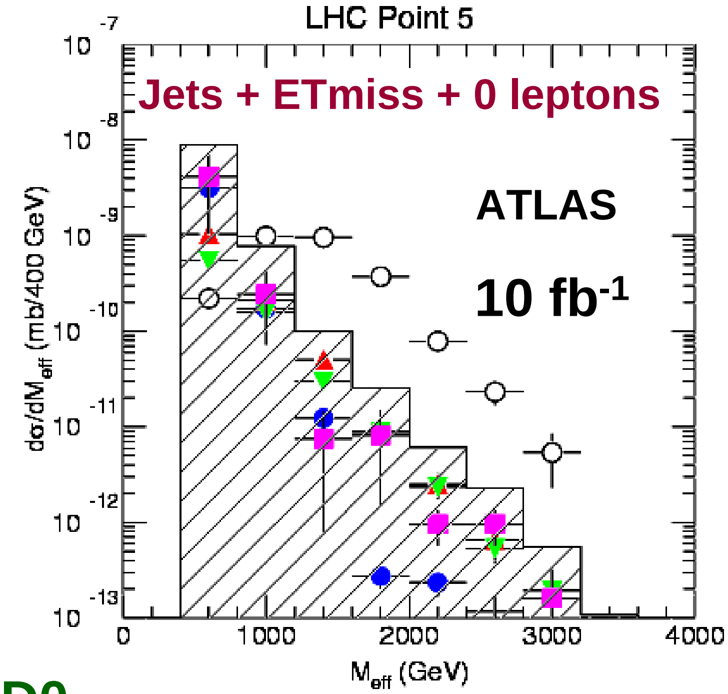


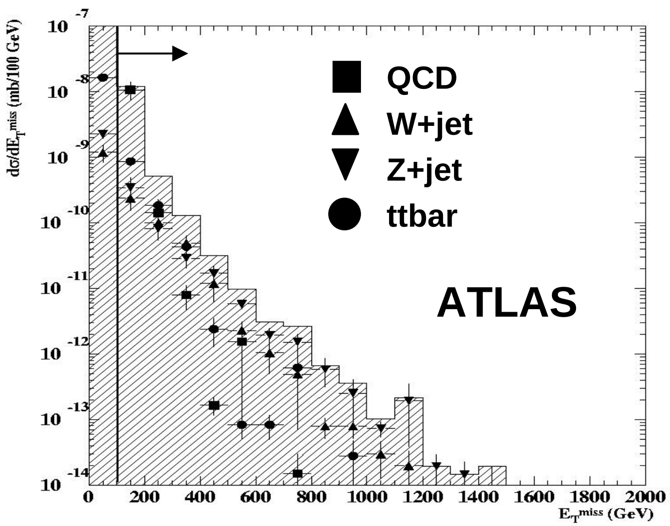
Preparations for 1st Physics

- Preparations needed to ensure efficient/reliable searches for/measurements of SUSY particles in timely manner:
  - Initial calibrations (energy scales, resolutions, efficiencies etc.);
  - Minimisation of poorly estimated SM backgrounds;
  - Estimation of remaining SM backgrounds;
  - Development of useful tools.
- Different situation to Run II (no previous σ measurements at same $\sqrt{s}$)
- Will need convincing bckgrnd. estimate with little data as possible.
- Background estimation techniques will change depending on integrated lumi.
- Ditto optimum search channels & cuts.
- Aim to use combination of
  - Fast-sim;
  - Full-sim;
  - Estimations from data.
- Use comparison between different techniques to validate estimates and build confidence in (blind) analysis.
- Aim to study with full-sim (DC2) data

Background Estimation

- **Main backgrounds:**
  - Z + n jets
  - W + n jets
  - ttbar
  - QCD
- **Also:**
  - Single top
  - WW/WZ/ZZ
- **Generic approach :**
  - Select low E_T^{miss} background calibration samples;
  - Extrapolate into high E_T^{miss} signal region.

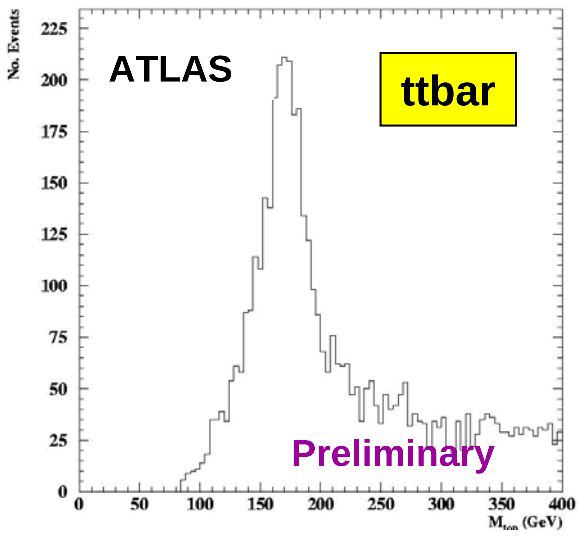


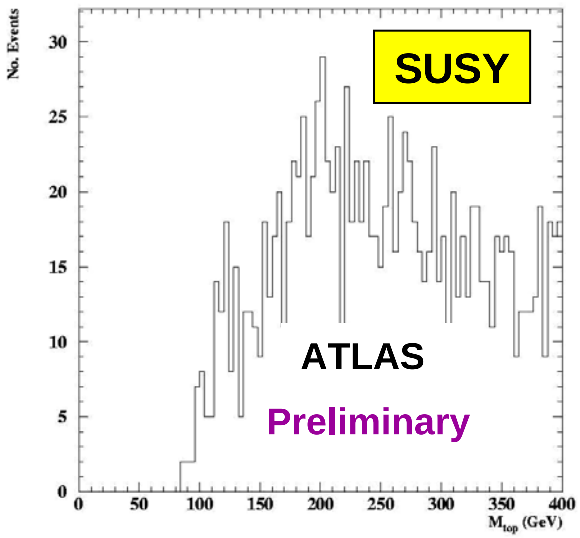


- **Used by CDF / D0**
- **Extrapolation non-trivial.**
  - Must find variables uncorrelated with E_T^{miss}
- **Several approaches developed.**
- **Most promising: Use Z (➔ ll) + jets to estimate Z (➔ νν) / W (➔ lν) + jets**

Top Background

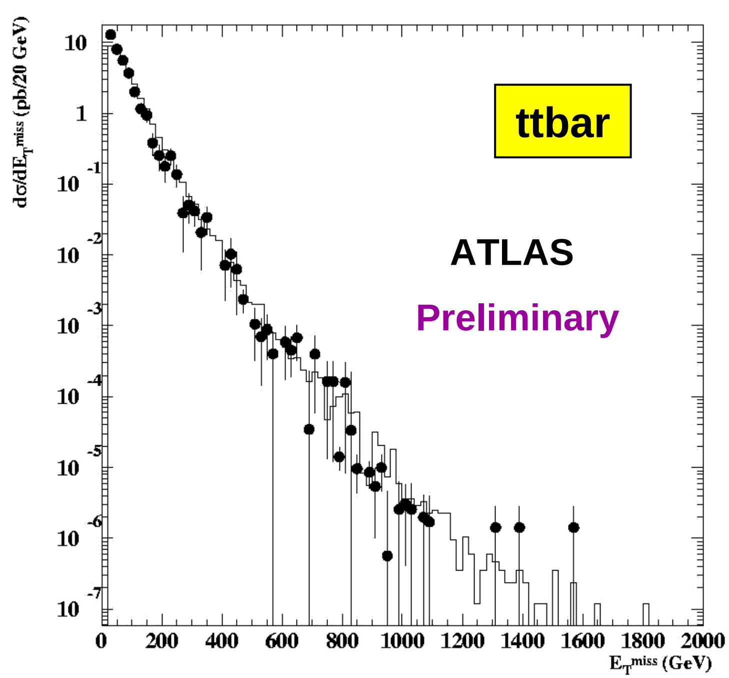
- Estimation using simulation possible (normalised to data ttbar selection) – cross-check with data
- Isolate clean sample of top events using mass constraint(s).
- Then plot E_T^{miss} distribution (large statistical errors), compare with same technique applied to SUSY events (SPS1a benchmark model).
- Reconstruct leptonic W momentum from ETmiss vector and W mass constraint (analytical approach – quadratic ambiguity).
- Select solution with greatest W p_T.
- Select b-jet with greatest p_T.
- Plot invariant mass of combination.

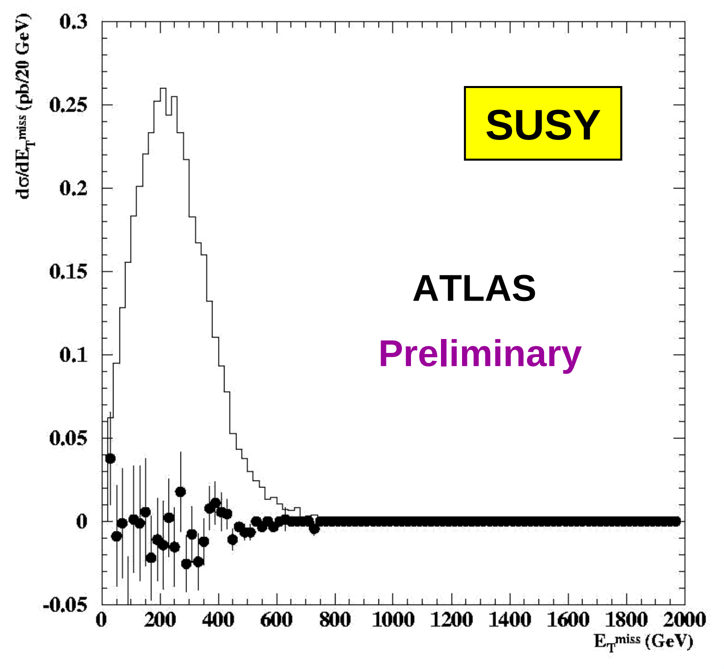




Top Background

- Select events in peak and examine ETmiss distribution.
- Subtract combinatorial background with appropriately weighted (from MC) sideband subtraction.
- Good agreement with top background distribution in SUSY selection.





- With this tuning does not select SUSY events (as required)
- Promising approach but more work needed (no btag etc.)

Histogram – 1 lepton SUSY selection (no b-tag)
Data points – background estimate

Supersummary

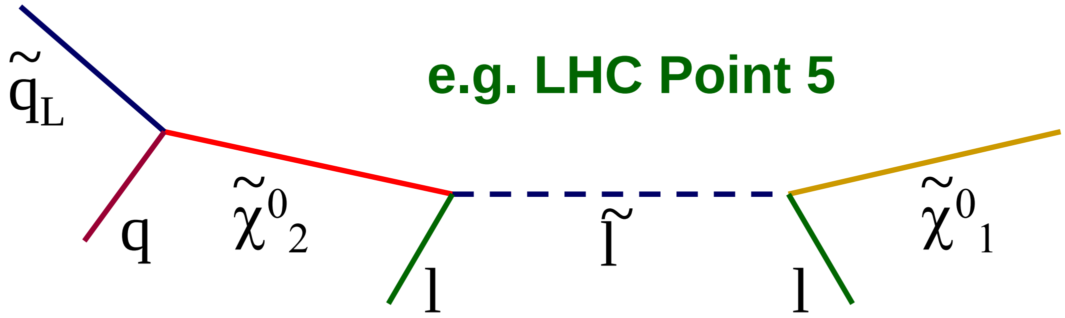
- The LHC will be <u>THE PLACE</u> to search for, and hopefully study, SUSY from 2007 onwards (at least until ILC).
- SUSY searches will commence on Day 1 of LHC operation.
- Many studies of exclusive channels already performed.
- Lots of input from both theorists (new ideas) and experimentalists (new techniques).
- Renewed emphasis on use of full simulation tools.
- Big challenge for discovery will be understanding systematics.
- Big effort ramping up now to understand how to exploit first data in timely fashion
  - Calibrations
  - Background rejection
  - Background estimation
  - Tools
- Massive scope for further work!

BACK-UP SLIDES

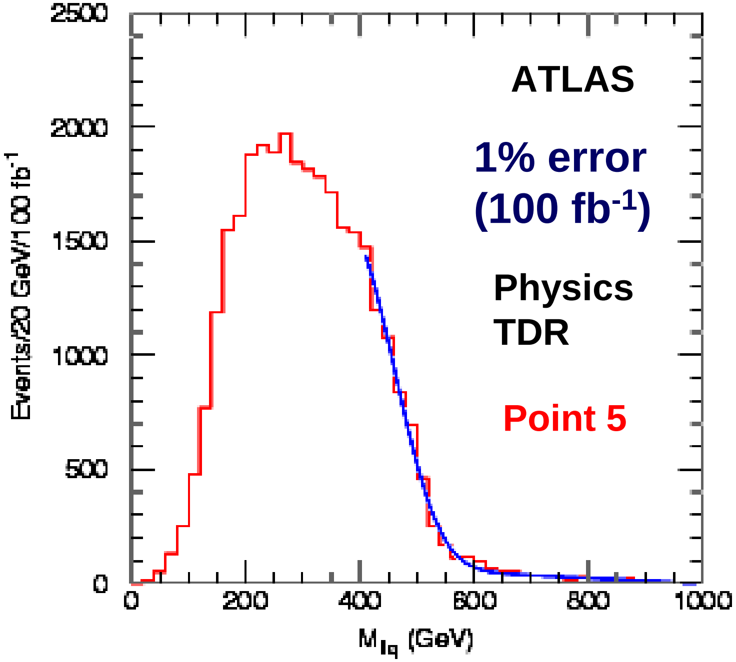
llq Edge

- Dilepton edges provide starting point for other measurements.
- Use dilepton signature to tag presence of $\tilde{\chi}^0_2$ in event, then work back up decay chain constructing invariant mass distributions of combinations of leptons and jets.

e.g. LHC Point 5



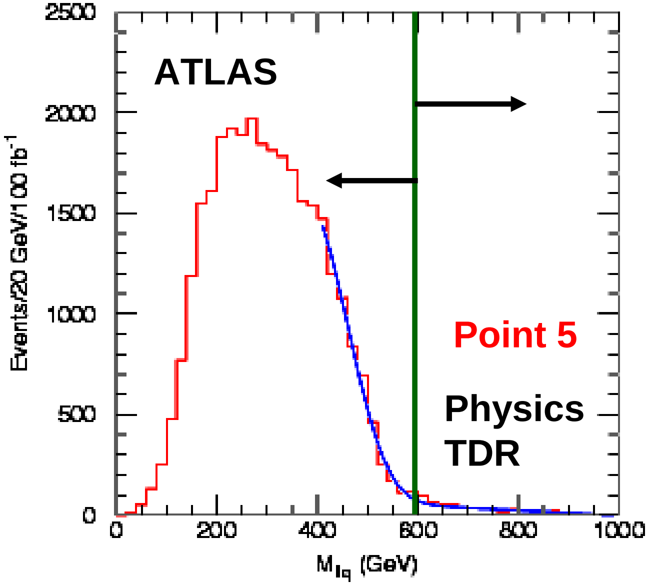
$$M_{llq}^{\max} = \left[\frac{(M^2_{\tilde{q}_L} - M^2_{\tilde{\chi}^0_2})(M^2_{\tilde{\chi}^0_2} - M^2_{\tilde{\chi}^0_1})}{M^2_{\tilde{\chi}^0_2}}\right]^{1/2} = 552.4\ \text{GeV}.$$

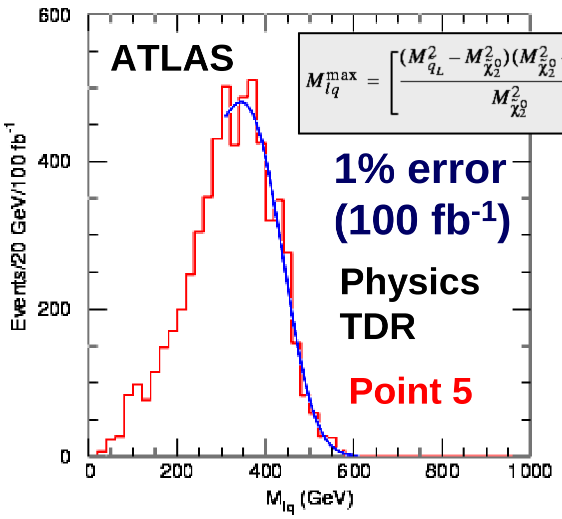


- Hardest jets in each event produced by RH or LH squark decays.
- Select smaller of two llq invariant masses from two hardest jets
  - Mass must be < edge position.
- Edge sensitive to LH squark mass.

lq Edge

- Complex decay chain at LHC Point 5 gives additional constraints on masses.
- Use lepton-jet combinations in addition to lepton-lepton combinations.
- Select events with only one dilepton-jet pairing consistent with slepton hypothesis
  - → Require one llq mass above edge and one below (reduces combinatorics).



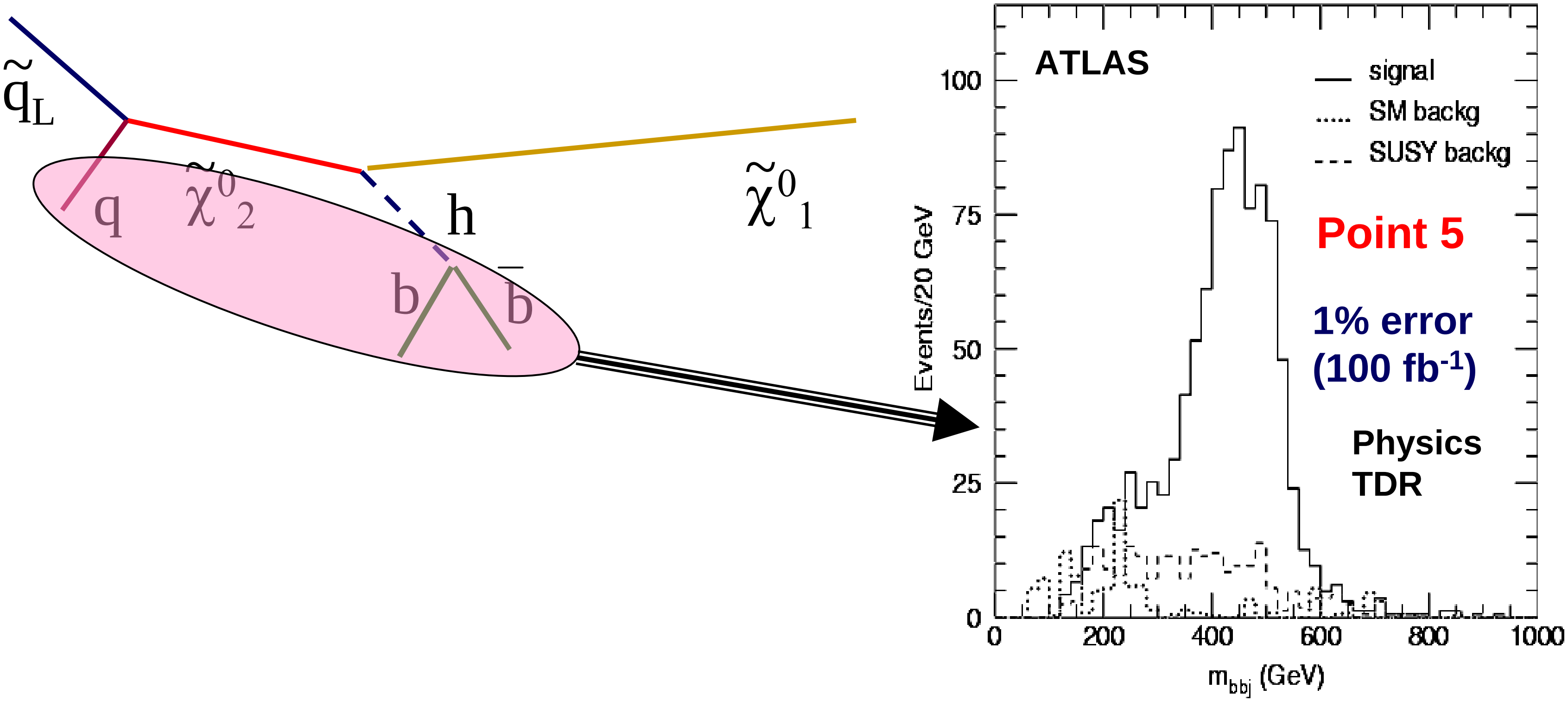


$$M_{lq}^{\max} = \left[\frac{(M_{\tilde{q}_L}^2 - M_{\tilde{\chi}_2^0}^2)(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{l}_R}^2)}{M_{\tilde{\chi}_2^0}^2}\right]^{1/2} = 479.3 \text{ GeV} .$$

- Construct distribution of invariant masses of 'slepton' jet with each lepton.
- 'Right' edge sensitive to slepton, squark and $\tilde{\chi}^0_2$ masses ('wrong' edge not visible).

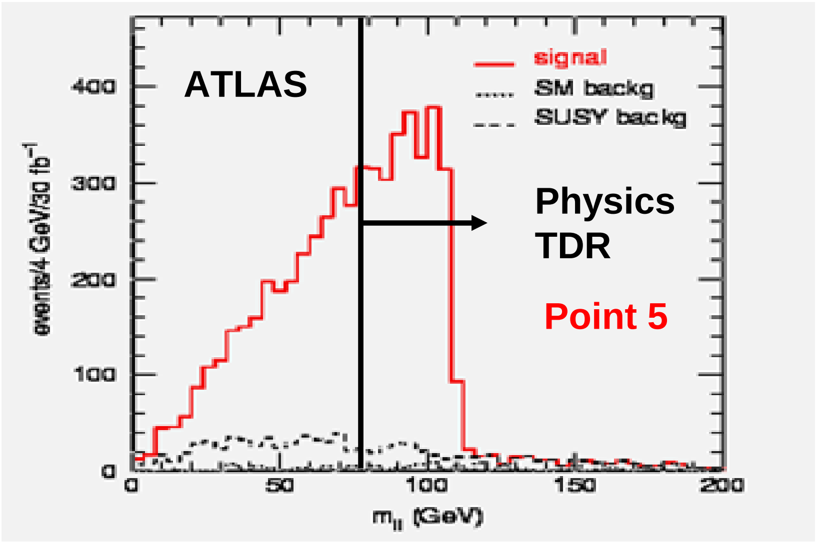
hq edge

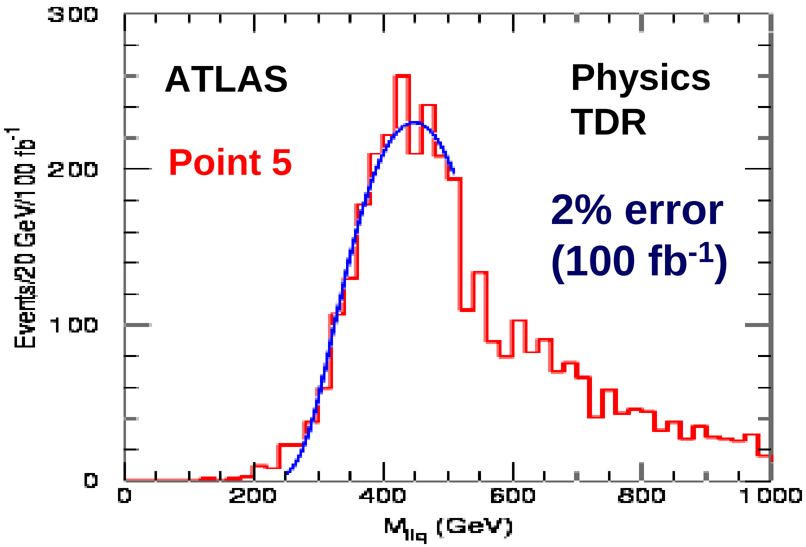
- If tan(β) not too large can also observe two body decay of $\tilde{\chi}^0_2$ to higgs and $\tilde{\chi}^0_1$.
- Reconstruct higgs mass (2 b-jets) and combine with hard jet.
- Gives additional mass constraint.



llq Threshold

- Two body kinematics of slepton-mediated decay chain also provides still further information (Point 5).
- Consider case where $\tilde{\chi}^0_1$ produced near rest in $\tilde{\chi}^0_2$ frame.
  - ➔ Dilepton mass near maximal.
  - ➔ p(ll) determined by p($\tilde{\chi}^0_2$).





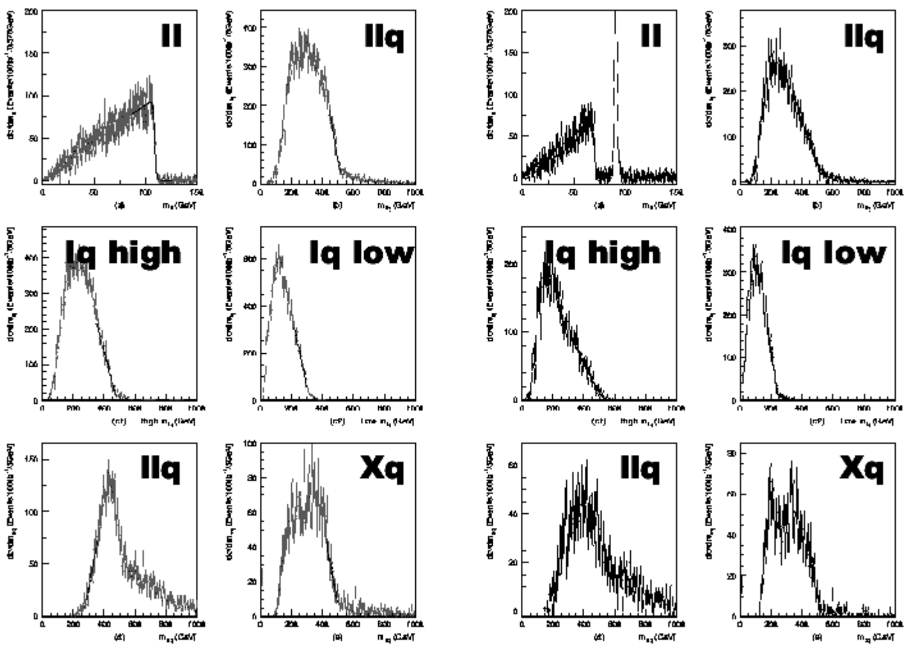
- Distribution of llq invariant masses distribution has maximum and <u>minimum</u> (when quark and dilepton parallel).
- llq threshold important as contains new dependence on mass of lightest neutralino.

Mass Reconstruction

- **Combine measurements from edges from different jet/lepton combinations.**

Related edge	Kinematic endpoint
l^+l^- edge	$(m_{ll}^{max})^2 = (\tilde\xi - \tilde l)(\tilde l - \tilde\chi)/\tilde l$
l^+l^-q edge	$(m_{llq}^{max})^2 = \begin{cases} \max\left[\frac{(\tilde q-\tilde\xi)(\tilde\xi-\tilde\chi)}{\tilde\xi}, \frac{(\tilde q-\tilde l)(\tilde l-\tilde\chi)}{\tilde l}, \frac{(\tilde q\tilde l-\tilde\xi\tilde\chi)(\tilde\xi-\tilde l)}{\tilde\xi\tilde l}\right] \\ \text{except for the special case in which } \tilde l^2 < \tilde q\tilde\chi < \tilde\xi^2 \text{ and} \\ \tilde\xi^2\tilde\chi < \tilde q\tilde l^2 \text{ where one must use } (m_{\tilde q} - m_{\tilde\chi^0_1})^2. \end{cases}$
Xq edge	$(m_{Xq}^{max})^2 = X + (\tilde q - \tilde\xi)\left[\tilde\xi + X - \tilde\chi + \sqrt{(\tilde\xi - X - \tilde\chi)^2 - 4X\tilde\chi}\right]/(2\tilde\xi)$
l^+l^-q threshold	$(m_{llq}^{min})^2 = \begin{cases} [\ 2\tilde l(\tilde q-\tilde\xi)(\tilde\xi-\tilde\chi) + (\tilde q+\tilde\xi)(\tilde\xi-\tilde l)(\tilde l-\tilde\chi) \\ -(\tilde q-\tilde\xi)\sqrt{(\tilde\xi+\tilde l)^2(\tilde l+\tilde\chi)^2 - 16\tilde\xi\tilde l^2\tilde\chi}\ ]/(4\tilde l\tilde\xi) \end{cases}$
$l^{\pm}_{near}q$ edge	$(m_{l_{near}q}^{max})^2 = (\tilde q - \tilde\xi)(\tilde\xi - \tilde l)/\tilde\xi$
$l^{\pm}_{far}q$ edge	$(m_{l_{far}q}^{max})^2 = (\tilde q - \tilde\xi)(\tilde l - \tilde\chi)/\tilde l$
$l^{\pm}q$ high-edge	$(m_{lq(high)}^{max})^2 = \max\left[(m_{l_{near}q}^{max})^2, (m_{l_{far}q}^{max})^2\right]$
$l^{\pm}q$ low-edge	$(m_{lq(low)}^{max})^2 = \min\left[(m_{l_{near}q}^{max})^2, (\tilde q - \tilde\xi)(\tilde l - \tilde\chi)/(2\tilde l - \tilde\chi)\right]$
M_{T2} edge	$\Delta M = m_{\tilde l} - m_{\tilde\chi^0_1}$

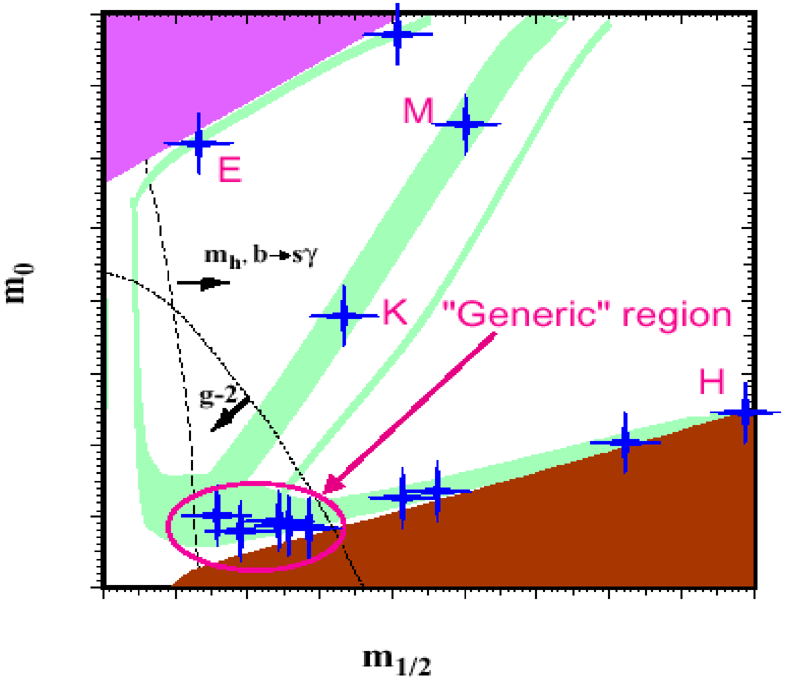
Table 4: The absolute kinematic endpoints of invariant mass quantities formed from decay chains of the types mentioned in the text for known particle masses. The following shorthand notation has been used: $\tilde\chi = m^2_{\tilde\chi^0_1}$, $\tilde l = m^2_{\tilde l_R}$, $\tilde\xi = m^2_{\tilde\chi^0_2}$, $\tilde q = m^2_{\tilde q}$ and X is $m^2_{\tilde X}$ or $m^2_{\tilde b}$ depending on which particle participates in the "branched" decay.

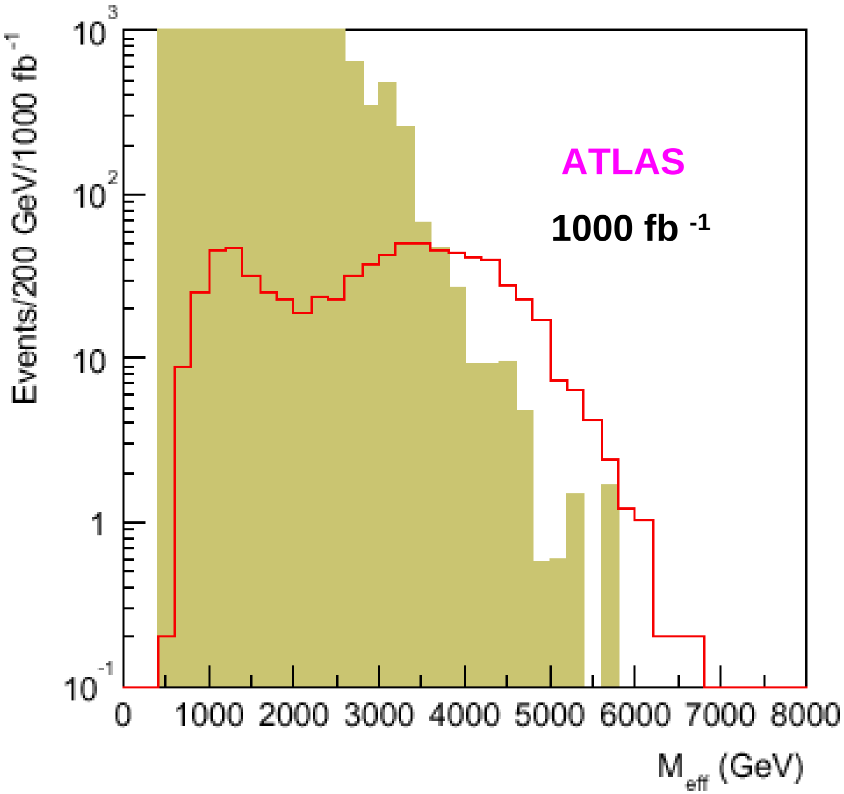


- **Gives sensitivity to masses (rather than combinations).**

High Mass mSUGRA

- **ATLAS study of sensitivity to models with high mass scales**
- **E.g. CLIC Point K ➔ Potentially observable … but hard!**

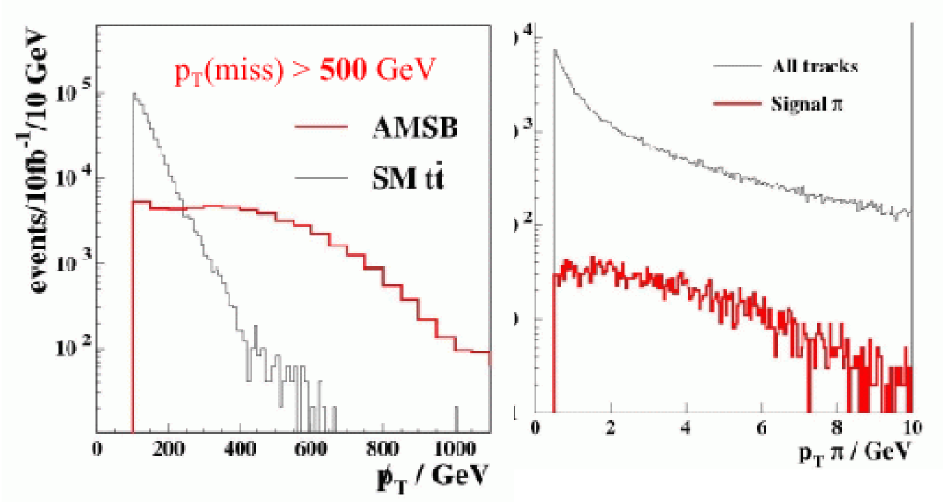


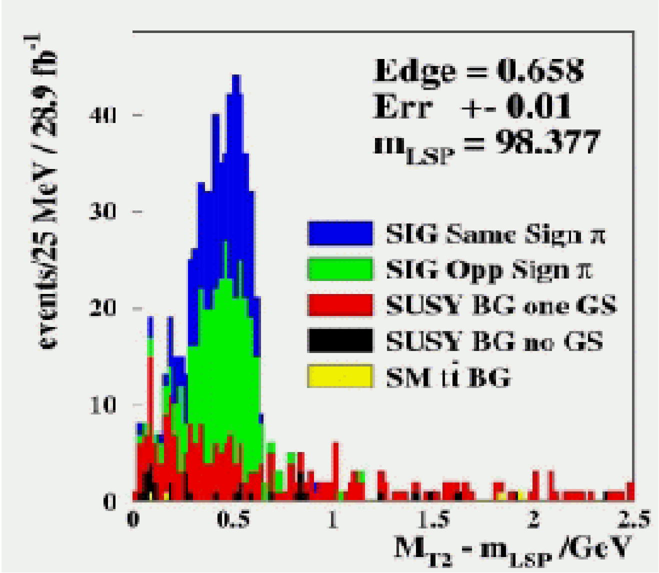


- **Characteristic double peak in signal M_{eff} distribution (Point K).**
- **Squark and gluino production cross-section reduced due to high mass.**
- **Gaugino production significant**

AMSB

- Examined RPC model with $\tan(\beta) = 10$, $m_{3/2}$=36 TeV, m_0=500 GeV, sign(μ) = +1.
- $\tilde{\chi}^{+/-}_1$ near degenerate with $\tilde{\chi}^0_1$.
- Search for $\tilde{\chi}^{+/-}_1 \rightarrow \pi^{+/-}\tilde{\chi}^0_1$ (Δm = 631 MeV → soft pions).

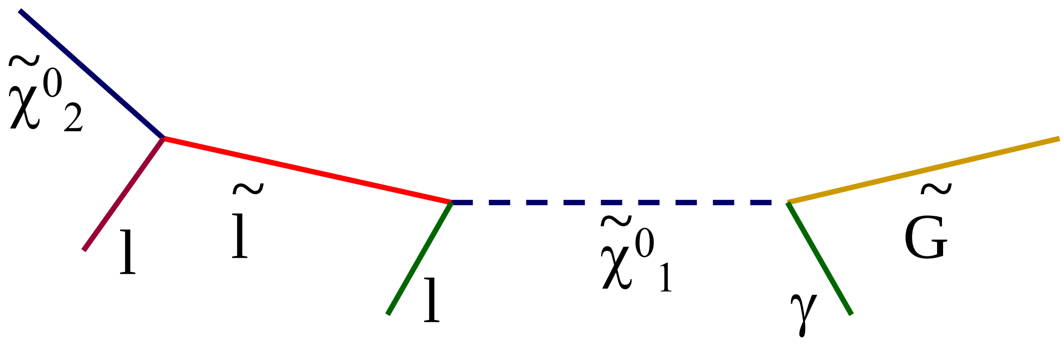




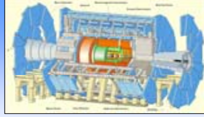
- Also displaced vertex due to phase space ($c\tau$=360 microns).
- Measure mass difference between chargino and neutralino using m_{T2} variable (from mSUGRA analysis).

GMSB

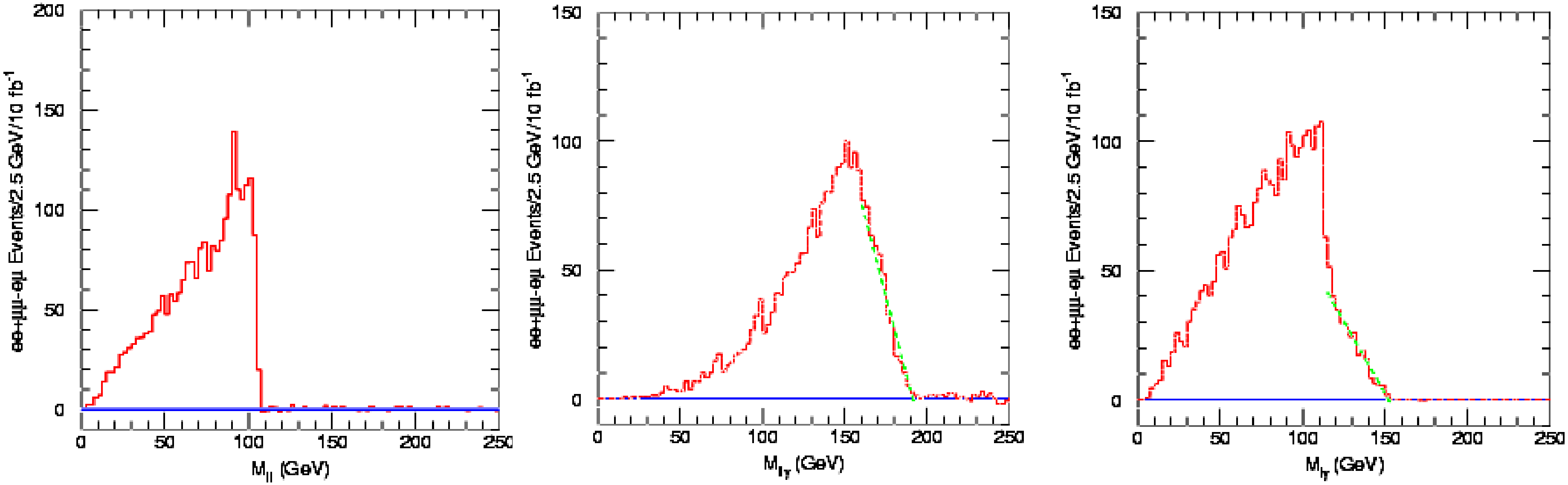
- Kinematic edges also useful for GMSB models when neutral LSP or very long-lived NLSP escapes detector.
- Kinematic techniques using invariant masses of combinations of leptons, jets and photons similar.
- Interpretation different though.
- E.g. LHC Point G1a (neutralino NLSP with prompt decay to gravitino) with decay chain:



GMSB



- Use dilepton edge as before (but different position in chain).
- Use also lγ, llγ edges (c.f. lq and llq edges in mSUGRA).
- Get <u>two</u> edges (bonus!) in lγ as can now see edge from 'wrong' lepton (from χ^0_2 decay). Not possible at LHCC Pt5 due to masses.

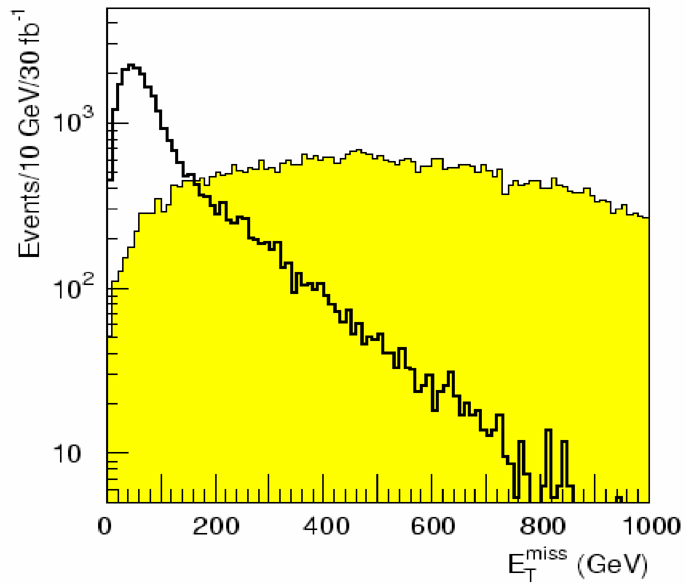


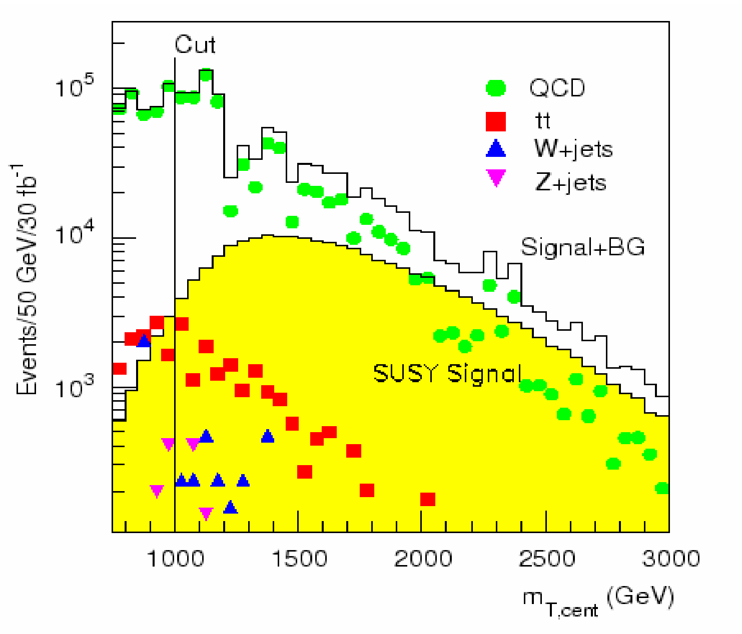
- Interpretation easier as can assume gravitino massless:

$$M^2_{\tilde{l}_R} = \frac{(M^{(1)}_{l\gamma})^2 (M^{(2)}_{l\gamma})^2}{(M^{\max}_{ll})^2} \quad M^2_{\tilde{\chi}^0_1} = M^2_{\tilde{l}_R} - (M^{(1)}_{l\gamma})^2 \quad M^2_{\tilde{\chi}^0_2} = M^2_{\tilde{l}_R} + (M^{(2)}_{l\gamma})^2 \quad (M^{\max}_{ll\gamma})^2 = (M^{(1)}_{l\gamma})^2 + (M^{(2)}_{l\gamma})^2 \,.$$

R-Parity Violation

- Missing E_T for events at SUGRA point 5 with and without R-parity violation
- RPV removes the classic SUSY missing E_T signature





- Use modified effective mass variable taking into account p_T of leptons and jets in event

$$m_{T,cent} = \sum_{\eta<2} p_T^{jet,lepton}$$

R-Parity Violation

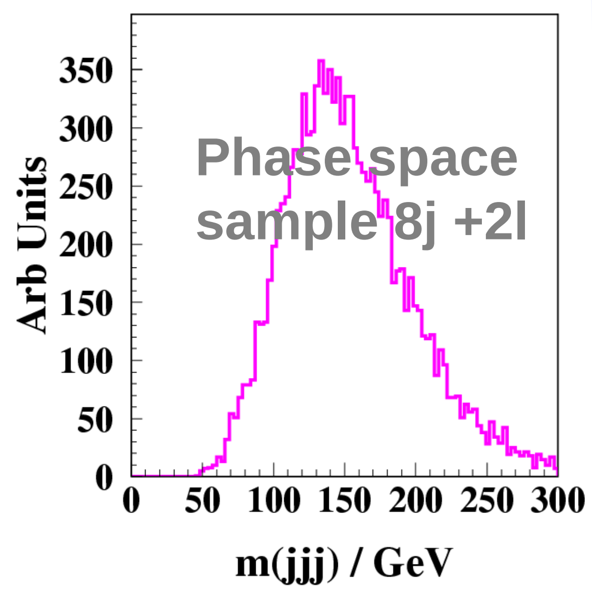
- **Baryon-Parity violating case hardest to identify (no leptons).**
  - **Worst case: λ''_{212} - no heavy-quark jets**
- **Test model studied with decay chain:**

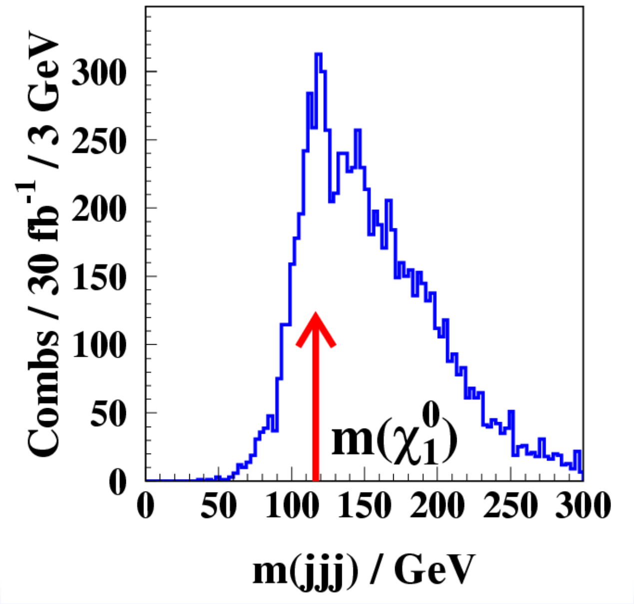
$$\tilde{q}_L \rightarrow \tilde{\chi}_2^0 q \rightarrow \tilde{l}_R l q \rightarrow \tilde{\chi}_1^0 l l q$$

- **Lightest neutralino decays via BPV coupling:**

$$\tilde{\chi}_1^0 \rightarrow cds$$

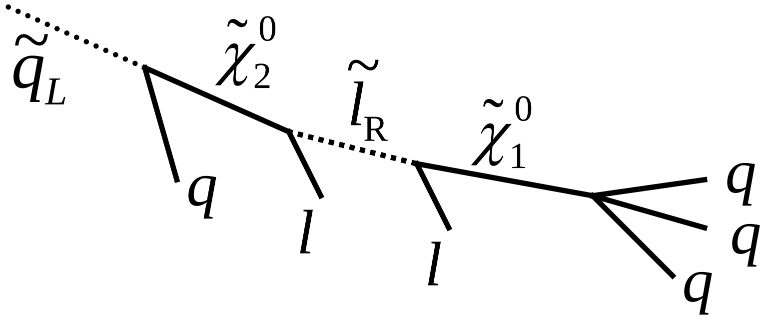
- **Reconstruct neutralino mass from 3-jet combinations (<u>but</u> large combinatorics : require > 8 jets!)**



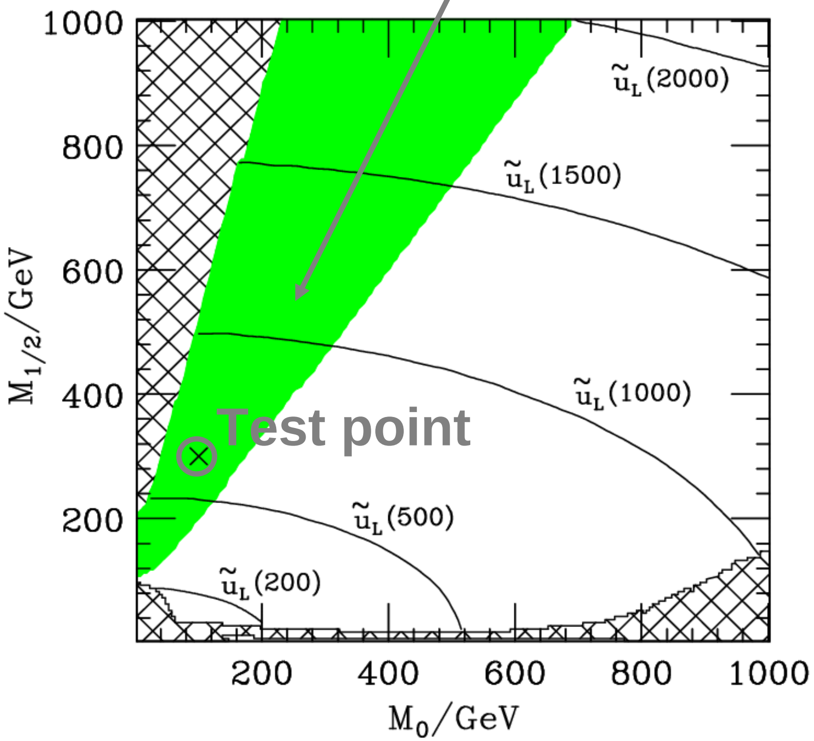


R-Parity Violation

- **Use extra information from leptons to decrease background.**
- **Sequential decay of $\tilde{q}_L$ to $\tilde{\chi}_1^0$ through $\tilde{\chi}_2^0$ and $\tilde{l}_R$ producing Opposite Sign, Same Family (OSSF) leptons**

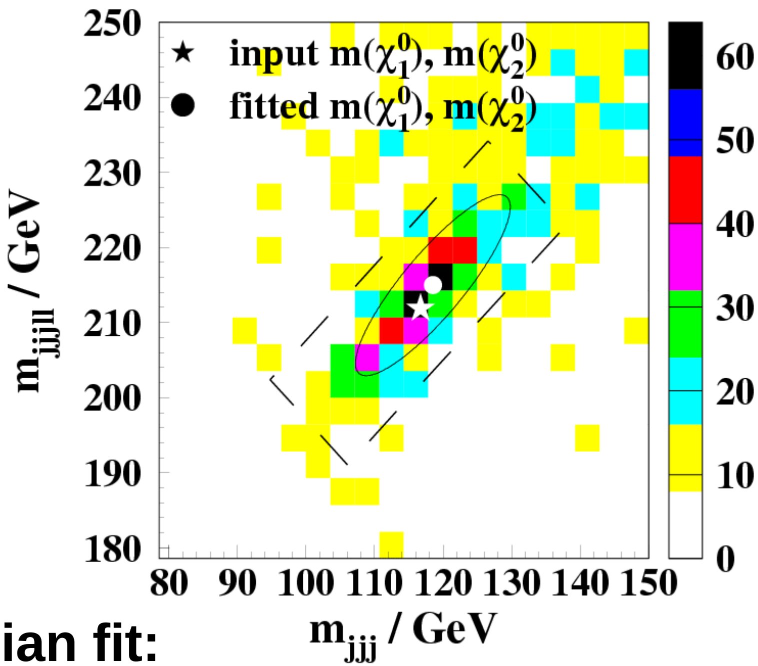


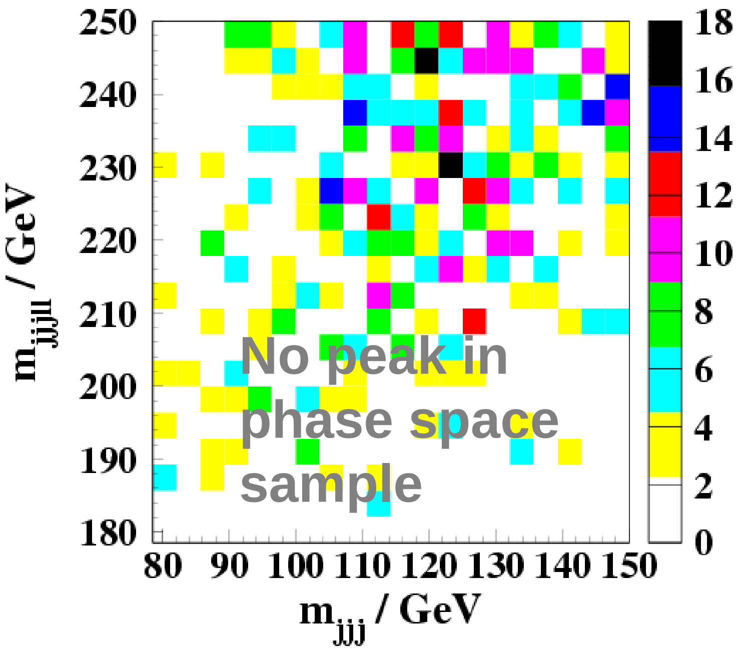
Decay via $\tilde{l}_R$ allowed where $m(\tilde{\chi}_2^0) > m(\tilde{l}_R)$



R-Parity Violation

- **Perform simultaneous (2D) fit to 3jet and 3jet + 2lepton combination (measures mass of $\tilde{\chi}^0_2$).**





Gaussian fit:

$m(\tilde{\chi}^0_1)$ **= 118.9 ± 3 GeV, (116.7 GeV)**

$m(\tilde{\chi}^0_2)$ **= 218.5 ± 3 GeV (211.9 GeV)**

- **Jet energy scale uncertainty ≈ 3% ⇒ 3 GeV systematic**

- **Can also measure squark and slepton masses.**

R-Parity Violation

- **Different λ”$_{ijk}$ RPV couplings cause LSP decays to different quarks:**

$$\tilde{\chi}_1^0 \rightarrow q_1 q_2 q_3$$

- **Identifying the dominant λ” gives insight into flavour structure of model.**
- **Use vertexing and non-isolated muons to statistically separate *c*- and *b*- from light quark jets.**
- **Remaining ambiguity from *d*↔*s***
- **Dominant coupling could be identified at > 3.5 σ**

Distinguishing		Vertexing		Muons		Combined
λ''_{ijk} from	λ''_{lmn}	χ^2 / df	P / %	χ^2 / df	P / %	σ
uds	udb	59.1/1	-	28.7/1	-	9.4
	usb	73.0/1	-	31.7/1	-	10.2
	cds	30.5/1	-	4.0/1	4	5.9
	cdb	106.9/1	-	47.2/1	-	12.4
	csb	113.4/1	-	49.2/1	-	12.8
udb	usb	1.6/2	44	0.4/1	54	1.4
	cds	10.3/2	1	13.0/1	-	4.8
	cdb	18.3/2	-	6.8/2	3	5
	csb	16.3/2	-	5.1/2	8	4.6
usb	cds	17.5/2	-	17.2/1	-	5.9
	cdb	12.1/2	-	5.1/1	2	4.2
	csb	9.9/2	1	3.1/1	8	3.6
cds	cdb	56.1/2	-	37.4/1	-	9.7
	csb	55.8/2	-	35.3/1	-	9.5
cdb	csb	0.6/2	72	1.3/2	51	1.4