SUSY in ATLAS: where we are, what is missing

what can Tevatron teach us

Giacomo Polesello

CERN and INFN, Sezione di Pavia

SUSY studies in ATLAS

Historical main lines of development:

- Study SUSY discovery under wide range of models
- Once SUSY is discovered, develop strategy for measurement of model parameters

Continuing work, constant collaboration with phenomenologist, tests of new ideas

After completion of physics TDR, and increasingly in the last years, modification of the emphasis:

LHC data-taking is nearing: SUSY is the new physics candidate with highest potential for early discovery. Get ready for data:

- Detailed mapping of signatures available with low data statistics
- Evaluate validity of previously studied signatures with full detector simulation
- Assess level of understanding of detector performance necessary for discovery and strategy to achieve it

The large variety of signals available in SUSY challenges the performance of the ATLAS detector in all sectors.

Follow the projected steps in the experimental study of SUSY theories and point out the key experimental issues for:

- Trigger
- Discovery
- Parameter Measurement
- Model constraining

Triggering on SUSY

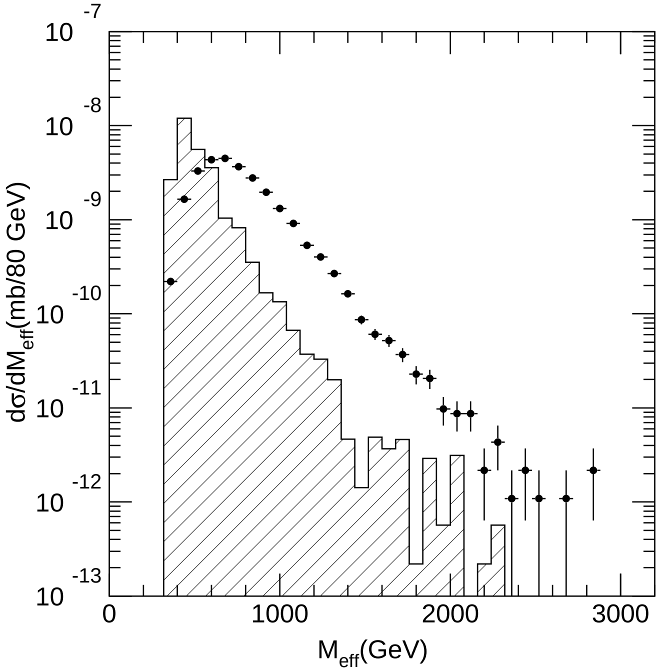
Model independent SUSY signature: multi-jet + Etmiss

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

ATLAS strategy: Inclusive approach: $\not\!\!E_T + 1$ jet and 4-jet triggers, keep lowest threshold compatible with affordable rate.

Low cuts: easier signal observation and possibility of more detailed background studies

Baseline: $\not\!\!E_T > 70$ GeV, 1 Jet with $E_T > 70$ GeV. Rate ~20 Hz at 2×10^{33} cm^{-2}s^{-1}.



Example:Point with m($\tilde{q}$, $\tilde{g}$)=400 GeV

Require $\not\!\!E_T > 80$ GeV, 1 Jet $E_T > 80$ GeV

Plot: $M_{\rm eff} \equiv \Sigma_i |p_{T(i)}| + E_T^{\rm miss}$

With harder cuts the signal peak would not be observable

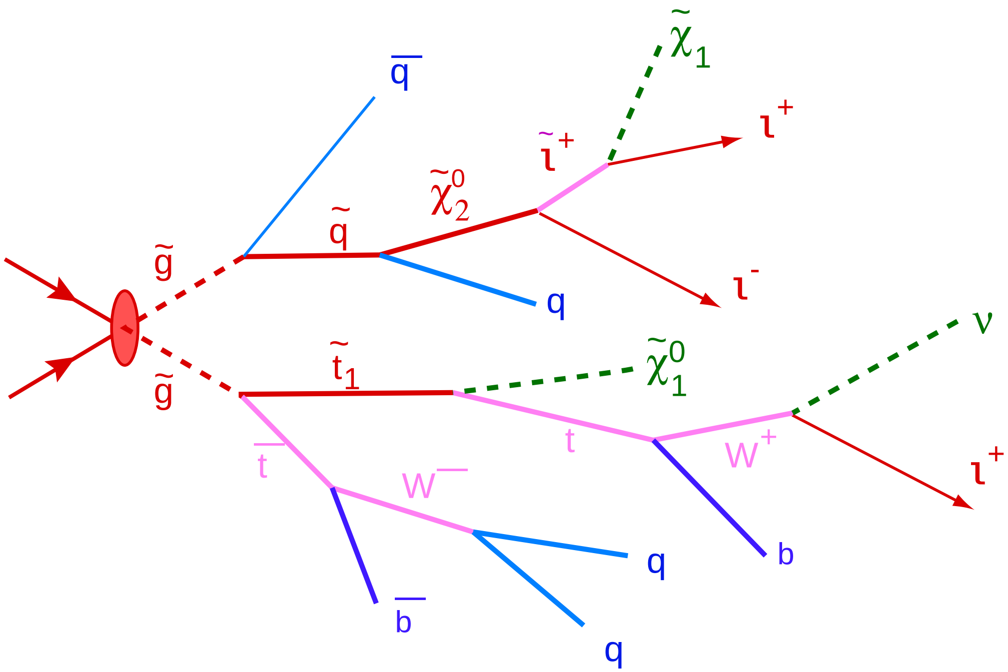
Good separation of signal and background looks possible, but need to verify with better multi-parton MonteCarlos

Susy discovery

Address general features of SUSY models:

$\tilde{g}$ and $\tilde{q}$ strongly produced, cross-section comparable to QCD at same $Q^2 \Rightarrow$ dominant

If R_p conserved, $\tilde{g}$ and $\tilde{q}$ cascade to undetected LSP. Multiple signatures:



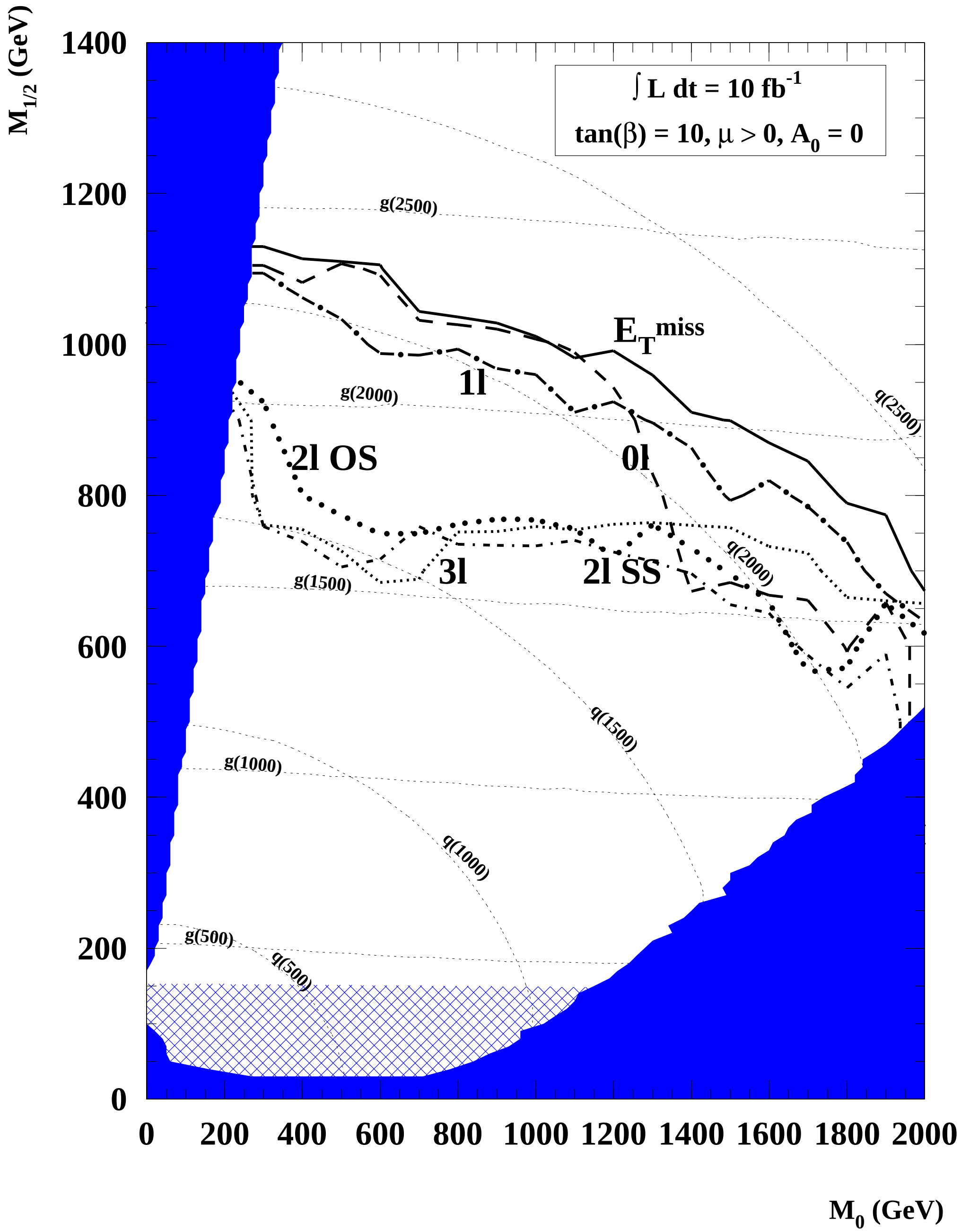
- $\not{E}_T$: from LSP escaping detection
- High E_T jets: guaranteed if unification of gaugino masses assumed
- Spherical events: From Tevatron limits squarks/gluinos must be heavy ($\gtrsim$ 400 GeV).
- Multiple leptons: from decays of Charginos/neutralinos typically present in cascade

Mostly models with $\tilde{\chi}_1^0$ LSP studied in detail.

If $\tilde{G}$ LSP (e.g. GMSB) additional signatures from NLSP decays

If R_p not conserved: $\tilde{\chi}_1^0$ decays to 3-leptons, 2 leptons+1jet, 3 jets. $\not{E}_T$ signature lost

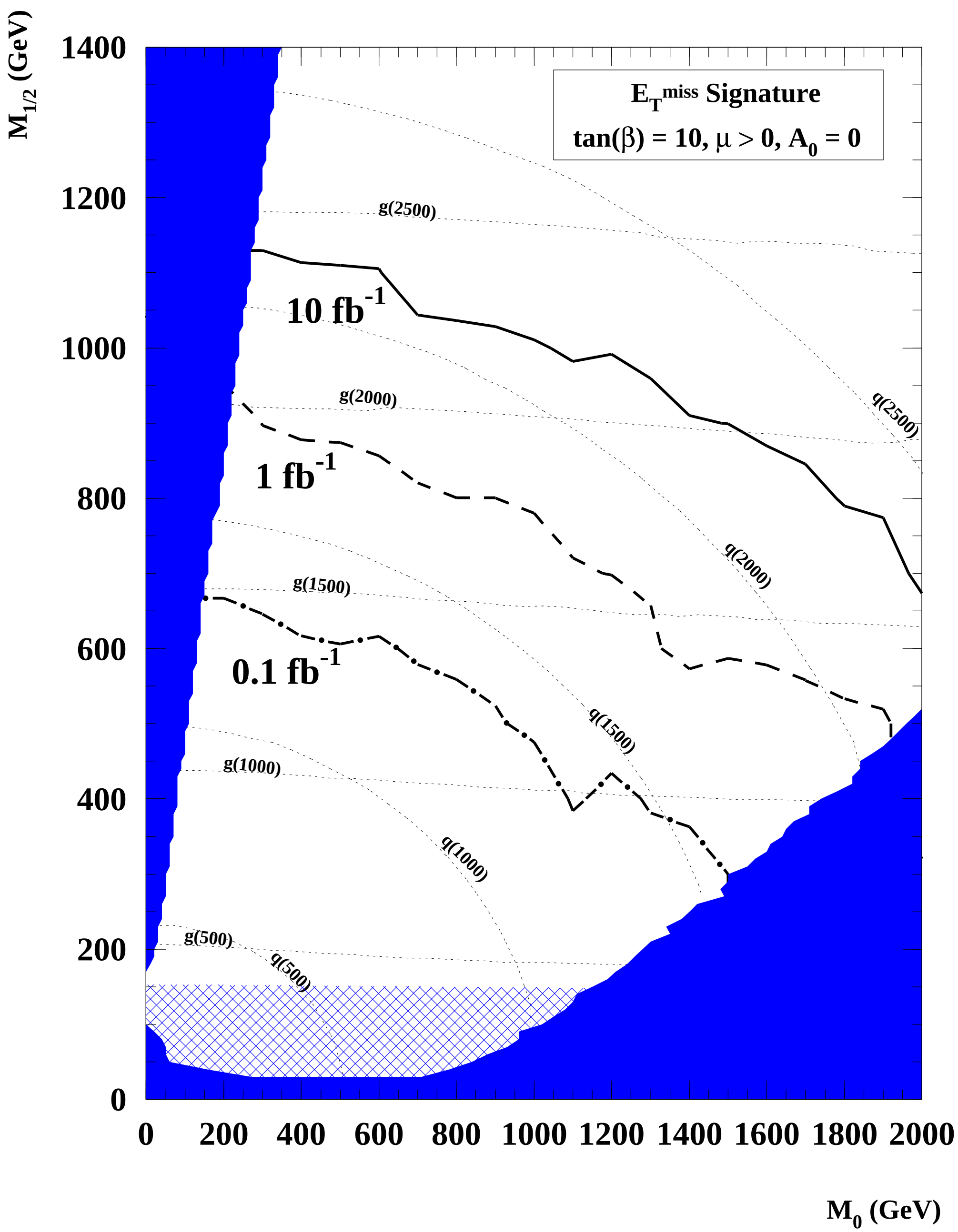
Inclusive reach in mSUGRA parameter space



Multiple signatures on most of parameter space

- $\not\!\!E_T$ ⇐ Dominant signature
- $\not\!\!E_T$ with lepton veto
- One lepton
- Two leptons Same Sign (SS)
- Two leptons Opposite Sign (OS)

Significant reach from $\not\!\!E_T$ signature from earliest phases of the experiment



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

- $\sim$1300 GeV in "one week"
- $\sim$1800 GeV in "one month"
- $\sim$2200 GeV in one year

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

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

Ultimate reach in the 2.5-3 TeV region

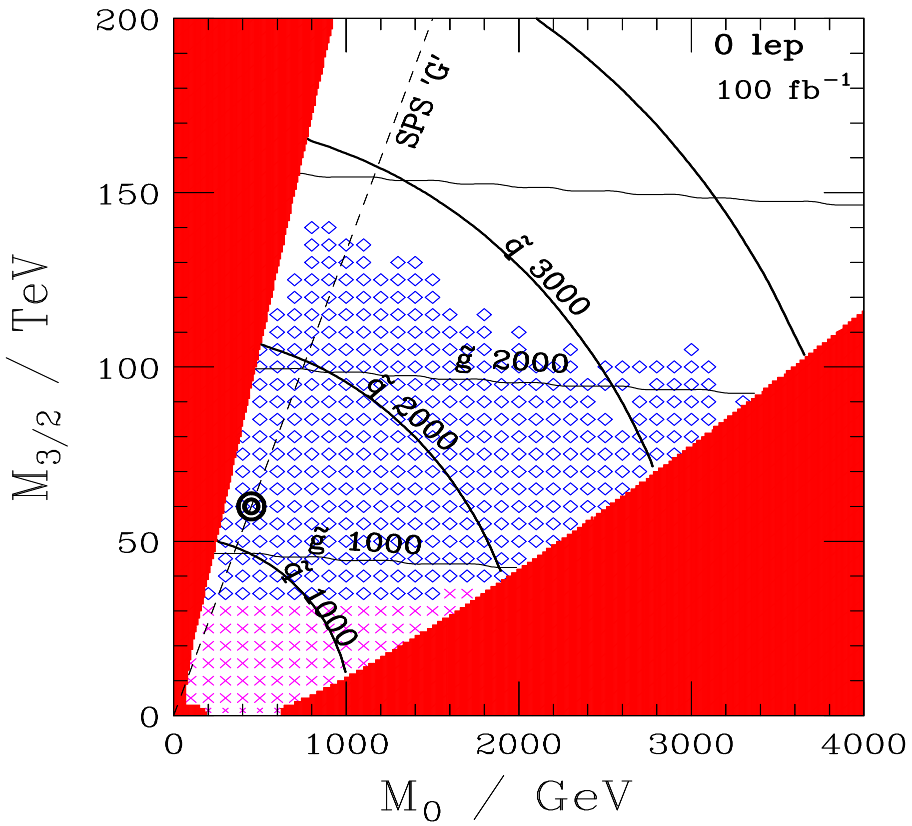
A factor two change in background moves the curves by a few tens of GeV

Models other than MSUGRA have been studied:

GMSB with prompt NLSP ($\tilde{\ell}_R$ or $\tilde{\chi}_1^0$) easier than mSUGRA because additional handles

GMSB with long lived $\tilde{\ell}_R$ very easy because $\tilde{\ell}_R$ identifiable through TOF measurement

AMSB, detailed inclusive study recently performed as for mSUGRA



Model parameters: M_0, $M_{3/2}$

Signatures include:

$\not{E}_T$, jets, a varying number of leptons

Reach for 100 fb^{-1}:

$m(\tilde{q})$=2800 GeV or $m(\tilde{q})$=2100 GeV

Similar to mSUGRA

Studied also models with R-parity violation: hardest case when $\tilde{\chi}_1^0$ decays to three jets

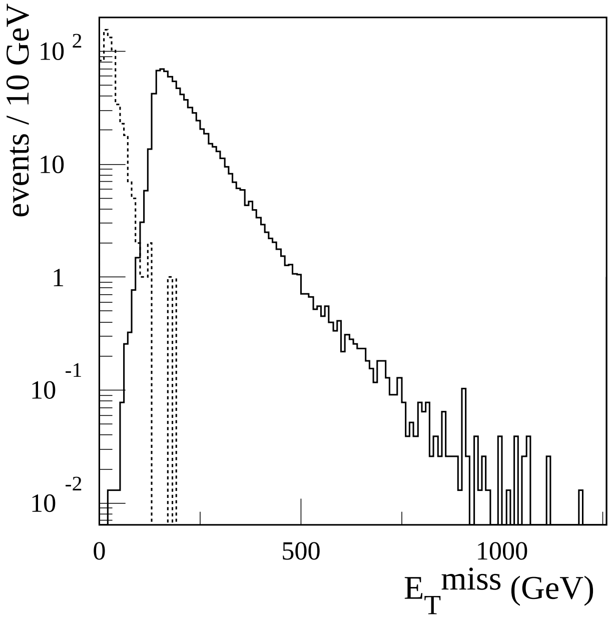
$\Rightarrow$ study in progress

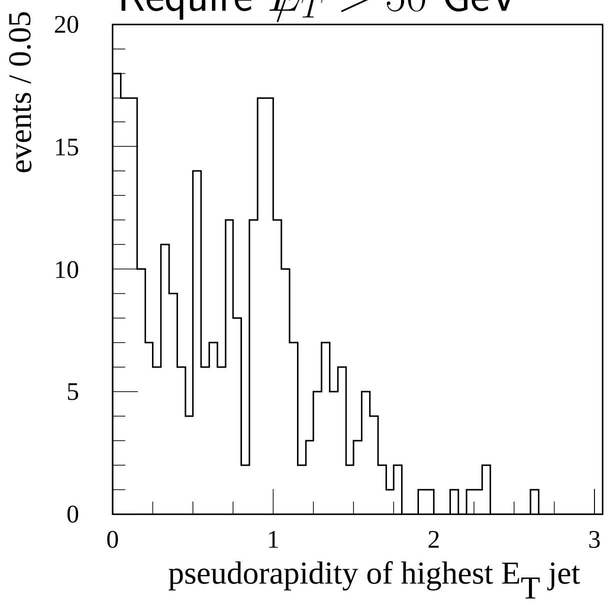
Excellent control of $\not\!\!E_T$+jets backgrounds crucial for SUSY discovery

- Real $\not\!\!E_T$ from ν in $W, Z + jets$, $\bar{t}t \Rightarrow$. Use data samples of fully reconstructed events
- Instrumental $\not\!\!E_T$ from mismeasured multi-jet events. Control detector response by studying balance in 2-jet events, $Z \to \mu\mu$+jet events.

TDR study: use fully simulated $Z \to \mu\mu$ with $p_T(Z) > 200$ GeV

Dotted: measured $\not\!\!E_T$, full: jet undetected





Two events with high $\not\!\!E_T$: real ν

Very active field of study, group of volunteers in SUSY group focusing on different aspects of $\not\!\!E_T$ control, expect results of new studies by June

Measurement of model parameters

- Select final-state signatures identifying exclusive decay chains
- Extract constraints on sparticle masses and couplings
- From measured quantities try to constrain underlying model

Studies performed on selected points in parameter space for predictive models with well defined mass hierarchy and decay patterns (mSUGRA, GMSB, AMSB) Select decay chains involving leptons (e,μ), b's, τ's

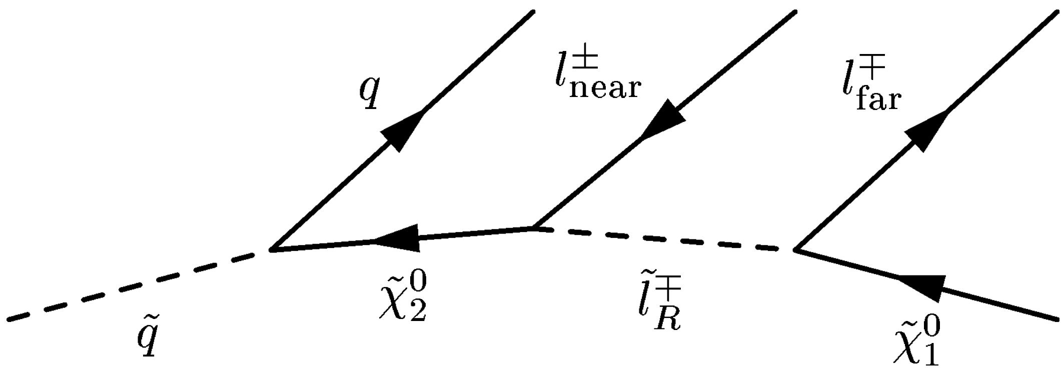
R-parity conservation $\Rightarrow$ two undetected LSP's per event

$\Rightarrow$ no mass peaks, kinematic constraints from edges and endpoints in kinematic distributions

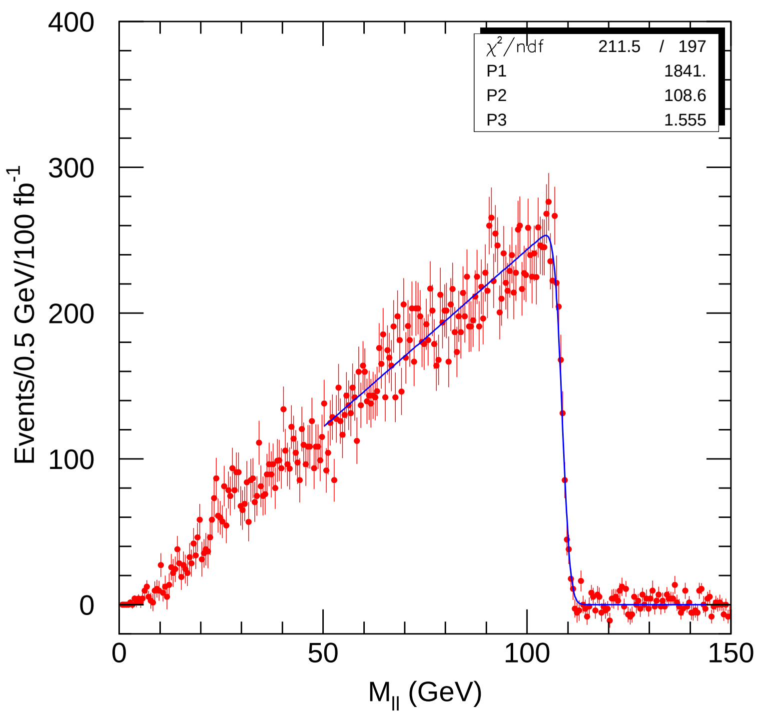
If a chain of at least three two-body decays can be isolated, full reconstruction of masses and momenta of involved particles possible

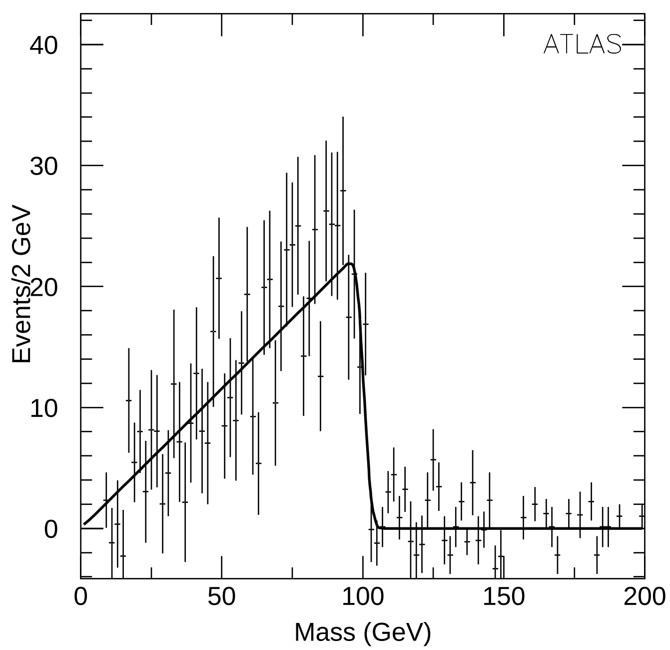
Kinematic edges can be expressed as a function of the masses of the involved sparticles

Example: full reconstruction of squark decays in models with light $\tilde{\ell}_R$ ($m_{\tilde{\ell}_R} < m_{\tilde{\chi}_2^0}$):



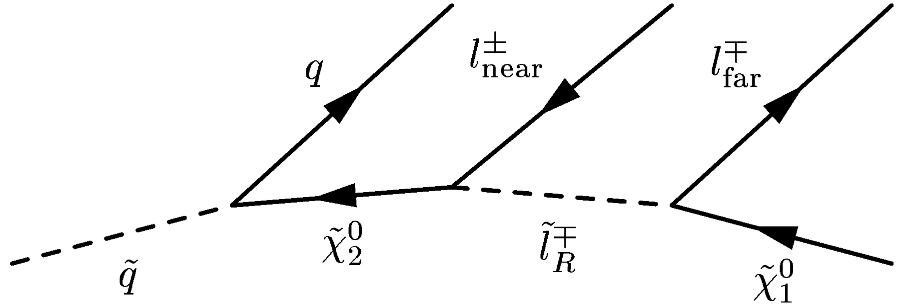
Start with lepton-lepton invariant mass. Plot $e^+e^- + \mu^+\mu^- - e^{\pm}\mu^{\mp}$

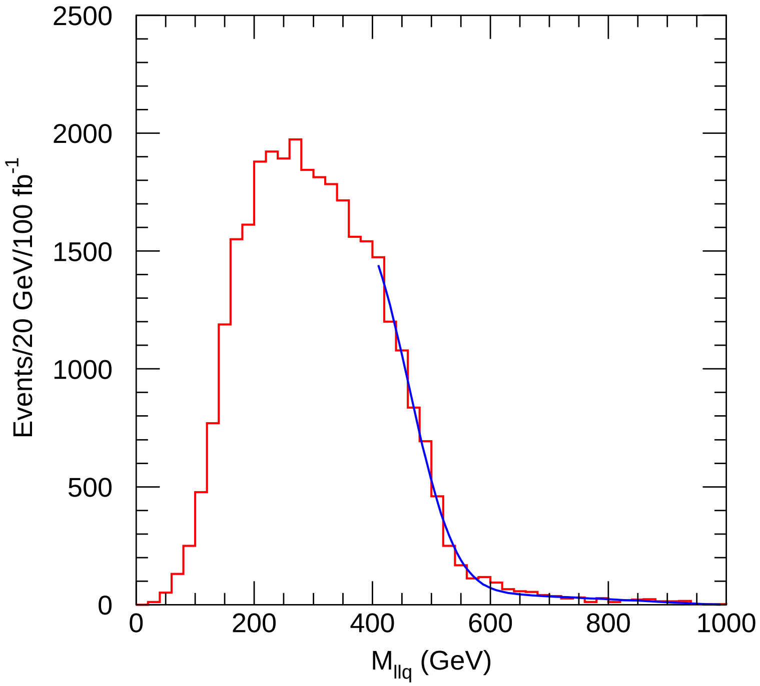


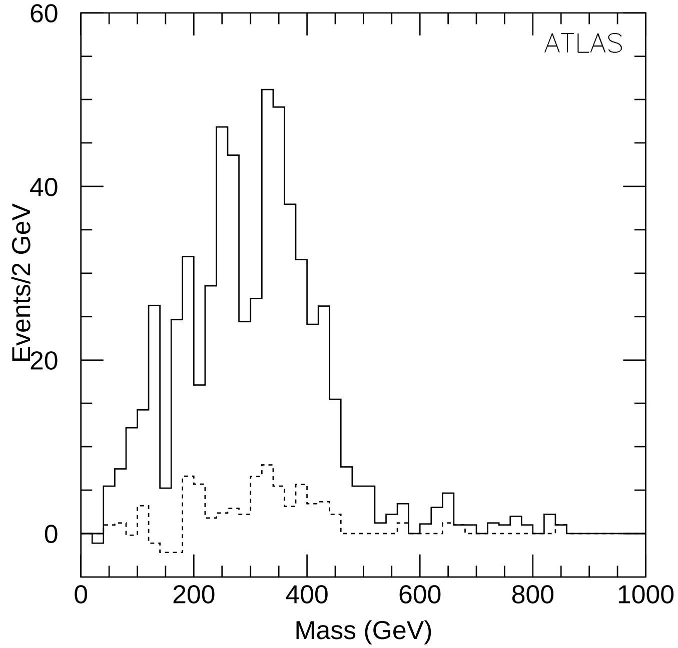


Clear edge both with fast (left, 100 fb^{-1}), and full simulation (right, 5 fb^{-1})

Lepton-lepton-jet edges







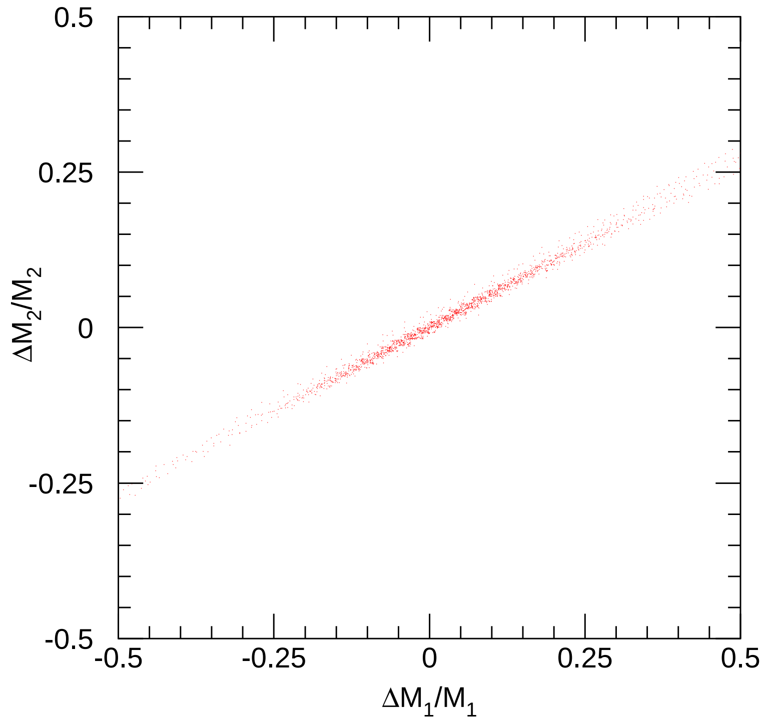
$m(\ell\ell j)$ For fast (left, 100 fb^{-1}), and full simulation (right, 5 fb^{-1})

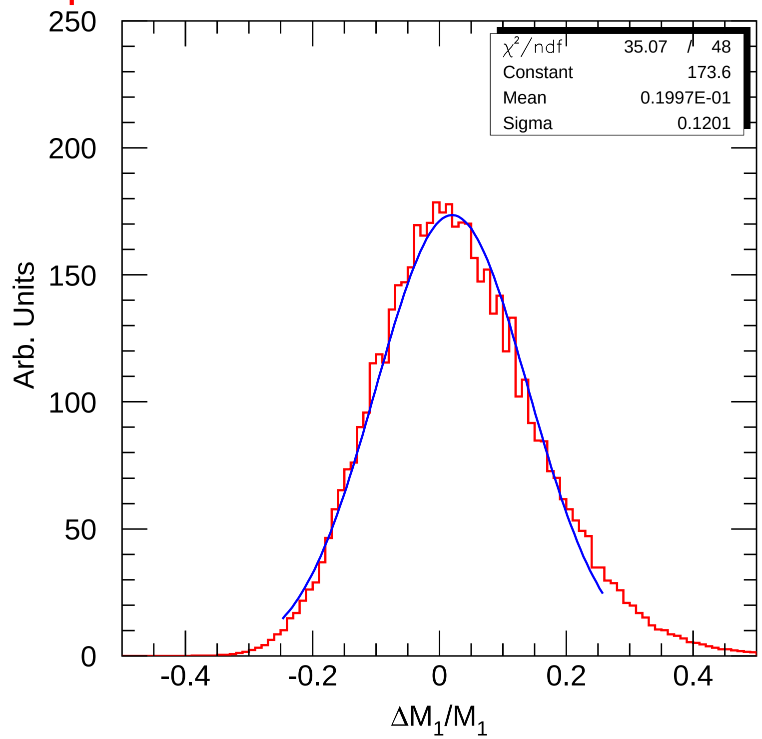
For considered model, found 5 edge measurements:

$m(\ell\ell), m(\ell\ell j)_{min}, m(\ell\ell j)_{max}, m(\ell_1 j), m(\ell_2 j)$

$\Rightarrow$ enough constraints for model-independent determination of four masses

Strong correlation between masses of measured sparticles





$\tilde{\chi}_1^0$ mass measured with $\sim 12\%$ precision for 100 fb^{-1}

Main experimental systematics:

- Shape of edges
- Energy scale of jets and leptons: described in detail in plenary sessions

Use measured masses as an input in the study of model-dependent signatures mSUGRA model used as a benchmark for parameter determination studies

Results obtained for mSUGRA often apply to more general models with high $|\mu|$

Even in this constrained framework, work is far from finished:

Most of original work on parameter determination focused on mass measurement of:

a) squarks of first two generation b) lighter neutralinos

High statistics signals, straightforward experimental signatures (e, μ).

Addressed sparticles only allow to cover part of the mSUGRA parameters, m_0, $m_{1/2}$.

More recently addres complex signatures sensitive to $\tan\beta$, A, μ:

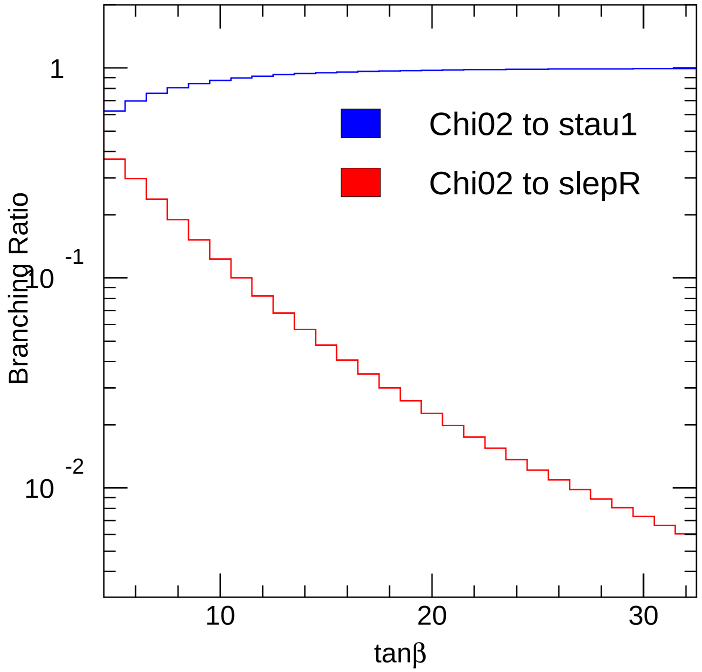
- stop-sbottom sector
- stau system
- heavier gauginos
- first approach to branching fractions
- Spin measurements

Problem, model-dependence of signature increases with complexity

Strike a balance between learning new techniques and excess of detail

Stau signatures

To achieve good control of SUSY models, crucial to be able to study $\tilde{\chi}^0_2 \rightarrow \tilde{\tau}_1 \tau$



For increasing $\tan\beta$ larger mixing in $\tilde{\tau}$ sector:

- Decrease of $\tilde{\tau}_1$ mass with respect to ℓ_R
- In mSUGRA enhanced coupling to Wino $\tilde{\chi}^0_2$

$\tilde{\chi}^0_2 \rightarrow \tilde{\tau}_1 \tau$ dominates over $\tilde{\chi}^0_2 \rightarrow \tilde{\ell}_R \ell$

For significant region in parameter space both signals still detectable at high $\tan\beta \Rightarrow$

handle on $\tilde{\tau}$ mixing

Knowledge of $\tilde{\tau}_1$ mass necessary in order to predict the density of $\tilde{\chi}^0_1$ Dark Matter

WMAP results favour almost-degeneracy between $\tilde{\tau}_1$ and $\tilde{\chi}^0_1$. Full simulation study of soft τ detection in progress (ATLAS)

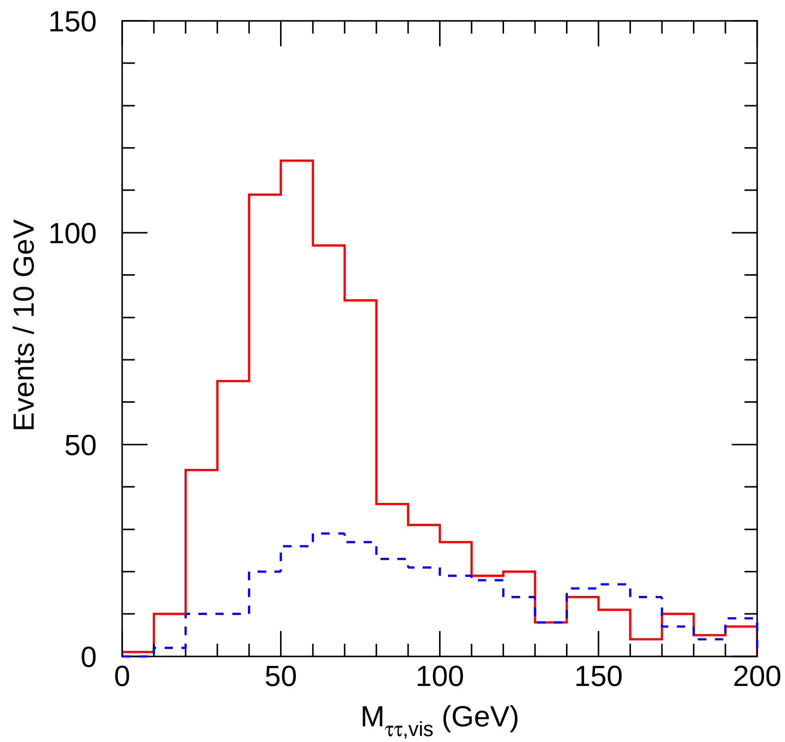
ATLAS Point 5 ($m_0 = 100$ GeV, $m_{1/2} = 300$ GeV, $\tan\beta = 6$, $A = -300$ GeV, $\mu > 0$)

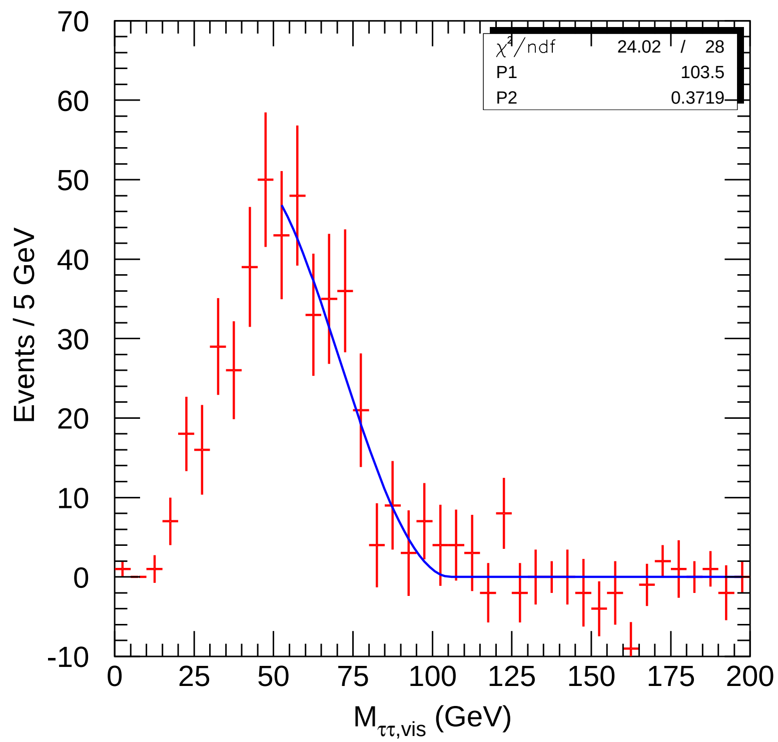
Full simulation on 5 fb^{-1}

Suppress Standard Model background with cuts on $\not{E}_T$, M_{eff}, jet multiplicity

Select decays $\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau$ requiring two jets tagged as hadronic τ decays.

Calculate invariant mass of $\tau^+\tau^-$ candidates





Subtract misidentified QCD jets using same-sign pairs

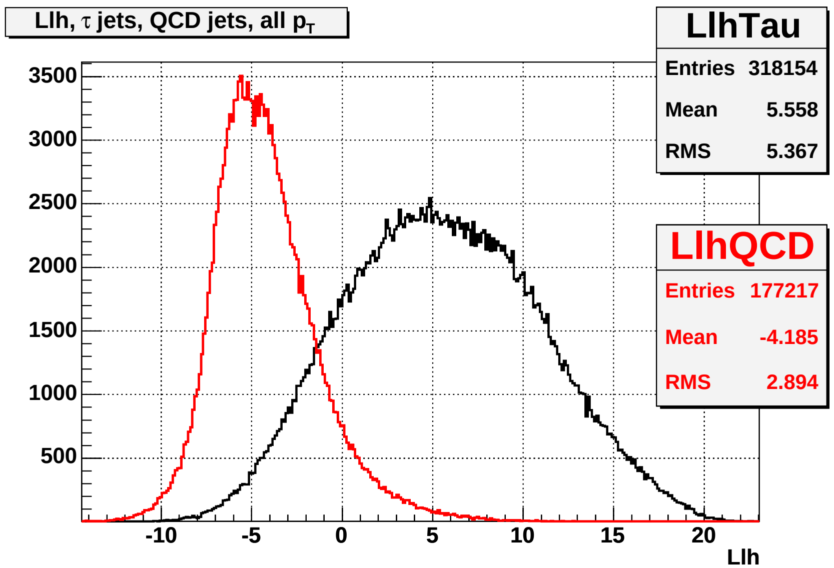
Main ingredient: Identification of τ hadronic decays

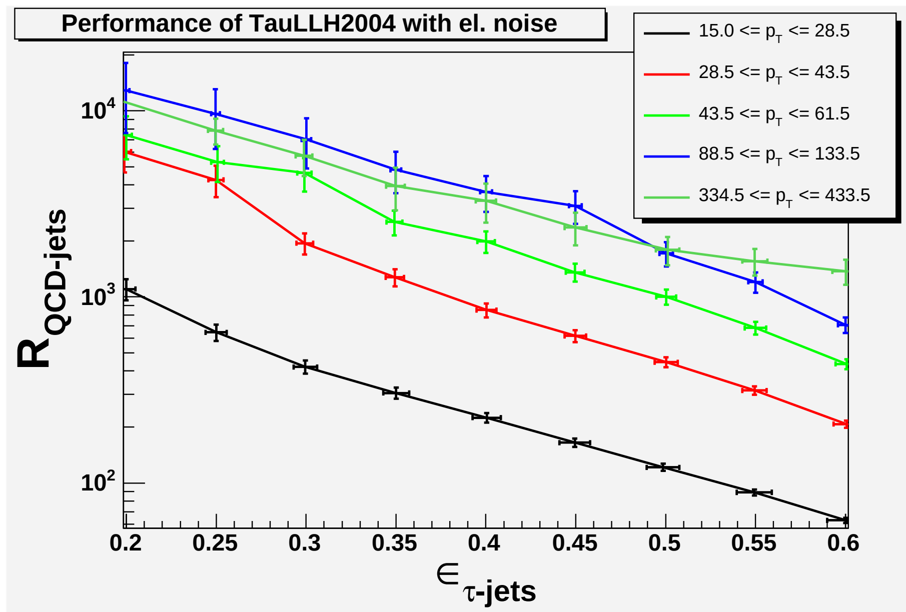
Exploit difference between hadronic decays of τ's and QCD jets:

- Low track multiplicity ($1 < N_{tr} < 3$), charge
- Narrow jet in calo (Radius in EM calo, Number of strips in presampler)
- Impact parameter

Recent ATLAS study: build likelihood function in bins of jet P_T ($15 < P_T < 600$ GeV)

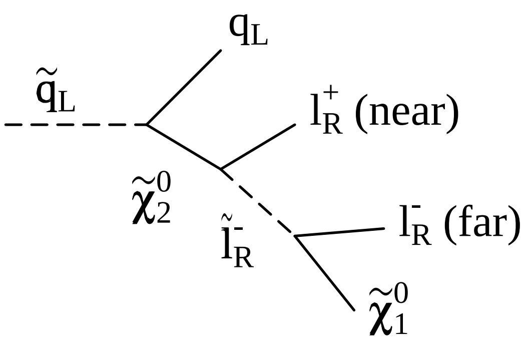
Also studied effect of electronic noise on identification algorithm





Still to study: pile-up effects, extend study to lower P_T

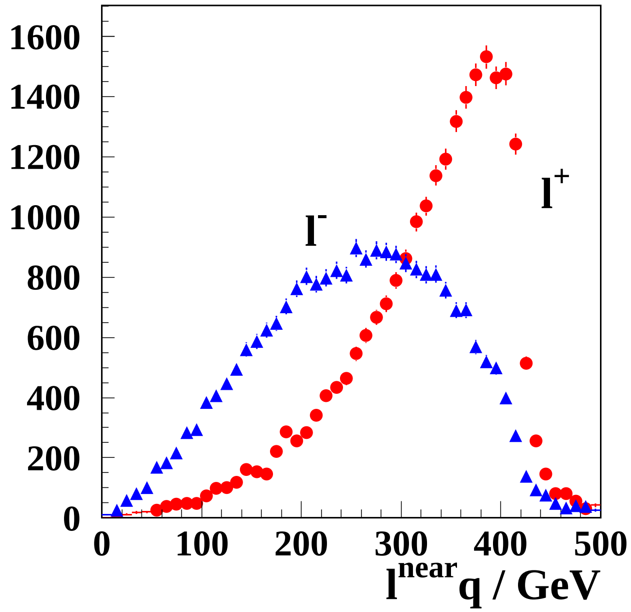
Spin measurements



$\ell(near)q$ invariant mass distributions measure angular distribution of products of $\tilde{\chi}_2^0$ decay, and thence $\tilde{\chi}_2^0$ spin

Very different distributions for ℓ^+ (red) and ℓ^- (blue), but:

- $\bar{q}$ experimentally indistinguishable from q, and distributions exchanged if initial state is antisquark instead of squark
- Some contamination in sample of $\ell(near)$ from $\ell(far)$



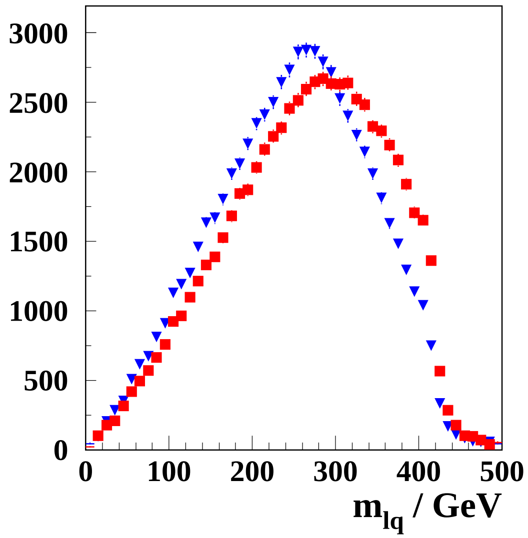
Parton level

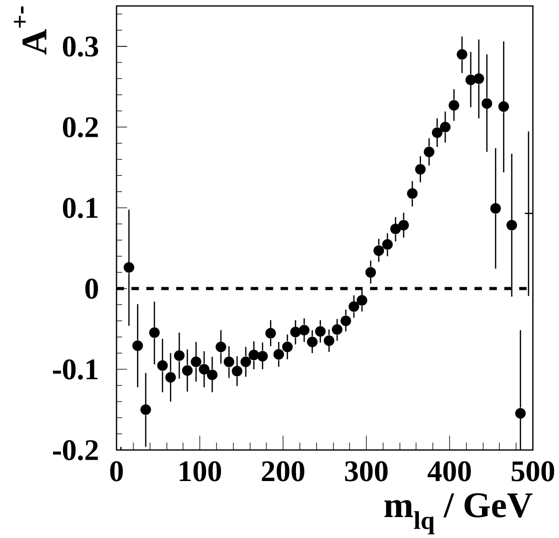
Study performed for ATLAS Point 5

Exploit the fact that LHC is a proton-proton machine: higher probability of producing squarks than antisquarks

Mass distribution for $\ell(far)$ only shows small $\pm$ asymmetry

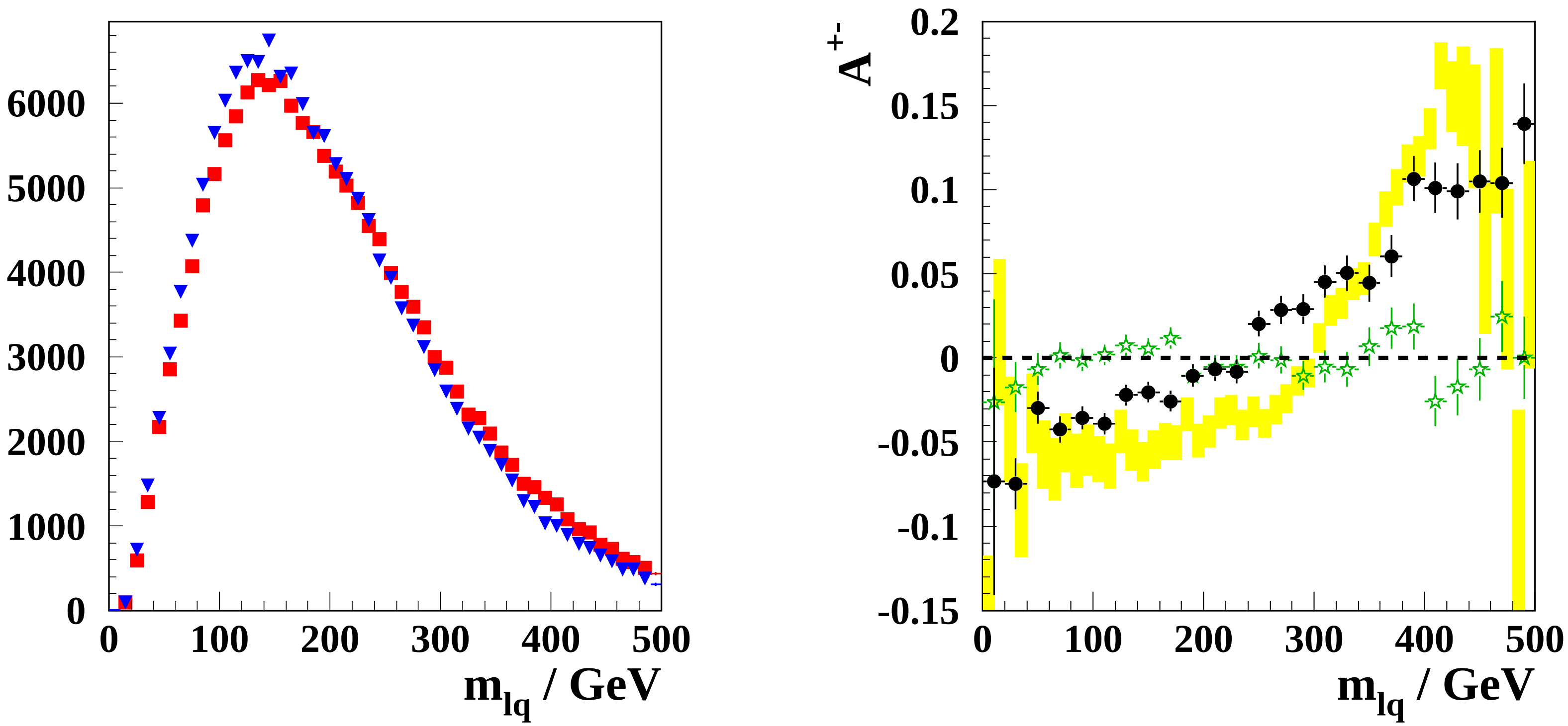
At parton level significant difference between distributions for ℓ^+ (red) and ℓ^+ (blue)





Asymmetry distribution: $A^{\pm} = \frac{\ell^+ - \ell^-}{\ell^+ - \ell^-}$. Shape indicates that $\tilde{\chi}_2^0$ spin is 1/2

Fast simulation level



Charge asymmetry survives detector smearing

Similar asymmetry shape as at parton level

If spin correlation switched off in HERWIG, recover flat asymmetry shape

For studied point 150 fb^{-1} sufficient to observe asymmetry

Additional measurements build on measured $\tilde{q}_L$, $\tilde{\ell}_R$, $\tilde{\chi}^0_2$, $\tilde{\chi}^0_1$ masses:

- Measure slepton left direct production
- Use shorter decay chains to measure additional masses: $\tilde{q}_R \to \tilde{\chi}^0_1 q$, $\tilde{q}_L \to \tilde{\chi}^0_4 q$, ...

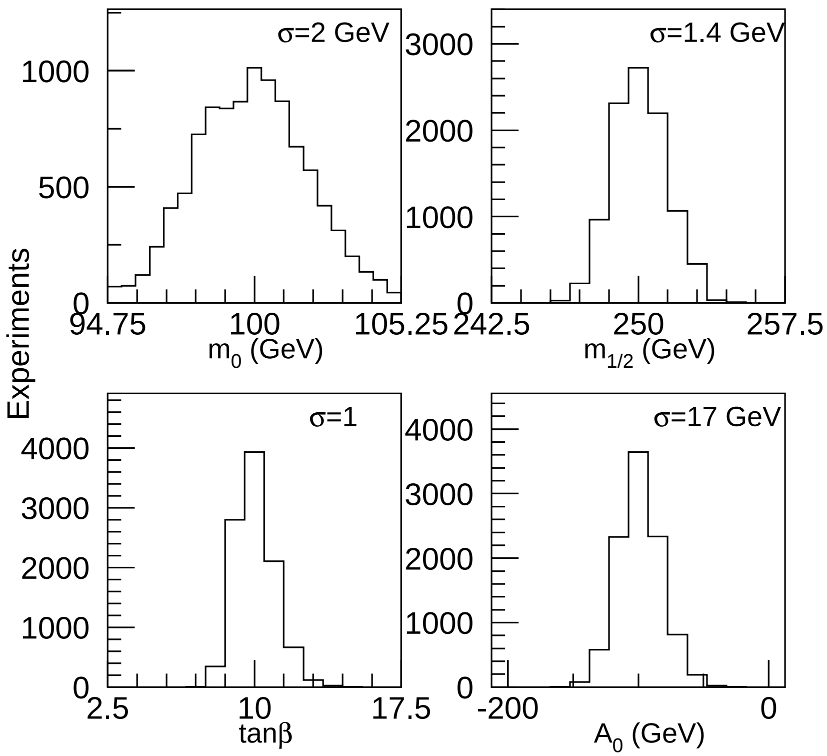
Measurements for SPS1a ($m_0 = 100$ GeV, $m_{1/2} = 250$ GeV, $\tan\beta = 10$, $A = -100$ GeV, $\mu > 0$)

		Errors		
Variable	Value (GeV)	Stat. (GeV)	Scale (GeV)	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
$m(\ell_L) - m(\tilde{\chi}^0_1)$	106.1	1.6	0.1	1.6
$m_{\ell\ell}^{max}(\tilde{\chi}^0_4)$	280.9	2.3	0.3	2.3
$m_{\tau\tau}^{max}$	80.6	5.0	0.8	5.1
$m(\tilde{g}) - 0.99 \times m(\tilde{\chi}^0_1)$	500.0	2.3	6.0	6.4
$m(\tilde{q}_R) - m(\tilde{\chi}^0_1)$	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

Constraints on SUSY model from measurements

Measured mass relations can be used to constrain models

Simplest approach: postulate SUSY breaking model, and verify if any set of the model parameters fits measured quantities. Exercise performed for SPS1a postulating mSUGRA



- m_0 dominated by sleptons ($\Delta m_0 \sim 2\%$)
- $m_{1/2}$ " by light gauginos ($\Delta m_{1/2} \sim 0.6\%$)
- Need $\tilde{b}_1$ and $\tilde{b}_2$ for $\tan\beta$, otherwise long tails
- Trilinear couplings A_0 related to μ, fixed by $\tilde{\chi}^0_4$
- Wrong μ sign ruled out by bad fit

Measurements at the LHC can constrain SUSY models

Exercise relies on correct interpretation of kinematic signatures as SUSY decay chains

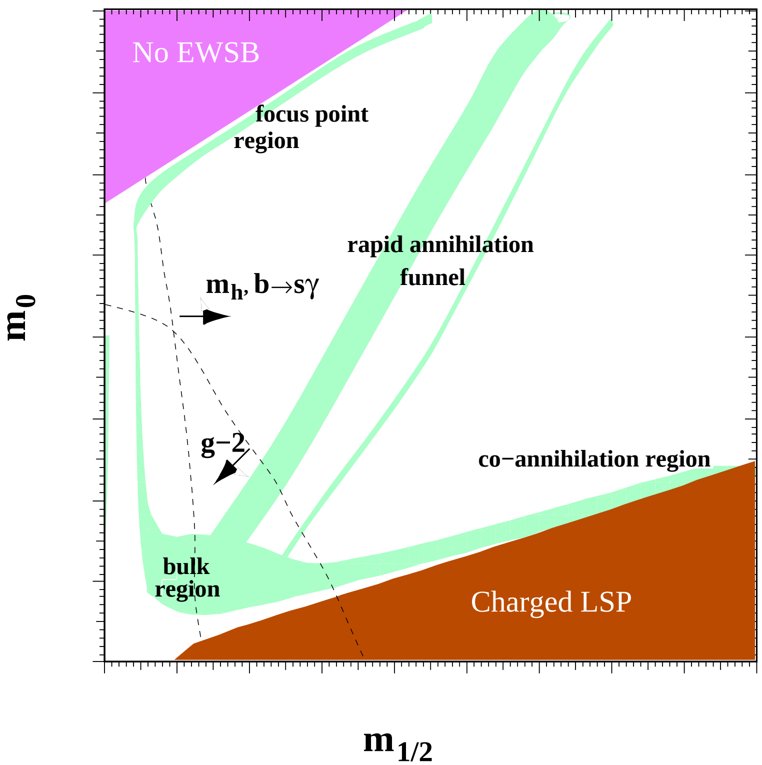
Spin information needed to confirm SUSY interpretation (in progress)

Ongoing work: use Dark Matter as a guidance

Detailed ATLAS studies concentrated in favourable "bulk" region, now badly shrunk by WMAP

Boost annihilation via degeneration 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.):



- Coannihilation region: small $m(\tilde{\chi}_1^0) - m(\tilde{\tau})$ (1-10 Gev).

  Similar to bulk, but softer leptons!

- 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

- Focus Point: high m_0, significant higgsino content.

  Sfermions outside LHC reach, study gluino decays.

  Try direct gaugino productions when gluinos too heavy

- Additional degenerate possibilities, e.g. light stop

Evaluate ATLAS potential for selected models with the above signatures.

Example: preliminary plots for 'easy' point in focus point region (T. Lari)

Select mSUGRA point (ISA7.69):

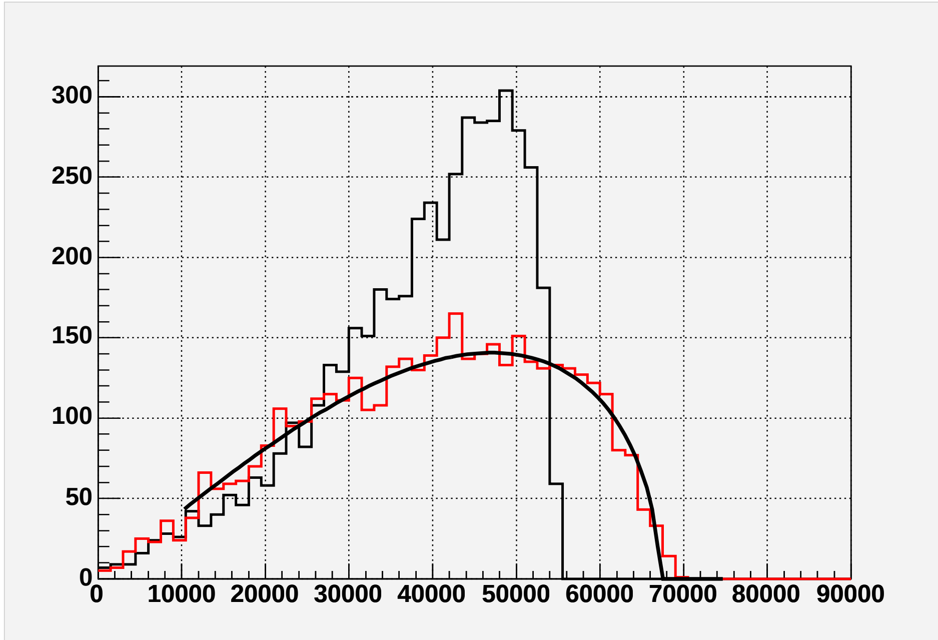
$m_0 = 3400$ GeV, $m_{1/2} = 300$ GeV,

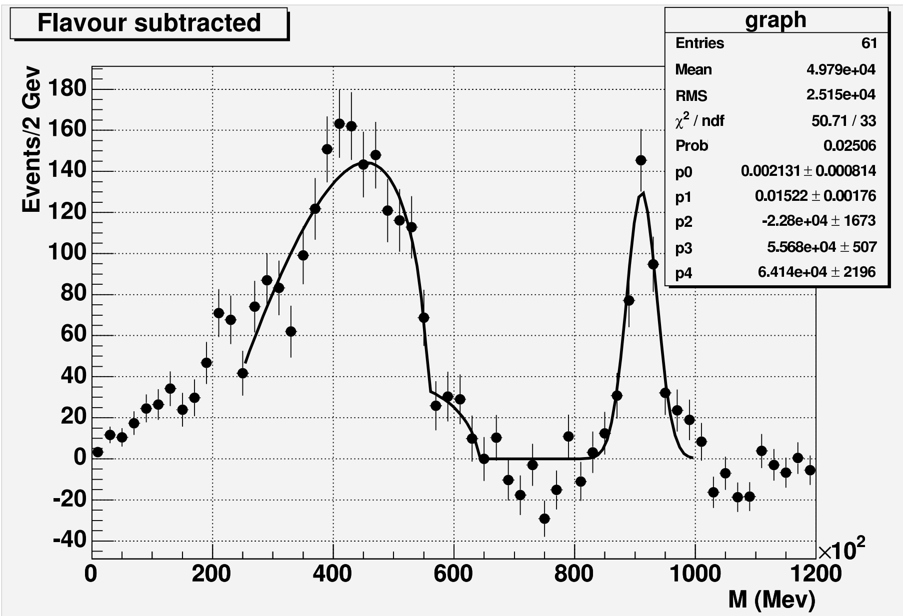
$\tan\beta = 10$, $A = 0$, $\mu > 0$, $m_t = 175$ GeV

$m_{\tilde{g}} = 854$ GeV. Study chains:

$\tilde{g} \to \tilde{\chi}_2^0 qq \to \ell\ell\tilde{\chi}_1^0 qq$

$\tilde{g} \to \tilde{\chi}_3^0 qq \to \ell\ell\tilde{\chi}_1^0 qq$





Require $\not\!\!E_T > 100$ GeV, $M_{eff} > 750$ GeV, $P_t(J1) >$100 GeV

Plot invariant mass of OS-SF lepton pair with flavour subtraction (300 fb^{-1})

Might be able to observe structure from $\tilde{\chi}_3^0$

Life beyond mSUGRA

Alternative SUSY breaking mechanisms: in many case "exotic" signatures allowing unique identification of model, and good starting point for reconstruction:

- Gauge Mediated Susy Breaking (GMSB): non-pointing photons, heavy stable muon-like particles.
- Anomaly Mediated Study breaking (AMSB): soft pions from $\tilde{\chi}_1^{\pm} \rightarrow \pi \tilde{\chi}_1^0$ decay.
- Split SUSY: heavy long-lived R-hadrons

The detector design was found able to cope with unexpected signatures !!

Generalize studies to less constrained models, by releasing unification constraints:

- Give up gaugino mass unification: can yield models with degenerate spectra
- Free value of $\mu \Rightarrow$ higgsino-like light neutralinos
- Decouple scale of third generation sfermions $\Rightarrow$ inverted hierarchy models
- Non-diagonal slepton mixing matrices: Lepton Flavour Violation
- Complex mixing matrices: CP violation

A few analyses existing or started, still lots of work to do

What about the Tevatron?

If SUSY is discovered at the Tevatron, invaluable guidance

Discovery would probably provide basic information on gaugino sector

Help focusing searches on specific signatures/classes of models

If SUSY is not discovered at Tevatron, main impact on development of discovery strategy. Two main inputs:

- Define for us where we can be sure NOT to find SUSY

  In order to perform a successful search, need to define control samples in our data, i.e. kinematic configurations which are not polluted by signal

  Difficult, as SUSY is produced strong, and has large variety of signatures. Use configurations excluded by Tevatron as guidance

- They can transfer us their experience on the hunt for sources of $\not\!\!E_T$
  - SM $\not\!\!E_T$+jets probably quite different as we are typically dominated by huge $\bar{t}t$ cross-section.

    Can profit from experience on using well reconstructed leptonic W/Z events to calibrate understanding of simulation programs, or directly to predict complex background signatures involving leptons and multijets
  - Instrumental $\not\!\!E_T$ extremely difficult to model, and sensitive to all kind of unexpected performance 'features' of detector

    We should build on Tevatron experience on tracking these problems, and on the techniques developed to employ the large QCD samples to map possible sources of $\not\!\!E_T$ in data

Conclusions

The ATLAS experiment is getting ready for taking data at the LHC in 2007

Some clear conclusions reached from many years of studies

R-parity conserving SUSY can be easily discovered for a SUSY mass scale of 1-2 TeV

If SUSY is discovered, it should be possible to measure the masses of some of the sparticle and to constrain the SUSY breaking model

Continue to investigate models which have good theoretical motivations, but present difficult signatures

Main emphasis is in developing strategy for mastering backgrounds to SUSY discovery, both physical and instrumental, for rapid and robust discovery

Can profit from techniques developed at Tevatron to this purpose