SUSY signatures at the LHC

Giacomo Polesello

INFN, Sezione di Pavia

Introduction

In the last 20 years, SUSY most popular template for exploration of new physics at the LHC

Large number of signatures proposed, addressing large spectrum of possibilities

Classical signatures are based on minimal SUSY model (MSSM), with two undetected particles in the final state Rather generic model, posing interesting experimental problems for the discovery

Very useful benchmark for development of techniques for understanding the nature of underlying model. Still very active field of phenomenological investigation

Focus on discovery and measurement strategies for MSSM with R-parity conservation

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

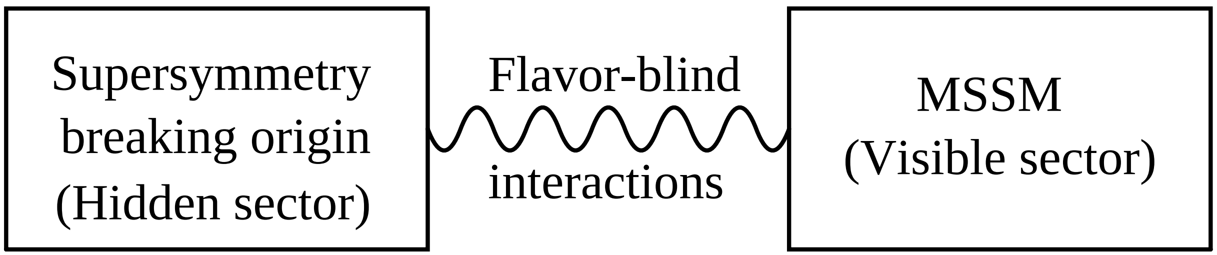
Left and right partners of fermions can be mixed ($\tilde{t}_1, \tilde{t}_2$), charginos and neutralinos result from the mixing of gauginos and higgsinos

Several mass measurements necessary to reconstruct soft breaking parameters

Models of SUSY breaking

Use pattern of soft breaking parameters to understand nature of SUSY breaking

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



Phenomenological predictions determined by messenger field. Examples of popular proposals, yielding sparticle masses and couplings as a function of few parameters

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

$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sgn}\,\mu$ (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.

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

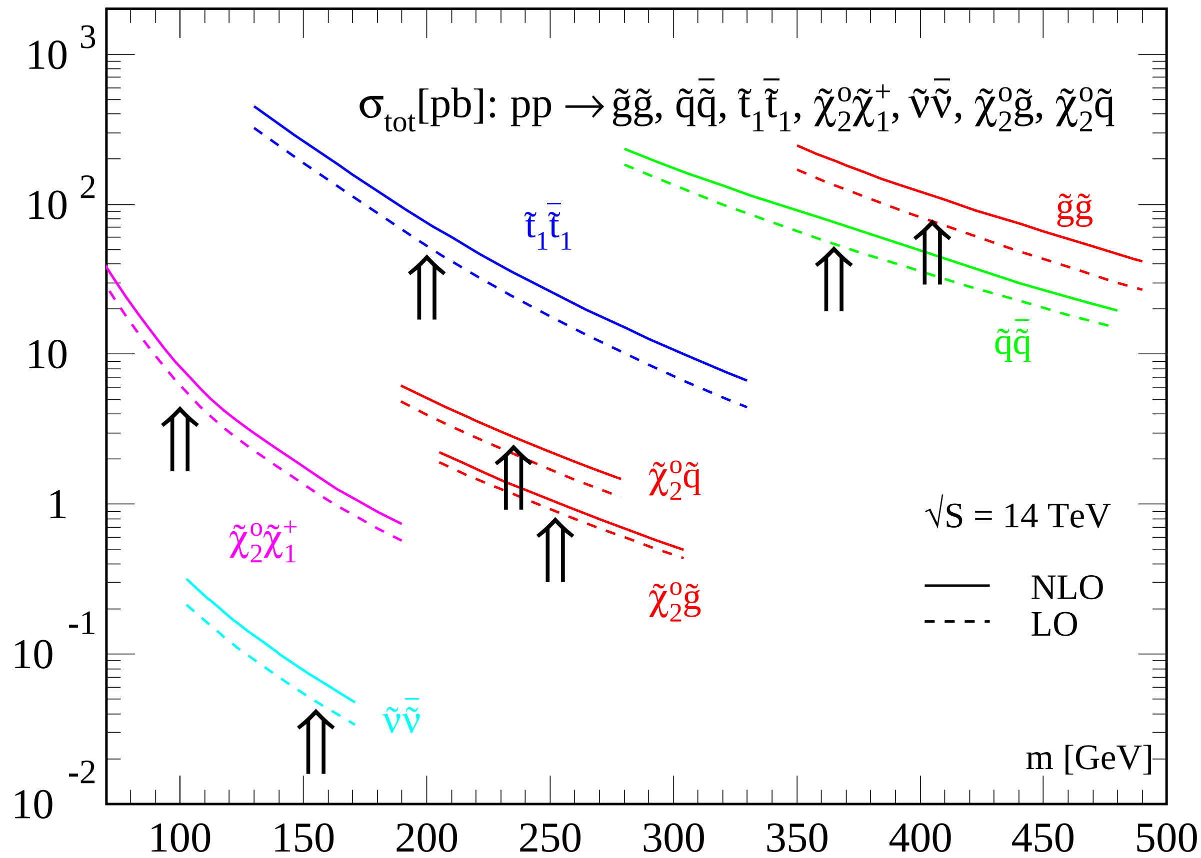
Structure enshrined in Monte Carlo generators (e.g ISAJET)

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 $\Rightarrow$ production dominated by colored sparticles: squarks and gluinos if light enough

Squark and gluino production cross-section $\sim$ only function of squark and gluino mass



Production cross-section $\sim$ independent from details of model:

- $\sigma_{SUSY} \sim 50$ pb for $m_{\tilde{q},\tilde{g}} \sim 500$ GeV
- $\sigma_{SUSY} \sim 1$ pb for $m_{\tilde{q},\tilde{g}} \sim 1000$ GeV

Features of SUSY events at the LHC

Broad band parton beam: all processes on at the same time: different from e^+e^- colliders where one can scan in energy progressively producing heavier particles

Bulk of SUSY production is given by squarks and gluinos, which are typically the heaviest sparticles

$\Rightarrow$ If R_p conserved, complex cascades to undetected LSP, with large multiplicities of jets and lepton 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!

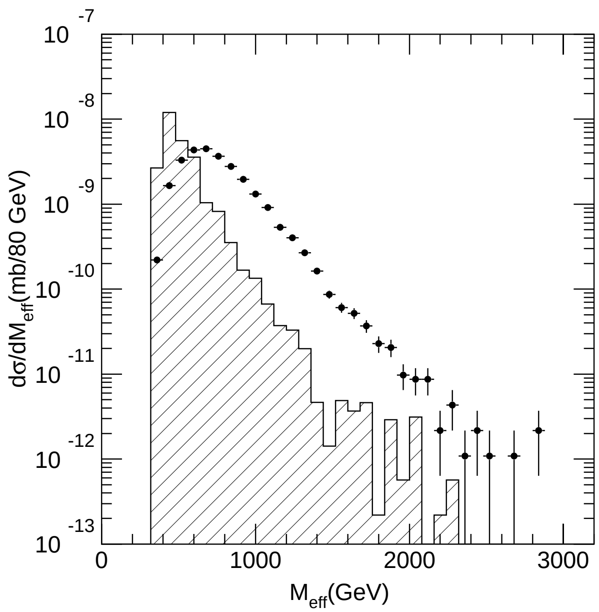
First step on inclusive SUSY: triggering

ATLAS inclusive approach: $\not{E}_T + 1$ jet and multi-jet triggers

Keep lowest threshold compatible with affordable rate.

- high signal efficiency
- possibility of more detailed background studies

Ex. $\not{E}_T > 70$ 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:

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

With higher cuts the signal turn on would not be observable

In addition: flexible array of trigger selections helps to cover with high efficiency wealth of SUSY signatures

SUSY discovery:basic strategy

SUSY covers very broad range of phenomenologies. Go for simple signatures which address general class of models

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

Most important features of SUSY events used for discovery:

- $\not{E}_T$: from LSP escaping detection
- High E_T jets: variables: N_{jets}, $P_T(jet_1)$, $P_T(jet_2)$ $\Sigma_i |p_{T(i)}|$ $\Delta\phi(jet - \not{E}_T)$

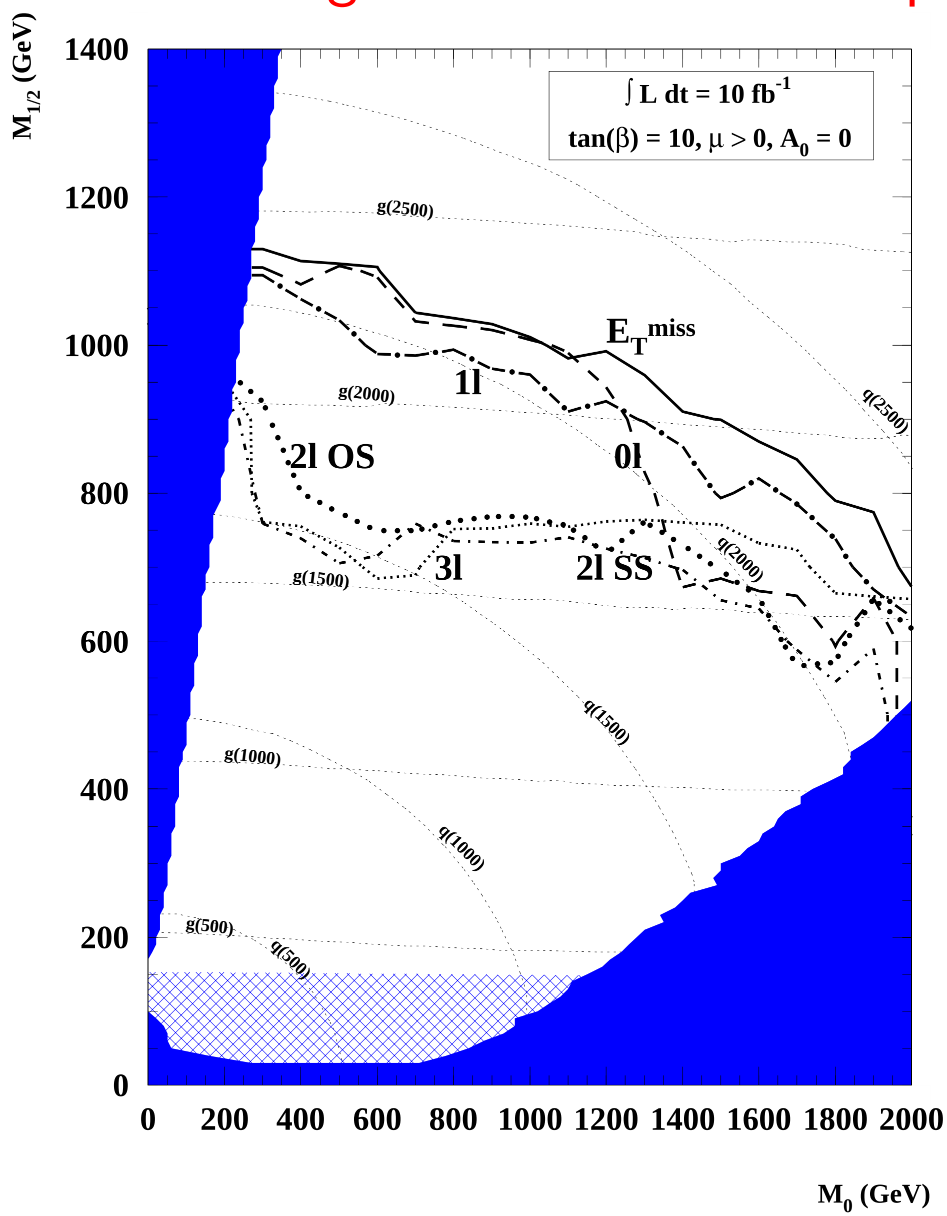
  guaranteed if squarks/gluinos not too degenerate with gauginos, e.g. if unification of gaugino masses assumed. Variables:
- Spherical events: variable S_T

  From Tevatron limits squarks/gluinos must be heavy ($\gtrsim$ 400 GeV).
- Multiple leptons: from decays of Charginos/neutralinos typically present in cascade

Define criteria on sets of basic inclusive signatures for RPC SUSY with $\tilde{\chi}_1^0$ LSP

Alternative options have often final states with additional leptons, photons, CHAMPS, easier to select.

Inclusive signatures in mSUGRA parameter space

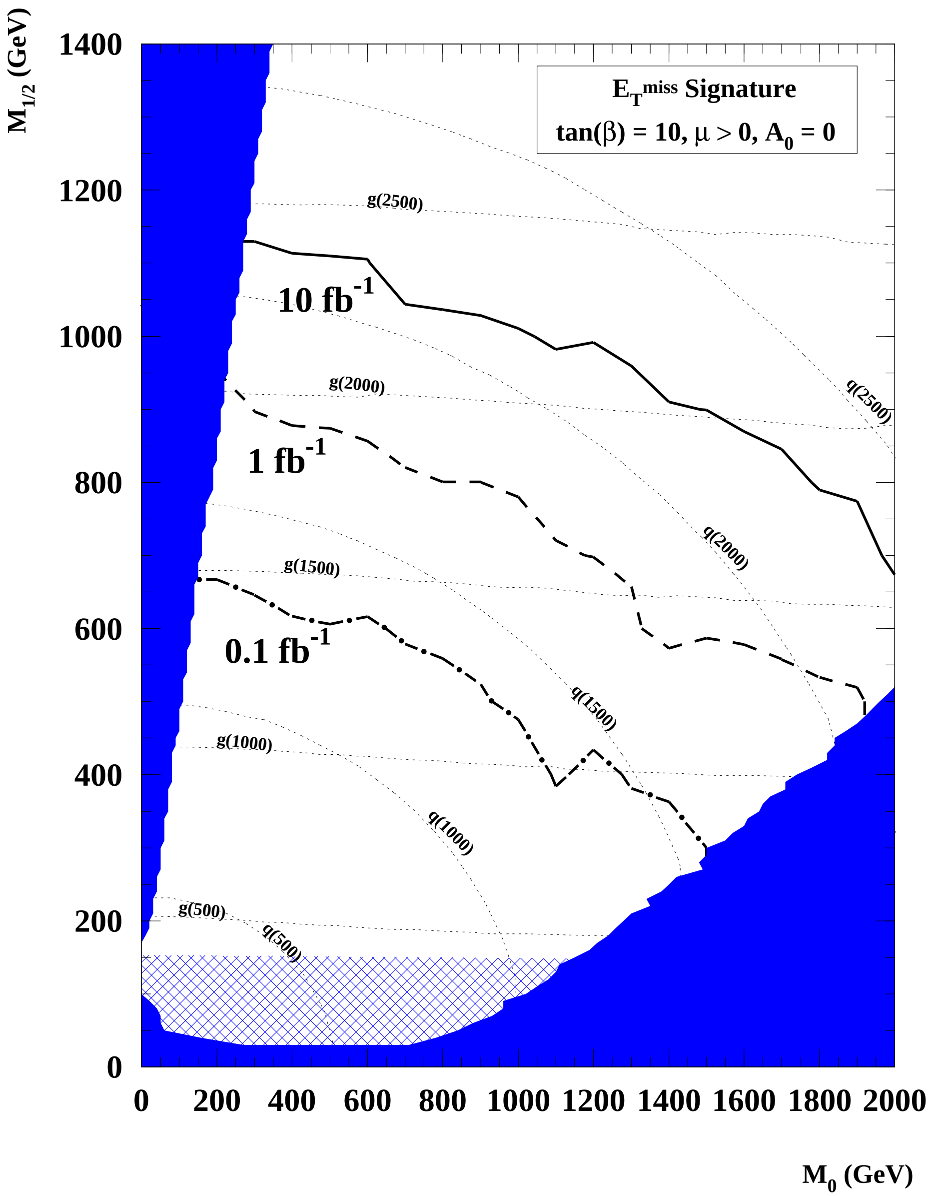


Multiple signatures on most of parameter space

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

When first signal observed with a signature, look for it also in other channels

Discovery reach as a function of luminosity



- $\sim$1300 GeV in 100 pb^{-1}
- $\sim$1800 GeV in 1 fb^{-1}
- $\sim$2200 GeV in 10 fb^{-1}

Fast discovery from signal statistics

Time for discovery determined by:

- Time to understand detector performance ($\not\!\!E_T$ tails, lepton id, jet scale)
- Time to collect sufficient statistics of SM control samples: W, Z+jets, $\bar{t}t$

Two main background classes:

- Instrumental $\not\!\!E_T$
- Real $\not\!\!E_T$ from neutrinos

Backgrounds to $\not\!\!E_T +$ jets analysis

Instrumental $\not\!\!E_T$ from mismeasured multi-jet events:

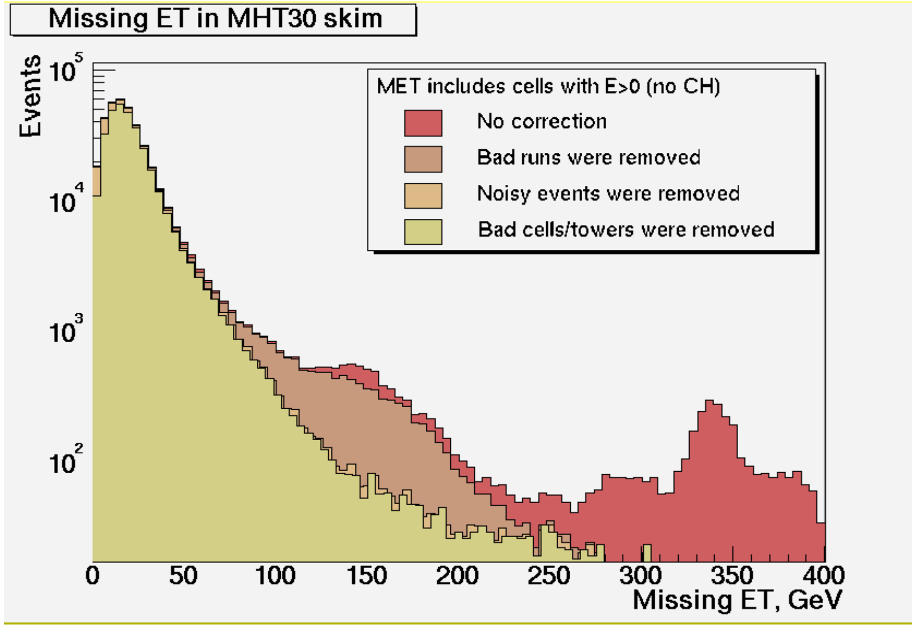
Many sources: gaps in acceptance, dead/hot cells, non-gaussian tails, etc.

Require detailed understanding of tails of detector performance.

Reject events where fake $\not\!\!E_T$ likely.

- beam-gas and machine backgrounds
- displaced vertexes
- hot cells
- $\not\!\!E_T$ pointing along jets
- jets in regions of poor response

See effect of $\not\!\!E_T$ cleaning in D0



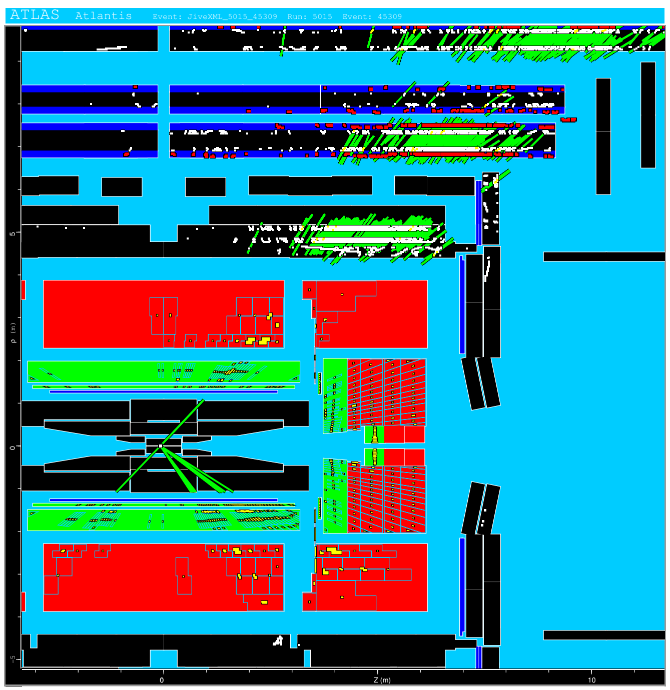
All detector and machine garbage will end up in $\not\!\!E_T$ trigger Long and painstaking work before all the sources of instrumental $\not\!\!E_T$ are correctly identified

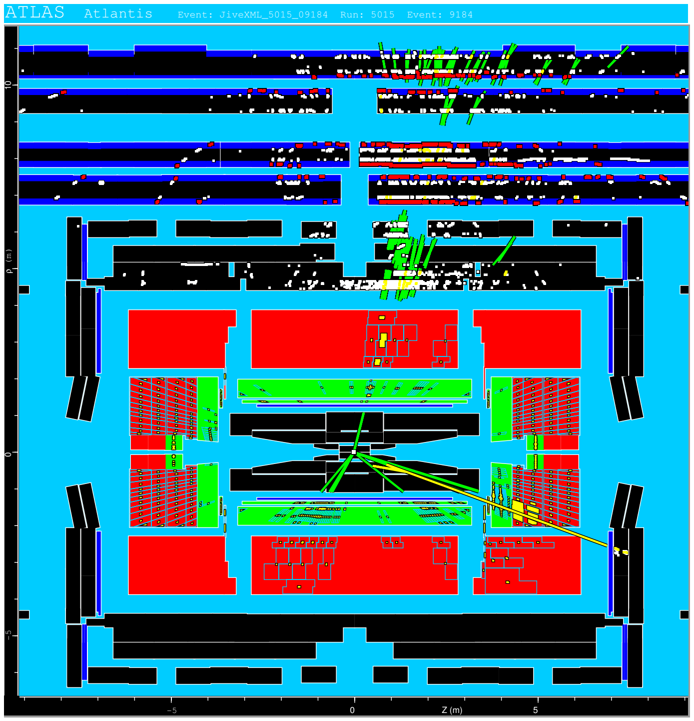
Example from ATLAS: scan of $\not{E}_T$ tails

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



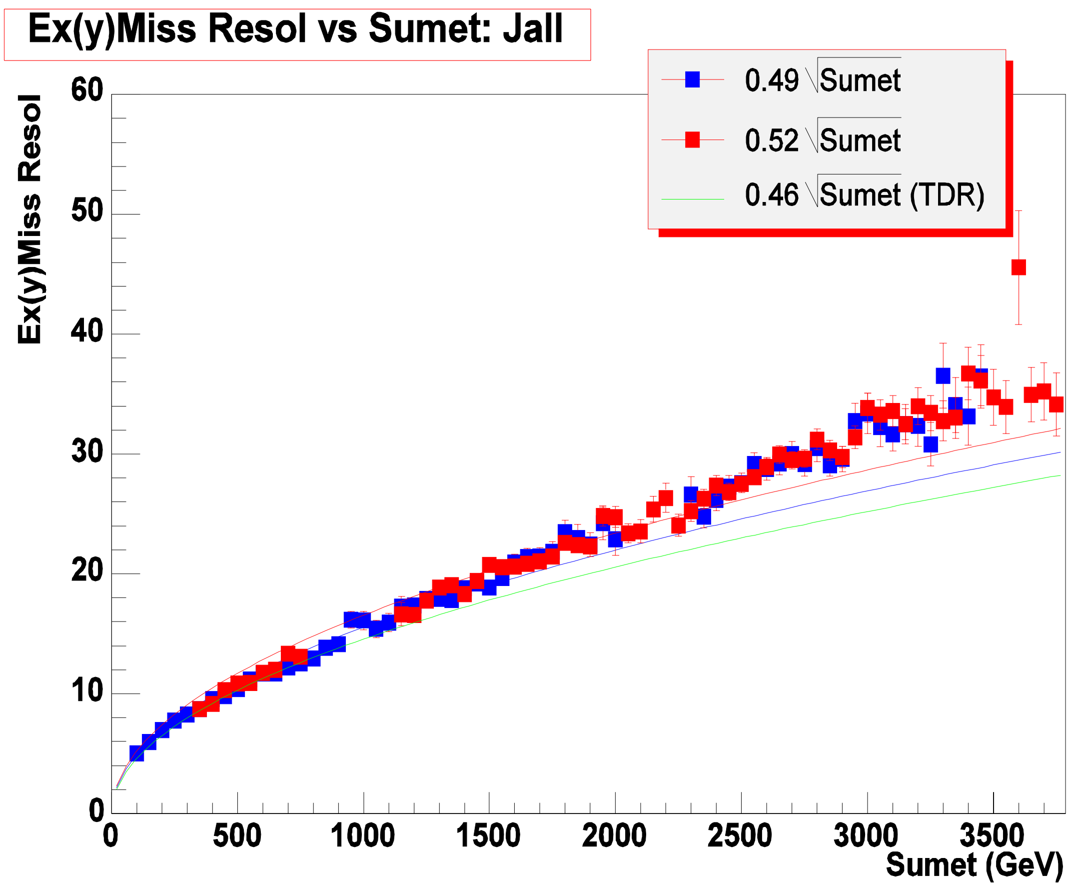


Problematic events characterised by large occupancy in muon chambers

$\not{E}_T$ significance

Once tails understood, consider $\not{E}_T$ 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 (D. Cavalli)

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

Use $\not{E}_T$ significance of observed signal as selection criterion

Very urgent task at startup is measuring $\not{E}_T$ resolution from data

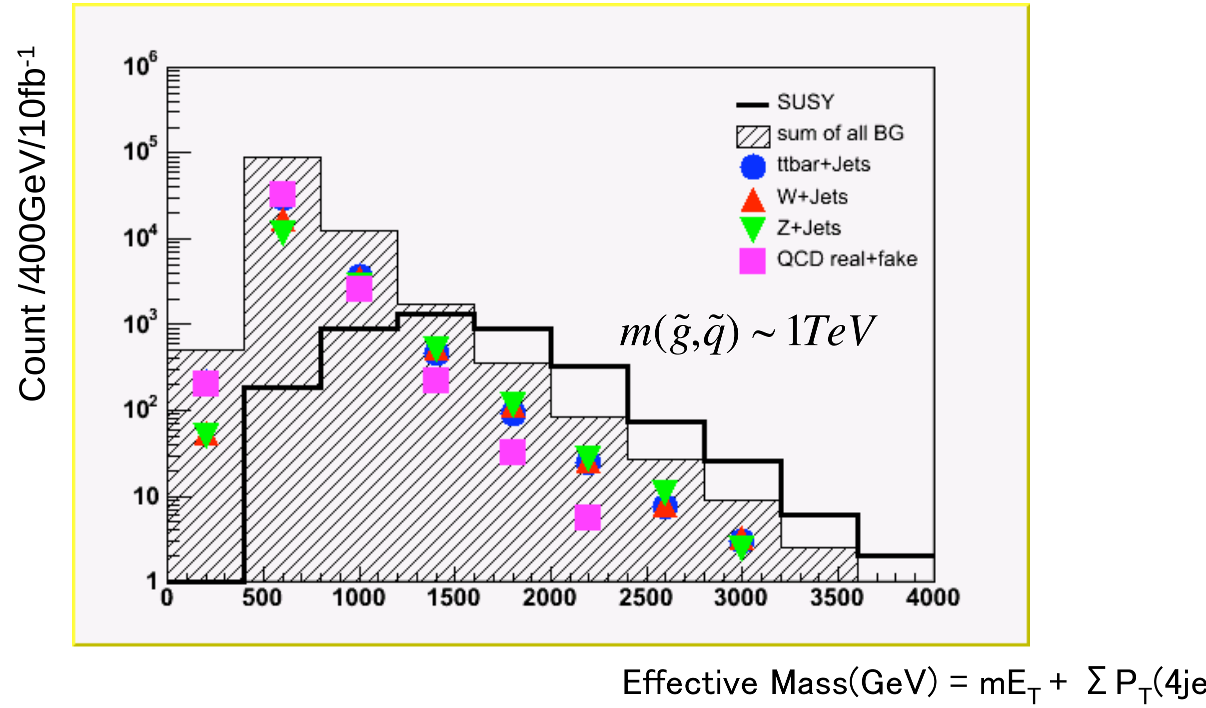
Control of $\not\!\!E_T$ from Standard Model processes

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

(S. Asai et al.)

SUSY selection:

- $\not\!\!E_T > 100$ GeV
- At least 1 jet with $p_T > 100$ GeV
- At least 4 jets with $p_T > 50$ GeV



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

Comparable contributions from: • $\bar{t}t$+jets • W+jets • Z+jets

Counting experiment: need precise estimate of background processes in signal region

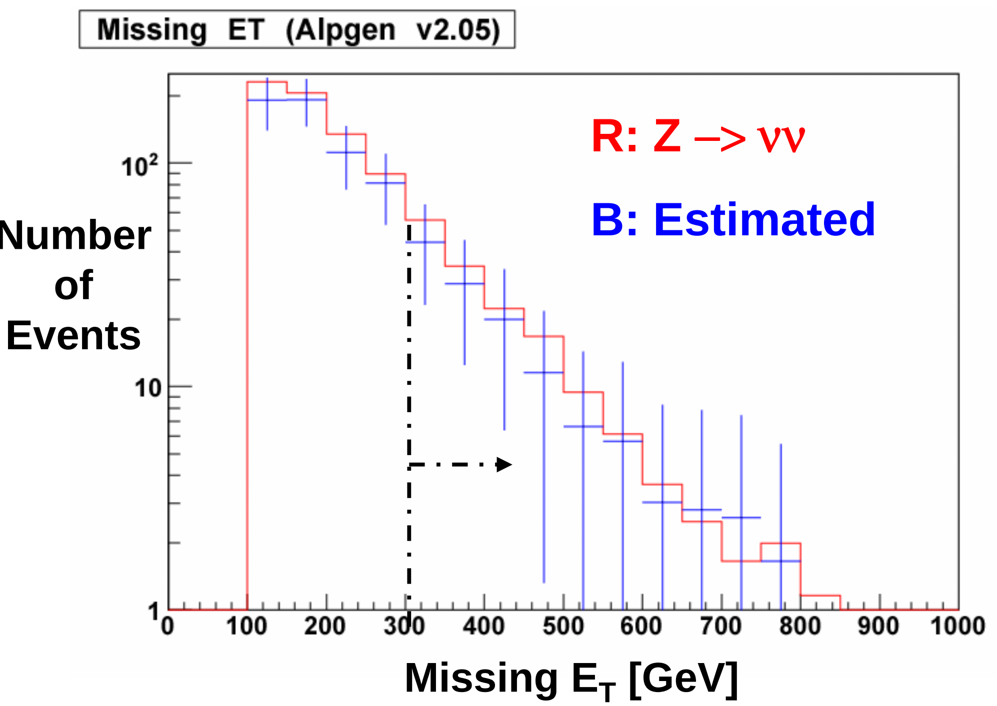
Complex multi-body final states: can not rely on MonteCarlo alone. Need both data and MonteCarlo

The simplest case: $Z \to \nu\nu +$ jets

Preliminary ATLAS fast simulation study of Y. Okawa et al.

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

Same cuts as for SUSY analysis (4 jets+Etmiss), throw away μ's and calculate $\not{p}_T$ of events from μ momenta (normalized to 1 fb^{-1})



Main problem is correct normalisation and shape distortion from $Z \to \mu\mu$ selection

Need to correct for:

- Efficiency for μ (experimental)
- Acceptance of $\mu^+\mu^-$ pairs (MonteCarlo)

Again, combination of data and MonteCarlo needed for firm estimate

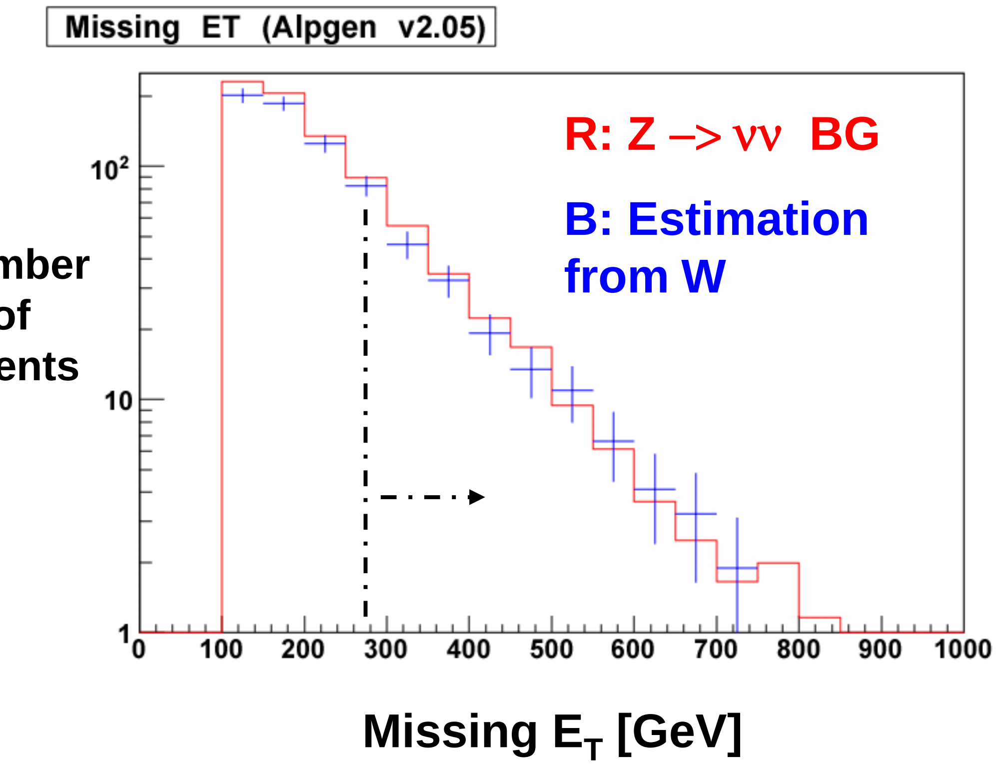
Good prediction of background shape, but statistically limited: $\sim 30\%$ for 1 fb^{-1}

Improve statistics: use $W \to \mu\nu$?

Try to simulate $Z \to \nu\nu$+jets using $W \to \mu\nu$+jets

Select events with SUSY cuts, estimate $\not{E}_T$ from P_T of $\mu\nu$ system

10 times more statistics than using $Z \to \mu\mu$



Error on signal and background equivalent

Good reproduction of shape

Promising approach, need to understand effect of difference between W and Z production mechanism on estimate

Additional inclusive signatures

$\not{E}_T$+jets signature is most powerful and least model-dependent

SM and instrumental backgrounds might require long time before convincing signal can be claimed

With most recent evaluation of SM backgrounds, shoulder in M_{eff} distribution disappears

Need to optimize search strategy by tackling in parallel all of the inclusive discovery channels

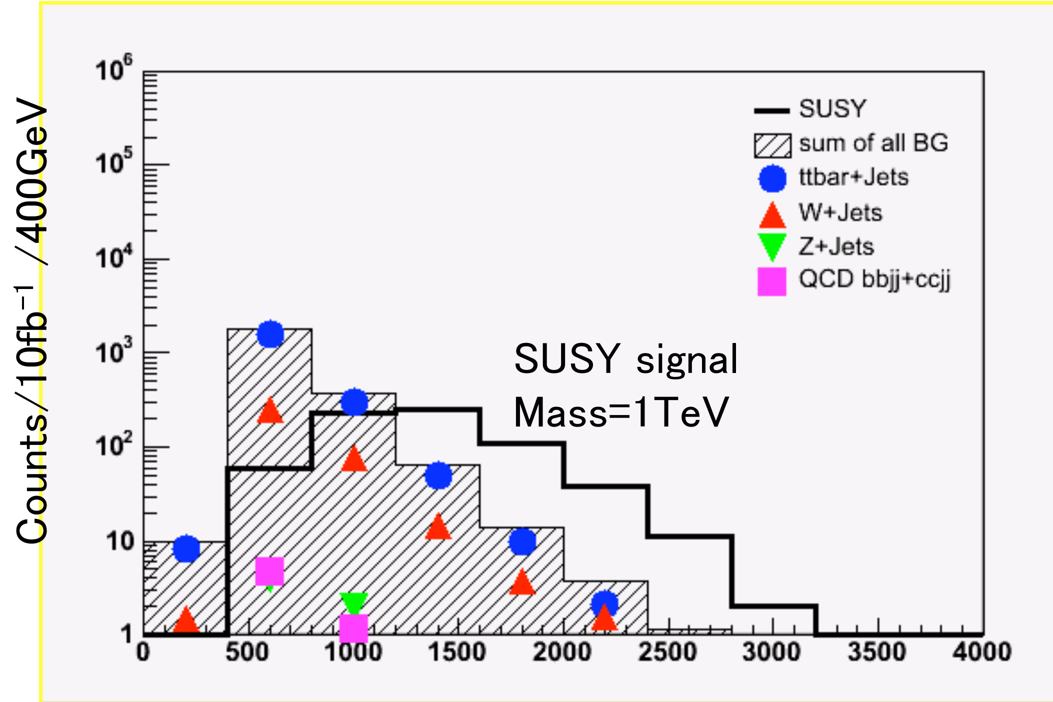
Example: single lepton + jets + $\not{E}_T$

Smaller number of backgrounds:

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

Shoulder might be observable

Main experimental difficulty: correct estimate of contribution from fake leptons

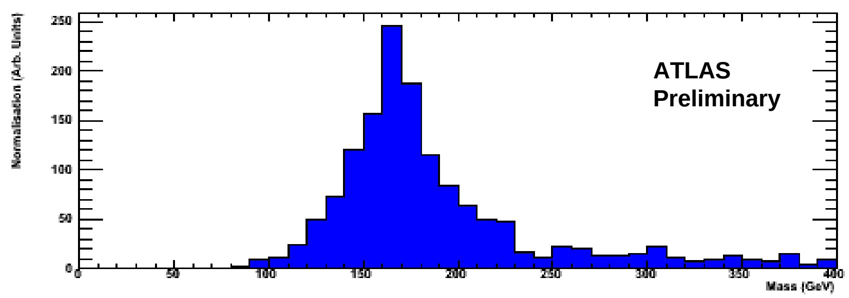


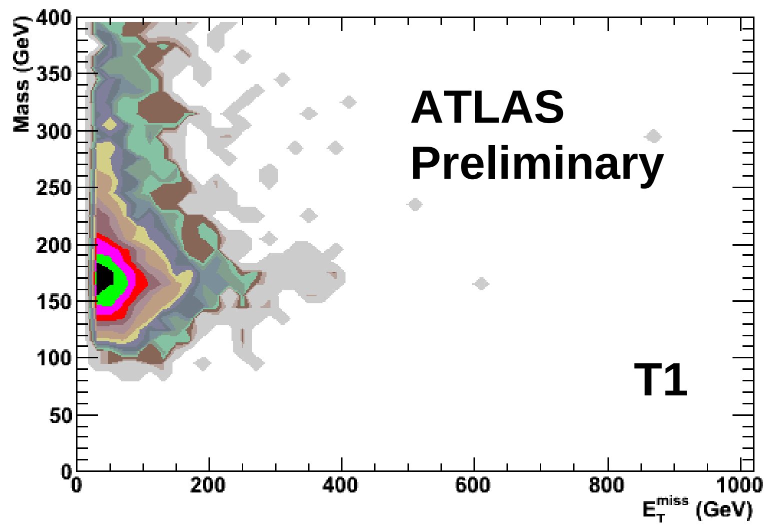
1-lepton inclusive analysis. Control of top background

Preliminary ATLAS exercise (Dan Tovey) to evaluate top background using top data

Standard semileptonic top analysis based on request of 1 isolated lepton, $\not\!\!E_T$, 4 or more jets

Very similar to cuts for SUSY analysis with looser $\not\!\!E_T$ requirement. If harden $\not\!\!E_T$ cuts, sample contaminated with SUSY





Technique:

- Select semi-leptonic top candidates
- Pure top sample by fully reconstructing top events ($\not\!\!E_T$ and W mass constraint)
- Apply SUSY cuts to pure top sample, and normalize to data at low $\not\!\!E_T$
- Predict top background at high $\not\!\!E_T$

It can only work if $m(top)$ uncorrelated with $\not\!\!E_T$

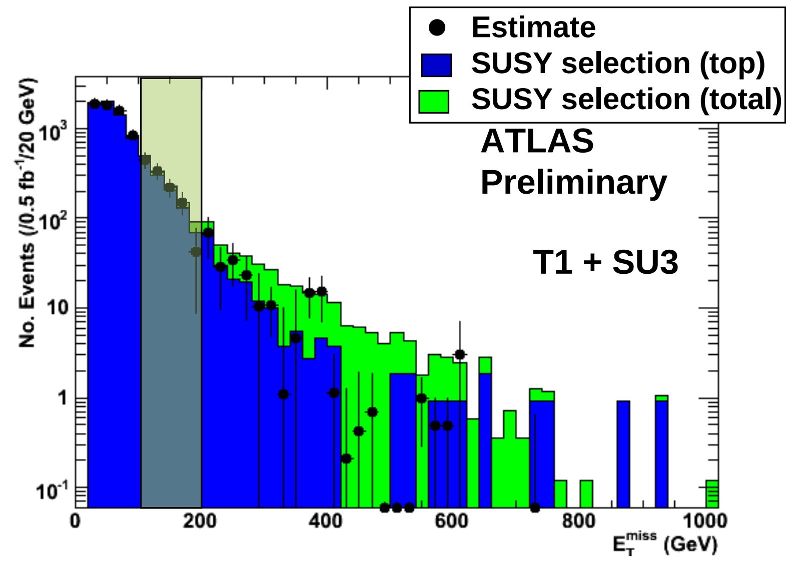
Top background results

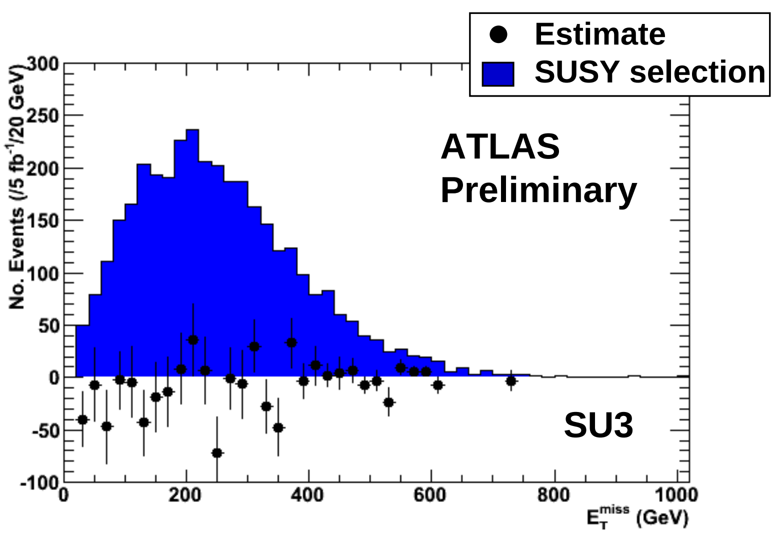
Consider mix of top sample and SUSY sample with ~ 600 GeV mass scale

Apply SUSY cuts:

- $\not{E}_T > 20$ GeV (to be hardened later)
- At least 4 GeV with $p_T > 40$ GeV
- Exactly 1 lepton with $p_T > 20$ GeV

Normalize pure top sample to full sample for $100 < \not{E}_T < 200$ GeV





Accurate prediction of top background

SUSY signal unaffected by subtraction procedure

Preliminary exercise, work in progress to evaluate all systematic implications

2-leptons + $\not\!\!E_T$ + jets inclusive search

Significantly lower reach than other channels, but also lower backgrounds

Various different topologies, corresponding to different configuration of SM backgrounds

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

Interesting possibility: flavour-correlated signal. Example:

$$\begin{array}{llll} \tilde{q}_L \to & \tilde{\chi}_2^0 \quad q & & \\ & \hookrightarrow \tilde{\ell}_R^{\pm} \quad \ell^{\mp} & & \\ & & \hookrightarrow \tilde{\chi}_1^0 \quad \ell^{\pm} & \end{array}$$

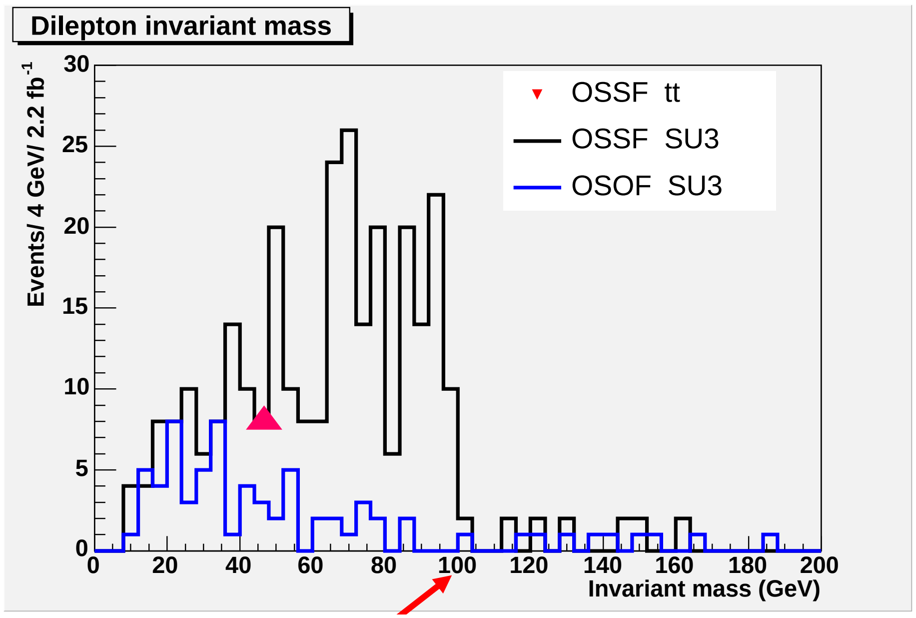
Only $Z/\gamma \to e^+e^-, \mu^+\mu^-$ has correlated flavours

All backgrounds except Z can be exactly subtracted (modulo lepton efficiencies)

2-lepton invariant mass

Events with two leptons selected: build the invariant mass of the two leptons

Plot $m(\ell\ell)$ for OSSF and OSOF samples (U.de Sanctis et al.) for ATLAS sample point SU3, light sleptons, SUSY scale ∼600 GeV



ATLAS preliminary

Statistics in plot is 2.2 fb^{-1}

Top background negligible

Observe clear structure, strong evidence for new physics

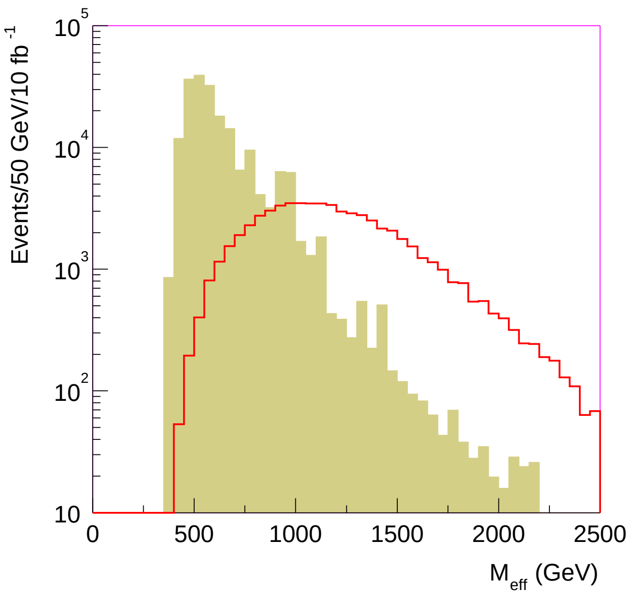
If we are lucky first and clearest evidence from this channel

This kind of structure will be main handle to SUSY parameter measurement

SUSY mass scale from inclusive analysis

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

Simple variable sensitive to sparticle mass scale: $M_{\text{eff}} = \Sigma_i |p_{T(i)}| + E_T^{\text{miss}}$ where $p_{T(i)}$ is the transverse momentum of jet



M_{eff} distribution: signal (red), background (brown)

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

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

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

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

What might we know after inclusive analyses?

Assume we have a MSSM-like SUSY model with $m_{\tilde{q}} \sim m_{tg} \sim 600$ GeV

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

- Undetectable particles in the final state $\not{E}_T$
- Production of particles with mass∼600 GeV (M_{eff} study) and with couplings of ∼QCD strength (X-section)
- Some of the produced particles are coloured (jets in the final state)
- Some of the new particles are Majorana (excess of same-sign lepton pairs)
- Lepton flavour ∼ conserved in first two generations (same number of leptons and muons)
- Decays of neutral particle into two particles with lepton quantum numbers (excess of Opposite-Sign/Same-Flavour (OS-SF) leptons)
- ....

Some sparse pieces of a giant jigsaw puzzle. Proceed to try exclusive analyses to fill in some of the gaps

Establishing SUSY experimentally

Assume an excess seen in inclusive analyses: how does one verify wheteher it is actually SUSY? 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, • BR's of cascade decays, • production cross-sections, • angular decay distributions

Precise measurements of such observable not completely straightforward at the LHC: develop a strategy based on detailed MC study of reasonable candidate models

Measurement of model parameters: LHC strategy

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:

- Choose 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

In last ten years developed techniques for mass and spin measurements in complex SUSY decay kinematics

Focus today on most promising techniques for mass and spin measurements

Show in detail application to an "easy" model point

Measurement of SUSY masses

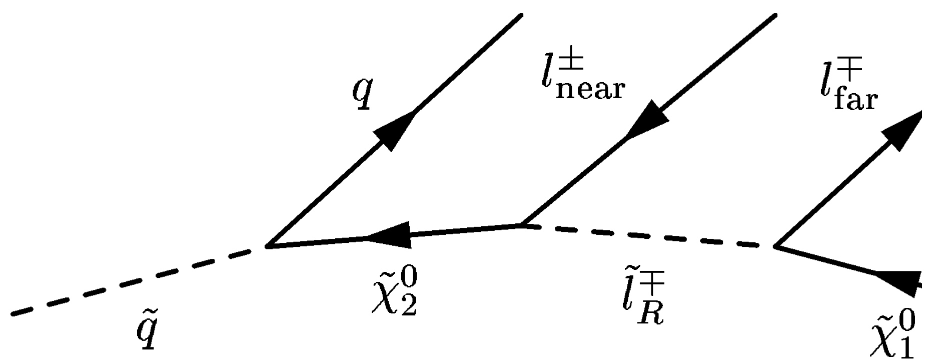
Identify exclusive decay chains including leptons or b-jets (QCD bckg.)

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

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

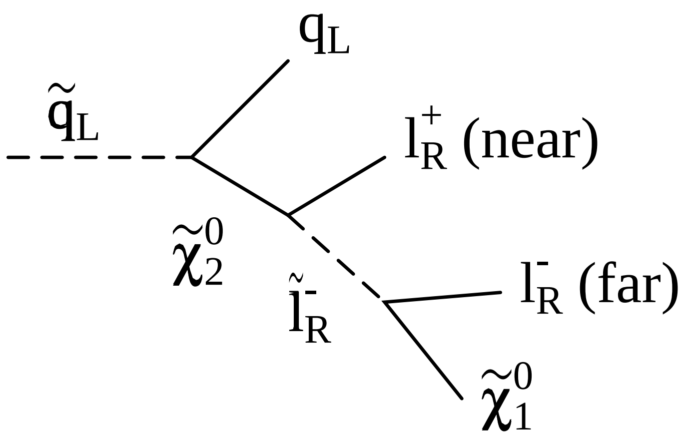
Key result (Paige, Hinchliffe): If a chain of at least three two-body decays can be isolated, can measure masses and momenta of involved particles in model-independent way.

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



Edges and thresholds in invariant mass distributions among visible products functions of sparticle masses

Complete results for $\tilde{q}_L \to \tilde{\ell}\ell$ decay chain: (Allanach et al. hep-ph/0007009)



l^+l^- edge $\quad (m_{ll}^{\text{max}})^2 = (\tilde{\xi} - \tilde{l})(\tilde{l} - \tilde{\chi})/\tilde{l}$

l^+l^-q edge $\quad (m_{llq}^{\text{max}})^2 = (\tilde{q} - \tilde{\xi})(\tilde{\xi} - \tilde{\chi})/\tilde{\xi}$

$$l^+l^-q \text{ thresh} \quad (m_{llq}^{\text{min}})^2 = \begin{cases} [\;\; 2\tilde{l}(\tilde{q} - \tilde{\xi})(\tilde{\xi} - \tilde{\chi}) \\ +(\tilde{q} + \tilde{\xi})(\tilde{\xi} - \tilde{l})(\tilde{l} - \tilde{\chi}) \\ \quad -(\tilde{q} - \tilde{\xi})\sqrt{(\tilde{\xi} + \tilde{l})^2(\tilde{l} + \tilde{\chi})^2 - 16\tilde{\xi}\tilde{l}^2\tilde{\chi}} \;\;] \\ /(4\tilde{l}\tilde{\xi}) \end{cases}$$

$l^\pm_{\text{near}}q$ edge $\quad (m_{l_{\text{near}}q}^{\text{max}})^2 = (\tilde{q} - \tilde{\xi})(\tilde{\xi} - \tilde{l})/\tilde{\xi}$

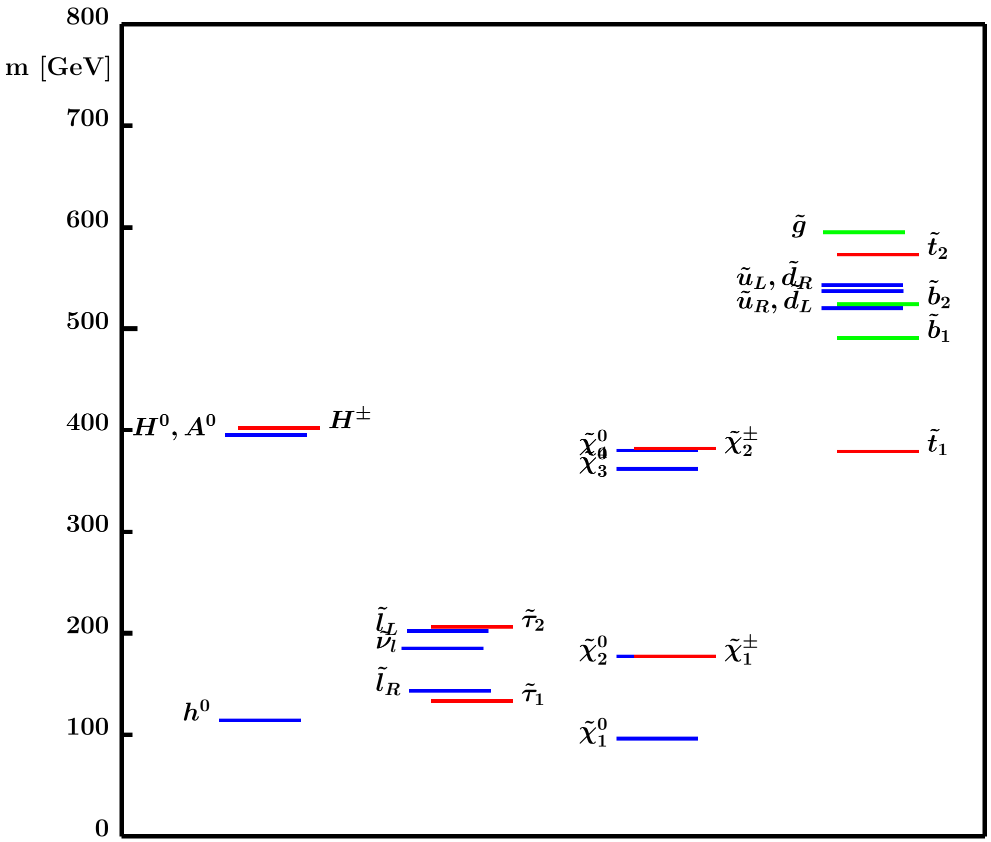
$l^\pm_{\text{far}}q$ edge $\quad (m_{l_{\text{far}}q}^{\text{max}})^2 = (\tilde{q} - \tilde{\xi})(\tilde{l} - \tilde{\chi})/\tilde{l}$

With $\quad \tilde{\chi} = m^2_{\tilde{\chi}^0_1}, \qquad \tilde{l} = m^2_{\tilde{l}_R}, \qquad \tilde{\xi} = m^2_{\tilde{\chi}^0_2}, \qquad \tilde{q} = m^2_{\tilde{q}}$

Example: Point SPS1a

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

Friendly to a 1 TeV linear Collider, with appropriate Dark Matter density



Total cross-section: ~50 pb

Relevant Branching ratios

BR($\tilde{g} \to \tilde{q}_L q$) ~25%   BR($\tilde{g} \to \tilde{q}_R q$) ~40%

BR($\tilde{g} \to \tilde{b}_1 b$) ~17%

BR($\tilde{q}_L \to \tilde{\chi}_2^0 q$) ~30%   BR($\tilde{q}_L \to \tilde{\chi}^\pm q'$) ~60%

BR($\tilde{\chi}_2^0 \to \tilde{\ell}_R \ell$)=12.6%   BR($\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau$)=87%

Analysis strategy for mass determination

- Start from long decay chain identifiable: $\tilde{q}_L \to \tilde{\ell}\ell$
- Measure $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\ell}_R}$, $m_{\tilde{\chi}_2^0}$, $m_{\tilde{q}_L}$ from the $\tilde{q}_L \to \tilde{\ell}\ell$ decay chain using edge meaasurements
- Go up the decay chain one step: address $\tilde{g} \to \tilde{b}b$
- Identify processes leading to easily identifiable shorter decay chains:

  $\tilde{\chi}_2^0 \to \tilde{\tau}_1\tau$

  $\tilde{\chi}_4^0 \to \tilde{\ell}\ell$

  $pp \to \tilde{\ell}\tilde{\ell}, \quad \tilde{\ell} \to \ell\tilde{\chi}_1^0$

  $\tilde{q}_R \to q\tilde{\chi}_1^0$

  Build invariant mass distributions for these chains and extract masses using previously measured $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_2^0}$

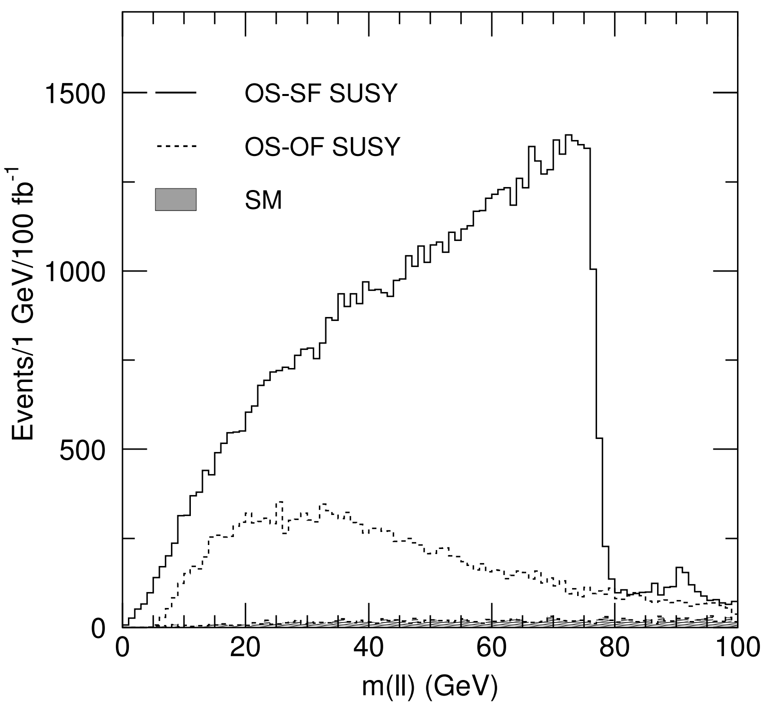
First step in analysis is basic building block, $\to$ describe in detail

Isolate SUSY signal by requiring:

- At least four jets: $p_{T,1} > 150$ GeV, $p_{T,2} > 100$ GeV, $p_{T,3} > 50$ GeV.
- $M_{\text{eff}} \equiv E_{T,\text{miss}} + p_{T,1} + p_{T,2} + p_{T,3} + p_{T,4} > 600$ GeV, $E_{T,\text{miss}} > \max(100 \text{ GeV}, 0.2 M_{\text{eff}})$
- Exactly two opposite-sign same-flavour e, μ (OSSF) with $p_T(l) > 20$ GeV and $p_T(l) > 10$ GeV

W and Z suppressed by jet requirements, and $\bar{t}t$ by hard kinematics

Build lepton-lepton invariant mass for selected events



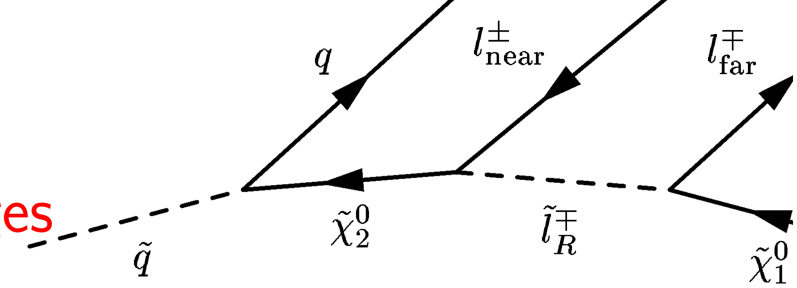
SM background almost negligible

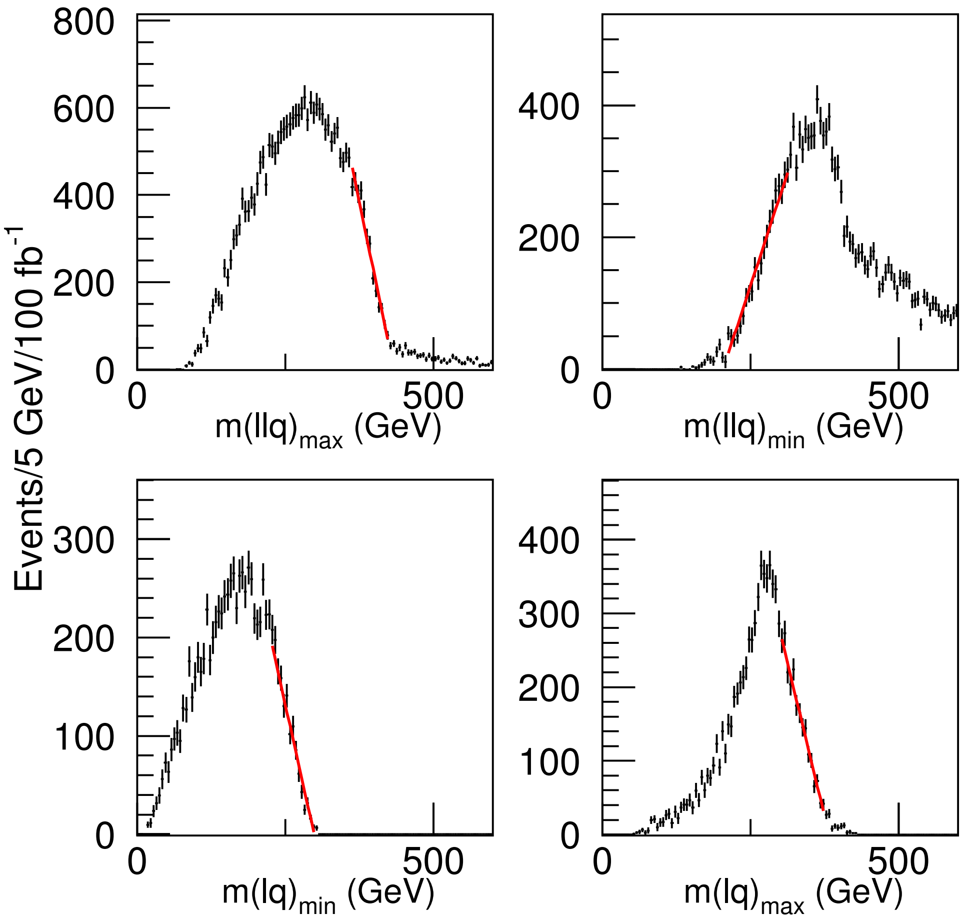
SUSY background mostly uncorrelated $\tilde{\chi}_1^{\pm}$ decays Subtract SUSY and SM background using flavour correlation:

$e^+e^- + \mu^+\mu^- - e^{\pm}\mu^{\mp}$

For 100 pb^{-1} error dominated by 0.1% uncertainty on lepton energy scale

Lepton-lepton-jet edges





Distributions fall ∼linearly to end point.

Shapes modified by resolutions and backgrounds, recently progress in using full shape

Statistical uncertainty from linear fit at the %

Enough constraints to solve for masses of four involved sparticles

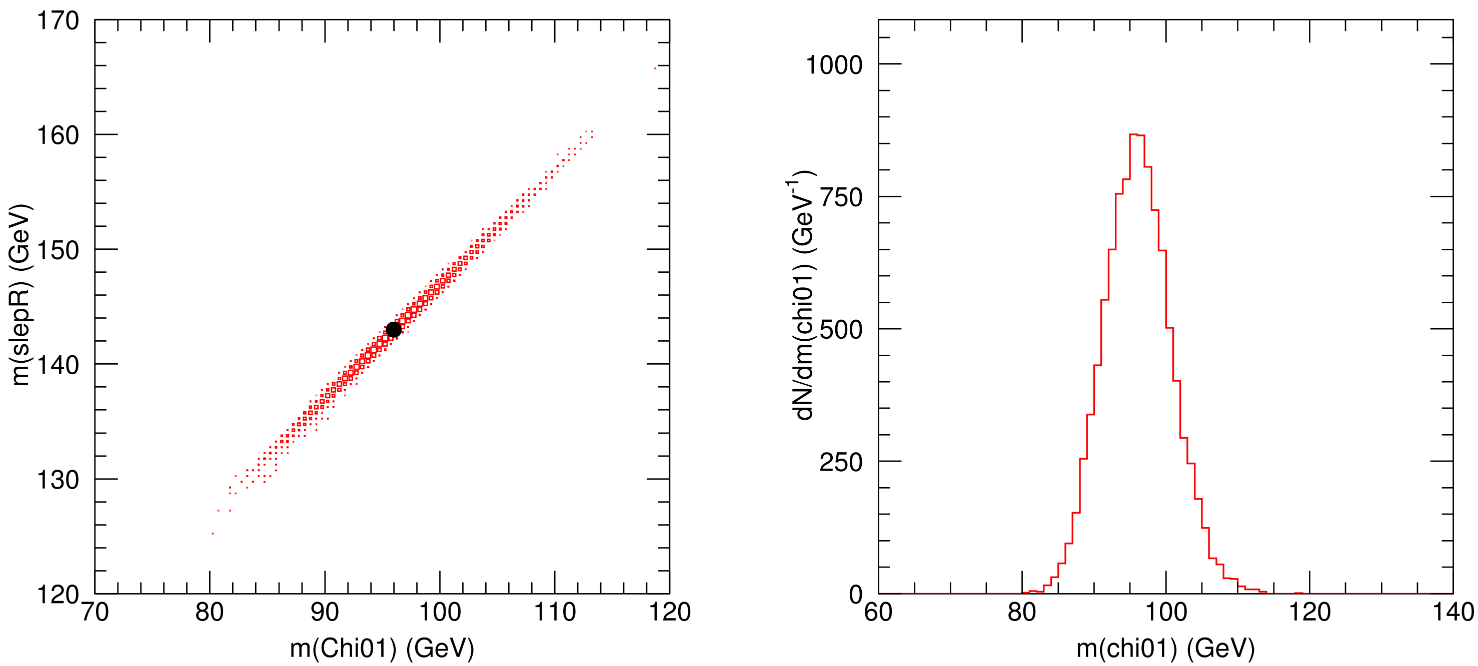
Strong correlation among calculated sparticle masses, as edges measure mass differences

Five end-points measured: can solve for sparticle masses

Sparticle mass calculation

Generate sets of edge measurements normal distributed according to statistical errors estimated for 300 fb^{-1}. For each set solve constraints for sparticle masses.

Strong correlation among masses, as kinematic constraints measure mass differences



Probability distributions for reconstructed masses $\sim$ gaussian

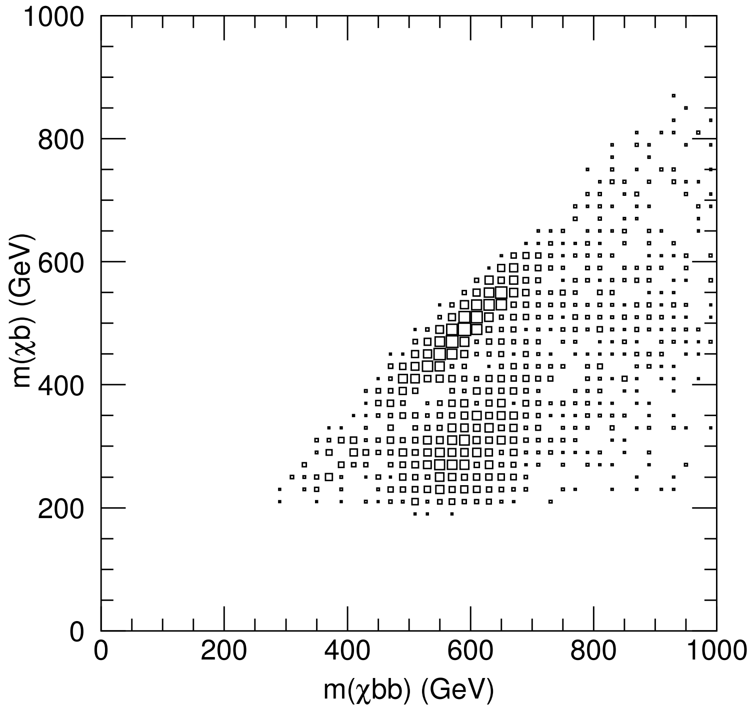
$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\ell}_R$ masses reconstructed with ~ 5 GeV , $\tilde{q}_L$ mass with ~ 9 GeV (300 fb^{-1})

Statistical and E-scale errors only, systematics should also be considered

Gluino-sbottom mass reconstruction

Go up the decay chain: study $\tilde{g} \to \tilde{b}_1 b \to \tilde{\chi}_2^0 bb \to \ell\ell bb$ (SPS1a)

For $m_{\ell+\ell-}$ near edge, $\tilde{\chi}_1^0 \sim$ at rest $\Rightarrow \vec{p}(\tilde{\chi}_2^0) \simeq (1 - \frac{m(\tilde{\chi}_1^0)}{m(\ell\ell)})\vec{p}_{\ell\ell}$ with $\vec{p}_{\ell\ell} = \vec{p}_{\ell 1} + \vec{p}_{\ell 2}$



Select events with:

Two OS-SF leptons, $65 < m_{\ell\ell} < 78$ GeV

Two jets tagged as b

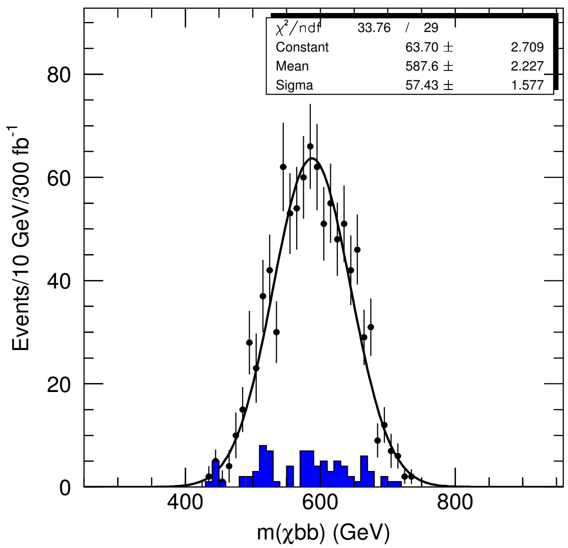
Reconstruct approximate $\tilde{\chi}_2^0$ momentum

Plot $m(\tilde{\chi}_2^0 b)$ versus $m(\tilde{\chi}_2^0 bb)$ (flavour subtracted)

(two entries per event) $\Rightarrow$ observe structure

Select peak region in scatter plot by choosing $b - \tilde{\chi}_2^0$ pairing (sbottom mass) such that $m(\tilde{\chi}_2^0 bb)$-$m(\tilde{\chi}_2^0 b) < 150$ GeV

Typically hardest jet selected because $m(\tilde{b}) - m(\tilde{\chi}_2^0) > m(\tilde{g}) - m(\tilde{b})$



Gluino mass measurement

Require $380 < m(\tilde{\chi}_2^0 b) < 600$ GeV

Plot $m(\tilde{\chi}_2^0 bb)$ distribution

Peak width determined by approximation on $p(\tilde{\chi}_2^0)$

Statistical error: $\pm 4(2.2)$ Gev for 100 (300) fb^{-1}

Dominated by 1% error on hadronic energy scale

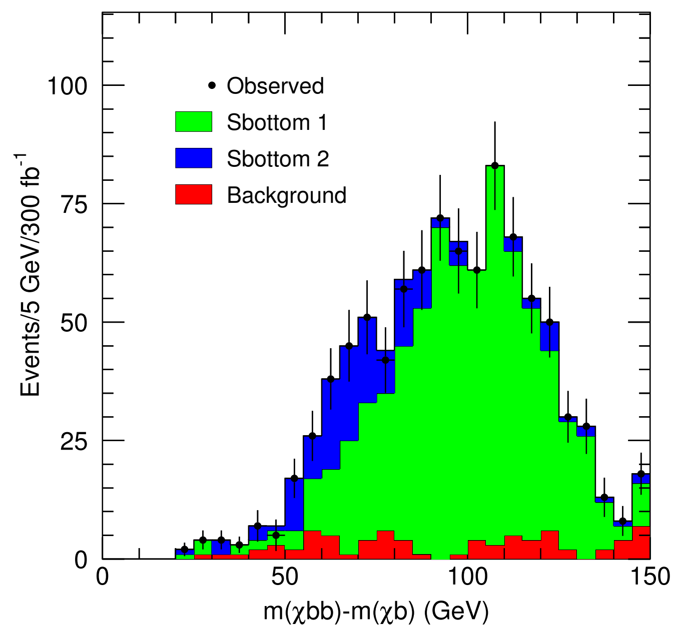
Sbottom mass measurement

Mixture of $\tilde{g} \to \tilde{b}_1 b$ and $\tilde{g} \to \tilde{b}_2 b$

$m(\tilde{\chi}_2^0 b)$ strongly correlated with $m(\tilde{\chi}_2^0 bb)$

$\Rightarrow$ plot $m(\tilde{\chi}_2^0 bb)$-$m(\tilde{\chi}_2^0 b)$

With 300 fb^{-1} and excellent control of b-jet response one might be able to distinguish two peaks

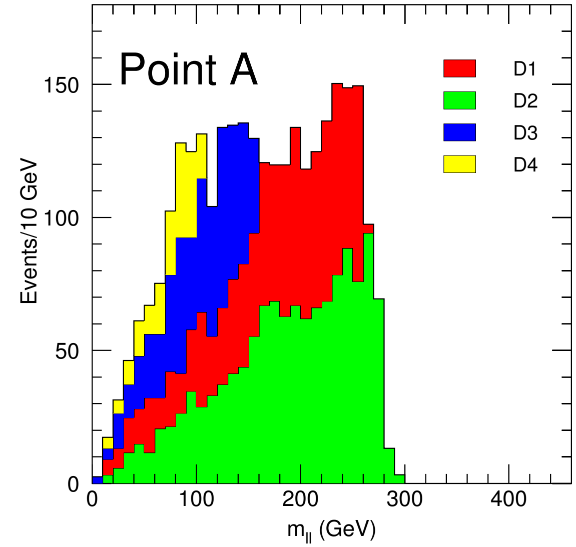


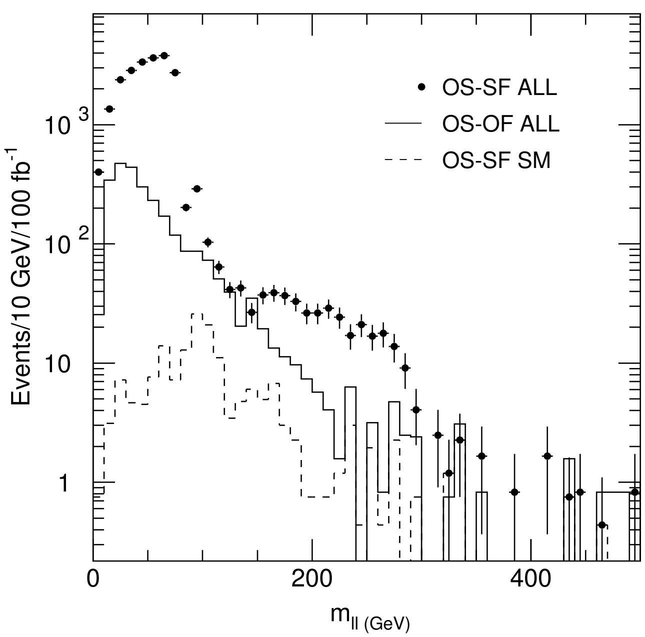
Measurement of $\tilde{\chi}_4^0$ mass

OS-SF dilepton invariant mass for:

$$\tilde{q}_L \rightarrow \tilde{\chi}_4^0 \; q$$
$$\hookrightarrow \tilde{\ell}_R^{\pm} \; \ell^{\mp}$$
$$\hookrightarrow \tilde{\chi}_1^0 \; \ell^{\pm} \qquad [D1]$$

$$\tilde{q}_L \rightarrow \tilde{\chi}_4^0 \; q$$
$$\hookrightarrow \tilde{\ell}_L^{\pm} \; \ell^{\mp}$$
$$\hookrightarrow \tilde{\chi}_1^0 \; \ell^{\pm} \qquad [D2]$$
$$\hookrightarrow \tilde{\chi}_2^0 \; \ell^{\pm} \qquad [D3]$$





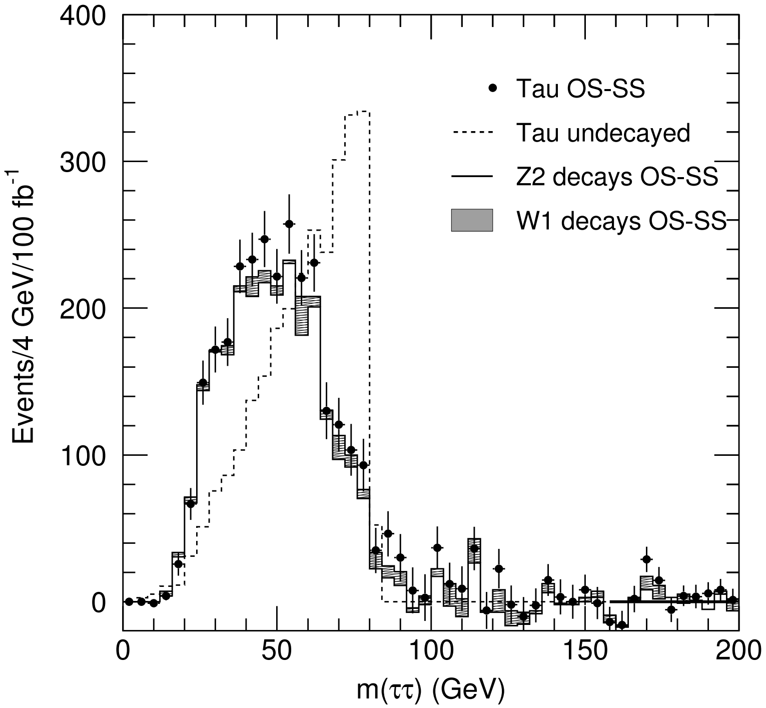
Measurement of edge position function of $m(\tilde{\chi}_4^0)$, $m(\tilde{\ell}_L)$, $m(\tilde{\chi}_1^0)$

If $m(\tilde{\ell}_L)$ measured in direct production, measure $m(\tilde{\chi}_4^0)$ with $\sim$4 GeV precision for 100 fb^{-1}

Measurement of $\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau$

Exploit excellent ATLAS tagging capability for τ jets

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



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

Two measurements sensitive to $\tilde{\tau}$ mixing possible:

- Position of $\tau\tau$ end point: sensitive to $\tilde{\tau}_1$ mass

Detailed study on achievable precision in progress.

Assume here variation between 0.5 and 5 GeV

- Number of events in edge can be used to measure: $BR(\tilde{\chi}_2^0 \to \tilde{\ell}_R \ell)/BR(\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau)$

No detailed experimental study available: assume 10% systematic uncertainty

For model SPS1a can access the following kinematic measurements (300 fb^{-1}):

		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
$m(\ell_L) - m(\tilde{\chi}_1^0)$	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

Based on these measurements, plus cross-sections, plus Br's, plus the higgs sector can try to reconstruct SYSY breaking parameters

Interpretation of results

The measurements do not depend a priori on a special choice of the model

For instance, we can state that in the data appear the decays:

$$
\begin{array}{l}
a \to b \quad q \\
\qquad \hookrightarrow c \;\; \ell^{\mp} \\
\qquad\qquad \hookrightarrow d \;\; \ell^{\pm}
\end{array}
$$

$$
\begin{array}{l}
a \to b \quad q \\
\qquad \hookrightarrow e \;\; \tau \mp \\
\qquad\qquad \hookrightarrow d \;\; \tau^{\pm}
\end{array}
$$

Where we know the masses of a, b, c, d, e, and we might conjecture that a, b, d appearing in both decays are the same having the same masses

So we have a mass hierarchy, some of the decays related these particles and, perhaps, the relative rates

Having decay chains help restricting the possibilities, if one imposes some conservations, e.g. charges or quantum numbers

Model dependence enters when we try to give a name to the particles, and match them to a template decay chain

Among the models proposed to solve the hierarchy problem, various options providing a full spectrum of new particles, with cascade decays:

- Universal extra-dimensions: first KK excitation of each of the SM fields
- Little Higgs with T parity

Special feature of SUSY: if one identifies the heavy partners through their quantum numbers, the spins of all of them are wrong by $1/2$

Worth investigating if exploiting the identified chains one can obtain information on the sparticle spins

Sparticle spins in squark decay chain

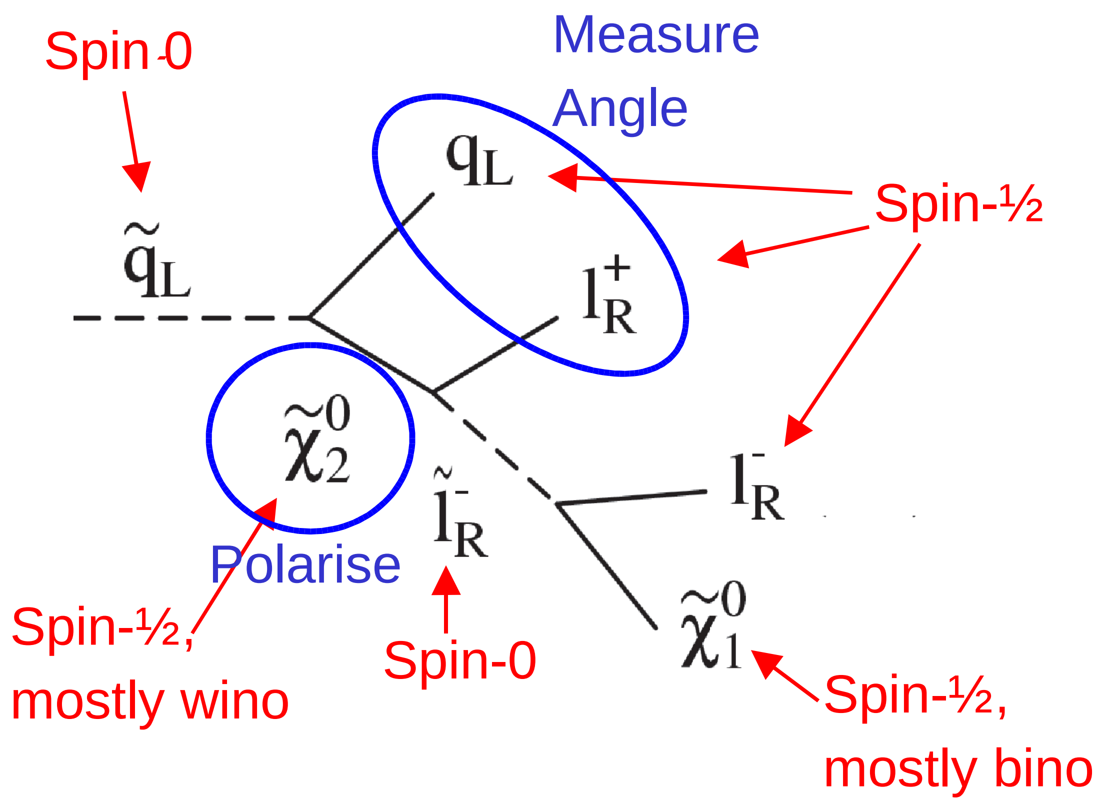
Technique first proposed by A. Barr

Consider usual squark decay chain in SPS1a point

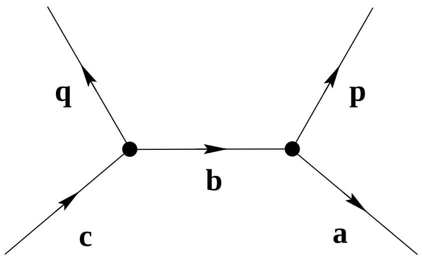
Three visible particles in final state: 1 jet, two leptons

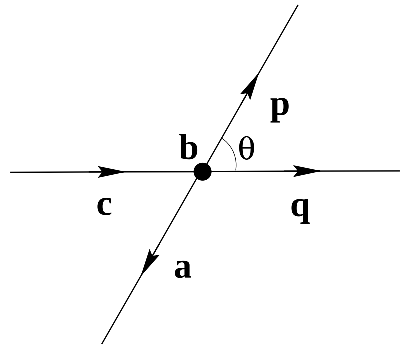
Spin analyser is the angle between the quark and the lepton from $\tilde{\chi}_2^0$ decay

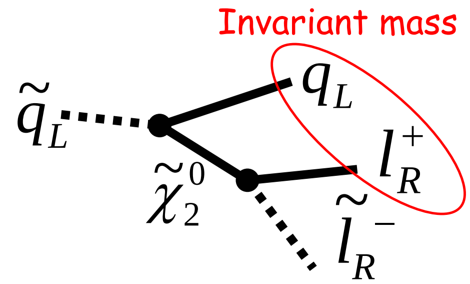
No dynamic information from angle between two leptons, as $\tilde{\ell}_R$ is spin zero



Invariant mass distribution for visible particles







The angle θ between the two visible particles in rest frame of b related to m_{pq} as:

$$m_{pq}^2 = 2|\vec{p_p}||\vec{p_q}|(1-\cos\theta) \quad \text{and} \quad (m_{pq}^{max})^2 = 4|\vec{p_p}||\vec{p_q}|$$

for p, q massless

We can thus define the dimensionless variable:

$$\hat{m}^2 = \frac{m_{pq}^2}{(m_{pq}^{max})^2} = \frac{1}{2}(1-\cos\theta) = \sin^2\frac{\theta}{2}$$

For intermediate particle with spin zero:

$$\frac{dP}{d\cos\theta} = \frac{1}{2} \quad \Rightarrow \frac{dP}{d\hat{m}} = 2\hat{m}$$

Spin 1/2: two cases:

- Lepton same helicity as quark:

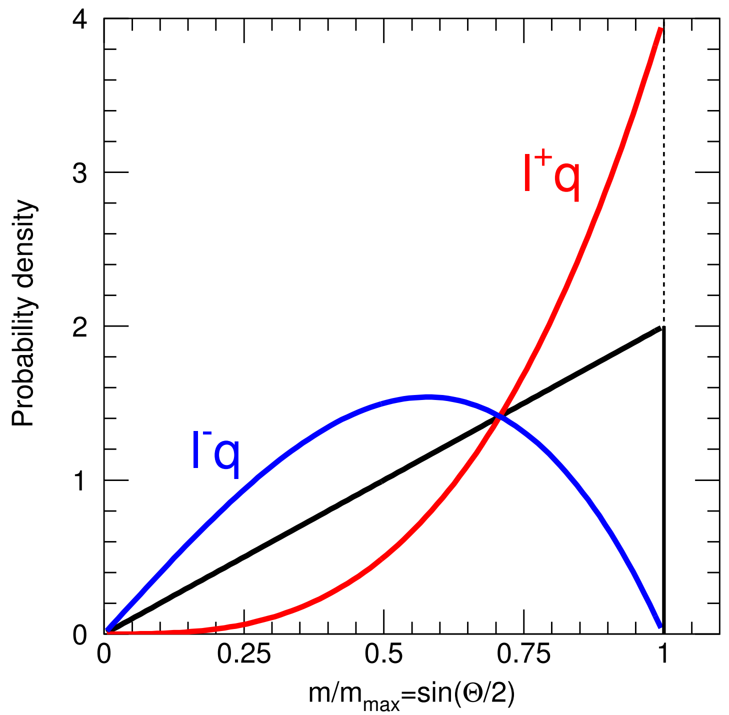
  l^+q, $l^-\bar{q}$ for $\tilde{q}_L$, $\tilde{\ell}_R$

  $$\frac{dP}{d\cos\theta} = \frac{1}{2}(1-\cos\theta) \quad \Rightarrow \frac{dP}{d\hat{m}} = 4\hat{m}^3$$

- Lepton opposite helicity to quark:

  l^-q, $l^+\bar{q}$ for $\tilde{q}_L$, $\tilde{\ell}_R$

  $$\frac{dP}{d\cos\theta} = \frac{1}{2}(1+\cos\theta) \quad \Rightarrow \frac{dP}{d\hat{m}} = 4\hat{m}(1-\hat{m}^2)$$



Difference in shape of m_{ℓ^+q} and m_{ℓ^-q}: indication for $\tilde{\chi}_2^0$ spin $1/2$

Experimental measurement

$\ell^{near}q$ shows nice charge asymmetry:

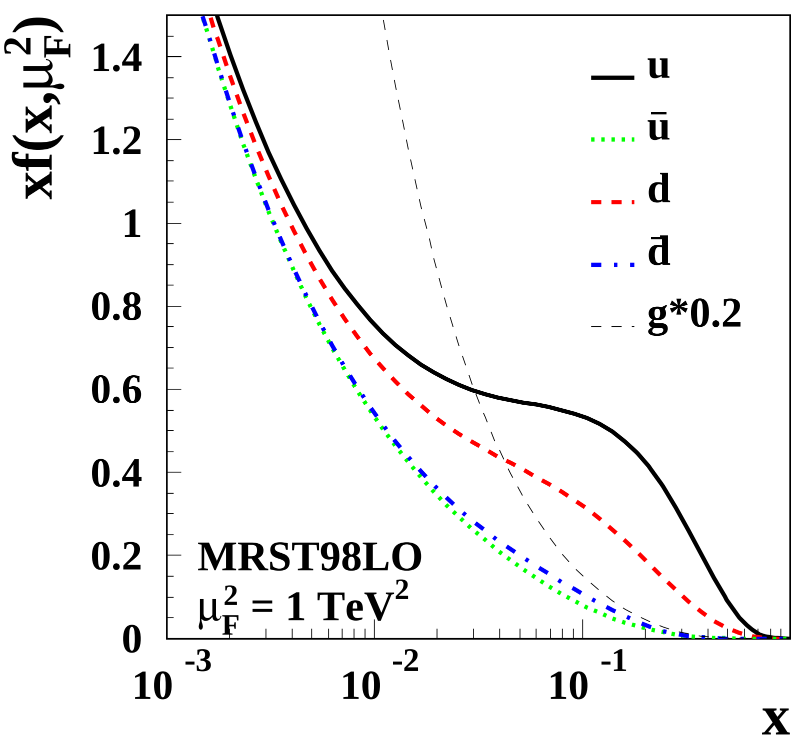
$\Rightarrow$ Excellent probe of $\tilde{\chi}_2^0$ spin

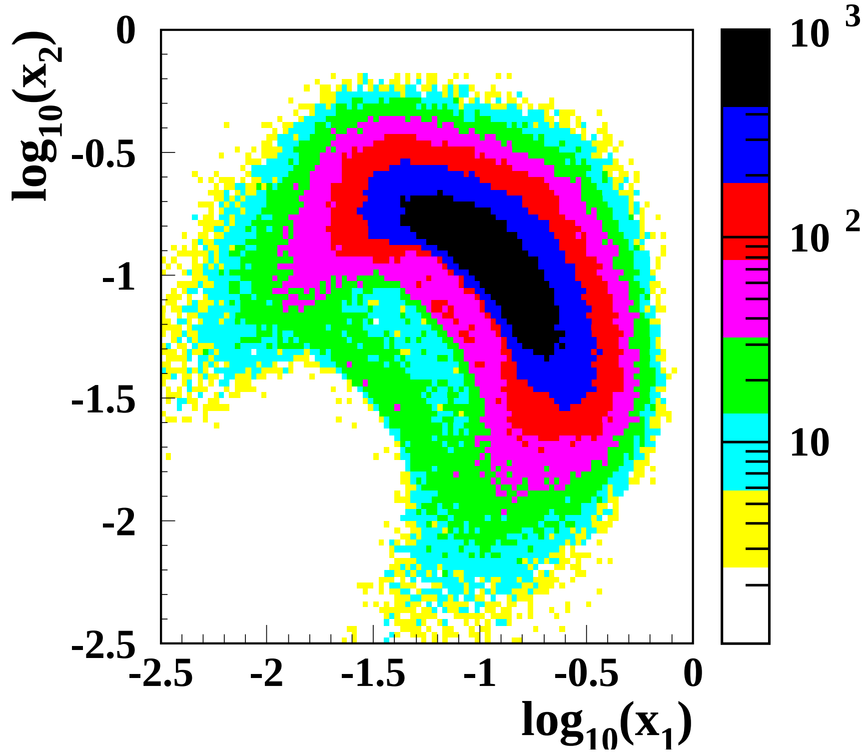
Experimental problems in measurement:

- Can't tell quark jet from anti-quark
  - Both q and $\bar{q}$ appear in decay chain
  - pp Collider $\longrightarrow$ PDF favour production of squarks over anti-squarks
- Two leptons in the event
  - We are only interested in the first lepton (from neutralino decay)
  - Plot ℓ^+q and ℓ^-q, minimal distorsion of asymmetry from ℓ^{far}

Production asymmetry

For squark production in considered model ($m_{\tilde{q}} \sim 600$ GeV), dominant contribution of $x \sim 0.1$

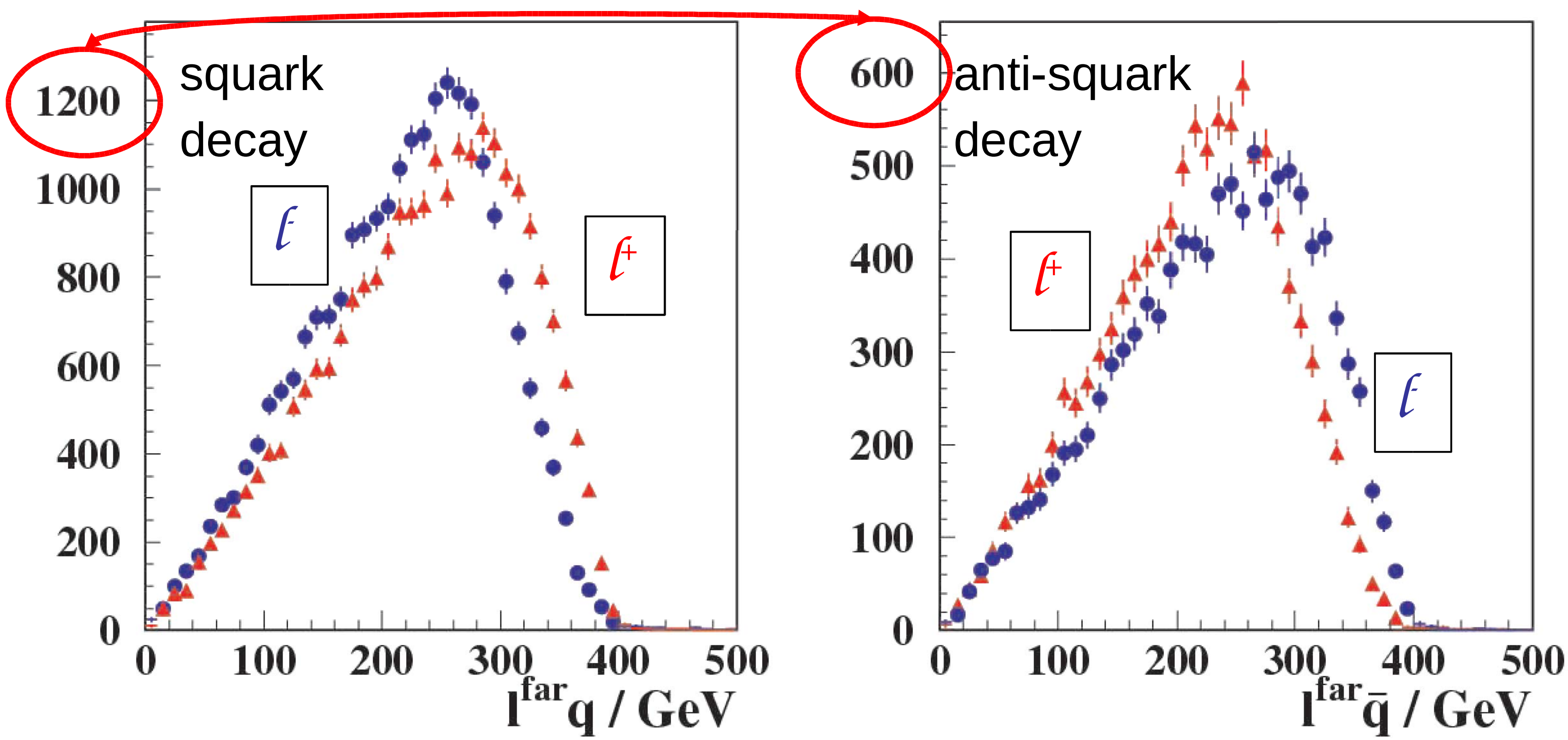




At $x \sim 0.1$ dominant contribution of valence quarks

$\ell^{far} q$ invariant mass

Lepton from slepton decay only: not directly measurable

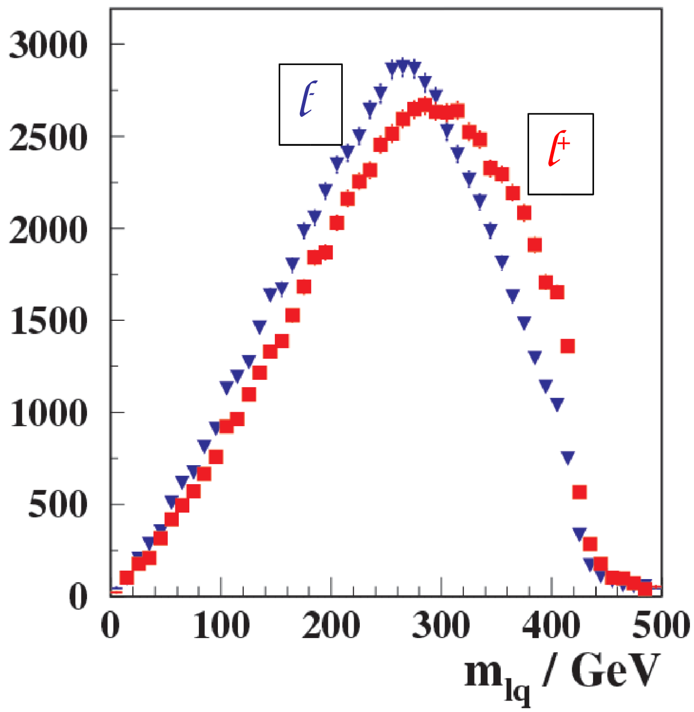


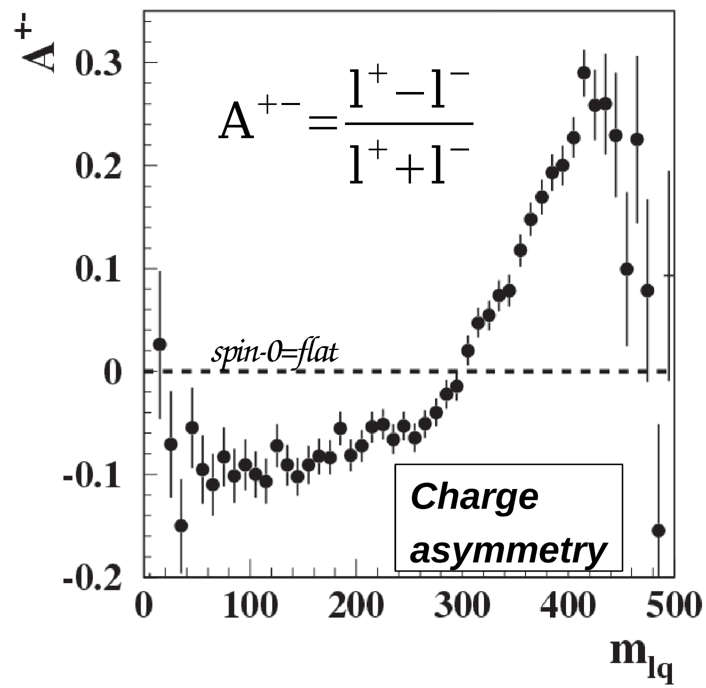
Small residual asymmetry from boost of slepton in $\tilde{\chi}_2^0$ rest frame

Parton level

We now build at parton level on simulated events the lepton-jet invariant mass, and take the bin-by-bin asymmetry of ℓ^+ and ℓ^- distributions

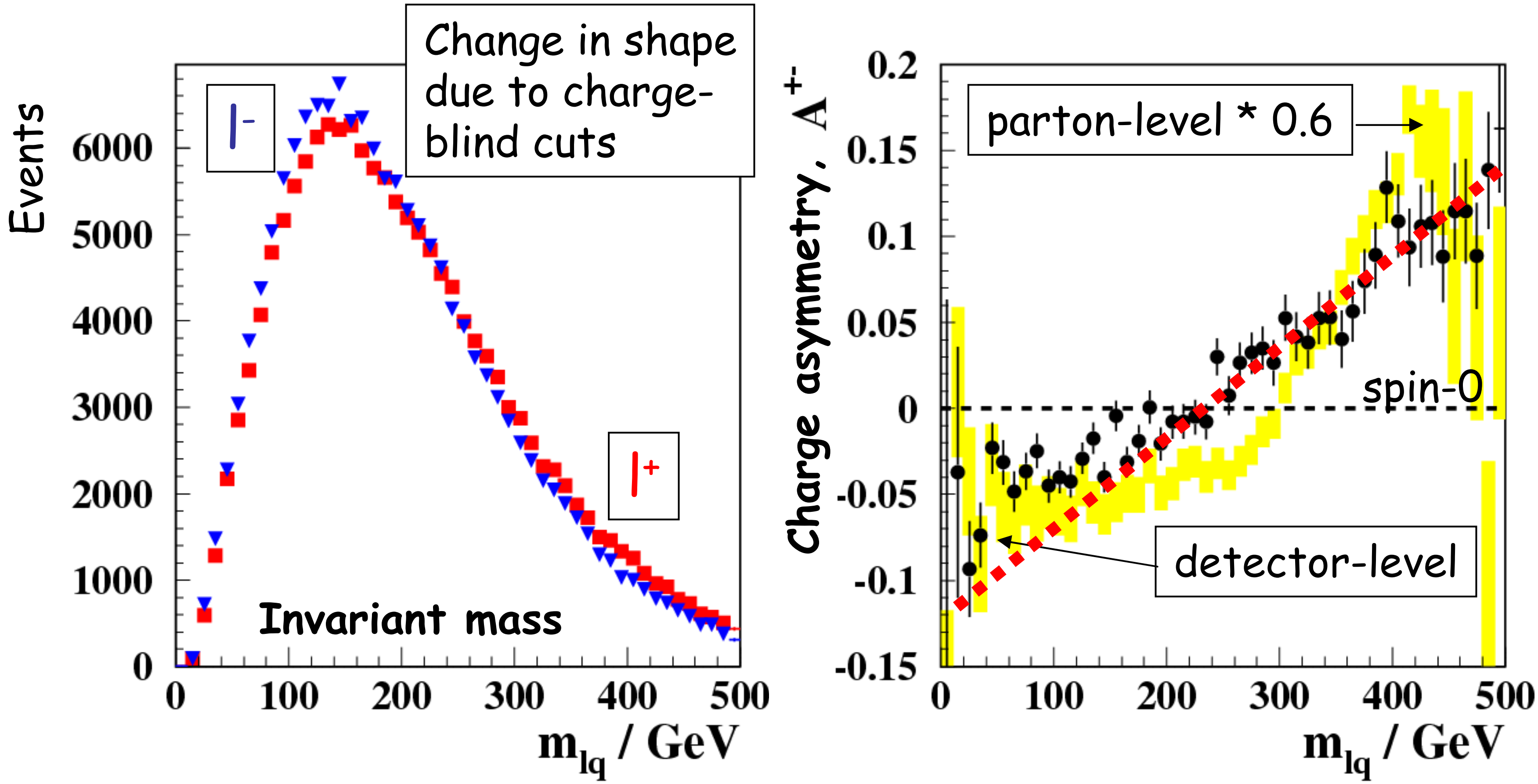
Experimentally measurable: both q and $\bar{q}$ in plot, both near and far lepton





Shape shows clear deviation from what expected for spin-zero $\tilde{\chi}_2^0$

After parametrised detector simulation



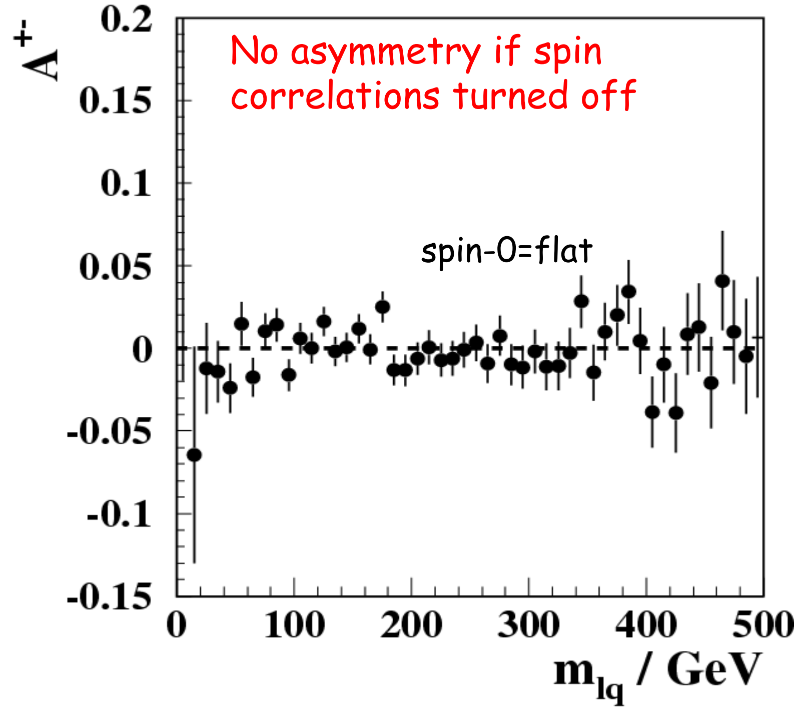
Charge asymmetry survives detector simulation

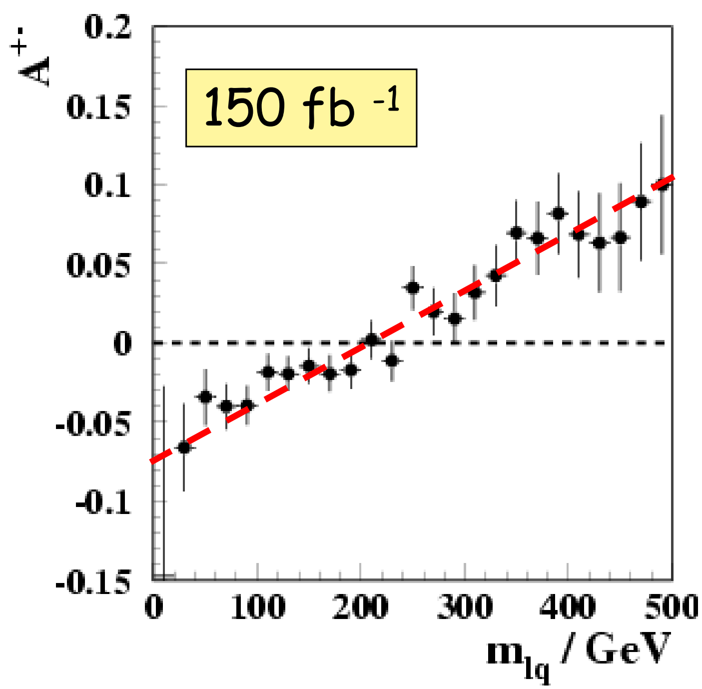
Similar shape for asymmetry as at parton level, but with BG and smearing

- Use HERWIG Monte Carlo
- Can switch off spin correlations

Distribution for scalar $\tilde{\chi}_2^0$:

- Consistent with flat
- Not consistent with spin-$1/2$ $\tilde{\chi}_2^0$





Previous plots with very high statistics

(5 years high luminosity)

- Show shape clearly
- Necessary luminosity depends on MSSM parameters
- For considered model 150 fb^{-1} sufficient

Comparison with spin 1

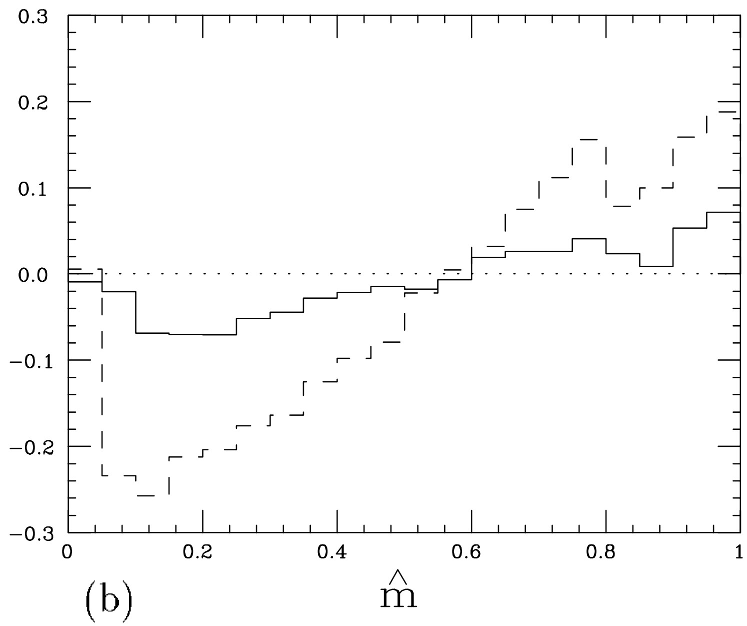
For the SPS1a SUSY model, it can be shown that $\tilde{\chi}_2^0$ is not a scalar

In competing models (UED) spin of partner of Z is 1, as in Standard Model

Not studied in previous analysis because model not available in MC generator

Comparison with spin one performed by theorists (Smillie, Webber) with very rough detector simulation

Same spectrum of sparticle masses as for SPS1a point with two spin assignments: SM-like (solid lines), SUSY (dashed lines)



Two spin assignments:

SM-like (solid lines), SUSY (dashed lines)

Excellent discrimination also against spin one case

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 Standard Model backgrounds

Once convincng signal claimed, try to pin dow what kind of SM extesnsion generated deviation

Definition of most effective approach strongly depends on features of observed signal

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

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