SUSY at the LHC - experimental

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Introduction

For 20 years SUSY most popular template for exploration of new physics

SUSY: large class of models with many possible signatures

Canonical model for experimental studies is MSSM with R-parity conservation

Prototype of a generic model with:

- Rich spectrum of new particles
- Complex decay chains
- Two undetected particles in final state (LSP)

Different experimental challenges in different phases of SUSY studies:

- Discovery based on challenging and varied signatures, dominated by $\not{E}_T$ from undetected LSP
- Measurement of sparticle masses/couplings requires development of new spectroscopic techniques
- In recent times new non-SUSY models with similar features proposed: issue of model discrimination
- Connection with low energy and astrophysical data: reconstruction of weak-scale model

The LHC machine

Energy: $\sqrt{s}$=14 TeV

LEP tunnel: 27 Km circumference

1232 Superconducting dipoles, field 8.33 T

Luminosity:

- peak$\sim 10^{33}$ cm^{-2}s^{-1} - initial "low luminosity"

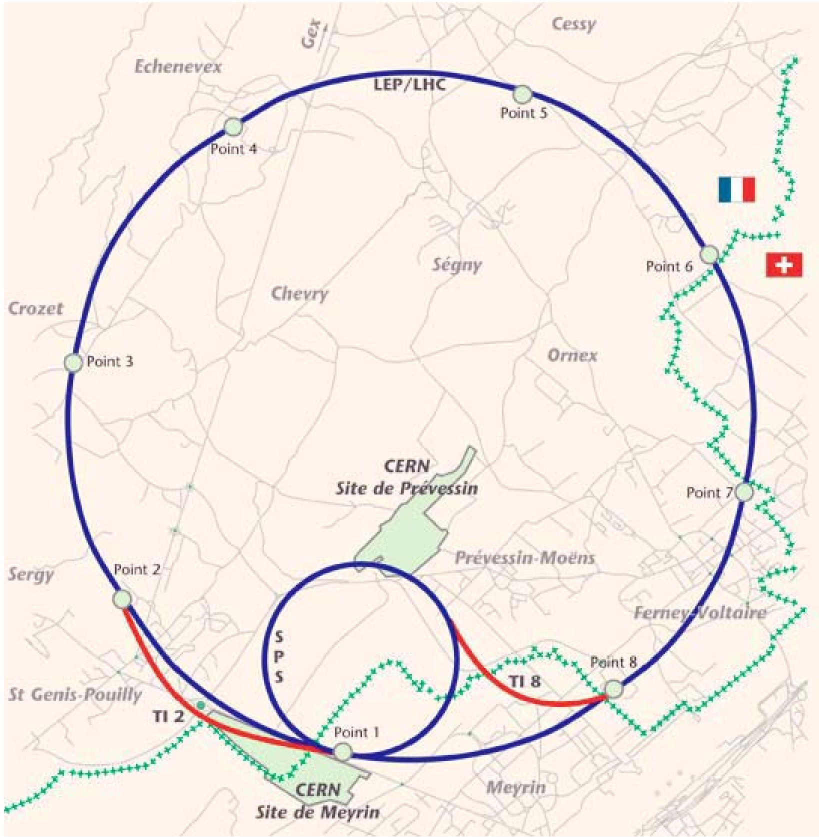
$$\int \mathcal{L}\mathrm{dt} = 10\ \mathrm{f}b^{-1}\ \text{per year}$$

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

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

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

Inter-bunch space: 25 ns $\Rightarrow\sim 23$ inelastic interactions per crossing at full luminosity



Eight sectors

Point 1: ATLAS General purpose

Point 2: ALICE Heavy ions

Point 5: CMS General purpose

Point 8: LHCb B-physics

ATLAS detector

Precision Muon Spectrometer,

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

Fast response for trigger

Good *p* resolution

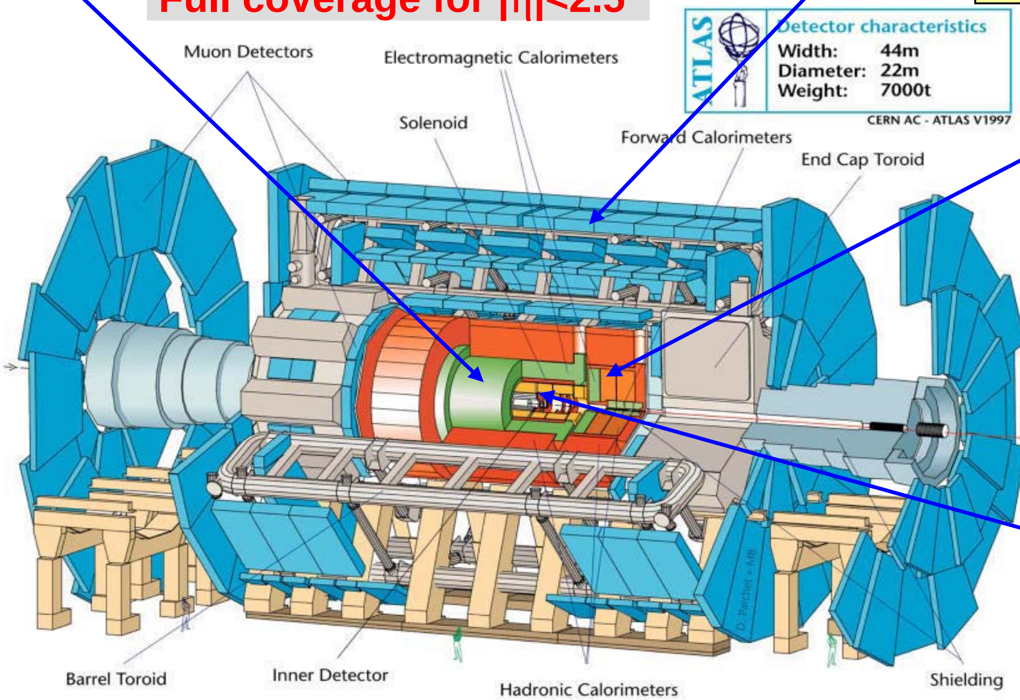
(e.g., A/Z' $\to \mu\mu$, H $\to 4\mu$)

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

excellent electron/photon identification

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

Full coverage for $|\eta|<2.5$



Hadron Calorimeters,

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

Good jet and E_T miss performance

(e.g., H $\to\tau\tau$)

Inner Detector:

Si Pixel and strips (SCT) &

Transition radiation tracker (TRT)

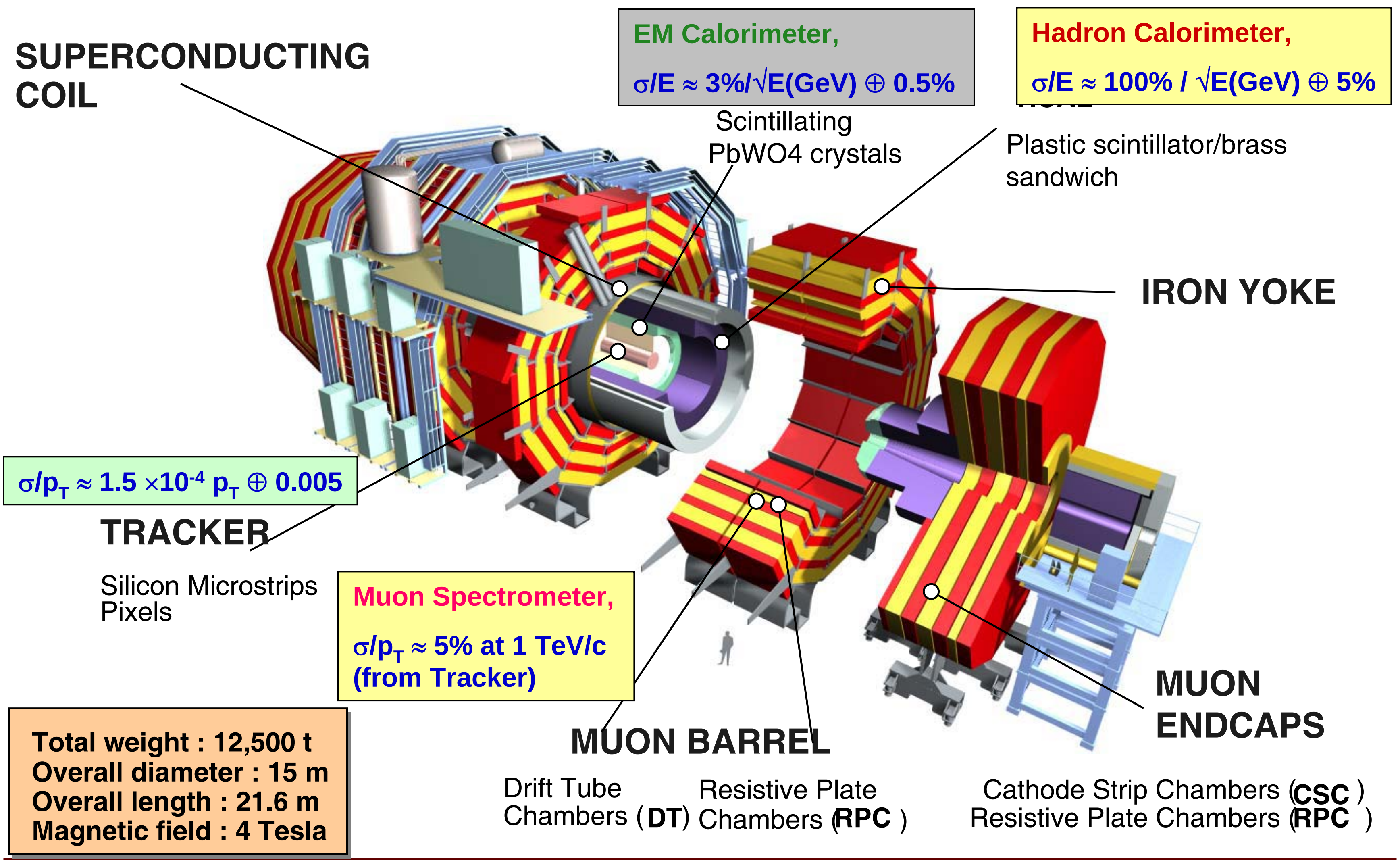
$\sigma/p_T \approx 5 \times 10^{-4}\, p_T \oplus 0.001$

Good impact parameter res.

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

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

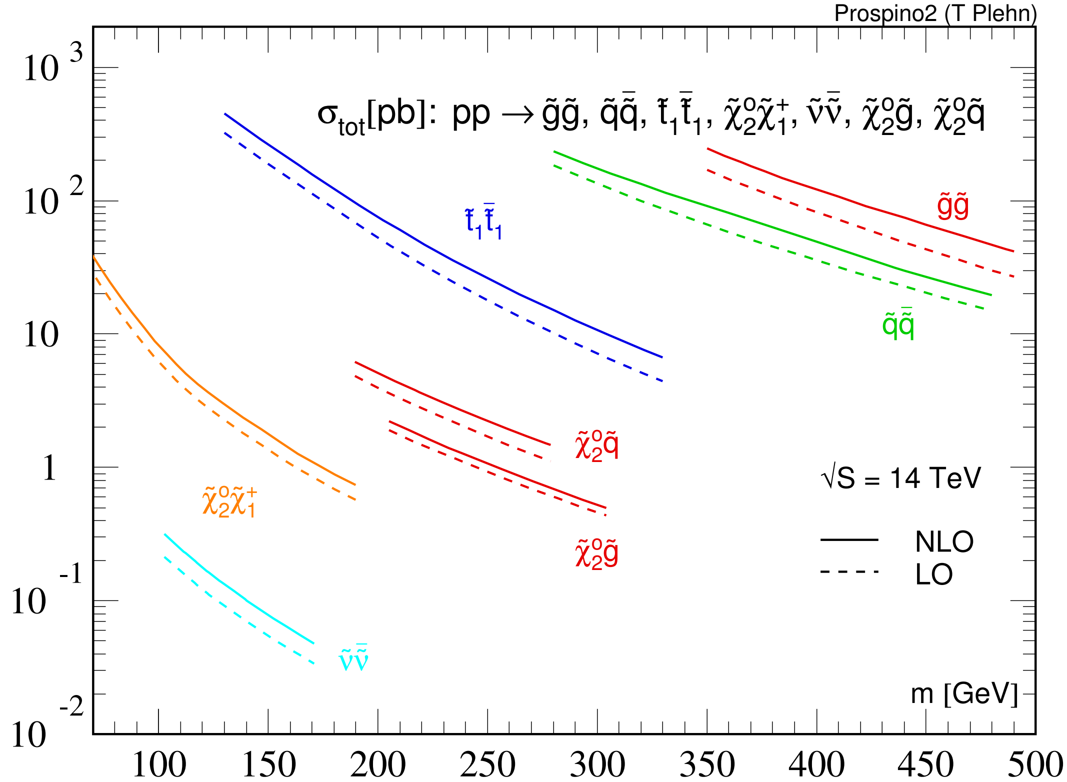
CMS detector



SUSY at the LHC: general features

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

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



- $\sigma_{SUSY} \sim 50$ 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 leptons produced in the decay.

Both negative and positive consequences:

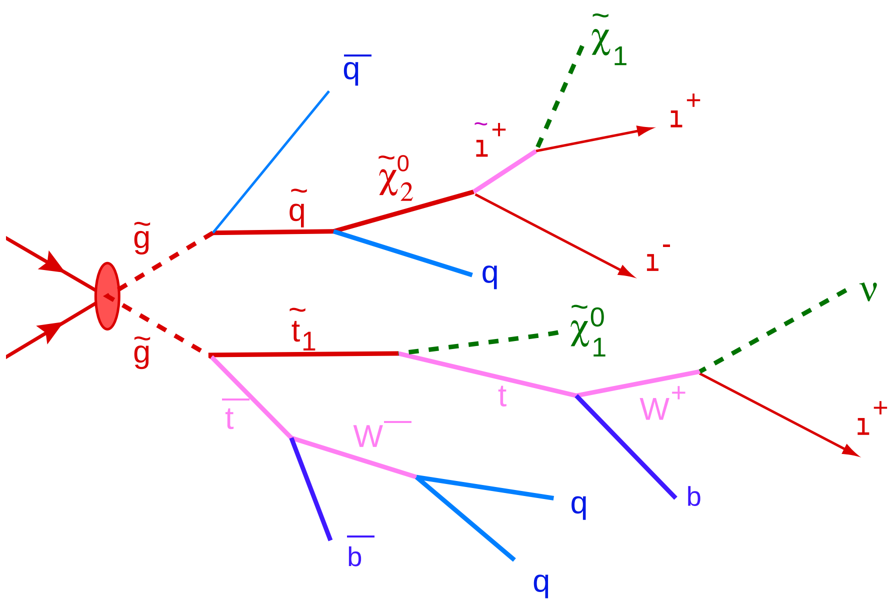
- Many handles for the discovery of deviations from SM, and rich and diverse phenomenology to study
- Unraveling of model characteristics will mostly rely on identification of specific decay chains: difficult to isolate from the rest of SUSY events

SUSY is background to SUSY!

SUSY discovery: basic strategy

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

Details of cascade decays are a function of model parameters. Focus on robust signatures covering large classes of models and large rejection of SM backgrounds



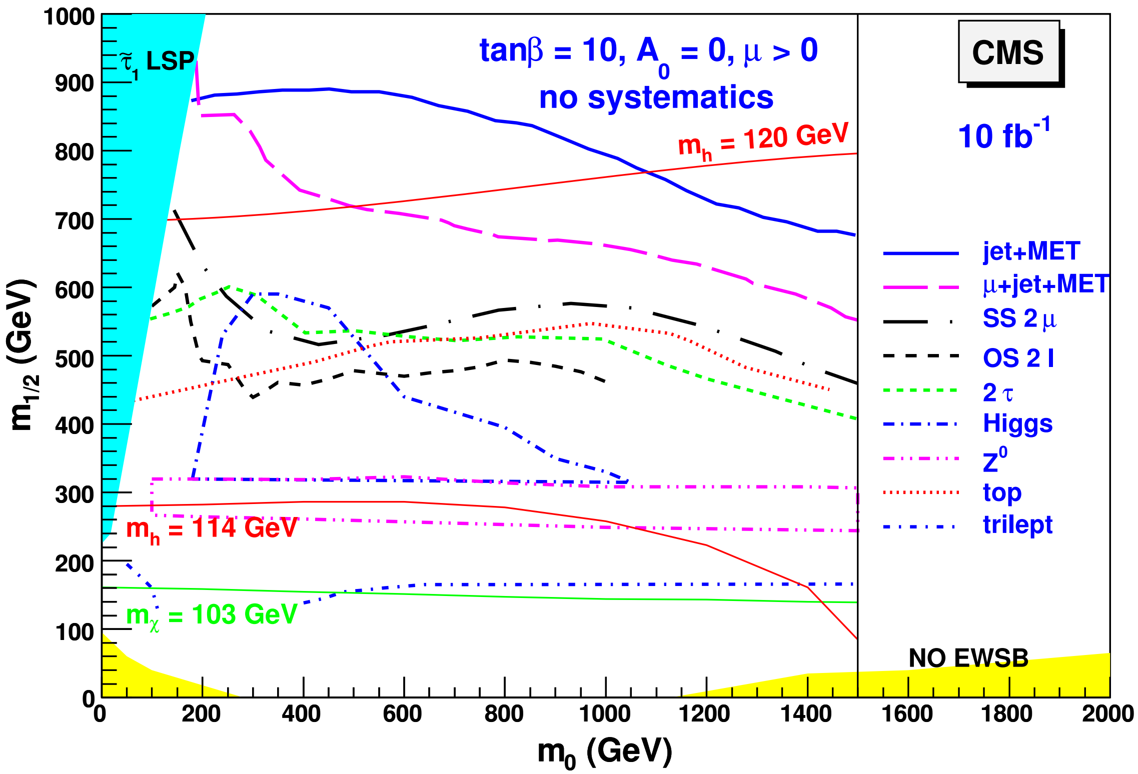
- $\not{E}_T$: from LSP escaping detection
- High E_T jets: guaranteed if unification of gaugino masses assumed.
- Multiple leptons (Z): from decays of Charginos/neutralinos in cascade
- Multiple τ-jets or b-jets (h): Often abundant production of third generation sparticles

Define basic selection criteria on these variables for RPC SUSY with $\tilde{\chi}_1^0$ LSP

Optimisation of criteria on parameter space ongoing, will define set of topologies, and for each define sets of cuts aimed respectively at high and low SUSY masses

Alternative LSP options with different signatures also under study

Inclusive signatures in mSUGRA parameter space



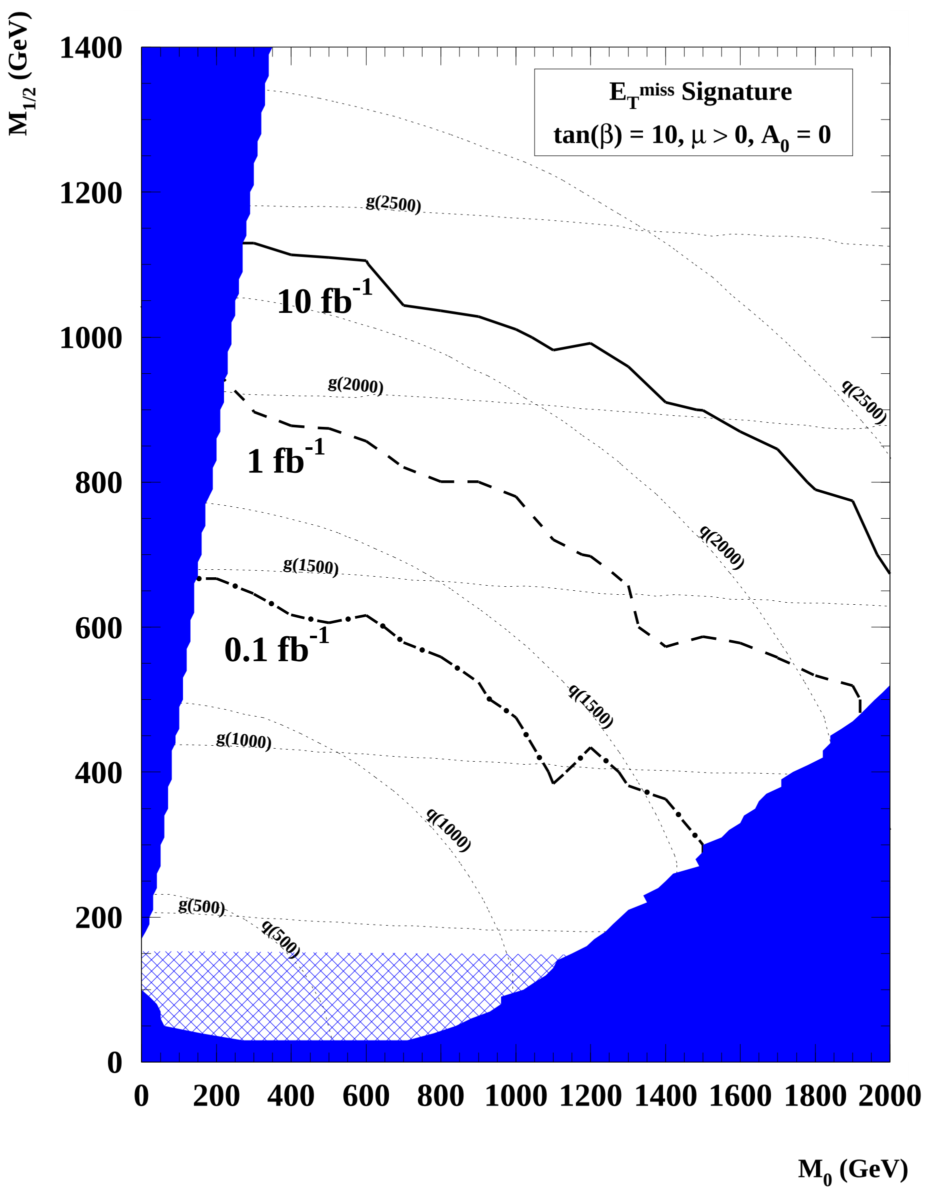
Multiple signatures over most of parameter space

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

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

ATLAS (preliminary) tried also scan in model with non universal higgs masses, with in principle different decay patterns, and result are very similar

Discovery reach as a function of luminosity



Already with ∼100 pb^{-1} statistical reach well above Tevatron limits BUT

Only in few instances SUSY signal has distinctive kinematic features

Main selection tool both at trigger and analysis level is $\not{E}_T$: difficult variable to master experimentally

Two main background classes:

- Instrumental $\not{E}_T$: need to understand performance tails
- Real $\not{E}_T$ from neutrinos: need to collect sufficient statistics of SM control samples:

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

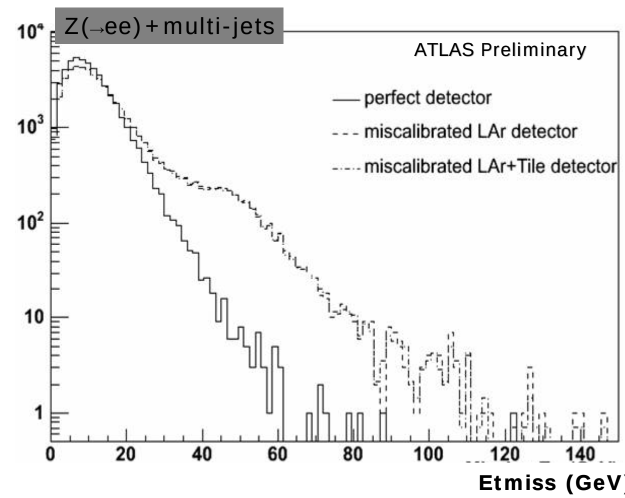
Instrumental backgrounds to $\not\!\!E_T+$ jets analysis

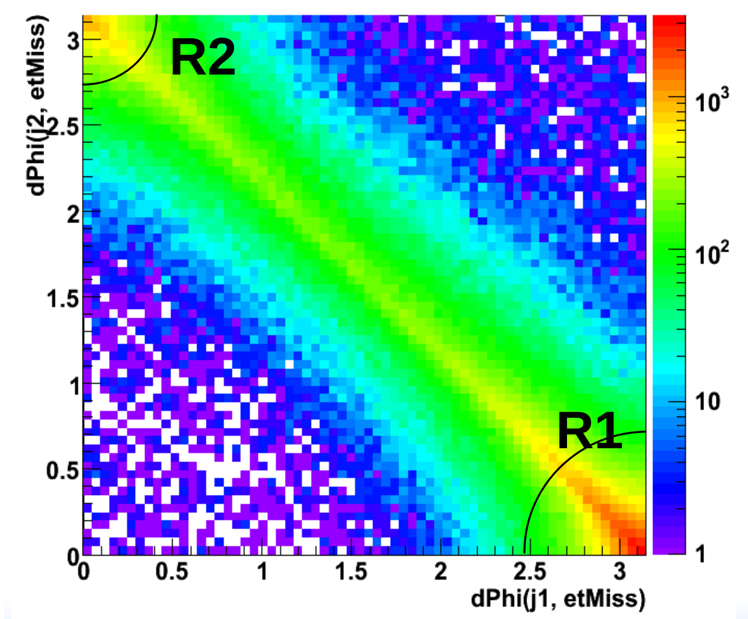
$\not\!\!E_T$ from mismeasured multi-jet events:

Populated by detector and machine problems

- Reject runs with detector malfunctioning
- Reject events with noise in the detector
- Remove bad cells

Example: effect of dead channels in ATLAS calorimeter





Next step is rejection of topologies which likely to yield instrumental $\not\!\!E_T$ (cleaning cuts).

When this done:

- Understand tails of $\not\!\!E_T$ performance
- Data-driven estimate of residual background (little help from MC), might need high-statistics sample

Probably 1 fb^{-1} on tape before we get there

Data-driven estimate of instrumental background

MonteCarlo estimate of QCD background hard

Requires complete understanding of detector

⇒ Develop data-driven estimate (ATLAS preliminary)

1: Measure jet smearing function:

- Select events with:

$\not{E}_T > 60$ GeV, $\Delta\phi(\not{E}_T, jet) < 0.1$

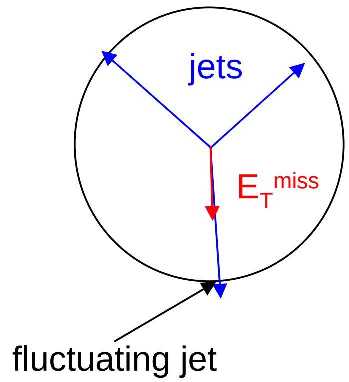
- Estimate true E_T of jet closest to $\not{E}_T$ as:

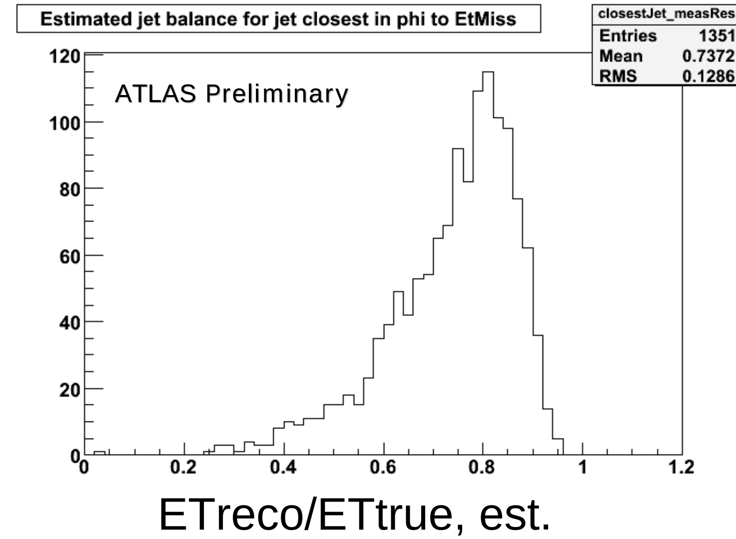
$E_T^{true} = p_T^{reco} + \not{E}_T$

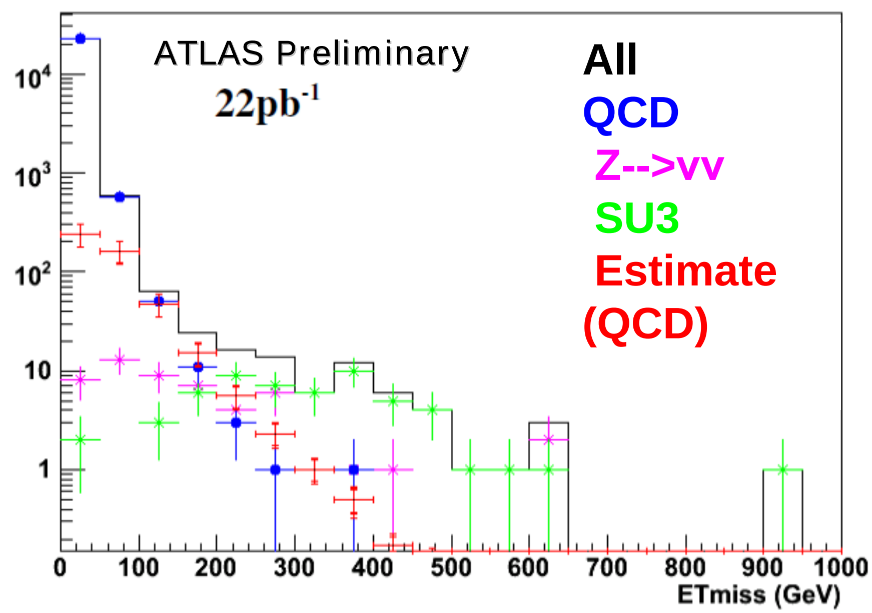
2: Take low $\not{E}_T$ jet events and smear jets with measured smearing function

3: Normalize to data

QCD $\not{E}_T$ tail nicely reproduced







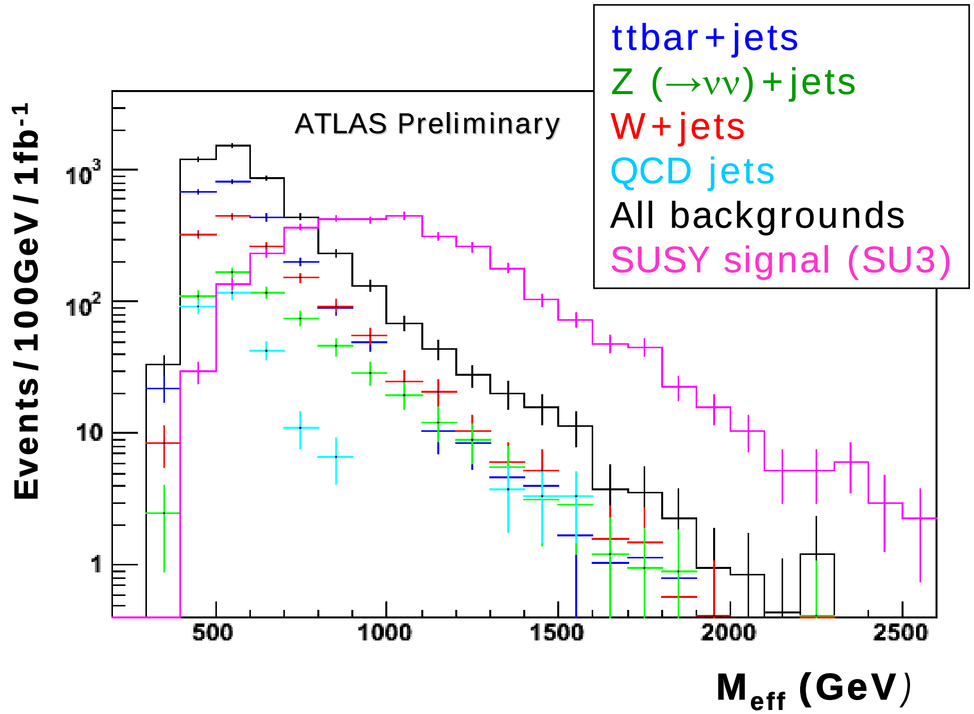
Control of $\not{E}_T$ from Standard Model processes

Real $\not{E}_T$ from ν production in SM:

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



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

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

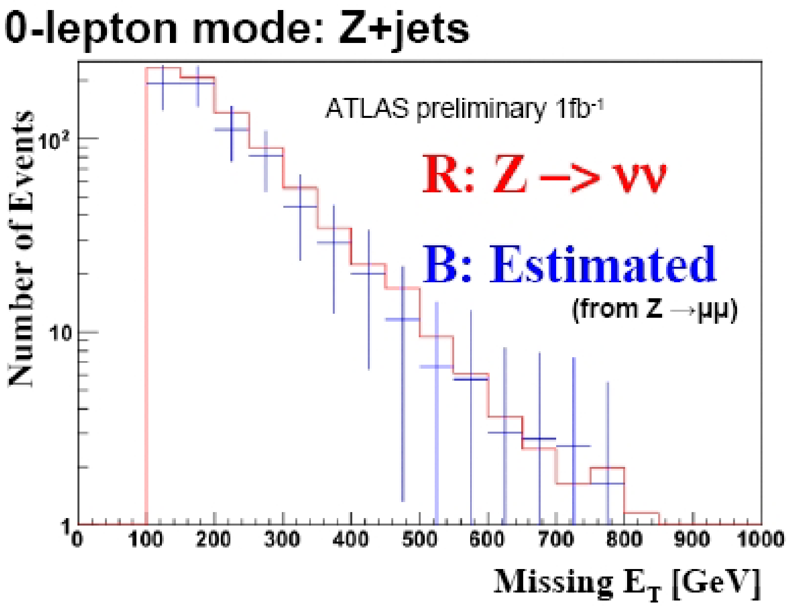
Counting experiment: need precise estimate of background processes in signal region

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

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

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

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)

Good prediction of background shape

Large statistical errors if $Z \to \ell\ell$ data used for both shape and normalisation

Can use more MC information (e.g. use data only for normalisation and MC for shape), at the price of additional systematics

Additional inclusive signatures

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

BUT control of SM and instrumental backgrounds might require long time before discovery

Optimize search strategy by tackling in parallel all of the inclusive discovery channels

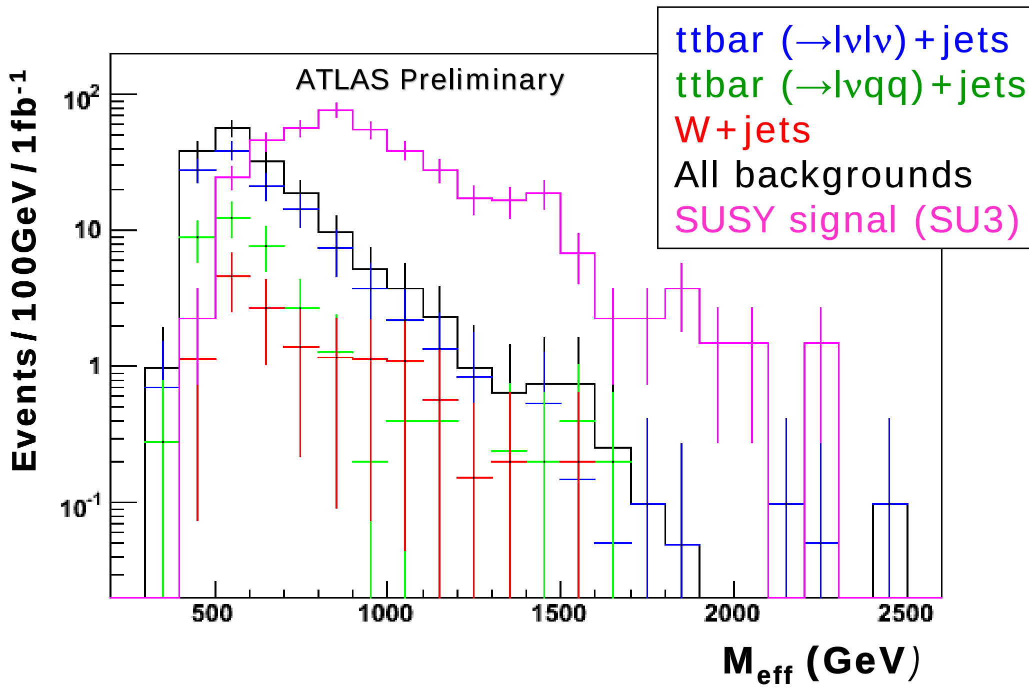
Example: single lepton + jets + $\not\!\!E_T$

Smaller number of backgrounds:

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

Shoulder m M_{eff} might be observable

If adequate lepton ID achieved, background dominated by SM events with neutrinos: $\bar{t}t$, W+jets



Establishing SUSY experimentally

Assume an excess seen in inclusive analyses: how does one verify whether 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 observables requires development of ad-hoc techniques at the LHC: develop a strategy based on detailed MC study of reasonable candidate models

Measurement of SUSY masses

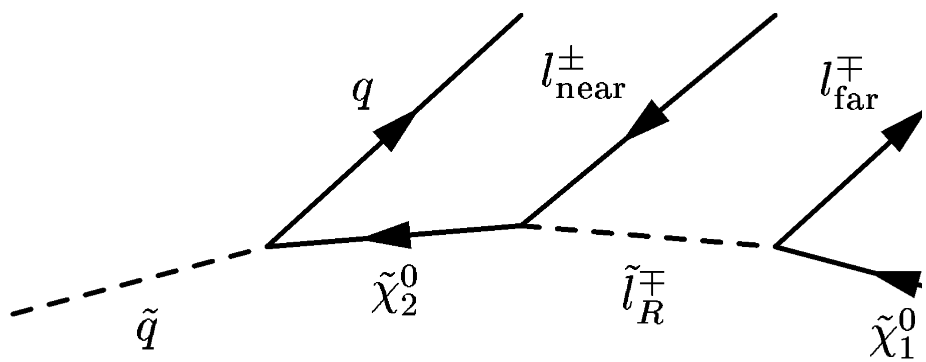
Identify exclusive decay chains including leptons or b-jets (QCD bckg.)

R-parity conservation ⇒ two undetected LSP's per event

⇒ 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

Example: Point SPS1a

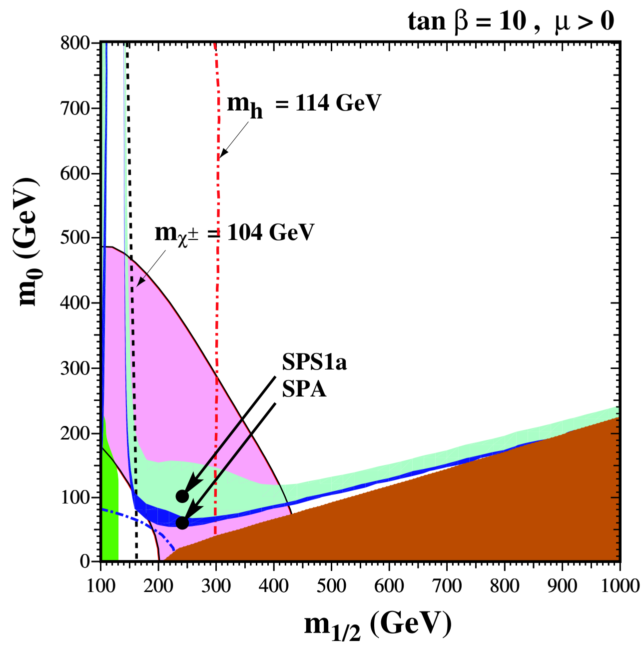
Snowmass Point 1

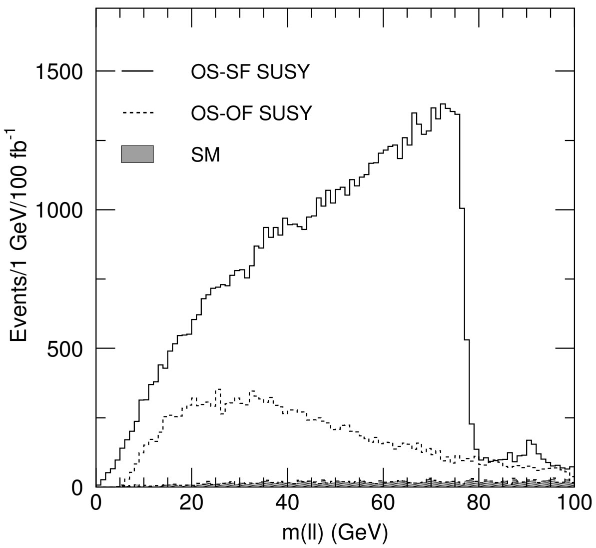
$m_0 = 100$ GeV, $m_{1/2} = 250$ GeV $A = -100$ GeV, $\tan\beta = 10$, $\mu > 0$

Total cross-section: $\sim$50 pb, BR($\tilde{\chi}_2^0 \to \tilde{\ell}_R \ell$)=12.6%

SPA: similar point, compatible with WMAP:

$m_0 = 70$ GeV, $m_{1/2} = 250$ GeV $A = -300$ GeV, $\tan\beta = 10$, $\mu > 0$





Lepton-lepton edge

Select events with high jet multiplicity and $\not{E}_T$

Require two opposite-sign same-flavour e, μ (OSSF)

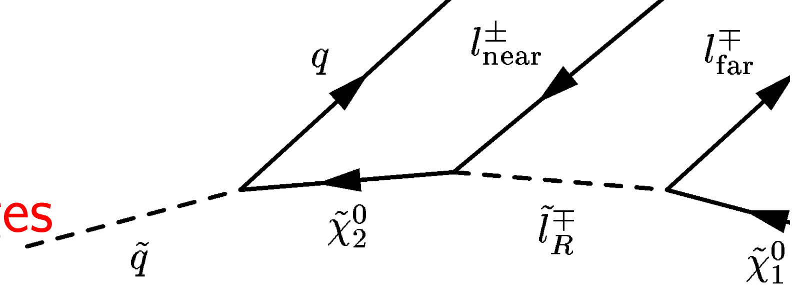
SUSY background: uncorrelated $\tilde{\chi}_1^{\pm}$ decays

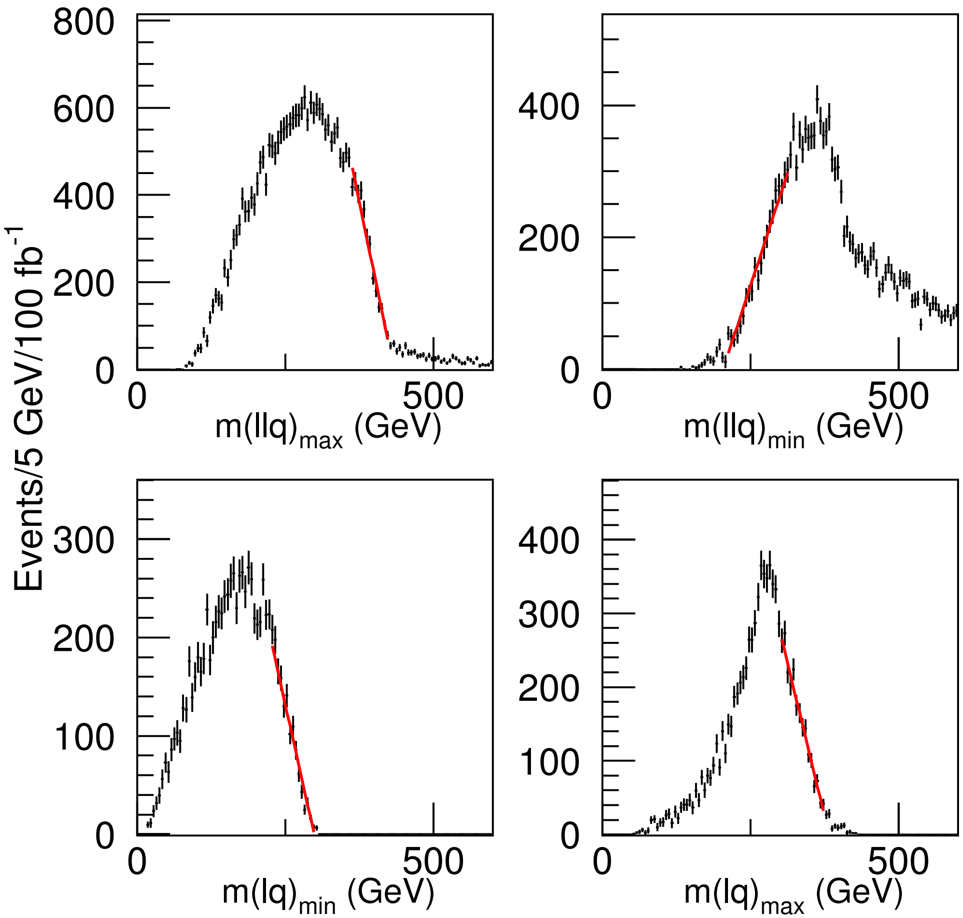
Subtract SUSY and SM background via flavour correlation:

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

Fit to sharp edge + Gaussian smearing

Lepton-lepton-jet edges





Distributions fall $\sim$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 (5) to solve for masses of four involved sparticles

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

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

Statistical and E-scale errors only

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:

$$
\begin{array}{lll}
a \longrightarrow b & q & \\
\quad\hookrightarrow & c \;\; \ell^{\mp} & \\
 & \quad\hookrightarrow & d \;\; \ell^{\pm}
\end{array}
$$

$$
\begin{array}{lll}
a \longrightarrow b & q & \\
\quad\hookrightarrow & e \;\; \tau\mp & \\
 & \quad\hookrightarrow & d \;\; \tau^{\pm}
\end{array}
$$

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

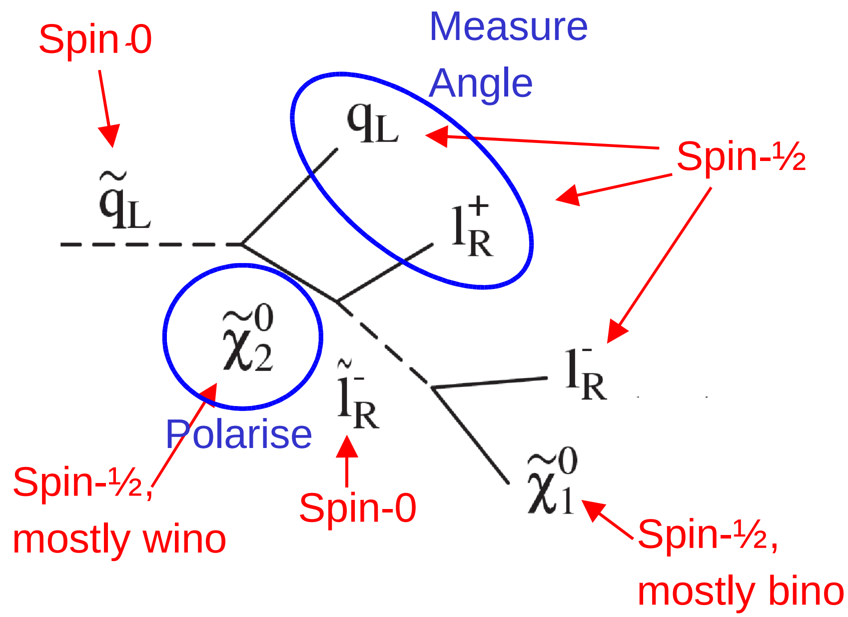
Sparticle spins in squark decay chain

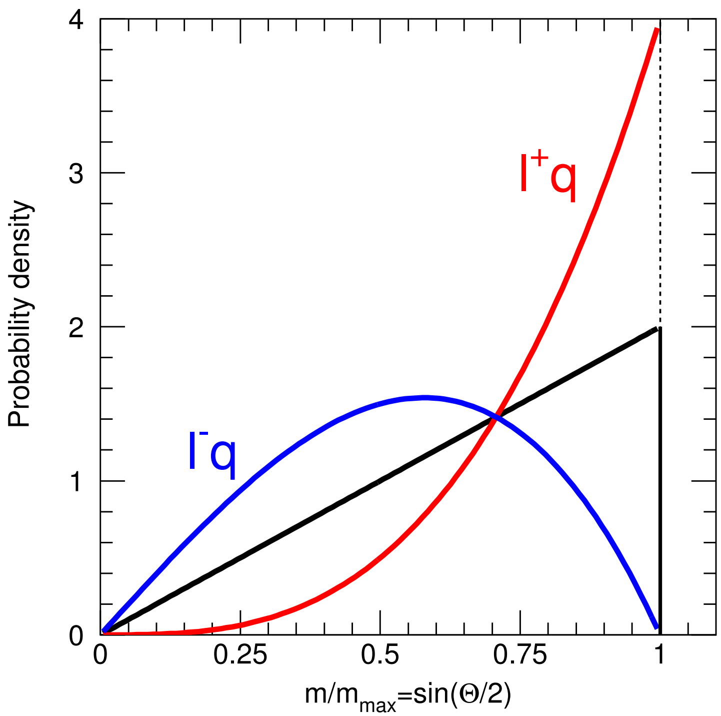
Technique first proposed by A. Barr

Squark decay chain in SPS1a point

Final state: 1 jet, two leptons + $\not{E}_T$

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





Define the dimensionless variable:

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

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

Experimental measurement

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

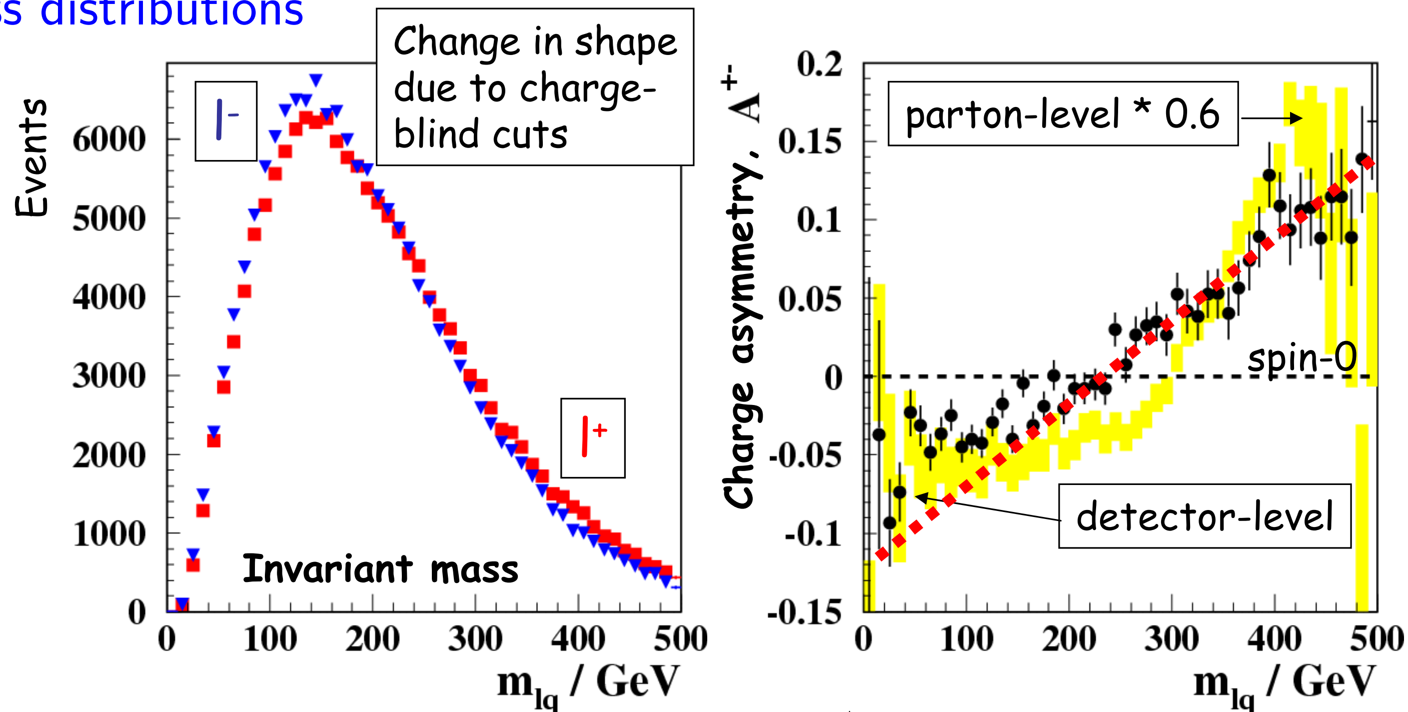
$\Rightarrow$ Excellent probe of $\tilde{\chi}_2^0$ spin

Experimental problems in measurement:

- $\ell^+q = \ell^-\bar{q}$ and can't tell quark jet from anti-quark jet
  - q ($\bar{q}$) in decay chain come from squark (antisquark)
  - pp Collider $\rightarrow$ PDF favour production of squarks over anti-squarks, excess of quarks in decay chain
- Two leptons in the event, a priori indistinguishable
  - We are only interested in the first (near) lepton (from neutralino decay)
  - Second (far) lepton comes from the decay of a spin-0 particle, $\tilde{\ell}$: expect almost no distortion of asymmetry from invariant mass of jet with far lepton

Experimental asymmetry

From a sample of events in parametrised simulation build $\ell^+ j$ and $\ell^- j$ invariant mass distributions



Build bin-by bin charge asymmetry: $A = \frac{\ell^+ - \ell^-}{\ell^+ + \ell -}$

Strong dilution through detector smearing and background effects

Effect still observable, need approximately 150 fb^{-1}

Discrimination against spin-1 $\tilde{\chi}^0_2$ also possible if spectrum not too degenerate

Conclusions

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

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

Can typically confirm signal through multiple signatures

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

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

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

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