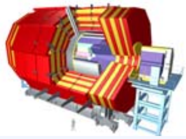
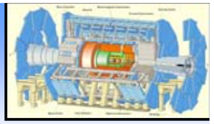




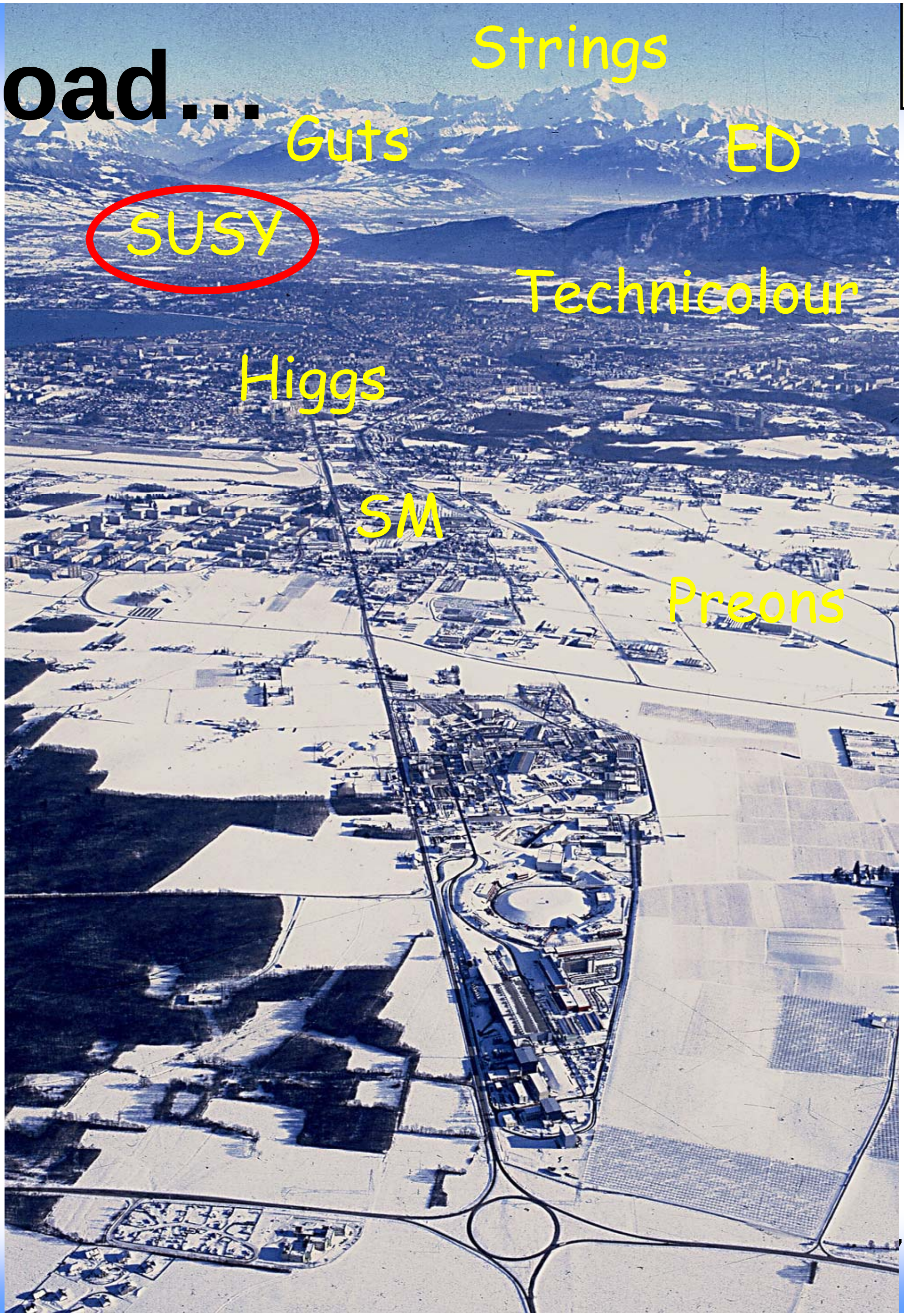
The Road to Discovery

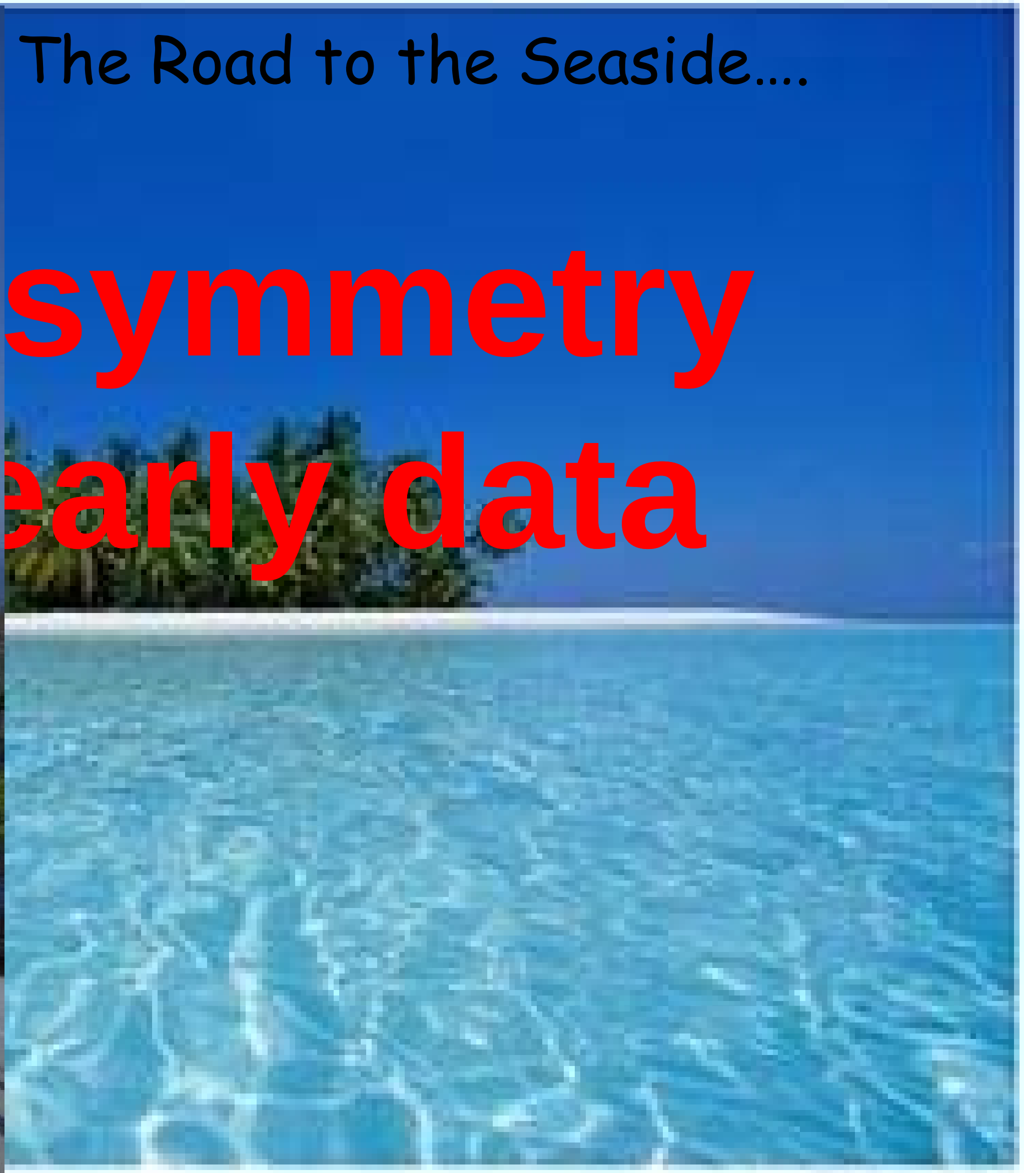
Andy Parker

Cambridge University

Along the road…

Which way to SUSY?



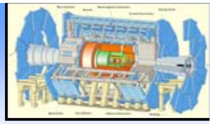


The Road to the Seaside….

symmetry

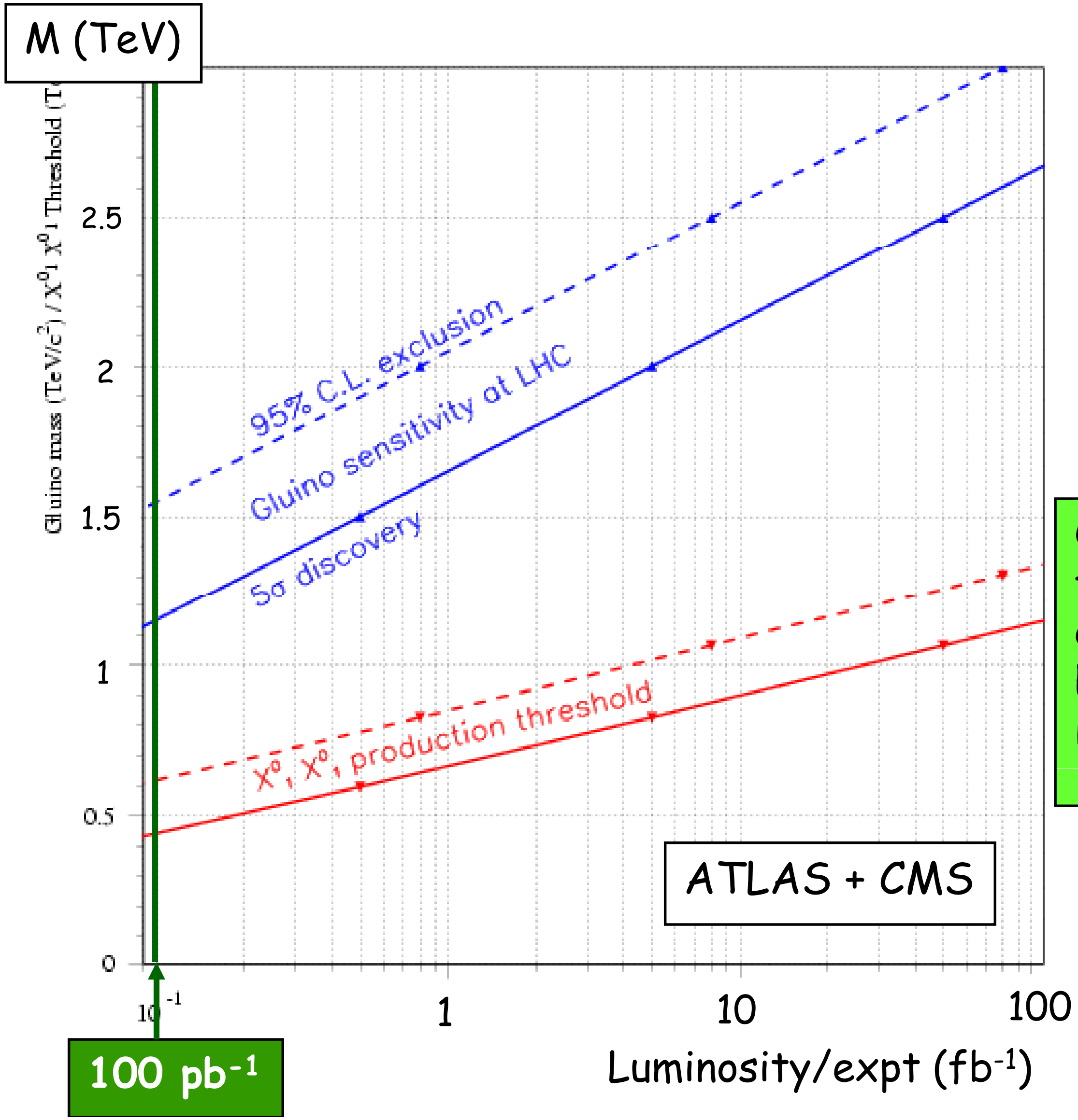
early data

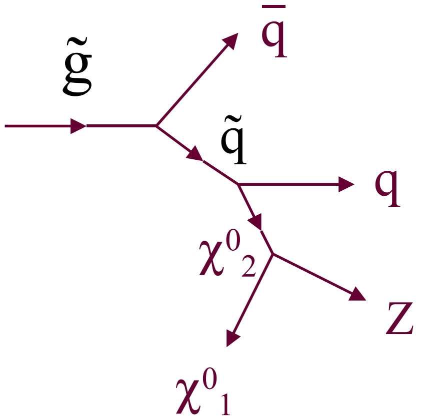
Example of "early" discovery: Supersymmetry ?



If SUSY at TeV scale → could be found "quickly" …. thanks to:

- large $\tilde{q},\tilde{g}$ cross-section → ≈ 10 events/day at 10^{32} for $m(\tilde{q},\tilde{g}) \sim 1$ TeV
- spectacular signatures (many jets, leptons, missing E_T)



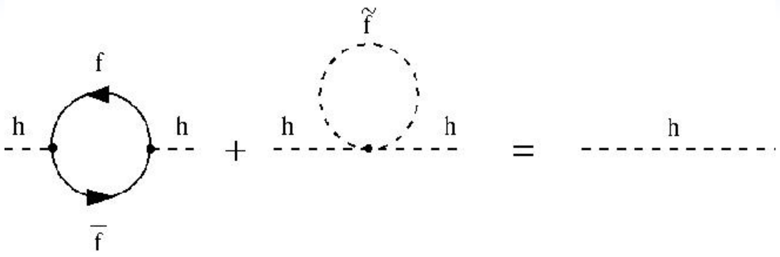


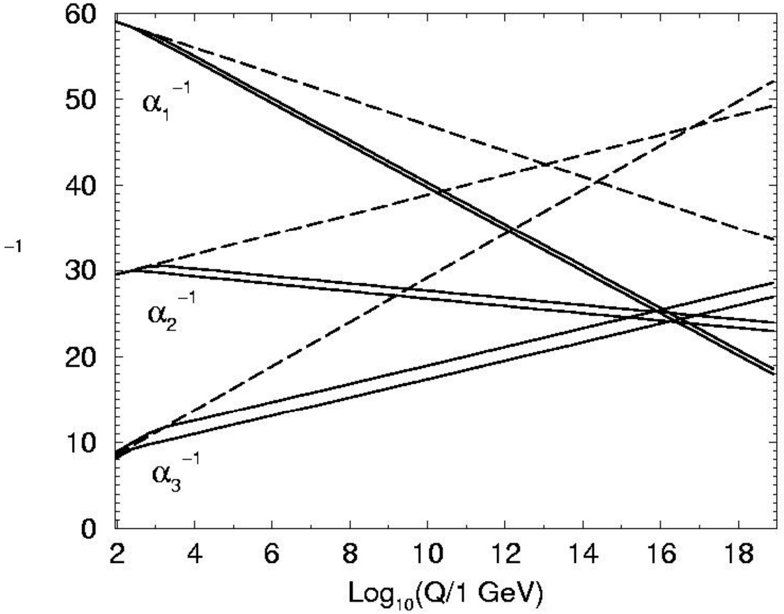
Our field, and planning for future facilities, will benefit a lot from quick determination of scale of New Physics. E.g. with 100 (good) pb^{-1} LHC could say if SUSY accessible to a ≤1 TeV ILC

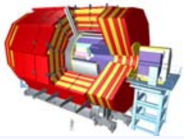
BUT: understanding E_T^{miss} spectrum (and tails from instrumental effects) is one of the most crucial and difficult experimental issue for SUSY searches at hadron colliders.

The attraction of SUSY

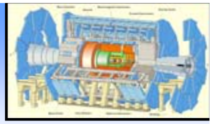
- SUSY provides partners for all SM fields
  - stabilises Higgs mass against loop corrections. Leads to h mass <135 GeV
  - Good agreement with LEP and EW global fits
  - SUSY modifies running of SM gauge couplings ‘just enough’ to give Grand Unification at single scale.
  - Many people consider (low mass) SUSY to be too attractive to be wrong





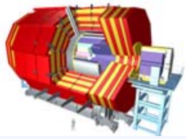


R-Parity

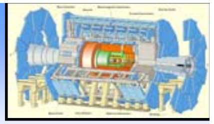


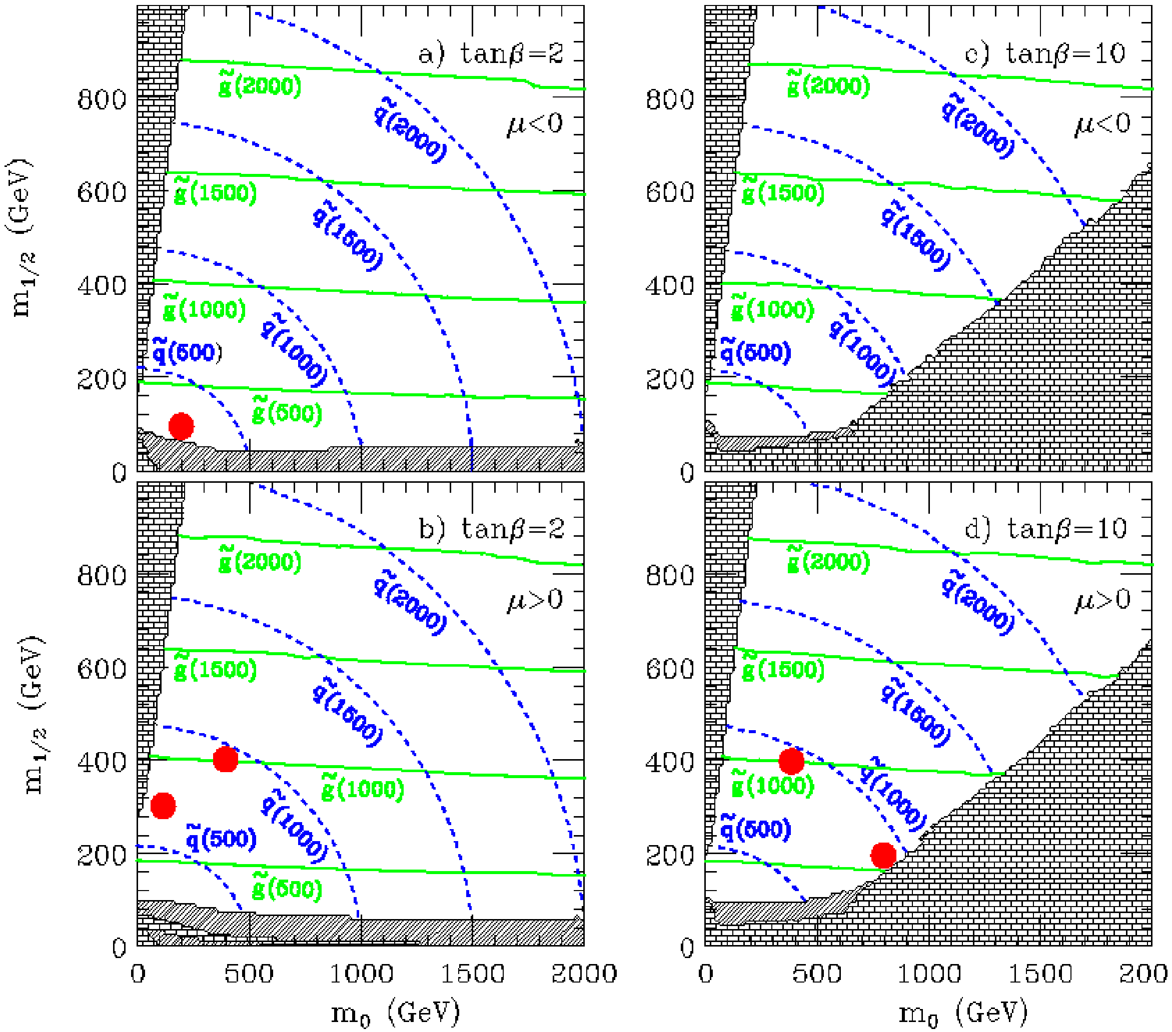
R-parity conservation important for experimental searches:

- any initial state must have $R_P = +1$, so SUSY particles must be produced in pairs. Requires energies 2x the SUSY mass.
- Any SUSY particle decay must be to a state with $R_P = -1$, and so each final state contains another SUSY particle.
- The lightest SUSY particle (the LSP) must be stable.
- A stable LSP (unless very heavy) must be electrically neutral and weakly interacting to have escaped detection. This is just what is required for dark matter.
- R-parity violating models exist, but can cause proton decay



Prediction of SUSY masses





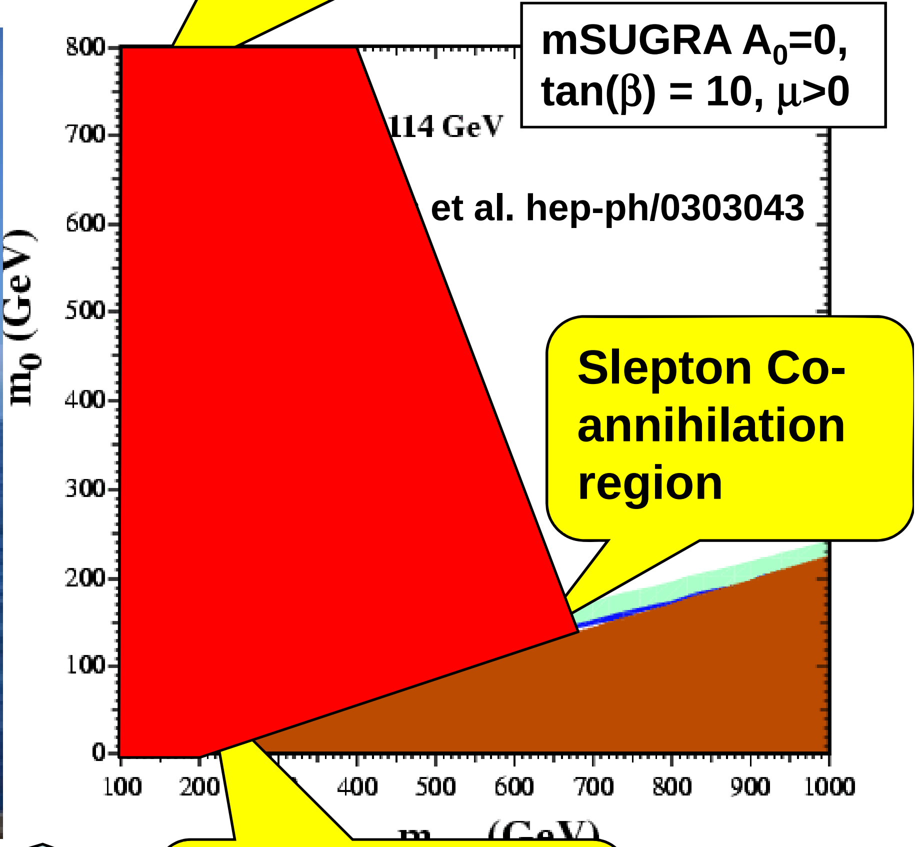
Squark and gluino masses in $m_{1/2}$,m_0 plane

Start from SUGRA parameters, solve 26 renormalisation group equations numerically to predict physical masses after SUSY and electroweak symmetry breaking.

- Benchmark points in mSUGRA parameter space:
  - LHCC Points 1-6; Post-LEP benchmarks (Battaglia et al.); Snowmass Points and Slopes (SPS); etc…

The SUSY Island?

SUSY -just over there?



'Focus point' region: annihilation to gauge bosons

mSUGRA $A_0=0$, $\tan(\beta) = 10$, $\mu>0$

Slepton Co-annihilation region

'Bulk' region: t-channel slepton exchange

WMAP constraints

The problem with SUSY

- But SUSY is broken, giving high SUSY particle masses.
  - Breaking mechanism in “hidden sector” not understood: SUGRA, GMSB, AMSB
  - 105 parameters in MSSM, almost all from SUSY breaking.
- Normally shown plots with just 2 parameters (m_0 and $m_{1/2}$), based on mSUGRA -> small part of real parameter space (even within MSSM)
- Cannot trust DM constraints - modified gravity? GMSB? RPV?

SUSY- just over there?

Trying to isolate tiny region in huge parameter space

Can theory guide us?

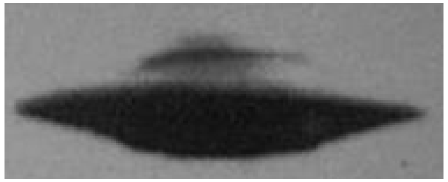
30000 models!

Figure 4: Number of Higgs

Worried about
your search strategy?

Number of Higgs doublets

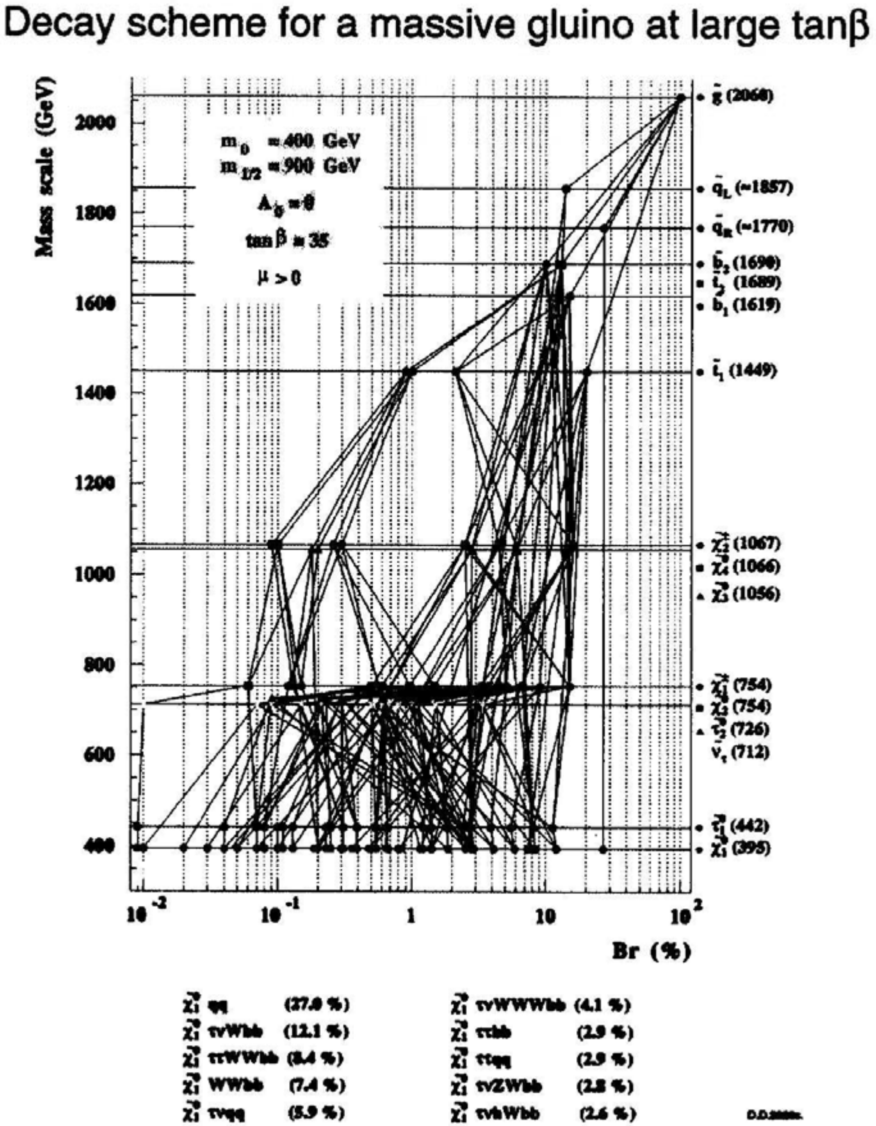
MSSM
(1 model)



The situation in 2006 –
A lot of string vacuua

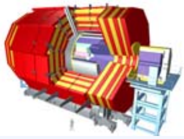
hep-th 0411129 SUSY spectra from special string vacua

SUSY decay chains

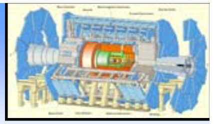


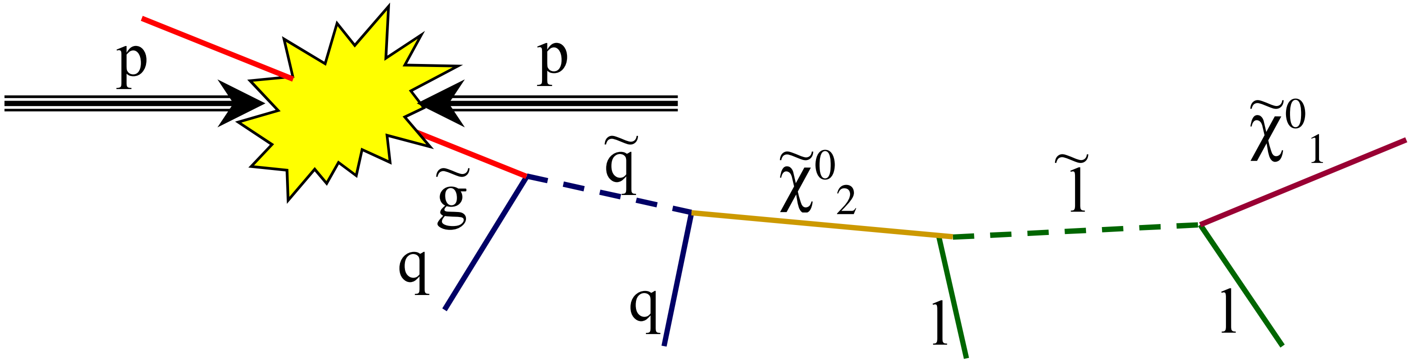
SUSY Decay chains are very complex, and the details depend on the model parameters.

Small changes can switch masses around



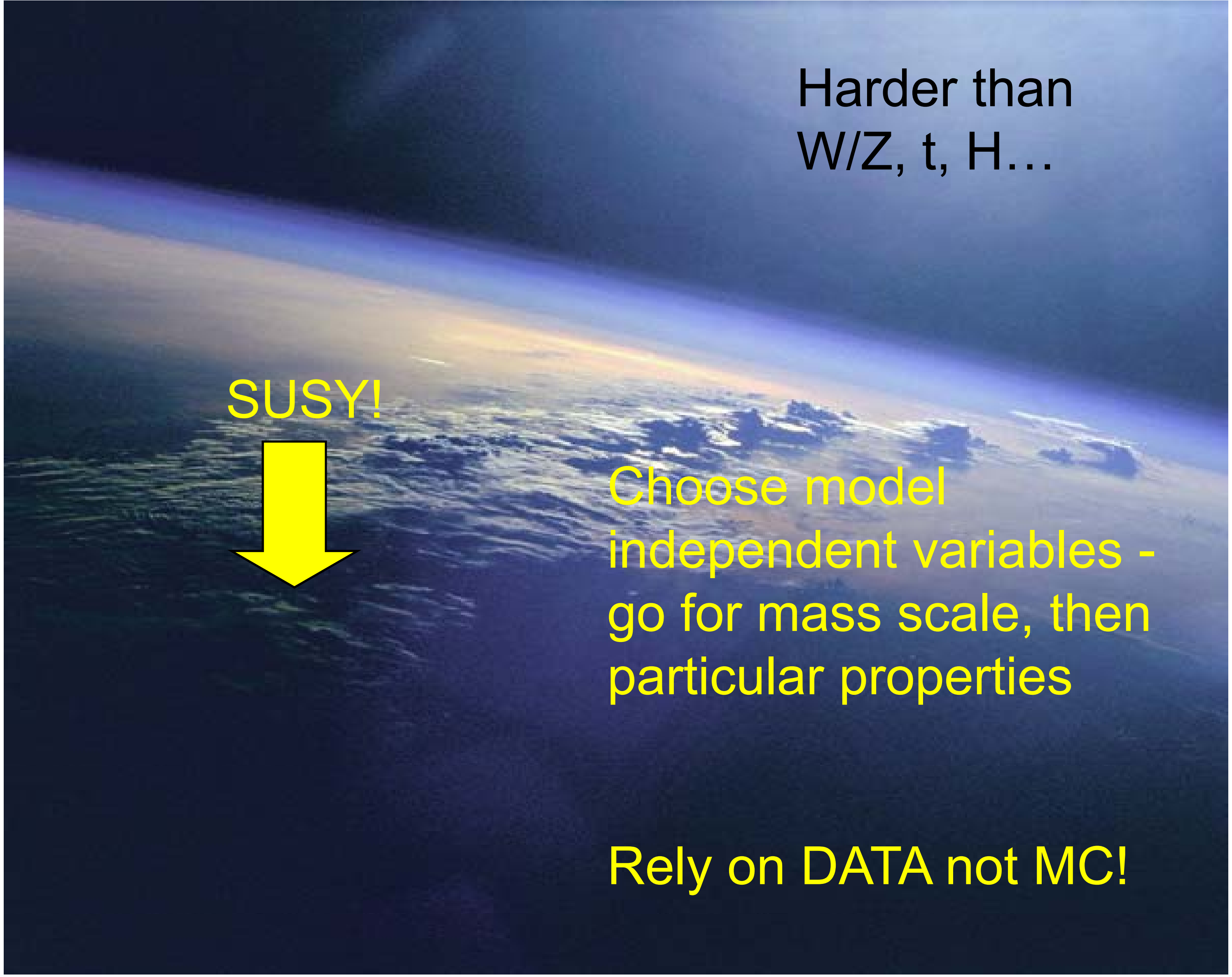
SUSY Signatures





- 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 $t \rightarrow Wb$.
- Biggest physics background is neutrino emission (eg $Z \rightarrow \nu\nu$)

Closing in on SUSY

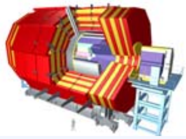


Harder than
W/Z, t, H…

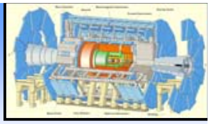
SUSY!

Choose model independent variables - go for mass scale, then particular properties

Rely on DATA not MC!



Strategy for SUSY Searches



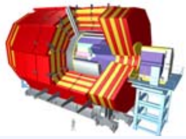
Search for inclusive signals, measure SUSY mass scale. Inclusive signals contain a distinct signature which can be produced by many processes.

Make detailed measurements of exclusive modes, extract kinematic end-points and combinations of masses, in as model independent way as possible. Use global fits to extract model parameters.

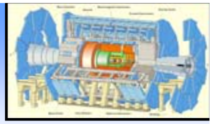
Discovery of SUSY is simple: understanding is not!

http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/TDR/access.html

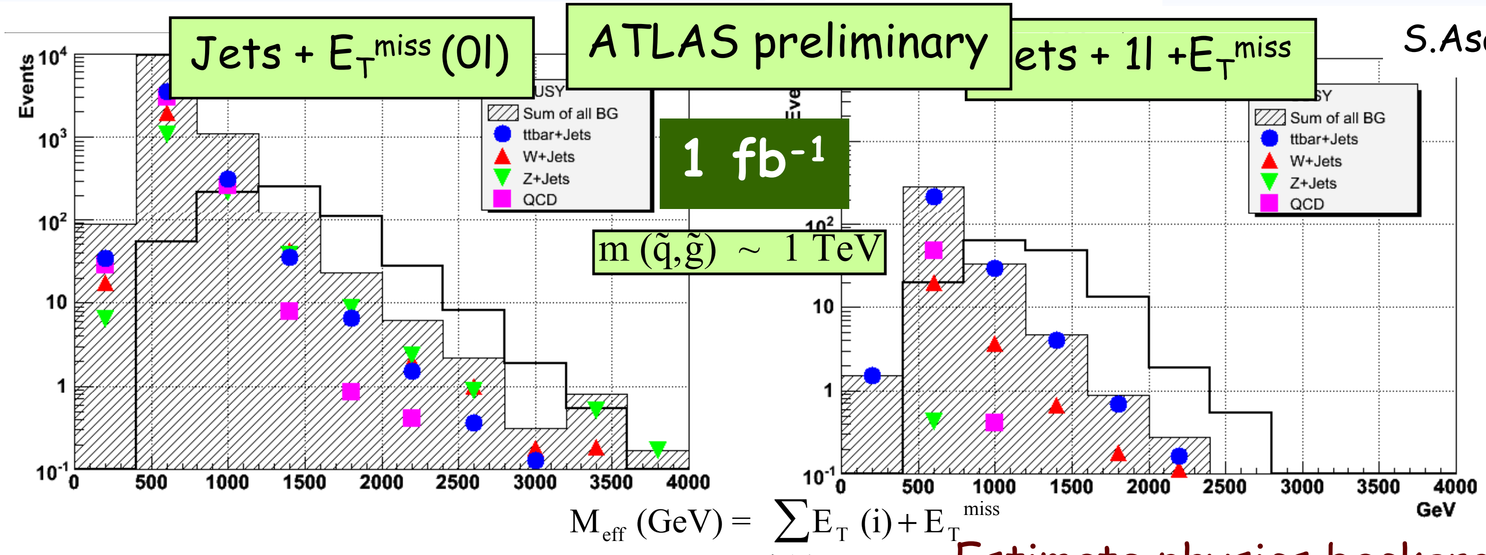
http://cmsdoc.cern.ch/cms/cpt/tdr/index.html for complete information.



Inclusive SUSY search



S.Asai



Jets + E_T^{miss} (0l)

ATLAS preliminary

Jets + 1l + E_T^{miss}

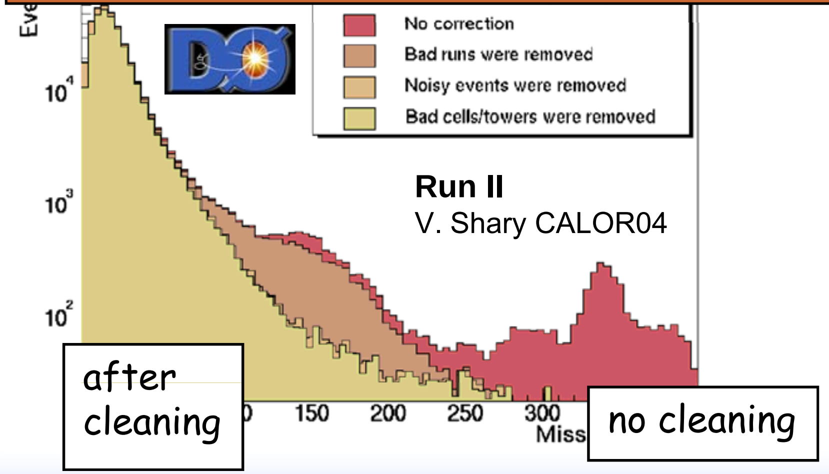
$1\ fb^{-1}$

$m(\tilde{q},\tilde{g}) \sim 1\ TeV$

$$M_{eff}\ (GeV) = \sum_{i=1,4} E_T\ (i) + E_T^{miss}$$

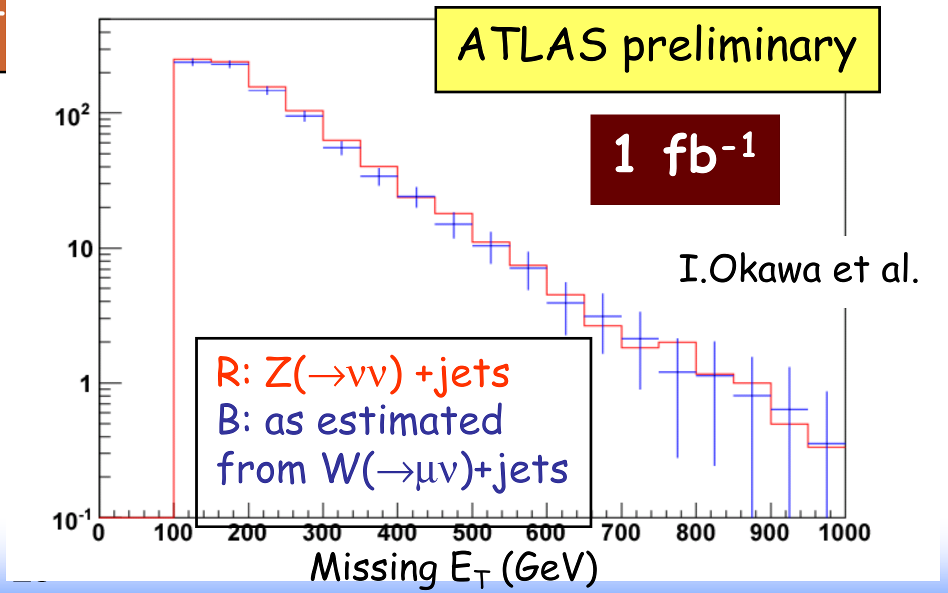
Estimate physics backgrounds using data (control samples)

E_T^{miss} spectrum contaminated by cosmics, beam-halo, machine/detector problems, et



after cleaning

no cleaning



ATLAS preliminary

$1\ fb^{-1}$

I.Okawa et al.

R: $Z(\rightarrow\nu\nu)$ +jets

B: as estimated from $W(\rightarrow\mu\nu)$+jets

Andy Parker

Inclusive SUSY search reach

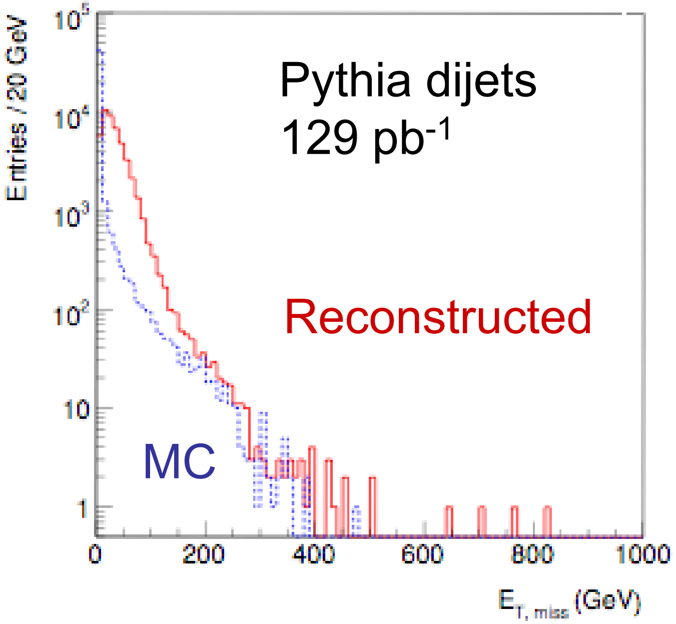
Observe that best reach is obtained in processes with jets and missing p_T. - here the signature simply relies on the missing energy from the two LSP's leaving the event.

But a single lepton can improve S/B. This is because many heavy SUSY particles produce leptons in their decay chains.

Events with multiple leptons have less background, but do not give such good reach, because they rely on the production of weakly interacting particles, and hence have lower rates, and poorer statistics.

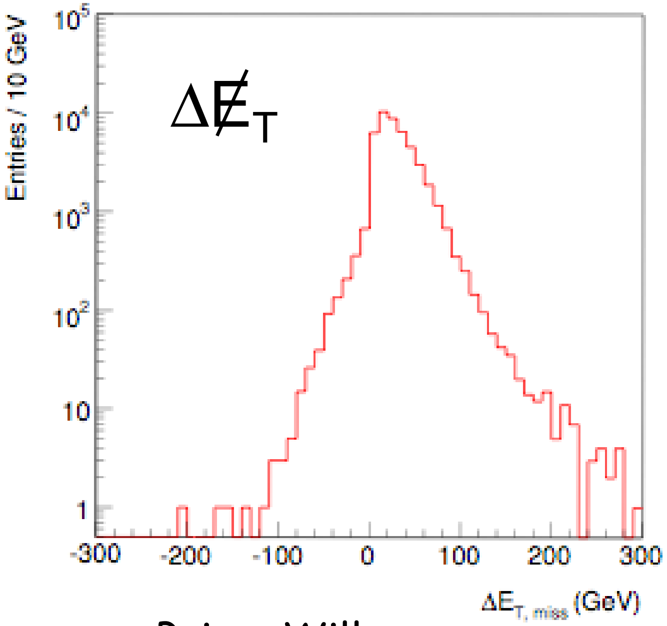
The reach does not depend greatly on the other parameters (sgn(μ) and tanβ).

Missing ET studies



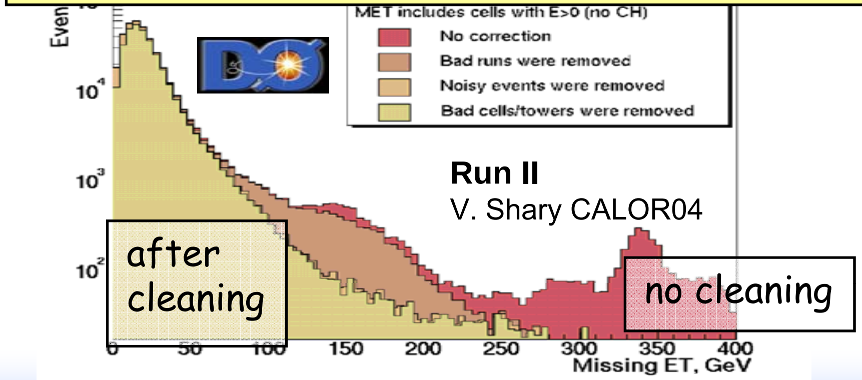
Pythia dijets
129 pb^{-1}

Reconstructed



Paige, Willocq

E_T^{miss} spectrum contaminated by cosmics, beam-halo, machine/detector problems, etc.



Run II
V. Shary CALOR04

after cleaning

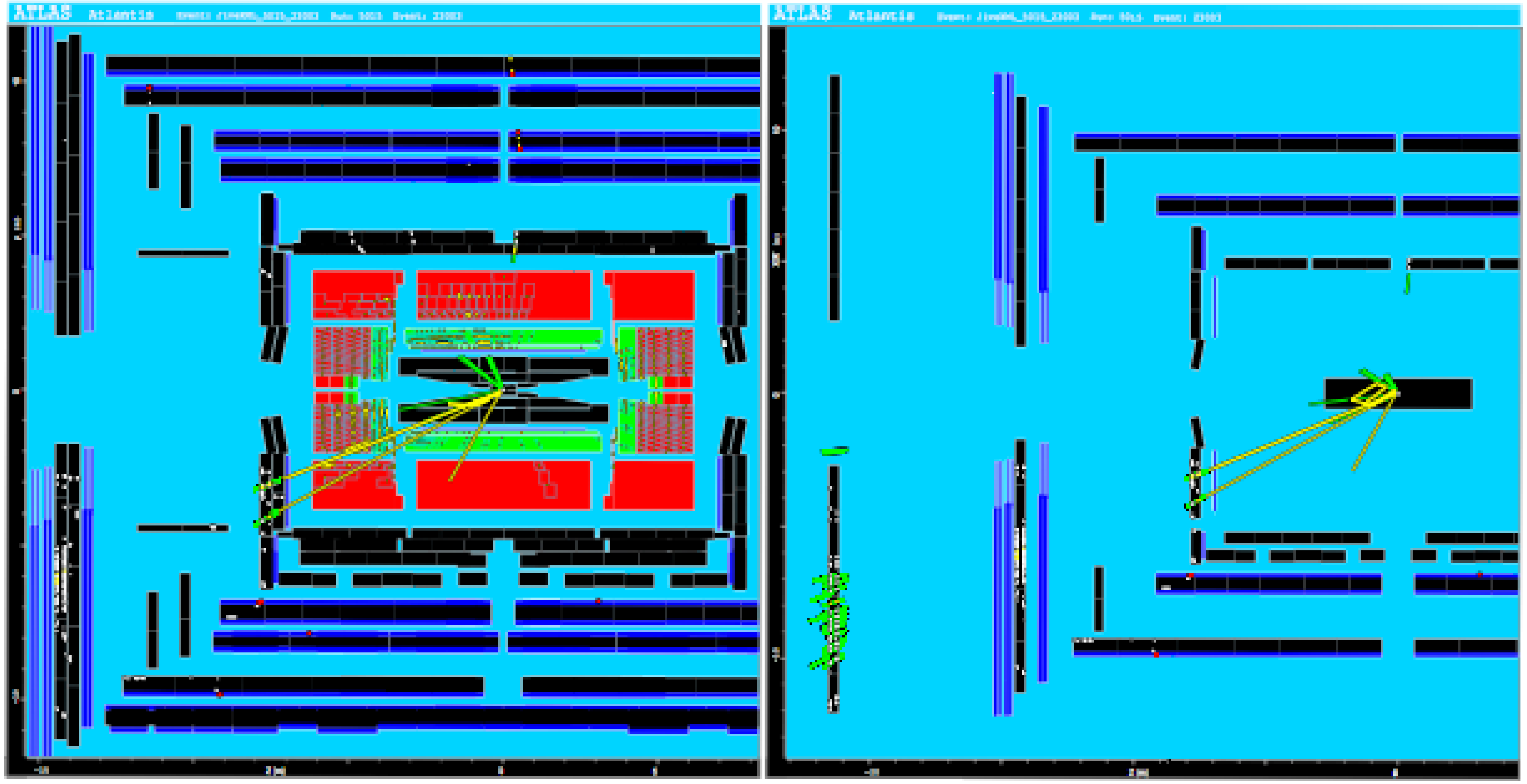
no cleaning

Study of dijet events shows resolution in missing ET and tails in reconstruction.

Fake missing ET

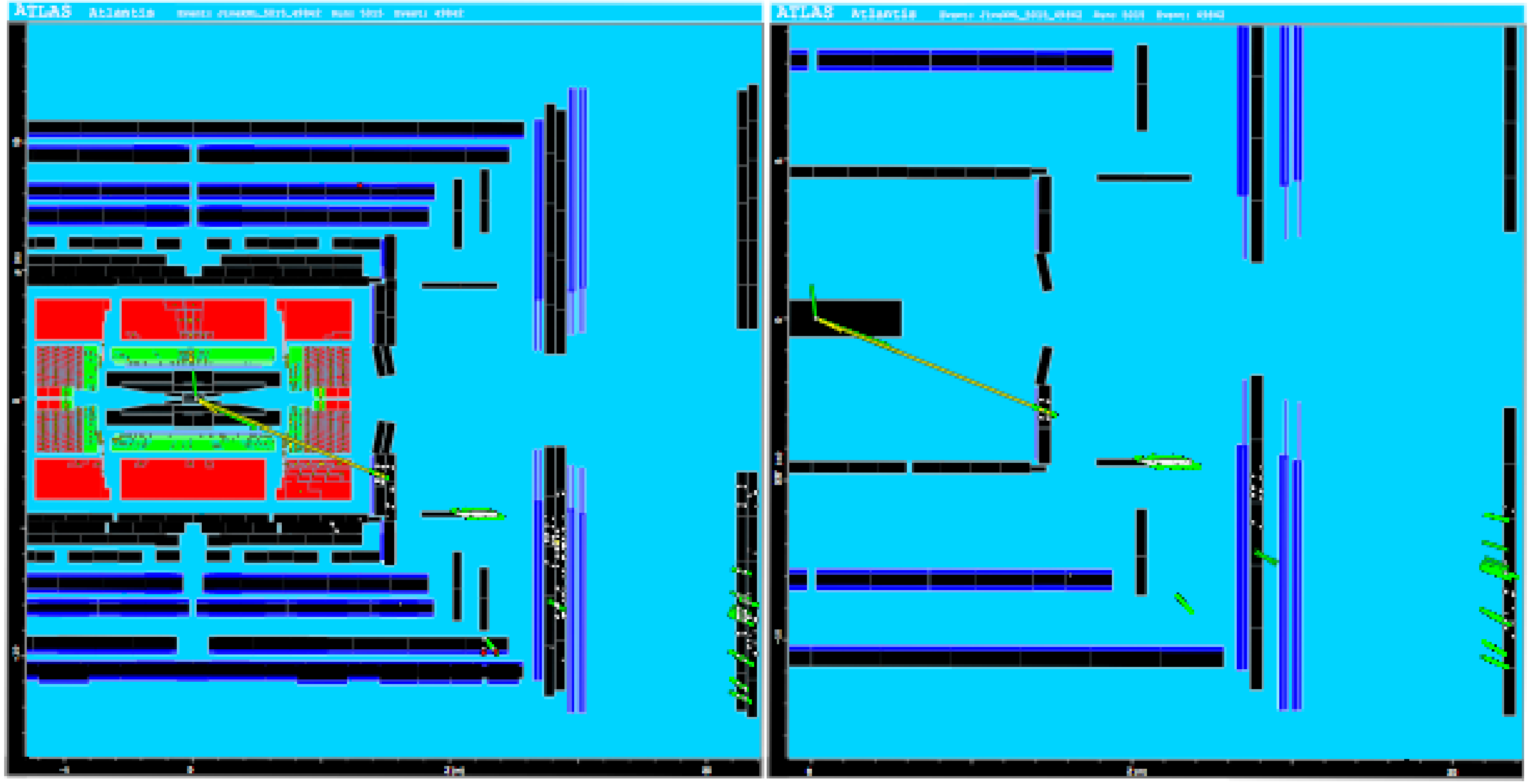
Four events with shower from TileExt/HEC crack giving fake muons:

Event 23003: $\not{E}_T = 508\,\mathrm{GeV}$, three muons with $520\,\mathrm{GeV}$:



Muon with $-495\,\mathrm{GeV}$ matches ID track with $-172 \pm 17\,\mathrm{GeV}$?

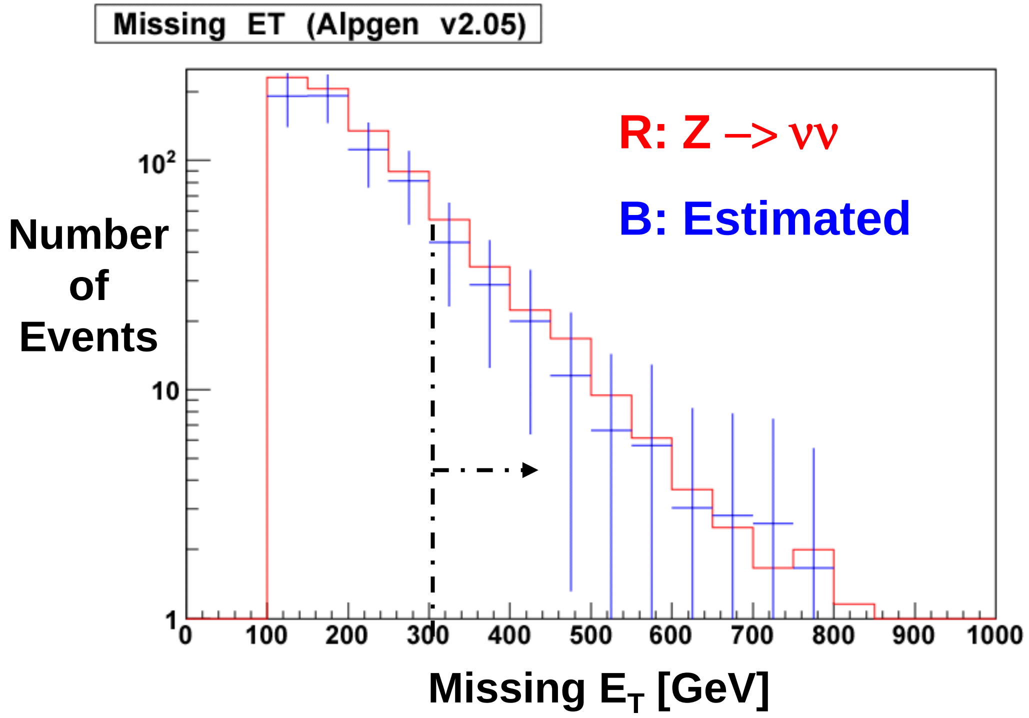
Event 49842: $E_T = 1266\,\mathrm{GeV}$, one muon with $1310\,\mathrm{GeV}$:



Muon with $1310\,\mathrm{GeV}$ matches ID track with $111 \pm 5.4\,\mathrm{GeV}$? Give Moore credit for effort here. . . .

Z –> νν Missing E_T Distribution

Okawa et al



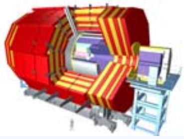
This blue distribution is obtained from Z –> μμ events

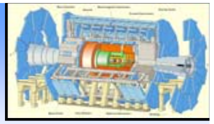
Muon reconstruction efficiencies and Z Decay branching fractions are considered

Number of Event ($E_T$miss > 300GeV)
157 +/- 13 (Z –> νν)
142 +/- 39 (Z –> μμ)

They are consistent, and the estimation is successful.

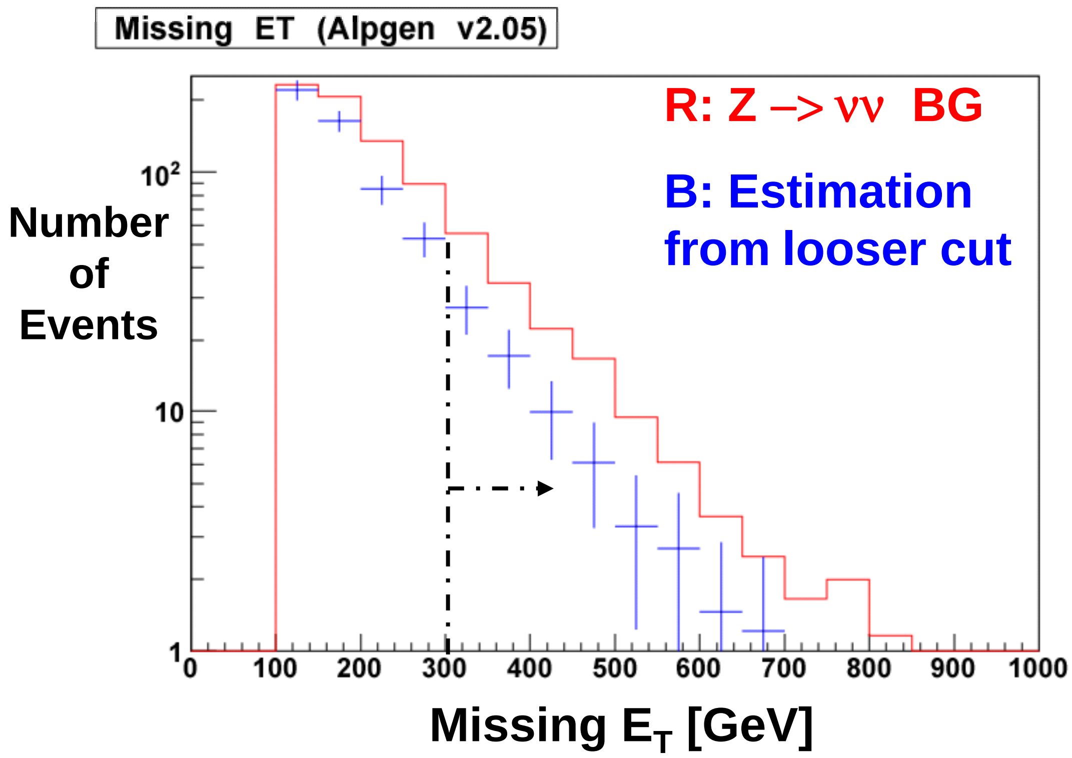
But statistically limited





$Z \to \nu\nu$ Missing E_T Distribution Extrapolation from Looser Cut

Okawa et al



Number of events

(missing E_T > 300 GeV)

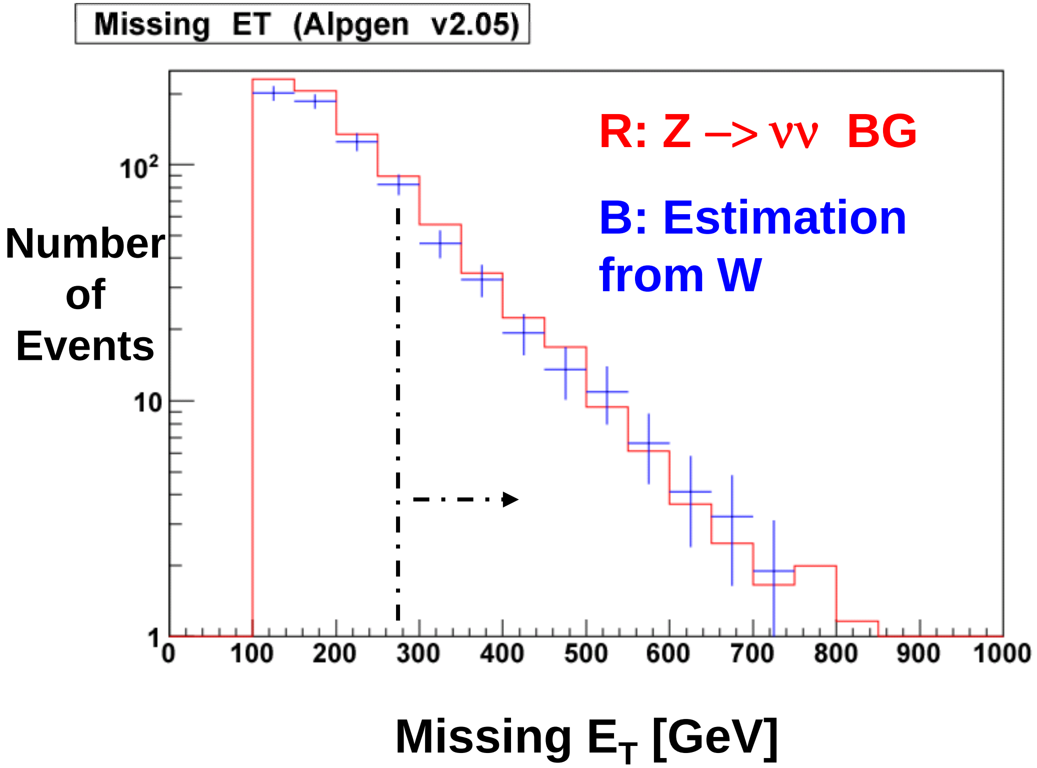
157 +/- 13 ($Z \to \nu\nu$)
77.9 +/- 10.9 ($Z \to \mu\mu$)

Monte Carlo

Loose selection samples have a lot more statistics, and errors are small as we have expected.

But the kinematics seems to be different.

Estimations from W+n jet Samples



Okawa et al

Number of Event ($E_T$miss > 300GeV)

157 +/- 13 (Z –> νν)

134 +/- 10 (W –> μν)

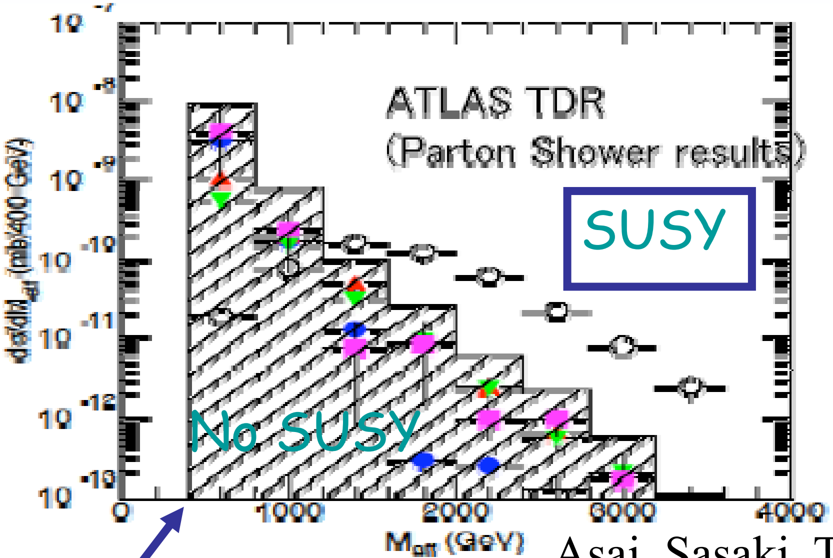
W sample gives better statistics and good match to Z distribution

SUSY Mass Scale

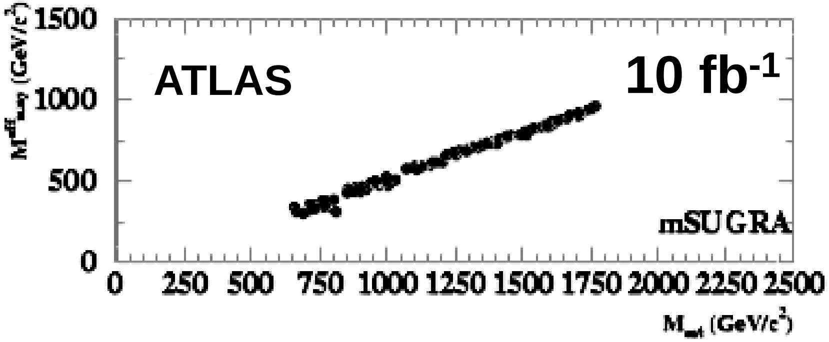
Look at hardest jets/leptons

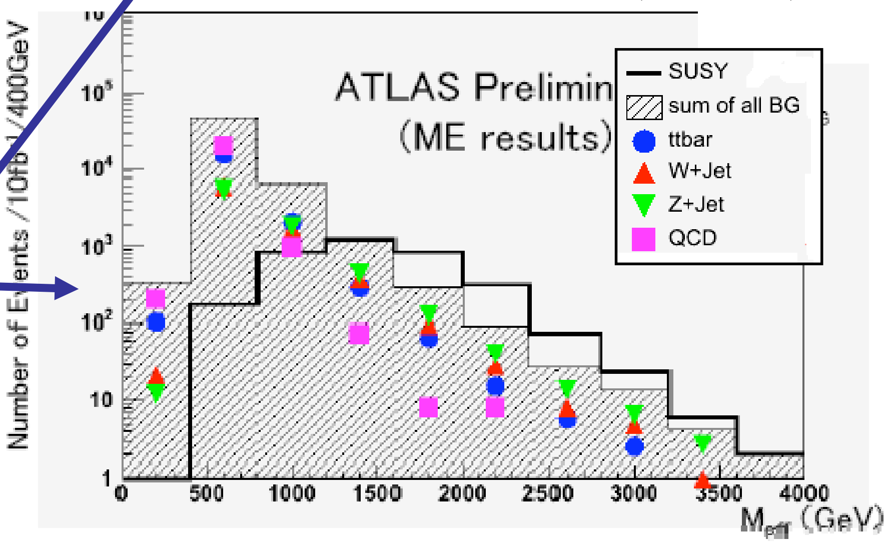
$$M_{eff} = E_T^{miss} + \sum_{i=1,4} p_T^i$$

Distribution peaked at ~2x SUSY mass scale



Asai, Sasaki, Tanaka

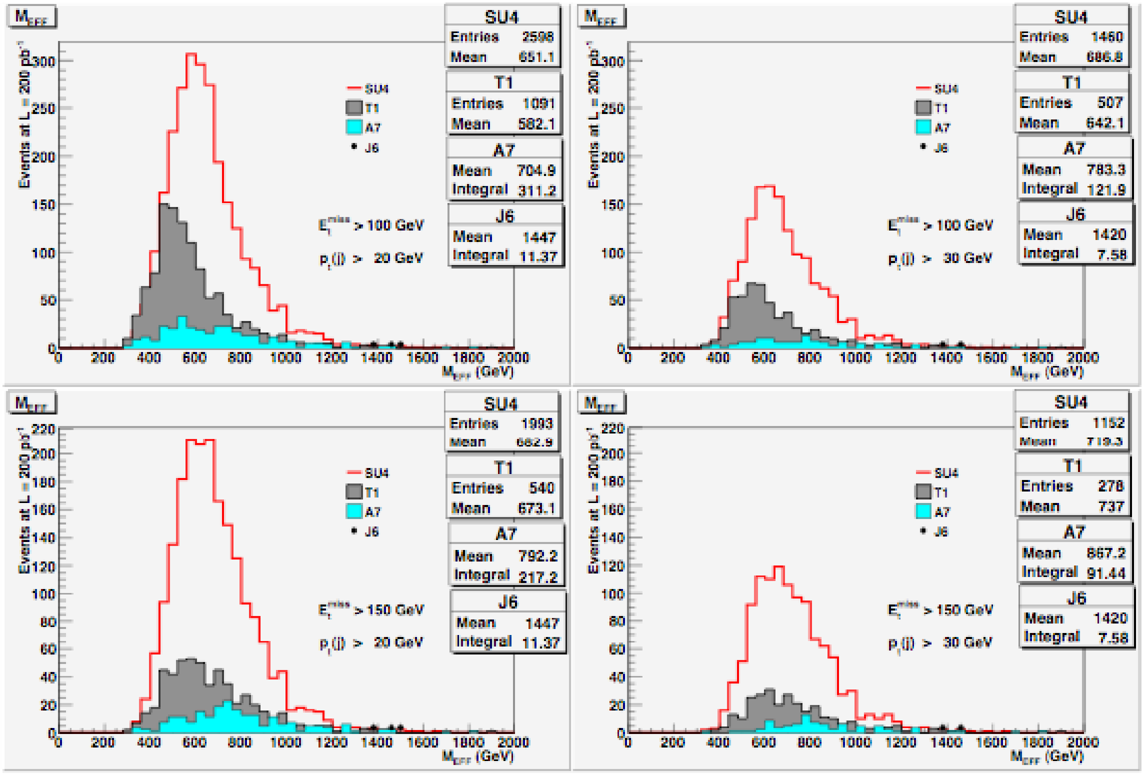




Parton shower MC underestimates rate of high mass, high multiplicy background

Meff at point SU4

M_{EFF} of the events passing selection cuts



$S/B > 1$ for $M_{EFF} > 400$ GeV

SU4 $< M_{EFF} >$ is higher than 650 GeV ; $M_{\tilde{q}\tilde{g}} = \min(m(\tilde{g}), m(\tilde{q})) \sim 400$ GeV

Krstic et al - Belgrade

Point SU4:

m_0 = 200 GeV

$m_{1/2}$ = 160 GeV

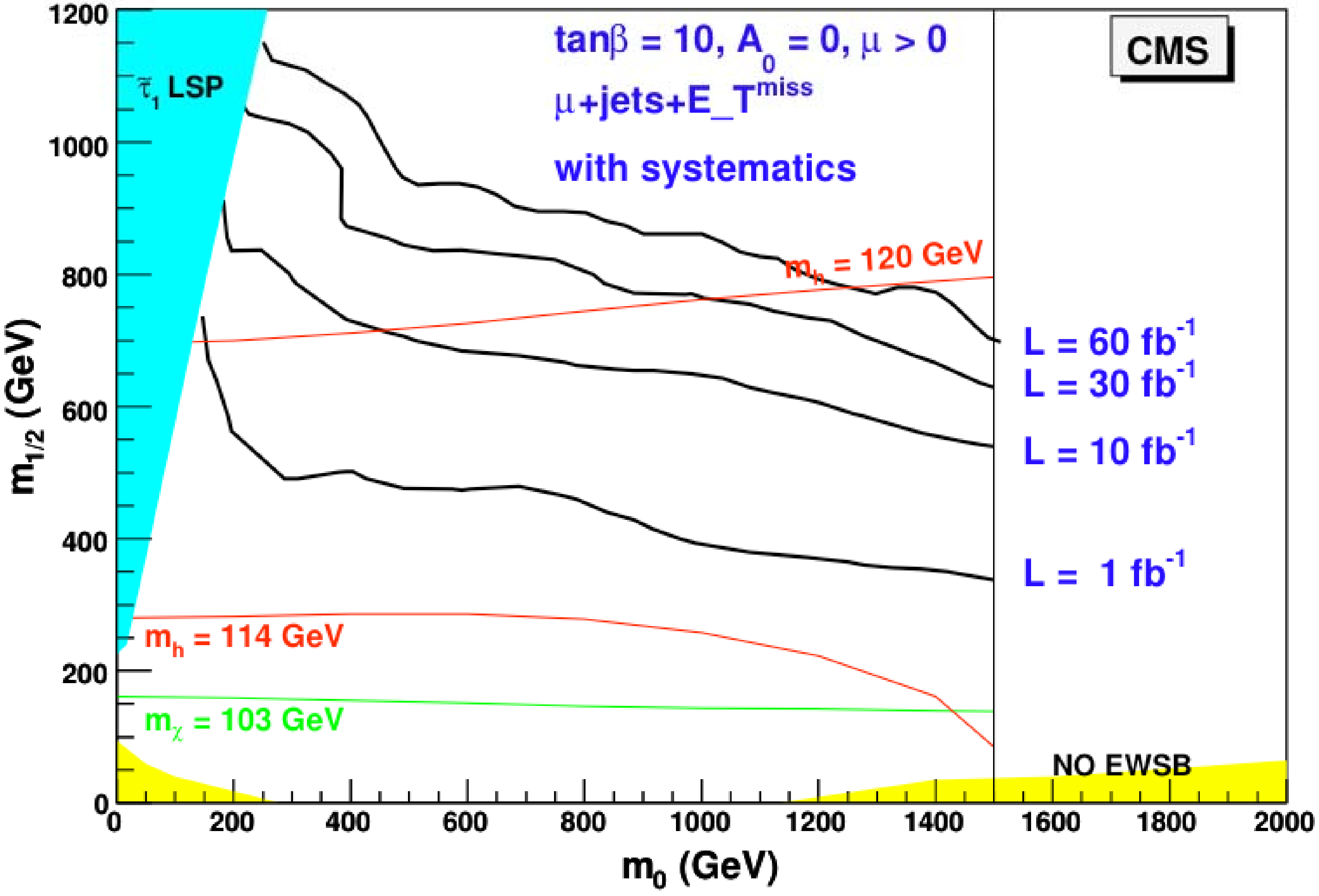
σ= 230 pb

σ-> 200-300k events in 2008?

Cf ttbar σ = 883 pb

Large production rates, large excess at high M_{eff}.

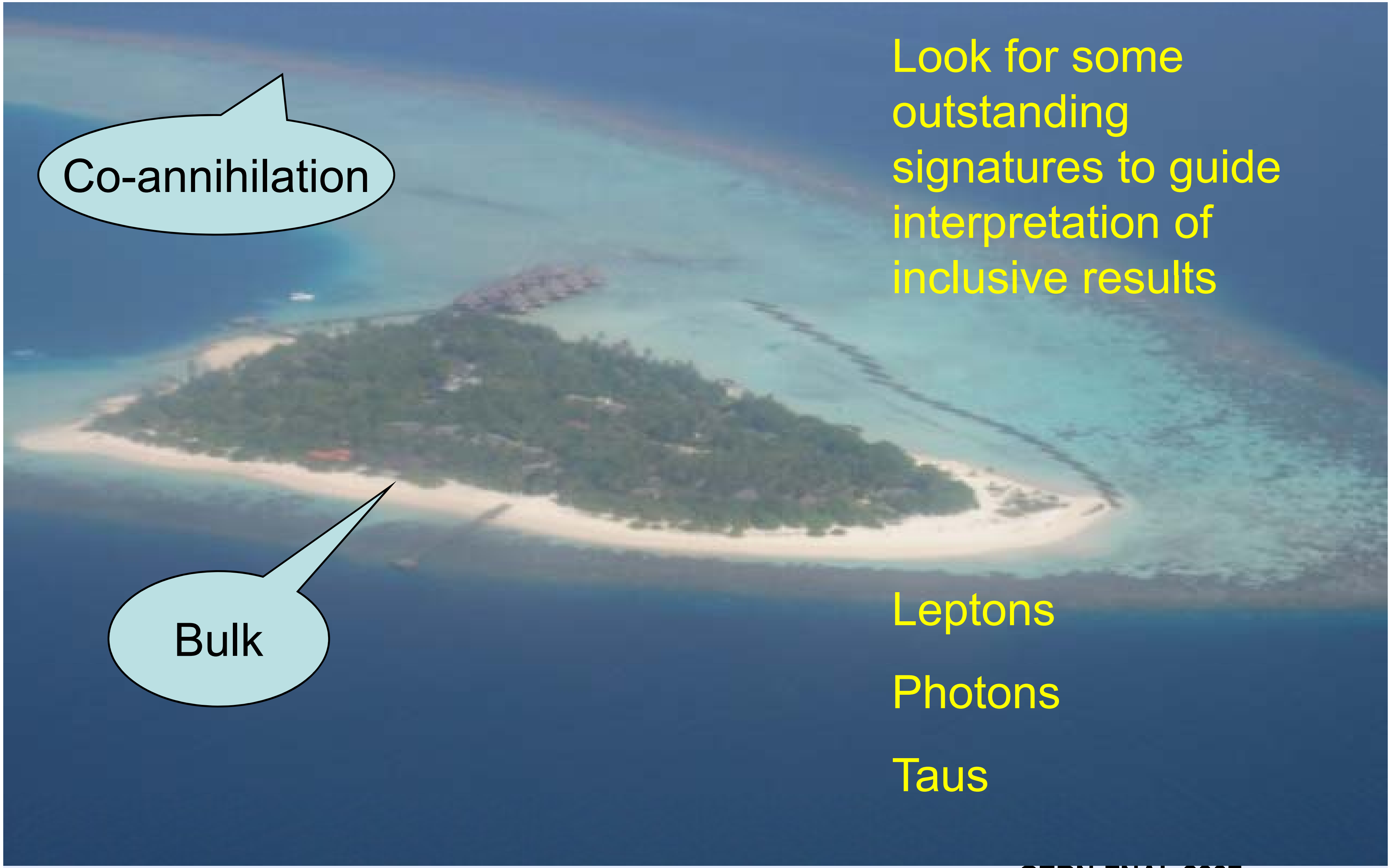
CMS inclusive μ+jets



Inclusive search in μ+jets+E_t^{miss} channel

E_t^{miss}>210 GeV
E_t^{Jet}>730 GeV

Finding the best spot…



Look for some outstanding signatures to guide interpretation of inclusive results

Leptons

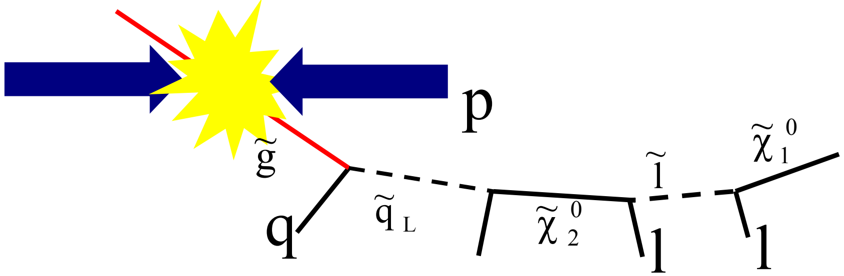
Photons

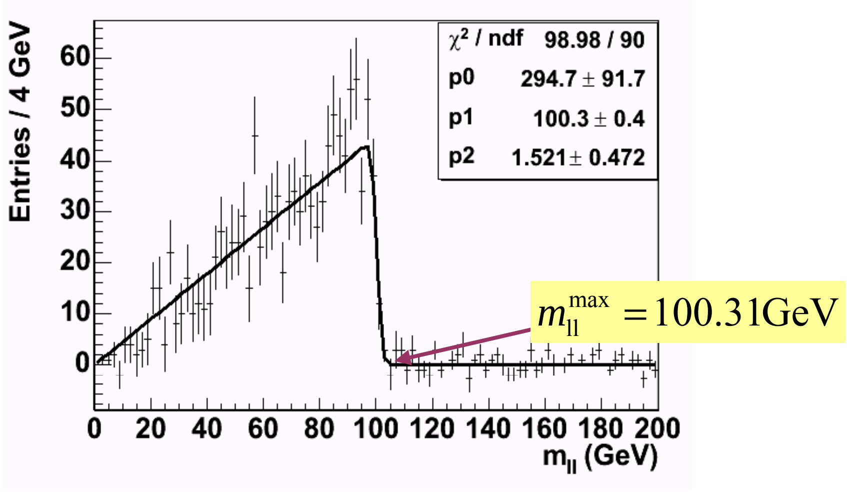
Taus

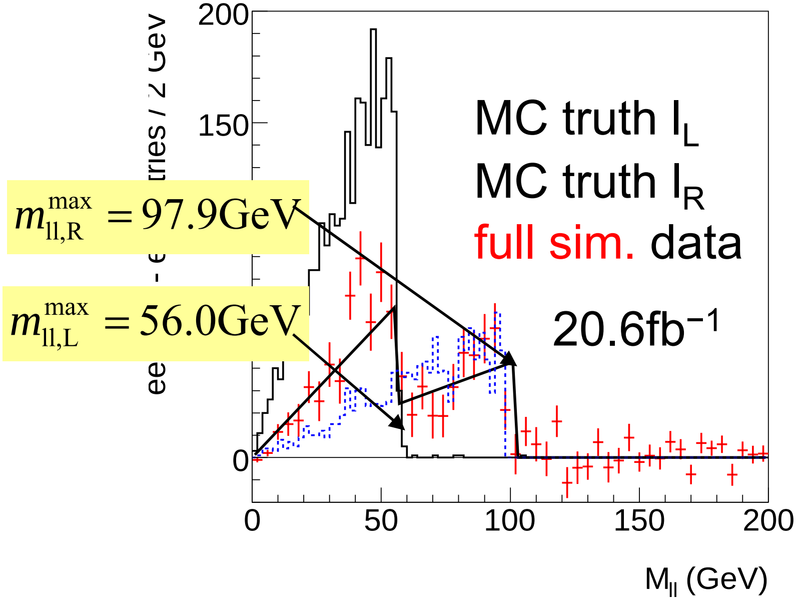
Leptonic signatures

Aracena - Bern

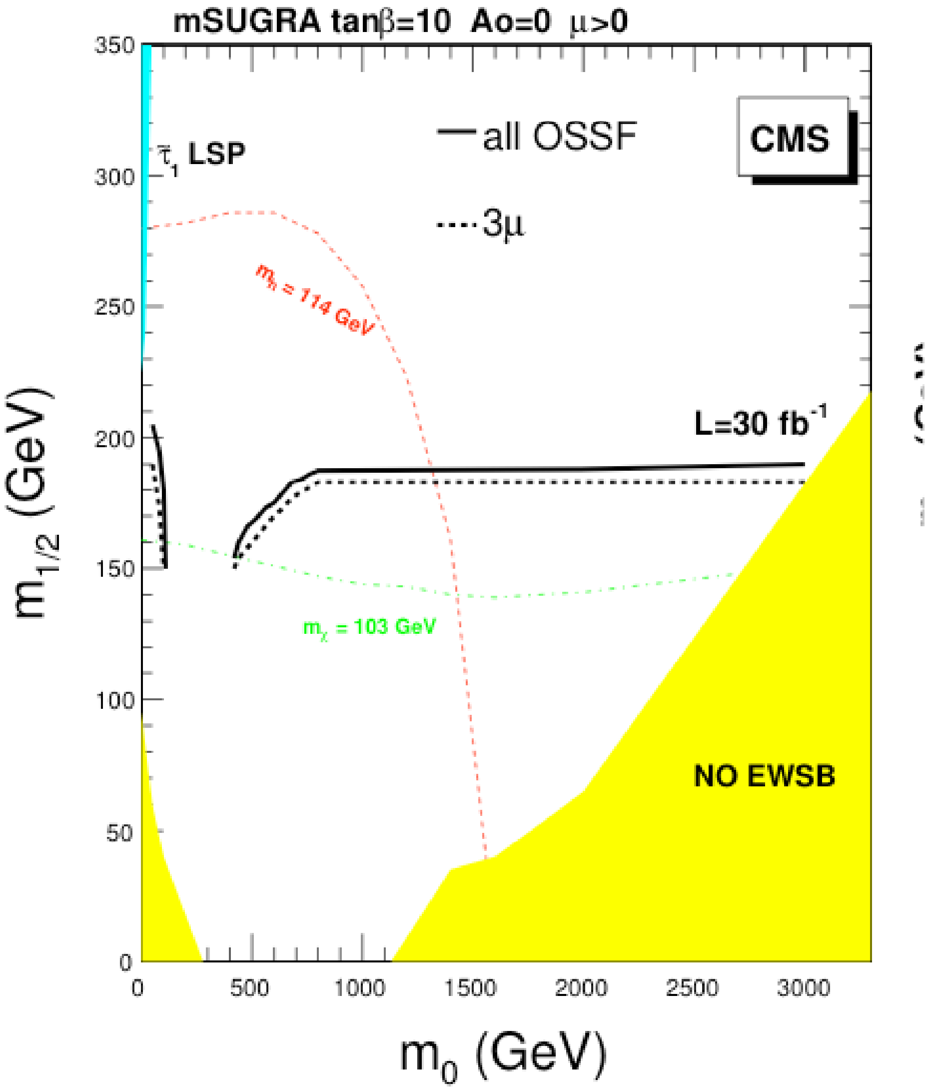
- **In many SUSY scenarios we look at leptonic decays of neutralinos:**





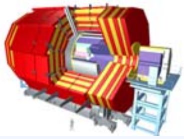


CMS trilepton search

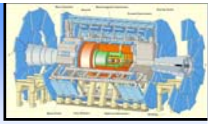


$$pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$$

Trileptons give access to chargino/neutralino production.
Reach is small because weak production mechanism -> low statistics.
Clean signature.



Exclusive SUSY processes

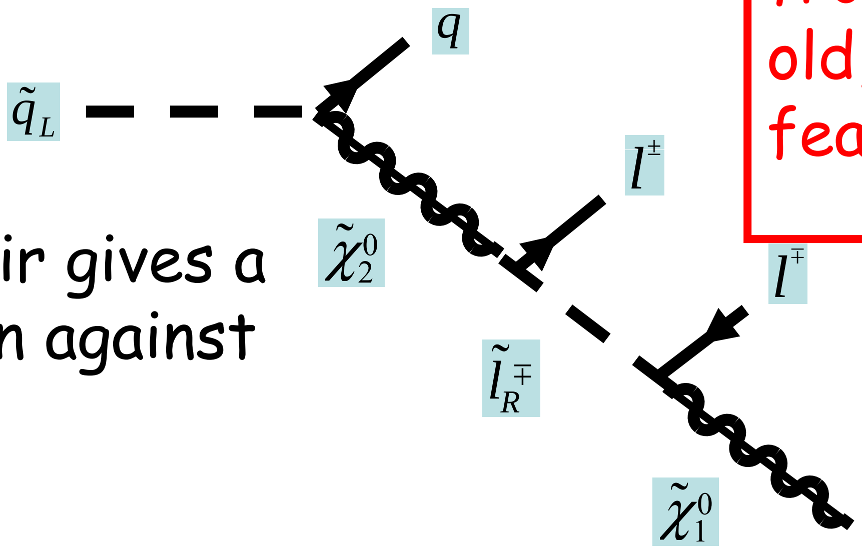


Look for processes with a defined set of particles in the final state, from a particular decay chain.

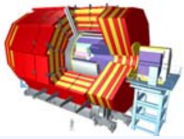
This requires that the process can be identified cleanly - so cannot use pure jet+missing energy channels.

A useful decay mode is from the chain

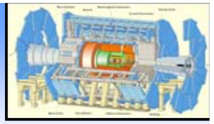
Example analysis from ATLAS TDR - old, but shows main features



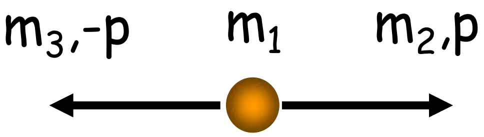
The lepton pair gives a good rejection against background.



Each step in the chain is a two body decay.

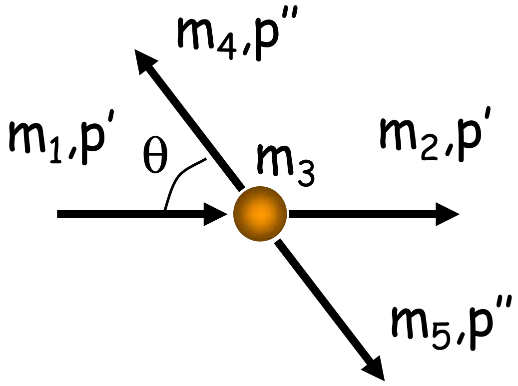


The momentum of the outgoing particles is fixed in the rest frame of the parent, and is only a function of the 3 masses.



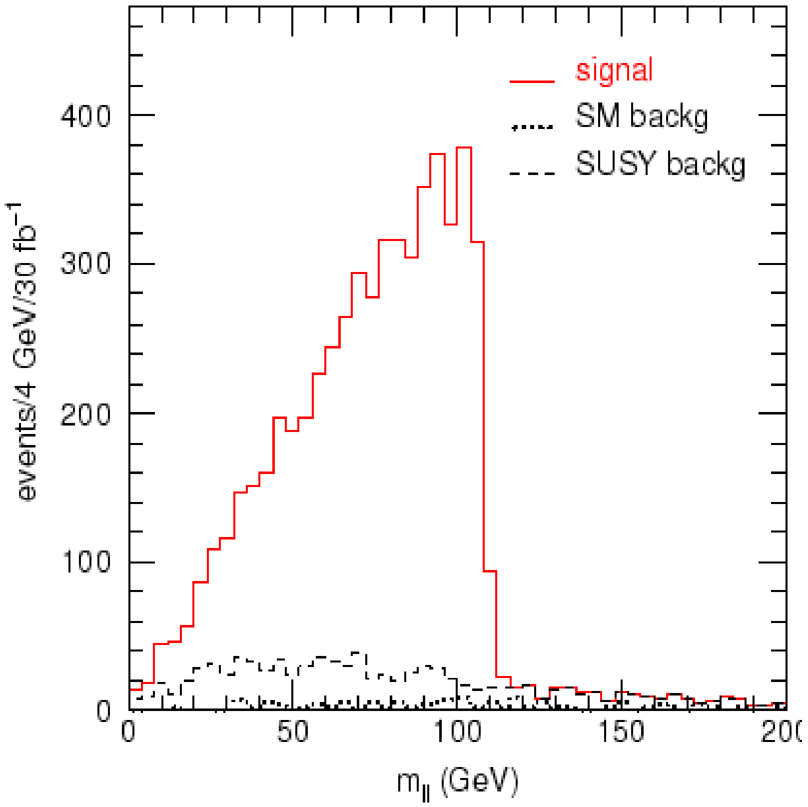
Consider two successive 2-body decays in the rest frame of particle 3:

Invariant masses of pairs of particles given by masses and θ only



Invariant mass distributions will show “edges” at max and min allowed values.

The Dilepton Edge

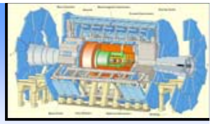


$$\tilde{\chi}_2^0 \rightarrow \tilde{\ell}_R^{\pm} \ell^{\mp} \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$$

Invariant mass of lepton pairs, for simulated data at point 5

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

- Edge position can be measured to 0.5 GeV with 30 fb^{-1}
- 5800 signal events, 880 SUSY background, 120 SM background - note dominant backgroud is from SUSY



The edge in the dilepton spectrum is a strong signal, clearly due to new dynamics.

The leptons in the signal must be of opposite sign and from the same family, since the slepton carries the family information down the chain. Most background comes from processes with unrelated leptons.

eg: WW, or chargino pairs create equal numbers of μμ, ee, eμ and μe events.

Hence most background can be subtracted using opposite sign eμ pairs.

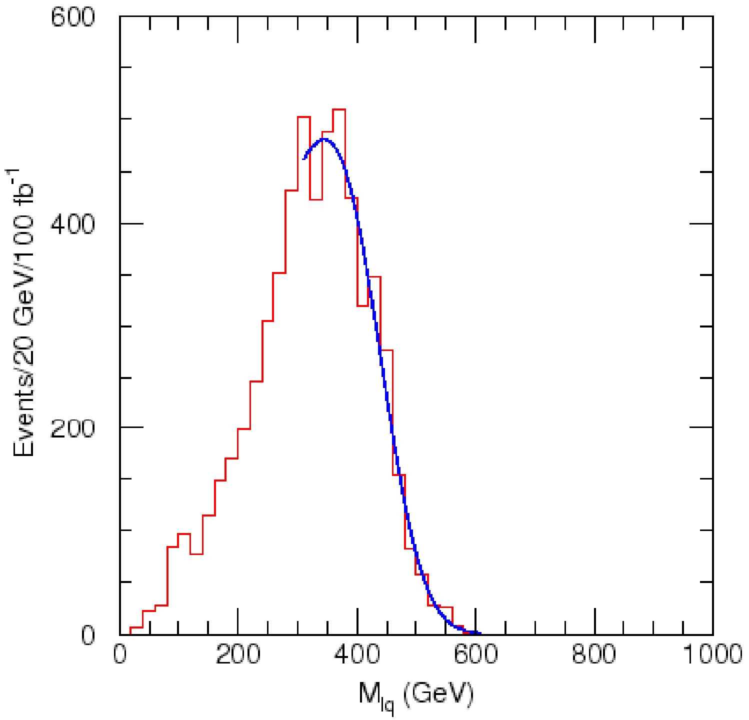
The position of the edge depends on the masses of the slepton and the two neutralinos.

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

Building the chain

$$\tilde{q}_L \rightarrow \tilde{\chi}_2^0 q \rightarrow \tilde{\ell}_R^{\pm} \ell^{\mp} q \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^- q$$

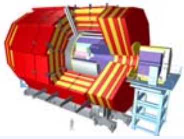
4 unknown masses in this decay chain. One constraint so far from dilepton edge

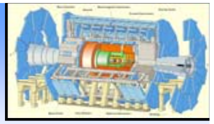


M(lq)
where l is the first lepton produced in chain

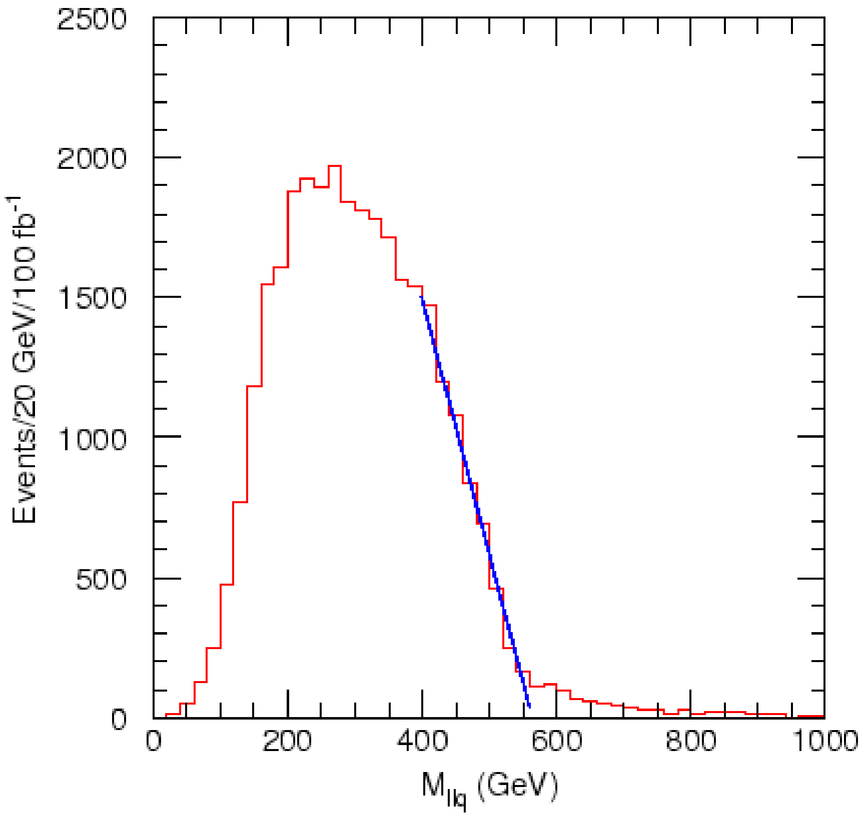
$$M_{lq}^{\max} = \left[\frac{\left(M_{\tilde{q}_L}^2 - M_{\tilde{\chi}_2^0}^2\right)\left(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{l}_R}^2\right)}{M_{\tilde{\chi}_2^0}^2} \right]^{1/2}$$

…get another constraint.





$$\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{\ell}_R^{\pm} \ell^{\mp} q \to \tilde{\chi}_1^0 \ell^+ \ell^- q$$



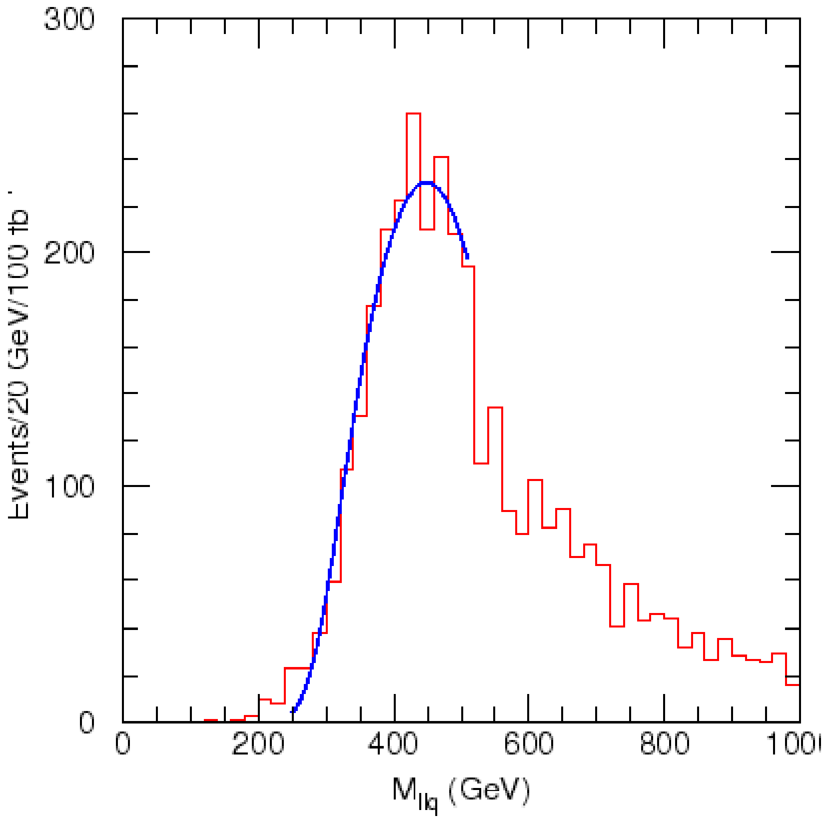
M(llq)

Mass of lepton pair and quark

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

One more constraint…3 so far…

$\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{\ell}_R^{\pm} \ell^{\mp} q \to \tilde{\chi}_1^0 \ell^+ \ell^- q$



M(llq)

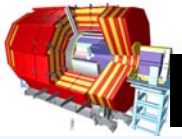
(after some angular selections)

Dilepton+quark mass also has a minimum value which can be measured.

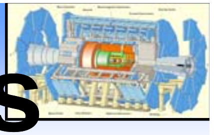
Now have 4 constraints on 4 unknown masses.
⇒ Can solve for all SUSY masses

Can also use information from

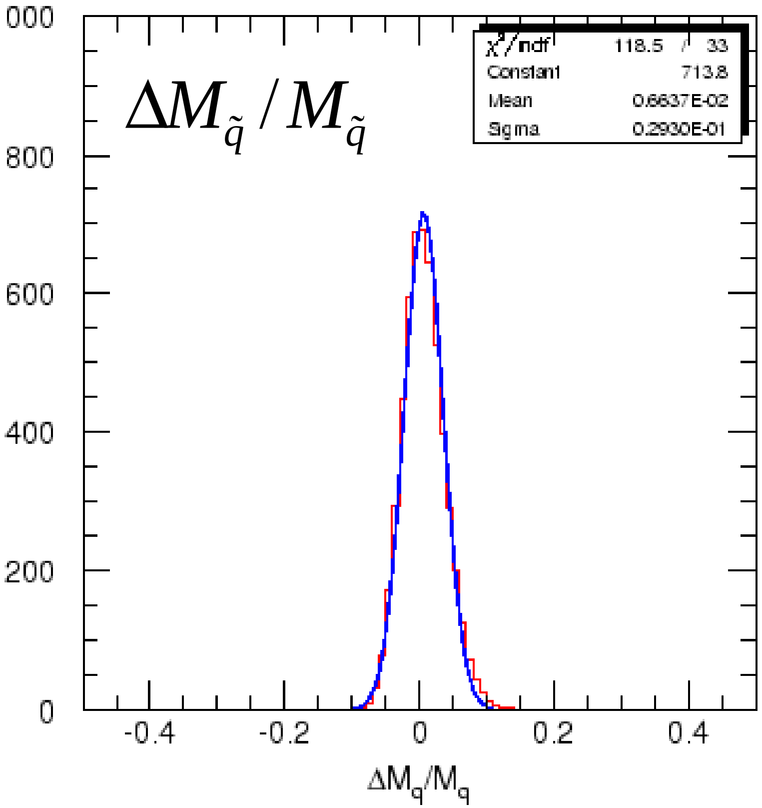
$$q_L \to \tilde{\chi}_2^0 q \to \tilde{\chi}_1^0 hq \qquad h \to b\bar{b}$$



Determination of SUSY masses

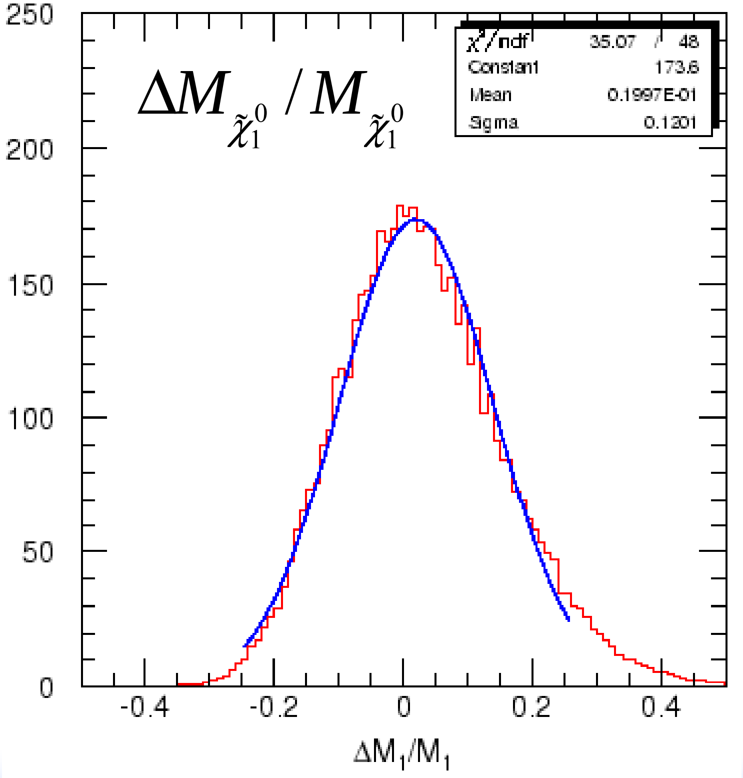


All 4 masses measured from kinematic constraints alone, including the invisible neutralinos (two leave every event…).

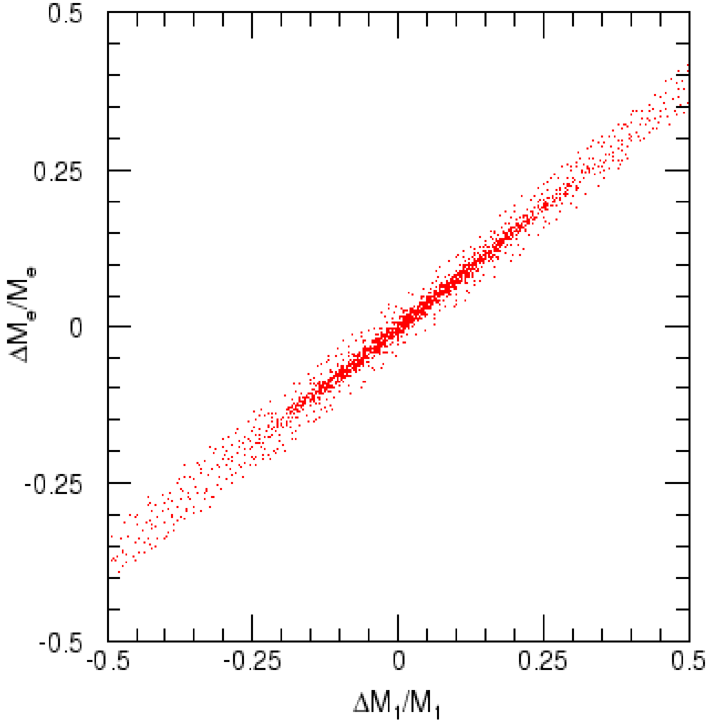


Fractional errors on masses

$\tilde{q}$	±3%	$\tilde{\chi}_2^0$	±6%
$\tilde{\ell}$	±9%	$\tilde{\chi}_1^0$	±12%

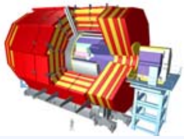


Correlations between mass determinations

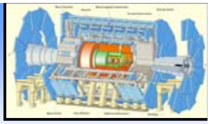


Slepton vs neutralino masses

- Masses determined by the model independent method are highly correlated by common neutralino mass
- Errors are controlled by the measured error on the llq threshold.



Fits to SUGRA models

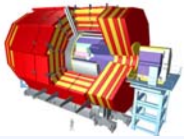


Input measurements and **output parameters** for SUSY fit at Point 5

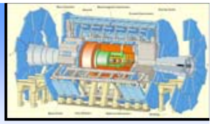
	Low-Luminosity
h mass	92.9 ±1.0 GeV
Dilepton endpoint	108.92 ±0.50 GeV
lq endpoint	478.1 ±11.5 GeV
Ratio of lq/lq endpoints	0.865 ±0.060
llq threshold	271.8 ±14.0 GeV
hq endpoint	552.5 ±10.0 GeV
hq threshold	346.5 ±17.0 GeV

	Low-luminosity	High-Luminosity
m_0	100 +4.1 −2.2 GeV	100.0 ± 1.4 GeV
$m_{1/2}$	300.0 ± 2.7 GeV	300.0 ± 1.7 GeV
$\tan(\beta)$	2.00 ± 0.10	2.00 ± 0.09

Sgn(μ) also determined, but data is insensitive to A_0



Problems with mass measurements

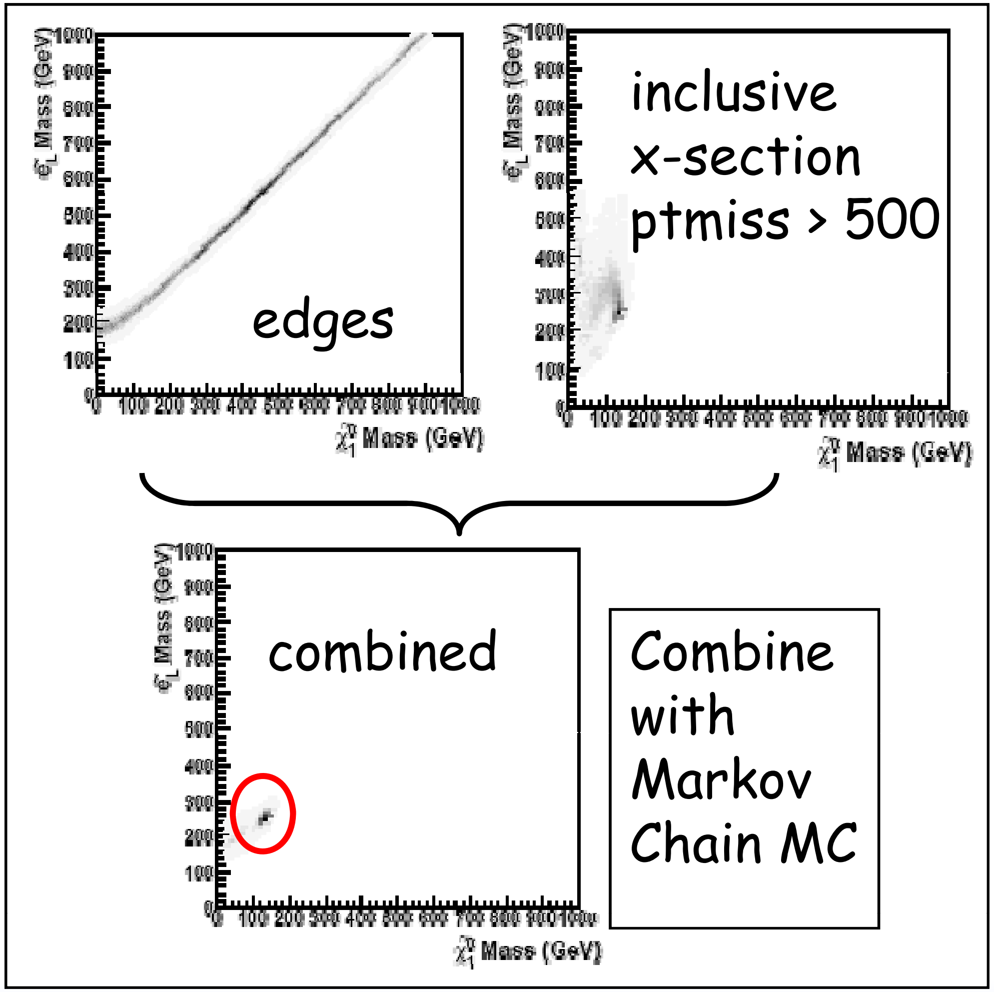


- Analyses work in particular scenario (mSUGRA, GMSB, etc)
- Mass differences measured well, LSP mass poorly
- Decay chain may not exist, or change character across parameter space
- Arkani-Hamed, Kane, Thaler, and Wang look at “inverse map” from 1808 LHC observables to theory parameter space
- Lester, Parker, White use Markov Chain Monte Carlo methods to include many observables and reduce model dependence.

Constraining masses with cross-section information

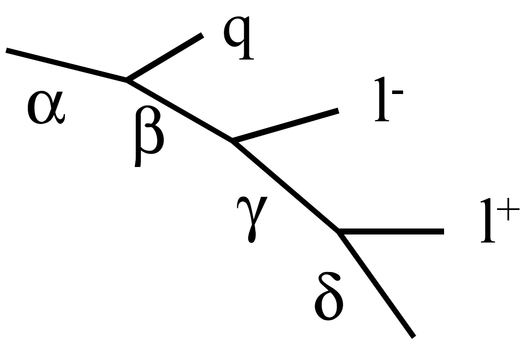
Lester, Parker, White
hep-ph/0508143

- Edges best for mass *differences*
  - Formulae contain differences in m^2
  - Overall mass- scale hard at LHC
- X-sec changes rapidly with mass scale
  - Use inclusive variables to constrain mass scale
  - E.g. >500 GeV ptmiss



Combine with Markov Chain MC

Ambiguities in identification



- May not be possible to identify which particles participate in which decay chains
  - Ambiguity in kinematic edge results
- Can permute neutralino states and L,R sleptons

Lester, Parker, White
hep-ph/0508143

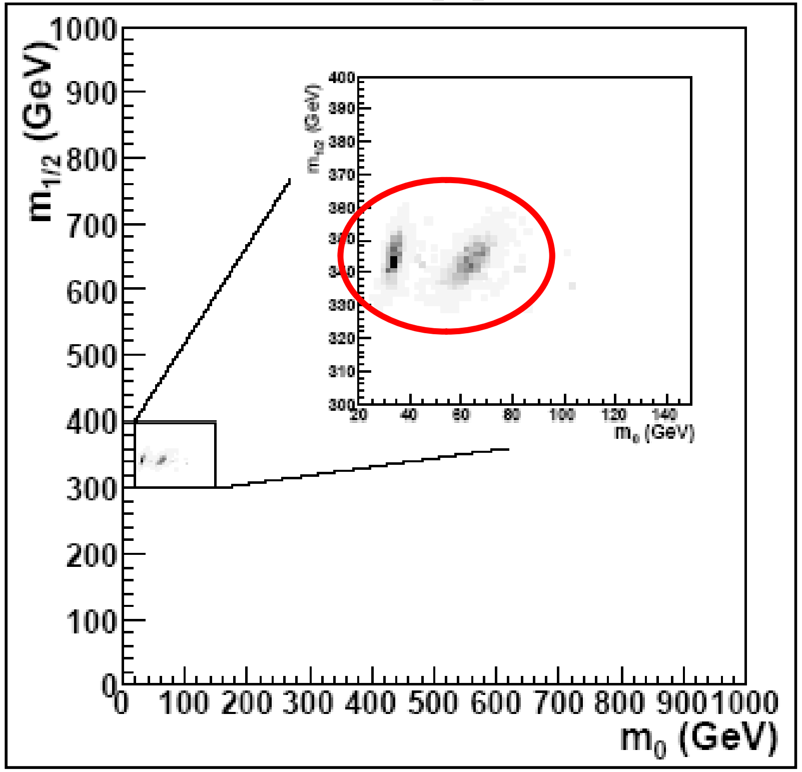
Name	Hierarcrchy
H_1	$m_{\tilde{q}} > m_{\tilde{\chi}_2^0} > m_{\tilde{e}_L} > m_{\tilde{\chi}_1^0}$
H_2	$m_{\tilde{q}} > m_{\tilde{\chi}_3^0} > m_{\tilde{e}_L} > m_{\tilde{\chi}_1^0}$
H_3	$m_{\tilde{q}} > m_{\tilde{\chi}_3^0} > m_{\tilde{e}_L} > m_{\tilde{\chi}_2^0}$
H_4	$m_{\tilde{q}} > m_{\tilde{\chi}_4^0} > m_{\tilde{e}_L} > m_{\tilde{\chi}_1^0}$
H_5	$m_{\tilde{q}} > m_{\tilde{\chi}_4^0} > m_{\tilde{e}_L} > m_{\tilde{\chi}_2^0}$
H_6	$m_{\tilde{q}} > m_{\tilde{\chi}_4^0} > m_{\tilde{e}_L} > m_{\tilde{\chi}_3^0}$
H_7	$m_{\tilde{q}} > m_{\tilde{\chi}_2^0} > m_{\tilde{e}_R} > m_{\tilde{\chi}_1^0}$
H_8	$m_{\tilde{q}} > m_{\tilde{\chi}_3^0} > m_{\tilde{e}_R} > m_{\tilde{\chi}_1^0}$
H_9	$m_{\tilde{q}} > m_{\tilde{\chi}_3^0} > m_{\tilde{e}_R} > m_{\tilde{\chi}_2^0}$
H_{10}	$m_{\tilde{q}} > m_{\tilde{\chi}_4^0} > m_{\tilde{e}_R} > m_{\tilde{\chi}_1^0}$
H_{11}	$m_{\tilde{q}} > m_{\tilde{\chi}_4^0} > m_{\tilde{e}_R} > m_{\tilde{\chi}_2^0}$
H_{12}	$m_{\tilde{q}} > m_{\tilde{\chi}_4^0} > m_{\tilde{e}_R} > m_{\tilde{\chi}_3^0}$

12 different mass hierarchies which lead to qll final state in a series of 2-body decays

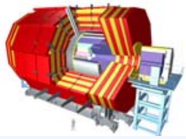
Dealing with ambiguities

Lester, Parker, White
hep-ph/0508143

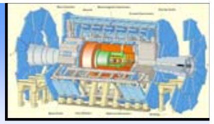
1. Start with experimental observables
   - Kinematic edges etc
2. Use Markov Chain Monte Carlo to explore parameter space
   - Fold in ambiguities
3. Parameterise by low-scale or high-scale parameters



- Find islands of probability
- Fuller exploration of parameter space



The Inverse Problem



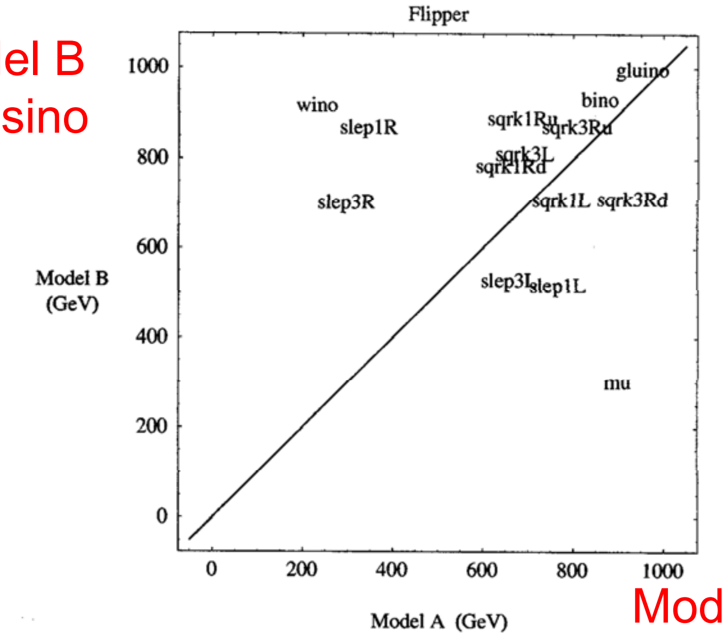
Arkani-Hamed, Kane, Thaler, and Wang hep-ph/0512190

Study "inverse map" from LHC signatures to theoretical parameter space, by studying separation in signature space.

1808 signatures mapped to 15-D parameter space.

Only 5 or 6 independent variables due to correlations!

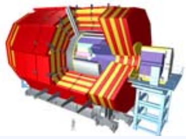
Signatures map to isolated islands in parameter space, showing 10-100 degenerate solutions



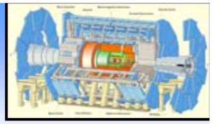
Model B
higgsino
LSP

Model A
wino LSP

Example of a "flipper" - two models where states flip masses depending on the exact parameters



The dilepton edge

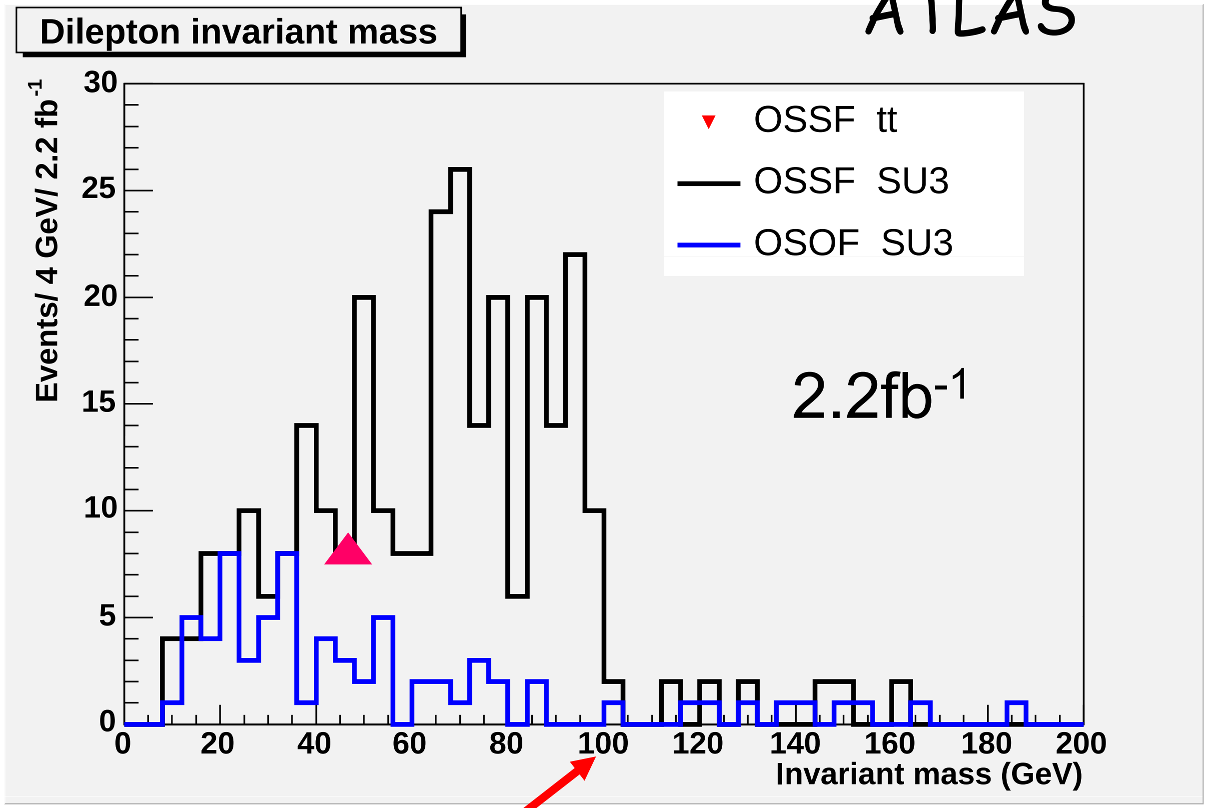


Reco leptons : pT > 10 GeV, η < 2.5, and isolation – TDR CUTS (ID 3)

$$\tilde{\chi}_2^0 \to \tilde{l}_R^{\pm} l^{\mp} \to l^{\mp} l^{\pm} \chi_1^0$$

$$\boxed{\begin{array}{l} OSSF \equiv e^+e^-, \mu^+\mu^- \\ OSOF \equiv e^-\mu^+, e^+\mu^- \end{array}}$$

ATLAS



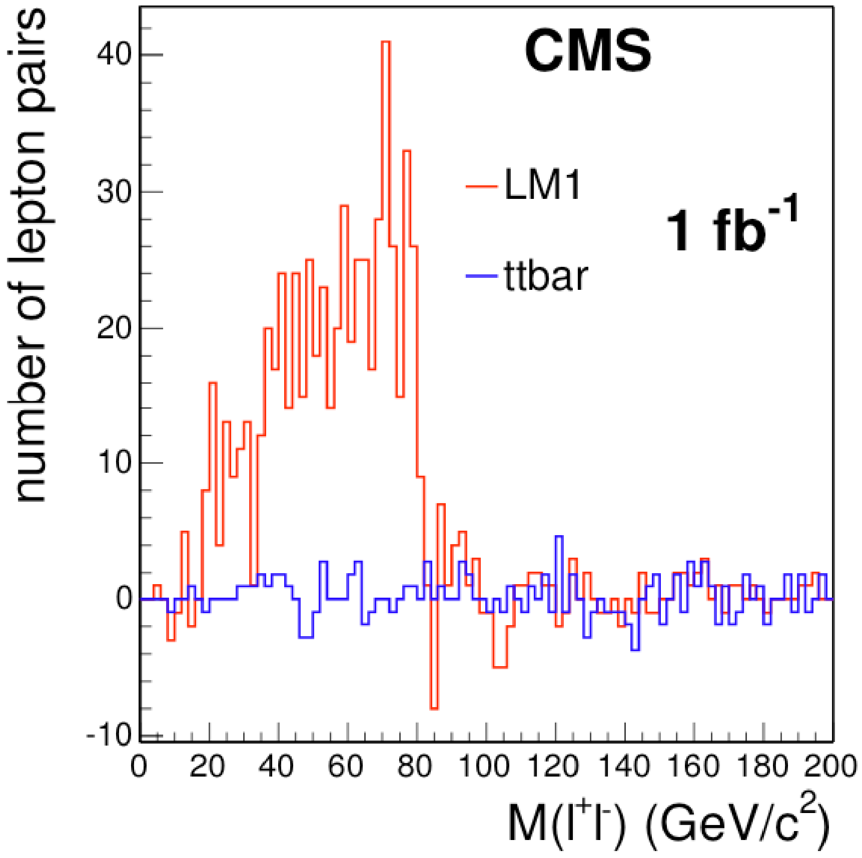
- Evidence for a clear excess in the 40-100 GeV region;
- Negligible ttbar bkg: it’s only 1 event normalised to SU3 statistic!
- Probably flavour subtraction (to estimate SUSY bkg) works at high values of invariant mass;

U. De Sanctis, T. Lari, C. Troncon

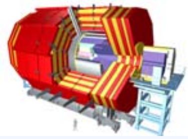
INFN and University of Milan

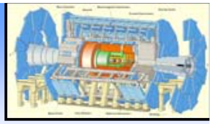
$$M(\chi_2^0) - M(\chi_1^0) = 100.7\,GeV$$ Expected value

CMS dilepton edge



Similar analysis from CMS TDR - clean signature found with 1fb^{-1}





BACK-UP SLIDES