Physics with the Atlas Detector at the LHC

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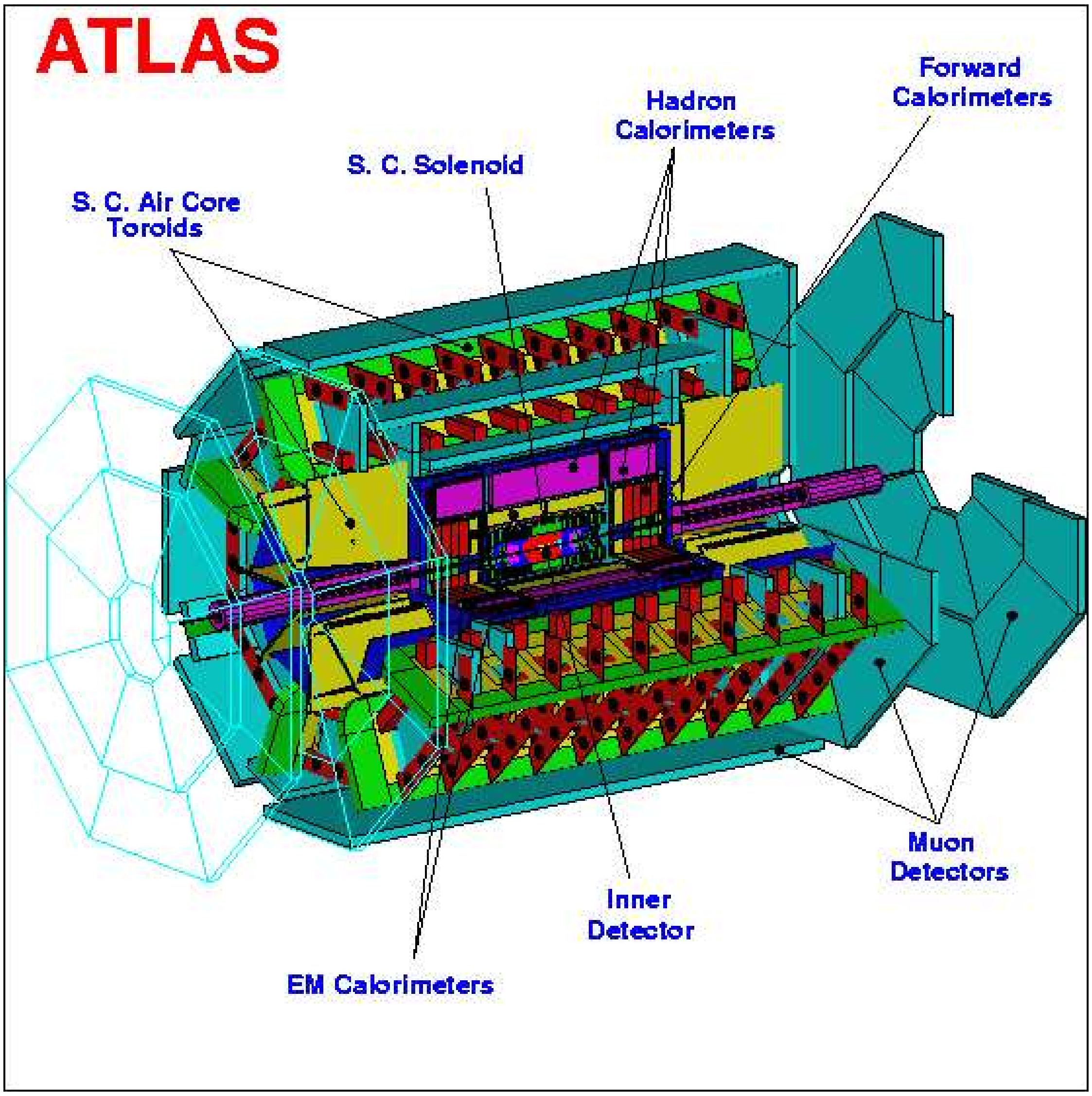


The Big Physics Question

Origin of Weak Interaction Symmetry Breaking

Other issues

- New gauge bosons?
- Compositeness
- New Quarks
- Top couplings
- b-physics
- Heavy Ions

LHC is the only approved facility with enough energy/luminosity to be sure of addressing

the Big Question

ATLAS will fully exploit this opportunity.

What do we need to detect?

We do not know what we will find

Therefore must be able to detect whatever is produced.

- quark/gluon jets
  with flavor tag if possible
- photons
- leptons
- Missing E_T

But LHC is not just a discovery machine.

- Need to make detailed precision measurements

Illustrate ATLAS capability with some examples.

Higgs Physics

Very challenging benchmarks, characterized by low rates and poor signal/background.

Needs full LHC luminosity for complete search

Important Standard Model Higgs Processes.

- $pp \to H \to \gamma\gamma$
- $pp \to H \to \ell^+\ell^-\ell^+\ell^-$
- $pp \to H \to ZZ(\to \ell^+\ell^-\nu\overline{\nu})X$ **at large mass**

Others

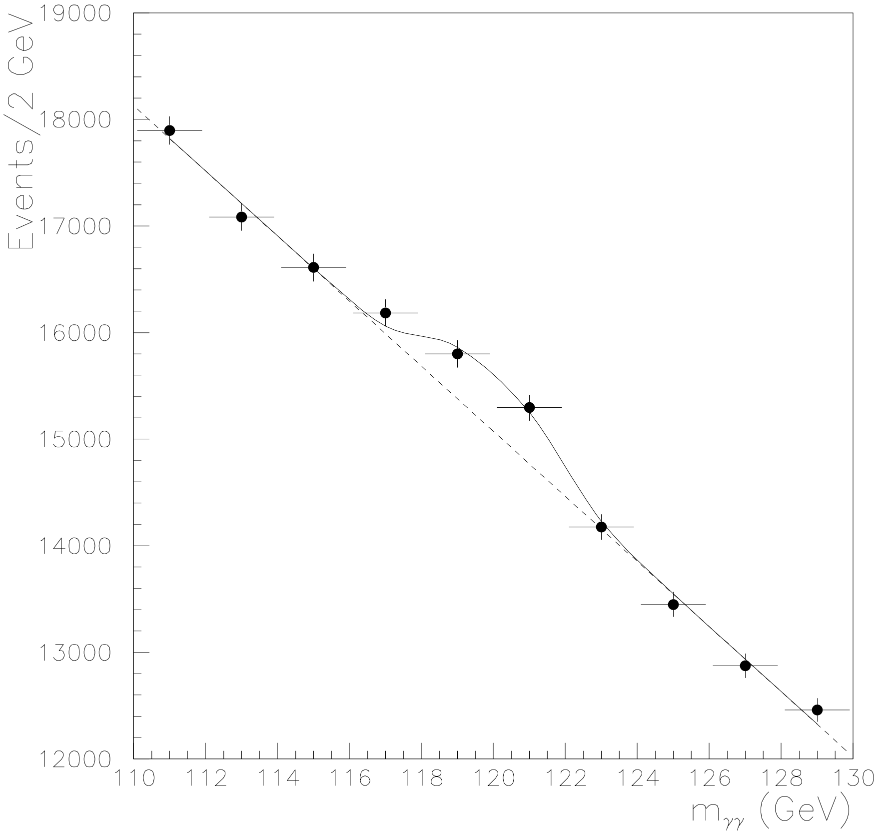
- $pp \to H(\to b\overline{b})W(\to \ell^+\nu)$
- $pp \to H \to W(\to jet + jet)W(\to \ell^+\nu)$ **at large mass**

Would like see more than one mode

- **test model**
- **learn about couplings**

Higgs with ATLAS

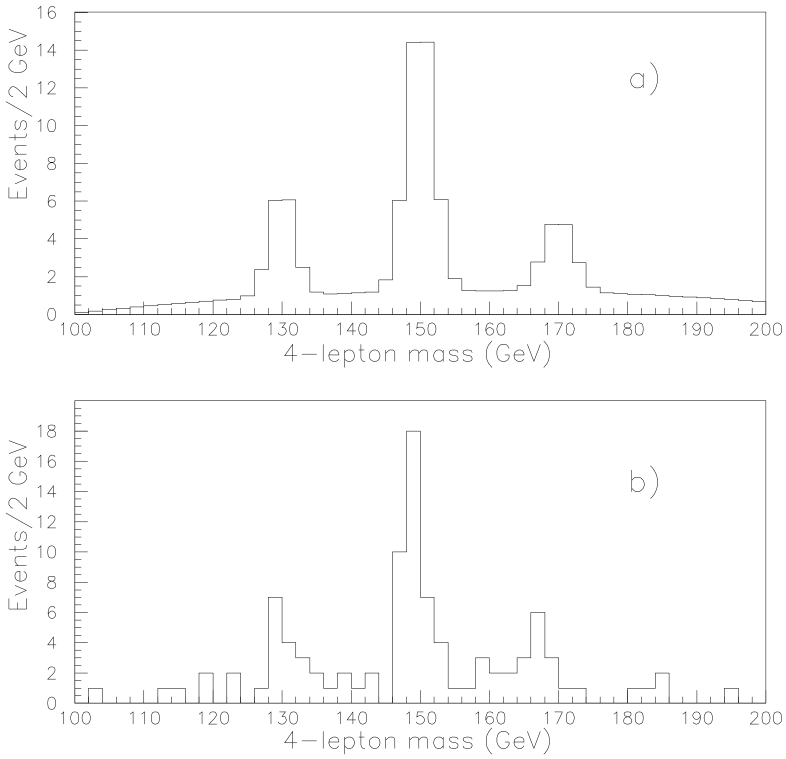
- $\gamma\gamma$ **mode needs good resolution** – S/B **small**
- jet/γ **rejection sufficient** (GEANT studies).
- $100\mathbf{fb}^{-1}$ **assumed**



- γ **pointing needed at high luminosity. Fine segmentation of first section of EM calorimeter**
  $\sigma(\theta) \sim 60 mrad/\sqrt{E}$

- **Background negligible in $ZZ^* \to 4\ell$**

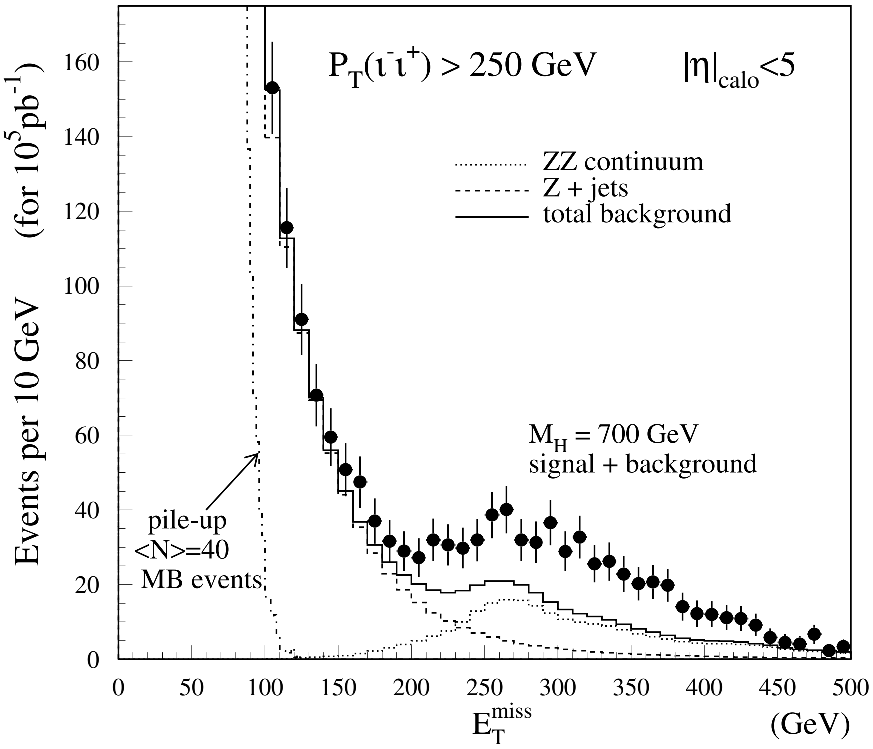
  simulation for 3 masses at 30 fb^{-1}



- **Mass resolution is comparable in $\gamma\gamma$ and ZZ^***

- **Light Higgs – can measure**
  $\sigma(H) \times BR(H \to \gamma\gamma)$,
  $\sigma(t\bar{t}H) \times BR(H \to \gamma\gamma)$,
  $\sigma(H) \times BR(H \to ZZ^*)$,

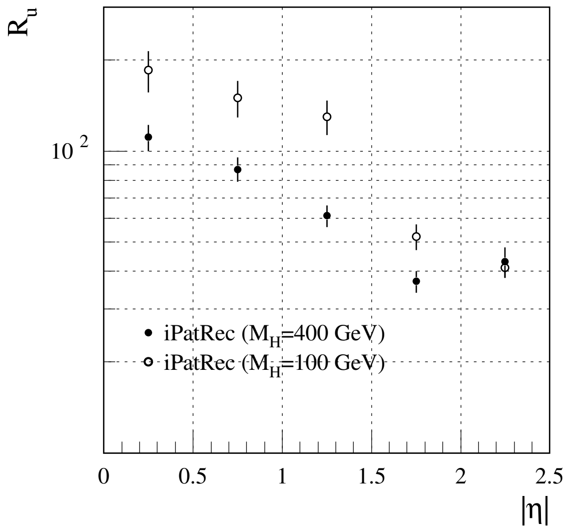
- $H \to ZZ \to 4\ell$ **for** $M_H \lesssim 600$ **GeV**
- **Need** $Z(\to \ell\ell)Z(\to \nu\overline{\nu})$ **at high mass.**
  Dominant background is $ZZ(\to \nu\overline{\nu})$ **not detector effects.**

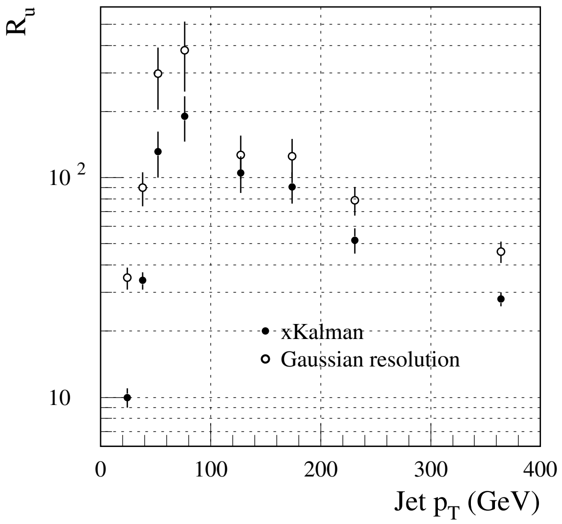


Signal clearly visible

Other modes

- $H \to b\bar{b}$
  Use WH or $t\bar{t}H$ for trigger. $(W \to \ell\nu)$
  With b-tagging efficiency of 50% and background rejection of 50,





  Fake and real background from $Wb\bar{b}$ and $t\bar{t}$ comparable
  Very Hard
  Could confirm discovery in another mode.
  and provide extra information

- $H \to WW \to e\nu + jets$
  Jet mass cuts insufficient
  Need Forward jet tag $(|\eta| > 3)$ and central jet veto.
  Hermetic Calorimeter

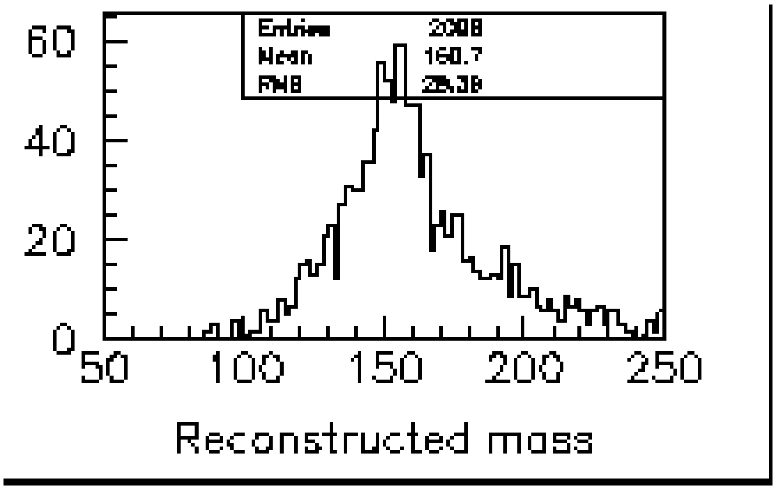
Non Minimal Higgs

Many possible options

Arises in all "beyond the standard model"

New channels appear

- $A \to \tau\tau$
  τ direction from decay products.
  Missing E_T then gives reconstructed $\tau\tau$ mass



- $H/A \to \mu^+\mu^-$
- $t \to bH^+(\to \tau\nu)$
- Cascade decays of one Higgs into another
  $H \to hh \to \gamma\gamma b\bar{b}$
  $A \to Zh$

Difficult to quantify expectations

Very Model dependent

Almost certain that other new states will exist and that these will be easier to see than the Higgs *e.g.* **Supersymmetry**

SUSY Higgs Summary

- **LHC (+LEP II) can exclude entire** $M_A - \tan\beta$ **plane at 95%** 10^5 **pb**$^{-1}$
- **LHC and LEP II have at least 2 measurements over much of the plane**

BUT

If Supersymmetry is correct, Higgs physics will not be the main focus of LHC.
Many easier signals...

SUSY

Sparticle Spectrum model dependent

Must perform consistent study

Minimal model

- **Unification all scalar masses (m_0) at GUT scale**
- **Unification all gaugino masses ($m_{1/2}$) at GUT scale**
- **Three more parameters** $\tan\beta = v_1/v_2$
  $sign(\mu)$ **(superpotential has $\mu H_1 H_2$)**
- **Trilinear term A, important only for 3rd generation**
- **Full mass spectrum predicted**

In general $m_{squark} > m_{slepton}$, $m_{gluino} > m_{\tilde{W}}$

Splitting between $m_{\tilde{e}_l}$ **and** $m_{\tilde{e}_r}$

Stop is usually lightest squark

SUSY particles produced in pairs

Lightest SUSY particle (LSP) is stable – Missing E_T

Other models have different (easier) signals
e.g. **2 isolated photons in every event**

SUSY at LHC

Past studies show LHC excellent for SUSY

High luminosity and c.m. energy
$\rightarrow$ sensitivity for large mass range

Many clear signatures

- $\not{E}_T$
- High Multiplicity of large p_t jets
- Many leptons
- Copious b production

Clear separation of SUSY from Standard Model

An ATLAS strategy to study SUSY:

Once SUSY signal is observed, how will ATLAS differentiate between models?

Can we rule out models by showing them to be inconsistent with the data?

Can we constrain parameters of candidate models?

In SUSY, masses and branching ratios are model dependent

- signatures and backgrounds model dependent
- signatures provide information on SUSY parameters

The Strategy

Step 1:

First evidence from excess of events in

- $\not\!\!E_T$,
- jets, or
- leptons

Cross section and $\not\!\!E_T$ scale establish mass scale of new physics

Step 2:

Study simple distributions to check that SUSY is candidate explanation

Step 3:

- test predictions of candidate models
- for surviving models, determine parameters

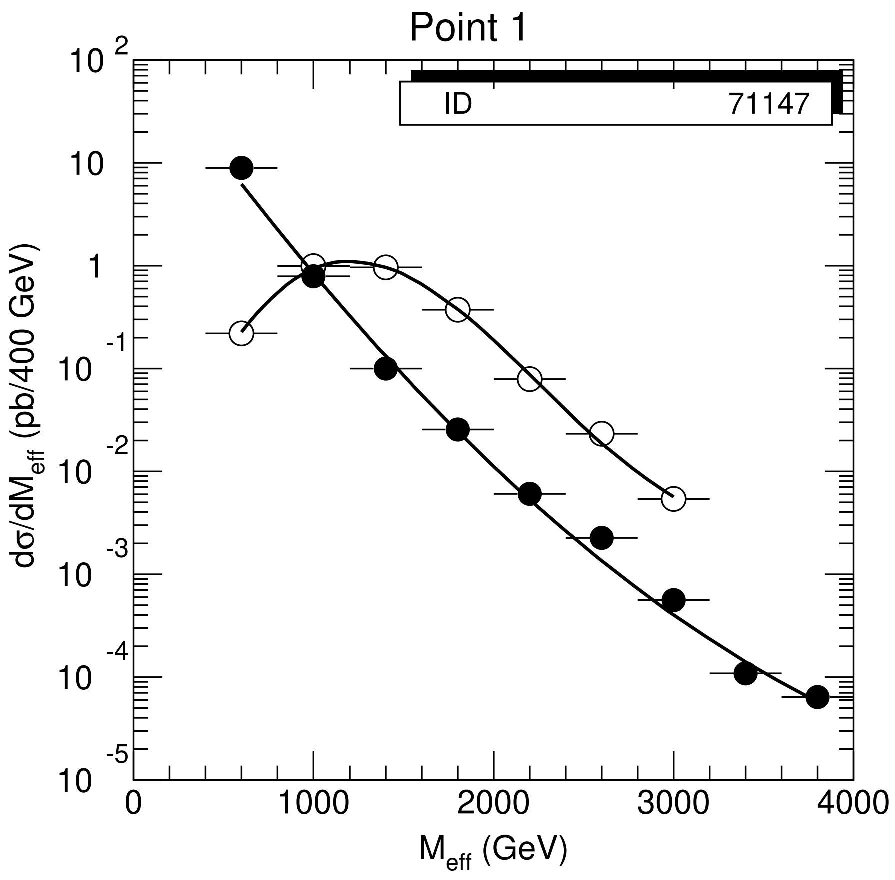
Ultimate goal: over-constrained global fit à la LEP

Step 1: Establishing the SUSY Mass scale

Select events with at least 4 jets and Missing E_T

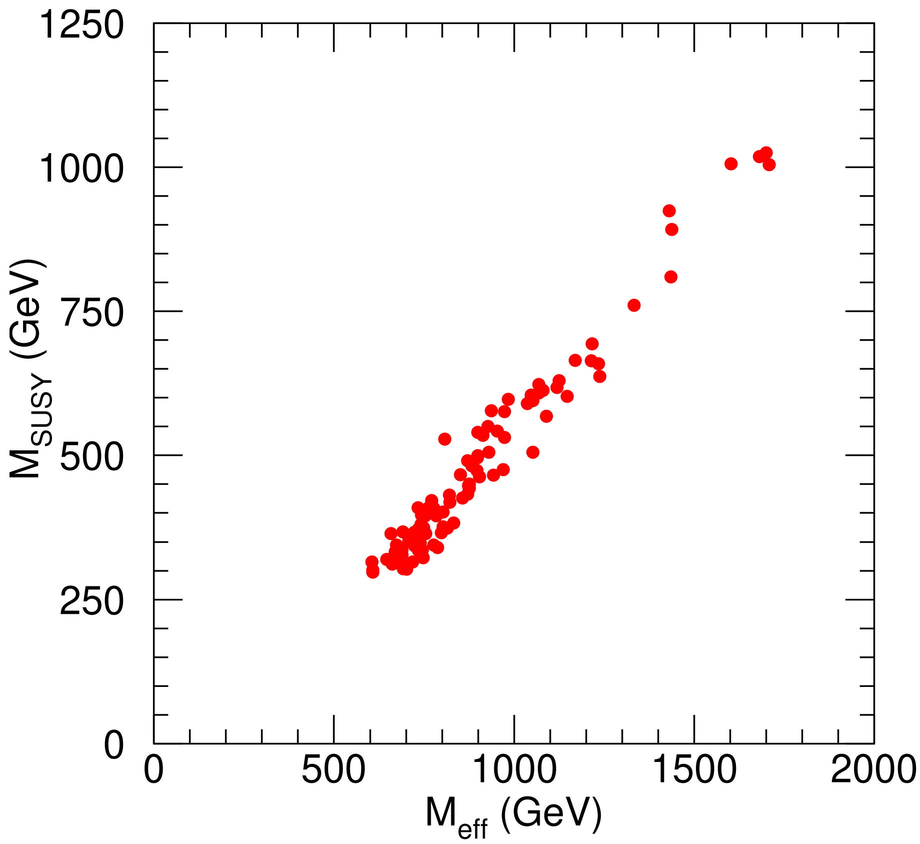
A simple variable:

$$M_{\text{eff}} = P_{t,1} + P_{t,2} + P_{t,3} + P_{t,4} + \not{E}_T$$



At high M_{eff} see non-SM signal (open points) emerging from SM background (solid points)

Peak in M_{eff} distribution correlates well with SUSY mass scale



$$M_{\mathrm{SUSY}} = \min(M_{\tilde{u}}, M_{\tilde{g}})$$

Use this and similar global distributions to establish that new physics exists and determine its mass scale

SUSY Spectrum for a case study

($m_0 = 100$ **GeV**, $m_{1/2} = 300$ **GeV**, **Tan(β)=2.1**)

- **Gluino** $m_{\tilde{g}} = 767$ **GeV**
- $m_{\tilde{q}_r} = 663$ **GeV**, $m_{\tilde{q}_l} = 685$ **GeV**
  $m_{\tilde{t}_1} = 498$ **GeV**, $m_{\tilde{t}_2} = 717$ **GeV**
  $m_{\tilde{b}_1} = 635$ **GeV**, $m_{\tilde{b}_2} = 662$ **GeV**
- **Sleptons** $m_{\tilde{e}_l} = 239$ **GeV**, $m_{\tilde{e}_r} = 157$ **GeV**
- **Neutralinos** $m_{\chi_1} = 121$ **GeV**, $m_{\chi_2} = 231$ **GeV**,
  $m_{\chi_3} = 479$ **GeV**, $m_{\chi_4} = 505$ **GeV**
- **Charginos** $m_{\tilde{\chi}_1^+} = 230$ **GeV**, $m_{\tilde{\chi}_2^+} = 502$ **GeV**
- **Higgs** $m_h = 104.1$ **GeV**, $m_H = 619$ **GeV**,
  $m_A = 615$ **GeV**, $m_{H^+} = 619$ **GeV**

General Features:

- $m_{\tilde{g}} \sim m_{\tilde{q}} \sim 700$ **GeV**
- **BR**$(\chi_2^0 \to \tilde{\chi}_1^0 h)$ **= 62% (often true)**
- **Large slepton yield**

$$\begin{array}{rl} \chi_2 \to & \tilde{\ell}^+ \ \ell^- \\ & \to \ell^+ \chi_1 \end{array}$$ **6% per species and charge**

- **Democratic gluino decays:**
  $\tilde{g} \to \tilde{t}t$ **allowed**
- **Event rates are large.**

Selection of $h \to b\bar{b}$ and $\tilde{q} \to \chi_2^0 q$

Strategy:
Look for $\tilde{q}\tilde{q}$ events where one $\tilde{q}$ decays via

$$\tilde{q} \to \tilde{\chi}_2^0 q,\ \ \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h,\ \ h \to b\bar{b}\,,$$

and the other via

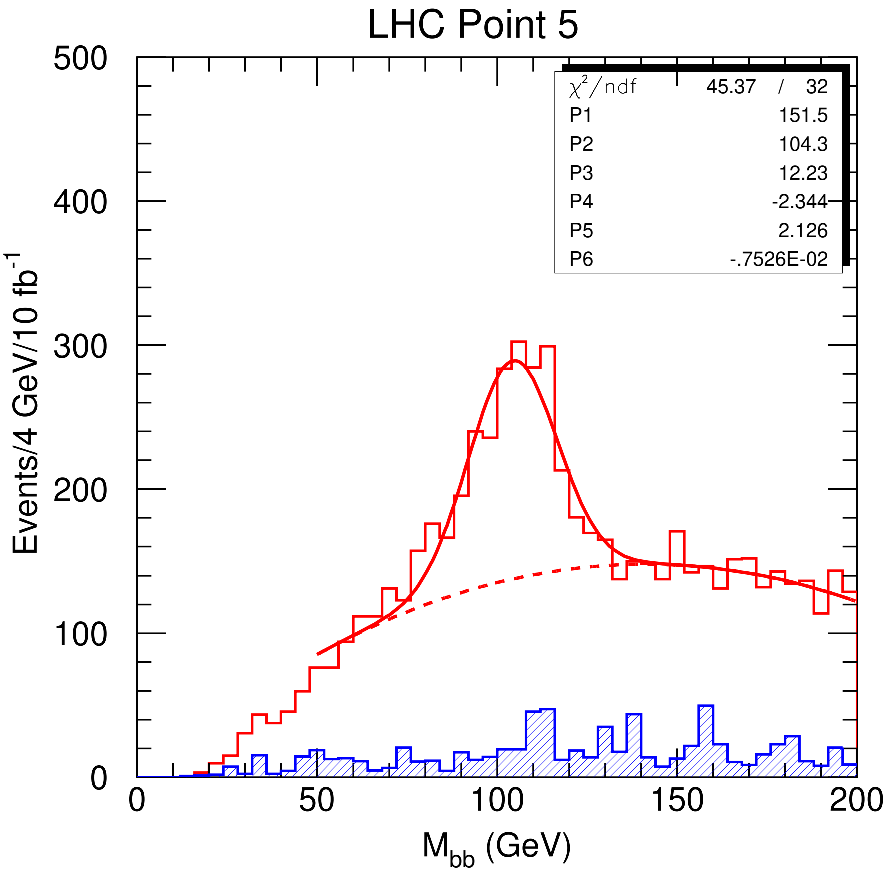
$$\tilde{q} \to \tilde{\chi}_1^0 q\,,$$

Events have, jets, b-jets (from H) and missing E_T from $\tilde{\chi}_1^0$
Select events with :

- $\not{E}_T > 100\,\mathrm{GeV}$
- ≥ 4 **jets with** $p_T > 50\,\mathrm{GeV}$ **and** $p_{T,1} > 100\,\mathrm{GeV}$
- **Transverse sphericity** $S_T > 0.2$
- $M_{\mathrm{eff}} > 800\,\mathrm{GeV}$
- $\not{E}_T > 0.2 M_{\mathrm{eff}}$
- **2 b-jets with** $p_{T,b} > 25$ **GeV and** $|\eta| < 2$

Reconstructed Higgs Mass

Look at the invarient mass of $b\bar{b}$ system

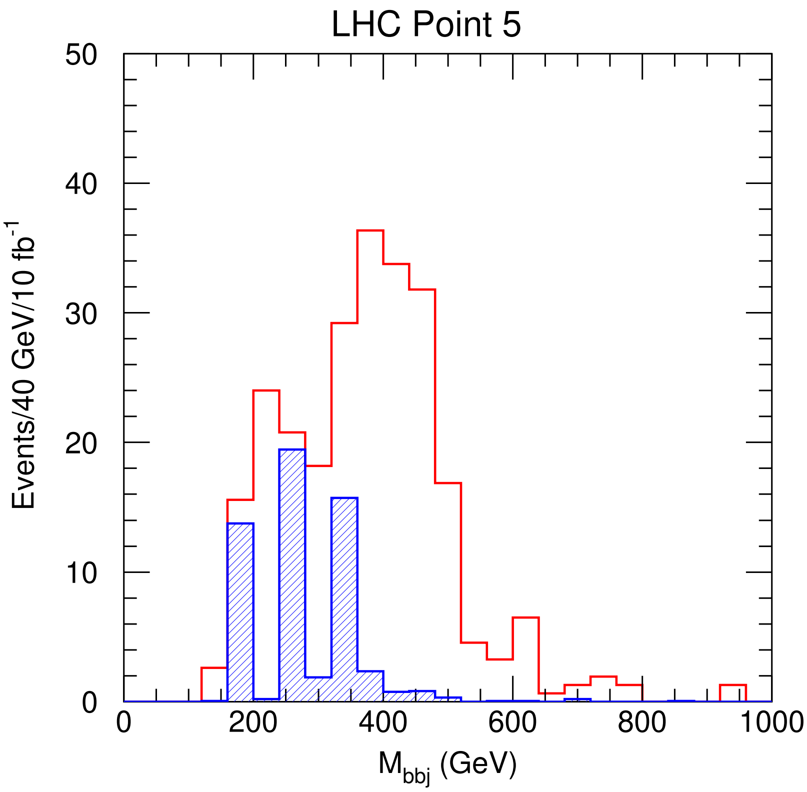


- Rates here correspond to 1/30 of design luminosity
- Standard Model Background (Blue histogram) is very small
- Higgs is discovered this way
- Signal is present in many SUSY models

Reconstruction of $\tilde{q}_L \to q\chi_2(\to h\tilde{\chi}_1^0)$

- **Use events with two b jets in Higgs invariant mass region**
- **Require two additional jets with $P_t > 75$ GeV**
- **Plot smaller of two $h + jet$ mass combinations**

$\to$ **expect an edge near $M(\tilde{q}_L) - M(\tilde{\chi}_1^0) = 565\,\mathrm{GeV}$.**



Detailed understanding of shape of edge requires more work.
Statistical uncertainty on mass difference ~ 40 GeV (1 year low luminosity)

$W \to q\overline{q}$ and $\tilde{q} \to qW\tilde{\chi}_1^0$

Strategy:

Look for gluon pairs where one gluino decays via

$$\tilde{g} \to \tilde{q}_L\bar{q},\ \tilde{q}_L \to \tilde{\chi}_1^{\pm}q,\ \tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 W^{\pm},\ W^{\pm} \to q\bar{q}\,,$$

and the other via

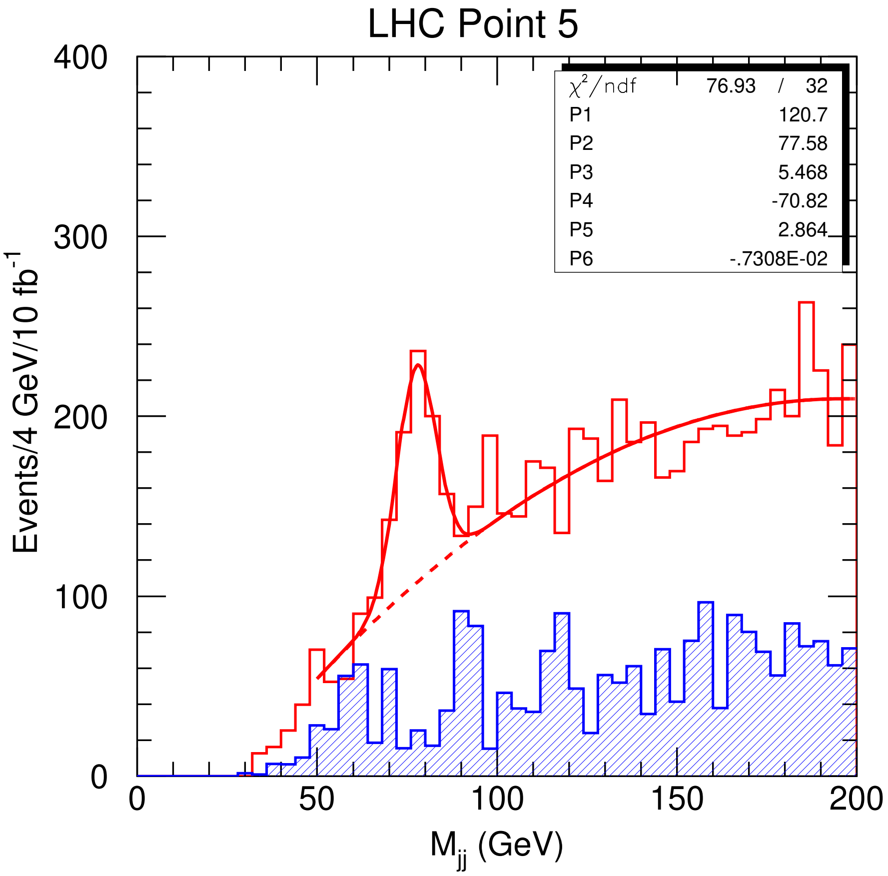
$$\tilde{g} \to \tilde{q}_R q,\ \tilde{q}_R \to \tilde{\chi}_1^0 q\,,$$

$\to$ two hard jets and two softer jets from W.

Select events with:

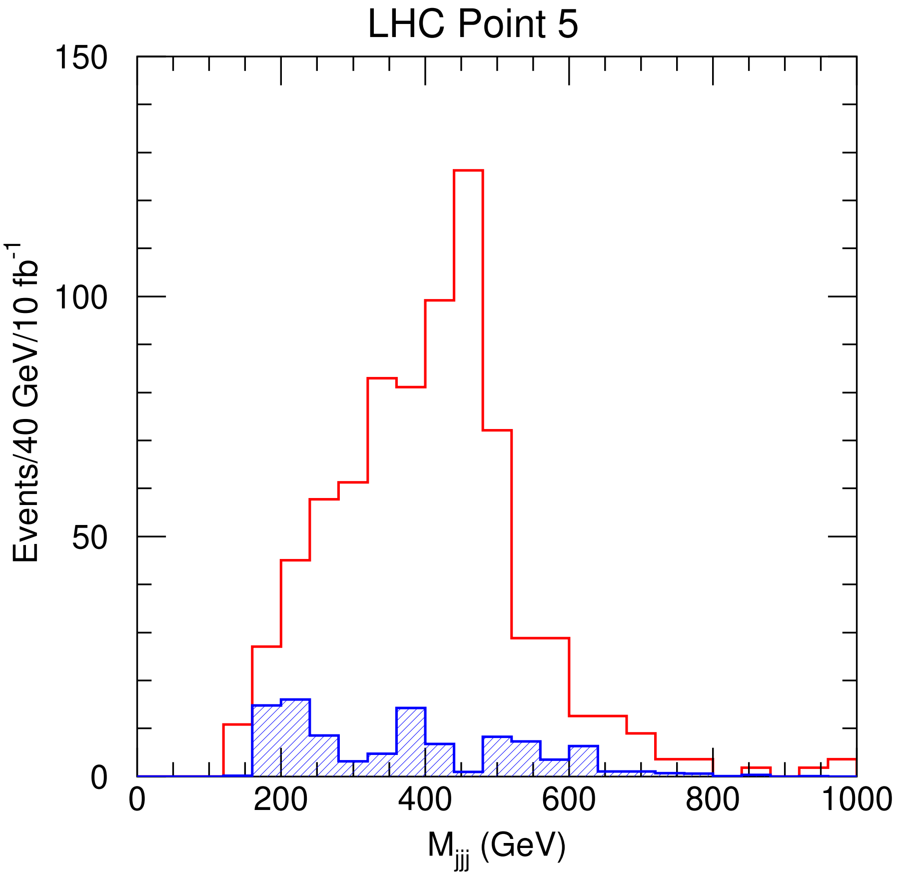
- $\not{E}_T > 100\,\mathrm{GeV}$
- **≥ 4 jets with $p_{T1,2} > 200\,\mathrm{GeV}$, $p_{T3,4} > 50\,\mathrm{GeV}$, and** $\eta_{3,4} < 2$
- **Transverse sphericity** $S_T > 0.2$
- $M_{\mathrm{eff}} > 800\,\mathrm{GeV}$
- $\not{E}_T > 0.2M_{\mathrm{eff}}$
- **Jets 3 and 4 are <u>NOT</u> b-jets**

Reconstruction of $W \to q\bar{q}$



- **Clear Peak at W mass**
- **More background than Higgs case**
- **COMBINE "W" with another jet**

Plot smaller of two $q\bar{q}j$ masses



Edge in same place as previous analysis (consistency check and additional statistics)

Selection of $\tilde{\chi}_2^0 \to \tilde{\ell}\ell \to \tilde{\chi}_1^0 \ell\ell$

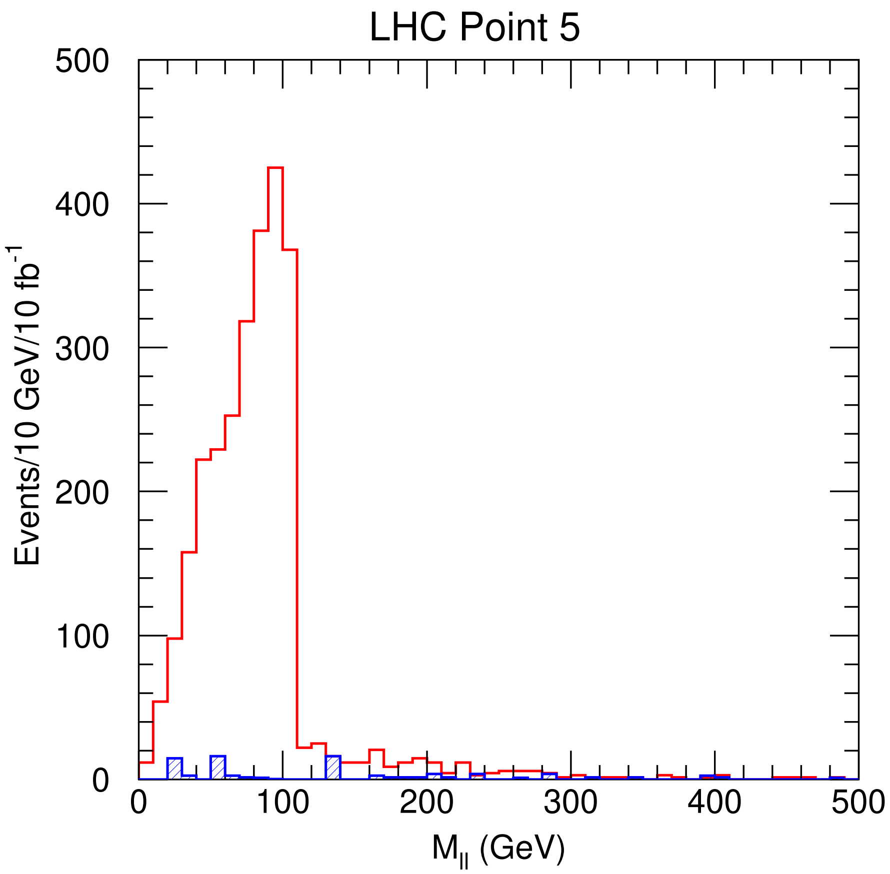
Since slepton is light

$$\tilde{\chi}_2^0 \to \tilde{\ell}_R \ell \to \tilde{\chi}_1^0 \ell^+ \ell^-$$

Select events with

- $M_{\rm eff} > 800\,{\rm GeV}$
- $\not{E}_T > 0.2 M_{\rm eff}$
- ≥ 1 **jet with** $p_{T,1} > 100\,{\rm GeV}$
- $\ell^+\ell^-$ **pair with** $p_{T,\ell} > 10\,{\rm GeV}$**,** $\eta_\ell < 2.5$
- ℓ **isolation cut:** $E_T < 10\,{\rm GeV}$ **in** $R = 0.2$
- **Transverse sphericity** $S_T > 0.2$

Reconstruct $\ell^+\ell^-$ Invariant Mass



$M_{\ell\ell}$ exhibits an edge at kinematic bound

$$M_{\ell\ell}^{\max} = M_{\tilde{\chi}_2^0}\sqrt{1 - \frac{M_{\tilde{\ell}}^2}{M_{\tilde{\chi}_2^0}^2}}\sqrt{1 - \frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{\ell}}^2}} \approx 108\,\mathrm{GeV}\,,$$

Uncertainty ~ 1 GeV

Precise lepton measurements are essential

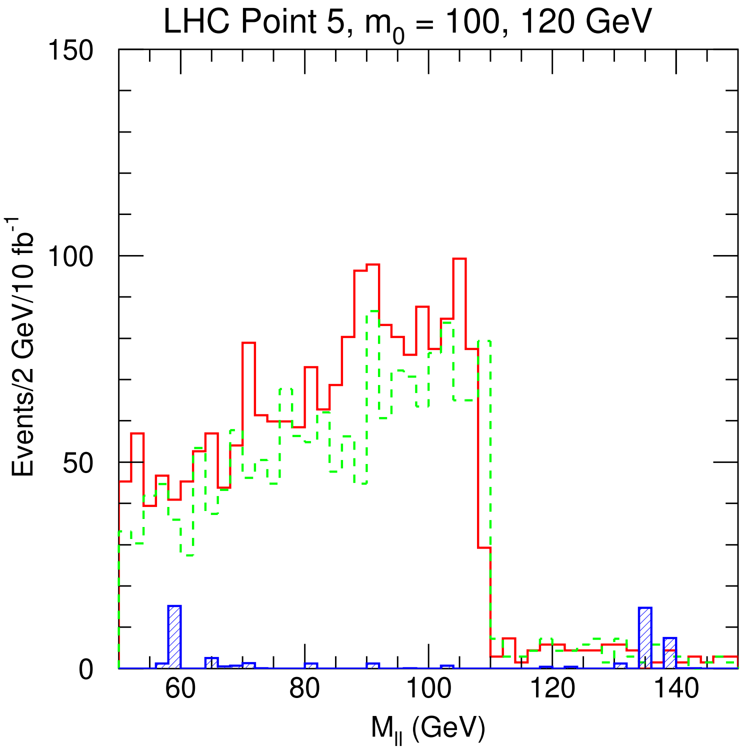
Sensitivity to m_0

Generate events with m_0 shifted from 100 GeV to 120 GeV

- **Changes $m_{\tilde{\ell}}$ by 13 GeV**
- **Does not shift $\tilde{g}$, $\tilde{\chi}_2$ or $\tilde{\chi}_1^0$ masses.**

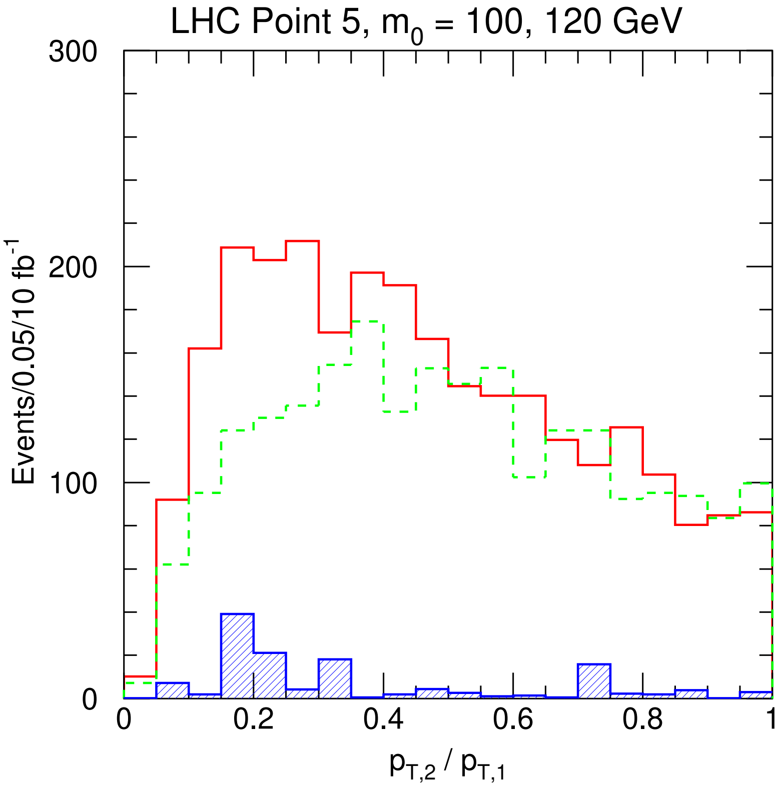
Study effect of $m_{\tilde{\ell}}$ on distributions

- **$M_{\ell\ell}$ Endpoint**
- **Shape of $p_T(\ell_2)/p_T(\ell_1)$**



→ observable shift in $M_{\ell\ell}$ endpoint 2 GeV

Also, shape of $p_T(\ell_2)/p_T(\ell_1)$ changes with $m_{\tilde{\ell}}$



Can determine m_0 to ~ 5 GeV if all other parameters held fixed.

Summary

This study requires all components of ATLAS to operate together

- jets Calorimeter
- b-jets Si, Muons + Calorimeter
- electrons EM calorimeter + Tracking
- Muons Tracking + Muon system
- Missing E_T Forward calorimeter!
- Photons EM calorimeter

What might we learn?

Using constraints measured quantities:

$$
\begin{array}{lcl}
m_{\chi_2^0}\sqrt{1-\frac{M_{\tilde{\ell}}^2}{M_{\tilde{\chi}_2^0}^2}}\sqrt{1-\frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{\ell}}^2}} & = & 108.1\pm\ \mathbf{1\ GeV} \\
M_{\tilde{q}} - M_{\tilde{\chi}_1^0} & = & 565\pm\ \mathbf{40\ GeV} \\
M_h & = & 104.1 \pm 3\ \mathbf{GeV}
\end{array}
$$

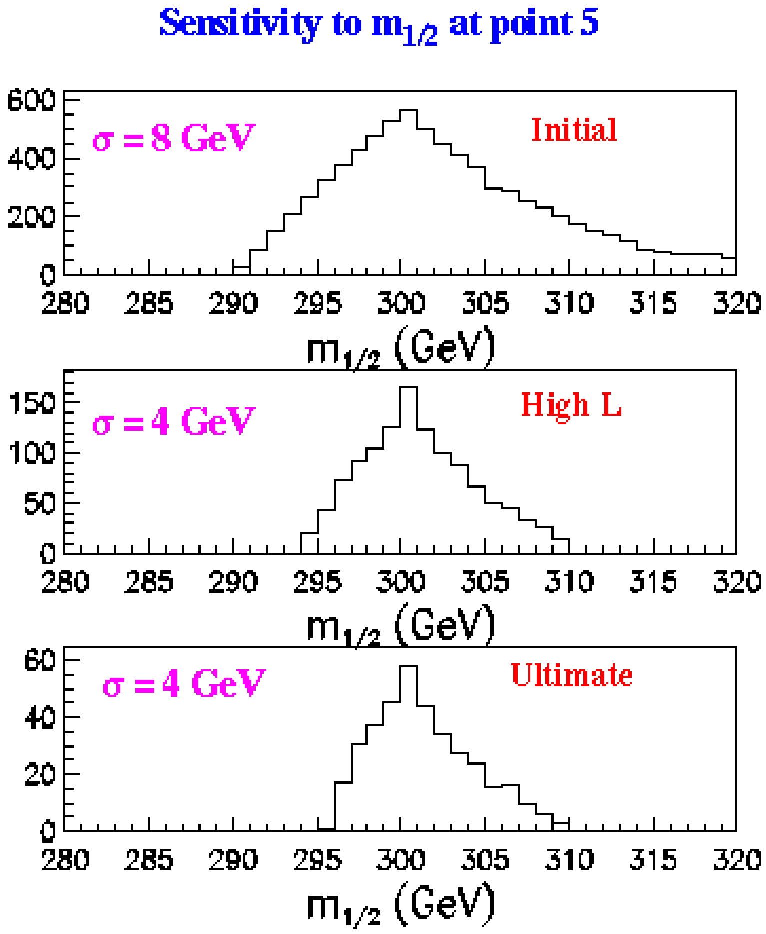
Result:

$$
\begin{array}{lcl}
M_{1/2} & = & 298^{+16}_{-9}\ \mathbf{GeV} \\
M_0 & = & 100^{+12}_{-8}\ \mathbf{GeV} \\
\tan(\beta) & = & 1.8^{+0.3}_{-0.5}
\end{array}
$$

With the full Luminosity expect significantly smaller errors

$$
\begin{array}{lcl}
M_{1/2} & = & 300 \pm 4\ \mathbf{GeV} \\
M_0 & = & 100 \pm 3\ \mathbf{GeV} \\
\tan(\beta) & = & 2.1 \pm 0.08
\end{array}
$$

How precision improves with luminosity



Conclusions

- **If Standard model is right and LEP does not find Higgs, LHC will discover it and measure mass.**
- **LHC can find SUSY if it exists**
- **LHC can do precision measurements**
- **Details depend on the model**
- **Some general features** *but*
- **Every case is peculiar** *must cover all of them*
- **Power of ATLAS much greater than the sum of its parts.**