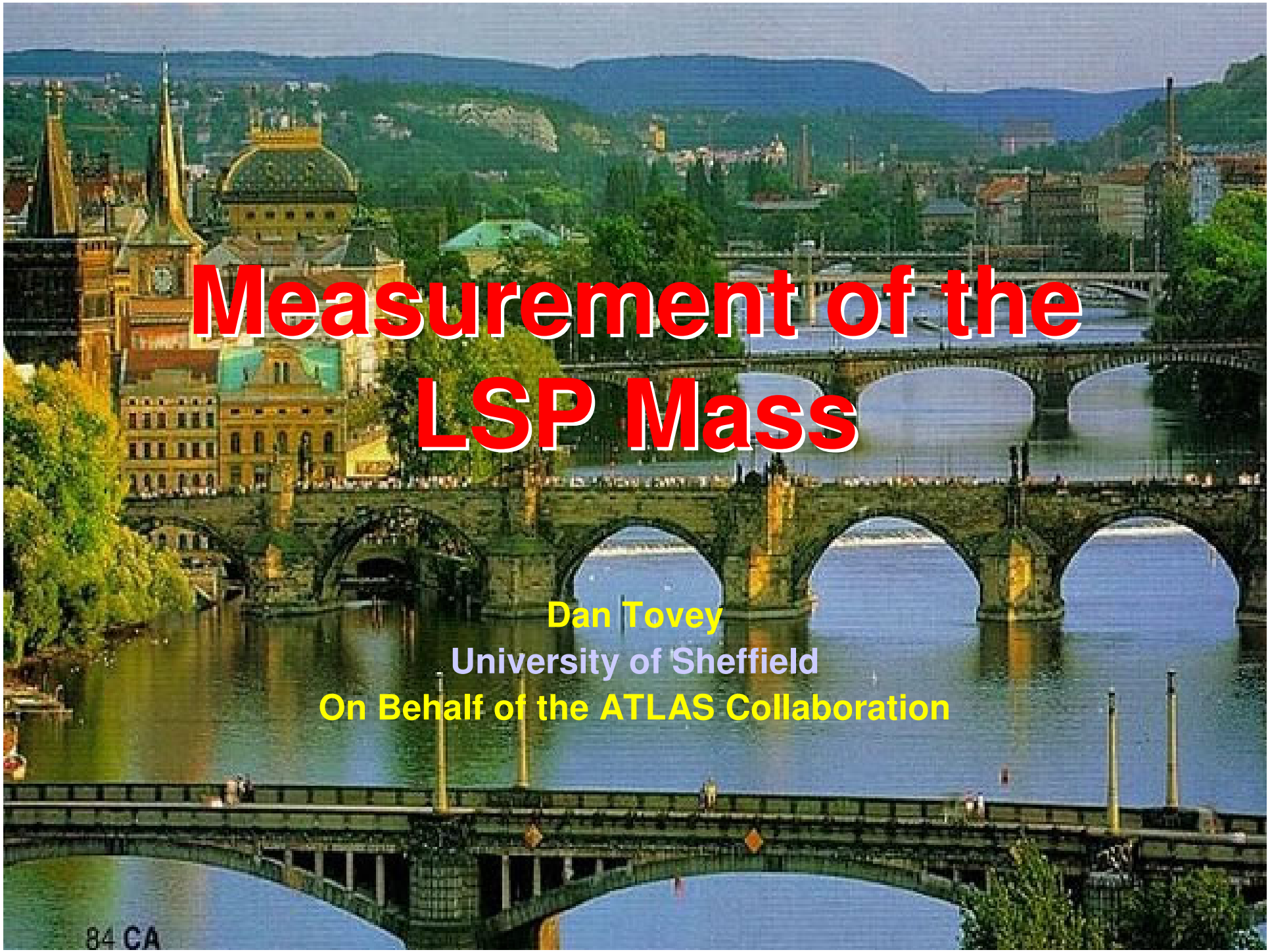

Measurement of the LSP Mass

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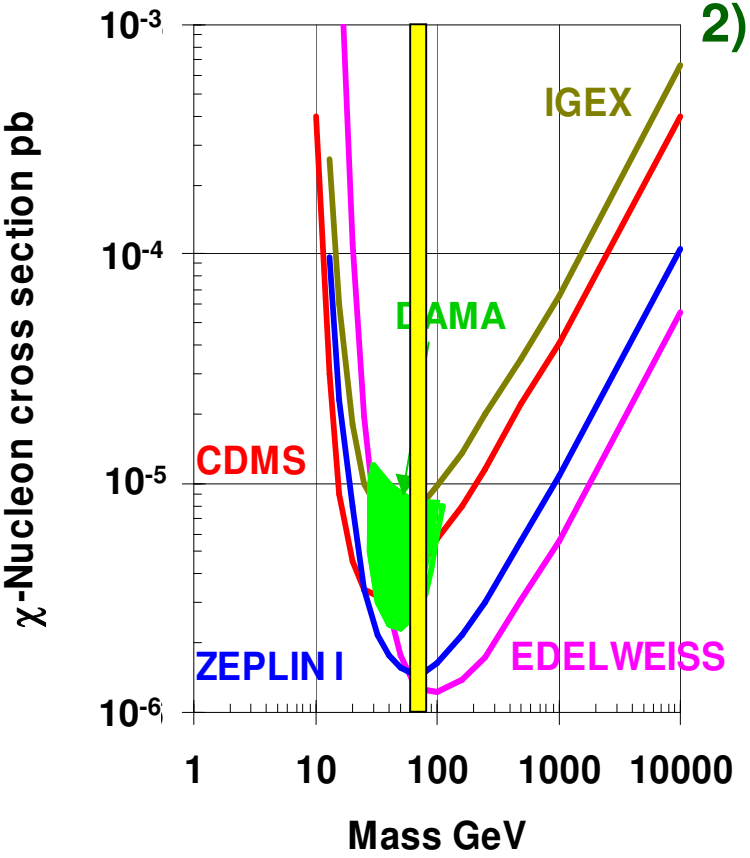
Contents

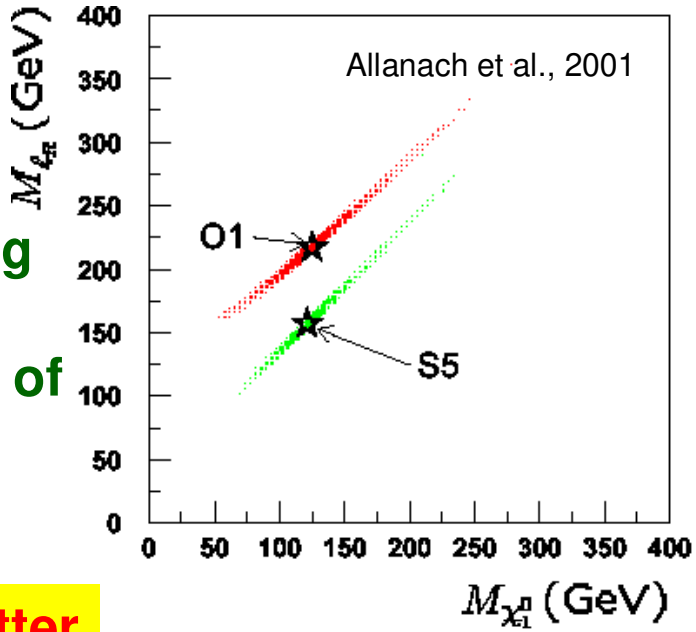
- Motivation: Why measure the LSP mass?
  - Will assume LSP ≡ lightest neutralino in this talk
  - Natural in many SUSY models (constrained MSSM etc.)
  - Will also assume R-Parity is conserved (RPV beyond scope of this talk)
- SUSY particle mass measurements at the LHC
- Measurement technique
- Measurements using invariant mass 'edges'
- Measurement combination: extracting particle masses

Why Measure the LSP Mass?

1) Using mass of lightest neutralino and RH sleptons can discriminate between SUSY models differing only in slepton mass.



2) Use as starting point for measurement of other masses (gluino etc.)



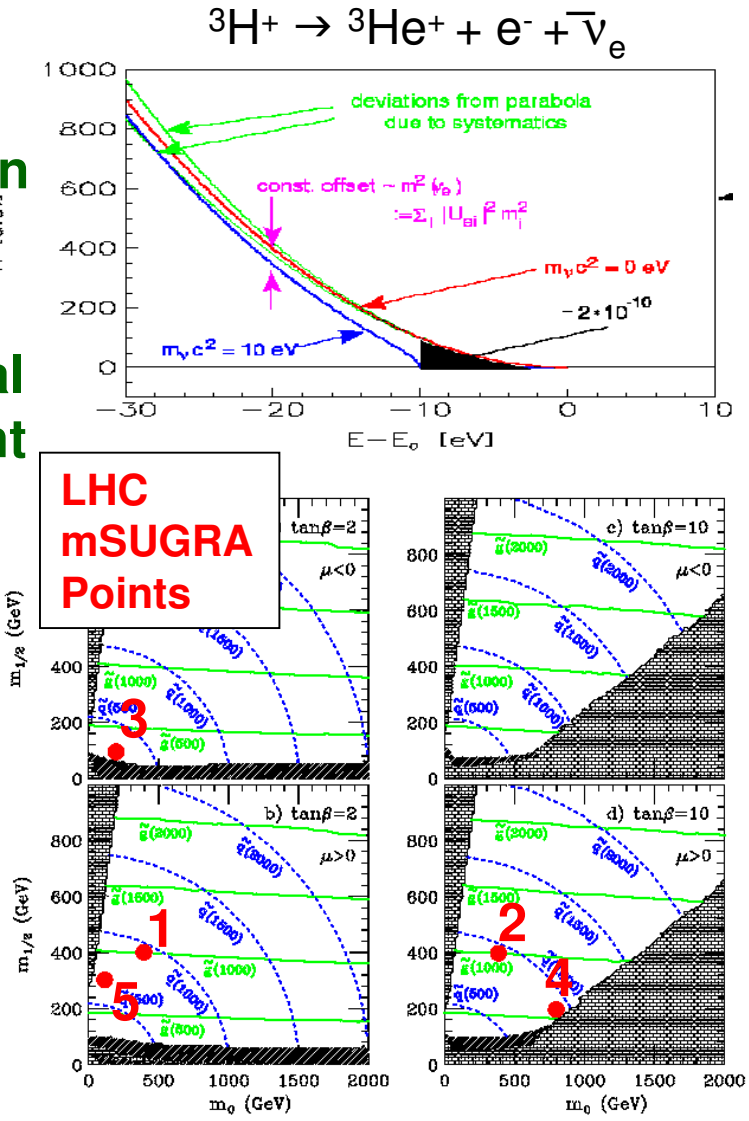
SUSY Dark Matter

3) Lightest Neutralino LSP excellent Dark Matter candidate.
   - Test of compatibility between LHC observations and signal observed in Dark Matter experiments.

4) etc …

Neutralino Mass Measurement

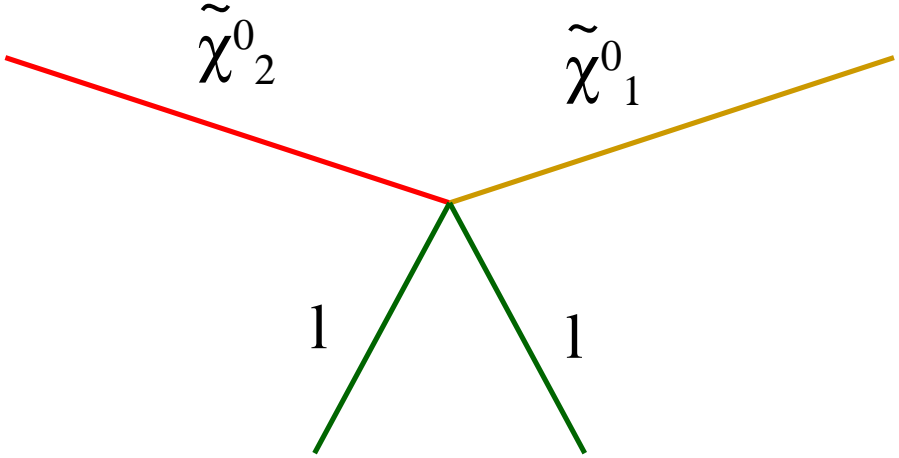
- **Following any discovery of SUSY next task will be to measure parameters.**
- Will not know a priori SUSY model chosen by Nature → model-independent measurements crucial.
- In R-Parity conserving models two neutral LSPs (often the lightest neutralino) / event
  - Impossible to measure mass of each sparticle using one channel alone
- Instead use kinematic end-points to measure combinations of masses.
- Old technique used many times before:
  - ν mass from β decay end-point
  - W mass at RUN II using Transverse Mass.
- Difference here is that we don't know mass of neutrals (c.f. ν).

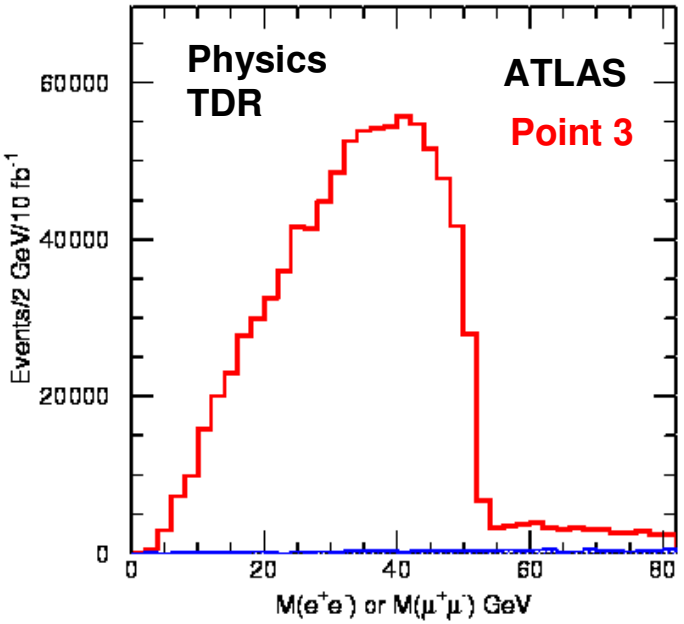


Dilepton Edge

Hinchliffe, Paige et al., 1998

- Classic example (and easiest to perform): OS SF dilepton edges.
- Important in regions of parameter space where three-body decays of $\tilde{\chi}^0_2$ dominate (e.g. LHC Point 3).





- Can perform SM background subtraction using OF distribution

$$e^+e^- + \mu^+\mu^- - e^+\mu^- - \mu^+e^-$$

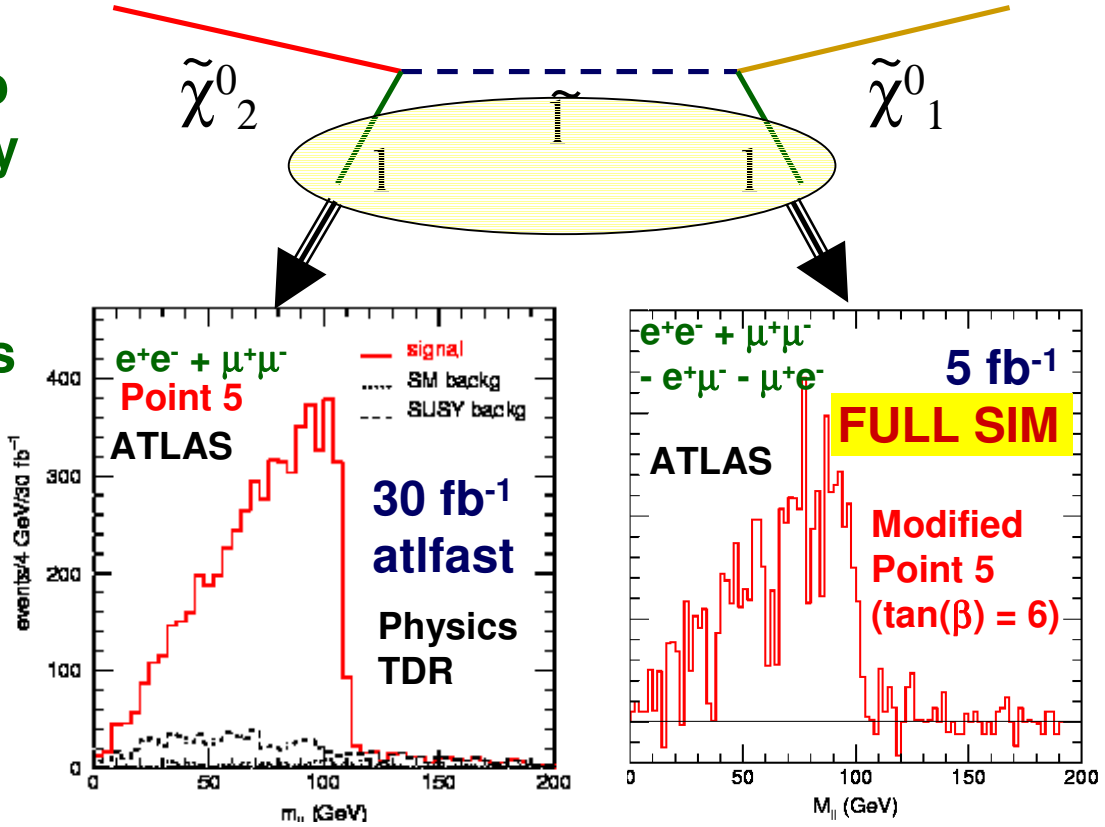
- Position of edge measures $m(\tilde{\chi}^0_2) - m(\tilde{\chi}^0_1)$ with precision ~ 0.1%.

Dilepton Edge

Polesello et al., 1997

- When kinematically accessible $\tilde{\chi}^0_2$ can undergo sequential two-body decay to $\tilde{\chi}^0_1$ via a right-slepton.
- Also results in sharp OS SF dilepton invariant mass edge sensitive to combination of masses of sparticles.
- Can perform SM & SUSY background subtraction using OF distribution

  $e^+e^- + \mu^+\mu^- - e^+\mu^- - \mu^+e^-$
- Position of edge (LHC Point 5) measured with precision ~ 0.5% (30 fb^{-1}).

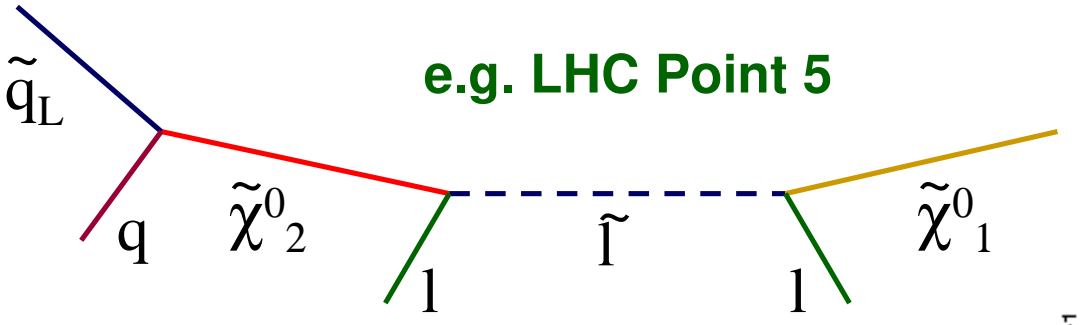


$$M_{ll}^{\max} = M(\tilde{\chi}_2^0)\sqrt{1-\frac{M^2(\tilde{l}_R)}{M^2(\tilde{\chi}_2^0)}}\sqrt{1-\frac{M^2(\tilde{\chi}_1^0)}{M^2(\tilde{l}_R)}} = 108.93 \text{ GeV}$$

llq Edge

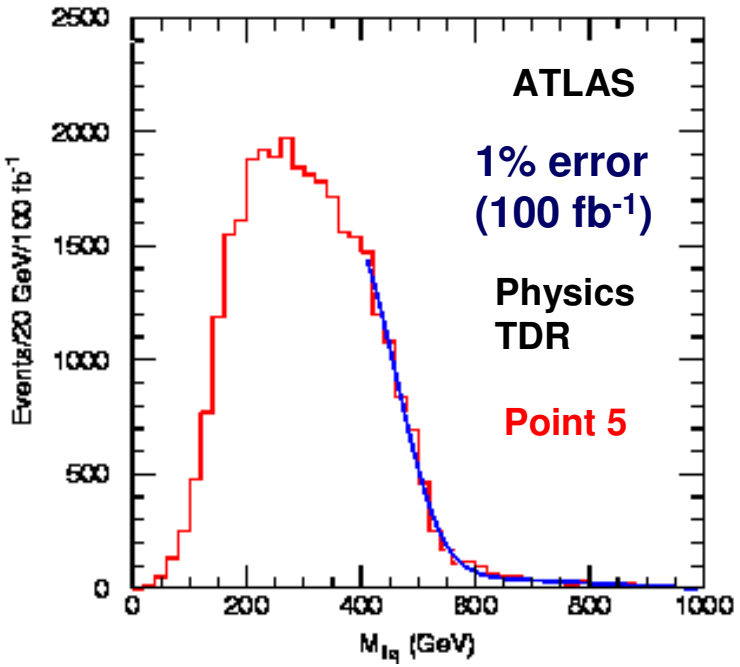
Bachacou et al., 1999

- Dilepton edges provide starting point for other measurements.
- Use dilepton signature to tag presence of $\tilde{\chi}^0_2$ in event, then work back up decay chain constructing invariant mass distributions of combinations of leptons and jets.



e.g. LHC Point 5

$$M_{llq}^{\max} = \left[\frac{(M^2_{\tilde{q}_L} - M^2_{\tilde{\chi}^0_2})(M^2_{\tilde{\chi}^0_2} - M^2_{\tilde{\chi}^0_1})}{M^2_{\tilde{\chi}^0_2}}\right]^{1/2} = 552.4 \text{ GeV}.$$

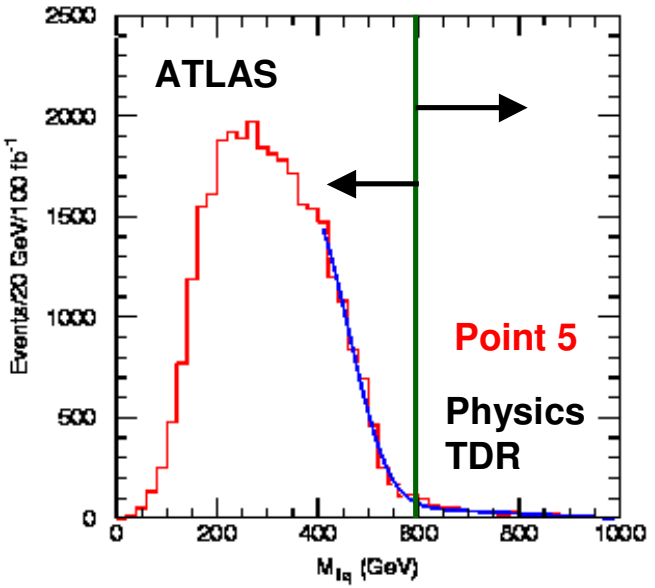


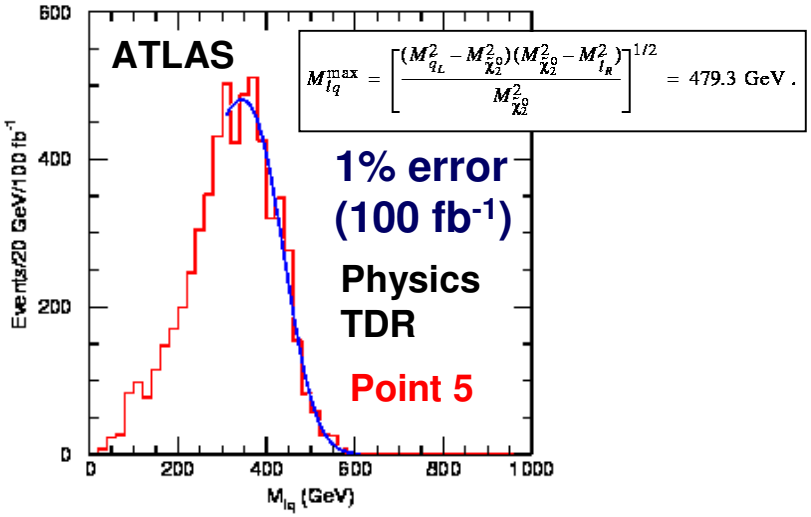
- Hardest jets in each event produced by RH or LH squark decays.
- Select smaller of two llq invariant masses from two hardest jets
  - Mass must be ≤ edge position.
- Edge sensitive to LH squark mass.

lq Edge

- Complex decay chain at LHC Point 5 gives additional constraints on masses.
- Use lepton-jet combinations in addition to lepton-lepton combinations.
- Select events with only one dilepton-jet pairing consistent with slepton hypothesis
  - → Require one llq mass above edge and one below (reduces combinatorics).

Bachacou et al., 1999

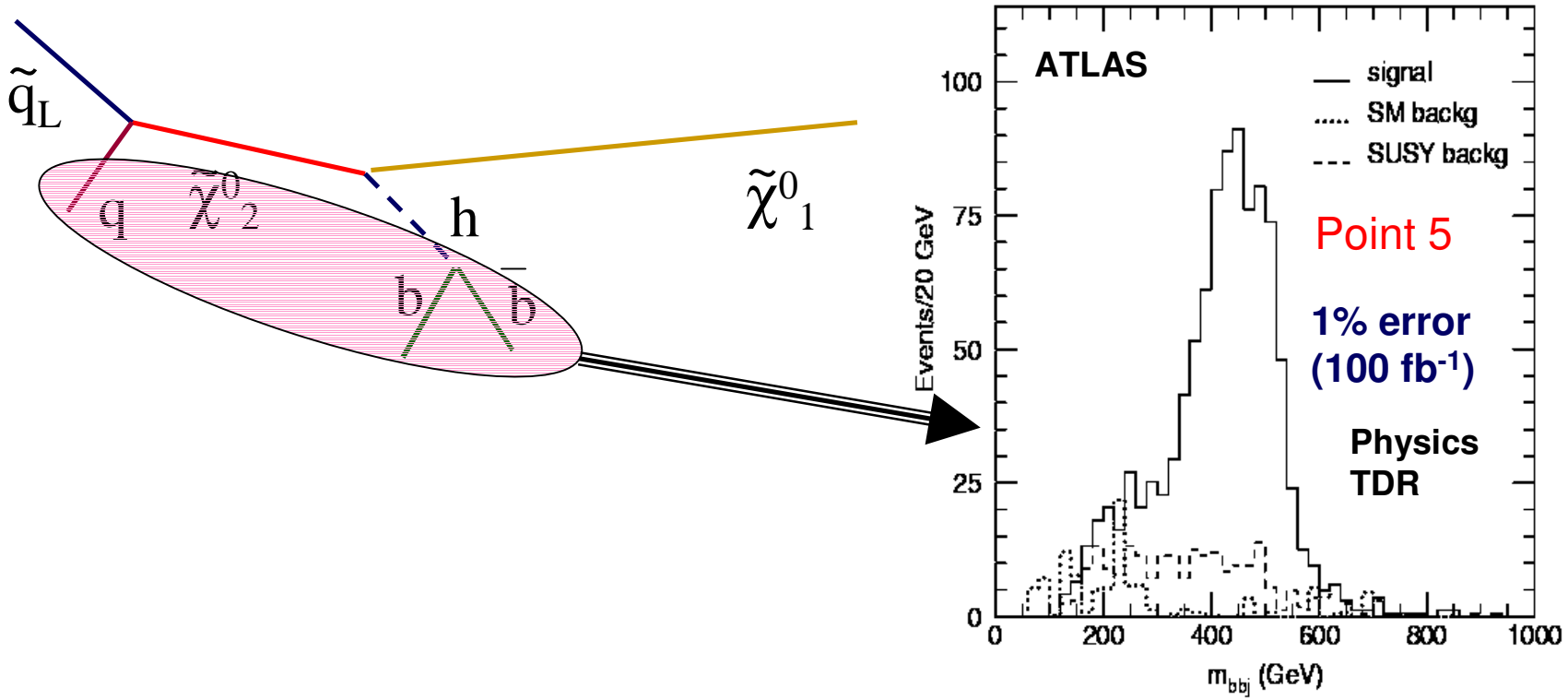




- Construct distribution of invariant masses of 'slepton' jet with each lepton.
- 'Right' edge sensitive to slepton, squark and $\tilde{\chi}^0_2$ masses ('wrong' edge not visible).

hq edge

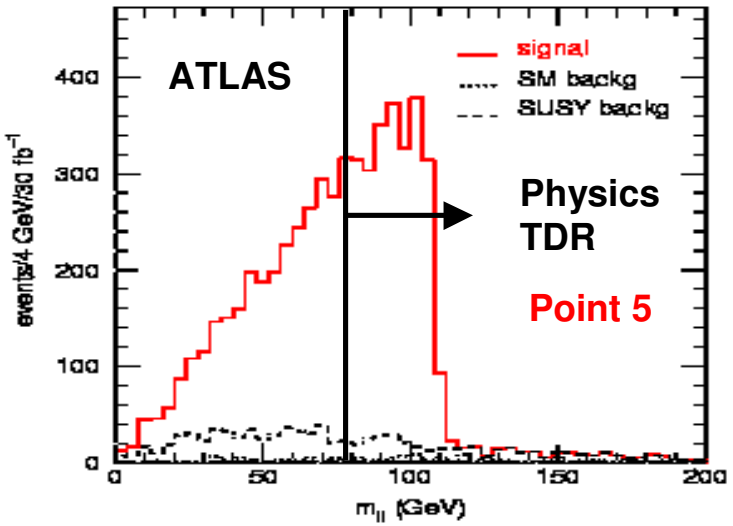
- If tan(β) not too large can also observe two body decay of $\tilde{\chi}^0_2$ to higgs and $\tilde{\chi}^0_1$.
- Reconstruct higgs mass (2 b-jets) and combine with hard jet.
- Gives additional mass constraint.

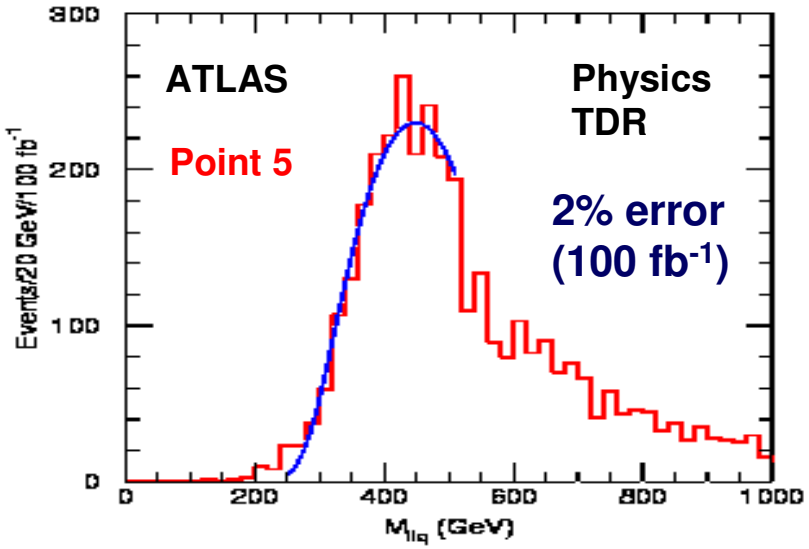


llq Threshold

- Two body kinematics of slepton-mediated decay chain also provides still further information (Point 5).
- Consider case where $\tilde{\chi}^0_1$ produced near rest in $\tilde{\chi}^0_2$ frame.
  - Dilepton mass near maximal.
  - p(ll) determined by p($\tilde{\chi}^0_2$).

Bachacou et al., 1999





- Distribution of llq invariant masses distribution has maximum and minimum (when quark and dilepton parallel).
- llq threshold important as contains new dependence on mass of lightest neutralino.

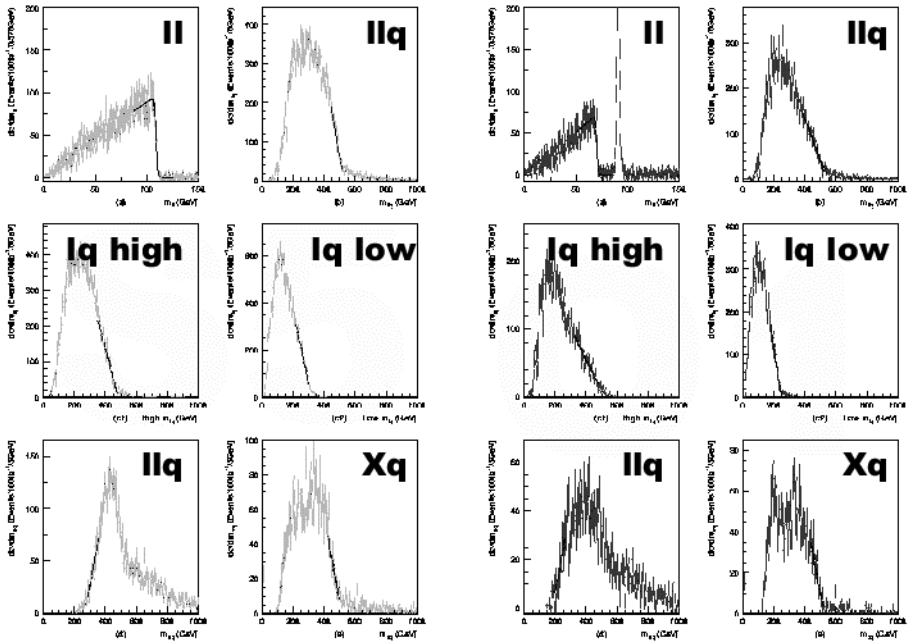
Mass Reconstruction

- **Combine measurements from edges from different jet/lepton combinations.**

Related edge	Kinematic endpoint
l^+l^- edge	$(m_{ll}^{\max})^2 = (\tilde{\xi} - \tilde{l})(\tilde{l} - \tilde{\chi})/\tilde{l}$
l^+l^-q edge	$(m_{llq}^{\max})^2 = \begin{cases} \max\left[\frac{(\tilde{q}-\tilde{\xi})(\tilde{\xi}-\tilde{\chi})}{\tilde{\xi}}, \frac{(\tilde{q}-\tilde{l})(\tilde{l}-\tilde{\chi})}{\tilde{l}}, \frac{(\tilde{q}-\tilde{\xi})(\tilde{\xi}-\tilde{l})}{\tilde{q}}\right] \\ \text{except for the special case in which } \tilde{l}^2 < \tilde{q}\tilde{\chi} < \tilde{\xi}^2 \text{ and} \\ \tilde{\xi}^2\tilde{\chi} < \tilde{q}\tilde{l}^2 \text{ where one must use } (m_{\tilde{q}} - m_{\tilde{\chi}_1^0})^2. \end{cases}$
Xq edge	$(m_{Xq}^{\max})^2 = X + (\tilde{q} - \tilde{\xi})\left[\tilde{\xi} + X - \tilde{\chi} + \sqrt{(\tilde{\xi} - X - \tilde{\chi})^2 - 4X\tilde{\chi}}\right]/(2\tilde{\xi})$
l^+l^-q threshold	$(m_{llq}^{\min})^2 = \begin{cases} [\ 2\tilde{l}(\tilde{q} - \tilde{\xi})(\tilde{\xi} - \tilde{\chi}) + (\tilde{q} + \tilde{\xi})(\tilde{\xi} - \tilde{l})(\tilde{l} - \tilde{\chi}) \\ \quad -(\tilde{q} - \tilde{\xi})\sqrt{(\tilde{\xi} + \tilde{l})^2(\tilde{l} + \tilde{\chi})^2 - 16\tilde{\xi}\tilde{l}^2\tilde{\chi}}\ ]/(4\tilde{\xi}^2) \end{cases}$
$l^{\perp}_{\text{near}}q$ edge	$(m_{l^{\perp}_{\text{near}}q}^{\max})^2 = (\tilde{q} - \tilde{\xi})(\tilde{\xi} - \tilde{l})/\tilde{\xi}$
$l^{\pm}_{\text{far}}q$ edge	$(m_{l^{\pm}_{\text{far}}q}^{\max})^2 = (\tilde{q} - \tilde{\xi})(\tilde{l} - \tilde{\chi})/\tilde{l}$
$l^{\pm}q$ high-edge	$(m_{lq(\text{high})}^{\max})^2 = \max\left[(m_{l_{\text{near}}q}^{\max})^2, (m_{l_{\text{far}}q}^{\max})^2\right]$
$l^{\pm}q$ low-edge	$(m_{lq(\text{low})}^{\max})^2 = \min\left[(m_{l_{\text{near}}q}^{\max})^2, (\tilde{q} - \tilde{\xi})(\tilde{l} - \tilde{\chi})/(2\tilde{l} - \tilde{\chi})\right]$
M_{T2} edge	$\Delta M = m_{\tilde{q}} - m_{\tilde{\chi}_1^0}$

Table 4: The absolute kinematic endpoints of invariant mass quantities formed from decay chains of the types mentioned in the text for known particle masses. The following shorthand notation has been used: $\tilde{\chi} = m^2_{\tilde{\chi}_1^0}$, $\tilde{l} = m^2_{\tilde{l}_R}$, $\tilde{\xi} = m^2_{\tilde{\chi}_2^0}$, $\tilde{q} = m^2_{\tilde{q}}$ and X is $m^2_{\tilde{\Lambda}}$ or $m^2_{\tilde{G}}$ depending on which particle participates in the "branched" decay.

Allanach et al., 2001



- **Gives sensitivity to masses (rather than combinations).**

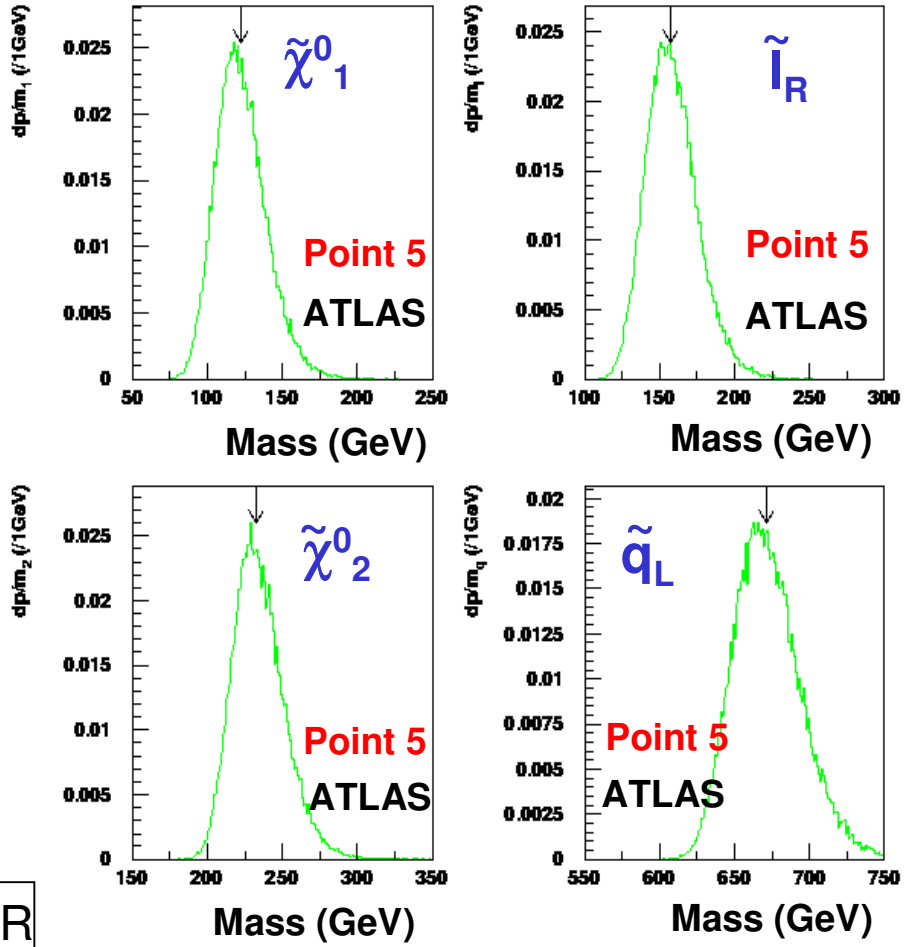
Mass Reconstruction

- Numerical solution of simultaneous edge position equations.
- Gives pseudo model-independent measurements
- Note interpretation of chain model-dependent.
- Powerful technique applicable to wide variety of R-Parity conserving models.

Sparticle	Expected precision (100 fb^{-1})
$\tilde{q}_L$	± 3%
$\tilde{\chi}^0_2$	± 6%
$\tilde{l}_R$	± 9%
$\tilde{\chi}^0_1$	± 12%

Physics TDR
Point 5

Allanach et al., 2001



Summary

- Lightest Neutralino is the Lightest SUSY Particle in many models.
- Measurement of SUSY particle masses in R-Parity conserving models complicated by presence of two LSPs in each event.
- Use of kinematic edges and combinations of edges necessary to reconstruct individual masses.
- Will allow test of SUSY model (CMSSM / mSUGRA, MSSM etc.).
- Will also provide useful test of SUSY Dark Matter hypothesis.