Showdown for SUSY: LHC and ILC

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Outline

- **Model features**
- **Global LHC signals**
- **Spectrum measurements at LHC**
- **Odd ball signatures**
- **Where the ILC may fit in**
- **Conclusions and outlook**

Plots from ATLAS unless otherwise shown

What are we looking for?

- If SUSY is relevant to EW symmetry breaking, must has sparticles below TeV.
- Some SUSY signals interfere with others: Must use a consistent model for simulation
- Too many parameters to study most general model
- Too many models to study all of them: LHC will cull them
- While waiting, kook for common features
- Attempt to extrapolate to the "real world"

Sparticle Spectra

- LHC has large mass reach, may produce many sparticles, complex analyzes
- ILC may produce only a few: more model independent analyzes possible.
- Use SUGRA model as baseline: Probably wrong but well defined
  Spectrum is given by 4 parameters.
  $\tan\beta = v_1/v_2$, m_0, $m_{1/2}$ Gluino mass strongly correlates with $m_{1/2}$, slepton mass with m_0.
  Higgs mass is derived

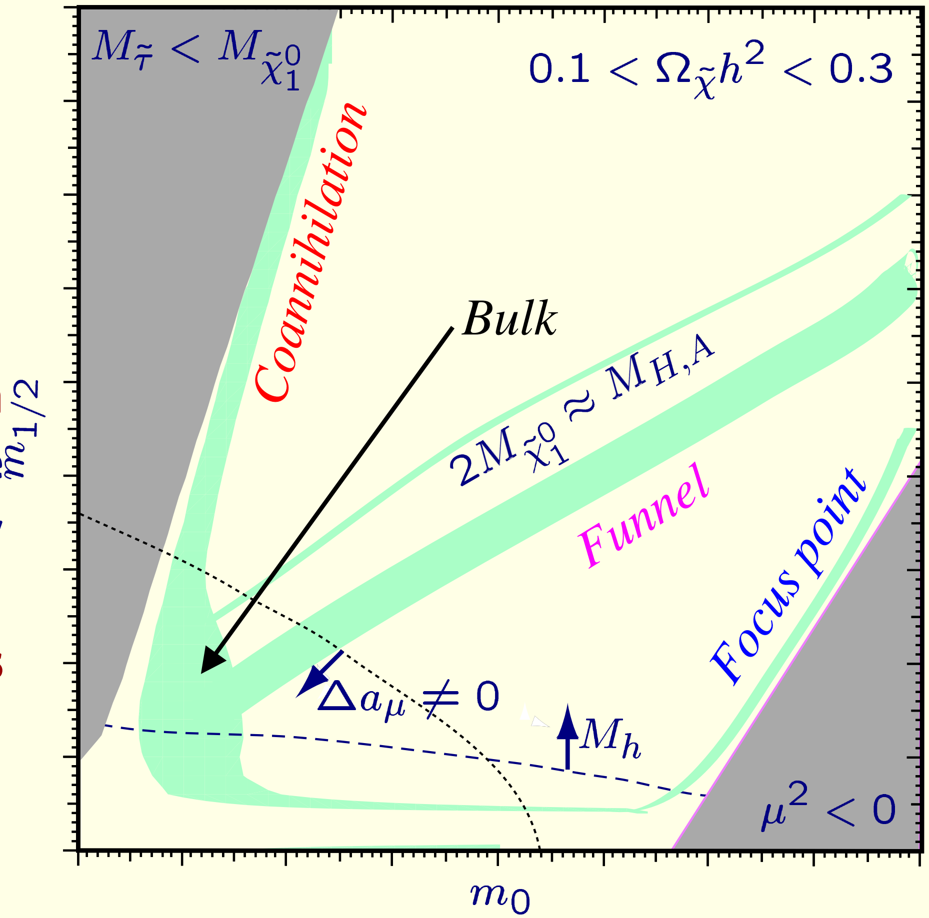
  R parity good – neutral LSP stable – all events have 2 LSP's in them
  $\Rightarrow$ missing E_T

  If μ large then $\tilde{\chi}_1^0$ is $\tilde{B}$ and $\tilde{\chi}_2^0$ is $\tilde{W}$; heavier $\tilde{\chi}$ are Higgsino
  LSP could be Dark matter.

Where to look

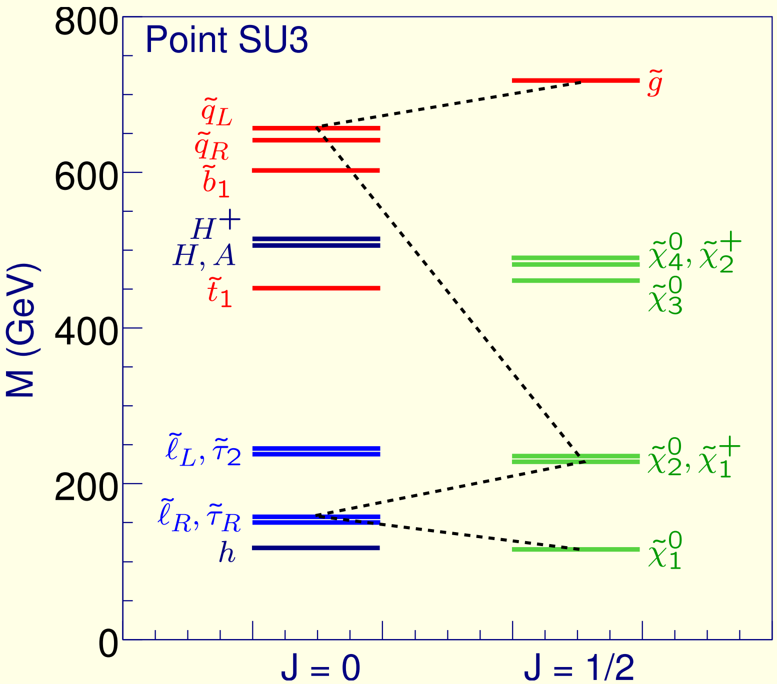
Take model seriously: really!?!

Too much dark matter unless LSP light or annihilation enhanced usually by some almost degeneracy, but also by content of LSP
If SUSY explains $(g-2)_\mu$, masses are small

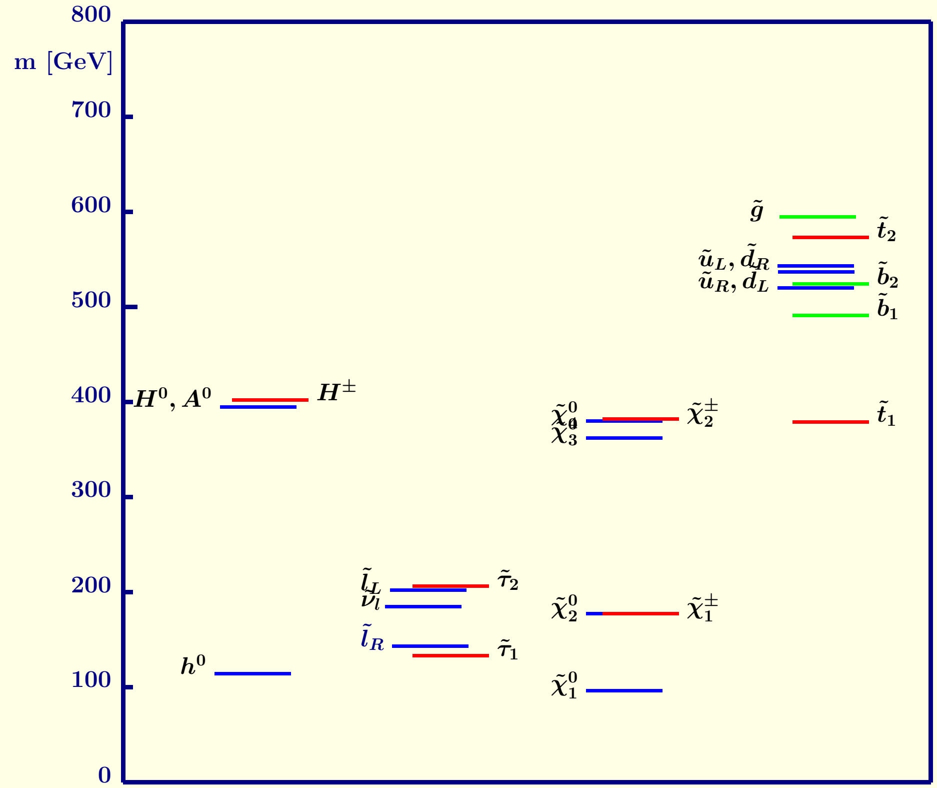


Caveat emptor: Don't take this too seriously

Two typical spectra



Used in ATLAS studies: important decays shown



SPS1a: used in many LHC/ILC comparisons

Note that initial ILC cannot produce everything.

Discovery at LHC

Could appear at Tevatron but LHC is only two years away

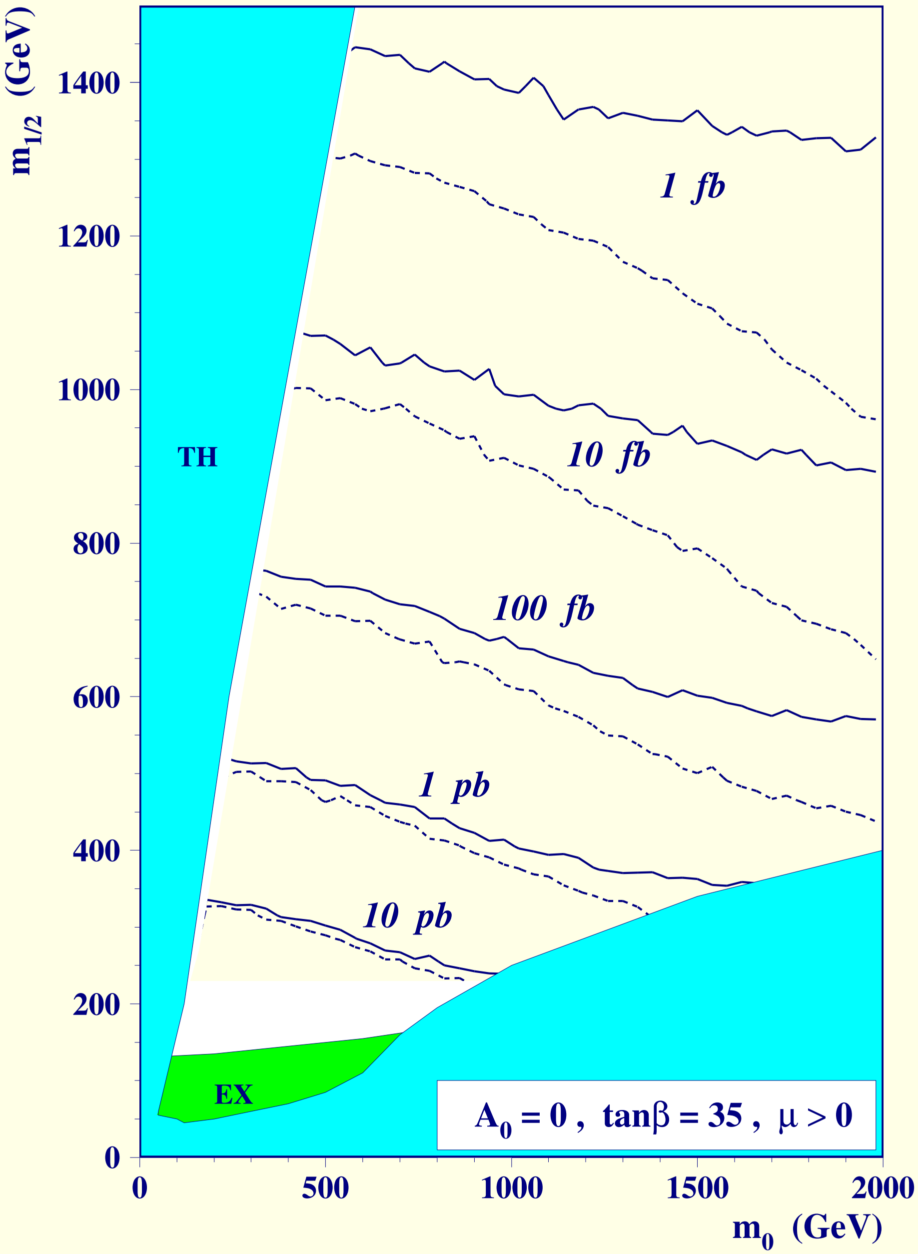
For typical spectra, gluino and squark production dominates

Cascade then produces jets, leptons and missing E_T

Sensitivity in channels with and without leptons is comparable

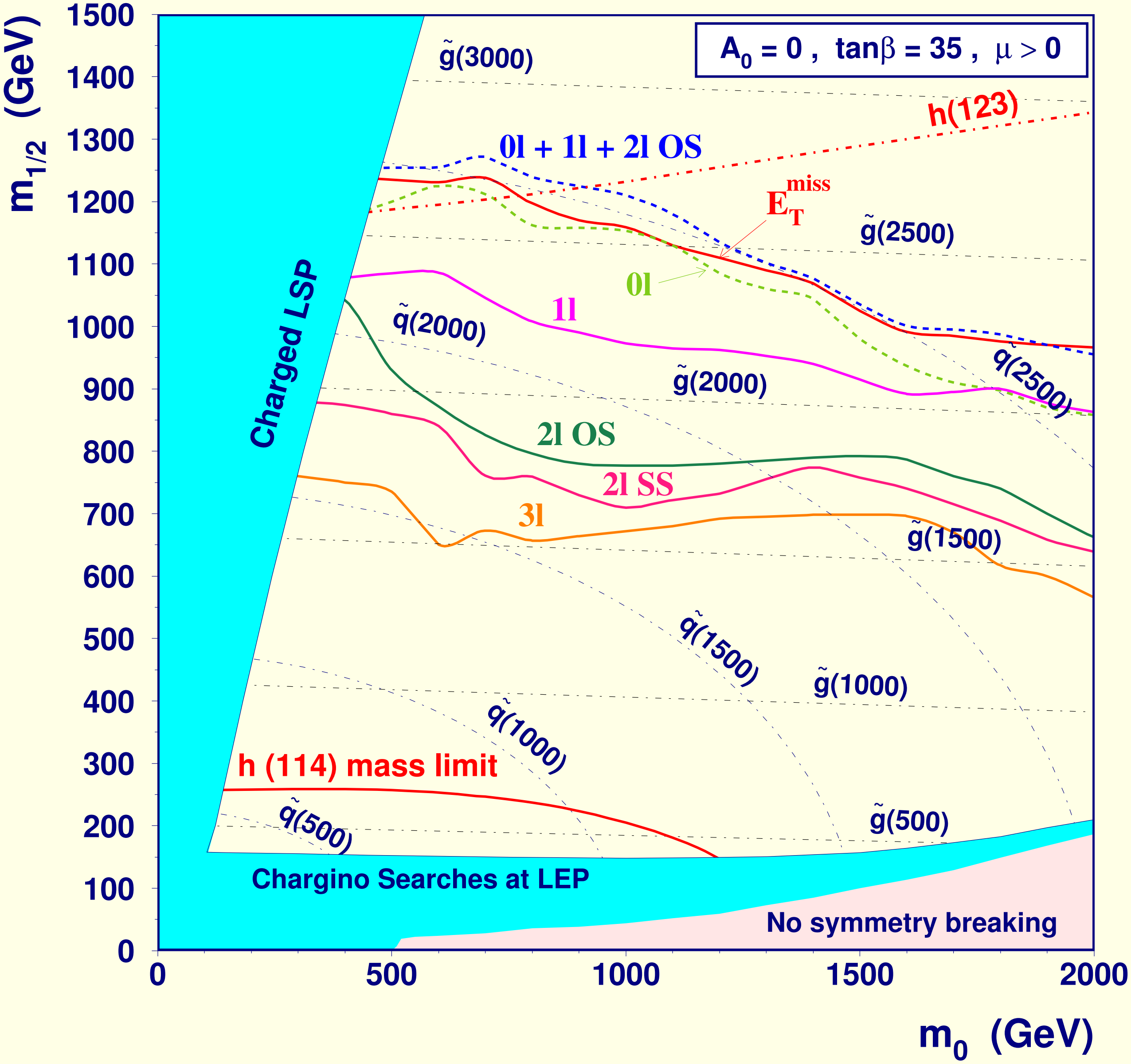
Backgrounds are dominated by top, and $W/Z + jets$

Discovery will set mass scale of squarks/gluinos


m_{1/2} (GeV)
1400
1200
1000
800
600
400
200
0
0
500
1000
1500
2000
m_0 (GeV)
TH
EX
1 fb
10 fb
100 fb
1 pb
10 pb
A_0 = 0 , tanβ = 35 , μ > 0

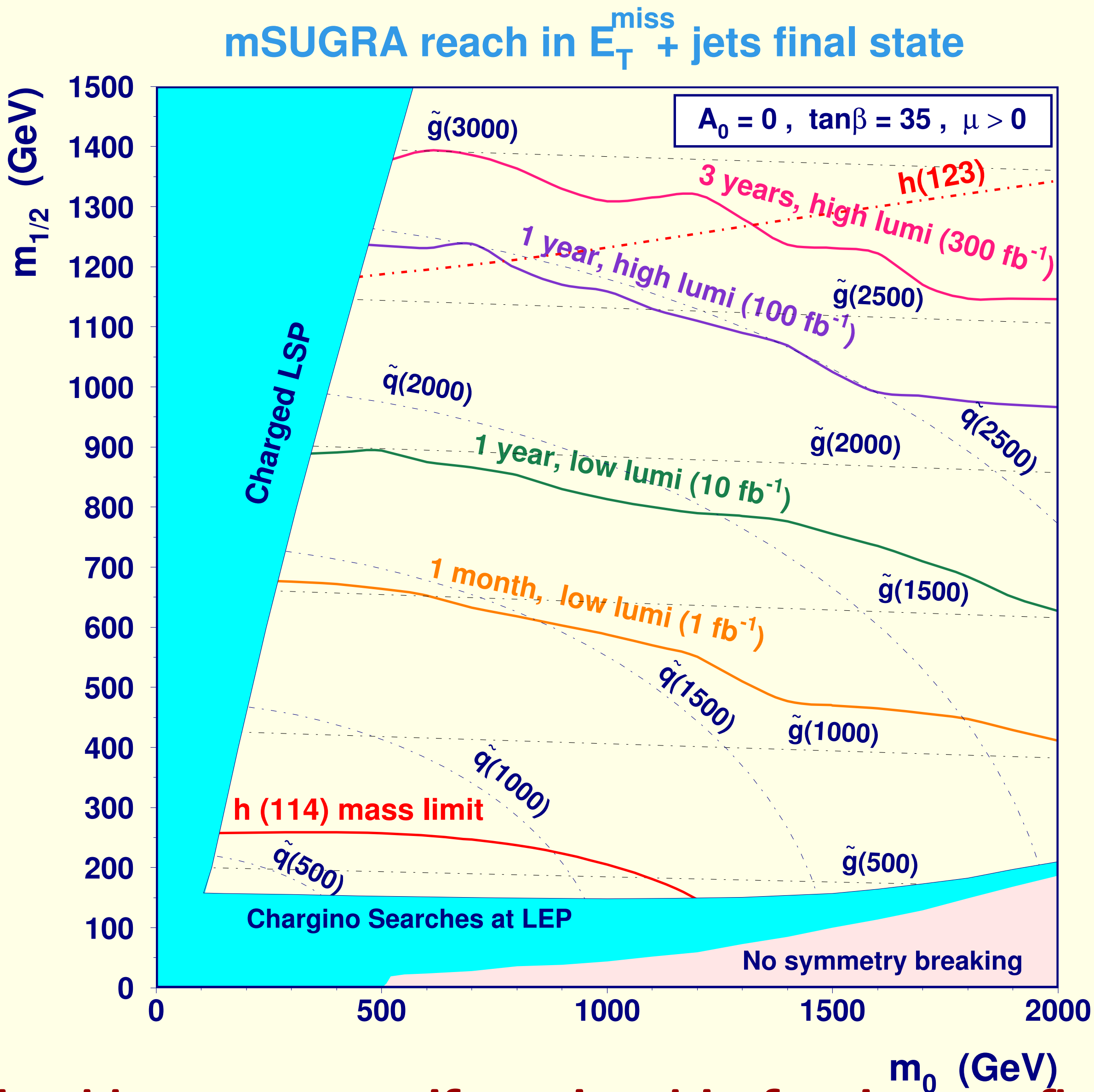
CMS

mSUGRA reach in various final states for 100 fb^{-1}



CMS

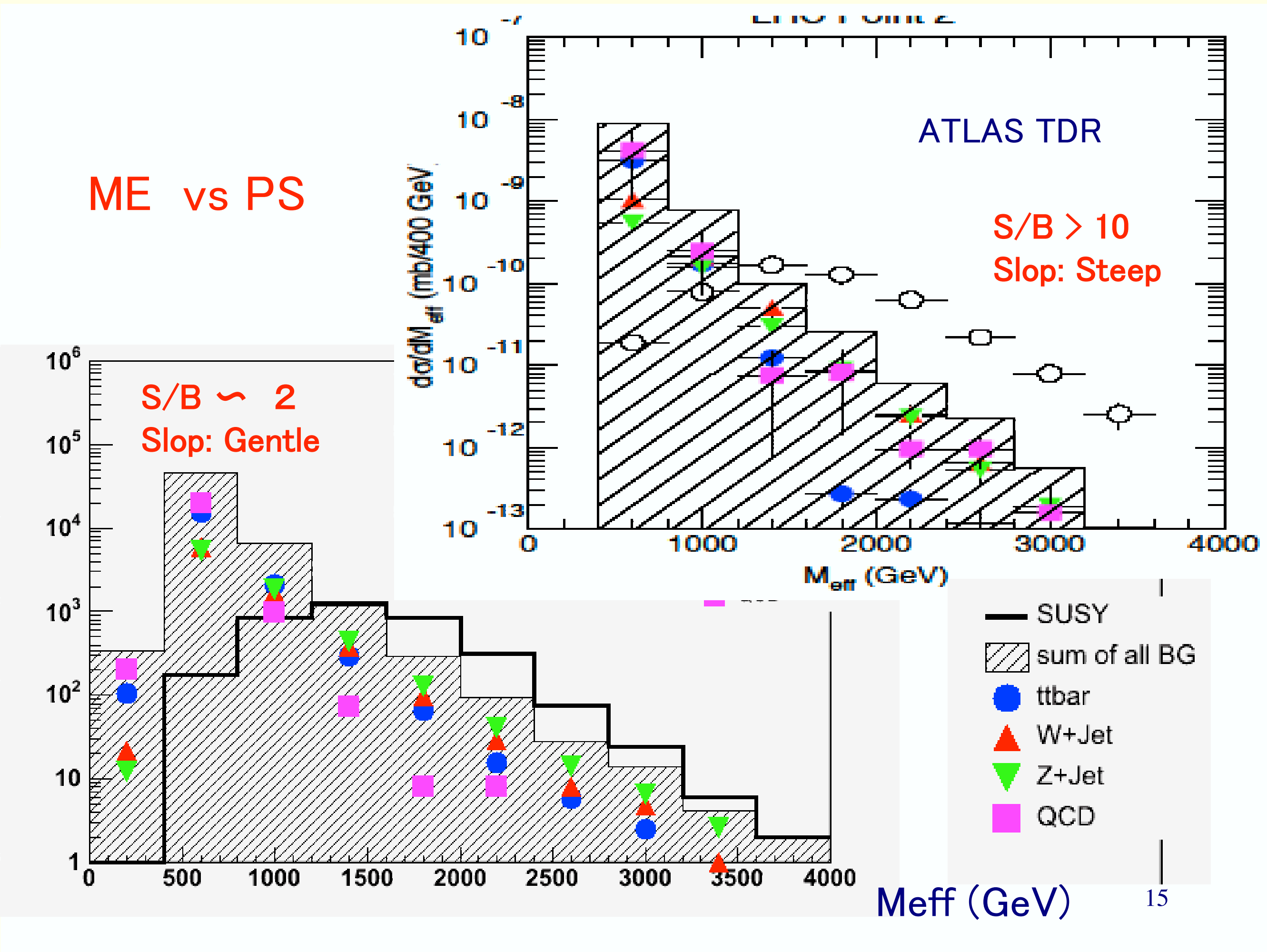
Energy of LHC is most crucial: reach increases slowly with luminosity



Should get nervous if no signal in few inverse fb

How robust is this?

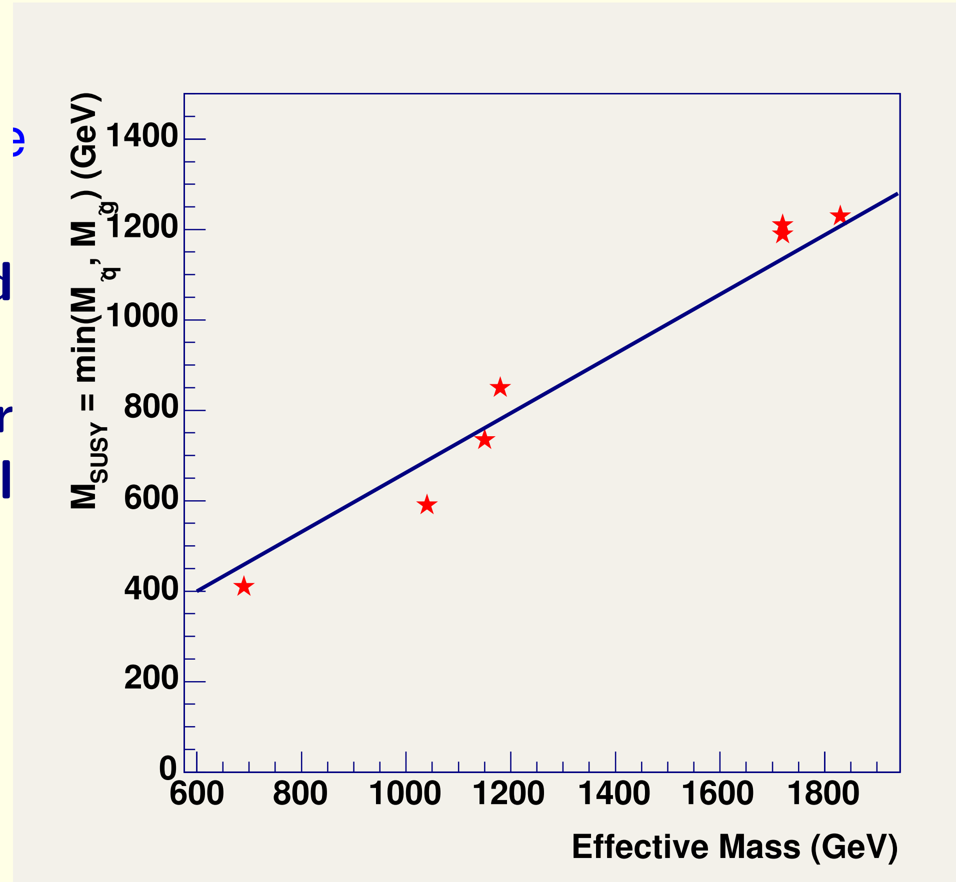
Backgrounds based on showering MC may underestimate multi-jet final states.



May lower reach slightly
Plot shows all jet state
Signal in Lepton+jets+miss
is more robust

Asai et al

Mass scale from Discovery



Correlation between peak of M_{eff} and SUSY masses

Plot shows SUGRA, correlation weaker but still present, in more general models

Tovey

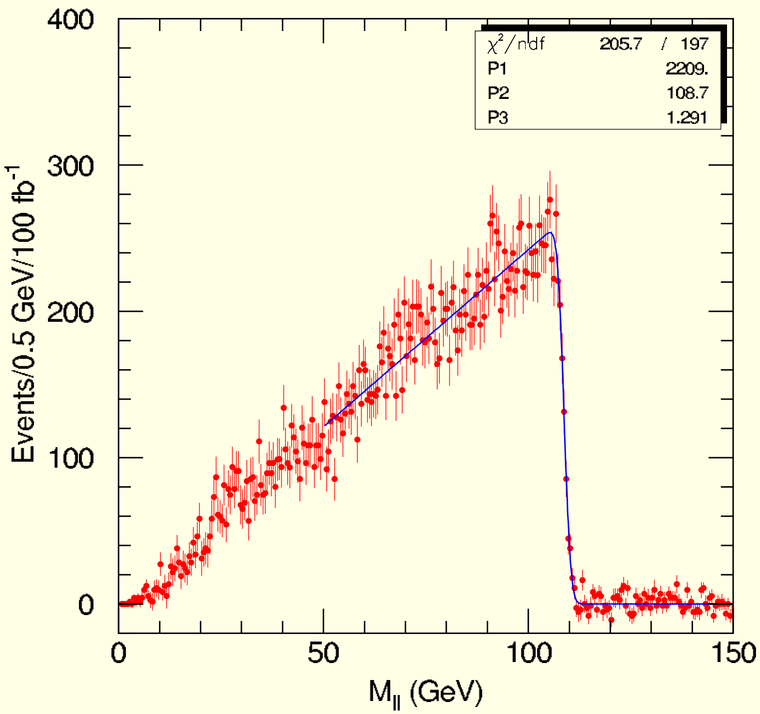
Mass measurements at LHC:I

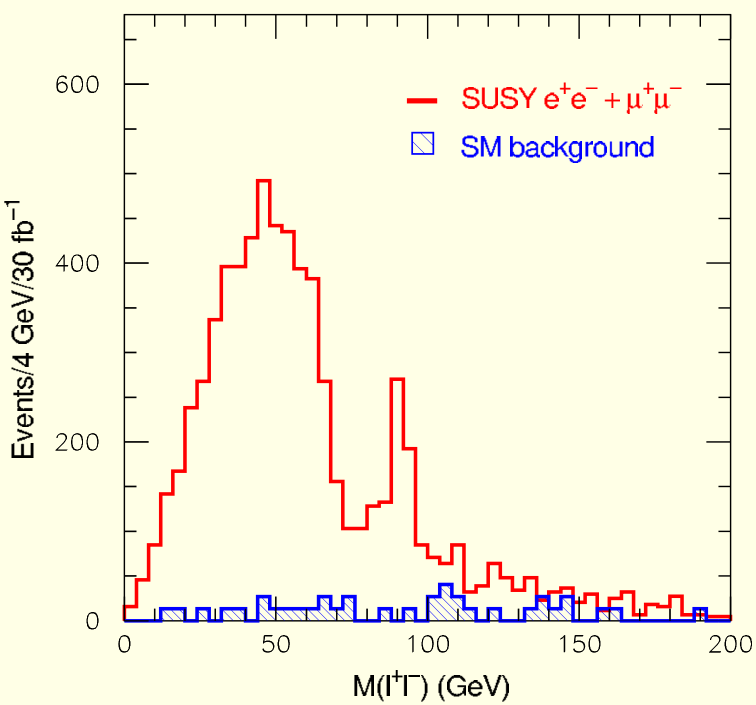
Detailed signals depend on spectra and decays: Typical example.

Isolated leptons indicate presence of t, W, Z, weak gauginos or sleptons

Key decays are $\widetilde{\chi}_2 \to \widetilde{\ell}^+\ell^-$ and $\widetilde{\chi}_2 \to \widetilde{\chi}_1\ell^+\ell^-$

Mass of opposite sign same flavor leptons is constrained by decay





Decay via real slepton: $\widetilde{\chi}_2 \to \widetilde{\ell}^+\ell^-$

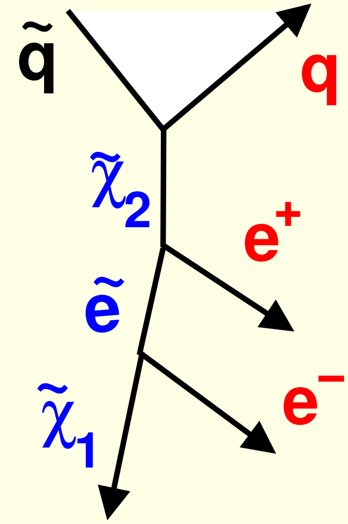
Plot shows $e^+e^- + \mu^+\mu^- - e^\pm\mu^\mp$

Decay via virtual slepton: $\widetilde{\chi}_2 \to \widetilde{\chi}_1\ell^+\ell^-$

and Z from other SUSY particles

Building on Leptons

Decay $\tilde{q}_L \to q\tilde{\chi}_2^0 \to q\tilde{\ell}\ell \to q\ell\ell\tilde{\chi}_1^0$



Identify and measure decay chain

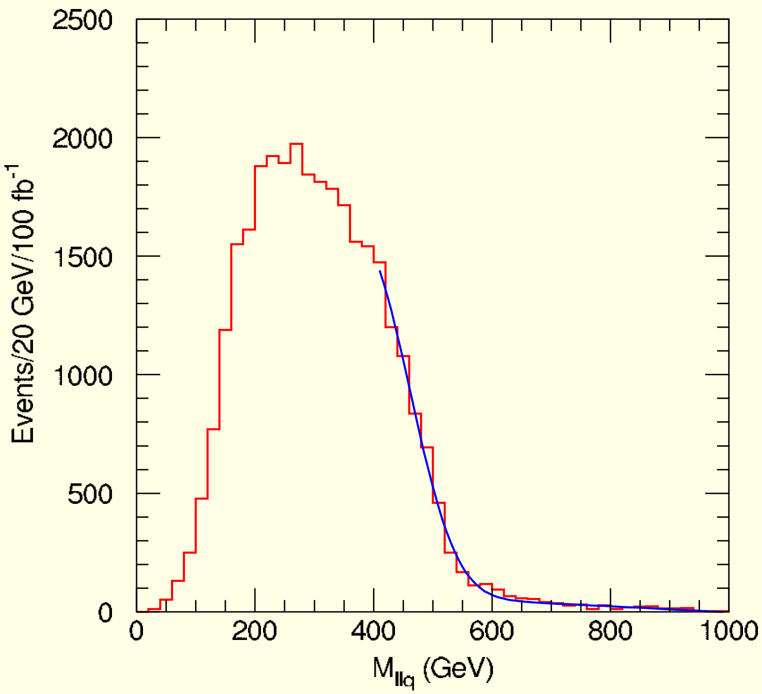
- **2 isolated opposite sign leptons;** $p_t > 10$ **GeV**
- ≥ 4 **jets; one has** $p_t > 100$ **GeV, rest** $p_t > 50$ **GeV**
- $\not\!\!E_T > max(100, 0.2M_{eff})$

Mass

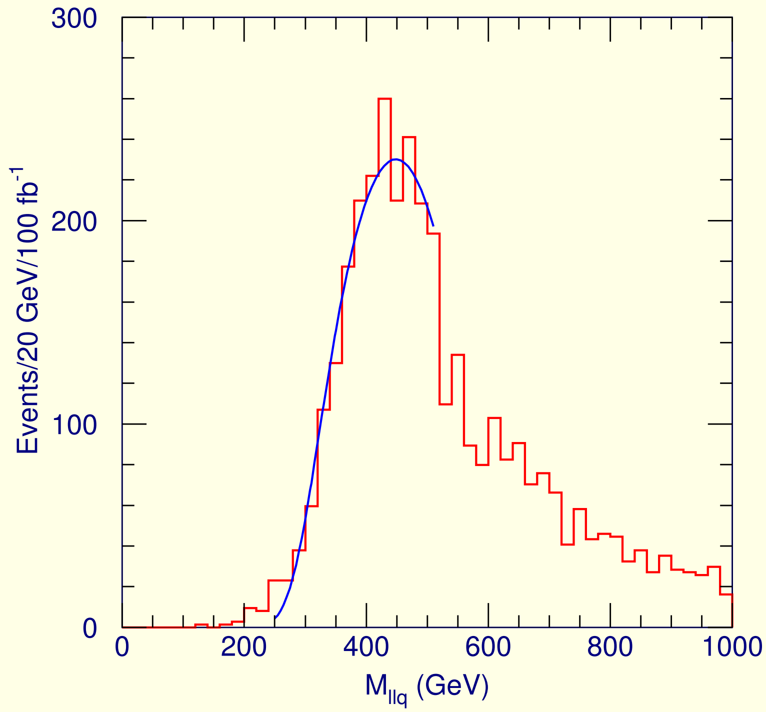
of $q\ell\ell$ **system has max at**

$$M_{\ell\ell q}^{\max} = [\frac{(M_{\tilde{q}_L}^2 - M_{\tilde{\chi}_2^0}^2)(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{\chi}_1^0}^2)}{M_{\tilde{\chi}_2^0}^2}]^{1/2} = 552.4\,\mathrm{GeV}$$

and min at 271 GeV



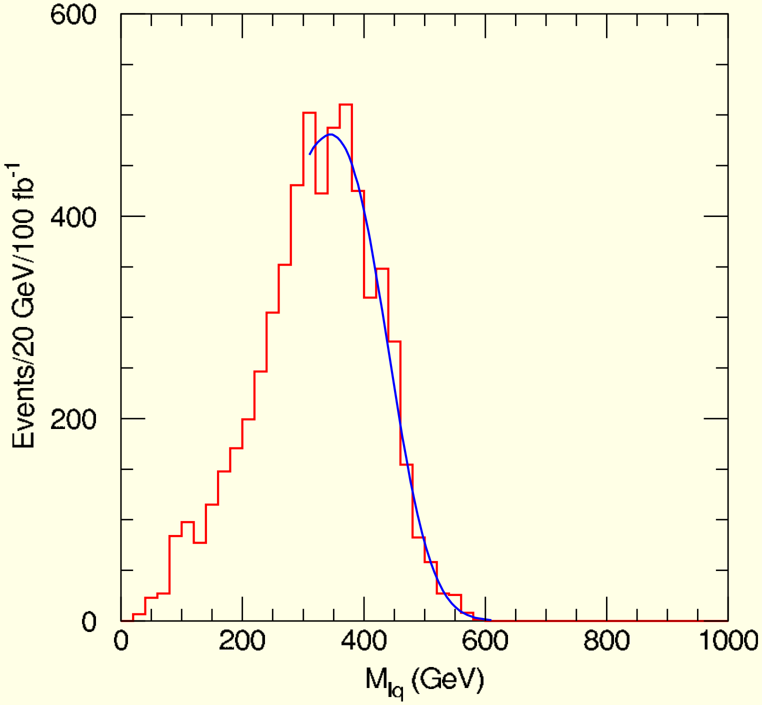
smallest mass of possible $\ell\ell jet$ **combinations**



largest mass of possible $\ell\ell jet$ **combinations**

Kinematic structure clearly seen

Can also exploit ℓjet mass

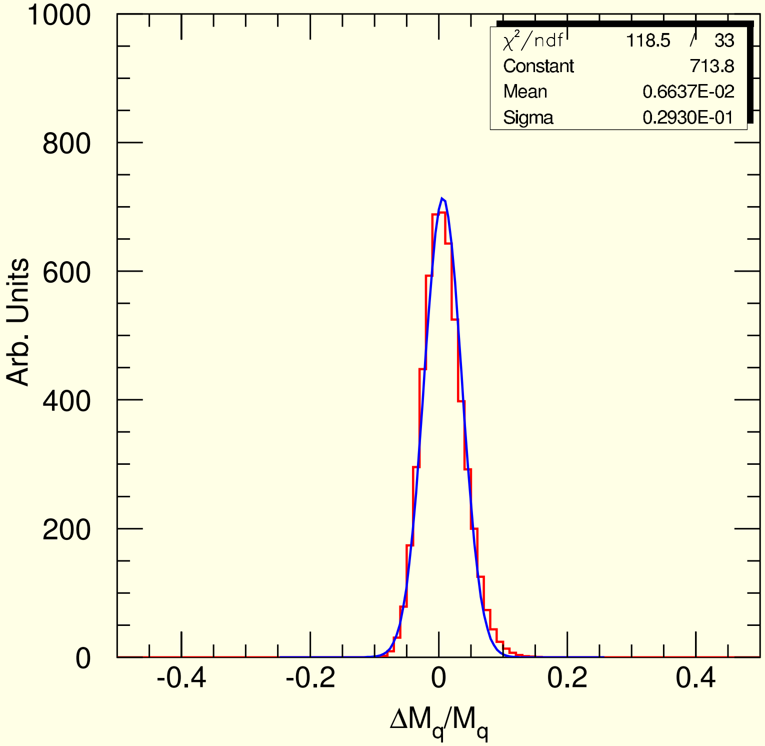


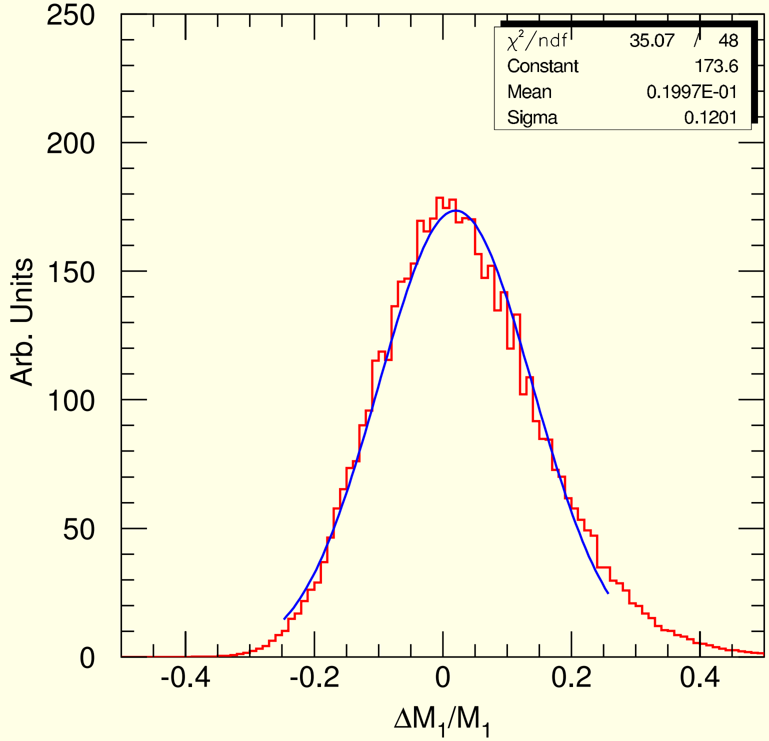
Can now solve for the masses. Note that no model is needed

Very naive analysis has 4 constraints from $lq, llq_{upper}, llq_{lower}, ll$ masses

4 Unknowns, $m_{\tilde{q}_L}, m_{\tilde{e_R}}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^0}$

Errors are 3%, 9%, 6% and 12% respectively

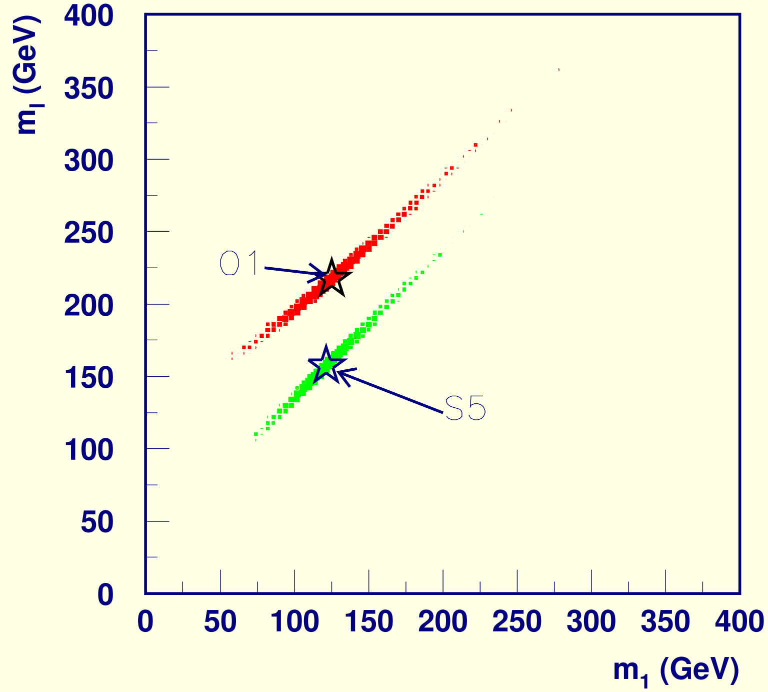




. **Squark mass** . **LSP mass**

Mass of unobserved LSP is determined

Errors are strong correlated and a precise independent determination of one mass reduces the errors on the rest. Allanach *et.al.*



This precision is probably good enough to test a model

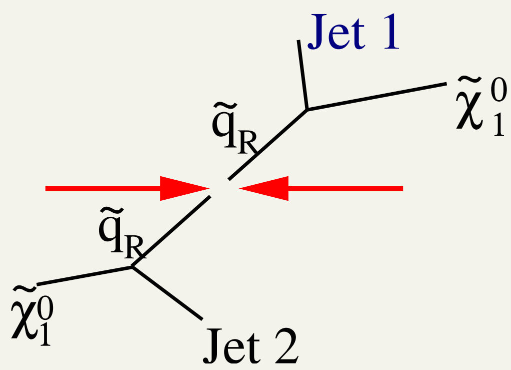
It is not good enough to measure LSP mass without model: Need one other precise measurement (ILC)

s-tranverse mass. Definition

- Select Events:

  $pp \to X + \tilde{q}_R\tilde{q}_R \to X + q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$

  - 2 Jets with $P_T >$200GeV
  - Δ(j1-j2)$>$1
  - Missing $E_T >$400GeV



- Partition $\vec{\not{E}}_T = \vec{\not{E}}_{T,1} + \vec{\not{E}}_{T,2}$ in all possible ways and compute:

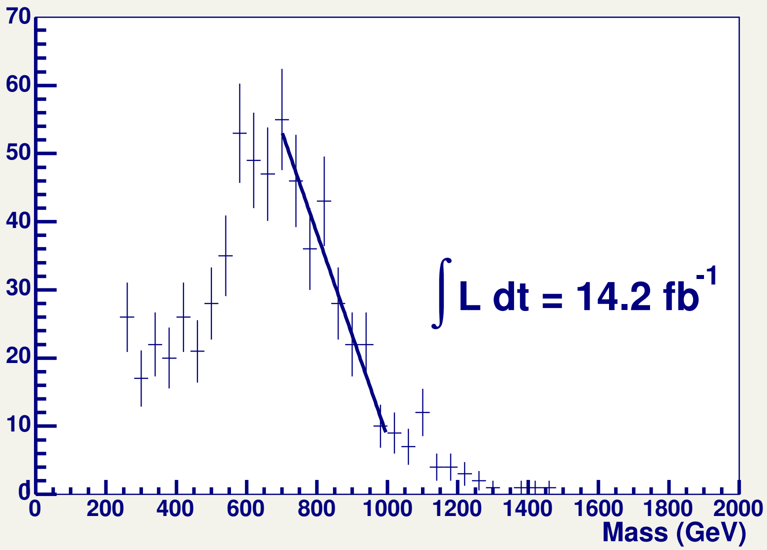
$$M_T^2 = \min_{\vec{\not{E}}_{T,1},\vec{\not{E}}_{T,2}} \left[\max\{m_T^2(P_{T,j1}, \not{E}_{T,1}, M_{\tilde{\chi}_1^0}), m_T^2(P_{T,j2}, \not{E}_{T,2}, M_{\tilde{\chi}_1^0})\}\right]$$

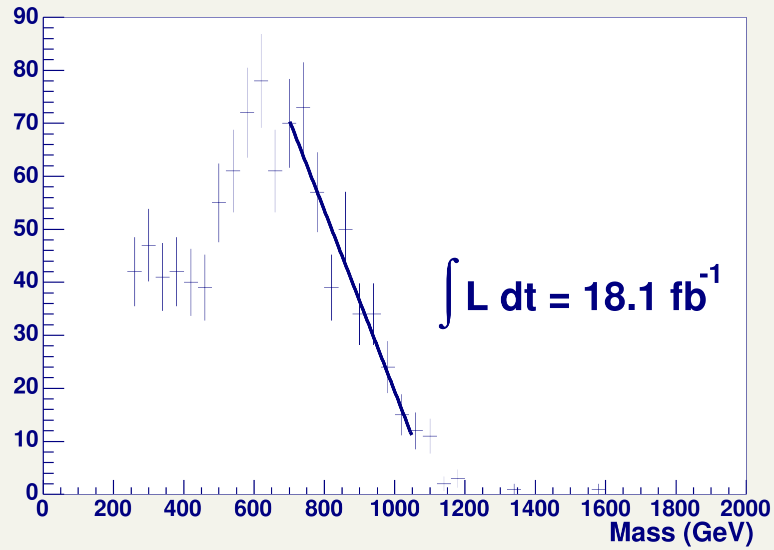
- M_T^2 depends on the choice of $M(\tilde{\chi}_1^0)$

s-tranverse mass for the SU5 point

Fit the end-point with a straight line and extrapolate to the x-axis
Use “true” value of M($\tilde{\chi}_1^0$)

(Ola Kristoff Oye)





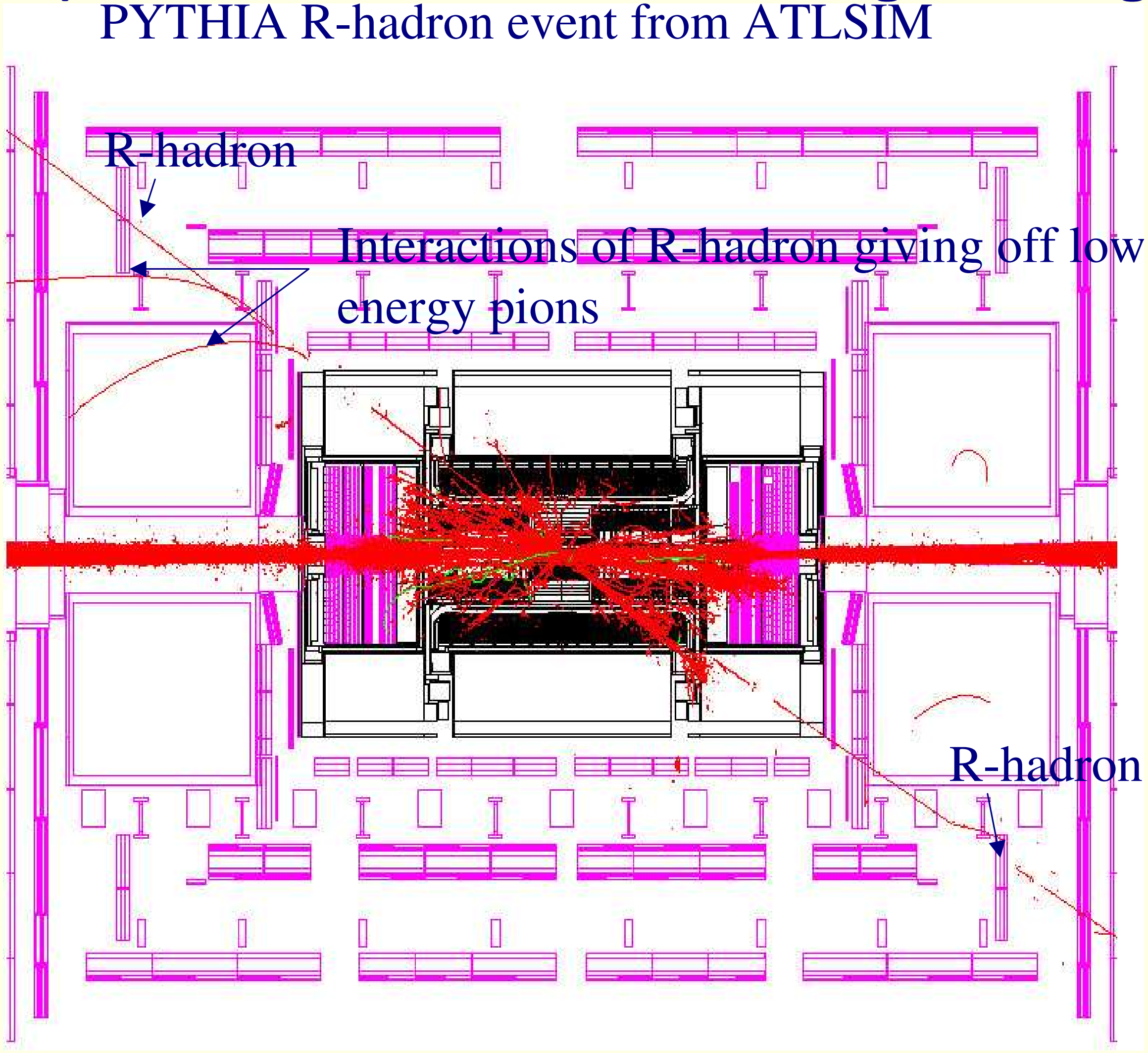
From the fit: $M(\tilde{q}_R) = 1056 \pm 181$GeV
Generator: $M(\tilde{q}_R) = 1190$GeV

From the fit: $M(\tilde{q}_R) = 1113 \pm 164$GeV
Generator: $M(\tilde{q}_R) = 1210$GeV

Again Limited by LSP mass uncertainty

Odd Ball: R-hadron

Long lived or quasi stable gluino produces "cannon ball" that charge exchanges

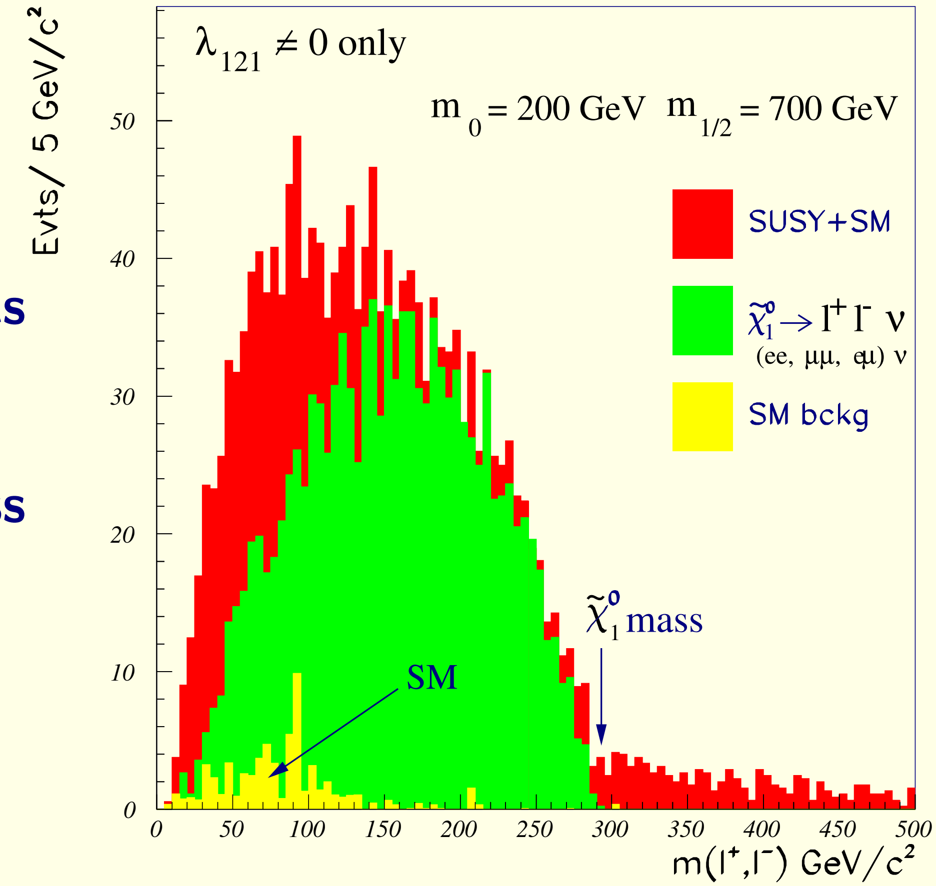


as it passes through detector

Odd Ball:R parity broken?

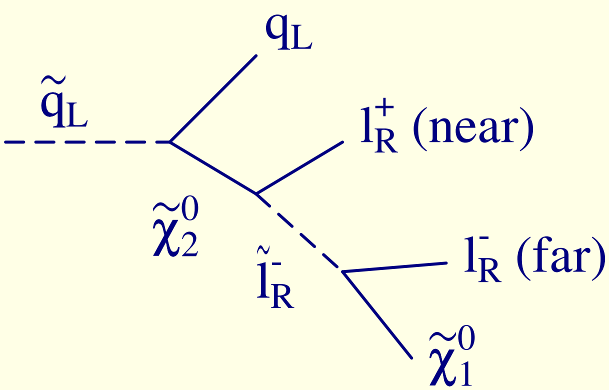
Note that missing energy is not needed

LSP unstable: can decay either to jets or leptons
Jet case has no missing $\not{E}_T$
Lepton case (shown) has much less missing $\not{E}_T$



Spin measurements at LHC?

Conventional wisdom says that you need LC for this but...

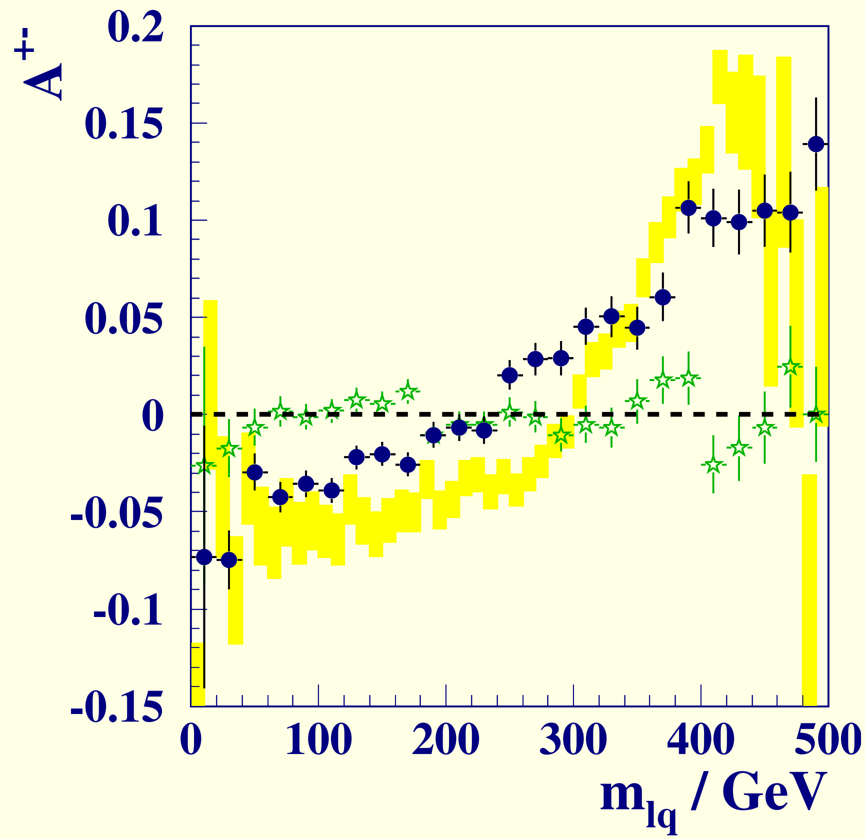


Angle between q and e^- in $\tilde{\chi}_2^0$ rest frame is sensitive to spin correlations.

But effect washes out if we do not know which lepton comes out first: Use kinematics

But effect washes out if average over q and $\overline{q}$: LHC is a pp machine: more $\tilde{q}$ than $\tilde{\overline{q}}$

Form an asymmetry from invariant mass distribution of lepton and jet



$A = \frac{(l^+q)-(l^-q)}{(l^+q)+(l^-q)}$

Green:spin correlation off
Yellow: No detector ($\times 0.6$)
Needs at least $100\mathrm{fb}^{-1}$

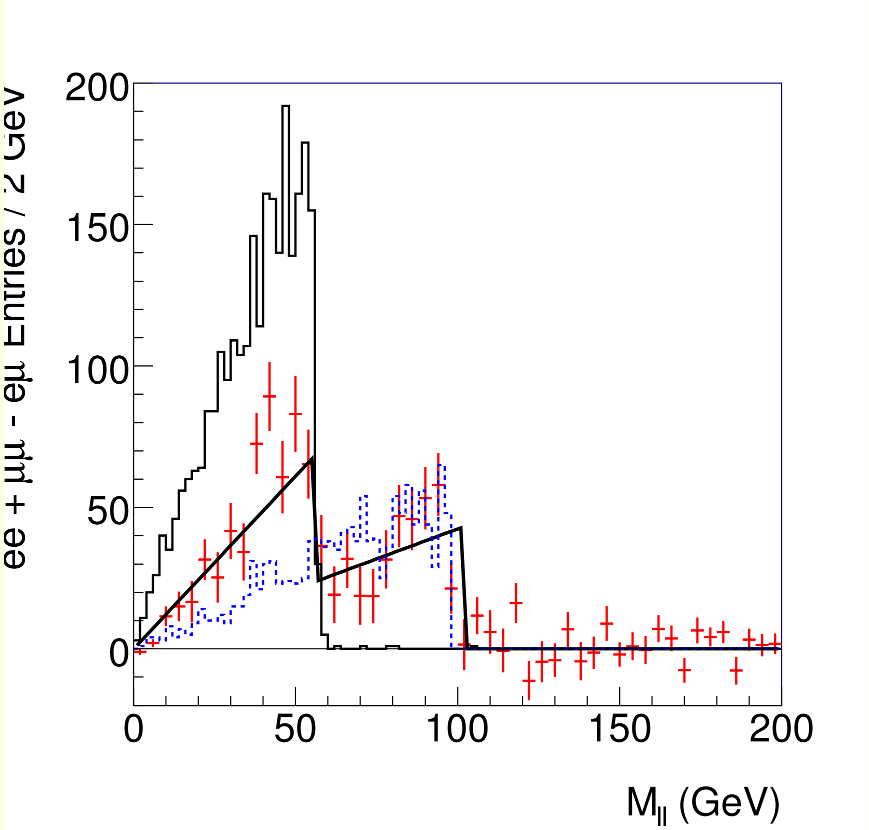
Barr

Difficult cases I: Small mass gaps

Co-annihilation region: Near degeneracy between LSP and sleptons.Soft leptons and more messy decays.

$\tilde{q}_L \to q\widetilde{\chi}_2^0$ **then** $\widetilde{\chi}_2^0(260) \to \widetilde{\ell}_R(153)\ell \to \ell\ell\widetilde{\chi}_1^0(136)$ **and** $\widetilde{\chi}_2^0 \to \widetilde{\ell}_L(255)\ell \to \ell\ell\widetilde{\chi}_1^0(136)$

Leptons can still be found despite small mass gaps



ATLAS

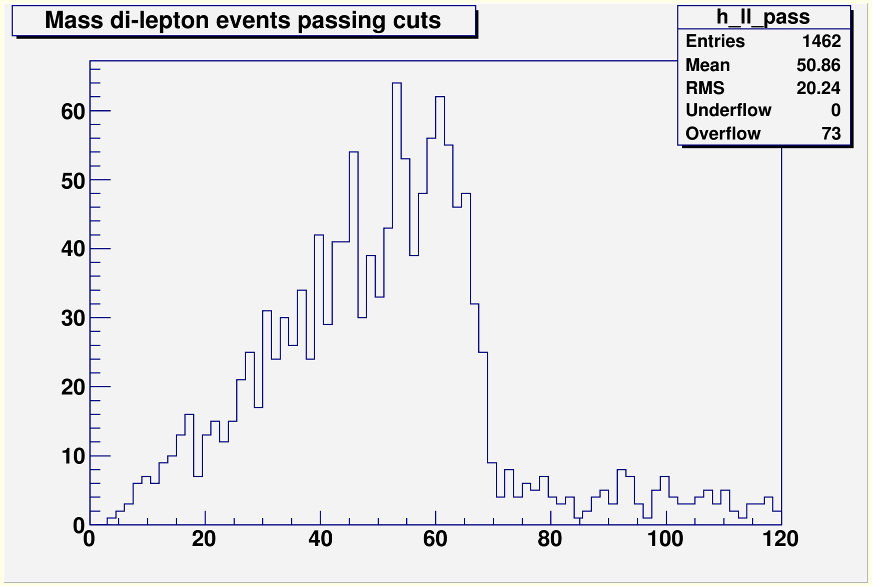
Difficult cases II: Taus

Much harder if leptons are taus: must use hadronic decays
See talk by Ignacio Aracena (parallel session).

Difficult cases III:Focus point

Large m_0, squarks and sleptons inaccessible.

Dilepton structure still present if $\tilde{g} \rightarrow q\bar{q}\widetilde{\chi}_2^0$



Tompkins, Zerwas

At larger masses, rates drop as only direct $\widetilde{\chi}_1^+\widetilde{\chi}_1^0$ is possible

Small mass gap and needed jet veto makes this very hard.(Baer et al)

How do we know its SUSY?

I'll worry about this after something is discovered

ILC: A note of reality

Plots typically show 100 fb^{-1}

- **It's** 2005
- **TDR** $t_0 - a - b - c$
- **Site selection** $t_0 - a - b$
- **Funding approval** $t_0 - a$
- **Construction start** t_0
- **Physics running start** $t_0 + d$
- **100** fb^{-1} **accumulated at one energy** $t_0 + d + 3$
- **1000** fb^{-1} **(Snowmass run plan)** $t_0 + d + 6$

EHLQ is 21 years old and I'm still waiting
http://www.interactions.org/linearcollider/gde/

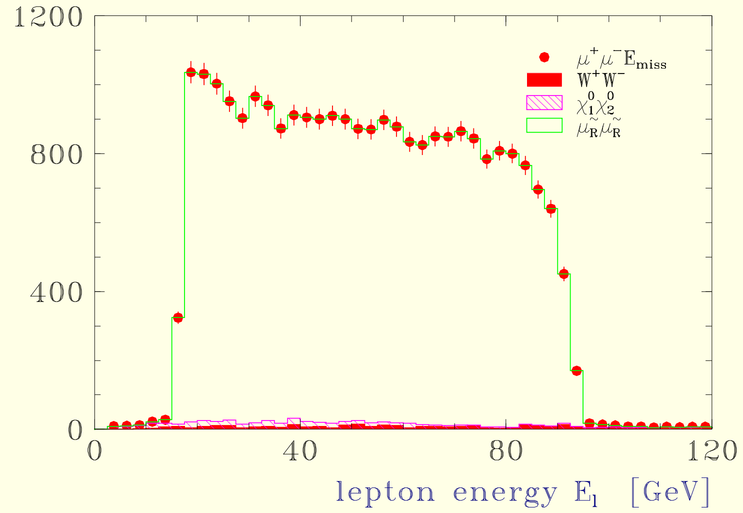
My comments

- Polarized positrons are an upgrade: live without them
- $\gamma\gamma$ and γe are upgrades: live without them
- Threshold scans are wasteful of luminosity: live without them
- Focus on precision and difficult LHC scenarios
- Example: Find all the gauginos and measure mixings.

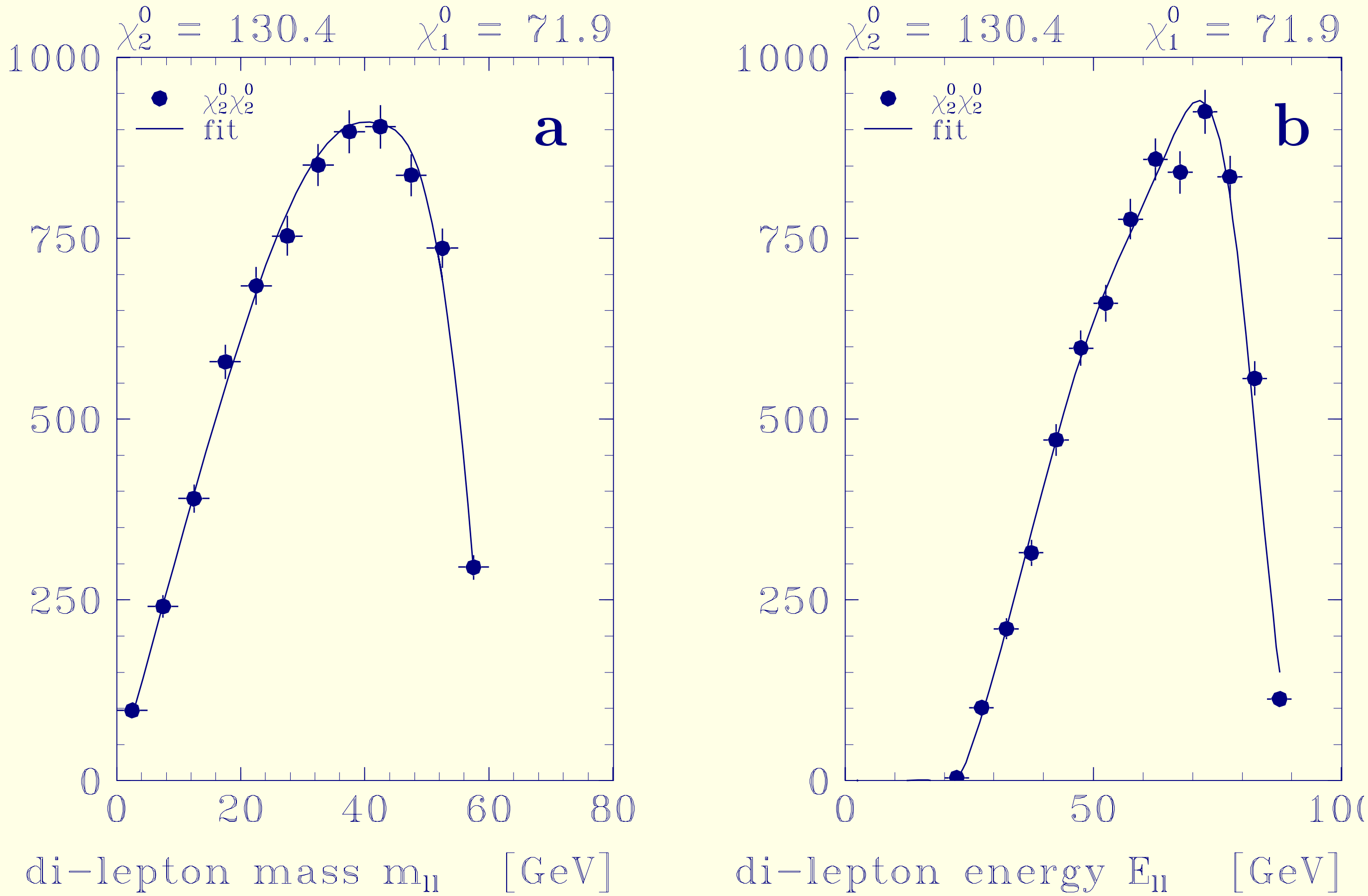
Mass measurements at LC: End points

Pair production of $m\tilde{u}_R$
Events have $\mu^+\mu^-$ and missing energy
Note small SM background
Can determine both $\widetilde{\chi}_1^0$ and $\tilde{\mu}$ mass to ~ 0.5%
SUSY background is zero in this study as machine is below threshold for other sparticles.

Martyn, DESY/LC



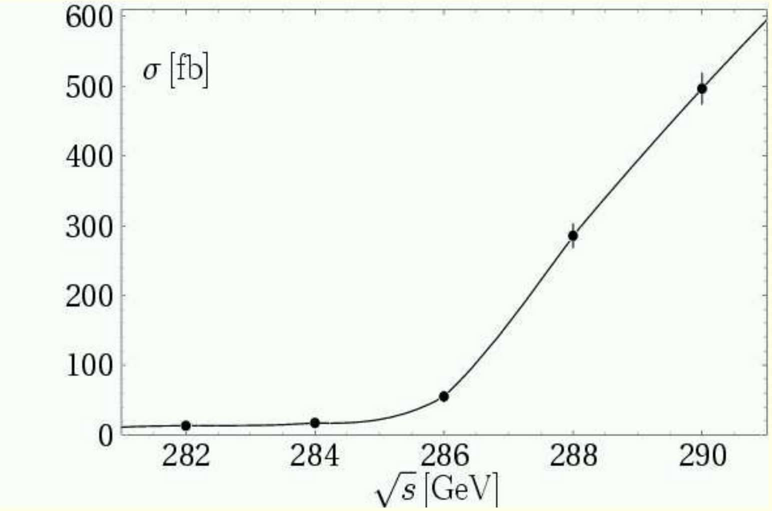
At larger energy can produce heavier gauginos $e^+e^- \to \widetilde{\chi}_2^0\widetilde{\chi}_2^0 \to \ell^+\ell^-\ell^+\ell^-\widetilde{\chi}_1^0\widetilde{\chi}_1^0$



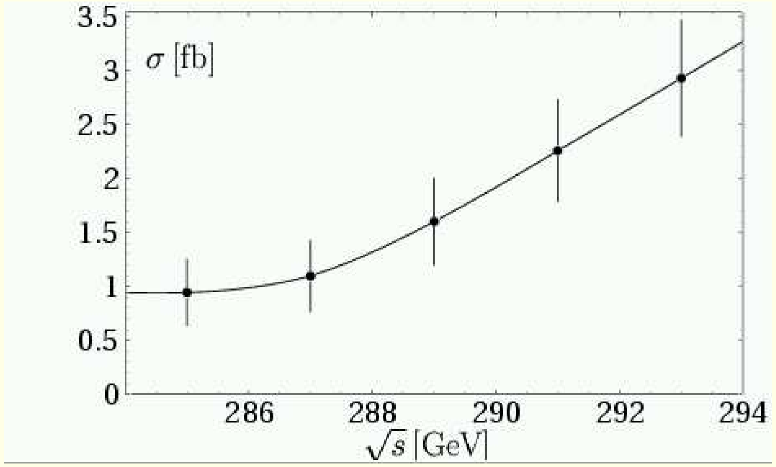
Measures both $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^0$ masses

Mass measurements at LC: Scans

Very precise measurements from energy dependence of rates



$\tilde{\mu}_R$ **threshold**



$\tilde{e}_R$ **threshold**

Note that these are very demanding of luminosity.($1\mathrm{fb}^{-1}$ per point)

But 50 MeV errors are possible

Freitas etal

Precision at ILC

- **Known partonic initial energy is vital**
- **LHC limited by correlations with poorly measured LSP mass**
- **One precise mass has huge impact**
- **ILC can lower error on LSP mass to 50 MeV**

Discovery cannot be far off

"The train is already late" (Altarelli): Fine tuning is a problem already.

We expected gauginos in the LEP range
Tevatron "window" is small but low masses are more likely

If masses are low and model is "not too complicated", LHC will fix it and ILC will be "LEP for SUSY"

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An era is about to end
Low energy SUSY has provided employment for > 20 years
It will be discovered or die in the next 6 years.