Beyond the SM at ILC

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Impact of LHC 10 fb^{-1} on ILC:
- Energy
- Luminosity
- Polarization
- GigaZ

for signals in:
- Missing Energy
- Multi gauge bosons
- Lepton resonances
- "other"

Motivational Slide

- I'm sure most of you are finding the Standard model to be similar to some personal relationships:
  - Incredibly beautiful and successful the first years
  - Puzzling in middle life ... but still satisfying, dear
  - Lacking in content and unaccountable in later life
- There are many other attractive models out there
  - In our case they are uncomfortably massive, but have the potential to unite the relevant energy scales
- Our impossible task is to anticipate what is going to move in (after LHC) and have the right kind of house ready for it.

ILC Machine & Detector Parameters

To begin, we need to understand what ILC parameters could be influenced by LHC early discoveries:

- New Physics mass scale ⇒ machine energy
- NP cross sections ⇒ luminosity and run plan
- NP emphasis on jets vs leptons ⇒ calorimetry, tracking
- NP model ⇒
  - Quality and type of polarized beams
  - Importance of forward detector region, beamstrahlung
  - Need for detector sensitivity to long-lived particles

(In any scenario I can think of the missing energy measurement has to be the best we can achieve)

Run Planning

- LHC's NP influences the ILC energy and polarisation choices, as well as whether we need to shut down to install more RF for higher luminosity.
  - Scans for spin measurement are costly (lumi budget)
  - Scans for resonances are way costly
  - Will need to determine best place(s) for production running
    - Likely to be 500 GeV
    - … or highest yield point for specific new particle
- Maybe precision is the way to go
  - Might have to run at 350 GeV for tt production
  - … or GigaZ conversion
- Polarisation optimum depends on NP
  - Longitudinal or transverse
  - P_+,P_- chosen to max S/B, identify coupling, cf R vs L, scan?,…

ILC Baseline Parameters

The baseline parameters were established by a WWS committee (S. Komamiya, D. Son, P.Grannis, M.Oreglia, F.Richard, R.-D.Heuer) in 2003 and reexamined in 2006

- The maximum energy should be 500 GeV with energy range for physics between 200 GeV and 500 GeV, i.e. the collider has also to allow for energy scans at all centre-of-mass energy values between 200 GeV and 500 GeV.
- Luminosity and reliability of the machine should allow the collection of **500 fb^{-1} in the first four years of running. (**Full scan of 100 fb^{-1} may take a year.)
- Electron polarisation of at least 80%

“Upgrades”,“Options” to Baseline

- The energy of the machine should be upgradeable to approximately 1 TeV
- **Doubling the integrated luminosity** to a total of 1 ab^{-1} within two additional years of running
- Positron polarisation at or above 50% is desirable in the whole energy range.
- Running at the Z^0 with a luminosity of several 10^{33} /cm^2/s (GigaZ running); Running at the WW threshold with a luminosity of several 10^{33} /cm2/s
- e^-e^- collider at any energy value up to the e+e- maximum energy.
- (polarized) photons, or electrons and photons, from backscattered laser beams.

The effect of these parameters will be examined in the following slides

Questions to Working Groups

The parameter Group issued a few questions to the working groups in all regions mainly addressing the issues of integrated luminosity, energy, beam energy spread, and positron polarisation.

WG's were asked to specifically address the following issues:

At what amount of integrated luminosity are systematic effects becoming dominant?

Is there any impact of decreasing (increasing) beamstrahlung by a factor of two relative to the standard parameters, i.e. trading off luminosity vs background?

Is there any benefit from electron plus positron polarisation (80 and 60%) or from increased electron polarisation in the absence of positron polarisation?

Are there other accelerator parameters strongly influencing the measurement?

SUSY WG Answer

- What is the achievable precision for the measurement of sparticle properties (in particular the masses)?
- Consider the lightest stau in the co-annihilation region assuming a mass difference to the LSP of 5 GeV. How much luminosity is needed to reach a precision comparable to the one expected from the measurements with the Planck satellite
- What is the achievable precision for the measurement of sparticle properties (in particular the masses) assuming the case of neutralino production $\chi_1\chi_2$.

Wide range of SUSY models makes clear predictions difficult
Essentially all measurements are statistically limited at least up to 500 fb^{-1}
there are, however, scenarios (e.g. stau-coannihilation channel) where 300 fb^{-1} at 600 GeV already match Planck accuracy (2%)
→ max energy and luminosity desirable
Beamstrahlung is not an issue for endpoint method
(contrary to threshold scans for the determination of masses)
Positron polarisation helps, may even be important for some scenarios

NP Working Group Answer

What is the achievable precision for the measurement of a Z'?
Please give in particular the expected error on g_V and g_A, at two different energies: 500 GeV and 1 TeV.

At 500 GeV at least 500 fb^{-1} (800 fb^{-1}) with 60% (w/o) positron polarisation required to exceed sensitivity expected for LHC
Beamstrahlung should be no problem

Taking into account also other important channels (e.g. TGC's) calls primarily for E and L, positron polarisation beneficial in all cases studied

Conclusion:

- The original baseline parameters are the best we can do now
- GDE did not need to make any significant descoping
- The UPGRADE and OPTIONS will be where LHC results have the biggest effect
- … now on to examine the NP signatures

1) Missing Energy Signatures

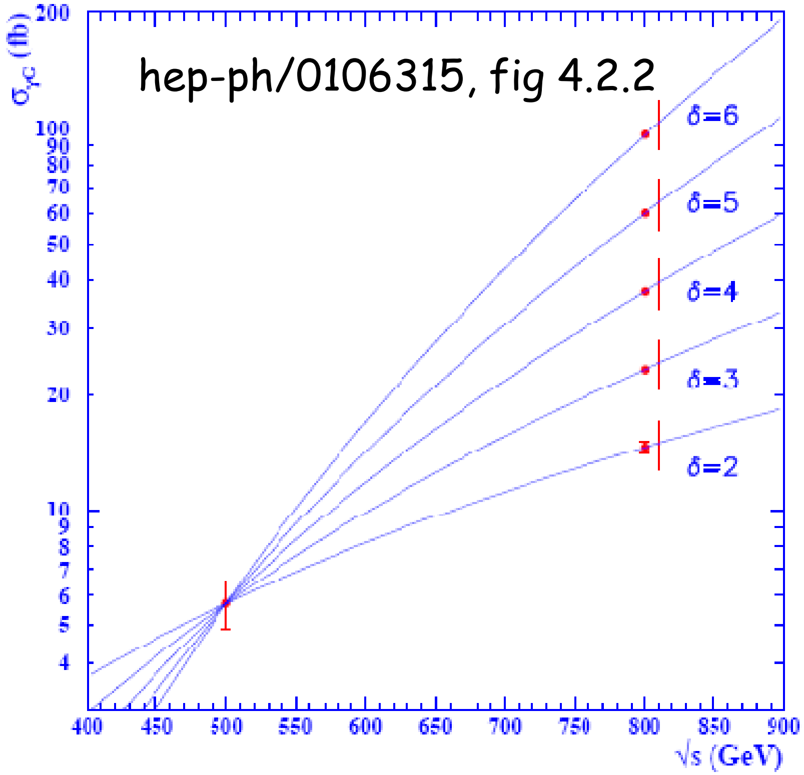
- Likely cause: holes in detectors and bad E_{jet} calibration
- 2nd likely cause: SUSY
- … but don't forget ExDim and Little Higgs models
- So the questions are:
  - What can LHC see with 10 fb^{-1}
  - Will mass range necessitate ILC-1000 or precision EW
  - Is stau-LSP mass difference small
  - Is there a spectrum/couplings warranting higher P_+
- SUSY production cross sections often large, but not always for the post-LHC particles
  - Polarised cross sections the key to ID
- ExDim cross sections generally large

Large ExDim Models

- $4+\delta$ dimensions
- KK graviton spectrum can be very dense for $M_D \sim 1$ TeV, so ILC uses γG_{KK} production
- Very identifiable final state:
  - Photon + large E_{miss}
- Big polarised beam enhancement
- Study in TESLA TDR shows ILC power to discriminate for δ by comparing cross section at 500 and 800 GeV

Sensitivity for M_D (TeV)

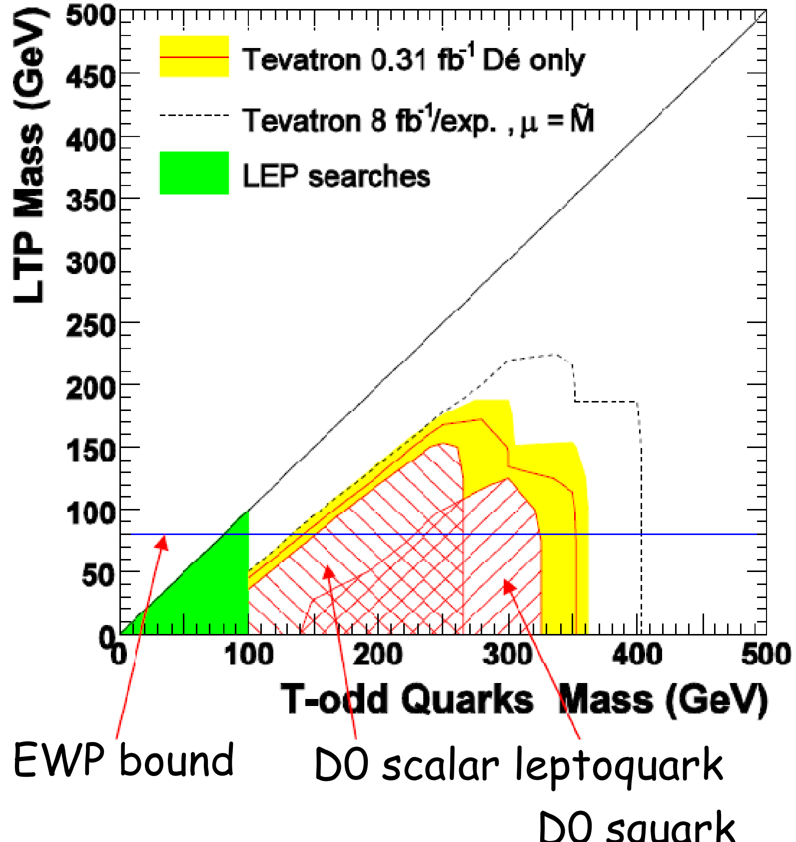
δ	2	3	4	5	6
$M_D(P_{-,+}=0)$	5.9	4.4	3.5	2.9	2.5
$M_D(P_-=0.8)$	8.3	5.8	4.4	3.5	2.9
$M_D(P_-=0.8, P_+=0.6)$	10.4	6.9	5.1	4.0	3.3



hep-ph/0106315, fig 4.2.2

LHM with T Parity

- Little Higgs model can incorporate T parity
  - Discrete symmetry introduced to cure ills, like R-parity
  - Results in mirror leptons and quarks
  - Signature: dijet + E_{miss} or dilepton + E_{miss}
  - High production cross section and current bounds might allow for this at ILC-500, but higher energy likely



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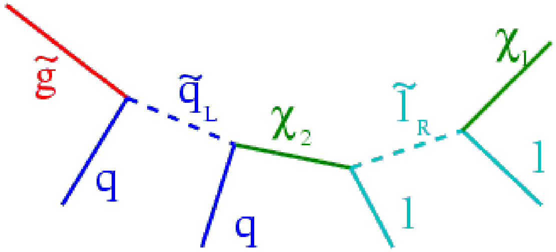
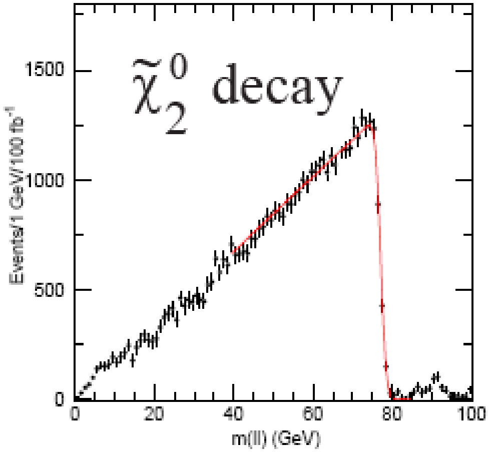
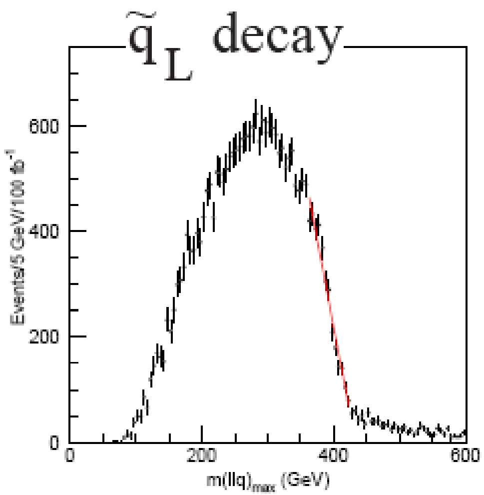
LHC SUSY Signatures





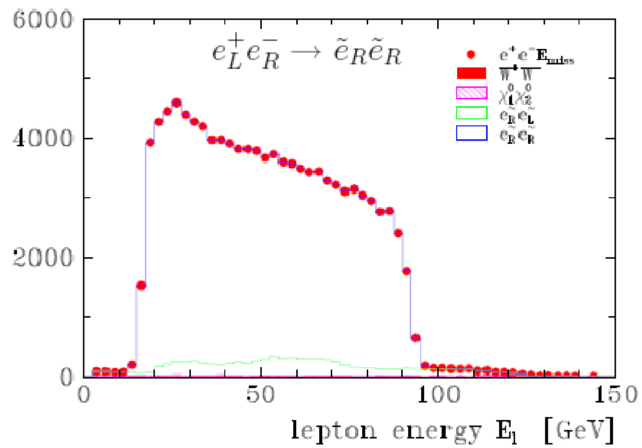


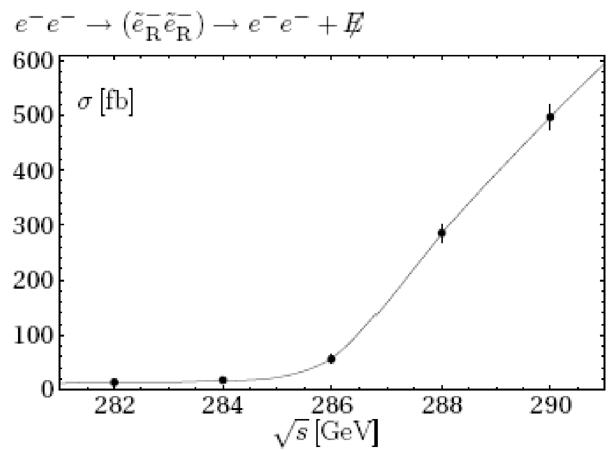
- squark decay chain
  - high p_T multi-jets
  - isolated leptons
  - large missing energy
- Measure mass differences:
  - Endpoints, various transverse masses
  - M_{LSP} not well measured… needed as underpinning of model
- Probably will identify more massive states…confusion down the decay chain

hep-ph/0403133

ILC SUSY

- Excellent resolution on LSP
  - 100 MeV resolution on LSP just from endpoint energies and E_{cm}
  - But can also do threshhold scan
    - Perhaps as good as 50 MeV
    - Gives spin
- SUSY mixing parameters measured by polarised cross sections and polarisation asymmetries
  - Polarised beams allow mixing parameters to be measured in model independent way





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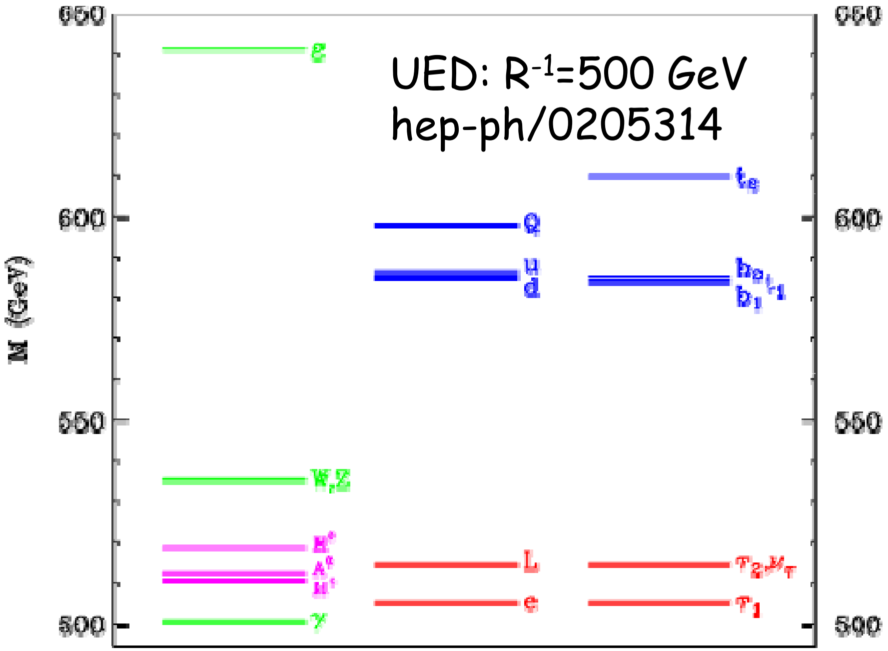
SUSY SM2 Cross Sections

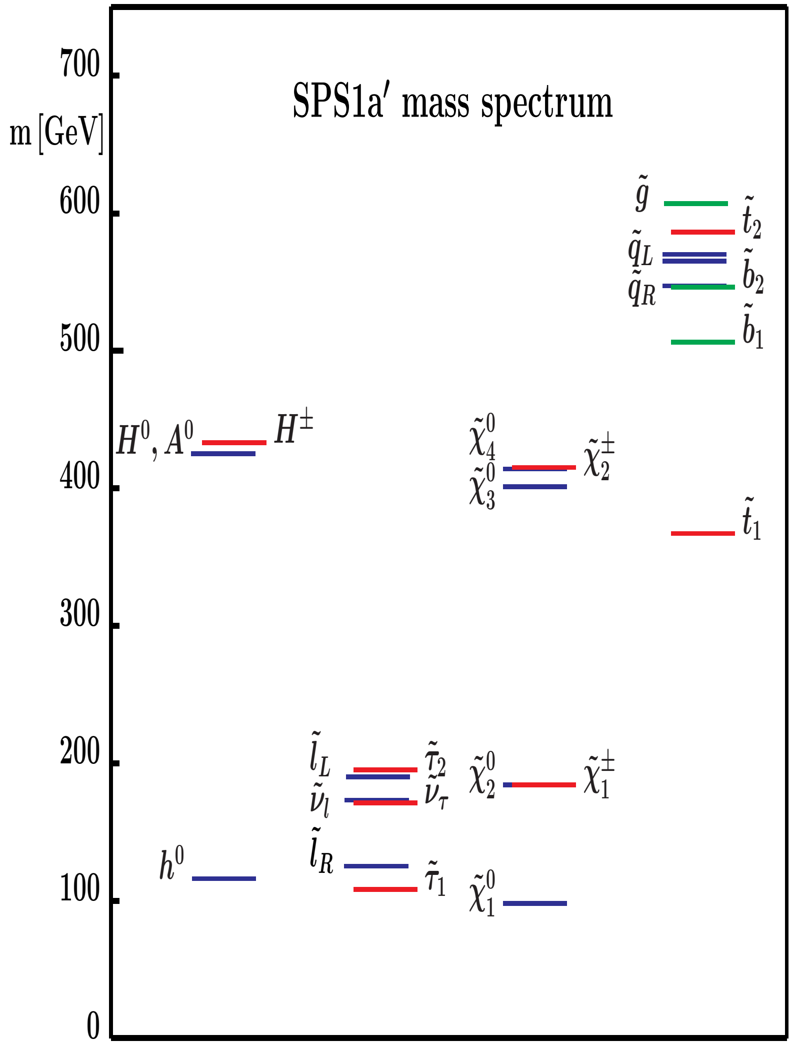
SUSY "SM2" polarised cross sections at E_{cm}=500 GeV (from hep-ex/0211002)

Reaction	σ_L (fb)	σ_R (fb)
$\tilde{\chi}_1^0 \tilde{\chi}_2^0$	105	25
$\tilde{\chi}_1^0 \tilde{\chi}_3^0$	4	16
$\tilde{\chi}_2^0 \tilde{\chi}_2^0$	139	16
$\tilde{\chi}_1^+ \tilde{\chi}_1^-$	310	36
$\tilde{\nu}_\varepsilon \tilde{\nu}_\varepsilon^*$	929	115
$\tilde{\nu}_\mu \tilde{\nu}_{\mu *}$	18	14
$\tilde{\tau}_1^+ \tilde{\tau}_1^-$	35	88
$\tilde{\tau}_1^\pm \tilde{\tau}_2^\mp$	2	1

Reaction	σ_L (fb)	σ_R (fb)
$\tilde{\nu}_\varepsilon \tilde{\nu}_\varepsilon^*$	929	115
$\tilde{\nu}_\mu \tilde{\nu}_{\mu *}$	18	14
$\tilde{e}_L^+ \tilde{e}_L^-$	105	17
$\tilde{e}_R^+ \tilde{e}_R^-$	81	546
$\tilde{e}_R^+ \tilde{e}_L^-$	17	152
$\tilde{e}_L^+ \tilde{e}_R$	152	17
$\tilde{\mu}_R^+ \tilde{\mu}_R^-$	30	87
$\tilde{\mu}_L^+ \tilde{\mu}_L^-$	38	12

SUSY vs UED



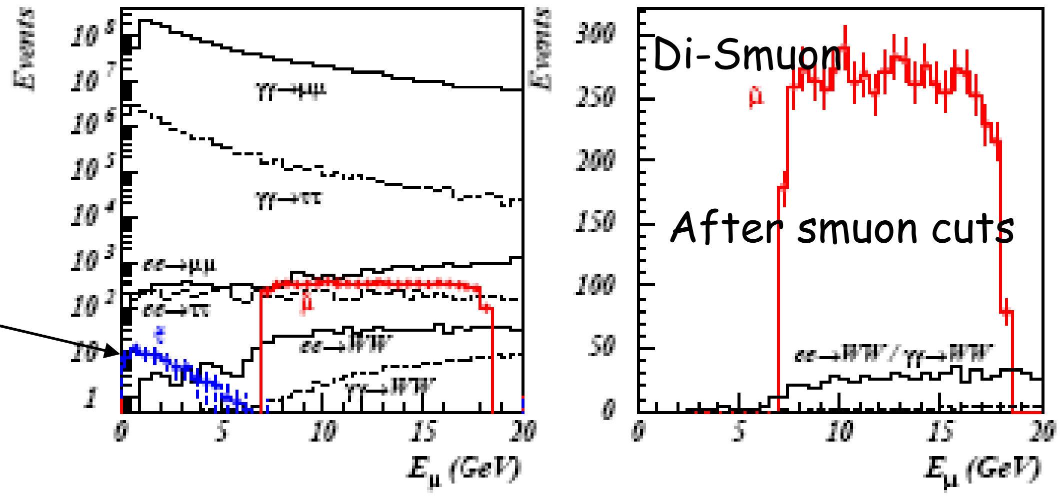


ILC resolution may be essential to differentiate models

Issues with DM Candidates

- The SUSY parameters giving credible LSP DM candidates generally result in a very small mass difference (5-10 GeV) between the lightest slepton (generally stau) and the LSP
- One "coannihilation" point D' has m_{stau}=217 GeV and m_{LSP}=212 GeV
  - stau-stau production @ 50fb for E_{cm}=600, Pol=80/60% (hep-ph/0408226)
    - But $\gamma\gamma \rightarrow ee\tau\tau$ @ 1nb!!! … this is the big problem
- Can identify mstau from high "edge" of lepton energy spectrum

stau



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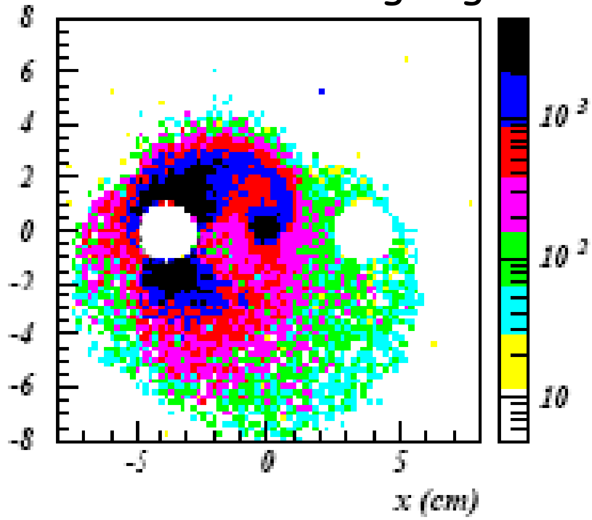
Need Forward Veto

- The have a chance at this, need to veto $\gamma\gamma$ background by tagging forward electron(s)
- Tradeoff between large integrated luminosity needed (300 fb^{-1} for this study which matches PLANCK precision) and beam background
- Polarised initial state effective in reducing WW and SUSY background
  - Increases signal x2
  - Suppresses WW background
  - Essential for $\tilde{\chi}^0_2$ BRs to disentangle contributions from $\tilde{e}_L\tilde{e}_R$ and $\tilde{e}_R\tilde{e}_R$

20 mrad crossing angle



Beamstrahlung background

hep-ph/0406010
hep-ph/0408226

2) Multi Gauge bosons

- …the general scenario where Z'-Z interference causes cross sections and asymmetries to wander from SM expectation
- Various models can offer the Z', W', so how to differentiate?
  - Many SM extensions, Little Higgs, ExDim
- ILC-500 mass scale already below established limit of 600 GeV
    - Precision EW … maybe GigaZ
    - Production of other new particles in the model???

- Polarisation tuning of couplings crucial here
  - Polarising both beams increases P_{eff} and reduces uncertainty on measurements of A_{LR}
  - Transverse polarization may become necessary, depending on model (ie, for ID of spin-2 exchange)
- Luminosity will need to be high

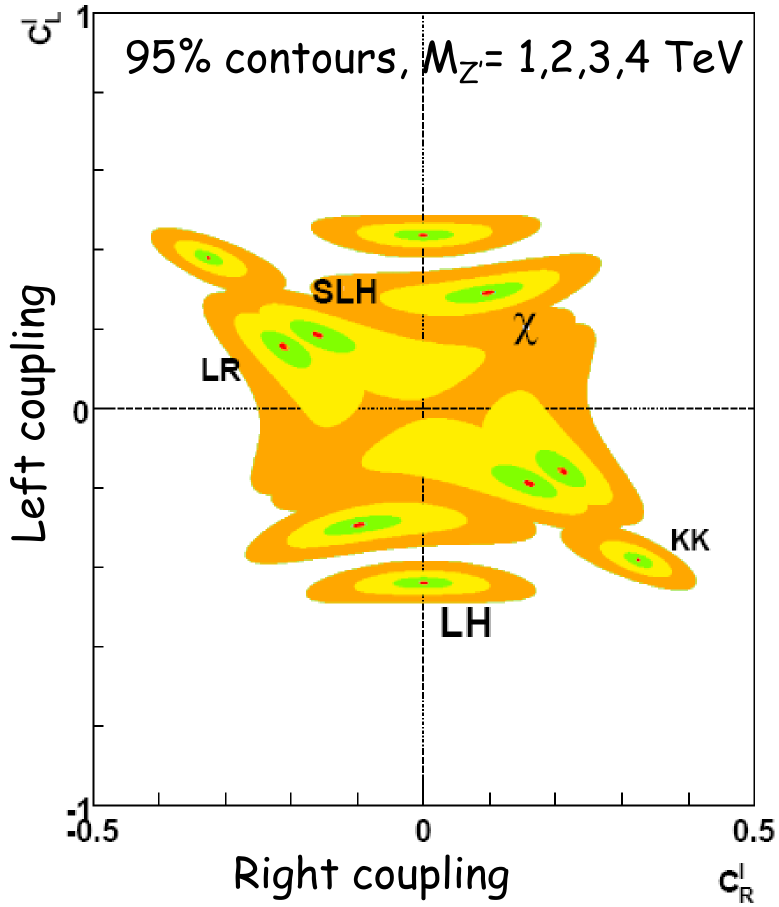
Pol Impurity

P_-/P_+	0	60%
80%	0.11	0.028
90%	0.053	0.013
95%	0.026	-.006

Identifying the Z' Model

- Popular topic lately…I'll show hep-ph/0609119
- Observables: dimuon production polarized σ, A_{LR}, A_{FB}
- Lots of lumi needed: here we show 500 GeV, 1 ab^{-1},
  - Polarisation crucial: 80%/60%

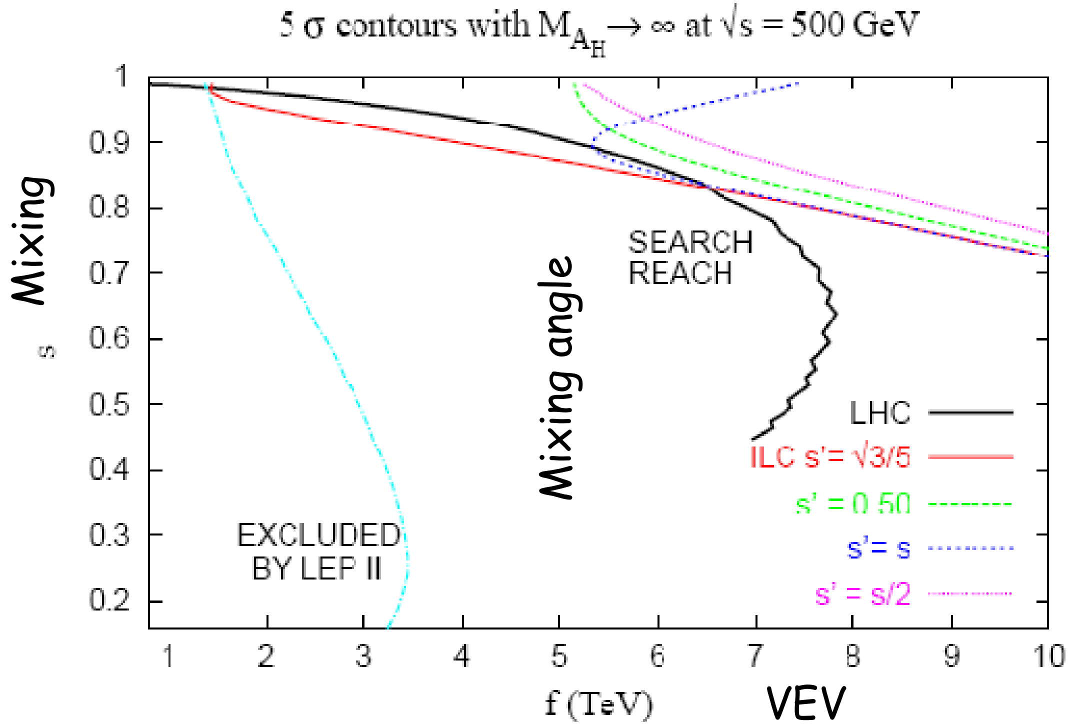
- Models:
  - E6 c model
  - LR symmetric
  - Littelest Higgs
  - Simplest Little Higgs
  - KK excitations in ED



hep-ph/0511335

More on LHM

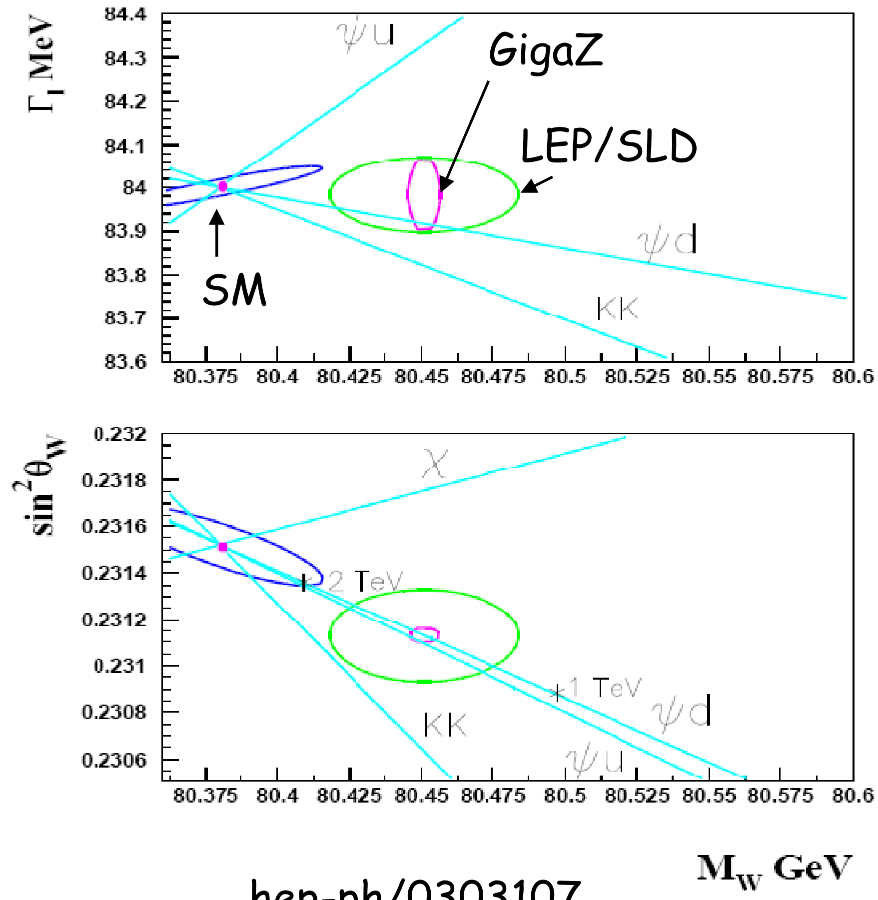
- These models have extra gauge bosons … masses generally > TeV
  - Also W', t'
- ILC needs to precision measure difermion and ZH production
  - Can reach beyond LHC in this manner … possibly find the more massive Z" after LHC sees the lower mass one



hep-ph/0211374

What GigaZ can do

- Can get good mass reach and model-discrimination from high statistics Precision EW
  - Measure:
    - the W mass
    - - $\sin^2\theta^{lept}$ (leptonic asymmetries)
    - - the leptonic width Γ_ℓ



hep-ph/0303107

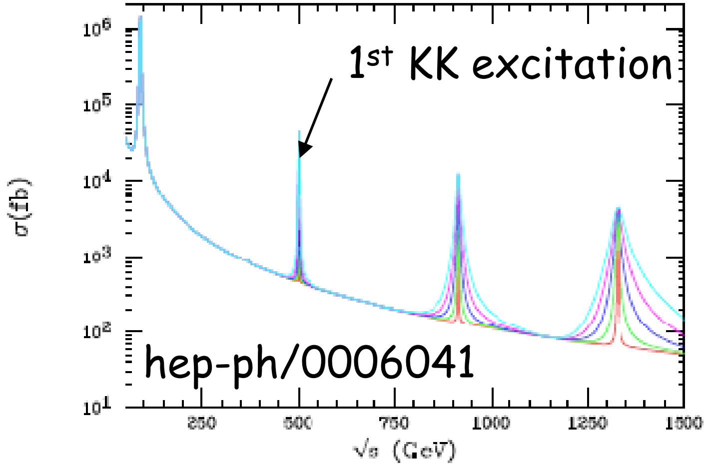
3) Lepton Resonances

- Smart money: KK resonances … Extra Dimension models
  - Also Littlest Higgs Model, Z', Strong EWSB
- LHC mass again triggers whether to go for ILC-1000 or precision
  - In most cases the likelihood is a mass scale beyond direct production at ILC
    - Except possibly for KK resonances
  - But if LHC sees a multi-TeV resonance in, eg, WW scattering, measurement of form factors at ILC can be more precise than the direct LHC observation
  - some models not easy for LHC but very clear for ILC

- Polarization: in these cases effective for reducing backgrounds
- ee,$\gamma\gamma$ option ??? Not clear

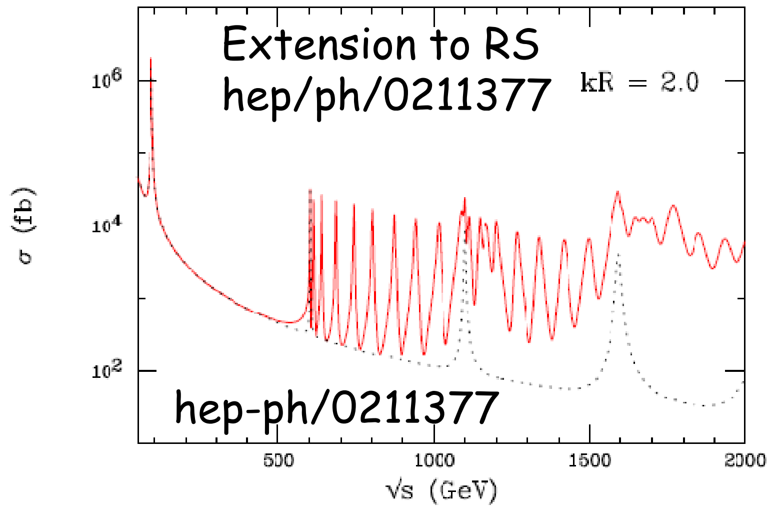
KK Resonance example

- In warped ExDim models there are KK excitations of the SM particles
  - Unlike ADD, the graviton masses are EW scale
  - Resonance spectrum is well-separated
- Production cross sections are large



Colors = various κ/M_{planck}, the effective coupling

- ILC-1000 needed to establish a spectrum
  - More interesting spectrum in extensions to RS … difficult for LHC

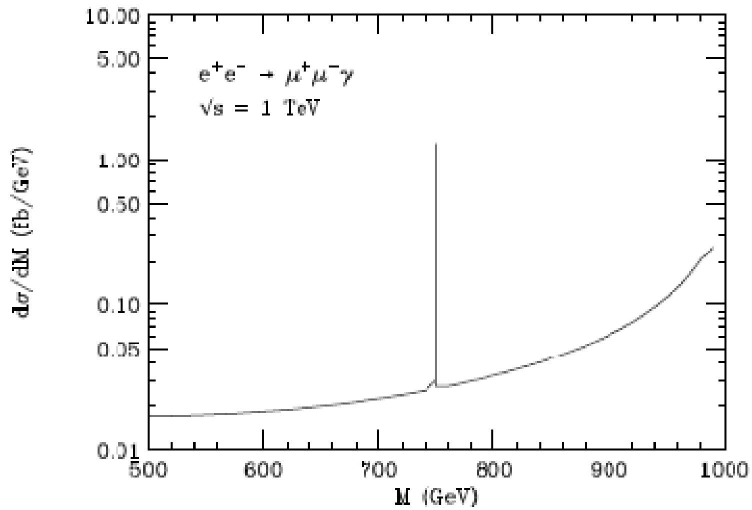


Narrow Graviton Resonance

- Example from JoAnne Hewett:

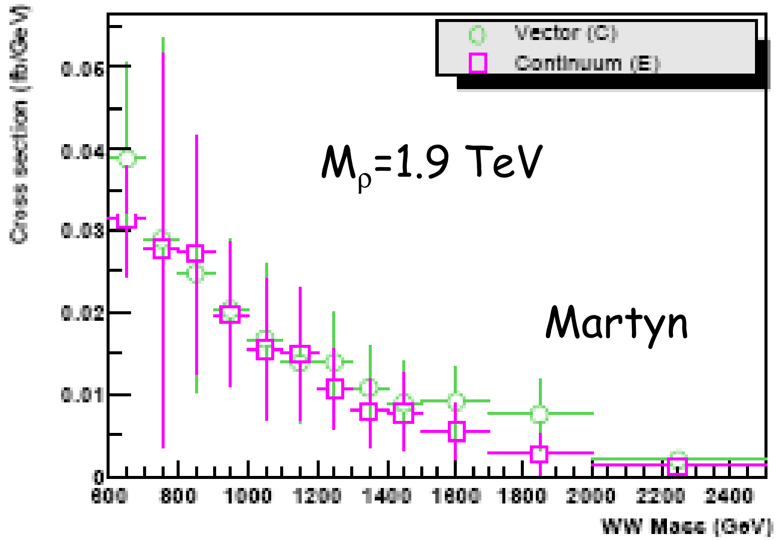
  extend RS with brane curvature for graviton

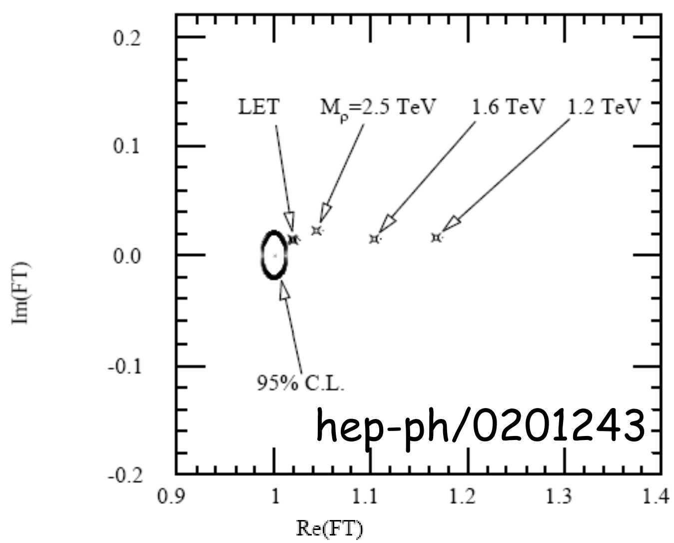
  750 GeV KK state with $\gamma_\pi = -8$ and $\kappa/M_{Pl} = 0.025$ … reduced coupling leads to much lower production rate … hard for LHC
- But very narrow resonance good for ILC …
  - Look for narrow resonance in radiative return
  - … but will need ILC-1000



Strong EWSB example

- Suppose LHC sees a resonance structure in WW
  - It will be a weak effect:
- At ILC the techni-ρ will enhance we known SM cross section and alter th WW,ZZ decay topology similar to anomalous coupling
- By precision measurement of cross sections and measurement of decay angles, ILC has higher sensitivity to the NP parameters
  - Shown here is the effect on a pion-like form factor measured at ILC (hep-ph/0106046)



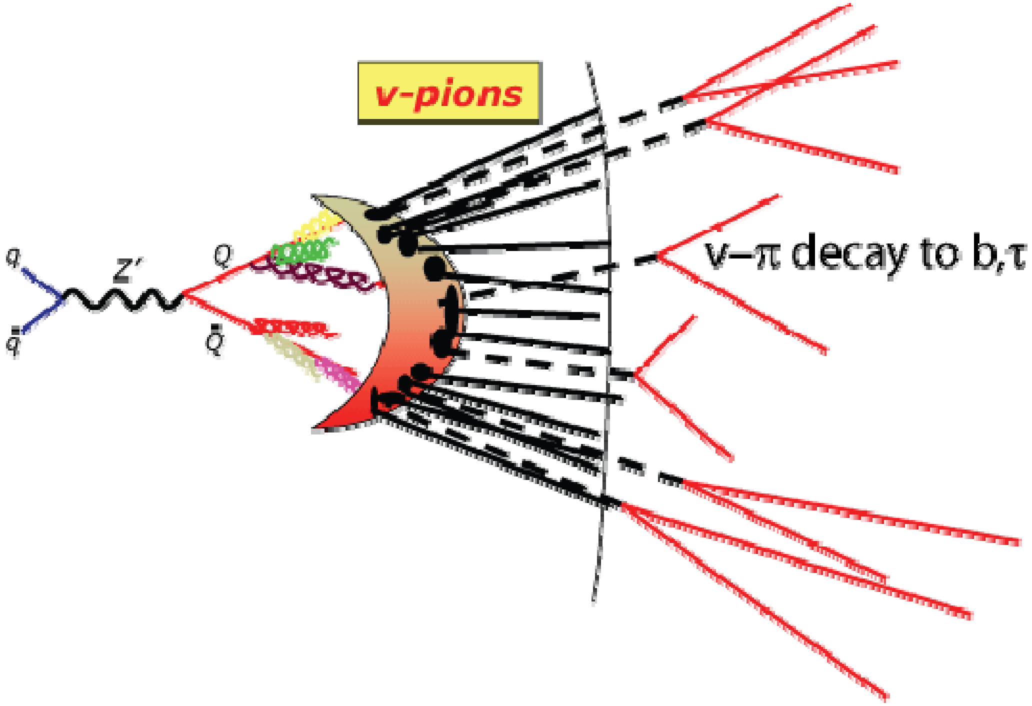


4) Other New Physics/Signals

- Obvious topolgies not covered so far:
  - Anomalous single or diphoton production
    (… rad return too) … well, mentioned in Z' section
      … need to work on other single-photon signatures
  - Long-lived particles
- Hidden Valley models (from Matt Strassler)
  - New unseen particle sectors communicating via high-mass messenger to SM … <u>many</u> possible models…maybe low cross sections
  - Possible features:
    - High-multiplicity, variable final states
    - Many low-momentum partons
      - Unusual parton clustering
      - Breakdown of jet/parton matching
    - Sharp alteration of Higgs,SUSY decays;
  - ILC: remote vertices, anomalies in precision EW

HV Dijet Production

MET
Many b's, taus
Muon/electron resonances or endpoints
Highly displaced jet pairs or lepton pairs



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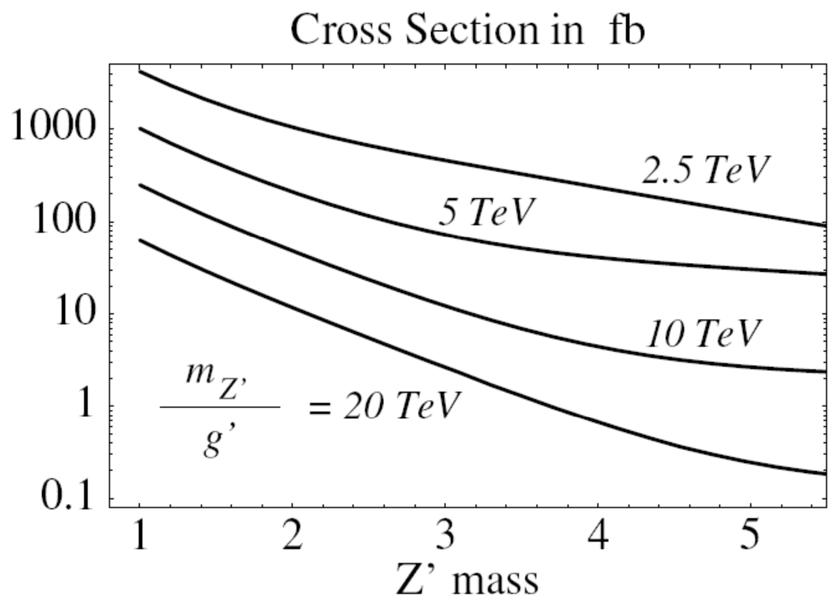

Concluding Thoughts

- ILC opens new window to some NP (beyond LHC) via precision EW
- LHC identification of NP may lead to tradeoffs in ILC design
  - E vs Lumi, or polarisation vs E, or run plan
    - Example: run at higher E/lower lumi; or phase in klystron upgrade
  - May influence detector choices
    - Upgrades as results come in
    - Perhaps an argument for bringing in 2nd or 3rd detector later???
- ILC backfeed to LHC likely to create much better understanding of NP, eg SUSY or UED
- As long as LHC gives us indications of NP, however vague, it is important to follow up at ILC … even if we don't quite know where to aim
  - ILC has different tools /cf LHC…might steer LHC in different direction
  - As dataset increases at both LHC and ILC the picture is likely to change
- Godspeed to LHC… give us the clues ASAP!