Physics Beyond 500 GeV at a Linear Collider

- Compelling Physics case for 500 GeV LC!
- Both LHC and LC will be needed to discover the origin of Electroweak Symmetry Breaking and its associated New Physics
- In every model, there are further important LC experiments at higher energy

– Hewett
– HEPAP sub-panel
– SLAC, May 2001

e^+e^- Colliders play an essential role in the illumination of New Phenomena

- e^+e^- colliders are discovery machines and are complementary to hadron colliders operating at similar energy regions
  - This is sustained by history

500–1000 GeV is a discovery region and adds to the search capability of LHC in many scenarios

- e^+e^- collisions offer ideal tools to intensively study new phenomena
  - » cleanliness, polarization, known $\sqrt{s}$
  - Precisely determine its properties
  - Unravel the underlying theory

500–1000 GeV allows for precise diagnostic tests of new physics

Imperative that we study EWSB and the New Physics which accompanies it!

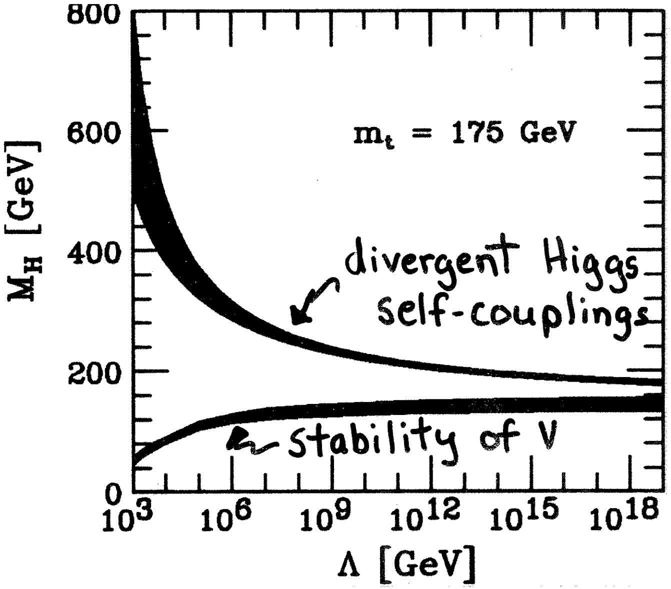
Standard Model is an effective theory

- What is origin of EWSB
- How is hierarchy generated and stabilized
- Gravity is not incorporated
- What generates fermion masses and mixings

New Physics Exists! But, at what scale?

1) Weakly-coupled SM
   - $\Lambda_{NP} < M_{GUT}$ for most values of m_h
   - EWSB stability crisis

   New Physics must appear by few TeV!



2) Strongly-coupled SM

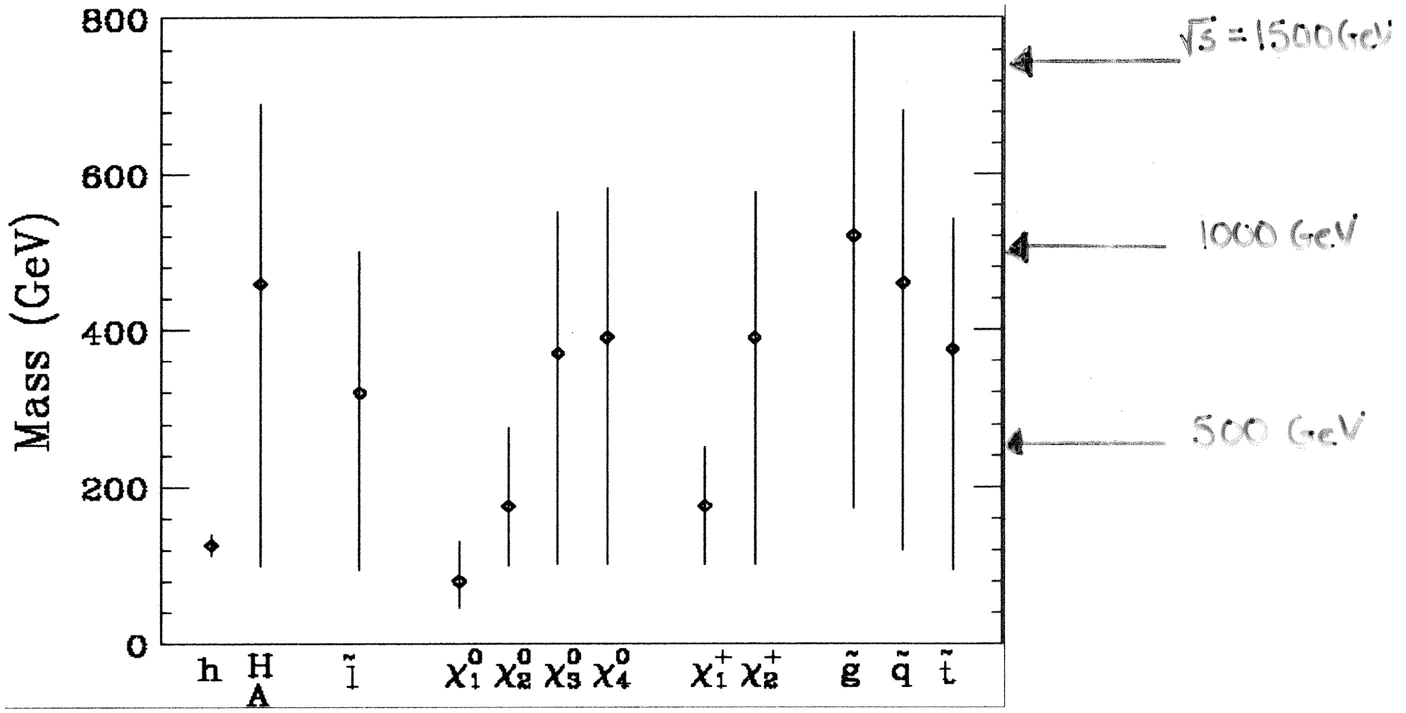
   WW scattering unitarized at scale of few TeV

Expect New Physics at the TeV scale !!

Scenario I: New Physics appears at 500 GeV $\Rightarrow$ Expect more at higher energies

Example: Supersymmetry

Minimal Supersymmetry Naturalness Bounds



$\sqrt{s} = 1500$ GeV

1000 GeV

500 GeV

To fully explore Supersymmetry:

1. Study Heavy Higgs spectrum: H^0, A^0, $H^\pm$
2. Study $\chi^\pm_2$, $\chi^0_{3,4}$ $\Rightarrow$ measure M_2, μ, $\tan\beta$
3. Study $\tilde{t}$, $\tilde{b}$ mixing $\Rightarrow$ determines A_t, A_b

Within SUSY: μ, $A_{t,b}$ drive EWSB

Naturalness implies: Discover SUSY @ 500 GeV

Full investigation of EWSB requires higher energy

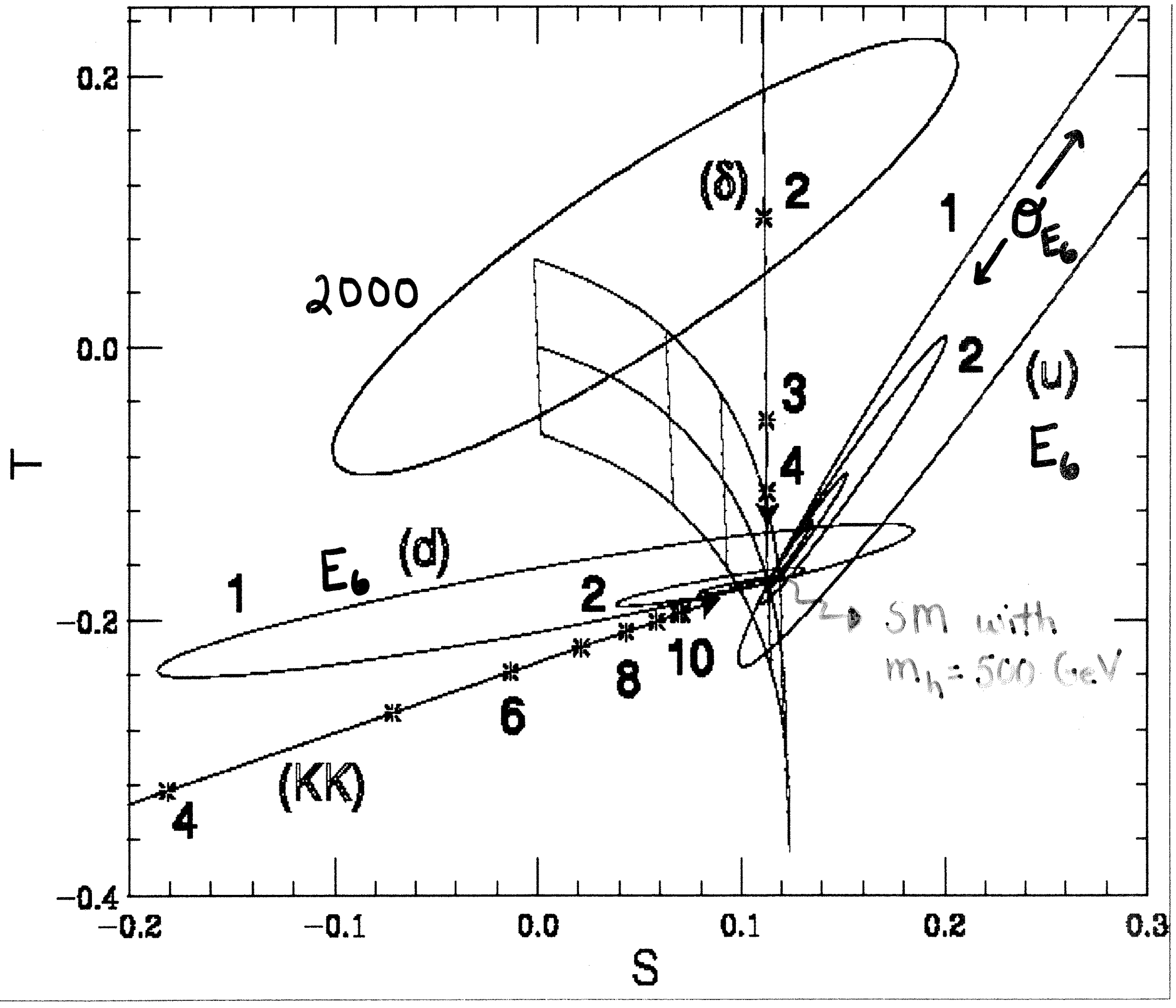
Scenario II: New Physics above 500 GeV

Precision EW data: Heavy Higgs contributions must be compensated by New Physics

Example 1: Extended Gauge Sectors

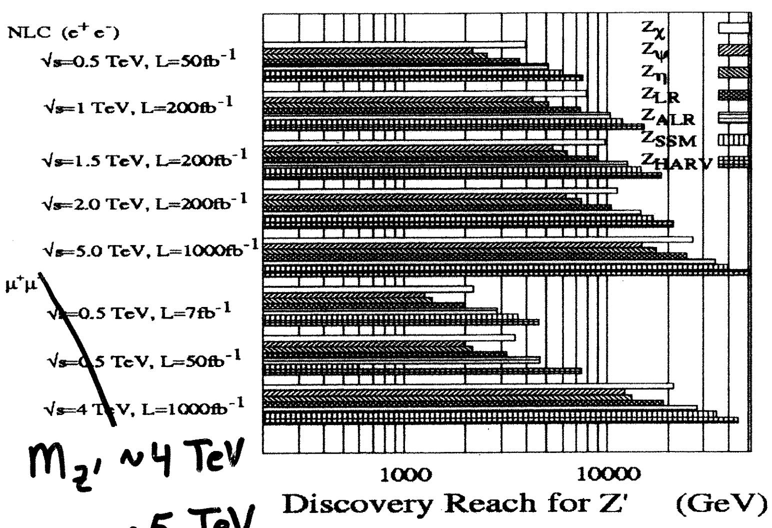
Data allows m_h = 500 GeV <u>if</u> Z' is of ~ few TeV

Holds for numerous extended models!



Peskin Wells

Few TeV Z' within reach of LHC and LC



LC: Indirect search via interference with γ / Z

LHC: Direct search for narrow Breit-Wigner

Godfrey etal

LHC

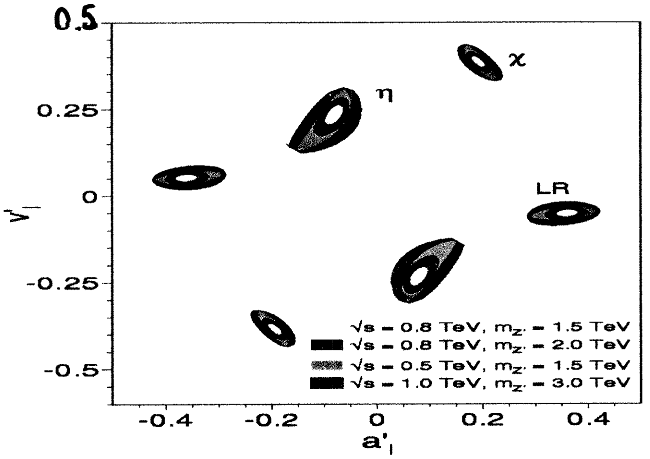
10 fb^{-1} $m_{Z'}$ ~4 TeV

100 fb^{-1} ~5 TeV

fairly model independent

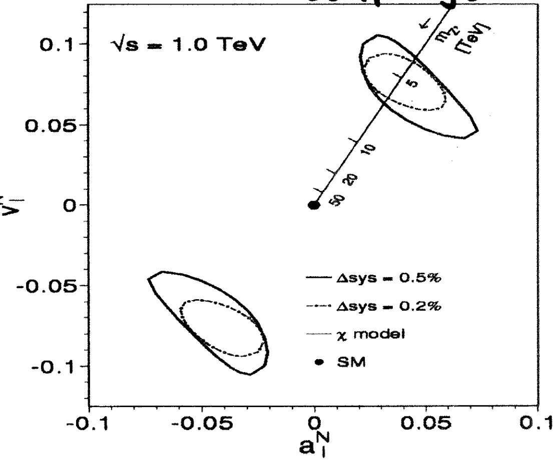
- Discover Z' @ LHC in Drell-Yan (if it couples to quarks)
- Determine Z' couplings @ LC → unravel underlying theory
  - » via study of polarized & unpol dist'btns in $e^+e^- \to f\bar{f}$
- Go to very high $\sqrt{s}$ and sit on resonance

Coupling Fit : $M_{Z'}$ known



Unknown

Normalized Couplings: $\sqrt{\frac{s}{m_{Z'}-s}}$



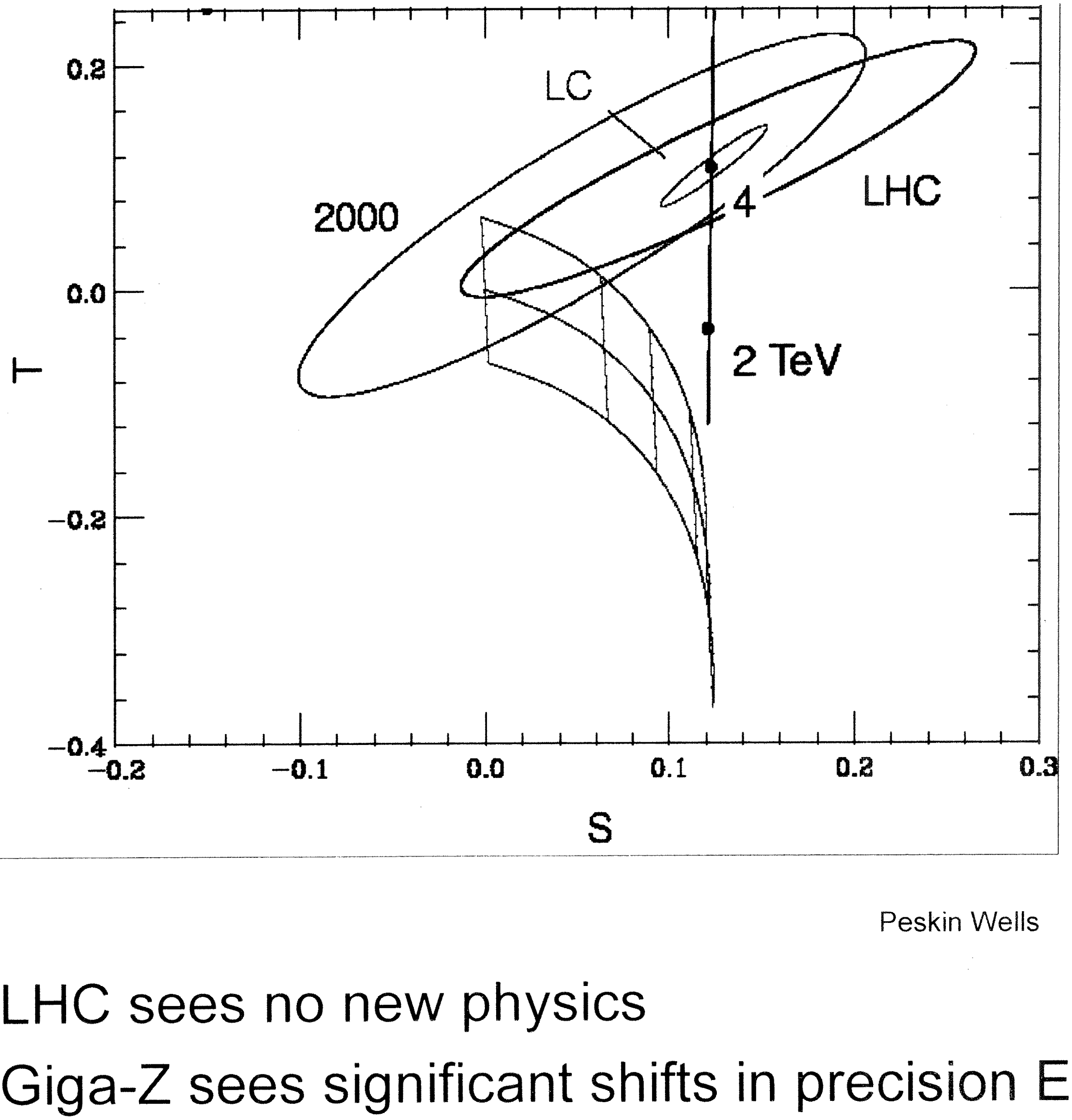
Riemann

Example 2: Topcolor Seesaw

Dobrescu – Hill

Higgs at ~ TeV

New singlet quark ~ 5 TeV



Peskin Wells

- LHC sees no new physics
- Giga-Z sees significant shifts in precision EW

Scenario III: Strong WW Scattering

Example 1: $e^+e^- \to W^+W^-$ - Gauge Boson self-couplings

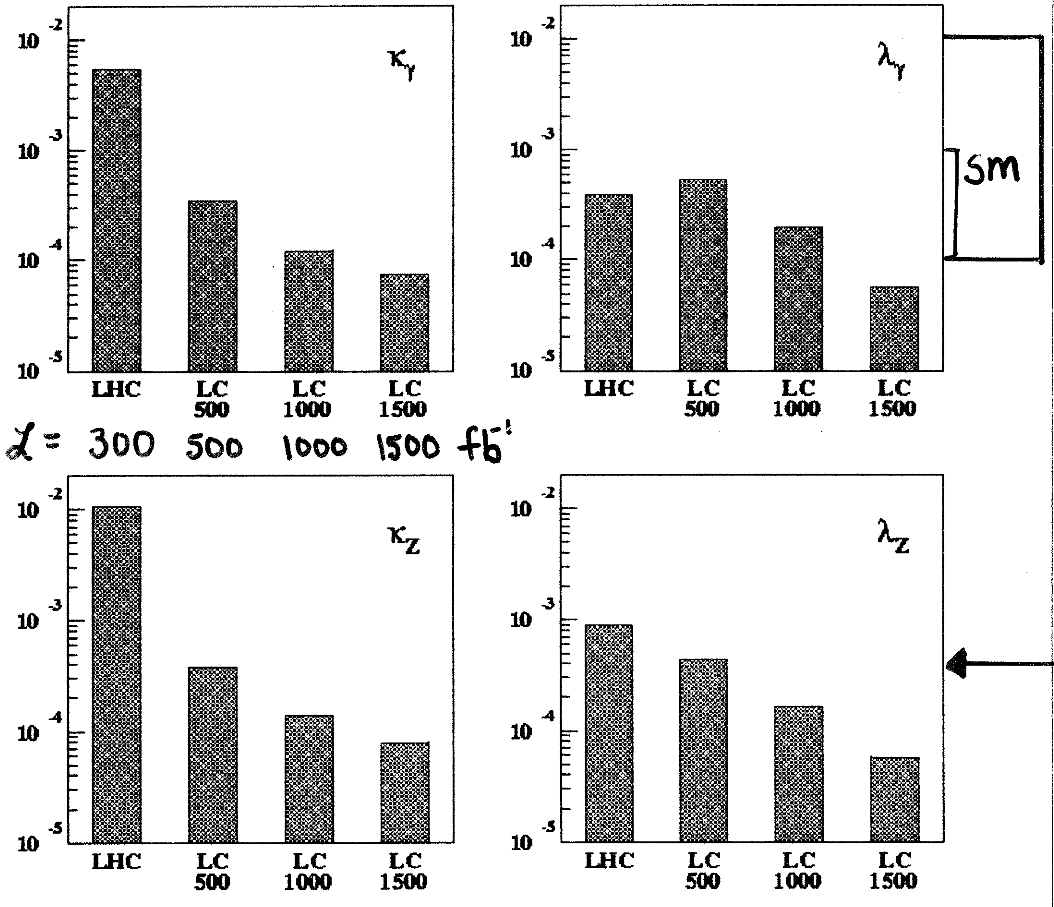
Provides window to NP associated with EWSB

SM, SUSY, strong WW interactions induce anomalous couplings

LC: Sensitive to 5 kinematic angles:

Production ∠, polar & azimuthal decay ∠'s for W^+ and W^-

LC yields most precise measurement



Model expectations

$\mathcal{L} =$ 300 500 1000 1500 fb^{-1}

probes strong EWSB to 3-4 TeV

Barklow

Example 2: $e^+e^- \to W_L W_L$ (Technicolor)

Develops complex form factor when interactions become strong - **analogy with π form factor**

$$F_T = \exp\left[\frac{1}{\pi}\int_0^\infty ds'\,\delta(s',M_\rho,\Gamma_\rho)\left\{\frac{1}{s'-s-i\varepsilon}-\frac{1}{s'}\right\}\right]$$

$$\delta\left(s,M_\rho,\Gamma_\rho\right)=\frac{s}{96\pi v^2}+\frac{3\pi}{8}\left[\tanh\left[\frac{s-m_\rho^2}{m_\rho\Gamma_\rho}\right]+1\right]$$

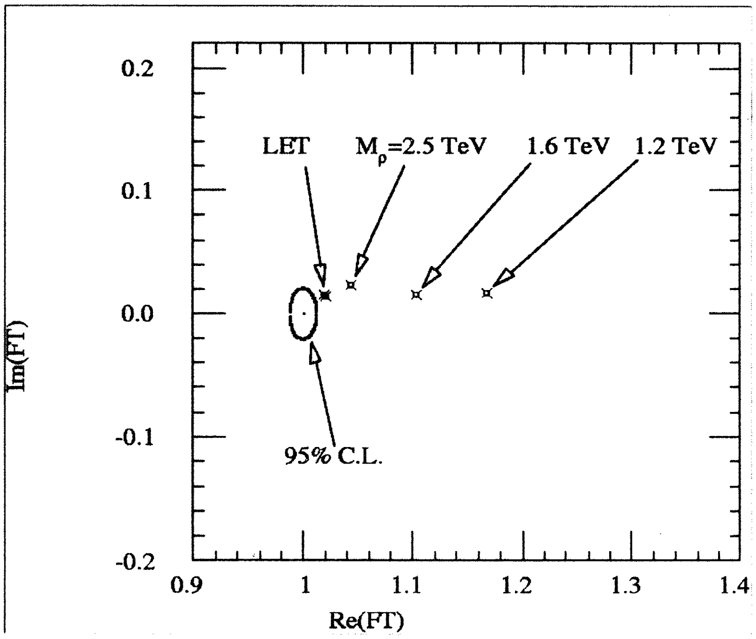
Low Energy Thm: applies to $W_L W_L$ scattering below a resonance

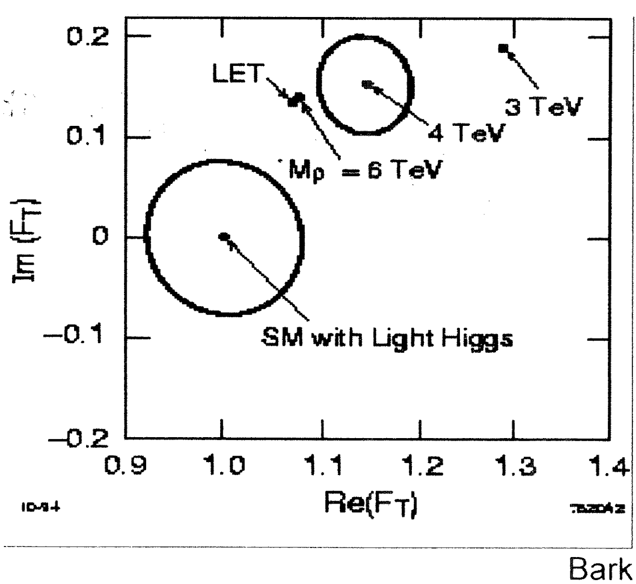
M_ρ, Γ_ρ = vector resonance mass, width

F_T measured from W_L production and decay ∠'s

Possible to disentangle from TGC's and deduce mass of vector resonance

$\sqrt{s}$ = 500 GeV (500 fb^{-1}) $\sqrt{s}$ = 1500 GeV (200 fb^{-1})





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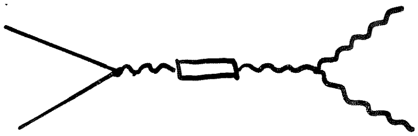
Sensitivity to vector resonance

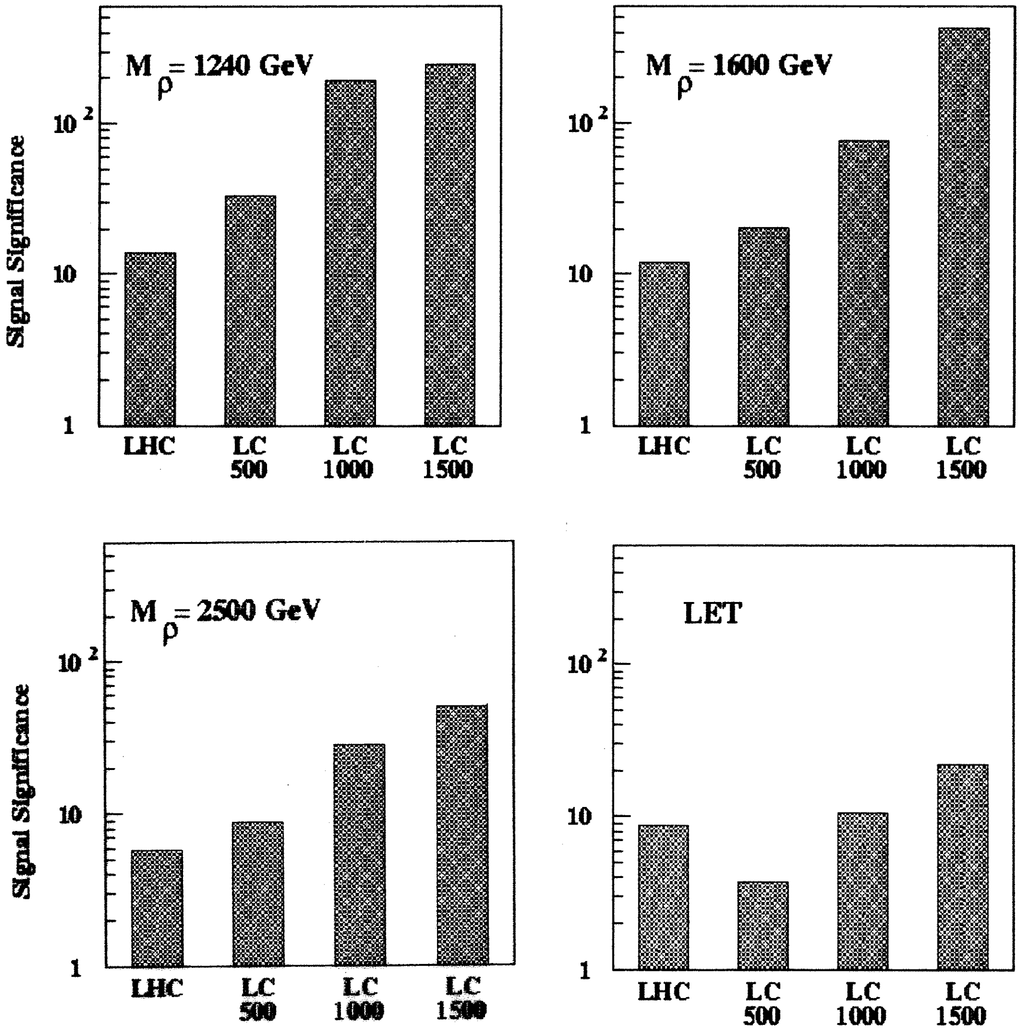


Combine channels: $e^+e^- \to \underbrace{\nu\bar{\nu}WW,\ \nu\bar{\nu}ZZ},\ \underbrace{W_LW_L}$

Probes I=J=0 I=J=1 channel

- LHC sees bump, while LC is insensitive to Γ_ρ
- Large LC signals can probe vector resonance in detail !

  i.e., Evolution of $F_T(\hat{s})$ studied via ISR



Barklow

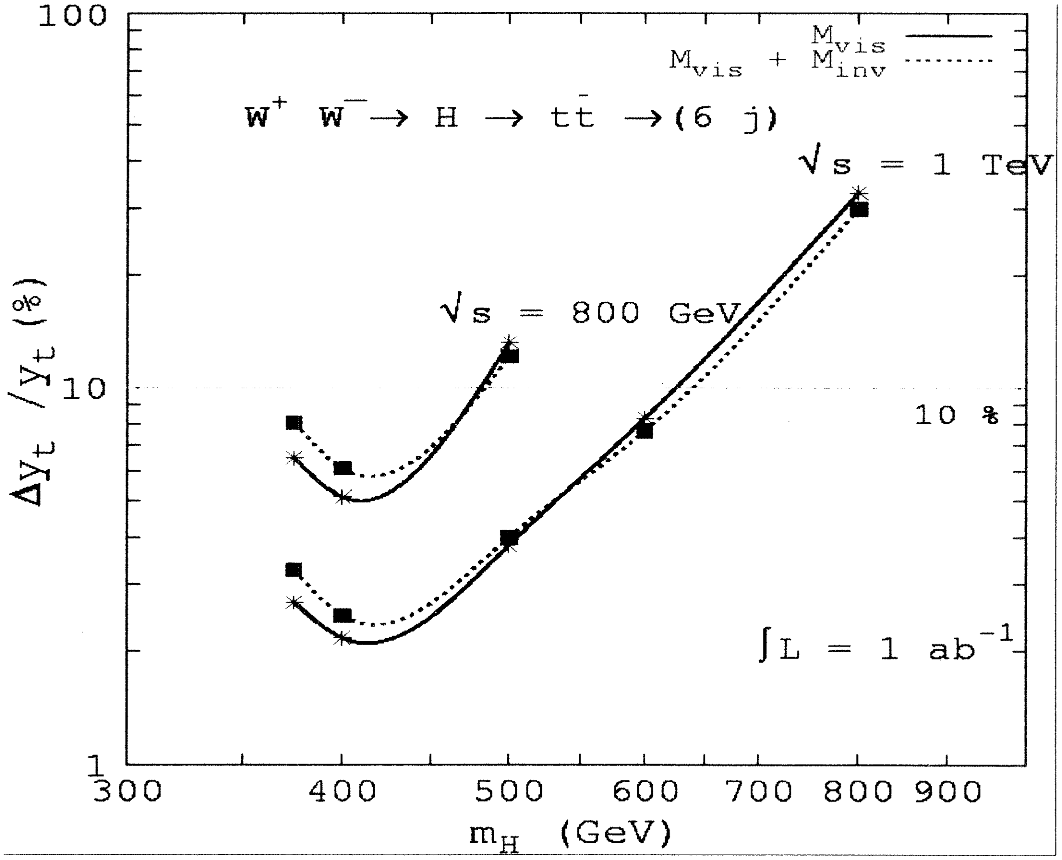
Example 3: $e^+e^- \to \nu\bar{\nu}t\bar{t}$

LC afford unique access to $WW \to t\bar{t}$

- Study vector resonances
- Study heavy Higgs resonant contribution

⇒ Determine $t\bar{t}h$ Yukawa coupling!

Relative precision on Yukawa determination



5σ signal

Alcarez,
Ruiz-Morales

Scenario IV: Extra Dimensions

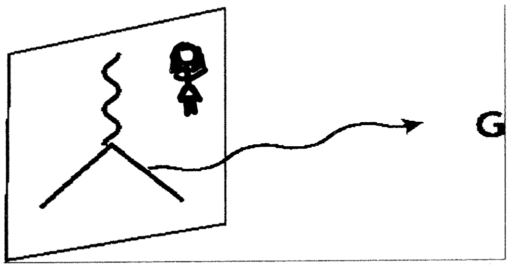
Insight into string physics

Example 1: Large Extra Dimensions

Arkani-Hamed,
Dimopoulos, Dvali

$M^2_{Pl} = V_\delta M_*^{2+\delta}$; Solves hierarchy if $M_* \sim$ TeV

Graviton Emission:



SM stuck to brane
Gravity propagates in bulk
Graviton appears as $\not{E}_T$

Discovery Reach in TeV for M_*

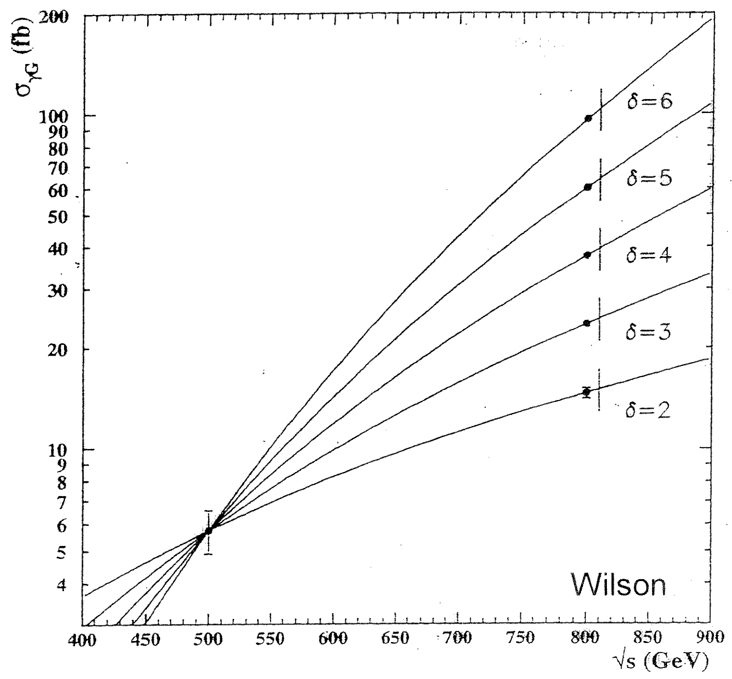
$e^+e^- \to \gamma + G_n$	$\sqrt{s}$ = 800 GeV	2	4	6
LC	$P_{-,+} = 0$	5.9	3.5	2.5
LC	$P_- = 0.8$	8.3	4.4	2.9
LC	$P_- = 0.8$, $P_+ = 0.6$	10.4	5.1	3.3
$pp \to g + G_n$		2	3	4
LHC		4–7.5	4.5 – 5.9	5.0 – 5.3

Discovery range where effective theory is valid

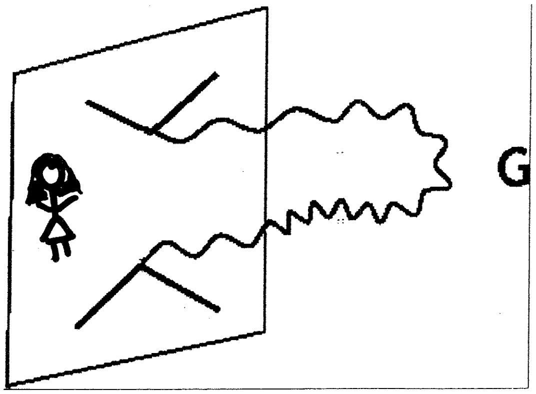
–Discovery likely at at LHC
–LC probes theory

Spectrum varies with δ as $\sqrt{s}$ increases

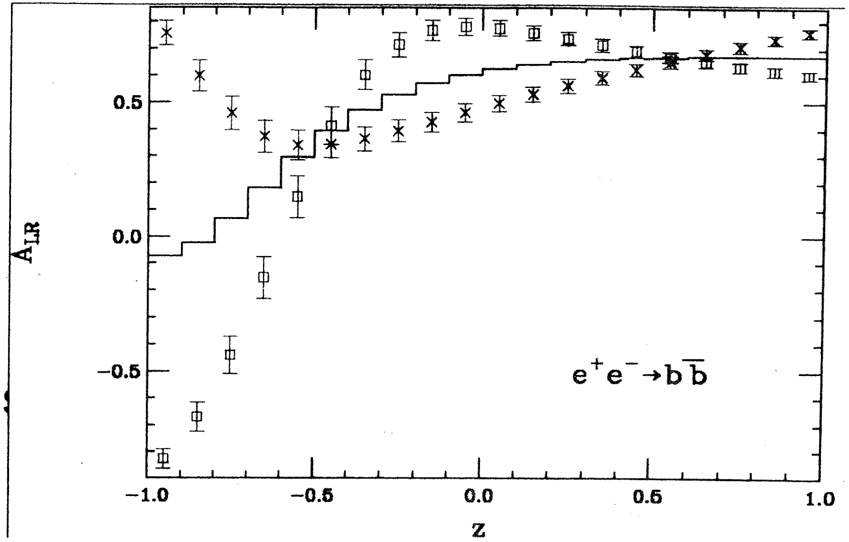
$\Rightarrow$ Determine M_* and δ !



Graviton Exchange



Polarized ∠ Dist'btn
In $e^+e^- \to b\bar{b}$



Deviations in SM processe
Search for new processes

JLH

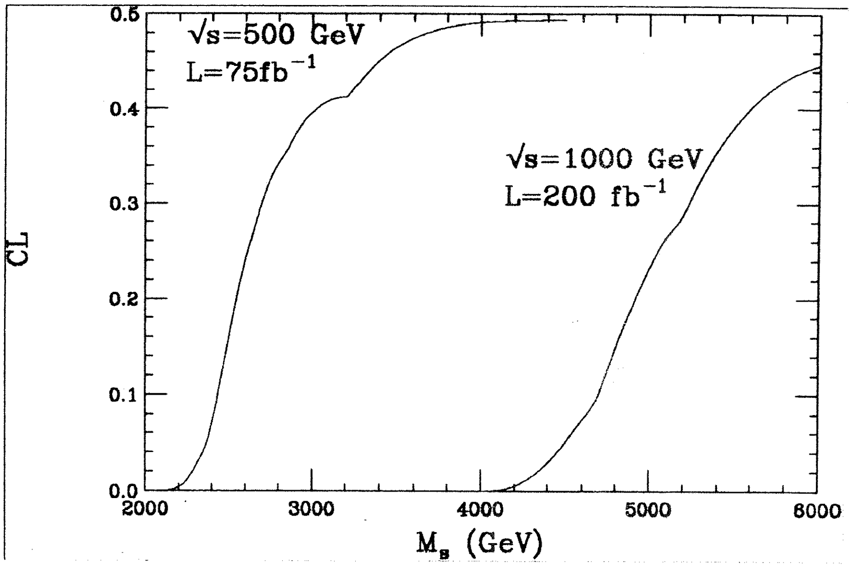
LC :	$e^+e^- \to f\bar{f}$	$\sqrt{s}$ = 500 GeV	4.1
		$\sqrt{s}$ = 1000 GeV	7.2
	$\gamma\gamma \to WW$	$\sqrt{s}$ = 1000 GeV	13.0
LHC:	$pp \to \ell^+\ell^-$		6.0

Search Reach at 95% CL
(in TeV)

Angular Dist'btns reveal
spin-2 exchange!

Confidence Level of fit of
spin-2 data to spin-1
hypothesis

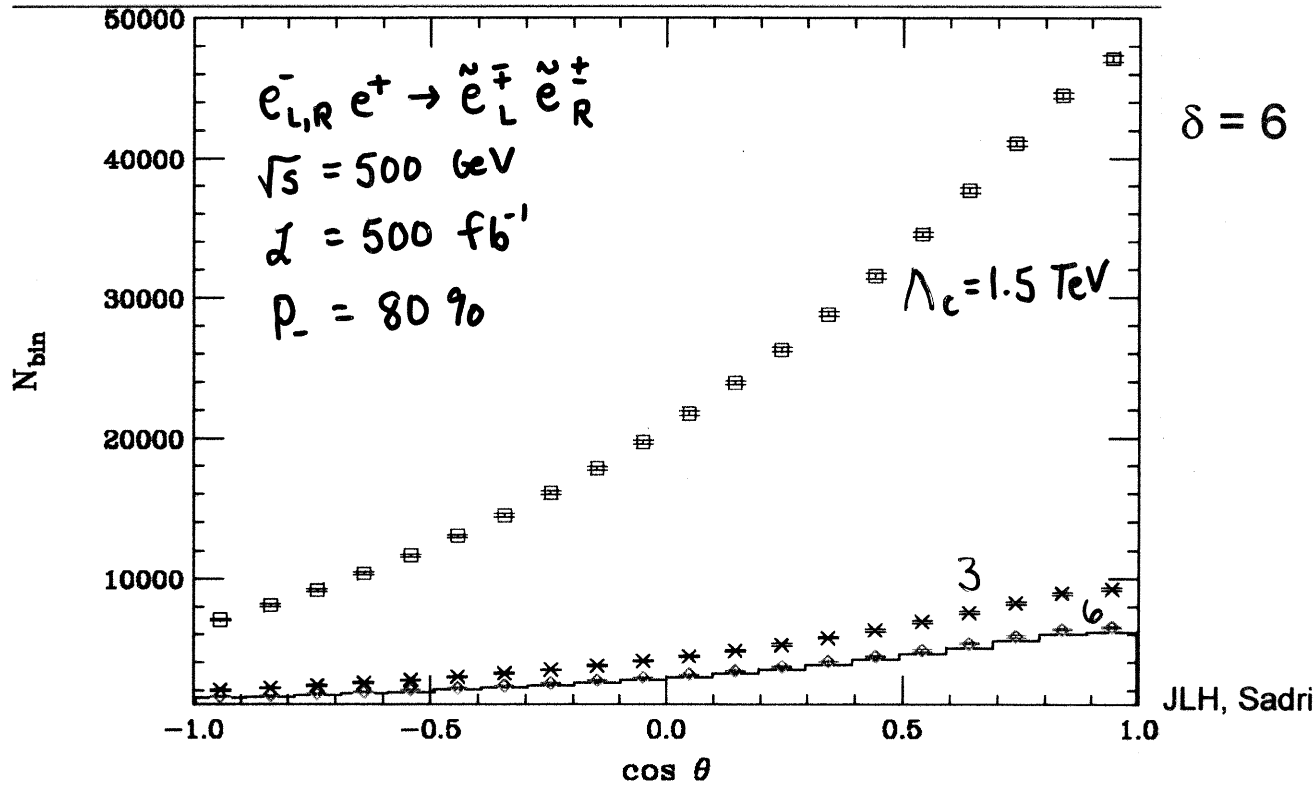
Spin-2 determined almost
Up to kinematic limit !



JLH

Supersymetric Large Extra Dimensions

- Exchange KK towers of Gravitons and Gravitinos!
- Large t-channel contribution to $e^+e^- \to \tilde{e}^+\tilde{e}^-$ from Gravitino exchange



Sensitivity in excess of $M_* \sim 10$ TeV @ $\sqrt{s} = 500$ GeV

Unique sensitive probe to a supersymmetric bulk!

LHC: Small signal in squark pair production
gluino production needs to be studied

Example 2: Localized Gravity (Randall-Sundrum)

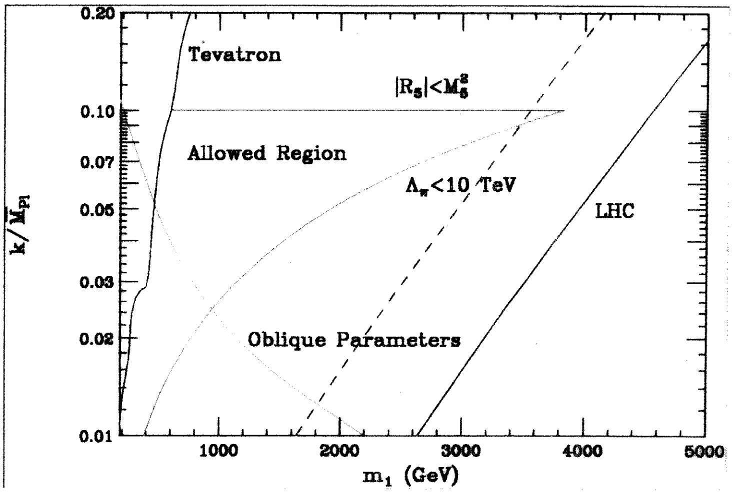
Hierarchy generated by exp. $\Lambda_{EW} = e^{-kr\pi} M_{Pl}$

Phenomenology governed by 2 parameters:

k : space curvature ~ 0.1 M_{Pl}

m_1: 1st KK mass
~ 0.5-1.0 TeV

Summary of Constraints

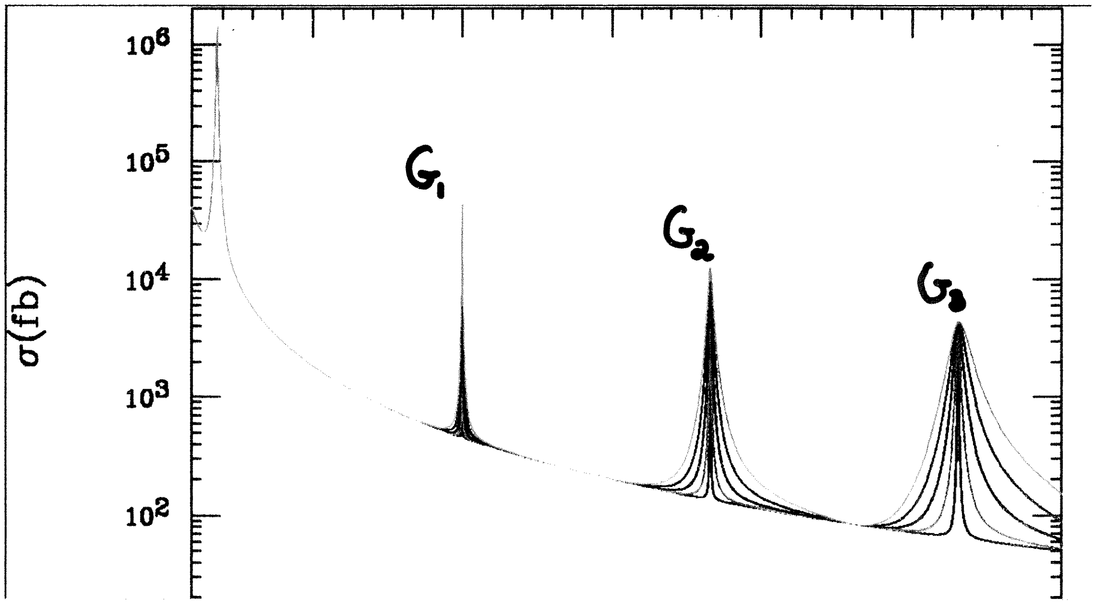


Davoudiasl, JLH, Rizzo

- Gravitons produced as direct resonance
- LHC explores entire parameter space via Drell-Yan!

If discovered at LHC, LC becomes a Graviton Factory!

Can explore Graviton self-couplings and test gravity



Example 3: TeV^{-1} Extra Dimensions (Fat Branes)

- Arise naturally from string theory
- Mechanism to suppress proton decay

Antoniadis

Arkani-Hamed, Schmaltz

Gauge bosons free to propagate in $R_c \sim$ TeV

$\Rightarrow$ Degenerate KK towers for γ / Z / W / g

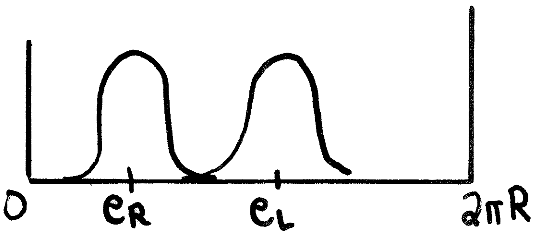
Discovery Reach for KK γ / Z (TeV)

Run II		2 fb^{-1}	1.1
LHC		100 fb^{-1}	6.3 ~ 8.0
LEP II			3.1
LC	$\sqrt{s}$ = 0.5 TeV	500 fb^{-1}	13.0
LC	$\sqrt{s}$ = 1.0 TeV	500 fb^{-1}	23.0
LC	$\sqrt{s}$ = 1.5 TeV	500 fb^{-1}	31.0

Ala Z' search

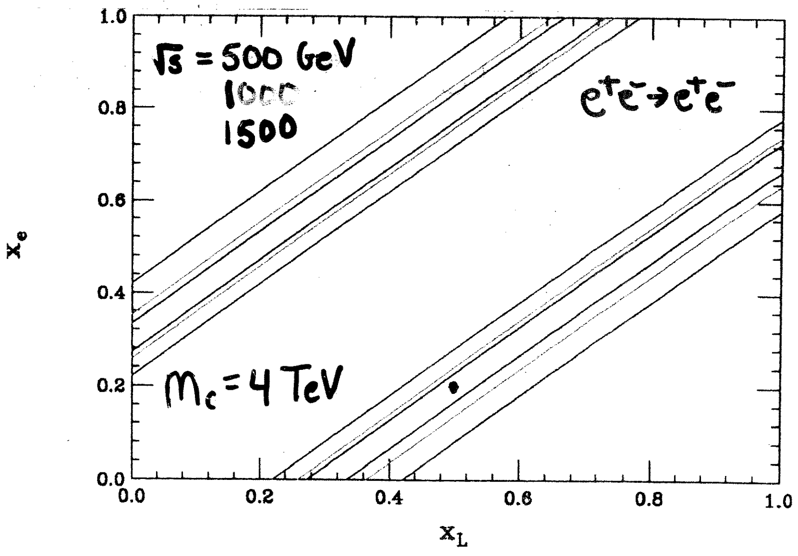
Separated fermions

Fermions can be localized At different points in a Fat-brane



This can be probed in clear scattering environment at high energies

Bhabha Scattering probes relative location of e_L & e_R !



Rizzo

Conclusions

- Comparable discovery potential for LHC and LC!

  ⇒ In many cases LHC discovers New Physics and LC determines its properties and reveals the underlying theory

- 500 GeV LC has large discovery and elucidation potential
- Every physics scenario we've explored benefits from upgrade to higher energy!

- However, our limited imagination does not span full range of alternatives allowed by current data
- We must be prepared to discover the unexpected!

⇒ We need exploration of the same energy frontier by <u>both</u> e^+e^- and hadron colliders!