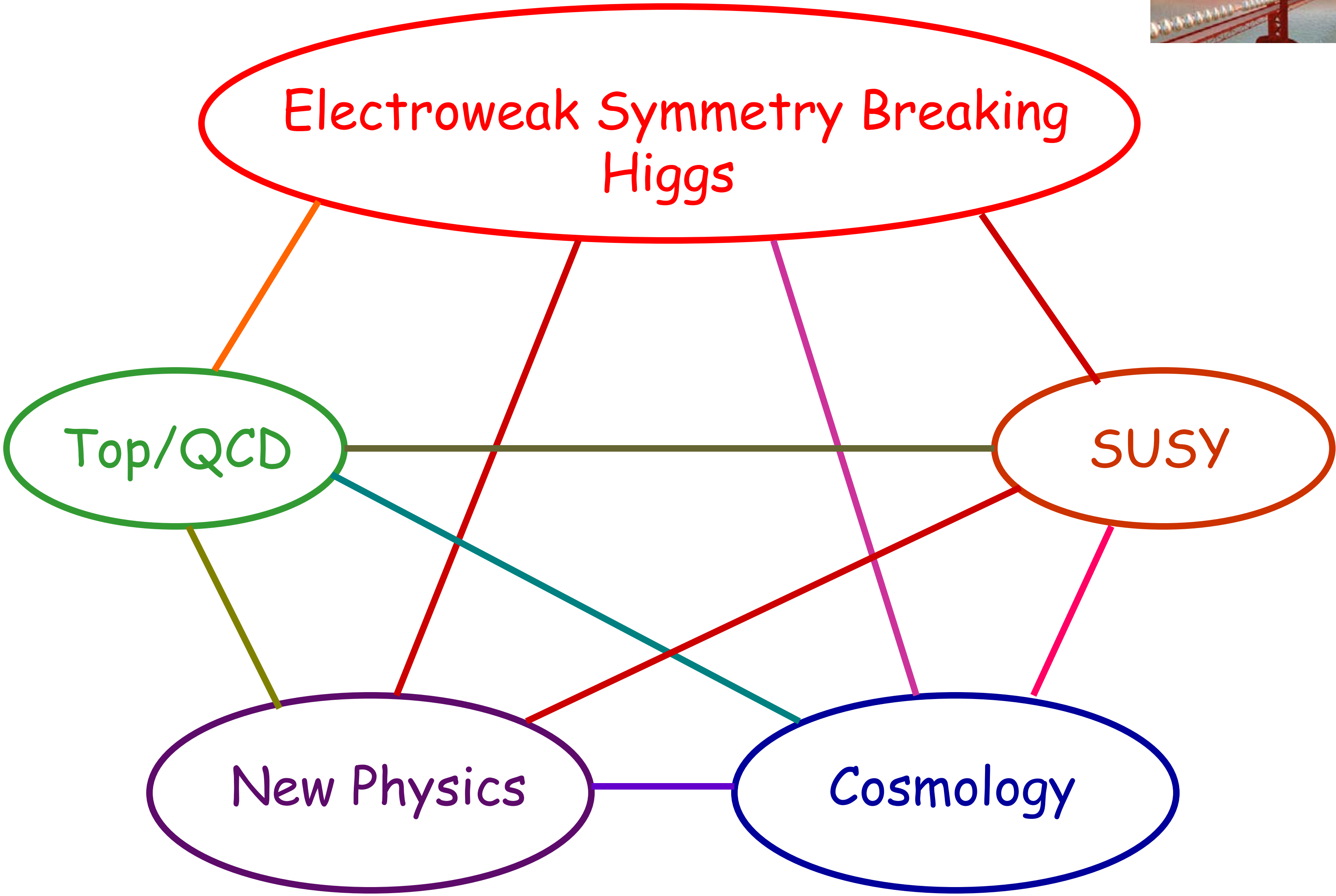
New Physics at TeV Scale & Precision EW Studies

Steve Godfrey
Carleton University

LCWS 2005, Stanford, March 22 2005

Why New Physics at TeV ?

- Believe standard model is low energy effective theory
- Expect some form of new physics to exist beyond the SM
- Don't know what it is
- Need experiments to to show the way


Electroweak Symmetry Breaking
Higgs
Top/QCD
SUSY
New Physics
Cosmology

Models of New Physics

- Little Higgs
- Extra dimensions (ADD, RS, UED…)
- Higgsless Model
- Extended gauge sectors (S. Nandi)
  - Extra U(1) factors: $E_6 \to SU(5) \times U(1)_\chi \times U(1)_\psi$
  - Left-Right symmetric model: $SU(2)_L \times SU(2)_R \times U(1)$
- Technicolour
- Topcolour
- Non-Commutative theories

Many, many models

What do these models have in common?
How do we distinguish them?

I want to focus on predictions of the models; <u>NOT</u> the theoretical nitty gritty details

(Dimopolous)

So start with a rather superficial overview of some recent models

To sort out the models we need to elucidate and complete the TeV particle spectrum

Many types of new particles:

- Extra gauge bosons
- Vector resonances
- New fermions
- Extended Higgs sector
- Pseudo Goldstone bosons
- Leptoquarks…

Little Higgs

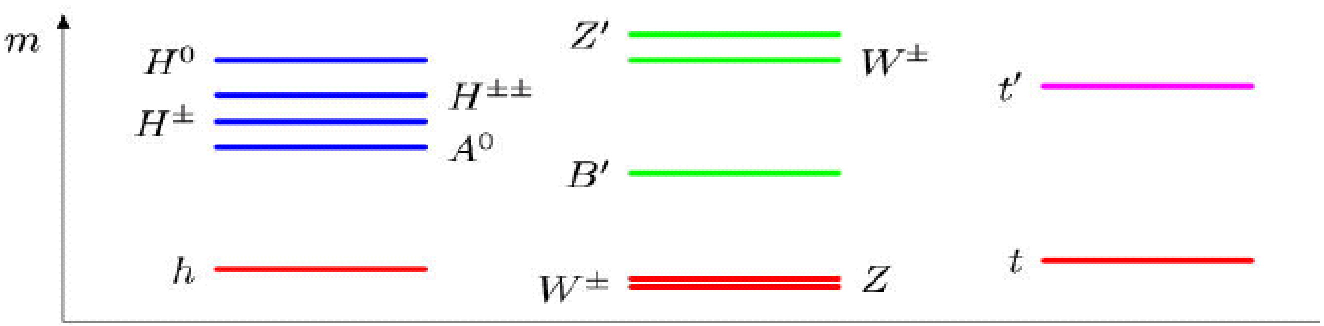
Arkani-Hamed et al hep-ph/0206021

- The little Higgs models are a new approach to stabilize the weak scale against radiative corrections

10 TeV — New Strong Dynamics; Global Symmetry

1 TeV — Symmetries Broken; Pseudo-Goldstone Scalars; New Gauge Bosons related to SU(2): $W_H^{\pm}$ Z_H B_H; New Heavy Top cancels quadratic divergences

100 GeV — Light Higgs; SM vector bosons & fermions



Parameters:

f~vev

s, s': GB mixing angles

Extra Dimensions

In most scenarios our 3-dimensional space is a 3-brane embedded in a D-dimensional spacetime

Basic signal is KK tower of states corresponding to a particle propagating in the higher dimensional Space-time

The details depend on geometry of extra dimensions

Many variations

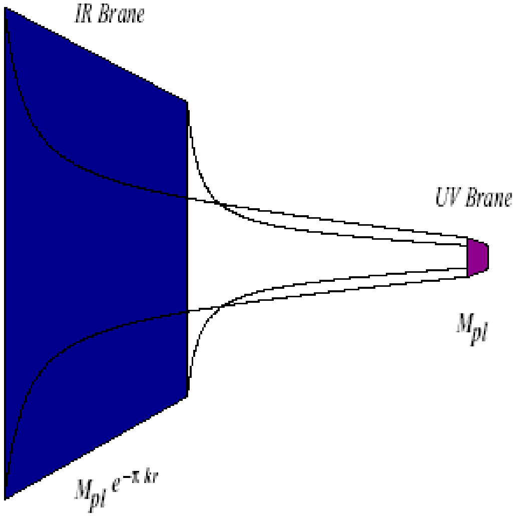
ADD Type of Extra Dimensions

(Arkani-Hamed Dimopoulos Dvali)

- Have a KK tower of graviton states in 4D which behaves like a continuous spectrum
- Graviton tower exchange effective operators: $i\frac{4\lambda}{M_H^4}T^{\mu\nu}T_{\mu\nu}$
- Leads to deviations in $e^+e^- \to f\bar{f}$ dependent on λ and s/M_H
- Also predicts graviscalars and gravitensors propagating in extra dimensions
- Mixing of graviscalar with Higgs leads to significant invisible width of Higgs

Randall Sundrum Model

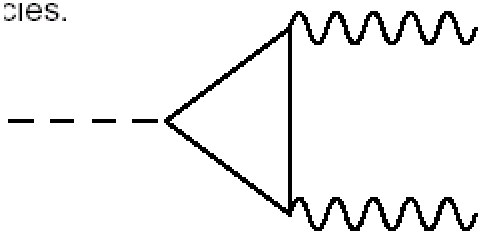
- 2 3+1 dimensional branes separated by a 5th dimension



- Predicts existence of the ***radion*** which corresponds to fluctuations in the size of the extra dimension

- Radion couplings are very similar to SM Higgs except for anomalous couplings to gluon and photon pairs
  - Radion can mix with the Higgs boson
  - Results in changes in the Higgs BR's from SM predictions

- Also expect large couplings for KK states of
  - Expect supression of $h \to WW,\ ZZ$
  - Enhancement of $h \to gg,\ \gamma\gamma$



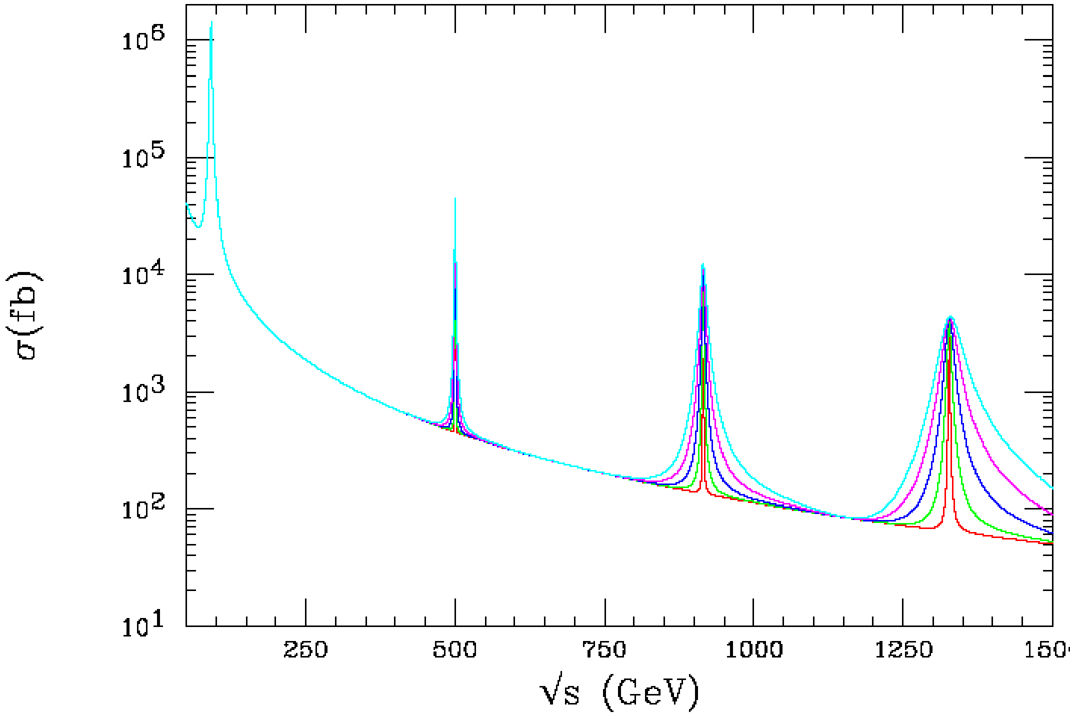
Randall-Sundrum Gravitons:

- The spectrum of the graviton KK states is discrete and unevenly spaced

- Expect production of TeV scale graviton resonances in 2-fermon channels

Has 2 parameters;

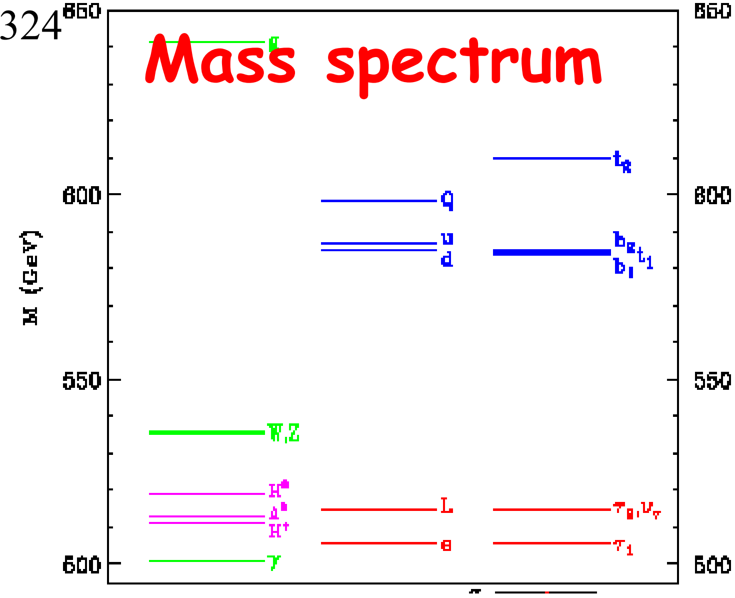
- mass of the first KK state
- coupling strength of the graviton (controls the width)

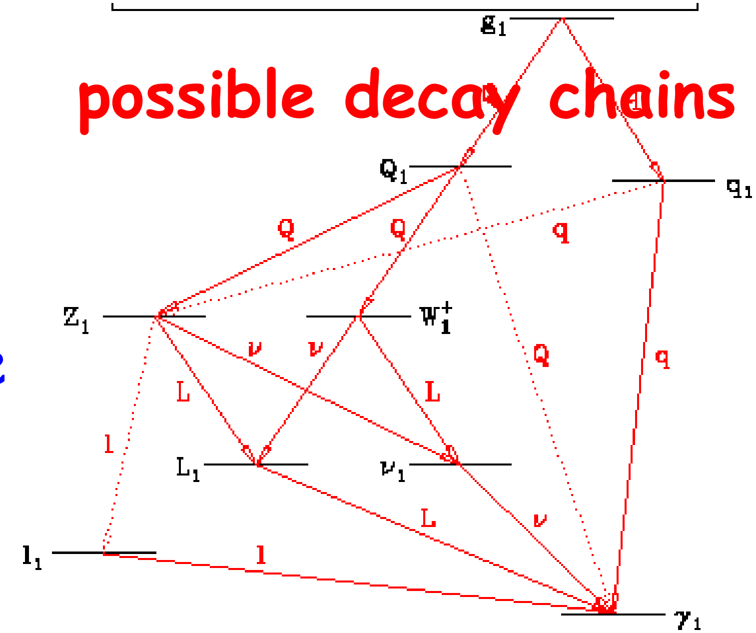


Universal Extra Dimensions

Appelquist, Cheng, Dobrescu, hep-ph/0012100
Cheng, Matchev, Schmaltz, hep-ph/0204324

- All SM particles propagate in the bulk
- KK towers for SM particles with spin quantum numbers identical to SM particles
- Spectrum resembles that of SUSY
- Have conservation of KK number at tree level leading to KK parity = $(-1)^n$
- Ensures that lightest KK partners are always pair produced
- So lightest KK particle is stable



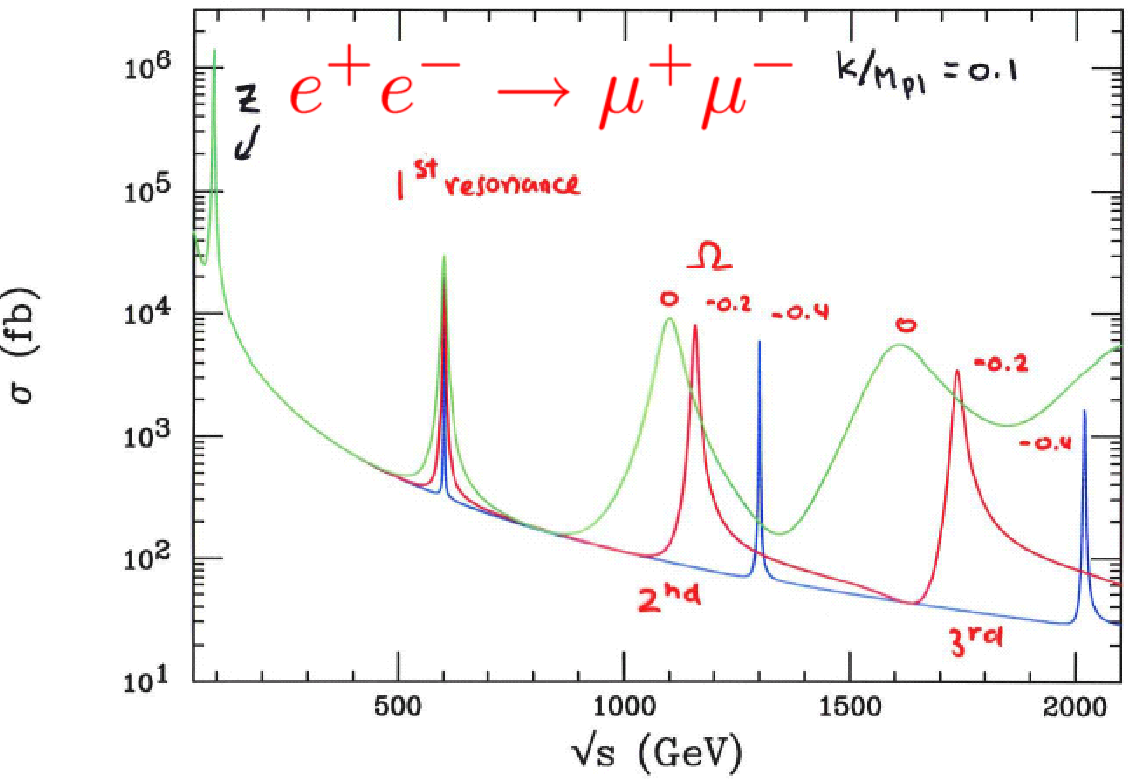


Higher Curvature TeV-scale Gravity

Rizzo [hep-ph/0503…]

- EH is at best an effective theory below M_*
- Terms from UV completion (strings?) may be important as we approach M_*

- Implications are:
  - KK mass shifts
  - New features in Black hole production



Summary of Model Predictions

Models Predict:

- Extra Higgs (doublets & triplets)
- Radions, Graviscalars
- Gravitons
- KK excitations of γ, Z, W …
- Extra gauge bosons

What do these models have in common?

- Almost all of these models have new s-channel structure at ~TeV scale
- Either from extended gauge bosons or new resonances

How do we distinguish the models?

Need to map out the low energy particle content

Precision Electroweak Measurements

- How do we discover the new physics?
- How do we identify the new physics?

- Likely that discoveries at the LHC will get us started
- But will need the ILC to discriminate between models

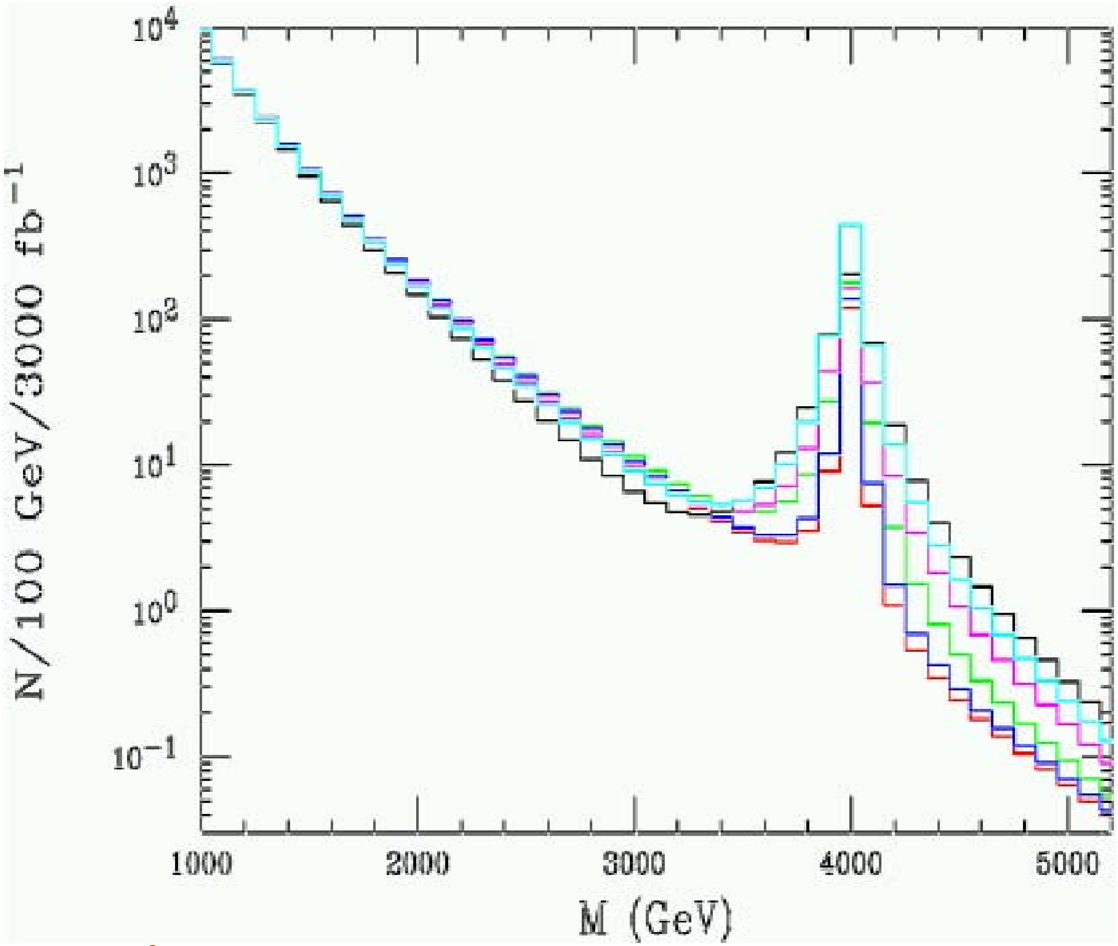
Possible Routes:

- Direct Discovery
- Indirect discovery assuming specific models
- Indirect tests of New Physics via L_{eff}

Tools:

- Di-fermion channel
- Anomalous gauge boson couplings
- Anomalous fermion couplings
- Higgs couplings

LHC Discovers S-channel Resonance !!



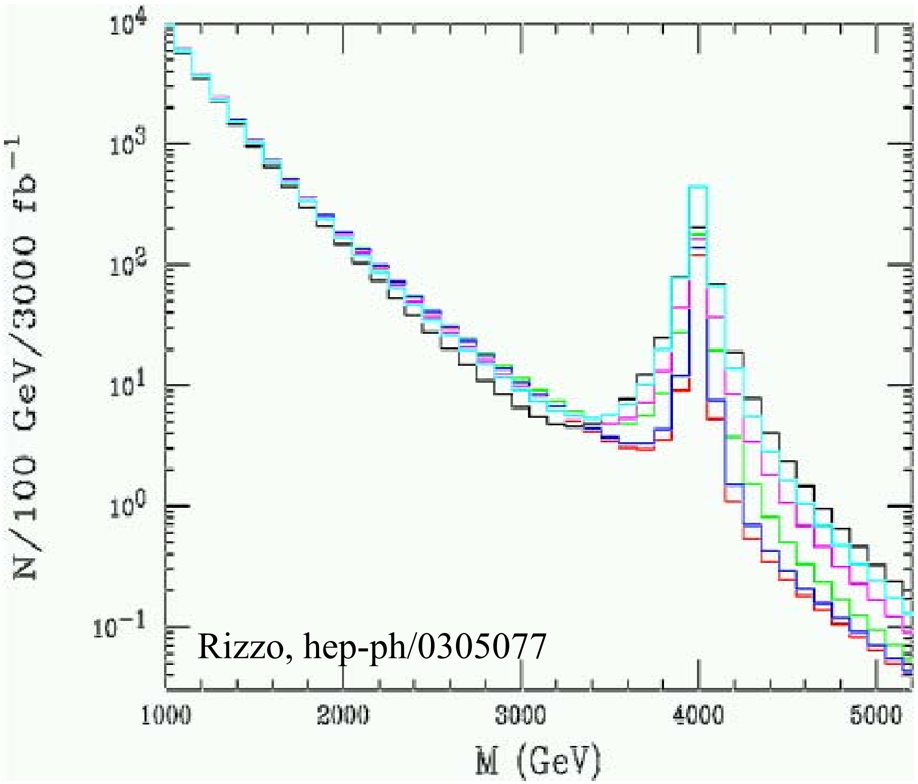
What is it?

Many possibilities for an s-channel resonances:

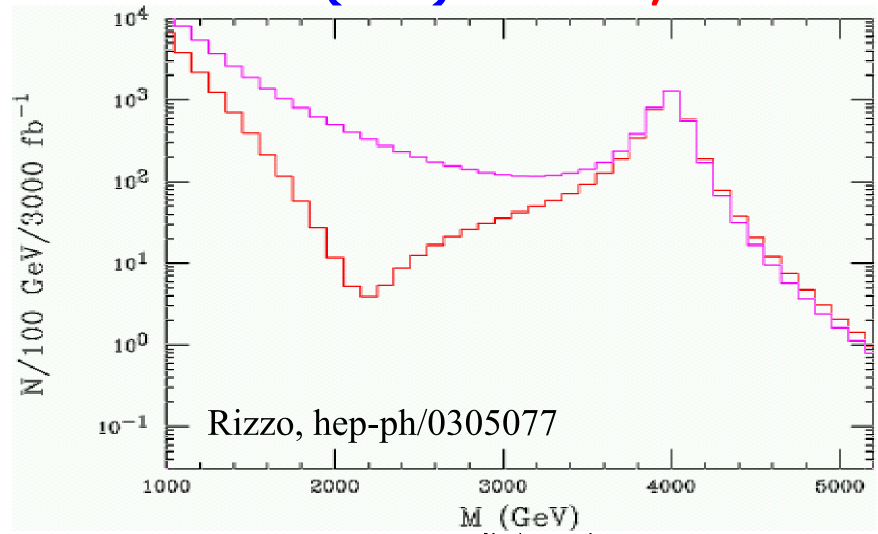
graviton, KK excitations, Z′ …

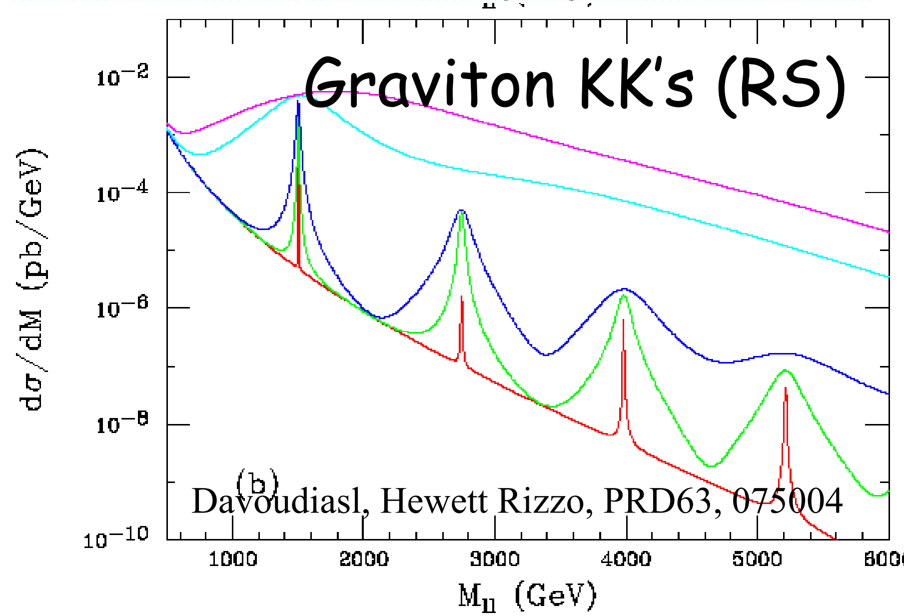
LHC can give some information:

Z': ψ, χ, η, LR, ALR, SSM

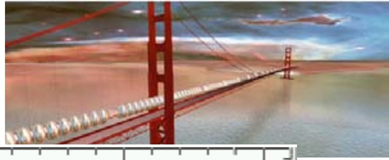


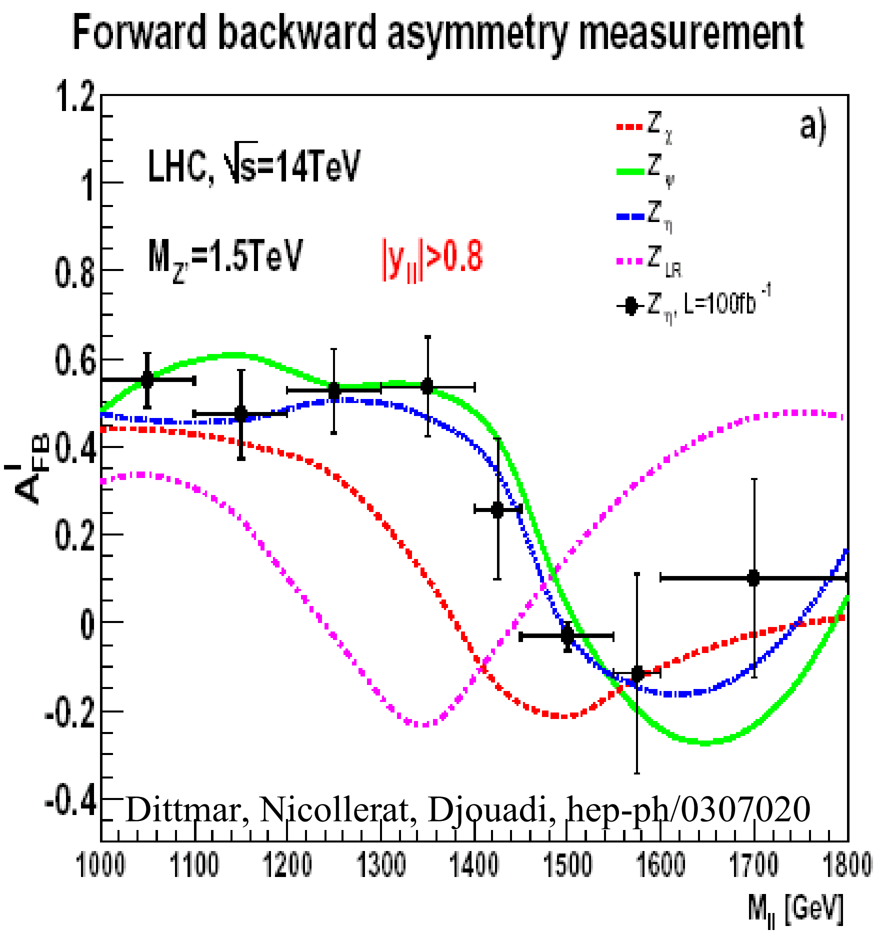
KK (RS): D=0, D=πR

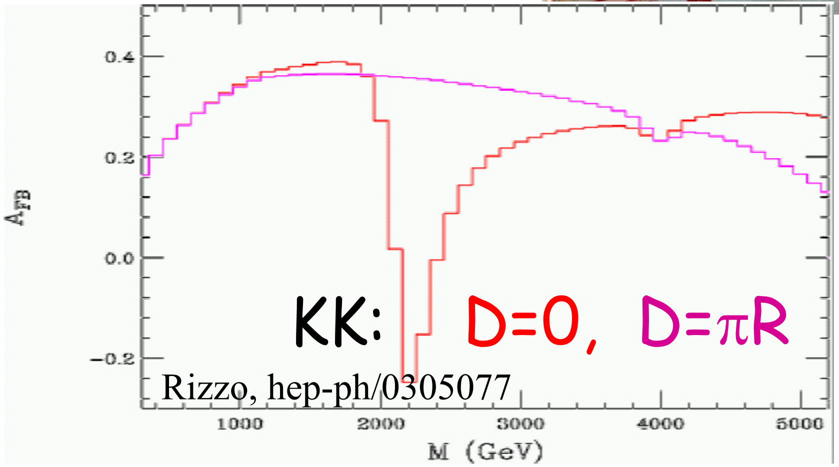


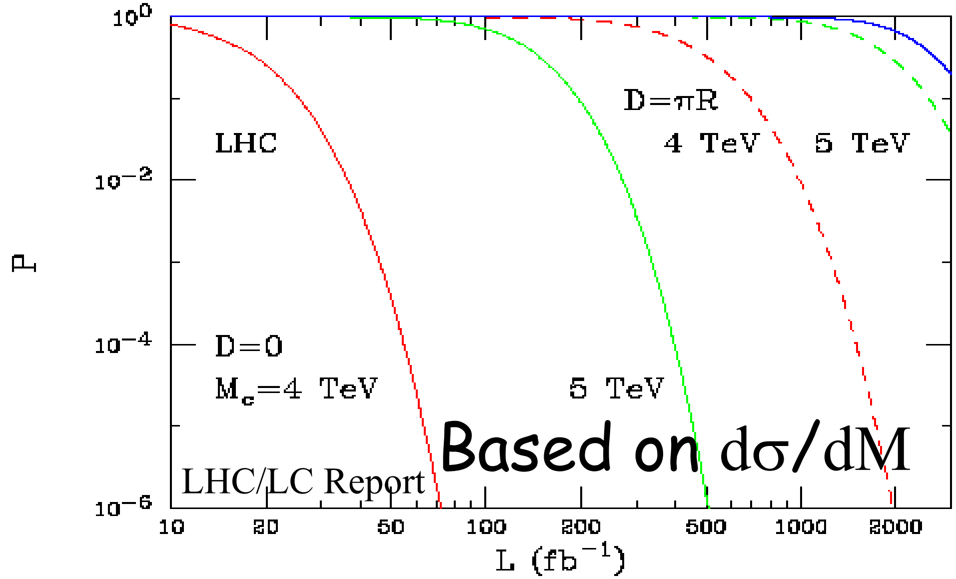


Forward Backward Asymmetries









LHC can resolve to some extent but requires significant luminosity

But this is a LC talk…

Start by assuming the LHC discovers single rather heavy resonance

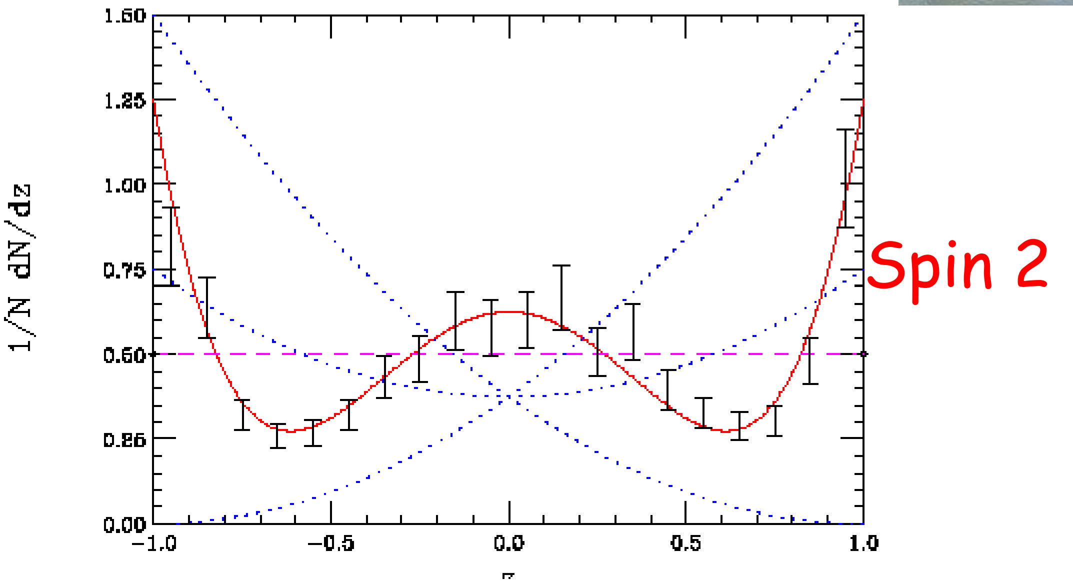
What is it?

Tools are:

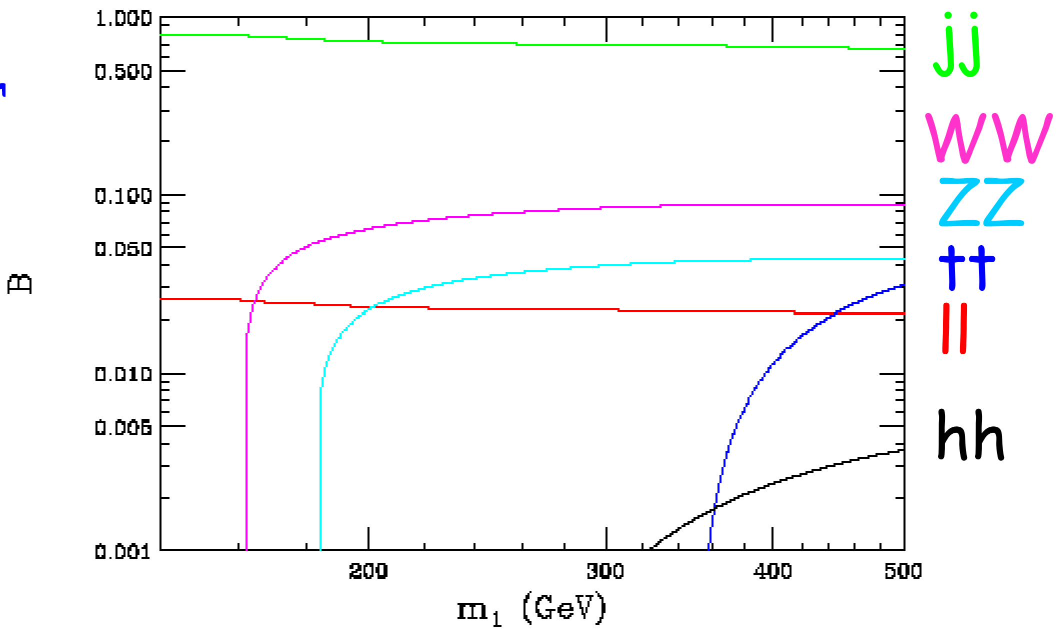
- Cross sections & Widths
- Angular Distributions
- Couplings (decays, polarization…)

On resonance production of (RS) Gravitons

Use angular distributions to test against different spin hypothesis

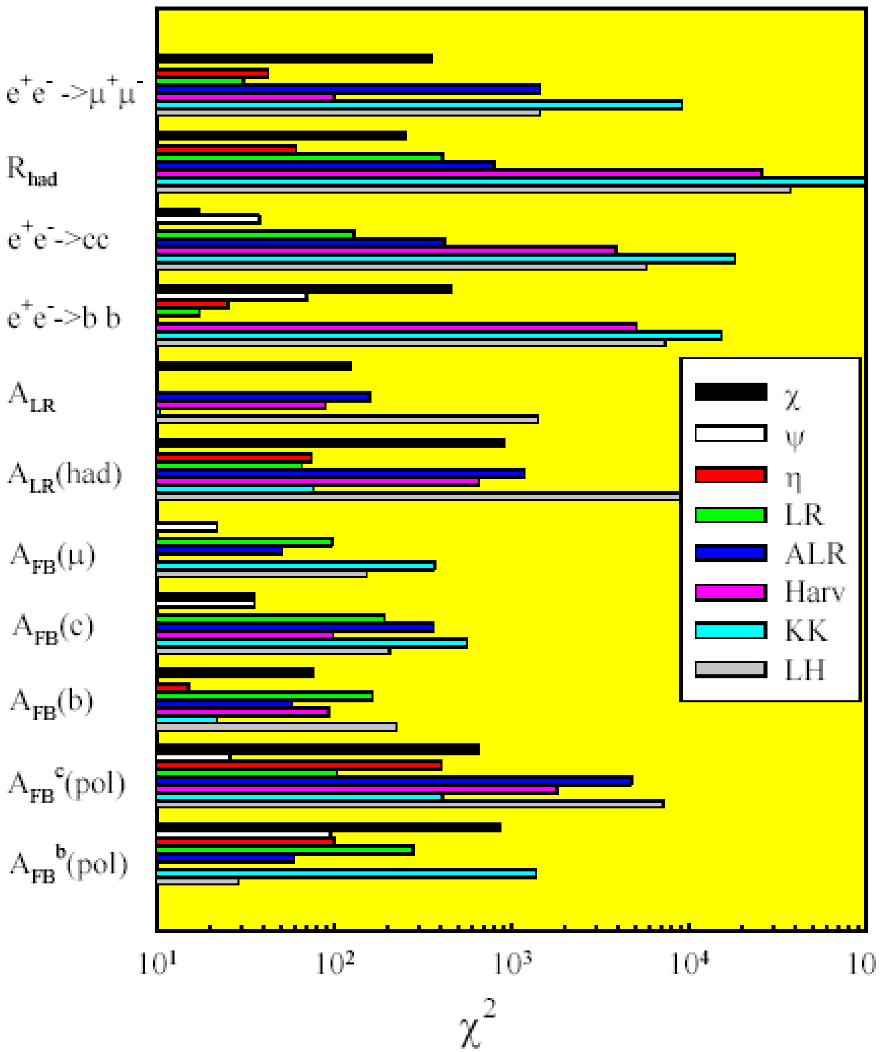


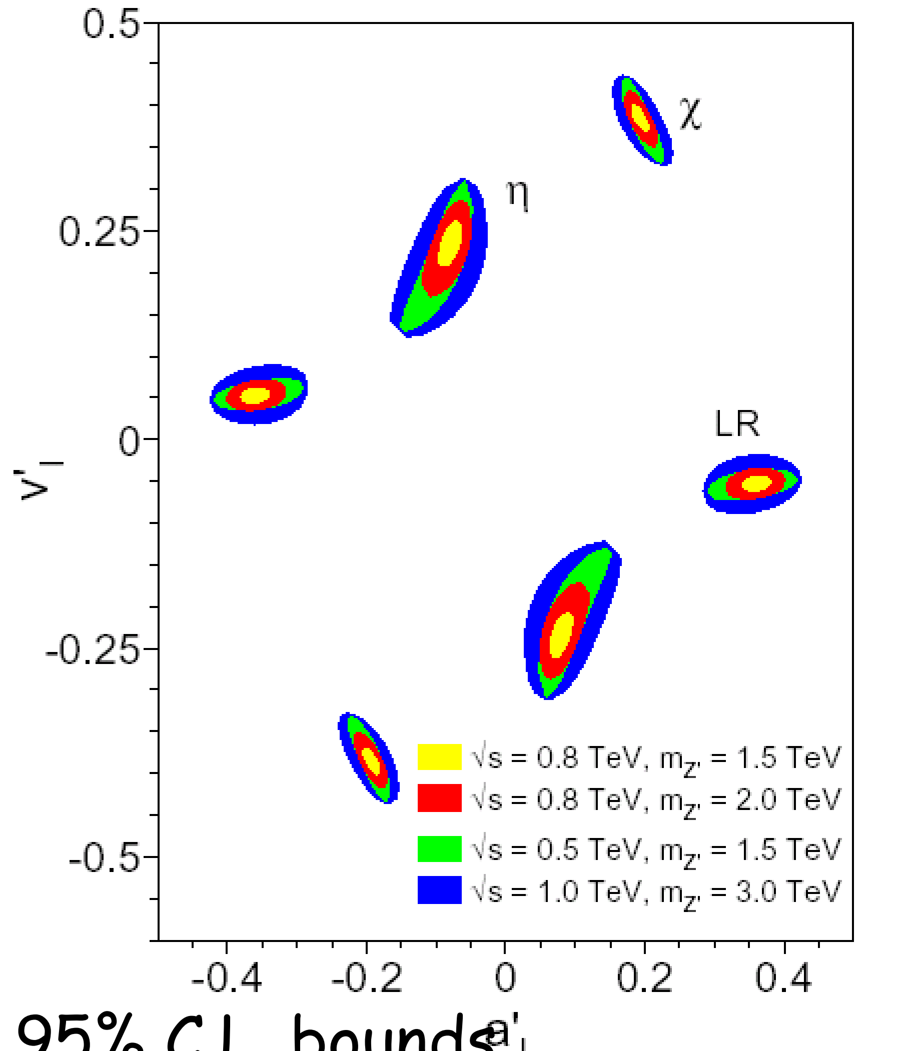
Measure BR's to test for Universal couplings



Z' couplings

Extraction of Z' couplings assuming $M_{Z'}$ is known from LHC





95% C.L. bounds

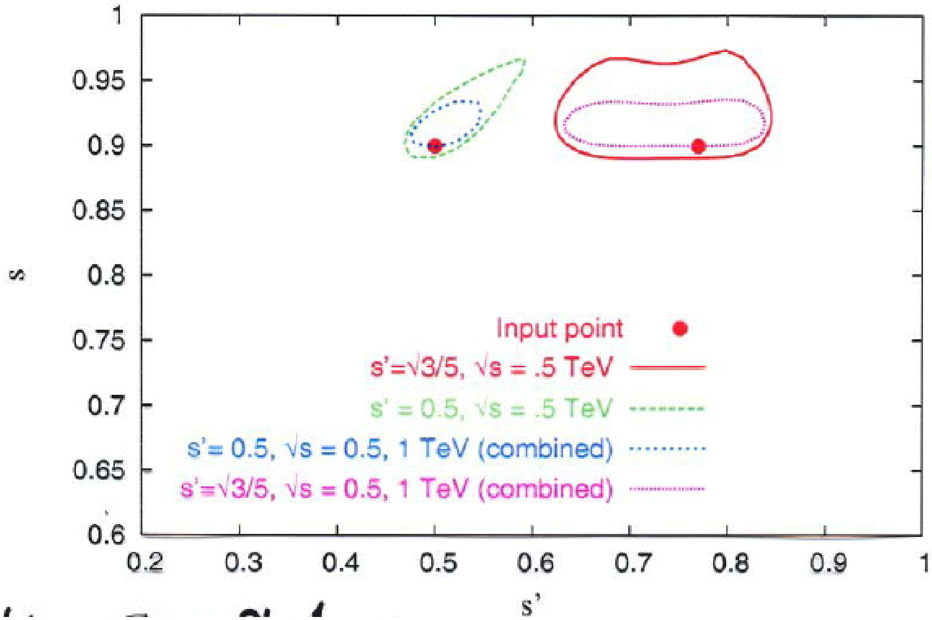
$L=1\ ab^{-1}$ $\Delta L=0.2\%$, $P_-=0.8$, $P_+=0.6$, $\Delta P=0.5\%$

Measuring Little Higgs Parameters

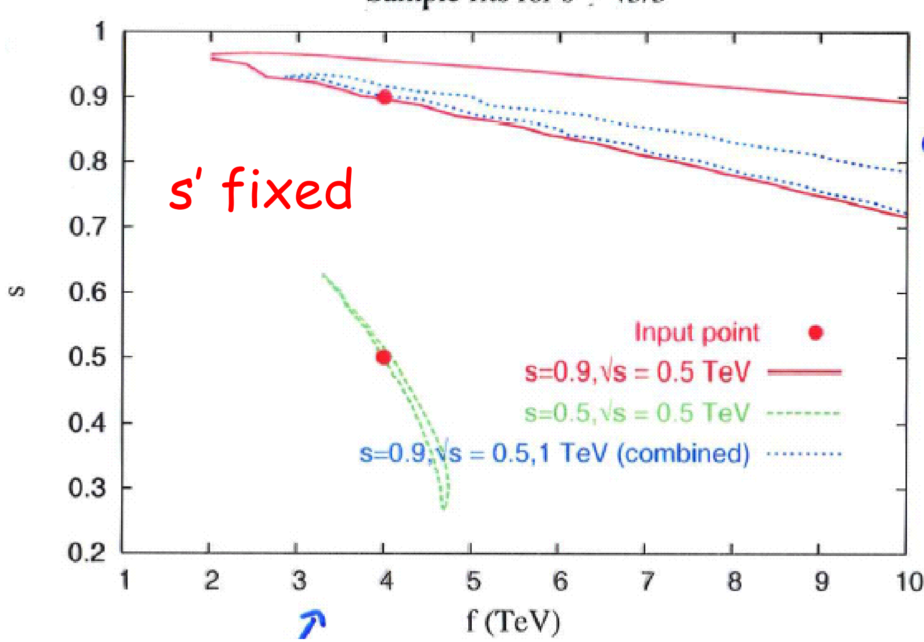
J. Conley, M.P. Le, J. Hewett

$$e^+e^- \to f\bar{f}$$

$M_H = 3.3$ TeV $\quad m_{A_H} \to \infty$



M_H not known from LHC

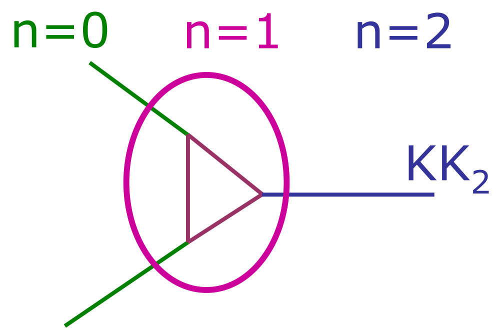


$$\mathcal{L} = 500 \text{ fb}^{-1}$$

UED KK Z' 's Signals

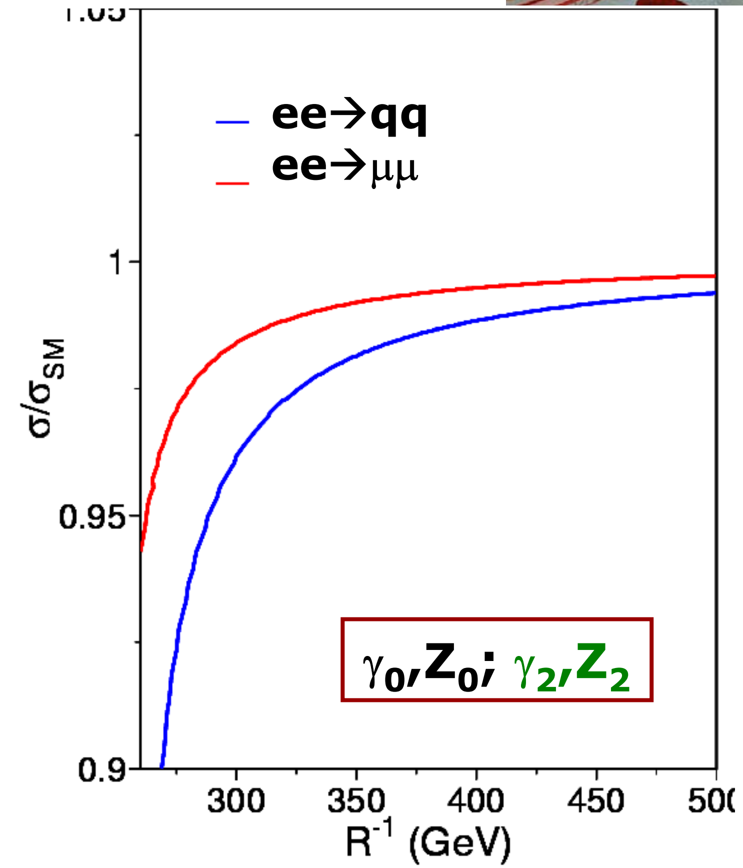
S. Riemann

KK-number conservation ➔



γ_2, Z_2 → $f_0 f_0$ couplings

couplings much smaller than SM couplings



Excluded at 95% C.L.

$\gamma_2 < 2\sqrt{s}$

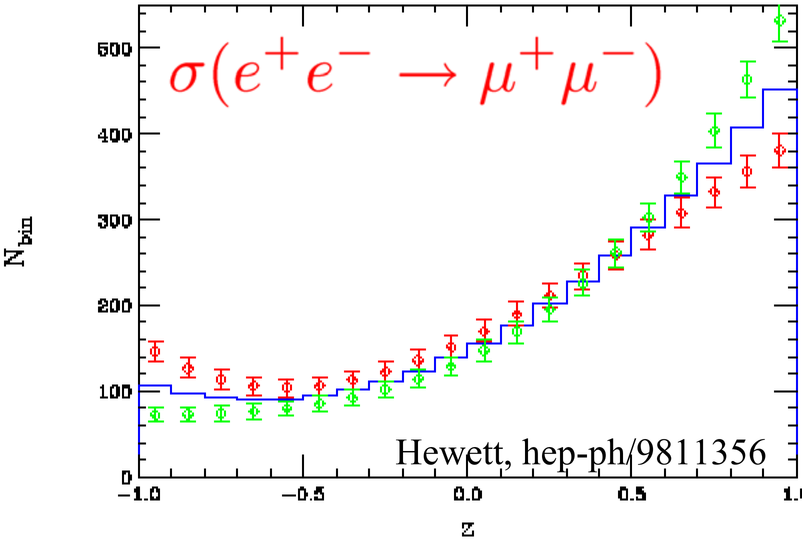
$Z_2 < 2\sqrt{s}$ for $\Lambda R=20$

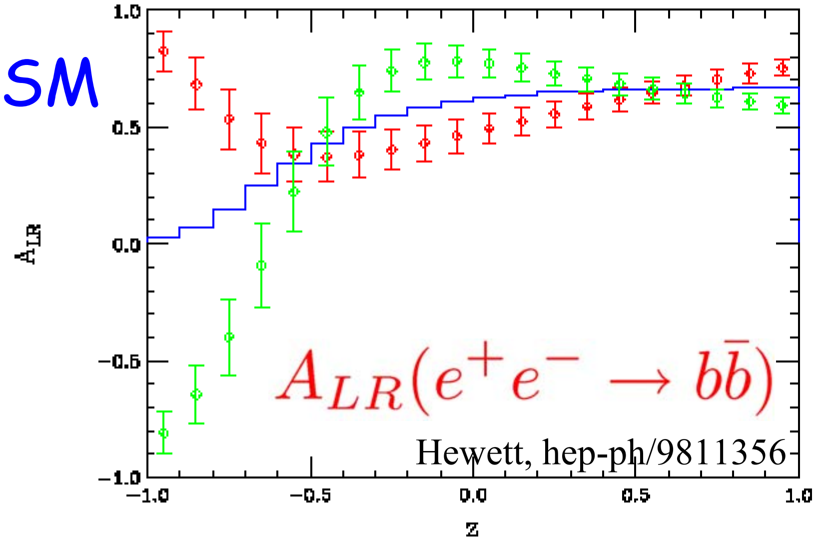
Indirect Signatures for Gravitons

Interference of exchange of virtual graviton KK states with SM amplitudes

ADD: $i\dfrac{4\lambda}{M_H^4}T^{\mu\nu}T_{\mu\nu}$

Leads to deviations in $e^+e^- \to f\bar{f}$ dependent on both λ and s/M_H



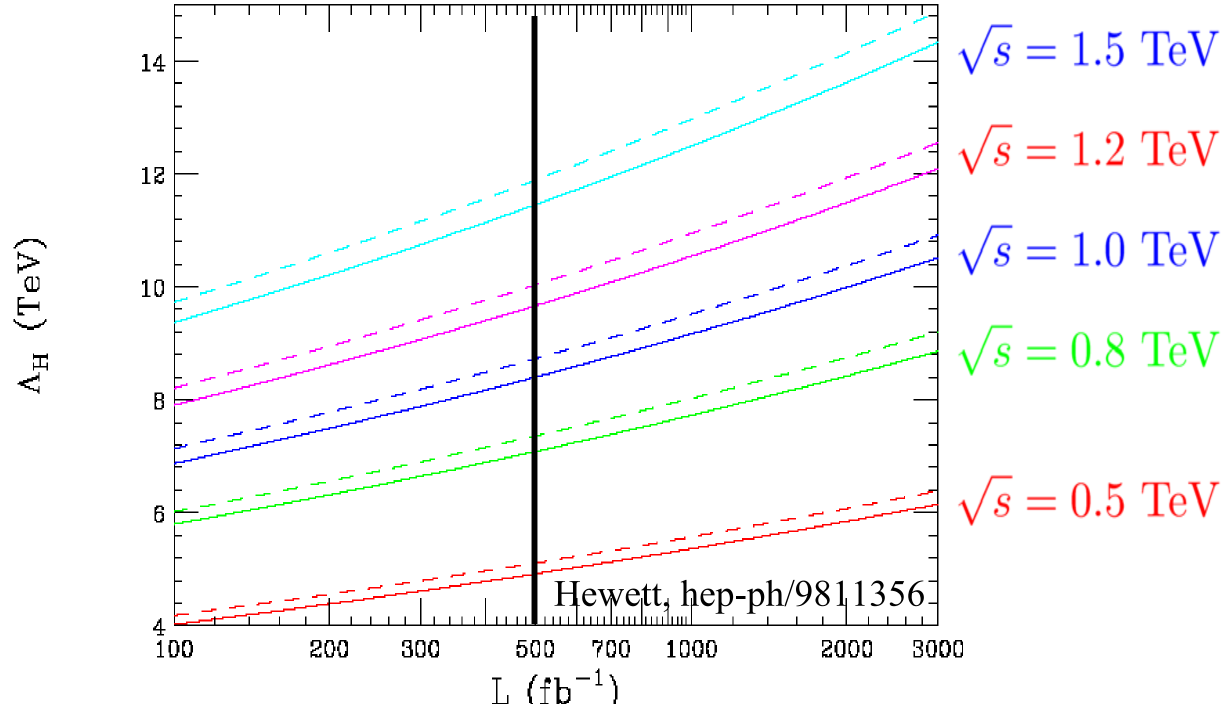


$\sqrt{s} = 5$ TeV $\quad L = 1\ \mathrm{ab}^{-1} \quad M_s = 15$ TeV $\quad \lambda = \pm 1$

Limits on Λ_H

Osland Pankov & Paver hep-ph/0304123

$e^+e^- \to f\bar{f}$ $\quad f = (e,\ \mu,\ \tau,\ c,\ b,\ t)$ $\quad \sigma,\quad A_{FB},\quad A_{LR},\quad P_\tau$



M_H [TeV] $\sqrt{s} = 0.5$ TeV (long. pol.)	$\mathcal{L}_{\rm int}$ [fb^{-1}] 100	300	500
unpolarised beams	2.3	2.6	2.9
$(\mathbf{P}_{e^-}, \mathbf{P}_{e^+}) = (+80\%, 0)$	2.5	2.8	3.05
$(\mathbf{P}_{e^-}, \mathbf{P}_{e^+}) = (+80\%, -60\%)$	2.45	3.0	3.25

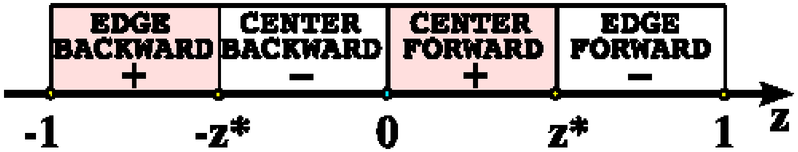
Can use multipole moments to distinguish spin 2 from spin 1

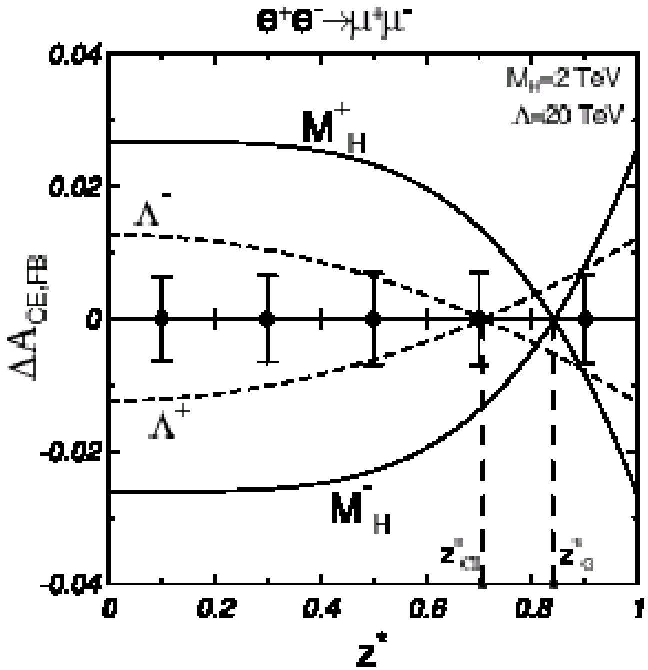
ID ADD Graviton Exchange

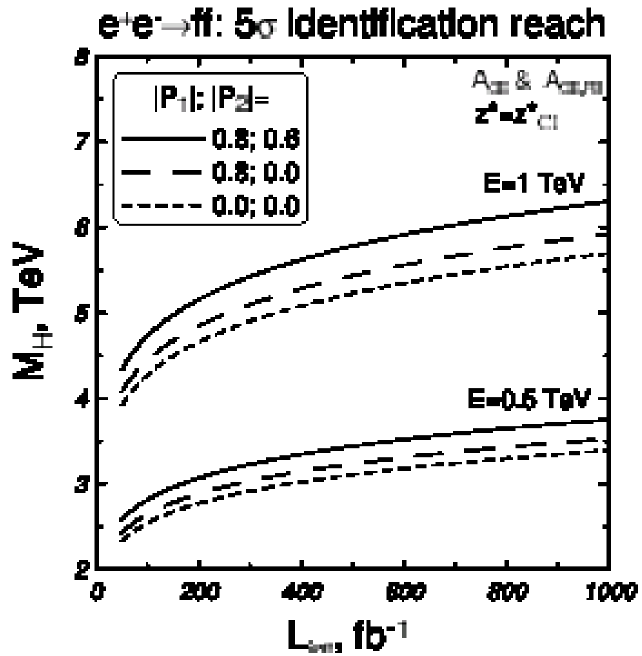
Pankov & Paver hep-ph/0501170

Suitable observables can divide possible models into subclasses

- To identify graviton exchange
- Forward-Backward Centre-Edge asymmetries: $\sigma_{\mathrm{CE,FB}} = \sigma_{\mathrm{C,FB}} - \sigma_{\mathrm{E,FB}}$







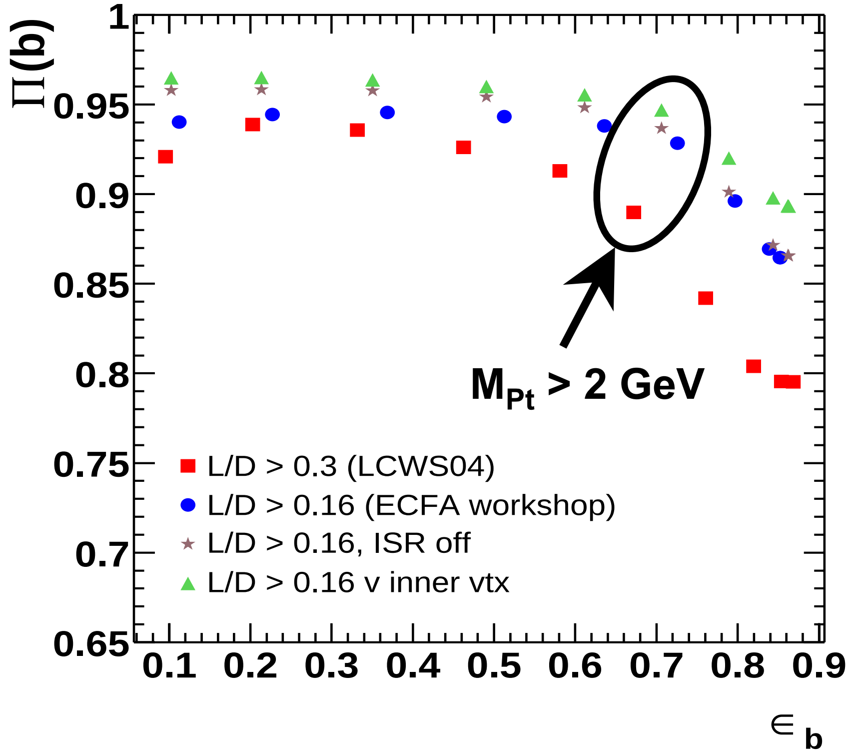
LC: 5σ ident. reach on $M_H = 3.5 - 5.8$ TeV at $\sqrt{s} = 0.5 - 1$ TeV and $\mathcal{L}_{\mathrm{int}} = 500\, fb^{-1}$

ILC Vertex Detector

S. Hillert

LCFI

b-tagging an extremely powerful tool in ID'ing models
So b-purity vs efficiency is an important issue



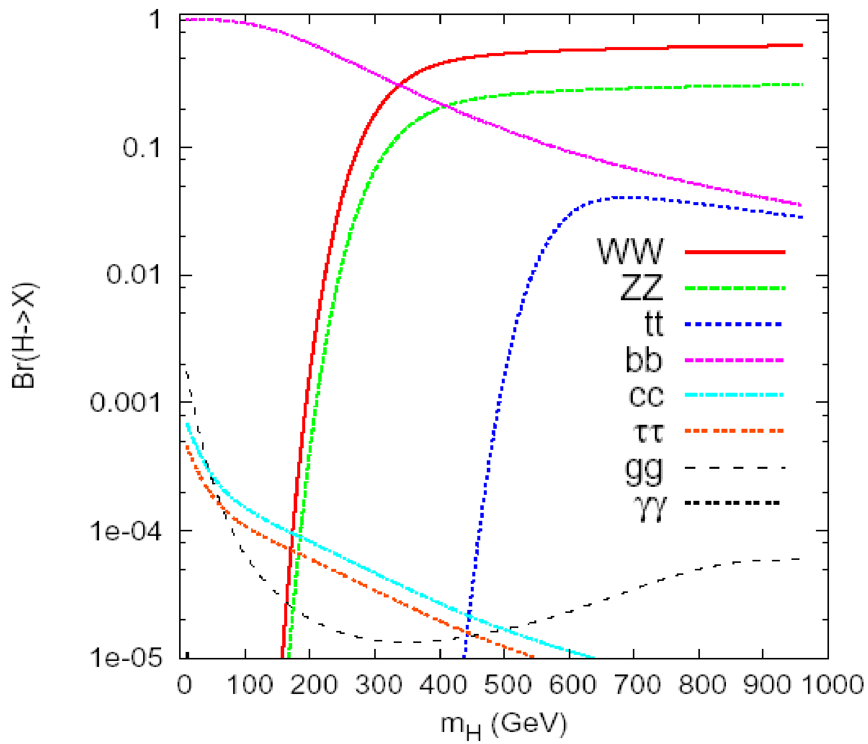
Luminosity and beam parameter measurements was another important issue discussed

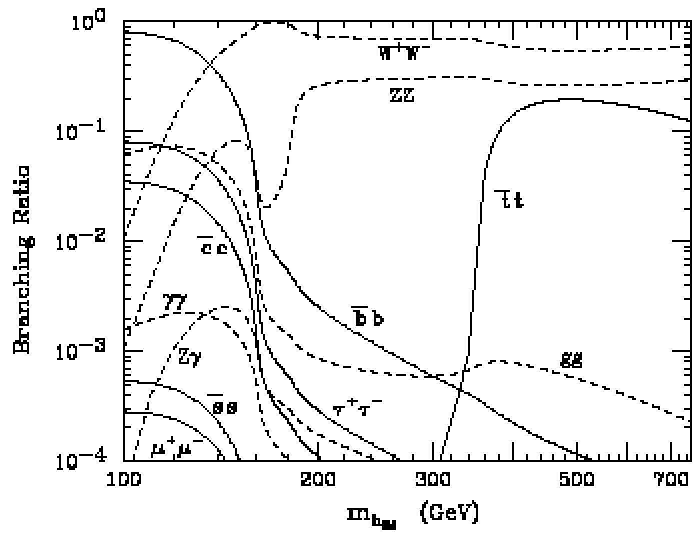
R. Ingbir & E. Torrence

Higgs Properties in RS Model

B. Lillie

Higgs Branching Ratios



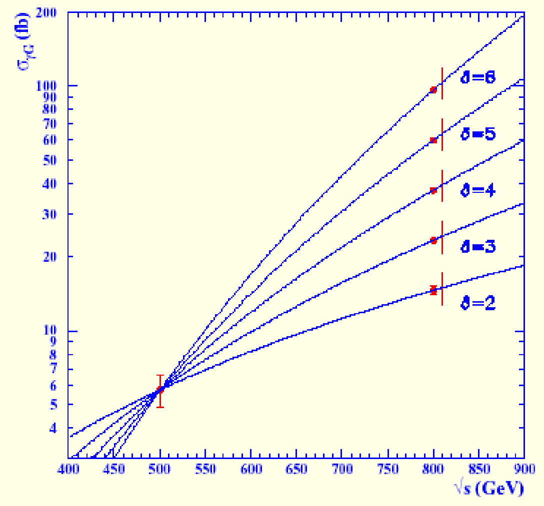


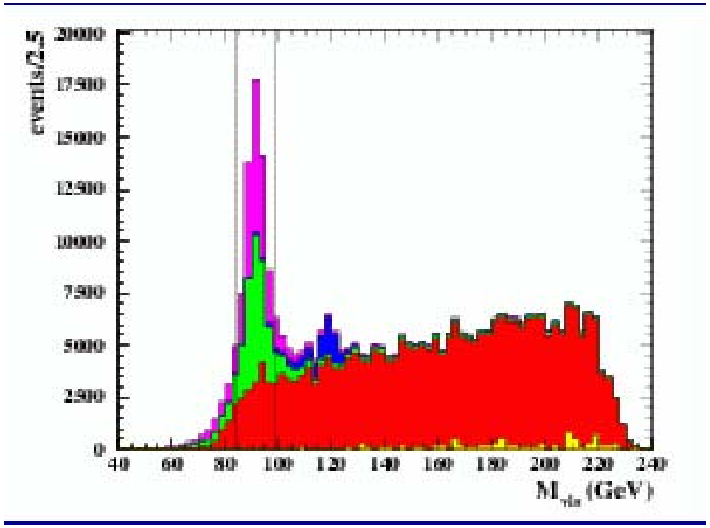
- Higgs production enhanced at LHC and γγ reduced at ILC
- Higgs decays are substantially modified

Invisible Higgs Width in ADD

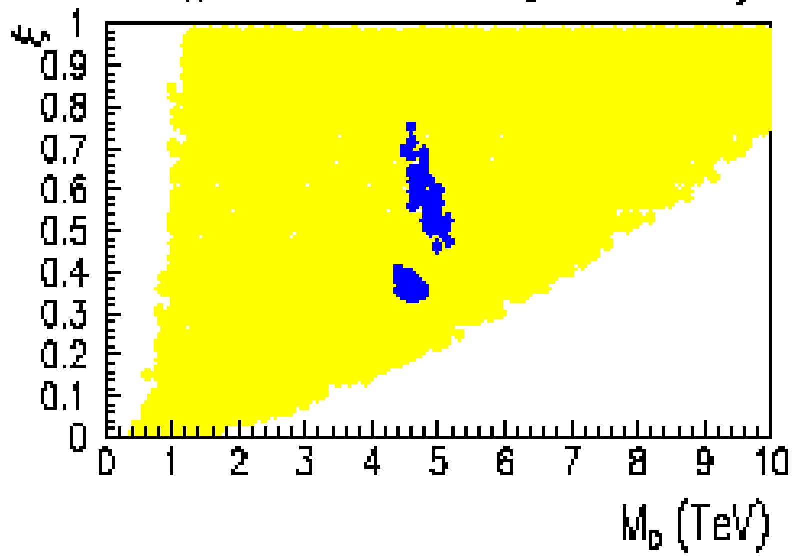
M. Battaglia, D. Dominici, J. Gunion, J. Wells

- Relevant parameters are:
  - Mixing between Higgs and graviscalar: ξ
  - Number of extra dimensions: δ
  - M_D scale
- Invisible width due to mixing vs direct decay
- ILC can measure invisible width directly and using HZ production





δ = 2, M_H = 120 GeV, M_D=5 TeV, ξ=.5



Little Higgs vs SM Higgs

Partial widths are modified due to heavy particles running in the loop and by shifts to the SM W boson and t-quark

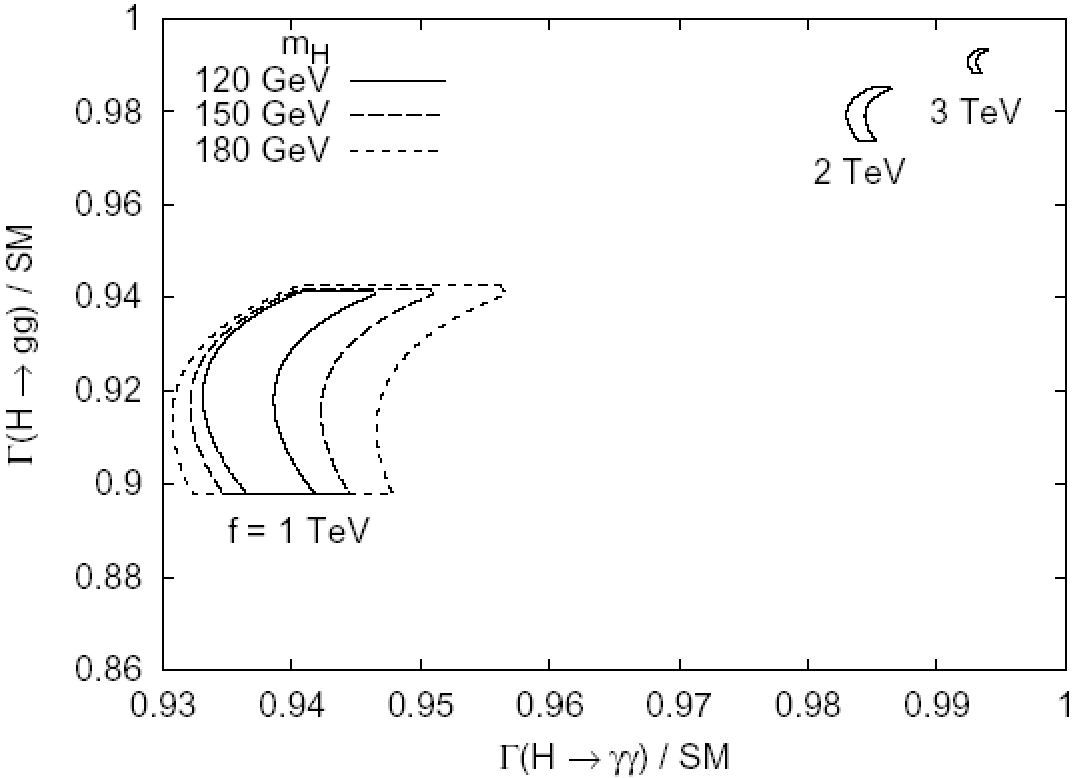


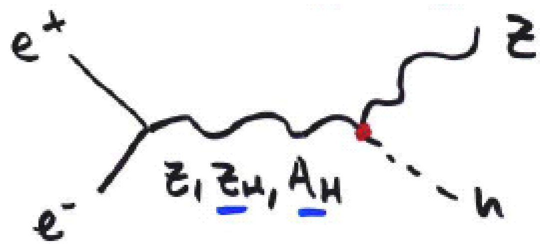
Figure 3.61: Range of values of $\Gamma(H \to gg)$ versus $\Gamma(H \to \gamma\gamma)$ accessible in the Littlest Higgs model normalized to the SM value, for $m_H = 120, 150, 180$ GeV and $f = 1, 2, 3$ TeV. From Ref. [292].

Measuring Little Higgs Parameters

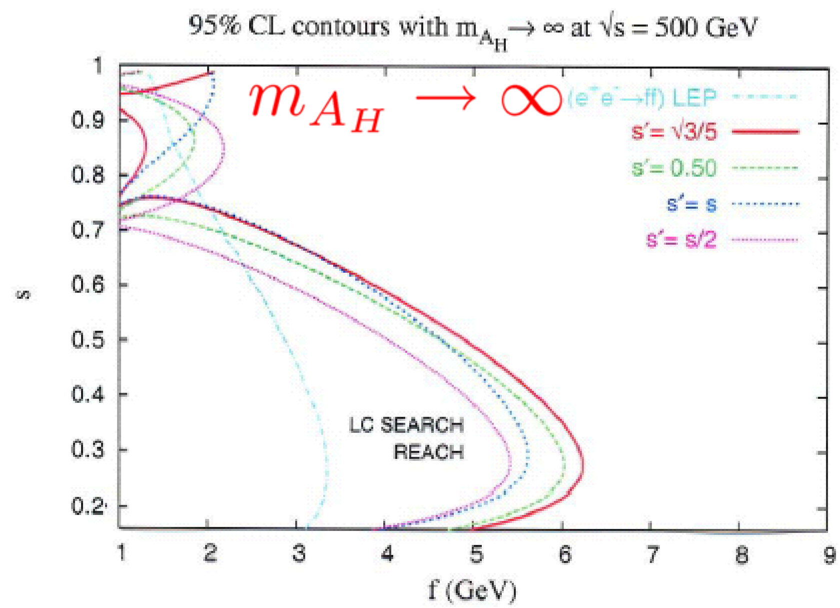
J. Conley, M.P. Le, J. Hewett

$$e^+e^- \to Zh$$

Hallmark of Little Higgs models is coupling of heavy gauge bosons to Zh



Expect deviations from SM in σ_{Zh}



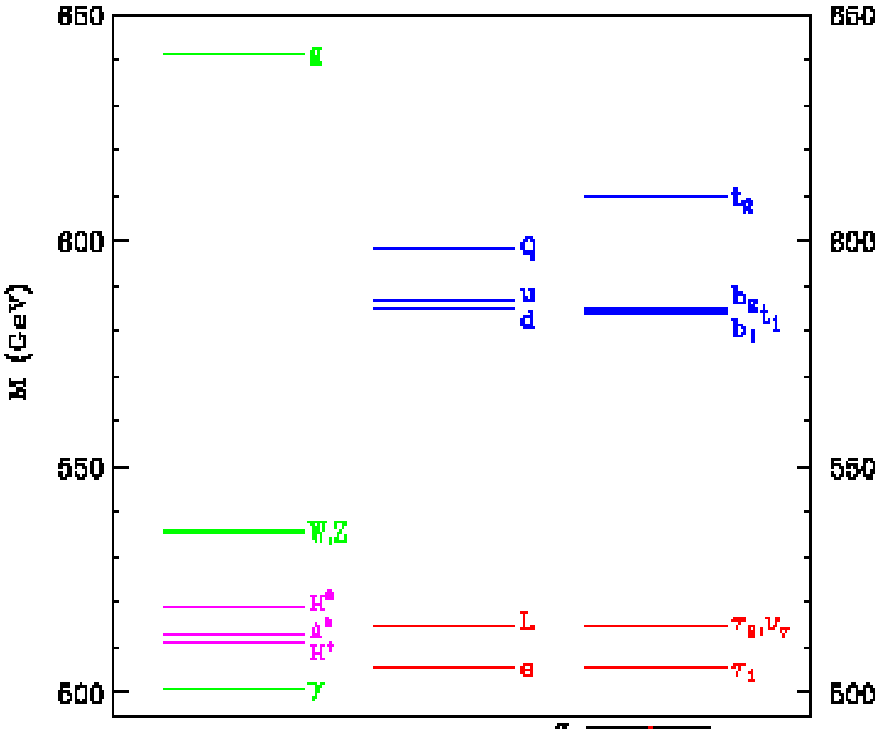
$$\mathcal{L} = 500\ \mathrm{fb}^{-1}$$

- ILC covers most of the interesting parameter space
- $e^+e^- \to Zh$ confirms in some regions of parameter space feature of LH

UED

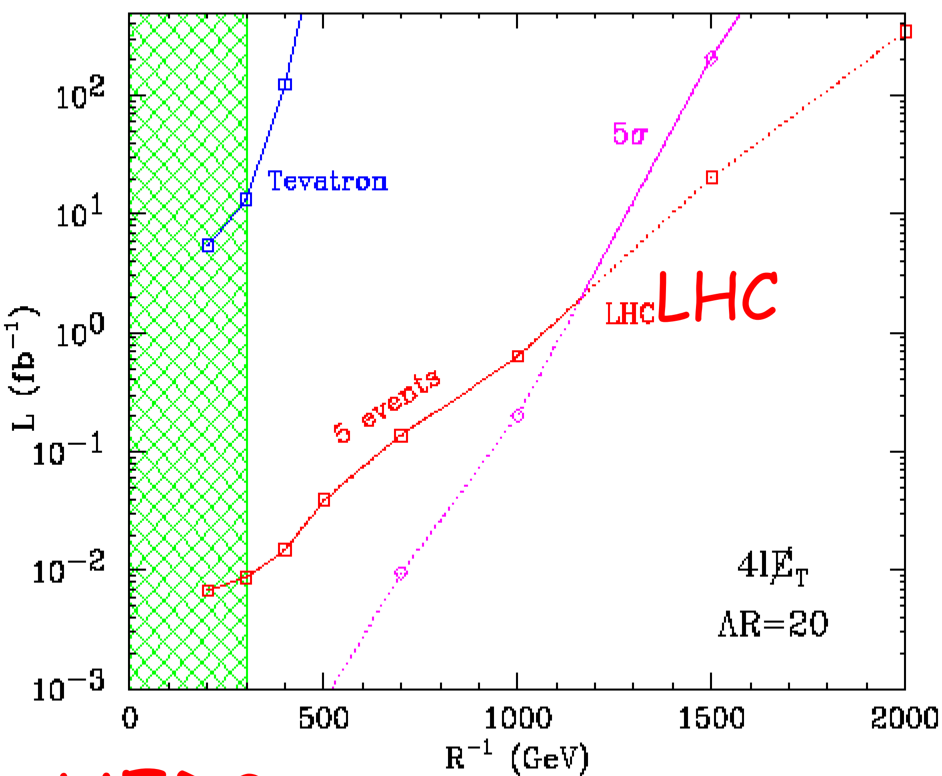
K.C. Kong [hep-ph/0502041]

The KK spectrum in UED resembles that of SUSY



Discovery Reach at LHC in

$$Q_1 Q_2 \to Z_1 Z_1 \to 4\ell + \not{E}_T$$

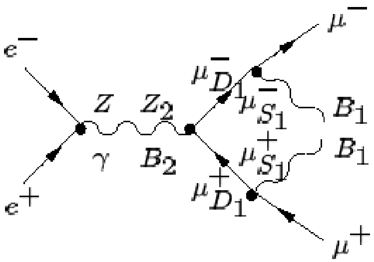


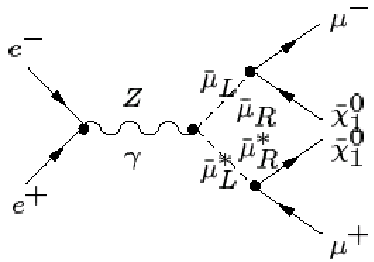
SUSY or UED?

UED

K.C. Kong [hep-ph/0502041]

- But spins of SUSY particles different from KK particles
- Use: $e^+e^- \rightarrow \mu^+\mu^- + \not{E}_T$





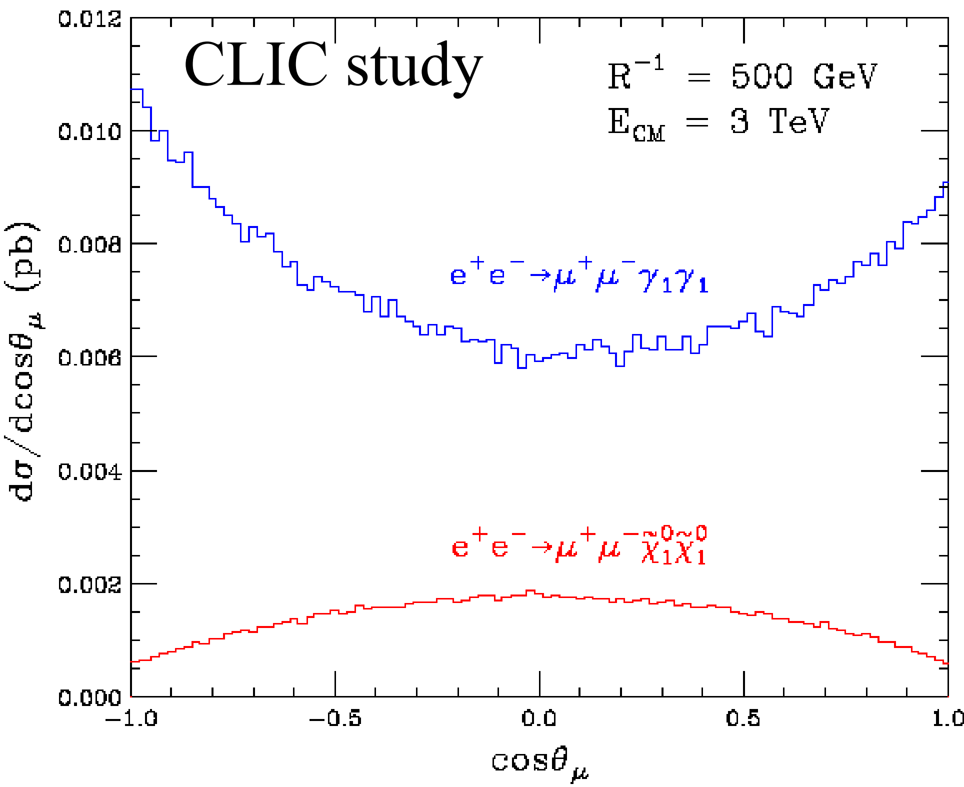
And angular distributions to Distinguish between UED and SUSY

$$\left(\frac{d\sigma}{d\cos\theta}\right)_{UED} \sim 1 + \cos^2\theta$$

$$\left(\frac{d\sigma}{d\cos\theta}\right)_{SUSY} \sim 1 - \cos^2\theta$$

Can also use threshold scans

And energy distributions

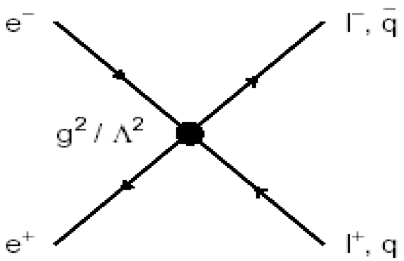


Precision Measurements and Effective Lagrangians

W. Kilian
P. Osland, A. Pankov & N. Paver

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^p} \mathcal{O}_i^{(4+p)}$$

Contact Interactions:



- New interactions can be parametrized in terms of 4-fermion interactions if $\sqrt{s} \ll \Lambda$

$$L = \sum_{i,j=L,R} \eta_{ij} \frac{g^2}{\Lambda_{ij}^2} \left(\bar{f}_i \gamma^\mu f_i\right)\left(\bar{F}_i \gamma^\mu F_i\right) \qquad \Lambda \sim M_{Z'}$$

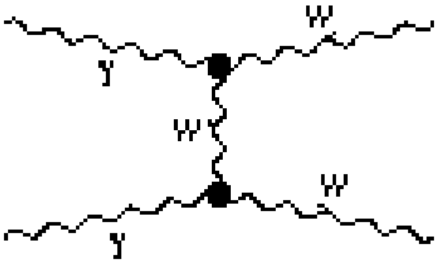
- Contact terms related to Z' parameters

$$\frac{\eta_{LL}}{\Lambda^2} \frac{\eta_{RR}}{\Lambda^2} = \frac{\eta_{LR}}{\Lambda^2} \frac{\eta_{RL}}{\Lambda^2} \approx \frac{g_L^e}{M_{Z'}} \frac{g_L^F}{M_{Z'}} \frac{g_R^e}{M_{Z'}} \frac{g_R^f}{M_{Z'}}$$

- Obtain similar expressions for leptoquark exchange etc

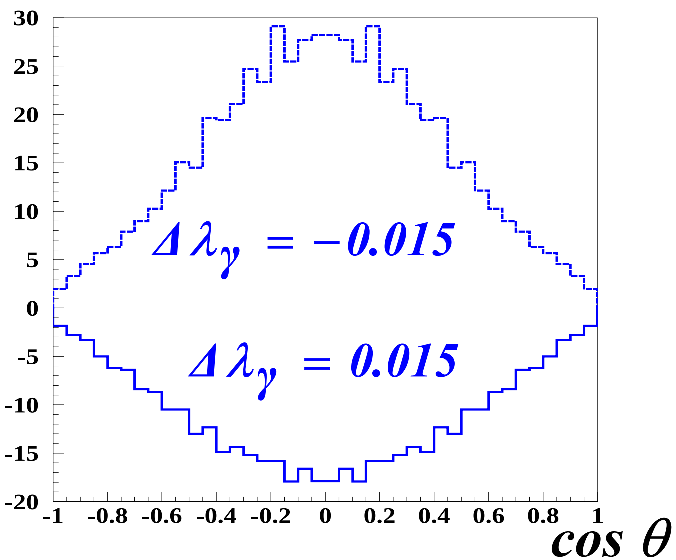
Trilinear γWW Couplings in γγ

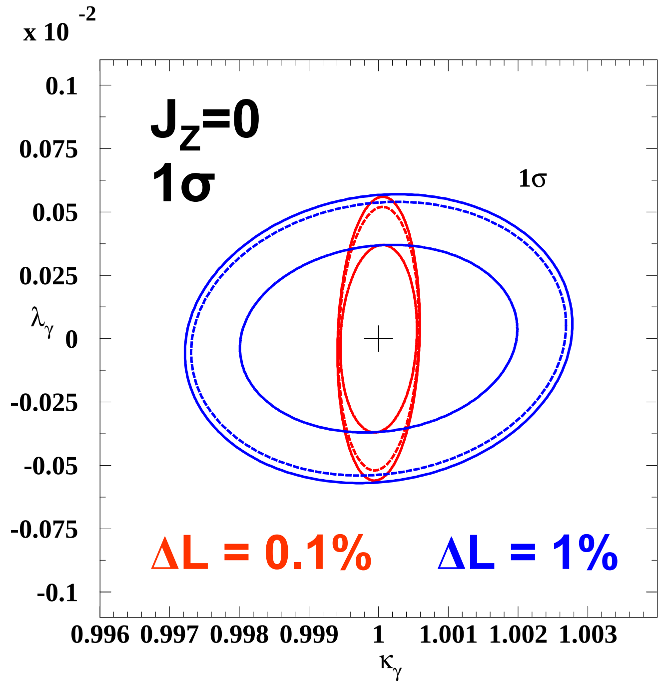
K.Mönig, J.Sekaric
DESY-Zeuthen



$$\gamma\gamma \rightarrow W^+W^- \rightarrow q\bar{q}q\bar{q}$$

$$\sqrt{S_{ee}} = 500GeV$$



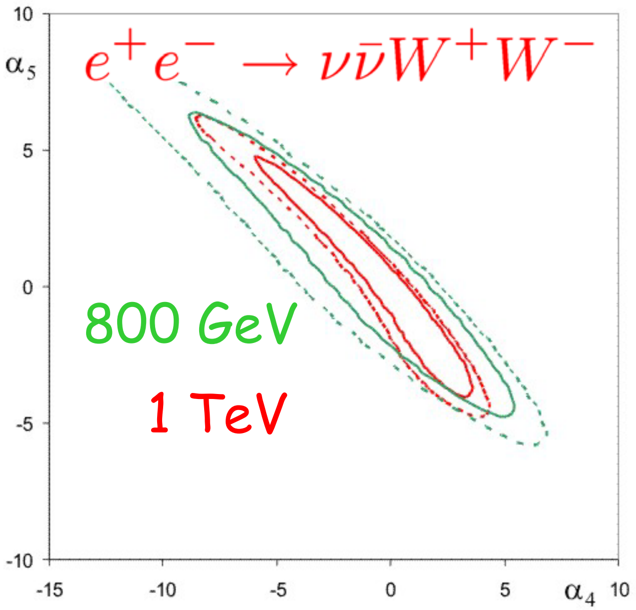


500 GeV	γe $\int L\Delta t \approx 160/230\ fb^{-1}$	$\gamma\gamma$ $\int L\Delta t \approx 1000\ fb^{-1}$	e+e- $\int L\Delta t = 500\ fb^{-1}$
ΔL	0.1%	0.1% (1%)	-
$\Delta\kappa_\gamma \cdot 10^{-4}$	10.0 / 11.0	7.0 / 5.9 (28)	3.6[1]
$\Delta\lambda_\gamma \cdot 10^{-4}$	4.9 / 6.7	4.8 / 5.6 (5.7)	11.0[1]

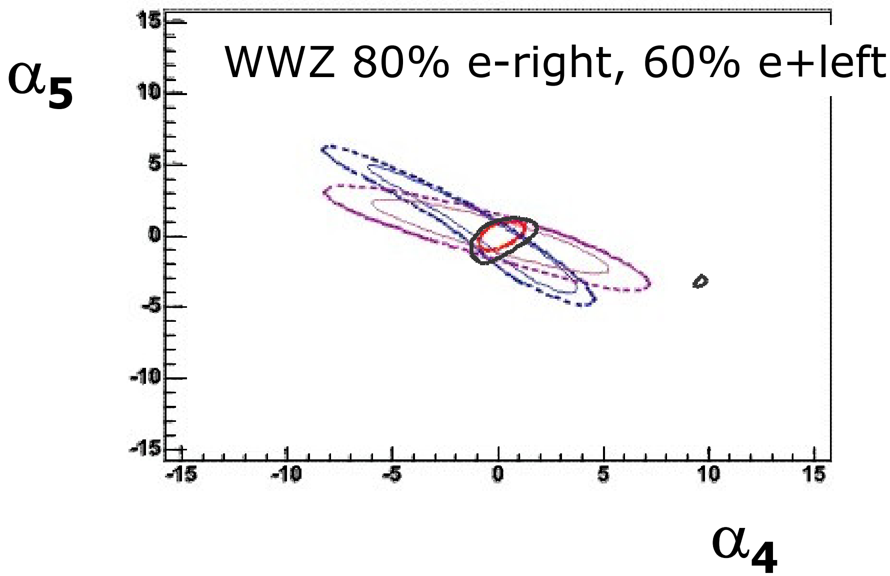
 P.Krstonosic

Can parametrize weak boson scattering as quartic couplings in effective Lagrangian:

Eg.
$$L_4 = \frac{\alpha_4}{16\pi^2} tr\left(V_\mu V_\nu\right) tr\left(V^\mu V^\nu\right)$$



$e^+e^- \rightarrow W^+ W^- Z$

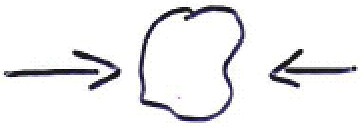


Major step towards a full and consistent set of limits done

Black Hole Production at the ILC

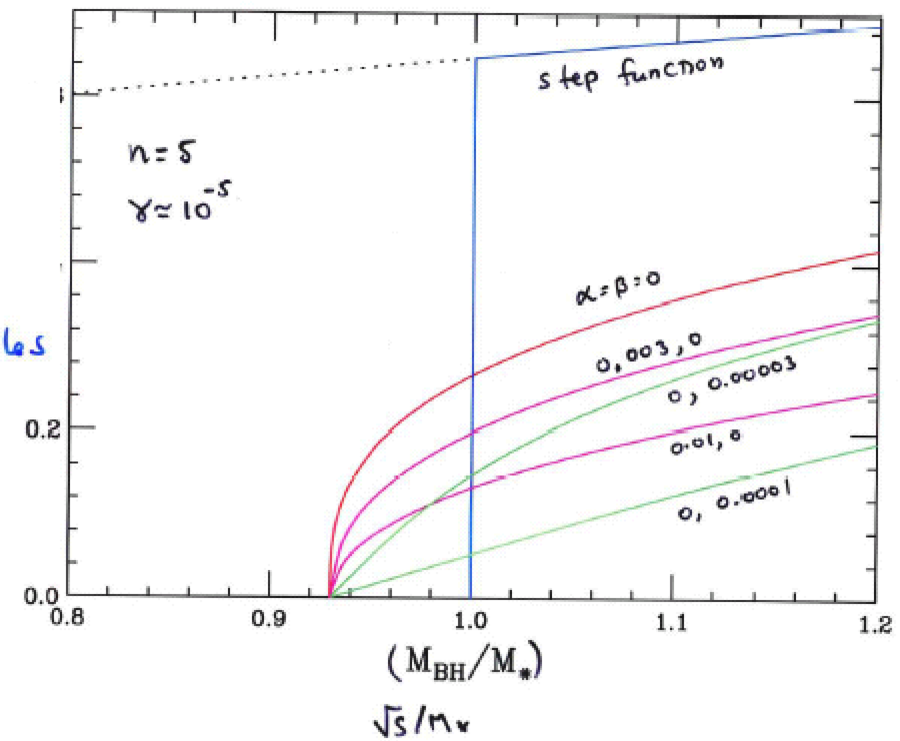
ADD: Modification of Black Hole Properties

Rizzo [hep-ph/0503…]



$$\hat{\sigma} \simeq \pi R_s^2 \, \delta(\hat{s} - M_*^2)$$

↳ decays by 'Hawking radiation' very rapidly into SM particles



Threshold shapes will tell us:

(α,β,γ)…

Conclusions

- The Linear Collider can make precision measurements

- It is needed to disentangle the underlying physics
  - If s-channel resonance discovered at LHC need ILC for precision measurements of its properties
  - If light Higgs discovered at LHC need ILC to determine the underlying theory
  - For certain new physics has higher reach than LHC
  - precision measurements at LC using input from the LHC

- Need to continue to work on LHC physics to strengthen the argument that the ILC is needed

March 22, 20??

The Director of the ILCL issues a press release:

"This result will send theorists back to their drawing boards"*

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