Electron Collider Physics

Symposium on Lepton Colliders

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Lepton Collider

- The case for a lepton collider will be built at the CERN LHC
  - Starting at 7 TeV, continuing at 14 TeV …
- We will soon know what that case might be
  - Hallelujah!
    - The long wait is over …
  - It's exciting – and frightening – to finally have the tools we need!

Electron Collider

- High-energy electron colliders are linear. Why?
- Circular machines suffer synchrotron radiation
  - Power loss: $$\frac{dP}{dt} \propto \frac{E^4}{m^4 R^2}$$
  - Electrons are much lighter than protons (and muons), so synchrotron radiation is a real show stopper for circular machines at high energies
  - Three times the energy ⇨ nine times the radius!

Linear Collider

- What are the advantages of a linear collider?
- A linear collider annihilates electrons and positrons at *well-defined* CM energies
- It allows a clean look at the underlying physics
  - LHC: Broadband initial state
  - LC: Precise, well-controlled initial state
- History shows that both have their place
  - Both are discovery machines …

ILC vs CLIC

- At present, there are two options:
  - ILC (International Linear Collider)
    - 1.3 GHz superconducting RF
    - 500 GeV – 1 TeV in the CM
  - CLIC (Compact Linear Collider)
    - 12 GHz warm copper RF, powered by drive beam
    - 500 GeV – 1 TeV – 3 TeV (?) in the CM
- Many common subsystems, with the ultimate energy limited by cost and wall plug power …

ILC vs CLIC

- The ILC will be ready to propose in 2013
  - The GDE produced an RDR in 2008, and is preparing a TDR for late 2012
- CLIC will be ready at some point in the future
  - The CLIC Collaboration is preparing a CDR for late 2011, and is aiming for a TDR later in the decade, perhaps 2016
- The physics case is the same!

ILC vs CLIC

- The eventual decision will be made on grounds of technical maturity, cost, and upgrade potential
  - Informed by LHC physics
- In this talk I'll focus on physics
  - I will only discuss first-stage linear colliders …
  - With CM energies below 1 TeV
- That is all we can expect in the foreseeable future …

CLIC Parameters

Center-of-mass energy	CLIC 500 GeV		CLIC 3 TeV	
Beam parameters	Relaxed	Nominal	Relaxed	Nominal
Accelerating structure	502		G	
Total (Peak 1%) luminosity	$8.8(5.8)\cdot10^{33}$	$2.3(1.4)\cdot10^{3}$	$7.3(3.5)\cdot10^{33}$	$5.9(2.0)\cdot10^{34}$
Repetition rate (Hz)	50			
Loaded accel. gradient MV/m	80		100	
Main linac RF frequency GHz	12			
Bunch charge10^{9}	6.8		3.72	
Bunch separation (ns)	0.5			
Beam pulse duration (ns)	177		156	
Beam power/beam MWatts	4.9		14	
Hor./vert. norm. emitt($10^{-6}/10^{-9}$)	7.5/40	4.8/25	7.5/40	0.66/20
Hor/Vert FF focusing (mm)	4/0.4	4 / 0.1	4/0.4	4 / 0.1
Hor./vert. IP beam size (nm)	248 / 5.7	202 / 2.3	101/3.3	40 / 1
Hadronic events/crossing at IP	0.07	0.19	0.28	2.7
Coherent pairs at IP	10	100	$2.5\ 10^{7}$	$3.8\ 10^{8}$
BDS length (km)	1.87		2.75	
Total site length km	13.0		48.3	
Wall plug to beam transfert eff	7.5%		6.8%	
Total power consumption MW	~~129.4~~ 241		~~415~~ 568	

Linear Collider

- ILC requirements
  - Physics between 200 and 500 GeV
  - Calibration at 91 GeV
  - Luminosity of 500 fb^{-1} in four years
  - Electron polarization > 80%
  - Stable at the 0.1% level
- The requirements are physics driven, so they should apply to CLIC as well

Linear Collider

- ILC options
  - Upgradeable for physics up to 1 TeV
  - Positron polarization > 50%
  - GigaZ
  - e^-e^-
  - $e^-\gamma$ and $\gamma\gamma$
- And likewise for CLIC ...

Physics Case

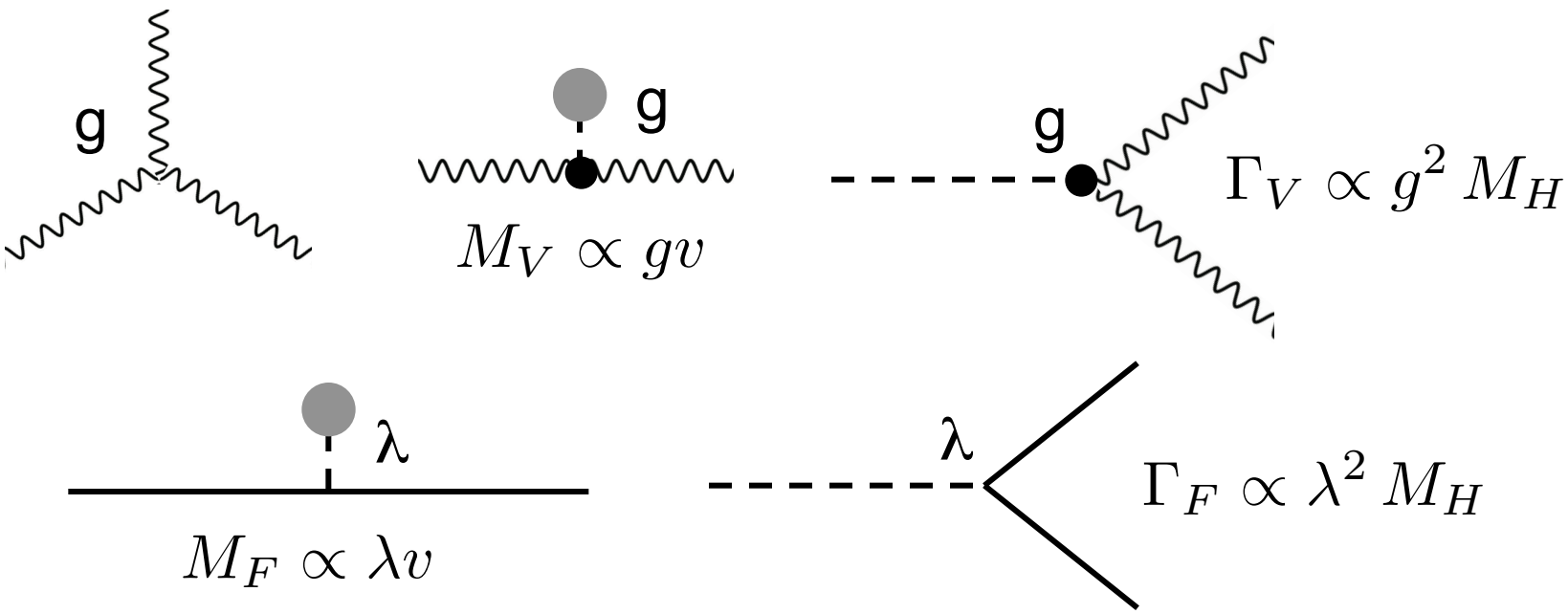
- As of now, the physics case for a 500 GeV linear collider rests primarily on the Higgs
  - There may be other new physics in range, especially electroweak physics
  - But we are unlikely to know for sure based on results from the 7 TeV LHC
- We need to argue based on what we know we will accomplish
  - Discoveries beyond that are an added bonus

Higgs Boson

- But that's OK: The Higgs is different!
  - It's a fundamental spin-zero boson that fills the vacuum
    - Bose-Einstein condensate…
    - Which implies that space itself is a superconductor!
- It is a radically new kind of particle
  - Not seen since the earliest moments of the Universe!

Higgs Boson

- To be *the* Higgs, a Higgs must obey some very special relations …



Masses and decay rates are related!

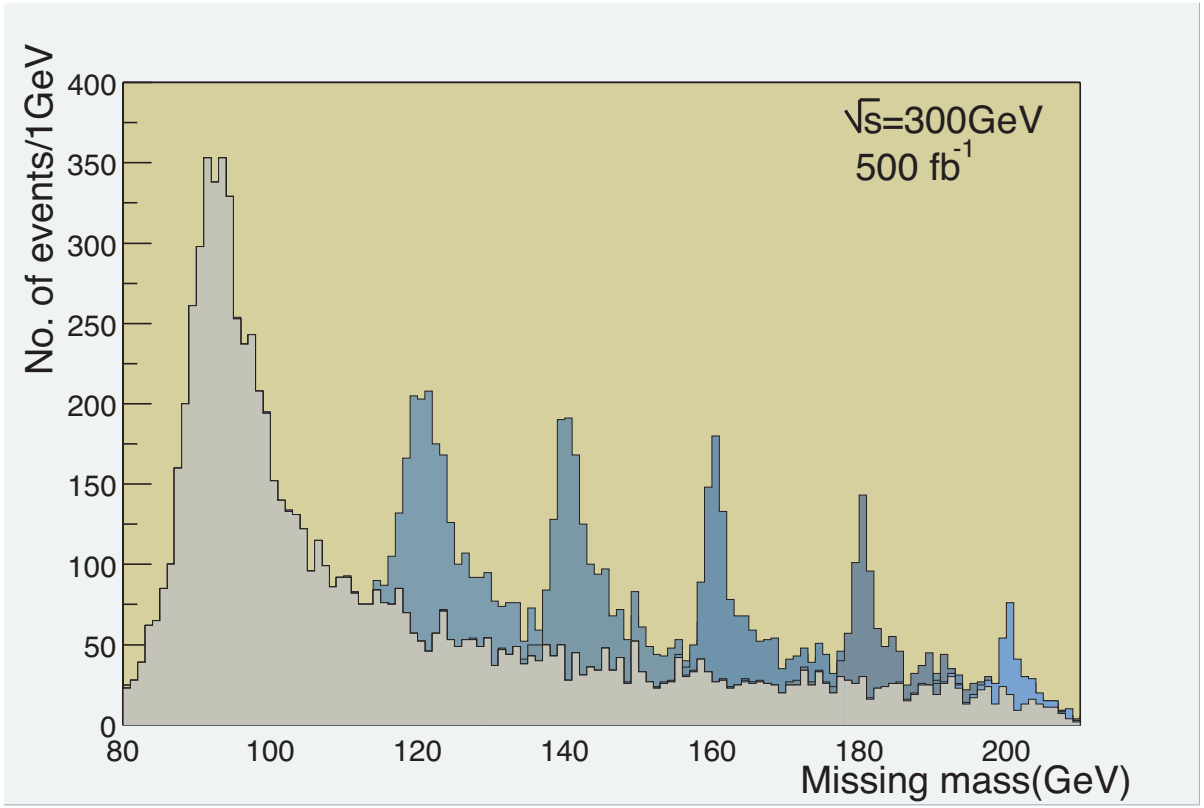
Higgs Boson

- Great claims demand great evidence …
  - To separate fact from fiction. That's the basis of science!
- Therefore, given a candidate Higgs, we need to determine its properties – to figure out what it is – and to see how it works
  - Is a Higgs is *the* Higgs, or is it an imposter?
  - To answer the question, we need to measure
    - Its mass, spin, couplings …

Higgs Boson

- At a linear collider, the Higgs can't hide!

$e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^- X$

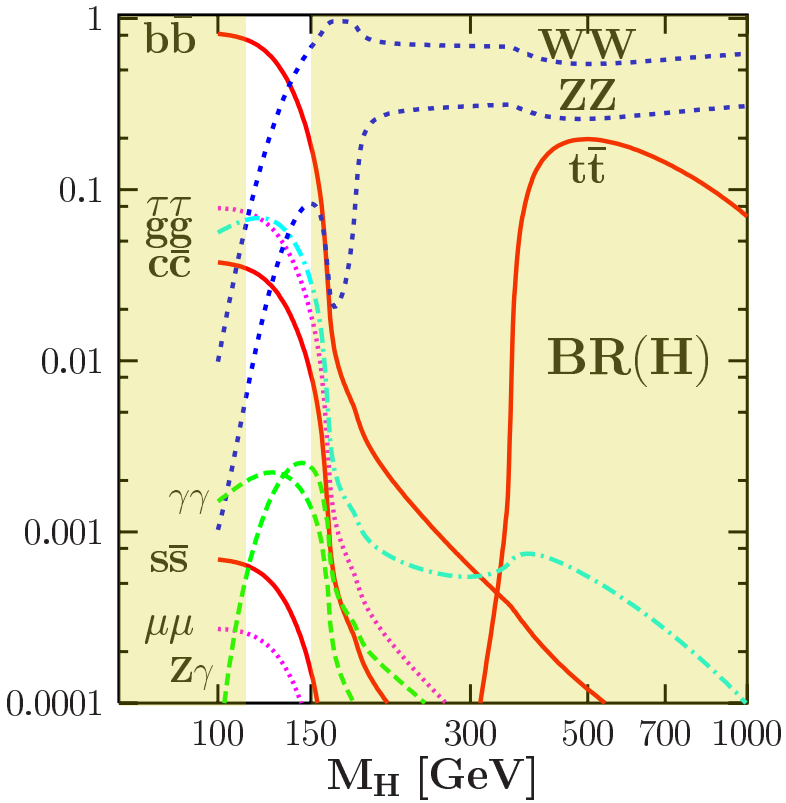


From Z recoil!

Higgs Boson

- Higgs decays depend on the Higgs mass

  Allowed region: $115 < M_H < 150$ GeV



Higgs Boson

- Measure Higgs mass

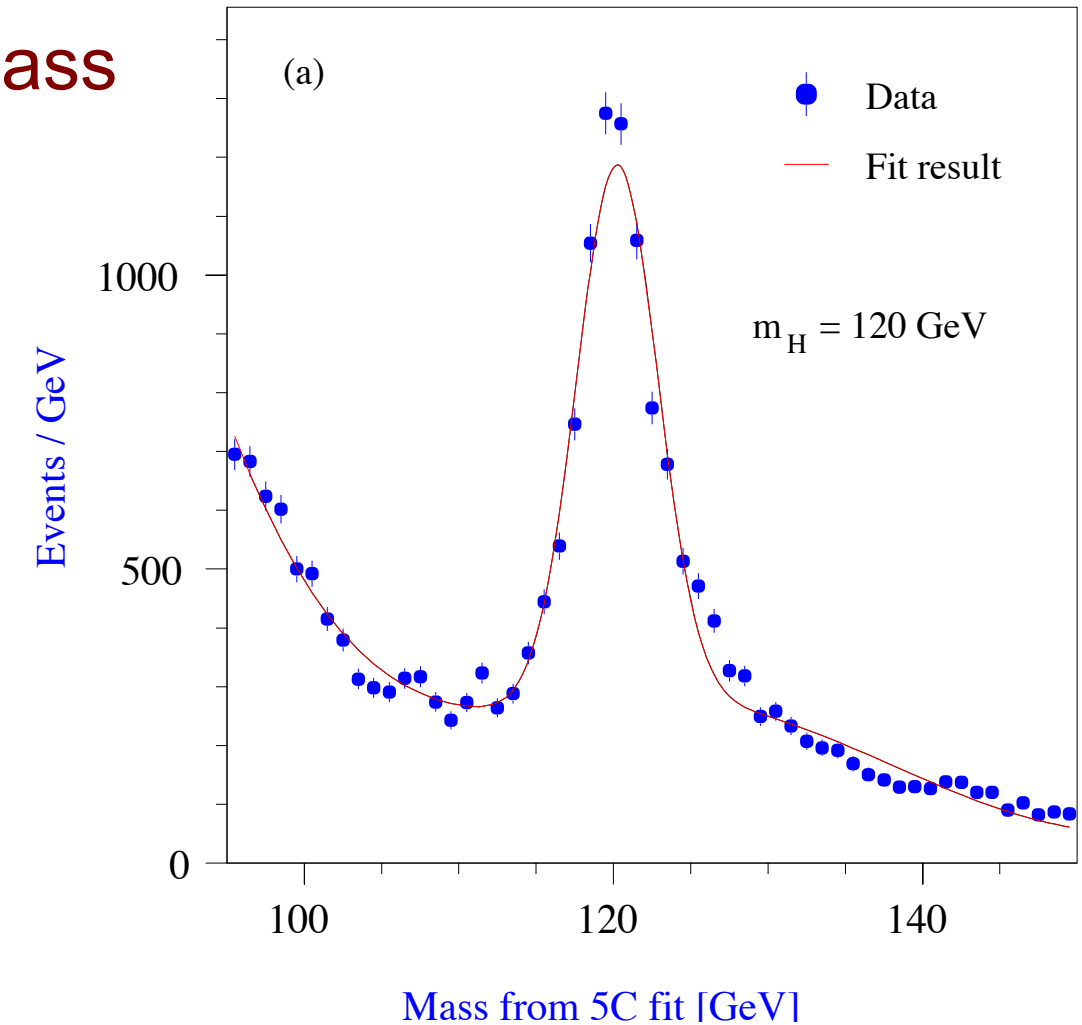
  $\Delta M_H \approx \pm 40$ MeV

  This plot:

  $e^+e^- \rightarrow b\bar{b}q\bar{q}$

  $\sqrt{s} = 350$ GeV

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



Higgs Boson

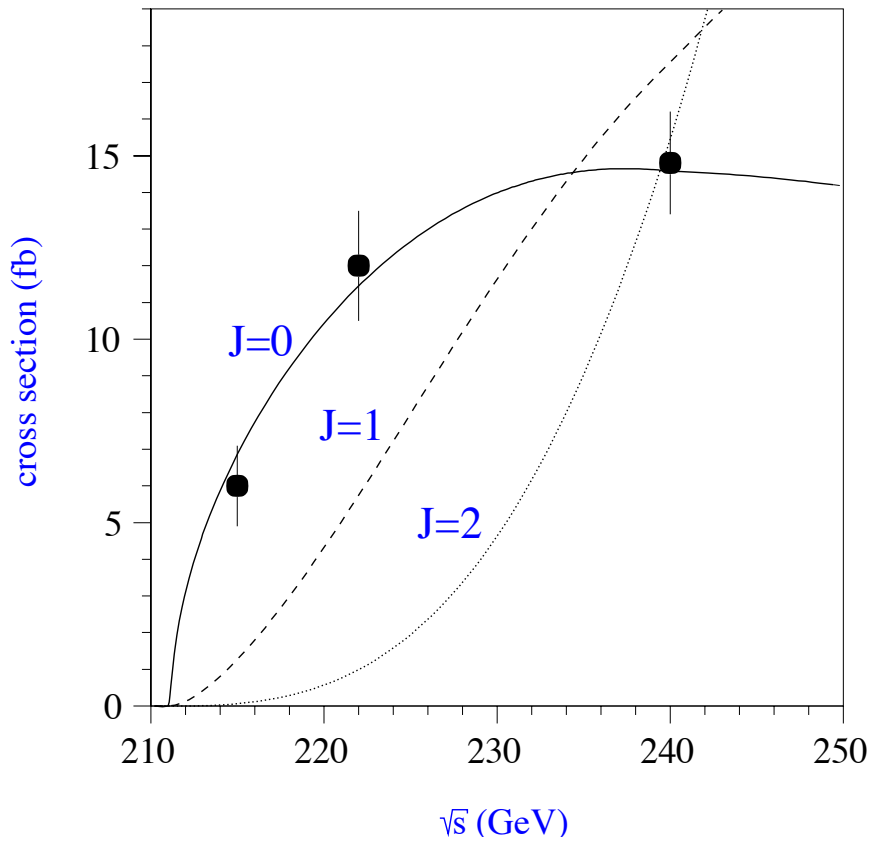
- Determine Higgs spin

  Threshold energy scan

  Spin 0!

  This plot:

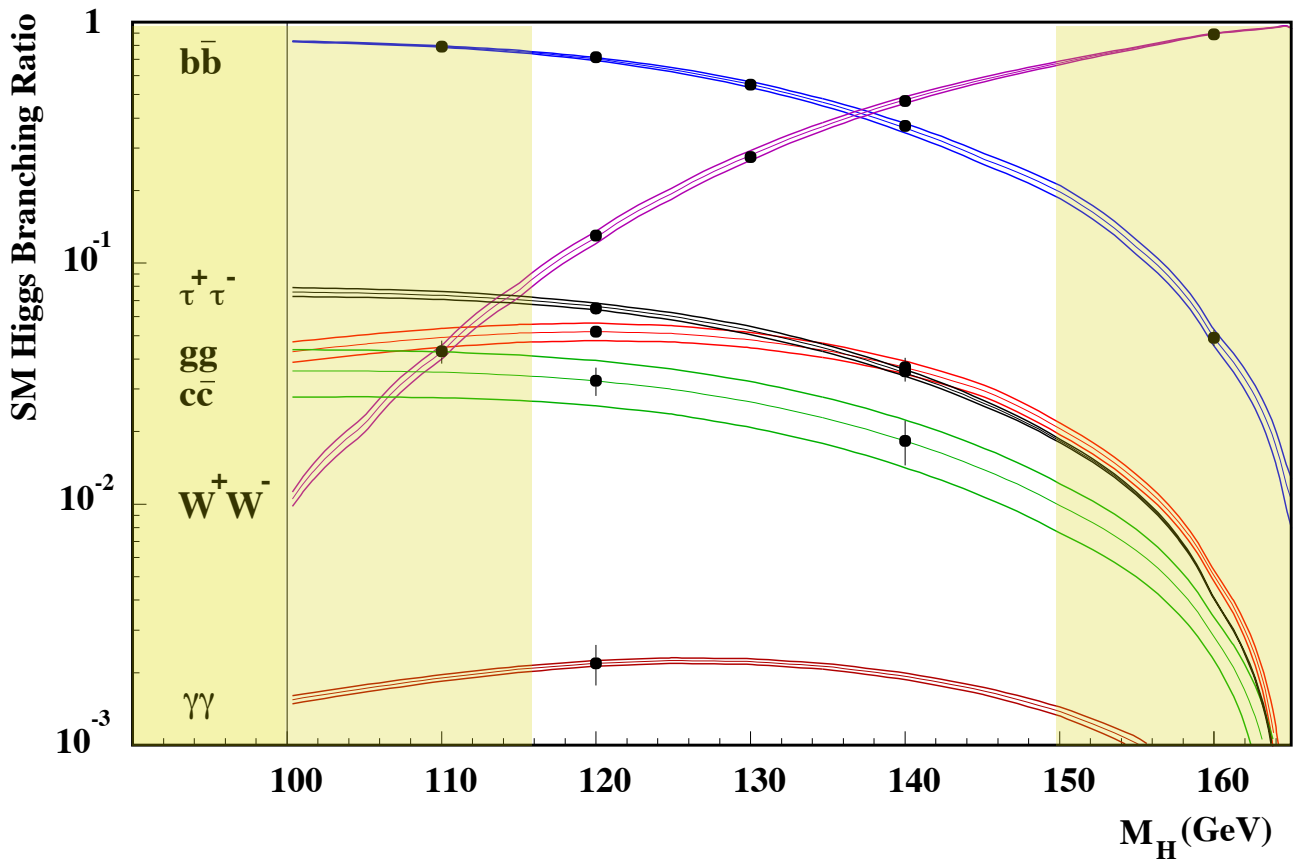
  L = 20 fb^{-1} per point



Higgs Boson

- Measure Higgs branching ratios

This plot: $\sqrt{s}$ = 350 GeV, L = 500 fb^{-1}



Higgs Boson

- Determine Higgs couplings

  g_{HWW} and g_{HZZ}

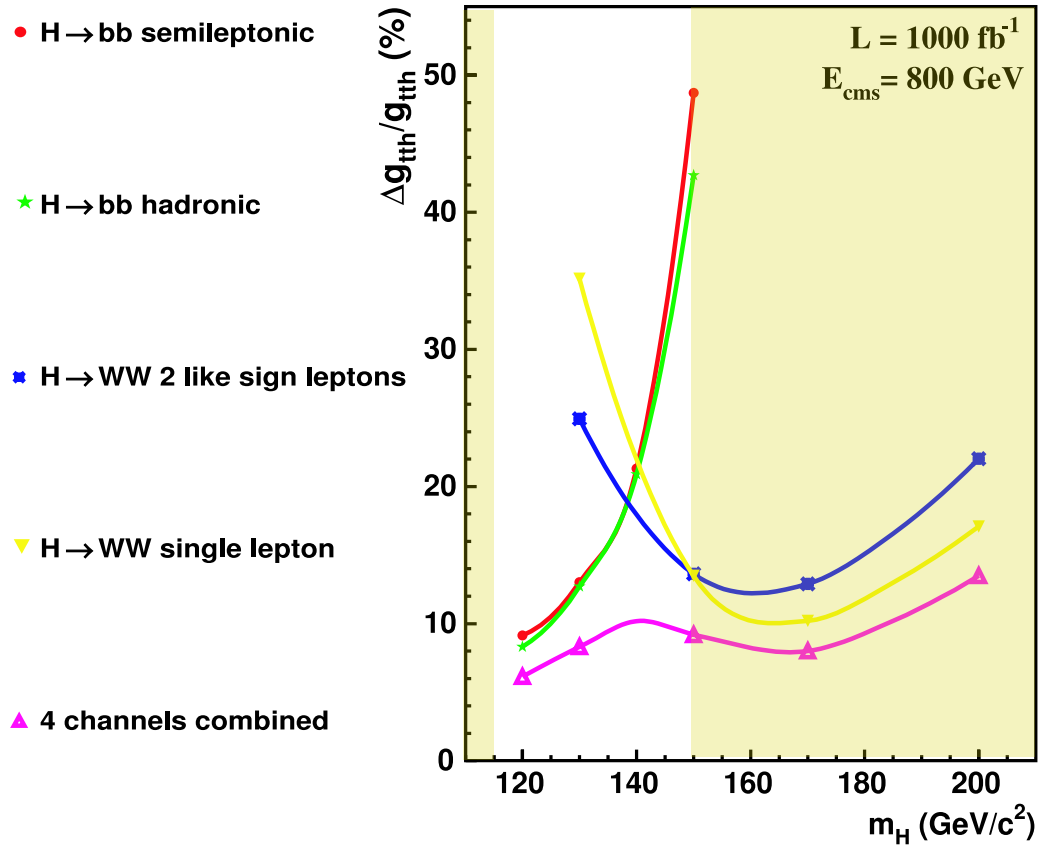
  to 1 – 2 %

  Sensitive test!

  Tops too:

  $\lambda_{Ht\bar{t}}$

  to < 10%



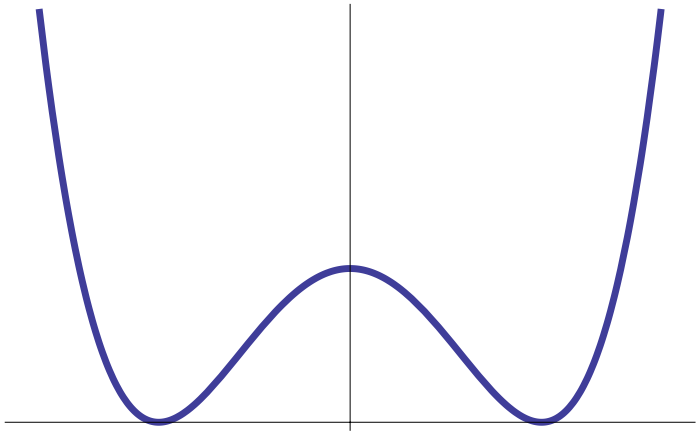
Higgs Boson

- Measure Higgs trilinear self-coupling

λ_{HHH}

to 12%

for M_H = 120 GeV, $\sqrt{s}$ = 1000 GeV, L = 1000 fb^{-1}



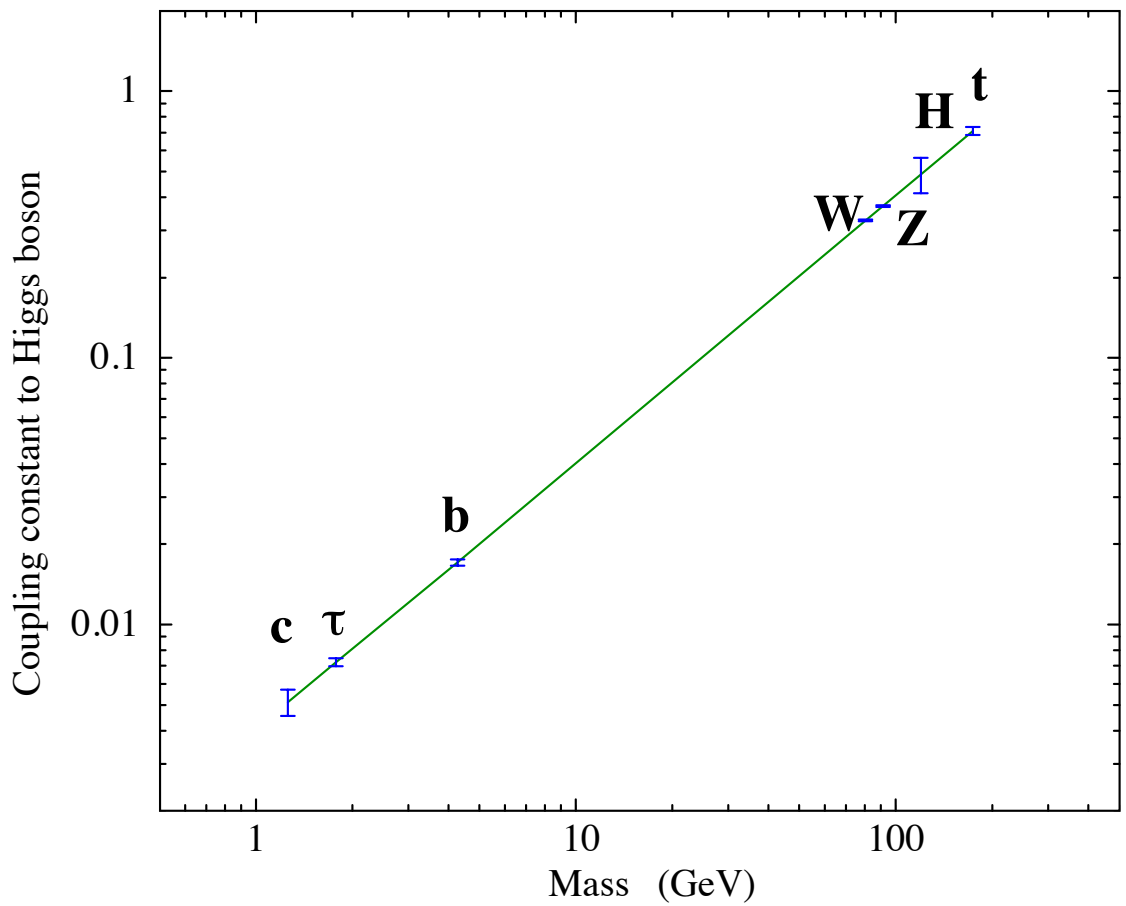
Test of Higgs potential

$\lambda_{HHH} = \sqrt{2}\, M_H$

$$V(H) = \frac{1}{2} M_H^2 H^2 + \sqrt{2}\, M_H H^3 + \cdots$$

Higgs Boson

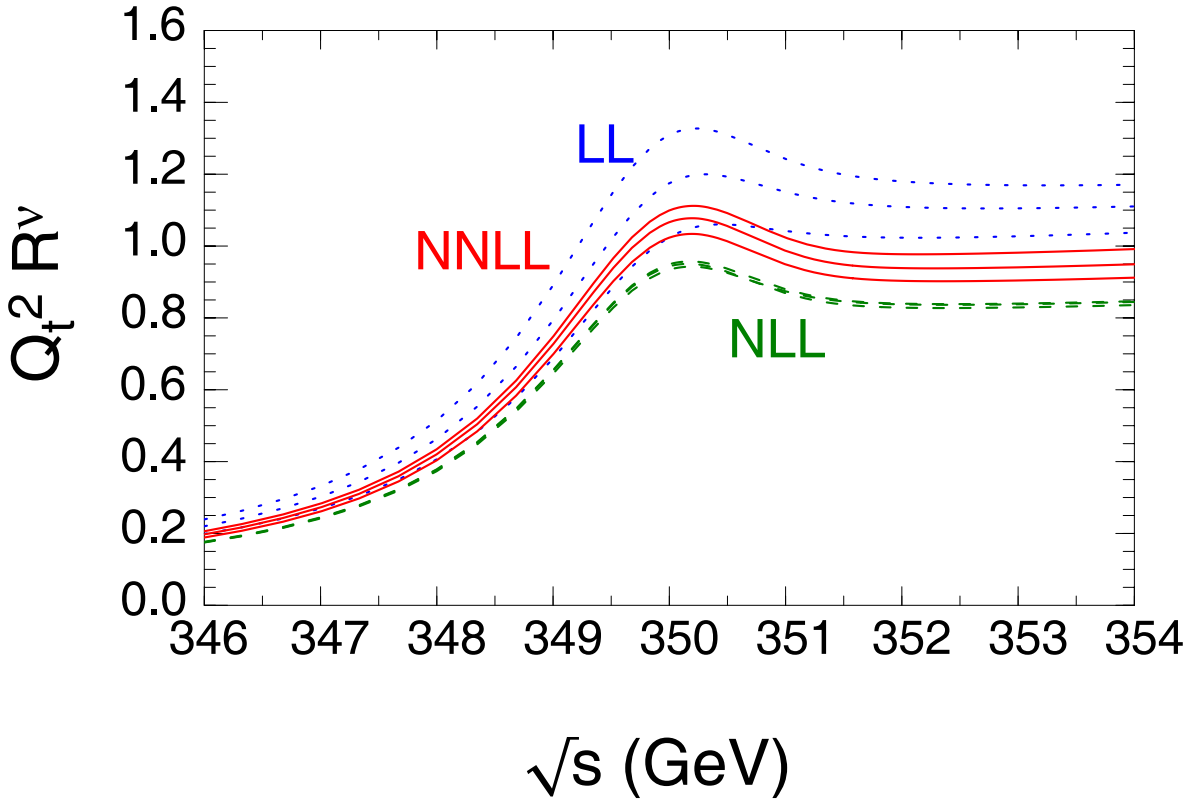
- Is a Higgs *the* Higgs? The ultimate test …



This plot is even more interesting if the Higgs is not “standard”

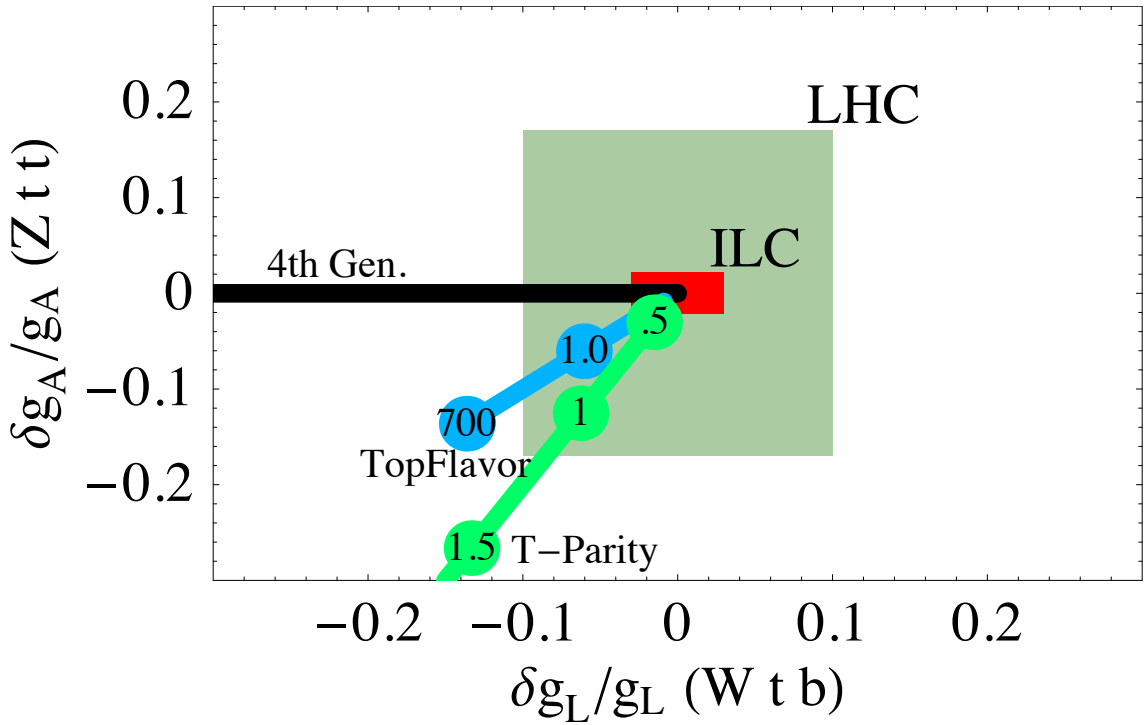
Top Quark

- A threshold scan can determine the top quark mass to 100 – 200 MeV



Top Quark

- Top quark couplings are an excellent place to search for new physics



New Force

- The LC can search for Z' bosons up to very high energies

This plot:

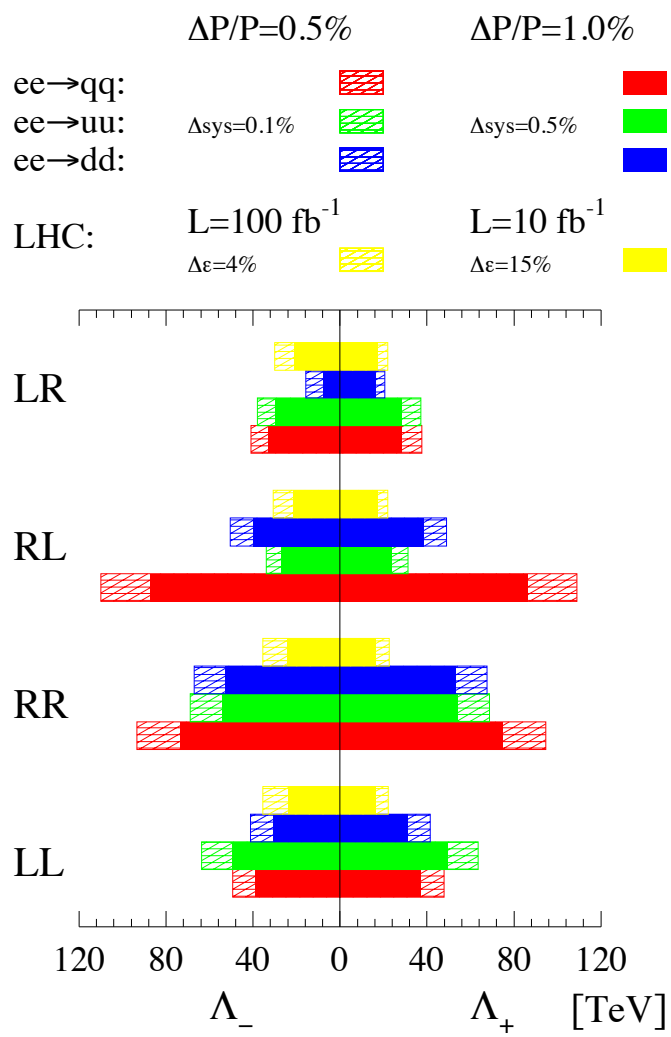
$e^+e^- \rightarrow$ hadrons

$\sqrt{s}$ = 500 GeV

L = 1000 fb^{-1}

$P(e^-) = 0.8$

$P(e^+) = 0.6$



New Force

- The LC can search for Z' bosons up to very high energies

This plot:

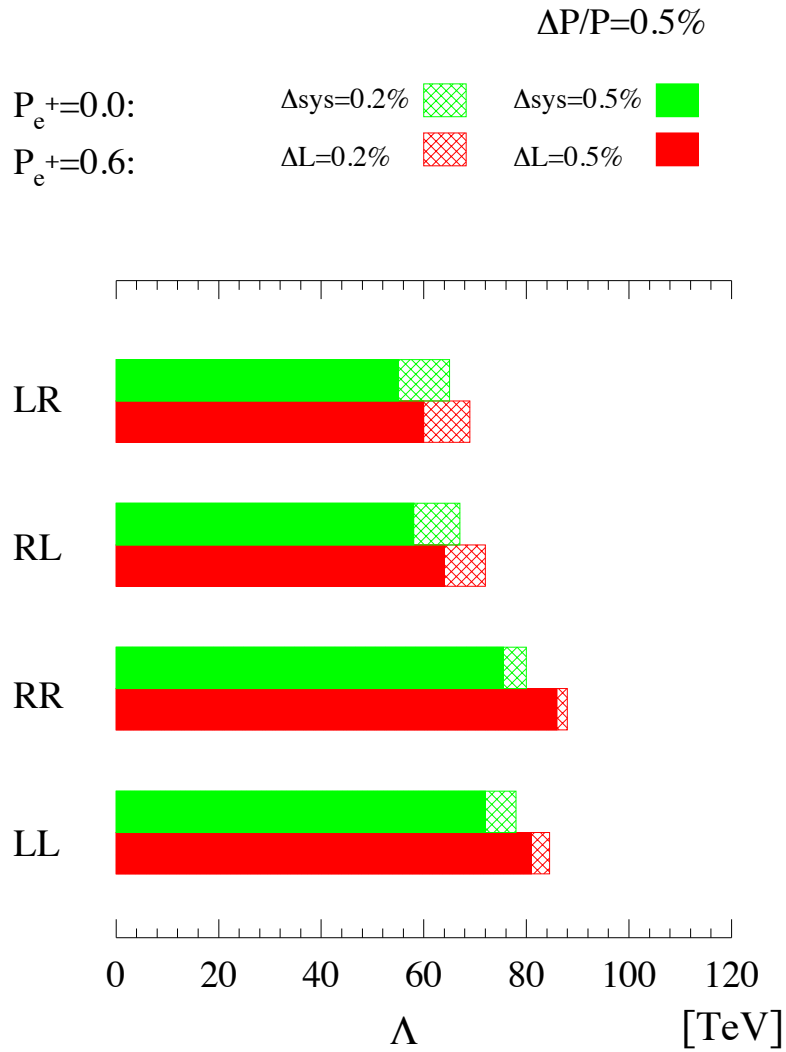
$e^+e^- \rightarrow \mu^+\mu^-$

$\sqrt{s}$ = 500 GeV

L = 1000 fb^{-1}

$P(e^-) = 0.8$

$P(e^+) = 0.0, 0.6$



New Force

- The LC can distinguish one Z' from another …

This plot:

3 TeV Z'

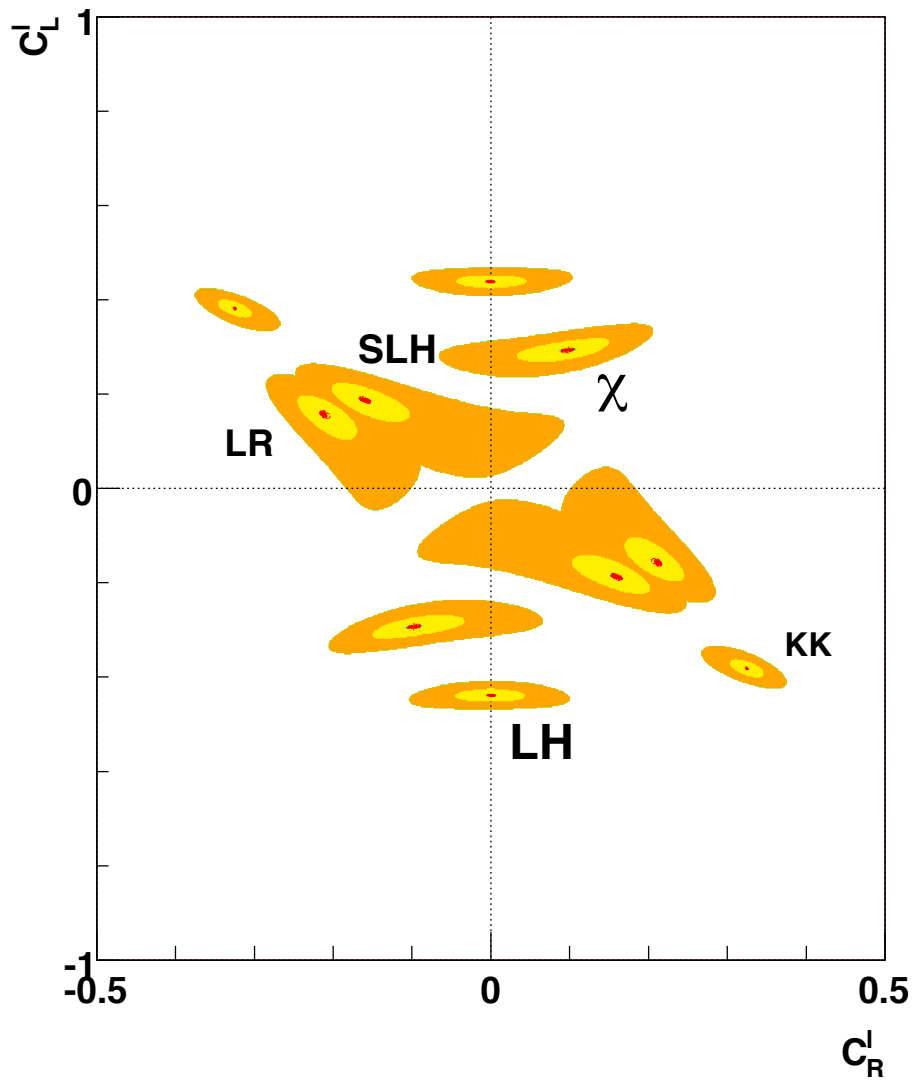
$e^+e^- \rightarrow$ fermions

$\sqrt{s}$ = 500 GeV

L = 1000 fb^{-1}

$P(e^-) = 0.8$

$P(e^+) = 0.6$



Other Possibilities

- Of course, the story continues. The linear collider is versatile. So no matter what the new physics, it has a role to play – if the physics is within its reach …
  - Supersymmetry: charginos, neutralinos, sleptons
  - Extra dimensions: KK gravitons, photons, leptons
  - Little Higgs: New tops, Higgs particles, gauge bosons
  - Dark Matter: WIMPS …

Conclusions

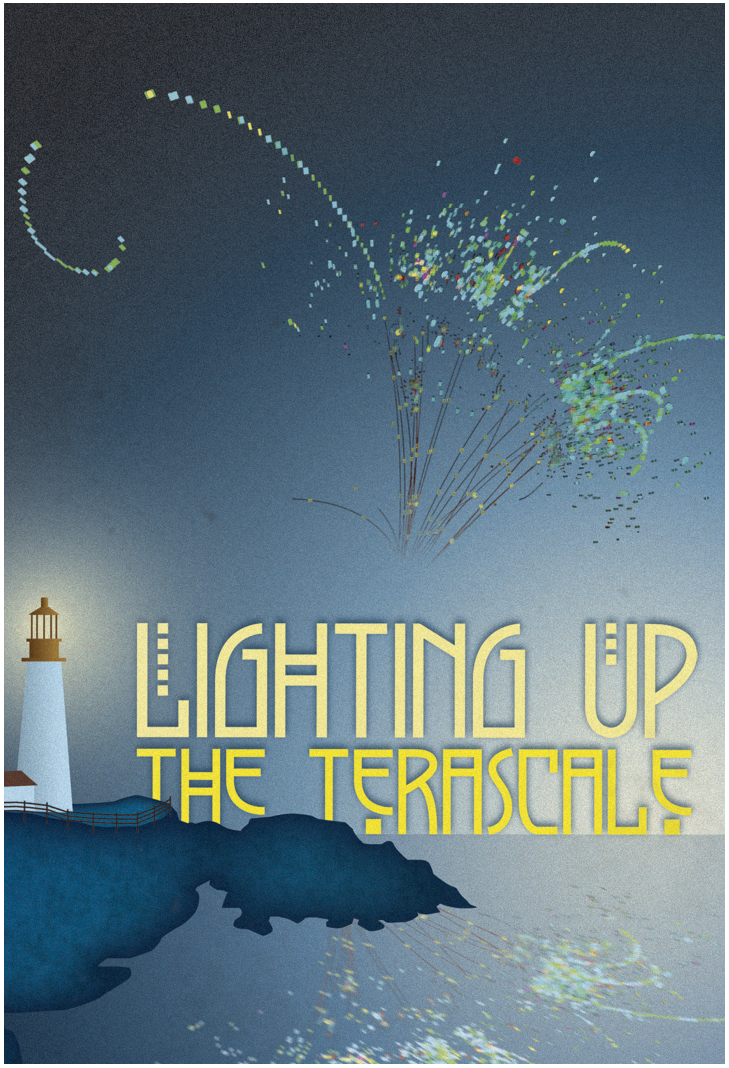
- With its polarized beams, adjustable energy, and clean collisions, the LC is well-suited to probing the Higgs – and to disentangling any other new physics that the LHC finds
- The catch is that the LC's reach is limited to CM energies less than of order 1 TeV
  - We might or might not be lucky …
- But we cannot count on luck
  - We must base the physics case on what we know

Conclusions

- Fortunately, the Higgs provides an excellent place to start
  - With it, we can do pathbreaking physics while we aggressively pursue higher energies – by developing a higher gradient linear collider, a muon collider, or other advanced accelerator techniques
- But first, we must find the Higgs – or whatever takes its place!

Information

- For more information, visit
  - www.interactions.org/ quantumuniverse
  - www.linearcollider.org
  - clic-study.org



All unattributed plots are taken from the ILC RDR, available at interactions.org