

# *Physics with 500 GeV LC*



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LC Retreat

Santa Cruz, June 27, 2002

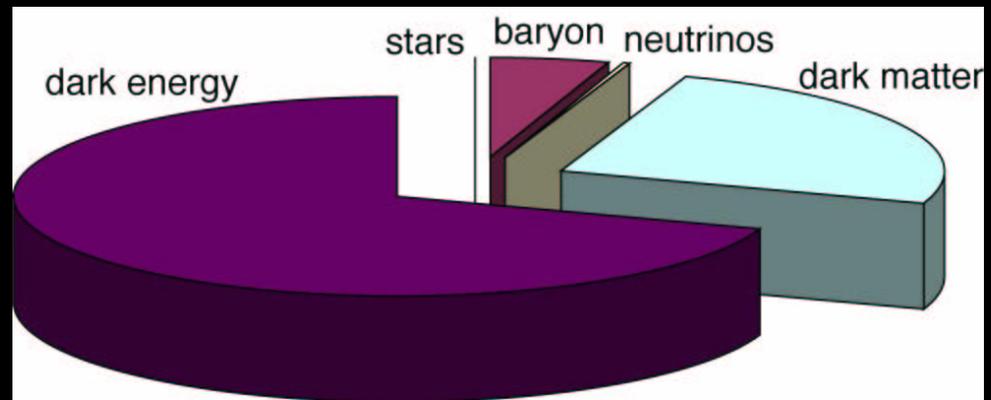
*We are interested in  
things we don't see*



# *Energy budget of Universe*



- Stars and galaxies are only 0.1%
- Neutrinos are ~0.1–10%
- Rest of ordinary matter (electrons and protons) are ~5%
- Dark Matter ~25%
- Dark Energy ~70%
- Anti-Matter 0%
- Higgs boson  $\sim 10^{62}\%$ ??



# *The Cosmic Questions*



- What is Dark Matter?
- What is Dark Energy?
- How much is Neutrino component?
- Is Higgs Boson really there?
- Where did Anti-Matter go?

# Synergy at TeV scale

- Dark Matter

$$\Omega_M = \frac{0.756(n+1)x_f^{n+1}}{g^{1/2}\sigma_{ann}M_{Pl}^3} \frac{3s_0}{8\pi H_0^2} \approx \frac{\alpha^2 / (TeV)^2}{\sigma_{ann}}$$

- Fermi (Higgs) scale

$$v \sim 250 \text{ GeV}$$

- Dark Energy

$$\rho_\Lambda \sim (2 \text{ meV})^4 \text{ vs } (TeV)^2 / M_{Pl} \sim 0.5 \text{ meV}$$

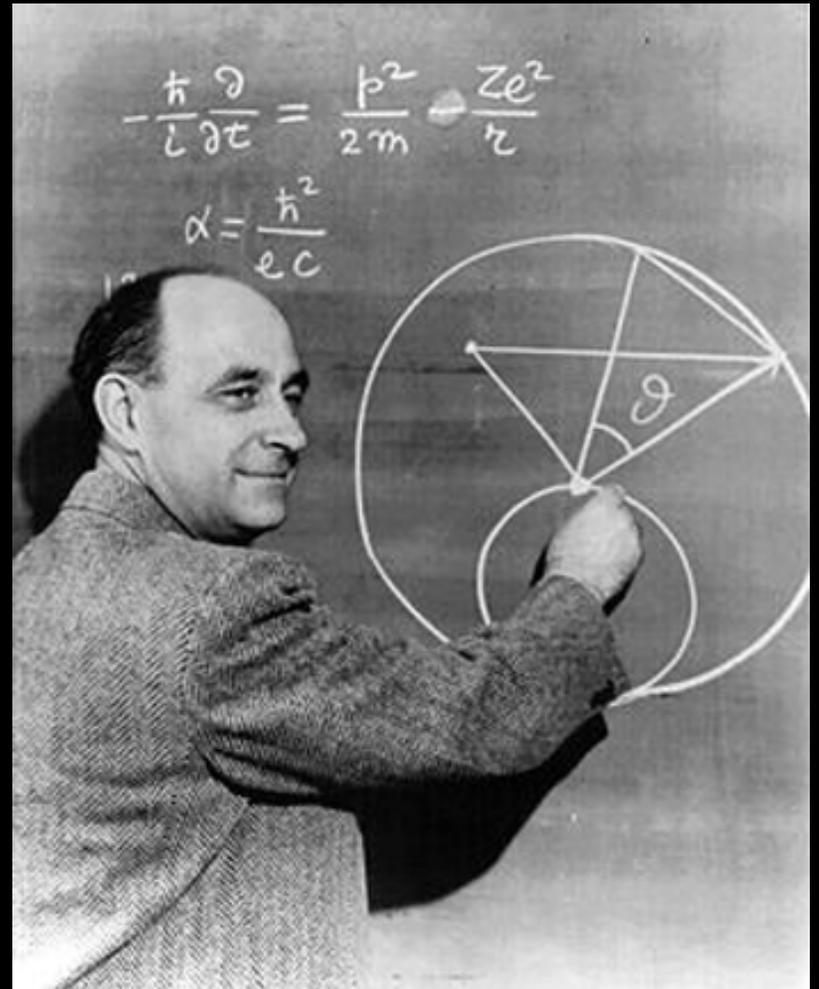
- Neutrino

- $(\Delta m_{LMA}^2)^{1/2} \sim 7 \text{ meV vs } (TeV)^2 / M_{Pl} \sim 0.5 \text{ meV}$

- *TeV-scale physics likely to be rich*

# *Fermi's dream era*

- Fermi formulated the first theory of weak force (1933)
- Knew the required energy to study the problem:  $\sim \text{TeV}$
- **We are finally getting there!**

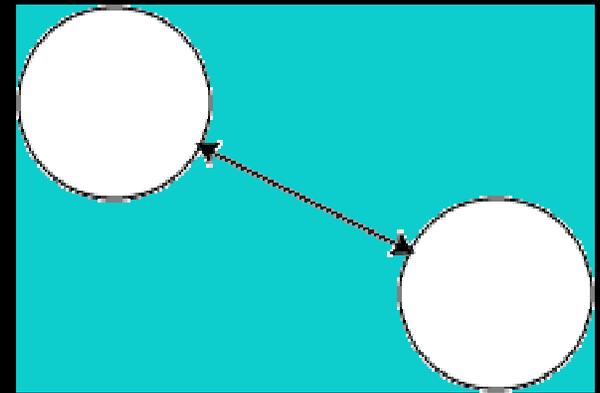


# *Higgs Boson*

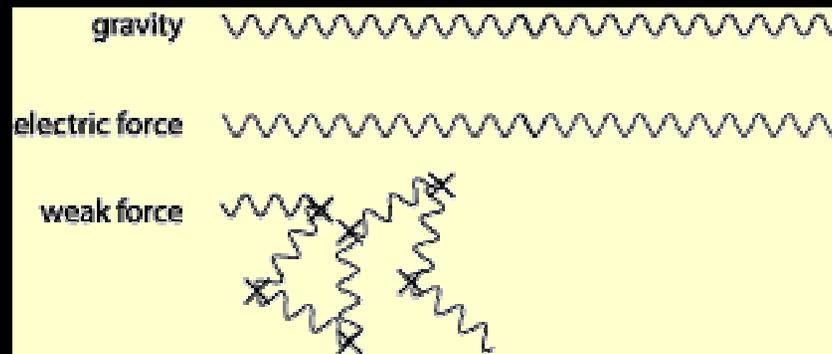


# *Mystery of the “weak force”*

- **Gravity** pulls two massive bodies (*long-ranged*)
- **Electric force** repels two like charges (*long-ranged*)
- **“Weak force”** pulls protons and electrons (*short-ranged*) acts only over  $10^{-16}$  cm [need it for the Sun to burn!]



# *Something is in the Universe*



- There is something filling our Universe
- It doesn't disturb gravity or electric force
- It does disturb weak force and make it short-ranged
- What is it??

# *Like a superconductor*



- In a superconductor, magnetic field gets repelled (Meißner effect), but penetrates only over “penetration length”
  - ⇒ Magnetic field is short-ranged!

## Imagine a physicist living in a superconductor

- Finally figured:
  - magnetic field must be long-ranged
  - there must be mysterious charge-two condensate in his “Universe”
  - But doesn’t know what the condensate is, nor why it condenses
  - Doesn’t have enough energy to break up Cooper pairs

That’s the stage where we are!

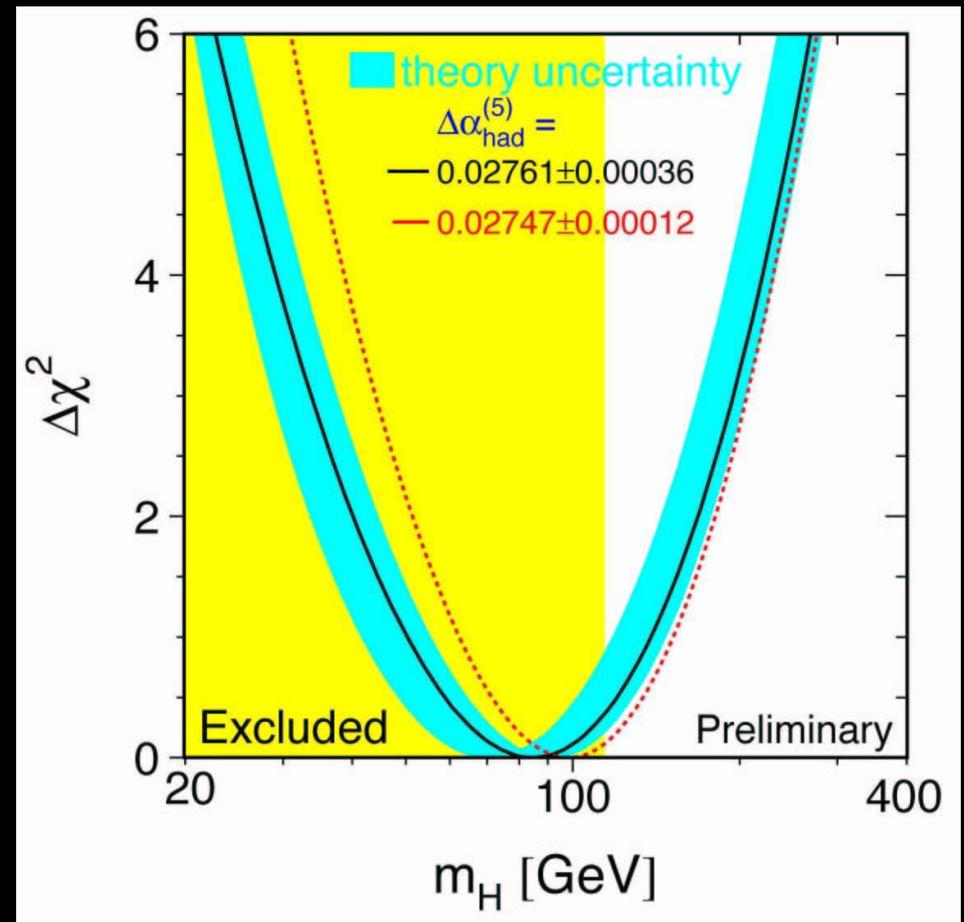
# Higgs Boson is Most Likely “Just Around the Corner”

- All current data combined, sensitive to quantum effects of the Higgs boson

$$m_H < 196 \text{ GeV (95\% CL)}$$

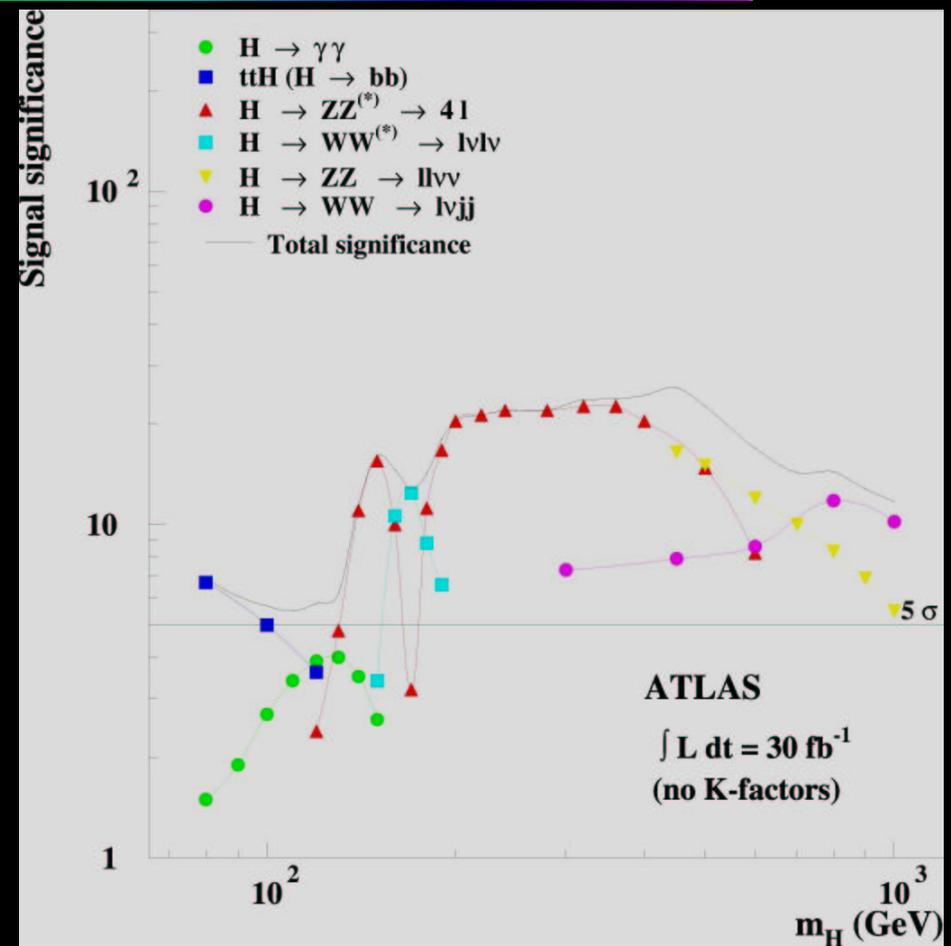
(LEPEWWG Winter 2002)

- Tevatron at Fermilab, IL, has chance to discover Higgs boson by 2008



# Higgs Boson at LHC

- LHC would discover Standard Model Higgs boson of any mass within 3 years! (2011?)
- Does it settle the issue? *I'm afraid not.*
- Suppose  $H \rightarrow \gamma\gamma$  discovered, cross checked by  $ttH$  final state
- Technipion? Scalar or pseudo-scalar? Does it couple to  $W/Z$ ?



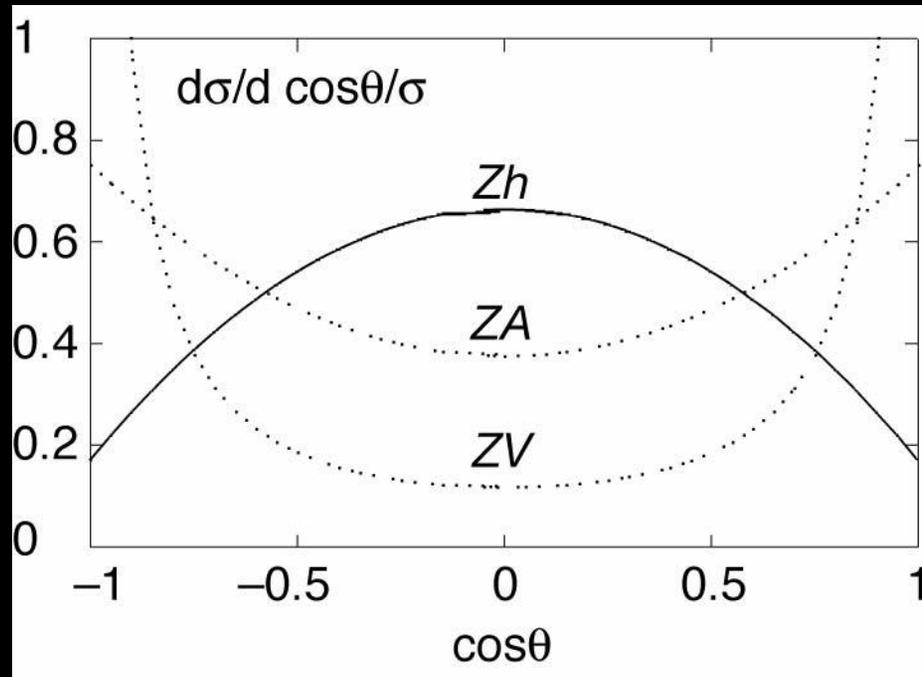
# Questions to be answered



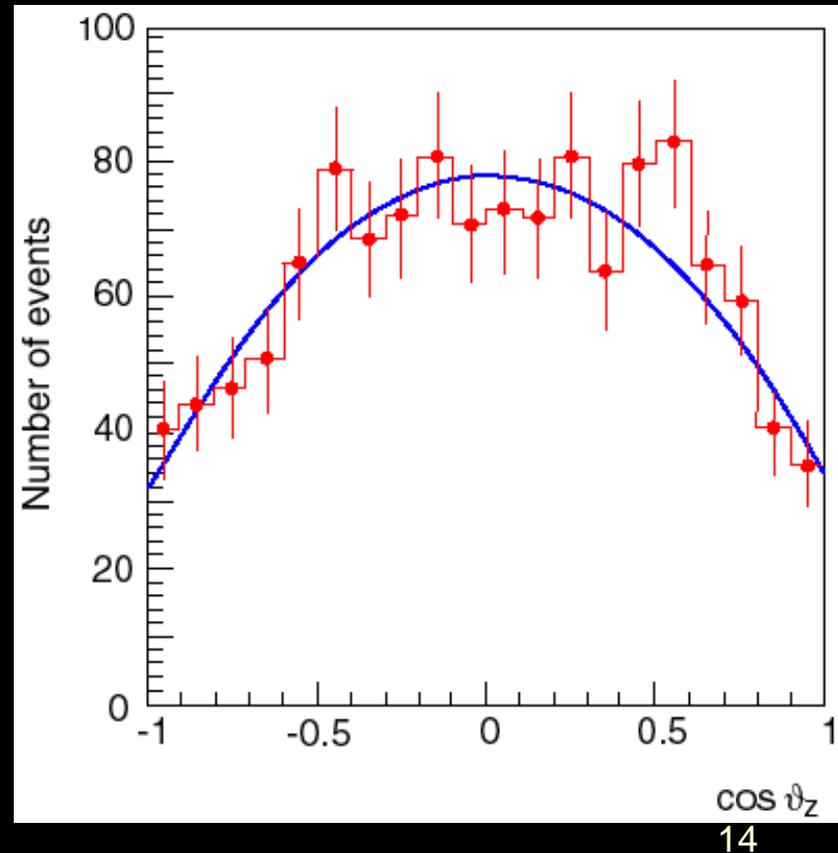
- Is the particle discovered really *the* Higgs boson?
  - Is it really responsible for particle masses?
  - Does this have the right quantum number  $0^+$ ?
  - Is it condensed in the Universe?
- Prove it is *the* “Origin of Mass”
  - Spin/Parity
  - Couplings
  - *Vacuum expectation value*
  - Branching Ratios

# Higgs Boson at LC

- Angular distribution in  $e^+e^- \rightarrow ZX$  depends on  $X=h, A, V$

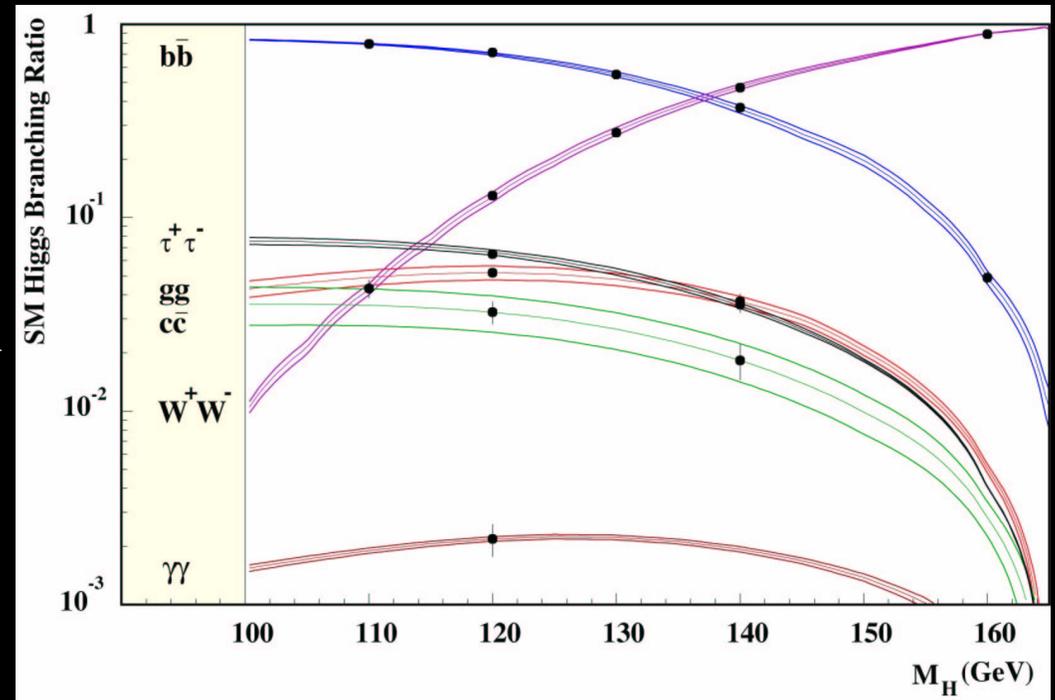


*Is it a  $0^+$  boson?*



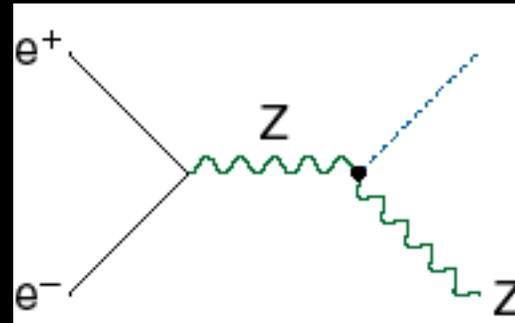
# Higgs Boson at LC

- Branching Fractions test the relation  $\text{coupling} \propto \text{mass}$   
 $\Rightarrow$  proves that Higgs Boson is the “Origin of Mass” (Battaglia)



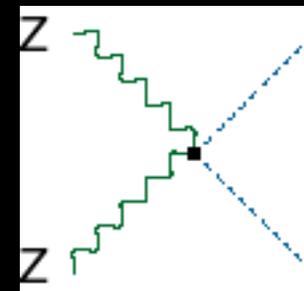
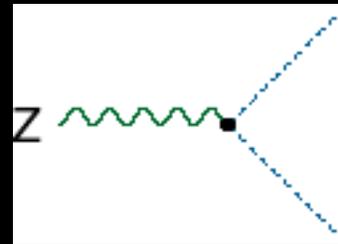
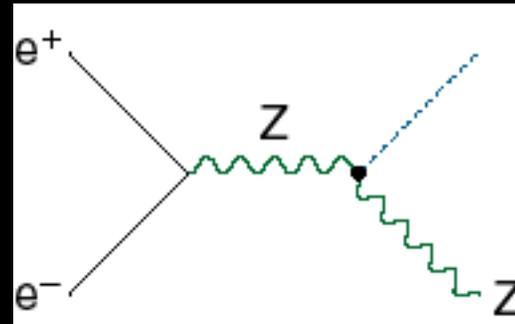
# Higgs Boson at LC

- $ZH$  final state
- $A_{LR}$  proves it is due to  $s$ -channel  $Z$ -exchange



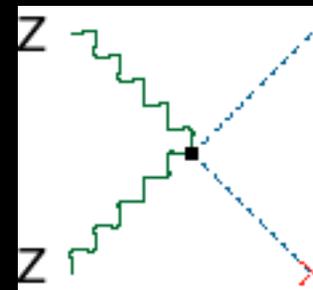
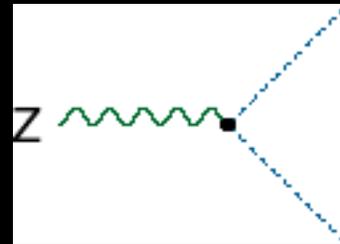
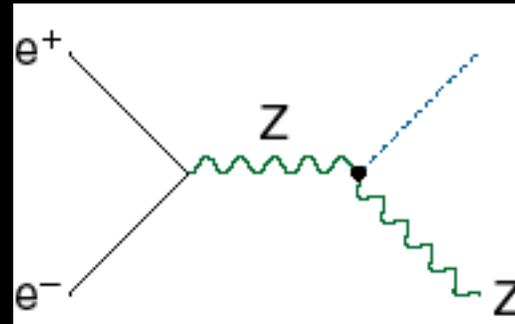
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- We know  $Z$ : gauge boson,  $H$ : scalar boson  
 $\Rightarrow$  only two vertices



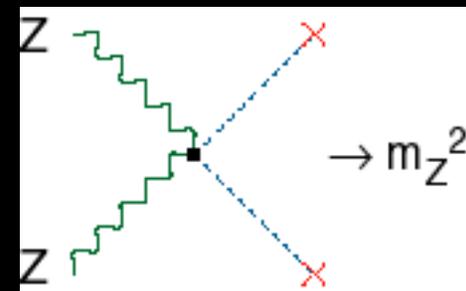
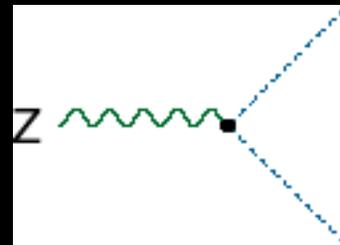
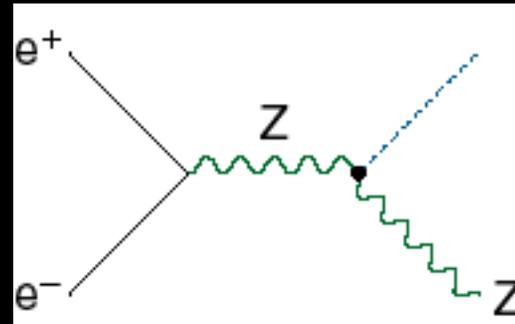
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# Higgs Boson at LC

- $ZH$  final state
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- We know  $Z$ : gauge boson,  $H$ : scalar boson  $\Rightarrow$  only two vertices
- Need a VEV to get  $ZZH$  vertex  $\Rightarrow$  proves it is the origin of  $m_Z$



HM, LBNL-38891

# *Absolute confidence is crucial for a major discovery*



- “New York Times” level confidence  
*“Origin of Mass Uncovered”*  
still a long way to
- “Halliday-Resnick” level confidence  
*“We have learned that masses of all elementary particles originate in the condensate of so-called Higgs boson of mass  $124\text{GeV}/c^2$ .”*

# *Post-Higgs Problem*



# *Post-Higgs Problem*



- We see “what” is condensed
- But we still don’t know “why”
- Two problems:
  - Why anything is condensed at all
  - Why is the scale of condensation  $\sim \text{TeV} \ll M_{Pl}$
- Explanation likely to be at  $\Lambda \sim \text{TeV}$  scale because Higgs self-energy  $\delta m_H^2 \sim \Lambda^2$

# Three Directions



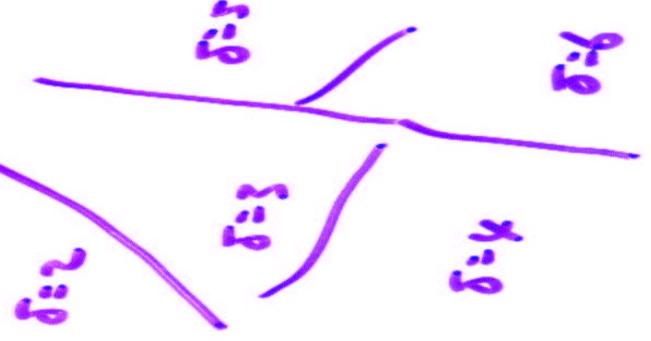
- History repeats itself
  - Crisis with electron solved by anti-matter
  - Double #particles again  $\Rightarrow$  supersymmetry
- Learn from Cooper pairs
  - Cooper pairs composite made of two electrons
  - Higgs boson may be fermion-pair composite  
 $\Rightarrow$  technicolor
- Physics *ends* at TeV
  - Ultimate scale of physics: quantum gravity
  - May have quantum gravity at TeV  
 $\Rightarrow$  hidden dimensions

# EXTRA DIMENSION

techni-color  
 Randall Sundrum I  
 topcolor

Randall-Sundrum I

large extra



SUSY

Scherk-Schwarz

composite

anomaly med

MSUGRA

gauge med  
 gaugino med

$+R_p$

dim

G



$\delta=7$   
 M theory

$4\kappa$   
 $\lambda$



# *Task*

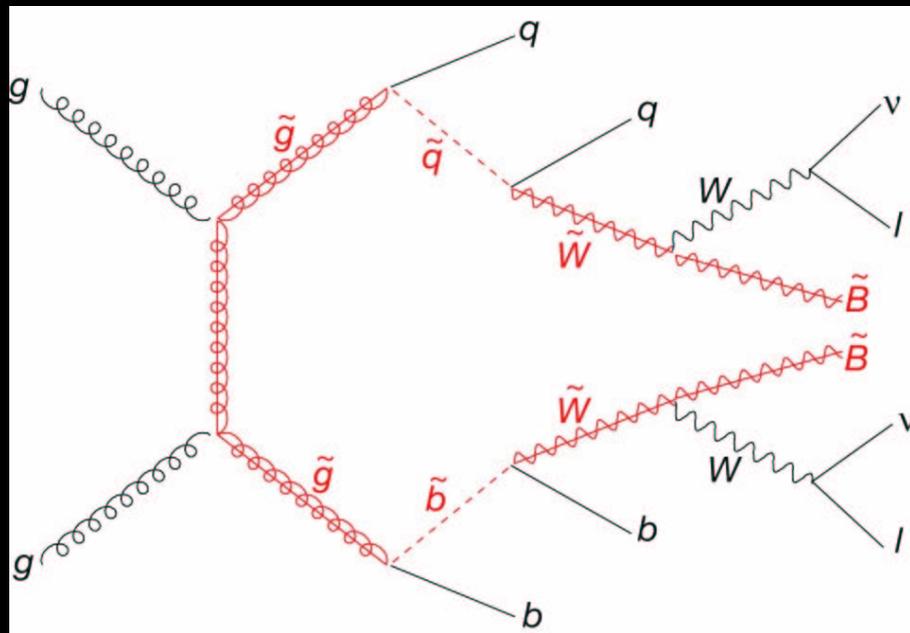


- Find physics responsible for condensation
- We can eliminate many possibilities at LHC
- But new interpretations necessarily emerge
- Elucidate what that physics is
  - Reconstruct the Lagrangian from measurements

# Many theories look alike

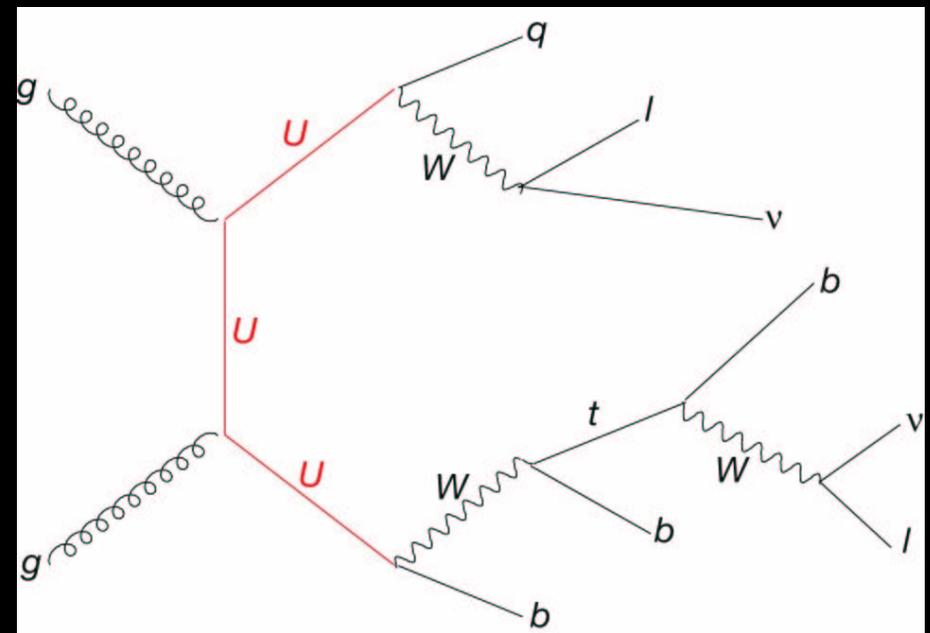
## Supersymmetry

- Missing energy, high  $p_T$  jets, leptons,  $b$ ,  $t$ ,  $\tau$



## Fourth generation

- Missing energy, high  $p_T$  jets, leptons,  $b$ ,  $t$ ,  $\tau$



# *Many theories look alike*

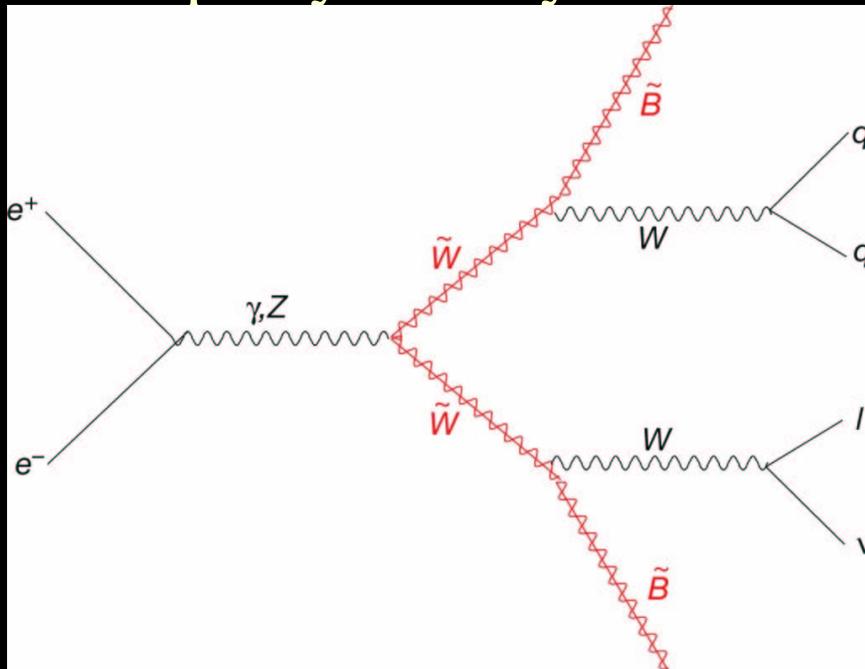


- Pseudo-Nambu-Goldstone bosons in technicolor
- Universal Extra Dimensions (Cheng, Matchev, Schmaltz)
  - Lightest Kaluza-Klein states  $\sim$  LSP
- If models well-defined and only a few parameters, LHC can exclude many interpretations of data
- Race will be on:
  - theorists coming up with new interpretations
  - experimentalists excluding new interpretations

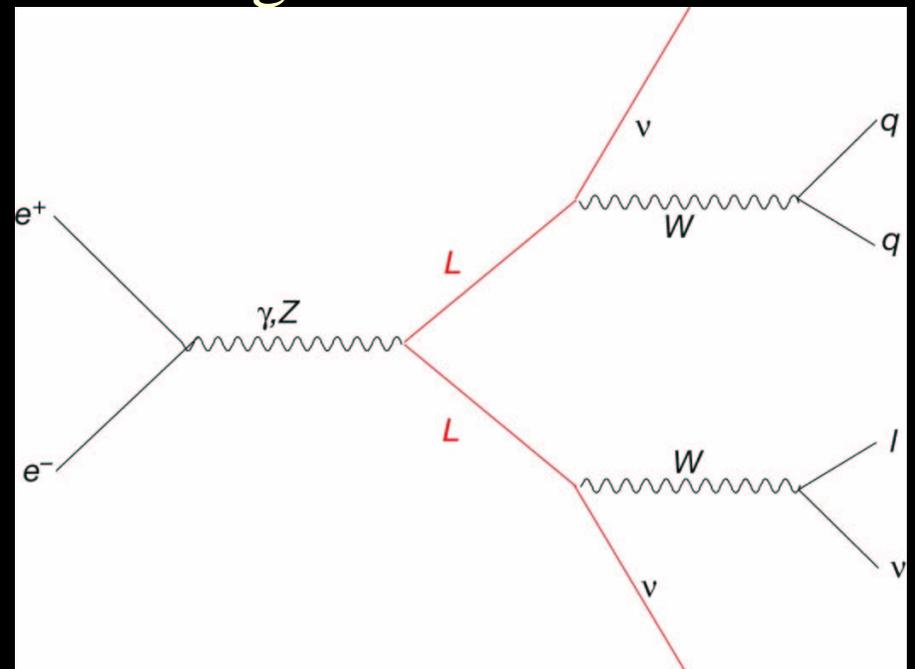
$\Rightarrow$  A *loooong* process of elimination
- Crucial information is in *details*

# *LC is good at details*

## Supersymmetry



## Fourth generation



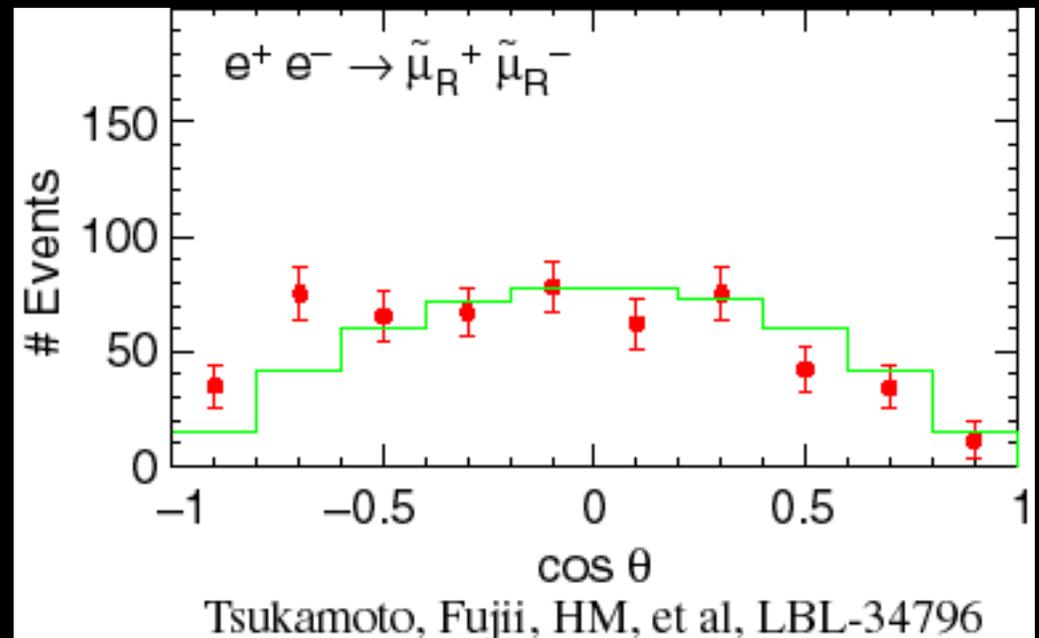
$E_{jj}$  distribution tells if  $m_{\tilde{B}} \neq 0$

Cross sections vs polarization determine quantum numbers 29

# Supersymmetry at LC

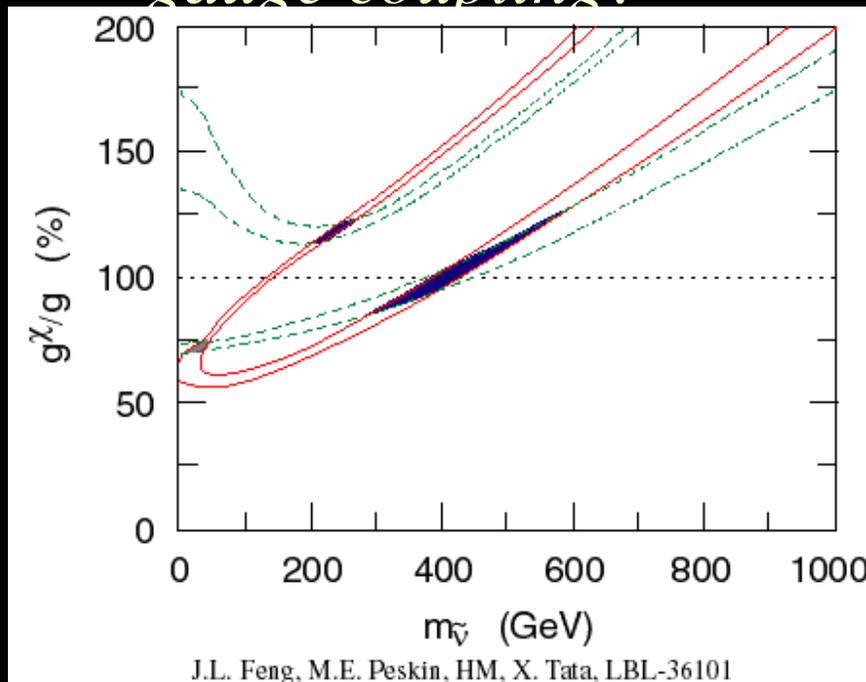
- Discovery at Tevatron Run II or LHC
- Test they are really superpartners
  - Spins differ by 1/2
  - Same  $SU(3) \times SU(2) \times U(1)$  quantum numbers
  - Supersymmetric couplings

*Spin 0?*

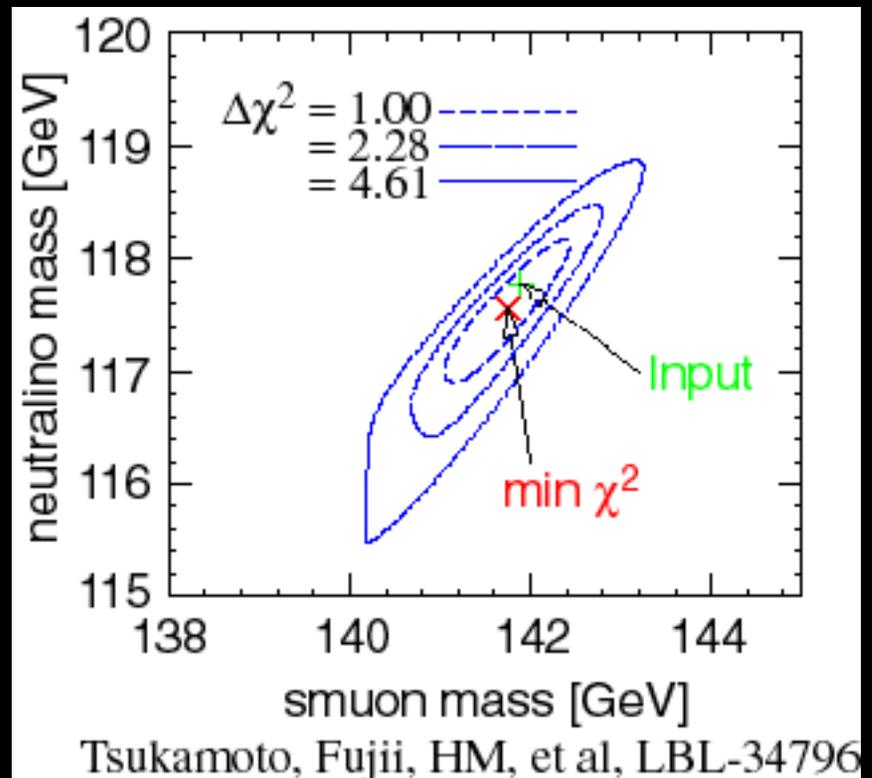


# Supersymmetry at LC

Is gaugino coupling =  
gauge coupling?



## Mass Measurement

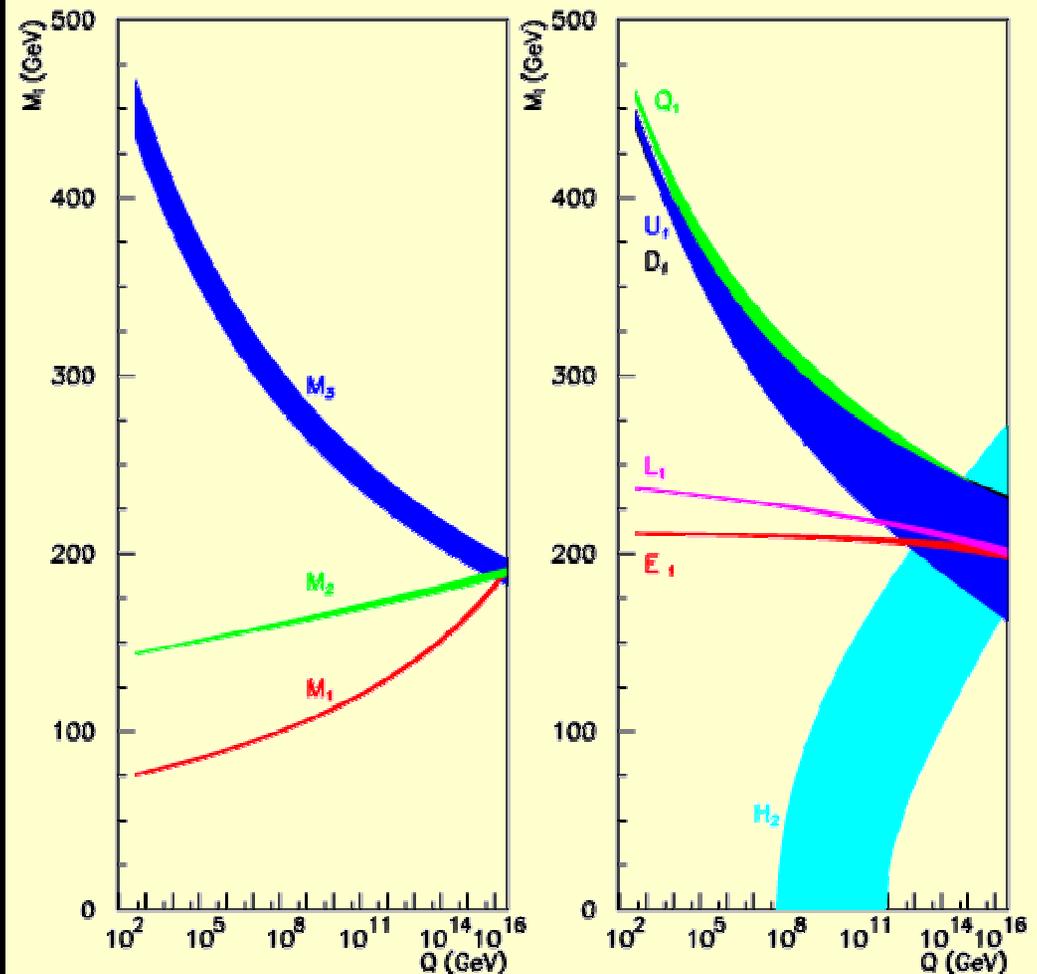


# Superpartners as probe

- Most exciting thing about superpartners beyond existence:

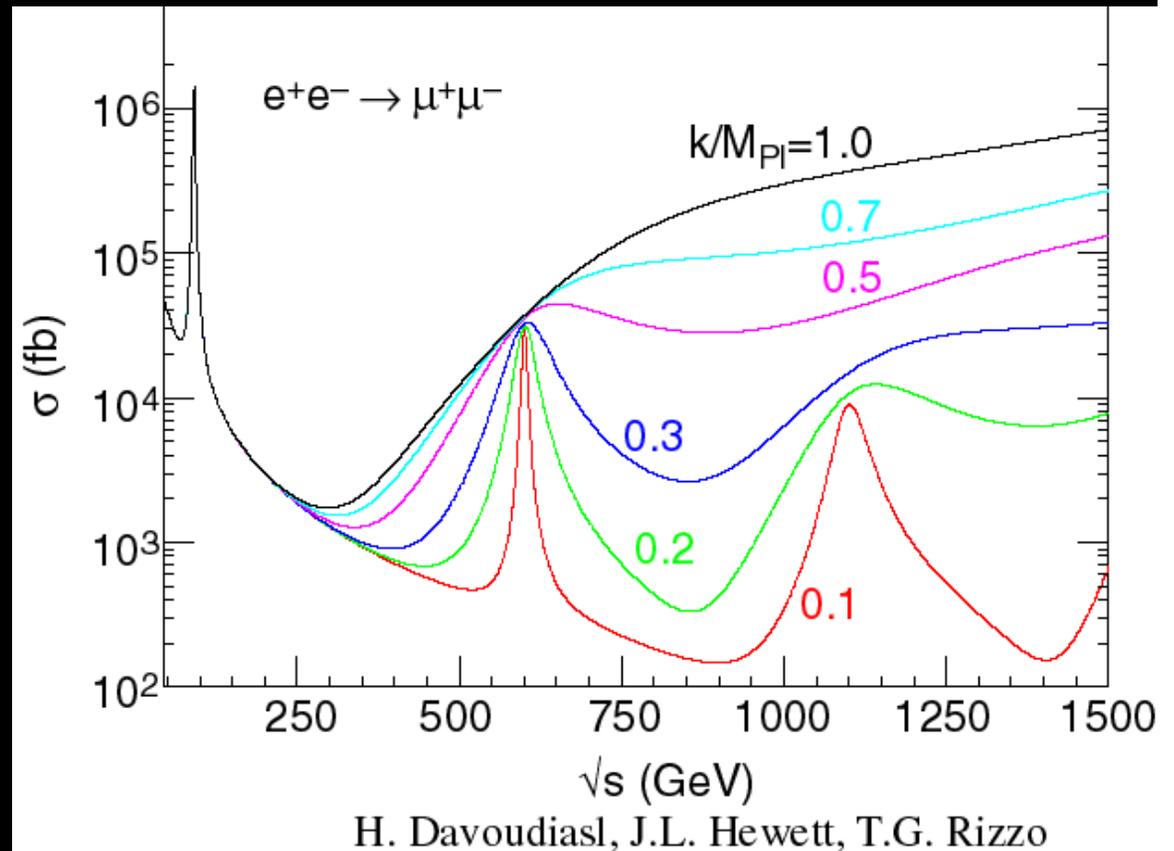
They carry information of small-distance physics to something we can measure

*“Are forces unified?”*



# Hidden Dimensions

Randall-Sundrum  
scenario with  
warped extra 1D  
 $\Rightarrow$  TeV-scale KK  
gravitons  
 $\Rightarrow$  determine the  
shape of the  
hidden  
dimension



# *Produce Dark Matter*



- Dark Matter likely to be TeV-scale electrically neutral weakly interacting particle (*e.g.*, LSP, Lightest KK)
- With LC, measure its mass, couplings
- Can calculate its cosmic abundance
- If it agrees with cosmological observation, we understand Universe back to  $10^{-12}$  sec after the Big Bang

# Conclusion



- Physics at TeV scale likely to be rich
- To fully understand it, we will likely need *a lot* of detailed information
- LC will study new particles one by one  
⇒ reconstruct the fundamental Lagrangian
- Then we would like to move on further with absolute confidence