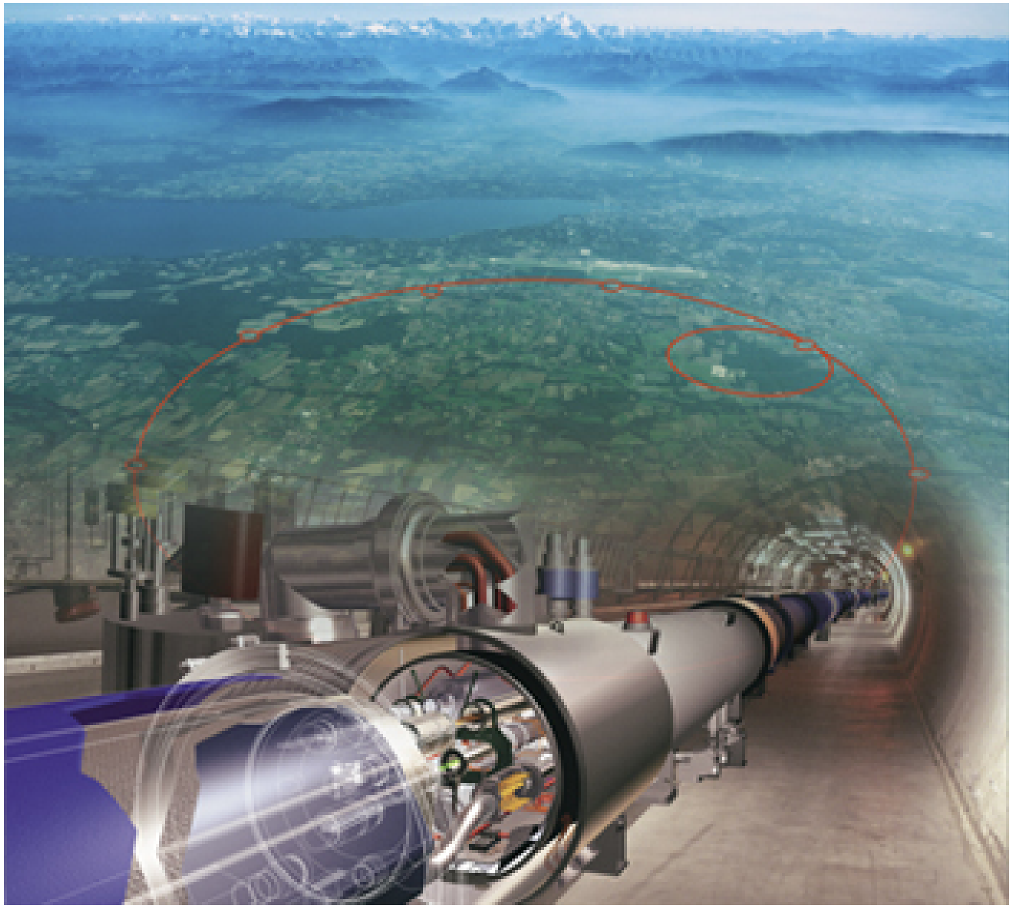
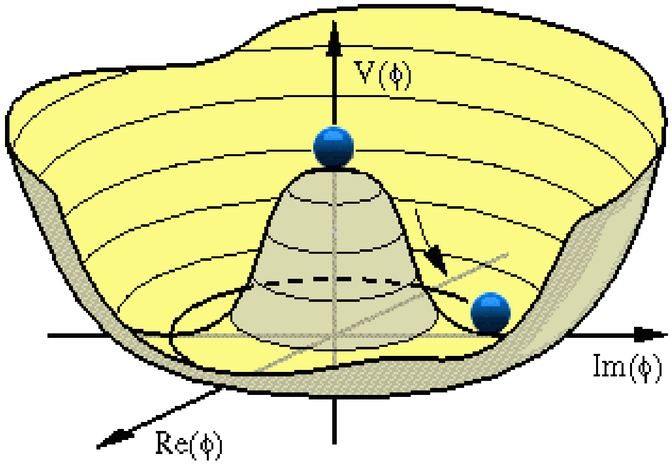
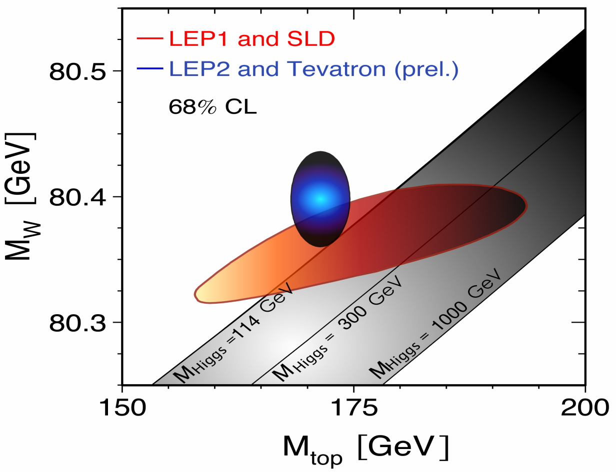
Why Does the W Have Mass?
Uncovering the Source of Electroweak Symmetry Breaking







Marjorie Shapiro
UC Berkeley/LBL

March 5, 2007

Outline

- Weak Decays and the W-Boson
- Introduction to EWSB
- Current Experimental Constraints
- The Next Generation of Experiments: the LHC
- Beyond the Standard Model
- Conclusions

A Historical Perspective: β-decay

- First theory formulated by Fermi (1934)
- 4-point Interaction with coupling G_F

F. A. Scott, *Phys. Rev.* **48**, 391 (1935)

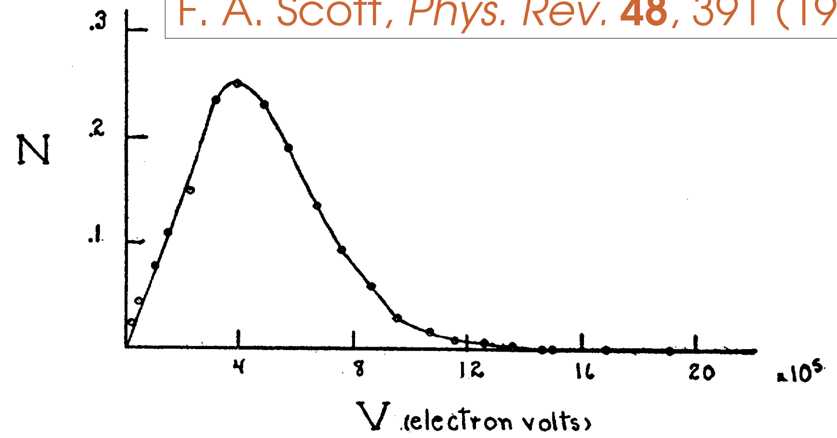
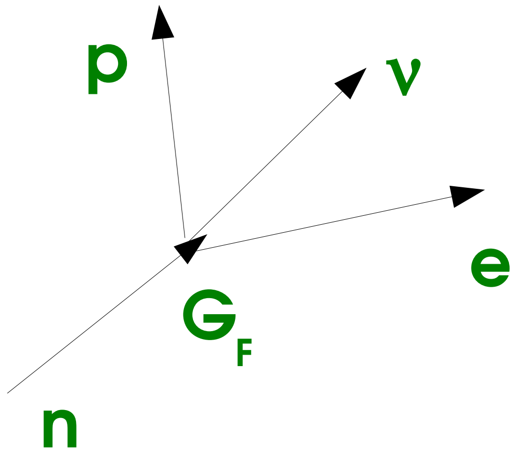


FIG. 5. Energy distribution curve of the beta-rays.



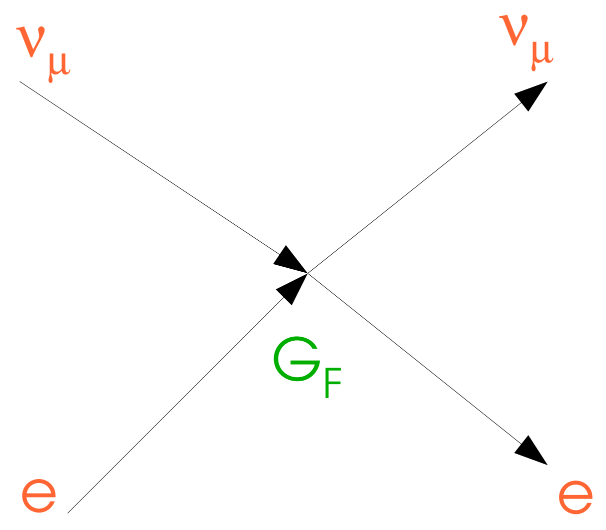
$$G_F = 1.166\times10^{-5}\,GeV^{-2}$$

But 4-Point Interaction is Only a Low Energy Effective Theory

- G_F has dimensions GeV^{-2}
- Consider, eg e-ν scattering:

  $\sigma(\nu_\mu e \rightarrow \nu_\mu e) \propto G_F^2\, E^2_{CM}$

  – At high energy, σ violates unitary



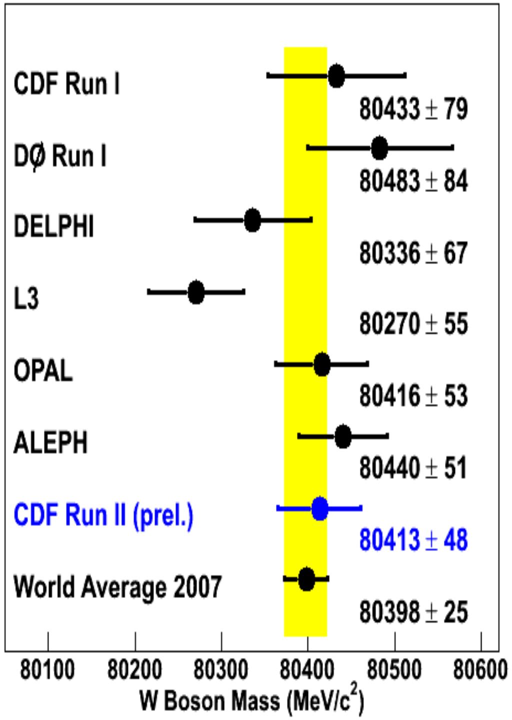
Must modify behavior of theory at high energy

Solution: Replace 4-Point Function with W Propagator

- In analogy with QED, force mediated by vector boson: the W-boson
- If W has mass:

$$\frac{G_F}{\sqrt{2}} \rightarrow \frac{g^2}{q^2 - M_W^{\ 2}}$$

- Short range nature of Weak force explained by mass of W (uncertainty principle: $\Delta E \Delta t \geq \hbar$)



Today we know:

$M(W) = 80.398 \pm 0.025$ GeV/c^2

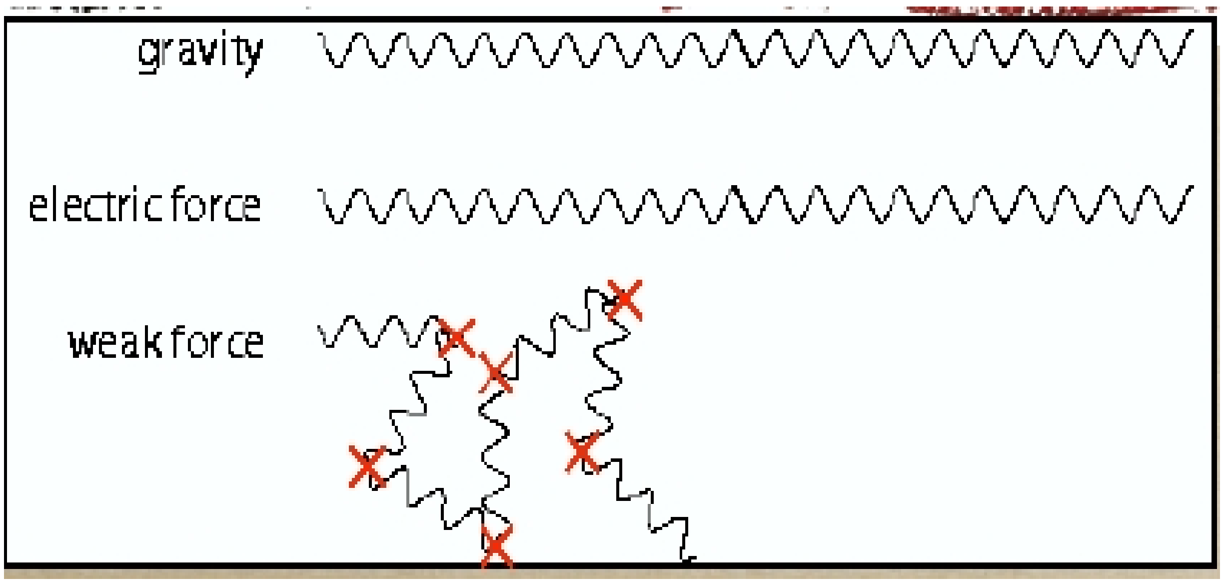
But Massive W Introduces Its Own Problems

- Success of QED: Relativistic Field Theory
  - Local gauge invariance specifies form of γ-fermion interaction
  - Only known class of renormalizable theory
- Massless photon a consequence of gauge invariance

How can we introduce a massive W in the context of quantum field theory?

Giving the W Mass

- There is something filling our Universe
- It doesn't disturb gravity or EM Interactions
- Interactions with Weak Bosons generate mass dynamically



Courtesy of
H Murayama

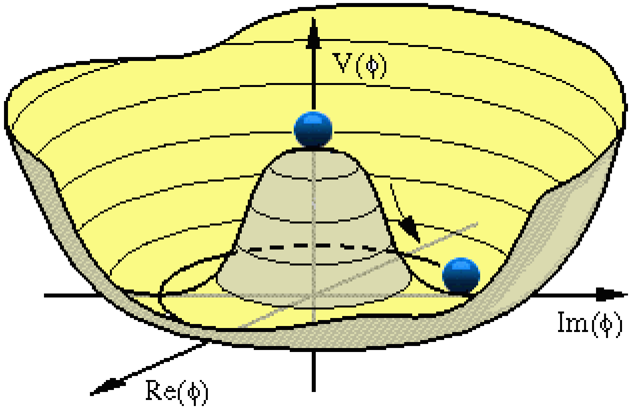
Electroweak Symmetry Breaking

- To maintain local gauge invariance, Lagrangian cannot include mass terms for fermions or for gauge bosons
- Instead, break symmetry dynamically:
  - Initial State (vacuum) breaks symmetry or
  - New interaction outside the SM

EWSB in the Standard Model

- Introduce a new field
  - Complex Scalar Doublet
- Scalar field couples to potential V

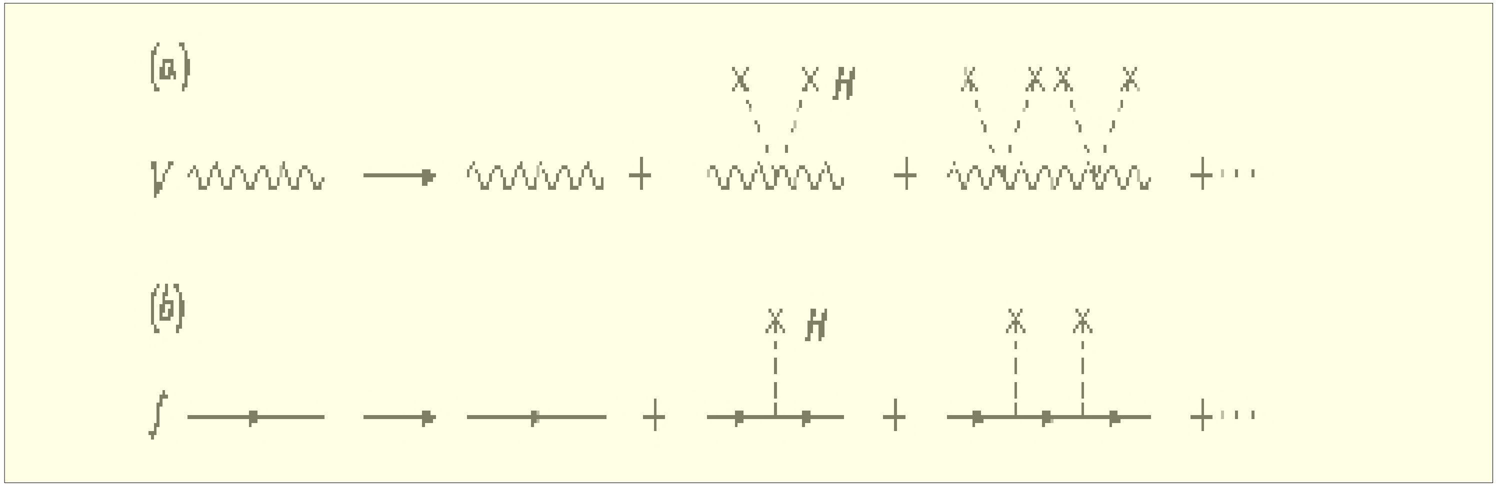
$$V(\phi)=\frac{\lambda}{2}\left[|\phi|^2-\frac{\nu^2}{2}\right]$$



- Lowest energy state degenerate and requires non-zero VeV
- Choice of physical vacuum breaks EW Symmetry

Standard Model Phenomenolgy

- In addition to massive charged W-boson, ∃ a massive neutral boson, the Z
- One physical scalar: **the Higgs**
- Interaction with Higgs generates mass for W and Z and fundamental fermions



SM Solution Works, But Leaves Many Unanswered Questions

- Why EWSB at all?
  - Introduction of unmotivated potential
- Why is W mass ~80 GeV?
  - Difficult to prevent radiative corrections from forcing W/Z mass to M_{Planck}

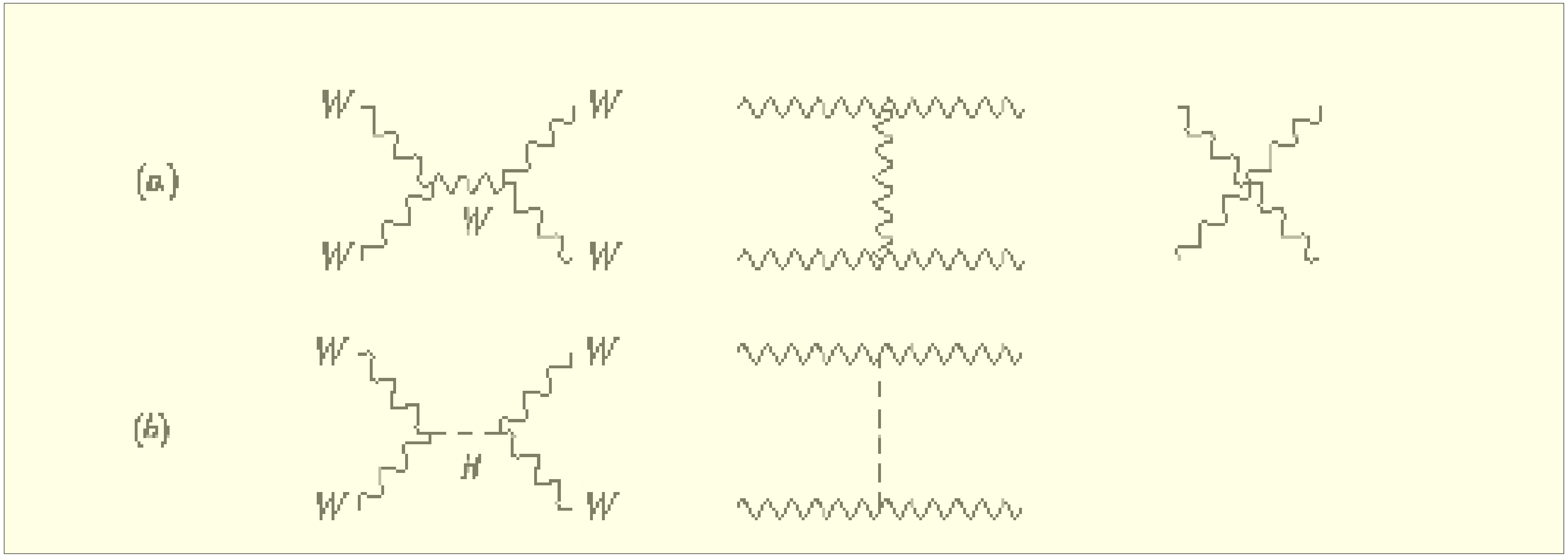
Most particle physicists there is something beyond the Standard Model

Three Alternatives to Standard Model

- Introduce a New Symmetry (eg Supersymmetry)
  - Just as antimatter introduced to solve problem of negative energy states in QED,
- Replace Fundamental Higgs with Composite
  - Like Cooper pairs in Superconductivity
- Introduce New Physics that Moves Planck Scale Down
  - Extra spacial dimensions: Quantum Gravity at energies achievable using accelerators???

We Know Solution Must Be at TeV Scale

- Consider longitudinal WW Scattering:

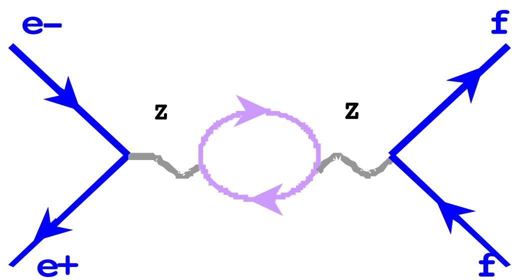


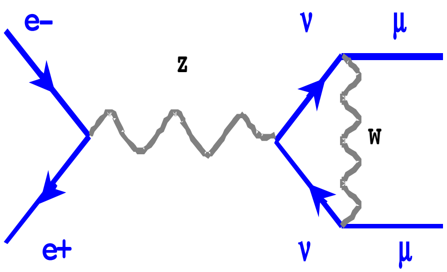
S-wave unitary violated unless Higgs or alternative appears at mass scale below ~1.2 TeV

Success of Standard Model Limits the Options

- SM makes specific, concrete predictions
- To lowest order in perturbation theory, only 3 parameters:
  - Choose to use 3 best measured: α, G_F , m(z)
  - Theory then predicts m(W) in terms of these parameters
- Radiative corrections test structure of theory
- Any BSM physics must be consistent with measurements:
  - (g-2) of μ
  - Precision measurements of Z decays
  - Lepton and Baryon Number Conservation

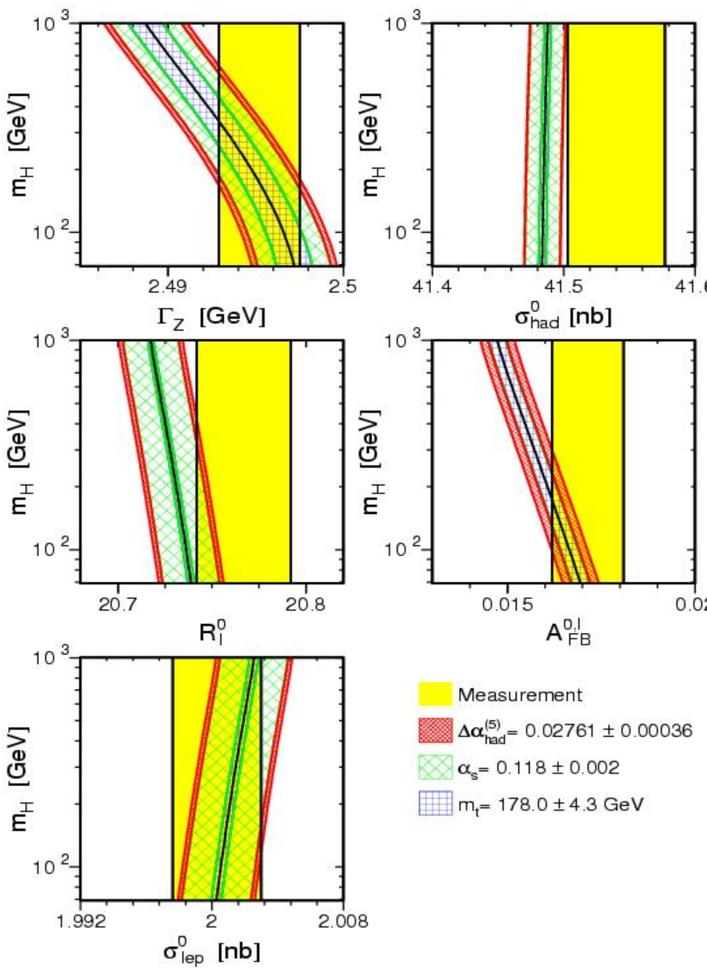
Precision Measurements from LEP: $e^+e^- \to Z$

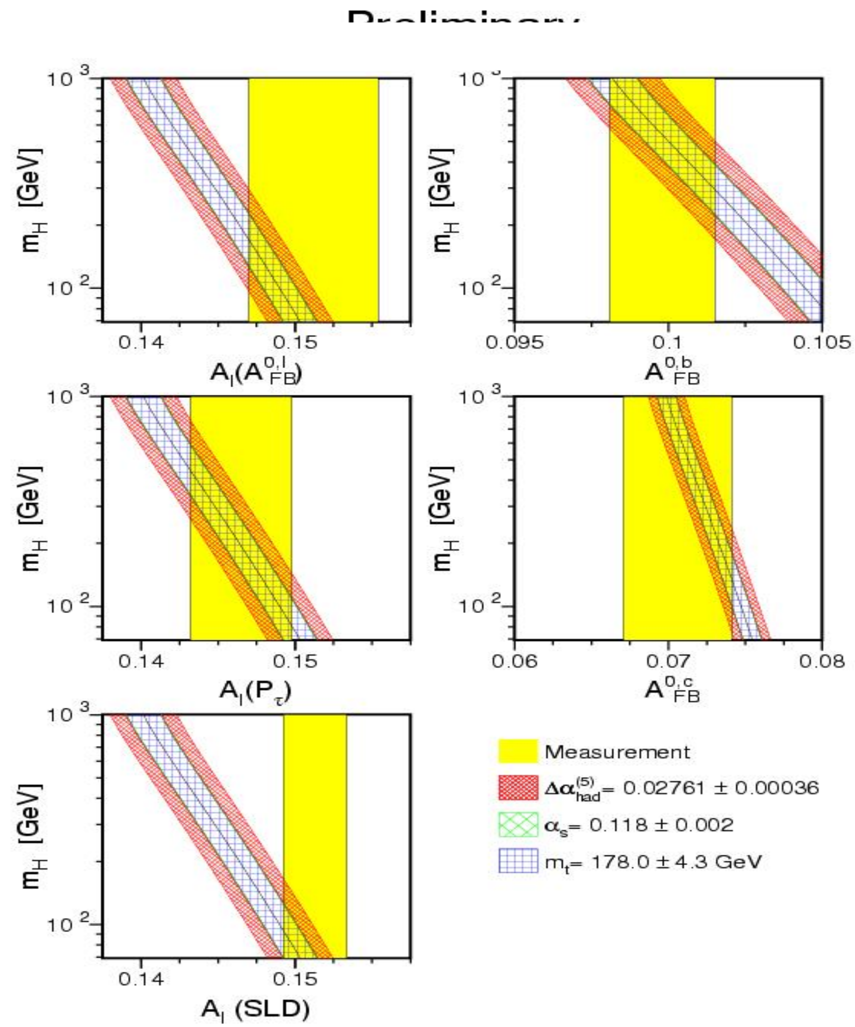




- EW Radiative Corrections sensitive to virtual particles through loop corrections
- Source of EWSB by definition couples to W and Z
- Data in excellent agreement with SM
- Places severe constraints on characteristics of particles that appear in these loops

How Consistent are Measurements from LEP?

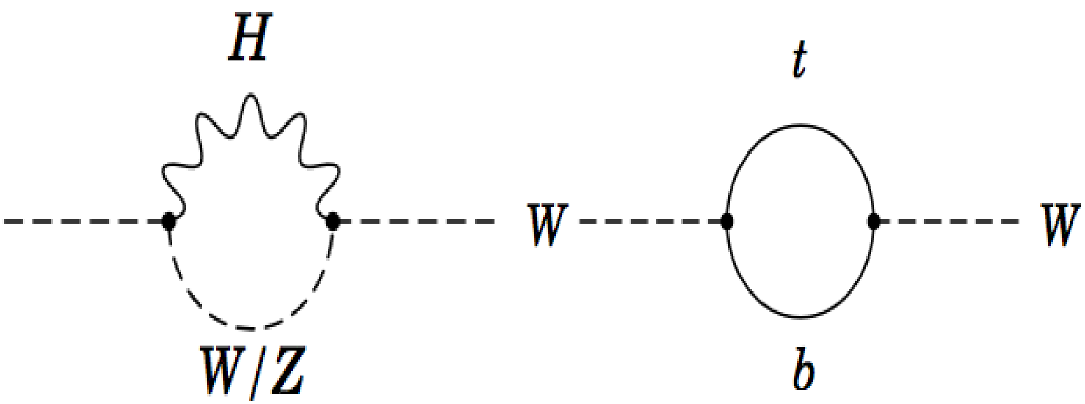




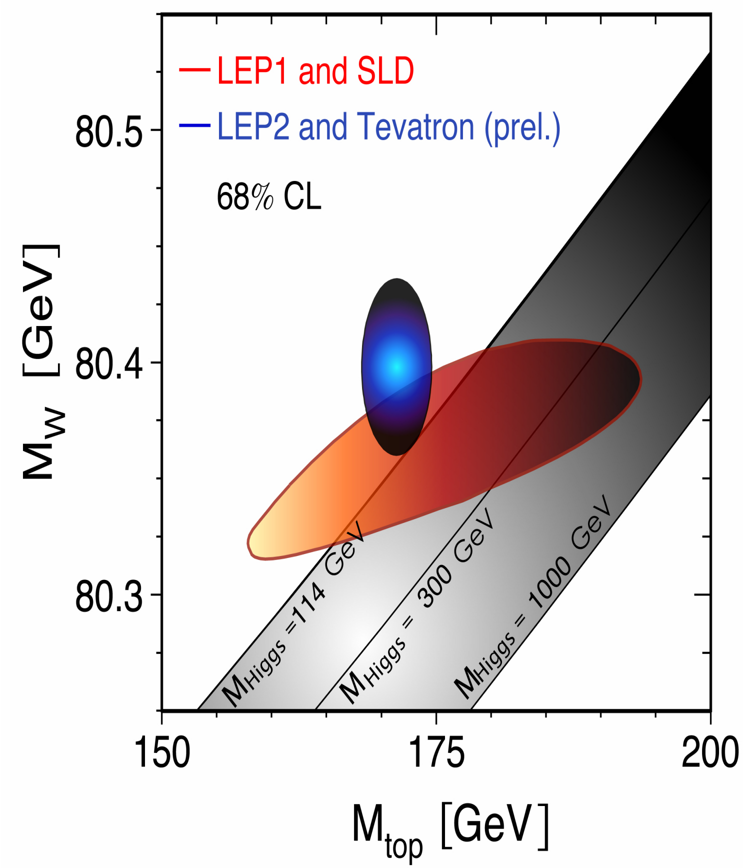
Radiative Corrections quadratic in Top Mass

But logarithmic in Higgs Mass

Among Most Sensitive Constrants on m(Higgs): M(W) vs M(top)

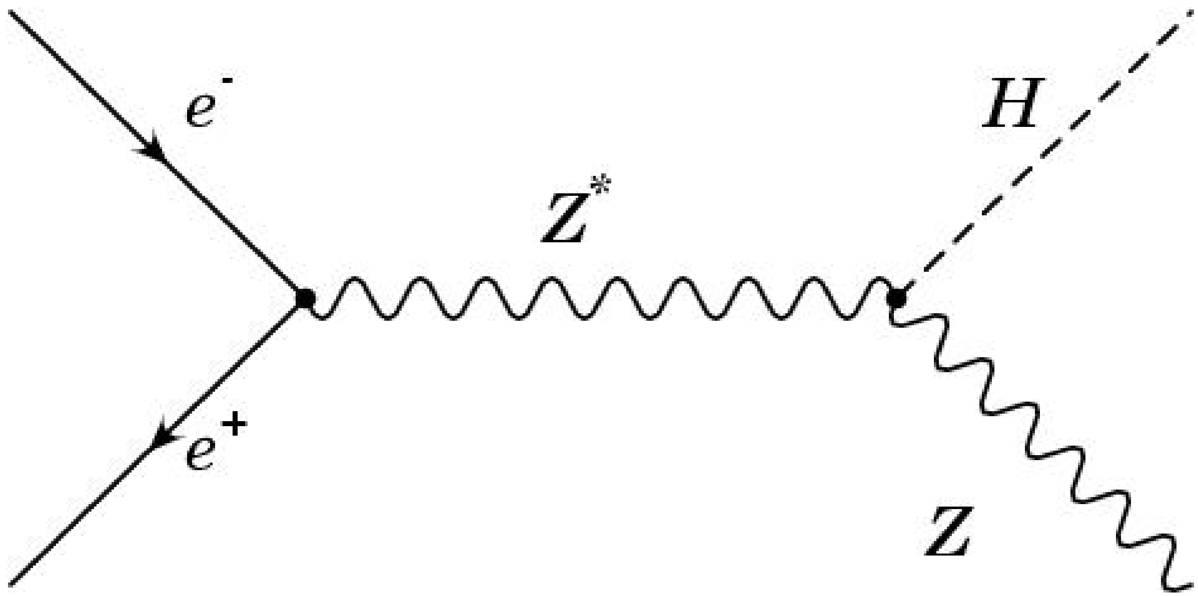


- W/Z mass ratio sensitive to radiative corrections
- Z mass known to high precision (LEP) so couch results as M(W) vs M(top)



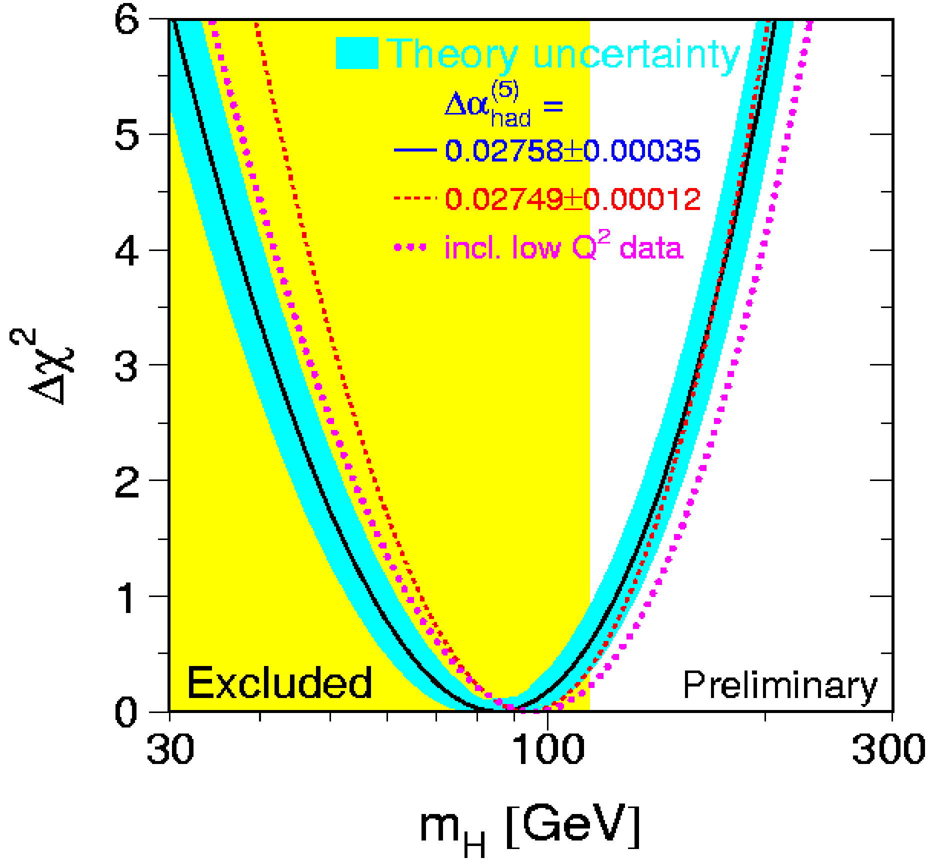
In context of SM, data favors light Higgs

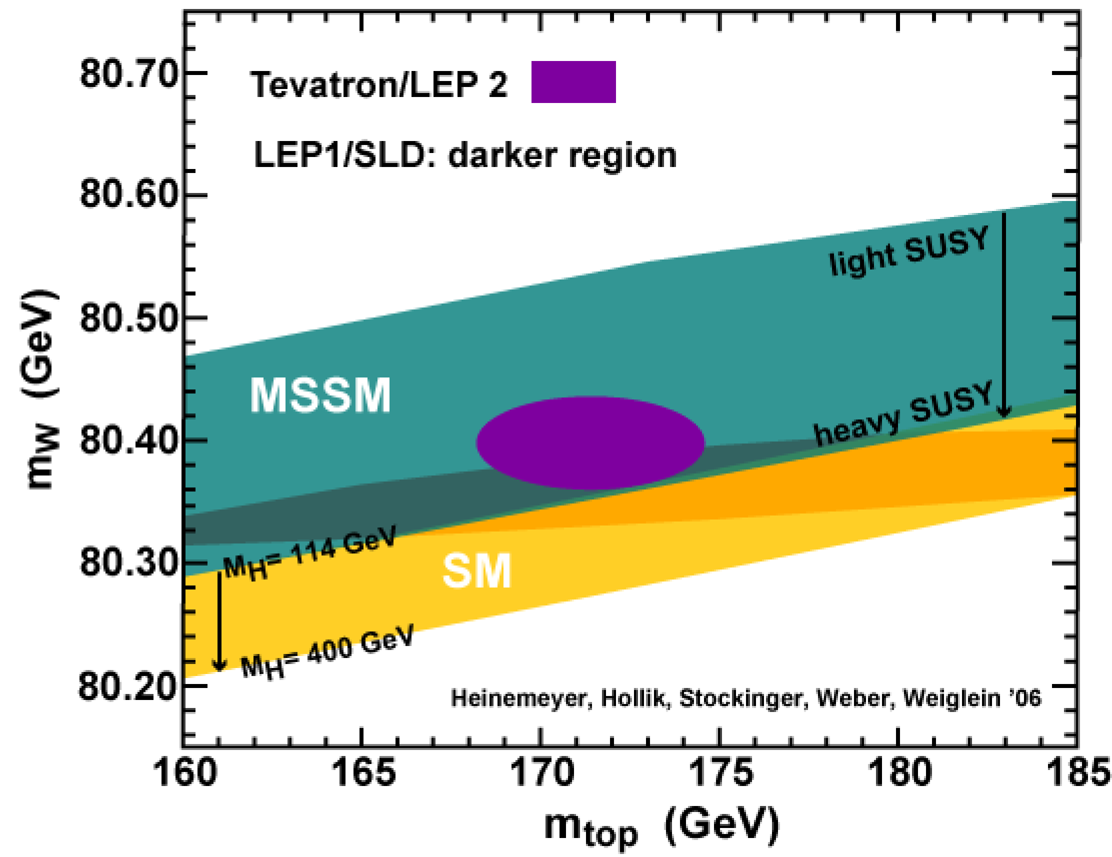
Direct Search for Higgs at LEP-II



- If Higgs light enough, direct production at LEP-II would have been possible
- No Higgs Observed: m(H) > 114.4 GeV (95% cl)

Existing Constraints on Higgs Mass





Within SM, higgs predicted to be close to current exclusion limit

Extensions to SM introduce new particles: modify constraints

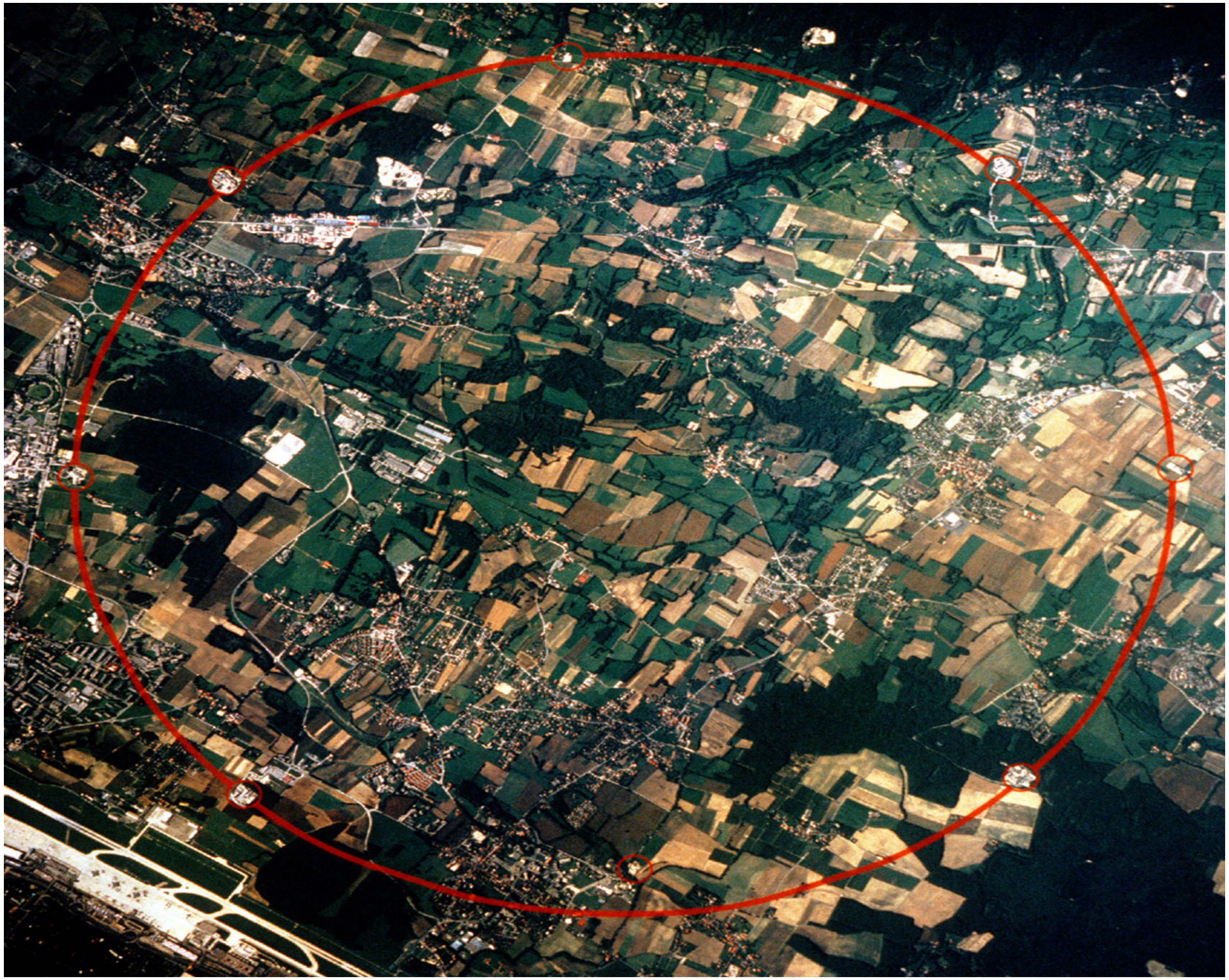
Summary of Current Situation

- Measurements (just) in agreement with SM
- Remains (at least) one particle or interaction to find (the source of EWSB)
- Higgs is only one possibility
- <u>Goal for the Next 10 Years:</u>
  - Determine the source of EWSB
  - Measure properties of particle(s) or interactions
  - Relate observations to other outstanding problems in particle physics:
    - Dark Matter ?
    - Gravity ?

The Next Step: Large Hadron Collider

- Technology makes it difficult to build high energy electron colliders
  - Design of linear collider in progress, but first data at least 10 years away
- High enegy proton collider (LHC) designed with discovery of source of EWSB
  - Startup at full energy in mid-2008 (pilot run at lower energy in Fall 2007)

LHC: Located at CERN (Geneva, Switzerland)



Uses LEP tunnel (24 Kilometer Circumference)

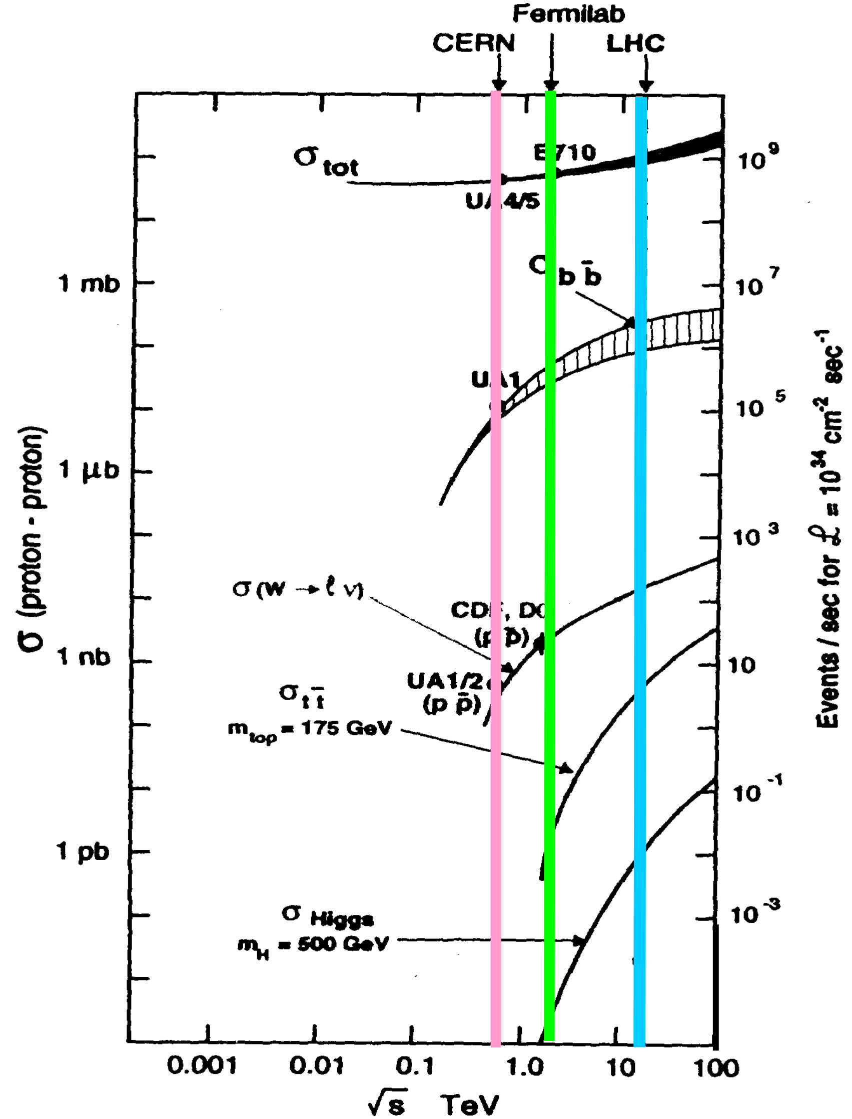
LHC Features: Key Parameters

- Energy: 14 TeV (7 x Tevatron)
- Intensity:
  - Initial 10 fb^{-1}/year (5 x Tevatron)
  - Design: 100 fb^{-1}/year
- First Data: Summer 2008
- Operation in "initial luminosity" mode for 1st 3 years

New energy frontier, so discoveries possible even with very small data samples !

LHC Physics Program Very Broad

- pp collisions occur via interactions of quarks and gluons
- Strong interactions: cross section large
- Weakly produced: smaller rates
  - Must have capability to detect rare processes



For this talk, will concentrate on processes relevant for EWSB

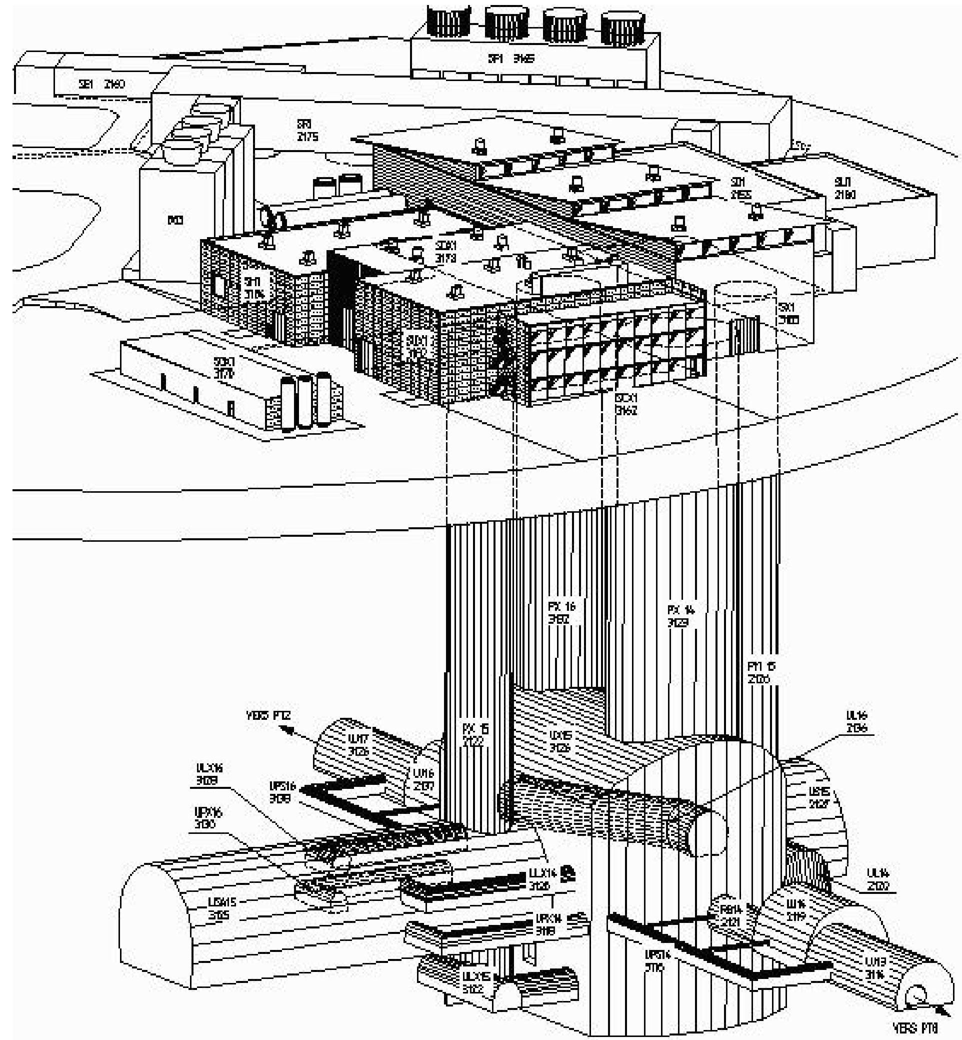
Detectors for the LHC

- Two Big Detectors Designed to Study Physics at the High Energy Frontier
  - ATLAS and CMS
  - Similar goals, different design trade-offs
- One Detector Optimize to Study B-Decays
  - LHCB
- One Detector Optimized for Heavy Ion Colliisions
  - Alice

I will discuss status of ATLAS (my experiment)

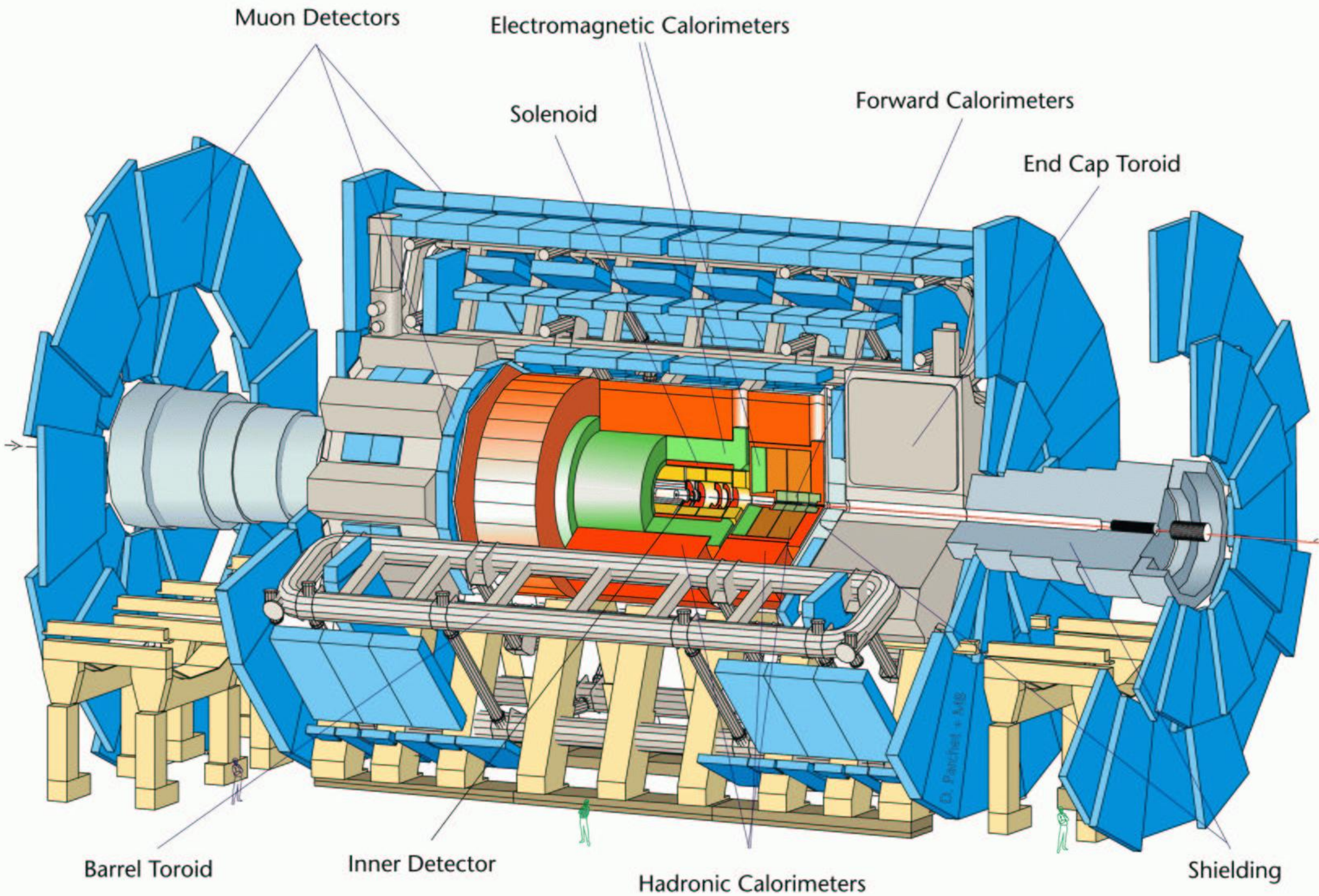
Similar for CMS (UC Davis members)

The ATLAS Experiment



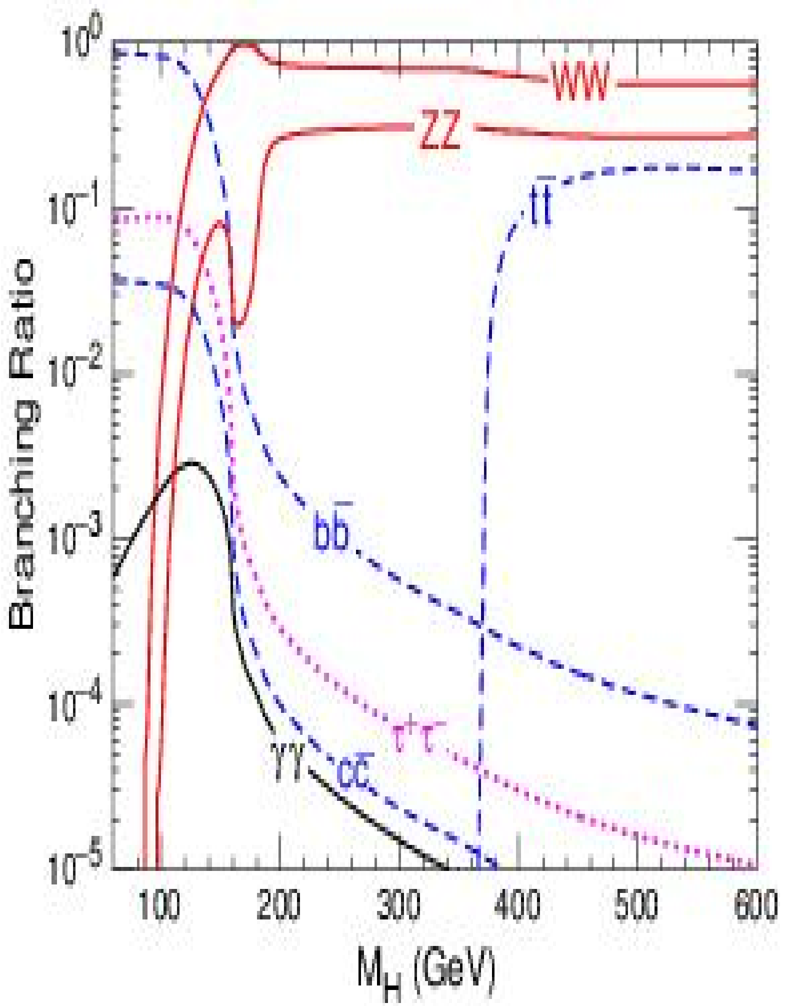
Superimpose detector on 5 story LHC office building for scale

D712/mb-26/06/97



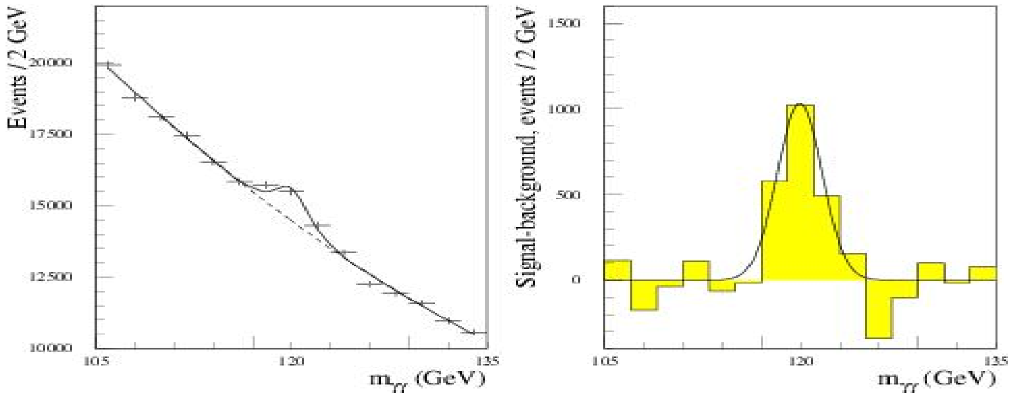
Searching for the SM Higgs

- Higgs decay modes depend on Higgs' mass
- Higgs couples to heavies accessible particles
- Some modes easier to observe than others
- Greatest experimental difficulties in low mass region

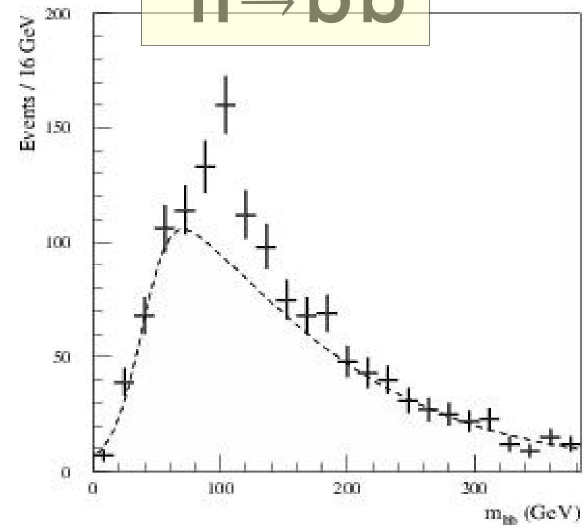


Observing the Higgs With ATLAS:
Must Search in Mulitple Modes

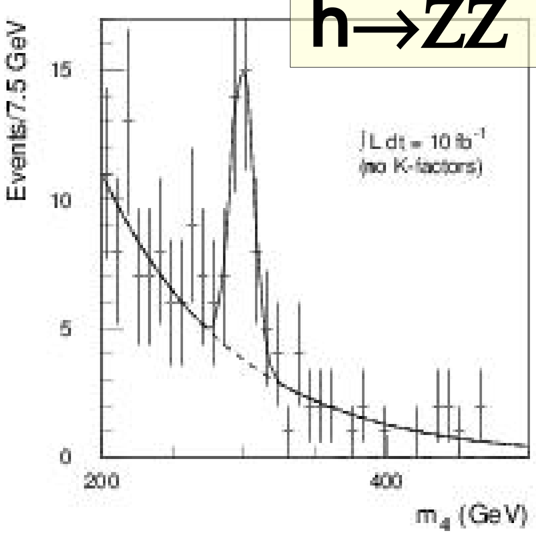
$h \to \gamma\gamma$



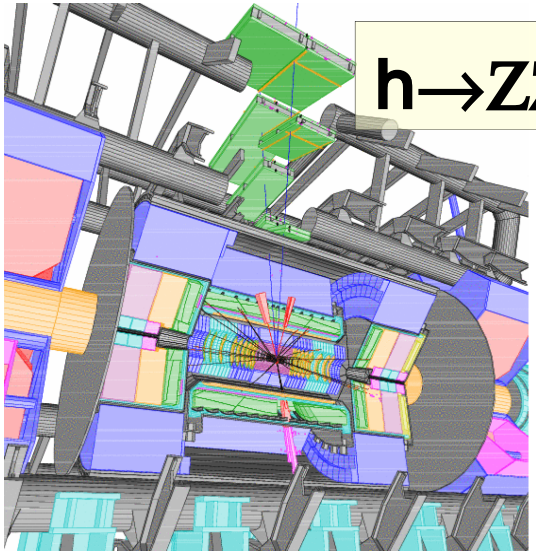
$h \to b\bar{b}$



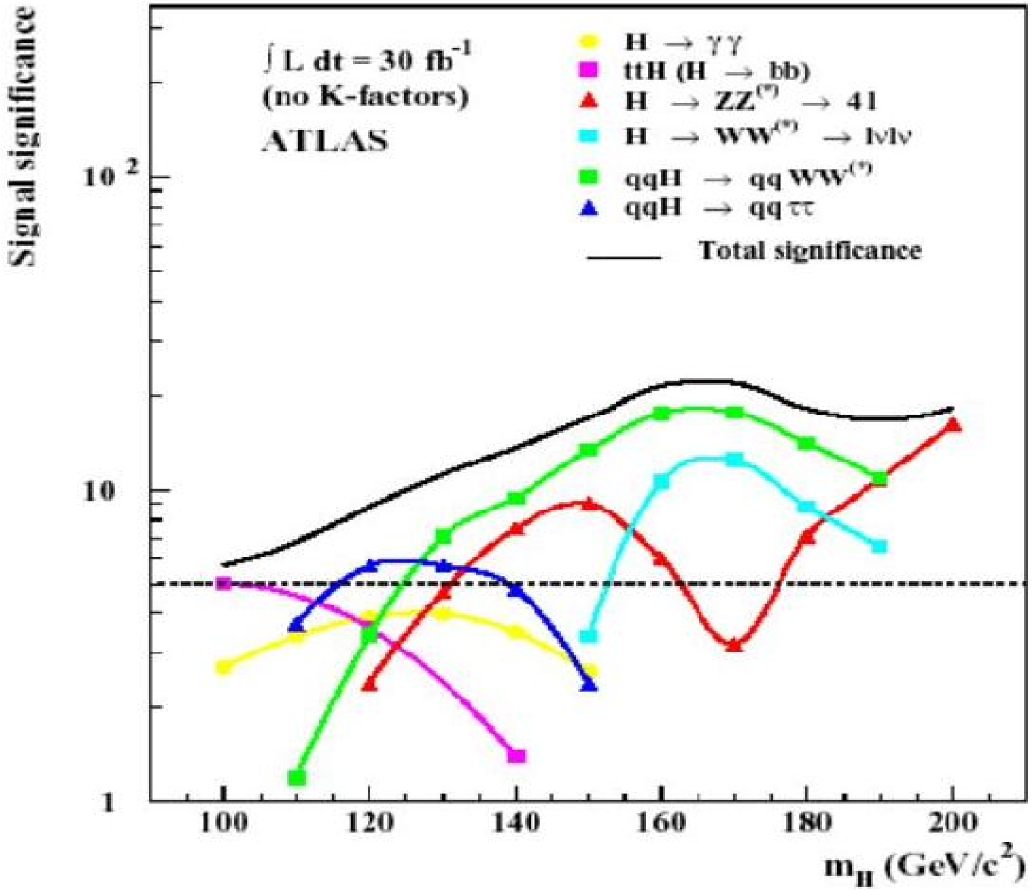
$h \to ZZ$



$h \to ZZ$



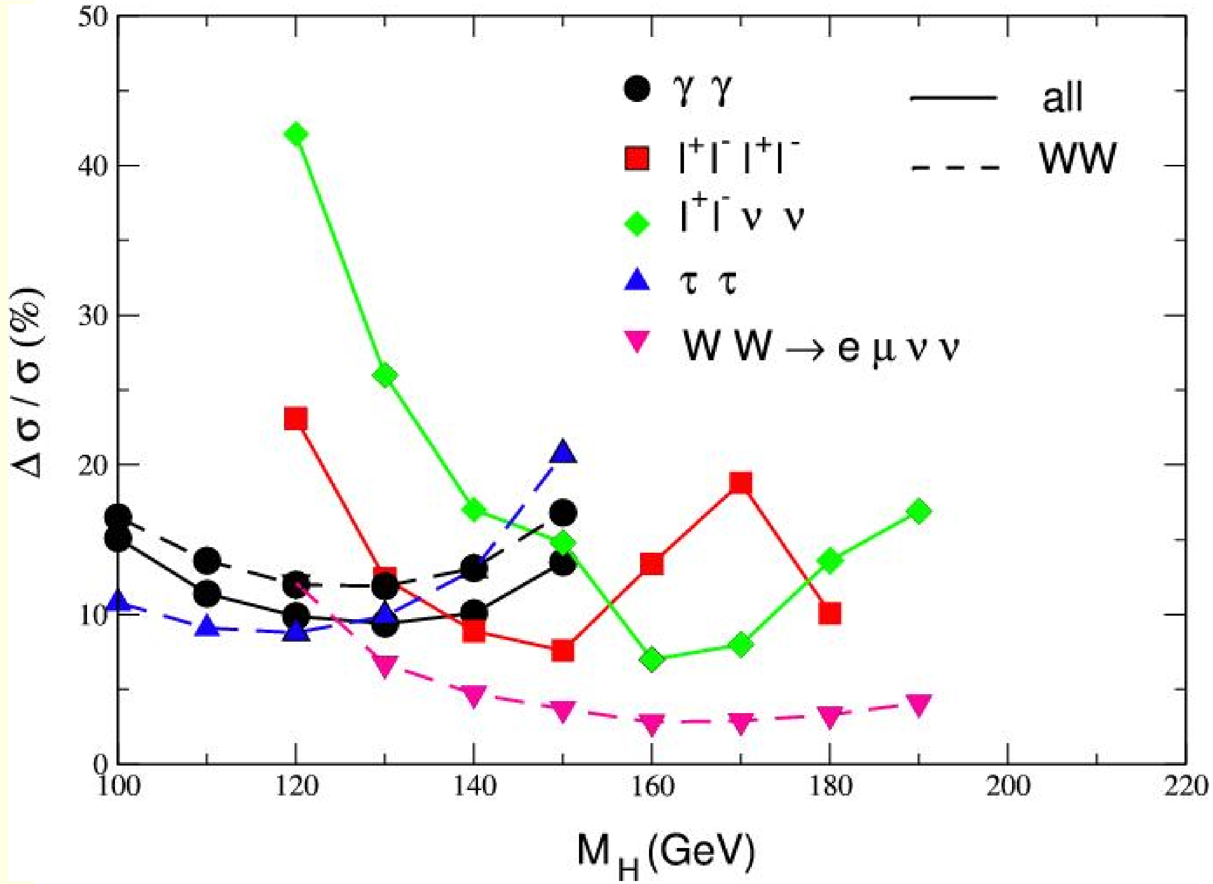
Higgs Sensitivity vs Mass



3 Years Initial Luminosity Running

Measuring Higgs Properties

- $\frac{BR(H\to\gamma\gamma)}{BR(H\to b\bar{b})}$ for $80 < M_H < 130$
- $\frac{BR(H\to\gamma\gamma)}{BR(H\to ZZ^*)}$ for $125 < M_H < 155$
- $\frac{g(t\bar{t}H)}{g(HWW)}$ for $80 < M_H < 130$
- $\frac{g(HZZ)}{g(HWW)}$ for $160 < M_H$
- $\frac{BR(H\to\gamma\gamma)}{BR(H\to\tau\tau)}$ for $110 < M_H < 155$
- $\frac{BR(H\to\gamma\gamma)}{BR(H\to WW^*)}$ for $120 < M_H < 155$



(Expected Error on BF shown in %)

Precision depends on Higgs Mass

But the Higgs is Not Typical

- Higgs coupling to light quarks and gluons small
  - Production cross sections much lower than other processes
- Sometimes must look at non-dominant decays
  - Eg $h \rightarrow \gamma\gamma$
- Beyond-the-Standard-Model processes often accessible with much less luminosity:
  - Strongly produced final states
  - Moderate masses

In such cases, may discover source of EWSB through observation of new phenomena

Supersymmetry (SUSY)

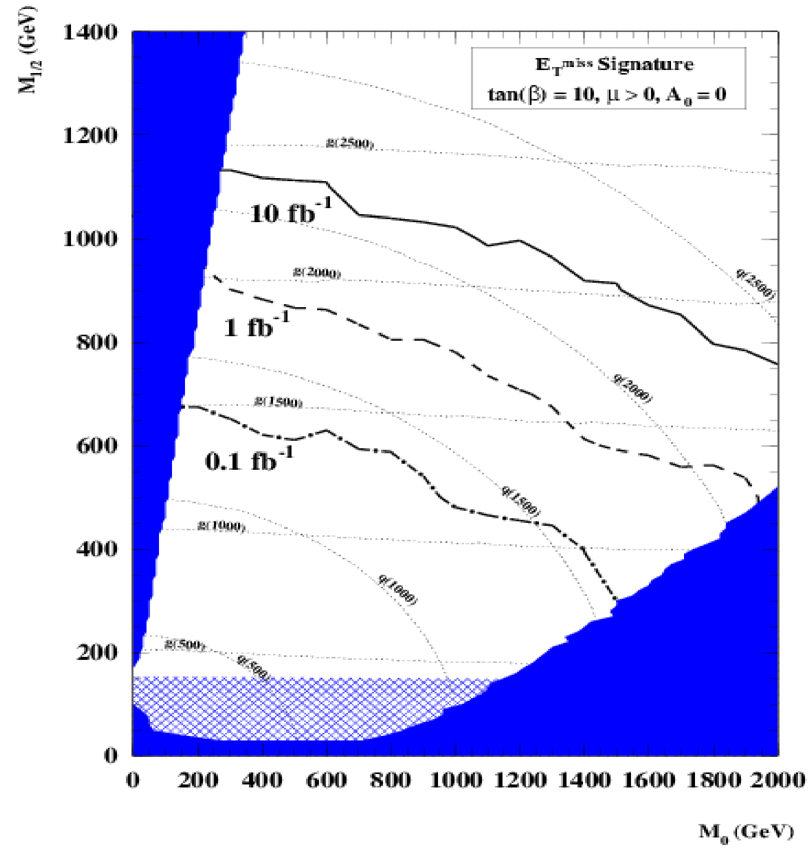
- Partner for every known particle
  - Fermions have spin 0 partners
  - Bosons have spin ½ partners
- Theoretically favored extension to SM
  - Solves hierarchy problem (sparticle and particle loops cancel)
  - Provides Dark Matter candidate
  - Required by String Theory (but not necessarily at EWSB scale)
- 5 Higgs bosons (h, H, A, $H^{\pm}$)

Standard Model Particles		SUSY Partners		
Particles	States	Sparticles	States	Mixtures
quarks (q) (spin-$\frac{1}{2}$)	$\binom{u}{d}_L$, u_R, d_R $\binom{c}{s}_L$, c_R, s_R $\binom{t}{b}_L$, t_R, b_R	squarks ($\tilde{q}$) (spin-0)	$\binom{\tilde{u}}{\tilde{d}}_L$, $\tilde{u}_R$, $\tilde{d}_R$ $\binom{\tilde{c}}{\tilde{s}}_L$, $\tilde{c}_R$, $\tilde{s}_R$ $\binom{\tilde{t}}{\tilde{b}}_L$, $\tilde{t}_R$, $\tilde{b}_R$	$\tilde{t}_{1,2}$, $\tilde{b}_{1,2}$
leptons (l) (spin-$\frac{1}{2}$)	$\binom{e}{\nu_e}_L$, e_R $\binom{\mu}{\nu_\mu}_L$, μ_R $\binom{\tau}{\nu_\tau}_L$, τ_R	sleptons ($\tilde{l}$) (spin-0)	$\binom{\tilde{e}}{\tilde{\nu}_e}_L$, $\tilde{e}_R$ $\binom{\tilde{\mu}}{\tilde{\nu}_\mu}_L$, $\tilde{\mu}_R$ $\binom{\tilde{\tau}}{\tilde{\nu}_\tau}_L$, $\tilde{\tau}_R$	$\tilde{\tau}_{1,2}$
gauge/Higgs bosons (spin-1, spin-0)	g, Z, γ, h, H, A $W^{\pm}$, $H^{\pm}$	gauginos/Higgsinos (spin-$\frac{1}{2}$)	$\tilde{g}$, $\tilde{Z}$, $\tilde{\gamma}$, $\tilde{H}_1^0$ $\tilde{W}^{\pm}$, $\tilde{H}^{\pm}$	$\tilde{\chi}^0_{1,2,3,4}$ $\tilde{\chi}^{\pm}_{1,2}$
graviton (spin-2)	G	gravitino (spin-$\frac{3}{2}$)	$\tilde{G}$	

Most SUSY models impose R-parity:
Lightest SUSY particle stable (LSP)
→ "missing energy" (like ν)

How Fast Can SUSY Be Found?

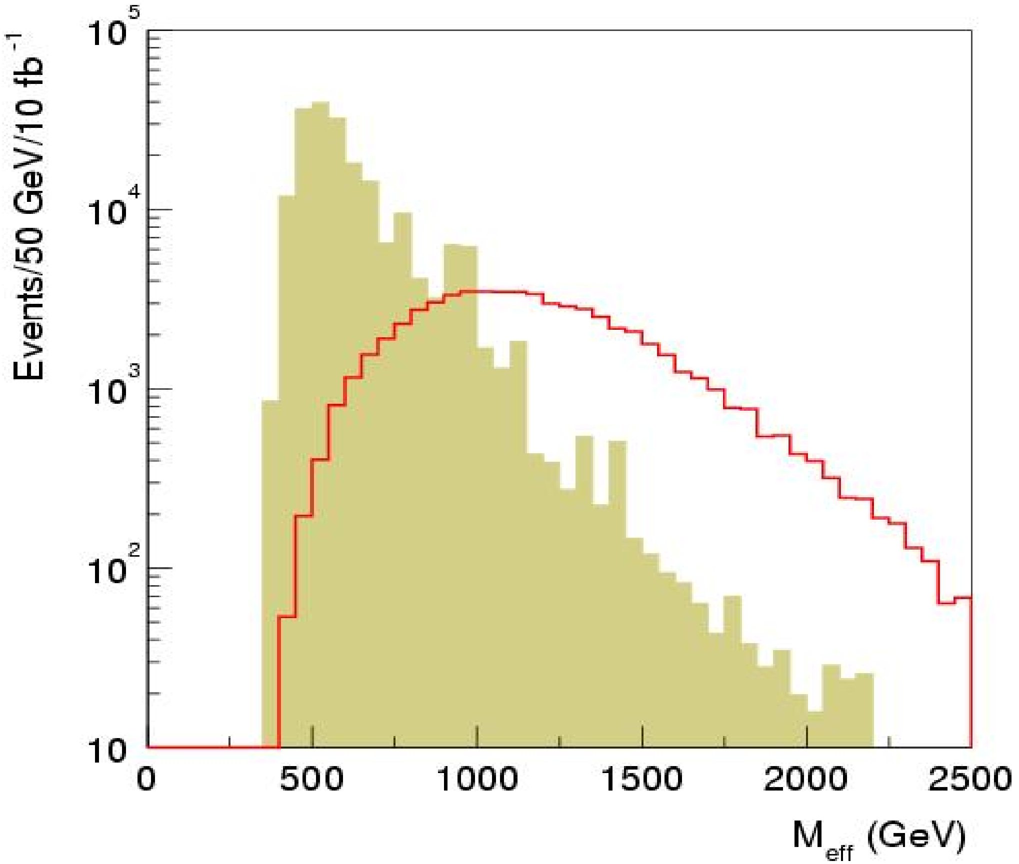
- Plot shows reach in SUSY space
- Solid regions not allows
- Hatched region ruled out by LEP
- Contours in luminosity for specifed squark and gluino masses
- Example: 100 pb^{-1} adequate to discover 1 TeV gluino



Must be ready for new physics on Day 1 !

How SUSY Might First Be Observed

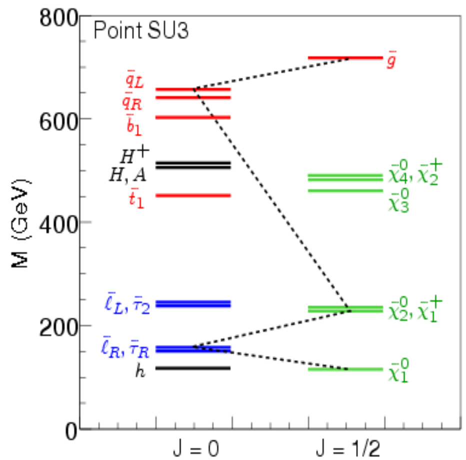
- Heavy SUSY particles decay to quarks, gluons and leptons
- LSP leaves missing energy
- Look for objects with at least 4 high pT objects plus missing energy
- Example has SUSY masses ~700 GeV

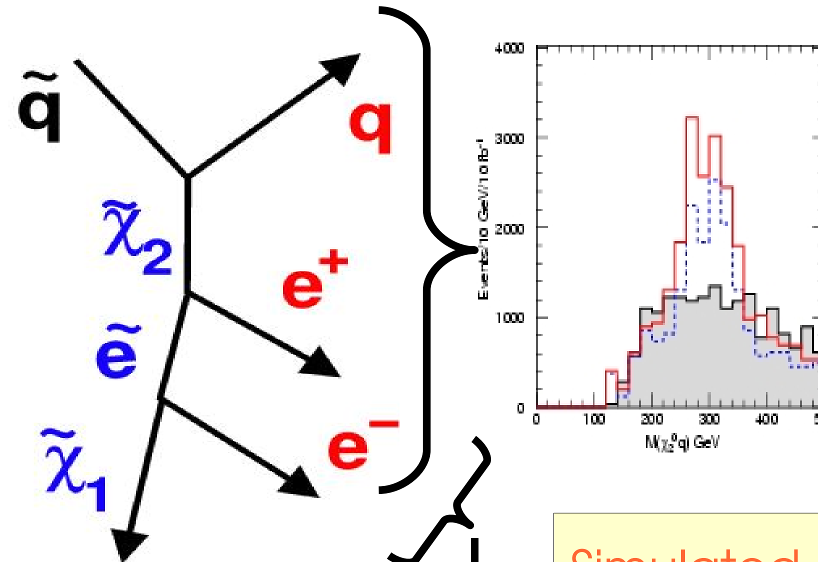


Example typical of models with new particles (strongly coupled) at large mass

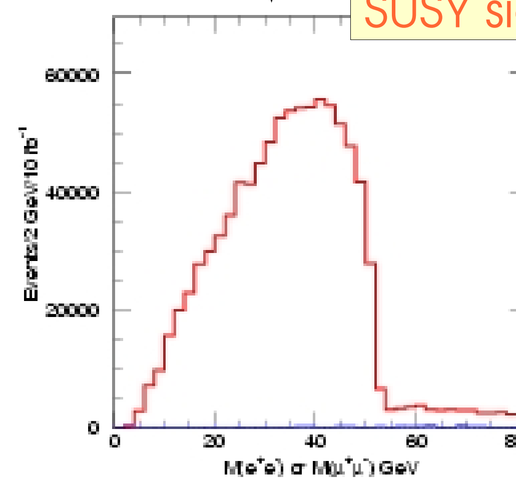
If SUSY Observed, Will Require Many Measurements to Constrain Model

- Basic Principle: Work down decay chains
  - Measure masses and mass differences
  - Test universality among generations
- Example: squark decay



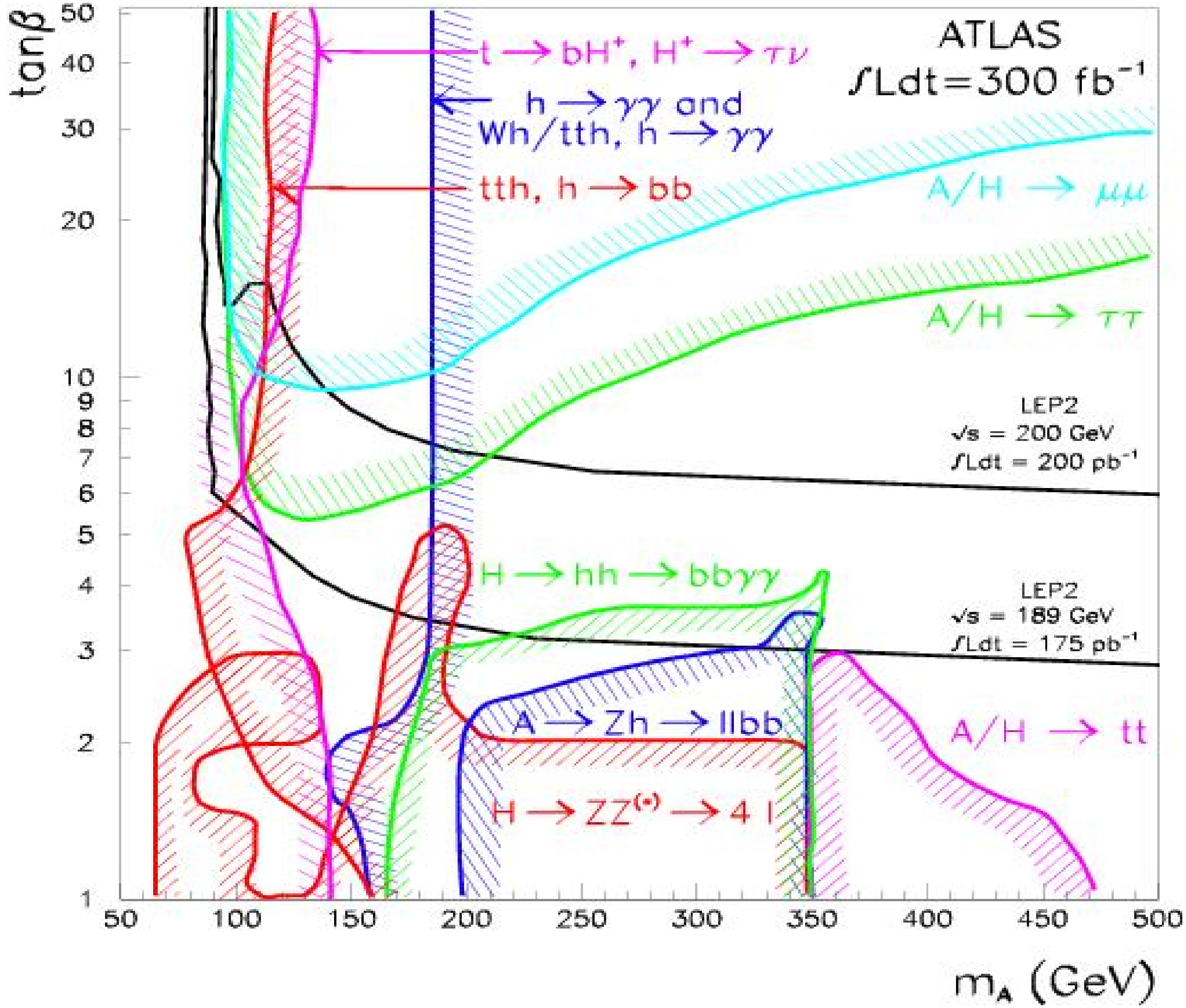


Simulated SUSY signals



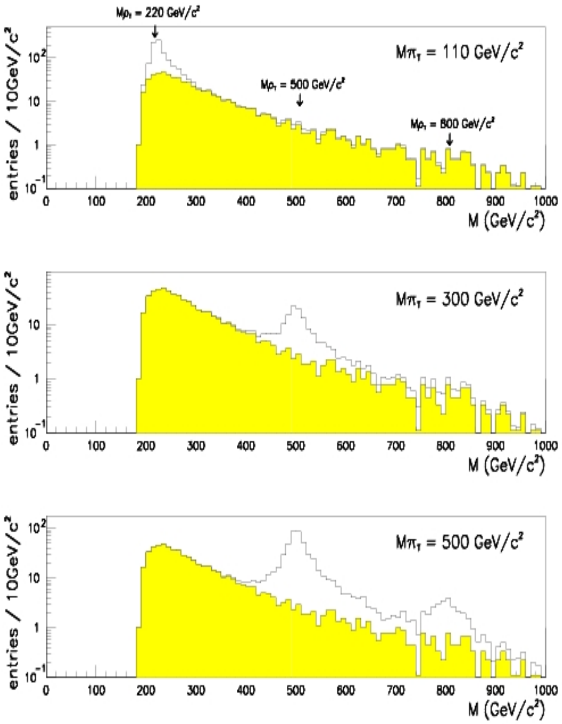
How about SUSY Higgs?

- Complicated, model dependent
- In most cases can only observe <u>some</u> of the SUSY higgs



Technicolor

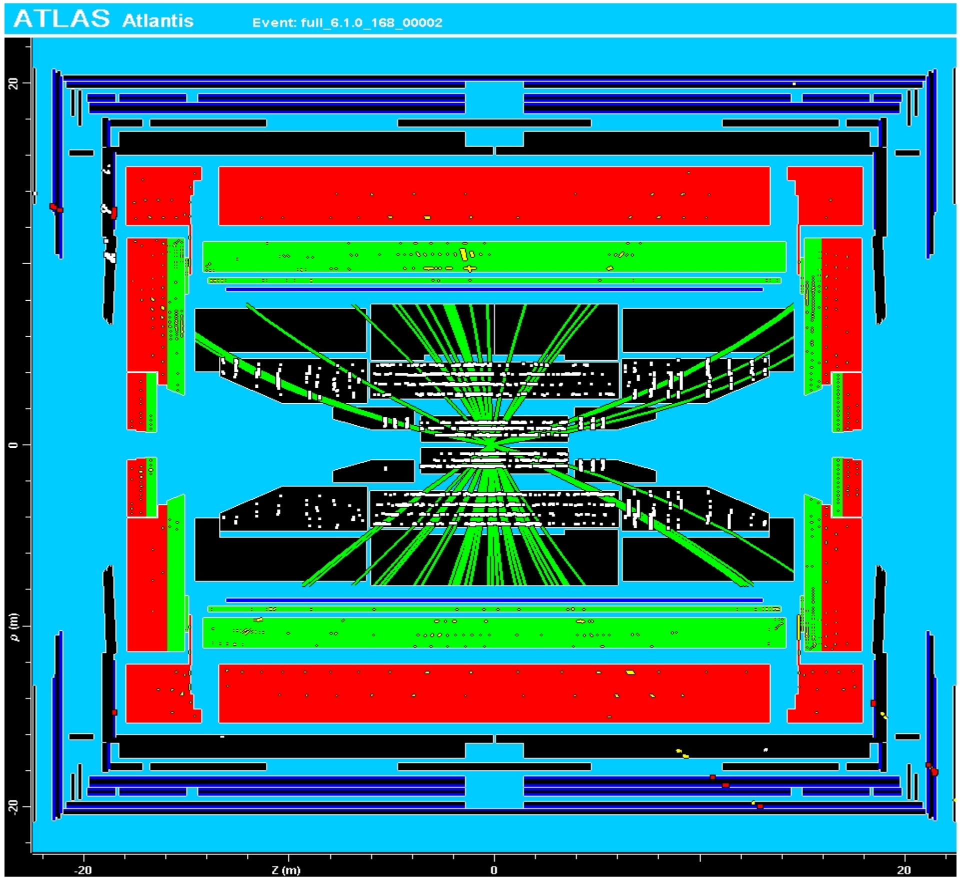
- Here fundamental Higgs replaced by a composite particle
- A natural candidate: $t\bar{t}$ pairs
- Many technicolor models already ruled out
- Signatures: resonances in top-pairs, WW, WZ, ZZ



Simulated signals for technicolor signals

Extra Dimensions

- Why is the Planck scale so different from EWSB scale?
- Perhaps it isn't:
  - Extra dimensions change Gauss's Law
  - Can bring scale for gravity to become strong to TeV scale
- New interactions can drive EWSB



Simulated example of mini-black hole
Quantum Gravity at the LHC??

Conclusions

- Mass of all known particles generated dynamically via EWSB
- Many possibilities exist: SM, SUSY, Technicolor, Extra Dimensions
- But we know EWSB scale ~ 1 TeV, within reach of the LHC
- We will determine experimentally which solution is correct

Exciting Times Ahead !!