S. Dawson

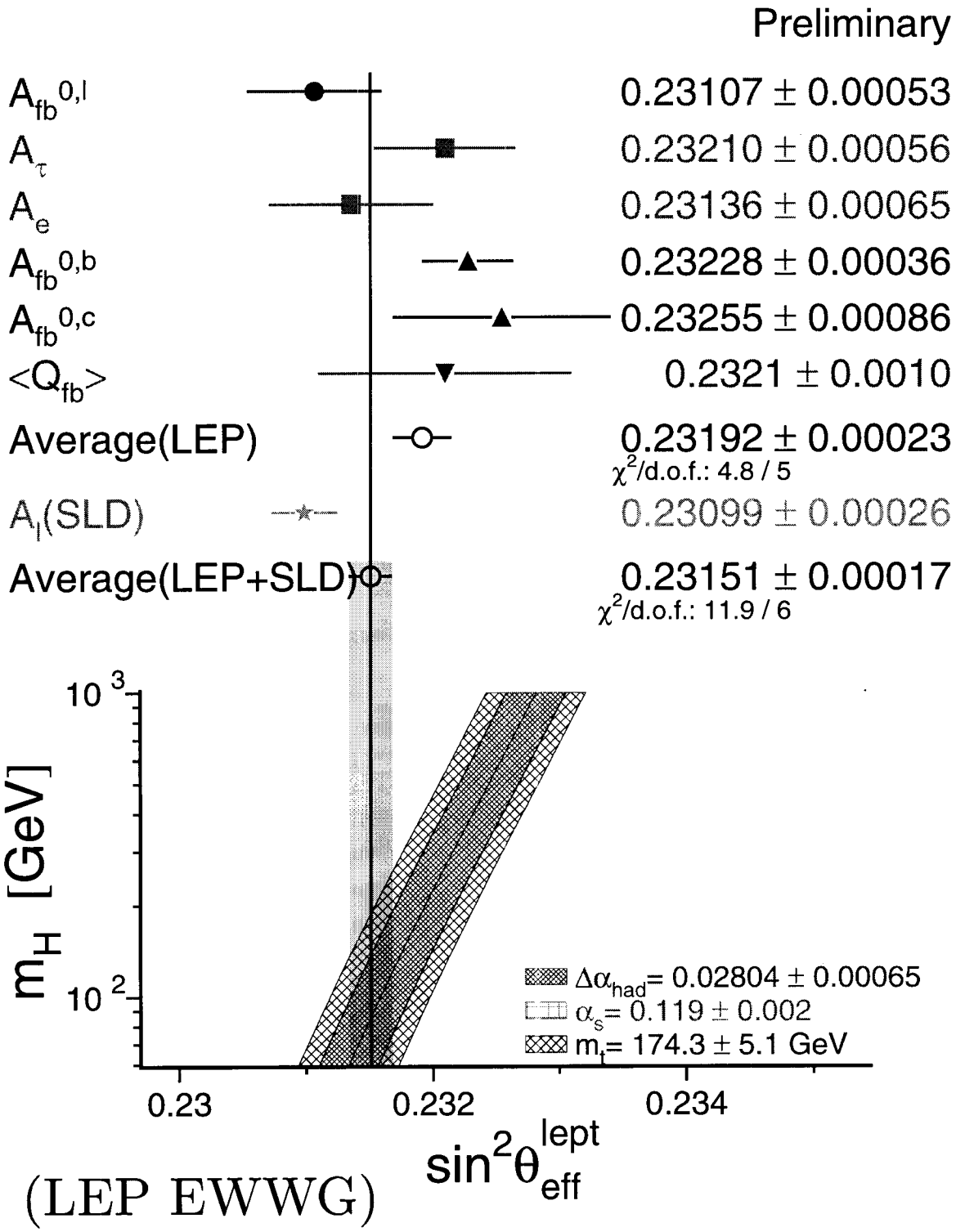
September, 1999

Physics in 2006:

Where will we be?

- Results from the Tevatron and LHC
- Can we predict the open questions of 2006?
- Will there be a physics motivation for a high energy e^+e^- or a $\mu^+\mu^-$ collider?

- EW theory confirmed to .1 % level



(LEP EWWG)

Electroweak Symmetry Breaking only unconfirmed area of SM

- Predicts physical Higgs boson with VEV, $v = \frac{2M_W}{g}$
- Higgs couplings to fermions $\sim \frac{M_f}{v}$
- Higgs mass only free parameter

Consistency of theory limits M_h:

- If no new physics before M_{pl}

$$130\ GeV < M_h < 180\ GeV$$

Must find Higgs!

The Electroweak Sector

Standard Model Higgs Program:

- Find the Higgs
- Verify its properties (couplings/mass)
- Verify spontaneous symmetry breaking mechanism

Current limit from direct searches at LEPII:

$$M_h > 95 \ GeV \qquad at \ 95\% \ cl$$

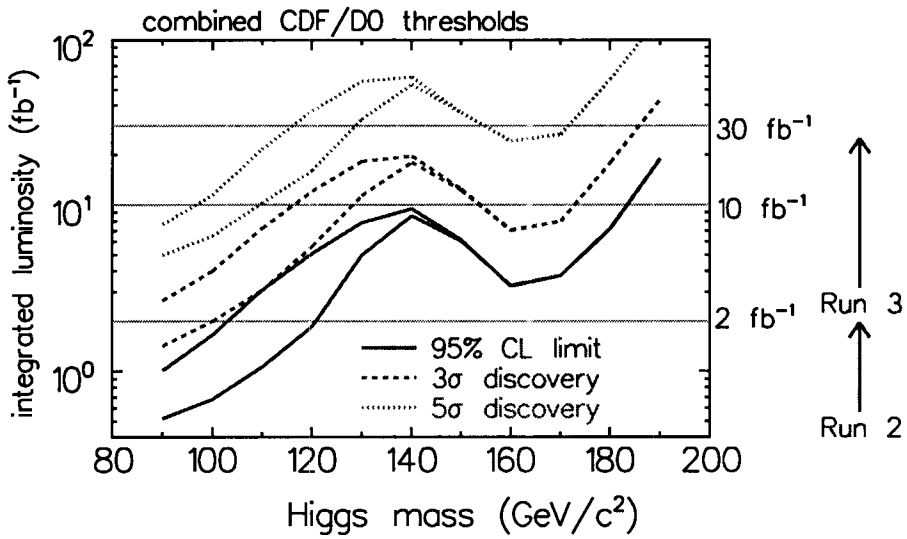
LEPII will find:

$$M_h < 105 \ GeV$$

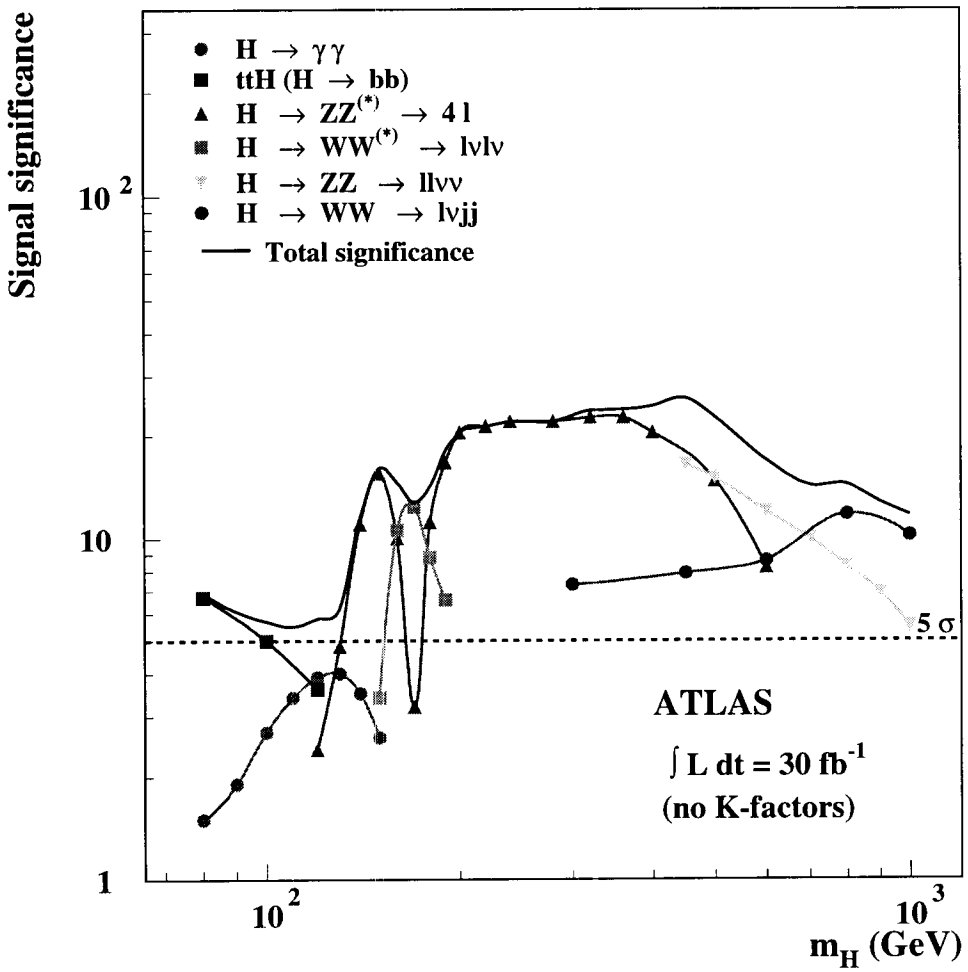
$$(\text{at } \sqrt{s} = 205 \ GeV \text{ and } \int \mathcal{L} = 160 \ pb^{-1})$$

Fermilab Higgs Study:

- Combines small signals from many channels
- Max $S/\sqrt{B}$ in any channel .9 for 1 fb^{-1}
- Needs high luminosity for discovery
- With $10 fb^{-1}$, 5σ discovery level is $M_h < 95\ GeV$



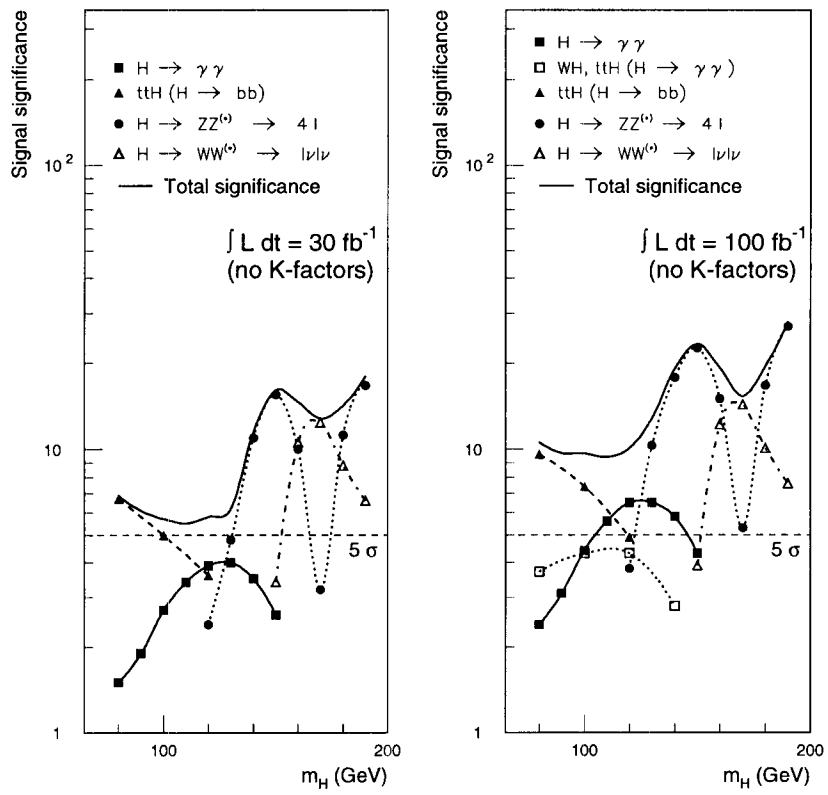
LHC will find Higgs up to $M_h < 800\ GeV$



- $t\bar{t}h$ dominates low mass signal

(ATLAS Physics TDR)

Before LC, Higgs will be discovered if it exists!



- With 100 fb^{-1} at LHC can find Higgs in multiple channels for all M_h!
- Absolute rates provide some confirmation of couplings

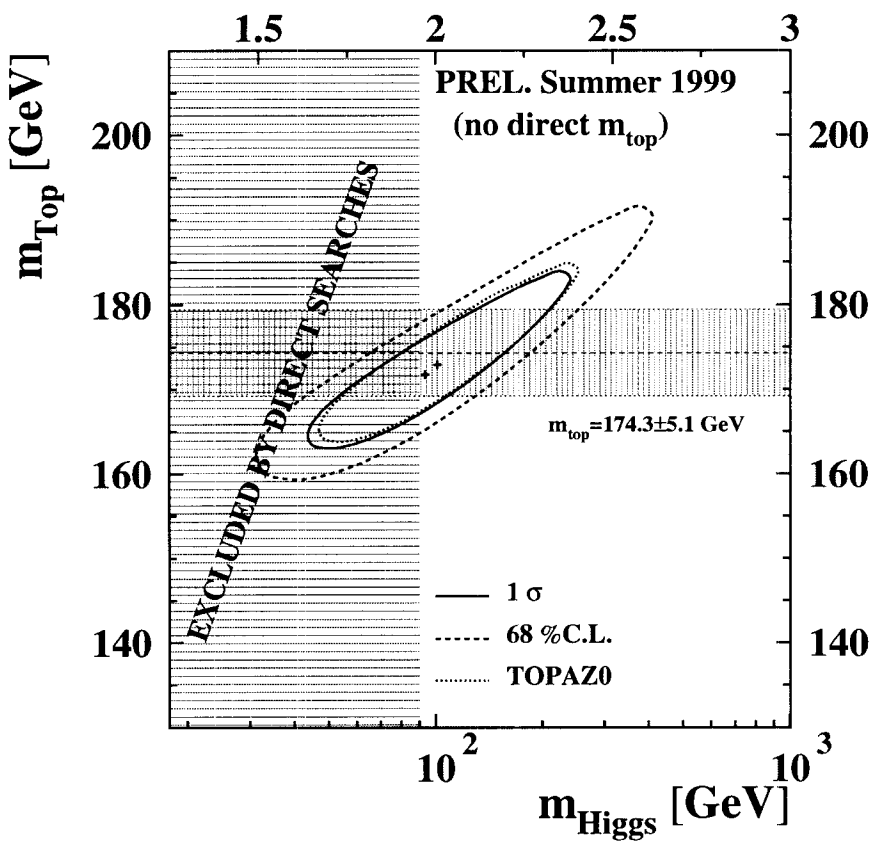
Compare direct measurement/ indirect limit:

$$M_h < 217 \ GeV \qquad at \ 95\% \ cl$$

Contributions to EW observables $\sim log(M_h)$

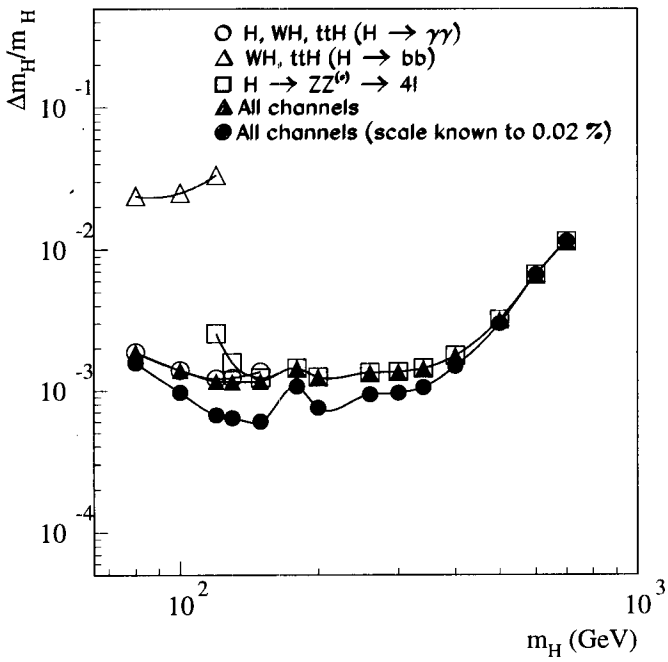
$$\delta\rho = \frac{11g^2}{96\pi^2 \tan^2\theta_W} \log\left(\frac{M_h}{M_W}\right)$$

Checks theory at quantum level



(LEP EWWG)

LHC with 300 fb^{-1} direct measurement:



(ATLAS Physics TDR)

Indirect Measurements			
Collider	ΔM_W	ΔM_t	$\frac{\delta M_H}{M_H}$
LEPII, TeV	30 MeV	4 GeV	57 %
LHC	15 MeV	2 GeV	26 %
500 GeV LC	15 MeV	200 MeV	17 %

(Accomando et al, TESLA study)

Supersymmetric models useful for comparison with SM

- SUSY has 5 Higgs bosons: $h, H, A, H^{\pm}$

- Absolute upper bound on lightest Higgs:

$$M_h < 110 - 130 \ \ GeV$$

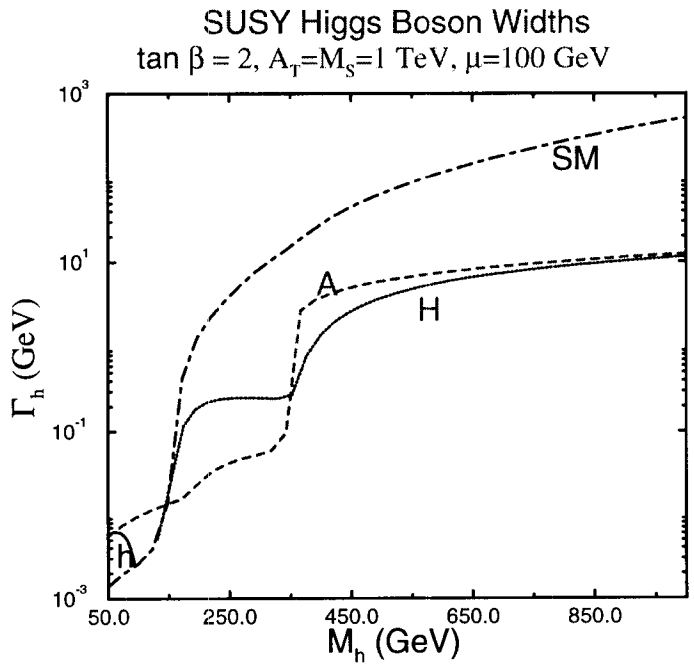
- Relations between masses of Higgs bosons:

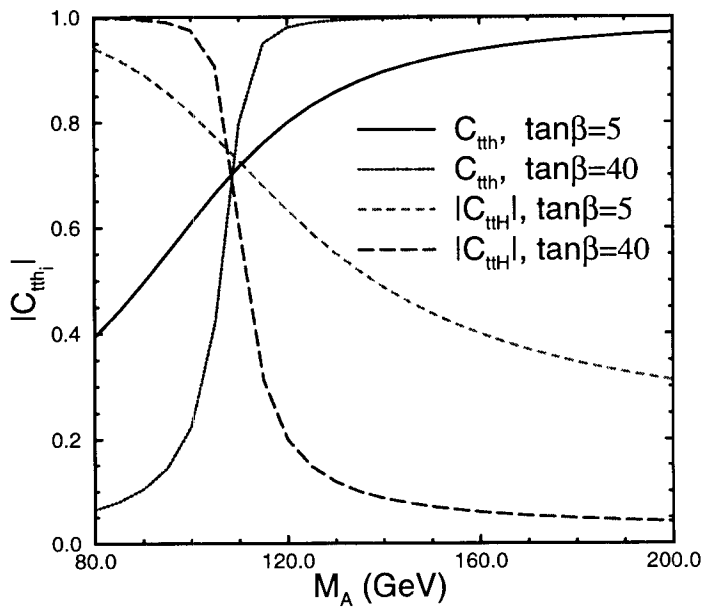
  2 free parameters: $\tan\beta$, M_A

- Goal is to probe regions in $\tan\beta - M_A$ plane

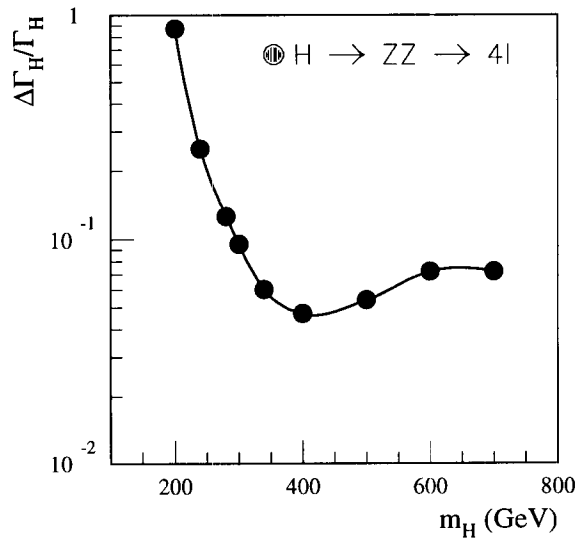
Verify Higgs Properties

- SUSY Higgs width, couplings different from SM





- At LHC with $\int \mathcal{L} = 300 fb^{-1}$:



(ATLAS Physics TDR)

Measurements of individual modes can discriminate between models

- Example: SM $t\bar{t}h$ production

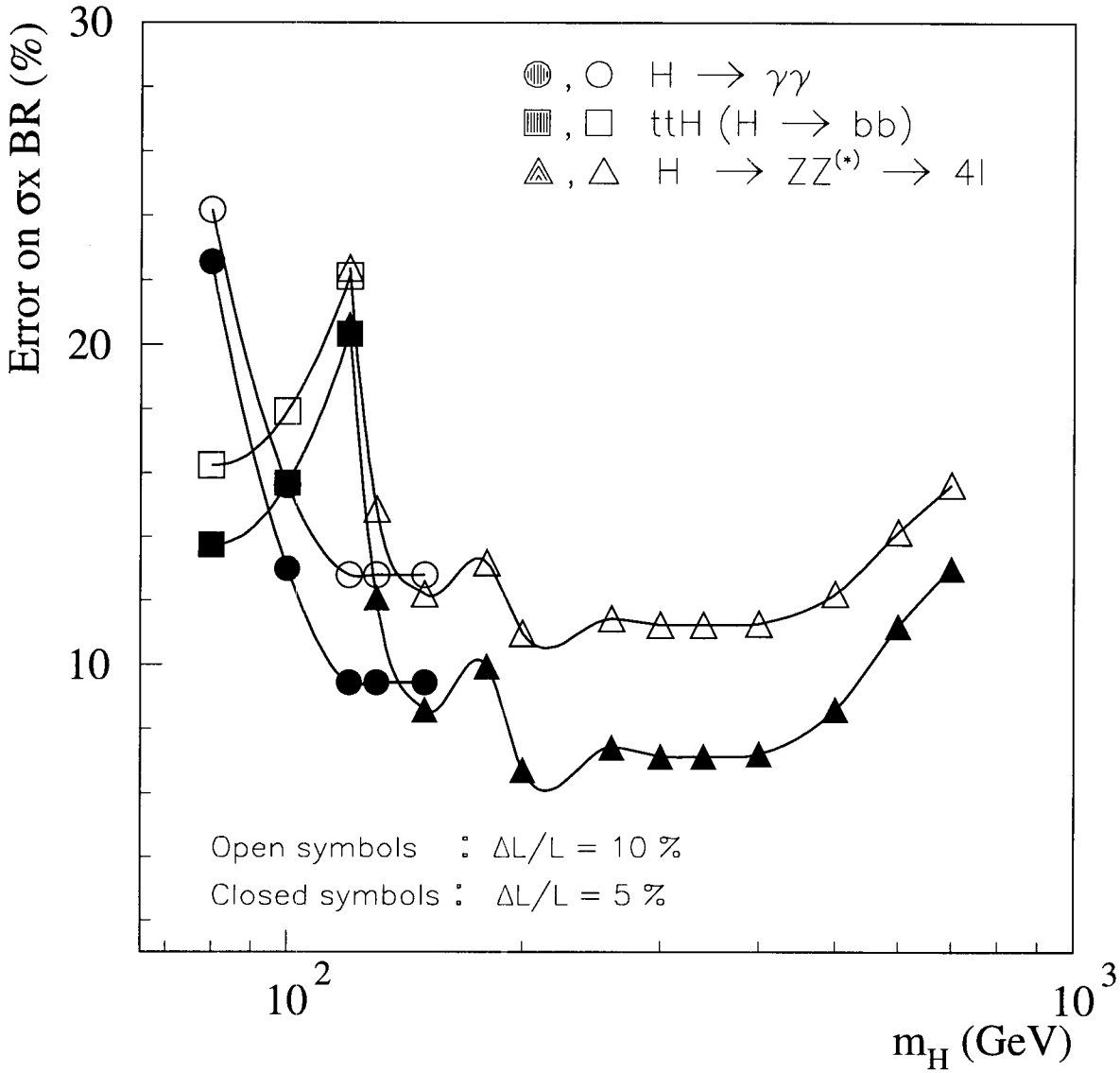
$\frac{\delta g_{ttH}}{g_{tth}}$ in e^+e^- with 1000 fb^{-1}		
$M_H(GeV)$	$\sqrt{s} = 500\ GeV$	$\sqrt{s} = 1\ TeV$
100	.08	.06
110	.12	.06
120	.21	.07
130	.44	.08

(Baer, Dawson, Reina)

- Rates at $\sqrt{s} = 500\ GeV$ low because of phase space suppression
- LHC with 300 fb^{-1}, $\frac{\delta g_{ttH}}{g_{ttH}} \sim 25\ \%$

(Snowmass, 96)

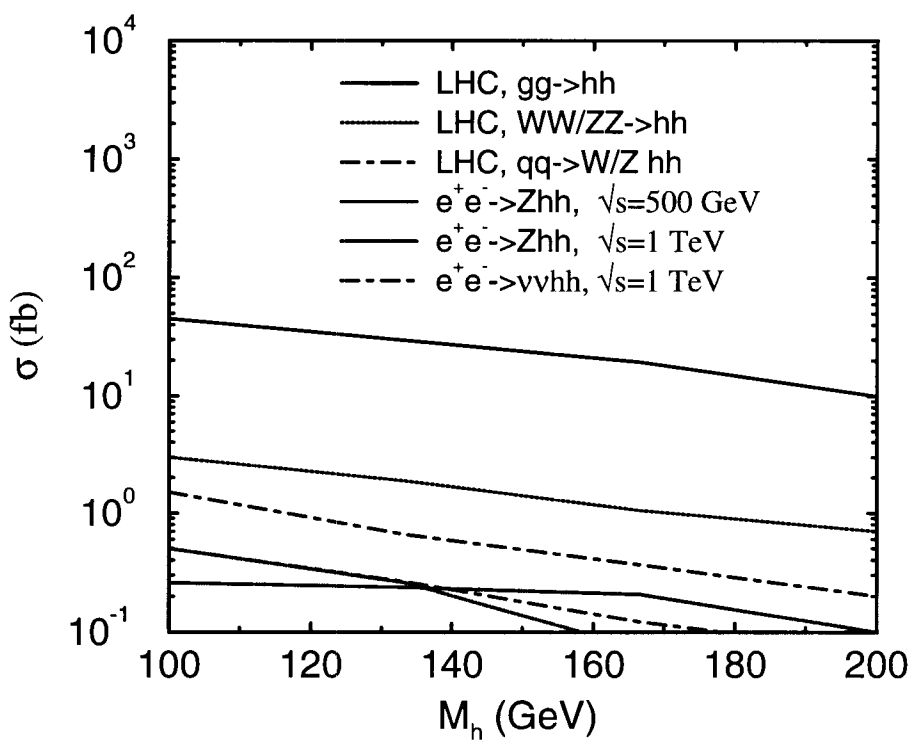
LHC with 300 fb^{-1}

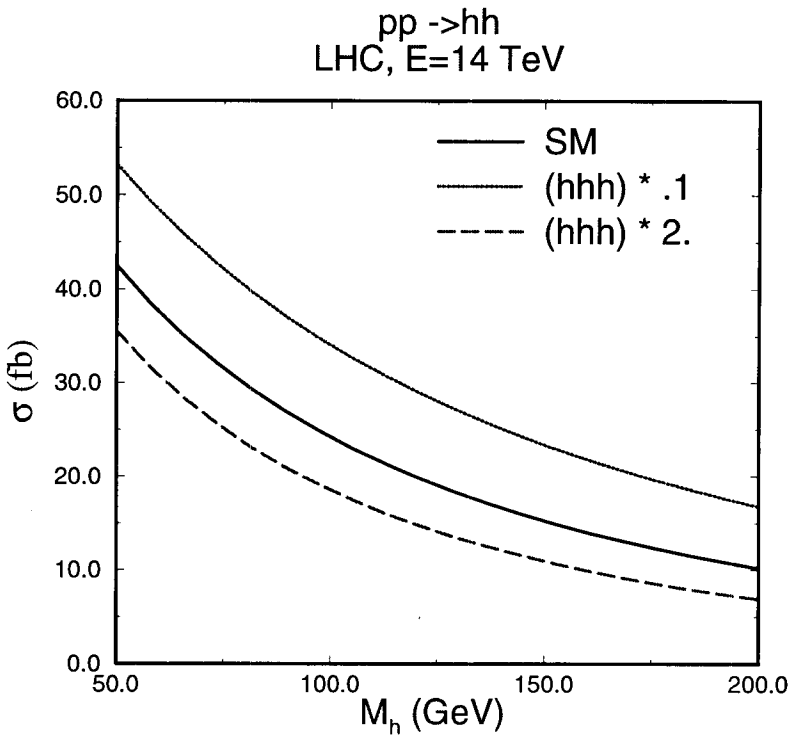


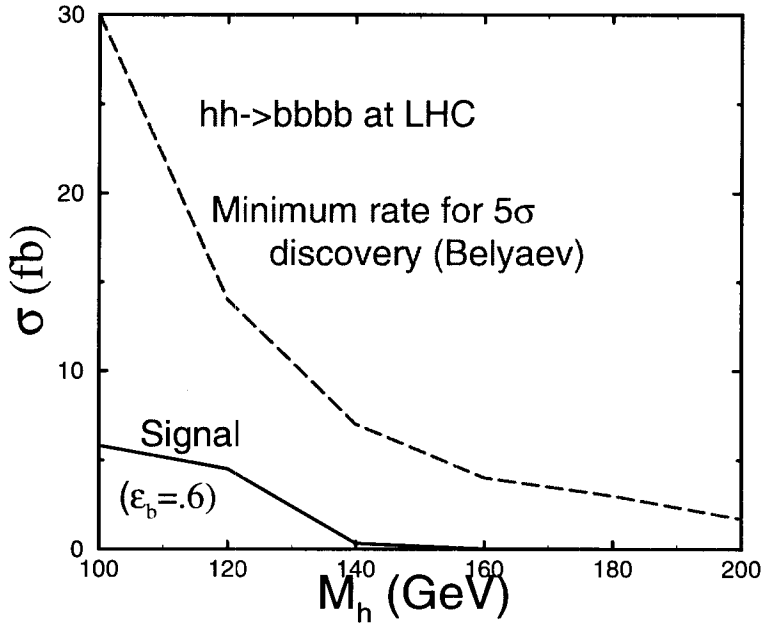
Verify structure of Higgs Potential
Standard Model:

$$V = \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right)^2$$
$$= \frac{M_h^2}{2} h^2 + \frac{M_h^2}{2v} h^3 + \frac{M_h^2}{8v^2} h^4$$

- Need to measure multi-Higgs production
- New physics could change tri-linear and quartic Higgs couplings

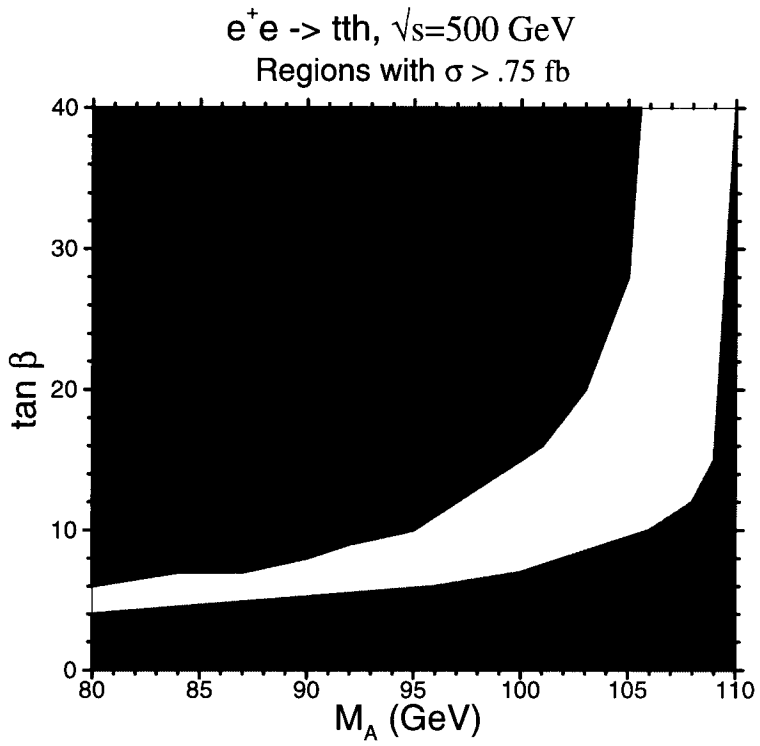






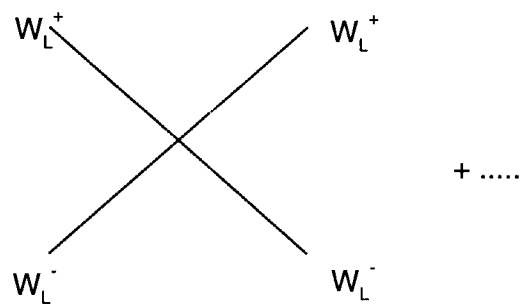
- Must wait for next machine to do this physics!

- New possibilities in MSSM:
  - When kinematically allowed, resonance effect from $gg \to H \to hh$
  - Can have hh, hH, HH, Ah, AH, AA production



Strong Electroweak Symmetry Breaking

Suppose there is no Higgs?



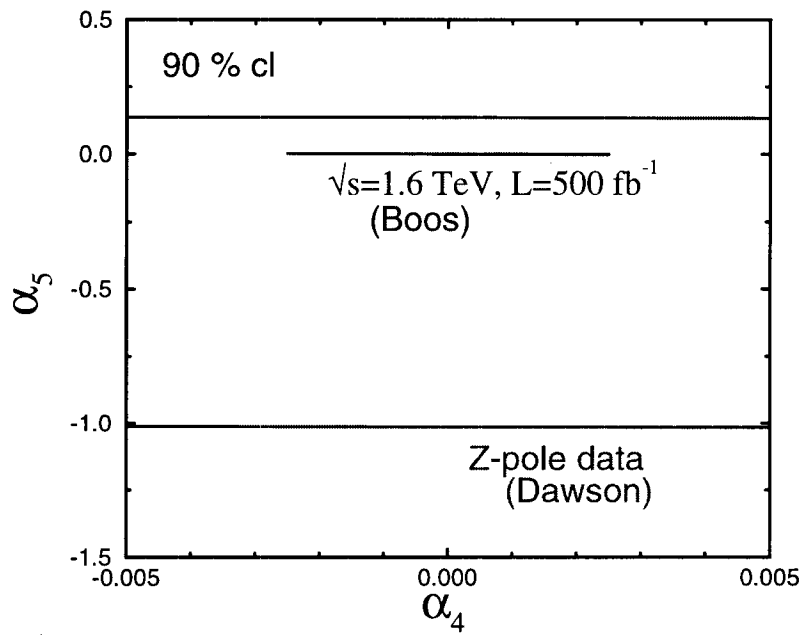
$$\mathcal{A}\left(V_L^+ V_L^- \to V_L^+ V_L^-\right) \sim \frac{s}{v^2}$$

- Effects grow with energy; unitarity violated at $\sqrt{s_c} \sim 3\ TeV$
- Above $\sqrt{s_c}$, see resonances, $\rho_T, \omega_T, \ldots$
- Higgs-less theory non-renormalizable
- Systematic expansion in $\frac{s}{\Lambda^2}$
  (Λ is scale of new physics)

$$\mathcal{L} \sim \mathcal{L}_{SM} + \sum_i \alpha_i \mathcal{L}_i + \ldots.$$

- Expect $\alpha_i \sim \frac{v^2}{\Lambda^2}$

- Example: α_4, α_5 contribute to 4-point functions in
  - Precision measurements
  - LHC, $VV \to VV$
  - High energy LC

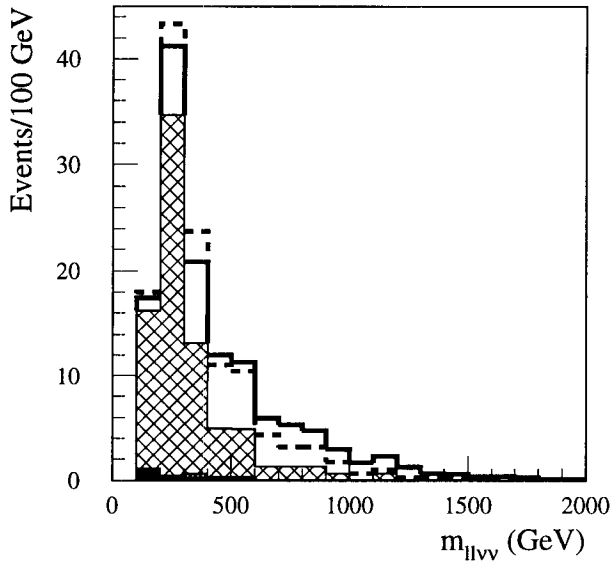


- Cannot do this physics with l^+l^- collider at $\sqrt{s} = 500\ GeV$

Very hard at LHC;

Small number of events (1-15)

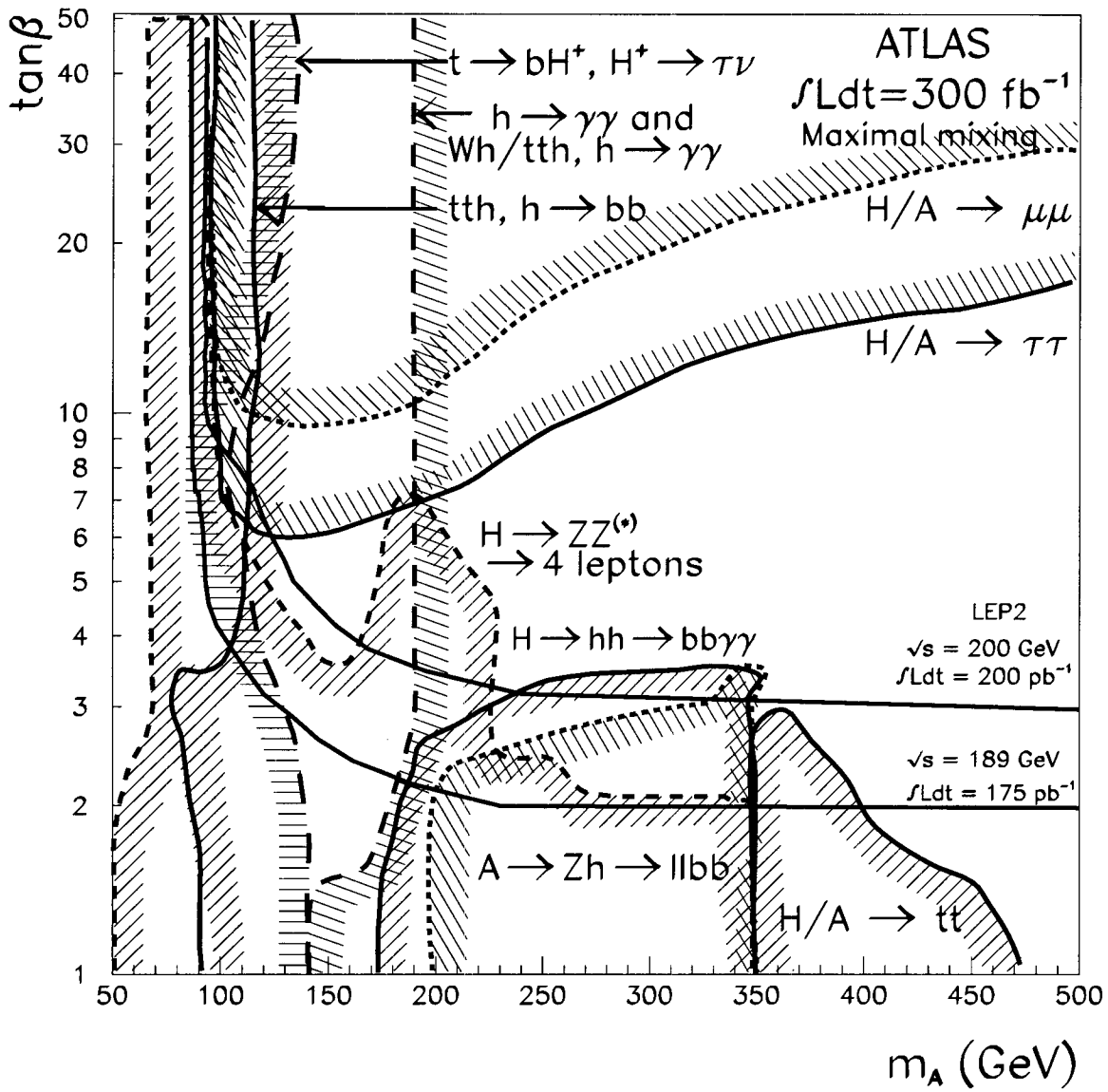
300 fb^{-1}, $W^+W^+ \to ll\nu\nu$



- High energy really wins for strong symmetry breaking!

Unravel the spectrum of SUSY

- LHC cannot find heavy Higgs in some regions of parameter space
- LC could find heavy Higgs for intermediate $\tan\beta$, $M_H \sim M_A$



Open EW Questions in 200x

- Will have some measurements of Higgs mass, couplings
  Want more precise couplings to discriminate between models
- $hhh, hhhh$ couplings in SM unknown
  In SUSY, some regions of parameter space probed
- Not much info on strong EW symmetry breaking;
  High energy wins big here