Higgs Signals at the ilc

Rick Van Kooten
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The LHC Early Phase for the ILC
Fermilab
12 – 14 April 2007

Higgs Physics at the ILC: Implications of Early Results from LHC

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Questions

- *What could be the impact of early LHC results on the choice of the ultimate ILC energy range and the ILC upgrade path? Could there be issues that would need to be implemented into the ILC machine and detectors design from the start?*

  Higgs: ILC priority benchmark for doing precision property measurements; a lot of thought already into it for machine & detector

- *Could there be cases that would change the consensus about the physics case or an ILC with an energy of about 500 GeV?*

- *What are the prospects for LHC/ILC interplay based on early LHC data?*

Overview

- Case 1: Detection of one state with properties that are compatible with those of a Higgs boson

→ ILC: precision measurement of properties

  → impact on machine energy, upgrade path

  → LHC/ILC interplay

Is it really a Higgs boson?

Is it really the SM Higgs boson?

Overview

- Case 1: Detection of one state with properties that are compatible with those of a Higgs boson

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→ impact on machine energy, upgrade path

e.g., Hey, it's light. Can we do enough with a lower-energy ILC?

→ LHC/ILC interplay

- Case 2: No experimental evidence for a Higgs boson at the early stage of the LHC
  - Is actually there, but hard to detect at the LHC

→ LHC/ILC interplay *Possible to observe it with ILC?*

Overview

- Case 1: Detection of one state with properties that are compatible with those of a Higgs boson

➡ ILC: precision measurement of properties

➡ impact on machine energy, upgrade path

e.g., Hey, it's light. Can we do enough with a lower-energy ILC?

➡ LHC/ILC interplay

- Case 2: No experimental evidence for a Higgs boson at the early stage of the LHC
  - Is actually there, but hard to detect at the LHC

➡ LHC/ILC interplay *Possible to observe it with ILC?*

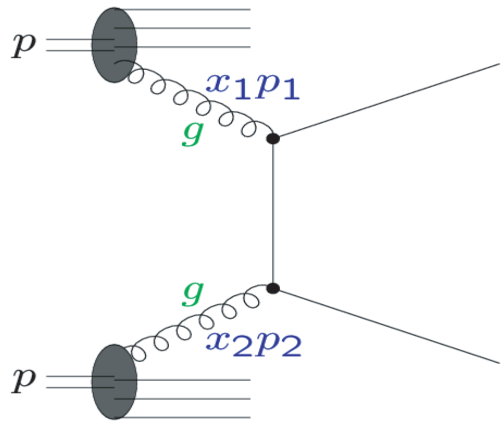
  - Is *really* not there

➡ impact on machine energy, upgrade path (e.g., GigaZ, and/or very high energy)

➡ LHC/ILC interplay

Motherhood

LHC: pp scattering at 14 TeV



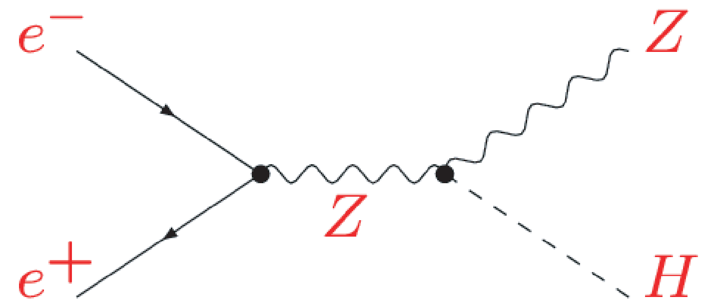
Scattering process of proton constituents with energy up to several TeV, strongly interacting

mass reach

- huge QCD backgrounds, low signal–to–background ratios

From G. Weiglein

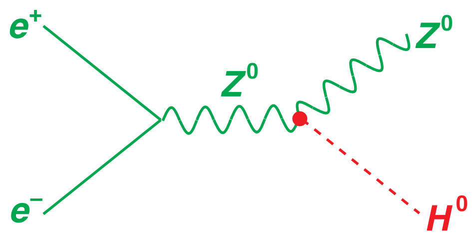
ILC: e^+e^- scattering at ~0.5–1 TeV



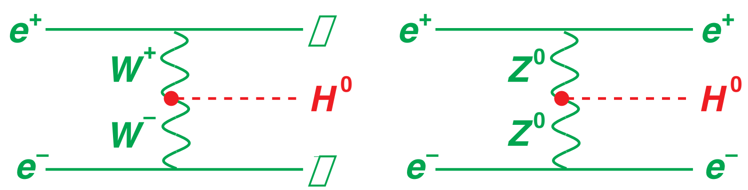
Clean exp. environment: well-defined initial state, tunable energy, beam polarization, GigaZ, $\gamma\gamma$, $e\gamma$, e^-e^- options, . . .

- rel. small backgrounds high-precision physics
- relatively low rates, energy limited

Higgs Production at ILC

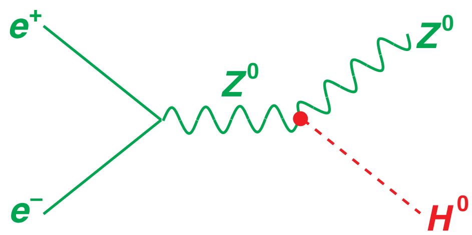


- "Higgs"strahlung



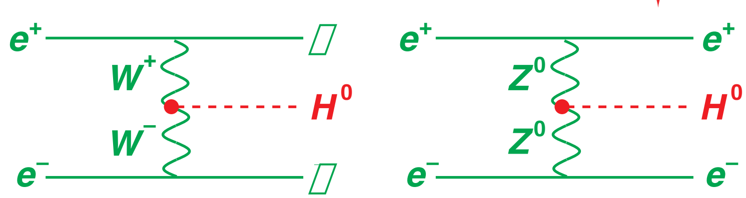
- Fusion

Higgs Production at ILC



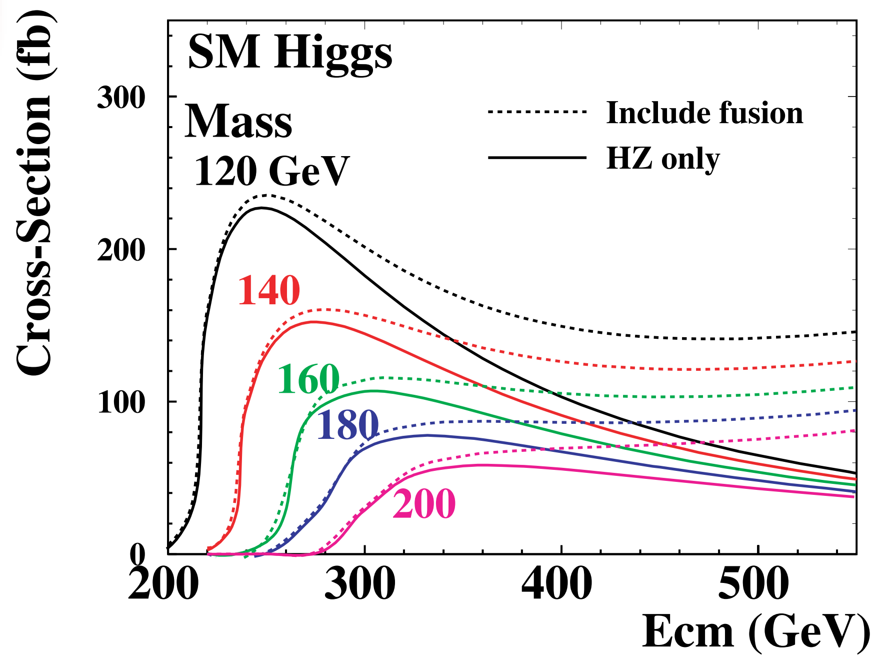
- "Higgs"strahlung
- Precision mode

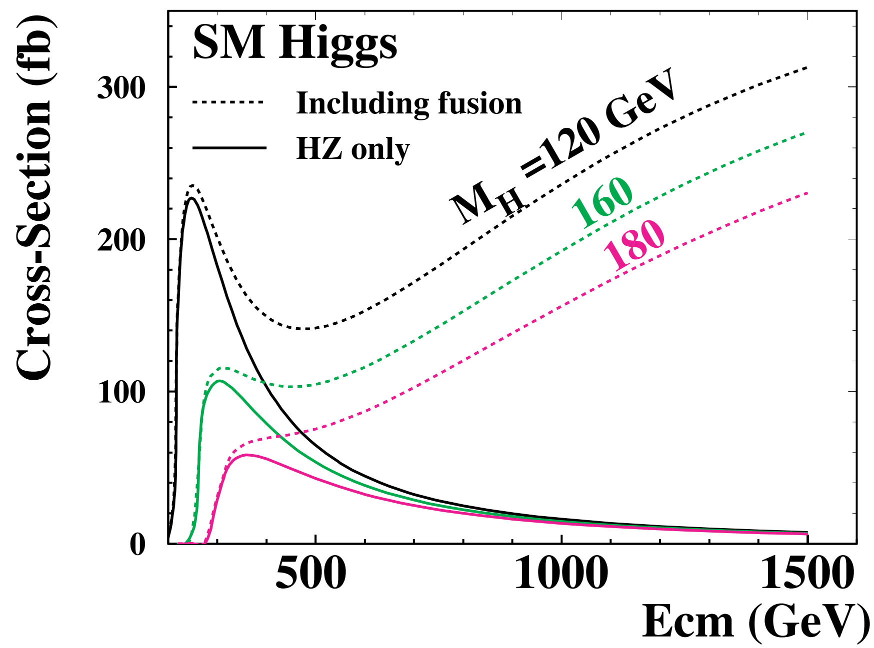
Beam polarization:
reduce multi-boson backg.
& change relative fractions



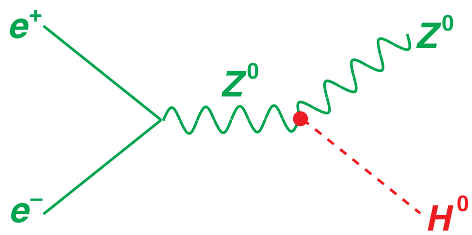
- Fusion
- "Reach" mode

If Standard Model Higgs:

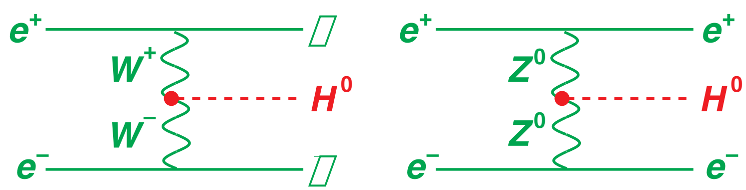




Higgs Production at ILC



- "Higgs"strahlung
- Precision mode



- Fusion
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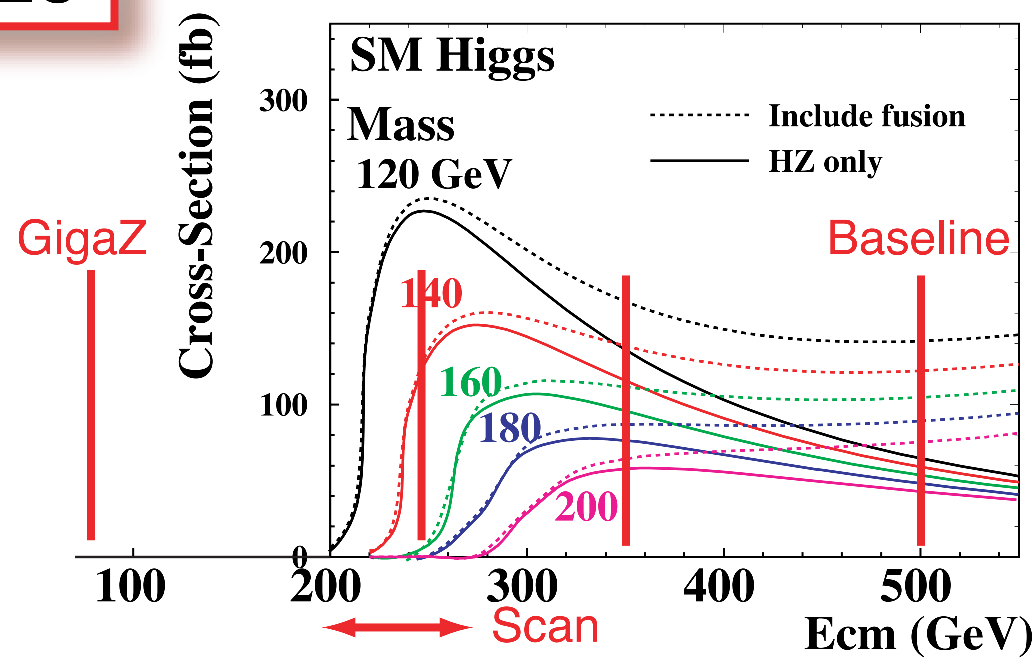
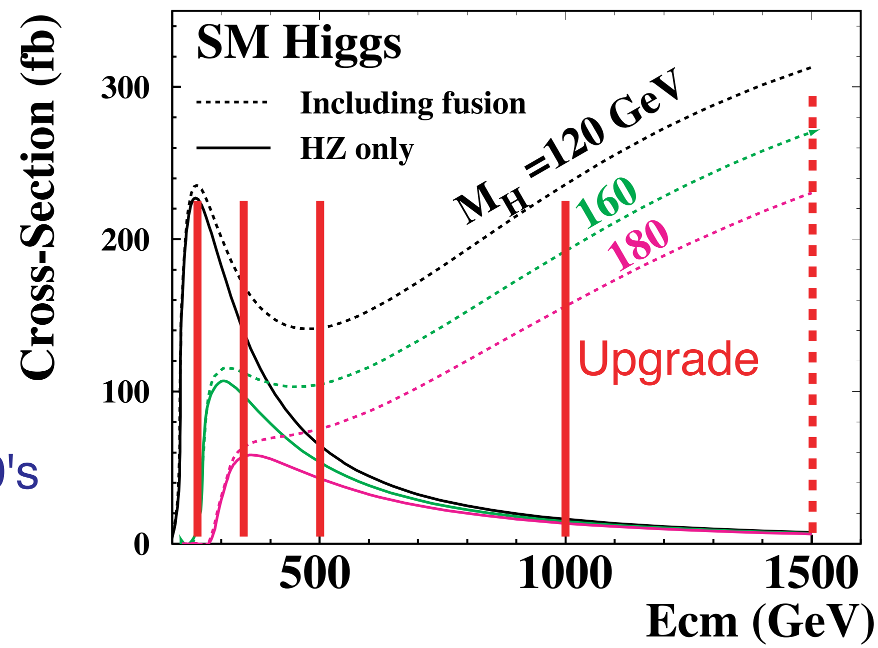
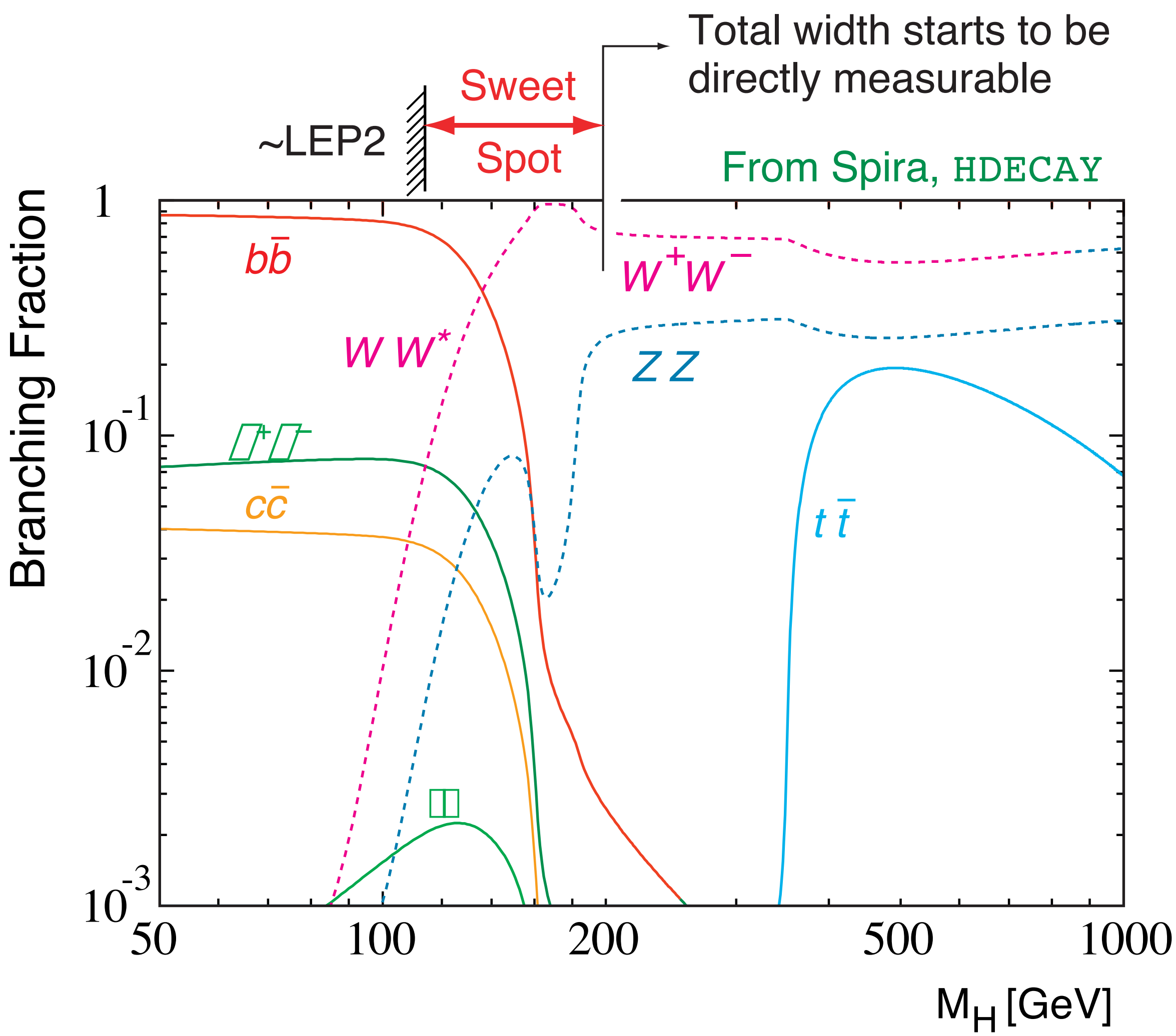
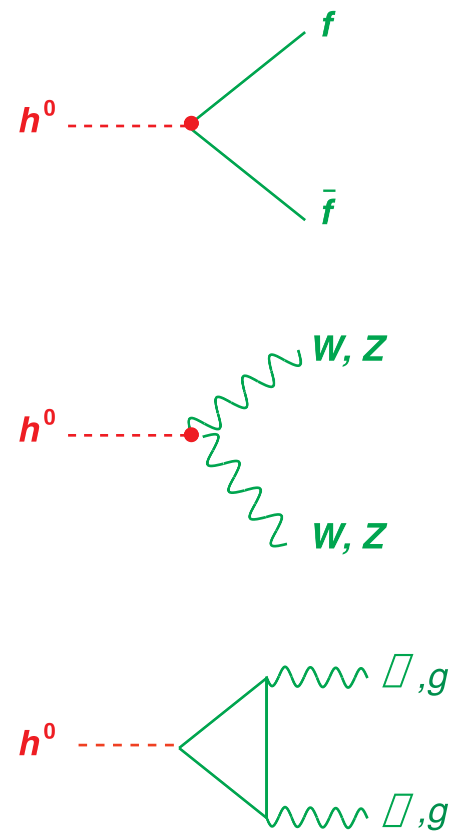




- Copious production! 1000's to 10,000's of Higgstrahlung and *WW*-fusion events per year.

Higgs Decay (SM-like)





- Branching ratios and cross sections give the couplings

Measure its Properties

Is it really a Higgs boson? Is it the SM Higgs boson?

- Mass $\square = M_h^2/v$ Consistent w/ EW constraints?

(ultimately, both LHC & ILC find mass to < 0.1%; to be useful, needs "match" of ILC m_{top} precision)

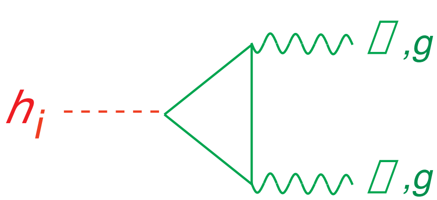
- Yukawa couplings: (mass to fermions?) $g_{ffH} \,\square\, m_f$? Br's, □
- Mass to vector bosons: $g_{VVH} \,\square\, M_V$? Br's, □ $V = Z,W$

More than one Higgs?

$\square \frac{M_V^2}{v^2} w_i \quad \square\, w_i^2 = v^2$

Fully generate mass of Z ?

- Decays to other bosons: Br's, □



Sensitive to new physics

- Form of Higgs Potential, self-coupling, $\square_{HHH}$ $\square_{ZHH}$

- Total Width (direct) or Br's, □ (indirect)

- Spin, parity, CP nature

Threshold, Ang. dist.□□□

Time constraints: won't be able to include other options of ILC (□□, e□, ee)

Measure its Properties

Is it really a Higgs boson? Is it the SM Higgs boson?

- ✓ Mass   □ = M_h^2/v Consistent w/ EW constraints?

(ultimately, both LHC & ILC find mass to < 0.1%; to be useful, needs "match" of ILC m_{top} precision)

- ✓ Yukawa couplings: g_{ffH} □ m_f ?   *Br*'s, □
  (mass to fermions?)
  Some, low prec.

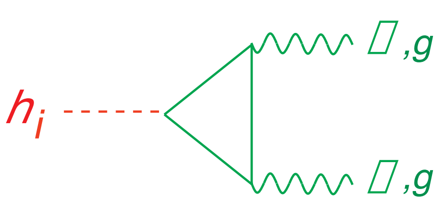
- ✓ Mass to vector bosons: g_{VVH} □ M_V ?   *Br*'s, □
  low prec
  $V = Z, W$

More than one Higgs?

□ $\frac{M_V^2}{v^2} w_i$ □ $w_i^2 = v^2$

Fully generate mass of *Z* ?

- Decays to other bosons: *Br*'s, □



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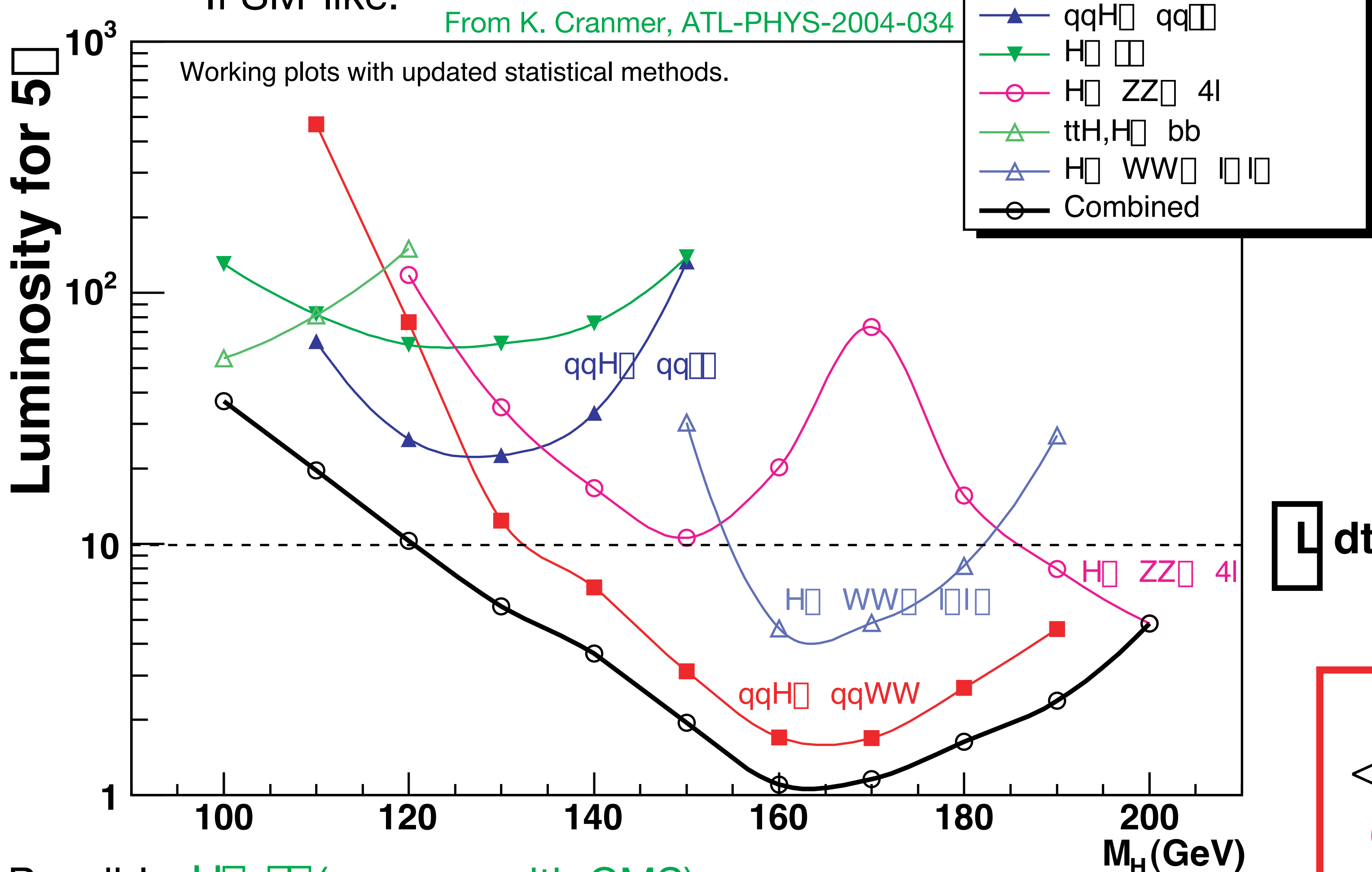
LHC Gives Single State ...

If SM-like:



□L dt = 10 fb^{-1}

Mass from
<1% to ~3%
(ZZ) (□□)

Possible: H□ □□(more so with CMS)

Possible: qqH□ qq □□
(partic. if
SUSY *h*)

qqH□ qqWW
H□ WW□ l□l□
Likely

H□ ZZ□ 4l
Likely

M_h < 180 – 200 GeV? LHC-ILC Interplay

- LHC does not measure absolute total production cross section, instead:

$$\sigma(H) \times Br(H \to X) = \frac{\sigma(H)^{SM}}{\Gamma_{\rm prod}^{SM}} \cdot \frac{\Gamma_{\rm prod}\Gamma_{\rm decay}}{\Gamma_{\rm tot}}$$

Narrow-width approximation

- Gives *combinations* of widths, couplings
  - $g_{HVV} < 1.05\,\Gamma_{HVV}^{SM}$
  - Observe $H \to VV$ in weak vector boson fusion (WBF)

Duhrssen et al., hep-ph/0407190

- Get absolute couplings

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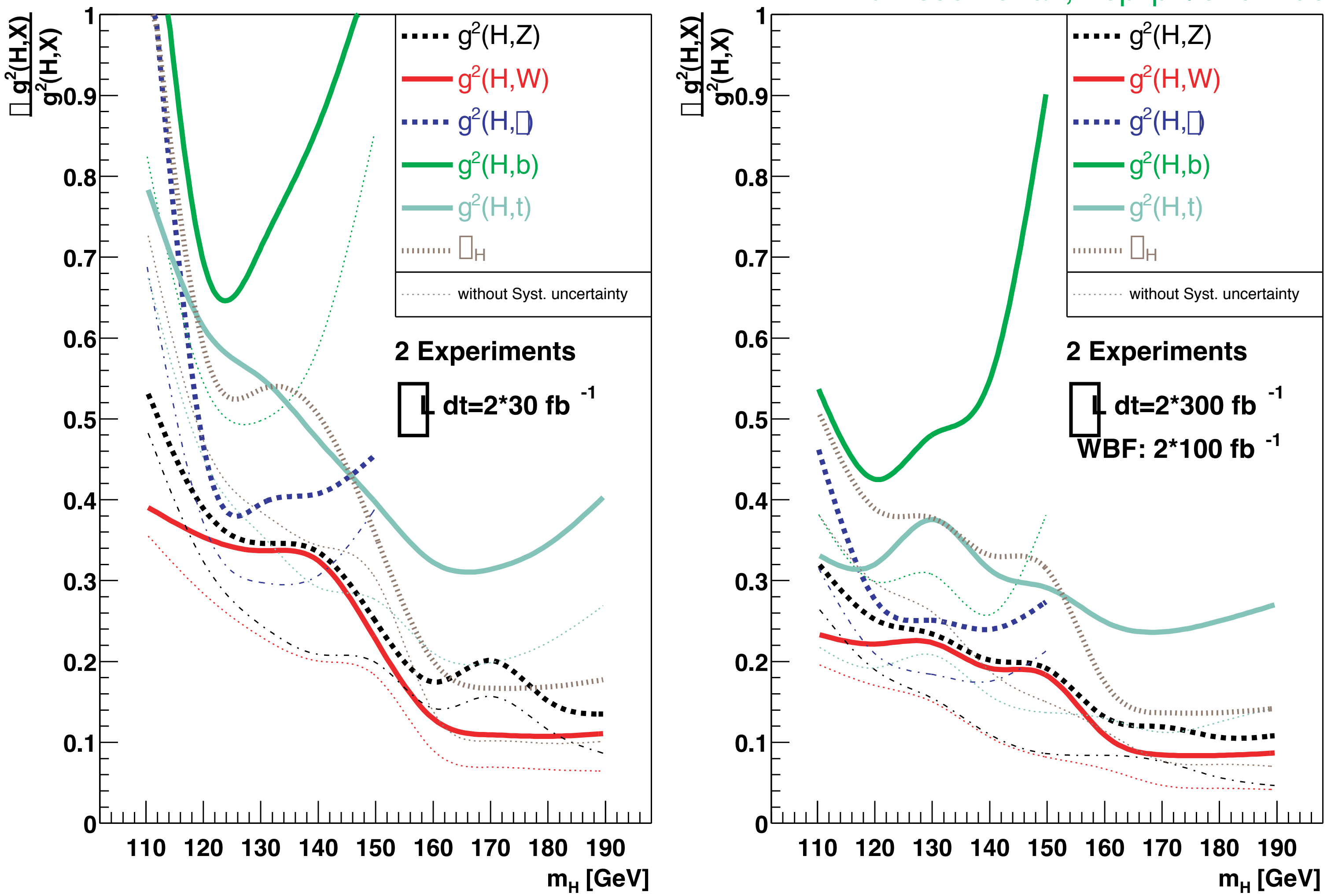
Caveats

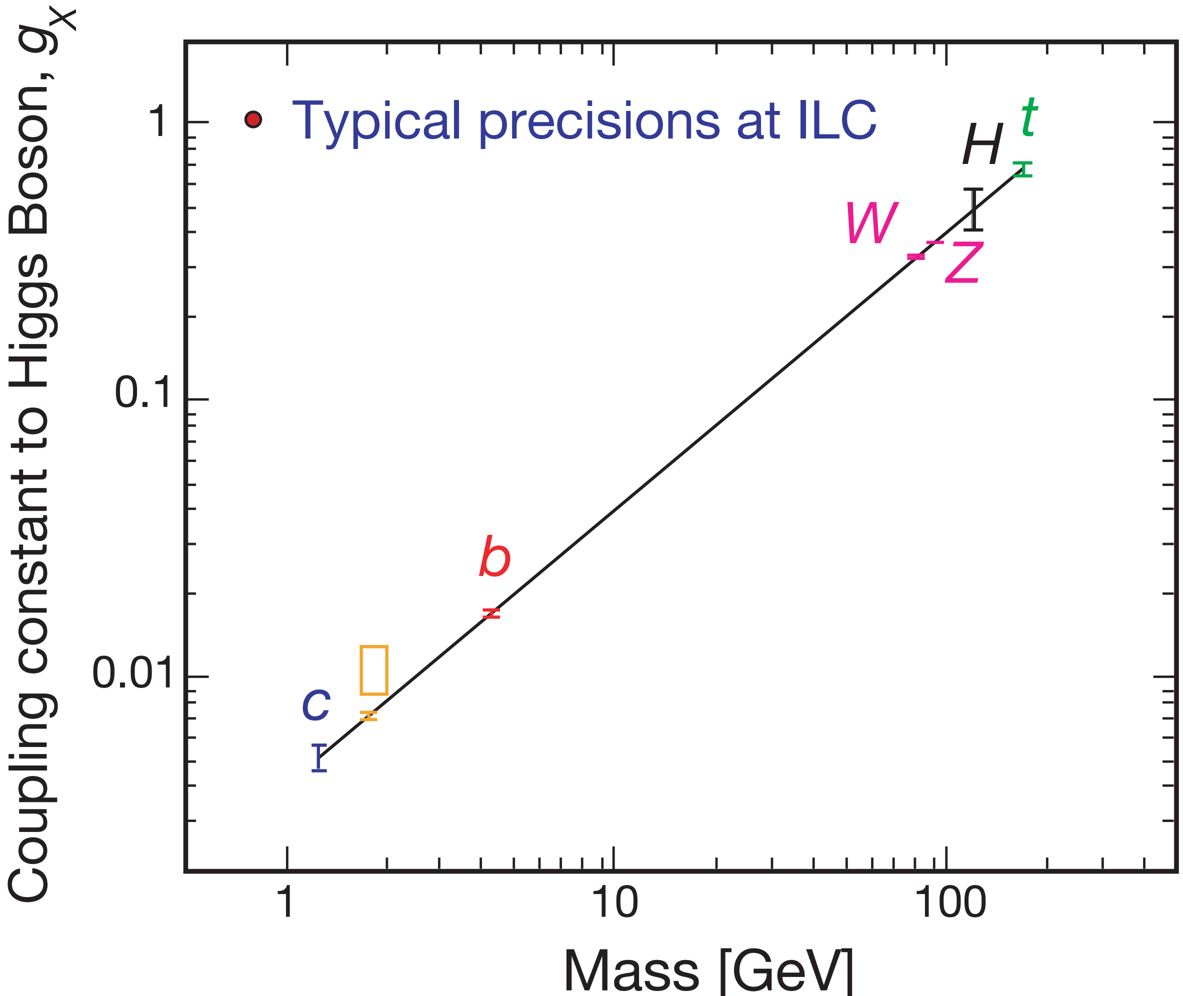
- Valid only in weakly-interacting models
- What if WBF rate significantly above or below SM?
- Interesting physics in that 5%

Duhrssen et al., hep-ph/0407190



- Gives uncertainties on g^2_{HXX} (not on g_{HXX})
- Note differences with and without systematic errors

What do we want?



Is it really a Higgs boson?

Does it couple to mass?

Single Higgs boson generating all of the mass?

Yukawa couplings:

u-type vs. *d*-type (*t* vs. *b*)

quark vs. lepton (*b* vs. □)

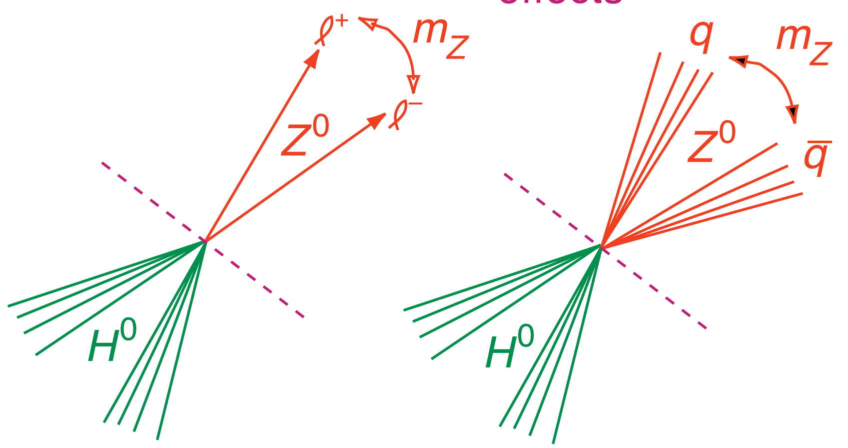
2nd gen. vs. 3rd gen (*c* vs. *t*)

Couplings at ILC

Recoil mass:

$$m^2_{\mathrm{recoil}} = s - 2E_Z\sqrt{s} - M_Z^2$$

Include bremstrahlung and beamstrahlung effects

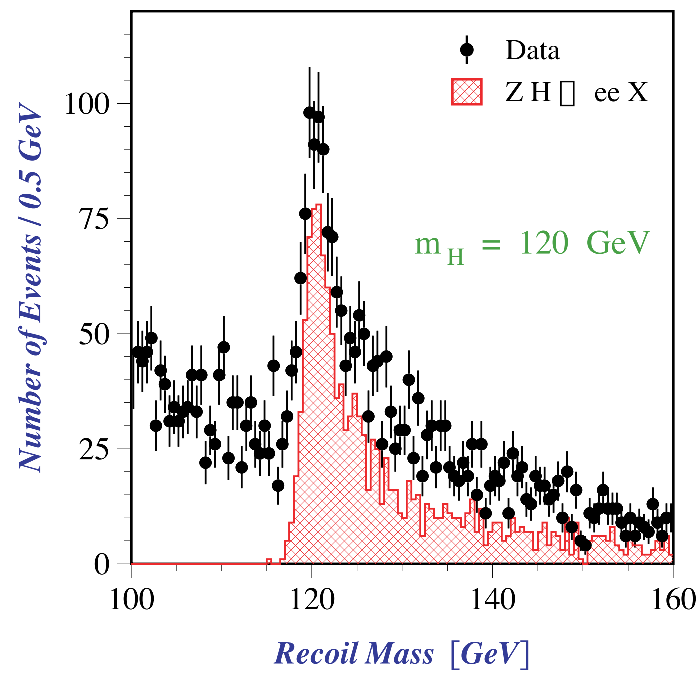


All decays to X, find branching fractions to a few %

- More precision from

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

TESLA CDR Detector
Garcia-Abia, Lohmann



- $\sqrt{s}$ = 350 GeV, 500 fb^{-1}
- Cross section,

$$\frac{\Delta\sigma_{ZH}}{\sigma_{ZH}} = 3.5\%$$

$$\Rightarrow \quad \frac{\Delta g_{ZZH}}{g_{ZZH}} = 1.8\%$$

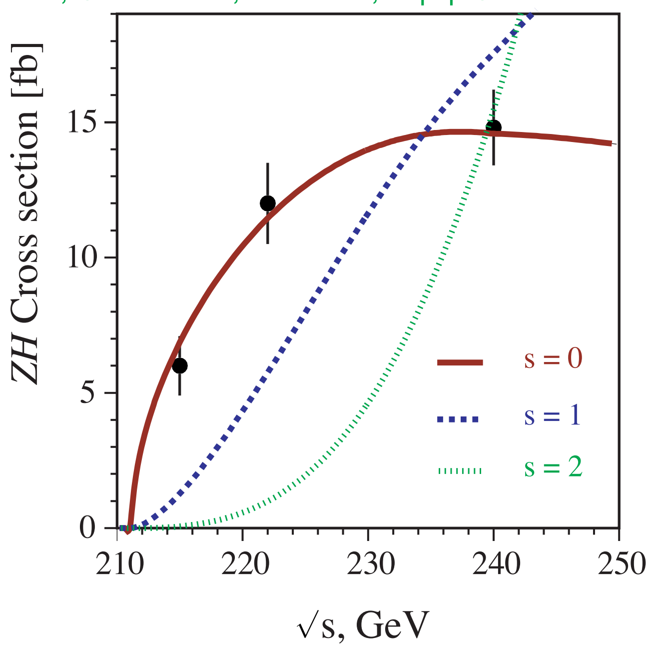
Possible implications of LHC single state on ILC energy:

- Higgs observable up to mass of ~350 GeV for 500 GeV machine

Optimal Energy?

- Spin (scalar)

Dova, Garcia-Abia, Lohmann; hep-ph/0302113



m_h = 120 GeV
20 fb^{-1}/point

- Capability to scan in energy part of baseline design

- If $m_h < 200$ GeV from LHC,
and

$\sqrt{s} \sim 350$ GeV or just above threshold best for Br's, cross sections, couplings, etc.
(see also F. Richard, P. Bambade LAL 07-03)

why not just have the ILC be a low-energy "Higgs factory"?

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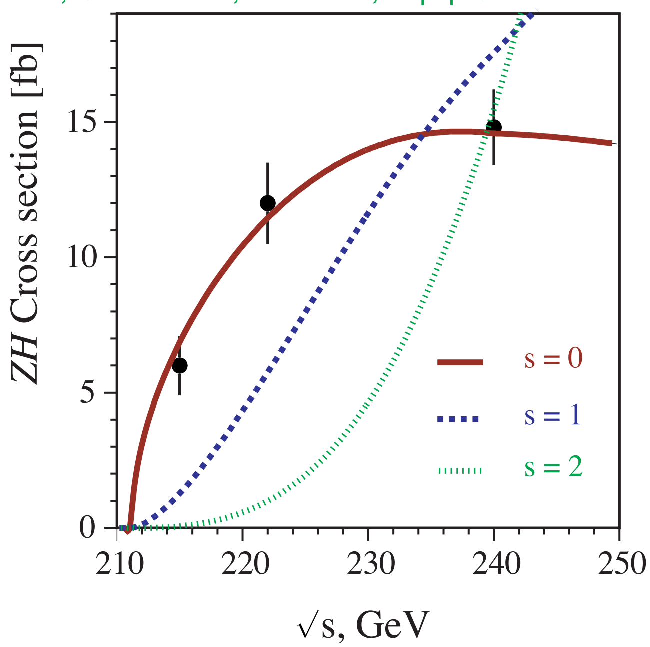

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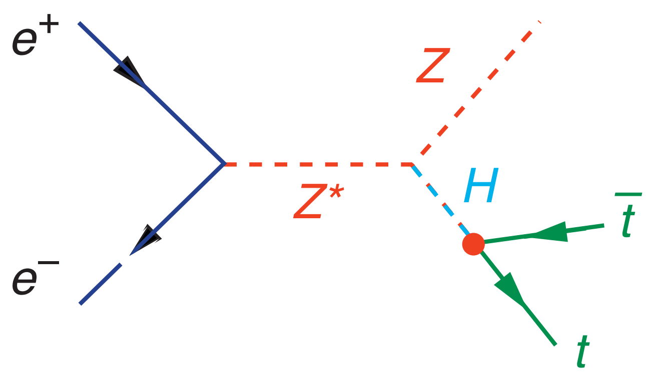
why not just have the ILC be a low-energy "Higgs factory"?

- Because of the importance of:
  - *tth*
  - Higgs self-coupling (Higgs potential)
  - Rare Br's

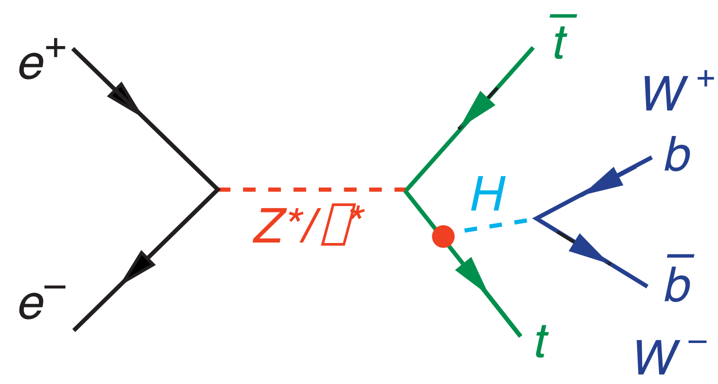
Plus more LHC-ILC interplay

Coupling to top, g_{ttH}

- Heavy Higgs



- But if light, radiation off top

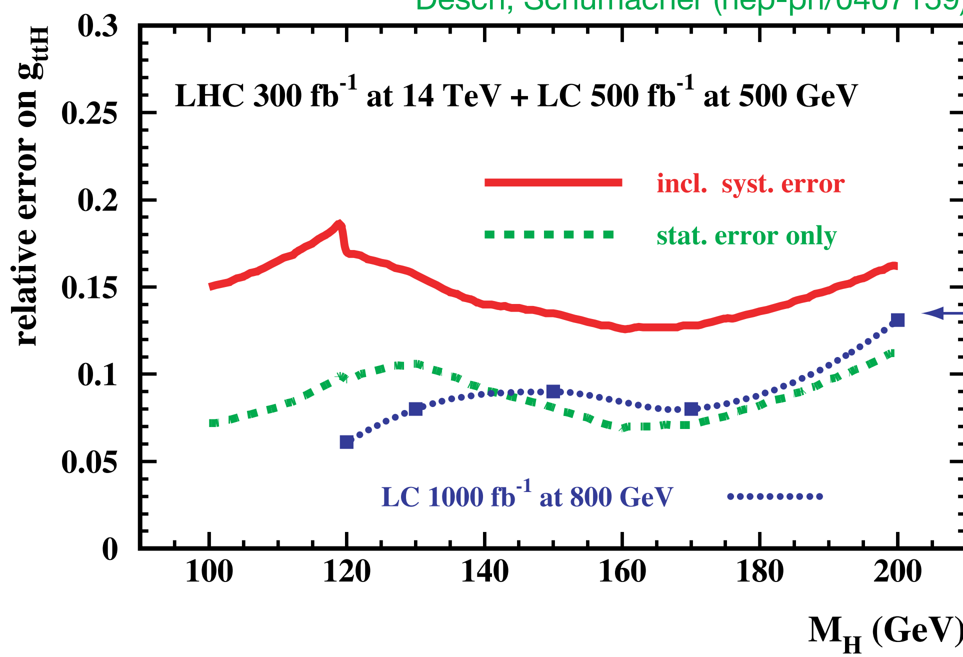


Coupling to top, g_{ttH}

- Marginal measurement at 500 GeV ILC, but by then, may have measurement of $\sigma \times Br$ due to $gg \to t\bar{t}H \to t\bar{t}b\bar{b},\ t\bar{t}W^+W^-$ at the LHC

Input precision Br's from 350–500 GeV ILC for these decays

Desch, Schumacher (hep-ph/0407159)



Gay, Besson, Winter ('04)

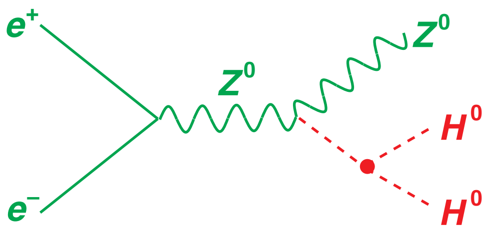
- ...and then move to precision measurement after energy upgrade:

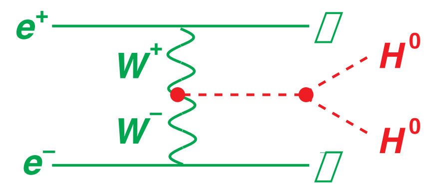
$$\frac{\Delta g_{ttH}}{g_{ttH}} = 6 - 13\ \%\ \text{for Higgs masses } 120 - 200\ \text{GeV}$$

(800 GeV ILC with 1000 fb^{-1})

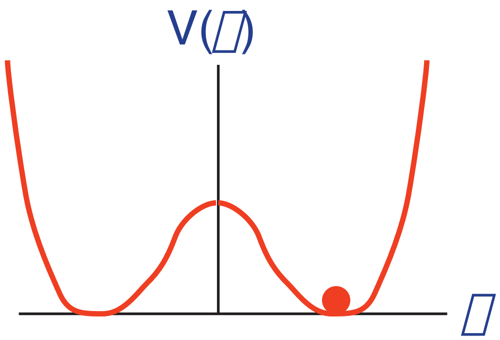
Higgs Potential: Self-Coupling, λ

Is it condensating? (resulting in spontaneous symmetry breaking...)





- m_h < 200 GeV: no self-coupling from LHC



Standard Model

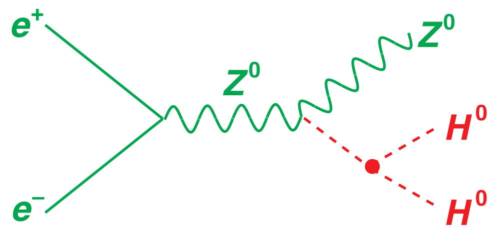
$$V(\phi) = \lambda(|\phi|^2 - v^2)^2$$

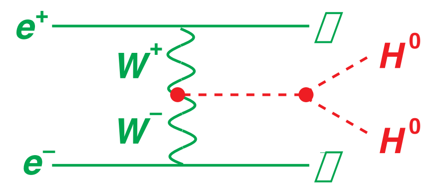
$$\mathcal{L} = \lambda v^2 H^2 + \lambda v H^3 + \tfrac{1}{4}\lambda H^3$$

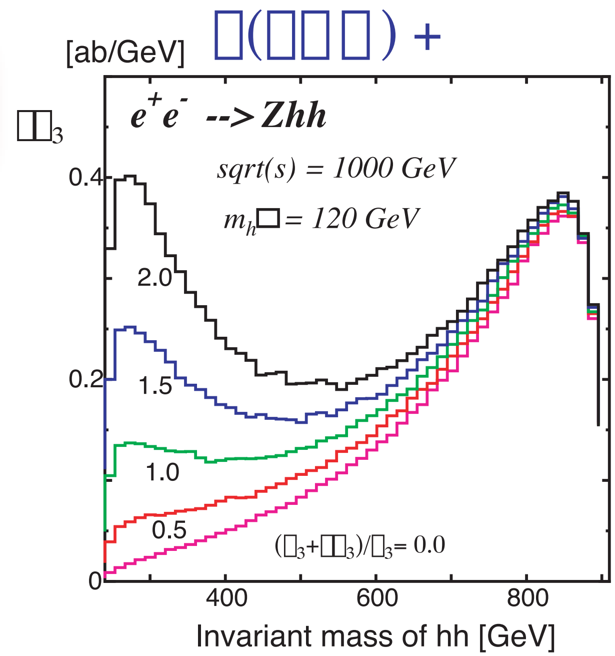
$$\lambda_{HHH} = 3M_H^2/M_Z^2$$

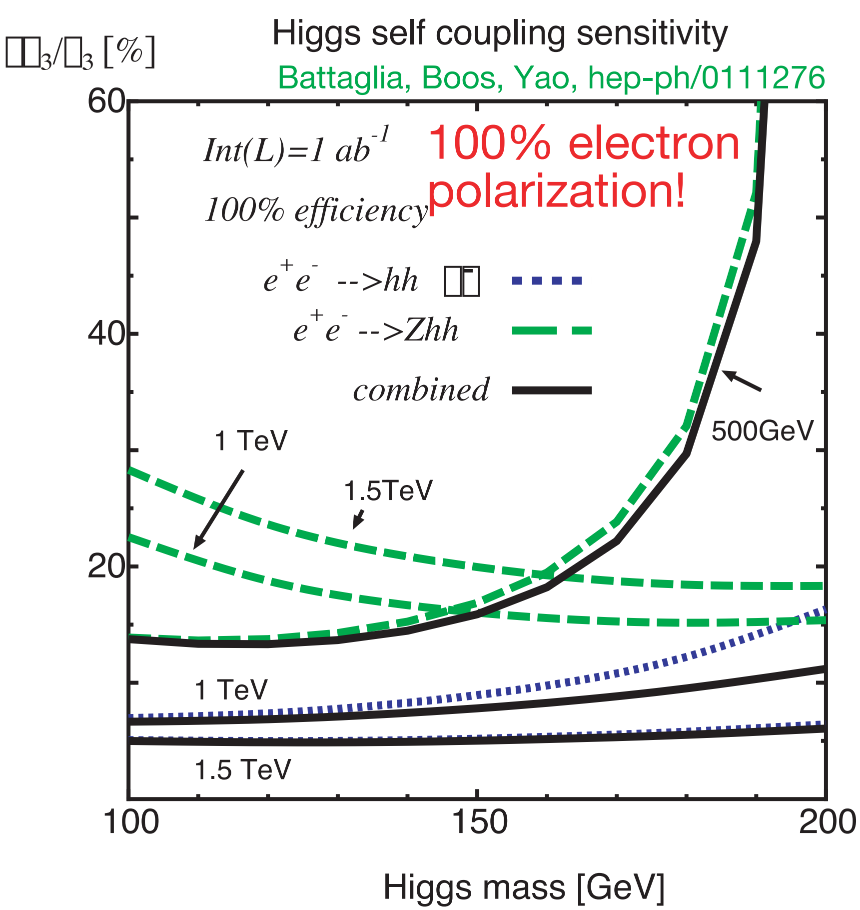
(in units of $\lambda_0 = M_Z^2/v \sim 33.8$ GeV)

Higgs Potential: Self-Coupling, □









- m_h < 140 GeV: ILC with *Zhh* at 500 GeV is better, □□/□ < 20%
- 140 < m_h < 200 GeV: ILC with □□*h* at 1-1.5 TeV

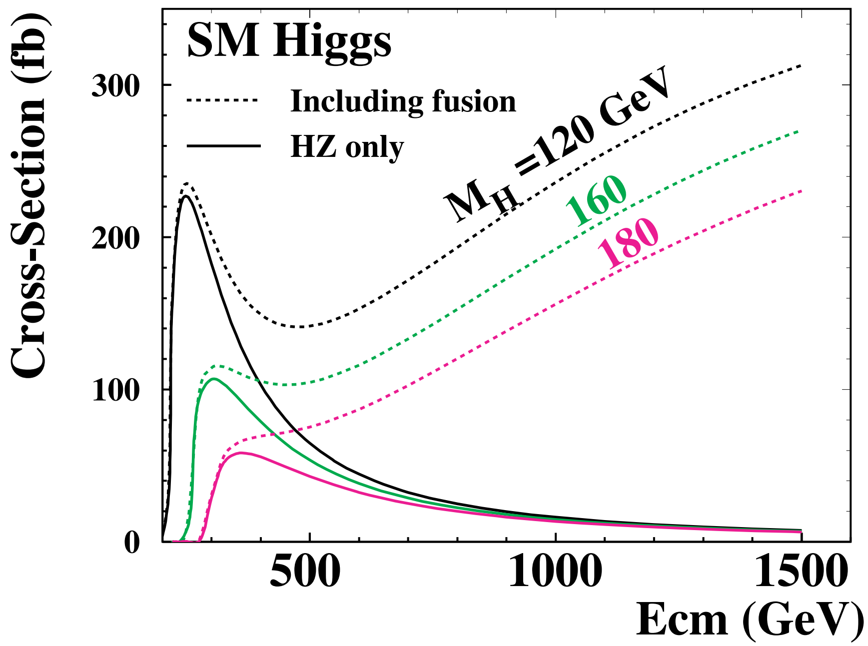
  Continue checks with more with realistic simulations & backgrounds...
  (80% pol.baseline)!

  (e.g.,Gay, Barklow, Rosca; Bangalore '06)
- Heavier Higgs? SLHC

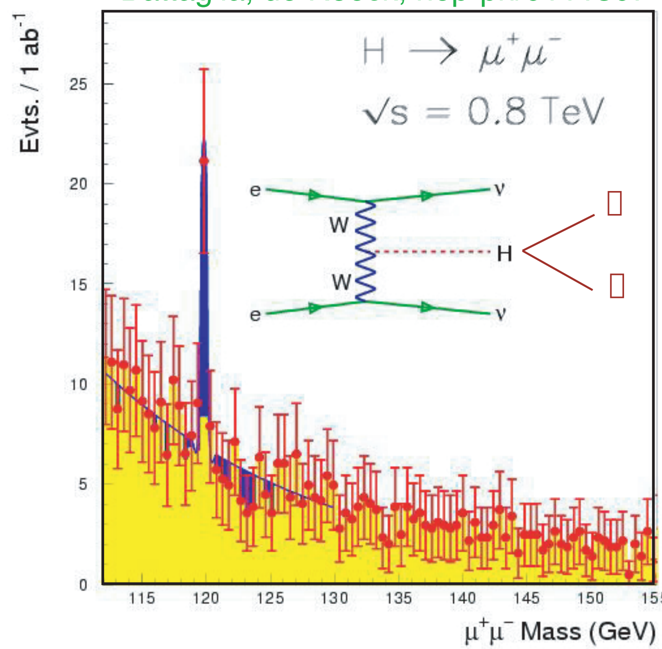
  (but would need input from ILC: g_{tth} , g_{WWh}, $□_{tot}$)

Couplings from Rare Br's

- Crank it up for the fusion process:



Battaglia, de Roeck, hep-ph/0111307



$\square g_{\square\square h}/g_{\square\square h} = 0.16$,
800 GeV, 1000 fb^{-1}

Test universality: $g_{\square\square h}/g_{\square\square h}$
$= m_{\square}/m_{\square}$?

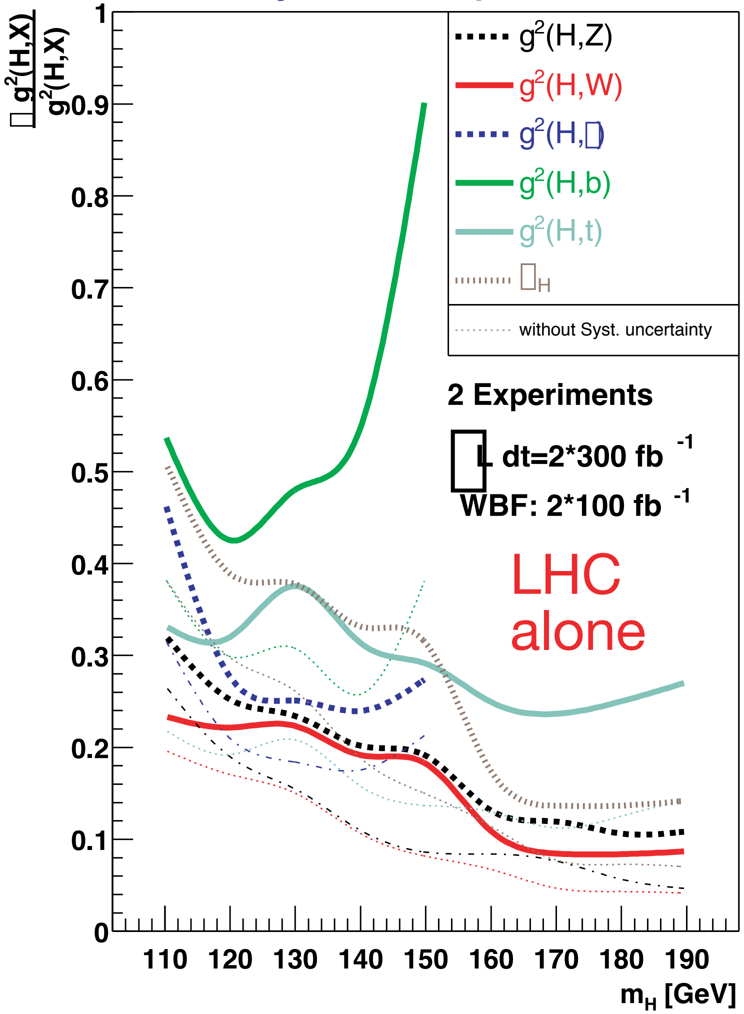
- Similar for $h \to b\bar{b}$ (rare, i.e., *Br* ~ 0.2% at m_h = 200 GeV)

Desch (hep-ph/0311092)

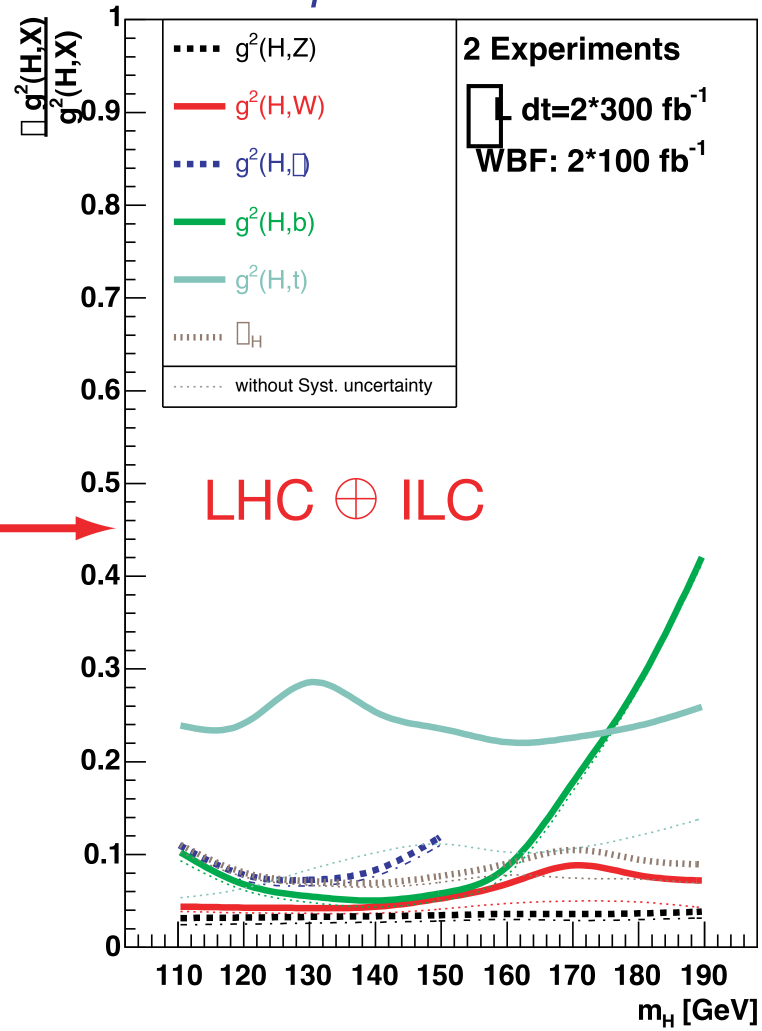
- ...and $h \to \gamma\gamma$

Combine Information

With theory assumptions:



Model Independent:

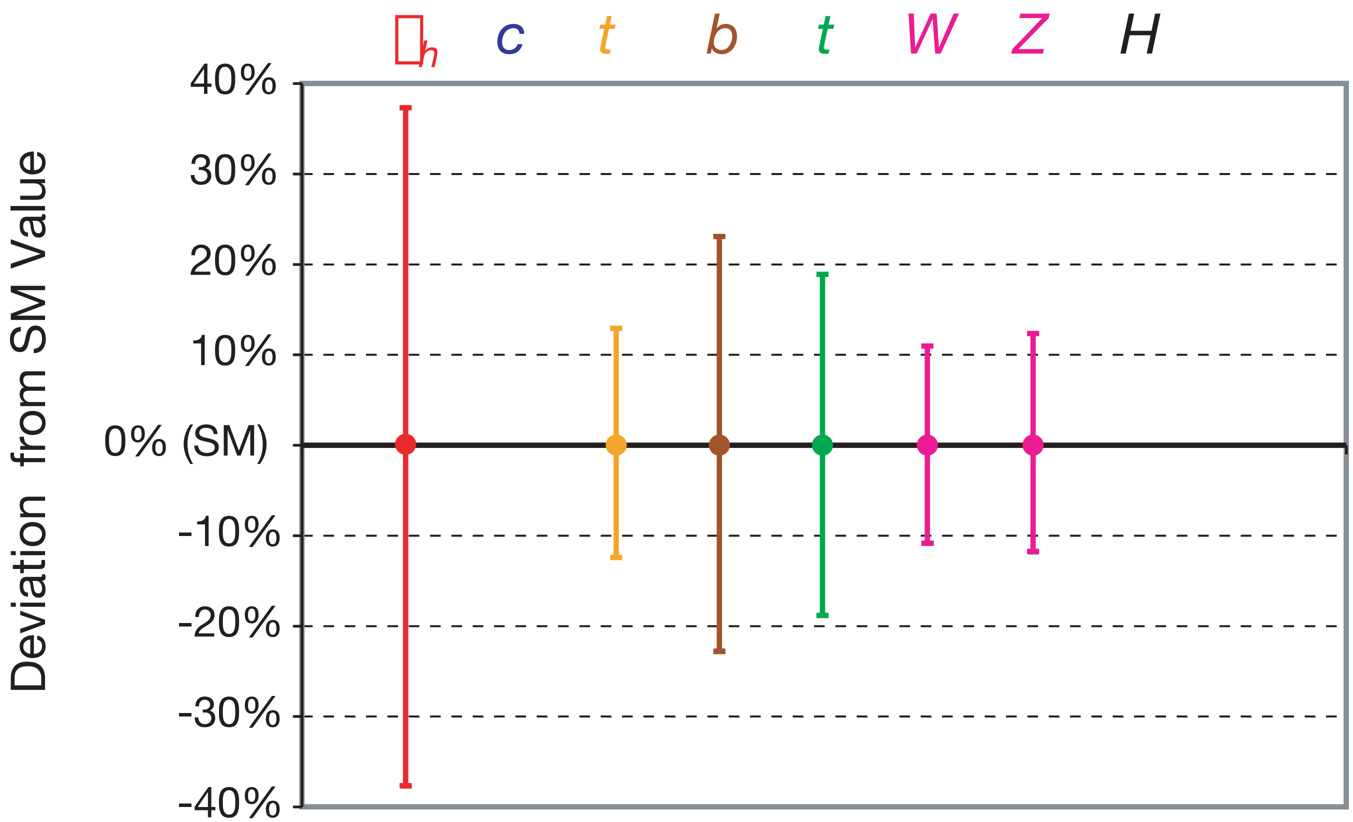


- Gives uncertainties on g^2_{HXX} (not on g_{HXX})

Precision needed on Couplings?

Adapted from S. Yamashita

With theory assumptions   LHC alone: 2 x 300 fb $^{-1}$



- e.g, single state, $m_h = 130$ GeV

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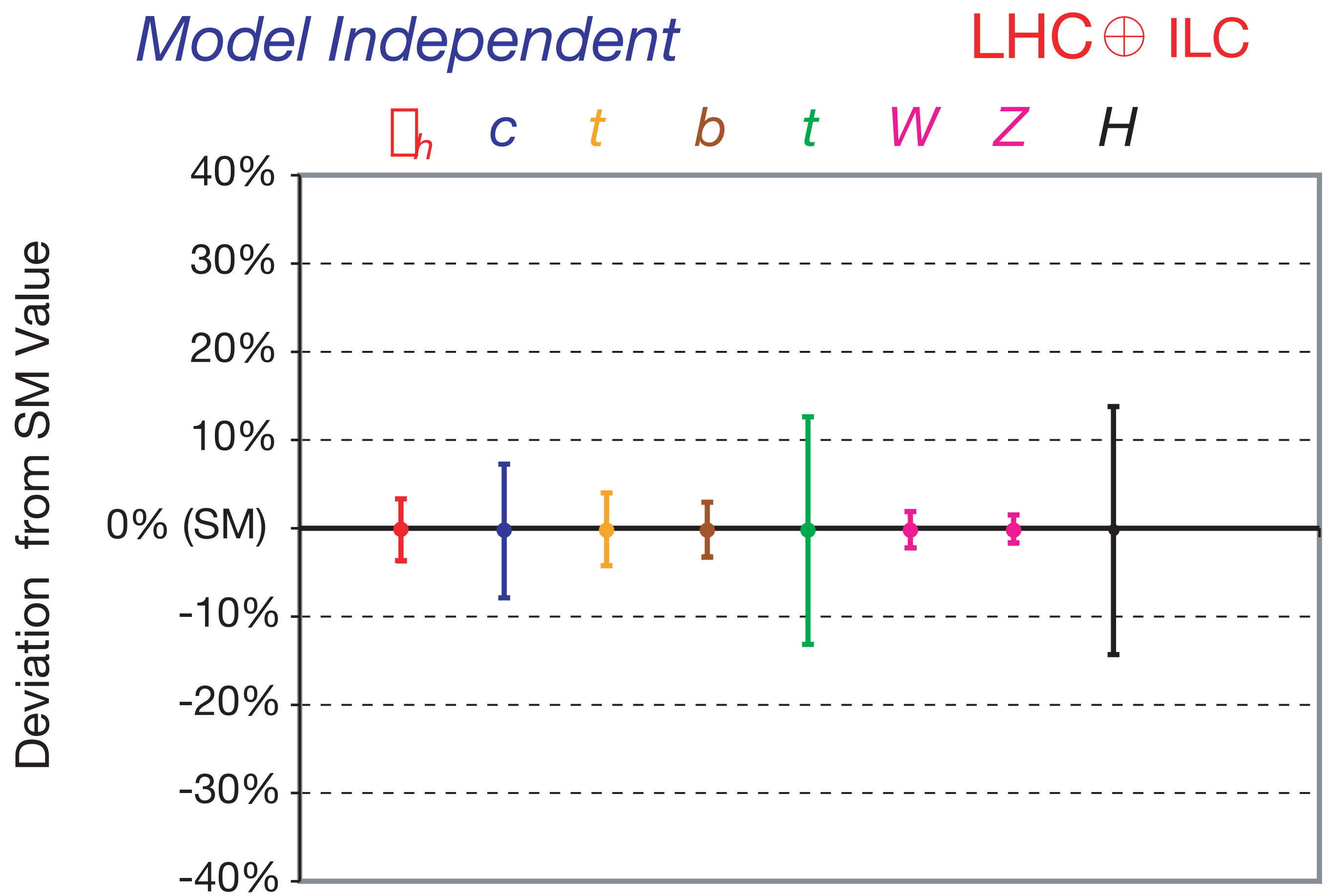


- e.g, single state, $m_h = 130$ GeV

Systematics

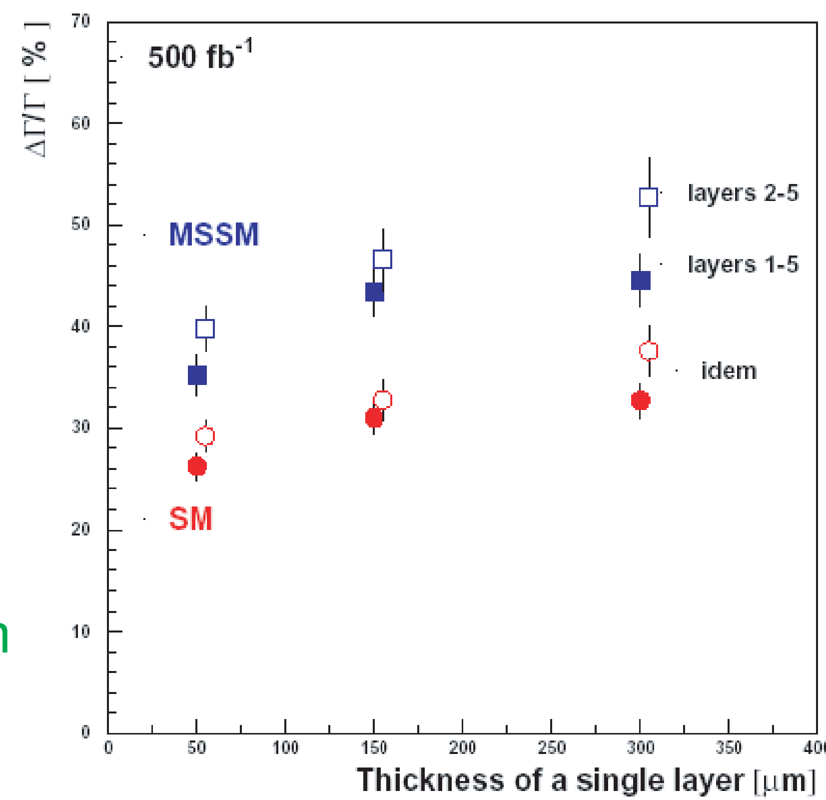
- All these precision results rely intimately on:
  - Jet finding / jet clustering
  - Jet energy calculation (particle flow)
  - *b*, *c*, top, □ tagging
  - *W*, *Z* tagging
  - Kinematic constraint fits

particularly for multijet low-stats *tth*, self-coupling

particularly for the Br "sweet spot", $m_h < 180$ GeV

and now with full GEANT simulation, with full or close-to-full software reconstruction - huge amount of work! (particularly if detector designs are still in development)

Example: impact of silicon sensor thickness on charm branching fraction

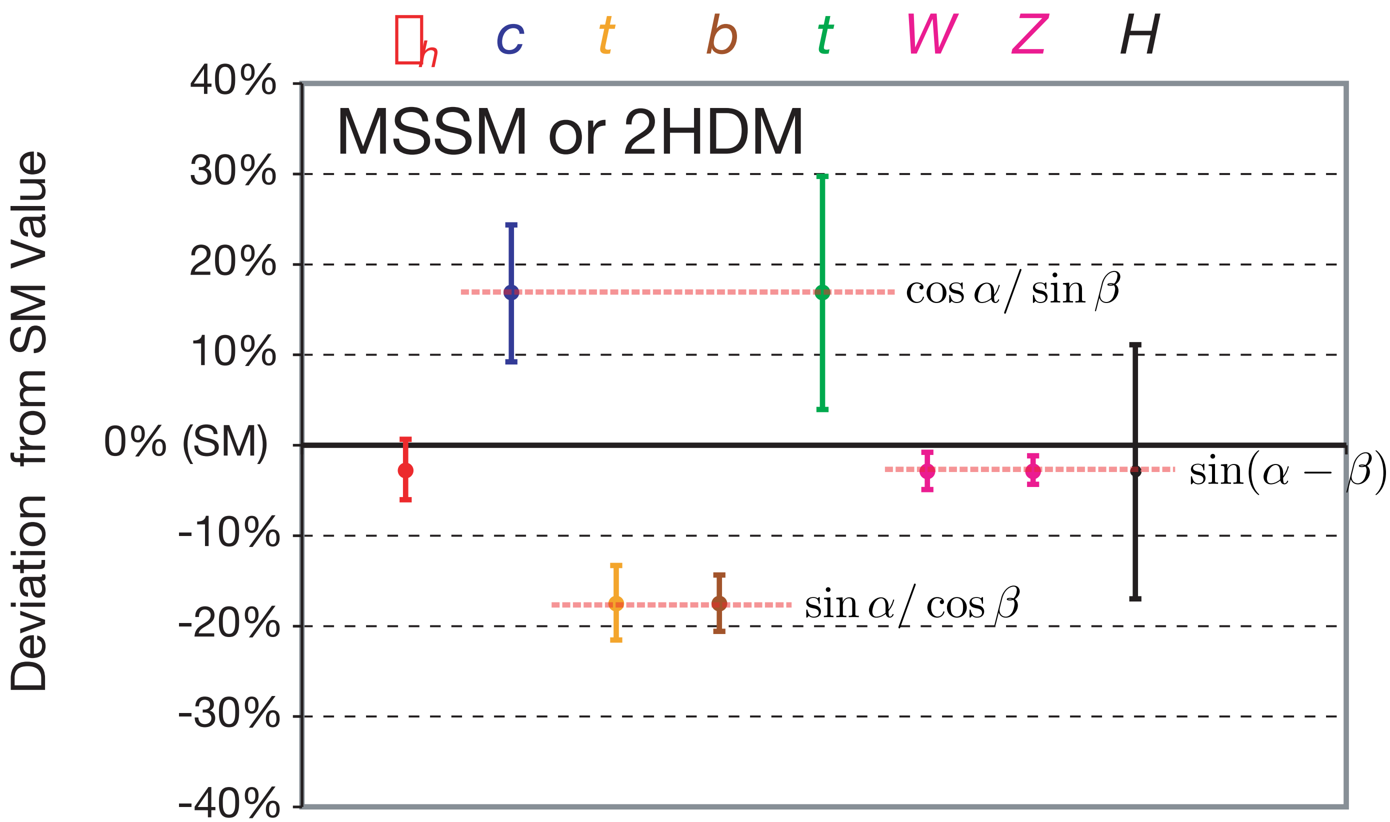


layer thickness $50\mu m$

Precision needed on Couplings?

Adapted from S. Yamashita

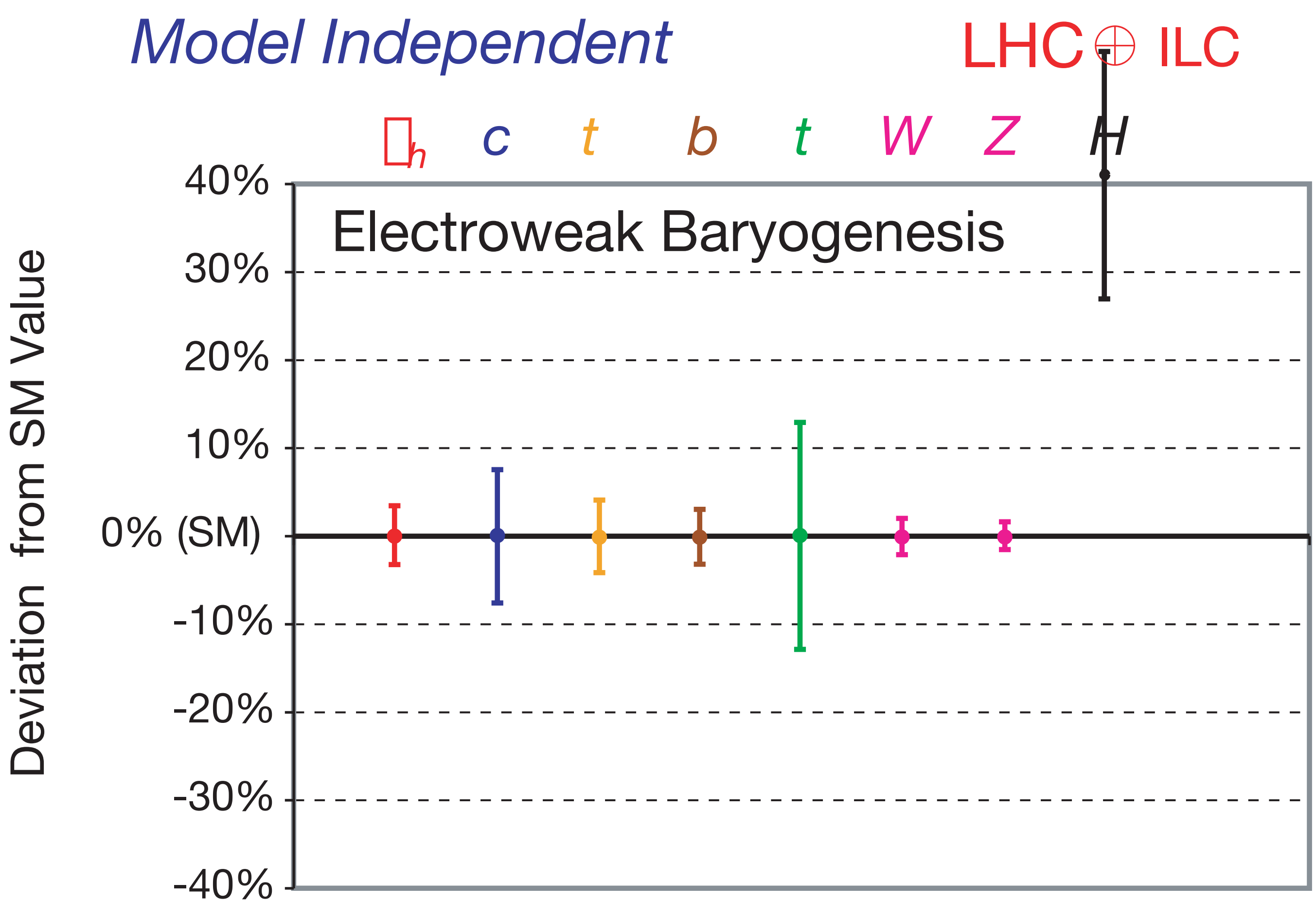
Model Independent LHC ⊕ ILC



- e.g, single state, $m_h = 130$ GeV
- With possibility of observation of $H^{\pm}$; other SUSY particles at LHC

Precision needed on Couplings?

Adapted from S. Yamashita



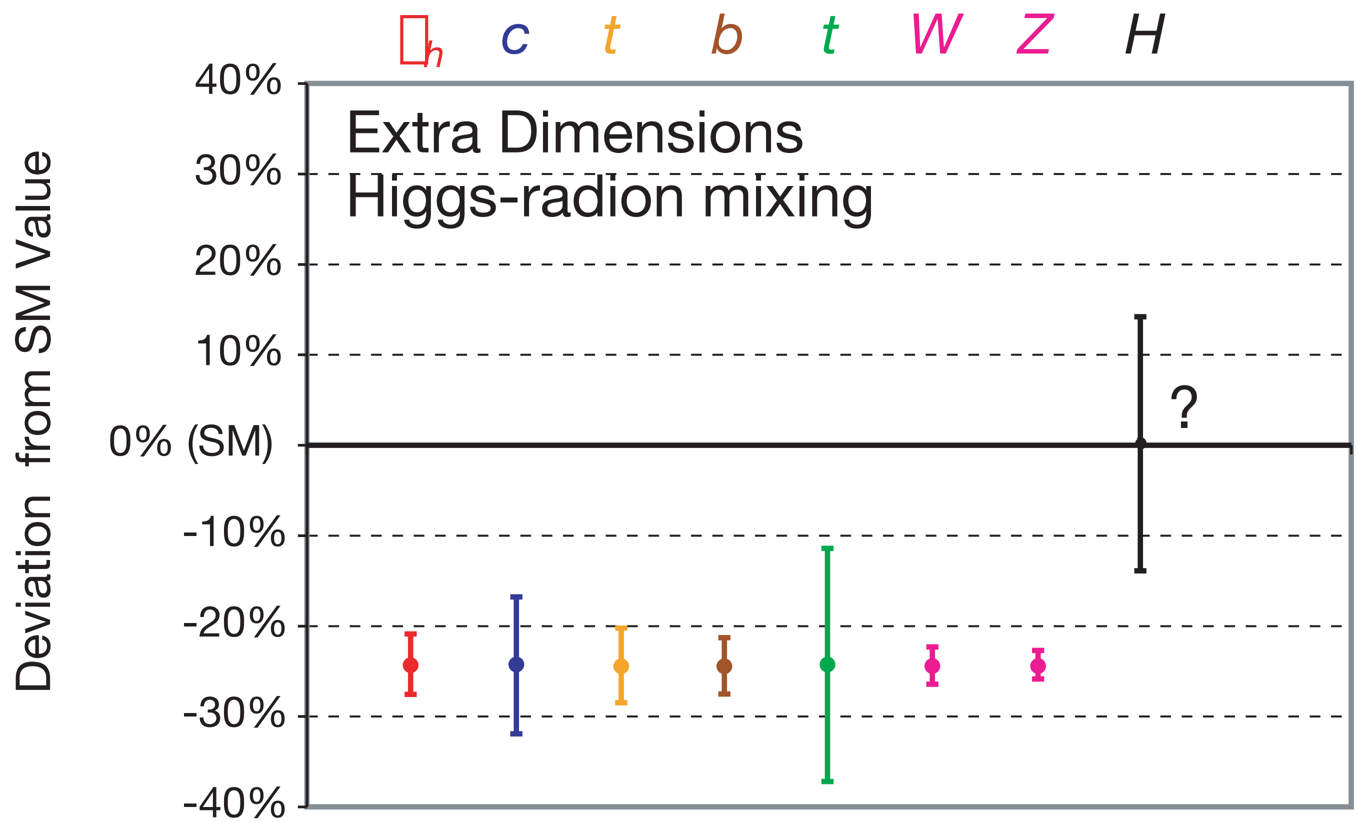
- e.g, single state, $m_h = 130$ GeV

Precision needed on Couplings?

Adapted from S. Yamashita

Model Independent

LHC ⊕ ILC



- e.g, single state, $m_h = 130$ GeV

and nifty interplay case where that LHC single state may not be a Higgs

Higgs-Radion Mixing

Battaglia et al., Phys.Lett.B568:92-102,2003

- Models with 3-branes in extra-dimensions predict a radion, ▯, can mix with the Higgs

  → modified Higgs properties may be difficult to detect at the LHC

- That early LHC single state could be a radion, and not seeing the Higgs (swamped by background)

$$gg \to \phi \to ZZ^* \to 4\ell$$

- ILC guarantees observation of both Higgs & radion

$$e^+e^- \to Zh,\ Z\phi$$

  over full parameter space, and precision measurements can determine the mixing

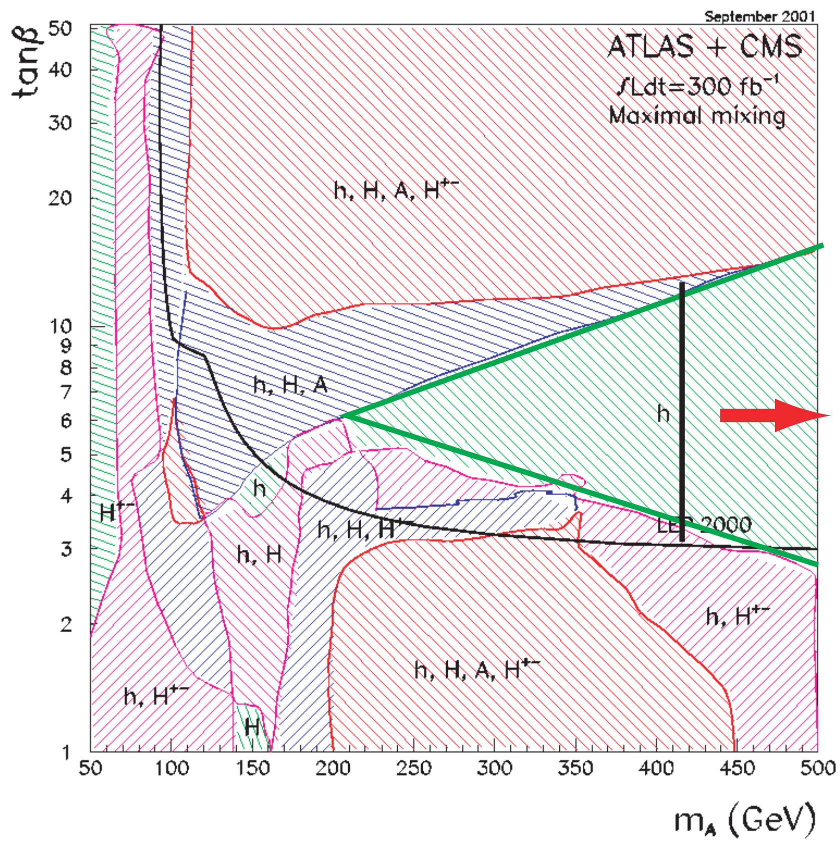
- LHC can see heavy Kaluza-Klein excitations

SUSY Higgs

- Single Higgs-like state at LHC?

→ Could be in a region where both LHC and ILC will see only the single lightest Higgs (although LHC could potentially observe decays into sparticles with ILC input)

$$H \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0$$

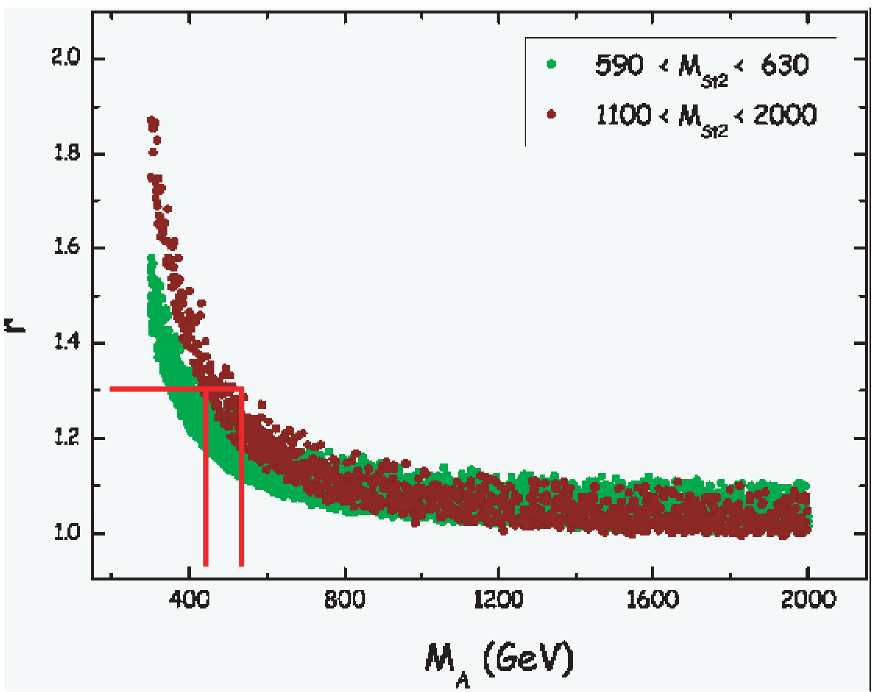


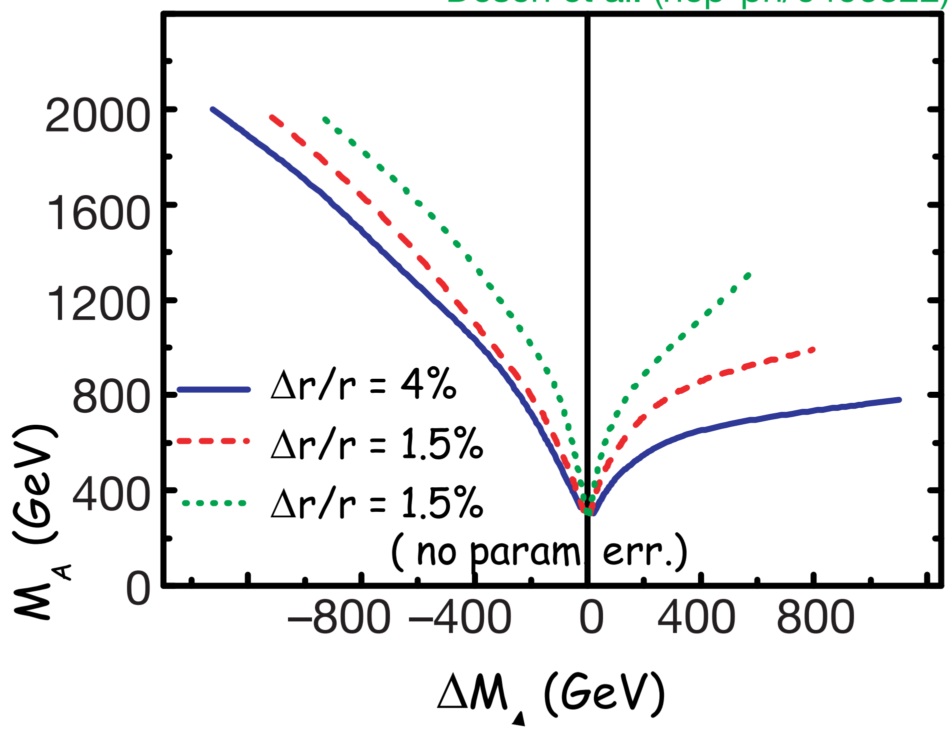
"The Wedge"

SUSY Higgs

- Precision ILC measurement of $r = \dfrac{[Br(h \to b\bar{b})/Br(h \to WW^*)]_{\mathrm{MSSM}}}{[Br(h \to b\bar{b})/Br(h \to WW^*)]_{\mathrm{SM}}}$
- Combine LHC and ILC info on SUSY spectrum (this case, SPS1a)

Desch et al. (hep-ph/0406322)



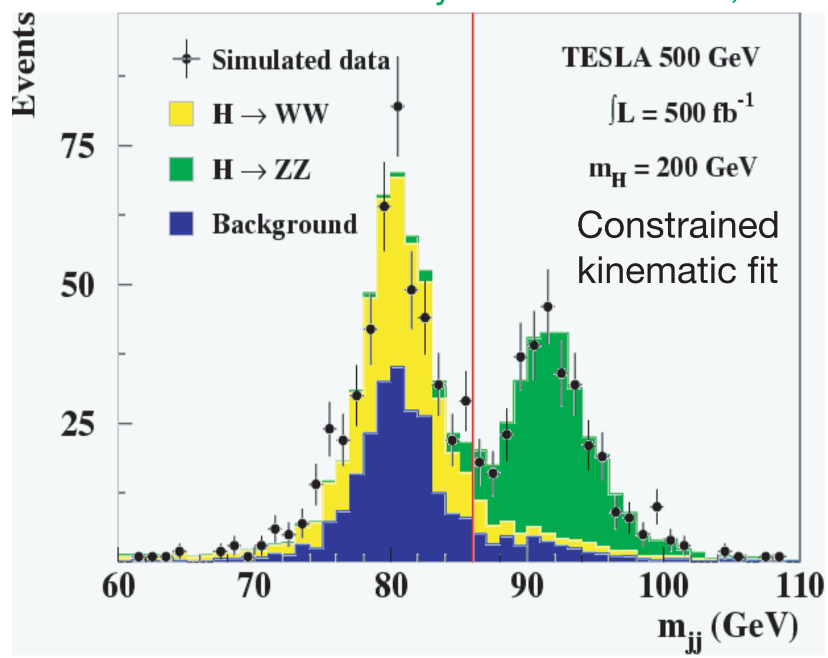


- No implications on initial energy for ILC (for Br's), but could give feedback on subsequent upgrade path

Single LHC State with M_h > 200 GeV?

- Far fewer fermion couplings now accessible!
- Still look for them though!
- g_{ZZh} , g_{WWh} still determined to 2 – 9% for 200 < m < 320 GeV with 500 fb^{-1} at a 500 GeV ILC
- If m_h > 350 GeV skip initial ILC run at 500 GeV?
- Spin, other quantum numbers?
- Demand detector requirements not thought of? ("standard" is the W/Z mass separation)

Desch, Meyer, Eur.Phys.J.C35:171-176,2004



Start measuring width directly

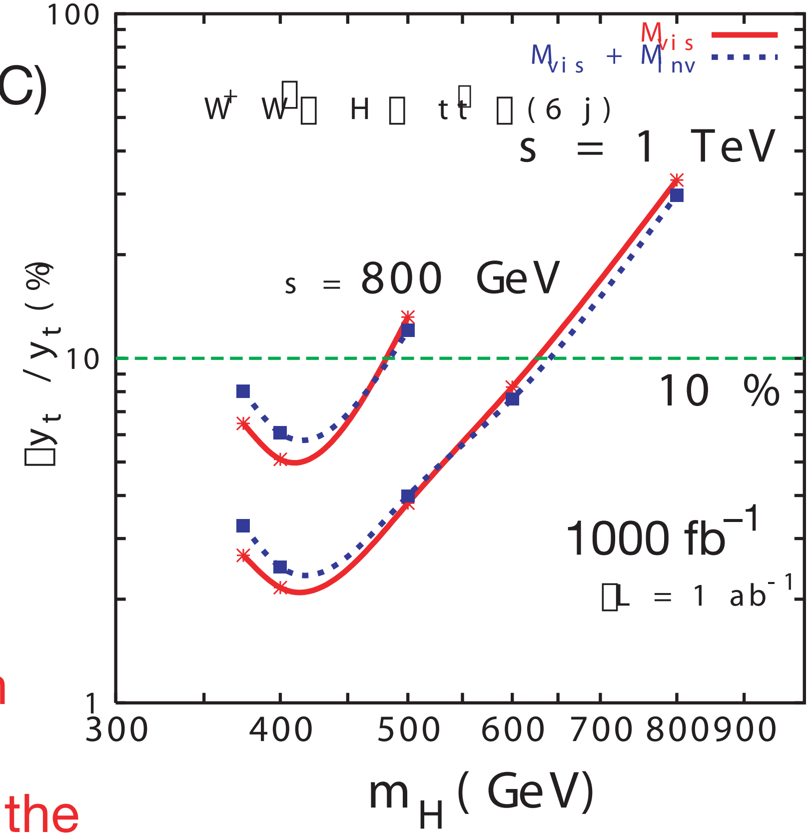
Single LHC State with M_h > 200 GeV?

- If $m_h > 2m_{top}$ then $h \to t\bar{t}$

  (tough at LHC, more interplay w/ ILC)

  g_{tth} to better than 10% for $m_h < 650$ GeV

Alcarez, Morales, PRL 86, 3726 (2001)



- What about the range 200 GeV < $m_h < 2m_{top}$?

- How to get at other couplings?

- How far can the ILC realistically go in Higgs mass for measuring self-coupling? Will this determine the "top-end" of the upgrade path?

Clearly a lot to be looked into...

Single LHC State with M_h > 200 GeV?

- What if *really* heavy?

  500 GeV < m_h < 1 TeV ?

  → source of extra contributions in EW precision measurements may be obscure

  → GigaZ and scanning *WW* threshold

Tension between running at highest energies
and still being able to go down to lowest energies

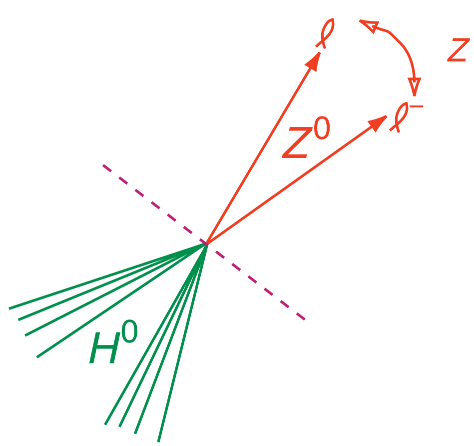
LHC	ILC
Observes Heavy Higgs	Out of kinematic range
Non-standard decays of light Higgs; swamped by background	Observes light Higgs regardless of decay

No evidence of Higgs at early stage LHC

- Is actually there, but difficult/impossible to detect at the LHC

Recoil mass:

$$m^2_{\rm recoil} = s - 2E_Z\sqrt{s} - M^2_{\ell\ell}$$



Identify peak(s) in recoil mass, look for *all* decays: invisible, light jets, gluons, SUSY, even if overlapping

- *Any* new scalar coupling to Z can be found via recoil method $e^+e^- \to Zh$ *regardless* of decay

(also new scalars from Little Higgs, etc.)

In general, method better at lower energy ILC

No evidence of Higgs at early stage LHC

Possibly a more relevant question:

Are *WW* interactions perturbative up to the TeV scale?

Yes → Higgs-like state must be there

→ ILC can see the state(s) that is regulating the bad energy behavior   Initial energy 500 GeV ILC fine

No → New physics involved, some strong interactions

→ How are precision EW measurements being compensated?   Back to tension between possibly running ILC at higher initial energies but wanting EW precision from GigaZ and WW scans

Soooo, how soon can we know if WW interactions remaining perturbative at the LHC?

No evidence of Higgs at early stage LHC

- Is actually there, but difficult/impossible to detect at the LHC

Just a few examples:

Berger et al., Phys.Rev.D66:095001,2002

- $h \to \mathrm{jets}$ of no particular flavor content; in MSSM with very light $\tilde{b}$ with *R*-parity violating decays evading LEP limits

If $Br(h \to \mathrm{jets}) \approx (2-5) \times Br(h \to b\bar{b})$ difficult to observe at LHC; no problem at initial energy ILC

e.g., Boudjema, Belanger, Godbole; hep-ph/0206311

- MSSM with light stop quarks suppressing *ggh* coupling, reducing standard gluon-fusion discovery modes at LHC or enhanced branching fraction $Br(h \to \chi_1^0 \chi_1^0)$ (LHC can detect invisible Br's up to ~0.25–0.30); no problem at initial energy ILC

$\tilde{t}\tilde{t}h$ possible

No evidence of Higgs at early stage LHC

- Is actually there, but difficult/impossible to detect at the LHC

Just a few examples:

Gunion, Dermisek, et al., e.g. hep-ph/0510322

- NMSSM models, add Higgs singlet, get additional scalar (three CP-even states) and pseudoscalar

$h_i \rightarrow a_1 a_1$

CP even   Very light CP-odds

$a \rightarrow b\bar{b}$

$a \rightarrow \tau^+\tau^-$

LHC: $WW \rightarrow h_i \rightarrow aa$, 4-*b* state swamped by background

ILC: $e^+e^- \rightarrow Zh \rightarrow Zaa \rightarrow Zb\bar{b}b\bar{b}, b\bar{b}\tau^+\tau^-$

Detect both in recoil method

Check if $Br(a \rightarrow \tau^+\tau^-)/Br(a \rightarrow b\bar{b})$ consistent with CP-odd scalar

No problem at initial energy ILC

No change in energy strategy;
no significant additional detector capabilities
(beyond strict control of systematics for couplings)

No evidence of Higgs at early stage LHC

- Is *really* not there
- Strongly-interacting sector or a mix of strong and weak interactions
- Look at 6-fermion processes at LHC & ILC, anomalous gauge couplings
- Resonances at high energy (LHC, measure masses)
- If beyond reach of LHC, indirect sensitivity at ILC to very heavy reasonances (think Tristan and the *Z*...)
- If within reach of LC, measure the couplings in detail (particularly with polarized beams)

Impossible to tell early on, but could eventually lead to possibly running ILC at higher initial energies but wanting EW precision from GigaZ and WW scans

Summary

At the early stages of LHC:

- Case 1: Detection of one state with properties that are compatible with those of a Higgs boson

$m_h < 200$ GeV — Initial energy of 500 GeV and upgrade path to 1 TeV justified; need higher energies for complete couplings

$m_h > 200$ GeV — Most uncertainty, much depends on what is observed outside the Higgs sector (e.g., GigaZ *and* higher energy as $m_h\uparrow$)

- Case 2: No experimental evidence for a Higgs boson at the early stage of the LHC

Will be too early to tell if:

Is actually there, but hard to detect at the LHC

or

Is *really* not there

- LHC-ILC interplay *everywhere*
- More complete simulations needed to verify precision performance

Acknowledgments

- Tireless efforts of the ILC working groups, LHC/ILC Study Group
- The comprehensive summary documents, analysts, editors, and references therein:

  Physics Interplay of the LHC and the ILC, hep-ph/0410364, Phys. Rept. 426 (2006) 47.

  Toward High Precision Higgs-Boson Measurements at the ILC, hep-ph/0511332, Snowmass '05 Report