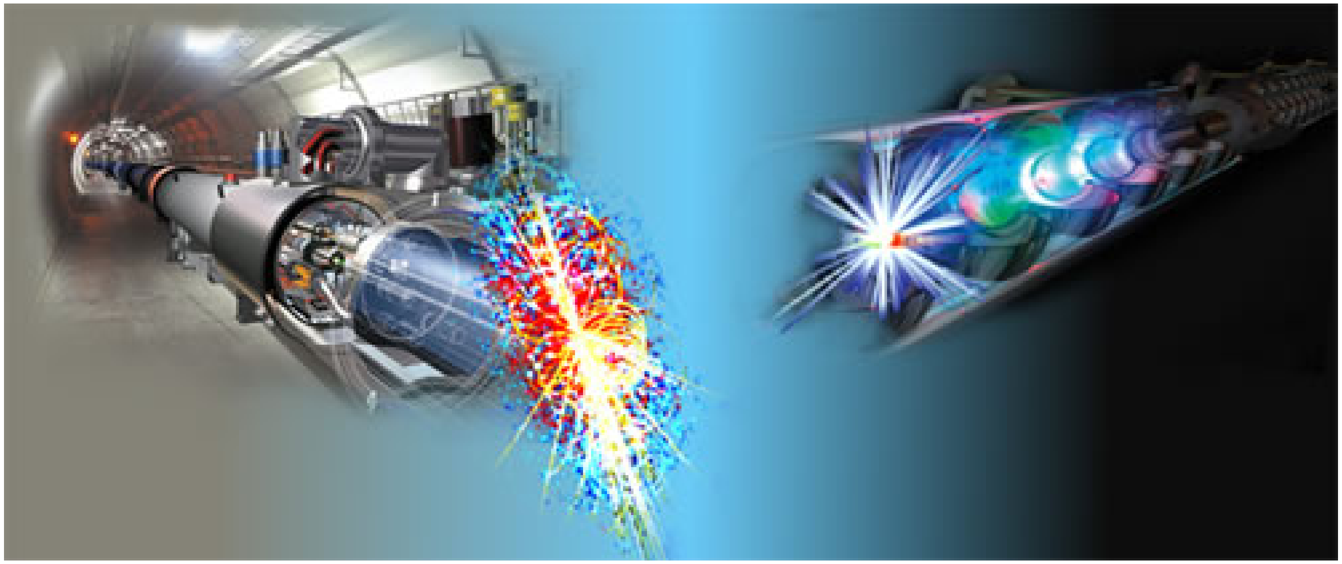
Complementarity of the LHC and ILC



Heather Logan
Carleton University

APS April meeting 2008

The LHC physics menu is very rich and exciting.

CMS Physics Technical Design Report, Volume II: Physics Performance, CERN-LHCC-2006-021
ATLAS detector and physics performance technical design report, Volume 2, CERN-LHCC-99-15
+ many more recent updates

The ILC physics menu is also very rich and exciting.

A. Djouadi et al., "International Linear Collider Reference Design Report, Volume 2: Physics at the ILC," arXiv:0709.1893 [hep-ph]

Great talks have been given about these already.

Monday: Abe Seiden, "The U.S. role in the LHC"
Mike Harrison, "The U.S. role in the ILC"

But that is not the topic of this talk.

This talk: complementarity of LHC and ILC

What can be learned from LHC + ILC
that cannot be learned from LHC alone
or from ILC alone

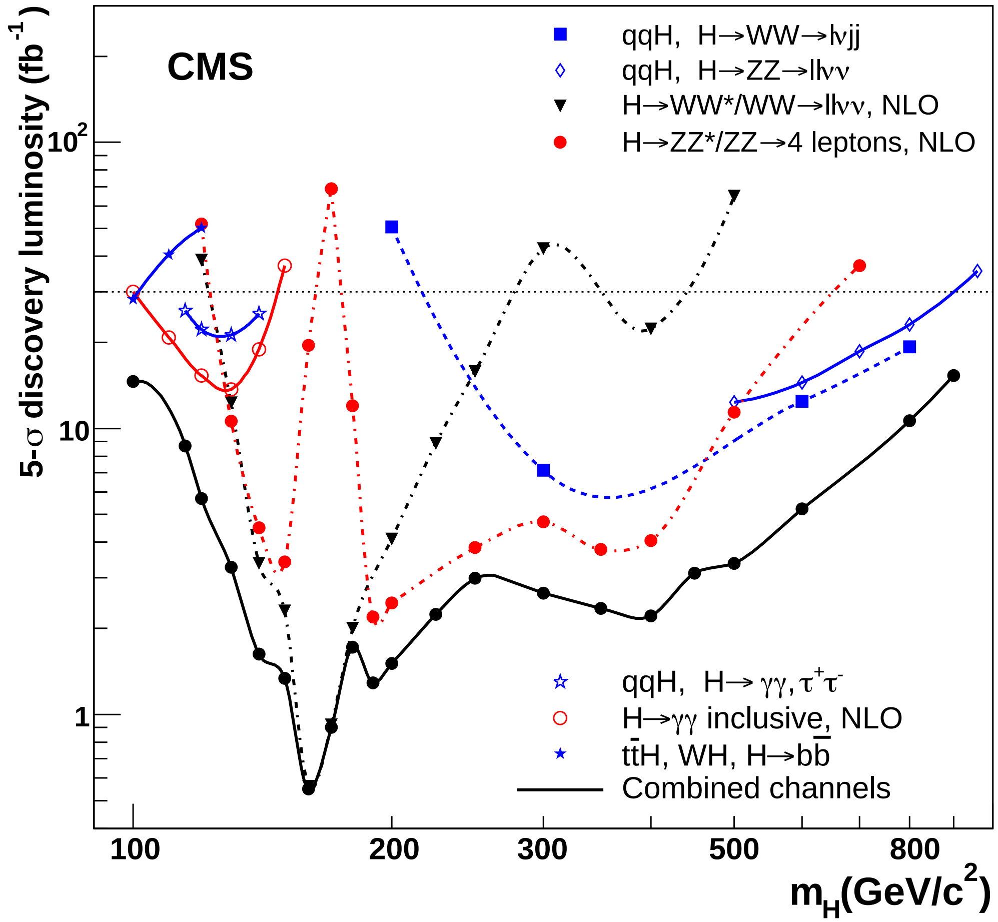
G. Weiglein et al. [LHC/ILC Study Group], "Physics interplay of the LHC and the ILC," Phys. Rept. **426**, 47 (2006) [hep-ph/0410364]
+ more recent updates

This implies some kind of combined analyses
(or just using input from one machine for analyses at the other)

Will give three examples:
- Higgs
- SUSY
- Z'

Higgs

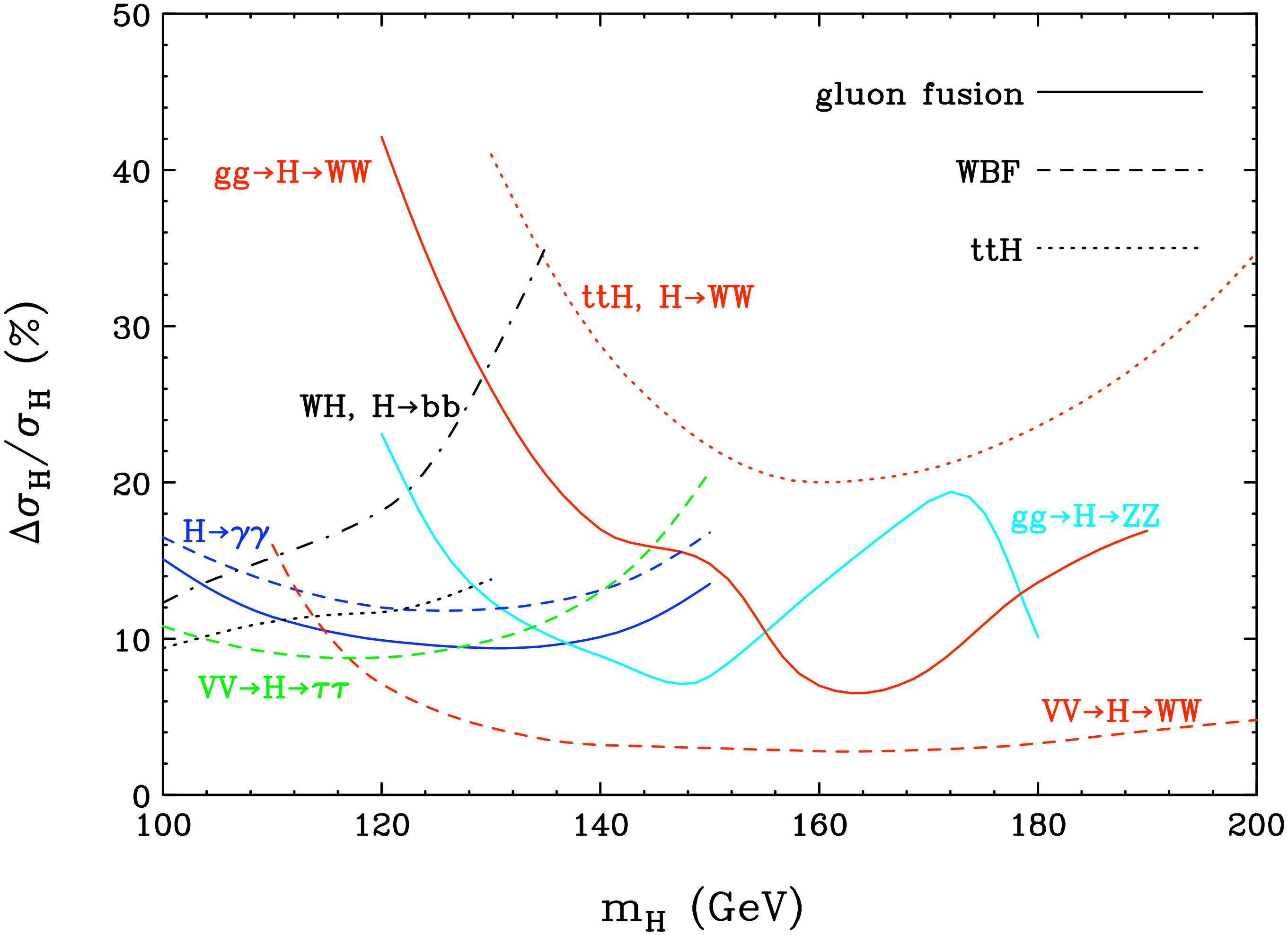
If the Higgs is sufficiently Standard-Model–like, its discovery is guaranteed at LHC.



CMS Physics TDR, via ILC RDR

Measure the mass...

... and measure rates in each channel.

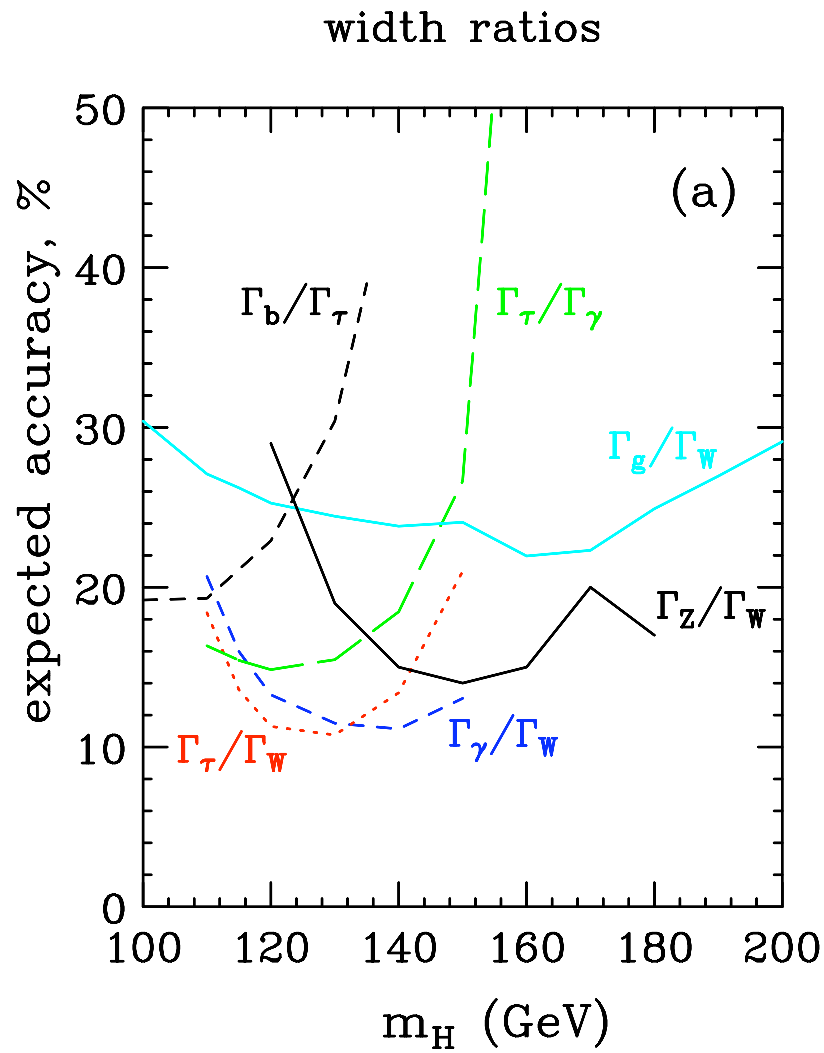


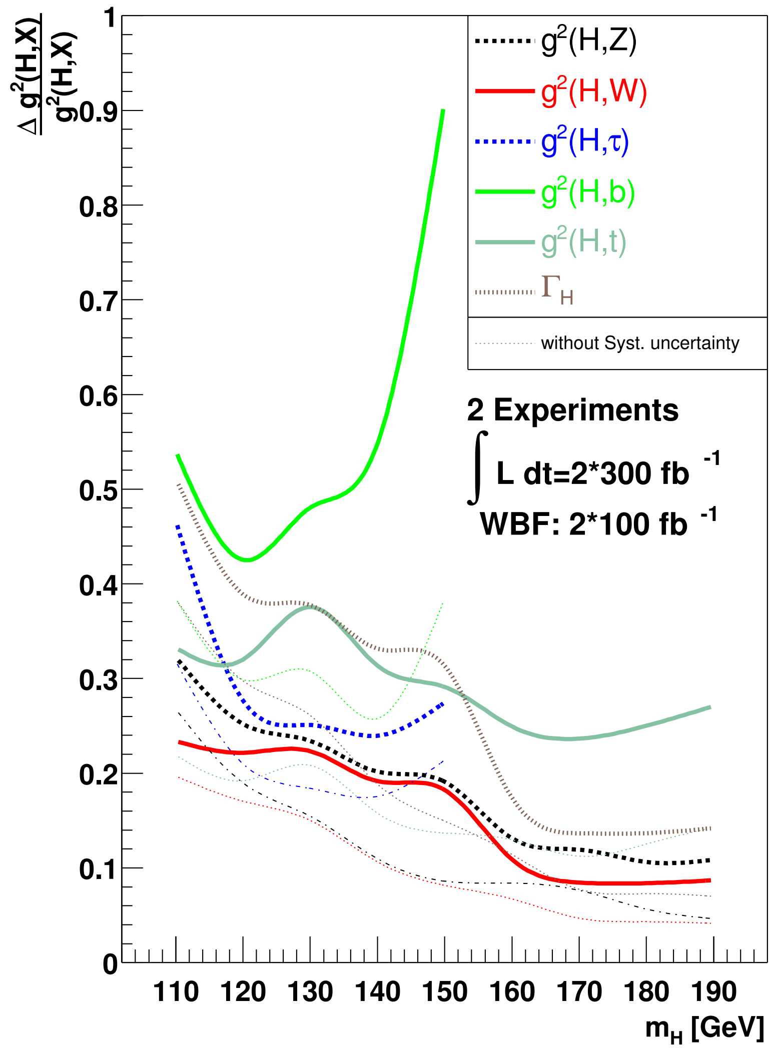
LHC, 200 fb^{-1} (except 300 fb^{-1} for $ttH, H \to bb$, $WH, H \to bb$). Zeppenfeld, hep-ph/0203123

Given M_H, rates are completely determined in SM.

Check if rates are consistent with SM predictions!

Ratios of rates give ratios of partial widths.
Adding mild theory assumptions allows to fit Higgs couplings.

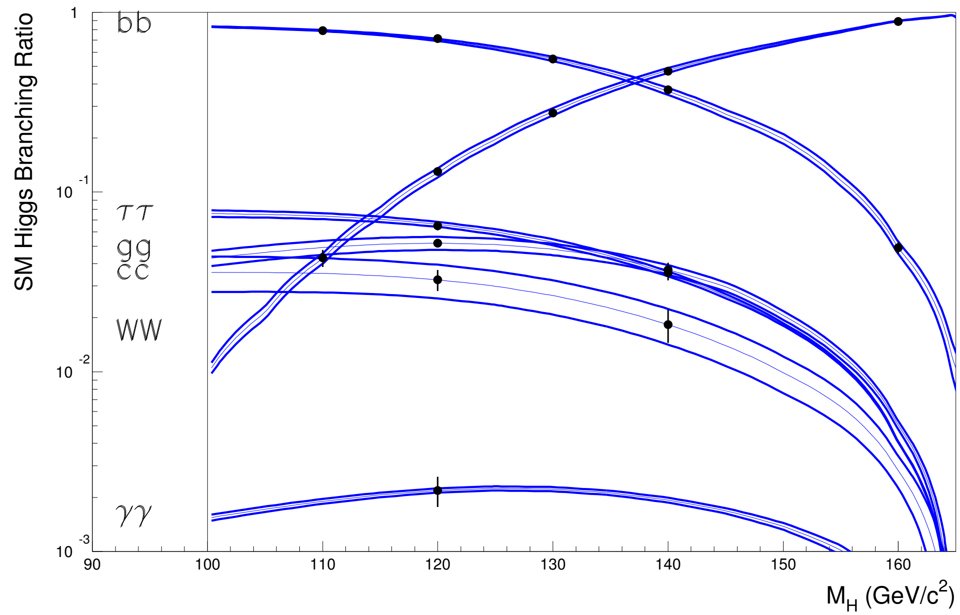




[L] 200 fb^{-1} (except 300 fb^{-1} for $ttH(\to bb)$, $WH(\to bb)$). Zeppenfeld, hep-ph/0203123
[R] Dührssen, Heinemeyer, H.L., Rainwater, Weiglein & Zeppenfeld, hep-ph/0406323

ILC: High-precision measurements of Higgs production couplings, decay branching ratios.

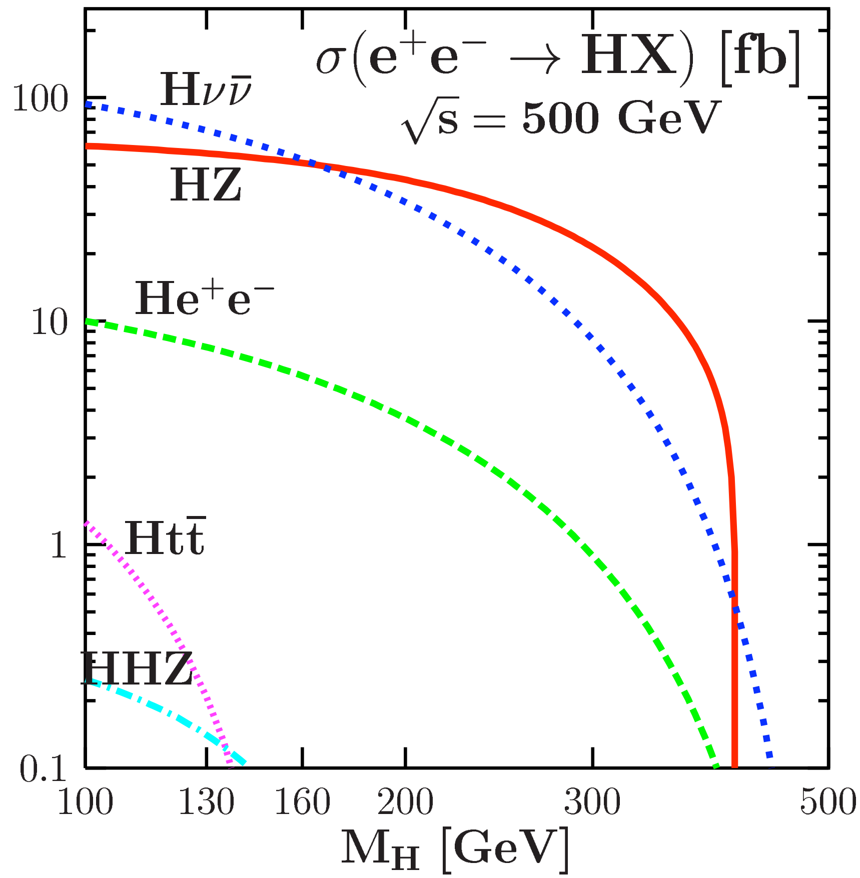
Decay mode	Relative precision (%)
$b\bar{b}$	1.0–2.4
$c\bar{c}$	8.1–12.3
$\tau^+\tau^-$	4.6–7.1
gg	4.8–10
WW	3.6–5.3
$\gamma\gamma$	23–35



ILC RDR, 500 fb^{-1} at 350-500 GeV, for $m_H = 120$ GeV — Battaglia & Desch

Enables model-independent extraction of Higgs couplings, constraints on non-SM Higgs.

However:



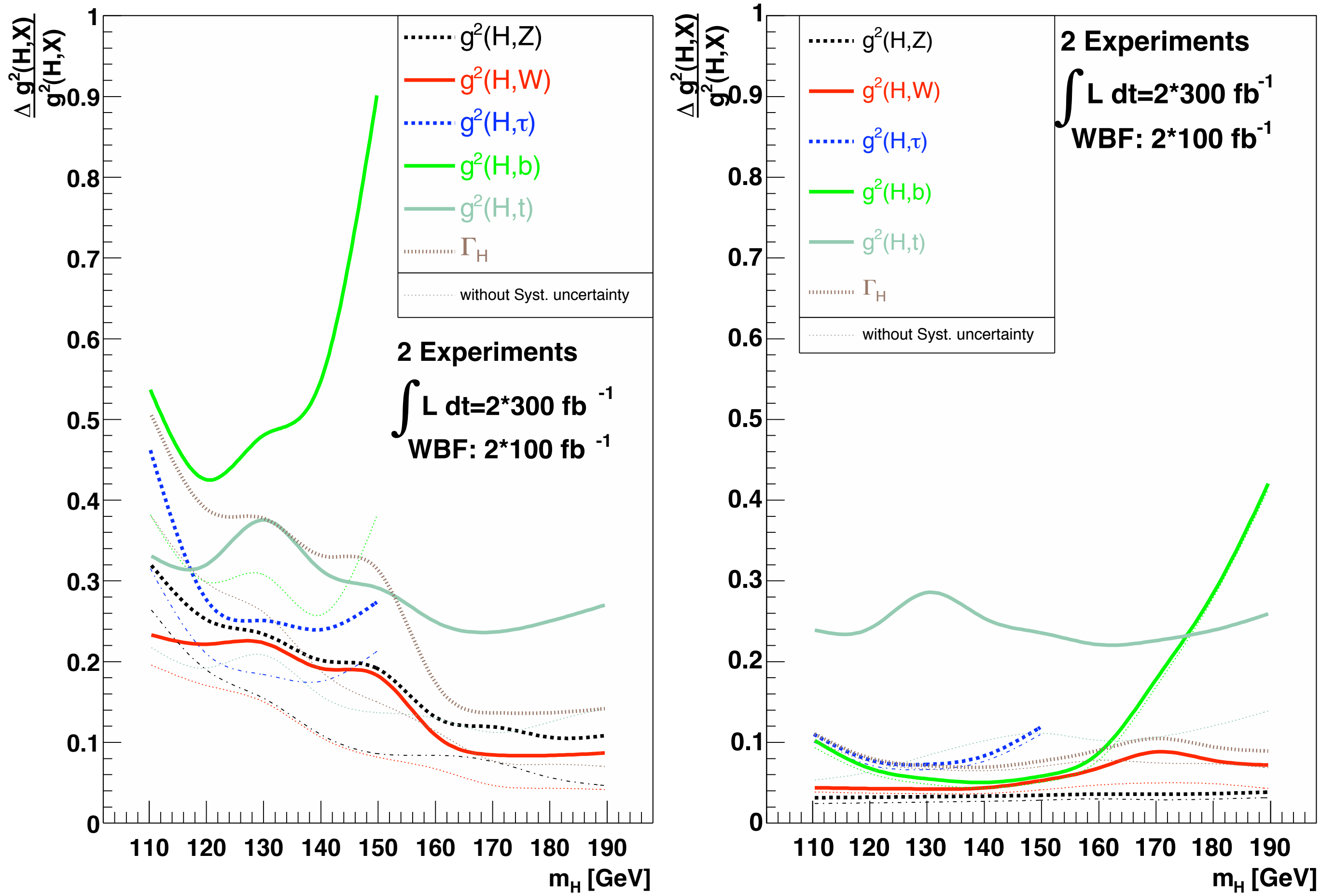
ILC RDR, arXiv:0709.1893

ttH kinematically limited at 500 GeV ILC

Why is top so heavy? Special role in EW symmetry breaking?

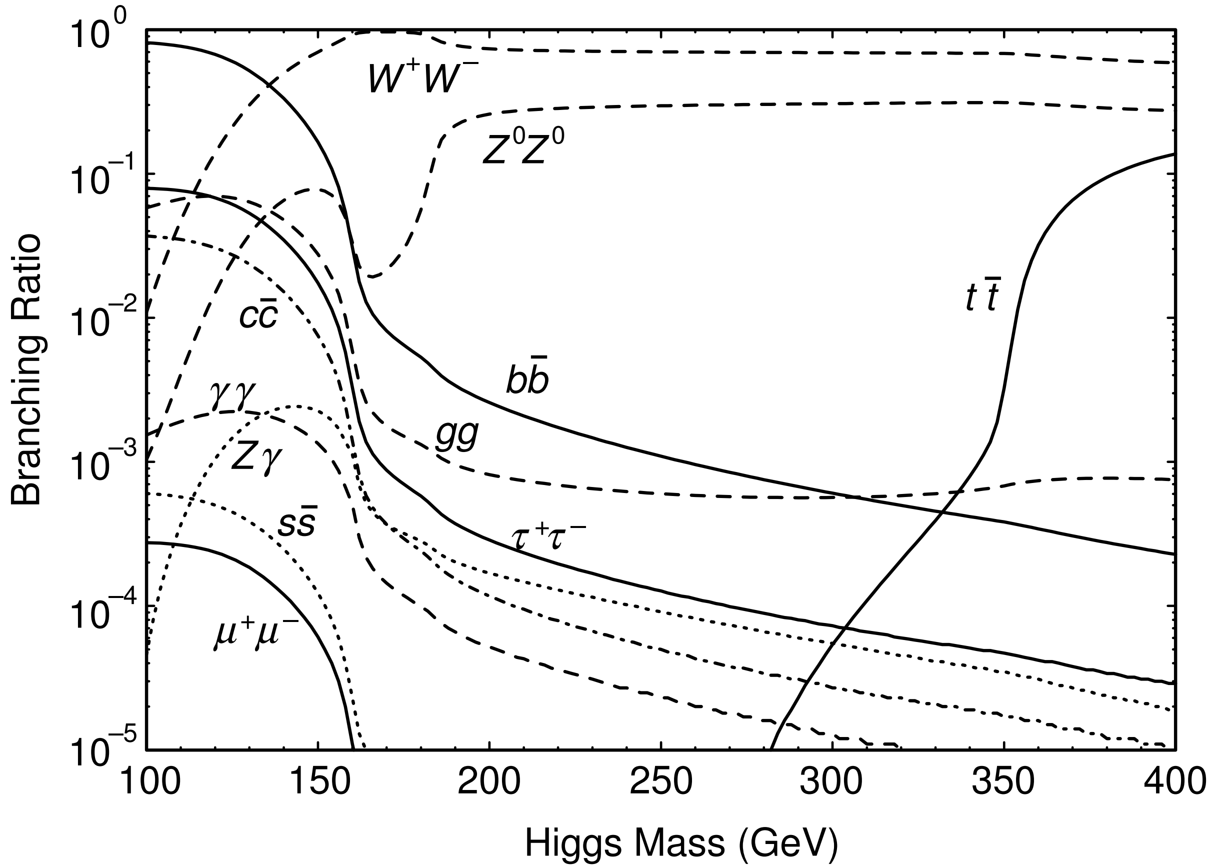
Combined fit using LHC + ILC500: precision mostly dominated by ILC. No ILC $t\bar{t}H$ measurement included.

$t\bar{t}H$ coupling better than LHC alone due to ILC input to LHC fit.



G. Weiglein, hep-ph/0508181

However:

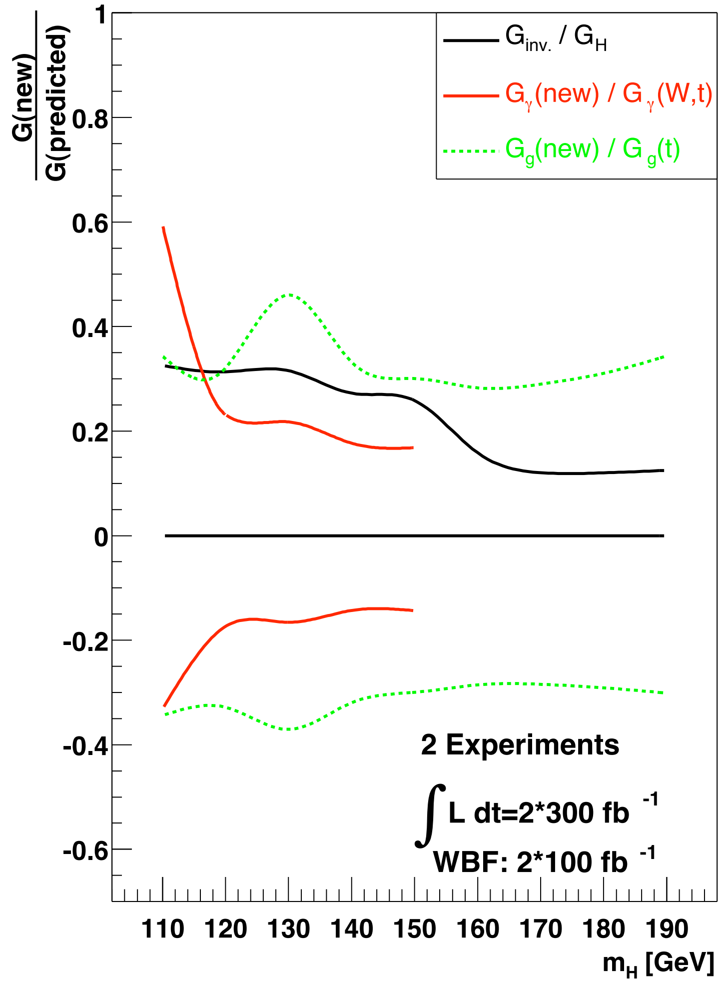


HDECAY

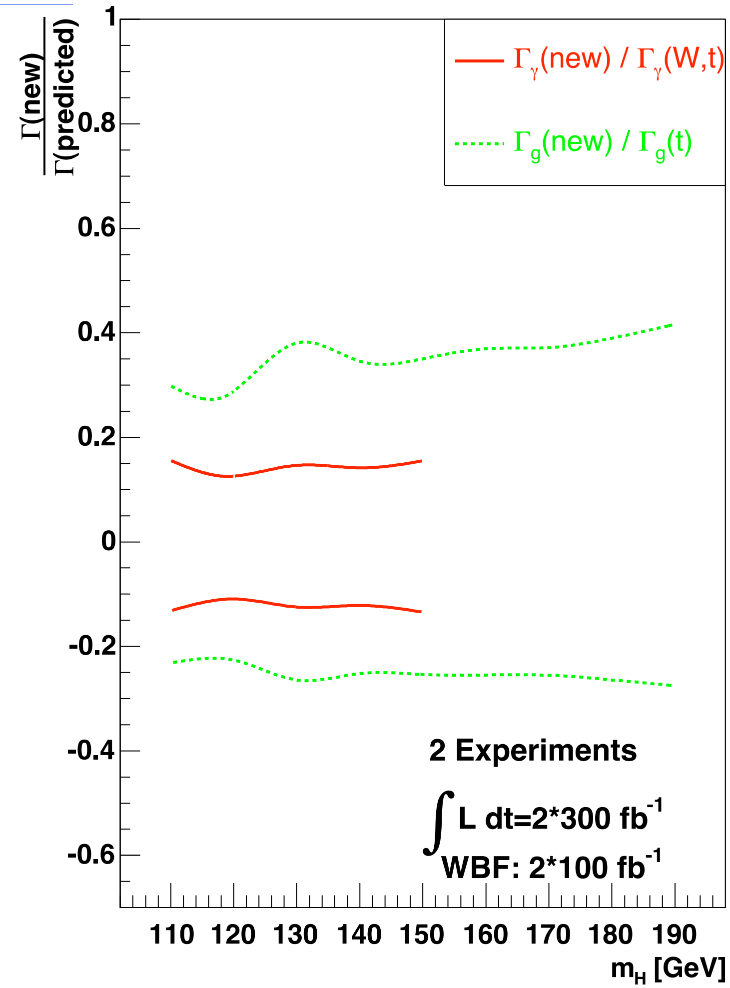
$H \to \gamma\gamma$ is a rare mode: statistics limited at ILC
BR measurement $\sim$ 20–35% precision at ILC

Does anything new run in the loop?

LHC only



Combined fit including ILC500

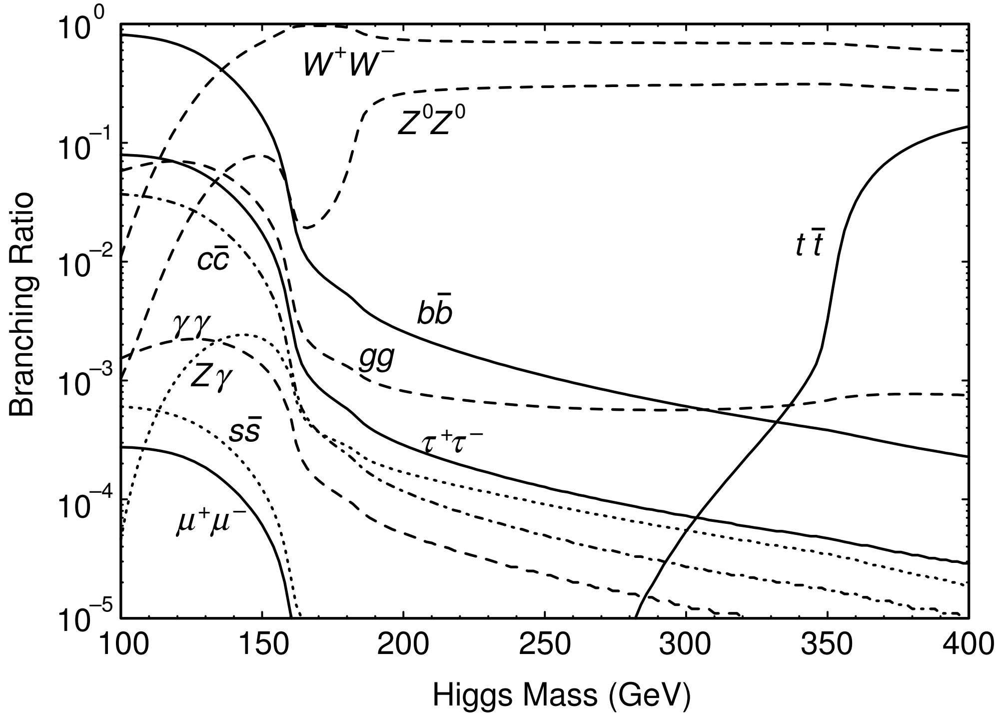


Talk by S. Heinemeyer, LHC/ILC mtg, SLAC, March 2005

Sensitivity comes from LHC, but need ILC to nail down other couplings (especially at low M_H).

Note also ggH coupling measurement at higher Higgs masses.

However:



HDECAY

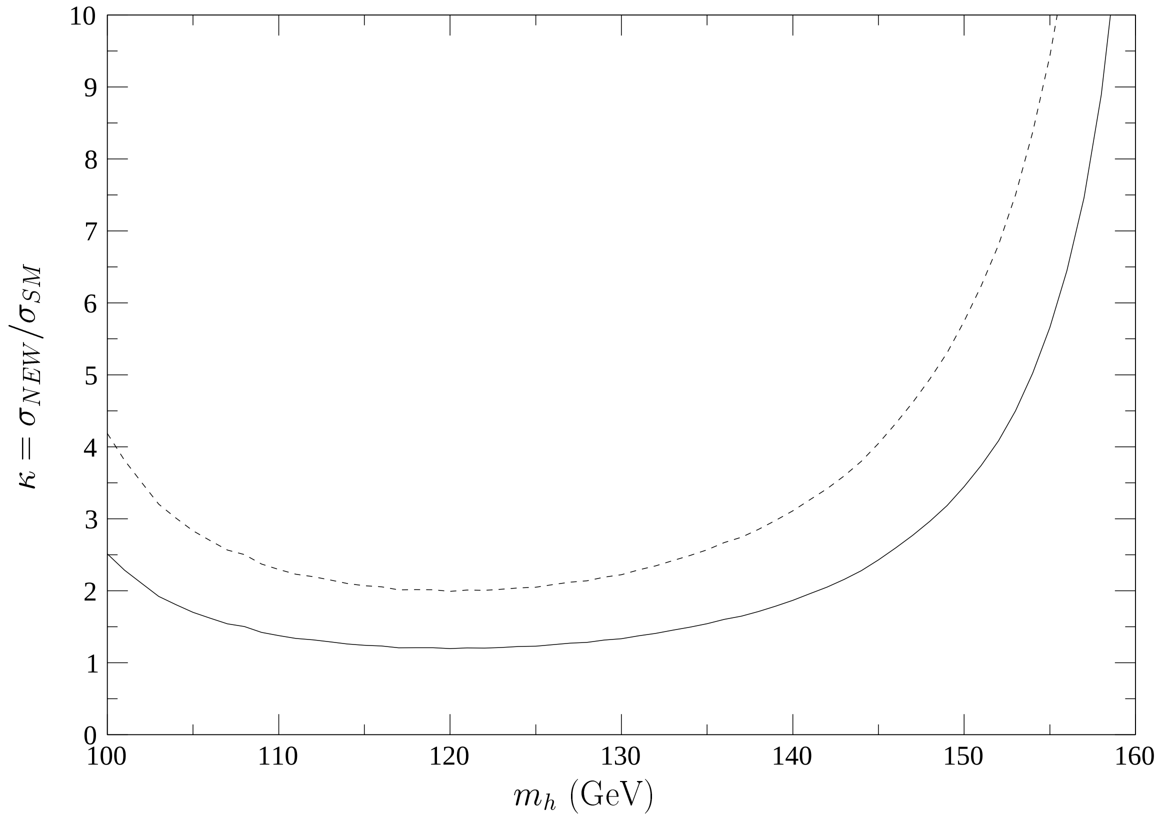
$H \to \mu\mu$ is an extremely rare mode: BR $\sim 3 \times 10^{-4}$

Light Higgs production: $\sim$ 60 fb from ZH, $\sim$ 80 fb from WBF
$\Rightarrow \quad \sim 20$ $H \to \mu\mu$ events in 500 fb^{-1}
Best you could do is $4\sigma \leftrightarrow 25\%$ meas. before any cuts

Do second-generation fermions behave the same as third-generation?

$H \to \mu\mu$ at LHC, from inclusive production:

y axis: enhancement factor needed over SM rate



Han & McElrath, hep-ph/0201023

LHC, 300 fb^{-1} $\times$ 2 detectors; solid $= 3\sigma$, dashed $= 5\sigma$.

Reach similar in WBF Cranmer & Plehn, hep-ph/0605268

Combined analysis might get you something decent.

Benchmark measurement for Super LHC (10$\times$ LHC luminosity)

The point:

- LHC has mass reach: ttH
- LHC has high lumi: $H\gamma\gamma$, $H\mu\mu$?

- ILC has low background: precision measurements of decay BRs, including dominant, hadronic $b\bar{b}$
- ILC has clean, precisely-calculated production: decay-independent precision measurements of production cross sections

Combined: get more than either machine alone

SUSY

LHC:

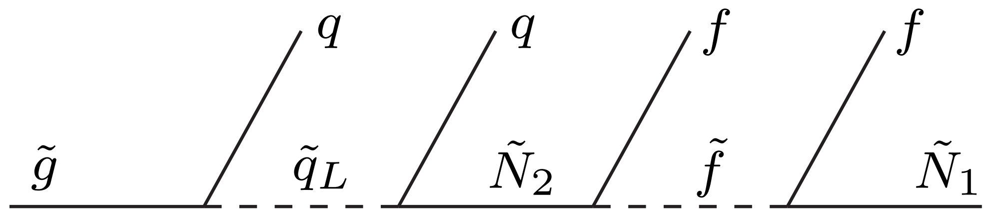
- Kinematic access to heavy (colored) SUSY particles (squarks, gluinos)
- Mass differences from decay chains

ILC:

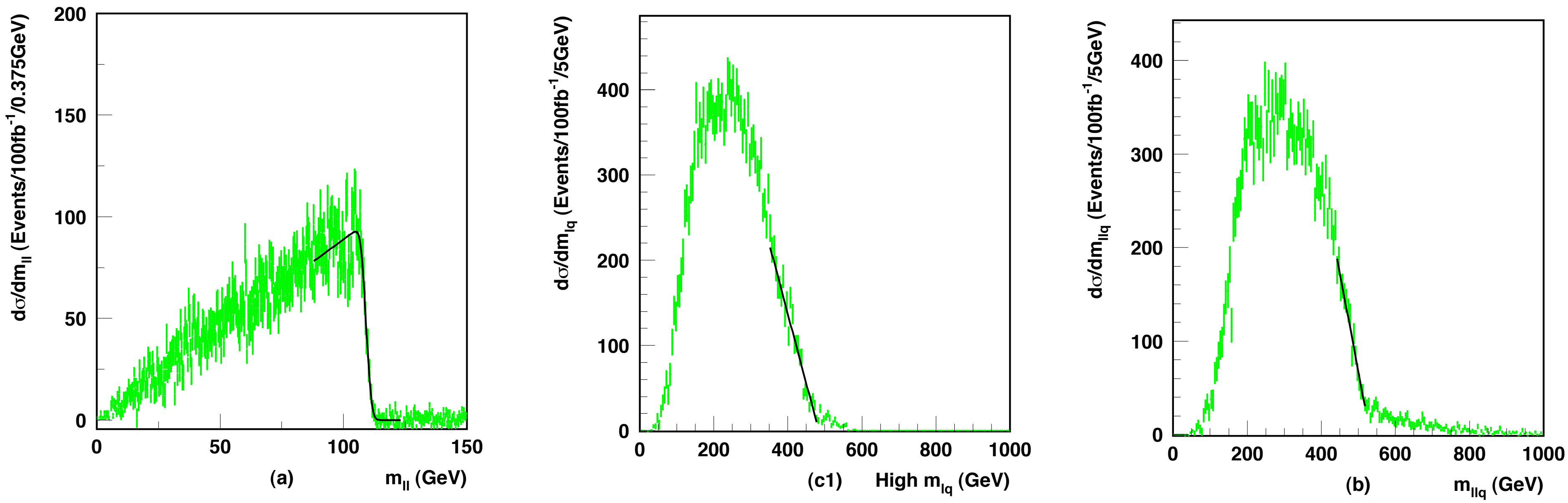
- Access to uncolored SUSY particles (within kinematic reach)
- Precision measurement of LSP mass
- Precision measurements of couplings of light charginos, neutralinos $\rightarrow$ composition

Measuring the SUSY particle mass spectrum

Cascade decays



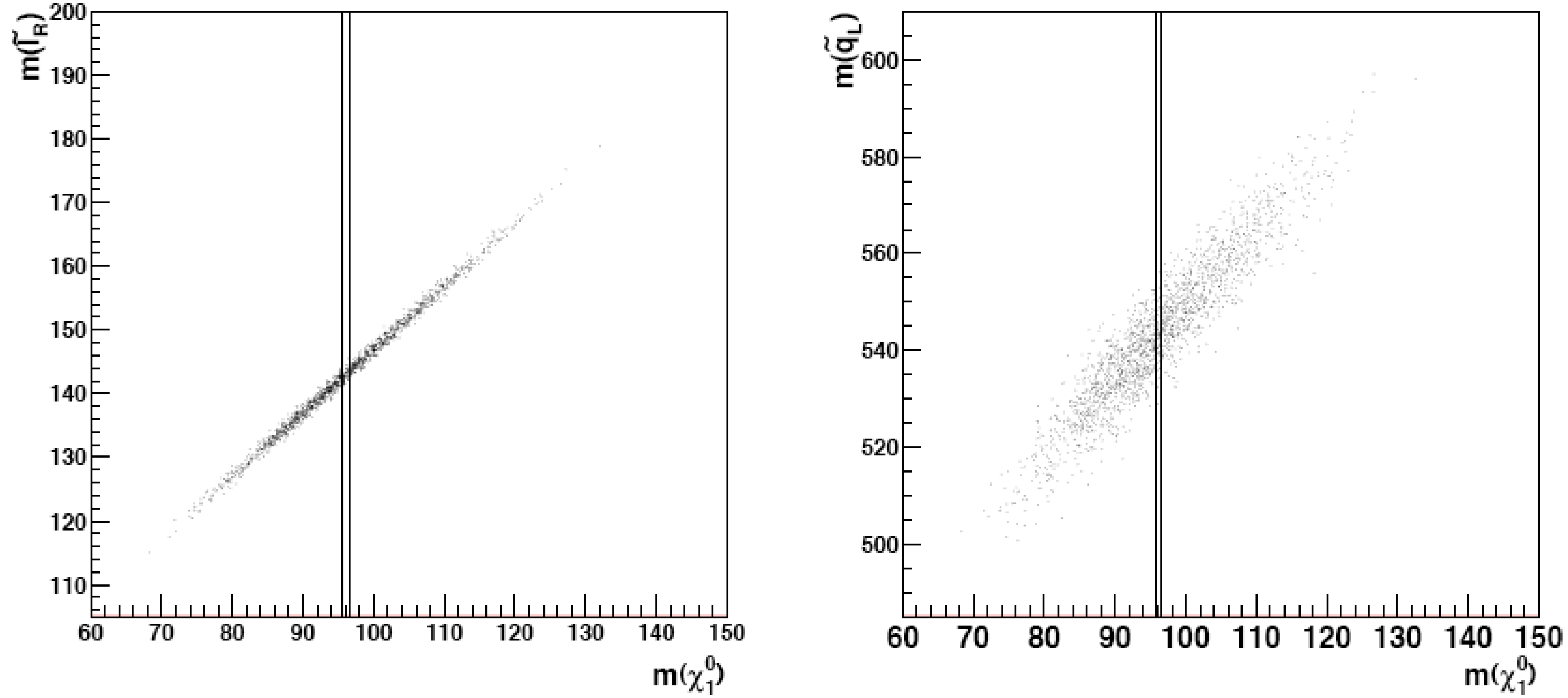
Use kinematic edges to get mass differences in decay chain



Paige, hep-ph/0211017

Because LHC sensitivity comes from mass differences, mass uncertainties are correlated.

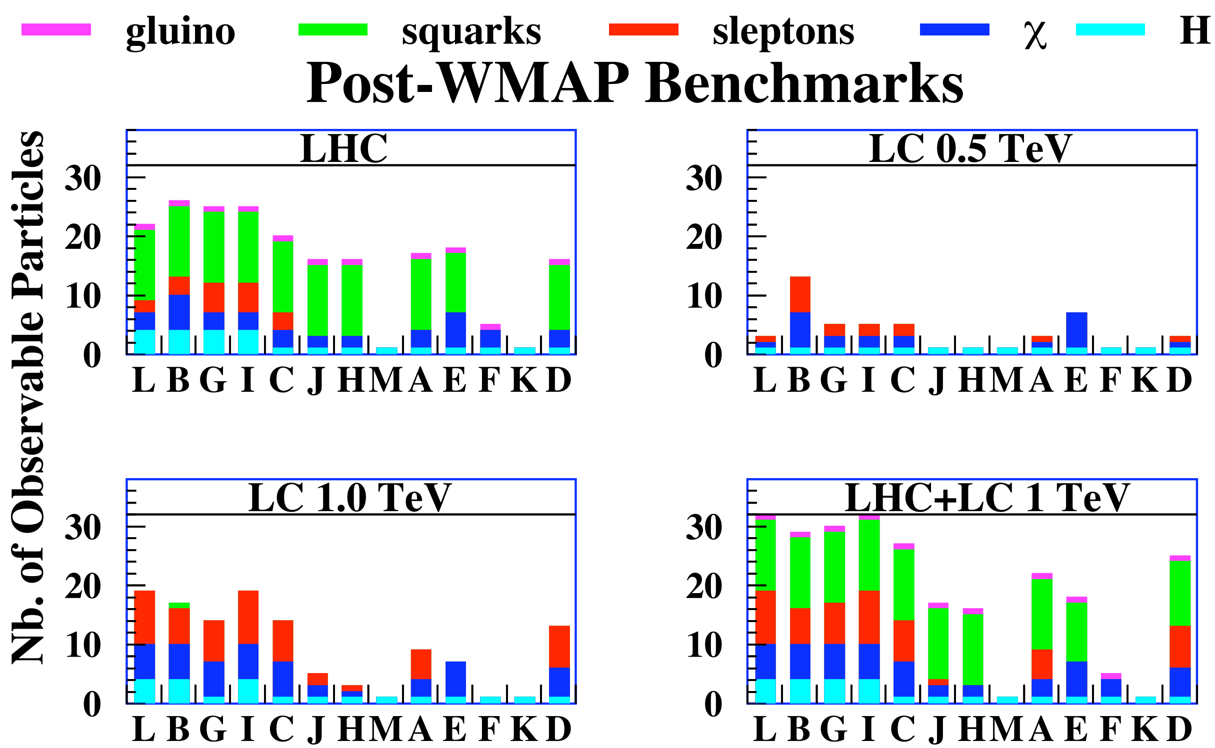
ILC input: precision measurement of LSP mass collapses the degeneracy!



M. Chiorboli et al., in Physics Interplay of the LHC and ILC, hep-ph/0410364

SPS1a; dots are LHC, vertical bands are ILC measurement $\sigma = 0.2\%$

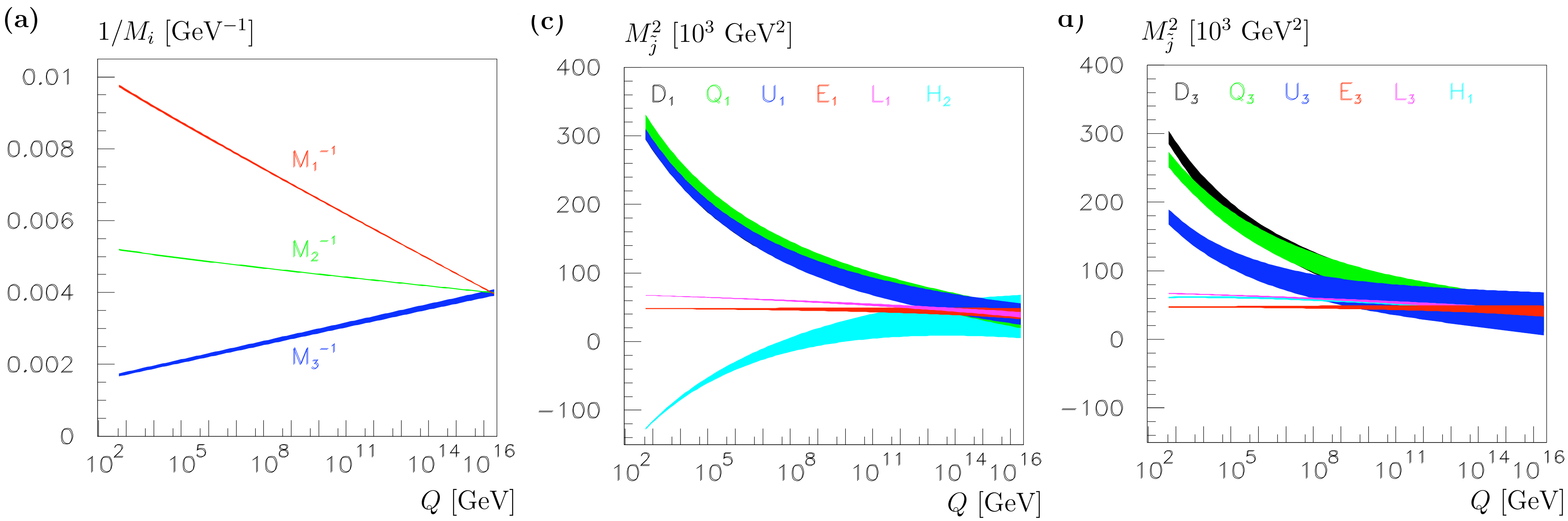
ILC can see lighter states: precision mass measurements, chargino/neutralino sector parameters.



Battaglia et al., hep-ph/0306219

Need LHC for the heavier states: complete the mass spectrum with ILC input for decay chain reconstruction.

Weak-scale SUSY parameters + RGEs → run up to high scale.
Probe grand unification, SUSY breaking pattern.



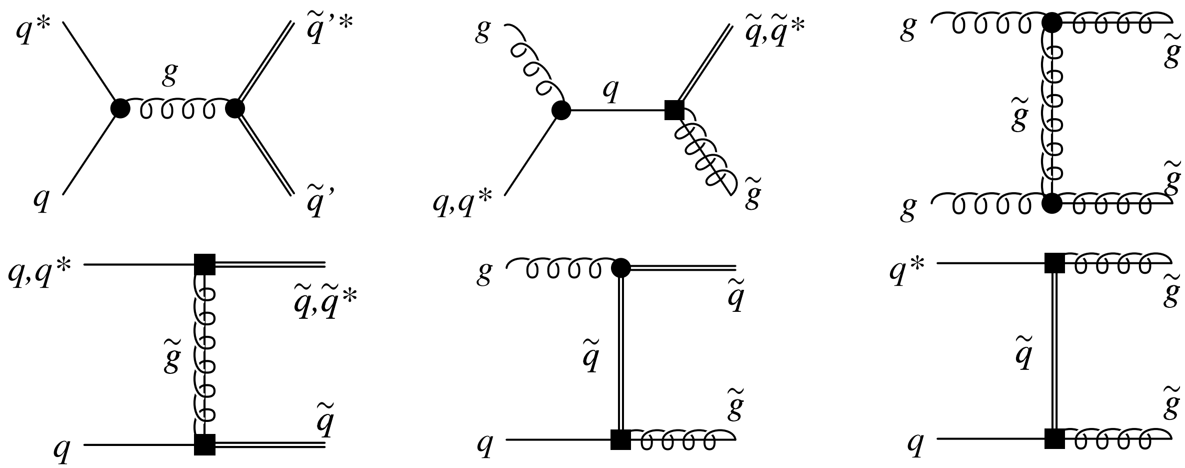
Blair, Porod & Zerwas, hep-ph/0210058 [mSUGRA]

Requires ILC precision meas. of lighter masses, couplings.

Requires LHC reach for heavier masses.

Another example: testing SUSY coupling relations

Gauge couplings $\leftrightarrow$ gaugino Yukawa couplings:
Gluon-quark-quark coupling $\leftrightarrow$ gluino-squark-quark coupling.



Freitas & Skands, hep-ph/0606121

LHC analysis, but requires ILC input for squark decay BRs.

Another example: MSSM vs. NMSSM

NMSSM is the MSSM plus one extra singlet superfield: 5th neutralino, extra Higgs scalar and pseudoscalar.

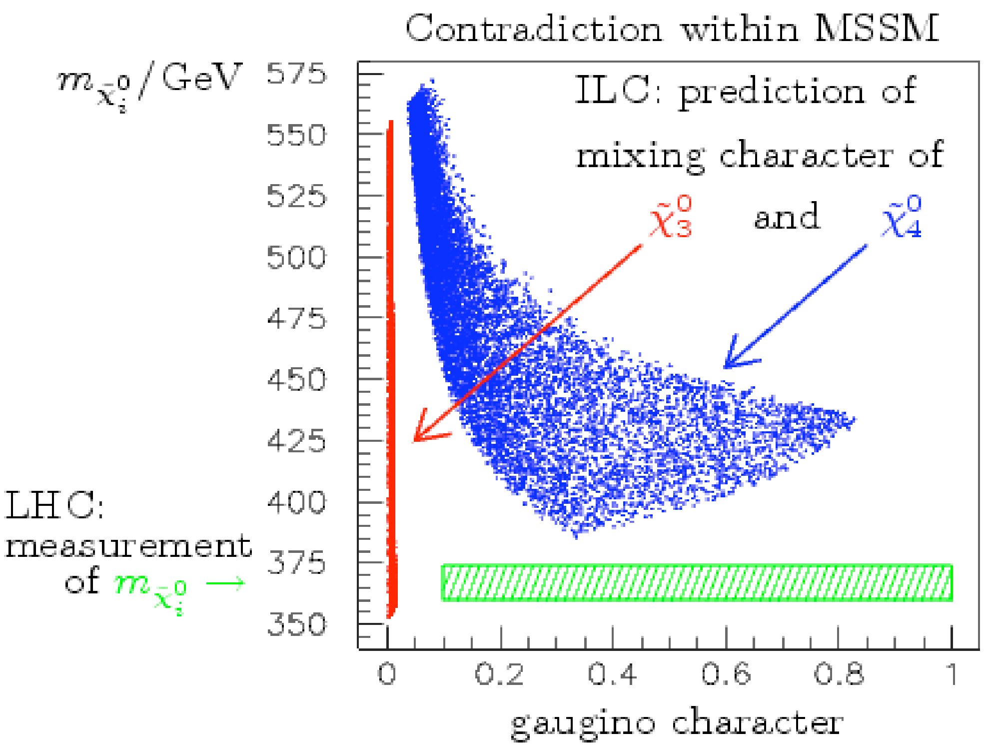
Masses and cross sections of accessible neutralinos, charginos can look identical between MSSM and NMSSM at LHC and at ILC500.

How do we check?

ILC: Measure masses, cross sections, branching ratios of ligher charginos/neutralinos; assume MSSM and extract M_1, M_2, μ, $\tan\beta$.

Assume MSSM and predict mass, gaugino content of neutralinos 3 and 4.

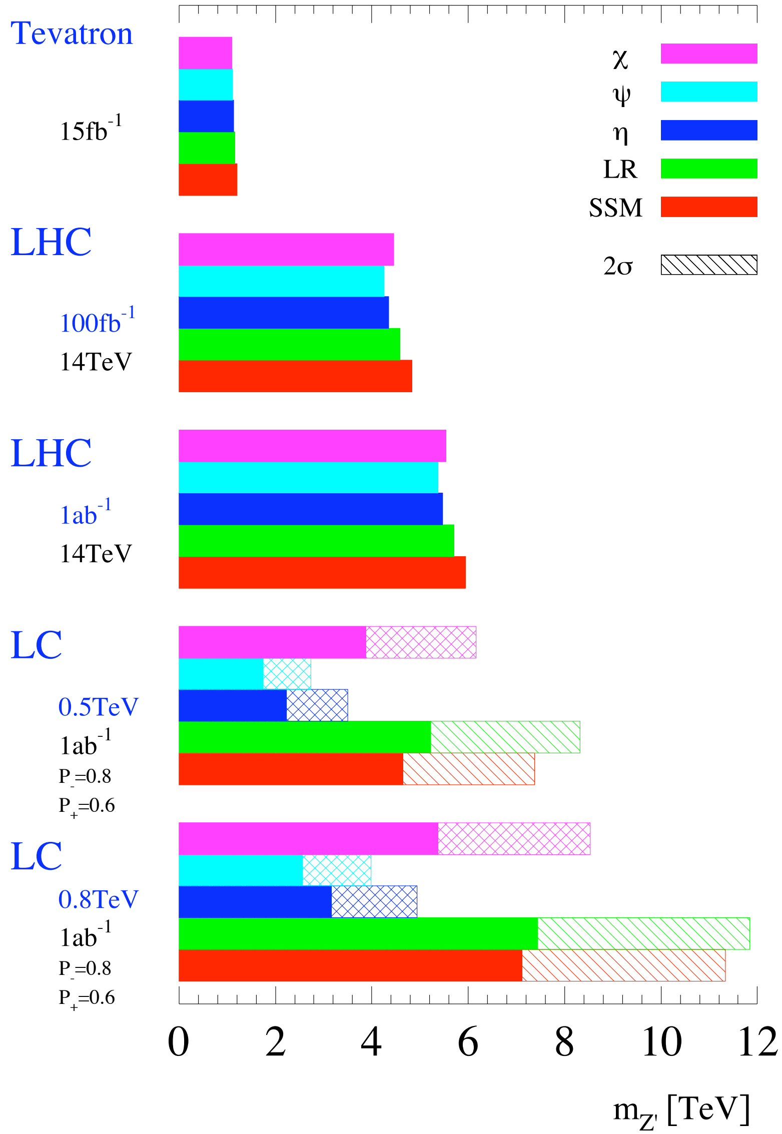
Compare LHC measurement: contradiction!



Moortgat-Pick et al., hep-ph/0508313

Z'

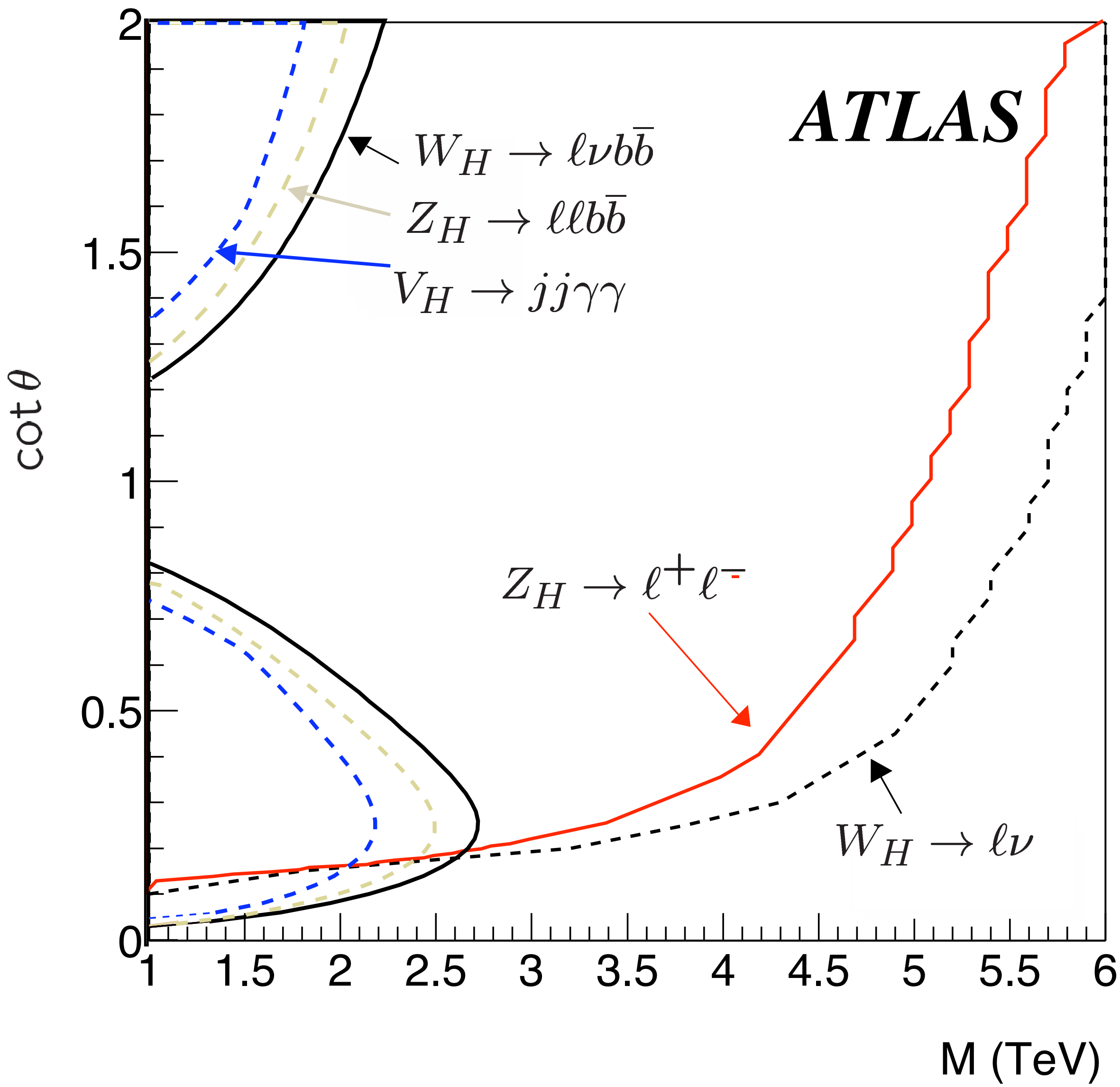
LHC and ILC have comparable "reach" for Z-primes.



S. Riemann, in ILC RDR, arXiv:0709.1893

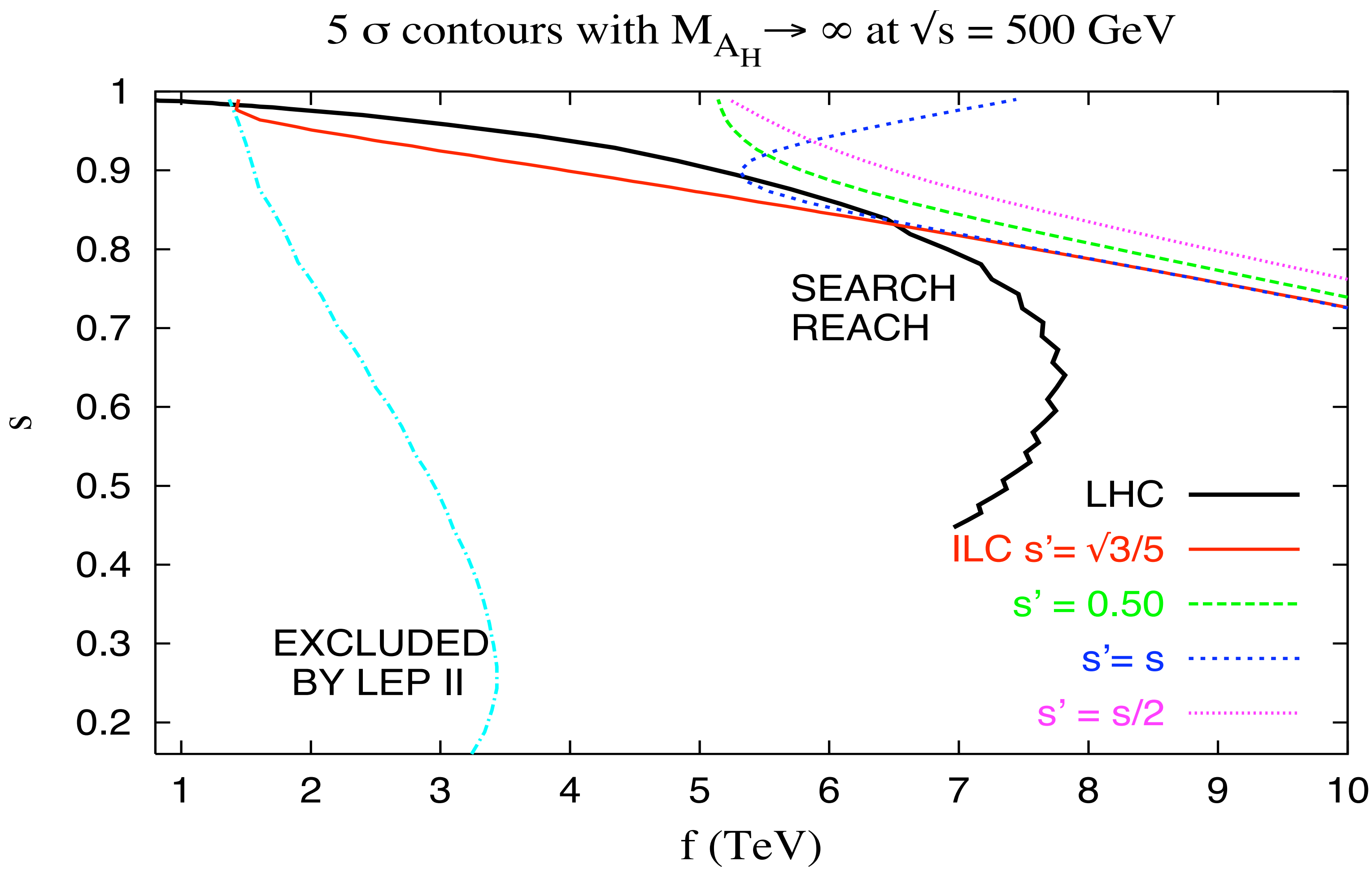
But what does that mean?

One example: Z_H in the Littlest Higgs model.



Azuelos et al, hep-ph/0402037: 5σ discovery reach w/ 300 fb^{-1}

Comparable reach for 5σ signal at ILC:



Conley, Hewett & Le, hep-ph/0507198: 500 fb^{-1} at 500 GeV

But these are very different types of signals.

LHC: direct discovery of Z' resonance in dileptons.

Can measure mass of Z' very accurately.

Hard time measuring couplings:
- get only a rate in dileptons
- Forward/backward asymmetry dependent on rapidity cuts
- Maybe $t\bar{t}$ final state

ILC: sensitivity to Z' through off-shell interference with Z, γ exchange in $e^+e^- \to f\bar{f}$.

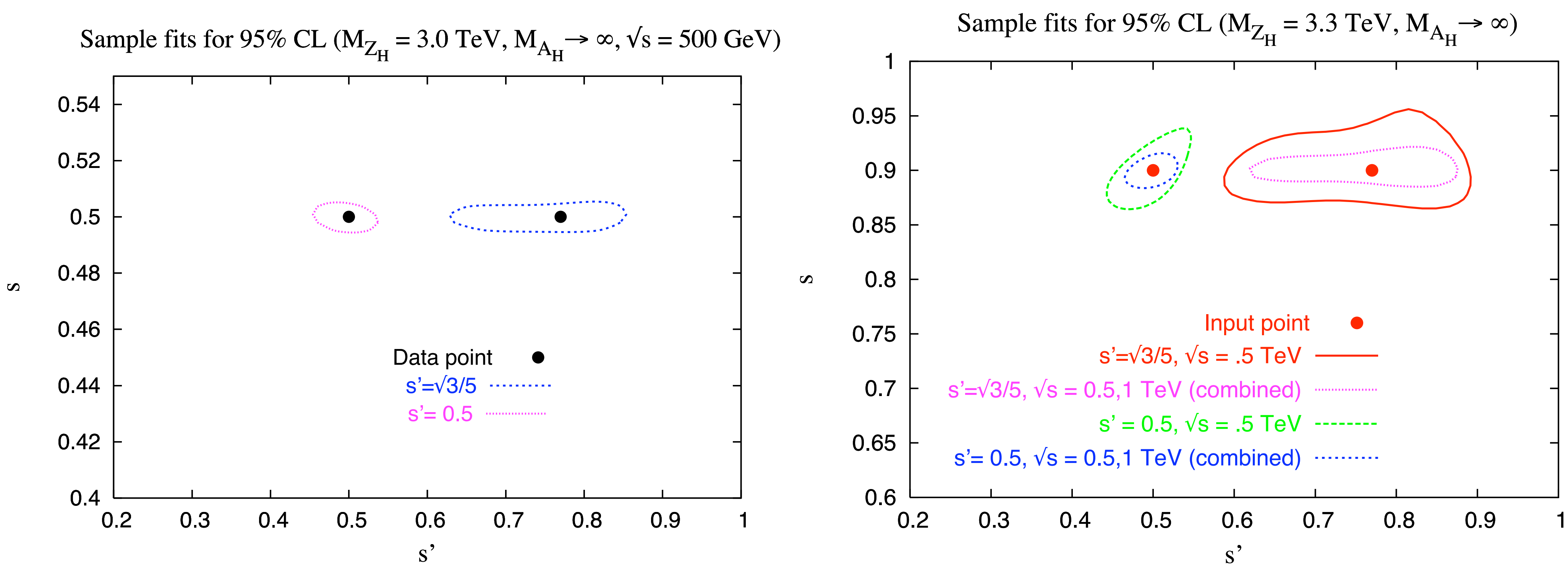
No direct measurement of mass.

Sensitivity to left/right handed couplings to multiple fermion species.

But magnitudes of couplings are mixed up with Z' mass from the propagator.

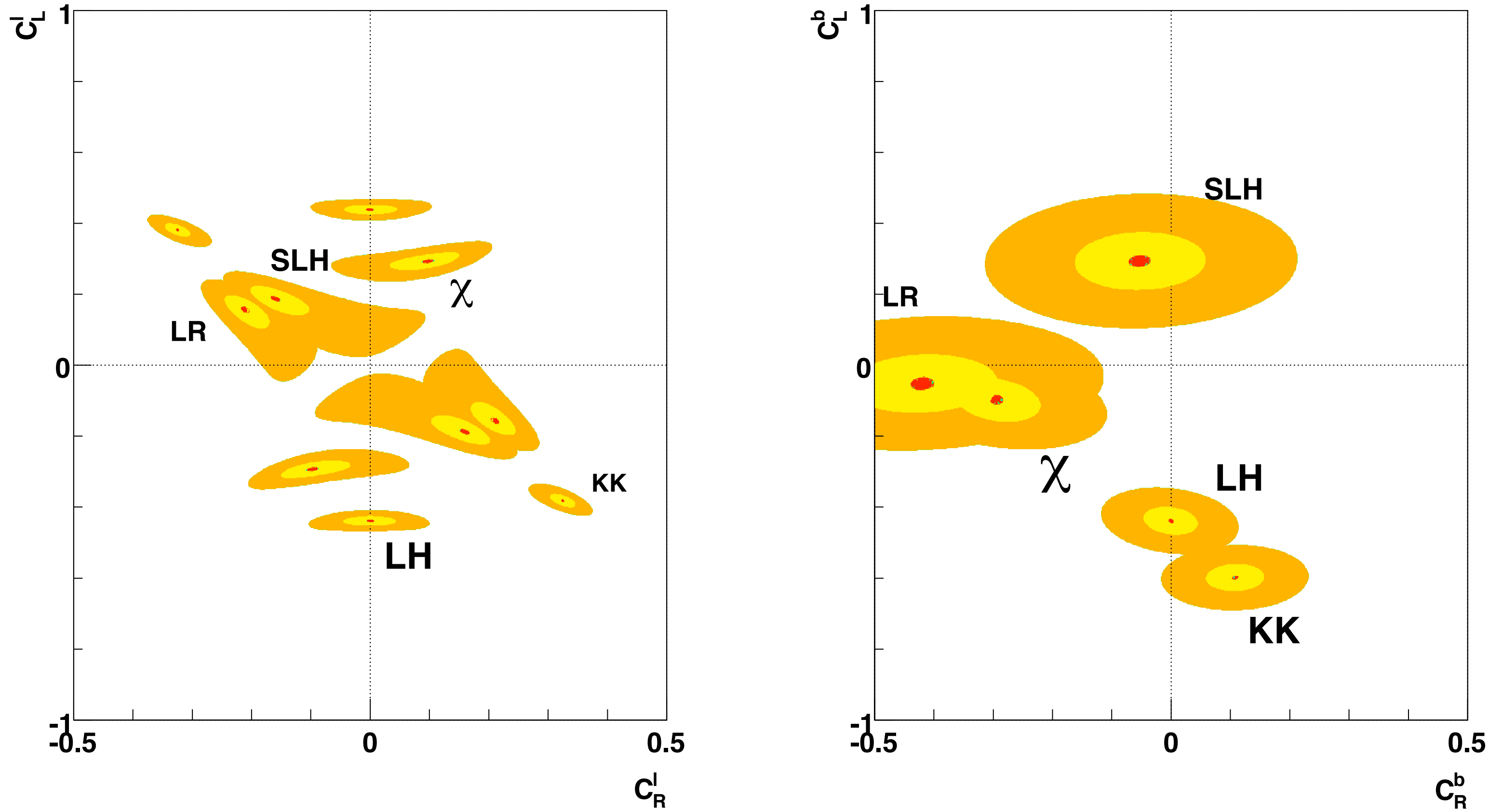
ILC: interference between γ, Z and Z' exchange well below Z' threshold. Need $M_{Z'}$ input from LHC.

Littlest Higgs Z_H example: with mass from LHC, can fit couplings and extract model parameters.



Conley, Hewett & Le, hep-ph/0507198: 500 fb^{-1} at 500 GeV

Applies to general models: measure left/right fermion couplings. Need mass of resonance as input from LHC!



Godfrey, Kalyniak & Tomkins, hep-ph/0511335: 1 ab^{-1} at 500 GeV, $M_{Z'} = 1, 2, 3$ TeV.

- Extended gauge group
- TeV-size extra dimensions
- Compositeness (Technicolor, Randall-Sundrum)

Summary

LHC will open up the TeV-scale frontier.

- Electroweak symmetry breaking?
- Dark matter?
- New forces?
- Supersymmetry?
- Extra dimensions?
- Something we haven't thought of yet??

ILC will provide the precision measurements needed to understand the new physics.

ILC analyses will not be done in isolation: important inputs from LHC physics.

LHC analyses should not allow information to be "lost": be prepared to come back with ILC data and break correlated uncertainties.