Physics at the ILC

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1. The bigger picture

2. Physics we can do for sure at the ILC

3. Physics we can do likely at the ILC

4. How to go ahead?

1. The bigger picture

The ILC could start operations in the middle of the next decade

World of High Energy Physics in the year ~ 2025:

LHC detectors (ATLAS/CMS) will have accumulated $\sim 300\,\mathrm{fb}^{-1}$

Initial LHC physics goals are accomplished:

– state compatible with a Higgs found
  corresponding couplings (ratios) measured to 5–30%
– SUSY-like signatures observed (if realized at the EW scale)
  (or not . . . ???)
– Extra dimensions or . . . -like signatures observed
  (or not . . . ???)

LHC probably awaits luminosity upgrade

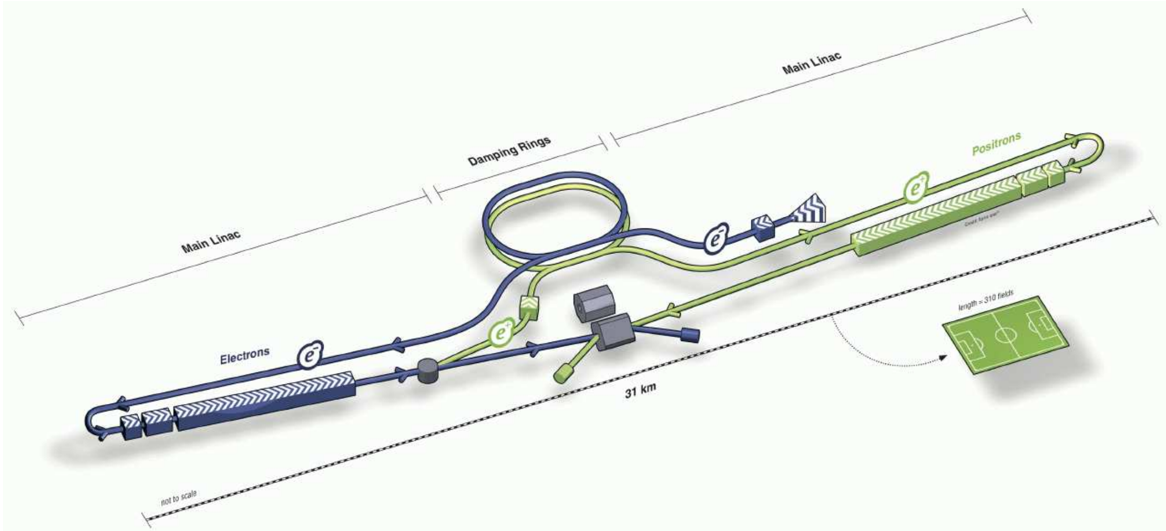
What can the ILC add?

⇒ Implicit in the physics to follow!

Linear e^+e^- collider, $\sqrt{s} = 250 - 1000$ GeV

based on superconducting cavities (cold technology)

Schematic:



Energies: $\sqrt{s} = 250$ GeV, 350 GeV, 500 GeV ... 1000 GeV

Possible features:
- two detectors in one interaction region (push-pull)
- undulator based e^+ source
- polarized beams for e^- and e^+ ($P_{e^-} = 80\%$, $P_{e^+} = 60\%$)
- tunable energy

Other ILC options:

- GigaZ:
  running with high luminosity at low energies (Z pole, WW threshold)

- $\gamma\gamma$:
  use both beams to produce high-energy photons
  (e.g. heavy Higgs production in the s channel, $\Gamma(H \to \gamma\gamma)$, . . .)

- $e^-\gamma$:
  use one e^- beam to produce high-energy photons
  produce charged particles in the s channel

- e^-e^-:
  produce doubly charged particles in the s channel

$\Rightarrow$ to optimize physics potential!

Physics at the ILC $\Rightarrow$ determined by experimental data!

Physics at the ILC ⇒ determined by experimental data!

What we know for sure:

- discovery of a Higgs particle
- top quark
- gauge bosons: $W^{\pm}, Z$
- ...

⇒ clear physics case

Physics at the ILC $\Rightarrow$ determined by experimental data!

What we know for sure:

– discovery of a Higgs particle
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$\Rightarrow$ clear physics case

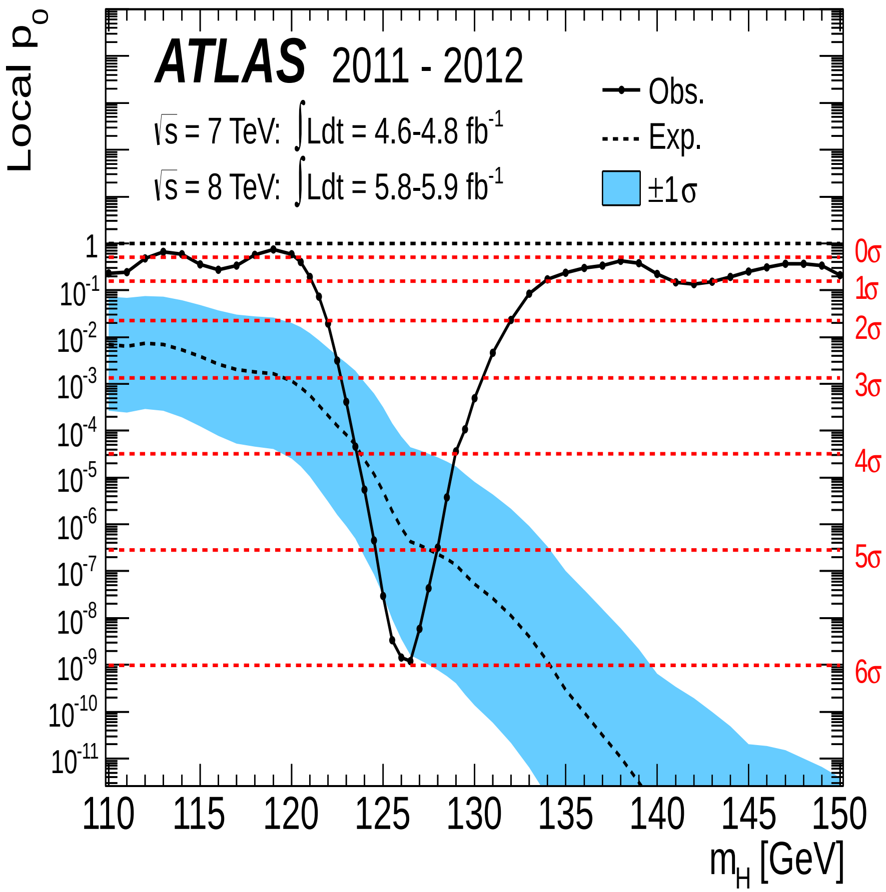
Other experimental data:

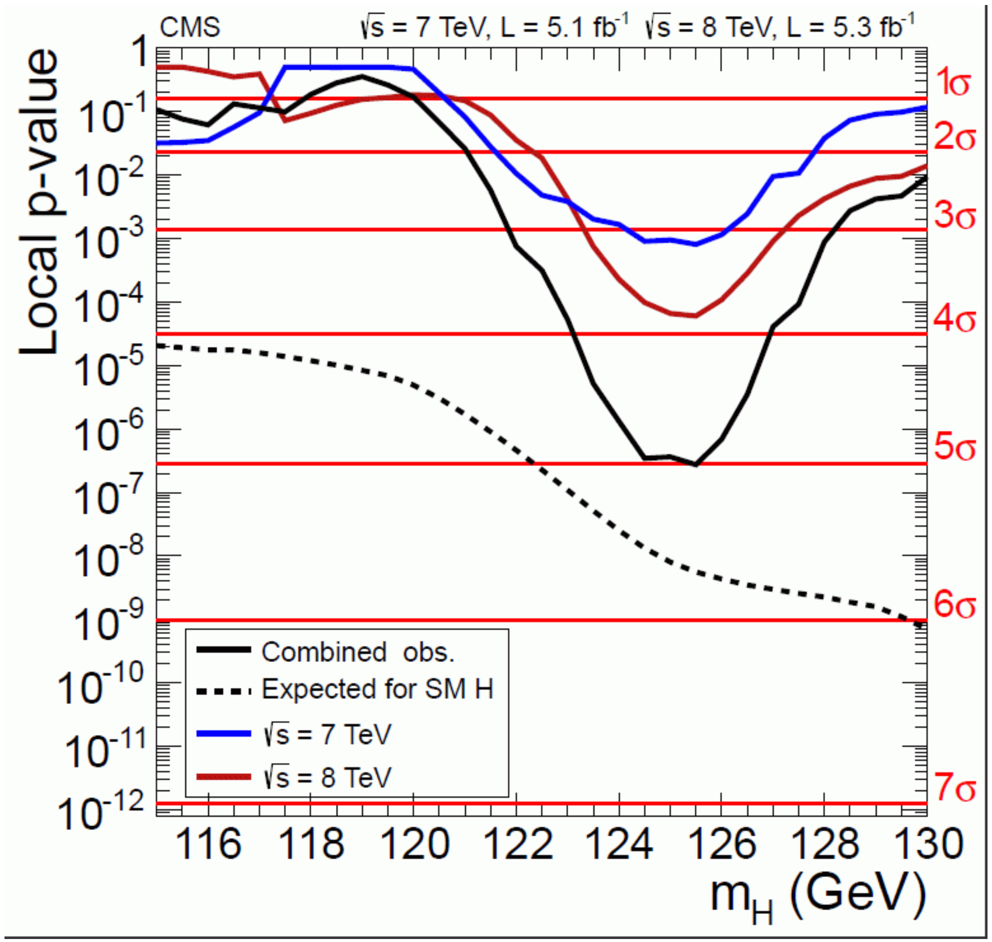
– dark matter
– the anomalous magnetic moment of the muon, $(g-2)_\mu$
– ...

$\Rightarrow$ "likely" (additional) physics case

2. Physics we can do for sure at the ILC

We have a discovery!





We have a discovery!

But what is it?

Q: Is it a Higgs boson? ⇒ yes according to CERN!

Q: Is it “the” Higgs boson (i.e. of the SM)?

Q: Is it a supersymmetric Higgs boson?

Q: Is it a Higgs boson of a different model?

Q: Is it an impostor?

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How can we decide?

How can we establish the Higgs mechanism?

Investigating the Higgs Mechanism

What has to be done?

Find the new particle

Investigating the Higgs Mechanism

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1. Find the new particle
2. measure its mass ($\Rightarrow$ ok?)

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Investigating the Higgs Mechanism

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Investigating the Higgs Mechanism

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Investigating the Higgs Mechanism

What has to be done?

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L = LHC,

Investigating the Higgs Mechanism

What has to be done?

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L = LHC, L = LHC (partially/unclear),

Investigating the Higgs Mechanism

What has to be done?

1. Find the new particle	done		
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L = LHC, L = LHC (partially/unclear), I = ILC, I = ILC (doable?)

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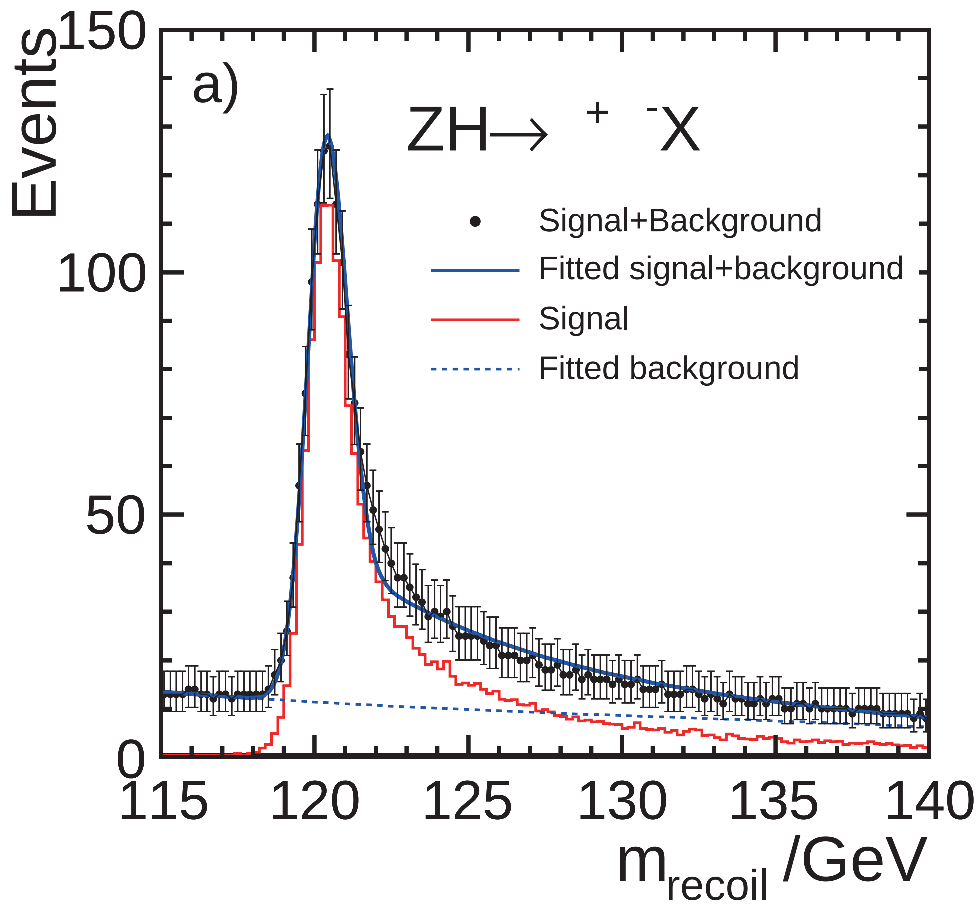
L = LHC, L = LHC (partially/unclear), I = ILC, I = ILC (doable?)

The LHC can investigate the Higgs mechanism and tell us a lot!

We need the ILC to fully establish the Higgs mechanism!

Model independent cross section measurement

Z-recoil method: $e^+e^- \to ZH \to \mu^+\mu^- X$

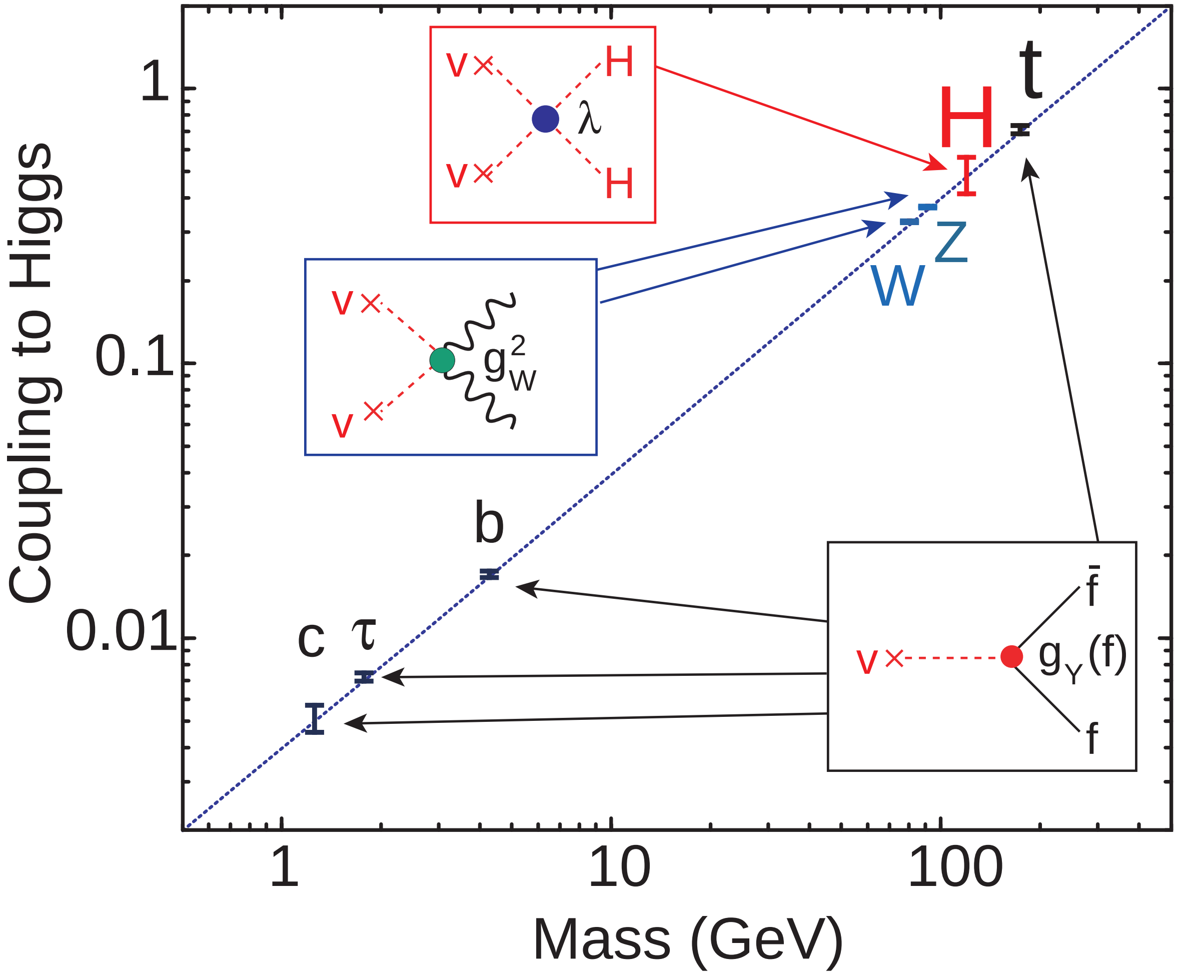


$\Rightarrow$ crucial for a model independent coupling measurement! $\delta M_H^{\text{exp}} \lesssim 0.05$ GeV

Higgs mechanism: mass $\propto$ coupling

[*taken from K. Fuji '13*]

$\Rightarrow$ clear, testable prediction!



$\Rightarrow$ ILC can test all three types!

ILC: absolute couplings, total width, invisible width, . . .

Expected precision for fermionic and gauge decay modes: [ILC TDR '13]

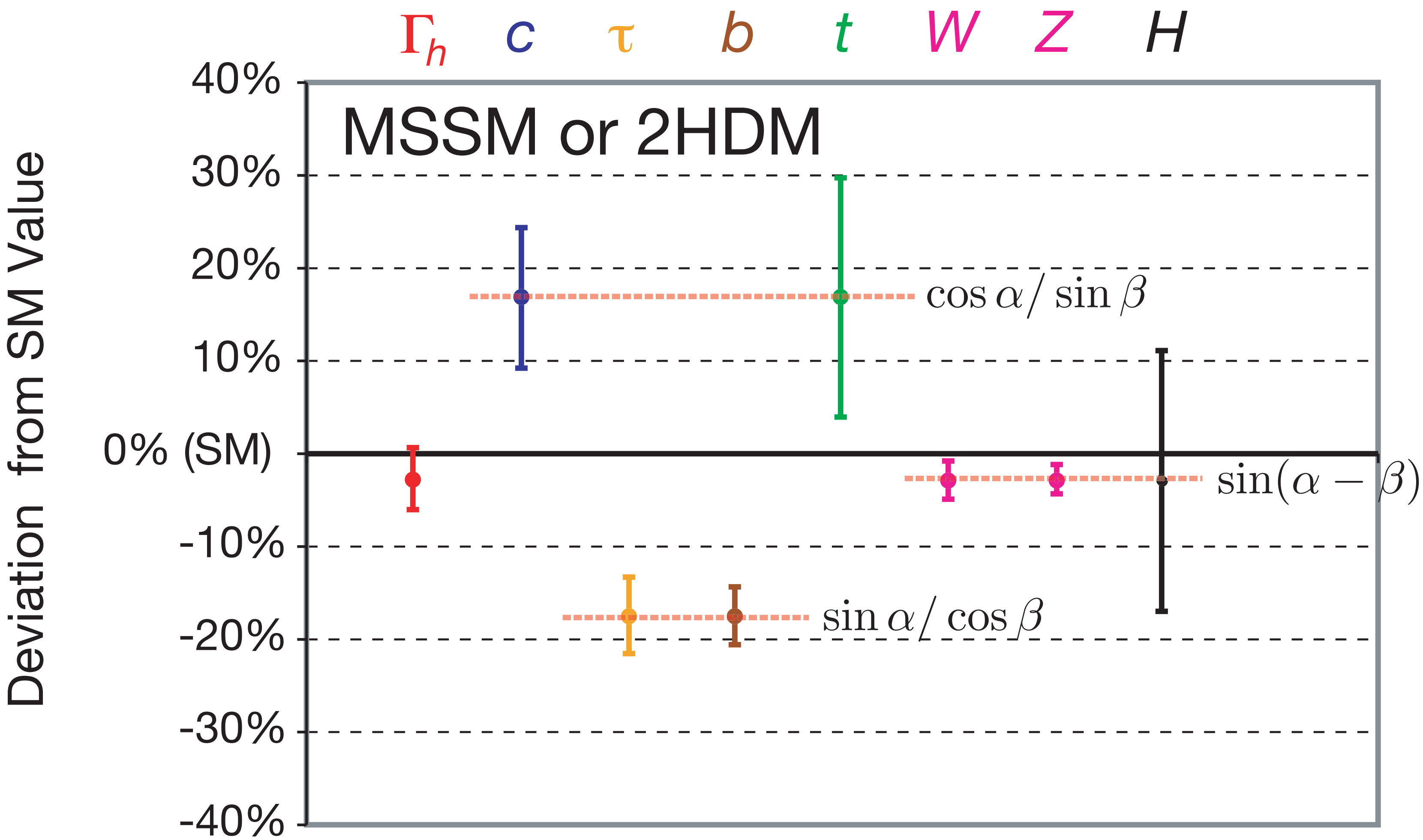
	$\Delta(\sigma \cdot \text{BR})/(\sigma \cdot \text{BR})$			$\Delta g/g$
mode	ZH @ 250 GeV (250 fb^{-1})	ZH @ 500 GeV (500 fb^{-1})	$\nu\bar{\nu}H$ @ 500 GeV (500 fb^{-1})	combined
$H \to b\bar{b}$	1.0%	1.6%	0.60%	1.3%
$H \to \tau^+\tau^-$	3.6%	4.6%	11%	1.8%
$H \to c\bar{c}$	6.9%	11%	5.2%	2.3%
$H \to gg$	8.5%	13%	5.0%	2.4%
$H \to WW^*$	8.1%	12.5%	3.0%	1.9%
$H \to ZZ^*$	26%	34%	10%	4.7%
$H \to \gamma\gamma$	23-30%	29-38%	19-5%	(13-17%)

Total width: $\Delta\Gamma_H/\Gamma_H$: 4.8% – 1.2%

Invisible width: $\Delta\Gamma_{\text{inv}}/\Gamma_{\text{inv}}$: 0.44 – 0.26% ($\sqrt{s} = 250 - 1000$ GeV)

$\Rightarrow$ discrimination between models! $\Rightarrow$ possible deviations: $\mathcal{O}$ (few%)

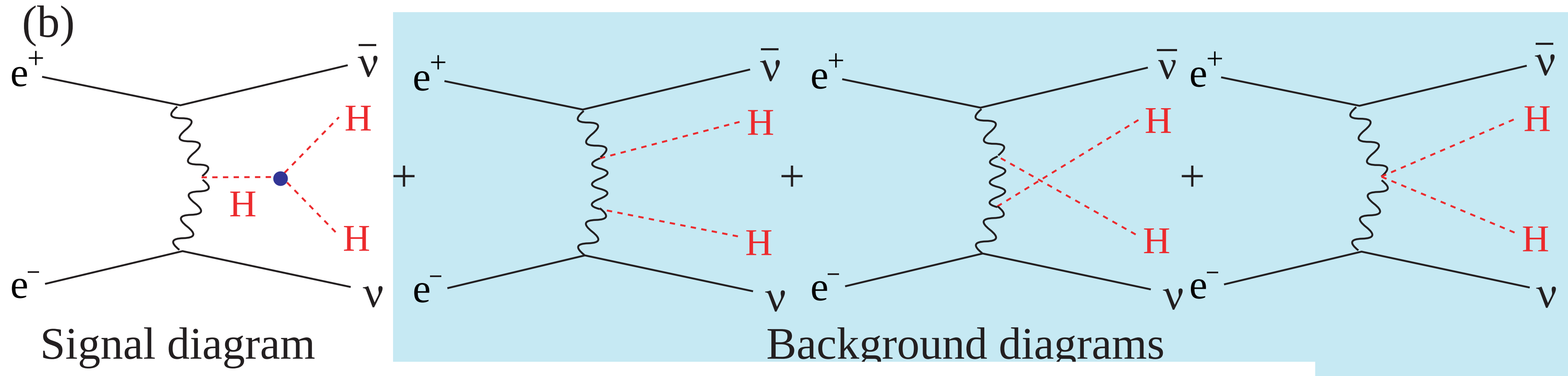
Example: Higgs couplings in the 2HDM:

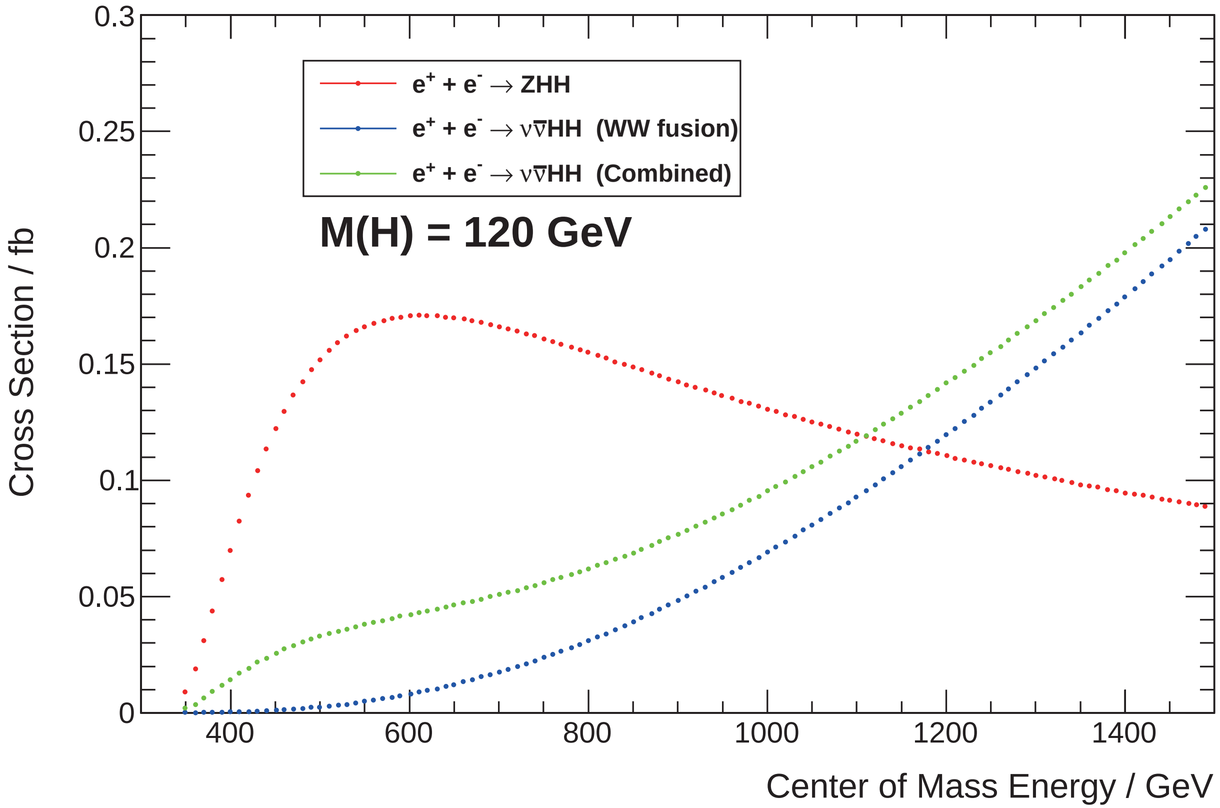


$\Rightarrow$ measurable deviations

Particularly challenging: Higgs self-coupling

[ILC TDR '13]

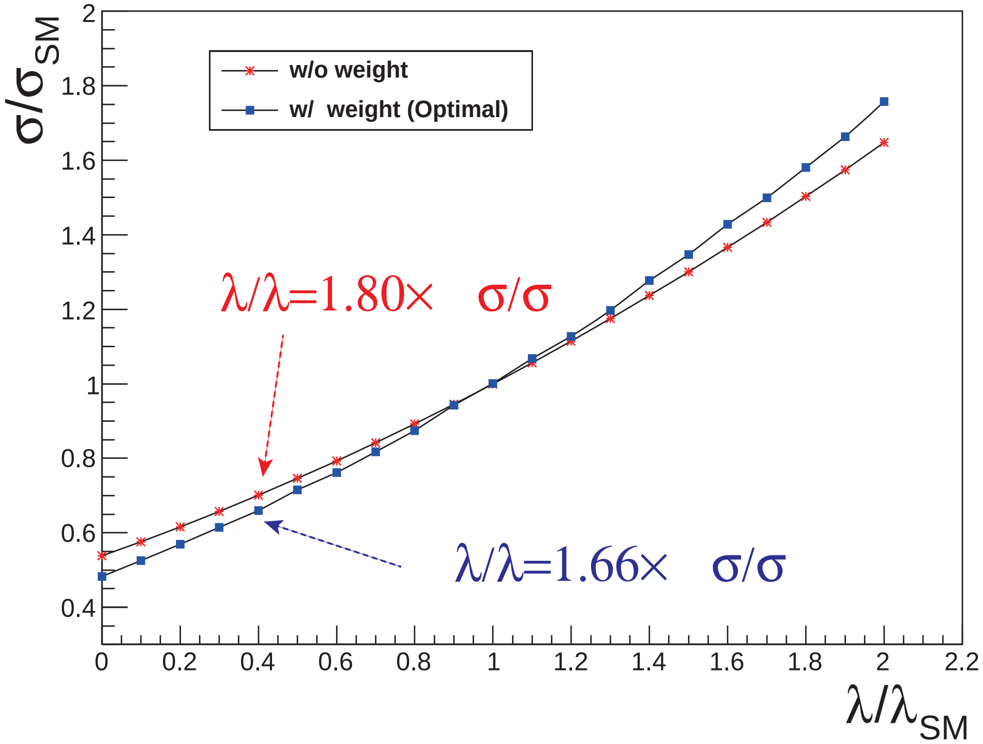




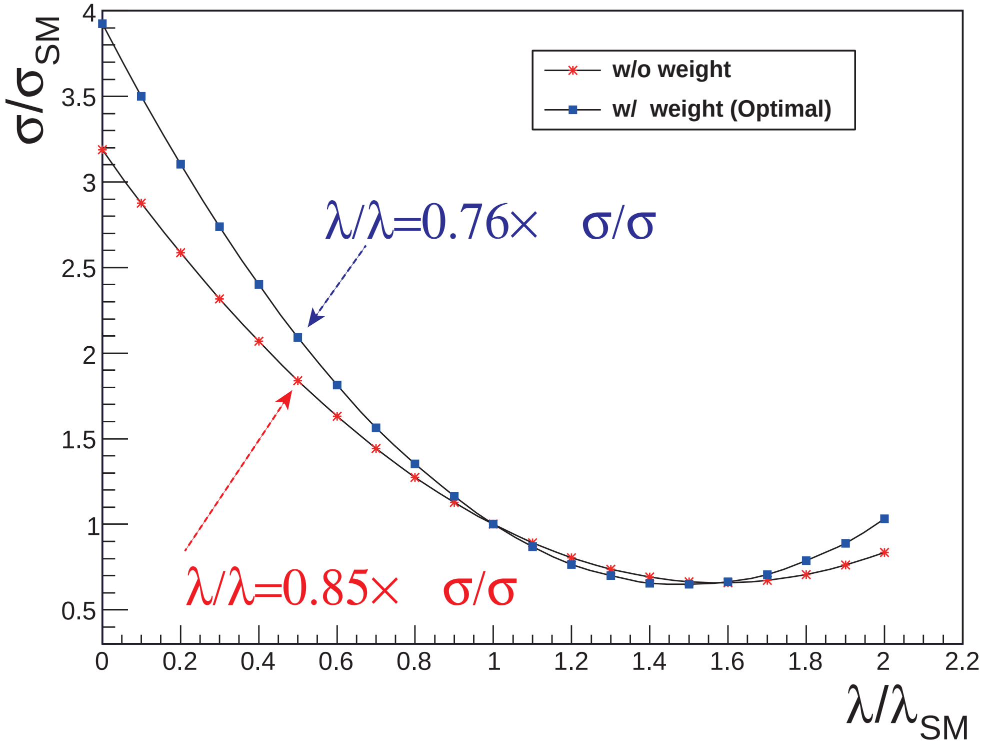
Sensitivity to triple Higgs coupling λ:

[taken from K. Fuji '13]

ZHH@500 GeV



$\nu\bar{\nu}HH$@1000 GeV

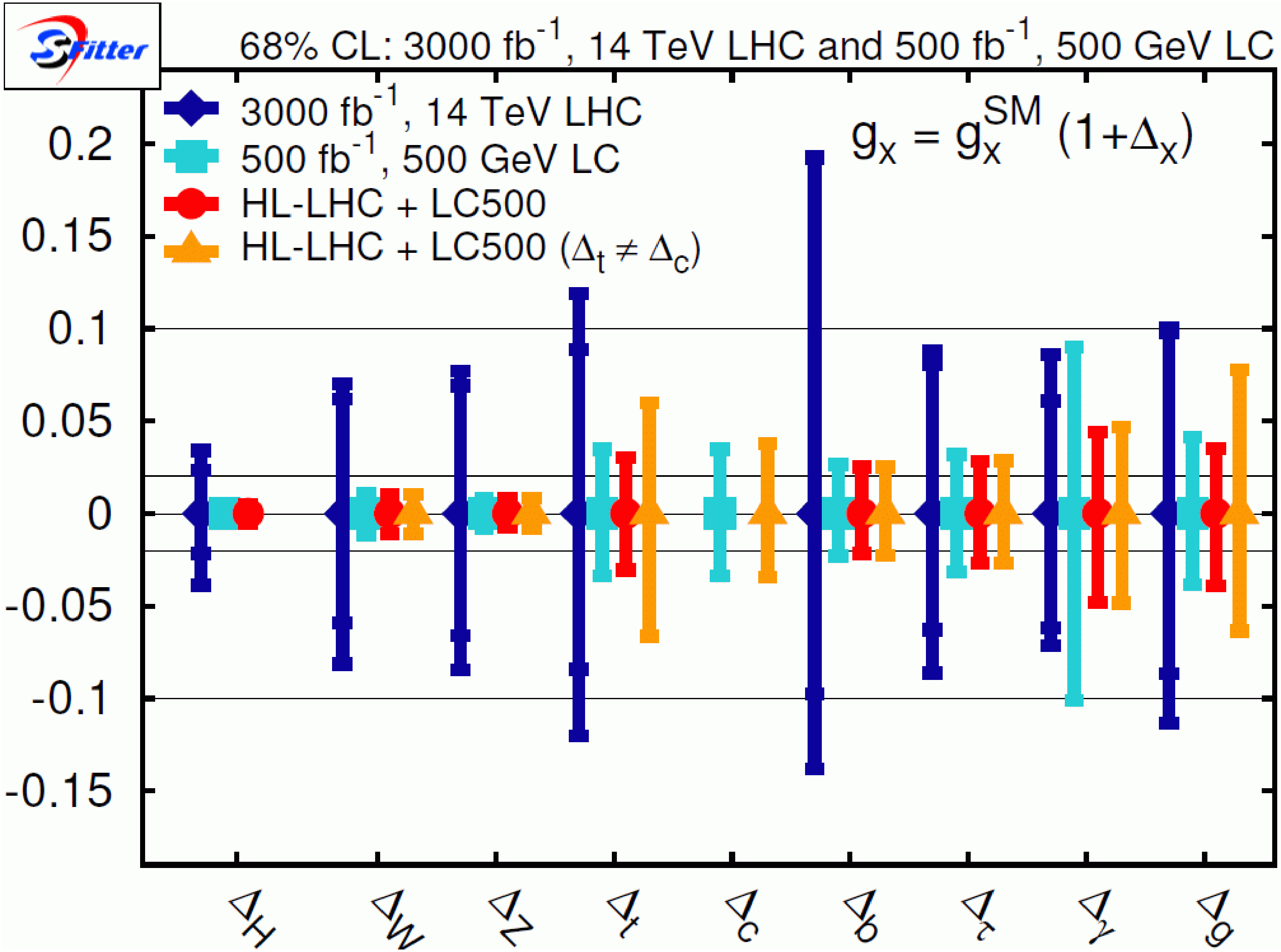


$\Rightarrow$ currently full simulations are performed

Expected sensitivity on λ: $\sim$ 21% (2 ab^{-1} @ 1000 GeV) *[ILC TDR '13]*

Fitting all Higgs couplings together

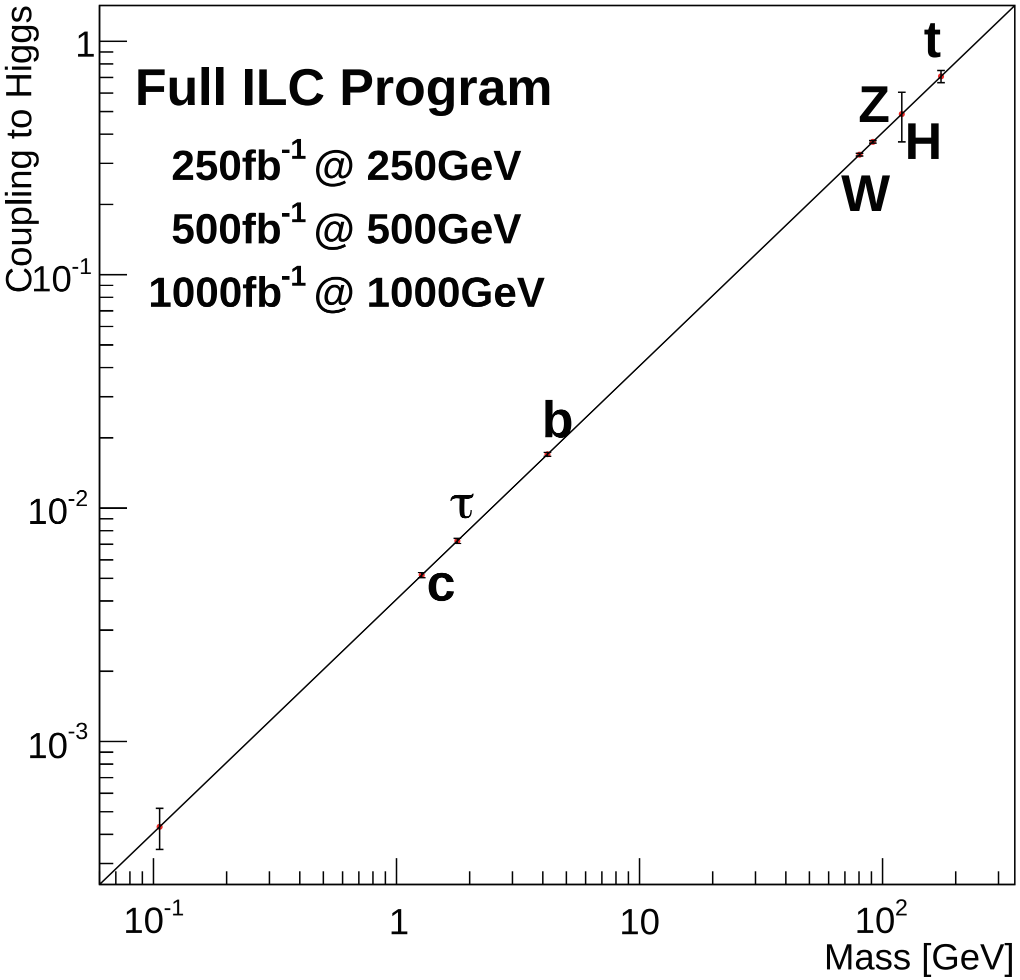
(note: LHC requires theory assumptions)



⇒ clear and strong improvement from ILC measurements!

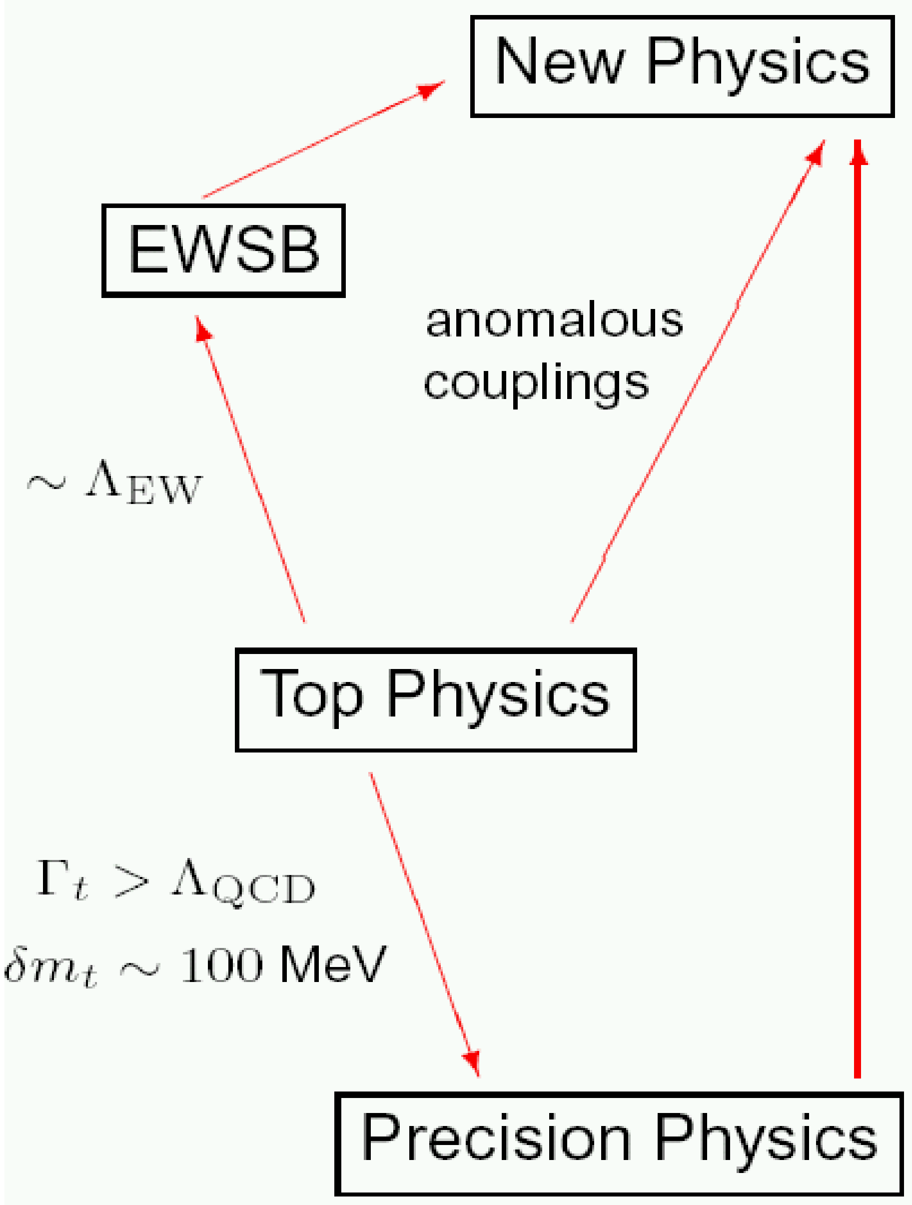
Higgs mechanism: mass $\propto$ coupling

putting everything together:



$\Rightarrow$ any deviation from straight line indicates BSM physics!

Top physics at the ILC



EWSB: just a heavy quark?
special role for t in EWSB?
strong constraint on any model

Precision physics:
$\delta m_t^{\rm exp}$ leading parametric uncertainty
$\to$ could obscure new physics

SUSY: m_t crucial input parameter
drives SSB/unification

Many BSM models: heavier top partners

LHC: measurements of
mass, BRs, asymmetries

ILC: high precision of everything
incl. couplings

What is the top mass?

Particle masses are not direct physical observables
one can only measure cross sections, decay rates, . . .

Additional problem for the top mass:

what is the mass of a colored object?

Top pole mass is not IR safe (affected by large long-distance contributions), cannot be determined to better than $\mathcal{O}(\Lambda_{\rm QCD})$

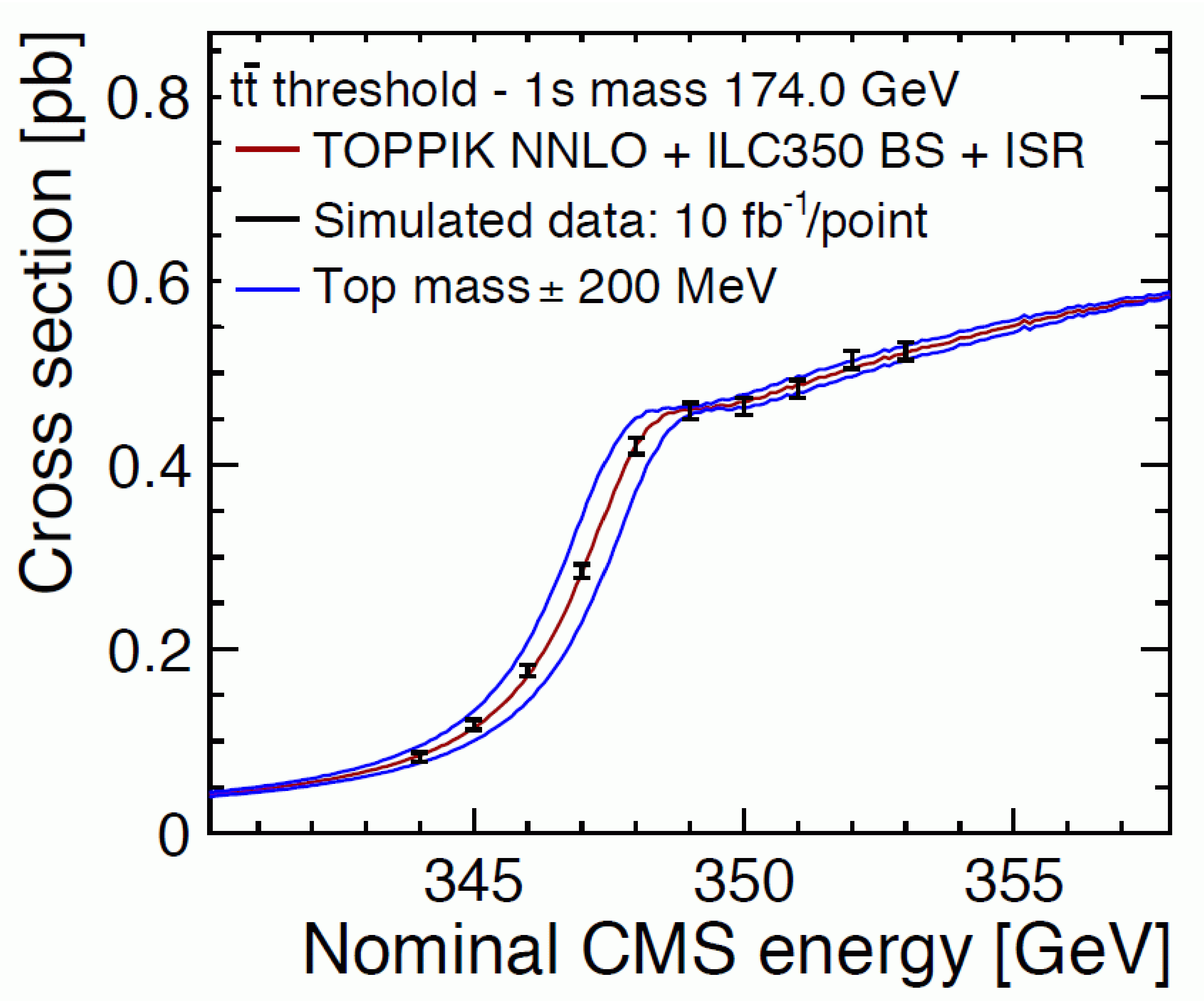
Measurement of m_t:

- At Tevatron, LHC:
  kinematic reconstruction, fit to invariant mass distribution
  $\Rightarrow$ "MC" mass, close to "pole" mass?

- At the ILC: unique possibility
  threshold scan $\Rightarrow$ threshold mass $\Rightarrow$ **SAFE!**
  transition to other mass definitions possible, $\delta m_t \lesssim 100$ GeV

At the ILC: unique possibility [ILC TDR '13]

threshold scan ⇒ threshold mass ⇒ **SAFE!**

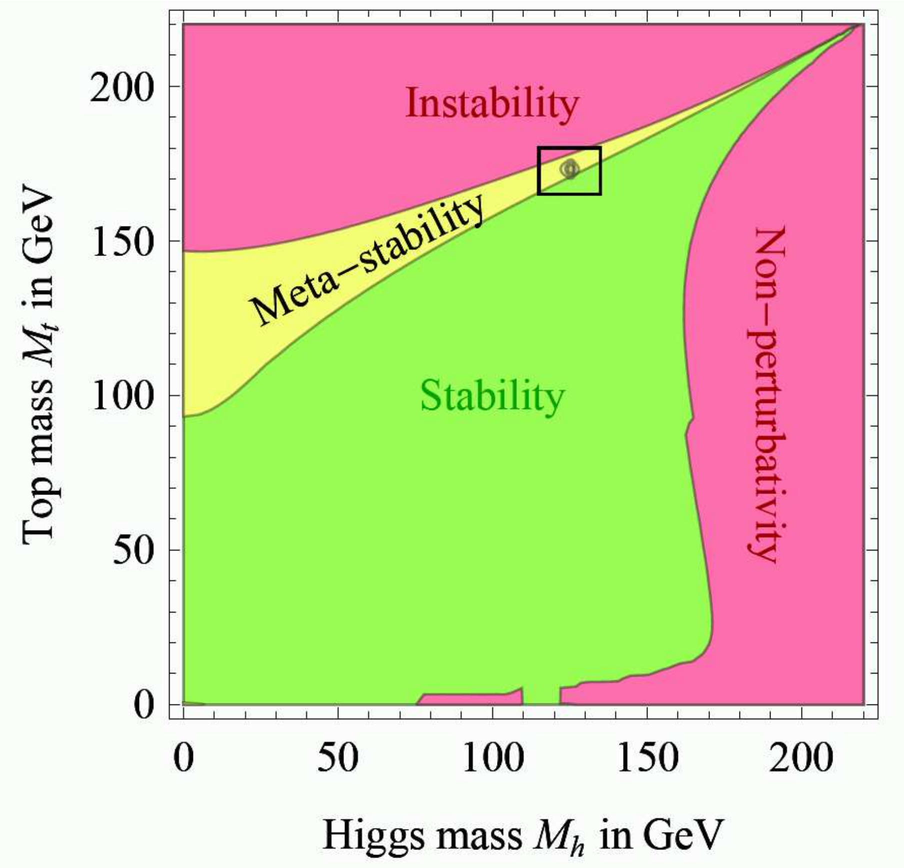


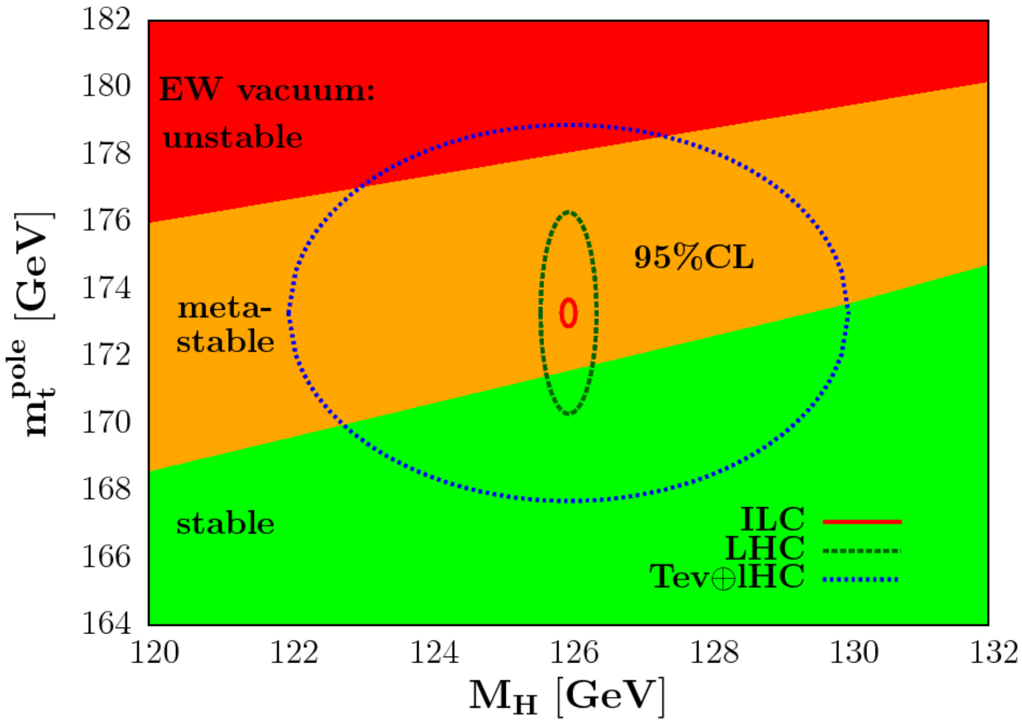
transition to other mass definitions possible ⇒ $\delta m_t^{\text{exp+theo}} \sim 0.1$ GeV

Top mass in the SM: crucial for the **Fate of the universe**

[*Degrassi et al. '12*] [*Alehkin et al. '12*]

Is the Higgs potential (and thus our universe) stable?
(neglecting gravity/Planck scale)

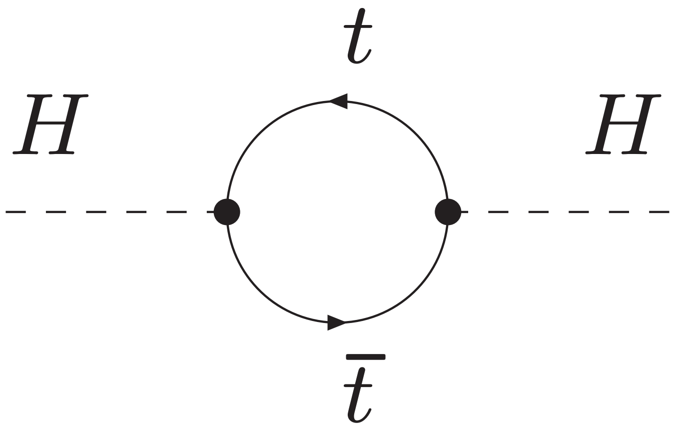




⇒ ILC precision for m_t needed!

Top/Higgs physics in BSM:

Nearly any model: large coupling of the Higgs to the top quark:



$\Rightarrow$ one-loop corrections $\Delta M_H^2 \sim G_\mu m_t^4$

$\Rightarrow$ M_H depends sensitively on m_t in all models where M_H can be predicted (SM: M_H is free parameter)

SUSY as an example: $\Delta m_t \approx \pm 1$ GeV $\Rightarrow$ $\Delta M_h \approx \pm 1$ GeV

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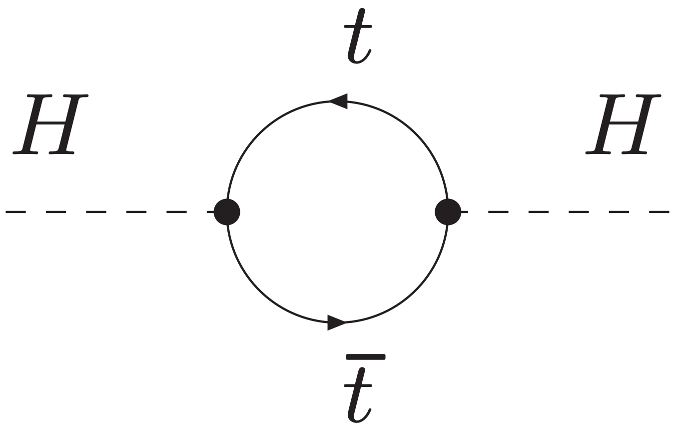

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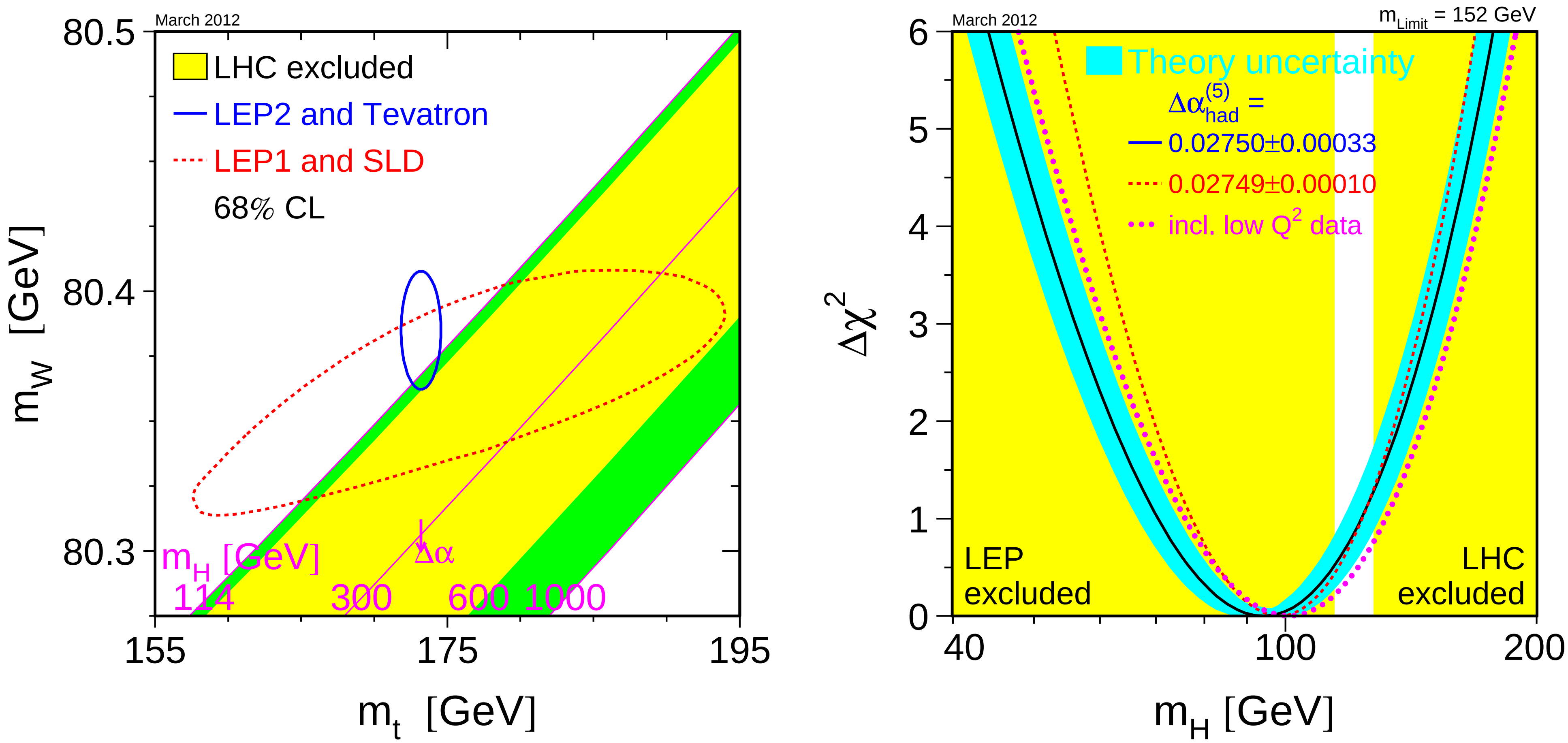
$\Rightarrow$ Precision Higgs physics needs ILC precision top physics

Precision Tests of the SM (and beyond)

⇒ indirect prediction of the Higgs mass in the SM *[LEPEWWG '12]*



⇒ fits with today's precision

Improvements with the ILC:

Experimental errors of the precision observables:

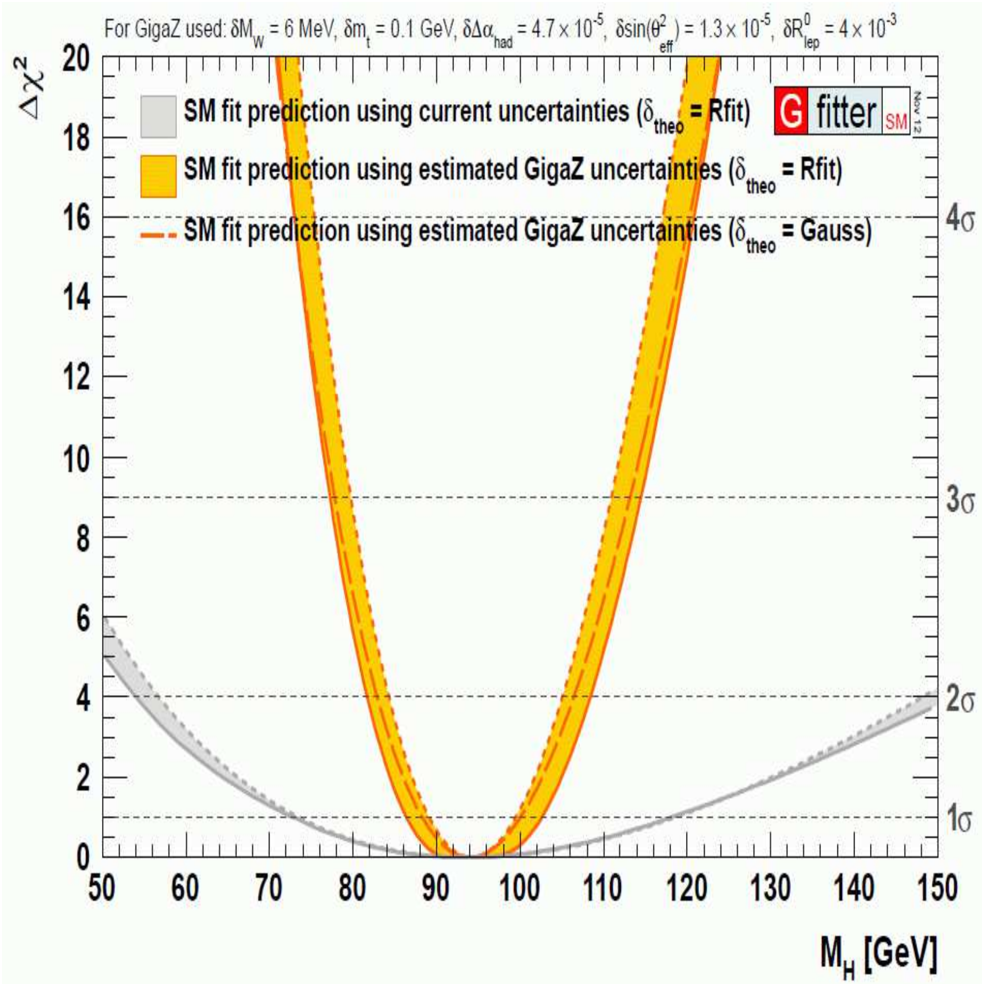
	today	Tev./LHC	ILC	GigaZ
$\delta\sin^2\theta_{\mathrm{eff}}(\times 10^5)$	16	16	–	1.3
δM_W [MeV]	15	$\lesssim 15$	5-6	5-6
δm_t [GeV]	0.9	$\lesssim 1$	0.1	0.1

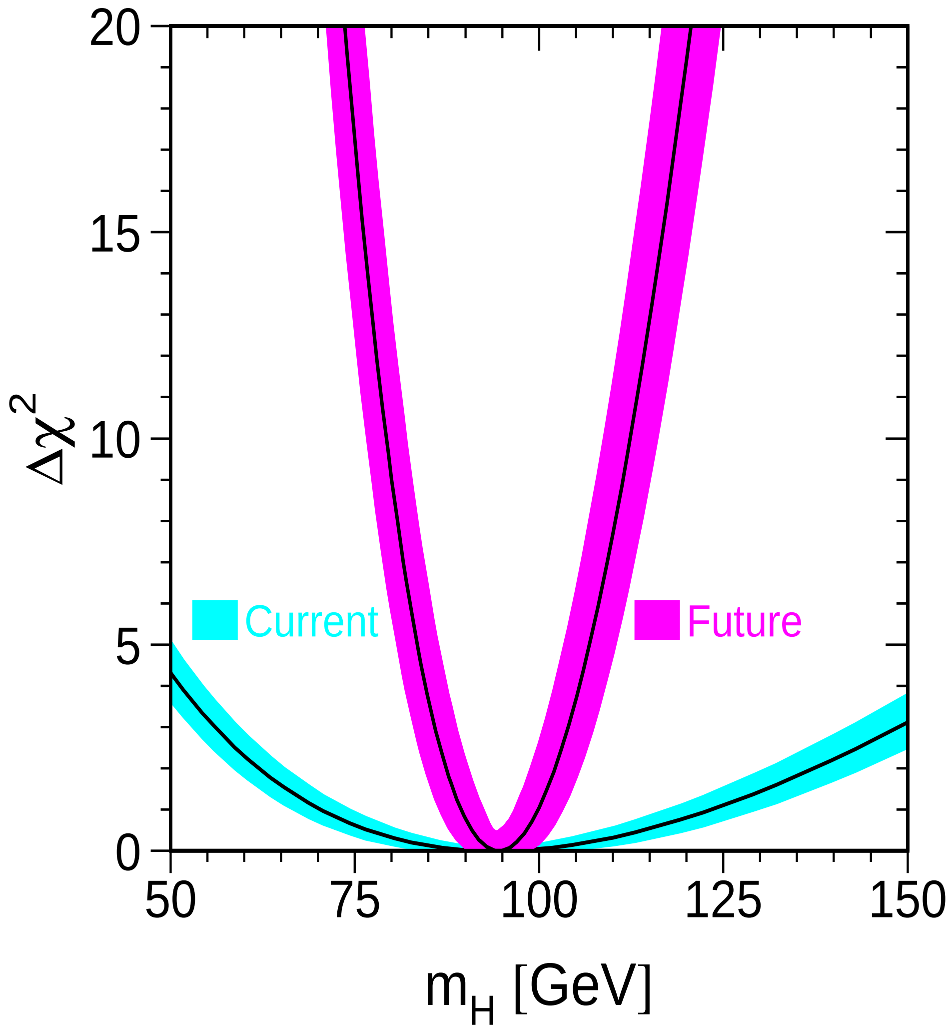
M_W: from direct reconstruction and threshold scan
[*G. Wilson '13*]

$\sin^2\theta_{\mathrm{eff}}$: 1/2 year GigaZ run, polarization important

α_s : Improvement from GigaZ run

Most precise M_H test with the ILC: [GFitter '13] [LEPEWWG '13]





⇒ $\delta M_H^{\text{ind}} \lesssim 10$ GeV

⇒ extremely sensitive test of SM (and BSM) possible

3. Physics we can do likely at the ILC

The SM cannot be the ultimate theory!

Some facts:

1. the hierarchy problem
   gravity is not included

2. Dark Matter is not included

3. neutrino masses are not included

4. anomalous magnetic moment of the muon
   shows a $\sim 4\,\sigma$ discrepancy

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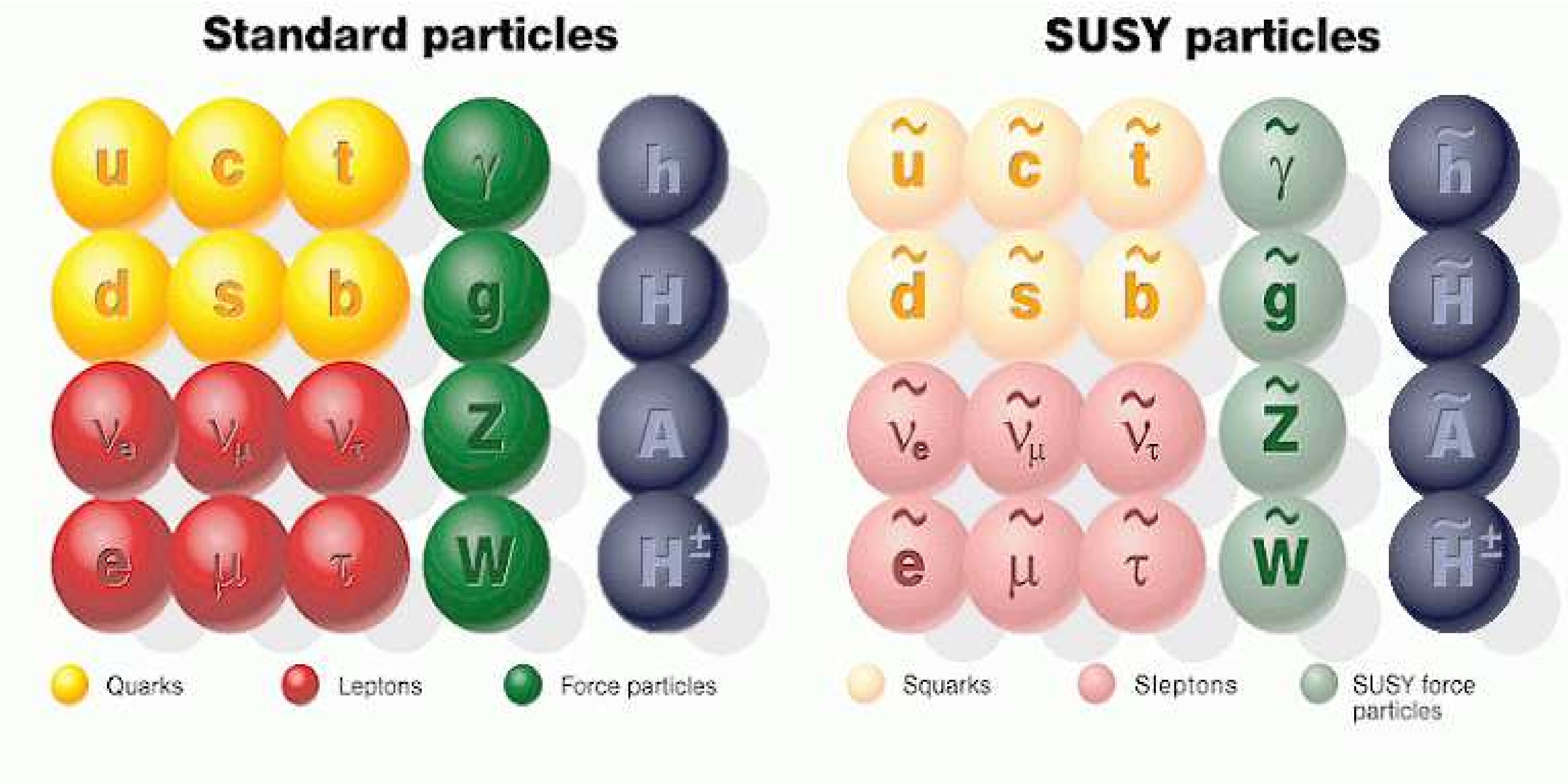
Supersymmetry as a show case:



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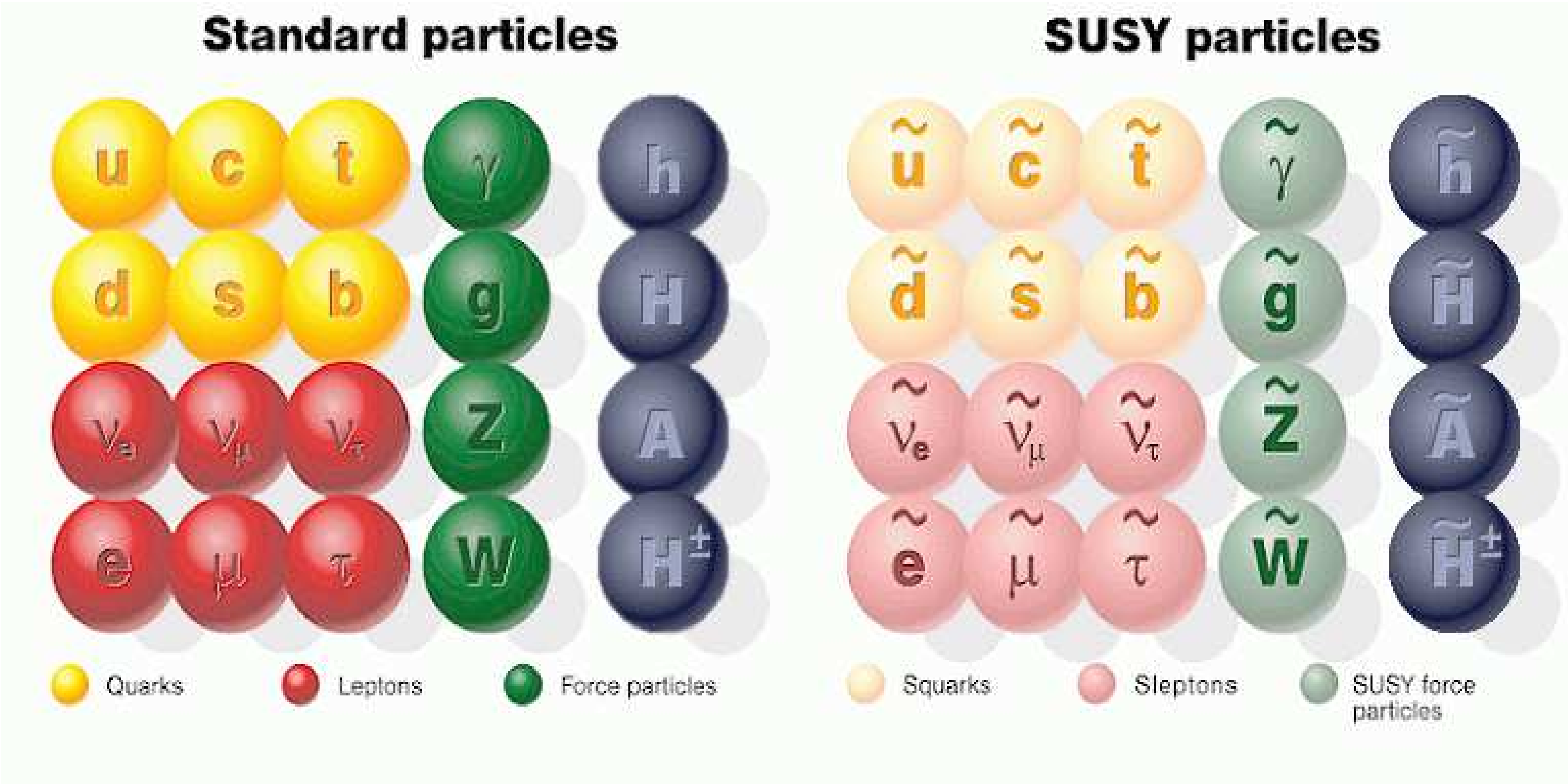


⇒ Hierarchy prob., DM, $(g-2)_\mu$ solved, more Higgses, . . . ⇒ Cases I, II, III

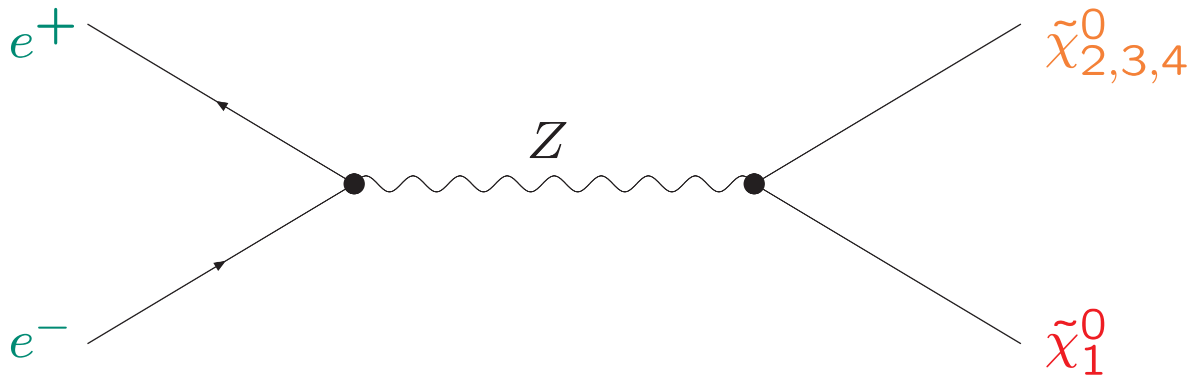
Case I: Dark Matter: is it a particle? [*taken from Ellis '13*]

… postulate a new particle:	
– QM and Special Relativity:	Antimatter
– Nuclear spectra:	Neutron
– Continuous spectrum in β decay:	Neutrino
– Nucleon-nucleon interactions:	Pion
– Absence of lepton number violation:	Second neutrino
– Flavour SU(3):	Ω^-
– Flavour SU(3):	Quarks
– FCNC:	Charm
– CP violation:	Third generation
– Strong dynamics:	Gluons
– Weak interactions:	$W^\pm$, Z^0
– Renormalizability:	H
– Dark matter:	**WIMP/axion?**

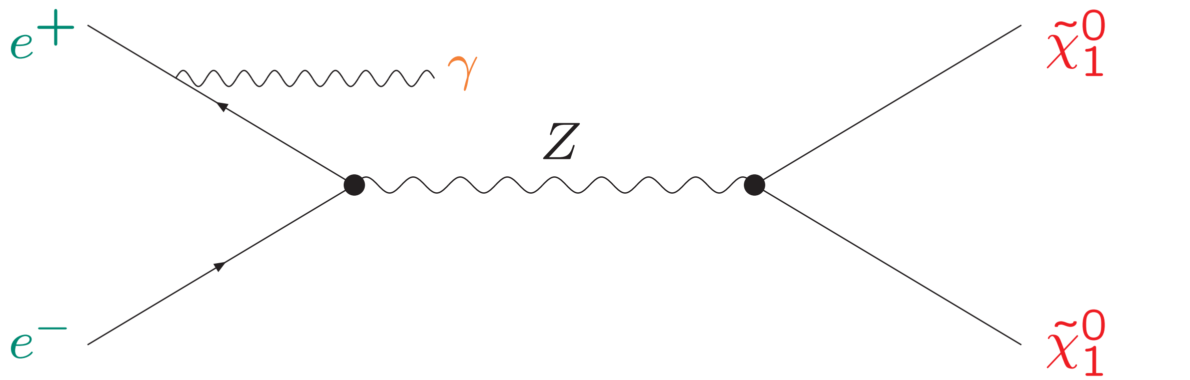
$\Rightarrow$ "particle concept" works!

Supersymmetry: Lightest neutralino as Dark Matter

Production with a heavier particle:

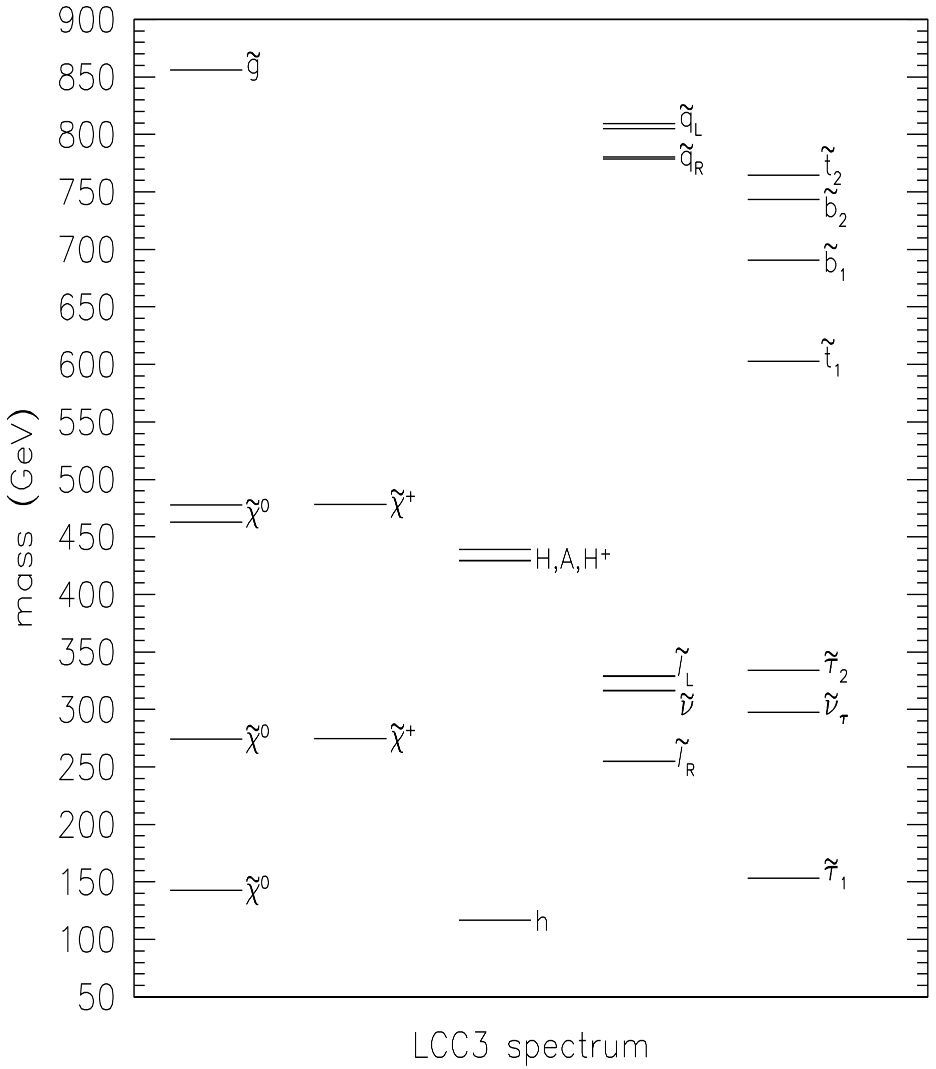


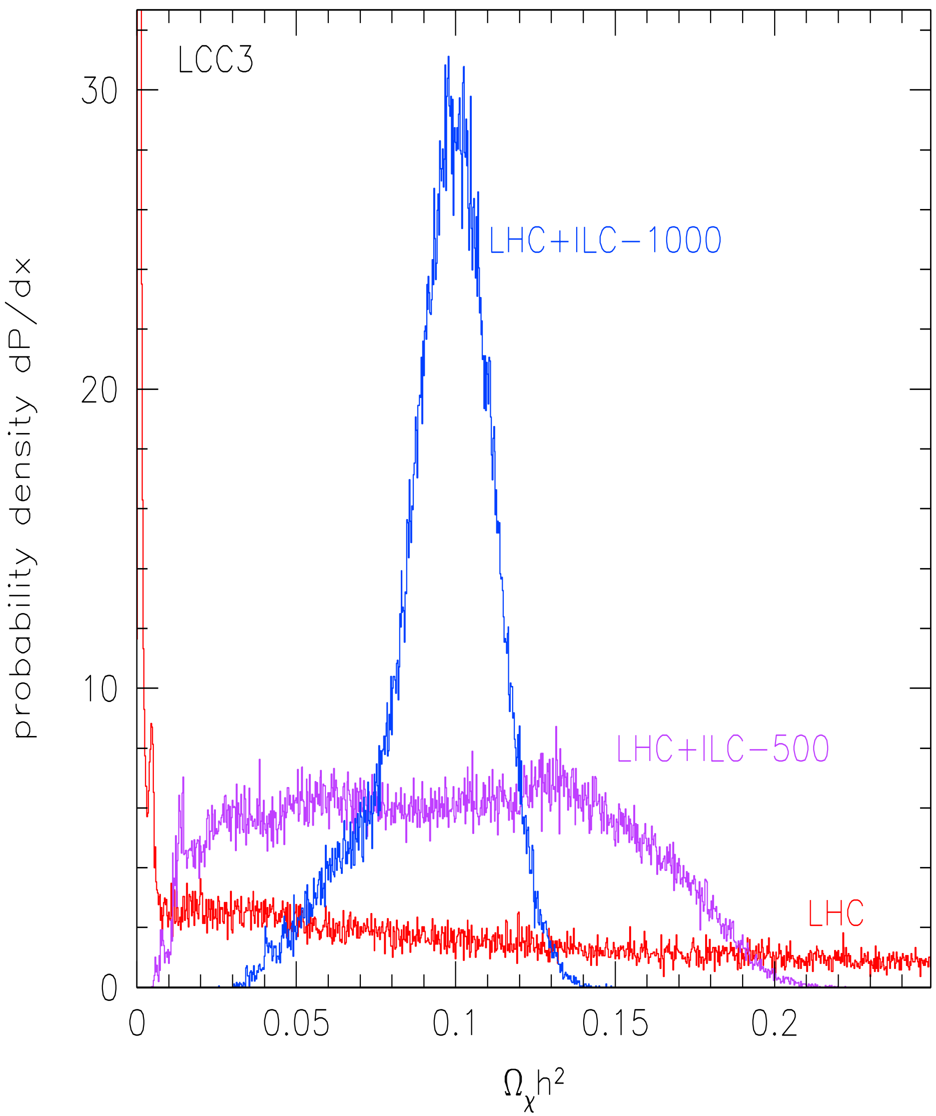
Production with an initial state radiation photon:



Reconstructing DM at the ILC:

[*ILC TDR '13*]

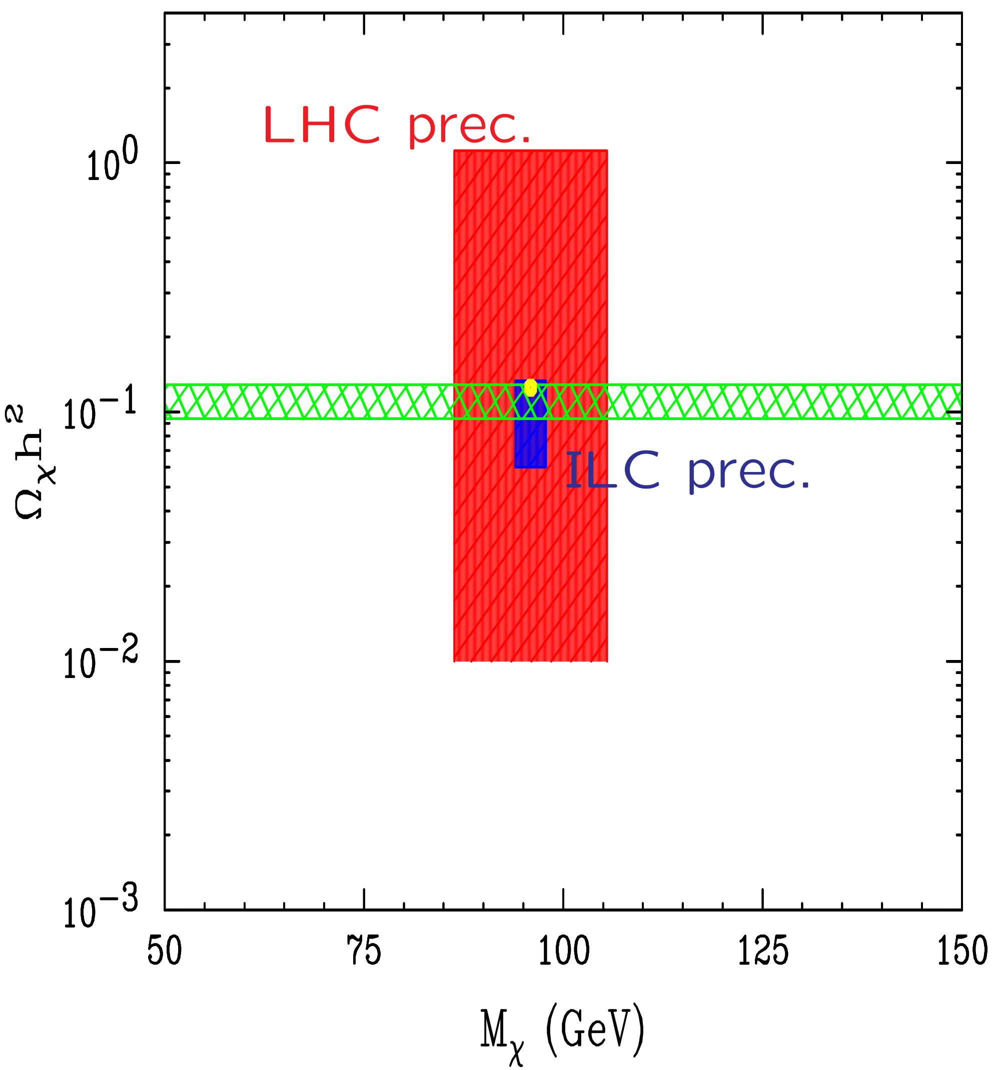


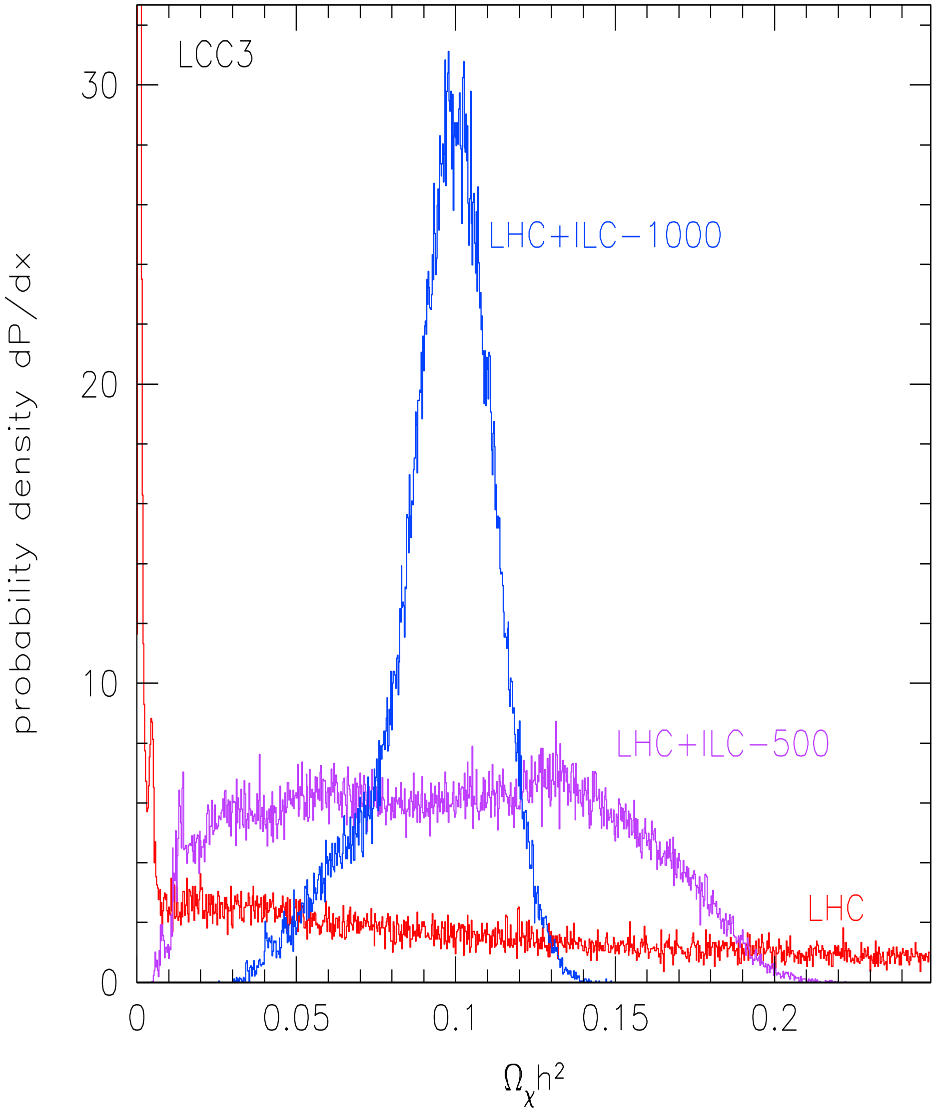


⇒ DM can be reconstructed!

Reconstructing DM at the ILC:

[ILC TDR '13]

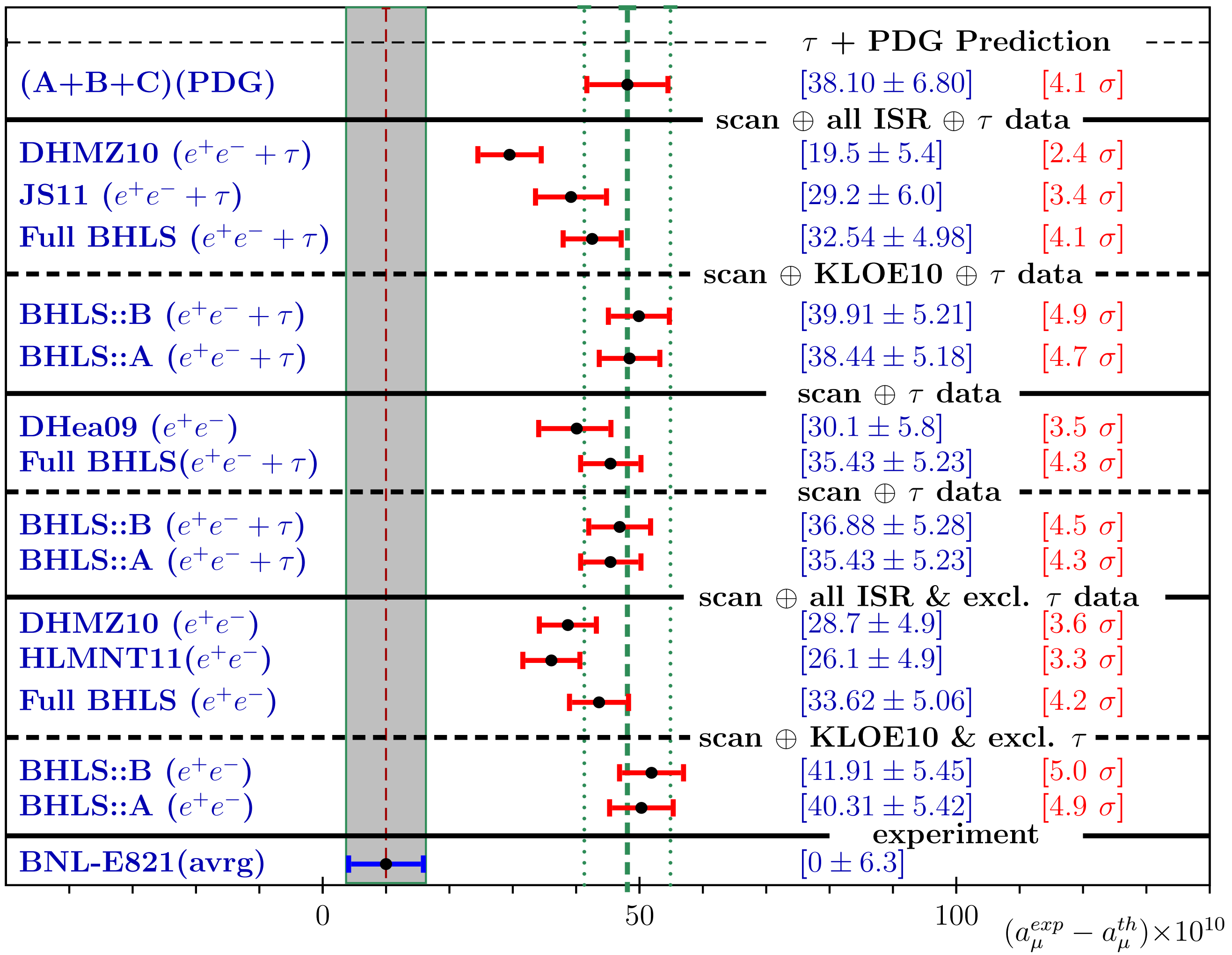




⇒ DM can be reconstructed to match astrophysical data!

Case II: Latest analysis on $(g-2)_\mu$:

[*M. Benayoun, P. David, L. DelBuono, F. Jegerlehner '12*]



⇒ more than $4\,\sigma$ deviation! ⇒ BSM physics needed?!

BSM example: SUSY easily explains the deviation:

Feynman diagrams for MSSM 1L corrections:

– Diagrams with chargino/sneutrino exchange

– Diagrams with neutralino/smuon exchange

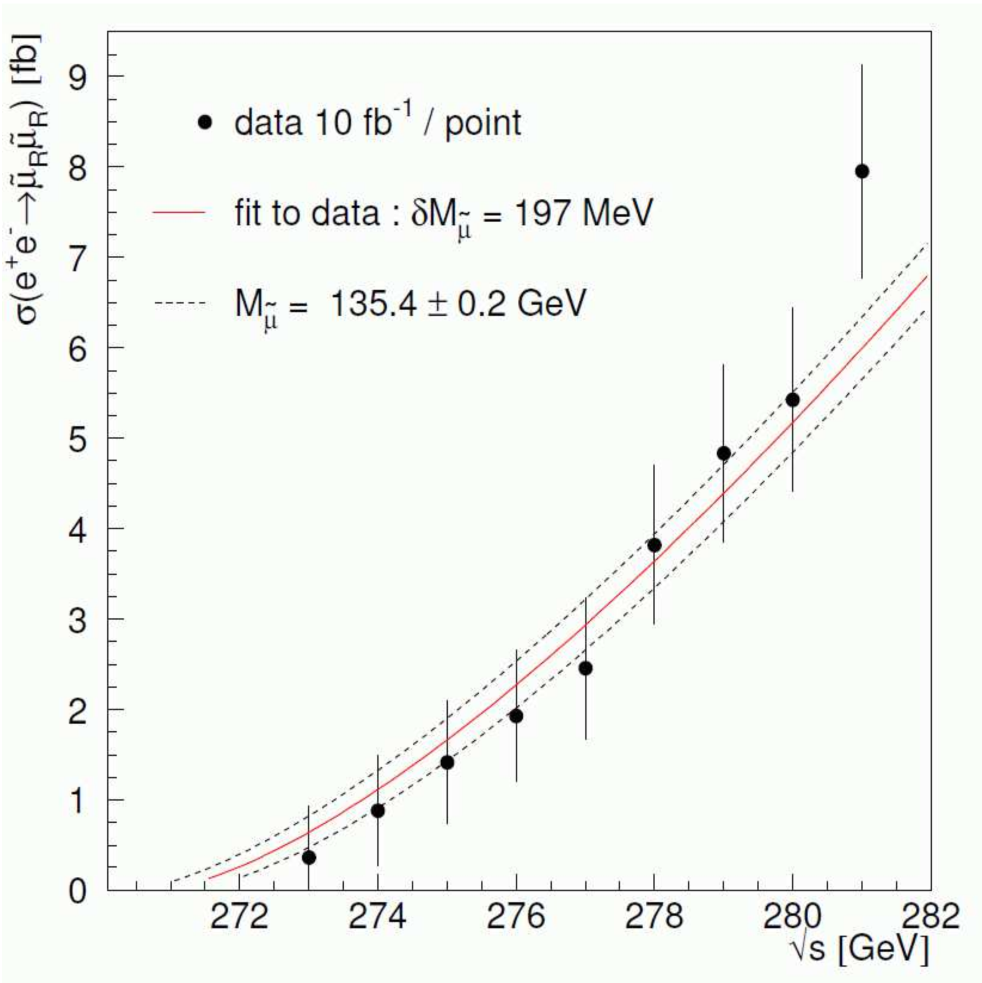
Experimental results require:

– not too heavy sclar muons, neutrinos

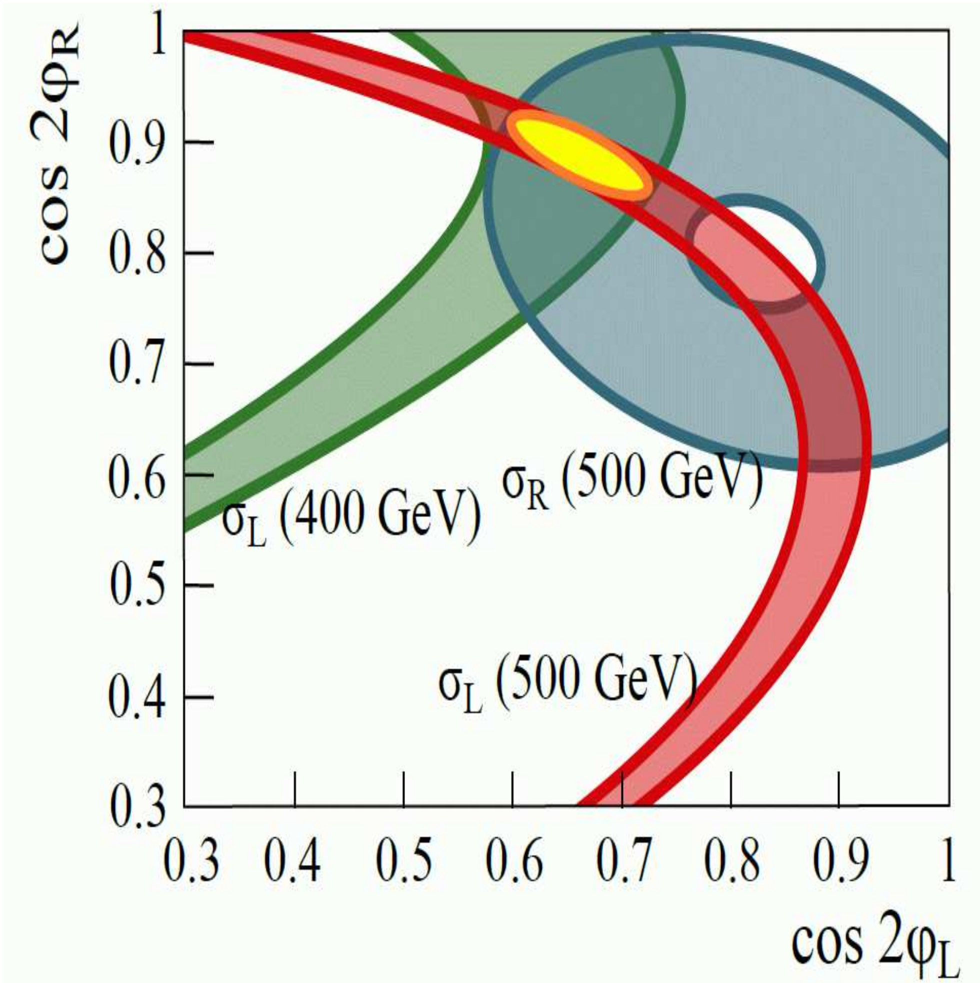
– not too heavy charginos, neutralinos

⇒ precision ILC analyses

smuon mass



chargino parameter



⇒ (sub)per-cent precision possible at the ILC

Case III: A light Higgs boson below 125 GeV

We have discovered a Higgs at $\sim$ 125 GeV

$\Rightarrow$ this need not be the lightest Higgs in the spectrum!

In principle also possible:

$$M_{h_1} < 125 \text{ GeV}$$
$$M_{h_2} \approx 125 \text{ GeV}$$

Consequences:
- several Higgs bosons very light
- rich(er) Higgs phenomenology

Constraints:
- direct searches for the lightest Higgs
- direct searches for other heavier neutral Higgses
- direct searches for the charged Higgses
- flavor constraints (BR($B_s \to \mu^+\mu^-$) etc.)

Is such a light Higgs detectable at the LHC and/or ILC?

LHC:

– $h_2 \to h_1 h_1$ strongly suppressed for $M_{h_1} \gtrsim 63$ GeV

– so far no LHC searches for a Higgs with $M_{h_1} \lesssim 100$ GeV (difficult . . .)

– Possible: SUSY $\to$ SUSY h_1 , e.g. $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h_1$

ILC:

– good SUSY production mode: $e^+e^- \to hA$

– good general production mode: $e^+e^- \to t\bar{t}h_1$

$\Rightarrow$ could be a unique opportunity for the ILC!

Possible scenario:

The LHC finds only a SM-like Higgs and nothing else

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⇒ Only the ILC+GigaZ can find deviations from the SM predictions via the various precision measurements or new discoveries

⇒ Only the ILC+GigaZ can point towards extensions of the SM

4. How to go ahead?

(Not only) my personal view:

Discovery of a Higgs particle

together with top, $W^{\pm}$, Z, . . . , DM, $(g-2)_{\mu}$, . . .

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Staged approach:

- ILC as a Higgs and top factory
  - start at lower energies to produce $\mathcal{O}\left(10^5\right)$ Higgs bosons
  - go to higher energies for top physics
  - go to higher energies for Higgs-top, λ_{HHH}
  - go to higher energies for TeV scale exploration
- go to other options: GigaZ, $\gamma\gamma$, ...

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Back-up

Measurement of the Higgs boson spin

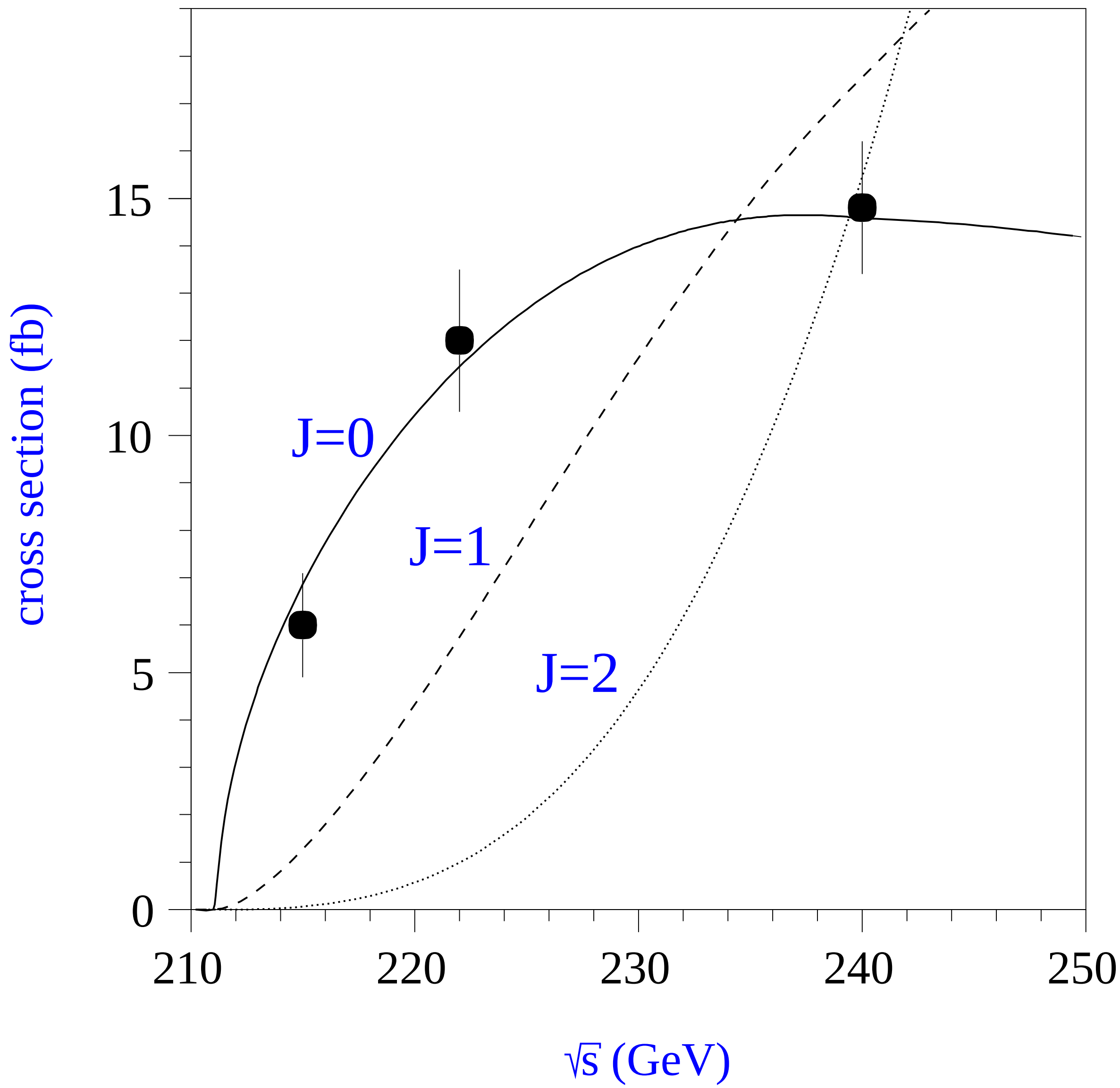
$\Rightarrow$ easy at the ILC

[*M. Schumacher '01*]

Threshold scan for
$\sigma(e^+e^- \to ZX)$:

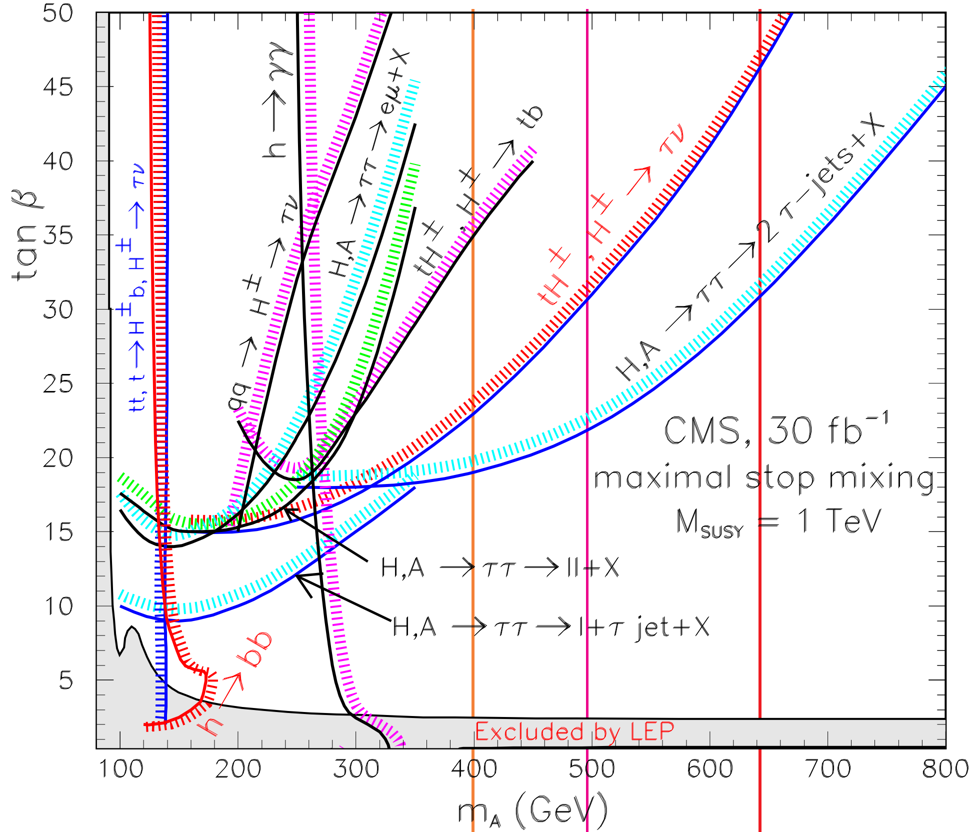
$X = H \Rightarrow \sigma \sim \beta$
(β from kinematics)

$20\,\text{fb}^{-1}$
$\Rightarrow$ identification easy



Indirect determination of unknown Higgs sector parameters

LHC/ILC reach for MSSM Higgs bosons:



LHC:

h : all $M_A - \tan\beta$ plane

H, A : unreachable parts

CMS, 30 fb^{-1}, $m_h^{\max}$ scenario: $\Rightarrow$

ILC:

kinematic limit: $M_A \lesssim \sqrt{s}/2$

$\to \sqrt{s} = 800$ GeV

$\to \sqrt{s} = 1000$ GeV

$\gamma\gamma$:

kinematic limit: $M_A \lesssim 0.8\sqrt{s}$

ILC: $\sqrt{s} = 800$ GeV

$\sqrt{s} = 1000$ GeV

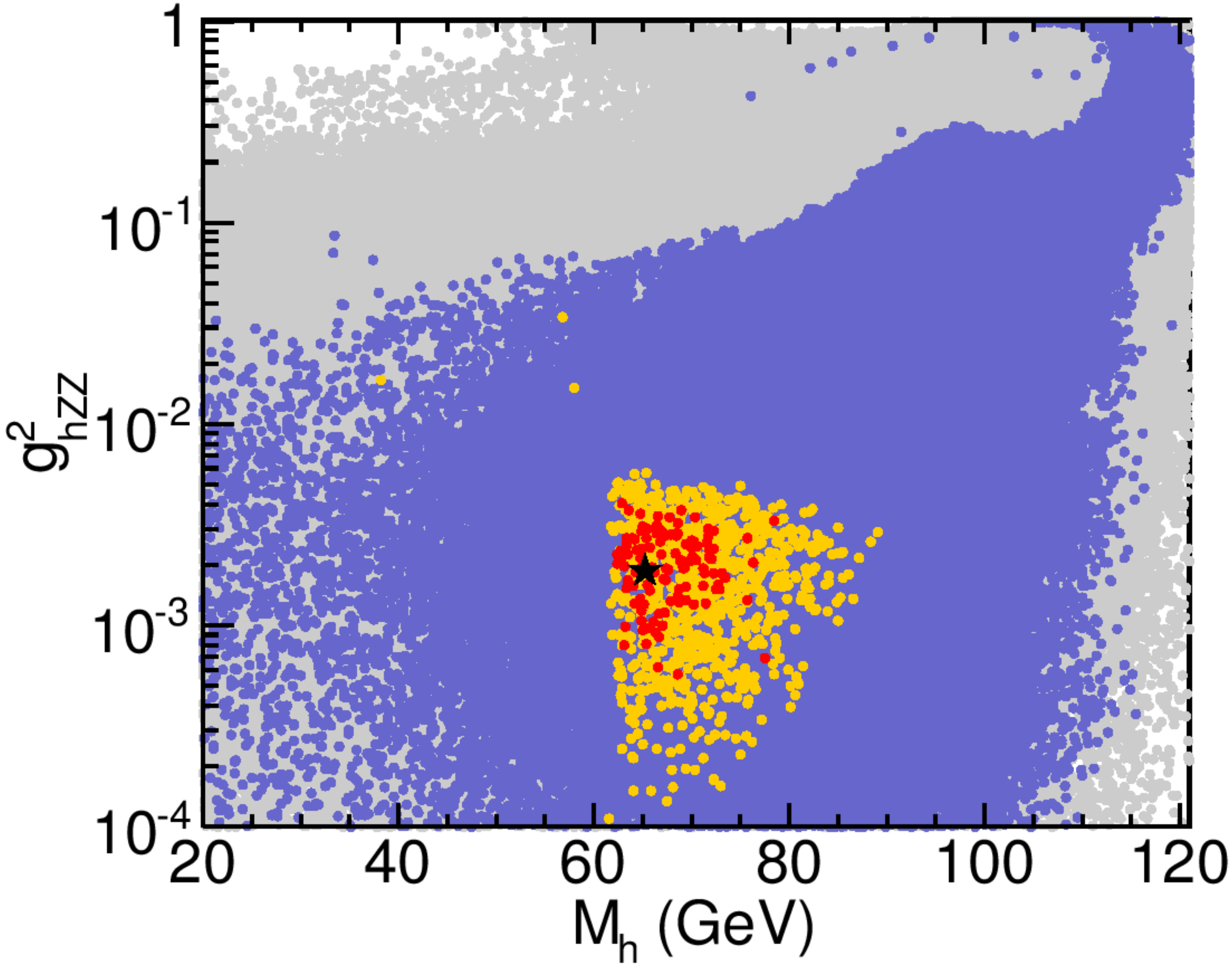
$\gamma\gamma$: $\sqrt{s} = 800$ GeV

Q: Is it possible to extend the reach for heavy Higgs bosons ?

A: Yes, by direct and indirect measurements

Where is the light Higgs in the "heavy Higgs case"?

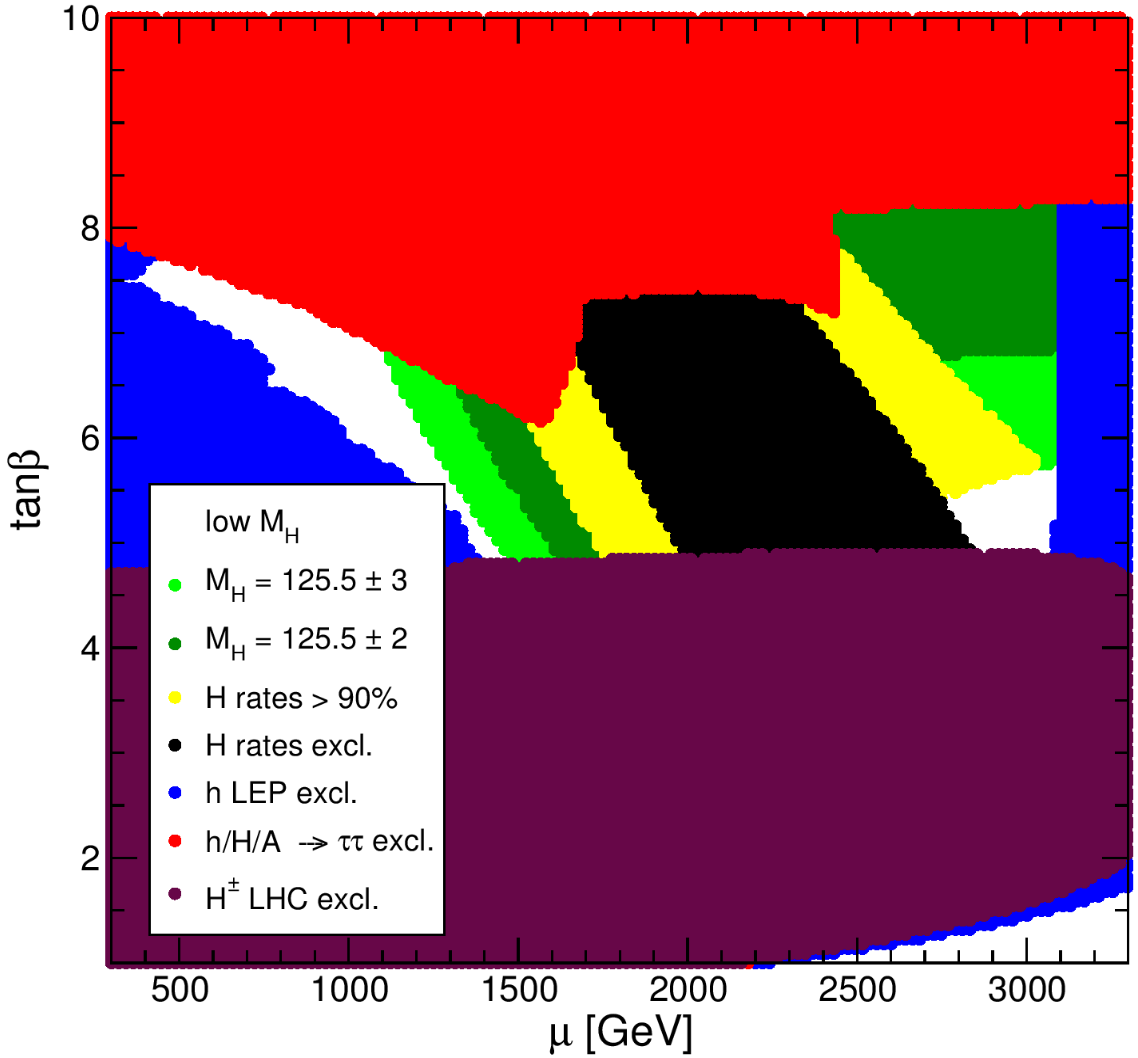
[*P. Bechtle, S.H. O. Stål, T. Stefaniak, G. Weiglein, L. Zeune '12*]



$\Rightarrow$ low M_h values, strongly reduced couplings

low-M_H scenario:

[*M. Carena, S.H., O. Stål, C. Wagner, G. Weiglein '13*]



$$m_t = 173.2 \text{ GeV},$$
$$M_A = 110 \text{ GeV},$$
$$M_{\text{SUSY}} = 1500 \text{ GeV},$$
$$M_2 = 200 \text{ GeV},$$
$$X_t^{\text{OS}} 2.45 M_{\text{SUSY}}$$
$$A_b = A_\tau = A_t,$$
$$m_{\tilde{g}} = 1500 \text{ GeV},$$
$$M_{\tilde{l}_3} = 1000 \text{ GeV} \; .$$

$\Rightarrow M_H \approx 125.5$ GeV can in principle be realized