Let's start with the most important result:

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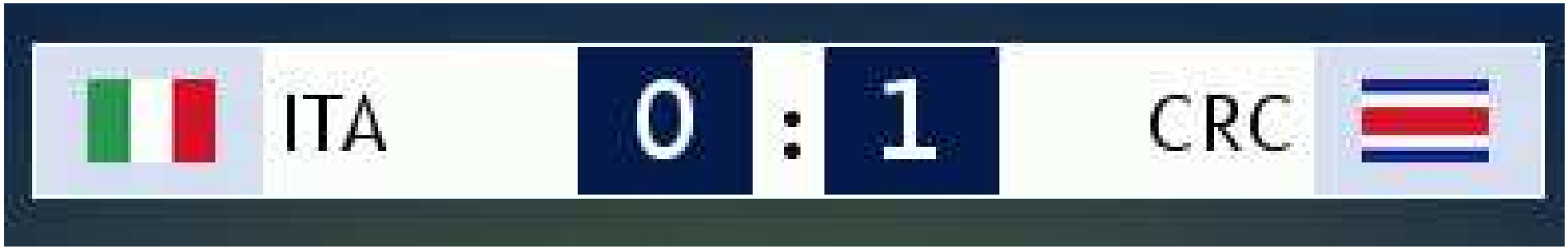

Higgs at the ILC

Sven Heinemeyer, IFCA (Santander)

New York, 06/2014

1. Higgs at the ILC
2. Higgs coupling determination
3. What can be done only at the (I)LC
4. Indirect Higgs tests at the ILC
5. (In)Direct ILC reach for heavy MSSM Higgs bosons
6. Conclusions $\oplus$ my personal view

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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5. measure self-couplings

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Investigating the Higgs Mechanism

What has to be done?

1. Find the new particle done
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Investigating the Higgs Mechanism

What has to be done?

1. Find the new particle — done
2. measure its mass ($\Rightarrow$ ok?) — done
3. measure coupling to gauge bosons
4. measure couplings to fermions
5. measure self-couplings
6. measure spin, $\mathcal{CP}$, quantum numbers . . .

Investigating the Higgs Mechanism

What has to be done?

1. Find the new particle	done	
2. measure its mass ($\Rightarrow$ ok?)	done	L
3. measure coupling to gauge bosons		L
4. measure couplings to fermions		L
5. measure self-couplings		
6. measure spin, $\mathcal{CP}$, quantum numbers ...		

L = LHC,

Investigating the Higgs Mechanism

What has to be done?

1. Find the new particle	done	
2. measure its mass ($\Rightarrow$ ok?)	done	L
3. measure coupling to gauge bosons		L
4. measure couplings to fermions		L
5. measure self-couplings		L
6. measure spin, $\mathcal{CP}$, quantum numbers ...		L

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

Investigating the Higgs Mechanism

What has to be done?

1. Find the new particle	done		
2. measure its mass ($\Rightarrow$ ok?)	done	L	I
3. measure coupling to gauge bosons		L	I
4. measure couplings to fermions		L	I
5. measure self-couplings		L	I
6. measure spin, $\mathcal{CP}$, quantum numbers ...		L	I

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

Investigating the Higgs Mechanism

What has to be done?

1. Find the new particle	done		
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The LHC can investigate the Higgs mechanism and tell us a lot!

Investigating the Higgs Mechanism

What has to be done?

1. Find the new particle	done		
2. measure its mass ($\Rightarrow$ ok?)	done	L	I
3. measure coupling to gauge bosons		L	I
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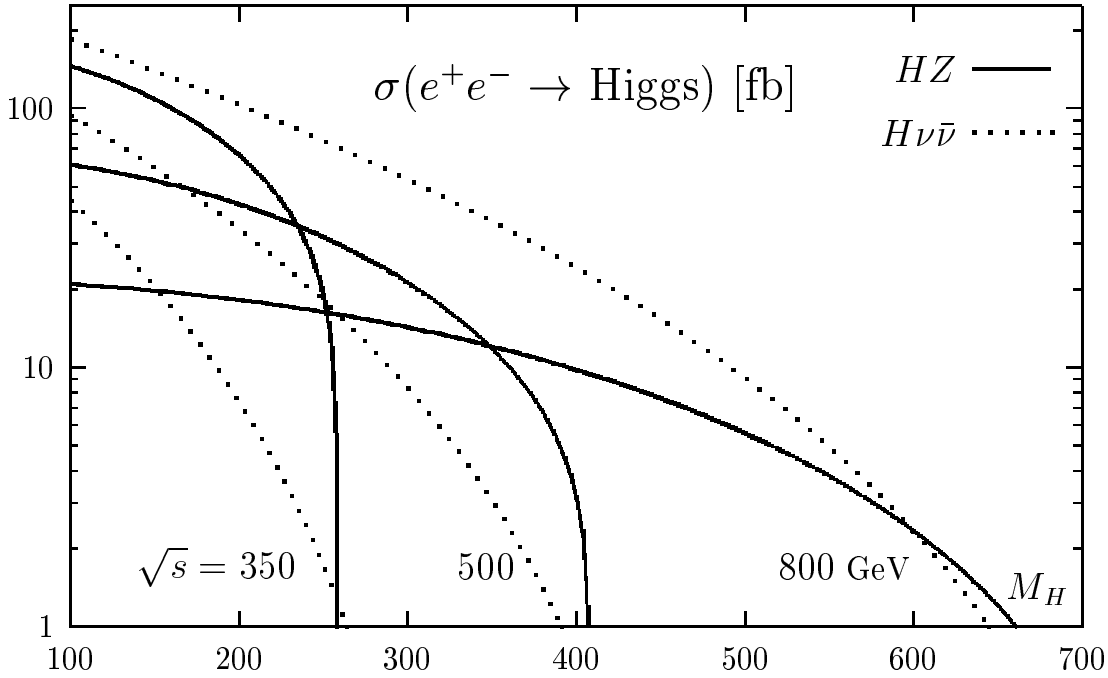
L = LHC, L = LHC (partially/unclear), I = ILC, I = ILC (doable?)

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

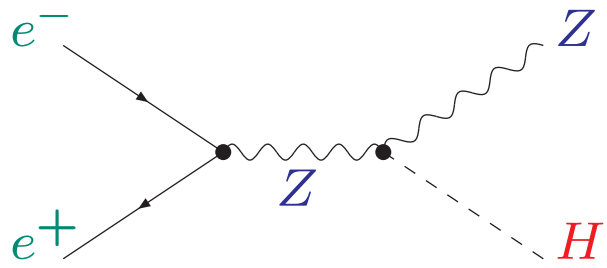
We need the ILC to fully establish the Higgs mechanism!

1. Higgs at the ILC

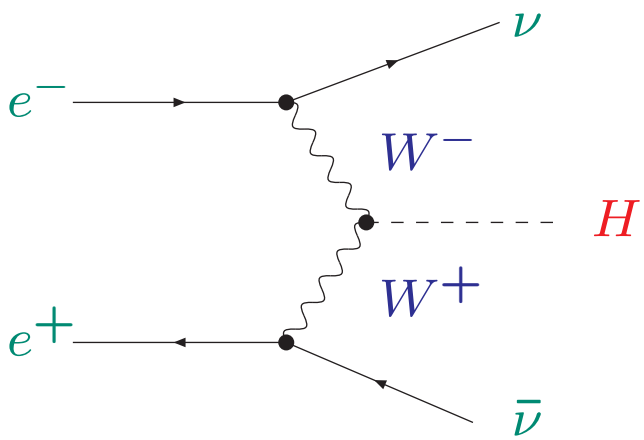
Higgs production at the ILC:



Higgs-strahlung:
$e^+e^- \to Z^* \to ZH$



weak boson fusion (WBF):
$e + e- \to \nu\bar{\nu}H$

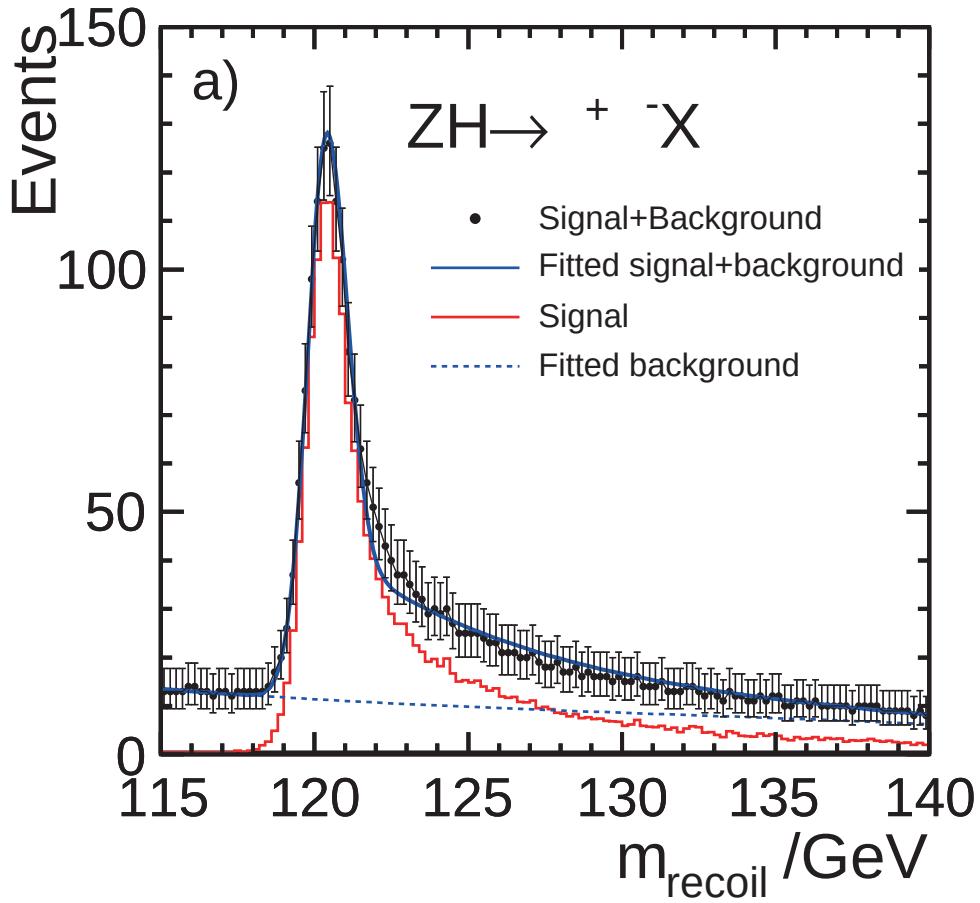


$\Rightarrow$ Measurement of masses, couplings, ... in per cent/per mille

Model independent cross section measurement

[ILC TDR '13]

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

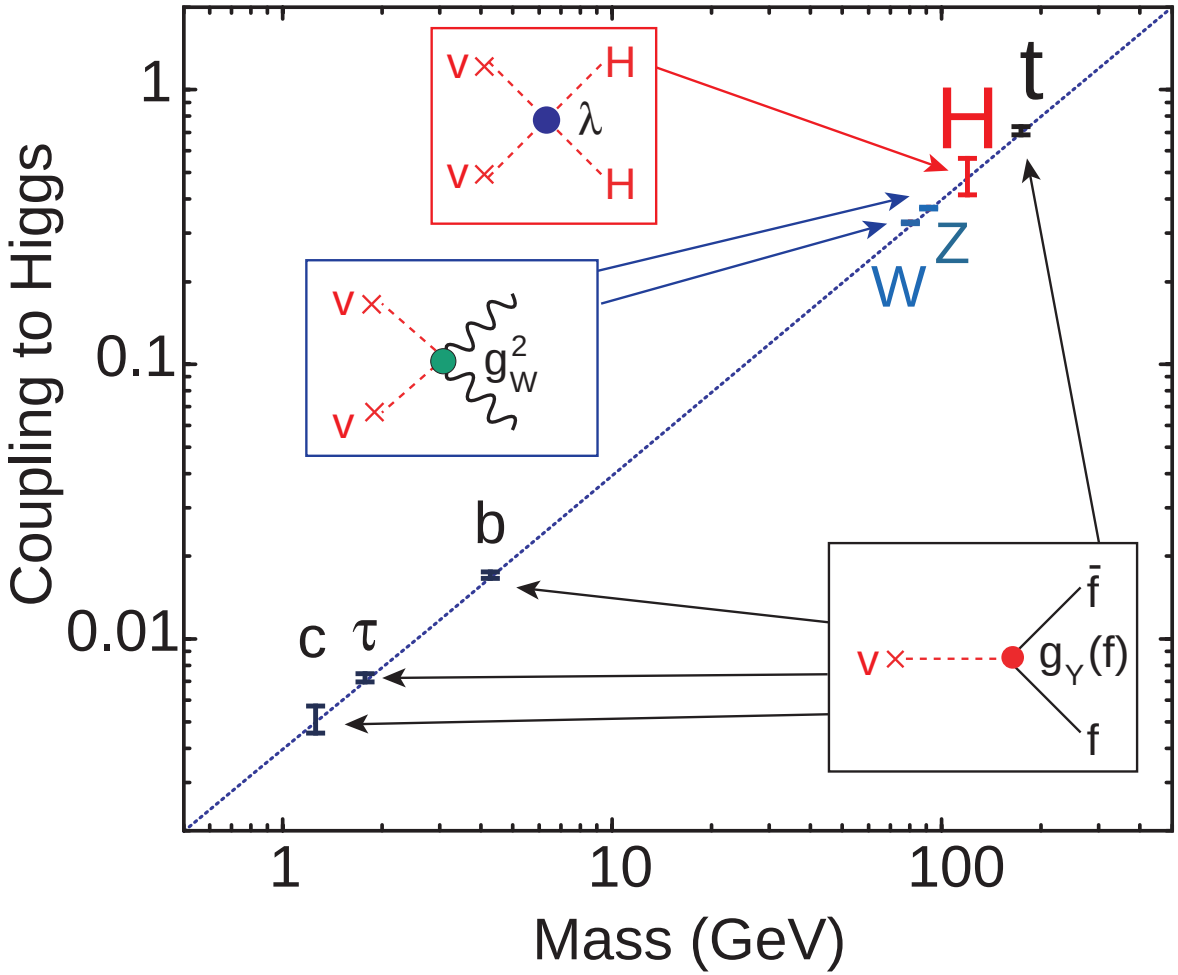


⇒ crucial for a model independent coupling measurement! $\delta M_H^{\text{exp}} \lesssim 0.05$ GeV

Higgs mechanism: mass ∝ coupling

[taken from K. Fuji '13]

⇒ clear, testable prediction!



⇒ ILC can test all three types!

More complete future options:

LHC300, HL-LHC, ILC250, ILC500, ILC1000, ILC1000-LumiUp

Future scenario	PDF	α_s	m_c, m_b, m_t	THU[1]	BR($H \to$ NP) constraint
LHC300 (S1)	100%	100%	all 100%	100%	conservative, Eq. (13)
LHC300 (S2, csv.)	50%	100%	all 100%	50%	conservative, Eq. (13)
LHC300 (S2, opt.)	50%	100%	all 100%	50%	optimistic, Eq. (15)
HL-LHC (S1)	100%	100%	all 100%	100%	conservative, Eq. (14)
HL-LHC (S2, csv.)	50%	100%	all 100%	50%	conservative, Eq. (14)
HL-LHC (S2, opt.)	50%	100%	all 100%	50%	optimistic, Eq. (16)
ILC250	-	50%	all 50%	50%	$\sigma(e^-e^+ \to ZH)$
ILC500	-	50%	all 50%	50%	$\sigma(e^-e^+ \to ZH)$
ILC1000	-	50%	all 50%	50%	$\sigma(e^-e^+ \to ZH)$
ILC1000-LumiUp	-	50%	all 50%	50%	$\sigma(e^-e^+ \to ZH)$
HL-LHC $\oplus$ ILC250 $(\sigma_{ZH}^{\text{total}})^2$	50%	50%	all 50%	50%	$\sigma(e^-e^+ \to ZH)$
HL-LHC $\oplus$ ILC250	50%	50%	all 50%	50%	$\sigma(e^-e^+ \to ZH)$
HL-LHC $\oplus$ ILC500	50%	50%	all 50%	50%	$\sigma(e^-e^+ \to ZH)$
HL-LHC $\oplus$ ILC1000	50%	50%	all 50%	50%	$\sigma(e^-e^+ \to ZH)$
HL-LHC $\oplus$ ILC1000-LumiUp	50%	50%	all 50%	50%	$\sigma(e^-e^+ \to ZH)$

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

	$\Delta(\sigma \cdot \mathrm{BR})/(\sigma \cdot \mathrm{BR})$			$\Delta g/g$
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%
$H \to c\bar{c}$	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%
$H \to \tau^+\tau^-$	3.6%	4.6%	11%	1.8%

Direct determination of total width: $\Delta\Gamma_H/\Gamma_H$: $\sim$ 4% (500 GeV (500 fb^{-1}))

$\Rightarrow$ discrimination between models!

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

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$H \to gg$	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%)

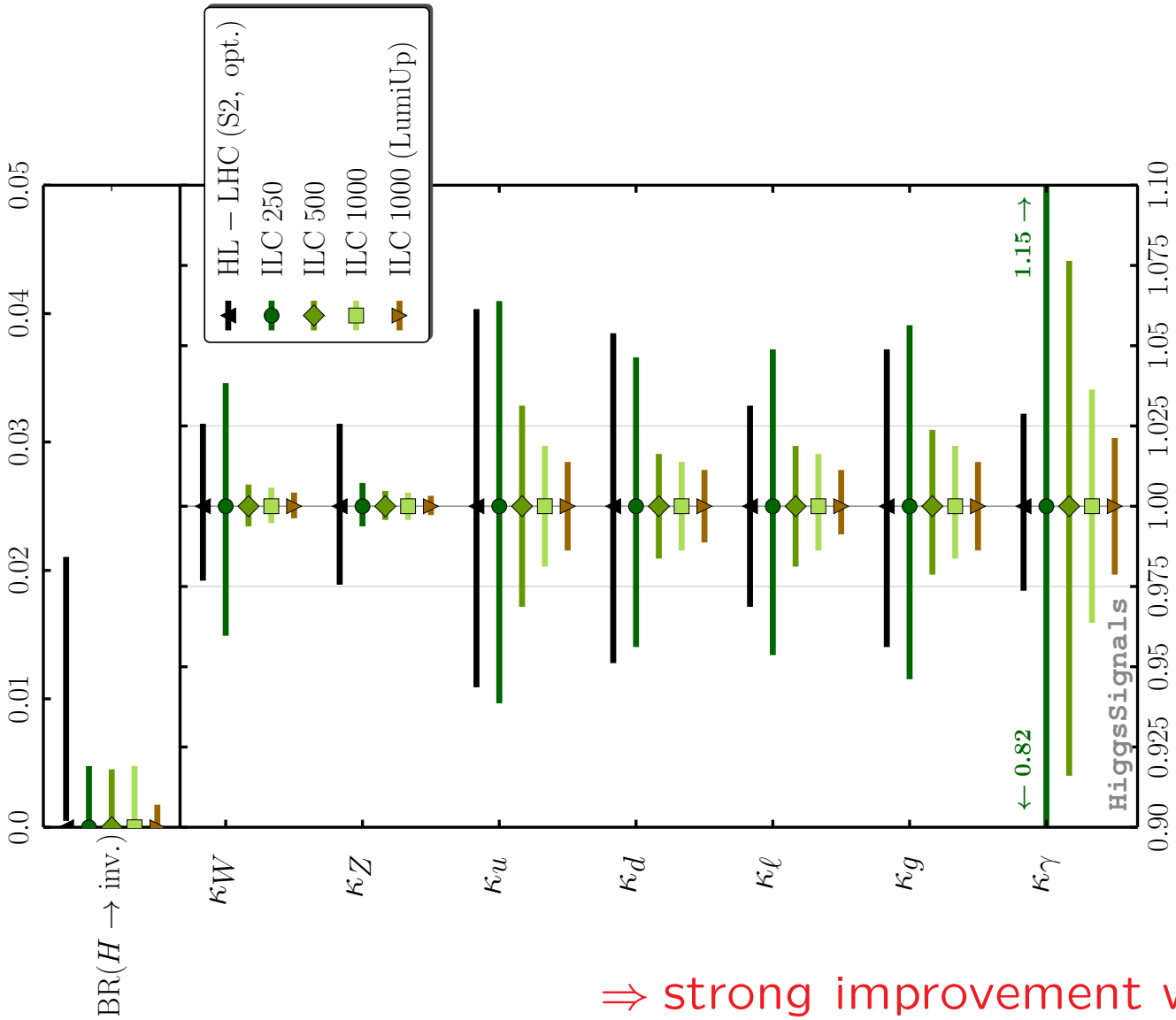
Total width: $\Delta\Gamma_H/\Gamma_H$: 4.8% – 1.2%

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

HL-LHC vs. ILC in the most general κ framework:

[*P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '14*]

assumption: $\mathrm{BR}(H \to \mathrm{NP}) = \mathrm{BR}(H \to \mathrm{inv.})$

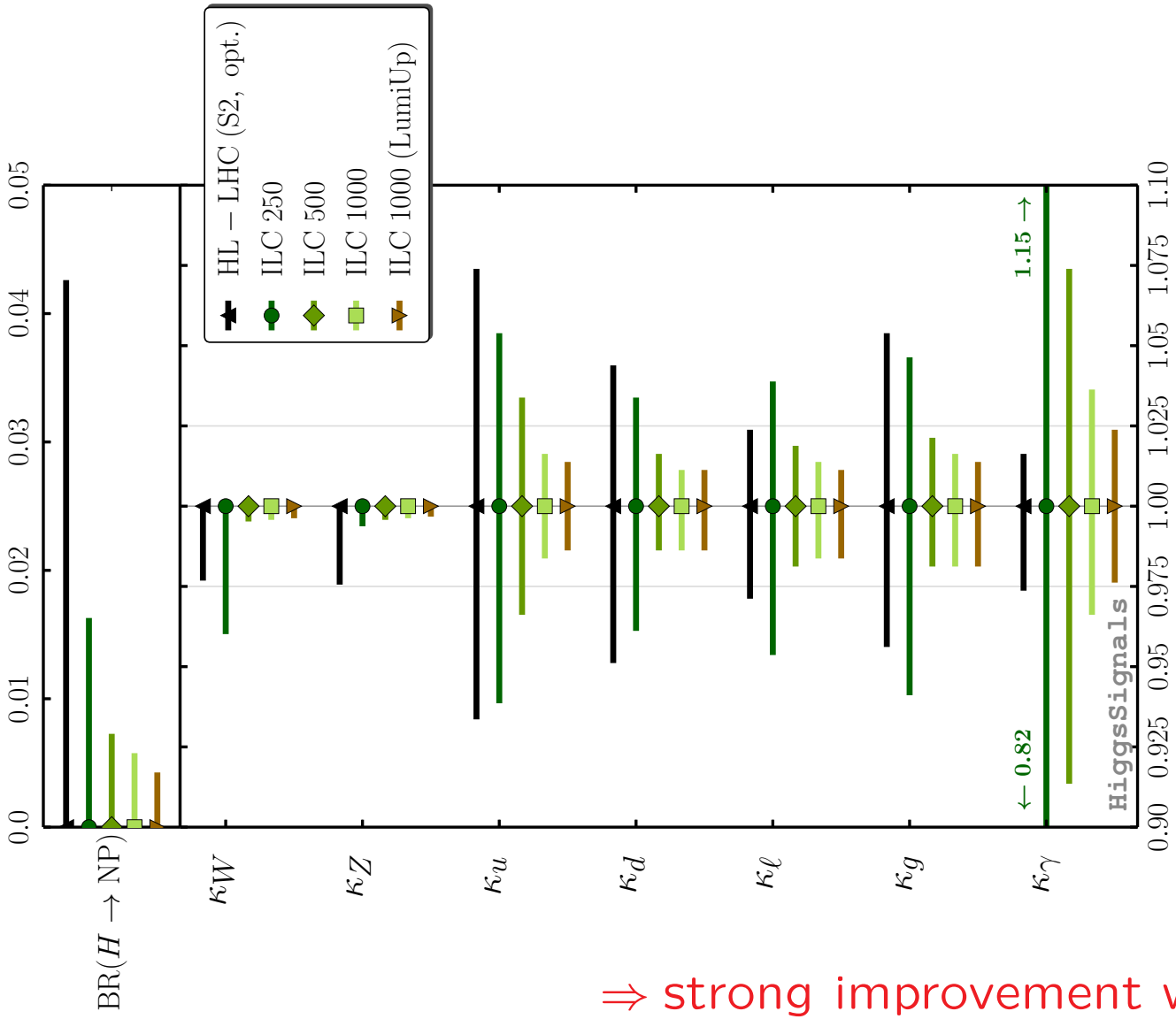


$\Rightarrow$ strong improvement with the ILC

HL-LHC vs. ILC in the most general κ framework:

[*P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '14*]

assumption: $\kappa_V \leq 1$

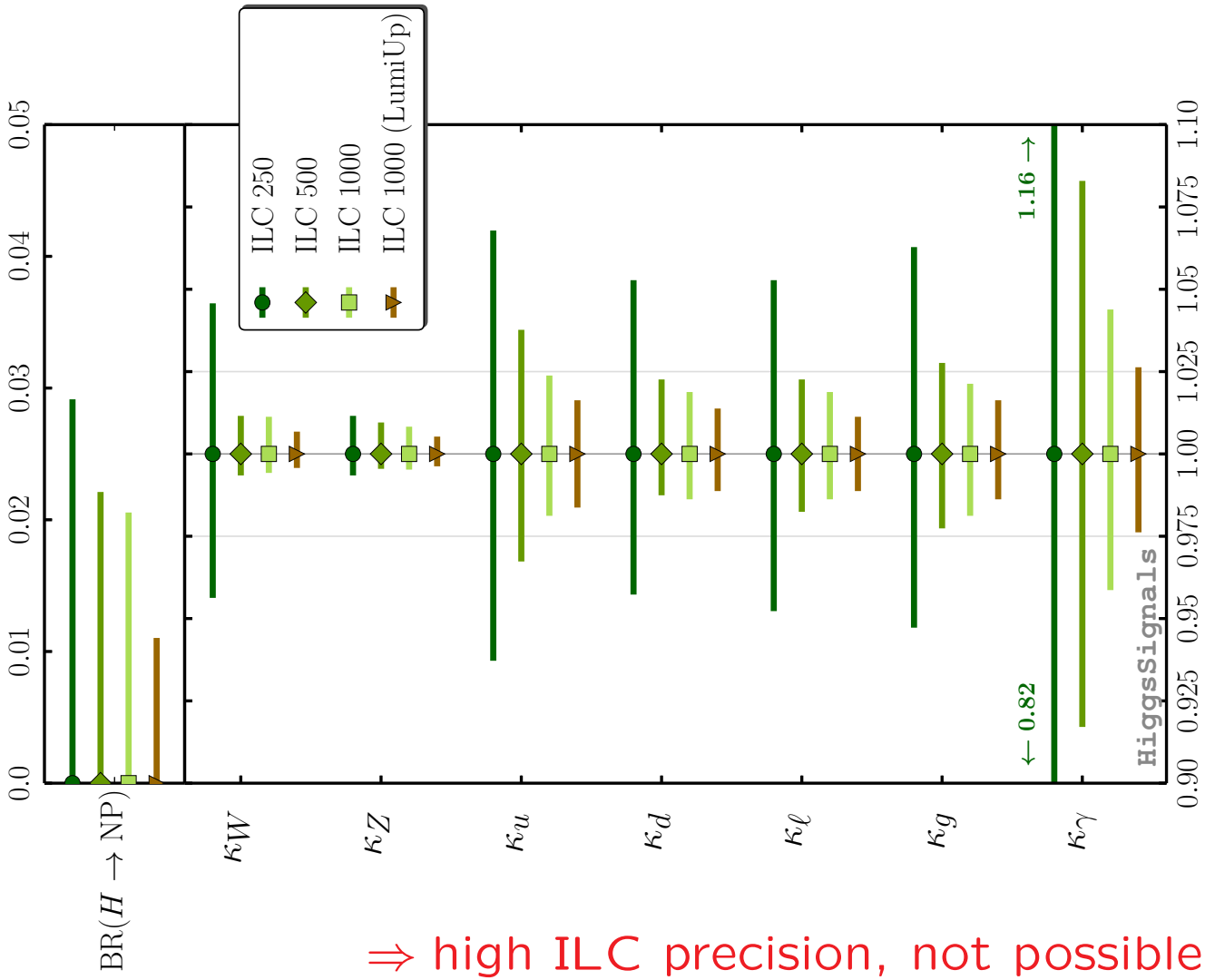


⇒ strong improvement with the ILC

HL-LHC vs. ILC in the most general κ framework:

[*P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '14*]

no theory assumptions, full fit

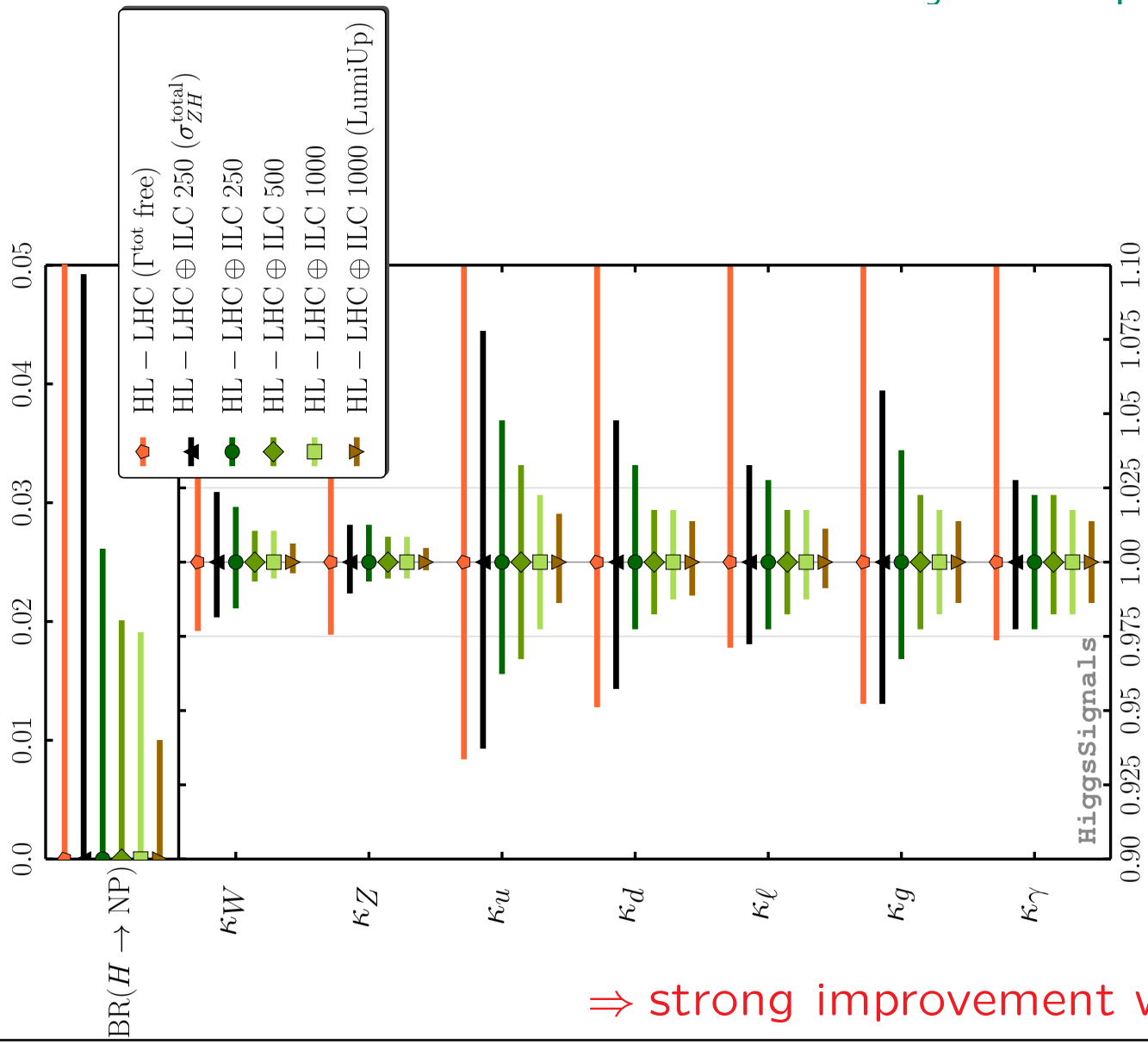


$\Rightarrow$ high ILC precision, not possible at the LHC

HL-LHC vs. ILC in the most general κ framework:

[*P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '14*]

no theory assumptions, full fit



$\Rightarrow$ strong improvement with the ILC

2. Higgs coupling determination

LHC always measures $\sigma \times$ BR

$\Rightarrow$ Total width $\Gamma_{H,\text{tot}}$ cannot be measured without further theory assumptions.

Recommendation of the LHCHXSWG:

$\Rightarrow$ Higgs coupling strength scale factors: κ_i
For each benchmark (except overall coupling strength) two versions are proposed:
with and without taking into account the possibility of additional contributions to the total width

– additional contributions to $\Gamma_{H,\text{tot}}$ are allowed:

$\Rightarrow$ Determination of ratios of scaling factors, e.g. $\kappa_i\,\kappa_j/\kappa_H$

– no additional contributions to $\Gamma_{H,\text{tot}}$ are allowed:

$\Rightarrow$ Determination of κ_i (evaluated to NLO QCD accuracy)

Higgs coupling determination at the ILC

Some (I)LC specifics:

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

$\Rightarrow$ total measurement of Higgs production cross section

$\Rightarrow$ NO additional theoretical assumptions needed for absolute determination of partial widths

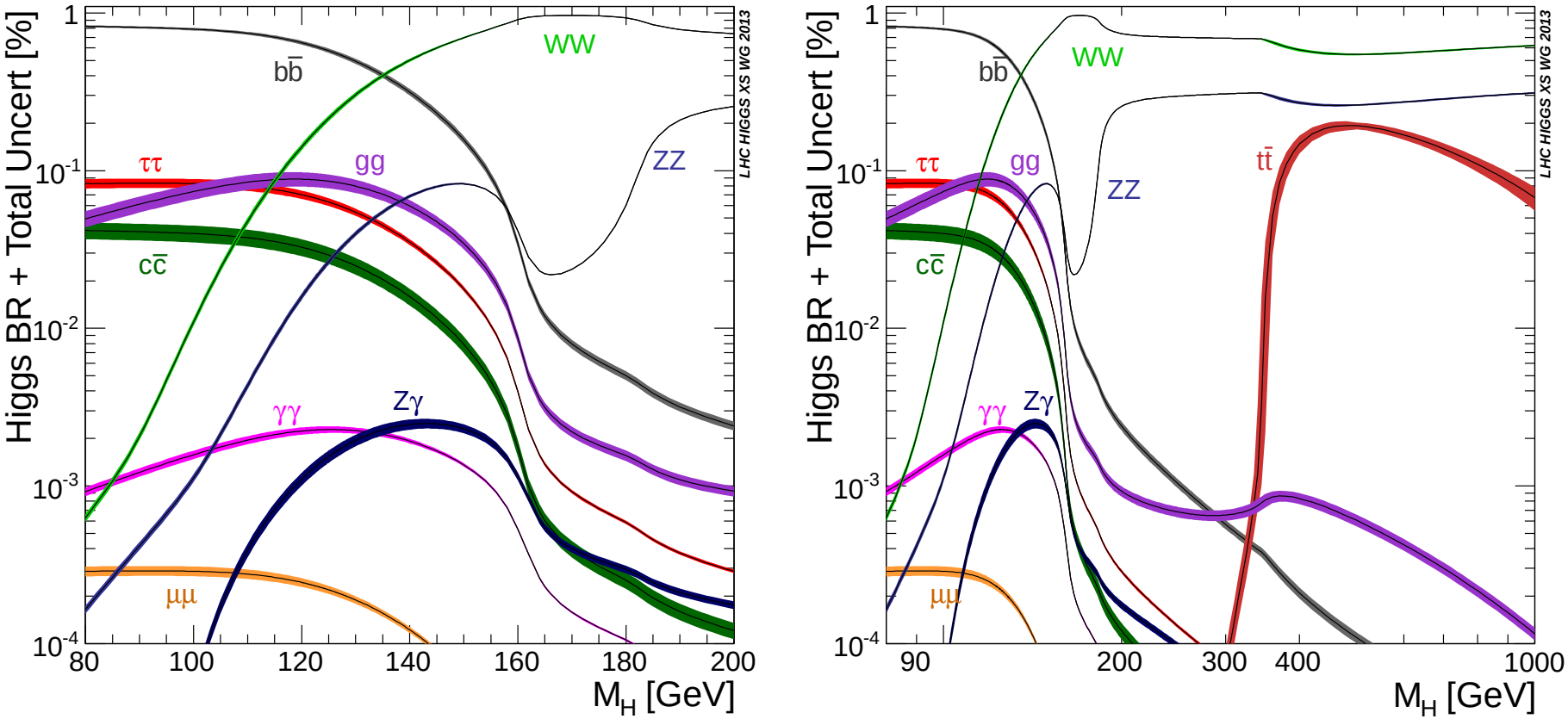
$\Rightarrow$ all observable channels can be measured with high accuracy

$\Rightarrow$ SM cross section predictions at the 1% accuracy level

$\Rightarrow$ take cross section measurement as given

$\Rightarrow$ concentrate on theory BR uncertainties from now on

Latest SM Higgs BR predictions:



Based on HDECAY and Prophecy4f:

$$\Gamma_H = \Gamma^{\mathrm{HD}} - \Gamma^{\mathrm{HD}}_{ZZ} - \Gamma^{\mathrm{HD}}_{WW} + \Gamma^{\mathrm{P4f}}_{4f}$$

Theoretical uncertainties: General recipe: [*LHCHXSWG '11*]

1. Parametric Uncertainties: $p \pm \Delta p$
   - Evaluate partial widths and BRs with p, $p + \Delta p$, $p - \Delta p$ and take the differences w.r.t. central values
   - Upper $(p + \Delta p)$ and lower $(p - \Delta p)$ uncertainties summed in quadrature to obtain the Combined Parametric Uncertainty

2. Theoretical Uncertainties:
   - Calculate uncertainty for partial widths and corresponding BRs for each theoretical uncertainty
   - Combine the individual theoretical uncertainties linearly to obtain the Total Theoretical Uncertainty

   $\Rightarrow$ estimate based on "what is included in the codes"!

3. Total Uncertainty:

   Linear sum of the Combined Parametric Uncertainty and the Total Theoretical Uncertainties

Current parametric uncertainties:

Parameter	Central Value	Uncertainty	$m_q(m_q)$
$\alpha_s(M_Z)$	0.119	± 0.002(90% CL)	
m_c	1.42 GeV	± 0.03 GeV$(2\,\sigma)$	1.28 GeV
m_b	4.49 GeV	± 0.06 GeV$(2\,\sigma)$	4.16 GeV
m_t	172.5 GeV	± 2.5 GeV	165.4 GeV

- m_b, m_c: one-loop pole masses
  those masses accidentally show negligible dependence on α_s, so that their variation can be done independently from α_s
- m_b, m_c uncertainties:
  [*K. Chetyrkin, J. Kühn, A. Maier, P. Maierhöfer, P. Marquard, M. Steinhauser, C. Sturm [arXiv:0907.2110]*]
  $\Rightarrow$ Lattice data much more optimistic . . .
  $\Rightarrow$ but no consensus, not even in the lattice community . . . ?!

Current theoretical uncertainties:

Partial Width	QCD	Electroweak	Total
$H \to b\bar{b}/c\bar{c}$	$\sim 0.1\%$	~ 1–2% for $M_H \lesssim 135$ GeV	$\sim 2\%$
$H \to \tau^+\tau^-/\mu^+\mu^-$		~ 1–2% for $M_H \lesssim 135$ GeV	$\sim 2\%$
$H \to t\bar{t}$	$\lesssim 5\%$	$\lesssim 2$–5% for $M_H < 500$ GeV	$\sim 5\%$
		$\sim 0.1(\frac{M_H}{1\ \text{TeV}})^4$ for $M_H > 500$ GeV	~ 5–10%
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$
$H \to Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$
$H \to WW/ZZ \to 4f$	$< 0.5\%$	$\sim 0.5\%$ for $M_H < 500$ GeV	$\sim 0.5\%$
		$\sim 0.17(\frac{M_H}{1\ \text{TeV}})^4$ for $M_H > 500$ GeV	~ 0.5–15%

- QCD corrections: scale change by factor 2 and 1/2
- EW corrections: missing HO estimation based on the known structure and size of the NLO corrections
- Different uncertainties on a given channel added linearly

$\Rightarrow$ Strong improvement in ~ 10 years possible, but . . .

. . . they have to be consistently implemented into codes!

$\Rightarrow$ intrinsic uncertainty can/will be sufficiently under control?!

Current uncertainties on decay widths:

[YR3, arXiv:1307.1347]

Channel	Γ [MeV]	$\Delta\alpha_s$	Δm_b	Δm_c	Δm_t	THU
$H \to b\bar{b}$	2.36	$^{+2.3\%}_{-2.3\%}$	$^{-3.2\%}_{+3.3\%}$	$^{-0.0\%}_{+0.0\%}$	$^{-0.0\%}_{+0.0\%}$	$^{-2.0\%}_{+2.0\%}$
$H \to \tau^+\tau^-$	$2.59 \cdot 10^{-1}$	$^{+0.0\%}_{+0.0\%}$	$^{-0.0\%}_{+0.0\%}$	$^{-0.0\%}_{+0.0\%}$	$^{-0.1\%}_{+0.1\%}$	$^{-2.0\%}_{+2.0\%}$
$H \to \mu^+\mu^-$	$8.99 \cdot 10^{-4}$	$^{+0.0\%}_{+0.0\%}$	$^{-0.0\%}_{+0.0\%}$	$^{-0.0\%}_{-0.1\%}$	$^{-0.1\%}_{+0.0\%}$	$^{-2.0\%}_{+2.0\%}$
$H \to c\bar{c}$	$1.19 \cdot 10^{-1}$	$^{+7.0\%}_{-7.1\%}$	$^{-0.1\%}_{-0.1\%}$	$^{-6.1\%}_{+6.2\%}$	$^{-0.1\%}_{+0.0\%}$	$^{-2.0\%}_{+2.0\%}$
$H \to gg$	$3.57 \cdot 10^{-1}$	$^{-4.1\%}_{+4.2\%}$	$^{-0.1\%}_{-0.1\%}$	$^{-0.0\%}_{+0.0\%}$	$^{+0.2\%}_{-0.2\%}$	$^{-3.0\%}_{+3.0\%}$
$H \to \gamma\gamma$	$9.59 \cdot 10^{-3}$	$^{-0.0\%}_{+0.0\%}$	$^{-0.0\%}_{+0.0\%}$	$^{-0.0\%}_{+0.0\%}$	$^{-0.0\%}_{+0.0\%}$	$^{-1.0\%}_{+1.0\%}$
$H \to Z\gamma$	$6.84 \cdot 10^{-3}$	$^{-0.0\%}_{+0.0\%}$	$^{-0.0\%}_{+0.0\%}$	$^{-0.1\%}_{+0.0\%}$	$^{-0.1\%}_{+0.0\%}$	$^{-5.0\%}_{+5.0\%}$
$H \to WW^*$	$9.73 \cdot 10^{-1}$	$^{-0.0\%}_{+0.0\%}$	$^{-0.0\%}_{+0.0\%}$	$^{-0.0\%}_{+0.0\%}$	$^{-0.0\%}_{+0.0\%}$	$^{-0.5\%}_{+0.5\%}$
$H \to ZZ^*$	$1.22 \cdot 10^{-1}$	$^{-0.0\%}_{+0.0\%}$	$^{-0.0\%}_{+0.0\%}$	$^{-0.0\%}_{+0.0\%}$	$^{-0.0\%}_{+0.0\%}$	$^{-0.5\%}_{+0.5\%}$

Data available for $M_H = 122$ GeV, 126 GeV, 130 GeV

$\Rightarrow$ used for ATLAS and CMS evaluations $\Rightarrow$ provided to Snowmass/Higgs

Theory uncertainties at the "ILC times"?

Parametric uncertainties:

- largely driven by δm_b $\Rightarrow$ improvement unclear (to me)
  lattice community does not seem to agree
- some improvement in α_s possible

Intrinsic uncertainties:

$H \to b\bar{b}, H \to c\bar{c}$: EW corrections can be included (they are known at 1L)

$H \to \tau^+\tau^-, H \to \mu^+\mu^-$: EW corrections can be included
(they are known at 1L)

$H \to gg$: improvement difficult

$H \to \gamma\gamma$: already very precise ...

$H \to Z\gamma$: EW corrections could help ...

$H \to WW^*, H \to ZZ^*$: already very precise, two-loop corrections unclear

$\Rightarrow$ intrinsic uncertainty can/will be sufficiently under control?!

RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN

Input Parameters

Lepage, Mackenzie, Peskin [arXiv:1404.0319]

- How well can the Higgs BRs be predicted in the future?
- Limitation due to parametric errors?
- use lattice gauge theory to improve α_s, m_b, and m_c
  (e.g. using current-current correlators)
  (stated errors already now quite small)
- optimistic projection for lattice improvements:

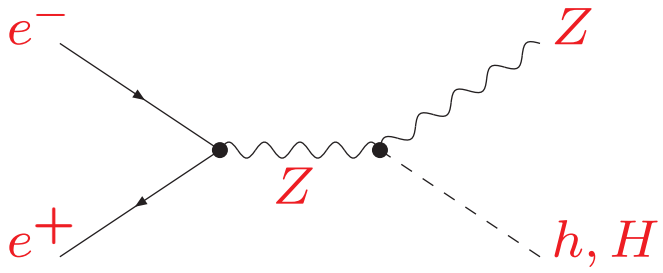
	$\delta m_b(10)$	$\delta\alpha_s(m_Z)$	$\delta m_c(3)$	δ_b	δ_c	δ_g
current errors [10]	0.70	0.63	0.61	0.77	0.89	0.78
+ PT	0.69	0.40	0.34	0.74	0.57	0.49
+ LS	0.30	0.53	0.53	0.38	0.74	0.65
+ LS^2	0.14	0.35	0.53	0.20	0.65	0.43
+ PT + LS	0.28	0.17	0.21	0.30	0.27	0.21
+ PT + LS^2	0.12	0.14	0.20	0.13	0.24	0.17
+ PT + LS^2 + ST	0.09	0.08	0.20	0.10	0.22	0.09
ILC goal				0.30	0.70	0.60

(errors in %)

time-scale: 10-15 years

Search for neutral SUSY Higgs bosons:

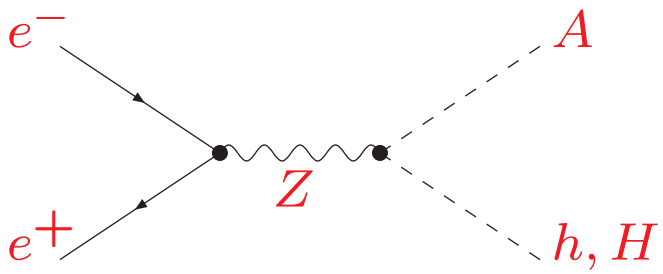
$e^+e^- \to Zh, ZH$



$$\sigma_{hZ} \approx \sin^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$

$$\sigma_{HZ} \approx \cos^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$

$e^+e^- \to Ah, AH$



$$\sigma_{hA} \propto \cos^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$

$$\sigma_{HA} \propto \sin^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$

$\Rightarrow$ some Higgs bosons can decouple, but not all

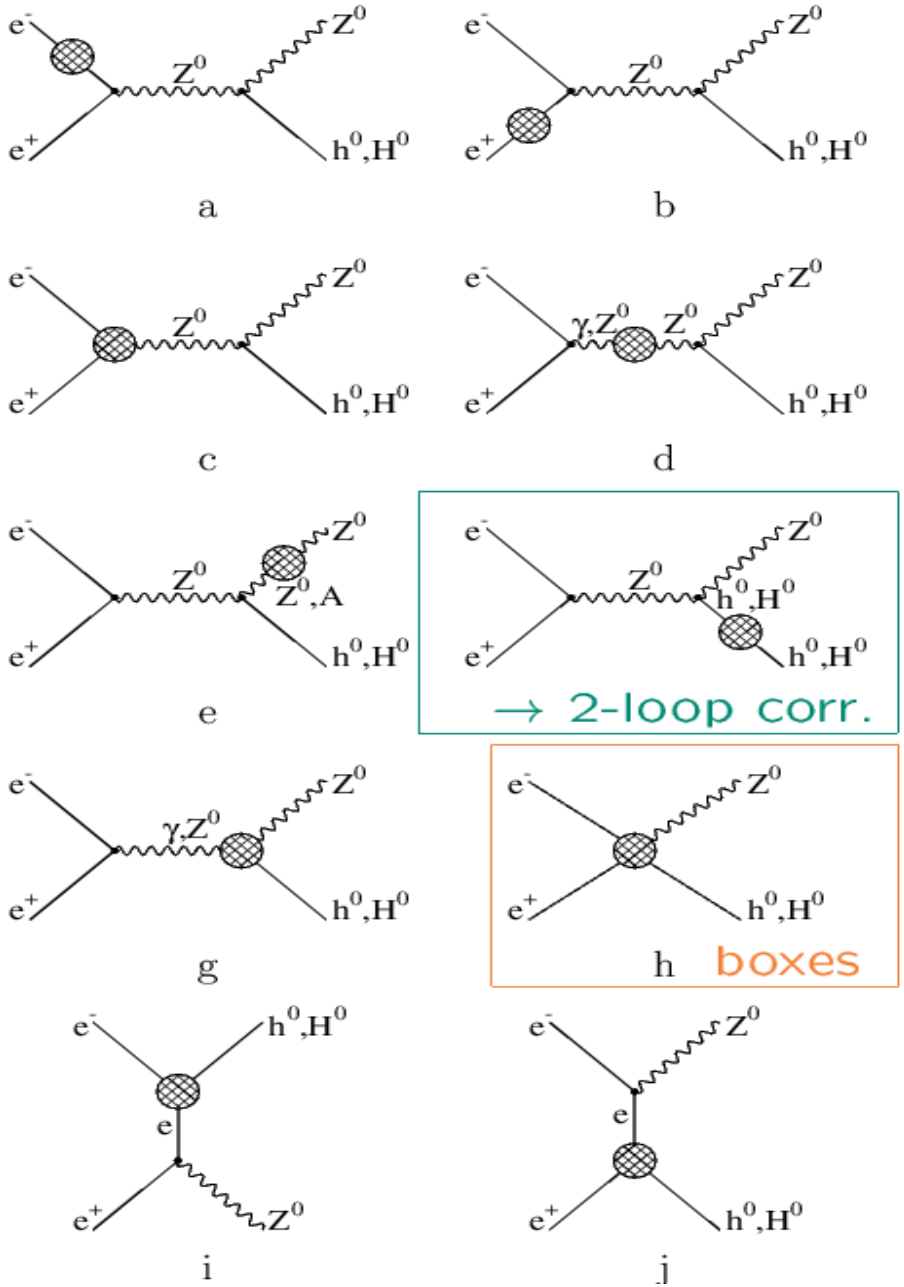
$\Rightarrow$ heavy SUSY Higgses have to be pair produced, $M_A \lesssim \sqrt{s}/2$

Status of $e^+e^- \to Zh$ in the MSSM

Only full one-loop calculation in the rMSSM:

[*S.H., W. Hollik, J. Rosiek, G. Weiglein '01*]

Feynman diagrams $\Rightarrow$



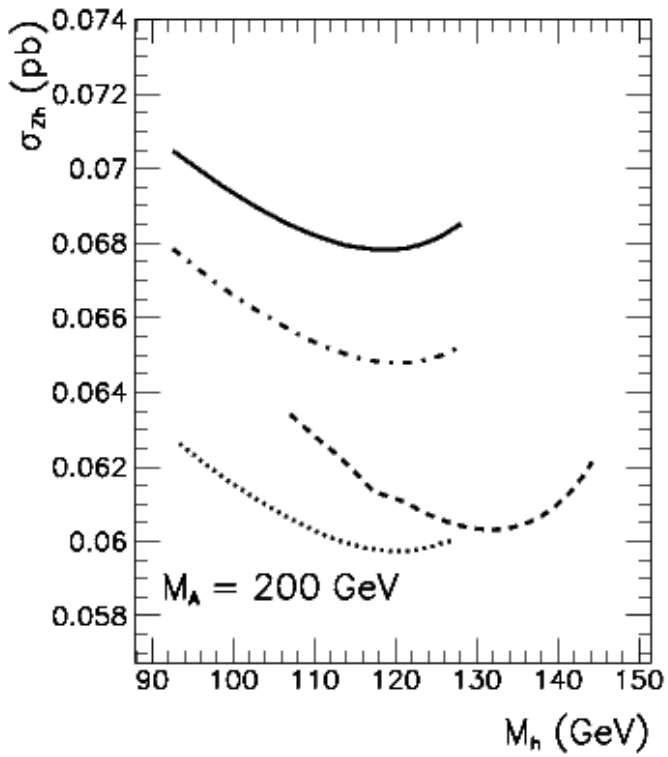
$e^+e^- \to hZ$, $\sqrt{s} = 500$ GeV, maximal $\tilde{t}$ mixing:

$M_{\tilde{q}} = 1$ TeV, $M_{\tilde{l}} = 300$ GeV, $M_2 = \mu = 200$ GeV

$M_A = 200$ GeV, $\tan\beta$ varied

solid: FD 2L (with box) , dot-dashed: FD 2L (no box)

dashed: FD 1L , dotted: $\alpha_{\rm eff}$ RG approximation

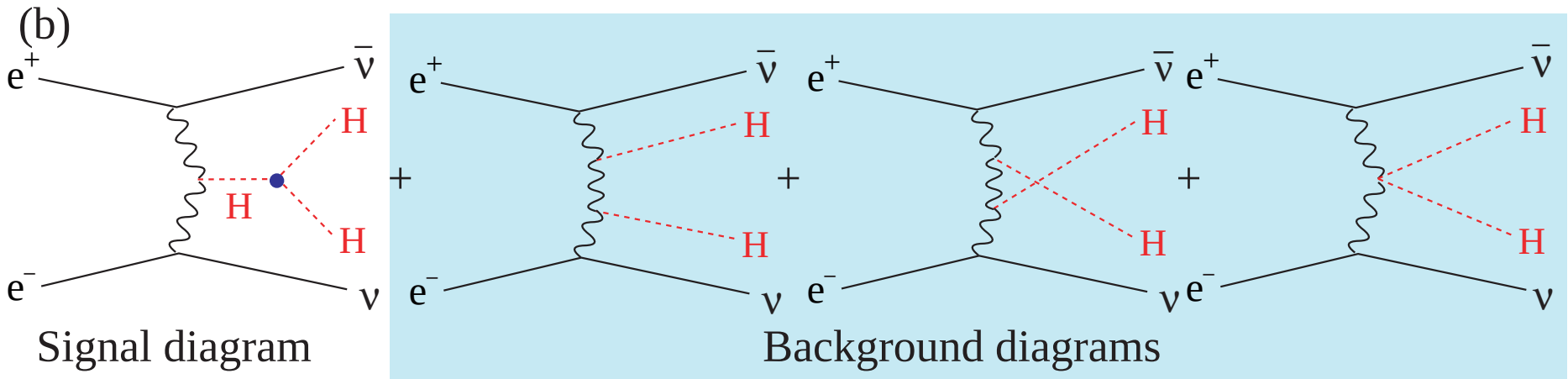


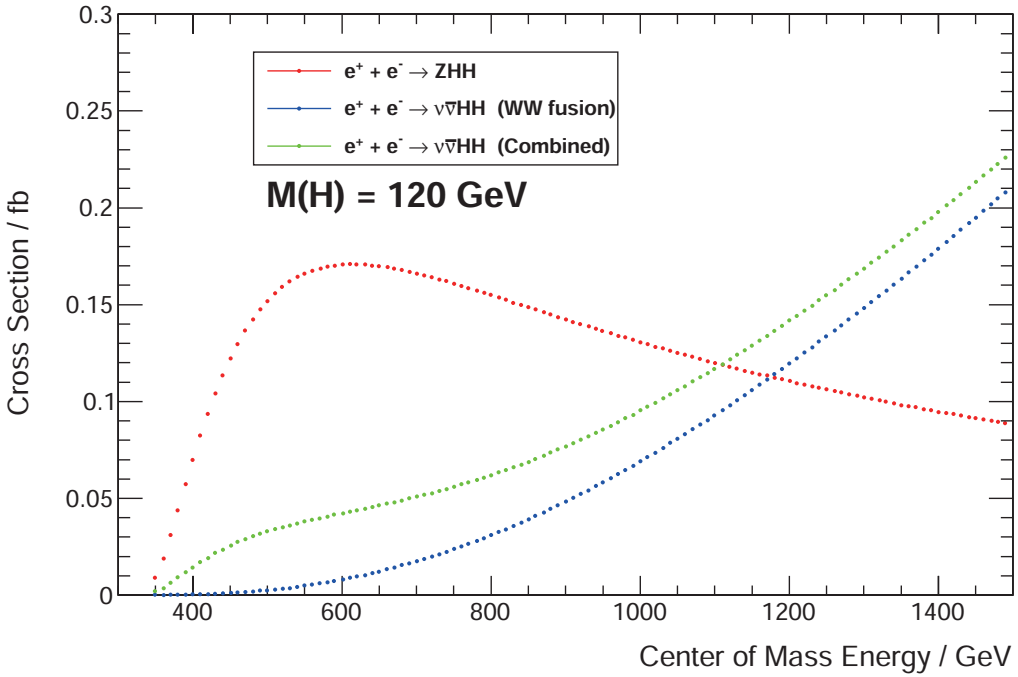
$\Rightarrow$ diagrammatic 2L result necessary to reach ILC precision! cMSSM??

3. What can be done only at the (I)LC

Measurement of the Higgs boson self-coupling

[ILC TDR '13]

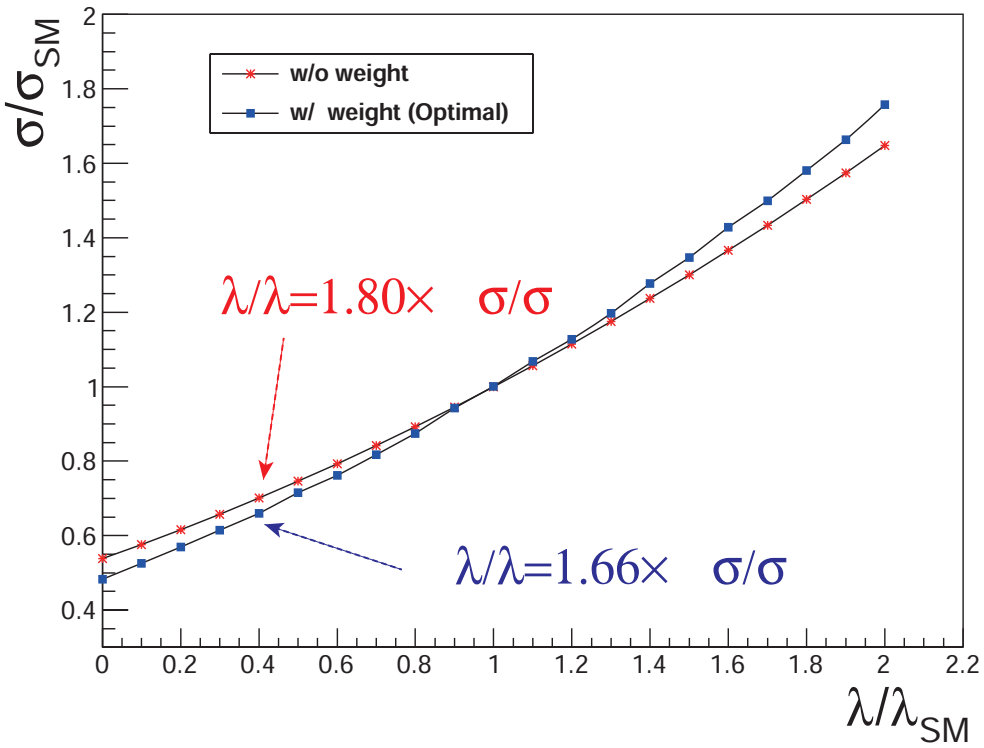




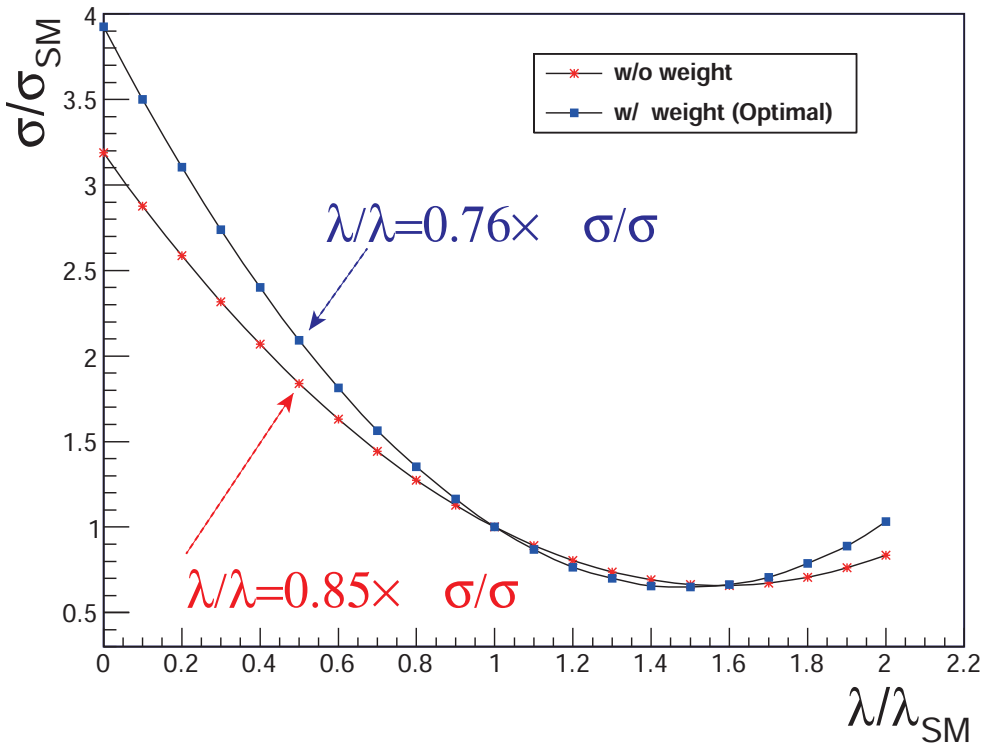
Sensitivity to triple Higgs coupling λ:

[taken from K. Fuji '13]

ZHH@500 GeV



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

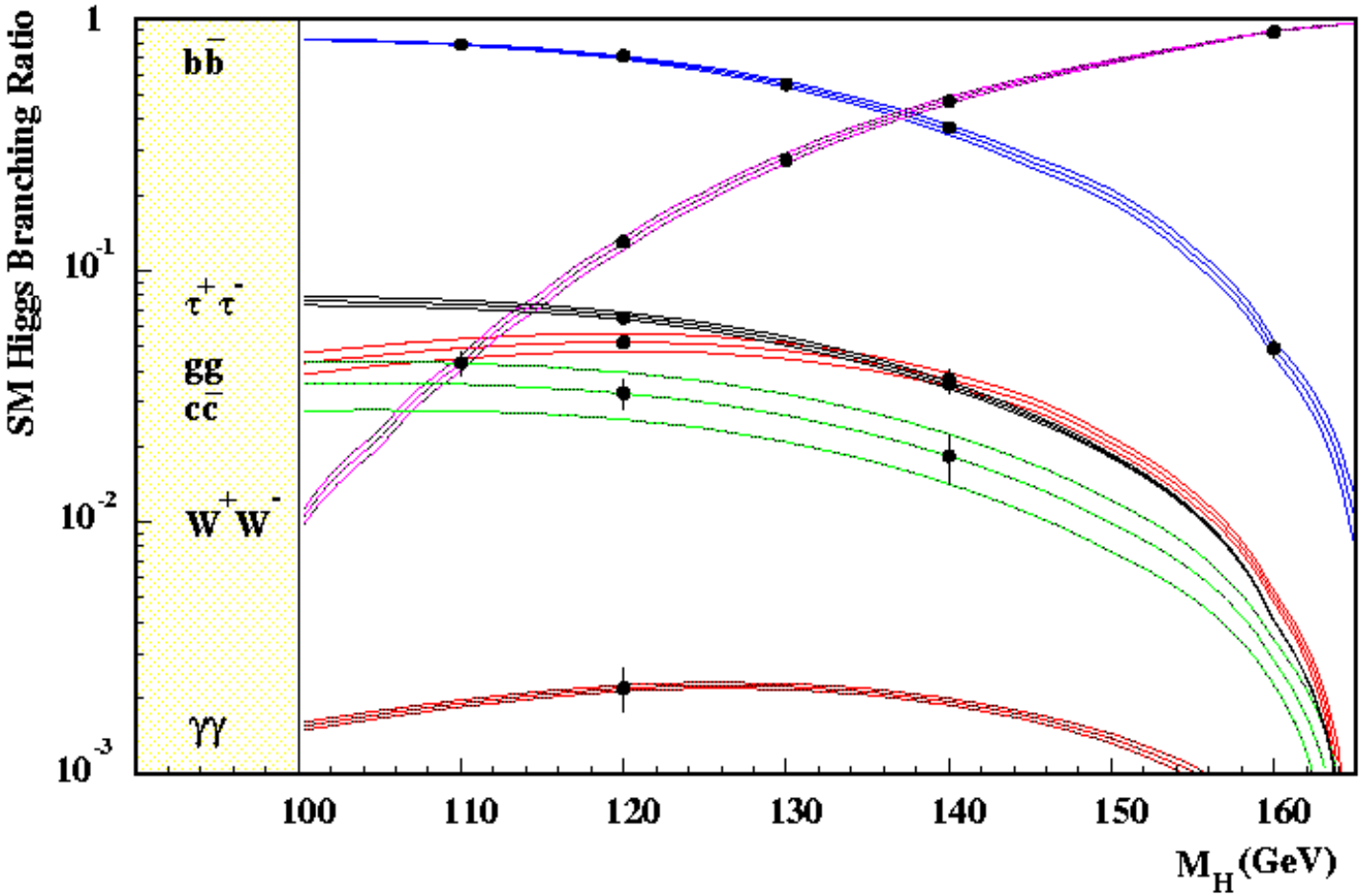


$\Rightarrow$ currently full simulations are performed

Expected sensitivity on λ: $\sim$ 15% (2 ab^{-1} @ 1000 GeV) [ILC TDR '13]

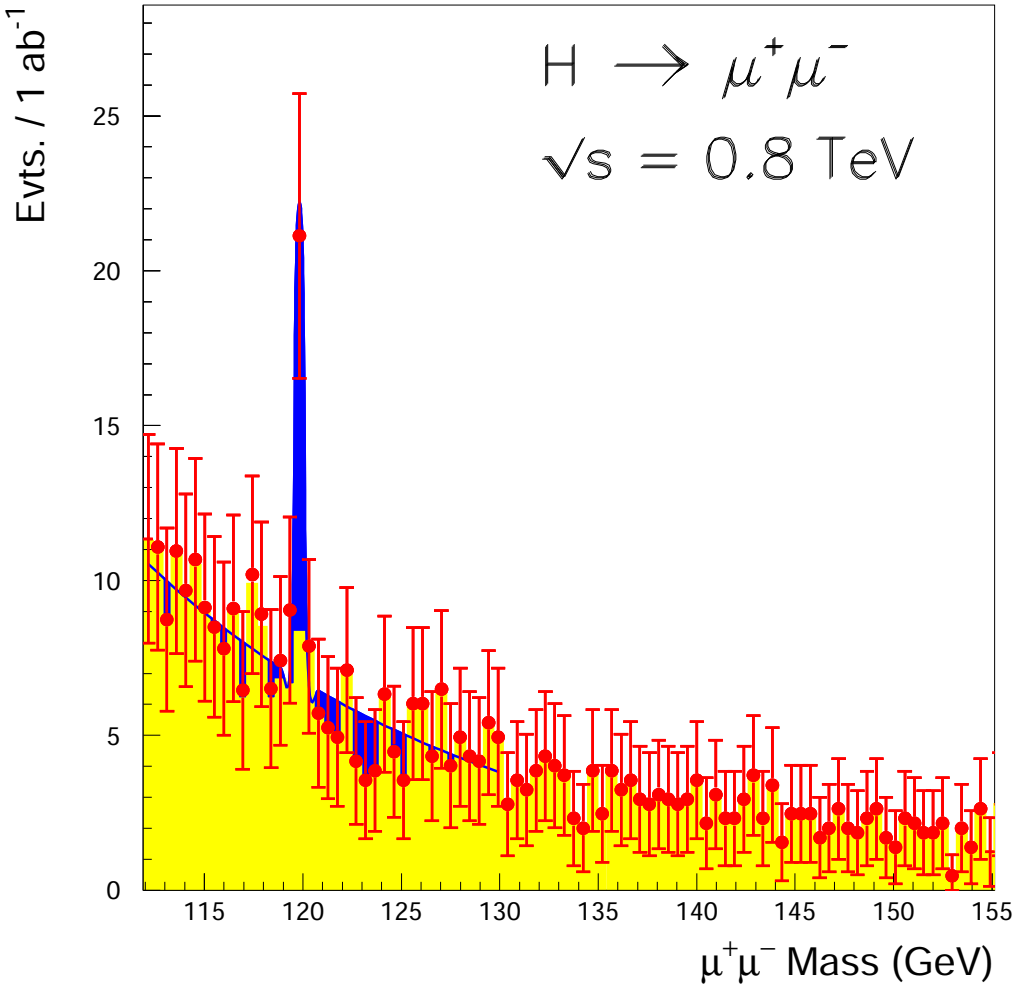
Higgs couplings to the second family!

⇒ coupling to the c quark:



Higgs couplings to the second family!

⇒ coupling to the muon:

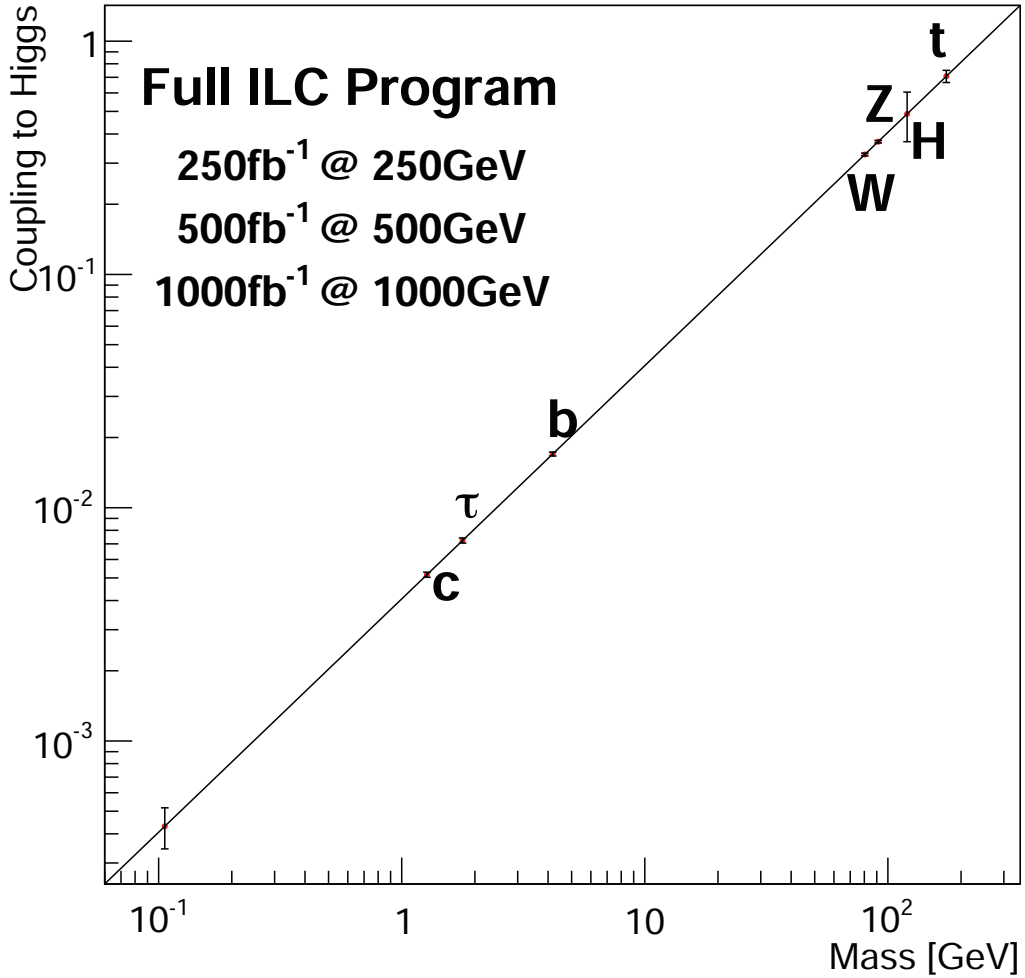


$(M_H = 120\ \text{GeV},\ \sqrt{s} = 800\ \text{GeV},\ \mathcal{L}_{\text{int}} = 1\,\text{ab}^{-1})$

Higgs mechanism: mass $\propto$ coupling

[ILC TDR '13]

putting everything together:

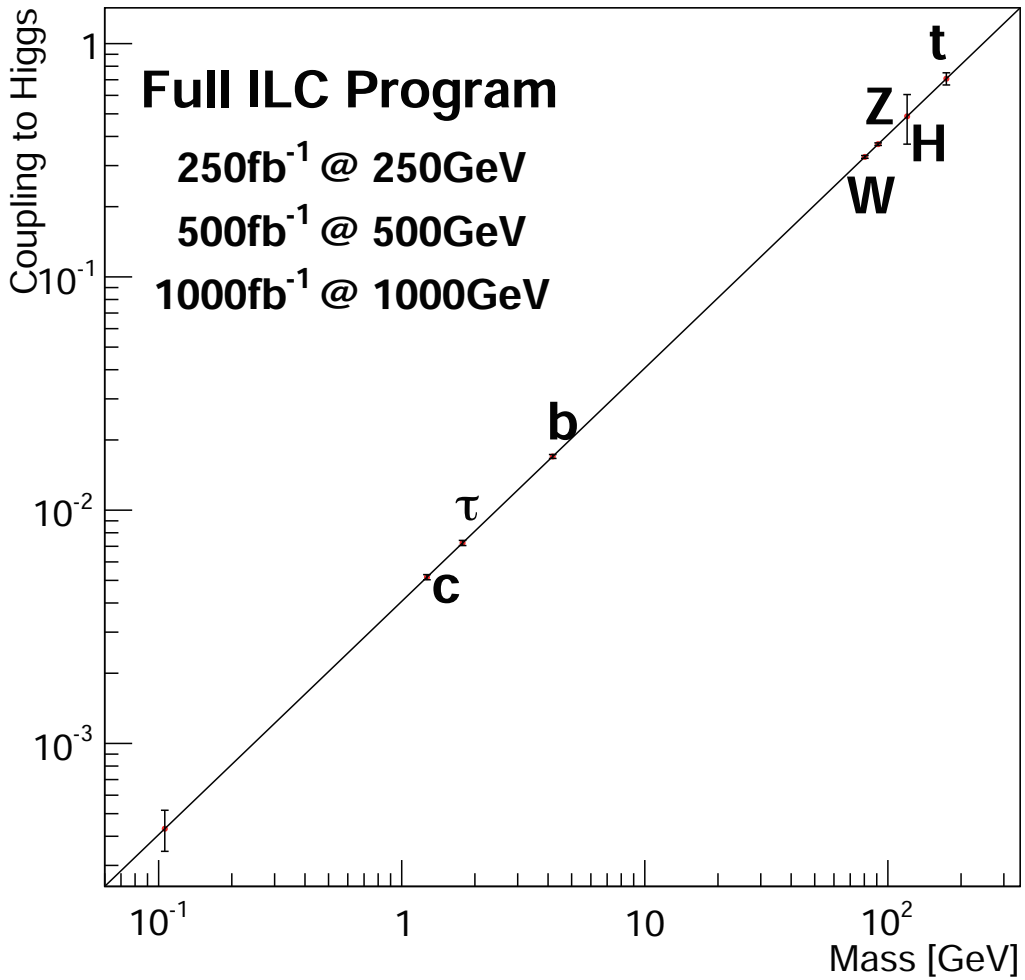


$\Rightarrow$ any deviation from straight line indicates BSM physics!

Higgs mechanism: mass $\propto$ coupling

[ILC TDR '13]

putting everything together:



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

Or lack of sufficient higher-order corrections?

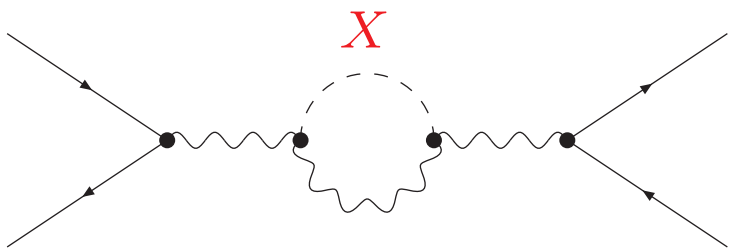
4. Indirect Higgs tests at the ILC

Comparison of observables with theory:

Precision data:		Theory:
$M_W, \sin^2\theta_{\text{eff}}, a_\mu, \ldots$	$\leftrightarrow$	SM, MSSM , . . .

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections, e.g. X



$\Downarrow$

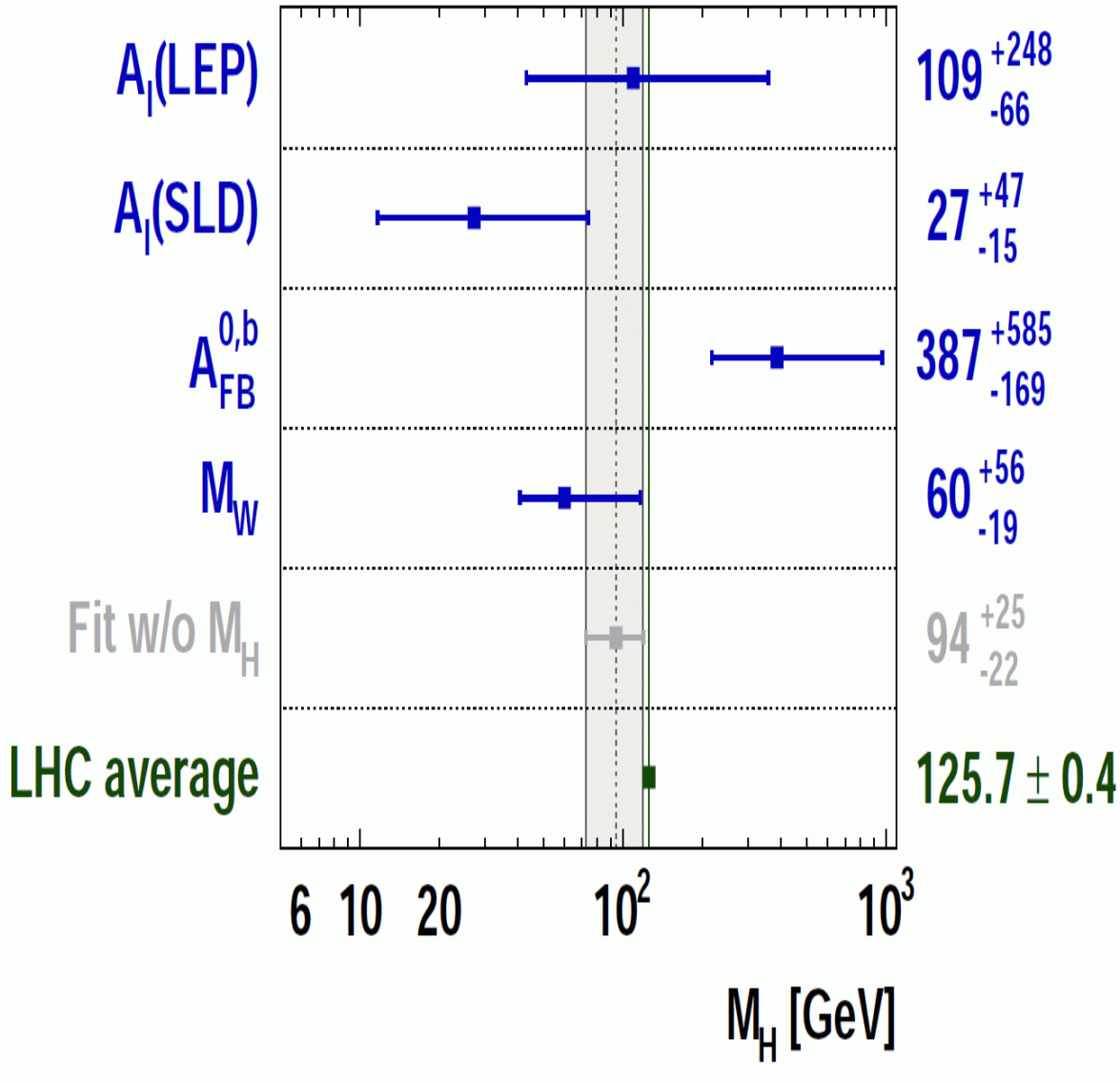
SM: limits on M_H

Very high accuracy of measurements and theoretical predictions needed

Results for M_H from most sensitive EWPO:

light Higgs preferred by:
M_W, A_l^{LR} (SLD)

heavier Higgs preferred by:
A_b^{FB} (LEP)
$\Rightarrow$ keeps SM alive



[*GFitter '12*]

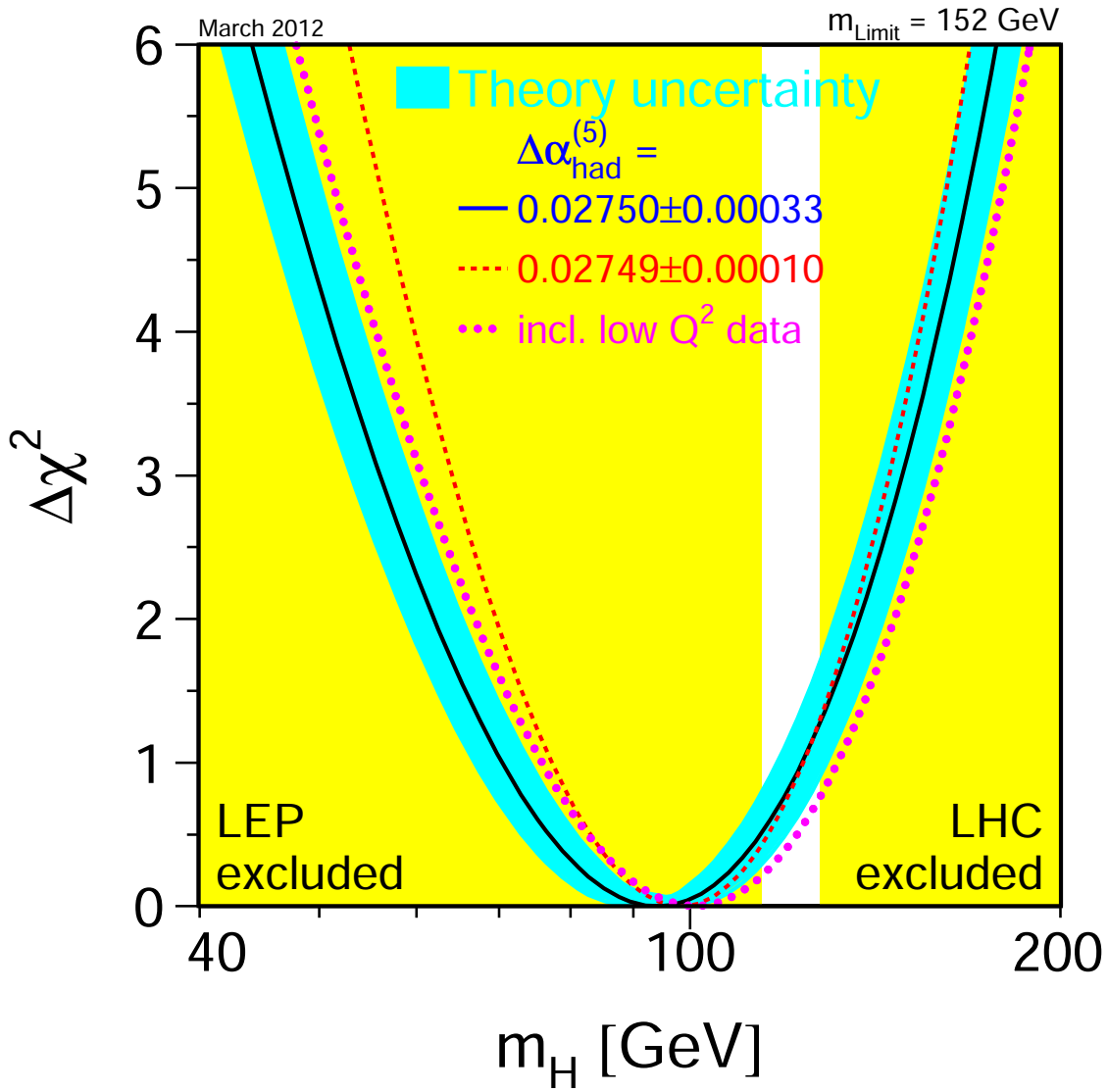
$\Rightarrow$ light Higgs boson preferred

Global fit to all SM data:

[*LEPEWWG '12*]

$\Rightarrow M_H = 94^{+29}_{-24}$ GeV

$M_H < 152$ GeV, 95% C.L.



Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of Higgs mechanism

$\Rightarrow$ Prediction before discovery: in the SM: $M_H \lesssim 160$ GeV

Experimental errors of the precision observables:

	today	Tev./LHC	ILC	GigaZ
$\delta \sin^2\theta_{\text{eff}} (\times 10^5)$	16	16	–	1.3
δM_W [MeV]	15	$\leq$15	~ 3	~ 3
δm_t [GeV]	0.9	$\leq$1	0.1	0.1

Relevant SM parametric errors: $\delta(\Delta\alpha_{\text{had}}) = 5 \times 10^{-5}$, $\delta M_Z = 2.1$ MeV

	$\delta m_t = 2$	$\delta m_t = 1$	$\delta m_t = 0.1$	$\delta(\Delta\alpha_{\text{had}})$	δM_Z
$\delta \sin^2\theta_{\text{eff}}$ [10^{-5}]	6	3	0.3	1.8	1.4
ΔM_W [MeV]	12	6	1	1	2.5

Current and future errors:

Current:

$$\delta m_t^{\rm exp} = 0.9 \text{ GeV}, \qquad \delta(\Delta\alpha_{\rm had}) = 3.5 \times 10^{-4}$$

$$\text{SM}: \delta M_W^{\rm theory} \approx \pm 4 \text{ MeV}, \qquad \delta \sin^2\theta_{\rm eff}^{\rm theory} \approx \pm 4.7 \times 10^{-5}$$

$$\text{MSSM}: \delta M_W^{\rm theory} \approx \pm(5-10) \text{ MeV}, \qquad \delta \sin^2\theta_{\rm eff}^{\rm theory} \approx \pm(5-7) \times 10^{-5}$$

$$\delta m_t: \quad \delta M_W^{\rm para} \approx \pm 5.5 \text{ MeV}, \qquad \delta \sin^2\theta_{\rm eff}^{\rm para} \approx \pm 7 \times 10^{-5}$$

$$\delta(\Delta\alpha_{\rm had}): \quad \delta M_W^{\rm para} \approx \pm 6.5 \text{ MeV}, \qquad \delta \sin^2\theta_{\rm eff}^{\rm para} \approx \pm 13 \times 10^{-5}$$

$$\delta M_W^{\rm exp} \approx \pm 15 \text{ MeV}, \qquad \delta \sin^2\theta_{\rm eff}^{\rm exp} \approx \pm 16 \times 10^{-5}$$

Future:

$$\text{SM}: \delta M_W^{\rm theory} \gtrsim \pm 1 \text{ MeV}, \qquad \delta \sin^2\theta_{\rm eff}^{\rm theory} \gtrsim \pm 1.5 \times 10^{-5}$$

$$\text{MSSM}: \delta M_W^{\rm theory} \gtrsim \pm(2-4) \text{ MeV}, \qquad \delta \sin^2\theta_{\rm eff}^{\rm theory} \gtrsim \pm(2.5-3.5) \times 10^{-5}$$

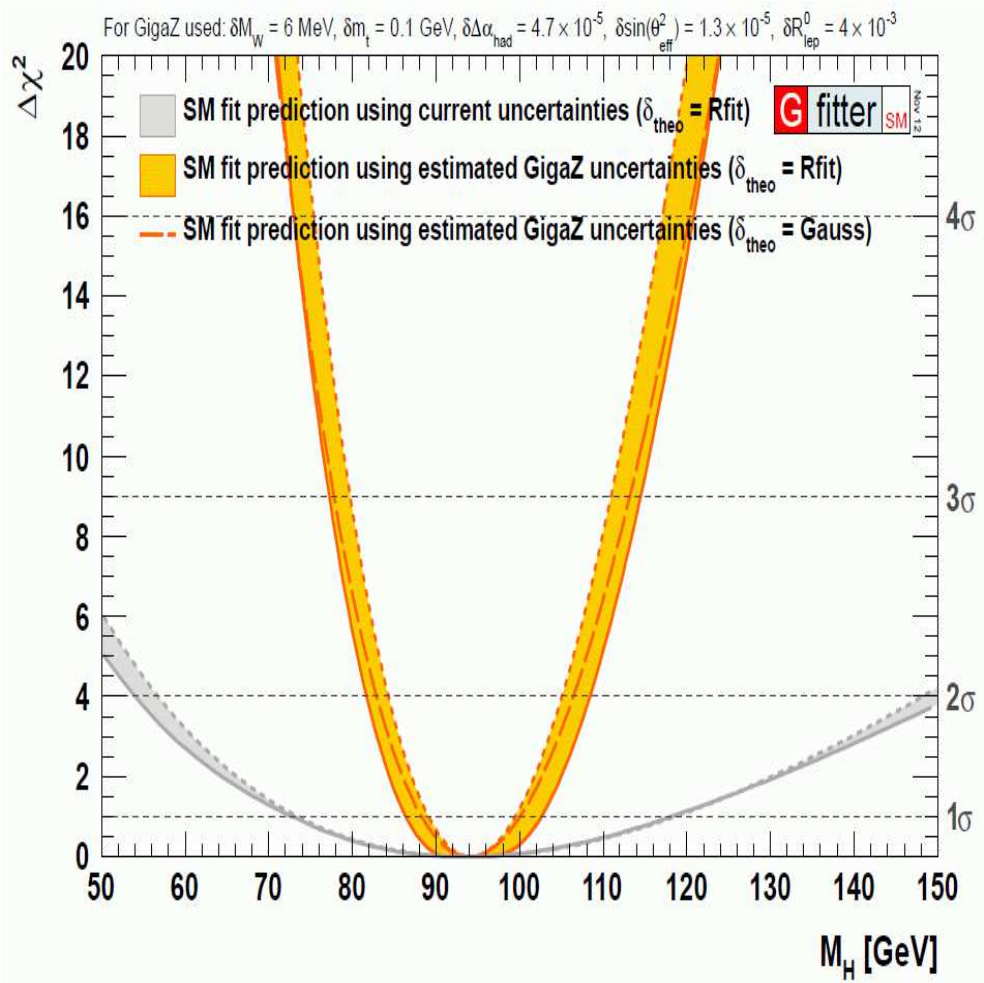
$$\delta m_t: \quad \delta M_W^{\rm para} \approx \pm 1 \text{ MeV}, \qquad \delta \sin^2\theta_{\rm eff}^{\rm para} \approx \pm 0.4 \times 10^{-5}$$

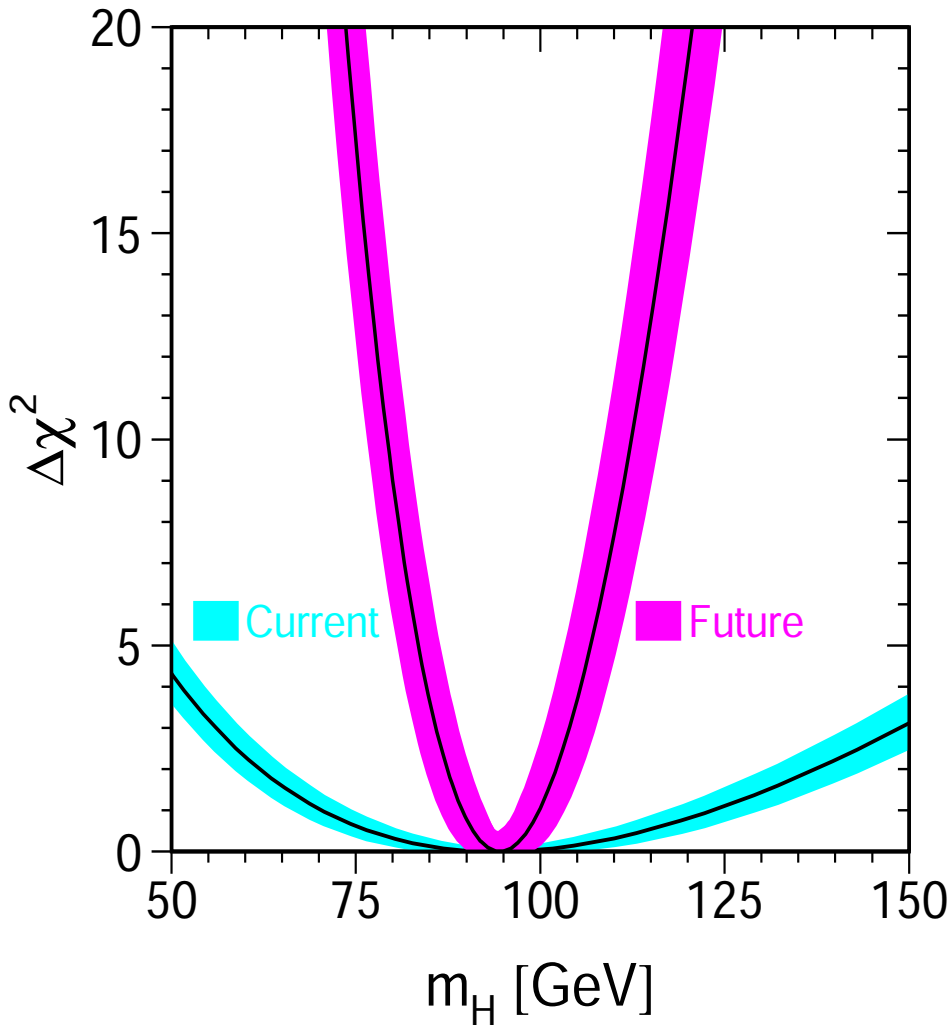
$$\delta(\Delta\alpha_{\rm had}): \quad \delta M_W^{\rm para} \approx \pm 1 \text{ MeV}, \qquad \delta \sin^2\theta_{\rm eff}^{\rm para} \approx \pm 1.8 \times 10^{-5}$$

$$[\text{GigaZ}]: \quad \delta M_W^{\rm exp} \approx \pm 3 \text{ MeV}, \qquad \delta \sin^2\theta_{\rm eff}^{\rm exp} \approx \pm 1.3 \times 10^{-5}$$

Most precise M_H test with the ILC:

[*GFitter '13*] [*LEPEWWG '13*]





$\Rightarrow \delta M_H^{\text{ind}} \approx \pm 6$ GeV

$\Rightarrow$ extremely sensitive test of SM (and BSM) possible

5. (In)Direct ILC reach for heavy MSSM Higgs bosons

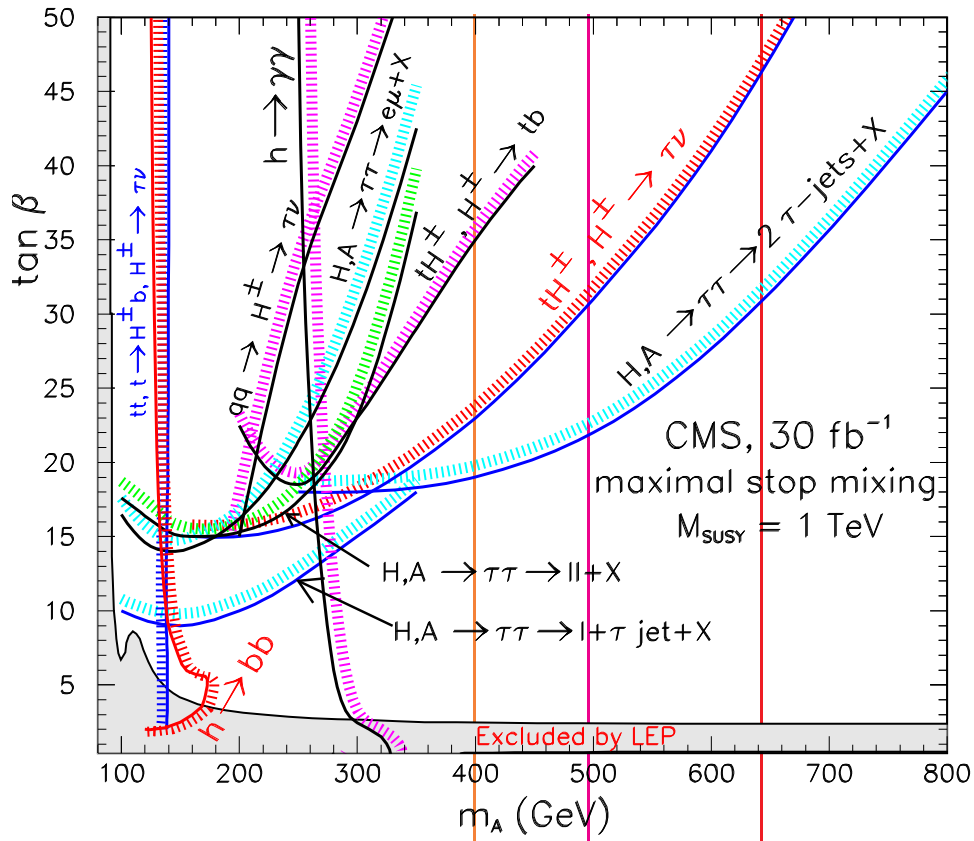
Compare LHC/ILC reach for MSSM Higgs bosons:

LHC:

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

H, A : unreachable parts

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



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

$\sqrt{s} = 1000$ GeV

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

ILC:

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

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

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

$\gamma\gamma$:

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

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

A: Yes, by direct and indirect measurements

$\Rightarrow$ indirect determination of M_A in LHC wedge

Existing LHC analyses neglect:

– MSSM intrinsic uncertainties
– parametric SM uncertainties
– anticipated parametric MSSM uncertainties

$\Rightarrow$ existing analyses unrealistic

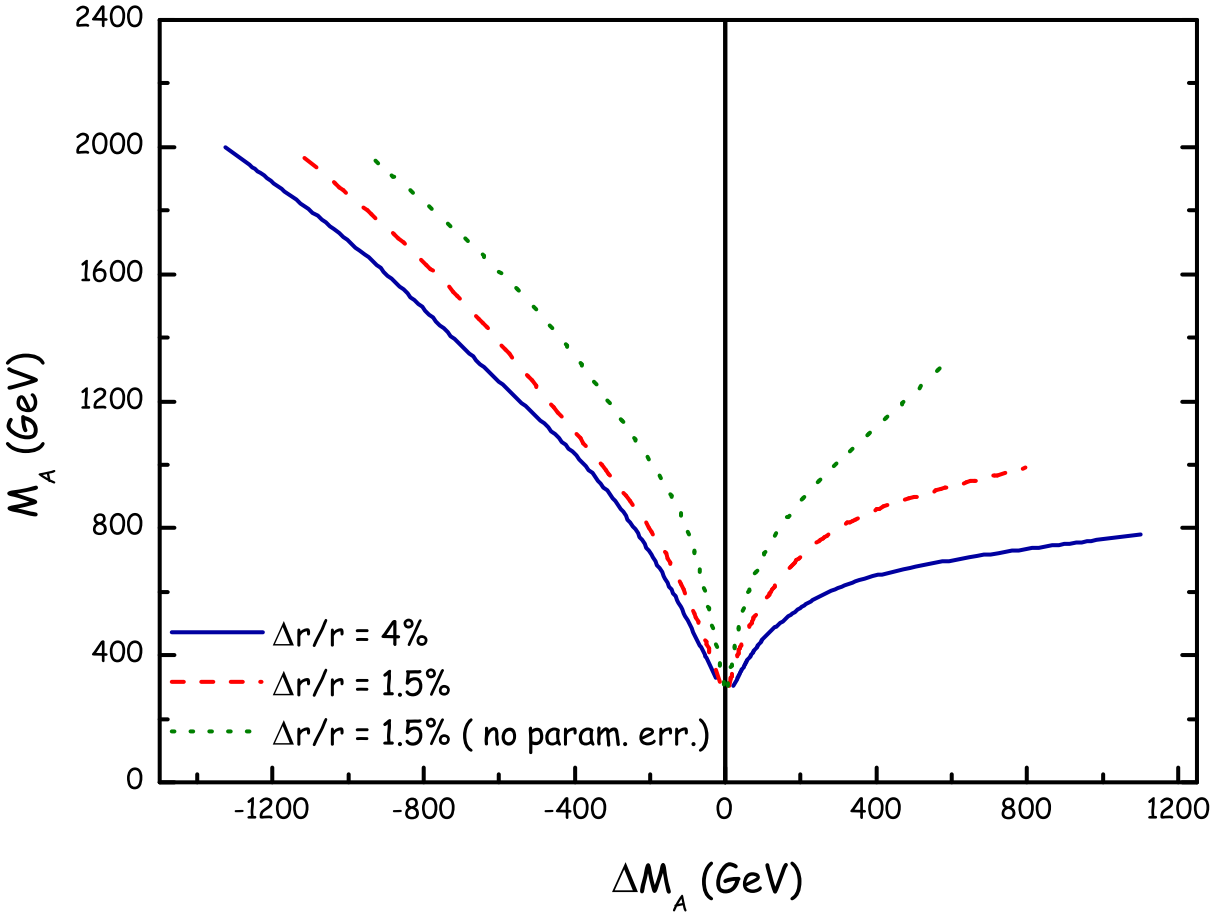
One analysis includes all uncertainties: [*K. Desch et al. '04*]

$\Rightarrow$ needs ILC uncertainty of

$$r \equiv \frac{\left[\mathrm{BR}(h \to b\bar{b})/\mathrm{BR}(h \to WW^*)\right]_{\mathrm{MSSM}}}{\left[\mathrm{BR}(h \to b\bar{b})/\mathrm{BR}(h \to WW^*)\right]_{\mathrm{SM}}}$$

$+$ input for masses, mixing angles from LHC $\oplus$ ILC

Analysis using r: [K. Desch et al. '04]



$\Delta r/r = 4\%$: upper limit on M_A up to $M_A \lesssim 800$ GeV

$\Delta r/r = 1.5\%$: $\Delta M_A/M_A = 20(30)\%$ for $M_A = 600(800)$ GeV

inclusion of parametric errors crucial for reliable bounds

6. Conclusions

- **The ILC is crucial to fully establish the Higgs mechanism!**
- Z-recoil method crucial for model independent mass and coupling determination
- Only(?) with the ILC a coupling fit without assumption on the Higgs width can be performed

  $\Rightarrow$ precisions at/below the per-cent level!
- Theory requirement:
  - intrinsic uncertainties under control $\Rightarrow$ feasible ?!

    $\rightarrow$ much more complicated/unclear in BSM models!
  - parametric uncertainties under control $\Rightarrow$ controversial ?!
- Indirect consistency test of the SM:

  ILC precision on EWPO $\delta M_H \approx \pm 6$ GeV
- MSSM Higgs searches:

  ILC can substantially extend the LHC reach

  $\Rightarrow$ theoretical precision not yet reached . . .

My personal view:

Finding a particle that is compatible with
a light (SM-like?) Higgs boson
is the **best case** scenario for the ILC

How to go ahead?

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How to go ahead?

- ILC as a Higgs (and top) factory
- Staged approach?
  - 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 TeV scale exploration
- go to other options: GigaZ, $\gamma\gamma$, ...

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$\Rightarrow$ best case scenario the ILC!

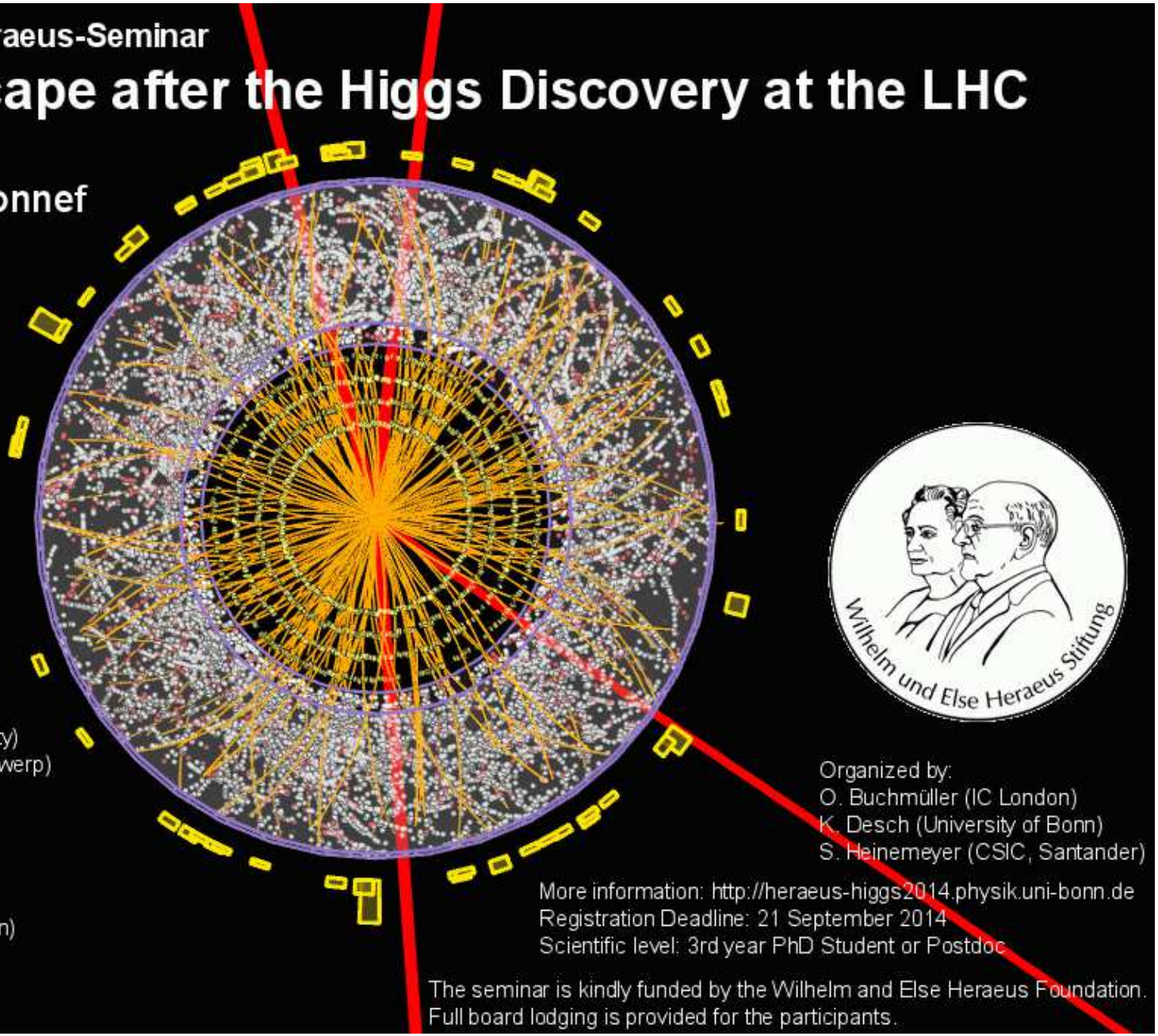
$\Rightarrow$ We have to use our Annus mirabilis in our favor!!

573. Wilhelm und Else Heraeus-Seminar

Physics Landscape after the Higgs Discovery at the LHC

5.-7.November 2014

Physikzentrum Bad Honnef



Invited speakers:

Markus Cristinziani (University of Bonn)
John Ellis (CERN, King's college)
Lyn Evans (CERN)
Tobias Golling (University of Yale)
JoAnne Hewett (SLAC)
Gino Isidori (INFN Frascati)
Marumi Kado (LAL, Orsay)
Roman Kogler (University of Hamburg)
Michael Krämer (RWTH Aachen University)
Albert de Roeck (CERN, University of Antwerp)
Keith Olive (University of Minnesota)
Teresa Marrodan (MPI Heidelberg)
Margarete Mühlleitner (KIT)
Christian Sander (University of Hamburg)
Andreas Schopper (CERN)
Dominik Stöckinger (University of Dresden)
Roberto Tenchini (INFN Pisa)
Tejinder Virdee (IC London)
Georg Weiglein (DESY)

Wilhelm und Else Heraeus Stiftung

Organized by:
O. Buchmüller (IC London)
K. Desch (University of Bonn)
S. Heinemeyer (CSIC, Santander)

More information: http://heraeus-higgs2014.physik.uni-bonn.de
Registration Deadline: 21 September 2014
Scientific level: 3rd year PhD Student or Postdoc

The seminar is kindly funded by the Wilhelm and Else Heraeus Foundation.
Full board lodging is provided for the participants.

Apply - it's worth it! :-)