Theory Uncertainties in LC Higgs Coupling Measurements

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LHC Higgs Cross Section Working Group (BR)

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All the details:

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/BRs

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Investigating the Higgs Mechanism

What has to be done?

Find the new particle

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Investigating the Higgs Mechanism

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L = LHC,

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Investigating the Higgs Mechanism

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

We need the ILC to fully establish the Higgs mechanism!

Higgs coupling determination at the LHC

LHC always measures $\sigma \times \mathrm{BR}$

$\Rightarrow$ Total width $\Gamma_{H,\mathrm{tot}}$ 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 $\Gamma_{H,\mathrm{tot}}$ are allowed:

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

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

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

Higgs coupling determination at the LC

Some 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

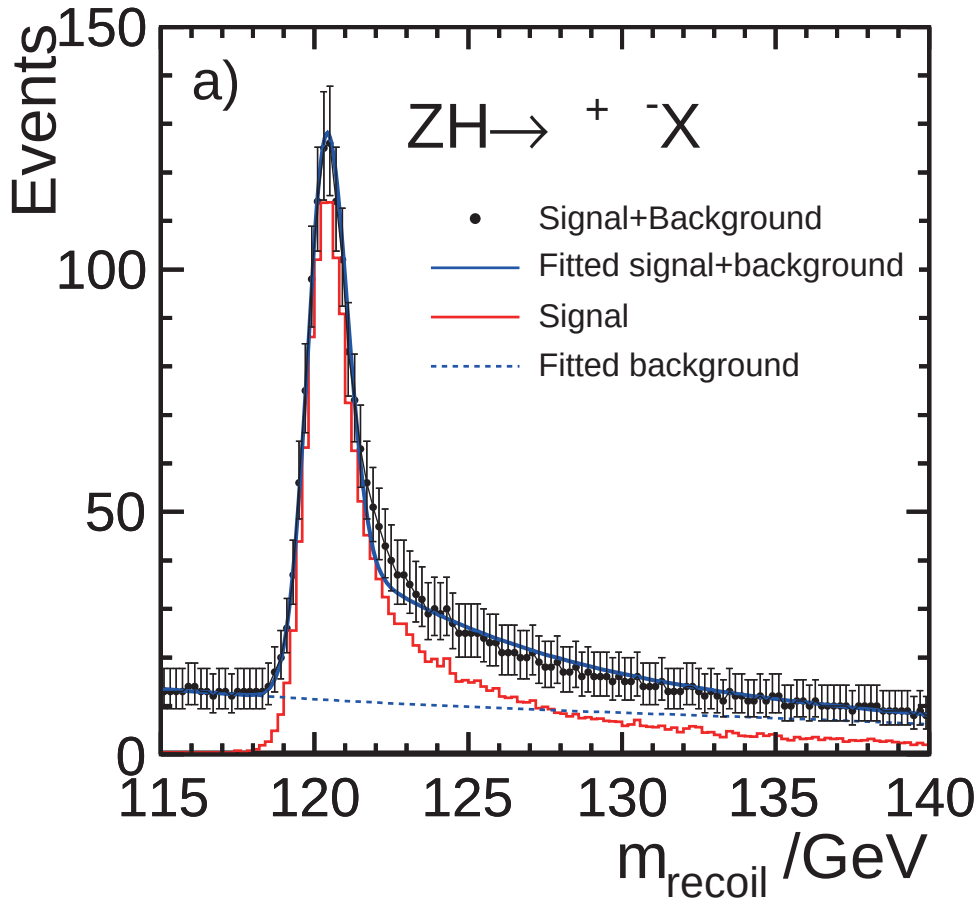
$\Rightarrow$ take cross section measurement as given

$\Rightarrow$ concentrate on BR uncertainties from now on

Model independent cross section measurement

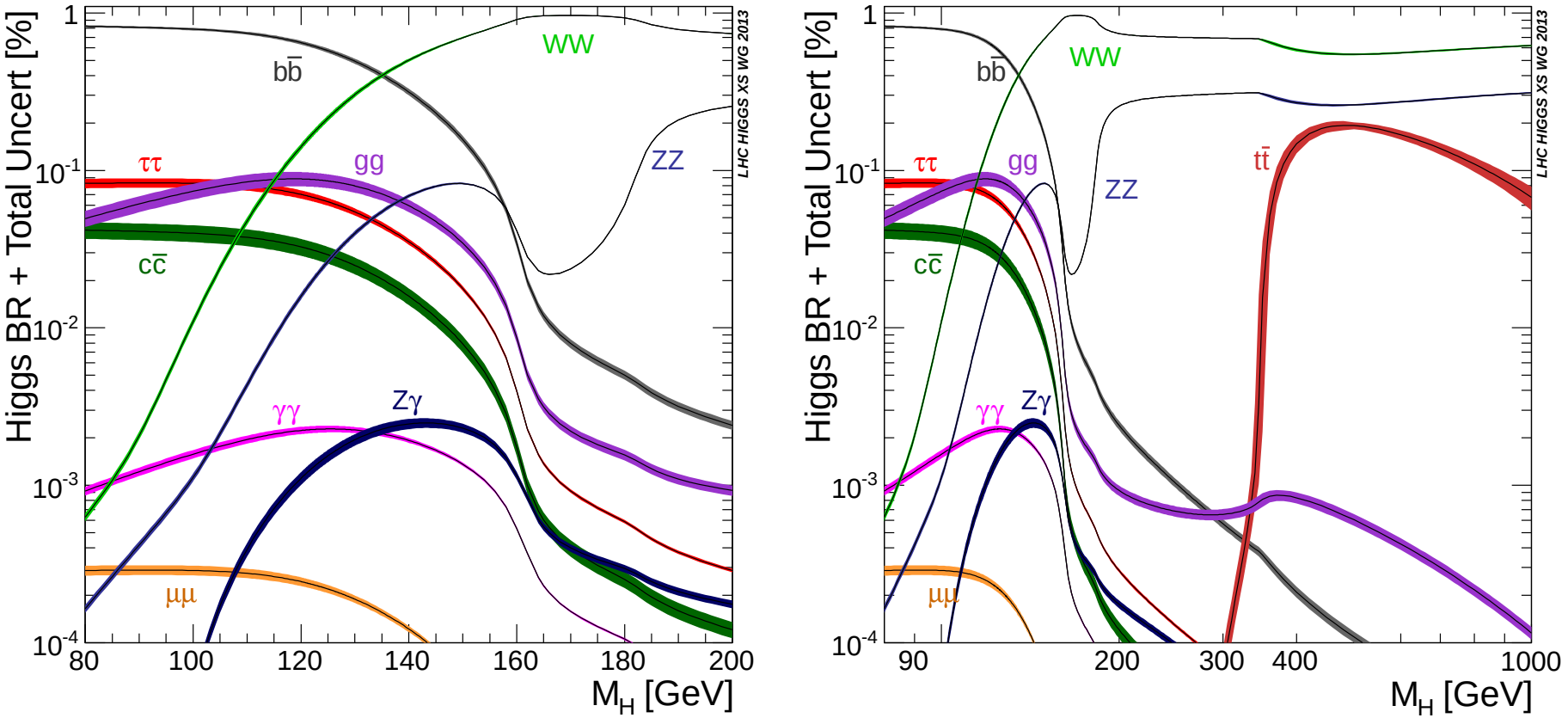
[*ILC TDR '13*]

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



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

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

3. Total Uncertainty:

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

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

Comments:

- 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]]
  (PDG uncertainties much larger . . .)

Theoretical uncertainties:

Partial Width	QCD	Electroweak	Total
$H \to b\bar{b}/c\bar{c}$	$\sim 0.1\%$	$\sim$ 1–2% for $M_H \lesssim 135$ GeV	$\sim 2\%$
$H \to \tau^+\tau^-/\mu^+\mu^-$		$\sim$ 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	$\sim$ 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	$\sim$ 0.5–15%

Comments:

- 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
- For $M_H > 500$ GeV: higher-order heavy-Higgs corrections dominate error
- Different uncertainties on a given channel added linearly

Full BR uncertainty overview:

$M_H = 126$ GeV			
Decay	TU [%]	PU [%]	Total [%]
$H \to \gamma\gamma$	± 2.7	± 2.2	± 4.9
$H \to b\bar{b}$	± 1.5	± 1.9	± 3.3
$H \to \tau\tau$	± 3.5	± 2.1	± 5.6
$H \to WW$	± 2.0	± 2.2	± 4.1
$H \to ZZ$	± 2.0	± 2.2	± 4.2

But:

To take into accout correlations it is better/easier to work with uncertainties for the individual decay widths

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	$^{-2.3\%}_{+2.3\%}$	$^{+3.3\%}_{-3.2\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+2.0\%}_{-2.0\%}$
$H \to \tau^+\tau^-$	$2.59{\cdot}10^{-1}$	$^{+0.0\%}_{+0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.1\%}_{-0.1\%}$	$^{+2.0\%}_{-2.0\%}$
$H \to \mu^+\mu^-$	$8.99{\cdot}10^{-4}$	$^{+0.0\%}_{+0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{-0.1\%}_{-0.0\%}$	$^{+0.0\%}_{-0.1\%}$	$^{+2.0\%}_{-2.0\%}$
$H \to c\bar{c}$	$1.19{\cdot}10^{-1}$	$^{-7.1\%}_{+7.0\%}$	$^{-0.1\%}_{-0.1\%}$	$^{+6.2\%}_{-6.1\%}$	$^{+0.0\%}_{-0.1\%}$	$^{+2.0\%}_{-2.0\%}$
$H \to gg$	$3.57{\cdot}10^{-1}$	$^{+4.2\%}_{-4.1\%}$	$^{-0.1\%}_{-0.1\%}$	$^{+0.0\%}_{-0.0\%}$	$^{-0.2\%}_{+0.2\%}$	$^{+3.0\%}_{-3.0\%}$
$H \to \gamma\gamma$	$9.59{\cdot}10^{-3}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+1.0\%}_{-1.0\%}$
$H \to Z\gamma$	$6.84{\cdot}10^{-3}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.1\%}$	$^{+0.0\%}_{-0.1\%}$	$^{+5.0\%}_{-5.0\%}$
$H \to WW^*$	$9.73{\cdot}10^{-1}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.5\%}_{-0.5\%}$
$H \to ZZ^*$	$1.22{\cdot}10^{-1}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.5\%}_{-0.5\%}$

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 in the future?

Parametric uncertainties:

– largely driven by $\delta m_b \Rightarrow$ improvement unclear (to me)
– 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

Summary:

- SM Higgs BRs evaluated by combining HDECAY and Prophecy4f
- Parametric uncertainties: α_s, m_b, m_c, m_t
- Theoretical uncertainties: estimate of missing QCD and EW corrections
- Total uncertainties: linear sum
- Available from LHCHXSWG: uncertainties for BRs and decay widhts (the latter preferred for correlations)
- Results used for ATLAS and CMS evaluations

  $\Rightarrow$ should be used for LC evaluations!

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