Precision Electroweak Calculations: Future Plans

Sven Heinemeyer, IFCA (CSIC, Santander)

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1. Introduction

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LHC/ILC/TLEP/. . . will provide (high!) accuracy measurements!

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Theoretical calculations should be viewed as
an essential part of all (current and future)
High Energy Physics programs

“My” subgroup: Precision EW calculations (I)

Theory predictions: assessment of uncertainties, and how to improve on

1) Electroweak precision observables

– W boson mass, M_W
– effective weak leptonic mixing angle, $\sin^2\theta_{\text{eff}}$
– partial and todal Z boson widths
– . . .

2) Higgs observables

– Higgs boson mass, M_h (in BSM models)
– Production cross sections ???
– branching ratios ???
– . . .

“My” subgroup: Precision EW calculations (II)

Theory predictions: assessment of uncertainties, and how to improve in

1. SM
2. SM + Higgs singlet
3. 2HDM(s)
4. MSSM
5. NMSSM + other extensions
6. . . .

⇒ only models partially “ready” so far: SM, MSSM
⇒ coordination with “Model building and New Physics” subgroup!
⇒ check with LHCHXSWG SWG3 ?!

General idea:

Evaluate intrinsic uncertainties

Evaluate parametric uncertainties

- analyze various sources of missing higher-order corrections
- analyze them depending on where you are in the parameter space
- based on implemented/coded corrections rather than on theoretically available calculations

⇒ Observable by observable

⇒ Model by model

⇒ Physics gain ?

(“zero uncertainties” as limit)

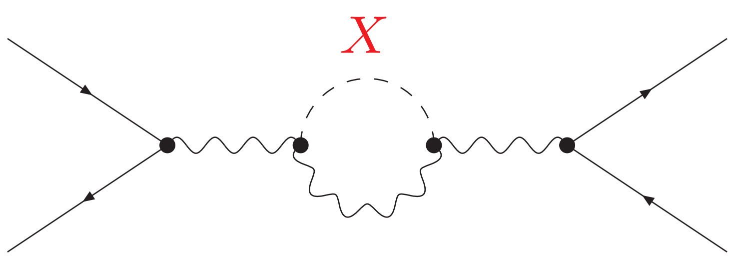
2. Electroweak Precision Observables

Comparison of observables with theory:

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

$\Downarrow$

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



$\Downarrow$

SM: limits on M_H,   BSM: limits on M_X

Very high accuracy of measurements and theoretical predictions needed
$\Rightarrow$ only models "ready" so far: SM, MSSM

Current status:

SM result for M_W and $\sin^2\theta_{\text{eff}}$:

- full one-loop
- full two-loop
- leading 3-loop via $\Delta\rho$
- leading 4-loop via $\Delta\rho$

Our MSSM result for M_W and $\sin^2\theta_{\text{eff}}$:

- full SM result (via fit formel)
- full MSSM one-loop (incl. complex phases)
- all existing two-loop $\Delta\rho$ contributions

$\Rightarrow$ non-$\Delta\rho$ one-loop and $\Delta\rho$ two-loop contributions sometimes non-negligible!

Other models:

- one-loop corrections in SM + H singlet
- one-loop corrections in (some?) 2HDM(s)
- . . . ??

The W boson mass

Experimental accuracy:

Today: LEP2, Tevatron: $M_W^{\rm exp} = 80.385 \pm 0.015$ GeV

ILC/TLEP:
- polarized threshold scan
- kinematic reconstruction of W^+W^- [G. Wilson '13]
- hadronic mass (single W)

$\delta M_W^{\rm exp,TLEP} \lesssim 1$ MeV (from thr. scan) $\Leftarrow$ theory uncertainties neglected

Theoretical accuracies:

intrinsic today: $\delta M_W^{\rm SM,theo} = 4$ MeV, $\delta M_W^{\rm MSSM,today} = 5 - 10$ MeV

intrinsic future: $\delta M_W^{\rm SM,theo,fut} = 1$ MeV, $\delta M_W^{\rm MSSM,fut} = 2 - 4$ MeV

parametric today: $\delta m_t = 0.9$ GeV, $\delta(\Delta\alpha_{\rm had}) = 10^{-4}$, $\delta M_Z = 2.1$ MeV

$\delta M_W^{{\rm para},m_t} = 5.5$ MeV, $\delta M_W^{{\rm para},\Delta\alpha_{\rm had}} = 2$ MeV, $\delta M_W^{{\rm para},M_Z} = 2.5$ MeV

parametric future: $\delta m_t^{\rm ILC/TLEP} = 0.1$ GeV, $\delta(\Delta\alpha_{\rm had})^{\rm fut} = 5 \times 10^{-5}$

$$\Delta M_W^{{\rm para,fut},m_t} = 1 \text{ MeV}, \quad \Delta M_W^{{\rm para,fut},\Delta\alpha_{\rm had}} = 1 \text{ MeV}$$

The effective weak leptonic mixing angle: $\sin^2\theta_{\rm eff}$

Experimental accuracy:

Today: LEP, SLD: $\sin^2\theta_{\rm eff}^{\rm exp} = 0.23153 \pm 0.00016$

GigaZ/TeraZ: both beams polarized, Blondel scheme

$$\delta\sin^2\theta_{\rm eff}^{\rm exp,ILC} = 3\times10^{-6} \quad \Leftarrow \text{theory uncertainties neglected}$$

Theoretical accuracies: $[10^{-6}]$

intrinsic today: $\delta\sin^2\theta_{\rm eff}^{\rm SM,theo} = 47 \quad \delta\sin^2\theta_{\rm eff}^{\rm MSSM,today} = 50-70$

intrinsic future: $\delta\sin^2\theta_{\rm eff}^{\rm SM,theo,fut} = 15 \quad \delta\sin^2\theta_{\rm eff}^{\rm MSSM,fut} = 25-35$

parametric today: $\delta m_t = 0.9$ GeV, $\delta(\Delta\alpha_{\rm had}) = 10^{-4}$, $\delta M_Z = 2.1$ MeV

$$\delta\sin^2\theta_{\rm eff}^{{\rm para},m_t} = 70, \quad \delta\sin^2\theta_{\rm eff}^{{\rm para},\Delta\alpha_{\rm had}} = 36, \quad \delta\sin^2\theta_{\rm eff}^{{\rm para},M_Z} = 14$$

parametric future: $\delta m_t^{\rm ILC/TLEP} = 0.1$ GeV, $\delta(\Delta\alpha_{\rm had})^{\rm fut} = 5\times10^{-5}$

$$\Delta\sin^2\theta_{\rm eff}^{{\rm para,fut},m_t} = 4, \quad \Delta\sin^2\theta_{\rm eff}^{{\rm para,fut},\Delta\alpha_{\rm had}} = 18$$

The top quark mass: m_t

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 $\mathcal{O}(\Lambda_{\rm QCD})$

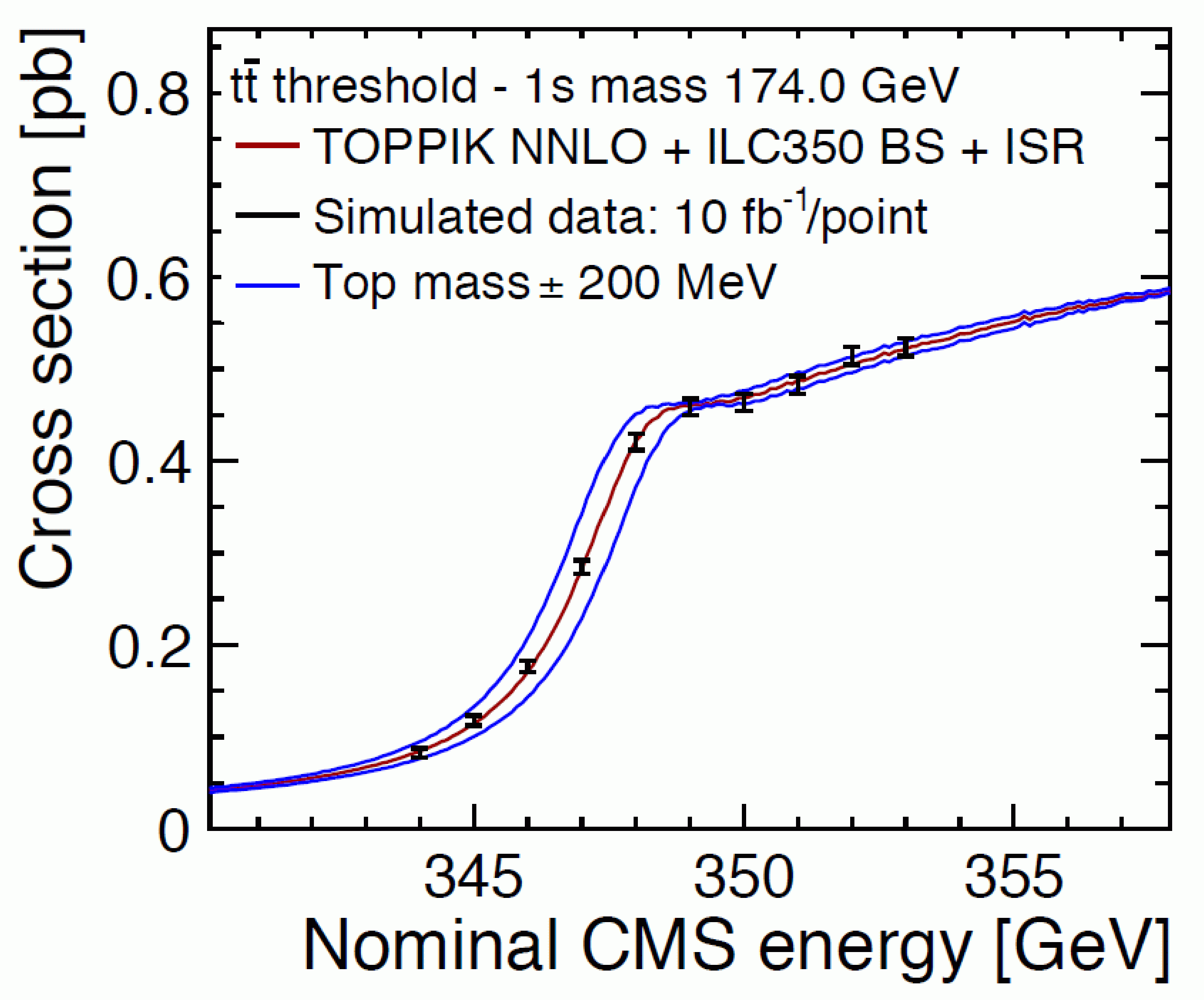
Measurement of m_t:

- At Tevatron, LHC:
  kinematic reconstruction, fit to invariant mass distribution
  $\Rightarrow$ "MC" mass, close to "pole" mass? $\delta m_t^{\rm exp,LHC} \lesssim 1$ GeV

- At e^+e^- colliders: unique possibility
  threshold scan $\Rightarrow$ threshold mass $\Rightarrow$ **SAFE!**
  transition to other mass definitions possible, $\delta m_t^{\rm exp,ILC} \lesssim 0.03$ GeV

At e^+e^- colliders: unique possibility [ILC TDR '13]

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



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

⇒ dominated by theory uncertainty!

3. Higgs observables

1. Higgs boson masses in BSM models
   $\to$ MSSM is prime exampe (and show case)

2. Higgs boson production cross sections
   (concentrate on H_{125}?!)

3. Higgs boson branching ratios
   (concentrate on H_{125}?!)

4. What is needed for tripple (or quartic??) Higgs coupling?

5. ???

The embarrasing situation:

The Higgs mass accuracy: experiment vs. theory:

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Experiment:

ATLAS: $M_h^{\text{exp}} = 125.36 \pm 0.37 \pm 0.18$ GeV

CMS: $M_h^{\text{exp}} = 125.03 \pm 0.27 \pm 0.15$ GeV

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to match the experimental accuracy!

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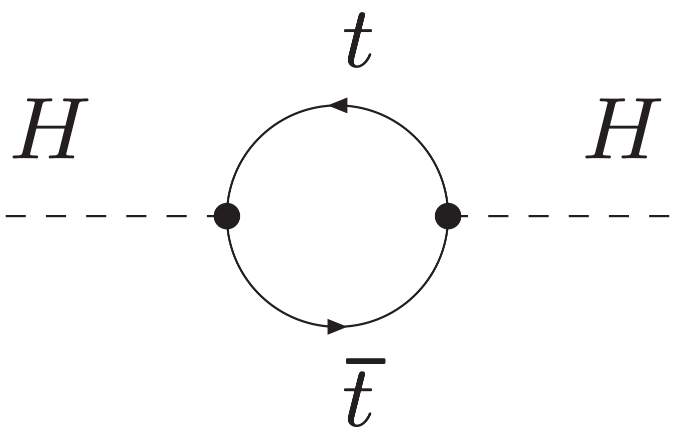
$\Rightarrow$ Theory prediction must be improved
to match the experimental accuracy!

$\Rightarrow$ dedicated working group has been formed to take care . . . (KUTS)

Parametric uncertainty from m_t:

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



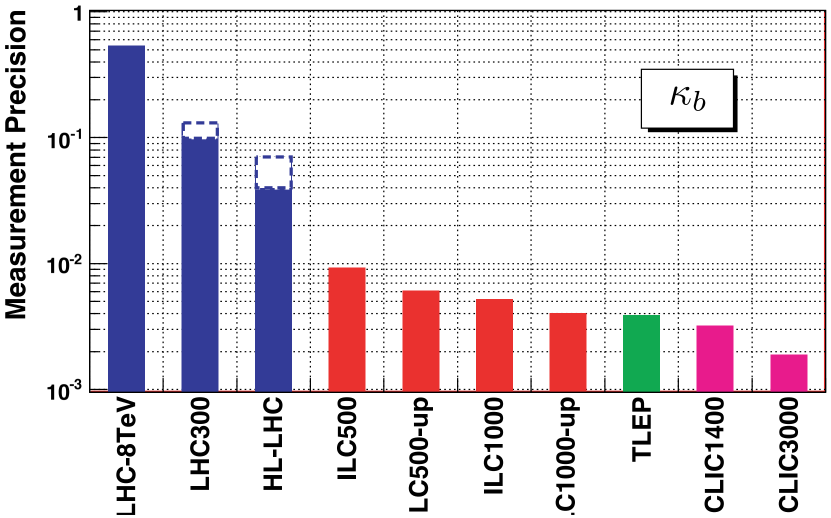
⇒ one-loop corrections $\Delta M_H^2 \sim G_\mu m_t^4$

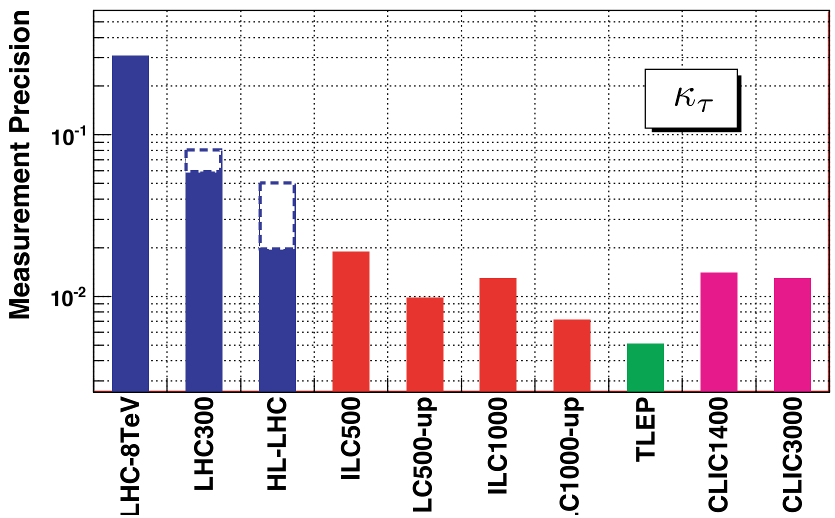
⇒ M_H depends sensitively on m_t in all models where M_H can be predicted (SM: M_H is free parameter)

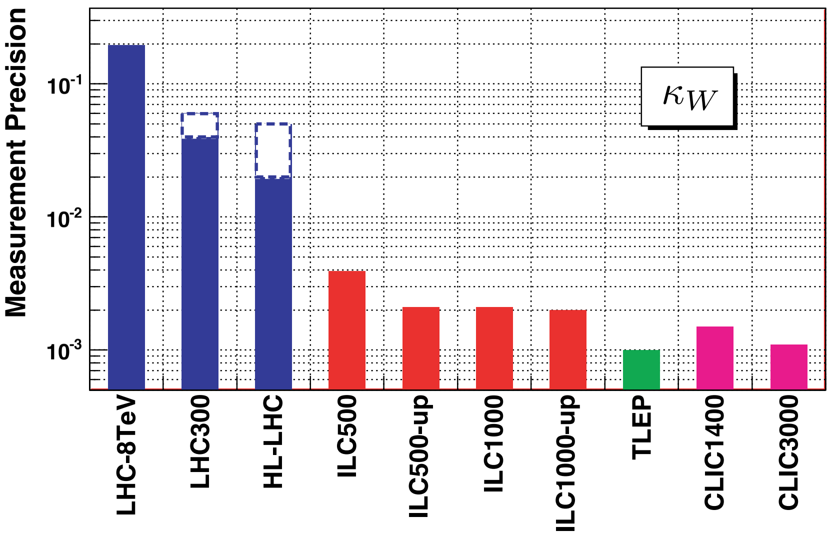
SUSY as an example: $\Delta m_t \approx \pm 1$ GeV ⇒ $\Delta M_h \approx \pm 1$ GeV ???

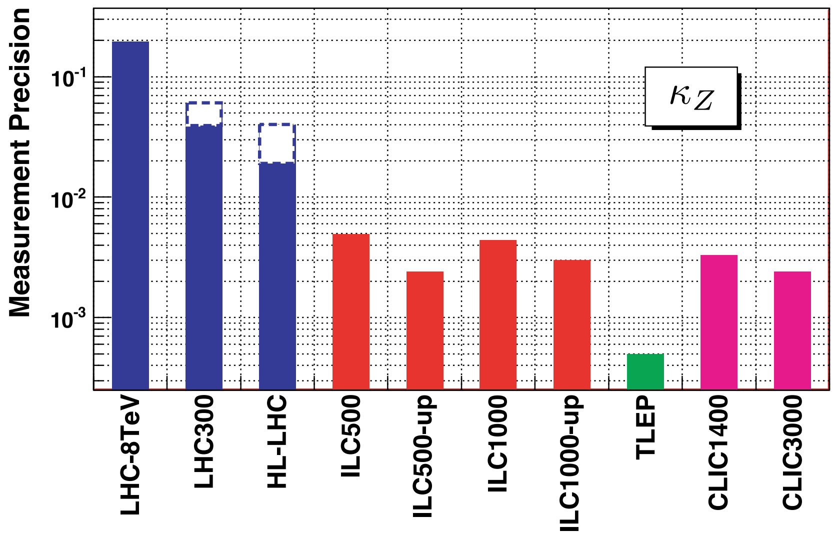
⇒ Precision Higgs physics needs e^+e^- precision of $\Delta m_t \sim 100$ MeV
⇒ $\Delta M_h \sim 100$ MeV cannot be surpassed (soon)

Future expectations for Higgs couplings: *[Snowmass Higgs Report '13]*









$\Rightarrow$ can the sub-percent/permille level be matched by theory?

Some specifics on Higgs coupling determination at e^+e^- collider:

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 (disentangle XS and BR!)

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

Cross section calculations:

$\Rightarrow$ SM cross section predictions at the 1% accuracy level
$\Rightarrow$ improvements necessary . . . full 2-loop calculations and more . . . ?!

Branching ratio calculations:

Current accuracy: at the "few per-cent" level (depending on channel)
$\Rightarrow$ improvements necessary . . . LHCHXWSG BR subgroup . . . ?!

4. Future Plans

Options for the evaluation of the parametric uncertainties:

Relevant SM parameters:

$$m_t, \quad m_b(?), \quad \alpha_s, \quad \alpha, \ldots ???$$

$\Rightarrow$ model dependent choice ?!

$\Rightarrow$ assessment of future accuracy ?!

Options for the evaluation of intrinsic uncertainties:

1. Take the known contribution at n-loop and $(n-1)$-loop and thus estimate the $n+1$-loop contribution:

$$\frac{(n+1)^{(\text{estimated})}}{n^{(\text{known})}} \approx \frac{n^{(\text{known})}}{(n-1)^{(\text{known})}}$$

   $\Rightarrow$ simplified example! Has to be done
   "coupling constant by coupling constant"

2. Variation of $\mu^{\overline{\text{DR}}}$ (QCD, EW!)

3. Compare different renormalizations

4. ???

Objective 1: maximum physics gain if TH uncertainties negligible

$\rightarrow$ (unrealistic) best-case scenario

$\Rightarrow$ hesitant to put too much energy into a precise analysis
better: rough assessment based on O2

Objective 2: Assessment of TH uncertainties and impact

$\rightarrow$ intrinsic uncertainties, parametric uncertainties

SM: "base line", lower limit on uncertainties

Assessment of status of uncertainties (v. 0.1): done for SM, MSSM
$\Rightarrow$ redo, refine, ...

$\Rightarrow$ identify people for assessment:
$\Rightarrow$ there are not too many ... (easy to identify, bad for the job)
$\Rightarrow$ definition of responsibles for work packages

Concerning the parametric uncertainties:

Experimental determination $\Rightarrow$ coordinate with other WGs!

How are TH uncertainties taken into account? (responsibility?)

Objective 3: New observables?

$\rightarrow$ higher statistics, clean environment, . . .

– coupling constants: α_s, α, $\Delta\alpha_{\text{had}}$, . . .
– anomalous couplings
– rare (SM particle) decays

$\Rightarrow$ definition of work packages

Who are the experts for experimental extraction? $\Rightarrow$ coordinate . . .

Experimental method? (who are the experts here?)
$\Rightarrow$ Assessment of theory uncertainties $\Rightarrow$ model dependent!

Expectation for BSM?

Objective 4: Assessment of man power

$\Rightarrow$ not too many in this field
When can calculation be done to achieve TH precision?
$\Rightarrow$ difficult to tell TH what to do
(Note: TH does not outperfrom itself as usually EXP does . . .)

5. Conclusions

- Experimental precision must be matched with theory precision!

- EWPO $\oplus$ Higgs can give valuable information about SM, BSM
  $\rightarrow$ only SM, MSSM "ready"
  Most relevant: M_W, $\sin^2\theta_{\text{eff}}$, (m_t), $\ldots \oplus M_h$, g_{hxx}, $\ldots$

- Intrinsinc and parametric uncertainties!
  $\Rightarrow$ Physics gain ? ("zero uncertainties" as limit)

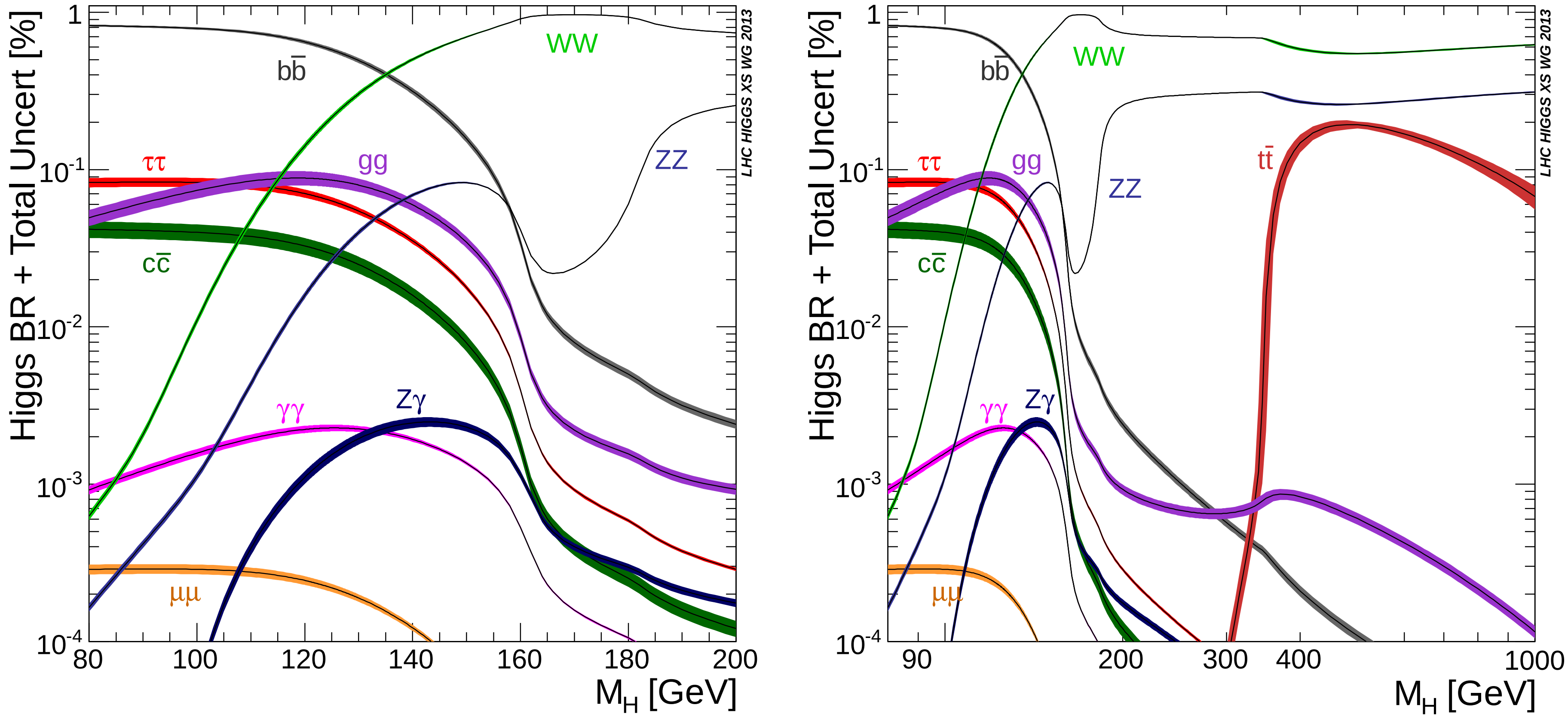
- Which model??
  SM! MSSM! SM + HS?! 2HDM?! NMSSM?! What more??
  $\Rightarrow$ identify the (few) people $\Rightarrow$ work packages

- – coordinate with "Model building and NP" (to avoid double work)
  – coordinate with LHCHXSWG SWG3 ?!
  – coordinate with KUTS (M_h) ?!

- Experimental extraction of observables and parameters:
  TH uncertainties taken into account?
  $\Rightarrow$ coordinate with EXP groups!

Back-up

Latest SM Higgs BR predictions:



Based on HDECAY and Prophecy4f:

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

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
$H \to b\bar{b}/c\bar{c}$	$\sim 0.1\%$	$\sim$ 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%

– 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

⇒ Strong improvement in $\sim$ 20 years possible, but . . .
. . . they have to be consistently implemented into codes!
⇒ 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% $+2.3\%$	$+3.3\%$ -3.2%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+2.0\%$ -2.0%
$H \to \tau^+\tau^-$	$2.59\cdot10^{-1}$	$+0.0\%$ $+0.0\%$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.1\%$ -0.1%	$+2.0\%$ -2.0%
$H \to \mu^+\mu^-$	$8.99\cdot10^{-4}$	$+0.0\%$ $+0.0\%$	$+0.0\%$ -0.0%	-0.1% -0.0%	$+0.0\%$ -0.1%	$+2.0\%$ -2.0%
$H \to c\bar{c}$	$1.19\cdot10^{-1}$	-7.1% $+7.0\%$	-0.1% -0.1%	$+6.2\%$ -6.1%	$+0.0\%$ -0.1%	$+2.0\%$ -2.0%
$H \to gg$	$3.57\cdot10^{-1}$	$+4.2\%$ -4.1%	-0.1% -0.1%	$+0.0\%$ -0.0%	-0.2% $+0.2\%$	$+3.0\%$ -3.0%
$H \to \gamma\gamma$	$9.59\cdot10^{-3}$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+1.0\%$ -1.0%
$H \to Z\gamma$	$6.84\cdot10^{-3}$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.1%	$+0.0\%$ -0.1%	$+5.0\%$ -5.0%
$H \to WW^*$	$9.73\cdot10^{-1}$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.5\%$ -0.5%
$H \to ZZ^*$	$1.22\cdot10^{-1}$	$+0.0\%$ -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

Future theory uncertainties?

Parametric uncertainties:

– largely driven by $\delta m_b \Rightarrow$ 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
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HOCHSCHULE
AACHEN
RWTH

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

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BR report – Alexander Mück – p.7/ 13