Phenomenology: Introduction and News

Sven Heinemeyer, IFCA (CSIC, Santander)

Pisa, 02/2015

Phenomenology studies

The phenomenological studies are coordinated by John Ellis and Chistophe Grojean, and are organized in five working groups:

- Working Group 1: QCD and γγ physics (joint exp/th). Convener: Peter Skands
- Working Group 2: Precision EW calculations. Convener: Sven Heinemeyer
- Working Group 3: Flavour physics (joint exp/th). Convener: Jernej Kamenik
- Working Group 4: Model building and new physics. Convener: Andreas Weiler
- Working Group 5: Global analysis, combination, complementarity. Convener: John Ellis

⇒ concentrate on WG 2 . . .

Experimental situation:

LHC/ILC/FCC-ee/... 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

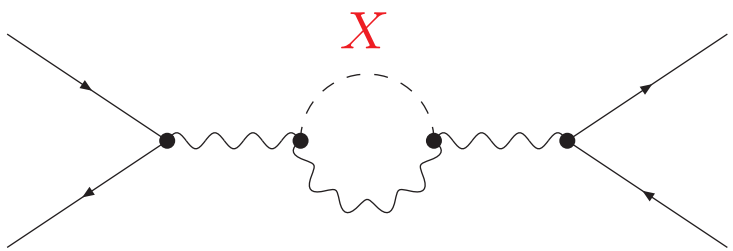
General idea: Precision Observables

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

WG 2: 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 ???
- ...

??? : still not clear who takes care

WG 2: Precision EW calculations (II)

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

- SM : obviously . . .
- MSSM : taken as showcase, gives approximations for missing corrections in other SUSY models

Models to be kept in mind, but without detailed investigation:

- SM + Higgs singlet
- 2HDM(s)
- NMSSM + other extensions
- . . .

⇒ coordination with "Model building and New Physics" subgroup!
⇒ check with LHCHXSWG SWG3 ?!

WG 2: Precision EW calculations (II)

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WG 2: Precision EW calculations (III)

Another model to be investigated:

SM + dim 6 Ops.

→ "extreme case" with all new physics scales heavy

– evaluate EWPO

– which dim 6 Ops. are relevant wrt. future precision?

⇒ more in Ayres' talk

General idea to match the experimental uncertainties:

Evaluate intrinsic uncertainties

Evaluate parametric uncertainties

Intrinsic and parametric uncertainties added linearly or in quadrature?

- 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 ??
  $\Rightarrow$ at least take consistency of varios calculations into account!

$\Rightarrow$ Observable by observable

Compare to anticipated experimental accuracy

$\Rightarrow$ Physics gain ?

("zero uncertainties" as limit ??)

Higgs observables

1. Higgs boson masses in BSM models
   $\rightarrow$ MSSM is prime exampe (and show case)
   $\Rightarrow$ KUTS will take care?!

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

3. Higgs boson branching ratios
   (concentrate on H_{125}?!)
   $\Rightarrow$ LHCHXSWG BR subgroup will take care?!

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

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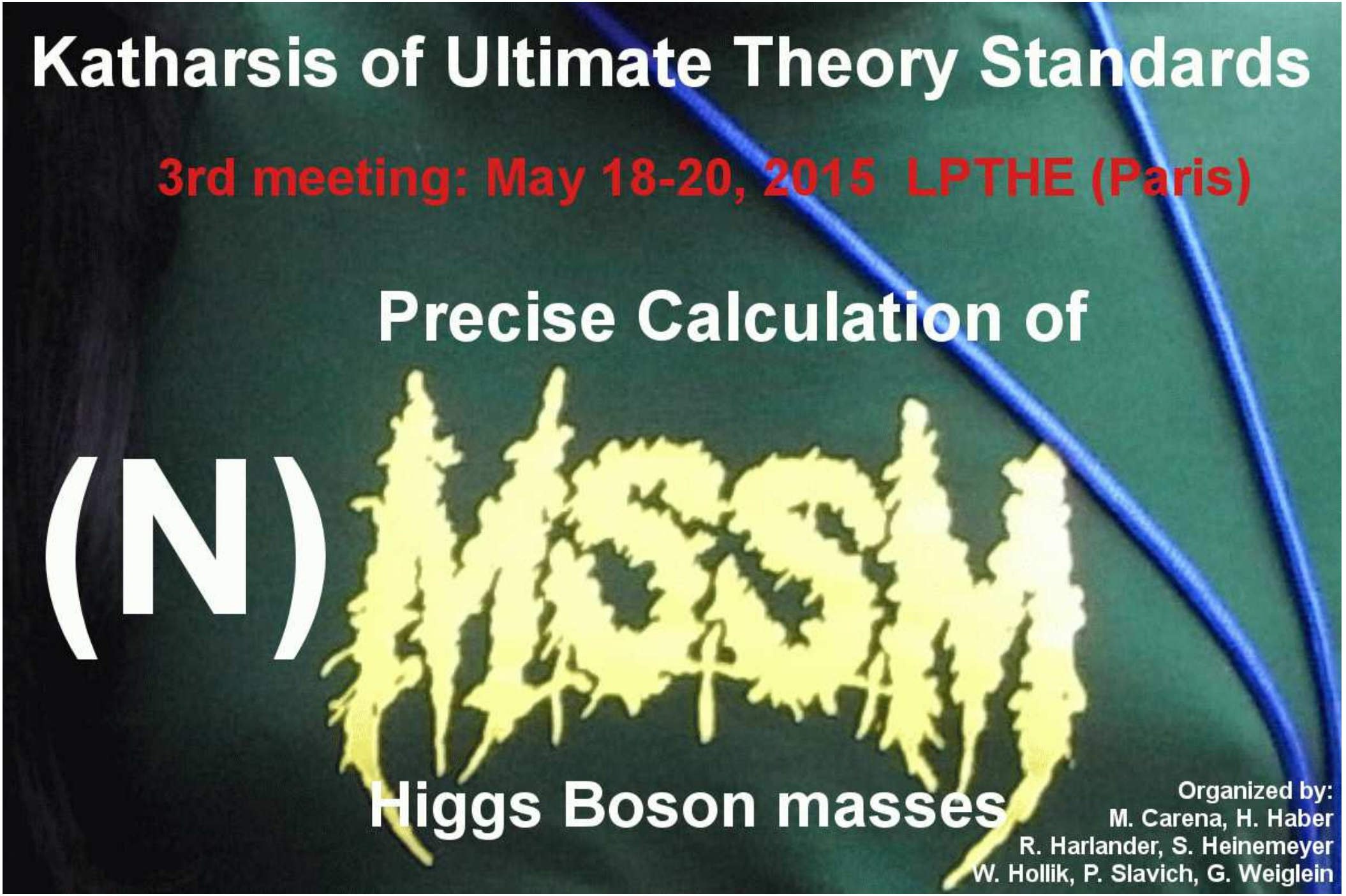
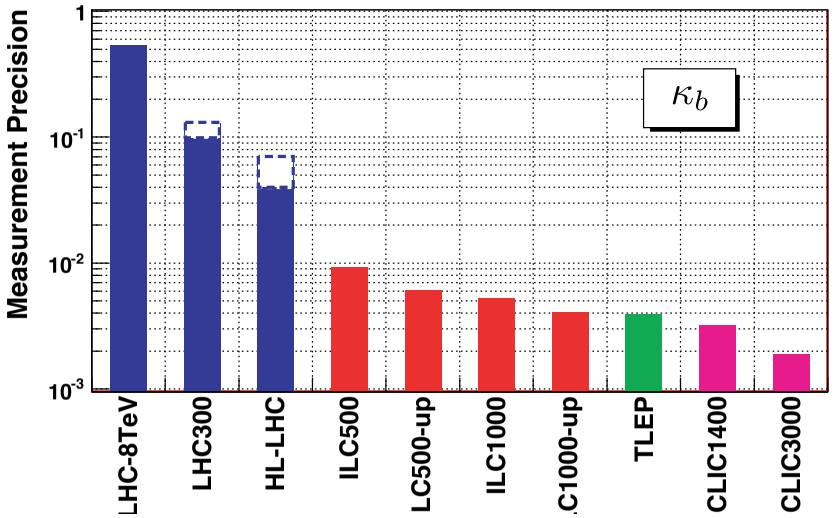
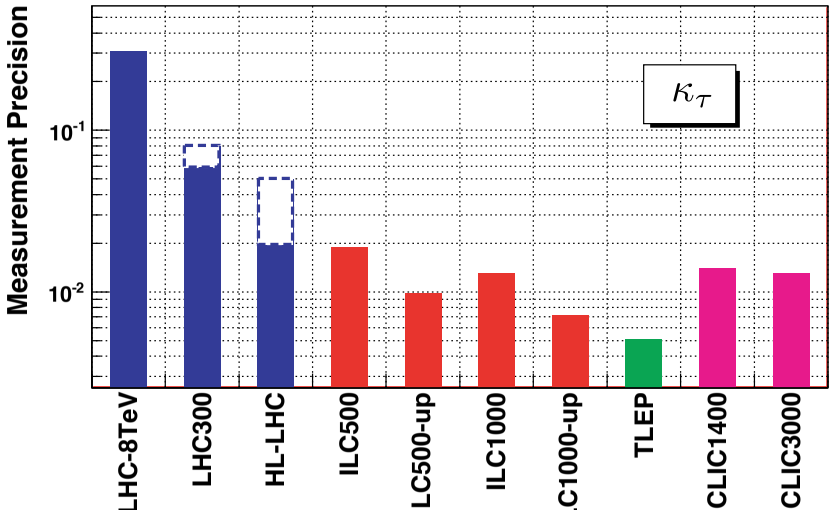
$\Rightarrow$ dedicated working group has been formed to take care . . . (KUTS)

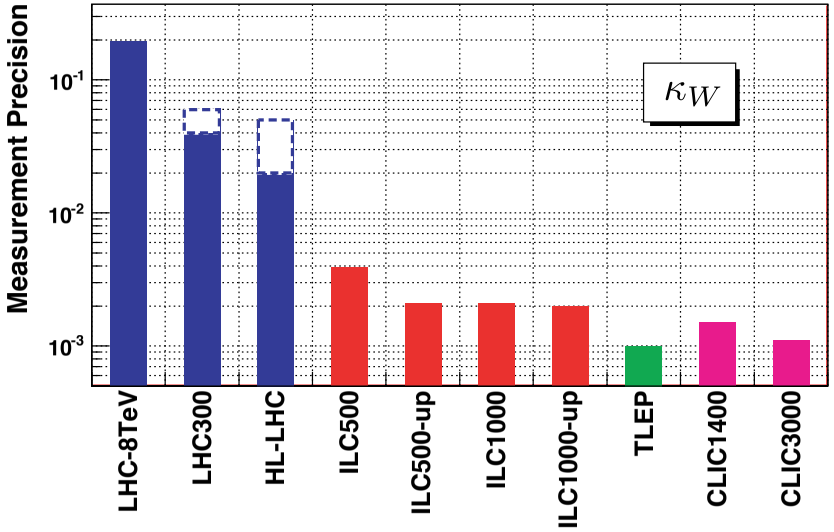

Katharsis of Ultimate Theory Standards
3rd meeting: May 18-20, 2015 LPTHE (Paris)
Precise Calculation of
(N)
Higgs Boson masses
Organized by:
M. Carena, H. Haber
R. Harlander, S. Heinemeyer
W. Hollik, P. Slavich, G. Weiglein

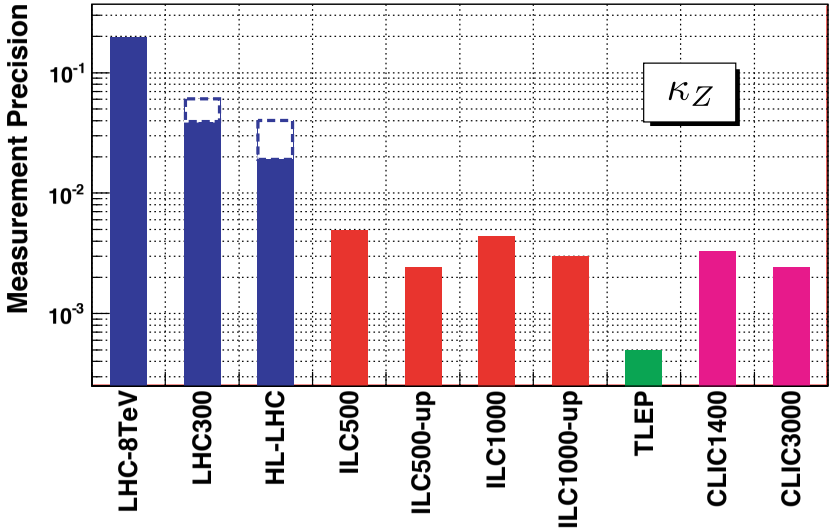
Future expectations for Higgs couplings:

[*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 . . . ?!

Future Plans for uncertainty evaluation (all observables):

⇒ more in Ayres' talk!

Options for the evaluation of the parametric uncertainties:

Relevant SM parameters:

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

⇒ model dependent choice ?!

⇒ 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. ???

Pheno session is going in the right direction! :-)

14:00 - 15:40 **Phenomenology**

Fitting the EW/Higgs/TGC precision measurements and sensitivity to new physics, with past and prospective data, in effective field theory and in specific new physics models.

- 14:00 **Introduction and news** *15'*
  Speaker: Sven Heinemeyer
- 14:20 **About projected theory uncertainties** *15'*
  Speaker: Aryes Freitas
- 14:40 **Precision observables in the Standard Model: a reexamination** *25'*
  Speaker: Giuseppe Degrassi (ROMA3)
- 15:10 **EFT analysis of Higgs and EW data** *25'*
  Speaker: Yotam Soreq

15:40 - 16:10 Coffee break

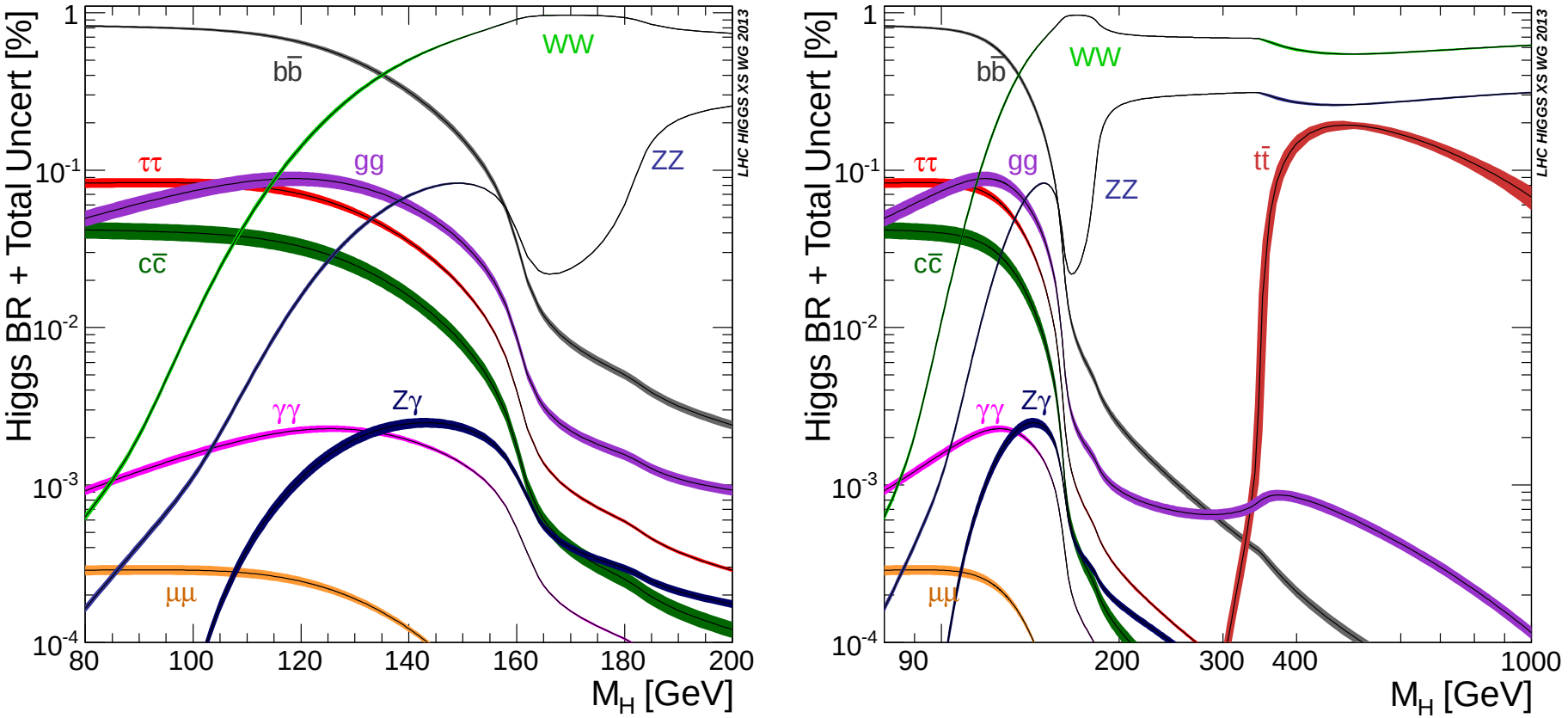
16:10 - 18:00 **Phenomenology**

Fitting the EW/Higgs/TGC precision measurements and sensitivity to new physics, with past and prospective data, in effective field theory and in specific new physics models.

- 16:10 **1-loop EW constraints on composite Higgs** *15'*
  Speaker: Matteo Salvarezza
- 16:30 **Direct and indirect constraints on composite Higgs models** *25'*
  Speaker: Oleksii Matsedonskyi (P)
- 17:00 **Exclusive Higgs decays and light quark Yukawa couplings** *25'*
  Speaker: Yotam Soreq
- 17:30 **Sterile Neutrinos at Future Lepton Colliders** *25'*
  Speaker: Oliver Fischer

Back-up

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	$\pm$0.002(90% CL)	
m_c	1.42 GeV	$\pm$0.03 GeV($2\,\sigma$)	1.28 GeV
m_b	4.49 GeV	$\pm$0.06 GeV($2\,\sigma$)	4.16 GeV
m_t	172.5 GeV	$\pm$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: UPDATE: now included in Hdecay

⇒ re-analysis of intrinsic uncertainties by LHCHXSWG-BR!

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

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

$\Rightarrow$ used for ATLAS and CMS evaluations

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:

$H \to b\bar{b}, H \to c\bar{c}$: UPDATE: EW corrections are included
(were known at 1L for long time)

$H \to \tau^+\tau^-, H \to \mu^+\mu^-$: UPDATE: EW corrections are included
(were known at 1L for long time)

$H \to gg$: improvement difficult

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

$H \to Z\gamma$: EW corrections could help (also known!) ...

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

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

RHEINISCH-
WESTFÄLISCHE
TECHNISCHE
HOCHSCHULE
AACHEN

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