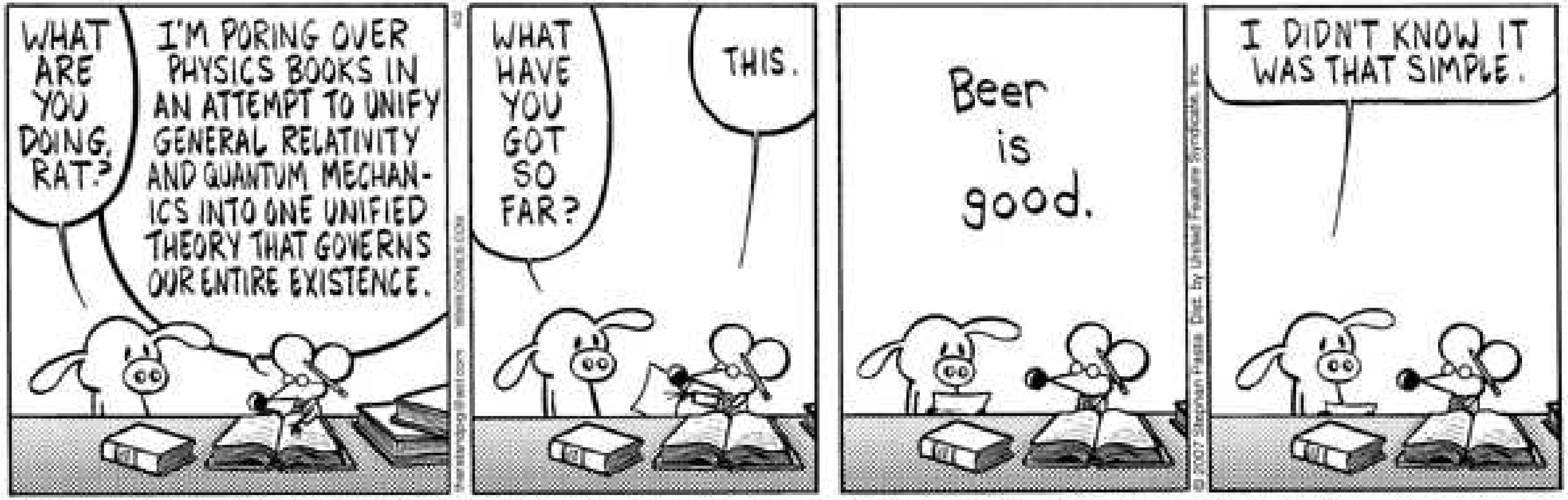

WHAT ARE YOU DOING, RAT?
I'M PORING OVER PHYSICS BOOKS IN AN ATTEMPT TO UNIFY GENERAL RELATIVITY AND QUANTUM MECHANICS INTO ONE UNIFIED THEORY THAT GOVERNS OUR ENTIRE EXISTENCE.
WHAT HAVE YOU GOT SO FAR?
THIS.
Beer is good.
I DIDN'T KNOW IT WAS THAT SIMPLE.
© 2007 Stephan Pastis Dist. by United Feature Syndicate, Inc.

Precision EW Calculations

Sven Heinemeyer, IFT/IFCA (CSIC, Madrid/Santander)

Rome, 04/2016

1. Introduction

2. Electroweak Precision Observables

3. Higgs Observables

4. Conclusions

1. Introduction

Experimental situation:

LHC/ILC/FCC-ee/CEPC/. . . will provide (high!) accuracy measurements!

1. Introduction

Experimental situation:

LHC/ILC/FCC-ee/CEPC/. . . will provide (high!) accuracy measurements!

Theory situation:

measured observables have to be compared with theoretical predictions
(in various models: SM, MSSM, . . .)

1. Introduction

Experimental situation:

LHC/ILC/FCC-ee/CEPC/. . . will provide (high!) accuracy measurements!

Theory situation:

measured observables have to be compared with theoretical predictions
(in various models: SM, MSSM, . . .)

Measured data is only meaningful if it is matched with theoretical calculations (masses, couplings) at the same level of accuracy

1. Introduction

Experimental situation:

LHC/ILC/FCC-ee/CEPC/. . . will provide (high!) accuracy measurements!

Theory situation:

measured observables have to be compared with theoretical predictions
(in various models: SM, MSSM, . . .)

Measured data is only meaningful if it is matched with
theoretical calculations (masses, couplings) at the same level of accuracy

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

FCC-ee: Phenomenology working groups:

The FCC-ee design study

Since 12/02/2014, the TLEP design study is part of the FCC design study as FCC-ee

Home | About FCC-ee and TLEP | Organization | Archive | Events | The FCCs | Contact/Join us

Home » Organization » Phenomenology studies

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: Ayres Freitas, Sven Heinemeyer
- Working Group 3: Flavour physics (joint exp/th). Convener: Jernej Kamenik
- Working Group 4: Model building and new physics. Convener: Matthew Philip McCullough, Andreas Weiler
- Working Group 5: Global analysis, combination, complementarity. Convener: John Ellis

⇒ work done for WG2 :-)

Where we need theory prediction:

1. Prediction of the measured quantity
   Example: M_W
   $\rightarrow$ at the same level or better as the experimental precision

2. Prediction of the measured process to extract the quantity
   Example: $e^+e^- \to W^+W^-$
   $\rightarrow$ better than then "pure" experimental precision

Where we need theory prediction:

1. Prediction of the measured quantity
   Example: M_W
   $\to$ at the same level or better as the experimental precision

2. Prediction of the measured process to extract the quantity
   Example: $e^+e^- \to W^+W^-$
   $\to$ better than then “pure” experimental precision

Two types of theory uncertainties:

1. intrinsic: missing higher orders

2. parametric: uncertainty due to exp. uncertainty in SM input parameters
   Example: m_t, m_b, α_s, $\Delta\alpha_{\text{had}}$, ...

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. ???

My personal time scale wish/estimate for "our future":

1. exploit the LHC

2. construct the ILC as quickly as possible in Japan

3. after LHC construct the FCC at CERN
   depending on physics outcome of LHC/ILC:
   decide whether to start with FCC-ee or FCC-hh

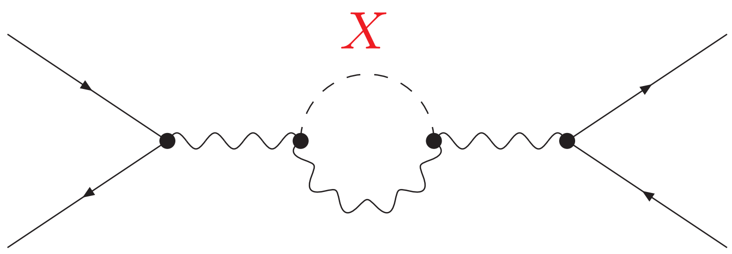
2. Electroweak Precision Observables

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

Precision observables in the SM and the MSSM

M_W, $\sin^2\theta_{\text{eff}}$, M_h, $(g-2)_\mu$, b physics, . . .

A) Theoretical prediction for M_W in terms

of $M_Z, \alpha, G_\mu, \Delta r$:

$$M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{\pi\,\alpha}{\sqrt{2}\,G_\mu}(1 + \Delta r)$$

$\Updownarrow$

loop corrections

Evaluate Δr from μ decay $\Rightarrow M_W$

One-loop result for M_W in the SM:

[A. Sirlin '80] , [W. Marciano, A. Sirlin '80]

$$\Delta r_{1-\text{loop}} = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + \Delta r_{\text{rem}}(M_H)$$

$$\sim \log\frac{M_Z}{m_f} \qquad \sim m_t^2 \qquad \log(M_H/M_W)$$

$$\sim 6\% \qquad \sim 3.3\% \qquad \sim 1\%$$

Precision observables in the SM and the MSSM

M_W, $\sin^2\theta_{\rm eff}$, M_h, $(g-2)_\mu$, b physics, . . .

A) Theoretical prediction for M_W in terms

of $M_Z, \alpha, G_\mu, \Delta r$:

$$M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{\pi\,\alpha}{\sqrt{2}\,G_\mu}\,(1 + \Delta r)$$

$\Updownarrow$

loop corrections

B) Effective mixing angle:

$$\sin^2\theta_{\rm eff} = \frac{1}{4\,|Q_f|}\left(1 - \frac{{\rm Re}\,g_V^f}{{\rm Re}\,g_A^f}\right)$$

Higher order contributions:

$$g_V^f \to g_V^f + \Delta g_V^f, \quad g_A^f \to g_A^f + \Delta g_A^f$$

Corrections to M_W, $\sin^2\theta_{\rm eff}$ → approximation via the ρ-parameter:

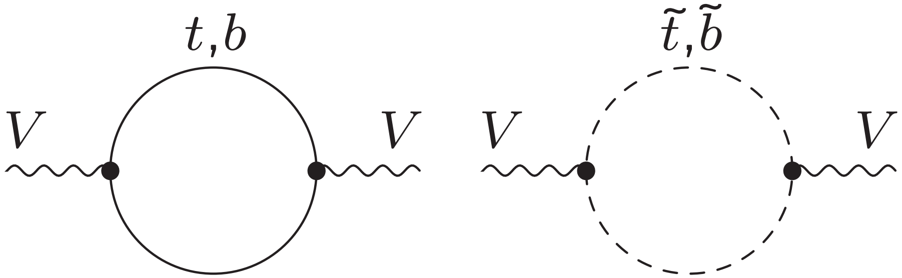
ρ measures the relative strength between
neutral current interaction and charged current interaction

$$\rho = \frac{1}{1-\Delta\rho} \qquad\qquad \Delta\rho = \frac{\Sigma_Z(0)}{M_Z^2} - \frac{\Sigma_W(0)}{M_W^2}$$

(leading, process independent terms)

$\Delta\rho$ gives the main contribution to EW observables:

$$\Delta M_W \approx \frac{M_W}{2}\frac{c_{\rm W}^2}{c_{\rm W}^2 - s_{\rm W}^2}\Delta\rho, \qquad\qquad \Delta\sin^2\theta_W^{\rm eff} \approx -\frac{c_{\rm W}^2 s_{\rm W}^2}{c_{\rm W}^2 - s_{\rm W}^2}\Delta\rho$$



$\Delta\rho^{\rm SUSY}$ from $\tilde{t}/\tilde{b}$ loops > 0 $\quad\Rightarrow M_W^{\rm SUSY} \gtrsim M_W^{\rm SM}$, $\sin^2\theta_{\rm eff}^{\rm SUSY} \lesssim \sin^2\theta_{\rm eff}^{\rm SM}$

$\Delta\rho^{\text{SUSY}}$ from $\tilde{t}/\tilde{b}$ loops > 0 $\Rightarrow M_W^{\text{SUSY}} \gtrsim M_W^{\text{SM}}$, $\sin^2\theta_{\text{eff}}^{\text{SUSY}} \lesssim \sin^2\theta_{\text{eff}}^{\text{SM}}$

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!

The W boson mass

Experimental accuracy:

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

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

$\delta M_W^{\text{exp,ILC(FCC-ee)}} \lesssim 3\,(1)$ MeV (from thr. scan) $\Leftarrow$ TU neglected

Theoretical accuracies:

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

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

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

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

parametric future: $\delta m_t^{\text{fut}} = 0.05$ GeV, $\delta(\Delta\alpha_{\text{had}})^{\text{fut}} = 5 \times 10^{-5}$, $\delta M_Z^{\text{ILC/FCC-ee}} = 1/0.1$ MeV

$\Delta M_W^{\text{para,fut},m_t} = 0.5$ MeV, $\Delta M_W^{\text{para,fut},\Delta\alpha_{\text{had}}} = 1$ MeV, $\Delta M_W^{\text{para,fut},M_Z} = 0.2/0.02$ MeV

M_W from threshold scan:

Not only $e^+e^- \to W^{(*)}W^{(*)}$, but $e^+e^- \to WW \to$ 4f needed

Current status:

full one-loop for $2 \to 4$ process

[*A. Denner, S. Dittmaier, M. Roth, D. Wackeroth '99-'02*]

$\Rightarrow$ extraction of M_W at the level of ~ 6 MeV

Most recent improvement:

leading 2L corrections from EFT

[*Actis, Beneke, Falgari, Schwinn '08*]

$\Rightarrow$ impact on M_W at the level of ~ 3 MeV

$\Rightarrow$ full 2L for $2 \to 4$ process not foreseeable

Potentially possible:

2L resummed higher-order terms for $e^+e^- \to WW$ and $W \to ff'$

$\Rightarrow$ extraction of M_W at ~ 1 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

$$\delta\sin^2\theta_{\rm eff}^{\rm exp,ILC(FCC-ee)} = 13\,(6) \times 10^{-6} \qquad \Leftarrow \text{TU neglected}$$

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

$$\delta\sin^2\theta_{\rm eff}^{{\rm para},m_t} = 30, \quad \delta\sin^2\theta_{\rm eff}^{{\rm para},\Delta\alpha_{\rm had}} = 36, \quad \delta\sin^2\theta_{\rm eff}^{{\rm para},M_Z} = 14$$

parametric future: $\delta m_t^{\rm fut} = 0.05$ GeV, $\delta(\Delta\alpha_{\rm had})^{\rm fut} = 5 \times 10^{-5}$, $\delta M_Z^{\rm ILC/FCC-ee} = 1/0.1$ MeV

$$\Delta\sin^2\theta_{\rm eff}^{{\rm para,fut},m_t} = 2, \ \Delta\sin^2\theta_{\rm eff}^{{\rm para,fut},\Delta\alpha_{\rm had}} = 18, \ \Delta\sin^2\theta_{\rm eff}^{{\rm para,fut},M_Z} = 6.5/0.7$$

SM input: 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?

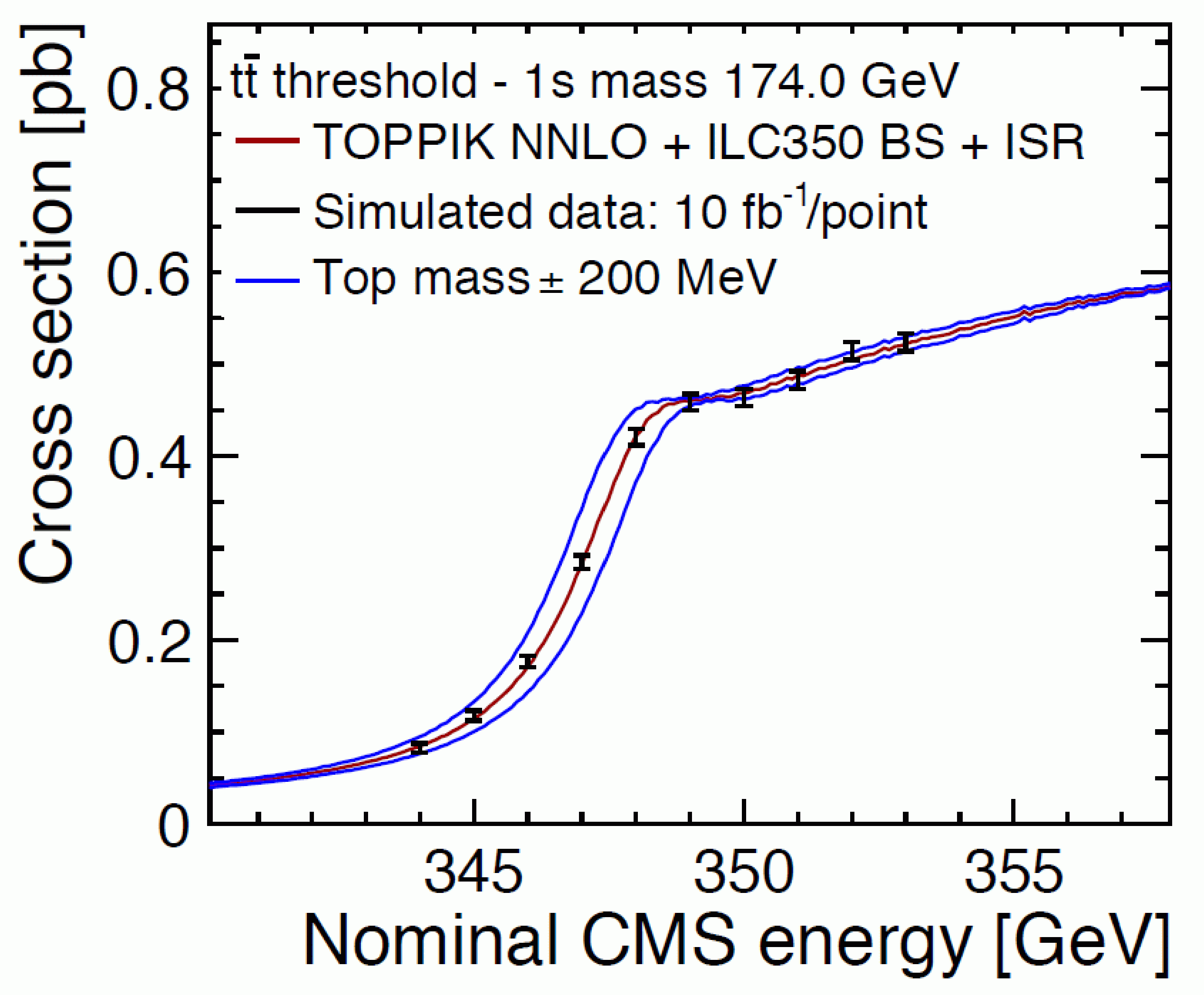
Top pole mass is not IR safe (affected by large long-distance contributions), cannot be determined to better than $\mathcal{O}(\Lambda_{\rm QCD})$

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, $\delta m_t^{\rm exp,ILC/FCC-ee} \lesssim 0.03$ GeV

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

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

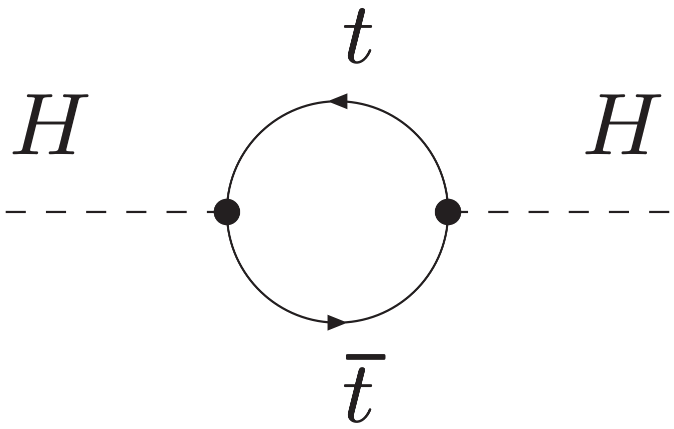


transition to other mass definitions possible ⇒ $\delta m_t^{\text{exp+theo}} \lesssim 0.1$ GeV

⇒ dominated by theory uncertainty! ⇒ ILC and FCC-ee so far similar!

Top/Higgs physics in BSM:

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



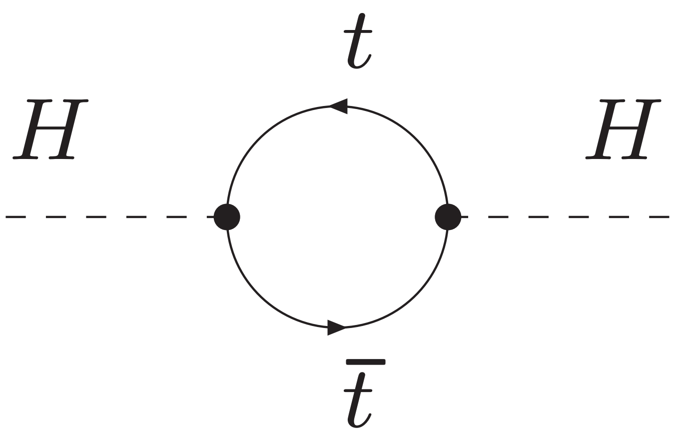
$\Rightarrow$ one-loop corrections $\Delta M_H^2 \sim G_\mu m_t^4$

$\Rightarrow$ 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

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

$\Rightarrow$ Precision Higgs physics needs ILC/FCC-ee precision top physics

SM input: $\Delta\alpha_{\text{had}}$ $\Rightarrow$ could be limiting factor!

From $e^+e^- \to$ had. using dispersion relation

today: $\delta(\Delta\alpha_{\text{had}}) \sim 10^{-4}$
possible improvement in the future: $\delta(\Delta\alpha_{\text{had}}) \sim 5 \times 10^{-5}$

Direct determination at FCC-ee from $e^+e^- \to f\bar{f}$ off the Z peak

[*P. Janot '15*]
possible improvement in the future: $\delta(\Delta\alpha_{\text{had}}) \sim 2 \times 10^{-5} \Rightarrow$ TU neglected

Calculation of $e^+e^- \to f\bar{f}$ needed at 3-loop and beyond: [*A. Freitas '16*]
current techniques (2L/3L): corrections of $\sim 10^{-3}$
new calculation methods (2L/3L): corrections of $\sim 10^{-4}$
unknown methods 3L: $\lesssim 10^{-5}$
unknown methods 4L: $\sim 10^{-5}$
(+ higher-orders in real photon emission)
$\Rightarrow$ improvement unclear

Theory and parametric uncertainties

4/11

	ILC	FCC-ee	perturb. error with 3-loop†	Param. error ILC*	Param. error FCC-ee**
M_W [MeV]	3–5	~ 1	1	2.6	1
Γ_Z [MeV]	~ 1	~ 0.1	$\lesssim 0.2$	0.5	0.06
R_b [10^{-5}]	15	$\lesssim 5$	5–10	< 1	< 1
$\sin^2\theta^\ell_{\rm eff}$ [10^{-5}]	1.3	0.6	1.5	2	2

† **Theory scenario:** $\mathcal{O}(\alpha\alpha_s^2)$, $\mathcal{O}(N_f\alpha^2\alpha_s)$, $\mathcal{O}(N_f^2\alpha^2\alpha_s)$

(N_f^n = at least n closed fermion loops)

Parametric inputs:

* **ILC:** $\delta m_t = 100$ MeV, $\delta\alpha_s = 0.001$, $\delta M_Z = 2.1$ MeV

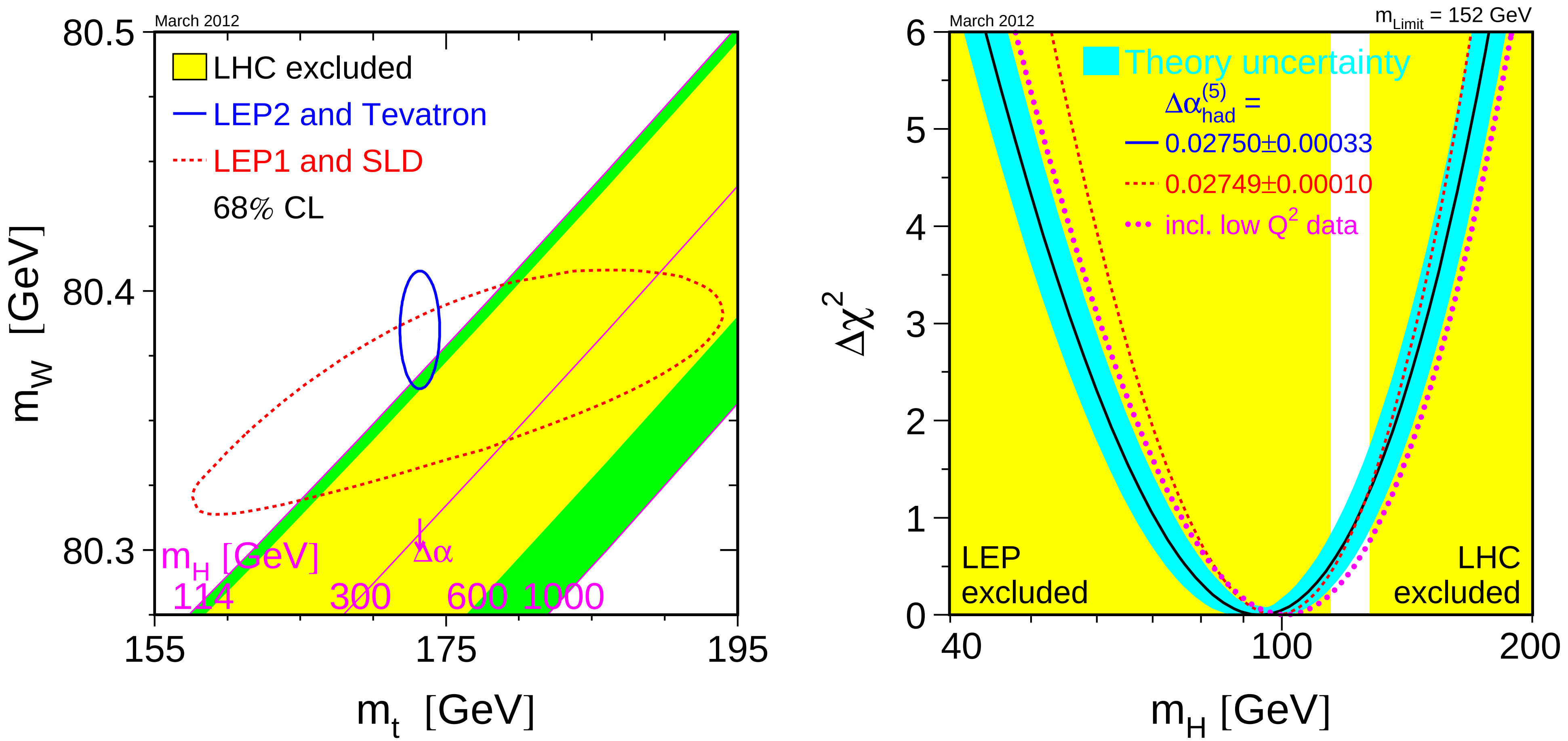
****FCC-ee:** $\delta m_t = 50$ MeV, $\delta\alpha_s = 0.0001$, $\delta M_Z = 0.1$ MeV

also: $\delta(\Delta\alpha) \sim 5 \times 10^{-5}$

Note: ILC parametric somewhat pessimistic

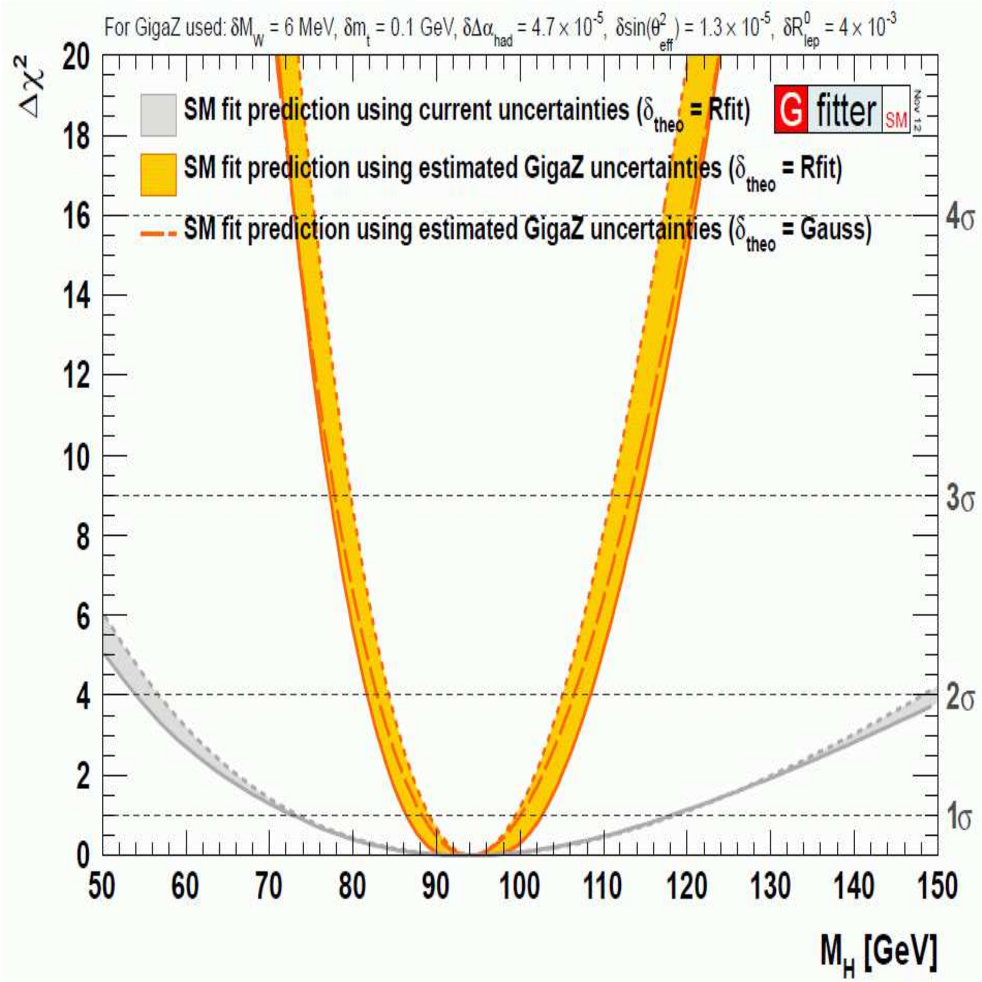
Precision Tests of the SM (and beyond)

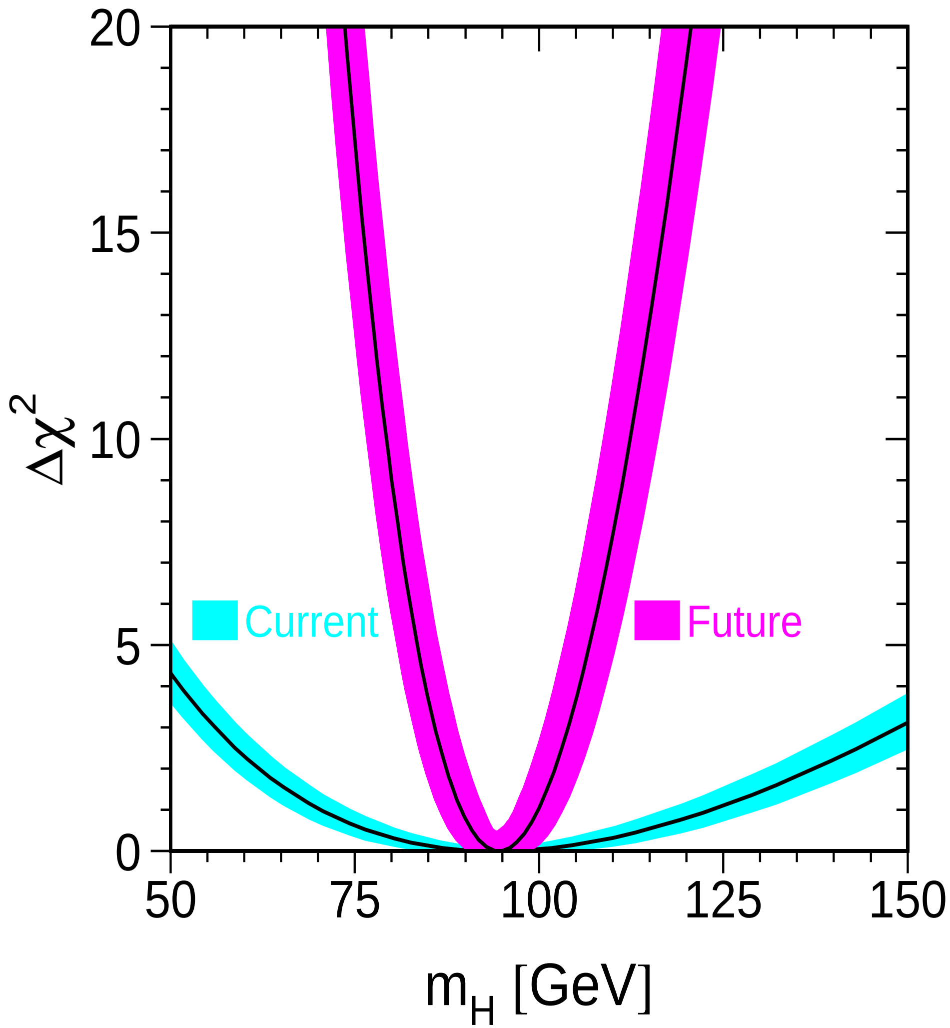
⇒ indirect prediction of the Higgs mass in the SM *[LEPEWWG '12]*



⇒ fits with today's precision

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





$\Rightarrow \delta M_H^{\rm ind} \lesssim 6$ GeV $\Leftarrow$ no FCC-ee analysis done so far

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

3. Higgs observables: Higgs couplings

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) various versions are proposed:
with and without additional theory assumptions

– no additional theory assumptions:

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

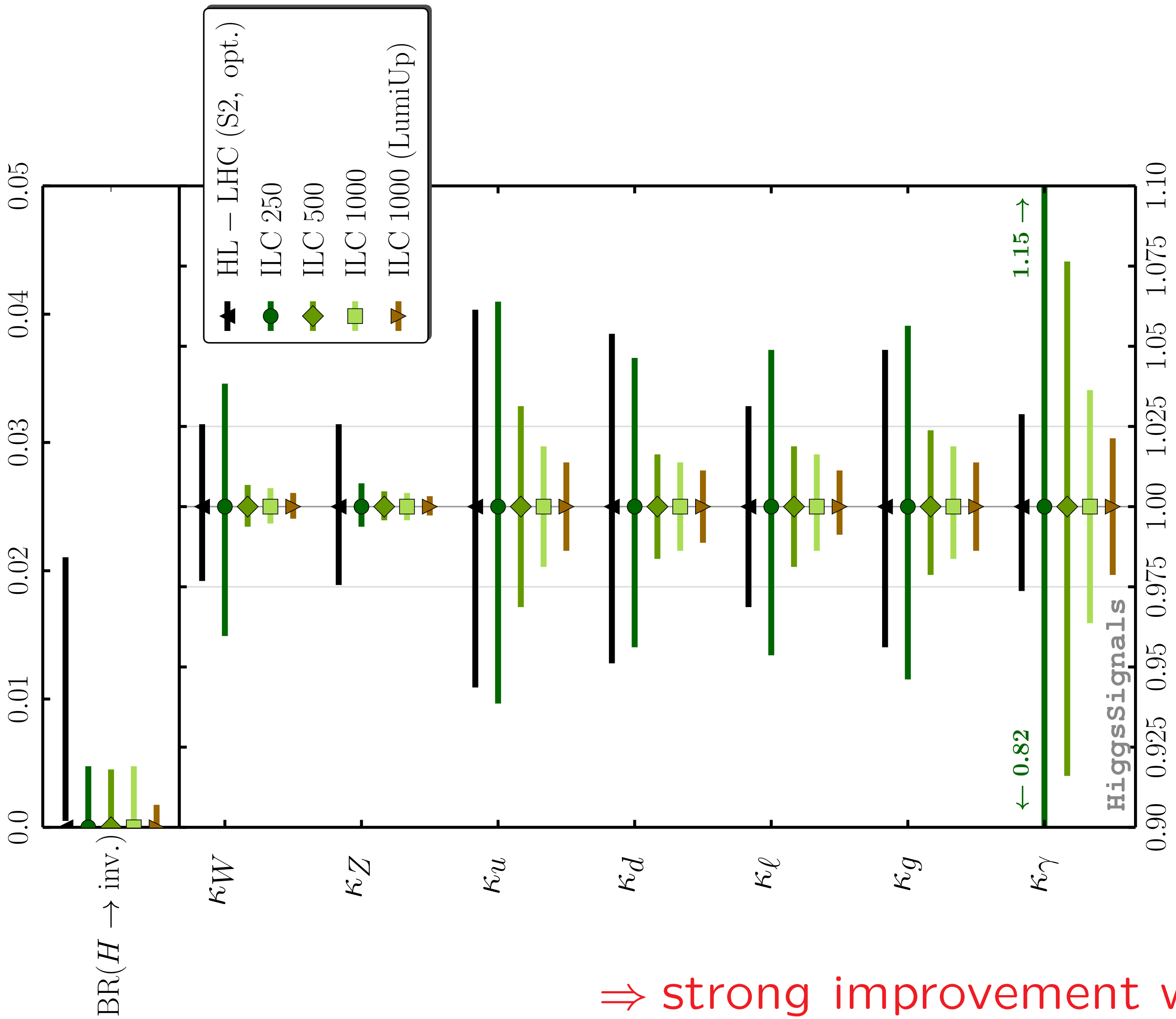
– additional theory assumptions (on $\Gamma_{H,\text{tot}}$ or $\kappa_{W,Z}$ or $H \to$ NP)

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

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

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

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

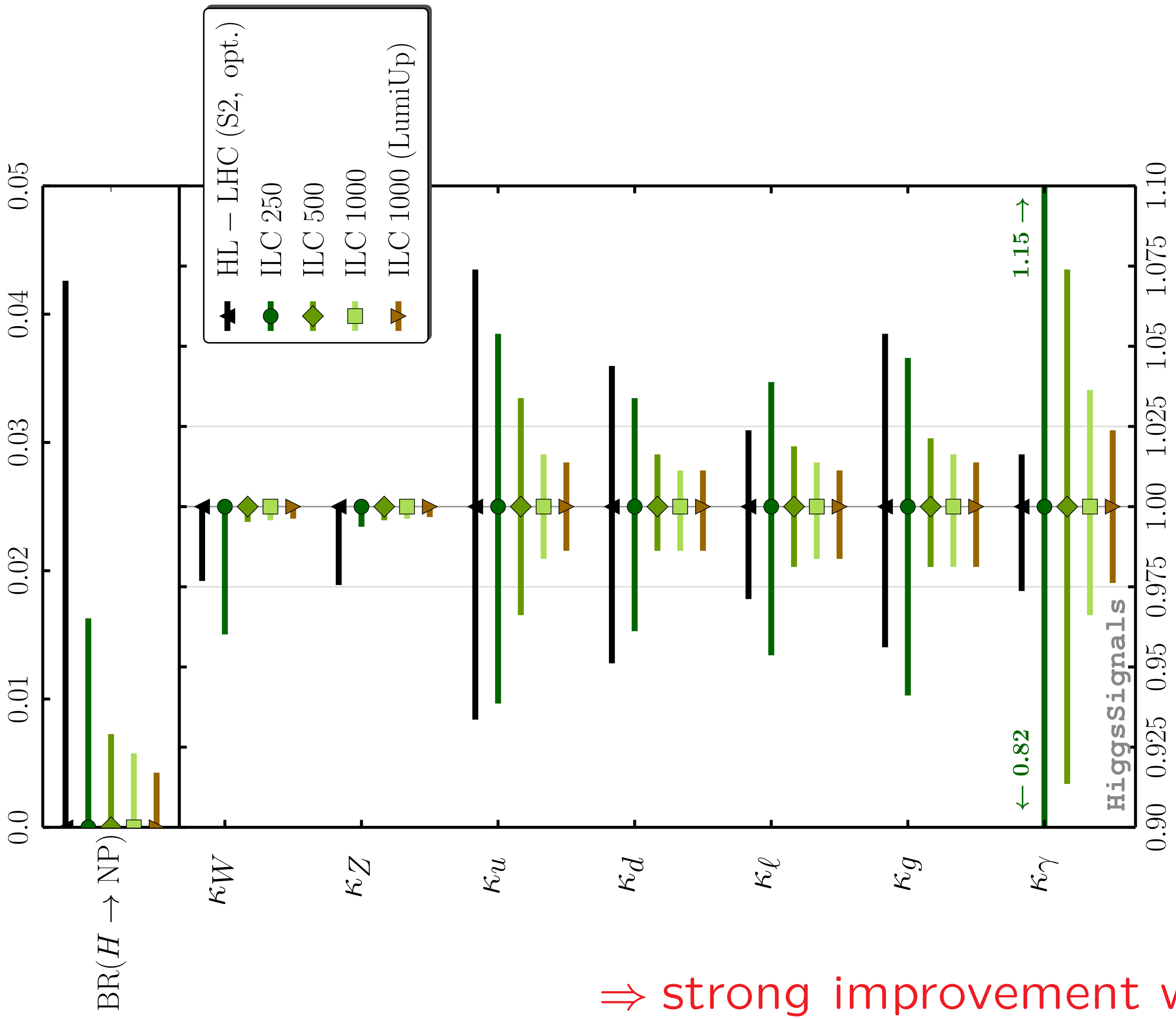


⇒ strong improvement with the ILC

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

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

assumption: $\kappa_V \leq 1$

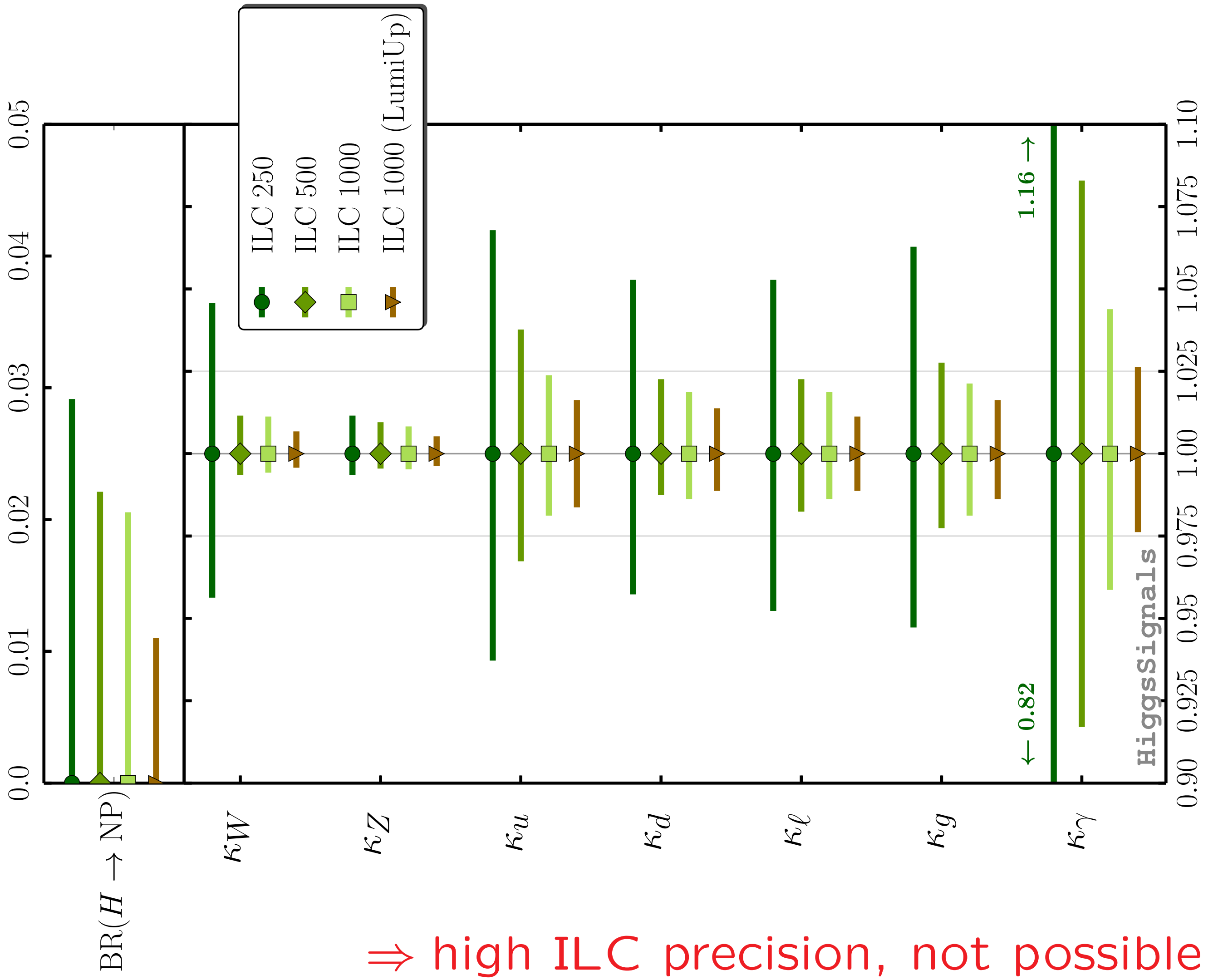


⇒ strong improvement with the ILC

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

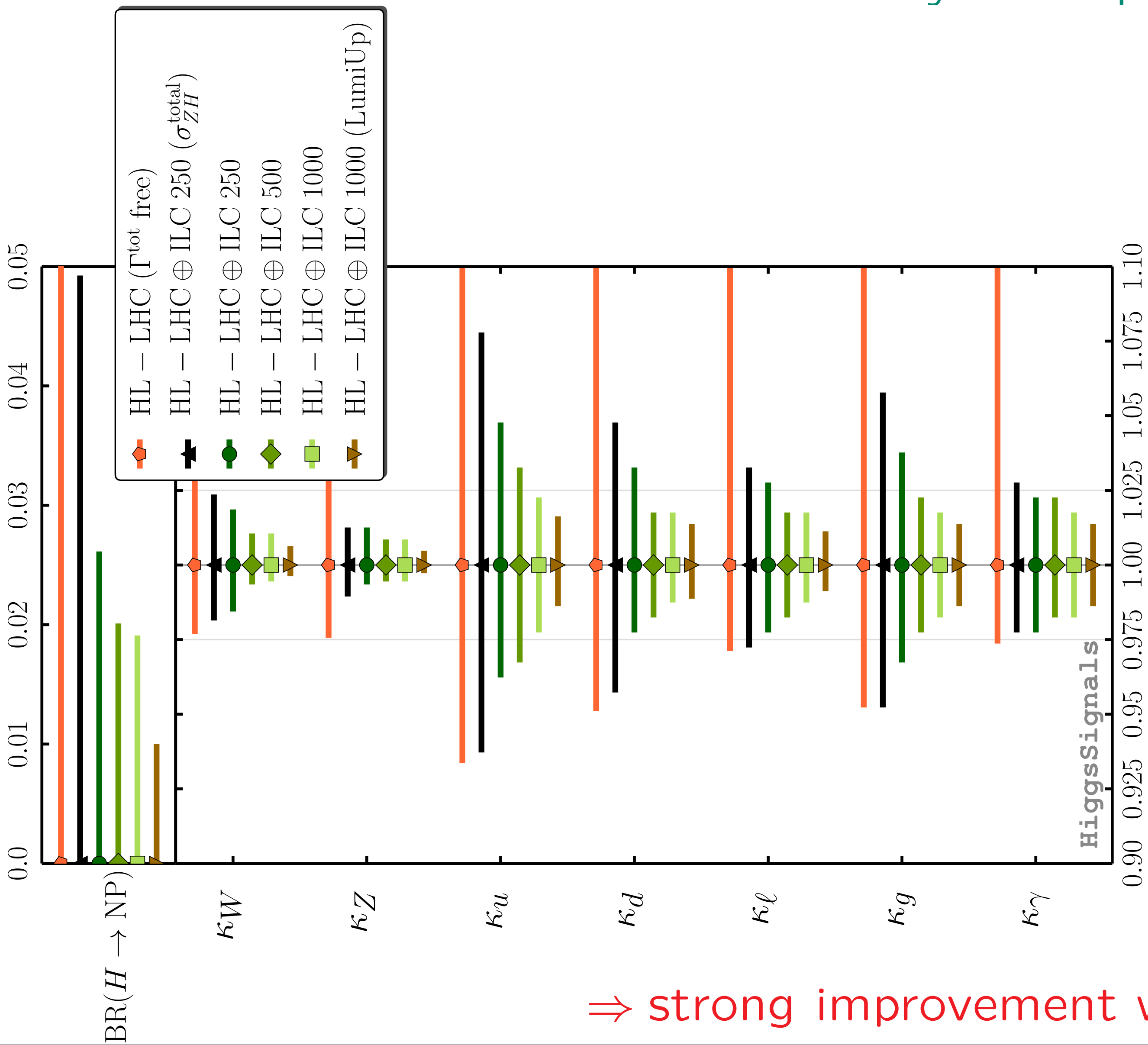


⇒ high ILC precision, not possible at the LHC

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

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

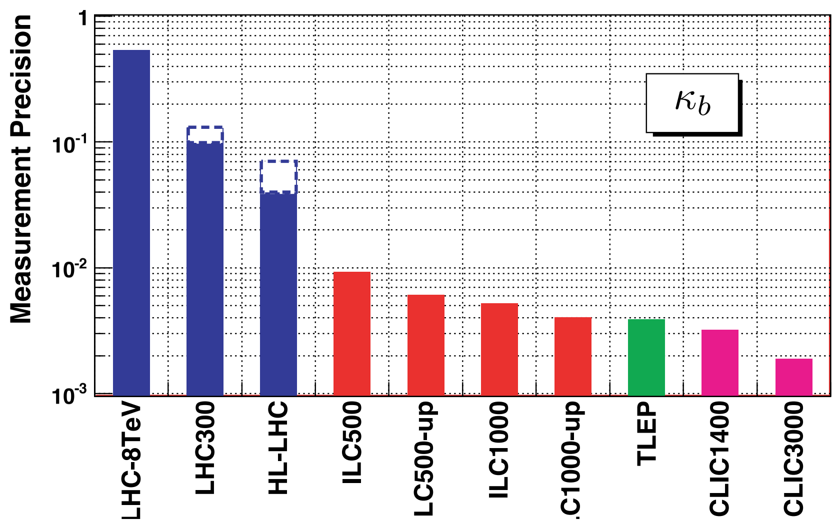
no theory assumptions, full fit

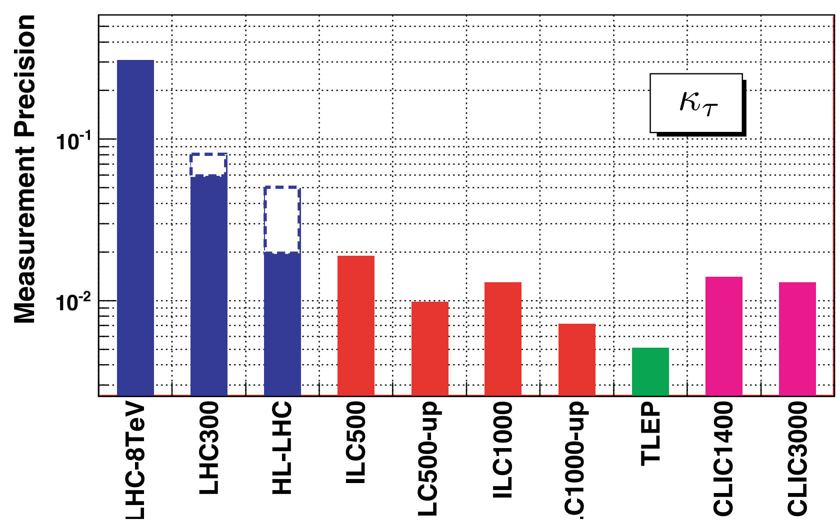


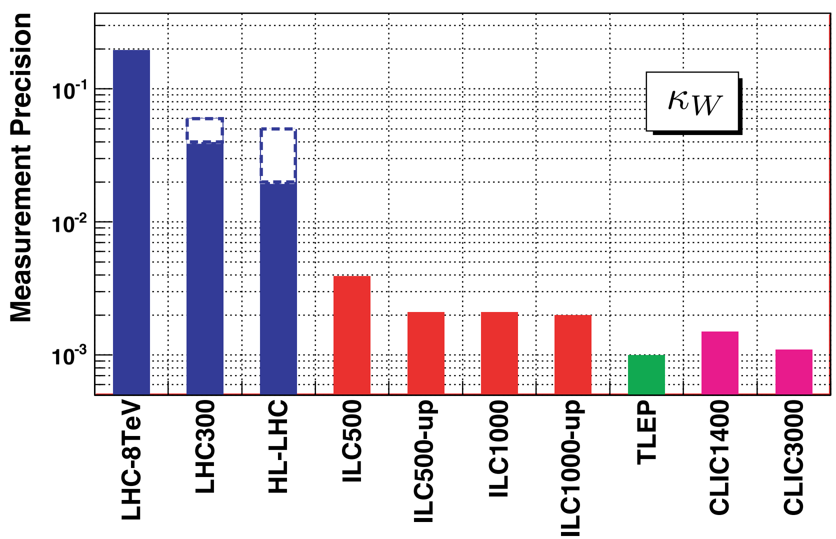
$\Rightarrow$ strong improvement with the ILC

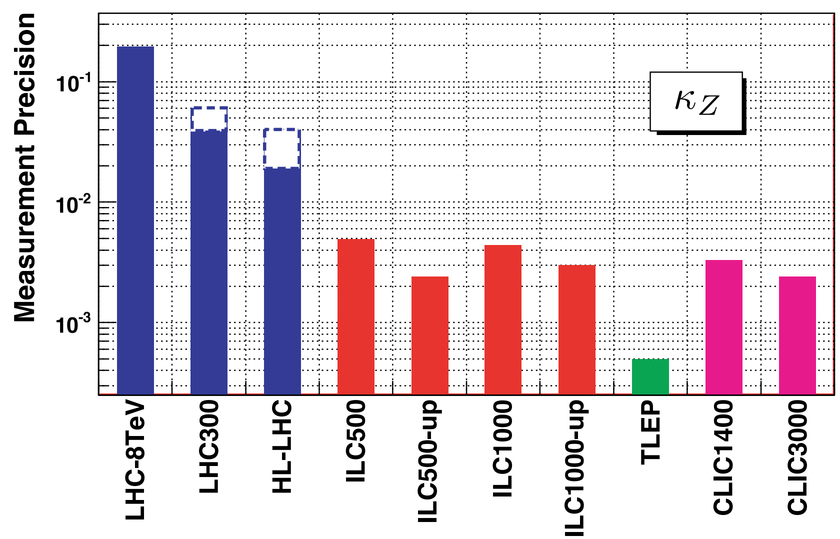
ILC vs. FCC-ee:

[*Snowmass Higgs Report '13*]









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

Higgs coupling determination at e^+e^- collider

Some 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

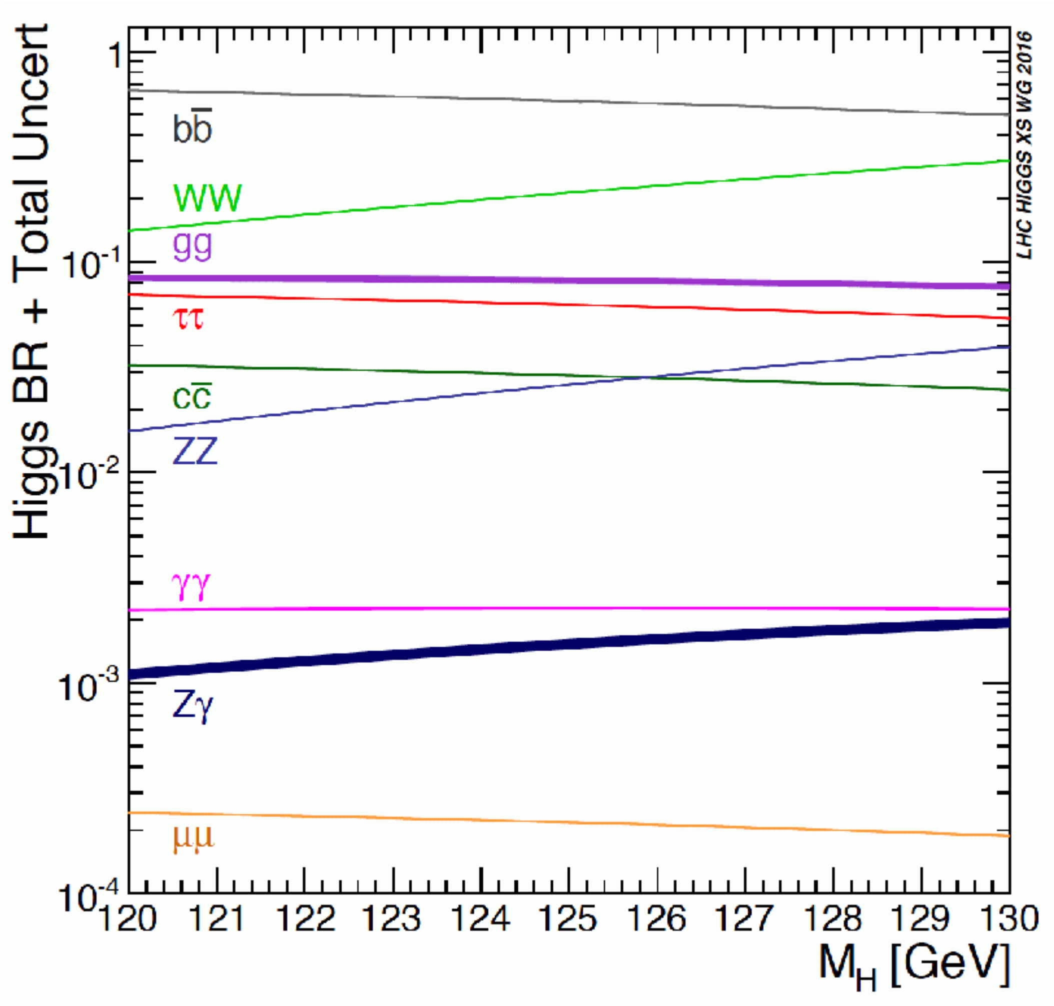
$\Rightarrow$ all observable channels can be measured with high accuracy

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

$\Rightarrow$ improvements necessary . . . full 2-loop calculations and more . . . ?!

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

Latest SM Higgs BR predictions:



Based on HDECAY and Prophecy4f:

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

Theoretical uncertainties: General recipe:

[LHCHXSWG BR group '15]

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

   ⇒ 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	$\overline{\text{MS}}$ masses	Uncertainty
$\alpha_s(M_Z)$	0.118		± 0.0015
m_c	1.403 GeV	$m_c(3\text{ GeV}) = 0.986$ GeV	± 0.026 GeV
m_b	4.505 GeV	$m_b(m_b) = 4.18$ GeV	± 0.03 GeV
m_t	172.5 GeV	$m_t(m_t) = 162.7$ GeV	± 0.8 GeV

Uncertainties: “consensus” of LHCHXSWG

m_b uncertainty crucial

$\Rightarrow$ Lattice data much more optimistic . . .

$\Rightarrow$ but no consensus, not even in the lattice community . . . ?!

Current theoretical uncertainties:

[LHCHXSWG BR group '15]

Partial Width	QCD	Electroweak	Total
$H \to b\bar{b}/c\bar{c}$	$\sim 0.2\%$	$\sim 0.5\%$ for $M_H \lesssim 500$ GeV	$\sim 0.5\%$
$H \to \tau^+\tau^-/\mu^+\mu^-$		$\sim 0.5\%$ for $M_H \lesssim 500$ GeV	$\sim 0.5\%$
$H \to t\bar{t}$	$\lesssim 5\%$	$\sim 0.5\%$ for $M_H < 500$ GeV	$\sim 5\%$
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$
$H \to Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$
$H \to WW/ZZ \to 4f$	$< 0.5\%$	$\sim 0.5\%$ for $M_H < 500$ GeV	$\sim 0.5\%$

- 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
$H \to b\bar{b}$	2.38	-1.4% $+1.4\%$	$+1.7\%$ -1.7%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.5\%$ -0.5%
$H \to \tau^+\tau^-$	$2.56{\cdot}10^{-1}$	$+0.0\%$ $+0.0\%$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.1\%$ -0.1%	$+0.5\%$ -0.5%
$H \to \mu^+\mu^-$	$8.90{\cdot}10^{-4}$	$+0.0\%$ $+0.0\%$	$+0.0\%$ -0.0%	-0.1% -0.0%	$+0.0\%$ -0.1%	$+0.5\%$ -0.5%
$H \to c\bar{c}$	$1.18{\cdot}10^{-1}$	-1.9% $+1.9\%$	-0.0% -0.0%	$+5.3\%$ -5.2%	$+0.0\%$ -0.0%	$+0.5\%$ -0.5%
$H \to gg$	$3.35{\cdot}10^{-1}$	$+3.0\%$ -3.0%	-0.1% $+0.1\%$	$+0.0\%$ -0.0%	-0.1% $+0.1\%$	$+3.2\%$ -3.2%
$H \to \gamma\gamma$	$9.28{\cdot}10^{-3}$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+1.0\%$ -1.0%
$H \to Z\gamma$	$6.27{\cdot}10^{-3}$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.1%	$+0.0\%$ -0.1%	$+5.0\%$ -5.0%
$H \to WW^*$	$8.74{\cdot}10^{-1}$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.5\%$ -0.5%
$H \to ZZ^*$	$1.07{\cdot}10^{-1}$	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.0\%$ -0.0%	$+0.5\%$ -0.5%

Data available for $M_H = 124$ GeV, 125 GeV, 126 GeV

$\Rightarrow$ substantially larger than κ precision at ILC/FCC-ee

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:

$H \to b\bar{b}, H \to c\bar{c}$: higher-order EW corrections ??

$H \to \tau^+\tau^-, H \to \mu^+\mu^-$: higher-order EW corrections ?

$H \to gg$: 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

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

⇐ | ⟵⟶ | ⇒

BR report – Alexander Mück – p.7/ 13

4. Conclusions

- Experimental precision must be matched with theory precision!
- EWPO can give valuable information about SM, BSM
  $\to$ only SM, MSSM "ready"
  Most relevant: M_W, $\sin^2\theta_{\rm eff}$, (m_t), ...
- Current theory uncertainties of M_W, $\sin^2\theta_{\rm eff}$ not sufficient
  Future theory uncertainties: M_W in SM: FCC-ee goals hard to match
  M_W in MSSM: even harder
  $\sin^2\theta_{\rm eff}$ in SM: more than a $\mathcal{O}(5)$ missing
  $\sin^2\theta_{\rm eff}$ in MSSM: even worse
- Top quark mass: mainly theory driven. Improvement at FCC-ee?
- $\Delta\alpha_{\rm had}$: could be the limiting factor , Improvement at FCC-ee?
- Higgs couplings: XS and BR have to be under control
  Can sub-percent/permille level be matched?
  - XS: 1% possible, full 2-loop calculations needed?!
  - BR: intrinsic uncertainties could be brought down below 1%
    parametric uncertainties have (to me) unclear perspective

Back-up