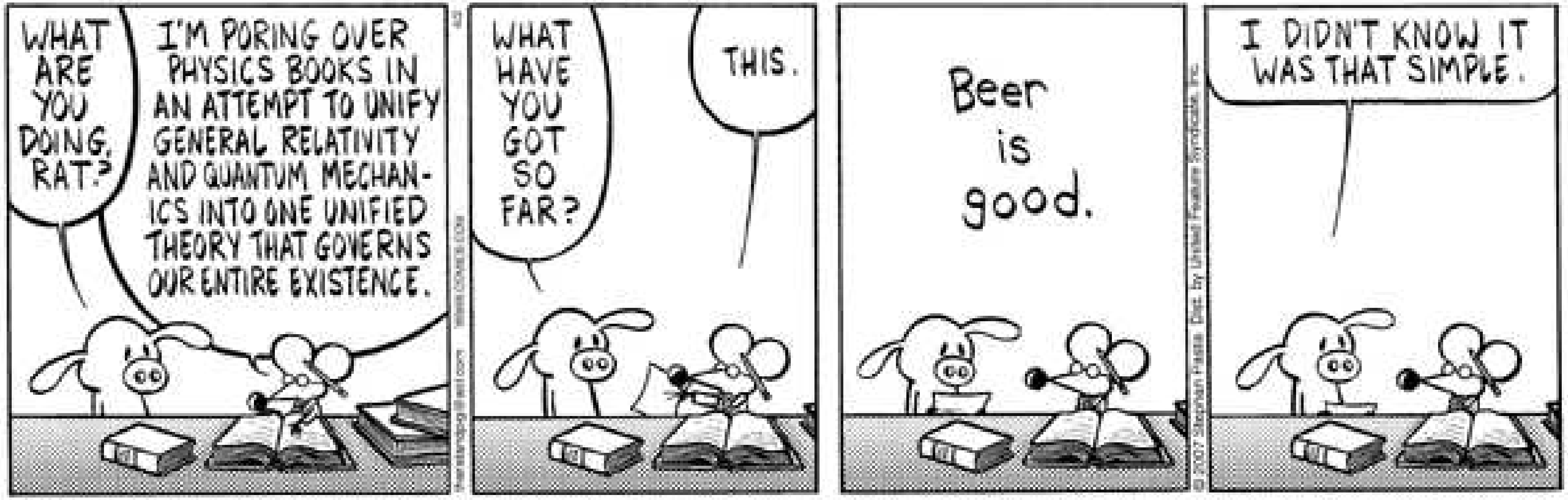
WHAT ARE YOU DOING, RAT?
I'M PORING OVER PHYSICS BOOKS IN AN ATTEMPT TO UNIFY GENERAL RELATIVITY AND QUANTUM MECHANICS INTO ONE UNIFIED THEORY THAT GOVERNS OUR ENTIRE EXISTENCE.
WHAT HAVE YOU GOT SO FAR?
THIS.
Beer is good.
I DIDN'T KNOW IT WAS THAT SIMPLE.

Theoretical Uncertainties for EW/Higgs Precision Measurements at CEPC

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

Beijing, 11/2019

1. Motivation
2. Electroweak Precision Observables (EWPOs)
3. SM Higgs
4. BSM Higgs: what can we learn?
5. Conclusions

1. Introduction

Experimental situation:

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

Theory situation:

– Measurements are performed using theory predictions

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

Full uncertainty is given by the (linear) sum of experimental and theoretical uncertainties!

⇒ Experimetal precision can only fully be exploited with theory uncertainties at the same level of accurady!

Many results shown here based on: [arXiv:1906.05379]
Write-up for FCC-ee physics WG2 – Precision EW Calculations

Theoretical uncertainties for electroweak and Higgs-boson precision measurements at FCC-ee

A. Freitas*[1], S. Heinemeyer*[2], M. Beneke[3], A. Blondel[4], S. Dittmaier[5], J. Gluza[6,7], A. Hoang[8], S. Jadach[9], P. Janot[10], J. Reuter[11], T. Riemann[6,12], C. Schwinn[13], M. Skrzypek[8], and S. Weinzierl[14]

⇒ Here: focus on e^+e^- precision

⇒ should be taken into account by "exp groups"!

⇒ Here: current status and future of EWPO/Higgs TH calculations
what may be achievable in TH calc. in $\mathcal{O}(20)$ years

Where we need theory prediction:

1. Prediction of the measured quantity
   Example: M_W, $\Gamma(H \to b\bar{b})$
   $\to$ at the same level or better as the experimental precision

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

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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. Determine all prefactors of a certain diagram class (couplings, group factors, multiplicities, mass ratios) and assume the loop is $\mathcal{O}(1)$
2. 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"

3. Variation of $\mu^{\overline{\text{MS}}}$ (QCD!, EW?)
4. Compare different renormalizations

$\Rightarrow$ Mostly used here: 1 & 2

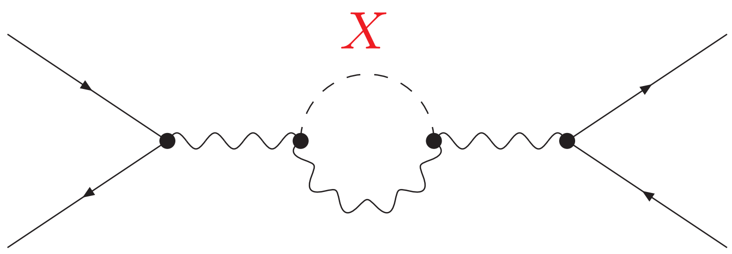
2. Electroweak Precision Observables

Comparison of observables with theory:

Precision data: $M_W, \sin^2\theta_{\rm eff}, a_\mu,\ M_h$	$\leftrightarrow$	Theory: 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

All the EWPO:

M_W (best from threshold scan)

$$\sigma^0_{\text{had}} = \sum_q \sigma_q(M_Z^2),$$

$$\Gamma_Z = \sum_f \Gamma[Z \to f\bar{f}],$$ (from a fit to $\sigma_f(s)$ at various values of s)

$$R_\ell = \left[\sum_q \sigma_q(M_Z^2)\right] / \sigma_\ell(M_Z^2),$$ $(\ell = e, \mu, \tau)$

$$R_q = \sigma_q(M_Z^2) / \left[\sum_q \sigma_q(M_Z^2)\right],$$ $(q = b, c)$

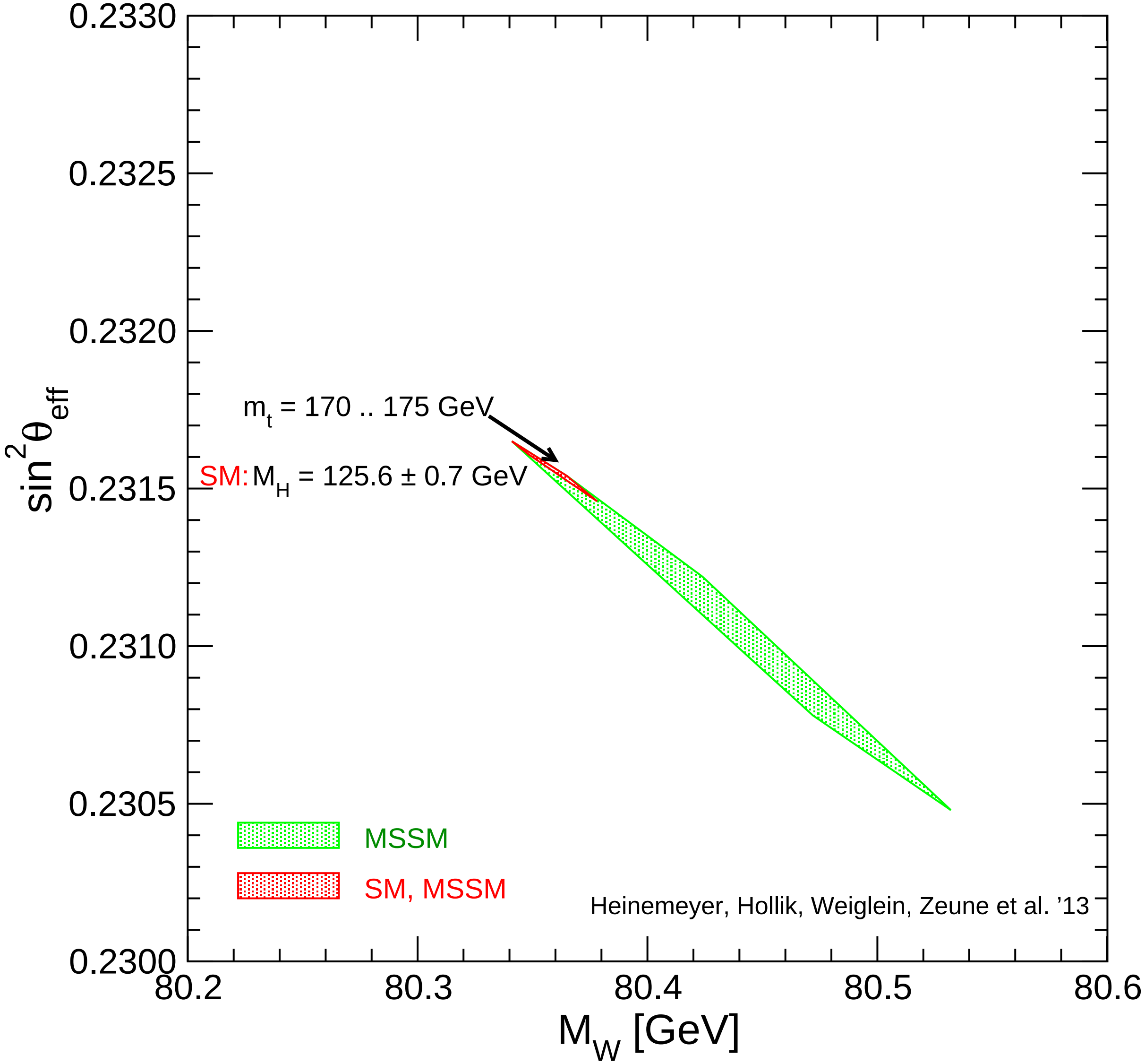
$$A^f_{\text{FB}} = \frac{\sigma_f(\theta < \frac{\pi}{2}) - \sigma_f(\theta > \frac{\pi}{2})}{\sigma_f(\theta < \frac{\pi}{2}) + \sigma_f(\theta > \frac{\pi}{2})} \equiv \frac{3}{4}\mathcal{A}_e\mathcal{A}_f,$$

$$A^f_{\text{LR}} = \frac{\sigma_f(P_e < 0) - \sigma_f(P_e > 0)}{\sigma_f(P_e < 0) + \sigma_f(P_e > 0)} \equiv \mathcal{A}_e|P_e|$$

$$\mathcal{A}_f = 2\frac{g_{V_f}/g_{A_f}}{1 + (g_{V_f}/g_{A_f})^2} = \frac{1 - 4|Q_f|\sin^2\theta^f_{\text{eff}}}{1 - 4|Q_f|\sin^2\theta^f_{\text{eff}} + 8(|Q_f|\sin^2\theta^f_{\text{eff}})^2}$$ $(f = \ell, b, \ldots)$

What M_W and $\sin^2\theta_{\text{eff}}$ precision do we want?

[*S.H., W. Hollik, G. Weiglein, L. Zeune et al. '13*]



MSSM band:
scan over
SUSY masses

overlap:
SM is MSSM-like
MSSM is SM-like

SM band:
variation of m_t

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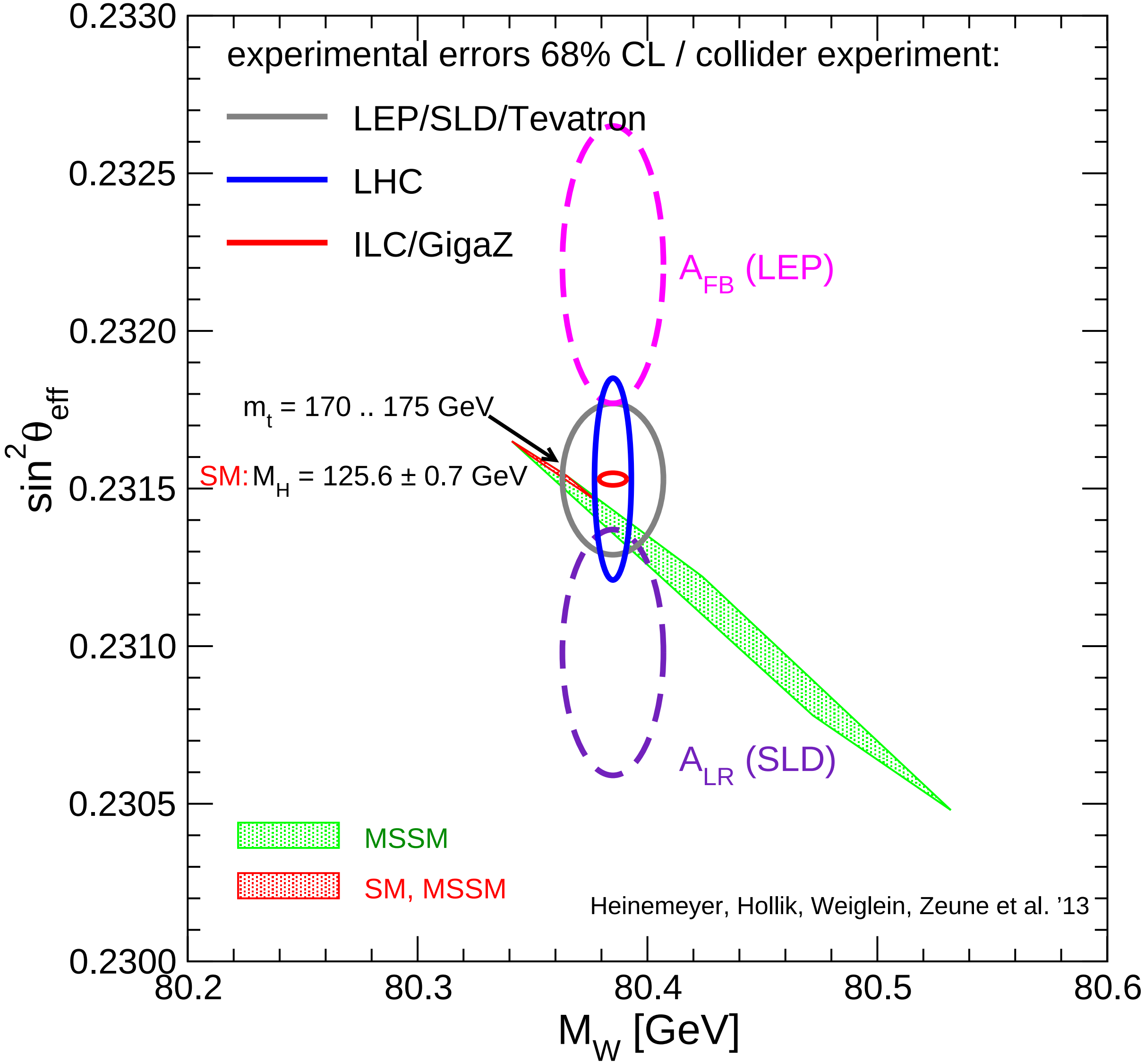

MSSM band:
scan over
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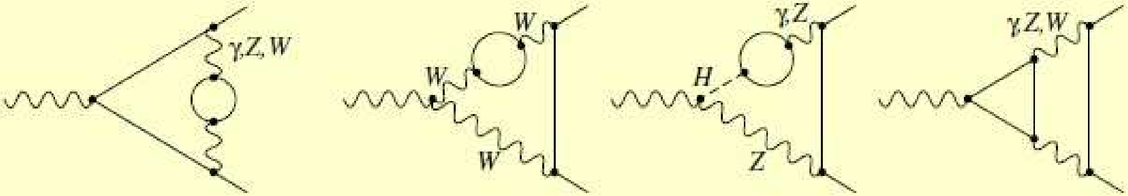
variation of m_t

EWPO Status

Existing higher-order corrections to the EWPO

[*taken from A. Freitas*]

Known corrections to Δr, $\sin^2\theta^f_{\rm eff}$, g_{Vf}, g_{Af}:



- Complete NNLO corrections (Δr, $\sin^2\theta^\ell_{\rm eff}$) Freitas, Hollik, Walter, Weiglein '00
  Awramik, Czakon '02; Onishchenko, Veretin '02
  Awramik, Czakon, Freitas, Weiglein '04; Awramik, Czakon, Freitas '06
  Hollik, Meier, Uccirati '05,07; Degrassi, Gambino, Giardino '14
- "Fermionic" NNLO corrections (g_{Vf}, g_{Af}) Czarnecki, Kühn '96
  Harlander, Seidensticker, Steinhauser '98
  Freitas '13,14
- Partial 3/4-loop corrections to ρ/T-parameter
  $\mathcal{O}(\alpha_t\alpha_s^2)$, $\mathcal{O}(\alpha_t^2\alpha_s)$, $\mathcal{O}(\alpha_t\alpha_s^3)$ Chetyrkin, Kühn, Steinhauser '95
  Faisst, Kühn, Seidensticker, Veretin '03
  Boughezal, Tausk, v. d. Bij '05
  Schröder, Steinhauser '05; Chetyrkin et al. '06
  Boughezal, Czakon '06

  $(\alpha_t \equiv \frac{y_t^2}{4\pi})$

Intrinsic uncertainties:

Quantity	current experimental unc.	current intrinsic unc.	
M_W [MeV]	15	4	$(\alpha^3, \alpha^2\alpha_s)$
$\sin^2\theta^\ell_{\text{eff}}$ $[10^{-5}]$	16	4.5	$(\alpha^3, \alpha^2\alpha_s)$
Γ_Z [MeV]	2.3	0.5	$(\alpha^2_{\text{bos}}, \alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2)$
R_b $[10^{-5}]$	66	15	$(\alpha^2_{\text{bos}}, \alpha^3, \alpha^2\alpha_s)$
R_l $[10^{-3}]$	25	5	$(\alpha^2_{\text{bos}}, \alpha^3, \alpha^2\alpha_s)$

Parametric uncertainties:

Quantity	$\delta m_t = 0.9$ GeV	$\delta(\Delta\alpha_{\text{had}}) = 10^{-4}$	$\delta M_Z = 2.1$ MeV
δM_W^{para} [MeV]	5.5	2	2.5
$\delta\sin^2\theta^{\ell,\text{para}}_{\text{eff}}$ $[10^{-5}]$	3.0	3.6	1.4

$\Rightarrow$ Current intrinsic/parametric uncertainties are substantially smaller than current experimental uncertainties :-)

Intrinsic uncertainties:

NEW: α^2_{bos} calc. [*Dubovyka et al. '18*]

Quantity	current experimental unc.	current intrinsic unc.	
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Additional uncertainty for 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 $\sim$ 6 MeV

Most recent improvement:

leading 2L corrections from EFT

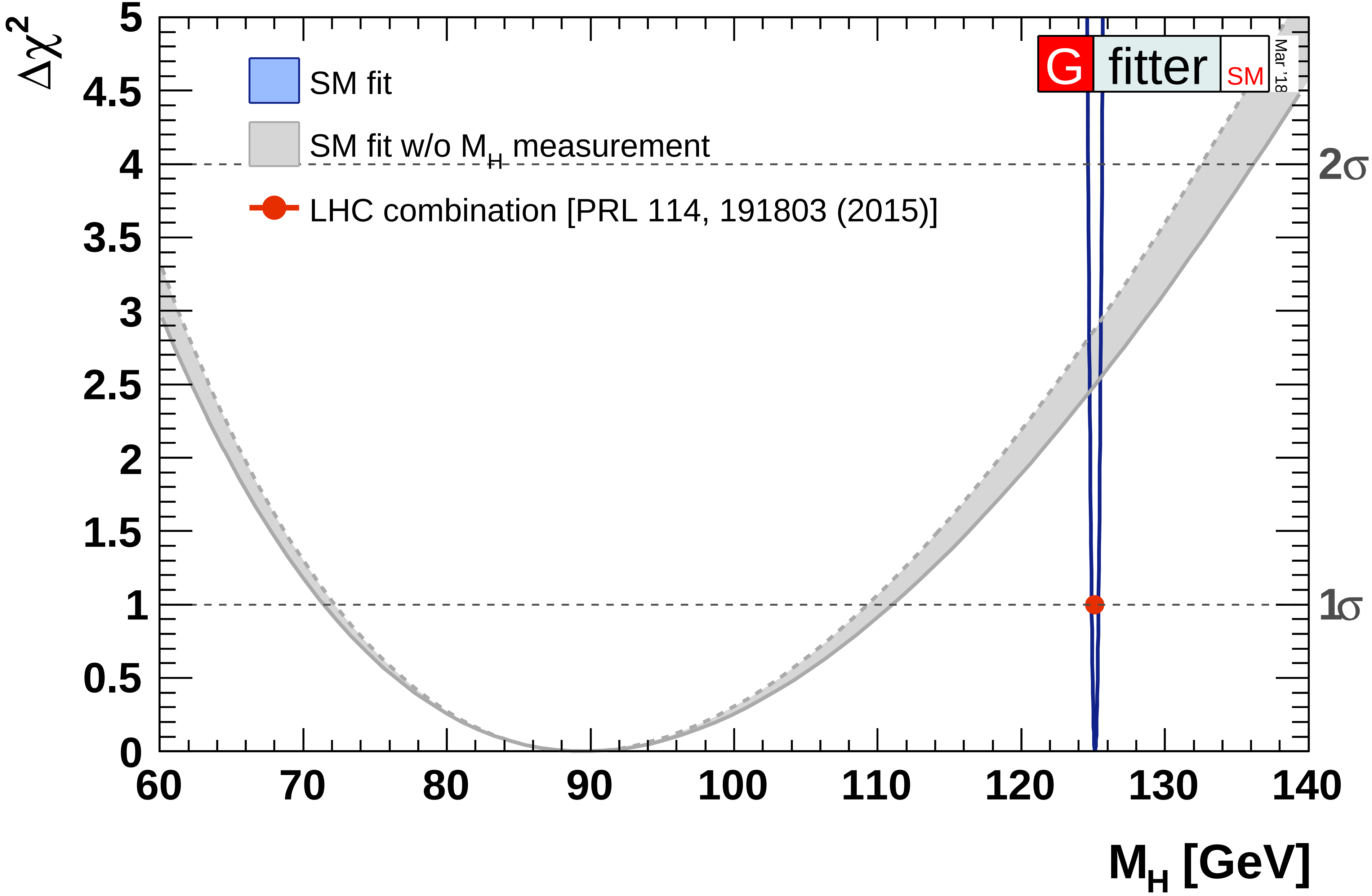
[*Actis, Beneke, Falgari, Schwinn '08*]

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

$\Rightarrow$ well under control for LEP data

Current fit to M_H:

[GFitter '18]



EWPO Future

Our future estimates:

– assume to go substantially beyond what is known now

– assume that many theorists will put many^2 hours of work into it (motivation?)

– do not assume that magically new calculational methods are invented

– are overall optimistic

⇒ they should be taken seriously!

⇒ An honest evaluation of theory uncertainties will increase the robustness of a future collider physics case!

What is needed to match the CEPC precision?

Compare:

1. CEPC (pure) experimental (anticipated) precision

2. Intrinsic uncertainties

3. Parametric uncertainties
   $\to$ taking into account the improved precision of SM paramters at the CEPC

Combined uncertainty:

$$\text{total} = \sqrt{\text{experimental}^2 + \text{parametric}^2} + \text{intrinsic}$$

Intrinsic uncertainties: $\Rightarrow$ can be the limiting factor!

Quantity	ILC	CEPC/FCC-ee	Current intrinsic unc.		Projected unc.
M_W [MeV]	3	0.5	4	$(\alpha^3, \alpha^2\alpha_s)$	1
$\sin^2\theta^\ell_{\text{eff}}$ $[10^{-5}]$	1.3	0.6	4.5	$(\alpha^3, \alpha^2\alpha_s)$	1.5
Γ_Z [MeV]	1	0.1	0.5	$(\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2)$	0.2 (?)
R_b $[10^{-5}]$	15	6	15	$(\alpha^3, \alpha^2\alpha_s)$	7 (?)
R_l $[10^{-3}]$	10??	1	5	$(\alpha^3, \alpha^2\alpha_s)$	1.5 (?)

These calculations are required for the projection:

– complete $\mathcal{O}\left(\alpha\alpha_s^2\right)$ corrections

– fermionic $\mathcal{O}\left(\alpha^2\alpha_s\right)$ corrections

– double-fermionic $\mathcal{O}\left(\alpha^3\right)$ corrections

– leading four-loop corrections enhanced by the top Yukawa coupling

– the $\mathcal{O}\left(\alpha^2_{\text{bos}}\right)$ corrections are done now [*Dubovyka et al. '18*]

For these calculations, qualitatively new developments of existing loop integration techniques will be required, but no conceptual paradigm shift.

Parametric uncertainties:

1. M_H: better than 50 MeV $\Rightarrow$ negligible

2. M_Z: $\sim$ 0.1 MeV with negligible theory uncertainties $\Rightarrow$ negligible

3. $\alpha_s(M_Z)$: from (mainly) R_ℓ
   $\delta\alpha_s^{\text{exp}} \sim 10^{-4}$, $\delta\alpha_s^{\text{theo}} \sim 1.5 \times 10^{-4}$

4. m_t: from threshold scan
   $\delta m_t^{\text{exp}} \sim \mathcal{O}(10 \text{ MeV})$
   $\delta m_t^{\text{theo}} \sim 50$ MeV (NNNLO/NNLL $\oplus$ $1S \to \overline{\text{MS}}$ $\oplus$ $\delta\alpha_s$)

5. m_b: from lattice calculations $\Rightarrow$ negligible for EWPO
   $\delta m_b \sim 10$ MeV (still under discussion, too optimistic?)

6. $\Delta\alpha_{\text{had}}$: BES III and Belle II: $\delta(\Delta\alpha_{\text{had}}) \sim 5 \times 10^{-5}$
   better from measurements "around the Z pole?

Uncertainty budget for m_t:

[*talk by A. Hoang '15*]

$\delta\alpha_s(M_z) = 0.001$

Msbar mass error budget (from threshold scan)

$(\delta M_t^{\mathrm{SD-low}})^{\mathrm{exp}}$	$(\delta M_t^{\mathrm{SD-low}})^{\mathrm{theo}}$	$(\delta\overline{m}_t(\overline{m}_t))^{\mathrm{conversion}}$	$(\delta\overline{m}_t(\overline{m}_t))^{\alpha_s}$
40 MeV	50 MeV	7 – 23 MeV	70 MeV

$\Rightarrow$ improvement in α_s crucial

e^+e^- collider: precision measurement:

$$R_l := \frac{\Gamma(Z \to \text{ hadrons})}{\Gamma(Z \to l^+l^-)}$$

Improvement down to $\delta^{\text{exp}}\alpha_s \sim 0.001 - 0.0001$ possible?!

Note: TH uncertainty (assuming fermionic 3-loop corrections):

$\delta R_l^{\text{theo}} \sim 0.0015 \Rightarrow \delta\alpha_s^{\text{theo}} \sim 0.00015$ $\Rightarrow$ hard to beat . . .

M_W parametric:

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

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

parametric future: $\delta m_t^{\text{fut}} = 0.05$ GeV, $\delta(\Delta\alpha_{\text{had}})^{\text{fut}} = 5\times10^{-5}$, $\delta M_Z^{\text{ILC/CEPC/FCC-ee}} = 1/0.1$ MeV

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

$\sin^2\theta_{\text{eff}}$ parametric: $[10^{-5}]$

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

$$\delta\sin^2\theta_{\text{eff}}^{\text{para},m_t} = 3.0, \quad \delta\sin^2\theta_{\text{eff}}^{\text{para},\Delta\alpha_{\text{had}}} = 3.6, \quad \delta\sin^2\theta_{\text{eff}}^{\text{para},M_Z} = 1.4$$

parametric future: $\delta m_t^{\text{fut}} = 0.05$ GeV, $\delta(\Delta\alpha_{\text{had}})^{\text{fut}} = 5\times10^{-5}$, $\delta M_Z^{\text{ILC/CEPC/FCC-ee}} = 1/0.1$ MeV

$$\Delta\sin^2\theta_{\text{eff}}^{\text{para,fut},m_t} = 0.2, \ \Delta\sin^2\theta_{\text{eff}}^{\text{para,fut},\Delta\alpha_{\text{had}}} = 1.8, \ \Delta\sin^2\theta_{\text{eff}}^{\text{para,fut},M_Z} = 0.65/0.07$$

Additional uncertainty for 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 $\sim$ 6 MeV

Most recent improvement:

leading 2L corrections from EFT

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

$\Rightarrow$ impact on M_W at the level of $\sim$ 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 $W \to f f'$

$\Rightarrow$ extraction of M_W at $\sim$ 1 MeV?? $\oplus$ pure exp. uncertainty of $\sim$ 3/0.5 MeV

Summary of future parametric uncertainties:

Quantity	ILC	CEPC/FCC-ee	future parametric unc.	Main source
M_W [MeV]	$3 \oplus 1$	$0.5 \oplus 1$	1	$\delta(\Delta\alpha_{\rm had})$
$\sin^2\theta^\ell_{\rm eff}$ $[10^{-5}]$	1.3	0.6	2	$\delta(\Delta\alpha_{\rm had})$
Γ_Z [MeV]	1	0.1	0.5	
R_b $[10^{-5}]$	15	6	< 1	$\delta\alpha_s$

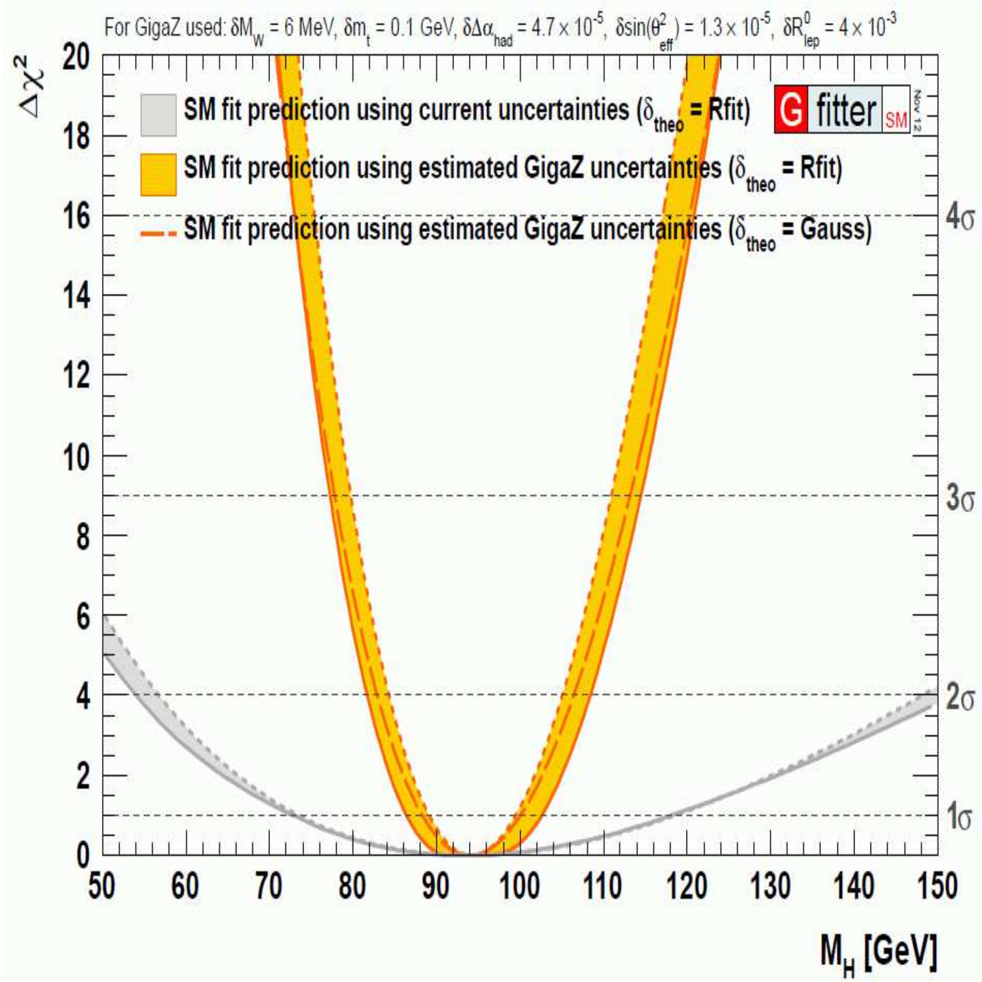
⇒ add quadratic to experimental uncertainties!

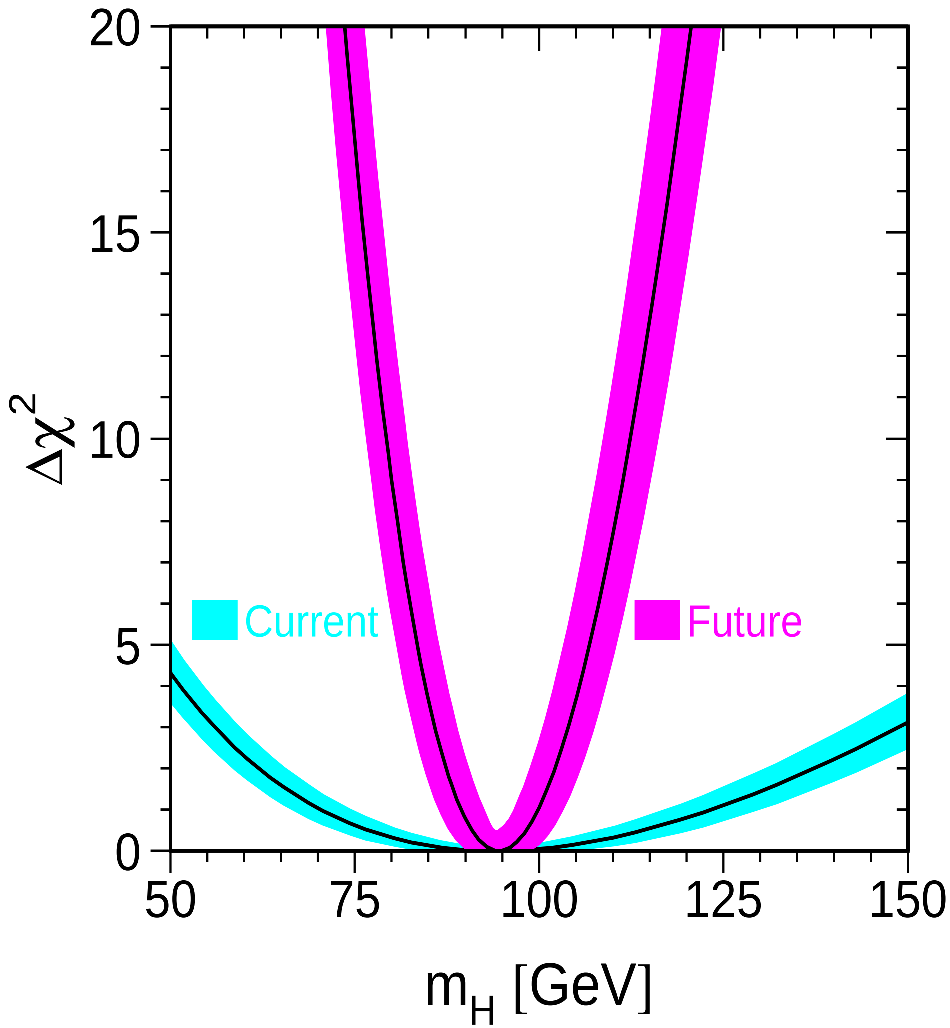
⇒ add linearly to intrinsic uncertainties!

$$\text{total} = \sqrt{\text{experimental}^2 + \text{parametric}^2} + \text{intrinsic}$$

Precise M_H test with the ILC precision:

[GFitter '13] [LEPEWWG '13]





$\Rightarrow \delta M_H^{\rm ind} \lesssim 6$ GeV $\Leftarrow$ to be redone incl. all TH unc.

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

One more word of caution:

The above numbers have all been obtained assuming the SM as calculational framework.

The SM constitutes the model in which highest theoretical precision for the predictions of EWPO can be obtained.

We know that BSM physics must exist! (DM, gravity, . . .)

As soon as BSM physics will be discovered, an evaluation of the EWPO in any preferred BSM model will be necessary.

The corresponding theory uncertainties, both intrinsic and parametric, can then be larger (as known for the MSSM).

A dedicated theory effort (beyond the SM) would be needed in this case.

3. SM Higgs (the easy case)

Initial measurement: $\sigma \times$ BR

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

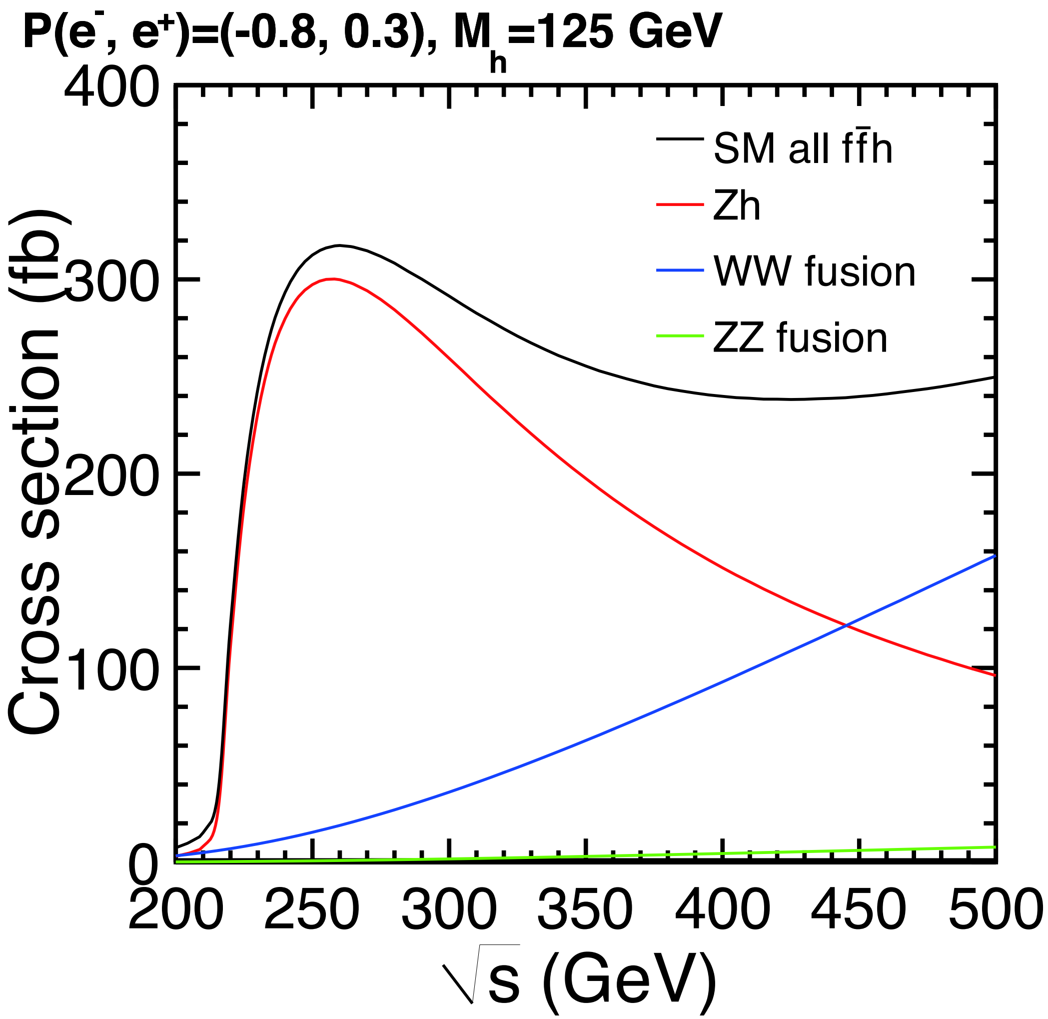
$\Rightarrow$ measurement of the Higgs production cross section

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

$\Rightarrow$ indirect measurement of total width

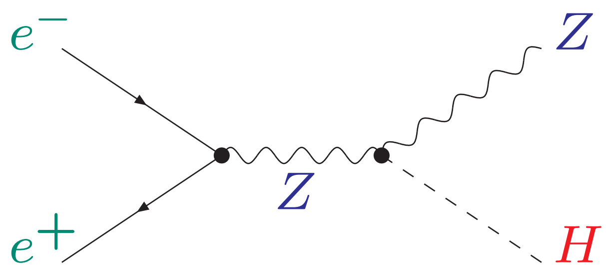
$\Rightarrow$ direct extraction of partial widths (couplings)

Higgs production cross sections:



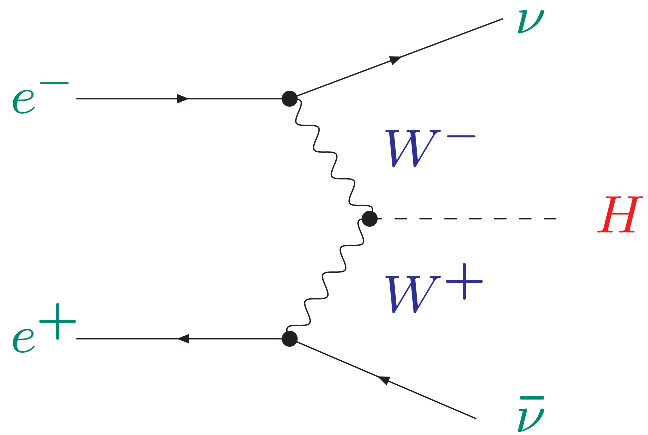
Higgs-strahlung:

$e^+e^- \to Z^* \to ZH$



weak boson fusion (WBF):

$e+e- \to \nu\bar{\nu}H$



$\sqrt{s} \sim$ 250 GeV, Higgs-strahlung dominated

$e^+e^- \to ZH$:

$\delta\sigma_{HZ}^{\text{exp}} \sim 0.4\%$

full one-loop available, corrections of 5-10%

rough estimate: $\delta\sigma_{HZ}^{\text{theo}} \sim 1\%$ from missing two-loop corrections

Two-loop corrections for $2 \to 2$ can in principle be done . . .
$\mathcal{O}(\alpha_t\alpha_s)$ corrections: 1.3% *[Y. Gong, Z. Li, X. Xu, L. Yang '16]*

⇒ theory uncertainties sufficiently small
⇒ full two-loop for $2 \to 2$ should be done!

$e^+e^- \to \nu\bar{\nu}H$:

small contribution . . .

Partial two-loop calculation (with closed fermion loops)
can in principle be done . . .

⇒ theory uncertainties sufficiently small

Decay width 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

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

3. Total Uncertainty:

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

Intrinsic uncertainties for decay widths:

[arXiv:1905.03764]

"ILC/CEPC/FCC-ee" = expected precision on g^2_{Hxx} (incl. HL-LHC meas.)

Partial width	QCD	electroweak	total	future	ILC/CEPC/FCC-ee
$H \to WW \to$ 4f	$<$ 0.5%	$<$ 0.3%	$\sim$ 0.5%	$\lesssim$ 0.4%	0.6/1.9/0.8%
$H \to ZZ \to$ 4f	$<$ 0.5%	$<$ 0.3%	$\sim$ 0.5%	$\lesssim$ 0.3%	0.4/0.4/0.3%
$H \to gg$	$\sim$ 3%	$\sim$ 1%	$\sim$ 3.2%	$\sim$ 1%	1.7/2.2/1.8%
$H \to \gamma\gamma$	$<$ 0.1%	$<$ 1%	$<$1%	$<$ 1%	2.4/2.4/2.4%
$H \to Z\gamma$	$\lesssim$ 0.1%	$\sim$ 5%	$\sim$ 5%	$\sim$ 1%	22/13/20%
$H \to b\bar{b}$	$\sim$ 0.2%	$<$ 0.3%	$<$ 0.4%	$\sim$ 0.2%	1.2/1.8/1.3%
$H \to c\bar{c}$	$\sim$ 0.2%	$<$ 0.3%	$<$ 0.4%	$\sim$ 0.2%	2.4/4.0/2.6%
$H \to \tau^+\tau^-$	–	$<$ 0.3%	$<$ 0.3%	$<$ 0.1%	1.3/1.9/1.3%
$H \to \mu^+\mu^-$	–	$<$ 0.3%	$<$ 0.3%	$<$ 0.1%	7.8/7.8/7.8%
$\Gamma_{\rm tot}$				$\sim$ 0.3%	1.1/1.8/1.2%

$\Rightarrow$ non-negligible for $H \to WW/ZZ \to$ 4f

Future parametric uncertainties for decay widths:

decay	fut. intr.	fut. para. m_q	para. α_s	para. M_H	ILC/CEPC/FCC-ee
$H \to WW$	$\lesssim 0.4\%$	–	–	$\sim 0.1\%$	0.6/1.9/0.8%
$H \to ZZ$	$\lesssim 0.3\%$	–	–	$\sim 0.1\%$	0.4/0.4/0.3%
$H \to gg$	$\sim 1\%$		0.5%	–	1.7/2.2/1.8%
$H \to \gamma\gamma$	$< 1\%$	–	–	–	2.4/2.4/2.4%
$H \to Z\gamma$	$\sim 1\%$	–	–	$\sim 0.1\%$	22/13/20%
$H \to b\bar{b}$	$\sim 0.2\%$	0.6%	$< 0.1\%$	–	1.3/1.8/1.3%
$H \to c\bar{c}$	$\sim 0.2\%$	$\sim 1\%$	$< 0.1\%$	–	2.4/4.0/2.6%
$H \to \tau^+\tau^-$	$< 0.1\%$	–	–	–	1.3/1.0/1.3%
$H \to \mu^+\mu^-$	$< 0.1\%$	–	–	–	7.8/7.8/7.8%
Γ_{tot}	$\sim 0.3\%$	$\sim 0.4\%$	$< 0.1\%$	$< 0.1\%$	1.1/1.8/1.2%

Γ_{tot} applies "to all" (partial cancelations . . .)
$\Rightarrow$ possible impact particular on ZZ, WW

Future theory uncertainties?

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?!

Parametric uncertainties:

– largely driven by δm_b $\Rightarrow$ possible improvement not fully clarified (lattice community does not seem to agree)

– some improvement in α_s possible

One word of caution:

The above numbers have all been obtained assuming the SM as calculational framework.

The SM constitutes the model in which highest theoretical precision for the predictions of EWPO can be obtained.

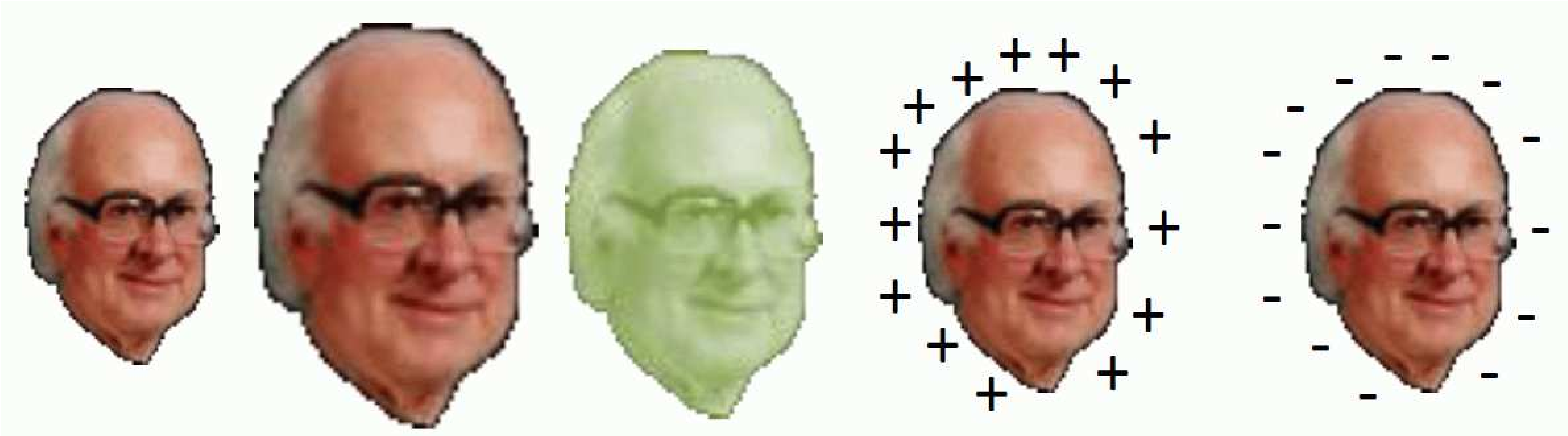
We know that BSM physics must exist! (DM, gravity, . . .)

As soon as BSM physics will be discovered, an evaluation of the Higgs predictions in any preferred BSM model will be necessary.

The corresponding theory uncertainties, both intrinsic and parametric, can then be larger (as known for the MSSM).

A dedicated theory effort (beyond the SM) would be needed in this case.

4. BSM Higgs (the difficult case)



– let's assume that we do see a deviation

– **What do we learn from that?**

Required precision for Higgs couplings?

MSSM example:

$$\kappa_V \approx 1 - 0.5\% \left(\frac{400\ \text{GeV}}{M_A}\right)^4$$

$$\kappa_t = \kappa_c \approx 1 - \mathcal{O}\,(10\%) \left(\frac{400\ \text{GeV}}{M_A}\right)^2 \cot^2\beta$$

$$\kappa_b = \kappa_\tau \approx 1 + \mathcal{O}\,(10\%) \left(\frac{400\ \text{GeV}}{M_A}\right)^2$$

Composite Higgs example:

$$\kappa_V \approx 1 - 3\% \left(\frac{1\ \text{TeV}}{f}\right)^2$$

$$\kappa_F \approx 1 - (3-9)\% \left(\frac{1\ \text{TeV}}{f}\right)^2$$

⇒ couplings to bosons in the per mille range

⇒ couplings to fermions in the per cent range

⇒ theory/experimental match?

Let us assume that we do see a deviation

What do we learn from that?
How do we learn something from that?

⇒ We have to compare the observed deviation with predicted deviations

⇒ Preferrably with the predicted deviations in a concrete models
(A comparison with an EFT result subsequently requires the mapping to concrete models anyway . . .)

⇒ Needed: sufficiently precise predictions in BSM model
close to ready: MSSM, NMSSM
(I am not aware of uncertainty estimates in other models)

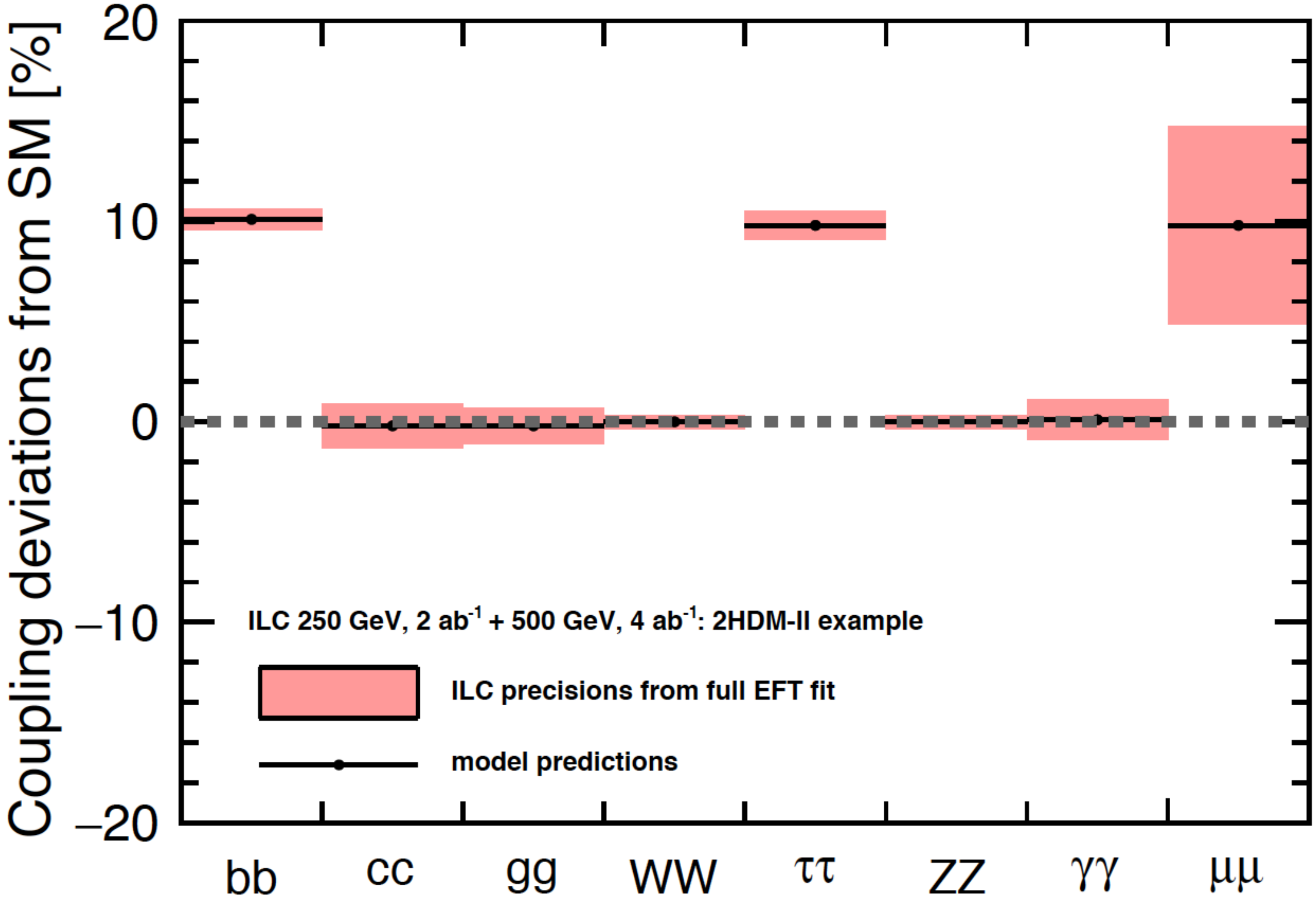
⇒ in the following:

model prediction (w/o TH unc.) ⇔ ILC precision (ILC500)

⇒ "Wäscheleinen-Plots"

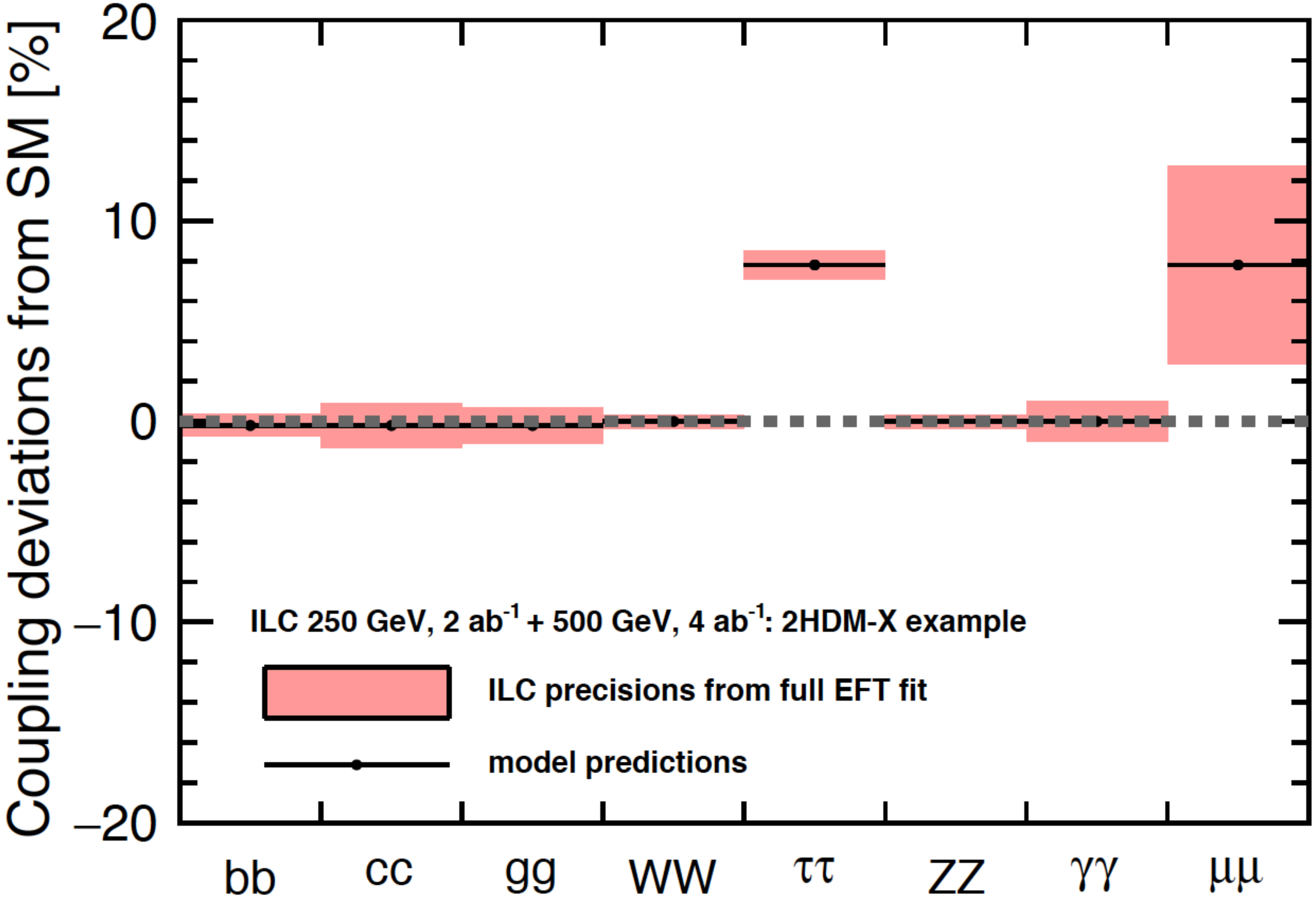
Wäscheleine I: ILC precision vs. 2HDM type II prediction:

[*T. Barklow et al., '17*]



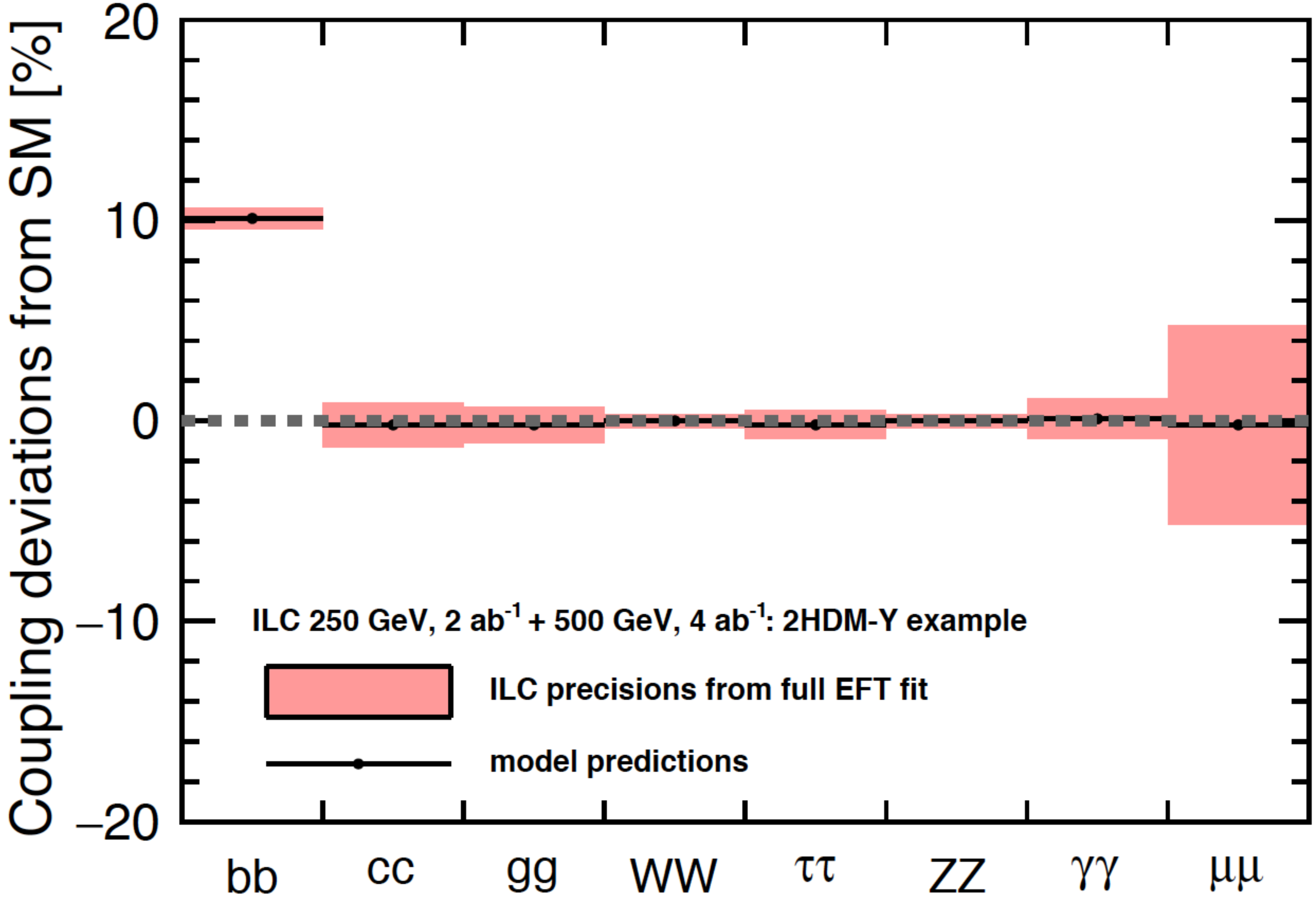
Wäscheleine II: ILC precision vs. 2HDM type X prediction:

[*T. Barklow et al., '17*]



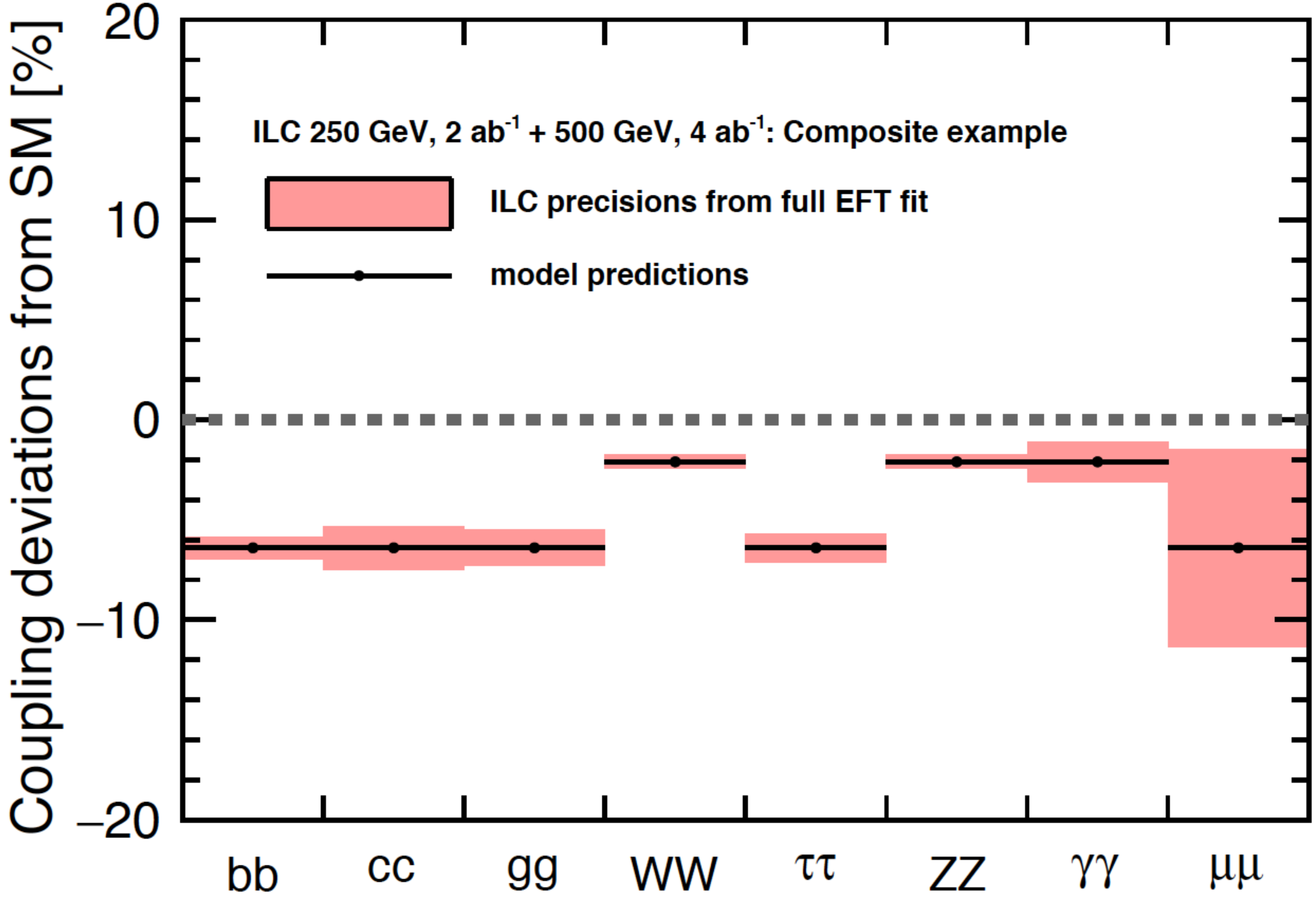
Wäscheleine III: ILC precision vs. 2HDM type Y prediction:

[*T. Barklow et al., '17*]



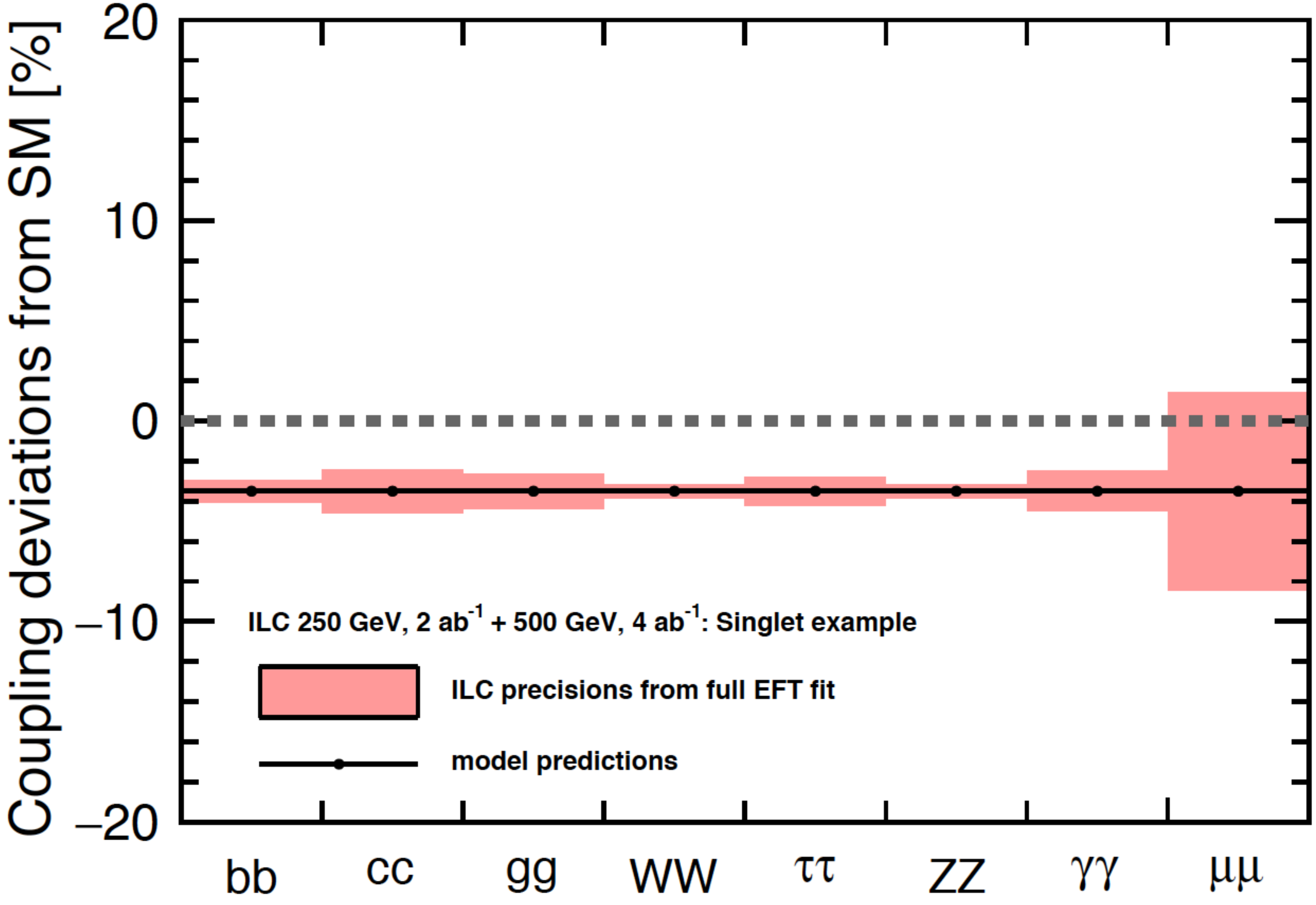
Wäscheleine IV: ILC precision vs. Composite Higgs prediction:

[*T. Barklow et al., '17*]



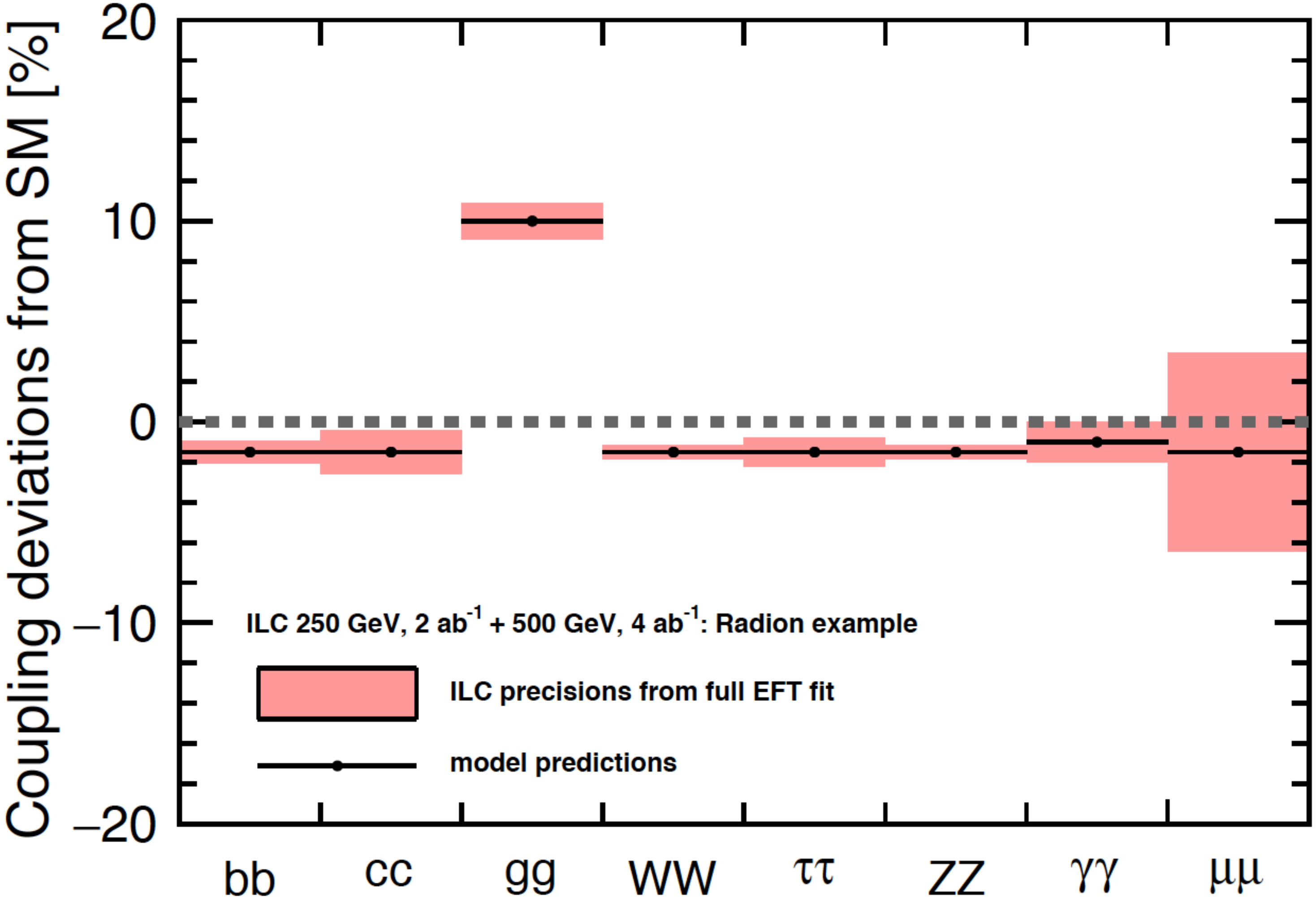
Wäscheleine V: ILC precision vs. HxSM prediction:

[*T. Barklow et al., '17*]



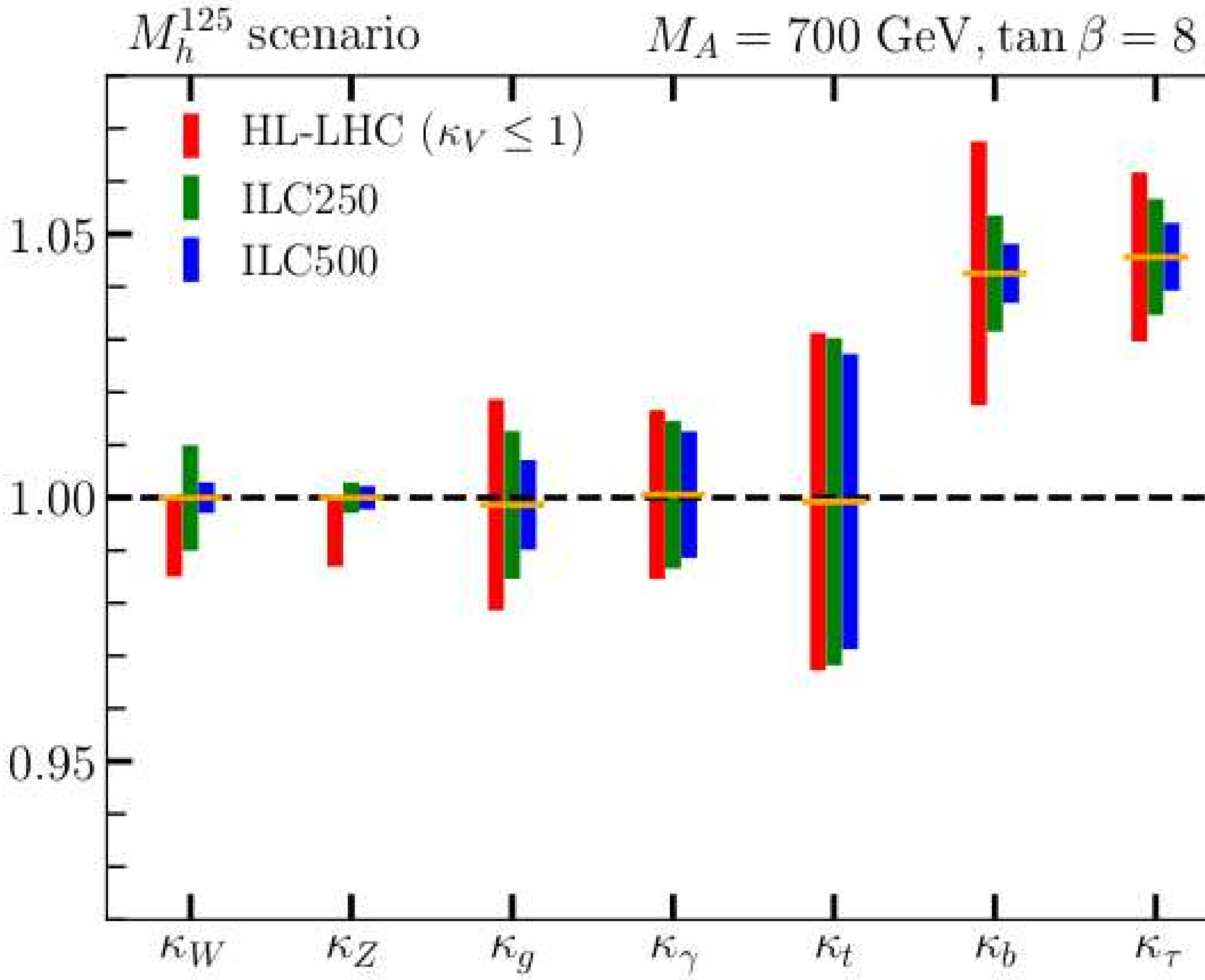
Wäscheleine VI: ILC precision vs. Higgs-Radion prediction:

[*T. Barklow et al., '17*]



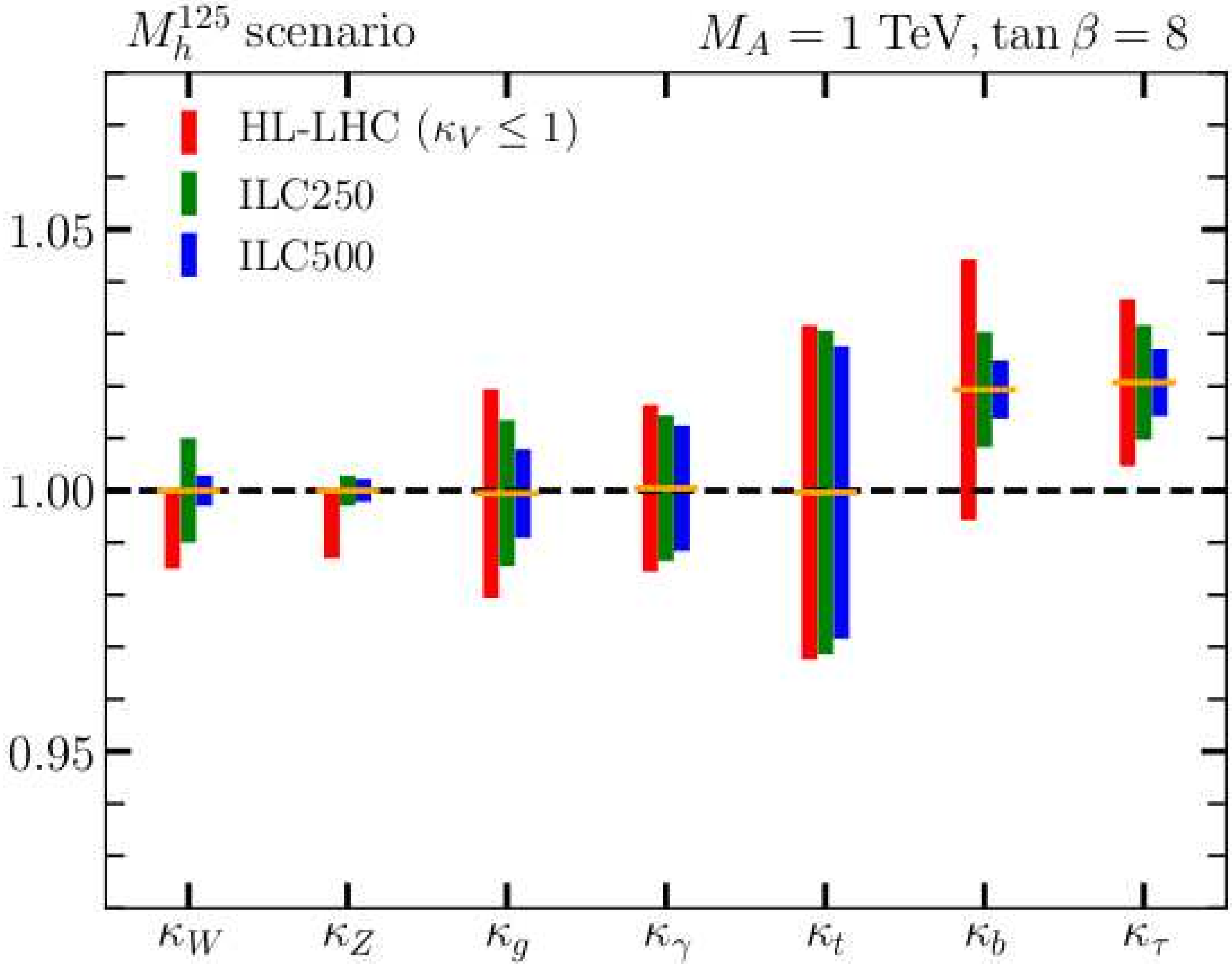
MSSM Wäscheleine I: ILC precision vs. M_h^{125} ($M_A = 700$ GeV, $\tan\beta = 8$)

[*H. Bahl et al – PRELIMINARY*]



MSSM Wäscheleine II: ILC precision vs. M_h^{125} ($M_A = 1000$ GeV, $\tan\beta = 8$)

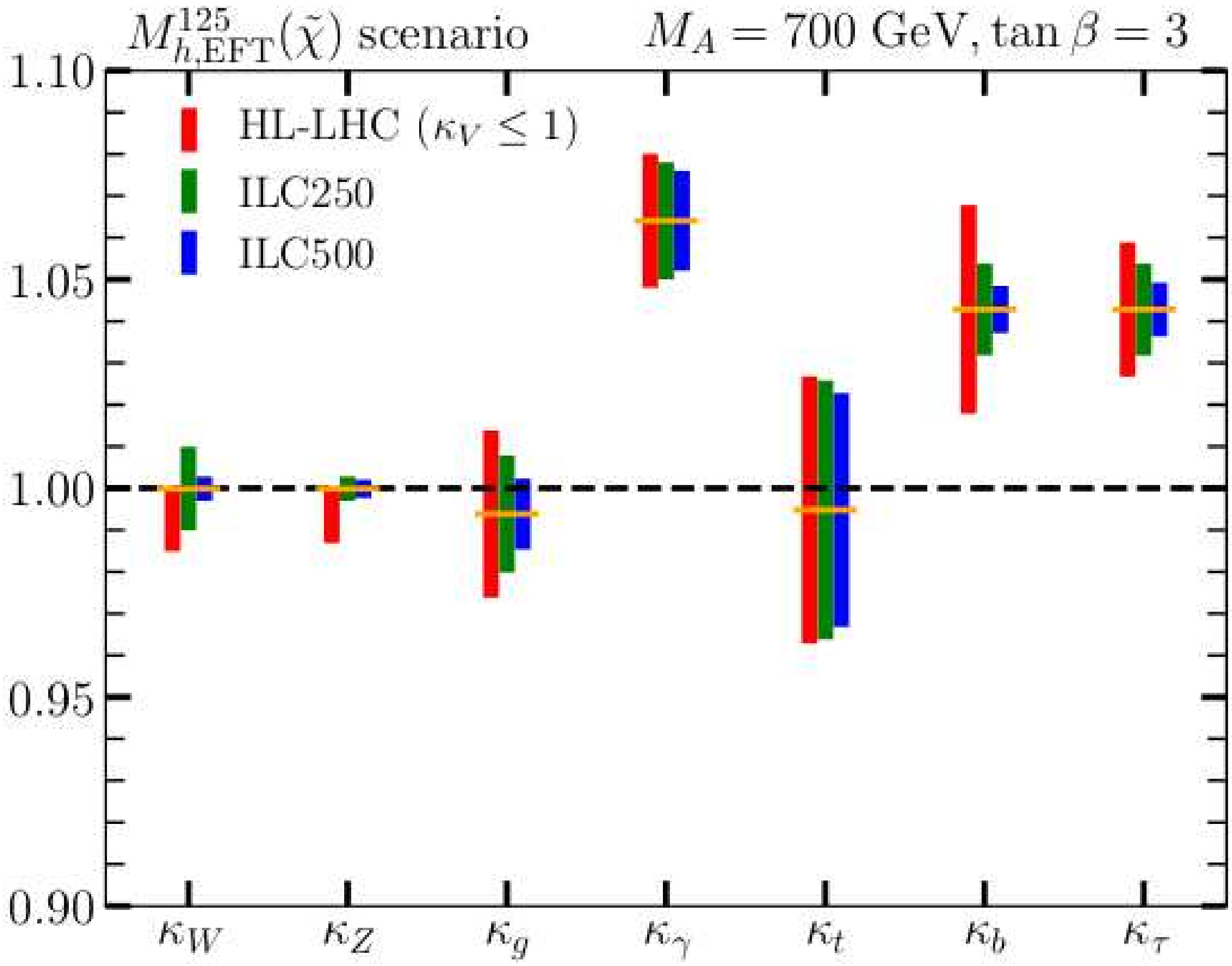
[*H. Bahl et al – PRELIMINARY*]



$\Rightarrow$ only ILC measurements allows to set upper limit on M_A

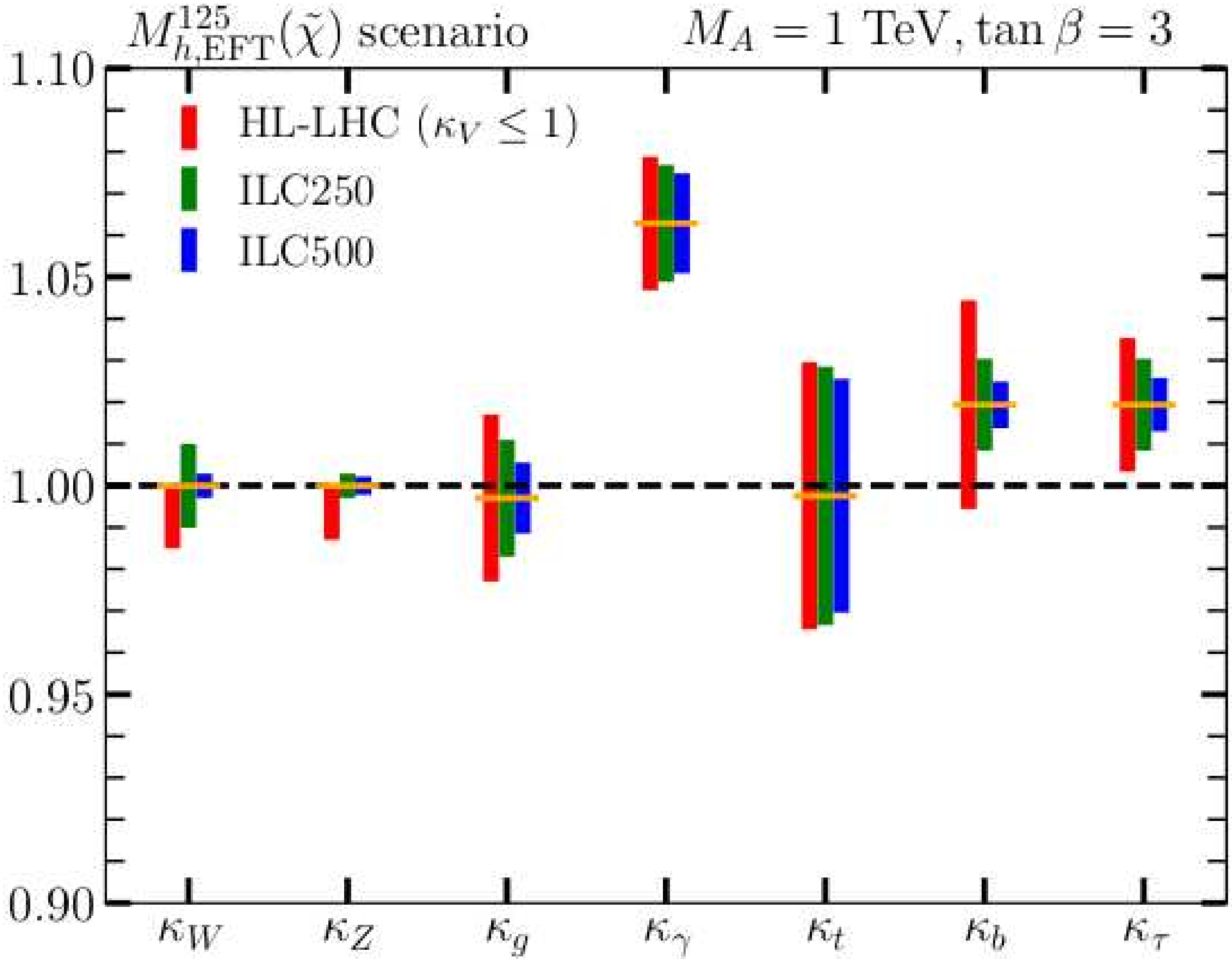
MSSM Wäscheleine III: ILC vs. $M_h^{125,\mathrm{EFT}}(\tilde{\chi})$ ($M_A = 700$ GeV, $\tan\beta = 3$)

[*H. Bahl et al – PRELIMINARY*]



MSSM Wäscheleine IV: ILC vs. $M_h^{125,\text{EFT}}(\tilde{\chi})$ ($M_A = 1000$ GeV, $\tan\beta = 3$)

[*H. Bahl et al – PRELIMINARY*]



$\Rightarrow$ only ILC measurements allows to set upper limit on M_A

5. Conclusions

- High anticipated experimental precision for Higgs/EWPO at future e^+e^- colliders
- Crucial: theory uncertainties: intrinsic and parametric

$$\text{total} = \sqrt{\text{experimental}^2 + \text{parametric}^2} + \text{intrinsic}$$

- We give (realistic/optimistic) estimates for future intrinsic and parametric uncertainties
- EWPO: intrinsic unc. larger than anticipated experimental unc.
  parametric unc. often larger than experimental uncertainties
  $\Rightarrow$ particularly true for M_W and $\sin^2\theta_{\text{eff}}$
- SM Higgs: cross section can be under control with full $2 \to 2$ calc.
  intrinsic unc. can be relevant for $H \to WW/ZZ \to 4f$
  parametric unc. can be relevant, in particular for $H \to WW/ZZ \to 4f$
- Uncertainties should be taken into account by experimental analyses!
- BSM Higgs: deviations in per-cent range $\Rightarrow$ What can we learn?
  $\Rightarrow$ Compare e^+e^- precision with concrete BSM expectations
  $\Rightarrow$ Wäscheleinen-Plots (ILC500 vs. BSM)
  $\Rightarrow$ clear distinction between (selection of) models possible


Further Questions?