Precision Electroweak Calculations for Z, WW, Higgs @ e^+e^- colliders

Stefan Dittmaier

Albert-Ludwigs-Universität Freiburg

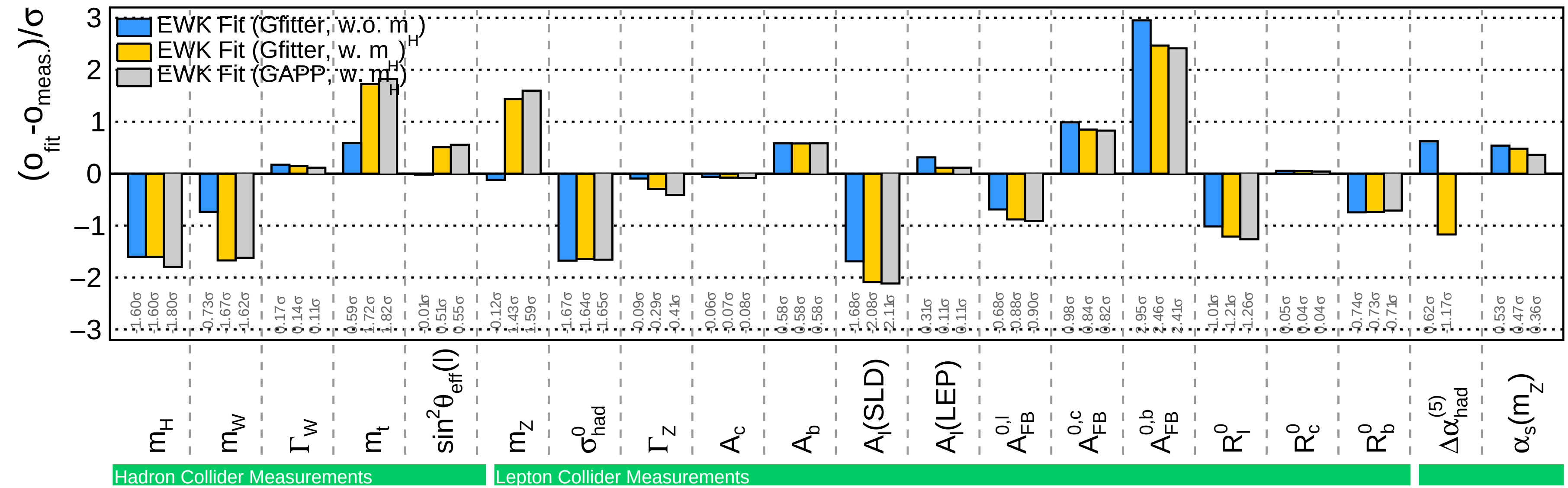
Contents

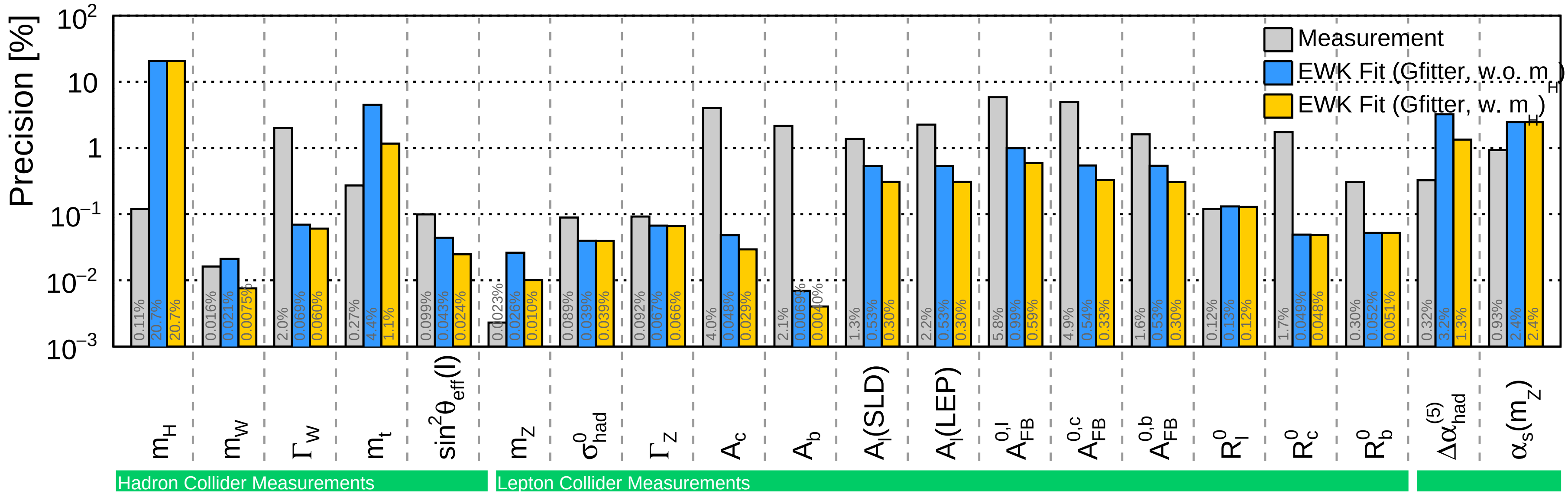
Mission of this talk

- review physics prospects for EW precision measurements at possible future e^+e^- colliders
- reflect corresponding theory requirements
- raise issues for discussion about feasibility

Current status of (not only) EW precision physics

Erler, Schott '19

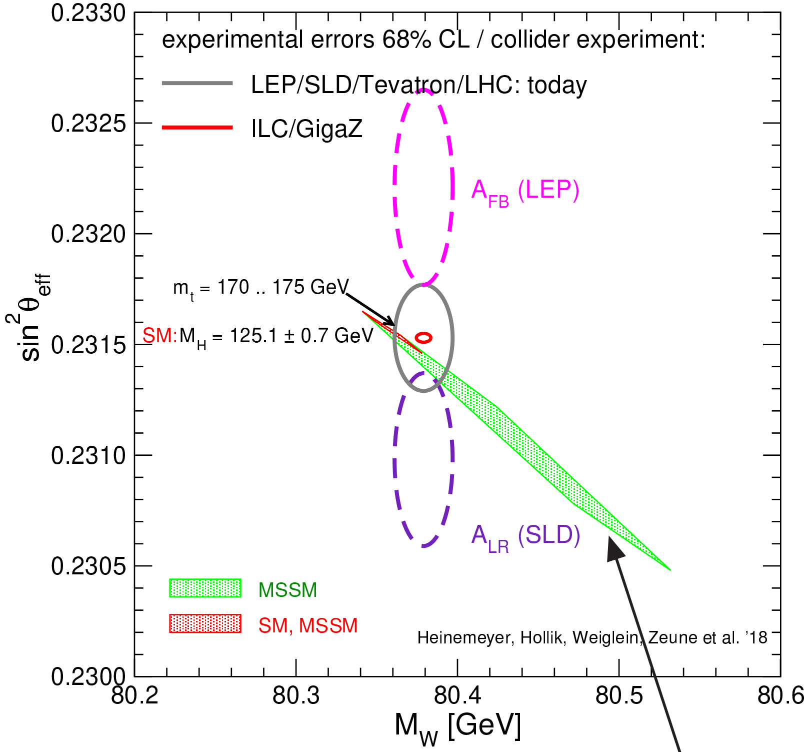




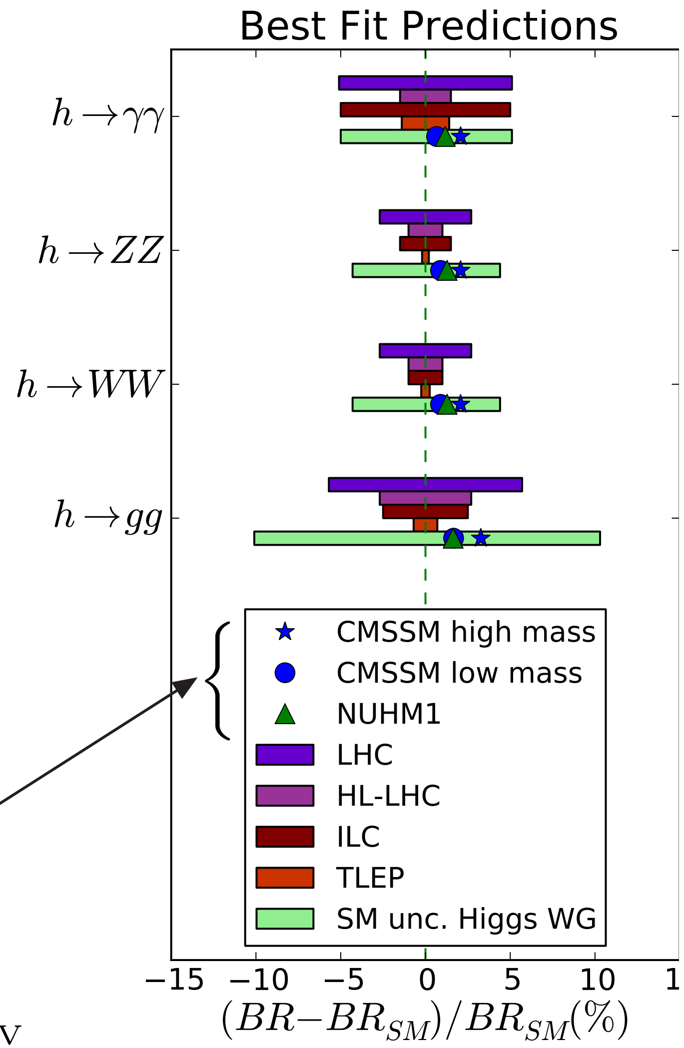
$\Rightarrow$ Future increase in precision is great experimental and theory challenge!

Typical prospects for future high-precision e^+e^- EW physics

EW PO @ ILC 1504.01726 (updated)



Higgs precision @ ILC/TLEP 1308.6176



Fantastic indirect sensitivity
to physics beyond the SM!

Baselines: LHC/HL-LHC: $300\mathrm{fb}^{-1}/3000\mathrm{fb}^{-1}$ @ 14 TeV
ILC: $250\mathrm{fb}^{-1}$ (pol.) @ 250 GeV
TLEP: $4 \times 2.5\mathrm{ab}^{-1}$ @ 240 GeV

Experimental errors and theory uncertainties

Experimental errors:

systematic errors
statistical errors } $\rightarrow$ LHC status + projections to HL/HE-LHC, ILC, FCC-ee
= input for this talk

Theory uncertainties in predictions: $\rightarrow$ main subject of this talk on EW side

- Intrinsic uncertainties due to missing higher-order corrections, estimated from
  - ◇ generic scaling of higher order via coupling factors
  - ◇ renormalization and factorization scale variations
  - ◇ tower of known corrections, e.g. $\Delta_{\mathrm{NNLO}} \sim \delta^2_{\mathrm{NLO}}$ if δ_{NLO} known
  - ◇ different variants to include/resum leading higher-order effects
- Parametric uncertainties due to errors in input parameters, induced by
  - ◇ experimental errors in measurements
  - ◇ theory uncertainties in analyses

Note:
Estimates of theory uncertainties often (too) optimistic in projections of exp. results...

GigaZ/TeraZ

–

ultra-high precision physics at the Z resonance

Central EW precision (pseudo-)observables at the Z pole

FCC-ee: update of Blondel et al., 1901.02648 (in prep.); ILC: Moortgat-Pick et al., 1504.01726

	experimental accuracy			intrinsic theory uncertainty		
	current	ILC	FCC-ee	current	current source	prospect
$\Delta M_Z\,[\mathrm{MeV}]$	2.1	–	0.1			
$\Delta \Gamma_Z\,[\mathrm{MeV}]$	2.3	1	0.1	0.4	$\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2$	0.15
$\Delta \sin^2\theta^\ell_{\mathrm{eff}}\,[10^{-5}]$	23	1.3	0.6	4.5	$\alpha^3, \alpha^2\alpha_s$	1.5
$\Delta R_b\,[10^{-5}]$	66	14	6	11	$\alpha^3, \alpha^2\alpha_s$	5
$\Delta R_\ell\,[10^{-3}]$	25	3	1	6	$\alpha^3, \alpha^2\alpha_s$	1.5

Theory requirements for Z-pole pseudo-observables:

- needed:
  - ◇ EW and QCD–EW 3-loop calculations
  - ◇ $1 \to 2$ decays, fully inclusive
- problems:
  - ◇ technical: massive multi-loop integrals, γ_5
  - ◇ conceptual: pseudo-obs. on the complex Z-pole

$\hookrightarrow$ Enormous challenge, but feasible (anticipating progress + support!)

Central EW precision (pseudo-)observables at the Z pole

FCC-ee: update of Blondel et al., 1901.02648 (in prep.); ILC: Moortgat-Pick et al., 1504.01726

	experimental accuracy			intrinsic th. unc.		parametric unc.	
	current	ILC	FCC-ee	current	prospect	prospect	source
ΔM_Z[MeV]	2.1	–	0.1				
$\Delta\Gamma_Z$[MeV]	2.3	1	0.1	0.4	0.15	0.1	α_s
$\Delta \sin^2\theta_{eff}^{\ell}[10^{-5}]$	23	1.3	0.6	4.5	1.5	2(1)	$\Delta\alpha_{had}$
$\Delta R_b[10^{-5}]$	66	14	6	11	5	1	α_s
$\Delta R_\ell[10^{-3}]$	25	3	1	6	1.5	1.3	α_s

Parametric uncertainties of EW pseudo-observables:

- QCD: (talk by F.Caola)
  - ◇ most important: $\delta\alpha_s \sim 0.00015$ @ FCC-ee?
    $\hookrightarrow$ α_s from EW POs competitive $\Rightarrow$ cross-check with other results!
  - ◇ quark masses m_t, m_b, m_c
- $\Delta\alpha_{had}$: $\delta(\Delta\alpha_{had}) \sim 5(3)\times 10^{-5}$ for/from FCC-ee?
  - ◇ new exp. results from BES III / Belle II on $e^+e^- \to$ hadrons
  - ◇ $\Delta\alpha_{had}$ from fit to radiative return $e^+e^- \to \gamma +$ hadrons
- other EW parameters: M_Z, M_W, M_H less critical (improved at ILC/FCC-ee)

Further theory issues:

- Full line-shape prediction to NNLO EW $+$ leading effects beyond
  - ◇ technical progress in 2- and multi-loop amplitudes/integrals
  - ◇ conceptual progress in NNLO EW corrections (unstable particles!)
  - ◇ improvements on leading ISR corrections beyond NNLO
  - ◇ leading EW corrections beyond NNLO
- Validity of pseudo-observable approach
  - ◇ better field-theoretical foundation of Z-pole pseudo-observables (complex pole definition, absorptive parts, continuum subtraction)
  - ◇ Improved Born Approximation (IBA)
    to parametrize line-shape via pseudo-obs.
    ($+$ precise concept to treat non-resonant parts)
  - ◇ careful validation of IBA against full $\mathrm{e}^+\mathrm{e}^- \to \mathrm{Z}/\gamma \to f\bar{f}$ prediction

$\hookrightarrow$ Impact on experimental analysis possible
(continuum subtraction, self-consistency conditions, etc.)

WW production and W-boson mass

W-boson mass measurements vs. prediction from μ decay

ILC: Baak et al., 1310.6708 FCC-ee: Update of Blondel et al., 1901.02648 (in prep.)

	experimental accuracy				theory uncertainty				
		σ_{WW} @ threshold			intrinsic			parametric	
	current	LEP2	ILC	FCC-ee	current	source	prospect	prospect	source
ΔM_W[MeV]	13	200	3–6	0.5–1	3	$\alpha^3, \alpha^2\alpha_s$	1	1(0.6)	$\Delta\alpha_{had}$

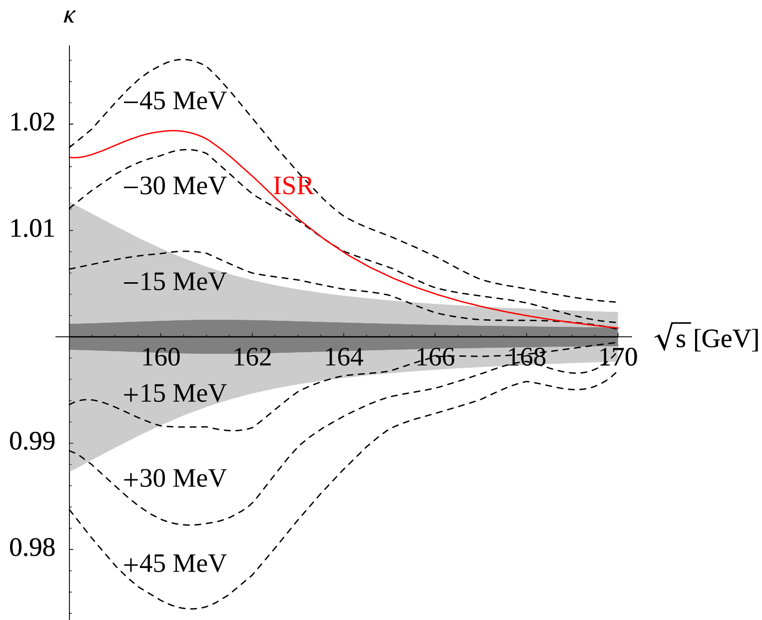
complicated reconstructions (current)

basically counting experiments (σ_{WW} @ threshold)

M_W calculated from μ decay (theory uncertainty)

Sensitivity of σ_{WW} to M_W:

Beneke et al. '07



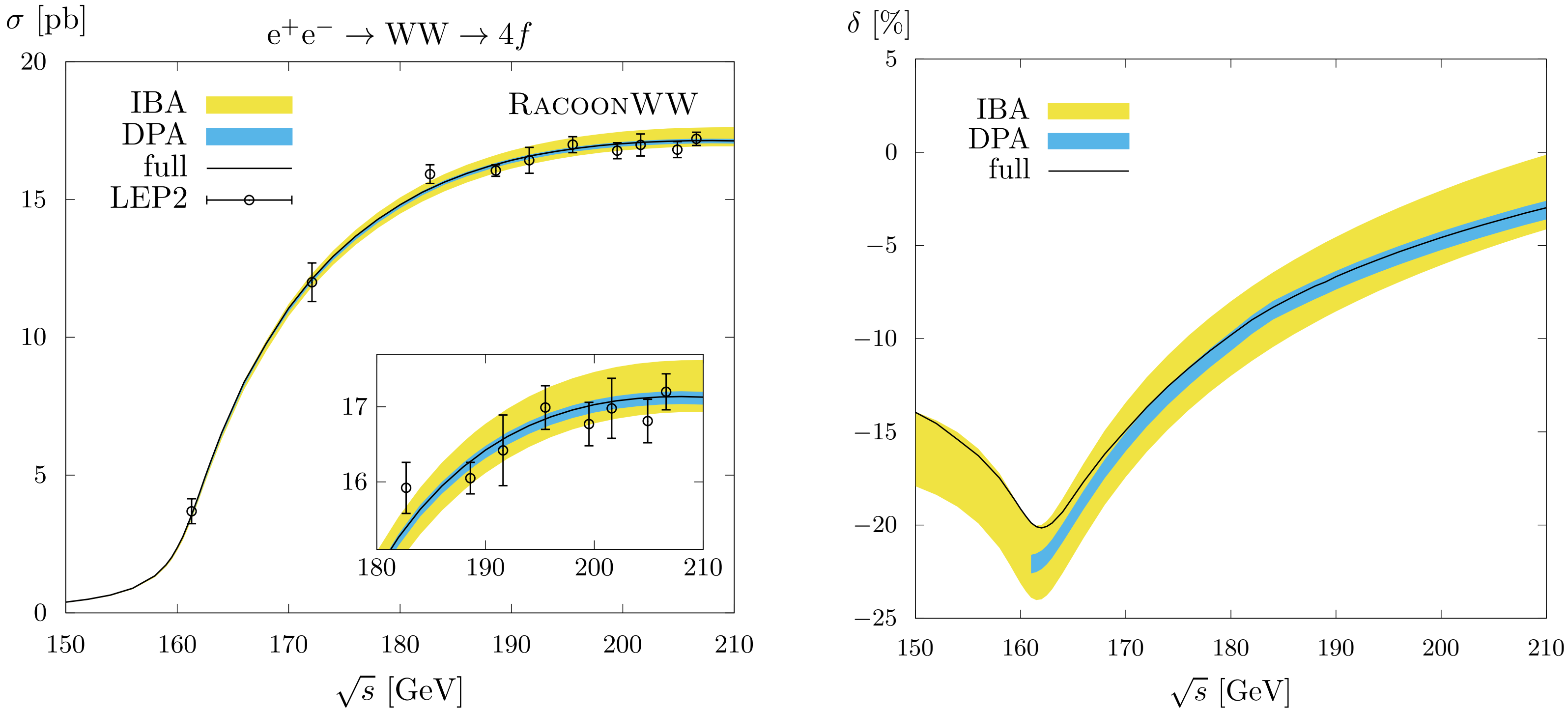
$$\kappa = \frac{\sigma_{WW}(s, M_W + \delta M_W)}{\sigma_{WW}(s, M_W)}$$

$\Delta\kappa = 0.1\%\,(0.02\%) \;\leftrightarrow\; \delta M_W = 1.5\,(0.3)\,\text{MeV}$
for $\sqrt{s} = 161\,\text{GeV}$

$\Rightarrow$ FCC-ee requires $\Delta_{TH} \sim 0.02\%$ in σ_{WW}

Shaded areas / ISR curve:
some uncertainties of NLO(EFT) calculation,
improveable via full NLO($ee \to 4f$) and NNLO(EFT)

State-of-the-art prediction of σ_{WW} in LEP2 energy range



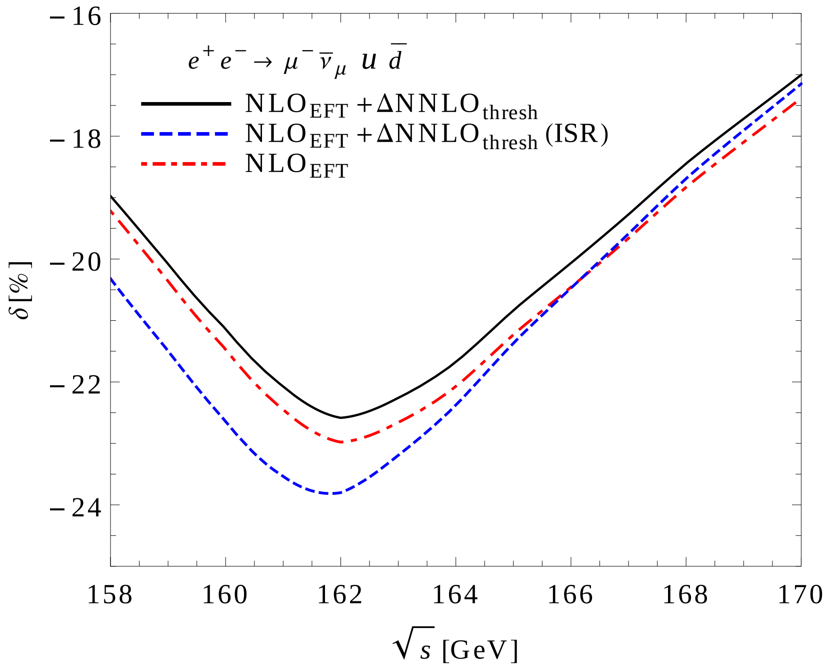
- IBA = based on leading-log ISR and universal EW corrections ($\Delta \sim 2\%$)
  $\hookrightarrow$ shows large ISR impact near threshold (also by GENTLE)
- DPA = "Double-Pole Approximation" (leading term of resonance expansion)
  $\hookrightarrow$ $\Delta \sim 0.5\%$ above threshold, not applicable at threshold — RacoonWW, YFSWW
- "full" = full NLO prediction for $\mathrm{e}^+\mathrm{e}^- \to 4f$ via charged current — Denner at al. '05
  $+$ leading-log improvements for ISR beyond NLO
  $\hookrightarrow$ $\Delta \sim 0.5\%$ everywhere

Improvements for $\sigma_{\rm WW}$ @ threshold via EFT Beneke et al. '07; Actis et al. '08

EFT provides expansion of $\sigma_{\rm WW}$ for $\beta = \sqrt{1-4M_{\rm W}^2/s} \sim \sqrt{\Gamma_{\rm W}/M_{\rm W}} \sim \sqrt{\alpha}$:

$$\sigma_{\rm WW} = C\alpha^2\beta\Bigg[1 + c^{(0)}\beta \qquad \text{LO}$$
$$+ \alpha\left(\frac{c_1^{(1)}}{\beta} + c_2^{(1)}\ln\beta L_{\rm e} + c_3^{(1)} L_{\rm e} + c_4^{(1)} + c_5^{(1)}\beta\right) \qquad \text{NLO}$$
$$+ \underbrace{\alpha^2\left(\frac{c_1^{(2)}}{\beta^2} + \frac{c_2^{(2)}}{\beta} + c_3^{(2)}\ln^2\beta L_{\rm e}^2 + c_4^{(2)}\ln\beta L_{\rm e}^2 + \dots\right)}_{\text{leading NNLO parts known}} + \dots\Bigg] \qquad \text{NNLO}$$

NNLO ↓ required for FCC-ee



ISR enhancement factor $L_{\rm e} = \ln(m_{\rm e}/M_{\rm W})$

Resummation of leading $(\alpha L_{\rm e})^n$ and subleading $\alpha(\alpha L_{\rm e})^{n-1}$ ISR necessary!

Theory issues in scan of $\sigma_{\mathrm{WW}}(s)$ over WW threshold

- Definition of σ_{WW} via $4f$ final states
  - ◇ $\mathrm{e}^{\pm}$ final states: separation or inclusion of single-W channels?
    $\hookrightarrow$ TH precision versus EXP accuracy
  - ◇ Hadronic final states: separation of multi-jet events (2j,3j,4j,. . .)
    $\hookrightarrow$ TH precision versus EXP accuracy
- Required for the best achievable theory prediction for σ_{WW}:
  - ◇ Full NLO $\mathrm{e}^+\mathrm{e}^- \to 4f$ prediction for each $4f$ type
    (interferences with ZZ and forward-$\mathrm{e}^{\pm}$ channels)
  - ◇ full NNLO EFT calculation (only leading terms available)
  - ◇ leading 3-loop Coulomb-enhanced EFT corrections
  - ◇ matching of all fixed-order $\mathrm{e}^+\mathrm{e}^- \to 4f$ and threshold-EFT ingredients
  - ◇ convolution of matched and corrected XS with higher-order ISR

  $\hookrightarrow$ Estimate of theory uncertainty: $\Delta \sim 0.01$–0.04% for σ_{WW} @ threshold

  Update of Blondel et al., 1901.02648 (in preparation)

Improved M_{W} prediction from μ decay

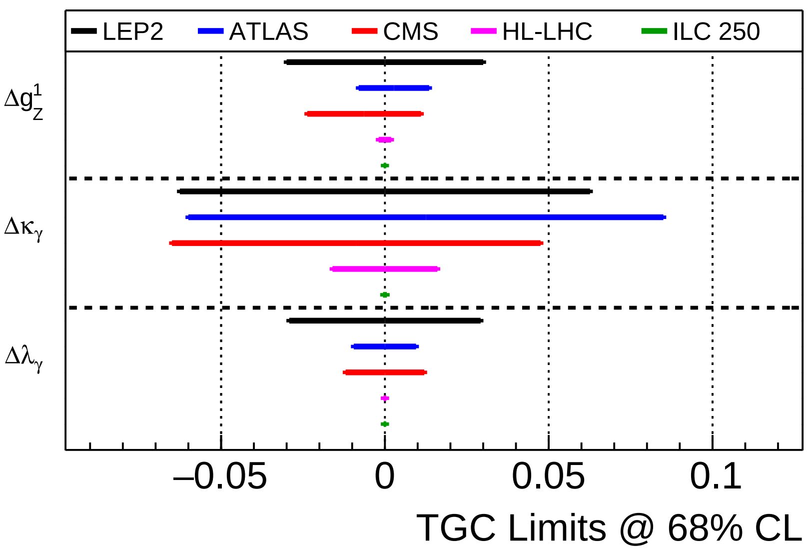
- Massive 3-loop computations (vacuum graphs, self-energies)

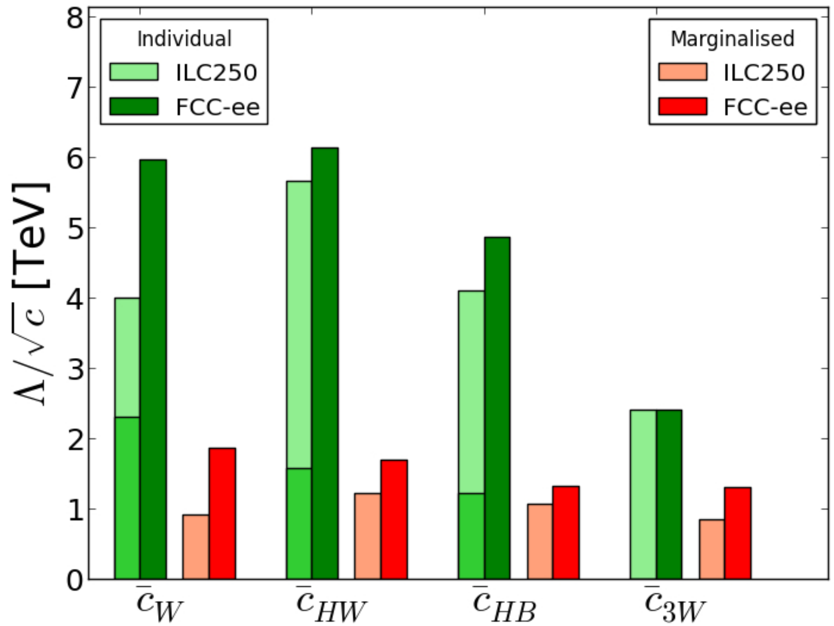
WW production beyond LEP2 energy range

- Ideal for precision study of anomalous TGCs (no formfactors for damping required)
- SMEFT framework:
  sensitivity to dim-6 operators complementary to Higgs analyses

Ellis, You '15

Bambade et al. '19





- Impact of $\Delta\kappa_\gamma$ on $\mathrm{d}\sigma_{\mathrm{WW}}$:

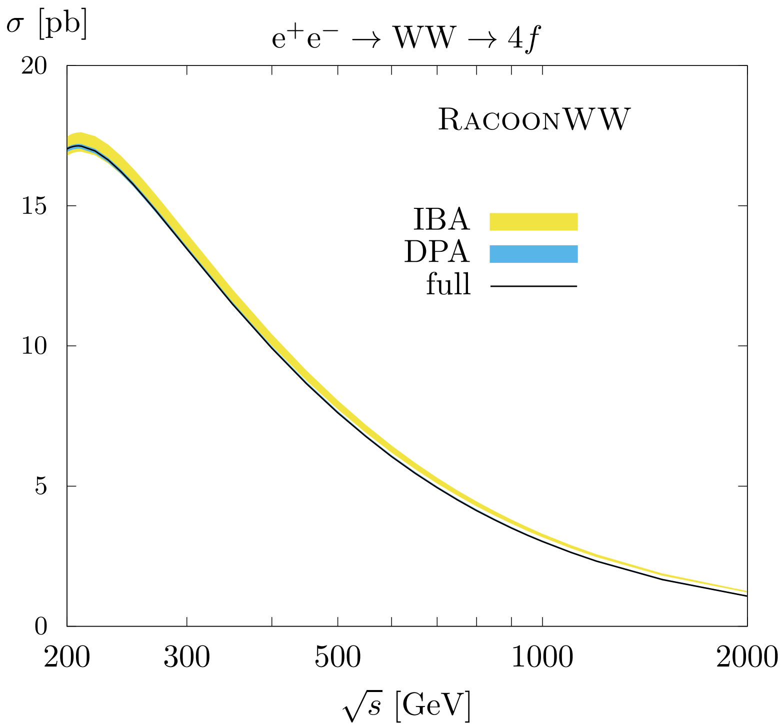
$\sqrt{s}/\mathrm{GeV}$	200	250	500
$\Delta\kappa_\gamma$	0.05	0.004	0.001
$\mathrm{d}\sigma_{\mathrm{WW}}(\kappa_\gamma)/\mathrm{d}\sigma_{\mathrm{WW}}^{\mathrm{SM}} - 1$	3%	$\sim 0.5\%$	$\sim 0.5\%$

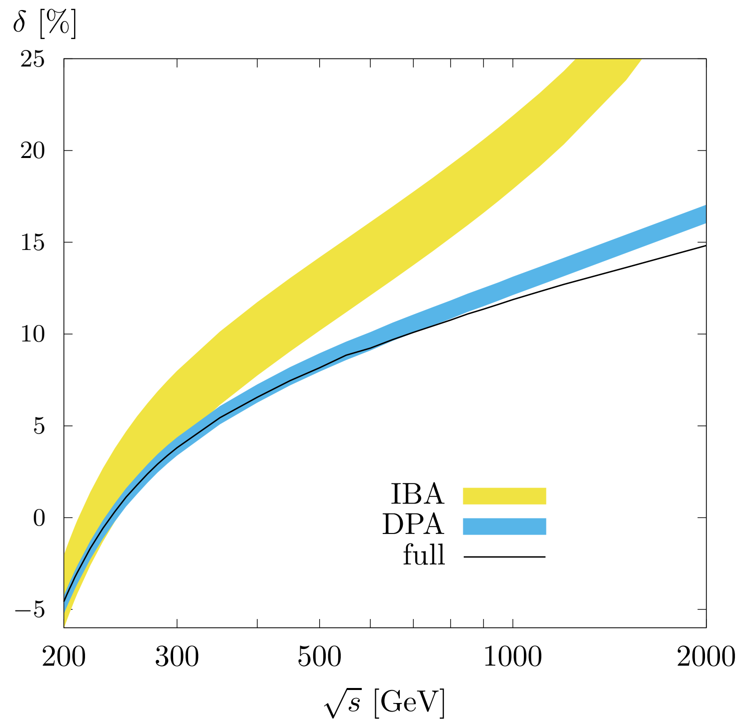
$\hookrightarrow$ SM precision limits reach in TGCs for moderate $\sqrt{s}$!

WW production beyond LEP2 energy range

Fixed-order NLO + leading-log ISR prediction:

Denner at al. '05





Note: large non-universal weak corrections + sizeable off-shell effects

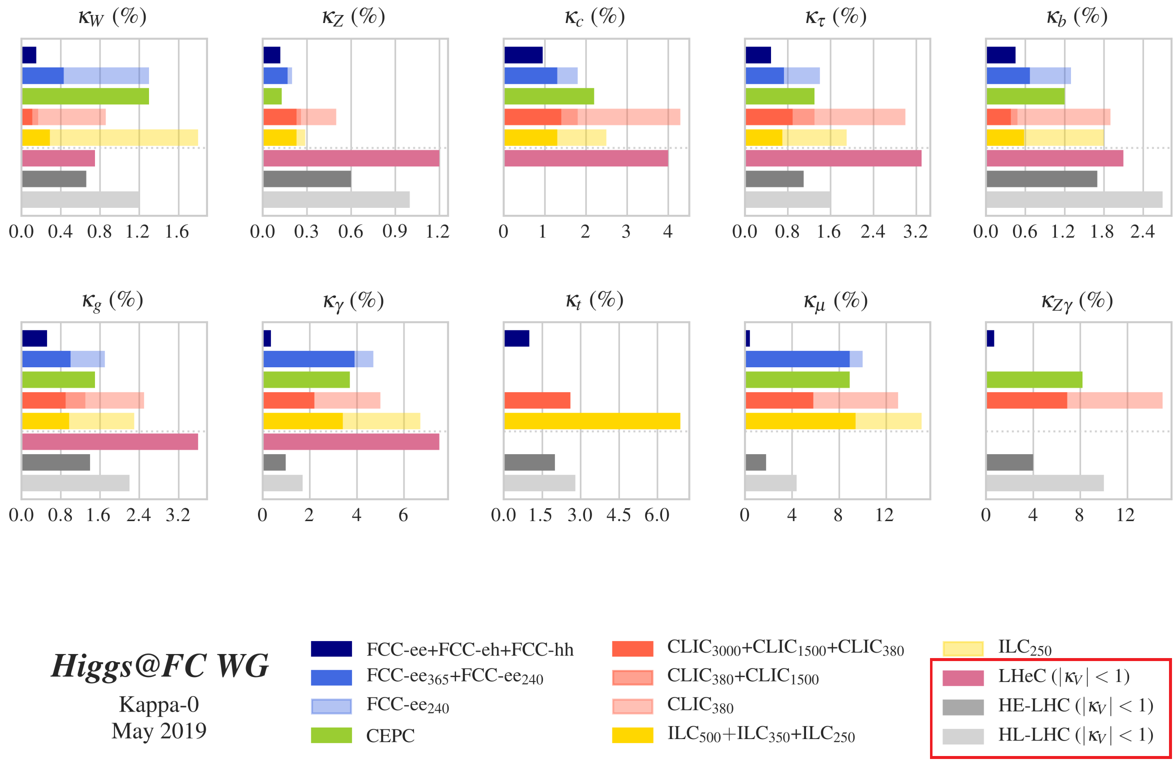
Achievable precision:

- by full NLO for $e^+e^- \to 4f$ + leading NNLO corrections + ISR resummation
- estimate: $\Delta \sim 0.5\%$ in distributions ($\sim 1\%$ in tails) up to $\sqrt{s} \sim 1\,\mathrm{TeV}$

e^+e^- colliders as Higgs factories

Higgs couplings analyses at present and future colliders

de Blas et al., 1905.03764



- Many different assumptions in different analyses! Read fine-print!
  Important details: $\Gamma_{\mathrm{H,BSM}} = 0$? $|\kappa_{\mathrm{W}}|, |\kappa_{\mathrm{Z}}| \le 1$? $\kappa_\gamma, \kappa_{\mathrm{g}}$ independent?
- Theory limitations!
  H couplings $\neq$ free parameters, rescaled model $\neq$ consistent field theory
  $\hookrightarrow$ QCD corrections often ok, but EW corrections $(\sim 5\%)$ inconsistent!
  $\hookrightarrow$ Coupling rescalings (e.g. κ framework) uncertain to $\sim 5\%$!
  $\Rightarrow$ Use EFT like SM-EFT (with corrections)!

Higgs decay widths and Higgs couplings at ILC and FCC-ee

LHC HXS WG; de Blas et al., 1905.03764; HL-LHC: Cepeda et al., 1902.00134;
ILC: Bambade et al., 1903.01629 FCC-ee: update of Blondel et al., 1901.02648 (in prep.)

	experimental accuracy			theory uncertainty			param. unc.	
	HL-LHC	ILC250	FCC-ee	current	source	prospect	prospect	source
$H \to b\bar{b}$	4.4%	2%	0.8%	0.4%	α_s^5	0.2%	0.6%	m_b
$H \to \tau\tau$	2.9%	2.4%	1.1%	0.3%	α^2	0.1%	negligible	
$H \to \mu\mu$	8.2%	8%	12%	0.3%	α^2	0.1%	negligible	
$H \to gg$	1.6% (prod.)	3.2%	1.6%	3.2%	α_s^4	1%	0.5%	α_s
$H \to \gamma\gamma$	2.6%	2.2%	3.0%	1%	α^2	1%	negligible	
$H \to \gamma Z$	19%			5%	α	1%	0.1%	M_H
$H \to WW$	2.8%	1.1%	0.4%	0.5%	$\alpha_s^2, \alpha_s\alpha, \alpha^2$	0.3%	0.1%	M_H
$H \to ZZ$	2.9%	1.1%	0.3%	0.5%	$\alpha_s^2, \alpha_s\alpha, \alpha^2$	0.3%	0.1%	M_H

Note: e^+e^- colliders from $\sigma_{e^+e^-\to ZH}$ with *inclusive* Higgs decays!
$\hookrightarrow$ Absolute normalization of Higgs BRs

Theory issues:

- Higgs off-shell effects: $\Gamma_{\mathrm{H}}/M_{\mathrm{H}} \sim 0.00003$ (compare: $\Gamma_{\mathrm{Z}}/M_{\mathrm{Z}} \sim 0.03$)
  - ◇ if Higgs fully reconstructable $\to$ isolation of Higgs pole via cuts
    $\hookrightarrow$ factorization of XS into production and decay parts
    (straightforward check at LO and NLO)
  - ◇ if Higgs not fully reconstructable (e.g. $\mathrm{H} \to \mathrm{WW} \to 2\ell 2\nu$)
    $\hookrightarrow$ inclusion of off-shell effects required (full off-shell NLO calculations)
- Multi-loop vertex corrections:
  - ◇ massive 2-loop vertex corrections (NNLO EW)
  - ◇ massless multi-loop corrections (4-/5-loop QCD for $\mathrm{H} \to \mathrm{b\bar{b}}/\mathrm{gg}$)
- 2-loop corrections for $\mathrm{e^+e^-} \to \mathrm{ZH}, \nu\bar{\nu}\mathrm{H}$:
  - ◇ full NNLO calculation for σ_{ZH}
  - ◇ leading NNLO effects for $\sigma_{\nu\bar{\nu}\mathrm{H}}$
- Physics beyond the SM:
  - ◇ model independent: EFT approaches with higher-order corrections
  - ◇ specific models: full NLO studies (+beyond if relevant)

Conclusions

ILC and FCC-ee have great potential for high-precision Z, WW, and Higgs physics

Can theory provide the necessary precision?

$\hookrightarrow$ Optimists: "Yes. No show-stoppers seen, great progress can be anticipated."

Sceptics: "Enormous challenge! Conceptual progress difficult to extrapolate."

Some warnings:

- Produce solid and conservative uncertainty estimates!
- Always combine experimental and theoretical uncertainties!
- Employ different theoretical strategies and exp. analyses as much as possible! (e.g. for α_{s}, $\Delta\alpha_{\mathrm{had}}$)

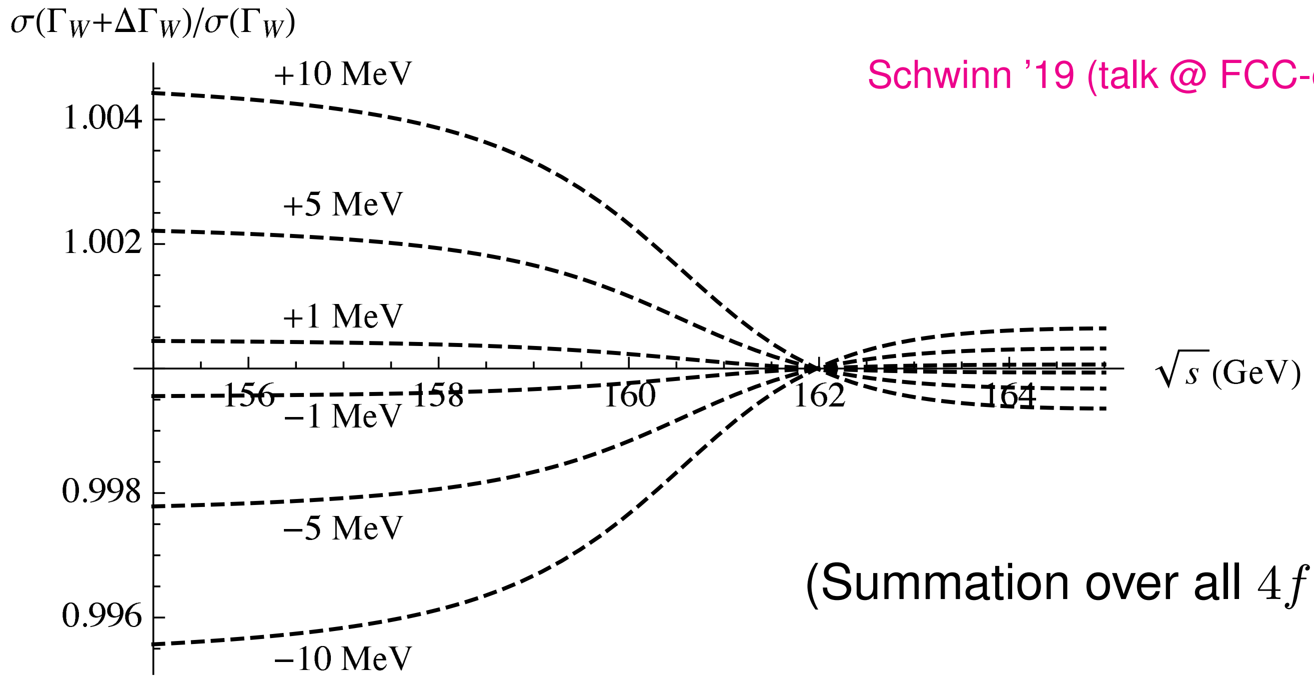
The greatest challenges: (+ many more very demanding tasks)

- Z:
  - ◇ full EW 2-loop calculation for off-shell $\mathrm{e}^+\mathrm{e}^- \to f\bar{f}$ + theoretically sound concept of pseudo-obervables
  - ◇ massive 3-loop calculations for $1 \to 2$ decays and μ decay
- WW:
  - ◇ NNLO threshold EFT calculation for $\mathrm{e}^+\mathrm{e}^- \to \mathrm{WW}$
- Higgs:
  - ◇ full EW 2-loop calculation for off-shell $\mathrm{e}^+\mathrm{e}^- \to \mathrm{ZH}$
  - ◇ massless 4-/5-loop QCD calculations for $1 \to 2$ decays

$\hookrightarrow$ Certainly takes another generation of bright minds!

Backup slides

Γ_W determination from energy scan @ WW threshold:



Schwinn '19 (talk @ FCC-ee Workshop, CERN)

(Summation over all $4f$ states)

Simultaneous fit of M_W and Γ_W by scan of σ_{WW}:

- FCC-ee study: 1703.01626

  2-point fit ($15\,\mathrm{ab}^{-1}$): $M_W = 0.41\,\mathrm{MeV},\ \Gamma_W = 1.1\,\mathrm{MeV}$

- CEPC study: 1812.09855

  3-point fit ($2.6\,\mathrm{ab}^{-1}$): $M_W = 1\,\mathrm{MeV},\ \Gamma_W = 2.8\,\mathrm{MeV}$