SECOND • ECFA • WORKSHOP

on e^+e^- Higgs / Electroweak / Top Factories

11-13 October 2023
Paestum / Salerno / Italy

M_W @ future e^+e^- colliders

Topics:

- Physics potential of future Higgs and electroweak/top factories
- Required precision (experimental and theoretical)
- EFT (global) interpretation of Higgs factory measurements
- Reconstruction and simulation
- Software
- Detector R&D

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W-boson mass measurements vs. prediction from μ decay

ILC: Baak et al., 1310.6708 FCC-ee: Freitas et al., 1906.05379

	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)	$\Delta\alpha_{had}$

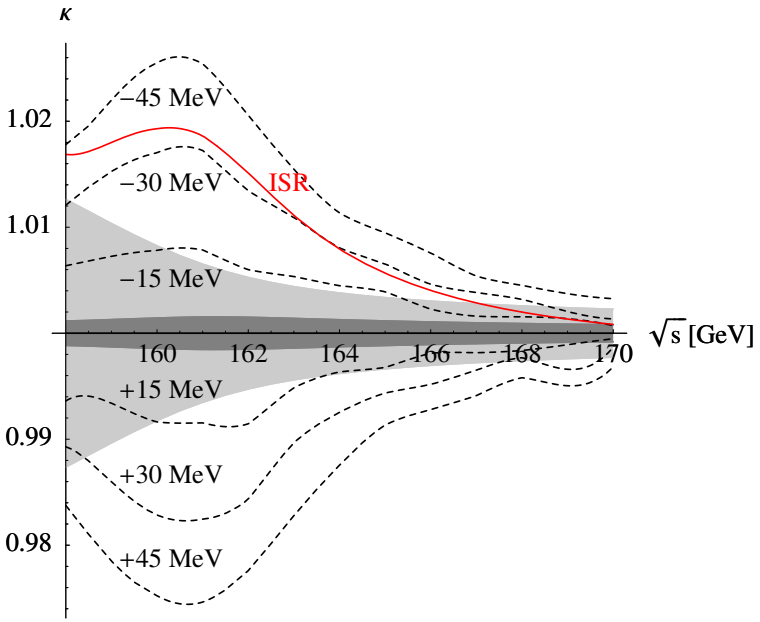
complicated reconstructions

basically counting experiments

M_W calculated from μ decay

Sensitivity of σ_{WW} to M_W:

Beneke et al. '07



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

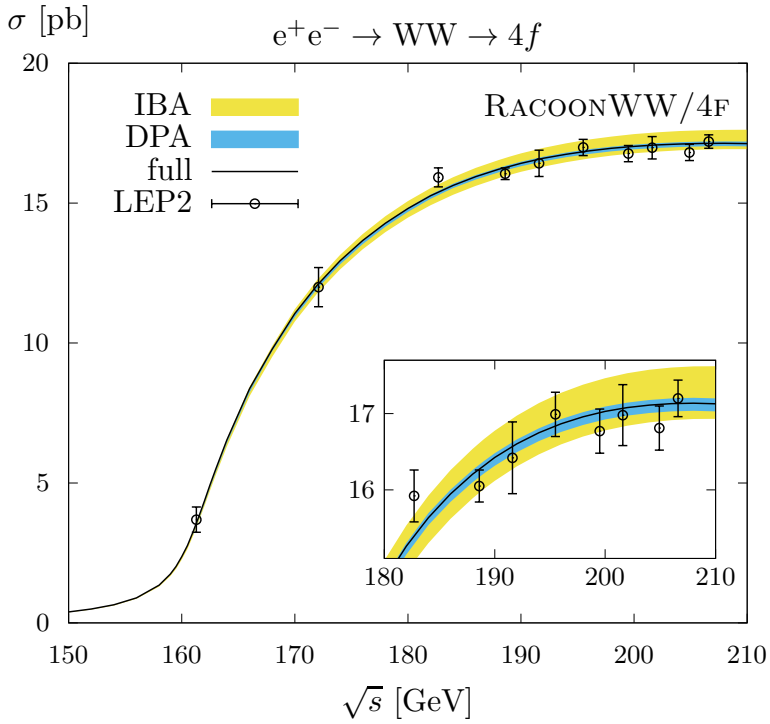
$\Delta\kappa = 0.1\%\,(0.02\%) \leftrightarrow \delta M_W = 1.5\,(0.3)\,\mathrm{MeV}$
for $\sqrt{s} = 161\,\mathrm{GeV}$

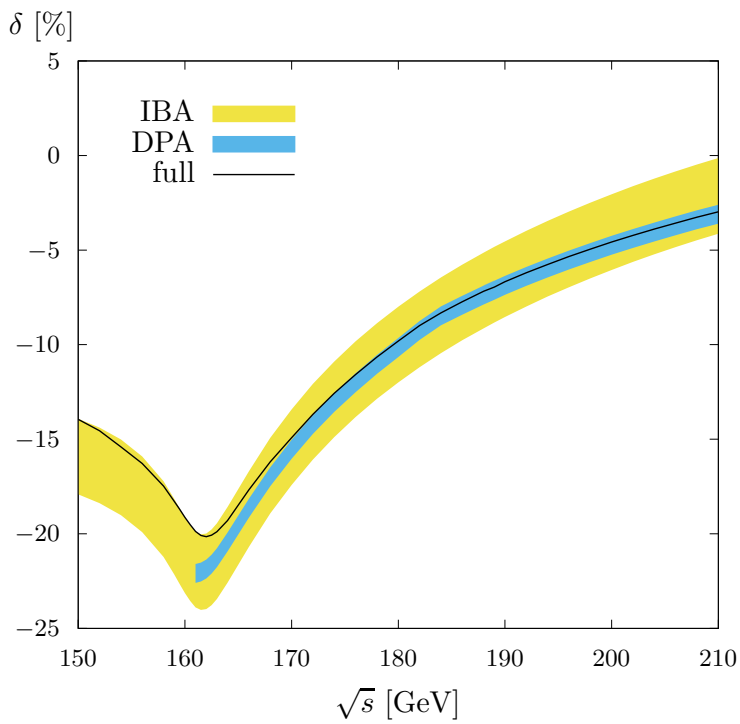
$\Rightarrow$ FCC-ee requires $\Delta_{TH} \sim 0.02\%$ in σ_{WW}

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

Denner, S.D., 1912.06823





- 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 $e^+e^- \to 4f$ via charged current Denner et al. '05
  + leading-log improvements for ISR beyond NLO
  $\hookrightarrow$ $\Delta \sim 0.5\%$ everywhere

Improvements for σ_{WW} @ threshold via EFT

Beneke et al. '07; Actis et al. '08

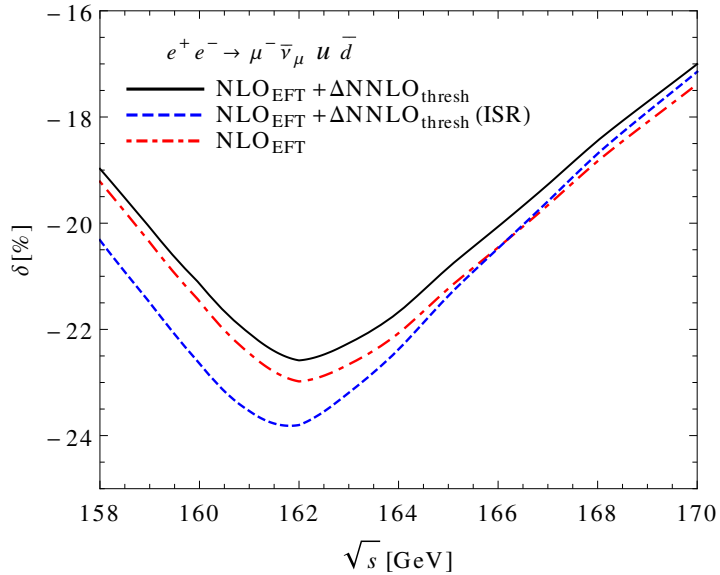
EFT provides expansion of σ_{WW} for $\beta = \sqrt{1-4M_{\mathrm{W}}^2/s} \sim \sqrt{\Gamma_{\mathrm{W}}/M_{\mathrm{W}}} \sim \sqrt{\alpha}$:

$$\sigma_{\mathrm{WW}} = C\alpha^2\beta\Big[\, 1 + c^{(0)}\beta \qquad \text{LO}$$

$$+ \alpha\left(\frac{c_1^{(1)}}{\beta} + c_2^{(1)}\ln\beta L_{\mathrm{e}} + c_3^{(1)}L_{\mathrm{e}} + c_4^{(1)} + c_5^{(1)}\beta\right) \qquad \text{NLO}$$

$$+ \alpha^2\underbrace{\left(\frac{c_1^{(2)}}{\beta^2} + \frac{c_2^{(2)}}{\beta} + c_3^{(2)}\ln^2\beta L_{\mathrm{e}}^2 + c_4^{(2)}\ln\beta L_{\mathrm{e}}^2 + \ldots\right)}_{\text{leading NNLO parts known}} + \ldots\Big] \qquad \text{NNLO}$$

↓ required for FCC-ee



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

Resummation of leading $(\alpha L_{\mathrm{e}})^n$ and subleading $\alpha(\alpha L_{\mathrm{e}})^{n-1}$ 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

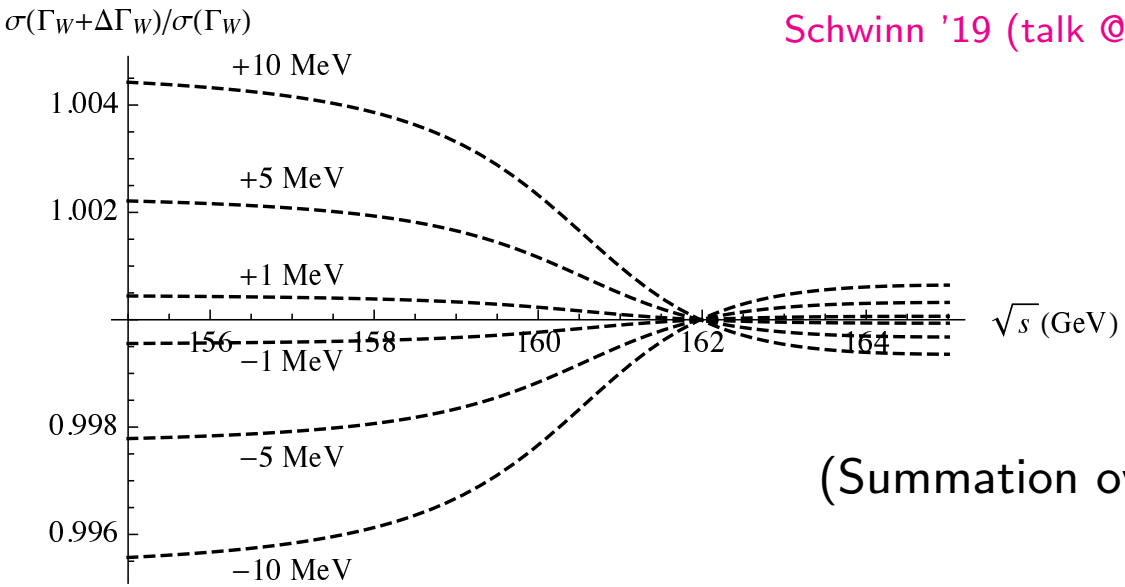
  $\hookrightarrow$ Estimate of theory uncertainty:

  $\Delta \sim 0.01\text{–}0.04\%$ for σ_{WW} @ threshold Freitas et al., 1906.05379

Improved M_{W} prediction from μ decay

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

Γ_W determination from energy scan @ WW threshold:



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

(Summation over all $4f$ states)

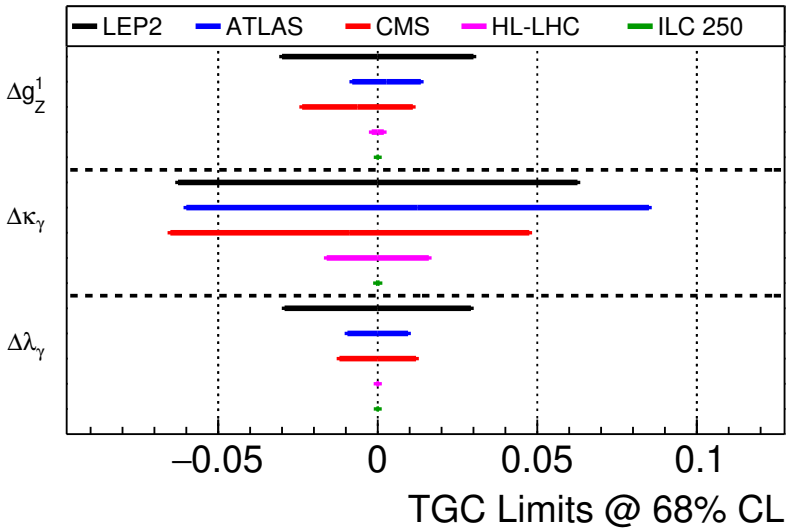
Simultaneous fit of M_W and Γ_W by scan of σ_{WW}:

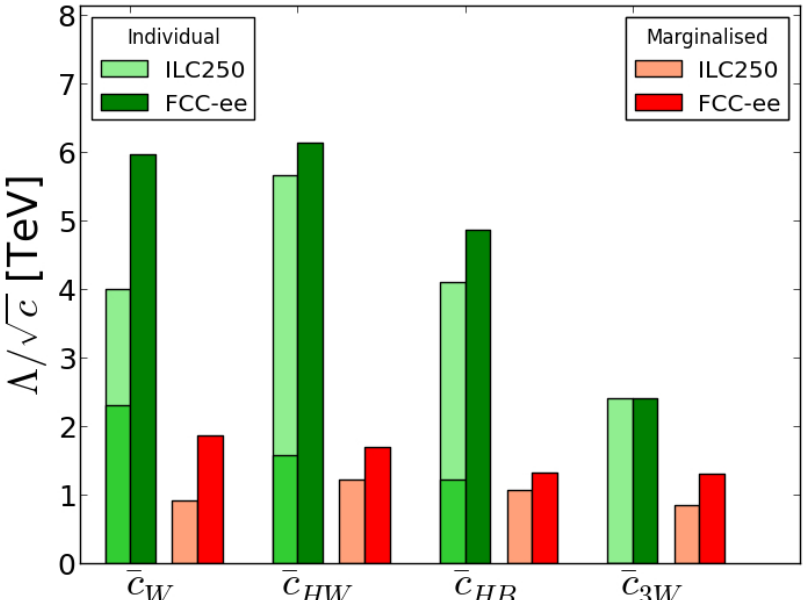
- FCC-ee study: 1703.01626
  2-point fit ($15\,\mathrm{ab}^{-1}$): $M_W = 0.41\,\mathrm{MeV},\ \Gamma_W = 1.1\,\mathrm{MeV}$
- CEPC study: 1812.09855
  3-point fit ($2.6\,\mathrm{ab}^{-1}$): $M_W = 1\,\mathrm{MeV},\ \Gamma_W = 2.8\,\mathrm{MeV}$

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 $\mathrm{d}\sigma_{\mathrm{WW}}$:

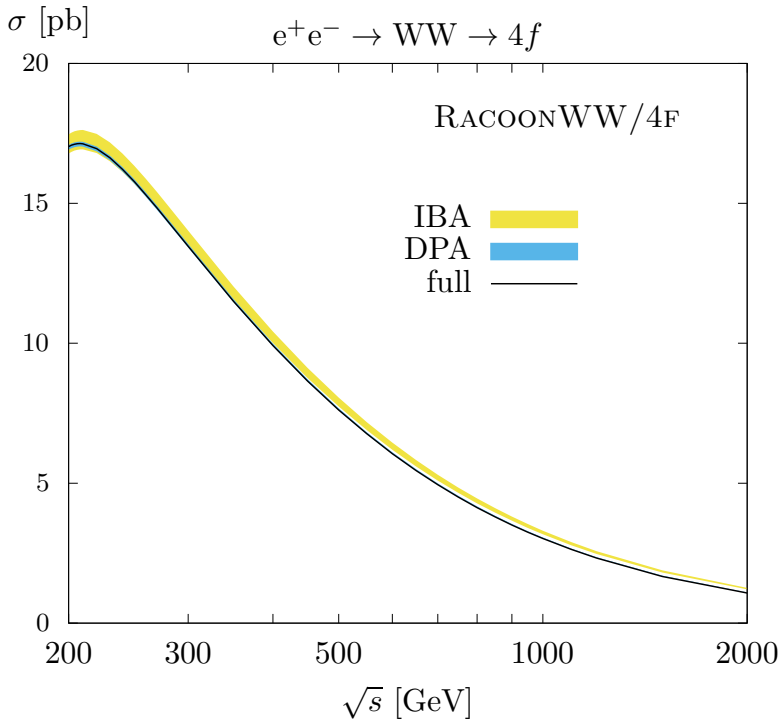
$\sqrt{s}/\mathrm{GeV}$	200	250	500
$\Delta\kappa_\gamma$	0.05	0.004	0.001
$\mathrm{d}\sigma_{\mathrm{WW}}(\kappa_\gamma)/\mathrm{d}\sigma^{\mathrm{SM}}_{\mathrm{WW}} - 1$	3%	$\sim 0.5\%$	$\sim 0.5\%$

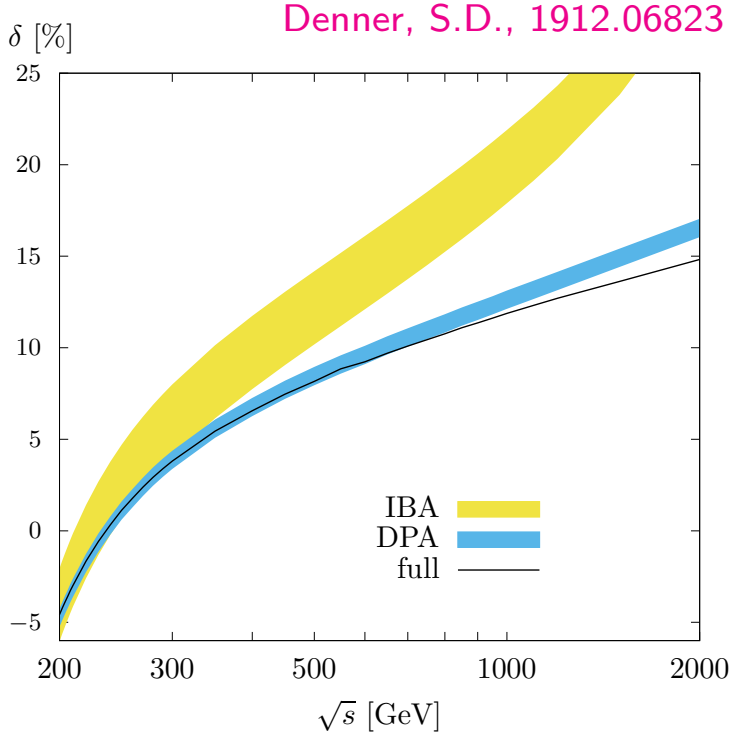
$\hookrightarrow$ SM precision limits reach in TGCs for moderate $\sqrt{s}$!

WW production beyond LEP2 energy range

Fixed-order NLO + leading-log ISR prediction:

Denner, S.D., 1912.06823





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 $\sqrt{s} \sim 1\,\mathrm{TeV}$