Status and perspectives for diboson theory predictions

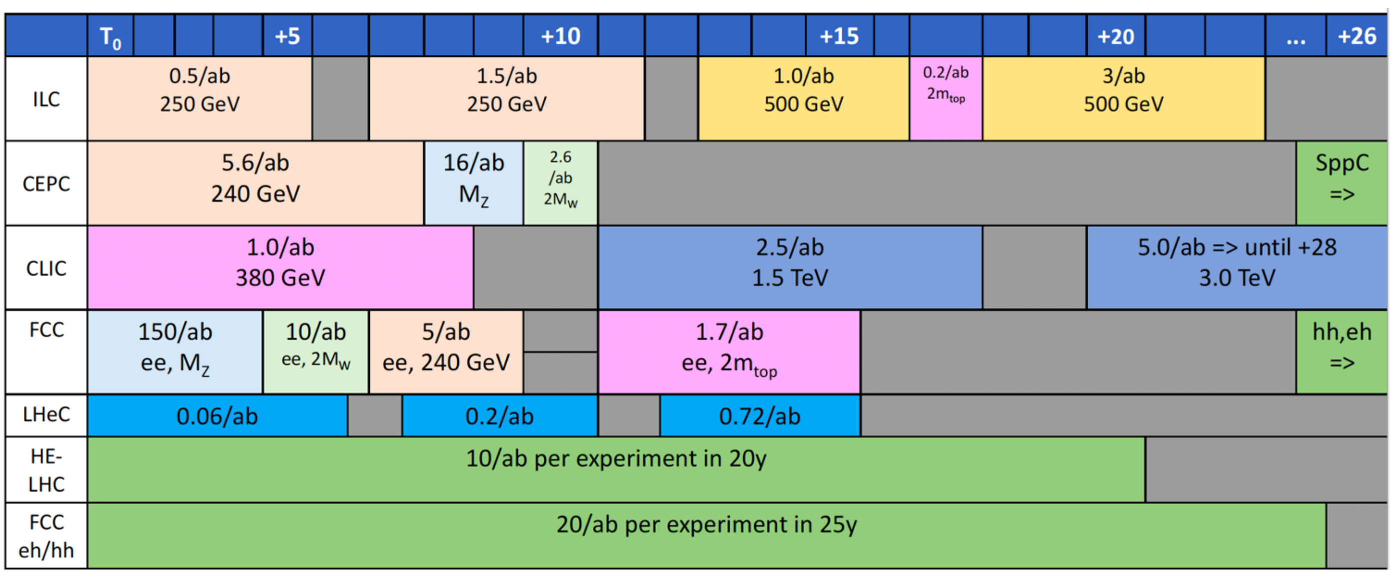
Christian Schwinn

— RWTH Aachen —

26 October, 2020

Diboson production $e^- e^+ \to VV' \to 4f$

- Explored at LEP 2 with $\mathcal{L} = 3\,\mathrm{fb}^{-1}$ from $\sqrt{s} = 161.3\text{-}206.6$ GeV
- Precision tests of standard model:
  - measurement of cross sections, m_W, Γ_W, triple-vector boson couplings
- Pushes methods of perturbative QFT for complicated processes:
  - gauge invariant definition of signals, consistent treatment of finite-width effects
  - many Feynman diagrams with different scales
- Important for precision physics at any future $e^- e^+$ collider



4-fermion signatures at LEP

(Schael et al. 2013)

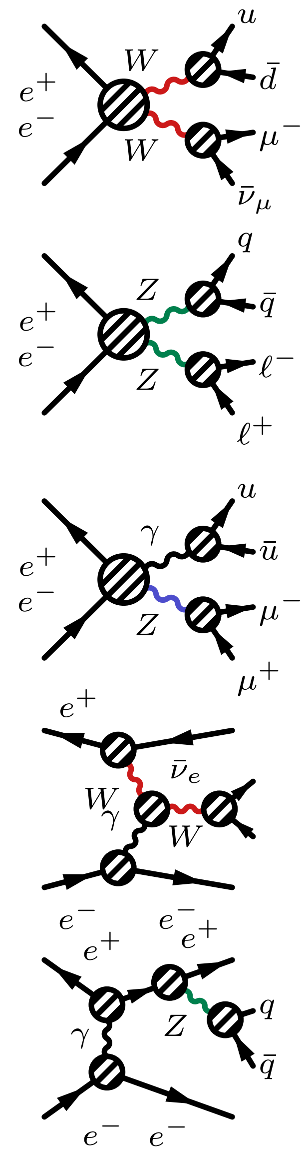
WW: σ_{WW}, M_W, Γ_W,BR_W,
anomalous couplings

ZZ: σ_{ZZ}

$Z\gamma$: $\sigma_{Z\gamma}$, anomalous couplings

$We\nu$: $\sigma_{We\nu}$,, anomalous couplings

Zee: σ_{Zee}



4-fermion signatures at LEP

(Schael et al. 2013)

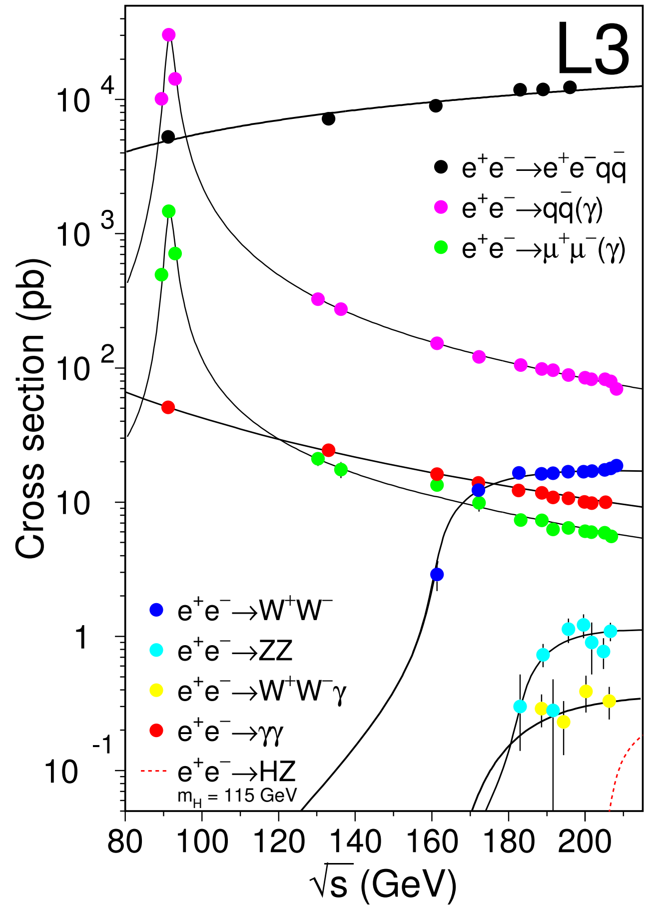
WW: σ_{WW}, M_W, Γ_W,BR_W,
anomalous couplings

ZZ: σ_{ZZ}

$Z\gamma$: $\sigma_{Z\gamma}$, anomalous couplings

$We\nu$: $\sigma_{We\nu}$,, anomalous couplings

Zee: σ_{Zee}



Theory for LEP2 (Grünewald et al. 2000)

- various NLO approximations
  (Pole appprox, fermion-loop scheme)
- dedicated process specific programs (RacoonWW (Denner et al.), YFSWW (Jadach et al.), WPHACT (Accomando/Ballestrero), WTO (Passarino), . . .)
- residual theory uncertainty $\Delta\sigma_{WW} \sim 0.5\%$ . . . $\Delta\sigma_{We\nu} \sim 5\%$

Theory challenges for diboson production at CEPC

Higgs factory mode

- Cross section with $\Delta\sigma_{WW} \sim 0.1\%$
- $\Delta M_W \sim 2.5\text{-}3$ MeV from kinematic reconstruction
- anomalous coupling measurements

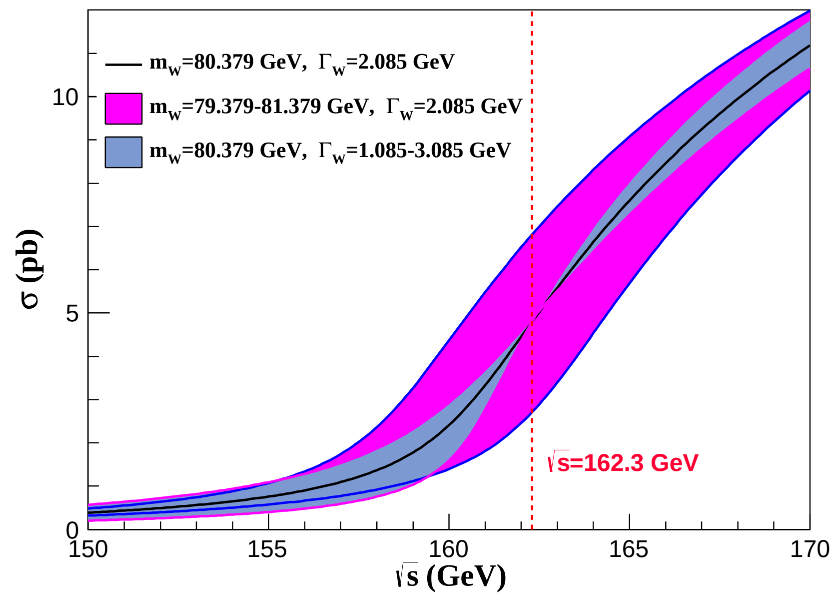
CEPC Mode	Z-factory	WW threshold	H factory
run time (y)	2	1	7
$\sqrt{s}$ [GeV]	91.2	158-172	240
$\mathcal{L}$ (ab^{-1})	8-16	2.6	5.6
W yield	-	10^7	10^8
Z yield	10^{11-12}	10^9	10^9

WW threshold

- Sensitivity to M_W

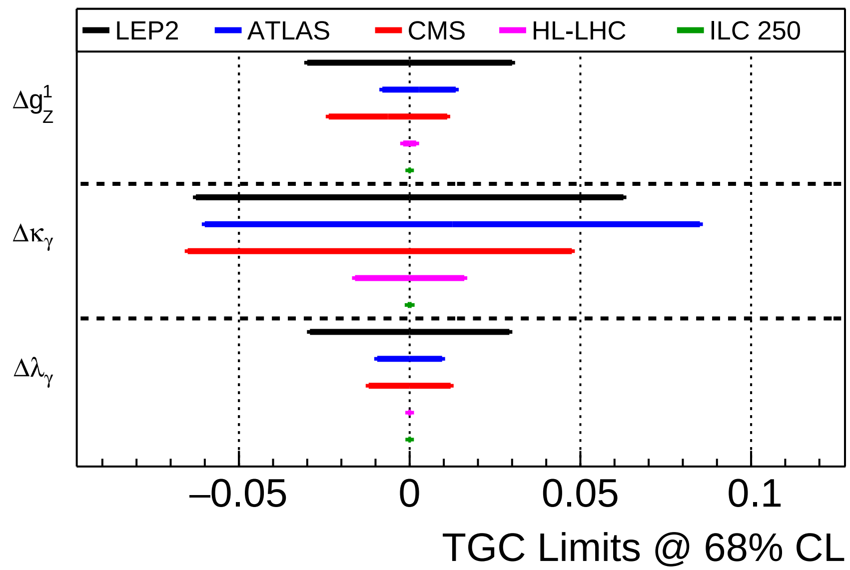
$$\Delta\sigma \sim 1\% \Leftrightarrow \Delta M_W \sim 15\,\text{MeV}$$

- CEPC sensitivity: (arXiv:1812.09855)
  $\Delta M_W \simeq 1\,\text{MeV},\ \Delta\Gamma_W \simeq 3.2\,\text{MeV}$
  (FCC-ee: $\Delta M_W \simeq 0.4\,\text{MeV},\ \Delta\Gamma_W \simeq 1.1\,\text{MeV}$)
- required theory precision
  $\delta\sigma_{WW}^{\text{th.}} < 0.01 - 0.05\%$



Beyond threshold: anomalous gauge couplings at $\sqrt{s} = 240\,\text{GeV}$

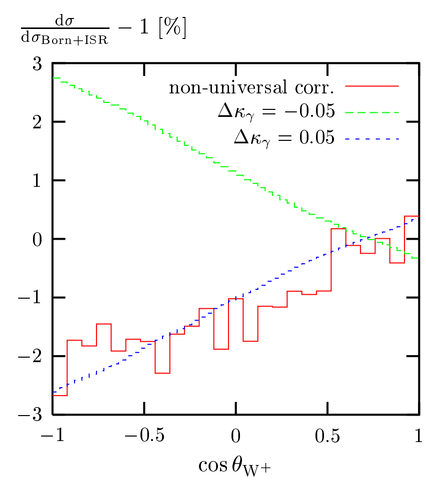
- traditional TGC parameters g_1^Z, $\kappa_{Z/\gamma}$, $\lambda_{Z/\gamma}$ related to coefficients of $D = 6$ operators , $\mathcal{L}_{D=6} = \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$
- recent SMEFT analyses of $e^-e^+ \to W^-W^+$ (Buchalla et al. 13; Bian et al. 15; Wells/Zhang 15; Ellis/You 15; Berthier et al. 16; de Blas et al. 19)
- some $\mathcal{O}_i$ affect both Higgs and EW measurements
  $\Rightarrow$ consistent EFT fit of FCC-ee data required



(Fujii et al. 17; ILC250: 2ab^{-1})

Beyond threshold: anomalous gauge couplings at $\sqrt{s} = 240\,\mathrm{GeV}$

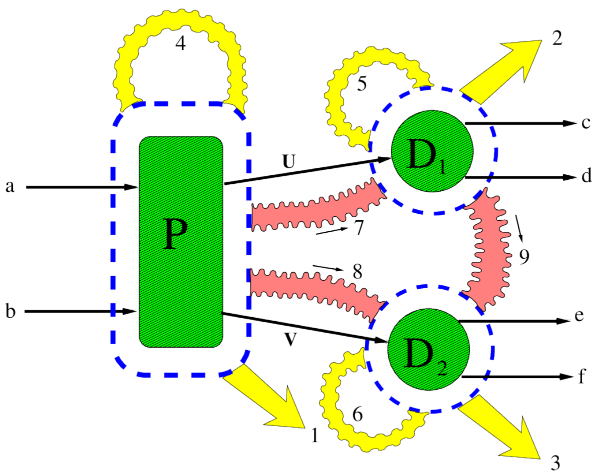
- traditional TGC parameters g_1^Z, $\kappa_{Z/\gamma}$, $\lambda_{Z/\gamma}$ related to coefficients of $D = 6$ operators , $\mathcal{L}_{D=6} = \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$
- recent SMEFT analyses of $e^-e^+ \to W^-W^+$ (Buchalla et al. 13; Bian et al. 15; Wells/Zhang 15; Ellis/You 15; Berthier et al. 16; de Blas et al. 19)
- some $\mathcal{O}_i$ affect both Higgs and EW measurements
  $\Rightarrow$ consistent EFT fit of FCC-ee data required
- Effect of non-universal EW corrections similar to size of TGCs accessible at LEP2
  (e.g, Denner et al. 01)



$\Rightarrow$ NNLO EW for $e^-e^+ \to W^-W^+$ required for FCC-ee accuracy

Double-pole expansion

- Systematic decomposition into factorizable corrections to production, decay; nonfactorizable soft photon corrections, non-resonant parts (Aeppli,v. Oldenbourgh, Wyler 93)
- Double pole approx. used at NLO for LEP2
  (RacoonWW (Denner et al. 99), YFSWW (Jadach et al. 99))
- Framework for YFS soft resummation also for non-factorizable corrections
  (Jadach et al. 19)
- extension to NNLO required for CEPC@240 GeV
- loss of accuracy near threshold



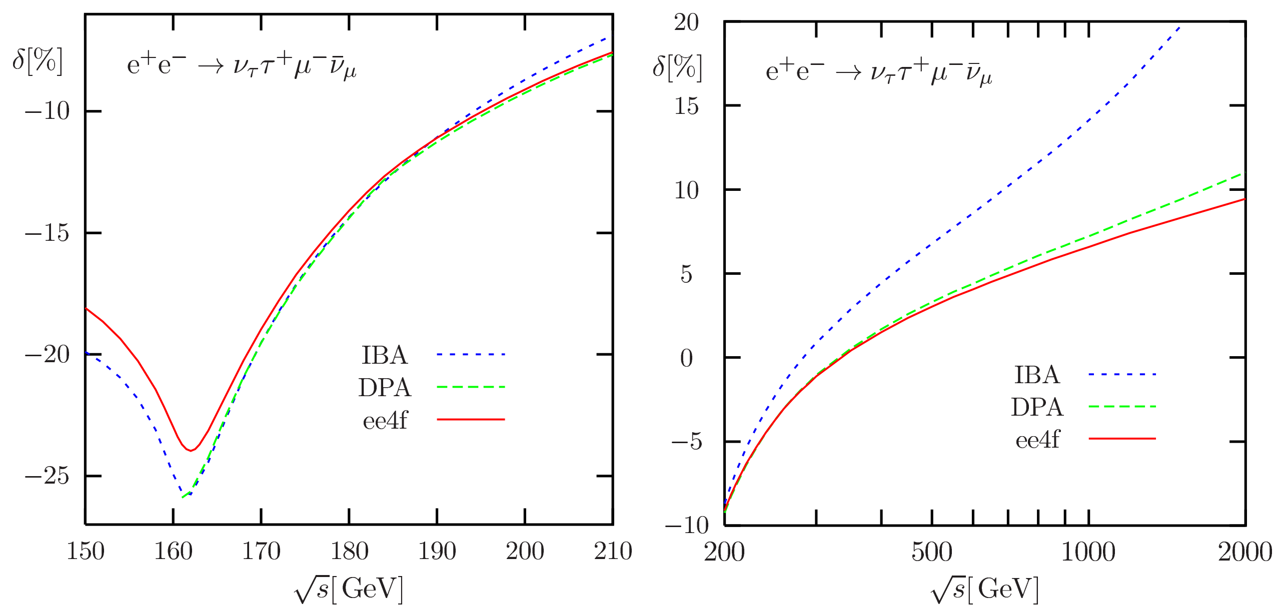
Full NLO calculation for $e^+e^- \to 4f$ (Denner, Dittmaier, Roth, Wieders 05)

- complex mass scheme for W decay width
- remaining uncertainty $\sim 0.5\%$ above and near threshold
- now possible with standard tools

  (`RECOLA, OpenLoops, MadLoops + SHERPA, MadGraph, ...` $\Rightarrow$ talk by Pellen)

  (implementations must be optimized for e^-e^+ (ISR, Beamstrahlung))

- Extension to NNLO very challenging ($\Rightarrow$ talks by Mandal, Buccioni);



NLO corrections near threshold

$$s - 4M_W^2 \sim M_W \Gamma_W \;\Rightarrow v \sim \sqrt{\Gamma_W/M_W} \sim \alpha^{1/2}$$

Schematic structure of NLO corrections to total cross section:

$$\Delta^{(1)}\sigma_{WW\to 4f}|_{s\approx 4M_W^2} \propto v\alpha \left[\frac{1}{v} + \ln v \ln\left(\frac{m_e}{M_W}\right) + \ln\left(\frac{m_e}{M_W}\right) + C^{(1)}\right] + \text{const} + \mathcal{O}(v)$$

Enhanced corrections in threshold limit

- mass logarithms $\ln\left(\frac{m_e}{M_W}\right)$: absorb in ISR structure functions

  (Skrzypek 92; $\overline{\text{MS}}$: fixed order: Blümlein et al. 11, Frixione 19, NLL: Bertone et al. 19)

- Coulomb corrections $\sim \alpha/v \sim$ screened by finite W-width

  $\Rightarrow$ Coulomb corrections $\sim \alpha^n (M_W/\Gamma_W)^{n/2} \sim \alpha^{n/2}$

  enhanced but resummation not necessary (Fadin et al. 95)

  (Method for all-order resummation known $\Rightarrow$ talk on $t\bar{t}$ by Hoang)

- soft $\ln v$ corrections $\sim \alpha \ln \alpha \sim 0.04$

  $\Rightarrow$ resummation not necessary

NLO corrections near threshold

$$s - 4M_W^2 \sim M_W\Gamma_W \Rightarrow v \sim \sqrt{\Gamma_W/M_W} \sim \alpha^{1/2}$$

Schematic structure of NLO corrections to total cross section:

$$\Delta^{(1)}\sigma_{WW\to 4f}|_{s\approx 4M_W^2} \propto v\alpha\left[\frac{1}{v} + \ln v \ln\left(\frac{m_e}{M_W}\right) + \ln\left(\frac{m_e}{M_W}\right) + C^{(1)}\right] + \text{const} + \mathcal{O}(v)$$

EFT expansion in $\alpha \sim \frac{\Gamma_W}{M_W} \sim v^2 \equiv \delta$ (Beneke/Falgari/CS/Signer/Zanderighi 07)

- systematically possible to include higher-order corrections
- worked out for total cross section near threshold
- difference of $\mathrm{NLO_{4f}}$ and $\mathrm{NLO_{EFT}}$ $\lesssim 1\%$

Leading NNLO corrections

- Coulomb-enhanced corrections $\sim \alpha^2/v^2, \alpha^2/v$ (Actis et al. 08)
  Numerical effect: $\Delta\sigma_{WW} \sim 0.5\%$; $[\delta M_W] \lesssim 3\,\mathrm{MeV}$

Prospects for CEPC/FCC-ee accuracy (CS in arXiv:1905.05078 [hep-ph])

How to achieve 0.01% accuracy for $e^-e^+ \to WW \to 4f$ near threshold?

Estimate size of NNLO-EFT corrections:

$$\mathcal{O}(\delta^2): \quad \underbrace{v^4}_{\text{Born}} \quad \underbrace{\alpha v^2}_{\text{included in NLO}_{4f}} \quad \underbrace{\alpha^2}_{\text{two-loop soft/hard}} \quad \underbrace{\alpha^3/v^2}_{\text{Coulomb-enhanced N}^3\text{LO}} \quad \underbrace{\alpha^4/v^4}_{\text{4th Coulomb}}$$

- $\mathcal{O}(\alpha^2)$ EFT corrections: estimate $C^{(2)} \approx (C^{(1)})^2$
  $\Delta\sigma_{\alpha^2} \approx 0.06\%$ $\Rightarrow$ mandatory for CEPC/FCC-ee
- subset of $\mathcal{O}(\alpha^3/v^2)$ corrections computable
  using known ingredients: (extension of Actis et al. 08)
  $\Delta\sigma_{\alpha^3} \sim 0.01\%$ $\Rightarrow$ relevant for CEPC/FCC-ee

Theory methods for WW threshold

Prospects for CEPC/FCC-ee accuracy (CS in arXiv:1905.05078 [hep-ph])

How to achieve 0.01% accuracy for $e^-e^+ \to WW \to 4f$ near threshold?

Estimate size of NNLO-EFT corrections:

$$\mathcal{O}(\delta^2): \quad \underbrace{v^4}_{\text{Born}} \quad \underbrace{\alpha v^2}_{\text{included in NLO}_{4f}} \quad \underbrace{\alpha^2}_{\text{two-loop soft/hard}} \quad \underbrace{\alpha^3/v^2}_{\text{Coulomb-enhanced N}^3\text{LO}} \quad \underbrace{\alpha^4/v^4}_{\text{4th Coulomb}}$$

- $\mathcal{O}(\alpha^2)$ EFT corrections: estimate $C^{(2)} \approx (C^{(1)})^2$
  $\Delta\sigma_{\alpha^2} \approx 0.06\%$ $\Rightarrow$ mandatory for CEPC/FCC-ee
- subset of $\mathcal{O}(\alpha^3/v^2)$ corrections computable
  using known ingredients: (extension of Actis et al. 08)
  $\Delta\sigma_{\alpha^3} \sim 0.01\%$ $\Rightarrow$ relevant for CEPC/FCC-ee

Is a full NNLO $e^-e^+ \to 4f$ calculation required? Naive estimate:

$$\sigma^{4\mathrm{f}}_{\mathrm{NNLO}}(s) - \sigma^{(2)}_{\mathrm{EFT}}(s) \approx \frac{\alpha}{s_w^2}\left(\sigma^{4\mathrm{f}}_{\mathrm{NLO}}(s) - \sigma^{(1)}_{\mathrm{EFT}}(s)\right) = \sigma^{4\mathrm{f}}_{\mathrm{Born}}(s) \times 0.02\%$$

$\Rightarrow$ effects need to be controlled!

CEPC can produce 10^7 $(161\text{GeV})/$ 10^8 (240GeV) W pairs

$\Rightarrow$ high-precision measurements of M_W, σ_{WW}, Γ_W, anomalous. couplings

W **mass measurement** from threshold scan:

- $\Delta M_W \lesssim 1\text{MeV}$ needs $\Delta\sigma_{e^+e^-\to 4f} \lesssim 0.5\%$
- requires NNLO and Coulomb-enhanced N^3LO in threshold expansion; full NNLO_{4f} for $\Delta M_W \sim 0.15\text{MeV}$?

  (CS 19; similar estimates obtained based on DPA: Jadach/Skrzypek 19

  not discussed: NLL ISR, QCD for $4j$ final states)

Continuum WW **production** in Higgs-factory mode

- $\Delta\sigma_{WW} \sim 0.1\%$, anomalous coupling measurements
- Pole expansion at NNLO appears appropriate

W-pair production near threshold

- For $\Gamma_W \to 0$ expect threshold behaviour

$$\sigma_{WW} \propto v = \sqrt{1 - \frac{4M_W^2}{s}}$$

- Finite decay width ($E = \sqrt{s} - 2M_W$)

$$v \to \frac{1}{\sqrt{2}} \sqrt{\frac{E}{M_W} + \sqrt{\frac{E^2}{M_W^2} + \frac{\Gamma^2}{M_W^2}}}$$

- constant shift

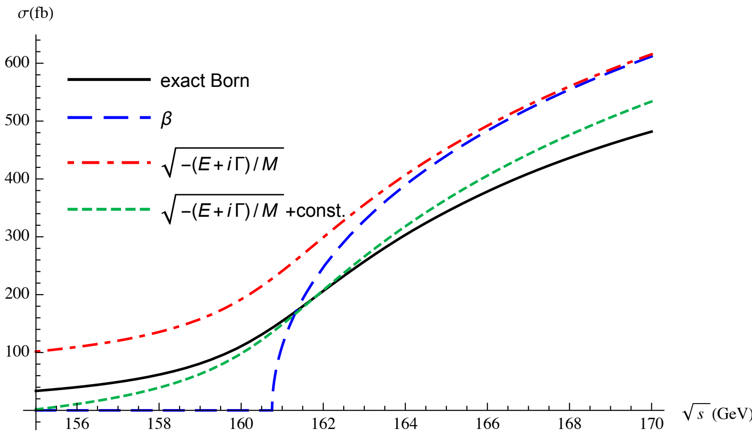
  (phase-space constraints;

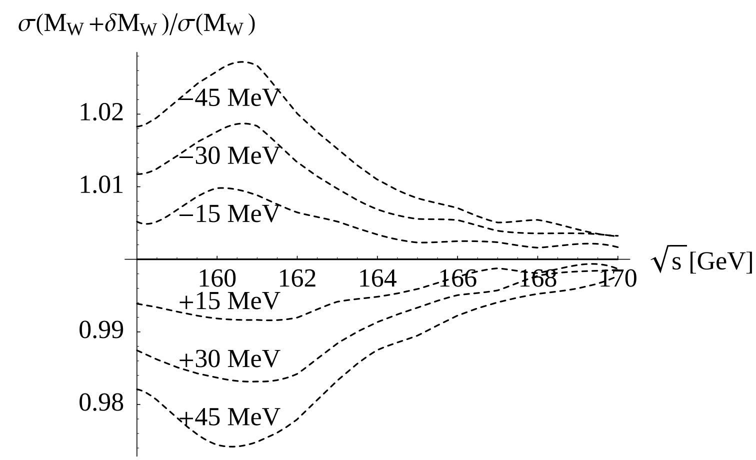
  non-resonant contributions)

- Sensitivity to M_W

$$\Delta\sigma \sim 1\% \Leftrightarrow \Delta M_W \sim 15\,\mathrm{MeV}$$

maximum near $\sqrt{s} = 161\,\mathrm{GeV}$



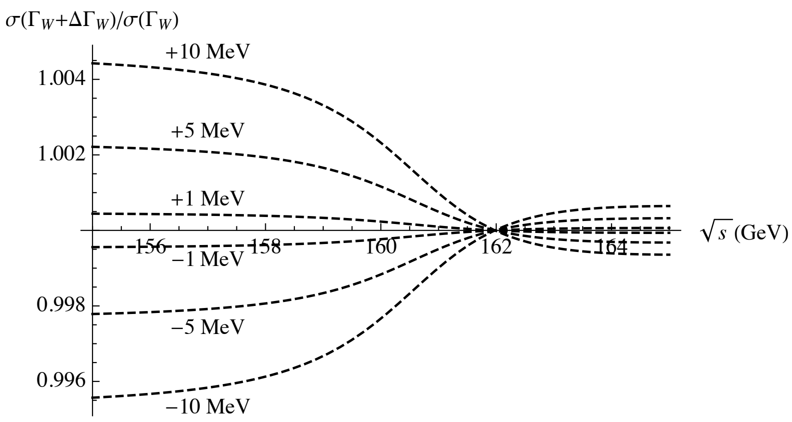


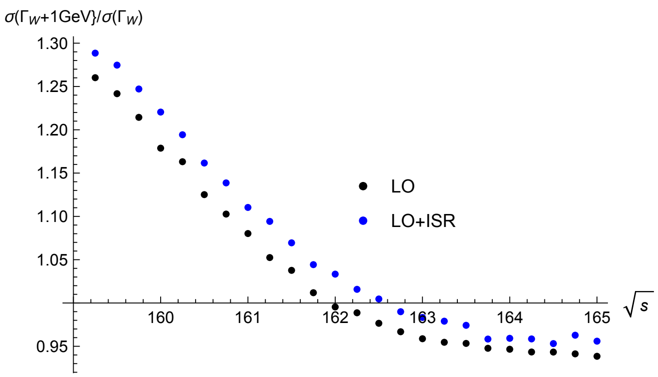
Prospect of $\Delta\Gamma_W \simeq 1.10\,\mathrm{MeV}$ at FCC-ee

- Currently $\Delta\Gamma_W^{\mathrm{exp.}} = 42\,\mathrm{MeV} \gg \Gamma_W^{\mathrm{EW-fit}} = 1\,\mathrm{MeV}$ (Gfitter, 18)
- α_s, CKM measurements using Γ_W (d'Enterria, Srebre 16)

Sensitivity of cross section to Γ_W:

- sensitivity to Γ_W below threshold: $\Delta\Gamma_W = 10\,\mathrm{MeV} \Leftrightarrow \Delta\sigma \sim 4‰$
- point with $\frac{d\sigma}{d\Gamma_W} = 0$ from interplay of $v \Leftrightarrow$ const. terms
  - arises for total cross section or if all $\mathrm{BR}_{W\to f\bar{f}}$ kept constant
  - stability under radiative corrections? ISR effect: $500\,\mathrm{MeV}$.



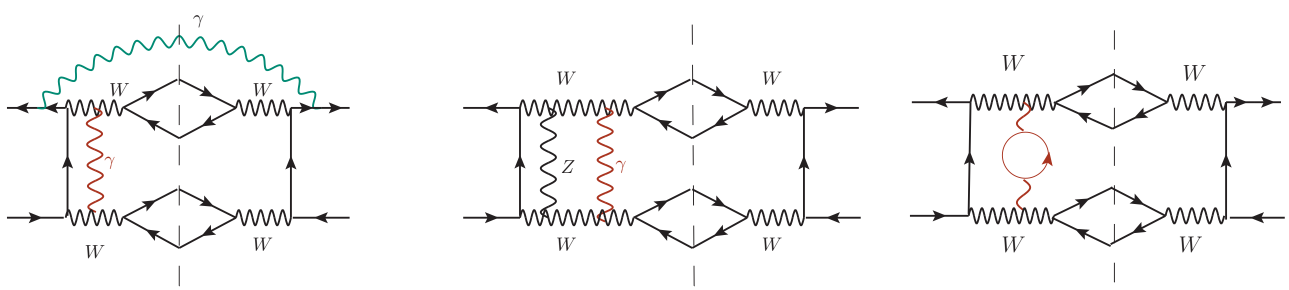


Leading NNLO corrections

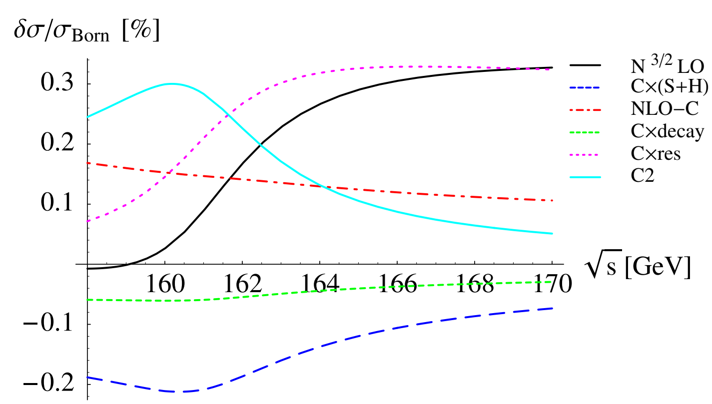
(Actis et al. 08)

$$\mathcal{O}(\delta^{3/2}): \quad \underbrace{\alpha v}_{\text{included in NLO}_{4f}} \quad \underbrace{\alpha^2/v}_{\text{Coulomb-enhanced NNLO}} \quad \underbrace{\alpha^3/v^3}_{\text{3rd Coulomb}}$$

$\mathcal{O}(\alpha^2/v)$ corrections:



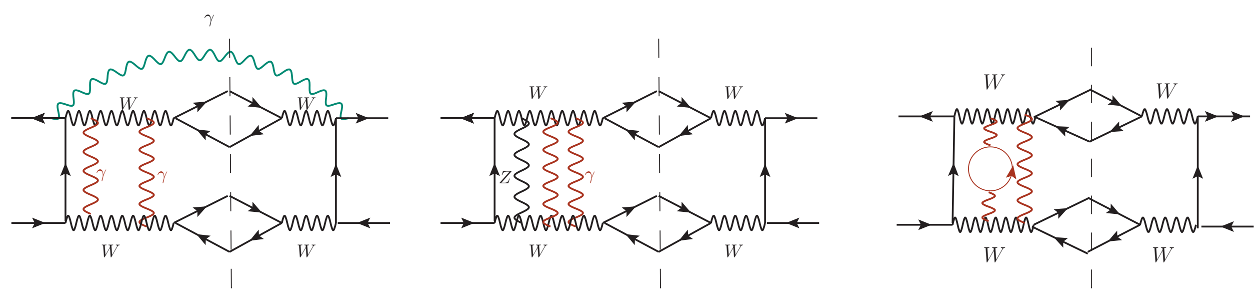
- combination of 1st Coulomb with NLO hard/soft
- NLO renormalization of V_{Coul}
- Numerical effect: < 5‰; $[\delta M_W] \lesssim 3\,\mathrm{MeV}$



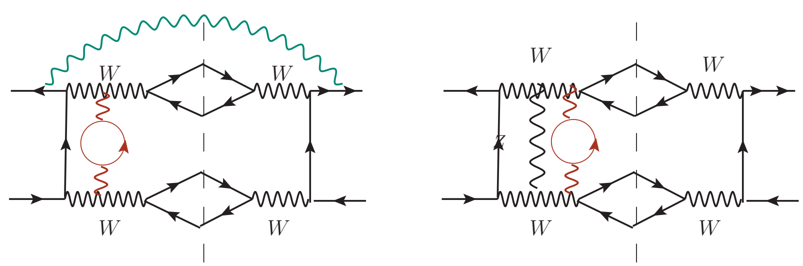
Leading $\mathcal{O}(\alpha^3)$ corrections

- $\delta^2 \sim \alpha^3/v^2$ corrections in NNLO$^{\rm EFT}$:
  Combination of second Coulomb with NLO soft/hard; $V_{\rm Coul}^{\rm NLO}$
  (Most contributions follow from soft/Coulomb factorization; extension of Actis et al. 08)
- $\delta^{5/2} \sim \alpha^3/v$ corrections:
  Combination of first Coulomb with NNLO soft/hard;
  $V_{\rm Coul}^{\rm NLO}$ with NLO soft/hard; $V_{\rm Coul}^{\rm NNLO}$
  (Can be computed once NNLO$^{\rm EFT}$ is known; see $pp \to t\bar{t}$, Piclum CS 18)

α^3/v^2



α^3/v



Leading $\mathcal{O}(\alpha^3)$ corrections

- $\delta^2 \sim \alpha^3/v^2$ corrections in NNLO$^{\rm EFT}$:
  Combination of second Coulomb with NLO soft/hard; $V_{\rm Coul}^{\rm NLO}$
  (Most contributions follow from soft/Coulomb factorization; extension of Actis et al. 08)

- $\delta^{5/2} \sim \alpha^3/v$ corrections:
  Combination of first Coulomb with NNLO soft/hard;
  $V_{\rm Coul}^{\rm NLO}$ with NLO soft/hard; $V_{\rm Coul}^{\rm NNLO}$
  (Can be computed once NNLO$^{\rm EFT}$ is known; see $pp \to t\bar{t}$, Piclum CS 18)

- Known subset of corrections:

  $\Delta\sigma_{\alpha^3} \sim 0.01\%$

  $\Rightarrow$ relevant for FCC-ee