Theory status of the W-pair threshold scan

Christian Schwinn

— RWTH Aachen —

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W-pair production

Success story at LEP2:

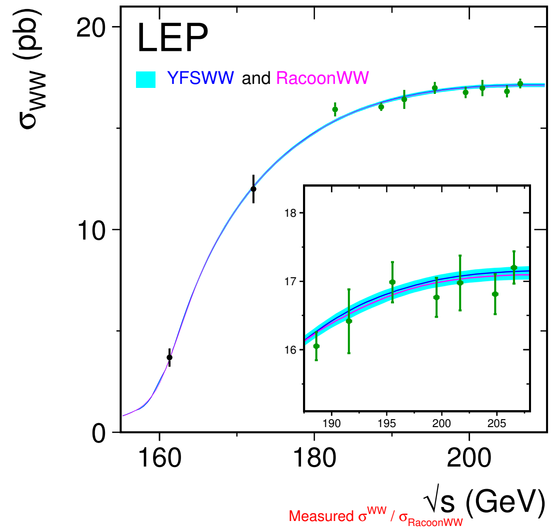
- σ_{WW}: 1%-level agreement with NLO theory

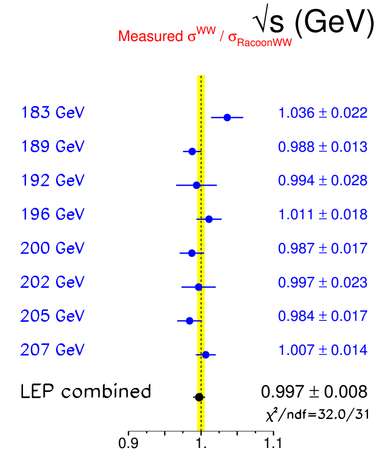
$\Rightarrow$ test of EW-sector of SM at quantum level

- measurement of branching rations (lepton universality)
- bounds on anomalous triple vector-boson couplings

$\Rightarrow$ test of non-abelian structure

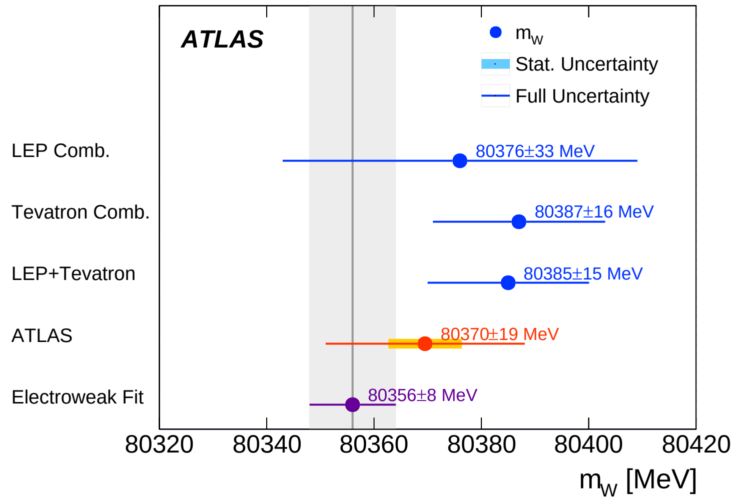
- W-mass measurement from kinematic reconstruction ($+\ \sigma_{WW}$ at threshold)

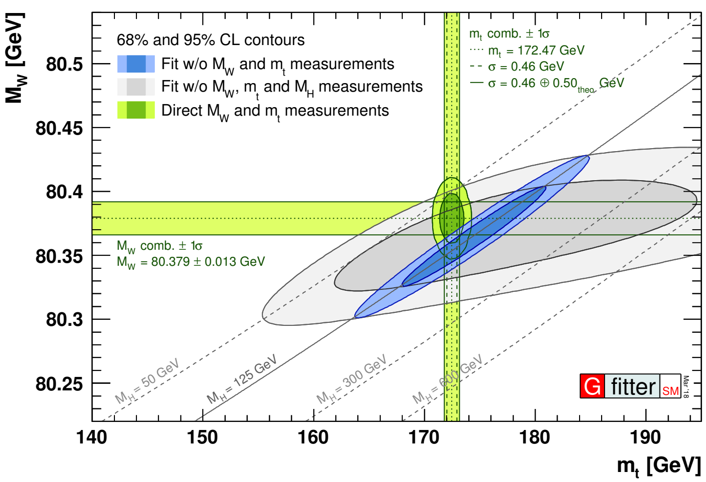


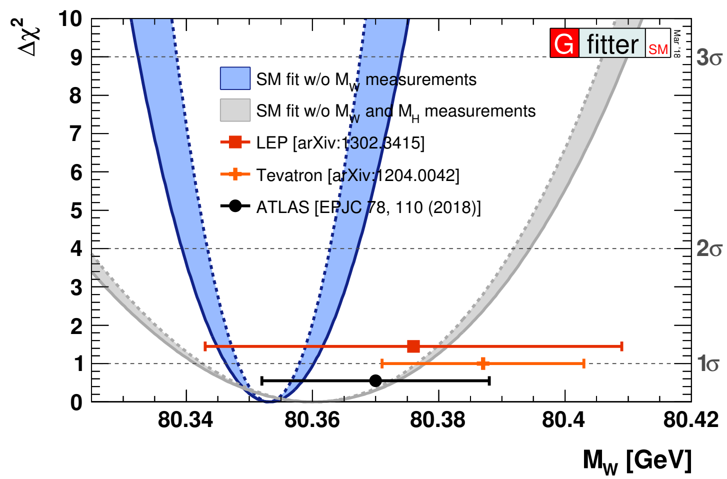


M_W **key observable of SM**

Current status LEP+Tevatron+LHC $\Delta M_W \sim 15\,\mathrm{MeV}$







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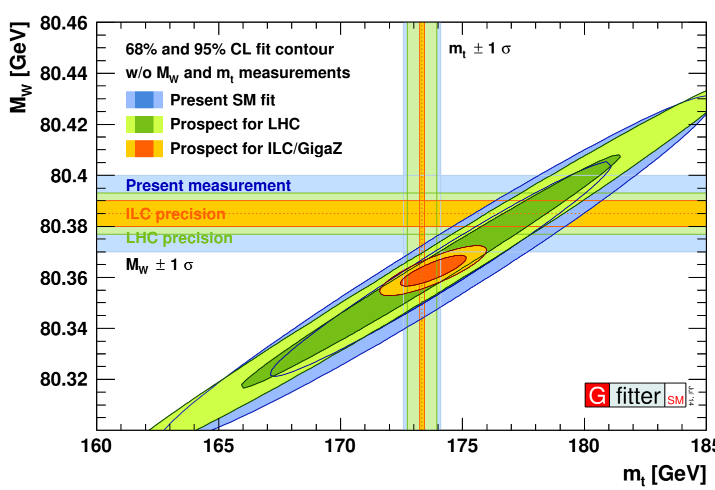
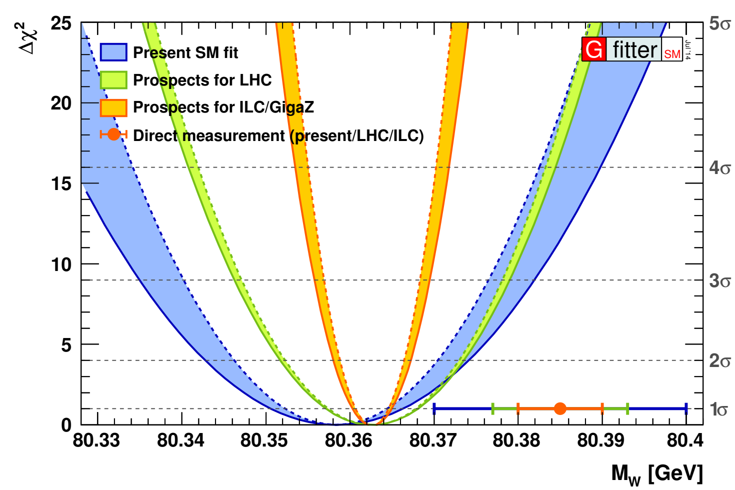
Prospects at future e^-e^+ colliders

$$\Delta M_W \sim 3\text{-}4\,\mathrm{MeV}(\mathrm{ILC}),\ 1\,\mathrm{MeV}(\mathrm{FCCee/CEPC})$$

	LHC	LHC	ILC/GigaZ	ILC	ILC	ILC	TLEP	SM prediction
$\sqrt{s}$ [TeV]	14	14	0.091	0.161	0.161	0.250	0.161	-
$\mathcal{L}[\mathrm{fb}^{-1}]$	300	3000		100	480	500	3000×4	-
ΔM_W [MeV]	8	5	-	4.1-4.5	2.3-2.9	3.6	1.2	4.2(3.0)
$\Delta \sin^2\theta^{\ell}_{\mathrm{eff}}$ $[10^{-5}]$	36	21	1.3	-	-	-	0.3	3.0(2.6)

(Snowmass EW report 13)





FCCee study: (1703.01626 [hep-ph])

- single point $\sqrt{s} = 161.4\,\mathrm{GeV}$

$$\Delta M_W \simeq 0.25\,\mathrm{MeV}$$

with $15\,\mathrm{ab}^{-1}$ if

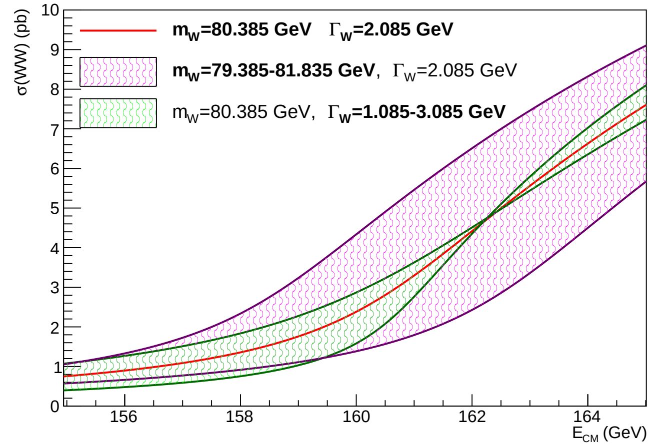
$$\delta\sigma^{\mathrm{th.}}_{WW} < 0.6\,\mathrm{fb}(\approx 0.01\%)$$

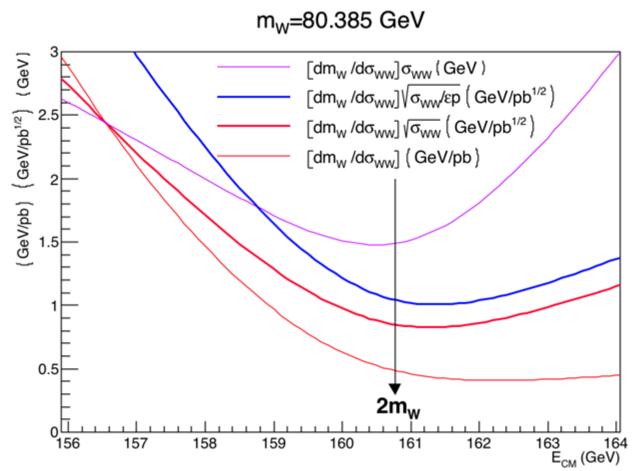
- simultaneous fit

$$\Delta M_W \simeq 0.41\,\mathrm{MeV},\ \Delta\Gamma_W \simeq 1.10\,\mathrm{MeV}$$

from two points

$$\sqrt{s} = 157.5,\ 162.3\,\mathrm{GeV}$$





CEPC CDR scenario:

- 4 points

$$\sqrt{s} = 157.5,\ 161.5,\ 162.3,\ 172.0\,\mathrm{GeV}$$

- with $2.6\mathrm{ab}^{-1}$

$$\Delta M_W \simeq 1\,\mathrm{MeV},\ \Delta\Gamma_W \simeq 2.8\,\mathrm{MeV}$$

W-pair production near threshold

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

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

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

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

- constant shift

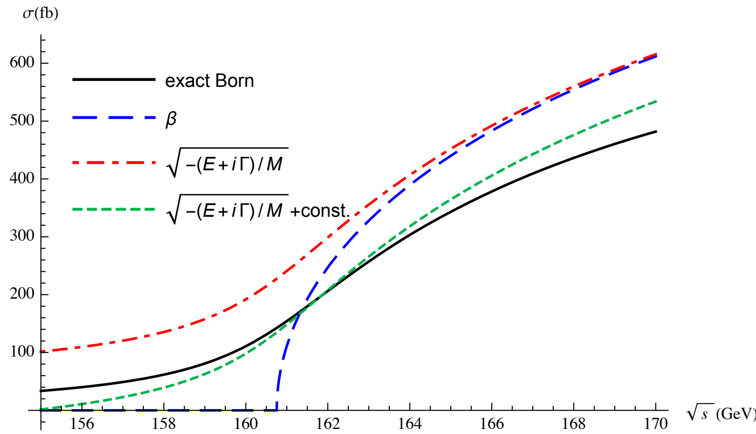
  (phase-space constraints;

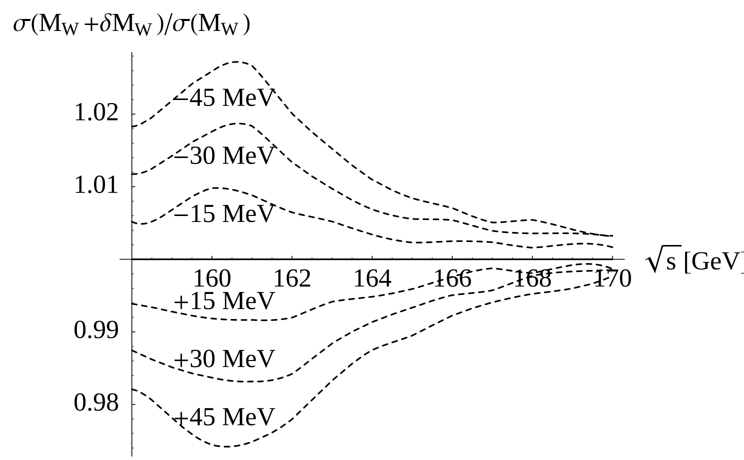
  non-resonant contributions)

- Sensitivity to M_W

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

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





Sensitivity to W-width

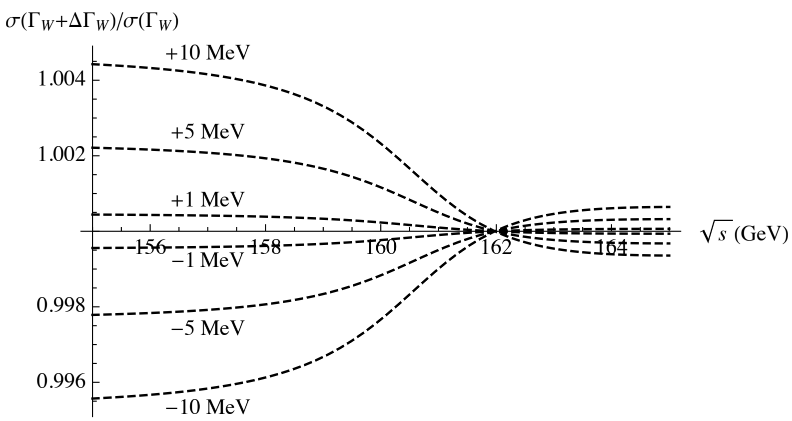
- $\Gamma_W^{\text{exp.}} = 2.085 \pm 0.042\,\text{GeV}$; EW fit: $\Gamma_W = 2.091 \pm 0.001\,\text{GeV}$ (Gfitter, 18)

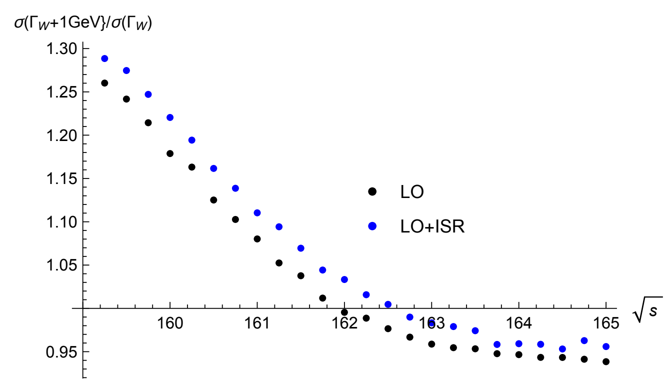
Consistent variation of width in theory calculations?

- implicitly $\sigma_{e^-e^+\to 4f} \propto \Gamma^{\text{SM}}_{W\to f_1\bar{f}_2}\Gamma^{\text{SM}}_{W\to f_3\bar{f}_4}/\Gamma_W^2$

$\Rightarrow$ rescale by $(\Gamma_W/\Gamma_W^{\text{SM}})^2$ to keep $\text{BR}_{W\to f\bar{f}}$ constant (physics motivation?)

- sensitivity to Γ_W below threshold: $\Delta\Gamma_W = 10\,\text{MeV} \Leftrightarrow \Delta\sigma \sim 4‰$
- point with $\frac{d\sigma}{d\Gamma_W} = 0$ from interplay of $\beta \Leftrightarrow$ const. terms in σ
- stability under radiative corrections? ISR effect: $500\,\text{MeV}$.





NLO corrections near threshold

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

Schematic structure of total cross section:

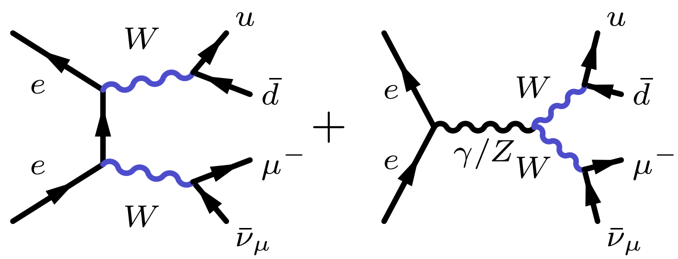
$$\Delta^{(1)} \sigma_{WW \to 4f}|_{s \approx 4M_W^2} \propto \beta\alpha \left[\frac{1}{\beta} + \ln\beta \ln\left(\frac{m_e}{M_W}\right) + \ln\left(\frac{m_e}{M_W}\right) + C^{(1)} \right] + \text{const} + \mathcal{O}(\beta)$$

Enhanced corrections in threshold limit

- mass logarithms $\ln\left(\frac{m_e}{M_W}\right)$: resum in ISR structure function
- Coulomb corrections $\sim \alpha/\beta \sim$ 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
  (Method for all-order resummation known $\Rightarrow t\bar{t}$)
- soft $\ln\beta$ corrections $\sim \alpha \ln\alpha \sim 0.04$
  $\Rightarrow$ resummation not necessary

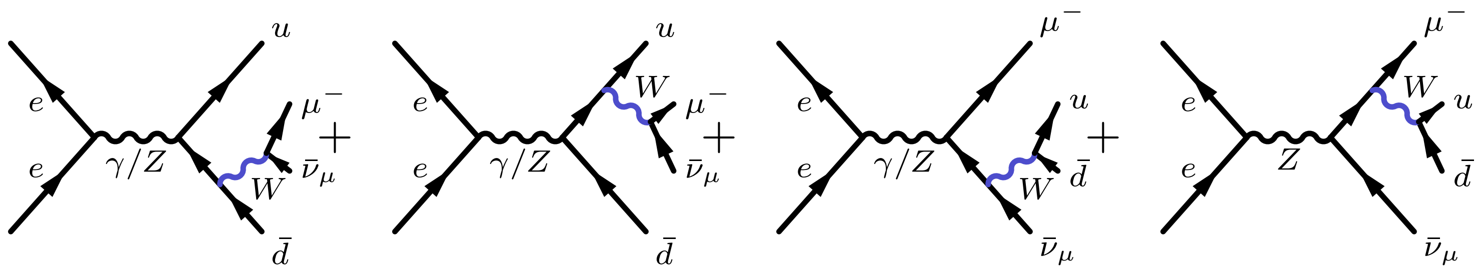
4-fermion production at tree level, e.g. $e^-e^+ \to \mu^-\bar{\nu}_\mu u\bar{d}$

Double resonant ('signal') diagrams (CC3):



But 10 diagrams in total:

CC3 +



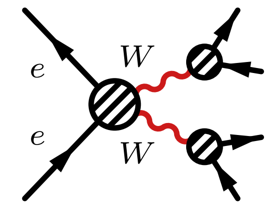
Only sum gauge invariant

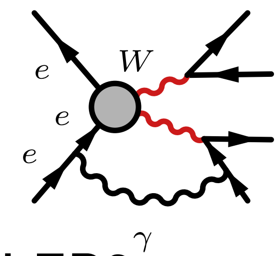
Need consistent scheme for finite width effects: (Beenakker et al. 96)

$\sqrt{s}$	200 GeV	500 GeV	1 TeV	5 TeV
Running width	672.96	225.45	62.17	123.76
Constant width	673.08	224.05	56.90	2.212

Theoretical methods for WW

NLO calculations in double pole approximation





- Factorizable EW corrections to production, decay of on-shell Ws
- Nonfactorizable soft photon corrections

  (Berends et al. 98; Denner et al. 99

  Vanish for σ_{tot}: Fadin/Khoze/Martin; Melnikov/Yakovlev 94)
- Implemented in Monte-Carlo programs used at LEP2: RacoonWW (Denner et al. 99), YFSWW (Jadach et al. 99)
- Estimate of DPA accuracy at NLO

$$\Delta\sigma_{\text{DPA}} \sim \frac{\Gamma_W}{M_W} \times \frac{\alpha}{\pi} \sim \mathcal{O}(0.1\%)$$

- Loss of accuracy at production threshold

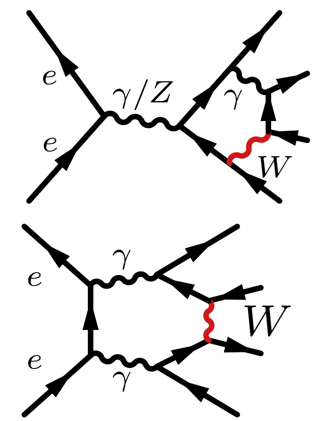
$$\Delta\sigma_{\text{DPA}} \sim \frac{\Gamma_W}{\sqrt{s}-2M_W} \times \frac{\alpha}{\pi} \sim \mathcal{O}(1\%)$$

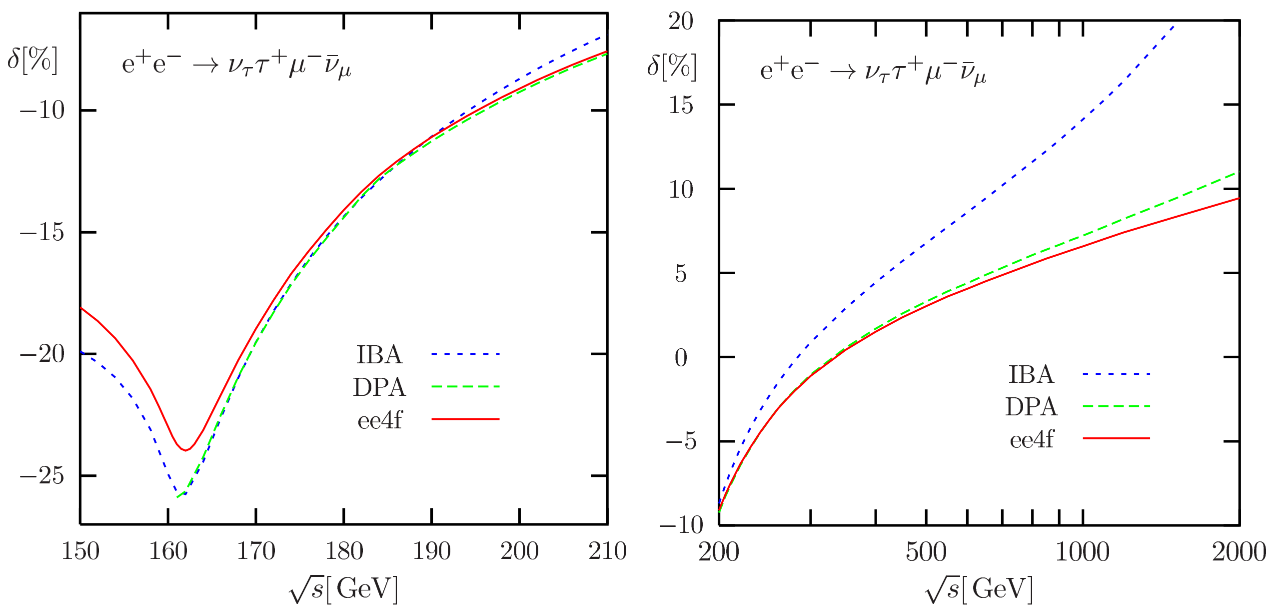
Full NLO calculation for $e^+e^- \to 4f$ (Denner, Dittmaier, Roth, Wieders 05)

- More than 1000 1-loop diagrams, 5, 6-point loop integrals

⇒ pioneering methods for six-point diagrams
now automated for LHC: `RECOLA`, `OpenLoops`, `MadLoops`

- complex mass scheme for W decay width
- fully differential calculation
- not easy to incorporate higher-order effects
- DPA not sufficient at threshold and for $\sqrt{s} > 500$ GeV



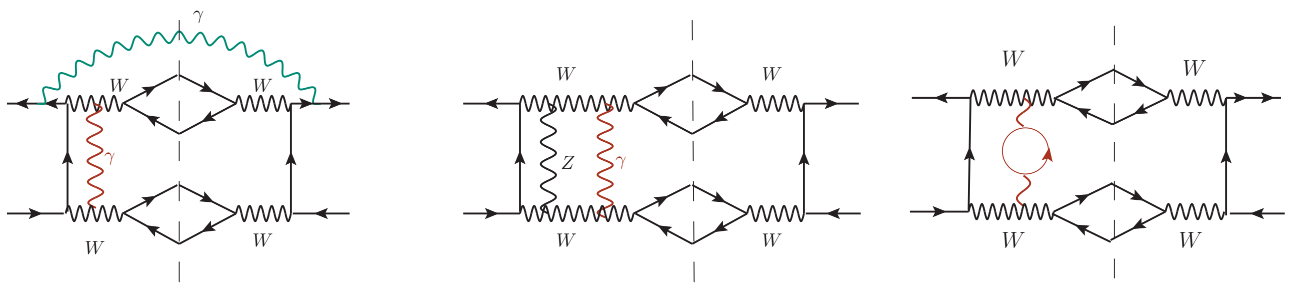


EFT expansion in $\alpha \sim \frac{\Gamma_W}{M_W} \sim \beta^2$ (Beneke/Falgari/CS/Signer/Zanderighi 07)

- systematically possible to include higher-order corrections
- limited to total cross section near threshold

Leading NNLO corrections

- 2nd Coulomb correction $\sim \alpha^2/\beta^2 \sim \alpha$ (Fadin et al. 95)
- Coulomb-enhanced corrections $\sim \alpha^2/\beta \sim \alpha^{3/2}$ (Actis et al. 08)



- Numerical effect: $\Delta\sigma_{WW} \sim 5‰$; $[\delta M_W] \lesssim 3\,\text{MeV}$

	$\sigma(e^-e^+ \to \mu^-\bar{\nu}_\mu u\bar{d})$(fb)			
$\sqrt{s}$ [GeV]	NLO_{EFT}	NLO_{ee4f} [DDRW]	$\Delta_{\text{NNLO}}(\alpha^2/\beta^2)$	$\Delta_{\text{NNLO}}(\alpha^2/\beta)$
161	117.5	118.77	0.44 (3.7‰)	0.15 (1.3‰)
170	397.8	404.5	0.25 (0.6‰)	1.6 (3.9‰)

ISR: resum leading logs

$$\beta_e = \frac{2\alpha}{\pi}\left(2\log\left(\frac{2M_W}{m_e}\right) - 1\right)$$

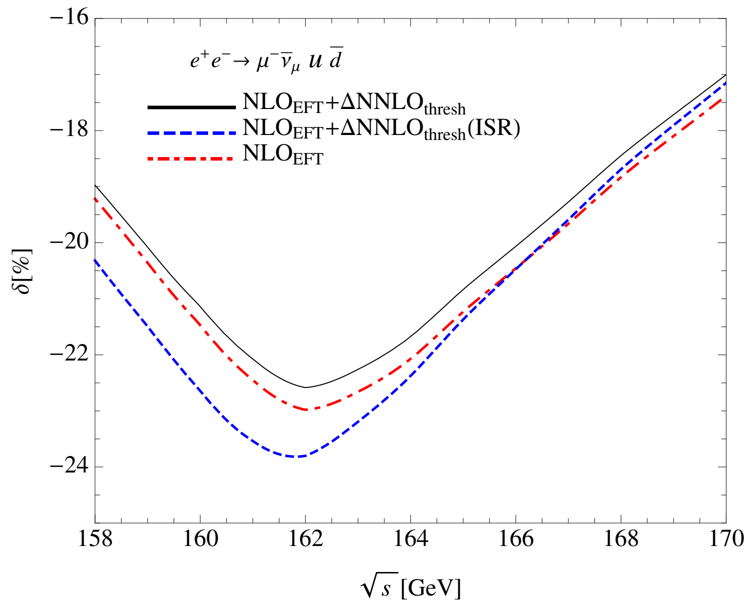
in electron structure functions: (Skrzypek 92)

$$\sigma_{\mathrm{NLO}}(s) = \int_0^1 dx_1 \int_0^1 dx_2 \Gamma_{ee}^{\mathrm{LL}}(x_1)\Gamma_{ee}^{\mathrm{LL}}(x_2)\left(\sigma_{\mathrm{tree}} + \Delta\hat{\sigma}_{\mathrm{NLO}}\right)$$

ISR for tree only ⇔ also for NLO:

$\sim 2\%$ NLL $\mathcal{O}(\alpha\beta_e)$ effect

⇒ NLL resummation important



Future improvements of theory predictions?

Implementation of state-of-the art calculations in public tools?

- NLO-EW $e^-e^+ \to 4f$ now possible with standard tools
  (`RECOLA`, `OpenLoops`, `MadLoops`)
  but not (yet) optimized for e^-e^+ (ISR, Beamstrahlung; ⇒ talk by Shao)
- Two-loop Coulomb-enhanced corrections for differential observables doable; (related: $t\bar{t}$ with Coulomb resummation in WHIZARD)
  (no guarantee of formal accuracy for general distributions)

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Full NNLO in EFT for total cross section

- Soft $\log\beta$ terms can be adapted from QCD results
- NNLO $\log(m_e/M_W)$ terms doable (c.f. Bhabha scattering)
- two-loop hard non-logarithmic corrections

  (from amplitudes for $e^+e^- \to W^+W^-$ at threshold: border of current capabilities)

  resulting uncertainty from cross-section calculation

  $$\Delta\sigma^{(2}_{\text{hard}} = \left(\frac{\alpha}{2\pi}\right)^2 c^{(2)}\sigma^{(0)} \sim (1-2)‰ \text{ for estimate } c^{(2)} = (c^{(1)})^2$$

Full NNLO for $e^+e^- \to 4f$: completely new methods needed

W **mass measurement** from threshold scan:

- error $\lesssim 1$ MeV needs $\sigma(e^+e^- \to 4f)$ with accuracy $< 1‰$

Full NLO corrections to $e^+e^- \to 4f$ (Denner et al. 05)

Coulomb-enhanced NNLO corrections

for σ_{tot} near threshold in EFT approach: (Actis et al. 08)

$5‰$ correction; remaining uncertainty $\Delta M_W \lesssim 3\,\mathrm{MeV}$

Next possible steps

- Implementation of Coulomb-enhanced NNLO corrections near threshold for distributions
- Logarithmic NNLO corrections in EFT

Full NNLO in EFT required for ultimate CEPC/FCCee precision

Estimate impact of uncertainties on mass measurement:

- Assume measurements O_i at $\sqrt{s} = 160, 161, \ldots 164, 170$ GeV
- Minimize

$$\chi^2(\delta M_W) = \sum_{i=1}^{6} \frac{(O_i - E_i(\delta M_W))^2}{2\sigma_i^2} .$$

where $E_i(\delta M_W)$: theoretical calculation for $M_W = M_W^{\text{ref}} + \delta M_W$

- take O_i: NLO EFT , E_i: Estimate of error

Example:

2nd Coulomb correction

$\Rightarrow \mathcal{O}(‰)$ (Fadin et al. 95)

$\Rightarrow$ $[\delta M_W]_{\text{C2}} < 4$ MeV