Theory status of the W-pair threshold scan

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W-pair production

Success story at LEP2:

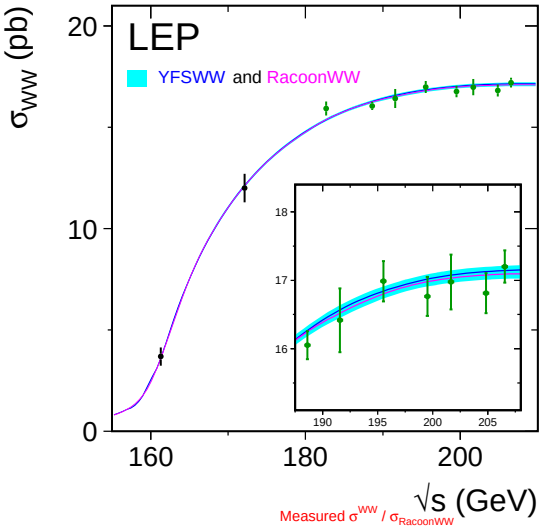
- σ_{WW}: 1%-level agreement with NLO theory

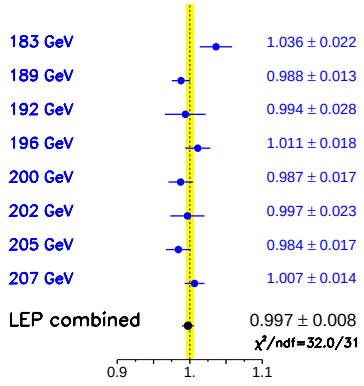
$\Rightarrow$ test of EW-sector of SM at quantum level

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

$\Rightarrow$ test of non-abelian structure

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

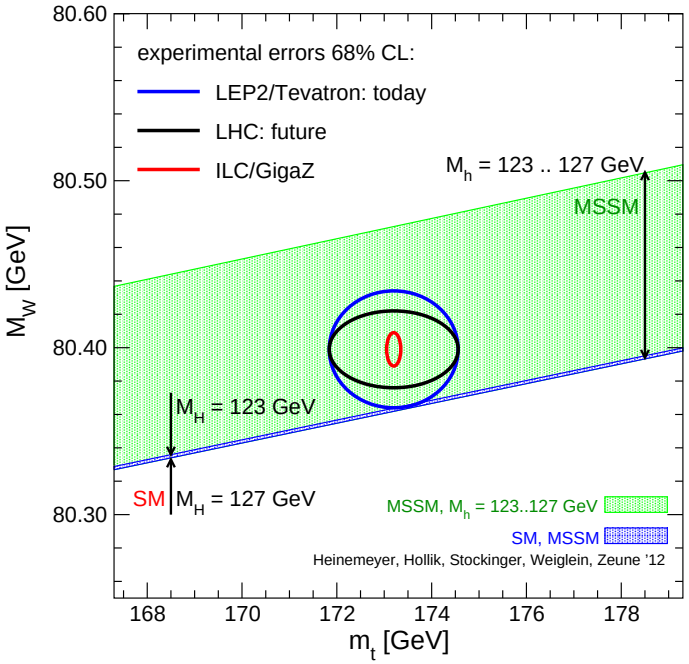




Future e^+e^- colliders

several concepts:

- LEP3/TLEP (240-350 GeV)
- ILC (500 GeV-1TeV),
- CLIC (≤ 3 TeV)



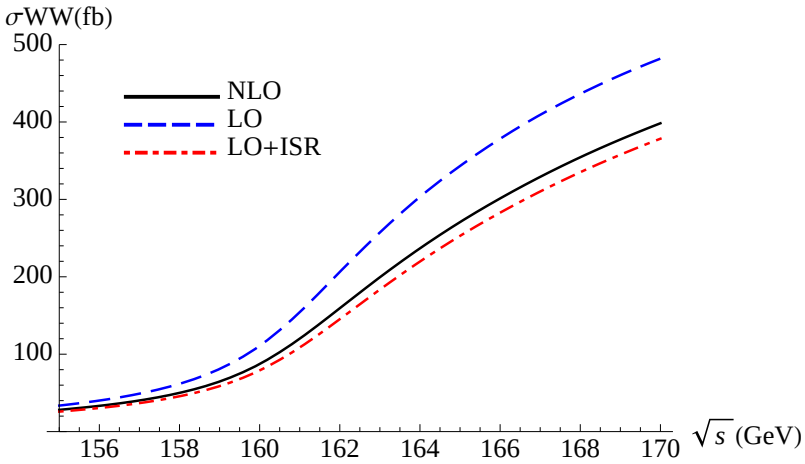
Projected accuracy of m_W measurement:

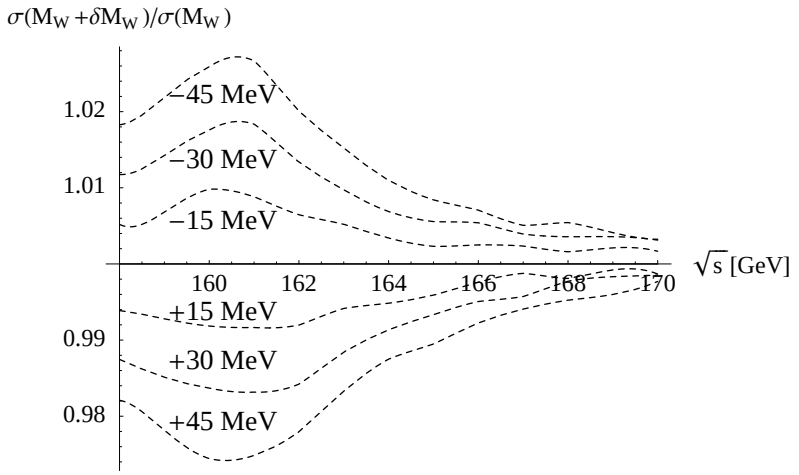
	LHC	LHC	ILC/GigaZ	ILC	ILC	ILC	TLEP	SM prediction
$\sqrt{s}$ [TeV]	14	14	0.091	0.161	0.161	0.250	0.161	-
$\mathcal{L}[\mathrm{fb}^{-1}]$	300	3000		100	480	500	3000×4	-
ΔM_W [MeV]	8	5	-	4.1-4.5	2.3-2.9	3.6	1.2	4.2(3.0)
$\Delta \sin^2\theta^\ell_{\mathrm{eff}}$ $[10^{-5}]$	36	21	1.3	-	-	-	0.3	3.0(2.6)

(Snowmass EW report 13)

Theory requirements:

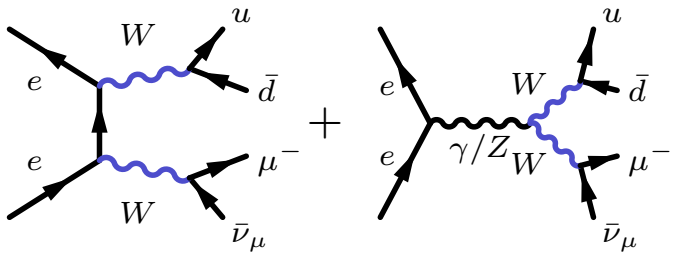
- **ILC** $\Delta M_W \lesssim 4$ MeV from threshold scan
  $\Leftrightarrow \Delta\sigma_{WW} \ll 1\%$ prediction for $\sqrt{s} \sim 160 - 170$ GeV
- **TLEP** goal $\Delta M_W < 1$ MeV
  theory uncertainty dominant!



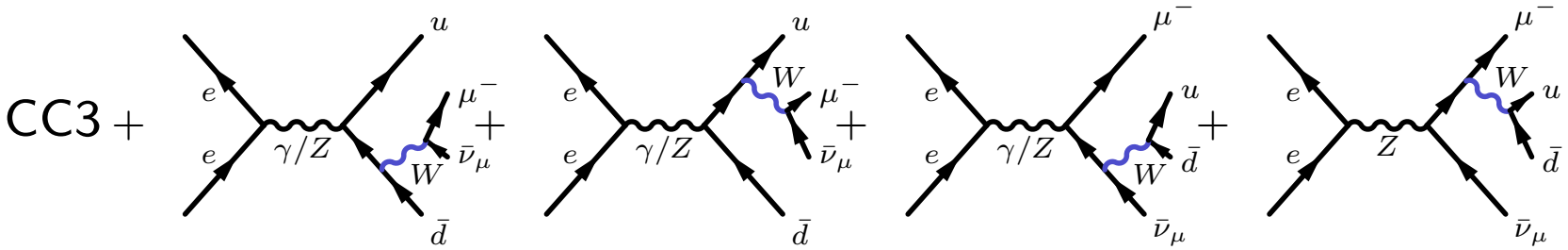


4-fermion production at tree level, e.g. $e^-e^+ \to \mu^-\bar{\nu}_\mu u\bar{d}$

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



But 10 diagrams in total:



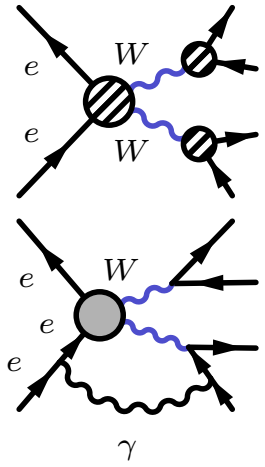
Only sum gauge invariant

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(3)	225.45(3)	62.17(1)	123.76(1)
Constant width	673.08(4)	224.05(3)	56.90(1)	2.212(6)

NLO calculations in double pole approximation

- Factorizable corrections to production, decay of on-shell Ws
- Nonfactorizable soft photon corrections (Berends et al. 98; Denner et al. 99)
- Implemented in Monte-Carlo programs used at LEP2: RacoonWW (Denner et al. 99), YFSWW (Jadach et al. 99)



Theory developments after LEP2:

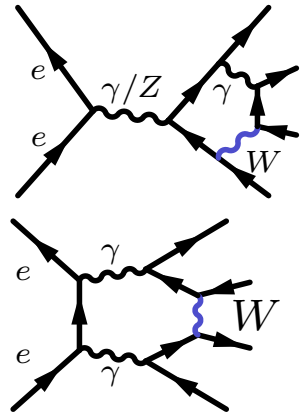
- Complete NLO calculation for charged current $e^+e^- \to 4f$ (Denner et al. 05)
- Log-enhanced NNLO corrections for $\hat{s} \gg M_W$ $\Rightarrow$ CLIC (Kühn et al. 07)
- NLO and leading NNLO correction in threshold expansion $\Rightarrow$ MegaW/TLEP (Beneke et al. 07, Actis et al. 08)

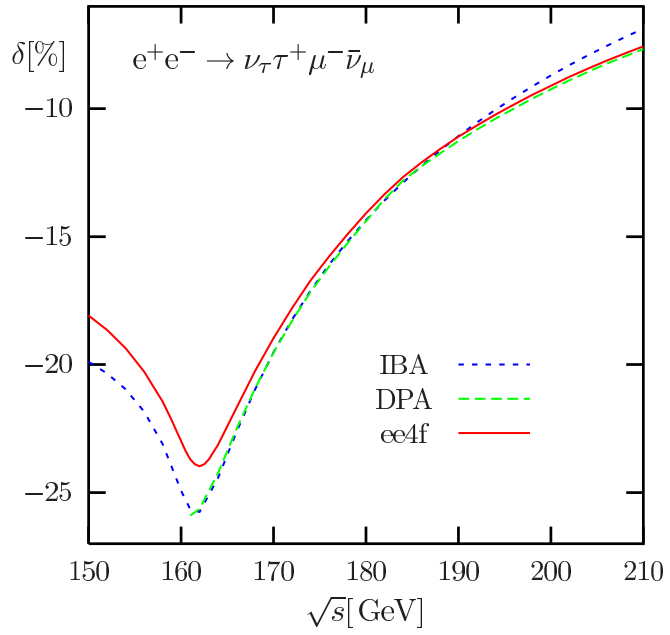
Full NLO calculation for $e^+e^- \to 4f$ (Denner, Dittmaier, Roth, Wieders 05)

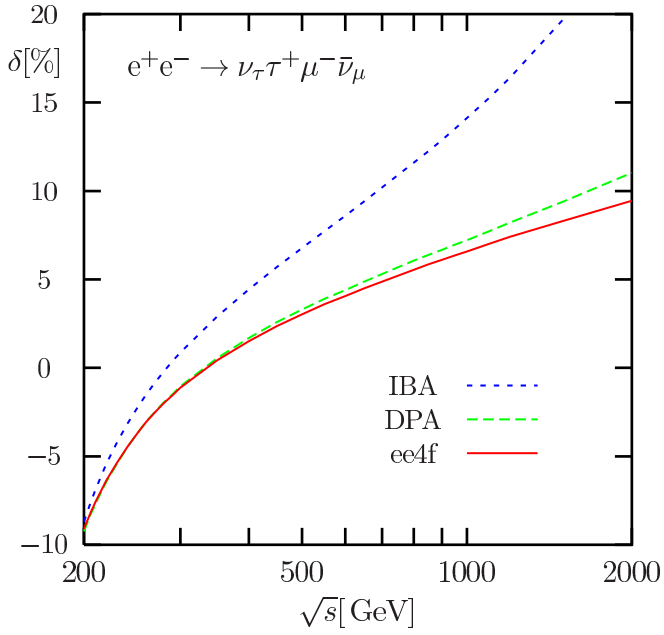
- More than 1000 1-loop diagrams
  5-point, 6-point loop integrals

$\Rightarrow$ new methods for six-point diagrams

- fully differential calculation
- complex mass scheme: replace $M^2 \to M^2 - \mathrm{i}M\Gamma$, everywhere,e.g. $\cos\theta_w = \frac{M_W}{M_Z}$







Enhanced corrections in threshold limit $\beta = \sqrt{1 - \frac{4M_W^2}{s}} \to 0$:

soft threshold logarithms $\sim (\alpha \log^2 \beta)^n$, Coulomb correction $\sim (\alpha/\beta)^n$

EFT approach: (Beneke/Falgari/CS/Signer/Zanderighi 07)

expansion in $\alpha \sim \frac{\Gamma_W}{M_W} \sim \frac{k_W^2 - M_W^2}{M_W^2}$

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)

	$\sigma(e^-e^+ \to \mu^- \bar{\nu}_\mu u \bar{d})$(fb)			
$\sqrt{s}$ [GeV]	NLO_{EFT}	NLO_{ee4f} [DDRW]	$\Delta_{\text{NNLO}}(\alpha^2/\beta^2)$	$\Delta_{\text{NNLO}}(\alpha^2/\beta)$
161	117.38(4)	118.77	0.44	0.15
170	399.9(2)	404.5(2)	0.2	1.6

- non-resonant NLO corrections
  included in NLO_{ee4f} but not in NLO_{EFT}: $\Delta\sigma_{WW} \sim 1\%$
- leading NNLO corrections: $\Delta\sigma_{WW} \sim \mathcal{O}(‰) \Rightarrow [\delta M_W]_{\text{C2}} < 4\,\text{MeV}$

ISR: resum leading logs

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

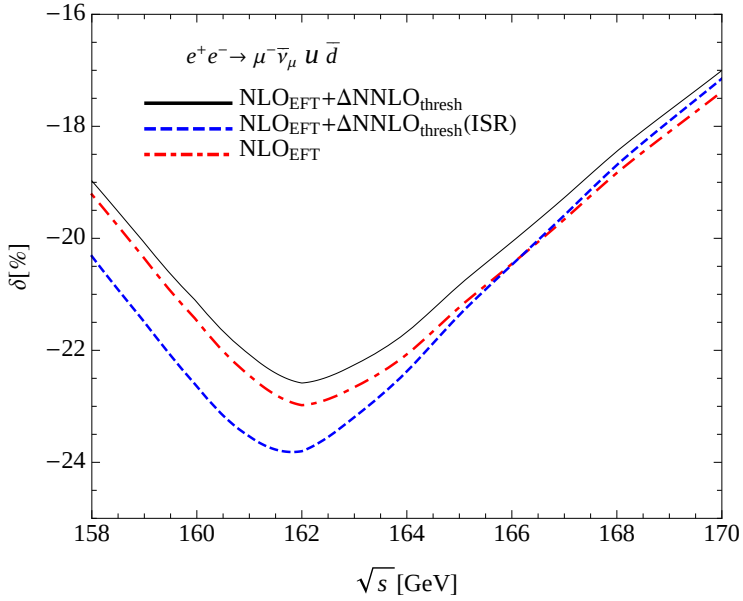
in electron structure functions: (Skrzypek 92)

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

Estimate missing NLL $\mathcal{O}(\alpha\beta_e)$:

ISR for tree only $\Leftrightarrow$ also for NLO

Uncertainty $\sim 2\%$ at threshold



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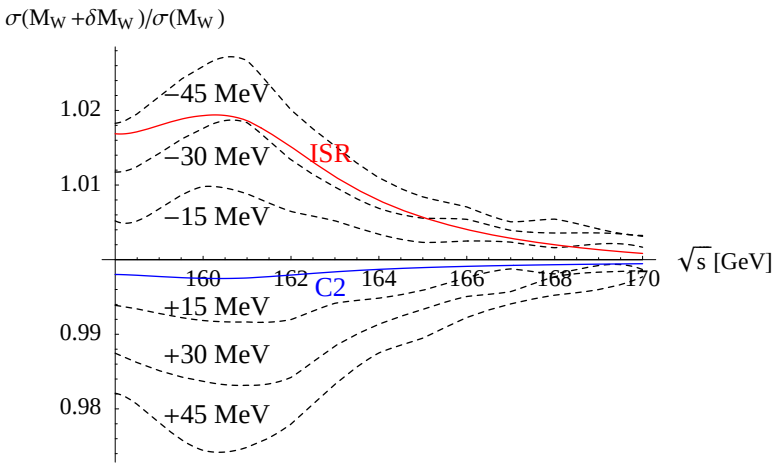
Estimate missing NLL $\mathcal{O}(\alpha\beta_e)$:

ISR for tree only $\Leftrightarrow$ also for NLO

Uncertainty $\sim 2\%$ at threshold

$$\Rightarrow \quad [\delta M_W]_{\text{ISR}} \approx 30\,\text{MeV}$$

$\Rightarrow$ NLL resummation important



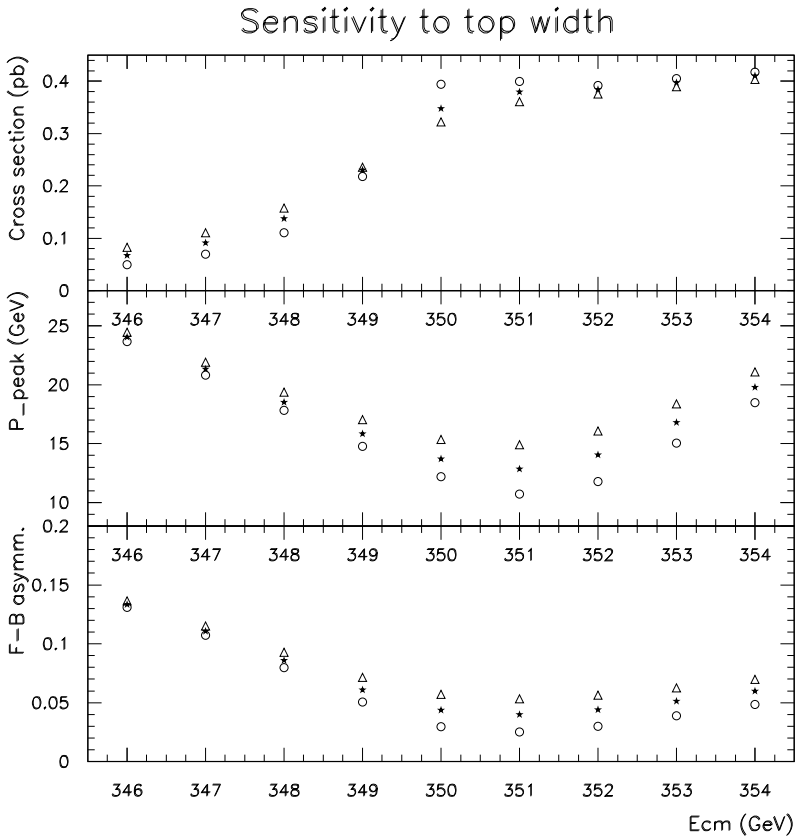
Sensitivity to W-width

$t\bar{t}$ threshold scan

- bound-state peak sensitive to Γ_t
- $\Delta\Gamma_t = 32$ MeV (300 fb^{-1} ILC)

  (Martinez/Miquel 02)

  $\Delta\Gamma_t = 11$ MeV (TLEP est.)
- interpretation as V_{tb} measurement (Fujii et al. 94)



(Martinez/Miquel 02, $\Delta\Gamma_t = 400$ MeV)

Sensitivity to W-width

$t\bar{t}$ threshold scan

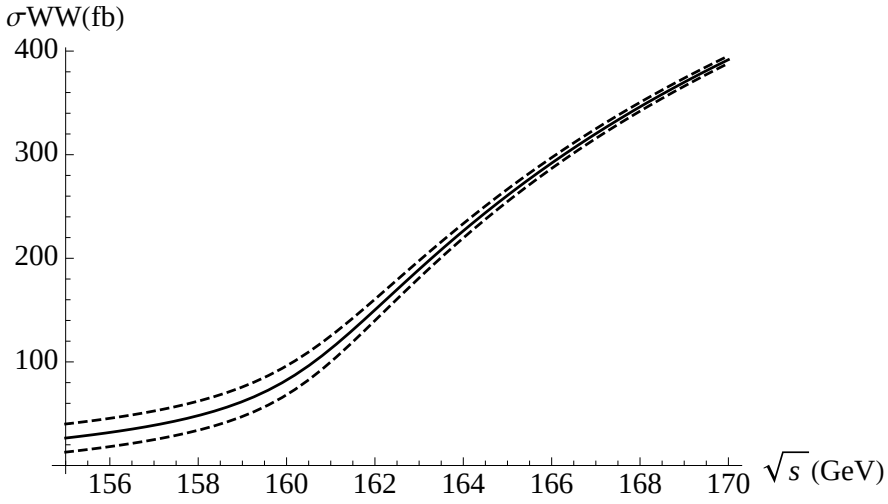
- bound-state peak sensitive to Γ_t
- $\Delta\Gamma_t = 32$ MeV (300 fb^{-1} ILC)

  (Martinez/Miquel 02)

  $\Delta\Gamma_t = 11$ MeV (TLEP est.)
- interpretation as V_{tb} measurement (Fujii et al. 94)

WW threshold scan

- no bound-state peak, sensitivity to Γ_W below threshold
- $\Delta\Gamma_W = 3$ MeV (PDG: 4.2 MeV) est. for 100 fb^{-1} ILC (Wilson 01)
- interpretation as α_s measurement



(preliminary, NLO EFT, no ISR,

$\Delta\Gamma_W = 20$ MeV. $\mathrm{Br}_{\mathrm{W}\to\mathrm{ff}}$ fixed.)

Summary and outlook

W-pair production crucial process at any future e^+e^- collider

- M_W measurement from threshold or direct reconstruction
- anomalous couplings

W mass measurement from threshold scan:

- error $\lesssim 5$ 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 $\Delta M_W \lesssim 4$ MeV (Actis et al. 08)

Largest remaining uncertainty:

- NLL treatment of ISR

Outlook

- Updated comparison of EFT/4f results planned

Summary and outlook

Future improvements of theory predictions?

Doable in principle:

- NNLO $\log\beta$, $\log(s/m_e^2)$ terms
- NNLO Coulomb corrections near threshold for distributions

Major effort, several years:

- NNLO EW corrections to on-shell $e^+e^- \to W^+W^-$

  (current frontier: first NNLO QCD $2 \to 2$ processes)

$\Rightarrow$ Input to full NNLO EFT calculation
Naive estimate for remaining uncertainty from cross-section calculation
$\Delta\sigma \sim \mathcal{O}(0.1‰)$, $\Delta M_W < 1$ MeV
ISR uncertainty?

Completely new methods needed:

- NNLO EW corrections to $e^+e^- \to 4f$

Bonus slides

Estimate impact on mass measurement:

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

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

  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

Resum leading logs

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

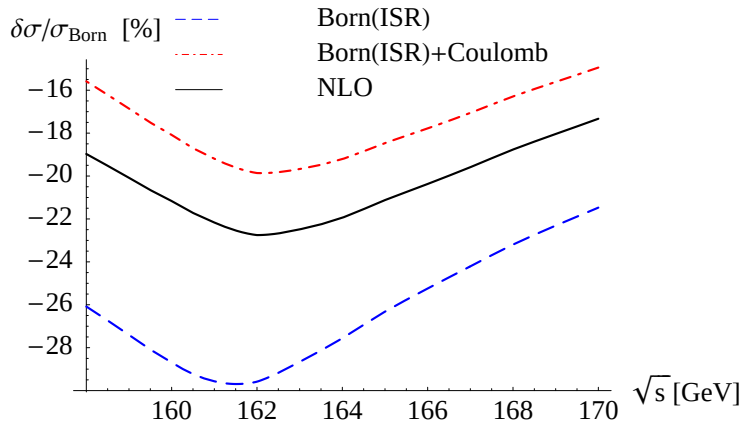
in electron structure functions:

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

with $$\Delta\widehat{\sigma}_{\mathsf{NLO}}(s) = \Delta\sigma_{\mathsf{NLO}}(s) - 2\frac{\beta_e}{4}\int_0^1 dx P(x)\sigma^{(0)}(xs)$$

Results:

- $\sim -25\%$ corrections from ISR
- $\sim +8\%$ Coulomb correction
- -3% soft+hard corrections



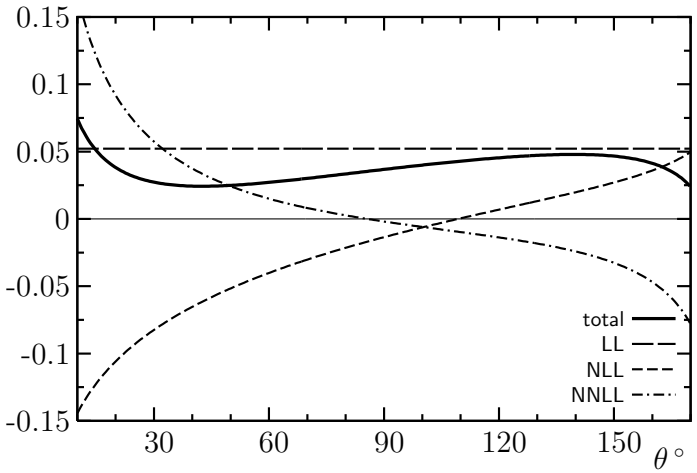
Enhanced Sudakov logarithms for high energies $s \gg M_W^2$

(Fadin et al. 00; Melles 01; Denner et al. 03; Beccaria et al. 03)

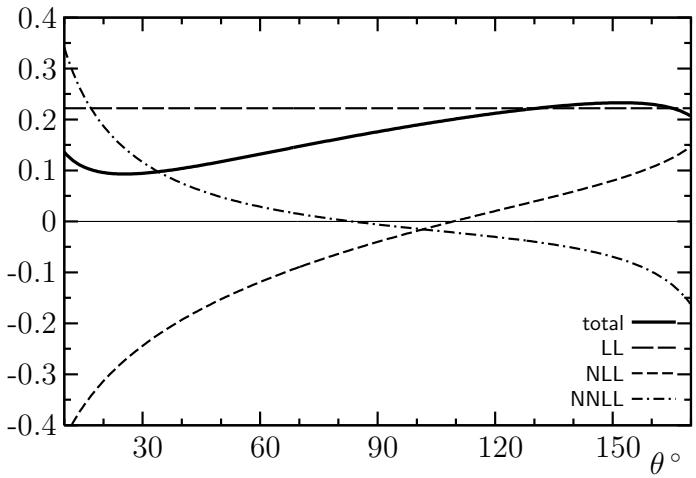
$$\underbrace{(\alpha \log^2(s/M_W^2))^n}_{\text{LL}}, \quad \underbrace{\alpha^n \log^{2n-1}(s/M_W^2))}_{\text{NLL}}, \quad \underbrace{\alpha^n \log^{2n-2}(s/M_W^2))}_{\text{NNLL}} \ldots$$

- NNLO-NNLL corrections for on-shell W-pair production:
  $\sim 5\%(s = 1 \text{ TeV}) - 15\%(s = 3 \text{ TeV})$ (Kühn/Penin/Metzler 07)

$\Rightarrow$ need to be taken into account at CLIC and 2nd phase of ILC



(transverse polarization)¡



1 TeV 3 TeV

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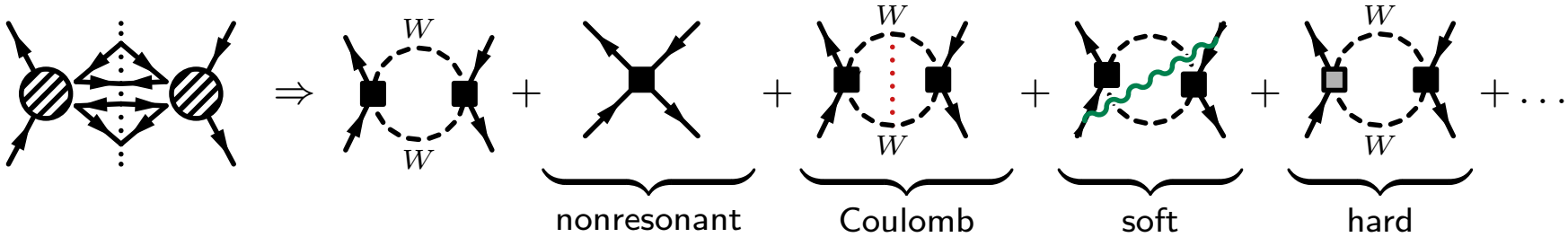
- expansion in $\alpha \sim \frac{\Gamma_W}{M_W} \sim \frac{k_W^2 - M_W^2}{M_W^2}$
- EFT for non-relativistic Ws, soft and Coulomb photons
- Coulomb correction cut off by finite W-width:

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

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

enhanced but resummation not necessary

- σ_{4f}^{tot} from imaginary part of forward-scattering amplitude:



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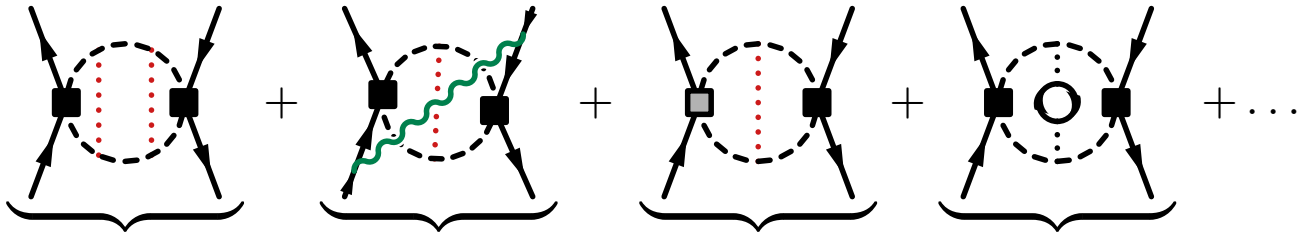

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