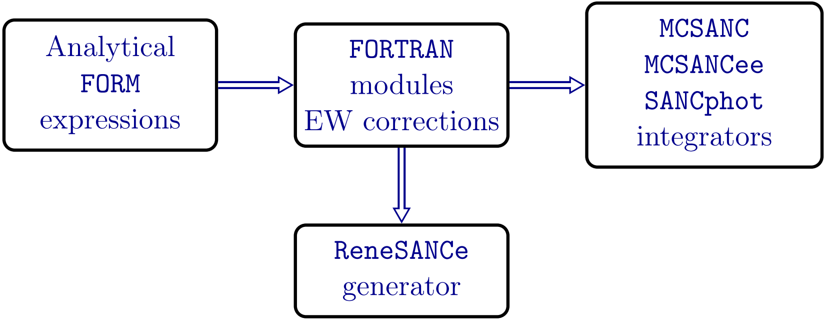
Electroweak radiative corrections to polarized top quark pair production

V. Yermolchyk
on befalf of SANC team

JINR; INP BSU

XIXth Workshop on High Energy Spin Physics
08 September 2023

The SANC framework and products family



Publications:

SANC – CPC 174 481-517
MCSANC – CPC 184 2343-2350; JETP Letters 103, 131-136
SANCphot – arXiv:2201.04350
ReneSANCe – CPC 256 107445; CPC 285 108646

SANC products are available at http://sanc.jinr.ru/download.php
ReneSANCe is also available at http://renesance.hepforge.org

SANC advantages:

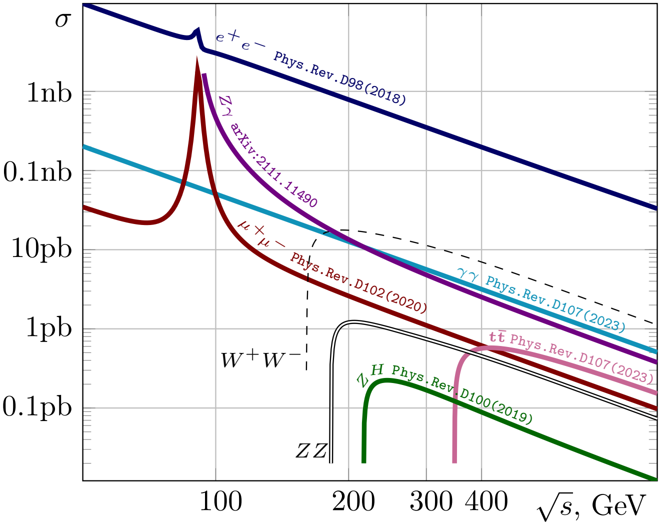
- full one-loop electroweak corrections
- higher order corrections
- massive case
- accounting for polarization effects
- full phase space operation
- results of ReneSANCe event generator and SANC integrators are thoroughly cross checked

Processes of interest

- Bhabha ($e^+e^- \to e^-e^+$), Phys. Rev. D 98, 013001.
- ZH ($e^+e^- \to ZH$), Phys. Rev. D 100, 073002.
- s-channel ($e^+e^- \to \mu^-\mu^+$, $e^+e^- \to \tau^-\tau^+$), Phys. Rev. D 102, 033004.
- s-channel ($e^+e^- \to t\bar{t}$), Phys. Rev. D 107, 113006.
- Photon-pair ($e^+e^- \to \gamma\gamma$), Phys. Rev. D 107, 073003.
- Muon-electron scattering ($\mu^+e^- \to \mu^+e^-$), Phys. Rev. D 105, 033009.
- Møller ($\mu^+\mu^+ \to \mu^+\mu^+$), JETP Lett. 115, 9.
- Zγ ($e^+e^- \to Z\gamma$).
- ZZ ($e^+e^- \to ZZ$).

- publication, available in release of the generator
- publication, in preparation for next release of the generator
- in preparation

Basic processes of SM for e^+e^- annihilation



The cross sections are given for polar angles between $10^o < \theta < 170^o$ in the final state.

Motivation

- Direct measurement of the top-quark mass.
- Both the photon and Z boson couplings of the top quark can be unambiguously measured using asymmetries.
- Importance for the search of BSM signals.

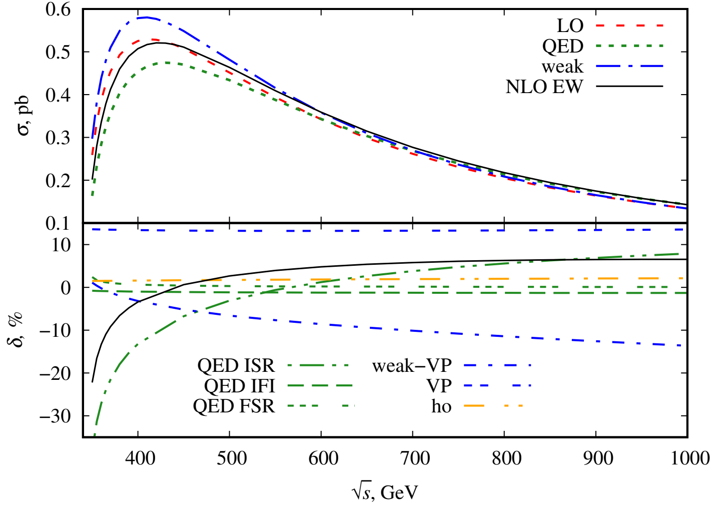
Radiative corrections to top-pair production

In unpolarized case the theoretical uncertainty for observables of top quark pair production at the one-loop level $\mathcal{O}(\alpha)$ were estimated for the first time in:
J. Fujimoto and Y. Shimizu, Mod. Phys. Lett. A 3 (1988) 581.

Beam polarization effects were investigated using the `GRACE-Loop` system in:
P. H. Khiem, E. Kou, Y. Kurihara, and F. Le Diberder, 1503.04247,
N. M. U. Quach, Y. Kurihara, K. H. Phan, and T. Ueda, Eur. Phys. J. C 78 (2018), no. 5 422.

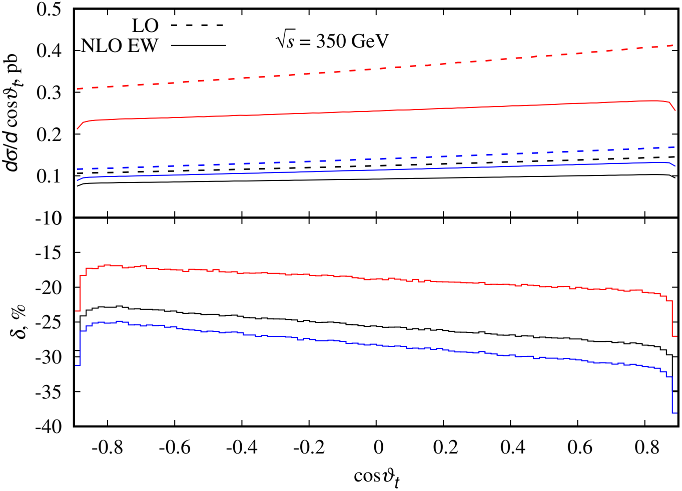
$e^+e^- \to t\bar{t}$, energy dependence

The LO and NLO EW corrected unpolarized cross sections and the relative corrections in parts as a function of the c.m.s. energy.



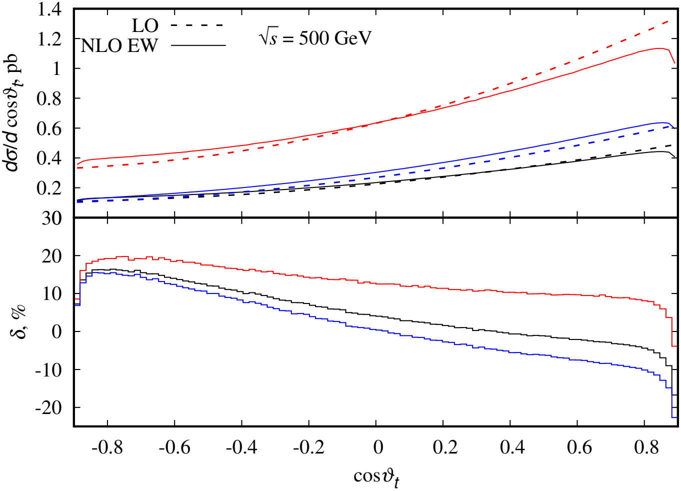
$e^+e^- \to t\bar{t}$, angle dependence, $\sqrt{s} = 350$ GeV

The unpolarized (black), and fully polarized, with $(P_{e^+}, P_{e^-} = +1, -1)$ (red) and $(-1, +1)$ (blue), initial beams for the energy $\sqrt{s} = 350$ GeV.



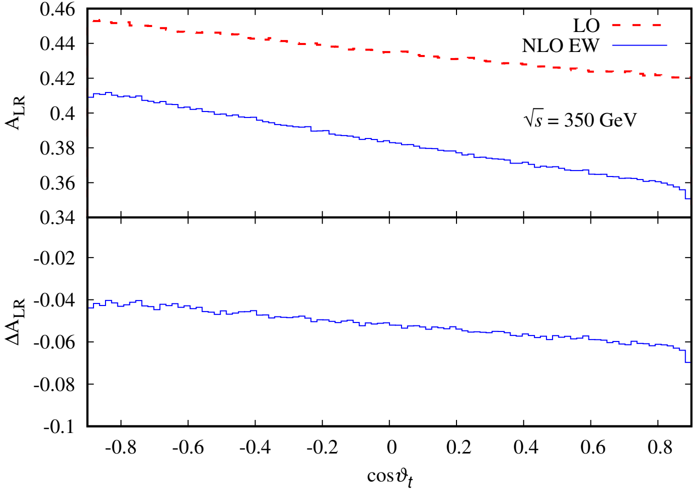
$e^+e^- \to t\bar{t}$, angle dependence, $\sqrt{s} = 500$ GeV

The unpolarized (black), and fully polarized, with $(P_{e^+}, P_{e^-} = +1, -1)$ (red) and $(-1, +1)$ (blue), initial beams for the energy $\sqrt{s} = 500$ GeV.



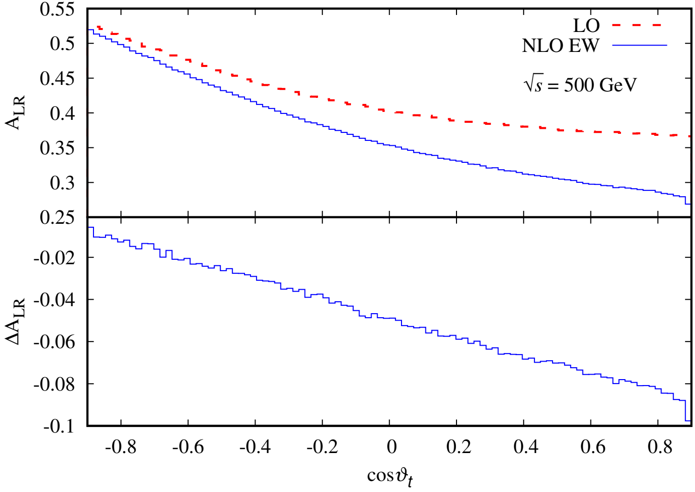
$e^+e^- \to t\bar{t}$, Left–Right Asymmetry, $\sqrt{s} = 350$ GeV

The asymmetry $A_{LR} = \frac{\sigma_{\mathrm{LR}} - \sigma_{\mathrm{RL}}}{\sigma_{\mathrm{LR}} + \sigma_{\mathrm{RL}}}$, in the Born and one-loop approximations.



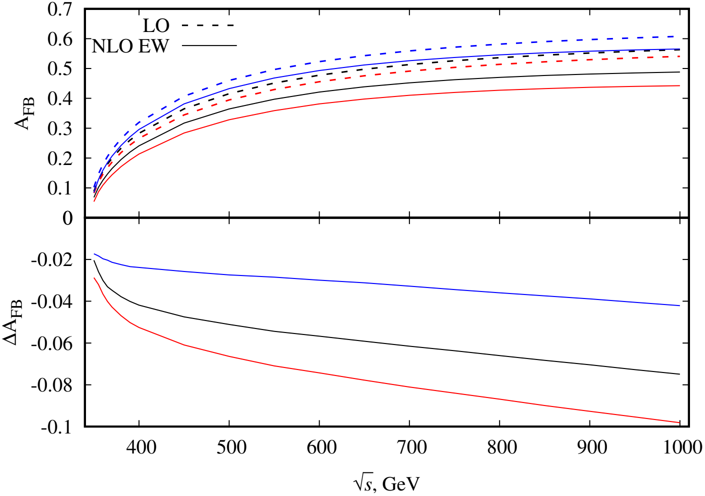
$e^+e^- \to t\bar{t}$, Left–Right Asymmetry, $\sqrt{s} = 500$ GeV

The asymmetry $A_{LR} = \frac{\sigma_{\rm LR} - \sigma_{\rm RL}}{\sigma_{\rm LR} + \sigma_{\rm RL}}$, in the Born and one-loop approximations.



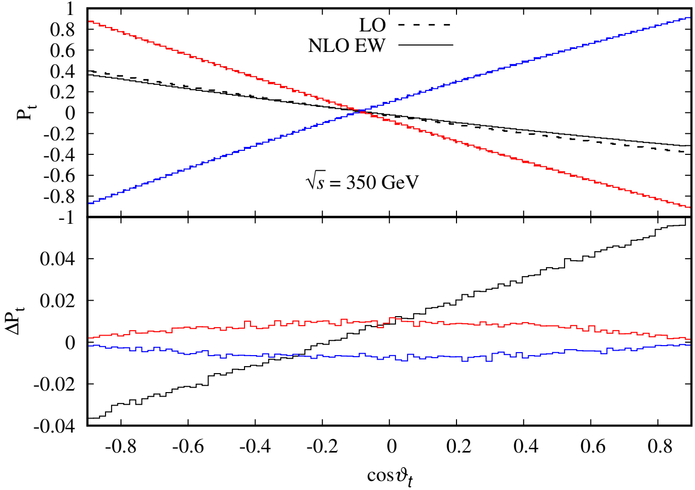
$e^+e^- \to t\bar{t}$, Forward–Backward Asymmetry

The asymmetry $A_{\mathrm{FB}} = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}}$, in the Born and one-loop approximations. The black lines are for the unpolarized initial beams while the red and blue ones are for the fully polarized cases $(P_{e^+}, P_{e^-} = +1, -1)$ and $(-1, +1)$.



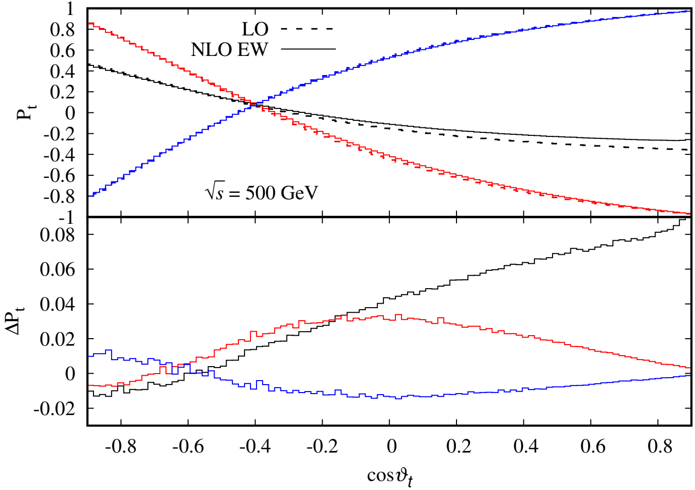
$e^+e^- \to t\bar{t}$, Final-State Fermion Polarization, $\sqrt{s} = 350$ GeV

Top quark polarization P_t in the Born and one-loop approximations. The black lines are for the unpolarized initial beams while the red and blue ones are for the fully polarized cases $(P_{e^+}, P_{e^-} = +1, -1)$ and $(-1, +1)$.

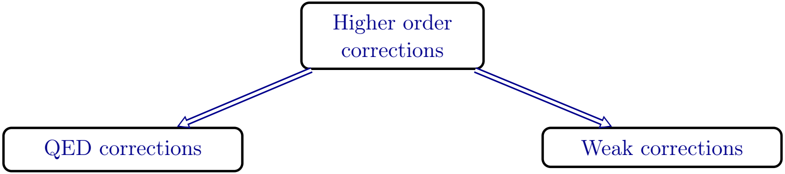


$e^+e^- \to t\bar{t}$, Final-State Fermion Polarization, $\sqrt{s} = 500$ GeV

Top quark polarization P_t in the Born and one-loop approximations. The black lines are for the unpolarized initial beams while the red and blue ones are for the fully polarized cases $(P_{e^+}, P_{e^-} = +1, -1)$ and $(-1, +1)$.



Higher order improvements



- Leading logarithmic (LL) approximation.
- Corrections to $\Delta\alpha$.
- Shower with matching.

- Corrections to $\Delta\rho$.
- Leading Sudakov logarithms.

Higher order improvements, QED

Basic formula:

$$\sigma^{\mathrm{LLA}} = \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_2 \mathcal{D}_{ee}(x_1)\mathcal{D}_{ee}(x_2)\sigma_0(x_1, x_2, s)\Theta(\mathrm{cuts}),$$

where $\sigma_0(x_1, x_2, s)$ – is the Born level cross section of the annihilation process with changed momenta of initial particles.

$\mathcal{D}_{ee}(x)$ describes the probability density of finding an electron with an energy fraction x in the initial electron beam.

[Kuraev, E.A.; Fadin, V.S. Sov. J. Nucl. Phys. 1985, 41, 466–472]

Higher order improvements, QED

The leading log is $L = \ln \frac{s}{m_l^2}$.

LO	1		
NLO	αL	α	
NNLO	$\frac{1}{2}\alpha^2 L^2$	$\frac{1}{2}\alpha^2 L$	$\frac{1}{2}\alpha^2$
N^3LO	$\frac{1}{6}\alpha^3 L^3$	$\frac{1}{6}\alpha^3 L^2$	...

In the LL approximation we can separate pure photonic (marked "γ") and the rest corrections which include pure pair and mixed photon-pair effects (marked as "pair").

$e^+e^- \to t\bar{t}$, $\sqrt{s}$ =350 and 500 GeV

Multiple photon ISR relative corrections δ (%) in the LLA approximation.

$\sqrt{s}$, GeV	350	500
$\mathcal{O}(\alpha L)$, γ	$-42.546(1)$	$-3.927(1)$
$\mathcal{O}(\alpha^2 L^2)$, γ	$+8.397(1)$	$-0.429(1)$
$\mathcal{O}(\alpha^2 L^2)$, e^+e^-	$-0.460(1)$	$-0.030(1)$
$\mathcal{O}(\alpha^2 L^2)$, $\mu^+\mu^-$	$-0.277(1)$	$-0.018(1)$
$\mathcal{O}(\alpha^3 L^3)$, γ	$-0.984(1)$	$+0.021(1)$
$\mathcal{O}(\alpha^3 L^3)$, e^+e^-	$+0.182(1)$	$-0.012(1)$
$\mathcal{O}(\alpha^3 L^3)$, $\mu^+\mu^-$	$+0.110(1)$	$-0.008(1)$
$\mathcal{O}(\alpha^4 L^4)$, γ	$+0.070(1)$	$+0.002(1)$

Higher order improvements, weak

Higher order improvements added to NLO cross section through $\Delta\rho$ parameter: $s_W^2 \to \bar{s}_W^2 \equiv s_W^2 + \Delta\rho\, c_W^2$.

$\mathcal{O}(\alpha)$	A. Sirlin, PRD22, (1980) 971, W.J. Marciano, A. Sirlin, PRD22 (1980) 2695; G. Degrassi, A. Sirlin, NPB352 (1991) 352, P. Gambino and A. Sirlin, PRD49 (1994) 1160
$\mathcal{O}(\alpha\alpha_s)$	A. Djouadi, C. Verzegnassi, PLB195 (1987) 265; B. Kiehl, NPB353 (1991) 567; B. Kniehl, A. Sirlin, NPB371 (1992) 141, PRD47 (1993) 883; A. Djouadi, P. Gambino, PRD49 (1994) 3499
$\mathcal{O}(\alpha\alpha_s^2)$	L. Avdeev et al., PLB336 (1994) 560;K.G. Chetyrkin, J.H. Kuhn, M. Steinhauser, PLB351 (1995) 331; PRL75 (1995) 3394; NPB482 (1996)
$\mathcal{O}(\alpha\alpha_s^3)$	Y. Schroder, M. Steinhauser, PLB622 (2005) 124; K.G. Chetyrkin et al., hep-ph/0605201; R. Boughezal, M. Czakon, hep-ph/0606232
$\mathcal{O}(\alpha^2)$	G. Degrassi, P. Gambino, A. Sirlin, PLB394 (1997) 188; M. Awramik, M. Czakon, A. Freitas, JHEP0611 (2006) 048

$e^+e^- \to t\bar{t}$, $\sqrt{s}$ =350 and 500 GeV

Integrated Born and weak contributions to the cross section and higher-order leading corrections in two EW schemes: $\alpha(0)$ and G_μ.

$\sqrt{s}$, GeV	350	500
$\sigma^{\text{Born}}_{\alpha(0)}$, pb	0.22431(1)	0.45030(1)
$\sigma^{\text{Born}}_{G_\mu}$, pb	0.24108(1)	0.48398(1)
$\delta^{\text{Born}}_{G_\mu/\alpha(0)}$, %	7.48(1)	7.48(1)
$\sigma^{\text{weak}}_{\alpha(0)}$, pb	0.25564(1)	0.47705(1)
$\sigma^{\text{weak}}_{G_\mu}$, pb	0.26055(1)	0.48420(1)
$\delta^{\text{weak}}_{G_\mu/\alpha(0)}$, %	1.92(1)	1.50(1)
$\sigma^{\text{weak+ho}}_{\alpha(0)}$, pb	0.25900(1)	0.48483(1)
$\sigma^{\text{weak+ho}}_{G_\mu}$, pb	0.25986(1)	0.48289(1)
$\delta^{\text{weak+ho}}_{G_\mu/\alpha(0)}$, %	0.33(1)	$-0.40(1)$

Integrated Born and one-loop cross sections

P_{e^+}, P_{e^-}	0,0	$-1,+1$	$+1,-1$
	$\sqrt{s} = 350$ GeV		
σ^{Born}, pb	0.22431(1)	0.25357(1)	0.64367(1)
σ^{NLO}, pb	0.16623(1)	0.20520(1)	0.45972(1)
δ^{NLO}, %	−25.90(1)	−19.07(1)	−28.58(1)
δ^{QED}, %	−39.87(1)	−40.03(1)	−39.79(1)
δ^{VP}, %	12.84(1)	17.51(1)	11.00(1)
$\delta^{\text{weak-VP}}$, %	1.11(1)	3.43(1)	0.20(1)
δ^{ho}, %	1.50(1)	1.55(1)	1.47(1)
	$\sqrt{s} = 500$ GeV		
σ^{Born}, pb	0.45030(1)	0.54028(1)	1.2609(1)
σ^{NLO}, pb	0.45865(1)	0.60072(1)	1.2334(1)
δ^{NLO}, %	1.86(1)	11.12(1)	−2.18(1)
δ^{QED}, %	−4.08(1)	−4.56(1)	−3.91(1)
δ^{VP}, %	12.58(1)	16.33(1)	10.97(1)
$\delta^{\text{weak-VP}}$, %	−6.63(1)	−5.63(1)	−9.24(1)
δ^{ho}, %	1.73(1)	1.82(1)	1.69(1)

Summary

- $e^+e^- \to t\bar{t}$ **process implemented**
- **Complete one-loop EW corrections**
- **Initial & final state polarization support**
- **Easy to investigate various asymmetries**
- **LL-accuracy improvements to cross section**
- **Higher order improvements through** $\Delta\rho$
- **The research is supported by grant of the Russian Science Foundation (project No. 22-12-00021)**

Thank you for your attention!