SANC: status, plans

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Higgs Physics, EW Physics, and generators tools for future electron positron Higgs factories

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JINR

`SANC` –
CEPC, Belle2, LHC, FCC, ILC, CLIC, ...

⇑

μela –
analysis of μe scattering data from the beam polarimeter of the SMC experiment at CERN

⇑

`HECTOR` and `polHECTOR` –
theoretical support for HERA

⇑

`ZFITTER` –
theoretical support for LEP-I and LEP-II

ZFITTER

ZFITTER

is a Fortran package for the evaluation of radiative corrections (quantum corrections), as predicted in the Standard Model of elementary particles, to a variety of observable quantities, notably those related to the Z-boson resonance peak.

The homepage of the **ZFITTER** project and collaboration is http://sanc.jinr.ru/users/zfitter/

DIZET

The Fortran package **DIZET**, a library for the calculation of electroweak radiative corrections, is part of the **ZFITTER** distribution. It can also be used in a standalone mode.

KKMC uses **DIZET** library for the calculation of higher order corrections in the electroweak/QCD Standard Model.

DIZET and ZFITTER plans of development

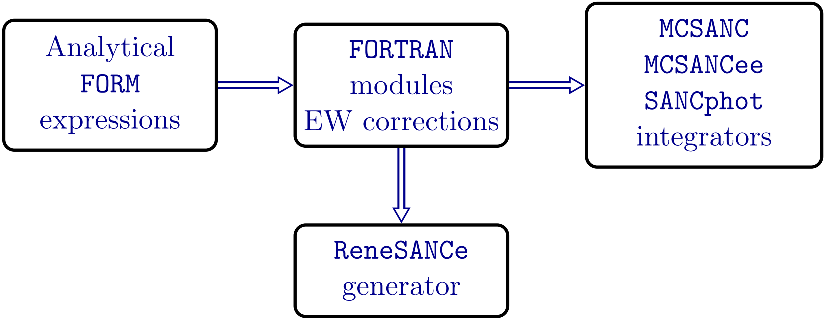
DIZET

- Implement $O(\alpha_t \alpha_s^3)$ corrections for Δr
- Implement $O(\alpha\alpha_s, \alpha\alpha_s^2)$ terms without large m_t approximation for Δr
- Add opportunity to estimate impact of different corrections on EWPO

ZFITTER

- Implement NLL corrections according [A.Arbuzov, U.Voznaya, JPG' 2023, arXiv:2212.01124]

The SANC framework and products family



Publications:

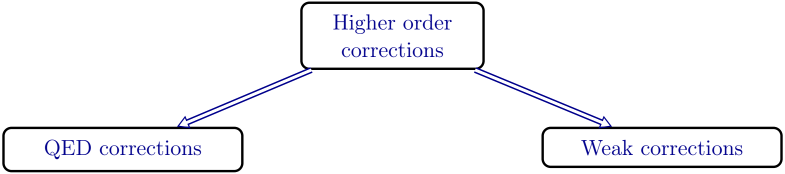
SANC – CPC 174 481-517
MCSANC – CPC 184 2343-2350; JETP Letters 103, 131-136
SANCphot – arXiv:2201.04350
ReneSANCe – CPC 256 107445; CPC 285 108646

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**

Higher order improvements



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

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

Higher order improvements, QED

Basic formula:

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

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	$\frac{1}{6}\alpha^3 L^3$	$\frac{1}{6}\alpha^3 L^2$	$\ldots$

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").

$e^+e^- \to ZZ$, $\sqrt{s}$ =250, 500 and 1000 GeV

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

$\sqrt{s}$, GeV	250	500	1000
$\mathcal{O}(\alpha L)$, γ	$-2.436(1)$	$+8.074(1)$	$+13.938(1)$
$\mathcal{O}(\alpha^2 L^2)$, γ	$-0.692(1)$	$-0.268(1)$	$+0.229(1)$
$\mathcal{O}(\alpha^2 L^2)$, e^+e^-	$-0.013(1)$	$+0.324(1)$	$+1.516(1)$
$\mathcal{O}(\alpha^2 L^2)$, $\mu^+\mu^-$	$-0.008(1)$	$+0.199(1)$	$+0.958(1)$
$\mathcal{O}(\alpha^3 L^3)$, γ	$+0.034(1)$	$-0.014(1)$	$-0.016(1)$
$\mathcal{O}(\alpha^3 L^3)$, e^+e^-	$-0.017(1)$	$-0.022(1)$	$-0.051(1)$
$\mathcal{O}(\alpha^3 L^3)$, $\mu^+\mu^-$	$-0.010(1)$	$-0.013(1)$	$-0.033(1)$
$\mathcal{O}(\alpha^4 L^4)$, γ	< 0.001	< 0.001	< 0.001

$e^+e^- \to t\bar{t}$, $\sqrt{s}$ =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	$+0.070(1)$	$+0.002(1)$

DGLAP

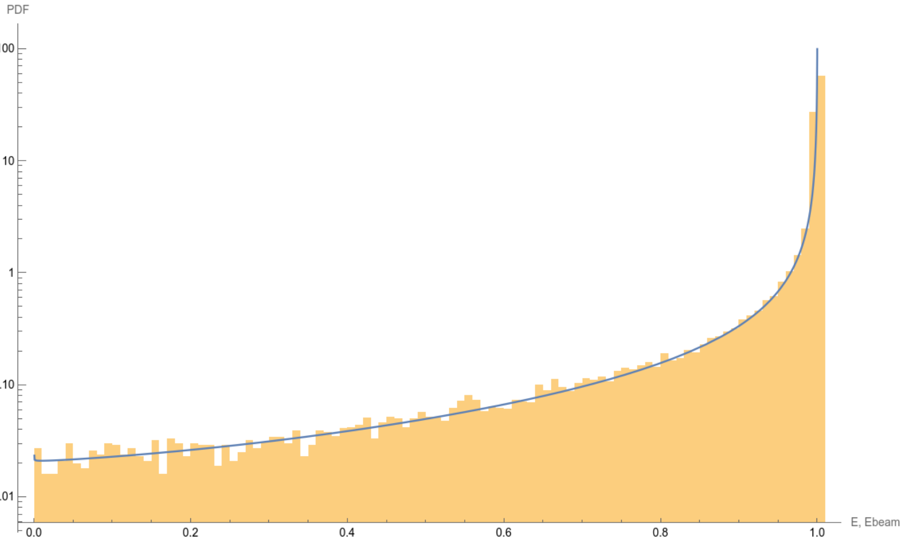
Dokshitzer–Gribov–Lipatov–Altarelli–Parisi (DGLAP) evolution equation:

$$Q^2 \frac{\partial}{\partial Q^2} D(x, Q^2) \;=\; \frac{\alpha}{2\pi} \int_x^1 \frac{dy}{y} P_+(y) D(\frac{x}{y}, Q^2)$$

Sudakov form factor:

$$\Delta(s_1, s_2) \;=\; \exp[-\frac{\alpha}{2\pi} \int_{s_2}^{s_1} \frac{dQ^2}{Q^2} \int_0^{1-\epsilon} dy P(y)]$$

Energy distribution of electrons according shower algorithm



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.

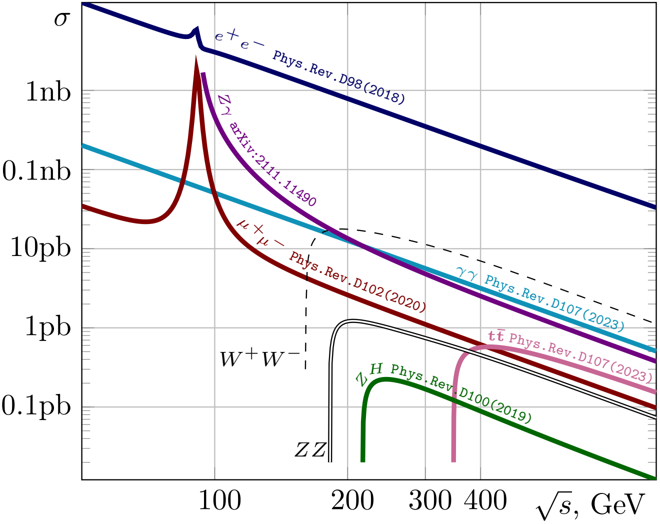
$\sqrt{s}$, GeV	350	500
$\sigma^{\text{Born}}_{\alpha(0)}$, pb	0.22431(1)	0.45030(1)
$\sigma^{\text{Born}}_{G_\mu}$, pb	0.24108(1)	0.48398(1)
$\delta^{\text{Born}}_{G_\mu/\alpha(0)}$, %	7.48(1)	7.48(1)
$\sigma^{\text{weak}}_{\alpha(0)}$, pb	0.25564(1)	0.47705(1)
$\sigma^{\text{weak}}_{G_\mu}$, pb	0.26055(1)	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)

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.
- Photon-pair ($e^+e^- \to \gamma\gamma$), Phys. Rev. D 107, 073003.
- s-channel ($e^+e^- \to t\bar{t}$), Phys. Rev. D 107, 113006.
- Muon-electron scattering ($\mu^+e^- \to \mu^+e^-$), Phys. Rev. D 105, 033009.
- Møller ($e^-e^- \to e^-e^-$, $\mu^+\mu^+ \to \mu^+\mu^+$), JETP Lett. 115, 9.
- Zγ ($e^+e^- \to Z\gamma$).
- ZZ ($e^+e^- \to ZZ$).
- WW ($e^+e^- \to W^+W^-$).

- 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.

Basic processes for luminosity measurements:

- $e^+e^- \to e^+e^-$, Phys. Rev. D 98, 013001
- $e^+e^- \to \mu^+\mu^-$, Phys. Rev. D 102, 033004
- $e^+e^- \to \gamma\gamma$, Phys. Rev. D 107, 073003

Bhabha scattering

BHLUMI:

- For small angle Bhabha
- only QED corrections, YFS

BHWIDE:

- For large angle Bhabha
- 1-loop EW, YFS

BabaYaga:

- Low-energy Bhabha
- only QED corrections?, PS

Bhabha scattering

BHAGEN-1PH:

- For electron/positron scattering in almost zero angle
- only $e^+e^- \to e^+e^-\gamma$ at tree level
- Polarized beams support

ReneSANCe:

- For all regions
- 1-loop EW, LL QED through ePDF, two-loop weak through $\Delta\rho$
- Polarized beams support

NNLO corrections for Bhabha scattering

Two-loop virtual pure QED RC were computed by A. Penin [PRL'2005, NPB'2006] and [T. Becher, K. Melnikov, JHEP'2007]

S. Actis, P. Mastrolia, G. Ossola, NLO QED Corrections to Hard-Bremsstrahlung Emission in Bhabha Scattering, Phys.Lett.B'2010

Processes of interest

- $\gamma\gamma \to \gamma\gamma$
- $\gamma\gamma \to Z\gamma$
- $\gamma\gamma \to ZZ$
- $\gamma\gamma \to ZH$
- $\gamma\gamma \to \nu\bar{\nu}$
- $\gamma\gamma \to l^- l^+$
- $\gamma\gamma \to W^- W^+$

First step to transversal polarization.

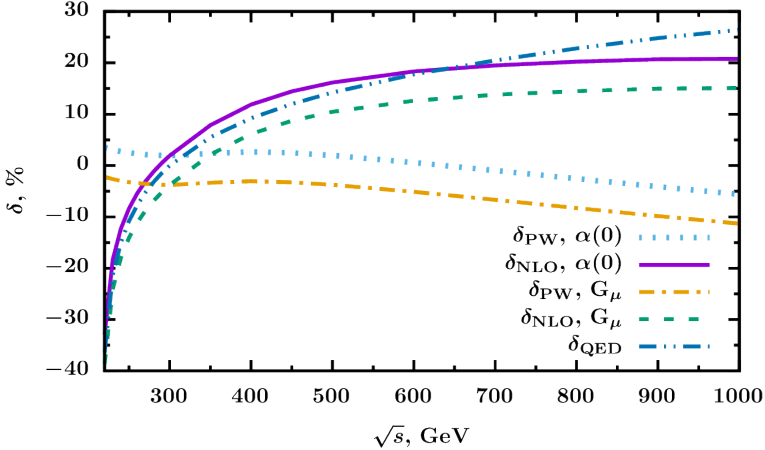
Distributions

For each process we provide all important distributions:

- Cross section over energy and angle distribution
- Asymmetries: Forward-Backward, Left-Right, ...
- Final-State Fermion Polarization

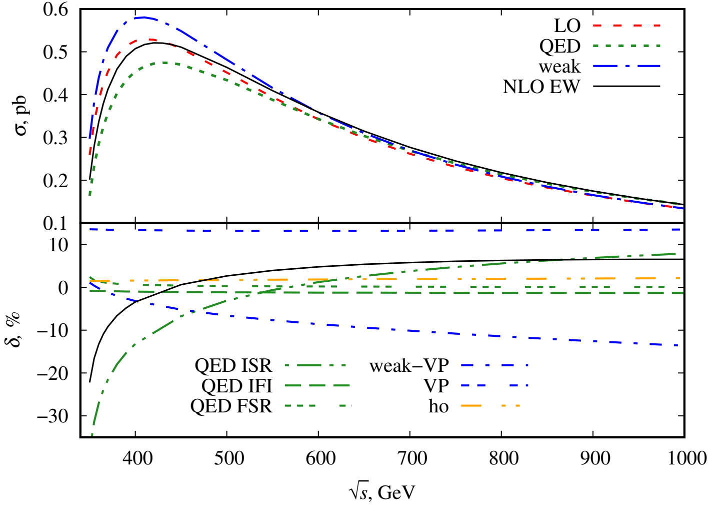
$e^+e^- \to ZH$, energy dependence

Pure weak (PW) and QED relative corrections in α_0 and G_μ EW-schemes.



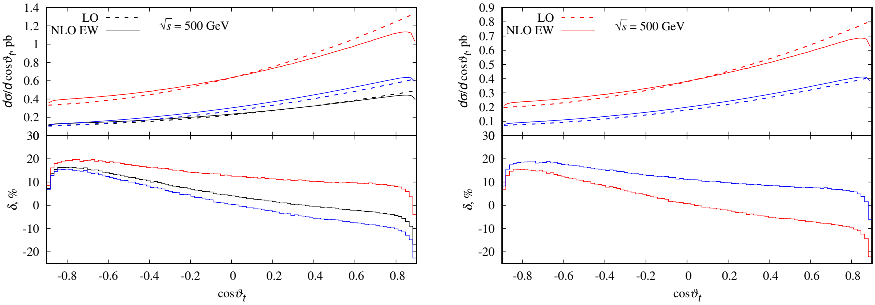
$e^+e^- \to t\bar{t}$, energy dependence

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



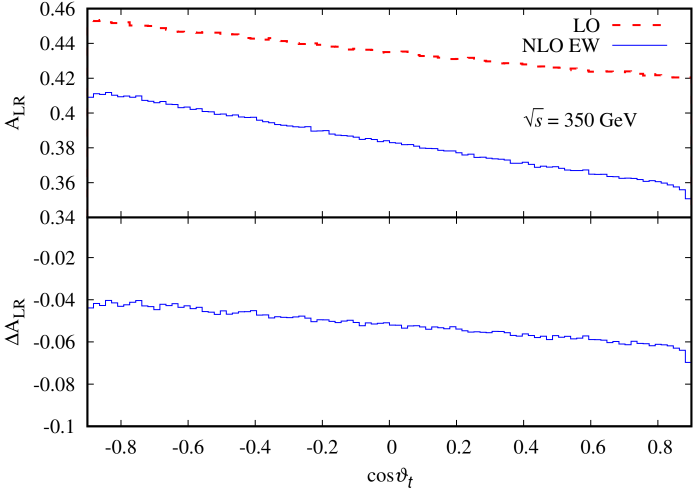
$e^+e^- \to t\bar{t}$, angle dependence

The left part corresponds to the unpolarized (black), and fully polarized, with $(P_{e^+}, P_{e^-} = +1, -1)$ (red) and $(-1, +1)$ (blue), initial beams, while the right one shows the partially polarized initial beams with $(P_{e^+}, P_{e^-} = (+0.3, -0.8)$ (red) and $(-0.3, +0.8)$ (blue) for the energy $\sqrt{s} = 350$ GeV.



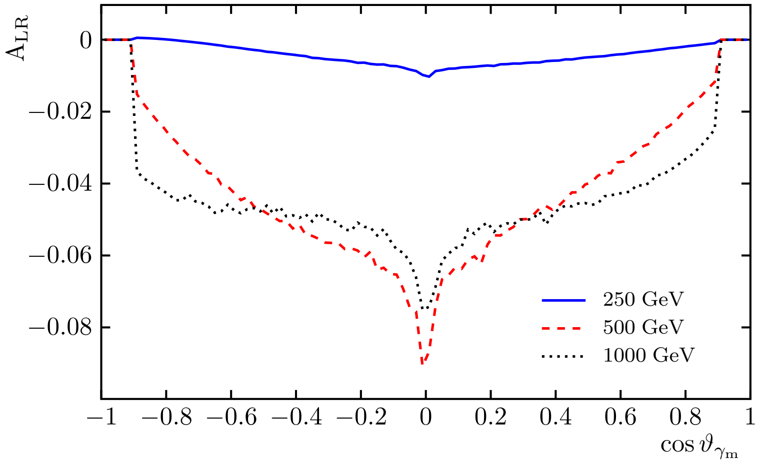
$e^+e^- \to t\bar{t}$, Left–Right Asymmetry, $\sqrt{s} = 350$ GeV

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



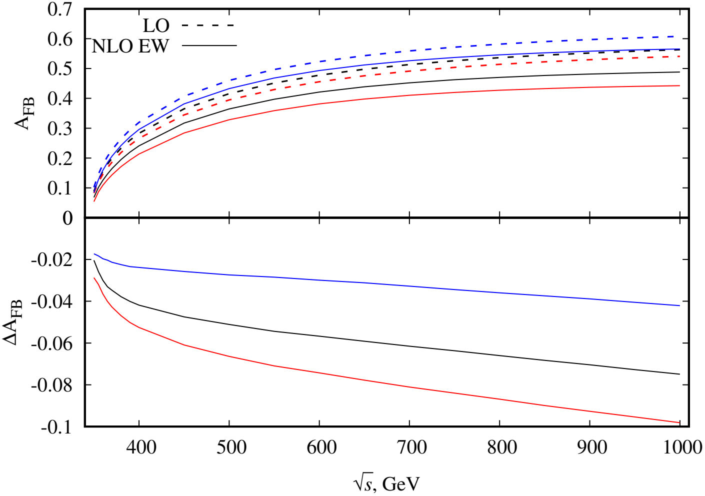
$e^+e^- \to \gamma\gamma$, Left–Right Asymmetry

Angular distributions for A_{LR} asymmetry over the highest energy photon angle ($\vartheta_{\gamma_{\mathrm{m}}}$) at several c.m. energies.

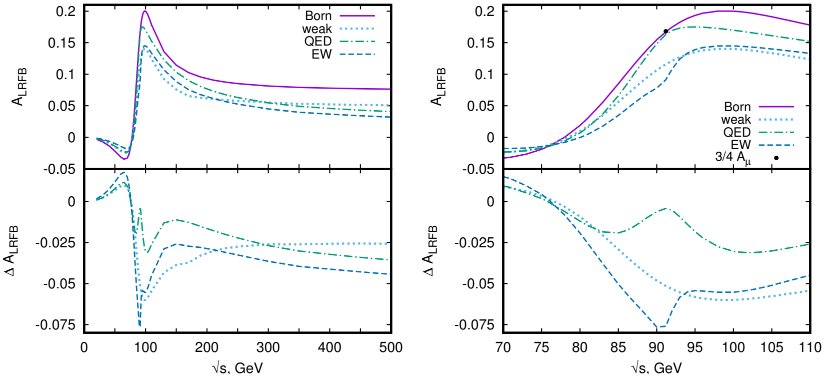


$e^+e^- \to t\bar{t}$, Forward–Backward Asymmetry

The asymmetry $A_{\rm FB} = \frac{\sigma_{\rm F}-\sigma_{\rm B}}{\sigma_{\rm F}+\sigma_{\rm B}}$, 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 $(-1, +1)$.

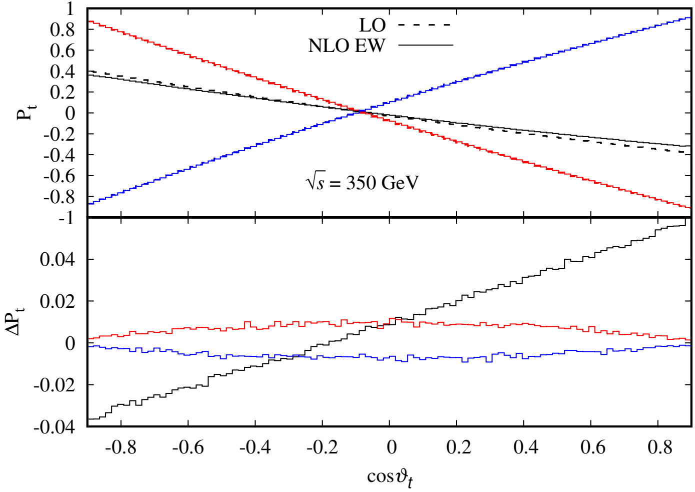


$e^+e^- \to \mu^+\mu^-$, Left–Right Forward–Backward Asymmetry

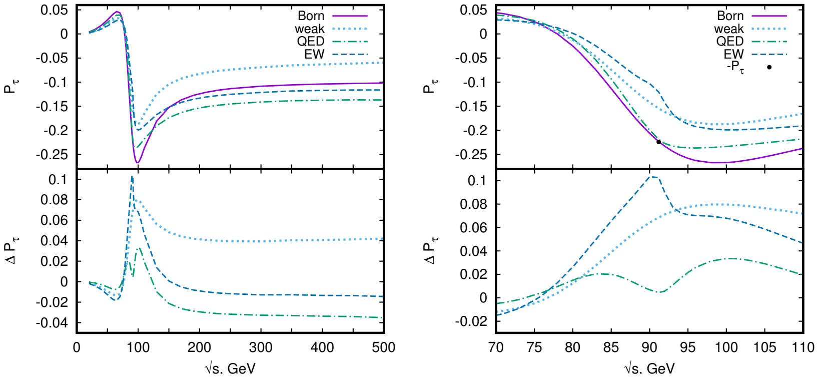


$e^+e^- \to t\bar{t}$, Final-State Fermion Polarization, $\sqrt{s} = 350$ GeV

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 $(-1, +1)$.



$e^+e^- \to \tau^+\tau^-$, Final-State Fermion Polarization



(**Left**) The P_τ polarization in the Born and 1-loop (weak, pure QED, and EW) approximations and ΔP_τ vs. c.m.s. energy in a wide range; (**Right**) the same for the Z peak region. The black dot indicates the value P_τ at the Z resonance.

RESUME: SANC

- **Monte Carlo tools of SANC provide:**
  - **Complete one-loop EW corrections**
  - **Initial & final state polarization support**
  - **Easy to investigate various asymmetries**
  - **LL-accuracy improvements to cross section**
  - **Higher order improvements throw $\Delta\rho$**
- **ReneSANCe provide:**
  - **Events with unit weights**
  - **Output in Standard Les Houches Format**
  - **Simple installation & usage**