Electroweak corrections to top-pair production at lepton colliders

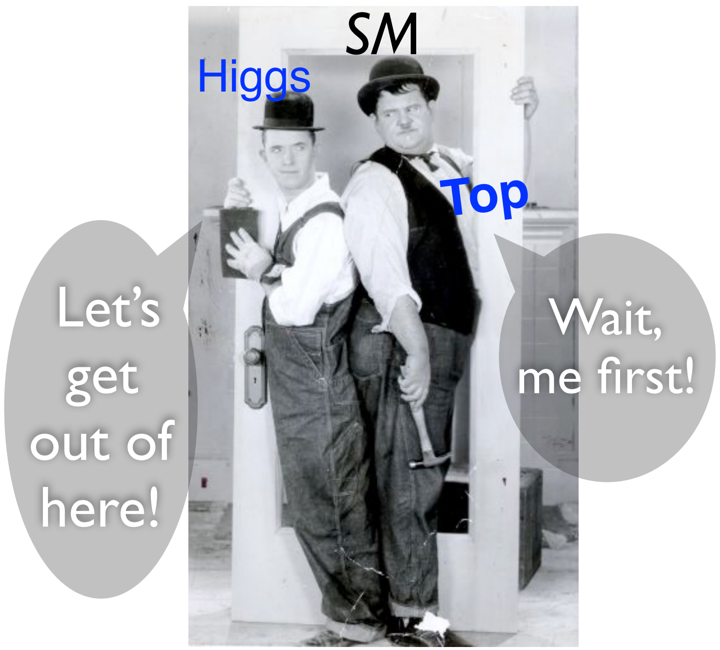
Emi Kou (ILCLab-Orsay)

in collaboration with Y. Kurihara, K. Khiem, F. Le Diberder, B. Mecaj, T. Moskalets, R. Poeschl, F. Richard …

Bi-Weekly meeting of Snowmass topics group EF03
30th July @ home

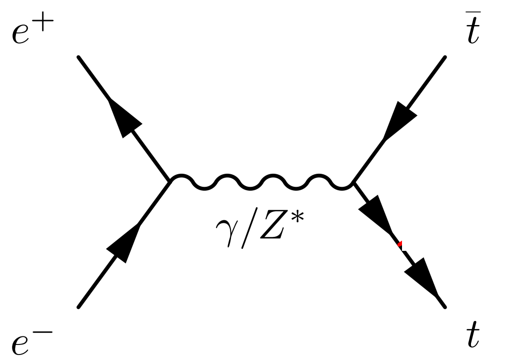
Top physics at ILC

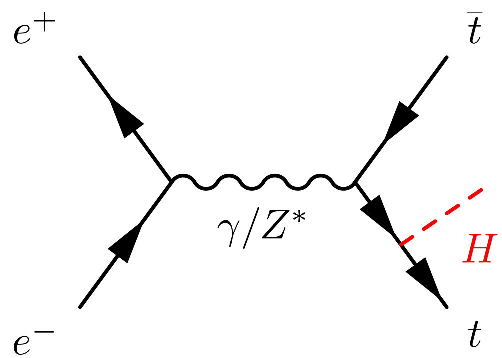
Top being only fermion with mass close to electroweak scale make us think that it has a special role in the physics beyond the SM. Top physics at ILC may open an unique window for discovery of new physics.



Top physics is one of the three pillars of ILC physics !*

i) top mass measurement at the threshold
ii) $t\bar{t}$-Z/γ anomalous coupling measurement
iii) $t\bar{t}$-Higgs coupling measurement



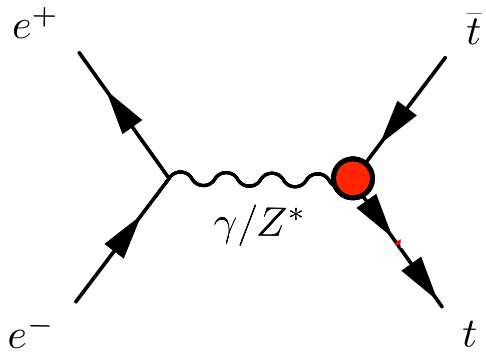


* *ILC baseline energy is 250 GeV.*
* *For i), energy upgrade to >350 GeV needed.*
* *For ii)&iii) energy upgrade to >500 GeV needed.*

The $t\bar{t}$-Z/γ anomalous coupling

- The tt-z/γ anomalous coupling is one of the important probes of new physics. Many new physics models predict significant deviations from SM.

$$\mathcal{L}_{\rm int} = \sum_{v=\gamma,Z} g^v \left[V_l^v \bar{t}\gamma^l (F_{1V}^v + F_{1A}^v \gamma_5) t + \frac{i}{2m_t} \partial_\nu V_l \bar{t} \sigma^{l\nu} (F_{2V}^v + F_{2A}^v \gamma_5) t \right]$$



8 form factors to describe the tt-z/γ anomalous coupling.

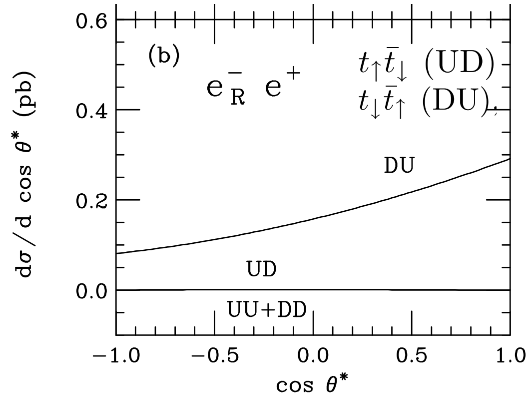
Spin correlation as a tool for discovery

Parke and Shadmi PLB387 ('96)

Top production and decays are very different form the other fermions. Many (interesting) angular correlations emerge, which can be used to extract various information.

Polarized beam useful!

ILC pol. beam option: $(e^-,e^+)=(\pm 0.8,\mp 0.3)$



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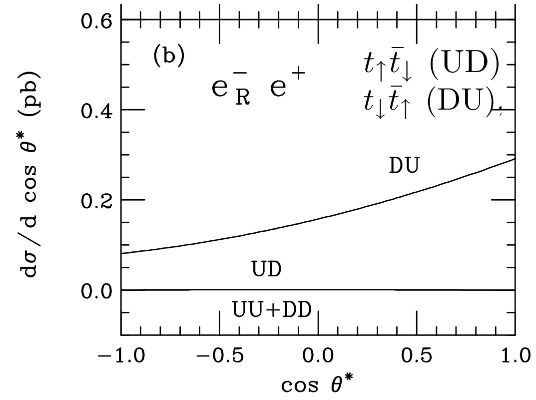
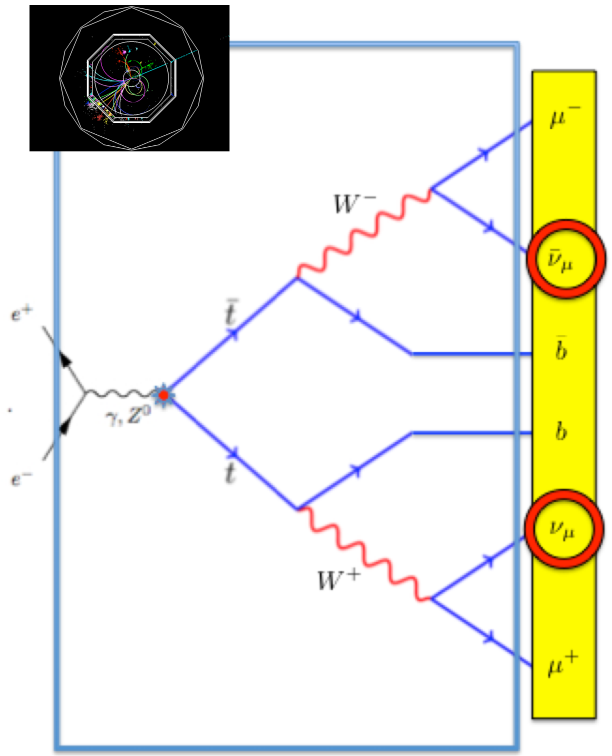




Example of fully leptons final state:
Angles for mu+, mu- and b, anti-b (7 angles)
Energies of mu+ and mu-
Energies of b and anti-b

A full kinematical information can be reconstructed!

Khiem, E.K. Kurihara, Le Diberder arXiv:1503:04247

Spin correlation as a tool for discovery

✳ The recent studies show that these form factor can be measured at precision of the per-mill level. *Khiem, et al arXiv:1503:04247*

The third measurements presented in table 5 comes from the TESLA TDR, assuming no e^+ polarization, and 300 fb^{-1} (uncertainties have been rescaled here to 500 fb^{-1}) and are 4 individual fits of the 4 CP-violating form factors: $\mathcal{R}\mathrm{e}\ \delta\tilde{F}^{\gamma}_{2A}$, $\mathcal{R}\mathrm{e}\ \delta\tilde{F}^{Z}_{2A}$, $\mathcal{I}\mathrm{m}\ \delta\tilde{F}^{\gamma}_{2A}$, and $\mathcal{I}\mathrm{m}\ \delta\tilde{F}^{Z}_{2A}$:

$$\sigma[\mathcal{R}\mathrm{e}\ \delta\tilde{F}^{\gamma}_{2A}] = 0.005 \quad ; \quad \sigma[\mathcal{R}\mathrm{e}\ \delta\tilde{F}^{Z}_{2A}] = 0.006 \quad ; \quad \sigma[\mathcal{I}\mathrm{m}\ \delta\tilde{F}^{\gamma}_{2A}] = 0.006 \quad ; \quad \sigma[\mathcal{I}\mathrm{m}\ \delta\tilde{F}^{Z}_{2A}] = 0.012 \qquad (29)$$

Semi-leptonic

to be compared with the double-leptonic simultaneous fit result (with polarized e^+

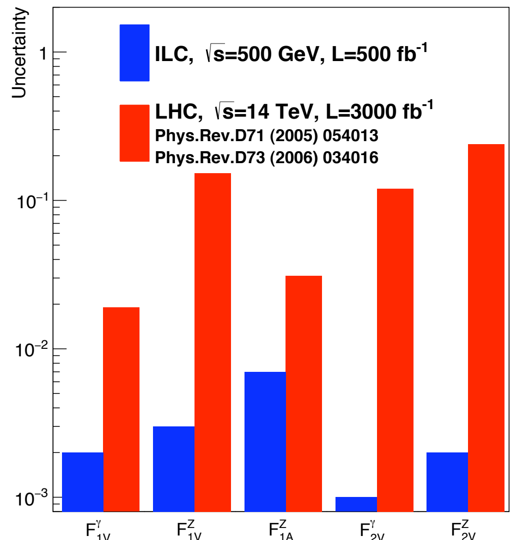
$$\sigma[\mathcal{R}\mathrm{e}\ \delta\tilde{F}^{\gamma}_{2A}] = 0.007 \quad ; \quad \sigma[\mathcal{R}\mathrm{e}\ \delta\tilde{F}^{Z}_{2A}] = 0.012 \quad ; \quad \sigma[\mathcal{I}\mathrm{m}\ \delta\tilde{F}^{\gamma}_{2A}] = 0.007 \quad ; \quad \sigma[\mathcal{I}\mathrm{m}\ \delta\tilde{F}^{Z}_{2A}] = 0.010 \qquad (30)$$

Fully-leptonic

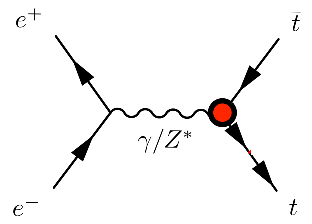
with small correlation coefficients.

But all these studies have been done at tree level…

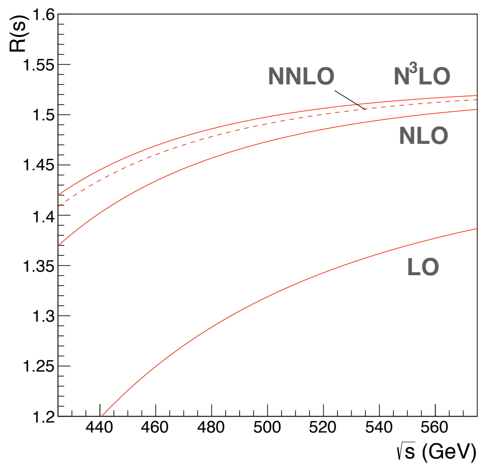
See also M.S.Amjad et al. 1505.06020



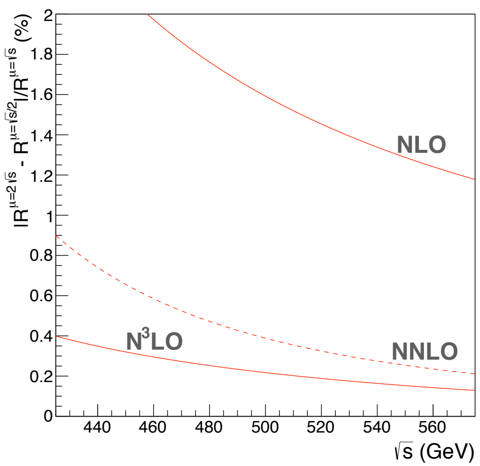
e+e- → ttbar beyond tree level



✴QCD corrections are known up to N³LO



(a) Perturbation series



(b) Scale variations

QCD correction (N³LO) is at the per mil level

Kiyo, Maier, Maierhofer, Marquard, NCP B823 ('09)
Bernreuther, Bonciani, Gehrmann, Heinesch, Leineweber. NPB750 ('06)
Hoang, Mateu, Zebarjad, NPB813 ('09)

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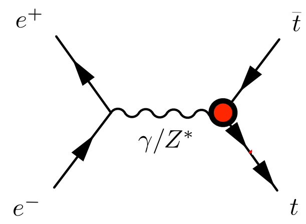
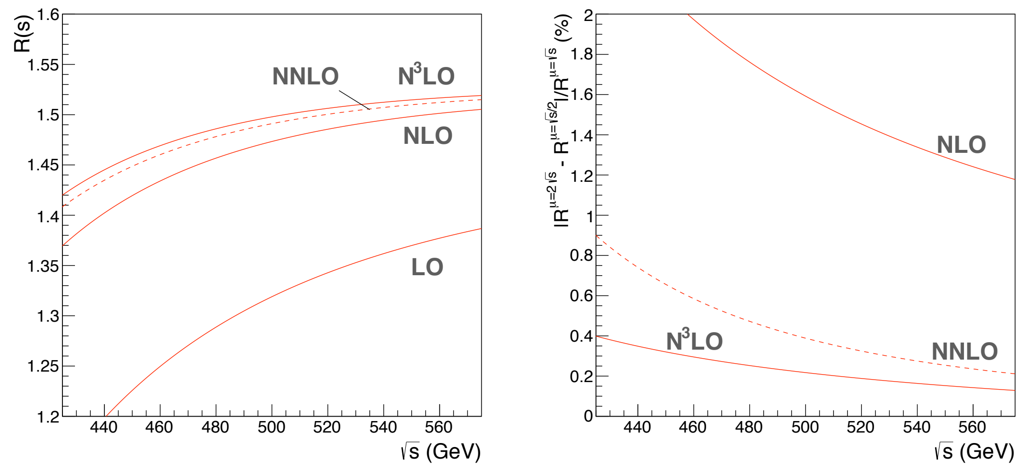


✳QCD corrections are known up to N^{3}LO



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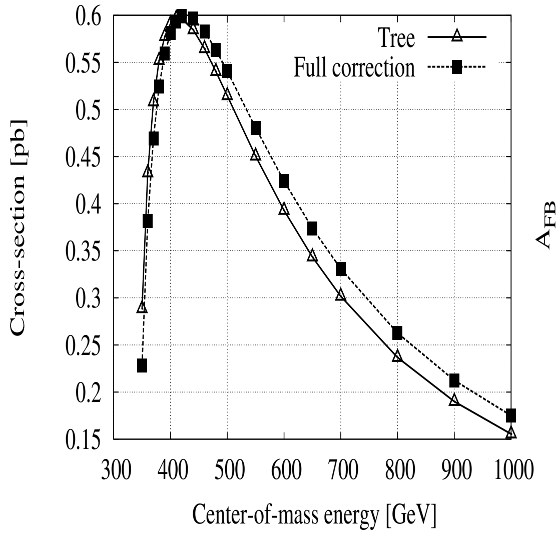
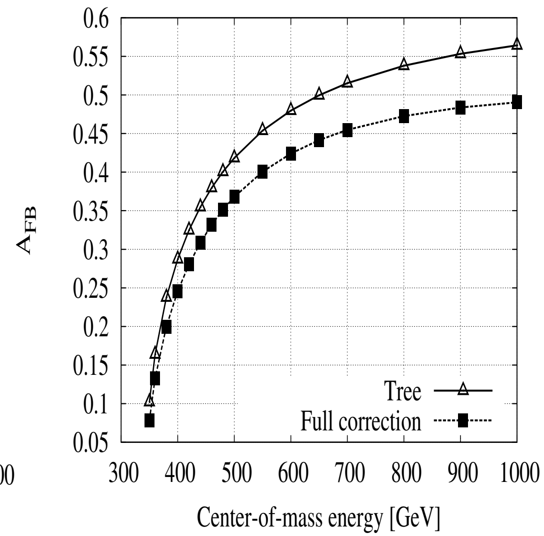
✳Electroweak corrections are known at one-loop level





EW correction at one-loop is
~5% for cross section
~10% for A_{FB}

Fleischer, Leike, Riemann, Werthenbach, EJPC31 ('03)
Kheim, Fujimoto, Ishikawa, Kaneko, Kato, arXive:1211.1112

Fujimoto, Shimizu, Mod. Phys. Lett. 3A ('88) 518
Beenkakker, van der Marck, Hollik, Nucl. Phys. B365('91) 24

e+e- → ttbar beyond tree level

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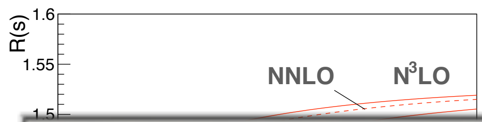
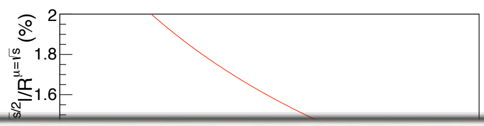




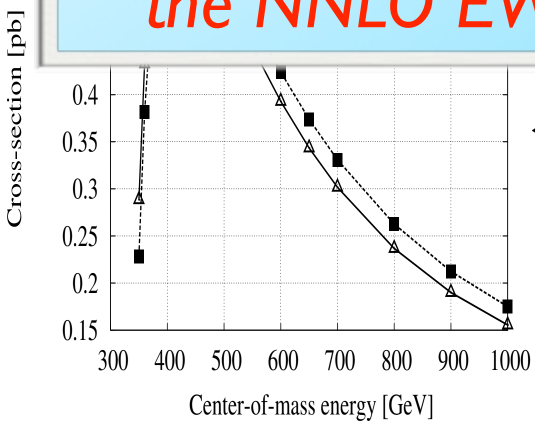
QCD correction (N³LO) is

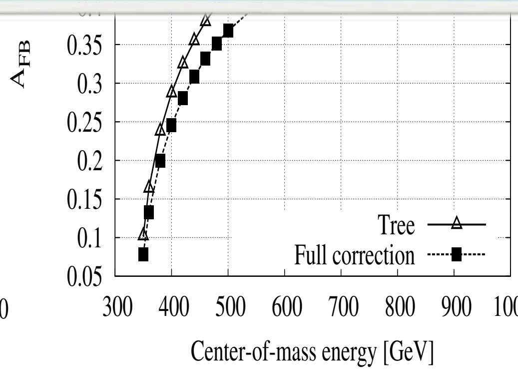
('09)
th,

- ✶ *It has been known since long that the NLO EW correction to the t-tbar production is quite sizable.*
- ✶ *ILC can (easily) access to these EW corrections and further perform a precision measurement of the SM couplings.*
- ✶ *To search for NP effect, we have to make the EW correction **under control** (nobody knows how to compute the NNLO EW correction for now!)*

is

~10% for A_{FB}





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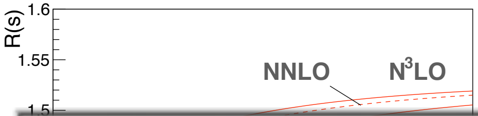
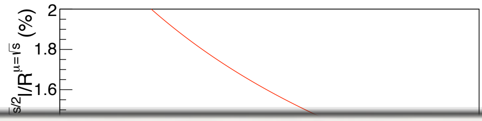
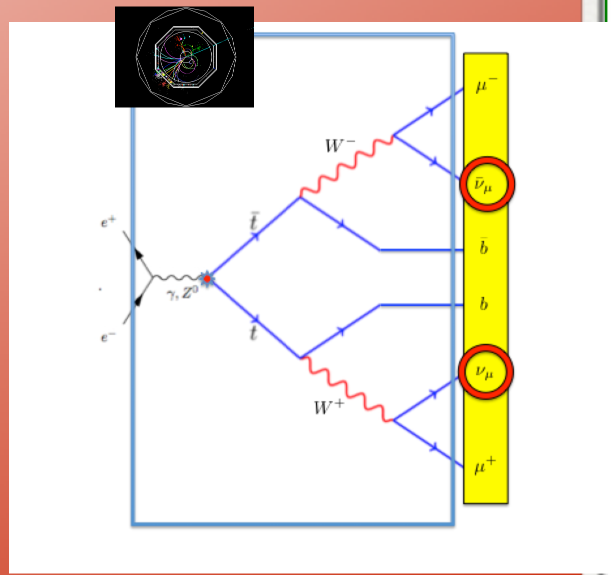


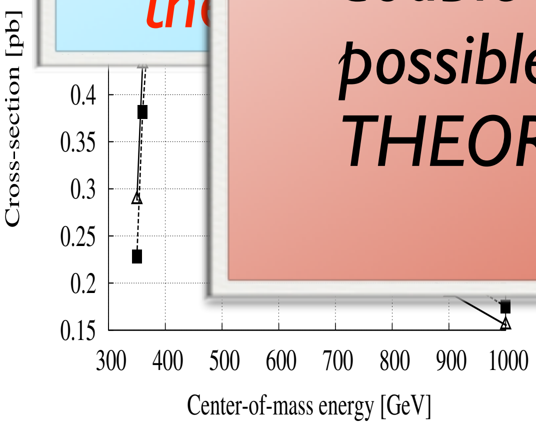


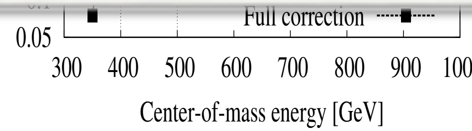
QCD correction (N^{3}LO) is

- ✳ *It has been known since long that the NLO EW correction to*
- ✳ *ILC pe*
- ✳
- ✳ *To co the*

- ✳ *We will eventually need computations of the higher order correction with 6 body final state. QCD correction might be still doable while EW correction is not possible as of today (specific THEORY EFFORTS NEEDED!)*







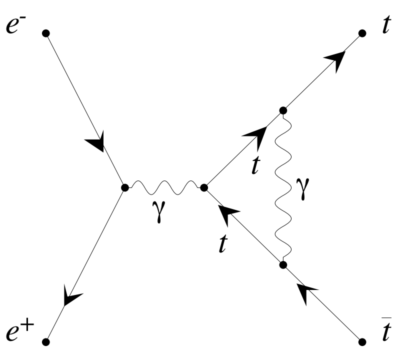
arXive:1211.1112

EW@ NLO with GRACE package

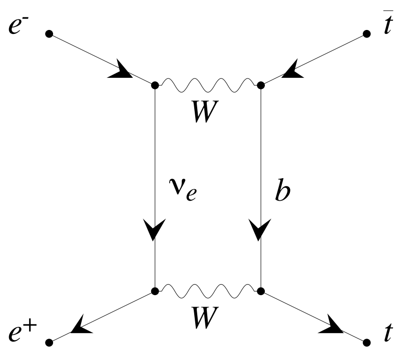
GRACE/GRACE-Loop package: Belanger et al, Phys.Rep.430, 117
Recent progress: Khiem et al, Eur. Phys. J. C 73 ('13), Quach et al, Eur. Phys. J. C78 ('18)

$$| M_0 + \alpha M_{\rm virtual} |^2 = | M_0 |^2 + 2\alpha Re \left(M_0^\dagger M_{\rm virtual} \right) + O(\alpha^2)$$

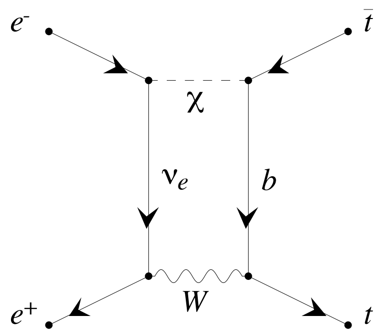
Graph 5



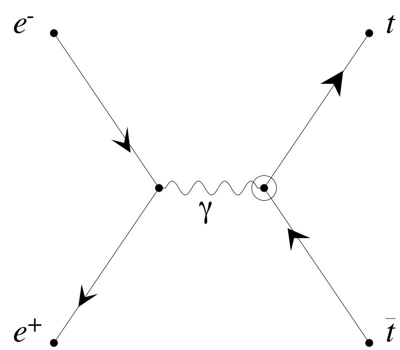
Graph 113



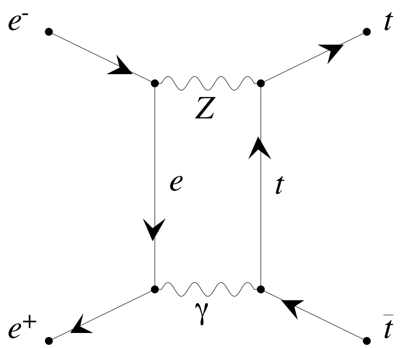
Graph 115



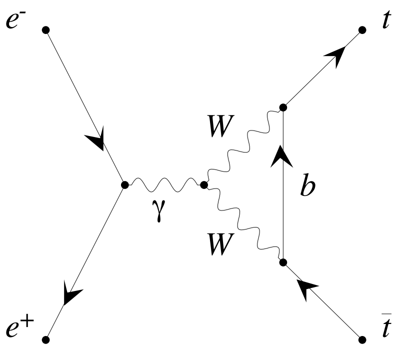
Graph 133



Graph 101



Graph 1

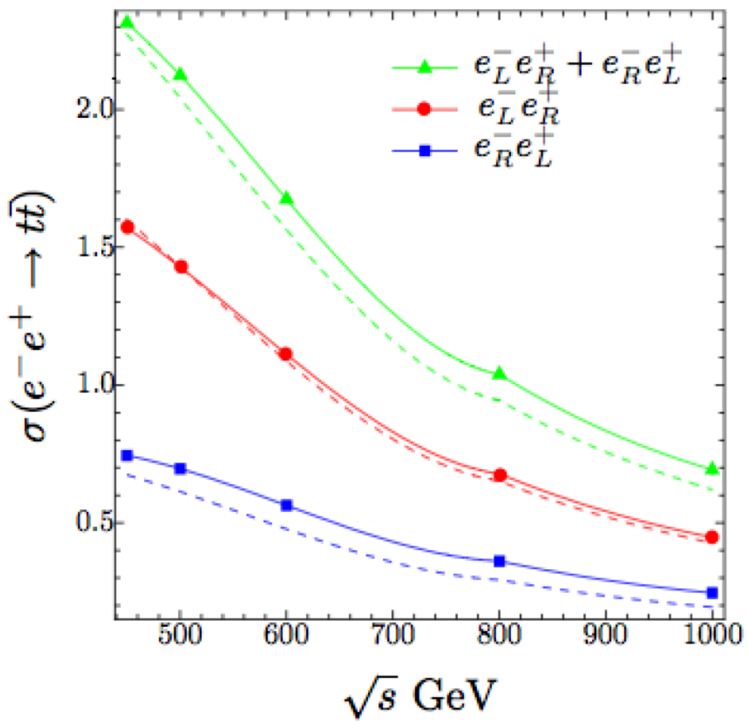


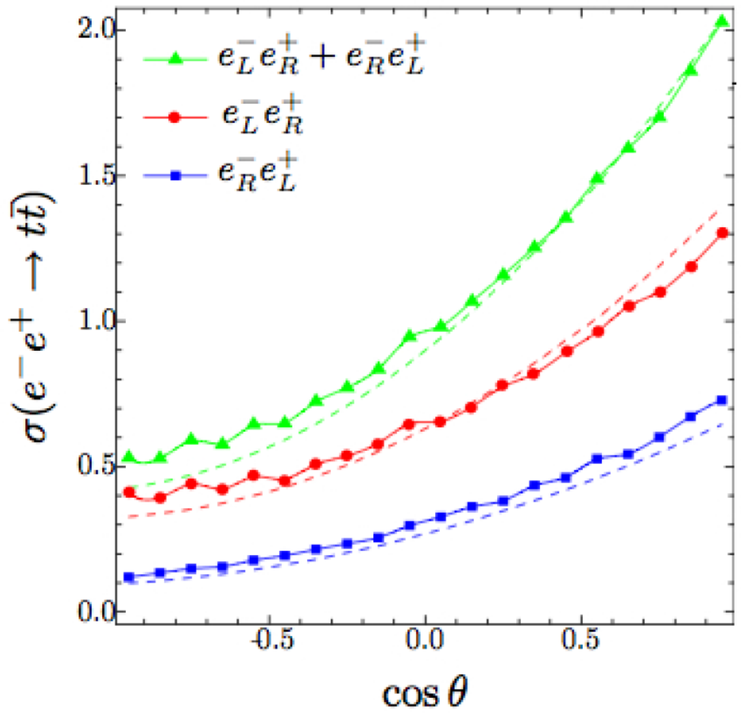
- ✓ 150 diagrams computed automatically
- ✓ 'tHoof-Feynman gauge (xi=1)
- ✓ Goldstone bosons, ghosts etc included
- ✓ Renormalisation; on-shell scheme
- ✓ IR-div: hard photon cut-off

Polarisation dependence of EW@NLO

It turned out that the size of the NLO correction depend strongly on the initial state polarisation.

Khiem, E.K. Kurihara, Le Diberder arXiv:1503:04247



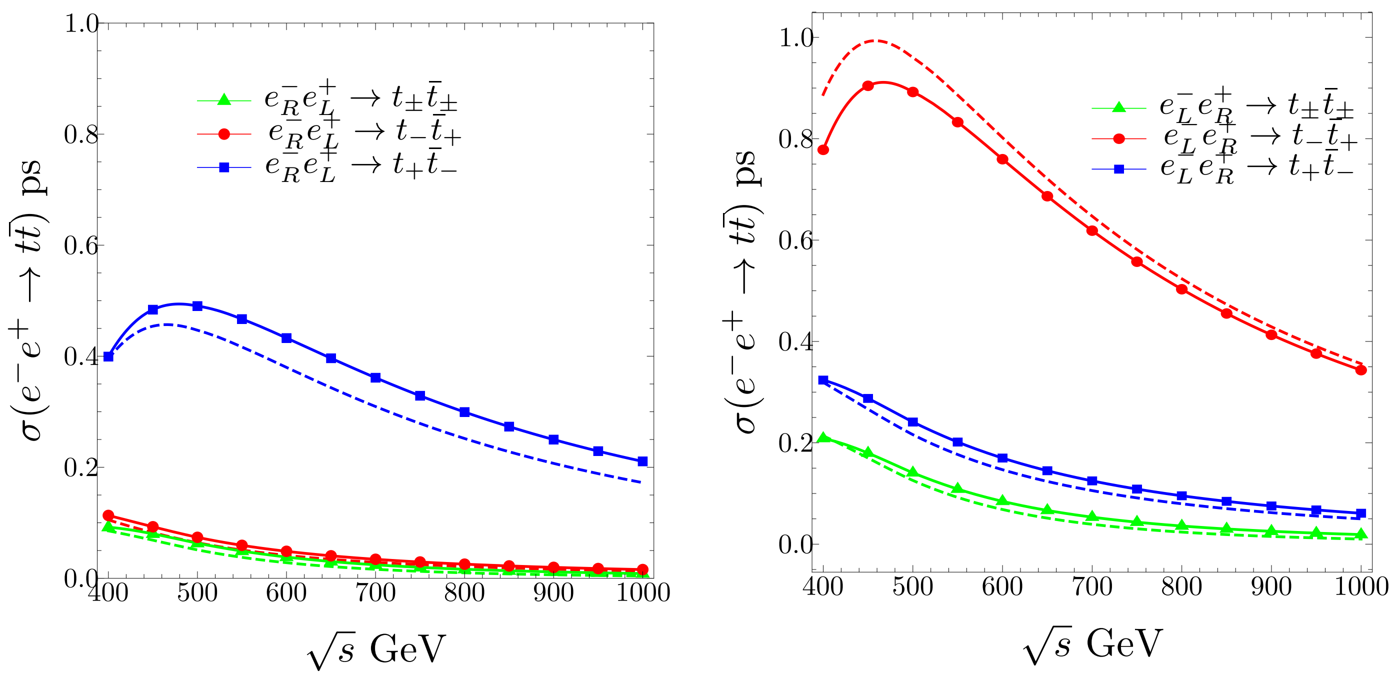


- large NLO correction to the cross section: $e^-_L e^+_R$
- large NLO correction to the forward-backward asymmetry: $e^-_R e^+_L$

Polarisation dependence of EW@NLO

It turned out that the size of the NLO correction depend strongly on the final state polarisation as well.

E.K.Y. Kurihara, B. Mecaj, T.Moskalets in preparation



- large NLO correction to the cross section: $e^-_R e^+_L \to t_+ \text{tbar}_-$
- large NLO correction to the forward-backward asymmetry: $e^-_L e^{+R} \to t_- \text{tbar}_+$

Polarisation dependence of EW@NLO

@500 GeV

Polarization	σ_{NLO}(pb)	σ_{Tree} (pb)	$\delta_{\rm NLO}(\%)$
$e^-_L e^+_R \to t_- \bar{t}_+$	0.892	0.960	~ -7.1
$e^-_L e^+_R \to t_+ \bar{t}_-$	0.241	0.216	~ 11.6
$e^-_L e^+_R \to t_- \bar{t}_-$	0.141	0.126	~ 12.0
$e^-_L e^+_R \to t_+ \bar{t}_+$	0.141	0.126	~12.0
$e^-_L e^+_R \to (t\bar{t})_{\rm tot.}$	1.415	1.427	~ -0.9
$e^-_R e^+_L \to t_+ \bar{t}_-$	0.490	0.447	~ 9.8
$e^-_R e^+_L \to t_- \bar{t}_+$	0.074	0.064	~ 15.2
$e^-_R e^+_L \to t_- \bar{t}_-$	0.063	0.051	~ 23.6
$e^-_R e^+_L \to t_+ \bar{t}_+$	0.063	0.051	~ 23.6
$e^-_R e^+_L \to (t\bar{t})_{\rm tot.}$	0.691	0.613	~ 12.6

$$\delta_{\rm NLO} \equiv \frac{\sigma_{\rm NLO} - \sigma_{\rm Tree}}{\sigma_{\rm NLO} + \sigma_{\rm Tree}}$$

Why NLO correction is large for $e^-_R e^+_L$?

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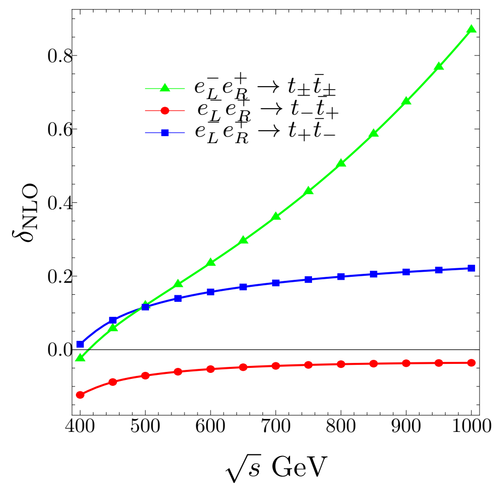
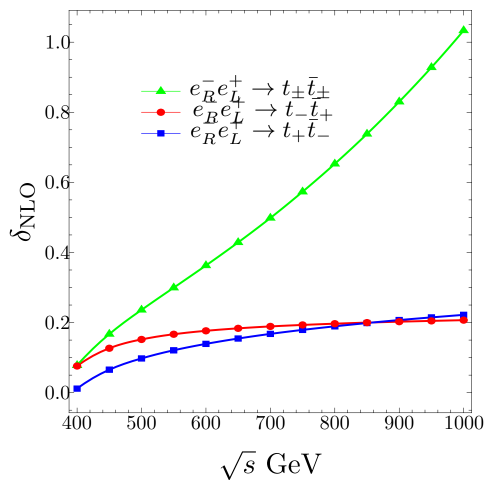
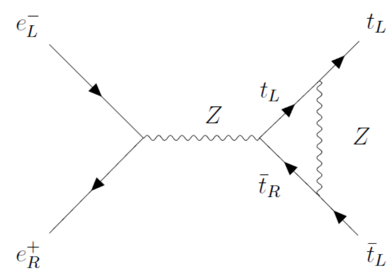
$$\delta_{\rm NLO} \equiv \frac{\sigma_{\rm NLO} - \sigma_{\rm Tree}}{\sigma_{\rm NLO} + \sigma_{\rm Tree}}$$

Forbidden at tree level at massless limit. But these contributions are very small in any case…







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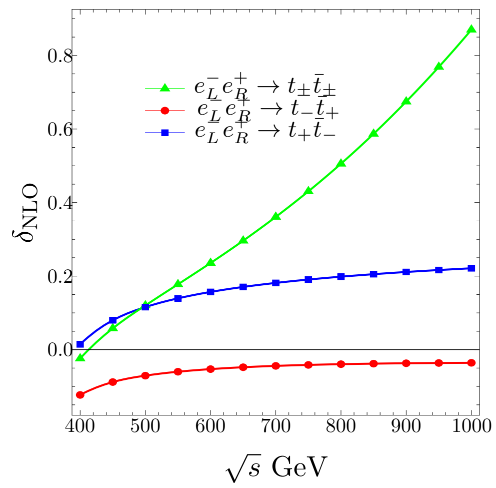
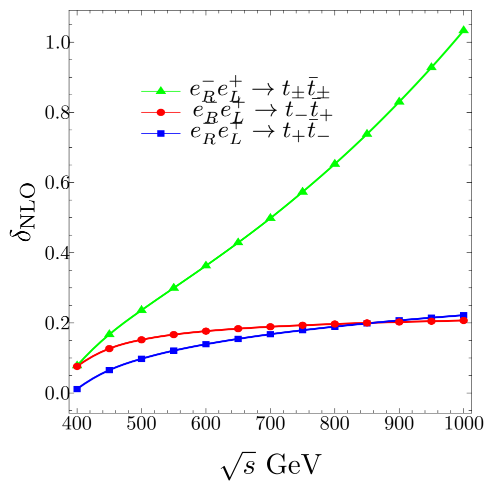
Why NLO correction is large for $e^-_R e^+_L$?

⇒ Because $t_\pm \bar{t}_\mp$ receive the same sign NLO correction.





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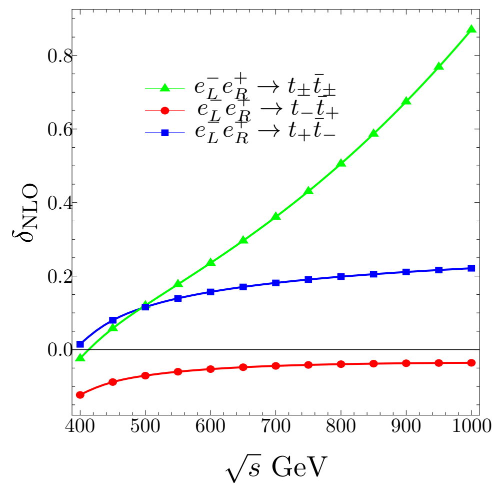
$e_R^- e_L^+ \to t_- \bar{t}_+$	0.074	0.064	$\sim$ 15.2
$e_R^- e_L^+ \to t_- \bar{t}_-$	0.063	0.051	$\sim$ 23.6
$e_R^- e_L^+ \to t_+ \bar{t}_+$	0.063	0.051	$\sim$ 23.6
$e_R^- e_L^+ \to (t\bar{t})_{\rm tot.}$	0.691	0.613	$\sim$ 12.6

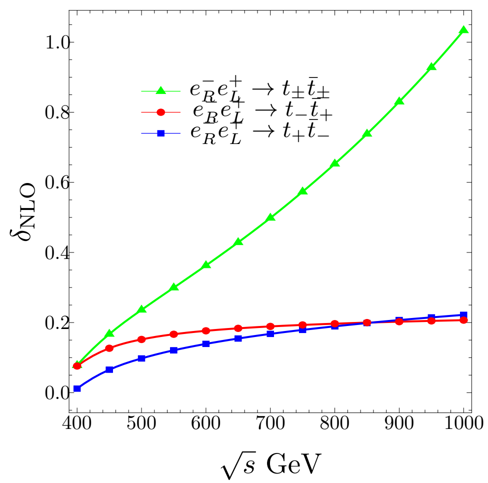
$$\delta_{\rm NLO} \equiv \frac{\sigma_{\rm NLO} - \sigma_{\rm Tree}}{\sigma_{\rm NLO} + \sigma_{\rm Tree}}$$

Why NLO correction is large for $e^-_R e^+_L$?

⇒ Because $t_\pm \bar{t}_\mp$ receive the same sign NLO correction.

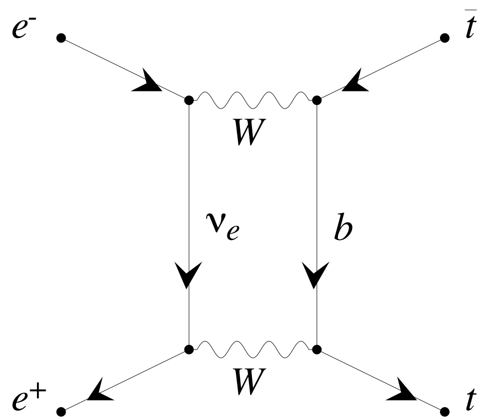
⇒ Then, why the sign of NLO corruption is opposite for $e^-_L e^+_R \to t_+ \bar{t}_-$ and $e^-_L e^+_R \to t_- \bar{t}_+$???





Polarisation dependence of EW@NLO

Obvious difference in NLO correction between two initial polarisation is the W box diagram (it is only for $e^-_L e^+_R$)!

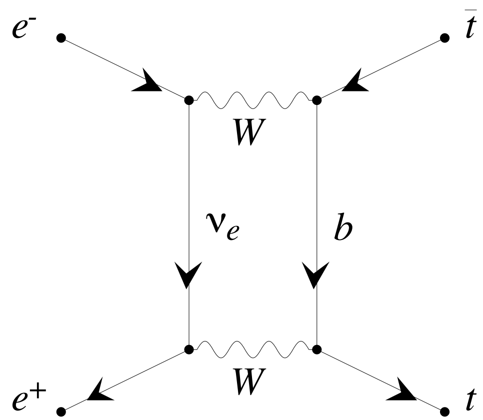


Polarization	$\sigma_{\text{NLO}} - \sigma_{\text{Tree}}$(pb)	$M_{\text{Tree}} \cdot M_{W-\text{box}}$ (pb)	The rest of NLO (pb)
$e^-_L e^+_R \to t_- \bar{t}_+$	-0.068	-0.161	0.093
$e^-_L e^+_R \to t_+ \bar{t}_-$	0.025	-0.006	0.031
$e^-_L e^+_R \to t_- \bar{t}_-$	0.015	-0.013	0.028
$e^-_L e^+_R \to t_+ \bar{t}_+$	0.015	-0.013	0.028
$e^-_L e^+_R \to (t\bar{t})_{\text{tot.}}$	0.013	-0.194	0.181
$e^-_R e^+_L \to t_+ \bar{t}_-$	0.044	0.000	0.044
$e^-_R e^+_L \to t_- \bar{t}_+$	0.010	0.000	0.010
$e^-_R e^+_L \to t_- \bar{t}_-$	0.012	0.000	0.012
$e^-_R e^+_L \to t_+ \bar{t}_+$	0.012	0.000	0.012
$e^-_R e^+_L \to (t\bar{t})_{\text{tot.}}$	0.077	0.000	0.077

@500 GeV

Polarisation dependence of EW@NLO

Obvious difference in NLO correction between two initial polarisation is the W box diagram (it is only for $e^-_L e^+_R$)!



⇒ BUT…

is the box diagram gauge independent???

Polarization	$\sigma_{\rm NLO} - \sigma_{\rm Tree}$(pb)	$M_{\rm Tree} \cdot M_{W-\rm box}$ (pb)	The rest of NLO (pb)
$e^-_L e^+_R \to t_- \bar{t}_+$	-0.068	-0.161	0.093
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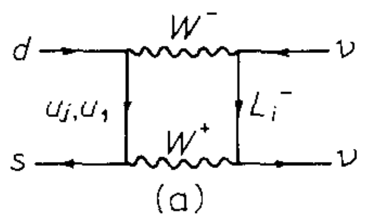
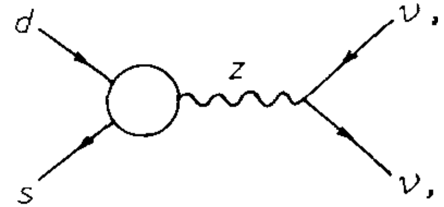
@500 GeV

Gauge dependence consideration

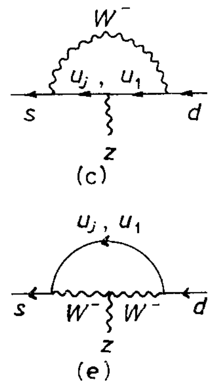
In the FCNC computation, the gauge dependence cancels between box and vertex correction diagrams…

Inami and Lim, PTP, 65 (‘81) 297





Phys.Lett.B 252 (1990) 676-682



For e+ e- -> bbbar, the box, we compute only the vertex correction… but it is because the box is very small near Z pole (also for on-shell Z, it is gauge-invariant)

Lynn and Stuart Phys.Lett.B 252 (’90) 676

Gauge dependence consideration

In the FCNC computation, the gauge dependence cancels between box and vertex correction diagrams…

Inami and Lim, PTP, 65 ('81) 297

✳ *Gauge invariant combination is*

W/Z/γ box + W/Z vertex + gauge boson self energy

pole (also for on-shell Z, it is gauge-invariant)

Lynn and Stuart Phys.Lett.B 252 ('90) 676

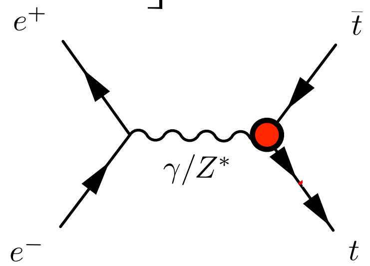
Conclusions

- The tt-z/γ anomalous coupling is one of the important probes of new physics. Many new physics models predict significant deviations from SM.
- Experimentally the form factor for tt-z/γ can be measured at the per-mill level.
- The electroweak NLO correction is known to reach to 5-10%. Thus, it has to be included in the future studies.
- The electroweak NLO correction is sensitive to the initial and final polarisation.
- The polarised ILC will allow us a more detailed study.
- Specific theoretical efforts are needed to make progress on the electroweak correction in the future.

Backup

e+e- → ttbar @ tree level

$$\mathcal{L}_{\rm int} = \sum_{v=\gamma,Z} g^v \left[V_l^v \bar{t}\gamma^l (F_{1V}^v + F_{1A}^v\gamma_5)t + \frac{i}{2m_t}\partial_\nu V_l \bar{t}\sigma^{l\nu}(F_{2V}^v + F_{2A}^v\gamma_5)t \right]$$



$$\begin{aligned}
\mathcal{M}(e_L\bar{e}_R \to t_L\bar{t}_R)^{\gamma/Z} &= c_L^{\gamma/Z}[F_{1V}^{\gamma/Z} - \beta F_{1A}^{\gamma/Z} + F_{2V}^{\gamma/Z}](1+\cos\theta)e^{-i\phi} \\
\mathcal{M}(e_L\bar{e}_R \to t_R\bar{t}_L)^{\gamma/Z} &= c_L^{\gamma/Z}[F_{1V}^{\gamma/Z} + \beta F_{1A}^{\gamma/Z} + F_{2V}^{\gamma/Z}](1-\cos\theta)e^{-i\phi} \\
\mathcal{M}(e_L\bar{e}_R \to t_L\bar{t}_L)^{\gamma/Z} &= c_L^{\gamma/Z}\gamma^{-1}[F_{1V}^{\gamma/Z} + \gamma^2(F_{2V}^{\gamma/Z} + \beta F_{2A}^{\gamma/Z})]\sin\theta e^{-i\phi} \\
\mathcal{M}(e_L\bar{e}_R \to t_R\bar{t}_R)^{\gamma/Z} &= c_L^{\gamma/Z}\gamma^{-1}[F_{1V}^{\gamma/Z} + \gamma^2(F_{2V}^{\gamma/Z} - \beta F_{2A}^{\gamma/Z})]\sin\theta e^{-i\phi} \\
\mathcal{M}(e_R\bar{e}_L \to t_L\bar{t}_R)^{\gamma/Z} &= -c_R^{\gamma/Z}[F_{1V}^{\gamma/Z} - \beta F_{1A}^{\gamma/Z} + F_{2V}^{\gamma/Z}](1-\cos\theta)e^{i\phi} \\
\mathcal{M}(e_R\bar{e}_L \to t_R\bar{t}_L)^{\gamma/Z} &= -c_R^{\gamma/Z}[F_{1V}^{\gamma/Z} + \beta F_{1A}^{\gamma/Z} + F_{2V}^{\gamma/Z}](1+\cos\theta)e^{i\phi} \\
\mathcal{M}(e_R\bar{e}_L \to t_L\bar{t}_L)^{\gamma/Z} &= c_R^{\gamma/Z}\gamma^{-1}[F_{1V}^{\gamma/Z} + \gamma^2(F_{2V}^{\gamma/Z} + \beta F_{2A}^{\gamma/Z})]\sin\theta e^{i\phi} \\
\mathcal{M}(e_R\bar{e}_L \to t_R\bar{t}_R)^{\gamma/Z} &= c_R^{\gamma/Z}\gamma^{-1}[F_{1V}^{\gamma/Z} + \gamma^2(F_{2V}^{\gamma/Z} - \beta F_{2A}^{\gamma/Z})]\sin\theta e^{i\phi}
\end{aligned}$$

where $\beta^2 = 1 - 4m_t^2/s, \gamma = \sqrt{s}/(2m_t)$ and the overall factors $c_{L/R}^{\gamma/Z}$ are:

$$c_L^\gamma = -1, \quad c_R^\gamma = -1, \quad c_L^Z = \left(\frac{-1/2 + s_w^2}{s_w c_s}\right)\left(\frac{s}{s-m_Z^2}\right), \quad c_R^Z = \left(\frac{s_w^2}{s_w c_s}\right)\left(\frac{s}{s-m_Z^2}\right)$$

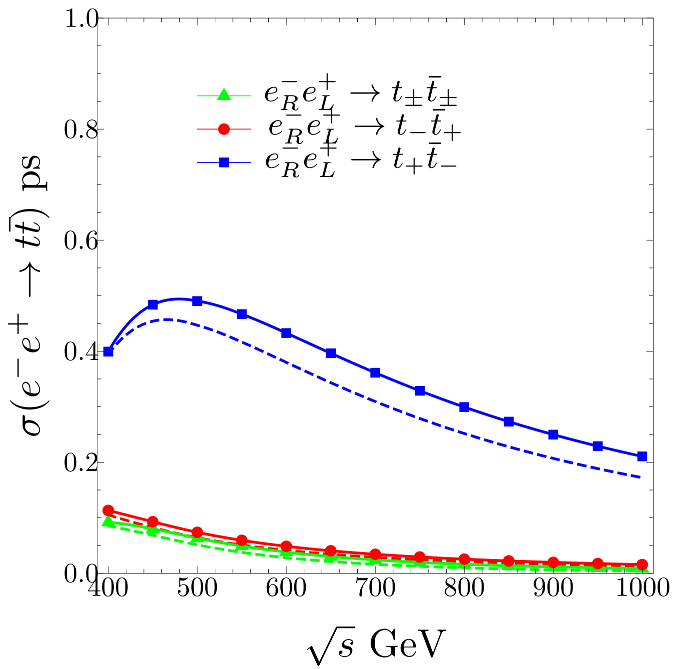
where $s_w = \sin\theta_w$ and $c_w = \cos\theta_W$, with θ_W being the weak mixing angle.

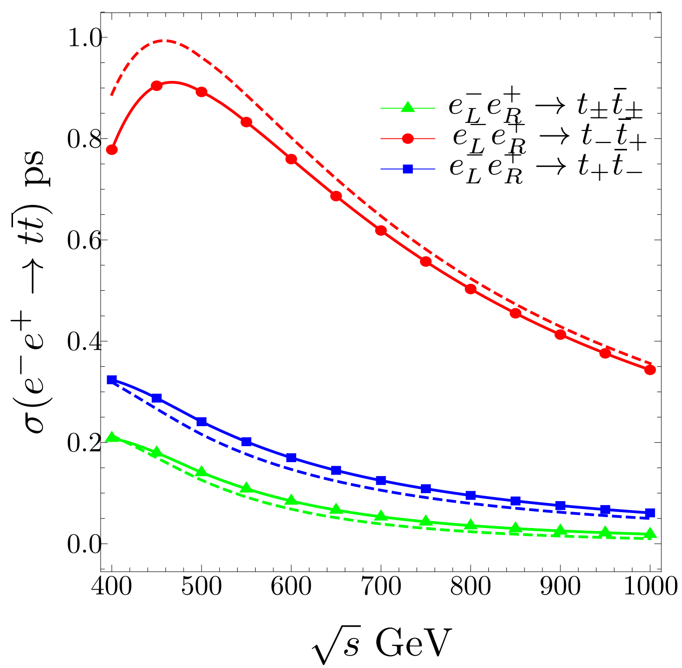
$$F_{1V}^{\gamma,SM} = -\frac{2}{3},\ F_{1A}^{\gamma,SM} = 0,\ F_{1V}^{Z,SM} = -\frac{1}{4s_w c_w}\left(1 - \frac{8}{3}s_w^2\right),\ F_{1A}^{Z,SM} = \frac{1}{4s_w c_w}, \quad F_{2V}^{\gamma} = Q_t(g-2)/2$$

Polarisation dependence of EW@NLO

It turned out that the size of the NLO correction depend strongly on the final state polarisation as well.

E.K.Y. Kurihara, B. Mecaj, T.Moskalets in preparation





- large NLO correction to the cross section: $e^-_R e^+_L \to t_+ \bar{t}_-$
- large NLO correction to the forward-backward asymmetry: $e^-_L e^{+R} \to t_- \bar{t}_+$