Precise test of gauge boson self couplings at the ILC

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Outline

- Gauge boson self couplings in the SM and the new physics
- The present research status of the gauge boson self couplings
- NLO calculations of $Z^0 Z^0 Z^0$ production at ILC
- $e^+e^- \rightarrow W^+W^-Z^0$ process research with NLO corrections at ILC
- Summary

Gauge boson self-coupling

- In the SM , $\mathrm{SU(2)_L \times U(1)_Y}$ gauge invariance provides stringent constraints on the strengthes of triple and quartic gauge boson couplings

$$\mathcal{L}_{WWV}/g_{WWV} = ig_1^V\left(W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}\right) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{i\lambda_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda},$$

where $V \equiv Z$ or γ and $W_{\mu\nu} \equiv \partial_\mu W_\nu - \partial_\nu W_\mu$, $V_{\mu\nu} \equiv \partial_\mu V_\nu - \partial_\nu V_\mu$, $g_{WW\gamma} = -e$, and $g_{WWZ} = -e\cot\theta_W$. In the standard model, $g_1^V = \kappa_V = 1$ and $\lambda_V = 0$.

Gauge boson self-coupling

$$\mathcal{L}_{sm} = \frac{v^2}{4}\mathrm{tr}(D_\mu U^\dagger D^\mu U) - \frac{1}{2}\mathrm{tr}(\mathcal{W}_{\mu\nu}\mathcal{W}^{\mu\nu}) - \frac{1}{2}\mathrm{tr}(\mathcal{B}_{\mu\nu}\mathcal{B}^{\mu\nu}).$$

where

$$U(x) \equiv \exp\left(\frac{i\tau^a\omega^a}{v}\right)$$

$$\mathcal{W}_\mu \equiv \frac{\tau^a}{2}W^a_\mu,$$

$$\mathcal{W}_{\mu\nu} \equiv \partial_\mu\mathcal{W}_\nu - \partial_\nu\mathcal{W}_\mu + ig_2\left[\mathcal{W}_\mu, \mathcal{W}_\nu\right],$$

$$\mathcal{B}_\mu \equiv \frac{\tau^3}{2}B_\mu,$$

$$\mathcal{B}_{\mu\nu} \equiv \partial_\mu\mathcal{B}_\nu - \partial_\nu\mathcal{B}_\mu,$$

$$D_\mu U \equiv \partial_\mu U + ig_2\mathcal{W}_\mu U - ig_Y U\mathcal{B}_\mu.$$

W^a_μ and B_μ are $SU(2)_L$ and $U(1)$ gauge fields, respectively.

Gauge boson self-coupling

$$\mathcal{L} = +\beta_1 \frac{v^2}{4}\mathrm{tr}(V_\mu T)\mathrm{tr}(V^\mu T) + \alpha_1 g_2 \mathrm{tr}\left(\mathcal{W}^{\mu\nu} U \mathcal{B}_{\mu\nu} U^\dagger\right)$$

$$+ i\alpha_2 g_Y \mathrm{tr}\left(U^\dagger [V_\mu, V_\nu] U \mathcal{B}^{\mu\nu}\right) + i\alpha_3 g_2 \mathrm{tr}\left([V_\mu, V_\nu]\mathcal{W}^{\mu\nu}\right)$$

$$+ \alpha_4 \mathrm{tr}(V_\mu V_\nu)\mathrm{tr}(V^\mu V^\nu) + \alpha_5 \mathrm{tr}(V_\mu V^\mu)\mathrm{tr}(V_\nu V^\nu)$$

$$+ \alpha_6 \mathrm{tr}(V_\mu V_\nu)\mathrm{tr}(T V^\mu)\mathrm{tr}(T V^\nu) + \alpha_7 \mathrm{tr}(V_\mu V^\mu)\mathrm{tr}(T V_\nu)\mathrm{tr}(T V^\nu)$$

$$+ \frac{1}{4}\alpha_8 g_2^2 \mathrm{tr}(T\mathcal{W}_{\mu\nu})\mathrm{tr}(T\mathcal{W}^{\mu\nu}) + \frac{i}{2}\alpha_9 g_2 \mathrm{tr}(T\mathcal{W}_{\mu\nu})\mathrm{tr}(T[V^\mu, V^\nu])$$

$$+ \frac{1}{2}\alpha_{10} \mathrm{tr}(T V_\mu)\mathrm{tr}(T V^\mu)\mathrm{tr}(T V_\nu)\mathrm{tr}(T V^\nu) + \alpha_{11} g_2 \epsilon^{\mu\nu\rho\lambda} \mathrm{tr}(T V_\mu)\mathrm{tr}(V_\nu \mathcal{W}_{\rho\lambda}),$$

where $V_\mu \equiv D_\mu U \cdot U^\dagger$, $T \equiv U\tau^3 U^\dagger$,

Gauge boson self-coupling

vertex	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8	α_9	α_{10}	α_{11}	β_1	processes
$WW\gamma$	○	○	○					○	○				$\rightarrow WW$, $e\nu W$
WWZ	○	○	○					○	○		○	○	$\rightarrow WW$, $e\nu W$
$ZZWW$	○		○		○		○					○	$\rightarrow WWZ$
$ZWZW$	○		○	○		○						○	$\rightarrow WWZ$
$Z\gamma WW$	○		○									○	$\rightarrow WW\gamma$
$ZZZZ$				○	○	○	○			○			$\rightarrow ZZZ$

Triple gauge couplings

- The triple gauge couplings (TGCs) have been well measured at the LEP2

The LEP Collaborations, *A combination of preliminary electroweak measurements and constraints on the standard model*, CERN-PH-EP/2004-069, arXiv: hep-ex/0412015v2.

Parameter	68% C.L.	95% C.L.
g_1^{Z}	$0.991^{+0.022}_{-0.021}$	$[0.949, \quad 1.034]$
κ_γ	$0.984^{+0.042}_{-0.047}$	$[0.895, \quad 1.069]$
λ_γ	$-0.016^{+0.021}_{-0.023}$	$[-0.059, \quad 0.026]$

Triple gauge couplings

- The CDF and D0 collaborations also performed some experiments about the diboson production and presented the limitations on anomalous TGCs

Mark S. Neubauer, FERMILAB-CONF-06-115-E, arXiv: hep-ex/0605066v2; Junjie Zhu, arXiv: 0907.3239v1; The D0 Collaboration, V. Abazov, *et al.*, *Combined measurements of anomalous charged trilinear gauge-boson couplings from diboson production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV*, FERMILAB-PUB-09-380-E, arXiv: 0907.4952v1.

D0: $-0.12 < \Delta g_1^Z < 0.19$, $-0.44 < \Delta\kappa_\gamma < 0.55$ and $-0.10 < \lambda_{Z,\gamma} < 0.11$

CDF: $-0.20 < \Delta g_1^Z < 0.29$, $-1.01 < \Delta\kappa_{Z,\gamma} < 1.27$ and $-0.16 < \lambda_{Z,\gamma} < 0.17$

Quartic gauge couplings

- Triple massive gauge boson production processes can be used to probe the quartic gauge couplings (QGCs)
- The precise predictions for the VVV production at hadron colliders were provided. NLO QCD corrections increase the cross sections about 70% for $W^+W^-Z^0$ production and 50% for $Z^0Z^0Z^0$ production.

A. Lazopoulos, K. Melnikov and F. Petriello, Phys. Rev. **D76** (2007) 014001; V. Hankele and D. Zeppenfeld, Phys. Lett. **B661** (2008) 103; T. Binoth, G. Ossola, C. G. Papadopoulos and R. Pittau, JHEP **0806** (2008) 082.

Gauge coupling at ILC

- The $e^+e^- \to W^+W^-$ processes is the most sensitive process for triple gauge boson couplings test at ILC
- Complete NLO calculations for $\mathrm{e^+e^-} \to 4f$ (include $\mathrm{e^+e^-} \to \mathrm{WW} \to 4f$)has been presented by A. Denner and etc. The NLO corrections is about 5%~10%。

A. Denner, S. Dittmaier, M. Roth and L. H. Wieders, Phys. Lett. **B612** (2005) 223; Nucl. Phys. **B724** (2005) 247.

Gauge coupling at ILC

- ILC is also sensitive to the quartic couplings. Two processes are important in this context:

  (1) triple gauge boson production:

  $$e^+e^- \to VVV$$

  (2) vector boson scattering: ($WZ \to WZ$ and $ZZ \to ZZ$)

  $$e^+e^- \to \ell_1\ell_2 VV'$$

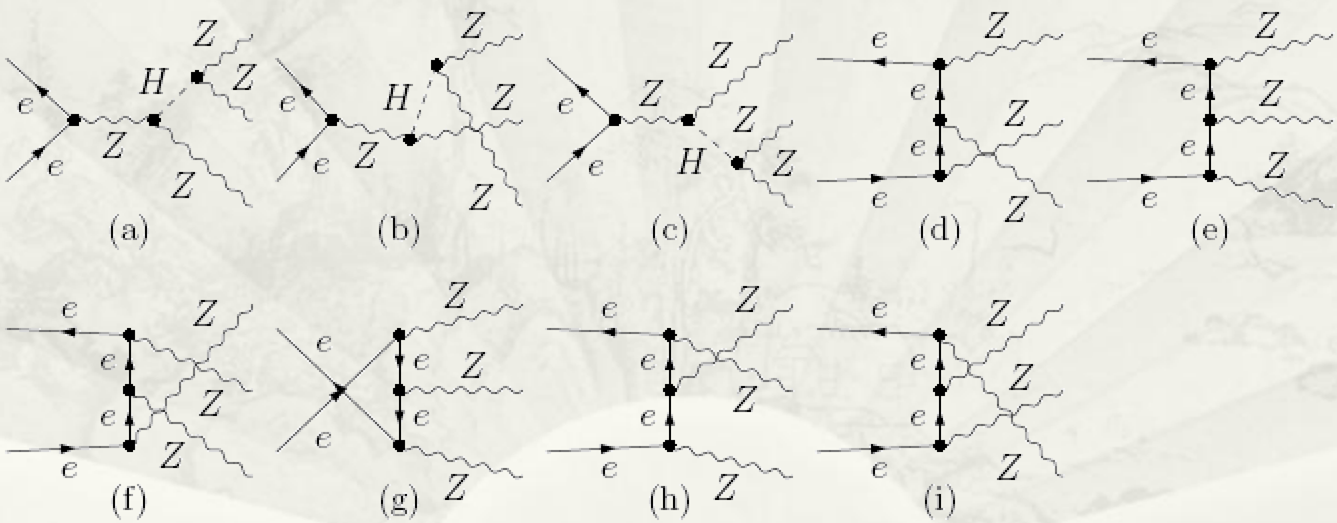
  with $\ell_{1,2} = e, \nu$ and $V, V' = W, Z$.

$Z^0 Z^0 Z^0$ productions at ILC

PHYSICAL REVIEW D **78,** 016007 (2008)

Complete one-loop electroweak corrections to ZZZ production at the ILC

Su Ji-Juan, Ma Wen-Gan, Zhang Ren-You, Wang Shao-Ming, and Guo Lei



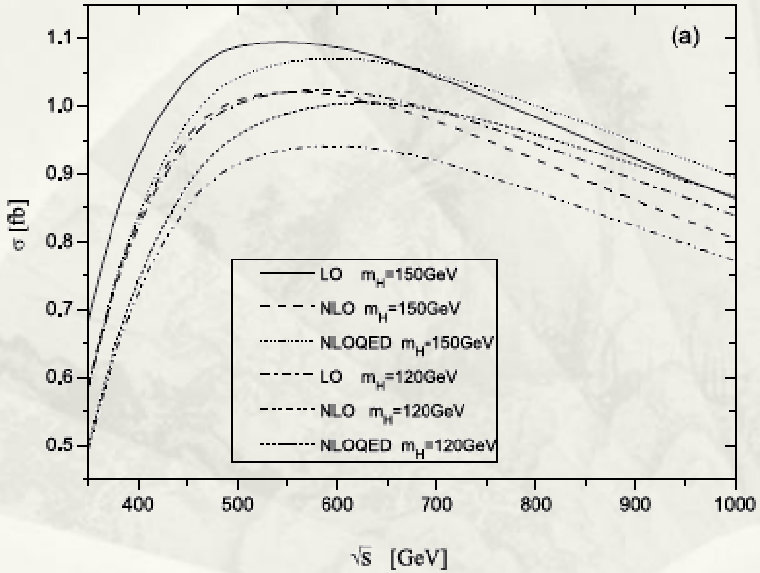
$Z^0 Z^0 Z^0$ productions at ILC

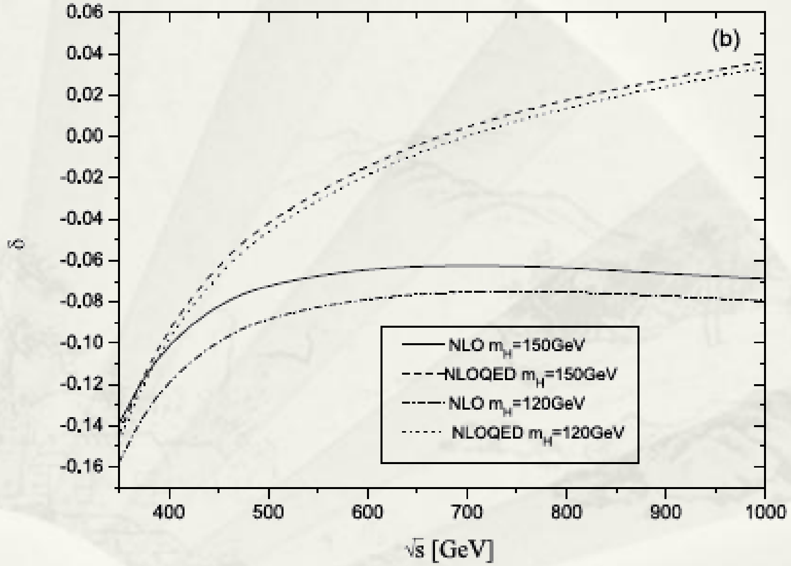
$$\begin{aligned}
m_e &= 0.51099892\ \text{MeV}, & m_\mu &= 105.658369\ \text{MeV}, & m_\tau &= 1776.99\ \text{MeV}, \\
m_u &= 66\ \text{MeV}, & m_c &= 1.25\ \text{GeV}, & m_t &= 174.2\ \text{GeV}, \\
m_d &= 66\ \text{MeV}, & m_s &= 95\ \text{MeV}, & m_b &= 4.7\ \text{GeV}, \\
m_W &= 80.403\ \text{GeV}, & m_Z &= 91.1876\ \text{GeV}.
\end{aligned}$$

$$\sqrt{s} = 500\ GeV\ \text{ and } m_H = 115\ GeV,\ 150\ GeV,\ 170\ GeV$$

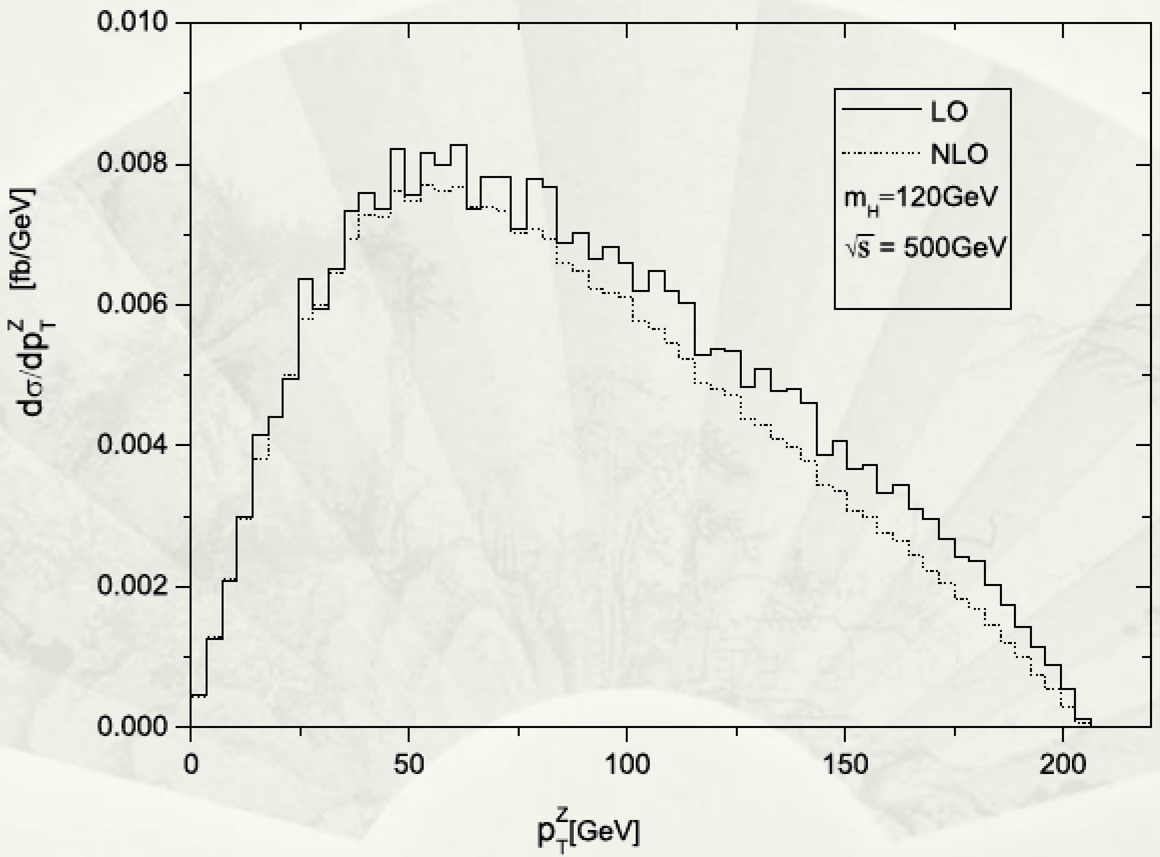
$m_H(GeV)$	$\sigma_{LO}(fb)$	$\sigma_{tot}(fb)$	$\Delta\sigma_{QED}(fb)$	$\Delta\sigma_{tot}(fb)$	$\delta_{QED}(\%)$	$\delta_{tot}(\%)$
115	1.0055(2)	0.9159(7)	-0.0451(7)	-0.0896(7)	-4.49(7)	-8.91(7)
150	1.0975(2)	1.0194(8)	-0.0444(8)	-0.0780(8)	-4.04(7)	-7.11(7)
170	1.2564(2)	1.1989(9)	-0.0393(8)	-0.0575(9)	-3.12(7)	-4.58(7)

$Z^0 Z^0 Z^0$ productions at ILC

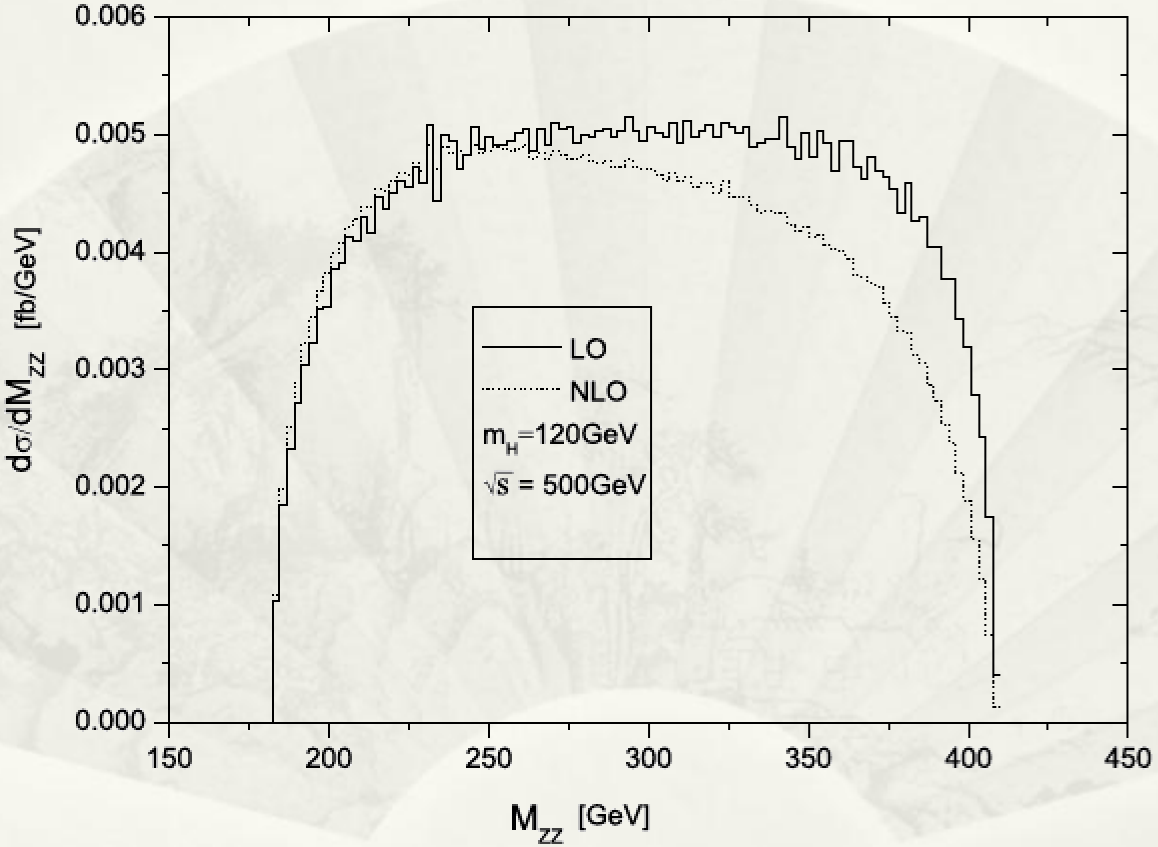




$Z^0Z^0Z^0$ productions at ILC



$Z^0 Z^0 Z^0$ productions at ILC



$W^+W^-Z^0$ productions at ILC

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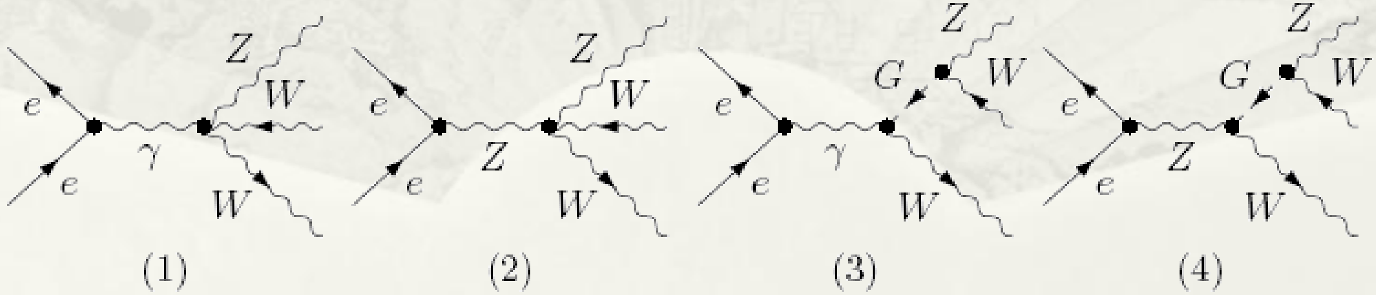
Full electroweak one-loop corrections to $W^+W^-Z^0$ production at the ILC

Sun Wei, Ma Wen-Gan, Zhang Ren-You *, Guo Lei, Song Mao

Erratum Physics Letters B 684 (2010) 281

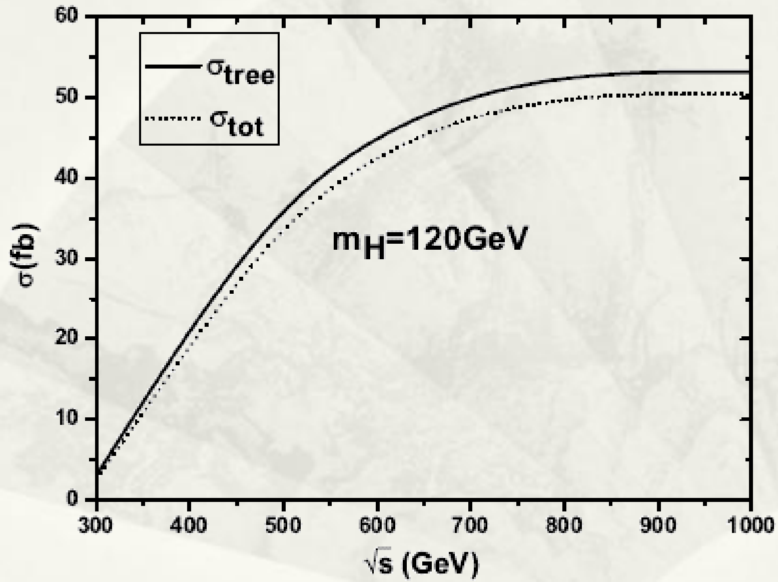


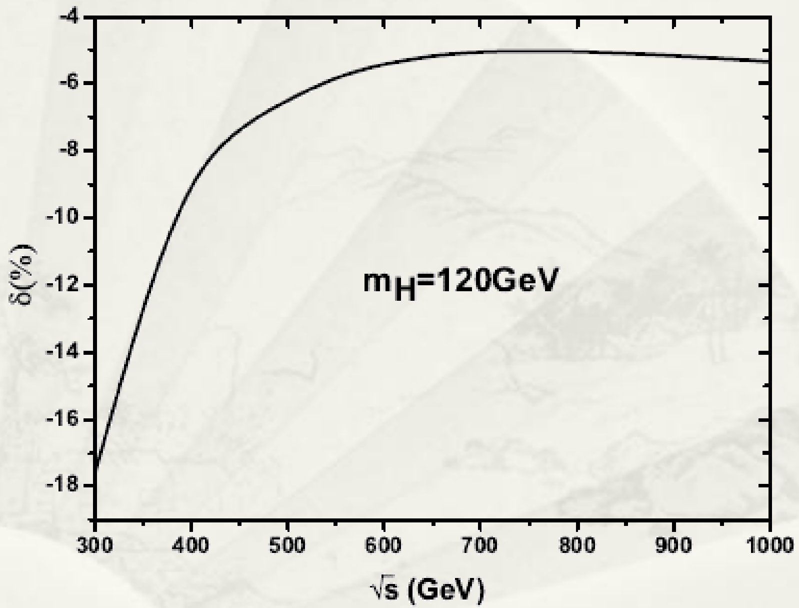
$W^+W^-Z^0$ productions at ILC

$m_Z = 91.1876\ GeV$, $m_W = 80.398\ GeV$, $\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} = 0.222646$,
$m_u = m_d = 66\ MeV$, $m_s = 104\ MeV$, $m_c = 1.27\ GeV$,
$m_b = 4.2\ GeV$, $m_t = 171.2\ GeV$, $m_e = 0.510998910\ keV$,
$m_\mu = 105.658389\ MeV$, $m_\tau = 1776.84\ MeV$,

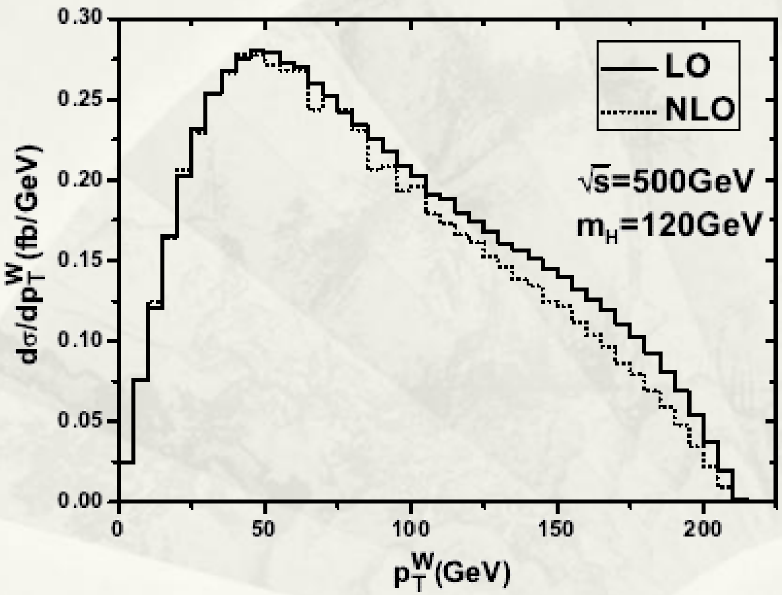
$\sqrt{s}$ (GeV)	$m_H(GeV)$	$\sigma_{tree}(fb)$	$\sigma_{tot}(fb)$	$\Delta\sigma_{tot}(fb)$	$\delta_{ew}(\%)$
300	120	2.9457(2)	2.427(2)	-0.519(2)	-17.62(7)
300	150	3.1605(2)	2.633(2)	-0.527(2)	-16.67(6)
500	120	35.810(4)	33.51(5)	-2.30(5)	-6.4(1)
500	150	36.035(4)	33.85(5)	-2.19(5)	-6.1(1)
800	120	52.34(1)	49.70(6)	-2.64(6)	-5.0(1)
800	150	52.46(1)	50.10(8)	-2.36(8)	-4.5(1)
1000	120	53.21(1)	50.37(8)	-2.84(8)	-5.3(1)
1000	150	53.28(1)	50.68(7)	-2.60(7)	-4.9(1)

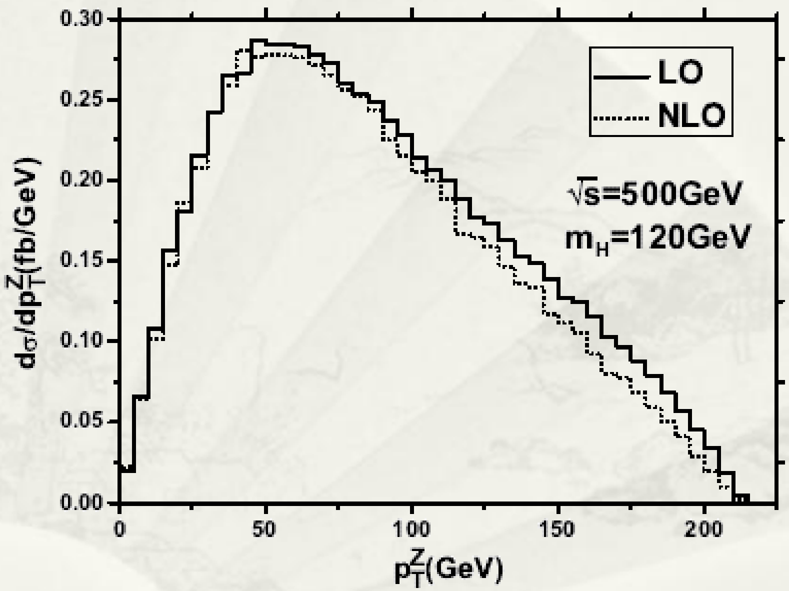
$W^+W^-Z^0$ productions at ILC



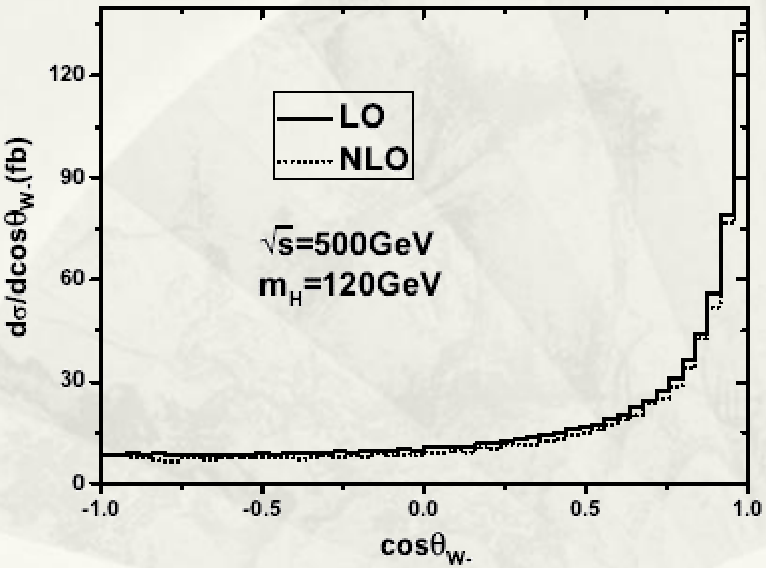


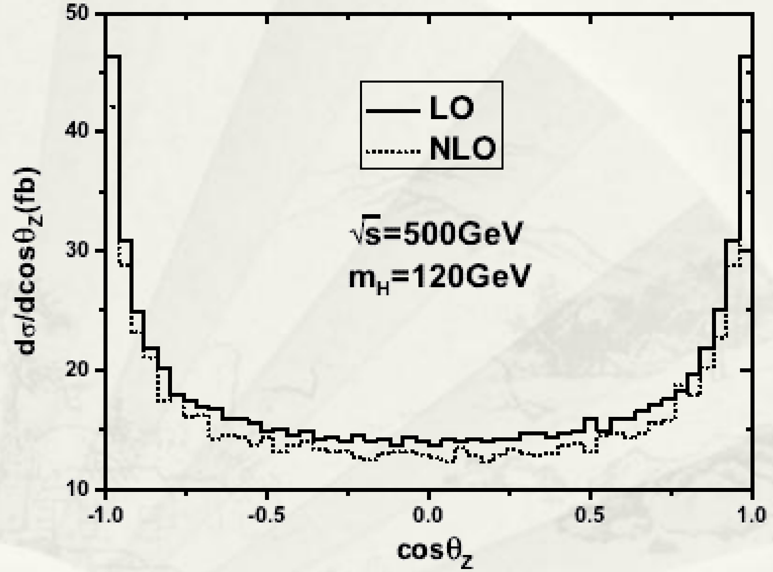
$W^+W^-Z^0$ productions at ILC



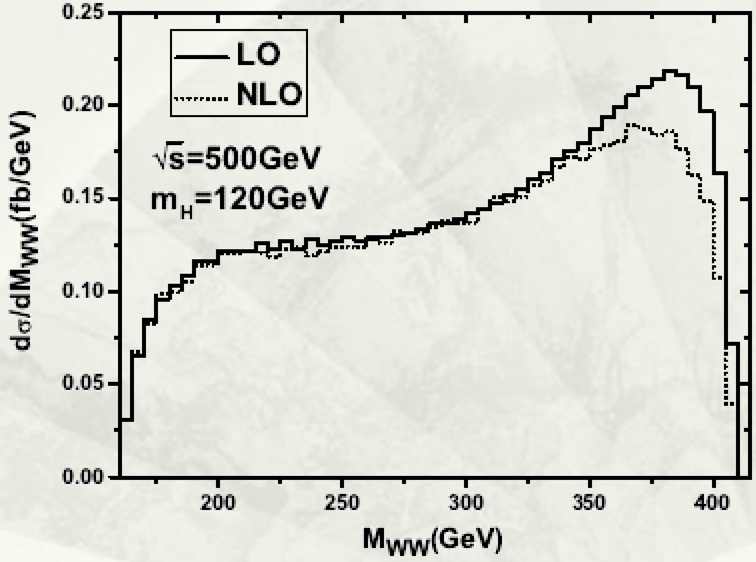


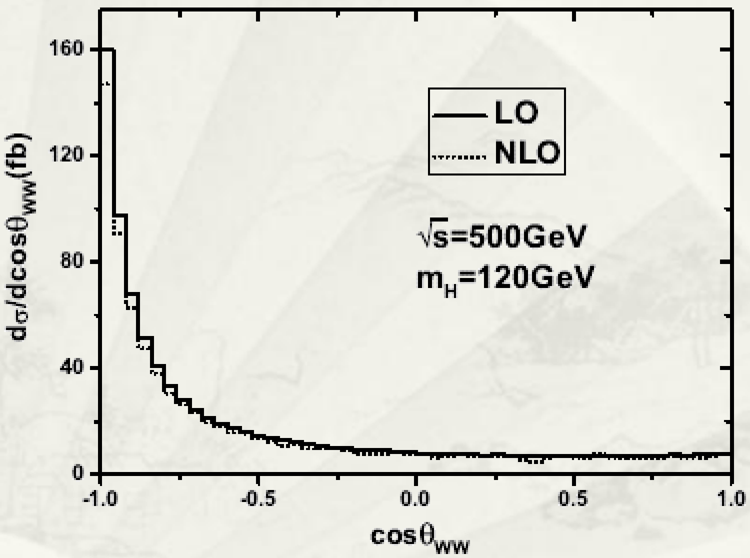
$W^+W^-Z^0$ productions at ILC





$W^+W^-Z^0$ productions at ILC





Other works of Processes

- Comparison of $e^+e^- \to W^+W^-Z$

$\sqrt{s}$ [TeV]		$M_H = 120\,\text{GeV}$ σ_{Born}[fb]	$M_H = 120\,\text{GeV}$ $\Delta\sigma_{NLO}$[fb]	$M_H = 150\,\text{GeV}$ σ_{Born}[fb]	$M_H = 150\,\text{GeV}$ $\Delta\sigma_{NLO}$[fb]
0.3	Our work	2.9457(2)	-0.519(2)	3.1605(2)	-0.527(2)
	Ref. [1]	2.94576(4)	-0.5240(3)	3.16043(4)	-0.5322(3)
0.5	Our work	35.810(4)	-2.30(5)	36.035(4)	-2.19(5)
	Ref. [1]	35.8076(8)	-2.359(3)	36.033(1)	-2.239(3)
0.8	Our work	52.34(1)	-2.64(6)	52.46(1)	-2.36(8)
	Ref. [1]	52.337(3)	-2.631(7)	52.452(4)	-2.468(8)
1.0	Our work	53.21(1)	-2.84(8)	53.28(1)	-2.60(7)
	Ref. [1]	53.196(4)	-2.771(8)	53.235(4)	-2.612(8)

[1] **NLO corrections to $e^+e^- \to W^+W^-Z$ and $e^+e^- \to ZZZ$**

F. Boudjema, L. D. Ninh, S. Hao, and M. M. Weber, arXiv:0912.4234.

Other works of Processes

- Comparison of $e^+e^- \to ZZZ$

$\sqrt{s}$ [GeV]		$M_H = 120$ GeV σ_{Born} [fb]	δ_{full} [%]	$M_H = 150$ GeV σ_{Born} [fb]	δ_{full} [%]
350	Our work	0.58696	-15.79	0.68422	-13.91
	Ref. [1]	0.586955(2)	-15.850(1)	0.684209(2)	-13.970(1)
370	Our work	0.70531	-13.79	0.80821	-12.00
	Ref. [1]	0.705303(2)	-13.822(1)	0.808196(3)	-11.986(1)
400	Our work	0.83409	-11.75	0.9375	-9.98
	Ref. [1]	0.834083(4)	-11.765(2)	0.937484(4)	-9.973(1)
450	Our work	0.95792	-9.79	1.05294	-8.06
	Ref. [1]	0.957904(5)	-9.763(3)	1.052917(5)	-8.044(2)
500	Our work	1.01384	-8.70	1.09754	-7.09
	Ref. [1]	1.013806(6)	-8.682(4)	1.097440(7)	-7.064(4)
600	Our work	1.03052	-7.77	1.09370	-6.36
	Ref. [1]	1.030489(9)	-7.714(6)	1.093668(9)	-6.289(6)
700	Our work	0.99611	-7.47	1.04437	-6.20
	Ref. [1]	0.99607(1)	-7.438(9)	1.04437(1)	-6.164(9)
800	Our work	0.94567	-7.50	0.98647	-6.61
	Ref. [1]	0.94563(1)	-7.46(1)	0.98343(1)	-6.30(1)
900	Our work	0.89168	-7.71	0.92196	-6.65
	Ref. [1]	0.89164(1)	-7.62(1)	0.92191(1)	-6.55(1)
1000	Our work	0.83892	-7.94	0.86366	-6.89
	Ref. [1]	0.83887(2)	-7.86(2)	0.86362(2)	-6.86(2)

Summary

- At present, The TGCs experiment results (LEP, Tevatron) agree with the SM prediction.
- NLO correction for gauge-self couplings process can not be neglected, which is about 50%-70% at LHC and 5%-10% at ILC.
- Future tasks for gauge-self couplings at ILC:

  (1) Precise calculations for gauge boson scatting processes;
  (2) Gauge-self couplings processes calculations of new physic effects.
  (3) Simulations, etc.

Thanks!