Study of A_LR using radiative return events at ILC250

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Physics at ILC 250

- Primary physics aim of ILC 250: measuring the **coupling constants between the Higgs boson and various other standard model (SM) particles**
- The coupling constants can deviate from their SM values because of possible Beyond the Standard Model (BSM) effects.
- The size of corrections to the SM predictions for the Higgs boson couplings:

$$a\frac{m_H^2}{M^2}$$

M: new particle mass [GeV]
m_H: 125 [GeV]
a: coefficients of order 1

$\rightarrow$ Need to measure the couplings with the precision ~1%

SM effective field theory (SMEFT)

- Lorentz invariant and SU(2) × U(1) gauge invariant dim-6 operators

$$\Delta\mathcal{L} = \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$
$$+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu}$$
$$+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu}$$
$$+i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + 4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L)$$
$$+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)$$

ILC, Higgs related part

(CP-Conserving)

- The useful observables for the SMEFT global fit include not only those from the reactions that directly involve the Higgs boson, but also those from Electroweak Precision Observables (EWPOs) for W and Z bosons.
  For example, left-right polarization asymmetry A_{LR} of the Z-pole cross section is important.

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$$\begin{aligned}\Delta\mathcal{L} = & \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3 \\ & + \frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a \Phi W^a_{\mu\nu}B^{\mu\nu} \\ & + \frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu} \\ & + i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + 4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L) \\ & + i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\end{aligned}$$

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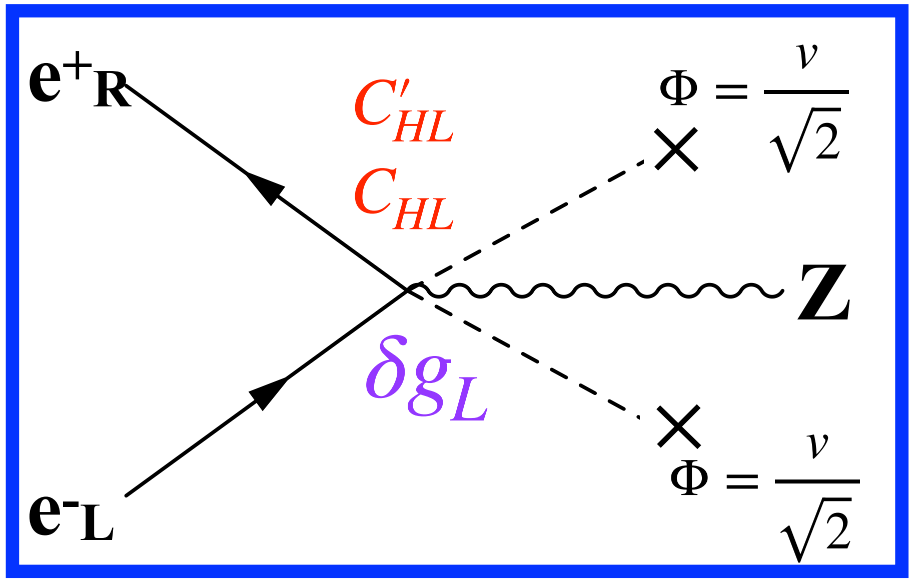
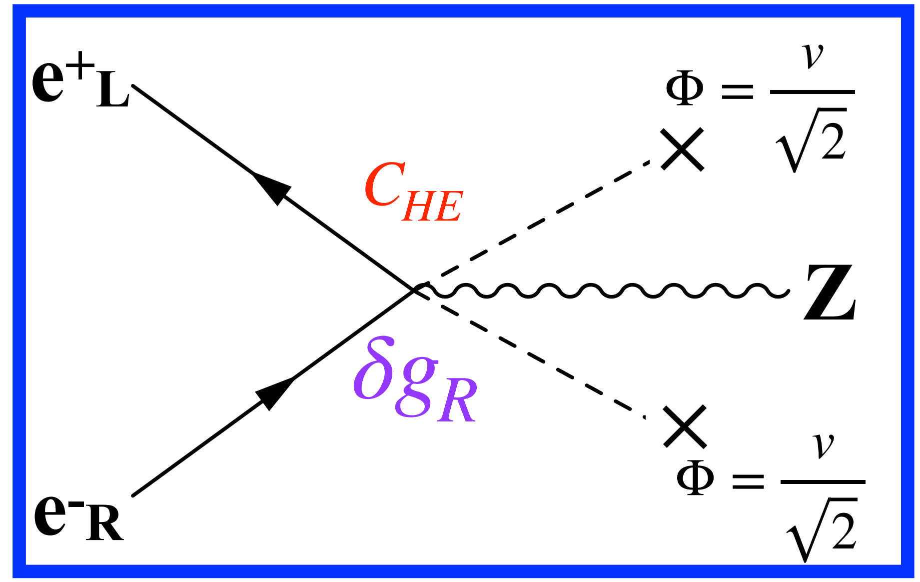
$$\Delta\mathcal{L} = i\frac{c_{HL}}{v^2}\boxed{(\Phi^\dagger \overleftrightarrow{D^\mu}\Phi)}(\bar{L}\gamma_\mu L) + 4i\frac{c\prime_{HL}}{v^2}\boxed{(\Phi^\dagger t^a \overleftrightarrow{D^\mu}\Phi)}(\bar{L}\gamma_\mu t^a L) + i\frac{\bar{c}_{HE}}{v^2}\boxed{(\Phi^\dagger \overleftrightarrow{D^\mu}\Phi)}(\bar{e}\gamma_\mu e)$$

$(vZ^\mu v)$ $(vt^a Z^\mu v)$ $(vZ^\mu v)$





$$g_L = \frac{g}{c_W}[(-\frac{1}{2} + s_W^2)(1 + \frac{1}{2}\delta Z_Z) - \frac{1}{2}(c_{HL} + c\prime_{HL}) - s_W c_W \delta Z_{AZ}]$$

$$g_R = \frac{g}{c_W}[(+s_W^2)(1 + \frac{1}{2}\delta Z_Z) - \frac{1}{2}c_{HE} - s_W c_W \delta Z_{AZ}]$$

$$\delta Z_Z = c_W^2(8c_{WW}) + 2s_W^2(8c_{WB}) + \frac{s_W^4}{c_W^2}(8c_{BB})$$

$$\delta Z_{AZ} = s_W c_W((8c_{WW}) - (1 - \frac{s_W}{c_W^2})(8c_{WB}) - \frac{s_W}{c_W^2}(8c_{BB})$$

$$\boxed{A_{LR} = A_e = \frac{g_{Le}^2 - g_{Re}^2}{g_{Le}^2 + g_{Re}^2}}$$

$$\boxed{\delta A_e = \frac{4g_{Le}^2 g_{Re}^2(\delta g_{Le} - \delta g_{Re})}{g_{Le}^4 - g_{Re}^4}}$$

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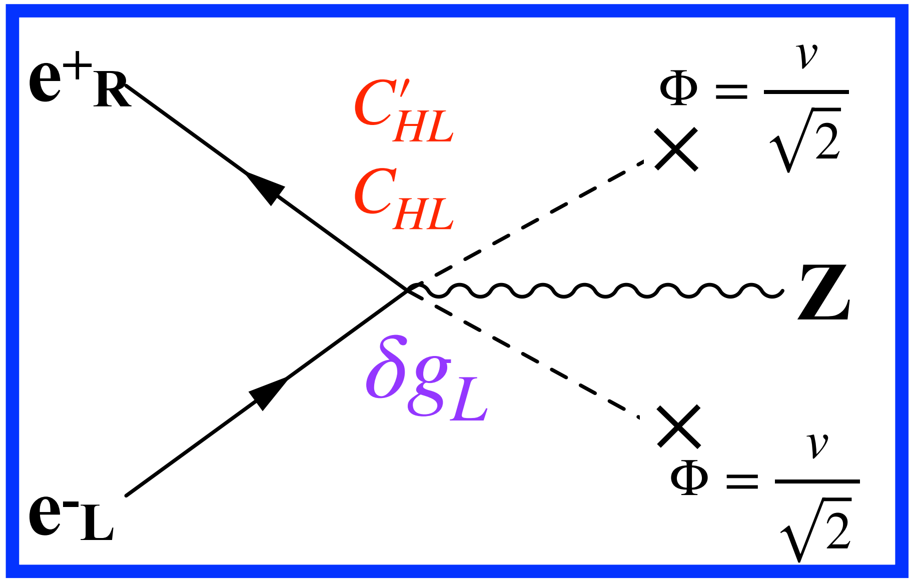
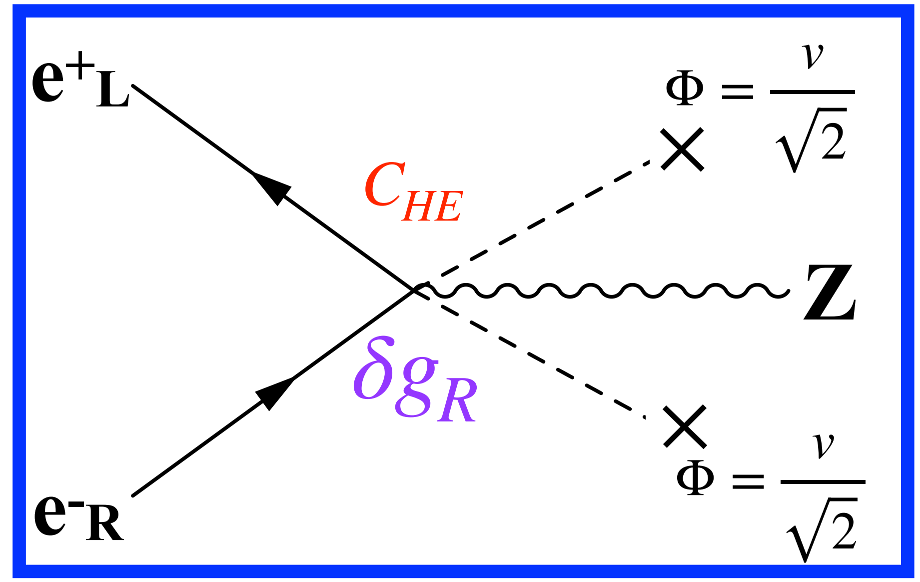




Current best measurement

A_{LR}= 0.1514 ± 0.0019 (statistic error) ± 0.0011(systematic error)

Need full detector simulation of radiative return events to check how much error we have at ILC 250

$$A_{LR} = A_e = \frac{g_{Le}^2 - g_{Re}^2}{g_{Le}^2 + g_{Re}^2}$$

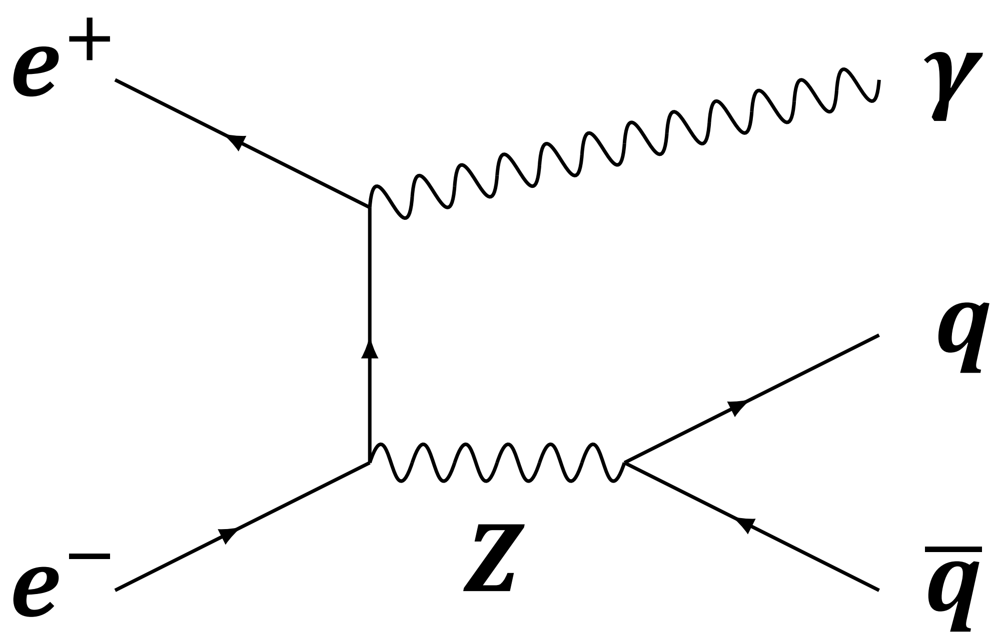
$$\delta A_e = \frac{4g_{Le}^2 g_{Re}^2(\delta g_{Le} - \delta g_{Re})}{g_{Le}^4 - g_{Re}^4}$$

Simulation Setup

Full simulation

- E_{CM}= 250 GeV
- $\int \mathscr{L} dt$ =900 fb^{-1} for each of the 2 polarization combinations
- $\sin\theta_W$ = 0.22225 which is equivalent to A_{LR} = 0.219298.

Signal: e^+e^- -> $Z\gamma$ -> 2 jets +γ



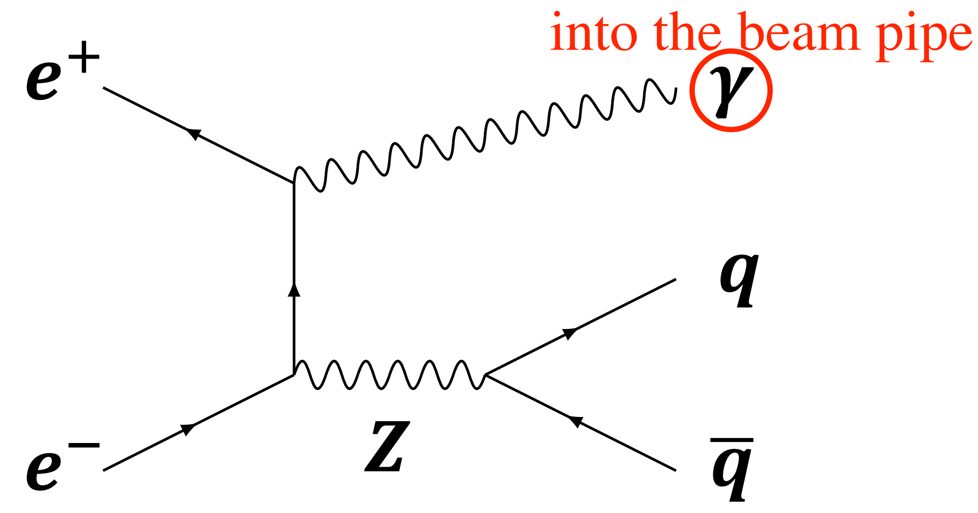
Background: All the events only with 2 jets in the final state

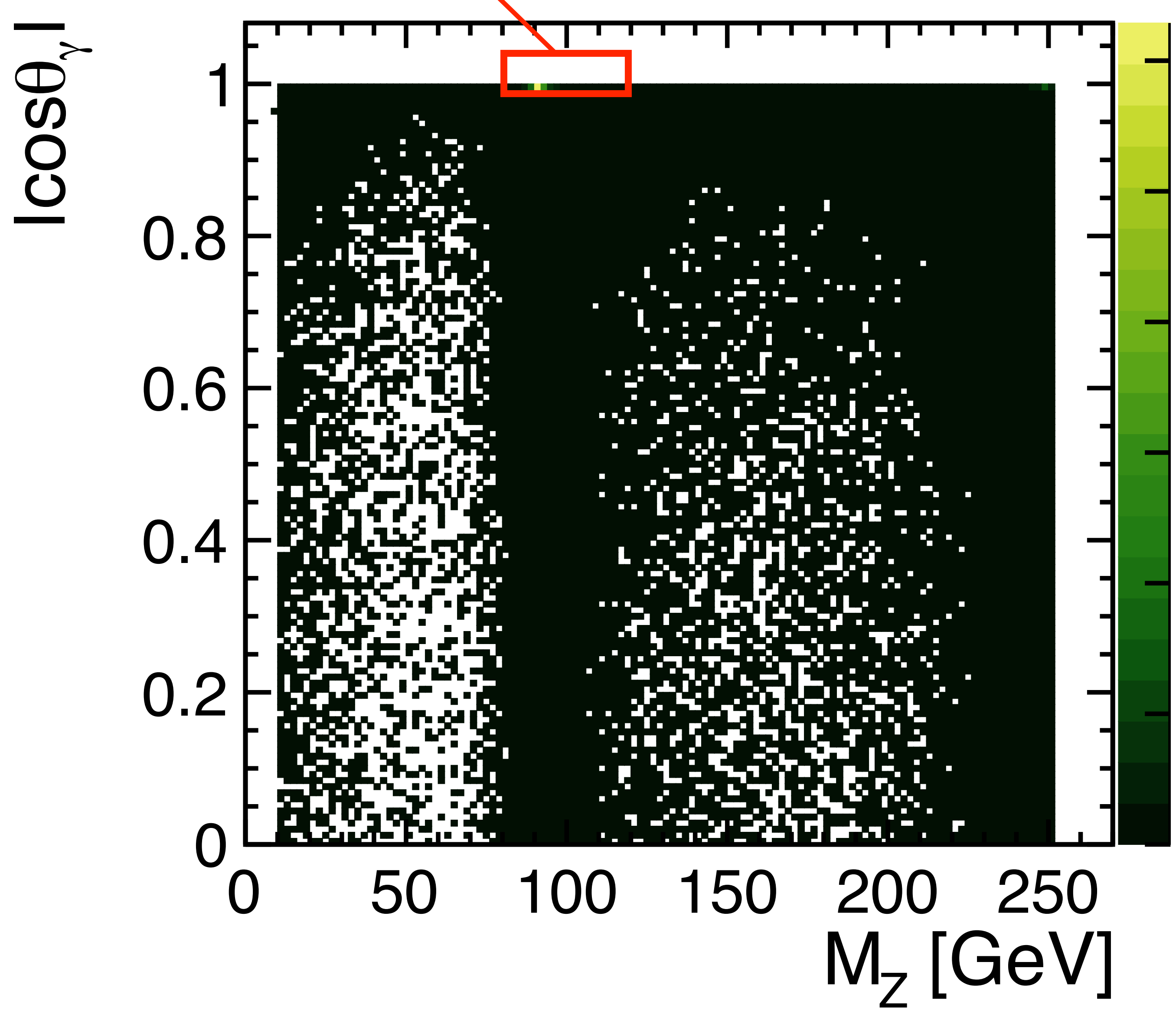
Signal event definition

Signal event: radiative return with photon escaping into beam pipe

A. 80 GeV < $M_{Z(truth)}$ < 120 GeV

B. $|\cos\theta\gamma_{(truth)}| > 0.999$

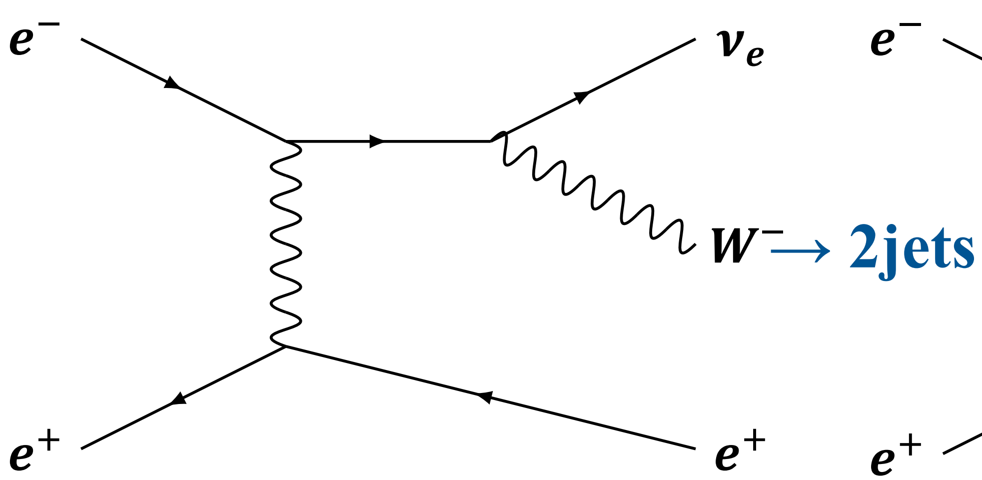




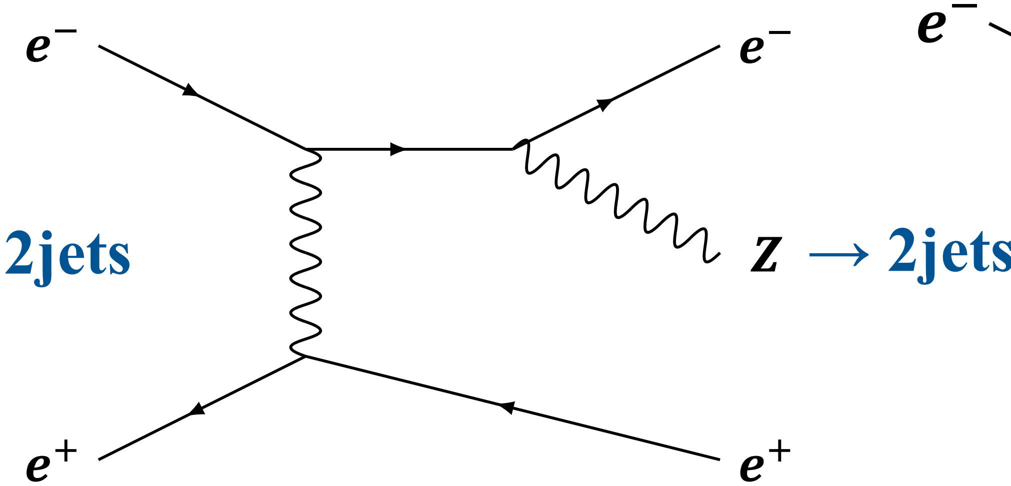
eLpR

Major backgrounds

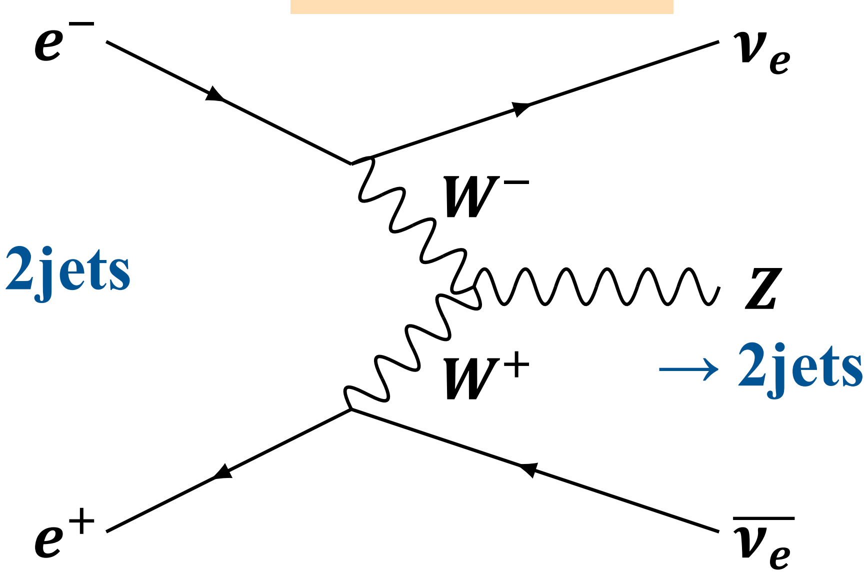
4f_sw_sl



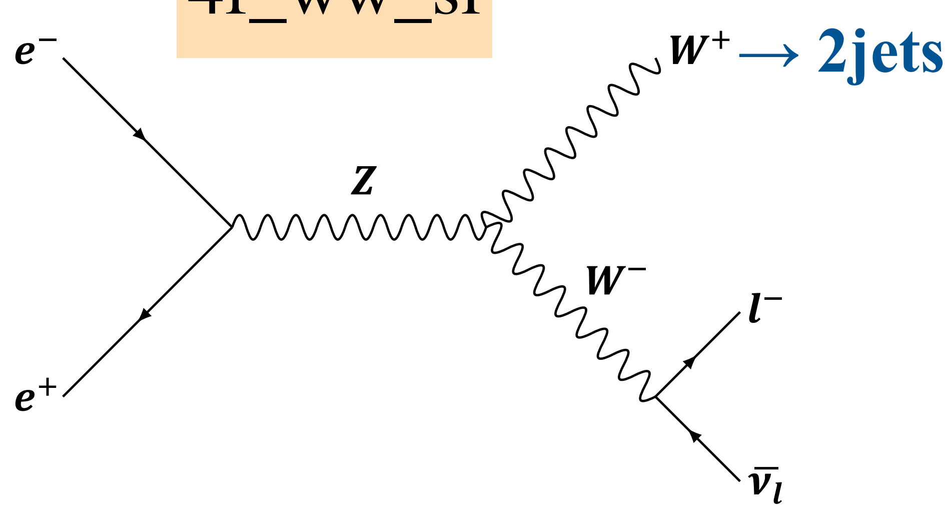
4f_sze_sl



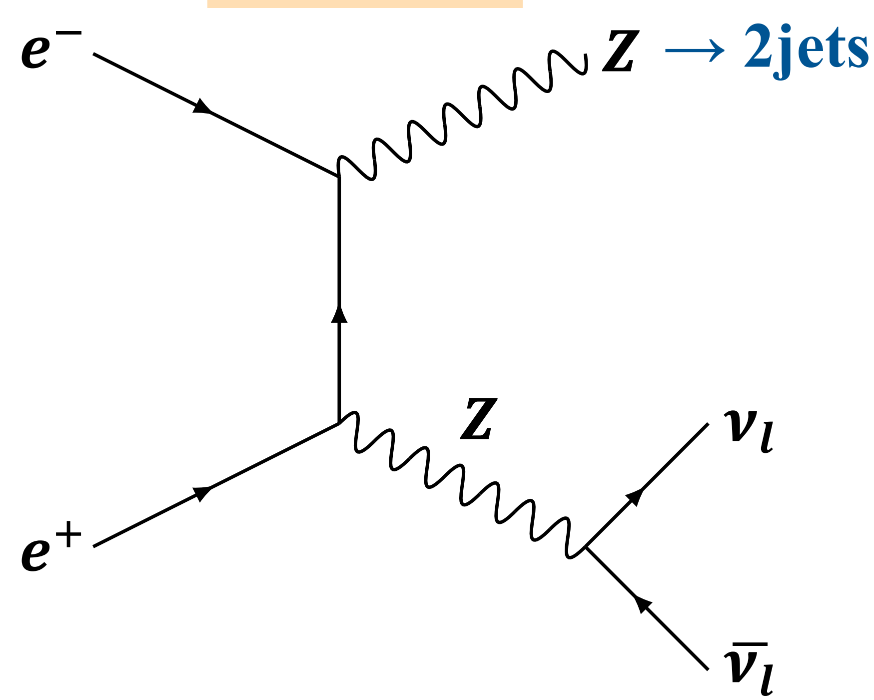
4f_sznu_sl



4f_ww_sl



4f_zz_sl



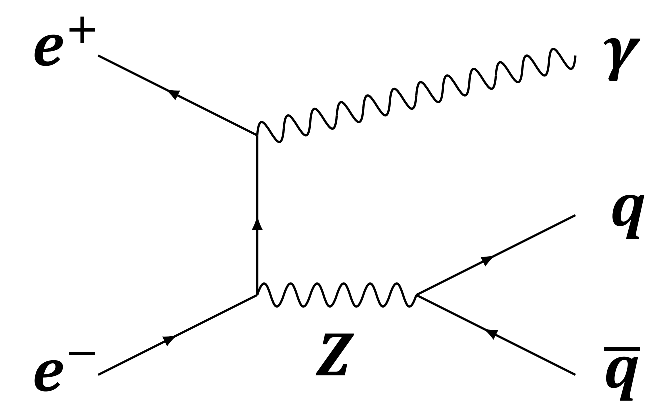
Event selection

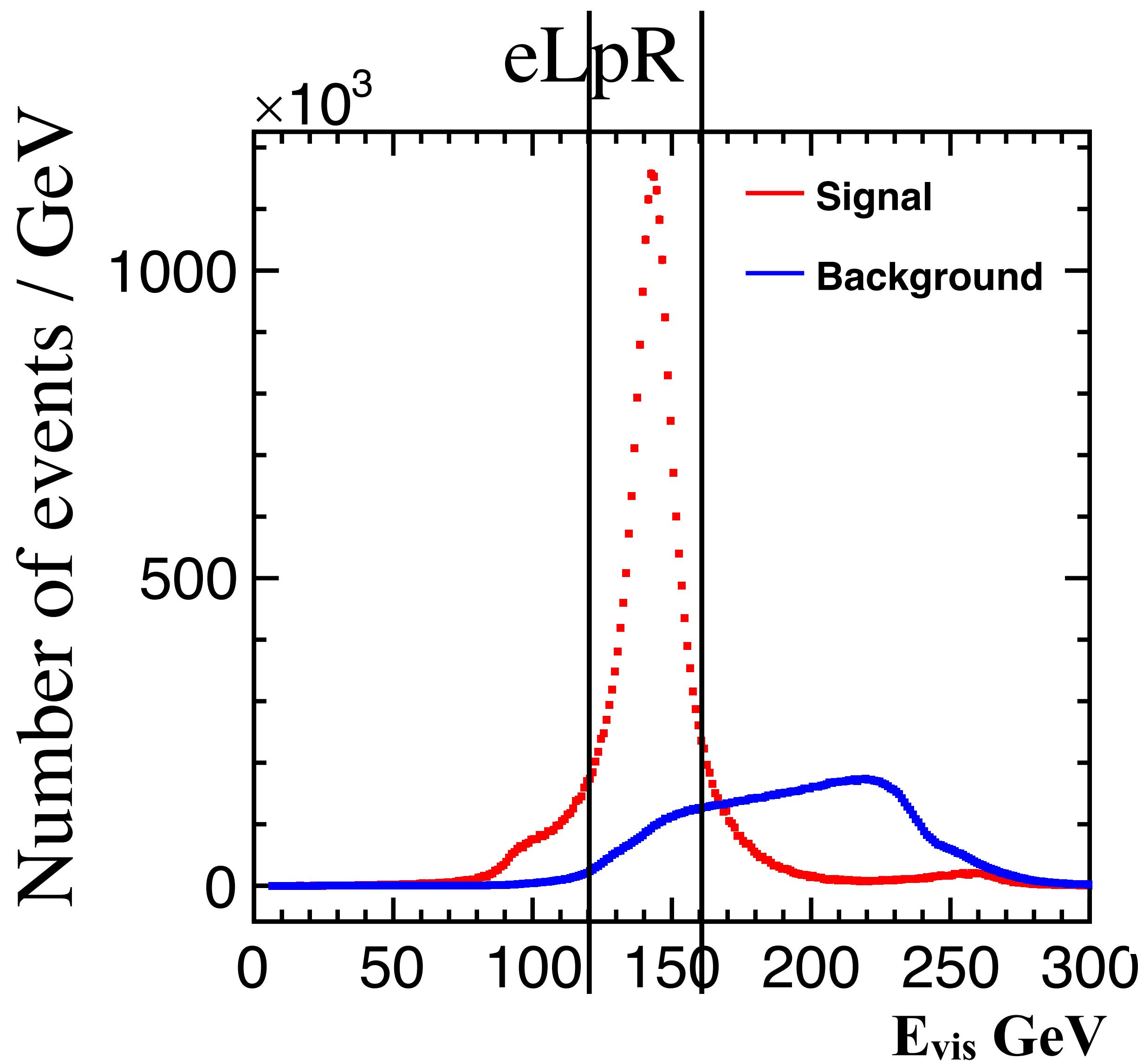
Cut 1 $N_{\gamma(E>50\,GeV)} = 0$

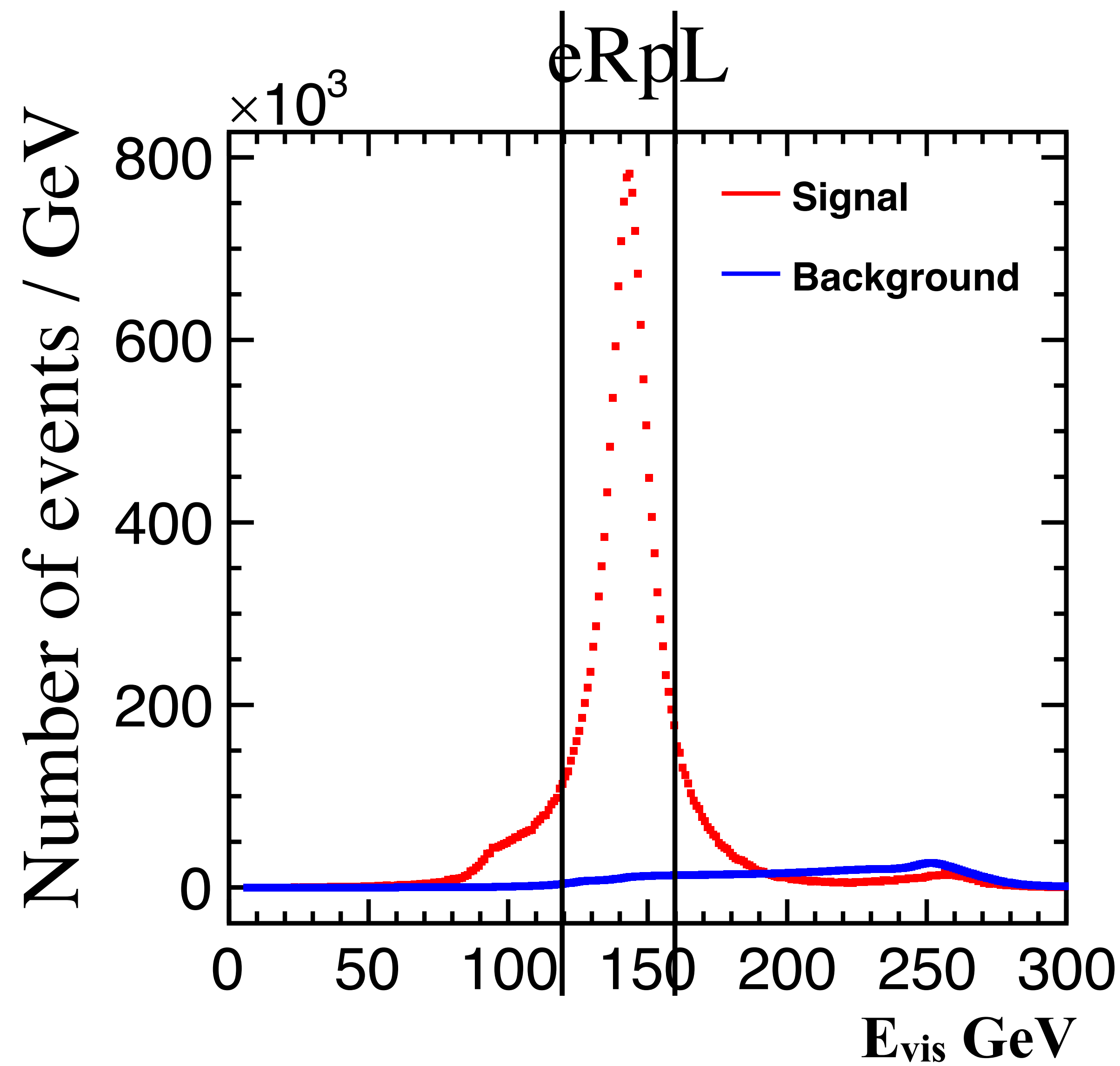
$\boxed{\text{Cut 2 } 120\,GeV < E_{vis} < 160\,GeV}$

Cut 3 $|\cos\theta_{2j}| > 0.95$

Cut 4 $50\,GeV < M_{2j} < 160\,GeV$







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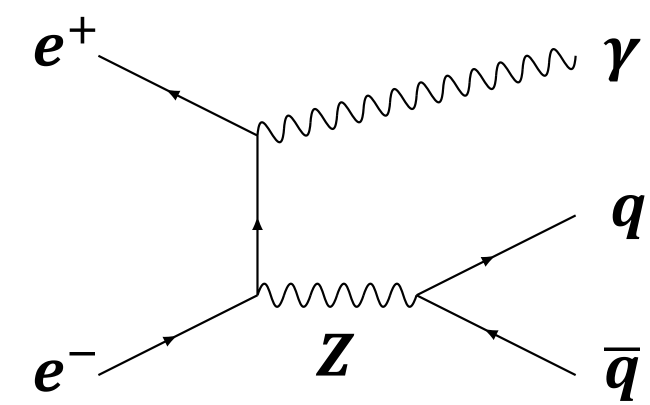

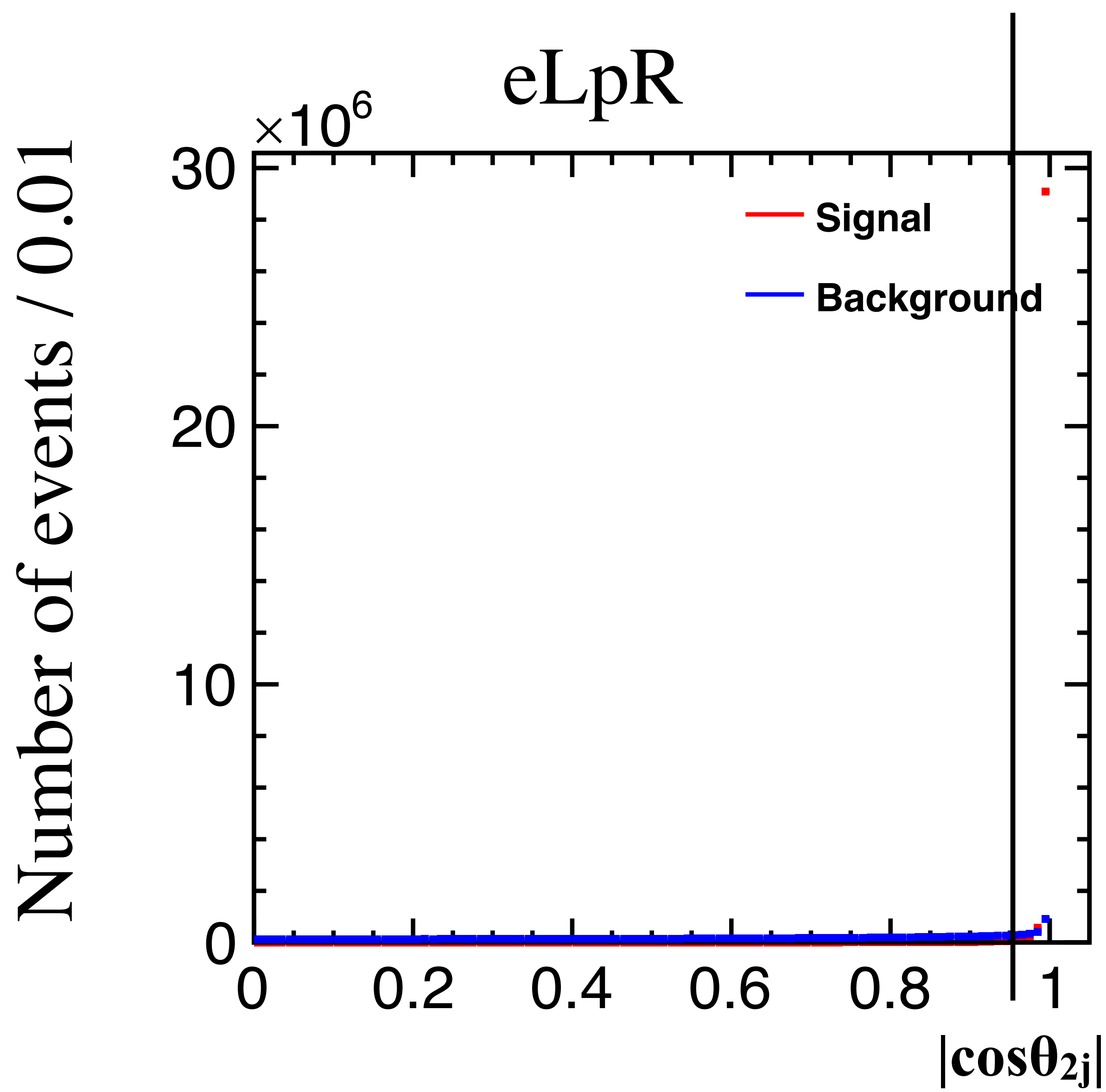

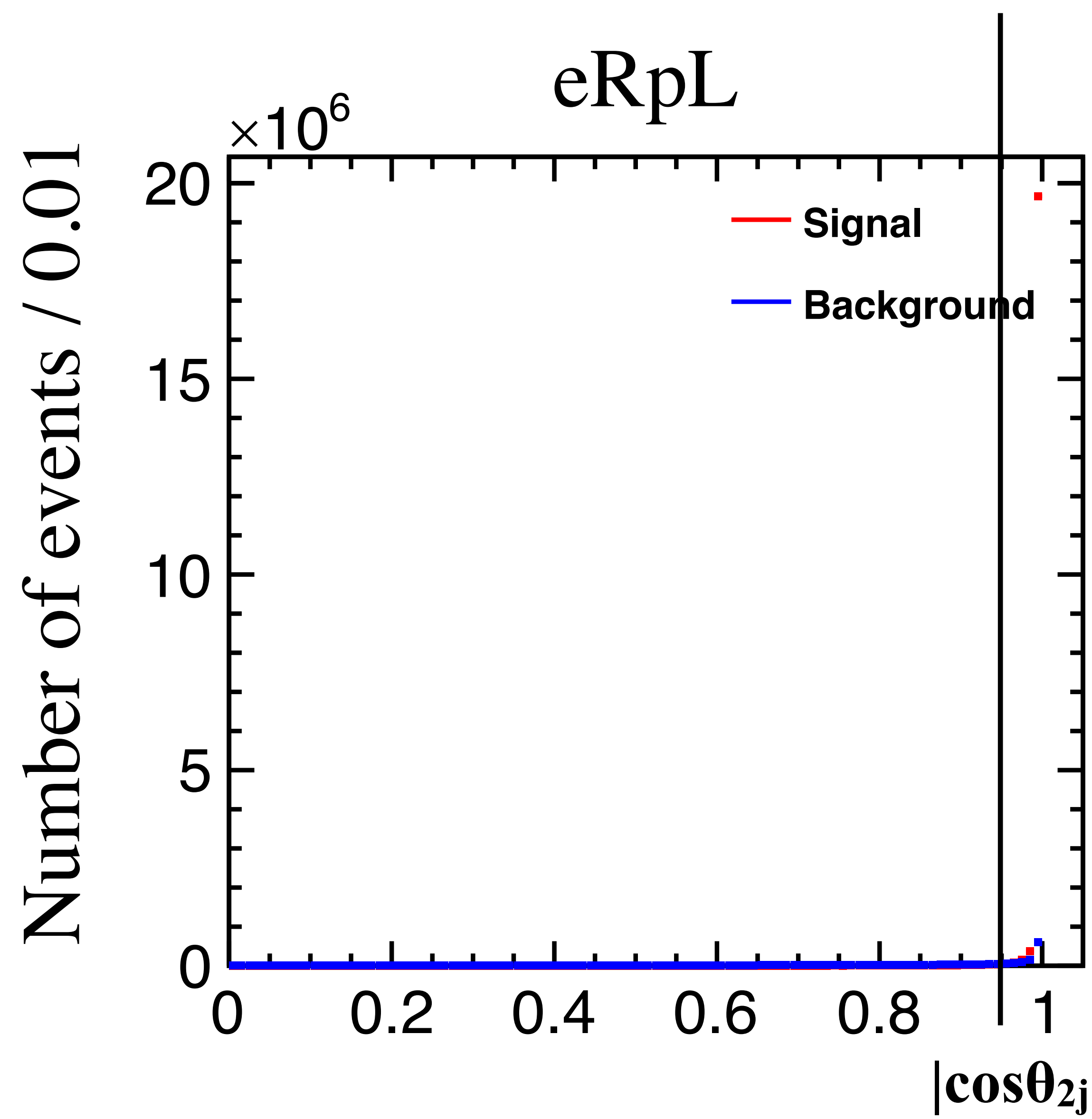

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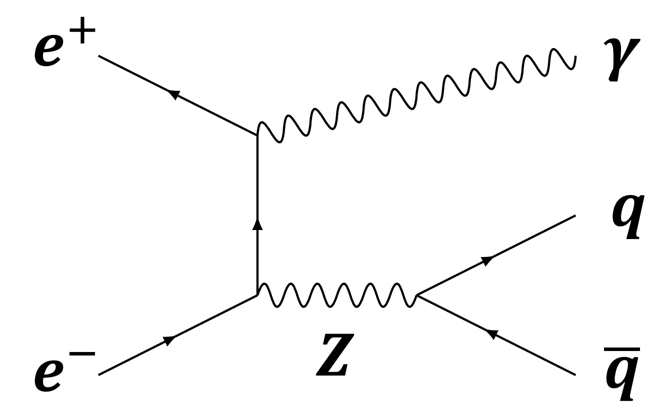
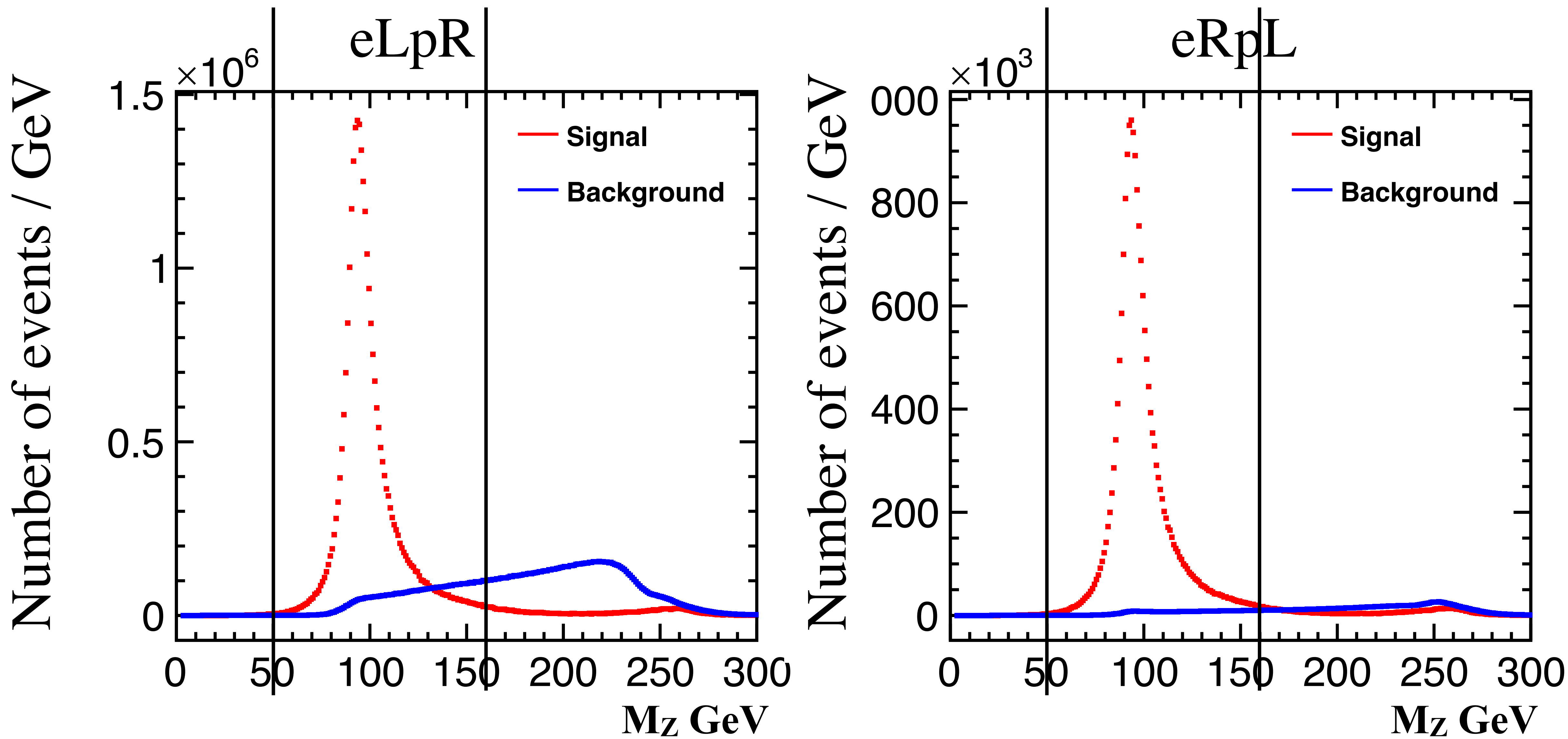




Cut Table

Number of events with (P_{e^-}, P_{e^+}) = (-0.8, +0.3) polarization

Process	Signal	4f_sw_sl	4f_sze_sl	4f_sznu_sl	4f_ww	4f_zz	Background Total
Expected	3.25017e+07	5.4719e+06	1.18316e+06	243096	9.89268e+06	455954	1.72468e+07
Cut 1	3.10963e+07	5.10134e+06	534339	241228	9.64957e+06	432962	1.59594e+07
Cut 2	2.44416e+07	566437	25287.2	140890	2.40774e+06	75801.6	3.21616e+06
Cut 3	2.44199e+07	61265.7	23784.1	18126.3	362353	60237.6	525767
Cut 4	2.44198e+07	61190	23730.7	18022.4	362353	60061.6	525358

Efficiency = 0.75134 ±0.00028 **B/S= 0.02151 for (-0.8, +0.3)**

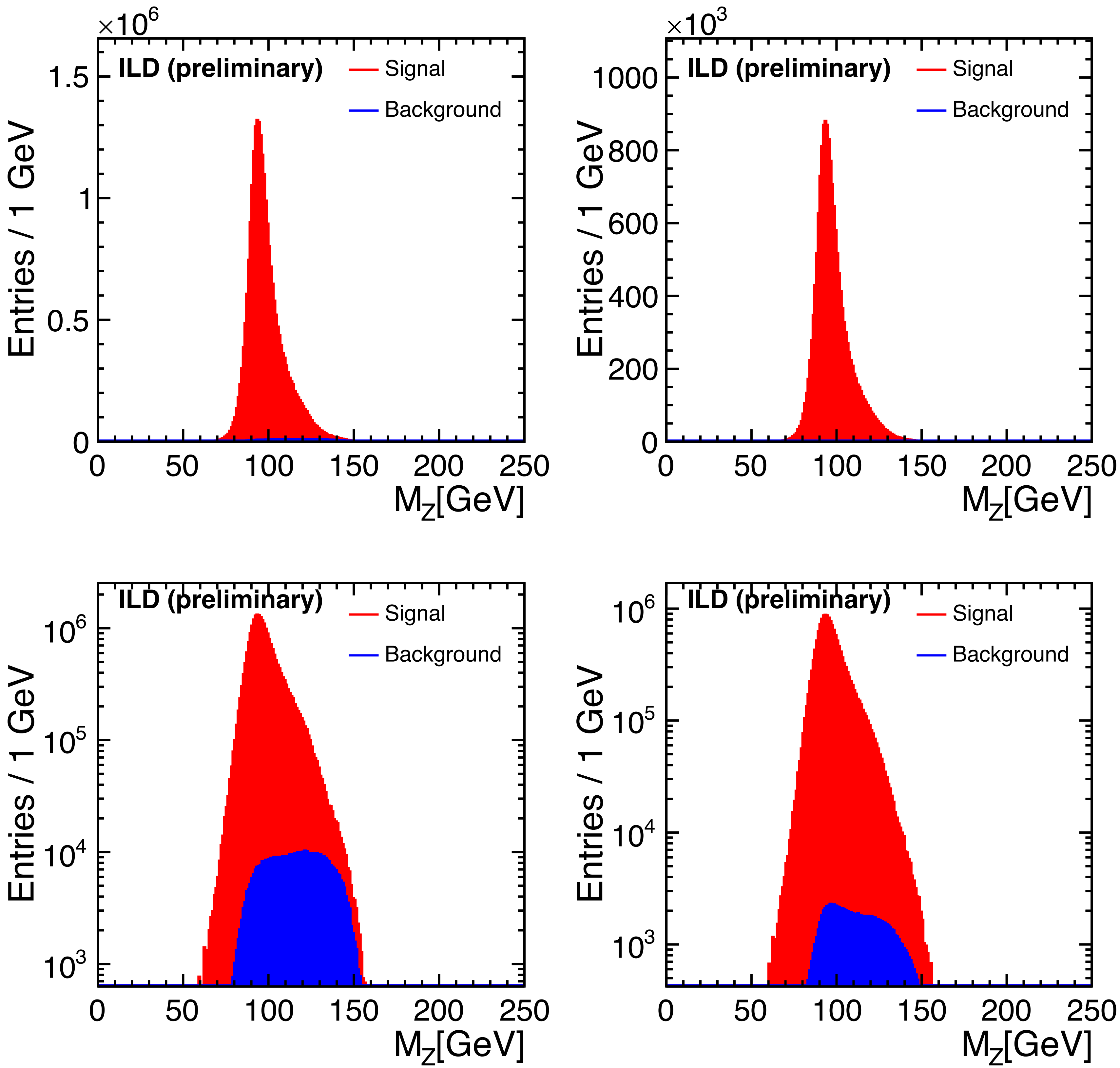
Number of events with (P_{e^-}, P_{e^+}) = (+0.8, -0.3) polarization

Process	Signal	4f_sw_sl	4f_sze_sl	4f_sznu_sl	4f_ww	4f_zz	Background Total
Expected	2.15581e+07	434154	1.08253e+06	83384	682874	272178	2.55512e+06
Cut 1	2.06154e+07	399858	455053	82533.5	666727	257213	1.86138e+06
Cut 2	1.62129e+07	66637.4	24657.1	54821.6	173510	50281.4	369907
Cut 3	1.61991e+07	11216.1	23192.1	7382.85	23112.3	41545.2	106448
Cut 4	1.6199e+07	11189.3	23132	7314.02	23112	41358.8	106106

Efficiency = 0.75141 ±0.00026 **B/S= 0.00655 for (+0.8, -0.3)**

Final Event Sample

$(P_{e^-}, P_{e^+}) = (-0.8, +0.3)$ $(P_{e^-}, P_{e^+}) = (+0.8, -0.3)$



B/S is indeed very good.

Estimation of A_{LR} precision (1)

$$A_{LR} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}.$$

L/R : 100% polarization

$$A_{LRobs} \equiv \frac{\sigma_{-+} - \sigma_{+-}}{\sigma_{-+} + \sigma_{+-}}$$

-/+ : Polarization at ILC

$$\sigma_{-+} = \frac{1}{4}(1+|P_-|)(1+|P_+|)\sigma_L + \frac{1}{4}(1-|P_-|)(1-|P_+|)\sigma_R$$

$$\sigma_{+-} = \frac{1}{4}(1-|P_-|)(1-|P_+|)\sigma_L + \frac{1}{4}(1+|P_-|)(1+|P_+|)\sigma_R$$

$$A_{LR} = A_{LRobs}\frac{1+|P_-||P_+|}{|P_-|+|P_+|} = A_{LRobs} \times f$$

The error of the A_{LR} can be expressed as

$$\left(\frac{\Delta A_{LR}}{A_{LR}}\right)^2 = \left(\frac{\Delta A_{LRobs}}{A_{LRobs}}\right)^2 + \left(\frac{\Delta f}{f}\right)^2$$

Estimation of A_{LR} precision (2)

Assume $\Delta|P_-|$ and $\Delta|P_+|$ are independent, then

$$\left(\frac{\Delta f}{f}\right)^2 = \left(\frac{|P_-|(1+|P_+|)(1-|P_+|)}{(|P_-|+|P_+|)(1+|P_-||P_+|)}\right)^2 \left(\frac{\Delta|P_-|}{|P_-|}\right)^2 + \left(\frac{|P_+|(1+|P_-|)(1-|P_-|)}{(|P_-|+|P_+|)(1+|P_-||P_+|)}\right)^2 \left(\frac{\Delta|P_+|}{|P_+|}\right)^2$$

As for the error of A_{LRobs}, defining

$$N_{-+} = \eta_{-+} L_{-+} \sigma_{-+} \qquad \alpha \equiv L_{-+} \eta_{-+}$$

$$N_{+-} = \eta_{+-} L_{+-} \sigma_{+-}, \qquad \beta \equiv L_{+-} \eta_{+-},$$

$$A_{LRobs} = \frac{\frac{N_{-+}}{\alpha} - \frac{N_{+-}}{\beta}}{\frac{N_{-+}}{\alpha} + \frac{N_{+-}}{\beta}},$$

N: number of events

η: selection efficiency

L: integrated luminosity

$\sim 6.81 \times 10^{-8} \times \sqrt{\langle \Delta\alpha \Delta\beta \rangle}$

Correlated parts of the error of α and β cancel in A_{LRobs}.

-> Δα and Δβ below only refer to uncorrelated parts.

$$\left(\frac{\Delta A_{LRobs}}{A_{LRobs}}\right)^2 = \left(\frac{2\left(\frac{N_{-+}}{\alpha}\right)\left(\frac{N_{+-}}{\beta}\right)}{\left(\frac{N_{-+}}{\alpha} - \frac{N_{+-}}{\beta}\right)\left(\frac{N_{-+}}{\alpha} + \frac{N_{+-}}{\beta}\right)}\right)^2 \left(\left(\frac{\Delta\alpha}{\alpha}\right)^2 + \left(\frac{\Delta\beta}{\beta}\right)^2 + \left(\frac{\Delta N_{-+}}{N_{-+}}\right)^2 + \left(\frac{\Delta N_{+-}}{N_{+-}}\right)^2\right)$$

Results

If errors of η, L, and polarization are negligible,

$A_{LR} = 0.22815 \pm 0.00017$

If we add polarization error $\Delta f/f = 0.001$,

Absolute error of $A_{LR} = 0.00021$

If $\Delta\alpha/\alpha = \Delta\beta/\beta$ (uncorrelated) = **0.00006 (i.e. 0.006%)**,

Absolute error = 0.000218 (cf. Abs. error at SLC = 0.00219)

In order to achieve 10 times better precision than SLC, we need to keep the uncorrelated part of the error on product of efficiency and luminosity below 0.006%.

Conclusion of A_{LR} measurement

- As A_{LR} is useful to constrain SMEFT parameters, it is motivated to improve this observable at the ILC. In order to access how much we can improve the precision, full simulation study including $e^+e^- \rightarrow \gamma Z$ process and various background processes are performed.
- In order to exclude the background processes, cut conditions are considered.
- For the radiative return events with hadronic decay and unseen signal photon case, background-to-signal ratios are 0.0215 and 0.00655 for $(P\ e^-, P\ e^+) = (-0.8, +0.3)$ and $(+0.8, -0.3)$ polarization respectively after the event selection.
- The **statistical error of the A_{LR}** is estimated to be 1.7×10^{-4} i.e. **13 times better than the overall error at the SLC** and in order to achieve 10 times better precision than SLC, we need to keep the uncorrelated part of the error on product of efficiency and luminosity below **0.006%**.