Optimal probe of New Physics at future e^+e^- Colliders

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Outline:

* Chapter-I: Optimal Observable Technique (OOT)
* Chapter-II: Example of OOT in NP dominance
* Chapter-III: Example of OOT in SM dominance
* Chapter-IV: OOT in presence of SM background
* Summary

Chapter-I (Optimal Observable Technique)

Beyond Standard Model:

Shortcomings of SM

- Hierarchy Problem
- Dark Matter
- Neutrino Mass
- Baryon Asymmetry

BSM Models/Theories

UV models

SUSY
Composite Higgs
Seesaw
LRSM
DM models

SMEFT

$$\mathcal{L}_{\texttt{EFT}} = \sum_{i,d>4} \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^d$$

$C_i =$ NP Couplings
$\Lambda =$ Scale of NP

BSM search at colliders:

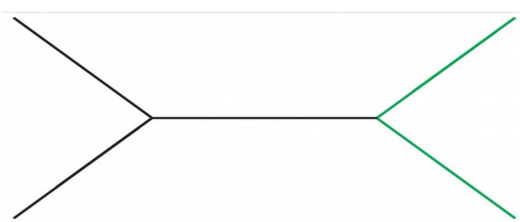
Build a Large Collider

Increase CM energy

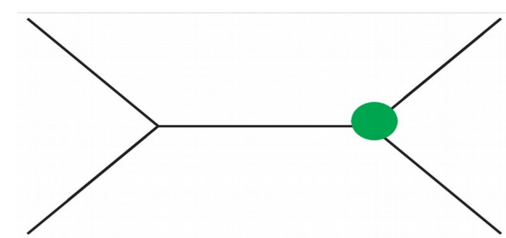
Discover new particles!

Measure the deviation via SM processes

Discover new physics indirectly!



(BSM dominated scenario)



(SM dominated scenario)

Statistical analysis plays a crucial role to elucidate both scenarios

χ^2 analysis:

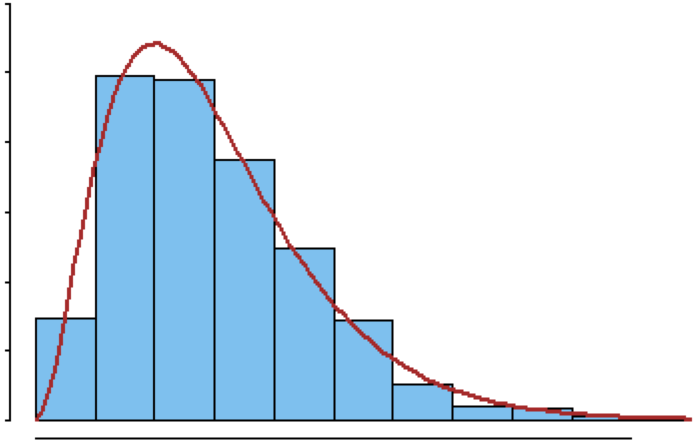
Definition:
$$\chi^2 = \frac{(\mathcal{O}^{\tt data} - \mathcal{O}(a,b)^{\tt theory})^2}{\sigma^2}$$

$$\Delta\chi^2 = \chi^2 - \chi^2_{\tt min} = n$$, provides $\sqrt{n}\sigma$ deviation.

Binned analysis:

$$\chi^2 = \sum_i \frac{\left(N_i^{\tt data} - N_i^{\tt theory}\right)^2}{N_i^{\tt data}}$$

$$\sigma = \sqrt{N_i^{\tt data}}$$



Optimal Observable Technique (OOT):

Case-I : BSM dominates over SM

(Phys. Rev. Lett. 77 (1996) 5172)

Observable:
$$\mathcal{O}_{BSM} = \frac{d\sigma}{d\Omega} = \sum_i g_i f_i(\phi)$$

Contains the information of ***NP*** parameters

Linearly independent functions

Covariance Matrix :
$$V_{ij} = \frac{M^{-1}_{ij}}{\mathcal{L}_{int}};$$

Optimal in a sense that $\frac{\partial V_{ij}}{\partial g_i} = 0$

Integrated Luminosity of the Collider

$$M_{ij} = \int \frac{f_i(\phi) f_j(\phi)}{\mathcal{O}_{BSM}} d\phi$$

Optimal Observable Technique (OOT):

Case-II : SM dominates over BSM

(Z. Phys. C 62 (1994))

Observable : $\mathcal{O} = \mathcal{O}_{SM} + \sum_i g_i f_i$

$$M_{ij} = \int \frac{f_i(\phi) f_j(\phi)}{O_{SM}} d\phi$$

Case-III : Non interfering SM background

Observable : $\mathcal{O}_{tot} = \mathcal{O}_{sig} + \mathcal{O}_{bkg} = \sum_i g_i f_i$

$$M_{ij} = \int \frac{f_i(\phi) f_j(\phi)}{\mathcal{O}_{tot}} d\phi$$

$$\chi^2 = \sum_i (g_i - g_i^0)(g_j - g_j^0) V_{ij}^{-1}; \quad g_i^0 = \text{`seed values'}$$

Chapter-II (Example of NP dominance)

based on

Probing heavy charged fermions at e^+e^- collider using Optimal Observable Technique, S. Bhattacharya, **S. Jahedi**, J. Wudka

(JHEP 05 (2022) 009)

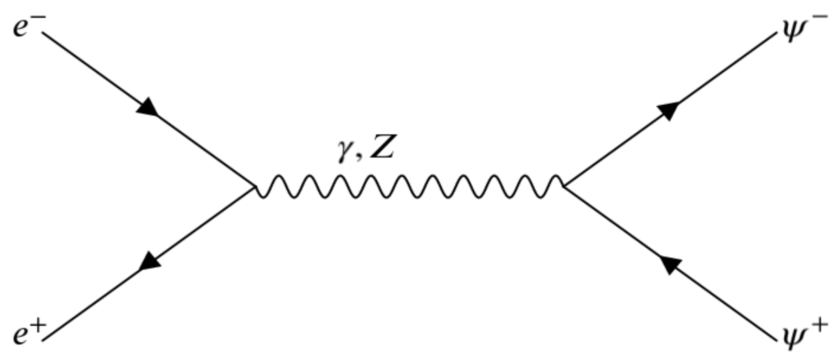
Gauge couplings with $\psi^{\pm}$:

Gauge couplings

- $\psi^+\psi^-\gamma : -ie_0\gamma^\mu$
- $\psi^+\psi^- Z : -\frac{ie_0}{s_{2W}}\gamma^\mu(a+b\gamma^5)$

Hypotheses

- **Vector like** (a=1, b=0)
- **Axial-vector like** (a=1, b=1)
- **Chiral like** (a=0, b=1)



Helicity Amplitudes:

$$\mathcal{M}(\lambda_{e^-},\, -\lambda_{e^-},\, \lambda_\psi,\, -\lambda_\psi) = -e_0^2\,(\lambda_{e^-}\lambda_\psi + \cos\theta)\,[1 + \xi\,(a + b\lambda_\psi\beta_\psi)]\ ; \quad \xi = \xi_1 + \lambda_{e^-}\xi_2$$

$$\mathcal{M}(\lambda_{e^-},\, -\lambda_{e^-},\, \lambda_\psi,\, \lambda_\psi) = -e_0^2\left(\frac{2m_{\psi^\pm}\lambda_\psi \sin\theta}{\sqrt{s}}\right)(1 + \xi a)$$

Cross-section:

$$\frac{d\sigma(P_{e^+},\,P_{e^-})}{d\Omega} = \sum_{\lambda_e^+=\pm1}\sum_{\lambda_e^-=\pm1}\frac{(1+\lambda_{e^-}P_{e^-})(1+\lambda_{e^+}P_{e^+})}{4}\left(\frac{d\sigma}{d\Omega}\right)_{\lambda_{e^-},\lambda_{e^+}} = \sum_i g_i f_i$$

$$g_1 = \alpha_0^2\frac{1-P_{e^-}P_{e^+}}{2}\left[1+2\xi_1 a+(\xi_1^2+\xi_2^2)\left(a^2+\frac{\beta_\psi^2}{2-\beta_\psi^2}b^2\right)-2P_{\tt eff}\left\{\xi_2 a+\xi_1\xi_2 a^2+\frac{\beta_\psi^2}{2-\beta_\psi^2}\xi_1\xi_2 b^2\right\}\right]$$

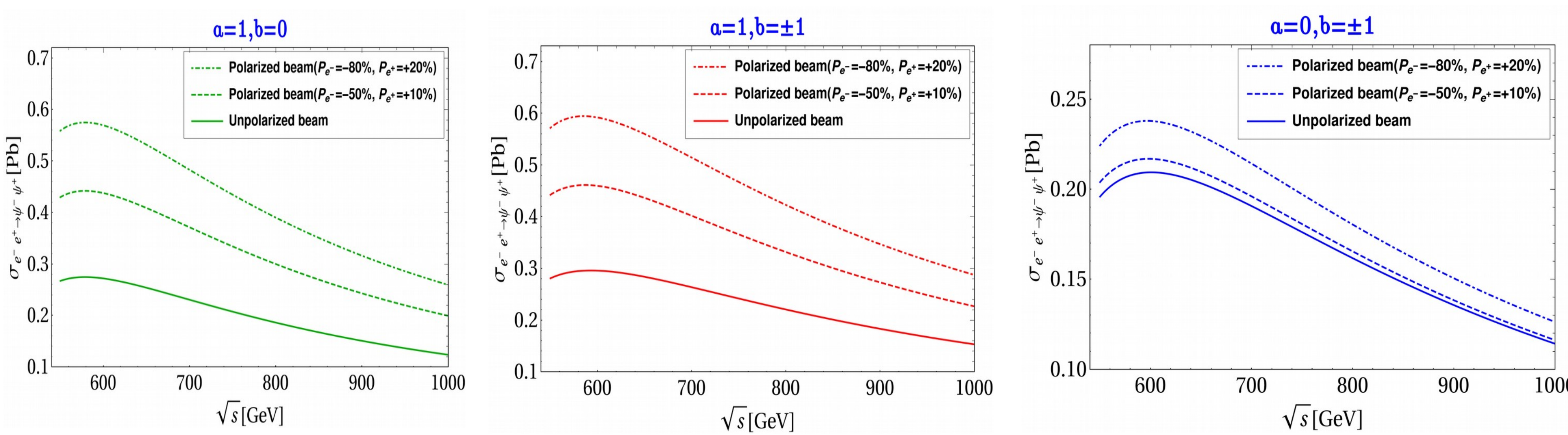
$$g_2 = \alpha_0^2\frac{1-P_{e^-}P_{e^+}}{2}\left[2\xi_2 b+4\xi_1\xi_2 ab-P_{\tt eff}\left\{2\xi_1 b+(\xi_1^2+\xi_2^2)ab\right\}\right]$$

$$g_3 = \alpha_0^2\frac{1-P_{e^-}P_{e^+}}{2}\left[1+2\xi_1 a+(\xi_1^2+\xi_2^2)(a^2+b^2)-2P_{\tt eff}\left\{\xi_2 a+\xi_1\xi_2(a^2+b^2)\right\}\right]$$

$$\xi_{1,2} = \text{SM couplings}$$

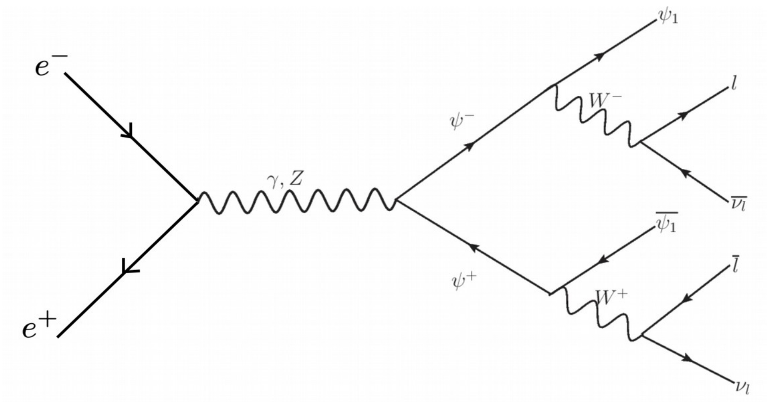
$$\{f_1,\,f_2,\,f_3\} = \frac{\beta_\psi}{2s}\left\{(2-\beta_\psi^2),\,\beta_\psi\cos\theta,\,\beta_\psi^2\cos^2\theta\right\} \qquad \beta_\psi = \sqrt{1-\frac{4m_\psi^2}{s}}$$

$$\boxed{\begin{aligned}P_{e^-} &= -80\%\\ P_{e^+} &= +20\%\end{aligned}}$$

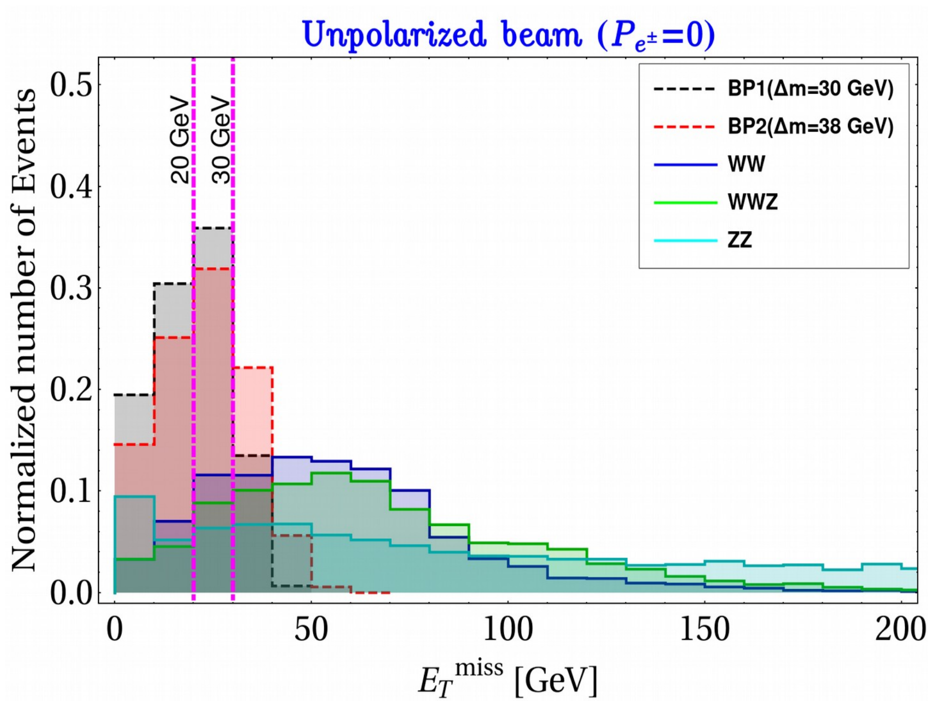


Event analysis:

Singlet-doublet model: $\psi^{\pm}, \psi_1$ and ψ_2



Missing transverse energy distribution



Final state signal:

$\ell^+\ell^-$ + missing energy

Cut flows:

$\mathcal{C}_1$: Events with 2 leptons

$\mathcal{C}_2$: $m_{\ell\ell} < |m_Z \pm 15|$ GeV

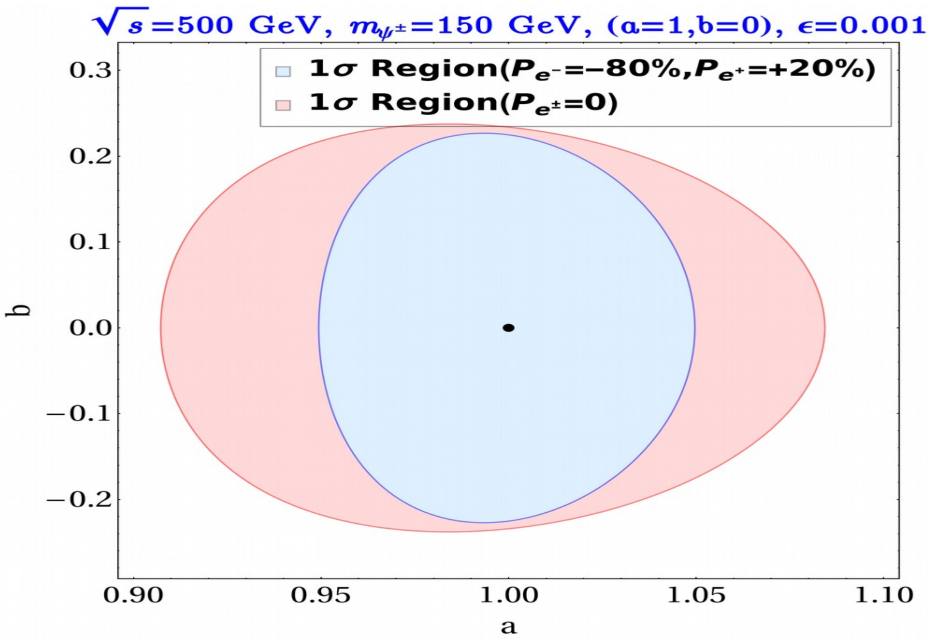
$\mathcal{C}_3$: $E_T^{\mathtt{miss}} < 30$ GeV

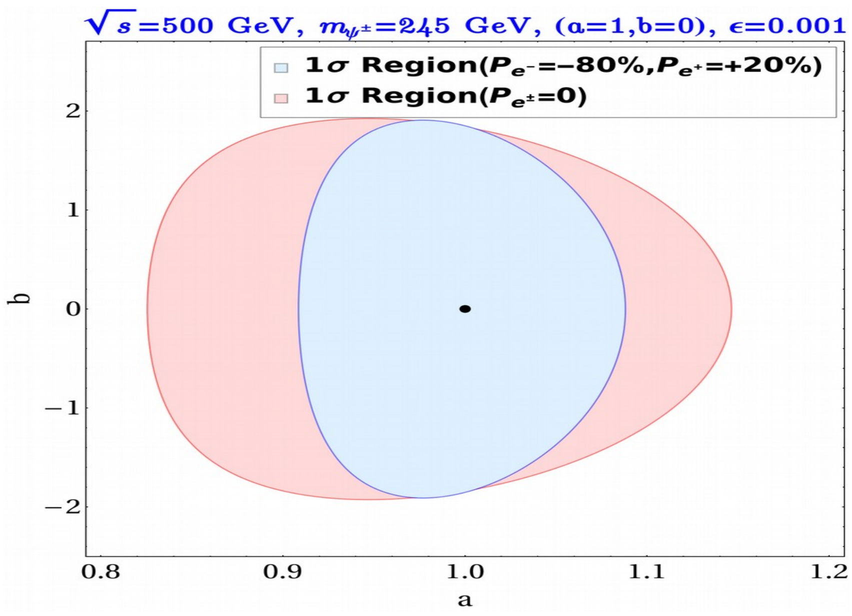
$$\epsilon = \frac{\sigma^{sig}}{\sigma^{prod}} = 0.006$$

Our choice

$$\epsilon = 0.001$$

1σ sigma regions:





- For lower charged fermion mass, the NP couplings are more precise.
- Judicious choice of beam polarization provides more strintgent parameter space.

Chapter-III (Example of SM dominance)

based on

Probing anomalous $ZZ\gamma\,\mathrm{and}\,\mathrm{Z}\gamma\gamma$ couplings at the e^+e^- collider using Optimal Observable Technique, **S. Jahedi**, J. Lahiri

(JHEP 04 (2023) 085)

Optimal determination of New Physics couplings: A comparative study, S. Bhattacharya, **S. Jahedi**, J. Wudka

(arXiv:2301.07721, In communication with JHEP)

Neutral triple gauge couplings:

Tripple gauge couplings

SM → W^+W^-V

BSM → ZVV

$(V = \gamma, Z)$

Dim-8 EFT Operators

CP even

$$\mathcal{O}_{\tilde{B}W} = iH^\dagger \tilde{B}_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H$$

CP odd

$$\mathcal{O}_{BW} = iH^\dagger B_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H$$
$$\mathcal{O}_{WW} = iH^\dagger W_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H$$
$$\mathcal{O}_{BB} = iH^\dagger B_{\mu\nu} B^{\mu\rho} \{D_\rho, D^\nu\} H$$

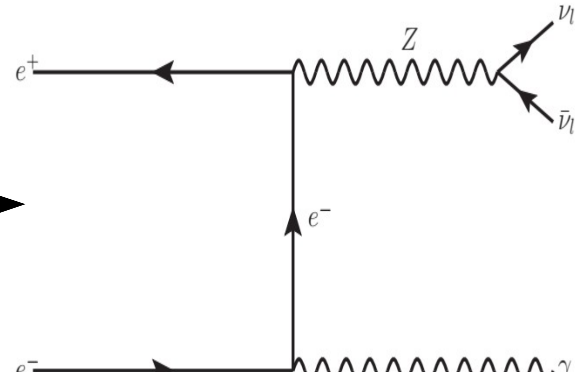
ATLAS constrains

$$pp \to Z(\nu\bar{\nu})\gamma$$

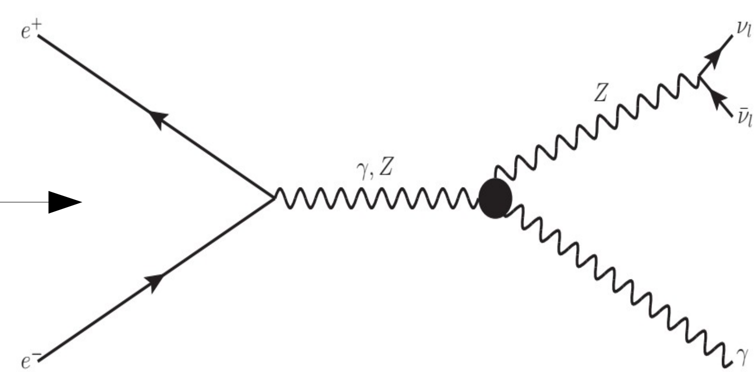
95% C.L.

$$-1.1\,\mathrm{TeV}^{-4} < \frac{\mathrm{C}_{\tilde{\mathrm{B}}\mathrm{W}}}{\Lambda^4} < 1.1\,\mathrm{TeV}^{-4}$$
$$-0.65\,\mathrm{TeV}^{-4} < \frac{\mathrm{C}_{\mathrm{BW}}}{\Lambda^4} < 0.64\,\mathrm{TeV}^{-4}$$
$$-2.3\,\mathrm{TeV}^{-4} < \frac{\mathrm{C}_{\mathrm{WW}}}{\Lambda^4} < 2.3\,\mathrm{TeV}^{-4}$$
$$-0.24\,\mathrm{TeV}^{-4} < \frac{\mathrm{C}_{\mathrm{BB}}}{\Lambda^4} < 0.24\,\mathrm{TeV}^{-4}$$

SM →



BSM →



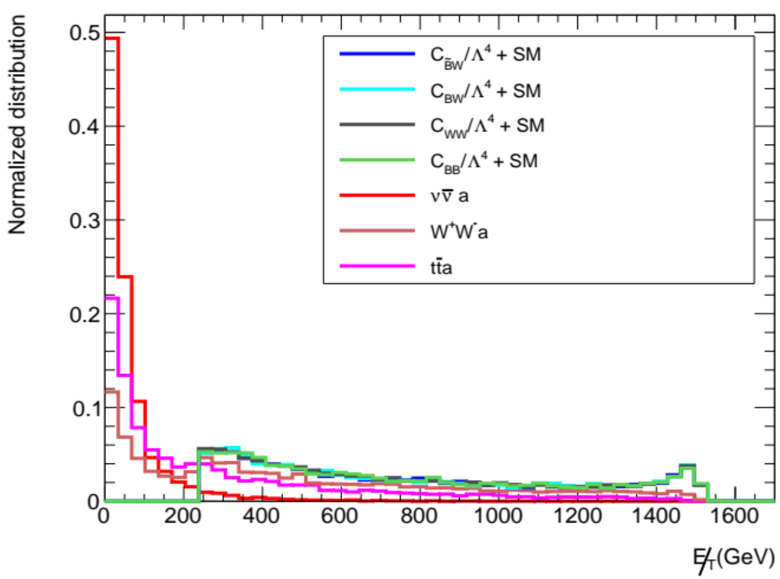
Event analysis:

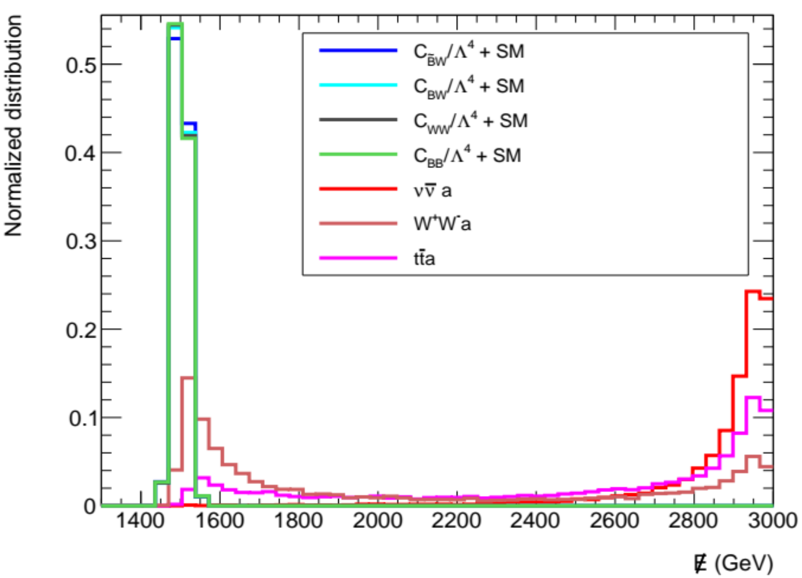
Final state signal: → Mono-photon+ missing energy

Collider Variables

→ Missing energy $= \not{E} = \sqrt{s} - \sum_{\ell,j,\gamma} E$

→ Missing transverse energy $= \not{E}_T = -\sqrt{(\sum_{\ell,j} p_x)^2 + (\sum_{\ell,j} p_y)^2}$





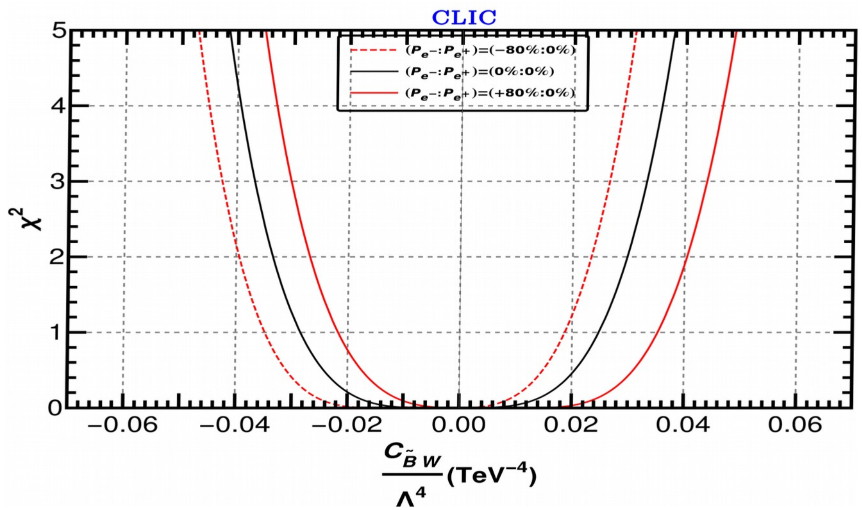
Cut-employed: →

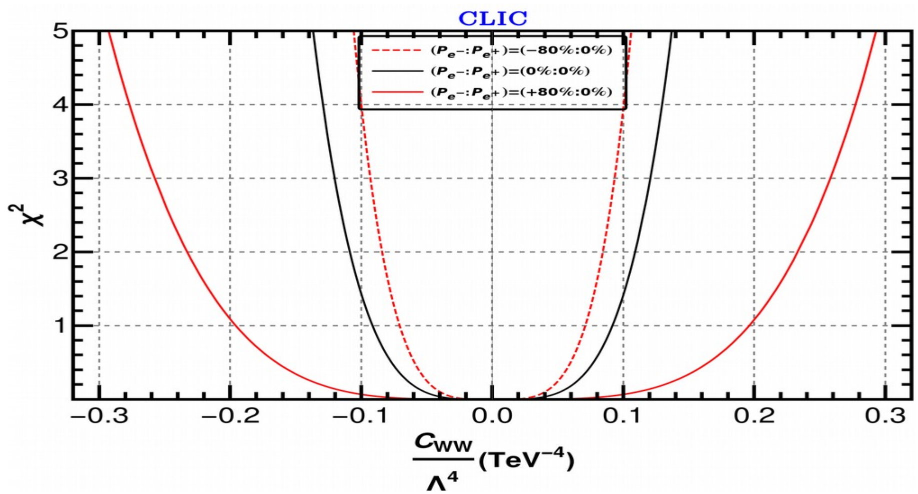
- $\mathcal{C}_1$:Events with one photon
- $\mathcal{C}_2$: $\not{E}_T$ > 500 GeV
- $\mathcal{C}_3$: 1440 GeV< $\not{E}$ <1560 GeV

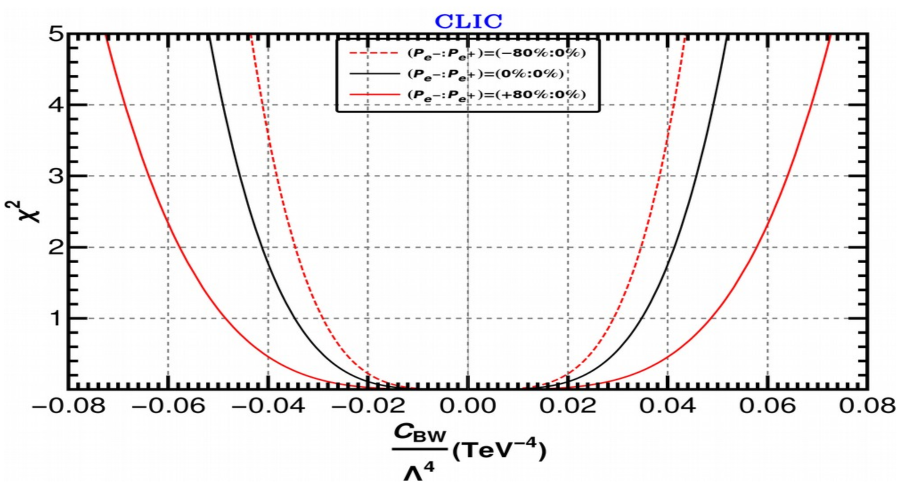
→ $\boxed{\epsilon = \frac{\sigma^{sig}}{\sigma^{prod}} \sim 0.1}$

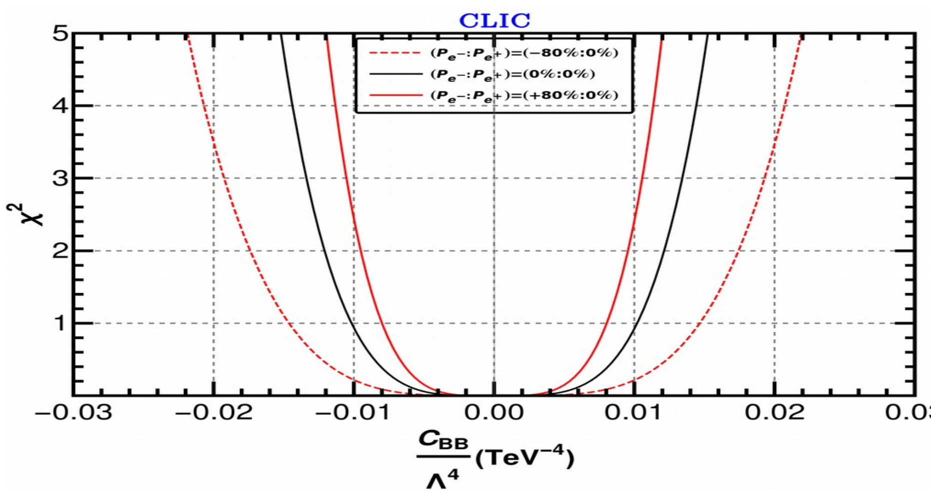
χ^2 variation:

$$\sqrt{S} = 3\,\mathrm{TeV},\ \mathcal{L}_{\mathtt{int}} = 1000\,\mathrm{fb}^{-1}$$



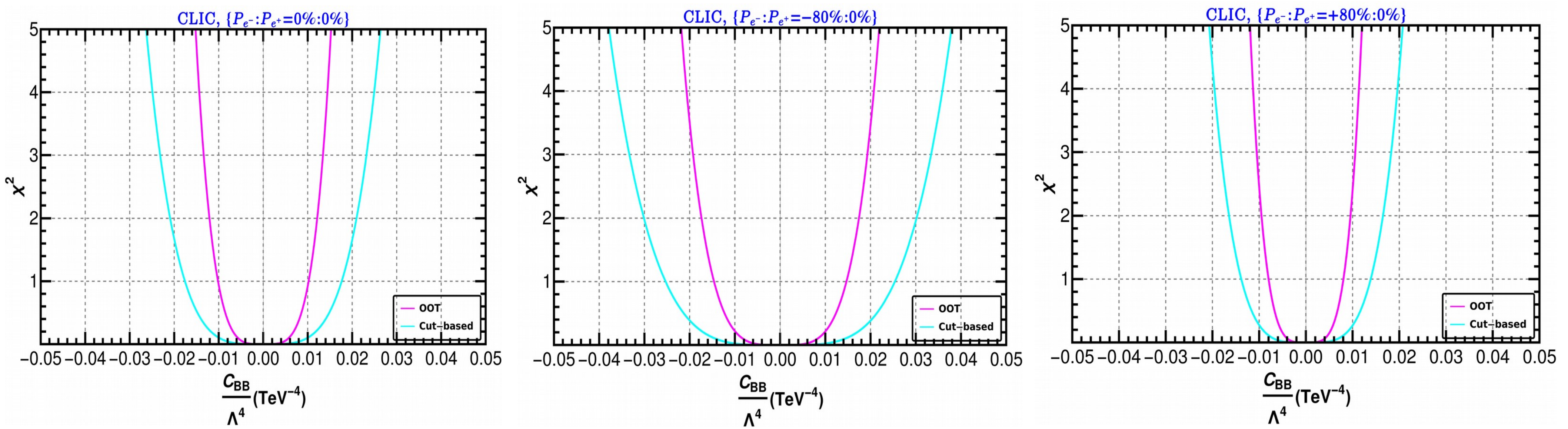






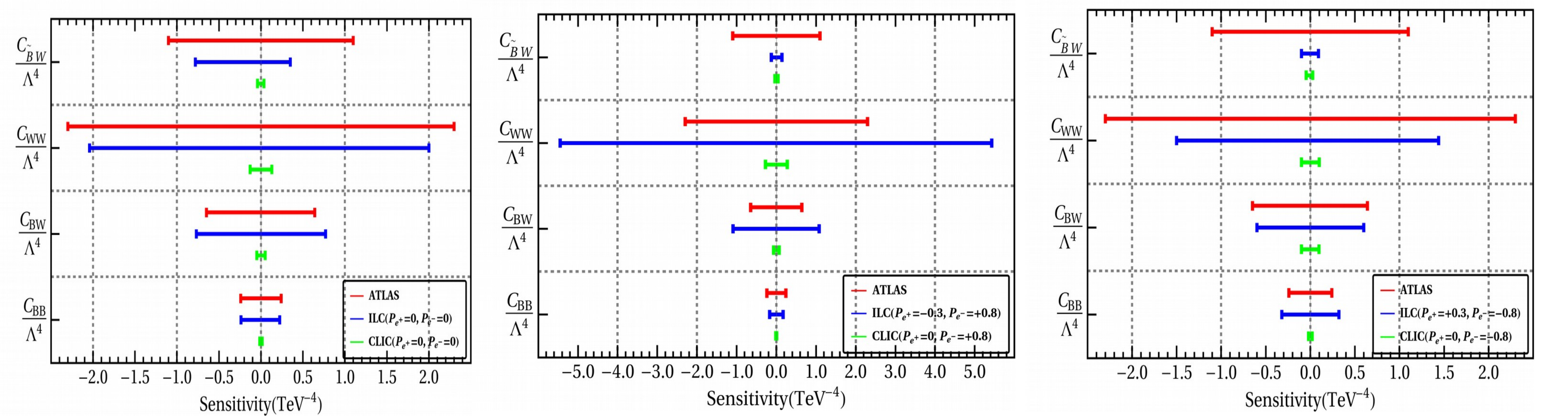
- $\left(\frac{C_{\tilde{B}W}}{\Lambda^4}\right), \left(\frac{C_{BW}}{\Lambda^4}\right), \left(\frac{C_{WW}}{\Lambda^4}\right) \longrightarrow \{P_{e^-} : P_{e^+} = -80\% : 0\%\}$
- $\left(\frac{C_{BB}}{\Lambda^4}\right) \longrightarrow \{P_{e^-} : P_{e^+} = +80\% : 0\%\}$

OOT vs binned analysis:



- .OOT limits are more stringent than binned limits by a factor of 1.7.

ATLAS VS ILC VS CLIC:



- CLIC outperforms ILC and ATLAS by a factor of 10.

Top quark pair production:

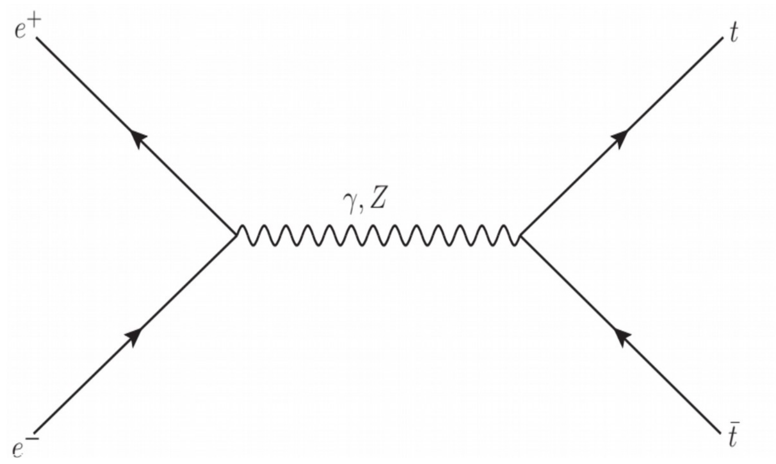
$e^+e^- \to t\bar{t}$

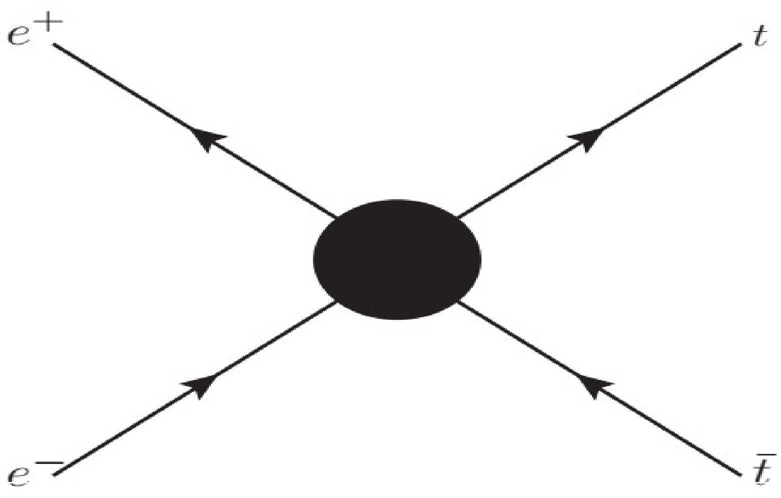
SM Contribution

- $e\bar{e}\gamma = -ie_0\gamma^\mu$
- $t\bar{t}Z = -\frac{ig}{c_w}(c_v - c_a\gamma^5)\gamma^\mu$

BSM contribution

- $\mathcal{O}_{lelq}^{(1)} = \frac{c_1}{\Lambda^2}\left(\bar{l}_p^j e_r\right)\epsilon_{jk}\left(\bar{q}_s^k u_t\right) + h.c.$
- $\mathcal{O}_{lelq}^{(3)} = \frac{c_2}{\Lambda^2}\left(\bar{l}_p^j \sigma^{\mu\nu} e_r\right)\epsilon_{jk}\left(\bar{q}_s^k \sigma_{\mu\nu} u_t\right) + h.c.$





Helicity amplitudes and beam polarization:

Amplitudes of $e^+e^- \to t\bar{t}$

Opposite helcity combination

Same helicity combination

SM contribution

- $M(\lambda,\, -\lambda; \lambda',\, -\lambda') = e_0^2 \left(\frac{\lambda\lambda' + \cos\theta}{\beta_z^2}\right) \left[\frac{2}{3}\beta_z^2 - \left(\frac{4^2 - 1 + \lambda}{4^2}\right)\left(1 - \frac{8^{2}}{3} - \beta_t \lambda'\right)\right]$
- $M(\lambda,\, -\lambda; \lambda',\, \lambda') = \frac{2e_0^2 m_t \lambda' \sin\theta}{\sqrt{s}} \left[\frac{2}{3} - \left(\frac{4^2 - 1 + \lambda}{4^2\, \beta_z^2}\right)\left(1 - \frac{8^{2}}{3}\right)\right]$

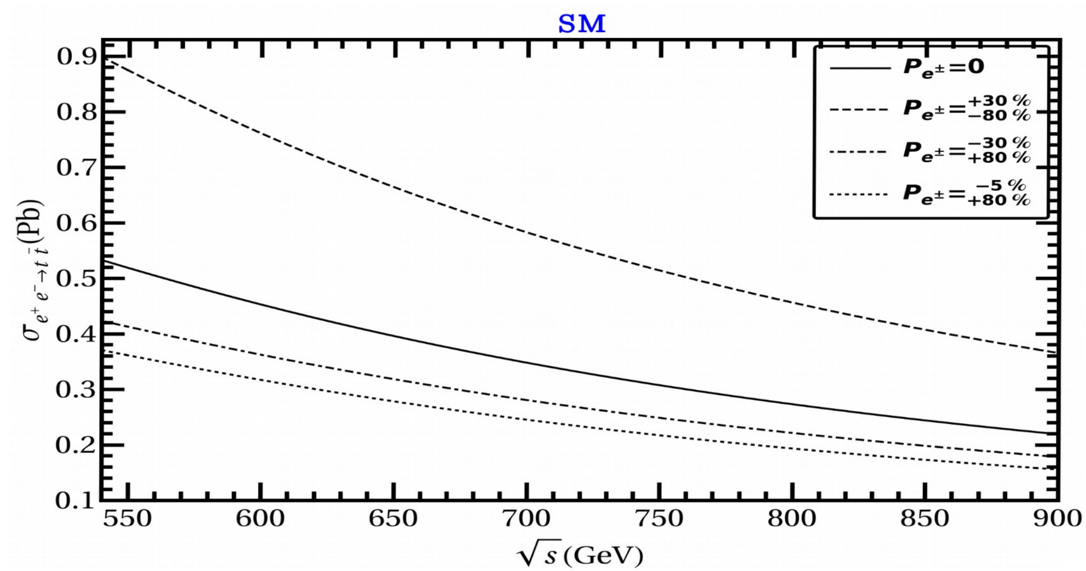
BSM contribution

- $M(\lambda,\, \lambda; \lambda',\, -\lambda') = \frac{4c_2 m_t \sqrt{s}}{\Lambda^2} \lambda \sin\theta$
- $M(\lambda,\, \lambda; \lambda',\, \lambda') = \frac{s}{2\Lambda^2}(\lambda\lambda'\beta_t - 1)\,(c_1 + 4c_2\lambda\lambda' \cos\theta)$

Choice of beam polarization

$P_{e^-} = +80\%$

$P_{e^+} = -5\%$



Differential cross-section:

$$\mathcal{O} = \frac{d\sigma_{\mathtt{tot}}}{d\Omega} = \frac{d\sigma_{\mathtt{SM}}}{d\Omega} + \sum_i g_i f_i$$

$P_{\mathtt{eff}} = \dfrac{P_{e^-} - P_{e^+}}{1 - P_{e^-}P_{e^+}}$

$\dfrac{d\sigma_{\mathtt{SM}}}{d\Omega}$

$$\frac{\alpha_0^2(1-P_{e^-}P_{e^+})}{3s}\Bigg\{1+\mathtt{C}(\xi_1 - P_{\mathtt{eff}}\xi_2) + 4(\xi_1^2 - 2P_{\mathtt{eff}}\xi_1\xi_2 + \xi_2^2)\left(\mathtt{C}^2 + \frac{\beta_t^2}{2-\beta_t^2}\right)$$
$$- \left[\xi_2(1+\mathtt{C}\xi_1) - 4P_{\mathtt{eff}}\left(4\xi_1 - (2\xi_1^2 - \xi_2^2)\mathtt{C}\right)\right]\beta_t\cos\theta +$$
$$\left[1+\mathtt{C}\left(\xi_1 - P_{\mathtt{eff}}\xi_2\right) + \frac{(2\mathtt{C}+1)}{4}(\xi_1^2 - 2P_{\mathtt{eff}}\xi_1\xi_2 + \xi_2^2) + \frac{\mathtt{C}(2-\mathtt{C})}{2}P_{\mathtt{eff}}\xi_1\xi_2\right]\beta_t^2\cos^2\theta\Bigg\}$$

$\xi_1 = \dfrac{1}{2s_{2\mathtt{w}}^2\beta_z^2}$

$\xi_2 = \dfrac{4s_{\mathtt{w}}^2 - 1}{2s_{2\mathtt{w}}^2\beta^2}$

$g_i's$

$$g_1 = (1+P_{e^-}P_{e^+})\left(c_1^2 + 16\frac{1-\beta_t^2}{1+\beta_t^2}c_2^2\right)$$
$$g_2 = -(1+P_{e^-}P_{e^+})c_1c_2$$
$$g_3 = (1+P_{e^-}P_{e^+})c_2^2$$

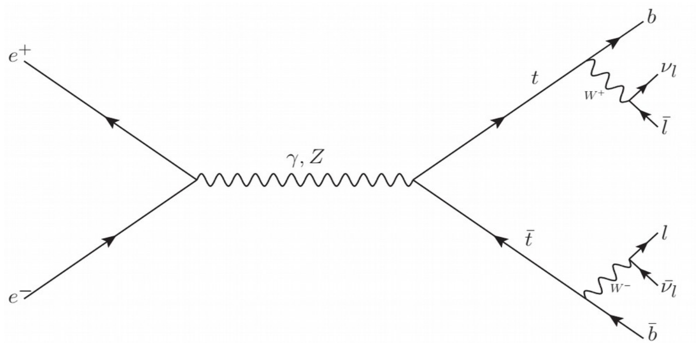
$\mathtt{C} = 3 - 12s_w^2$

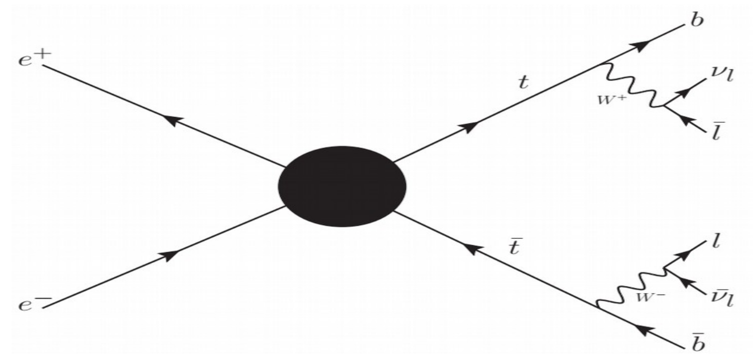
$f_i's$

$$f_1 = \frac{3\beta_t s}{256\pi^2\Lambda^4}(1+\beta_t^2)$$
$$f_2 = \frac{3\beta_t^2 s}{16\pi^2\Lambda^4}\cos\theta$$
$$f_3 = \frac{3\beta_t^3 s}{8\pi^2\Lambda^4}\cos^2\theta$$

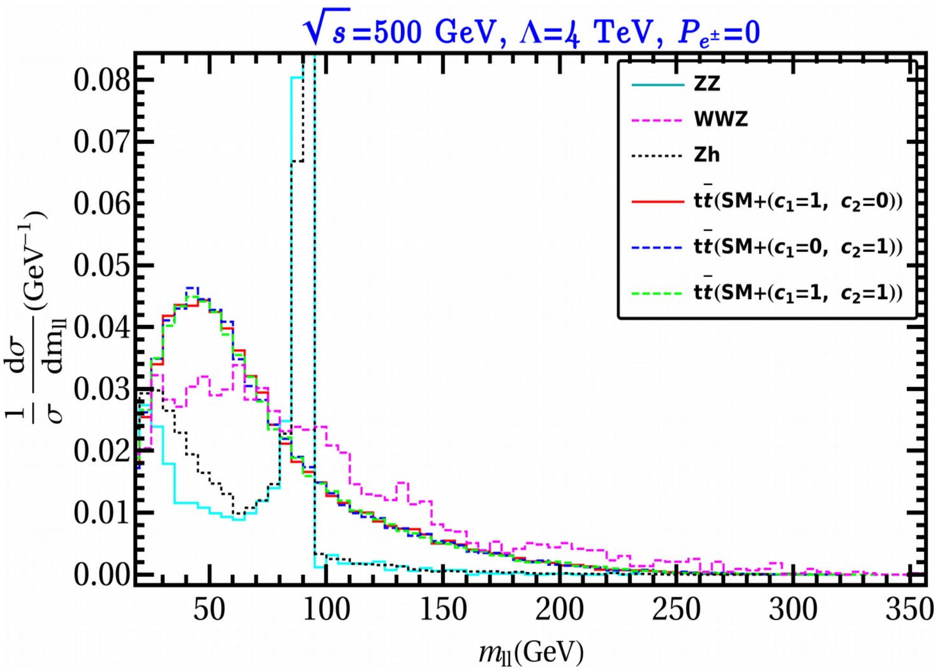
Linearly Independent

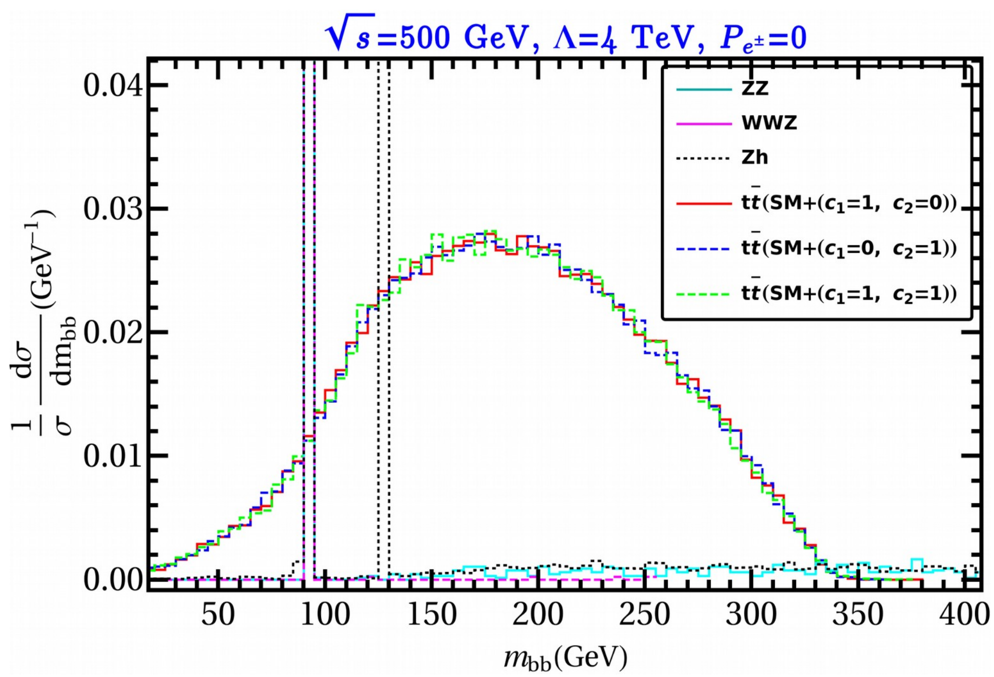
Event analysis:





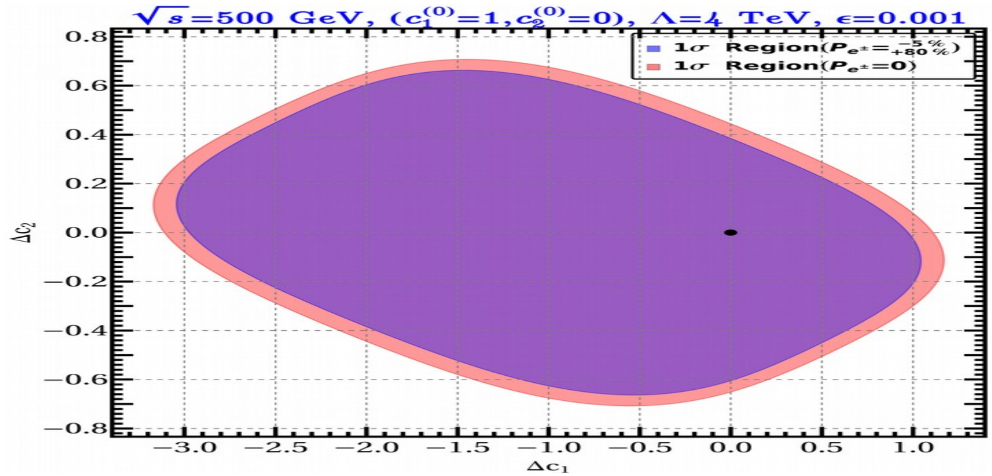
Final state signal → $2\ell 2b$ + missing energy

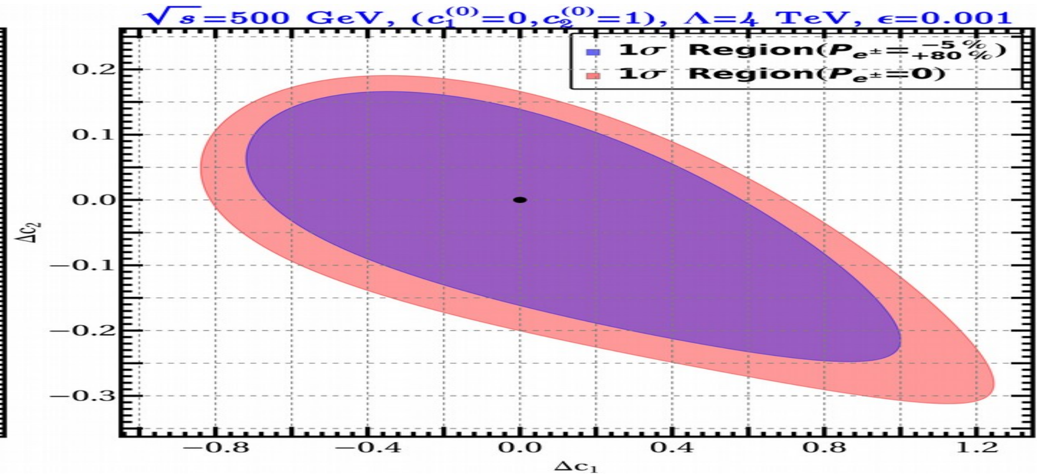


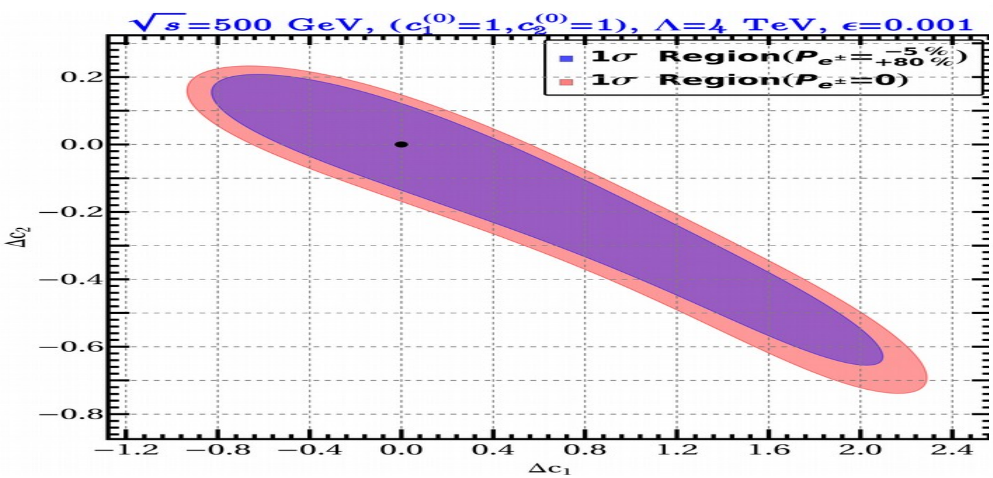


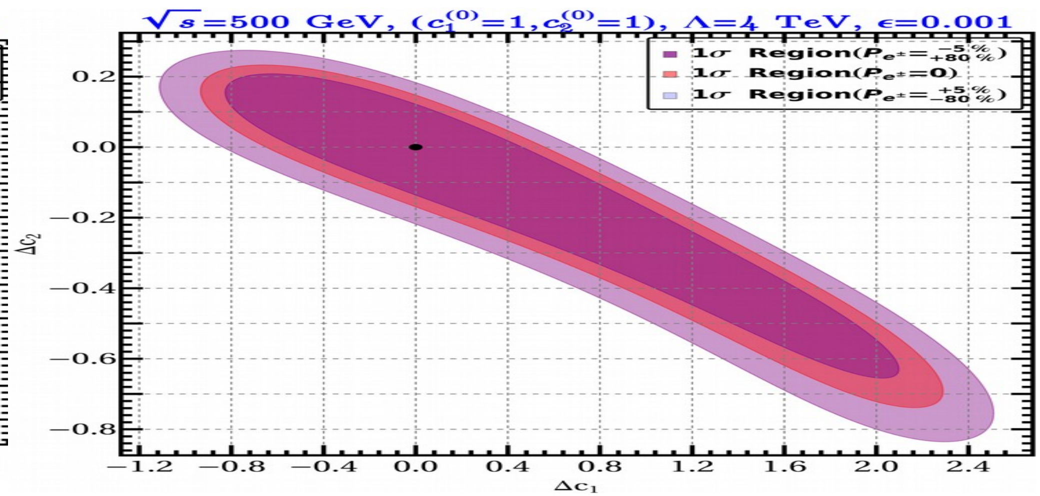
Efficiency factor (ϵ):~0.001

1σ regions:









- Tensor coupling is more precise than scalar couplings.
- Beam polarizations help to estimate the coupling more precisely.

Distinction of hypotheses:

Base Model

SM

$c_1^0 = 0,\ c_2^0 = 0$

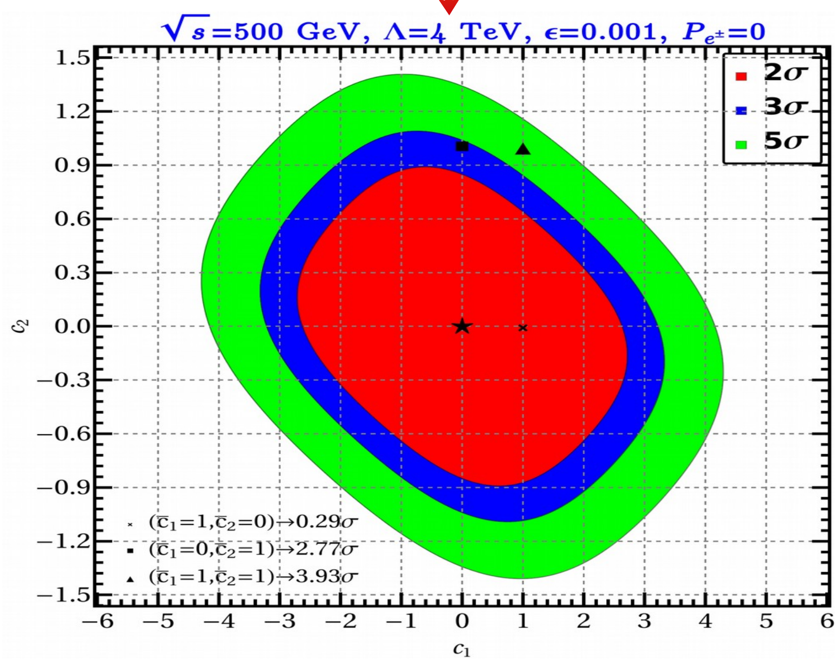
Hypotheses

$\bar{c}_1 = 1,\ \bar{c}_2 = 0$

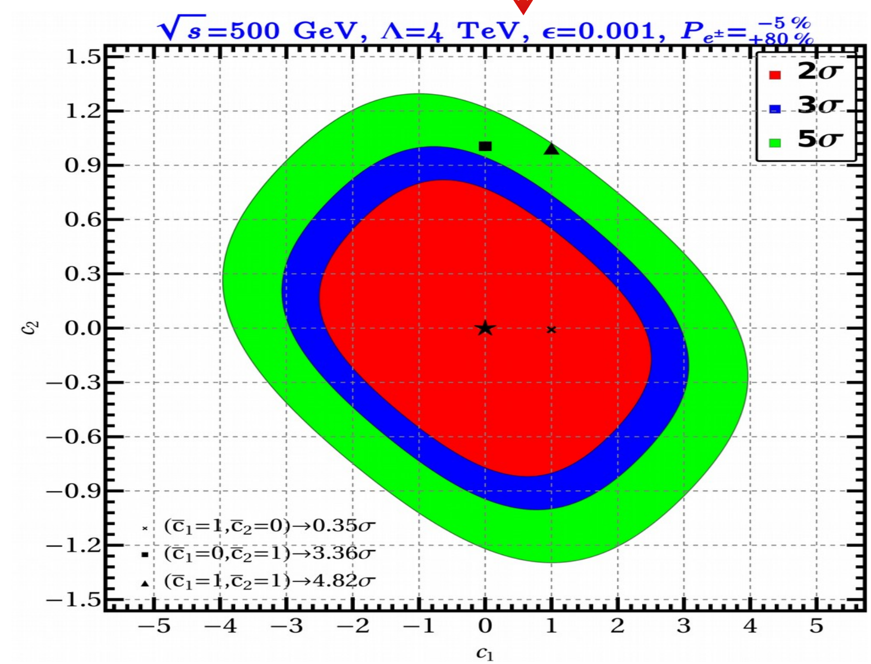
$\bar{c}_1 = 0,\ \bar{c}_2 = 1$

$\bar{c}_1 = 1,\ \bar{c}_2 = 1$

Unpolarized beam



Polarized beam



UV Completion of EFT operator:

- We have discussed the probe of EFT operators for O(1) couplings with NP scale ~ 4 TeV with CM energy 500 GeV.

- If CM energy is **greater** than the NP scale then we can probe the NP directly.

- Scalar operator can be gerenrated by integrating out the heavy scalars in 2 Higgs Doublet Model.

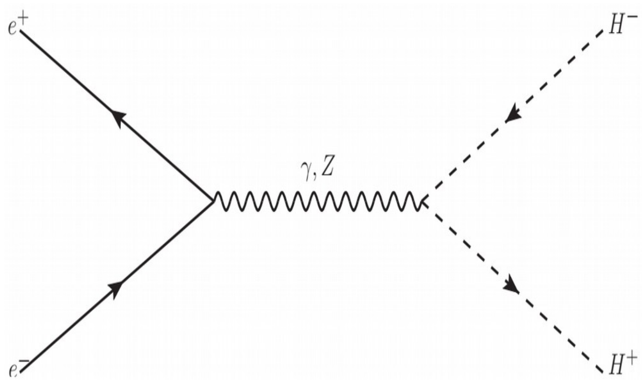
- Next, we probe charged higgs couplings through charged scalar pair production that falls into **BSM dominance scenario**.

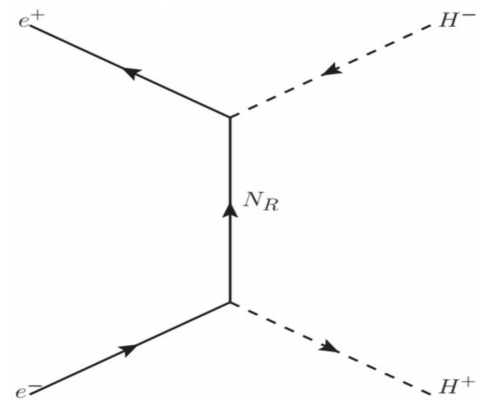
Gauge and Yukawa couplings with $H^{\pm}$:

Gauge Couplings: $\begin{cases} H^+H^-\gamma : -ie_0(p^\mu_{H^+} - p^\mu_{H^-}) \\ H^+H^-Z : -ia(P^\mu_{H^+} - P^\mu_{H^-}) \end{cases}$

Yukawa Coupling: $e^+ N_R H^- : b$

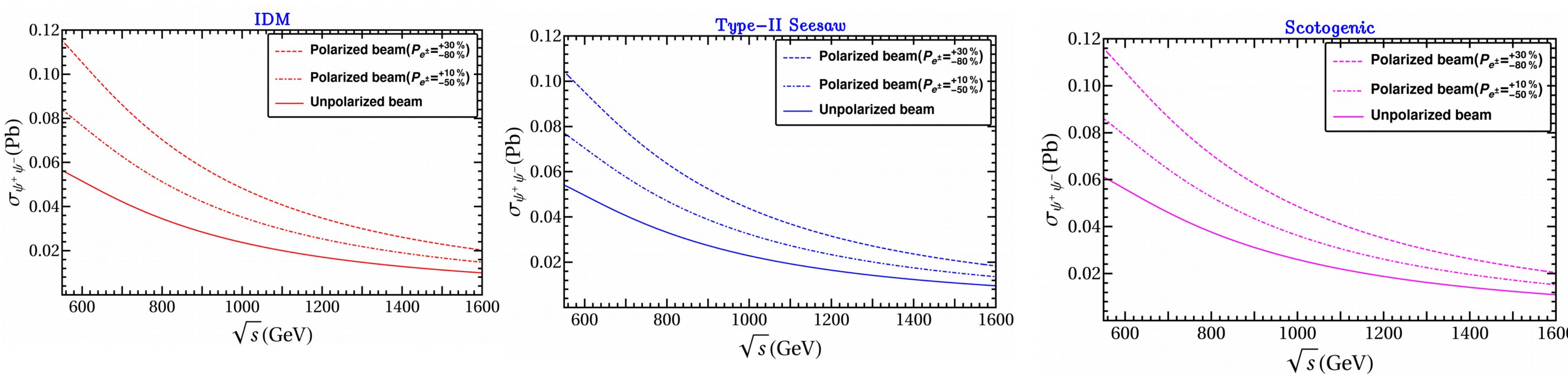
Models:
- Inert doublet (a=0.21, b=0)
- Type-II seesaw (a=0.17, b=0)
- Scotogenic (a=0.21, b=0.1)



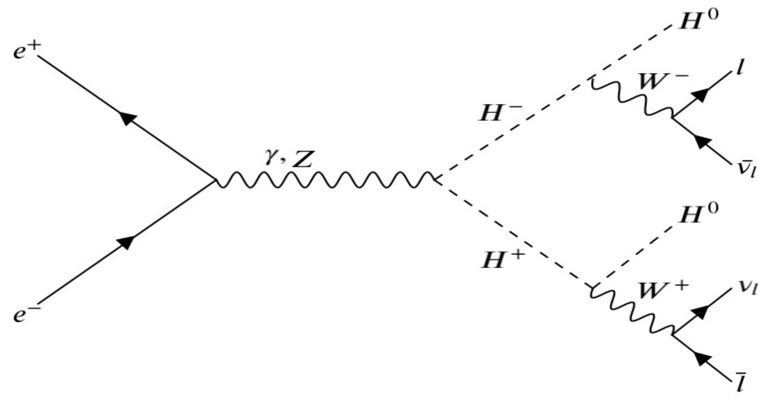


$$P_{e^-} = -80\%$$
$$P_{e^+} = +30\%$$

Helicity amplitude: $M(\lambda, -\lambda) = i\left[e_0^2 + ae_0\left(\frac{4s_w^2 - 1}{2s_{2w}} - \lambda\frac{1}{2s_{2w}}\right)\frac{s}{s - m_Z^2} + \frac{(1+\lambda)b^2}{4}\frac{s}{t - m_N^2}\right]\beta_{H^+}\sin\theta$



Event analysis:



Final state: $\ell^+\ell^-$+ missing energy

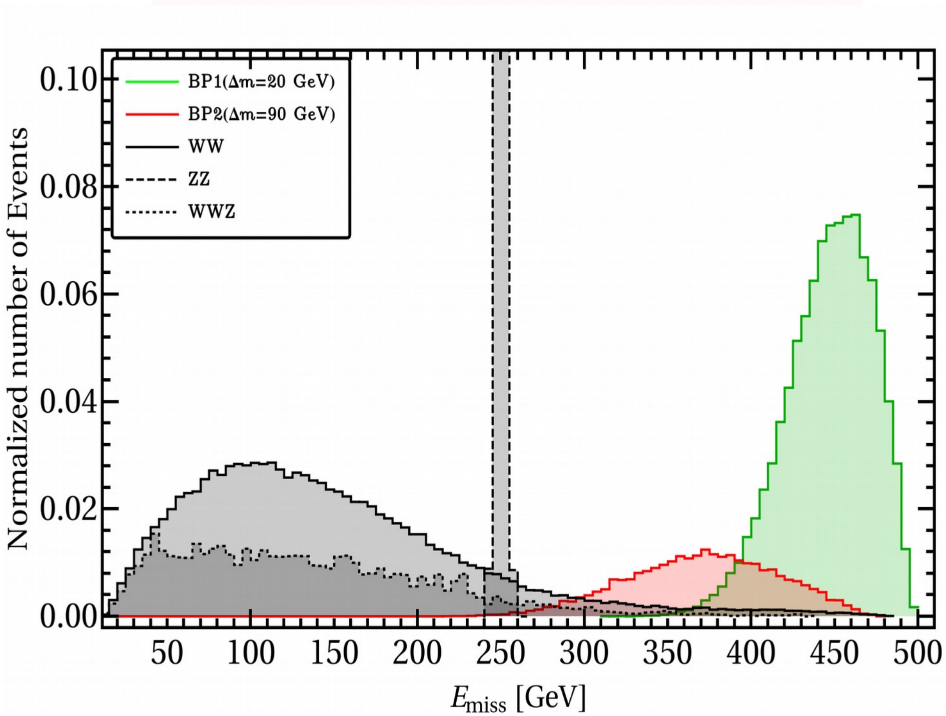
Cut flows:

$\mathcal{C}_1$: Events with 2 leptons

$\mathcal{C}_2$: $\not{E} \leq 370\,(300)$ for BP1 (BP2)

$$\text{Missing Energy } (\not{E}) = \sqrt{s} - \sum_i E_i^{\text{vis}}$$

Missing energy distribution



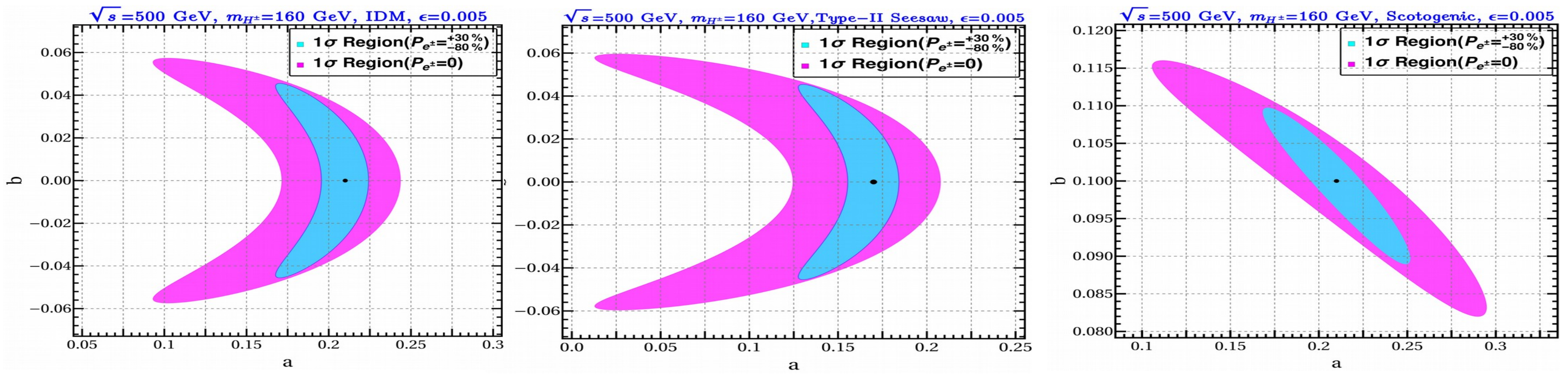
Efficiency factor (ϵ)

$$\epsilon = \frac{\sigma^{\text{FS}}}{\sigma^{\text{prod}}} = 0.015$$

Our choice

$$\epsilon \sim 0.005$$

1σ regions:



- Beam polarization plays crucial role to reduce the uncertainty in NP couplings.

- In case of BSM dominace, estimation of NP couplings are much better.

<u>Chapter-IV</u> (OOT in presence of SM background)

based on

Optimal New Physics estimation in presence of Standard Model background,

S. Bhattachrya, **S. Jahedi**, J. Lahiri, J. Wudka

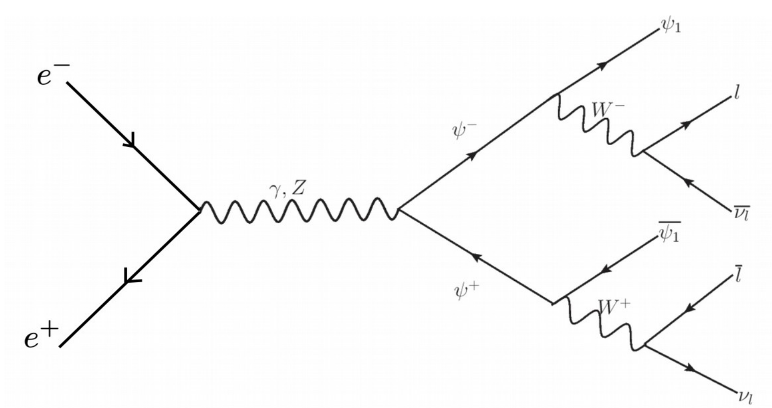
(In progress)

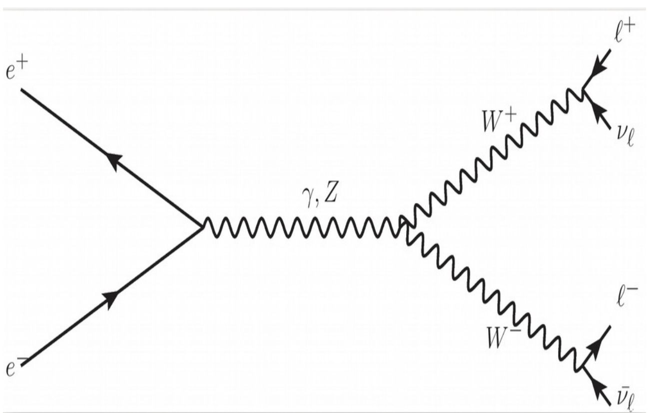
Signal and backgrounds:

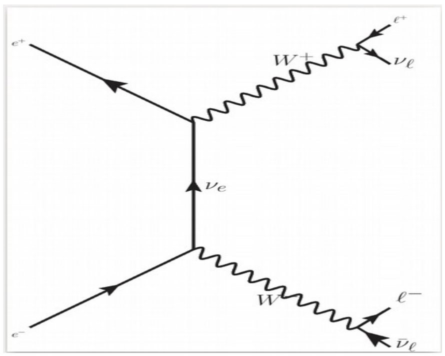
- Previous works are based on signal only hypothesis.
- We propose OOT in presence of SM backgrounds.

WW background

Singlet-doublet model: $\psi^{\pm}, \psi_1 \text{ and } \psi_2$



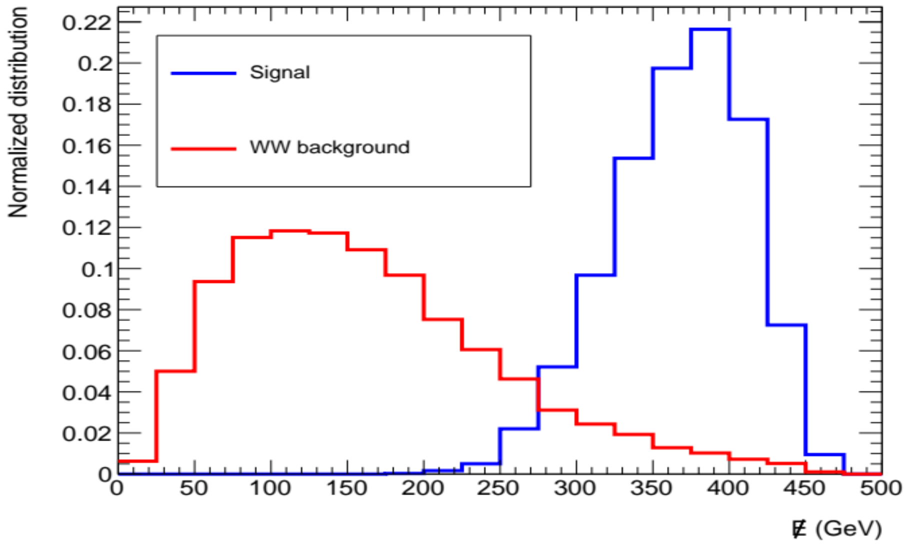




Final state signal: $\ell^+\ell^-$+ missing energy

Gradual background reduction:

Missing energy distribution

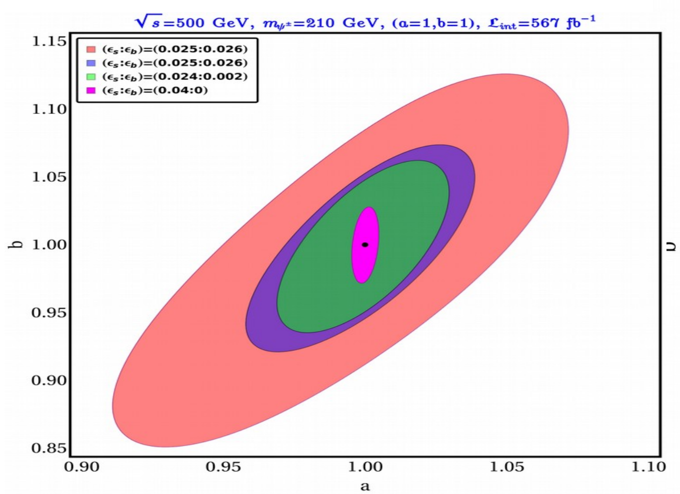


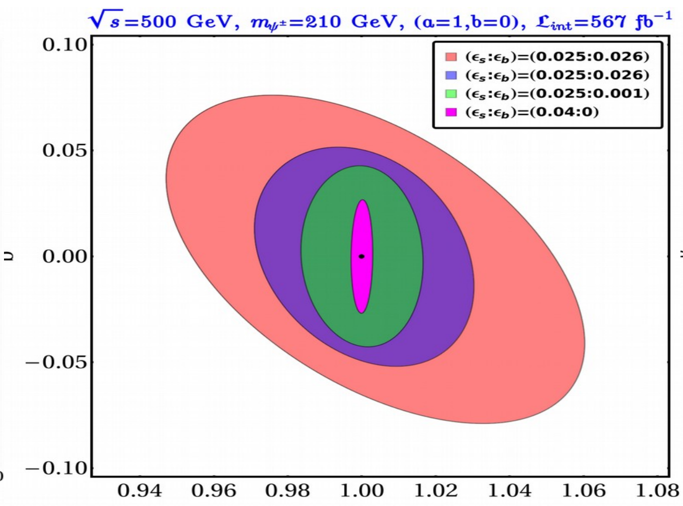
Cut flows:

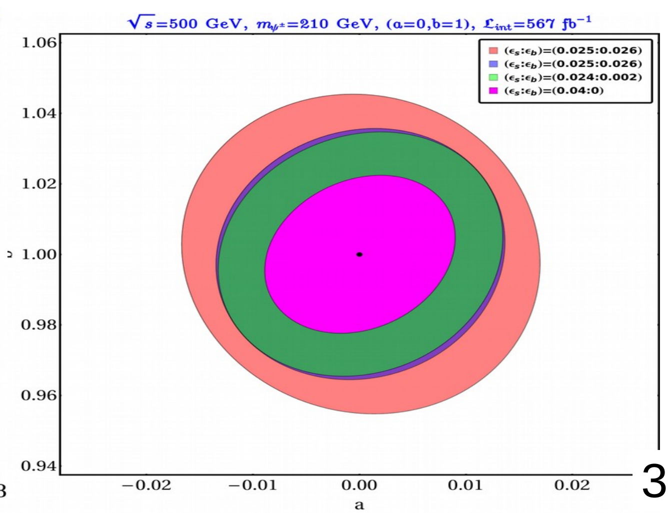
$\mathcal{C}_1$: Events with 2 leptons & $m_{\ell\ell} < |m_Z - 15|$ GeV

$\mathcal{C}_2$: $\not{E} > 225$ GeV

$\mathcal{C}_3$: $\not{E} > 325$ GeV

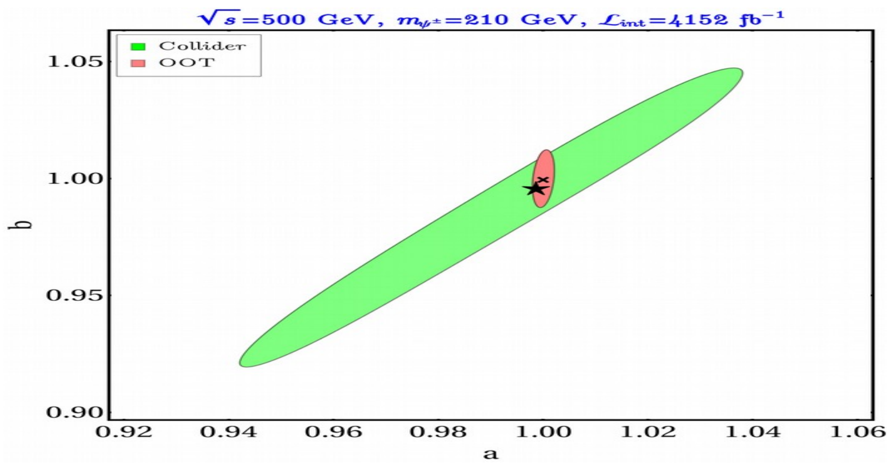




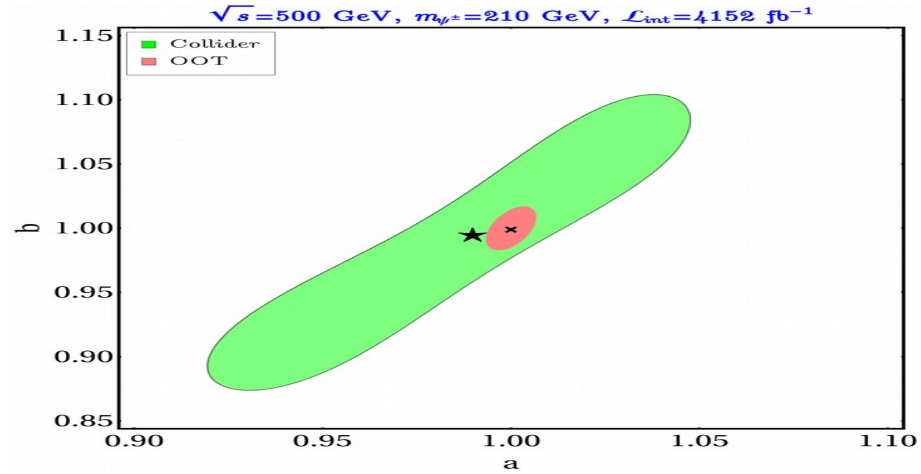


How OOT is better than Binned analysis:

i) Only signal

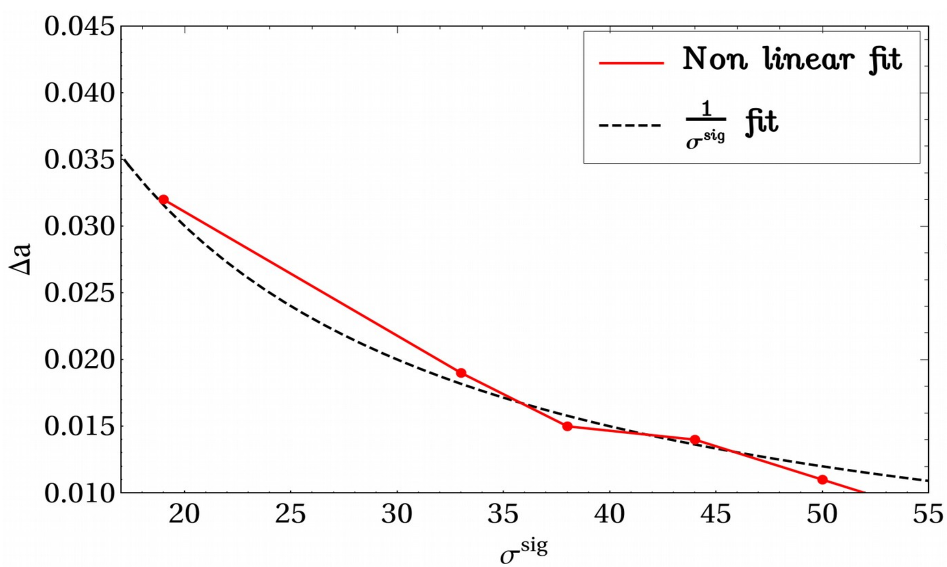


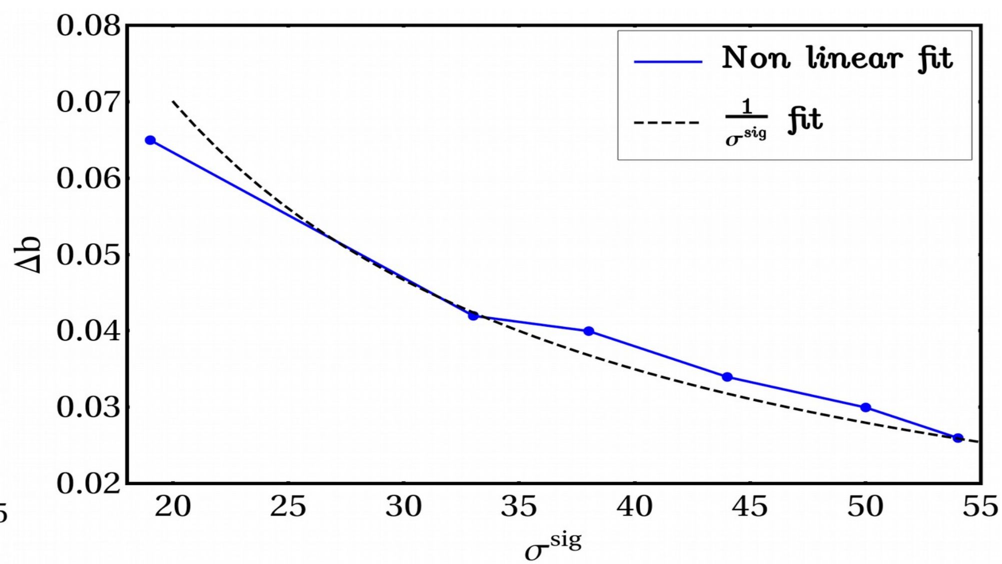
ii) signal+bkg



OOT sensitivity vs collider significance:

$$\boxed{\frac{\Delta g_1}{g_1} = \frac{\sqrt{S+B}}{S} = \frac{1}{\sigma^{\mathrm{sig}}}.}$$





Summary:

- OOT guides us to extract the **optimal** uncertainties of NP parameters and helps us to distinguish one model from another model.

- Beam polarization and luminosity play a crucial role to estimate NP couplings and segregate a hypothesis from a base model.

- In case of BSM dominated scenario, estimation of NP couplings are better.

- The more efficient the background reduction is, the more precise the uncertainties.

- OOT provides a better estimation of NP physics couplings compared to binned analysis.


THANK
YOU !