Constraining Higher Dimensional Operators in H to four leptons with off-shell production

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based on
arxiv:1403.4951
with J.Gainer, J. Lykken, K. Matchev and S. Mrenna

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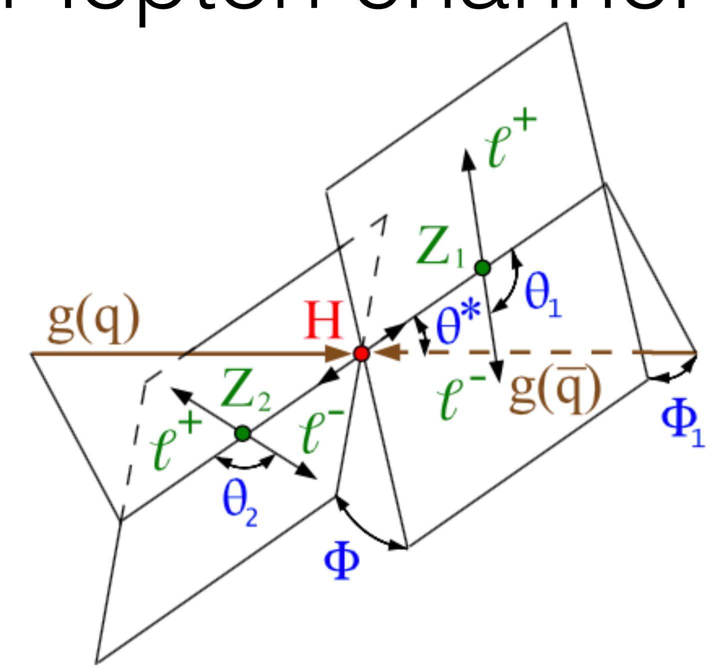
Higgs as an old story

- Long long time ago, we finally discovered a spin 0, CP-“even” particle whose mass ~ 125GeV in clean four leptonic signals (+ diphoton).
- To study a tensor structure of coupling for Higgs, CMS/ATLAS have utilized four-lepton channel @ Higgs on-shell mass window.



What else can we talk about Higgs measurement more than this?

- We will have LHC Run 2 with 14TeV and possibly FCCs (Future Circular Colliders)…
- With more energy, can we buy something else???

  (We take procedures into a level of experimentally achievable.)

- To study Higgs properties without prejudice, one can follow bottom up approach using general scattering amplitude,

$$\begin{aligned} A(H \to Z_1 Z_2) \quad = \quad & c_1(\epsilon_1^* \cdot \epsilon_2^*) + c_2(p_1 \cdot p_2)(\epsilon_1^* \cdot \epsilon_2^*) \\ & + c_3(p_1 \cdot \epsilon_2^*)(p_2 \cdot \epsilon_1^*) + c_4 \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\mu} \epsilon_2^{*\nu} p_1^\rho p_2^\sigma \\ & + c_5(p_1^2 + p_2^2)(\epsilon_1^* \cdot \epsilon_2^*) \end{aligned}$$

- Or using effective Lagrangian approach (here up to dim 5)

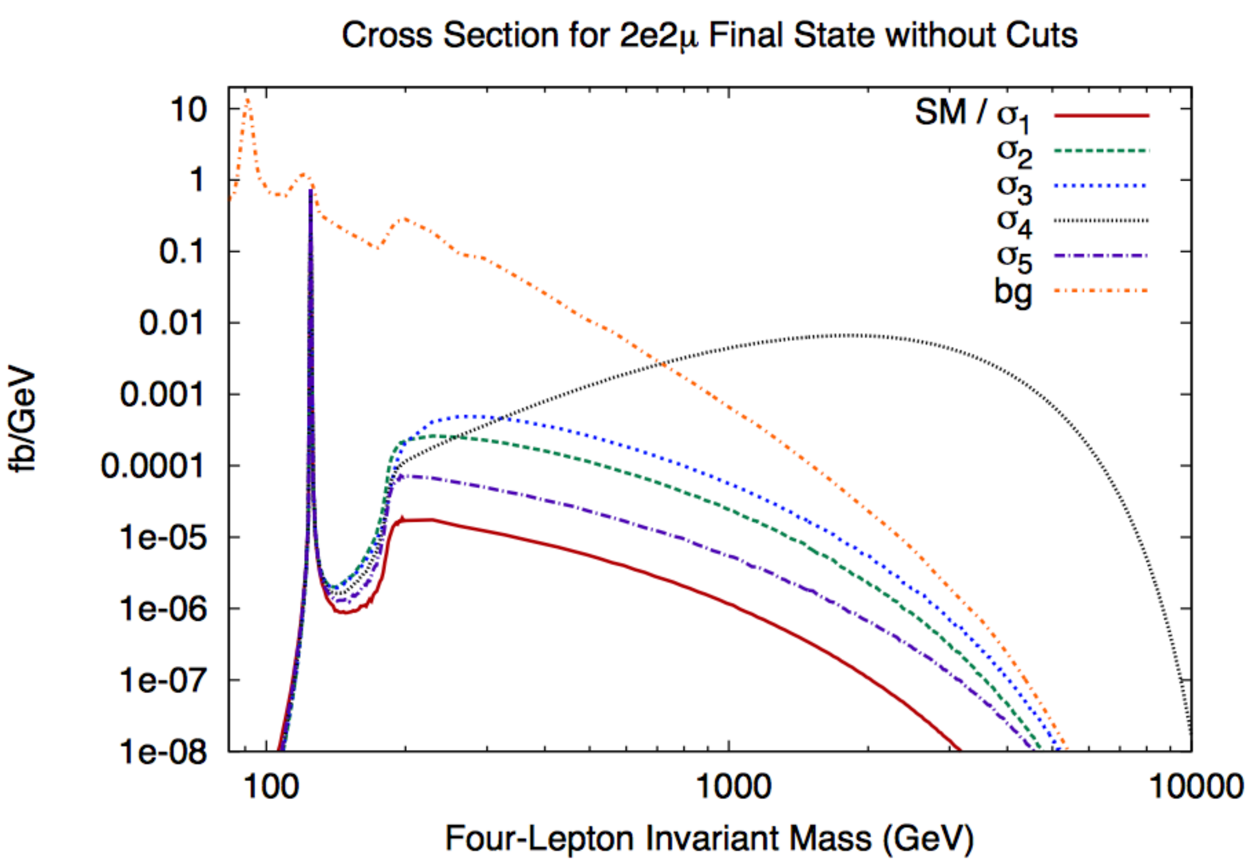
$$\mathcal{L} \supset \sum_{i=1}^{5} \kappa_i \mathcal{O}_i = -\kappa_1 \frac{m_Z^2}{v} X Z_\mu Z^\mu - \frac{\kappa_2}{2v} X F_{\mu\nu} F^{\mu\nu} - \frac{\kappa_3}{2v} X F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{\kappa_4 m_Z^2}{M_X^2 v} \Box X Z_\mu Z^\mu + \frac{2\kappa_5}{v} X Z_\mu \Box Z^\mu$$

- They are connected as
  - General amplitude is expressed in 5-d operator space.
- κ_4 operator is the same as κ_1 at the Higgs resonant point!

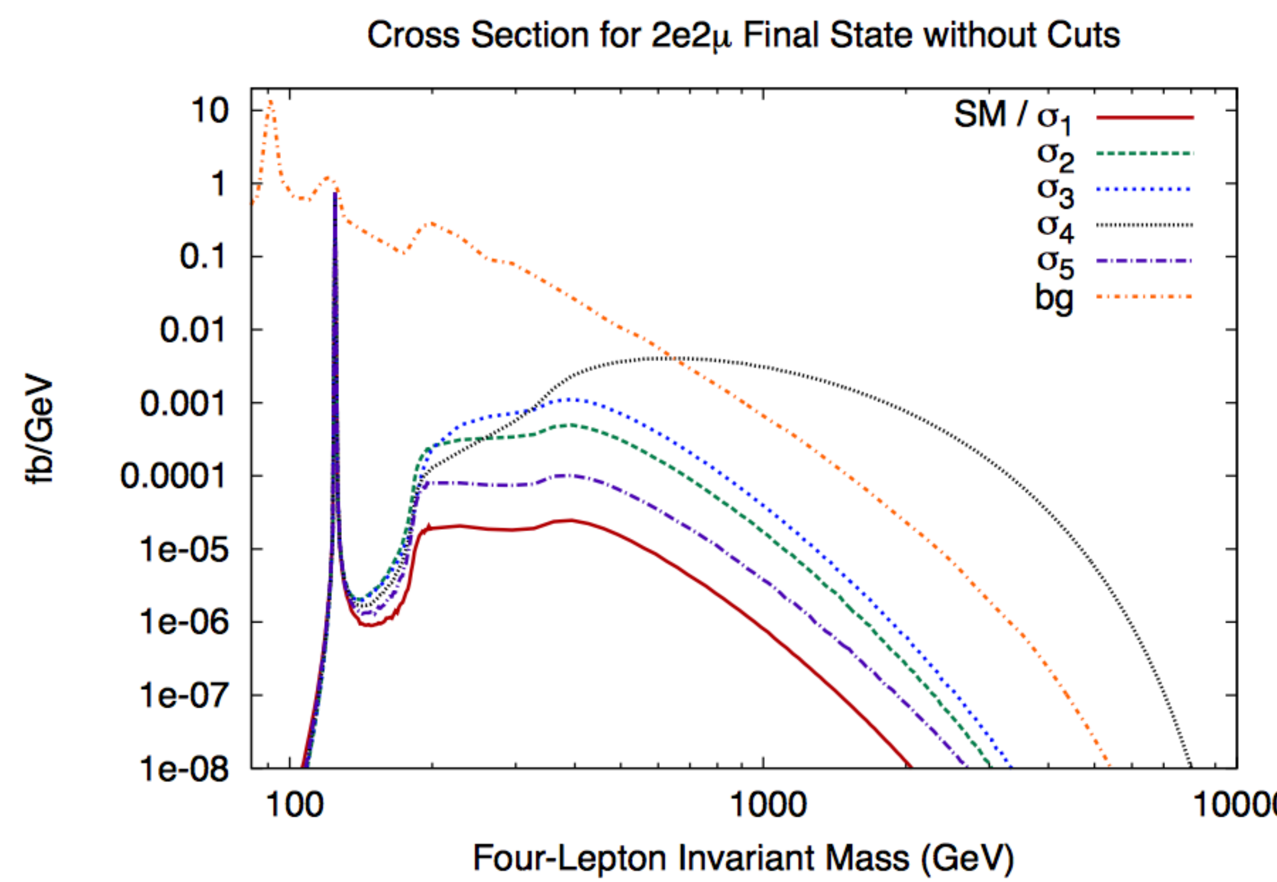
$$\begin{aligned} i\ \epsilon_1^* \cdot \epsilon_2^* \quad & \Longleftrightarrow \quad -\frac{1}{2} X Z_\mu Z^\mu, \\ i\ (p_1 \cdot p_2)(\epsilon_1^* \cdot \epsilon_2^*) \quad & \Longleftrightarrow \quad \frac{1}{2} X \partial_\mu Z_\nu \partial^\mu Z^\nu, \\ i\ (p_1 \cdot \epsilon_2^*)(p_2 \cdot \epsilon_1^*) \quad & \Longleftrightarrow \quad \frac{1}{2} X \partial_\mu Z_\nu \partial^\nu Z^\mu, \\ i\ \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*,\mu} \epsilon_2^{*,\nu} p_1^\rho p_2^\sigma \quad & \Longleftrightarrow \quad -\frac{1}{2} \epsilon_{\mu\nu\rho\sigma} \partial^\mu Z^\nu \partial^\rho Z^\sigma, \\ i\ (p_1^2 + p_2^2)(\epsilon_1^* \cdot \epsilon_2^*) \quad & \Longleftrightarrow \quad X Z_\mu \Box Z^\mu, \end{aligned}$$

- Thus, previous CMS/ATLAS analysis can not have a sensitivity for κ_4 (or along the κ_4-direction). To probe this operator we need to go beyond the resonant, i.e. off-shell production of Higgs.

- One concern is the production of Higgs, since we need to consider ggH coupling in non-resonant region

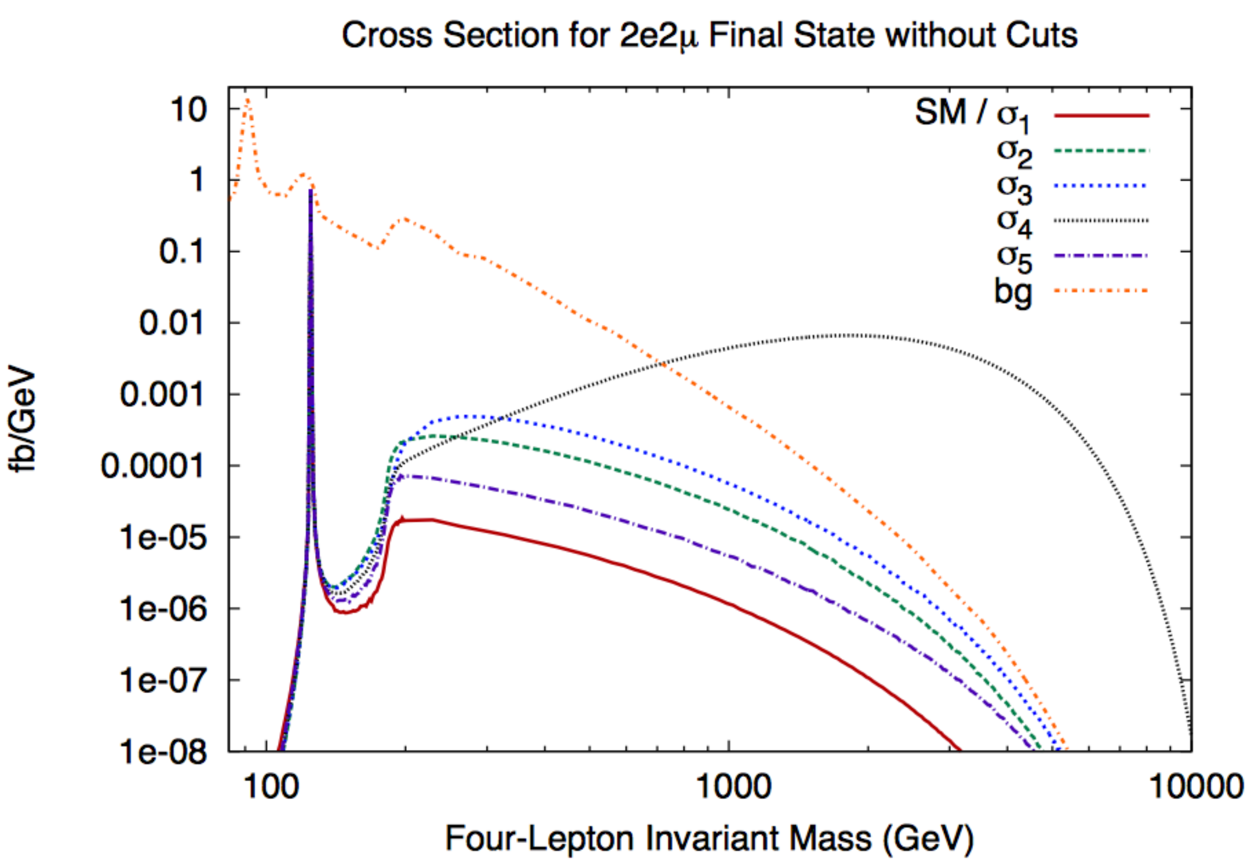


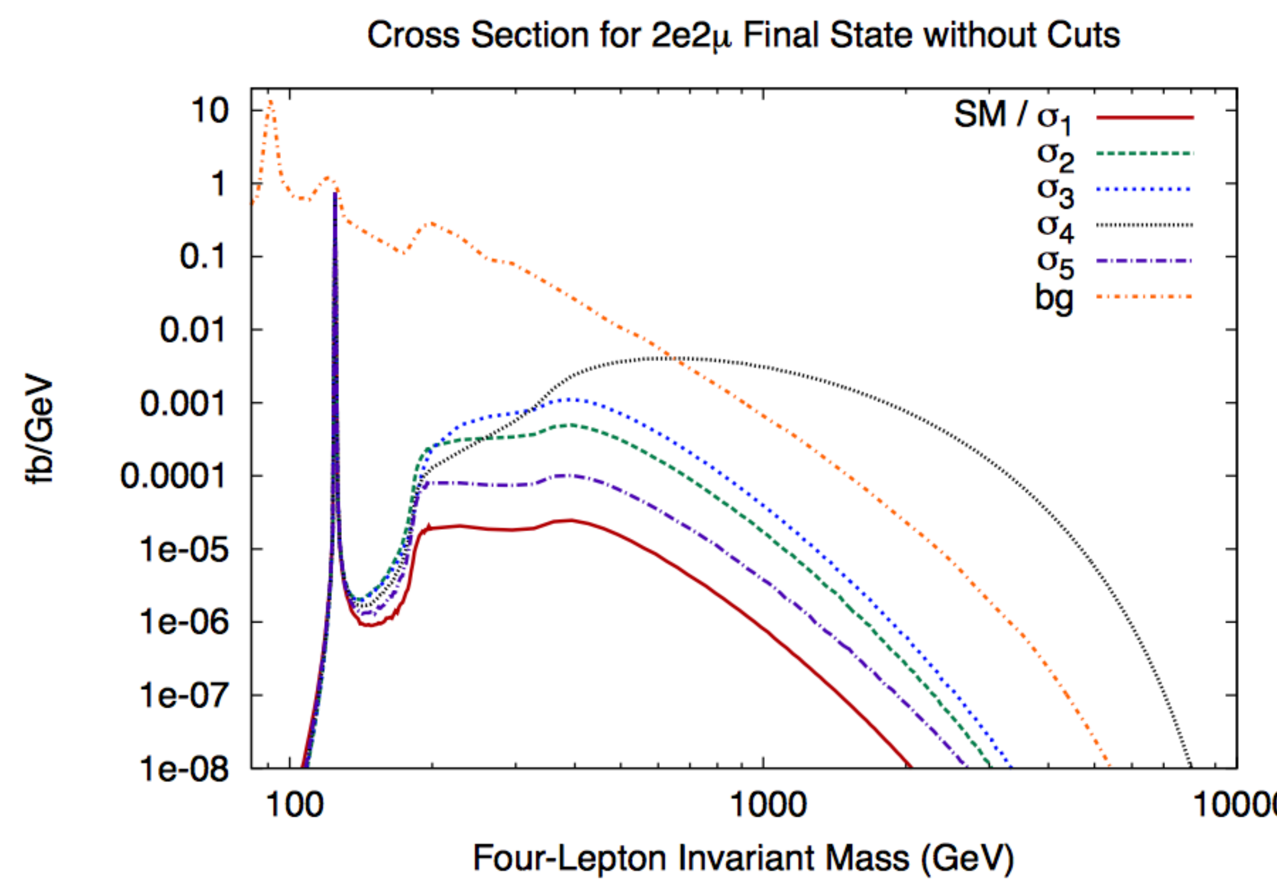
$$g_{ggX}(M_{4\ell}) = g_{ggX}(M_X)$$



$$g_{ggX}(M_{4\ell}) = \frac{\alpha_s(M_{4\ell})}{4\pi v}\sum_Q A^H_{1/2}(\tau_Q)$$

Operator	$\sigma > M_X$, fixed g_{ggX}	$\sigma > 250$ GeV, fixed g_{ggX}	$\sigma > M_X$, $g_{ggX}(M_{4\ell})$	$\sigma > 250$ GeV, $g_{ggX}(M_{4\ell})$
$\mathcal{O}_1$	0.005	0.004	0.009	0.008
$\mathcal{O}_2$	0.099	0.083	0.171	0.152
$\mathcal{O}_3$	0.206	0.186	0.366	0.341
$\mathcal{O}_4$	18.2	18.2	4.54	4.53
$\mathcal{O}_5$	0.023	0.018	0.037	0.032
LO BG	38.8	13.1	38.8	13.1





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- One more concern is the effect of Z-boson offshell especially operator k5 (that depends on the momentum of Z-boson strongly)

$$i\,(p_1^2 + p_2^2)(\epsilon_1^* \cdot \epsilon_2^*) \quad \Longleftrightarrow \quad X Z_\mu \Box Z^\mu$$

- We can understand this Z-boson off-shell contribution by

$$\sum_{\lambda=t_1,t_2,l,s} \epsilon_\mu^\lambda(p)\epsilon_\nu^\lambda(p) = -\eta_{\mu\nu} + \frac{p_\mu p_\nu}{m^2},$$

$$\begin{aligned}
\epsilon_\mu^{t_1}(p) &= (0, \cos\theta\cos\varphi, \cos\theta\sin\varphi, -\sin\theta)\ , \\
\epsilon_\mu^{t_2}(p) &= (0, -\sin\varphi, \cos\varphi, 0)\ , \\
\epsilon_\mu^{l}(p) &= \frac{1}{\sqrt{p^2}}\left(|\vec{p}|\ , p_0\frac{\vec{p}}{|\vec{p}|}\right)\ , \\
\epsilon_\mu^{s}(p) &= \sqrt{\frac{p^2 - m^2}{p^2 m^2}}\,p_\mu\ ,
\end{aligned}$$

- with polarisation vectors, where s component is for the off-shell vector boson, usually 0 for the on-shell vector boson.

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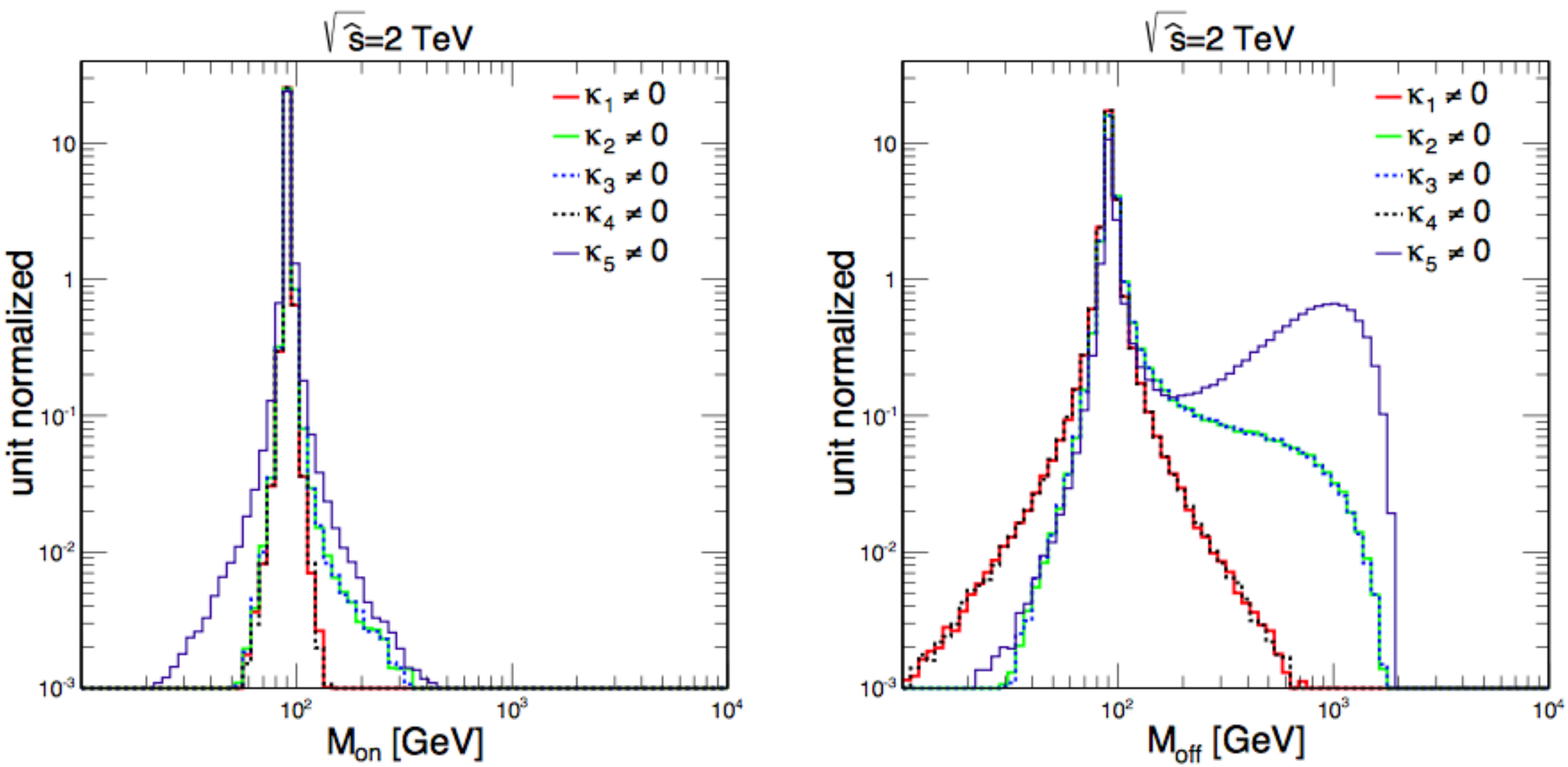
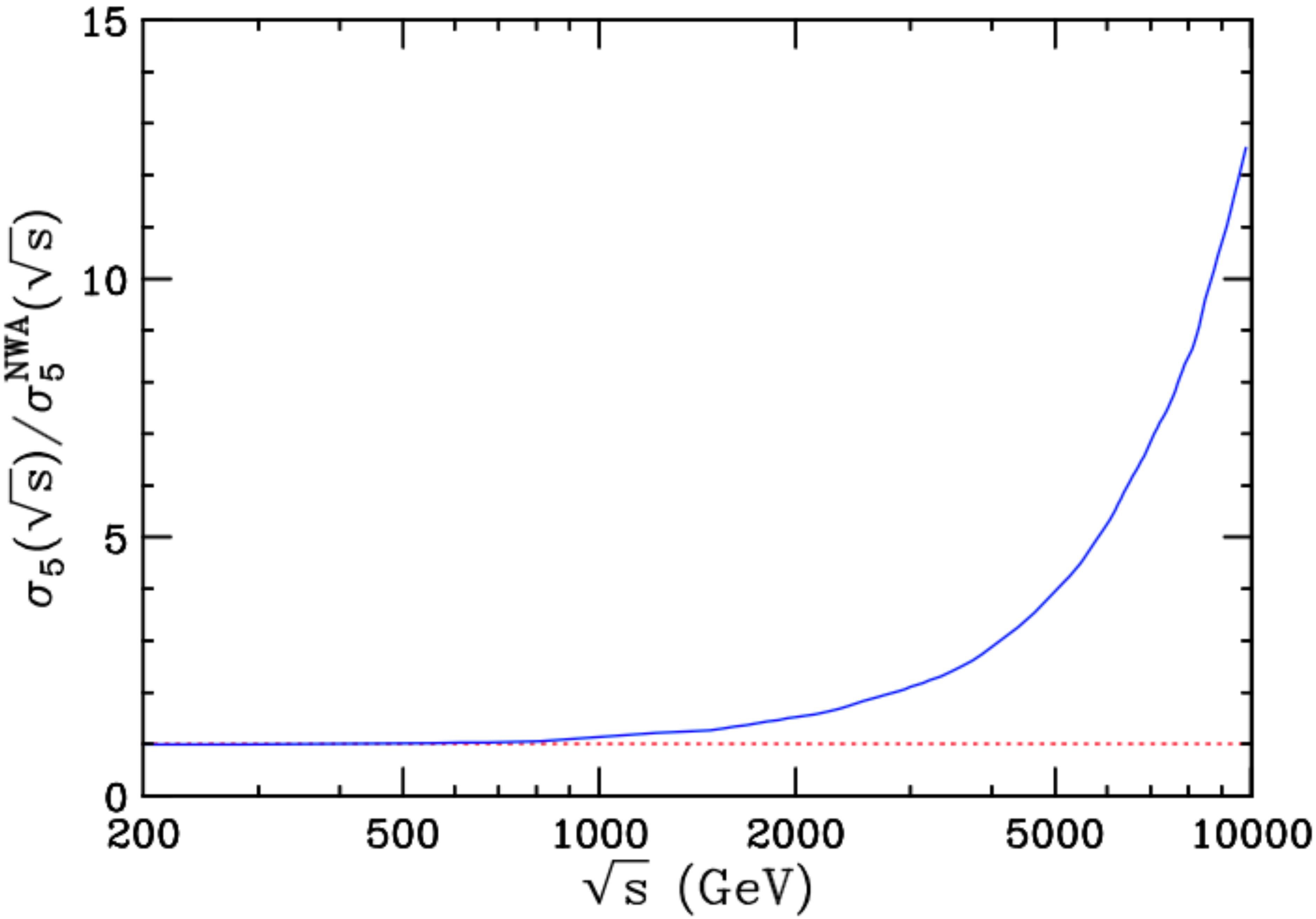


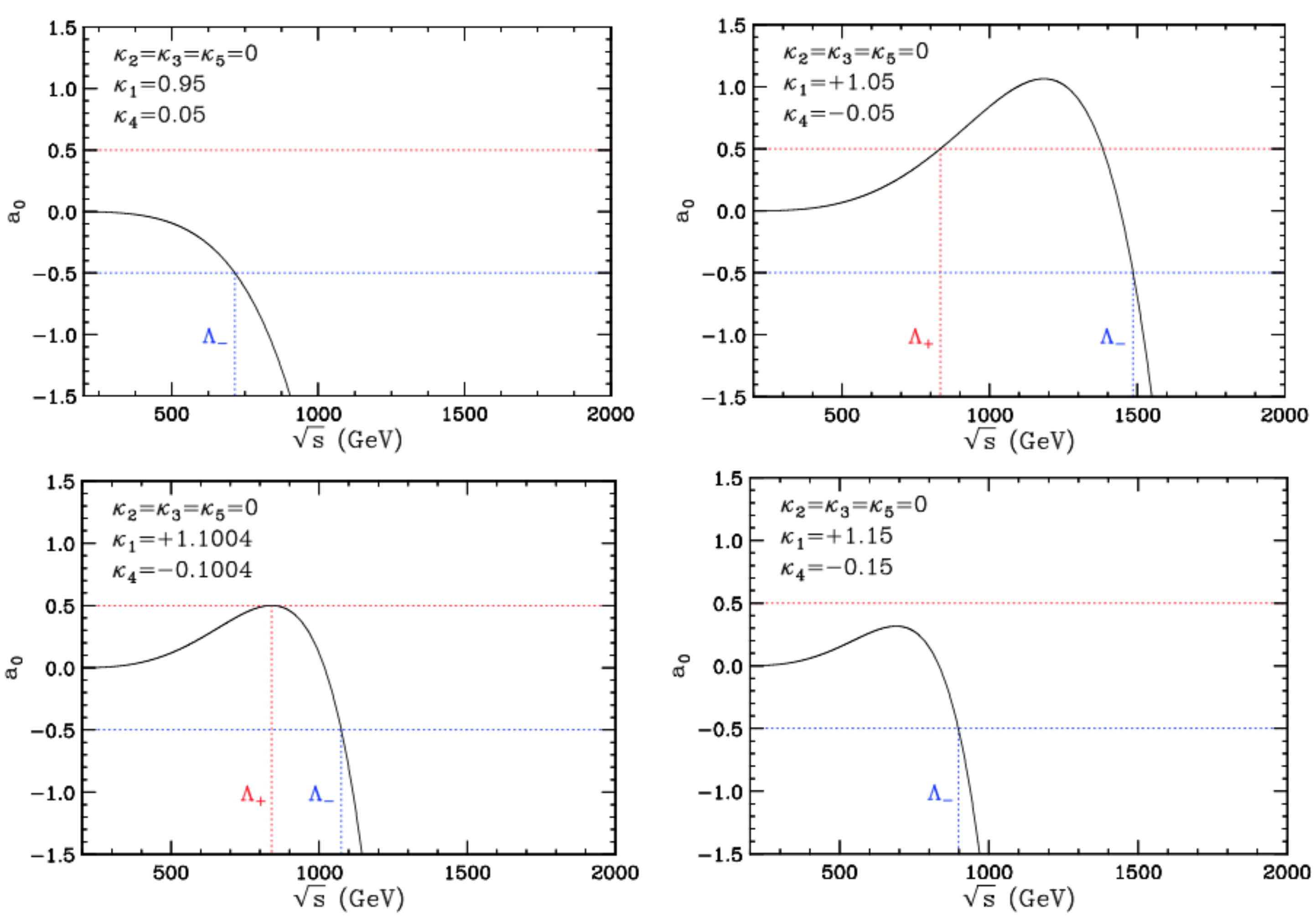
- Thus we can not use NWA to calculate LO cross section, especially for kappa5 operator.

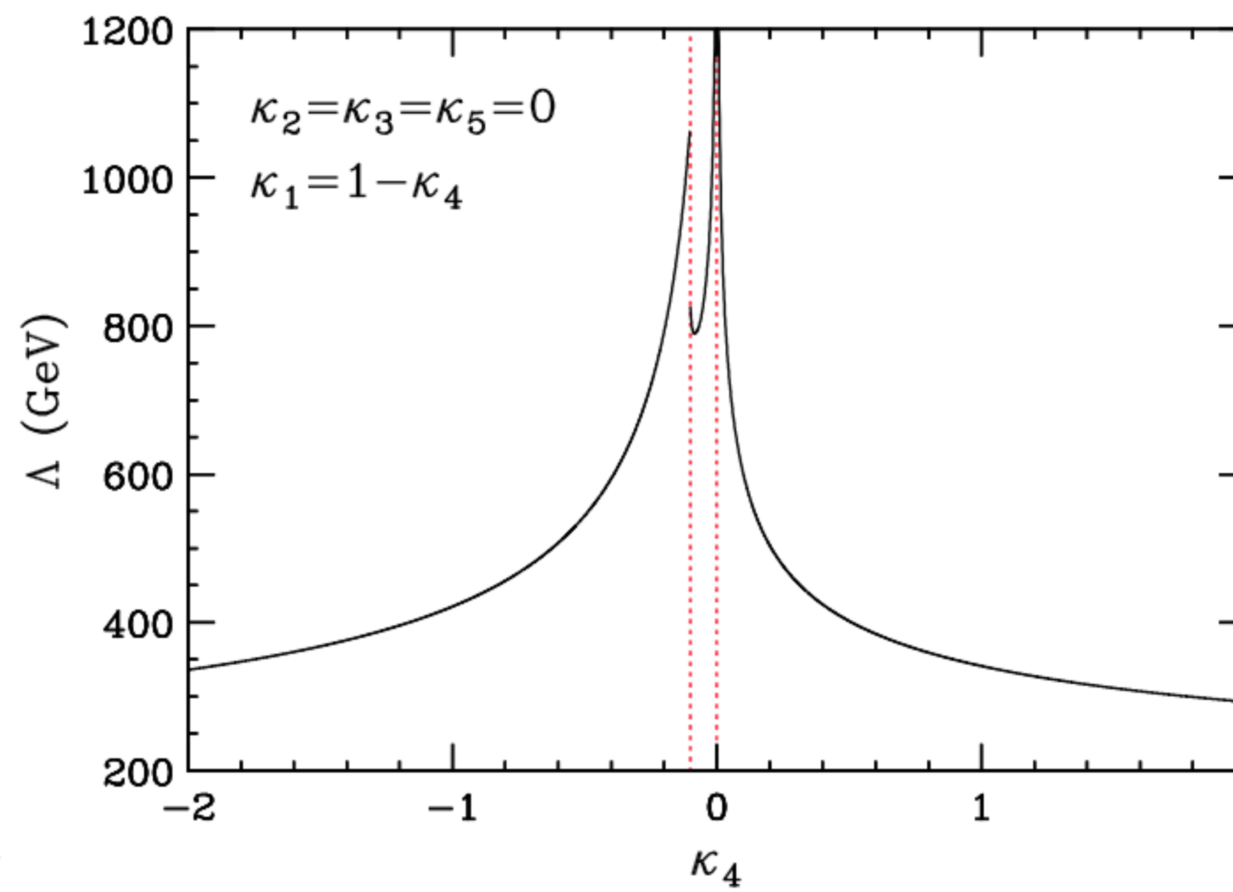


- Another issue is the unitarity bound for O4.
- Based on XZZ analysis, we consider $Z_L Z_L \to Z_L Z_L$

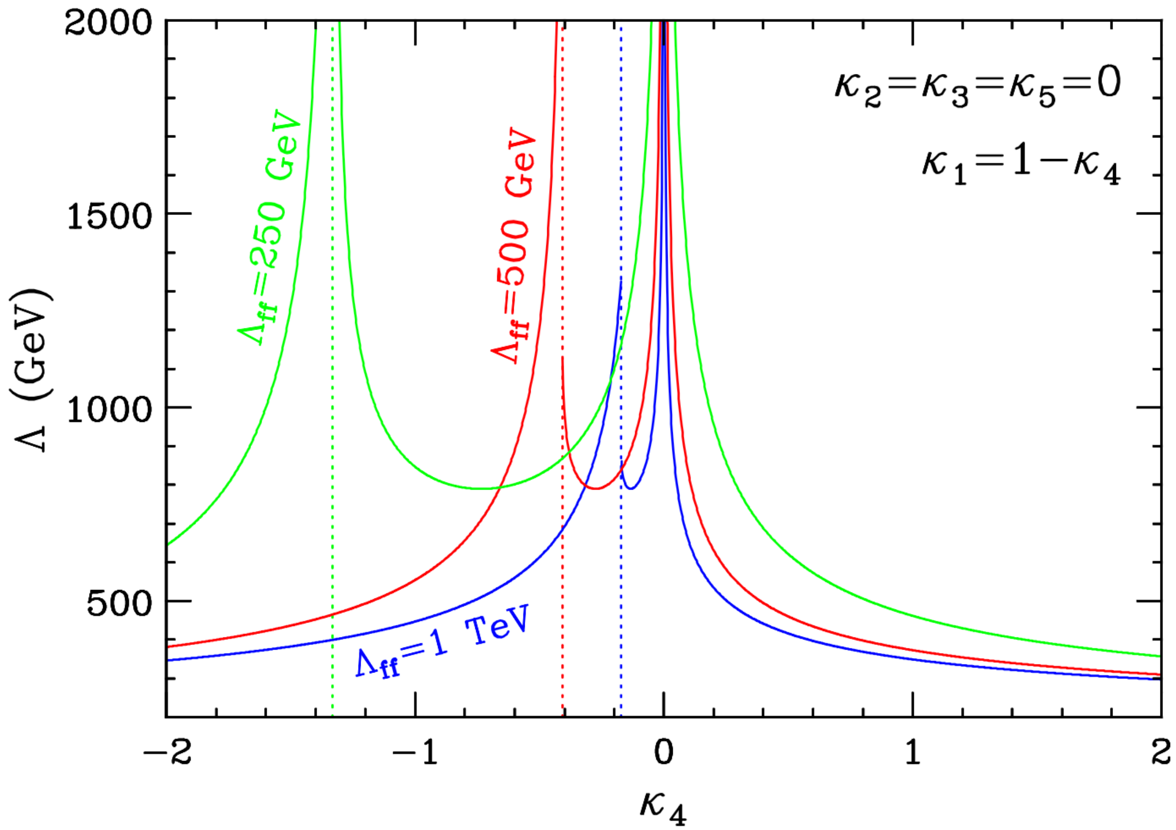
$$a_0(s) = \left(\frac{M_X^2}{32\pi v^2}\right)\left[\frac{(s/M_X^2)^2}{6}\left((10-3s/M_X^2)\kappa_4^2-20\kappa_4\right)-\left(3+\frac{M_X^2}{s-M_X^2}-\frac{2M_X^2}{s}\log\left(1+\frac{s}{M_X^2}\right)\right)\right]$$

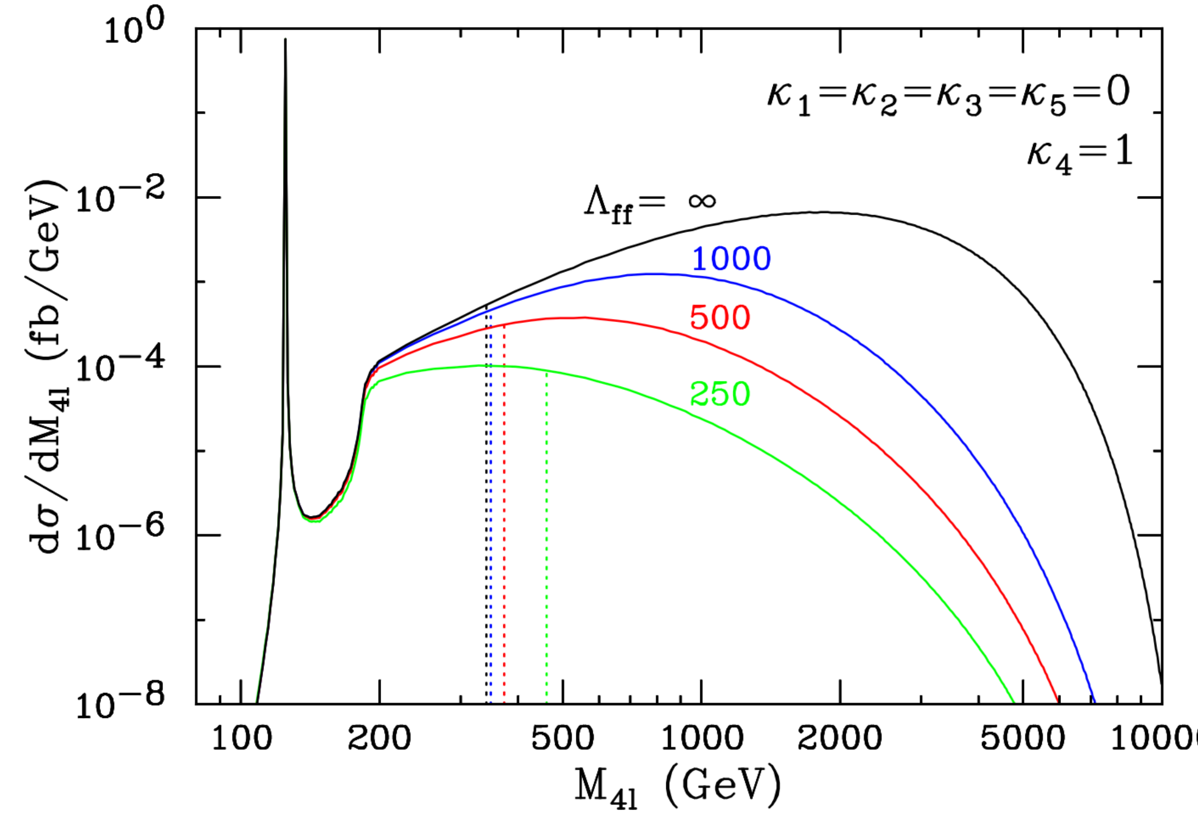
(here with kappa1 =1-kappa4)





- another approach is to use a "form" factor, $\kappa_4 \to \frac{1+M_X^2/\Lambda_{ff}^2}{1+s/\Lambda_{ff}^2} \times \kappa_4$





Λ_{ff} (GeV)	Λ (GeV)	$\sigma > M_X$, all $M_{4\ell}$ (fb)	$\sigma > M_X$, for $M_{4\ell} \leq \Lambda$ (fb)
∞	341.3	18.205 (4.544)	0.044 (0.065)
1000	349.2	1.526 (1.435)	0.043 (0.065)
500	373.0	0.333 (0.472)	0.038 (0.065)
250	461.8	0.064 (0.107)	0.026 (0.053)

with fixed ggX, (varying ggX)

cross section for SM ~ 0.009fb

LHC may be sensitive ultimately to an off-shell cross section 5 to 10 times greater than the SM value

- Back to onshell study, we can simply estimate the number of required events to probe the different coupling structure, by calculating the likelihood difference among different hypothesis,

$$\langle \Delta \log \mathcal{L} \rangle_{SM} = \left\langle \log \left[\left(\frac{\sigma_1}{\sigma_{\{\kappa_i\}}} \right) \left(\frac{d\sigma_{\{\kappa_i\}}}{d\mathbf{x}} \Big/ \frac{d\sigma_1}{d\mathbf{x}} \right) \right] \right\rangle_{SM} .$$

for example,

$$\frac{\Gamma_B}{\Gamma_A} = \frac{1}{\Gamma_A} \int \frac{d\Gamma_B}{d\mathbf{x}} d\mathbf{x} = \int \left(\frac{d\Gamma_B}{d\mathbf{x}} \Big/ \frac{d\Gamma_A}{d\mathbf{x}} \right) \left(\frac{d\Gamma_A}{d\mathbf{x}} \Big/ \Gamma_A \right) d\mathbf{x} = \left\langle \left(\frac{d\Gamma_B}{d\mathbf{x}} \Big/ \frac{d\Gamma_A}{d\mathbf{x}} \right) \right\rangle_A$$

$$\begin{aligned}
\chi_{11} &= (3+x)\left(\frac{M_Z^2}{M_{Z_1}M_{Z_2}}\right)^2, \\
\chi_{12} &= -\frac{3}{2}\left(\frac{M_Z^2}{M_{Z_1}M_{Z_2}}\right)^2\left(\frac{\hat{s}}{M_Z^2} - \frac{M_{Z_1}^2 + M_{Z_2}^2}{M_Z^2}\right), \\
\chi_{14} &= (3+x)\left(\frac{M_Z^2}{M_{Z_1}M_{Z_2}}\right)^2\left(\frac{\hat{s}}{M_X^2}\right), \\
\chi_{15} &= (3+x)\left(\frac{M_Z^2}{M_{Z_1}M_{Z_2}}\right)^2\left(\frac{M_{Z_1}^2 + M_{Z_2}^2}{M_Z^2}\right), \\
\chi_{22} &= 3+2x, \\
\chi_{24} &= -\frac{3}{2}\left(\frac{M_Z^2}{M_{Z_1}M_{Z_2}}\right)^2\left(\frac{\hat{s}}{M_X^2}\right)\left(\frac{\hat{s}}{M_Z^2} - \frac{M_{Z_1}^2 + M_{Z_2}^2}{M_Z^2}\right), \\
\chi_{25} &= -\frac{3}{2}\left(\frac{M_Z^2}{M_{Z_1}M_{Z_2}}\right)^2\left(\frac{M_{Z_1}^2 + M_{Z_2}^2}{M_Z^2}\right)\left(\frac{\hat{s}}{M_Z^2} - \frac{M_{Z_1}^2 + M_{Z_2}^2}{M_Z^2}\right), \\
\chi_{33} &= 2x, \\
\chi_{44} &= (3+x)\left(\frac{M_Z^2}{M_{Z_1}M_{Z_2}}\right)^2\left(\frac{\hat{s}}{M_X^2}\right)^2, \\
\chi_{45} &= (3+x)\left(\frac{M_Z^2}{M_{Z_1}M_{Z_2}}\right)^2\left(\frac{M_{Z_1}^2 + M_{Z_2}^2}{M_Z^2}\right)\left(\frac{\hat{s}}{M_X^2}\right), \\
\chi_{55} &= (3+x)\left(\frac{M_Z^2}{M_{Z_1}M_{Z_2}}\right)^2\left(\frac{M_{Z_1}^2 + M_{Z_2}^2}{M_Z^2}\right)^2.
\end{aligned}$$

$$\Gamma(X \to ZZ \to 4\ell) = \Gamma_{SM} \sum_{i,j} \gamma_{ij} \kappa_i \kappa_j$$

$$\begin{aligned}
\frac{(\hat{s})}{dM_{Z_2}} &= g_{ggX}^2 (g_L^2 + g_R^2)^2 \left(\frac{M_{Z_1}^5 M_{Z_2}^5 \sqrt{x}}{2^{14} 3^2 \pi^5 v^2 \hat{s}^2} \right) \left(\frac{\hat{s}}{\hat{s} - M_X^2} \right)^2 \\
&\quad \left(\frac{(2M_{Z_1} dM_{Z_1})(2M_{Z_2} dM_{Z_2})}{(M_{Z_1}^2 - M_Z^2)^2 + M_Z^2 \Gamma_Z^2)(M_{Z_2}^2 - M_Z^2)^2 + M_Z^2 \Gamma_Z^2)} \right) \sum_{i,j} \kappa_i \kappa_j \chi_{ij},
\end{aligned}$$

$$\left(\frac{d\Gamma_5}{d\mathbf{x}} \Big/ \frac{d\Gamma_1}{d\mathbf{x}} \right) = \left(\frac{M_{Z_1}^2 + M_{Z_2}^2}{M_Z^2} \right)^2, \qquad \gamma_{55} = \left\langle \left(\frac{M_{Z_1}^2 + M_{Z_2}^2}{M_Z^2} \right)^2 \right\rangle_{SM}$$

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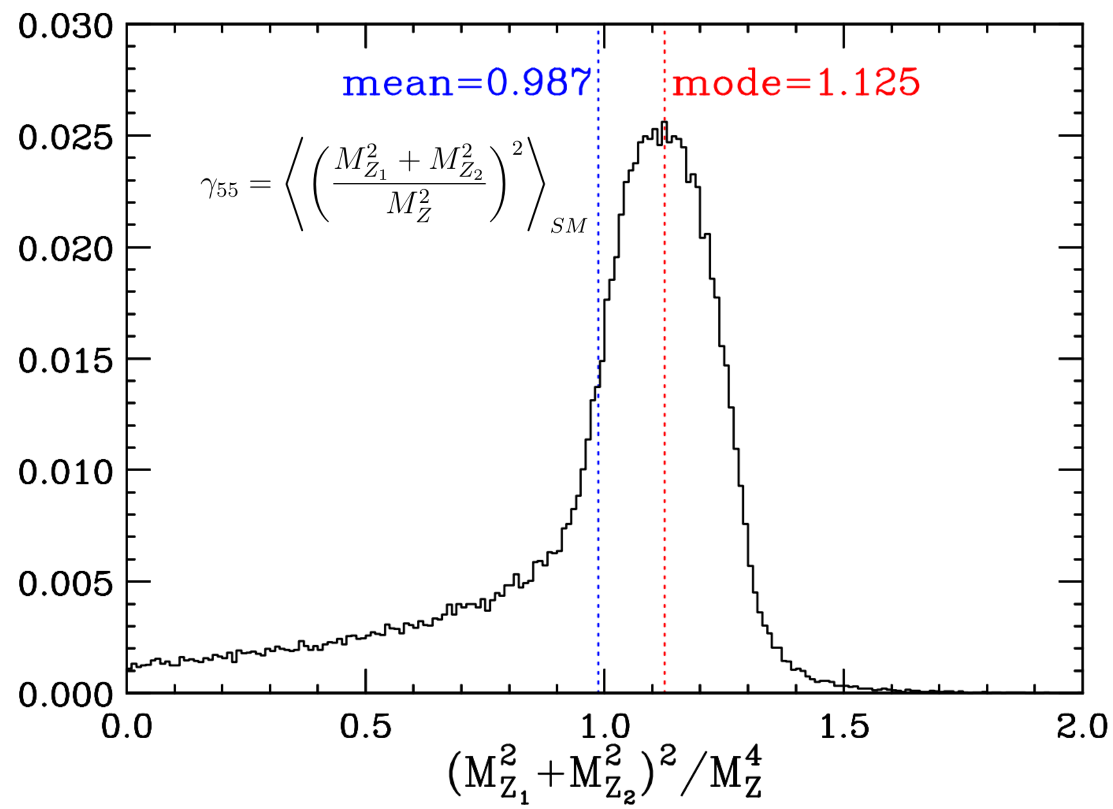
$\gamma_{11} = \gamma_{14} = \gamma_{44}$	γ_{22}	$\gamma_{12} = \gamma_{24}$	γ_{33}	$\gamma_{13} = \gamma_{23} = \gamma_{34} = \gamma_{35}$	γ_{25}	$\gamma_{15} = \gamma_{45}$	γ_{55}
1	0.090	−0.250	0.038	0	−0.250	0.978	0.987



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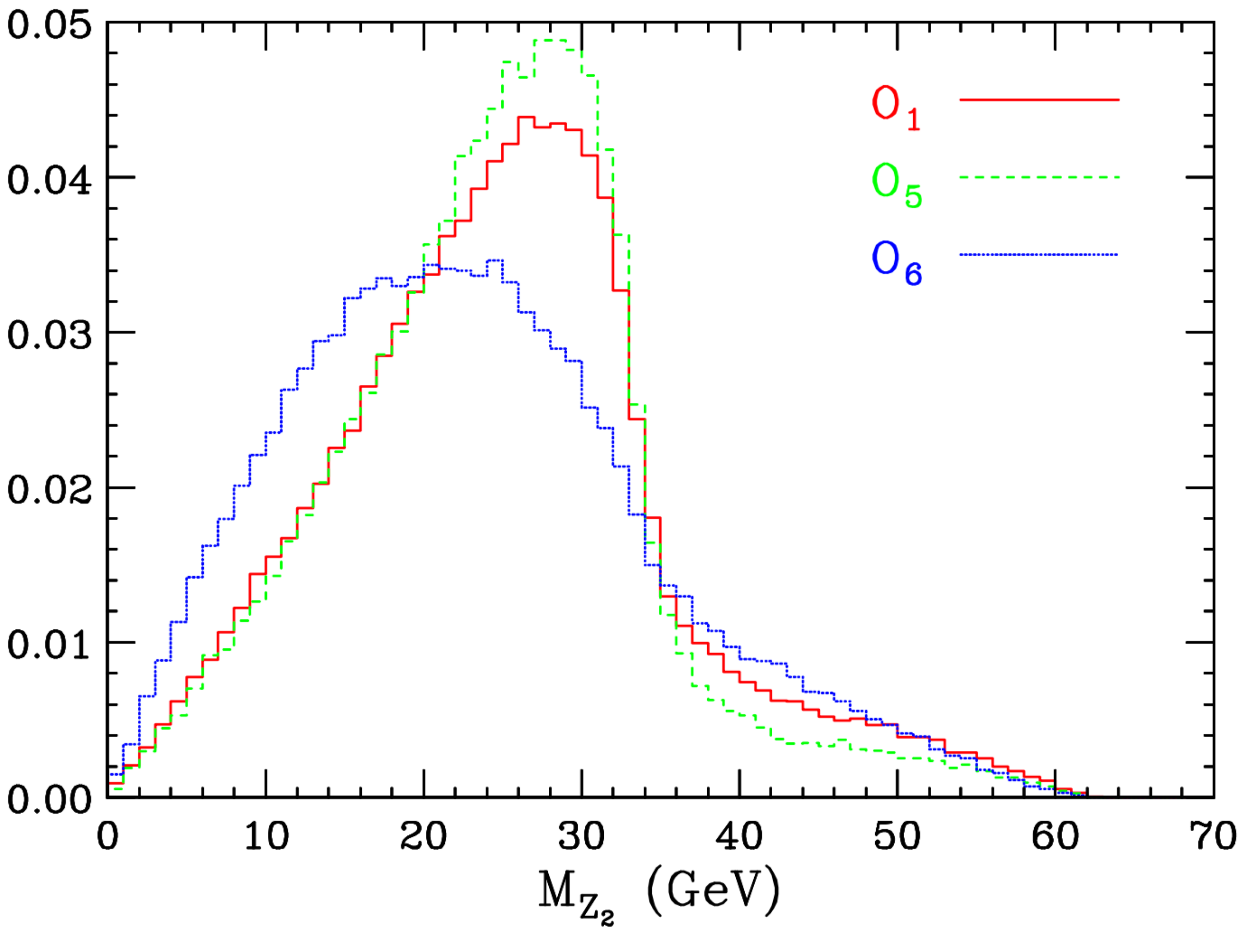

Here O6 is the different combination of operators to cover 5d space

	$\mathcal{O}_1$	$\mathcal{O}_2$	$\mathcal{O}_3$	$\mathcal{O}_4$	$\mathcal{O}_5$	$\mathcal{O}_6$
$2\langle \Delta \log \mathcal{L} \rangle_{SM}$	0	-0.747	-1.017	0	-0.178	-0.503
Events for 3σ Limit	———	12.0	8.85	———	50.5	17.9

Conclusion

- This study does not consider the interference effect between “Sig” and “Bkg”, but this points out the major issues for the off-shell analysis.

- To cover all possible operators, we need to have FCC (for O4)

- This study is only based on the very clean four lepton channel to have maximize efficiency. For different channels (WW for example) we will lose the efficiency through missing momentum from neutrino or sever bkg from QCD (hadronic W)