Pinning down the anomalous $WW\gamma$ coupling at the LHC

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- In this context, we shall focus on the indirect effect of NP in $WW\gamma$ coupling.
  - and determine the kinematic variables which can probe these effects better at the upcoming runs at the LHC.

Gauge self interactions

- The gauge kinetic term in the SM

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- The $WW\gamma$ interaction in SM correspond to

$$\mathcal{L}_{WW\gamma} = -i\,e\left(W^{\dagger}_{\mu\nu}W^{\mu}A^{\nu} - W^{\dagger}_{\mu}A_{\nu}W_{\mu\nu} + W^{\dagger}_{\mu}W_{\nu}A^{\mu\nu}\right)$$

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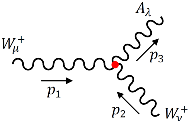
- Anomalous couplings after EWSB can be parameterized based on gauge invariance

$$\mathcal{L}_{aWW\gamma} = \kappa_{\gamma} W^{+}_{\mu} W^{-}_{\nu} A_{\mu\nu} + \frac{\lambda_{\gamma}}{m_W^2} W^{+}_{\mu\nu} W^{-}_{\nu\lambda} A_{\lambda\mu}$$

where, $\kappa_{\gamma} = \Delta\kappa_{\gamma} + 1$



$$i\Gamma^{WW\gamma}_{\mu\nu\lambda} = i\,e\Big[\,T^{(0)}_{\mu\nu\lambda}\,(p_1, p_2, p_3) + \Delta\kappa_\gamma\,T^{(1)}_{\mu\nu\lambda}\,(p_1, p_2, p_3) + \frac{\lambda_\gamma}{M_W^2}\,T^{(2)}_{\mu\nu\lambda}\,(p_1, p_2, p_3)\,\Big]$$

where,

$$\begin{aligned} T^{(0)}_{\mu\nu\lambda} &= g_{\mu\nu}\,(p_1 - p_2)_\lambda + g_{\nu\lambda}\,(p_2 - p_3)_\mu + g_{\lambda\lambda}\,(p_3 - p_1)_\nu \\ T^{(1)}_{\mu\nu\lambda} &= g_{\mu\lambda} p_{3\nu} - g_{\nu\lambda} p_{3\mu} \\ T^{(2)}_{\mu\nu\lambda} &= p_{1\lambda} p_{2\mu} p_{3\nu} - p_{1\nu} p_{2\lambda} p_{3\mu} - g_{\mu\nu}\,(p_2.p_3 p_{1\lambda} - p_3.p_1 p_{2\lambda}) \\ &- g_{\nu\lambda}\,(p_3.p_1 p_{2\mu} - p_1.p_2 p_{3\mu}) - g_{\mu\lambda}\,(p_1.p_2 p_{3\nu} - p_2.p_3 p_{1\nu}) \end{aligned}$$

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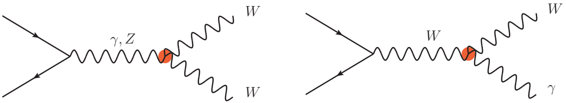

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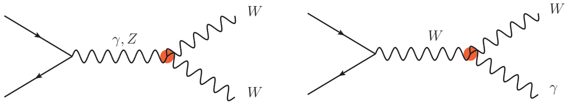
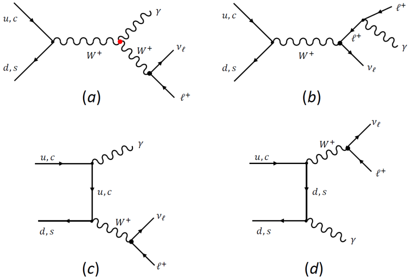


- However an independent probe/check of $WW\gamma$ and WWZ coupling is extremely important.

Our process



Strategy followed in the analysis:

- To enhance the sensitivities of the TGC's, we have optimized cuts
- Determine kinematic variables to render better separation between signal and backgrounds.

The matrix amplitude is parameterized as

$$\mathcal{M} = \mathcal{M}_{\rm SM} + \Delta\kappa_\gamma \mathcal{M}_\kappa + \frac{\lambda_\gamma}{M_W^2}\mathcal{M}_\lambda$$

$$\sigma = \sigma_{\rm SM} + \Delta\kappa_\gamma \sigma_{\kappa{\rm SM}} + (\Delta\kappa_\gamma)^2 \sigma_\kappa + \lambda_\gamma \sigma_{\lambda{\rm SM}} + (\lambda_\gamma)^2 \sigma_\lambda + \Delta\kappa_\gamma \lambda_\gamma \sigma_{\kappa,\lambda}$$

Cuts used in the analysis

Cuts on the final state objects photon, lepton and missing energy:

1. Transverse momentum: $p_{T\gamma} > 60$ GeV, $p_{T\ell} > 30$ GeV, $E_{T\,\mathrm{miss}} > 30$ GeV.
2. Psuedo-rapidity: $\eta_\ell < 2.5$ and $\eta_\gamma < 2.5$.
3. $\Delta R_{\ell\gamma} > 0.4$.
4. Transverse mass: $M_T^W > 30$ GeV.

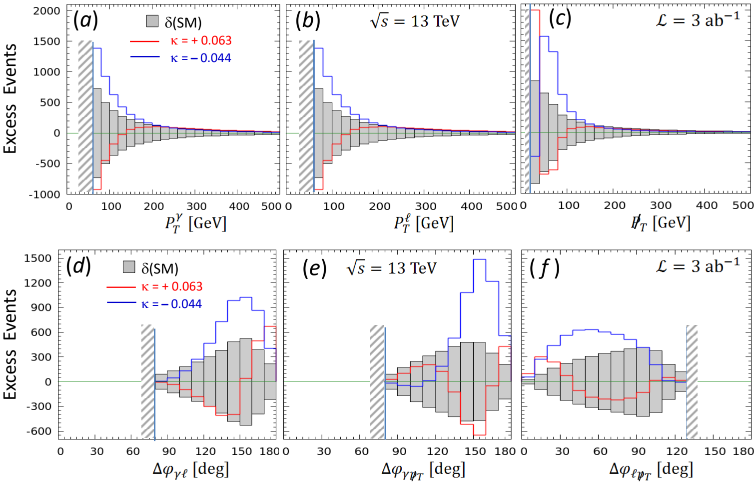
Efficiency with respect to different cuts:

Cuts	SM Background%	Signal($\Delta\kappa$ only)%	Signal (λ only)%
$p_{T_\gamma} > 60$ GeV	100	100	100
$p_{T_\ell} > 30$ GeV	78.6	84.4	88.6
$E_{T\,\mathrm{miss}} > 30$ GeV	40.5	68.6	77.8
$M_T{}^W > 30$ GeV	35.8	56.4	60.2
$\eta_\gamma < 2.5$	26.7	47.0	58.0
$\eta_\ell < 2.5$	20.3	40.9	56.2
$\Delta R_{\gamma\ell}$	18.9	40.9	56.1

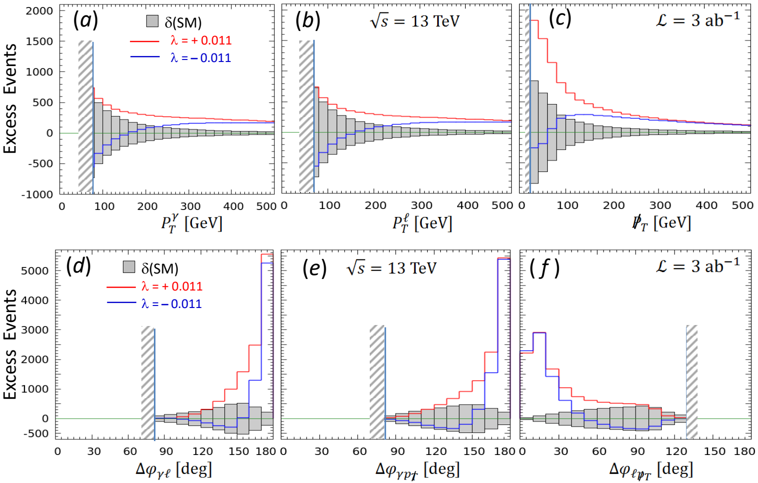
Kinematic variables used to improve the limits

- The NP operators contain derivative couplings.
- Kinematic variables for best separation between signal and background:
  - Transverse momentum (used mostly for the analyses)
  - Azimuthal angles ($\Delta\phi_{a,b} \equiv \frac{p_{T\,a}.p_{T\,b}}{p_{T\,a}p_{T\,b}}$)
- Variables used for our analysis:
  $p_{T\,\gamma}$, $p_{T\,\ell}$, $E_{T\,\mathrm{miss}}$
  $\Delta\phi_{(\gamma,\ell)}$, $\Delta\phi_{(\gamma,E_{T\,\mathrm{miss}})}$ and $\Delta\phi_{(\ell,E_{T\,\mathrm{miss}})}$.

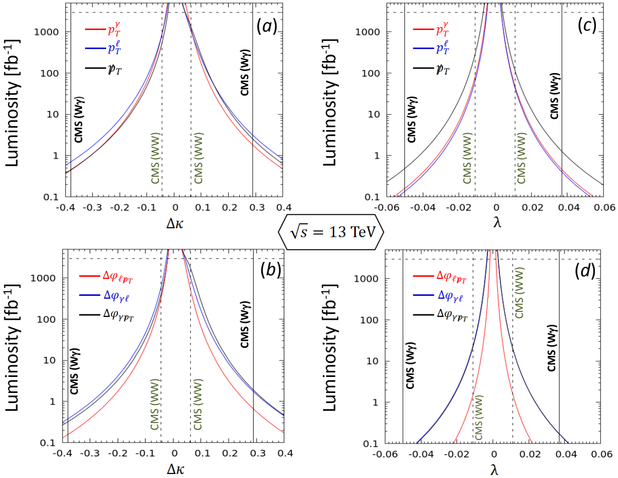
Distributions: $\Delta\kappa_\gamma$



Distributions: λ_γ

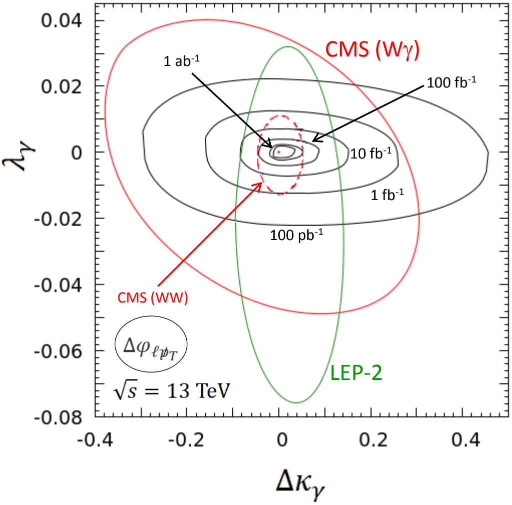


Projection of analysis: 1d Analysis



Projected regions which could be probed with significances 2σ

Projection of limits: 2d analysis



Summary and future directions

- We did a detailed study of $pp \to W\gamma \to \ell\nu\gamma$ to constrain the anomalous triple gauge boson couplings.
- Transverse momentum and Azimuthal angle are good discriminators.
- The NP effects in TGC will in general also modify the other couplings, incorporating them in a consistent framework has never be performed and one could look forward to such analyses in future.

Back-up slides

Mapping TGV's to higher dimensional operators

The dimension-6 operators which give rise to anomalous gauge couplings are:

$$
\begin{aligned}
\mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu} W^{\nu\lambda} W^{\mu}_{\lambda}] \\
\mathcal{O}_{W} &= (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi) \\
\mathcal{O}_{B} &= (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi)
\end{aligned}
$$

with,

$$
\Delta\kappa_\gamma = 1 + (c_W + c_B)\,\frac{M_W^2}{2\Lambda^2}\,,\, \lambda_\gamma = c_{WWW}\,\frac{3g^2 M_W^2}{2\Lambda^2}
$$

Similarly the anomalous WWZ couplings is given as

$$
\lambda_Z = \lambda_\gamma\,,\, \Delta\kappa_Z = \Delta g_1^Z - \tan^2\theta_W \Delta\kappa_\gamma
$$

Current limits on anomalous couplings