Probing anomalous triple and quartic gauge boson couplings via photon-photon scattering at the LHC

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Pinning down the gauge boson couplings in $WW\gamma$ production using forward proton tagging

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Abstract: In this paper, we explore the potential of the LHC to measure the rate of pp $\to$ p $WW\gamma$ p process, also to probe the new effective couplings contributing to the $WW\gamma$ and $WW\gamma\gamma$ vertices. The analysis is performed at the $\sqrt{s} = 13\,\text{TeV}$, in the di-leptonic decay channel, and assuming $300\,\text{fb}^{-1}$ integrated luminosity (IL). In addition to the presence of two opposite sign leptons, a photon, and missing energy, the distinctive signature of this process is the presence of two intact protons flying few millimeters from the initial beam direction in both sides of interaction points which suppress the background

Contents

Triple and quartic gauge couplings in the SM

Standard Model of particle physics is a Gauge Theory

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F_a^{\mu\nu}$$

- Gauge Interactions

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - igf^a_{bc}A^b_\mu A^c_\nu$$

$$+ i\bar{\psi}D\psi + h.c.$$

- Fermion Interactions

$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

- Yukawa Interactions

$$+ |D_\mu \phi|^2 - V(\phi)$$

- Higgs Potential

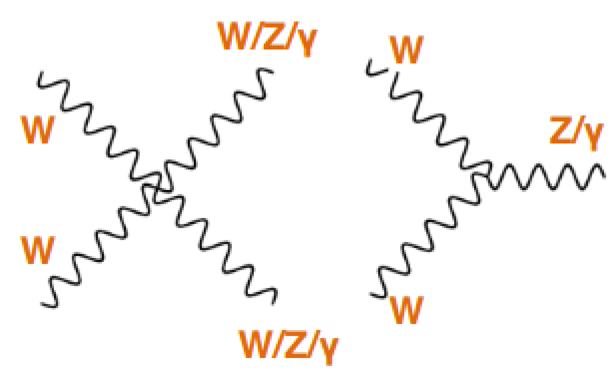
Boson self-couplings predicted by non-abelian U(1)xSU(2)xSU(3) Standard Model gauge group

Electroweak gauge group predicts:

- QGC: WWZZ, WWWW, WWZγ, WWγγ
- TGC: WWZ, WWγ

Neutral couplings absent in SM:

- ZZZZ, ZZγγ, ZZγ, ZZZ, ...



slide by: Jakob Salfeld-Nebgen-CERN LHC Seminar

Effective Field theory approach

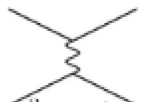
Effective Field Theory (EFT) approach used to probe for new physics in TGC and QGC

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}^i_{\rm dim-6} + \sum_j \frac{c_j}{\Lambda^4}\mathcal{O}^j_{\rm dim-8} + \ldots$$

$O_{i,j}$ gauge invariant operators, build from SM fields

Historic example: 4-fermion vertex (dim-6), Weak Interactions

$\Lambda = M_W$



$\propto \frac{g^2}{8}\frac{1}{q^2 - M_W^2}$ $\xrightarrow{q^2 << M_W^2}$

$\propto \frac{g^2}{8}\frac{1}{M_W^2} = \frac{G_F}{\sqrt{2}}$

$$\mathcal{L}^{(6)}_{WW\gamma} = ie(W^\dagger_{\mu\nu}W^\mu A^\nu - W^\dagger_\mu A_\nu W^{\mu\nu} + \kappa_\gamma W^\dagger_\mu W_\nu A^{\mu\nu} + \frac{\lambda_\gamma}{M_W^2}W^\dagger_{\delta\mu}W^\mu_\nu A^{\nu\delta}),$$

$$\mathcal{L}^{(6)}_{WW\gamma\gamma} = \frac{-e^2}{8}\frac{a_0^W}{\Lambda^2}A_{\mu\nu}A^{\mu\nu}W^{+\alpha}W^-_\alpha - \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2}A_{\mu\alpha}A^{\mu\beta}(W^{+\alpha}W^-_\beta + W^{-\alpha}W^+_\beta).$$

$$\mathcal{L}^{(8)}_{M,0,1,2,3} = \frac{f_{M,0}}{\Lambda^4}Tr[W_{\mu\nu}W^{\mu\nu}] \times [(D_\beta\Phi)^\dagger D^\beta\Phi] + \frac{f_{M,1}}{\Lambda^4}Tr[W_{\mu\nu}W^{\nu\beta}] \times [(D_\beta\Phi)^\dagger D^\mu\Phi]$$

$$+\frac{f_{M,2}}{\Lambda^4}[B_{\mu\nu}B^{\mu\nu}] \times [(D_\beta\Phi)^\dagger D^\beta\Phi] + \frac{f_{M,3}}{\Lambda^4}[B_{\mu\nu}B^{\nu\beta}] \times [(D_\beta\Phi)^\dagger D^\mu\Phi]$$

Effective Field theory approach

Effective Field Theory (EFT) approach used to probe for new physics in TGC and QGC

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}^i_{\mathrm{dim}-6} + \sum_j \frac{c_j}{\Lambda^4}\mathcal{O}^j_{\mathrm{dim}-8} + \ldots$$

$O_{i,j}$ gauge invariant operators, build from SM fields

Historic example: 4-fermion vert… …eractions

$\Lambda = M_W$

$\propto \frac{g^2}{8} \ldots = \frac{G_F}{\sqrt{2}}$

$$\frac{a_0^W}{\Lambda^2} = -\frac{4M_W^2}{g^2}\frac{f_{M,0}}{\Lambda^4} - \frac{8M_W^2}{g'^2}\frac{f_{M,2}}{\Lambda^4}$$

$$\frac{a_C^W}{\Lambda^2} = \frac{4M_W^2}{g^2}\frac{f_{M,1}}{\Lambda^4} + \frac{8M_W^2}{g'^2}\frac{f_{M,3}}{\Lambda^4},$$

$$\mathcal{L}^{(6)}_{WW\gamma} = ie(W^\dagger_{\mu\nu}W^{\mu \ldots} \ldots W^\dagger_\mu A_\nu W^{\mu\nu} + \kappa_\gamma W^\dagger_\mu W_\nu A^{\mu\nu} + \frac{\lambda_\gamma}{M_W^2}W^\dagger_{\delta\mu}W^\mu_\nu A^{\nu\delta}),$$

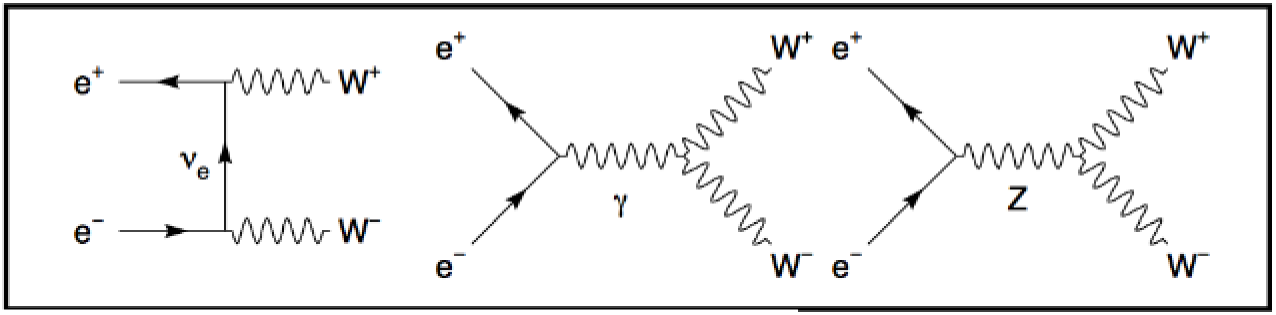
$$\mathcal{L}^{(6)}_{WW\gamma\gamma} = \frac{-e^2}{8}\frac{a_0^W}{\Lambda^2}A_{\mu\nu}A^{\mu\nu}W^{+\alpha}W^-_\alpha - \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2}A_{\mu\alpha}A^{\mu\beta}(W^{+\alpha}W^-_\beta + W^{-\alpha}W^+_\beta).$$

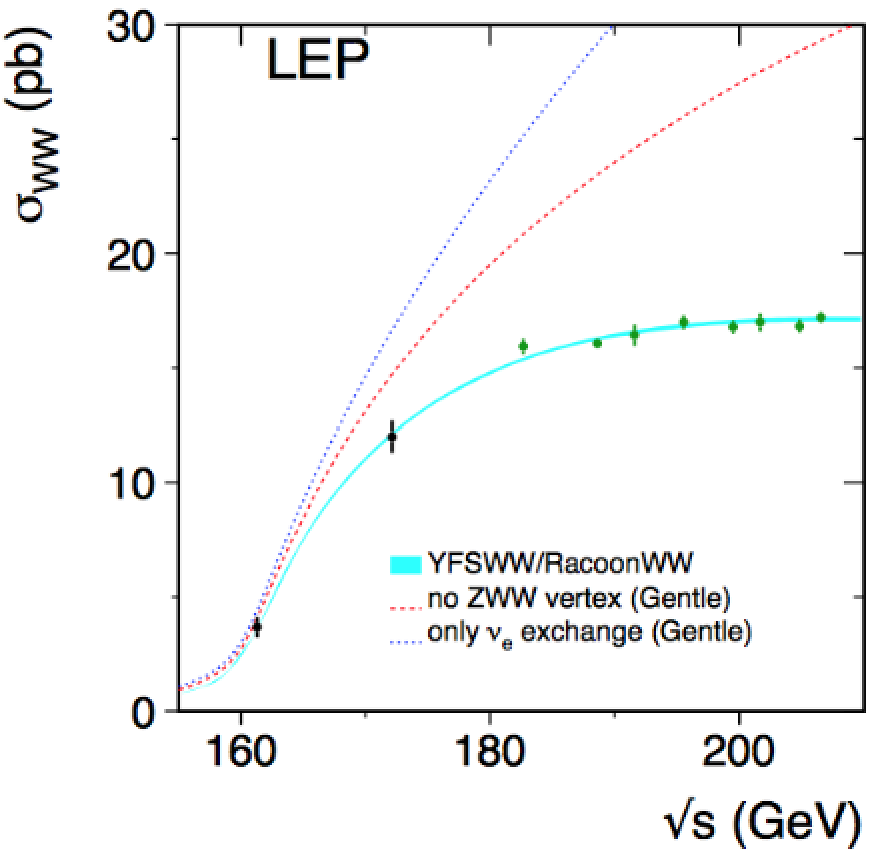
$$\mathcal{L}^{(8)}_{M,0,1,2,3} = \frac{f_{M,0}}{\Lambda^4}Tr[W_{\mu\nu}W^{\mu\nu}] \times [(D_\beta\Phi)^\dagger D^\beta\Phi] + \frac{f_{M,1}}{\Lambda^4}Tr[W_{\mu\nu}W^{\nu\beta}] \times [(D_\beta\Phi)^\dagger D^\mu\Phi]$$

$$+\frac{f_{M,2}}{\Lambda^4}[B_{\mu\nu}B^{\mu\nu}] \times [(D_\beta\Phi)^\dagger D^\beta\Phi] + \frac{f_{M,3}}{\Lambda^4}[B_{\mu\nu}B^{\nu\beta}] \times [(D_\beta\Phi)^\dagger D^\mu\Phi]$$

Probing TGCs and QGCs at collider

- **First experimental evidence at LEP2**





Z, gamma, neutrino propagation restore unitarity

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Probing TGCs and QGCs at collider

- The searches of the anomalous γWW and ZWW trilinear gauge boson couplings from WW and WZ production using lepton plus dijet final states as well as results from Wγ, WW, and WZ production with leptonic final states at Tevatron 8.6 fb^{-1} integrated luminosity and 1.96 TeV center-of-mass-energy.

- The production of Wγ and two jets where the W boson decays leptonically at LHC by CMS experiment at 19.7 fb^{-1} integrated luminosity and 8 TeV center-of-mass-energy.

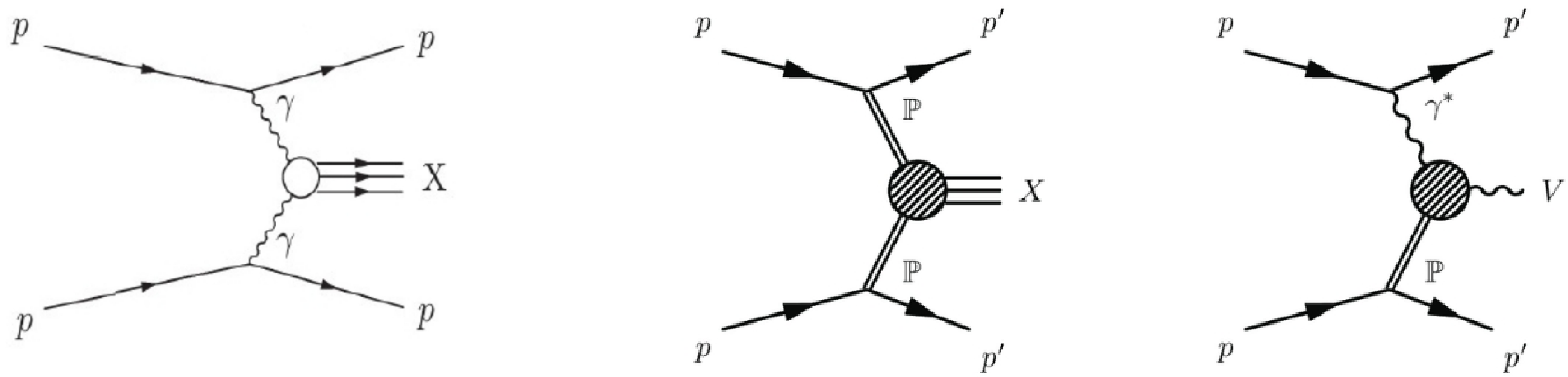
- The study of WWγ and WZγ triboson production using events from proton–proton collisions at a centre-of-mass energy of 8 TeV recorded with the ATLAS detector at the LHC and corresponding to an integrated luminosity of 20.2 fb^{−1}.

All Measurements are in good agreement with the SM prediction

Central Exclusive Production (CEP)

CEP: process of type **pp→ p+X+p**

- **Scattered protons survive the collision intact**
- No additional activity between the outgoing protons and the central system X (exclusive)
- **Particularly clean experimental conditions** thanks to the absence of proton remnants



γγ interactions **ℙℙ exchanges** **ℙγ fusions**

$$\xi = \frac{E_p - E_{p'}}{E_p}$$

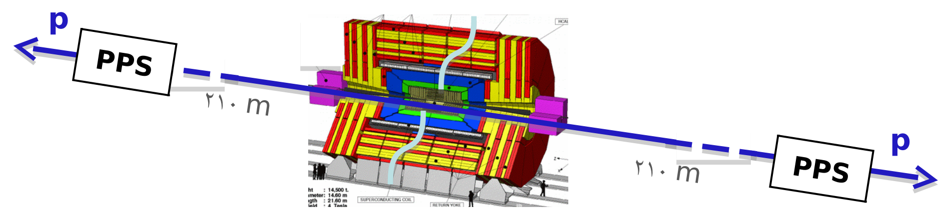
$$W_{miss} = 2\sqrt{E_{\gamma 1} E_{\gamma 2}} = \sqrt{\xi_1 \xi_2 s}$$

slide by: M.M. Obertino, Università di Torino, INFN Torino

CMS-TOTEM Precision Proton Spectrometer

- The **CMS-TOTEM Precision Proton Spectrometer** (CT-PPS) will allow precision proton measurements in the very forward regions on both sides of CMS during standard LHC running:

- Two stations for **tracking detectors** and two stations for **timing detectors** installed at ~210 m from the common CMS-TOTEM interaction point (IP) on both sides of the central apparatus.



- LHC magnets between IP and the detector station used to bend out of the beam envelope protons that have lost a small fraction of their initial momentum in the interaction

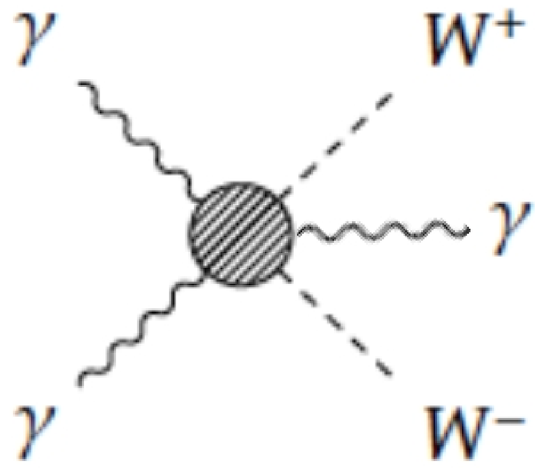
- Proton timing measurement from both sides of CMS allows to determine the **primary vertex**, correlate it with that of the central detector and reject pile-up

- Proton position and angle measurements, combined with the beam magnets, allow to determine the **momentum** of the scattered protons

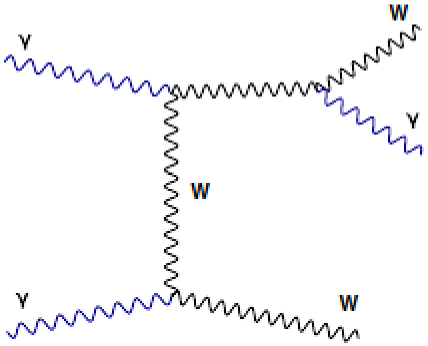
> **fractional energy loss (ξ) between 0.15% and 20%(50%)**
> **Time resolution ~10,30 ps**

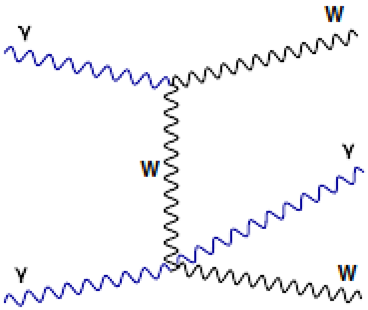
slide by: M.M. Obertino, Università di Torino, INFN Torino

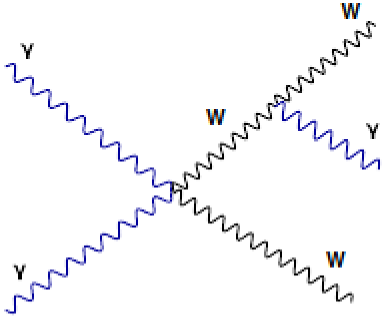
CEP of pair of W boson production plus photon



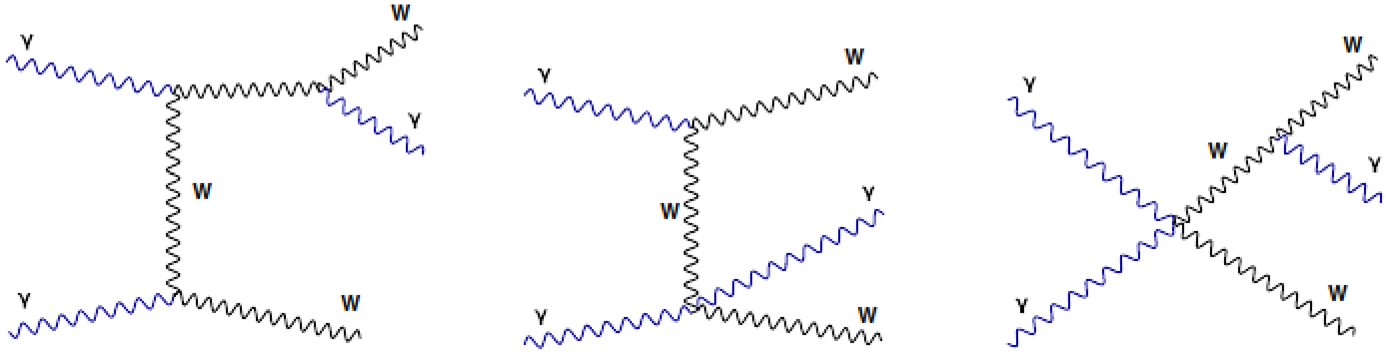
WWgamma production



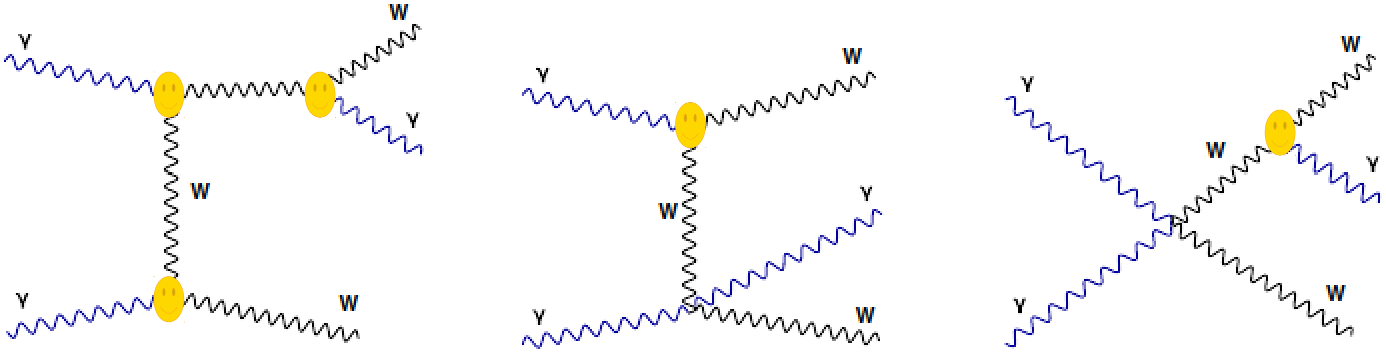




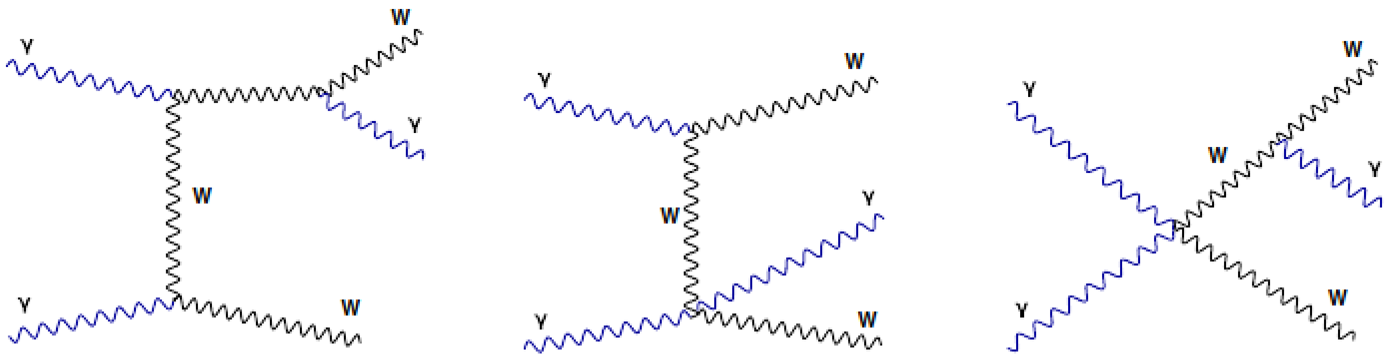
WWgamma production



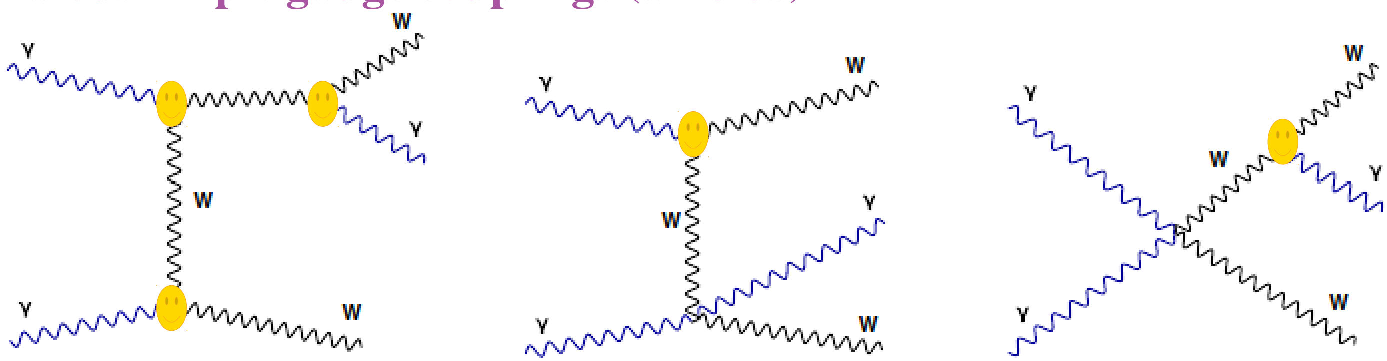
Anomalous Triple gauge couplings (aTGCs)



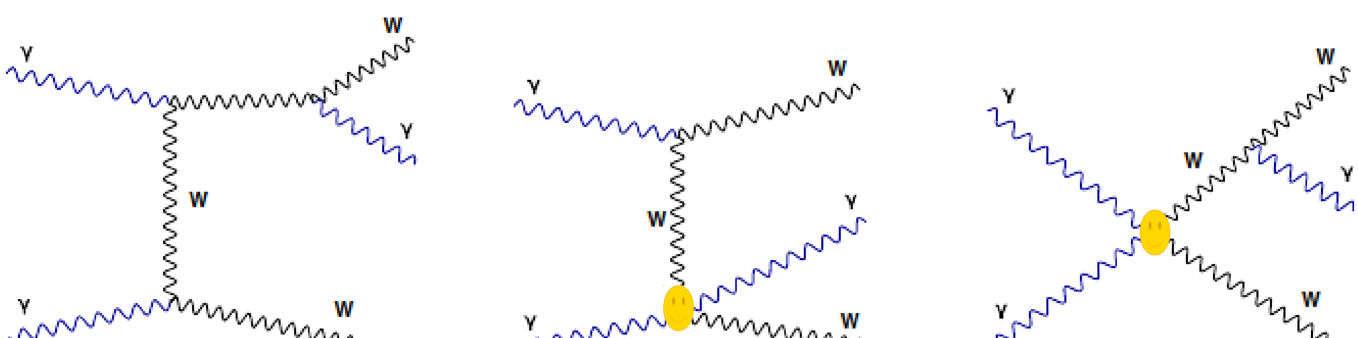
WWgamma production



Anomalous Triple gauge couplings (aTGCs)

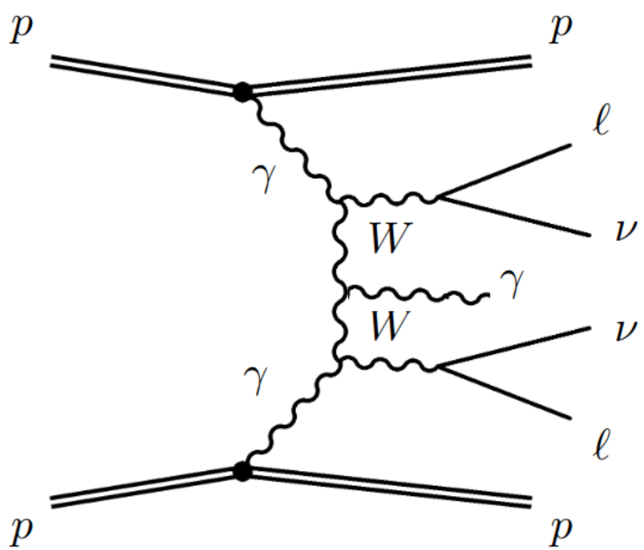


Anomalous Quartic gauge couplings (aQGCs)



Final state of signal

- Final state containing two lepton-one photon

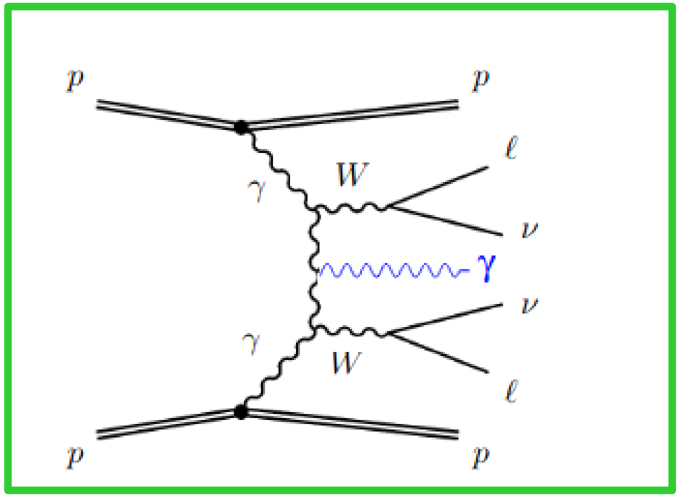


What are Backgrounds ?

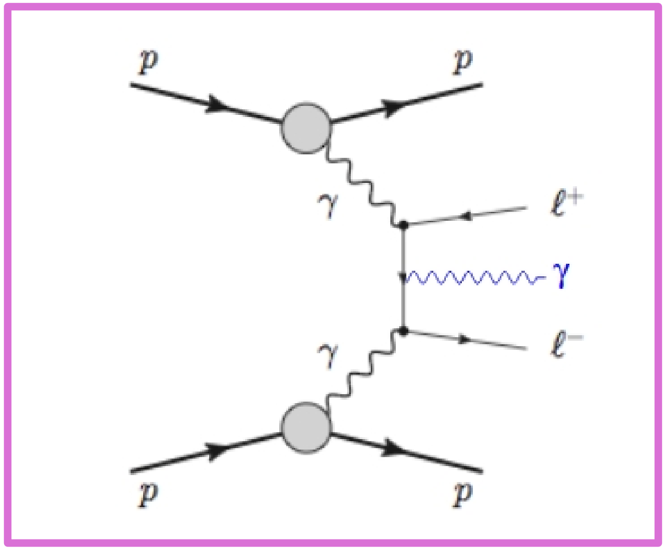
- $\gamma\gamma$ initiated process:
- Inclusive pp collision coincide with two protons from pile-up:
- Double pomeron exchange processes

Photon-photon initiated backgrounds

$\gamma\gamma \to W^+W^-\gamma$



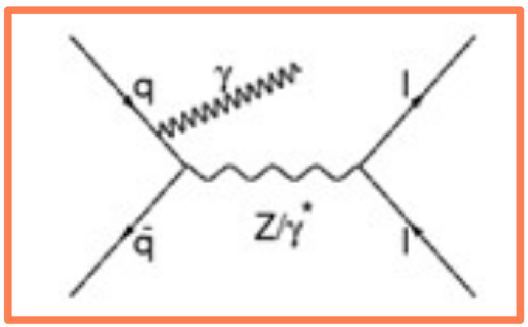
$\gamma\gamma \to l^+l^-\gamma$ / $\gamma\gamma \to \tau\bar{\tau}\gamma$



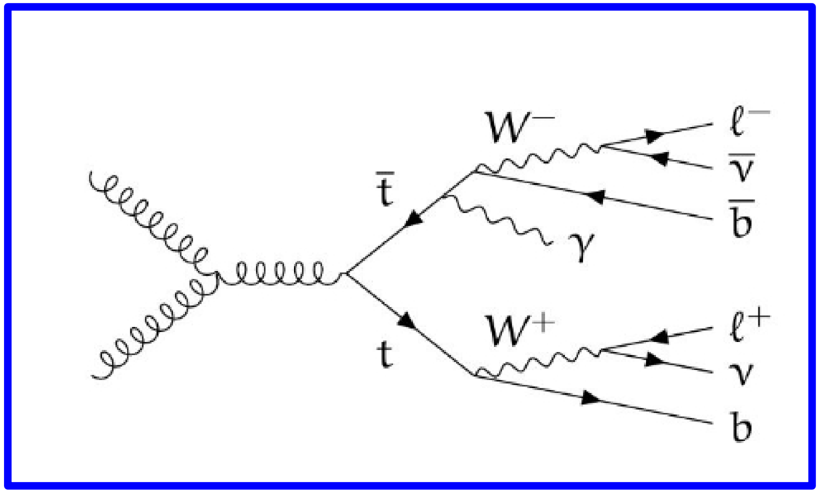
Inclusive backgrounds with pile-up protons

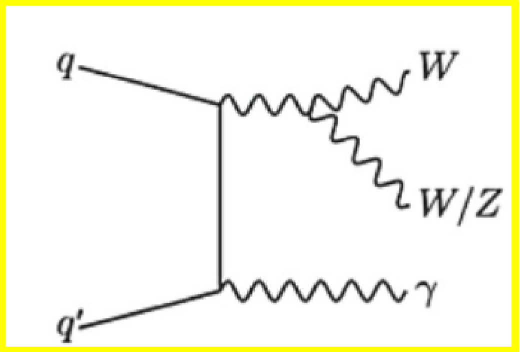
- The cross sections of these processes are several orders of magnitudes larger than the signal.
- they can contribute to our signal region only if they coincides with protons in the acceptance of FDs produced by interactions.

$pp \to \tau\bar{\tau}\gamma$ / $pp \to l\bar{l}\gamma$



$pp \to t\bar{t}\gamma$





$pp \to W^{\pm}Z\gamma$

$pp \to ZZ\gamma$

$pp \to W^{+}W^{-}\gamma$

Event selection and analyse strategy

Three categories of selection cuts:

- Type I: Central detector requirements.
- Type II: Applying on the tagged protons.
- Type III: Kinematic correlation between central detector and Forward detector.

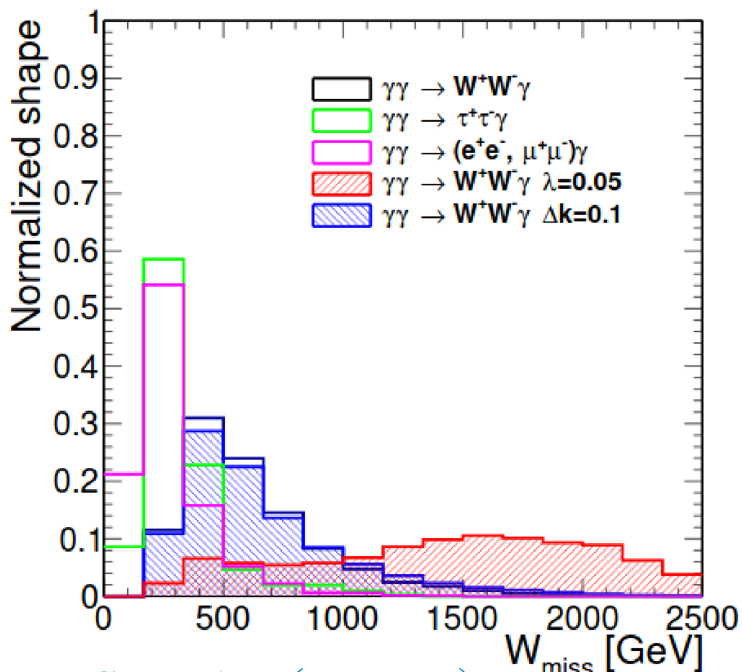
Selection (typeI):

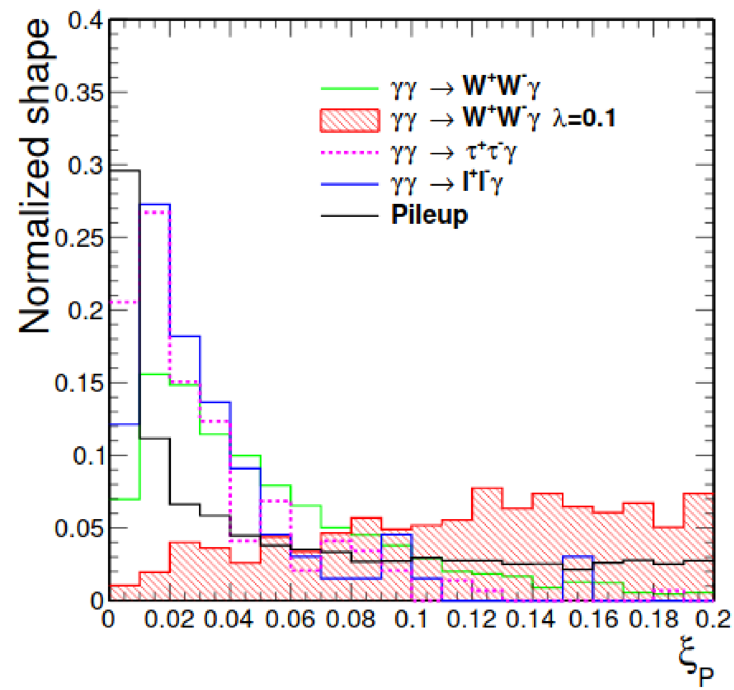
- two opposite sign well isolated leptons $p_{T,l} > 10\,\text{GeV}$ but at least one of them must pass $p_{T,l} > 20\,\text{GeV}$ and $|\eta_l| < 2.5$
- veto events containing any extra loose lepton with $p_{T,l} > 10\,\text{GeV}$ and $|\eta_l| < 2.5$
- one isolated photon with $p_{T,\gamma} > 20\,\text{GeV}$ and $|\eta_\gamma| < 2.5$.
- $\not{E} > 30\,\text{GeV}$ $\Delta R_{\gamma,l} = \sqrt{\Delta\phi^2 + \Delta\eta^2} > 0.5$.
- veto events containing more than one jets with $p_{T,j} > 40\,\text{GeV}$ and $|\eta_j| < 5.0$

Event selection and analyse strategy

Selection (typeII):

- at least one proton in each side of interaction point to be within the FD acceptance
- FD acceptance $0.0015 < \xi < 0.2$ and $0.0015 < \xi < 0.5$
  we require ξ to be greater than 0.008

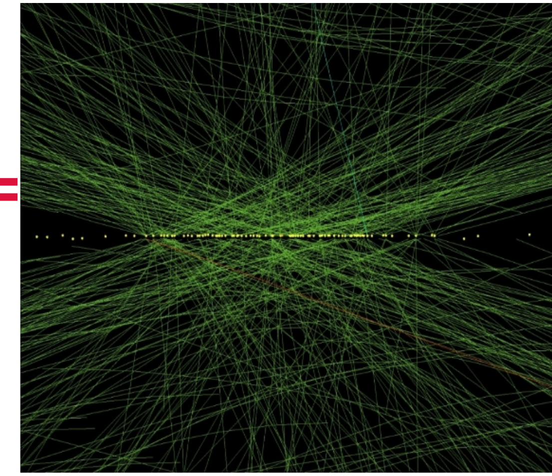




Selection (typeIII):

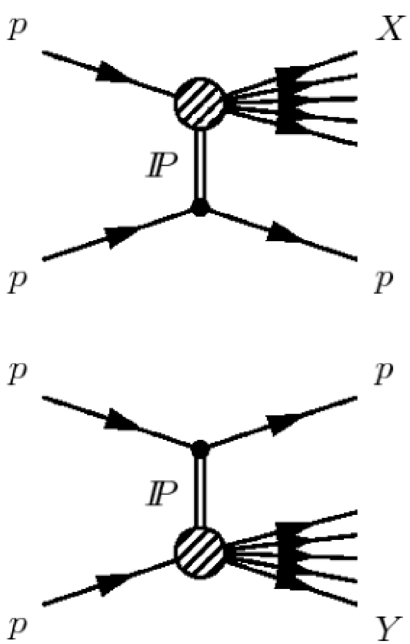
we restrict the protons missing mass $W_{\rm miss}$ to be larger than 200 GeV.

Pile-up interaction with proton

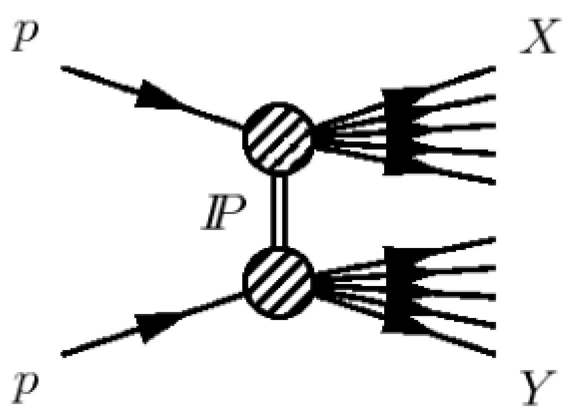


The mean value of pile-up
- 20-50 from Run I to II
- high luminosity LHC 140-200.

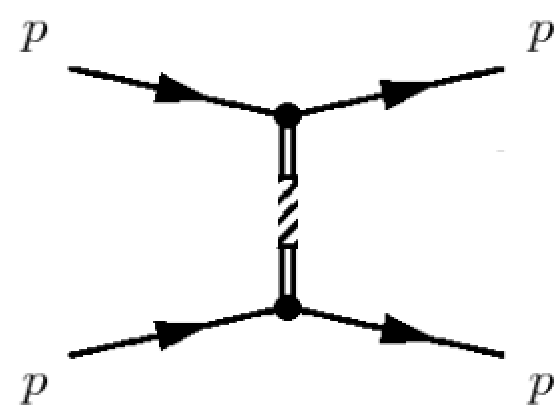
Single diffractive



Double diffractive

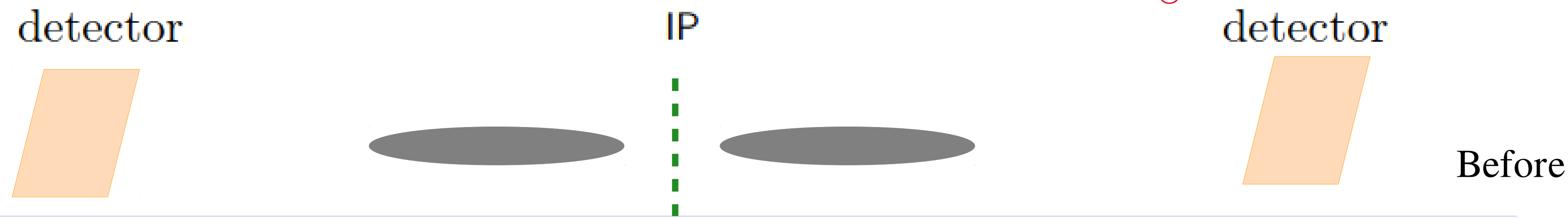


Proton-proton scattering

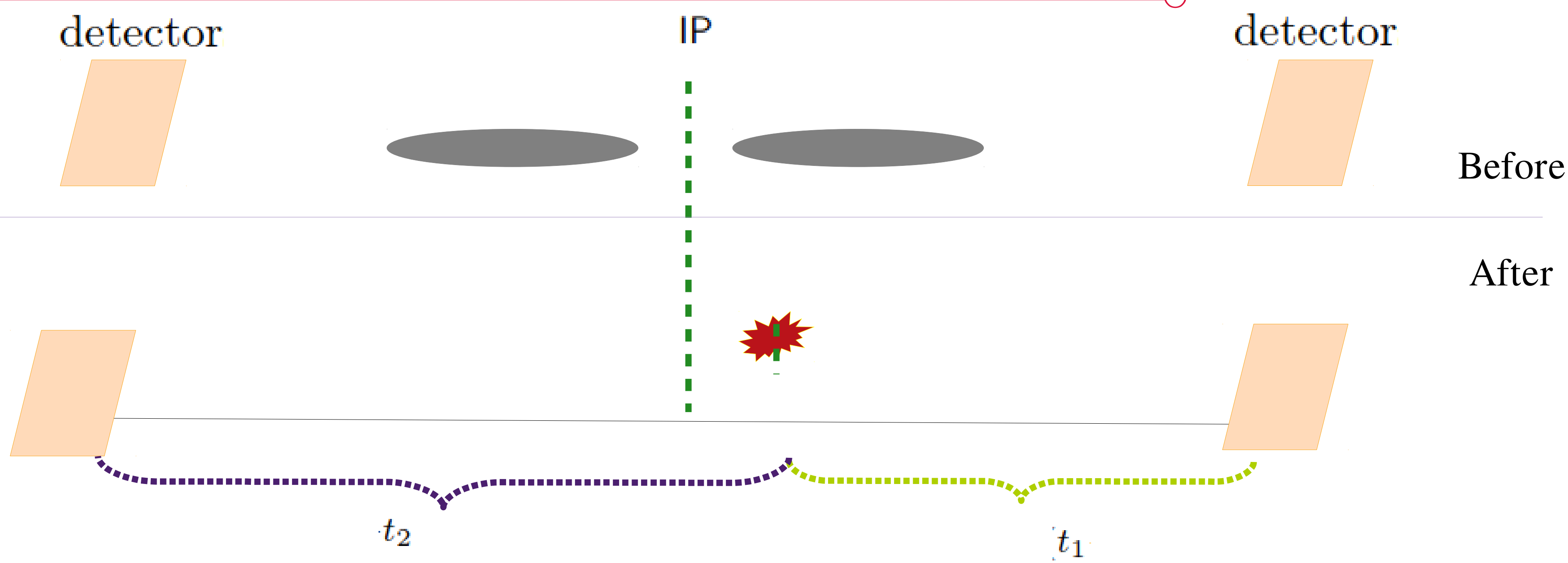


the elastic interactions suppress heavily due to the lower cut on the proton acceptance region $\xi > 0.008$.

Time of filght(type II selection)

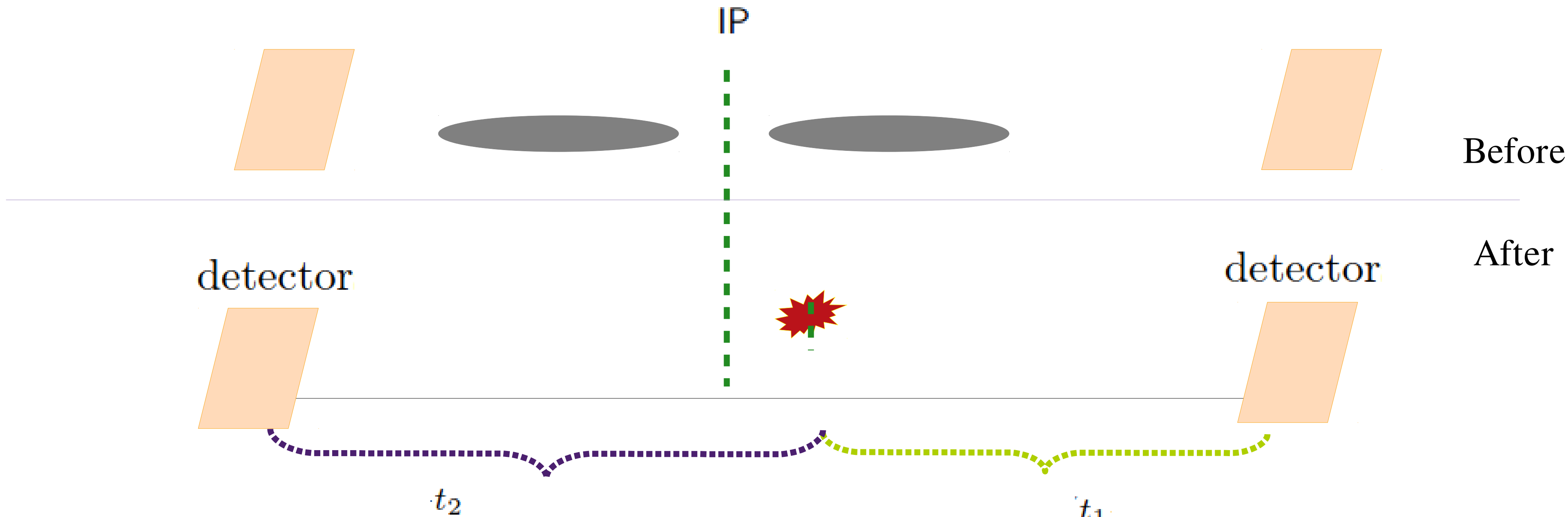


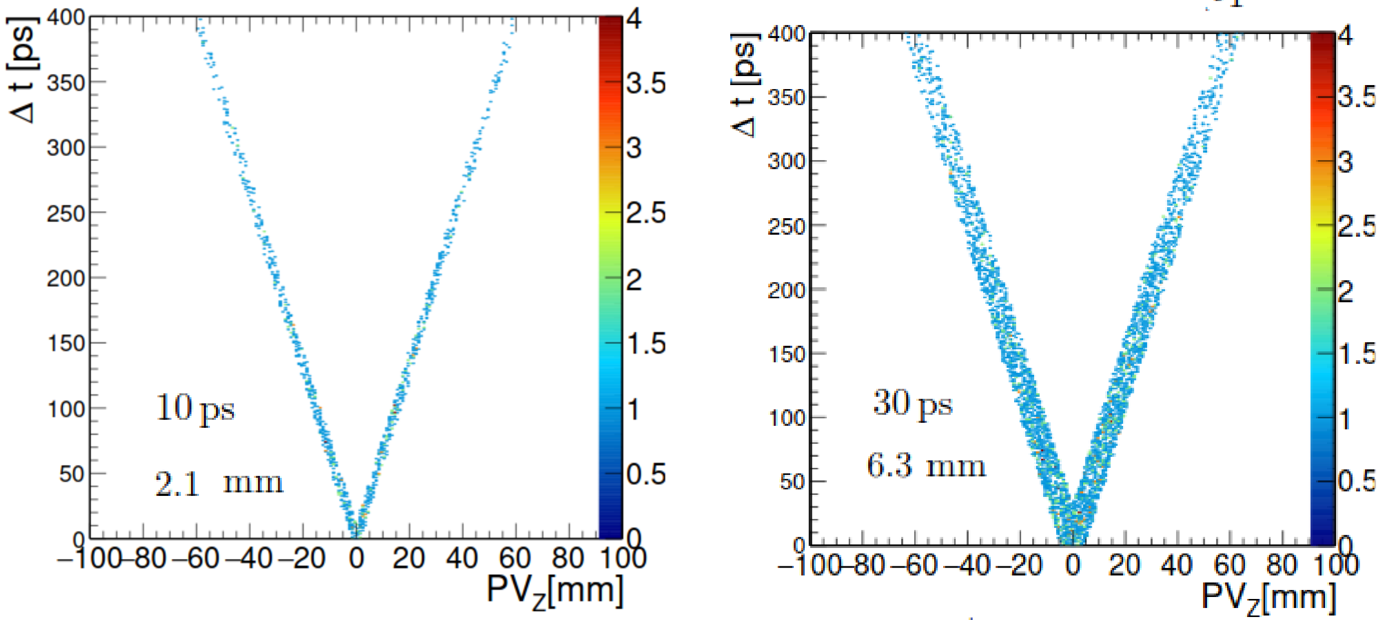
Time of filght(type II selection)



$$z_{\mathrm{PV}} \propto \frac{(t_1 - t_2)}{2}$$

Time of filght(type II selection)



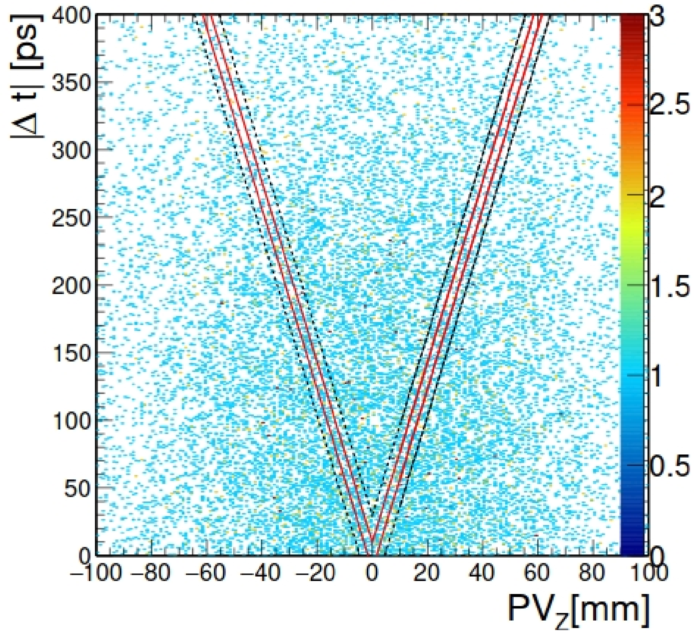


$$z_{\rm PV} \propto \frac{(t_1 - t_2)}{2}$$

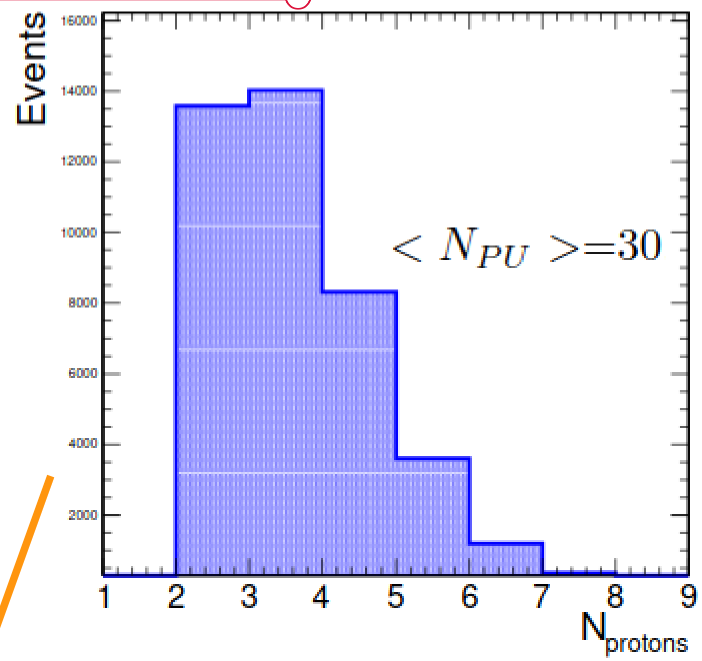
for the SM process $pp \to pW^+W^-\gamma p$.

Proton from pile up

$$\delta r = \sqrt{(Z_{\mathrm{PV}} - Z_{\mathrm{p1}})^2 + (Z_{\mathrm{PV}} - Z_{\mathrm{p2}})^2}$$



inclusive $W^+W^-\gamma$ process.



Multiplicity of pile-up protons passing

$0.008 < \xi < 0.2$

Double tagging efficiency						
	$< N_{PU} >$	10	30	50	100	140
Type II	$0.0015 < \xi < 0.2$	0.06	0.31	0.56	0.87	0.95
	$0.0015 < \xi < 0.5$	0.30	0.81	0.95	0.99	1.00
	$\xi > 0.008$	0.03	0.19	0.38	0.73	0.86
		0.26	0.76	0.93	0.99	1.00
	TOF	0.001	0.008	0.016	0.036	0.048
		0.010	0.04	0.06	0.011	0.157

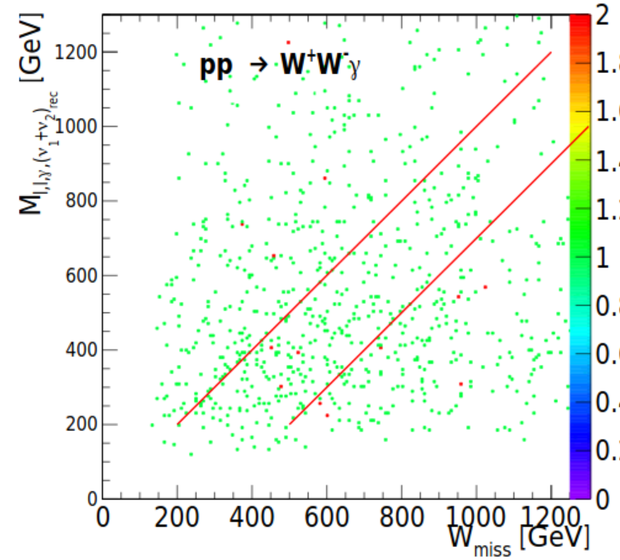
Mass reconstruction

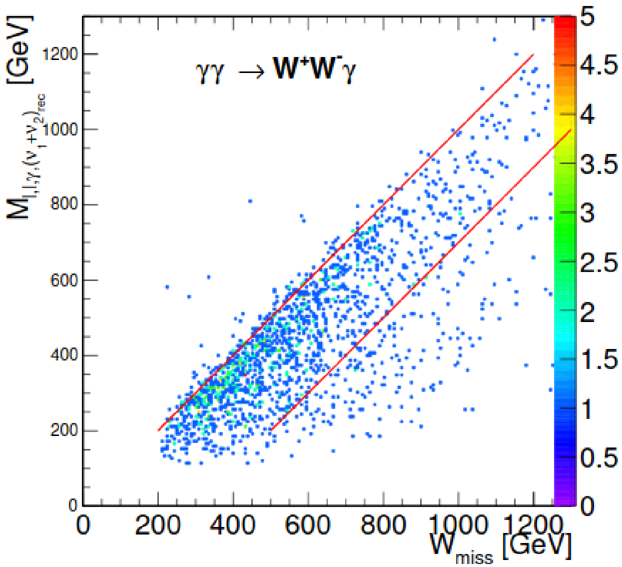
Selection (typeIII):

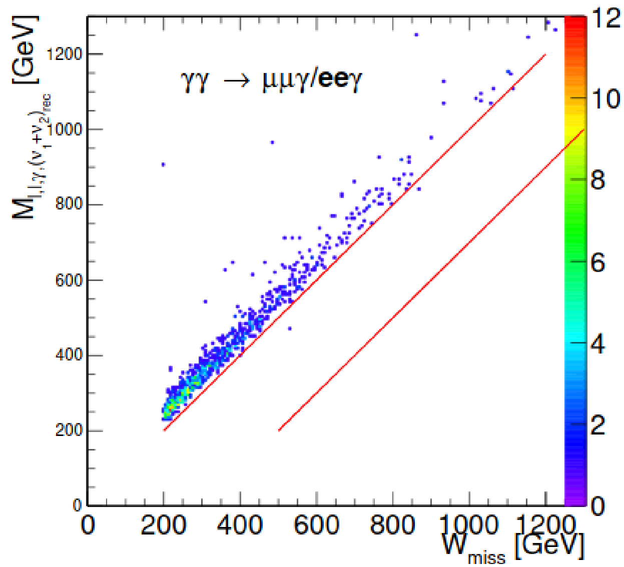
$$p_z(l_1) + p_z(l_2) + p_z(\gamma) + p_z(\nu_1+\nu_2) = p_z(\mathrm{p}_1) + p_z(\mathrm{p}_2)$$

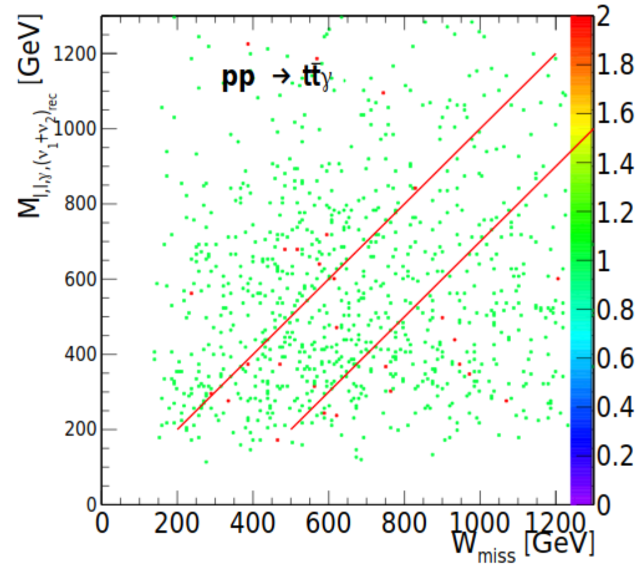
$$M_{l_1 l_2 \gamma(\nu_1+\nu_2)_{\mathrm{rec}}} = (p(l_1) + p(l_2) + p(\gamma) + p(\nu_1+\nu_2)_{\mathrm{rec}})^2$$

$$0 < W_{\mathrm{miss}} - M_{l_1 l_2 \gamma(\nu_1+\nu_2)_{\mathrm{rec}}} < 300$$









Yield of backgrounds

	$(\mathcal{L}=300\,\mathrm{fb}^{-1},\sqrt{s}=13\,\mathrm{TeV})$	$\mathrm{pp}\to\tau\bar{\tau}\gamma$ $e\mu(ee+\mu\mu)$	$\mathrm{pp}\to t\bar{t}\gamma$ $e\mu(ee+\mu\mu)$	$\mathrm{pp}\to W^{+}W^{-}\gamma$ $e\mu(ee+\mu\mu)$	$\mathrm{pp}\to ZZ\gamma$ $e\mu(ee+\mu\mu)$	$\mathrm{pp}\to W^{\pm}Z\gamma$ $e\mu(ee+\mu\mu)$	$\mathrm{pp}\to l\bar{l}\gamma$ $e\mu(ee+\mu\mu)$
Type I	$p_{T,l_1}>20\,\mathrm{GeV}, p_{T,l_2}>10\,\mathrm{GeV}$ $\lvert\eta_{l_1,l_2}\rvert<2.5,\ iso<0.15$	8519 (8411)	6106(6089)	560 (588)	0.07 (4)	23 (114)	949 (418763)
	$\not{E}>30\,\mathrm{GeV}$	4106 (4191)	5447(5409)	447 (469)	0.05 (2.2)	18 (92)	501 (171067)
	$p_{T,\gamma}>20\,\mathrm{GeV}, \lvert\eta_\gamma\rvert<2.5,\ iso<0.15$ $\Delta R_{\gamma,l_1}>0.5,\ \Delta R_{\gamma,l_2}>0.5$	1141 (1124)	2709(2516)	204 (210)	0.02 (1)	8 (41)	43 (60093)
	Veto $N_j>2,\ p_{T,j}>40\,\mathrm{GeV}$	1124(1119)	1101(1034)	201(205)	0.02(0.82)	7.77(39)	33(59649)
	$\lvert M_{l_1l_2}-m_Z\rvert>10\,\mathrm{GeV}$	1090 (1107)	282 (266)	609 (622)	0.015(0.07)	6.9 (8.8)	5(4446)
Type II	$0.008<\xi<0.2$ $0.008<\xi<0.5$	182(187) 858(772)	207(197) 219(202)	38(39) 137(140)	0.005(0.01) 0.01 (0.06)	1.2(1.8) 5.3 (7)	0(1035) 19(3396)
	TOF	0 (0) 23(23)	5.4(3.4) 17(24)	0.88(0.75) 3.3 (4)	0(0) 0(0.0009)	0.03 (0.006) 0.14(0.2)	0(19) 0 (100)
Type III	$W_{\mathrm{miss}}>200\,\mathrm{GeV}$	0(0) 23(23)	5.4(2.75) 17 (24)	0.76 (0.75) 3.3(4)	0 (0) 0(0.0009)	0.03(0.006) 0.14(0.2)	0(19) 0 (100)
	$0<W_{\mathrm{miss}}-M_{l_1l_2\gamma(\nu_1+\nu_2)_{\mathrm{rec}}}<300$	0 (0) 0 (0)	0(0) 1.36(0)	0.13 (0.06) 0.126 (0.126)	0 (0) 0(0.0009)	0(0) 0.006(0.006)	0(0) 0(0)

Yield of backgrounds

	$(\mathcal{L}=300\,\mathrm{fb}^{-1}, \sqrt{s}=13\,\mathrm{TeV})$	$\mathrm{pp}\to\tau\bar{\tau}\gamma$ $e\mu(ee+\mu\mu)$	$\mathrm{pp}\to t\bar{t}\gamma$ $e\mu(ee+\mu\mu)$	$\mathrm{pp}\to W^+W^-\gamma$ $e\mu(ee+\mu\mu)$	$\mathrm{pp}\to ZZ\gamma$ $e\mu(ee+\mu\mu)$	$\mathrm{pp}\to W^\pm Z\gamma$ $e\mu(ee+\mu\mu)$	$\mathrm{pp}\to l\bar{l}\gamma$ $e\mu(ee+\mu\mu)$
Type I	$p_{T,l_1}>20\,\mathrm{GeV}, p_{T,l_2}>10\,\mathrm{GeV}$ $\lvert\eta_{l_1,l_2}\rvert<2.5,\ iso<0.15$	8519 (8411)	6106(6089)	560 (588)	0.07 (4)	23 (114)	949 (418763)
	$\not{E}>30\,\mathrm{GeV}$	4106 (4191)	5447(5409)	447 (469)	0.05 (2.2)	18 (92)	501 (171067)
	$p_{T,\gamma}>20\,\mathrm{GeV}, \lvert\eta_\gamma\rvert<2.5,\ iso<0.15$ $\Delta R_{\gamma,l_1}>0.5,\ \Delta R_{\gamma,l_2}>0.5$	1141 (1124)	2709(2516)	204 (210)	0.02 (1)	8 (41)	43 (60093)
	Veto $N_j>2,\ p_{T,j}>40\,\mathrm{GeV}$	1124(1119)	1101(1034)	201(205)	0.02(0.82)	7.77(39)	33(59649)
	$\lvert M_{l_1l_2}-m_Z\rvert>10\,\mathrm{GeV}$	1090 (1107)	282 (266)	609 (622)	0.015(0.07)	6.9 (8.8)	5(4446)
Type II	$0.008<\xi<0.2$	182(187)	207(197)	38(39)	0.005(0.01)	1.2(1.8)	0(1035)
	$0.008<\xi<0.5$	858(772)	219(202)	137(140)	0.01 (0.06)	5.3 (7)	19(3396)
	TOF	0 (0) 23(23)	5.4(3.4) 17(24)	0.88(0.75) 3.3 (4)	0(0) 0(0.0009)	0.03 (0.006) 0.14(0.2)	0(19) 0 (100)
Type III	$W_{\mathrm{miss}}>200\,\mathrm{GeV}$	0(0) 23(23)	5.4(2.75) 17 (24)	0.76 (0.75) 3.3(4)	0 (0) 0(0.0009)	0.03(0.006) 0.14(0.2)	0(19) 0 (100)
	$0 < W_{\mathrm{miss}} - M_{l_1l_2\gamma(\nu_1+\nu_2)_{\mathrm{rec}}} < 300$	0 (0) 0 (0)	0(0) 1.36(0)	0.13 (0.06) 0.126 (0.126)	0 (0) 0(0.0009)	0(0) 0.006(0.006)	0(0) 0(0)

Yield of backgrounds

	$(\mathcal{L} = 300\,\text{fb}^{-1}, \sqrt{s} = 13\ \text{TeV})$	$\gamma\gamma \to W^+W^-\gamma$ $e\mu(ee+\mu\mu)$	$\gamma\gamma \to \tau\bar{\tau}\gamma$ $e\mu(ee+\mu\mu)$	$\gamma\gamma \to l^+l^-\gamma$ $e\mu(ee+\mu\mu)$
Type I	$p_{T,l_1} > 20$ GeV, $p_{T,l_2} > 10$ GeV $\lvert\eta_{l_1,l_2}\rvert < 2.5$, $iso < 0.15$	3.3 (3.4)	2.1 (2.2)	0.7 (464)
	$\not{E} > 30$ GeV	2.9 (2.9)	1.3 (1.4)	0.34 (188)
	$p_{T,\gamma} > 20$ GeV, $\lvert\eta_\gamma\rvert < 2.5$, $iso < 0.15$ $\Delta R_{\gamma,l_1} > 0.5$, $\Delta R_{\gamma,l_2} > 0.5$	1.5 (1.5)	0.5 (0.5)	0.02 (60)
	Veto $N_j > 2$, $p_{T,j} > 40$ GeV	1.5 (1.5)	0.5 (0.4)	0.03 (60)
	$\lvert M_{l_1 l_2} - m_Z\rvert > 10$ GeV	1.4 (1.4)	0.46 (0.4)	0.01 (52)
Type II	$0.008 < \xi < 0.2$, TOF $0.008 < \xi < 0.5$, TOF	1.2 (1.2) 1.28 (1.26)	0.2 (0.3) 0.22 (0.27)	0 (17) 0 (17)
Type III	$W_{\text{miss}} > 200$ GeV	1.2 (1.2) 1.28 (1.26)	0.18 (0.2) 0.18 (0.23)	0 (12) 0 (12)
	$0 < W_{\text{miss}} - M_{l_1 l_2 \gamma(\nu_1+\nu_2)_{\text{rec}}} < 300$	0.94 (0.94) 0.98 (0.99)	0.15 (0.2) 0.15 (0.2)	0 (0.066) 0 (0.067)

Yield of backgrounds

	$(\mathcal{L} = 300\,\text{fb}^{-1}, \sqrt{s} = 13\ \text{TeV})$	$\gamma\gamma \to W^+W^-\gamma$ $e\mu(ee+\mu\mu)$	$\gamma\gamma \to \tau\bar{\tau}\gamma$ $e\mu(ee+\mu\mu)$	$\gamma\gamma \to l^+l^-\gamma$ $e\mu(ee+\mu\mu)$
Type I	$p_{T,l_1} > 20$ GeV, $p_{T,l_2} > 10$ GeV $\lvert\eta_{l_1,l_2}\rvert < 2.5$, $iso < 0.15$	3.3 (3.4)	2.1 (2.2)	0.7 (464)
	$\not{E} > 30$ GeV	2.9 (2.9)	1.3 (1.4)	0.34 (188)
	$p_{T,\gamma} > 20$ GeV, $\lvert\eta_\gamma\rvert < 2.5$, $iso < 0.15$ $\Delta R_{\gamma,l_1} > 0.5$, $\Delta R_{\gamma,l_2} > 0.5$	1.5 (1.5)	0.5 (0.5)	0.02 (60)
	Veto $N_j > 2$, $p_{T,j} > 40$ GeV	1.5 (1.5)	0.5 (0.4)	0.03 (60)
	$\lvert M_{l_1l_2} - m_Z\rvert > 10$ GeV	1.4 (1.4)	0.46 (0.4)	0.01 (52)
Type II	$0.008 < \xi < 0.2$, TOF	1.2 (1.2)	0.2 (0.3)	0 (17)
	$0.008 < \xi < 0.5$, TOF	1.28 (1.26)	0.22 (0.27)	0 (17)
Type III	$W_{\text{miss}} > 200$ GeV	1.2 (1.2) 1.28 (1.26)	0.18 (0.2) 0.18 (0.23)	0 (12) 0 (12)
	$0 < W_{\text{miss}} - M_{l_1l_2\gamma(\nu_1+\nu_2)_{\text{rec}}} < 300$	0.94 (0.94) 0.98 (0.99)	0.15 (0.2) 0.15 (0.2)	0 (0.066) 0 (0.067)

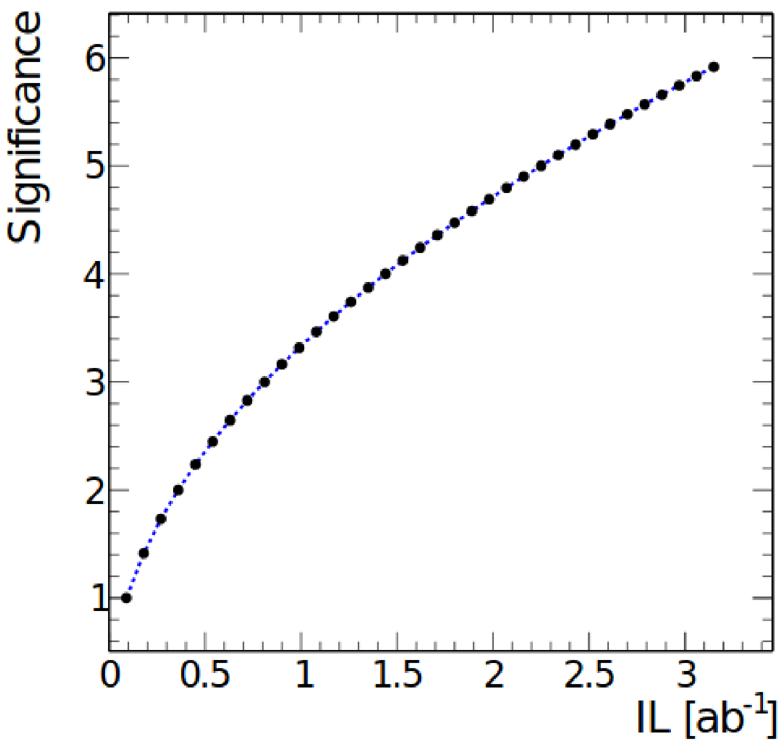
Double pomeron exchang

DPE→ $W^+W^-\gamma$ DPE→ $l^+l^-\gamma$

Backgrounds		
Process	DPE→ $W^+W^-\gamma$	DPE→ $l^+l^-\gamma$
Total cross section [fb]	5.5	7583
Gap survival rapidity [fb]	0.165	227.49
Type I selection cut eff [fb]	0.002	0.36
Type II selection cut eff [fb]	4e-6 (1e-4)	0e-5 (0e-5)
Type III selection cut eff [fb]	0e-6 (0e-4)	0e-5 (0e-5)
Final yield for 300 fb^{-1} $(ee, \mu\mu, e\mu)$)	0e-6 (0e-4)	0e-5 (0e-5)

SM measurment

- the measurements of this process needs a high amount of data.
- The advantage of having timing and tracking FDs allows us to measure this process in the high pile-up run conditions of the LHC.



SM measurment

- the measurements of this process needs a high amount of data.
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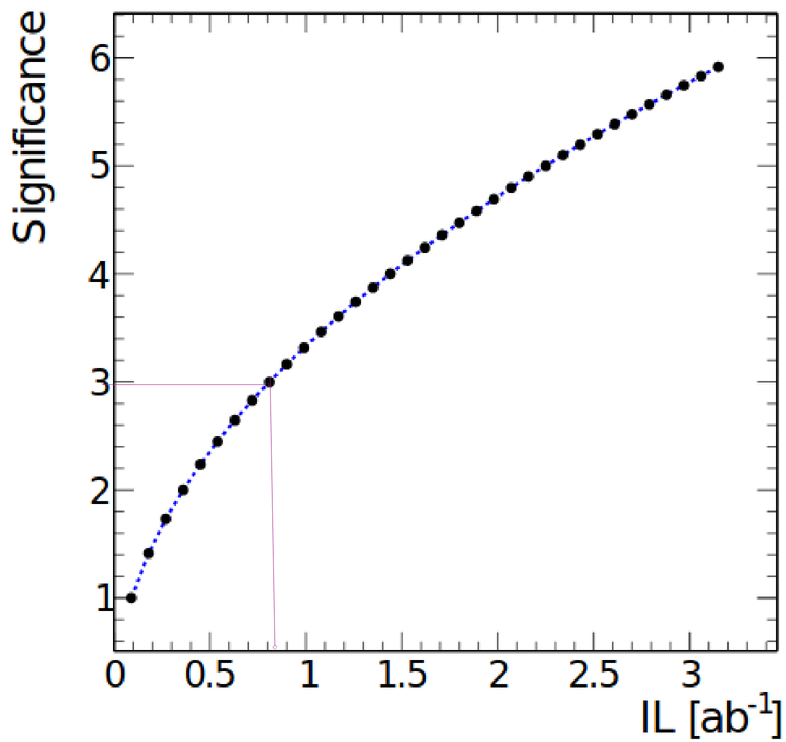
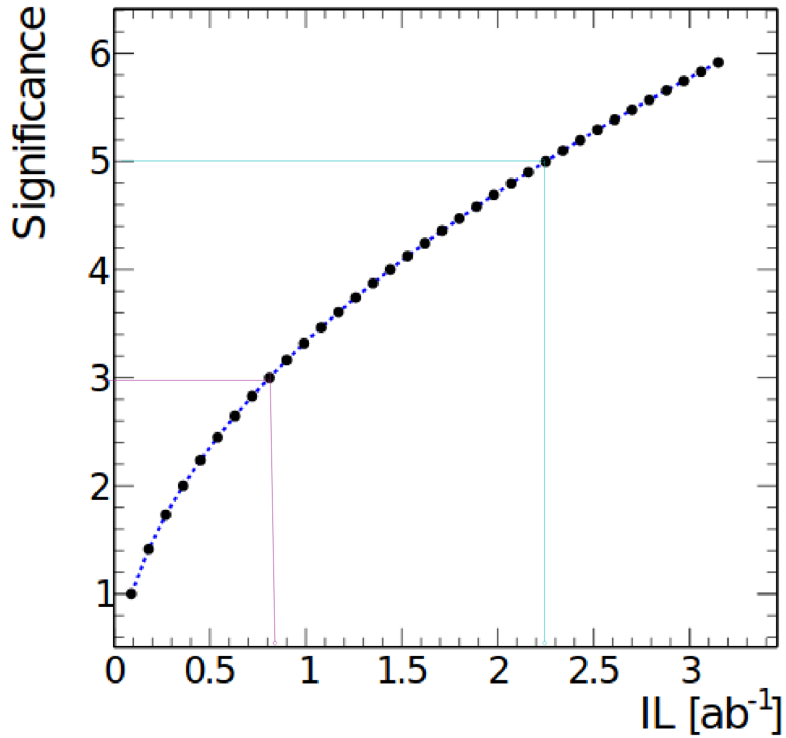


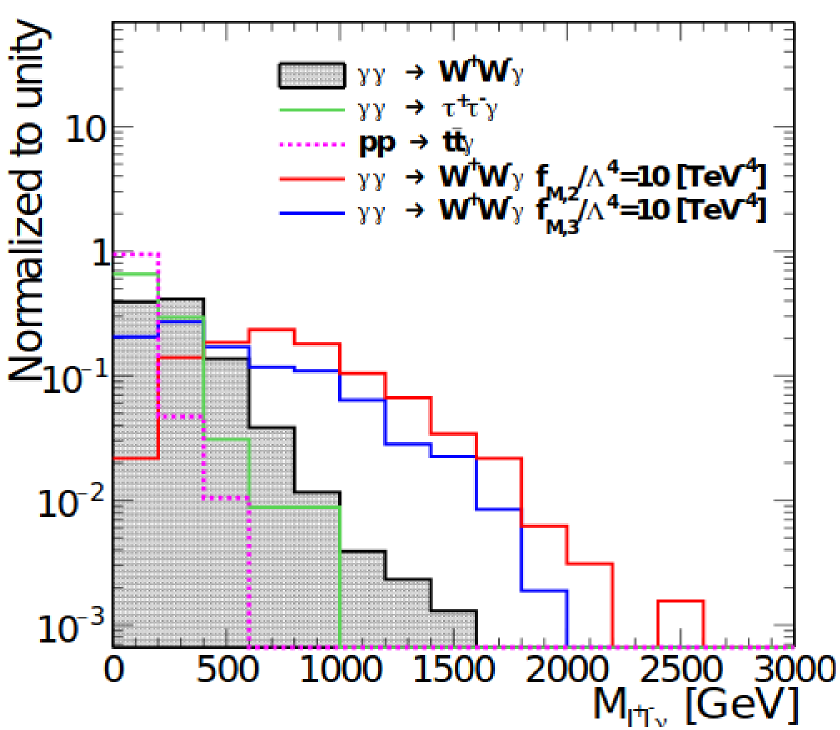
SM measurment

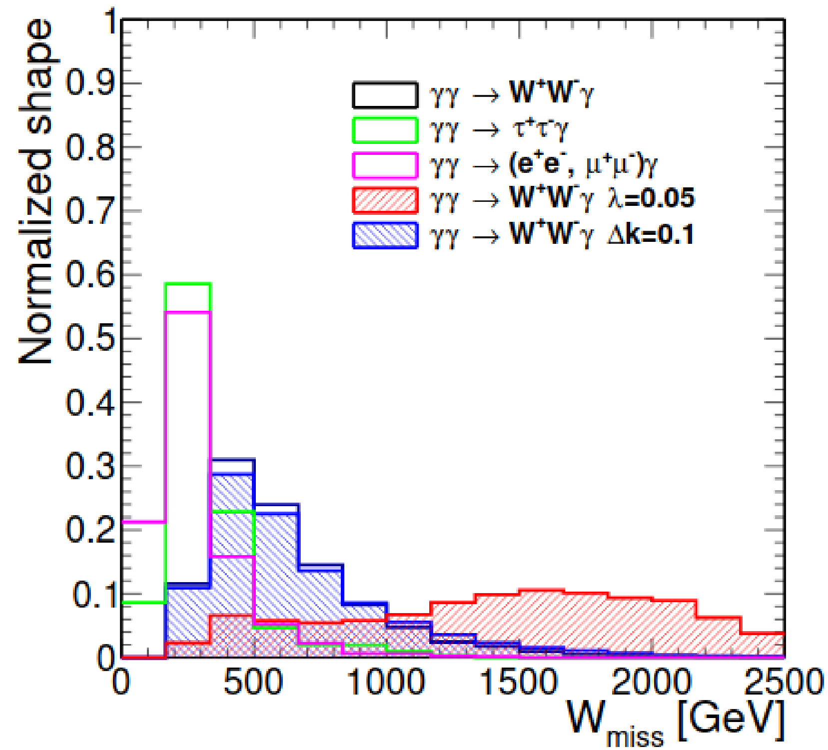
- the measurements of this process needs a high amount of data.
- The advantage of having timing and tracking FDs allows us to measure this process in the high pile-up run conditions of the LHC.

$< N_{PU} >= 30$



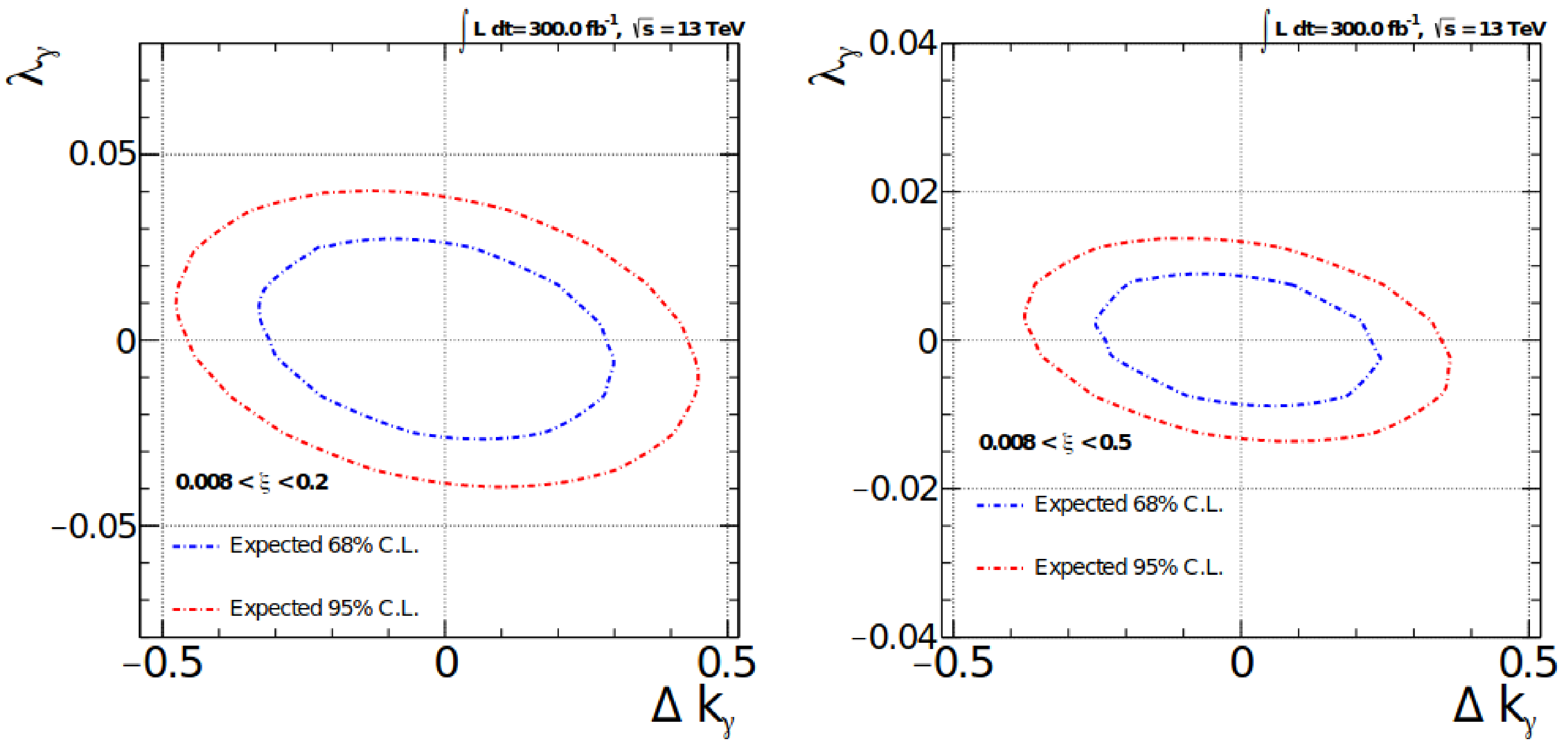
Anomalous couplings (aTGCs & aQGCs)





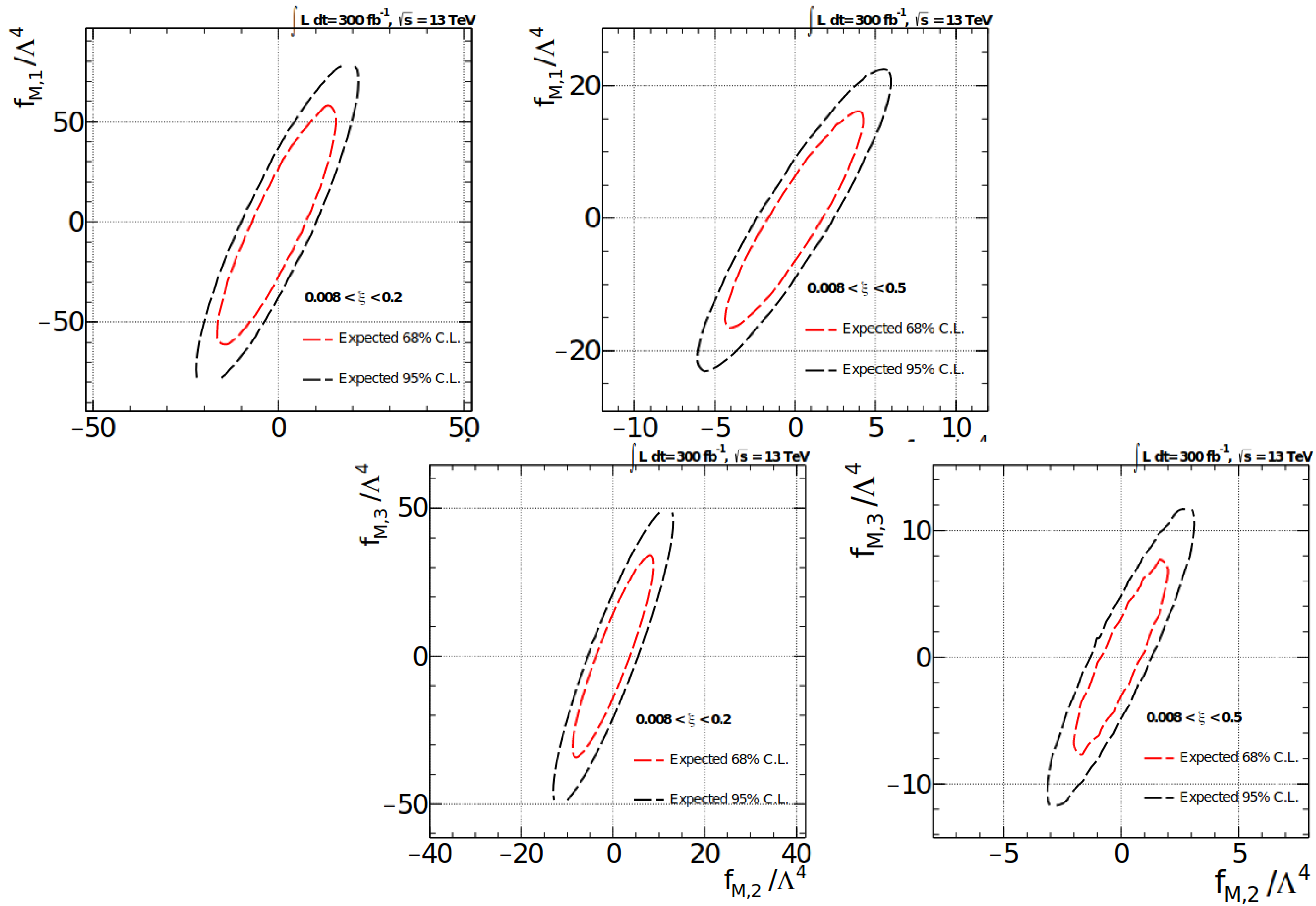
($\mathcal{L} = 300\,\mathrm{fb}^{-1}, \sqrt{s} = 13$ TeV)	Backgrounds $e\mu + ee + \mu\mu$	$\lambda = 0.05$ $e\mu + ee + \mu\mu$	$f_{M,1}/\Lambda^4 = 10$ TeV^{-4} $e\mu + ee + \mu\mu$	$f_{M,3}/\Lambda^4 = 10$ TeV^{-4} $e\mu + ee + \mu\mu$
Type I	6745.9	116	3.5	64
TOF,$0.008 < \xi < 0.2(0.5)$	38.8 (71.3)	7(85)	1.8 (2.9)	3 (43)
$W_{\mathrm{miss}} > 900$, $M_{l^+l^-\gamma} > 200(500)$ GeV, $W_{\mathrm{miss}} - M_{l_1 l_2 \gamma(\nu_1+\nu_2)_{\mathrm{rec}}} > 0$	0.3 (0.9)	7(79)	0.3 (1.1)	2 (38)

Constraints on aTGCs



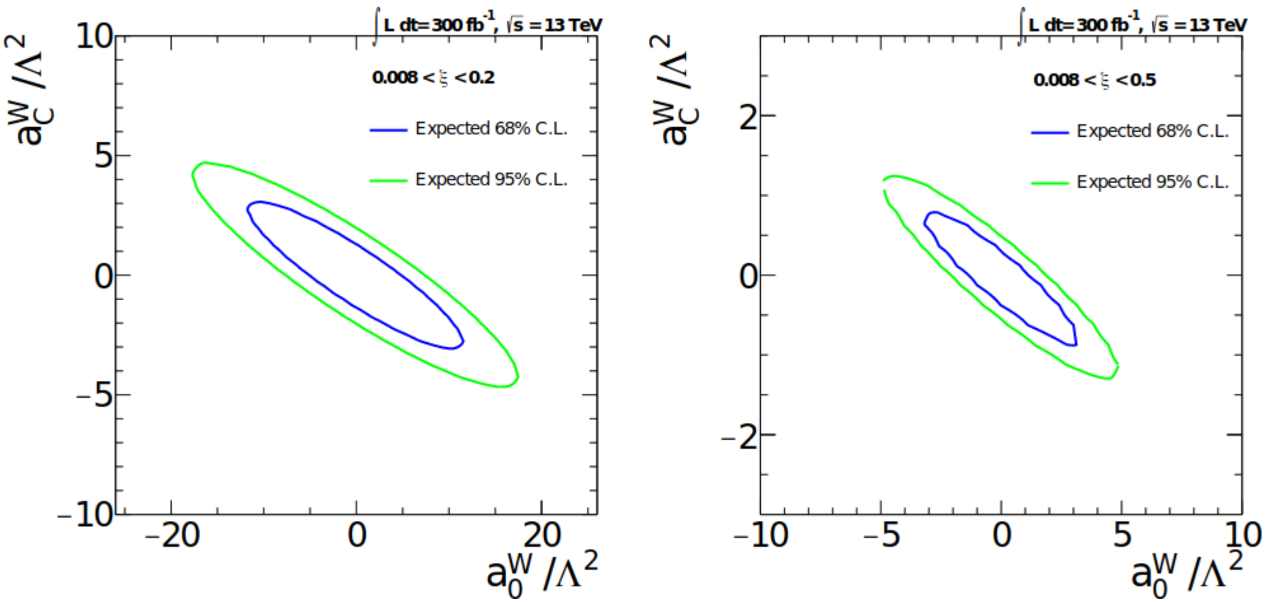
$(\mathcal{L} = 300\,\text{fb}^{-1}, \sqrt{s} = 13$ TeV$)$		
aTGCs	0.008< ξ <0.2	0.008< ξ <0.5
λ_γ	68% C.L. [-0.019,0.019] 95% C.L. [-0.032,0.032]	68% C.L. [-0.006,0.006] 95% C.L. [-0.011,0.011,]
$\Delta\kappa_\gamma$	68% C.L. [-0.16,0.15] 95% C.L. [-0.26,0.25]	68% C.L. [-0.17,0.16] 95% C.L. [0.30,0.29]

AQGCs



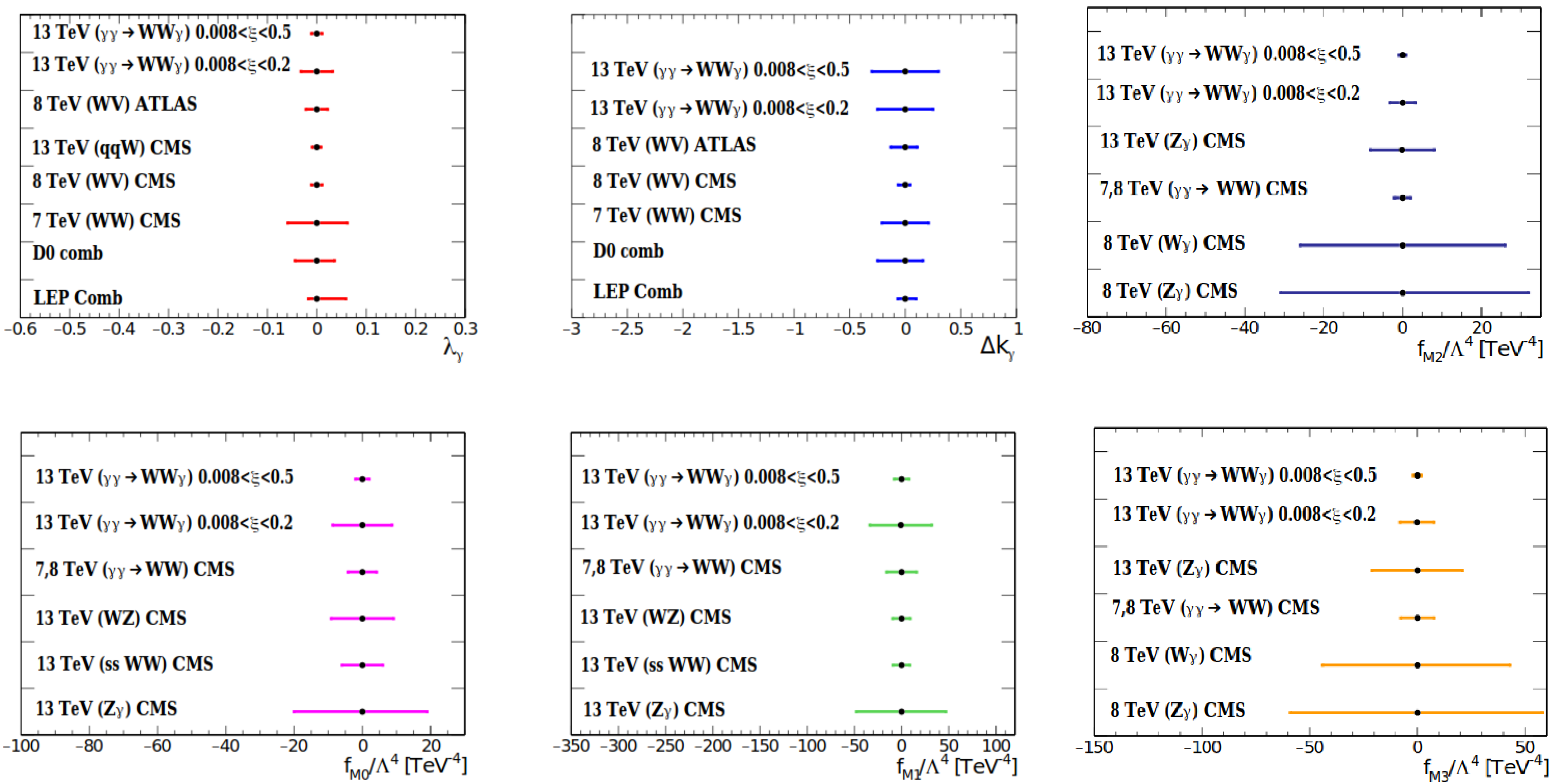
∫L dt=300 fb^-1, √s =13 TeV
f_{M,1}/Λ^4
0.008 < ξ < 0.2
Expected 68% C.L.
Expected 95% C.L.
∫L dt=300 fb^-1, √s =13 TeV
f_{M,1}/Λ^4
0.008 < ξ < 0.5
Expected 68% C.L.
Expected 95% C.L.
∫L dt=300 fb^-1, √s =13 TeV
f_{M,3}/Λ^4
0.008 < ξ < 0.2
Expected 68% C.L.
Expected 95% C.L.
f_{M,2}/Λ^4
∫L dt=300 fb^-1, √s =13 TeV
f_{M,3}/Λ^4
0.008 < ξ < 0.5
Expected 68% C.L.
Expected 95% C.L.
f_{M,2}/Λ^4

AQGCs dimension 6 and 8



68% and 95% Expected limit, ($\mathcal{L} = 300\,\text{fb}^{-1}$, $\sqrt{s} = 13$ TeV)		
dimension-8 aQGC	0.008< ξ <0.2	0.008< ξ <0.5
$f_{M,0}/\Lambda^4$(TeV^{-4})	68% C.L. [-5.7,5.7] 95% C.L. [-8.7,8.7]	68% C.L.[-1.3,1.3] 95% C.L. [-2.0,2.0]
$f_{M,1}/\Lambda^4$(TeV^{-4})	68% C.L. [-21.9,21.9] 95% C.L. [-32.8,32.8]	68% C.L. [-5.0,5.0] 95% C.L. [-7.7,7.7]
$f_{M,2}/\Lambda^4$(TeV^{-4})	68% C.L. [-1.9,1.9] 95% C.L. [-3.2,3.2]	68% C.L. [-0.5,0.5] 95% C.L. [-0.9,0.9]
$f_{M,3}/\Lambda^4$(TeV^{-4})	68% C.L. [-5.0,5.0] 95% C.L. [-7.9,7.9]	68% C.L. [-1.2,1.2] 95% C.L. [-1.9,1.9]
a_0^W/Λ^2(TeV^{-2})	68% C.L. [-1.1,1.1] 95% C.L. [-1.8,1.8]	68% C.L. [-0.3,0.3] 95% C.L. [-0.5,0.5]
a_C^W/Λ^2(TeV^{-2})	68% C.L. [-3.3,3.3] 95% C.L. [-5.2,5.2]	68% C.L. [-0.8,0.8] 95% C.L. [-1.2,1.2]

Comparing to previous results



Summary

- For the first time, the potential of the LHC to measure the CEP of $W^+W^-\gamma$ is explored.
- sensitivity of this process to the aTGCs and aQGCs is explored.
- Signal events suffer from two major sources of background
  - inclusive processes.
  - other CEP processes with the common final state particles.
- the presence of forward detectors with high resolution on momentum and arrival time of protons is vital to suppress background contributions.

Summary

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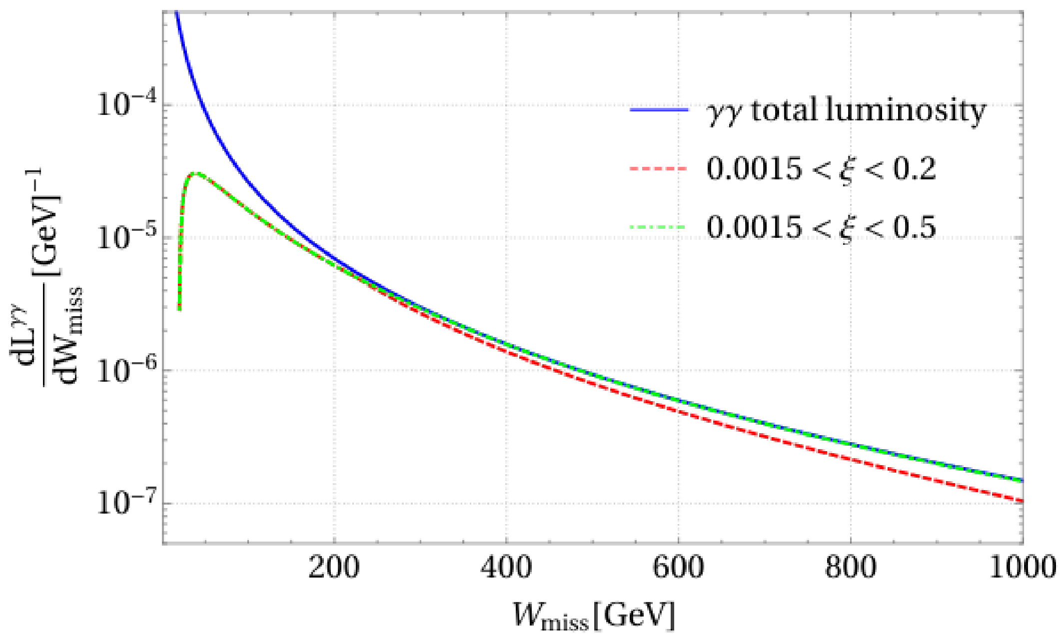
- Signal events suffer from two major sources of background
  - inclusive processes
  - other CEP processes with the common final state particles
- the presence of forward detectors with high resolution on momentum and arrival time of protons is vital to suppress background contributions.
- Thanks for your attention

Back up slides

Photon-Photon cross-section

- The cross section of the CEP process when two photons exchange, can be computed in theframework of the Equivalent Photon Approximation (EPA)

$$\frac{\mathrm{d}\sigma^{\gamma\gamma\to X}}{\mathrm{d}\Omega} = \int \frac{\mathrm{d}\sigma^{\gamma\gamma\to X}(W_{\mathrm{miss}})}{\mathrm{d}\Omega} \frac{\mathrm{d}\mathcal{L}^{\gamma\gamma}}{\mathrm{d}W_{\mathrm{miss}}} \mathrm{d}W_{\mathrm{miss}}$$



Form factor

$$a_{0,C}^{W} \to a_{0,C}^{W}\left(W_{\gamma\gamma}^{2}\right) = a_{0,C}^{W}\left(1 + \frac{W_{\gamma\gamma}^{2}}{\Lambda_{\text{cutoff}}^{2}}\right)^{-2}$$

Λ_{cutoff} : energy cutoff scale

Pomeron cross section

$$\frac{\sigma_{pp\to W^+W^-/l^+l^-}}{\sigma_{pp\to W^+W^-\gamma/l^+l^-\gamma}} = \frac{\sigma_{DPE\to W^+W^-/l^+l^-}}{\sigma_{DPE\to W^+W^-\gamma/l^+l^-\gamma}}.$$

values of 243.3 and 92.5