Exclusive diffractive results from CMS and TOTEM at the LHC

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On behalf of the CMS and TOTEM collaborations

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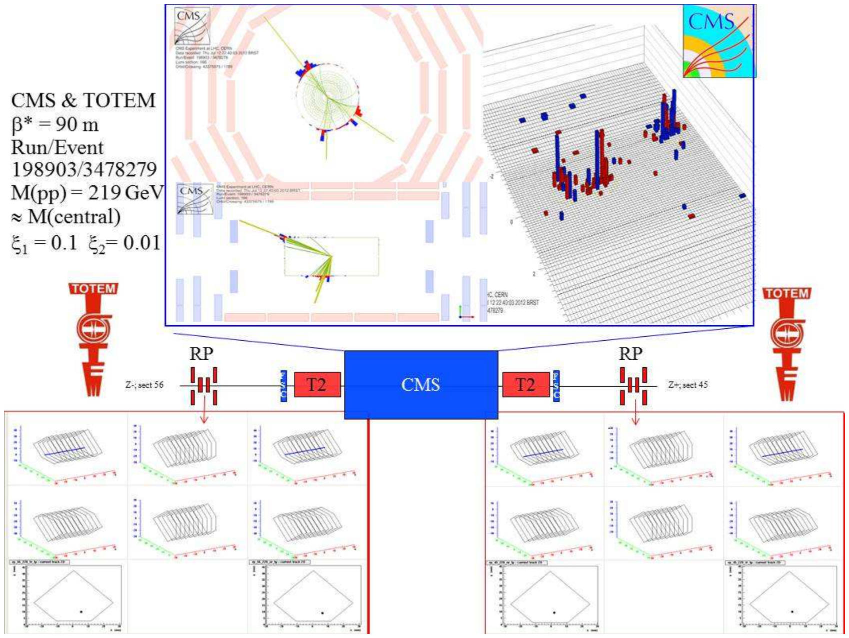
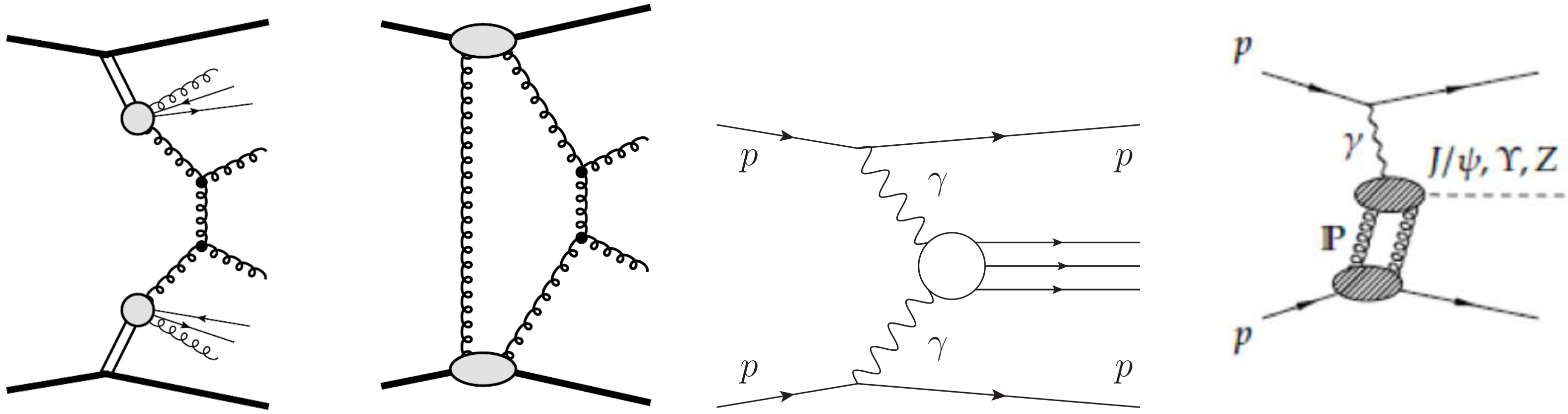


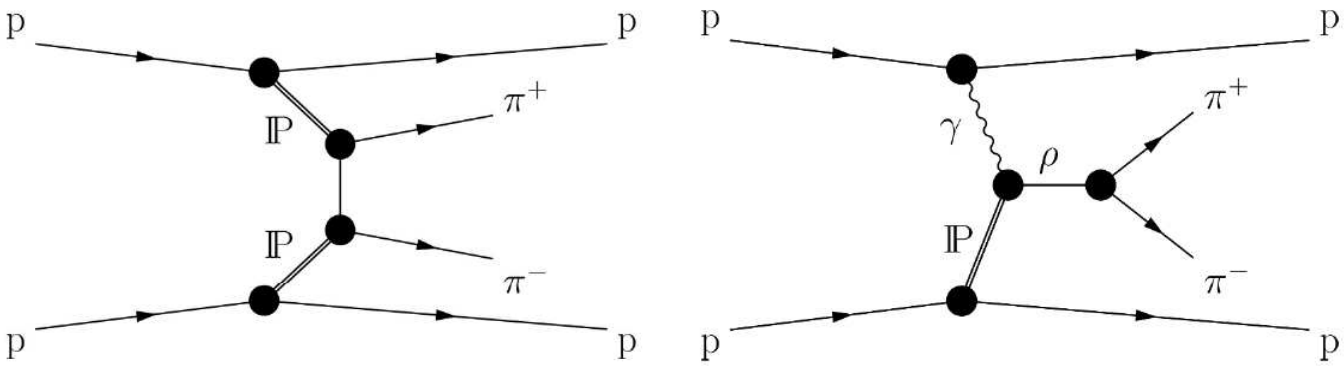
- Pion pair production
- WW pair production
- Observation of exclusive $\mu\mu$ production in CT-PPS and prospects

What do we call Exclusive Diffraction / γ exchange events?



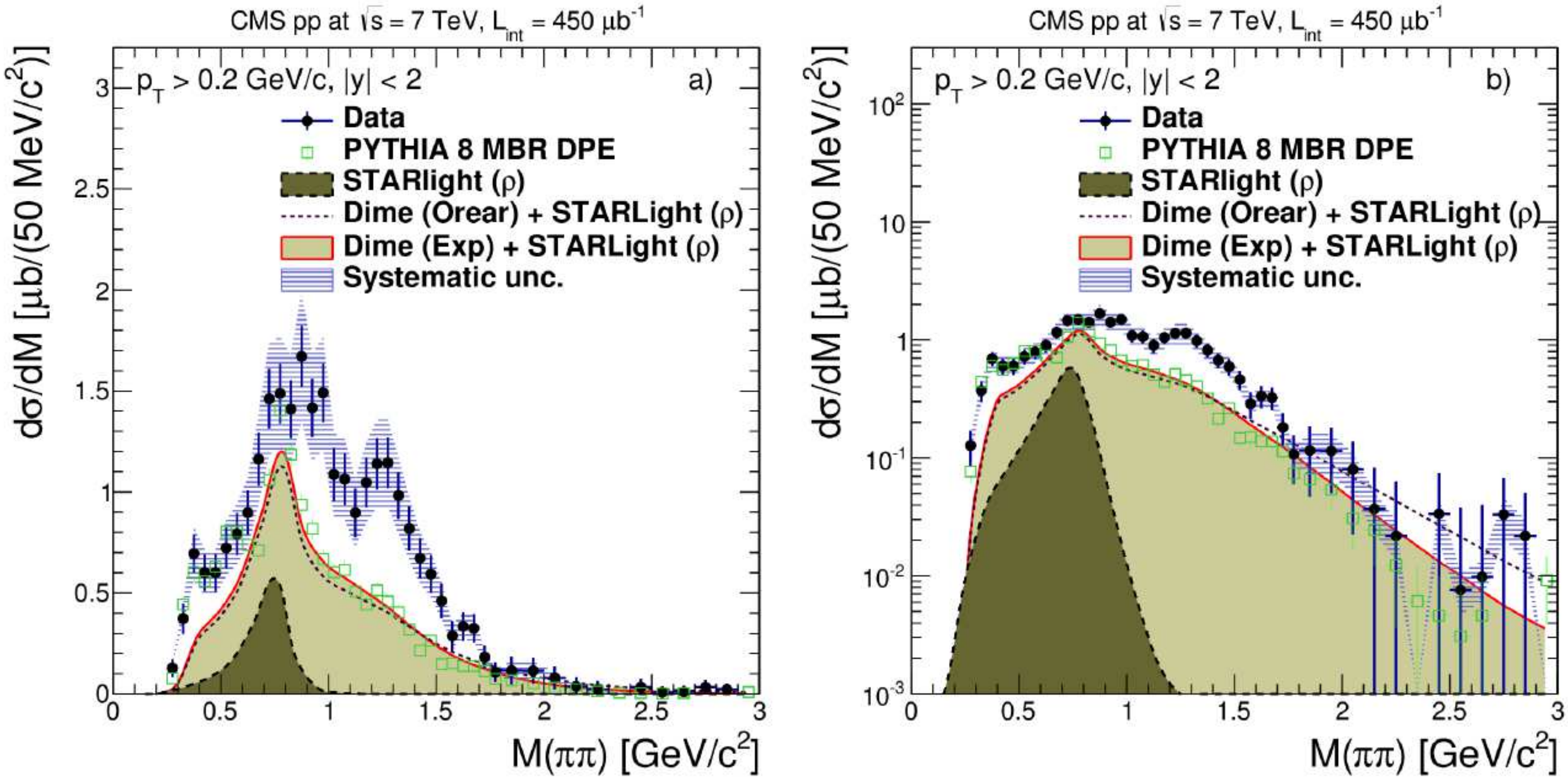
- Left diagram: Double Pomeron Exchange: some energy is "lost" in Pomeron remnants
- Next three diagrams: Exclusive production: the full energy is used to produce dijets, vector mesons, no energy loss
  - Dijet production via gluon exchange, QCD process (KMR)
  - Photon exchange
  - Vector meson production
- Possibility to reconstruct the properties of the object produced exclusively (via photon and gluon exchanges) from the tagged proton: system completely constrained
- Central exclusive production is a potential channel for BSM physics: sensitivity to high masses up to 1.8 TeV

CMS results on exclusive pion production



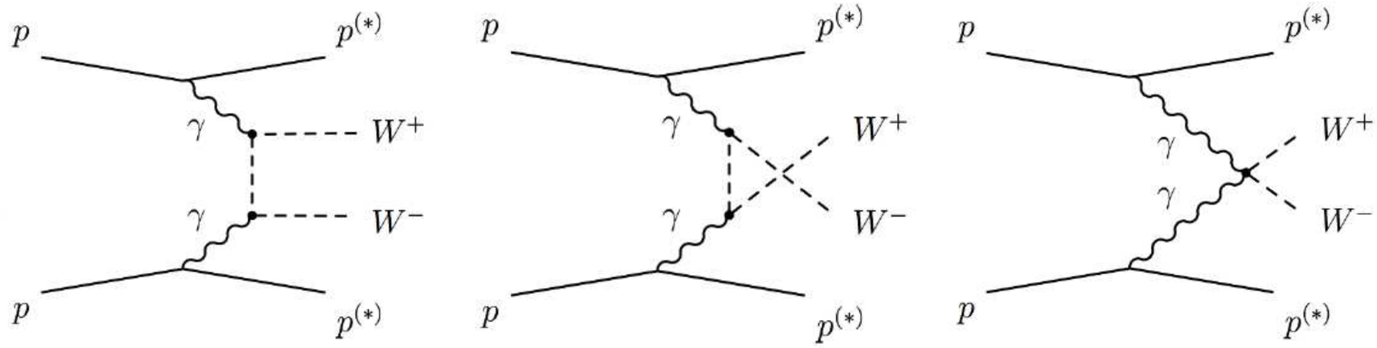
- Exclusive pion production in CMS
- Soft Pomeron exchange is dominant at low mass: Photon exchange contribution is much suppressed
- Measurement can be performed in special runs at low luminosity: no pile up, high cross section
- Experimental signature: only two opposite tracks from the same primary vertex; no additional signal in calorimeter; $p_T(\pi) > 0.2GeV$; $|y(\pi)| < 2$
- Background computed directly using data and same sign events (pure background sample)

CMS results on exclusive pion production



- Data compared to the predictions from DIME MC (DPE) and STARLIGHT MC (ρ contribution)
- Disagreement with theory especially in normalization as expected: MC does not contain proton dissociation events (ArXiv:1706.08310)
- $\sigma_{\pi^+\pi^-} = 26.5 \pm 0.3(stat) \pm 5.0(syst) \pm 1.1(lumi)$ μb

CMS results on exclusive WW production



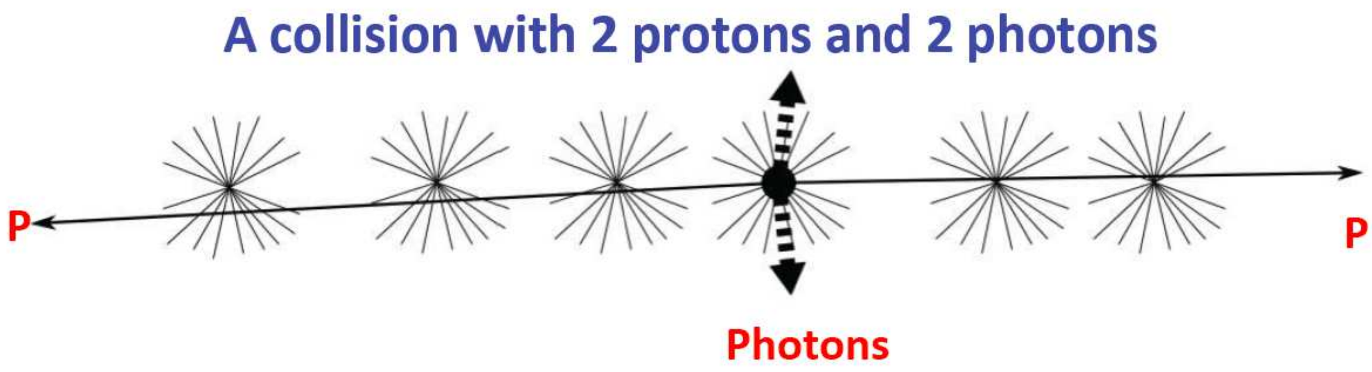
- Look for WW exclusive production
- Motivation: sensitive to $\gamma\gamma WW$ quartic anomalous couplings that could be a sign of new physics
- Quartic gauge anomalous $WW\gamma\gamma$ and $ZZ\gamma\gamma$ couplings parametrised by a_0^W, a_0^Z, a_C^W, a_C^Z

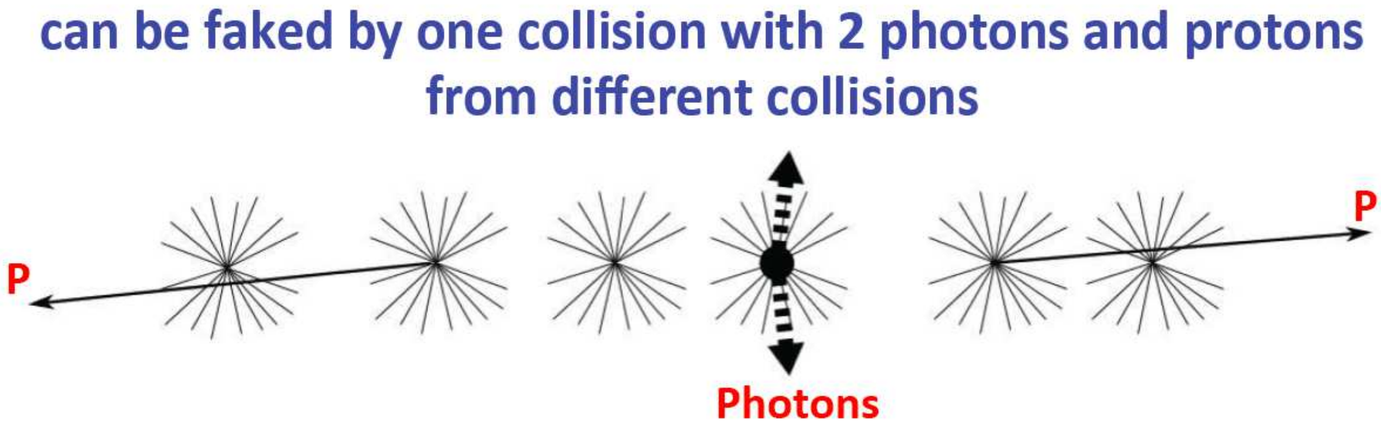
$$\mathcal{L}_6^0 \sim \frac{-e^2}{8}\frac{a_0^W}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W_\alpha^- - \frac{e^2}{16\cos^2(\theta_W)}\frac{a_0^Z}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}Z^\alpha Z_\alpha$$

$$\mathcal{L}_6^C \sim \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}(W^{+\alpha}W_\beta^- + W^{-\alpha}W_\beta^+) - \frac{e^2}{16\cos^2(\theta_W)}\frac{a_C^Z}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}Z^\alpha Z_\beta$$

- Anomalous parameters equal to 0 for SM

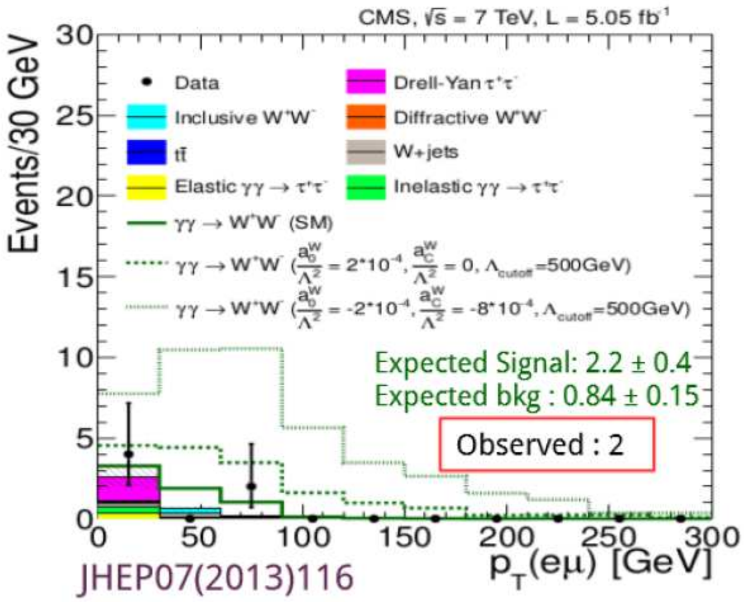
One aside: what is pile up at LHC?

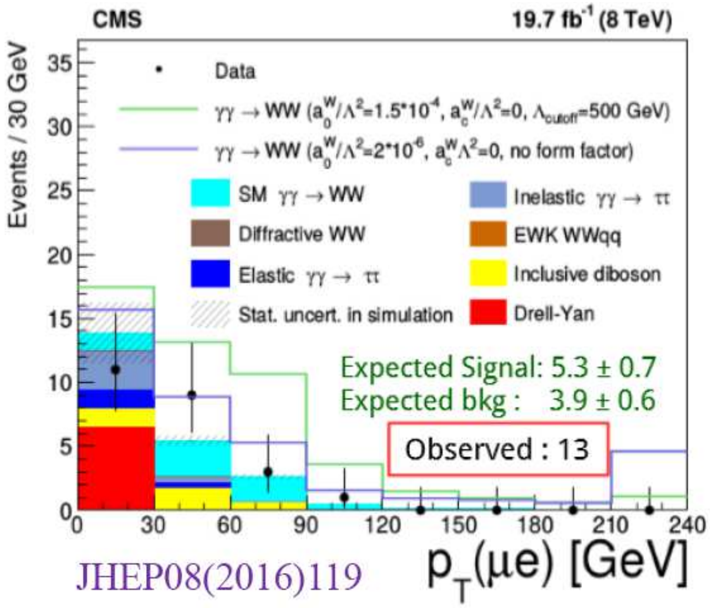




- Due to high number of protons in one packet, there can be more than one pp interaction when the packets collide
- Typically up to 50 pile up events in Run II (about 25-30 now)
- Analyses at high luminosity because of lower production cross section (exclusive WW, $\gamma\gamma$...): need to fight pile up!

CMS results on exclusive WW production

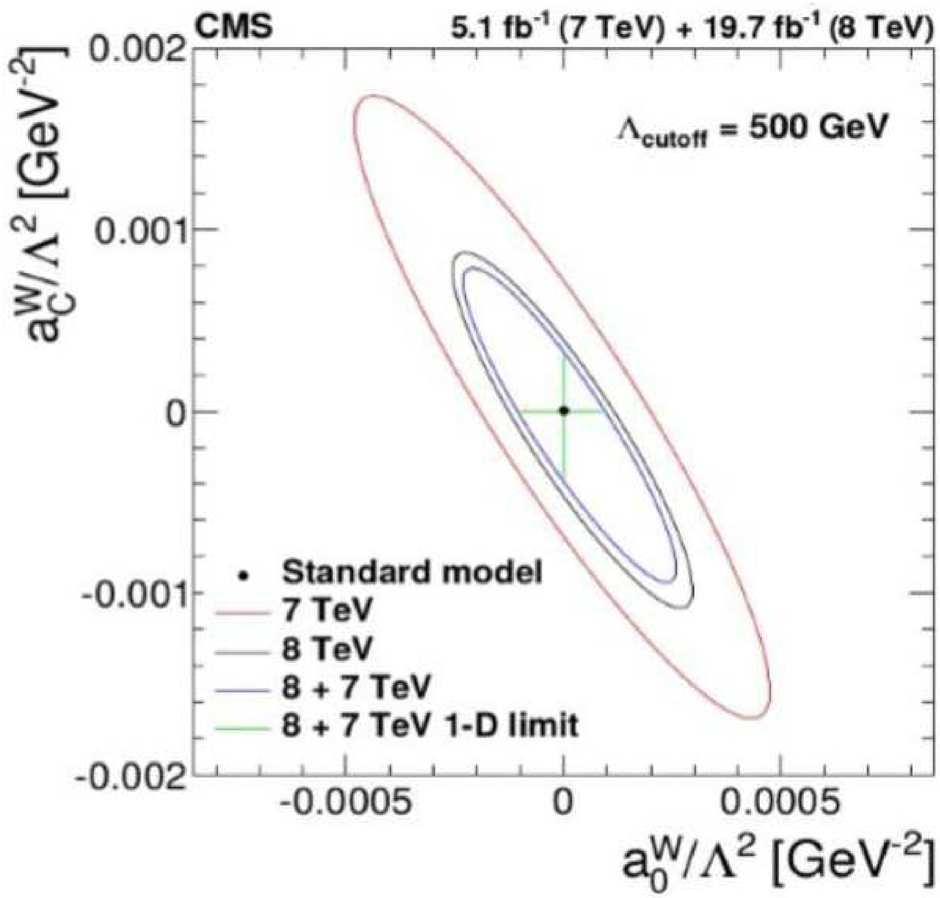




- Exclusive WW are rare (SM cross section of the order of 97 fb^{-1} $\rightarrow$ full luminosity needed and reject pile up background
- 2011 pp data at 7 TeV: 5.05 fb^{-1}
- 2012 pp data at 8 TeV: 19.7 fb^{-1}
- Exclusive selection: opposite sign $e\mu$ from common primary vertex, no extra track from vertex, $M_{e\mu} > 20$ GeV to avoid low mass resonances, $p_T^{e\mu} >$ 30 GeV to remove Drell Yan and $\gamma \rightarrow \tau\tau$
- $\sigma(pp \rightarrow pWWp \rightarrow p\mu ep = 2.2^{+3.3}_{-2.0}$ fb at 7 TeV (SM 4.0 $\pm$ 0.7 fb) and $\sigma(pp \rightarrow pWWp \rightarrow p\mu ep = 10.8^{+5.1}_{-4.1}$ fb at 8 TeV (SM: 6.2 $\pm$ 0.5 fb) after correction for proton dissociation
- Observed significance for 7 and 8 TeV combination: 3.4 σ

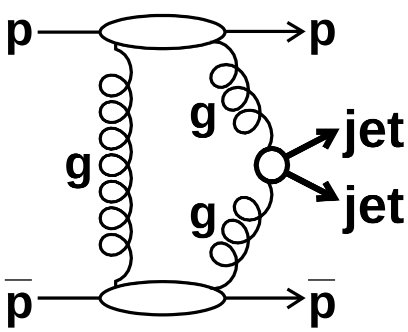
CMS results on exclusive WW production

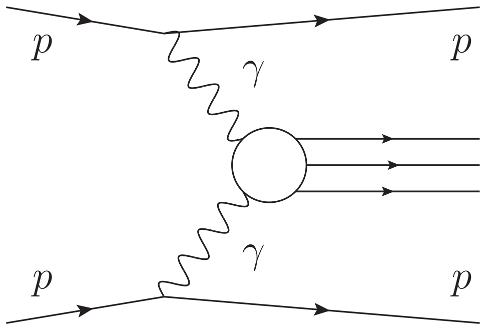
- Most stringent limits on $\gamma\gamma WW$ quartic anomalous coupling
- JHEP08 (2016) 119

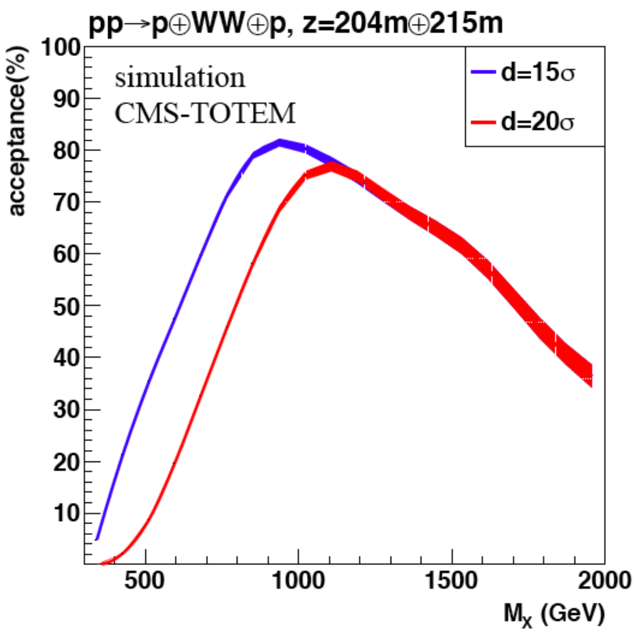


Dimension-6 AQGC parameter	7 TeV ($\times 10^{-4}$ GeV^{-2})	8 TeV ($\times 10^{-4}$ GeV^{-2})	7+8 TeV ($\times 10^{-4}$ GeV^{-2})
$a_0^W/\Lambda^2 (\Lambda_{cutoff} = 500\,\text{GeV})$	$-1.5 < a_0^W/\Lambda^2 < 1.5$	$-1.1 < a_0^W/\Lambda^2 < 1.0$	$-0.9 < a_0^W/\Lambda^2 < 0.9$
$a_C^W/\Lambda^2 (\Lambda_{cutoff} = 500\,\text{GeV})$	$-5 < a_C^W/\Lambda^2 < 5$	$-4.2 < a_C^W/\Lambda^2 < 3.4$	$-3.6 < a_C^W/\Lambda^2 < 3.0$

What is CT-PPS?

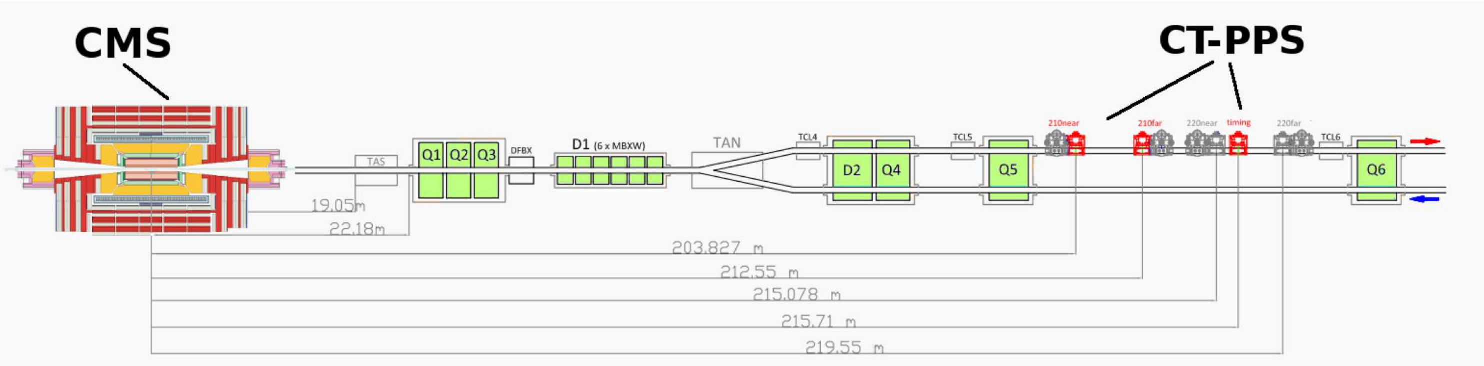


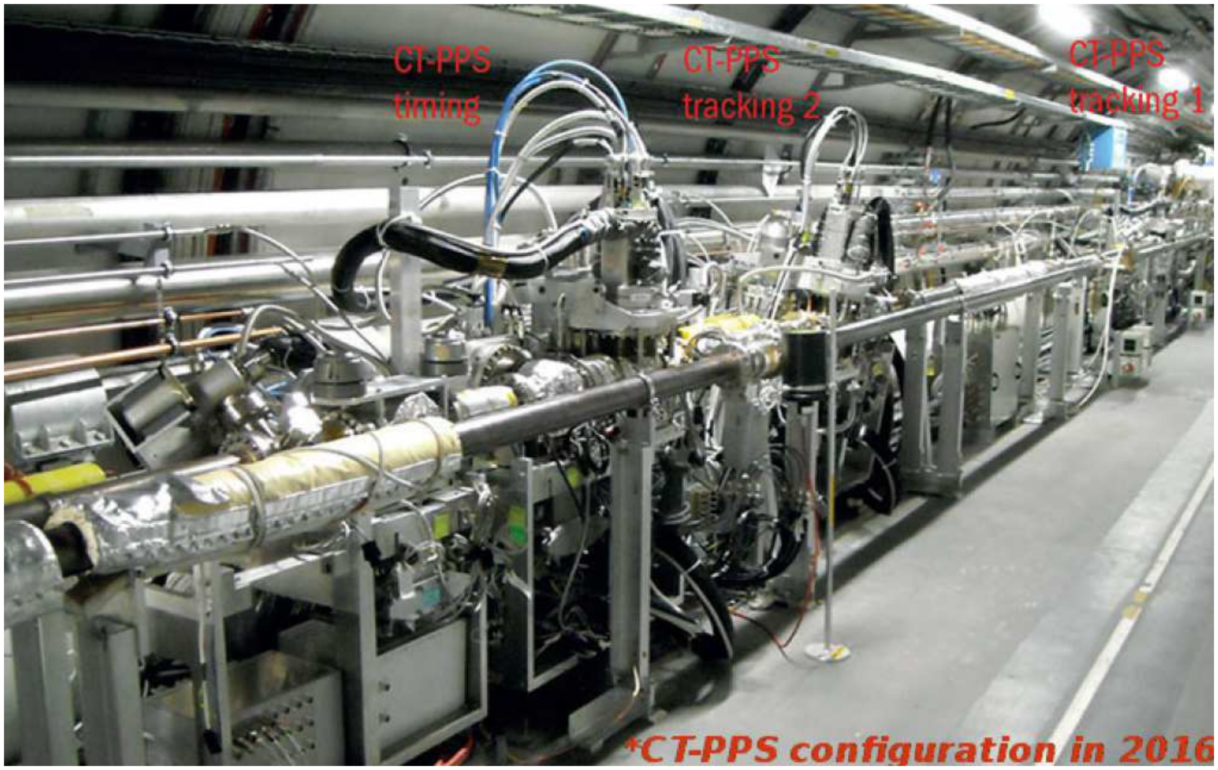




- Tag and measure protons at ± 210 m: AFP (ATLAS Forward Proton), CT-PPS (CMS TOTEM - Precision Proton Spectrometer)
- All anomalous coupling cross sections computed using the Forward Physics Monte Carlo (FPMC)
- Sensitivity to high mass central system, X, as determined using AFP/CT-PPS: Very powerful for exclusive states: kinematical constraints coming from AFP and CT-PPS proton measurements

What is CT-PPS?

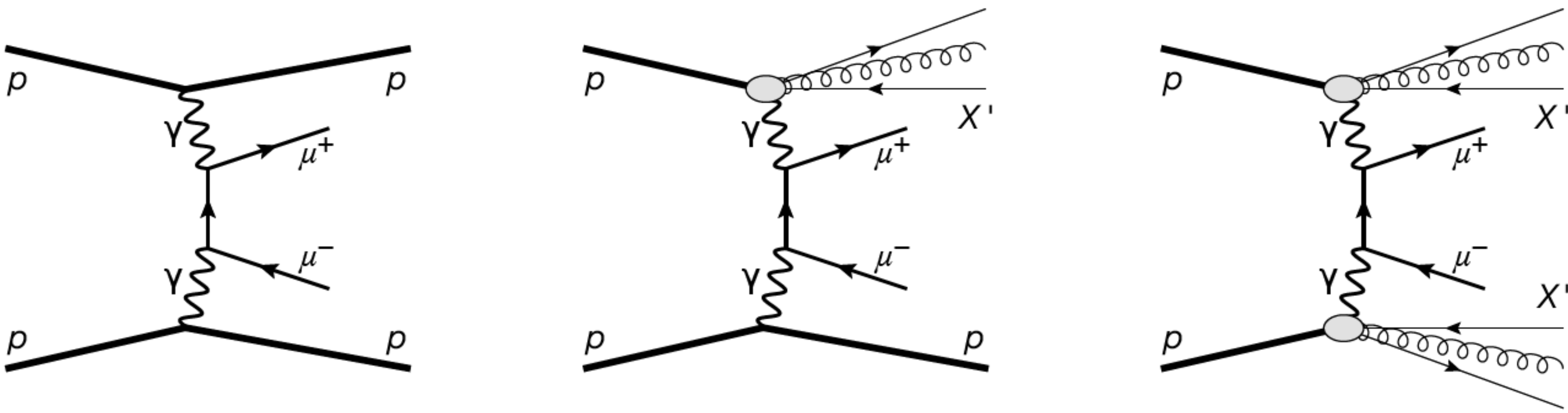




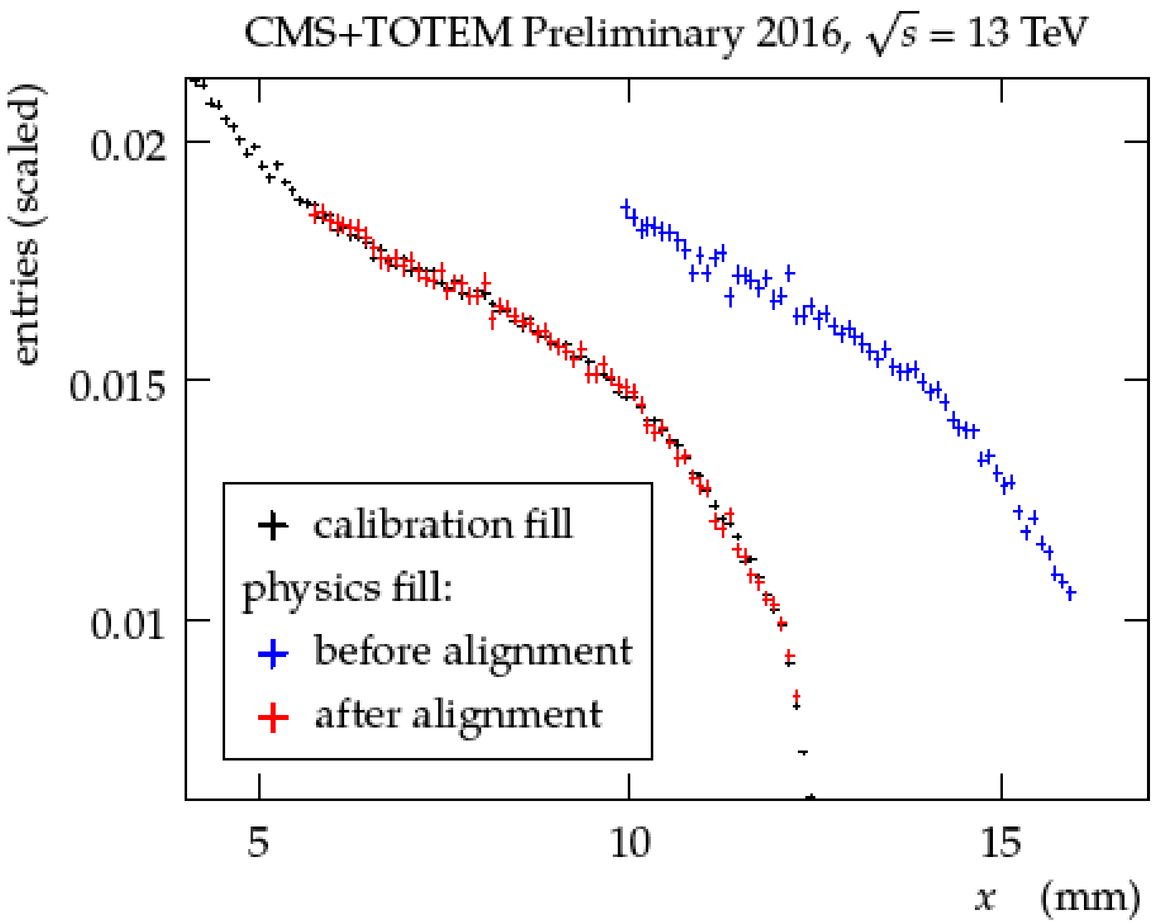
- Joint CMS and TOTEM project: https://cds.cern.ch/record/1753795
- LHC magnets bend scattered protons out of the beam envelope
- Detect scattered protons a few mm from the beam (both sides of CMS)
- First data taking in 2016:$\sim$ 15 fb^{-1}

Exclusive $\mu\mu$ production in CT-PPS

- Turn the LHC into a $\gamma\gamma$ collider: flux of quasi-real photons under the Equivalent Photon Approximation, dilepton production dominated by photon exchange processes
- Observation of exclusive dimuon production in CT-PPS
- First time a near-beam detector operates at a hadron collider at high luminosity
- Request only one proton tagged (< 1 event expected for double tagged events due to acceptance)
- Data-driven background estimate



CT-PPS alignment



- Step 1 - Absolute alignment: Use elastic $pp \to pp$ events in a special alignment run where both horizontal and vertical roman pots get very close to the beam
- Step 2 - Relative alignment: Use inclusive sample of protons triggered by CMS in standard runs and match distribution of proton track position to that of alignment runs

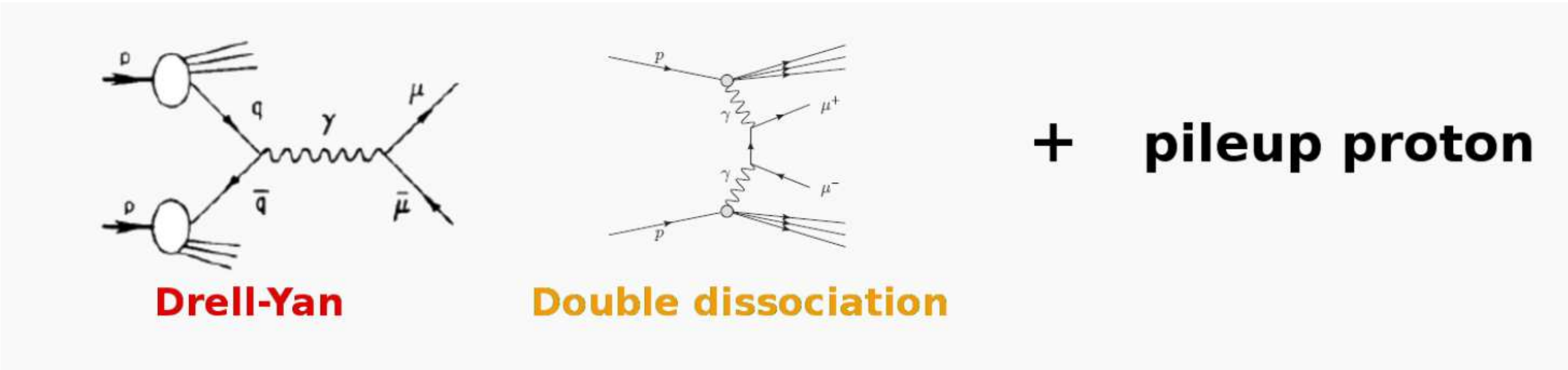
Observation of semi-exclusive dimuon production in CT-PPS: Strategy

- In order to select exclusive events: Look for correlation between direct proton ξ measurement using CT-PPS and using the dimuon system in CMS:

$$\xi^{\pm} = \frac{1}{\sqrt{s}}(p_T^{\mu_1} e^{\pm\eta^{\mu_1}} + p_T^{\mu_2} e^{\pm\eta^{\mu_2}}) \quad (1)$$

($\pm\eta$ solutions correspond to the protons in the $+z$ and $-z$ direction)

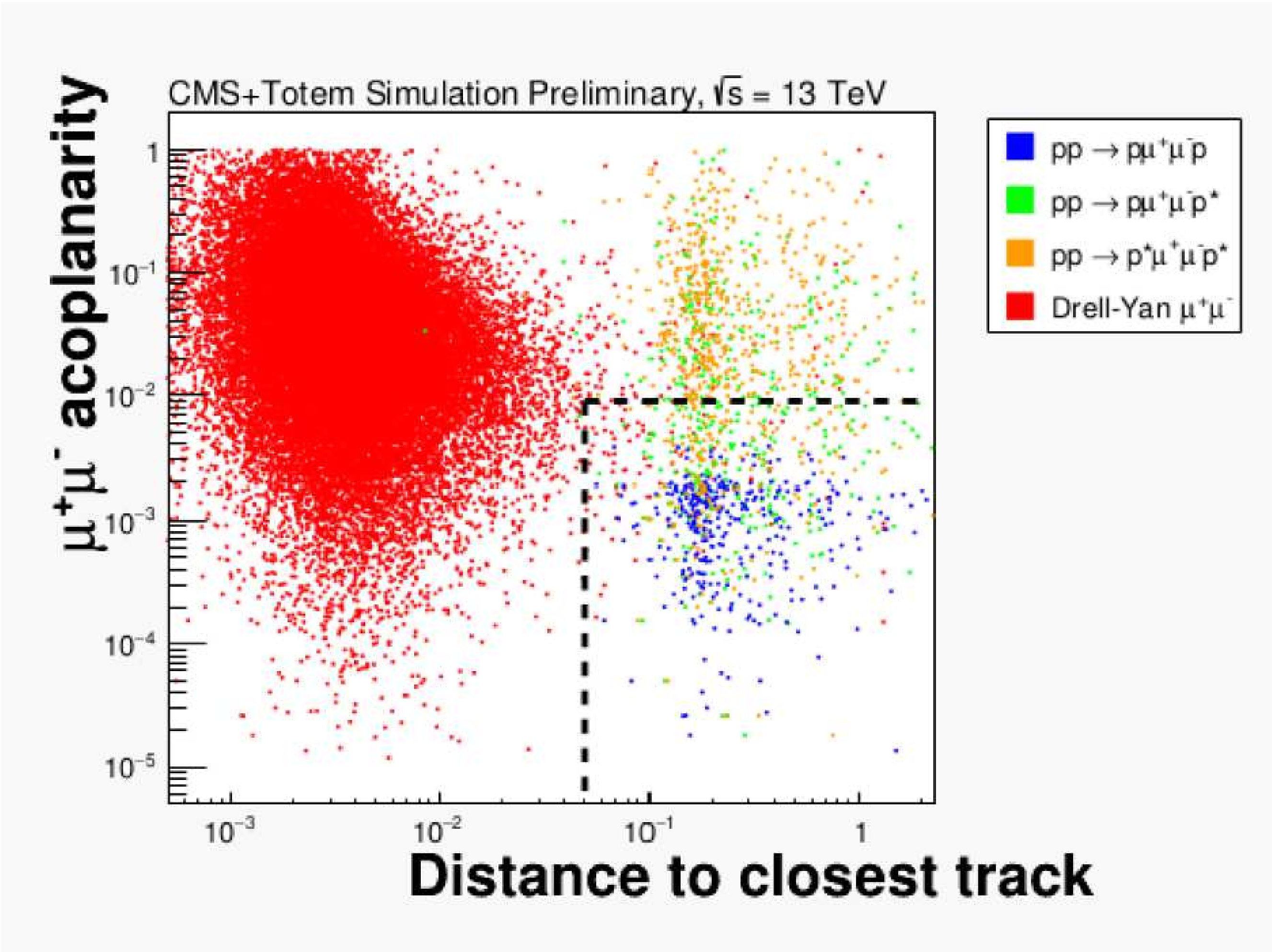
- Expected backgrounds:



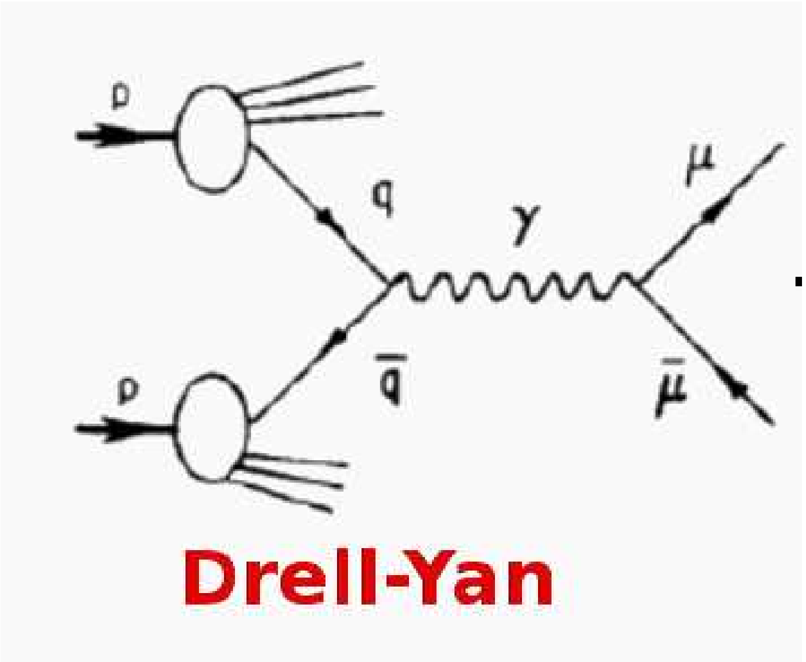
will fake signal (overlap with pile up or beam halo protons)

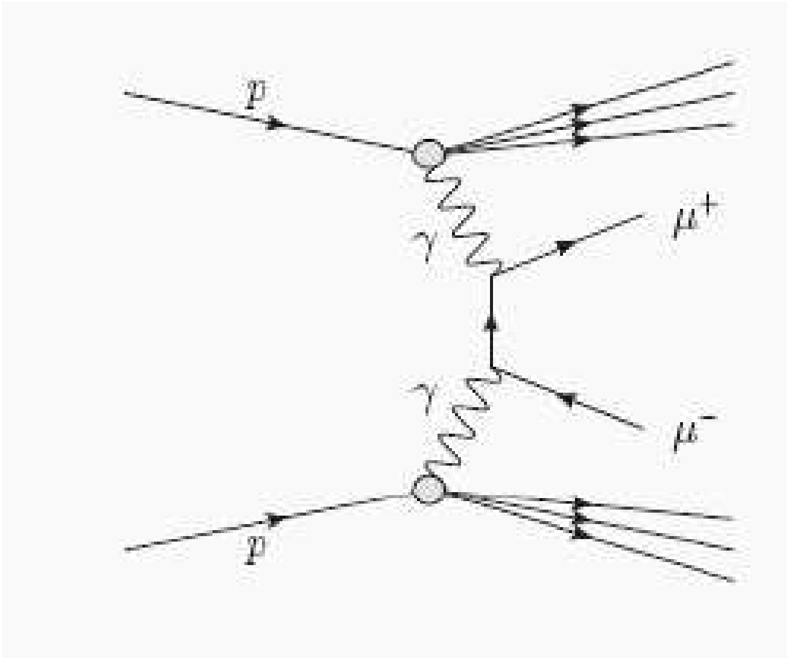
Event selection

- Request pair of opposite sign muons with $p_T > 50$ GeV and $M_{\mu\mu} > 110$ GeV above the Z boson peak
- To suppress background: Veto additional tracks around dimuon vertex (within 0.5 mm) and require back-to-back muons $|1 - \Delta\Phi/\pi| < 0.009$



Data driven background estimate

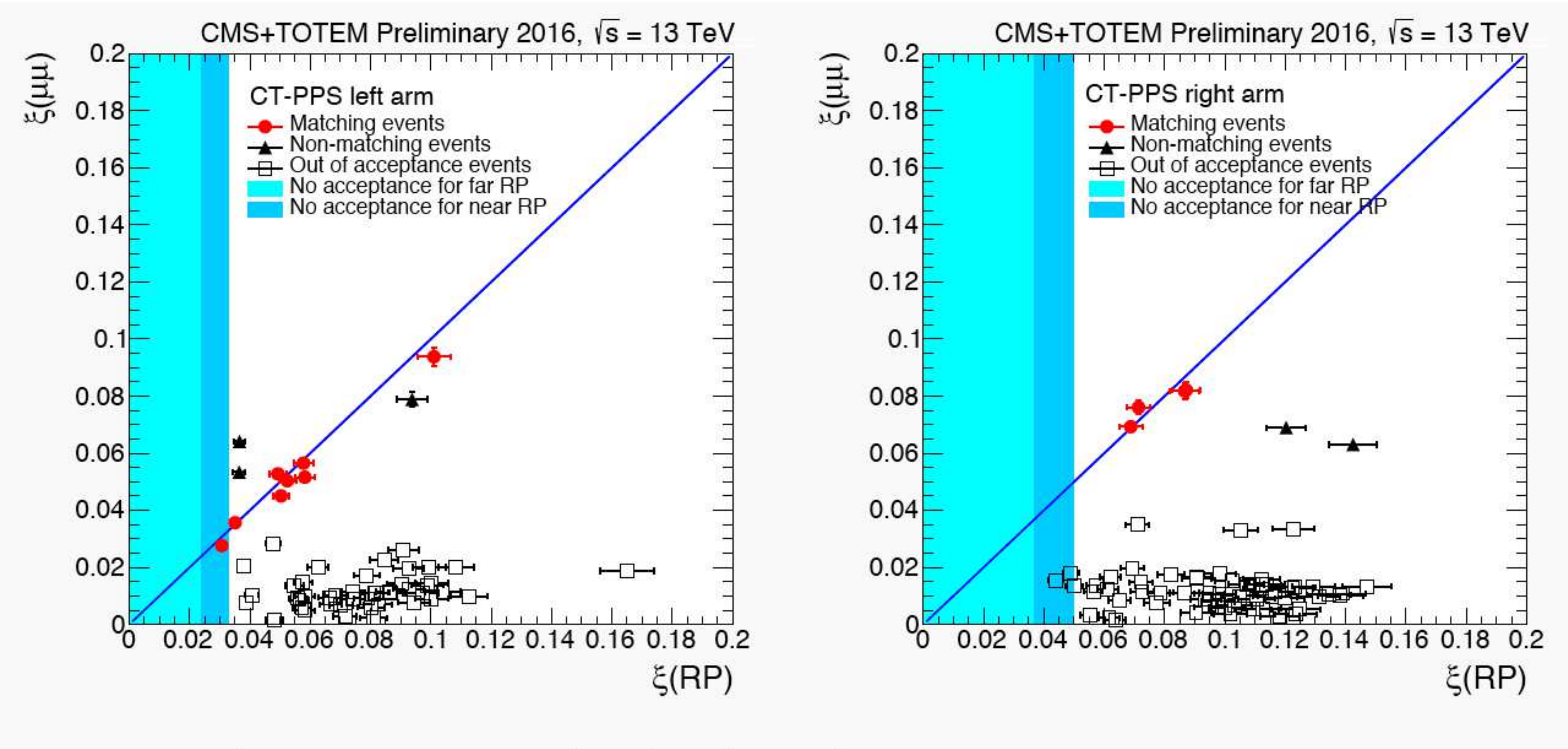




- Use sample of background protons from Z-peak events (data)
- Drell-Yan contribution: Count number of Z-peak events with $\xi(\mu\mu)$ and ξ(proton) correlated within 2σ and use MC to extrapolate from Z-peak region to signal region
- Double dissociative contribution: Mix double dissociative simulated events (LPAIR) and protons from data to derive number of matching events
- Total number of expected matching background events: $1.47 \pm 0.06(stat) \pm 0.52(syst)$

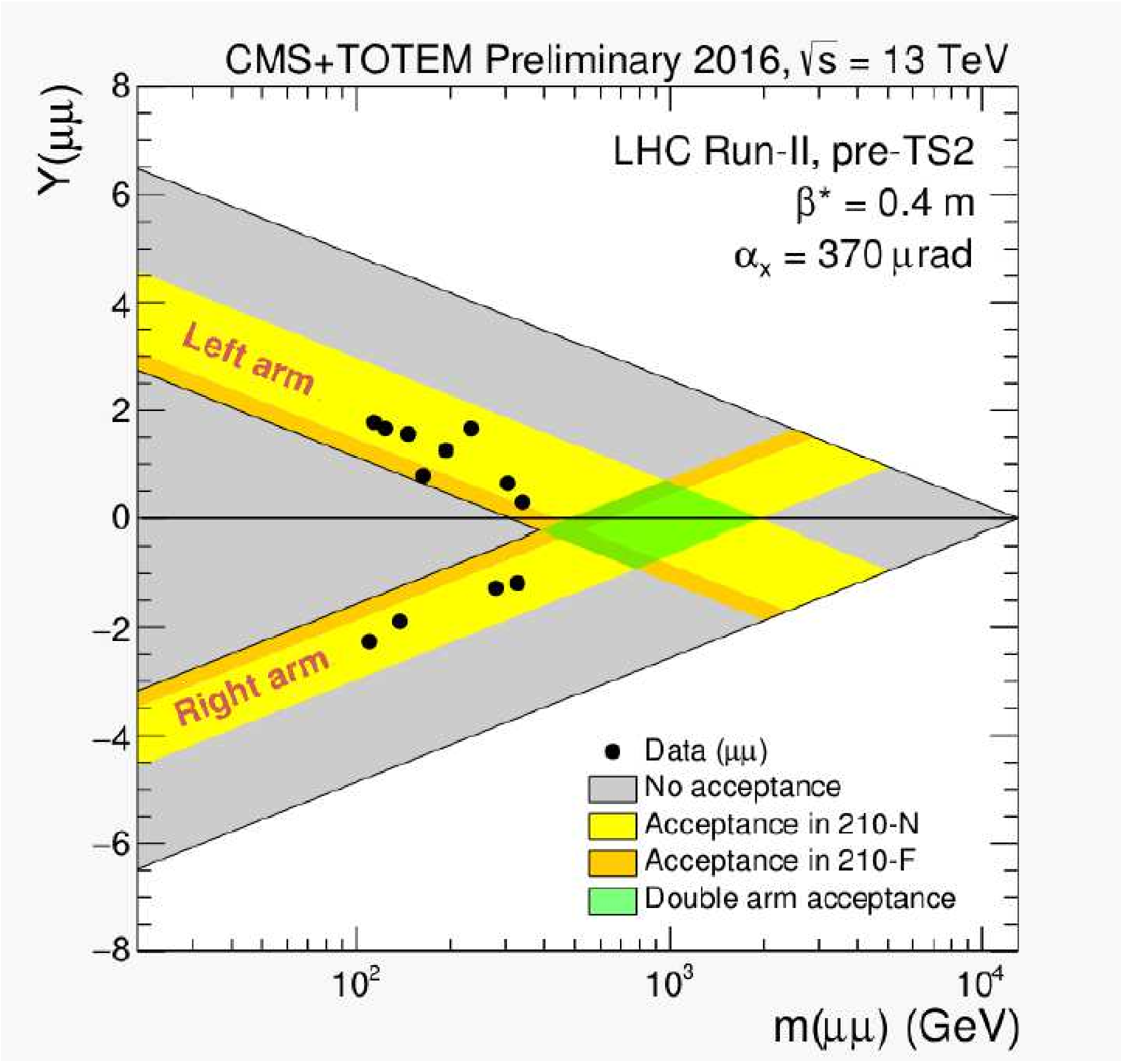
Observed signal

- First measurement of semi-exclusive di-muon process with proton tag
- CT-PPS works as expected (validates alignment, optics determination...)
- 17 events are found with protons in the CT-PPS acceptance and 12 $< 2\sigma$ matching
- Significance for observing 12 events for a background of $1.47 \pm 0.06(stat) \pm 0.52(syst)$: 4.3 σ

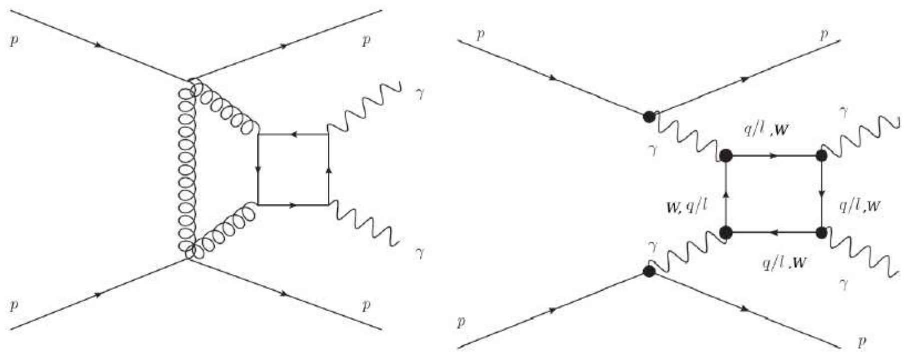


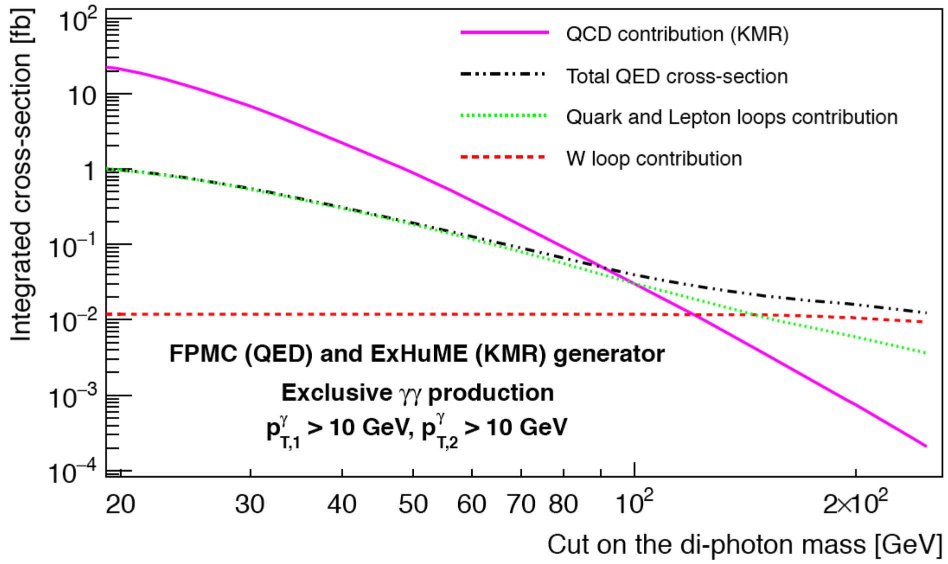
Summary of 12 candidates properties

- Dimuon invariant mass vs rapidity distributions in the range expected for single arm acceptance
- No event at higher mass that would be in the acceptance for double tagging
- Highest mass event: 341 GeV
- CMS-PAS-PPS-17-001



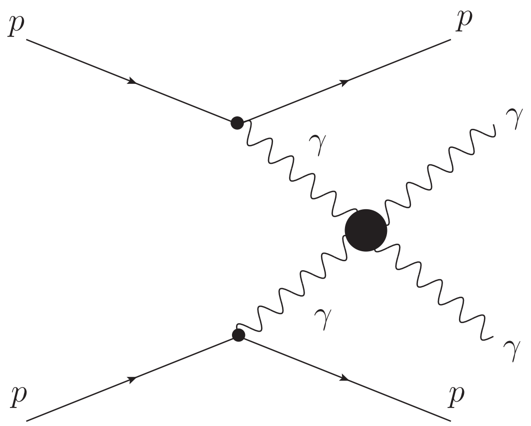
Additional photon exchange processes: diphoton production



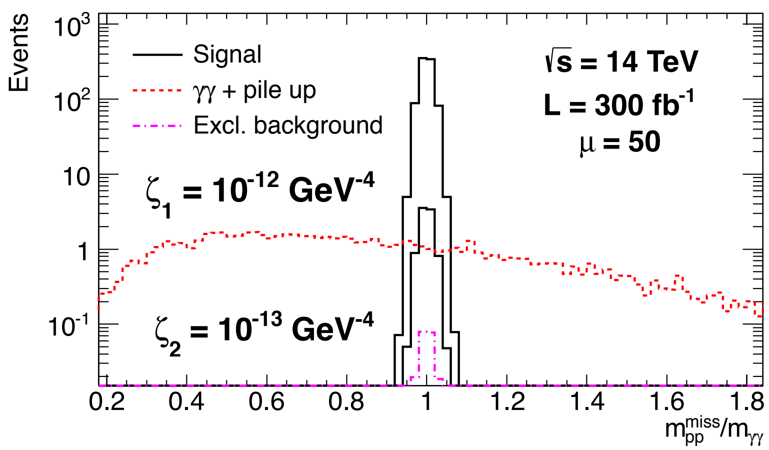


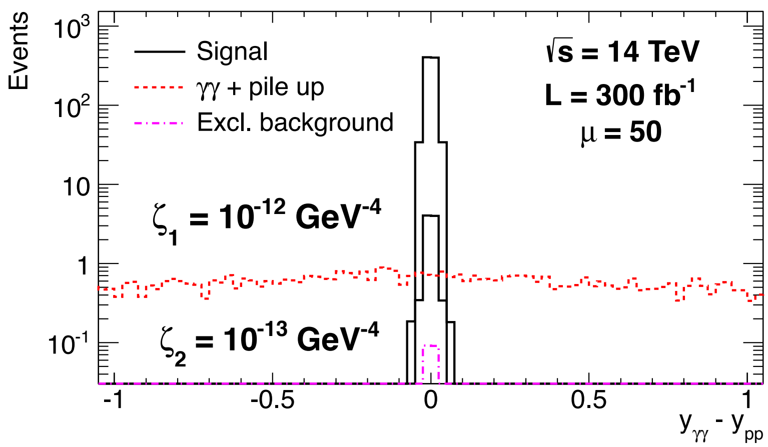
- SM QCD production dominates at low $m_{\gamma\gamma}$, QED at high $m_{\gamma\gamma}$
- Important to consider W loops at high $m_{\gamma\gamma}$
- At high masses (> 300 GeV), the photon induced processes are dominant
- **Conclusion: Two photons and two tagged protons means photon-induced process**

Search for quartic $\gamma\gamma$ anomalous couplings in AFP/CT-PPS



- Search for $\gamma\gamma\gamma\gamma$ quartic anomalous couplings
- Couplings predicted by extra-dim, composite Higgs models
- No background after cuts for 300 fb^{-1}
- Phenomenology studies in collaboration between C. Baldenegro, E. Chapon, O. Kepka, C. Royon, M. Saimpert, G. von Gersdorff, S. Fichet: Phys. Rev. D81 (2010) 074003; Phys.Rev. D89 (2014) 114004, JHEP 1502 (2015) 165; Phys. Rev. Lett. 116 (2016) no 23, 231801 and Phys. Rev. D93 (2016) no 7, 075031





Search for quartic $\gamma\gamma$ anomalous couplings

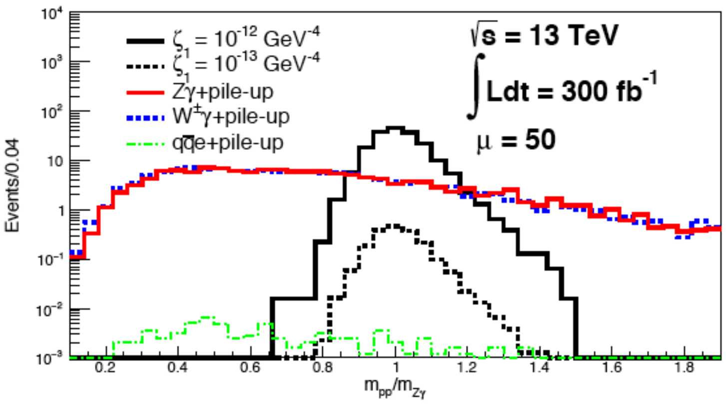
Cut / Process	Signal (full)	Signal with (without) f.f (EFT)	Excl.	DPE	DY, di-jet + pile up	$\gamma\gamma$ + pile up
$[0.015 < \xi_{1,2} < 0.15,$ $p_{T1,(2)} > 200, (100)$ GeV]	130.8	36.9 (373.9)	0.25	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	128.3	34.9 (371.6)	0.20	0	0.2	1023
$[p_{T2}/p_{T1} > 0.95,$ $\lvert\Delta\phi\rvert > \pi - 0.01]$	128.3	34.9 (371.4)	0.19	0	0	80.2
$\sqrt{\xi_1\xi_2 s} = m_{\gamma\gamma} \pm 3\%$	122.0	32.9 (350.2)	0.18	0	0	2.8
$\lvert y_{\gamma\gamma} - y_{pp}\rvert < 0.03$	119.1	31.8 (338.5)	0.18	0	0	0

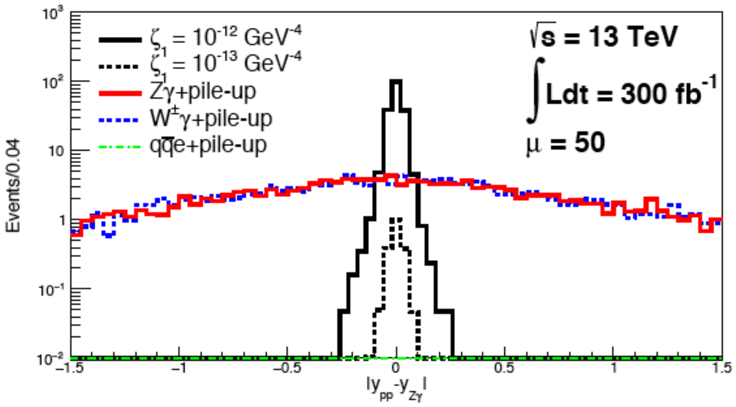
- Exclusivity cuts needed to reject background
- Exclusivity cuts using proton tagging needed to suppress backgrounds (Without exclusivity cuts using CT-PPS: background of 80.2 for 300 fb^{-1})

Luminosity	300 fb^{-1}	300 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
pile-up (μ)	50	50	50	200
coupling (GeV^{-4})	≥ 1 conv. γ 5 σ	≥ 1 conv. γ 95% CL	all γ 95% CL	all γ 95% CL
ζ_1 f.f.	$8 \cdot 10^{-14}$	$5 \cdot 10^{-14}$	$3 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$
ζ_1 no f.f.	$2.5 \cdot 10^{-14}$	$1.5 \cdot 10^{-14}$	$9 \cdot 10^{-15}$	$7 \cdot 10^{-15}$
ζ_2 f.f.	$2. \cdot 10^{-13}$	$1. \cdot 10^{-13}$	$6 \cdot 10^{-14}$	$4.5 \cdot 10^{-14}$
ζ_2 no f.f.	$5 \cdot 10^{-14}$	$4 \cdot 10^{-14}$	$2 \cdot 10^{-14}$	$1.5 \cdot 10^{-14}$

- Reaches the values predicted by extra-dim or composite Higgs models

$\gamma\gamma\gamma Z$ quartic anomalous coupling





Cut/Process	Signal ζ $(\tilde{\zeta} = 0)$	Signal $\zeta = \tilde{\zeta}$	γZ +pile-up	$W^{\pm}\gamma$ +pile-up	$jje^{\pm}$ +pile-up
$0.015 < \xi_{1,2} < 0.15$, $p_{T\gamma} > 150$ GeV $p_{Tjj} > 100$ GeV]	38.6	51.4	1951.8	1631	8.47
$m_{\gamma Z} > 700$ GeV	37	49.5	349.8	358.9	1.3
$p_{T\gamma}/p_{Tjj} > 0.90$, $\lvert\Delta\phi - \pi\rvert < 0.02$	33.8	45.1	144.7	145.4	0.54
$\sqrt{\xi_1\xi_2 s} = m_{\gamma Z} \pm 10\%$	28.2	35.7	19.7	19.3	0.1
$\lvert y_{pp} - y_{\gamma Z}\rvert < 0.05$	25.5	32.7	1.5	1.6	0

- Background of about 3.1 events for 300 fb-1, and about 25 events of signal for a coupling of 4 10^{-13} GeV^{-4}
- Reach better by three orders of magnitude with respect to standard methods at the LHC: Looking at Z boson decay into 3 photons
- C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1706 (2017) 142

Conclusion

- Many complementary results concerning exclusive diffraction at the LHC from CMS and TOTEM (CT-PPS) either using the "rapidity gap" technique or the proton tags
- CMS exclusive pion production: disagreement with theoretical expectations probably due to the fact that proton dissociation is not included in models
- Best limits on $\gamma\gamma WW$ anomalous couplings in CMS
- Exclusive di-muon production: First observation of high-mass exclusive dimuon production:. 17 events are found with protons in the CT-PPS acceptance and 12 with $< 2\sigma$ matching, which leads to a significance for observing 12 events for a background of $1.47 \pm 0.06(stat) \pm 0.52(syst)$ of 4.3 σ
- $\gamma\gamma\gamma\gamma$ couplings: Nice prospects for AFP and CT-PPS, highest possible sensitivities to $\gamma\gamma\gamma\gamma$, $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma Z$ anomalous couplings due to new resonances, extra-dim. or composite Higgs...