Phys.Rev.D90,032008(2014)
CMS-PAS: SMP-15-008

CMS Triple Boson Production Results

The Second China LHC Physics Workshop

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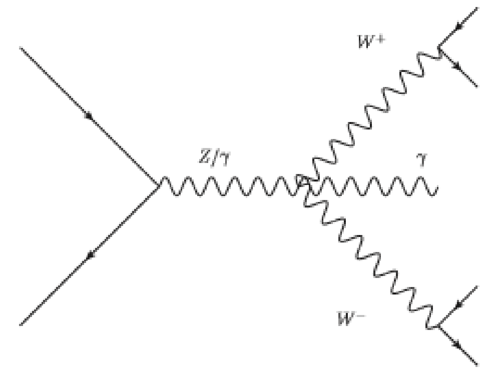
Peking University, Beijing

Motivations

Electroweak physics at the LHC

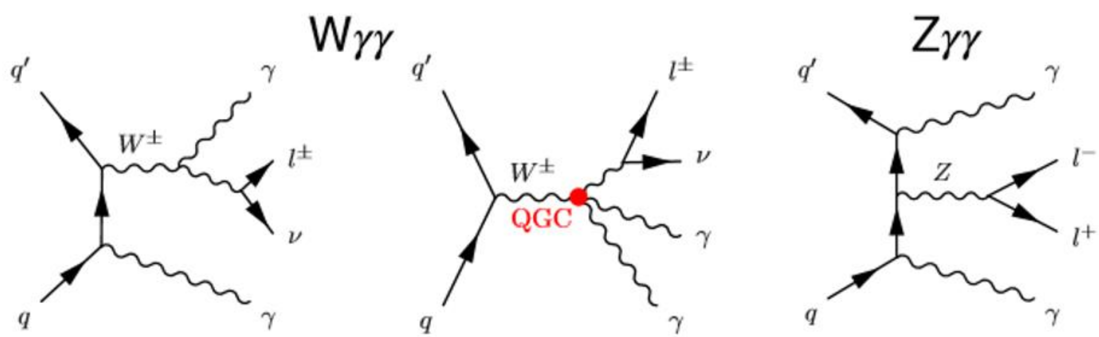
- Precise description of Standard Model background is crucial to new physics search in novel phase spaces
- Triple boson production is one of the rare processes that can be sensitive to new physics
- Deviations form the SM may live in high energy tails



WVγ Production
Phys. Rev. D 90, 032008 (2014)

Two tri-boson results from CMS @8 TeV

- WVγ Production
- W$\gamma\gamma$ and Z$\gamma\gamma$ productions



W$\gamma\gamma$ and Z$\gamma\gamma$ productions
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Many figures in the slides are taken from Josh Kunkle's talk

Anomalous Gauge Couplings

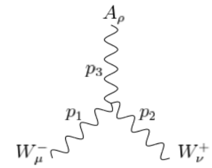
Probing gauge boson self interactions at the LHC

- Within the SM, the Gauge Lagrangian gives 6 vertices

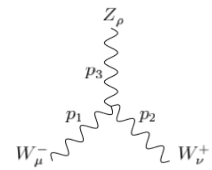
- The LEP parameterization considers dimension 6 operators, which is not consistent with a symmetry breaking sector with a Higgs boson

$$
\begin{aligned}
\mathcal{L}_6^0 &= -\frac{e^2}{16\Lambda^2} a_0 \mathrm{F}^{\mu\nu}\mathrm{F}_{\mu\nu}\, \vec{W}^{\alpha} \,.\, \vec{W}_{\alpha} \;, \\
\mathcal{L}_6^c &= -\frac{e^2}{16\Lambda^2} a_c \mathrm{F}^{\mu\alpha}\mathrm{F}_{\mu\beta}\, \vec{W}^{\beta} \,.\, \vec{W}_{\alpha} \;, \\
\mathcal{L}_6^n &= i\frac{e^2}{16\Lambda^2} a_n \epsilon_{ijk} W_{\mu\alpha}{}^{(i)} W_{\nu}{}^{(j)} W^{(k)\alpha}\mathrm{F}^{\mu\nu},
\end{aligned}
$$

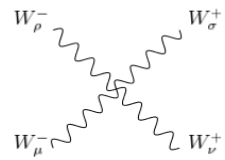
$$
\vec{W}_{\mu} = \begin{pmatrix} \frac{1}{\sqrt{2}}(W_{\mu}^{+} + W_{\mu}^{-}) \\ \frac{i}{\sqrt{2}}(W_{\mu}^{+} - W_{\mu}^{-}) \\ Z_{\mu}/\cos\theta_W \end{pmatrix},
$$



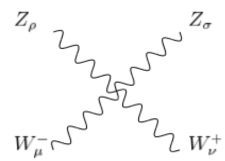
$i\, g\, \sin\theta_W\; ((p_1 - p_2)_\rho\, g_{\mu\nu} + (p_2 - p_3)_\mu\, g_{\nu\rho} + (p_3 - p_1)_\nu\, g_{\rho\mu})$



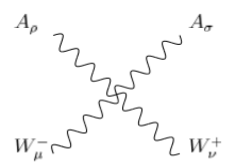
$i\, g\, \cos\theta_W\; ((p_1 - p_2)_\rho\, g_{\mu\nu} + (p_2 - p_3)_\mu\, g_{\nu\rho} + (p_3 - p_1)_\nu\, g_{\rho\mu})$



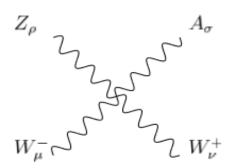
$i\, g^2\, (2g_{\mu\rho}\, g_{\nu\sigma} - g_{\mu\nu}\, g_{\rho\sigma} - g_{\mu\sigma}\, g_{\nu\rho})$



$i\, g^2 \cos^2\theta_W\; (2g_{\mu\nu}\, g_{\rho\sigma} - g_{\mu\rho}\, g_{\nu\sigma} - g_{\mu\sigma}\, g_{\nu\rho})$



$i\, g^2 \sin^2\theta_W\; (2g_{\mu\nu}\, g_{\rho\sigma} - g_{\mu\rho}\, g_{\nu\sigma} - g_{\mu\sigma}\, g_{\nu\rho})$



$i\, g^2 \cos\theta_W\; \sin\theta_W\; (2g_{\mu\nu}\, g_{\rho\sigma} - g_{\mu\rho}\, g_{\nu\sigma} - g_{\mu\sigma}\, g_{\nu\rho})$

Anomalous Gauge Couplings

Probing gauge boson self interactions at the LHC

QGCs from dimension 6 operators are in general manifested in a nonlinear sigma model, without a Higgs boson (sigma field integrated out).

After the Higgs discovery, we consider the SM as an effective field theory. This leads to many possible quartic interactions (Assuming no TGCs, Dimension 8).

$$\mathcal{L}^{NP} = \mathcal{L}^{SM(4)} + \cancel{\frac{1}{\Lambda}\mathcal{L}^5} + \boxed{\frac{1}{\Lambda^2}\mathcal{L}^6} + \cancel{\frac{1}{\Lambda^3}\mathcal{L}^7} + \boxed{\frac{1}{\Lambda^4}\mathcal{L}^8} + \cdots$$

Ignore lepton/baryon number violating terms

Dim-6, search for **aTGCs**

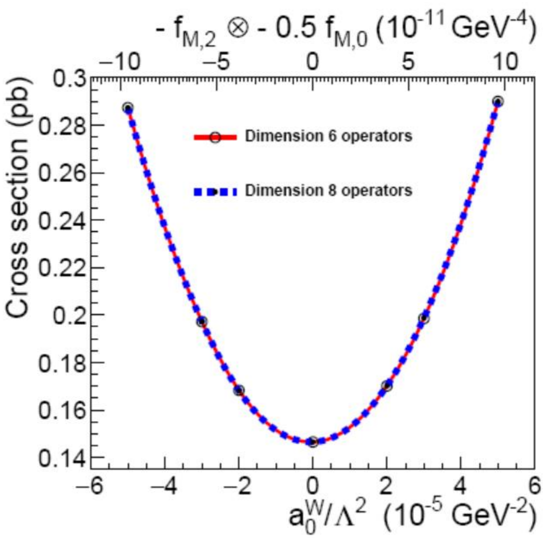
Dim-8, search for **aQGC** assuming no aTGC

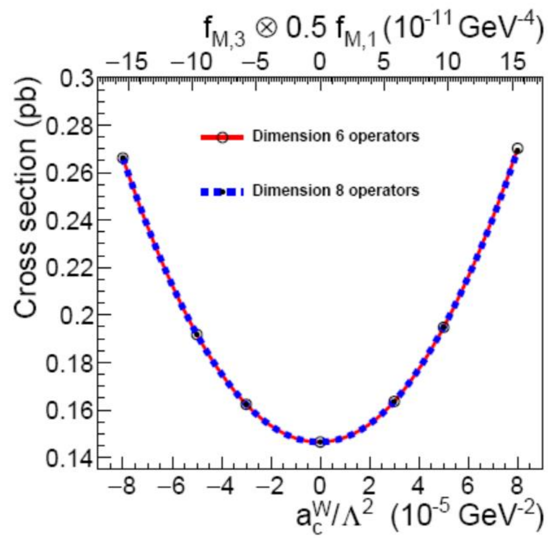
	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$	X	X	X	O	O	O	O	O	O
$\mathcal{L}_{M,0}$, $\mathcal{L}_{M,1}$,$\mathcal{L}_{M,6}$,$\mathcal{L}_{M,7}$	X	X	X	X	X	X	X	O	O
$\mathcal{L}_{M,2}$,$\mathcal{L}_{M,3}$, $\mathcal{L}_{M,4}$,$\mathcal{L}_{M,5}$	O	X	X	X	X	X	X	O	O
$\mathcal{L}_{T,0}$,$\mathcal{L}_{T,1}$,$\mathcal{L}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,5}$,$\mathcal{L}_{T,6}$,$\mathcal{L}_{T,7}$	O	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,9}$,$\mathcal{L}_{T,9}$	O	O	X	O	O	X	X	X	X

Anomalous Gauge Couplings

$WV\gamma$ operators: Selected set of SU(2)⊗U(1) invariant and C, P conserving operators, related to the $WW\gamma\gamma$ and $WWZ\gamma$ vertices

$$\mathcal{L}_{\mathrm{AQGC}} = -\frac{e^2}{8}\frac{a_0^W}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W^-_\alpha - \frac{e^2}{16}\frac{a_C^W}{\Lambda^2}F_{\mu\nu}F^{\mu\alpha}(W^{+\nu}W^-_\alpha + W^{-\nu}W^+_\alpha)$$
$$- e^2 g^2\frac{\kappa_0^W}{\Lambda^2}F_{\mu\nu}Z^{\mu\nu}W^{+\alpha}W^-_\alpha - \frac{e^2 g^2}{2}\frac{\kappa_C^W}{\Lambda^2}F_{\mu\nu}Z^{\mu\alpha}(W^{+\nu}W^-_\alpha + W^{-\nu}W^+_\alpha)$$
$$+ \frac{f_{T,0}}{\Lambda^4}\mathrm{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times \mathrm{Tr}[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}].$$





$W\gamma\gamma$, $Z\gamma\gamma$ operators:

$$\mathcal{L}_{M,2} = [B_{\mu\nu}B^{\mu\nu}] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,3} = [B_{\mu\nu}B^{\nu\beta}] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$
$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$
$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$

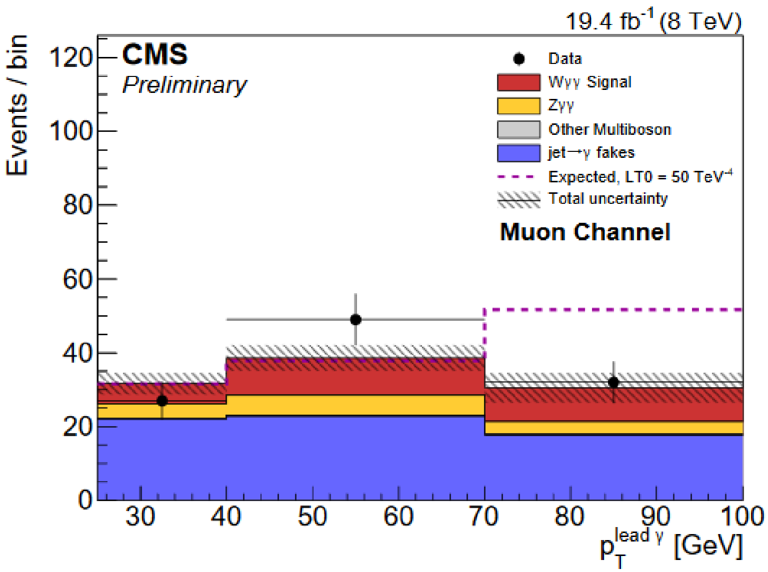
Replacing the Higgs doublet with its vev, one can find a way to match the parameters of dim6 and dim8 operators.

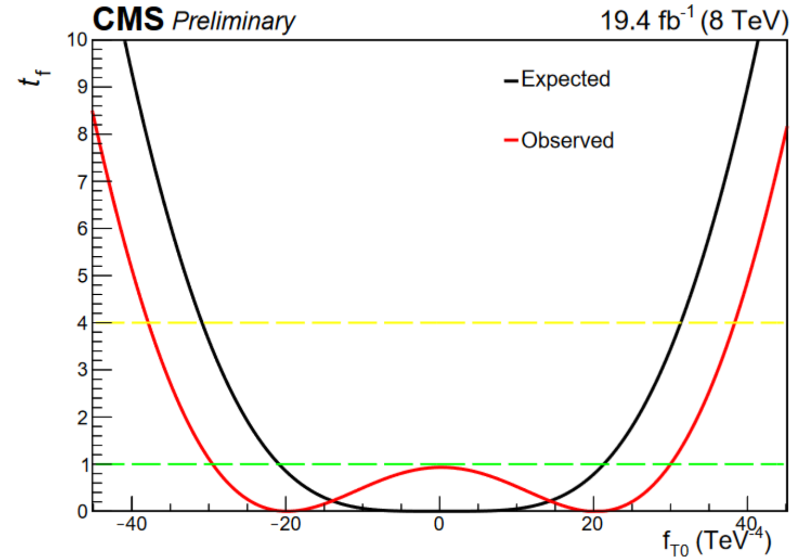
$$\frac{a_0^W}{\Lambda^2} = -\frac{4M_W^2}{g^2}\frac{f_{M,0}}{\Lambda^4} - \frac{8M_W^2}{g'^2}\frac{f_{M,2}}{\Lambda^4}$$
$$\frac{a_C^W}{\Lambda^2} = \frac{4M_W^2}{g^2}\frac{f_{M,1}}{\Lambda^4} + \frac{8M_W^2}{g'^2}\frac{f_{M,3}}{\Lambda^4},$$

$$f_{M,0} = 2 \times f_{M,2}$$

$$f_{M,1} = 2 \times f_{M,3}$$

Statistical Method





Likelihood based statistical study

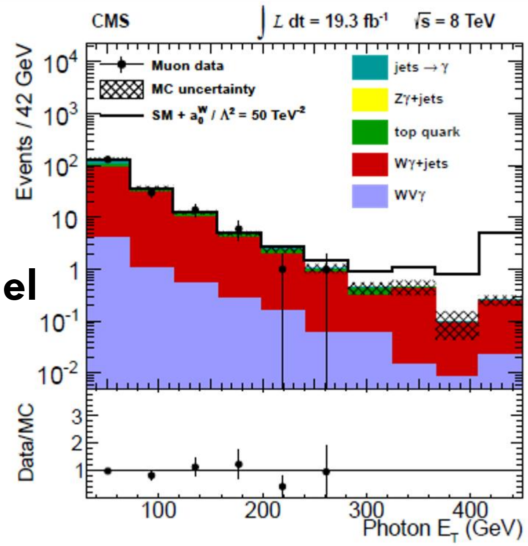
- L: likelihood function
- f: aQGC parameter
- θ: nuisance parameters
- t: test statistics

$$t_f = -2\ln \frac{L(f,\hat{\hat{\theta}})}{L(\hat{f},\hat{\theta})},$$

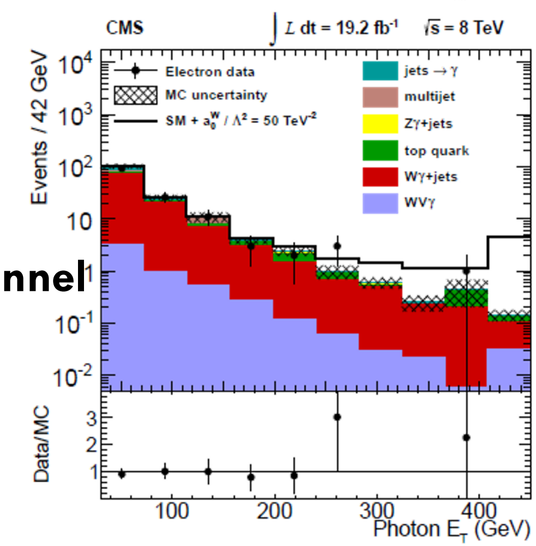
$$\begin{aligned}\mathcal{L}(f,\theta) &= norm(\theta)\cdot \boxed{Poisson(N|\ S+B)} \boxed{\prod_n^N P(p_{T,W}^n, f)} \\ &= norm(\theta)\cdot \frac{(B(\theta)+S(f,\theta))^N}{N!} e^{-(B(\theta)+S(f,\theta))} \prod_n^N \frac{S(f,\theta) f_S(p_{T,W}^n) + B(\theta) f_B(p_{T,W}^n)}{S(f,\theta)+B(\theta)}.\end{aligned}$$

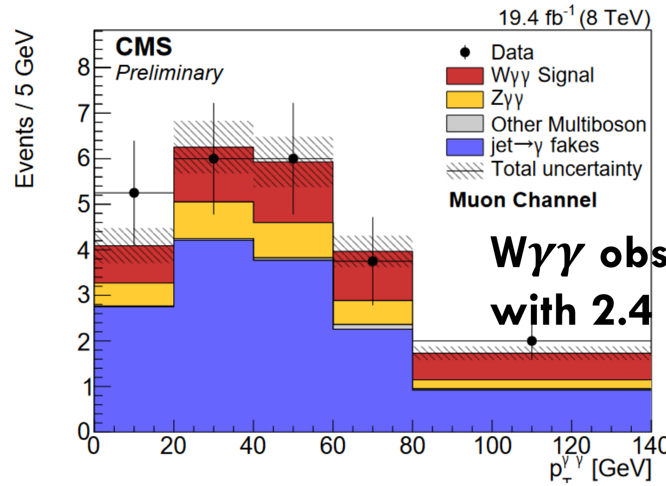
Results of Tri-Boson productions

WVγ, muon channel



WVγ, electron channel

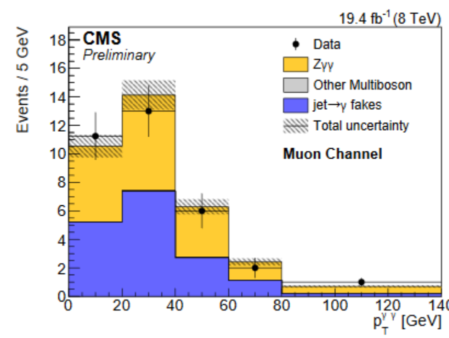


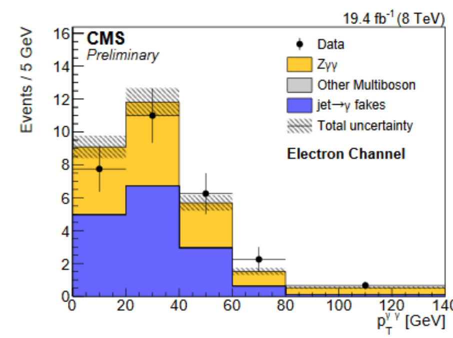


W$\gamma\gamma$ observed with 2.4 σ

$$\sigma^{\mathrm{NLO}}_{\mathrm{W}^{\pm}\gamma\gamma} \cdot \mathrm{BR}\left(\mathrm{W} \to \ell\nu\right) = 4.76 \pm 0.53\,\mathrm{fb} \quad \text{(Madgraph)}$$

$$\sigma^{\mathrm{fid}}_{\mathrm{W}^{\pm}\gamma\gamma} \cdot \mathrm{BR}\left(\mathrm{W} \to \ell\nu\right) = 6.0 \pm 1.8\,(\mathrm{stat}) \pm 2.3\,(\mathrm{syst}) \pm 0.2\,(\mathrm{lumi})\,\mathrm{fb}$$





$$\sigma^{\mathrm{NLO}}_{\mathrm{Z}\gamma\gamma} \cdot \mathrm{BR}\left(\mathrm{Z} \to \ell\ell\right) = 12.95 \pm 1.47\,\mathrm{fb} \quad \text{(Madgraph)}$$

$$\sigma^{\mathrm{fid}}_{\mathrm{Z}\gamma\gamma} \cdot \mathrm{BR}\left(\mathrm{Z} \to \ell\ell\right) = 12.7 \pm 1.4\,(\mathrm{stat}) \pm 1.8\,(\mathrm{syst}) \pm 0.3\,(\mathrm{lumi})\,\mathrm{fb}$$

Upper limit for WWγ and WZγ cross section at 95% C.L. : **241 fb**

- With photon $p_T > 10$ GeV
- ~ 3.4 times the SM cross section: WWγ + WZγ = 70.3 fb

Z$\gamma\gamma$ observed with 5.9 σ

Results of aQGC limits

95% exclusion limits on the aQGCs

$WV\gamma$ results

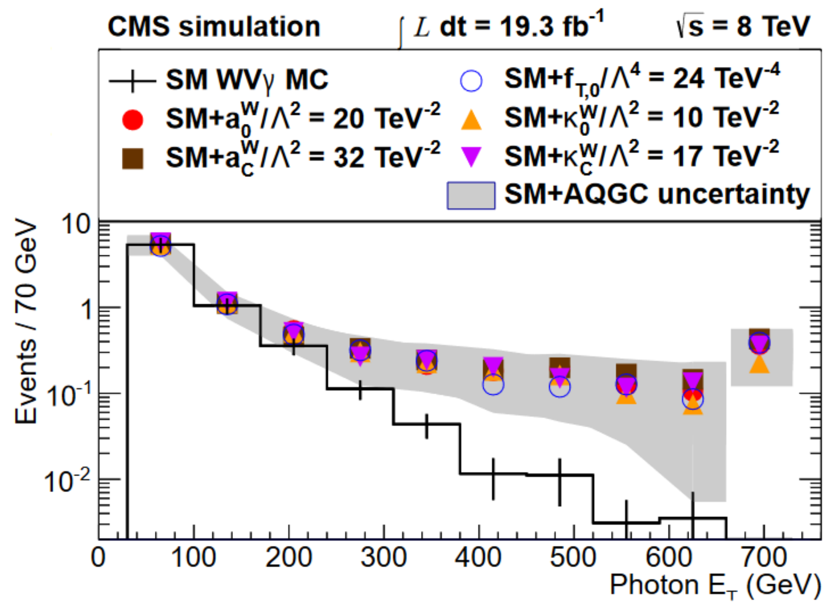
Observed limits	Expected limits
$-21 < a_0^W/\Lambda^2 < 20\,\mathrm{TeV}^{-2}$	$-24 < a_0^W/\Lambda^2 < 23\,\mathrm{TeV}^{-2}$
$-34 < a_C^W/\Lambda^2 < 32\,\mathrm{TeV}^{-2}$	$-37 < a_C^W/\Lambda^2 < 34\,\mathrm{TeV}^{-2}$
$-25 < f_{T,0}/\Lambda^4 < 24\,\mathrm{TeV}^{-4}$	$-27 < f_{T,0}/\Lambda^4 < 27\,\mathrm{TeV}^{-4}$
$-12 < \kappa_0^W/\Lambda^2 < 10\,\mathrm{TeV}^{-2}$	$-12 < \kappa_0^W/\Lambda^2 < 12\,\mathrm{TeV}^{-2}$
$-18 < \kappa_C^W/\Lambda^2 < 17\,\mathrm{TeV}^{-2}$	$-19 < \kappa_C^W/\Lambda^2 < 18\,\mathrm{TeV}^{-2}$

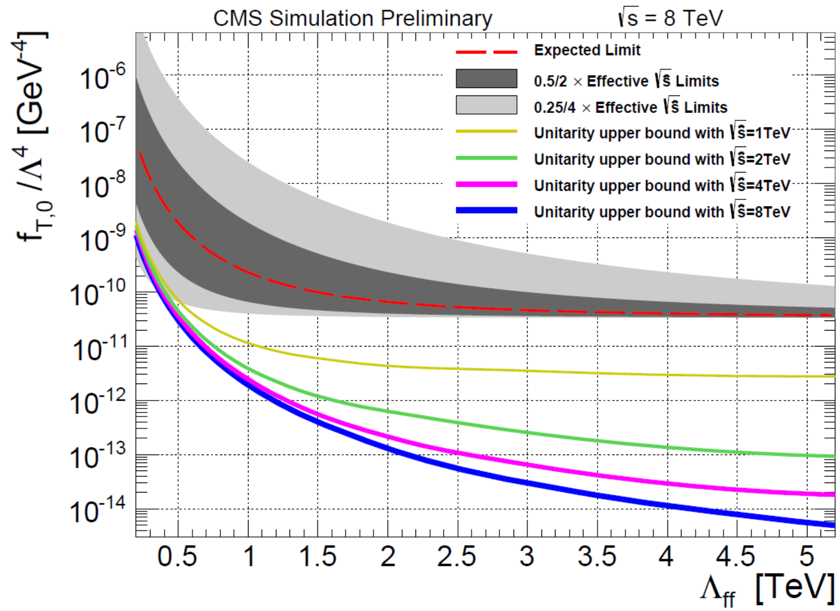
$W\gamma\gamma$ results

Expected Limits (TeV^{-4})	Observed Limits (TeV^{-4})
$-30.5 < \frac{f_{T0}}{\Lambda^4} < 31.1$	$-37.5 < \frac{f_{T0}}{\Lambda^4} < 38.1$
$-36.9 < \frac{f_{T1}}{\Lambda^4} < 37.5$	$-46.1 < \frac{f_{T1}}{\Lambda^4} < 46.9$
$-83.2 < \frac{f_{T2}}{\Lambda^4} < 83.2$	$-103 < \frac{f_{T2}}{\Lambda^4} < 103$
$-623 < \frac{f_{M2}}{\Lambda^4} < 603$	$-751 < \frac{f_{M2}}{\Lambda^4} < 729$
$-1080 < \frac{f_{M3}}{\Lambda^4} < 1110$	$-1290 < \frac{f_{M3}}{\Lambda^4} < 1340$

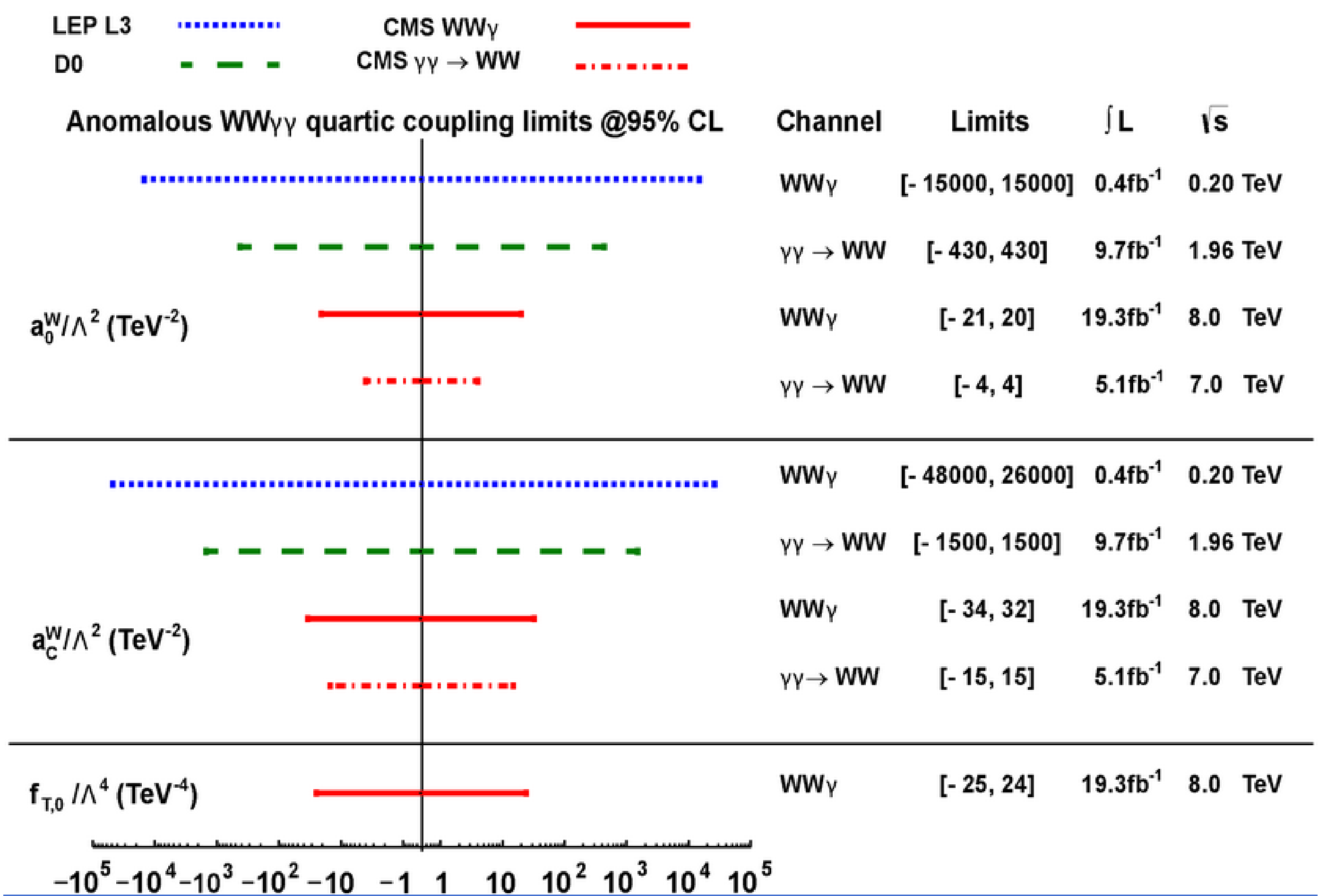
Unitarity bounds (solid lines) still more stringent than experimental bounds (dashed lines). From $WV\gamma$ analysis.

No form factor is applied





Comparison of existing limits



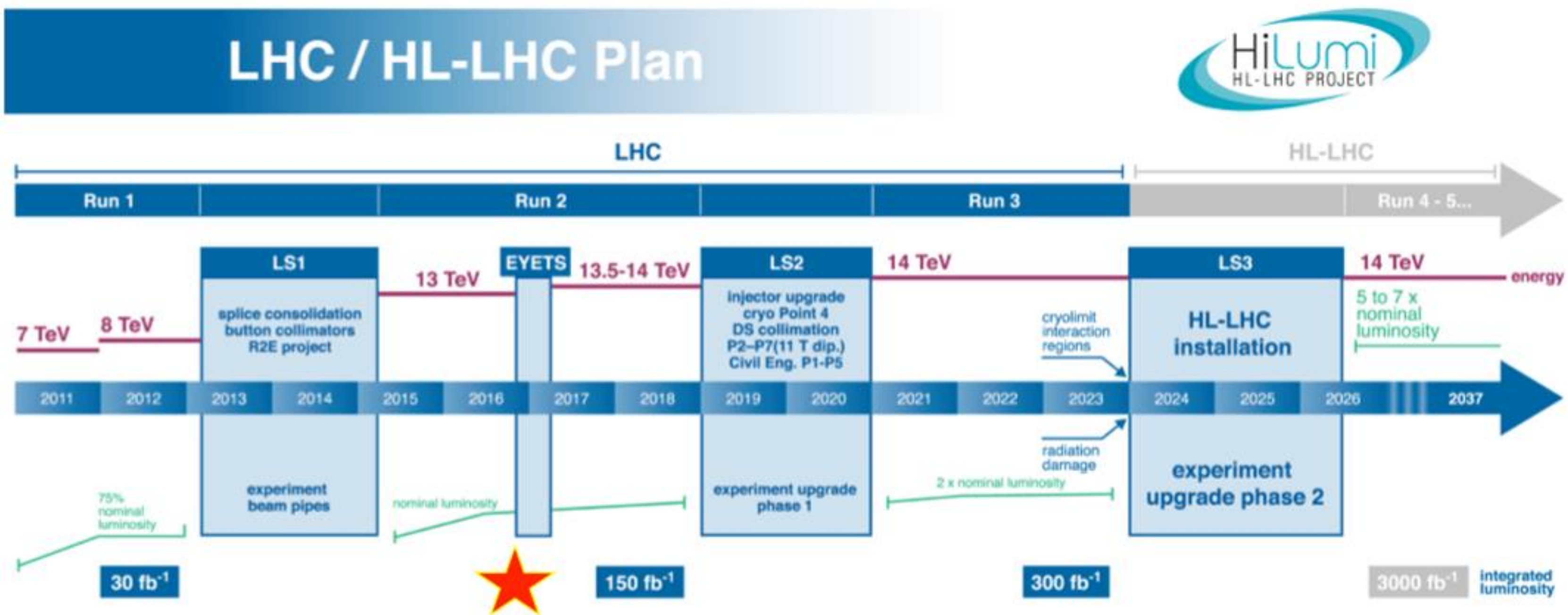
Exclusive $\gamma\gamma \rightarrow WW$ CMS : arXiv:1305.5596 (Λ_{ff} = 500 GeV)

OPAL: Phys.Rev. D70 (2004) 032005, arXiv:hep-ex/0402021

D0: arXiv:1305.1258

More stringent limits are now available from VBS experiments

Outlook



We are here!

With only 1-2% of the total expected luminosity recorded!

6 Dec 2016 Pásztor: EW Physics at LHC

By LS2, we'll have about 150 fb^{-1} data. More tri-boson productions will become visible and shape measurements will be improved.
More UV complete models will be matched to the effective field theory.