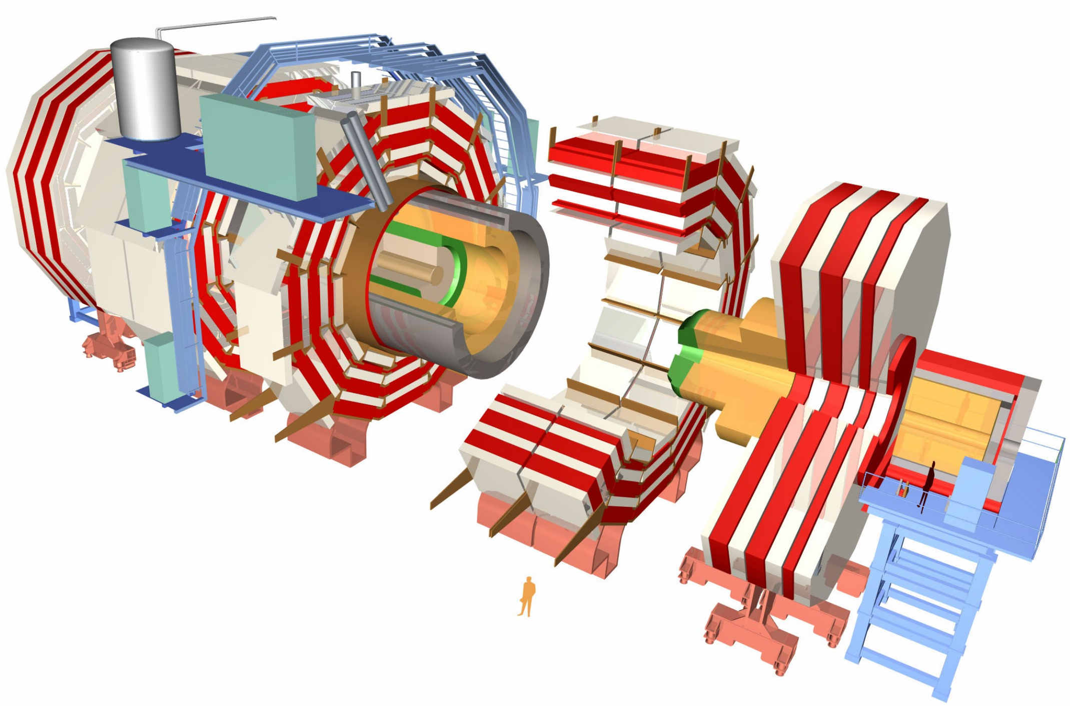
Latest Results on Anomalous Gauge Couplings from CMS

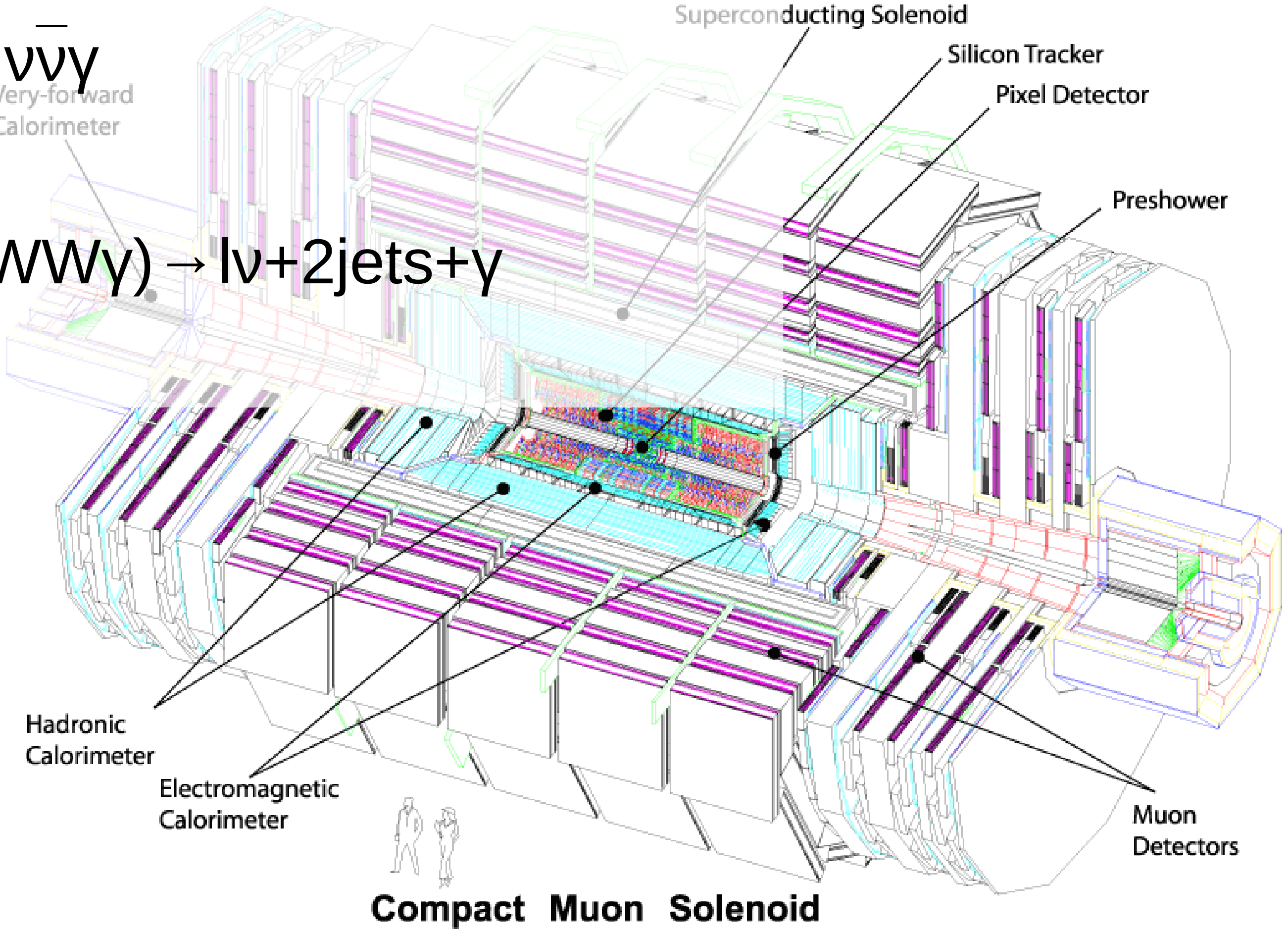
Ekaterina Avdeeva
University of Nebraska – Lincoln
On behalf of the CMS collaboration



PHOTON-2015 Conference
Budker Institute of Nuclear Physics, Novosibirsk
June 15th-19th 2015

Outline

- Introduction to anomalous gauge couplings
- Results from:
  - $Z\gamma \rightarrow l\bar{l}\gamma$, $Z\gamma \rightarrow \nu\bar{\nu}\gamma$
  - $WW \rightarrow 2l2\nu$
  - $WV\gamma$ ($WZ\gamma+WW\gamma$) $\rightarrow l\nu+2jets+\gamma$
- Conclusions



Introduction

(aTGC – anomalous Triple Gauge Coupling, aQGC – anomalous Quartic Gauge Coupling)

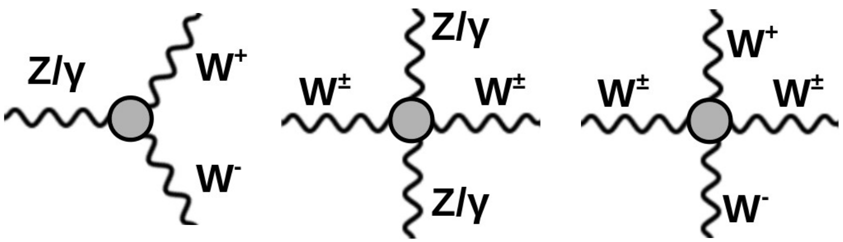
<u>We consider TGC and QGC vertexes with W, Z and γ which:</u>

(1) Obey charge conservation law

(2) Include at least one massive boson

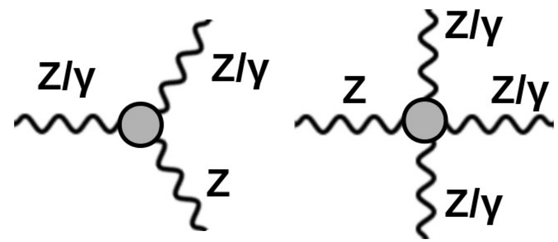
Charged TGC and QGC at tree level **present** in the Standard Model

WWγ, WWZ, WWZγ, WWγγ, WWWW, WWZZ



Neutral TGC and QGC at tree level **not present** in the Standard Model

ZZZ, ZZγ, Zγγ, ZZZZ, ZZZγ, ZZγγ, Zγγγ



TGC and QGC couplings can be parametrized with constants which

have certain values in the Standard Model for charged TGC/QGC;

deviation from these values would mean aTGC/aQGC

are equal to 0 in the Standard Model for neutral TGC/QGC;

any presence of such vertexes would mean aTGC/aQGC

we measure spectrum of kinematic variable of the process which might involve (a)TGC/(a)QGC and compare it to the Standard Model and aTGC/aQGC model predictions

List (not full) of aTGC/aQGC analyses in CMS

Searches for anomalous Triple Gauge Coupling:

[1] $Z\gamma \rightarrow l^+l^-\gamma$, 8 TeV: http://arxiv.org/abs/1502.05664

[2] $Z\gamma \rightarrow l^+l^-\gamma$ and $W\gamma \rightarrow l\nu\gamma$, **7 TeV:** http://arxiv.org/abs/1308.6832

[3] $Z\gamma \rightarrow \nu\bar{\nu}\gamma$, 7 TeV: http://arxiv.org/abs/1309.1117

[4] WW → $l\nu l\nu$, 8 TeV: http://cds.cern.ch/record/2002016?ln=en

[5] WW+WZ→$l\nu jj$, 7 TeV: http://arxiv.org/abs/1210.7544

[6] ZZ → 4l, 8 TeV: http://arxiv.org/abs/arXiv:1406.0113

[7] ZZ → 2l2ν, 8TeV: http://arxiv.org/abs/1503.05467

Searches for anomalous Quartic Gauge Coupling:

[8] $WZ\gamma$+$WW\gamma \rightarrow l\nu jj\gamma$, 8TeV: http://arxiv.org/abs/1404.4619

[9] $W^{\pm}W^{\pm}$+jj→ $l\nu l\nu$+jj, 8 TeV: http://arxiv.org/abs/1410.6315

[10] VBS $\gamma\gamma$ →WW→$l\nu l\nu$, 7 TeV: http://cds.cern.ch/record/1518733?ln=en

Z decay modes:

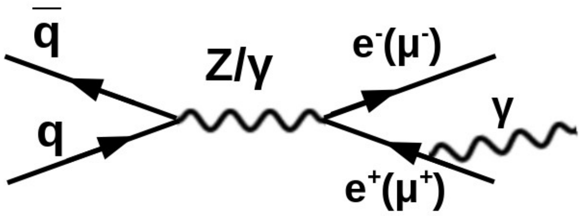
Mode	Br, %
e^+e^-	3.4
$\mu^+\mu^-$	3.4
$\tau^+\tau^-$	3.4
$\nu\bar{\nu}$	20.0
hadrons	69.9

W decay modes:

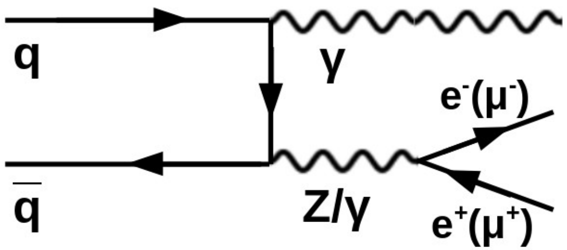
Mode	Br, %
$e\nu_e$	10.7
$\mu\nu_\mu$	10.6
$\tau\nu_\tau$	11.4
hadrons	67.4

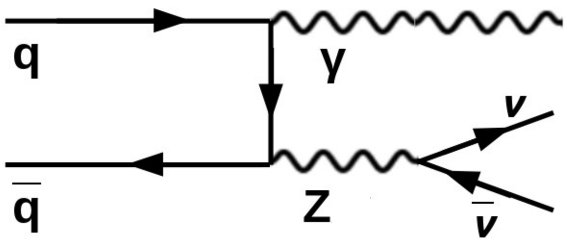
highlighted analyses are discussed in this presentation

Zγ Final State [1], [2], [3]

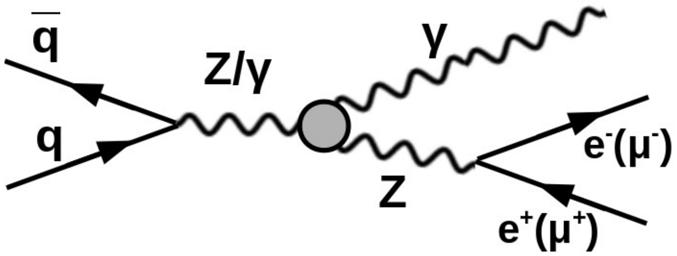


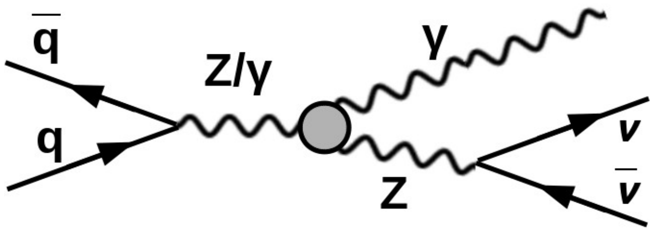
Final State Radiation (FSR) (for $Z\gamma \rightarrow l^+l^-\gamma$ only)





Initial State Radiation (ISR)





TGC diagrams. **Not present** in the Standard Model.

$Z\gamma \rightarrow l^+l^-\gamma$ process signature: charged lepton pair, and photon.

$Z\gamma \rightarrow \nu\bar{\nu}\gamma$ process signature: significant E_T^{miss} due to neutrinos, and photon.

$Z\gamma \rightarrow l^+l^-\gamma$. Selection and Background Estimation

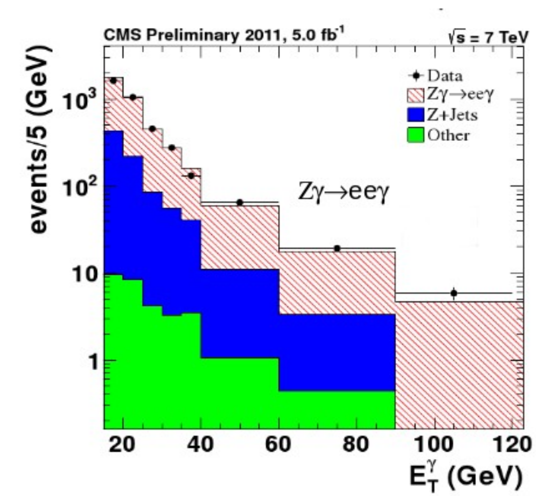
Event Selection:

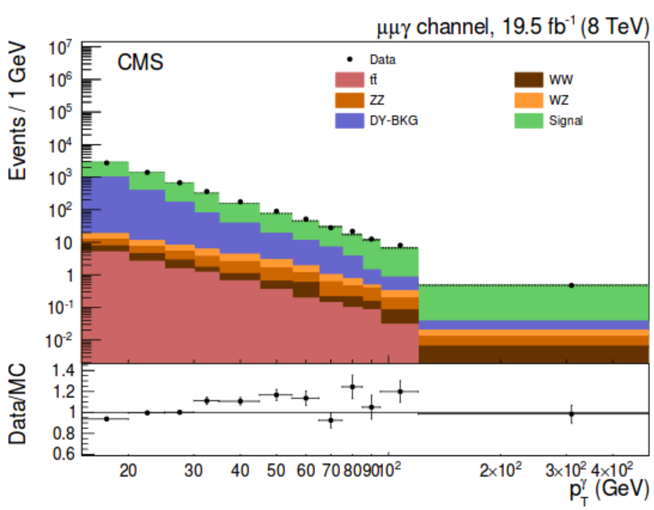
- well identified photon with E_T^{γ}>15 GeV, $|\eta^{\gamma}|$<1.44 or 1.57<$|\eta^{\gamma}|$<2.5
- 2 isolated well identified leptons p_T^{l}>20 GeV, M^{ll}>50 GeV
- $\Delta R(lep, \gamma) = \sqrt{\Delta\varphi^2 + \Delta\eta^2} > 0.7$

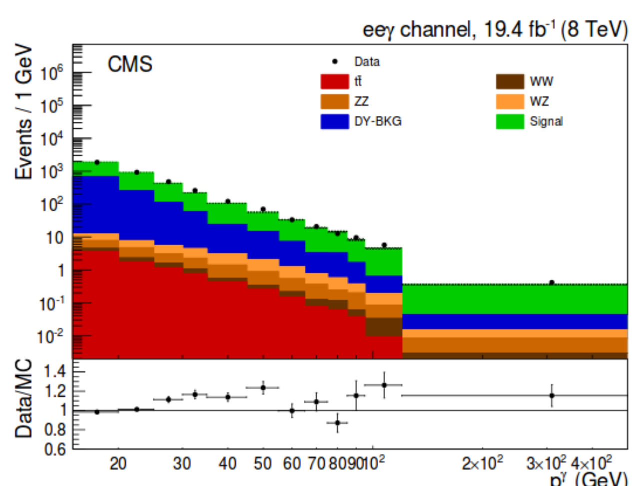
e^+e^- and $\mu^+\mu^-$ channels cosidered separately

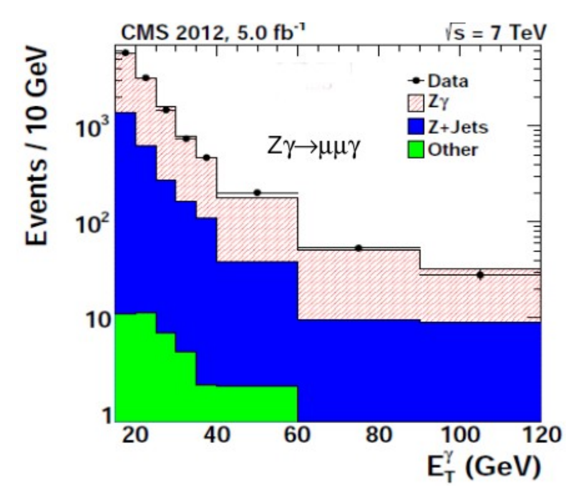
Background Estimation:

- **Z+jets (jets→γ misidentification):** template fits of one of photon variables; photon-like jet template taken from jet-enriched dataset; real photon template extracted using different methods for different cases
- **Other:** MC-based estimation

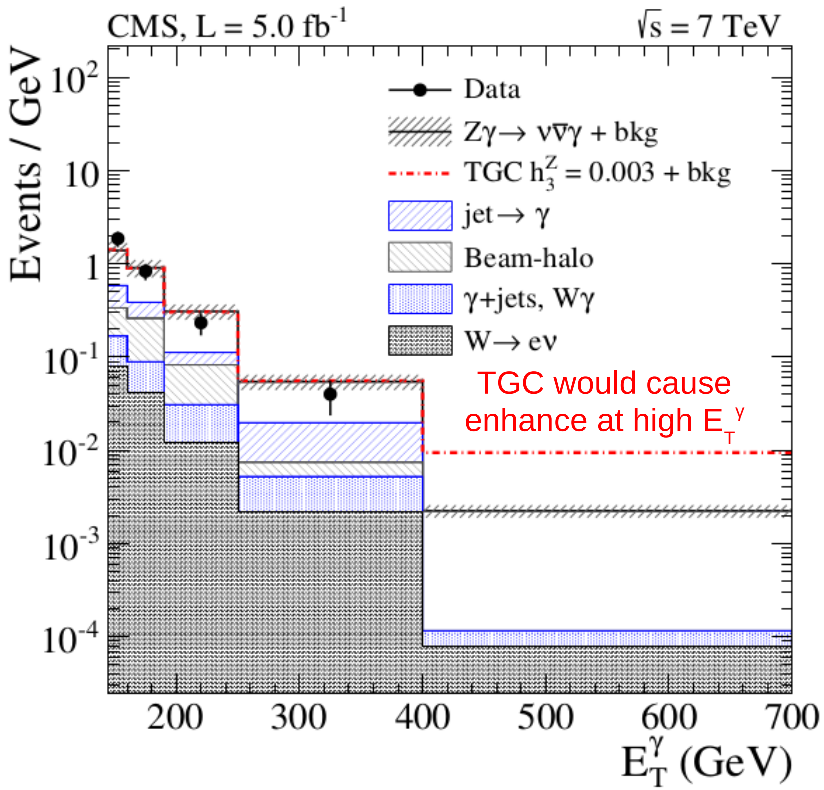








$Z\gamma \to \nu\bar{\nu}\gamma$. Selection and Background Estimation



Event Selection:

- well identified photon with E_T^γ>145 GeV, $|\eta^\gamma|$<1.4
- E_T^{miss}>130 GeV (due to neutrinos)
- events which contain other particles (which pass certain p_T threshold and quality criteria) are vetoed
- timing of photons measured in ECAL has to be consistent with beam crossing

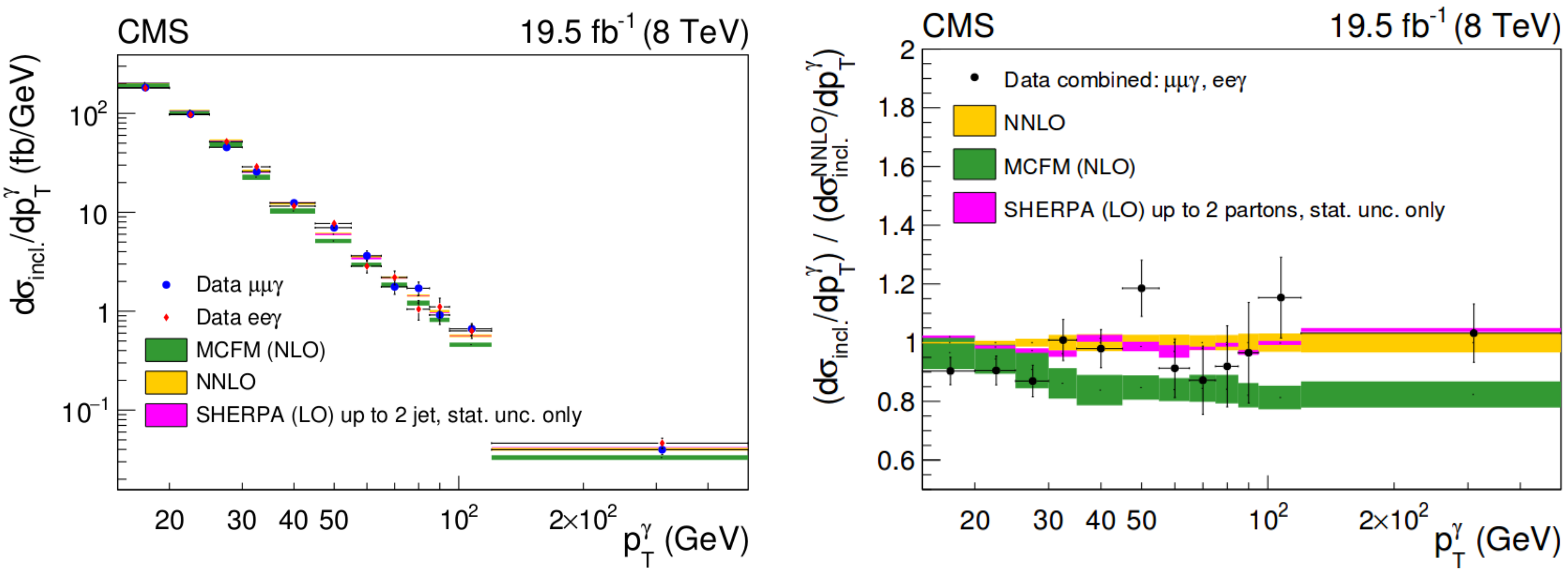
73 candidate events selected

Background Estimation:

- **jets→γ misidentification:** calculate misidentification ratio using events from jet-enriched dataset
- **beam-halo (machine induced particles):** estimated from events which are not consistent with beam crossing
- **e→γ misidentification:** estimated from control sample dominated by W→eν events
- **Wγ, γ+jets, γγ:** MC-based estimation

Total background estimate: 30.2±6.5, signal MC (Standard Model, NLO): 45.3±6.9

Zγ. Differential Cross Section



- Differential cross section measured for Zγ→l^+l^-γ (8 TeV)

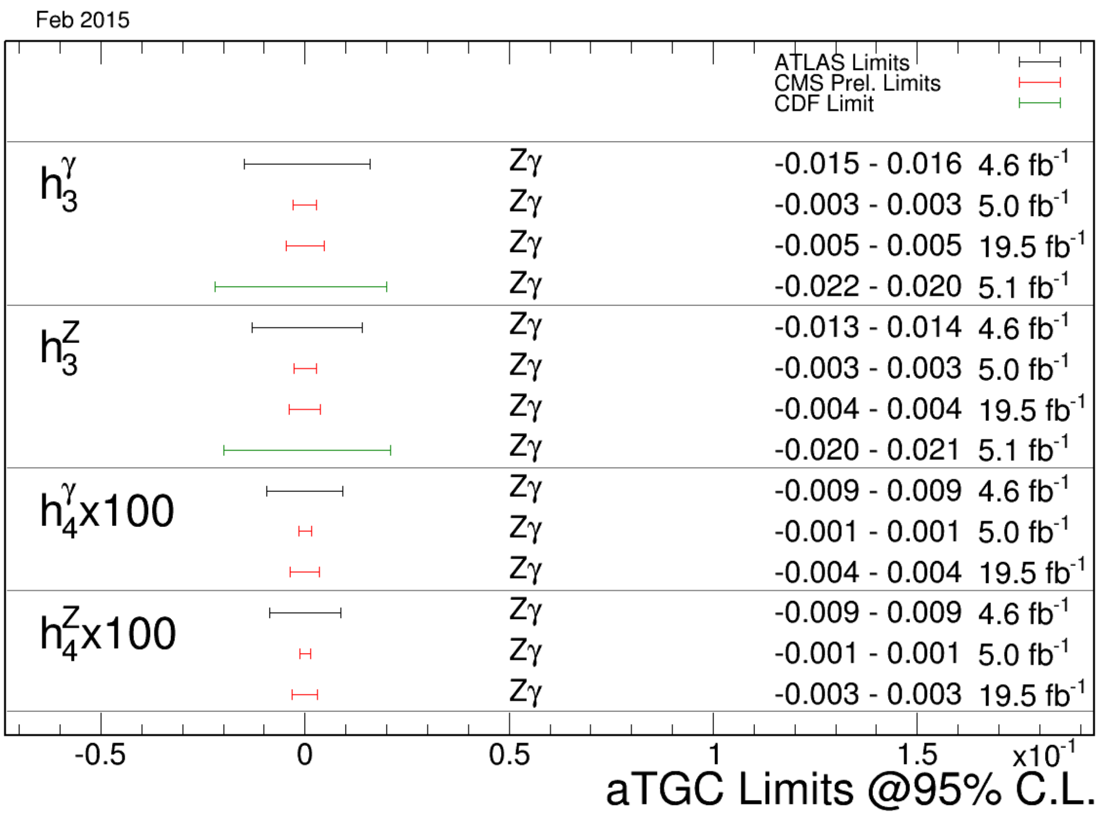
- Consistent with the Standard Model prediction

Zγ. aTGC Limits

$$
\begin{aligned}
L_{\mathrm{aTGC}} = \frac{e}{m_Z^2}\Big[& -[h_1^\gamma(\partial^\sigma F_{\sigma\mu}) + h_1^Z(\partial^\sigma Z_{\sigma\mu})]Z_\beta F^{\mu\beta} \\
& - h_3^\gamma(\partial_\sigma F^{\sigma\rho}) + h_3^Z(\partial_\sigma Z^{\sigma\rho})]Z^\alpha \tilde{F}_{\rho\alpha} \\
& - [\frac{h_2^\gamma}{m_Z^2}[\partial_\alpha\partial_\beta\partial^\rho F_{\rho\mu}] + \frac{h_2^Z}{m_Z^2}[\partial_\alpha\partial_\beta(\partial_\nu\partial^\nu + m_Z^2)Z_\mu]]Z^\alpha F^{\mu\beta} \\
& + [\frac{h_4^\gamma}{2m_Z^2}[\partial_\nu\partial^\nu\partial^\sigma F^{\rho\alpha}] + \frac{h_4^Z}{2m_Z^2}[(\partial_\nu\partial^\nu + m_Z^2)\partial^\sigma Z^{\rho\alpha}]]Z_\sigma \tilde{F}_{\rho\alpha}\Big]
\end{aligned}
$$

constants probed in these analyses

Results are consistent with the Standard Model Prediction

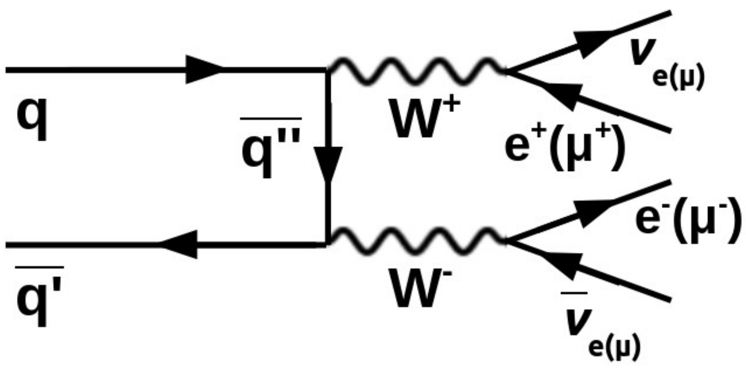


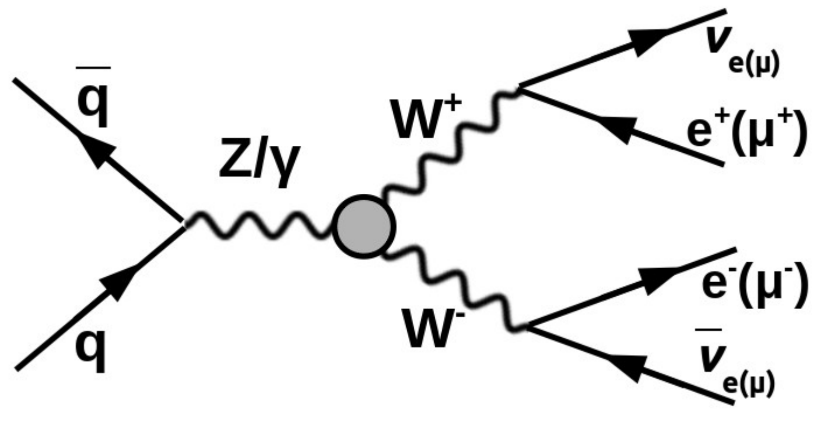
- Limits on aTGC ZZγ and Zγγ couplings are set(table shows limits on each constant in assumption of all other constants to be 0)

- Simultaneous limits on h_3^γ/h_4^γ and h_3^Z/h_4^Z constants are set (backup slide 22)

- 7 TeV (4.6 and 5.0 fb^{-1}) result is $Z\gamma \rightarrow l^+l^-\gamma$ + $Z\gamma \rightarrow \nu\bar{\nu}\gamma$ combined and provides the most stringent limits; **$Z\gamma \rightarrow \nu\bar{\nu}\gamma$ donimates the sensitivity to aTGC**

WW→lνlν Final State [4]





TGC. **Present** in the Standard Model

Process signature: two leptons (e^+e^-, $\mu^+\mu^-$, $e^+\mu^-$, or μ^+e^-), and significant E_T^{miss} due to neutrinos.

WW→lνlν. Selection and Backgrounds

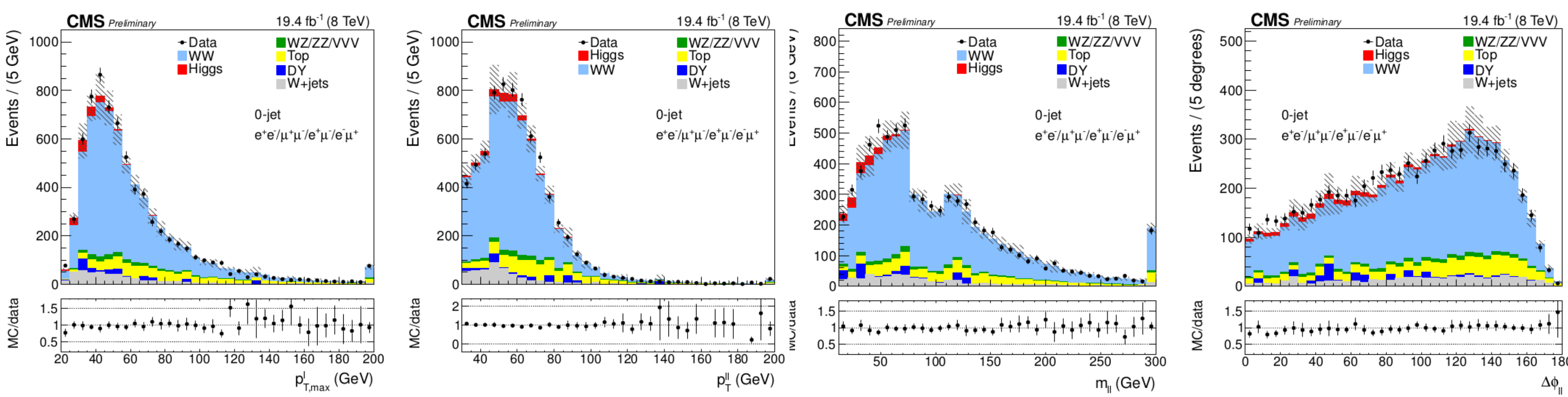
Event Selection:

- 2 well identified leptons with p_T^{lep}>20 GeV, $|\eta^{\mu}|$<2.4 / $|\eta^{e}|$<2.5,
- M^{ll}>12 GeV, $p_T^{\mu\mu/ee}$>45 GeV, $p_T^{\mu e}$>30 GeV
- E_T^{miss}>20 GeV (due to neutrinos)
- veto on events with 3rd lepton which passed p_T>10 GeV and certain quality criteria
- dilepton channels (ee, μμ, and eμ) are combined

For sample associated with 0 jets signal purity is 74%

Major Background:

- **$t\bar{t}$, tW:** estimated using top-tagged events and top-tagging efficiency determined from top-enriched sample

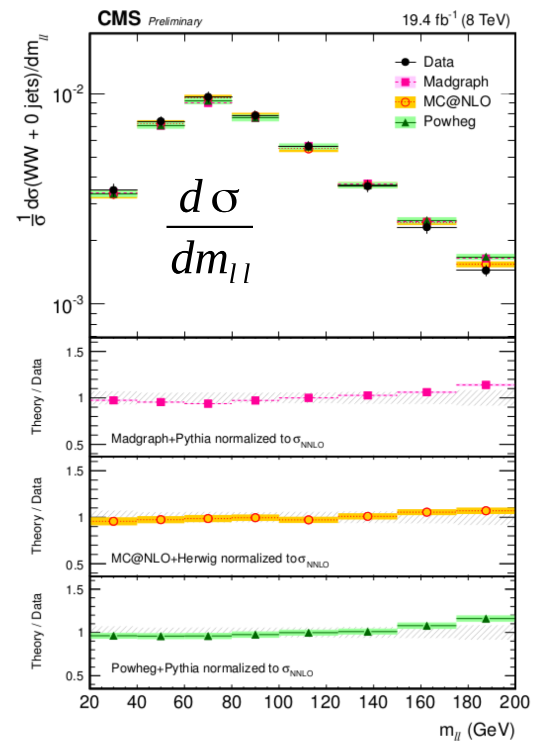


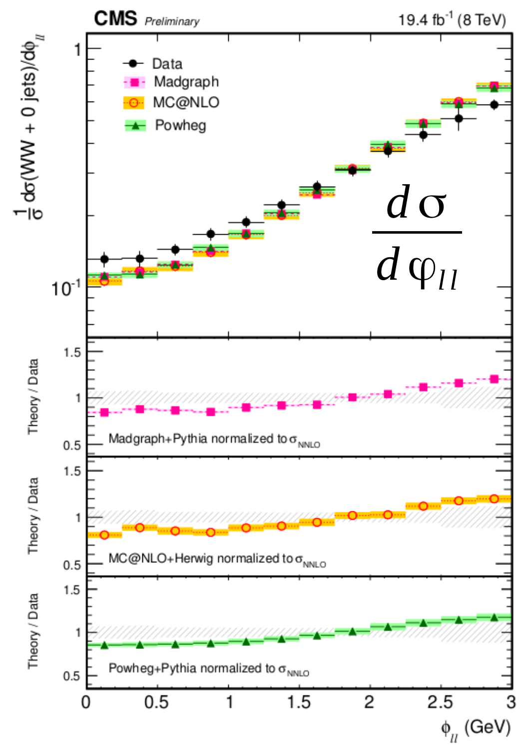
WW→lνlν. Differential Cross Sections

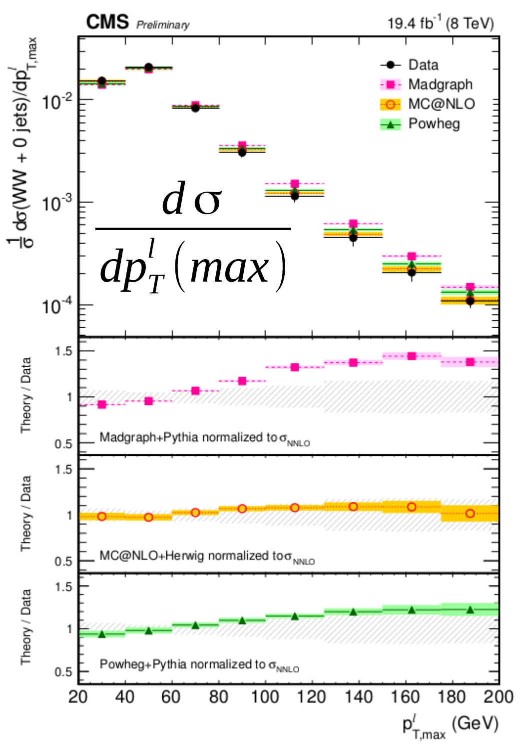
- Differential cross sections as functions of 4 kinematic variables

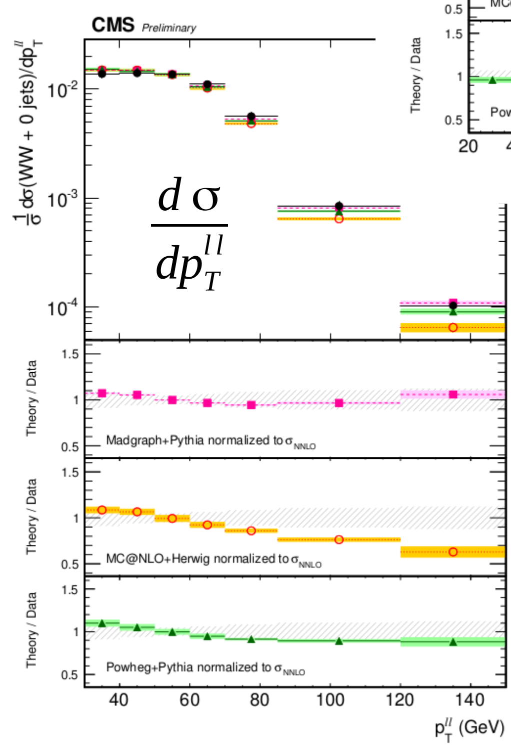
- Results are compatible with the theory NNLO prediction

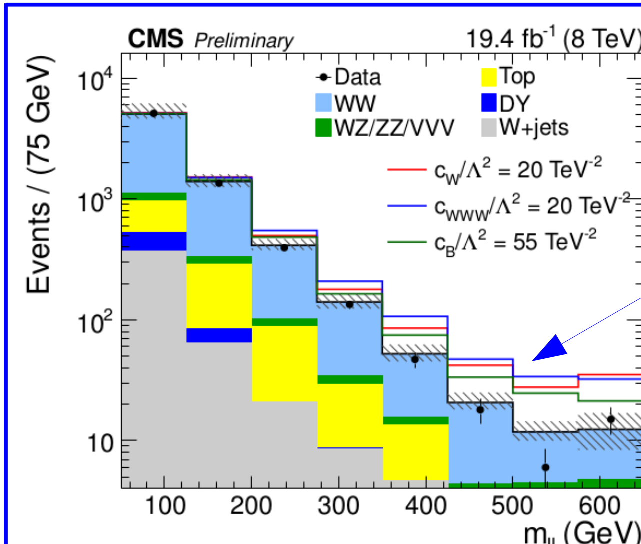
- ***m_{ll}* spectrum** is used to derive limits on WWZ aTGC coupling











aTGC would cause enhance

WW→lνlν. aTGC Limits

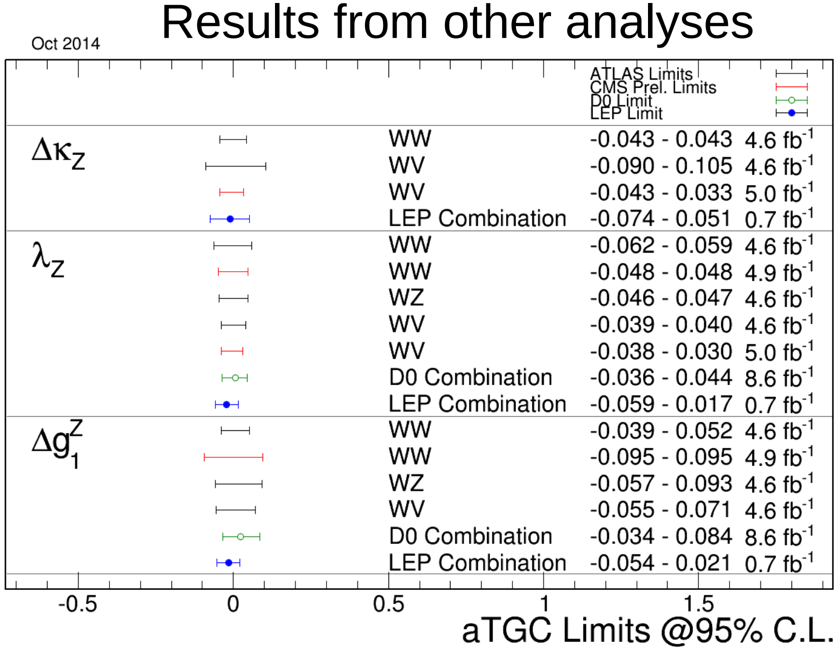
$$i\mathcal{L}_{eff}^{WWV} = g_{WWV}\Big[g_1^V V^\mu \left(W^-_{\mu\nu}W^{+\nu} - W^+_{\mu\nu}W^{-\nu}\right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2} V^{\mu\nu}W_\nu^{+\rho}W^-_{\rho\mu} + i g_5^V \varepsilon_{\mu\nu\rho\sigma}\left((\partial^\rho W^{-\mu})W^{+\nu} - W^{-\mu}(\partial^\rho W^{+\nu})\right)V^\sigma$$
$$+ i g_4^V W^-_\mu W^+_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu) - \frac{\tilde\kappa_V}{2} W^-_\mu W^+_\nu \varepsilon^{\mu\nu\rho\sigma}V_{\rho\sigma} - \frac{\tilde\lambda_V}{2m_W^2} W^-_{\rho\mu}W^{+\mu}{}_{\nu}\varepsilon^{\nu\rho\alpha\beta}V_{\alpha\beta}\Big]$$

Standard Model:
$$g_1^Z = g_1^\gamma = \kappa_Z = \kappa_\gamma = 1$$

Constants derived from this WW→lνlν analysis:

$$\mathcal{O}_{WWW} = \frac{c_{WWW}}{\Lambda^2}\mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_\rho^{\ \mu}], \quad \text{(corr. to } \lambda_\gamma\text{)}$$
$$\mathcal{O}_W = \frac{c_W}{\Lambda^2}(D^\mu\Phi)^\dagger W_{\mu\nu}(D^\nu\Phi), \quad \text{(corr. to } g_1^Z\text{)}$$
$$\mathcal{O}_B = \frac{c_B}{\Lambda^2}(D^\mu\Phi)^\dagger B_{\mu\nu}(D^\nu\Phi). \quad \text{(corr. to } \kappa_\gamma, g_1^Z\text{)}$$

Results from other analyses



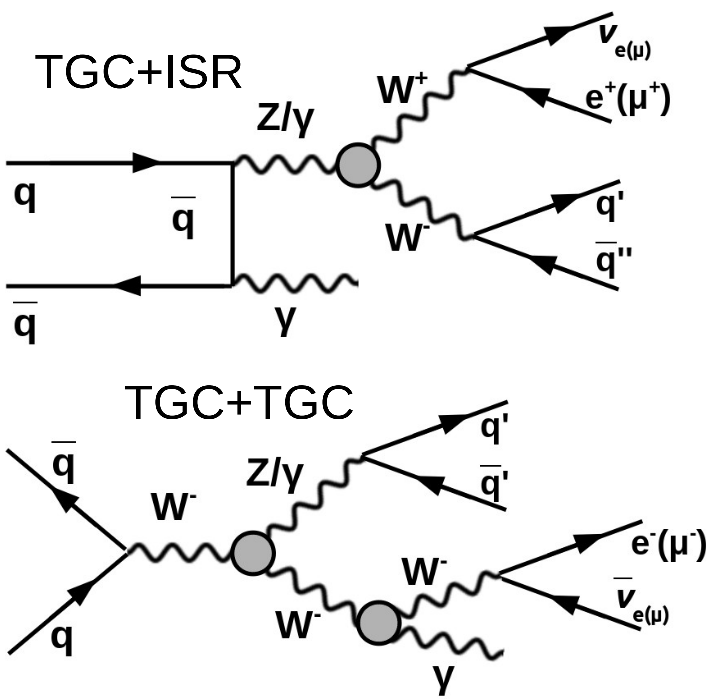
Coupling constant	This result 95% interval (TeV^{-2})	World average (TeV^{-2})
c_{WWW}/Λ^2	$[-5.7, 5.9]$	-5.5 ± 4.8 (from λ_γ)
c_W/Λ^2	$[-11.4, 5.4]$	$-3.9^{+3.9}_{-4.8}$ (from g_1^Z)
c_B/Λ^2	$[-29.2, 23.9]$	$-1.7^{+13.6}_{-13.9}$ (from κ_γ and g_1^Z)

- Limits in assumption of all other coupling constants to be 0 are set

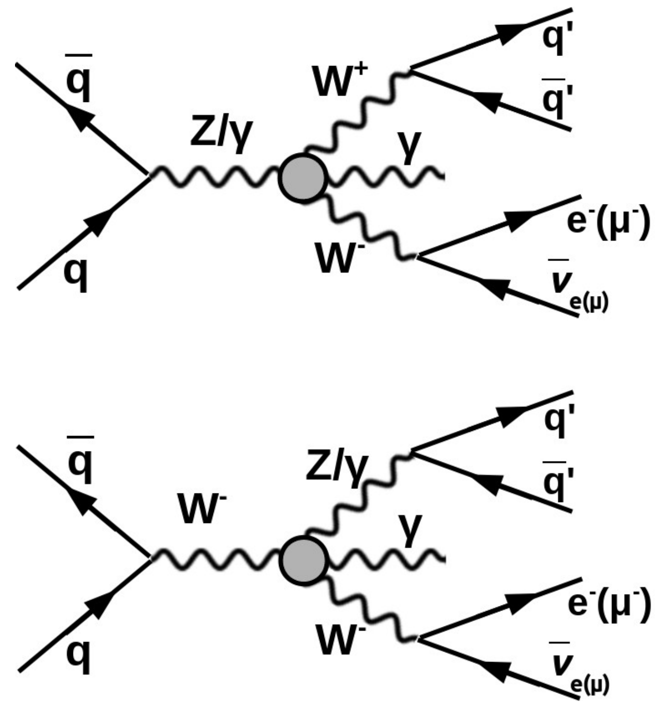
- Simultaneous limits from varying two constants at the same time are set (backup slide 23)

Results are consistent with the Standard Model prediction

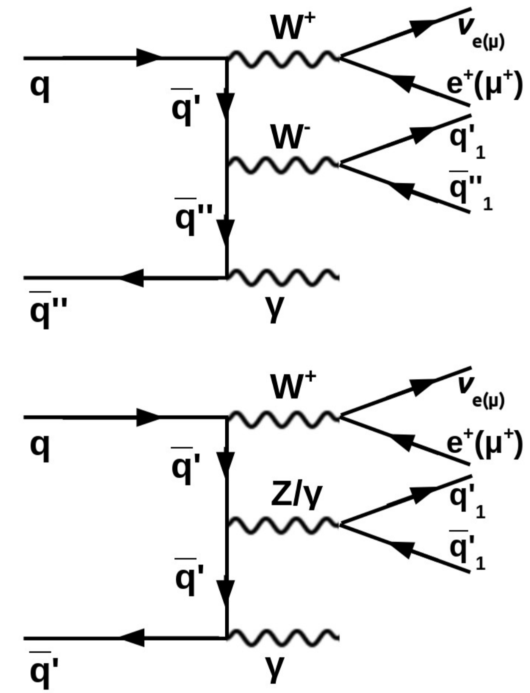
WVγ (WZγ+WWγ) and aQGC Searches [8]



TGC. **Present** in the Standard Model. **Not probed** in this analysis



QGC. **Present** in the Standard Model. **Probed** in this analysis



Radiations from quarks/antiquarks

Process signature: lepton, significant E_T^{miss} due to neutrino, two hadronic jets, and photon; WZγ+WWγ combined

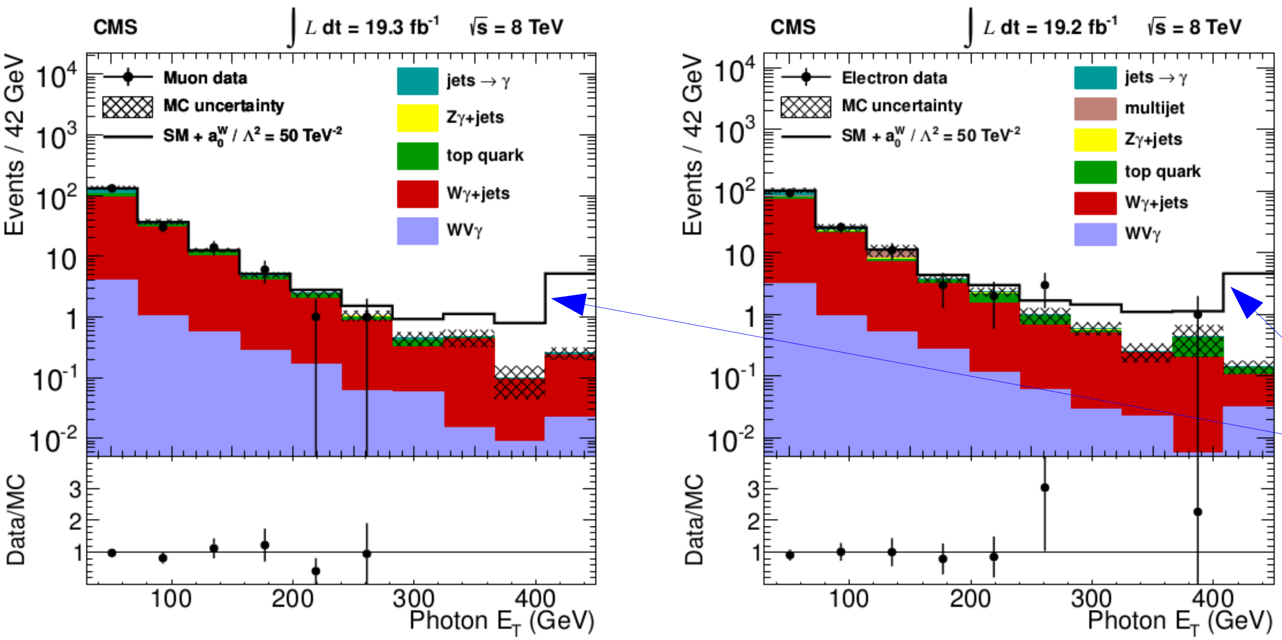
WVγ (WZγ+WWγ). Selection and Backgrounds

Event Selection:

- 1 well identified lepton, 2 well identified jets with $70 < m_{jj} < 100$ GeV
- E_T^{miss}>35 GeV (due to neutrino)
- WWγ+WZγ are combined, **two channels treated separately: $(e\nu_e)(jj)\gamma$ and $(\mu\nu_\mu)(jj)\gamma$**

Major Background:

- **Wγ+jets:** shape taken from MC, normalization estimated using fit in $m_{jj} < 70$ GeV and $m_{jj} > 100$ GeV ranges



Total uncertainty is larger than signal therefore cross section can not be measured, only upper limit on total cross section is possible

aQGC would cause enhance at high E_T^{γ}

WVγ (WZγ+WWγ). aQGC Limits

$$L_{aQGC} = L_1 + L_2 + L_3$$

$$L_1 = -\frac{e^2}{8}\frac{a_0^W}{\Lambda^2} F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W^-_\alpha - \frac{e^2}{16}\frac{a_C^W}{\Lambda^2} F_{\mu\nu}F^{\mu\alpha}\left(W^{+\nu}W^-_\alpha + W^{-\nu}W^+_\alpha\right)$$

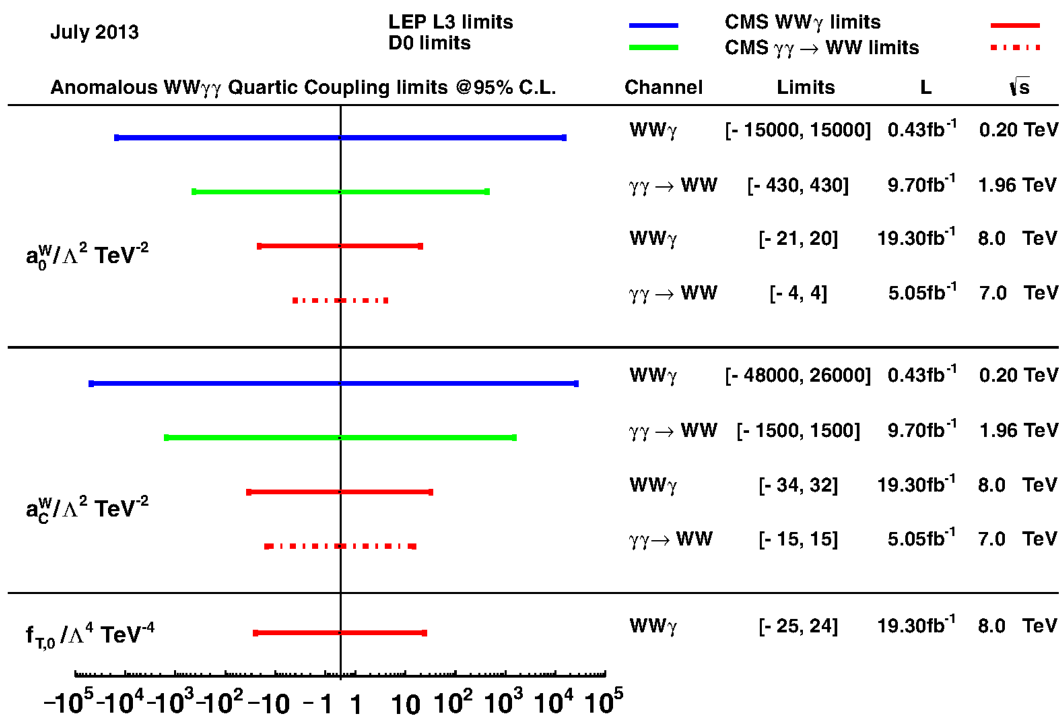
associated with WWγγ

$$L_2 = -e^2 g^2 \frac{\kappa_0^W}{\Lambda^2} F_{\mu\nu}Z^{\mu\nu}W^{+\alpha}W^-_\alpha - \frac{e^2 g^2}{2}\frac{\kappa_C^W}{\Lambda^2} F_{\mu\nu}Z^{\mu\alpha}\left(W^{+\nu}W^-_\alpha + W^{-\nu}W^+_\alpha\right)$$

associated with WWZγ; **first time ever measured**

$$L_3 = -\frac{f_{T,0}}{\Lambda^4} Tr[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times Tr[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}]$$

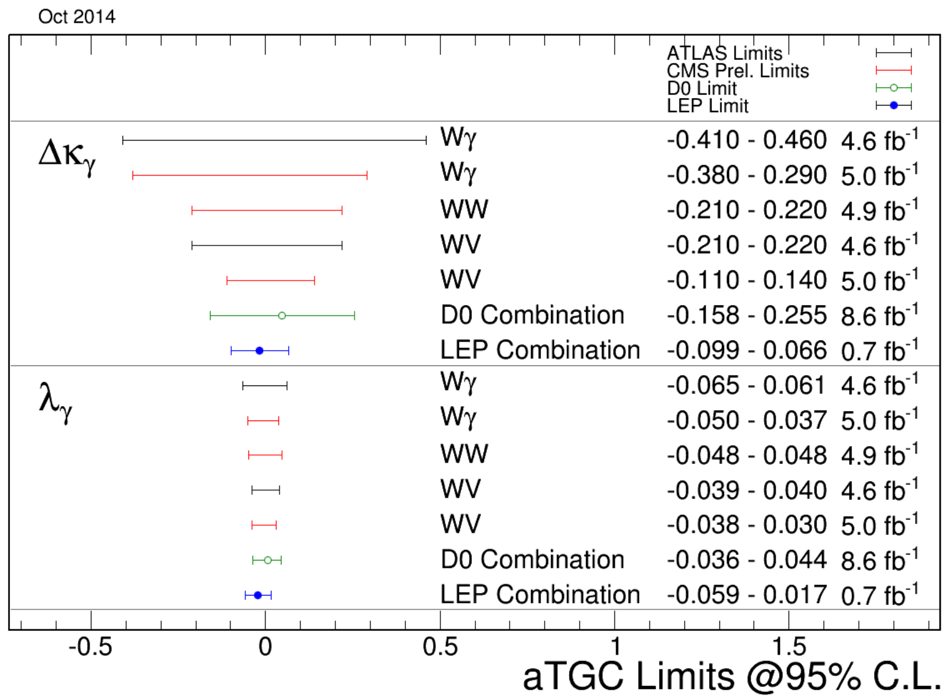
associated with both WWγγ and WWZγ; **first time ever measured**

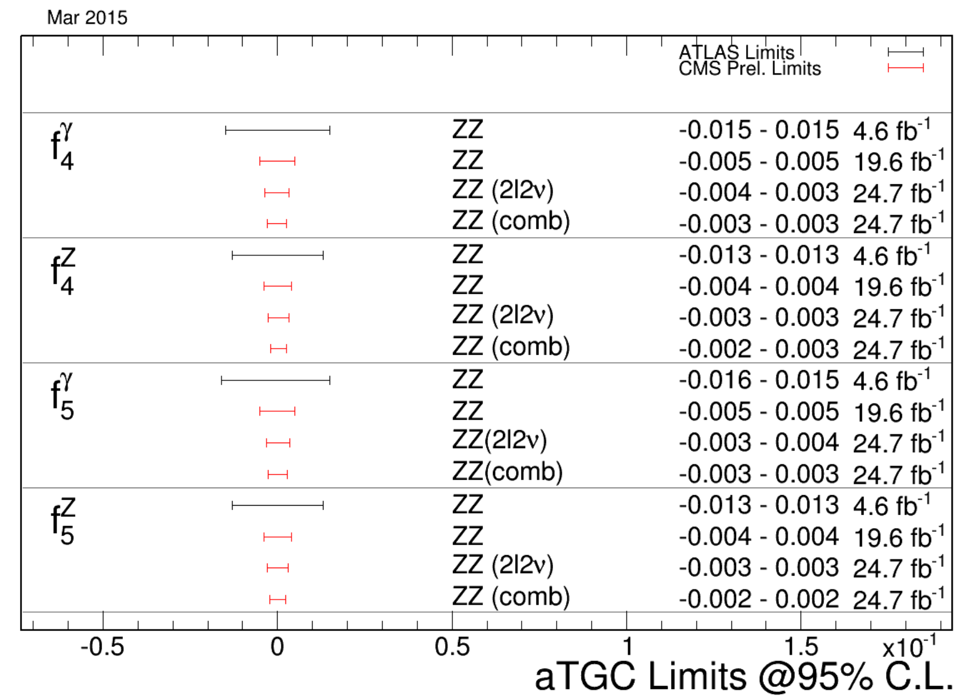


Observed limits
$-21 < a_0^W/\Lambda^2 < 20\ \mathrm{TeV}^{-2}$
$-34 < a_C^W/\Lambda^2 < 32\ \mathrm{TeV}^{-2}$
$-25 < f_{T,0}/\Lambda^4 < 24\ \mathrm{TeV}^{-4}$
$-12 < \kappa_0^W/\Lambda^2 < 10\ \mathrm{TeV}^{-2}$
$-18 < \kappa_C^W/\Lambda^2 < 17\ \mathrm{TeV}^{-2}$

All results are consistent with the Standard Model prediction

WWγ, ZZZ, ZZγ aTGC Limits [2], [5], [6], [7]





$$\mathcal{L}_{VZZ} = -\frac{e}{M_Z^2}\left\{\left[f_4^\gamma(\partial_\mu F^{\mu\alpha}) + f_4^Z(\partial_\mu Z^{\mu\alpha})\right] Z_\beta\left(\partial^\beta Z_\alpha\right) - \left[f_5^\gamma(\partial^\mu F_{\mu\alpha}) + f_5^Z(\partial^\mu Z_{\mu\alpha})\right]\tilde{Z}^{\alpha\beta}Z_\beta\right\}$$

$$\begin{aligned} i\mathcal{L}_{eff}^{WWV} = \; & g_{WWV}\Big[g_1^V V^\mu\left(W^-_{\mu\nu}W^{+\nu} - W^+_{\mu\nu}W^{-\nu}\right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \\ & \frac{\lambda_V}{m_W^2} V^{\mu\nu} W_\nu^{+\rho} W^-_{\rho\mu} + i g_5^V \varepsilon_{\mu\nu\rho\sigma}\left((\partial^\rho W^{-\mu})W^{+\nu} - W^{-\mu}(\partial^\rho W^{+\nu})\right)V^\sigma \\ & + i g_4^V W^-_\mu W^+_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu) - \frac{\tilde\kappa_V}{2} W^-_\mu W^+_\nu \varepsilon^{\mu\nu\rho\sigma}V_{\rho\sigma} - \frac{\tilde\lambda_V}{2m_W^2} W^-_{\rho\mu}W^{+\mu}{}_\nu \varepsilon^{\nu\rho\alpha\beta}V_{\alpha\beta}\Big] \end{aligned}$$

Standard Model:

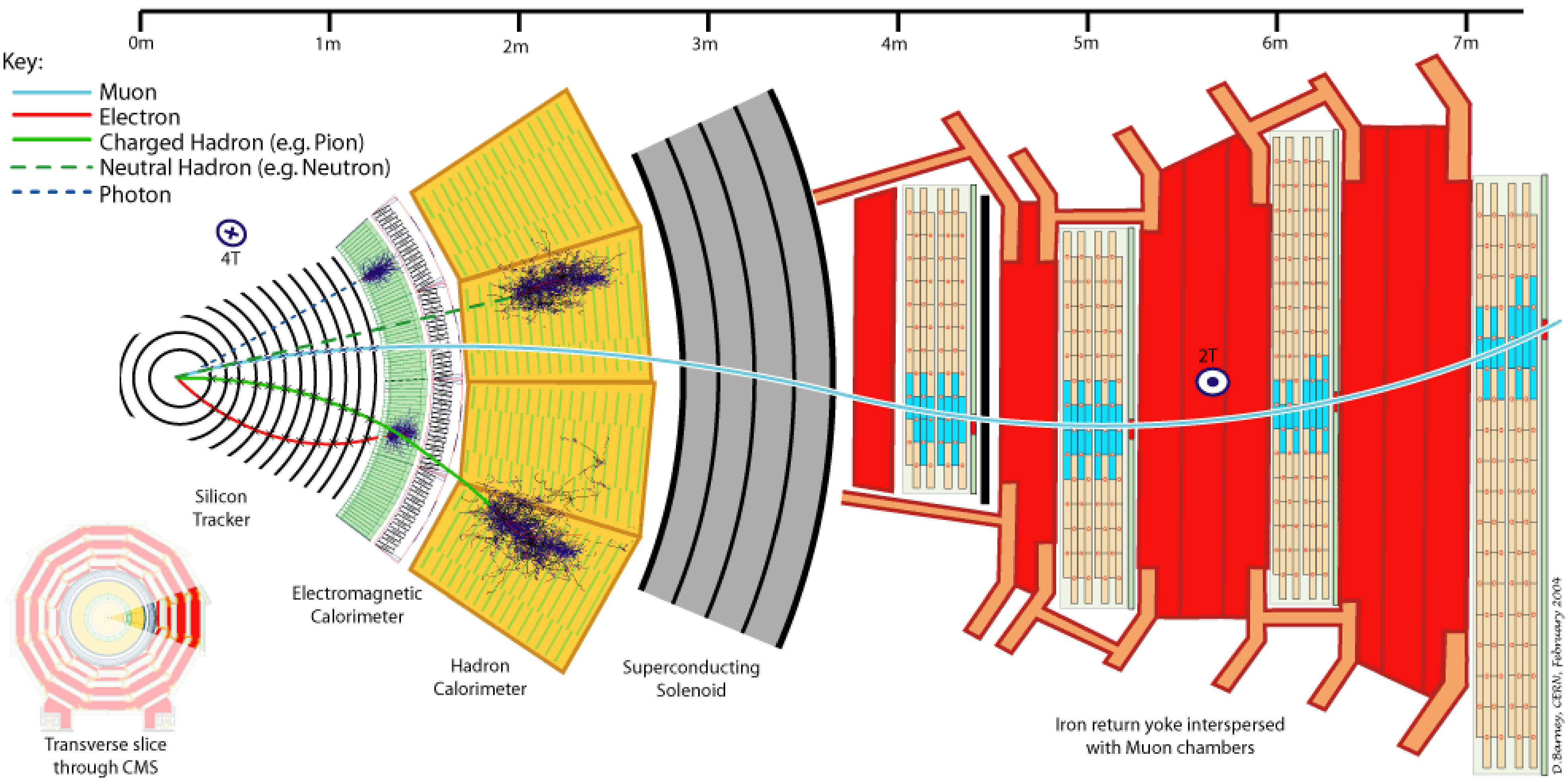
$$g_1^Z = g_1^\gamma = \kappa_Z = \kappa_\gamma = 1$$

Conclusions

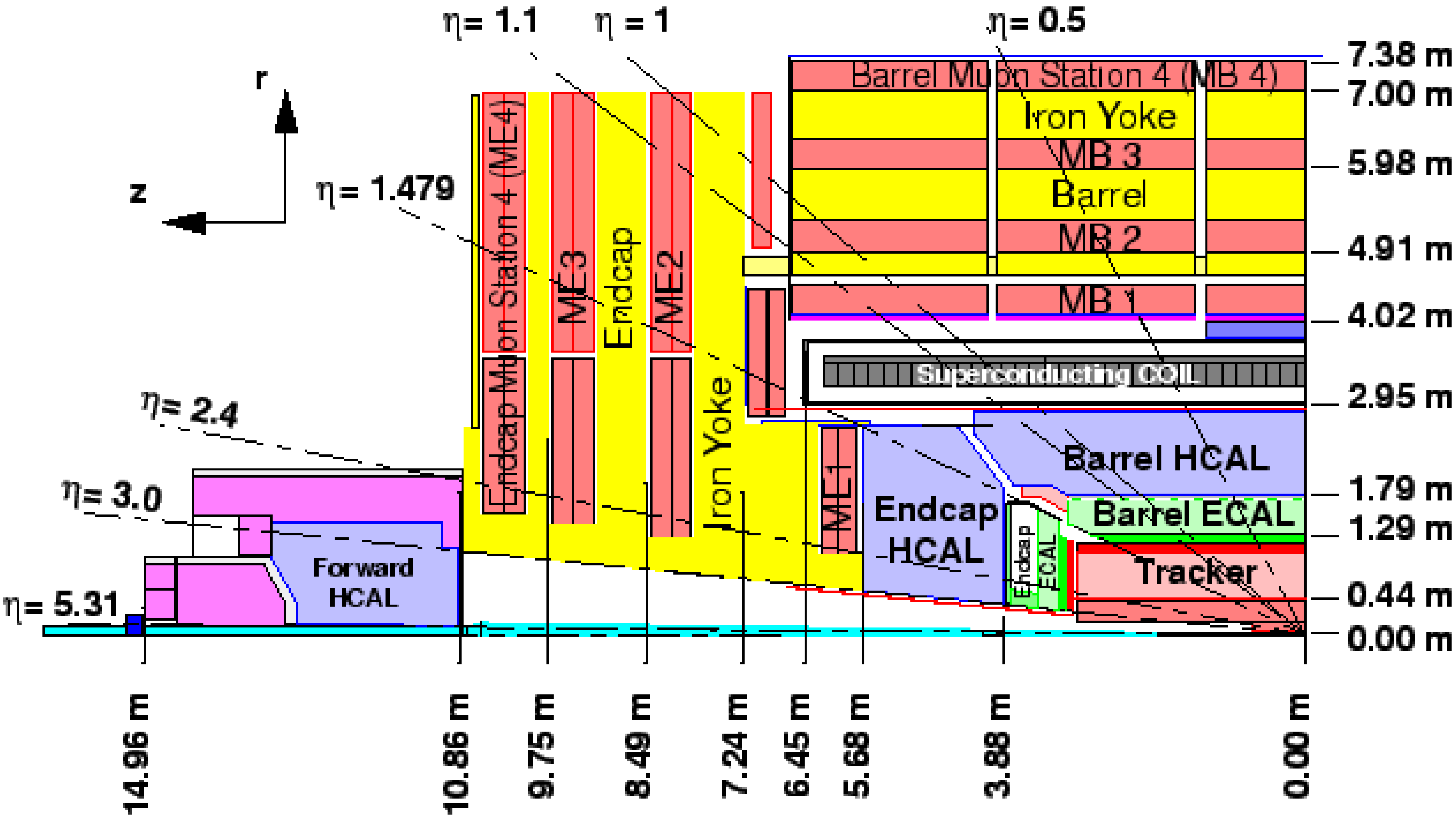
- The latest results on aTGC and aQGC searches with Zγ, WW, WVγ productions with 7 TeV and 8 TeV data in CMS are presented
- **The most stringent to date limits on ZZγ, Zγγ aTGC couplings are set**
- **The first ever limit on WWZγ aQGC coupling is set**
- Limits on WWZ, WWγγ anomalous coupling constants are set
- Other aTGC and aQGC analyses, not covered in this talk, have been performed in CMS (see slide 4)
- **All results are consistent with the Standard Model prediction**
- Several more 7 TeV and 8 TeV measurements are in progress
- More opportunities are expected with 13 TeV data

BACKUP SLIDES

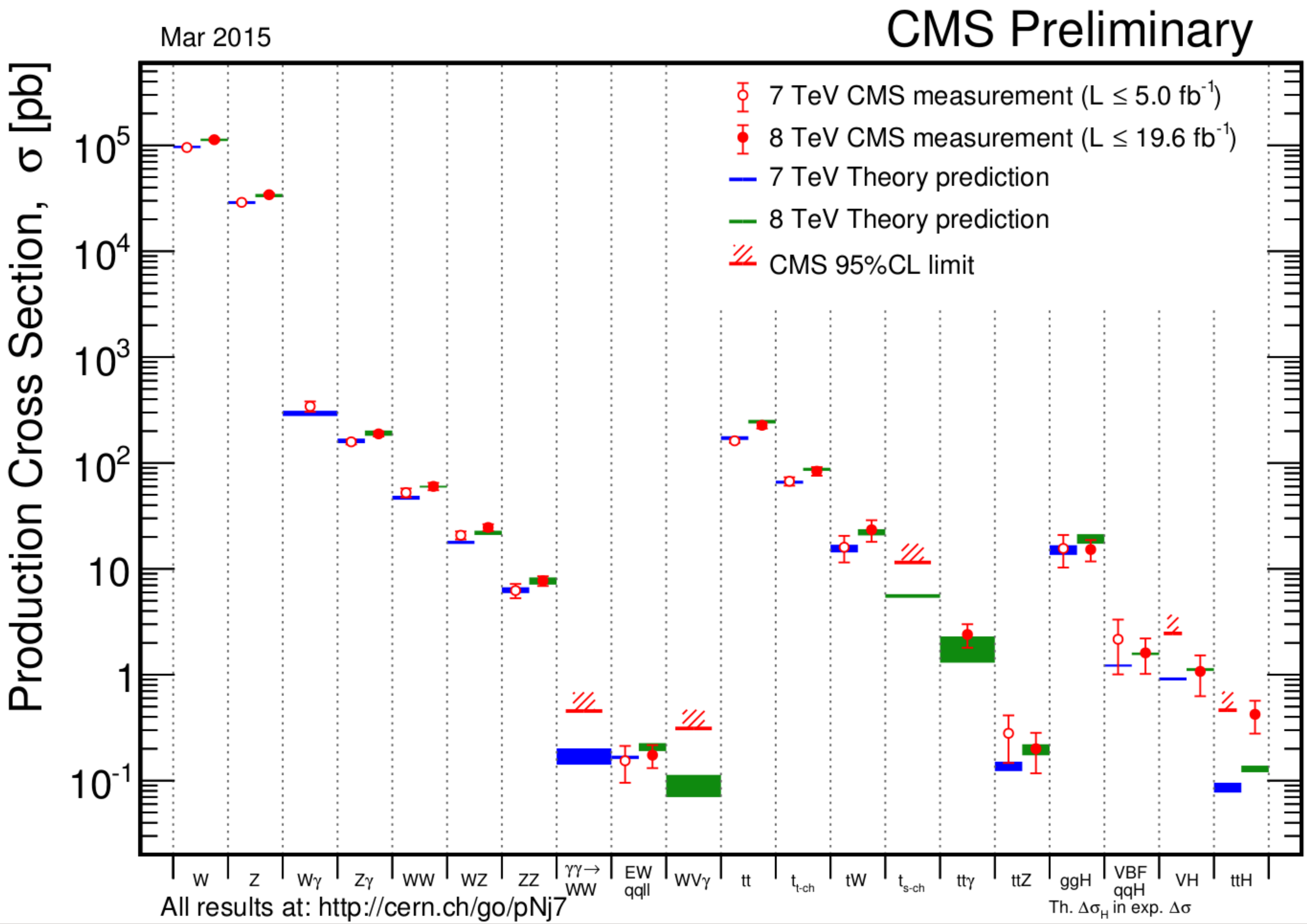
CMS. Particle Detection General View



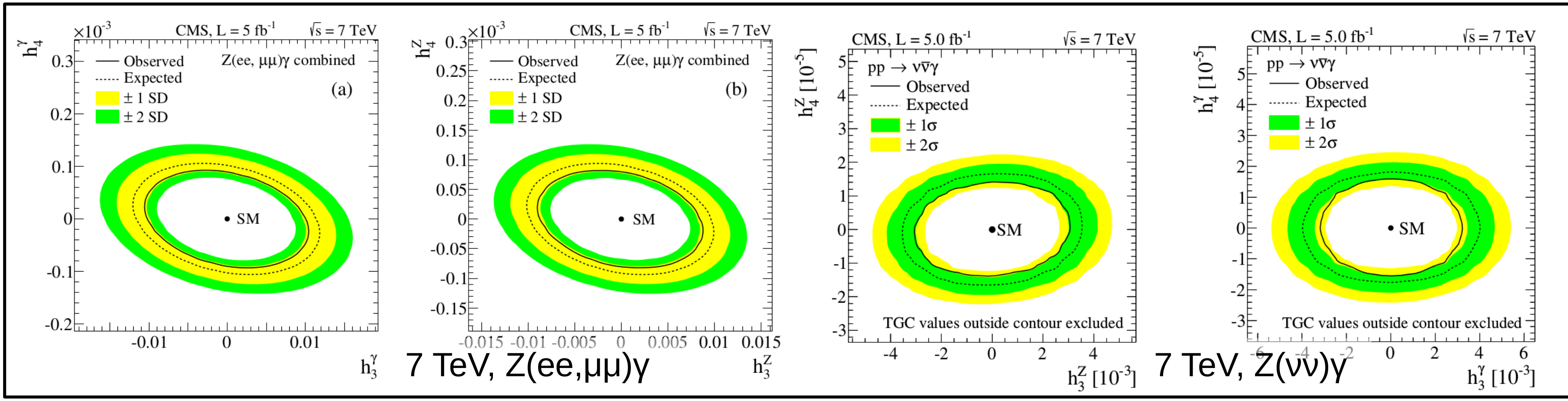
CMS. ¼ section in z-r plane



Production Cross Sections

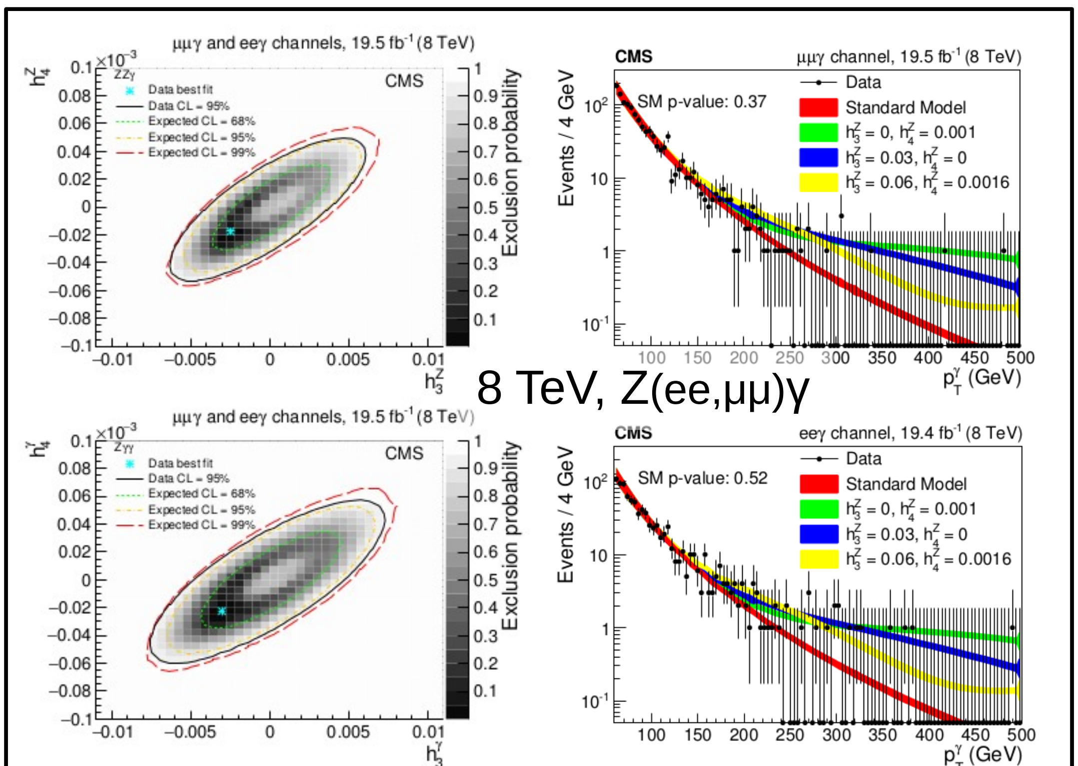


Zγ [1], [2], [3]. Simultaneous aTGC Limits



7 TeV, Z(ee,μμ)γ

7 TeV, Z(νν)γ



8 TeV, Z(ee,μμ)γ

WW→lνlν [4]. Simultaneous aTGC Limits