aQGC Sensitivity Studies from CMS

Kalanand Mishra, Fermilab

Working Group on Electroweak precision measurements at the LHC

(April 16, 2013)

Quartic couplings

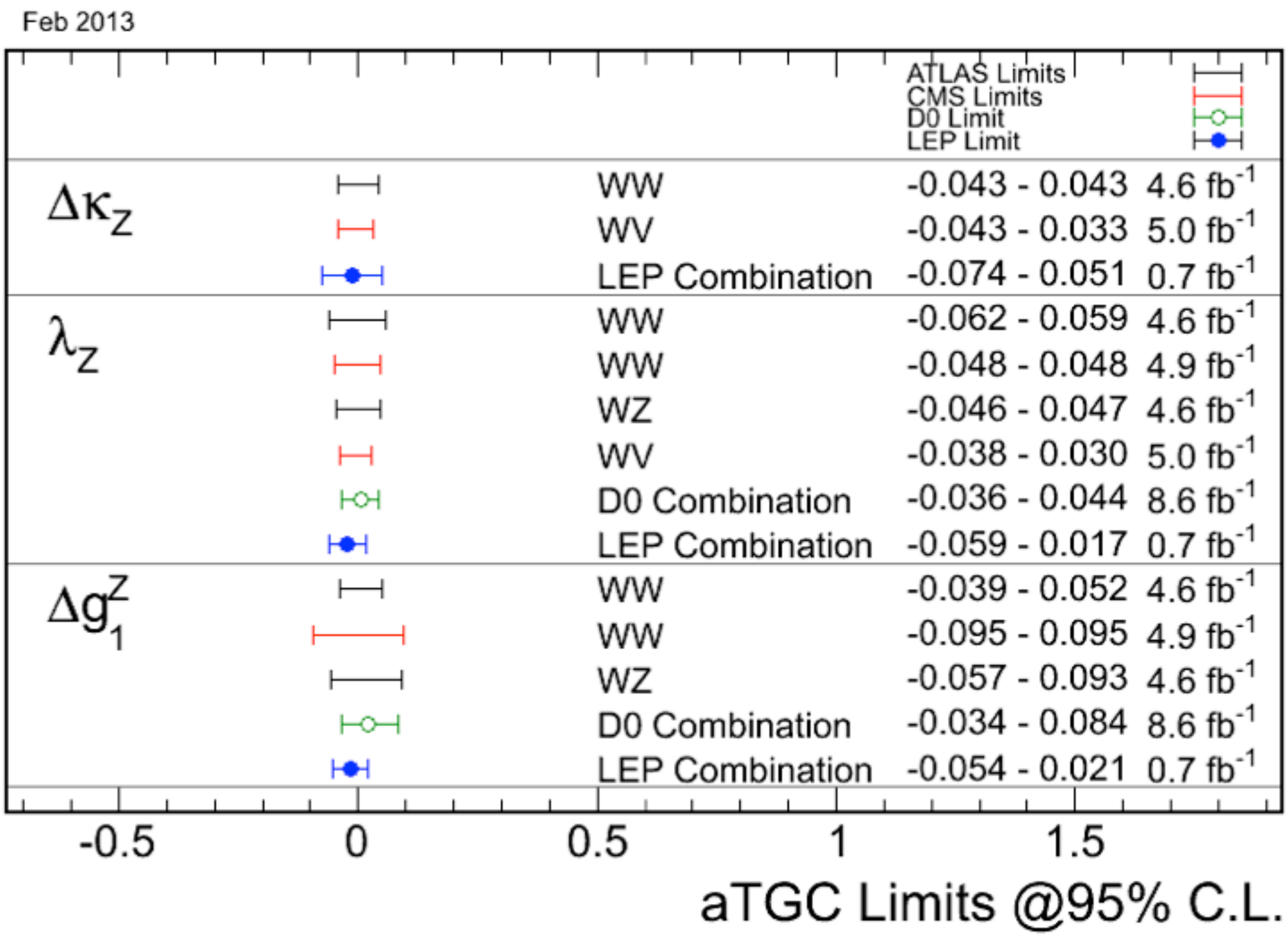
I will only talk about couplings involving W boson

- In the SM, the allowed couplings are:
  $WW\gamma\gamma$, $WWZ\gamma$, WWWW, WWZZ
- Observable in two topologies at the LHC
  - Triple gauge boson production (e.g., $W\gamma\gamma$, $WW\gamma$, WWW, WWZ)
  - Scattering process (e.g., $\gamma\gamma \rightarrow WW$, $WW \rightarrow WW$)
- Anomalous couplings introduced via effective Lagrangian
  - Should use the linear realization with light Higgs
  - aQGCs for SM allowed processes introduced at dimension 6
  - However they are the same operators as the aTGCs which are better measured (see next slide)
- Lowest independent aQGC interactions are dimension 8

Summary of charged aTGC measurements

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

in the notation of LEP parametrization hep-ph/9601233



- aTGCs entangled with aQGC, as explained in the following slides.
- Current constraints on aTGCs: < 10% deviation from SM. Expect to achieve a few % precision with 8 TeV data.

Anomalous quartic couplings in dimension 8

All D8 aQGC operators in Eboli's notation

hep-ph/0606118
Eboli et. al.

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu}$$
$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu}$$
$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right]$$
$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]$$

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$
$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$
$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$
$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}$$
$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$
$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

L_M have D6 equivalents (a_0, a_c), L_T are novel to D8

	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

aQGC D6 vs D8

- In the two realizations
  - Linear: all lowest order independent aQGCs are D8
  - Nonlinear: a number of dimensions, aQGCs involving γ are D6
- Consider $WW\gamma\gamma$
  - Largest contributing nonlinear terms:
    - Limits set on a/Λ^2

$$L_6^0 = -\frac{e^2}{16\Lambda^2}\, a_0\, F^{\mu\nu}\, F_{\mu\nu} \vec{W}^\alpha \cdot \vec{W}_\alpha$$

$$L_6^c = -\frac{e^2}{16\Lambda^2}\, a_c\, F^{\mu\alpha}\, F_{\mu\beta} \vec{W}^\beta \cdot \vec{W}_\alpha$$

  - Equivalent D8 terms (L_{M2}, L_{M3})
    - Limits set on q/Λ^4
    - Straightforward conversions

$$\frac{q_i}{\Lambda^4} = \frac{8a_i}{\Lambda^2 M_W^2}$$

- Expectations:
  - SM rate detectable with TGC and QGC contributions at e^2
  - aTGC and aQGC entangled, suppressed by q/Λ^4
  - Sensitivity on high p_T tail

Burden of legacy ....

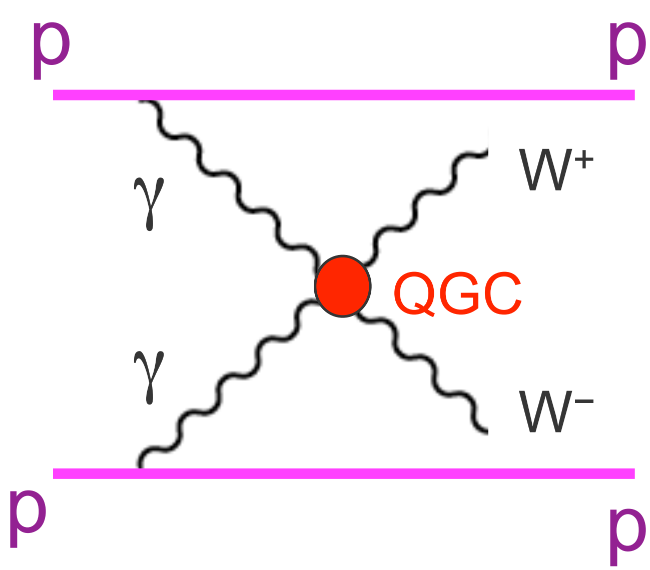
Almost all previous work in nonlinear realization

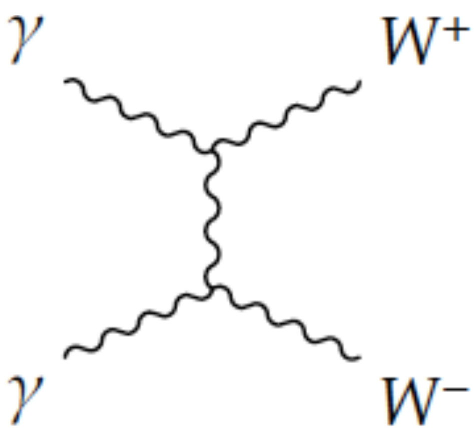
- Symmetries enforced without light Higgs
- Lower dimension D4, D6 aQGCs
- Have to connect with that work
  - LEP, LHC limits already set in that approach
  - they often use arbitrary form factors to dampen non-unitarity

Our current/proposed approach

- Adopt D8 (linear) approach for setting aQGC limits
- However, in order to easily compare with the existing results
  - use D6 equivalents for those operators which exist in both D6 and D8 realizations
  - operators that are novel in D8 are probed for the first time, so there is no legacy issues to take care of

Probing quartic couplings via $\gamma\gamma \rightarrow WW$ process





CMS analysis:

See talk by Jonathan Hollar

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ12010

Limits on aQGC without form-factors:

$$-2.80 \times 10^{-6} < a_0^W / \Lambda^2 < 2.80 \times 10^{-6} \text{ GeV}^{-2}$$

$$-1.02 \times 10^{-5} < a_C^W / \Lambda^2 < 1.02 \times 10^{-5} \text{ GeV}^{-2}$$

$\mathcal{O}(10^2)$ times more constraining than the LEP combined limit

Probing quartic couplings via VVV production

For example: WWγ production at LHC

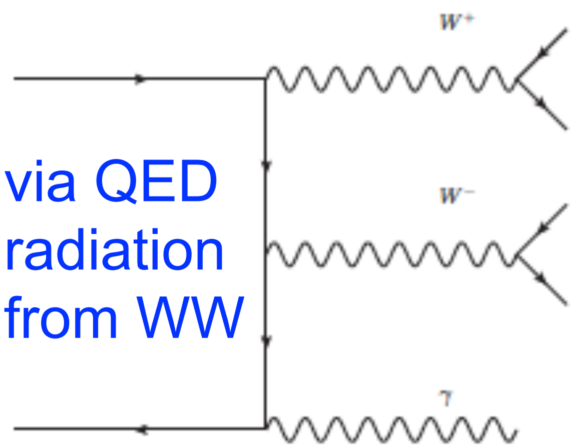
References:

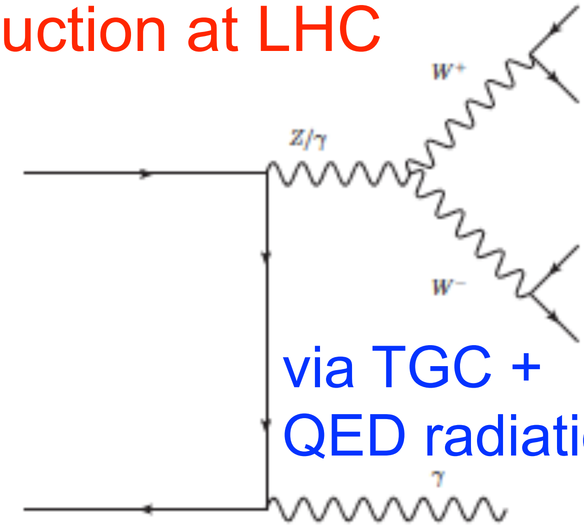
1.) Yang et al, arXiv: 1211.1641

2.) LEP combination, hep-ex/0612034

3.) Bozzi et al, arXiv: 0911.0438

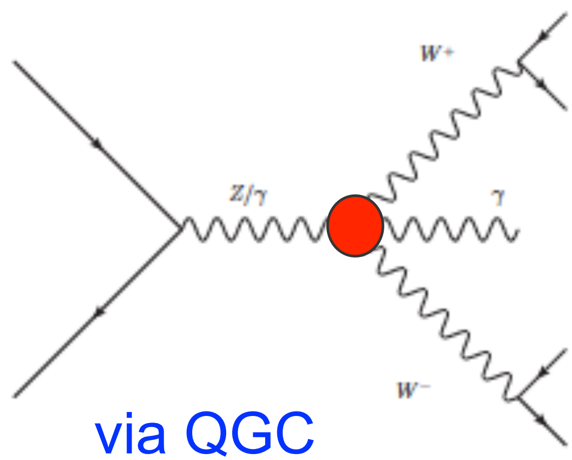
via QED radiation from WW





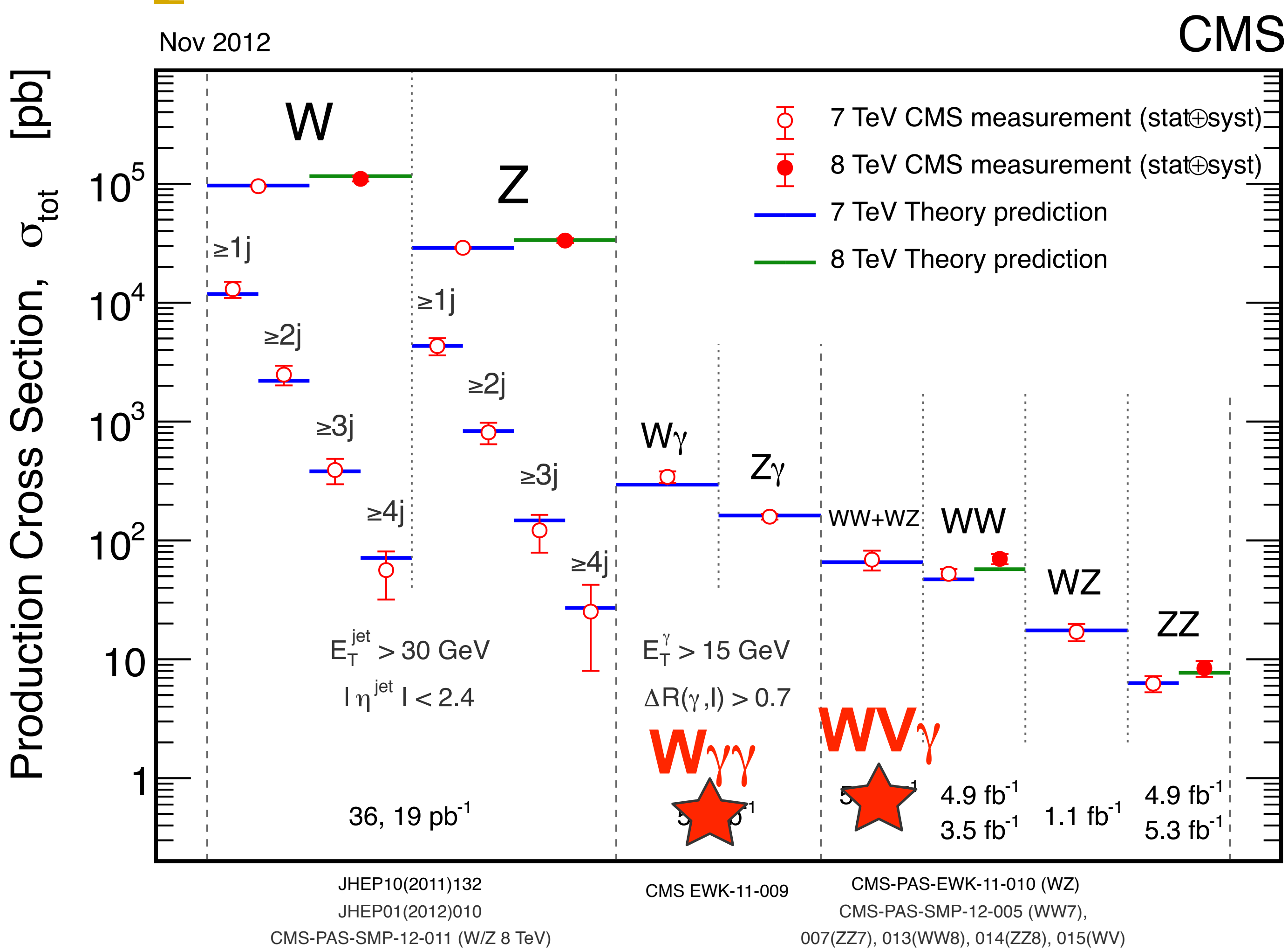
via TGC + QED radiation

- SM production highly suppressed
  - By a factor of 10^3 compared to WW
- aQGC at WWγγ and WWγZ vertices <u>can enhance production for high photon p_T events by several factors</u>



via QGC

Truly rare processes



- Sub-pb cross section
- Higher BR makes semi-leptonic channel more attractive
  - $\sigma \times BR$ for $WV\gamma \approx 60$ fb w/o cut on photon p_T, where V = W or Z →qq

WWγ, WZγ semi-leptonic channel expectations

- Within detector fiducial, expect 10−20 reconstructed WVγ events ($\gamma+\ell+E_T^{miss}$+jj) in 20 fb^{-1} of 8 TeV data
- Given small S/B, barely getting sensitive to SM WVγ signal
  - likely to set upper limit @ a few times the SM cross section
- Expect more constraining limits on aQGC than LEP

Simulation

LO Madgraph simulation

- process: p p > w+ w- a @ 8TeV LHC
- PDF (LO): CTEQ6L1, scale: default MadGraph setting
- generator cuts: $p_T^\gamma > 10$ GeV, $|\eta_\gamma| < 2.5$, $\Delta R(\gamma, j) > 0.5$

  (not Rja cut, but the cut as Eq.(3.4) in arXiv:0911.0438)

$$\sum_{i, R_{i\gamma} < R} p_T^{\text{parton}, i} \leq \frac{1 - \cos R}{1 - \cos \delta_0} p_T^\gamma \qquad \forall R \leq \delta_0,$$

NLO simulation & computation of k-factors

http://amcatnlo.cern.ch/

NLO QCD matched with Parton Shower (HERWIG or PYTHIA)

```
generate p p > w+ w- a [QCD]
output nlowwa
launch -m
```

4 core mode on a single 3.3GHz machine,

~21 hours to get 40k events

Output: (1) events.lhe.gz unweighted events (up to a sign), NLO matched with Parton shower level

(2) events_HERWIG6_0.hep.gz **stdHEP file, showered events**

Total cross sections:

LO: 0.1428 ± 0.0002 pb

NLO (CTEQ6M PDF): 0.2533 ± 0.0011 pb

K factor: 1.8

Some representative diagrams from aMC@NLO

Born

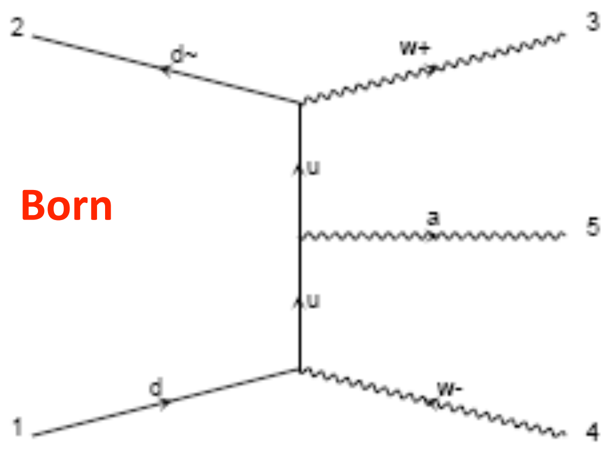
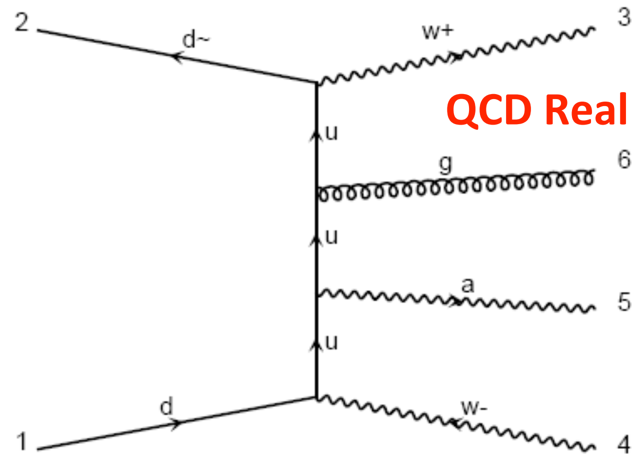


diagram 7 QCD=0, QED=3

QCD Real emission



real diagram 1 QCD=1, QED=3

One-loop QCD

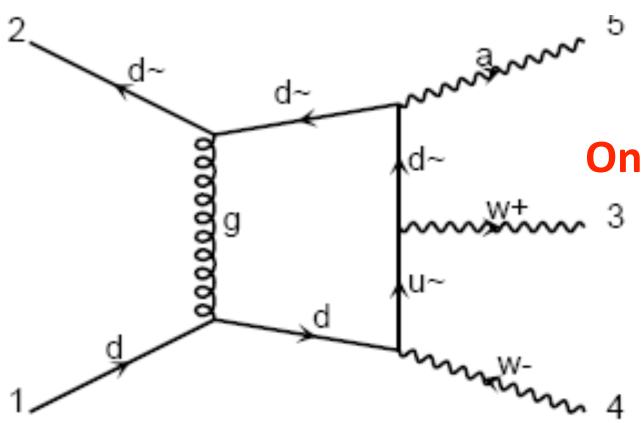


diagram 38 QCD=2, QED=3

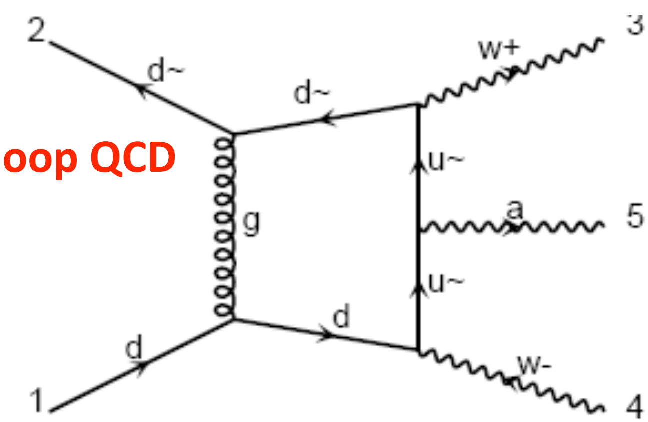
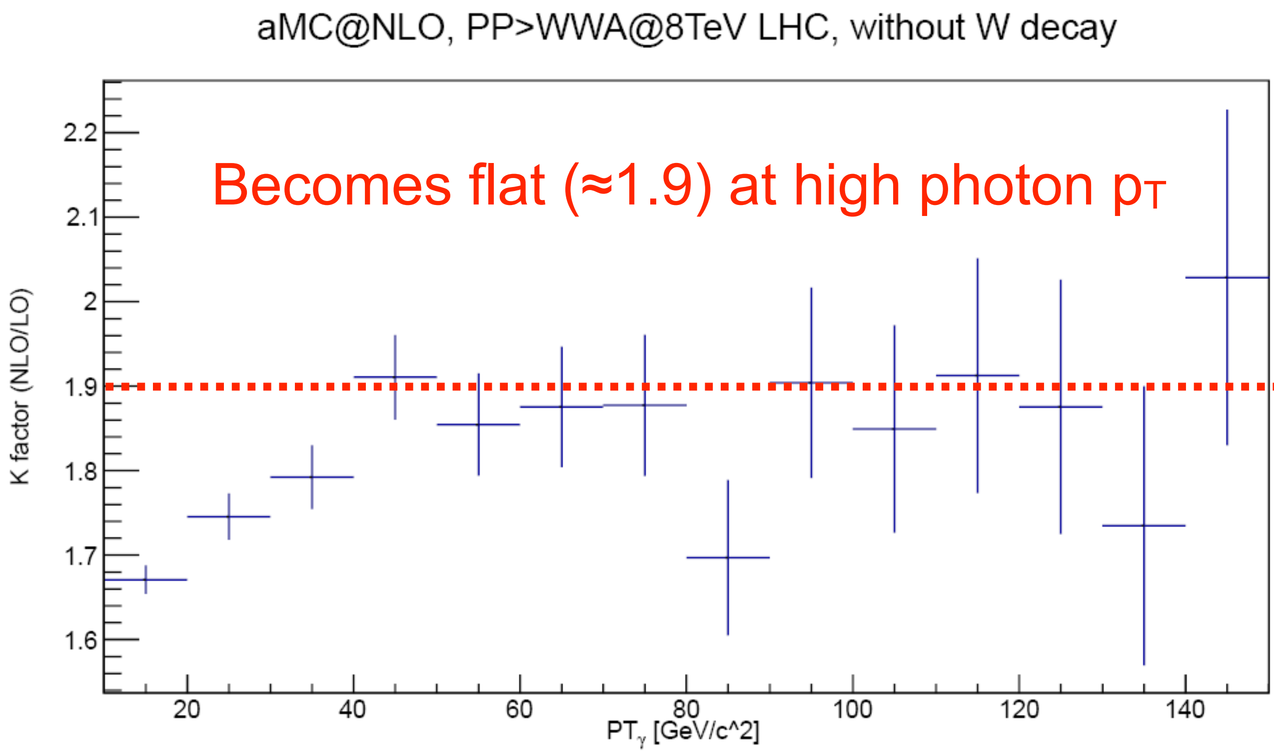


diagram 39 QCD=2, QED=3

k-factor depends on photon p_T

Requiring $p_T^{\gamma} > 10$GeV, $|\eta_\gamma| < 2.5$, $\Delta R(j,\gamma)>0.5$

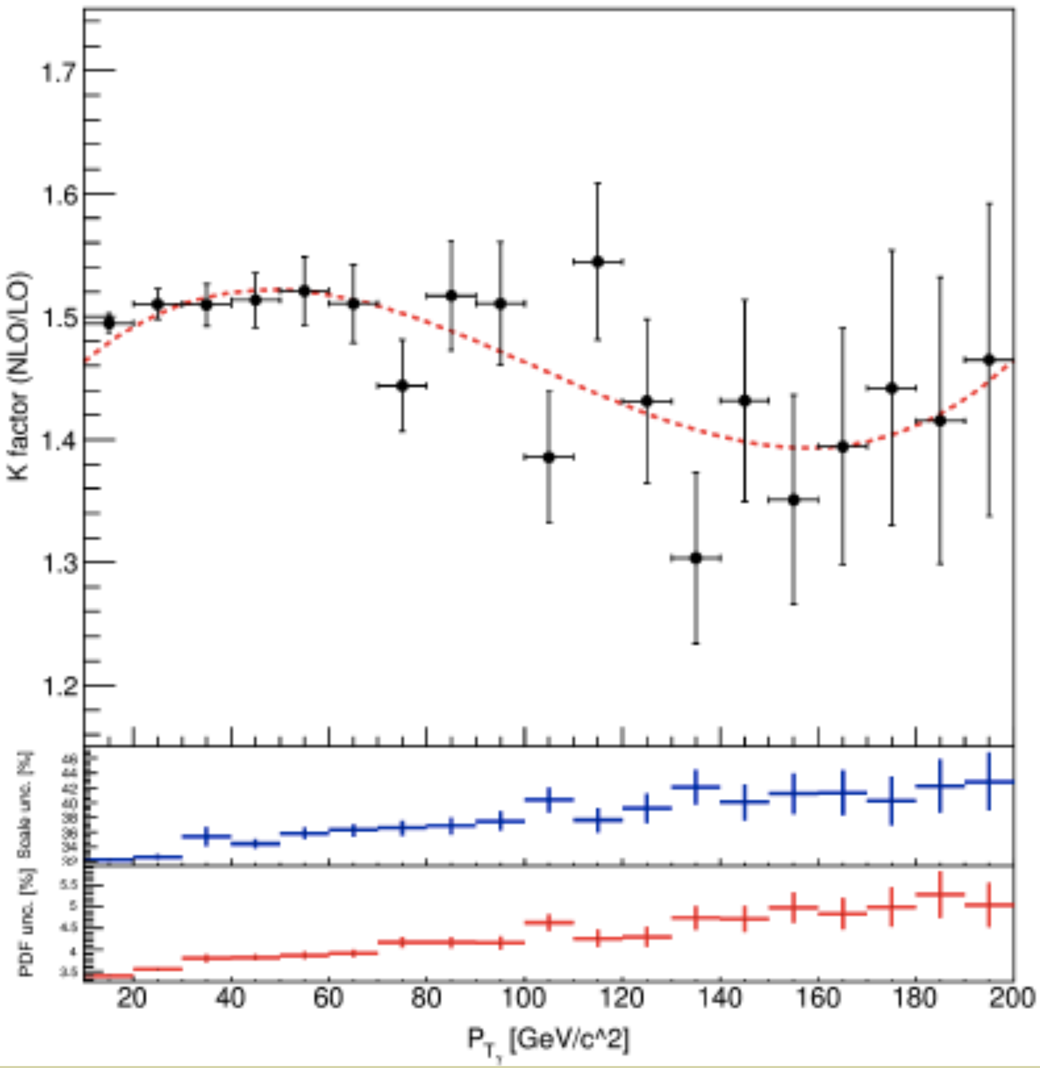


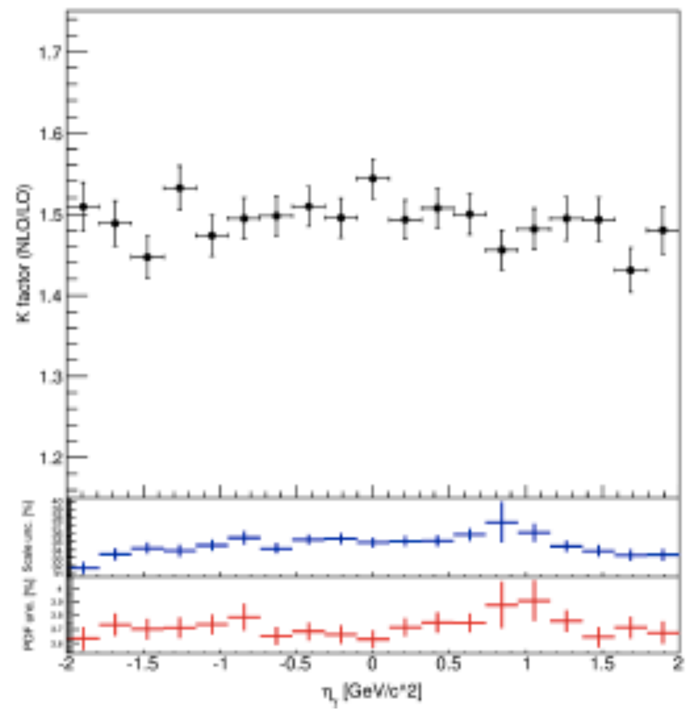
Note: W→jj's k-factor is $(1+\alpha_s/\pi)\sim1.04$, which is quite small

We use this p_T-dependent k-factor in our nominal analysis

k-factor after requiring jet veto

Additional jet veto for $p_T > 30$GeV and $|\eta| < 4.5$





Clearly, applying jet veto in this analysis is not a good idea !!!

Additional verifications

Have checked that

1.) k-factor, as a function of photon p_T, is consistent between $WW\gamma$ and $WZ\gamma$ within MC statistical uncertainties of the samples

2.) k-factor for aQGC events also seems consistent with the k-factor for SM within MC statistical uncertainties (checked several aQGC points)

We will verify both these conclusions again with larger aMC@NLO samples.

Limits on aQGC using MC analysis

Use generator-level quantities and apply correction factor for efficiency and acceptance effects

Event selection:

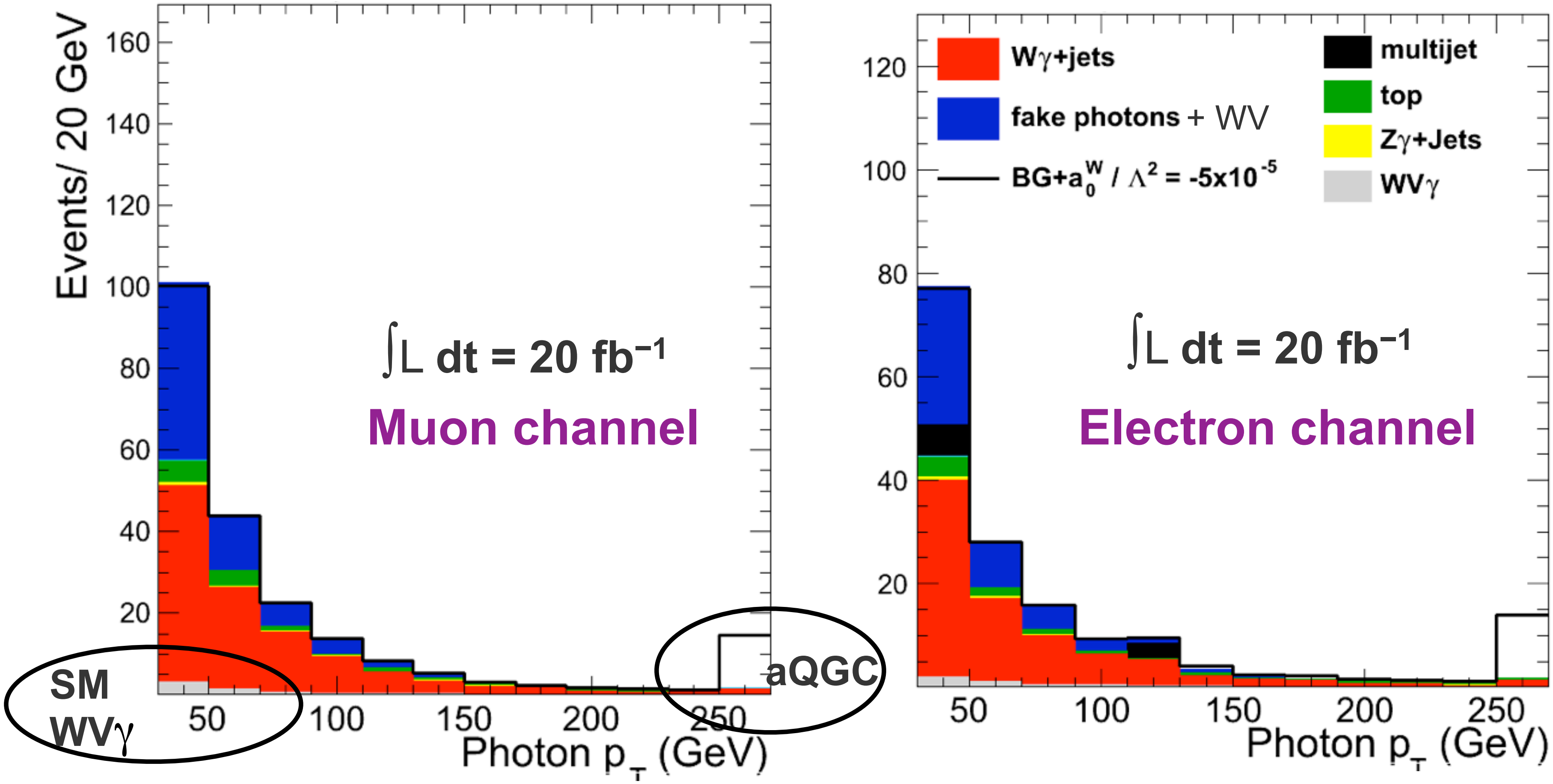
- Lepton p_T > 25 GeV, $|\eta| < 2.4$
- At least 2 non-b jets with p_T > 30 GeV, $|\eta| < 2.5$
- MET > 35 GeV
- Photon E_T > 30 GeV, $|\eta| < 1.44$, $\Delta R(\gamma,\ell) > 0.5$, $\Delta R(\gamma,j) > 0.5$
- $|\Delta\eta(j1,j2)| < 1.4$
- $70 < M_{jj} < 100$ GeV for the leading central jets

Expected yields in 20 fb^{-1} data with some optimized selection:

340 events, 12 $WV\gamma$ signal and 328 background ($W\gamma$+jets, WV+ fake photon, ttbar+γ, multi-jet)

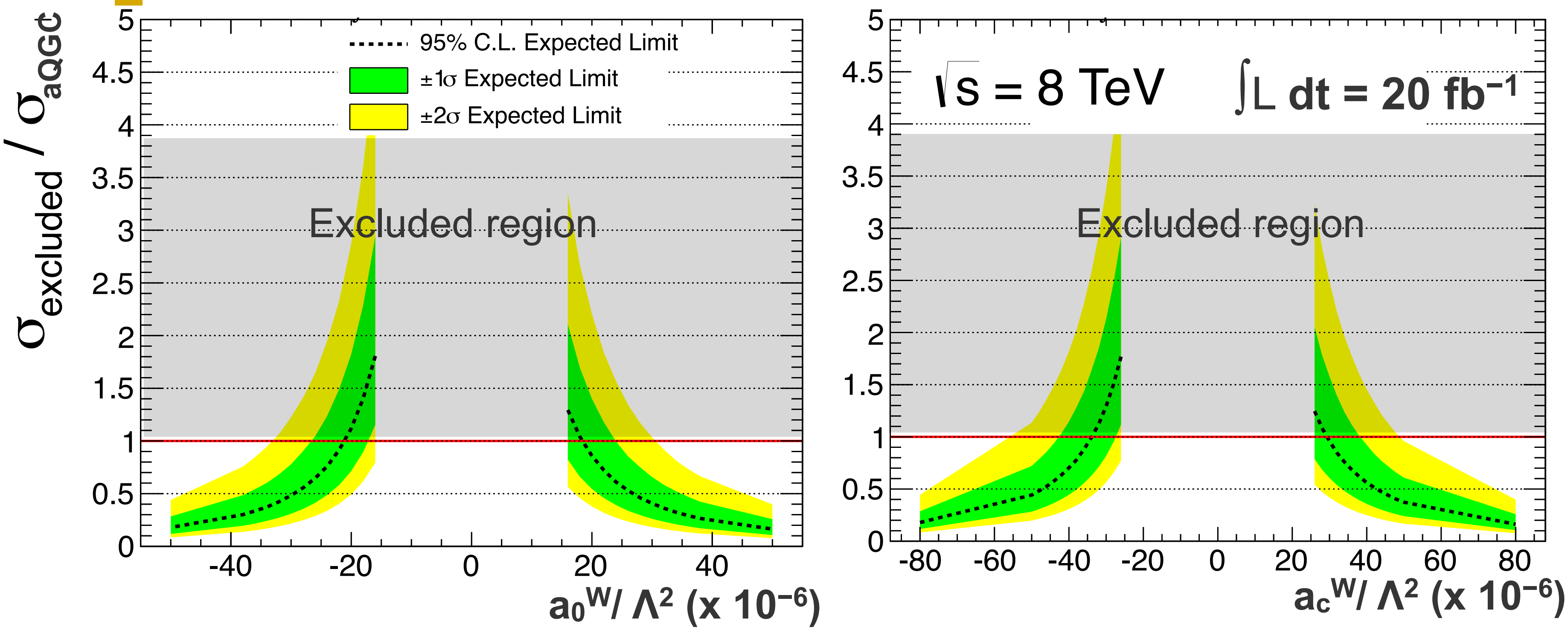
Use γ p_T as observable for setting limits on aQGC.

Observable: γ p_T distribution



Systematic uncertainties: aQGC signal strength 30%, background normalization 20%, experimental uncertainties (JES/R, efficiencies, lumi,...) each within 5%.

Expected limits on aQGCs



LHC WWγ channel expected limits (from each experiment at 95% CL):

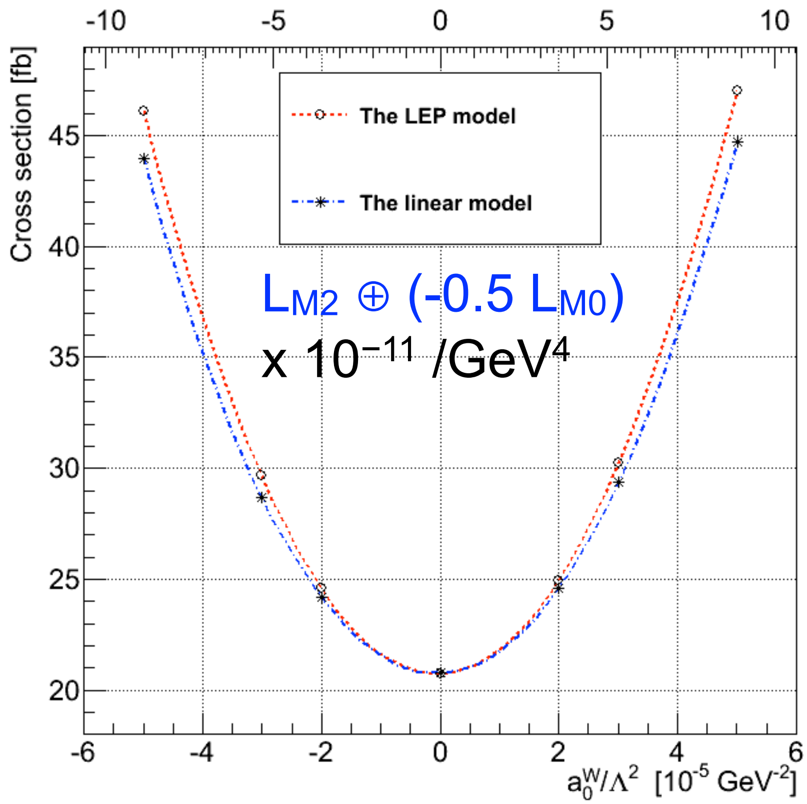
$-2.0 \times 10^{-5} < a_0^W/\Lambda^2 < 2.0 \times 10^{-5}$ $-3.5 \times 10^{-5} < a_c^W/\Lambda^2 < 3.0 \times 10^{-5}$

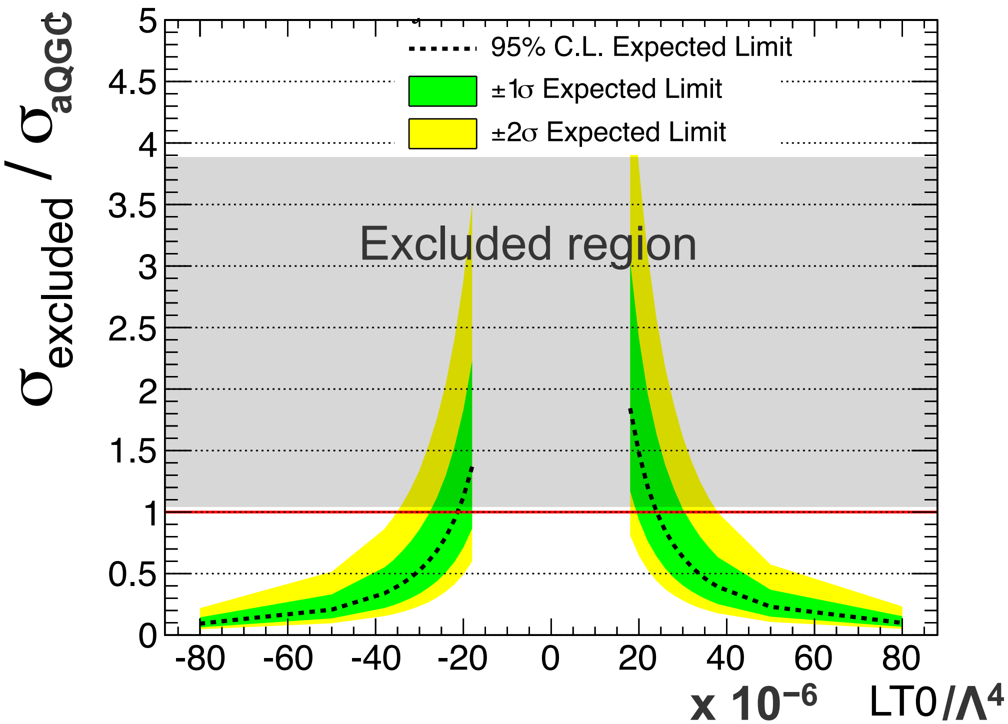
LEP limits

$W^+W^-\gamma$	a_0^W	$-0.020\,\mathrm{GeV}^{-2} < a_0^W/\Lambda^2 < 0.020\,\mathrm{GeV}^{-2}$
$W^+W^-\gamma$	a_c^W	$-0.053\,\mathrm{GeV}^{-2} < a_c^W/\Lambda^2 < 0.037\,\mathrm{GeV}^{-2}$

LHC limits 0(10^2) times more precise than the LEP combined limit

Expected limits II





Shows that coupling a0 in D6 realization can be expressed as linear combination of couplings L_M of D8 realization

Couplings L_T are novel to D8 realization. There is no D6 equivalent. We set limit on L_{T0} assuming other L_T's vanish (they all produce the ~same effect).

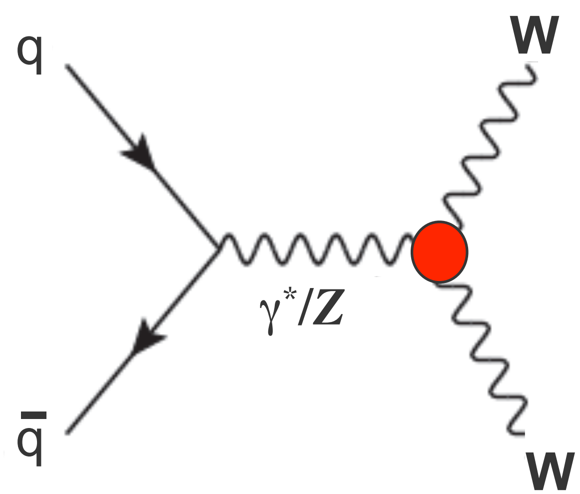
Summary

- Study of QGC and related states is a rich physics program
  - LHC data sufficient for sensitivity to SM QGC and aQGCs
  - New excitement after the discovery of a light Higgs boson
- CMS has dedicated effort to measure QGCs
  - in both multi-boson and scattering topologies
- Starting to set serious constraints on electroweak gauge boson couplings
  - Broke new ground by exceeding LEP aQGC limits by orders of magnitude
  - More results with improved precision soon, stay tuned!

Thank You !

BACKUP SLIDES

Measurements of gauge boson self couplings



- Gauge boson trilinear & quartic couplings emerges naturally from the non-abelian gauge symmetry structure of the SM.
- With $o(10^3)$ WW, $o(10^2)$ WZ, and o(dozens) ZZ events, quickly approaching precision measurement of gauge couplings.
  - Already improved over LEP and Tevatron in most cases.
- Measure anomalous coupling parameters in effective Lagrangian approach.

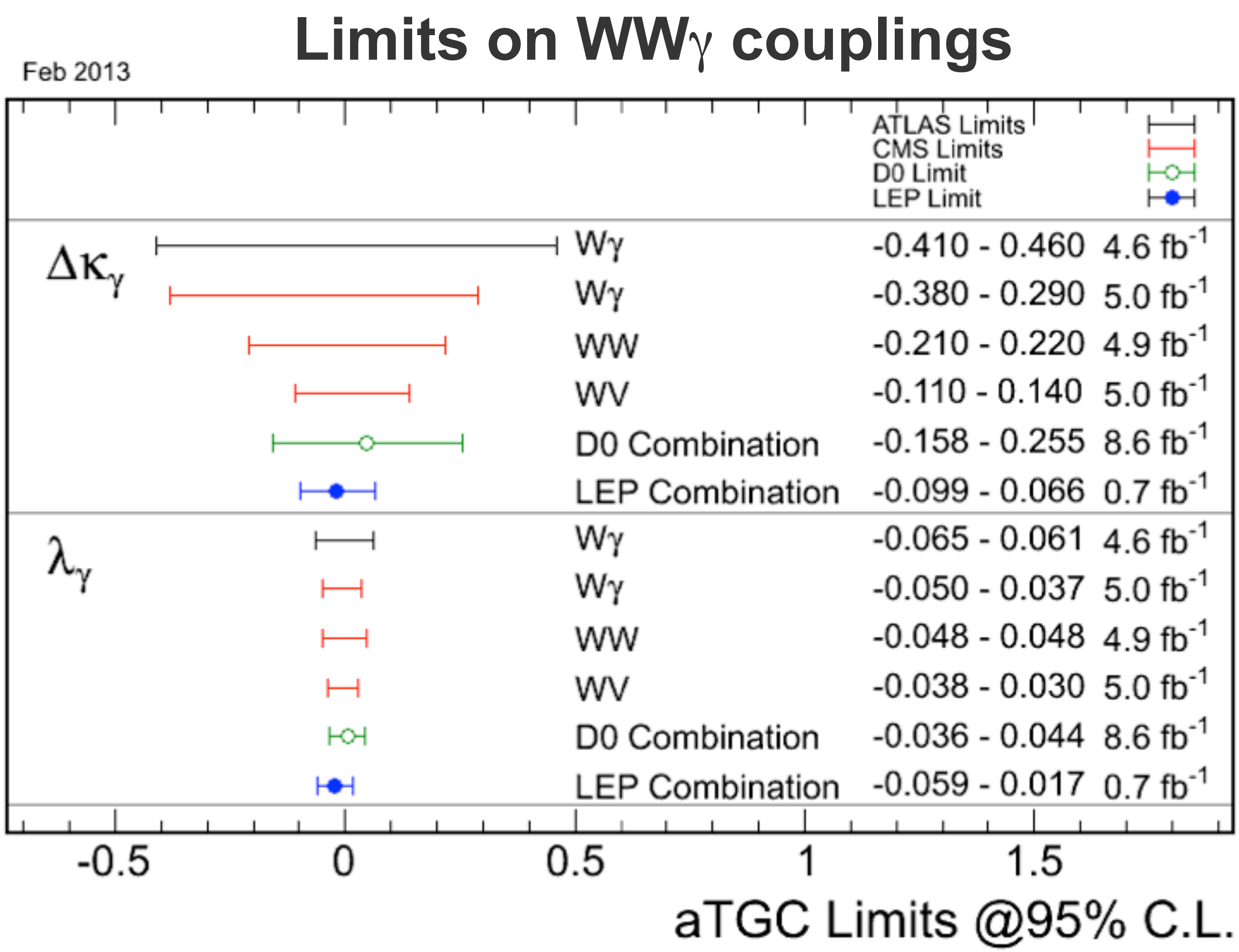
Let's do a quick overview of the current aTGC results

in the notation of LEP parametrization hep-ph/9601233

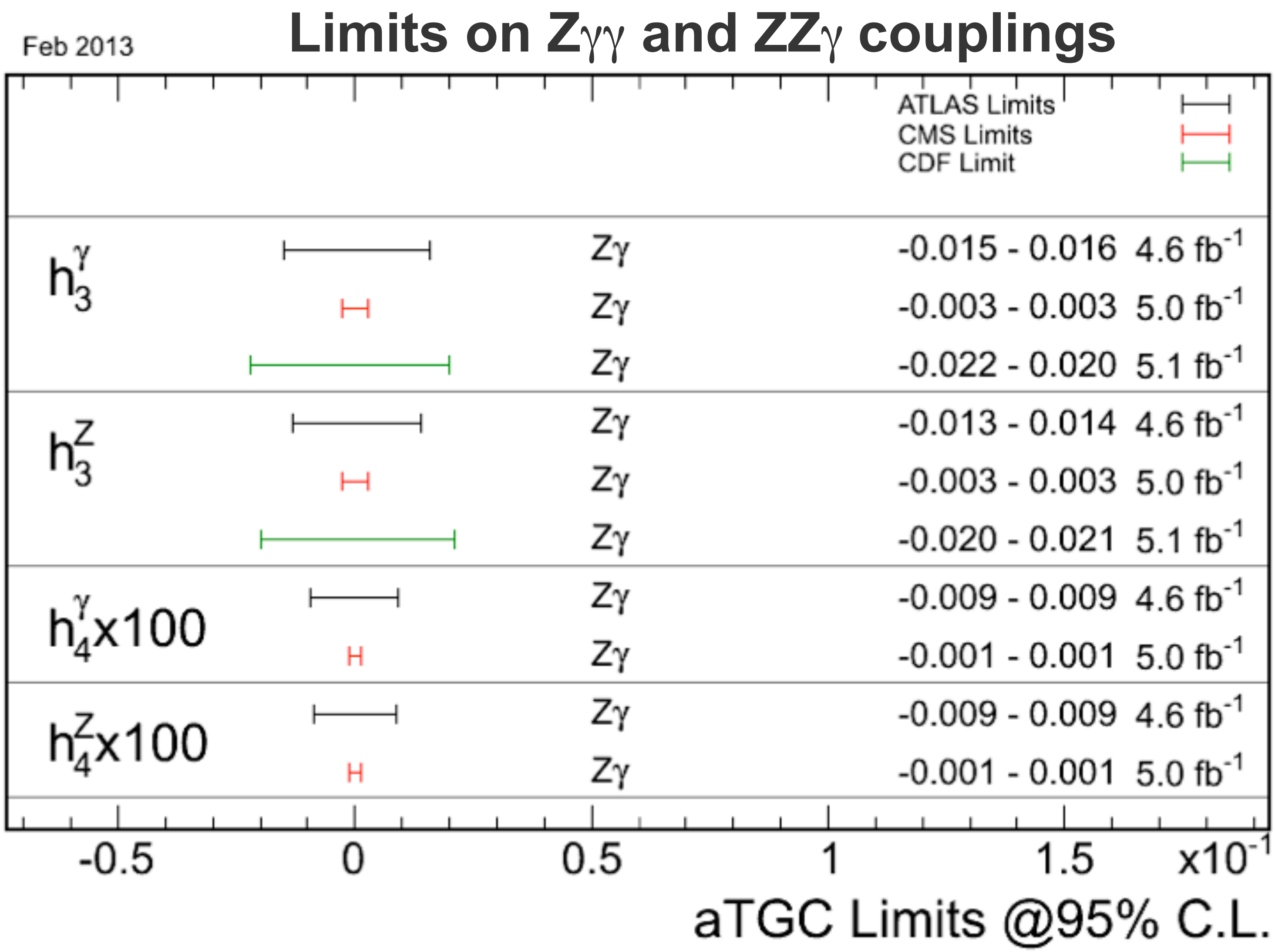
since they are also relevant for discussion of quartic couplings

Summary of aTGC measurements I

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

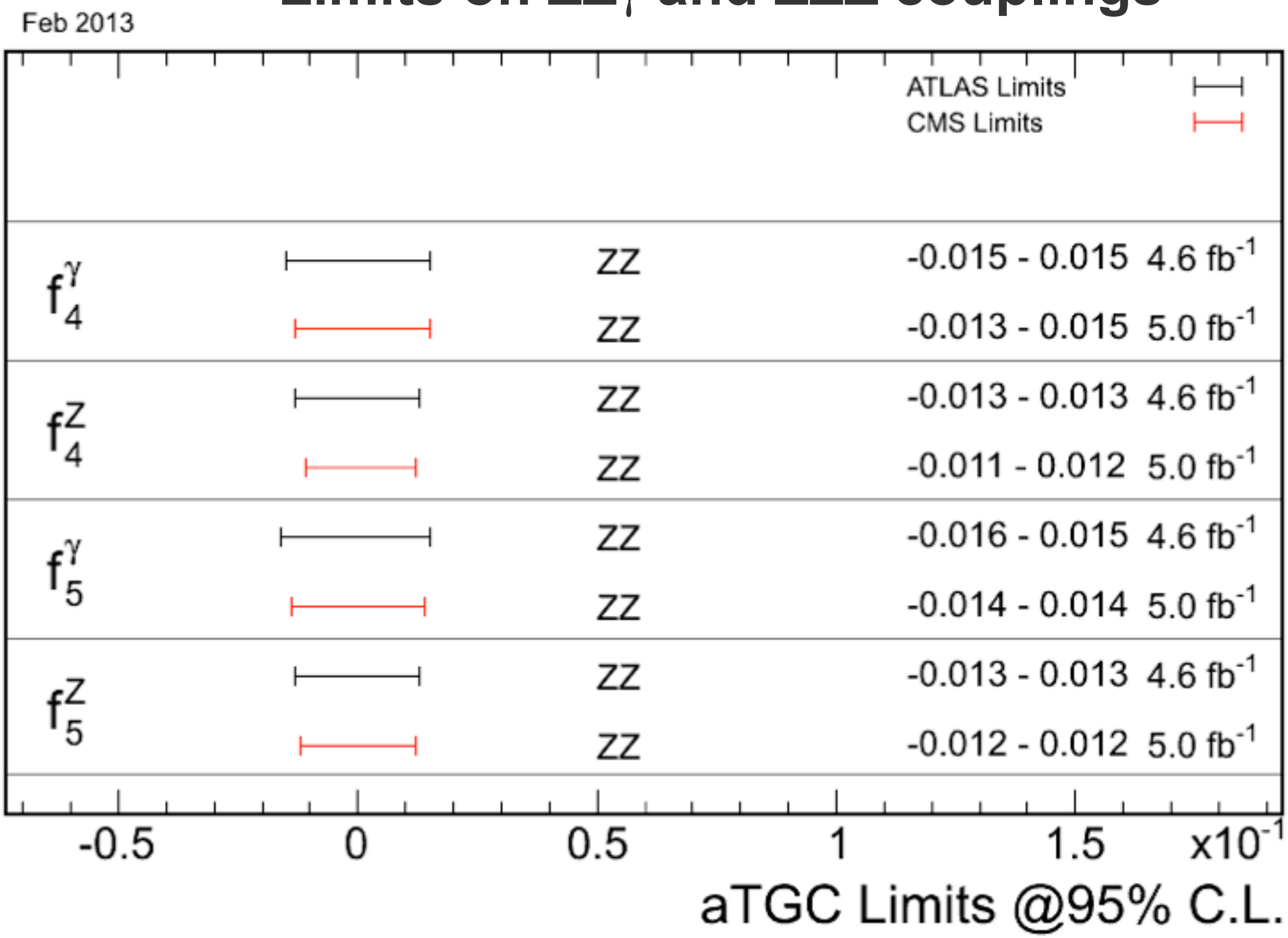


Summary of aTGC measurements II

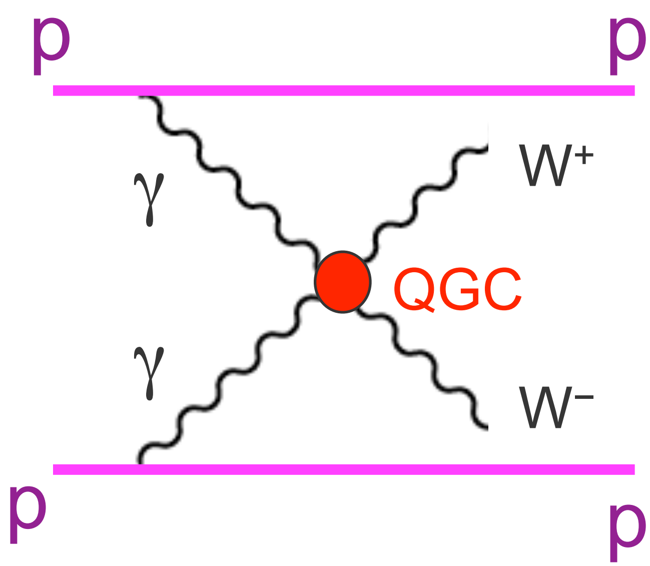


Summary of aTGC measurements III

Limits on ZZγ and ZZZ couplings



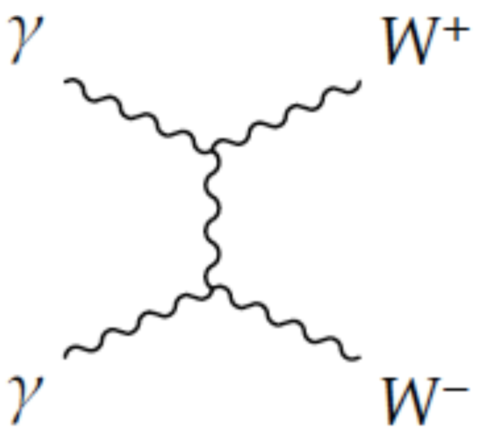
Probing quartic couplings via $\gamma\gamma \rightarrow WW$ process



CMS analysis:

Search for exclusive and quasi-exclusive two-photon production of $W^{\pm}W^{\mp}$ in the fully leptonic channel, $pp \rightarrow p^{(*)}W^{+}W^{-}p^{(*)} \rightarrow p^{(*)}\mu^{\pm}e^{\mp}p^{(*)}$

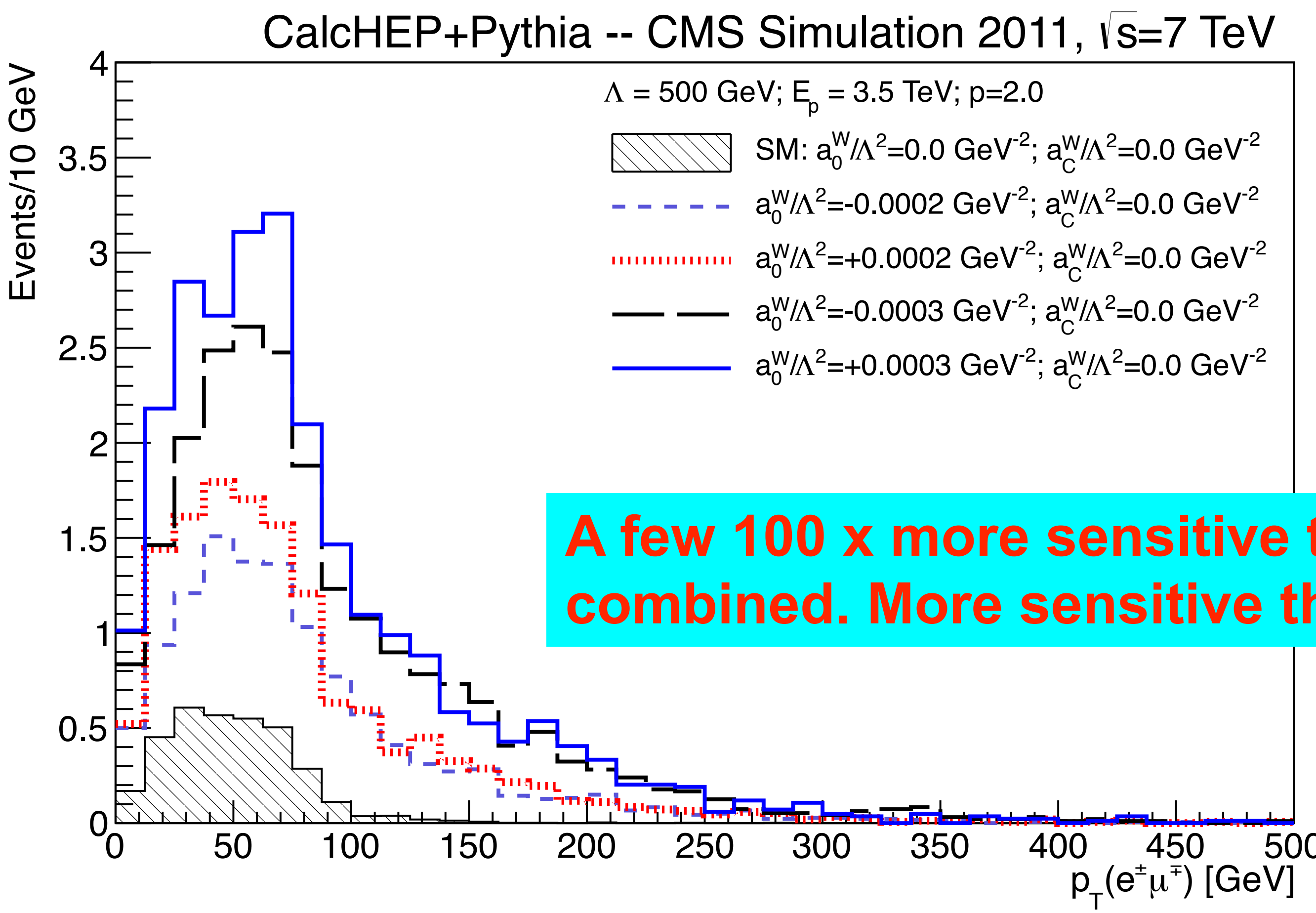
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ12010



Also investigate the tail of $p_T(\mu^{\pm}e^{\mp})$ in the region where the SM $\gamma\gamma \rightarrow WW$ contribution is small to look for pure aQGC

How sensitive we are to aQGC ?

Since backgrounds from same-flavor decays of W^+W^- are huge, only $\mu^\pm e^\mp$ channel is considered on quasi-exclusive signal.



A few 100 x more sensitive than LEP combined. More sensitive than VVV.

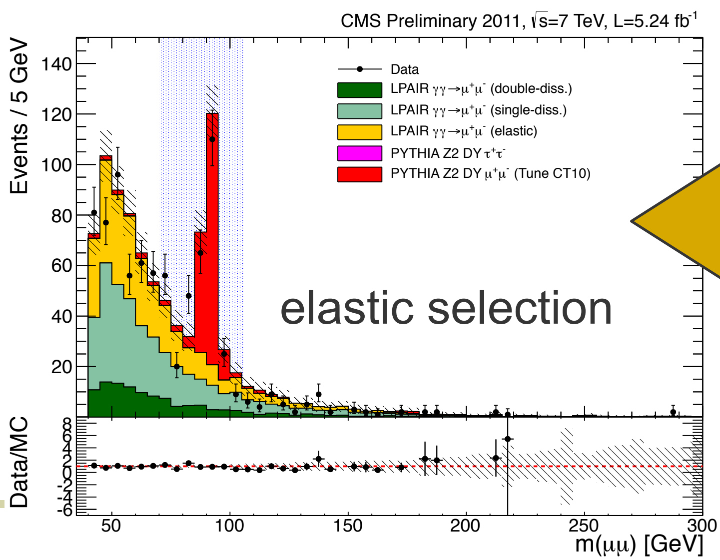
γγ→WW: CMS analysis details

Event Selection:

- lepton p_T > 20 GeV, $|\eta|$ < 2.4, isolated and well-identified
- $m(\mu^{\pm}e^{\mp})$ > 20 GeV, $p_T(\mu^{\pm}e^{\mp})$ > 30 GeV (to reduce $\gamma\gamma\rightarrow\tau^{+}\tau^{-}$)
- No extra tracks associated with $\mu^{\pm}e^{\mp}$ vertex

Selection step	Signal $\epsilon \times A$	Visible cross section (fb)	Events in data
Trigger and preselection	28.5%	1.4	9086
$m(\mu^{\pm}e^{\mp}) > 20$ GeV	28.0%	1.4	8200
Muon ID and Electron ID	22.6%	1.1	1222
$\mu^{\pm}e^{\mp}$ vertex with 0 extra tracks	13.7%	0.7	6
$p_T(\mu^{\pm}e^{\mp}) > 30$ GeV	10.6%	0.5	2

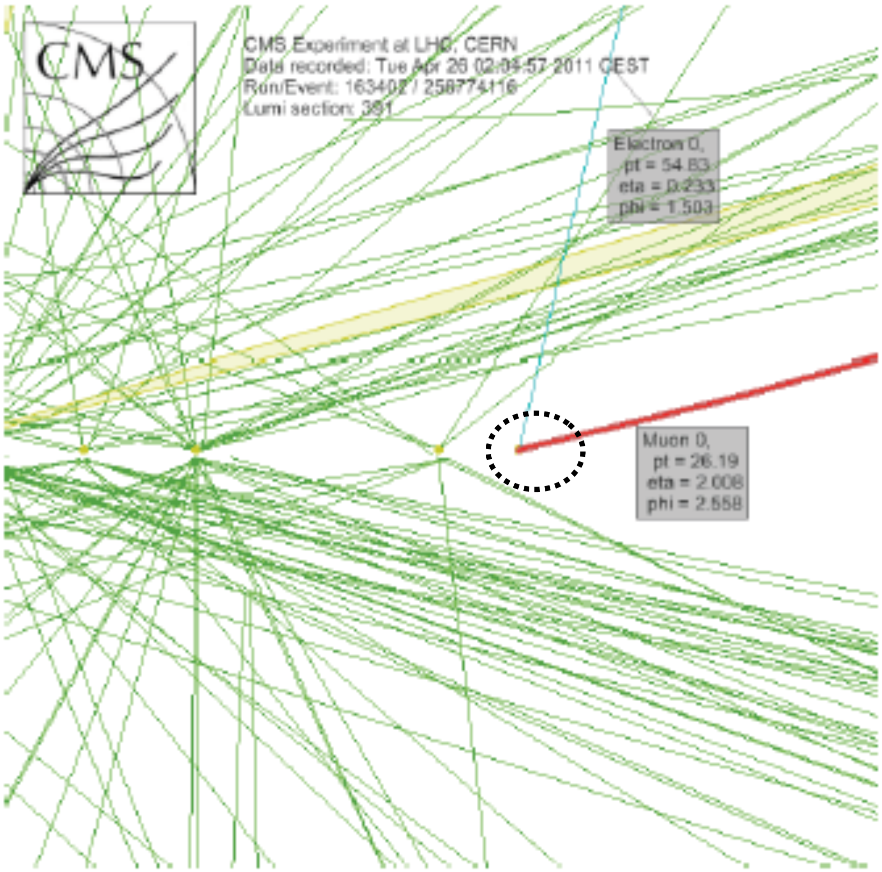
(Expect 2.2 ± 0.5 signal, 0.84 ± 0.13 bkgd)



Use exclusive $\mu^{+}\mu^{-}$ production as benchmark to validate efficiency of vertexing and exclusivity selection and pileup dependence.

Got 2 candidate γγ→WW events in 7 TeV data

Event #1

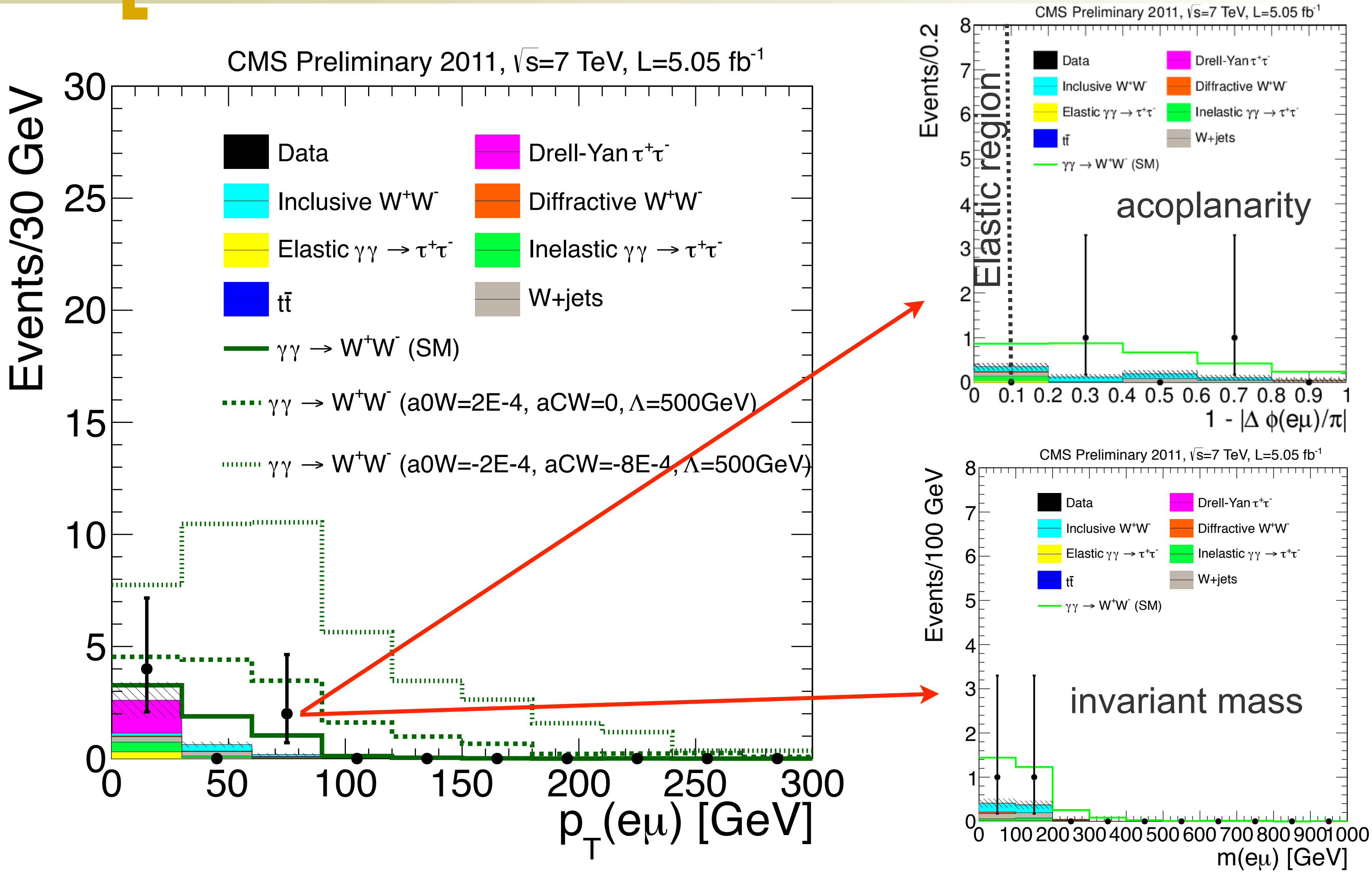


Event #2

$$\sigma(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^\pm e^\mp p^{(*)}) = 2.1^{+3.1}_{-1.9}\ \text{fb},$$

SM prediction = 3.8 ± 0.9 fb (including uncertainty in proton dissociation)

Kinematic distributions of signal-like events



Limits on aQGC

Observe no events in the high p_T region where SM contribution is small

within the acceptance of $p_T(\mu, e) > 20$ GeV, $|\eta(\mu, e)| < 2.4$, $p_T(\mu^\pm e^\mp) > 100$ GeV:

$$\sigma(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^\pm e^\mp p^{(*)}) < 1.9 \text{ fb}.$$

Limits on aQGC without form-factors (LHC preferred way):

$$-2.80 \times 10^{-6} < a_0^W/\Lambda^2 < 2.80 \times 10^{-6} \text{ GeV}^{-2} \ (a_C^W/\Lambda^2 = 0, \text{no form factor}),$$

$$-1.02 \times 10^{-5} < a_C^W/\Lambda^2 < 1.02 \times 10^{-5} \text{ GeV}^{-2} \ (a_0^W/\Lambda^2 = 0, \text{no form factor}),$$

Limits using a form-factor:

$$-0.00017 < a_0^W/\Lambda^2 < 0.00017 \text{ GeV}^{-2} \ (a_C^W/\Lambda^2 = 0, \Lambda = 500 \text{ GeV}),$$

$$-0.0006 < a_C^W/\Lambda^2 < 0.0006 \text{ GeV}^{-2} \ (a_0^W/\Lambda^2 = 0, \Lambda = 500 \text{ GeV}),$$

where the dipole form factor is

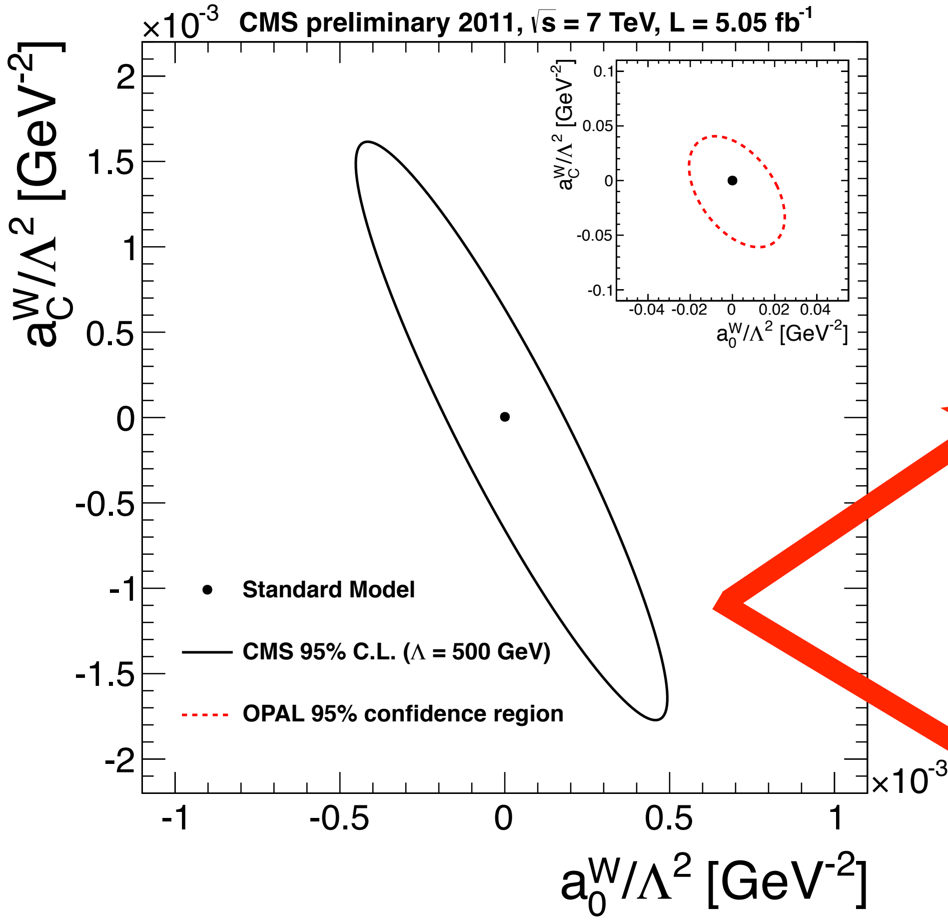
$$a_{0,C}^W(W_{\gamma\gamma}^2) = \frac{a_{0,C}^W}{\left(1 + \frac{W_{\gamma\gamma}^2}{\Lambda^2}\right)^p},$$

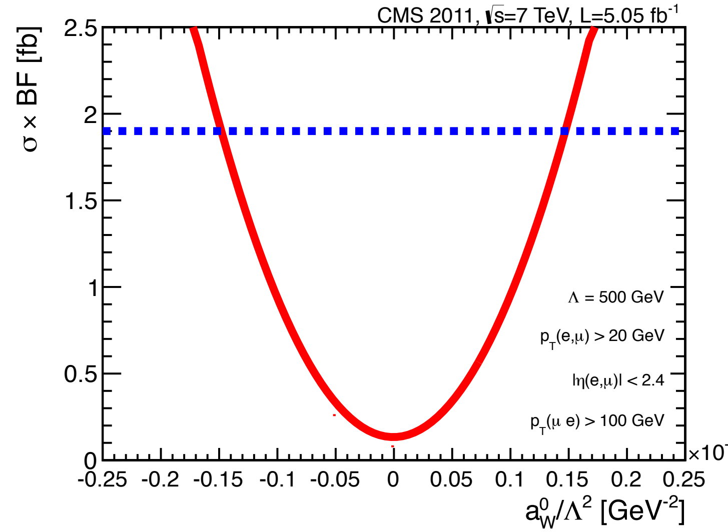
$W_{\gamma\gamma}$ = $\gamma\gamma$ center of mass energy

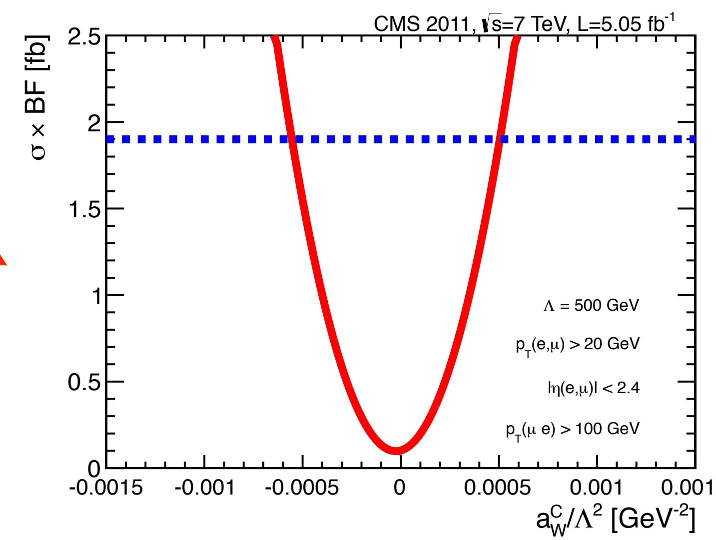
p = a free parameter = 2 by convention

Two orders of magnitude more constraining than the LEP combined limit.

Limits on aQGC: contour and signal strength



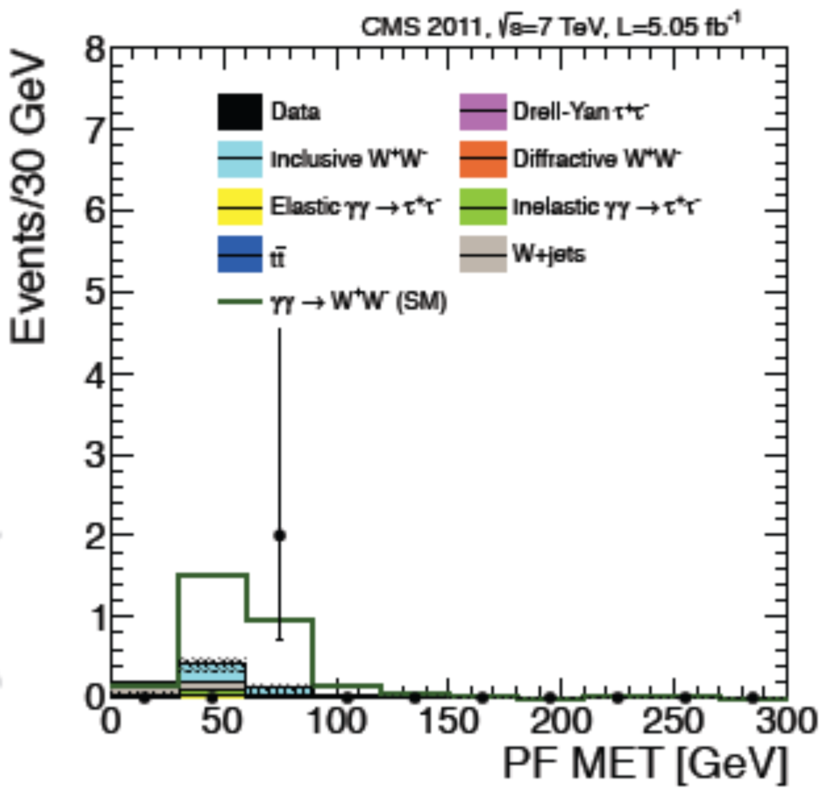


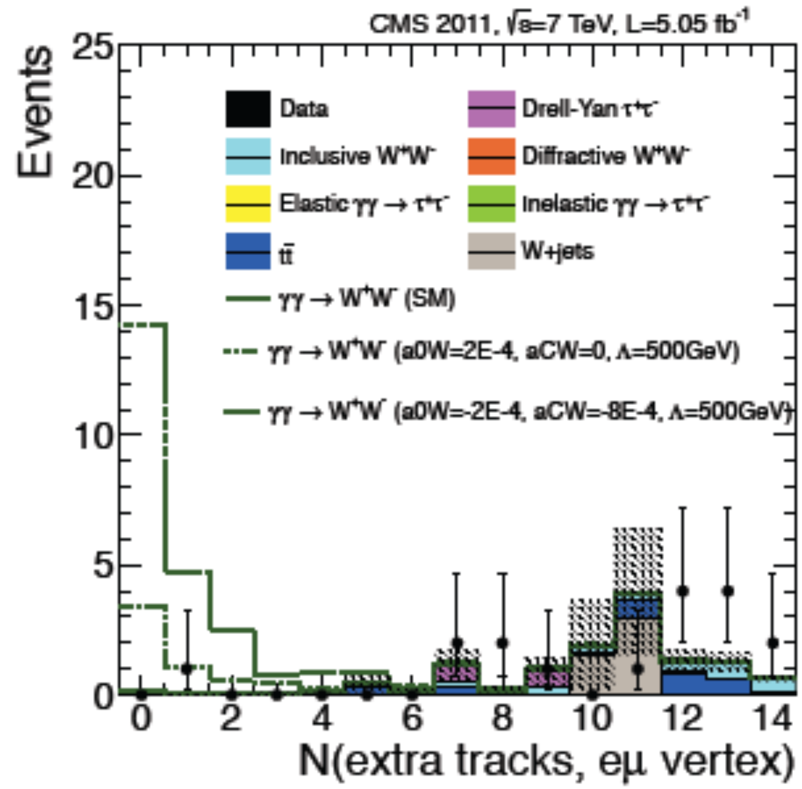


LEP limits

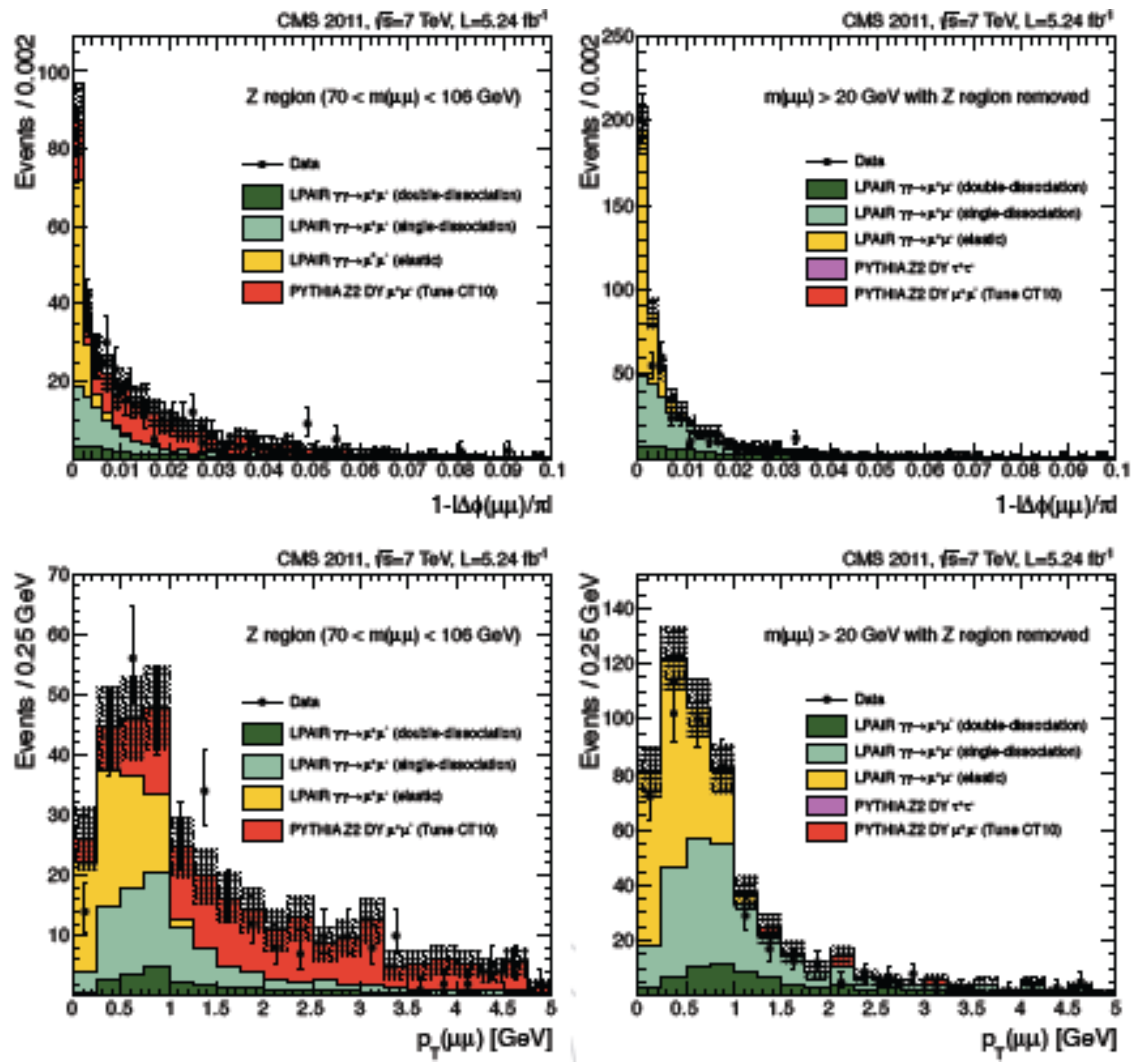
a_0^W	$-0.020\,\mathrm{GeV}^{-2} < a_0^W/\Lambda^2 < 0.020\,\mathrm{GeV}^{-2}$
a_c^W	$-0.053\,\mathrm{GeV}^{-2} < a_c^W/\Lambda^2 < 0.037\,\mathrm{GeV}^{-2}$

γγ→WW: more kinematic plots





γγ→WW: control region



$\gamma\gamma \rightarrow$WW: systematics I

Region	Data	Simulation	Data/Simulation
Elastic	820 ± 29	906.2 ± 30.1	0.905 ± 0.044
Dissociation	1312 ± 36	1829.5 ± 42.8	0.717 ± 0.026
Total	2132 ± 46	2735.7 ± 52.3	0.779 ± 0.023

a_0^W/Λ^2 [GeV^{-2}]	0	2×10^{-4}	-2×10^{-4}	7.5×10^{-6}	0
a_C^W/Λ^2 [GeV^{-2}]	0	0	-8×10^{-4}	0	2.5×10^{-5}
Λ [GeV]	-	500	500	No form factor	No form factor
Efficiency	$30.5 \pm 5.0\%$	$29.8 \pm 2.1\%$	$31.3 \pm 1.8\%$	$36.0 \pm 1.7\%$	$36.3 \pm 1.8\%$

Table 5: Signal efficiency of all trigger, reconstruction, and analysis selections, relative to the acceptance [$p_T(\mu, e) > 20$ GeV, $|\eta(\mu, e)| < 2.4$, $p_T(\mu^\pm e^\mp) > 100$ GeV] for the Standard Model and for four representative values of the anomalous couplings a_0^W/Λ^2 and a_C^W/Λ^2, with and without form factors.

$\gamma\gamma \to WW$: systematics II

	Uncertainty
Trigger and lepton identification	4.2%
Luminosity	2.2%
Vertexing efficiency	1.0%
Exclusivity and pileup dependence	10.0%
Proton dissociation factor	20.0%

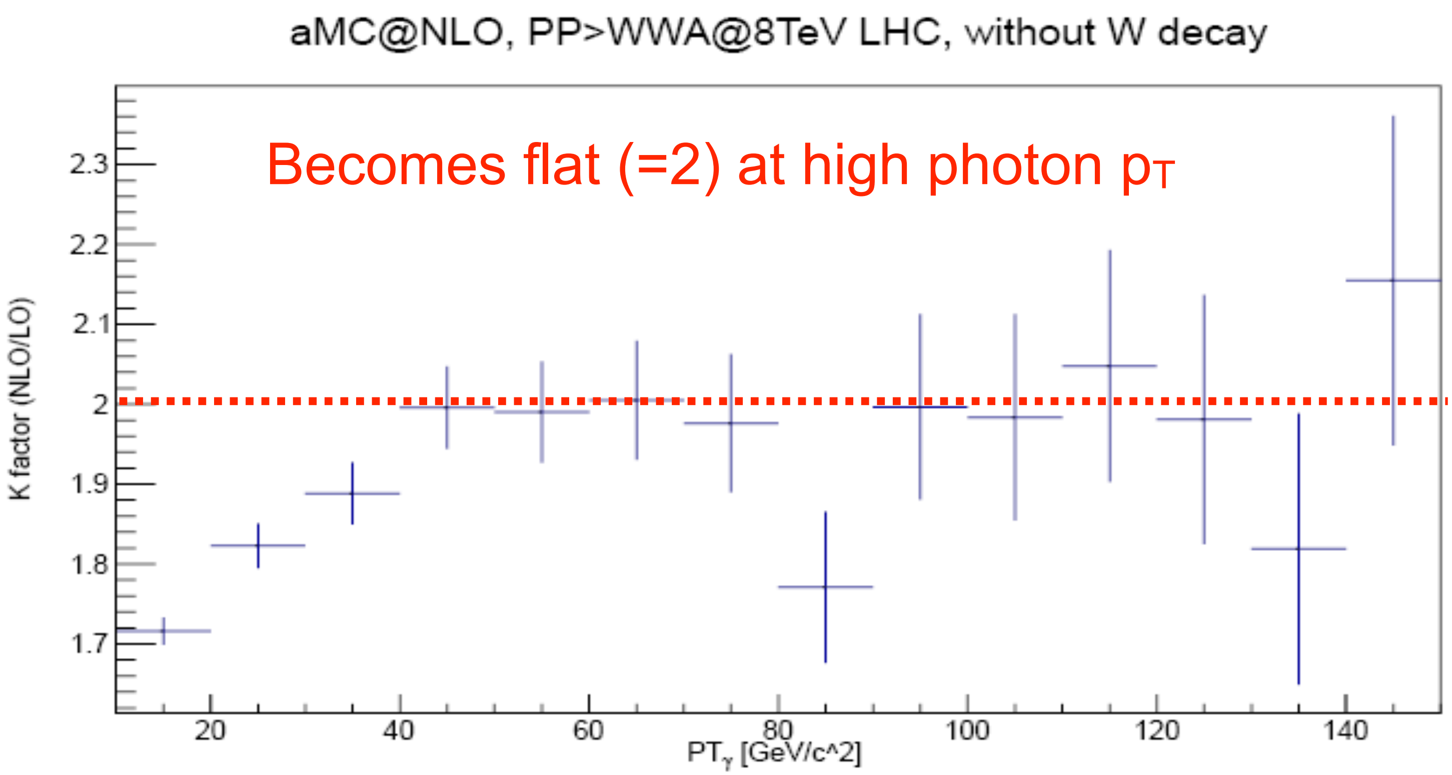
Table 4: Summary of systematic uncertainties affecting the signal.

Region	Data	Sum of MC backgrounds	MC $\gamma\gamma \to W^+W^-$ signal
Inclusive W^+W^-	43	46.2 ± 1.7	1.0
Inclusive Drell-Yan $\tau^+\tau^-$	182	256.7 ± 10.1	0.3
Exclusive $\gamma\gamma \to \tau^+\tau^-$	4	2.6 ± 0.8	0.7

Table 3: Background event yields for the three orthogonal control regions.

k-factor depends on photon p_T

Requiring only $p_T^{\gamma} > 10$GeV, $|\eta_{\gamma}| < 2.5$



Note: W→jj's k-factor is $(1+\alpha_s/\pi)$~1.04, which is quite small

Attempt to compute k-factor using VBFNLO

Compute k-factor independently using a different generator. Since VBFNLO doesn't have WWγ semi-leptonic final state, try WWZ as proxy.

VBFNLO 2.7.0 -- BETA 2 **(Configuration setting in the backup)**

PROCESS: 401 : p p --> W+ W- Z --> q q~ e- ve~ e- e+
TOTAL result (LO): 0.132 ± 9E-005 fb
TOTAL result (NLO): 0.333 ± 2E-004 fb
K-Factor: 2.535

PROCESS: 402 : p p --> W+ W- Z --> ve e+ q q~ e- e+
TOTAL result (LO): 0.127 ± 1E-005 fb
TOTAL result (NLO): 0.338 ± 4E-005 fb
Factor: 2.654

Note:
(1) It Is WWZ, not WWA, no Pta cut here
(2) Scale: WWZ invariant mass (VBFNLO default for this process).
(3) PDF's : Cteq6ll for LO and CT10 for NLO

Difference between aMC@NLO and VBFNLO might be due to different scale and PDF choices, and also due to intrinsic differences between WWZ vs WWγ. We are investigating it further.

Computation of scale and PDF uncertainties

- Reweight to get scale dependence and PDF uncertainty   Ref: arXiv1110.4738

Scale uncertainty

- Factor 0.5/2 around certral scale
- 3x3 values of weight
- δS = max – min

PDF uncertainty

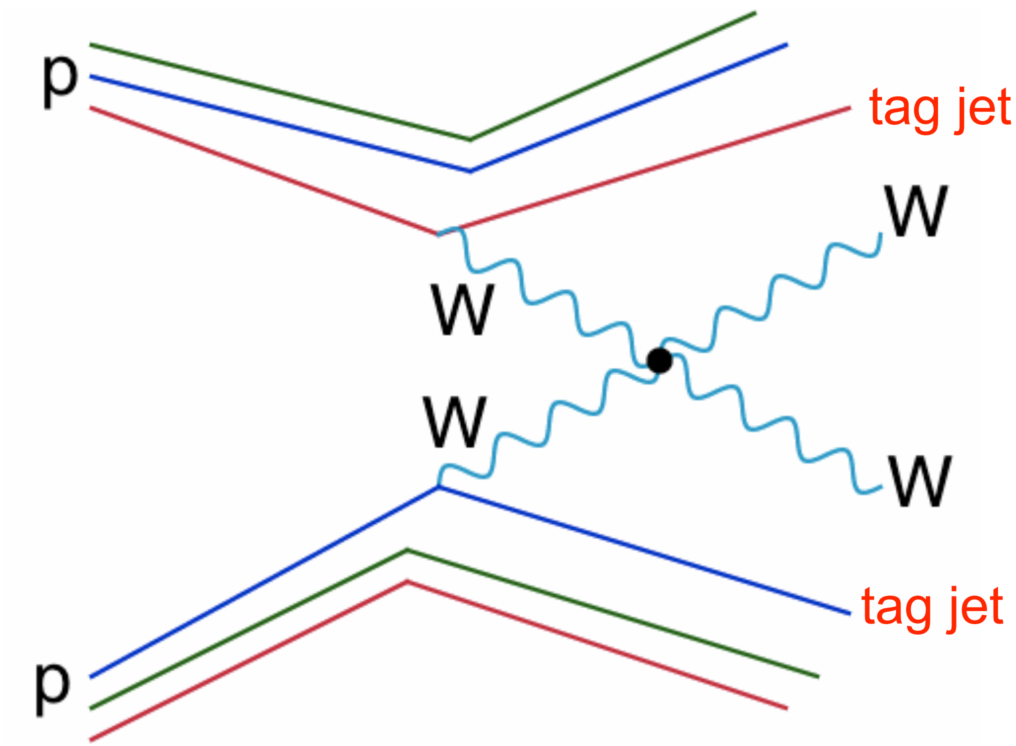
- MSTW2008nlo68cl
- 1 central + 20 pairs
- arXiv: 0201195v3   Eq(3)
- $$\Delta X = \frac{1}{2}\left(\sum_{i=1}^{N_p}\left[X(S_i^+) - X(S_i^-)\right]^2\right)^{1/2}$$

Information on VBFNLO cut parameters

minimum jet pt (PT_JET_MIN): 30.00 30.00 30.00
maximum jet rapidity (Y_JET_MAX): 4.5000000000000000
maximum parton pseudorapidity (Y_P_MAX): 5.0000000000000000
minimum jet-jet R-separation (RJJ_MIN): 0.50000000000000000
minimum number of jets (NJET_MIN): 2
exponent of generalised kT algorithm (PGENKTJET):
1.0000000000000000
minimum lepton-lepton R-separation (RLL_MIN):
0.50000000000000000
maximum lepton-lepton R-separation (RLL_MAX):
50.000000000000000
minimum jet-lepton R-separation (RJL_MIN): 0.0000000000000000
minimum jet-photon R-separation (RJG_MIN):
0.50000000000000000
minimum lepton-photon R-separation (RLG_MIN):
0.50000000000000000
minimum photon-photon R-separation (RGG_MIN):
0.50000000000000000
maximum photon-photon R-separation (RGG_MAX):
50.000000000000000
maximum lepton rapidity (Y_L_MAX): 2.5000000000000000
minimum lepton pt (PT_L_MIN): 25.000000000000000
minimum invariant dilepton mass (MLL_MIN):
30.000000000000000
maximum invariant dilepton mass (MLL_MAX):
14000.000000000000
maximum photon rapidity (Y_G_MAX): 1.5000000000000000
minimum photon pt (PT_G_MIN): 30.000000000000000
photon isolation cut (PHISOLCUT): 0.69999999999999996

efficiency of photon isolation cut (EFISOLCUT):
1.0000000000000000
minimum invariant lepton-photon mass (MLG_MIN):
0.0000000000000000
maximum invariant lepton-photon mass (MLG_MAX):
1.0000000000000000E+020
minimal missing transverse momentum (PTMISS_MIN):
30.000000000000000
minimum jet rapidity separation (ETAJJ_MIN):
1.3999999999999999
tagging jets in opposite hemispheres (YSIGN): F
leptons fall inside rapidity gap (LRAPIDGAP): F
min leptons y-dist from tagging jets (DELY_JL):
0.0000000000000000
photons fall inside rapidity gap (GRAPIDGAP): T
min photons y-dist from tagging jets (DELY_JG):
0.0000000000000000
dijet min mass cut on tag jets (MDIJ_MIN): 72.000000000000000
dijet max mass cut on tag jets (MDIJ_MAX): 98.000000000000000
veto criteria for jets (JVETO): F
minimum veto-tag y-dist (DELY_JVETO): 0.0000000000000000
maximum |y| for veto jet (YMAX_VETO): 5.0000000000000000
minimum pT for veto jet (PTMIN_VETO): 10.000000000000000
definition of tagging jets (DEF_TAGJET): 1
minimal pt for harder tagging jet (PTMIN_TAG_1):
30.000000000000000
minimal pt for softer tagging jet (PTMIN_TAG_2):
30.000000000000000

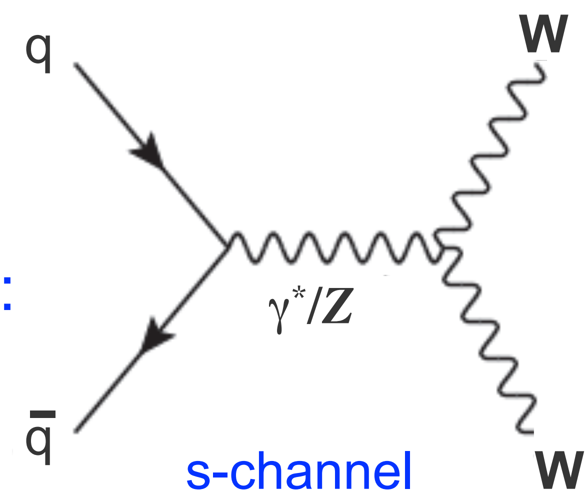
Probing quartic couplings via qq→WW VBF

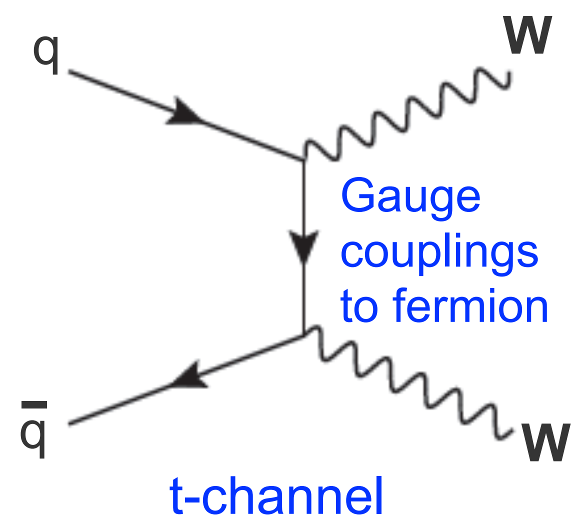


WW production and TGC

Need to measure WW production rate first !

WW production at Leading Order:





- Each diagram is divergent but the sum is finite !!!
- Higher order contribution is large: ~60% of the LO !

(see backup for details, if interested)

Anomalous couplings in WW/WZ production

5 independent couplings remain after assuming basic symmetry

$$\mathcal{L}_{anom} = ig_{WWZ}\left[\Delta g_1^Z \left(W^*_{\mu\nu}W^\mu Z^\nu - W_{\mu\nu}W^{*\mu}Z^\nu\right) + \Delta\kappa^Z W^*_\mu W_\nu Z^{\mu\nu} + \frac{\lambda^Z}{M_W^2} W^*_{\rho\mu} W^\mu_\nu Z^{\nu\rho}\right] + ig_{WW\gamma}\left[\Delta\kappa^\gamma W^*_\mu W_\nu \gamma^{\mu\nu} + \frac{\lambda^\gamma}{M_W^2} W^*_{\rho\mu} W^\mu_\nu \gamma^{\nu\rho}\right],$$

Equal coupling (HISZ) parametrization

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

Further assume that $\Delta g_1^Z = 0$ (SM), leaves two parameters: λ_Z , $\Delta\kappa_\gamma$

Coupling	Particle Data Group Fit
Λ_γ	$0.028^{+0.020}_{-0.021}$
Λ_Z	$0.088^{+0.060}_{-0.057}$
Δg_1^Z	$0.016^{+0.022}_{-0.019}$
$\Delta\kappa_\gamma$	$0.027^{+0.044}_{-0.045}$
$\Delta\kappa_Z$	$0.026^{+0.059}_{-0.056}$

LEP combination @ 95% CL

[-0.026, 0.208]

[-0.063, 0.115]

Tevatron (D∅)
arXiv:1208.5458

λ_Z: [-0.039, 0.042]

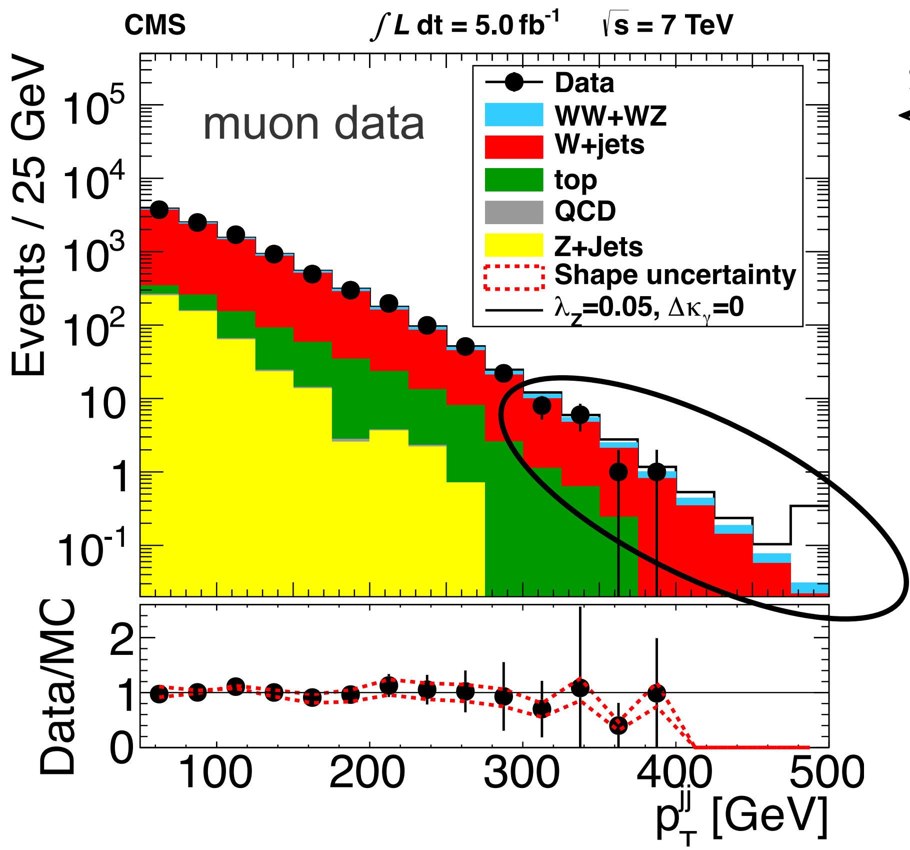
$\Delta\kappa_\gamma$: [-0.049, 0.124]

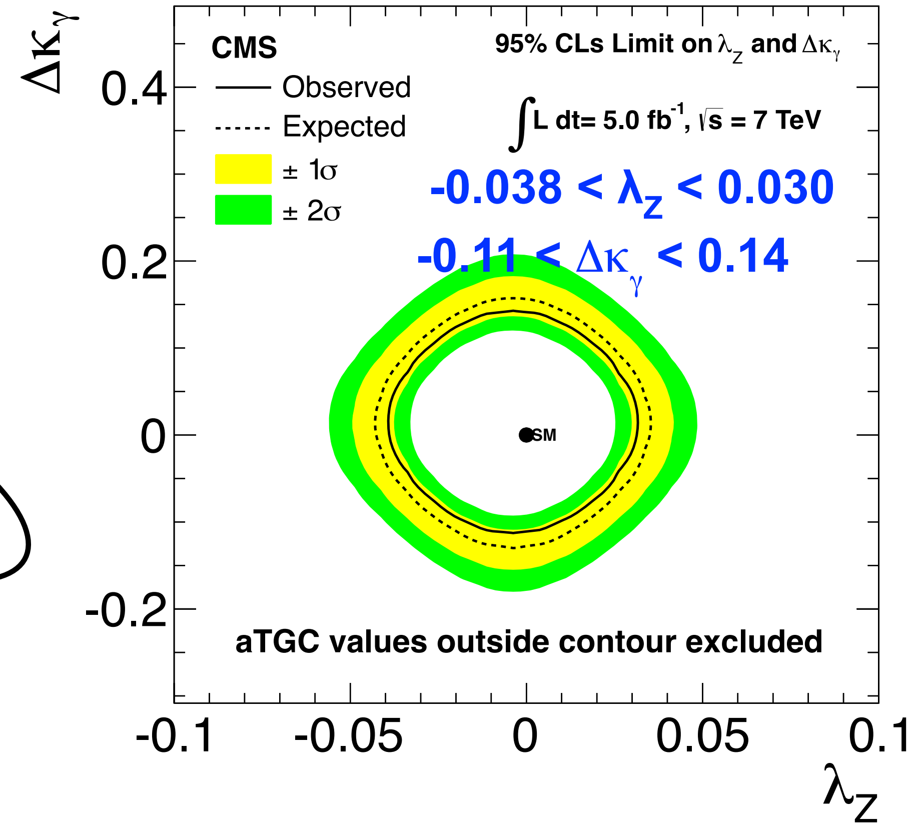
Note: assumes form factor of 2 TeV

ATLAS (arXiv:1208.1390) λ_Z: [-0.057, 0.093], $\Delta\kappa_\gamma$: [-0.37, 0.57]

Limits from WW/WZ→ℓνqq measurement

Use hadronic W p_T as the observable



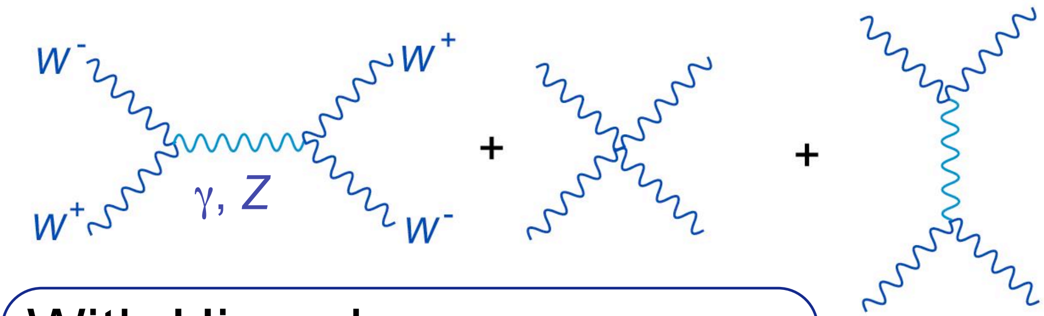


Anomalous couplings show up in high p_T tails. Model using MCFM.

☑ Improve upon the LEP limit in some cases.

Thinking of future: weak interaction @ high E

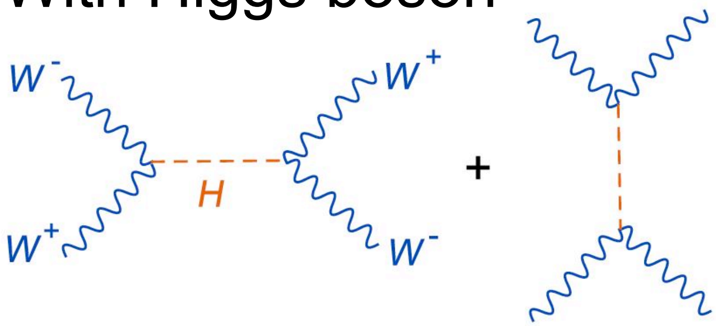
Without Higgs boson, WW scattering becomes divergent



$$= \frac{g^2 E^2}{2 m_W^2}(1 + \cos\theta)$$

unitarity violated: grows as E^2

With Higgs boson



$$= -\frac{g^2 E^2}{2 m_W^2}(1 + \cos\theta)$$

no problem now!

Higgs exchange needed to prevent unitarity violation in WW scattering at high energies or New Phenomena possible. With 20/fb, lνjj sensitive to weakly produced NP at 1 TeV.

Ballestrero et al, JHEP 1205, 083 (2012) [arXiv:1203.2771]