Probing Gauge Boson Quartic Couplings in Multi-boson Events

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(contributions from J Damgov, J Faulkner, Q Li, P Teles, D Yang)

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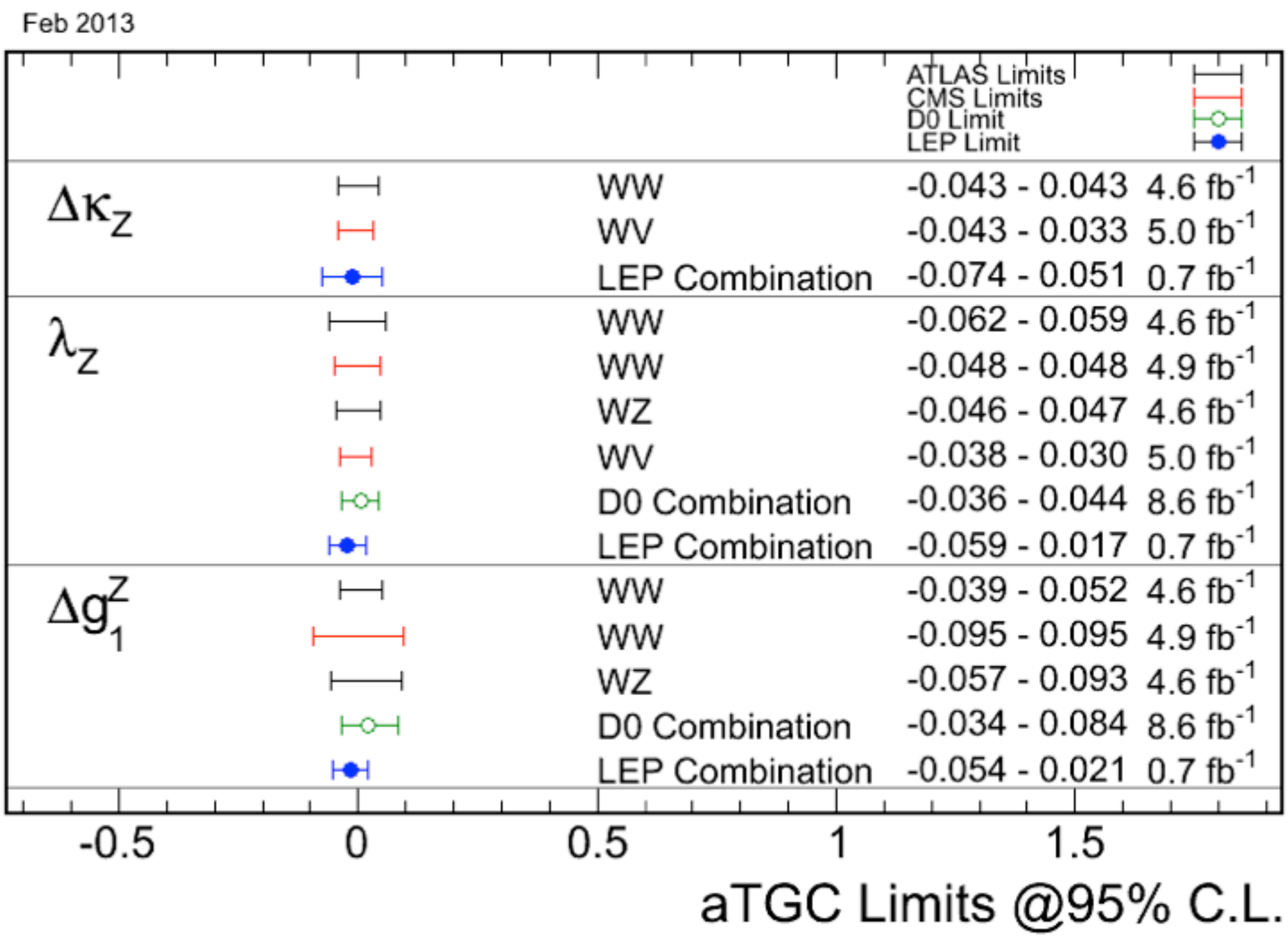
Quartic couplings

I will only talk about couplings involving W boson

- In the SM, the allowed couplings are:
  WW$\gamma\gamma$, WWZγ, WWWW, WWZZ
- Observable in two topologies at the LHC
  - Triple gauge boson production (e.g., W$\gamma\gamma$, WWγ, 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

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 ....

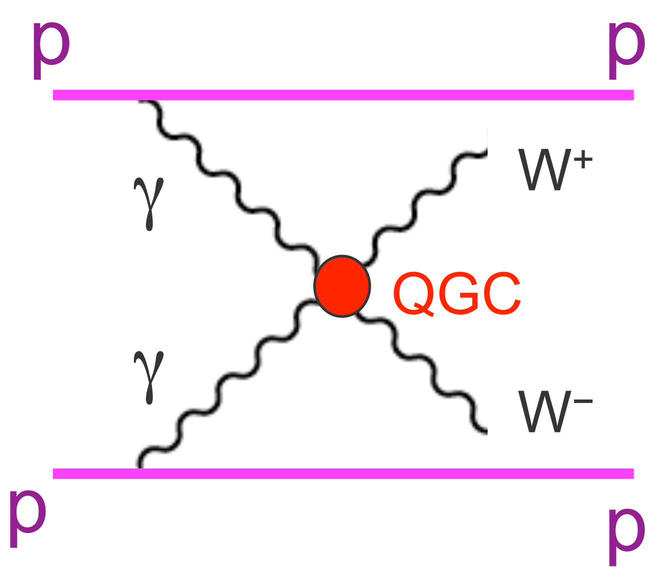
Almost all previous work in nonlinear realization

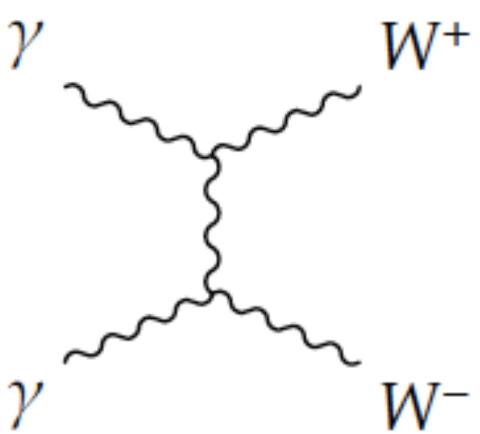
- Symmetries enforced without light Higgs
- Lower dimension D4, D6 aQGCs
- Have to connect with that work
  - -LEP, LHC limits already set in that approach
  - -they often use arbitrary form factors to dampen non-unitarity

Proposal to manage this burden

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

Quartic couplings in γγ→WW process





arXiv:1305.5596

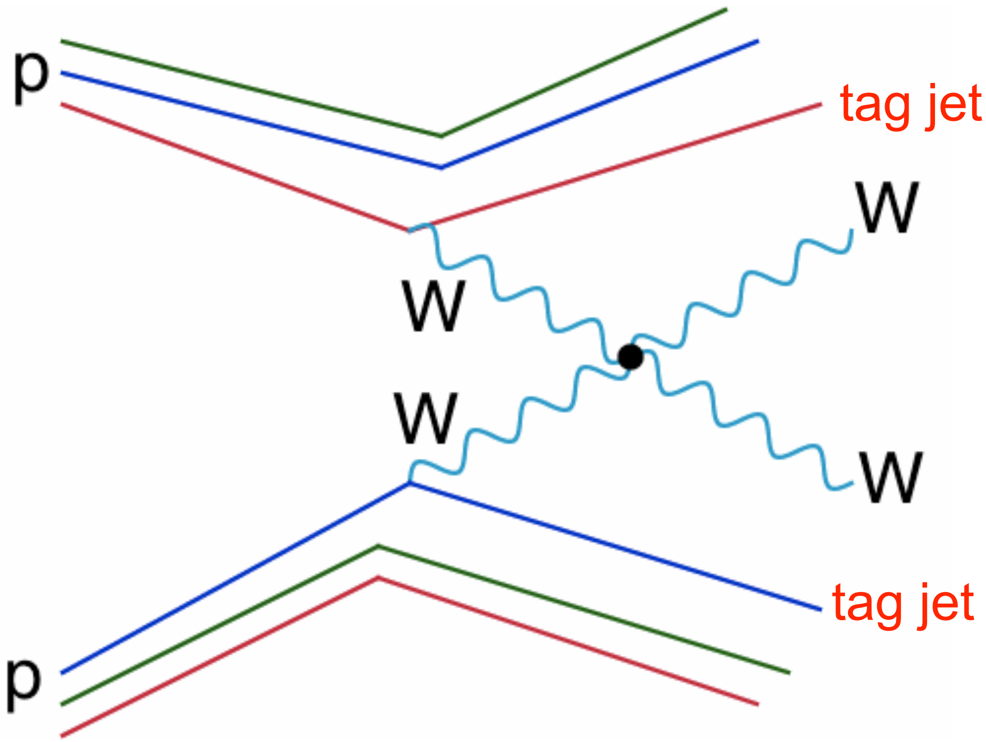
See talk by Jonathan Hollar in LHC-EWK-WG meeting on April 16.

Limits on aQGC without form-factors:

$$-2.80 \times 10^{-6} < a_0^W/\Lambda^2 < 2.80 \times 10^{-6}\ \mathrm{GeV}^{-2}$$
$$-1.02 \times 10^{-5} < a_C^W/\Lambda^2 < 1.02 \times 10^{-5}\ \mathrm{GeV}^{-2}$$

$o(10^2)$ times more constraining than the LEP combined limit

Quartic couplings via WW→WW VBF



arXiv:1303.6335,1304.4599, 1304.0080, 1305.0251, 1212.4158, 1212.3598, 1209.2389, 1203.2771, 1112.1171, hep-ph/0201098, ...

Lot of theoretical interest, only way to measure WWWW coupling, important for understanding EWSB.

Experimentally much harder, no measurement yet.

Probing quartic couplings via VVV production

For example: WWγ production at LHC

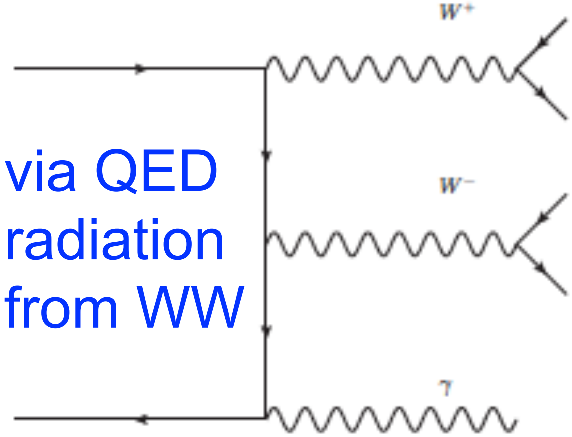
References:

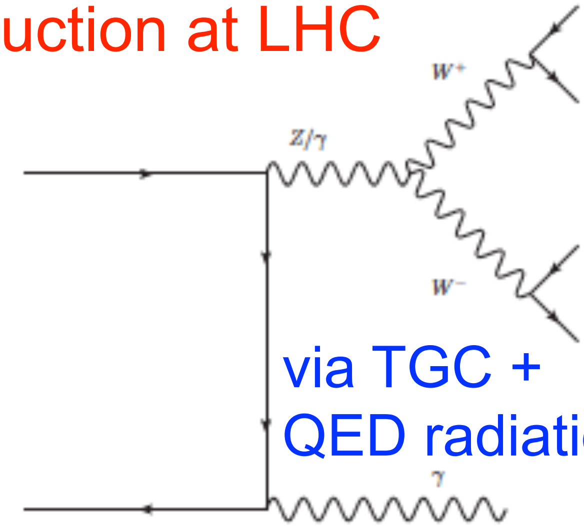
1.) Yang et al, arXiv: 1211.1641

2.) LEP combination, hep-ex/0612034

3.) Bozzi et al, arXiv: 0911.0438

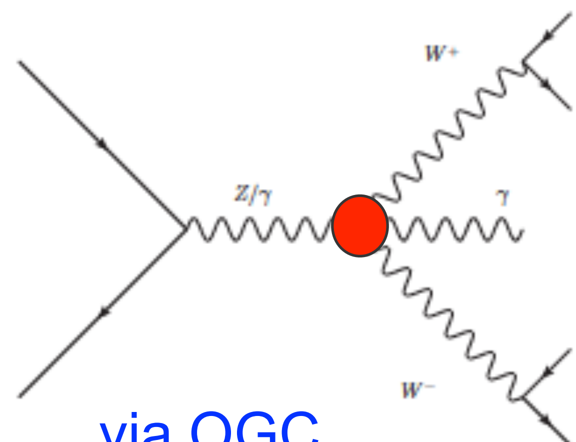
via QED radiation from WW





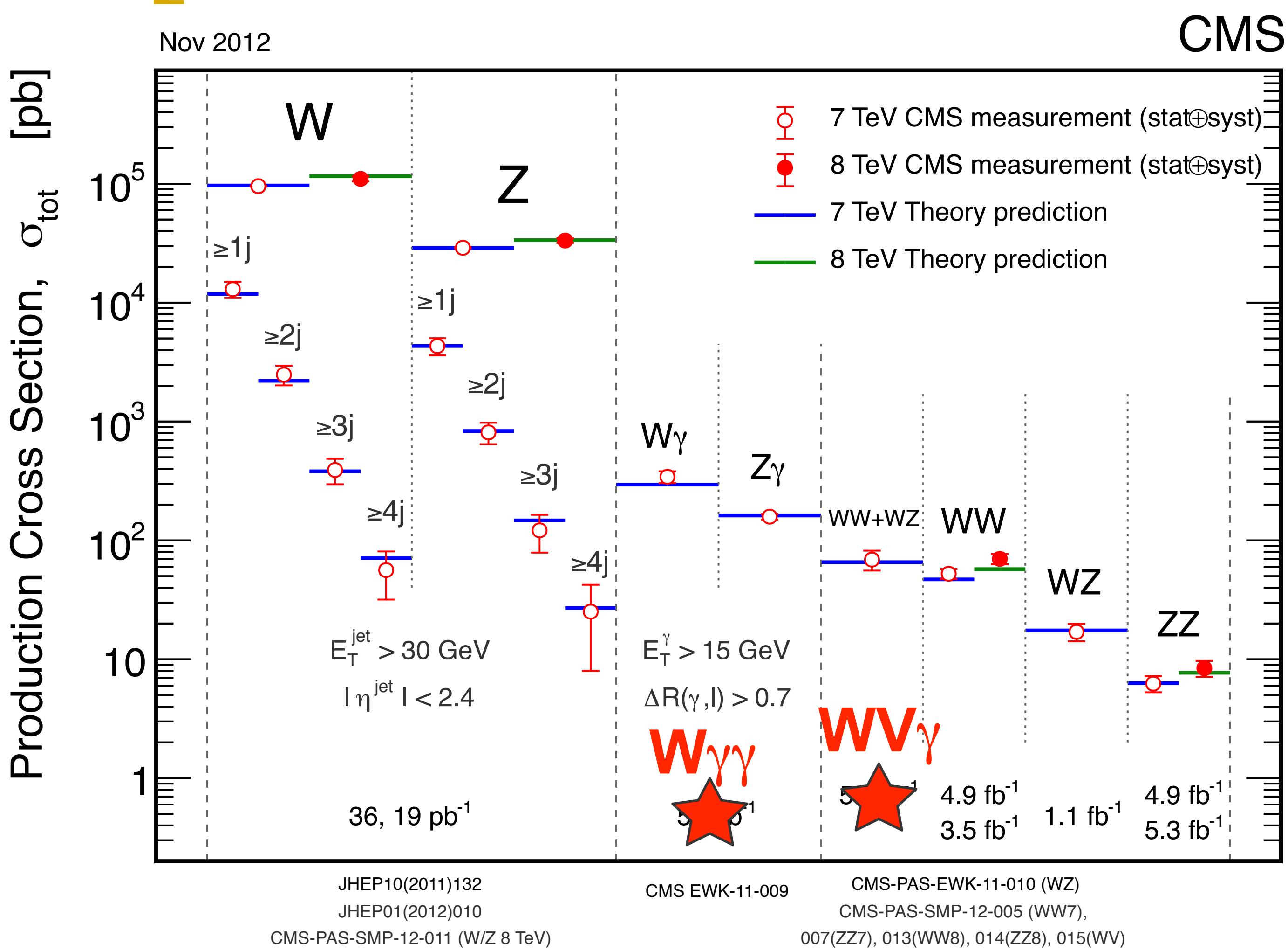
via TGC + QED radiation

- 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 attractive

-σ x BR for WVγ ≈ 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^γ > 10 GeV, $|\eta_\gamma|$ < 2.5, ΔR (γ,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

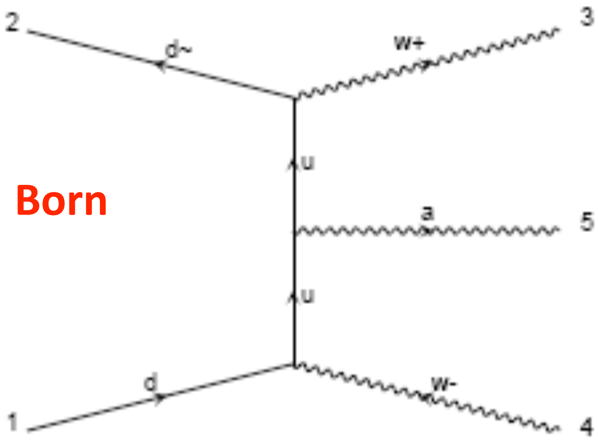
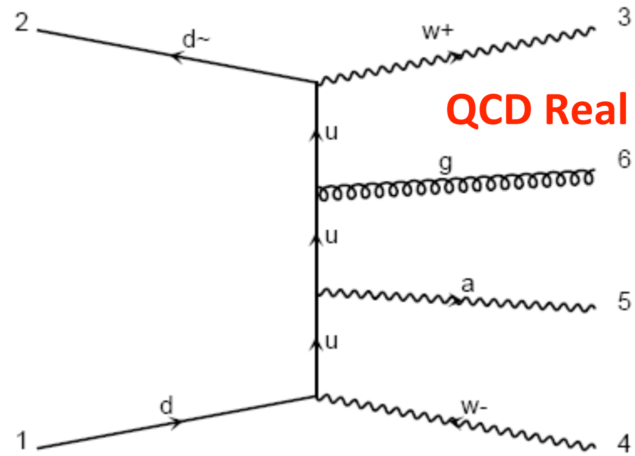


diagram 7 QCD=0, QED=3

QCD Real emission



real diagram 1 QCD=1, QED=3

One-loop QCD

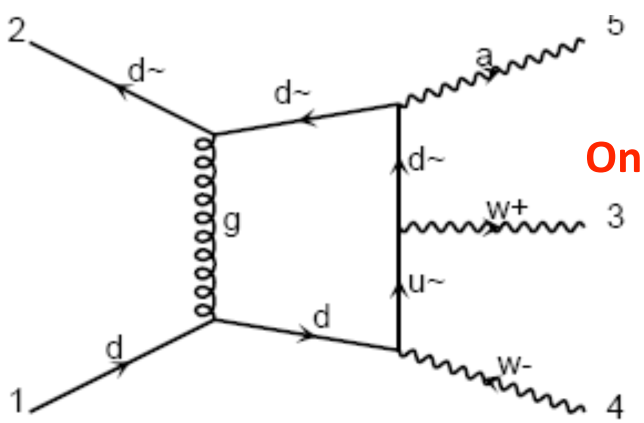


diagram 38 QCD=2, QED=3

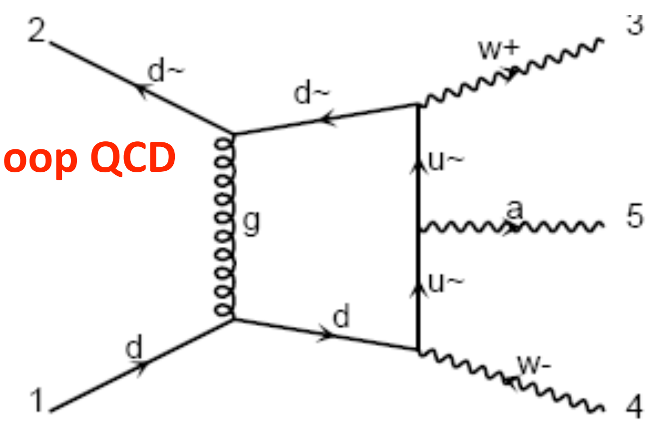


diagram 39 QCD=2, QED=3

Event selection and expected yields

- Event selection:
  - Lepton $p_T > 25$ GeV, $|\eta| < 2.4$, MET > 35 GeV
  - At least 2 non-b jets with $p_T > 30$ GeV, $|\eta| < 2.5$
  - 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

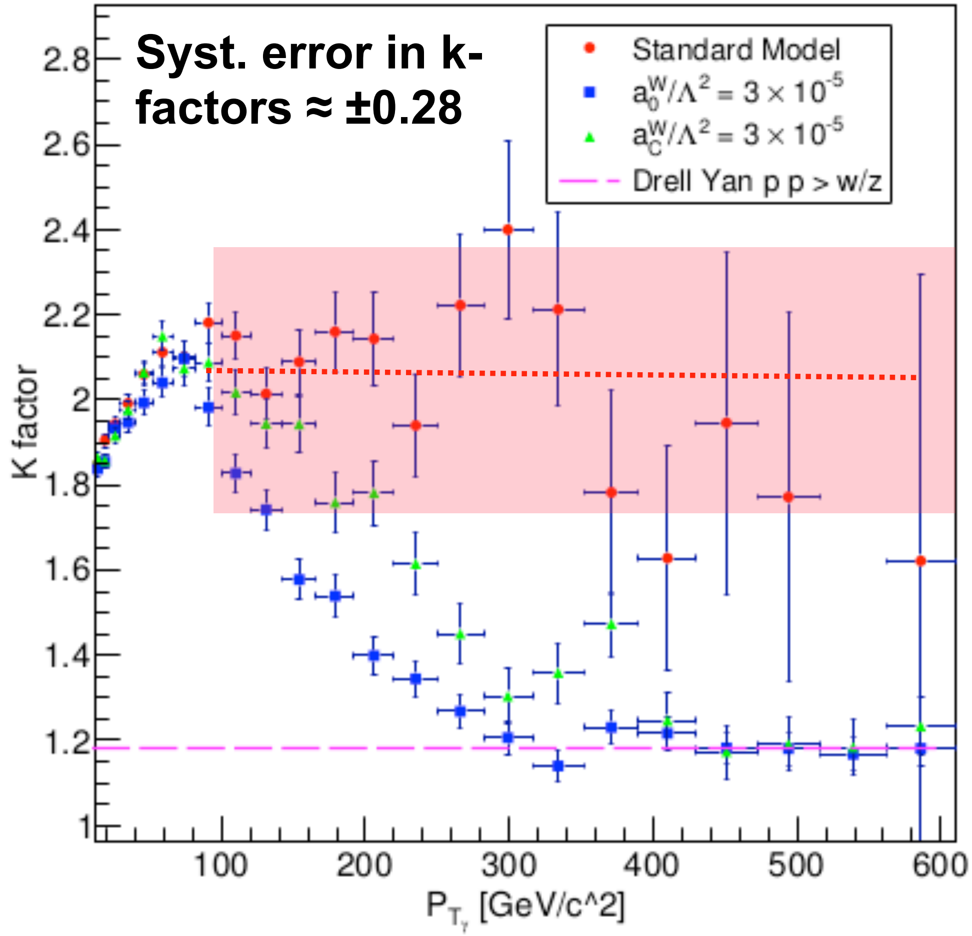
- Expected yields in 8 TeV, 20 fb^{-1} data with optimized selection: 340 events, 12 $WV\gamma$ signal and 328 background ($W\gamma$+jets, WV+ fake photon, ttbar+γ, multi-jet)

➡ NOT significant enough to see SM production

- Use γ p_T as observable for setting limits on aQGC.

WVγ k-factor depends on photon p_T

Also different for SM and aQGC. Specially crucial to account for this difference at high p_T.



At low p_T (<100 GeV):

- SM & aQGC have ~same k-factor

At high p_T (>300 GeV):

- SM (Red) k-factor ~2
- aQGC behaves like Drell-Yan (magenta): k-factor ~1.185

The near-constant k-factor at large p_T can be explained by the fact that only one Feynman diagram (4-gauge boson vertex one) get enhanced by the aQGC.

At medium p_T (100−300 GeV):

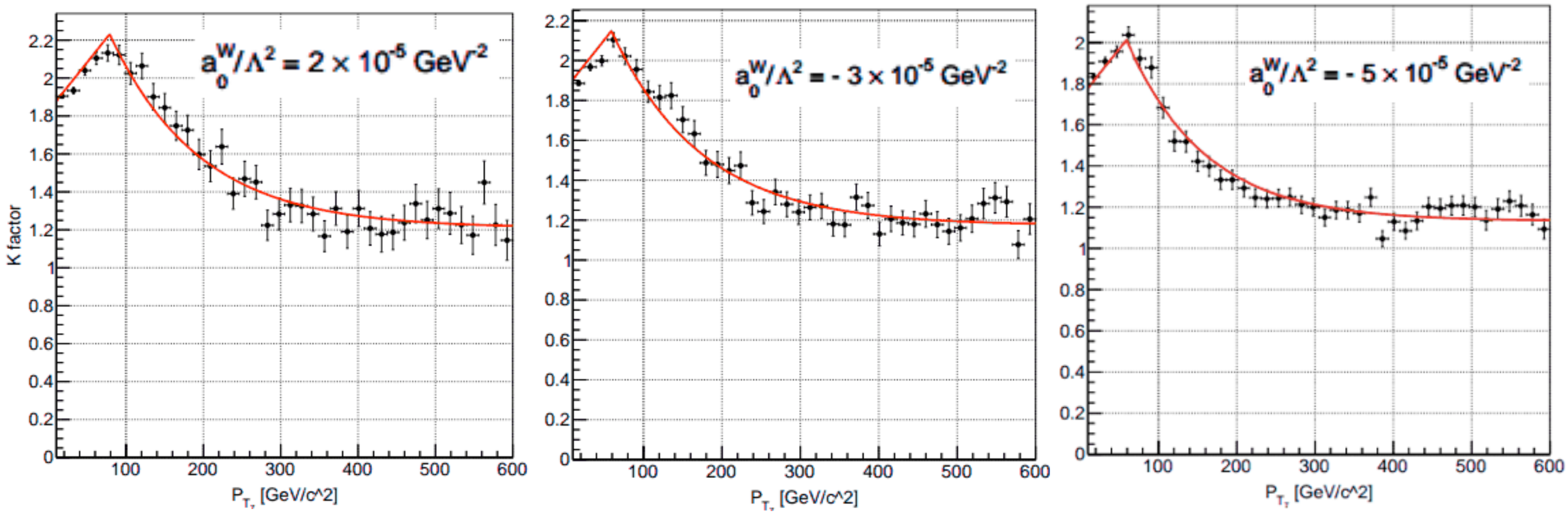
- aQGC k-factor decreases exponentially

Attempt to parametrize aQGC k-factors

Parametrization: Linear below the turnover point, exponential above it.

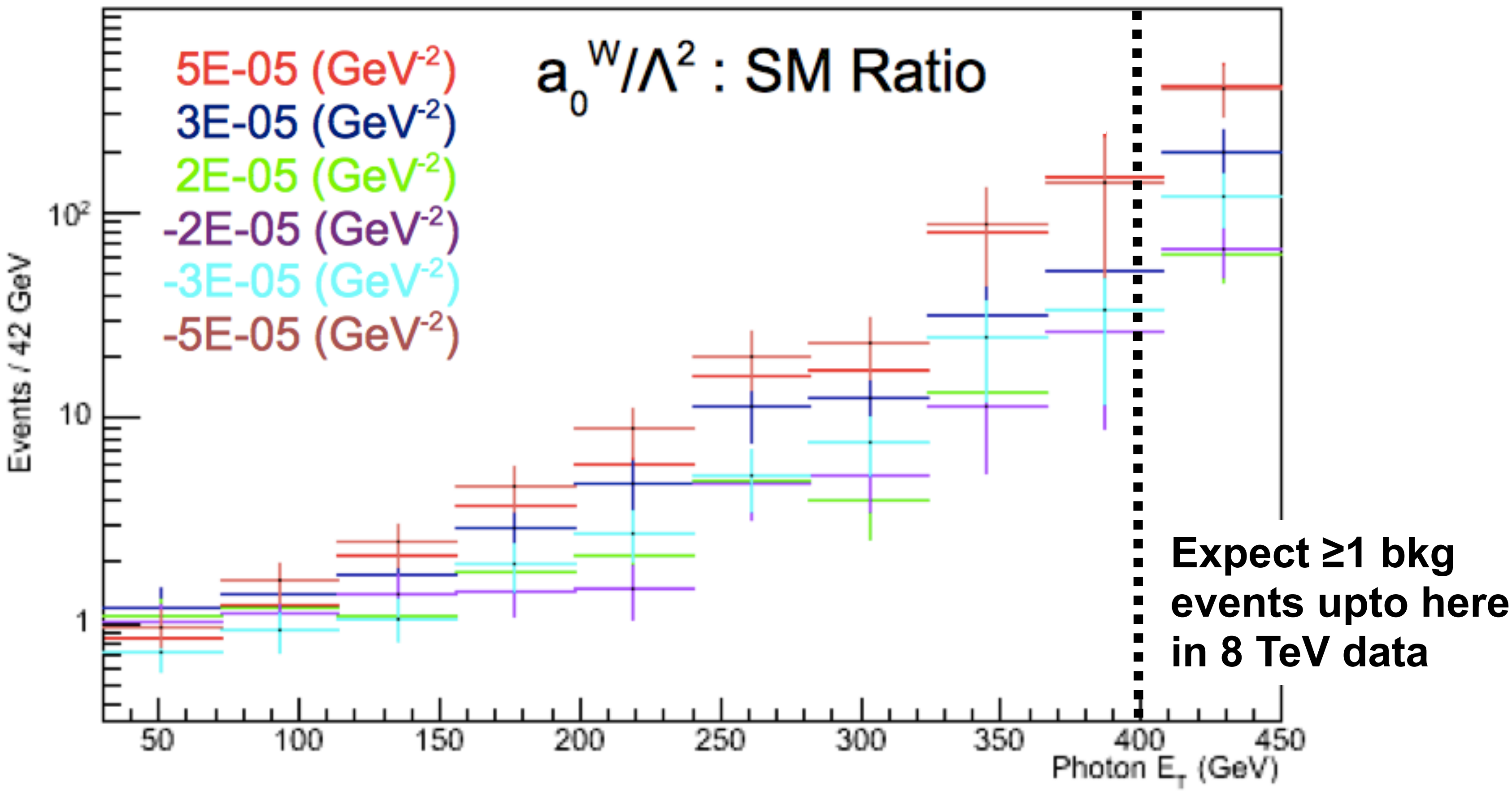
$(a - 1.185) * \exp(-b * (x - c)) + 1.185$ for $x > p_{T0}$

$d * x + (a - d * c)$ for $x < p_{T0}$



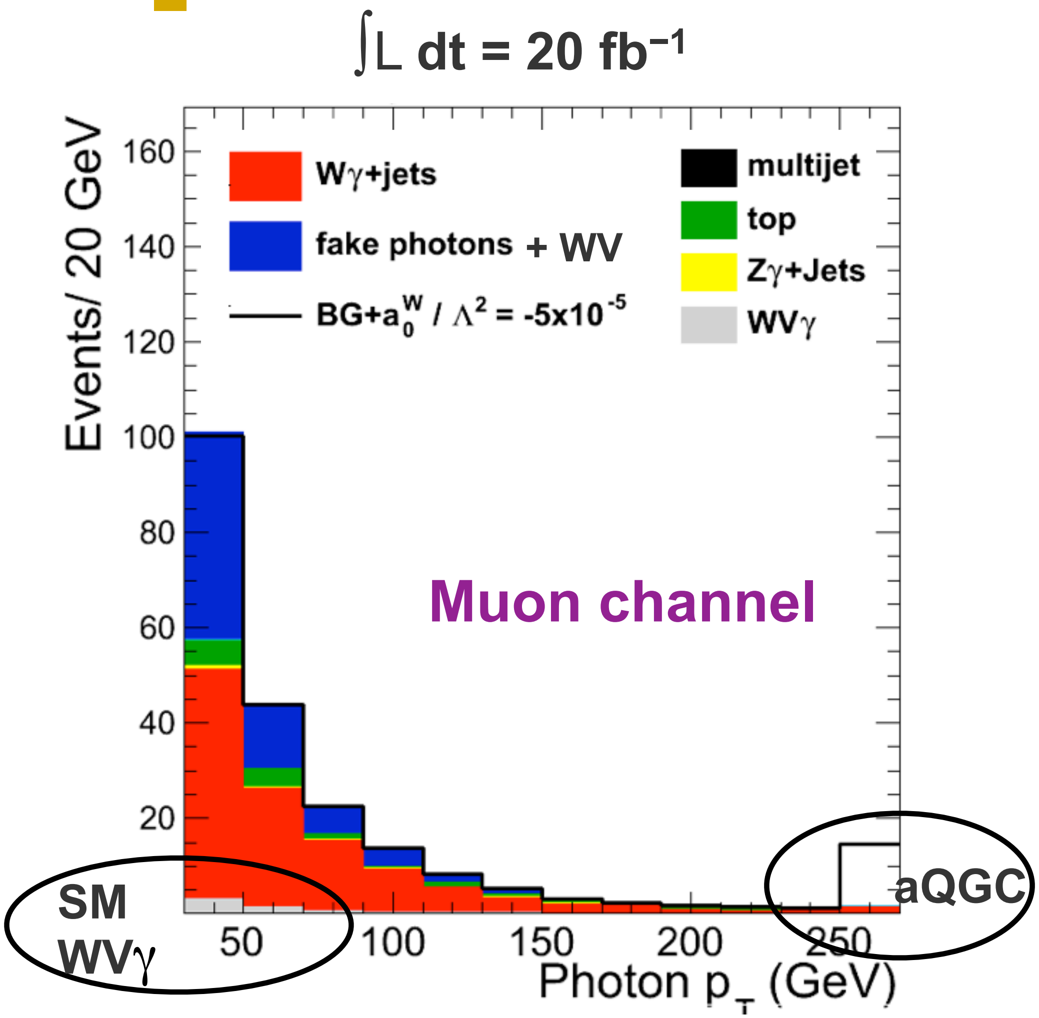
Although parametrization can be improved, limits derived using discrete k-factor and smooth function are essentially identical.

Sensitivity to aQGC



Studies ongoing to determine unitarity band, i.e., values of γ p_T and aQGC combination for which prediction becomes non-unitary.

Observable: γ p_T distribution



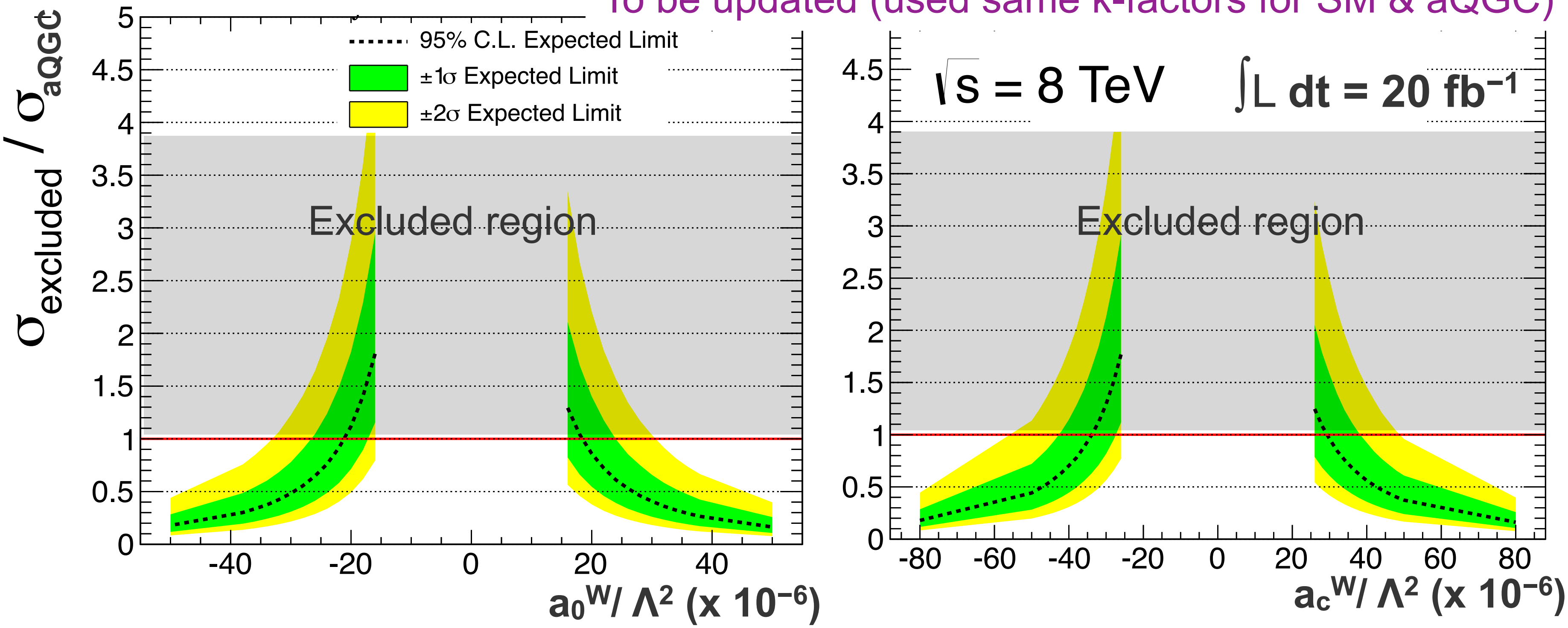
Main systematic uncertainties assumed:

- aQGC signal strength 30%
- Bkgd. normalization 20%
- Experimental uncertainties (JES/R, efficiencies, luminosity,...) each within 5%.

Studies ongoing to understand whether m(WWγ) is equally performant and/or less susceptible to non-unitarity.

Expected limits on aQGCs

To be updated (used same k-factors for SM & aQGC)



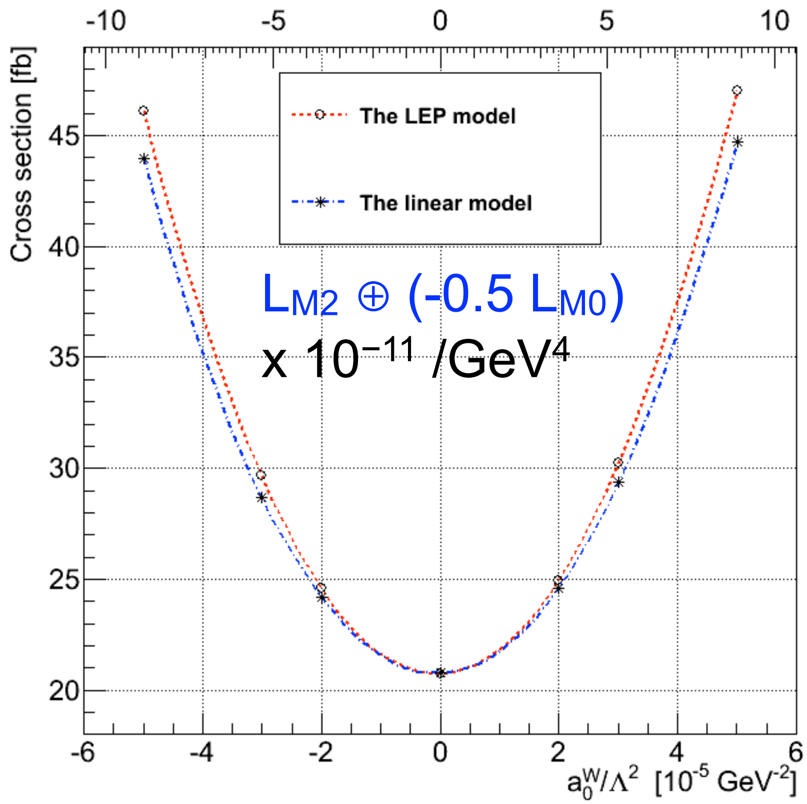
Expected limits: $-2 \times 10^{-5} < a_0^W/\Lambda^2 < 2 \times 10^{-5}$ $-3 \times 10^{-5} < a_c^W/\Lambda^2 < 3 \times 10^{-5}$

LEP limits
[NB: uses FF]

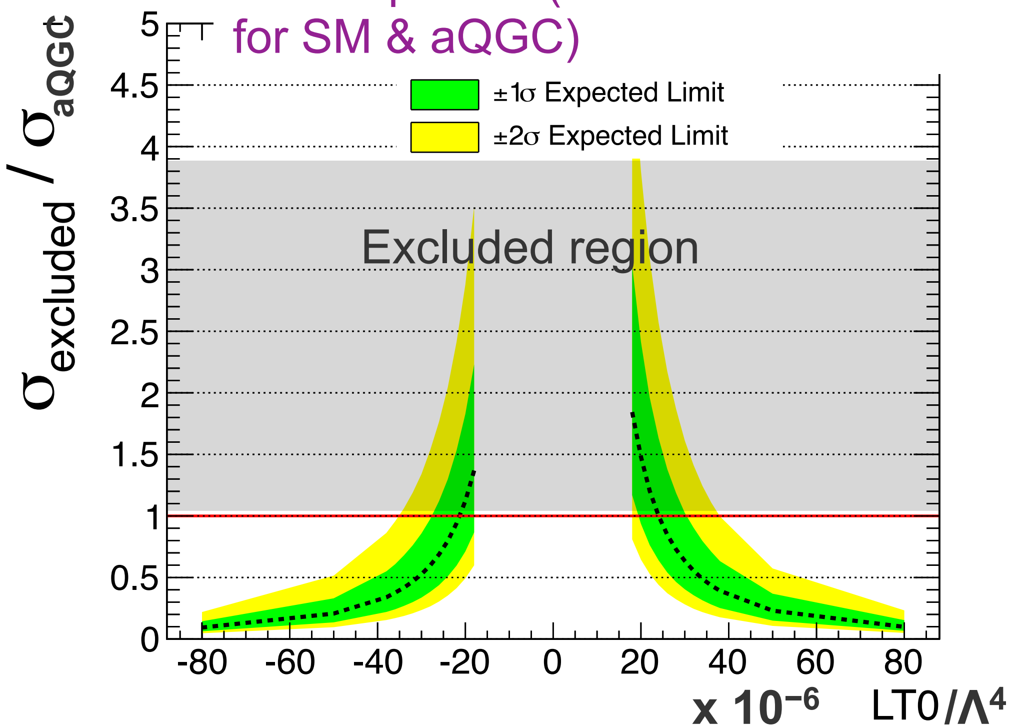
$W^+W^-\gamma$	a_0^W	$-0.020\,\mathrm{GeV}^{-2} < a_0^W/\Lambda^2 < 0.020\,\mathrm{GeV}^{-2}$
$W^+W^-\gamma$	a_c^W	$-0.053\,\mathrm{GeV}^{-2} < a_c^W/\Lambda^2 < 0.037\,\mathrm{GeV}^{-2}$

0(10^2) times more precise than LEP combined limit.
Less precise than exclusive $\gamma\gamma \rightarrow WW$ limit.

Expected limits II



To be updated (used same k-factors for SM & aQGC)



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).

Details of limit setting machinery

- Follow the RooStat-based framework used for LHC Higgs combination
  https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsCombination

- Description of ATLAS and CMS interfaces to this framework − and their validation of each others results − can be found here
  http://indico.cern.ch/conferenceDisplay.py?confId=120429
  (in particular, talks by Kyle Cranmer and Giovanni Petrucciani)

Limits shown in the previous slides computed using CMS interface to RooStats

(Used CLs limit and LHC test statistic, i.e., full profiling of nuisance parameters. See above links for detail.)

A binary package wrapping RooStats

- Takes as input either a simple text datacard for counting experiments (same format as L&S) or any RooStats HighLevelFactory file.
- Configures and runs RooStats methods, prints results and saves them to root files.
- Takes care of generating toys for expected limits, or averaging results of multiple runs.

Example data card

```
imax 2 number of bins
jmax 1 number of processes minus 1
kmax 12 number of nuisance parameters
----------------------------------------------------------------------------------------
shapes background   mu    mu_a0W.root   background $PROCESS_$SYSTEMATIC
shapes data_obs     mu    mu_a0W.root   data_obs
shapes signal       mu    mu_a0W.root   signal_a0w_m2
shapes background   el    el_a0W.root   background $PROCESS_$SYSTEMATIC
shapes data_obs     el    el_a0W.root   data_obs
shapes signal       el    el_a0W.root   signal_a0w_m2
----------------------------------------------------------------------------------------
bin              mu      el
observation     -1.0    -1.0
----------------------------------------------------------------------------------------
bin                          mu        mu            el        el
process                      signal    background    signal    background
process                      0         1             0         1
rate                         2.0       35.4          1.8       38.5
----------------------------------------------------------------------------------------
eff_e           lnN          -         -             1.03      -
eff_m           lnN          1.03      -             -         -
JER             lnN          1.02      -             1.02      -
JES             lnN          1.01      -             1.01      -
MET             lnN          1.01      -             1.01      -
PDF             lnN          1.05      -             1.05      -
signal_norm     lnN          1.30      -             1.30      -
el_backshape    shape1       -         -             -         1.0
lumi            lnN          1.03      -             1.03      -
mu_backshape    shape1       -         1.0           -         -
pileup          lnN          1.01      -             1.01      -
```

Cleanly tabulated effect on each background due to each source of systematic

Used lognormal distributions for all systematics

Broke systematics down into uncorrelated subsets

Start with a txt input, define a mathematical representation, and then prepare the ROOT workspace to be fed to the limit setter

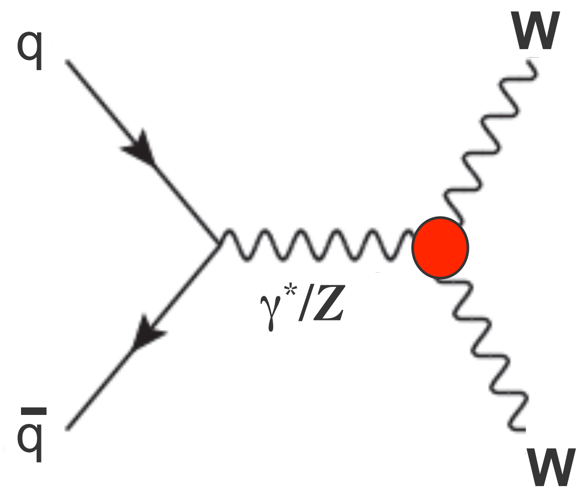
Summary

- 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
- LHC collaborations have dedicated effort to measure QGCs
  - in both multi-boson and scattering topologies
- Starting to set serious constraints on EWK gauge boson coupling
  - Already broke new ground with 8 TeV data by exceeding LEP aQGC limits by orders of magnitude
  - More studies underway – including development of new techniques & NLO computation – to improve precision at 13 TeV

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.

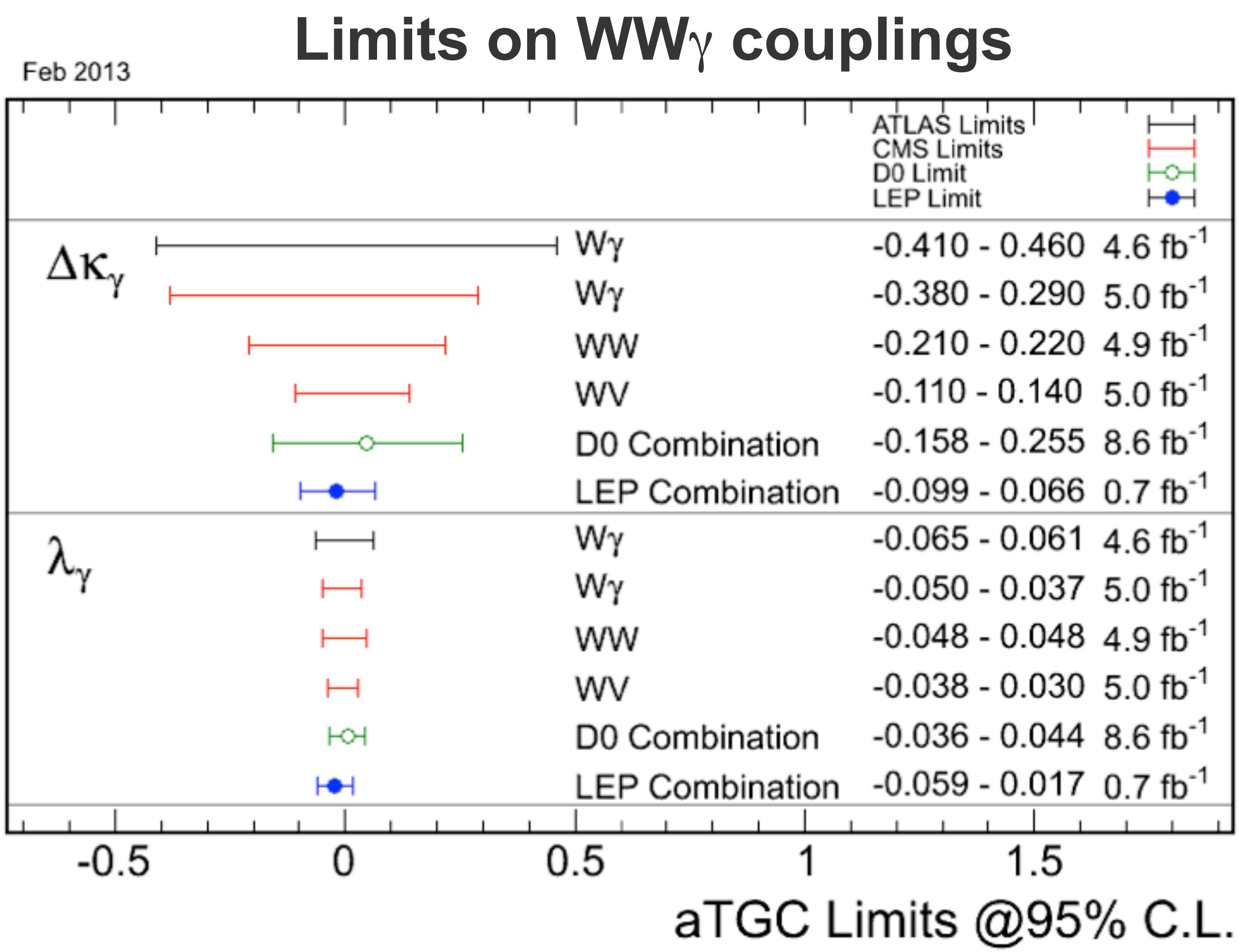
Let's do a quick overview of the current aTGC results

in the notation of LEP parametrization hep-ph/9601233

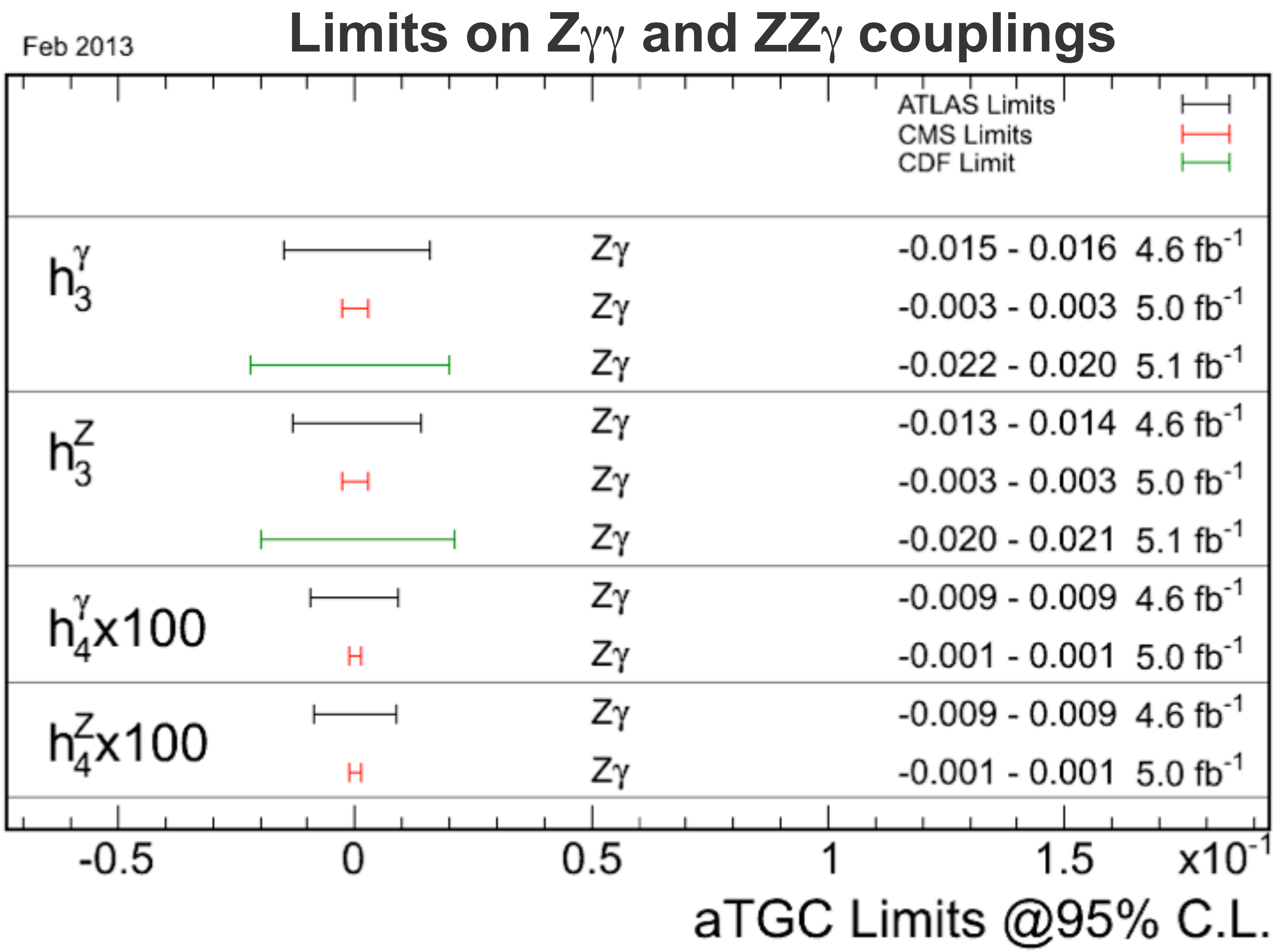
since they are also relevant for discussion of quartic couplings

Summary of aTGC measurements I

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

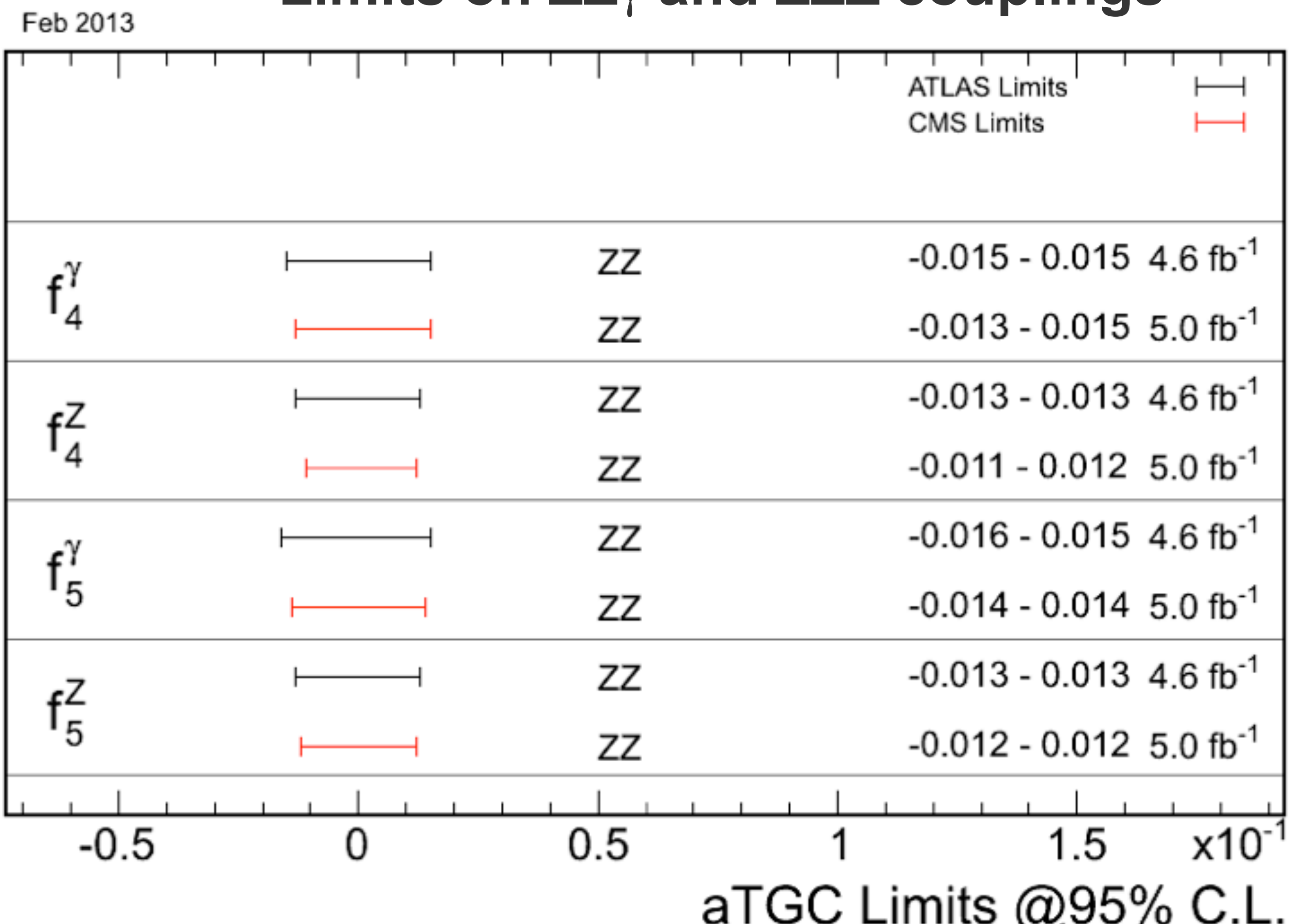


Summary of aTGC measurements II



Summary of aTGC measurements III

Limits on ZZγ and ZZZ couplings



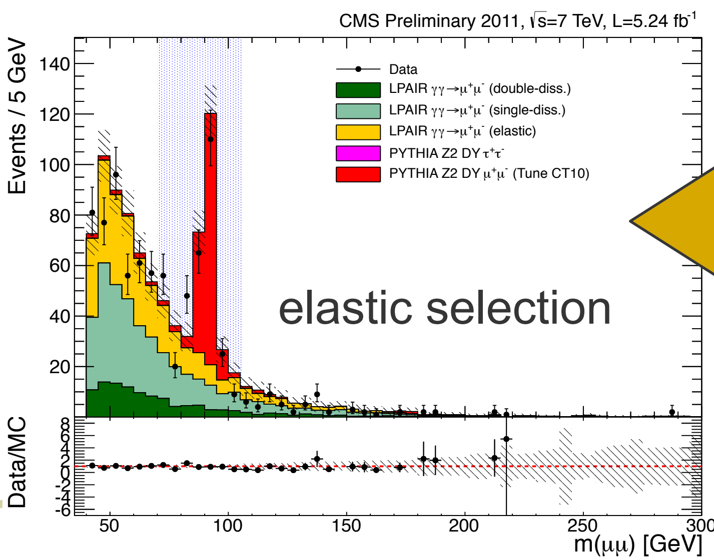
γγ→WW: CMS analysis details

Event Selection:

- lepton p_T > 20 GeV, |η| < 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

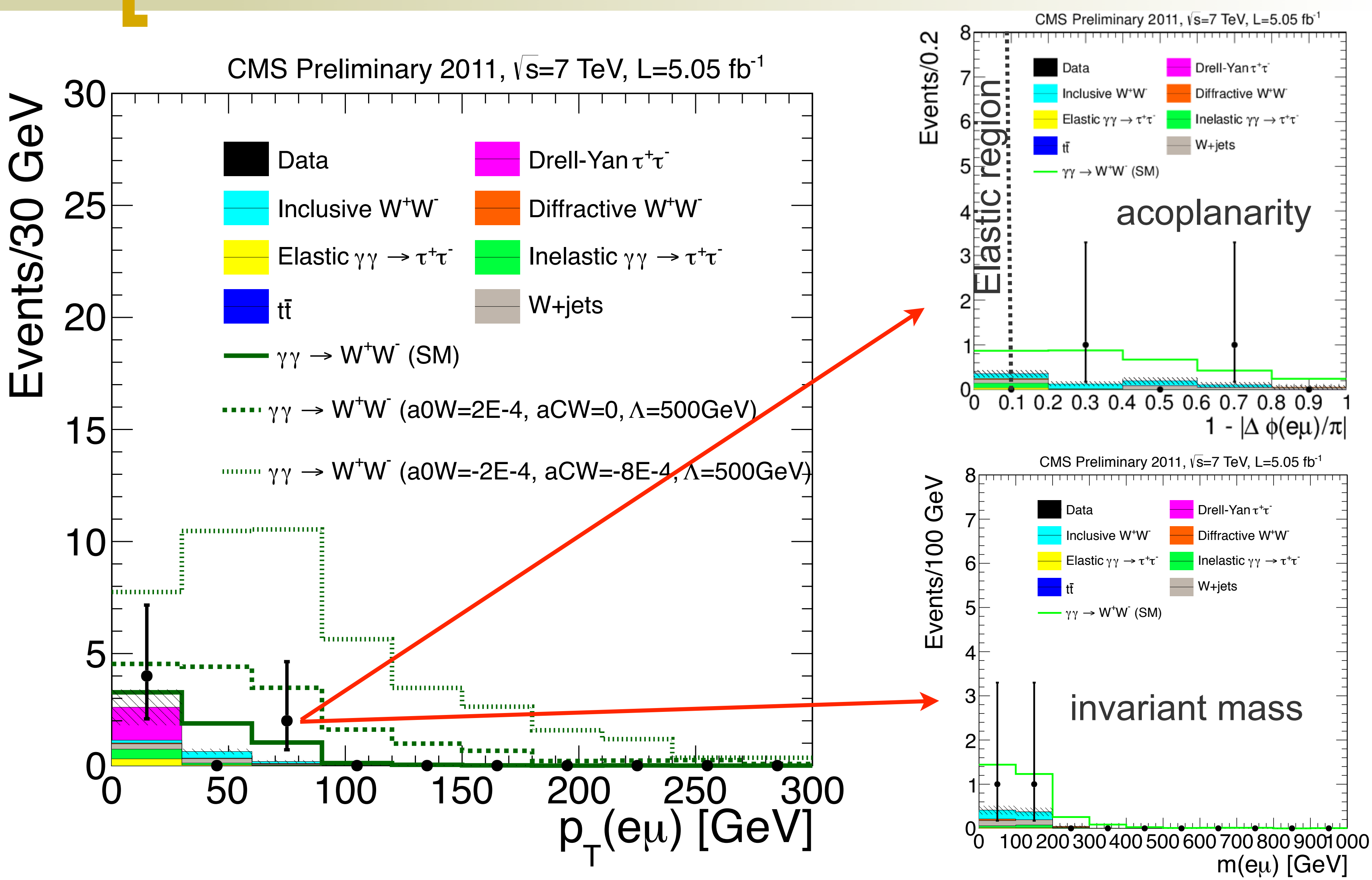
Selection step	Signal $\epsilon \times A$	Visible cross section (fb)	Events in data
Trigger and preselection	28.5%	1.4	9086
$m(\mu^{\pm}e^{\mp}) > 20$ GeV	28.0%	1.4	8200
Muon ID and Electron ID	22.6%	1.1	1222
$\mu^{\pm}e^{\mp}$ vertex with 0 extra tracks	13.7%	0.7	6
$p_T(\mu^{\pm}e^{\mp}) > 30$ GeV	10.6%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

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

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

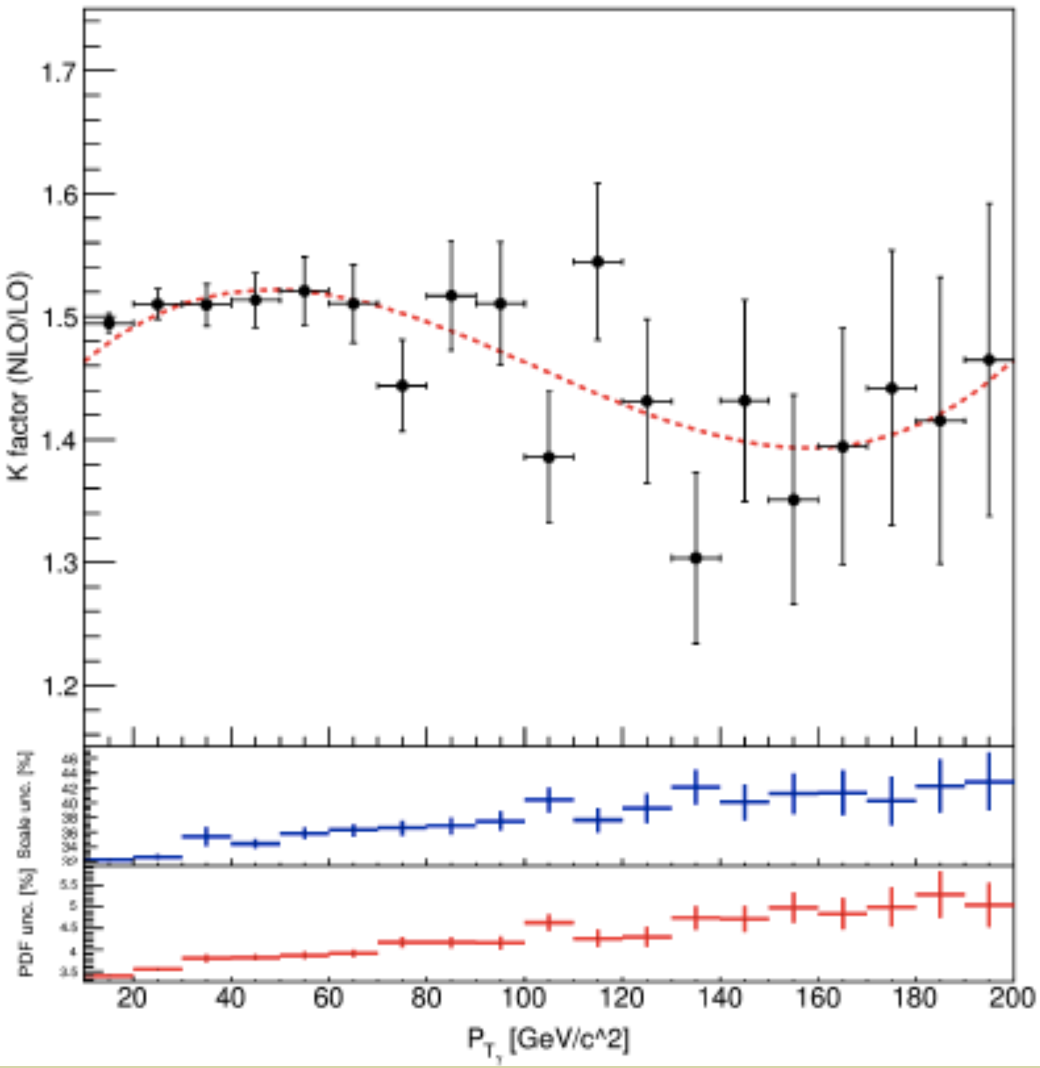
$W_{\gamma\gamma}$ = $\gamma\gamma$ center of mass energy

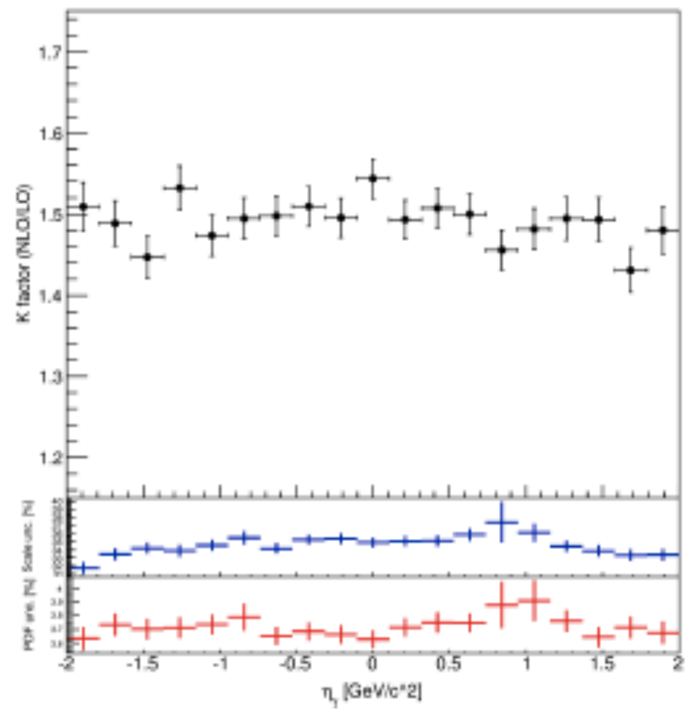
p = a free parameter = 2 by convention

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

SM WWγ k-factor after requiring jet veto

Additional jet veto for p_T > 30GeV and |η|< 4.5





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

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)
- $$\Delta X = \frac{1}{2}\left(\sum_{i=1}^{N_p}\left[X(S_i^+) - X(S_i^-)\right]^2\right)^{1/2}$$