

VVV at the LHC

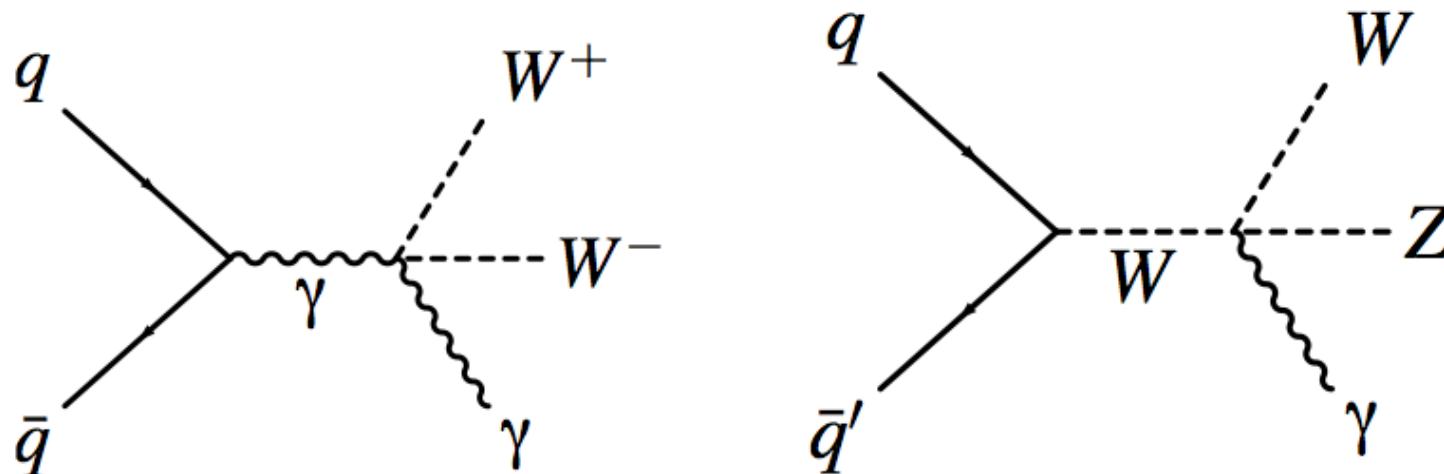
Veit Scharf
Kirchhoff-Institut für Physik
Universität Heidelberg



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Introduction



- production cross section measurement
 - test of gauge structure in electroweak sector
 - involves quartic gauge coupling vertices
- anomalous quartic couplings
 - probe new physics through deviation from predictions
 - expressed in model independent way (effective lagrangians)

Anomalous quartic couplings

- effective lagrangians parameterize low energy effects of BSM physics

$$L = L_{SM} + \sum_d \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)}$$

- different realizations for quartic interactions
- nonlinear realization of $SU(2)_L \times U(1)$ arxiv:0310141
 - lowest order genuine quartic interaction: dimension 6
- linear realization
 - lowest order genuine quartic interaction: dimension 8
- Higgs boson \rightarrow linear realization ?

Anomalous quartic couplings

- variety of parameters available that modify quartic couplings

	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

<http://feynrules.irmp.ucl.ac.be/wiki/AnomalousGaugeCoupling>

- in addition parameters from non-linear realization
 - conversion available
 - present limits on all parameters?

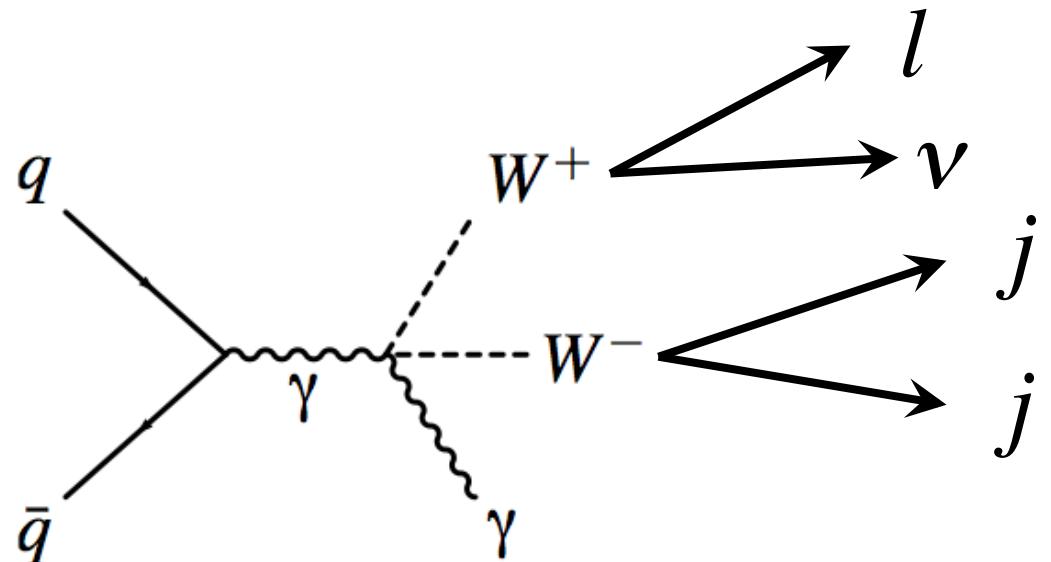
Typical processes

- cross sections for different processes from VBFNLO(2.7.0beta4)
 - parameterization different between VBFNLO and MadGraph
- leptonic decays within typical acceptance of ATLAS/CMS
 - $f_{T0} = 1500 \text{ TeV}^{-4}$ (VBFNLO) $\approx f_{T0} = 272 \text{ TeV}^{-4}$ (MadGraph)

Wγγ	$\sigma_{SM} = 16 \text{ fb}$	$\sigma_{f_{T0}} = 162 \text{ fb}$	$\frac{\sigma_{f_{T0}}}{\sigma_{SM}} = 10.7$
WWγ	$\sigma_{SM} = 5 \text{ fb}$	$\sigma_{f_{T0}} = 136 \text{ fb}$	$\frac{\sigma_{f_{T0}}}{\sigma_{SM}} = 24.4$
Zγγ	$\sigma_{SM} = 6 \text{ fb}$	$\sigma_{f_{T0}} = 44 \text{ fb}$	$\frac{\sigma_{f_{T0}}}{\sigma_{SM}} = 7.8$

Experimental Results

- one three boson analysis public
- "A Search for $WW\gamma$ and $WZ\gamma$ production and Anomalous Quartic Gauge Couplings in pp Collisions at $\sqrt{s} = 8 \text{ TeV}$ "
 - CMS PAS SMP-13-009
- leptonic decay of W boson
- hadronic decay of W/Z
 - larger branching fraction
 - hadronic W/Z experimentally difficult to distinguish
- using 19.3 fb^{-1} of pp data

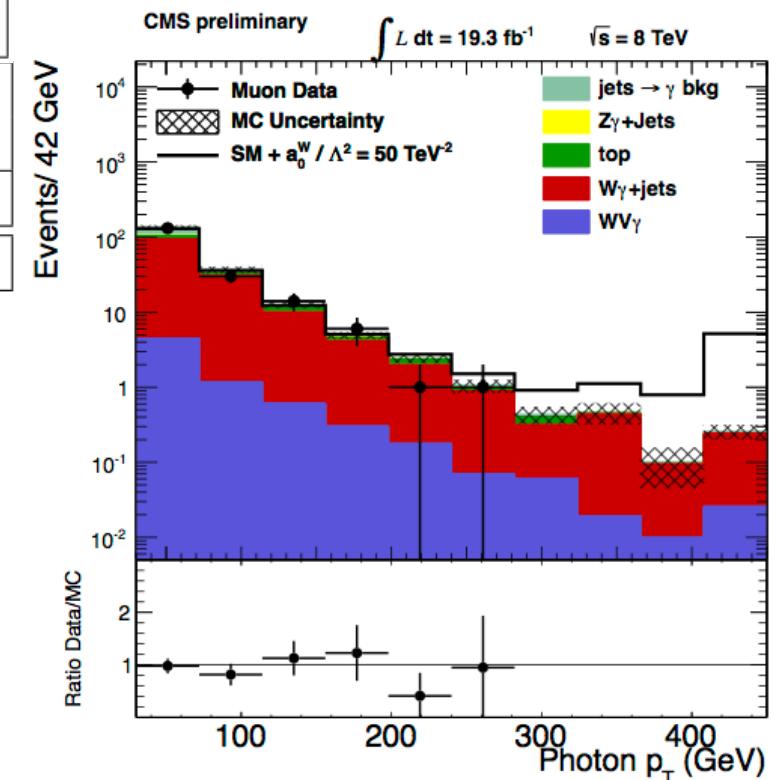


WV γ : cross section

- background dominated analysis
 - small production cross section compared to W γ +jets
 - combinatorial background (dijet mass resolution ≈ 10 GeV)

Process	muon channel number of events	electron channel number of events
SM WW γ	$6.3 \pm 0.1 \pm 1.5 \pm 0.3$	$4.7 \pm 0.1 \pm 1.1 \pm 0.2$
SM WZ γ	$0.6 \pm 0.0 \pm 0.1 \pm 0.0$	$0.5 \pm 0.0 \pm 0.1 \pm 0.0$
Total predicted	$193.9 \pm 3.9 \pm 10.8 \pm 1.0$	$147.6 \pm 4.8 \pm 9.6 \pm 0.7$
Data	183	139

- cross section not accessible with available data
- upper limit 241 fb @ 95% CL (3.4 x SM prediction)

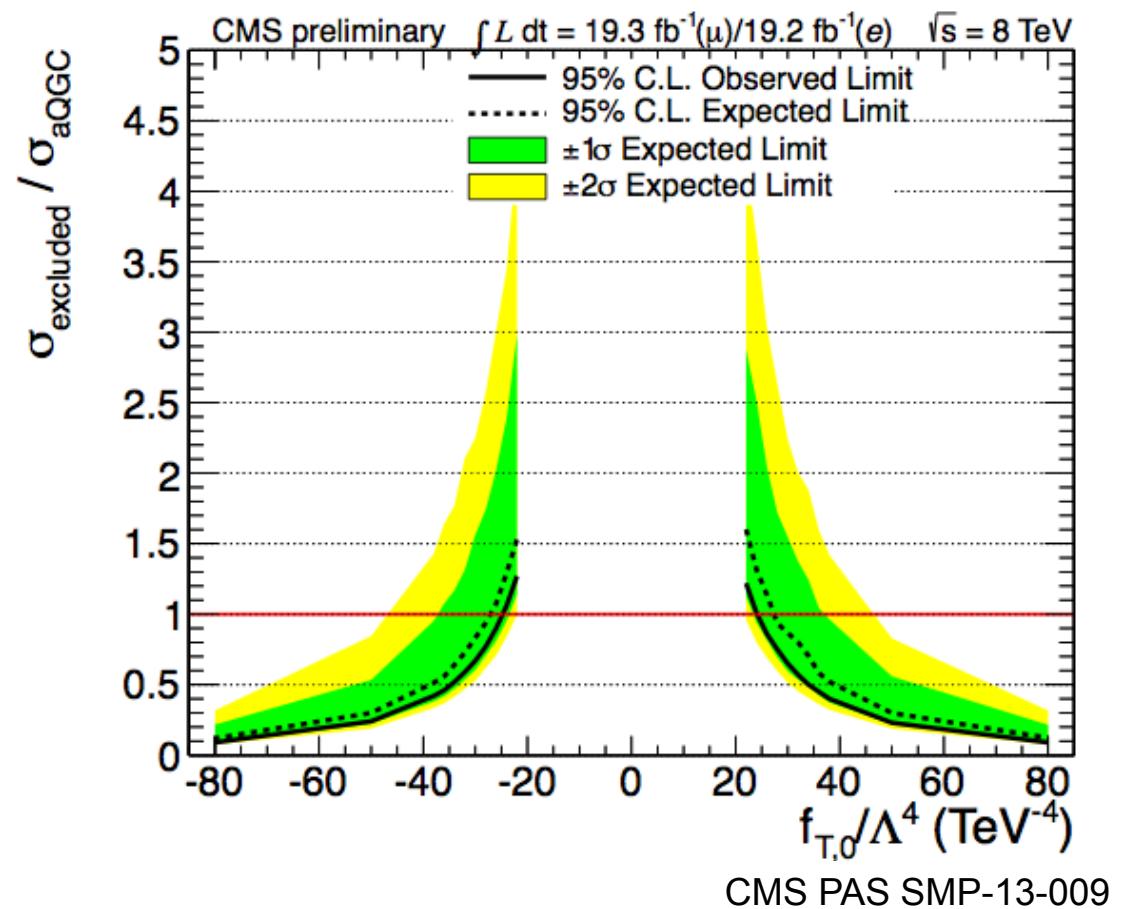


CMS PAS SMP-13-009

WV γ : Limits

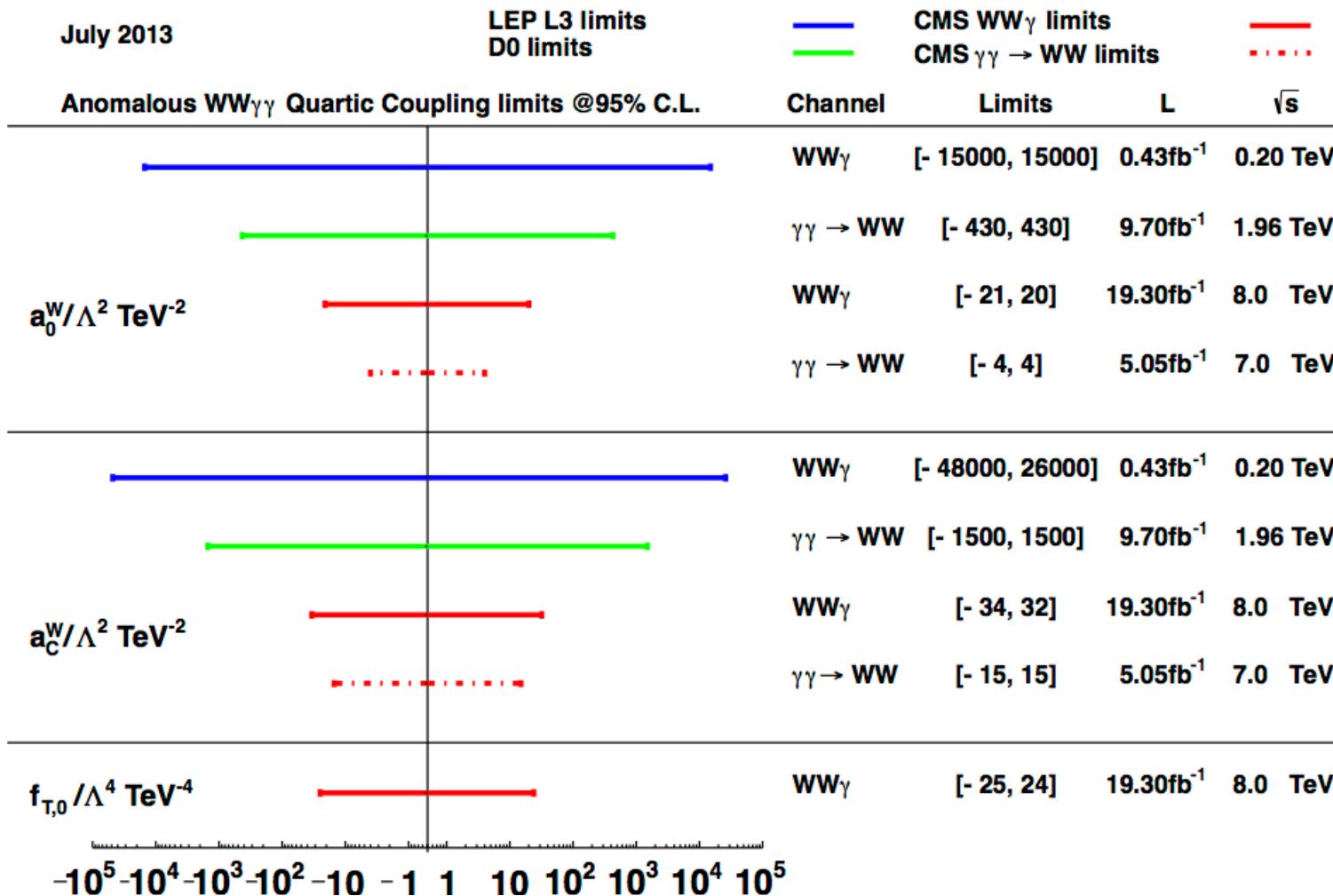
- observable: photon p_T distribution
- limits set w/o form-factors to ensure unitarity
- first ever limit on $f_{T,0}$
 - $-21 < a_0^W / \Lambda^2 < 20 \text{ TeV}^{-2}$,
 - $-34 < a_C^W / \Lambda^2 < 32 \text{ TeV}^{-2}$,
 - $-25 < f_{T,0} / \Lambda^4 < 24 \text{ TeV}^{-4}$,
 - $-12 < \kappa_0^W / \Lambda^2 < 10 \text{ TeV}^{-2}$, and
 - $-18 < \kappa_C^W / \Lambda^2 < 17 \text{ TeV}^{-2}$.

Observed Limits	
$-77 (\text{TeV}^{-4}) < f_{M,0} / \Lambda^4 < 81 (\text{TeV}^{-4})$	
$-131 (\text{TeV}^{-4}) < f_{M,1} / \Lambda^4 < 123 (\text{TeV}^{-4})$	
$-39 (\text{TeV}^{-4}) < f_{M,2} / \Lambda^4 < 40 (\text{TeV}^{-4})$	
$-66 (\text{TeV}^{-4}) < f_{M,3} / \Lambda^4 < 62 (\text{TeV}^{-4})$	



WW γ : Limits

- orders of magnitude better than LEP and TeVatron



CMS PAS SMP-13-009

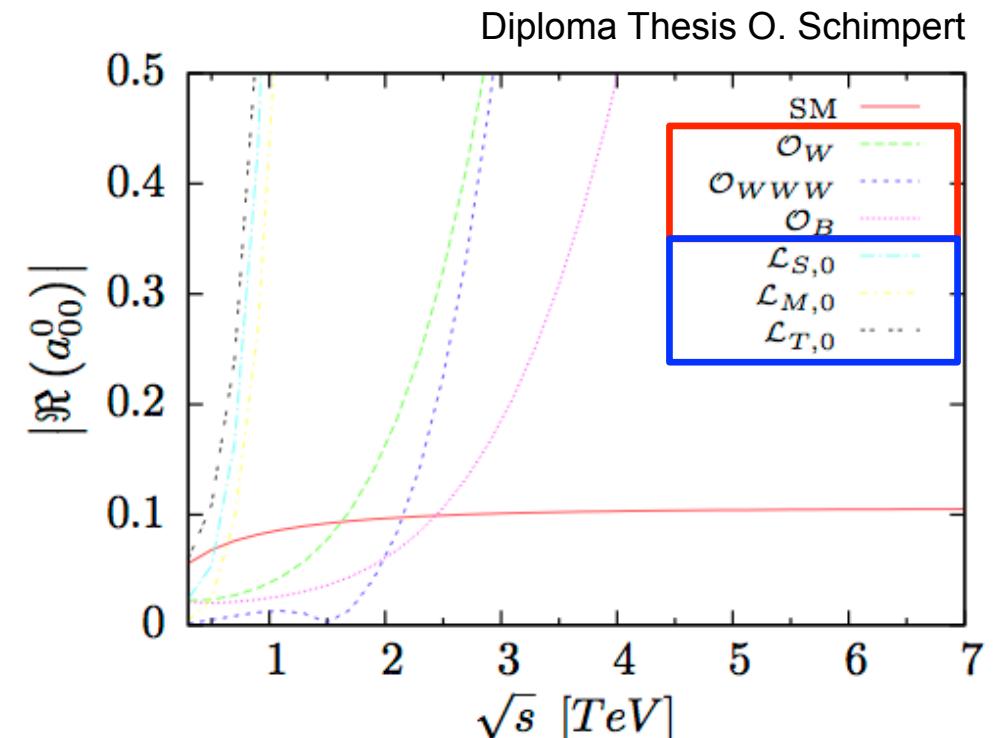
Problems for aQGC measurements

- problems for three boson measurements
 - Unitarity
 - Theory predictions
 - Computing time
- future problems (13, 14 TeV)
 - boosted W/Z bosons
 - fat jets containing all decay products
 - exploit jet substructure (à la top)

Problems: Unitarity

- current measurements still probe large couplings
- unitarity violated in the reach of the LHC

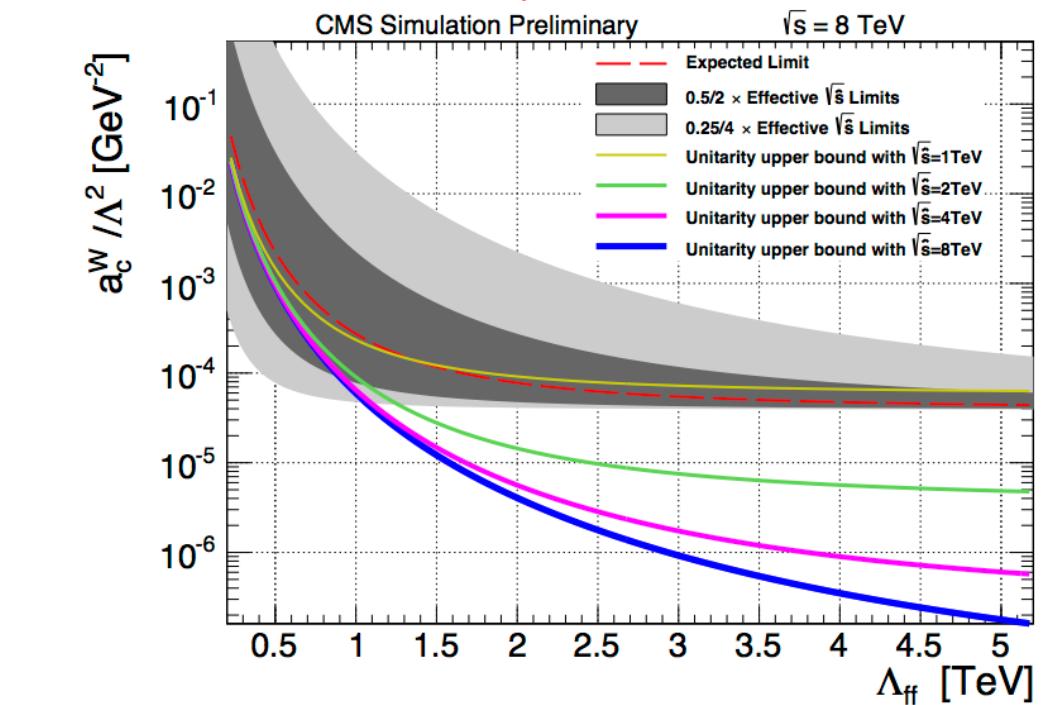
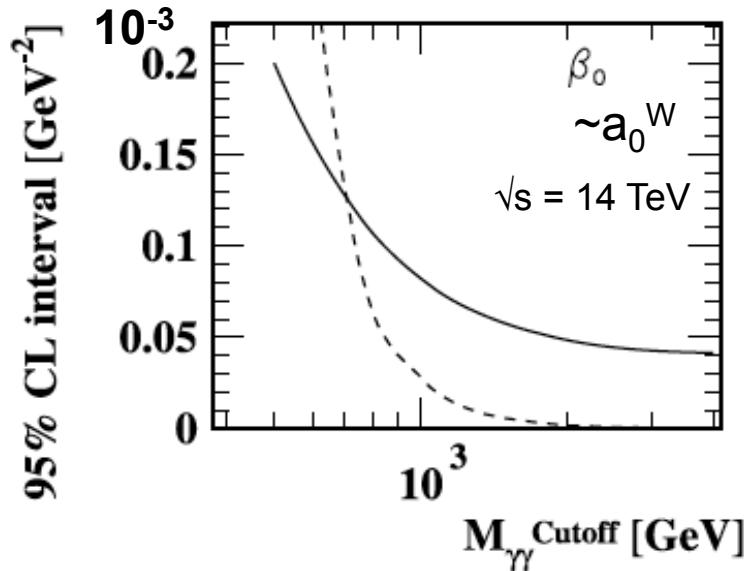
- how to present limits?
 - quote “plain” limits?
 - apply form factor $\frac{1}{\left(1 + \frac{s}{\Lambda_{FF}^2}\right)^n}$
 - clipping
- “plain limits”
 - no additional parameters
 - no physical meaning
 - unphysical limits



$$f_i/\Lambda^2 = 4 \text{ TeV}^{-2} \quad f_i/\Lambda^4 = 100 \text{ TeV}^{-4}$$

Problems: Unitarity

- form factor approach
 - two additional parameters
 - dipole form factor not sufficient



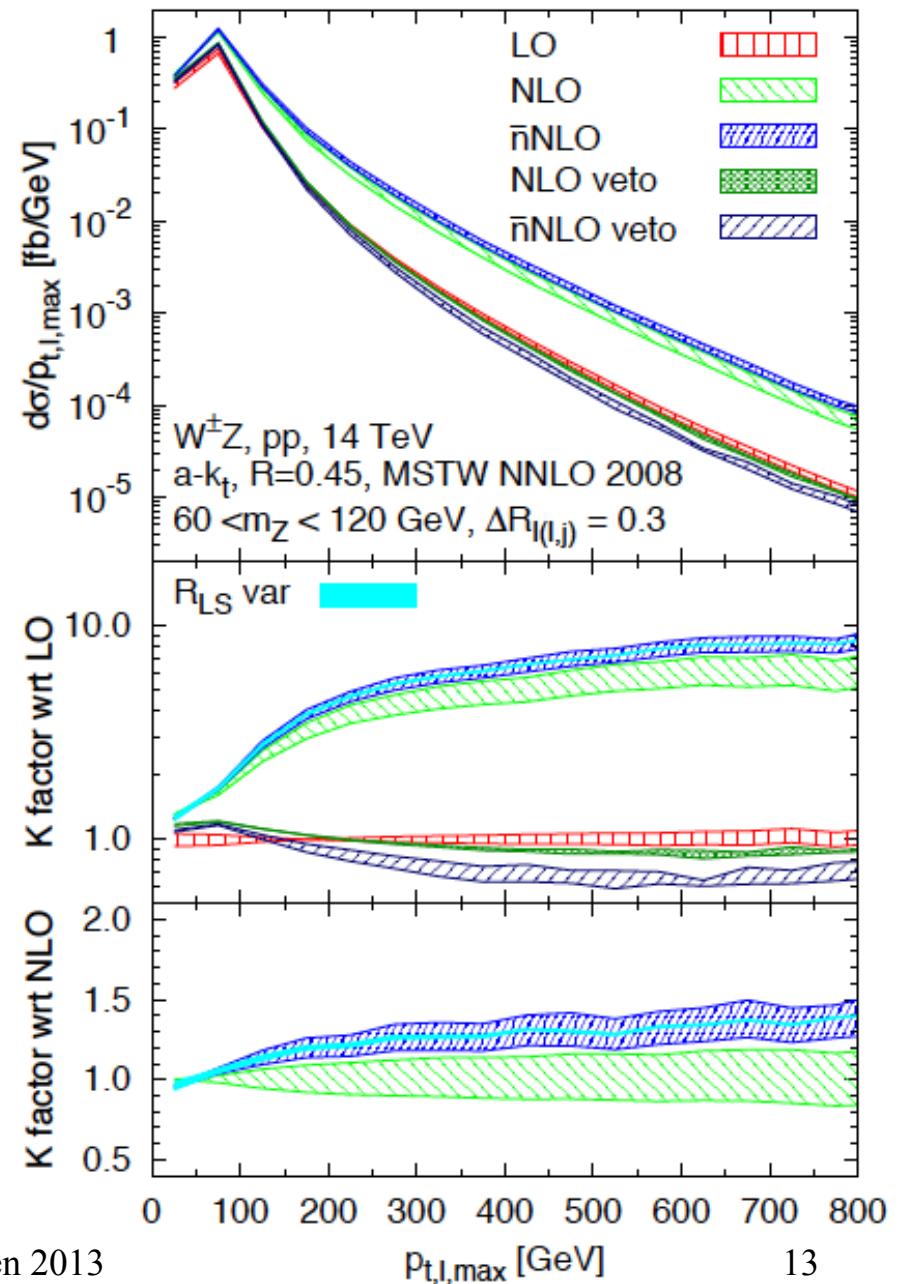
P.J.Bell,
Eur. Phys. J. C (2009) 64: 25–33

- clipping
 - evaluate limit as function of cutoff scale

Problems: Theory Predictions

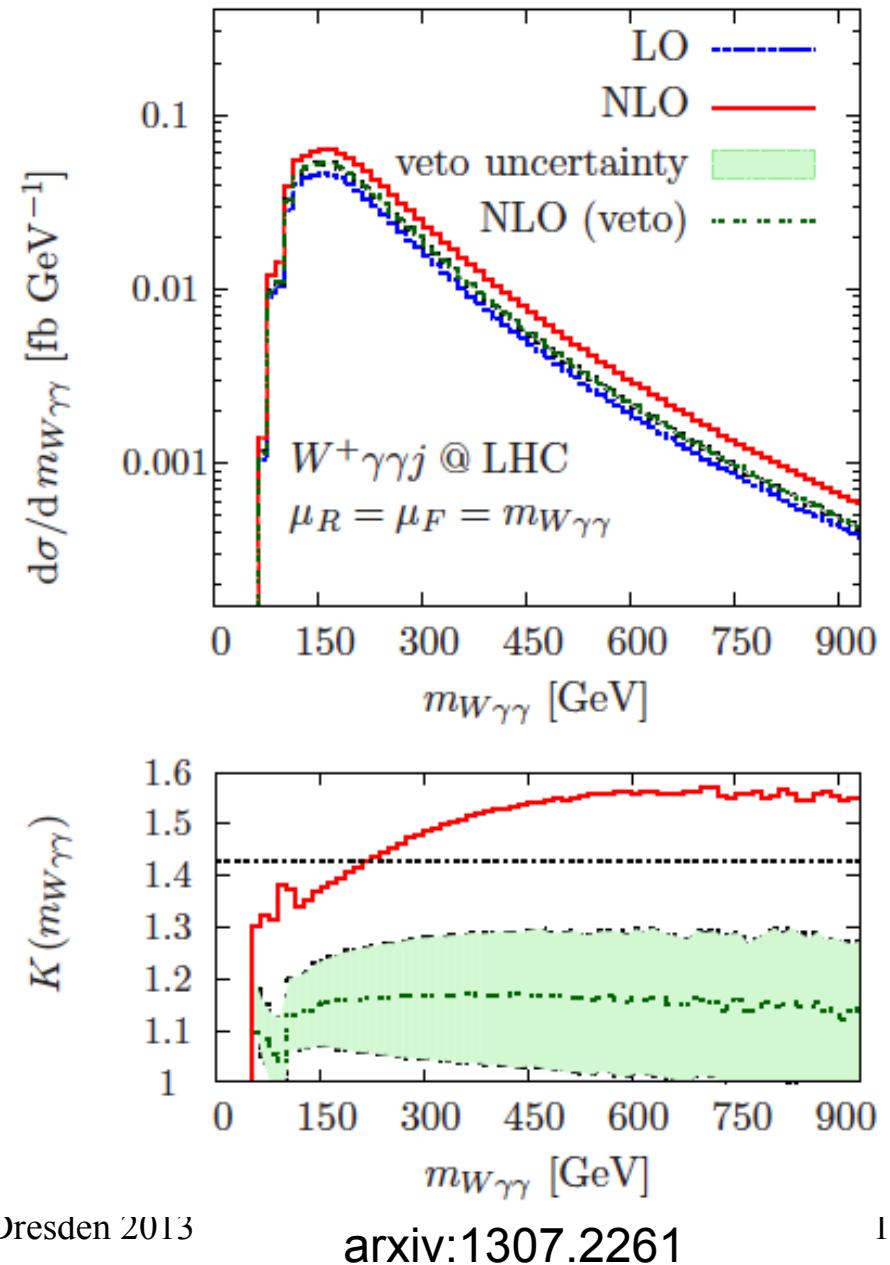
- potentially large higher order corrections
 - large k-factors for both SM / aQGC
 - higher orders: new topologies
- unincluded QCD corrections
→ spurious new physics
- veto jets?
 - only contribution from virtual two-loop corrections missing
 - large uncertainties
 - artificially small scale uncertainty with jet veto at NLO

arxiv:1307.2261



Problems: Theory Predictions

- large scale dependence
 - in interesting region at high p_T / high masses
- both SM and aQGC
 - larger uncertainty on $\frac{\sigma_{aQGC}}{\sigma_{SM}}$
- cross section predictions crucial input from theory



Conclusion

- three boson final states important test of SM
 - sensitive to BSM physics through anomalous couplings
 - important background
- variety of channels available
 - not all currently accessible
- one measurement already public
 - SM cross section $< 241\text{fb}$ @ 95% CL (3.4 times the prediction)
- problems include:
 - how to handle unitarity violations at the large couplings probed
 - large uncertainties on theory predictions for SM and aQGCs

Backup

Linear realization

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

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

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

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

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

$$\mathcal{L}_{T,5} = \text{Tr} \left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times B_{\alpha\beta} B^{\alpha\beta}$$

$$\mathcal{L}_{T,6} = \text{Tr} \left[\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta} \right] \times B_{\mu\beta} B^{\alpha\nu}$$

$$\mathcal{L}_{T,7} = \text{Tr} \left[\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \right] \times B_{\beta\nu} B^{\nu\alpha}$$

$$\mathcal{L}_{T,8} = B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta}$$

$$\mathcal{L}_{T,9} = B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha}$$

$$\mathcal{L}_{M,0} = \text{Tr} \left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right]$$

$$\mathcal{L}_{M,1} = \text{Tr} \left[\hat{W}_{\mu\nu} \hat{W}^{\nu\beta} \right] \times \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right]$$

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

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

$$\mathcal{L}_{M,4} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} D^\mu \Phi \right] \times B^{\beta\nu}$$

$$\mathcal{L}_{M,5} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} D^\nu \Phi \right] \times B^{\beta\mu}$$

$$\mathcal{L}_{M,6} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\nu} D^\mu \Phi \right]$$

$$\mathcal{L}_{M,7} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\mu} D^\nu \Phi \right]$$

Non-linear realization

$$\mathcal{L}_{aQGC} = \frac{a_0^W}{4g^2} \mathcal{W}_0^\gamma + \frac{a_c^W}{4g^2} \mathcal{W}_c^\gamma + \sum_i \kappa_i^W \mathcal{W}_i^Z + \mathcal{L}_{T,0} + \mathcal{L}_{T,1} + \mathcal{L}_{T,2}.$$

CMS PAS SMP-13-009

$$\mathcal{W}_0^Z = -e^2 g^2 F_{\mu\nu} Z^{\mu\nu} W^{+\alpha} W_\alpha^- ,$$

$$\mathcal{W}_c^Z = -\frac{e^2 g^2}{2} F_{\mu\nu} Z^{\mu\alpha} (W^{+\nu} W_\alpha^- + W^{-\nu} W_\alpha^+) ,$$

$$\mathcal{W}_1^Z = -\frac{e^2 g^2}{2 c_w s_w} F^{\mu\nu} (W_{\mu\nu}^+ W_\alpha^- Z^\alpha + W_{\mu\nu}^- W_\alpha^+ Z^\alpha) ,$$

$$\mathcal{W}_2^Z = -\frac{e^2 g^2}{2 c_w s_w} F^{\mu\nu} (W_{\mu\alpha}^+ W^{-\alpha} Z_\nu + W_{\mu\alpha}^- W^{+\alpha} Z_\nu) ,$$

$$\mathcal{W}_3^Z = -\frac{e^2 g^2}{2 c_w s_w} F^{\mu\nu} (W_{\mu\alpha}^+ W_\nu^- Z^\alpha + W_{\mu\alpha}^- W_\nu^+ Z^\alpha) .$$

$$\mathcal{W}_0^\gamma = -\frac{e^2 g^2}{2} F_{\mu\nu} F^{\mu\nu} W^{+\alpha} W_\alpha^- ,$$

$$\mathcal{W}_c^\gamma = -\frac{e^2 g^2}{4} F_{\mu\nu} F^{\mu\alpha} (W^{+\nu} W_\alpha^- + W^{-\nu} W_\alpha^+)$$

$$\frac{f_{M,0}}{\Lambda^4} = -\frac{g^4}{M_W^2} \frac{\kappa_0^w}{\Lambda^2},$$

$$\frac{f_{M,2}}{\Lambda^4} = -\frac{g^2 g'^2}{2 M_W^2} \frac{\kappa_0^b}{\Lambda^2},$$

$$\frac{f_{M,1}}{\Lambda^4} = \frac{g^4}{M_W^2} \frac{\kappa_c^w}{\Lambda^2},$$

$$\frac{f_{M,3}}{\Lambda^4} = \frac{g^2 g'^2}{2 M_W^2} \frac{\kappa_c^b}{\Lambda^2}.$$

arxiv:0310141

WV γ Background

Process	muon channel number of events	electron channel number of events
W γ +jets	$136.9 \pm 3.5 \pm 9.2 \pm 0.0$	$101.6 \pm 2.9 \pm 8.0 \pm 0.0$
WV γ +jet, jet $\rightarrow \gamma$	$33.1 \pm 1.3 \pm 4.6 \pm 0.0$	$21.3 \pm 1.0 \pm 3.1 \pm 0.0$
MC $t\bar{t}\gamma$	$12.5 \pm 0.8 \pm 2.9 \pm 0.5$	$9.1 \pm 0.7 \pm 2.1 \pm 0.4$
MC single top	$2.8 \pm 0.8 \pm 0.2 \pm 0.1$	$1.7 \pm 0.6 \pm 0.1 \pm 0.1$
MC Z γ +jets	$1.7 \pm 0.1 \pm 0.1 \pm 0.1$	$1.5 \pm 0.1 \pm 0.1 \pm 0.1$
multijets	$<0.2 \pm 0.0 \pm 0.1 \pm 0.0$	$7.2 \pm 3.6 \pm 3.6 \pm 0.0$
SM WW γ	$6.3 \pm 0.1 \pm 1.5 \pm 0.3$	$4.7 \pm 0.1 \pm 1.1 \pm 0.2$
SM WZ γ	$0.6 \pm 0.0 \pm 0.1 \pm 0.0$	$0.5 \pm 0.0 \pm 0.1 \pm 0.0$
Total predicted	$193.9 \pm 3.9 \pm 10.8 \pm 1.0$	$147.6 \pm 4.8 \pm 9.6 \pm 0.7$
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WV γ aQGC

