TECHNISCHE
UNIVERSITÄT
DRESDEN

Fakultät Mathematik und Naturwissenschaften, Fachrichtung Physik

Measurement of Electroweak (Multi-Gauge) Couplings

Symposium: Electroweak Precision – Status and Future

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ATLAS-D 2017, Dortmund, 6.9.2016

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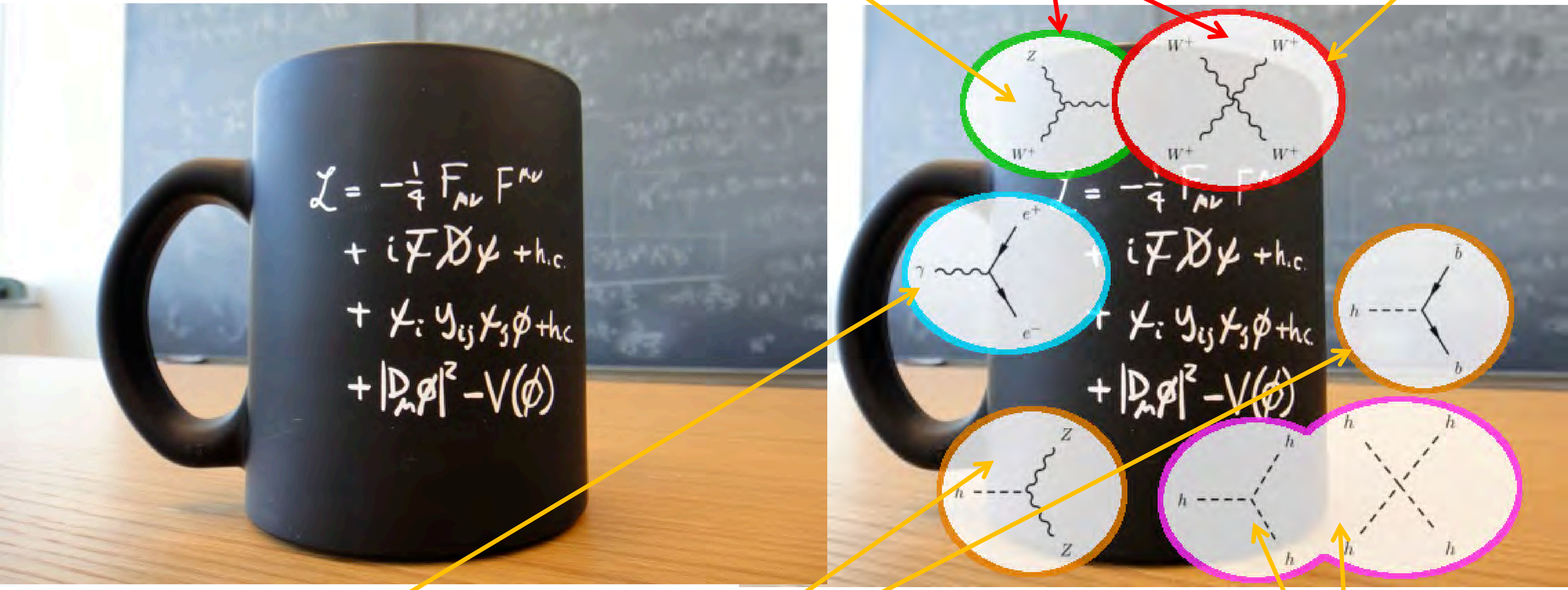
concept

The Standard Model Lagrangian

Precisely checked,
e.g. at LEP

Today's topic

About to be
investigated



© Christian Gumpert and www.quantumdiaries.org/2011/06/26/cern-mug-summarizes-standard-model-but-is-off-by-a-factor-of-2/

Most frequent
and best understood

Recently seen:
H→WW,ZZ and H→ ττ, tt

Not yet seen:
H→HH and H→ HHH

❖ Field Tensors have to be invariant under Gauge symmetries

- Electromagnetic U(1)

$$F_{\mu\nu} = \frac{\partial A_\nu}{\partial x_\mu} - \frac{\partial A_\mu}{\partial x_\nu} \rightarrow \quad F_{\mu\nu} = \begin{pmatrix} 0 & B_z & -B_y & -iE_x \\ -B_z & 0 & B_x & -iE_y \\ B_y & -B_x & 0 & -iE_z \\ iE_x & iE_y & iE_z & 0 \end{pmatrix}$$

→ Lagrange density term $(F_{\mu\nu})^2 = F_{\mu\nu}F^{\mu\nu}$
only contains term $\sim A^2$, no terms $\sim A^3$ or A^4

→ No triple nor quartic Photon vertices

- Weak SU(2) needs „covariant derivative“ D_μ because of weak charge

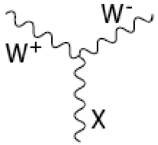
$W_{\mu\nu} = D_\mu W_\nu - D_\nu W_\mu =$

$$= \left(\partial_\mu + \left(\frac{ig_2}{2}\right)\mathbf{W}_\mu\right)\mathbf{W}_\nu - \left(\partial_\nu + \left(\frac{ig_2}{2}\right)\mathbf{W}_\nu\right)\mathbf{W}_\mu$$

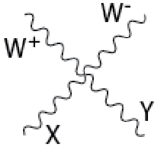
$$= \partial_\mu \mathbf{W}_\nu - \partial_\nu \mathbf{W}_\mu + \frac{ig_2}{2}(\mathbf{W}_\mu \mathbf{W}_\nu - \mathbf{W}_\nu \mathbf{W}_\mu)$$

→ Lagrange density term $(W_{\mu\nu})^2 = W_{\mu\nu}W^{\mu\nu}$
contains all terms $\sim W^2$, $\sim W^3$ and $\sim W^4$

→ triple (~g) and quartic (~g²) vertices:

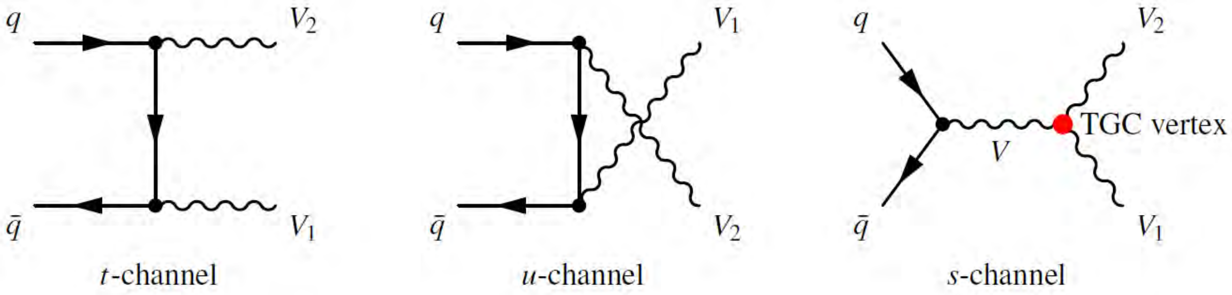


X is a photon or Z-boson.



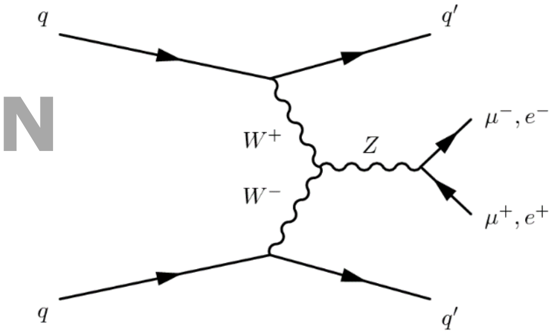
X and Y are any two electroweak bosons such that charge is conserved.

I) TGCs and aTGCs



DIBOSON PRODUCTION

- ATLAS, CMS pp → W^+W^- +X
- ATLAS, CMS pp → $W^\pm Z$ +X
- ATLAS, CMS pp → $W^\pm\gamma$ + X
- ATLAS, CMS pp → ZZ +X
- ATLAS, CMS pp → $Z\gamma$ + X



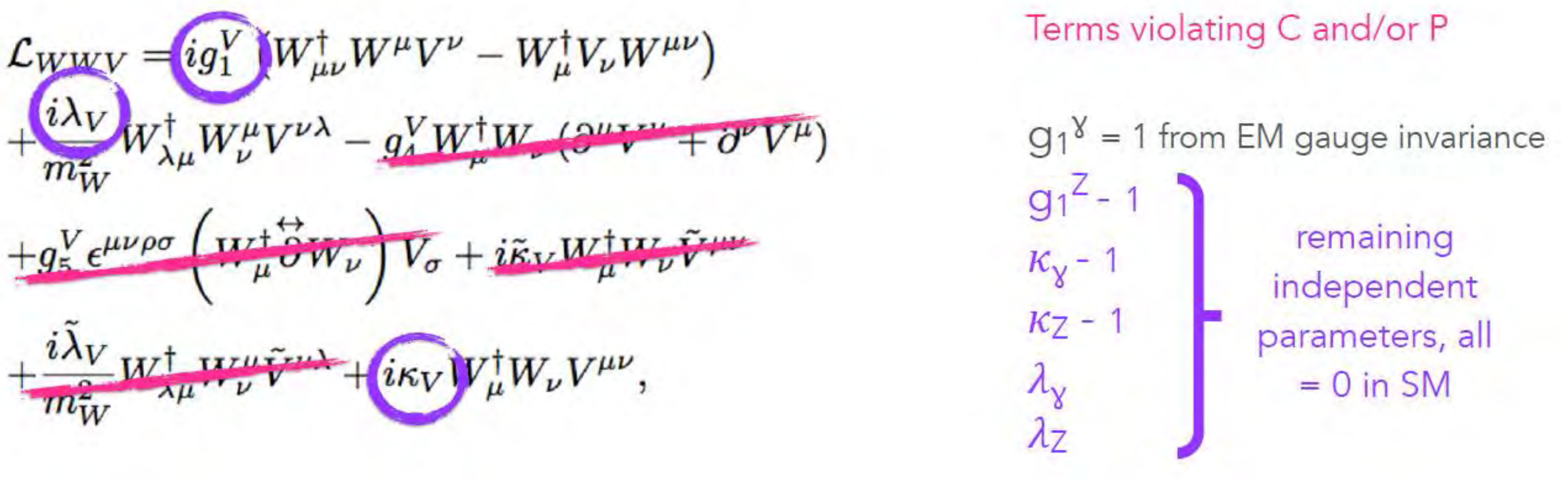
VBF BOSON PRODUCTION

- ATLAS, CMS pp → $W^\pm jj$
- ATLAS, CMS pp → Zjj

Anomalous aTGCs

- Traditional parameterisation of anomalous charged TGCs
  - Lorentz invariant and charge conserving (V = Z or γ)
  - After C and P invarianz 6 parameters remaining

K. Hagiwara, K. Hikasa, R.D. Peccei, D. Zeppenfeld, Nucl. Phys. B282 (1987) 253.



$$\mathcal{L}_{WWV} = ig_1^V \left(W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}\right) + \frac{i\lambda_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda} - \cancel{g_4^V W^\dagger_\mu W_\nu \left(\partial^\mu V^\nu + \partial^\nu V^\mu\right)} + \cancel{g_5^V \epsilon^{\mu\nu\rho\sigma} \left(W^\dagger_\mu \overleftrightarrow{\partial}_\rho W_\nu\right) V_\sigma} + \cancel{i\tilde{\kappa}_V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu}} + \cancel{\frac{i\tilde{\lambda}_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu \tilde{V}^{\nu\lambda}} + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu},$$

Terms violating C and/or P

g_1^γ = 1 from EM gauge invariance

$g_1^Z - 1$

$\kappa_\gamma - 1$

$\kappa_Z - 1$

λ_γ

λ_Z

remaining independent parameters, all = 0 in SM

© Claire Lee: MBI workshop Karlsruhe 2017:
https://indico.cern.ch/event/625573/timetable/?view=standard

- Non-SM parameters all violate unitarity at large √s
- Form factor

Charged (a)TGCs, 8 TeV W±W±

- ATLAS: several aTGC approaches calculated from leading lepton p_T
  - LEP

$$\Delta g_1^Z = \Delta k^Z + \tan^2\theta_W \Delta k^\gamma,$$
$$\lambda^\gamma = \lambda^Z,$$

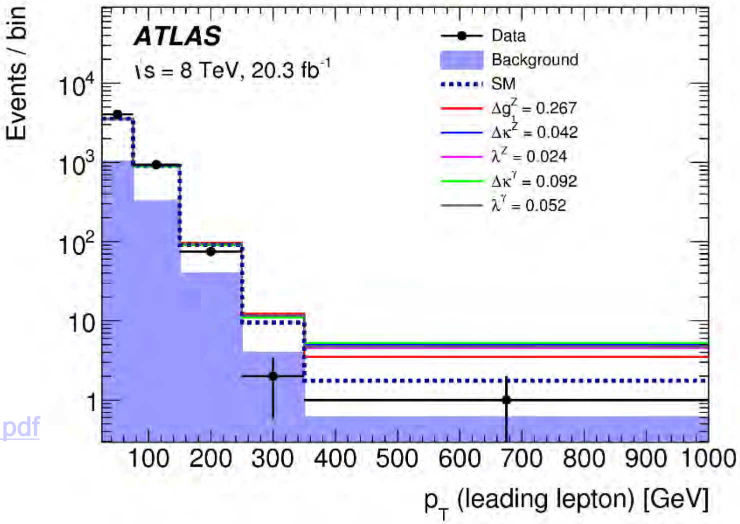
  - HISZ

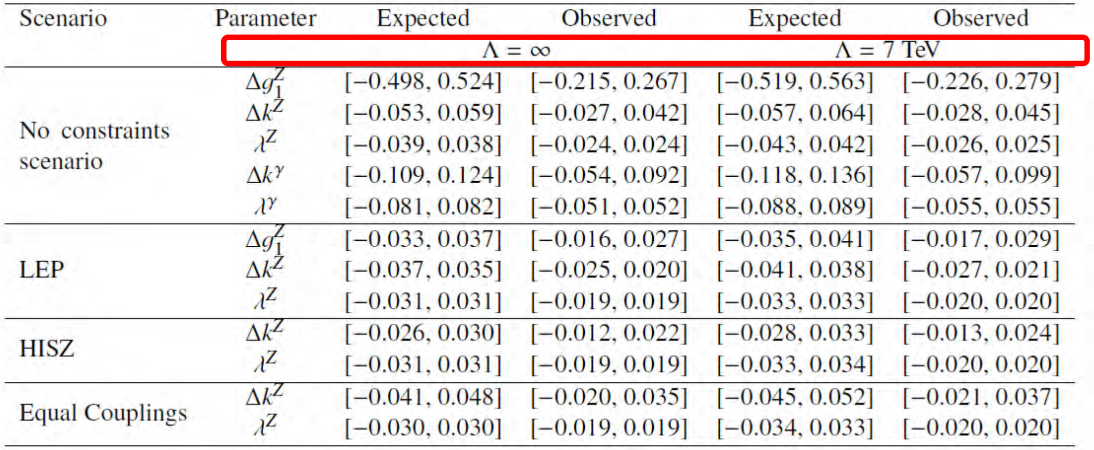
$$\Delta g_1^Z = \frac{\Delta k^Z}{\cos^2\theta_W - \sin^2\theta_W},$$
$$\Delta k^\gamma = 2\Delta k^Z \frac{\cos^2\theta_W}{\cos^2\theta_W - \sin^2\theta_W},$$
$$\lambda^\gamma = \lambda^Z.$$

  - Equal Couplings

$$g_1^Z = g_1^\gamma = 1,$$
$$\Delta k^\gamma = \Delta k^Z$$
$$\lambda^\gamma = \lambda^Z$$

https://arxiv.org/pdf/1603.01702.pdf





Scenario	Parameter	Expected	Observed	Expected	Observed
		$\Lambda = \infty$		$\Lambda = 7$ TeV	
No constraints scenario	Δg_1^Z	[−0.498, 0.524]	[−0.215, 0.267]	[−0.519, 0.563]	[−0.226, 0.279]
	Δk^Z	[−0.053, 0.059]	[−0.027, 0.042]	[−0.057, 0.064]	[−0.028, 0.045]
	λ^Z	[−0.039, 0.038]	[−0.024, 0.024]	[−0.043, 0.042]	[−0.026, 0.025]
	Δk^γ	[−0.109, 0.124]	[−0.054, 0.092]	[−0.118, 0.136]	[−0.057, 0.099]
	λ^γ	[−0.081, 0.082]	[−0.051, 0.052]	[−0.088, 0.089]	[−0.055, 0.055]
LEP	Δg_1^Z	[−0.033, 0.037]	[−0.016, 0.027]	[−0.035, 0.041]	[−0.017, 0.029]
	Δk^Z	[−0.037, 0.035]	[−0.025, 0.020]	[−0.041, 0.038]	[−0.027, 0.021]
	λ^Z	[−0.031, 0.031]	[−0.019, 0.019]	[−0.033, 0.033]	[−0.020, 0.020]
HISZ	Δk^Z	[−0.026, 0.030]	[−0.012, 0.022]	[−0.028, 0.033]	[−0.013, 0.024]
	λ^Z	[−0.031, 0.031]	[−0.019, 0.019]	[−0.033, 0.034]	[−0.020, 0.020]
Equal Couplings	Δk^Z	[−0.041, 0.048]	[−0.020, 0.035]	[−0.045, 0.052]	[−0.021, 0.037]
	λ^Z	[−0.030, 0.030]	[−0.019, 0.019]	[−0.034, 0.033]	[−0.020, 0.020]

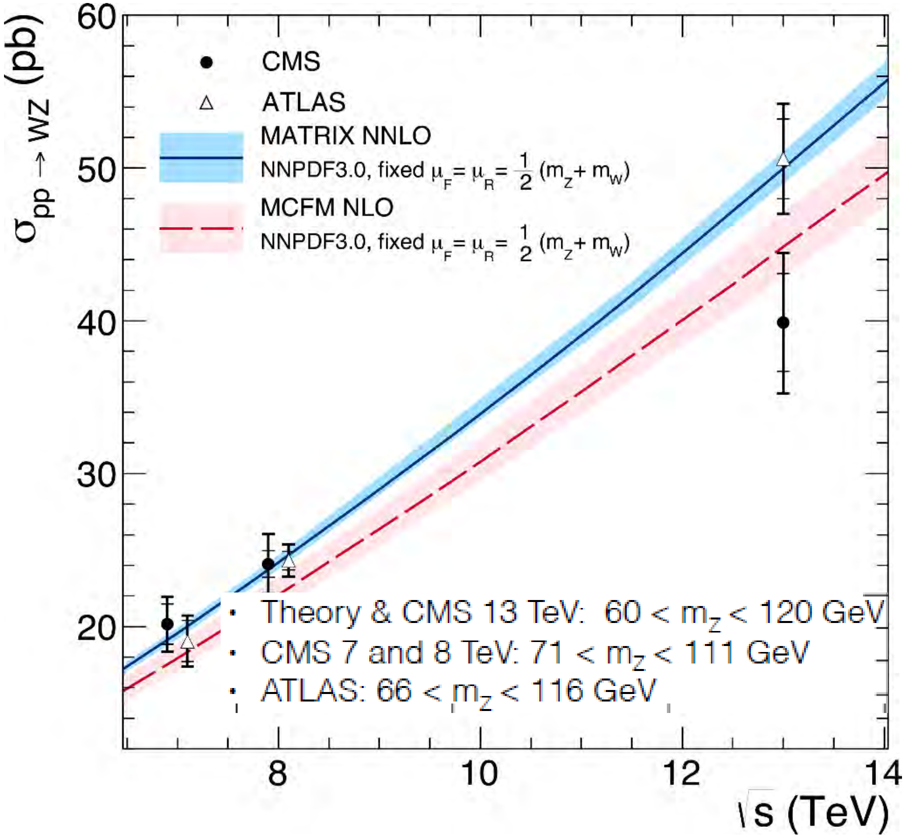
Table 11: The expected and observed 95% confidence intervals for the anomalous coupling parameters defined in the *no constraints* scenario, *LEP*, *HISZ* and *Equal Couplings* scenarios. The results are shown with $\Lambda = \infty$ and $\Lambda = 7$ TeV.

aTGC limits: hardly sensitive ob formfactor unitarization scale

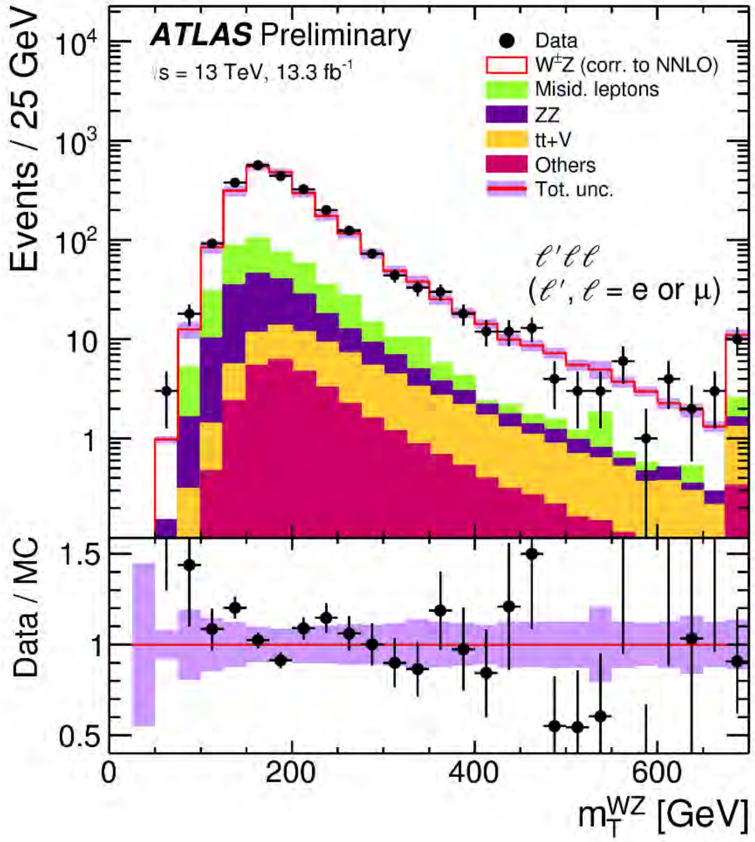
Charged (a)TGCs, 8+13 TeV $W^{\pm}Z$

- Fully leptionic 3l 1v final state: Clean, but small BR
  - Like for W^+W^-: NNLO needed, to describe the data
  - Dominant background depends on m_T (low: fake+ZZ, high: ttZ)

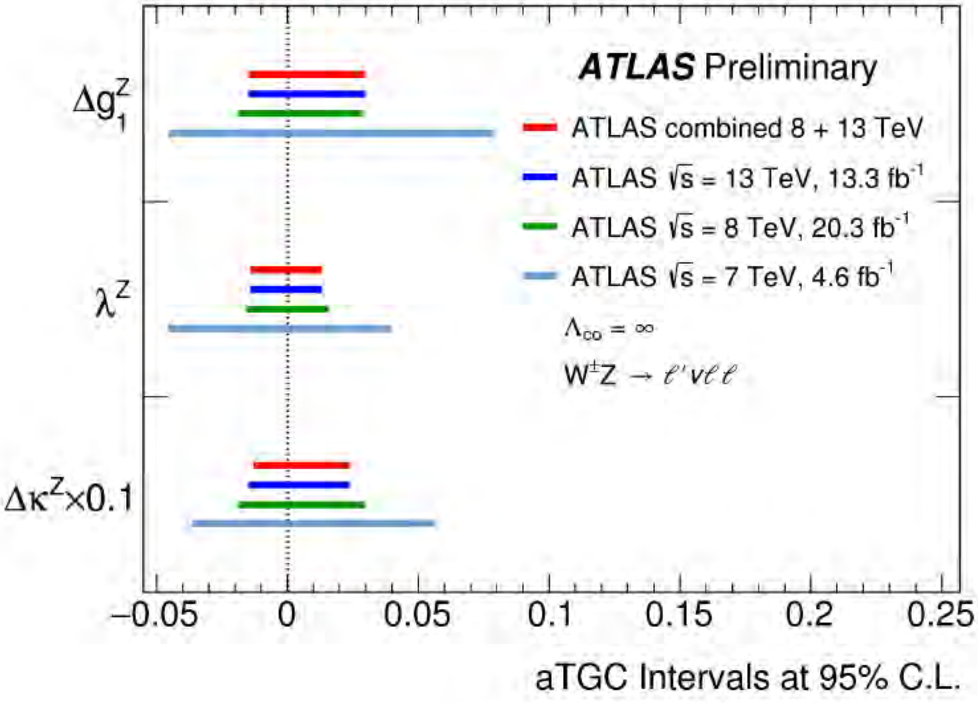
http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP-14-014



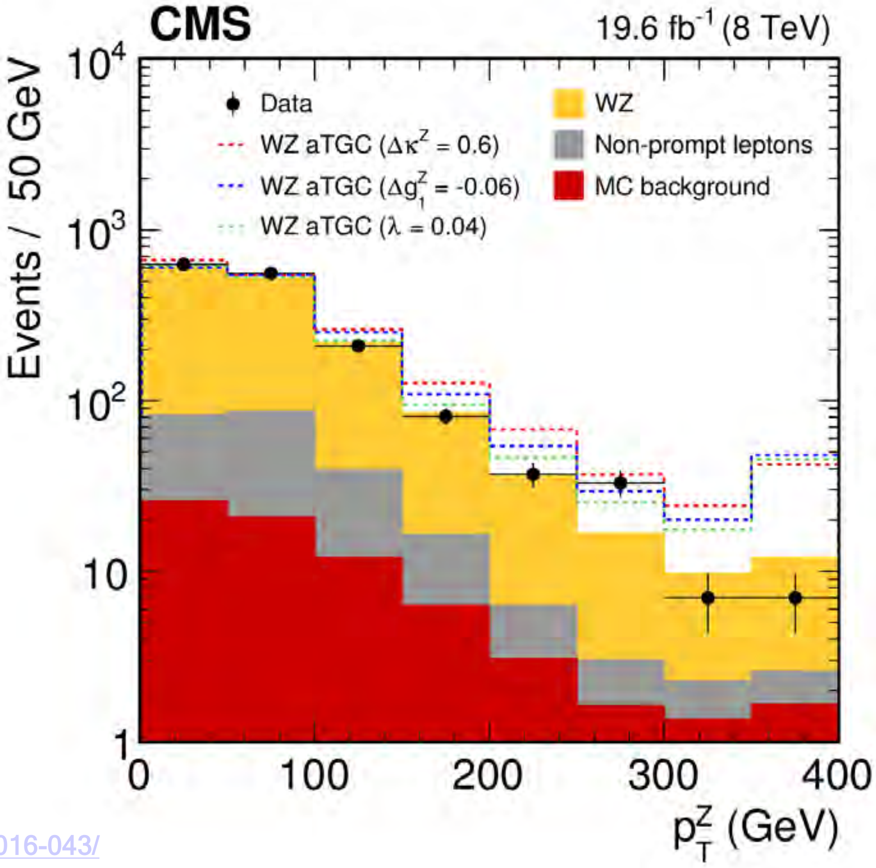
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-043/



❖ Similar aTGC limits from ATLAS and CMS



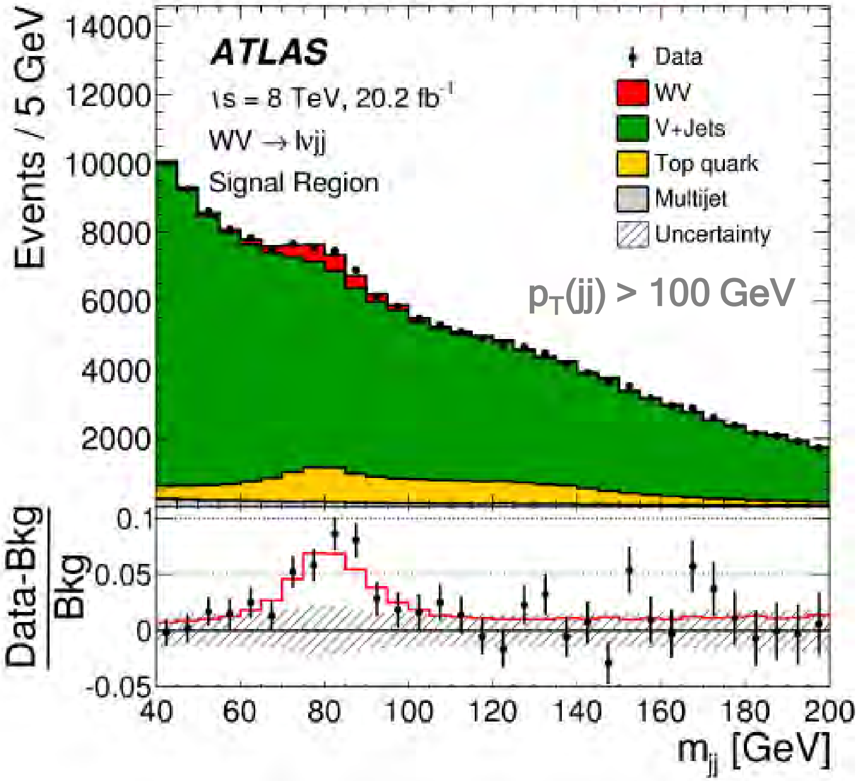
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-043/

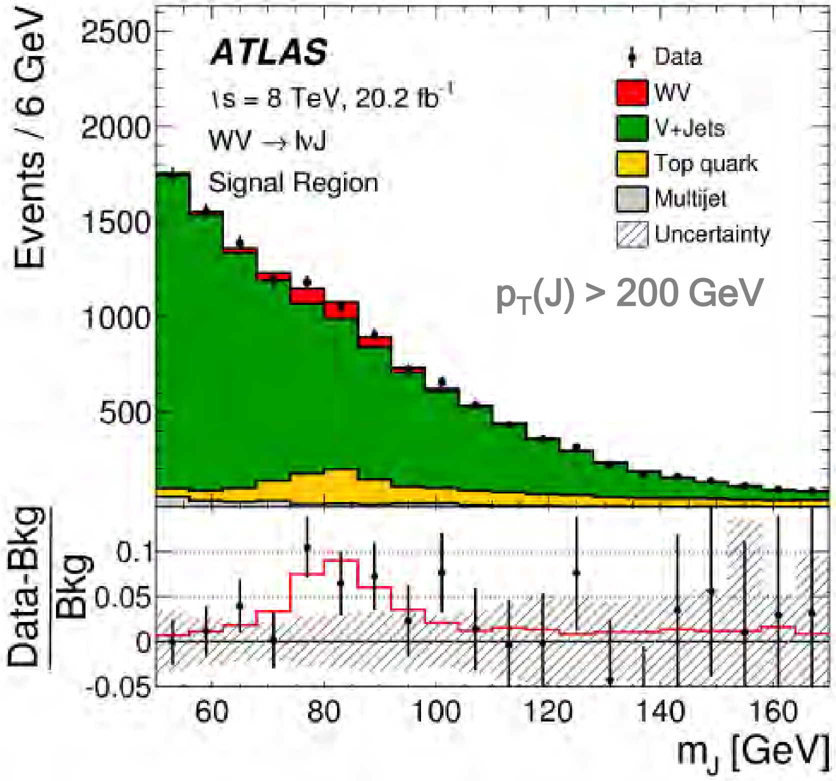


http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP-14-014

8 TeV **semileptonic** $W^{\pm}Z$

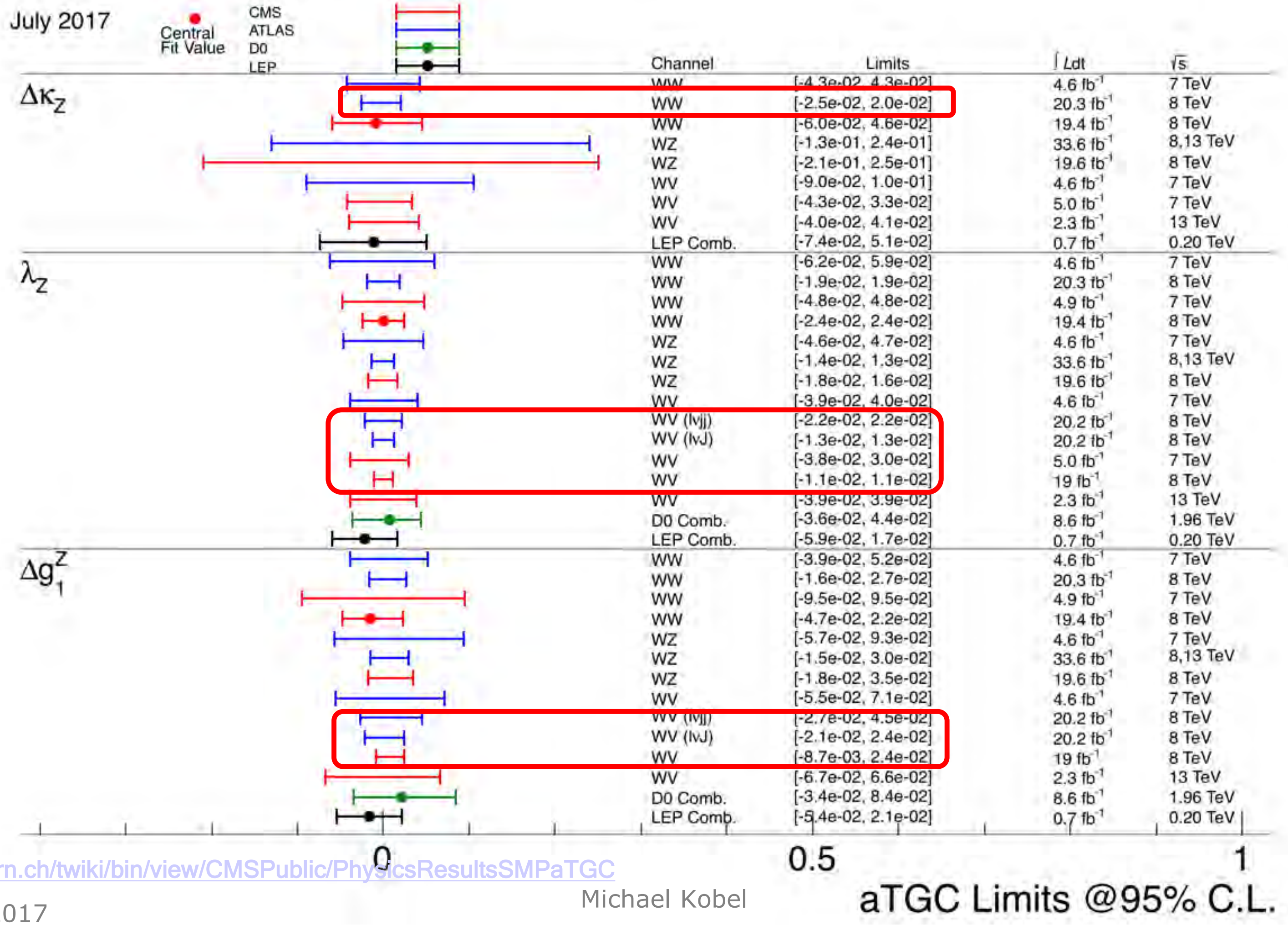
- Semi-leptonic (W or Z hadronic, resolved jj or fat jet J)
  - Huge background from V+Jets, but
  - 6 times larger BR and kinematics better reconstructed
  - Especially improved BSM sensitivity: **fat Jet J at large p_T tail** (for $p_T(J) > 600$ GeV signal increase ~x10 at 95% CL limit $\lambda=0.013$)





Current limits for aTGC for WWZ

- Several LHC channels have surpassed LEPcomb(~0.03-0.06)&TeVatron
  - WW best for $\Delta\kappa_Z$ (~0.02),
  - WZ & WV (esp→lvJ) best for $\Delta\lambda_Z$(~ 0.01) and Δg_1^Z(~ 0.02)

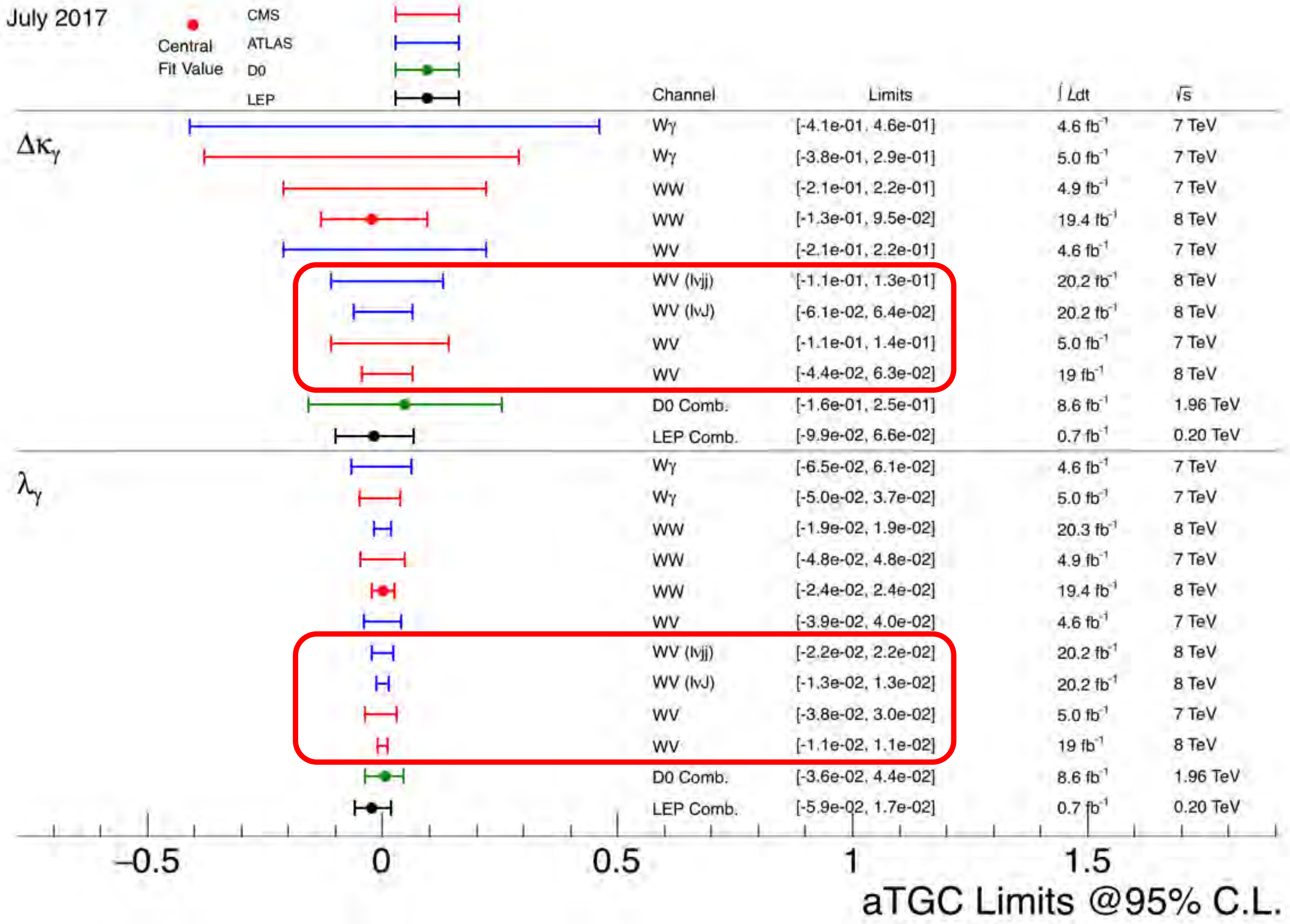


	Channel	Limits	∫ Ldt	√s
$\Delta\kappa_Z$	WW	[-4.3e-02, 4.3e-02]	4.6 fb^{-1}	7 TeV
	WW	[-2.5e-02, 2.0e-02]	20.3 fb^{-1}	8 TeV
	WW	[-6.0e-02, 4.6e-02]	19.4 fb^{-1}	8 TeV
	WZ	[-1.3e-01, 2.4e-01]	33.6 fb^{-1}	8,13 TeV
	WZ	[-2.1e-01, 2.5e-01]	19.6 fb^{-1}	8 TeV
	WV	[-9.0e-02, 1.0e-01]	4.6 fb^{-1}	7 TeV
	WV	[-4.3e-02, 3.3e-02]	5.0 fb^{-1}	7 TeV
	WV	[-4.0e-02, 4.1e-02]	2.3 fb^{-1}	13 TeV
	LEP Comb.	[-7.4e-02, 5.1e-02]	0.7 fb^{-1}	0.20 TeV
λ_Z	WW	[-6.2e-02, 5.9e-02]	4.6 fb^{-1}	7 TeV
	WW	[-1.9e-02, 1.9e-02]	20.3 fb^{-1}	8 TeV
	WW	[-4.8e-02, 4.8e-02]	4.9 fb^{-1}	7 TeV
	WW	[-2.4e-02, 2.4e-02]	19.4 fb^{-1}	8 TeV
	WZ	[-4.6e-02, 4.7e-02]	4.6 fb^{-1}	7 TeV
	WZ	[-1.4e-02, 1.3e-02]	33.6 fb^{-1}	8,13 TeV
	WZ	[-1.8e-02, 1.6e-02]	19.6 fb^{-1}	8 TeV
	WV	[-3.9e-02, 4.0e-02]	4.6 fb^{-1}	7 TeV
	WV (lvjj)	[-2.2e-02, 2.2e-02]	20.2 fb^{-1}	8 TeV
	WV (lvJ)	[-1.3e-02, 1.3e-02]	20.2 fb^{-1}	8 TeV
	WV	[-3.8e-02, 3.0e-02]	5.0 fb^{-1}	7 TeV
	WV	[-1.1e-02, 1.1e-02]	19 fb^{-1}	8 TeV
	WV	[-3.9e-02, 3.9e-02]	2.3 fb^{-1}	13 TeV
	D0 Comb.	[-3.6e-02, 4.4e-02]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-5.9e-02, 1.7e-02]	0.7 fb^{-1}	0.20 TeV
Δg_1^Z	WW	[-3.9e-02, 5.2e-02]	4.6 fb^{-1}	7 TeV
	WW	[-1.6e-02, 2.7e-02]	20.3 fb^{-1}	8 TeV
	WW	[-9.5e-02, 9.5e-02]	4.9 fb^{-1}	7 TeV
	WW	[-4.7e-02, 2.2e-02]	19.4 fb^{-1}	8 TeV
	WZ	[-5.7e-02, 9.3e-02]	4.6 fb^{-1}	7 TeV
	WZ	[-1.5e-02, 3.0e-02]	33.6 fb^{-1}	8,13 TeV
	WZ	[-1.8e-02, 3.5e-02]	19.6 fb^{-1}	8 TeV
	WV	[-5.5e-02, 7.1e-02]	4.6 fb^{-1}	7 TeV
	WV (lvjj)	[-2.7e-02, 4.5e-02]	20.2 fb^{-1}	8 TeV
	WV (lvJ)	[-2.1e-02, 2.4e-02]	20.2 fb^{-1}	8 TeV
	WV	[-8.7e-03, 2.4e-02]	19 fb^{-1}	8 TeV
	WV	[-6.7e-02, 6.6e-02]	2.3 fb^{-1}	13 TeV
	D0 Comb.	[-3.4e-02, 8.4e-02]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-5.4e-02, 2.1e-02]	0.7 fb^{-1}	0.20 TeV

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

Current 95% limits of aTGC for WWγ

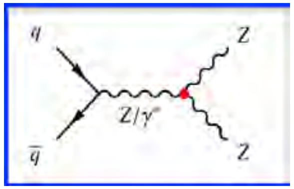
- for $\Delta\kappa_\gamma$ esp. WV at LHC (~0.05) has surpassed LEPcomb (~0.08)
- for $\Delta\lambda_\gamma$ most LHC channels surpass LEP(~0.04), e.g. WV@CMS:~ 0.01!

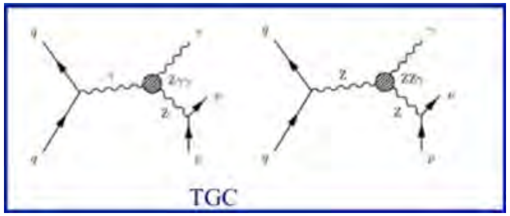


	Channel	Limits	$\int Ldt$	$\sqrt{s}$
$\Delta\kappa_\gamma$	Wγ	[-4.1e-01, 4.6e-01]	4.6 fb^{-1}	7 TeV
	Wγ	[-3.8e-01, 2.9e-01]	5.0 fb^{-1}	7 TeV
	WW	[-2.1e-01, 2.2e-01]	4.9 fb^{-1}	7 TeV
	WW	[-1.3e-01, 9.5e-02]	19.4 fb^{-1}	8 TeV
	WV	[-2.1e-01, 2.2e-01]	4.6 fb^{-1}	7 TeV
	WV (lνjj)	[-1.1e-01, 1.3e-01]	20.2 fb^{-1}	8 TeV
	WV (lνJ)	[-6.1e-02, 6.4e-02]	20.2 fb^{-1}	8 TeV
	WV	[-1.1e-01, 1.4e-01]	5.0 fb^{-1}	7 TeV
	WV	[-4.4e-02, 6.3e-02]	19 fb^{-1}	8 TeV
	D0 Comb.	[-1.6e-01, 2.5e-01]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-9.9e-02, 6.6e-02]	0.7 fb^{-1}	0.20 TeV
λ_γ	Wγ	[-6.5e-02, 6.1e-02]	4.6 fb^{-1}	7 TeV
	Wγ	[-5.0e-02, 3.7e-02]	5.0 fb^{-1}	7 TeV
	WW	[-1.9e-02, 1.9e-02]	20.3 fb^{-1}	8 TeV
	WW	[-4.8e-02, 4.8e-02]	4.9 fb^{-1}	7 TeV
	WW	[-2.4e-02, 2.4e-02]	19.4 fb^{-1}	8 TeV
	WV	[-3.9e-02, 4.0e-02]	4.6 fb^{-1}	7 TeV
	WV (lνjj)	[-2.2e-02, 2.2e-02]	20.2 fb^{-1}	8 TeV
	WV (lνJ)	[-1.3e-02, 1.3e-02]	20.2 fb^{-1}	8 TeV
	WV	[-3.8e-02, 3.0e-02]	5.0 fb^{-1}	7 TeV
	WV	[-1.1e-02, 1.1e-02]	19 fb^{-1}	8 TeV
	D0 Comb.	[-3.6e-02, 4.4e-02]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-5.9e-02, 1.7e-02]	0.7 fb^{-1}	0.20 TeV

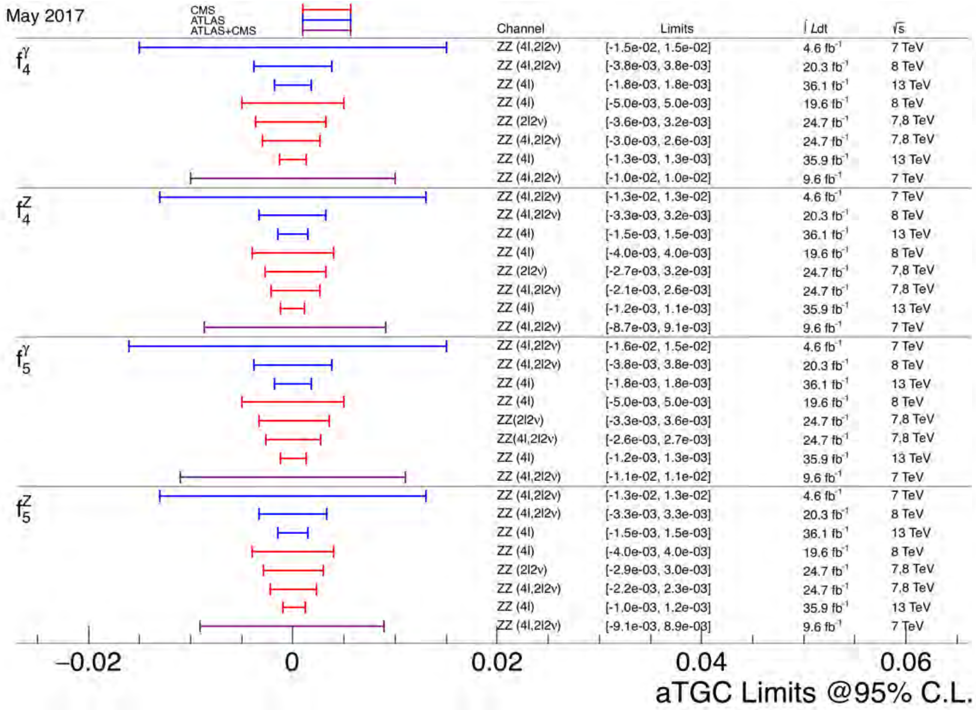
Current limits of neutral aTGC

- Zero in SM
  - ZZV (V=Z,γ): CP-viol f_4^V ($<10^{-3}$) CP-cons f_5^V ($<10^{-3}$)
  - ZγV (V=Z,γ): CP-viol $h_{1,2}^V$ () CP-cons $h_{3,4}^V$ ($<10^{-3}$, 3×10^{-6})
- Most sensitive due to high BR: Zγ → $\nu\nu\gamma$
- factors 10-100 better than at LEP!

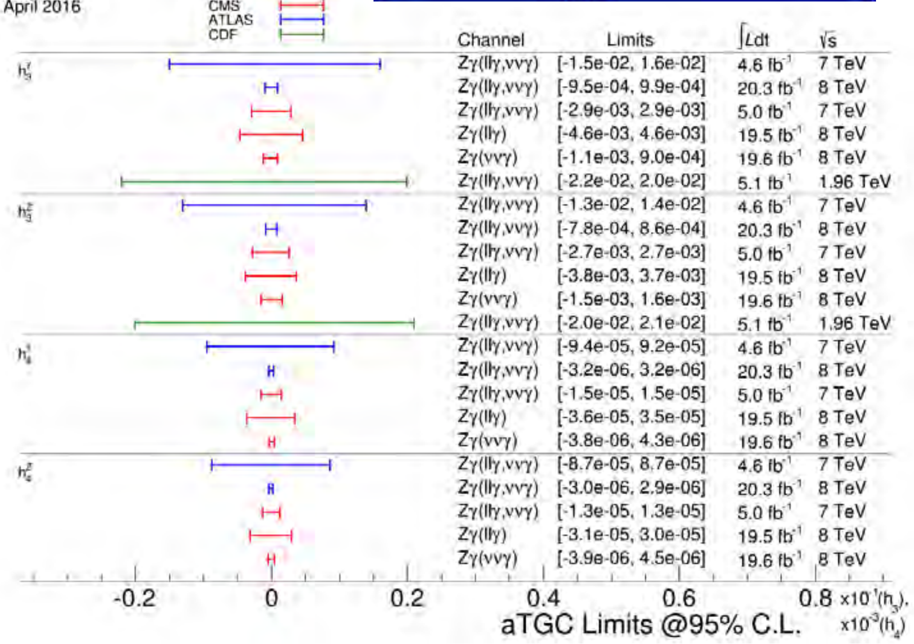




TGC



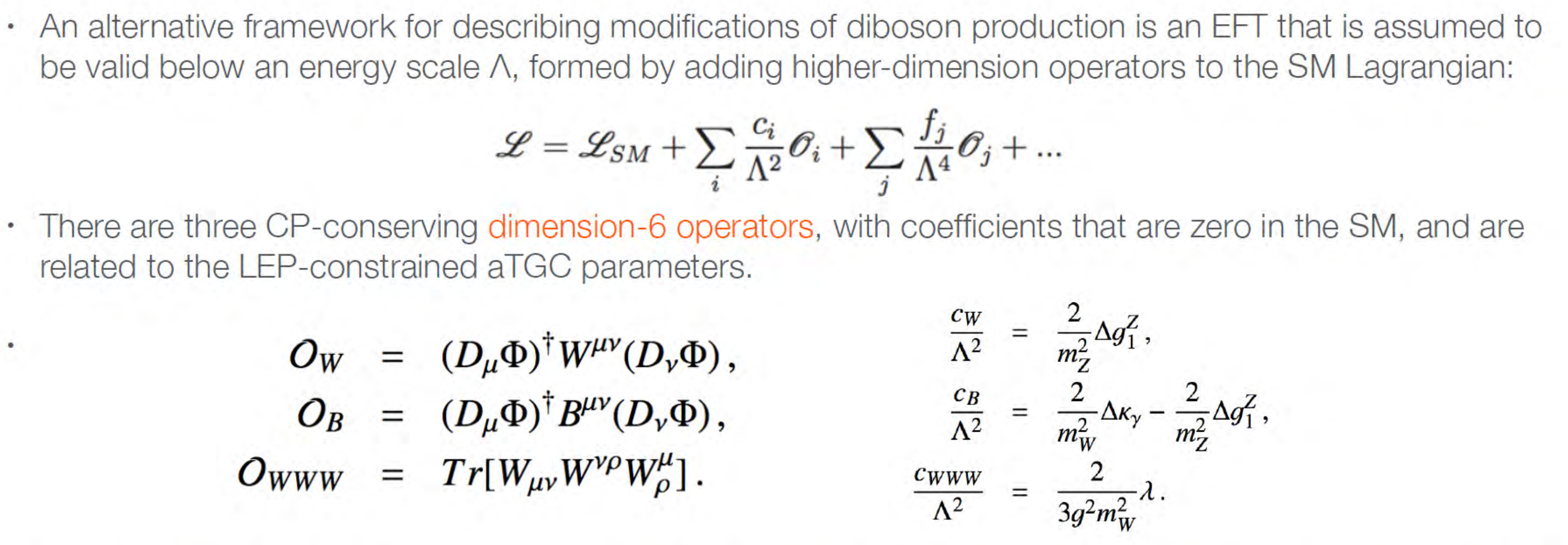
	Channel	Limits	$\int L dt$	$\sqrt{s}$
f_4^γ	ZZ (4l,2l2ν)	[-1.5e-02, 1.5e-02]	4.6 fb^{-1}	7 TeV
	ZZ (4l,2l2ν)	[-3.8e-03, 3.8e-03]	20.3 fb^{-1}	8 TeV
	ZZ (4l)	[-1.8e-03, 1.8e-03]	36.1 fb^{-1}	13 TeV
	ZZ (4l)	[-5.0e-03, 5.0e-03]	19.6 fb^{-1}	8 TeV
	ZZ (2l2ν)	[-3.6e-03, 3.2e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l,2l2ν)	[-3.0e-03, 2.6e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l)	[-1.3e-03, 1.3e-03]	35.9 fb^{-1}	13 TeV
	ZZ (4l,2l2ν)	[-1.0e-02, 1.0e-02]	9.6 fb^{-1}	7 TeV
f_4^Z	ZZ (4l,2l2ν)	[-1.3e-02, 1.3e-02]	4.6 fb^{-1}	7 TeV
	ZZ (4l,2l2ν)	[-3.3e-03, 3.2e-03]	20.3 fb^{-1}	8 TeV
	ZZ (4l)	[-1.5e-03, 1.5e-03]	36.1 fb^{-1}	13 TeV
	ZZ (4l)	[-4.0e-03, 4.0e-03]	19.6 fb^{-1}	8 TeV
	ZZ (2l2ν)	[-2.7e-03, 3.2e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l,2l2ν)	[-2.1e-03, 2.6e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l)	[-1.2e-03, 1.1e-03]	35.9 fb^{-1}	13 TeV
	ZZ (4l,2l2ν)	[-8.7e-03, 9.1e-03]	9.6 fb^{-1}	7 TeV
f_5^γ	ZZ (4l,2l2ν)	[-1.6e-02, 1.5e-02]	4.6 fb^{-1}	7 TeV
	ZZ (4l,2l2ν)	[-3.8e-03, 3.8e-03]	20.3 fb^{-1}	8 TeV
	ZZ (4l)	[-1.8e-03, 1.8e-03]	36.1 fb^{-1}	13 TeV
	ZZ (4l)	[-5.0e-03, 5.0e-03]	19.6 fb^{-1}	8 TeV
	ZZ(2l2ν)	[-3.3e-03, 3.6e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ(4l,2l2ν)	[-2.6e-03, 2.7e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l)	[-1.2e-03, 1.3e-03]	35.9 fb^{-1}	13 TeV
	ZZ (4l,2l2ν)	[-1.1e-02, 1.1e-02]	9.6 fb^{-1}	7 TeV
f_5^Z	ZZ (4l,2l2ν)	[-1.3e-02, 1.3e-02]	4.6 fb^{-1}	7 TeV
	ZZ (4l,2l2ν)	[-3.3e-03, 3.3e-03]	20.3 fb^{-1}	8 TeV
	ZZ (4l)	[-1.5e-03, 1.5e-03]	36.1 fb^{-1}	13 TeV
	ZZ (4l)	[-4.0e-03, 4.0e-03]	19.6 fb^{-1}	8 TeV
	ZZ (2l2ν)	[-2.9e-03, 3.0e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l,2l2ν)	[-2.2e-03, 2.3e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l)	[-1.0e-03, 1.2e-03]	35.9 fb^{-1}	13 TeV
	ZZ (4l,2l2ν)	[-9.1e-03, 8.9e-03]	9.6 fb^{-1}	7 TeV



	Channel	Limits	$\int L dt$	$\sqrt{s}$
h_3^γ	Zγ(llγ,$\nu\nu\gamma$)	[-1.5e-02, 1.6e-02]	4.6 fb^{-1}	7 TeV
	Zγ(llγ,$\nu\nu\gamma$)	[-9.5e-04, 9.9e-04]	20.3 fb^{-1}	8 TeV
	Zγ(llγ,$\nu\nu\gamma$)	[-2.9e-03, 2.9e-03]	5.0 fb^{-1}	7 TeV
	Zγ(llγ)	[-4.6e-03, 4.6e-03]	19.5 fb^{-1}	8 TeV
	Zγ($\nu\nu\gamma$)	[-1.1e-03, 9.0e-04]	19.6 fb^{-1}	8 TeV
	Zγ(llγ,$\nu\nu\gamma$)	[-2.2e-02, 2.0e-02]	5.1 fb^{-1}	1.96 TeV
h_3^Z	Zγ(llγ,$\nu\nu\gamma$)	[-1.3e-02, 1.4e-02]	4.6 fb^{-1}	7 TeV
	Zγ(llγ,$\nu\nu\gamma$)	[-7.8e-04, 8.6e-04]	20.3 fb^{-1}	8 TeV
	Zγ(llγ,$\nu\nu\gamma$)	[-2.7e-03, 2.7e-03]	5.0 fb^{-1}	7 TeV
	Zγ(llγ)	[-3.8e-03, 3.7e-03]	19.5 fb^{-1}	8 TeV
	Zγ($\nu\nu\gamma$)	[-1.5e-03, 1.6e-03]	19.6 fb^{-1}	8 TeV
	Zγ(llγ,$\nu\nu\gamma$)	[-2.0e-02, 2.1e-02]	5.1 fb^{-1}	1.96 TeV
h_4^γ	Zγ(llγ,$\nu\nu\gamma$)	[-9.4e-05, 9.2e-05]	4.6 fb^{-1}	7 TeV
	Zγ(llγ,$\nu\nu\gamma$)	[-3.2e-06, 3.2e-06]	20.3 fb^{-1}	8 TeV
	Zγ(llγ,$\nu\nu\gamma$)	[-1.5e-05, 1.5e-05]	5.0 fb^{-1}	7 TeV
	Zγ(llγ)	[-3.6e-05, 3.5e-05]	19.5 fb^{-1}	8 TeV
	Zγ($\nu\nu\gamma$)	[-3.8e-06, 4.3e-06]	19.6 fb^{-1}	8 TeV
h_4^Z	Zγ(llγ,$\nu\nu\gamma$)	[-8.7e-05, 8.7e-05]	4.6 fb^{-1}	7 TeV
	Zγ(llγ,$\nu\nu\gamma$)	[-3.0e-06, 2.9e-06]	20.3 fb^{-1}	8 TeV
	Zγ(llγ,$\nu\nu\gamma$)	[-1.3e-05, 1.3e-05]	5.0 fb^{-1}	7 TeV
	Zγ(llγ)	[-3.1e-05, 3.0e-05]	19.5 fb^{-1}	8 TeV
	Zγ($\nu\nu\gamma$)	[-3.9e-06, 4.5e-06]	19.6 fb^{-1}	8 TeV

Future: EFT approach

- Since LHC results have now surpassed LEP/TeVatron, the LHC aTGC Taskforce recommends to move towards to EFT dimension-6 EFT operators



- An alternative framework for describing modifications of diboson production is an EFT that is assumed to be valid below an energy scale Λ, formed by adding higher-dimension operators to the SM Lagrangian:

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathscr{O}_i + \sum_j \frac{f_j}{\Lambda^4}\mathscr{O}_j + \ldots$$

- There are three CP-conserving dimension-6 operators, with coefficients that are zero in the SM, and are related to the LEP-constrained aTGC parameters.

-

$$\begin{aligned} O_W &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)\,, \\ O_B &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)\,, \\ O_{WWW} &= Tr[W_{\mu\nu}W^{\nu\rho}W^\mu_\rho]\,. \end{aligned}$$

$$\begin{aligned} \frac{c_W}{\Lambda^2} &= \frac{2}{m_Z^2}\Delta g_1^Z\,, \\ \frac{c_B}{\Lambda^2} &= \frac{2}{m_W^2}\Delta\kappa_\gamma - \frac{2}{m_Z^2}\Delta g_1^Z\,, \\ \frac{c_{WWW}}{\Lambda^2} &= \frac{2}{3g^2m_W^2}\lambda\,. \end{aligned}$$

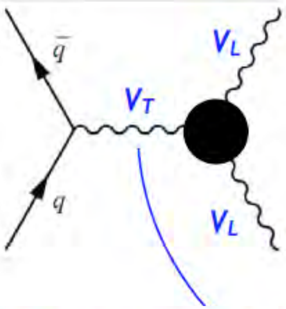
© Claire Lee: MBI workshop Karlsruhe 2017:
https://indico.cern.ch/event/625573/timetable/?view=standard

Future of Diboson TGC

- Talk of Alex Pomarol at MBI 2017 in Karlsruhe
  - *longitudinal* components are essential

For the case for **qq→** $V_L V_L$:

TGC:



$$\sim g^2 \frac{E^2}{\Lambda^2} \ll 1$$

Accuracy is needed to probe it!

But cross-sections dominated by the **transverse** components:

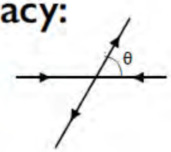
qq̄→WZ:

	σ_{tot}	σ_{LL}	σ_{LL}/σ_{tot}
8 TeV	12 pb	0.73 pb	6%
13 TeV	25 pb	1.5 pb	

its a background for the longitudinals!

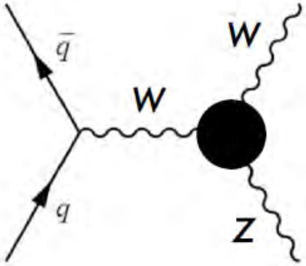
WZ production give the only chance to get accuracy:

- **Symmetries force $W_T Z_T$ go to zero for θ→90°**
- **Small background in their leptonic decays**



http://mbi2017.particle.kit.edu/

Franceschini,Panico,AP,Riva,
Wulzer, in preparation



$$\frac{\delta\mathcal{M}_{00}}{\mathcal{M}_{00}^{\rm SM}} = 1 - \frac{\hat{s}}{m_Z^2}\,\delta g_1^Z$$

Shift of the SM **WWZ-coupling**

Franceschini,Panico,AP,Riva,Wulzer

http://mbi2017.particle.kit.edu/

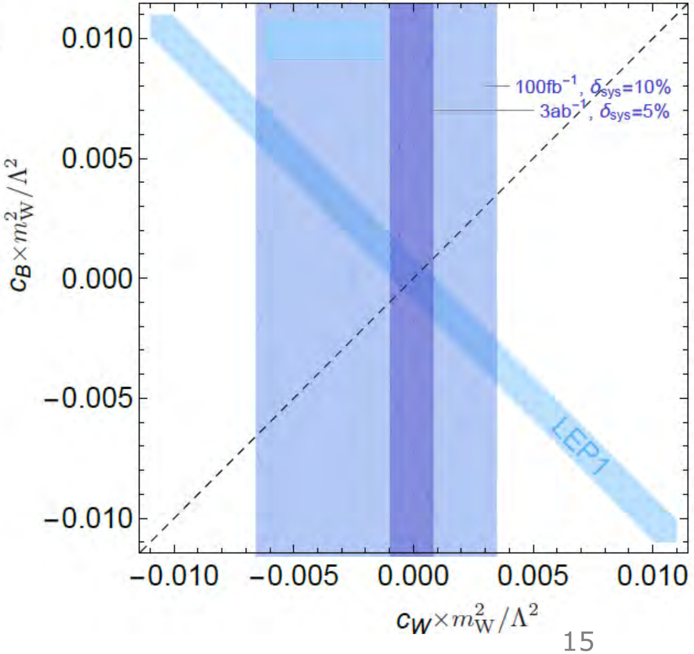
It size similar to the **S-parameter** bound at **LEP** at the per-mille:

$$\boxed{-g^2 c_{\theta_W}^2\,\delta g_1^Z \simeq \frac{g^2}{2}\hat{S}} \qquad \widehat{S} = (c_W + c_B)\frac{m_W^2}{\Lambda^2}$$

To test $\delta g_1^Z \sim 3\times10^{-3}$ ☛ **We must be able to see a 10 % deviation of WZ-production** at m_{WZ} >300 GeV ($\cos\theta<0.5$)

$$\begin{aligned}\frac{c_W}{\Lambda^2} &= \frac{2}{m_Z^2}\Delta g_1^Z\,,\\ \frac{c_B}{\Lambda^2} &= \frac{2}{m_W^2}\Delta\kappa_\gamma - \frac{2}{m_Z^2}\Delta g_1^Z\,,\\ \frac{c_{WWW}}{\Lambda^2} &= \frac{2}{3g^2 m_W^2}\lambda\,.\end{aligned}$$

LHC vs LEP (Composite Higgs)



VECTOR BOSON SCATTERING

ATLAS, CMS	$\gamma\gamma \rightarrow W^+W^-$
ATLAS, CMS	$W^\pm W^\pm \rightarrow W^\pm W^\pm$
ATLAS	$W^\pm Z/\gamma \rightarrow W^\pm Z$
ATLAS	$W^\pm V \rightarrow W^\pm V$
ATLAS; CMS	$W^+W^- \rightarrow Z\gamma$
CMS	$W^\pm V \rightarrow W^\pm\gamma$
CMS	$W^+W^- \rightarrow ZZ$

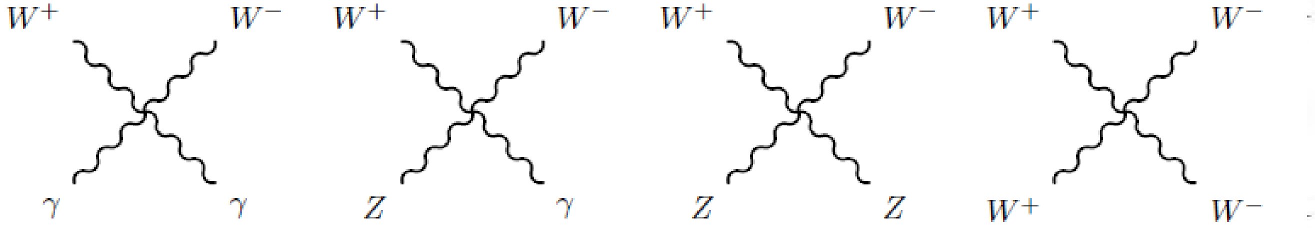
Yet Missing

$V\ V \rightarrow W^+W^-$ ($\bar{t}t$ background)

$V=W,Z$

What can we learn from **QGC?**

- Standard model:
  - $\mathcal{L}_{WWVV}$ contains the quartic gauge self-couplings (QGC)



$$\mathcal{L}_{WWVV} = -\frac{g^2}{4}\Big\{[2W_\mu^+W^{-\mu} + (A_\mu \sin\theta_W - Z_\mu \cos\theta_W)^2]^2 - [W_\mu^+W_\nu^- + W_\nu^+W_\mu^- + (A_\mu \sin\theta_W - Z_\mu \cos\theta_W)(A_\nu \sin\theta_W - Z_\nu \cos\theta_W)]^2\Big\}$$

  - no neutral self-couplings in the SM

- **1. Observe the SM QGC Processes with these vertices**
  - Pre-LHC: attempted for γγWW and γZWW, but not „really“ successful
- **2. Constrain anomalous Quartic Gauge Couplings (aQGC)**
  - Pre-LHC: loose limits by LEP and Tevatron for γγWW and γZWW
- **3. Test Eweak Symmetry breaking and Higgs properties**
  - Access through ZZWW and WWWW at large $\sqrt{\hat{s}} = M_{VV}$ >~ 1 TeV
  - **One of the core reasons, why LHC has been built!**

2. Beyond the SM: aQGC

- **Assume SM is effective theory of a more complex one**, as e.g.
  - Low-E Fermi-Theorie with 4f Vertex → Weak Gauge Bosons in SU(2)
  - Low-E Chiral QCD langrangian → Composite qq condensate, hadrons

- **Consider effective electroweak Langrangian**

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{\text{dimension } d} \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

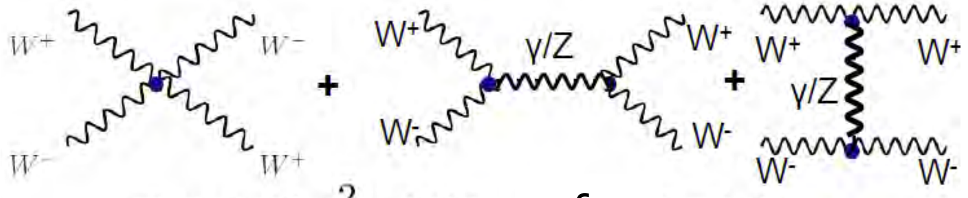
  - valid only, if new physics beyond kinematic reach ($\Lambda \gg \sqrt{\hat{s}}$)
  - model independent, complementary to direct searches
  - generally requires additional unitarization (re-introducing model dependence)

- **Relevant parameters for aQGC contributions**
  - Some d=8 parameters can be mapped to those for d=6 and d=4

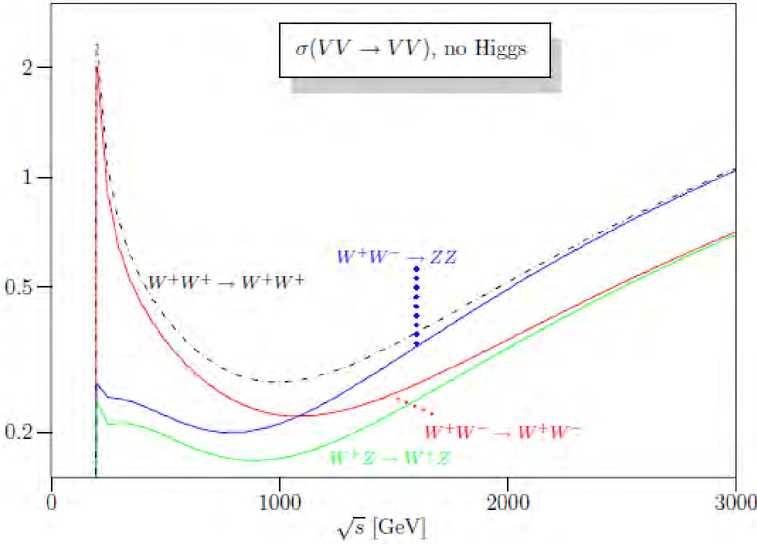
d=4	d=6	d=8
WWWW, WWZZ	WWZγ, WW$\gamma\gamma$	all VVVV
Chiral Lagrangian non-linear representation		Effective Operators linear representation
α_4 , α_5	a_0/Λ^2 , a_C/Λ^2	$f_{S,i}/\Lambda^4$, $f_{M,i}/\Lambda^4$, $f_{T,i}/\Lambda^4$
Appelquist et al. (1980)	Belanger et al. (1992)	Eboli et al. (2006)

3. Special Role of the Higgs Boson

- VBS Without Higgs contribution:

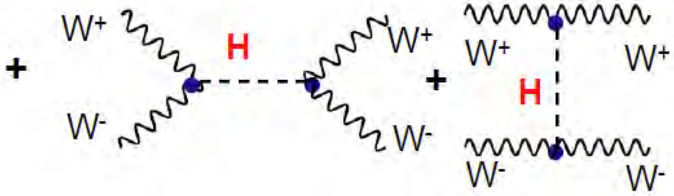


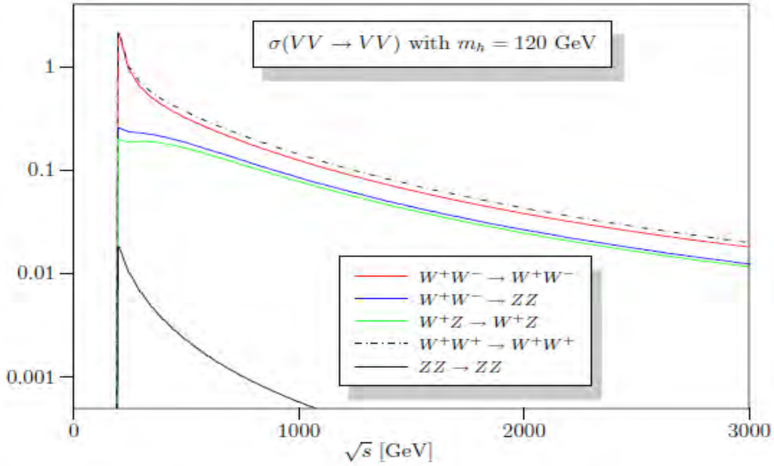
$$\sigma_{WW} \propto s^2 \to \infty \quad \text{for } s \to \infty$$



  - Violates „unitarity"(probability>1) at ~2 TeV

- Higgs contribution (or new physics, or both) needed





  - Higgs exactly cancels increase for large s

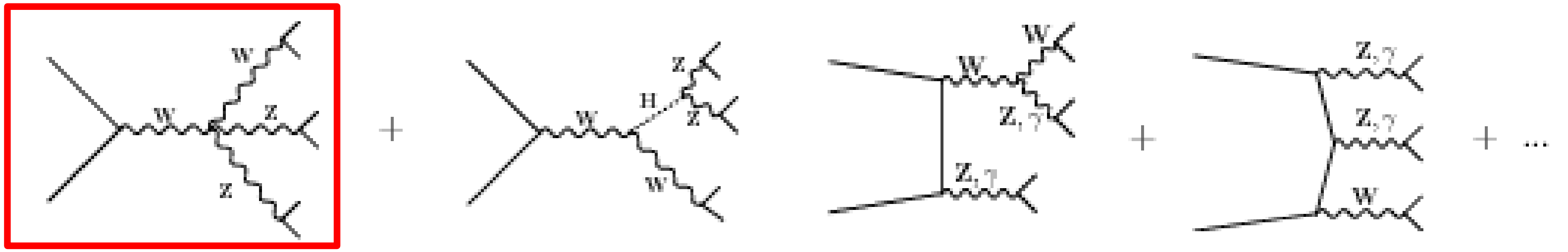
$$A(W_L W_L \to W_L W_L) \propto \frac{g_W^2}{v^2}\left(-s-t+\frac{s^2}{s-m_H^2}+\frac{t^2}{t-m_H^2}\right)$$

but *only* for SM H-WW coupling!

A. Alboteanu, W. Kilian, J. Reuter: http://arxiv.org/abs/0806.4145v1

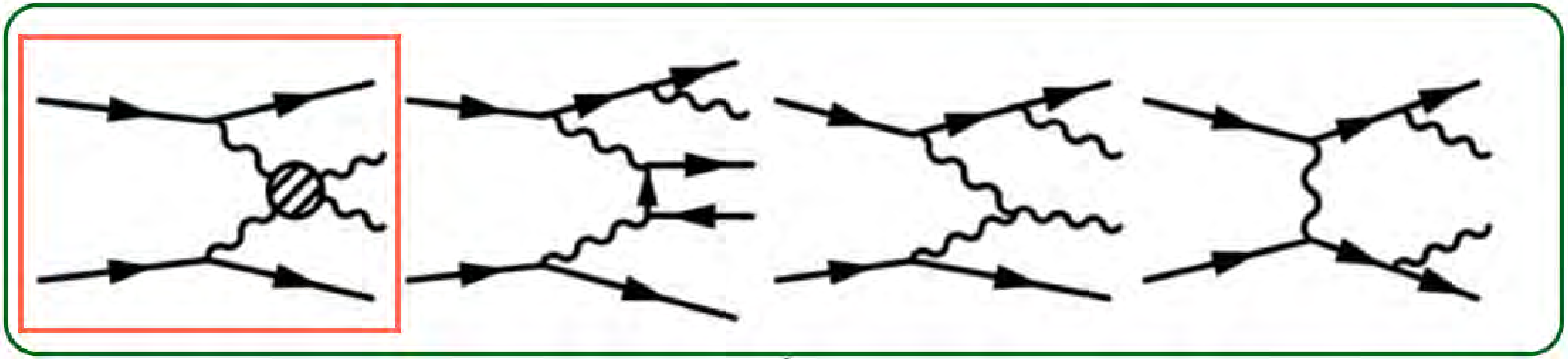
Quartic-Gauge-Couplings (QGC)

- **QGC Process** := Process, where a QGC vertex *contributes*
  - No reaction is ever mediated by a QGC Vertex alone
  - Even a gauge-invariant definition of the QGC contribution is not possible!
- Two classes of QGC processes are measurable (example diagrams)
  - **Triple Boson production, VVV**



QGC H-mediated TGC Fermion-mediated

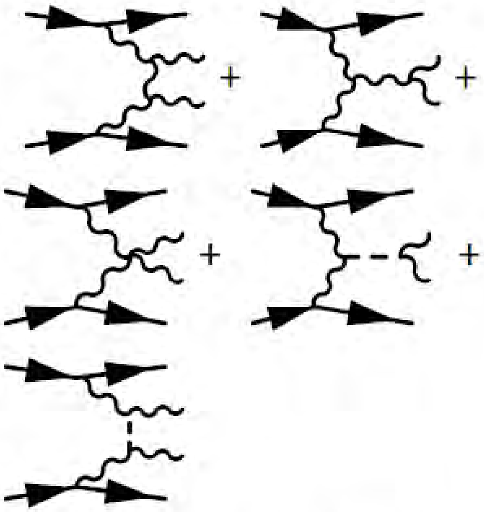
  - **Vector Boson Scattering (VBS), as VVjj or exclusive VV(pp)**



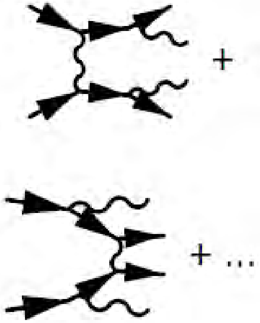
QGC+ H-mediated+ TGC virtual TGC Fermion-mediated

Event classification

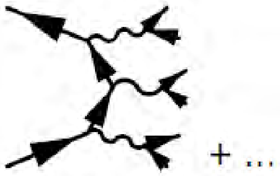
- VVjj-EW
  (V=W,Z)



VV scattering diagrams
(including triple and quartic gauge vertices, Higgs channels



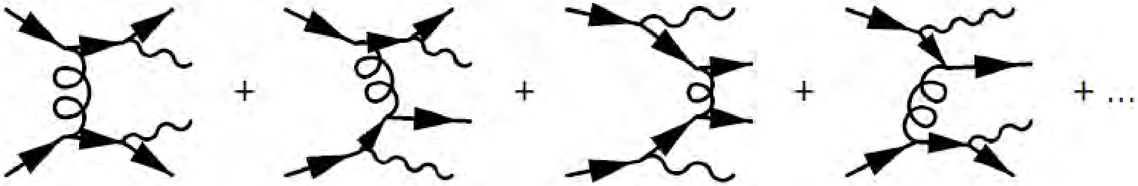
non-VBS EW diagrams
(not gauge invariantly separable)



VVV diagrams
(same $\mathcal{O}(EW)$, but can be gauge invariantly separated and suppressed by VBS topology cuts)

- VVjj-QCD

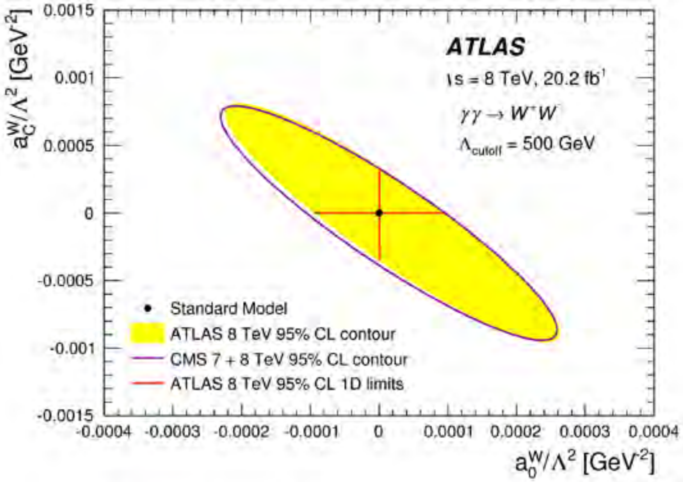
VVjj-QCD diagrams: $\mathcal{O}(EW) = 4 \oplus \mathcal{O}(QCD) = 2$

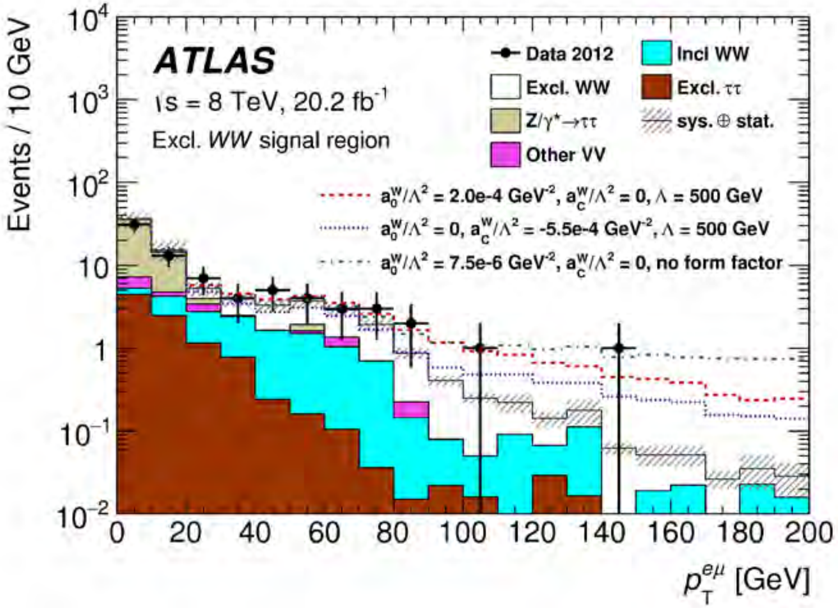


- Same final state, some kinematic suppression possible

Limit on aQGC from excl. $\gamma\gamma \rightarrow W^+W^-$

- ATLAS, 8 TeV https://arxiv.org/pdf/1607.03745.pdf
  - Measured(expected): σxBR: 6.4±2.2±1.4 fb (4.4±0.3 fb), 3 s.d.
  - 1D and 2D limits on a^W_0/Λ^2 and a^W_C/Λ^2 using form factor unitar. Λ_{FF} = 500 GeV





  - w/o unitarization: ~80 times better (!), but dominated by $\sqrt{\hat{s}}$ above unitarity
- Improved un-unitarized limits:
  - ÷2500 w.r.t. D0, ÷10.000 w.r.t. LEP

Comparison of New Physics scales Λ for a^W = 1

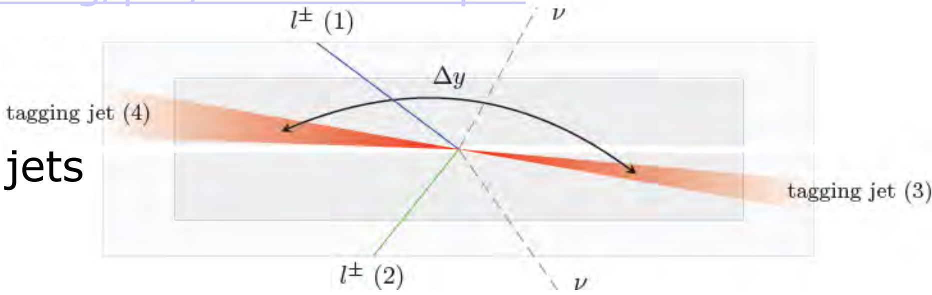
Λ (Λ_{FF})	LEP(0)	D0(500)	ATLAS / CMS(500)	ATLAS CMS(0)
a^W_0/Λ^2	7 GeV	20 GeV	105 GeV	950 GeV
a^W_C/Λ^2	5 GeV	10 GeV	55 GeV	500 GeV

- Unitarized limits
  - ÷25 improved w.r.t. D0 (i.e. factor 5 in scale Λ)
  - Still rather weak

VVjj via Vector Boson Scattering

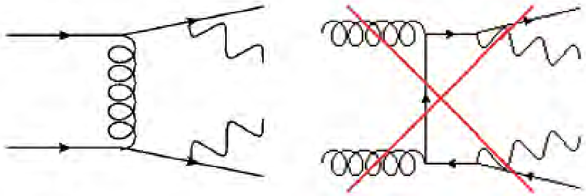
❖ First massive VV→VV analysis at LHC: W±W± → W±W±

- ATLAS, 8 TeV, 20.3 fb^{-1}, https://arxiv.org/pdf/1405.6241.pdf
- Distinct qq → VVjj topology:
  - tagging Jets with large Δy
  - leptons from VV → ℓν ℓν between jets

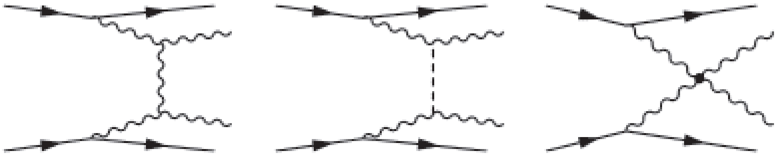


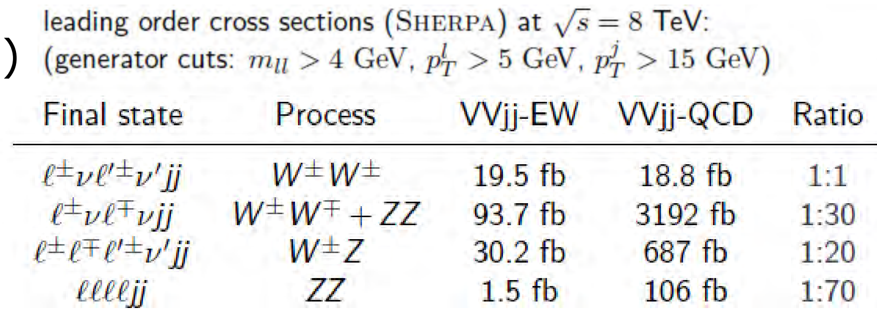
❖ VVjj has two process classes:

- W±W±jj-QCD:= $\mathcal{O}(\alpha_s^2 \times \alpha_W^4)$
  - Lowest order is pp→ W±W±+ **2j**,
  - no gg initial state (special for W±W±) → low background



- W±W±jj-EW:= $\mathcal{O}(\alpha_W^6)$
  - contains VBS part (t-channel +QGC)
  - interf(QCD-EW)~10% included



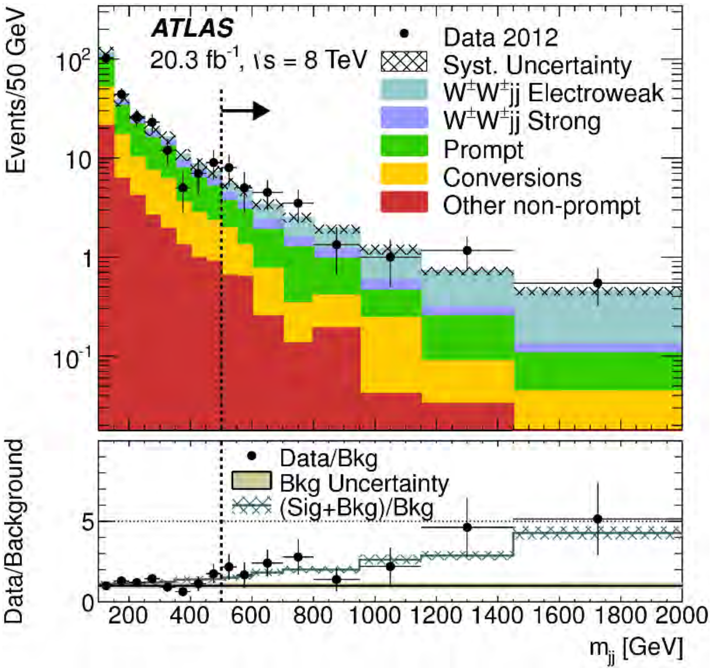


leading order cross sections (SHERPA) at $\sqrt{s} = 8$ TeV:
(generator cuts: $m_{ll} > 4$ GeV, $p_T^l > 5$ GeV, $p_T^j > 15$ GeV)

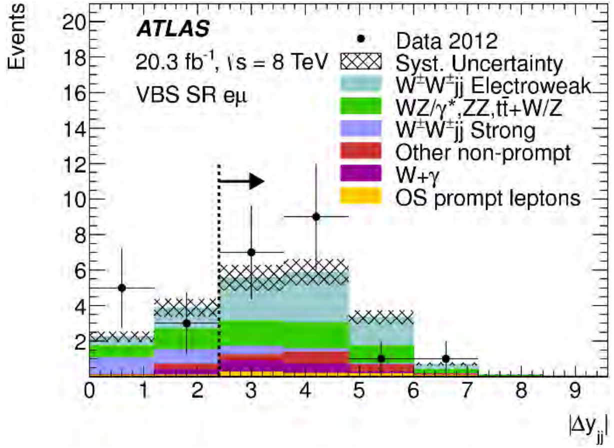
Final state	Process	VVjj-EW	VVjj-QCD	Ratio
$\ell^\pm\nu\ell'^\pm\nu' jj$	$W^\pm W^\pm$	19.5 fb	18.8 fb	1:1
$\ell^\pm\nu\ell^\mp\nu jj$	$W^\pm W^\mp + ZZ$	93.7 fb	3192 fb	1:30
$\ell^\pm\ell^\mp\ell'^\pm\nu' jj$	$W^\pm Z$	30.2 fb	687 fb	1:20
$\ell\ell\ell\ell jj$	ZZ	1.5 fb	106 fb	1:70

Result: Kinematics and x-section

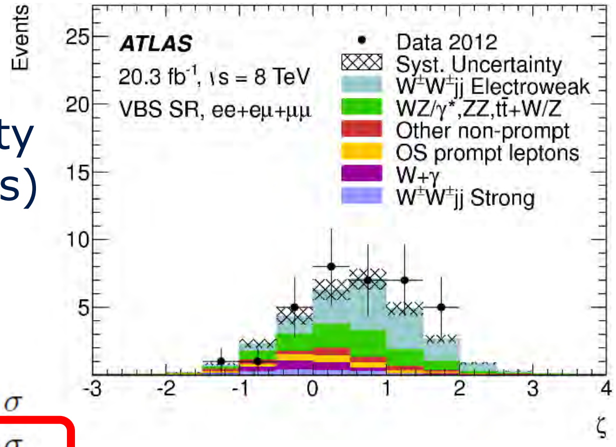
- Inclusive region: m_{jj} before cut



- VBS region: Δy_{jj} before cut



- VBS region: lepton centrality (>0: betw. Jets)



- Cross-section from event counting

inclusive region (EW+QCD)	$\sigma_{\text{fid}} = 2.1 \pm 0.5(\text{stat}) \pm 0.3(\text{syst})$ fb	4.5 σ
VBS signal region (EW)	$\sigma_{\text{fid}} = 1.3 \pm 0.4(\text{stat}) \pm 0.2(\text{syst})$ fb	3.6 σ

theory prediction (PowhegBox + Pythia8):

inclusive region (EW+QCD)	$\sigma_{\text{SM}} = 1.52 \pm 0.11$ fb	3.4 σ
VBS signal region (EW)	$\sigma_{\text{SM}} = 0.95 \pm 0.06$ fb	2.8 σ

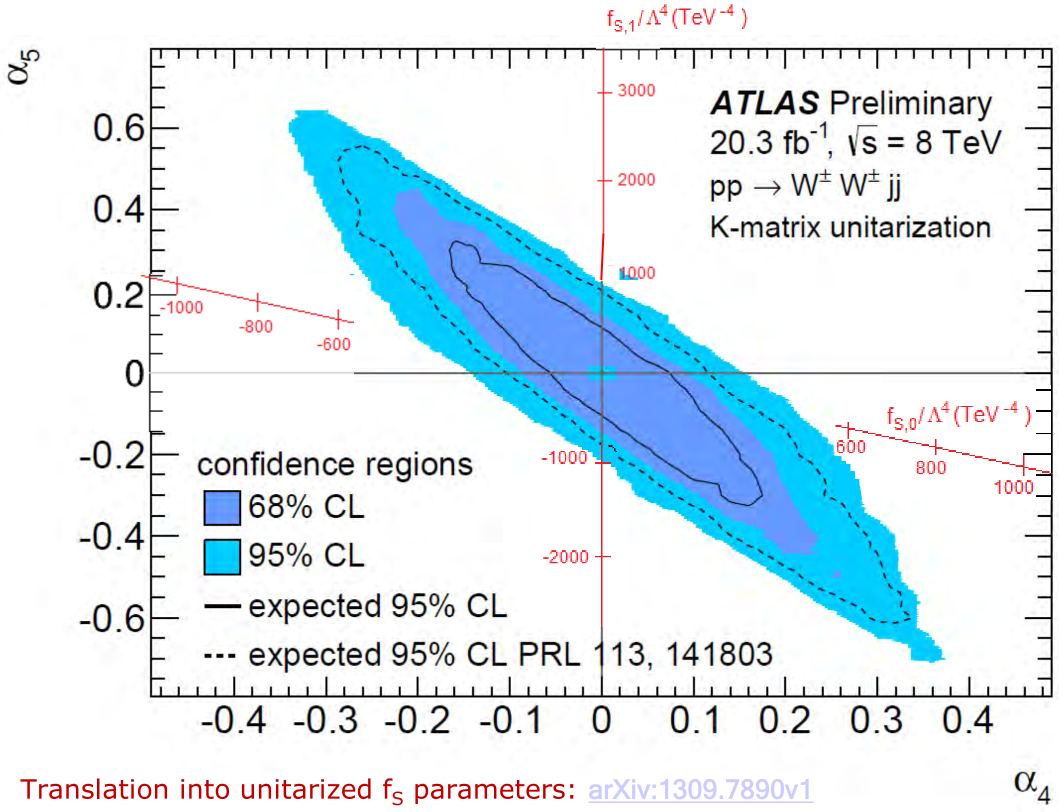
- **$W^\pm W^\pm$ → $W^\pm W^\pm$ was first evidence of electroweak VBS VV→VV**

ICHEP 2016: Improved Limits

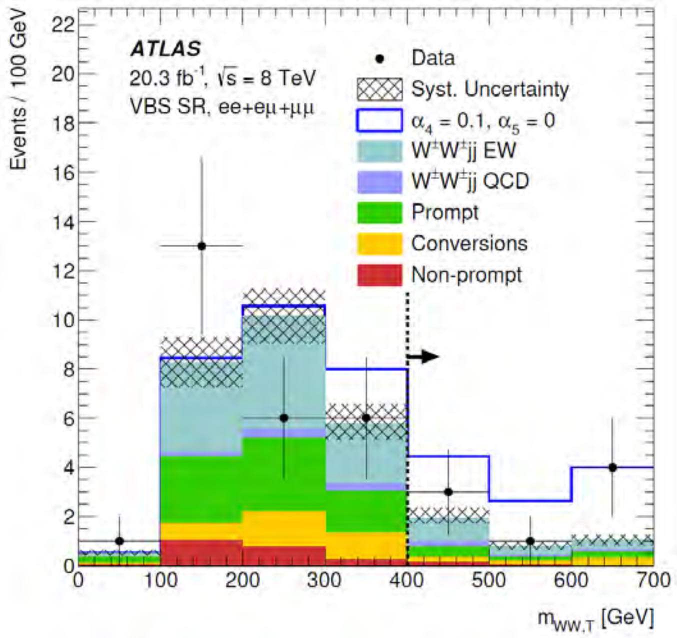
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2014-05/

- Improvement in sensitivity
  - PRL 2014: Extracted from **cross-section**
  - PRD 2017: **high $m_{WW,T}$ phase space**
    evts: SM VBS(EW): 1.7 evt, Bckg: 2.1, Data:8

$$m_{WW,T} = \sqrt{\left(\mathbf{P}_{\ell_1} + \mathbf{P}_{\ell_2} + \mathbf{P}_{E_T^{\text{miss}}}\right)^2}$$



Translation into unitarized f_S parameters: arXiv:1309.7890v1

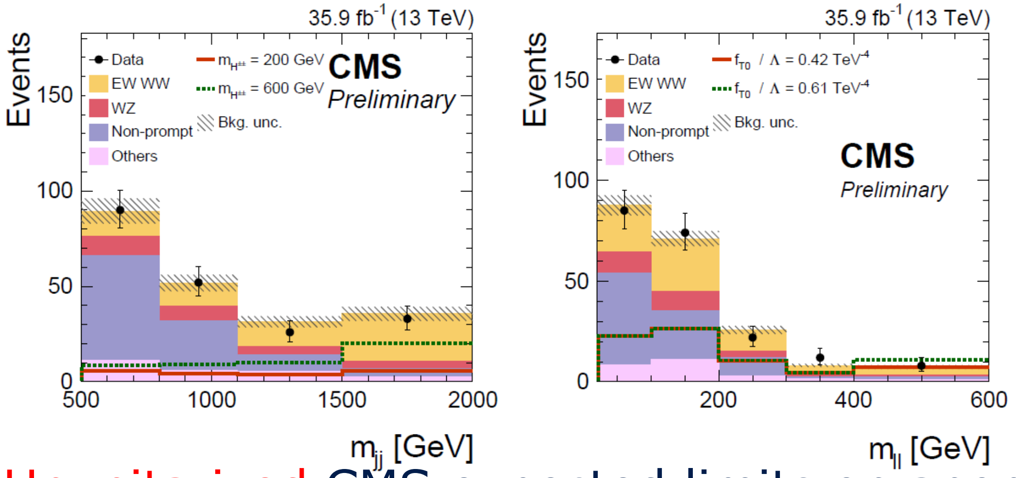


- 1-d limits expected
  - $-0.06 < \alpha_4 < 0.07$
    $-0.10 < \alpha_5 < 0.11$
- **1-d limits observed**
  - **$-0.14 < \alpha_4 < 0.15$**
    $-0.22 < \alpha_5 < 0.22$
  - With $\Lambda \sim v/\sqrt{\alpha}$
    (arxiv 1307.8170)

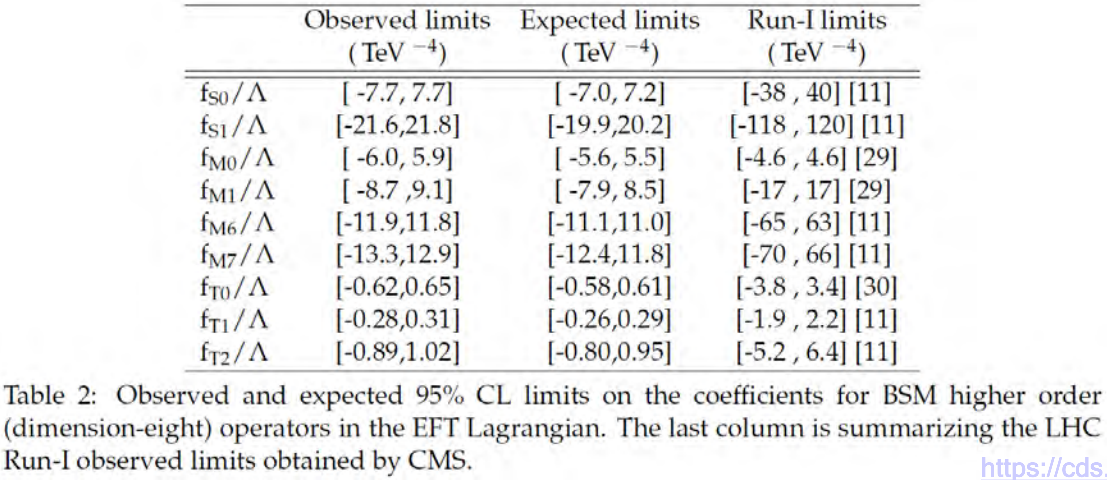
    $\Lambda > 500 - 650$ GeV

First *observation* of W±W±→ W±W±

- CMS: run II, expected sensitivity: 5.7 s.d., observed: 5.5 s.d



- Ununitarized CMS expected limits on anomalous QGC couplings:
  - ~30x(run II) ~5x (run I) better than $f_{S0,1}$ ATLAS K-Matrix (run I)



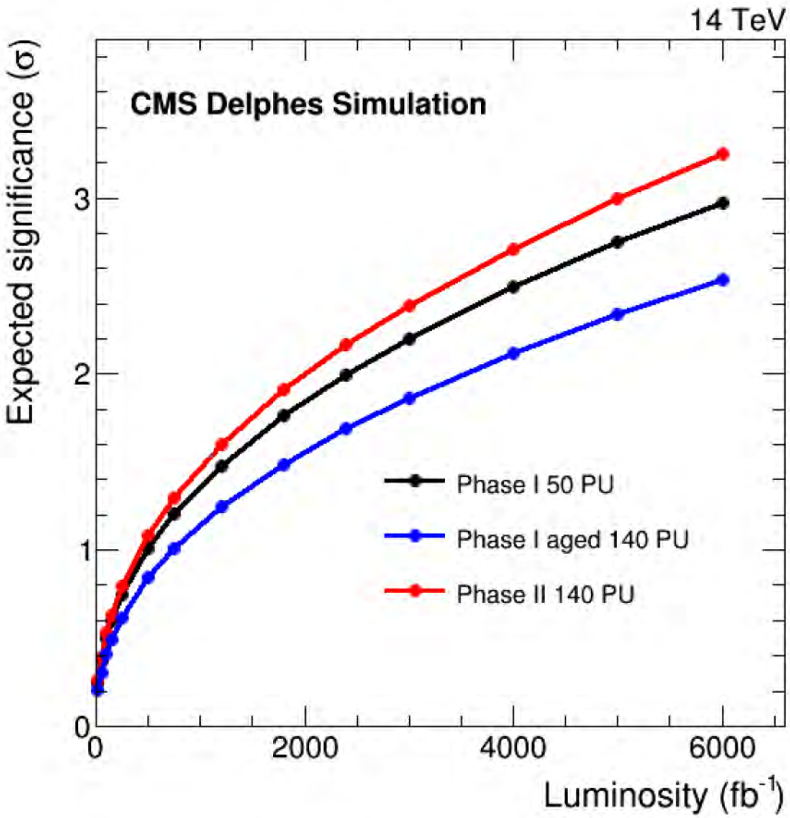
	Observed limits (TeV $^{-4}$)	Expected limits (TeV $^{-4}$)	Run-I limits (TeV $^{-4}$)
f_{S0}/Λ	[-7.7, 7.7]	[-7.0, 7.2]	[-38 , 40] [11]
f_{S1}/Λ	[-21.6,21.8]	[-19.9,20.2]	[-118 , 120] [11]
f_{M0}/Λ	[-6.0, 5.9]	[-5.6, 5.5]	[-4.6 , 4.6] [29]
f_{M1}/Λ	[-8.7 ,9.1]	[-7.9, 8.5]	[-17 , 17] [29]
f_{M6}/Λ	[-11.9,11.8]	[-11.1,11.0]	[-65 , 63] [11]
f_{M7}/Λ	[-13.3,12.9]	[-12.4,11.8]	[-70 , 66] [11]
f_{T0}/Λ	[-0.62,0.65]	[-0.58,0.61]	[-3.8 , 3.4] [30]
f_{T1}/Λ	[-0.28,0.31]	[-0.26,0.29]	[-1.9 , 2.2] [11]
f_{T2}/Λ	[-0.89,1.02]	[-0.80,0.95]	[-5.2 , 6.4] [11]

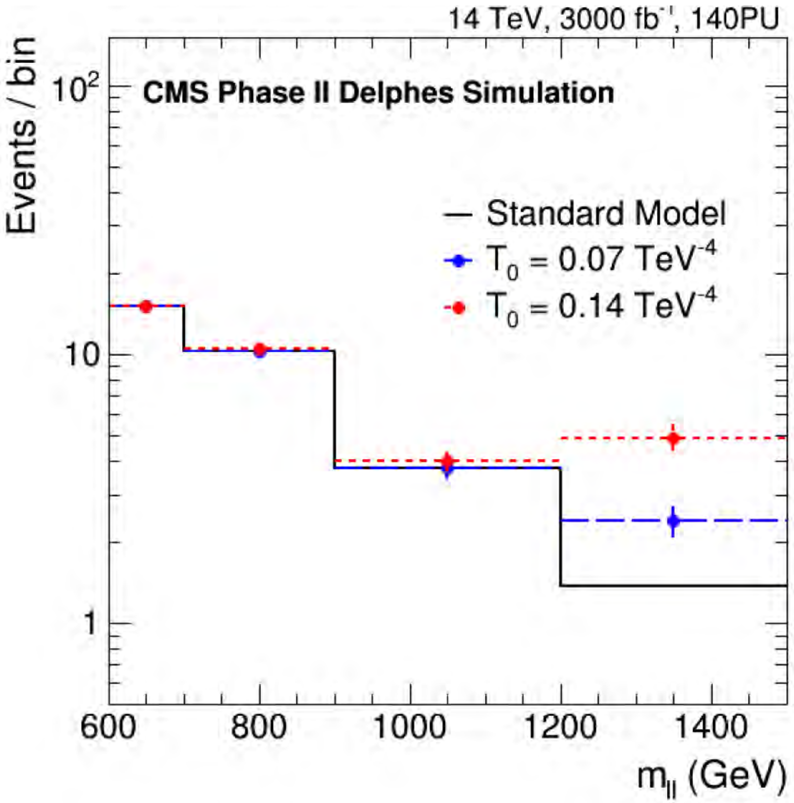
Table 2: Observed and expected 95% CL limits on the coefficients for BSM higher order (dimension-eight) operators in the EFT Lagrangian. The last column is summarizing the LHC Run-I observed limits obtained by CMS.

https://cds.cern.ch/record/2264525/files/SMP-17-004-pas.pdf

Future, example

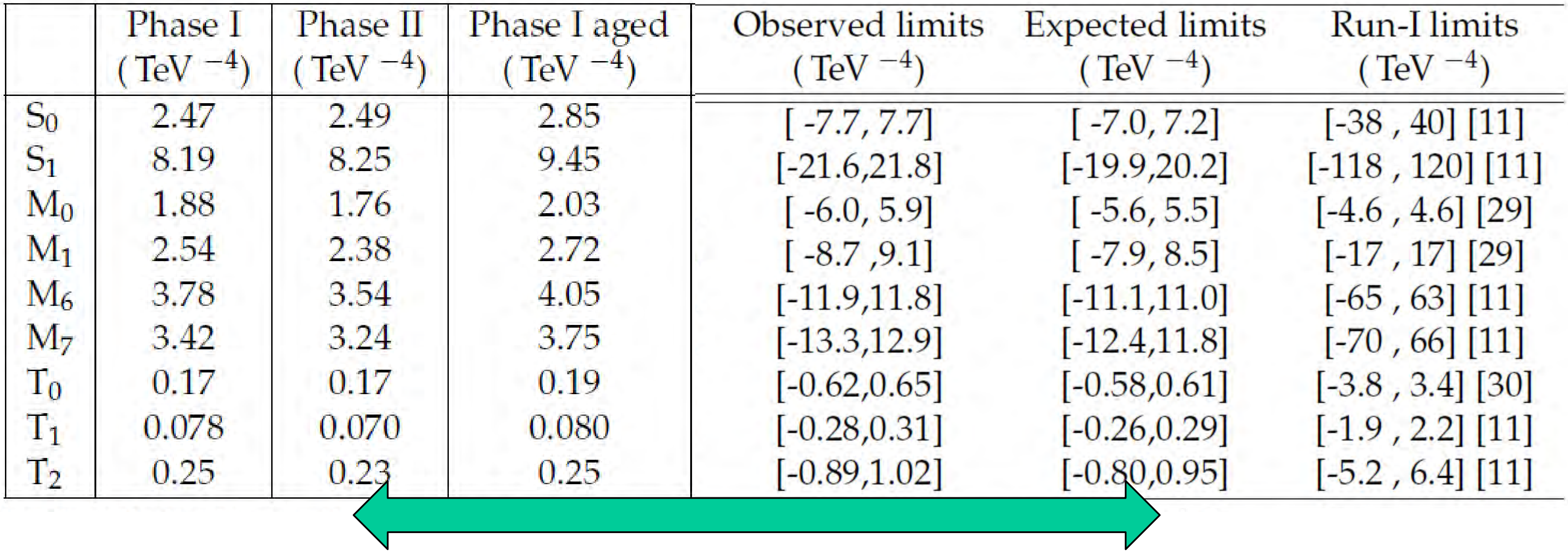
- *Prospects for VBS in same sign WW/WZ with High Luminosity LHC* CMS-PAS-SMP-14-008: https://cds.cern.ch/record/2220831





- Expected significance of measuring the **longitudinal** WW VBS cross section as a function of integrated luminosity

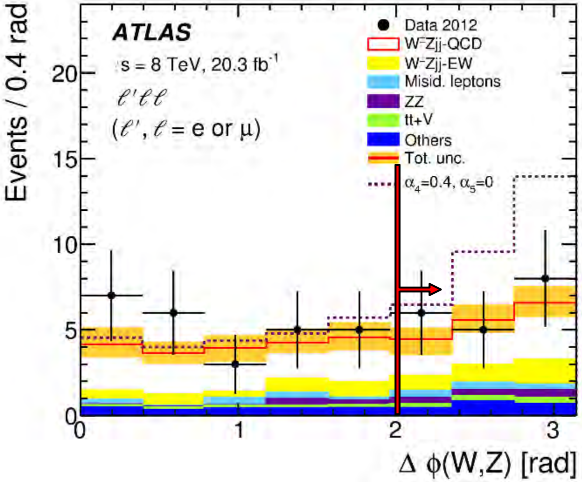
- *Prospects for VBS in same sign WW/WZ with High Luminosity LHC* CMS-PAS-SMP-14-008: https://cds.cern.ch/record/2220831
  - Expected limits for HL-LHC for 3ab^{-1} of data on dim-8 operators obtained from the dilepton mass distribution in same sign WW
  - HL-LHC run II ssWW run I (ssWW et al)

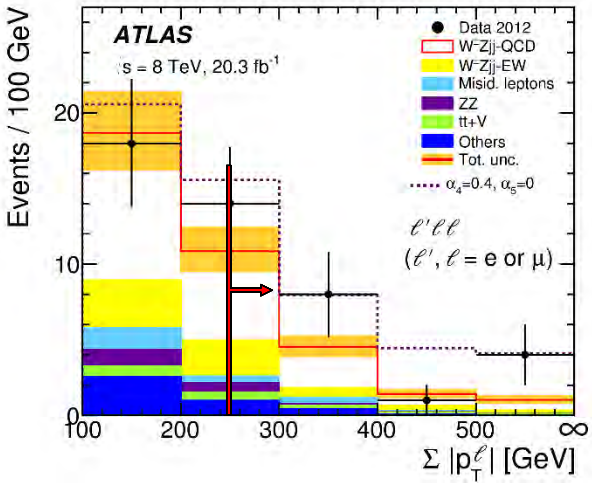


	Phase I (TeV $^{-4}$)	Phase II (TeV $^{-4}$)	Phase I aged (TeV $^{-4}$)	Observed limits (TeV $^{-4}$)	Expected limits (TeV $^{-4}$)	Run-I limits (TeV $^{-4}$)
S_0	2.47	2.49	2.85	[-7.7, 7.7]	[-7.0, 7.2]	[-38 , 40] [11]
S_1	8.19	8.25	9.45	[-21.6,21.8]	[-19.9,20.2]	[-118 , 120] [11]
M_0	1.88	1.76	2.03	[-6.0, 5.9]	[-5.6, 5.5]	[-4.6 , 4.6] [29]
M_1	2.54	2.38	2.72	[-8.7 ,9.1]	[-7.9, 8.5]	[-17 , 17] [29]
M_6	3.78	3.54	4.05	[-11.9,11.8]	[-11.1,11.0]	[-65 , 63] [11]
M_7	3.42	3.24	3.75	[-13.3,12.9]	[-12.4,11.8]	[-70 , 66] [11]
T_0	0.17	0.17	0.19	[-0.62,0.65]	[-0.58,0.61]	[-3.8 , 3.4] [30]
T_1	0.078	0.070	0.080	[-0.28,0.31]	[-0.26,0.29]	[-1.9 , 2.2] [11]
T_2	0.25	0.23	0.25	[-0.89,1.02]	[-0.80,0.95]	[-5.2 , 6.4] [11]

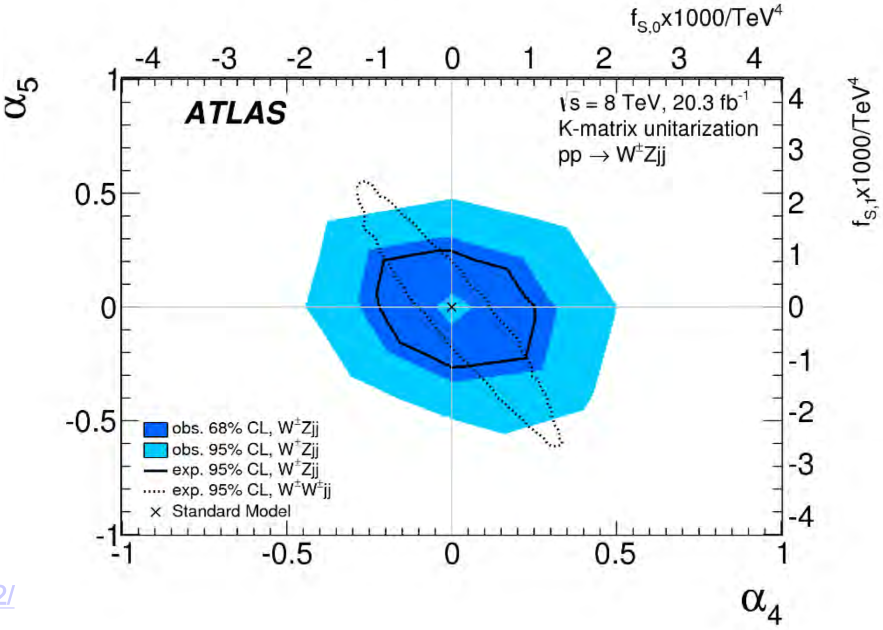
  - Only Factor ~ 3-4 improvement predicted @3ab^{-1} compared to run-II !?

First Search for WZ/γ → WZ





- Limits of aQGC
  - Yellow: SM WZjj-EW
  - dotted: aQGC $\alpha_4 = 0.4$
  - Two add. Cuts
    - $\Delta\phi(WZ)$
    - Sum p_T
  - Reduce by factor ~ 7 both SM WZjj-EW and backg.
  - Enhance aQGC effect



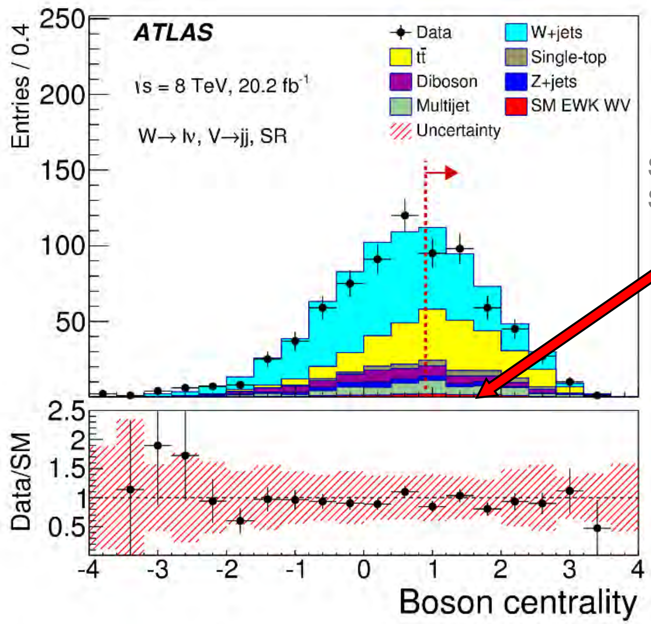
- Expected limits (K-Matrix unit.) improve upon $W^{\pm}W^{\pm}jj$-EW in some regions
  - Easy to translate in $f_{S0,1}$

$$\frac{f_{S,0(1)}}{\Lambda^4} = \alpha_{4(5)} \times \frac{16}{v^4}$$

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2014-02/

VBS WV+jj in semileptonic channel

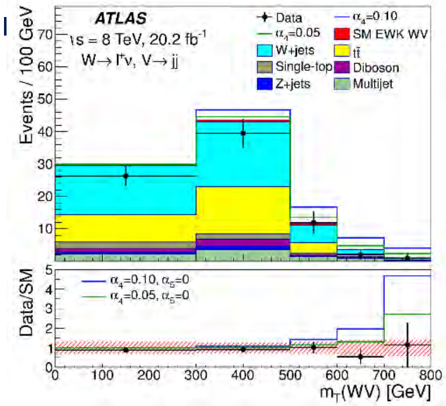
- ATLAS http://arxiv.org/abs/1609.05122
  - Can reconstruct boson kinematics
  - Background falls as you move to higher pTs, -> ideal for aQGC measurements
  - Signal from osWW, ssWW, WZ prevents translation between aQGC params

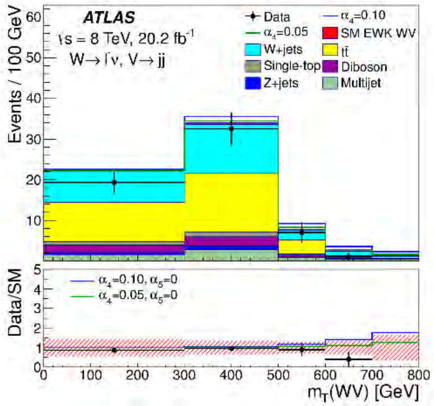


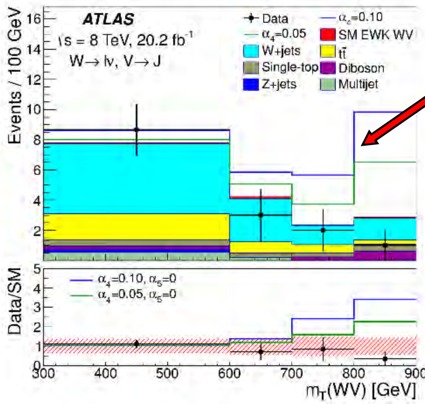
SM VBS Signal

- Tends to suffer from higher background : SM VBS hard to see

- Two main selection channels
  - **Resolved V → jj** **Merged V->J**







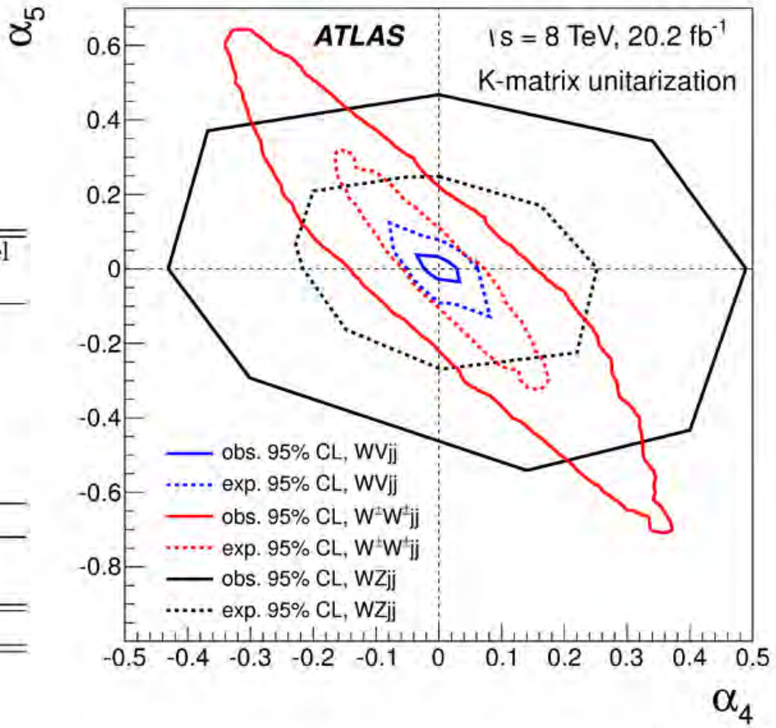
aQGC Effect

aQGC limits

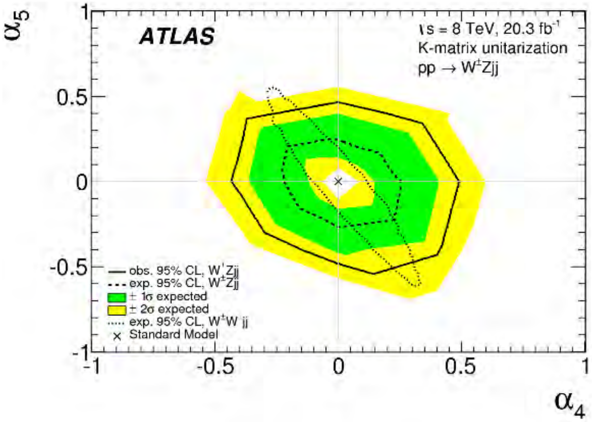
- Best sensitivity of all channels
  - Obs: Λ > 1500 GeV with $\Lambda \sim v/\sqrt{\alpha}$

$$-0.024 < \alpha_4 < 0.030 \text{ and } -0.028 < \alpha_5 < 0.033$$

	Resolved channel		Merged channel
	e^+ and μ^+	e^- and μ^-	e and μ
W + jets	92 ± 37	51 ± 29	19.4 ± 9.9
$t\bar{t}$	59 ± 18	63 ± 35	6.8 ± 2.8
Single-top	10.0 ± 5.6	5.5 ± 3.2	2.2 ± 1.2
Diboson	8.6 ± 5.7	10.8 ± 6.4	1.6 ± 1.2
Z + jets	4.5 ± 1.5	3.4 ± 2.4	0.58 ± 0.64
Multijet	16 ± 16	12 ± 12	1.8 ± 1.9
Total background	190 ± 53	145 ± 54	32 ± 12
EWK WV (SM)	3.66 ± 0.82	2.34 ± 0.56	0.54 ± 0.22
EWK WV ($\alpha_4 = 0.1, \alpha_5 = 0$)	21.0 ± 4.2	9.2 ± 1.9	15.1 ± 4.4
Data	173	131	32

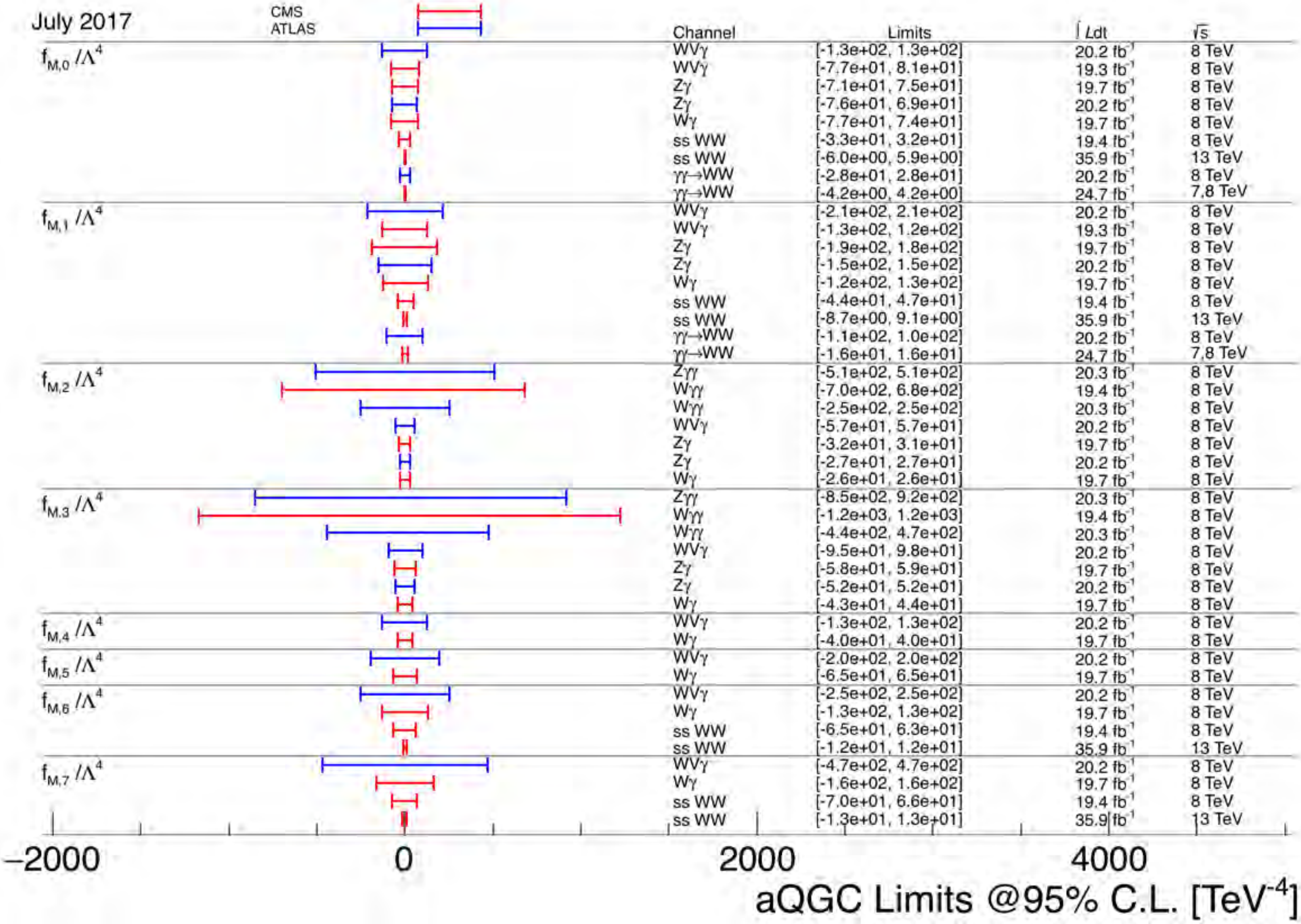


- Compare the *dashed* lines
  - Black : WZ (observed: excess)
  - Red: W$^\pm$W$^\pm$ (observed: excess)
  - Blue: WV (observed: deficit)
- Low statistics gives broad band for expected limit, example: WZ VBS, compared to (old) W$^\pm$W$^\pm$ VBS



Example: Limits on f_M/Λ^4

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



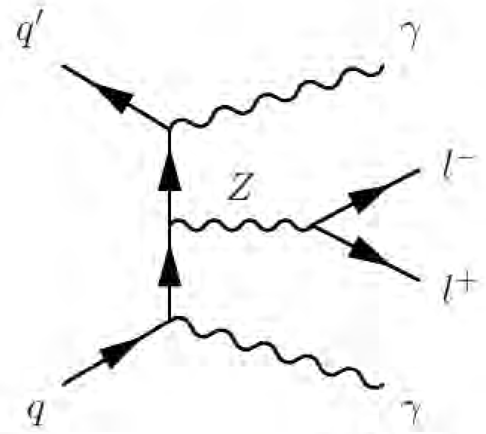
	Channel	Limits	$\int Ldt$	$\sqrt{s}$
$f_{M,0}/\Lambda^4$	$W V\gamma$	[-1.3e+02, 1.3e+02]	20.2 fb^{-1}	8 TeV
	$W V\gamma$	[-7.7e+01, 8.1e+01]	19.3 fb^{-1}	8 TeV
	$Z\gamma$	[-7.1e+01, 7.5e+01]	19.7 fb^{-1}	8 TeV
	$Z\gamma$	[-7.6e+01, 6.9e+01]	20.2 fb^{-1}	8 TeV
	$W\gamma$	[-7.7e+01, 7.4e+01]	19.7 fb^{-1}	8 TeV
	ss WW	[-3.3e+01, 3.2e+01]	19.4 fb^{-1}	8 TeV
	ss WW	[-6.0e+00, 5.9e+00]	35.9 fb^{-1}	13 TeV
	$\gamma\gamma\to WW$	[-2.8e+01, 2.8e+01]	20.2 fb^{-1}	8 TeV
	$\gamma\gamma\to WW$	[-4.2e+00, 4.2e+00]	24.7 fb^{-1}	7,8 TeV
$f_{M,1}/\Lambda^4$	$W V\gamma$	[-2.1e+02, 2.1e+02]	20.2 fb^{-1}	8 TeV
	$W V\gamma$	[-1.3e+02, 1.2e+02]	19.3 fb^{-1}	8 TeV
	$Z\gamma$	[-1.9e+02, 1.8e+02]	19.7 fb^{-1}	8 TeV
	$Z\gamma$	[-1.5e+02, 1.5e+02]	20.2 fb^{-1}	8 TeV
	$W\gamma$	[-1.2e+02, 1.3e+02]	19.7 fb^{-1}	8 TeV
	ss WW	[-4.4e+01, 4.7e+01]	19.4 fb^{-1}	8 TeV
	ss WW	[-8.7e+00, 9.1e+00]	35.9 fb^{-1}	13 TeV
	$\gamma\gamma\to WW$	[-1.1e+02, 1.0e+02]	20.2 fb^{-1}	8 TeV
	$\gamma\gamma\to WW$	[-1.6e+01, 1.6e+01]	24.7 fb^{-1}	7,8 TeV
$f_{M,2}/\Lambda^4$	$Z\gamma\gamma$	[-5.1e+02, 5.1e+02]	20.3 fb^{-1}	8 TeV
	$W\gamma\gamma$	[-7.0e+02, 6.8e+02]	19.4 fb^{-1}	8 TeV
	$W\gamma\gamma$	[-2.5e+02, 2.5e+02]	20.3 fb^{-1}	8 TeV
	$W V\gamma$	[-5.7e+01, 5.7e+01]	20.2 fb^{-1}	8 TeV
	$Z\gamma$	[-3.2e+01, 3.1e+01]	19.7 fb^{-1}	8 TeV
	$Z\gamma$	[-2.7e+01, 2.7e+01]	20.2 fb^{-1}	8 TeV
	$W\gamma$	[-2.6e+01, 2.6e+01]	19.7 fb^{-1}	8 TeV
$f_{M,3}/\Lambda^4$	$Z\gamma\gamma$	[-8.5e+02, 9.2e+02]	20.3 fb^{-1}	8 TeV
	$W\gamma\gamma$	[-1.2e+03, 1.2e+03]	19.4 fb^{-1}	8 TeV
	$W\gamma\gamma$	[-4.4e+02, 4.7e+02]	20.3 fb^{-1}	8 TeV
	$W V\gamma$	[-9.5e+01, 9.8e+01]	20.2 fb^{-1}	8 TeV
	$Z\gamma$	[-5.8e+01, 5.9e+01]	19.7 fb^{-1}	8 TeV
	$Z\gamma$	[-5.2e+01, 5.2e+01]	20.2 fb^{-1}	8 TeV
	$W\gamma$	[-4.3e+01, 4.4e+01]	19.7 fb^{-1}	8 TeV
$f_{M,4}/\Lambda^4$	$W V\gamma$	[-1.3e+02, 1.3e+02]	20.2 fb^{-1}	8 TeV
	$W\gamma$	[-4.0e+01, 4.0e+01]	19.7 fb^{-1}	8 TeV
$f_{M,5}/\Lambda^4$	$W V\gamma$	[-2.0e+02, 2.0e+02]	20.2 fb^{-1}	8 TeV
	$W\gamma$	[-6.5e+01, 6.5e+01]	19.7 fb^{-1}	8 TeV
$f_{M,6}/\Lambda^4$	$W V\gamma$	[-2.5e+02, 2.5e+02]	20.2 fb^{-1}	8 TeV
	$W\gamma$	[-1.3e+02, 1.3e+02]	19.7 fb^{-1}	8 TeV
	ss WW	[-6.5e+01, 6.3e+01]	19.4 fb^{-1}	8 TeV
	ss WW	[-1.2e+01, 1.2e+01]	35.9 fb^{-1}	13 TeV
$f_{M,7}/\Lambda^4$	$W V\gamma$	[-4.7e+02, 4.7e+02]	20.2 fb^{-1}	8 TeV
	$W\gamma$	[-1.6e+02, 1.6e+02]	19.7 fb^{-1}	8 TeV
	ss WW	[-7.0e+01, 6.6e+01]	19.4 fb^{-1}	8 TeV
	ss WW	[-1.3e+01, 1.3e+01]	35.9 fb^{-1}	13 TeV

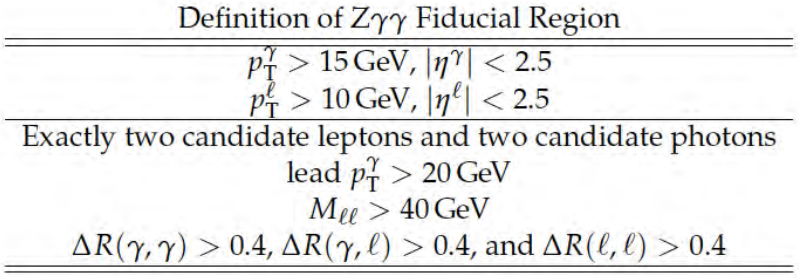
TRIPLE BOSON PRODUCTION

- CMS: $V/\gamma \rightarrow WV\gamma$
- ATLAS, CMS: $W \rightarrow W\gamma\gamma$,
- ATLAS, CMS: $Z/\gamma \rightarrow Z\gamma\gamma$
- ATLAS: $W \rightarrow WWW$

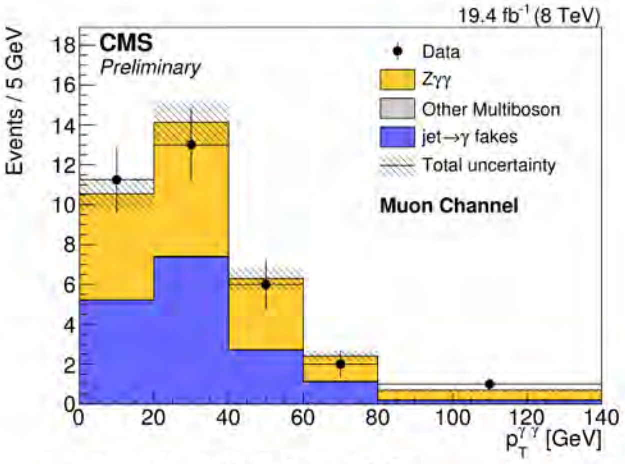
Zγγ (ATLAS, CMS)

- No neutral triple or quartic vertices in Zγγ in SM
- process produced via radiation, e.g.
- Limits an aT/QGC possible
- both CMS(Z→ee,μμ) and ATLAS (Z→ee,μμ,νν)
  SMP-15-008-pas.pdf and https://arxiv.org/pdf/1604.05232.pdf
- CMS analysis separated wrt. detector regions





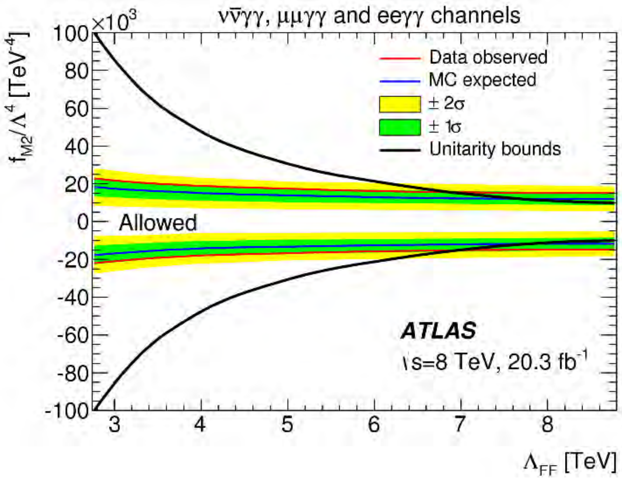
Definition of $Z\gamma\gamma$ Fiducial Region
$p_T^\gamma > 15\,\text{GeV}$, $\lvert\eta^\gamma\rvert < 2.5$ $p_T^\ell > 10\,\text{GeV}$, $\lvert\eta^\ell\rvert < 2.5$
Exactly two candidate leptons and two candidate photons lead $p_T^\gamma > 20\,\text{GeV}$ $M_{\ell\ell} > 40\,\text{GeV}$ $\Delta R(\gamma,\gamma) > 0.4$, $\Delta R(\gamma,\ell) > 0.4$, and $\Delta R(\ell,\ell) > 0.4$

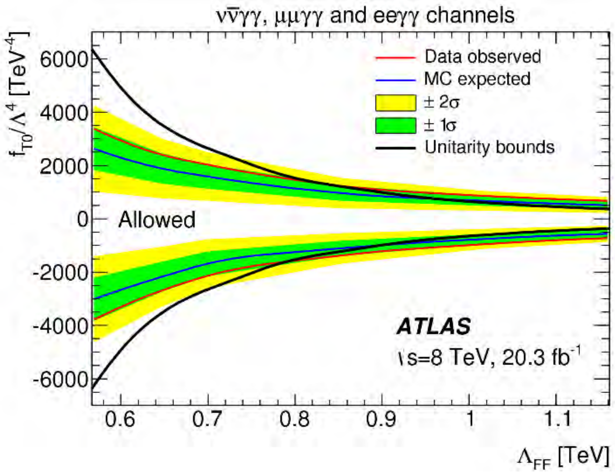


- Background: Z(γ)+Jets (misID)
- Cross-section
  - CMS: expected $\sigma^{\text{NLO}}_{Z\gamma\gamma} \cdot \text{BR}(Z \to \ell\ell) = 12.95 \pm 1.47\,\text{fb}$
    obs.: 5.9 s.d : $\sigma^{\text{fid}}_{Z\gamma\gamma} \cdot \text{BR}(Z \to \ell\ell) = 12.7 \pm 1.4\,(\text{stat}) \pm 1.8\,(\text{syst}) \pm 0.3\,(\text{lumi})\,\text{fb}$

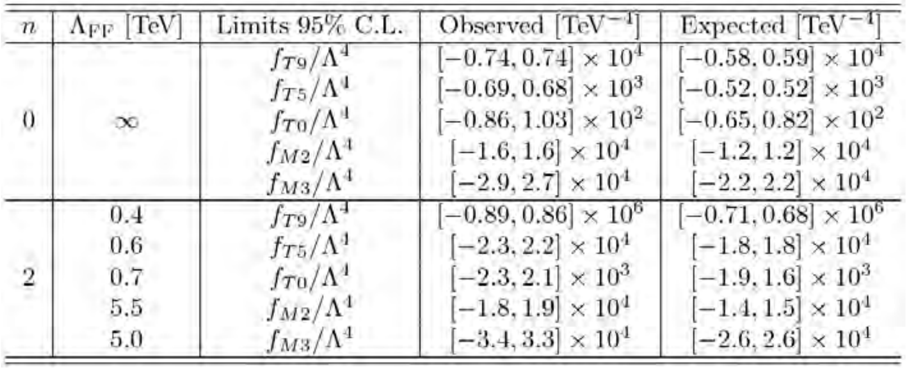
aQGC extraction (ATLAS)

- Special: small influence from unitarization, esp for f_M aQGCs
  - Limits stay near unitarity bound even for large form factor scale





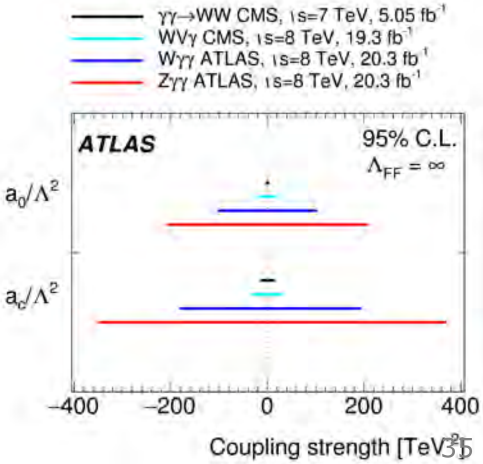
  - Extracted f_M aQGC limits not competitive with γγ→WW or WVγ



n	Λ_{FF} [TeV]	Limits 95% C.L.	Observed [TeV^{-4}]	Expected [TeV^{-4}]
0	∞	f_{T9}/Λ^4	$[-0.74, 0.74] \times 10^4$	$[-0.58, 0.59] \times 10^4$
		f_{T5}/Λ^4	$[-0.69, 0.68] \times 10^3$	$[-0.52, 0.52] \times 10^3$
		f_{T0}/Λ^4	$[-0.86, 1.03] \times 10^2$	$[-0.65, 0.82] \times 10^2$
		f_{M2}/Λ^4	$[-1.6, 1.6] \times 10^4$	$[-1.2, 1.2] \times 10^4$
		f_{M3}/Λ^4	$[-2.9, 2.7] \times 10^4$	$[-2.2, 2.2] \times 10^4$
2	0.4	f_{T9}/Λ^4	$[-0.89, 0.86] \times 10^6$	$[-0.71, 0.68] \times 10^6$
	0.6	f_{T5}/Λ^4	$[-2.3, 2.2] \times 10^4$	$[-1.8, 1.8] \times 10^4$
	0.7	f_{T0}/Λ^4	$[-2.3, 2.1] \times 10^3$	$[-1.9, 1.6] \times 10^3$
	5.5	f_{M2}/Λ^4	$[-1.8, 1.9] \times 10^4$	$[-1.4, 1.5] \times 10^4$
	5.0	f_{M3}/Λ^4	$[-3.4, 3.3] \times 10^4$	$[-2.6, 2.6] \times 10^4$

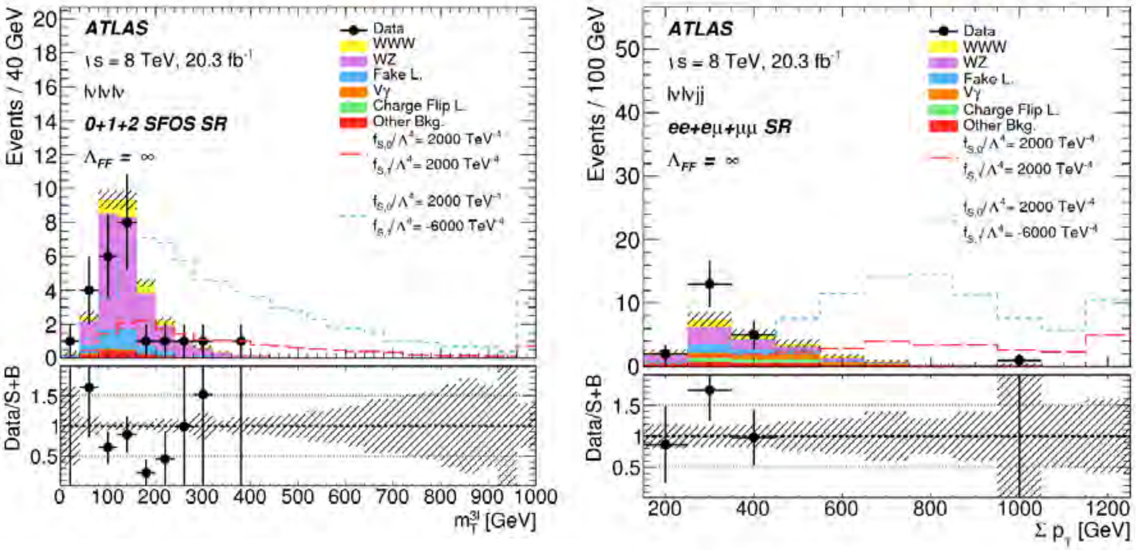
$$\frac{f_{M2}}{\Lambda^4} = -\frac{a_0}{\Lambda^2}\frac{s_w^2}{2v^2c_w^2},$$

$$\frac{f_{M3}}{\Lambda^4} = \frac{a_c}{\Lambda^2}\frac{s_w^2}{2v^2c_w^2}$$



WWW (ATLAS)

- First search for VVV triboson production
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-07/
- Leptonic and hadronic channel, both background dominated



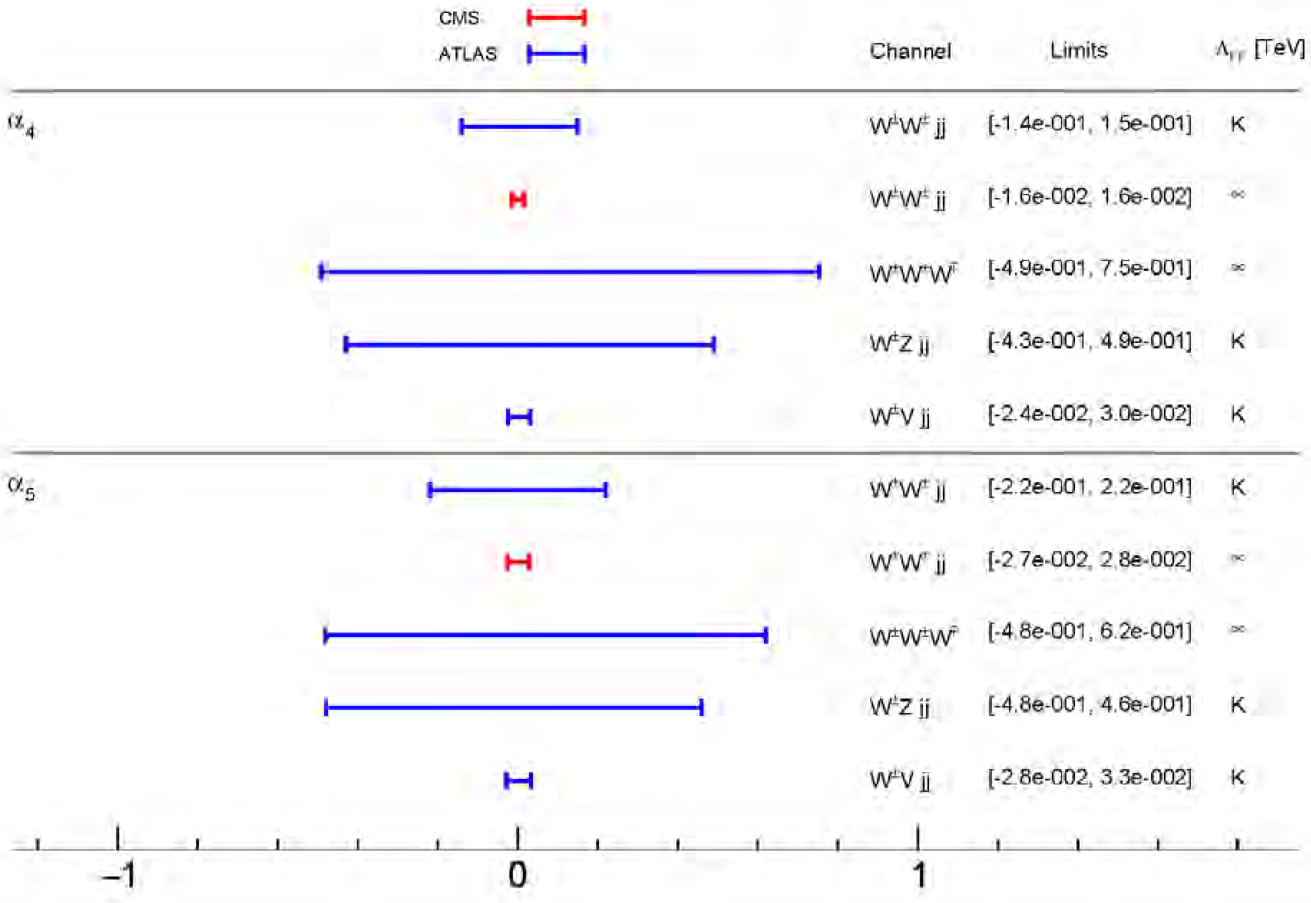
- Cross section „measured" on 1.0 s.d. level

		Cross section [fb]	
		Theory	Observed
Fiducial	$\ell\nu\ell\nu\ell\nu$	0.309 ± 0.007 (stat.) ± 0.015 (PDF) ± 0.008 (scale)	$0.31\ ^{+0.35}_{-0.33}$ (stat.) $^{+0.32}_{-0.35}$ (syst.)
	$\ell\nu\ell\nu jj$	0.306 ± 0.007 (stat.) ± 0.015 (PDF) ± 0.011 (scale)	$0.26\ ^{+0.42}_{-0.35}$ (stat.) $^{+0.20}_{-0.21}$ (syst.)
Total		241.5 ± 0.1 (stat.) ± 10.3 (PDF) ± 6.3 (scale)	230 ± 200 (stat.) $^{+150}_{-160}$ (syst.)

- Sensitivity $a_{4,5}$~0.7 and f_S not yet competitive with VBS channels

Overview aQGCs

- *Green, Meade, Pleier, „Multi-Boson Interactions at the Run 1 LHC“* *https://arxiv.org/abs/1610.07572* *, submitted to* Review of Modern Physics
- *Be careful when comparing ununitarized ($\Lambda_{FF}=\infty$) with K-matrix (K) !*

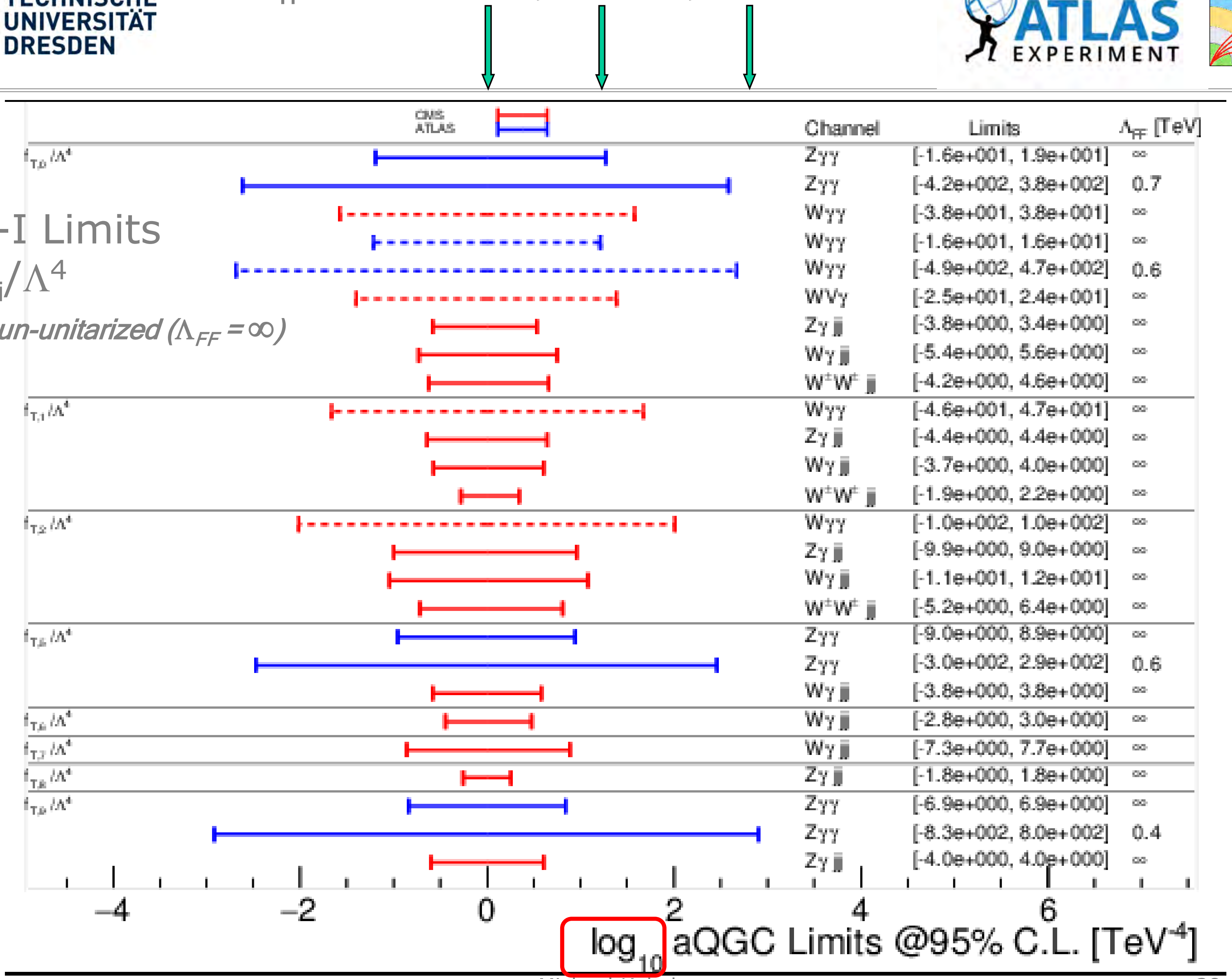


	Channel	Limits	Λ_{FF} [TeV]
α_4	$W^\pm W^\pm jj$	[-1.4e-001, 1.5e-001]	K
	$W^\pm W^\pm jj$	[-1.6e-002, 1.6e-002]	∞
	$W^\pm W^\pm W^\mp$	[-4.9e-001, 7.5e-001]	∞
	$W^\pm Z\ jj$	[-4.3e-001, 4.9e-001]	K
	$W^\pm V\ jj$	[-2.4e-002, 3.0e-002]	K
α_5	$W^\pm W^\pm jj$	[-2.2e-001, 2.2e-001]	K
	$W^\pm W^\pm jj$	[-2.7e-002, 2.8e-002]	∞
	$W^\pm W^\pm W^\mp$	[-4.8e-001, 6.2e-001]	∞
	$W^\pm Z\ jj$	[-4.8e-001, 4.6e-001]	K
	$W^\pm V\ jj$	[-2.8e-002, 3.3e-002]	K

For f_{Ti} =1: Λ=1TeV, 500GeV, 200 GeV

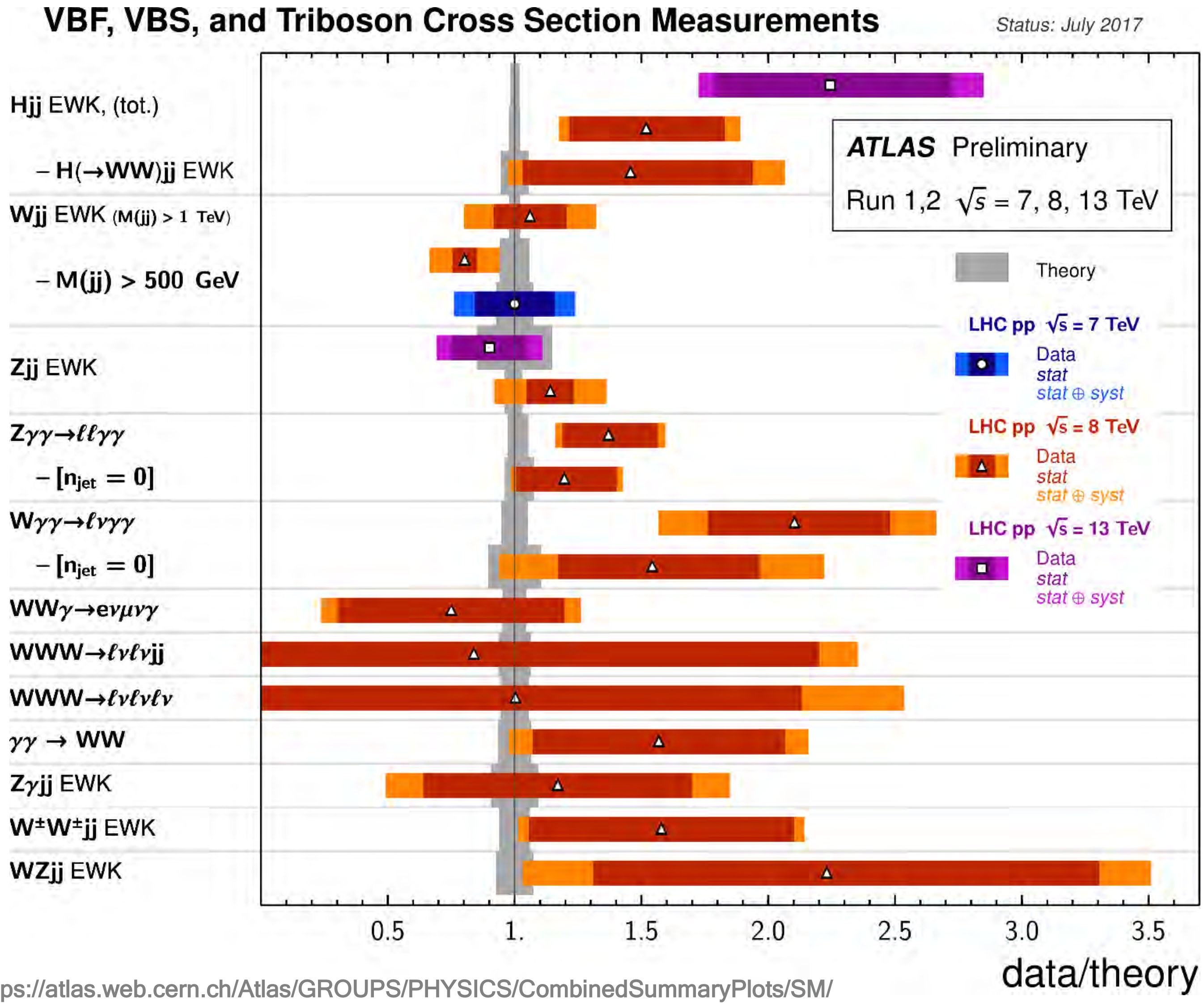
Run-I Limits of f_{Ti}/Λ^4

Mostly un-unitarized ($\Lambda_{FF} = \infty$)



	Channel	Limits	Λ_{FF} [TeV]
$f_{T,0}/\Lambda^4$	Zγγ	[-1.6e+001, 1.9e+001]	∞
	Zγγ	[-4.2e+002, 3.8e+002]	0.7
	Wγγ	[-3.8e+001, 3.8e+001]	∞
	Wγγ	[-1.6e+001, 1.6e+001]	∞
	Wγγ	[-4.9e+002, 4.7e+002]	0.6
	WVγ	[-2.5e+001, 2.4e+001]	∞
	Zγ ▮	[-3.8e+000, 3.4e+000]	∞
	Wγ ▮	[-5.4e+000, 5.6e+000]	∞
	W±W± ▮	[-4.2e+000, 4.6e+000]	∞
$f_{T,1}/\Lambda^4$	Wγγ	[-4.6e+001, 4.7e+001]	∞
	Zγ ▮	[-4.4e+000, 4.4e+000]	∞
	Wγ ▮	[-3.7e+000, 4.0e+000]	∞
	W±W± ▮	[-1.9e+000, 2.2e+000]	∞
$f_{T,2}/\Lambda^4$	Wγγ	[-1.0e+002, 1.0e+002]	∞
	Zγ ▮	[-9.9e+000, 9.0e+000]	∞
	Wγ ▮	[-1.1e+001, 1.2e+001]	∞
	W±W± ▮	[-5.2e+000, 6.4e+000]	∞
$f_{T,5}/\Lambda^4$	Zγγ	[-9.0e+000, 8.9e+000]	∞
	Zγγ	[-3.0e+002, 2.9e+002]	0.6
	Wγ ▮	[-3.8e+000, 3.8e+000]	∞
$f_{T,6}/\Lambda^4$	Wγ ▮	[-2.8e+000, 3.0e+000]	∞
$f_{T,7}/\Lambda^4$	Wγ ▮	[-7.3e+000, 7.7e+000]	∞
$f_{T,8}/\Lambda^4$	Zγ ▮	[-1.8e+000, 1.8e+000]	∞
$f_{T,9}/\Lambda^4$	Zγγ	[-6.9e+000, 6.9e+000]	∞
	Zγγ	[-8.3e+002, 8.0e+002]	0.4
	Zγ ▮	[-4.0e+000, 4.0e+000]	∞

VBF, VBS and Triboson



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/

Summary QGC and VBS

❖what have we achieved so far?

❖ 1. Observe the SM QGC Processes with QGC vertices

- Indications and evidences for several processes on 1-4 s.d.
- 1 process so far discovered on 5 s.d. level
- QGC contribution not uniquely to define, existence to be proven
- Precise measurements need much more data (HL LHC!)

❖ 2. Constrain anomalous Quartic Gauge Couplings (aQGC)

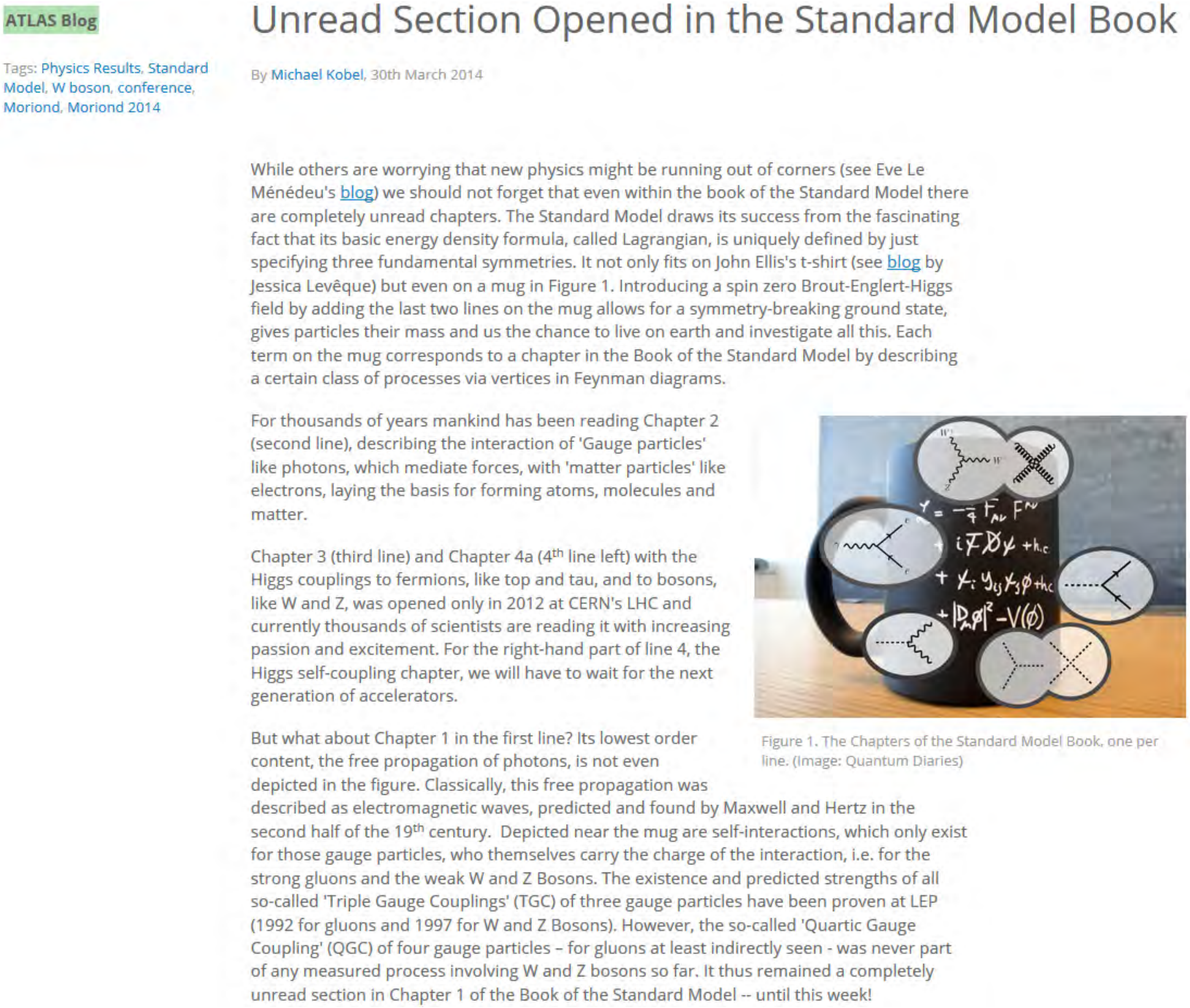
- A plethora of limits existing
- Limits correspond to New Physics scales Λ between 50 and 1500 GeV
- Lot of issues with different unitarizations and parameter sets
- Need more explicit models test (resonances, diff. distriubutions) and limits as clipping scan f(Λ_{cut}), see ATL-COM-PHYS-2017-433

❖ 3. Test Eweak Symmetry breaking and Higgs properties

- e.g. Longitudinal component $W_L W_L \rightarrow W_L W_L$ or composite Higgs: no sensitivity yet (HL LHC ?)

Still true: It‘s an unread section of SM

- https://atlas.cern/updates/atlas-blog/unread-section-opened-standard-model-book



ATLAS Blog

Tags: Physics Results, Standard Model, W boson, conference, Moriond, Moriond 2014

Unread Section Opened in the Standard Model Book

By Michael Kobel, 30th March 2014

While others are worrying that new physics might be running out of corners (see Eve Le Ménédeu's blog) we should not forget that even within the book of the Standard Model there are completely unread chapters. The Standard Model draws its success from the fascinating fact that its basic energy density formula, called Lagrangian, is uniquely defined by just specifying three fundamental symmetries. It not only fits on John Ellis's t-shirt (see blog by Jessica Levêque) but even on a mug in Figure 1. Introducing a spin zero Brout-Englert-Higgs field by adding the last two lines on the mug allows for a symmetry-breaking ground state, gives particles their mass and us the chance to live on earth and investigate all this. Each term on the mug corresponds to a chapter in the Book of the Standard Model by describing a certain class of processes via vertices in Feynman diagrams.

For thousands of years mankind has been reading Chapter 2 (second line), describing the interaction of 'Gauge particles' like photons, which mediate forces, with 'matter particles' like electrons, laying the basis for forming atoms, molecules and matter.

Chapter 3 (third line) and Chapter 4a (4th line left) with the Higgs couplings to fermions, like top and tau, and to bosons, like W and Z, was opened only in 2012 at CERN's LHC and currently thousands of scientists are reading it with increasing passion and excitement. For the right-hand part of line 4, the Higgs self-coupling chapter, we will have to wait for the next generation of accelerators.

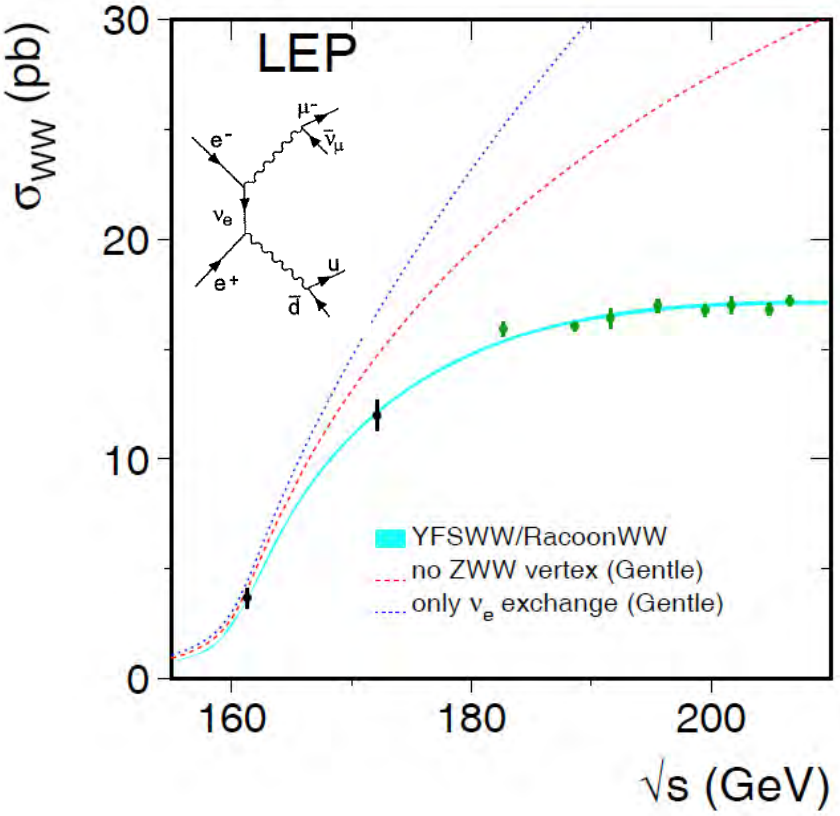
Figure 1. The Chapters of the Standard Model Book, one per line. (Image: Quantum Diaries)

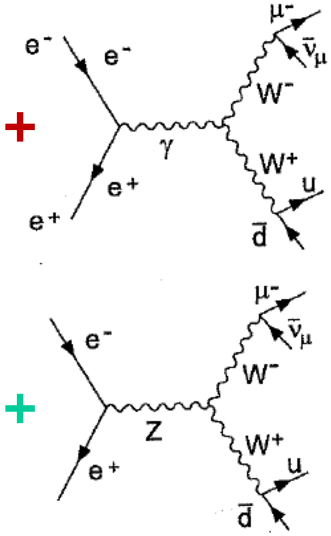
But what about Chapter 1 in the first line? Its lowest order content, the free propagation of photons, is not even depicted in the figure. Classically, this free propagation was described as electromagnetic waves, predicted and found by Maxwell and Hertz in the second half of the 19th century. Depicted near the mug are self-interactions, which only exist for those gauge particles, who themselves carry the charge of the interaction, i.e. for the strong gluons and the weak W and Z Bosons. The existence and predicted strengths of all so-called 'Triple Gauge Couplings' (TGC) of three gauge particles have been proven at LEP (1992 for gluons and 1997 for W and Z Bosons). However, the so-called 'Quartic Gauge Coupling' (QGC) of four gauge particles – for gluons at least indirectly seen - was never part of any measured process involving W and Z bosons so far. It thus remained a completely unread section in Chapter 1 of the Book of the Standard Model -- until this week!

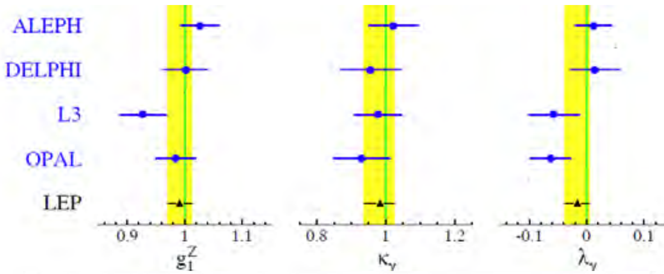
BACKUP

Proof for Triple WWγ and WWZ Vertex

- WW pair production at LEP-2 (published 2013): http://arxiv.org/pdf/1302.3415v2.pdf



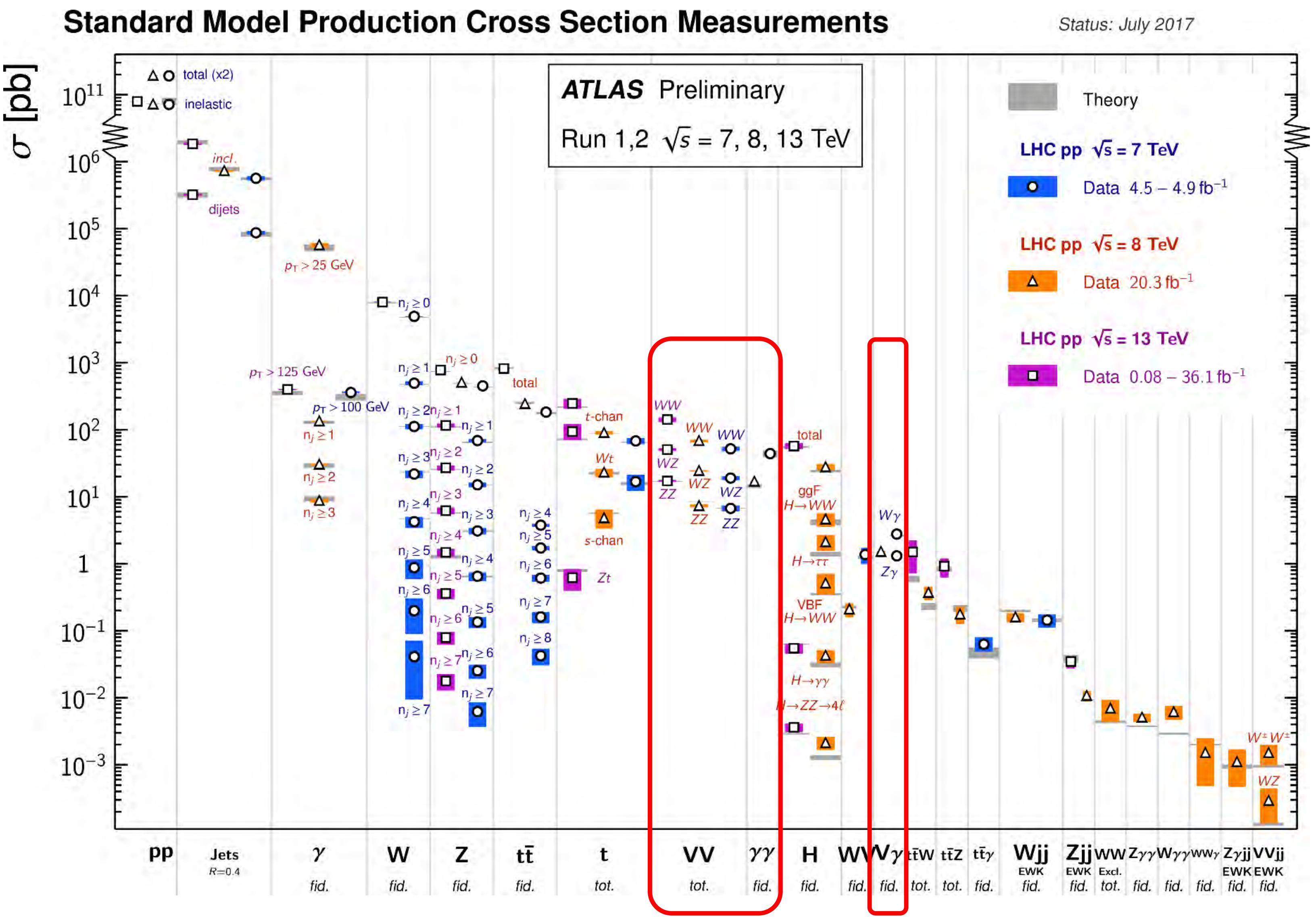




experiment		g_1^Z	κ_γ	λ_γ
ALEPH		$1.026^{+0.034}_{-0.033}$	$1.022^{+0.073}_{-0.072}$	$0.012^{+0.033}_{-0.032}$
DELPHI		$1.002^{+0.038}_{-0.040}$	$0.955^{+0.090}_{-0.086}$	$0\ .014^{+0.044}_{-0.042}$
L3		$0.927^{+0.042}_{-0.041}$	$0.978^{+0.071}_{-0.069}$	$-0.058^{+0.047}_{-0.044}$
OPAL		$0.984^{+0.035}_{-0.034}$	$0.929^{+0.085}_{-0.081}$	$-0.063^{+0.036}_{-0.036}$
LEP	68% C.L.	$0.991^{+0.022}_{-0.021}$	$0.984^{+0.042}_{-0.047}$	$-0.016^{+0.021}_{-0.023}$
	95% C.L.	$[0.949, 1.034]$	$[0.895, 1.069]$	$[-0.060, 0.026]$

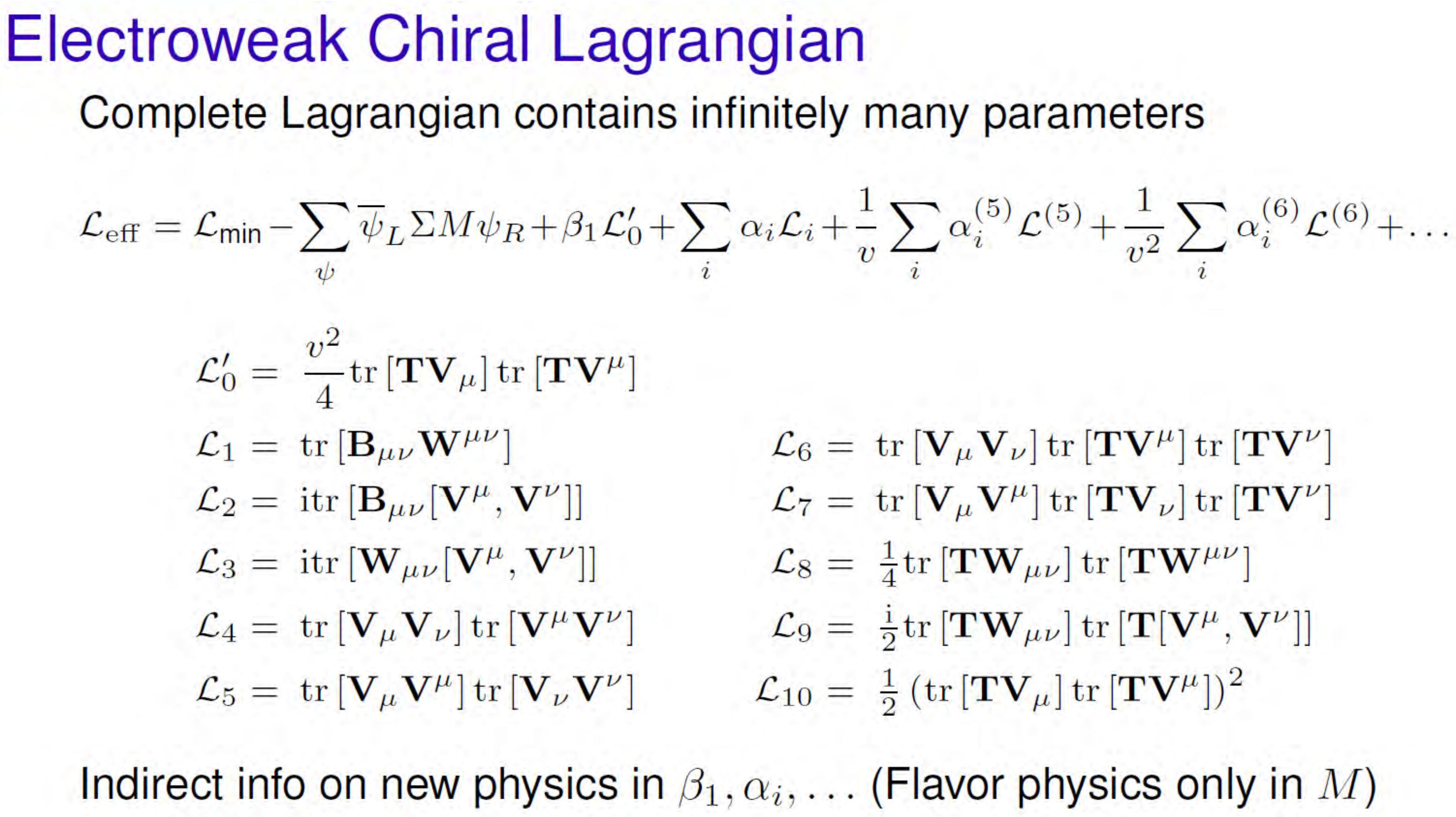
- *Each contribution rises with √s and would violate unitarity*
- *Only interference between all amplitudes limits the x-section*
- *Proof for existence of non-abelian TGC vertices*
- *Tested with a precision of 0.02 - 0.04, limit 0.03-0.06*

Standard Model Cross-Section Overview



Quartic gauge couplings beyond SM

- Theory
  - J. Reuter, talk at Bonn and http://arxiv.org/abs/hep-ph/0604048



Electroweak Chiral Lagrangian

Complete Lagrangian contains infinitely many parameters

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{min}} - \sum_{\psi} \overline{\psi}_L \Sigma M \psi_R + \beta_1 \mathcal{L}_0' + \sum_i \alpha_i \mathcal{L}_i + \frac{1}{v} \sum_i \alpha_i^{(5)} \mathcal{L}^{(5)} + \frac{1}{v^2} \sum_i \alpha_i^{(6)} \mathcal{L}^{(6)} + \dots$$

$$\mathcal{L}_0' = \frac{v^2}{4} \operatorname{tr}[\mathbf{T}\mathbf{V}_\mu] \operatorname{tr}[\mathbf{T}\mathbf{V}^\mu]$$

$$\begin{aligned}
\mathcal{L}_1 &= \operatorname{tr}[\mathbf{B}_{\mu\nu}\mathbf{W}^{\mu\nu}] & \mathcal{L}_6 &= \operatorname{tr}[\mathbf{V}_\mu\mathbf{V}_\nu] \operatorname{tr}[\mathbf{T}\mathbf{V}^\mu] \operatorname{tr}[\mathbf{T}\mathbf{V}^\nu] \\
\mathcal{L}_2 &= i\operatorname{tr}[\mathbf{B}_{\mu\nu}[\mathbf{V}^\mu, \mathbf{V}^\nu]] & \mathcal{L}_7 &= \operatorname{tr}[\mathbf{V}_\mu\mathbf{V}^\mu] \operatorname{tr}[\mathbf{T}\mathbf{V}_\nu] \operatorname{tr}[\mathbf{T}\mathbf{V}^\nu] \\
\mathcal{L}_3 &= i\operatorname{tr}[\mathbf{W}_{\mu\nu}[\mathbf{V}^\mu, \mathbf{V}^\nu]] & \mathcal{L}_8 &= \tfrac{1}{4}\operatorname{tr}[\mathbf{T}\mathbf{W}_{\mu\nu}] \operatorname{tr}[\mathbf{T}\mathbf{W}^{\mu\nu}] \\
\mathcal{L}_4 &= \operatorname{tr}[\mathbf{V}_\mu\mathbf{V}_\nu] \operatorname{tr}[\mathbf{V}^\mu\mathbf{V}^\nu] & \mathcal{L}_9 &= \tfrac{i}{2}\operatorname{tr}[\mathbf{T}\mathbf{W}_{\mu\nu}] \operatorname{tr}[\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]] \\
\mathcal{L}_5 &= \operatorname{tr}[\mathbf{V}_\mu\mathbf{V}^\mu] \operatorname{tr}[\mathbf{V}_\nu\mathbf{V}^\nu] & \mathcal{L}_{10} &= \tfrac{1}{2}\left(\operatorname{tr}[\mathbf{T}\mathbf{V}_\mu] \operatorname{tr}[\mathbf{T}\mathbf{V}^\mu]\right)^2
\end{aligned}$$

Indirect info on new physics in $\beta_1, \alpha_i, \dots$ (Flavor physics only in M)

Effective QGC in VBS

$$\mathcal{L}_4 = \alpha_4 \frac{g^2}{2} \left\{ \left[(W^+W^+)(W^-W^-) + (W^+W^-)^2 \right] + \frac{2}{c_W^2} (W^+Z)(W^-Z) + \frac{1}{2c_W^4} (ZZ)^2 \right\}$$

$$\mathcal{L}_5 = \alpha_5 \frac{g^2}{2} \left\{ (W^+W^-)^2 + \frac{2}{c_W^2} (W^+W^-)(ZZ) + \frac{1}{2c_W^4} (ZZ)^2 \right\}$$

- = Effective parametrization of physics beyond kinematic reach
  - e.g. resonances at new physics scale $\Lambda = \upsilon / \sqrt{\alpha_i}$
    - Wide: → continuum
    - Narrow: → particles
  - α parametrize low-mass tail of these resonances, e.g. $\alpha_5 = g_\sigma^2 \left(\frac{v^2}{8M_\sigma^2} \right)$

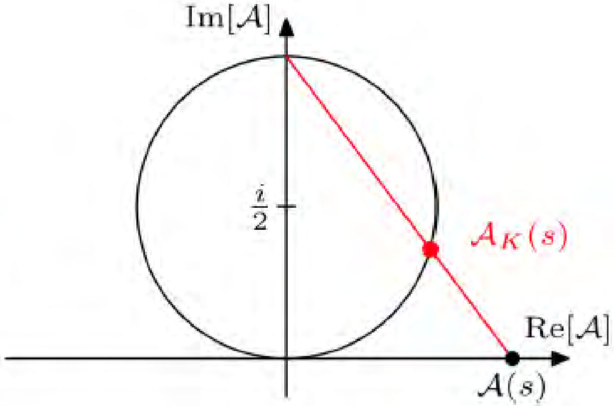
	$J = 0$	$J = 1$	$J = 2$
$I = 0$	σ^0 (Higgs ?)	ω^0 $(\gamma'/Z'$?)	f^0 (Graviton ?)
$I = 1$	$\pi^\pm, \pi^0$ (2HDM ?)	$\rho^\pm, \rho^0$ $(W'/Z'$?)	$a^\pm, a^0$
$I = 2$	$\phi^{\pm\pm}, \phi^\pm, \phi^0$ (Higgs triplet ?)	—	$t^{\pm\pm}, t^\pm, t^0$

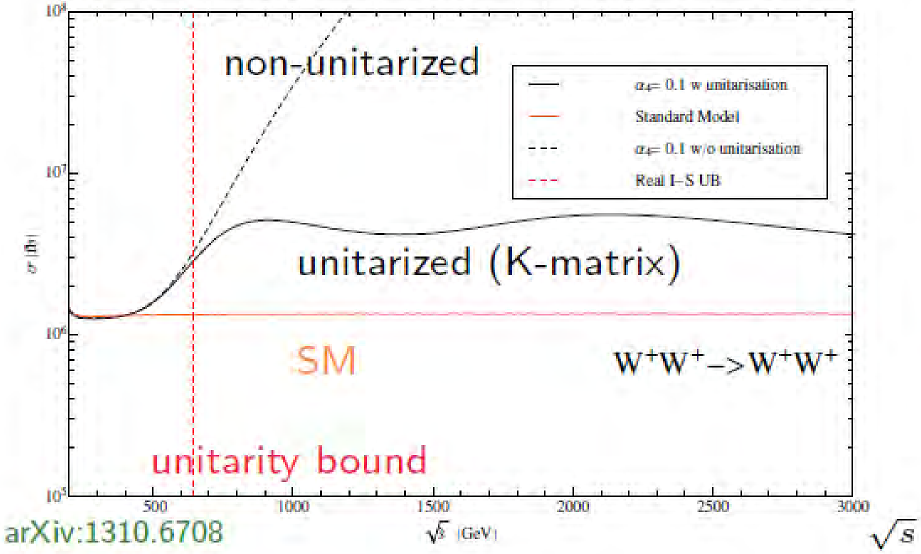
  - Unitarization only guaranteed for
    - Explicitly included resonance(s) at unique value(s) of *g*
    - effective parametrization always violates unitarity at some m_{VV}

Limits on aQGCs in $W^\pm W^\pm W^\pm W^\pm$ vertex

❖ Unitarization:

- **K-matrix** method (WHIZARD arXiv:0806.4145)
  - projecting the scattering amplitude $\mathcal{A}(s)$ on the Argand circle → saturation of the amplitude
  - retains the property of probing the entire kinematic phase space without being unphysical
  - only available for 2 → 2 processes so far





arXiv:1310.6708

WHIZARD cross section for $W^+W^+ \to W^+W^+$ with anomalous quartic gauge coupling α_4

Slide by Anja Vest, TU Dresden

A. Alboteanu, W. Kilian, and J. Reuter: http://arxiv.org/abs/0806.4145v1

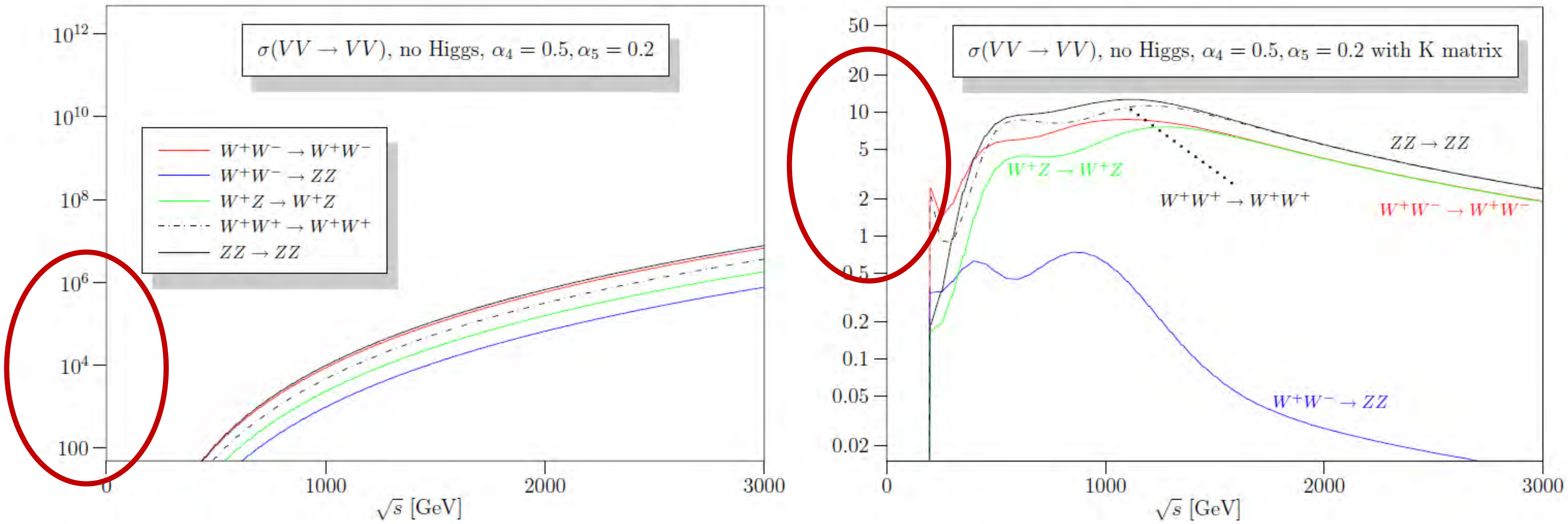
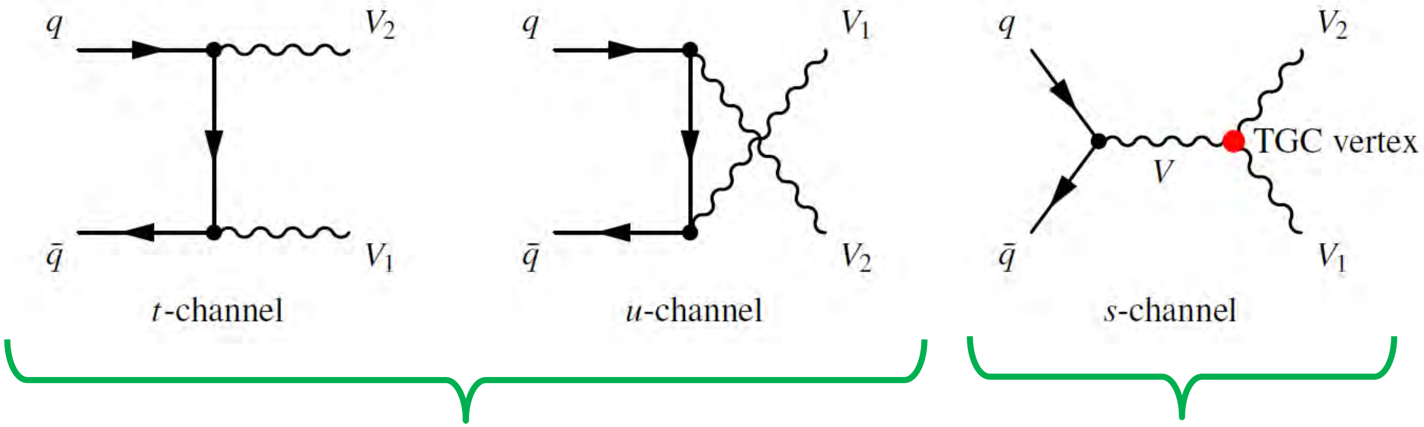


Figure 14: *Cross sections (in nanobarns) for the five different scattering processes of longitudinal weak gauge bosons: SM with a 120 GeV and a 1 TeV Higgs in the upper line, in the middle: SM without a Higgs without and with K-matrix unitarization, respectively. In the lower line, the case of* $\alpha_{4,5}$ *switched on are shown, on the left without, on the right with K matrix unitarization. The contribution from the forward region is cut out by a 15 degree cut around the beam axis.*

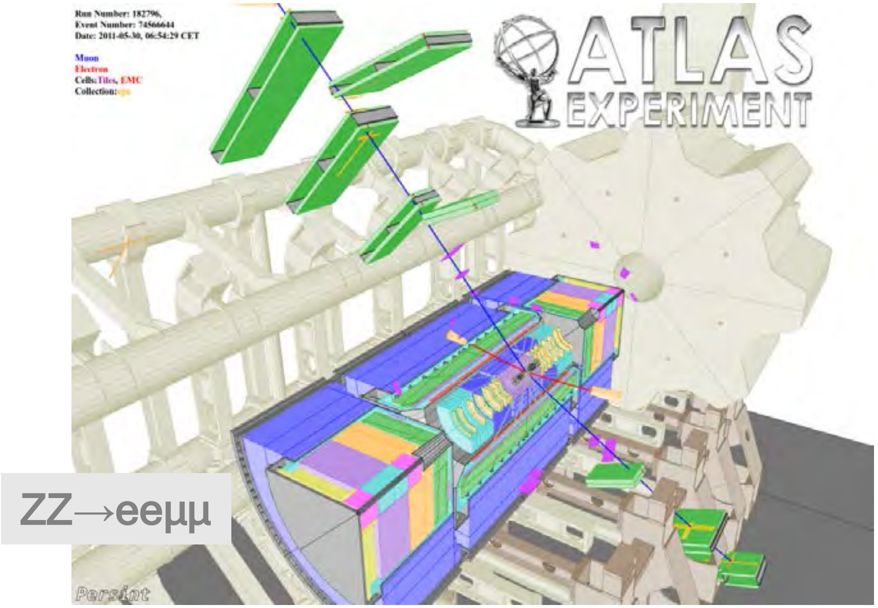
- Huge effect of unitarization above ~ 500 GeV (watch y-scale!)
- Explicit inclusion of resonances needed to be meaningful

Di-Boson Production at LHC



WW, WZ, Wγ, ZZ, Zγ

Z/γ →WW
W → WZ, Wγ
~~Z/γ → ZZ, Zγ~~ forbidden



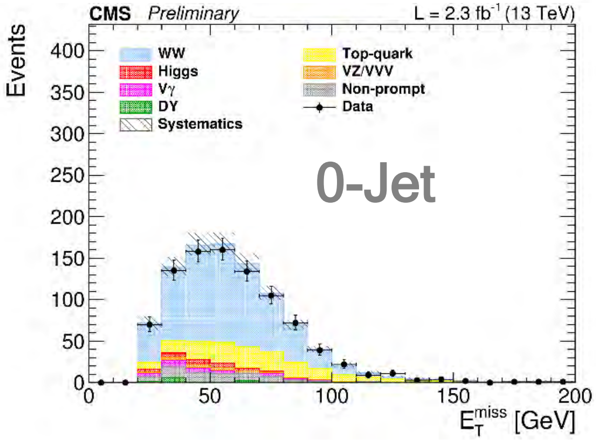
ZZ→eeμμ

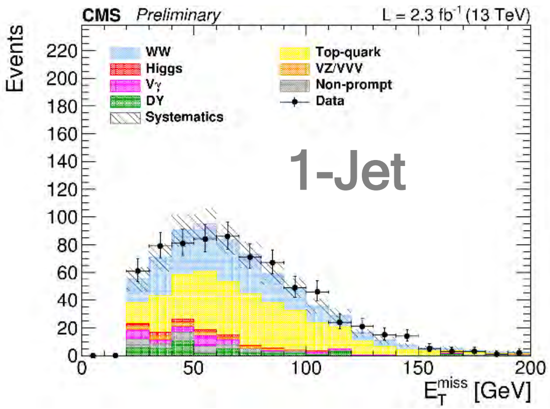
- **At LHC, di-boson decays to electrons and muons are measured:**

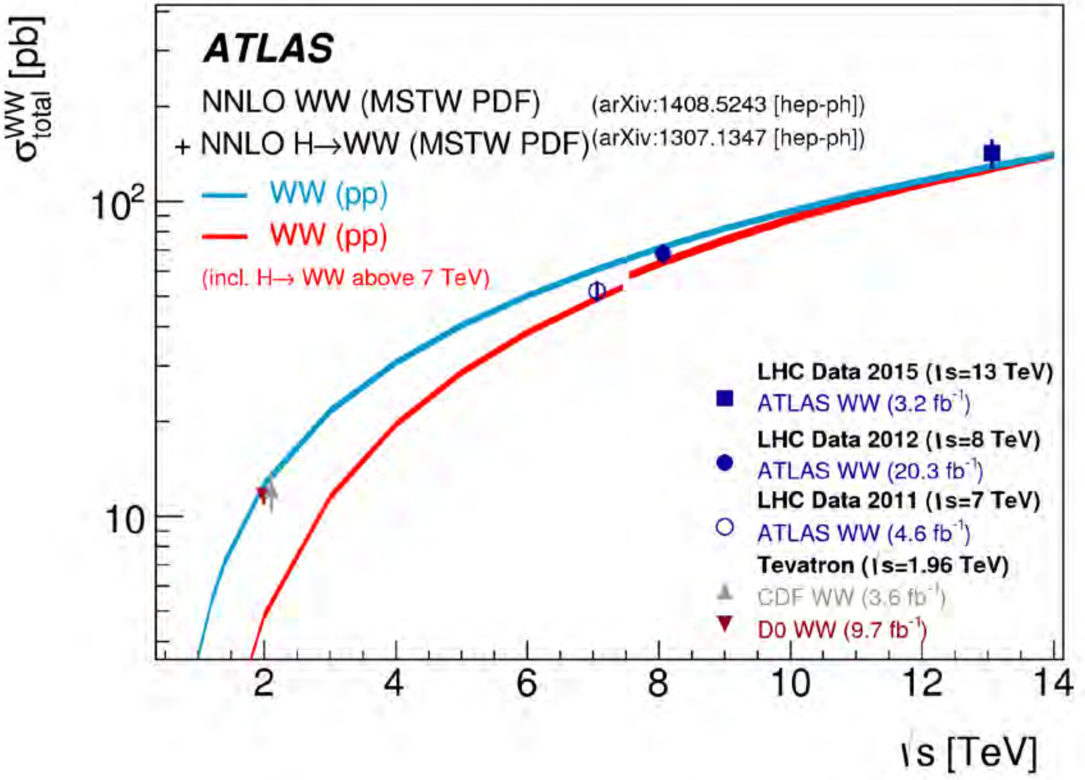
pp → ZW → ℓℓ ℓν
pp → WW → ℓν ℓν
pp → ZZ → ℓℓ ℓℓ, ℓℓ νν
pp → Zγ → ℓℓ γ
pp → Wγ → ℓν γ

13 TeV W^+W^- +X

- WW 13: so far only x-sections, NNLO needed for description

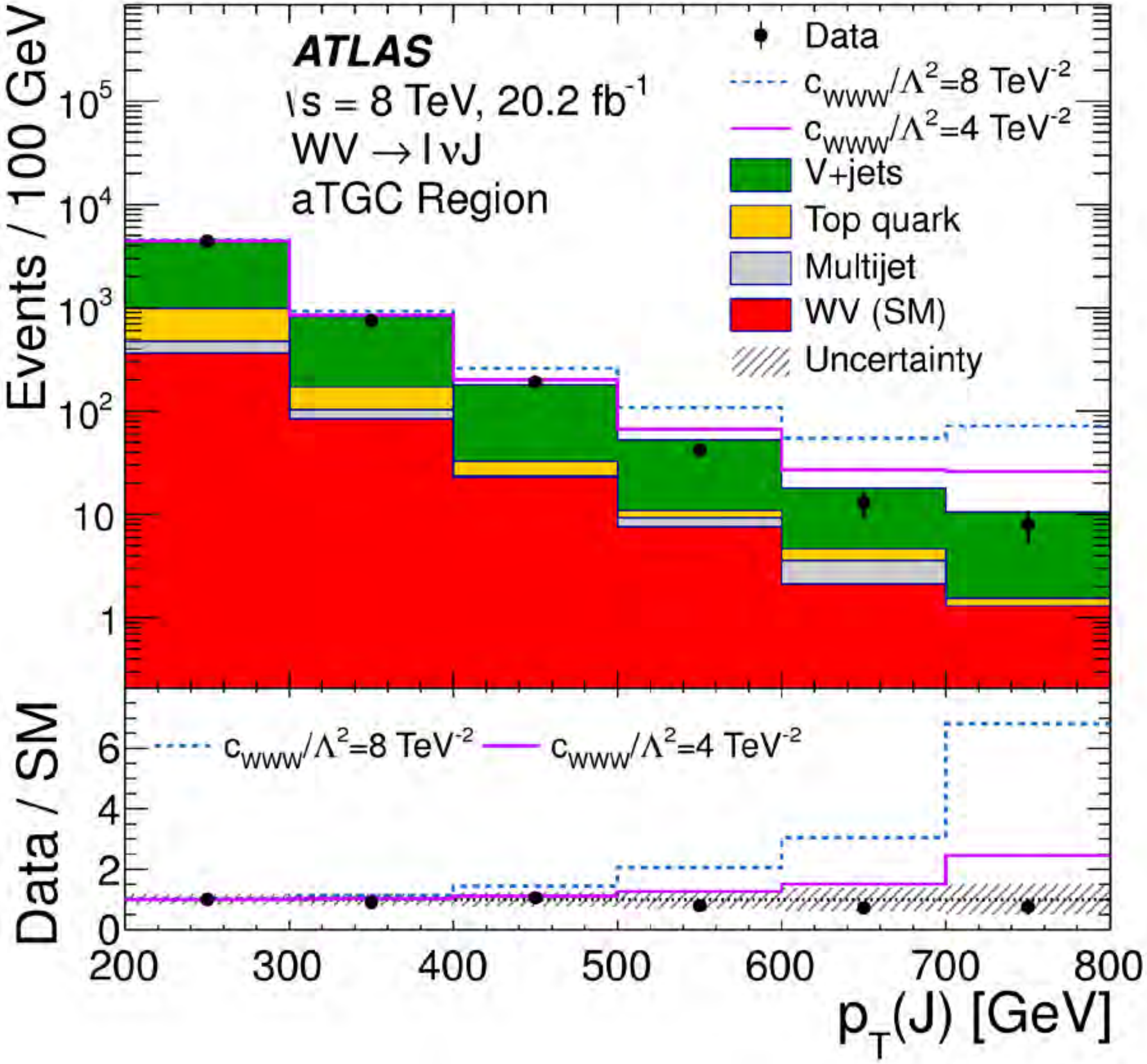






Category	Value ± stat. ± exp. syst. ± theo. syst. ± lumi. [pb]
0-jet	113.6 ± 6.3 ± 5.1 ± 6.5 ± 3.3
1-jet	135.3 ± 15.4 ± 34.0 ± 14.4 ± 6.0
Combination	115.3 ± 5.8 ± 5.7 ± 6.4 ± 3.6

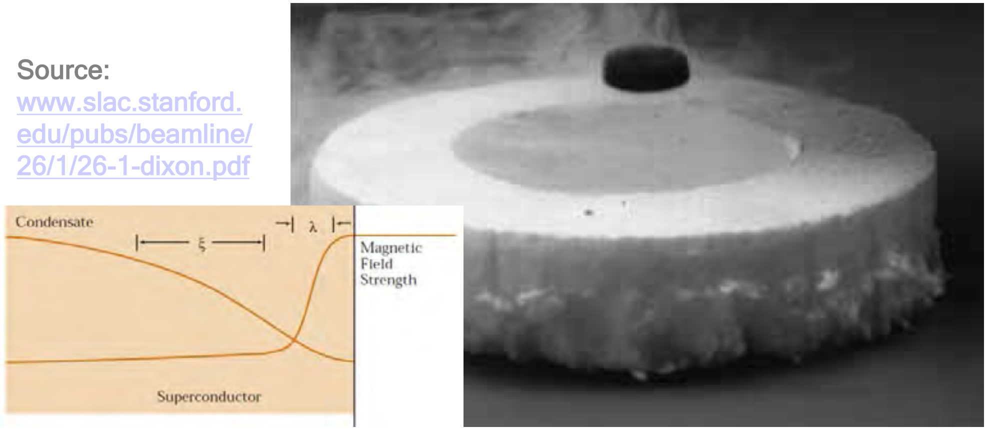
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-20/

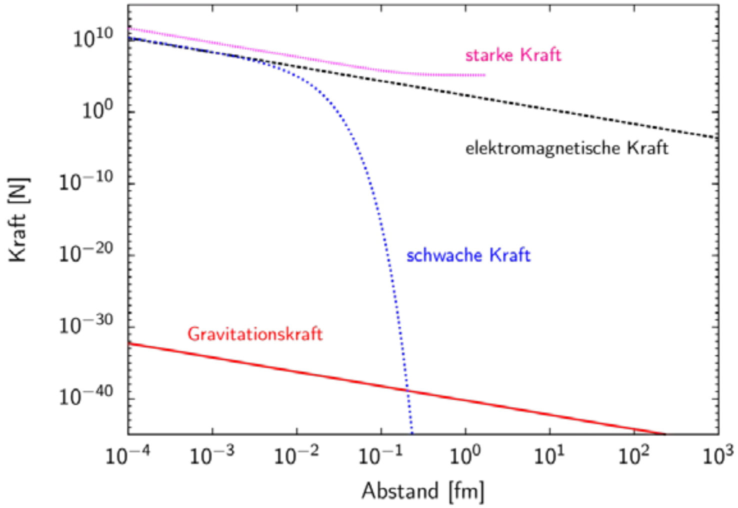

ATLAS
√s = 8 TeV, 20.2 fb^{-1}
WV → lνJ
aTGC Region
Data
c_{WWW}/Λ^2=8 TeV^{-2}
c_{WWW}/Λ^2=4 TeV^{-2}
V+jets
Top quark
Multijet
WV (SM)
Uncertainty
Events / 100 GeV
10^5
10^4
10^3
10^2
10
1
Data / SM
6
4
2
0
200
300
400
500
600
700
800
p_T(J) [GeV]

After all…

- The Spin 0 Field in a superconductor is not fundamental, but composite, 2 electrons (Cooper Pair) bound by „phonon interaction“

Source: www.slac.stanford.edu/pubs/beamline/26/1/26-1-dixon.pdf



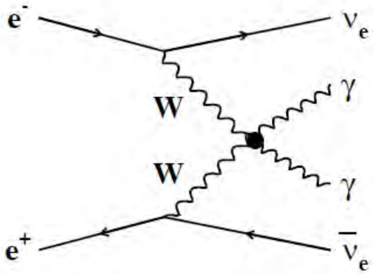


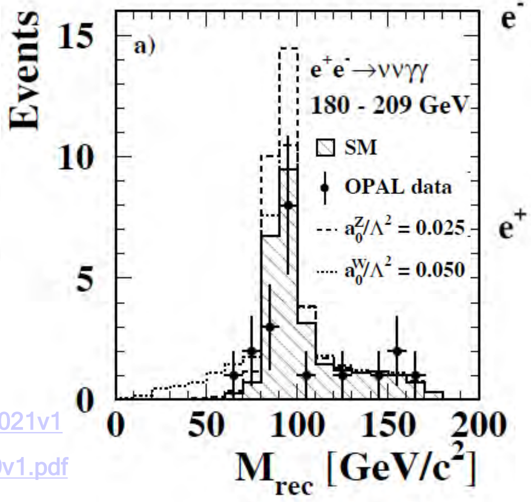
- So, perhaps the Higgs is not fundamental, but composite, bound by a 5th short-ranged Force? And maybe the W and Z, too?

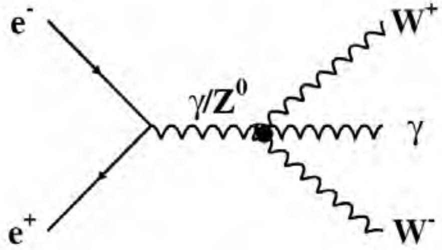
- Think at composite pions, and pion-pion scatteriung unitarized by hadronic (e.g. ρ) resonances!

1. QGC observation: Pre-LHC

❖ „observed“ QGC Processes at LEP: $e^+e^- \rightarrow \nu\nu\gamma\gamma$ and $W^+W^-\gamma$



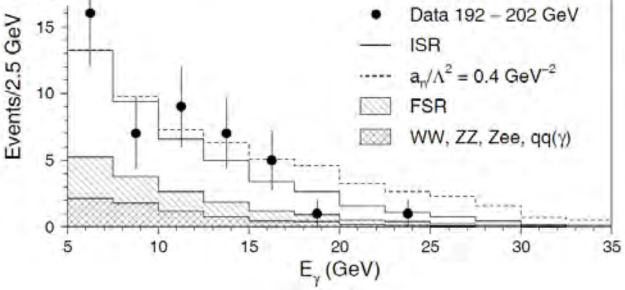




OPAL: http://arxiv.org/abs/hep-ex/0309013

L3: http://arxiv.org/pdf/hep-ex/0111029v1.pdf

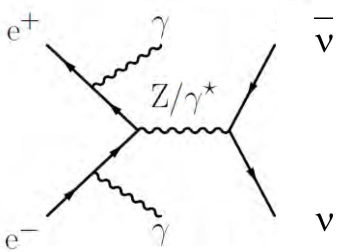
DELPHI: http://arxiv.org/pdf/hep-ex/0311004v1.pdf

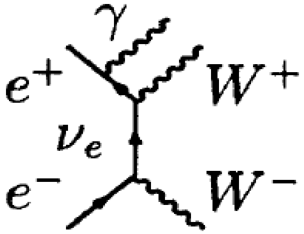


OPAL: http://arxiv.org/abs/hep-ex/0402021v1

L3: http://arxiv.org/pdf/hep-ex/0111029v1.pdf

- significant observation with small/negligble background
- But: consistent with ISR / FSR processes,
  which can be gauge-invariantly distinguished from QGC Processes





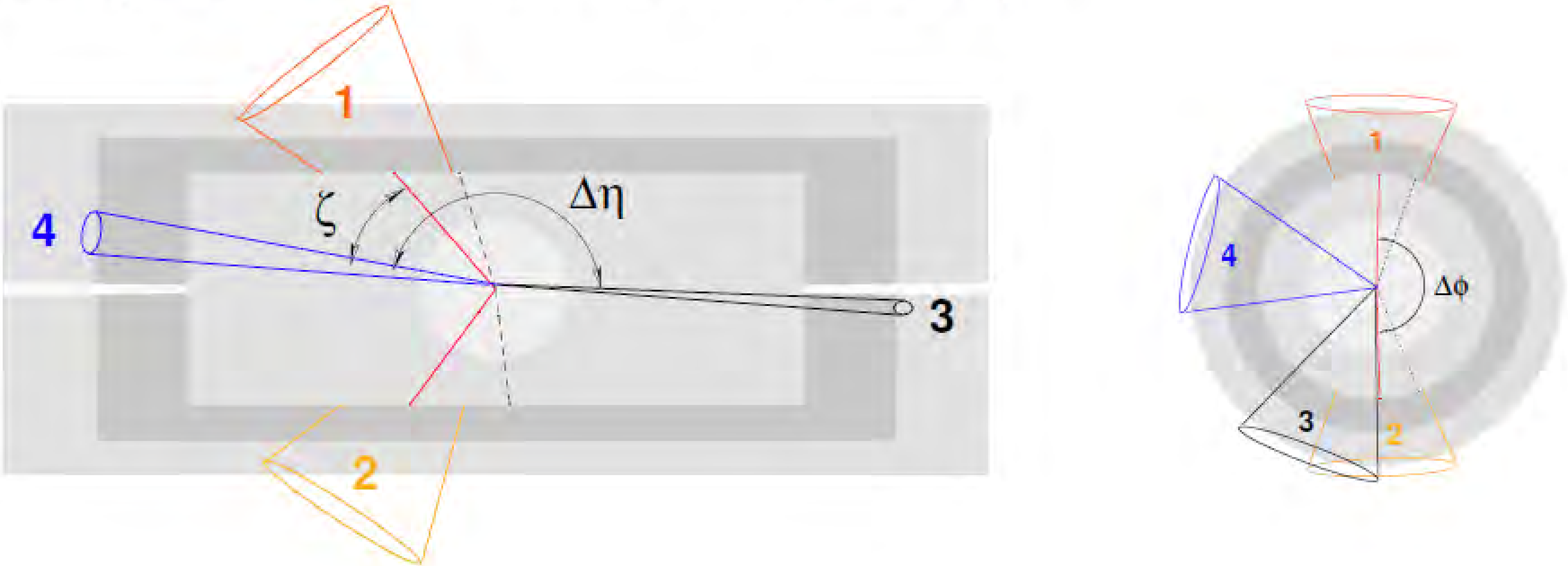
At $\sqrt{s}$= 200 GeV,
$\sigma_{WW\gamma}$ = 304 fb (QGCs included)
$\sigma_{WW\gamma}$ = 318 fb (QGCs excluded)
(M.Musy, Moriond 2001)

❖ → No „real“ observation of any QGC process at LEP (nor at Tevatron)

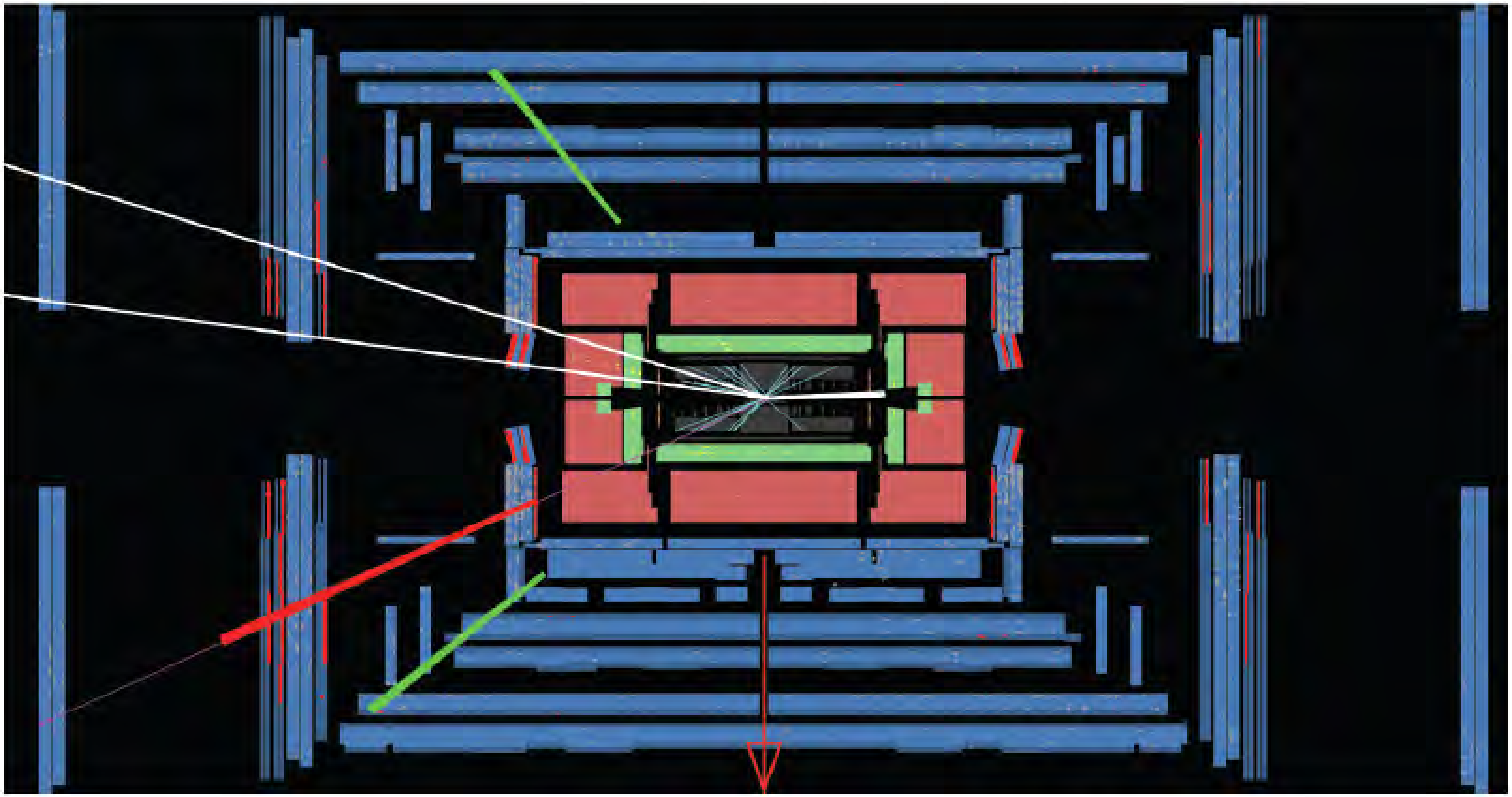
Signal Topology (leptonic final states)

- 2 high-energy „tagging" jets (#3, #4)
  - Dominantly very forward, large $\Delta\eta$ (>~3) between them
  - Large invariant m_{jj} (>~ 500 GeV)
- 2 (for WW), 3(for WZ) or 4 (for ZZ) leptons
  - Lying (mostly) „between" tagging jets, (centrality ζ ~> 0)

$$\zeta_{ll} \equiv \min\left\{\min\{\eta_1^l,\eta_2^l\} - \min\{\eta_1^{jet},\eta_2^{jet}\}, \max\{\eta_1^{jet},\eta_2^{jet}\} - \max\{\eta_1^l,\eta_2^l\}\right\}$$



Example for WZ-jj → $\mu^+\nu\ e^+e^-$-jj



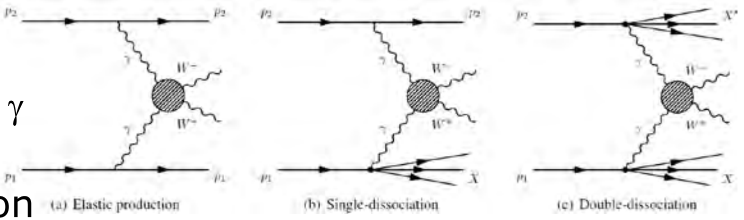
RunNumber: 204073
EventNumber: 16071790

jet1: $p_T = 170$ GeV, $\eta = 4.0$
jet2: $p_T = 38$ GeV, $\eta = -2.3$
$M_{jj} = 1713$ GeV

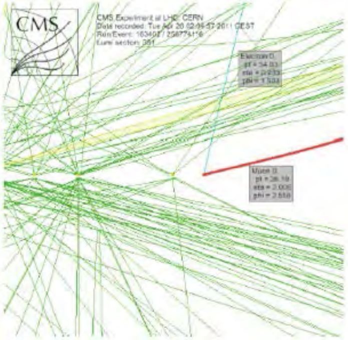
$p_T^{e^-} = 96$ GeV
$p_T^{e^+} = 87$ GeV
$M(e^+, e^-) = 92$ GeV
$p_T^{\mu^+} = 155$ GeV

„Exclusive“ $\gamma\gamma \rightarrow WW$, JHEP 07 (2013) 216

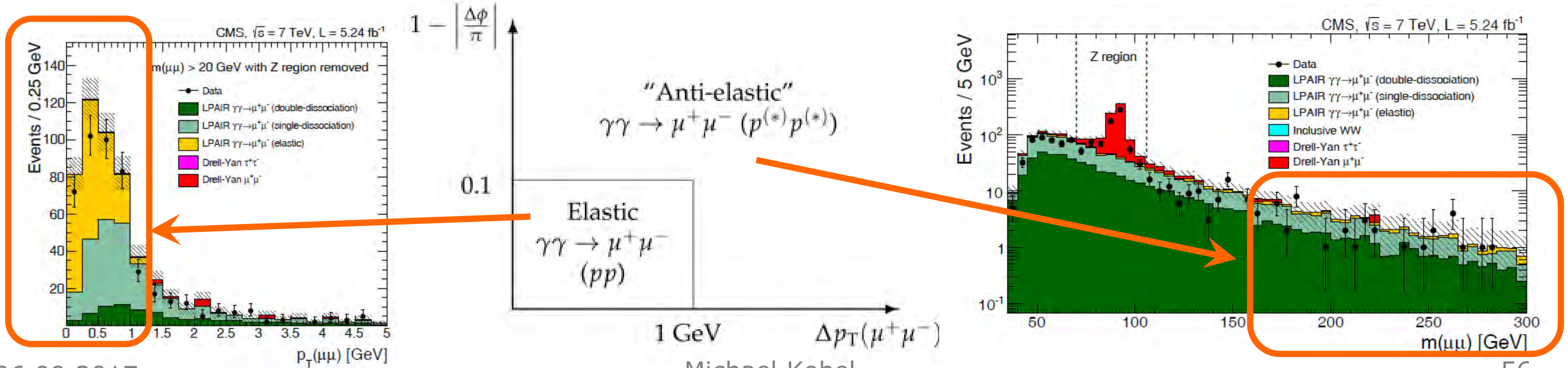
- **First VV→VV analysis at LHC: $\gamma\gamma \rightarrow WW$**
  CMS, 7+8 TeV, 5+20 fb^{-1}: https://arxiv.org/pdf/1604.04464v2.pdf
  - Via exclusive or quasi-exclusive W^+W^- production $pp \rightarrow p^{(*)}\,\gamma\gamma\, p^{(*)} \rightarrow p^{(*)}\, W^+W^-\, p^{(*)} \rightarrow p^{(*)}\, e^+\nu\, \mu^-\nu\, p^{(*)}$ jj γ in mixed flavor eμ channel
  - Both very forward-scattered protons escape detection



- Two major selection criteria
  - 0 extra tracks from vertex
  - p_T (eμ) > 30 GeV
  - Bins for aQGC: $p_T\,(e\mu) \in [30;130], [130;\infty]$ GeV



- Important control sample: $\gamma\gamma \rightarrow \mu^+\mu^-$ and e^+e^-
  - derive pp-rescattering effect on 0-track cut from data
  - Quasi-exclusive → dissociation $p^{(*)}$ scaling factor F=4.1±0.4 for $m_{\mu\mu} > 160$ GeV

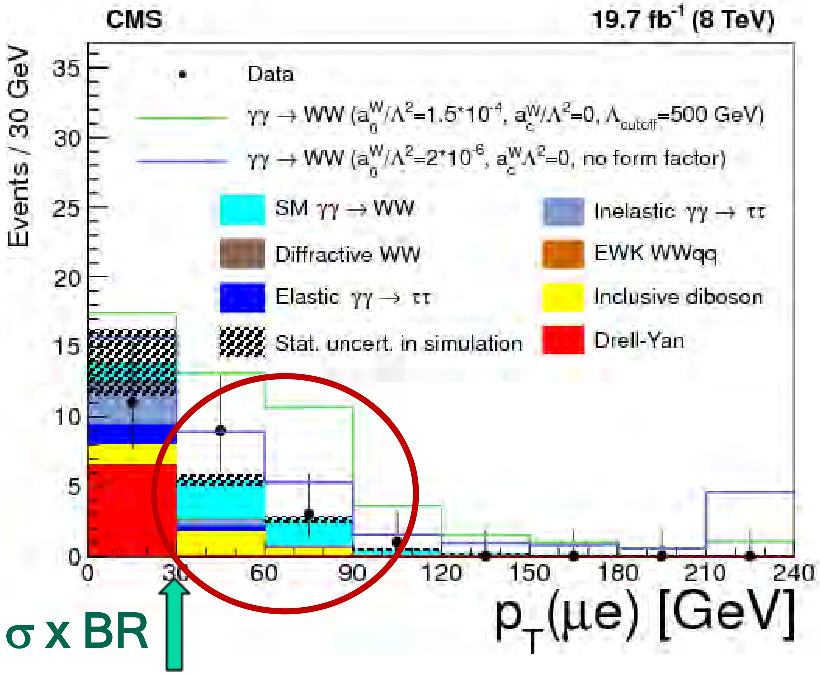


candidate events and cross-section

- Remaining background from control regions
  - Before p_T (eμ) > 30 GeV : ττ (from Drell-Yan and γγ)
  - After p_T (eμ) > 30 GeV : Di-Boson, esp. W^+W^-

- Event yield 7+8 TeV
  - Expected bckgr: 4.7 ± 0.6
  - Expected signal: 7.5 ± 0.7
  - Observed: 15

- Significances (expected)
  - 7 TeV: 0.8 (1.8) s.d.
  - 8 TeV: 3.2 (2.1) s.d.
  - 7+8 TeV: 3.4 (2.8) s.d.



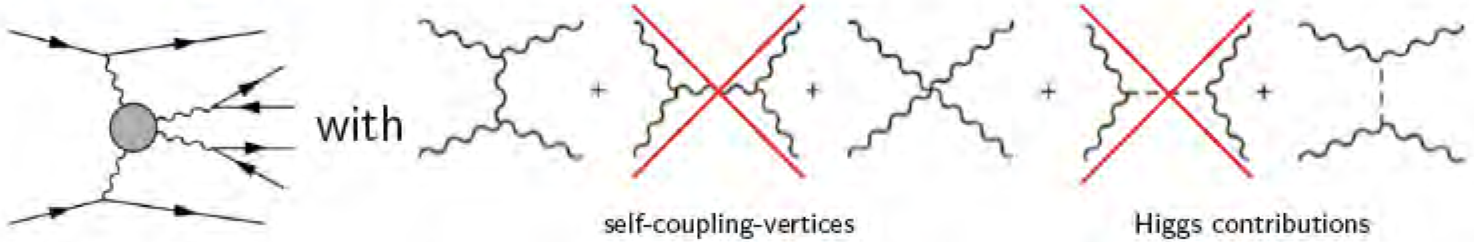
Cut for σ x BR

- Cross-sections extrapolated to full P.S at 8 TeV (7 TeV)
  - Predicted: σxBR = 6.2±0.5 fb (4.0±0.7 fb)
  - Measured: σxBR = $10.8_{-4.1}^{+5.1}$ fb ($2.2_{-2.0}^{+3.3}$ fb)

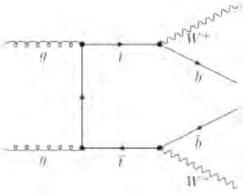
advantages of $W^\pm W^\pm jj$

- Contributing signal in Standard Model:

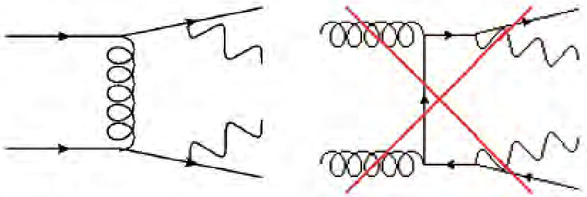
VBS Diagrams



- Charactristics of same-sign $W^\pm W^\pm jj$
  - No top background, would be opposite sign: $\bar{t}t \rightarrow W^+W^-jj$



  - Very low $W^\pm W^\pm jj$-QCD background :
    no initial state gg possible



  - Main background from WZjj-QCD (missing ℓ) or Wjj (fake ℓ)

Two analysis phase spaces

❖ Inclusive Region (EW:QCD ~ 3.5:1)

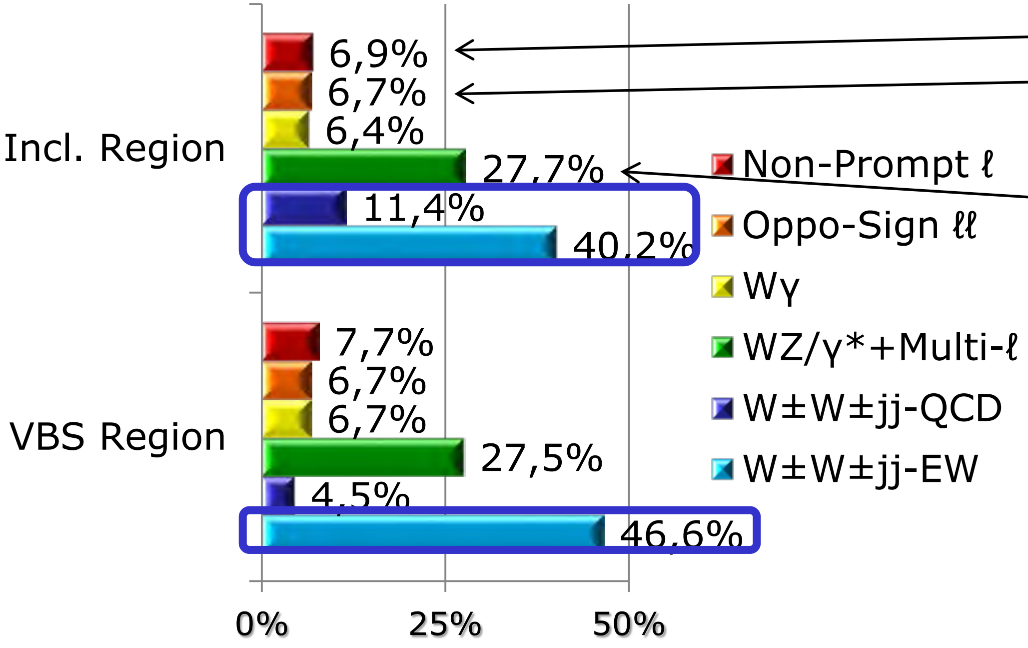
- **Exactly 2(e/μ):** $p_T > 25$ GeV
- **Neutrinos:** $p_T^{miss} > 40$ GeV
- **≥2 non-b Jets:** $p_T > 30$ GeV, $m_{jj} > 500$ GeV
- Other cuts: $m_{\ell\ell}>20$GeV, $\Delta R_{iso}(\ell)>0.3$, Z→ee veto

Measure $W^{\pm}W^{\pm}jj$ (incl. EW, QCD)

❖ VBS Region (EW : QCD ~ 10 : 1)

- **Rapidity gap:** $\Delta y_{jj} > 2.4$

Measure $W^{\pm}W^{\pm}jj$ EW and set aQGC limits

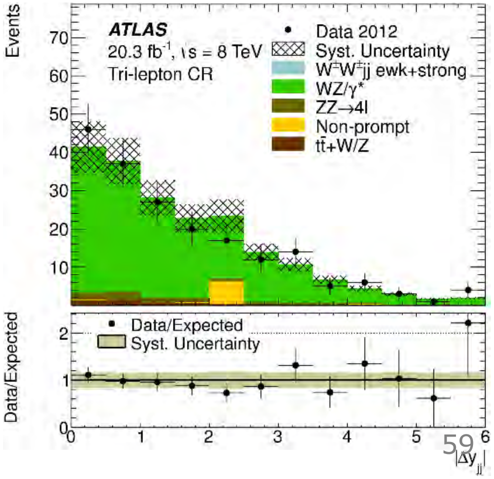


❖ Data driven background

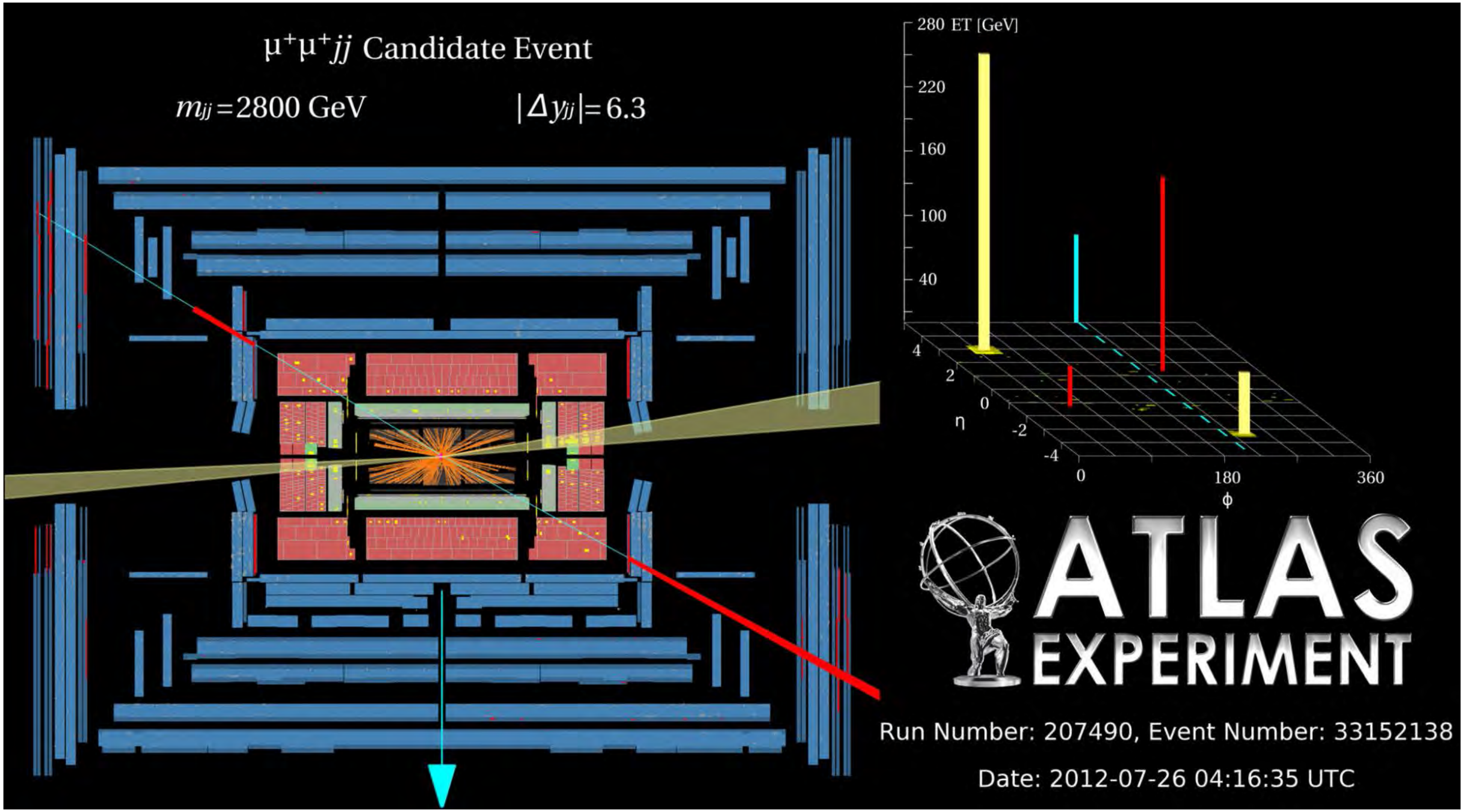
- Fake leptons (W+Jets, …)
- Charge mis-ID (Z+jets,…)

❖ Control regions

- Lost lepton (WZ/γ*+Jets, …)
- …



Candidate event

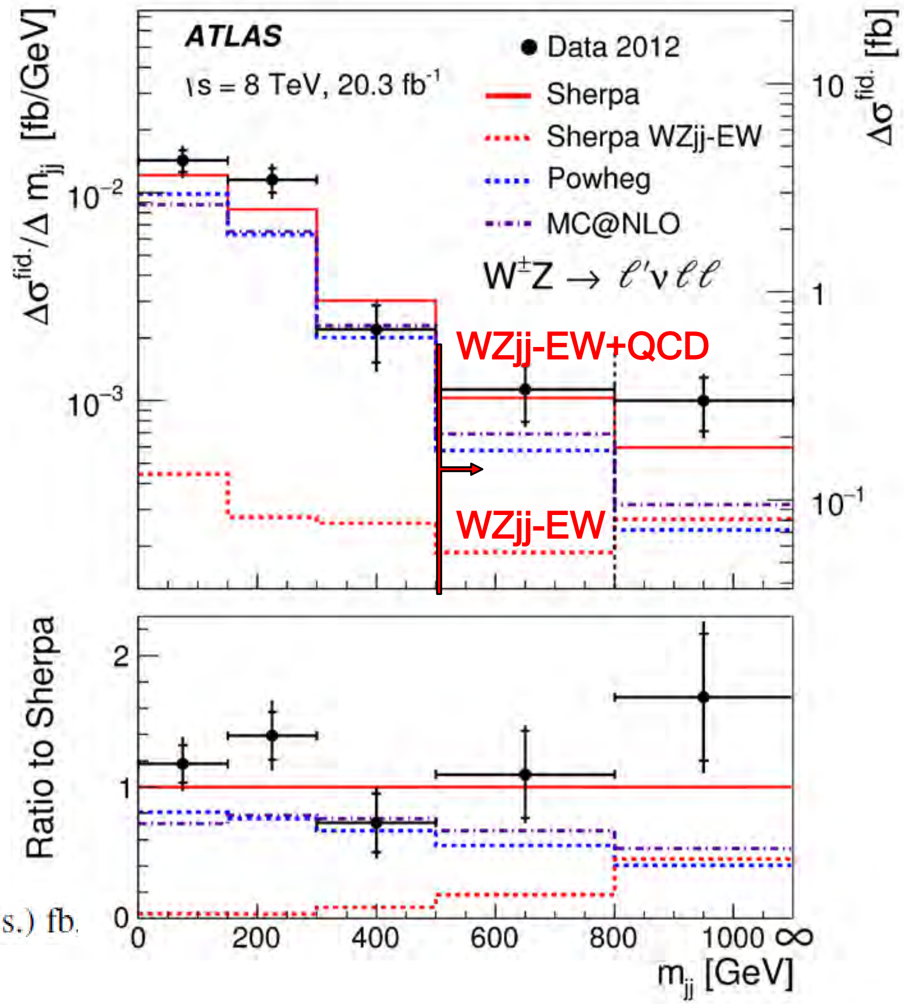


- $p_T(j_1)$ = 271 GeV, $p_T(j_2)$ =54 GeV

First Search for WZ/γ → WZ

- WZjj-EW is part of the 8 TeV inclusive ATLAS WZ paper
    - Inclusive WZ selection cuts +
    - 2 jets $p_T > 30$ GeV, $\eta < 4.5$
    - $m_{jj} > 500$ GeV
- Obs.(exp.) signif. 1.9(1.0) s.d.
    - 70% background WZjj-QCD
    - 10% Ztj -> ZW-bj
    - Expected signal: 7.4 evts
    - Obs. above bckg: 15.2 evts

Selection	VBS	aQGC
Data	45	9
Total Expected	37.2 ± 1.1	4.9 ± 0.3
WZjj-EW	7.4 ± 0.2	1.1 ± 0.1
WZjj-QCD	20.8 ± 0.8	2.8 ± 0.3
tZ	3.0 ± 0.1	0.3 ± 0.0
Misid. leptons	2.5 ± 0.6	0.1 ± 0.1
ZZ	1.9 ± 0.3	0.2 ± 0.1
$t\bar{t} + V$	1.6 ± 0.1	0.3 ± 0.0



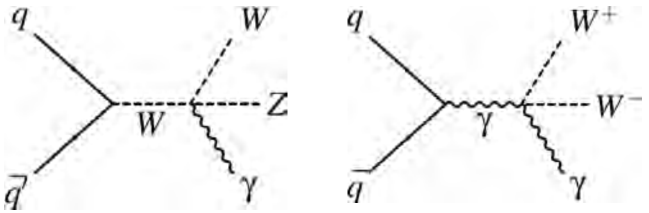
cross section for $WZjj$-EW production of $0.29^{+0.14}_{-0.12}$ (stat.) $^{+0.09}_{-0.1}$ (sys.) fb.
expectation of 0.13 ± 0.01 fb from VBFNLO

Triple Boson production at LHC

first accessible WWγ, WZγ, W$\gamma\gamma$, Z$\gamma\gamma$ …, later VVV

❖ First VVV analysis at LHC: WVγ = WZγ + WWγ → $\ell\nu$ jj γ

- CMS https://arxiv.org/abs/1404.4619
- 8 TeV data, 19.3 fb^{-1}
- Background dominated
- Limits on d=6 and d=8 aQGCs



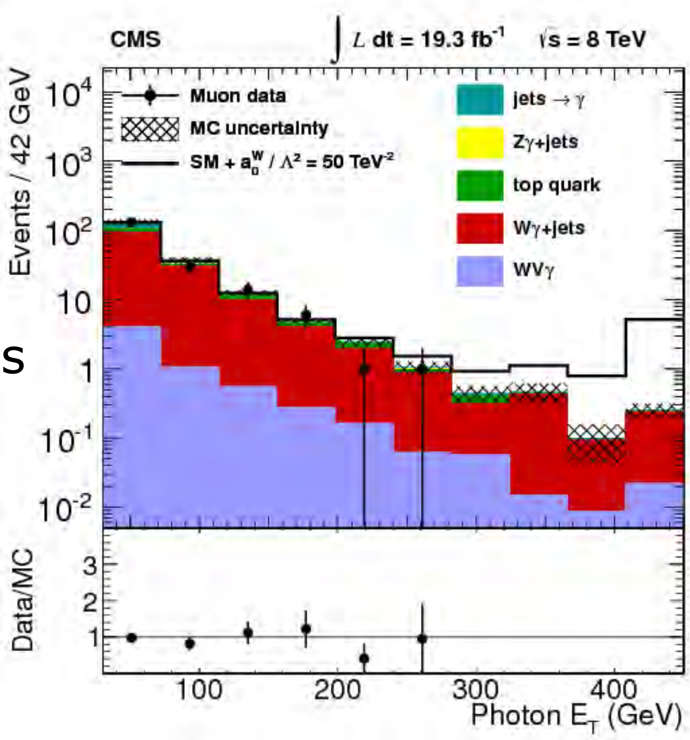
❖ main selection cuts

- $\ell\nu$: E_T^{miss} > 35 GeV, p_T >25(μ)-30(e) GeV
- jj: p_T >30 GeV, 70 GeV < m_{jj} < 100 GeV
- γ: p_T >30 GeV

❖ Main (75%) background and syst.: Wγ+jets

❖ Expected SM signal: 7 (5) events in μ (e)

- Observed: 183 (139) in μ (e)
- Expected: 194±12 (148±11) in μ(e)
- Cross-section limit 311 fb@95% = 3.4xSM



aQGC limits from WVγ

- Sensitive to aQGC in WWγγ and WWZγ vertices
- Limits on d=6 and d=8 aQGCs, setting all others to Zero

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

WWγγ WWZγ contributions

  - Transformation between d=6 and d=8: $\frac{q_i}{\Lambda^4} = \frac{8a_i}{\Lambda^2 M_W^2}$

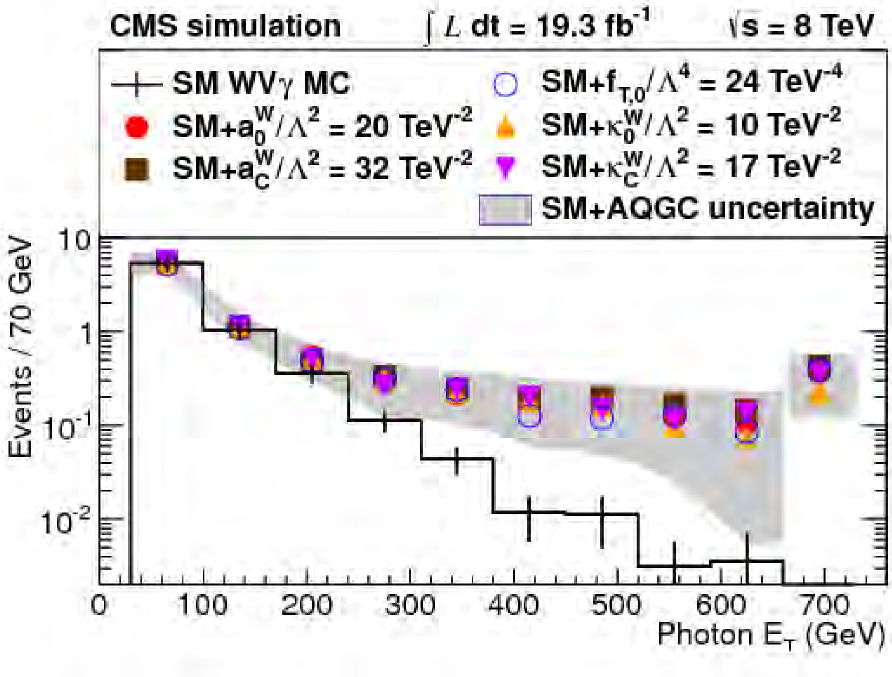
- Discriminating variable
  - high Photon E_T

- **Observed (~ expected) limits without unitarization**

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

  - Example: for $a_0^W = 1$

$$\Lambda_{WW\gamma\gamma} > \sqrt{\frac{a_0^W}{20}}TeV \approx 220GeV$$



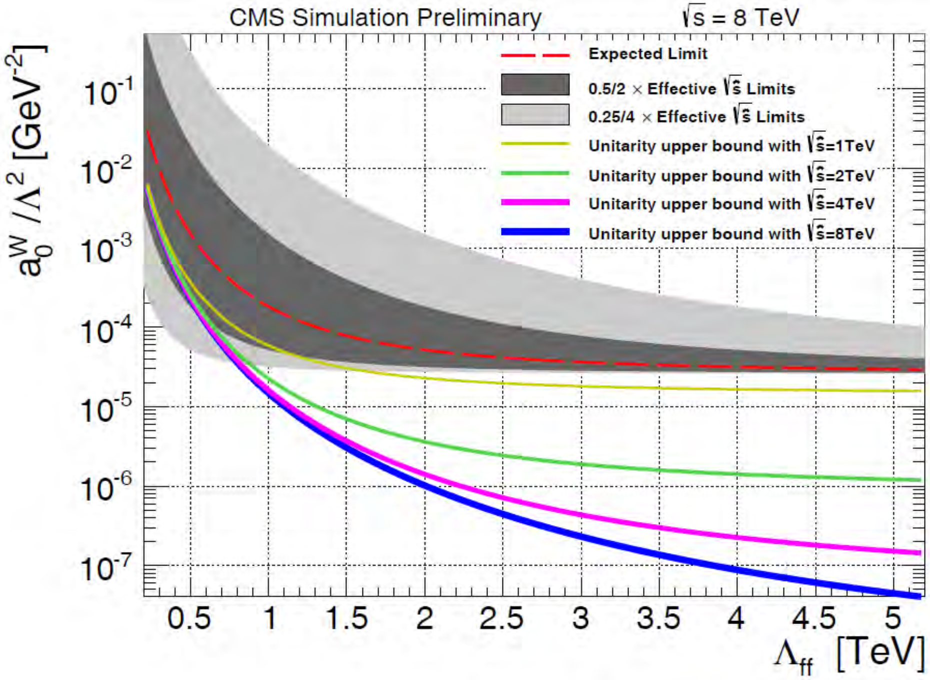
Unitarity issue

- But: any non-zero aQGC will violate unitarity
- Unitarization attempt: dipole form factor with n=2

$$\mathcal{F}(s) = \frac{1}{(1 + \hat{s}/\Lambda_{\mathrm{FF}}^2)^n}$$

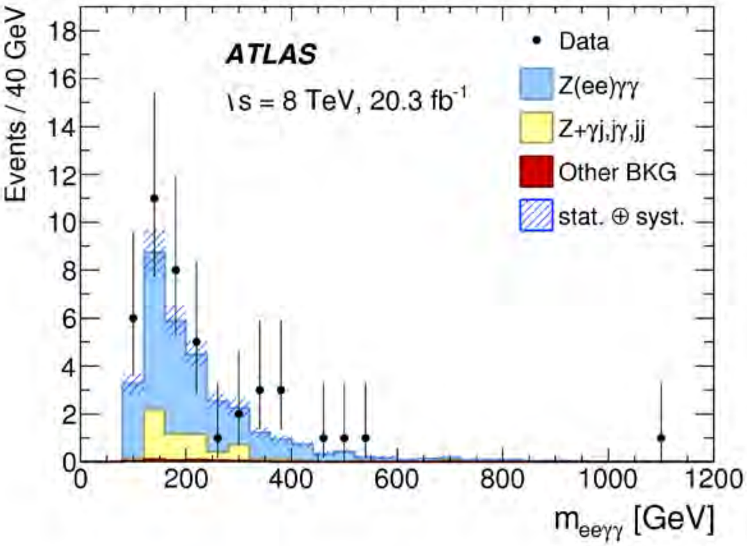
  - Damps high-ŝ events to **zero**, little effect on low-ŝ events
  - Plot: approx 2→2 unitarity upper bounds .vs. Λ_{FF} for several √ŝ

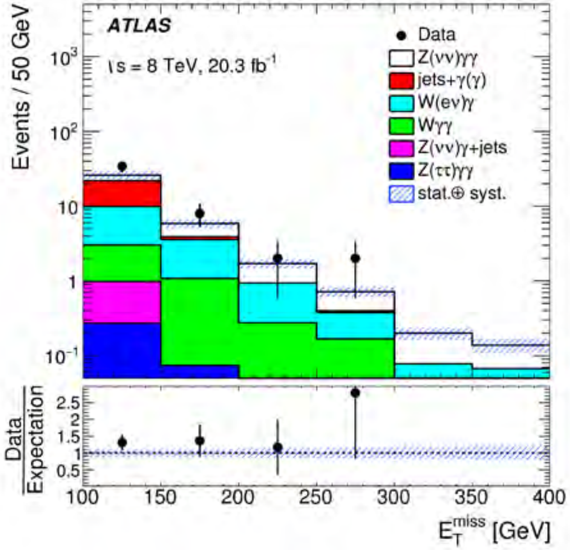
- Conclusion
  - typically √ŝ = 2 TeV for the values of aQGC parameters close to measured limit (green curve)
  - Expected ~ observed limit (dashed red line) always above this unitarity limit
  - **Limit is in non-unitary region, no matter which Λ_{FF} is chosen**

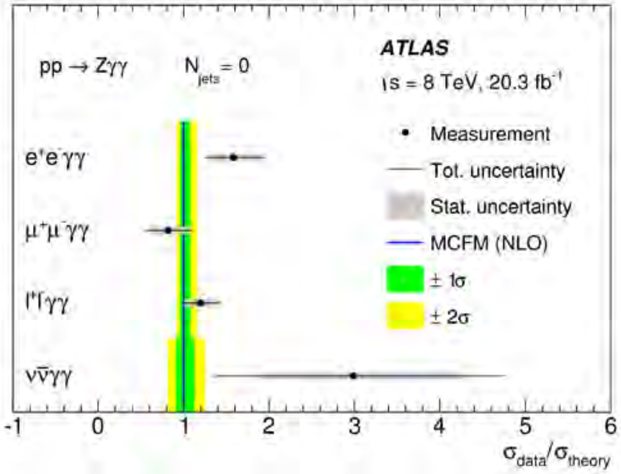


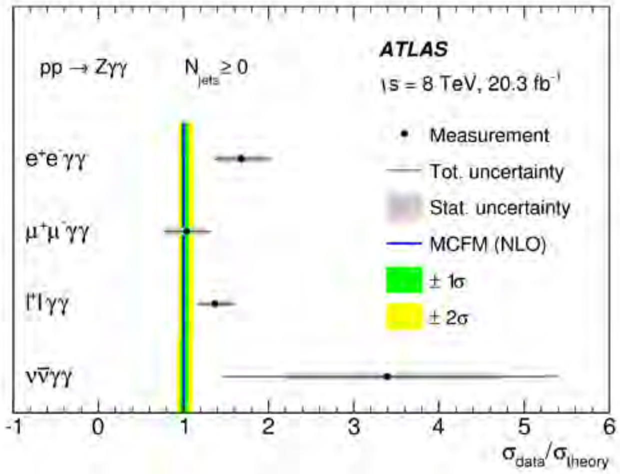
Z$\gamma\gamma$ (ATLAS)

- ATLAS: x-section in 0 and ≥0 jet, and Z→$\nu\nu$ (for aQGC)



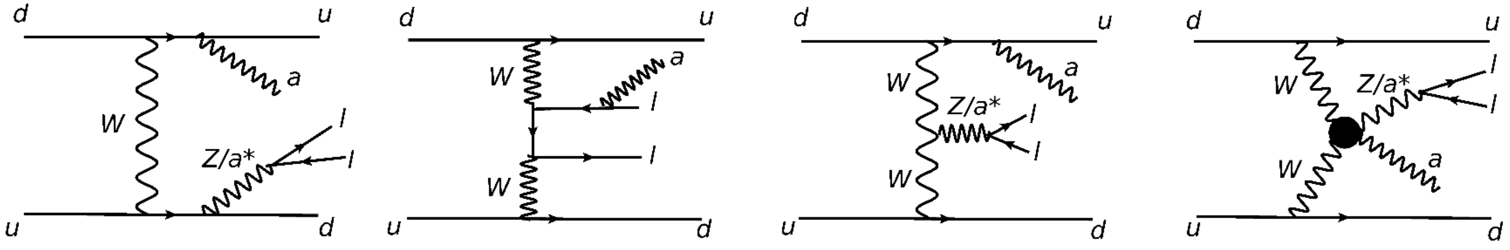




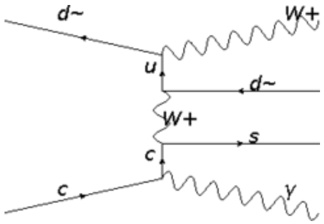


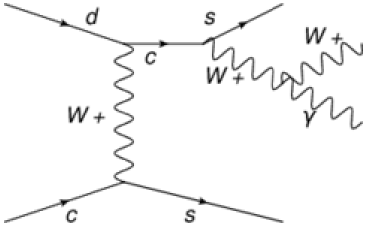
Wγjj and Zγjj (CMS)

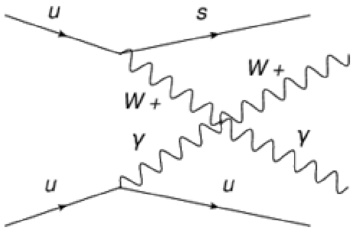
- Both contain Quartic Gauge Vertex



(a) Bremsstrahlung (b) Multiperipheral (c) VBF with TGC (d) VBF with QGC







- Wγjj

μ(e) + γ+ $\not{E}_T$ + 2 jets

Allow τ-lepton decays to μ,e

Major Backgrounds:

QCD Wγ+jets, Fake Photons

Zγjj

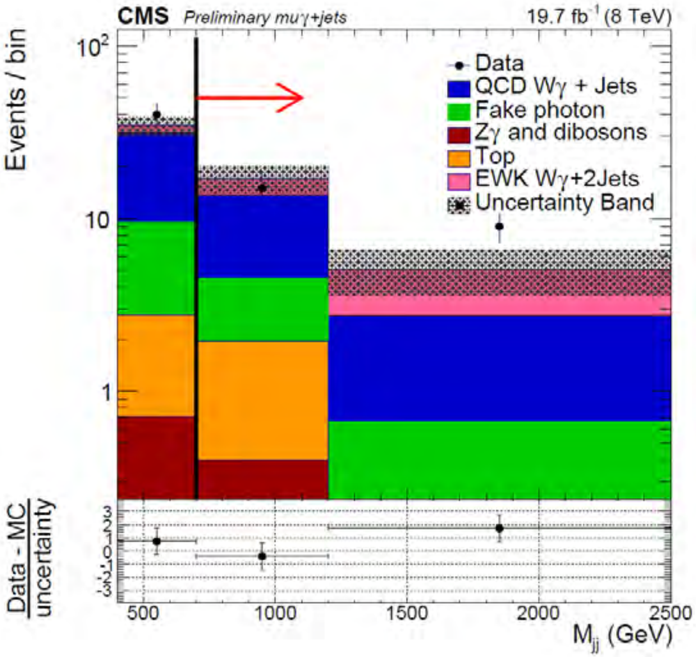
$\mu\mu$(ee) + γ + 2 jets

Allow τ-lepton decays to μ,e

Major Backgrounds:

QCD Zγ + Jets, Fake Photons

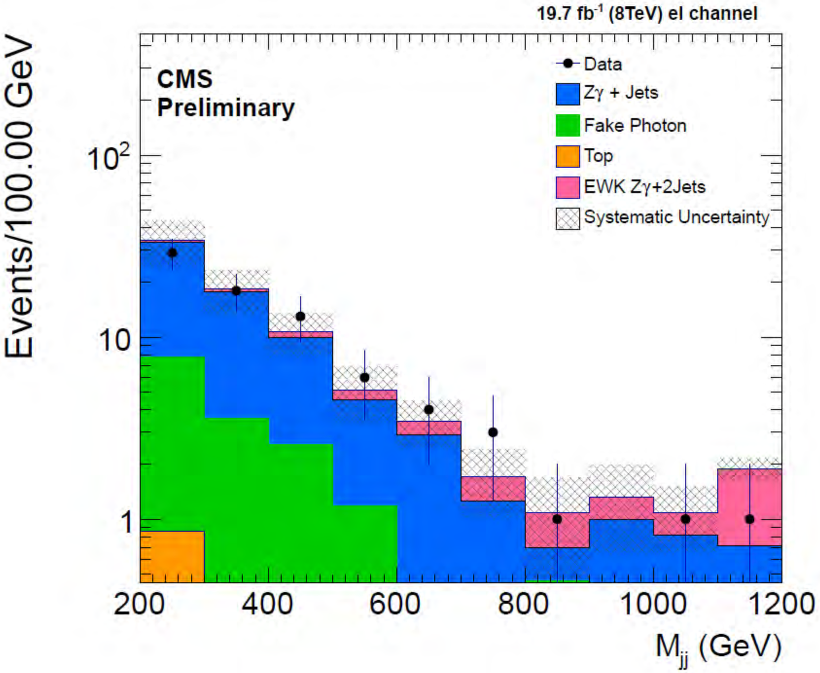
- Wγjj https://cds.cern.ch/record/2124432/



- EW signal strength: $\mu = 1.8_{-0.8}^{+1.0}$

- Significance (expected): 2.7 (1.5) s.d.

Zγjj https://cds.cern.ch/record/2048148/



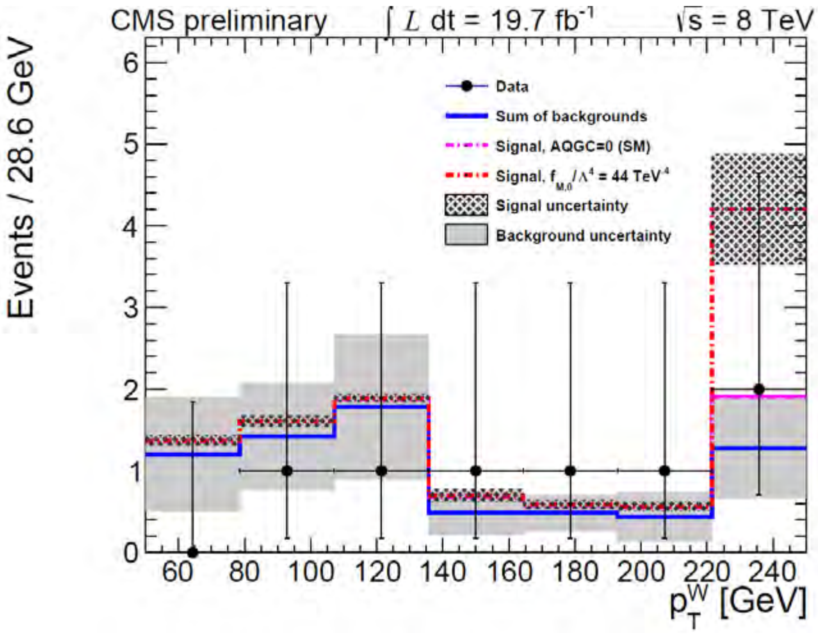
cross-section for m_{jj}>800 GeV: MADGRAPH: $0.78 \pm 0.09(scale) \pm 0.02(PDF)$
observed: $1.00 \pm 0.43(stat.) \pm 0.26(syst.) \pm 0.03(lumi.)$ fb,

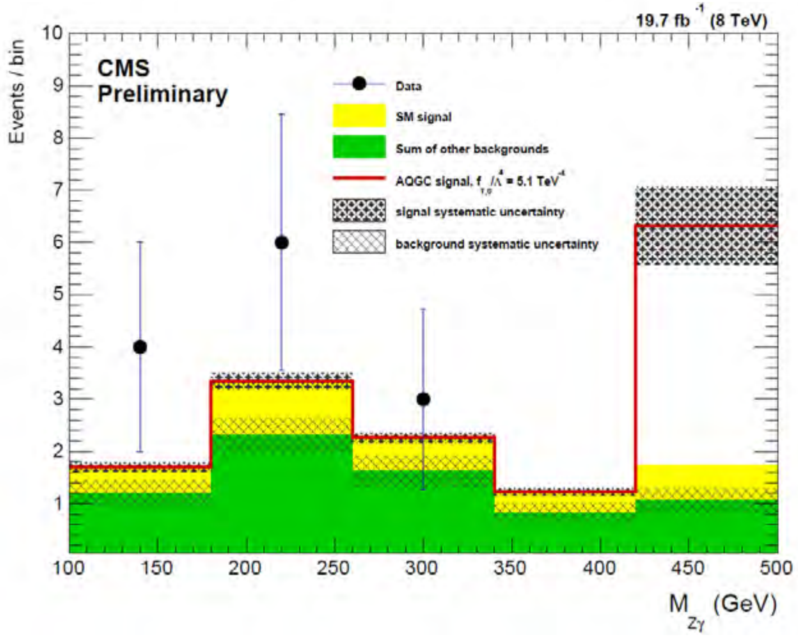
Significance (expected): 4.5 (4.3) s.d.

❖ aQGC limits from „overflow“ at large p_T^W or $m_{Z\gamma}$ in restricted PS

- $M_{jj} > 700$ GeV, $|\Delta\eta(j,j)| > 2.4$,
- $|y_{W\gamma} - (y_{j1} + y_{j2})/2.0| < 1.2$
- $p_T^\gamma > 200$ GeV
- $\not{E}_T > 20$ GeV,

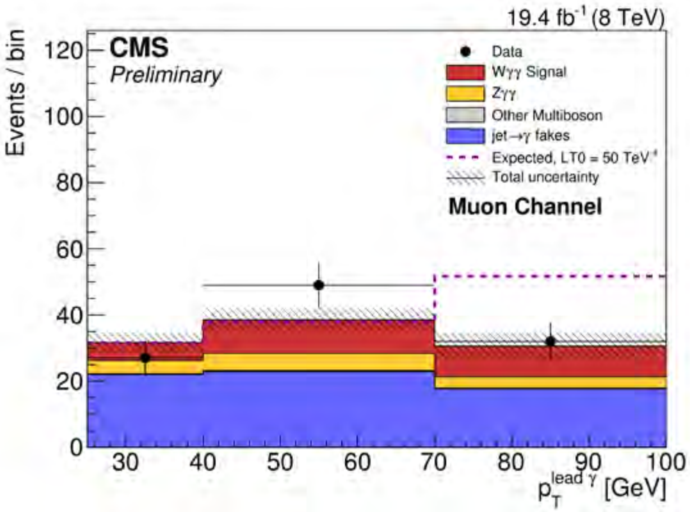
- $p_T^{j1,j2} > 30$ GeV, $|\eta^{j1,j2}| < 4.7$
- $M_{jj} > 400$ GeV, $\Delta\eta_{jj} > 2.5$
- $p_T^{l1,2} > 20$ GeV, $|\eta^{l1,l2}| < 2.4$
- 70 GeV $< M_{ll} <$ 110 GeV
- $p_T^\gamma > 60$ GeV, $|\eta^\gamma| < 1.4442$

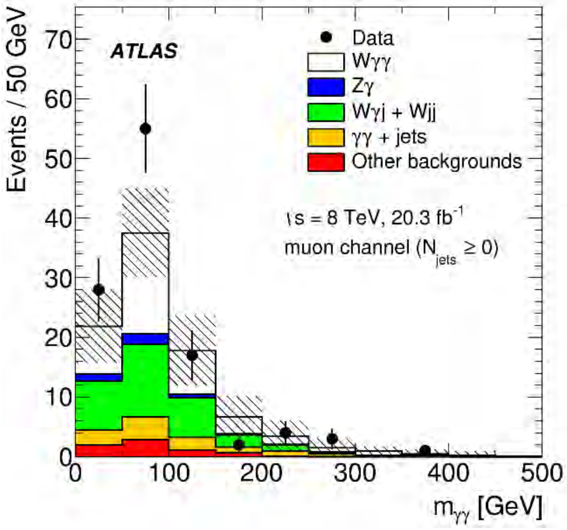




W$\gamma\gamma$ (ATLAS, CMS)

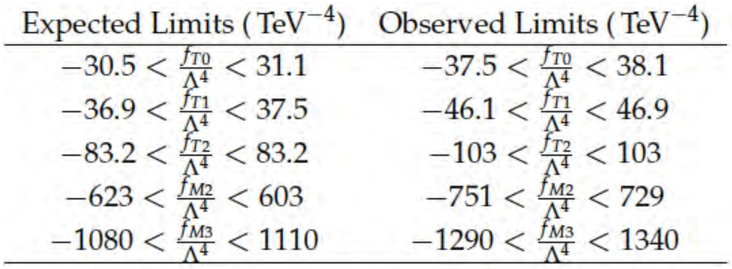
- Seen with 2.4 s.d. in CMS and 3 s.d. in ATLAS
  https://cds.cern.ch/record/2130360/files/SMP-15-008-pas.pdf https://arxiv.org/pdf/1503.03243v2.pdf



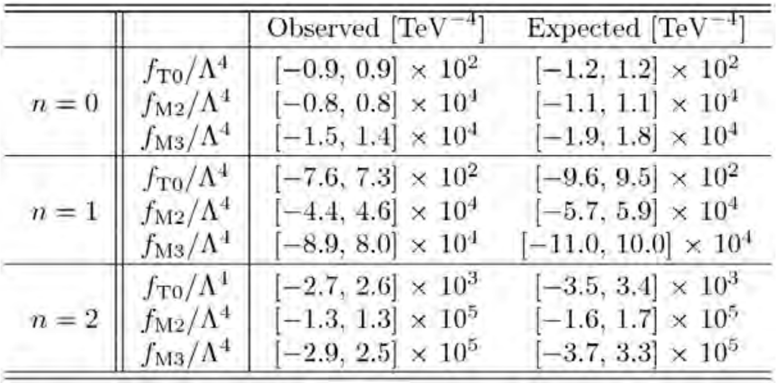


- aQGC: CMS from Z$\gamma\gamma$ + W$\gamma\gamma$

ATLAS from W$\gamma\gamma$ alone



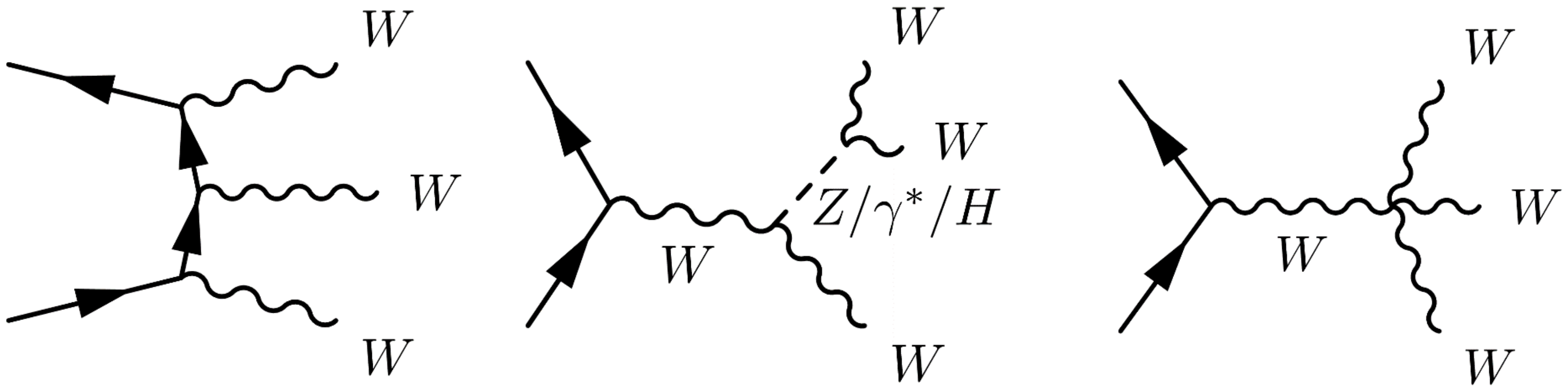
Expected Limits (TeV^{-4})	Observed Limits (TeV^{-4})
$-30.5 < \frac{f_{T0}}{\Lambda^4} < 31.1$	$-37.5 < \frac{f_{T0}}{\Lambda^4} < 38.1$
$-36.9 < \frac{f_{T1}}{\Lambda^4} < 37.5$	$-46.1 < \frac{f_{T1}}{\Lambda^4} < 46.9$
$-83.2 < \frac{f_{T2}}{\Lambda^4} < 83.2$	$-103 < \frac{f_{T2}}{\Lambda^4} < 103$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



		Observed [TeV^{-4}]	Expected [TeV^{-4}]
$n = 0$	f_{T0}/Λ^4	$[-0.9, 0.9] \times 10^2$	$[-1.2, 1.2] \times 10^2$
	f_{M2}/Λ^4	$[-0.8, 0.8] \times 10^4$	$[-1.1, 1.1] \times 10^4$
	f_{M3}/Λ^4	$[-1.5, 1.4] \times 10^4$	$[-1.9, 1.8] \times 10^4$
$n = 1$	f_{T0}/Λ^4	$[-7.6, 7.3] \times 10^2$	$[-9.6, 9.5] \times 10^2$
	f_{M2}/Λ^4	$[-4.4, 4.6] \times 10^4$	$[-5.7, 5.9] \times 10^4$
	f_{M3}/Λ^4	$[-8.9, 8.0] \times 10^4$	$[-11.0, 10.0] \times 10^4$
$n = 2$	f_{T0}/Λ^4	$[-2.7, 2.6] \times 10^3$	$[-3.5, 3.4] \times 10^3$
	f_{M2}/Λ^4	$[-1.3, 1.3] \times 10^5$	$[-1.6, 1.7] \times 10^5$
	f_{M3}/Λ^4	$[-2.9, 2.5] \times 10^5$	$[-3.7, 3.3] \times 10^5$

NEW: WWW (ATLAS)

- First search for VVV triboson production, paper imminent (today?)
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-07/



Leptonic Selection

- Exactly 3 leptons $p_T > 20$ GeV
- Maximally 1 jet $p_T > 25$ GeV
- $\Delta\Phi(lll, p_T^{miss}) > 2.5$
- No b-jet
- Z rejection cuts on m_{ll} and E_T^{miss}

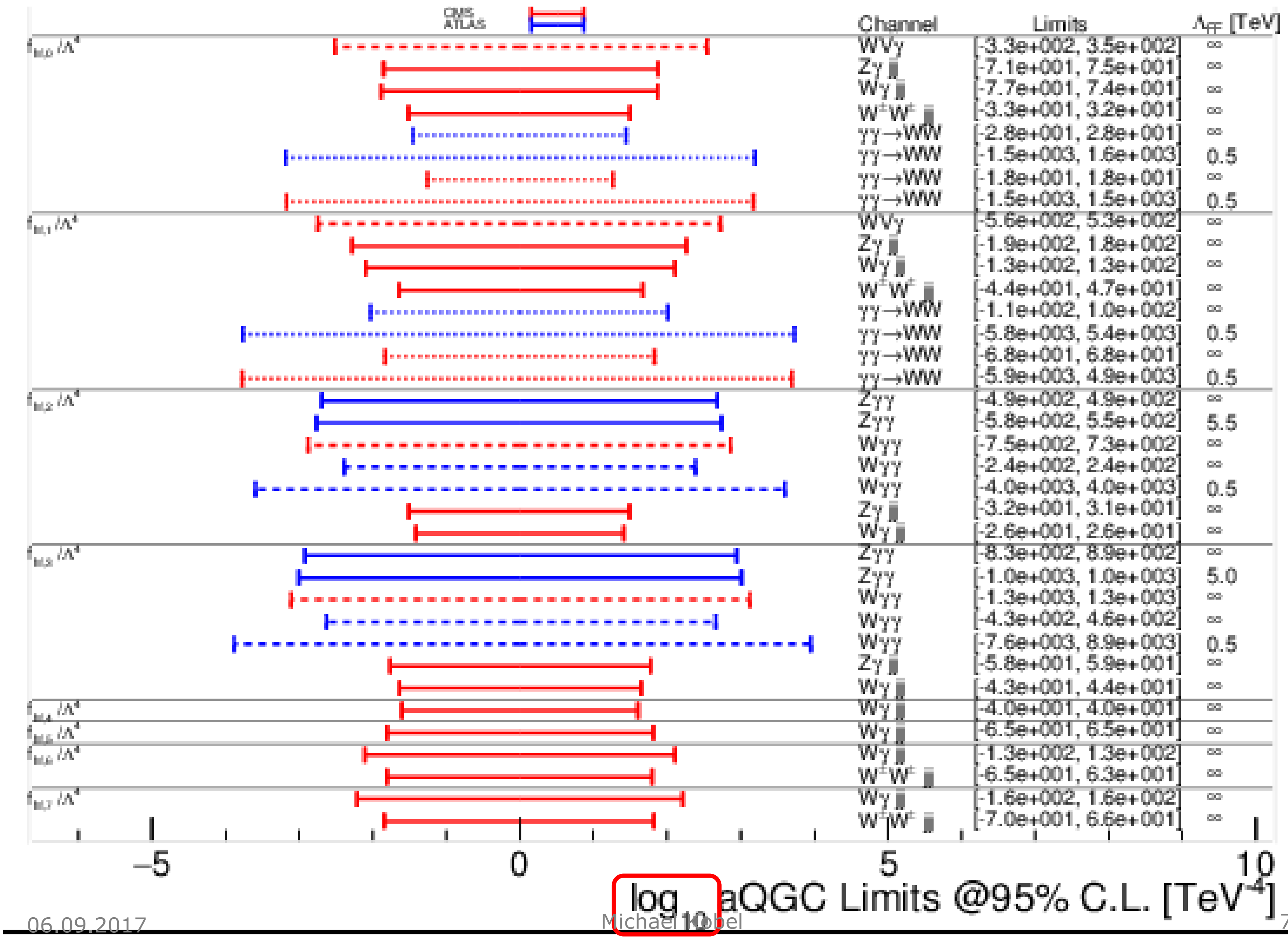
Hadronic Selection

- Exactly 2 same charge leptons $p_T > 30$ GeV
- 2 jets $p_T^{lead} > 30$ GeV, $p_T^{sublead} > 30$ GeV, 65 GeV $< m_{jj} <$ 105 GeV, $|\eta_{jj}| < 1.5$
- No b-jet
- $m_{ll} > 40$ GeV
- Z rejection cuts in channels with e^-

For f=1: Λ=1TeV Λ=100 GeV

Limits on f_M/Λ^4

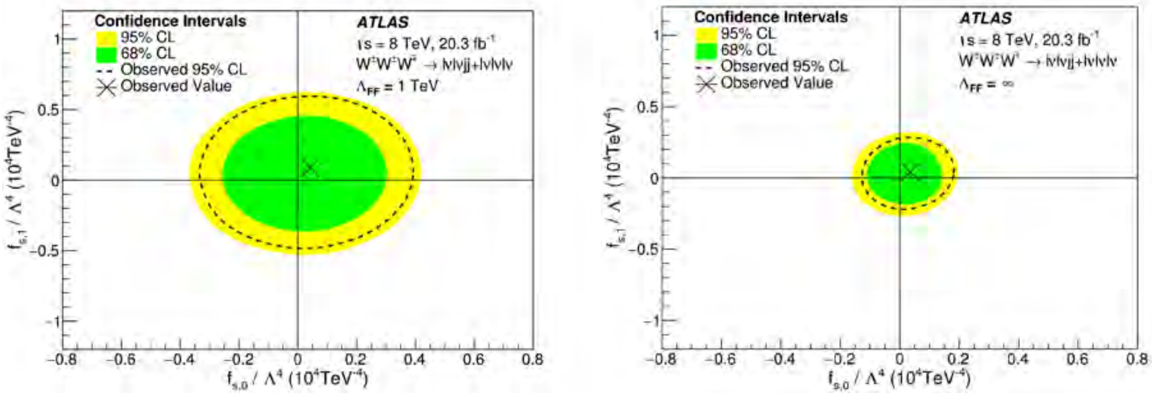
Mostly un-unitarized ($\Lambda_{FF}=\infty$)



	Channel	Limits	Λ_{FF} [TeV]
$f_{M,0}/\Lambda^4$	$WV\gamma$	[-3.3e+002, 3.5e+002]	∞
	$Z\gamma$	[-7.1e+001, 7.5e+001]	∞
	$W\gamma$	[-7.7e+001, 7.4e+001]	∞
	$W^{\pm}W^{\pm}$	[-3.3e+001, 3.2e+001]	∞
	$\gamma\gamma\to WW$	[-2.8e+001, 2.8e+001]	∞
	$\gamma\gamma\to WW$	[-1.5e+003, 1.6e+003]	0.5
	$\gamma\gamma\to WW$	[-1.8e+001, 1.8e+001]	∞
	$\gamma\gamma\to WW$	[-1.5e+003, 1.5e+003]	0.5
$f_{M,1}/\Lambda^4$	$WV\gamma$	[-5.6e+002, 5.3e+002]	∞
	$Z\gamma$	[-1.9e+002, 1.8e+002]	∞
	$W\gamma$	[-1.3e+002, 1.3e+002]	∞
	$W^{\pm}W^{\pm}$	[-4.4e+001, 4.7e+001]	∞
	$\gamma\gamma\to WW$	[-1.1e+002, 1.0e+002]	∞
	$\gamma\gamma\to WW$	[-5.8e+003, 5.4e+003]	0.5
	$\gamma\gamma\to WW$	[-6.8e+001, 6.8e+001]	∞
	$\gamma\gamma\to WW$	[-5.9e+003, 4.9e+003]	0.5
$f_{M,2}/\Lambda^4$	$Z\gamma\gamma$	[-4.9e+002, 4.9e+002]	∞
	$Z\gamma\gamma$	[-5.8e+002, 5.5e+002]	5.5
	$W\gamma\gamma$	[-7.5e+002, 7.3e+002]	∞
	$W\gamma\gamma$	[-2.4e+002, 2.4e+002]	∞
	$W\gamma\gamma$	[-4.0e+003, 4.0e+003]	0.5
	$Z\gamma$	[-3.2e+001, 3.1e+001]	∞
	$W\gamma$	[-2.6e+001, 2.6e+001]	∞
$f_{M,3}/\Lambda^4$	$Z\gamma\gamma$	[-8.3e+002, 8.9e+002]	∞
	$Z\gamma\gamma$	[-1.0e+003, 1.0e+003]	5.0
	$W\gamma\gamma$	[-1.3e+003, 1.3e+003]	∞
	$W\gamma\gamma$	[-4.3e+002, 4.6e+002]	∞
	$W\gamma\gamma$	[-7.6e+003, 8.9e+003]	0.5
	$Z\gamma$	[-5.8e+001, 5.9e+001]	∞
	$W\gamma$	[-4.3e+001, 4.4e+001]	∞
$f_{M,4}/\Lambda^4$	$W\gamma$	[-4.0e+001, 4.0e+001]	∞
$f_{M,5}/\Lambda^4$	$W\gamma$	[-6.5e+001, 6.5e+001]	∞
$f_{M,6}/\Lambda^4$	$W\gamma$	[-1.3e+002, 1.3e+002]	∞
	$W^{\pm}W^{\pm}$	[-6.5e+001, 6.3e+001]	∞
$f_{M,7}/\Lambda^4$	$W\gamma$	[-1.6e+002, 1.6e+002]	∞
	$W^{\pm}W^{\pm}$	[-7.0e+001, 6.6e+001]	∞

- Extraction of aQGC possible
  - Issue with unknown unitarity limit (not yet calculable for 1->3) -> limits derived with different Form-Factors

Λ_{FF} [TeV]	Expected CI [$\times 10^4$ TeV^{-4}] $f_{S,0}/\Lambda^4$	Expected CI [$\times 10^4$ TeV^{-4}] $f_{S,1}/\Lambda^4$	Observed CI [$\times 10^4$ TeV^{-4}] $f_{S,0}/\Lambda^4$	Observed CI [$\times 10^4$ TeV^{-4}] $f_{S,1}/\Lambda^4$
0.5	$[-0.81, 0.89]$	$[-1.00, 1.29]$	$[-0.77, 0.85]$	$[-1.01, 1.22]$
1	$[-0.37, 0.42]$	$[-0.52, 0.62]$	$[-0.31, 0.39]$	$[-0.48, 0.58]$
2	$[-0.24, 0.26]$	$[-0.33, 0.40]$	$[-0.19, 0.24]$	$[-0.29, 0.37]$
3	$[-0.19, 0.22]$	$[-0.29, 0.36]$	$[-0.16, 0.21]$	$[-0.25, 0.32]$
∞	$[-0.16, 0.19]$	$[-0.25, 0.31]$	$[-0.13, 0.18]$	$[-0.21, 0.27]$



  - Sensitivity to f_S parameters not competitive with VBS channels
  - Conversion of $\Lambda_{FF} = \infty$ limits into α_4 and α_5 yields e.g.

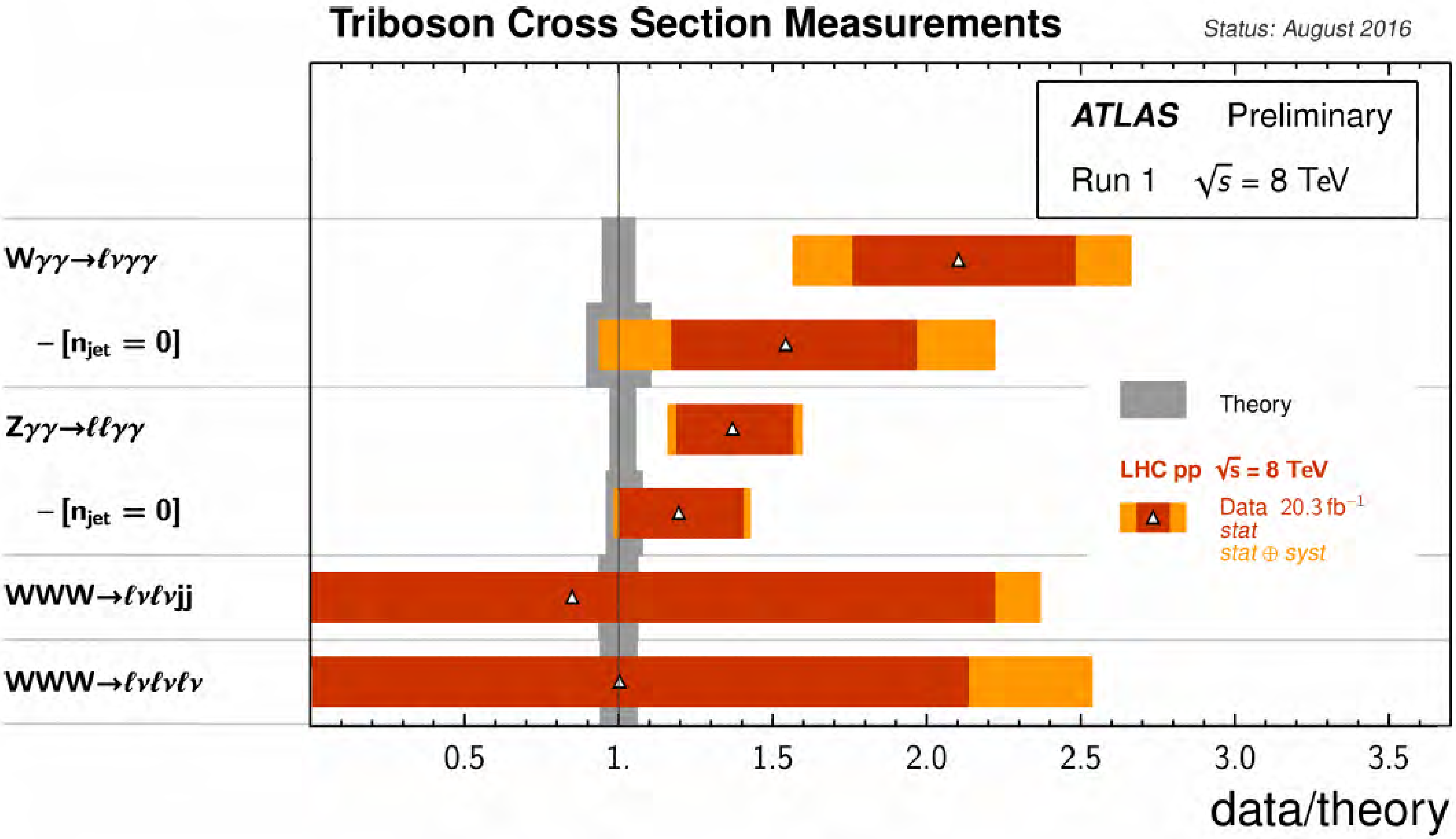
α_4 expected $[-0.62, 0.80]$, observed $[-0.49, 0.75]$

α_5 expected $[-0.58, 0.71]$, observed $[-0.48, 0.62]$

Triboson Summary ATLAS

- This is just the beginning of a new field!

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/ATLAS_k_SMSummary_TriBosonFiducialRatio_Simple/ATLAS_k_SMSummary_TriBosonFiducialRatio_Simple.png



❖ Smallest cross-sections measured at LHC