TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Mathematik und Naturwissenschaften, Fachrichtung Physik

Quartic Gauge Couplings: Tri-Boson Production and Vectorboson Scattering (experimental)

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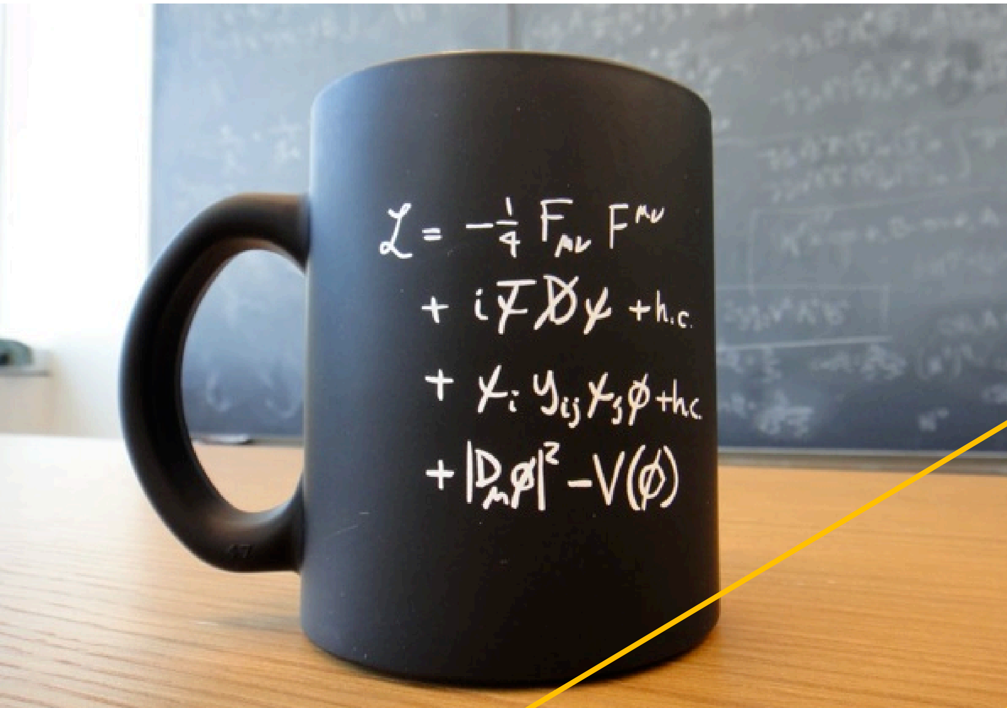
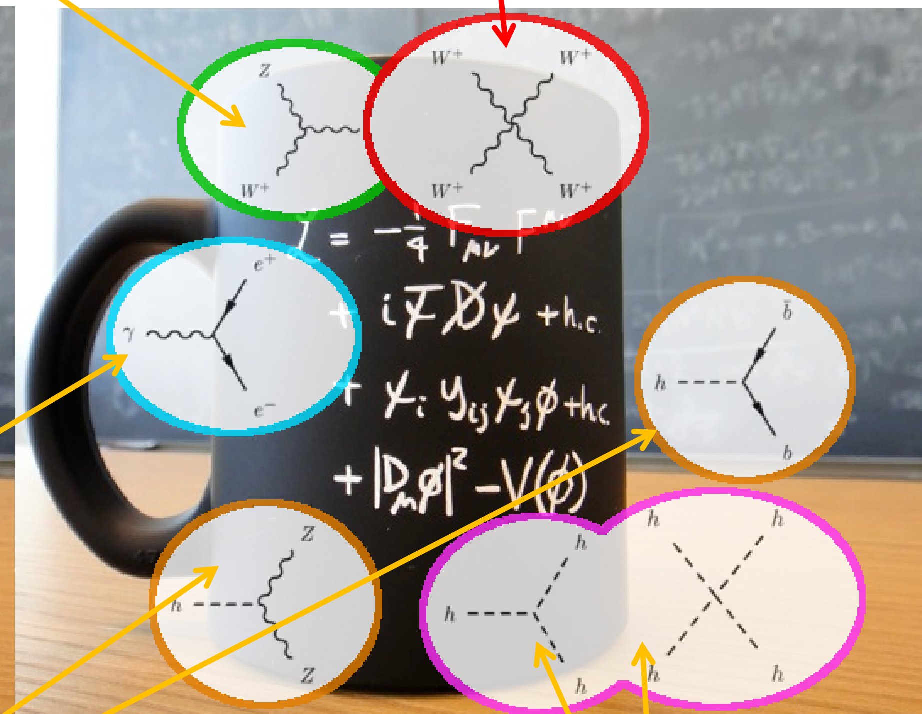
The Standard Model Lagrangian

Precisely checked, e.g. at LEP

Today‘s topic





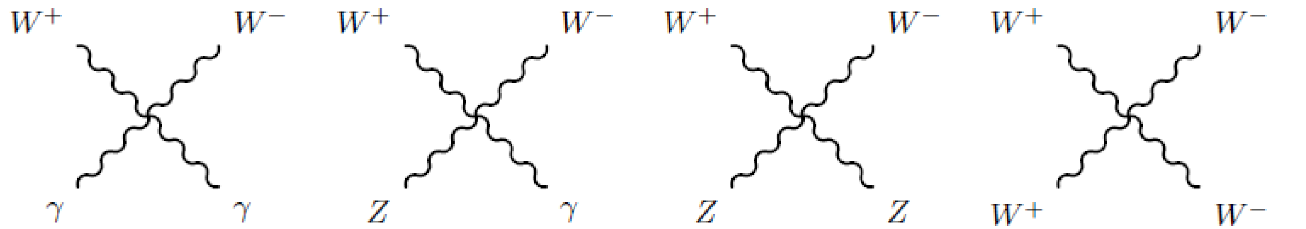
Most frequent and best understood

Recently seen: H→WW,ZZ and H→ ττ, tt

Not yet seen: H→HH and H→ HHH

What can we learn from QGC?

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



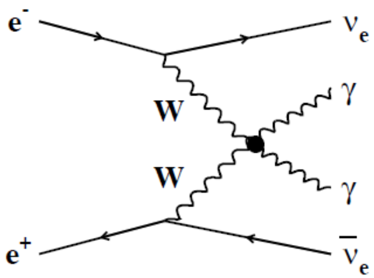
$$\mathcal{L}_{WWVV} = -\frac{g^2}{4}\Big\{[2W_\mu^+ W^{-\mu} + (A_\mu \sin\theta_W - Z_\mu \cos\theta_W)^2]^2$$
$$-[W_\mu^+ W_\nu^- + W_\nu^+ W_\mu^- + (A_\mu \sin\theta_W - Z_\mu \cos\theta_W)(A_\nu \sin\theta_W - Z_\nu \cos\theta_W)]^2\Big\}$$

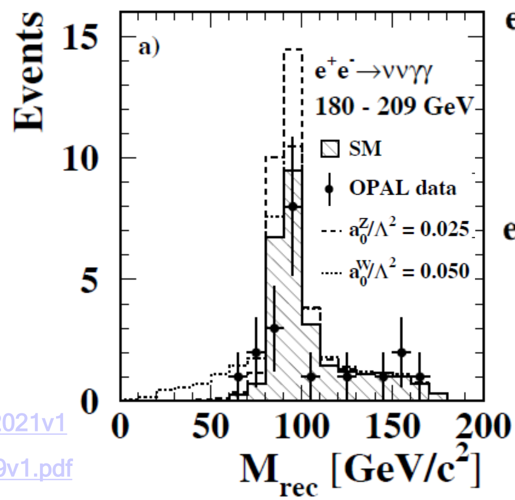
  - no neutral self-couplings in the SM

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

1. QGC observation: Pre-LHC

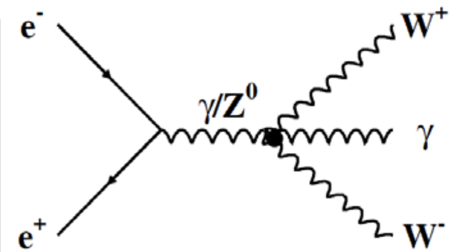
„observed" QGC Processes at LEP: $e^+e^- \rightarrow \nu\nu\gamma\gamma$ and $W^+W^-\gamma$





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

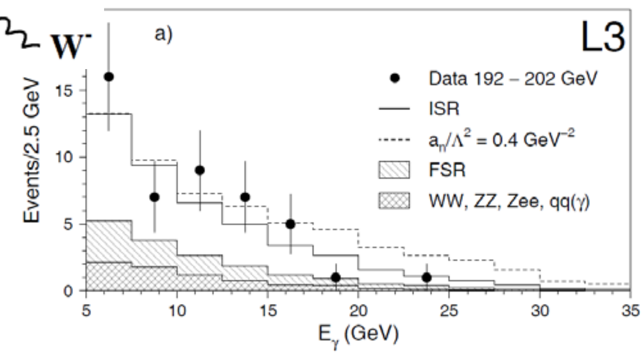
L3: http://arxiv.org/pdf/hep-ex/0111029v1.pdf



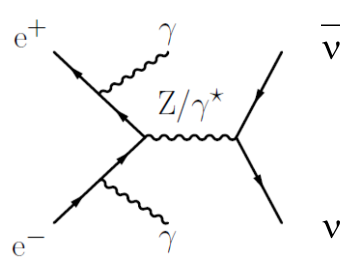
OPAL: http://arxiv.org/abs/hep-ex/0309013

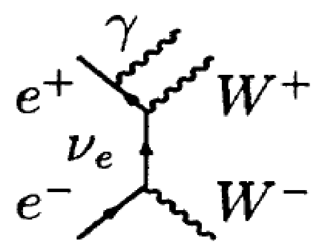
L3: http://arxiv.org/pdf/hep-ex/0111029v1.pdf

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



- 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)

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**

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

  - 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)

Effective QGC in VBS

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

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

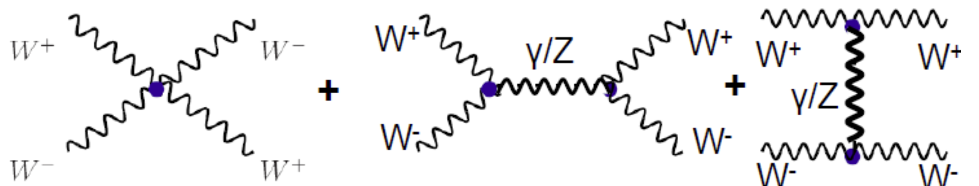
- = Effective parametrization of physics beyond kinematic reach
  - e.g. resonances at new physics scale $\Lambda = \upsilon / \sqrt{\alpha_i}$
    - Wide: → continuum
    - Narrow: → particles
  - α parametrize low-mass tail of these resonances, e.g. $\alpha_5 = g_\sigma^2 \left(\frac{v^2}{8M_\sigma^2}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

	$J=0$	$J=1$	$J=2$
$I=0$	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 ?)	—	$t^{\pm\pm}, t^\pm, t^0$

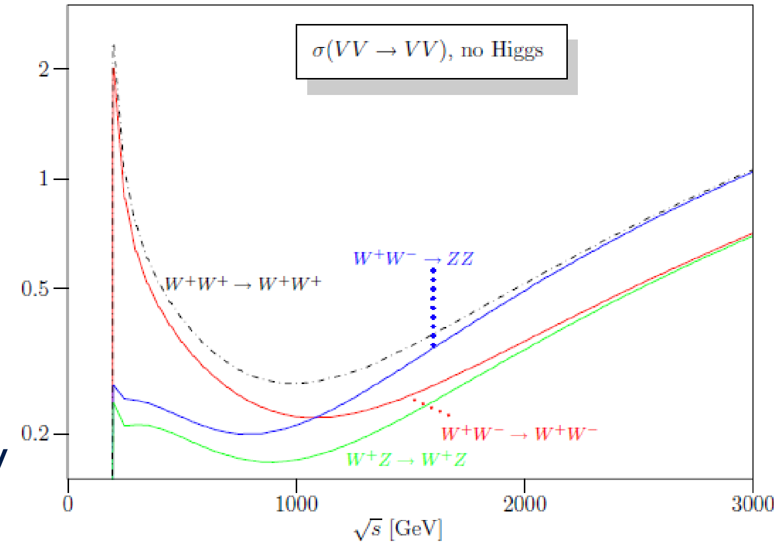
- Unitarization only guaranteed for
  - Explicitly included resonance(s) at unique value(s) of *g*
  - effective parametrization always violates unitarity at some m_{VV}

3. Special Role of the Higgs Boson

❖ VBS Without Higgs contribution:

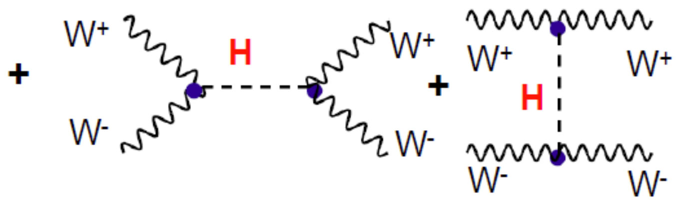


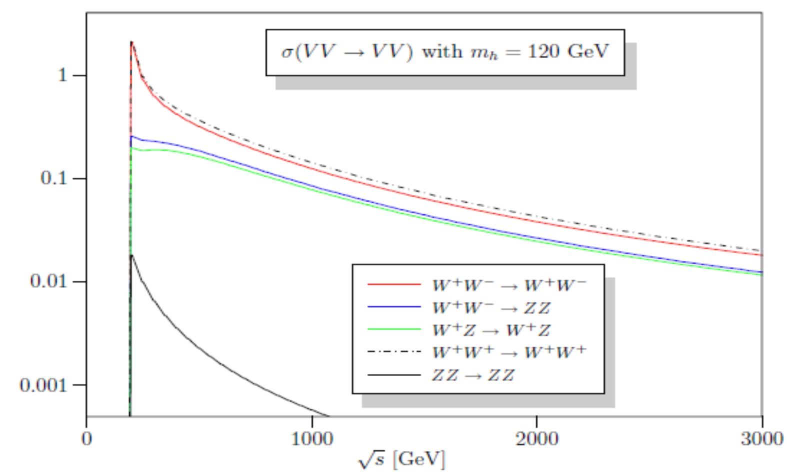
$\sigma_{WW} \propto s^2 \to \infty$ for $s \to \infty$



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

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





- Higgs exactly cancels increase for large s

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

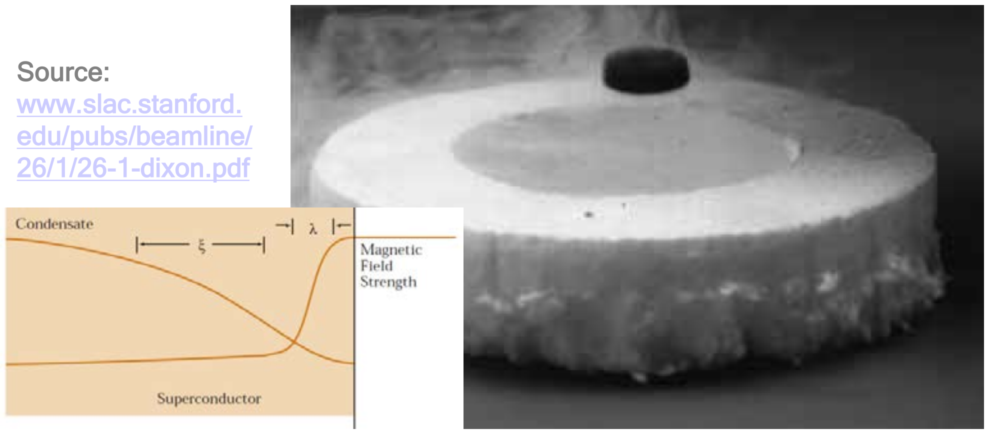
but *only* for SM H-WW coupling!

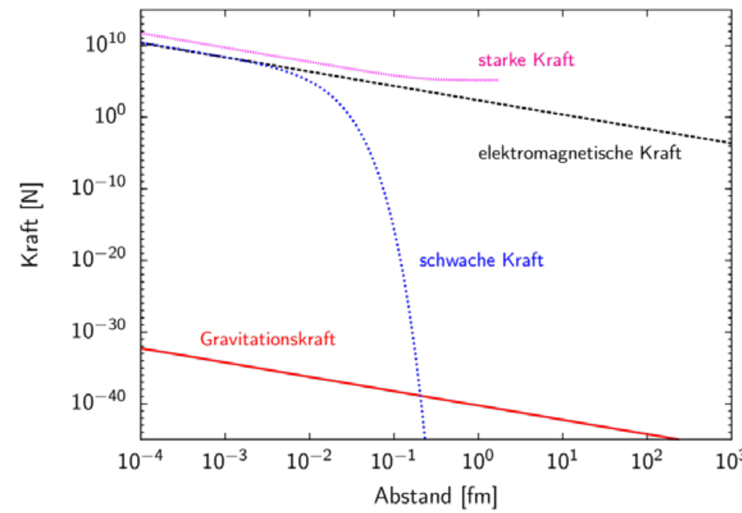
A. Alboteanu, W. Kilian, J. Reuter: http://arxiv.org/abs/0806.4145v1

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

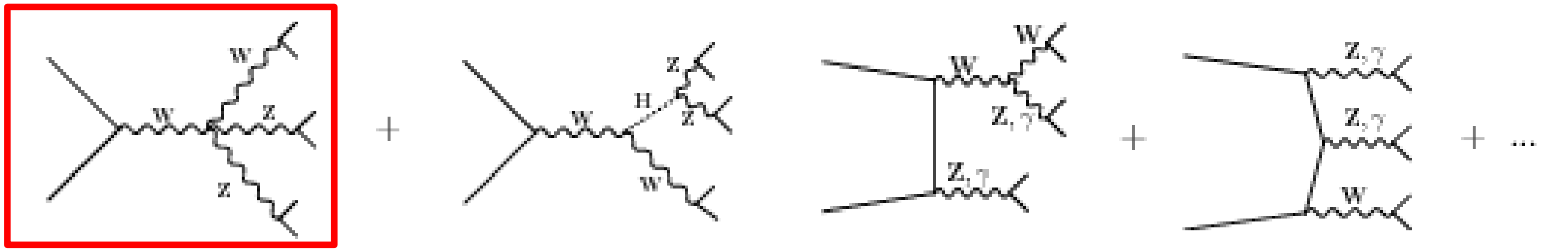




- So, perhaps the Higgs is not fundamental, but composite, bound by a 5th short-ranged Force? And maybe the W and Z, too?
- Think at composite pions, and pion-pion scatteriung unitarized by hadronic (e.g. ρ) resonances!

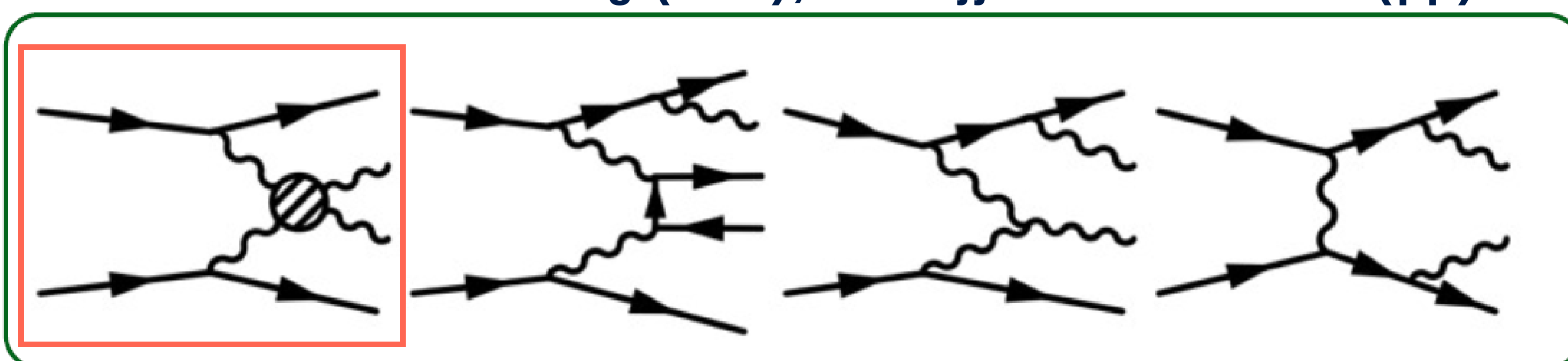
Quartic-Gauge-Couplings (QGC)

- **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

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 $W^\pm V \rightarrow W^\pm V$
- CMS $W^\pm V \rightarrow W^\pm \gamma$
- CMS $W^+W^- \rightarrow Z\gamma$

Yet Missing e.g.

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

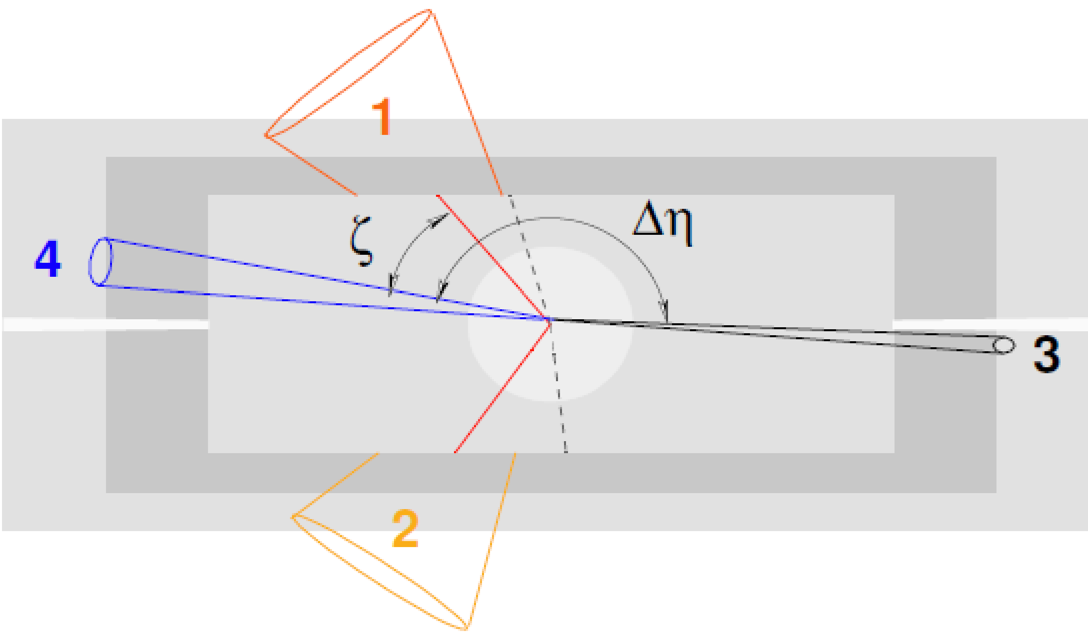
$ZZ \rightarrow ZZ$ (tiny x-section)

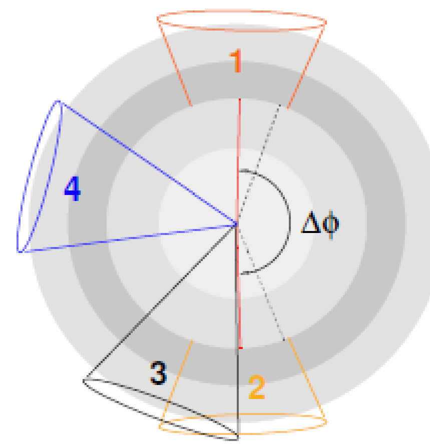
V=W,Z

Signal Topology (leptonic final states)

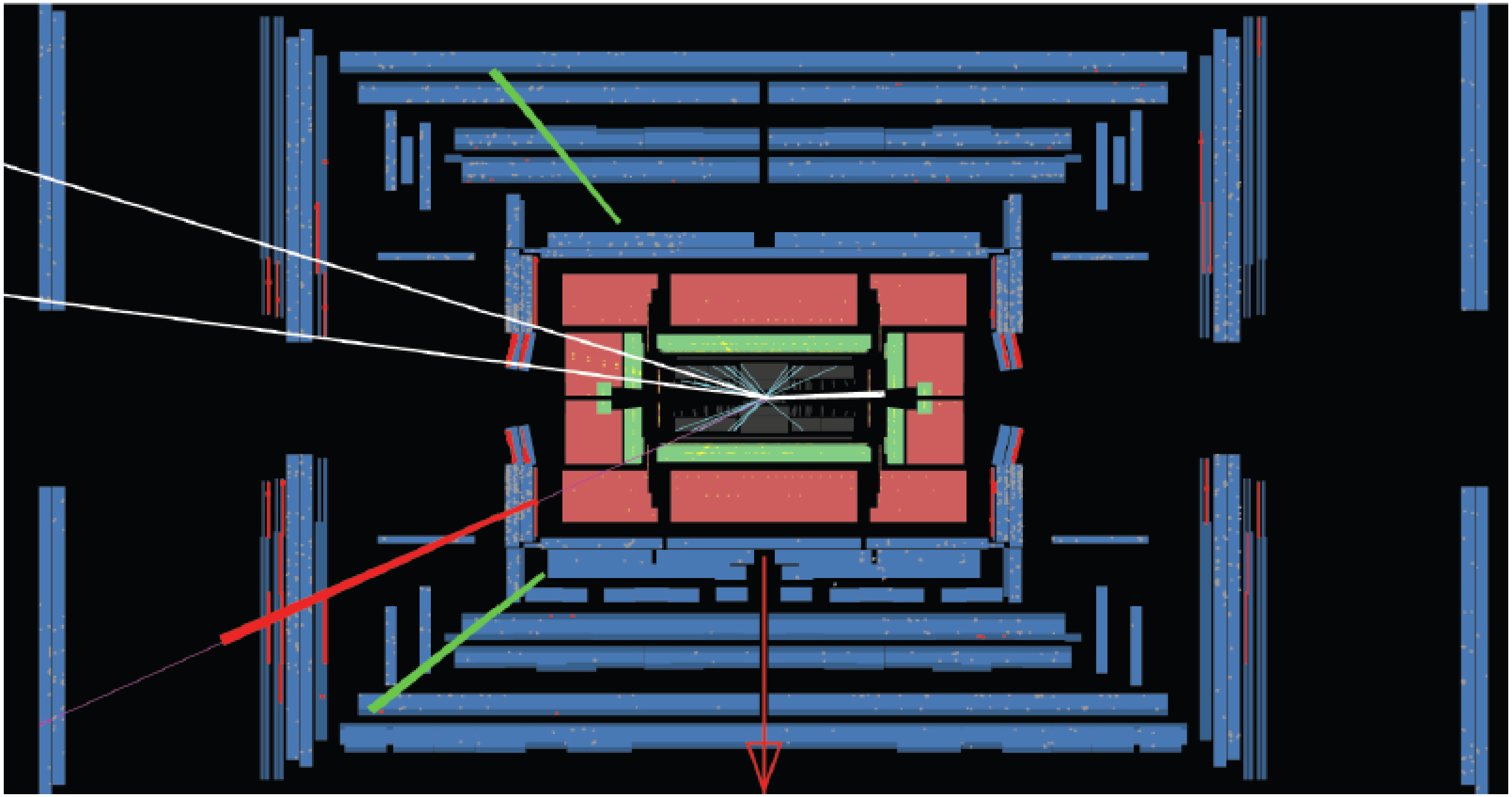
- 2 high-energy „tagging“ jets (#3, #4)
  - Dominantly very forward, large $\Delta\eta$ (>~3) between them
  - Large invariant m_{jj} (>~ 500 GeV)
- 2 (for WW), 3(for WZ) or 4 (for ZZ) leptons
  - Lying (mostly) „between“ tagging jets, (centrality ζ ~> 0)

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





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



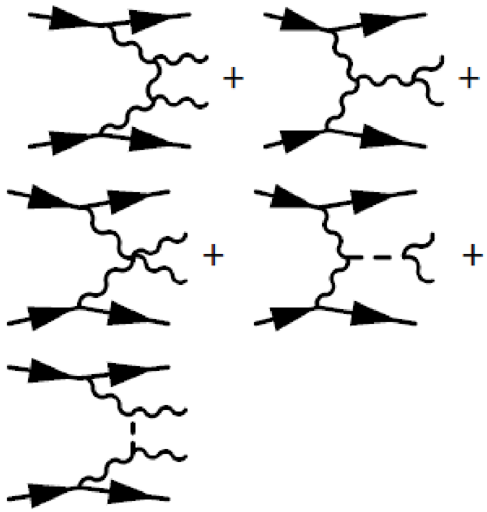
RunNumber: 204073
EventNumber: 16071790

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

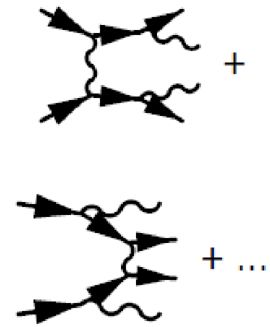
$p_T^{e^-} = 96$ GeV
$p_T^{e^+} = 87$ GeV
$M(e^+, e^-) = 92$ GeV
$p_T^{\mu^+} = 155$ GeV

Event classification

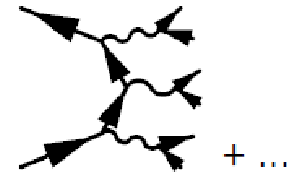
- VVjj-EW (V=W,Z)



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



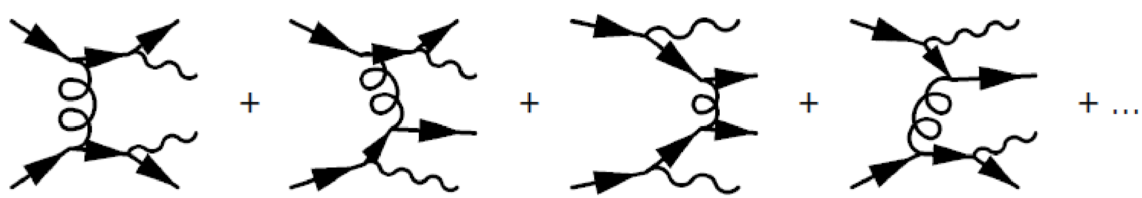
non-VBS EW diagrams
(not gauge invariantly separable)



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

- VVjj-QCD

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

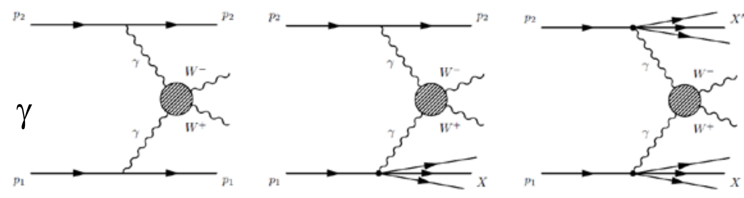


  - Same final state, some kinematic suppression possible

First VV→VV analysis at LHC: $\gamma\gamma \rightarrow WW$

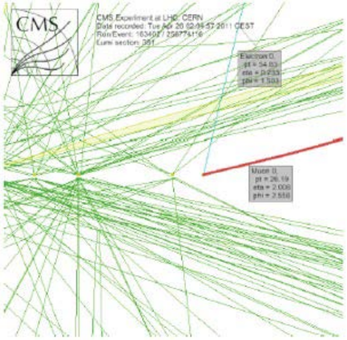
CMS, 7+8 TeV, 5+20 fb^{-1}: https://arxiv.org/pdf/1604.04464v2.pdf

- 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



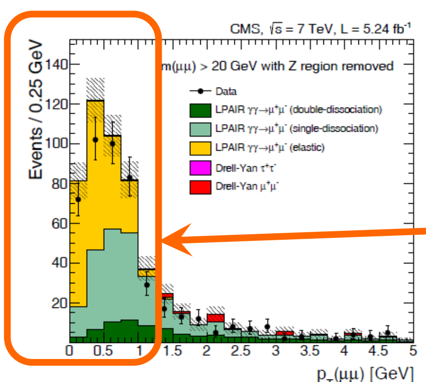
Two major selection criteria

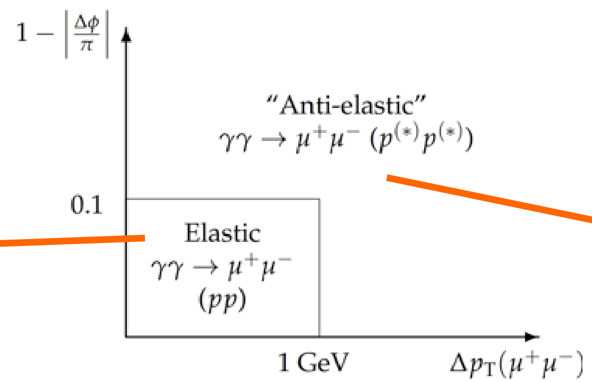
- 0 extra tracks from vertex
- p_T (eμ) > 30 GeV
- Bins for aQGC: p_T (eμ) ∈ [30;130], [130; ∞] GeV

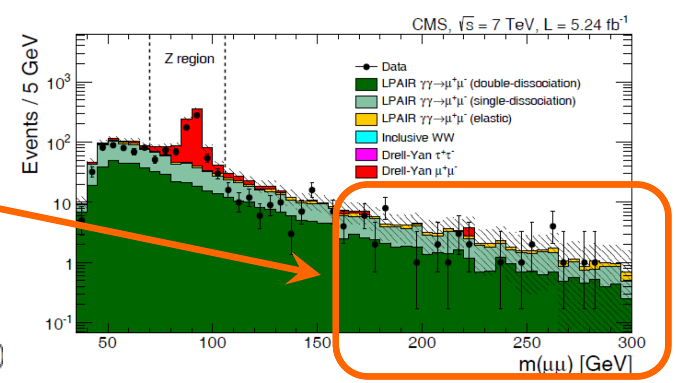


Important control sample: $\gamma\gamma \rightarrow \mu^+\mu^-$ and e^+e^-

- 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

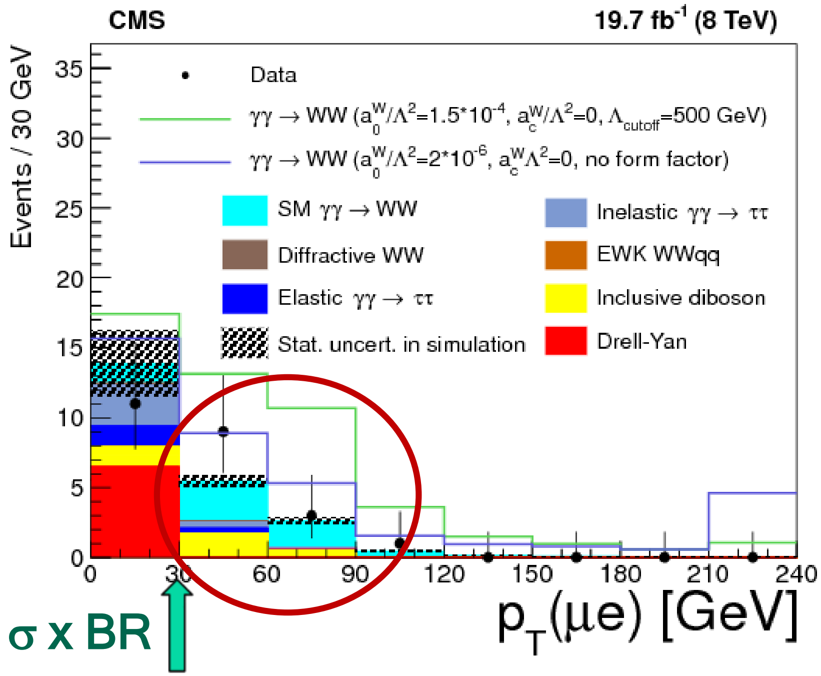
- Before p_T (eμ) > 30 GeV : ττ (from Drell-Yan and γγ)
- After p_T (eμ) > 30 GeV : Di-Boson, esp. W^+W^-

Event yield 7+8 TeV

- Expected bckgr: 4.7 ± 0.6
- Expected signal: 7.5 ± 0.7
- Observed: 15

Significances (expected)

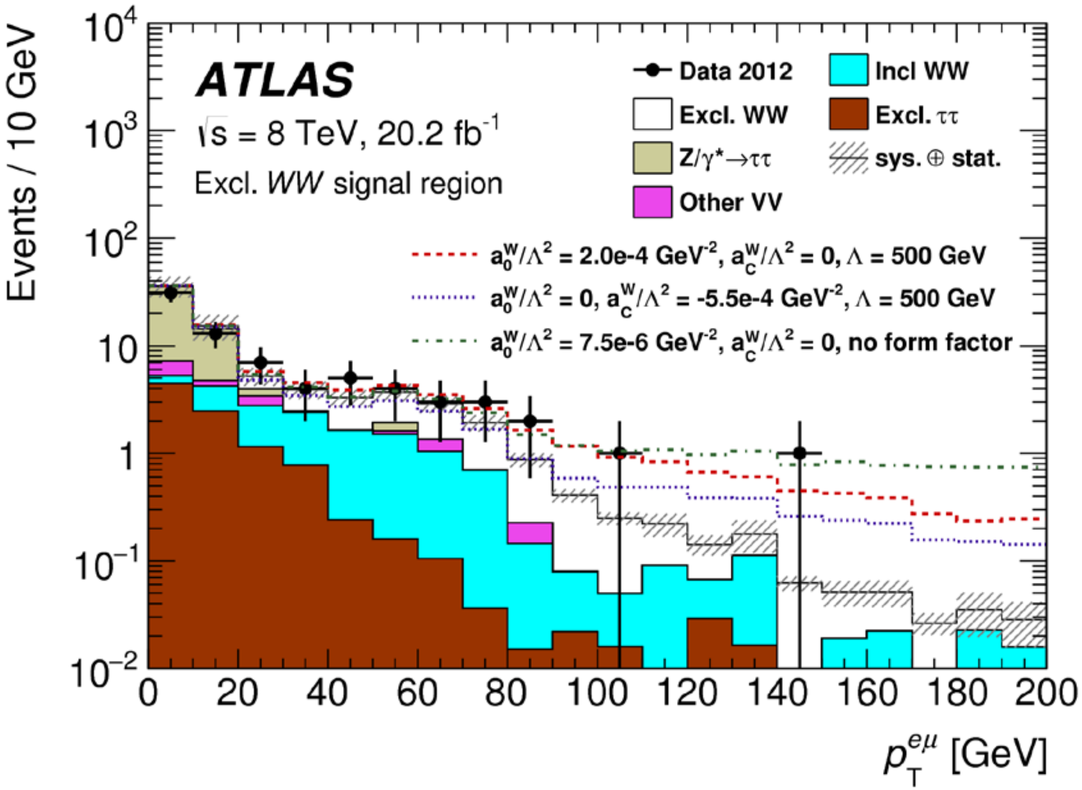
- 7 TeV: 0.8 (1.8) s.d.
- 8 TeV: 3.2 (2.1) s.d.
- 7+8 TeV: 3.4 (2.8) s.d.



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)

- ATLAS, 8 TeV, only https://arxiv.org/pdf/1607.03745.pdf
  - Measured(expected): σxBR: 6.4±2.2±1.4 fb (4.4±0.3 fb)
  - Significance: 3.0 s.d.

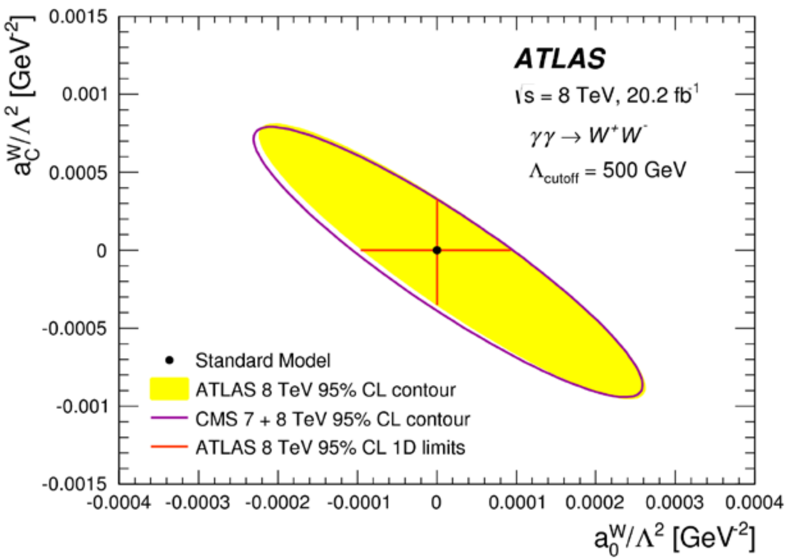


Limit on aQGC for $\gamma\gamma W^+W^-$

- 1D and 2D limits on a^W_0/Λ^2 and a^W_C/Λ^2
  - 1D, using form factor unitar. Λ_{FF} = 500 GeV

Dimension-6 AQGC parameter	7+8 TeV ($\times 10^{-4}$ GeV^{-2})
$a_0^W/\Lambda^2(\Lambda_{cutoff} = 500\,\text{GeV})$	$-0.9 < a_0^W/\Lambda^2 < 0.9$
$a_C^W/\Lambda^2(\Lambda_{cutoff} = 500\,\text{GeV})$	$-3.6 < a_C^W/\Lambda^2 < 3.0$

  - 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

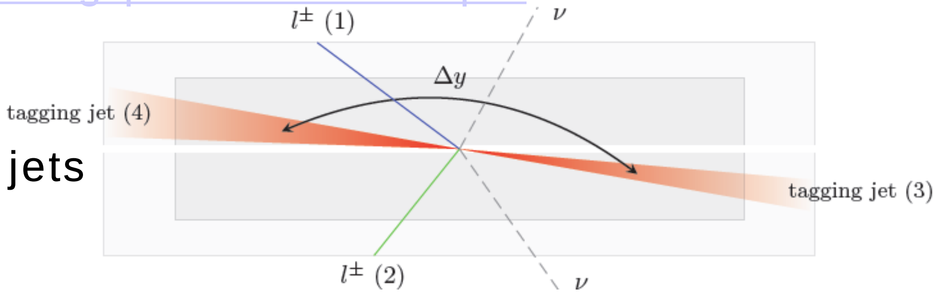
- Unitarized limits
  - ÷25 improved w.r.t. D0 (i.e. factor 5 in scale Λ)
  - Still rather weak

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

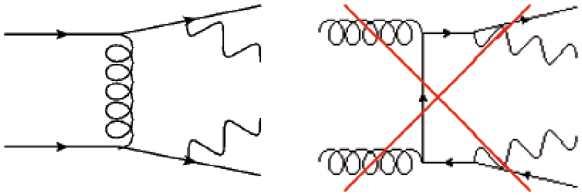
❖ First massive VV→VV analysis at LHC: W±W± → W±W±

- 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

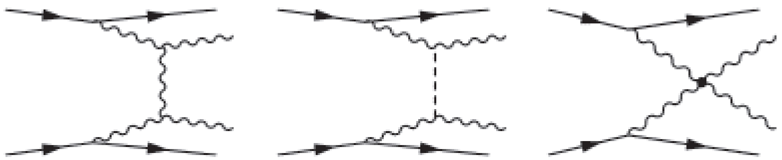


❖ VVjj has two process classes:

- 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

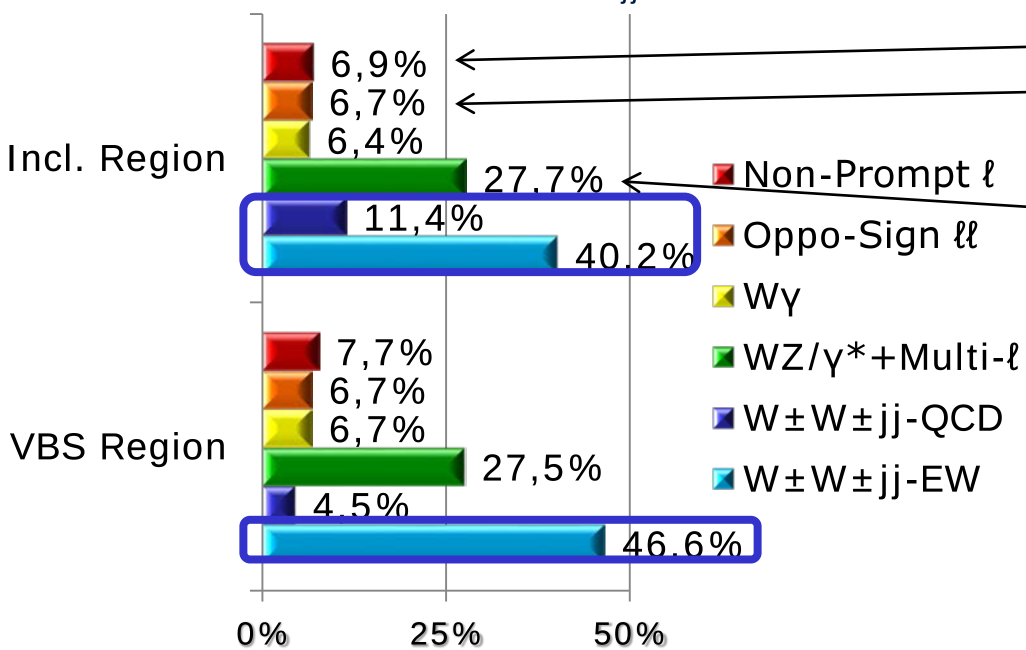
Two analysis phase spaces

- **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: $m_{\ell\ell}$>20GeV, $\Delta R_{iso}(\ell)$>0.3, Z→ee veto

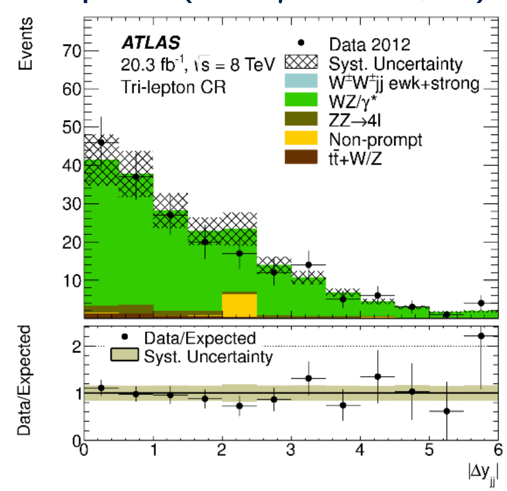
Measure $W^\pm W^\pm jj$ (incl. EW, QCD)

- **VBS Region (EW : QCD ~ 10 : 1)**
  - **Rapidity gap:** Δy_{jj} > 2.4

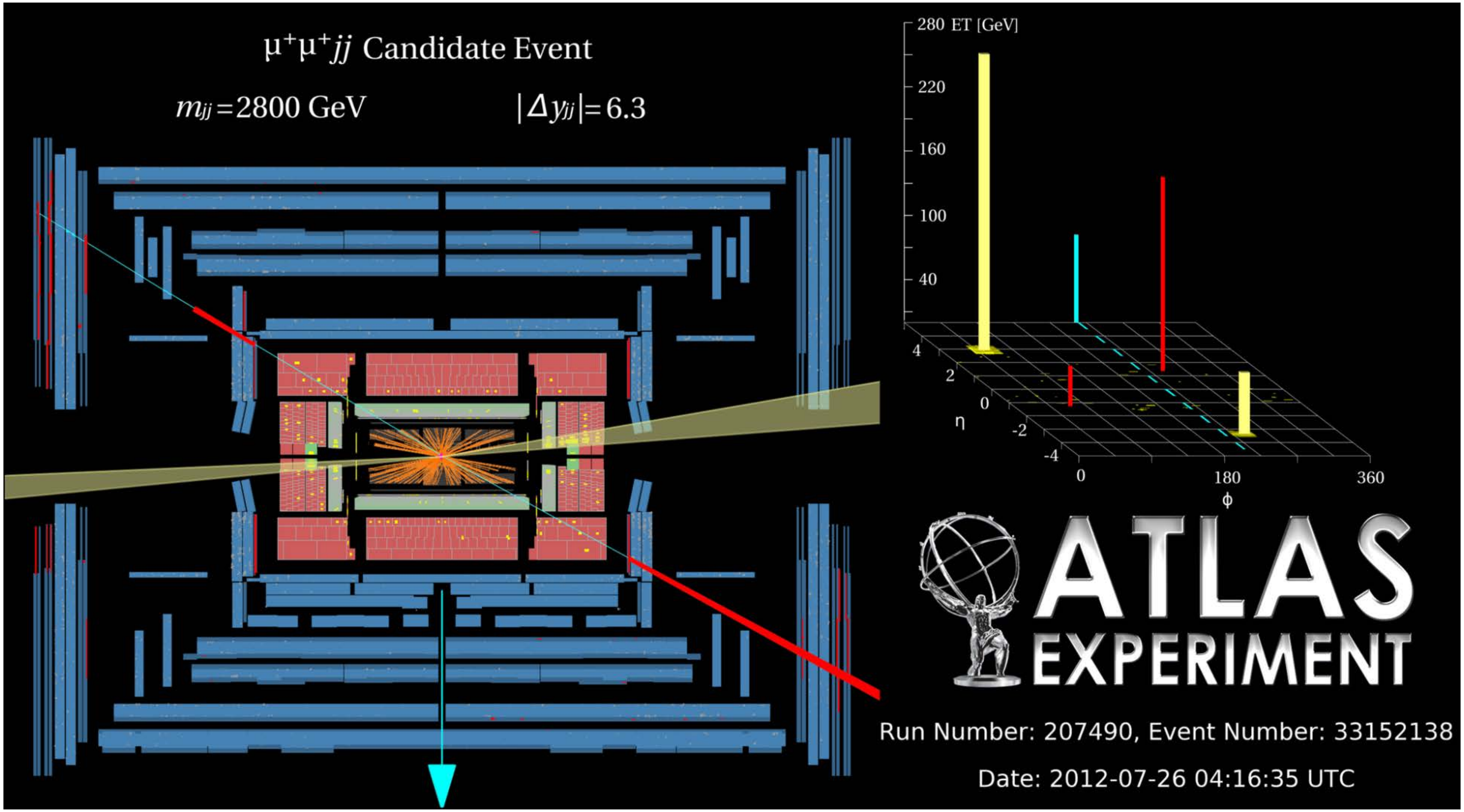
Measure $W^\pm W^\pm jj$ EW and set aQGC limits



- Data driven background
  - Fake leptons (W+Jets, ...)
  - Charge mis-ID (Z+jets,...)
- Control regions
  - Lost lepton (WZ/γ* +Jets, ...)
  - ...



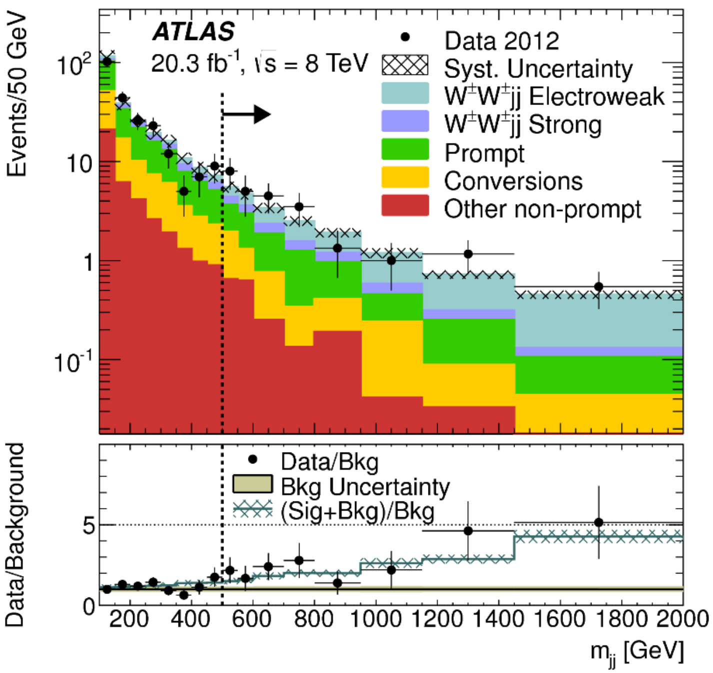
Candidate event



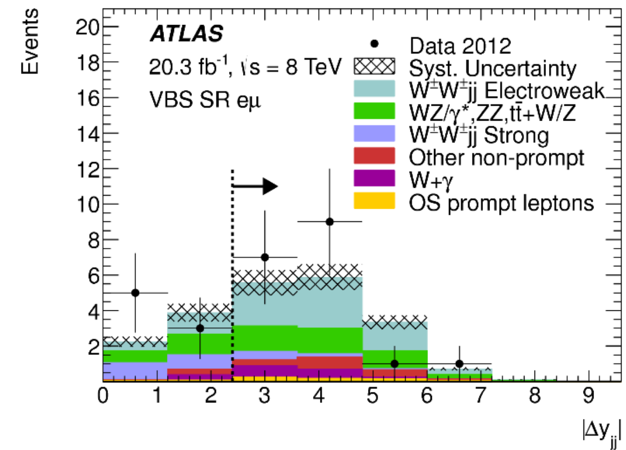
- $p_T(j_1)$ = 271 GeV, $p_T(j_2)$ =54 GeV

Result: Kinematics and x-section

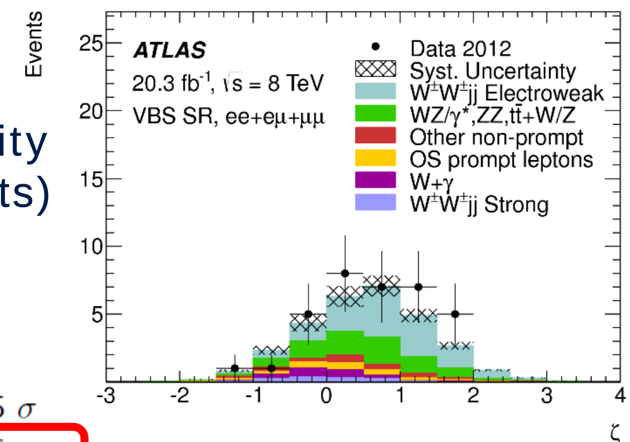
- Inclusive region: m_{jj} before cut



- 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

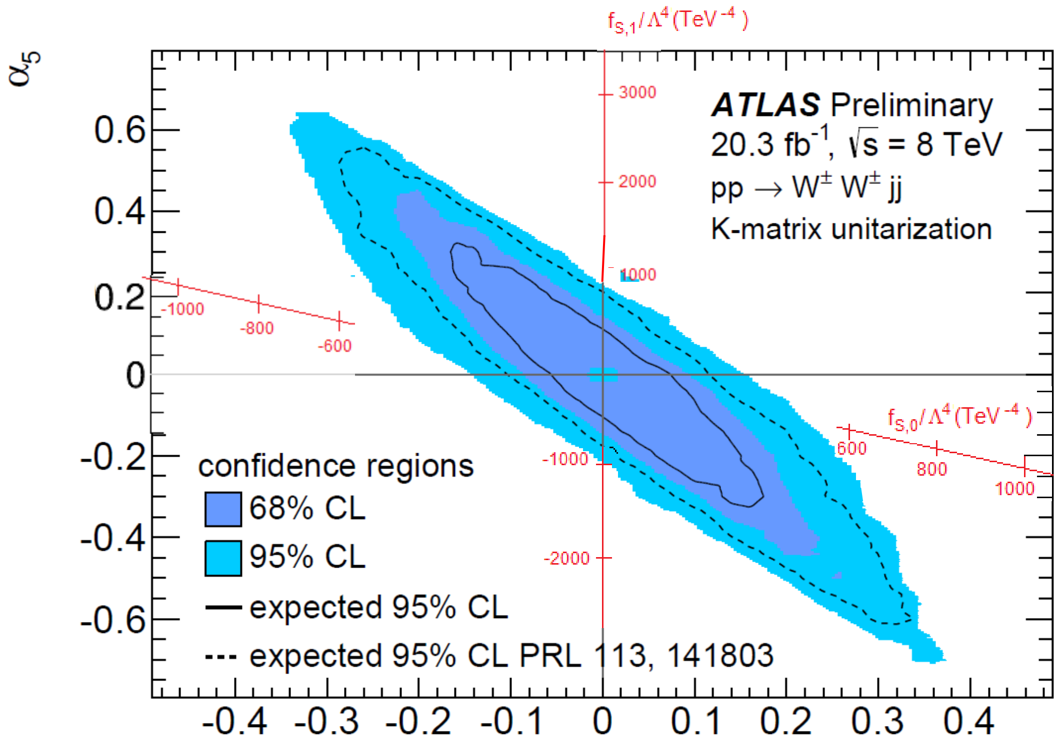
- **$W^\pm W^\pm \rightarrow W^\pm W^\pm$ is first observation of electroweak VBS VV→VV**

ICHEP 2016: Improved Limits

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

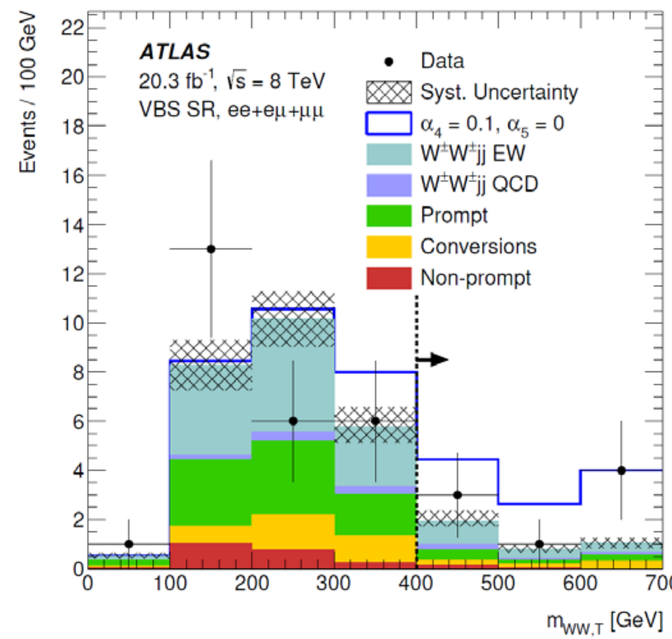
- Improvement in sensitivity
  - PRL 2014: Extracted from **cross-section**
  - ICHEP 2016: **high $m_{WW,T}$ phase space**
    evts: SM VBS(EW): 1.7 evt, Bckg: 2.1, Data:8

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



α_4

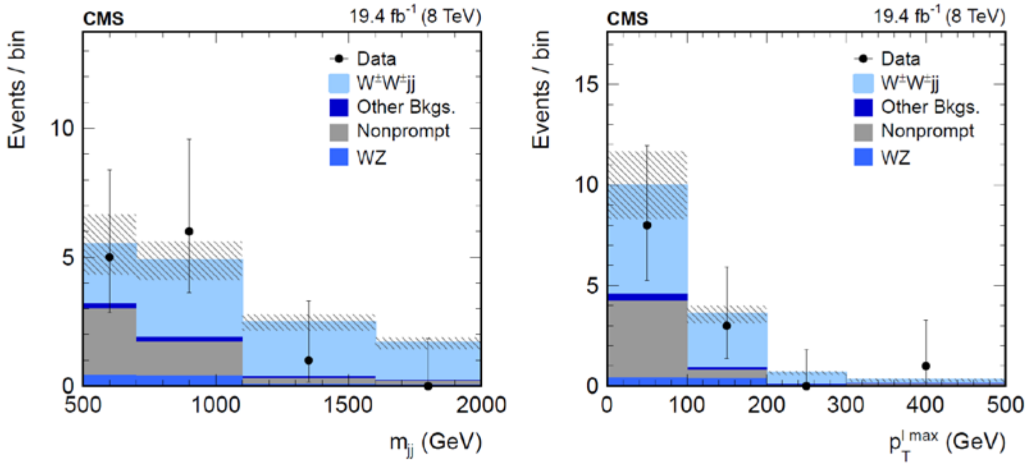
Translation into unitarized f_S parameters: arXiv:1309.7890v1



- 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)

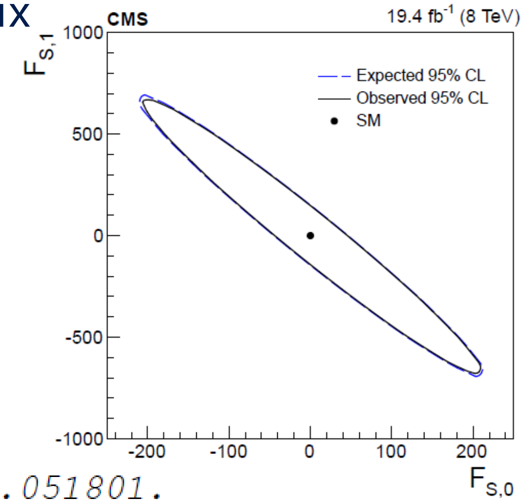
    $\Lambda > 500 - 650$ GeV

- CMS: same expected sensitivity: 2.9 s.d., observed: 1.9 s.d



- Ununitarized limits on anomalous couplings:
  - Narrower, and ~4-10x better than ATLAS K-Matrix

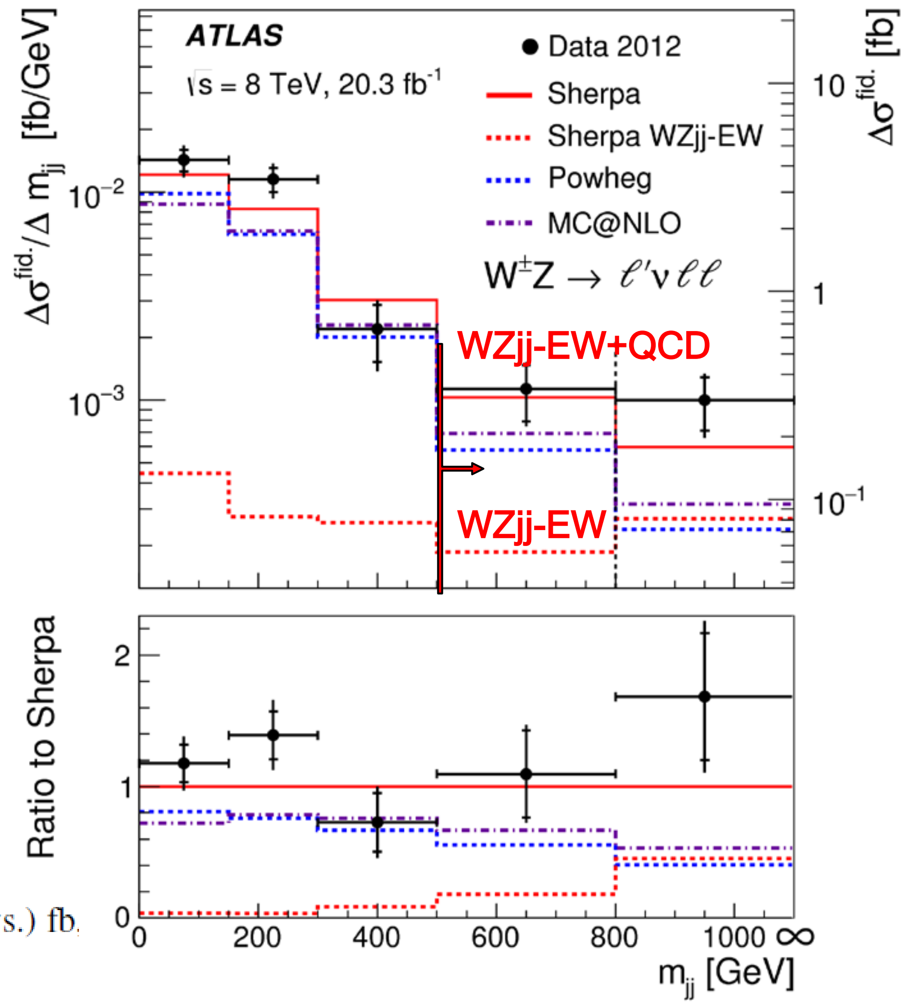
Operator coefficient	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity limit
$F_{S,0}/\Lambda^4$	−42	43	−38	40	0.016
$F_{S,1}/\Lambda^4$	−129	131	−118	120	0.050
$F_{M,0}/\Lambda^4$	−35	35	−33	32	80
$F_{M,1}/\Lambda^4$	−49	51	−44	47	205
$F_{M,6}/\Lambda^4$	−70	69	−65	63	160
$F_{M,7}/\Lambda^4$	−76	73	−70	66	105
$F_{T,0}/\Lambda^4$	−4.6	4.9	−4.2	4.6	0.027
$F_{T,1}/\Lambda^4$	−2.1	2.4	−1.9	2.2	0.022
$F_{T,2}/\Lambda^4$	−5.9	7.0	−5.2	6.4	0.08



Published in Physical Review Letters as doi:10.1103/PhysRevLett.114.051801.

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, η< 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

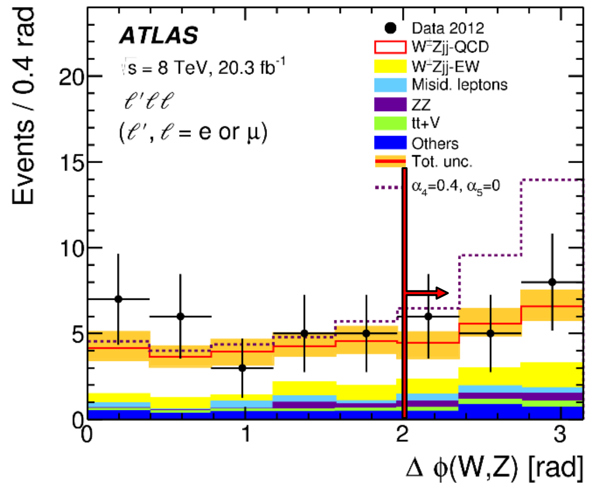


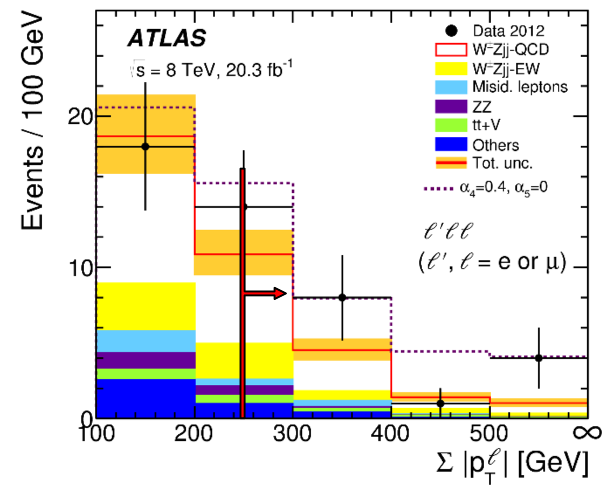
Selection	VBS	aQGC
Data	45	9
Total Expected	37.2 ± 1.1	4.9 ± 0.3
$WZjj$-EW	7.4 ± 0.2	1.1 ± 0.1
$WZjj$-QCD	20.8 ± 0.8	2.8 ± 0.3
tZ	3.0 ± 0.1	0.3 ± 0.0
Misid. leptons	2.5 ± 0.6	0.1 ± 0.1
ZZ	1.9 ± 0.3	0.2 ± 0.1
$t\bar{t} + V$	1.6 ± 0.1	0.3 ± 0.0

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

❖ Limits of aQGC

- Yellow: SM WZjj-EW
- dotted: aQGC α_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

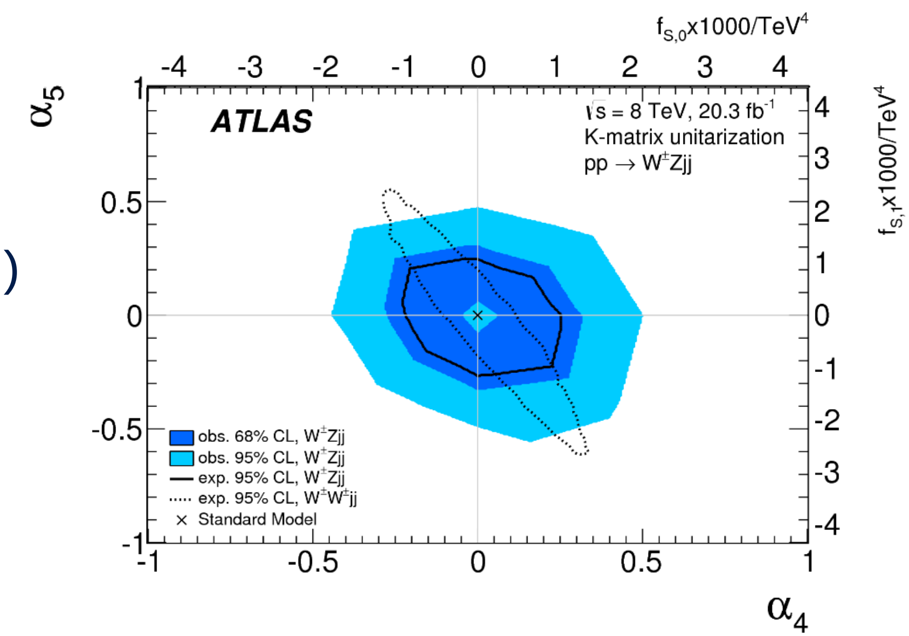




❖ Expected limits (K-Matrix unit.) improve upon $W^{\pm}W^{\pm}jj$-EW in some regions

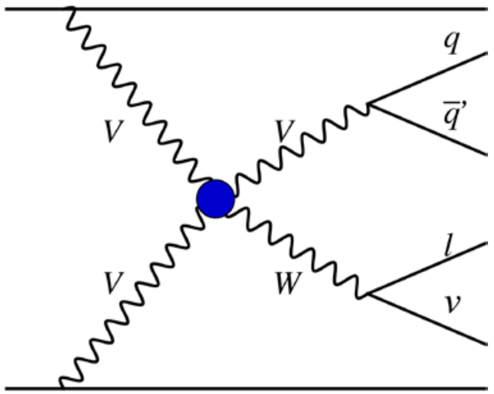
- Easy to translate in $f_{S0,1}$

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



VBS WV+jj in semileptonic channel

- New, ATLAS, just appeared http://arxiv.org/abs/1609.05122
- Advantages of semi-leptonic channel
  - Can reconstruct boson kinematics
  - Background falls as you move to higher pTs, -> ideal for aQGC measurements



- Signal from multiple sources
  - Opp.Sign WW, Same Sign WW, WZ
  - prevents translation between aQGC params
- Tends to suffer from higher background : SM VBS hard to see
- Two main selection channels
  - **Resolved V → jj**
    - $\geq$4 small-R jets
    - W jet pairs: $64 < m_{jj} < 96$ GeV
  - **Merged V->J**
    - $\geq$2 small-R jets
    - W-Jet: $64 < m_J < 96$ GeV, closest to m_W
  - Tagging jets: max m_{jj} pair remaining

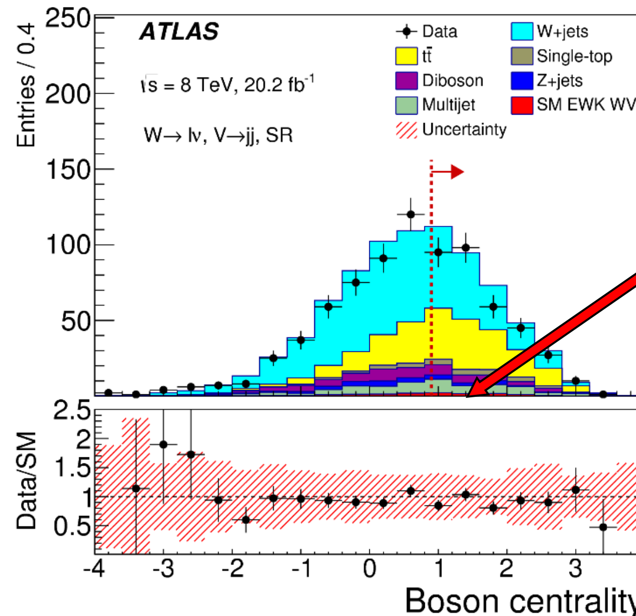
❖ Event Selection

- M(j,j) > 900 GeV (tag jets)
- MET > 30 GeV
- b-veto
- Boson centrality > 0.9

$$\zeta = min\{\Delta\eta_-, \Delta\eta_+\},$$

$$\Delta\eta_- = min\{\eta_i\} - min\{\eta_{j_{t1}}, \eta_{j_{t2}}\},$$

$$\Delta\eta_+ = max\{\eta_{j_{t1}}, \eta_{j_{t2}}\} - max\{\eta_i\}.$$

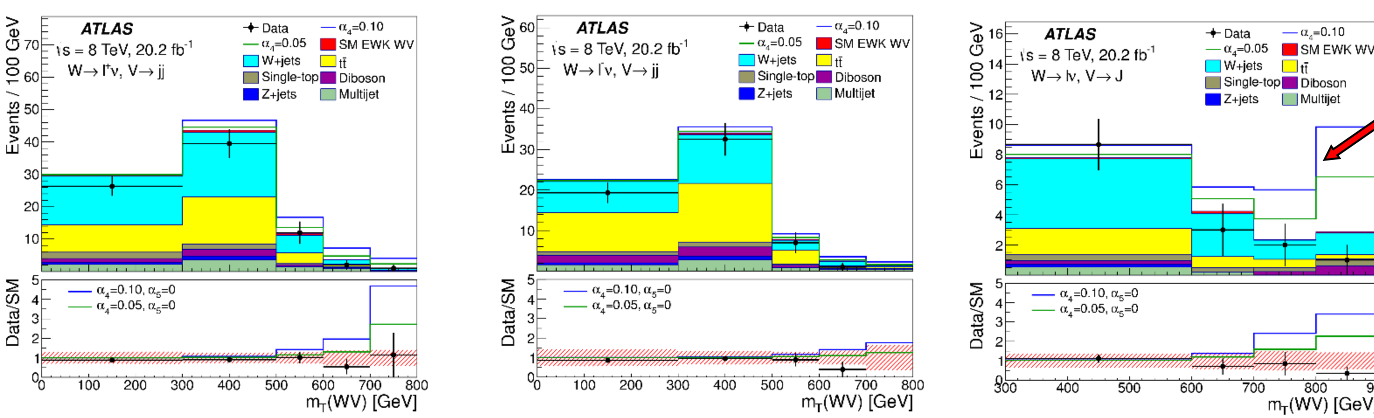


SM VBS Signal

❖ Dominant Background

- W+Jets, ttbar <- control regions

$$m_T(WV) = \sqrt{(E_T(V_{had}) + E_T(W_{lep}))^2 - (p_x(V_{had}) + p_x(W_{lep}))^2 - (p_y(V_{had}) + p_y(W_{lep}))^2}$$



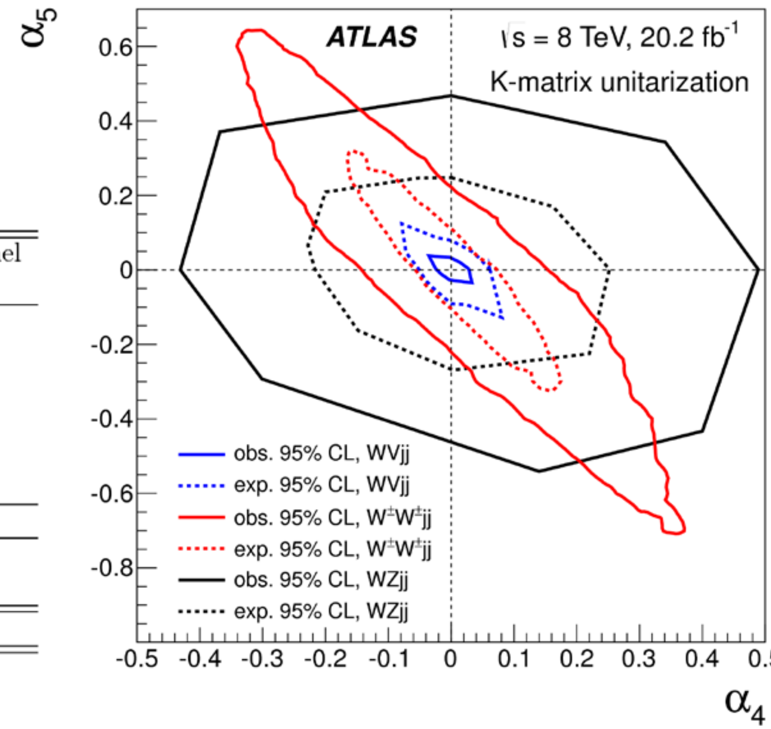
aQGC Effect

aQGC limits

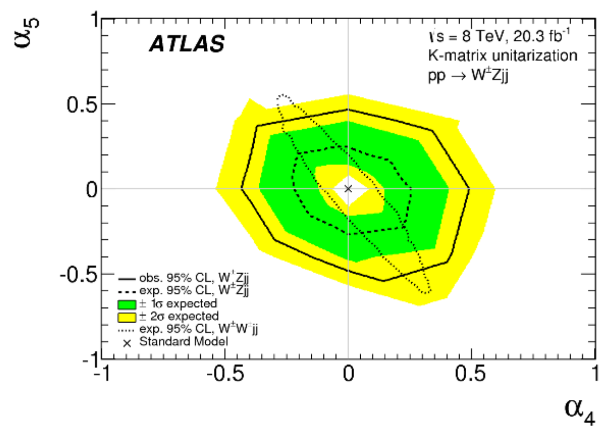
- Best sensitivity of all channels
  - Obs: Λ > 1500 GeV with $\Lambda \sim v/\sqrt{\alpha}$

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

	Resolved channel e^+ and μ^+	Resolved channel e^- and μ^-	Merged channel 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

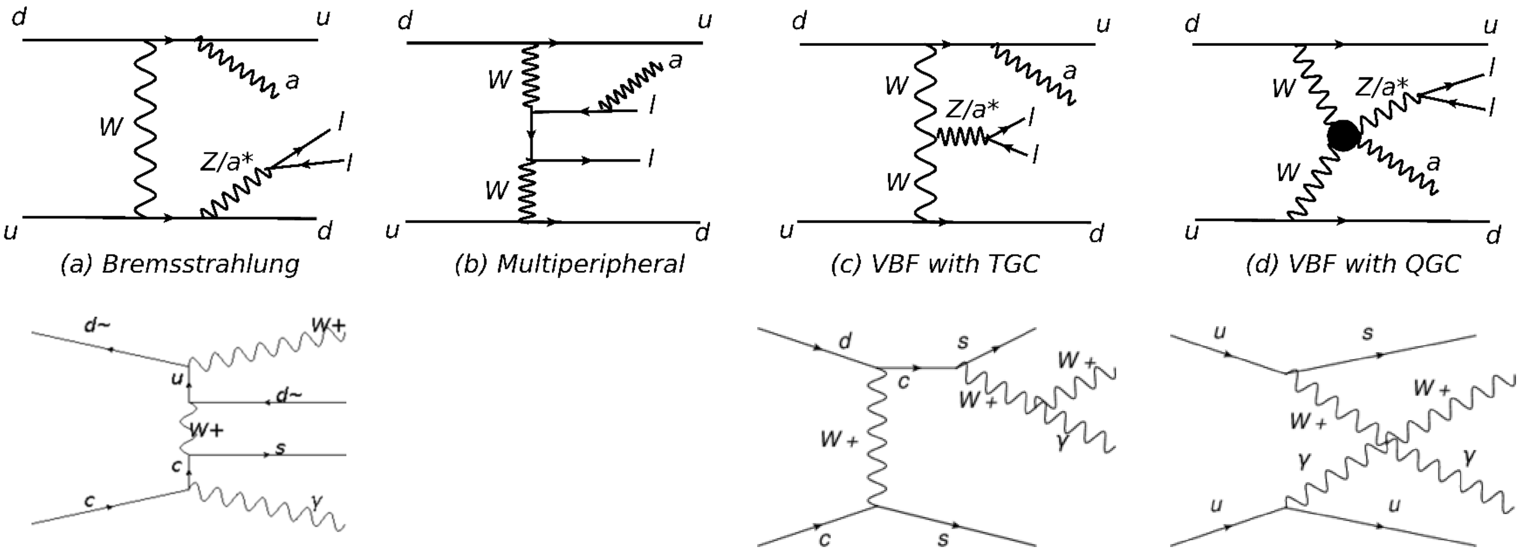


- Compare the *dashed* lines
  - Black : WZ (observed: excess)
  - Red: W±W± (observed: excess)
  - Blue: WV (observed: deficit)
- Low statistics gives broad band for expected limit, example:
  WZ VBS, compared to (old) W±W± VBS



Wγjj and Zγjj (CMS)

- Both contain Quartic Gauge Vertex



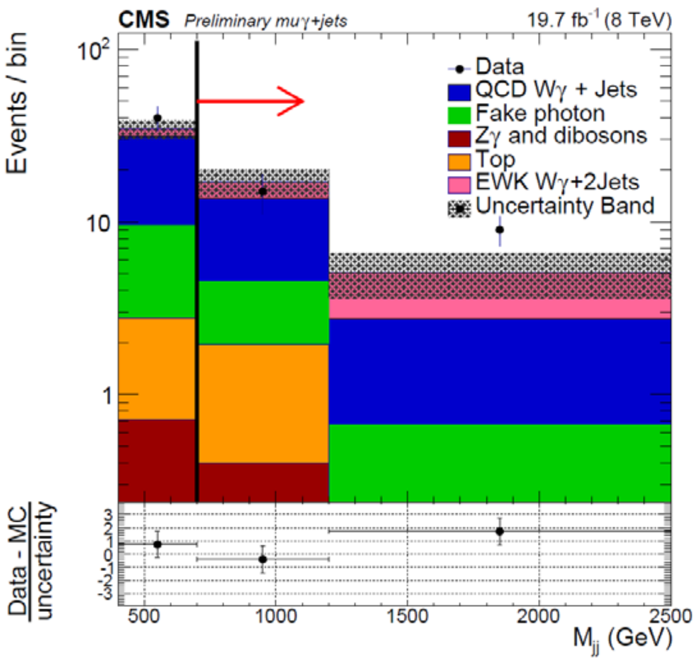
- Wγjj

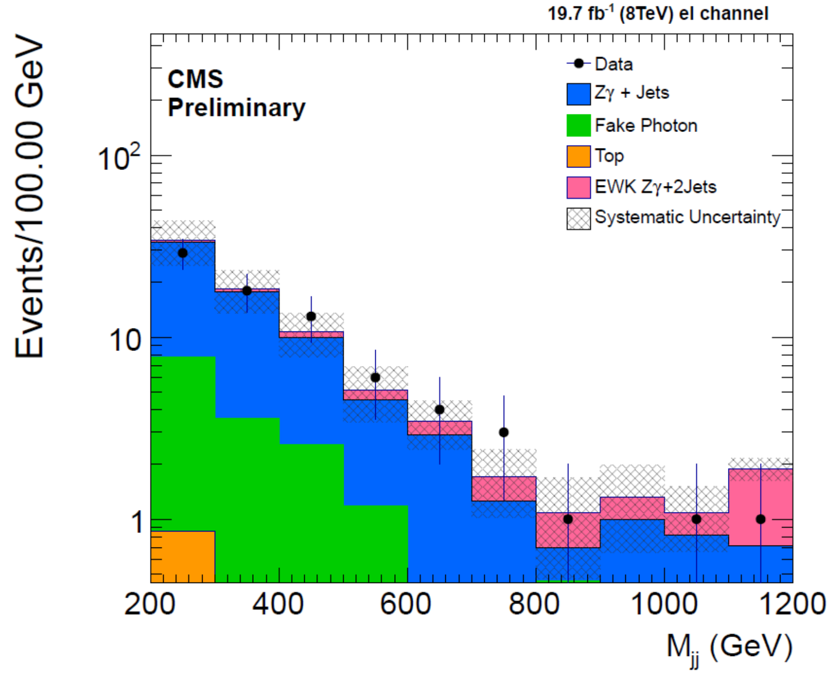
μ(e) + γ+ $\not{E}_T$ + 2 jets Allow τ-lepton decays to μ,e
Major Backgrounds: QCD Wγ+jets, Fake Photons

Zγjj

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





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

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,

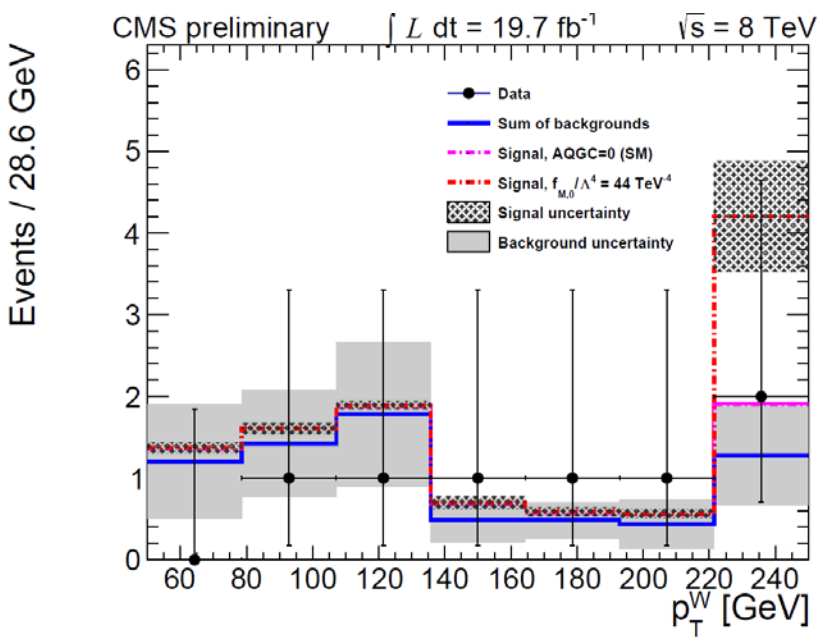
- ❖ Significance (expected): 2.7 (1.5) s.d.

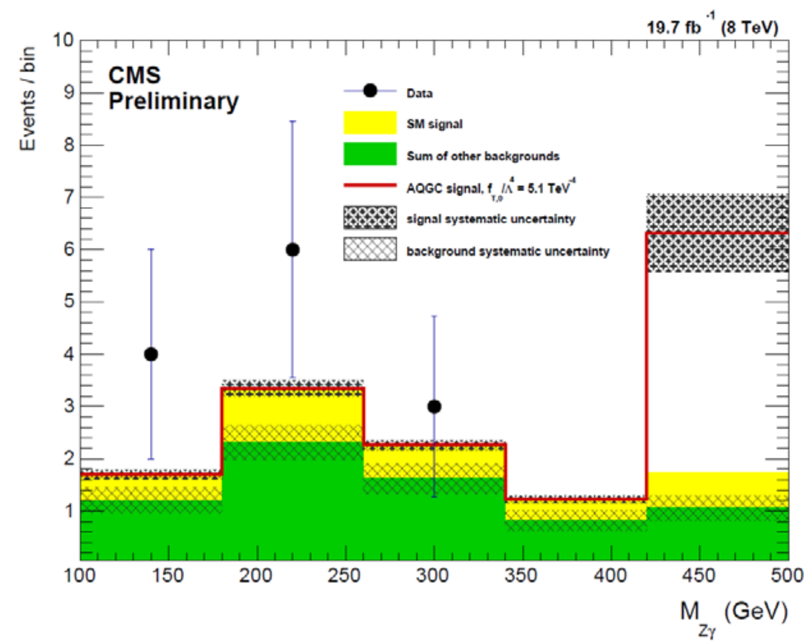
Significance (expected): 4.5 (4.3) s.d.

❖ 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, $|\eta^\gamma| < 1.4442$





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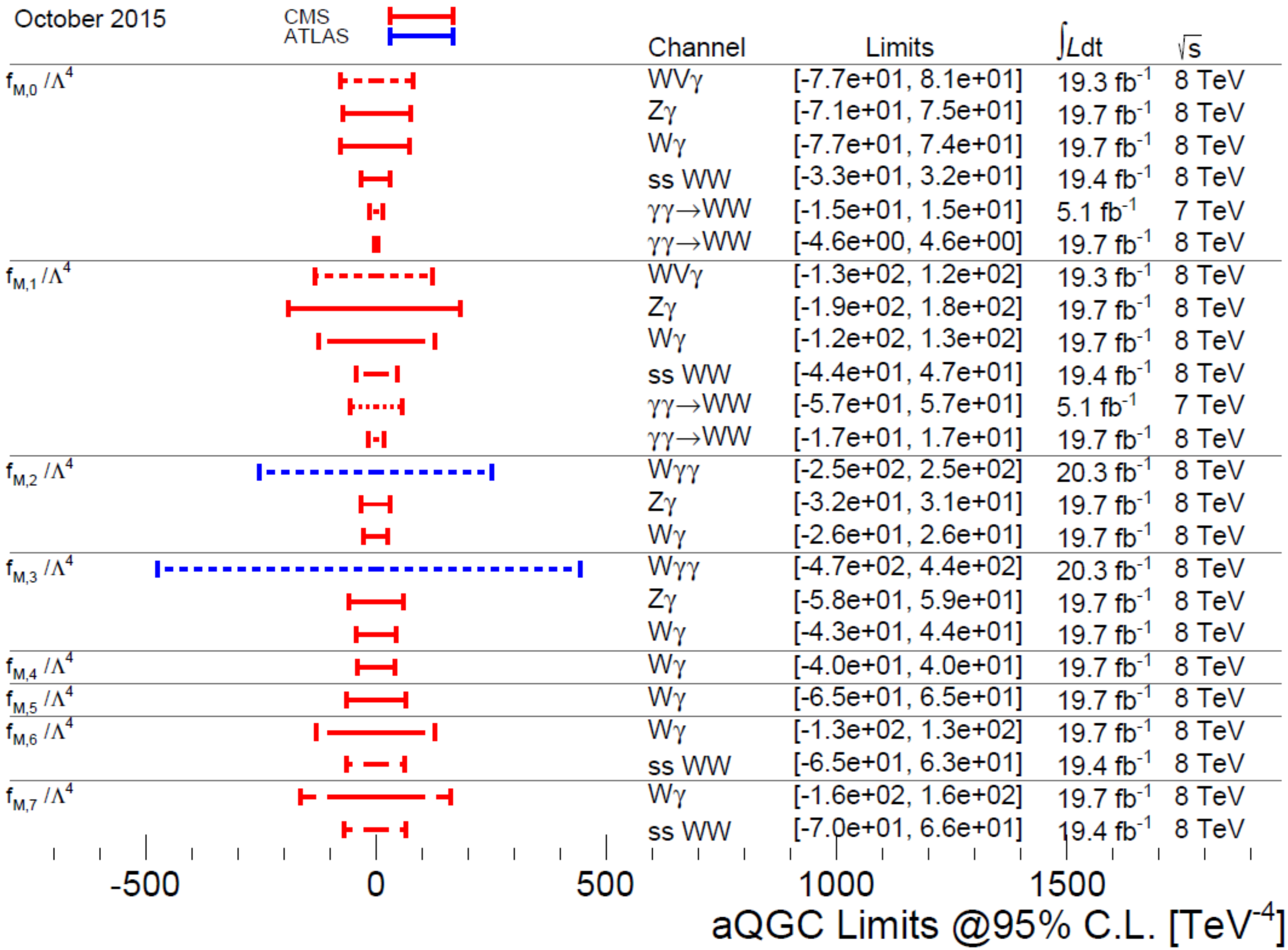
Example: Limits on f_M/Λ^4

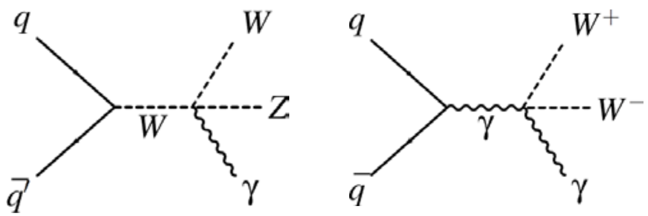


TRIPLE BOSON PRODUCTION

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

First VVV analysis at LHC: WVγ = WZγ + WWγ → ℓν 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



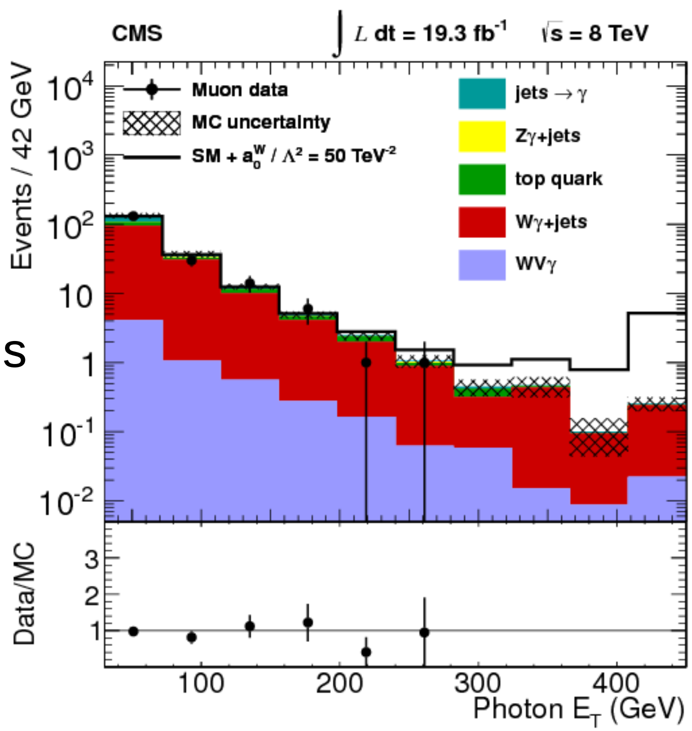
main selection cuts

- ℓν : 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

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

WWγγ — WWZγ contributions

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

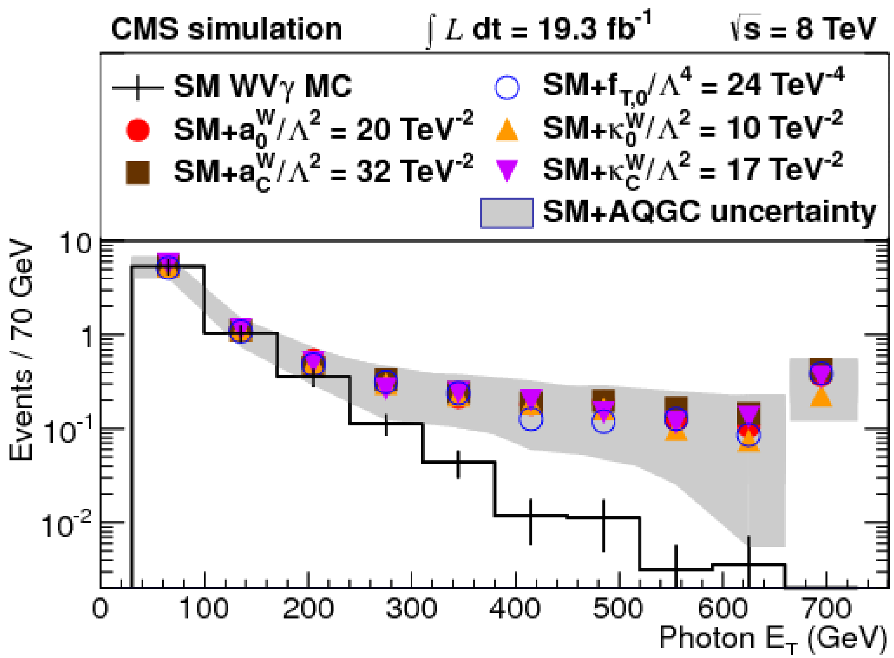
- Discriminating variable
  - high Photon E_T

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

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

  - Example: for $a_0^W = 1$

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



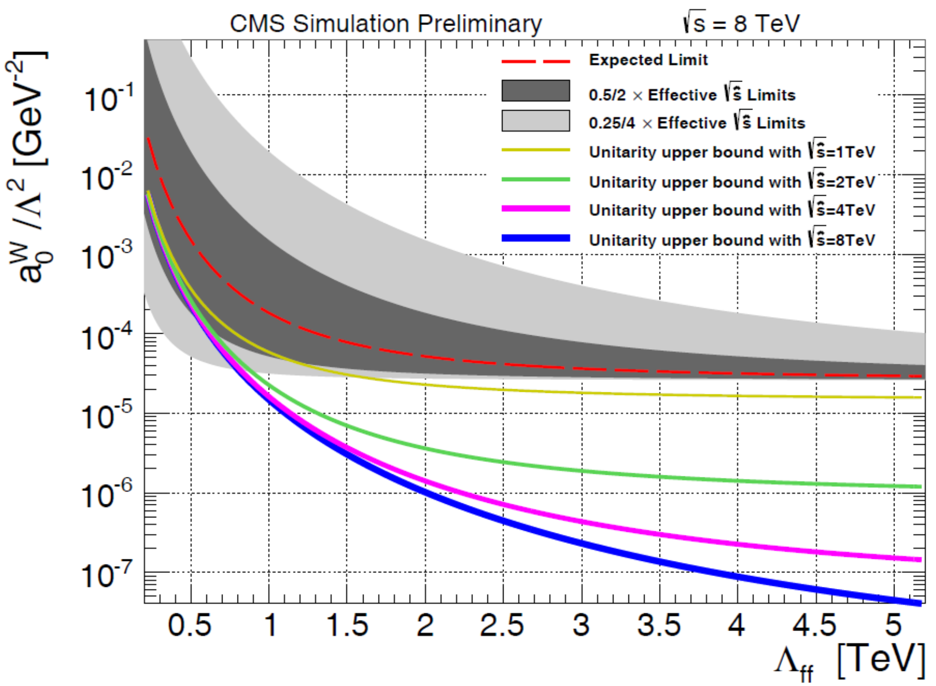
Unitarity issue

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

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

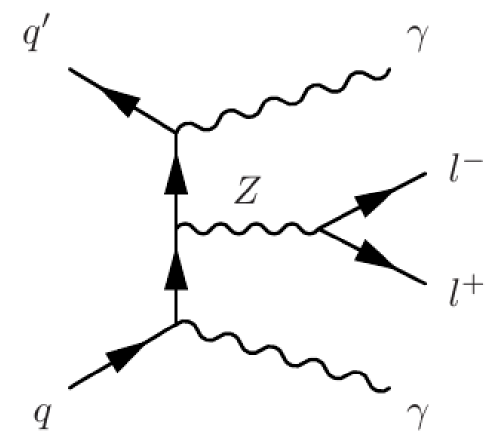
  - Damps high-ŝ events to **zero**, little effect on low-ŝ events
  - Plot: approx 2→2 unitarity upper bounds .vs. Λ_{FF} for several $\sqrt{\hat{s}}$

- Conclusion
  - typically $\sqrt{\hat{s}}$ = 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**

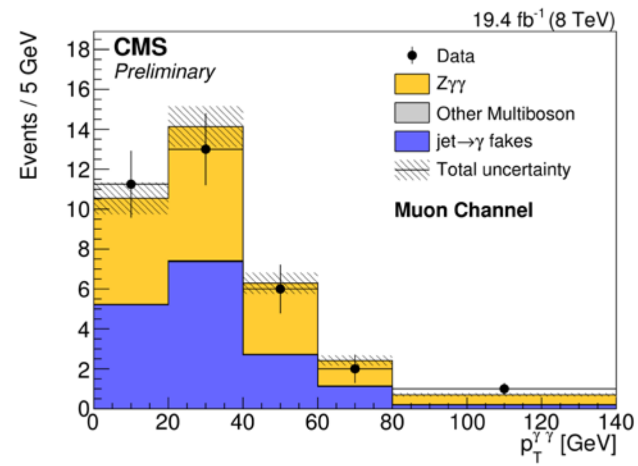


$Z\gamma\gamma$ (ATLAS, CMS)

- No neutral triple or quartic vertices in $Z\gamma\gamma$ 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

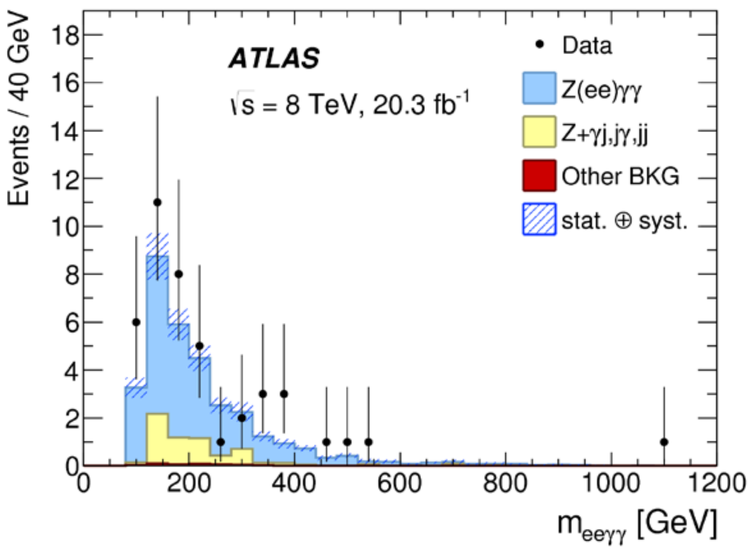


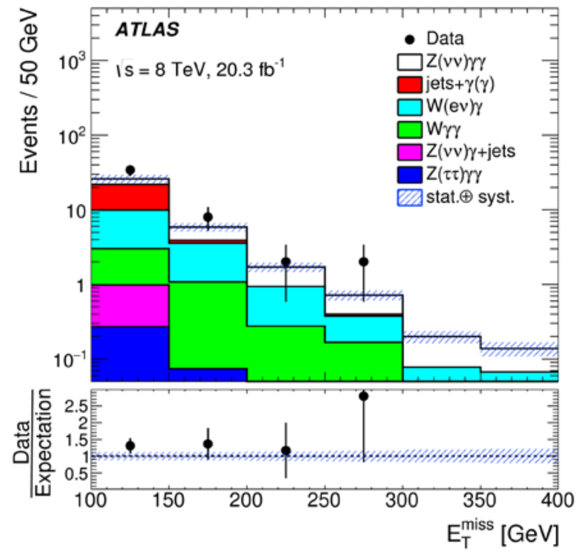
Definition of $Z\gamma\gamma$ Fiducial Region
$p_T^\gamma > 15\,\text{GeV}, \lvert\eta^\gamma\rvert < 2.5$
$p_T^\ell > 10\,\text{GeV}, \lvert\eta^\ell\rvert < 2.5$
Exactly two candidate leptons and two candidate photons
lead $p_T^\gamma > 20\,\text{GeV}$
$M_{\ell\ell} > 40\,\text{GeV}$
$\Delta R(\gamma,\gamma)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

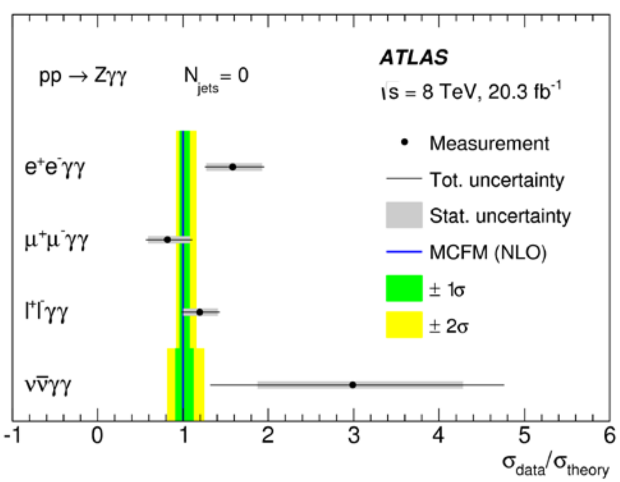


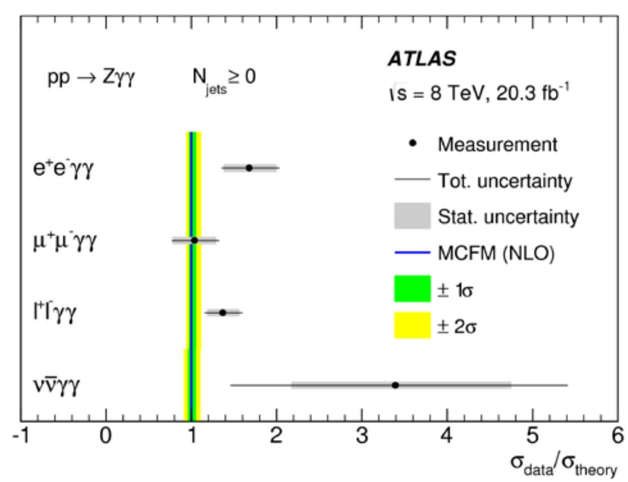
- Background: $Z(\gamma)$+Jets (misID)
- Cross-section
  - CMS: expected $\sigma^{NLO}_{Z\gamma\gamma} \cdot \text{BR}(Z \to \ell\ell) = 12.95 \pm 1.47\,\text{fb}$
    obs.: 5.9 s.d : $\sigma^{fid}_{Z\gamma\gamma} \cdot \text{BR}(Z \to \ell\ell) = 12.7 \pm 1.4\,(\text{stat}) \pm 1.8\,(\text{syst}) \pm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

❖ ATLAS: x-section in 0 and ≥0 jet, and Z→νν (for aQGC)



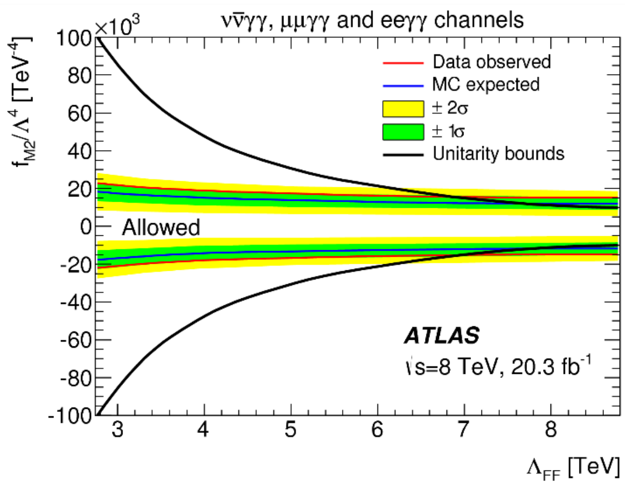


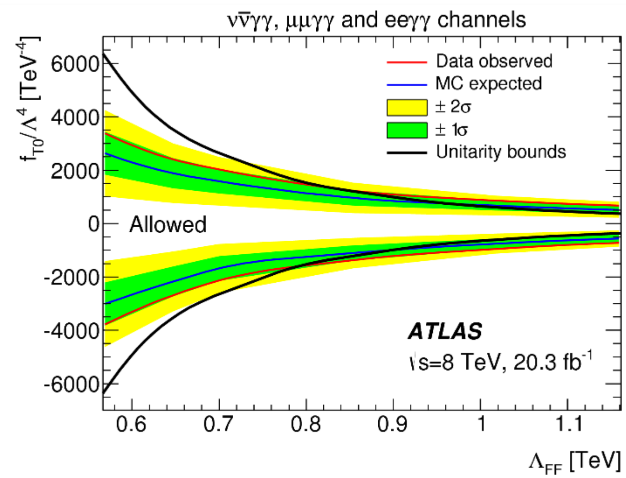




aQGC extraction (ATLAS)

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



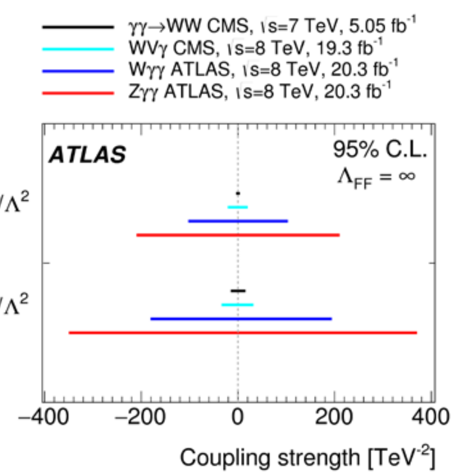


  - Extracted f_M aQGC limits not competitive with $\gamma\gamma \rightarrow WW$ or $WV\gamma$

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	$[-3.4, 3.3] \times 10^4$	$[-2.6, 2.6] \times 10^4$

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

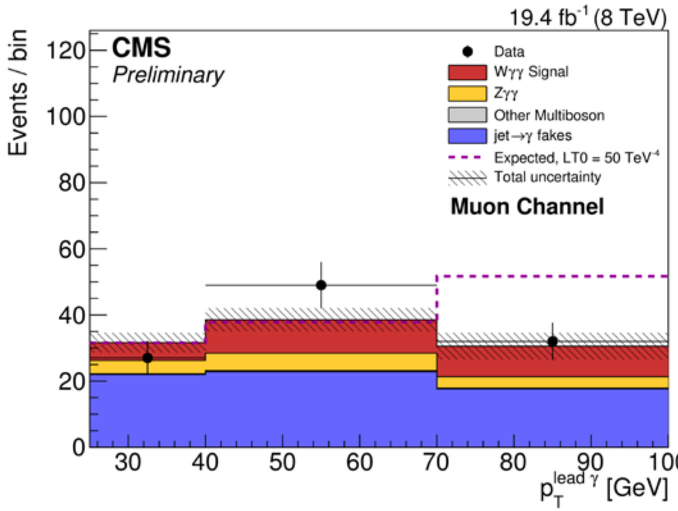
$$\frac{f_{M3}}{\Lambda^4} = \frac{a_c}{\Lambda^2}\frac{s_w^2}{2v^2c_w^2}$$

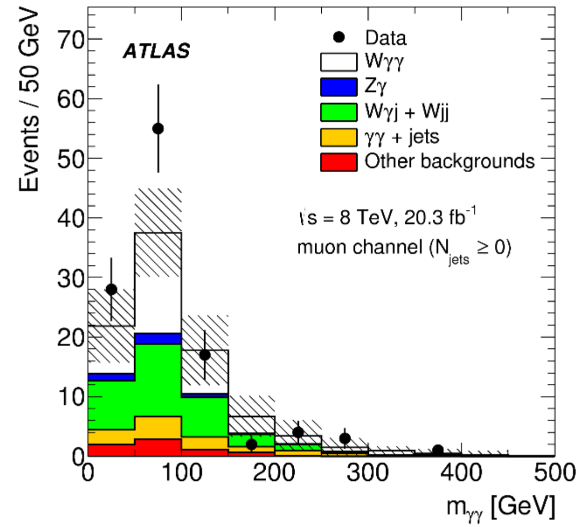


Wγγ (ATLAS, CMS)

- 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 Zγγ + Wγγ

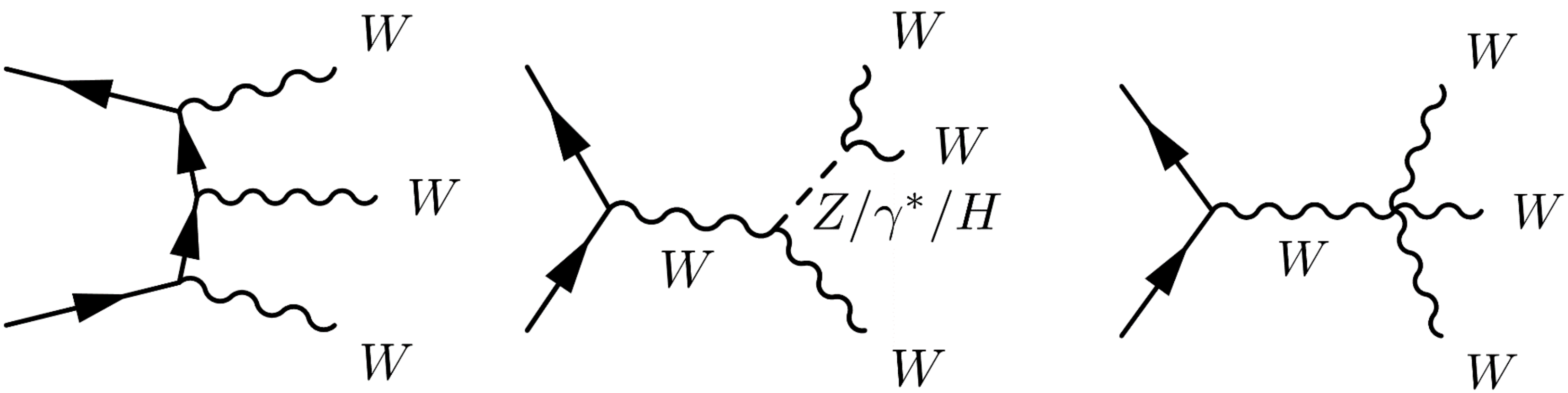
Expected Limits (TeV^{-4})	Observed Limits (TeV^{-4})
$-30.5 < \frac{f_{T0}}{\Lambda^4} < 31.1$	$-37.5 < \frac{f_{T0}}{\Lambda^4} < 38.1$
$-36.9 < \frac{f_{T1}}{\Lambda^4} < 37.5$	$-46.1 < \frac{f_{T1}}{\Lambda^4} < 46.9$
$-83.2 < \frac{f_{T2}}{\Lambda^4} < 83.2$	$-103 < \frac{f_{T2}}{\Lambda^4} < 103$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

ATLAS from Wγγ alone

		Observed [TeV^{-4}]	Expected [TeV^{-4}]
$n=0$	f_{T0}/Λ^4	$[-0.9, 0.9]\times10^2$	$[-1.2, 1.2]\times10^2$
	f_{M2}/Λ^4	$[-0.8, 0.8]\times10^4$	$[-1.1, 1.1]\times10^4$
	f_{M3}/Λ^4	$[-1.5, 1.4]\times10^4$	$[-1.9, 1.8]\times10^4$
$n=1$	f_{T0}/Λ^4	$[-7.6, 7.3]\times10^2$	$[-9.6, 9.5]\times10^2$
	f_{M2}/Λ^4	$[-4.4, 4.6]\times10^4$	$[-5.7, 5.9]\times10^4$
	f_{M3}/Λ^4	$[-8.9, 8.0]\times10^4$	$[-11.0, 10.0]\times10^4$
$n=2$	f_{T0}/Λ^4	$[-2.7, 2.6]\times10^3$	$[-3.5, 3.4]\times10^3$
	f_{M2}/Λ^4	$[-1.3, 1.3]\times10^5$	$[-1.6, 1.7]\times10^5$
	f_{M3}/Λ^4	$[-2.9, 2.5]\times10^5$	$[-3.7, 3.3]\times10^5$

NEW: WWW (ATLAS)

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



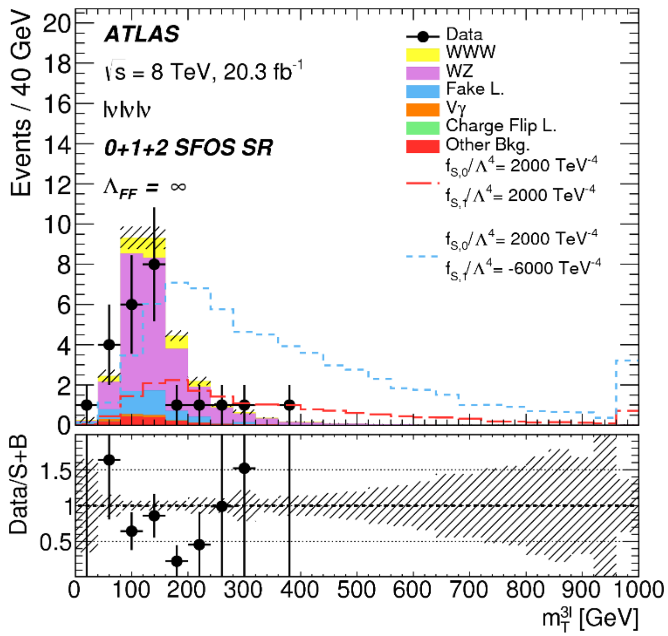
Leptonic Selection

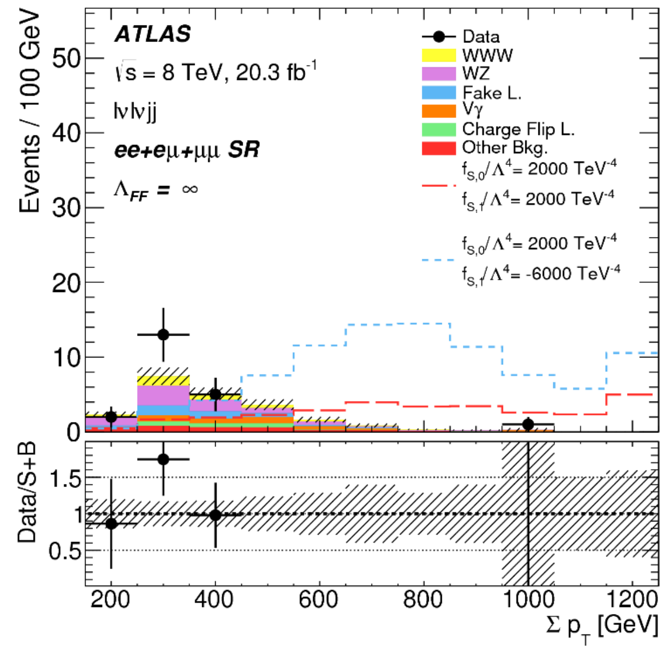
- Exactly 3 leptons $p_T > 20$ GeV
- Maximally 1 jet $p_T > 25$ GeV
- $\Delta\Phi(lll, p_T^{miss}) > 2.5$
- No b-jet
- Z rejection cuts on m_{ll} and E_T^{miss}

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^-

❖ Background dominated





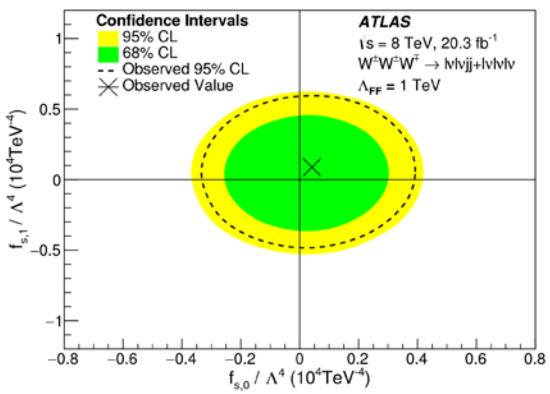
❖ Cross section „measured“ on 1.0 s.d. level

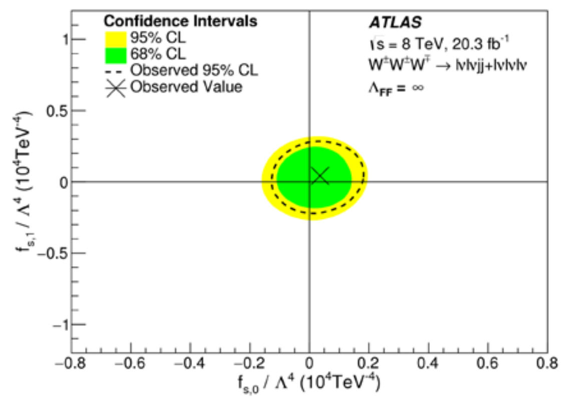
		Cross section [fb]	
		Theory	Observed
Fiducial	$\ell\nu\ell\nu\ell\nu$	0.309 ± 0.007 (stat.) ± 0.015 (PDF) ± 0.008 (scale)	$0.31\ ^{+0.35}_{-0.33}$ (stat.) $^{+0.32}_{-0.35}$ (syst.)
	$\ell\nu\ell\nu jj$	0.306 ± 0.007 (stat.) ± 0.015 (PDF) ± 0.011 (scale)	$0.26\ ^{+0.42}_{-0.35}$ (stat.) $^{+0.20}_{-0.21}$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

❖ 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]





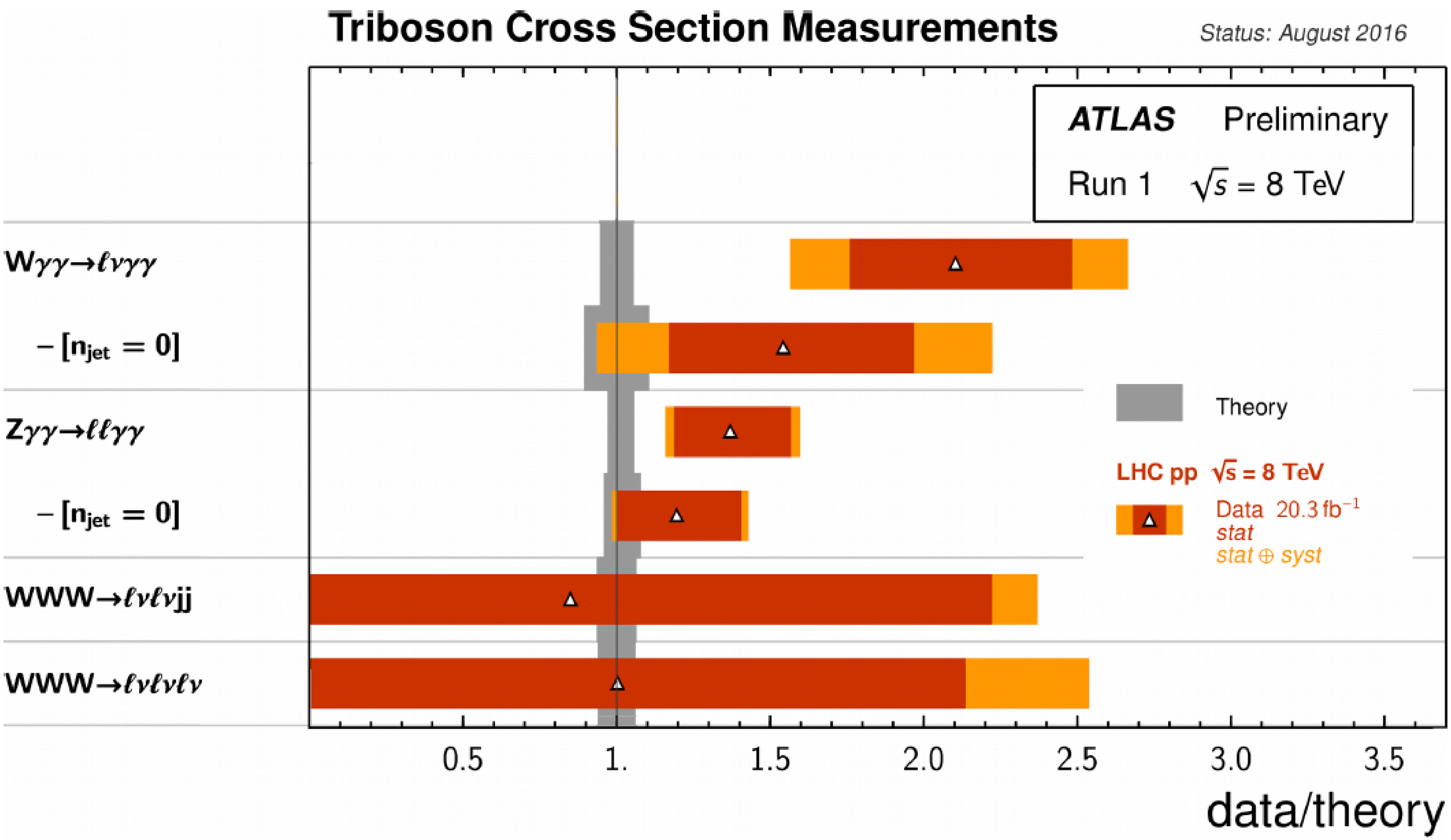
- Sensitivity to f_S parameters not competitive with VBS channels
- Conversion of $\Lambda_{FF} = \infty$ limits into α_4 and α_5 yields e.g.

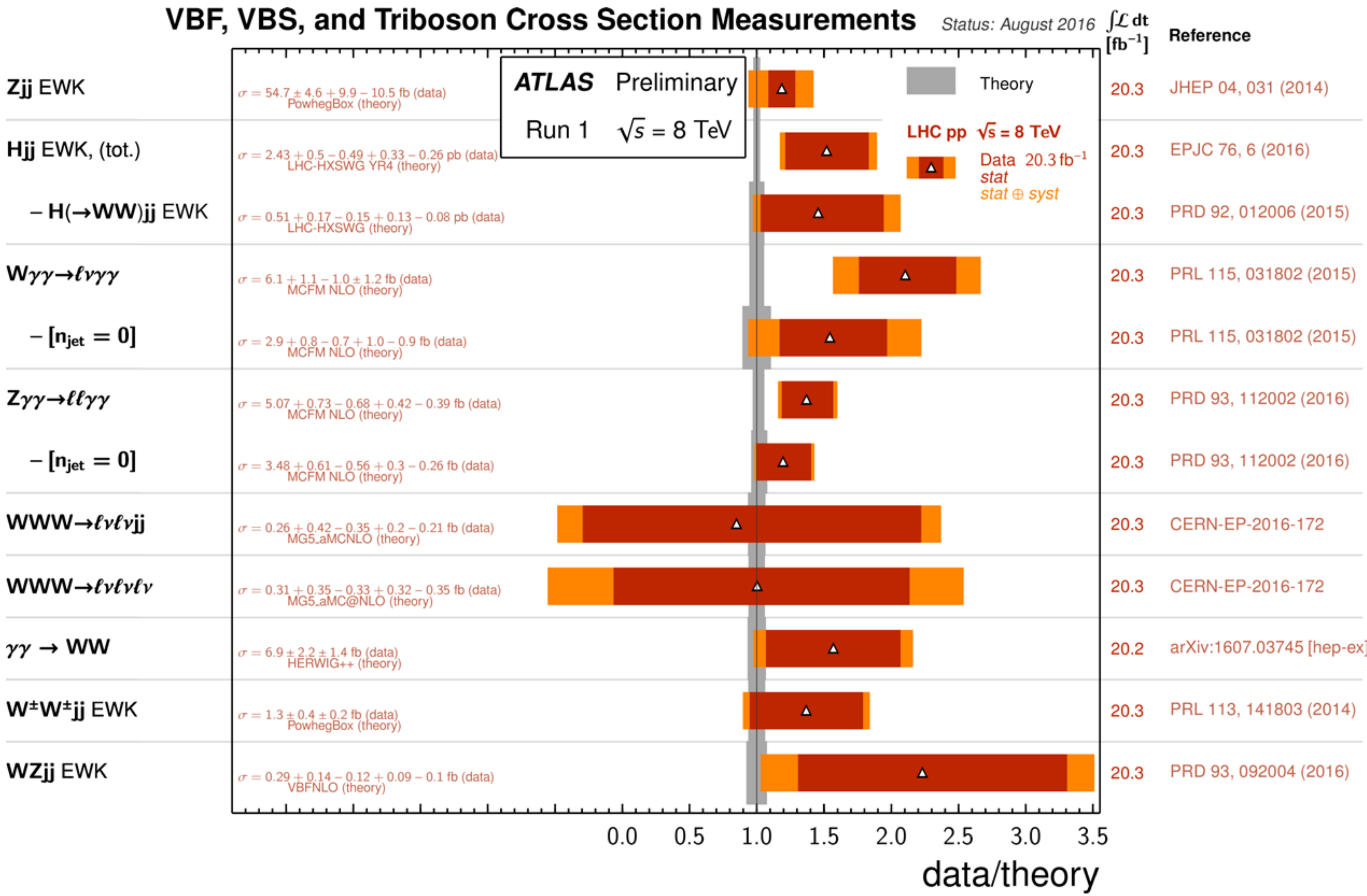
  α_4 expected [–0.62, 0.80], observed [–0.49, 0.75]

  α_5 expected [–0.58,0.71], observed [–0.48,0.62].

- This is just the beginning of a new field!

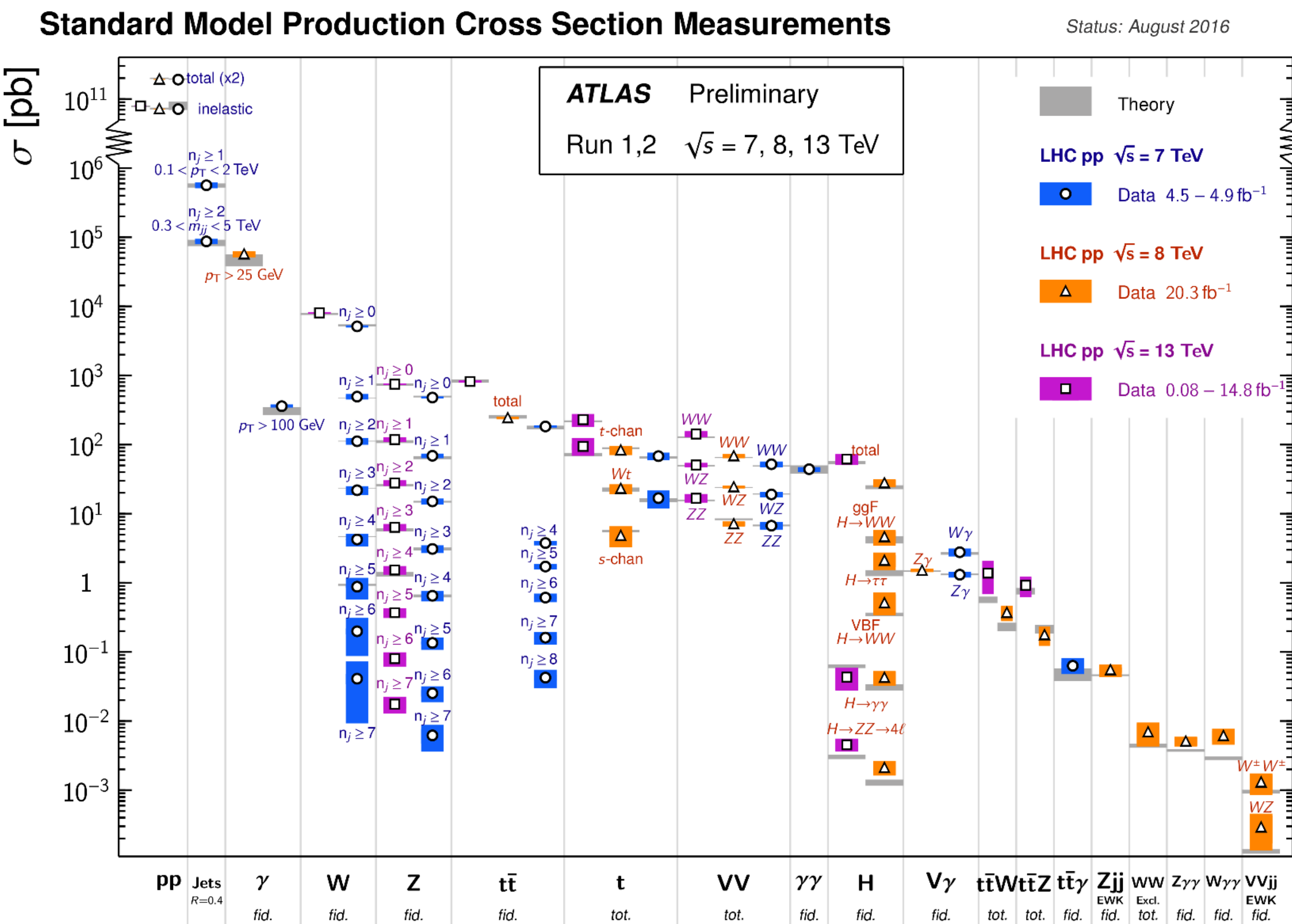
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/ATLAS_k_SMSummary_TriBosonFiducialRatio_Simple/ATLAS_k_SMSummary_TriBosonFiducialRatio_Simple.png





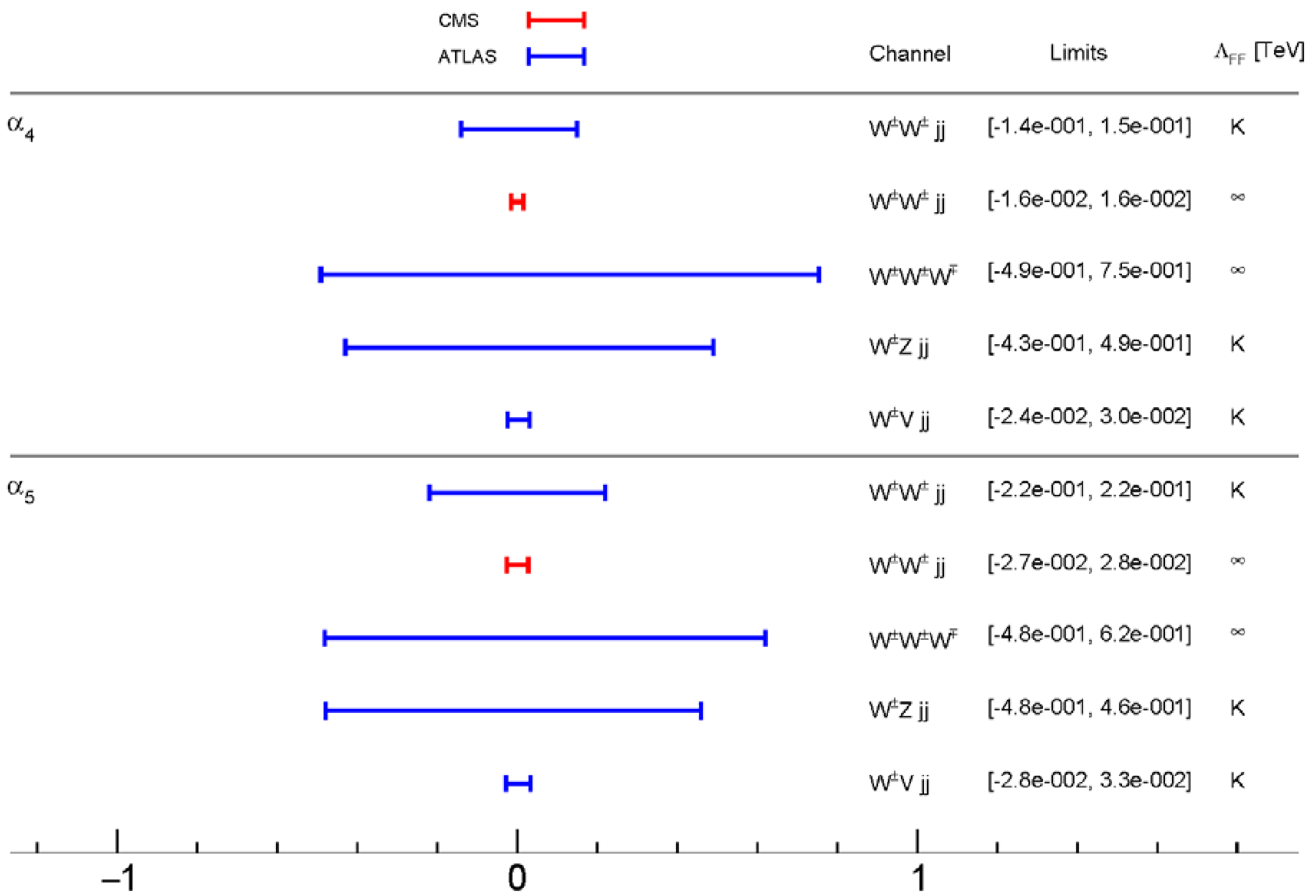
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/

❖ Smallest cross-sections measured at LHC



Overview aQGCs

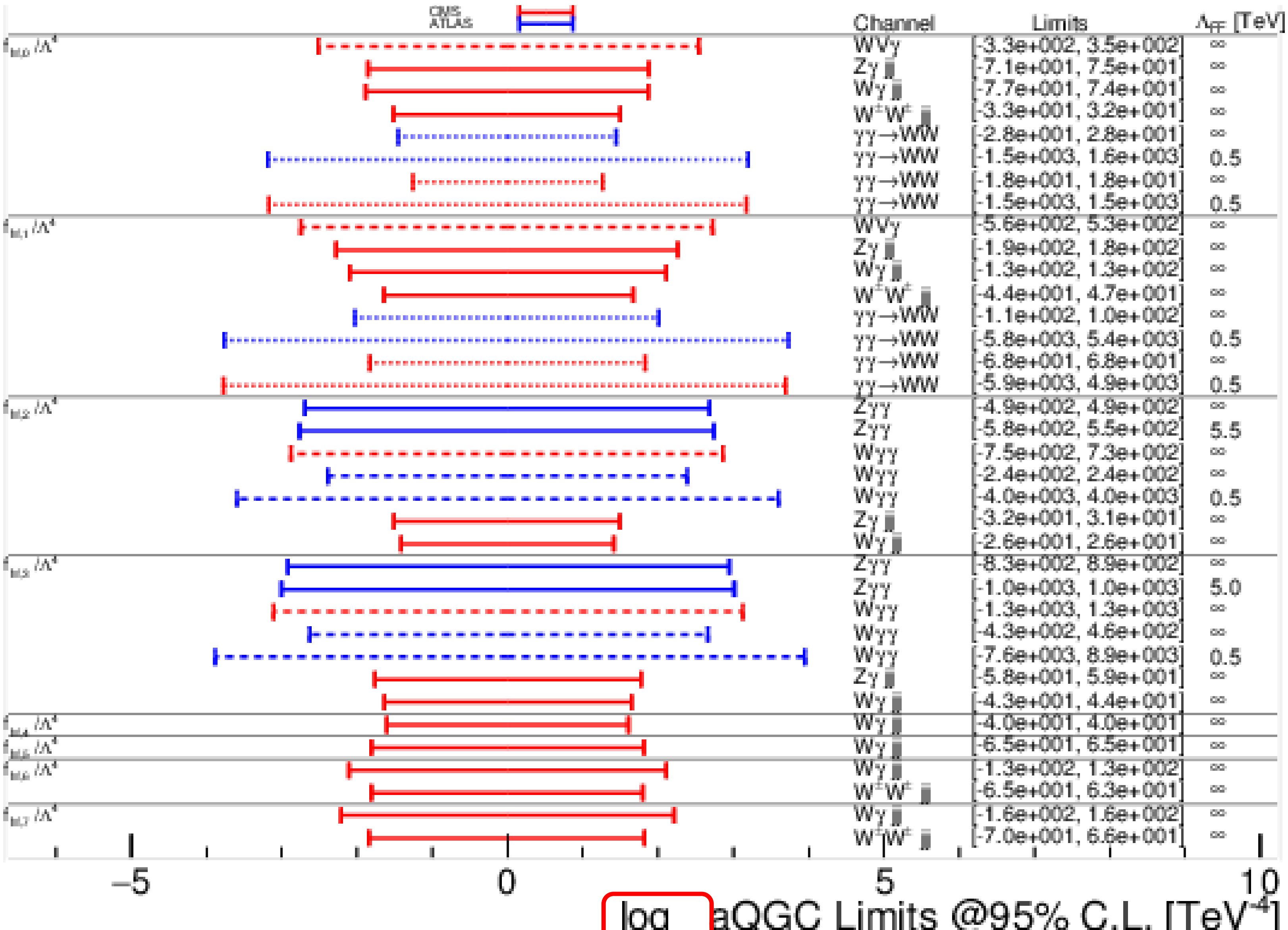
- To be published in Review of Modern Physics
  Green, Meade, Pleier, „Multi-Boson Interactions at the Run 1 LHC"
- *Be careful when comparing ununitarized ($\Lambda_{FF}=\infty$) with K-matrix (K)*



For f=1: Λ=1TeV Λ=100 GeV

Limits on f_M/Λ^4

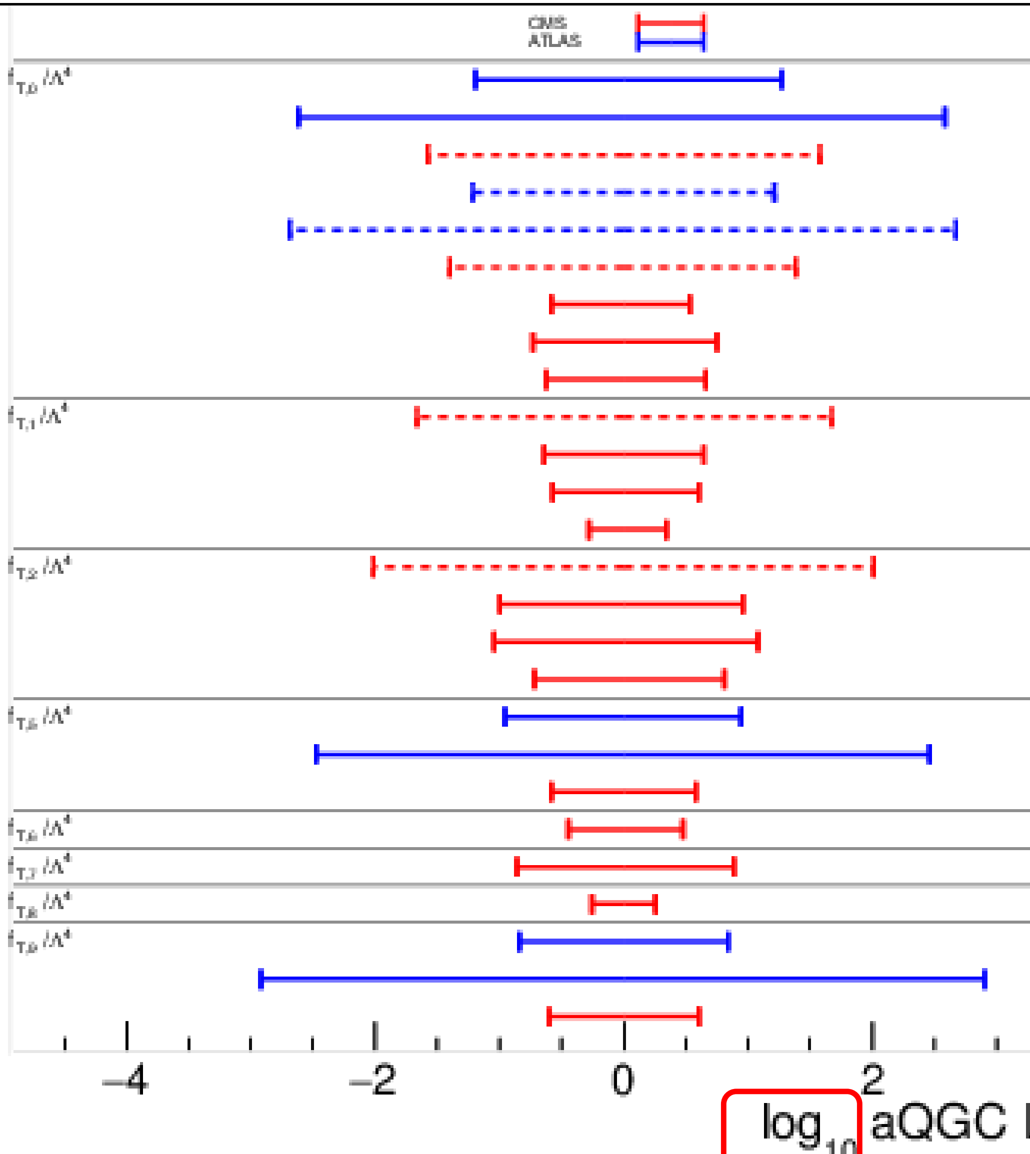
Mostly un-unitarized ($\Lambda_{FF} = \infty$)



For f=1: Λ=1TeV Λ=100 GeV

Limits of f_T/Λ^4

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



Channel	Limits	Λ_{FF} [TeV]
$Z\gamma\gamma$	[-1.6e+001, 1.9e+001]	∞
$Z\gamma\gamma$	[-4.2e+002, 3.8e+002]	0.7
$W\gamma\gamma$	[-3.8e+001, 3.8e+001]	∞
$W\gamma\gamma$	[-1.6e+001, 1.6e+001]	∞
$W\gamma\gamma$	[-4.9e+002, 4.7e+002]	0.6
$WV\gamma$	[-2.5e+001, 2.4e+001]	∞
$Z\gamma jj$	[-3.8e+000, 3.4e+000]	∞
$W\gamma jj$	[-5.4e+000, 5.6e+000]	∞
$W^\pm W^\pm jj$	[-4.2e+000, 4.6e+000]	∞
$W\gamma\gamma$	[-4.6e+001, 4.7e+001]	∞
$Z\gamma jj$	[-4.4e+000, 4.4e+000]	∞
$W\gamma jj$	[-3.7e+000, 4.0e+000]	∞
$W^\pm W^\pm jj$	[-1.9e+000, 2.2e+000]	∞
$W\gamma\gamma$	[-1.0e+002, 1.0e+002]	∞
$Z\gamma jj$	[-9.9e+000, 9.0e+000]	∞
$W\gamma jj$	[-1.1e+001, 1.2e+001]	∞
$W^\pm W^\pm jj$	[-5.2e+000, 6.4e+000]	∞
$Z\gamma\gamma$	[-9.0e+000, 8.9e+000]	∞
$Z\gamma\gamma$	[-3.0e+002, 2.9e+002]	0.6
$W\gamma jj$	[-3.8e+000, 3.8e+000]	∞
$W\gamma jj$	[-2.8e+000, 3.0e+000]	∞
$W\gamma jj$	[-7.3e+000, 7.7e+000]	∞
$Z\gamma jj$	[-1.8e+000, 1.8e+000]	∞
$Z\gamma\gamma$	[-6.9e+000, 6.9e+000]	∞
$Z\gamma\gamma$	[-8.3e+002, 8.0e+002]	0.4
$Z\gamma jj$	[-4.0e+000, 4.0e+000]	∞

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.
- No process so far discovered on 5 s.d. level
- QGC contribution not uniquely to defince, but existence proven(?)
- Precise measurements need much more data (HL LHC!)

2. Constrain anomalous Quartic Gauge Couplings (aQGC)

- A plethora of limits existing
- Lot of issues with different unitarizations and parameter sets
- Limits correspond to New Physics scales L between 50 and 1500 GeV
- Need more explicit models test (resonances, diff. distriubutions)

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 ?)