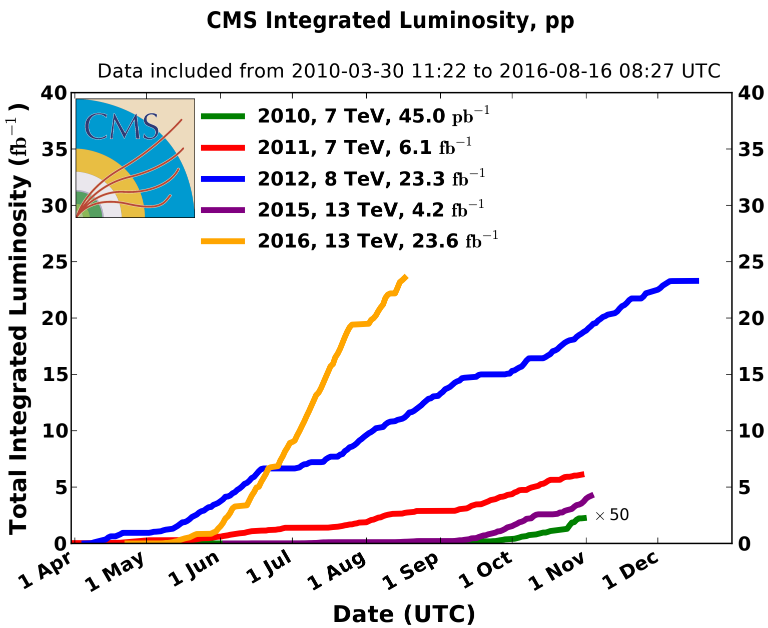
Results on VBF, Diboson Production and aTGCs part I

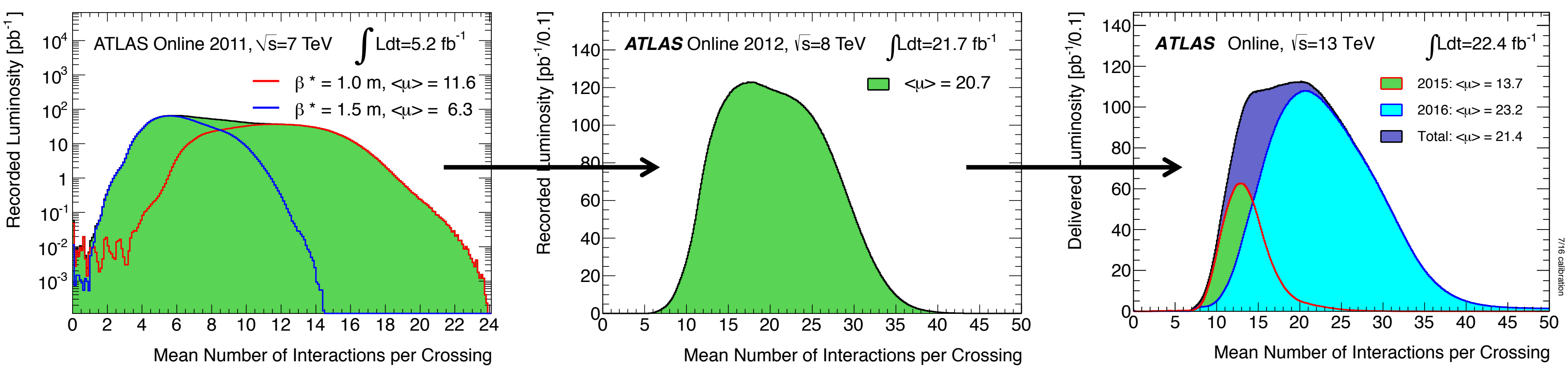
Senka Đurić
(University of Wisconsin-Madison)

On behalf of the CMS and ATLAS Collaborations

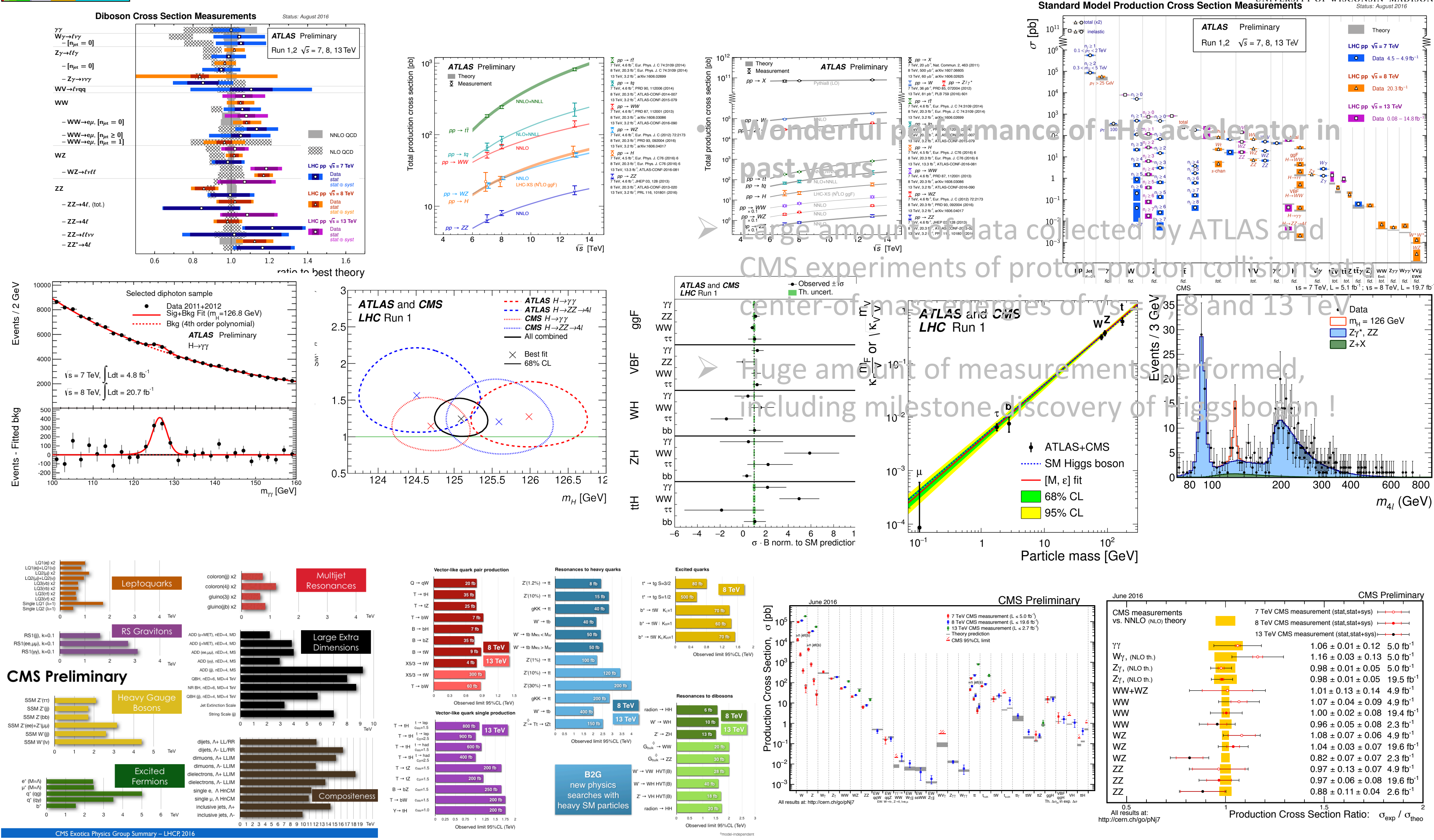
LHC performance



- **Wonderful performance of LHC accelerator in past years**
  - Large amount of data collected by ATLAS and CMS experiments of proton-proton collisions at a center-of-mass energies of $\sqrt{s}$ = 7, 8 and 13 TeV
  - Huge amount of measurements performed, including milestone discovery of Higgs boson !

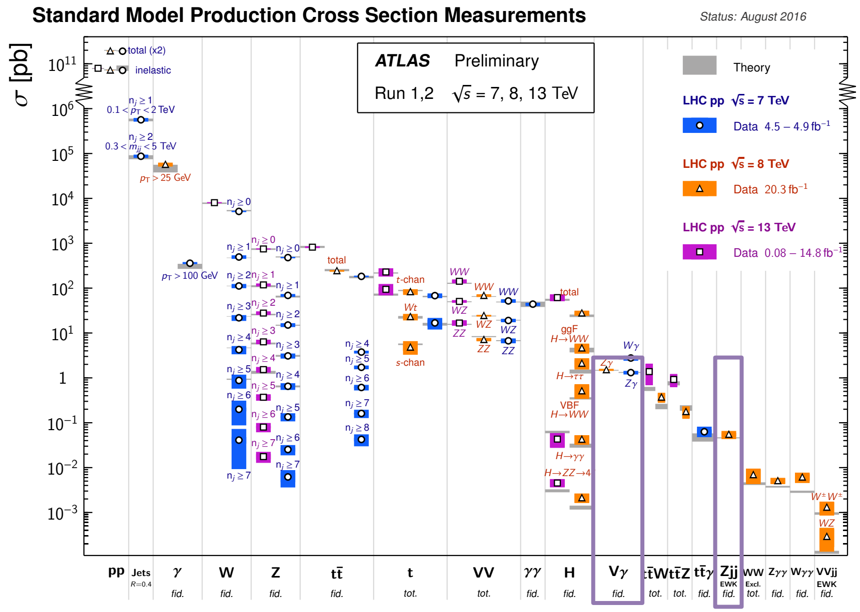


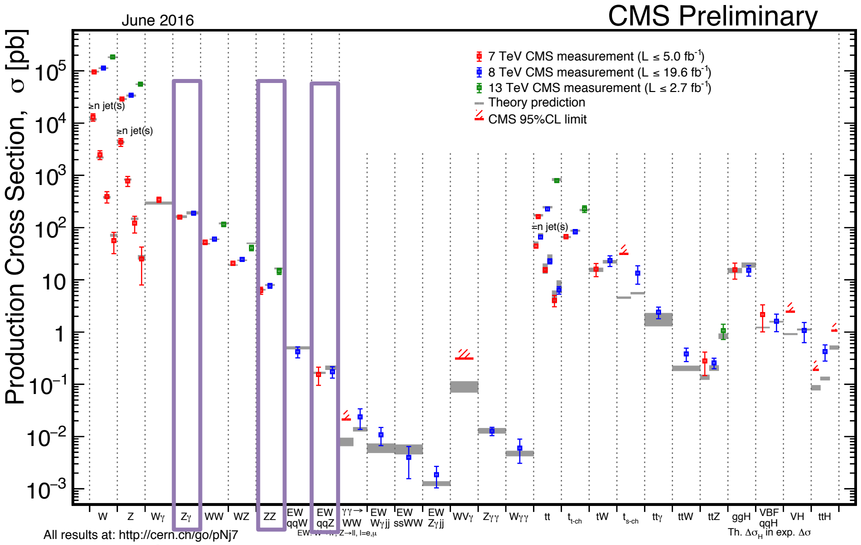
(Extreamly short!) Summary of ATLAS and CMS results



- Wonderful performance of LHC accelerator in past years
  - Large amount of data collected by ATLAS and CMS experiments of proton-proton collisions at a center-of-mass energies of √s = 7, 8 and 13 TeV
  - Huge amount of measurements performed, including milestone discovery of Higgs boson !

In this talk





ATLAS and CMS results:

- Neutral diboson production
  - ZZ -> 4l, 2l+2ν
  - Zγ -> 2l+γ, 2ν+γ
- Charged diboson production with semileptonic decay
  - WV(W/Z) -> lν+jj
- Electroweak Z production
  - Vector boson fusion (VBF) Z -> 2l

Related talks at MBI2016:

- K. Lohwasser (Charged diboson production and VBF W)
- K. Long (VV+jets)
- J. Searcy and J. Faulkner (VBS and aQGC)
- J. Djuvsland (triboson and aQGC)
- V. Dao and J. Lauwers (Run 2 LHC and HL-LHC)

Diboson production at LHC

Diboson production

- Important test of the Standard Model
- Large cross section of multiboson production at LHC in pp collisions
- Clean signature and small branching ratio for vector bosons decaying leptonicaly
- Not clean signature but large branching ratio for hadronic decays
- Backgrounds for New Physics and Higgs measurements

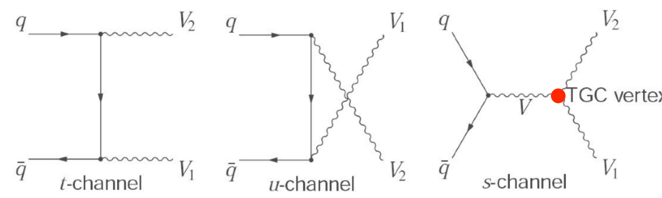
Sensitive to theoretical calculation

- Large NLO QCD corrections at high √s
- Non-negligible NNLO QCD and NLO QED corrections

Sensitive to new physics

- New particles decaying to vector bosons: W', Z', …
- Anomalies in vector boson scattering
- <u>Anomalies in triple boson vector boson couplings (aTGC) = **indirect search for New Physics**</u>

LO production diagrams (pp->VV)

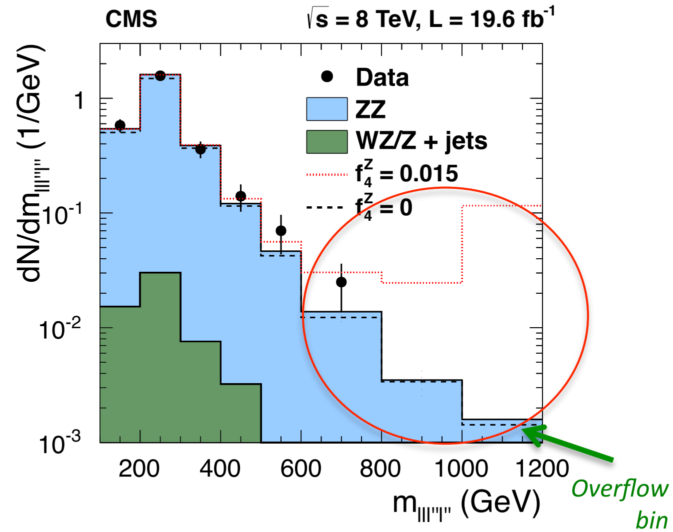


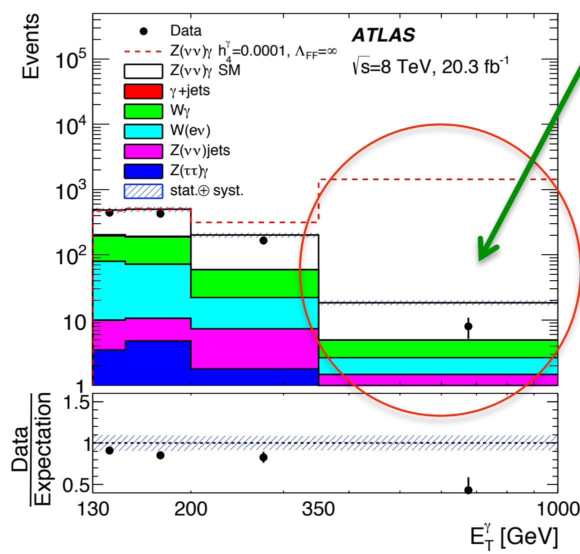
In most ATLAS and CMS multiboson analysis together with cross section measurement we measure anomalous gauge couplings

Anomalous coupling signature

- Anomalous couplings result in an **increase of cross section at high energies** $(\hat{s})$ -> observables dependent on the invariant mass of the diboson system and the boson p_T are particularly sensitive (m_{VV}, m_{ll}, pT_V, pT_l, …)
- Couplings are measured (or limits are set) by performing **binned fit in single sensitive observable**
- **Sensitivity mostly in highest bins**
  - **Last bin is always overflow bin**
  - **Limiting factor: observed statistics in the tail (primary) and systematic and statistical uncertainty on the signal model (secondary)**
- In different analyses: different observables are the most sensitive
- **Sensitivity depends on absolute size of anomalous coupling signal, absolute size of expected background and uncertainties**
  - **Expected limit increases with absolute increase of background, decrease of signal and increase of uncertainty**
- Binning is optimized to reach highest expected sensitivity
- Fit is usually performed simultaneously on electron and muon channel

PLB 740 (2015) 250



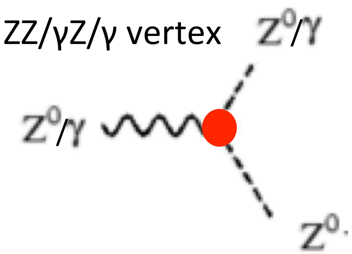


Phys. Rev. D 93, 112002 (2016)

ZZ and Zγ: Anomalous coupling parametrizations

Using additional assumptions to reduce the number of parameters

ZZ/γZ/γ vertex



EFFECTIVE VERTEX PARAMETRIZATION

add higher order operators that respect symmetries

Nucl. Phys. B282 (1987) 253

Assumptions Zγ channel: CP conservation

(Hagiwara *et al.*, Nucl.Phys.B282 (1987) 253 (+ missing "*i*" factor))

$$\Gamma^{\alpha\beta\mu}_{Z\gamma V} = i\, e \frac{q_V^2 - m_V^2}{m_Z^2} \Big\{ h_1^V \left(q_\gamma^\mu g^{\alpha\beta} - q_\gamma^\alpha g^{\beta\mu}\right) + h_2^V \frac{q_V^\alpha}{m_Z^2} \left(q_\gamma q_V\, g^{\beta\mu} - q_\gamma^\mu\, q_V^\beta\right) + h_3^V\, \epsilon^{\alpha\beta\mu\rho}\, q_{\gamma\rho} + h_4^V \frac{q_V^\alpha}{m_Z^2} \epsilon^{\mu\beta\rho\sigma}\, q_{V\rho}\, q_{\gamma\sigma} \Big\}$$

Assumptions ZZ channel: Electromagnetic gauge invariance

(Hagiwara *et al.*, Nucl.Phys.B282:253,1987)

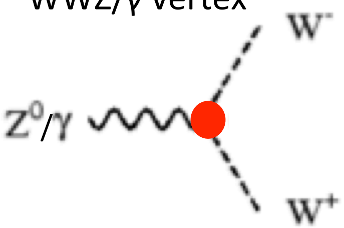
$$\Gamma^{\alpha\beta\mu}_{Z_1 Z_2 V} = i\, e \frac{q_V^2 - m_V^2}{m_Z^2} \Big\{ f_4^V \left(q_V^\alpha\, g^{\beta\mu} + q_V^\beta\, g^{\mu\alpha}\right) + f_5^V\, \epsilon^{\alpha\beta\mu\rho} \left(q_{Z_1\rho} - q_{Z_2\rho}\right) \Big\}$$

channel	couplings	parametrization	parameters	Dimensionality of operator
Zγ	ZZγ, γZγ	Effective vertex	h_3	dim6
			h_4	dim8
ZZ	ZZZ, γZZ		f_4	dim6
			f_5	dim6

WZ, WW, Wγ: Anomalous coupling parametrizations

Using additional assumptions to reduce the number of parameters

WWZ/γ vertex



PRD 41 (1990) 2113

Nucl. Phys. B282 (1987) 253

EFFECTIVE LAGRANGIAN PARAMETRIZATION

allow the couplings of SM operators to vary + add higher order operators that respect symmetries

(Hagiwara *et al.*, Nucl.Phys.B282:253,1987)

$$\begin{aligned}\Gamma^{\alpha\beta\mu}_{WWV} &= (1+\Delta g_1^V)[(q_1-q_2)^\mu g^{\alpha\beta} - q_1^\beta g^{\mu\alpha} + q_2^\alpha g^{\mu\beta}] \\ &+ (1+\Delta\kappa_V)[q_2^\alpha g^{\mu\beta} - q_1^\beta g^{\mu\alpha}] \\ &+ \frac{\lambda_V}{m_W^2}(q_1-q_2)^\mu\,[\frac{s}{2}g^{\alpha\beta} - q_2^\alpha q_1^\beta] \\ &+ i\, g_5^V\, \epsilon^{\mu\alpha\beta\rho}\,(q_1-q_2)_\rho\end{aligned}$$

Assumptions (14->3 independent parameters):
Electromagnetic gauge invariance, C and P conservation, Lagrangian SU(2)XU(1) invariant

$$\Delta g_1^Z = \Delta\kappa_Z + \tan^2\theta_W \Delta\kappa_\gamma \qquad \Delta g_1^Z = g_1^Z - 1,\ \Delta\kappa_{\gamma,Z} = \kappa_{\gamma,Z} - 1$$

valid for: $\sqrt{s} << \Lambda$

SU(3)xSU(2)xU(1) invariance by construction

Λ is large, of the order of the scale of New Physics

terms supressed by $\propto \frac{\sqrt{s}}{\Lambda}$

only the first terms are relevant

O_i are operator of (energy) "dimension n"

c_i are adimensional couplings of order ~ 1

allows systematic calculation of higher order corrections

EFFECTIVE FIELD THEORY PARAMETRIZATION

infinite sum of (non-renormalizable) Lagrangians:

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty}\sum_i \frac{c_i^{(n)}}{\Lambda^n}\mathcal{O}_i^{(n+4)}$$

Assumptions (5->3 independent parameters):
CP conservation

$$\begin{aligned}\mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}] \\ \mathcal{O}_W &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi) \\ \mathcal{O}_B &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)\end{aligned}$$

'HISZ' parametrization

Translation between two approaches:

$$\begin{aligned}g_1^Z &= 1 + c_W\frac{m_Z^2}{2\Lambda^2} \\ \kappa_\gamma &= 1 + (c_W + c_B)\frac{m_W^2}{2\Lambda^2} \\ \kappa_Z &= 1 + (c_W - c_B\tan^2\theta_W)\frac{m_W^2}{2\Lambda^2} \\ \lambda_\gamma &= \lambda_Z = c_{WWW}\frac{3g^2m_W^2}{2\Lambda^2}\end{aligned}$$

channel	couplings	parametrization	parameters	Dimensionality of operator
WV	ZWW, γWW	Effective Lagrangian	$\Delta\kappa$	dim4
	ZWW, γWW		λ	dim6
	ZWW		Δg^1_Z	dim4
	ZWW, γWW	Effective field theory	c_{WWW}/Λ^2	dim6
			c_B/Λ^2	dim6
			c_W/Λ^2	dim6

Statistical method: anomalous coupling measurement

$\vec{\theta}$ = nuisance parameters

$\vec{\alpha}$ = **anomalous coupling parameters**

L = likelihood function

$\lambda(\vec{\alpha})$ = profile likelihood ratio

maximizes L in θ, for specified α

$$\lambda(\vec{\alpha}) = \frac{L(\vec{\alpha},\hat{\hat{\vec{\theta}}}_{\vec{\alpha}})}{L(\hat{\vec{\alpha}},\hat{\vec{\theta}})}$$

maximize L in α and θ

test statistics: $t(\vec{\alpha}) = -2\ln\lambda(\vec{\alpha})$

Limit setting criteria (both supported by CMS statistics committee as methods for aC limit setting):

1. "deltaNLL" limit: use of Wilks theorem, distribution of t_α, under assumption α, is approximated with χ^2 distribution
   - Asymptotic, high statistics approximation
   - Fast but coverage is not guaranteed
2. "Feldman-Cousins (F-C)" limit: distribution of t_α, under assumption α, is determined by throwing toys
   - Computing time consuming but guaranties coverage

Usually the two methods agree within 10%.

Fitting aC parameters => measurement of aC parameters => due to large uncertainties wrt best value we quote 95% CL limits

Several definitions of expected limits are available

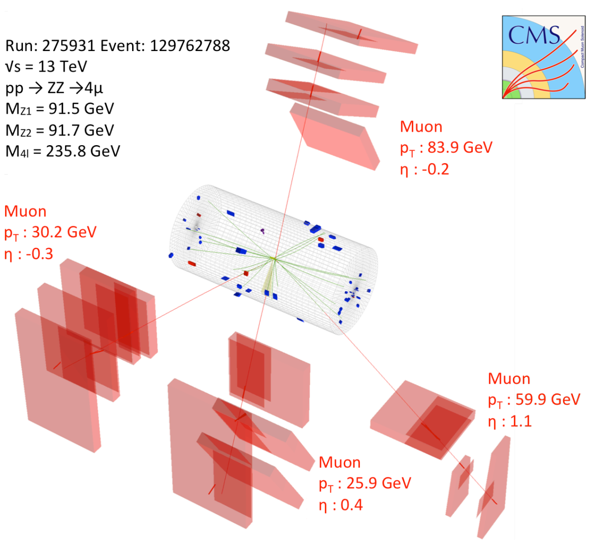
- Pre-fit or post-fit expected limit
- Toys or Asimov dataset
- ✓ Usually we have been using pre-fit Asimov dataset for expected limit

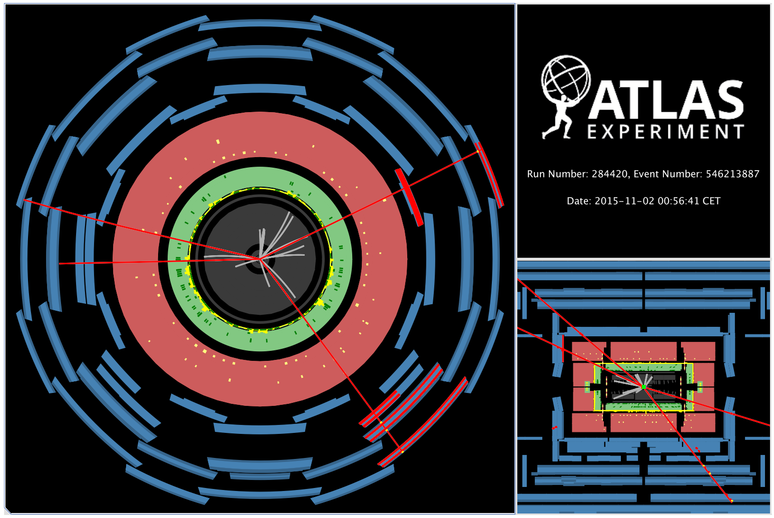
Systematic uncertainties covered via nuisance parameters.

Nuisance parameters are profiled.

Nuisance effect is lognormal (lnN) by default (CMS statistics committee recommendation).

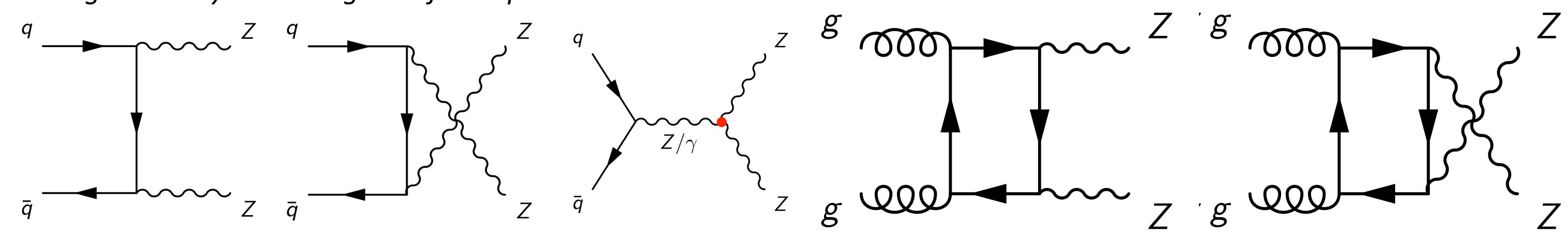
ZZ production at LHC





ZZ production at LHC

Leading order Feynman diagrams for ZZ production



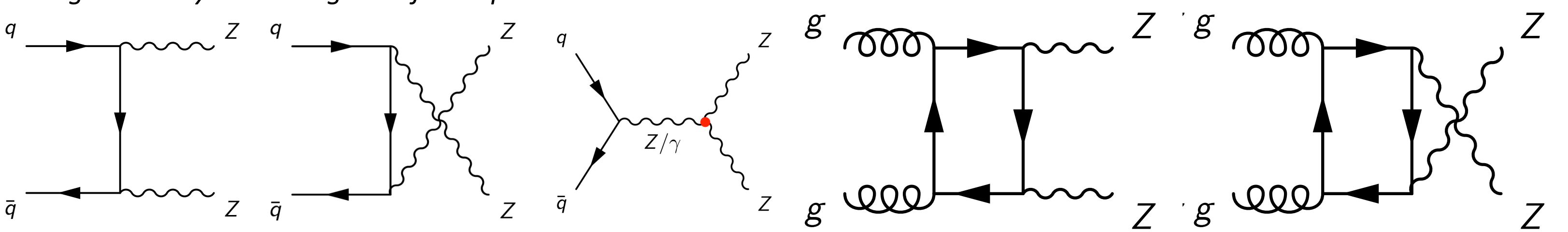
… + EWK production (see talk by J. Searcy and J. Faulkner)

New results!

ZZ		7 TeV	8 TeV		13 TeV
ATLAS	Z->4l	PRL 112, 231806 (2014)			-
	ZZ->4l	JHEP 03 (2013) 128 Cross section and aTGC measurement	ATLAS-CONF-2013-020 Cross section	PLB 753 (2016) 552-572 (4l) Differential and total cross section	PRL 116, 101801 (2016) Cross section
	ZZ->2l2v			-	-
CMS	Z->4l	JHEP 12 (2012) 034 Cross section	-		arXiv:1607.08834 (CMS-SMP-16-001) Cross section
	ZZ->4l	JHEP 01 (2013) 063 Cross section and aTGC measurement	PLB 740 (2015) 250, CMS-PAS-SMP-15-012 Cross section and aTGC measurement		
	ZZ->2l2v	EPJC 75 (2015) 511 Cross section and aTGC measurement			-

ZZ production at LHC

Leading order Feynman diagrams for ZZ production



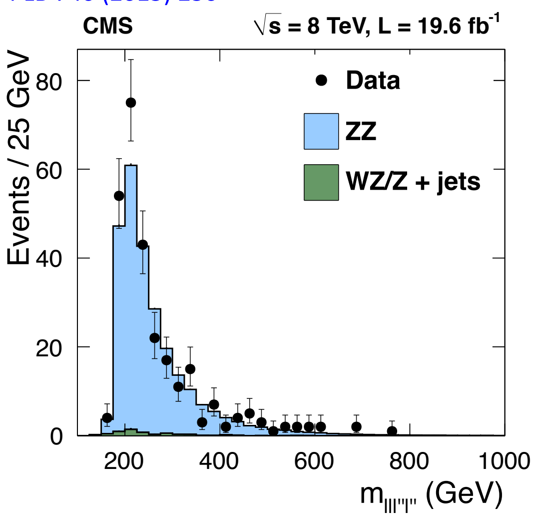
... + EWK production (see talk by J. Searcy and J. Faulkner)

ZZ->4l:
- ✓ Clean signal signature
- ✓ Low background
- ▪ Small BR

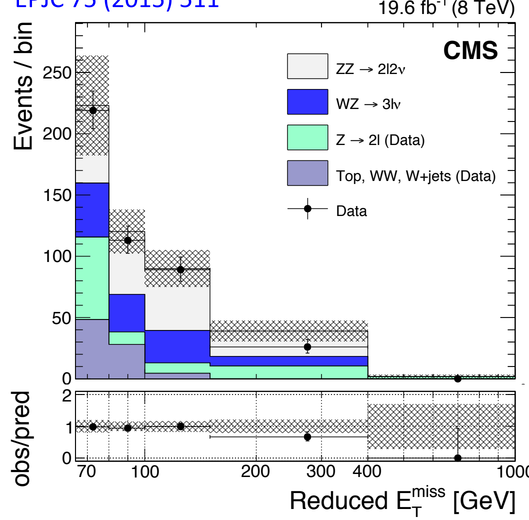
ZZ->2l2v:
- ✓ Clean signal signature
- ▪ Larger background
- ✓ Larger BR

ZZ->2l2j:
- ▪ Not clean signal signature
  - ▪ Large experimental systematic uncertainties
- ▪ Large background
- ✓ Large BR

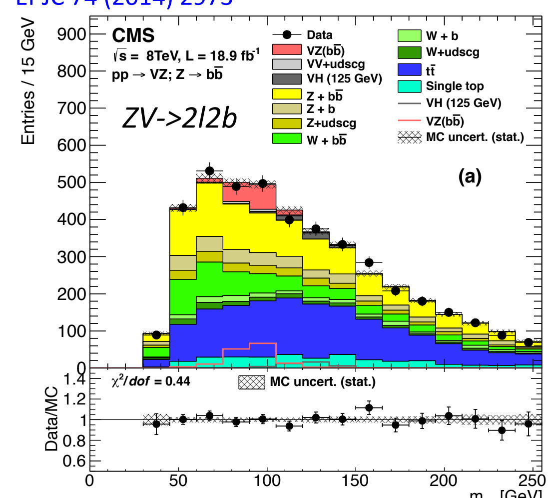
PLB 740 (2015) 250



EPJC 75 (2015) 511

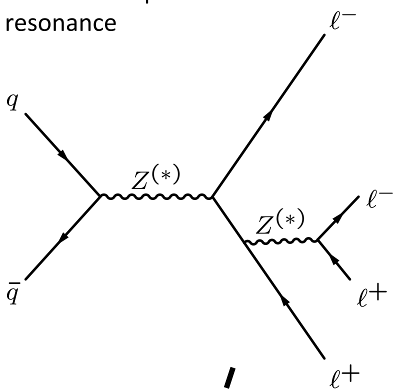


EPJC 74 (2014) 2973

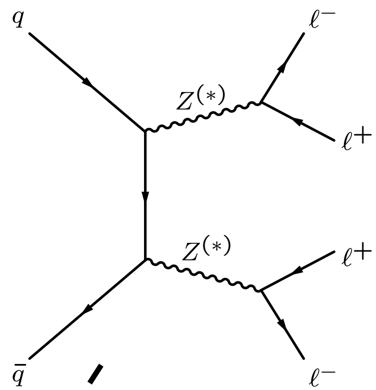


ZZ production modes

Dominant 4l production at Z resonance



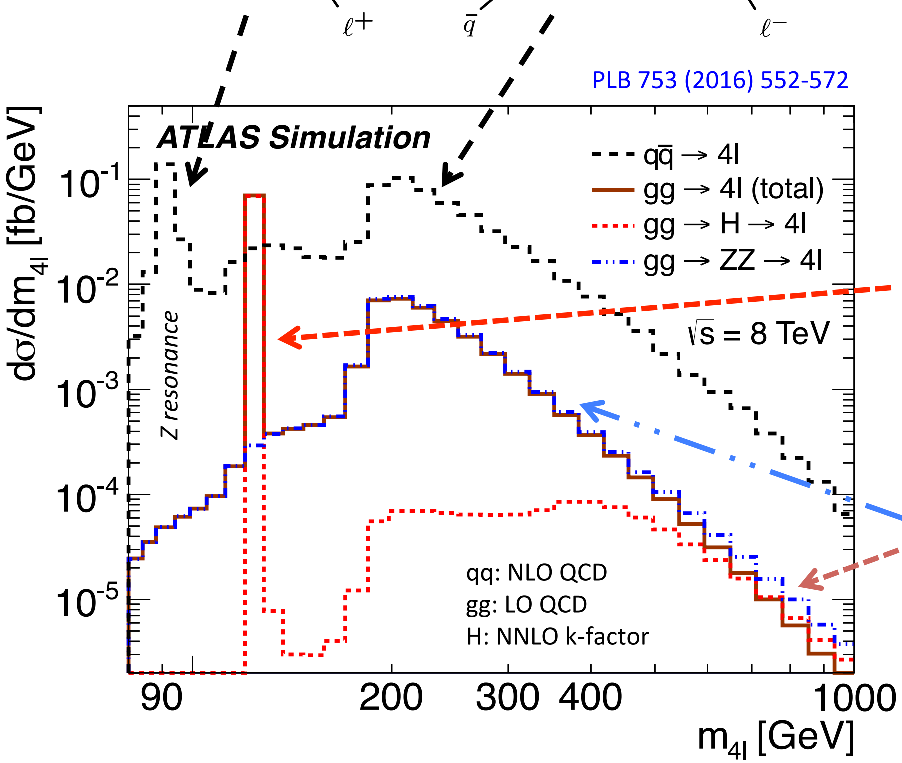
Dominant 4l production above the Z resonance



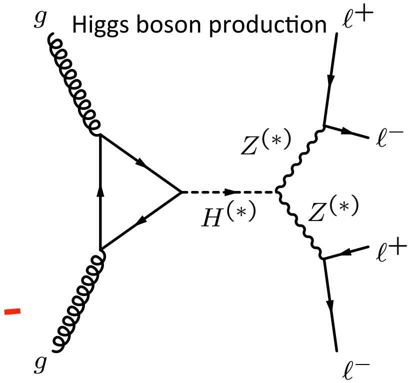
+ small contribution from qq VBS production

M_{4l} spectrum is essential for the study of the different production mechanisms !

PLB 753 (2016) 552-572

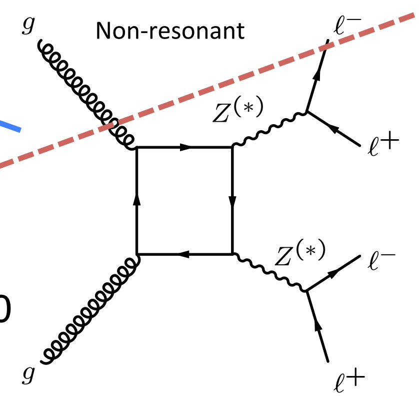


Higgs boson production



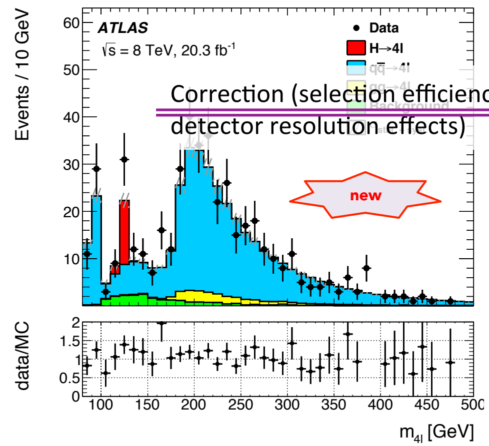
+ VBF, VH, ttH higgs production (<15% to higgs production)

Non-resonant

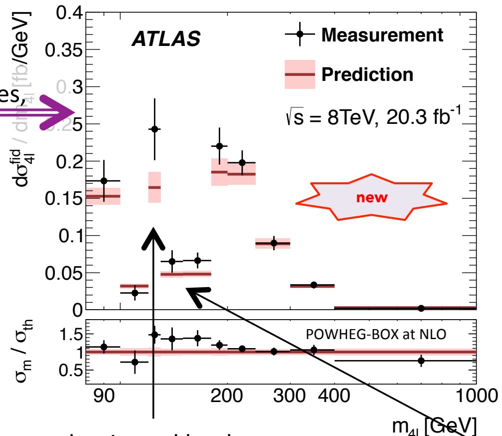


large destructive interference of ggH with ggF processes (high mass m_{4l})

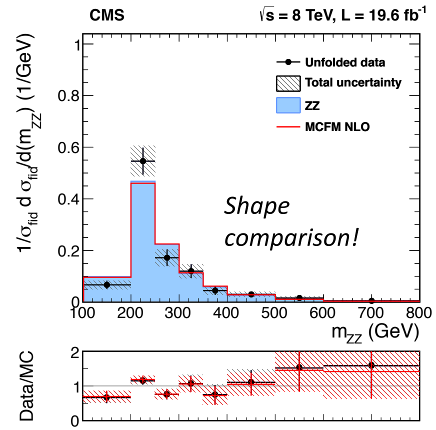
ZZ differential measurements



Correction (selection efficiencies, detector resolution effects)



dominated by the resonant Higgs-boson contribution



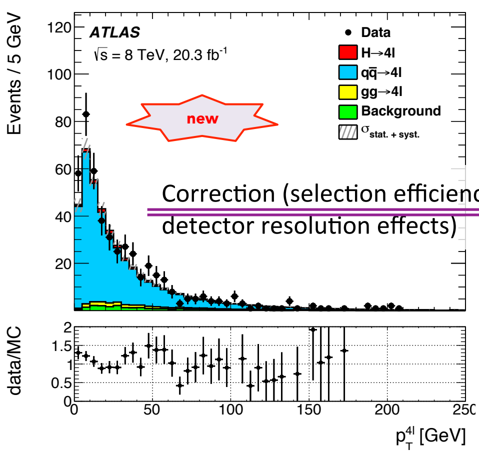
PLB 740 (2015) 250

M_{4l} **spectrum** is essential for the study of the different production mechanisms !

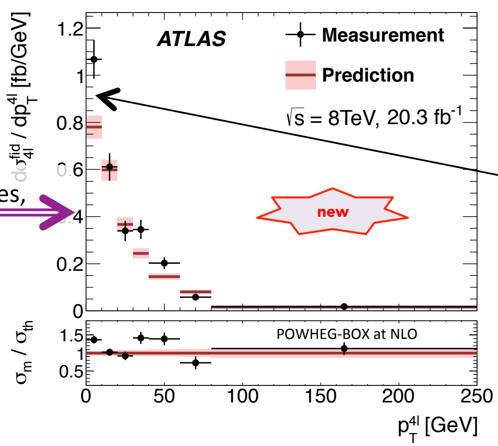
New differential measurement of ZZ+jets!

NLO EW K-factors not available for $M_{4l} < 2 \times M_Z$

PLB 753 (2016) 552-572

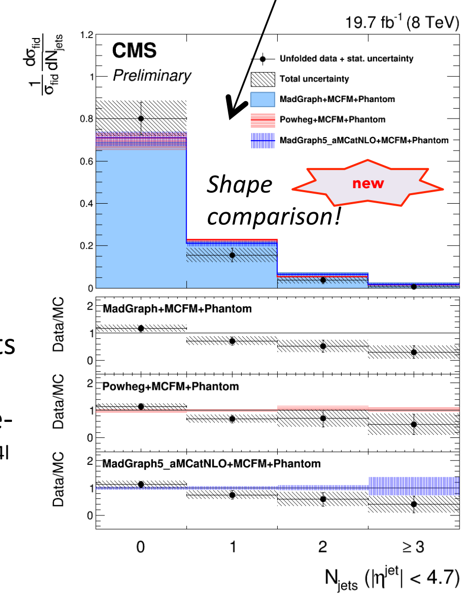


Correction (selection efficiencies, detector resolution effects)



p_T^{4l} **spectrum is sensitive to:**

- higher-order QCD corrections
- QCD resummation effects at small p_T^{4l}
- sensitive to top-loop effects in gg → H production as well as to anomalous triple-boson couplings at high p_T^{4l}



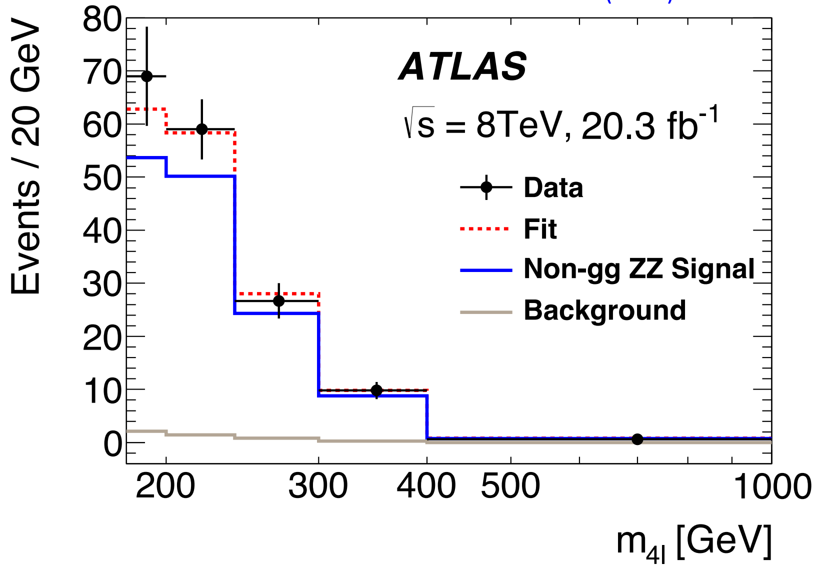
CMS-PAS-SMP-15-012

Uncertainties dominated by the statistical uncertainties of the data !

ZZ production from gg initial state?

new

PLB 753 (2016) 552-572



M_{4l} spectrum is essential for the study of the different production mechanisms !

➔ **Fitting the observed M_{4l} spectrum**

- Background: ZZ from qq initial state (NNLO QCD, NLO EWK) + background processes
- Signal: ZZ from gg initial state (LO QCD)

$$\mu_{gg} = 2.4 \pm 1.0(\text{stat.}) \pm 0.5(\text{syst.}) \pm 0.8(\text{theory})$$

Expected: (μ_{gg} = 1) <-> 3.1 fb

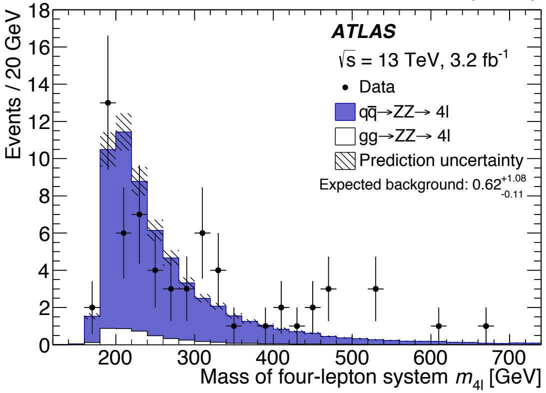
mainly due to the normalization uncertainty of the $q\bar{q} \rightarrow ZZ$ process

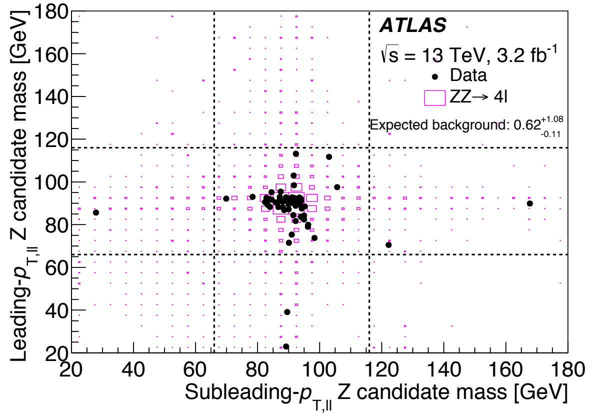
Uncertainty dominated by the statistical uncertainties of the data !

ZZ measurements with Run2 data

new

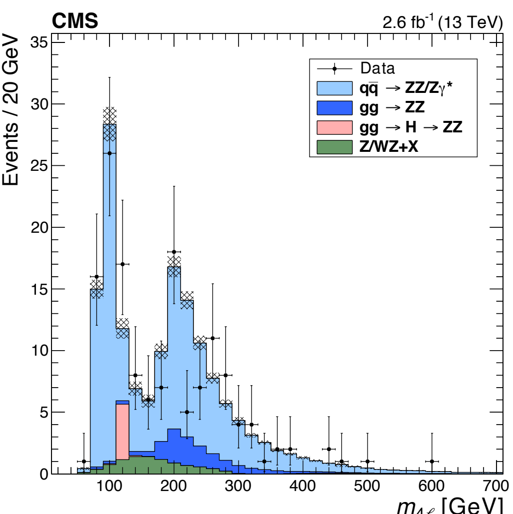
PRL 116, 101801 (2016)

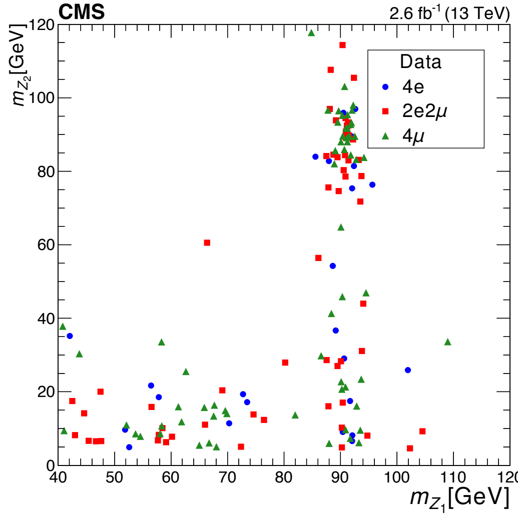




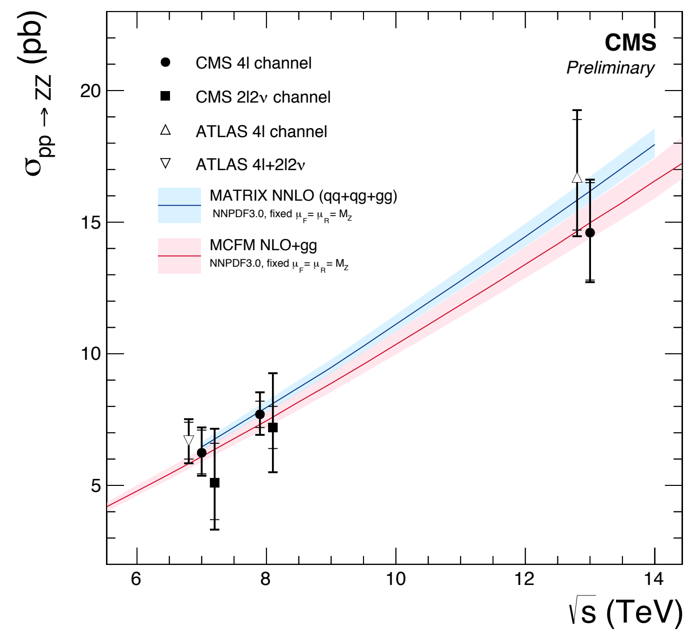
Measurement strategy and techniques similar to Run1

- Background from jets faking leptons estimated from data using fake rate / template fit method in CMS / ATLAS





arXiv:1607.08834
(CMS-SMP-16-001)



Good agreement with NLO and NNLO calculations across LHC $\sqrt{s}$!

Uncertainty dominated by the statistical uncertainties of the data !

Z->4l measurement with Run2 data

new

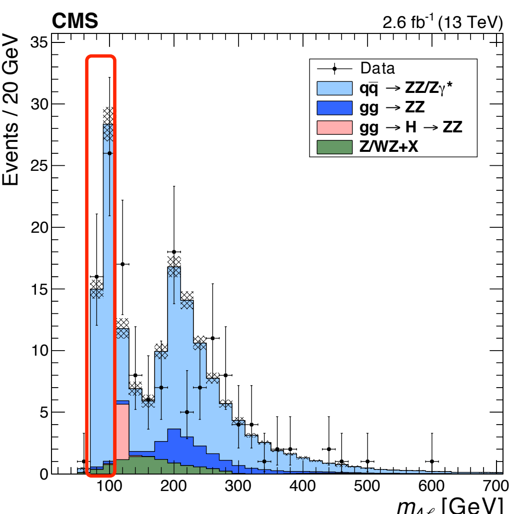
Cross section measurement	Fiducial requirements
Common requirements	$p_T^{\ell_1} > 20\,\mathrm{GeV}$, $p_T^{\ell_2} > 10\,\mathrm{GeV}$, $p_T^{\ell_{3,4}} > 5\,\mathrm{GeV}$, $\lvert\eta^\ell\rvert < 2.5$, $m_{\ell^+\ell^-} > 4\,\mathrm{GeV}$ (any opposite-sign same-flavor pair)
$Z \to \ell^+\ell^-\ell'^+\ell'^-$	$m_{Z_1} > 40\,\mathrm{GeV}$ $80 < m_{\ell^+\ell^-\ell'^+\ell'^-} < 100\,\mathrm{GeV}$
$ZZ \to \ell^+\ell^-\ell'^+\ell'^-$	$60 < m_{Z_1}, m_{Z_2} < 120\,\mathrm{GeV}$

Final state	Expected $N_{\ell^+\ell^-\ell'^+\ell'^-}$	Background	Total expected	Observed
4μ	$16.88 \pm 0.14 \pm 0.62$	$0.31 \pm 0.30 \pm 0.12$	$17.19 \pm 0.33 \pm 0.63$	17
$2e2\mu$	$15.88 \pm 0.14 \pm 0.87$	$0.37 \pm 0.27 \pm 0.15$	$16.25 \pm 0.31 \pm 0.88$	16
4e	$5.58 \pm 0.08 \pm 0.53$	$0.21 \pm 0.10 \pm 0.08$	$5.78 \pm 0.13 \pm 0.53$	6
Total	$38.33 \pm 0.21 \pm 1.19$	$0.89 \pm 0.42 \pm 0.22$	$39.22 \pm 0.47 \pm 1.21$	39

Including measurement of Z->4l!

$$\sigma_{\mathrm{fid}}(pp \to Z \to \ell^+\ell^-\ell'^+\ell'^-) = 30.5^{+5.2}_{-4.7}\,(\mathrm{stat})^{+1.8}_{-1.4}\,(\mathrm{syst}) \pm 0.8\,(\mathrm{lumi})\,\mathrm{fb},$$

Expected (NLO Powheg) = $27.9^{+1.0}_{-1.5} \pm 0.6$ fb



arXiv:1607.08834
(CMS-SMP-16-001)

$$\mathcal{B}(Z \to \ell^+\ell^-\ell'^+\ell'^-) = \frac{\sigma(pp \to Z \to \ell^+\ell^-\ell'^+\ell'^-)}{\mathcal{C}^{60-120}_{80-100}\,\sigma(pp \to Z \to \ell^+\ell^-)/\mathcal{B}(Z \to \ell^+\ell^-)},$$

Measurement for:
80 < M_{4l} < 100 GeV,
M_{l+l-}> 4 GeV

Correction for Z mass window, estimated using POWHEG

Calculated at NNLO with FEWZ v2.0

PDG value

$$\mathcal{B}(Z \to \ell^+\ell^-\ell'^+\ell'^-) = 4.9^{+0.8}_{-0.7}\,(\mathrm{stat})^{+0.3}_{-0.2}\,(\mathrm{syst})^{+0.2}_{-0.1}\,(\mathrm{theo}) \pm 0.1\,(\mathrm{lumi}) \times 10^{-6},$$

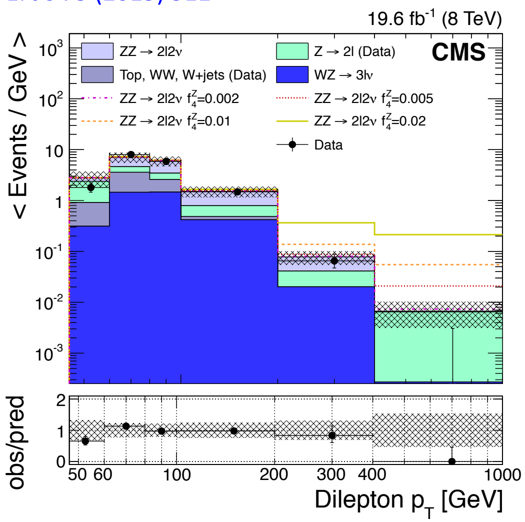
Expected (MG5_aMC@NLO) = 4.6×10^{-6}

Good agreement with SM expectation!

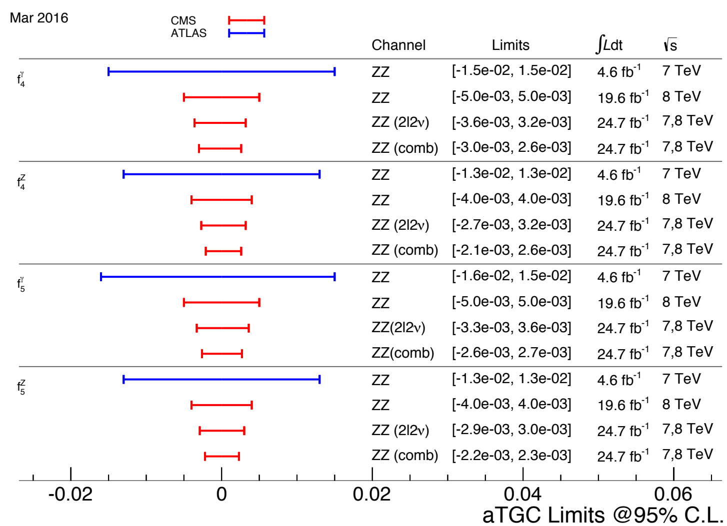
Statistics dominated measurement!

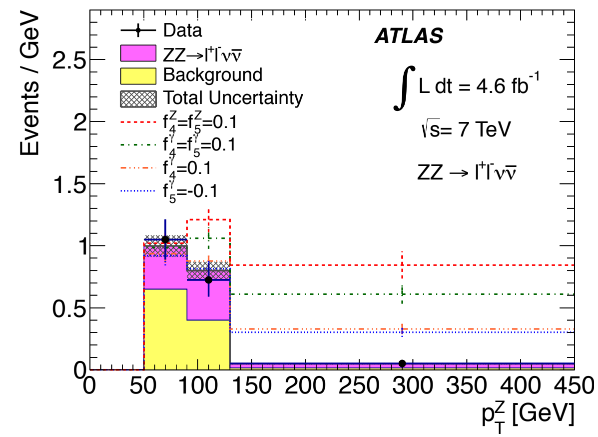
ZZ aTGC limits

EPJC 75 (2015) 511

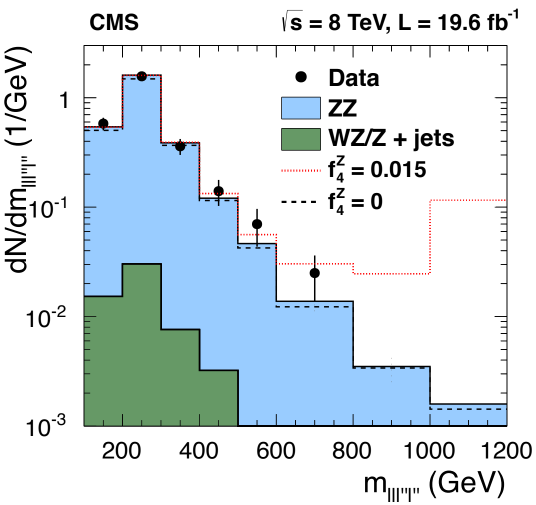


- Limits derived from binned fit to M(4l)/pT(ll) distribution in ZZ->4l/ZZ->2l2v
- No significant deviation in the high M/pT tail



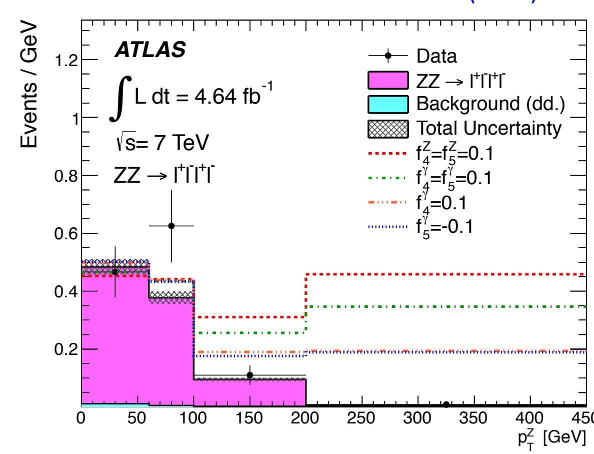


PLB 740 (2015) 250



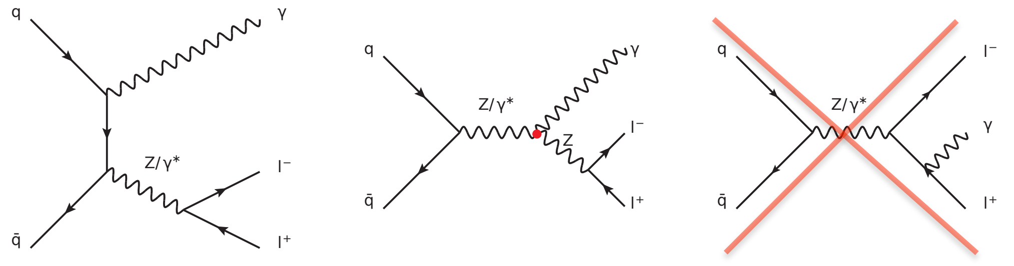
- Similar sensitivity from ZZ->4l and ZZ->2l2v channels !

JHEP 03 (2013) 128



Zγ production at LHC

Zγ->llγ & Zγ->ννγ production



Forbidden for Zγ->ννγ

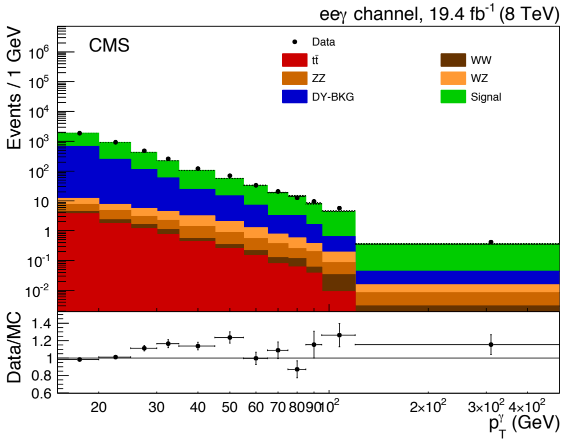
Zγ->llγ:
+ large S/B
+ clean signal signature
→ Good precision for cross section measurement

Zγ->ννγ:
+ larger BR
- Smaller S/B
- Significant instrumental background
→ Measurement limited to high p_T^γ
→ Good aTGC sensitivity

Zγ		7 TeV	8 TeV	13 TeV
ATLAS	Zγ->llγ	**PRD 87, 112003 (2013)** Cross section and aTGC measurement	**PRD 93, 112002 (2016)** Cross section and aTGC measurement	-
	Zγ->ννγ			-
CMS	Zγ->llγ	**PRD 89, 092005 (2014)** Cross section and aTGC measurement	**JHEP 04 (2015) 164** Cross section and aTGC measurement	-
	Zγ->ννγ	**JHEP 10 (2013) 164** Cross section and aTGC measurement	**PLB 760 (2016) 448** Cross section and aTGC measurement	**CMS-PAS-SMP-16-004** Cross section

Zγ->llγ production

JHEP 04 (2015) 164



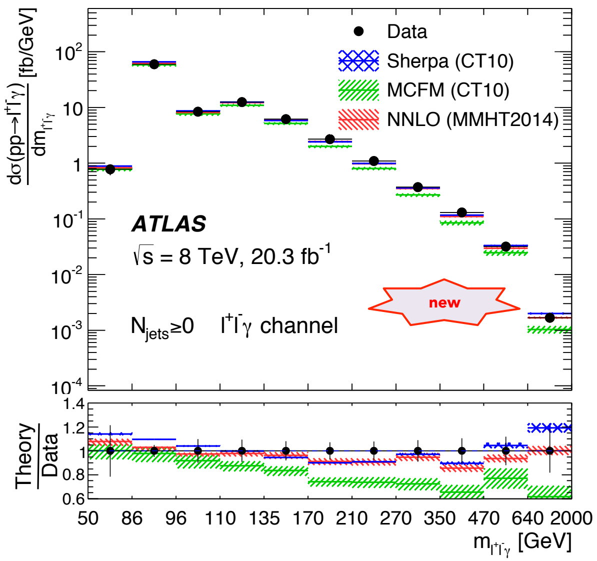
Basic selection:

- Two isolated leptons with significant pT(l)
- Opposite sign same flavor pair within Z mass window
- Isolated photon with significant pT(γ)

Backgrounds:

- Z+jets (template fit from two shower shape observables), ZZ, WZ, WW, top

PRD 93, 112002 (2016)

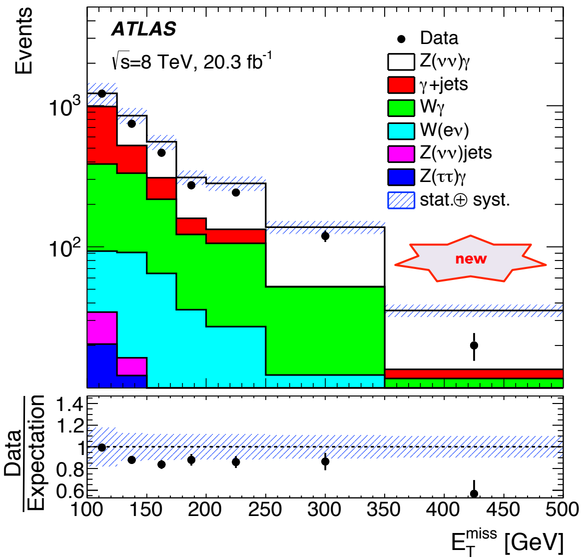


- Bkg dominated by events in which hadronic jets, which contain photons from π^0 or η decays, are misidentified as prompt photons = Z+jets
    - Estimated from data
        - ATLAS: two-dimensional sideband method ("ABCD method")
        - CMS: template fit from two shower shape observables
- Smaller backgrounds estimated from MC

- Systematics dominated measurement: uncertainty in the template method, photon energy scale and lepton isolation

Zγ->ννγ production

PRD 93, 112002 (2016)



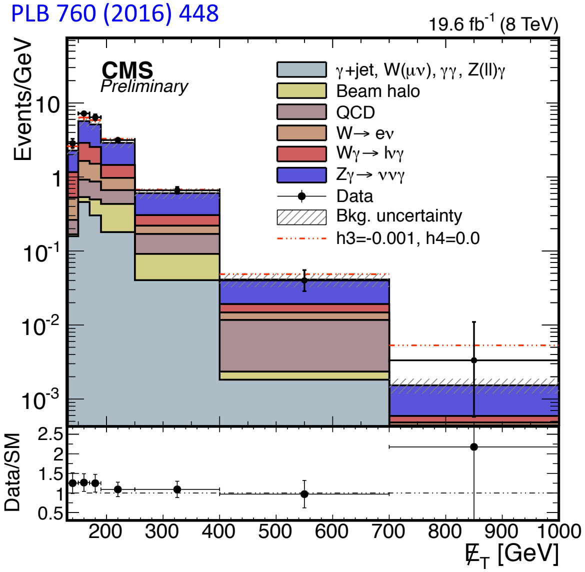
Basic selection:

- Very high MET (>140/100GeV CMS/ATLAS)
- Photon with large pT (>145/130GeV CMS/ATLAS)
- Lepton veto (reducing W and Wγ bkg)

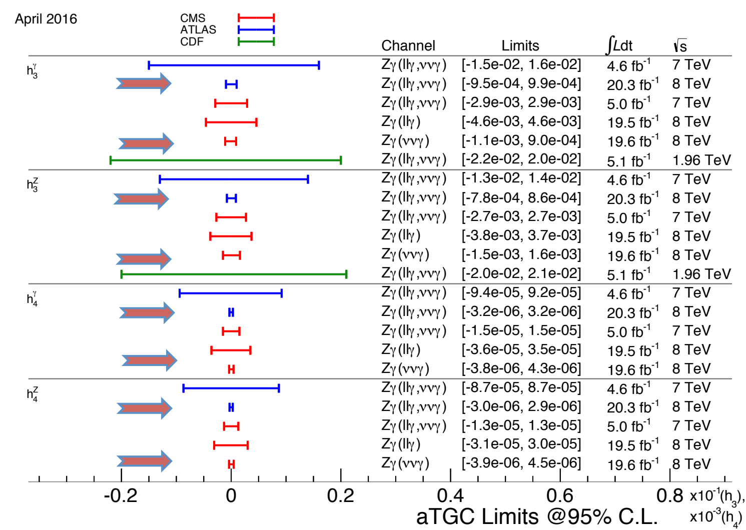
Backgrounds:

- W (fake rate/MC for e/μ), jets (fake rate), γ+jet(control region and MC), Vγ (MC and data control region), γγ, beam halo (timing information),…

PLB 760 (2016) 448



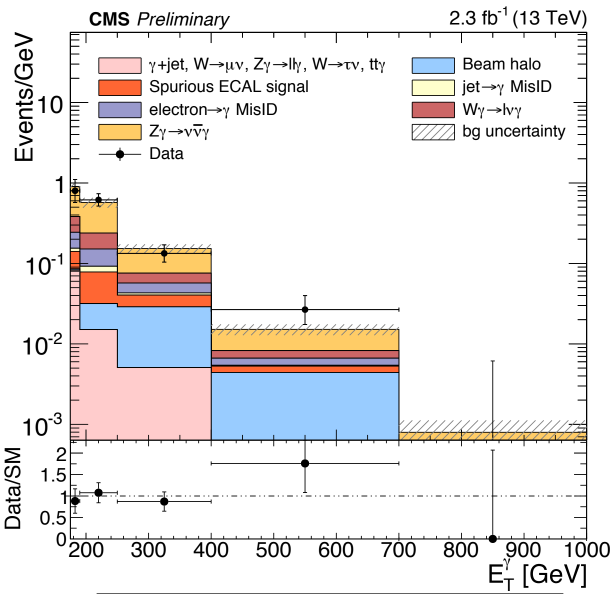
The most sensitive channel for ZZγ, γZγ vertices aTGC measurement due to access to high p_T^γ!



Zγ->ννγ measurement with Run2 data

new

CMS-PAS-SMP-16-004



Process	Estimate
$Z\gamma \to \nu\bar{\nu}\gamma$	41.74 ± 6.67
$W\gamma \to \ell\nu\gamma$	10.60 ± 1.58
$W \to e\nu$	7.80 ± 1.78
Jet $\to \gamma$ misidentified	1.75 ± 0.61
Beam halo	5.90 ± 4.70
Spurious ECAL signals	5.63 ± 2.20
Rare backgrounds	3.03 ± 0.69
Total Expectation	76.45 ± 8.82
Data	77

Sources	Effect on cross section (%)
Luminosity	3.3
PDF and QCD scale	6.8
Electroweak corrections	11.3
Jets misidentified as γ	1.3
Electron misidentified as γ	3.6
Beam halo	11.0
Spurious ECAL signals	5.0
E_T^{miss}, photon energy scales, pileup	7.1
Data/sim. scale factors	9.7

Basic selection wrt Run1:

- Higher MET requirement (>170GeV CMS)
- Higher photon pT (>175GeV) requirement due to on-line trigger selection

Backgrounds:

- Methods similar to Run1 analysis

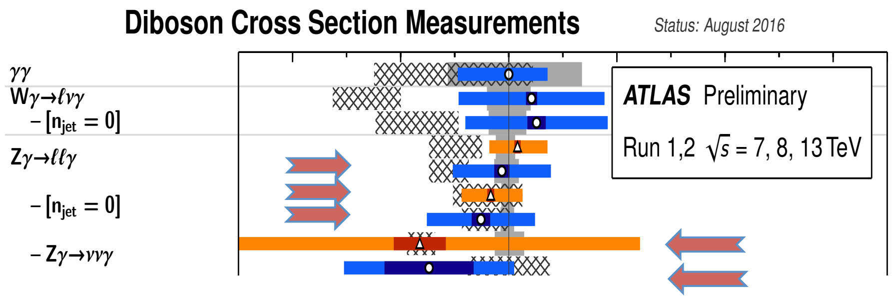
	σ(Zγ->ννγ) [fb]
	13 TeV
CMS	**66.5 ± 13.6 (stat) ± 14.3 (syst) ± 2.2 (lumi)** σNNLO = 65.5±3.3

Good agreement with SM expectation!

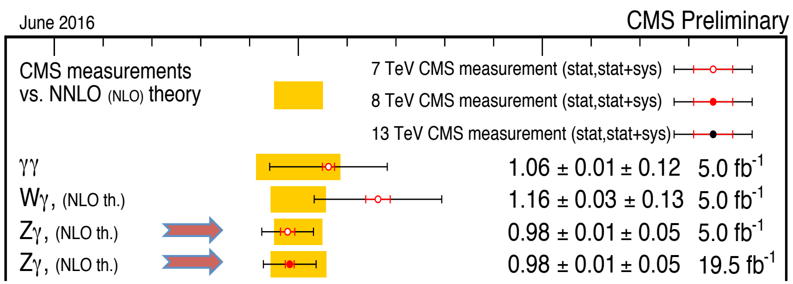
Dominant systematics:
theoretical uncertainty on signal,
non-collision background estimate (beam-halo)

Analysis with 2015 Run2 data (2.3fb^{-1}). Need more Run2 data to supersede Run1 aTGC sensitivity!

Zγ cross section results summary



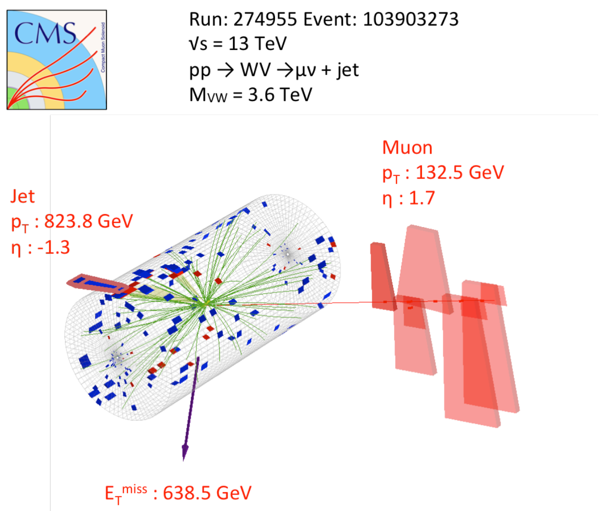
← Inclusive (Njets ≥ 0) and exclusive (Njets > 0) measurement!



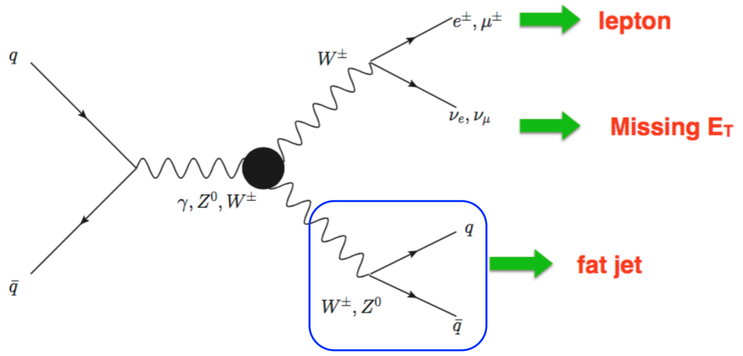
No significant discrepancy is observed between the data and the expectations.

Systematics dominated measurements !

WV->lvjj production at LHC



WV(WZ or WW)->lvjj production



Compared to purely leptonic decay mode:
- S/B much worse → stronger cuts need to extract the signal
- Larger experimental systematic
→ Can not provide as precise measurement of cross section as fully leptonic decays
+ 6x larger branching ratio
+ Clear mass peak
+ Access to higher boson pT and diboson mass -> important for aTGC measurements !!!

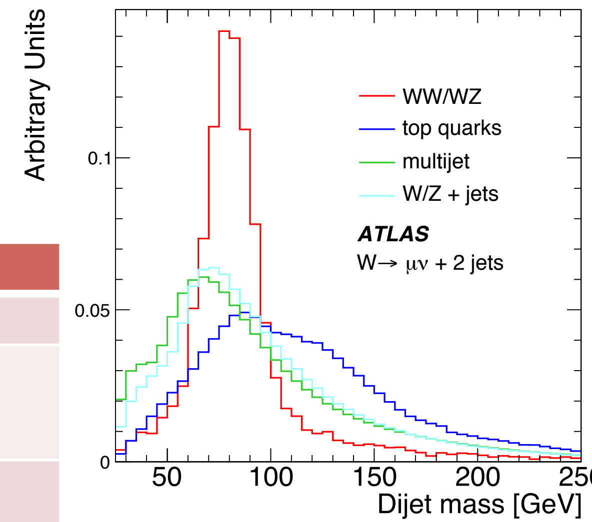
Basic selection:
- Lepton with sizable pT and $|\eta_{\mu(e)}|$ restriction
- Large MET, MTW
- Hadronic boson decay
  - Exactly 2 jets high pT jets (7 TeV analysis)
  - Boosted topology:
    - at least 1 high pT fat jet (AK8) pT>200GeV (13 TeV analysis)
    - M_{WV}>900GeV

Hadronic boson decay:
- Highly **boosted** boson will decay to two close jets reconstructed as single "fat jet"
  - Higher sensitivity to aTGC then non-boosted

Z(ll)+jets EWK	7 TeV	8 TeV	13 TeV
ATLAS	JHEP01 (2015) 049 Cross section and aTGC measurement	-	
CMS	EPJ. C 73 (2013) 2283 Cross section and aTGC measurement	-	CMS-PAS-SMP-16-012 aTGC measurement

WV(WZ or WW)->lvjj cross section measurement

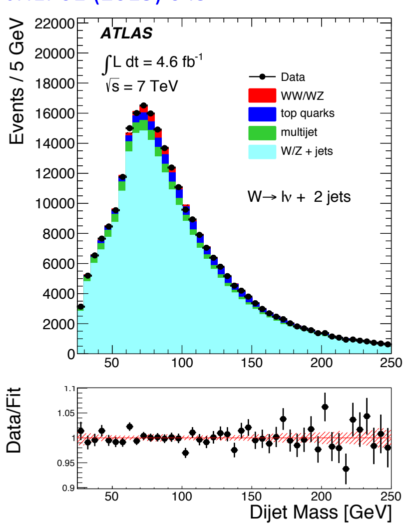
- shapes of the expected M_V distribution are used as templates for the cross section fit and background estimate
  - expected shapes and rates of the distributions are mainly obtained from the MC simulation samples
  - largest systematic uncertainties are from shape modeling, JES and JER

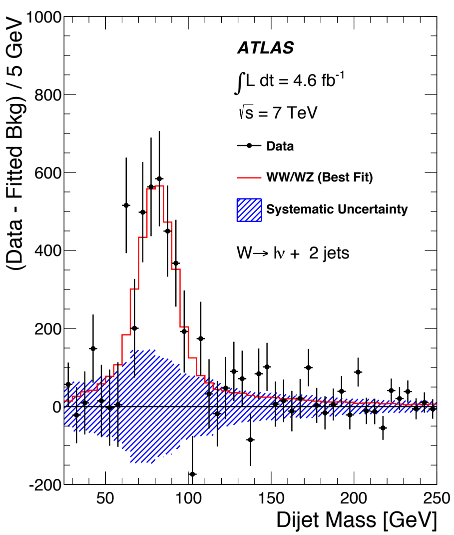


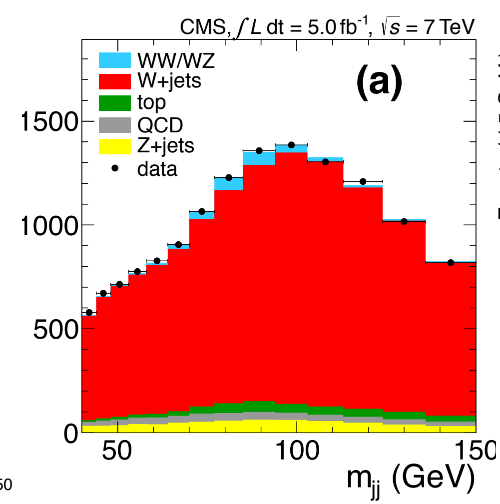
In comparison, measurements from fully leptonic WZ and WW decays provide uncertainty ~ 10%!

	σ(WZ+WW) [pb]
	7 TeV
ATLAS	**68 ± 7 (stat.) ± 19 (syst.)** σNLO(MC@NLO) = 61.1±2.2 **3.4σ significance**
CMS	**68.9 ± 8.7 (stat.) ± 9.7 (syst.) ± 1.5 (lum.)** σNLO(MCFM) = 65.6 ± 2.2 **4.3σ significance**

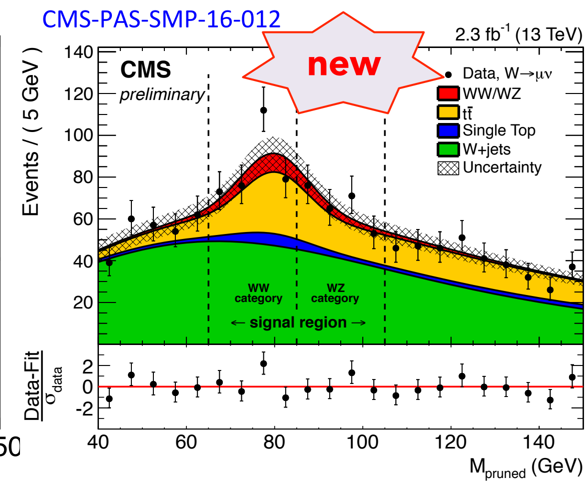
JHEP01 (2015) 049





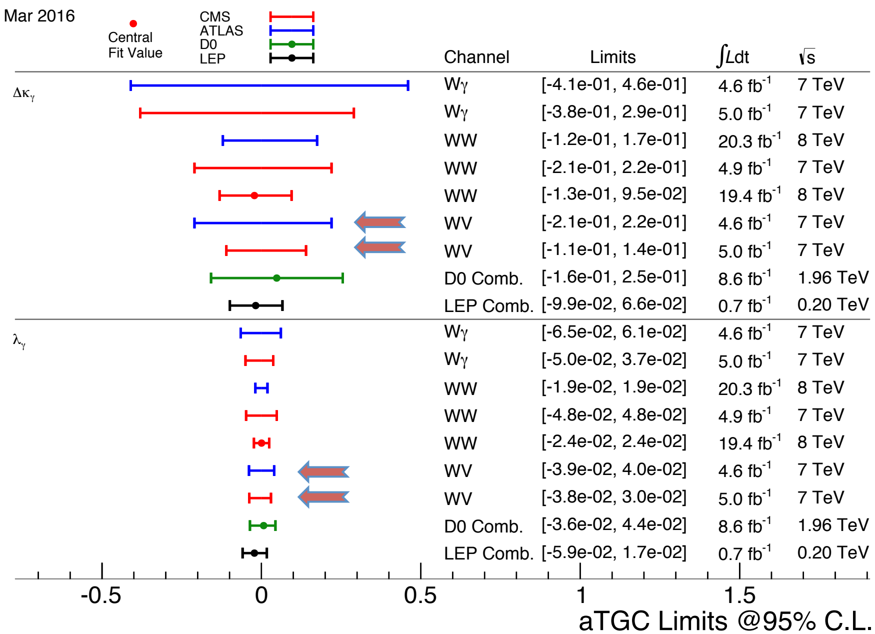


CMS-PAS-SMP-16-012



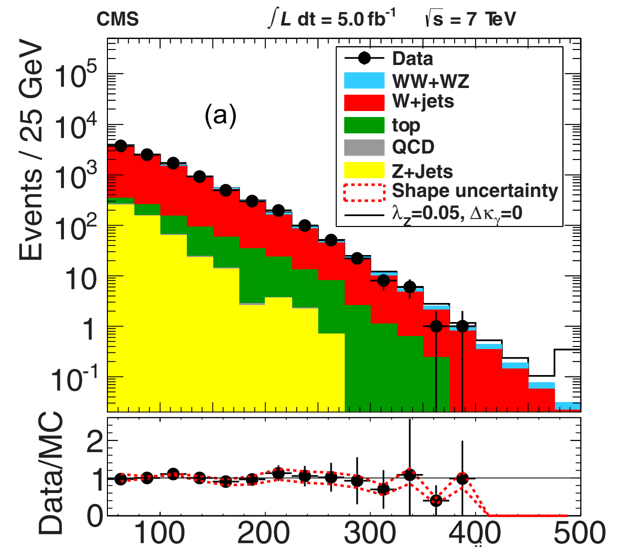
 EPJ. C 73 (2013) 2283

WV(WZ or WW)->lvjj aTGC measurement

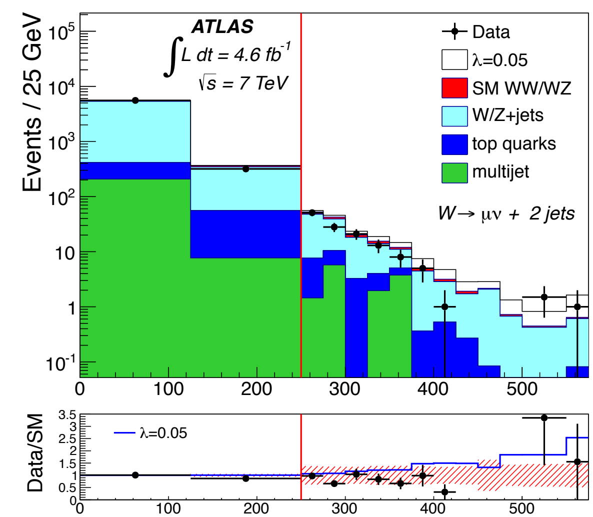


- no deviation in high pT tail is observed
- limits are extracted in a simultaneous **binned** maximum likelihood fit in pTjj

➢ Comparing to aTGC results from fully leptonic channels (using the same dataset) semileptonic WV provides the best sensitivity due to access to higher pT/diboson mass!



EPJ. C 73 (2013) 2283

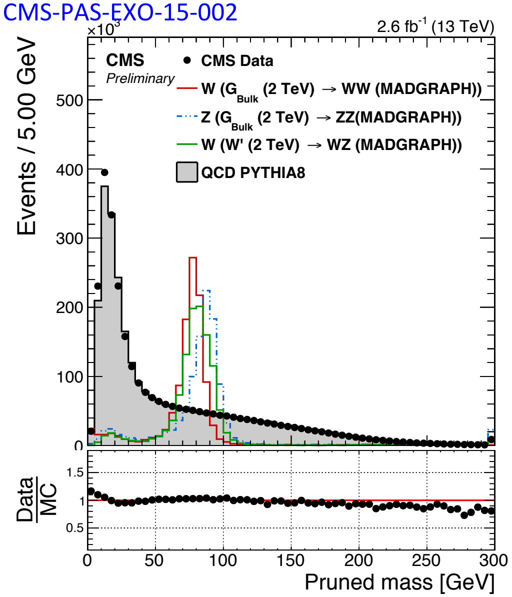


JHEP01 (2015) 049

WV(WZ or WW)->lvjj measurement with Run2 data

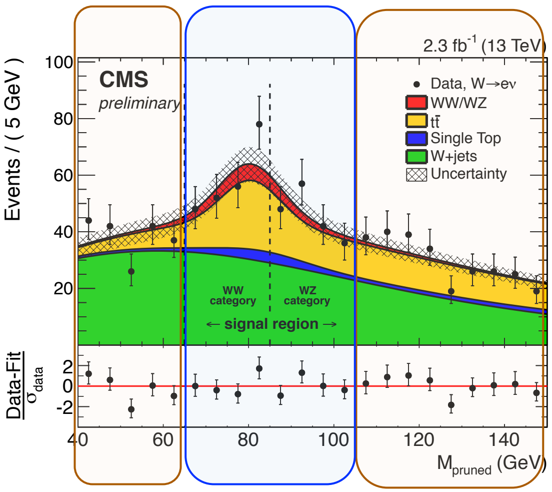
new

CMS-PAS-EXO-15-002



- large number of particles in jet -> bad resolution
  - jet pruning (generally grooming) removes **soft and large angle radiation**
- $M_{\text{boosted jet}}$ resolution does not allow separation between W and Z

CMS-PAS-SMP-16-012



Sideband:

- used to estimate contribution from leading backgrounds (Wjets, ttbar)
- Used to derive the shape of aTGC sensitive observable (M_{WV}) of the main background (Wjets)

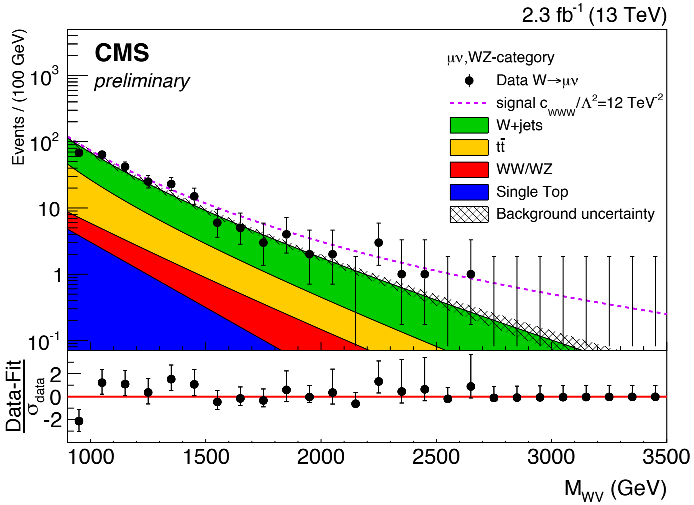
Signal region:

- WW and WZ processes have different sensitivities to some aTGC parameters
  - Splitting the signal region to WW- and WZ-like parts can help to distinguish aTGCs

- ttbar is also validated in two additional control regions

WV(WZ or WW)->lvjj measurement with Run2 data

new

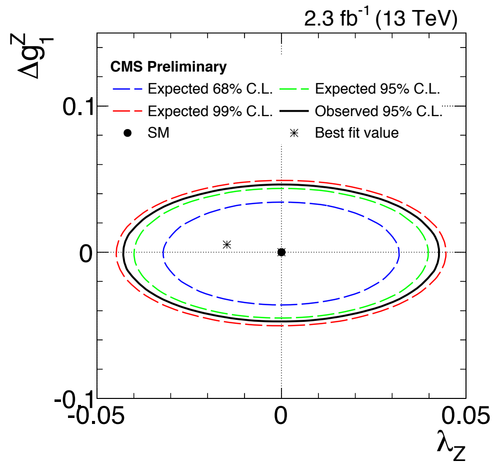


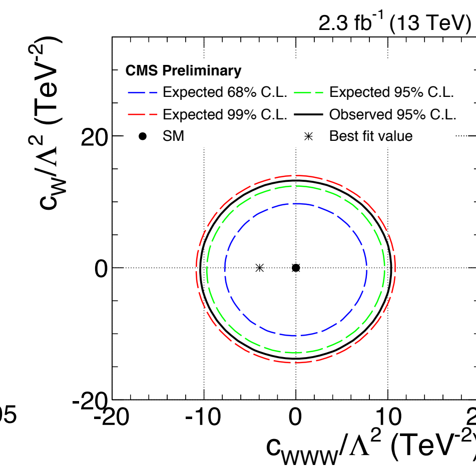
- in order to avoid the loss of signal efficiency in WZ events with $Z \rightarrow bb$ decays events that contain one or more b-tagged jet (away from fat jet) are rejected to reduce ttbar background
- challenging boosted topology also implies additional systematic uncertainty

- limits are extracted in a simultaneous **unbinned** maximum likelihood fit in M_{WV}
- **shape of the dominant bkg (Wjets) is estimated from data in control region**

CMS-PAS-SMP-16-012

	aTGC	expected limit	observed limit
EFT param.	$\frac{c_{WWW}}{\Lambda^2}$ (TeV^{-2})	[-8.73 , 8.70]	[-9.46 , 9.42]
	$\frac{c_W}{\Lambda^2}$ (TeV^{-2})	[-11.7 , 11.1]	[-12.6 , 12.0]
	$\frac{c_B}{\Lambda^2}$ (TeV^{-2})	[-54.9 , 53.3]	[-56.1 , 55.4]
Vertex param.	λ	[-0.036 , 0.036]	[-0.039 , 0.039]
	Δg_1^Z	[-0.066 , 0.064]	[-0.067 , 0.066]
	$\Delta\kappa_Z$	[-0.038 , 0.040]	[-0.040 , 0.041]

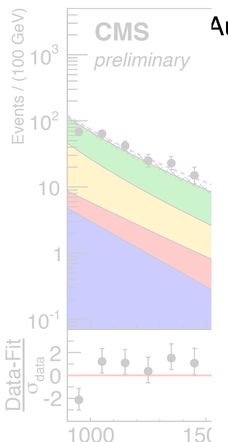


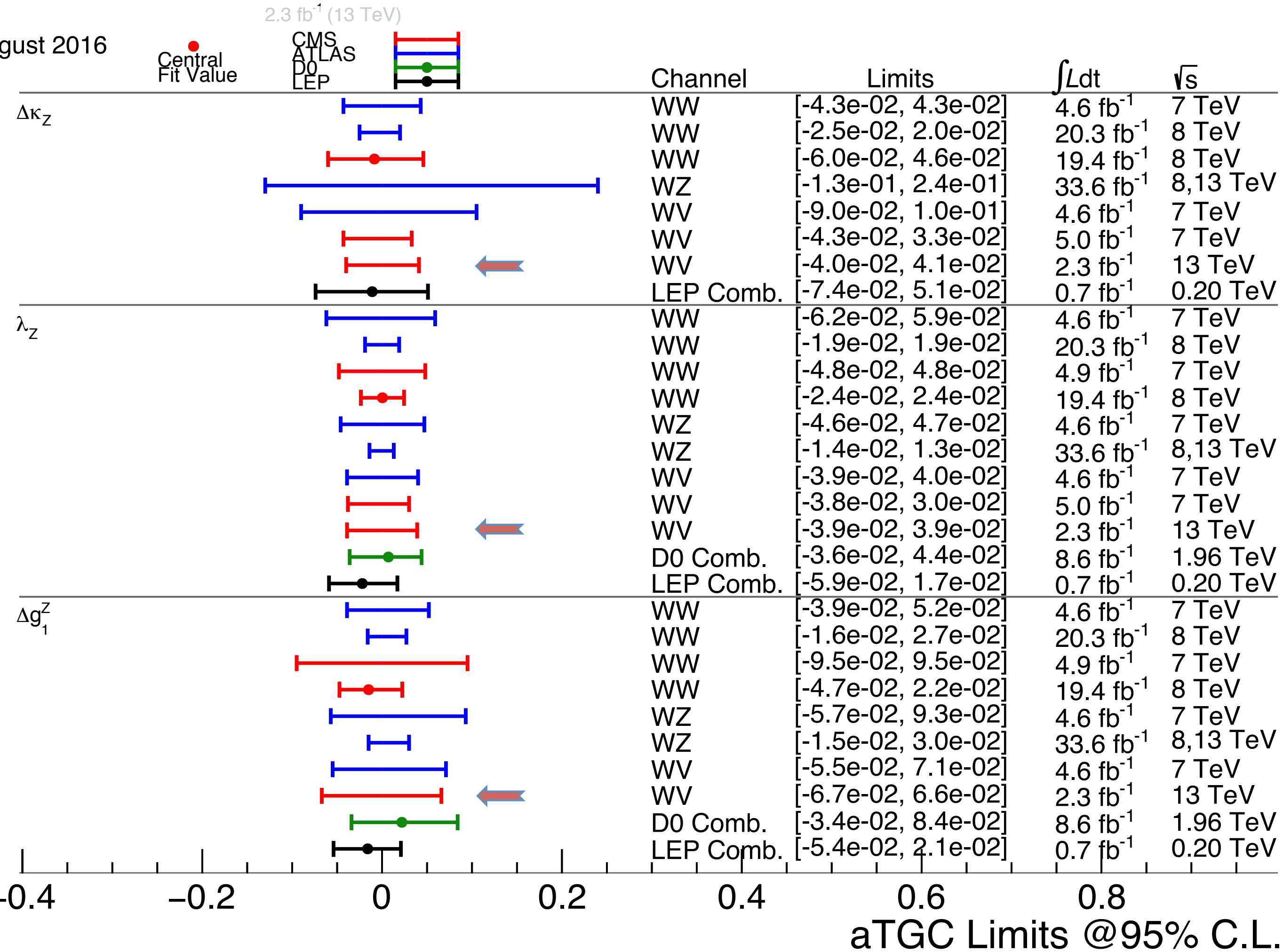


First CMS aTGC results with Run2 data!

WV(WZ or WW)->lvjj measurement with Run2 data

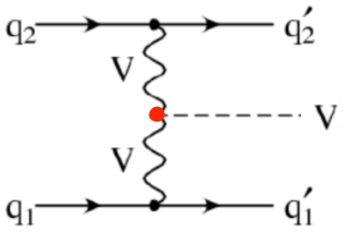
new



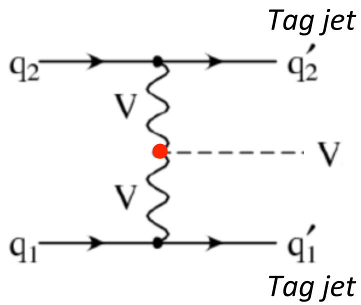


First CMS aTGC results with Run2 data!

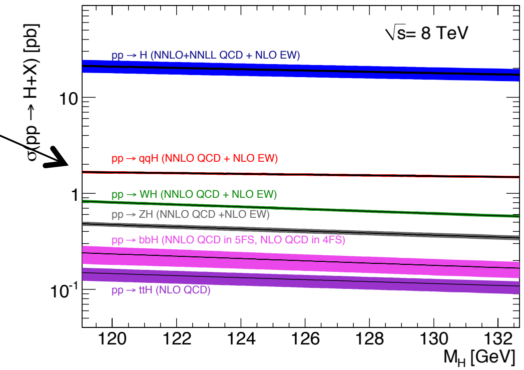
Vector Boson Fusion (VBF) Z production



Vector Boson Fusion (VBF)

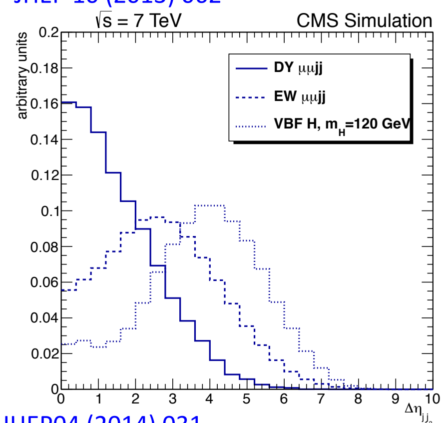


- **Higgs production** via Vector Boson Fusion is second production mechanism at LHC after ggH
- **EWK V+2 jets** production
    - Z+2 jets
    - W+2 jets (talk by K. Lohwasser)



- Possibility to measure aTGC but statistics (for now) too small to compete with measurements from inclusive VV production
- includes TGC vertex (VBF), suppressed by a factor ~2.5 by interference terms

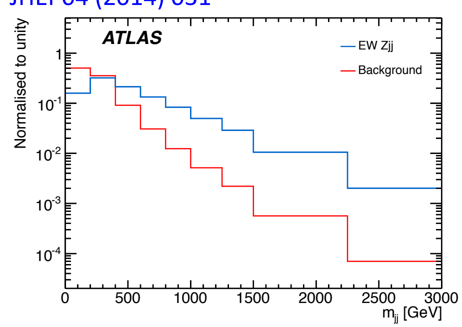
JHEP 10 (2013) 062



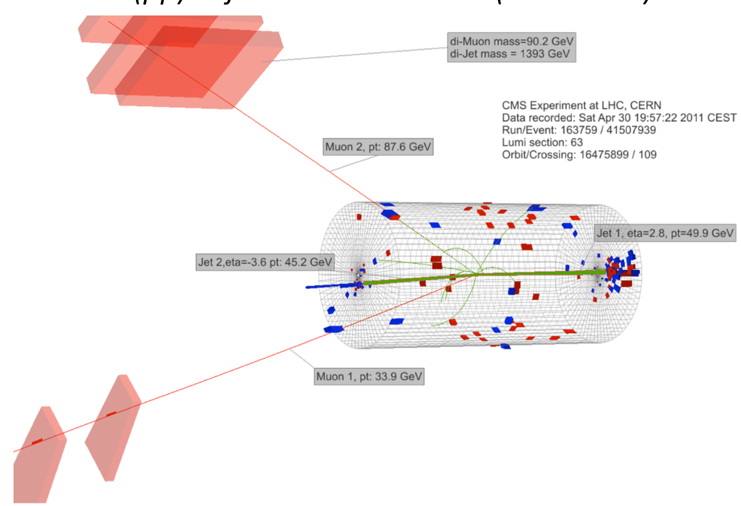
VBF characteristic signature:

- Two high pT jets in the forward-backward region
- Large rapidity separation between jets ($\Delta\eta_{jj}$), with low hadronic activity between them
- Large di-jet invariant mass (M_{jj})

JHEP04 (2014) 031



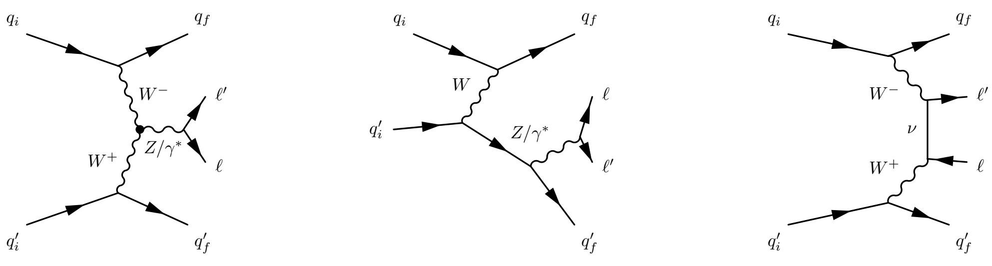
Z(μμ)+2 jets candidate event (CMS 7 TeV)



https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGCrossSectionsFigures

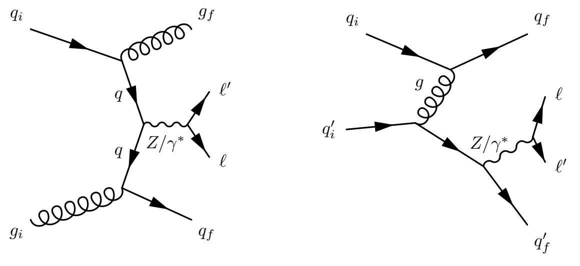
VBF: Z+jets production

*Feynman diagrams for dilepton production in association with two jets from purely electroweak contributions = **EWK signal***



VBF *bremsstrahlung-like* multiperipheral production

QCD background

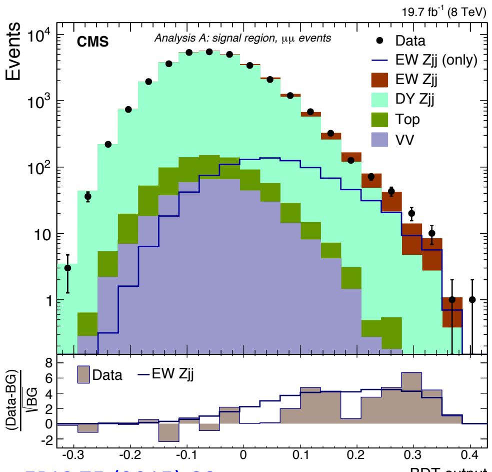


Drell–Yan production

presence of a large negative interference between the pure VBF process and the two other categories!

Z(ll)+jets EWK	7 TeV	8 TeV
ATLAS	-	**JHEP 04 (2014) 031** Cross section and aTGC measurement
CMS	**JHEP 10 (2013) 062** First measurement of the electroweak production	**EPJC 75 (2015) 66** Cross section measurement

VBF: Z+jets cross section results

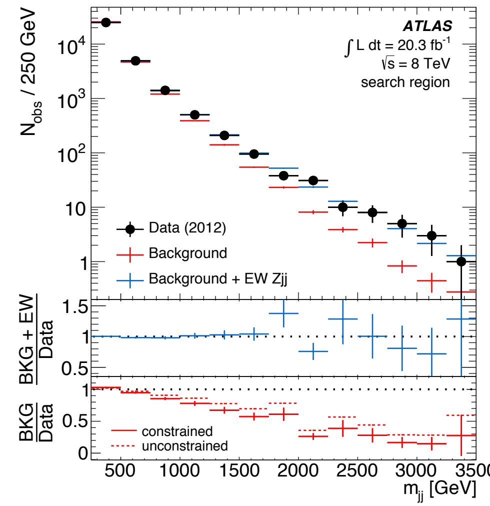


EPJC 75 (2015) 66

EWK cross section is measured with binned maximum likelihood template fit:

- CMS: fitting the MVA simultaneously across the control and signal categories the strength modifiers for the EW Zjj and DY Zjj processes (constrained)
- ATLAS: fitting the dijet invariant mass reconstructed in the search region

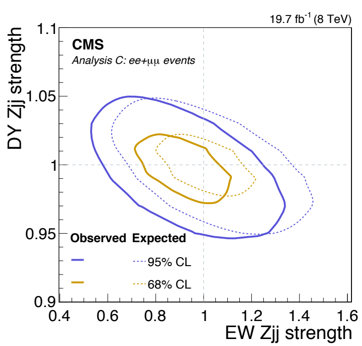
JHEP04 (2014) 031



Systematic dominated measurement!

- Main systematic (th): modeling of the DY Zjj background, interference with the EW Zjj signal, EWK signal modeling
- Dominant experimental systematic uncertainty: JES

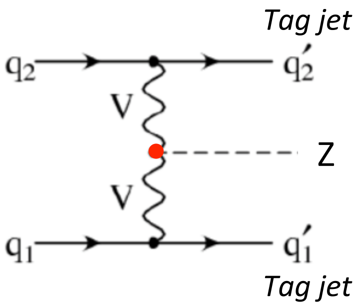
Background-only hypothesis is excluded with a significance greater than 5σ!



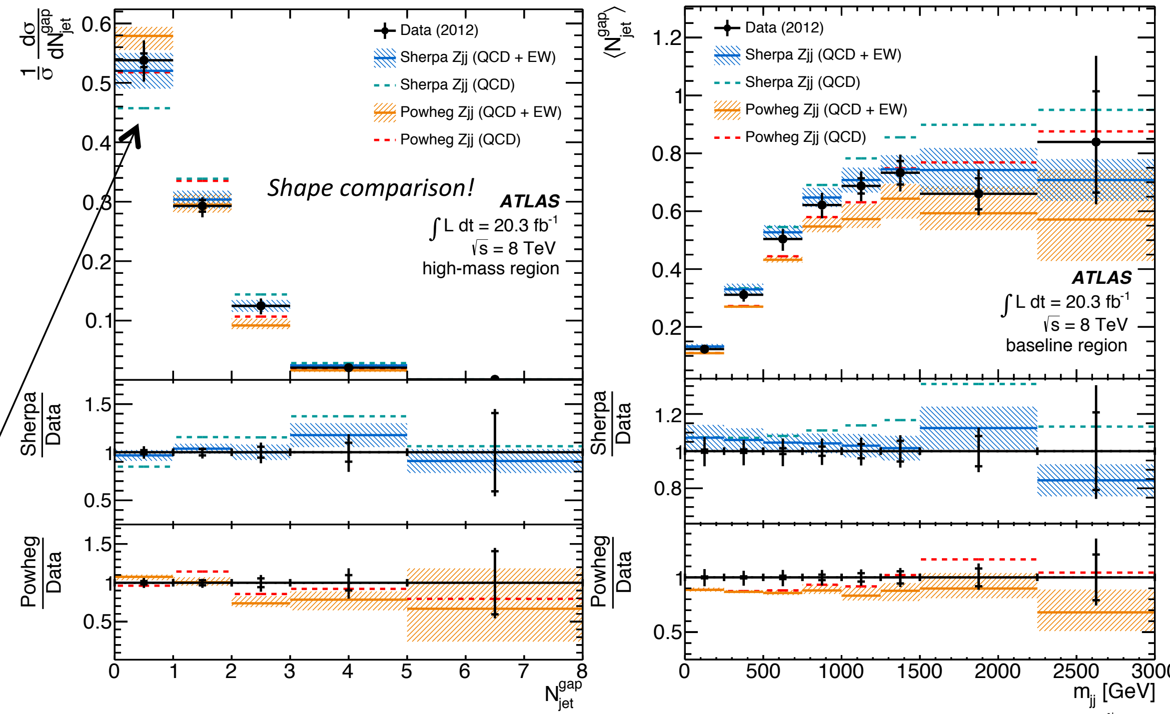
	σ(Z(ll)+2jets EWK) [fb]	
	7 TeV	**8 TeV**
ATLAS	-	**54.7±4.6(stat)+9.8(syst)±1.5(lumi)** σLO(Powheg) = 46.1±0.2(stat)+0.3(scale)±0.8(PDF)±0.5(model) **> 5 σ significance**
CMS	**154±24(stat.)±46(exp.syst.)±27(th.syst.)±3(lum.)** σNLO(VBFNLO) = 166 **2.6 σ significance**	**174±15(stat)±40(syst)** σLO(MG) = 208±18 **> 5 σ significance**

Cross sections are in different phase spaces!

VBF topology measurement

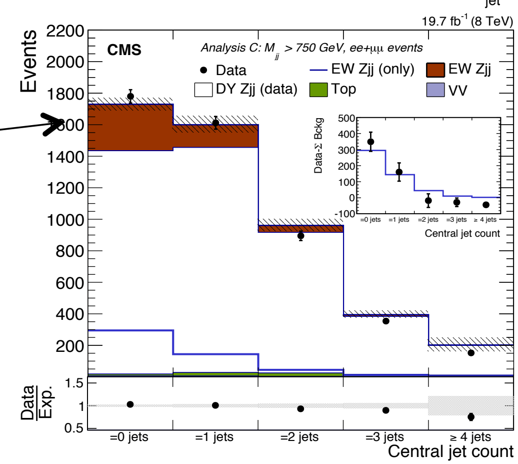


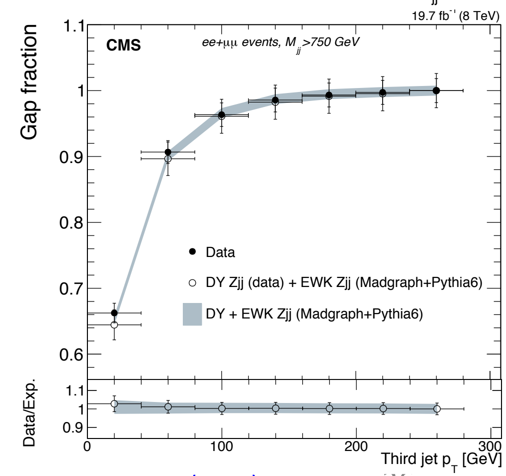
JHEP04 (2014) 031



Measurement of VBF topology

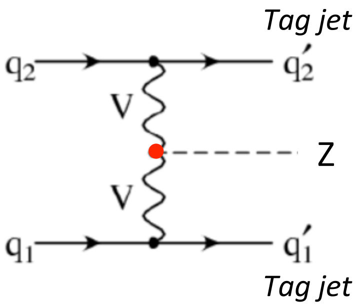
- Study of jets distributions and jet veto efficiency studies in a region with a larger contribution of EW Zjj processes
- Expected suppression of the hadronic activity in signal EWK events





EPJC 75 (2015) 66

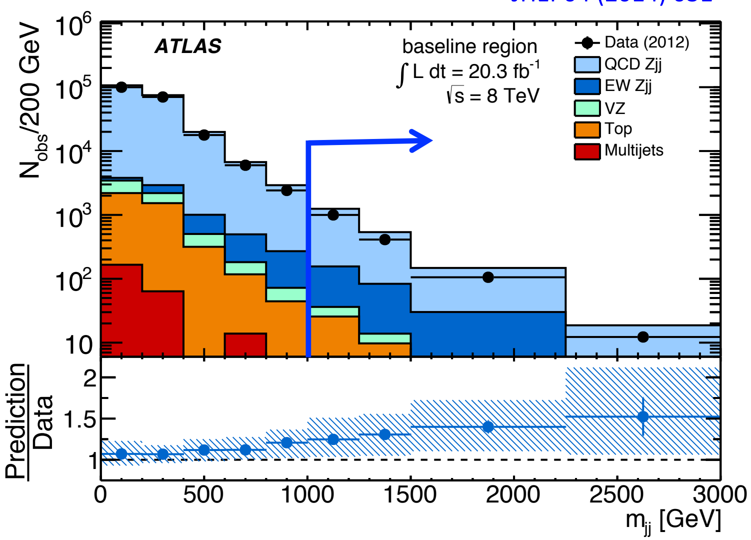
aTGC measurement from VBF



- Possibility to measure aTGC but statistics (for now) too small to compete with measurements from inclusive VV production
- TGC vertex (VBF), suppressed by a factor ~2.5 by interference terms

- **Extracted number of events in the search region with mjj > 1 TeV is used to place limits on the aTGCs**
  - this region is the least affected by the background normalisation and signal template shape

JHEP04 (2014) 031



- VV production: all three gauge bosons entering the WWZ vertex have time-like four- momentum
- VBF production: two of the gauge bosons entering the WWZ vertex have space-like four-momentum transfer
- ➢ EWK production offers a complementary test of aTGCs (effects of boson propagators present in EWK production are different from those in vector boson pair production)

aTGC	$\Lambda = 6\,\text{TeV}$ (obs)	$\Lambda = 6\,\text{TeV}$ (exp)	$\Lambda = \infty$ (obs)	$\Lambda = \infty$ (exp)
$\Delta g_{1,Z}$	$[-0.65, 0.33]$	$[-0.58, 0.27]$	$[-0.50, 0.26]$	$[-0.45, 0.22]$
λ_Z	$[-0.22, 0.19]$	$[-0.19, 0.16]$	$[-0.15, 0.13]$	$[-0.14, 0.11]$

Comparison with inclusive WZ results: limits from EWK production are ~10X looser

WZ inclusive ATLAS 8 TeV results: PRD 93, 092004 (2016)

Λ_{co}	Coupling	Expected	Observed
2 TeV	Δg_1^Z	$[-0.023\ ;\ 0.055]$	$[-0.029\ ;\ 0.050]$
	$\Delta\kappa^Z$	$[-0.22\ ;\ 0.36]$	$[-0.23\ ;\ 0.46]$
	λ^Z	$[-0.026\ ;\ 0.026]$	$[-0.028\ ;\ 0.028]$
15 TeV	Δg_1^Z	$[-0.016\ ;\ 0.033]$	$[-0.019\ ;\ 0.029]$
	$\Delta\kappa^Z$	$[-0.17\ ;\ 0.25]$	$[-0.19\ ;\ 0.30]$
	λ^Z	$[-0.016\ ;\ 0.016]$	$[-0.017\ ;\ 0.017]$
∞	Δg_1^Z	$[-0.016\ ;\ 0.032]$	$[-0.019\ ;\ 0.029]$
	$\Delta\kappa^Z$	$[-0.17\ ;\ 0.25]$	$[-0.19\ ;\ 0.30]$
	λ^Z	$[-0.016\ ;\ 0.016]$	$[-0.016\ ;\ 0.016]$

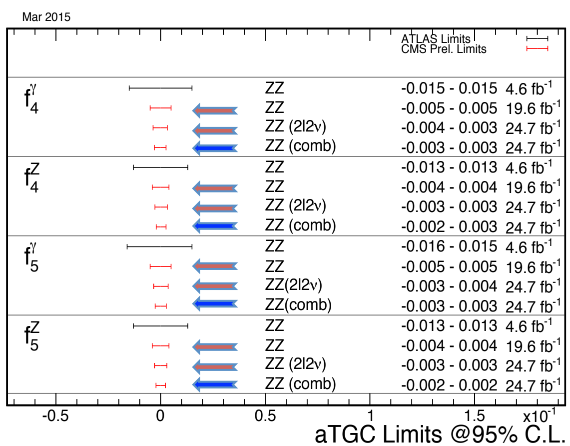
aTGC sensitivity and combinations

Combinations within experiments

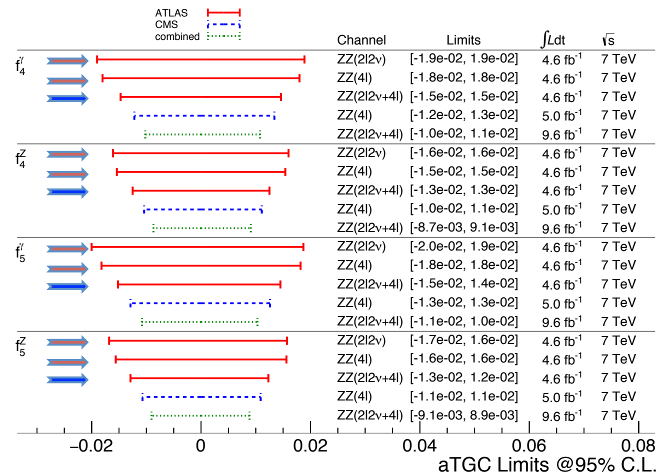
[ATLAS-CONF-2016-036 ; CMS-PAS-SMP-15-001]

Combination between channels with similar aTGC sensitivity: ZZ->4l and ZZ->2l2v channels.

CMS combination



ATLAS combination



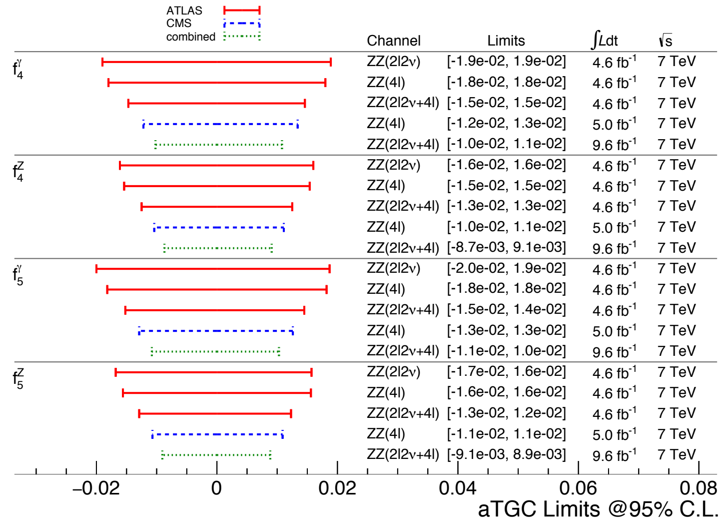
Gain: ~20% tighter limits.

Combinations between experiments: ATLAS and CMS ZZ 7TeV

new

ATLAS-CONF-2016-036 ; CMS-PAS-SMP-15-001

Observed limit	f_4^γ	f_4^Z	f_5^γ	f_5^Z
deltaNLL ATLAS	[-0.015, 0.015]	[-0.013, 0.013]	[-0.015, 0.015]	[-0.013, 0.012]
deltaNLL CMS	[-0.012, 0.013]	[-0.010, 0.011]	[-0.013, 0.013]	[-0.011, 0.011]
deltaNLL combined	[-0.010, 0.011]	[-0.0087, 0.0091]	[-0.011, 0.010]	[-0.0091, 0.0089]
F-C combined	[-0.010, 0.011]	[-0.0089, 0.0092]	[-0.011, 0.010]	[-0.0092, 0.0089]

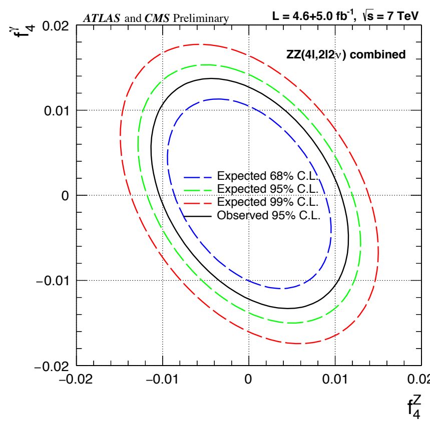


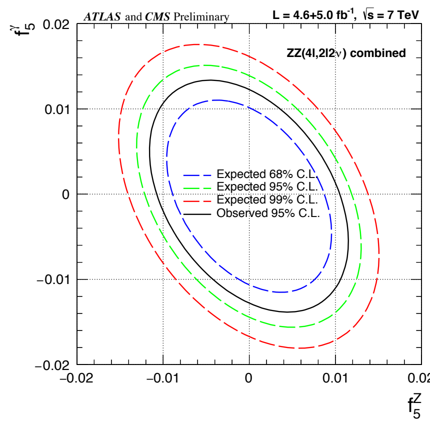
The sensitivity to aTGC parameters is improved by about 20% compared to the sensitivity of a single experiment.

<u>**First effort to combine ATLAS and CMS aTGC results**</u>

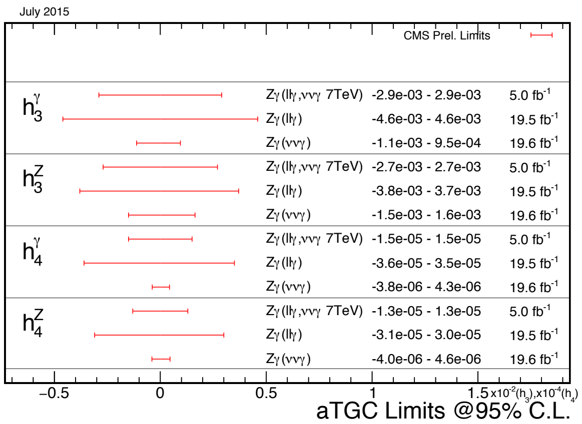
- ✓ **Synchronization of the ATLAS and CMS limit setting tools and statistical procedure**
- ✓ Requiring a good agreement between results of different tools is required to ensure consistency
- ✓ For the deltaNLL (FC) the results are in relative agreement at the 1% (5%) level

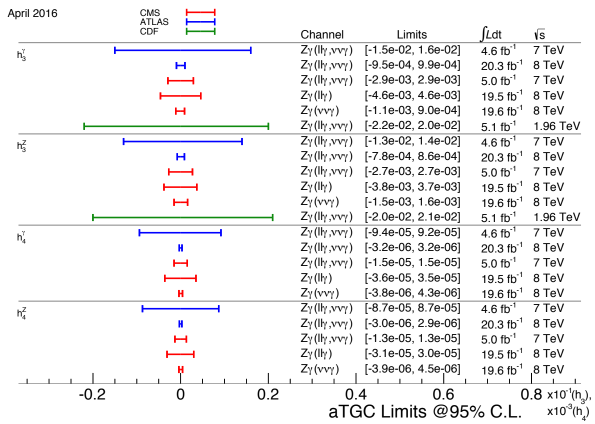
Combination procedure that can serve as guidance for future combinations of aTGC parameters at the LHC !





aTGC sensitivity vs time





Limits with 7 TeV data → *Limits with 8 TeV data* → *Limits with 13 TeV data (Run2)*

+ collision energy increasing

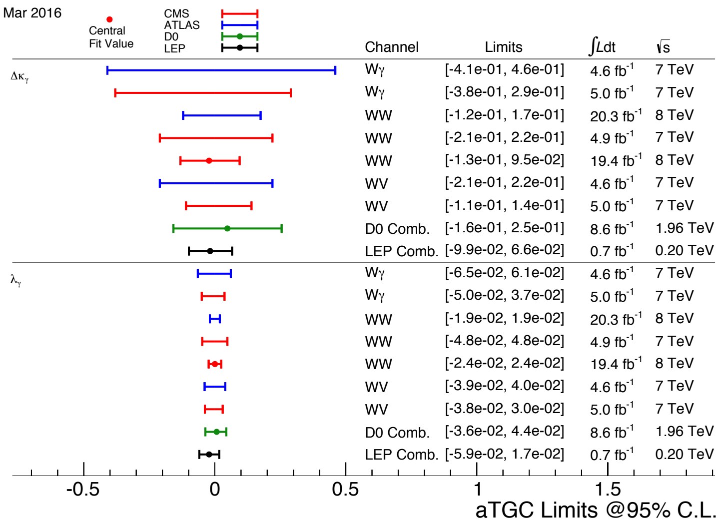
+ integrated luminosity increasing

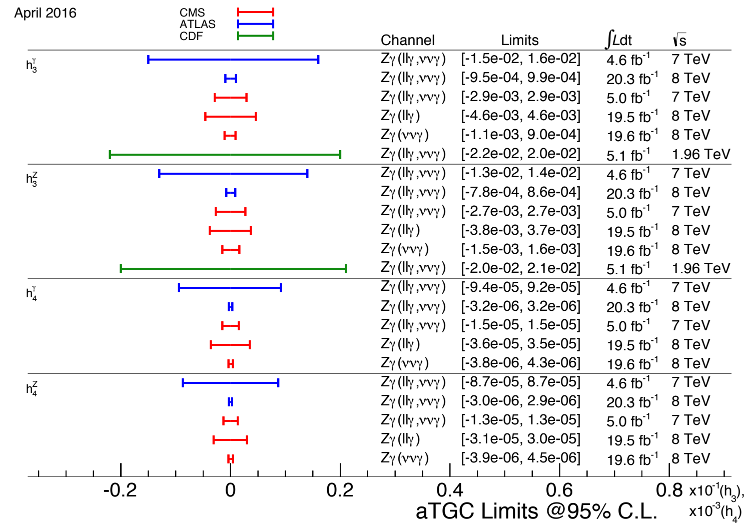
➔ Accessing higher diboson system masses/pT ➔ aTGC sensitivity increasing

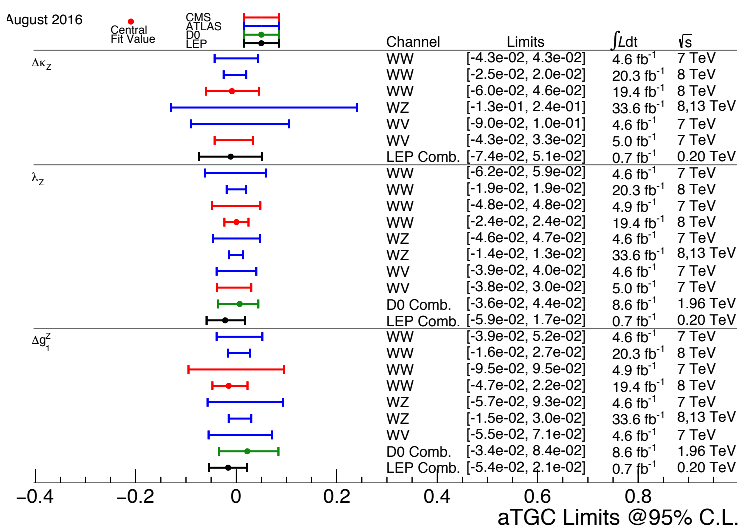
- but also more challenging conditions for measurements (higher PU, …)!

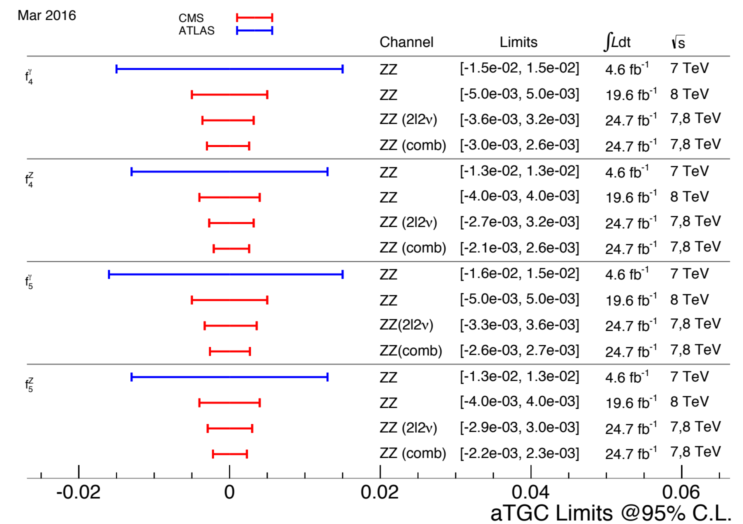
Upcoming analyses with Run2 2016 data will provide new world best limits!

aTGC summary

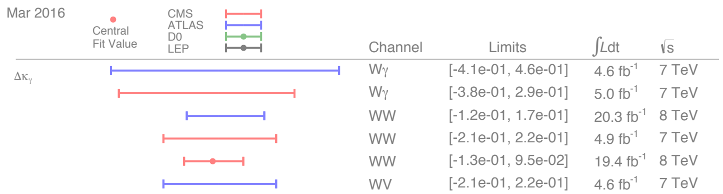


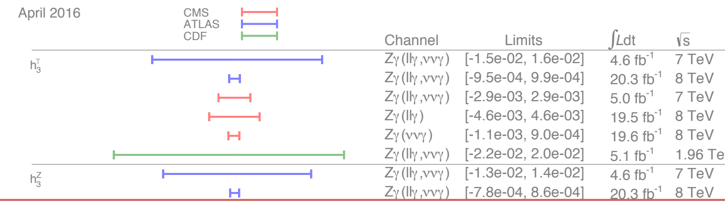




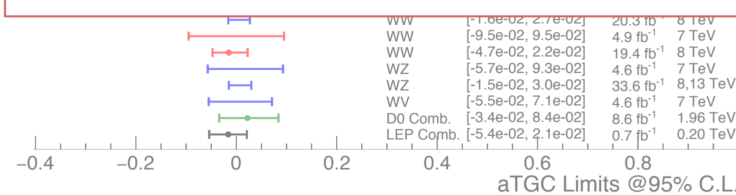


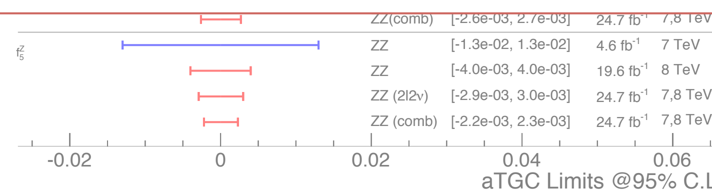
aTGC summary



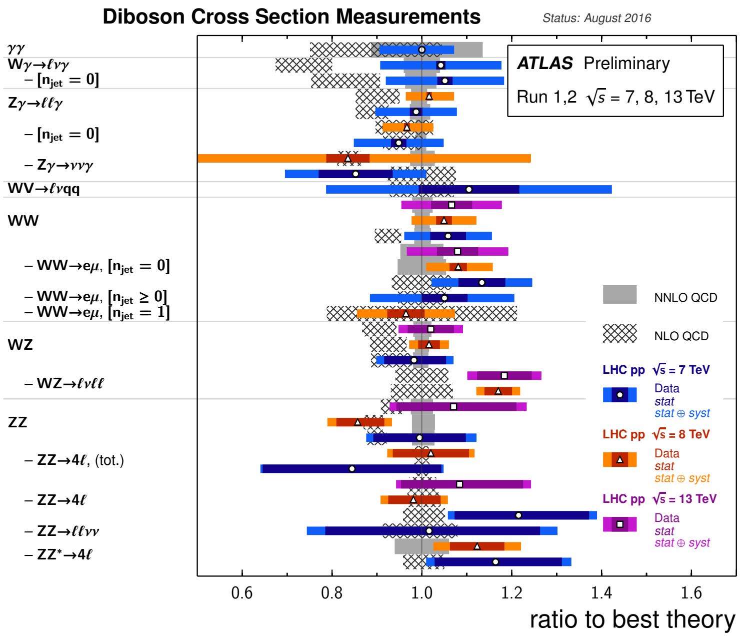


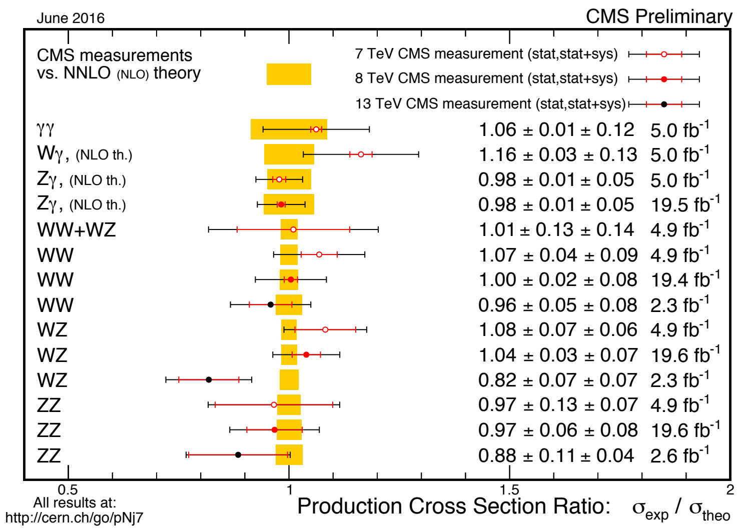
- No significant discrepancy is observed between data and the SM expectations in high mass/pT tails
    - Limits on aTGC parameters are set
- Results with Run2 data will provide more precise measurements/ limits of anomalous couplings
    - Combination prospects: ATLAS+CMS results, diboson + higgs production channels





Cross section summary

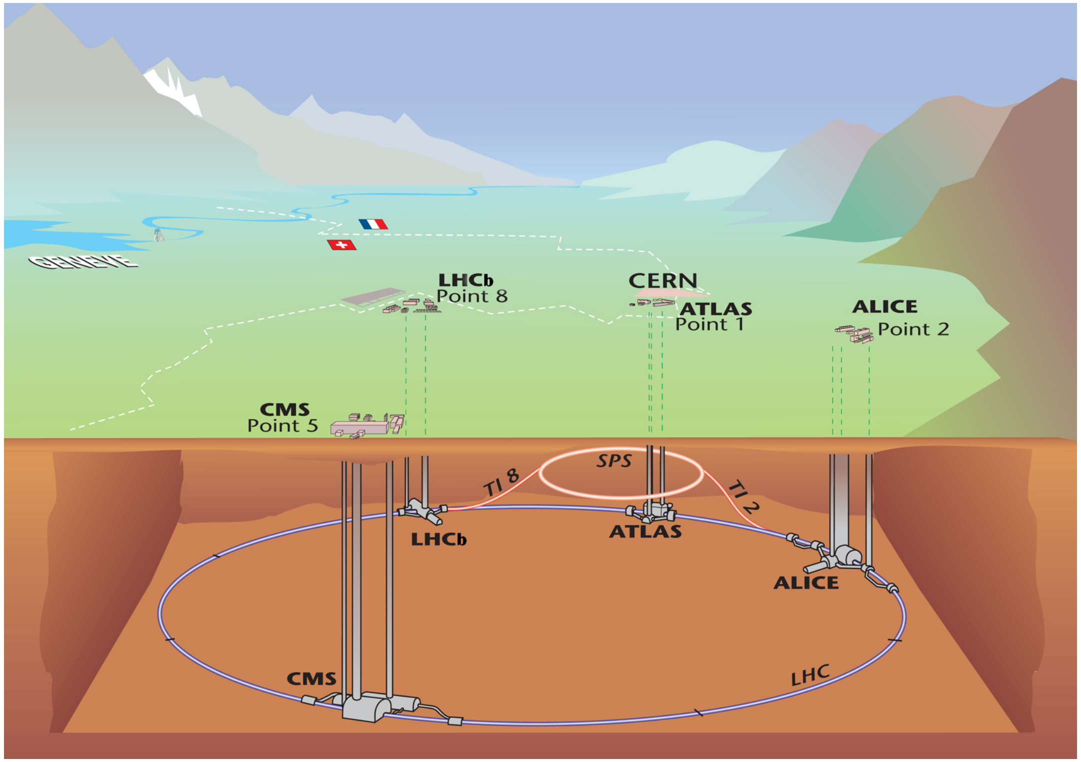




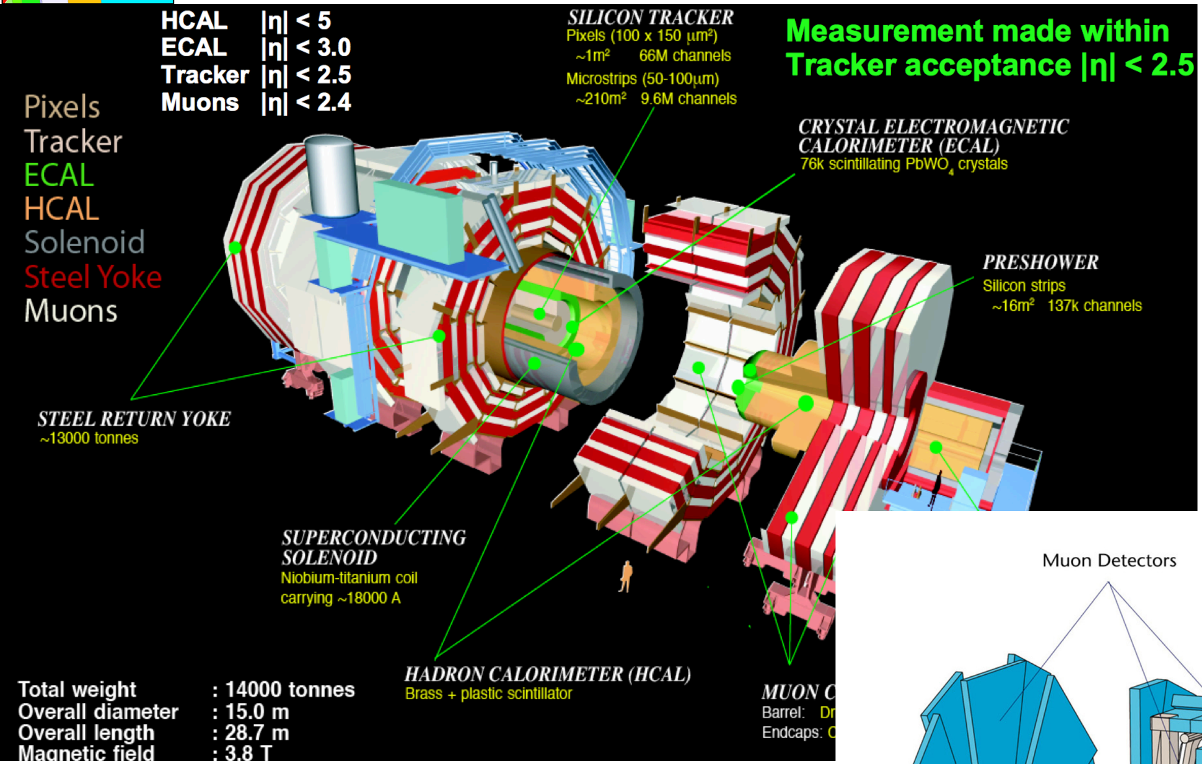
- ATLAS and CMS experiments provided numerous results in diboson channels with Run1 data (7 and 8 TeV)
- Results with Run2 data starting to come out
- Diboson and VBF production results are in good agreement with SM expectations

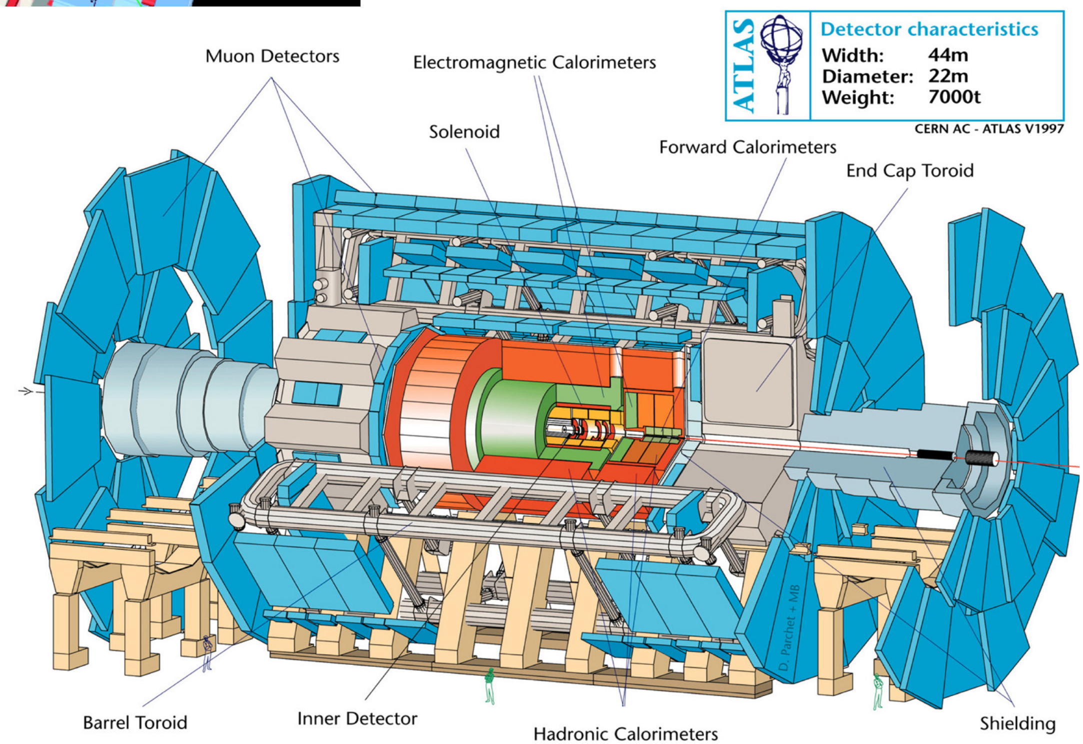
Backup

CMS and ATLAS experiments



CMS and ATLAS experiments





Senka Duric

Anomalous couplings as search for New Physics?

Two general ways to look for deviations from the SM:

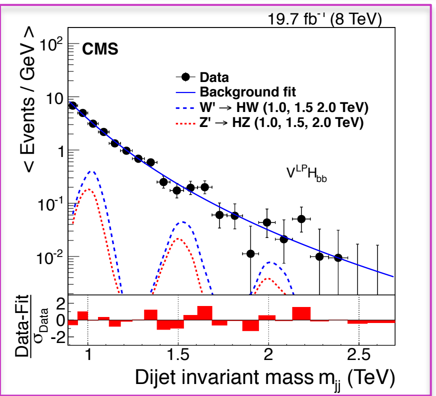
a) Assume a specific model of New Physics: SUSY scenario, dark matter, …

b) Look for model independent deviations and measure "the deviation from SM" (deviations still have to be parametrized) — Anomalous coupling measurement

And also choose between:

1. Looking for a peak in observed distribution

2. Looking for a deviation in the tails of observed distribution (broad deviation) — Anomalous coupling measurement



Submitted to JHEP
arXiv:1506.01443

Lagrangian that we feel at low energies can be expressed as the SM + additional terms

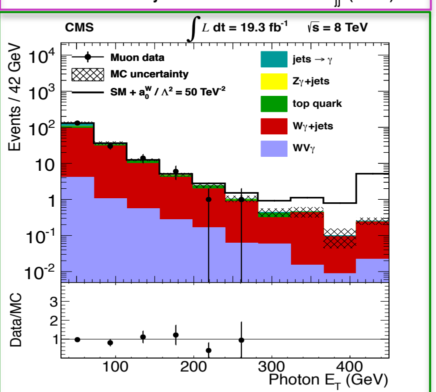
- **Effective vertex approach** (used in ZZ and Zγ analyses) — Nucl. Phys. B282 (1987) 253

$$\Gamma^{\alpha\beta\mu}_{Z_1 Z_2 V} = i\, e \frac{q_V^2 - m_V^2}{m_Z^2} \left\{ f_4^V \left(q_V^\alpha\, g^{\beta\mu} + q_V^\beta\, g^{\mu\alpha}\right) + f_5^V\, \epsilon^{\alpha\beta\mu\rho} \left(q_{Z_1\rho} - q_{Z_2\rho}\right) \right\}$$

$$\Gamma^{\alpha\beta\mu}_{Z\gamma V} = i\, e \frac{q_V^2 - m_V^2}{m_Z^2} \left\{ h_1^V \left(q_\gamma^\mu g^{\alpha\beta} - q_\gamma^\alpha g^{\beta\mu}\right) + h_2^V \frac{q_V^\alpha}{m_Z^2} \left(q_\gamma q_V\, g^{\beta\mu} - q_\gamma^\mu\, q_V^\beta\right) + h_3^V\, \epsilon^{\alpha\beta\mu\rho}\, q_{\gamma\rho} + h_4^V \frac{q_V^\alpha}{m_Z^2}\, \epsilon^{\mu\beta\rho\sigma}\, q_{V\rho}\, q_{\gamma\sigma} \right\}$$

- **Effective Lagrangian approach='phenomenological Lagrangian'** (WV analyses) — Phys. Rev. D41 (1990) 2113

$$\mathcal{L}_{SM} \longrightarrow \mathcal{L}_{WWV} = -ig_{WWV}\Big\{ g_1^V \left(W^+_{\mu\nu} W^{-\mu} V^\nu - W^+_\mu V_\nu W^{-\mu\nu}\right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2} W^+_{\mu\nu} W^{-\nu\rho} V_\rho{}^\mu - i g_5^V \epsilon^{\mu\nu\rho\sigma} \left[W^+_\mu(\partial_\rho W^-_\nu) - (\partial_\rho W^+_\mu) W^-_\nu\right] V_\sigma \Big\},$$



- **Effective Field Theory (EFT) approach** (WW analysis, VBF analyses and triboson analyses) — Phys. Rev. D48 (1993) 2182

$$\mathcal{L}_{SM} \longrightarrow \mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty} \sum_i \frac{c_i^{(n)}}{\Lambda^n} \mathcal{O}_i^{(n+4)}$$

Phys. Rev. D 90, 032008 (2014)

Statistical method: anomalous coupling measurement

$\vec{\theta}$ = nuisance parameters

$\vec{\alpha}$ = anomalous coupling parameters

L = likelihood function

$\lambda(\vec{\alpha})$ = profile likelihood ratio

$$\lambda(\vec{\alpha}) = \frac{L(\vec{\alpha}, \hat{\hat{\vec{\theta}}}_{\vec{\alpha}})}{L(\hat{\vec{\alpha}}, \hat{\vec{\theta}})}$$

Numerator: maximizes L in θ, for specified α

Denominator: maximize L in α and θ

test statistics: $t(\vec{\alpha}) = -2\ln\lambda(\vec{\alpha})$

Limit setting criteria (both supported by CMS statistics committee as methods for aC limit setting):

1. "deltaNLL" limit: use of Wilks theorem, distribution of t_α, under assumption α, is approximated with χ^2 distribution
   - Asymptotic, high statistics approximation
   - Fast but coverage is not guaranteed
2. "Feldman-Cousins (F-C)" limit: distribution of t_α, under assumption α, is determined by throwing toys
   - Computing time consuming but guaranties coverage

Usually the two methods agree within 10%.

Fitting aC parameters => measurement of aC parameters => due to large uncertainties wrt best value we quote 95% CL limits

Several definitions of expected limits are available

- Pre-fit or post-fit expected limit
- Toys or Asimov dataset
- ✓ Usually we have been using pre-fit Asimov dataset for expected limit

Systematic uncertainties covered via nuisance parameters.

Nuisance parameters are profiled.

Nuisance effect is lognormal (lnN) by default (CMS statistics committee recommendation).

Statistical method: anomalous coupling limit setting

$\vec{\theta}$ = nuisance parameters

μ = **signal strenght**

L = likelihood function

$\lambda(\mu)$ = profile likelihood ratio

$$\lambda_{\vec{\alpha}}(\mu) = \frac{L_{\vec{\alpha}}(\mu, \hat{\hat{\vec{\theta}}}_{\mu})}{L_{\vec{\alpha}}(\hat{\mu}, \hat{\vec{\theta}})}, \quad 0 \le \hat{\mu} \le \mu$$

maximizes L in θ, for specified μ

maximize L in μ and θ

For every α in anaomalous coupling parameter space!

test statistics: $t_{\vec{\alpha}}(\mu) = -2\ln\lambda(\mu)$

<u>Fitting signal strength</u> in every point in anomalous coupling space => testing individually points in parameter space => limit setting

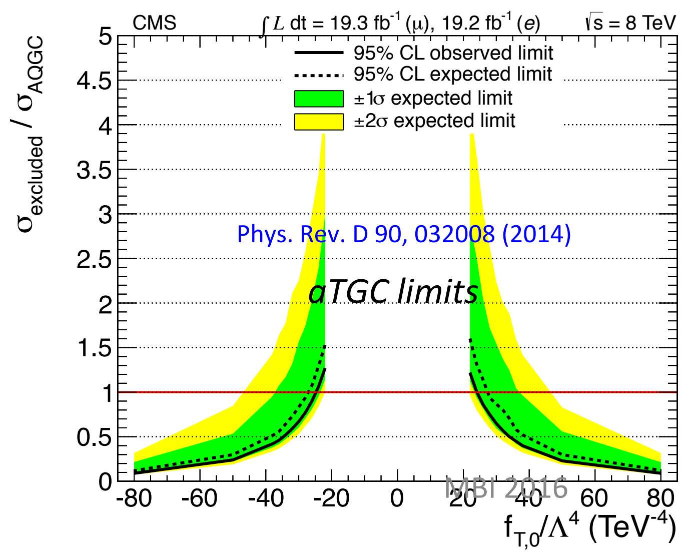
Limit setting criteria : Eur.Phys.J., C71:1554, 2011

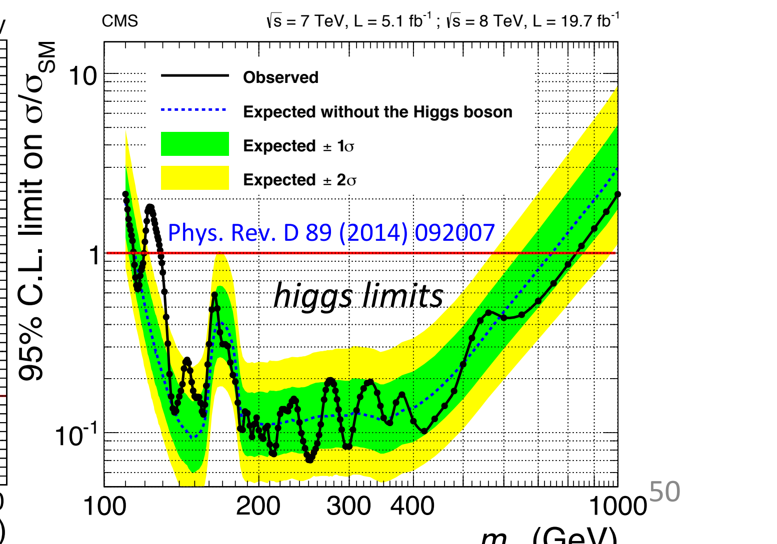
1. <u>"CLs" limit</u>: asymptotic calculation of CLs
   - Asymptotic, high statistics approximation
   - Fast but coverage is not guaranteed

$$CL_S = \frac{p_{S+B}}{1 - p_B}$$

Usually all three methods (deltaNLL, F-C, CLs) agree within 10%.

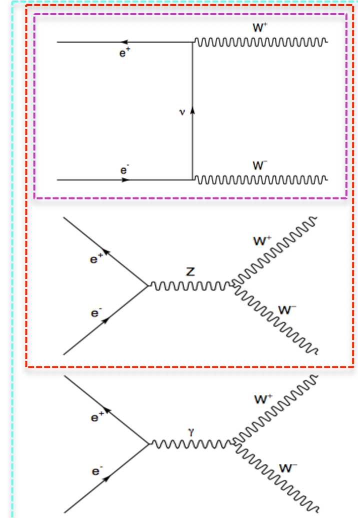
These are "higgs-like" limits.

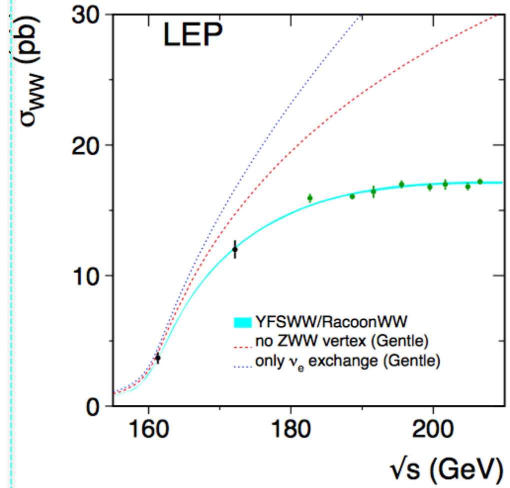




Vector boson couplings in SM

LEP2 confirmed the presence of the TGCs and the non-abelian structure of the $SU(2)_L \times U(1)_Y$ gauge simmetry



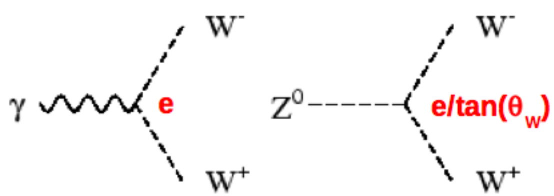


Phys. Rept. 532 (2013) 119

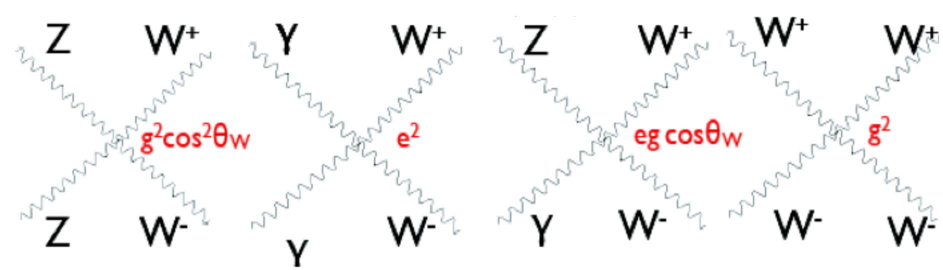
Triple and quartic vector boson couplings

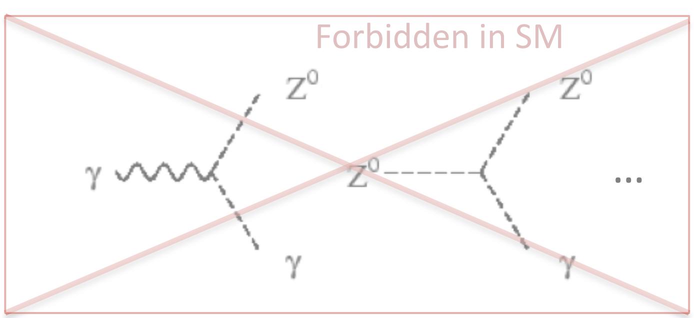
- Fundamental prediction of Standard Model (SM)
- Consequence of the non-Abelian nature of the SU(2)xU(1) gauge theory
- **Have exact values in SM!**

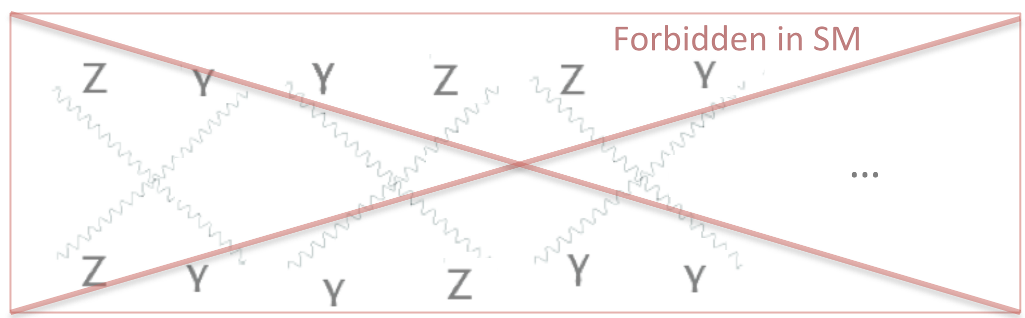
Triple gauge couplings (TGC)



Quartic gauge couplings (QGC)







Charged couplings are allowed at the tree level while neutral are forbidden in SM.

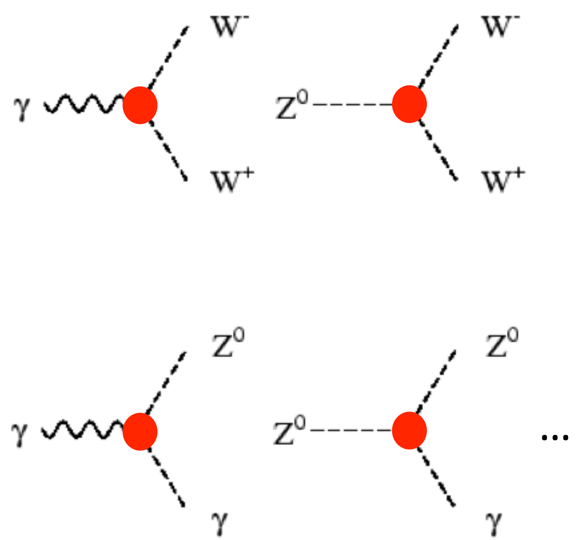
Deviation of vector boson couplings

Allowing vector boson couplings to vary away from SM values.

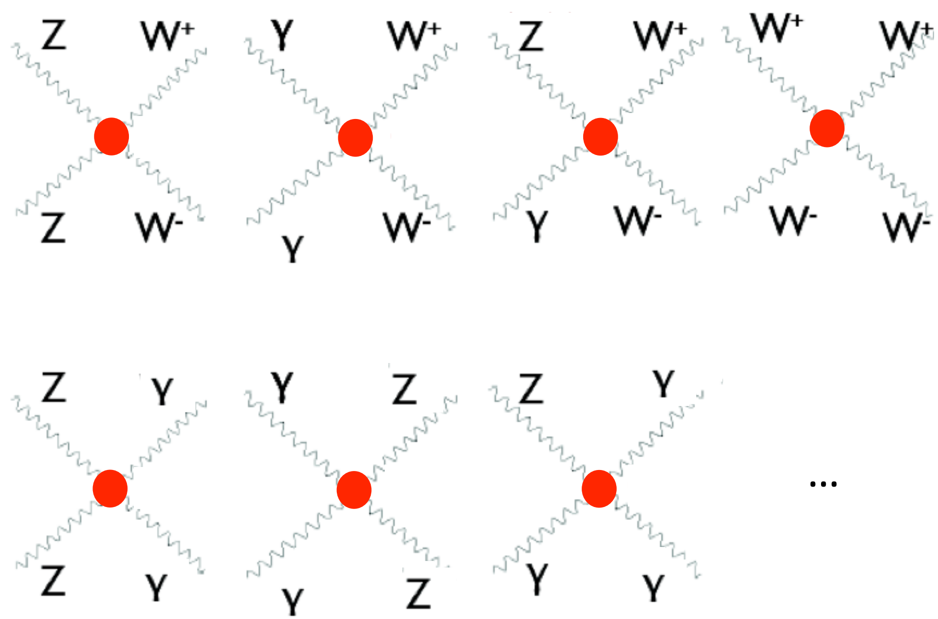
How to perform a measurement?

- Anomalous couplings contributions to gauge couplings have to be parametrized
- Ideally: performing global fit to all parameters ➔ too many independent variables
- **Need to apply assumptions (physically motivated) to reduce the number of paramaters to measure**

Anomalous Triple gauge couplings (aTGC)



Anomalous Quartic gauge couplings (aQGC)



Charged couplings are allowed at the tree level while neutral are forbidden in SM.

Anomalous coupling parametrizations: EFT summary

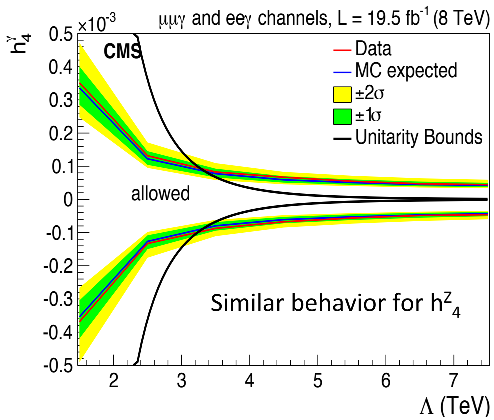
dim6 operators and vertices (aTGC and aQGC)

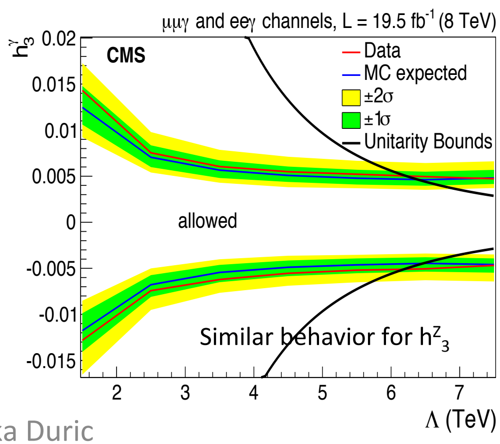
	$\mathcal{O}_{WWW}$	$\mathcal{O}_{WW}$	$\mathcal{O}_{W}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{B}$	$\mathcal{O}_{\tilde{B}}$	$\mathcal{O}_{\tilde{B}B}$	$\mathcal{O}_{\tilde{W}W}$	$\mathcal{O}_{\tilde{W}WW}$	$\mathcal{O}_{\tilde{D}W}$
WWZ	×		×		×	×			×	×
WWA	×		×		×	×			×	×
ZZH		×	×	×		×	×	×		
WWH		×	×					×		
AAH		×		×			×	×		
AZH		×	×	×	×	×	×	×		
WWWW	×		×						×	×
WWZZ	×		×						×	×
WWAA	×								×	×
WWAZ	×		×						×	×
WWHH		×	×					×		
ZZHH		×	×	×	×	×	×	×		
AZHH		×	×	×	×	×	×	×		
AAHH		×		×			×	×		

Unitarity: neutral and charged aTGC

- Limits with form factor of Λ_{FF}>~3 TeV give results similar to $\Lambda_{FF}=\infty$ (no form-factor)
- **Neutral TGC (ZγZ/γ and ZZZ/γ) results are in the unitarity violating regime**

$$h_i(s) = \frac{h_i}{(1+s/\Lambda^2)^i}$$

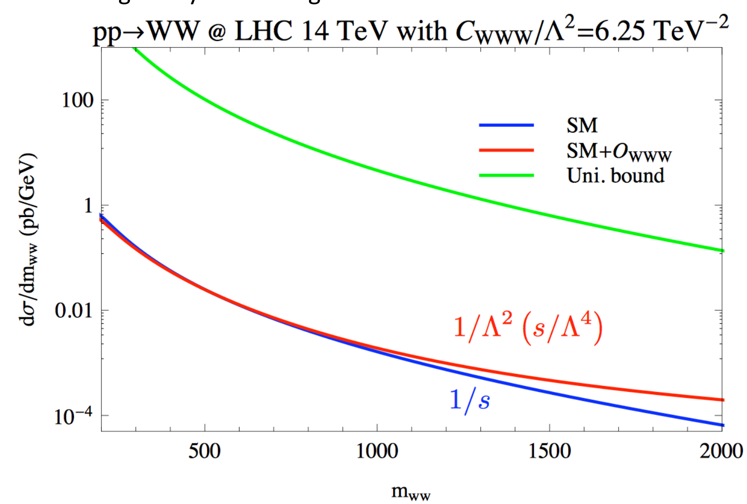




Phys. Rev. D30 (1984) 1513

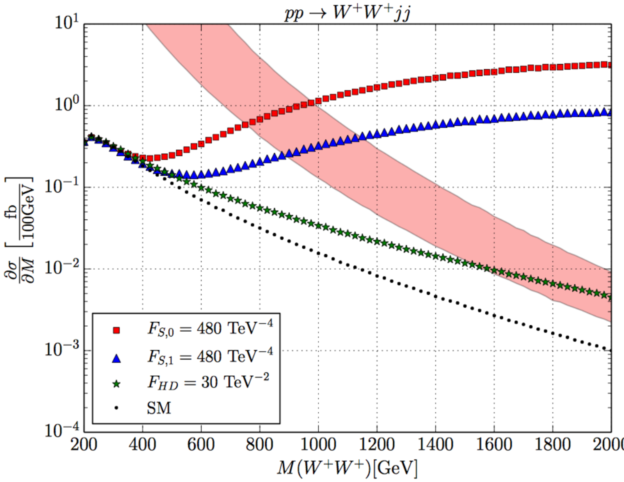
- For charged aTGCs (WWV vertex) observed limits are 2 orders of magnitude smaller then the unitarity bound
- **Charged aTGC results are in the unitarity non-violating regime**

Figure by Celine Degrande



J. High Energy Physics 04 (2015) 164

Question of unitarity



https://whizard.hepforge.org

- Any non-zero value of anomalous coupling will lead to tree-level unitarity violation at sufficiently high energy
- At these high energies we will not have an effective theory (that we see at energies where we perform the measurement) but full New Physics theory that conserves unitarity

Effective Lagrangian and effective vertex formulation

- Unitarity is preserved with applying a form-factor
  - Adding two new parameters and assuming their values a-priori: Λ_{FF} (form factor scale) and n
  - Form factor structure comes from New Physics structure
  - Form factor structure is unknown a-priori, so it is arbitrary

$$\alpha(\hat{s}) = \frac{\alpha_0}{(1+\hat{s}/\Lambda_{FF})^n}$$

Effective field theory formulation

- Already has a scale (new physics scale Λ)
- Usually no need of form-factor

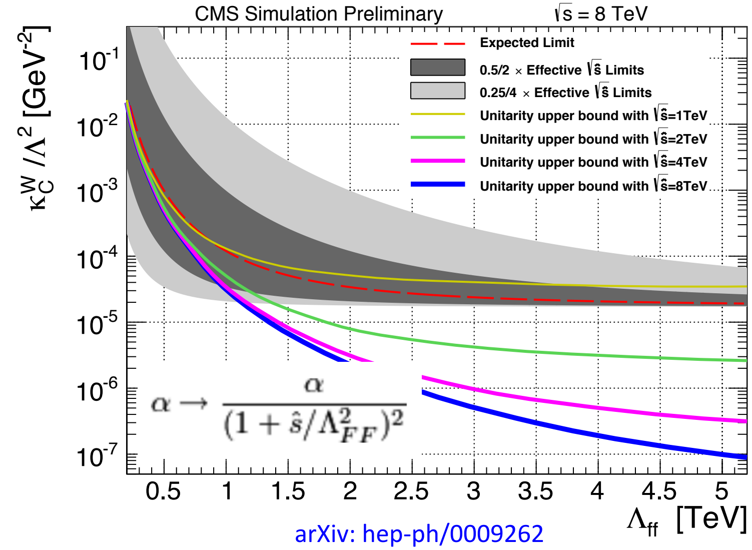
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty}\sum_i \frac{c_i^{(n)}}{\Lambda^n}\mathcal{O}_i^{(n+4)}$$

We will never observe the unitarity violation! However measurement can be “over-sensitive” if using models that break the unitarity for signal model building.

Translation between formulations possible only for no form-factor approach!

In CMS we have been setting limits without the use of form-factor, equivalent to $\Lambda_{FF}=\infty$.

Unitarity of measured anomalous coupling limits

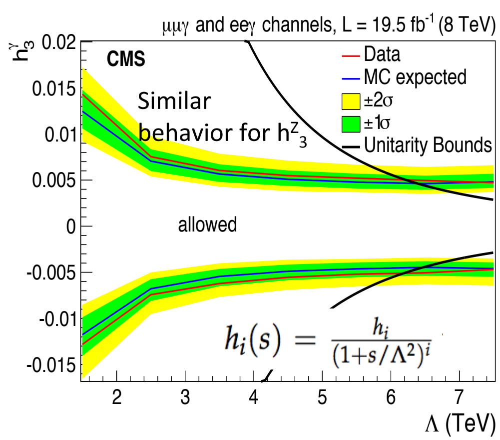


arXiv: hep-ph/0009262
Phys. Rev. D 90, 032008 (2014)

QGC (WVγ->lνjjγ)

- Limits with form factor of Λ_{FF}>~4 TeV give results similar to $\Lambda_{FF}=\infty$ (no form-factor)
- Effective field theory terms violate unitarity at parameter values close to the measured limits
- **For the case of dipol form factor neutral WWγZ/γ results are in the unitarity violating regime**

JHEP 04 (2015) 164
Phys. Rev. D30 (1984) 1513



Neutral TGC

- Limits with form factor of Λ_{FF}>~3 TeV give results similar to $\Lambda_{FF}=\infty$ (no form-factor)
- **Neutral TGC (ZγZ/γ and ZZZ/γ) results are close to unitarity bound for limits from Zγ->llγ, but in unitarity non-violating regime for limits from Zγ->ννγ**

Charged TGC

- Observed limits are 2 orders of magnitude smaller then the unitarity bound -> **results are in the unitarity non-violating regime**