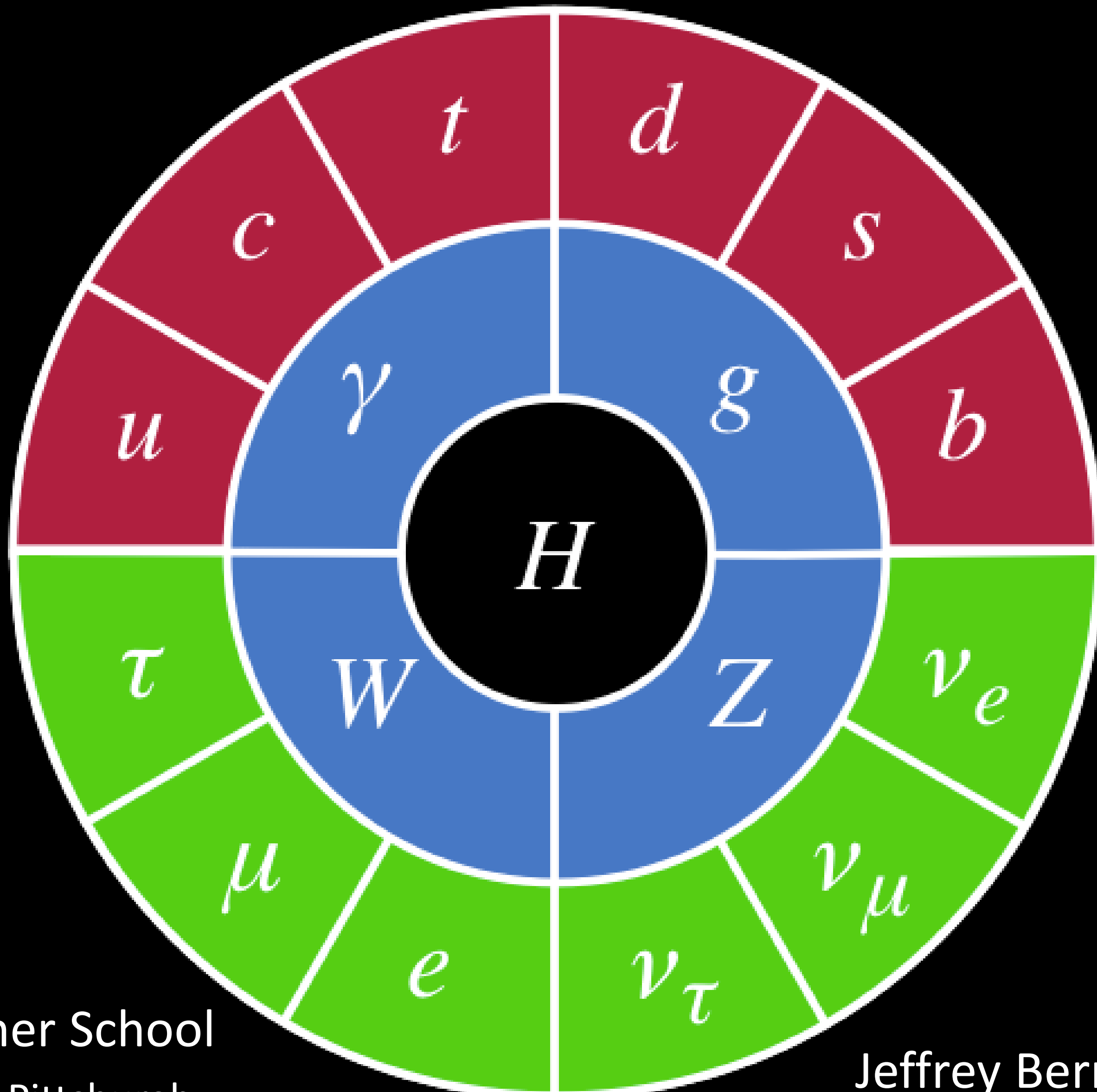
Standard Model Physics at the LHC: QCD, Top, Electroweak



CTEQ Summer School

July 16, 2015 Pittsburgh

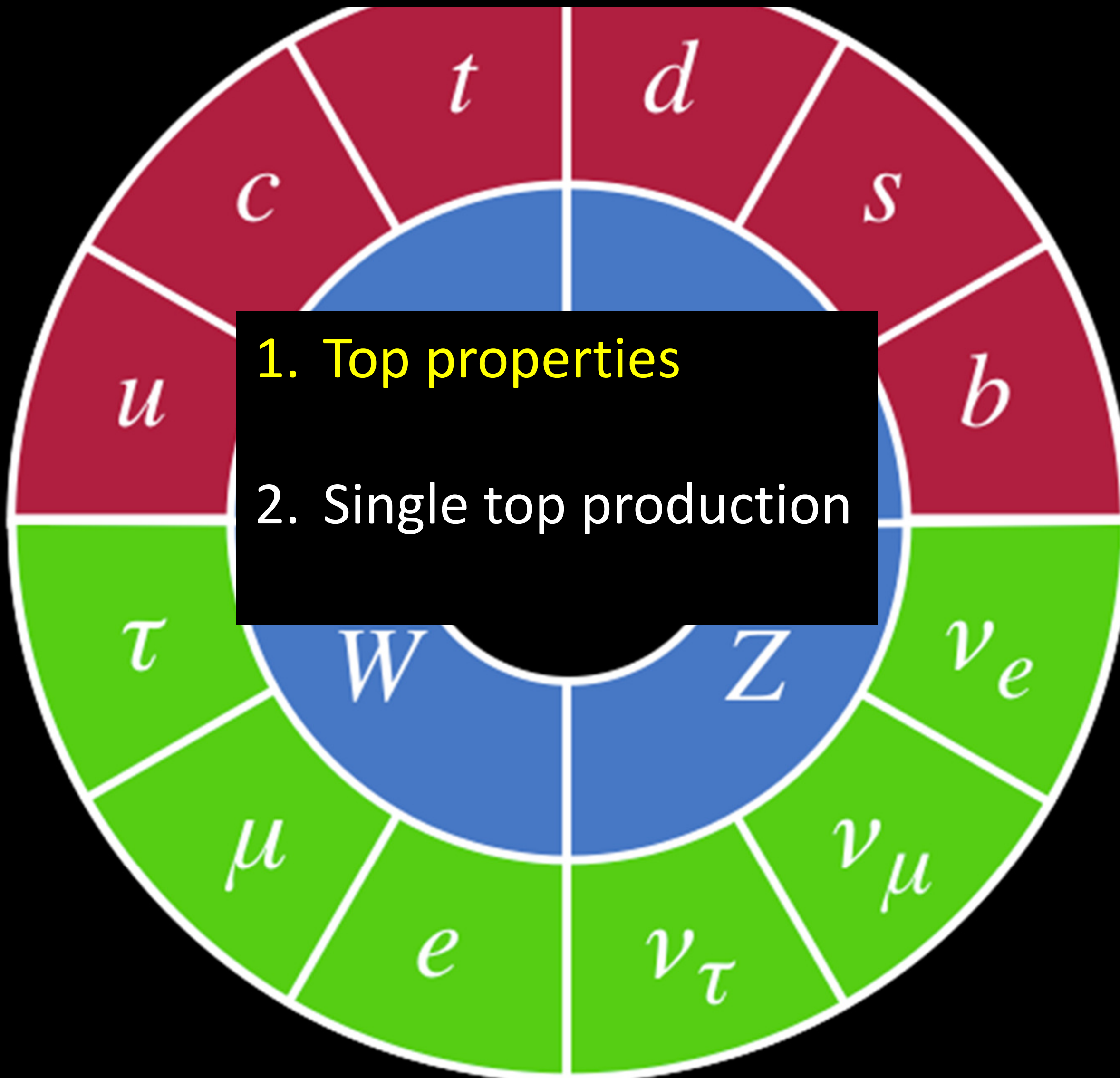
Jeffrey Berryhill (Fermilab)

CMS collaboration

Outline

1. Tests of QCD and jet production
    1. Jet cross sections
    2. The strong coupling
    3. Associated jet production
2. Measurements of the top quark
    1. Top pair production
    2. Top quark mass
    3. Top properties
    4. Single top production
3. Tests of the electroweak theory
    1. Vector boson production
    2. Diboson production and TGCs
    3. Vector boson scattering and QGCs

1. The top quark from the electroweak POV



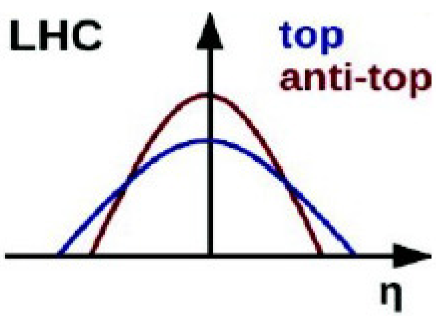
1. Top properties
2. Single top production

tt charge asymmetry

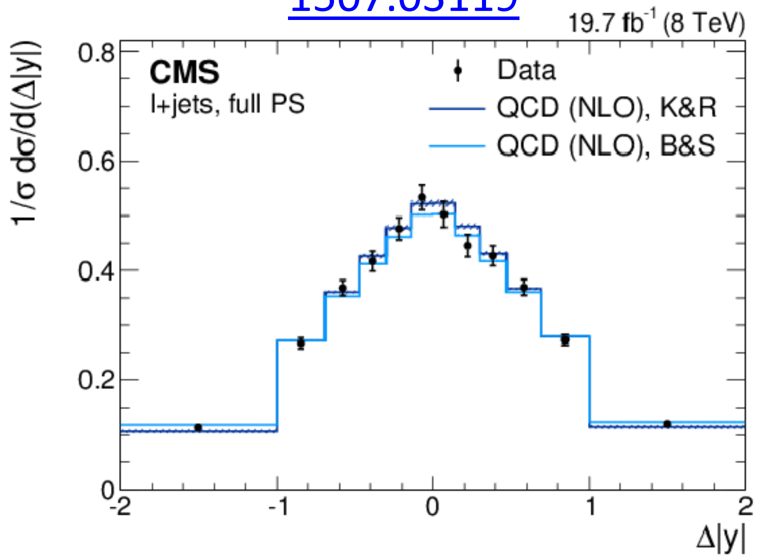
- ISR/FSR interference, LO-NLO interference induces **small SM asymmetry in production rapidity**
- Global AC is +0.001±0.0068±0.0037
- CMS 8 TeV data also bound AC differentially in y(tt), PT(tt), and m(tt)
- **Exotic tt interactions would modify AC vs. mass**
- **1.5 TeV effective axial-vector gluon coupling excluded**

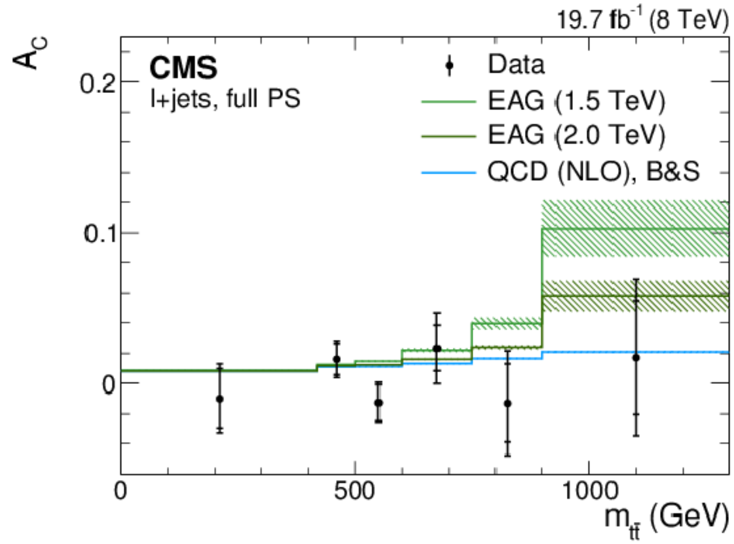
$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$

$$\Delta|y| \equiv |y_t| - |y_{\bar{t}}|$$



1507.03119





tt spin correlation

- Top and anti-top spins are correlated in SM tt production
- Non-zero correlation strength

Ahel = Nlike-Nunlike/ Nlike+Nunlike

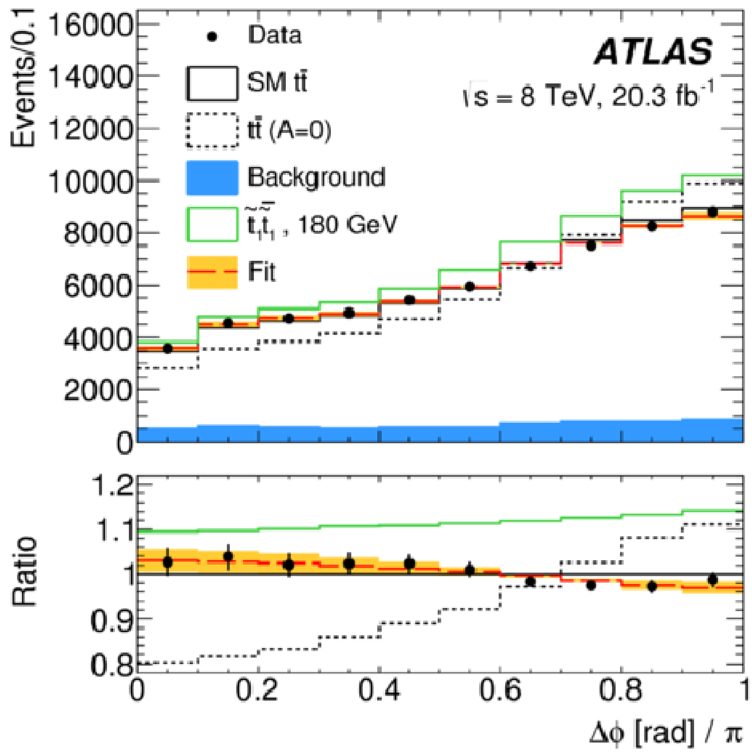
Asymmetry in events with tops aligned or antialigned wrt top dof

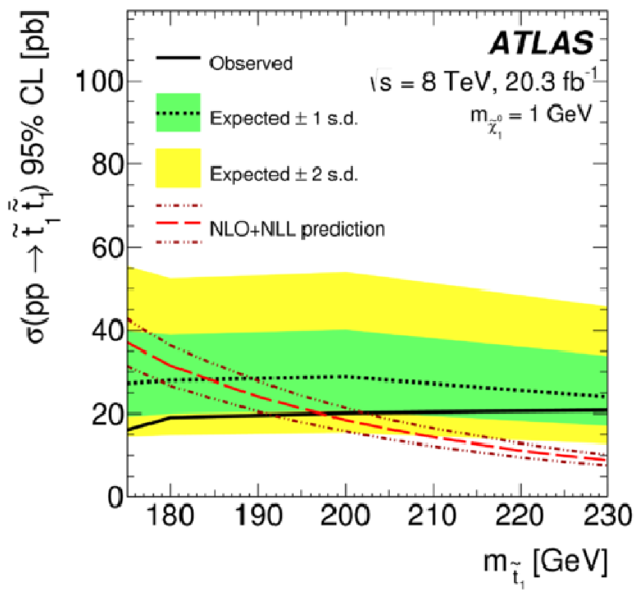
Ahel inferred from $\Delta\phi$ distribution in top dilepton pairs

Ahel = 0.38±0.04 consistent with SM value (0.32)

Excludes squeezed stop scenarios where top pair correlation is zero

PRL 114 (2015) 142001

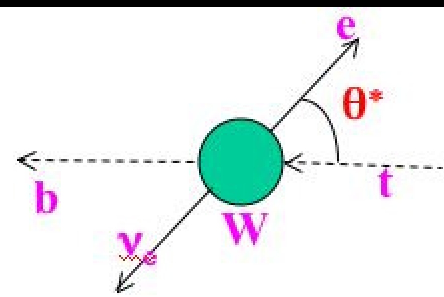




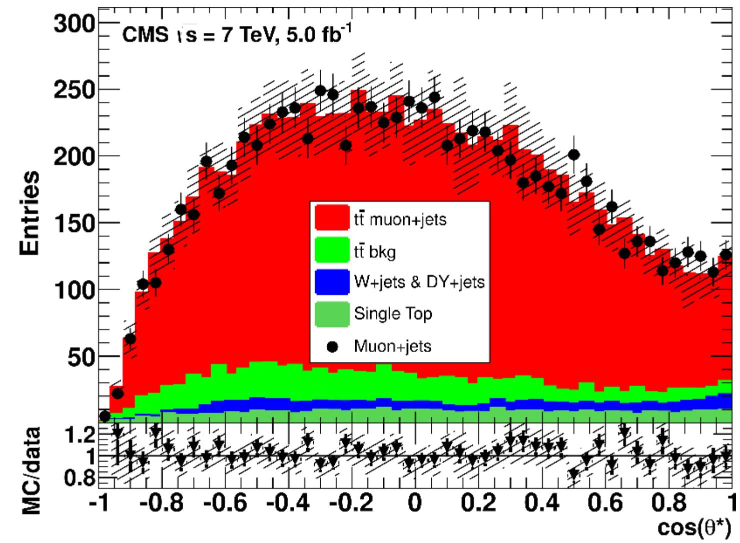
W boson helicity

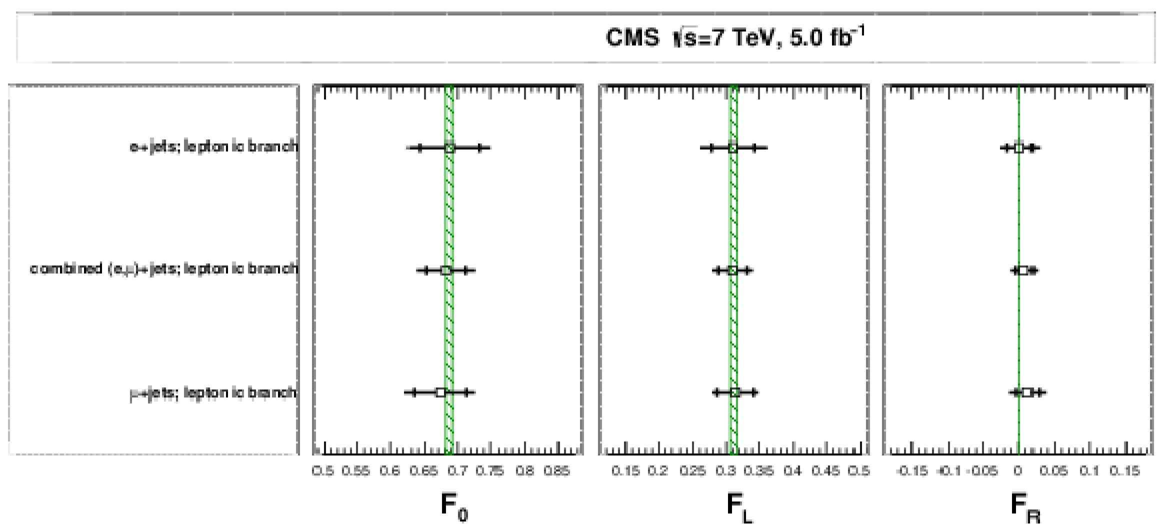
JHEP 10 (2013) 167

- **W helicity in SM top decay** is 70% longitudinal (F0), 30% left-handed (FL)
- In tt lepton+jets candidates, reconstruct cos θ*
- **Fit angular distribution** convolved with detector eff. and resolution
- **Helicity consistent with the SM**
- Anomalous dimension-six operators constrained



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}F_L\,(1-\cos\theta^*)^2 + \frac{3}{4}F_0(\sin\theta^*)^2 + \frac{3}{8}F_R\,(1+\cos\theta^*)^2$$

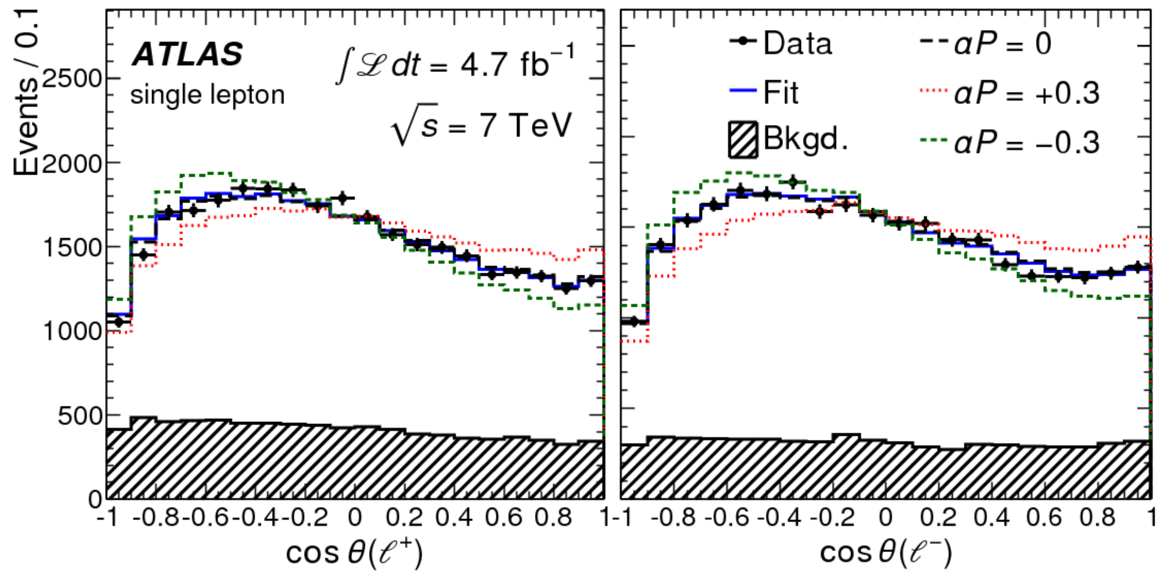


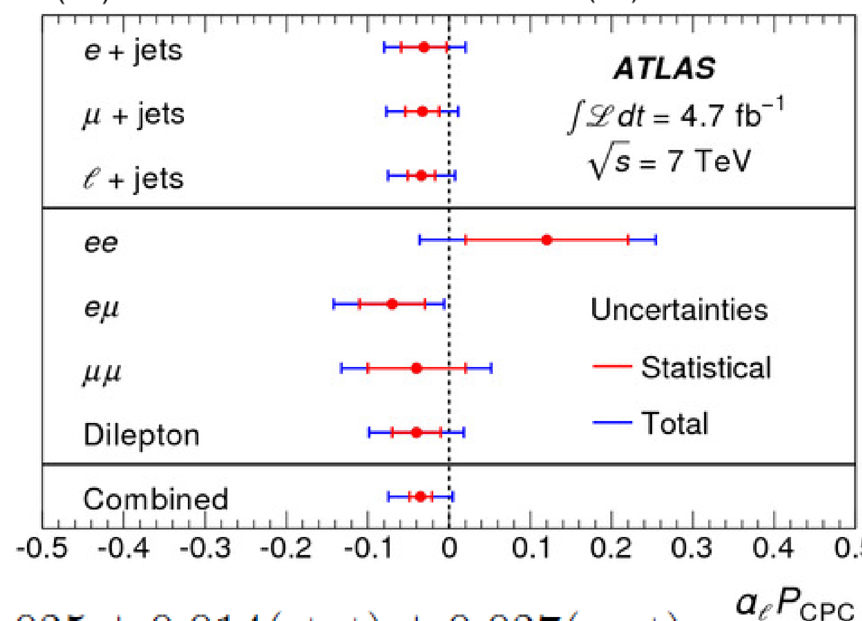


Top quark polarization

PRL 111 (2013) 232002

- Top quarks in tt production are unpolarized in the SM, but could be modified by new tt interactions
- In tt lepton+jets and dilepton candidates, reconstruct cos θ for leptons
- MLH fit for CP-conserving and violating polarization
- Consistent with SM





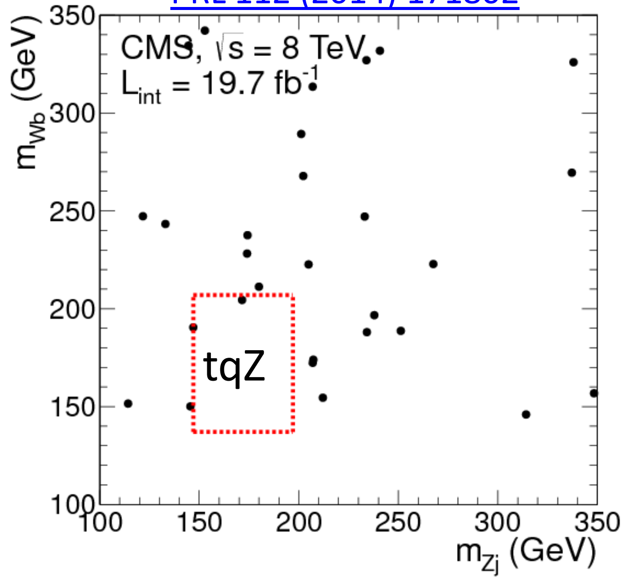
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 + \alpha_1 P_1 \cos\theta_1 + \alpha_2 P_2 \cos\theta_2 - C\cos\theta_1\cos\theta_2)\,, \quad (1)$$

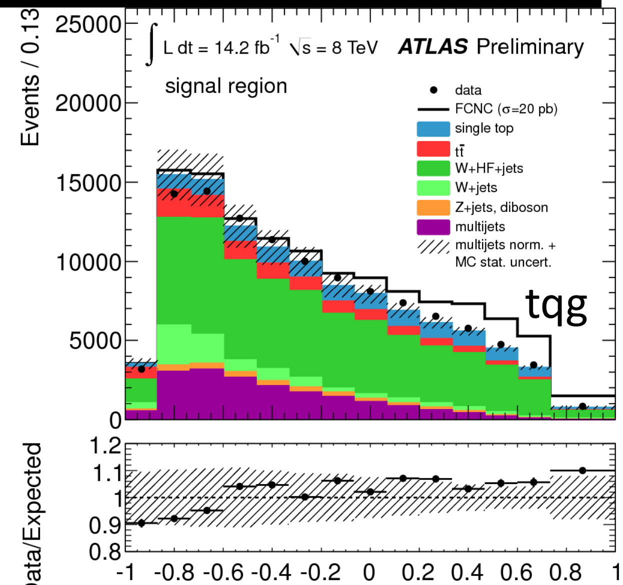
Wrt P of t in tt rest frame $\alpha_\ell P_{\mathrm{CPC}} = -0.035 \pm 0.014(\mathrm{stat}) \pm 0.037(\mathrm{syst})$

Rare t decays

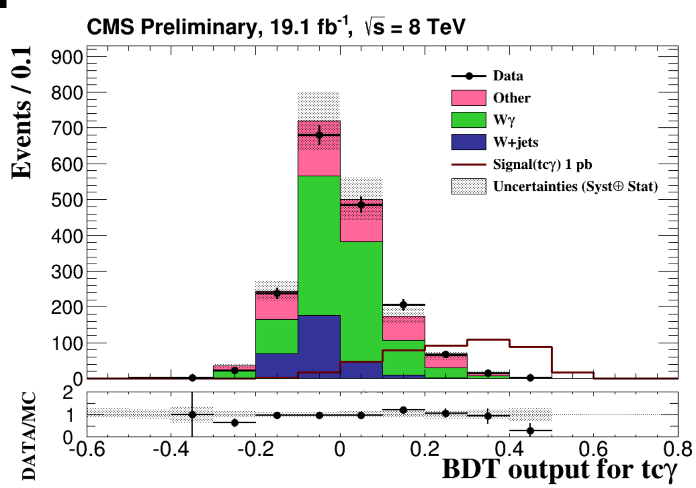
- Anomalous tqZ, tqg, and tqγ FCNC couplings sought in rare decays. Credible new physics rates at 10^{-4}-10^{-5} level
- tqZ, tqγ selected as tt with one less b, one more Z/γ. Limits in 10^{-3} 10^{-4} range
- Single top final state kinematics can be mined for tqg interactions at 10^{-5} level
- Next factor ten will probe the new physics rates in tqγ and tqZ

PRL 112 (2014) 171802

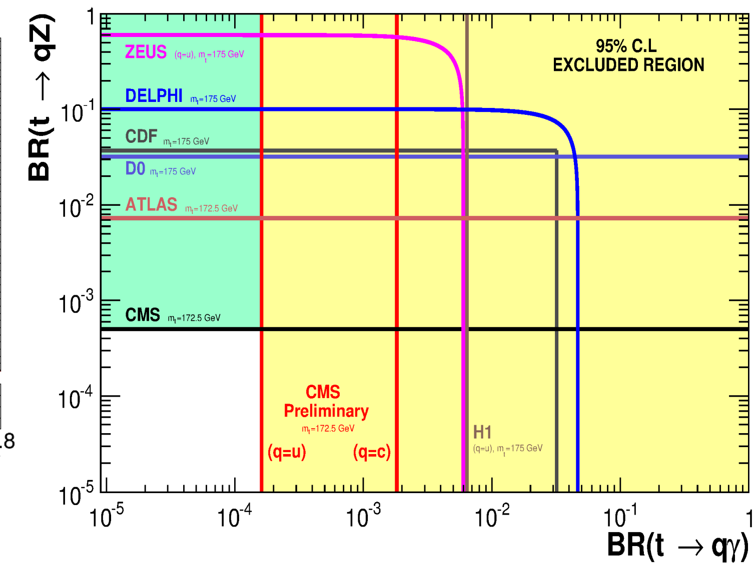




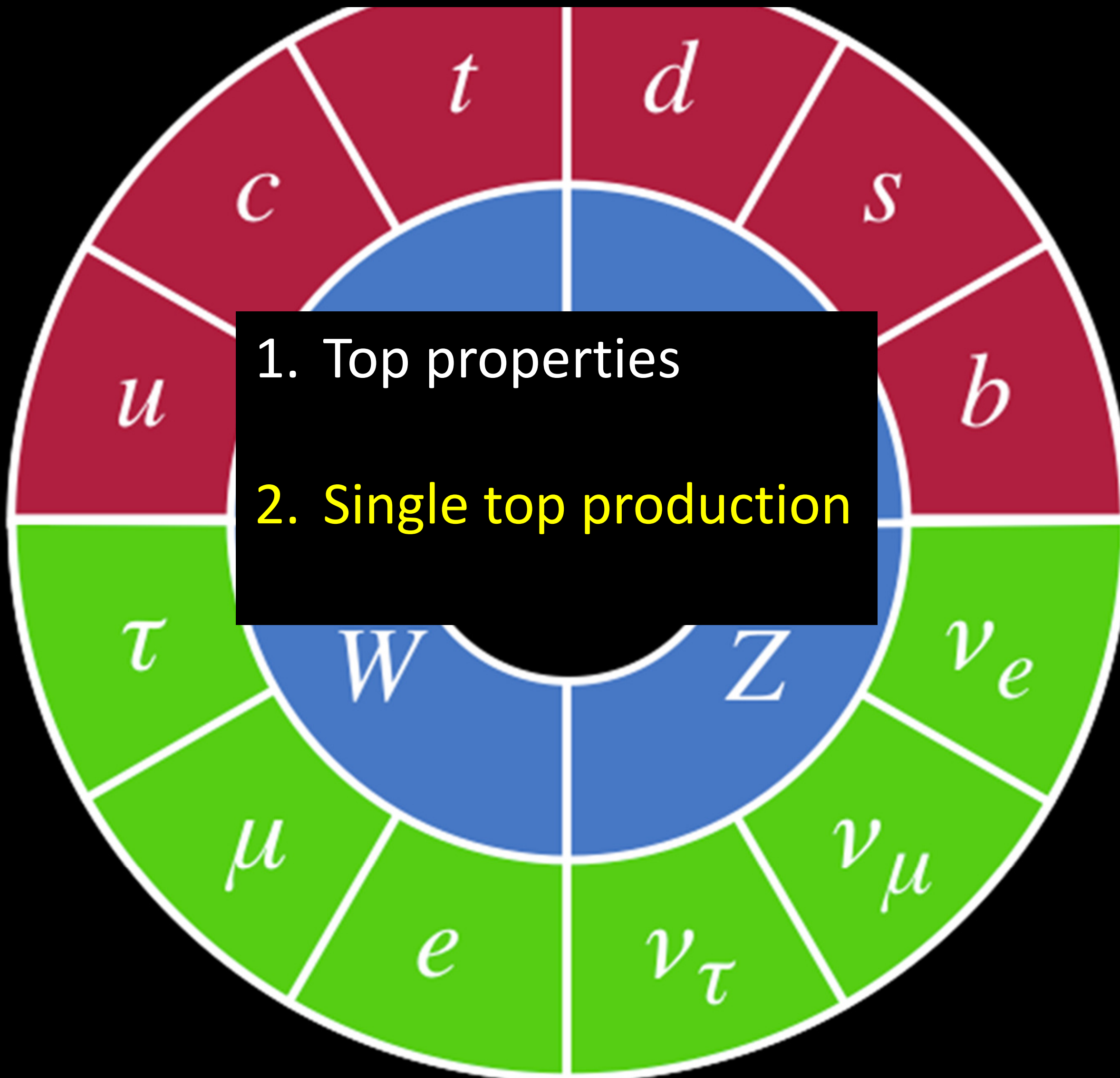
ATLAS-CONF-2013-063



CMS-PAS-TOP-14-003



1. The top quark from the electroweak POV



1. Top properties
2. Single top production

Single top production processes: t-channel

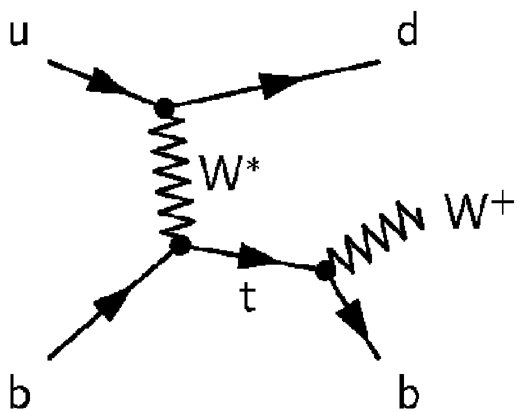
ATLAS-CONF-2014-007

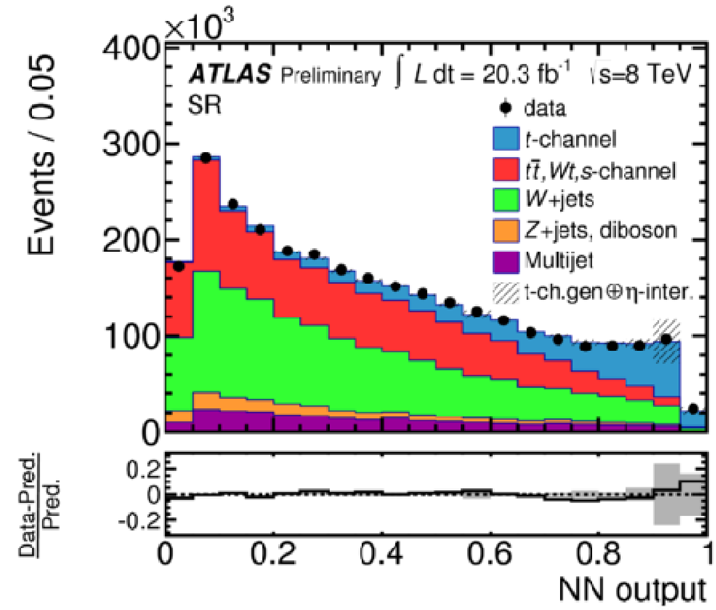
Electroweak t-channel single top production identified in W+ =2 jet =1 btag events

Discrimination of signal and tt background via 14-variable NN

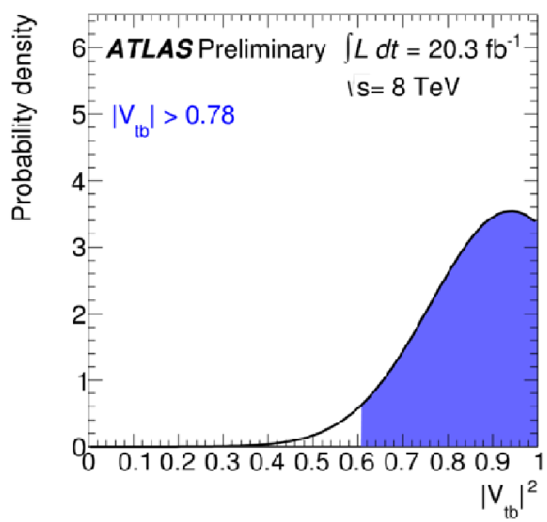
Cross section consistent with SM. JES and signal modelling dominant unc.

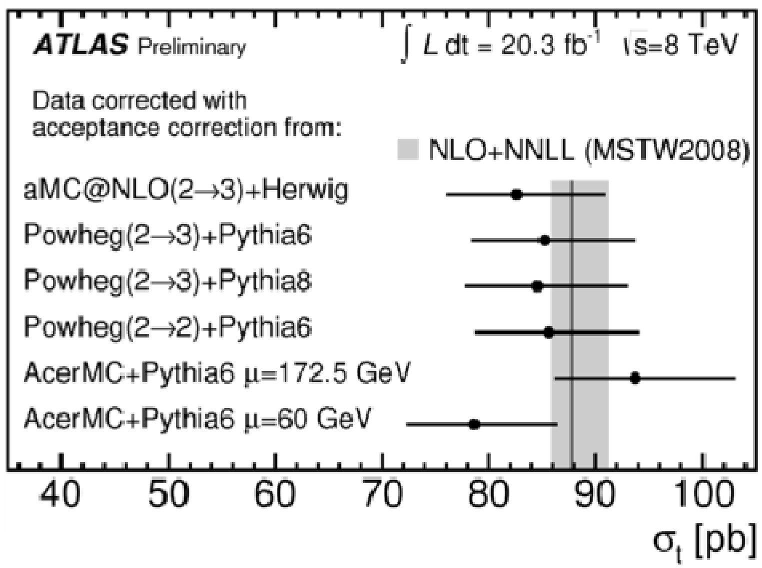
Vtb > 0.78 at 95%CL





$$\sigma_t = 82.6 \pm 1.2\,(\text{stat.}) \pm 11.4\,(\text{syst.}) \pm 3.1\,(\text{PDF}) \pm 2.3\,(\text{lumi.})\text{ pb}$$





Single top production processes: tW

PRL 112 (2014) 231802

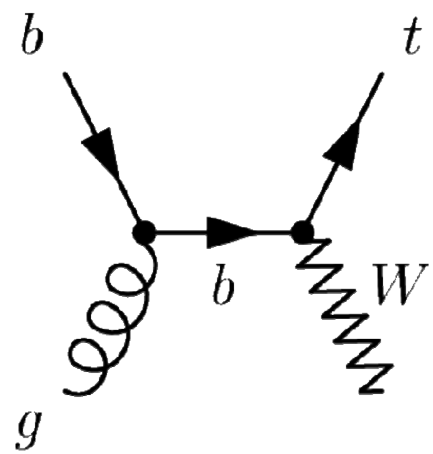
For dileptonic W decays, final state is dilepton+ =1 btag jet

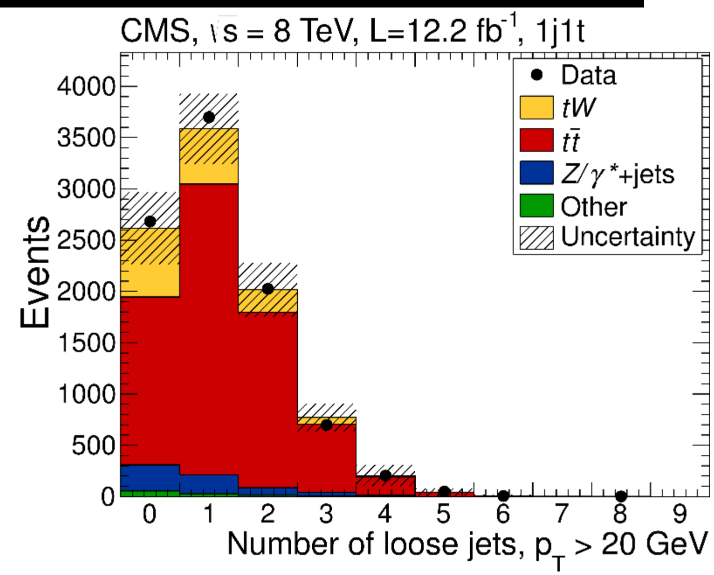
Discrimination for signal and tt background with kinematic BDT, including extra "loose jets"

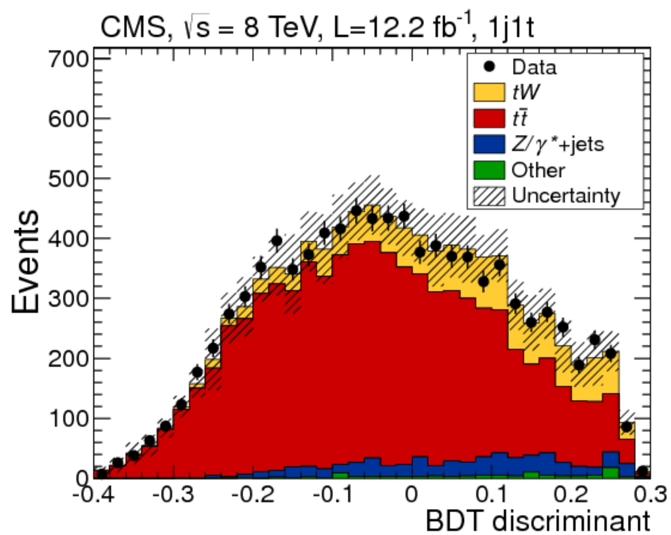
First observation at 6.1σ in CMS 8 TeV data. Agrees with SM at 23% level.

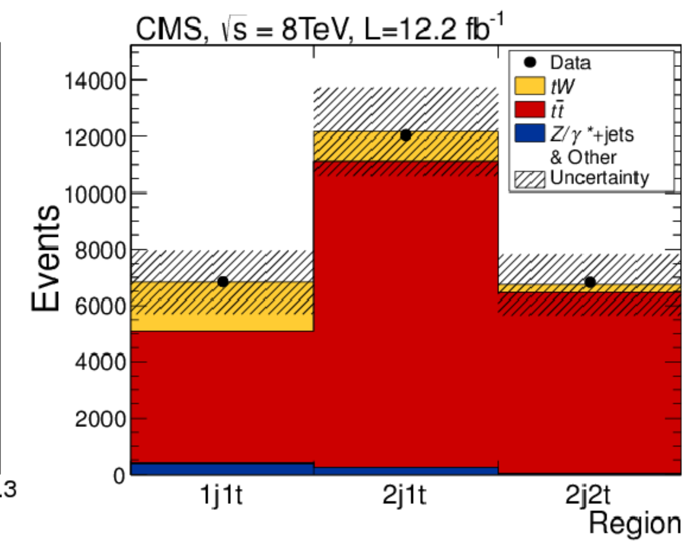
23.4±5.4 pb vs. SM 22 pb

Vtb > 0.78 @ 95%CL









Single top production processes: s-channel

PLB 740 (2015) 118

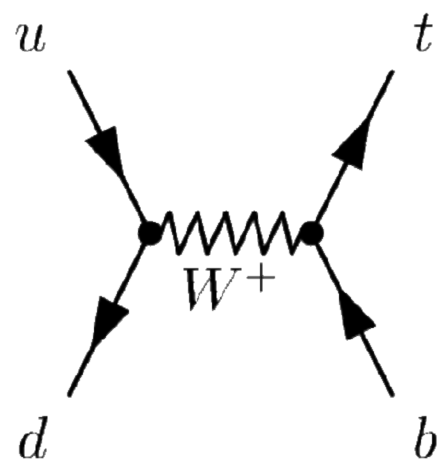
Smallest of the three channels tch = 4x Wt
Wt = 4x sch

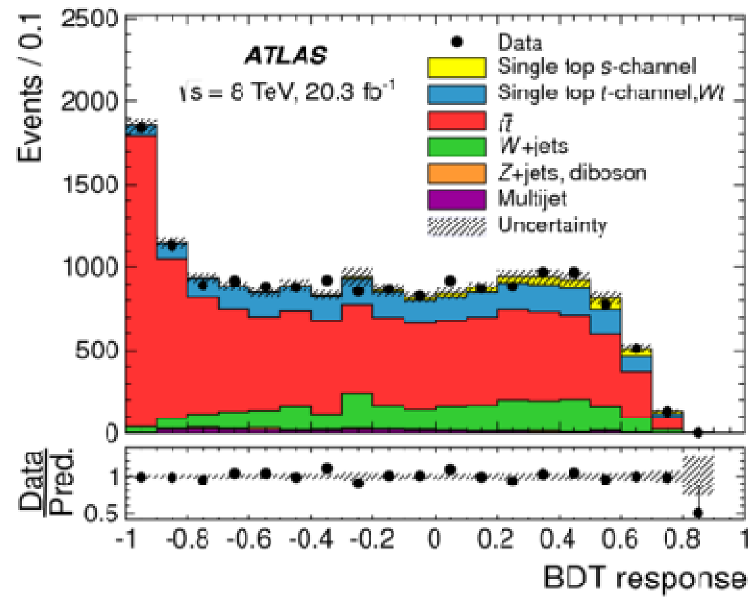
Final state is W+=2btag jets

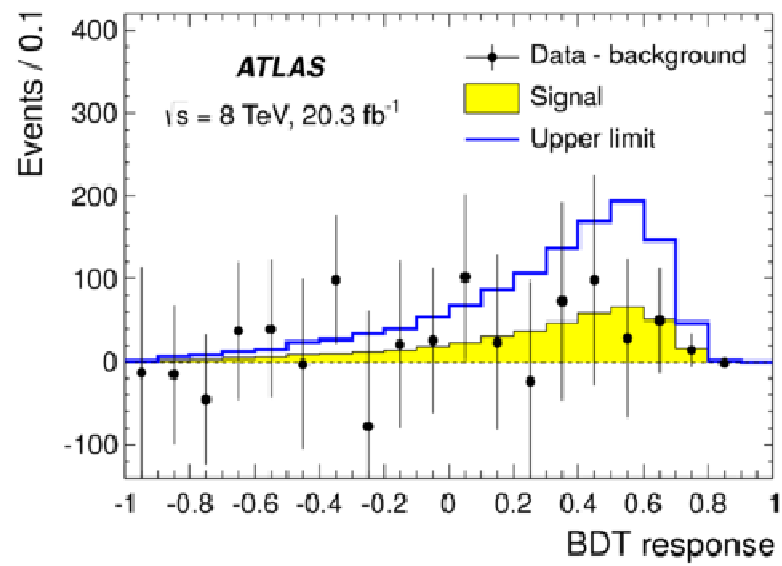
Kinematic BDT discriminates tt and t-channel backgrounds (angular variables most important)

1s excess consistent with SM rate (5.0±4.3 pb vs. 5.6 pb)

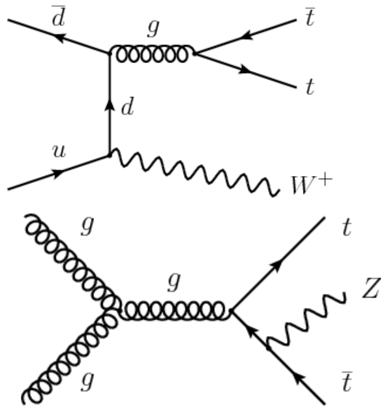
<14.6 pb @95% CL







Evidence of ttV production

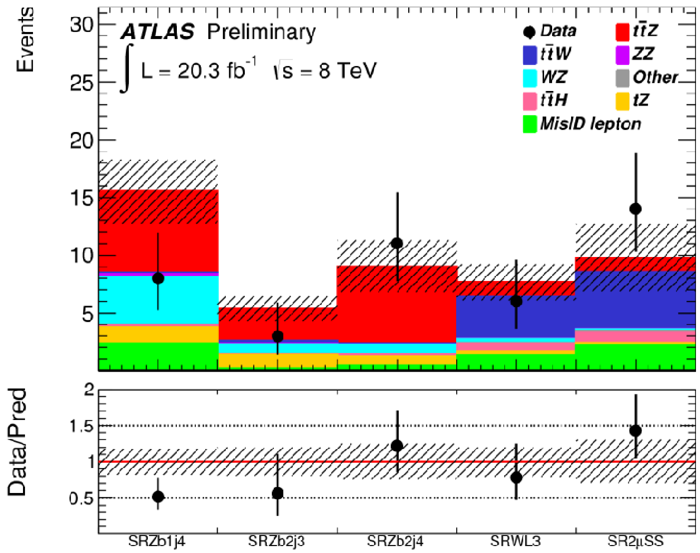


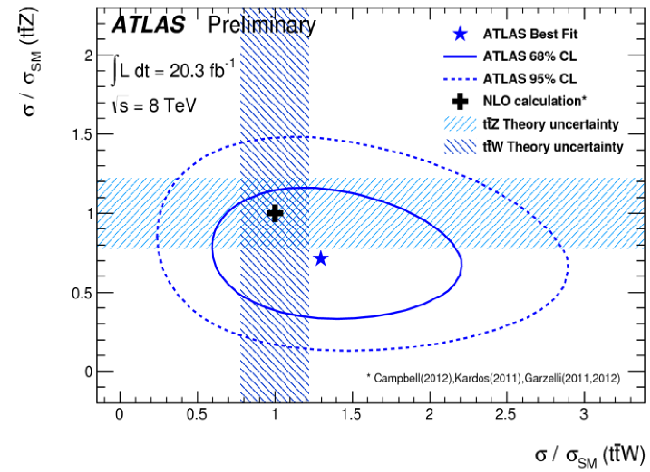
- Select SS 2-lepton,3-lepton, and 4-lepton + (>= 1b) jets events
- SS-2-lepton ttW-like, 3-lepton ttZ-like
- ATLAS:

ttW @ 3.1σ, ttZ @3.1σ,
ttV @ 4.9 σ

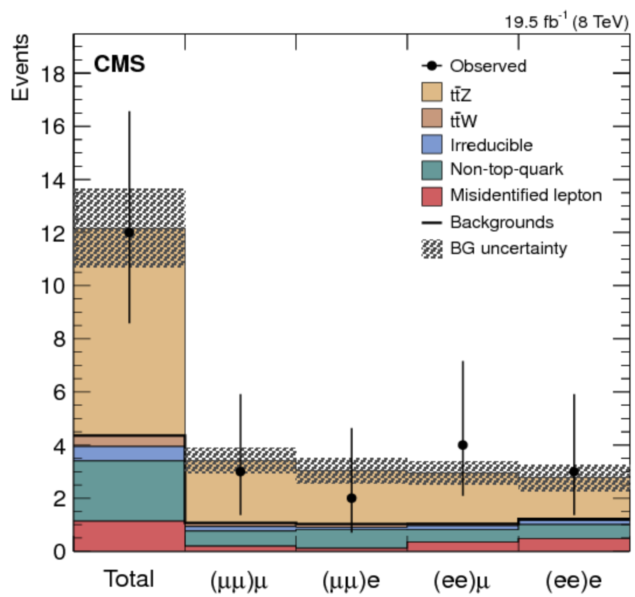
- CMS:

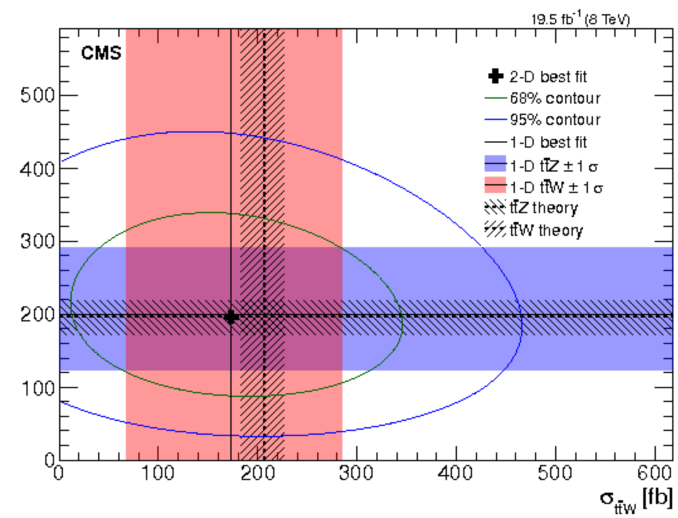
ttW @ 1.6σ, ttZ @ 3.1σ,
ttV @ 3.7σ





[ATLAS-CONF-2014-038]

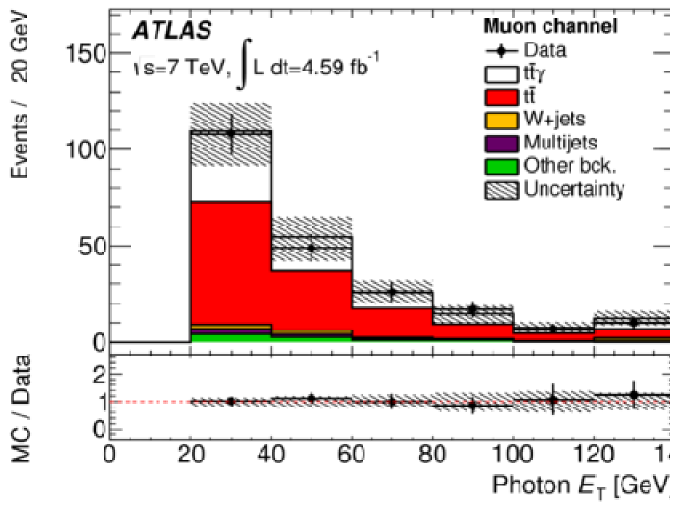


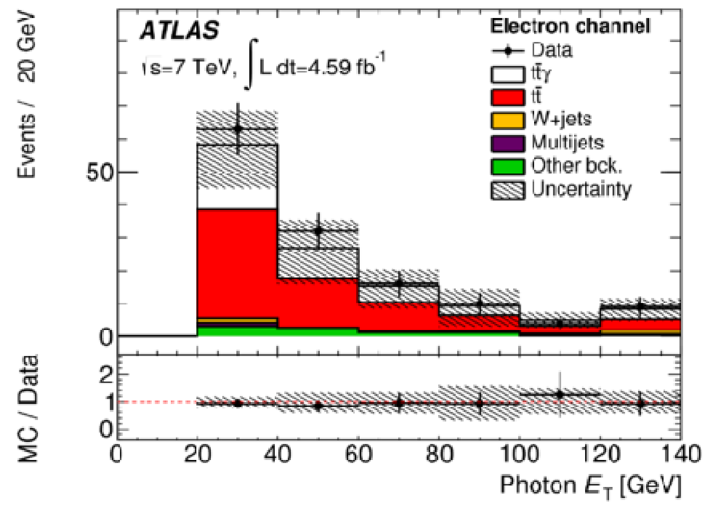


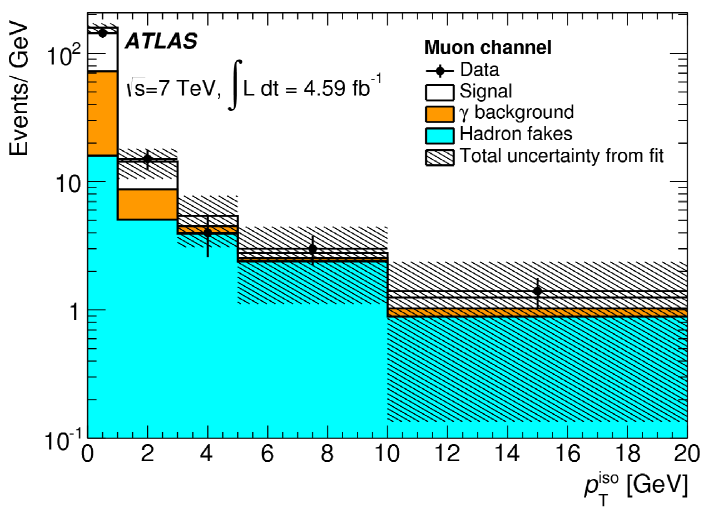
[arxiv:1406.7830]

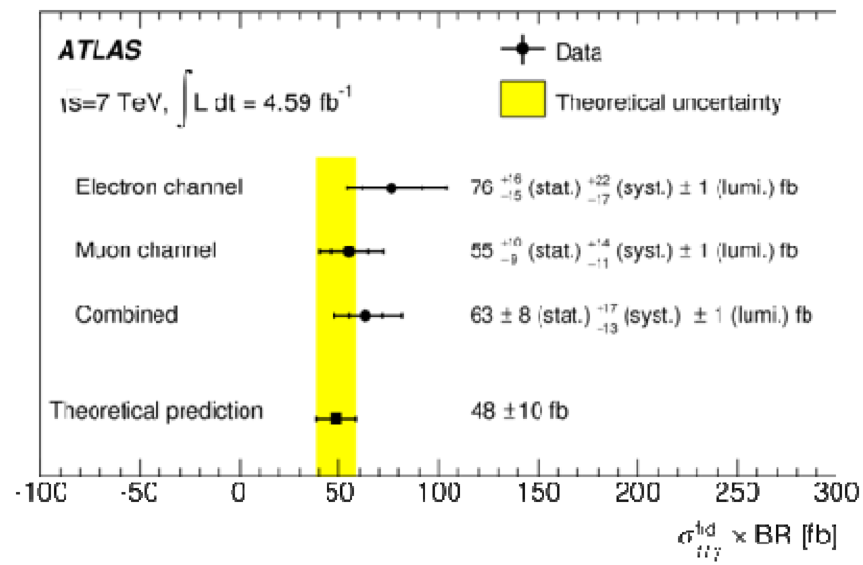
Observation of ttγ production

- **Lepton+jets tt candidates with photons > 20 GeV selected**
- **Fake photons subtracted via fit to track isolation**
- **5 sigma excess consistent with SM**



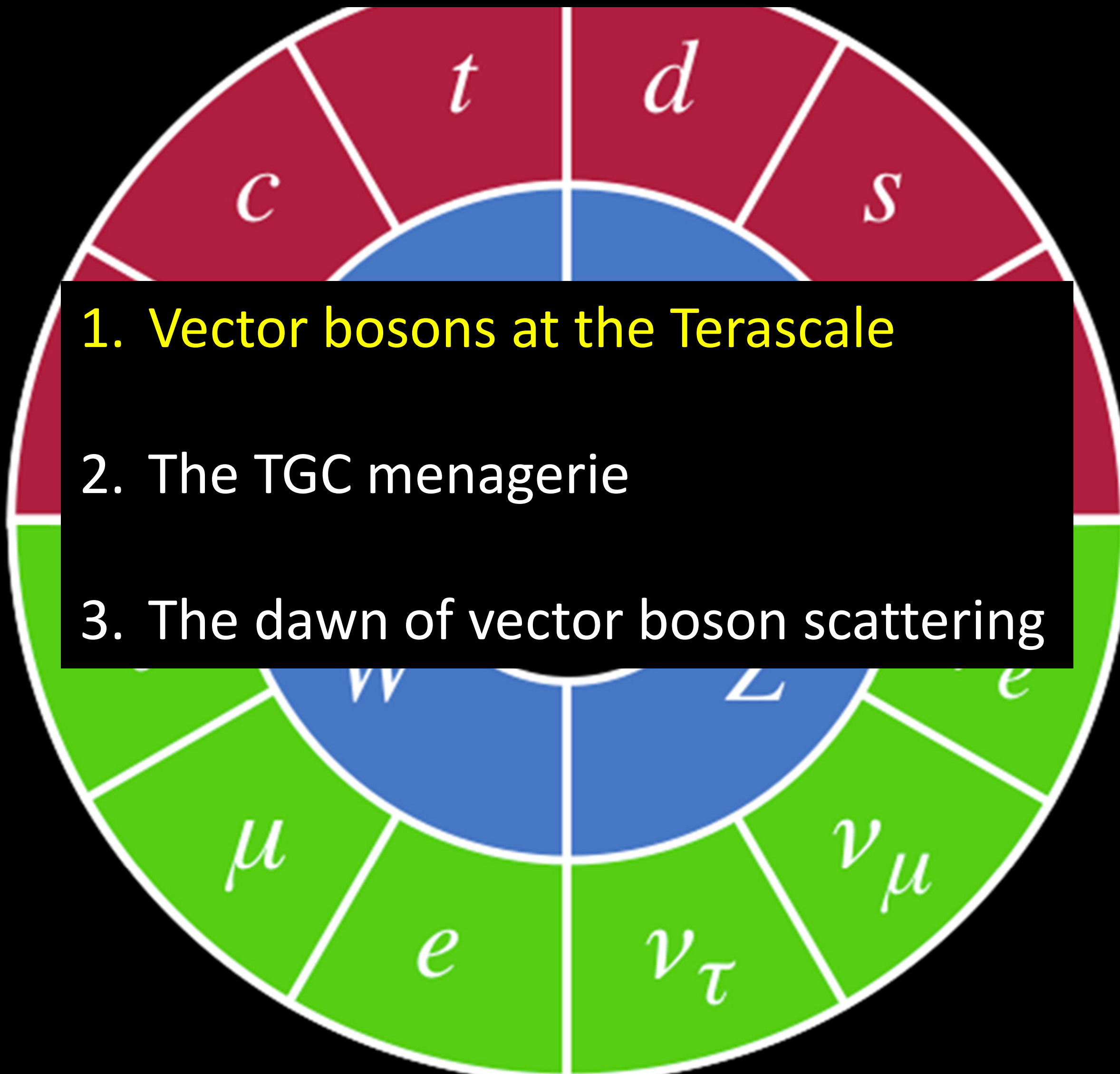






[PRD 91 (2015) 072007]

2. The electroweak vector bosons

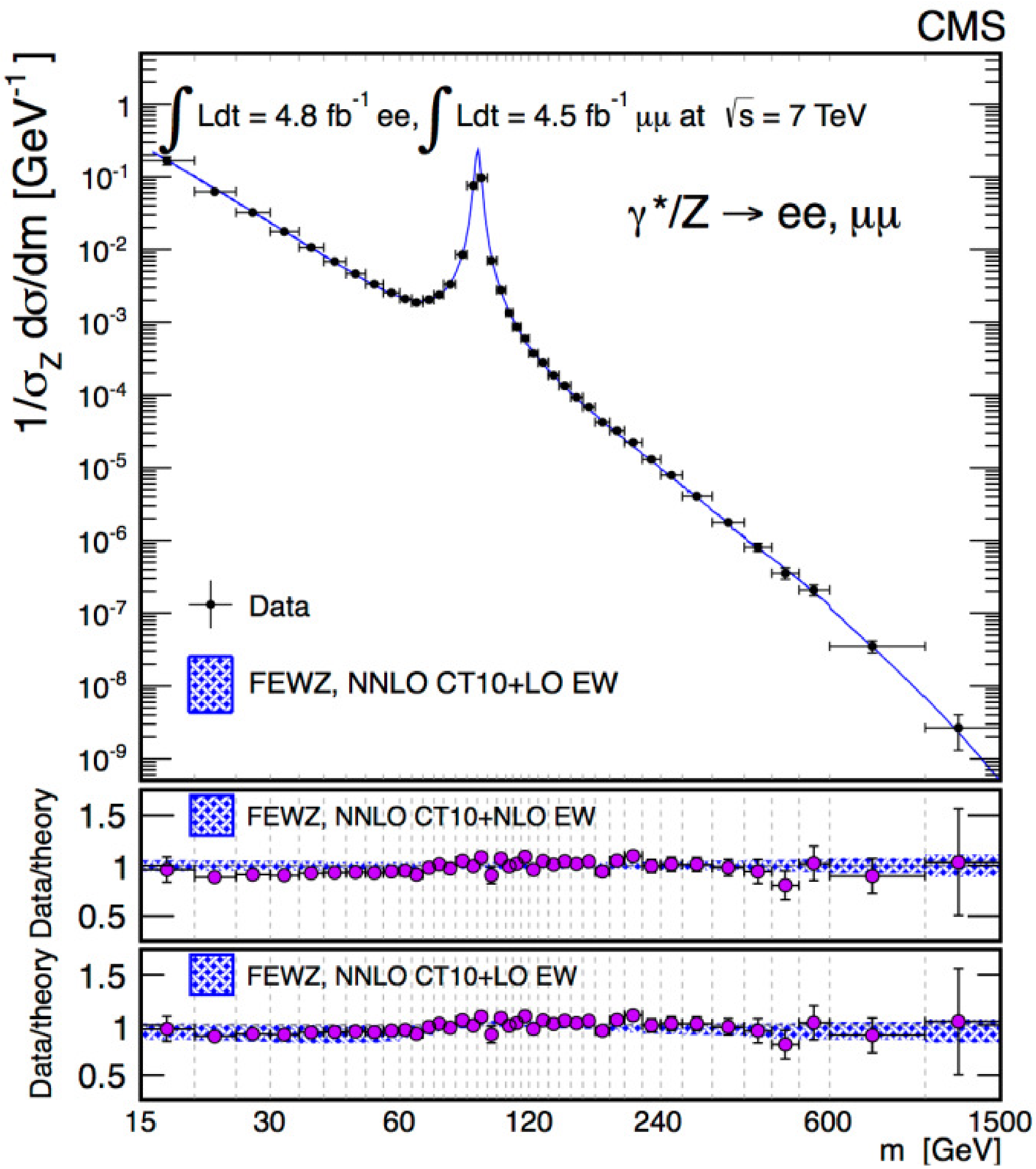


1. Vector bosons at the Terascale
2. The TGC menagerie
3. The dawn of vector boson scattering

Drell-Yan Cross Section at LHC (7 TeV)

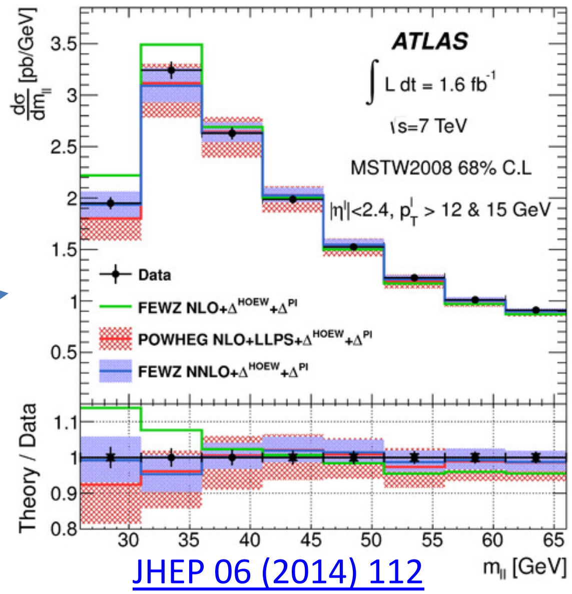
JHEP 12 (2013) 030

- Cross section vs. dilepton mass measured at 7 TeV, from **15-1500 GeV in mass**.
- 1M events/fb/experiment at 7 TeV!
- ee, μμ in agreement with each other and with the Standard Model

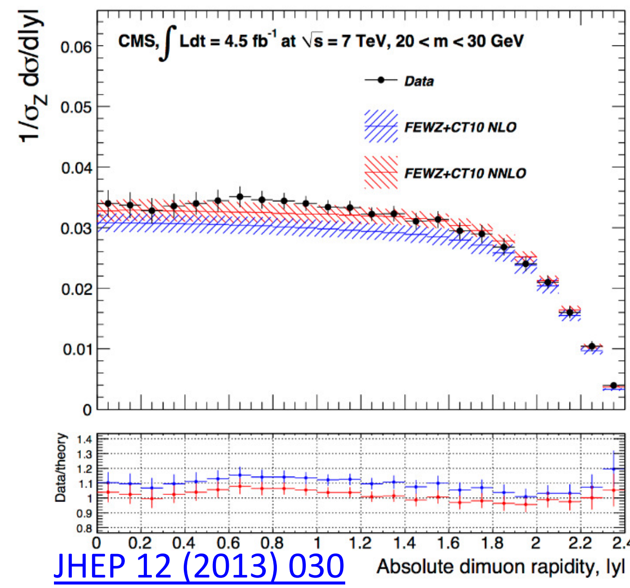


Drell-Yan Cross Section at LHC (7 TeV)

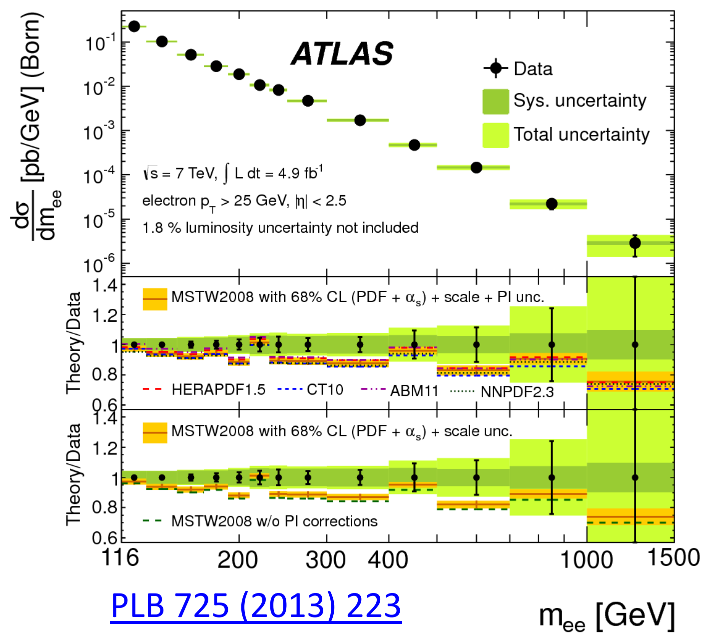
- NNLO QCD corrections are important at low mass (mostly boosted events)
- NLO EWK corrections and photon-induced production relevant at high masses. **Photon PDF is needed for accurate predictions.**



[JHEP 06 (2014) 112]

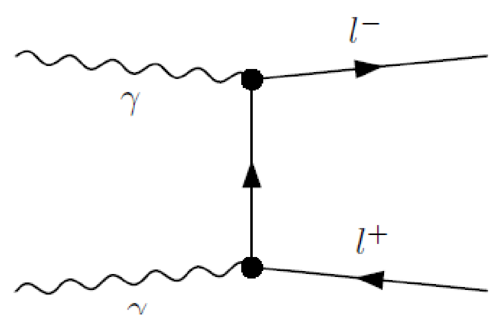


[JHEP 12 (2013) 030]



[PLB 725 (2013) 223]

FEWZ 3 NNLO QCD + NLO EWK + $\gamma\gamma \rightarrow l^+l^-$

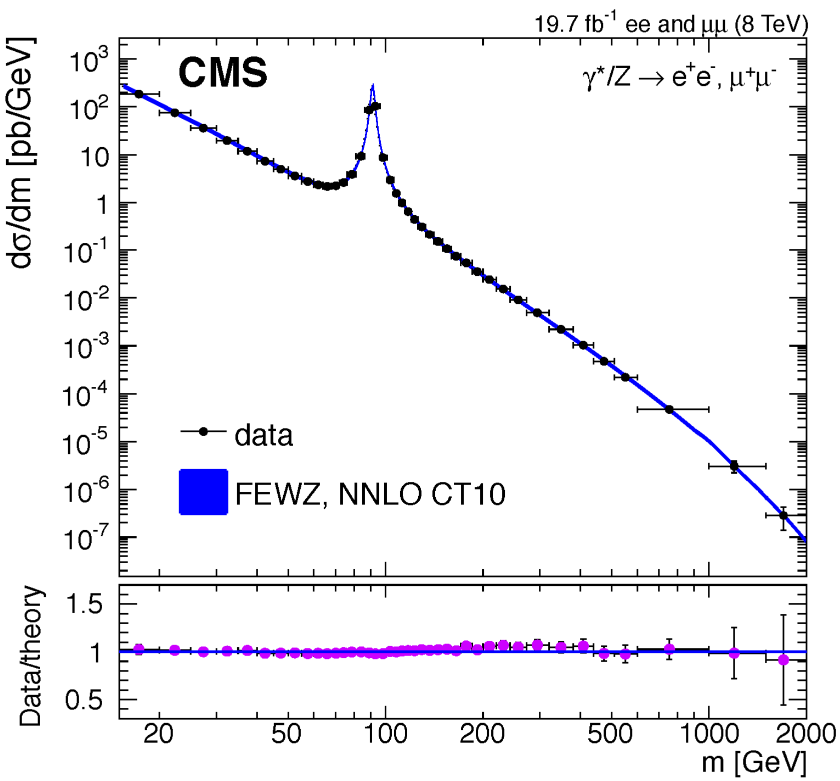


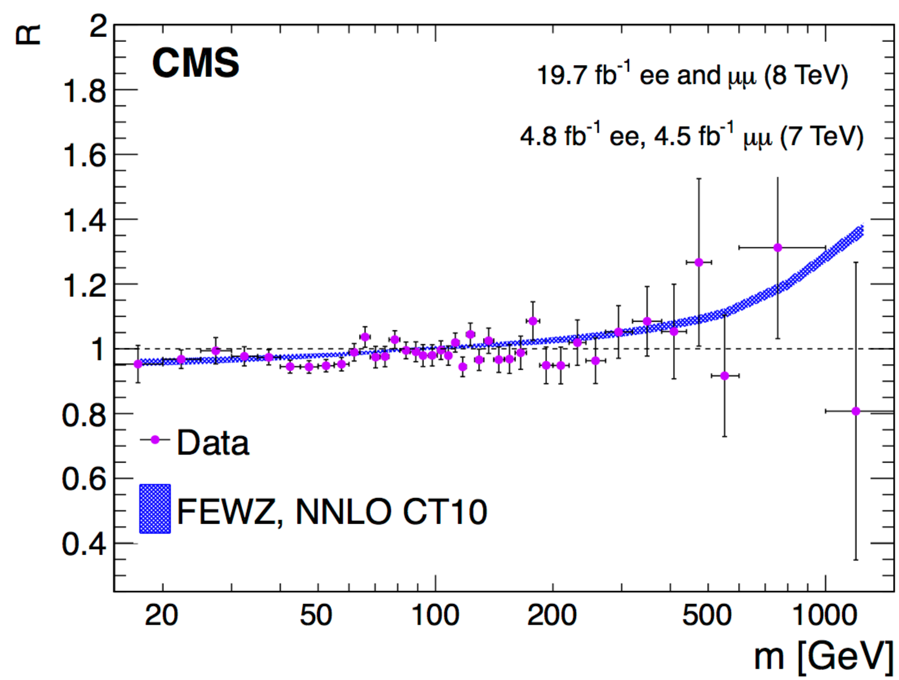
Drell-Yan Cross Section at LHC (8 TeV)

EPJC 75 (2015) 147

- Cross section vs. dilepton mass now measured at 8 TeV, from **15-2000 GeV in mass**.

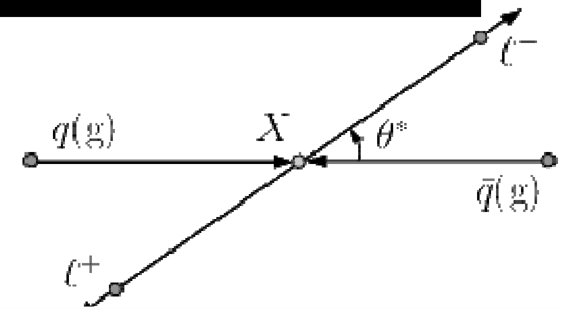
- **Differential double ratios** $(1/\sigma Z)(d\sigma/dm)_{8TeV}$ / $(1/\sigma Z)(d\sigma/dm)_{7TeV}$ measured for the first time





Weak mixing angle at hadron colliders

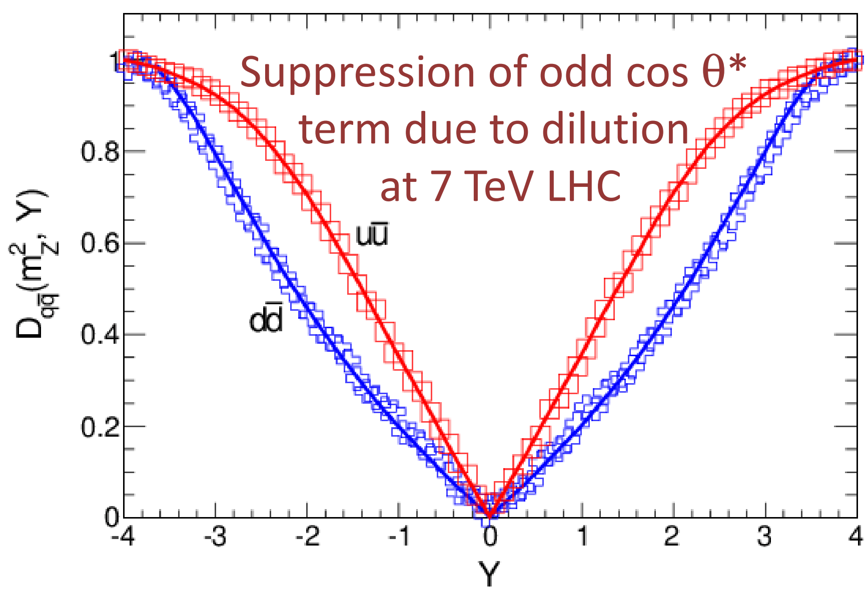
- In the dilepton CM, lepton angle with respect to axis of quark momentum is sensitive to interference effects: vector with axial-vector Z couplings, Z with photon, or Z with new physics



$$\hat{\sigma}_{q\bar{q}}(\hat{s}, \cos\theta^*; \theta_W) \propto \frac{3(\rho_V^{q\bar{q}\to\gamma})^2(\rho_V^{\gamma\to\ell\ell})^2}{2\hat{s}} \times (1+\cos^2\theta^*) + \frac{3}{2}\frac{\hat{s}}{(\hat{s}-m_Z^2)^2+m_Z^2\Gamma_Z^2} \times [((\rho_V^{q\bar{q}\to Z})^2+(\rho_A^{q\bar{q}\to Z})^2)((\rho_V^{Z\to\ell\ell})^2+(\rho_A^{Z\to\ell\ell})^2)(1+\cos^2\theta^*) + 8\rho_V^{q\bar{q}\to Z}\rho_A^{q\bar{q}\to Z}\rho_V^{Z\to\ell\ell}\rho_A^{Z\to\ell\ell}\cos\theta^*] + \frac{3(\hat{s}-m_Z^2)\rho_V^{q\bar{q}\to\gamma}\rho_V^{\gamma\to\ell\ell}}{(\hat{s}-m_Z^2)^2+m_Z^2\Gamma_Z^2} \times [\rho_V^{q\bar{q}\to Z}\rho_V^{Z\to\ell\ell}(1+\cos^2\theta^*) + 2\rho_A^{q\bar{q}\to Z}\rho_A^{Z\to\ell\ell}\cos\theta^*].$$

V-A int. ~ $\sin^2\theta_{eff}$ -1/4

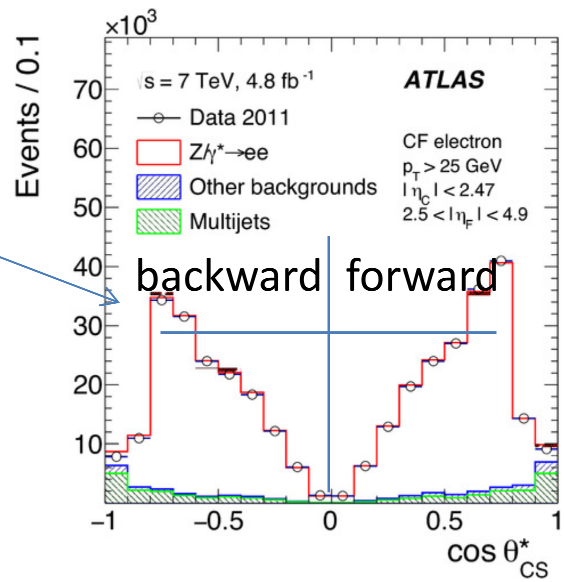
- This relation is (un)diluted in (pp) pp collisions, where reconstructed cos θ* axis is (strongly) weakly correlated with real quark axis.

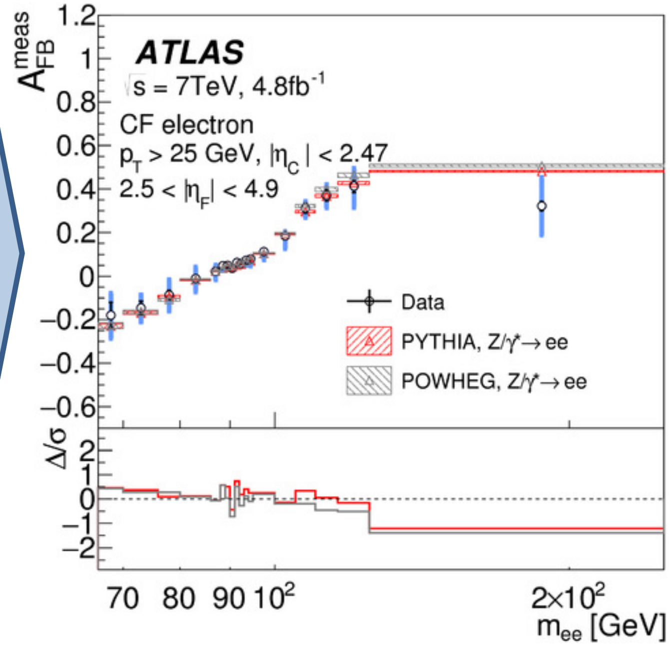


Weak mixing angle at hadron colliders

1503.03709

- Select central dilepton pairs, and also central-forward electrons with full 7 TeV dataset
- Raw AFB = Count forward/backward abundance in CS frame
- AFB in good agreement with PYTHIA * PHOZPR NNLO K-factor (MSTWNNLO2008)
- 1.8σ lower angle than LEP+SLD average



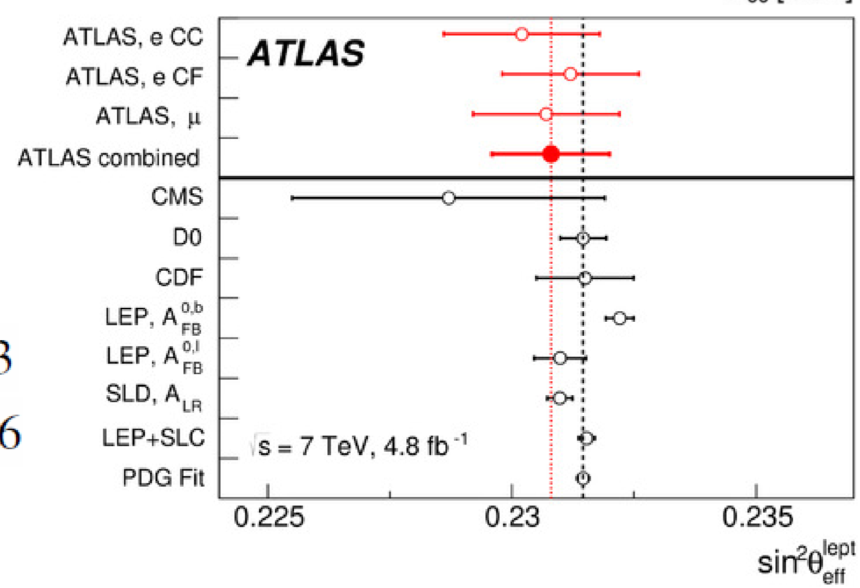


ATLAS 5/fb

$$\sin^2\theta_W^{\rm eff} = 0.2297 \pm 0.0004(\text{stat.}) \pm 0.0009(\text{syst.})$$

LEP + SLD

$$\sin^2\theta_W^{\rm eff} = 0.23153 \pm 0.00016$$

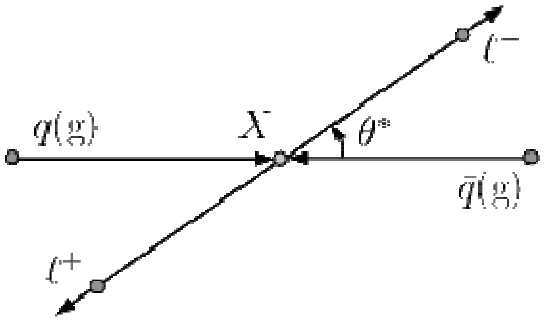


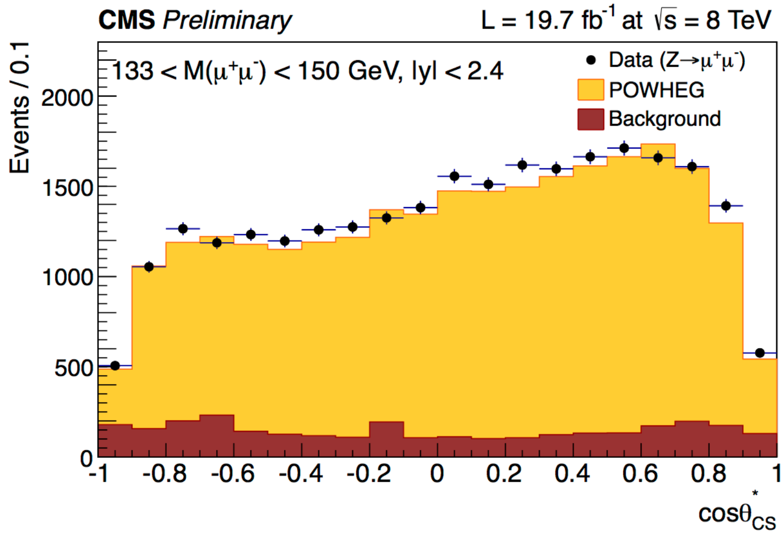
Drell-Yan AFB (8 TeV)

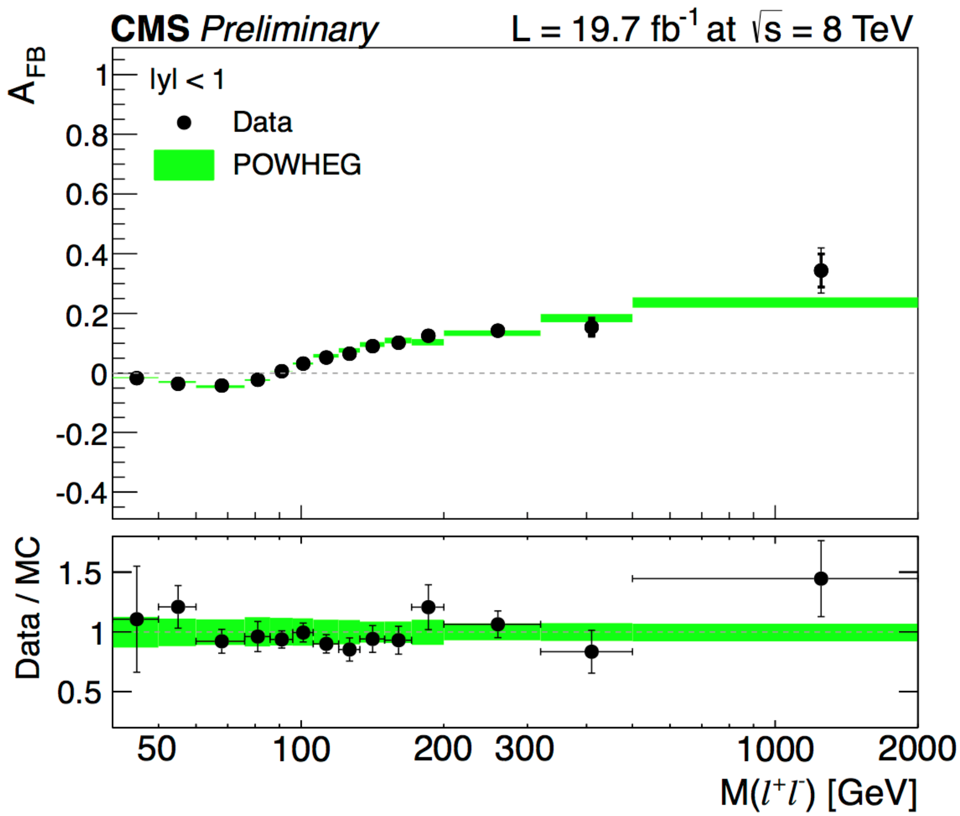
CMS-PAS-SMP-14-004

- Away from the Z-pole, Z/γ* interferences induces angular asymmetry in cos θ*

- AFB sampled as a function of the dilepton mass (in slices of dilepton rapidity)







Prospects for W mass at the LHC

- The LHC has excellent detectors and semi-infinite statistics and thus has a good a priori prospect for a <10-MeV measurement
- Biggest three obstacles to surmount:
- PDFs: sea quarks play a much stronger role than the Tevatron. Need at least 2X better PDFs.
- Momentum scale
- Recoil model/MET

ΔM_W [MeV]	LHC		
$\sqrt{s}$ [TeV]	8	14	14
$\mathcal{L}[\mathrm{fb}^{-1}]$	20	300	3000
PDF	10	5	3
QED rad.	4	3	2
$p_T(W)$ model	2	1	1
other systematics	10	5	3
W statistics	1	0.2	0
Total	15	8	5

arxiv:1310.6708

ATLAS-PHYS-PUB-2014-015

	MW-NLO	CT10nlo	MSTW2008CPdeutnlo	NNPDF30_nlo_as_118
W^+	+13 -12	+18 -22	+11 -10	+8 -10
W^-	+22 -22	+18 -23	+11 -10	+8 -9
$W^\pm$	+11 -11	+14 -18	+7 -7	+6 -5

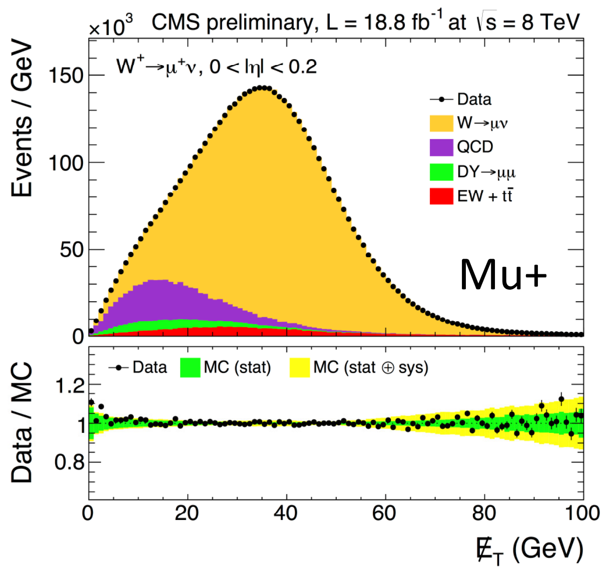
W charge asymmetry

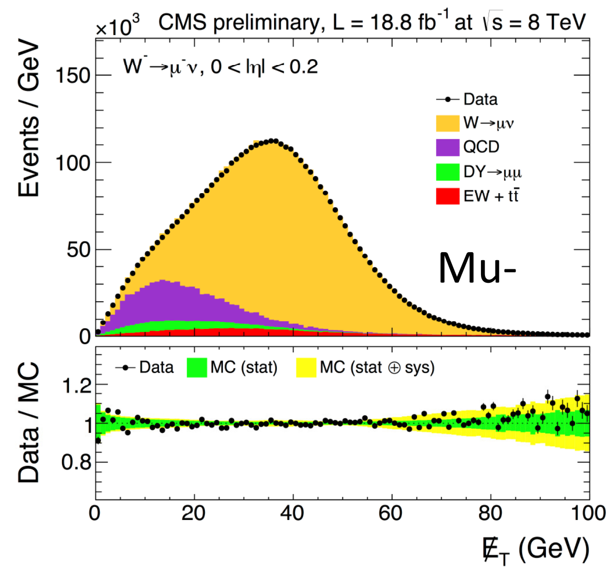
CMS-PAS-SMP-14-022

- At 8 TeV, ~5M W muon candidates produced per /fb
- Differential W charge asymmetry precisely probes u/d ratio vs. x

$$\mathcal{A}(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \to \ell^+\nu) - \frac{d\sigma}{d\eta}(W^- \to \ell^-\bar{\nu})}{\frac{d\sigma}{d\eta}(W^+ \to \ell^+\nu) + \frac{d\sigma}{d\eta}(W^- \to \ell^-\bar{\nu})}$$

- Recent CMS measurement can precisely extract a clean W asymmetry using ~20 million W candidates!



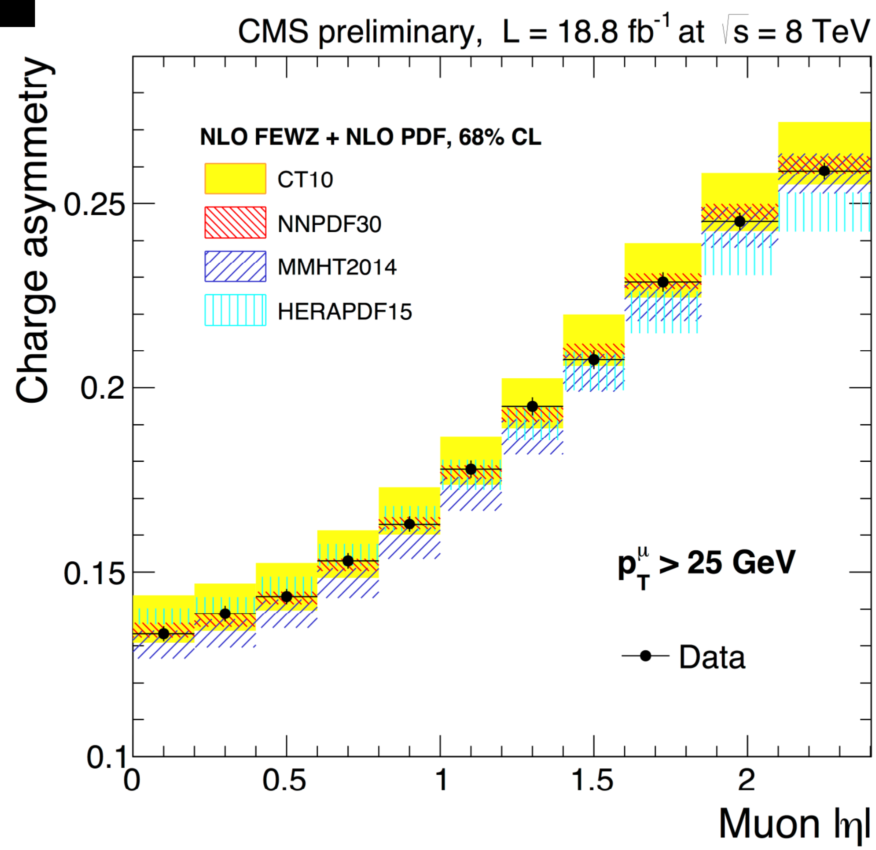


W charge asymmetry

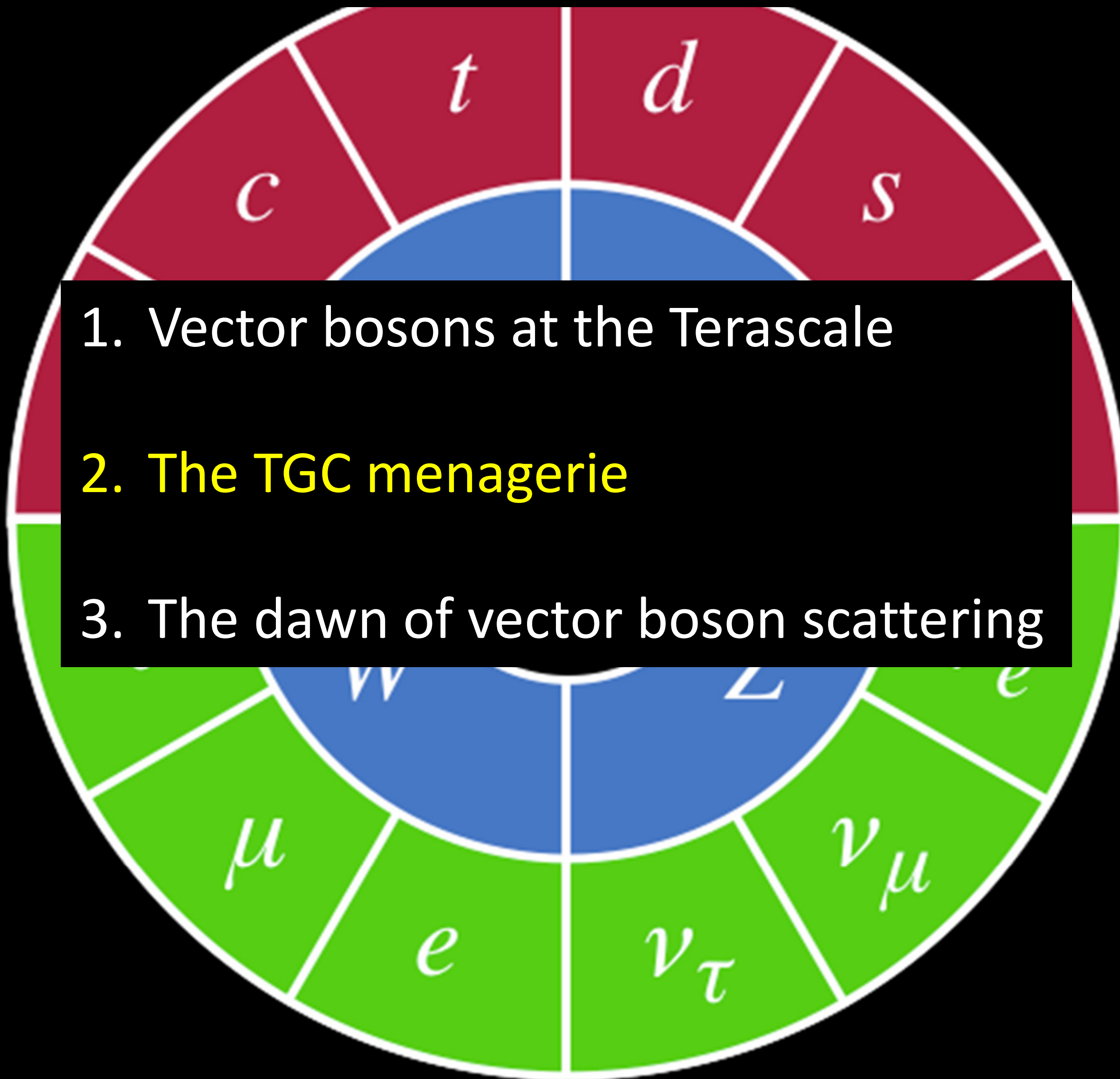
- At 8 TeV, ~5M W muon candidates produced per /fb
- Differential W charge asymmetry precisely probes u/d ratio vs. x

$$\mathcal{A}(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \to \ell^+\nu) - \frac{d\sigma}{d\eta}(W^- \to \ell^-\bar{\nu})}{\frac{d\sigma}{d\eta}(W^+ \to \ell^+\nu) + \frac{d\sigma}{d\eta}(W^- \to \ell^-\bar{\nu})}$$

- Asymmetry measured to 0.1% absolute per bin
- Has obvious constraining power for all PDF families



2. The electroweak vector bosons



1. Vector bosons at the Terascale
2. The TGC menagerie
3. The dawn of vector boson scattering

Effective Field Theory and Boson Interactions

- For generic new physics effects descended from some high energy scale Λ, explore operator product expansion with Wilson coefficients c_i

- Before EWSB, 5 gauge boson interaction terms respect gauge invariance (3 CP even + 2 CP odd)

UNBROKEN

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

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

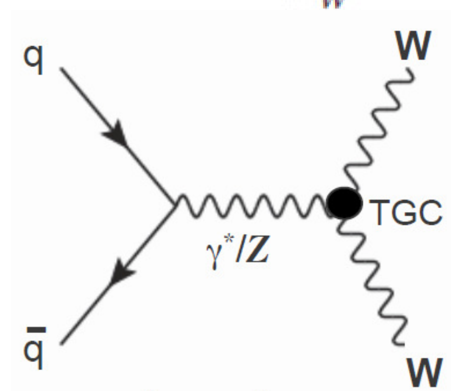
- After EWSB, induces trilinear VVV', VV'H, and quartic interactions with correlated coefficients.

- At dim 6, expect WWγ, WWZ interactions with 3 CP-even parameters (g1, k, λ)

- Manifested as high mass/momentum production tails

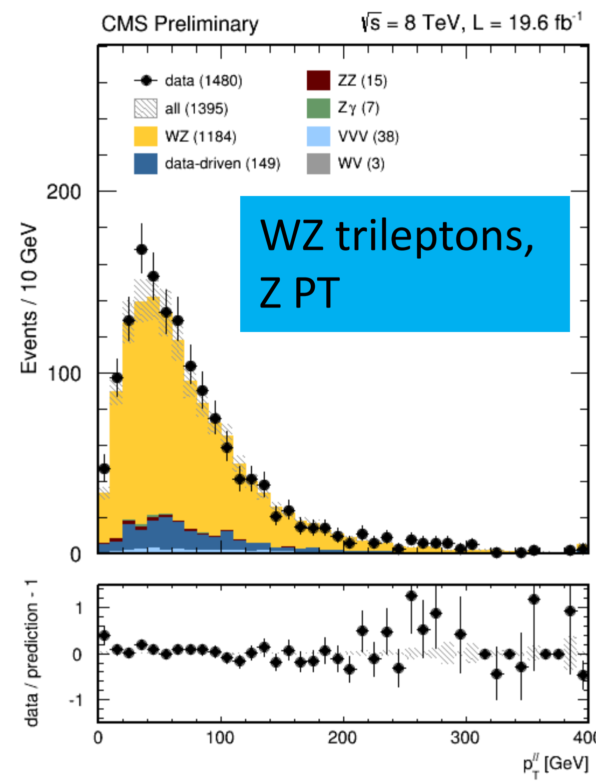
BROKEN

$$\mathcal{L} = i g_{WWV} \Big(g_1^V (W_{\mu\nu}^+ W^{-\mu} - W^{+\mu} W_{\mu\nu}^-) V^\nu + \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W_\mu^{\nu+} W_\nu^{-\rho} V_\rho^\mu + \tilde{\kappa}_V W_\mu^+ W_\nu^- \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2} W_\mu^{\nu+} W_\nu^{-\rho} \tilde{V}_\rho^\mu \Big)$$

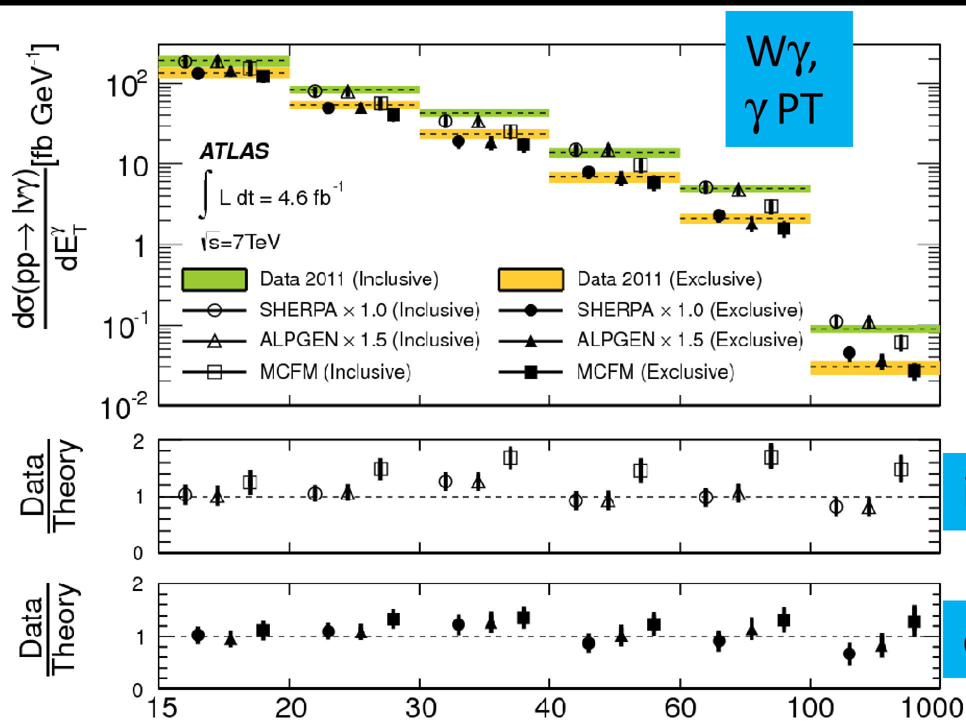


Wγ and WZ Production (7 TeV)

- LHC has thousands of high purity trilepton WZ candidates, tens of thousands of Wγ
- Photon and lepton fakes are the predominant background
- No evidence of new physics in high PT tails



[CMS-PAS-SMP-12-006](#)



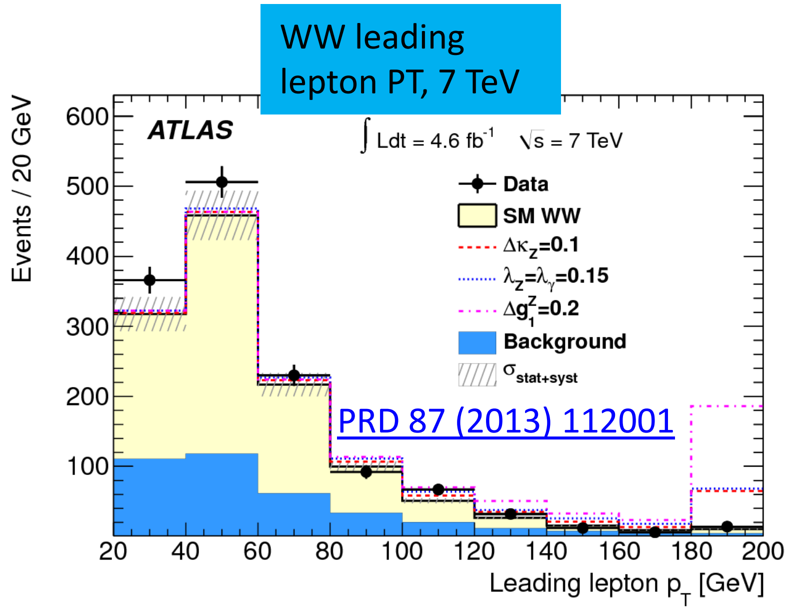
inclusive ← NNLO improves this

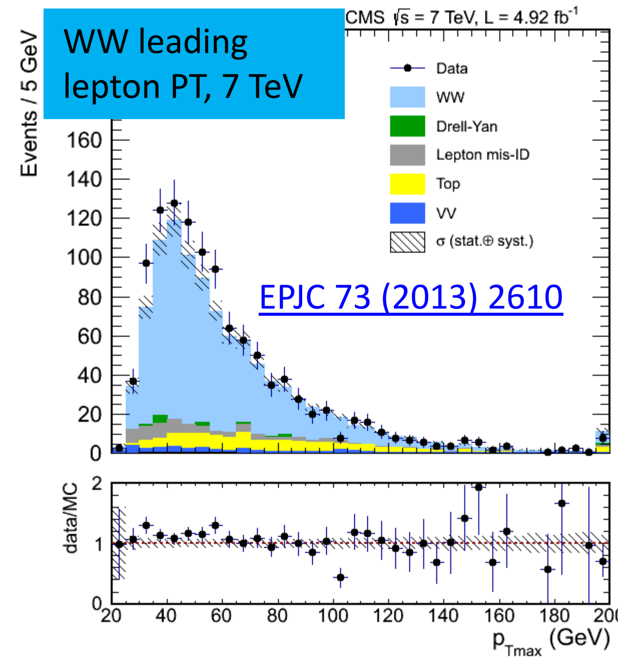
exclusive 0-jet

[PRD 87, 112003 (2013)](#)

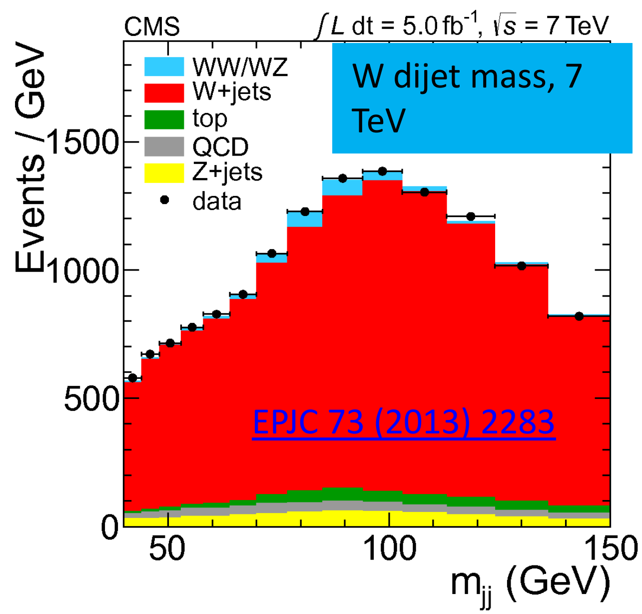
WW Production (7 TeV)

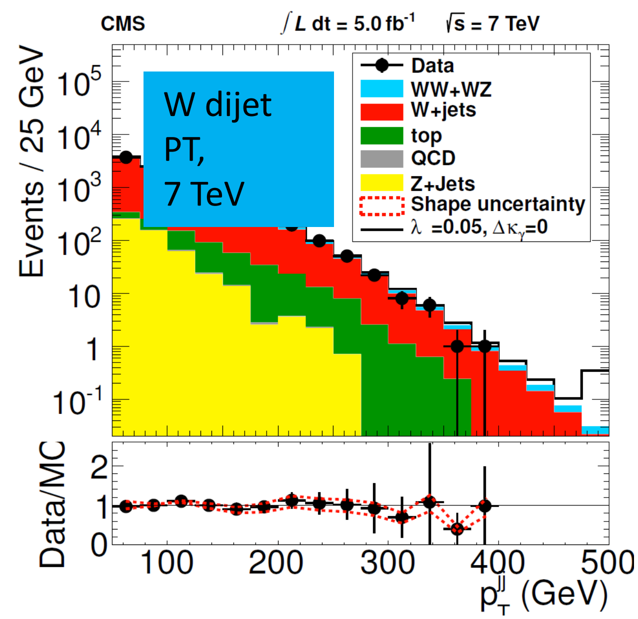
- Thousands of candidates in dilepton channel
- Leading lepton PT shows no anomalous contribution





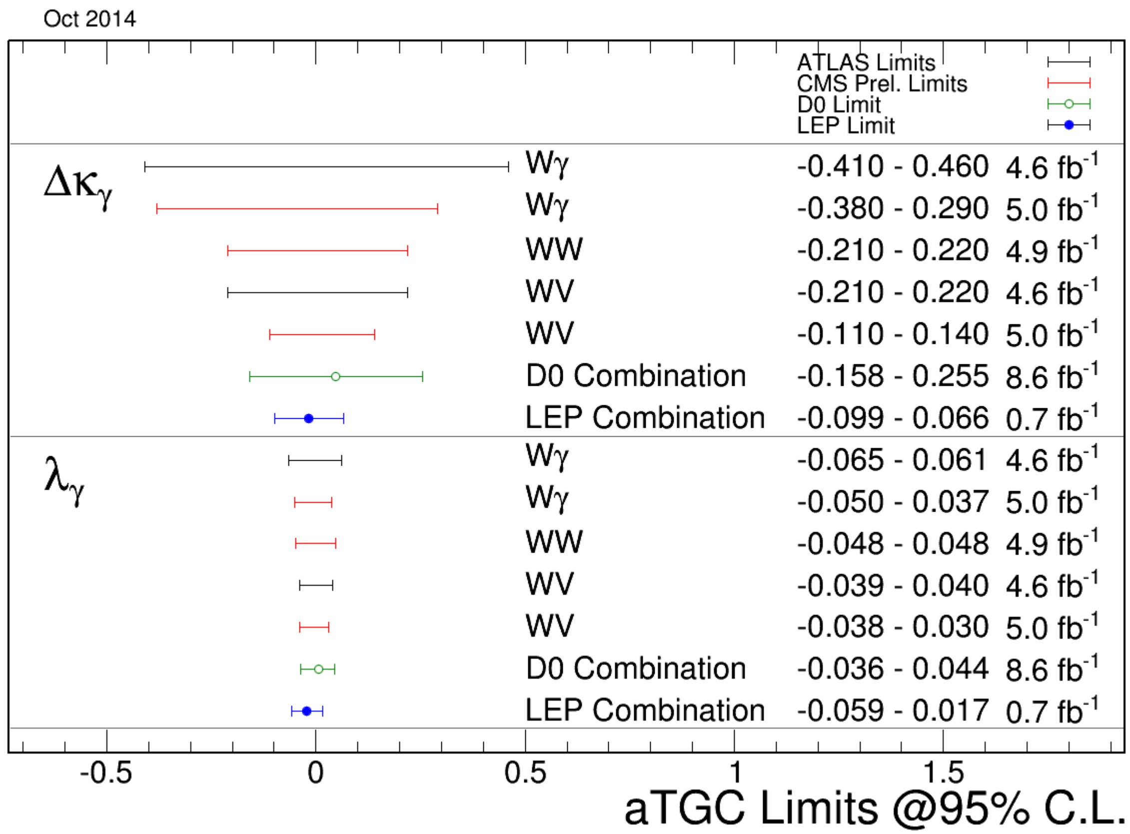
- Significant diboson signal in semileptonic channel
- Higher BR and low background at high PT gives superior TGC constraint





Charged aTGCs at 7 TeV: World Summary

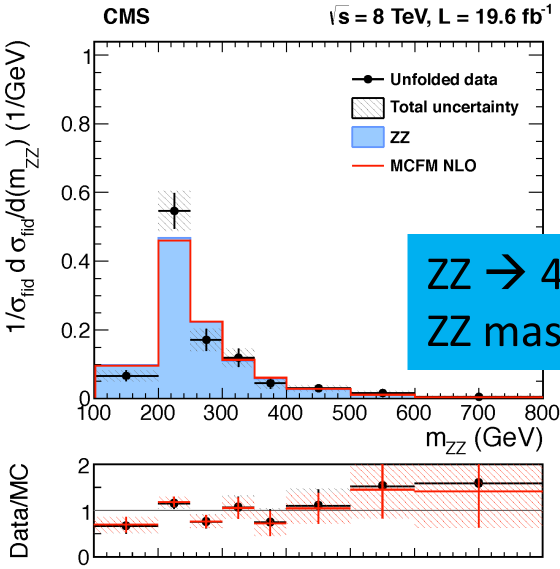
- Best single LHC 7 TeV measurements equal LEP2 or Tevatron combinations
- Semileptonic WW gives the best information on κ and λ, leptonic WW and WZ better for g.
- LHC 8 TeV will provide 2-3X better constraints, eclipsing LEP2
- Higgs-VV' couplings also compete here!
- Probing Λ ≈ 200-500 GeV for c ≈ 1



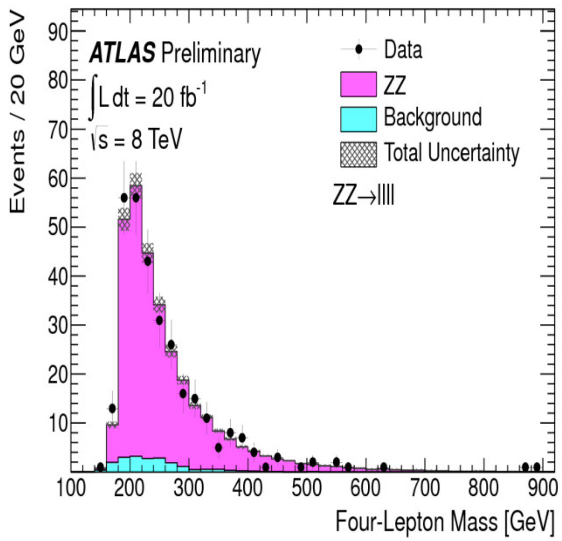
ZZ Production

ATLAS-CONF-2013-020
CMS-PAS-SMP-12-016
arxiv:1406.0113

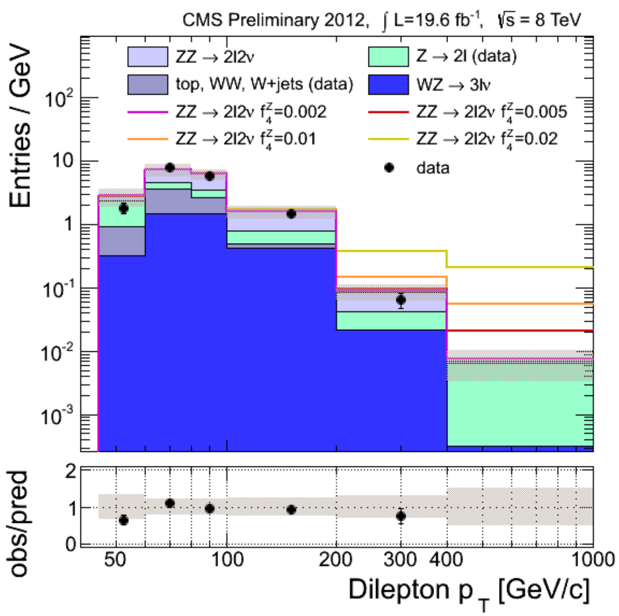
- ~300 ZZ to 4-lepton candidates observed at 8 TeV/experiment with SM rate and shapes
- ~200 ZZ to 2l2v candidates observed at 8 TeV, give best (dim 8) TGC constraint



ZZ → 4l
ZZ mass



ZZ → 2l2v
Z PT



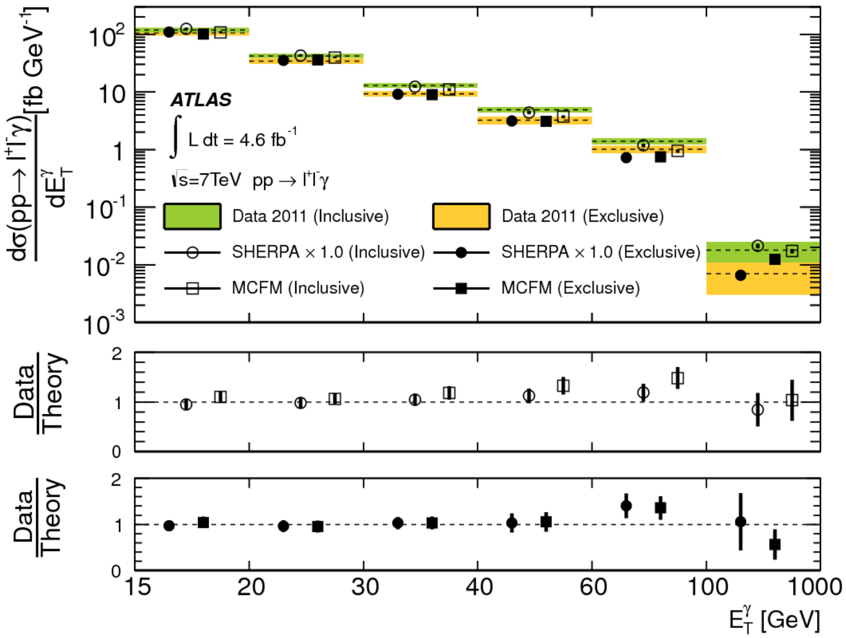
Zγ Production (7 TeV)

PRD 89 (2014) 092005

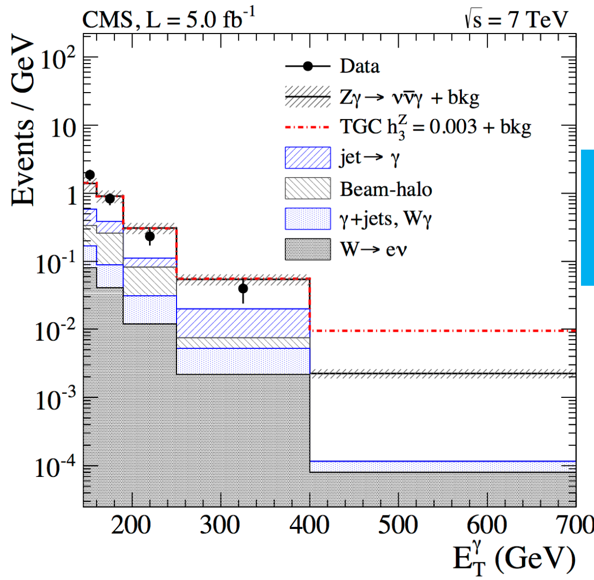
JHEP 10 (2013) 164

PRD 87 (2013) 112003

Zγ → llγ
γ PT



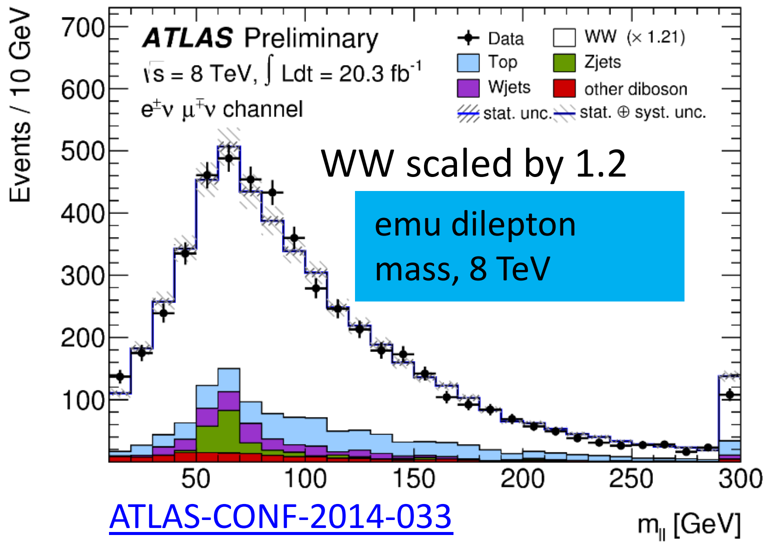
- Thousands of dilepton-photon events at 7 TeV agree with SM
- MET-photon channel: Higher BR and low background at high PT gives superior (dim 8) TGC constraint



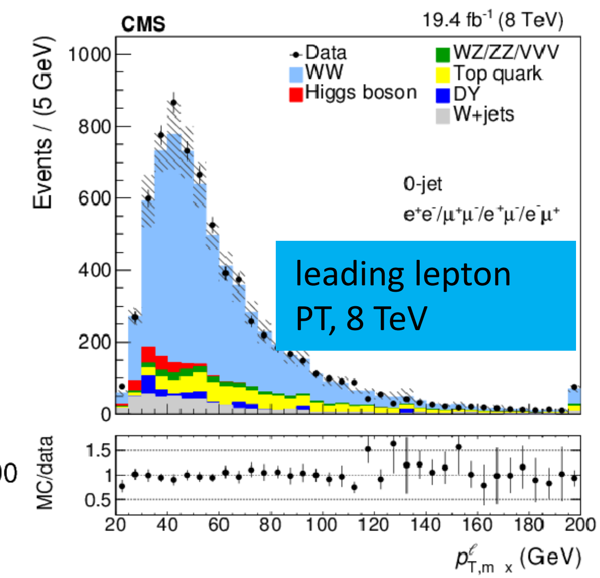
Zγ →MET+γ
γ PT

WW Production (8 TeV)

- **Kinematic shapes agree with prediction,**
- ~5000 emu ATLAS candidates with 20/fb!
- Systematics from jet veto acceptance, background methods
- Theory calculation being actively studied (jet vetoes, NNLO)
- ATLAS is 2σ high, CMS agrees with SM
- New TGC constraints from CMS world's best

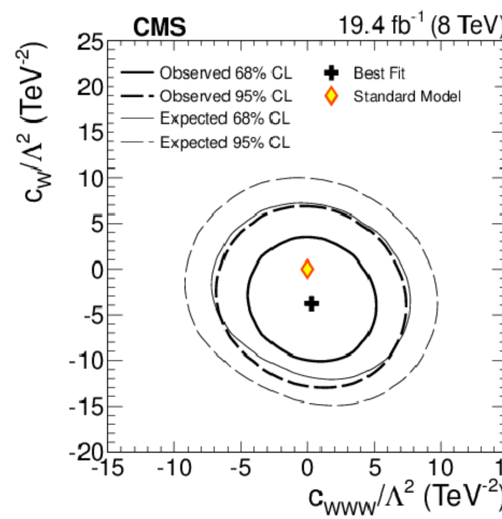


ATLAS-CONF-2014-033



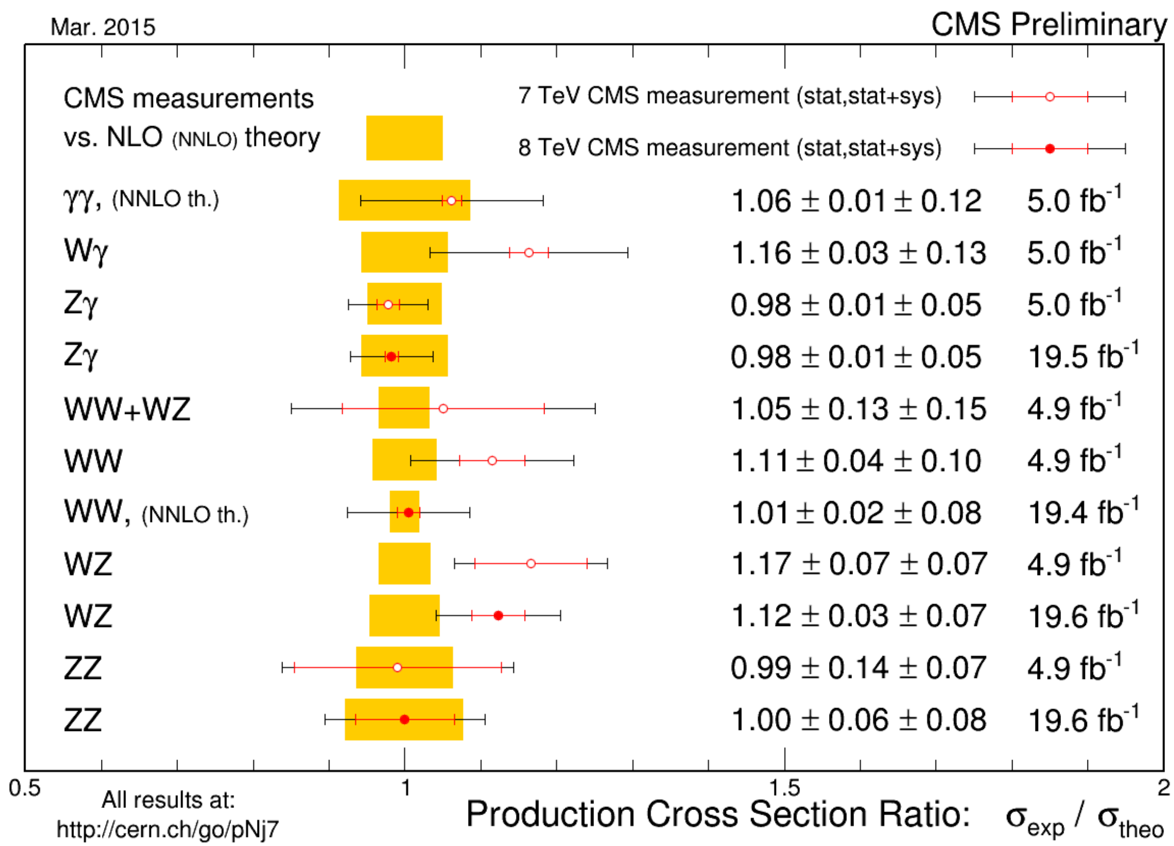
ATLAS 71.4±1.2 (stat.)±5.0 (syst.)±2.2 (lum.) pb (2σ) 1507.03268

CMS 60.1±0.9 (stat.)±4.5 (syst.)±1.6 (lum.) pb



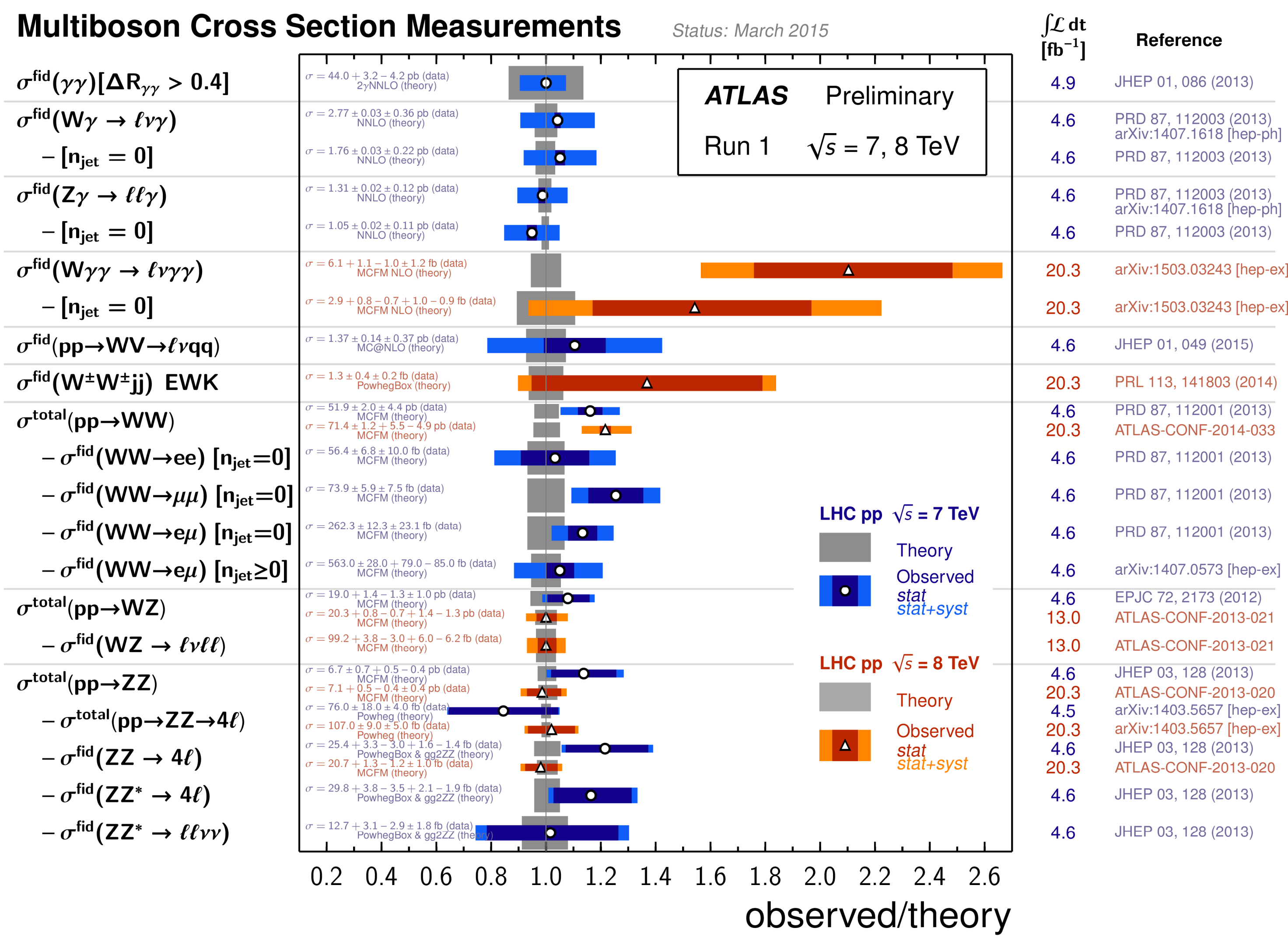
Diboson cross sections: World Summary

- CMS data
- No anomalies at the > 2σ level

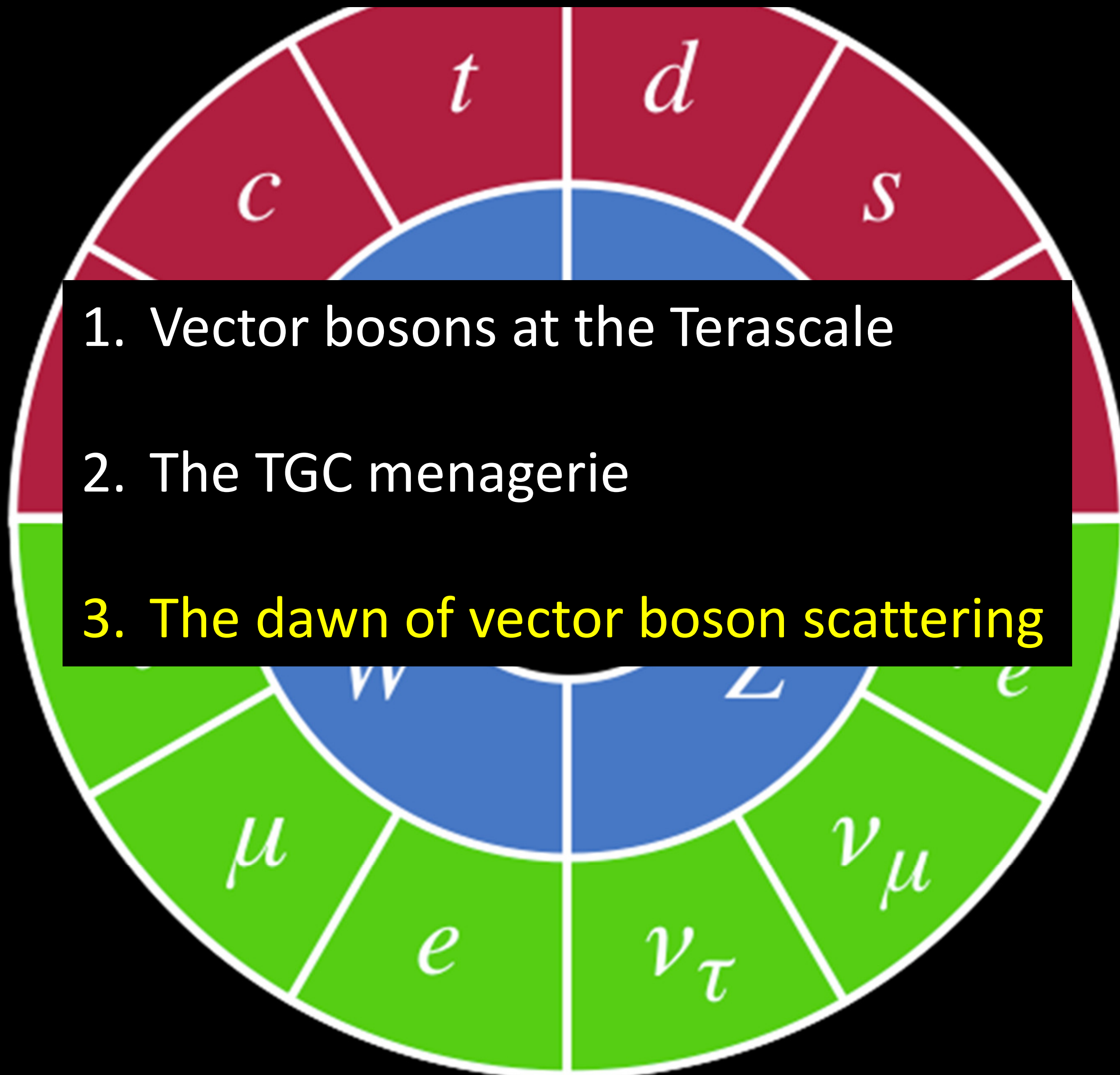


Diboson cross sections: World Summary

- ATLAS data
- WW at 8 TeV is 2.1σ high
- Wγγ is high



2. The electroweak vector bosons



1. Vector bosons at the Terascale
2. The TGC menagerie
3. The dawn of vector boson scattering

Electroweak Z + 2 jet production

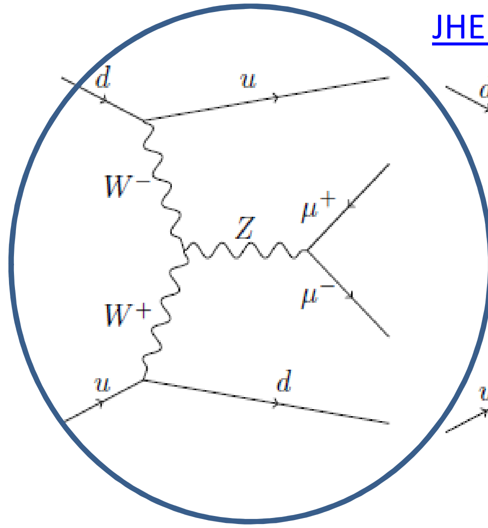
- VBF Z one of 3 (interfering)
EWK Z + 2 jet amplitudes

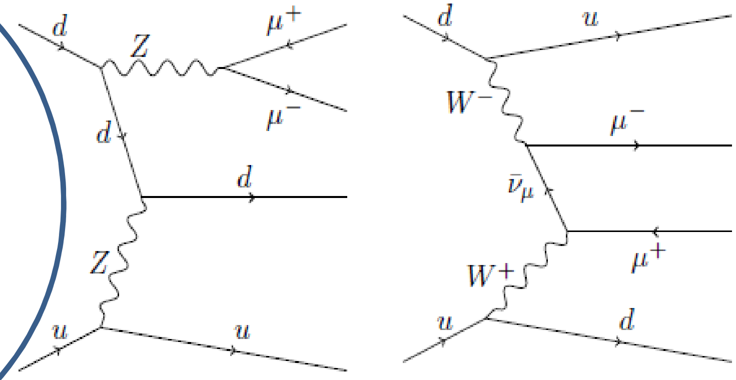
- Unique laboratory for studying rapidity gaps and VBF jet dynamics

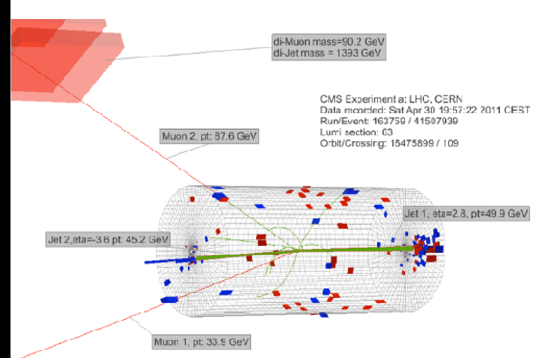
- Require dijet "VBF topology":
large dijet mass (250-1000 GeV)
large dijet Δy (or rapidity gap)
and other kinematic
information to separate from
QCD Z+ 2 jet

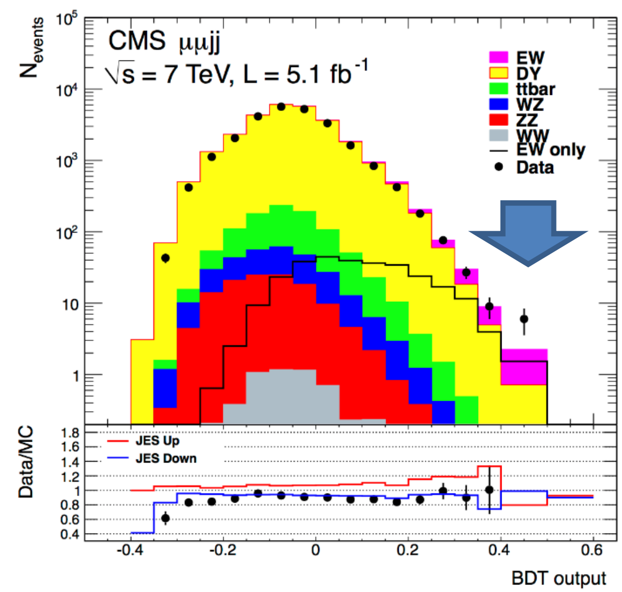
- CMS observed a 2.6σ signal in the 7 TeV data after a BDT selection

JHEP 04 (2014) 031   JHEP 10 (2013) 062





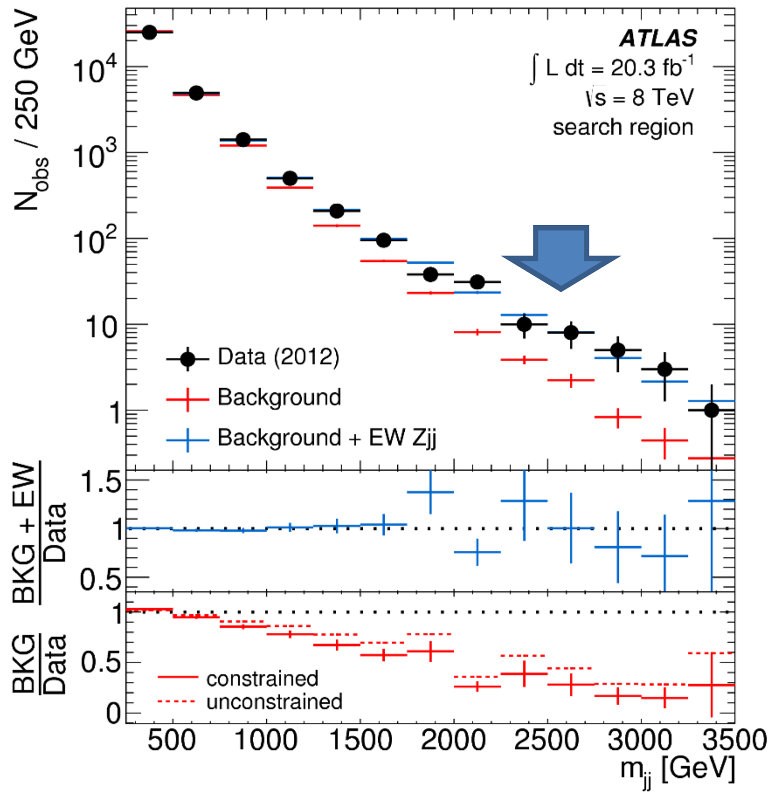


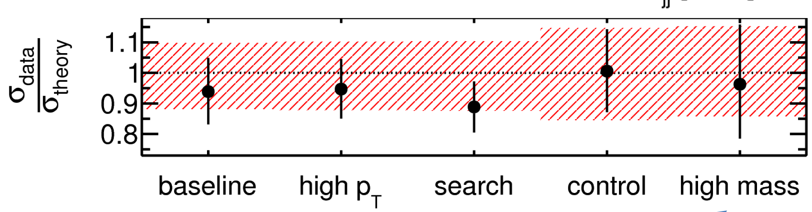


Electroweak Z + 2 jet production

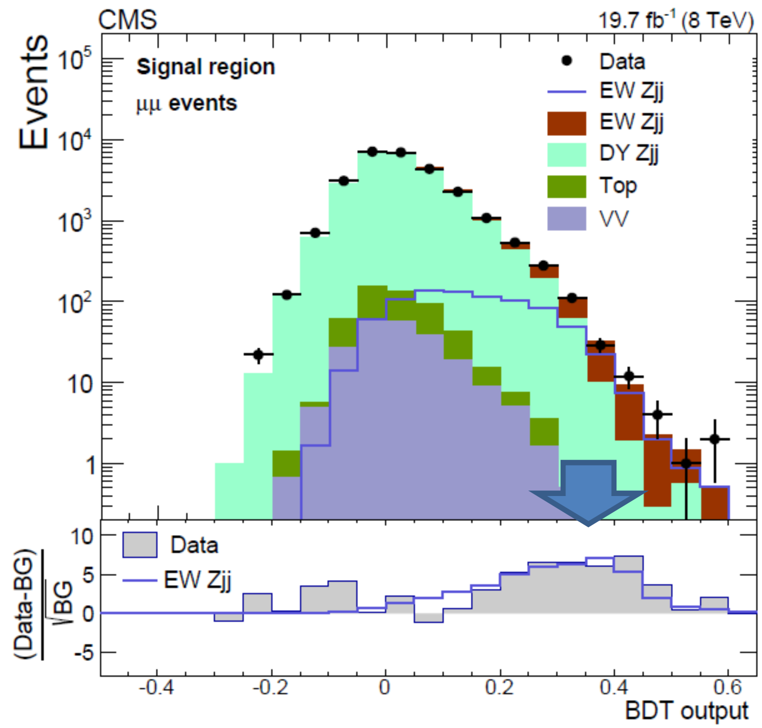
- **>5 σ evidence** has been reported by both experiments at 8 TeV, first published by ATLAS. Cross sections are consistent with SM predictions.

σ_{EWK} = 226 ± 44 fb
σ_{VBFNLO} = 239 fb





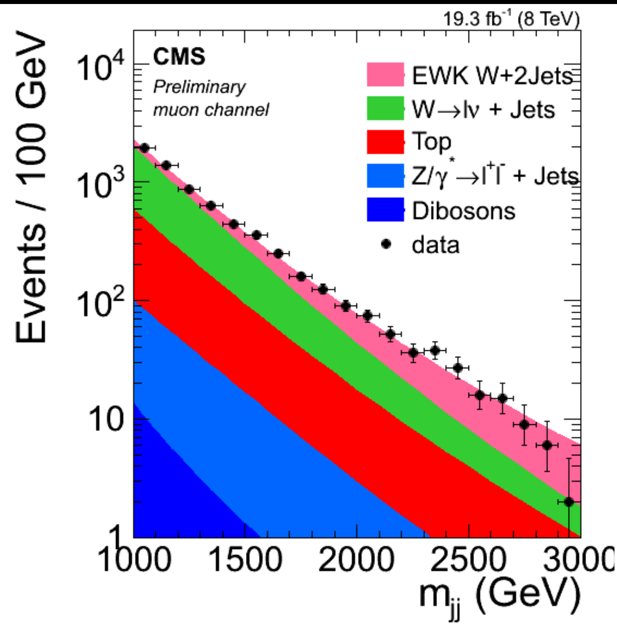
σ_{EWK} = 10.7 ± 2.1 fb
σ_{POWHEG} = 9.4 fb

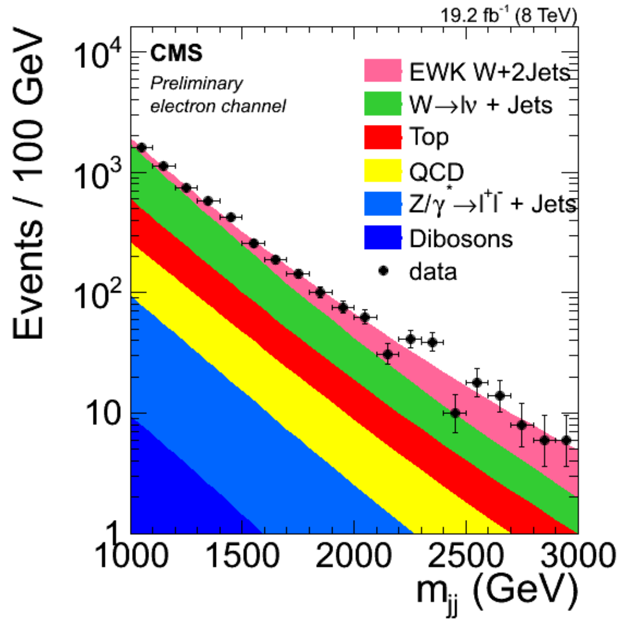


- After reweighting QCD Z+2 jets in sidebands, jet dynamics well-modeled in and around search regions

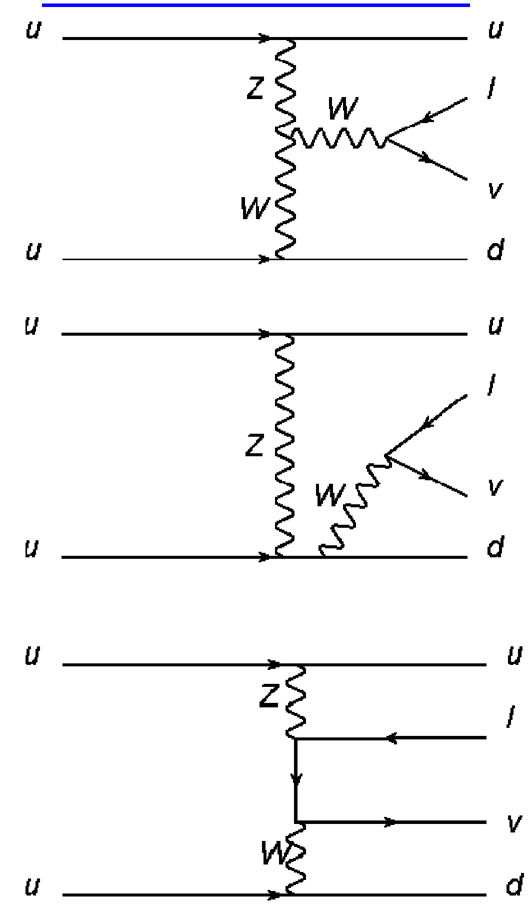
Electroweak W + 2 jet production

- **Recent observation of electroweak W+2 jet production as well. Consistent with SM.**





CMS-PAS-SMP-13-012



Madgraph SM = 0.5 pb

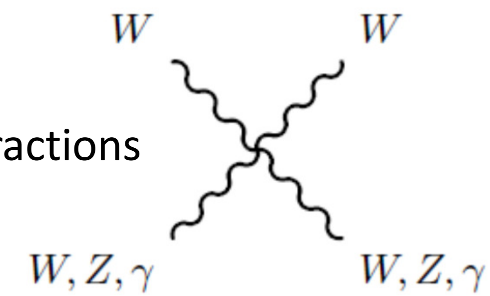
Event category	Measured cross section
μjj	0.43 ± 0.04 (stat.) ± 0.10 (syst.) ± 0.01 (lumi.) pb
ejj	0.41 ± 0.04 (stat.) ± 0.09 (syst.) ± 0.01 (lumi.) pb
combined μjj and ejj	0.42 ± 0.04 (stat.) ± 0.09 (syst.) ± 0.01 (lumi.) pb

QCD/EWK interference modelling, W+jets background modelling dominate systematics

Effective Field Theory for Quartic Couplings

- **SM has 4 quartic interactions (QGCs)**: WWWW, WWZZ, WWγγ, and WWZγ
- Dim 6 OPE has QGC correlated with TGC→dibosons dominate their constraints
- **19 new quartic terms become relevant at Dim 8**. Neutral 4 boson vertices can be non-zero (ZZZZ, ZZZγ, ZZγγ, Zγγγ).
- Manifested as **triboson or vector-boson scattering** phenomena

SM Quartic interactions



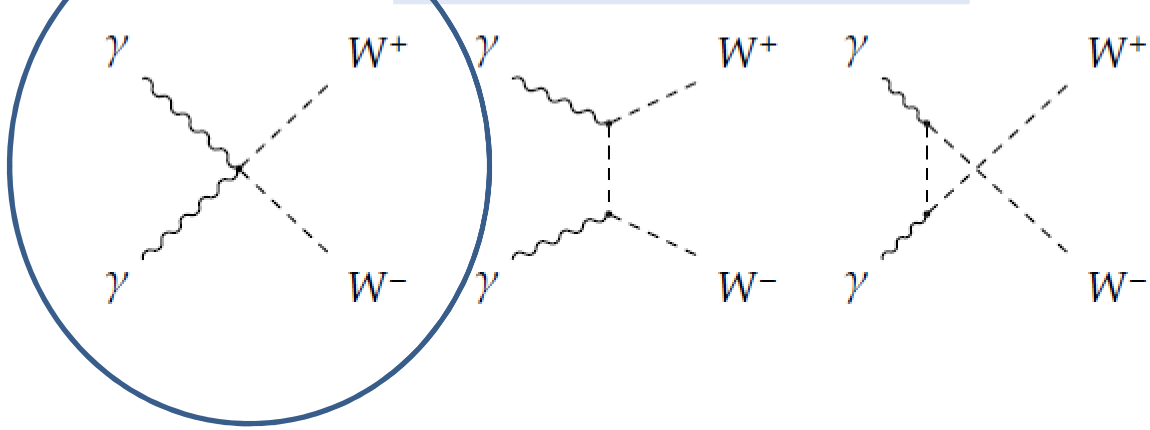
	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA
$\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$	X	X	X	O	O	O	O	O
$\mathcal{L}_{M,0}$, $\mathcal{L}_{M,1}$, $\mathcal{L}_{M,6}$, $\mathcal{L}_{M,7}$	X	X	X	X	X	X	X	O
$\mathcal{L}_{M,2}$, $\mathcal{L}_{M,3}$, $\mathcal{L}_{M,4}$, $\mathcal{L}_{M,5}$	O	X	X	X	X	X	X	O
$\mathcal{L}_{T,0}$, $\mathcal{L}_{T,1}$, $\mathcal{L}_{T,2}$	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,5}$, $\mathcal{L}_{T,6}$, $\mathcal{L}_{T,7}$	O	X	X	X	X	X	X	X
$\mathcal{L}_{T,9}$, $\mathcal{L}_{T,9}$	O	O	X	O	O	X	X	X

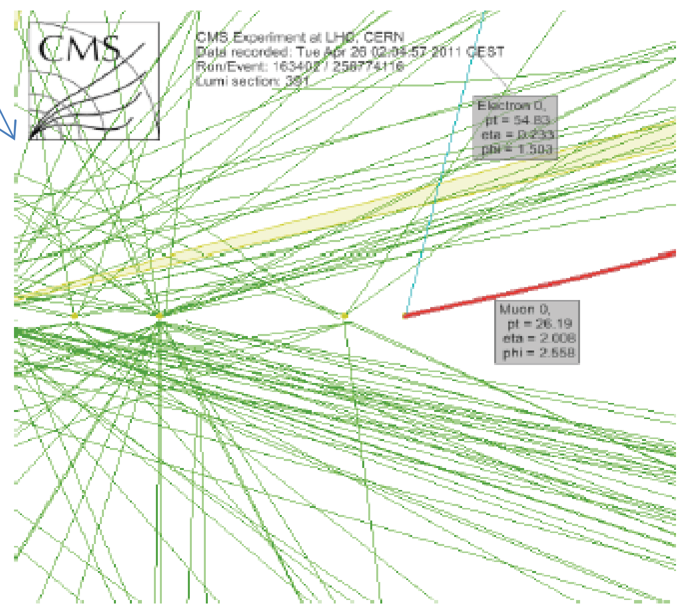
WW QGC via two-photon production

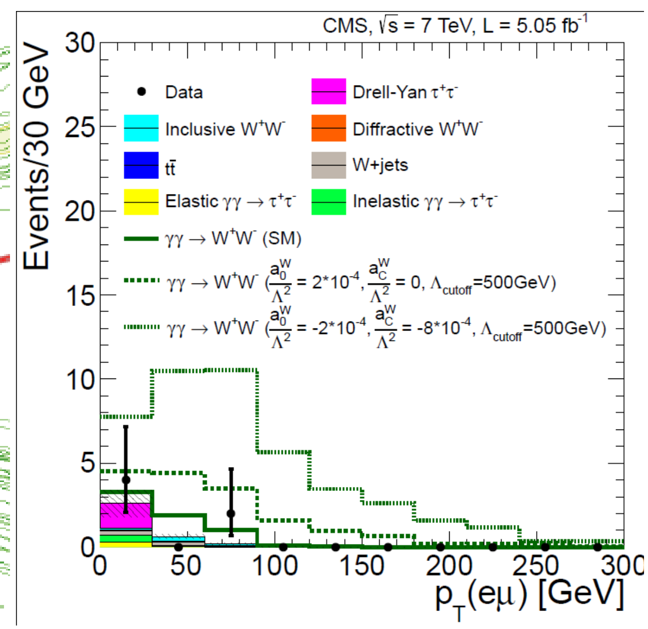
JHEP 1307 (2013) 116

- First search for photon-photon scattering production of WW
- WW$\gamma\gamma$ quartic gauge coupling one of the amplitudes
- Two eμ events observed with no UE present
- First quartic gauge coupling limits at LHC; WW$\gamma\gamma$ limit two orders better than LEP or Tevatron!

Two photon production of WW (s, t, and u channel)

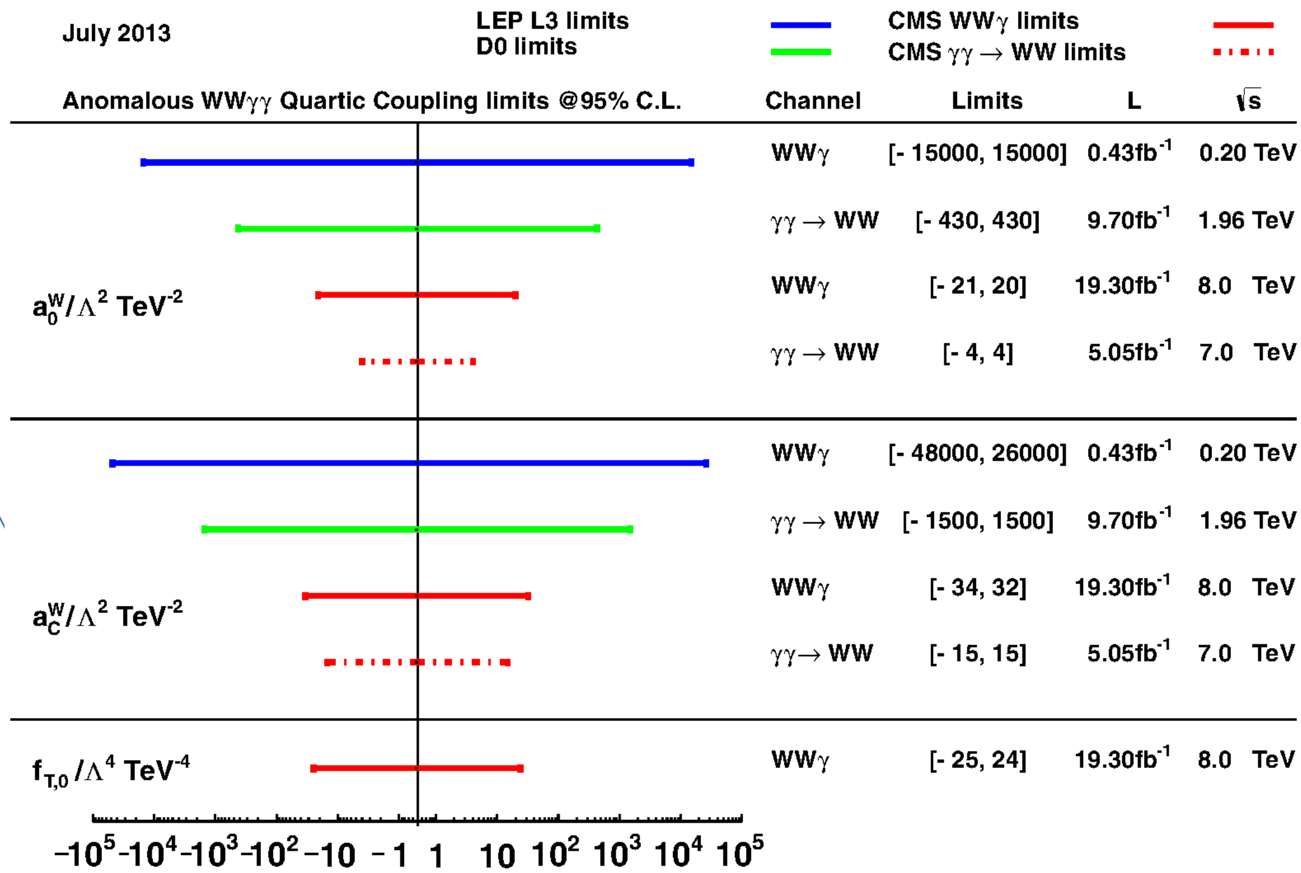






WW QGC via two-photon production

- First search for photon-photon scattering production of WW
- $WW\gamma\gamma$ quartic gauge coupling one of the amplitudes
- Two $e\mu$ events observed with no UE present
- First quartic gauge coupling limits at LHC; $WW\gamma\gamma$ limit two orders better than LEP or Tevatron!

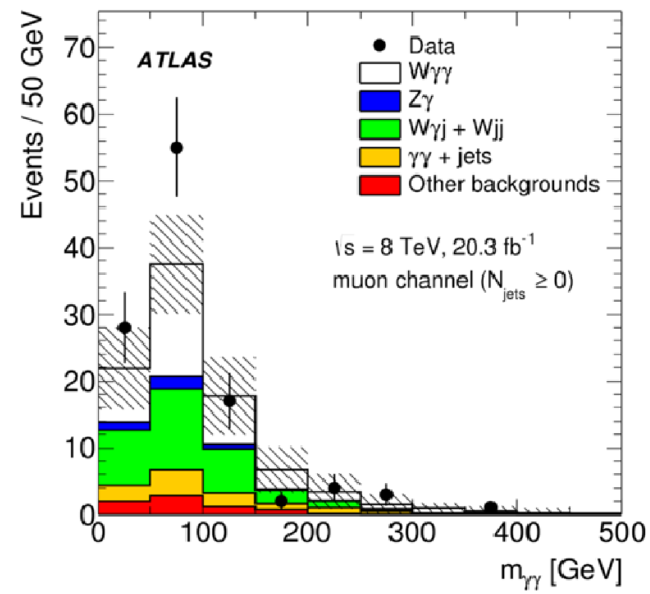


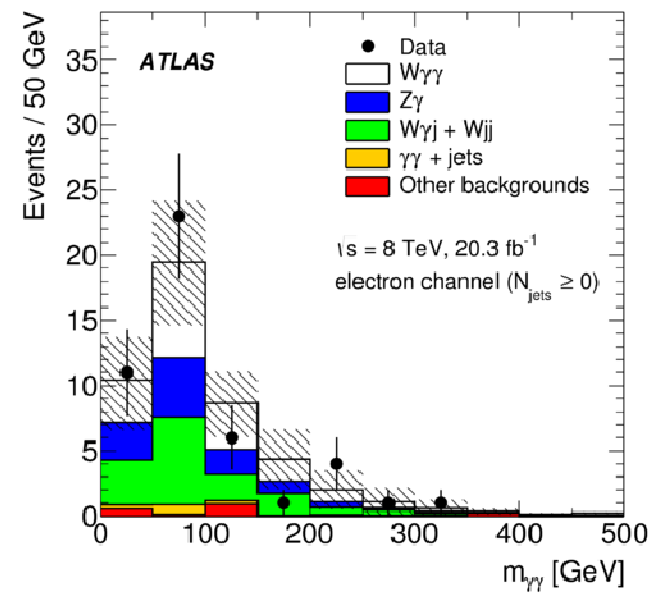
Wγγ evidence at LHC

[1503.03243](1503.03243)

- ~80 excess Wγγ events observed over background for photon PT > 20 GeV, significance is 3σ
- Fake photon background from W+jets is largest systematic
- aQGC limits obtained from Mγγ distribution

	Electron channel	Muon channel
	$N_{\text{jet}} \geq 0$	
$W\gamma$j + Wjj	$15.3 \pm 4.8(\text{stat.}) \pm 5.3(\text{syst.})$	$30.5 \pm 7.7(\text{stat.}) \pm 6.8(\text{syst.})$
$\gamma\gamma$ + jets	$1.5 \pm 0.6(\text{stat.}) \pm 1.0(\text{syst.})$	$11.0 \pm 4.0(\text{stat.}) \pm 4.9(\text{syst.})$
$Z\gamma$	$11.2 \pm 1.1(\text{stat.})$	$3.9 \pm 0.2(\text{stat.})$
Other backgrounds	$2.2 \pm 0.6(\text{stat.})$	$6.7 \pm 2.0(\text{stat.})$
Total background	$30.2 \pm 5.0(\text{stat.}) \pm 5.4(\text{syst.})$	$52.1 \pm 8.9(\text{stat.}) \pm 8.4(\text{syst.})$
Data	47	110

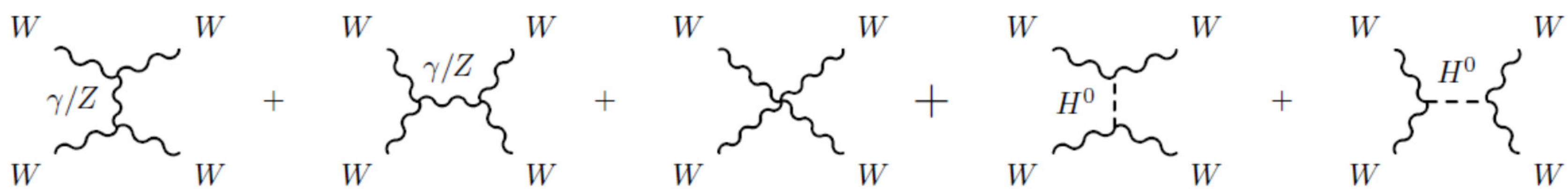




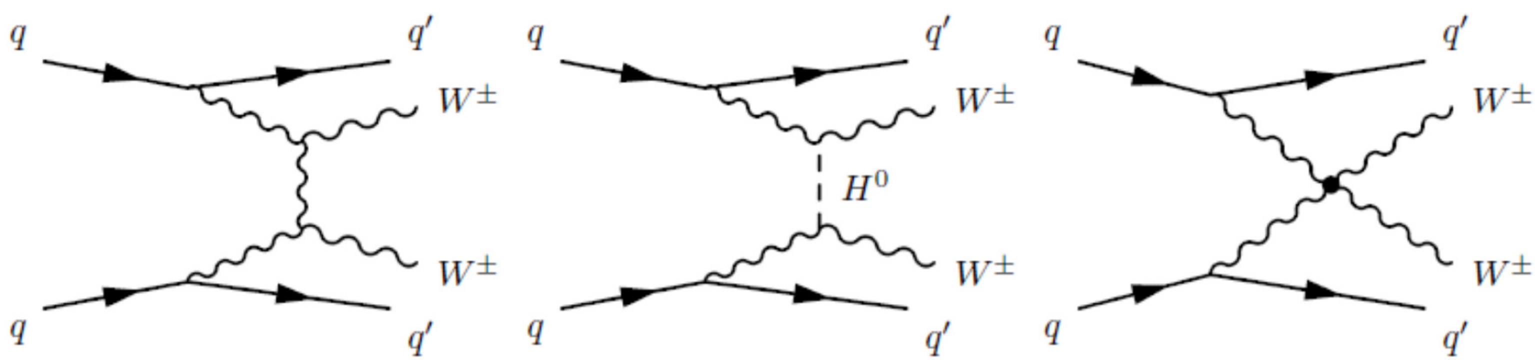
W±W± scattering at LHC

- SM electroweak symmetry breaking with Higgs essential to preserve **vector boson scattering cross section unitarity**

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



- **Same-sign WW vector boson scattering** production provides attractive S/B at LHC



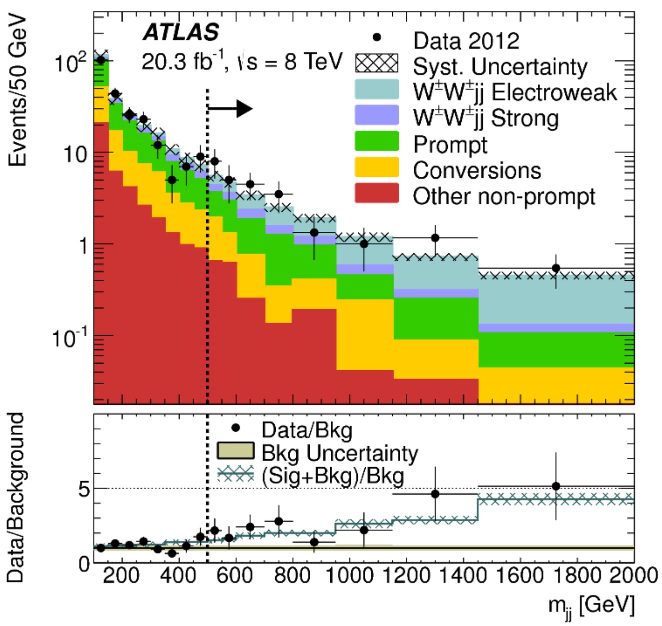
- Anomalous differential cross sections would indicate extended Higgs sector (e.g. **George-Machacek H++**), new particles, or (giant) **anomalous QGCs**

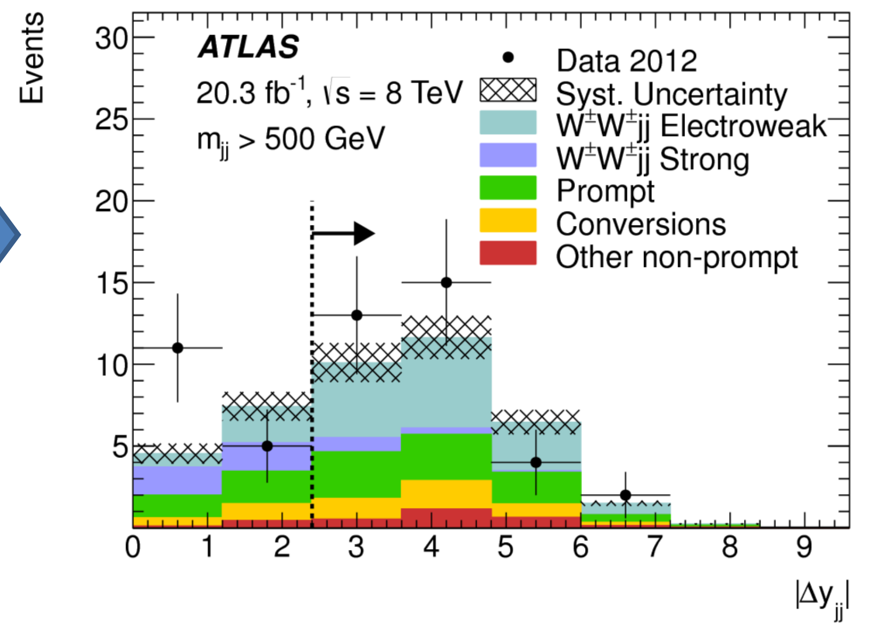
$W^{\pm}W^{\pm}$ scattering at LHC

PRL 113 (2014) 141803 PRL 114 (2015) 051801

- The 8 TeV data have been searched by both CMS and ATLAS for same-sign WW+2 jets

ATLAS: 500 GeV dijet mass and 2.4 rapidity gap define signal rich VBS region





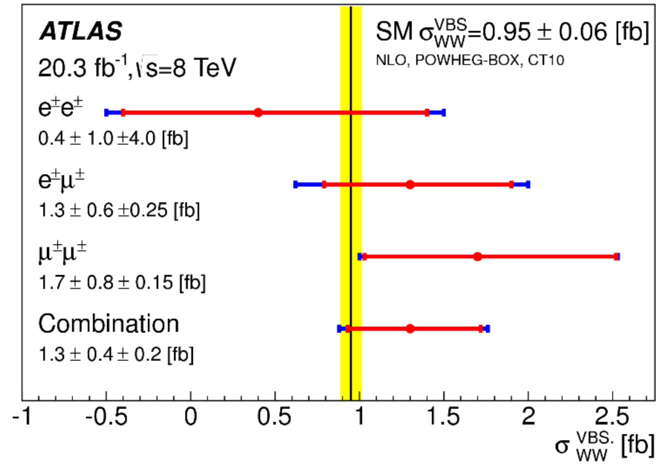
ATLAS: Good agreement with SM expectation in signal and control regions. Background mainly from real multilepton sources.

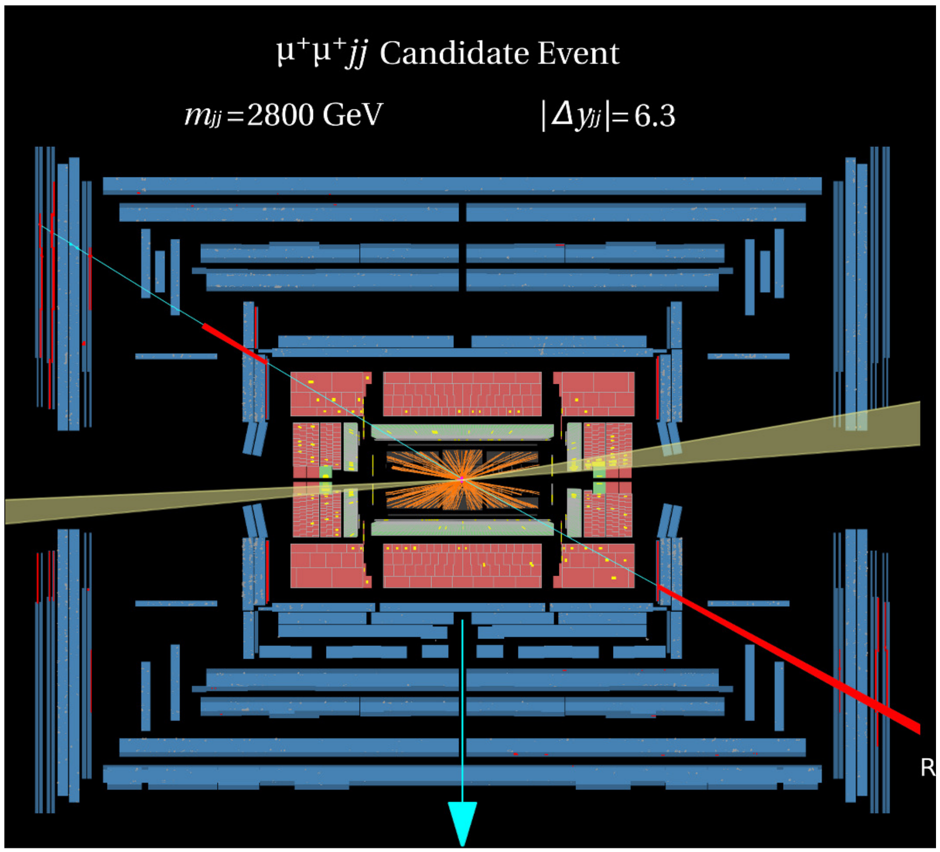
VBS Signal Region				
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	Total
$W^{\pm}W^{\pm}$jj Electroweak	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4	13.9 ± 1.2
$W^{\pm}W^{\pm}$jj Strong	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08	1.34 ± 0.26
$WZ/\gamma^*, ZZ, t\bar{t}+W/Z$	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5	8.2 ± 1.9
$W+\gamma$	0.7 ± 0.4	1.3 ± 0.7	–	2.0 ± 1.0
OS prompt leptons	1.39 ± 0.27	0.64 ± 0.24	–	2.0 ± 0.5
Other non-prompt	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19	2.3 ± 0.7
Total Predicted	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8	29.8 ± 3.5
Data	6	18	10	34

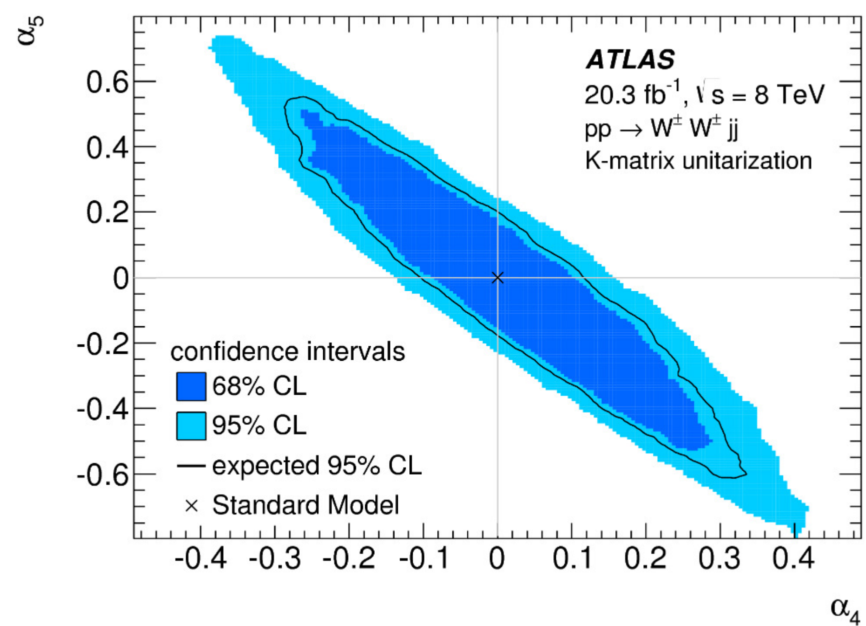
W±W± scattering at LHC

- Cross section in VBS region is SM-like with 3.6 σ significance (2.8 expected)
- **first evidence for vector boson scattering!**

- Limits obtained on aQGCs in a unitarized model, Λ ≈ 650 GeV for c ≈ 1



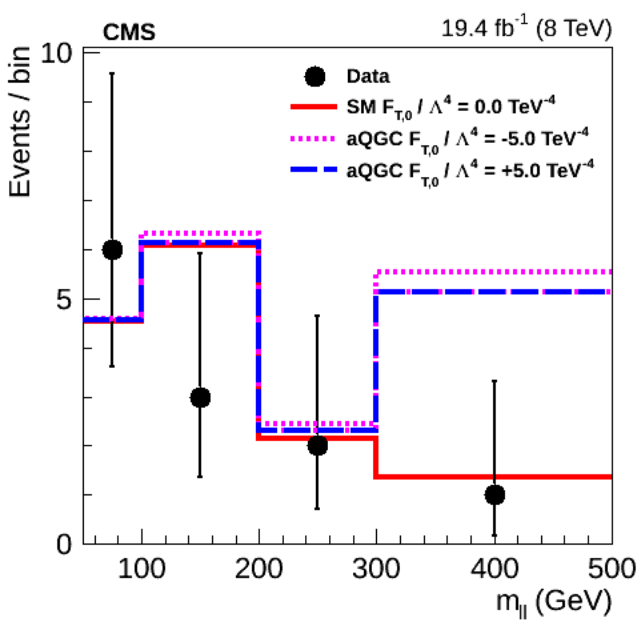


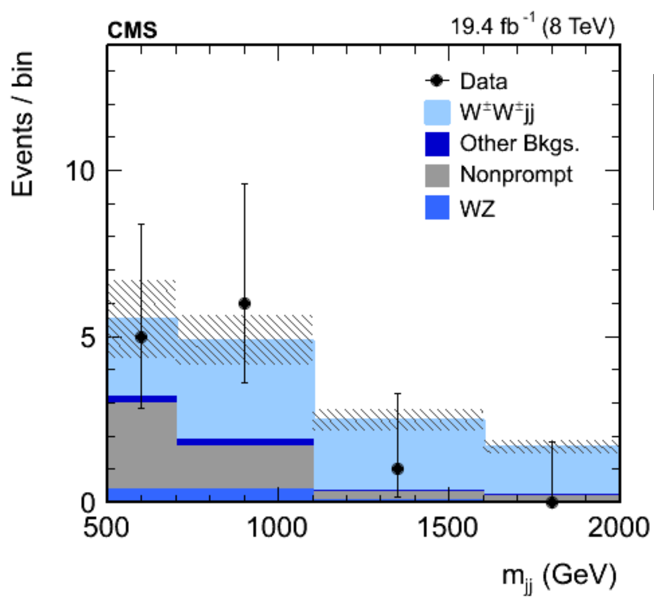


$W^{\pm}W^{\pm}$ scattering at LHC

- CMS: 500 GeV dijet mass and 2.5 dijet rapidity gap, with top veto, Z veto, and dilepton mass > 50 GeV
- Most remaining background is fake/non-prompt leptons
- Observed events agree with SM predictions

	Nonprompt	WZ	VVV	Wrong sign	WW DPS	Total bkg.	$W^{\pm}W^{\pm}jj$	Data
W^+W^+	2.1 ± 0.6	0.6 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	3.1 ± 0.6	7.1 ± 0.1	10
W^-W^-	2.1 ± 0.5	0.4 ± 0.1	0.1 ± 0.1	—	—	2.6 ± 0.5	1.8 ± 0.1	2
$W^{\pm}W^{\pm}$	4.2 ± 0.8	1.0 ± 0.1	0.3 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	5.7 ± 0.8	8.9 ± 0.1	12





2.0σ excess from VBS (3.1 expected)

4.0+2.4−2.0 (stat) +1.1−1.0 (syst) fb

VBFNLO: 5.8 ± 1.2 fb

Plus: limits on H++ production

Experimental SM milestones of LHC Run 1

1. Terascale production of jets, vector bosons, and tops
2. Uncovered novel production mechanisms: VBS WW, VBF Z and W, tW, ttV
3. Testing beyond NLO QCD: NLO+PS, NNLO, NLO EWK