WW, WZ, and ZZ Production

Masahiro Morii, Harvard University

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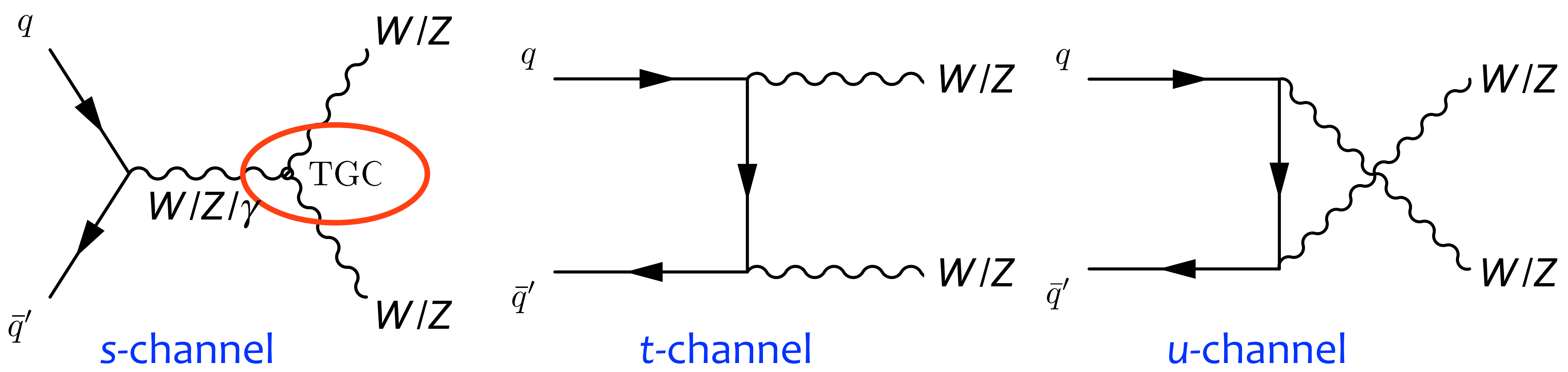
Diboson production

LO diagrams for *WW*, *WZ*, and *ZZ* production are



- Cross sections are calculated to NLO
- Gluon-gluon enters at NLO. Less than 10% of the cross section

Allows access to triple gauge couplings (TGCs)

- New physics may show up as anomalous (= non-SM) TGCs

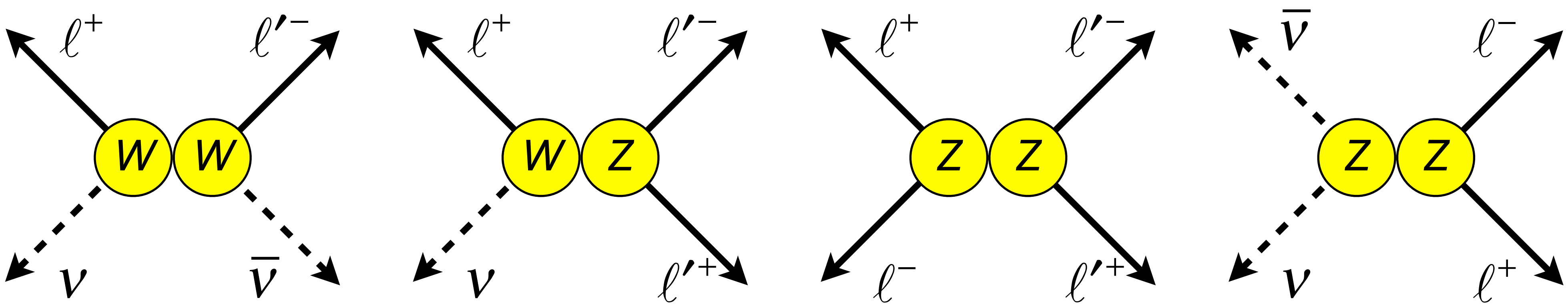
Important background to Higgs and beyond-SM searches

- Precise knowledge of cross sections and kinematical distributions are important

Measurements

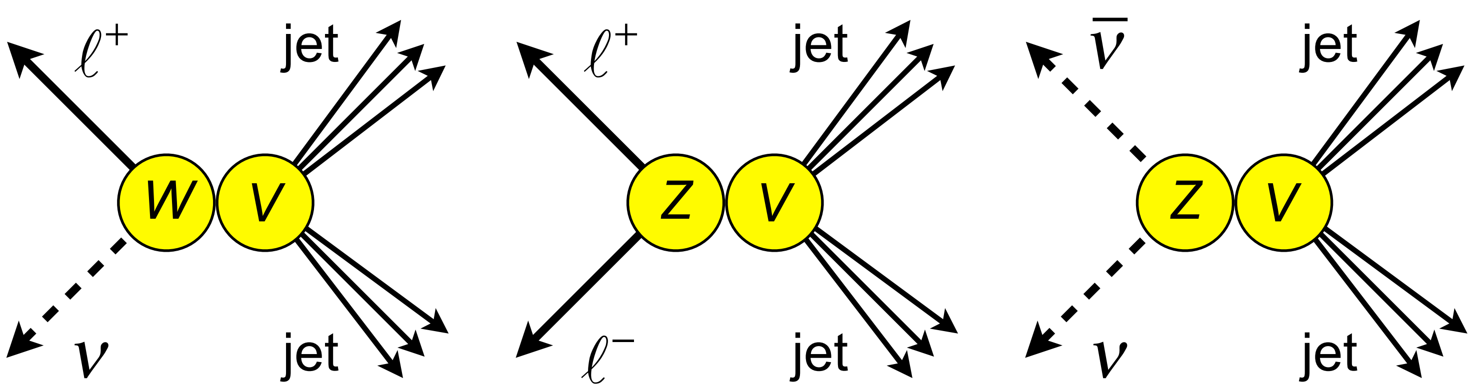
Leptonic final states ($\ell = e, \mu$ and $\nu = \nu_e, \nu_\mu, \nu_\tau$)

- High-p_T isolated leptons + missing E_T gives good S/B ratios
- Price: $\mathrm{Br}(W \to \ell\nu) = 22\%$, $\mathrm{Br}(Z \to \ell\ell) = 7\%$, $\mathrm{Br}(Z \to \nu\nu) = 20\%$



Semi-leptonic final states

- $\mathrm{Br}(W \to qq) = 68\%$, $\mathrm{Br}(Z \to qq) = 70\%$ ➔ More signal, but huge background



$V = W$ or Z

- b-jet identification can enhance $Z \to bb$ signal

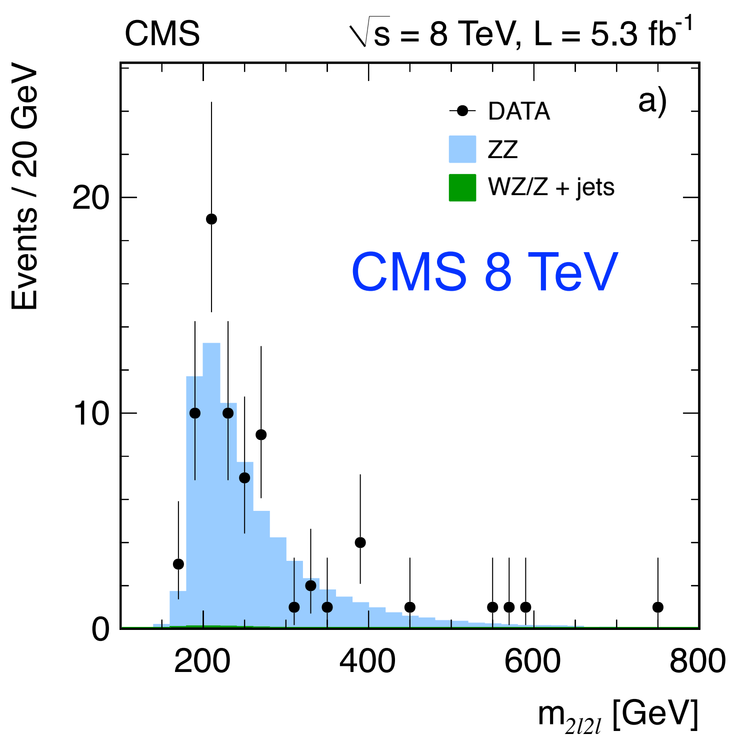
References

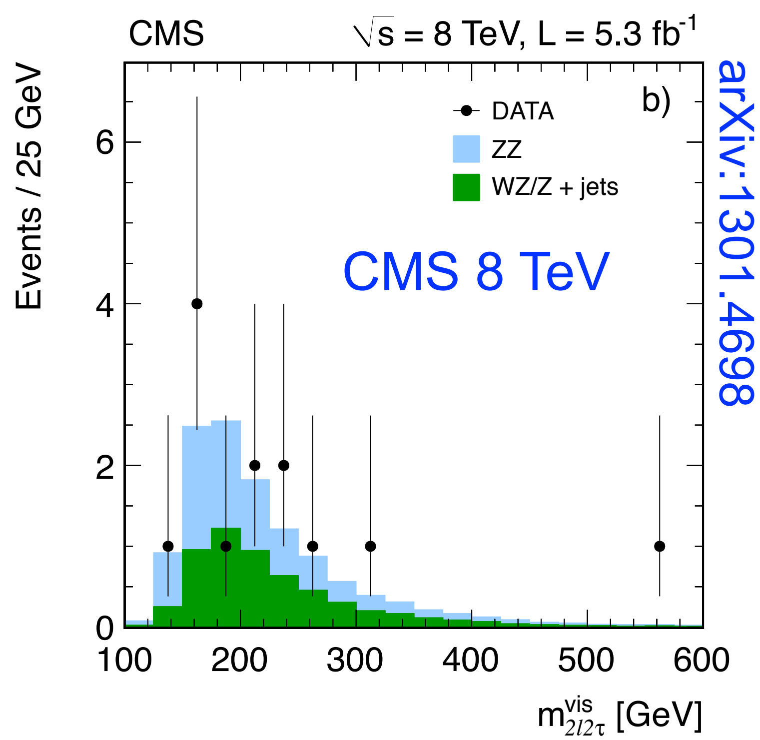
CDF	CDF note 10957	$ZZ \to \ell\ell\ell\ell, \ell\ell\nu\nu$ [9.7 fb^{-1}]
	CDF note 10973	$WW + WZ \to \ell\nu jj$ [8.9 fb^{-1}]
	CDF note 10968	$VV \to MET + jj$ [9.1 fb^{-1}]
	CDF note 10864	$ZW + ZZ \to \ell\ell jj$ [8.9 fb^{-1}]
	PRD 86 (2012) 031104	$WZ \to \ell\nu\ell\ell$ [7.1 fb^{-1}]
	PRL 104 (2010) 201801	$WW \to \ell\nu\ell\nu$ [3.6 fb^{-1}]
DØ	arXiv:1301.1243	$WW \to \ell\nu\ell\nu$ [9.7 fb^{-1}]
	PLB 718 (2012) 451	TGC limits based on the following three analyses
	PRL 108 (2012) 181803	$WW + WZ \to \ell\nu jj$ [4.3 fb^{-1}]
	PRD 85 (2012) 112005	$WZ \to \ell\nu\ell\ell$, $ZZ \to \ell\ell\nu\nu$ [8.6 fb^{-1}]
	PRD 84 (2011) 011103	$ZZ \to \ell\ell\ell\ell$ [6.4 fb^{-1}]
	arXiv:1204.4496	$WZ \to \ell\nu bb$ [7.5 fb^{-1}], $ZZ \to \nu\nu bb$ [8.4 fb^{-1}], and $ZZ \to \ell\ell bb$ [7.5 fb^{-1}]
ATLAS	ATLAS-CONF-2013-021	$WZ \to \ell\nu\ell\ell$ [13 fb^{-1}] **8 TeV**
	ATLAS-CONF-2013-020	$ZZ \to \ell\ell\ell\ell$ [20 fb^{-1}] **8 TeV**
	ATLAS-CONF-2012-157	$WW + WZ \to \ell\nu jj$ [4.7 fb^{-1}] 7 TeV
	arXiv:1211.6096	$ZZ \to \ell\ell\ell\ell, \ell\ell\nu\nu$ [4.6 fb^{-1}] 7 TeV
	arXiv:1210.2979	$WW \to \ell\nu\ell\nu$ [4.6 fb^{-1}] 7 TeV
	EPJC 72 (2012) 2173	$WZ \to \ell\nu\ell\ell$ [4.6 fb^{-1}] 7 TeV
CMS	CMS-PAS-FSQ-12-010	$\gamma\gamma \to WW \to e\nu\mu\nu$ [5.05 fb^{-1}] 7 TeV
	arXiv:1301.4698	$WW \to \ell\nu\ell\nu$ [3.5 fb^{-1}] and $ZZ \to \ell\ell\ell\ell$ [5.3 fb^{-1}] **8 TeV**
	JHEP 1301 (2013) 063	$ZZ \to \ell\ell\ell\ell$ [5.0 fb^{-1}] 7 TeV
	EPJC 73 (2013) 2283	$WW + WZ \to \ell\nu jj$ [5.0 fb^{-1}] 7 TeV
	CMS-PAS-SMP-12-005	$WW \to \ell\nu\ell\nu$ [4.9 fb^{-1}] 7 TeV
	CMS-PAS-EWK-11-010	$WZ \to \ell\nu\ell\ell$ [1.1 fb^{-1}] 7 TeV

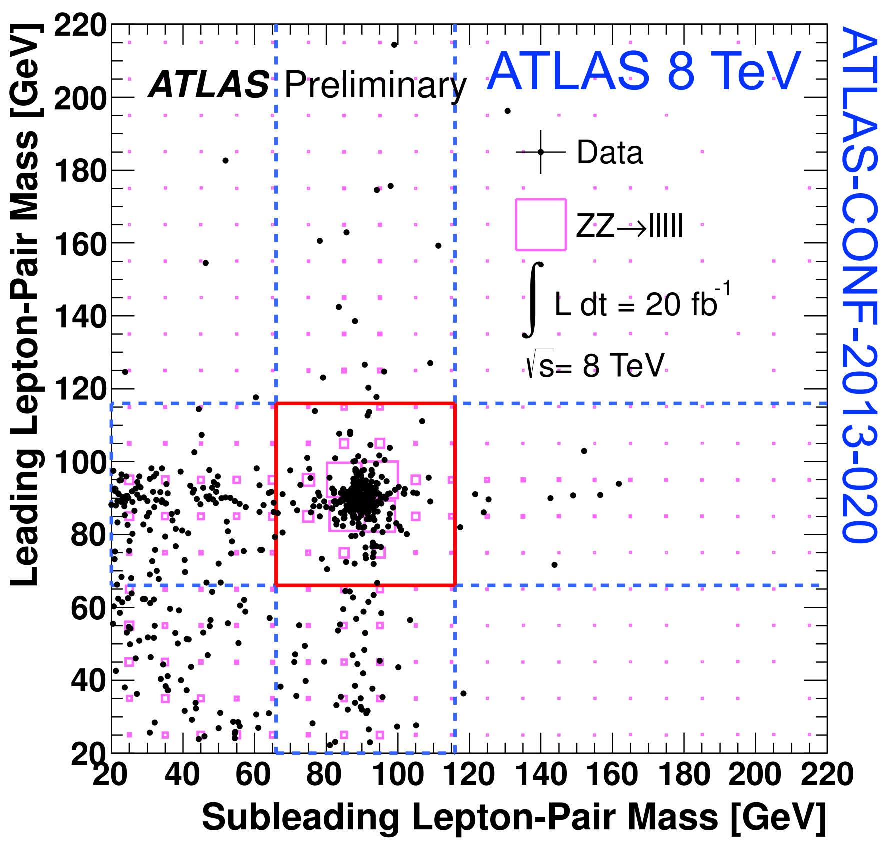
$ZZ \to \ell\ell\ell\ell$

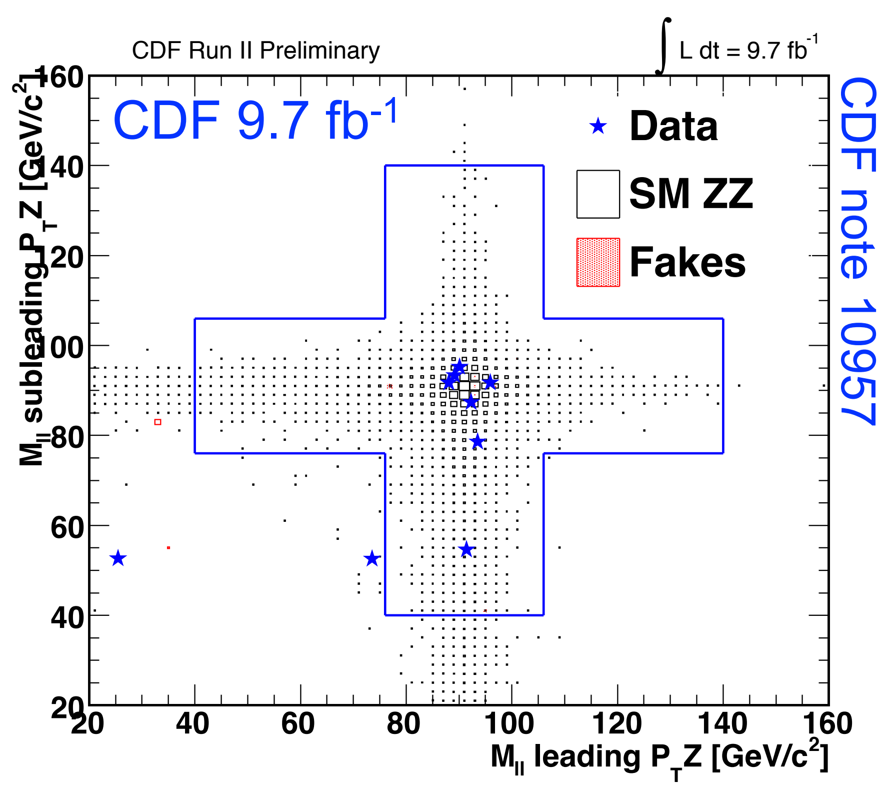
$ZZ \to \ell\ell\ell\ell$ is the cleanest of all channels

- Two e^+e^- or $\mu^+\mu^-$ pairs in loose Z mass windows
- Very small background from WZ and Z + jets
- CMS allows $Z \to \tau^+\tau^-$ for one Z





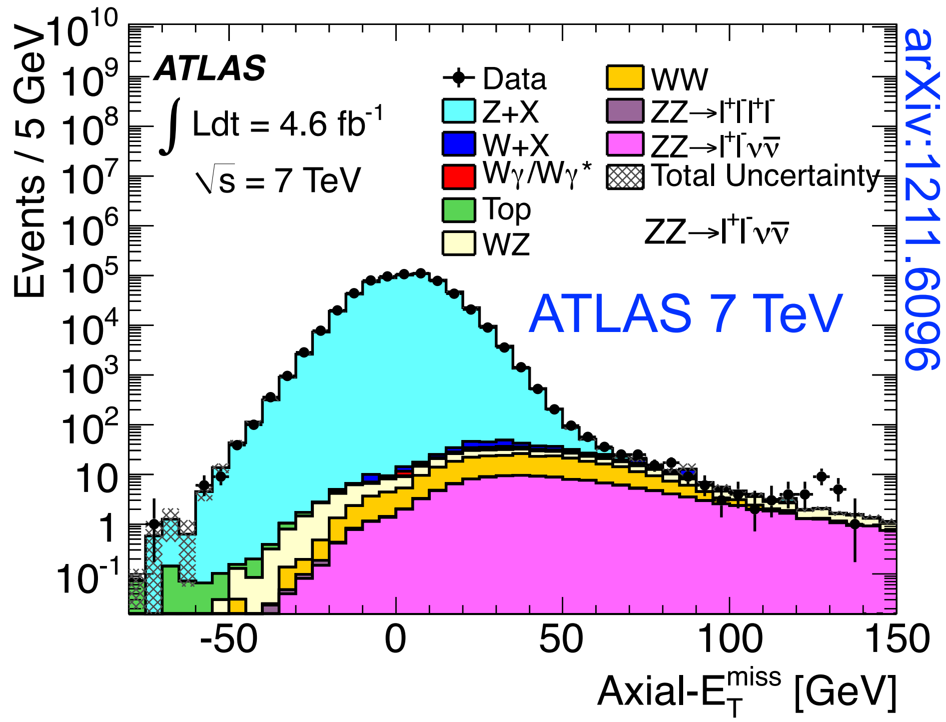


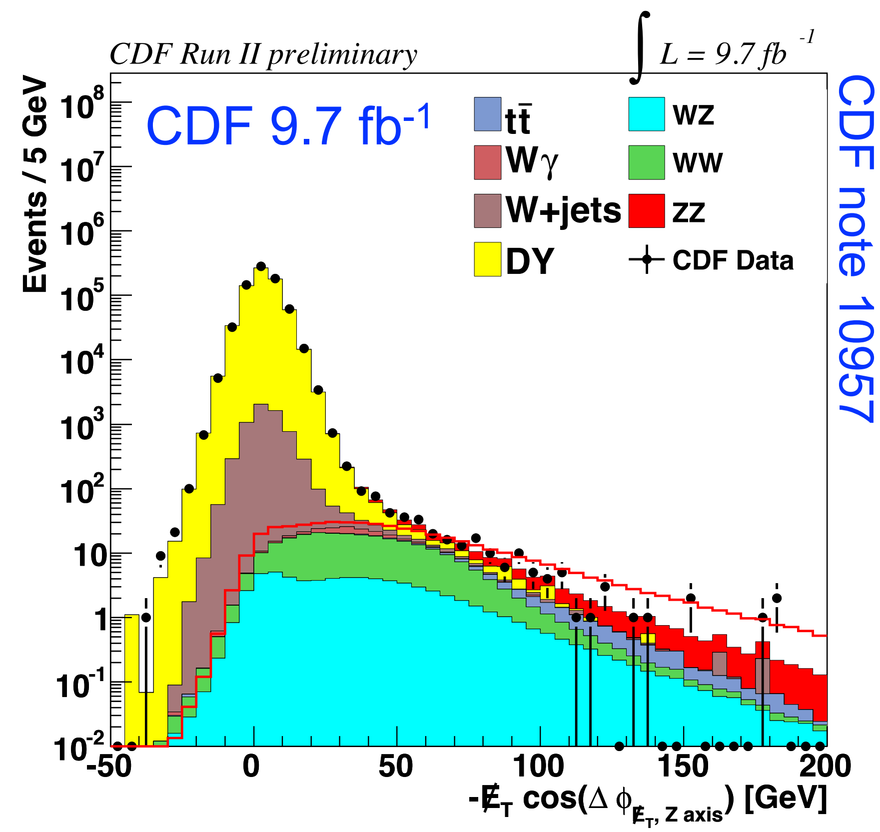


$ZZ \to \ell\ell\nu\nu$

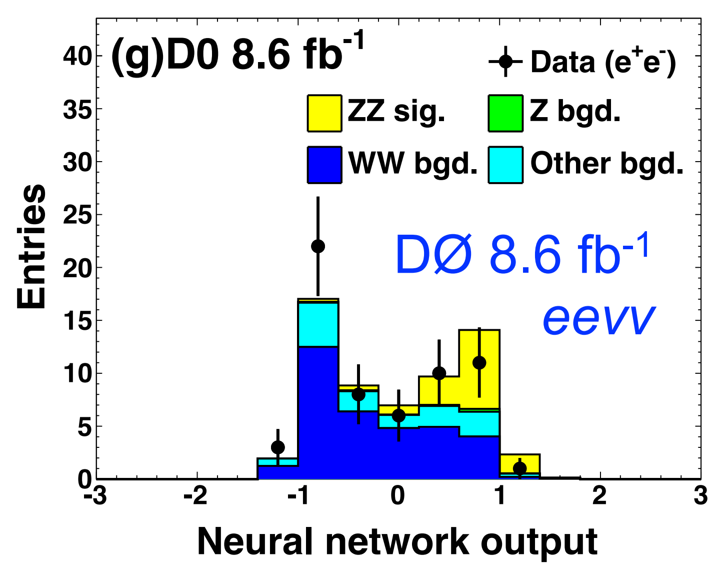
$ZZ \to \ell\ell\nu\nu$ looks for missing E_T recoiling against a $Z \to \ell\ell$

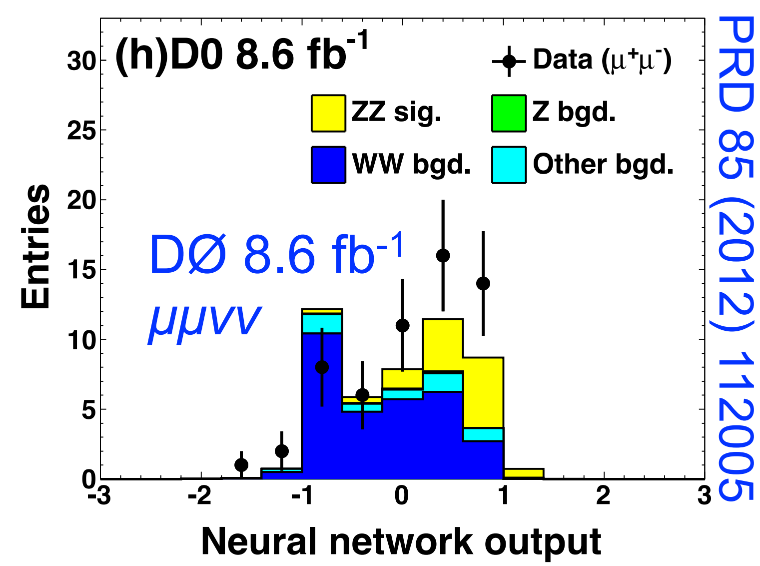
- Define "axial missing E_T" = $-\vec{E\!\!\!/}_T \cdot \vec{p}_T^{\,\ell\ell} \Big/ \left|p_T^{\ell\ell}\right|$





- CDF and DØ use neural-net discriminators to separate signal from background

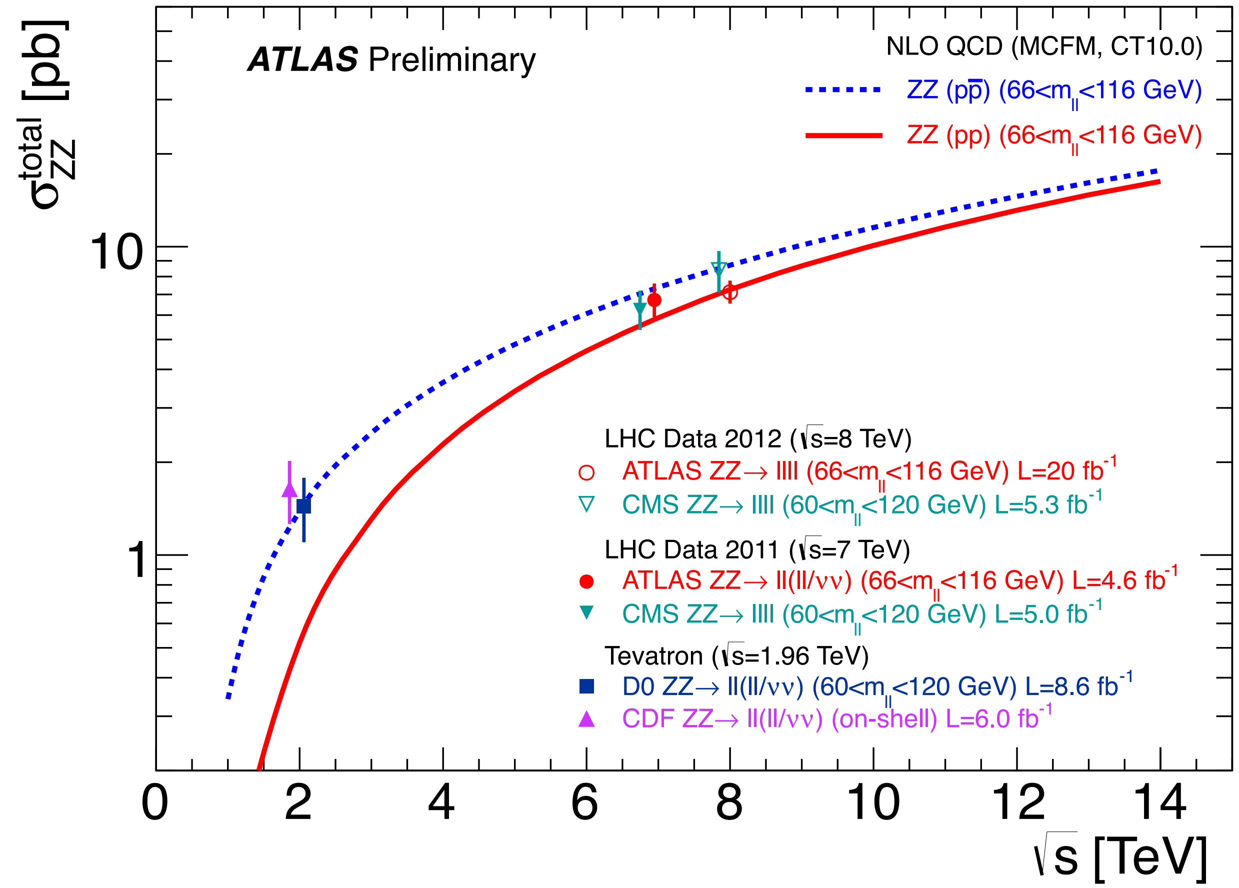




$ZZ \to \ell\ell\ell\ell$ and $\ell\ell\nu\nu$

	$\sqrt{s}$	$\int L\,dt$	Measured cross section (pb)	Theory (pb)	
CDF	1.96 TeV	9.7 fb^{-1}	$1.38 \pm 0.19(\text{stat})^{+0.20}_{-0.19}(\text{sys})$	1.4 ± 0.1	CDF note 10957
DØ	1.96 TeV	6.4–8.6 fb^{-1}	$1.40^{+0.43}_{-0.37}(\text{stat}) \pm 0.14(\text{sys})$	1.4 ± 0.1	PRD 85 (2012) 112005
ATLAS	7 TeV	4.6 fb^{-1}	$6.7 \pm 0.7(\text{stat})^{+0.4}_{-0.3}(\text{sys}) \pm 0.3(\text{lumi})$	$5.89^{+0.22}_{-0.18}$	arXiv:1211.6096
CMS	7 TeV	5.0 fb^{-1}	$6.24^{+0.86}_{-0.80}(\text{stat})^{+0.41}_{-0.32}(\text{sys}) \pm 0.14(\text{lumi})$	6.3 ± 0.4	EPJC 73 (2013) 2283
ATLAS	8 TeV	20 fb^{-1}	$7.1^{+0.5}_{-0.4}(\text{stat}) \pm 0.3(\text{sys}) \pm 0.2(\text{lumi})$	$7.2^{+0.3}_{-0.2}$	ATLAS-CONF-2013-020
CMS	8 TeV	5.3 fb^{-1}	$8.4 \pm 1.0(\text{stat}) \pm 0.7(\text{sys}) \pm 0.4(\text{lumi})$	7.7 ± 0.4	arXiv:1301.4698

- Measured cross sections agree with the SM prediction
  - NB: "total" cross section depends on the Z mass window
- Measurement precisions are statistics-limited
  - Leading systematic errors is the lepton identification efficiency

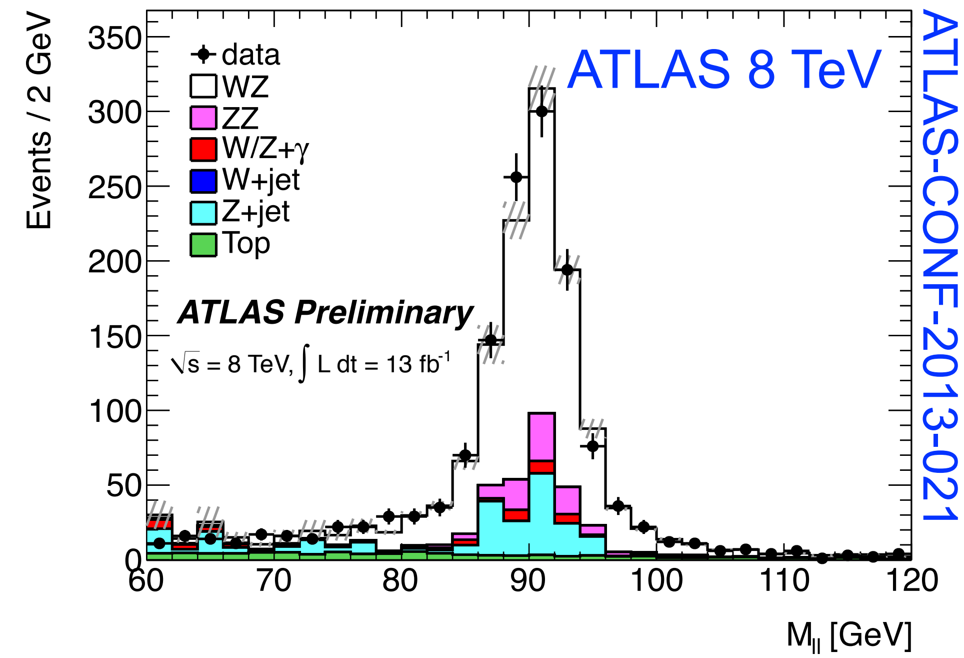


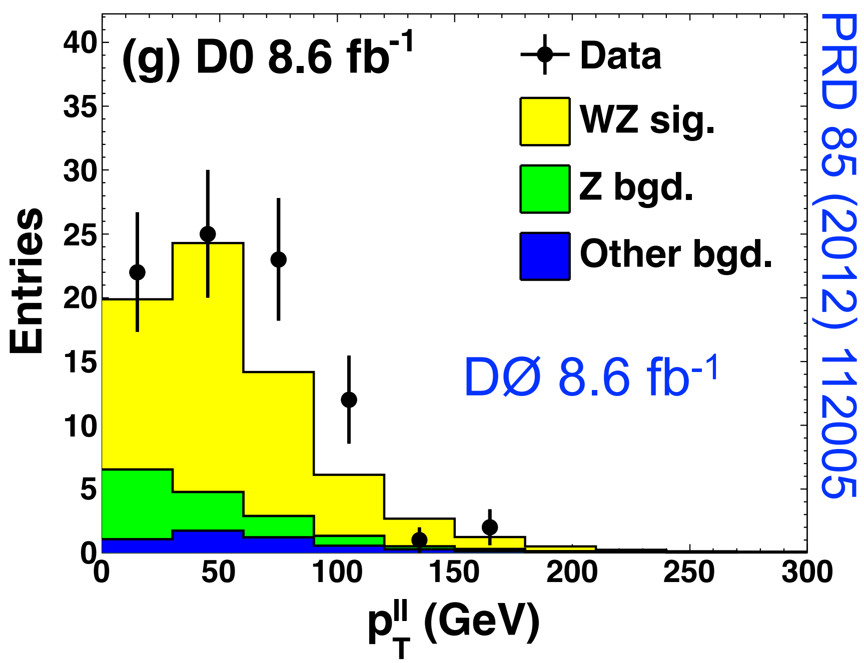
$WZ \to \ell\nu\ell\ell$

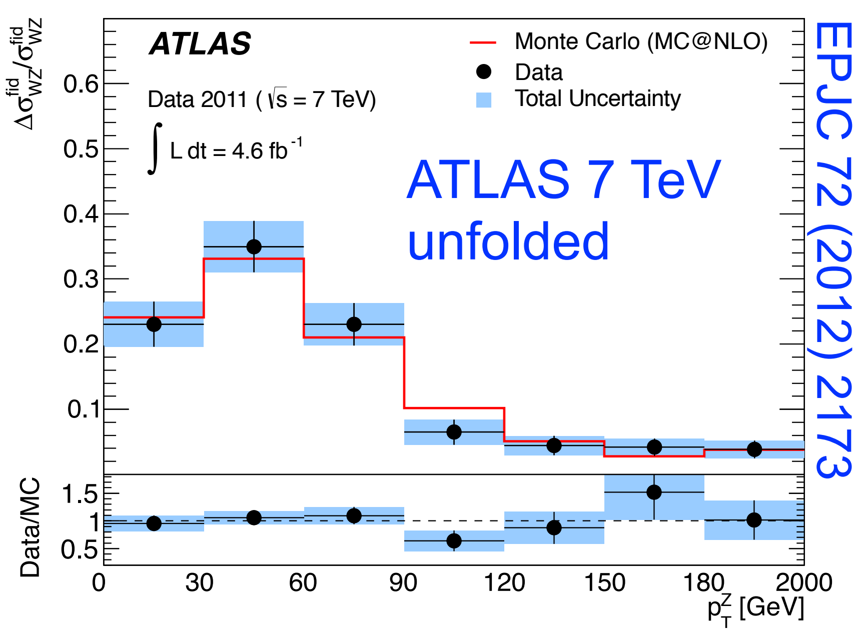
$WZ \to \ell\nu\ell\ell$ is quite clean: $S/B \sim 4$

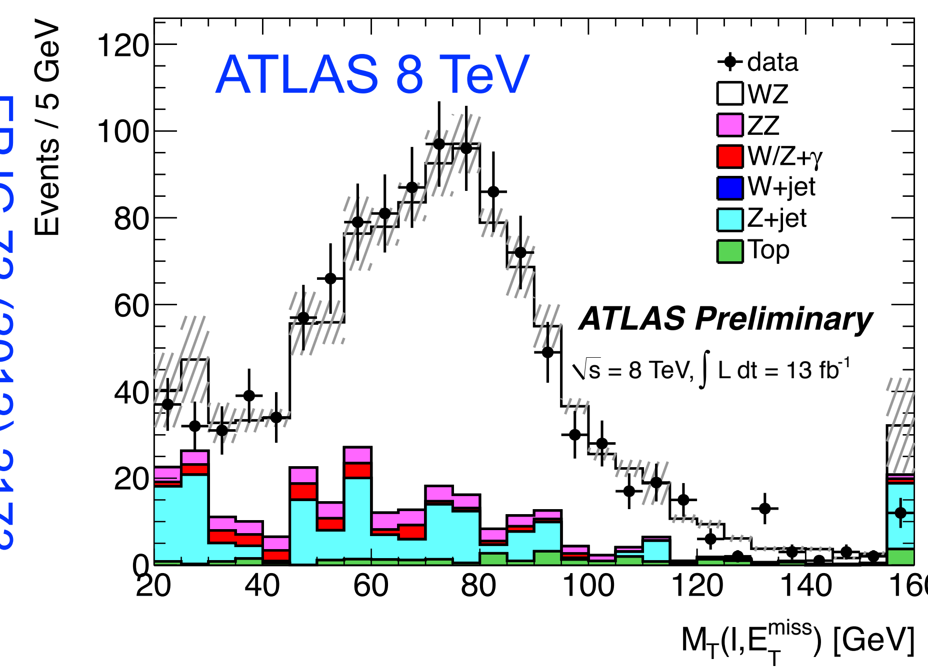
- e^+e^- or $\mu^+\mu^-$ pair in a tight Z mass window, plus one isolated lepton and missing E_T
- Loose cut on m_T of W candidate
- Background from Z + jets and ZZ

Enough statistics to measure kinematical distributions, e.g. $p_T(Z)$ and $m(WZ)$









- ATLAS "unfolded" (= corrected for experimental resolutions) $p_T(Z)$ and $m(WZ)$ distributions with 7 TeV data

$WZ \to \ell\nu\ell\ell$

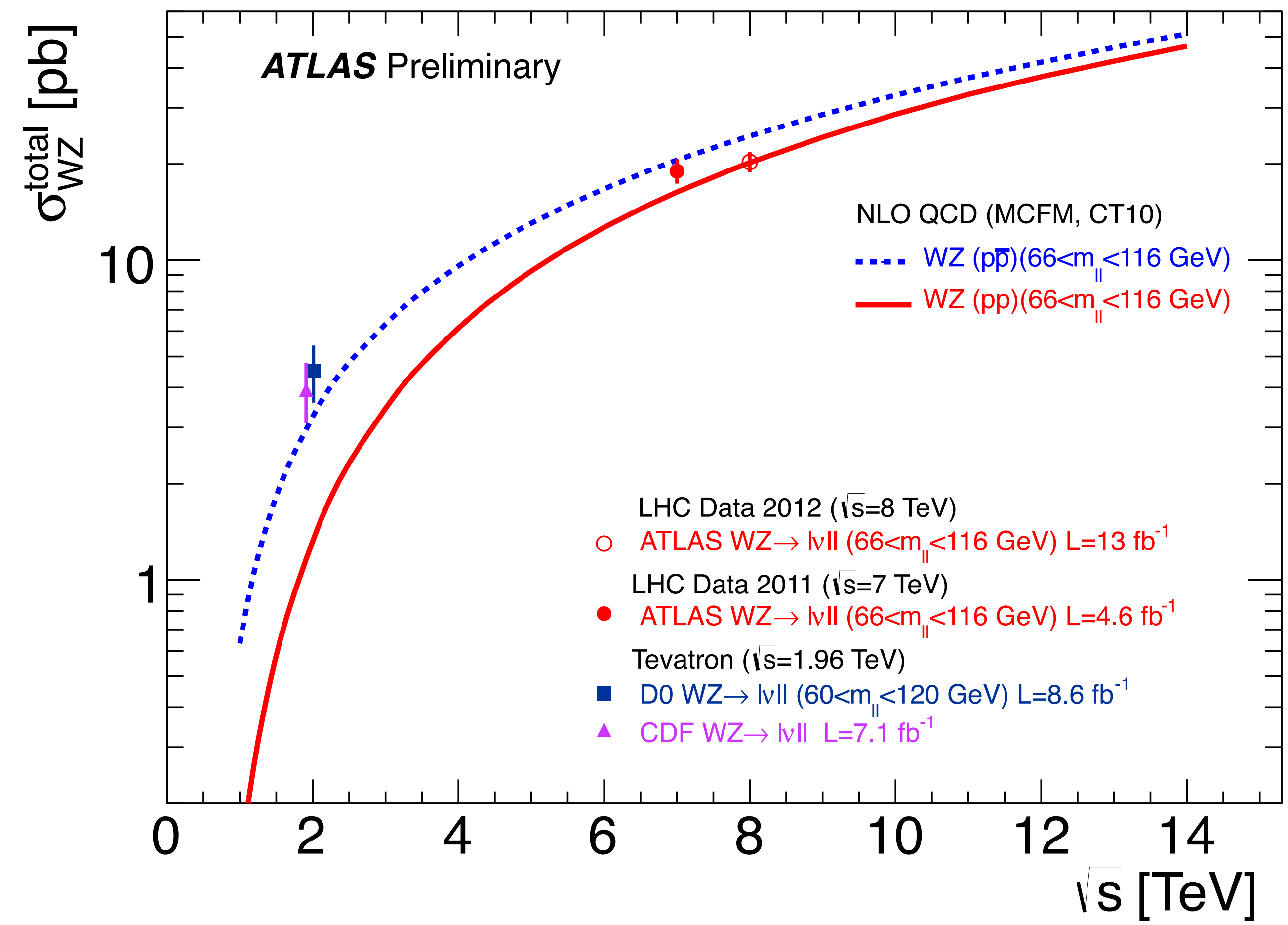
	$\sqrt{s}$	$\int L\,dt$	Measured cross section (pb)	Theory (pb)	
CDF	1.96 TeV	7.1 fb^{-1}	$3.93^{+0.60}_{-0.53}(\text{stat})^{+0.59}_{-0.46}(\text{sys})$	3.50 ± 0.21	PRD 86 (2012) 031104
DØ	1.96 TeV	8.6 fb^{-1}	$4.50 \pm 0.61(\text{stat})^{+0.16}_{-0.25}(\text{sys})$	3.21 ± 0.19	PRD 85 (2012) 112005
ATLAS	7 TeV	4.6 fb^{-1}	$19.0^{+1.4}_{-1.3}(\text{stat}) \pm 0.9(\text{sys}) \pm 0.4(\text{lumi})$	$17.6^{+1.1}_{-1.0}$	EPJC 72 (2012) 2173
CMS	7 TeV	1.1 fb^{-1}	$17.0 \pm 2.4(\text{stat}) \pm 1.1(\text{sys}) \pm 1.0(\text{lumi})$	(19.8 ± 0.1)	CMS-PAS-EWK-11-010
ATLAS	8 TeV	13 fb^{-1}	$20.3^{+0.8}_{-0.7}(\text{stat})^{+1.2}_{-1.1}(\text{sys})^{+0.7}_{-0.6}(\text{lumi})$	20.3 ± 0.8	ATLAS-CONF-2013-021

Measured cross sections agree with the SM prediction

- NB: "total" cross section depends on the *Z* mass window

Measurement precisions are statistics-limited

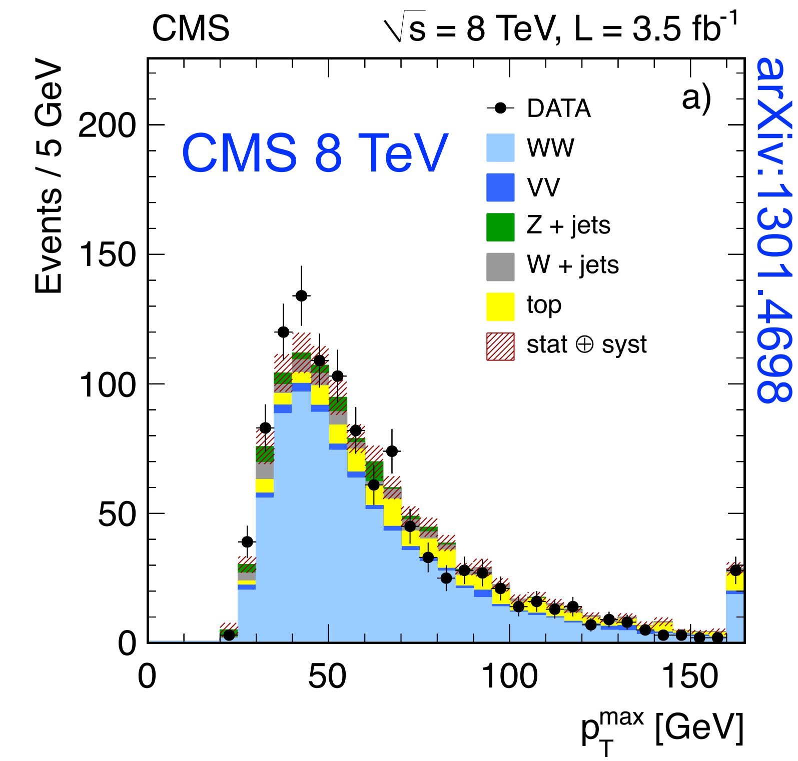
- Exception: ATLAS 8 TeV, 13 fb^{-1}
- Leading systematic error is *Z* + jets background estimate

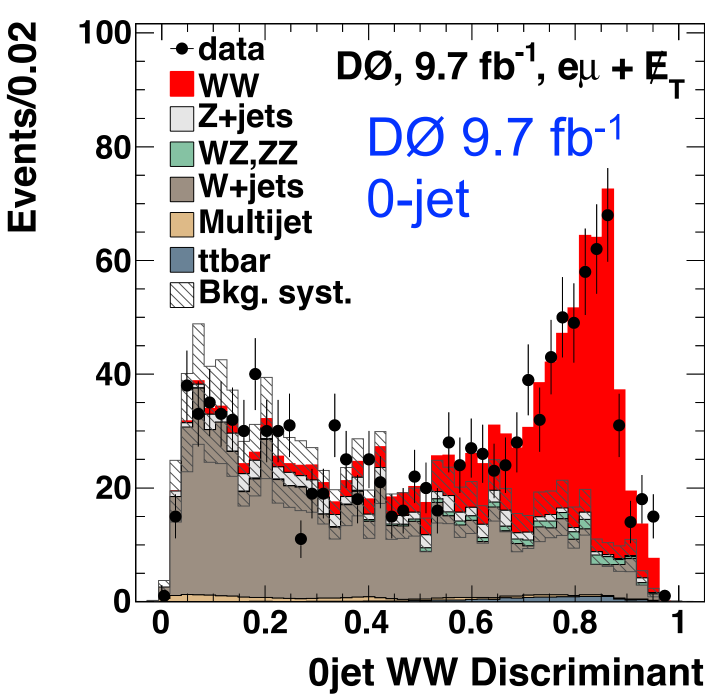


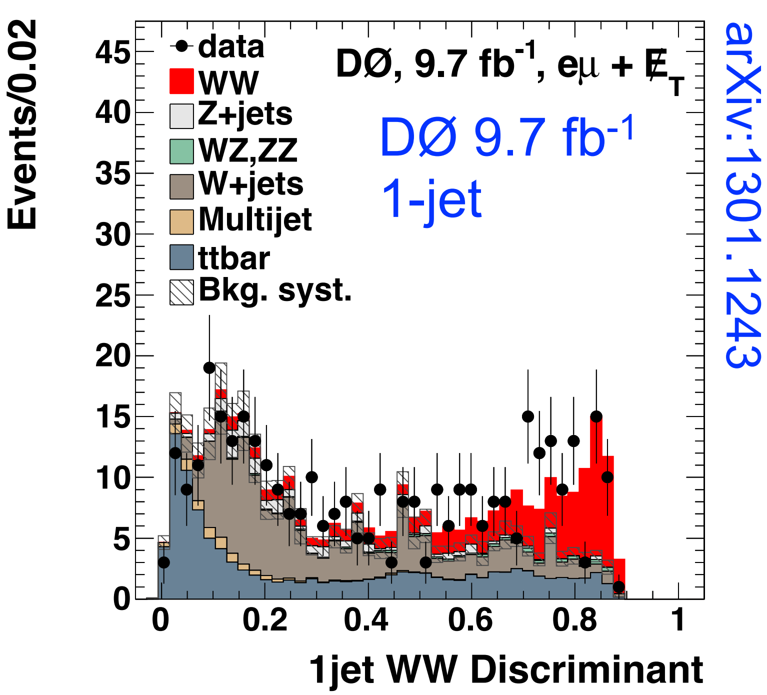
$WW \to \ell\nu\ell\nu$

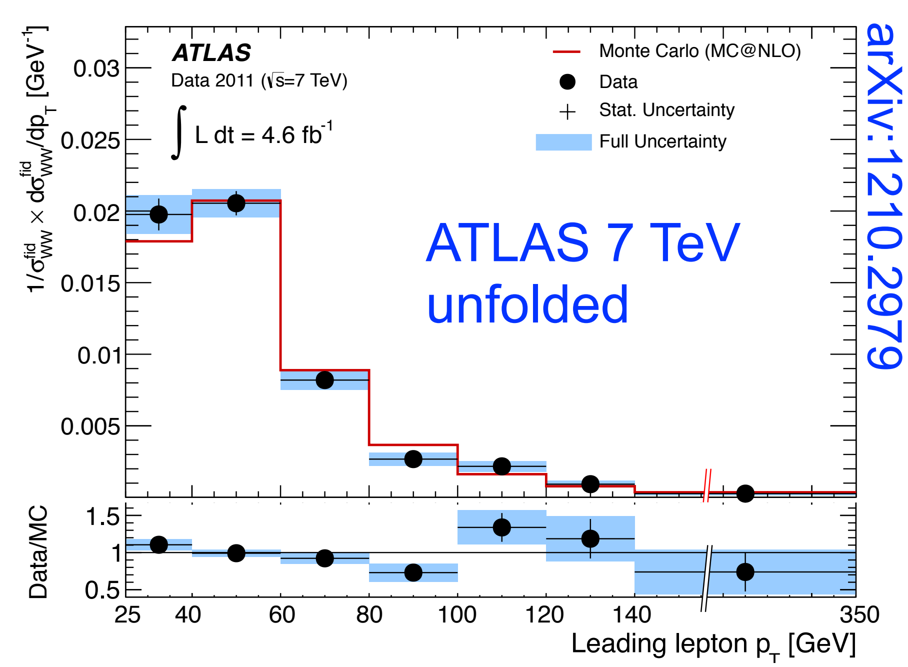
$WW \to \ell\nu\ell\nu$ needs a tight event selection to fight background

- Two isolated opposite-sign leptons
- Jet veto to suppress top background
  - DØ uses 0-jet and 1-jet samples
- More kinematical cuts to suppress $W/Z/\gamma^*$ + jets
  - ATLAS/CMS/CDF use a hard missing E_T cut for e^+e^- and $\mu^+\mu^-$ to suppress Z/γ^* + jets
  - DØ uses a BDT for e^+e^- or $\mu^+\mu^-$, m_T^{min} and m_{T2} for $e^\pm\mu^\mp$









- ATLAS also unfolded the leading lepton p_T distribution

$WW \to \ell\nu\ell\nu$

	$\sqrt{s}$	$\int L\,dt$	Measured cross section (pb)	Theory (pb)	
CDF	1.96 TeV	3.6 fb^{-1}	$12.1 \pm 0.9(\text{stat})^{+1.6}_{-1.4}(\text{sys})$	11.7 ± 0.7	PRL 104 (2010) 201801
DØ	1.96 TeV	9.7 fb^{-1}	$11.6 \pm 0.4(\text{stat}) \pm 0.6(\text{sys})$	11.3 ± 0.7	arXiv:1301.1243
ATLAS	7 TeV	4.6 fb^{-1}	$51.9 \pm 2.0(\text{stat}) \pm 3.9(\text{sys}) \pm 2.0(\text{lumi})$	$44.7^{+2.1}_{-1.9}$	arXiv:1210.2979
CMS	7 TeV	4.9 fb^{-1}	$52.4 \pm 2.0(\text{stat}) \pm 4.5(\text{sys}) \pm 1.2(\text{lumi})$	47.0 ± 2.0	CMS-PAS-SMP-12-005
CMS	8 TeV	3.5 fb^{-1}	$69.9 \pm 2.8(\text{stat}) \pm 5.6(\text{sys}) \pm 3.1(\text{lumi})$	$57.3^{+2.4}_{-1.6}$	arXiv:1301.4698

Cross sections at the LHC are slightly larger than the SM prediction

- Significances are small (+1.4σ, +1.0σ, +1.7σ) but starting to draw attention
  - Are the NLO calculations sufficiently precise?
  - Could this be a subtle sign of new physics?

Measurement precisions are systematics-limited

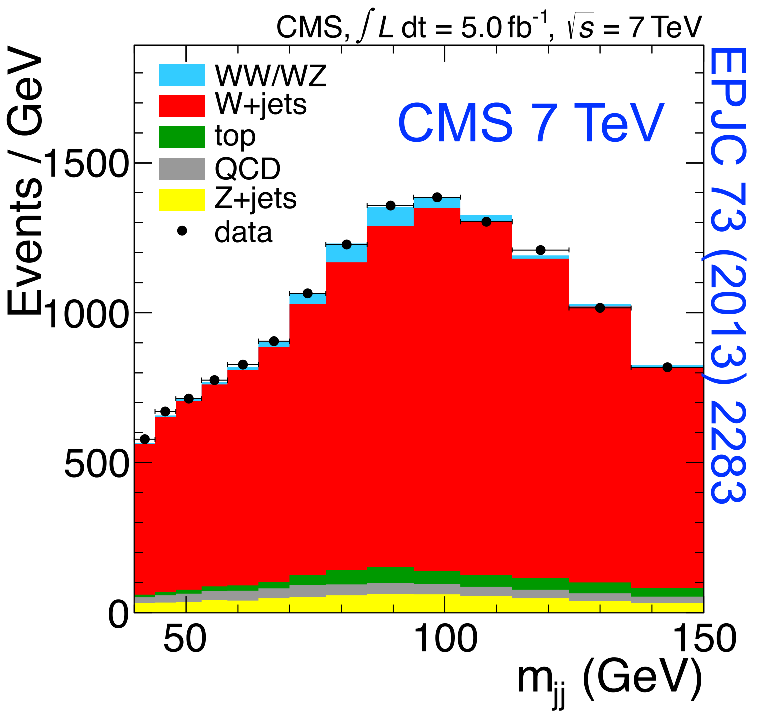
- Leading source of systematics is the jet veto
  - Experimental: jet-energy scale and resolution affects jet p_T threshold
  - Theoretical: number of jets in *WW* + jets

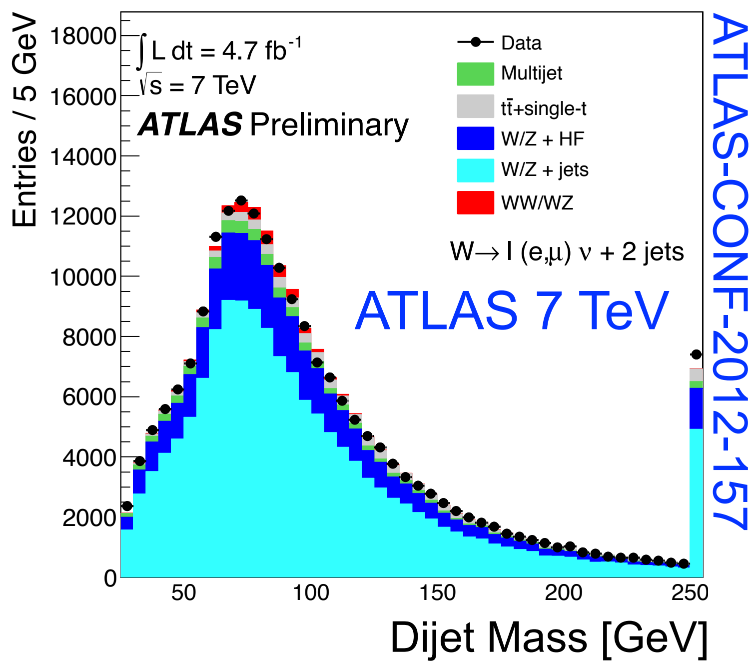
We still *really* want to see results from the full 8 TeV data

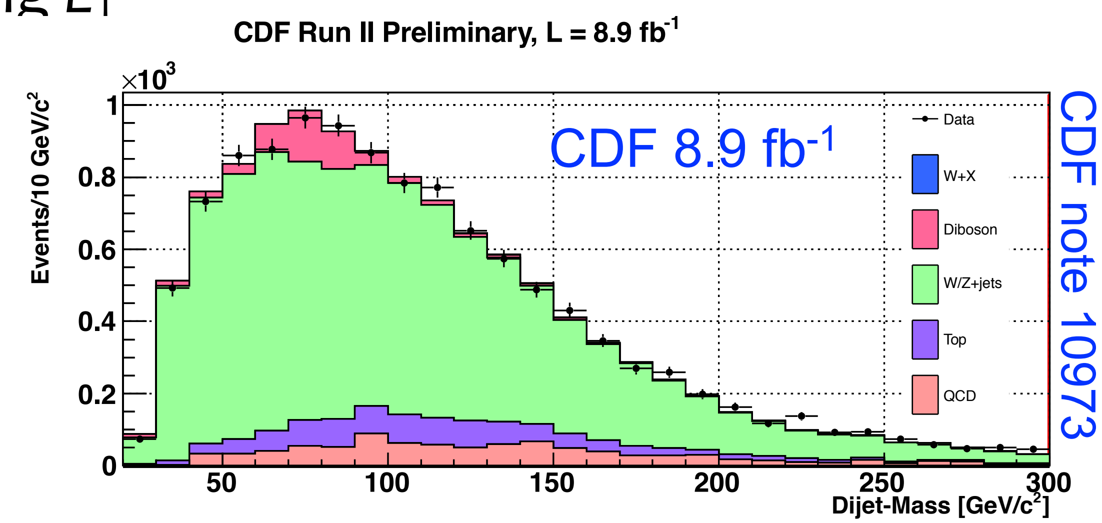
WW/WZ → ℓνjj

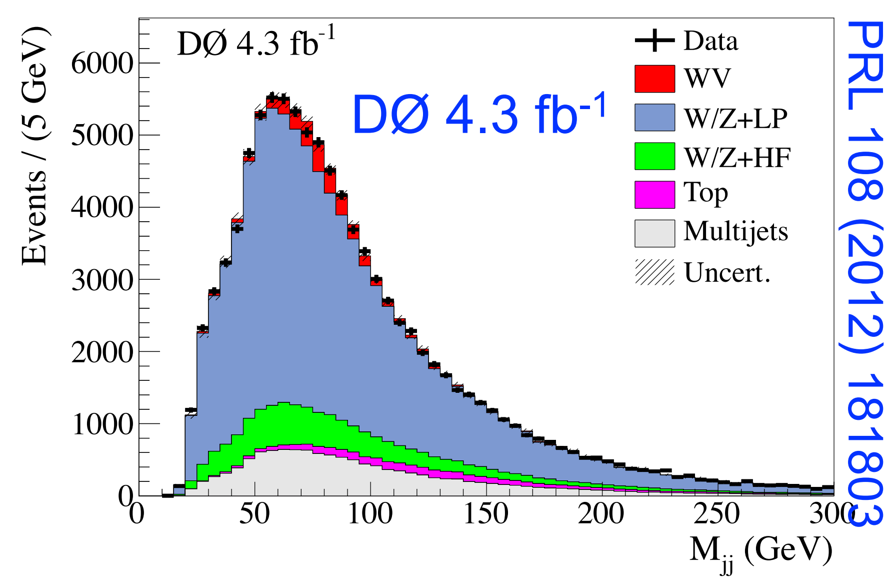
WW/WZ → ℓνjj is a tour de force of SM measurements

- Reconstruct a *W* candidate in one lepton + missing E_T
- Two jets with p_T > 25–30 GeV
- Fit the di-jet invariant mass distribution







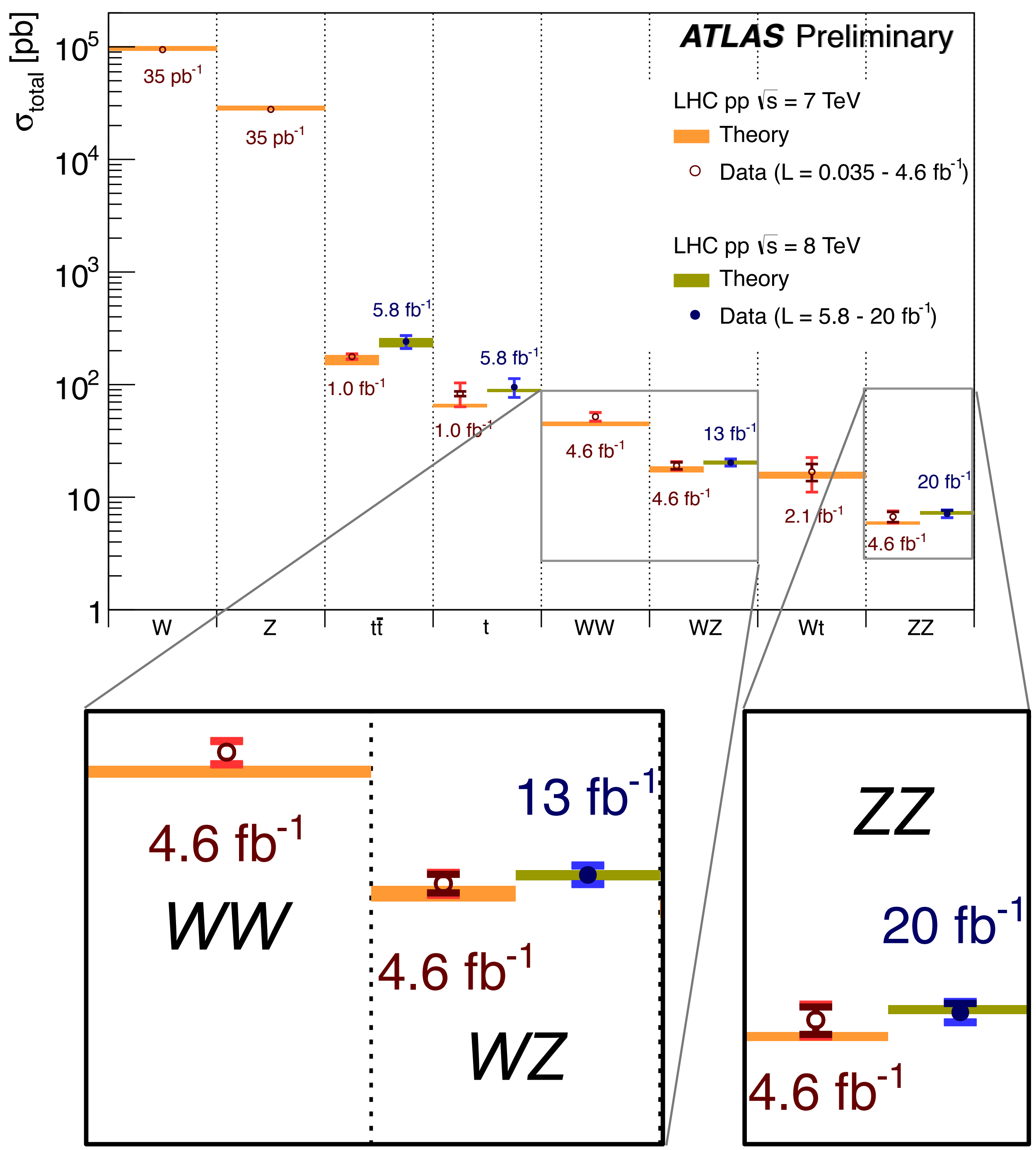


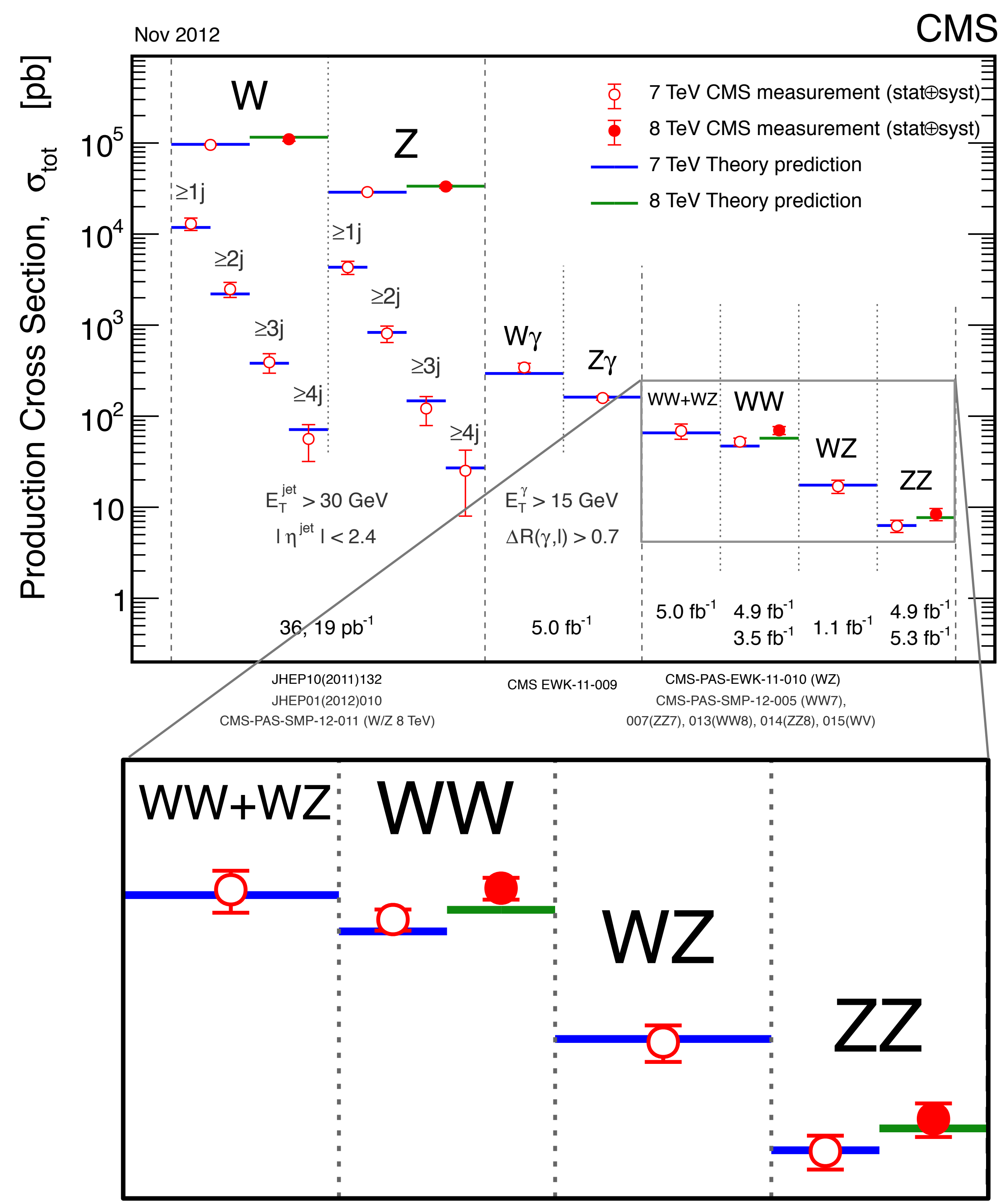
- Background must be exquisitely modeled

Signal is established by all experiments

- Precisions limited by both statistics and background modeling

Cross sections at the LHC





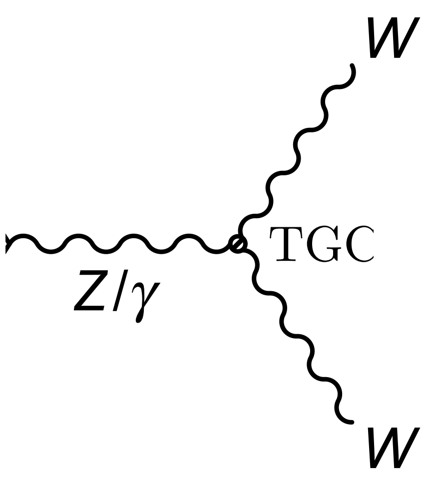
Triple Gauge Couplings

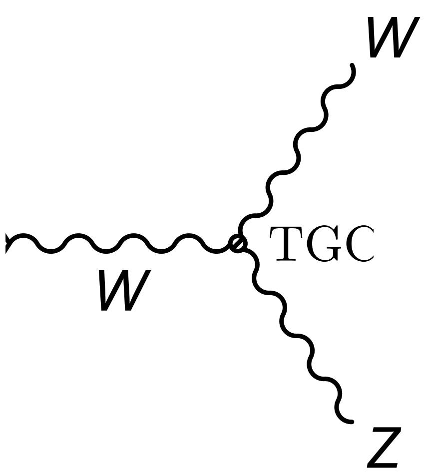
WWV ($V = Z/\gamma$) couplings ↔ WW and WZ (also $W\gamma$)

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = ig_1^V(W^+_{\mu\nu}W^{\mu}V^{\nu} - W^+_{\mu}V_{\nu}W^{\mu\nu}) + i\kappa_V W^+_{\mu}W_{\nu}V^{\mu\nu} + \frac{i\lambda_V}{m_W^2}W^+_{\lambda\mu}W^{\mu}_{\nu}V^{\nu\lambda}$$

- 5 parameters: $\Delta g_1^Z (\equiv g_1^Z - 1)$, $\Delta\kappa_Z (\equiv \kappa_Z - 1)$, $\Delta\kappa_\gamma (\equiv \kappa_\gamma - 1)$, λ_Z, λ_γ
- Additional constraints may be imposed

Equal coupling	$\Delta g_1^Z = 0$, $\Delta\kappa_Z = \Delta\kappa_\gamma$, and $\lambda_Z = \lambda_\gamma$
LEP scenario	$\Delta g_1^Z - \Delta\kappa_Z = \Delta\kappa_\gamma \tan^2\theta_W$ and $\lambda_Z = \lambda_\gamma$
HISZ scenario	$\Delta\kappa_Z = \Delta g_1^Z(\cos^2\theta_W - \sin^2\theta_W)$, $\Delta\kappa_\gamma = 2\Delta g_1^Z\cos^2\theta_W$ and $\lambda_Z = \lambda_\gamma$

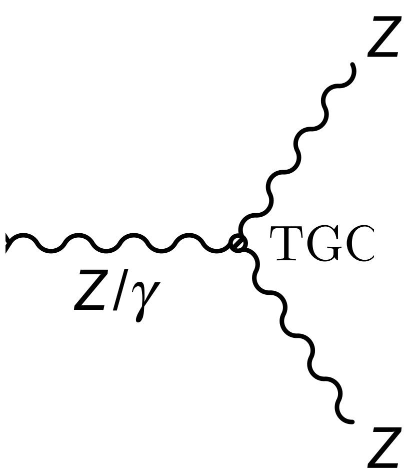




ZZV ($V = Z/\gamma$) couplings ↔ ZZ (also $Z\gamma$)

$$\mathcal{L}_{ZZV} = -\frac{e}{M_Z^2}\left[f_4^V(\partial_4^V V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta\right]$$

- 4 parameters: f_4^Z, f_4^γ, f_5^Z, f_5^γ

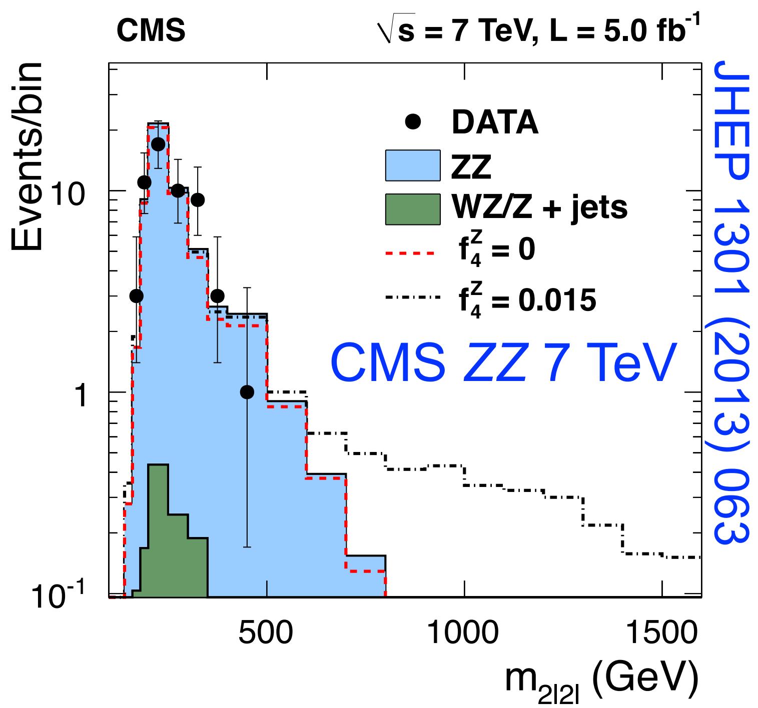


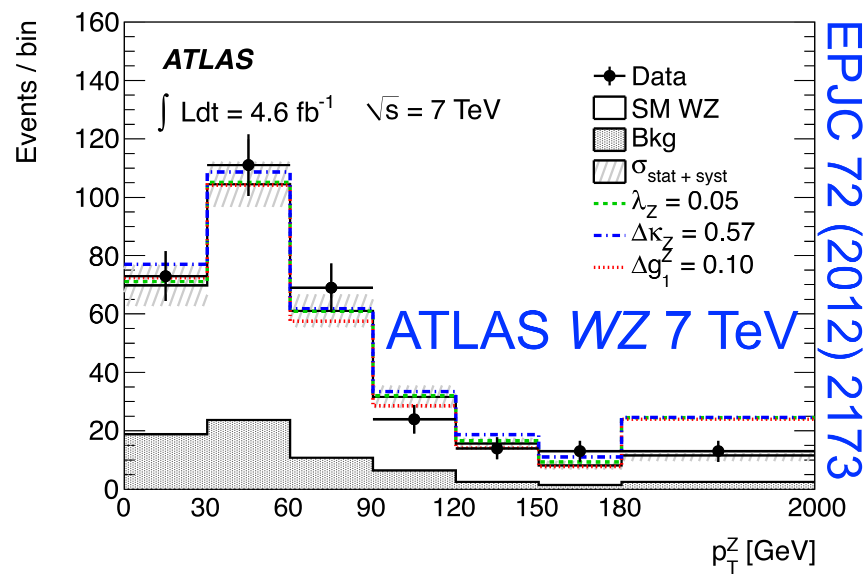
Parameters in red (*anomalous* TGCs) are zero in the SM

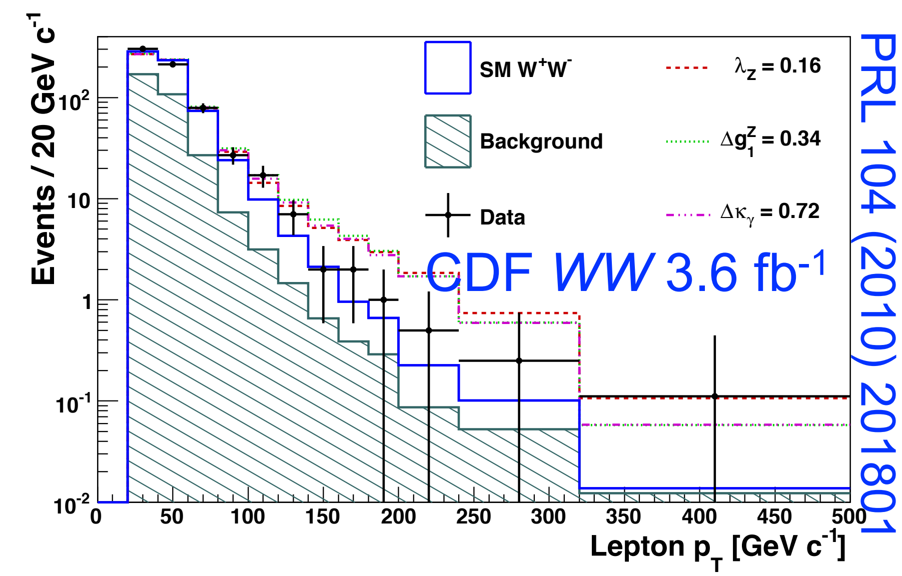
Triple Gauge Couplings

Effects of anomalous TGCs increase with $\hat{s}$

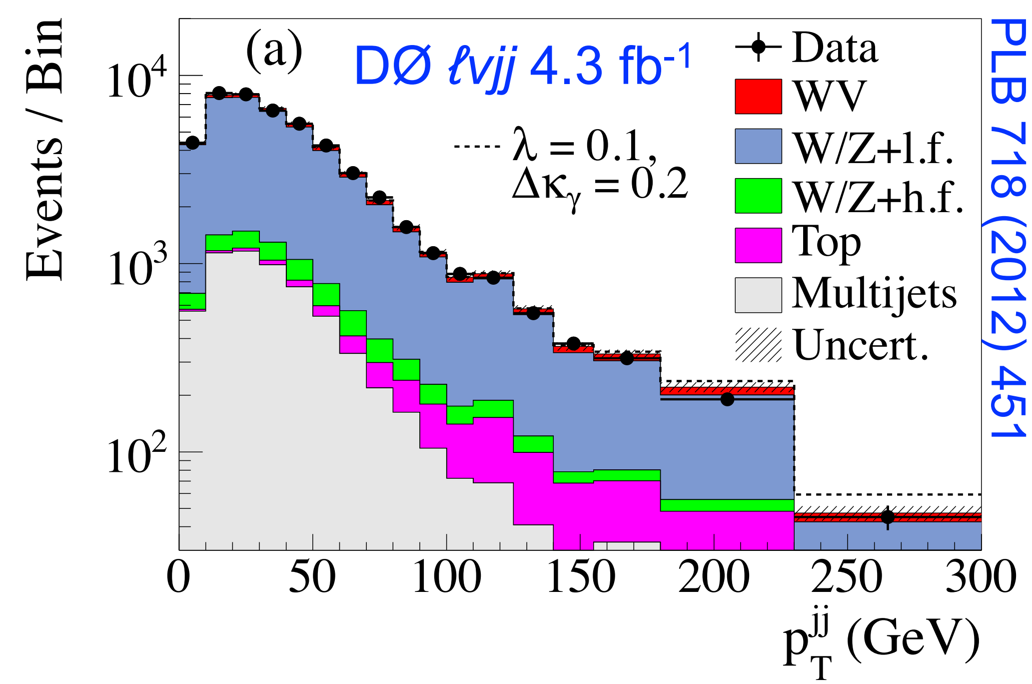
- Increase sensitivity by binning in, or selecting the upper tail of $\hat{s}$
- Observables: m_{ZZ} (for *ZZ*), p_T of *Z* (for *WZ* or *ZZ*), p_T of leading lepton (for *WW*)







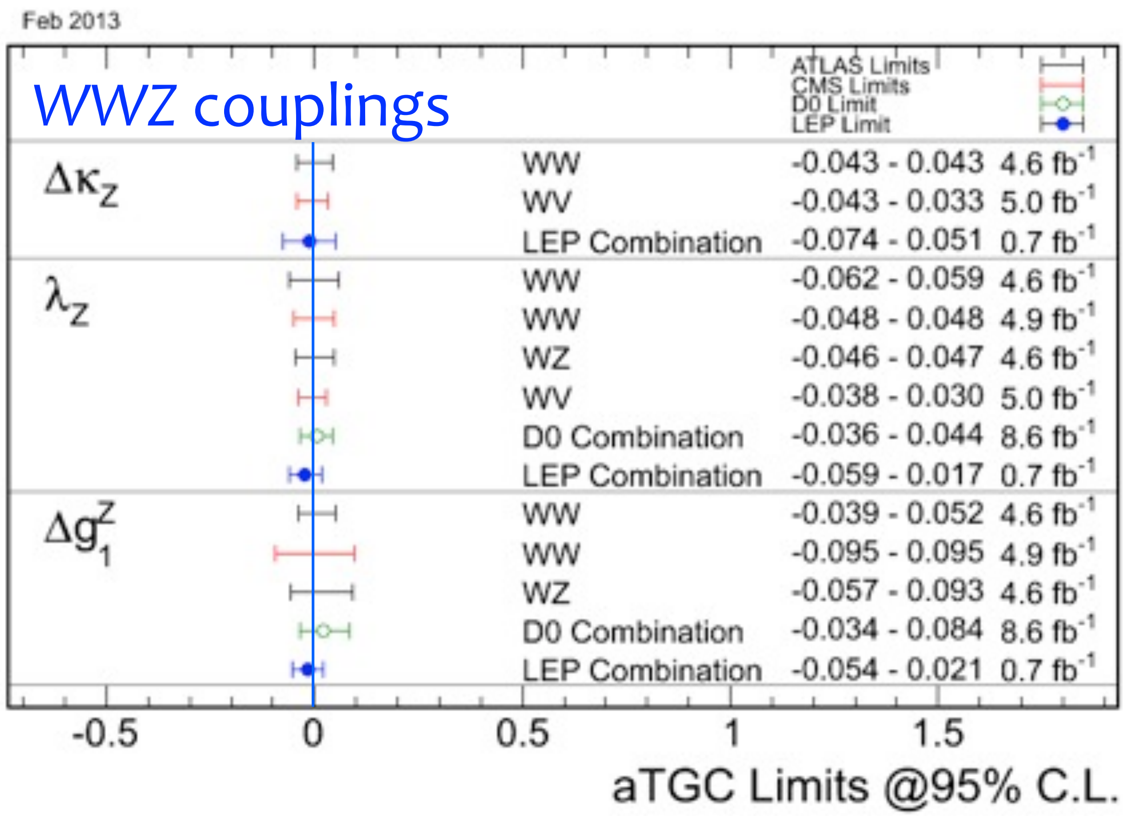
- Also used: p_T of di-jet in *WW*/*WZ* → *ℓνjj*

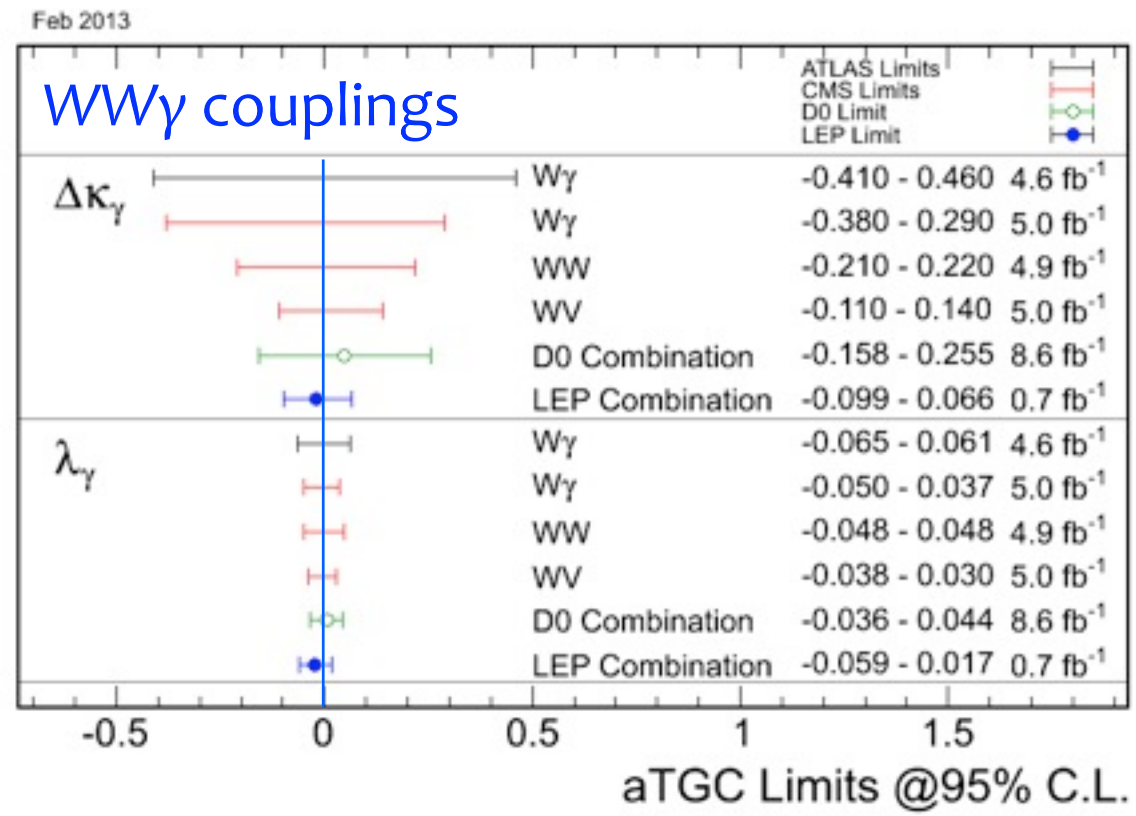


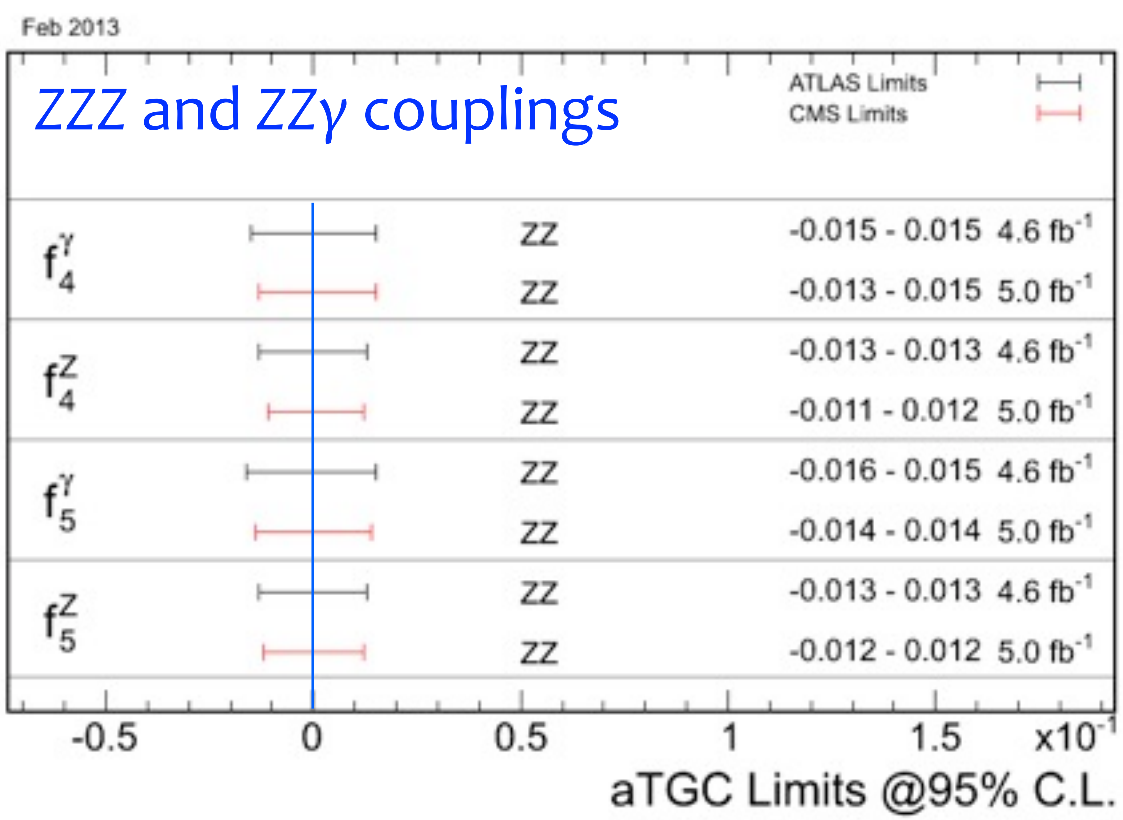
Extraction of TGC relies on NLO calculations: Powheg, MC@NLO, MCFM

- LO-to-NLO correction is substantial at large $\hat{s}$

TGC results







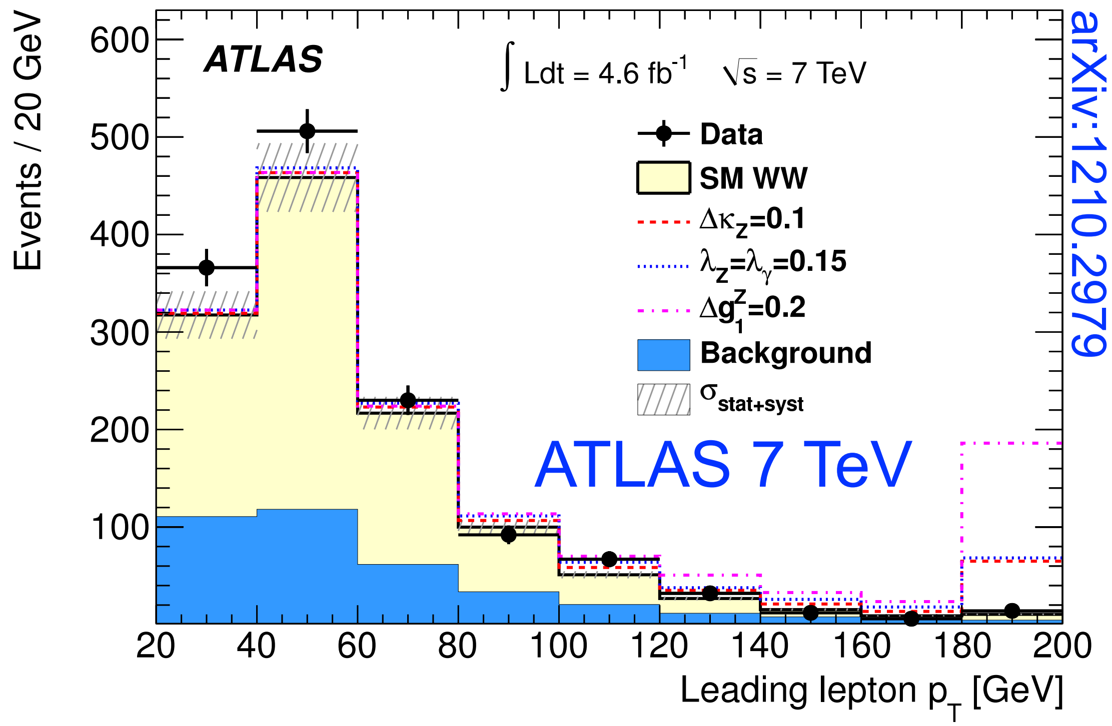
TGCs consistent with the SM

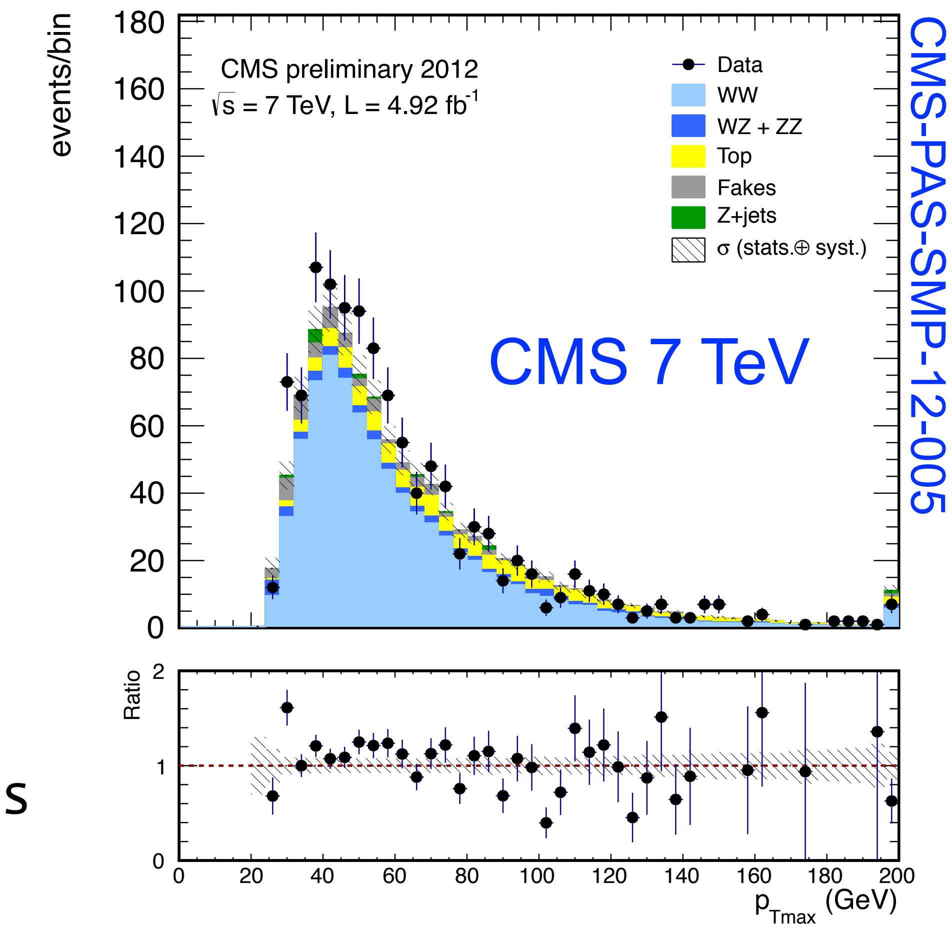
- Four of the *WWZ* and *WWγ* couplings are constrained to O(0.05)
  - Caveat: LEP scenario is used
  - $\Delta\kappa_\gamma$ remains less precise
- *ZZZ* and *ZZγ* couplings are constrained by the LHC results to O(0.01)

8 TeV data not included yet

Does it make sense?

Shouldn't the *WW* "excess" show up as anomalous TGCs?





- TGC sensitivity is concentrated in the highest bins of leading lepton p_T
- Excesses are mostly at low p_T where anomalous TGCs don't contribute

If the excess is real, it's not a kind of physics described with aTGCs

- i.e. not a heavy new particle in *s*-channel loop diagrams

Summary

WW, *WZ*, and *ZZ* measurements continue to improve

- CDF/DØ results with full Run-II data
- ATLAS/CMS results with (full or partial) 8 TeV data

Data are largely consistent with the SM prediction

- *WW* cross sections at the LHC slightly higher than expected
  - This has spurred theoretical investigations
  - Jet veto is the leading source of experimental/theoretical uncertainties
  - Analyze full 8 TeV data!

TGCs show no deviation from the SM

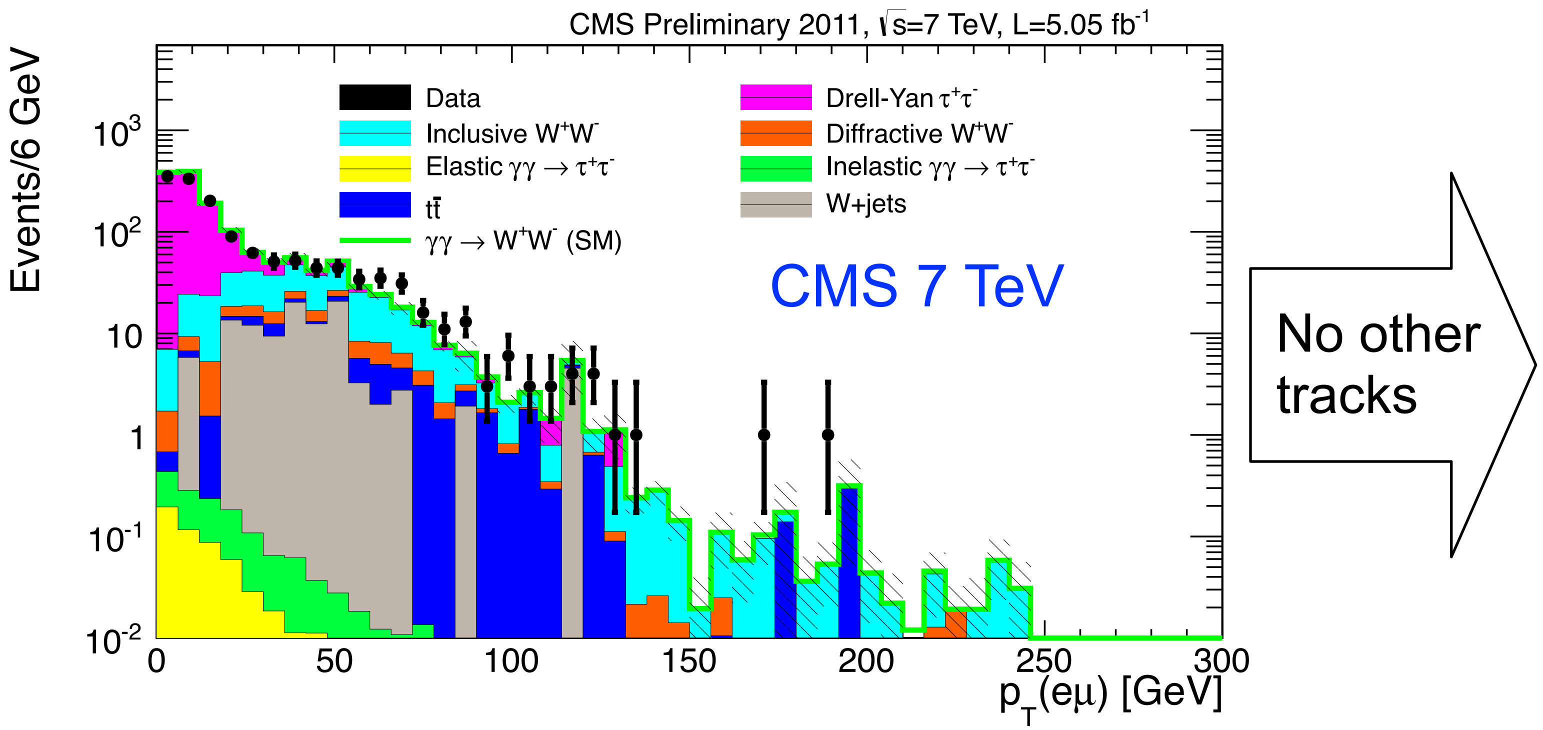
- Four (out of 5) *WWZ* and *WW*γ couplings constrained at ~0.05 level
  - $\Delta\kappa_\gamma$ remains less precise, but improving
- All *ZZZ* and *ZZ*γ couplings constrained at ~0.01 level
- 8 TeV data have yet to be used ➔ Expect improvements soon

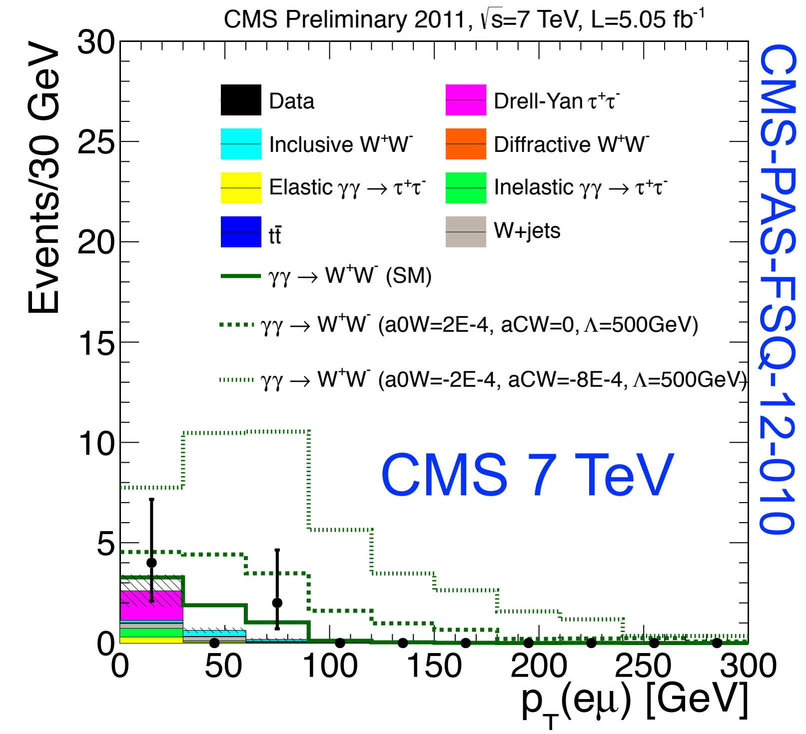
Backup Slides

Two-photon WW production

New measurement from CMS of $\gamma\gamma \rightarrow WW$

- Final state is $e^{\pm}\mu^{\mp}$ with no other tracks from the event vertex
- $p_T(e\mu)$ > 30 GeV suppresses $\tau\tau$ background





- 2 events observed. 2.2 ± 0.5 signal and 0.84 ± 0.13 (stat.) background expected

Limits are set on anomalous quartic gauge couplings (aQGCs)

$$-0.00017 < a_0^W/\Lambda^2 < 0.00017\,\text{GeV}^{-2}\ (a_C^W/\Lambda^2 = 0, \Lambda = 500\ \text{GeV}),$$
$$-0.0006 < a_C^W/\Lambda^2 < 0.0006\,\text{GeV}^{-2}\ (a_0^W/\Lambda^2 = 0, \Lambda = 500\ \text{GeV}),$$