Diboson Physics in CMS

- Ian Ross, University of Wisconsin-Madison on behalf of CMS

- LHC Days in Split

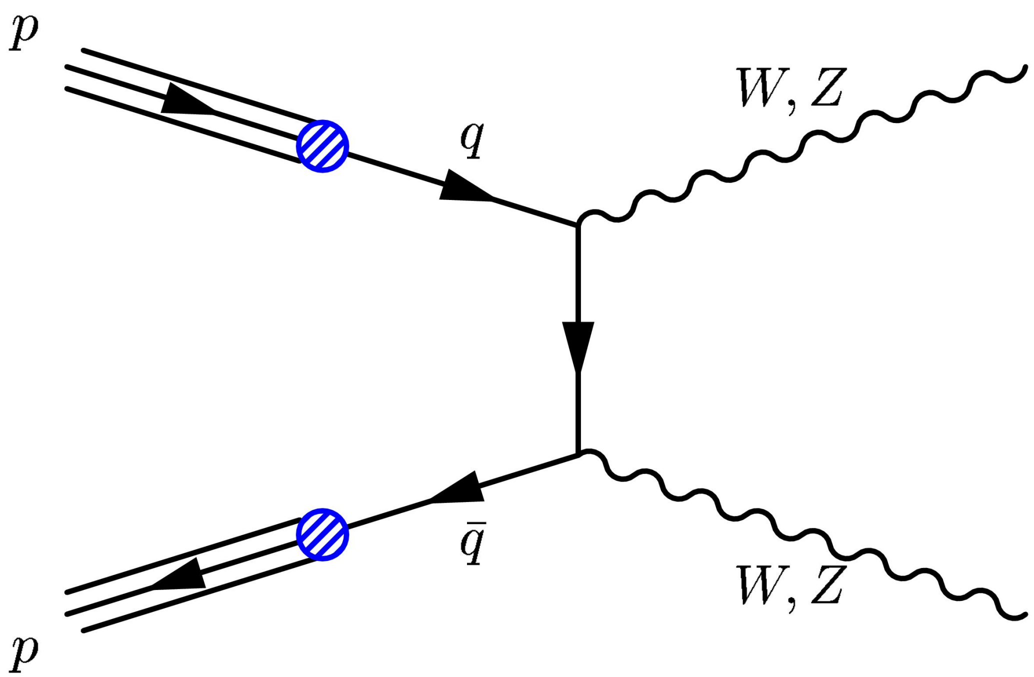
Overview

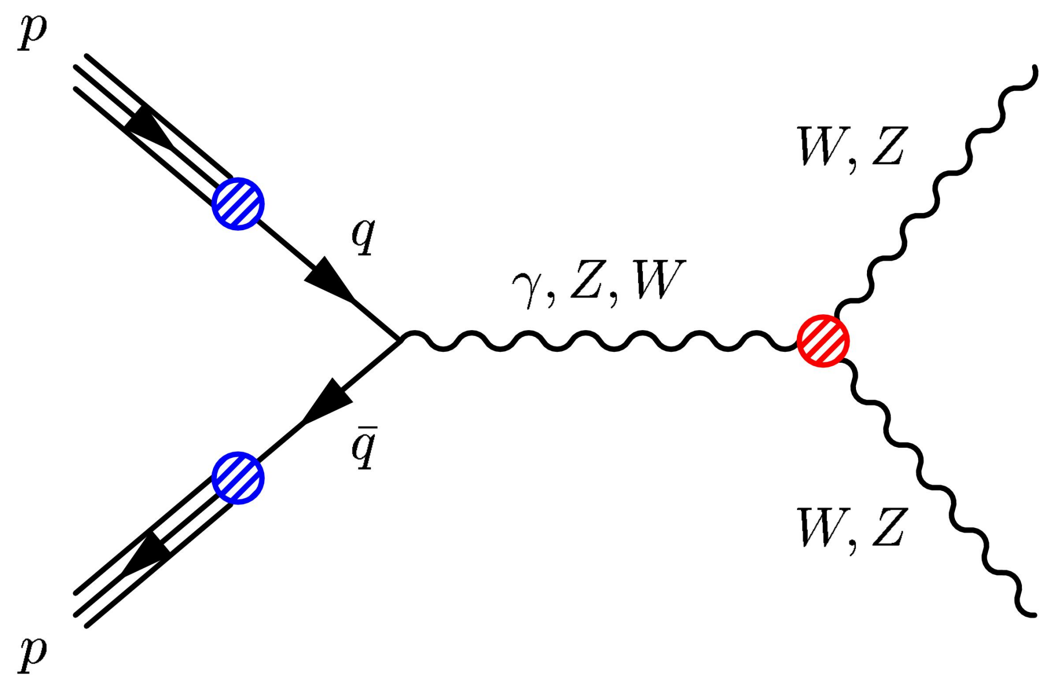
- Introduction
- Results
  - WW cross section (7 and 8 TeV)
  - WW/WZ in dijets (7 TeV)
    - Anomalous triple gauge coupling (aTGC) limits
  - WZ cross section (7 TeV)
  - $Z \rightarrow 4l$ branching ratio (7 TeV)
  - ZZ
    - Cross section (7 and 8 TeV)
    - aTGC limits (7 TeV)
  - $\gamma\gamma/V\gamma$ (7 TeV, 2010 only)
- Conclusions and CMS outlook

Introduction

- Diboson processes at the LHC
  - Standard Model measurements as physics benchmarks
    - Cross sections
    - Direct measurement of Triple Gauge Couplings (TGCs)
  - Higgs
    - SM ZZ and WW serve as irreducible background to Higgs searches
  - BSM physics
    - New particle decays (e.g. W' $\rightarrow$WZ)
    - Anomalous triple gauge couplings (aTGCs)

Diboson Production (Leading order)

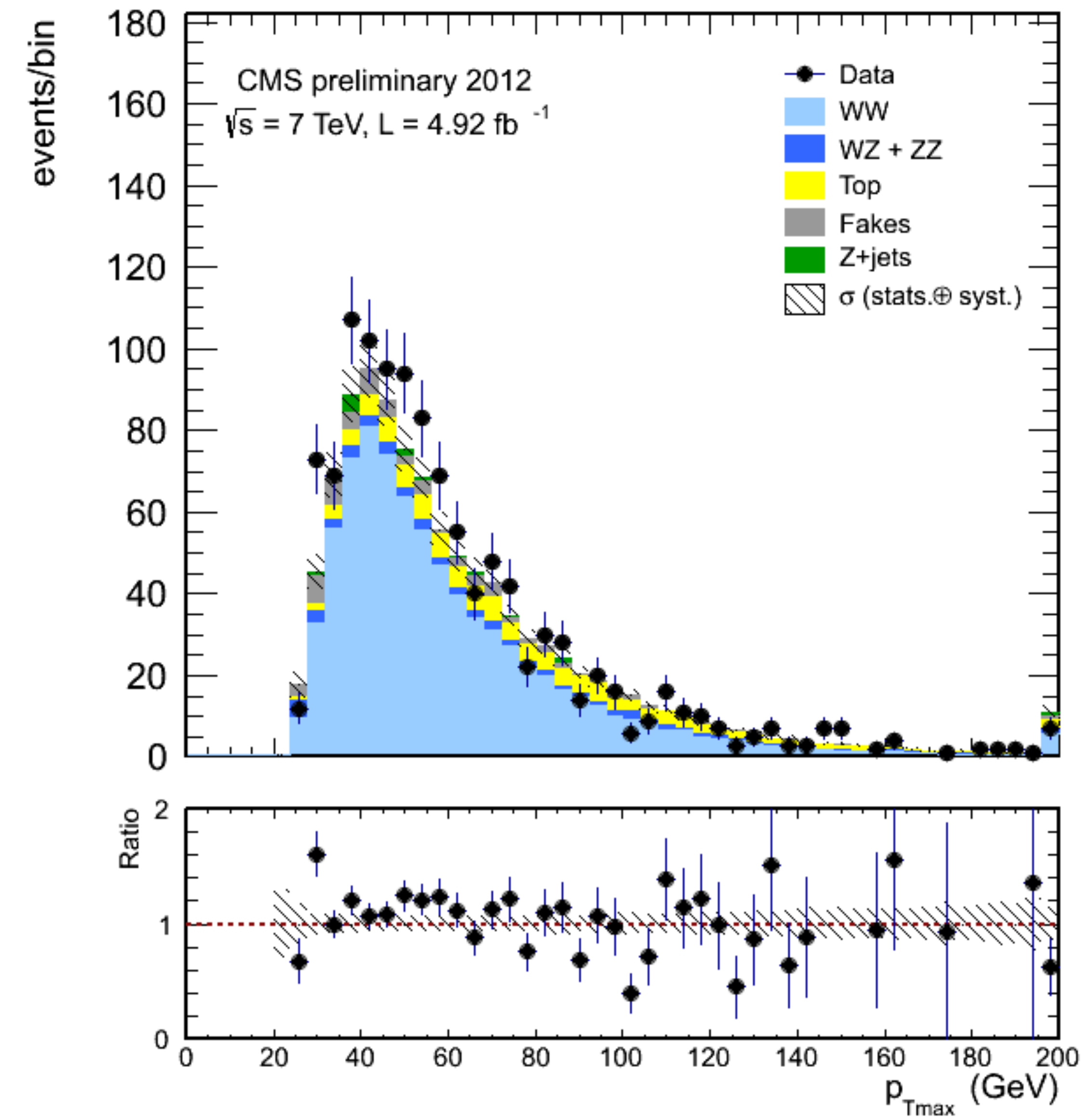




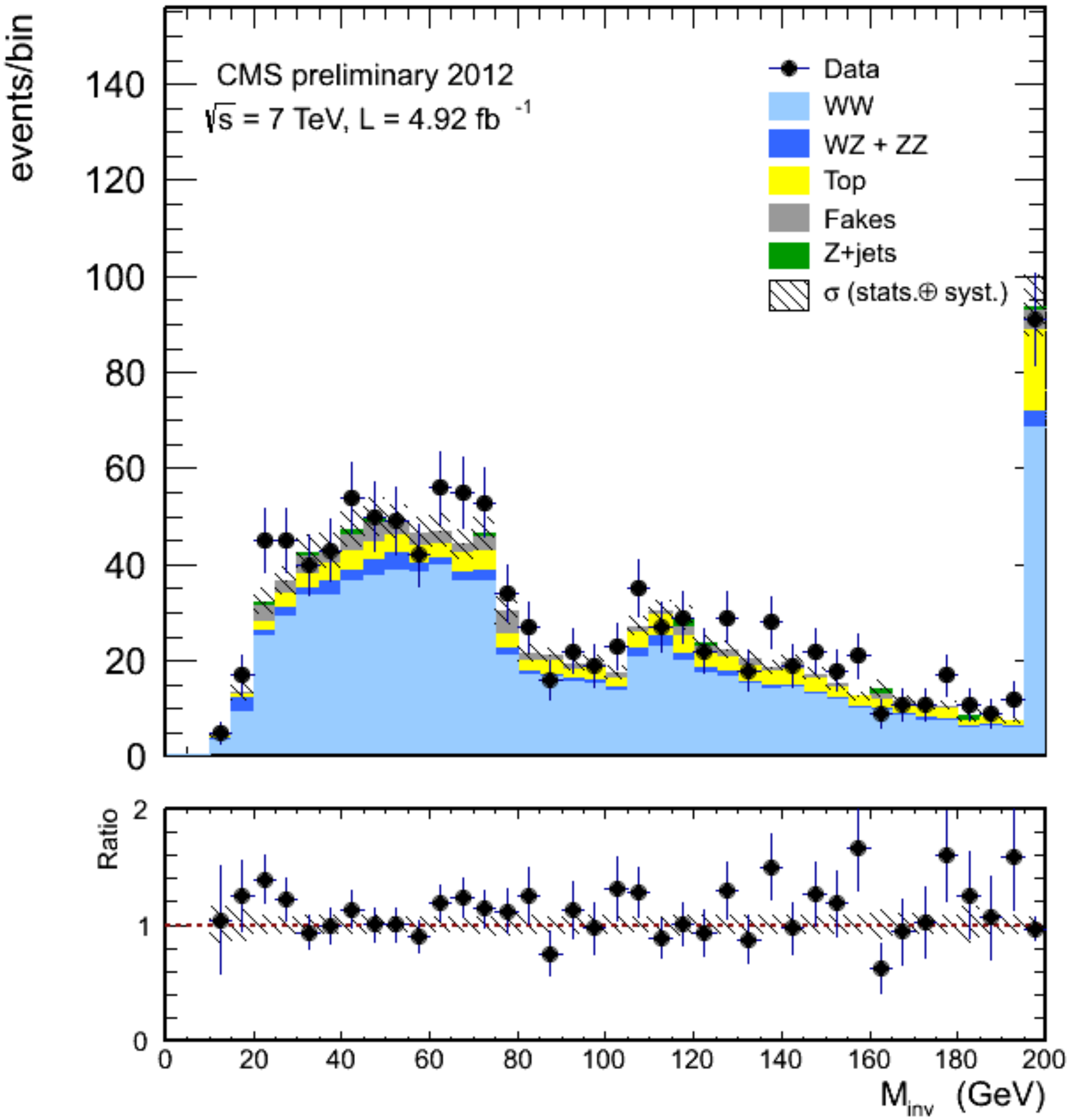
- Triple gauge couplings:
  - Charged triple gauge couplings (WWZ, WWγ) allowed
  - Neutral triple gauge couplings (ZZZ, ZZγ) forbidden in Standard Model
- Anomalous couplings lead to enhanced cross section, larger V p_T

WW→2l2ν, Analysis Overview

- Key features:
  - Non-resonant
  - Important in Higgs search
- Signature: two high p_T leptons + high ME_T
- Background treatment:
  - W+jets reduced using central- and b-jet vetoes, estimated from data via lepton fake rate extrapolation
  - Top background estimated from data via top veto fake rate
  - DY contribution (outside Z window) estimated by normalizing the simulation to the yield within the Z window



WW, 7 TeV (4.92 fb^{-1})



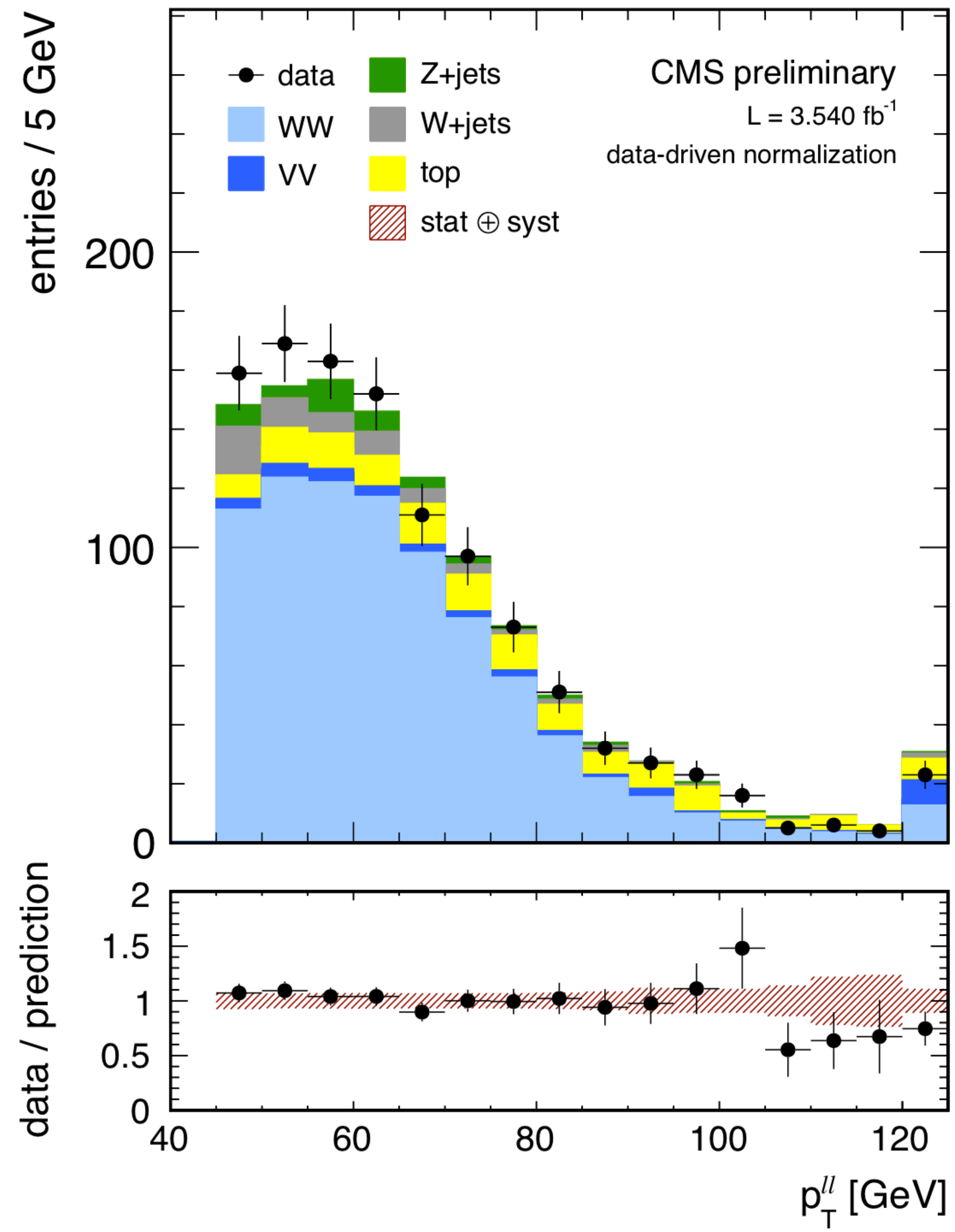
Sample	Yield ± stat. ± syst.
$gg \to W^+W^-$	$46.0 \pm 0.6 \pm 14.2$
$q\bar{q} \to W^+W^-$	$750.9 \pm 4.1 \pm 53.1$
$t\bar{t}$ +tW	$128.5 \pm 12.8 \pm 19.6$
W+jets	$59.5 \pm 3.9 \pm 21.4$
WZ+ZZ	$29.4 \pm 0.4 \pm 2.0$
Z/γ^*	$11.0 \pm 5.1 \pm 2.6$
$W+\gamma$	$18.8 \pm 2.8 \pm 4.7$
$Z/\gamma^* \to \tau\tau$	$0.0 \pm 1.0 \pm 0.1$
Total Background	$247.1 \pm 14.6 \pm 29.5$
Signal + Background	$1044.0 \pm 15.2 \pm 62.4$
Data	1134

$$\sigma_{WW} = 52.4 \pm 2.0\ (\text{stat.})\ \pm 4.5\ (\text{syst.})\ \pm 1.2\ (\text{lumi.})\ \text{pb.}$$

Theory: 47.0 ± 2.0 pb (MCFM)

WW, 8 TeV (3.54 fb^{-1})

sample	yield ± stat. ± syst.
$gg \to WW$	43.3 ± 1.0 ± 13.4
$qq \to WW$	640.3 ± 4.9 ± 47.4
$t\bar{t}$ + tW	131.6 ± 12.7 ± 19.5
W + jets	60.0 ± 4.3 ± 21.6
WZ + ZZ	27.4 ± 0.5 ± 2.9
Z/γ^*	42.5 ± 6.0 ± 9.9
$W\gamma + W\gamma^*$	13.6 ± 2.4 ± 4.3
total background	275.2 ± 14.9 ± 31.2
signal + background	958.8 ± 15.7 ± 58.3
data	1111 ± 33

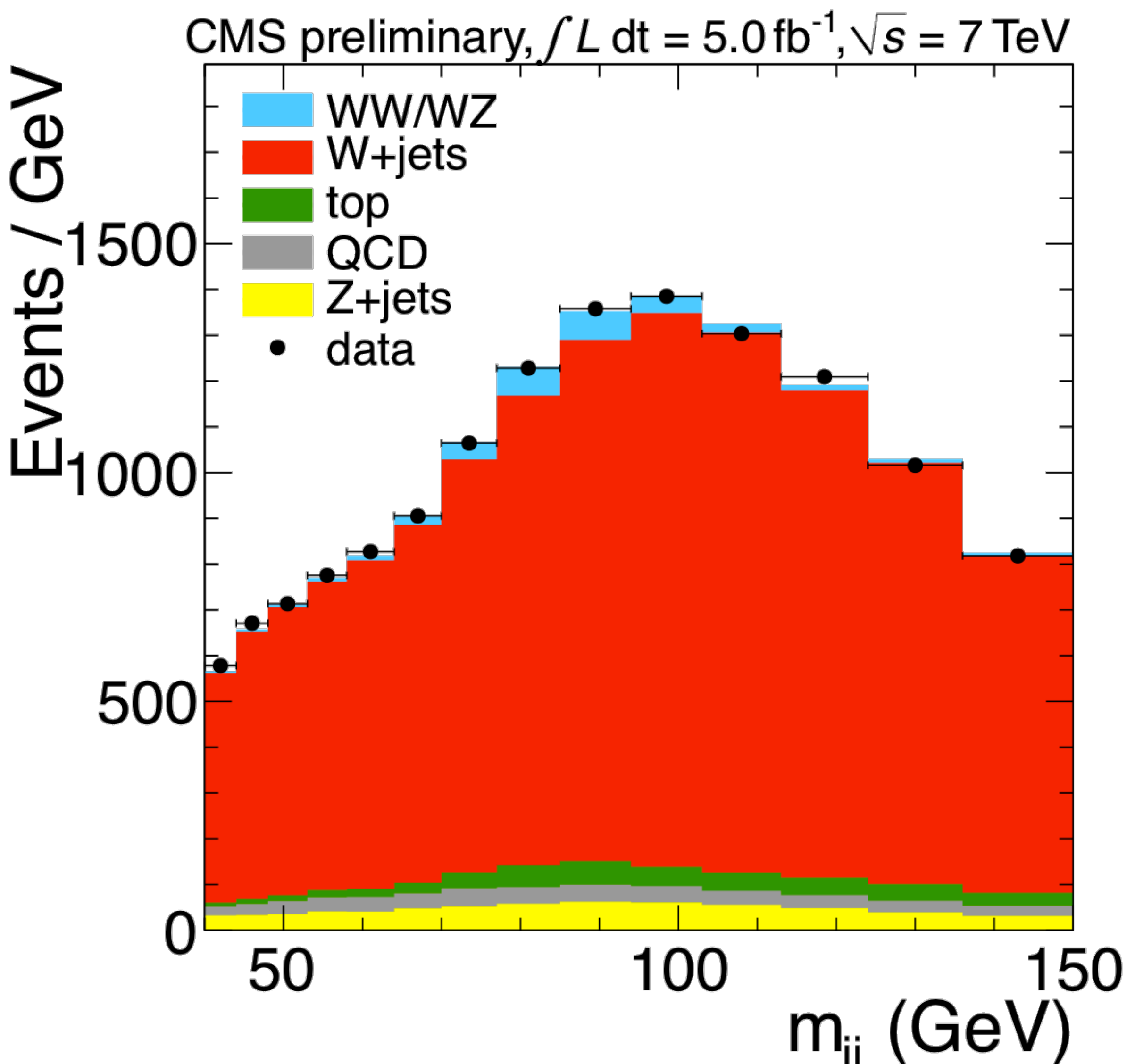


$$\sigma_{WW} = 69.9 \pm 2.8\ (\text{stat.}) \pm 5.6\ (\text{syst.}) \pm 3.1\ (\text{lumi.})\ \text{pb.}$$

Theory: $57.3^{+2.4}_{-1.6}$ pb (MCFM)

WW/WZ in dijets

- Key features:
  - Large branching ratio
  - Full handle on boson p_T
- Signature: Leptonically decaying W with exactly two non-b jets
- Background treatment:
  - Yields extracted via unbinned maximum likelihood fit to dijet invariant mass



- σ(WW+WZ) = 68.89 ± 8.71 (stat) ± 9.70 (syst) ± 1.52 (lumi) pb
  - Theory: 65.6 ± 2.2 pb

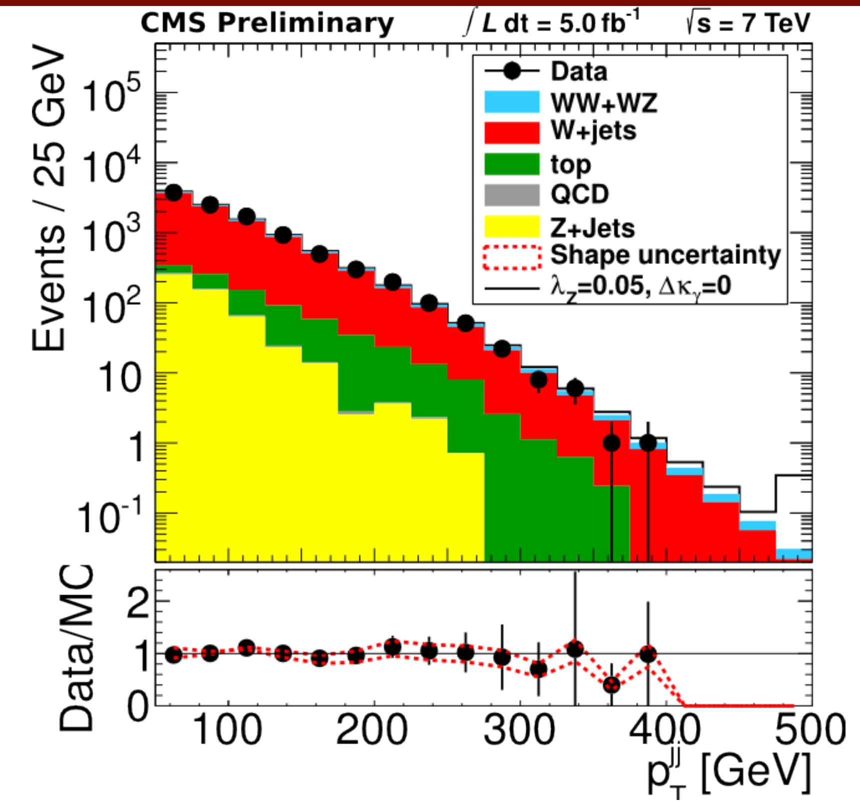
Process	Muon channel	Electron channel
Diboson (WW+WZ)	1899 ± 373	783 ± 306
W+jets	67384 ± 586	31644 ± 850
$t\bar{t}$	1662 ± 117	946 ± 67
Single top	650 ± 33	308 ± 17
Drell–Yan+jets	3609 ± 155	1408 ± 64
Multijet (QCD)	296 ± 317	4195 ± 867
Fit χ^2/dof (probability)	9.73/12 (0.64)	5.30/12 (0.95)
Total from fit	75420	39371
Data	75419	39365
Acceptance × efficiency ($\mathcal{A}\varepsilon$)	5.153×10^{-3}	2.633×10^{-3}
Expected WW+WZ yield from simulation	1697 ± 57	867 ± 29

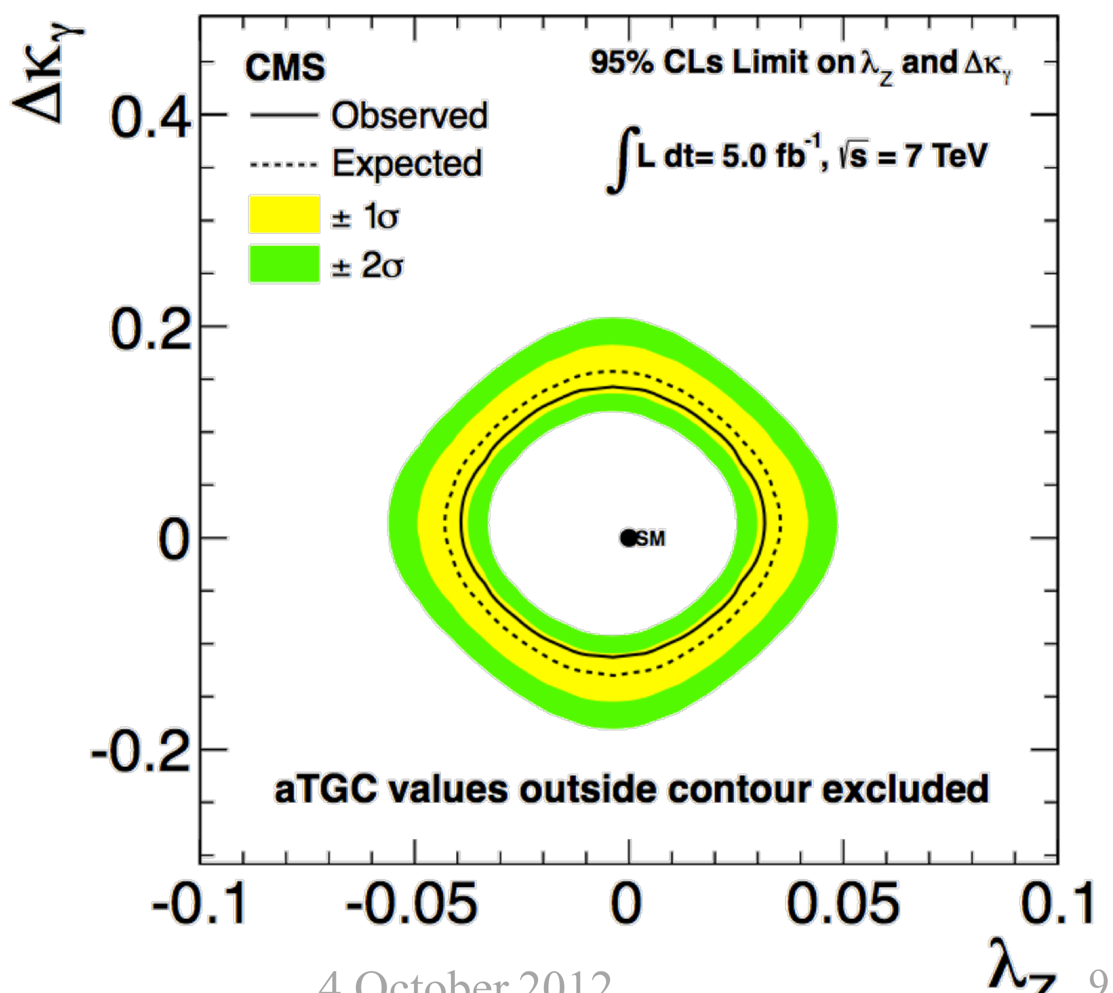
WW/WZ aTGC Limits

- Anomalous couplings parameterized via Δg^1_Z, λ_Z, and $\Delta\kappa_\gamma$
- Assume the SM value $\Delta g^1_Z = 0$, set limits on λ_Z and $\Delta\kappa_\gamma$
- Dijet pT chosen as observable
- Require:
  - $75 < m_{jj} < 90$ GeV
- Set 95% upper limit in (λ_Z, $\Delta\kappa_\gamma$) space using CLs methodology

$-0.038 < \lambda_Z < 0.030$

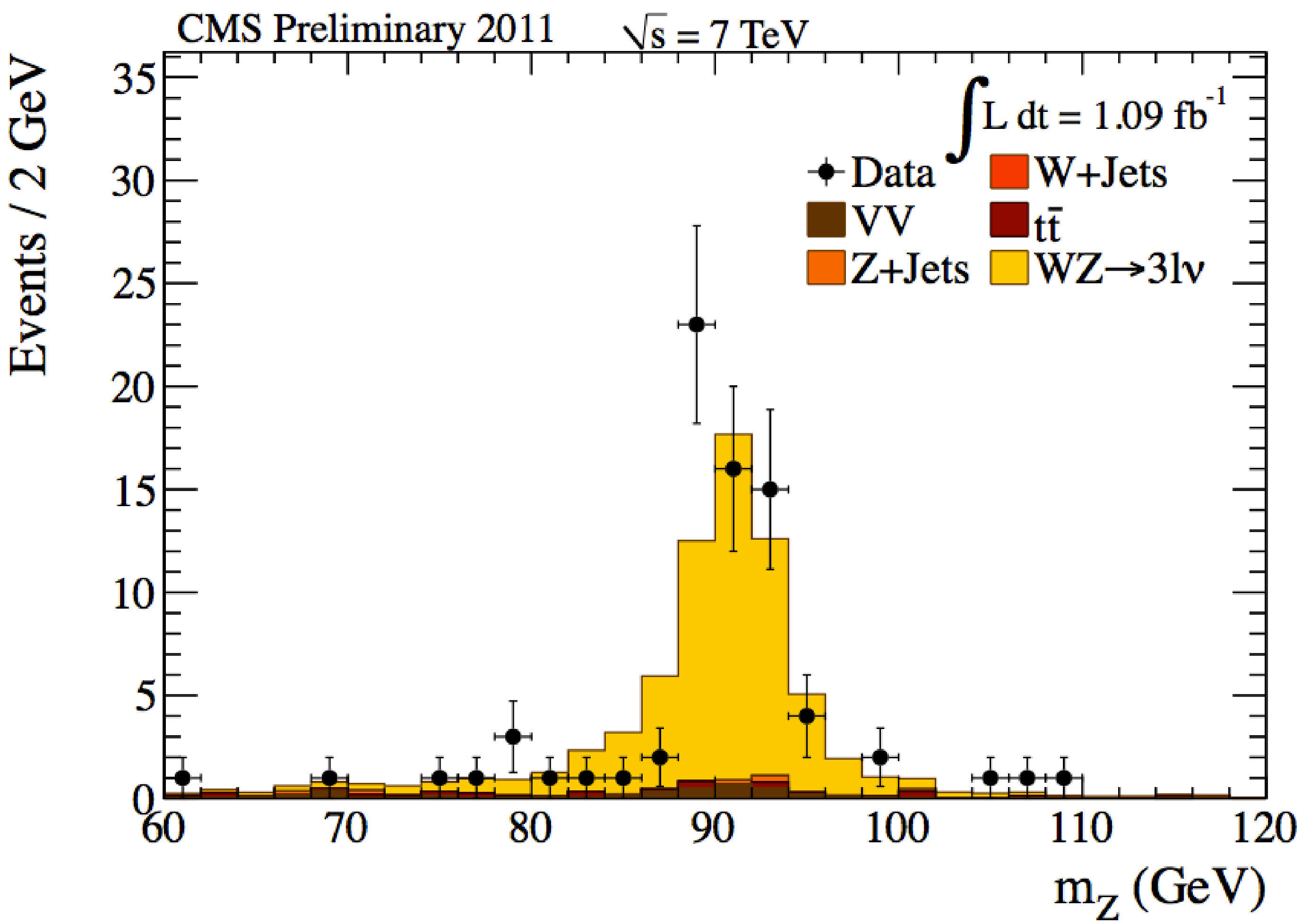
$-0.111 < \Delta\kappa_\gamma < 0.142$





WZ→3lν (1.09 fb^{-1} @ 7 TeV)

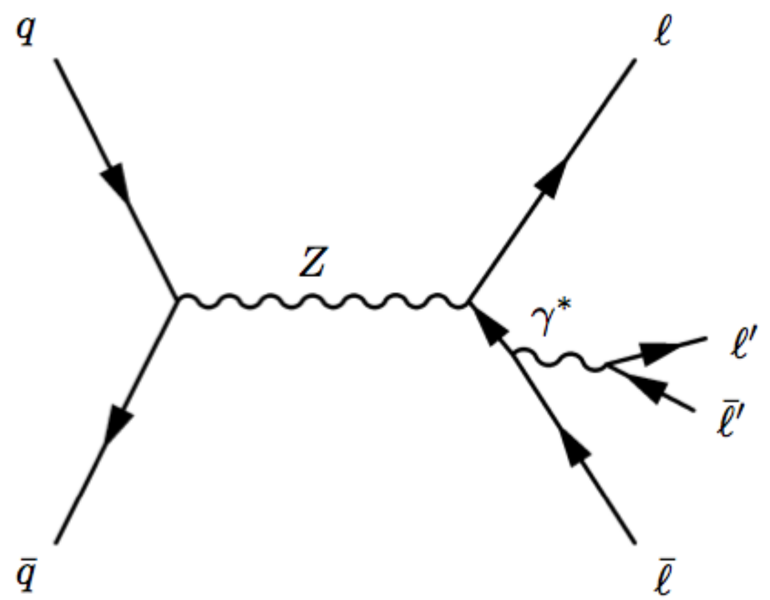
- Signature:
  - Two leptons consistent with $60 \leq M_{ll} \leq 120$, third lepton $+ME_T$
- Backgrounds:
  - Data-driven: Z+Jets, ttbar
  - From MC:
    - ZZ→4l, Zγ, WZ to τ decays
- Key systematics: Efficiency, theory, background estimations

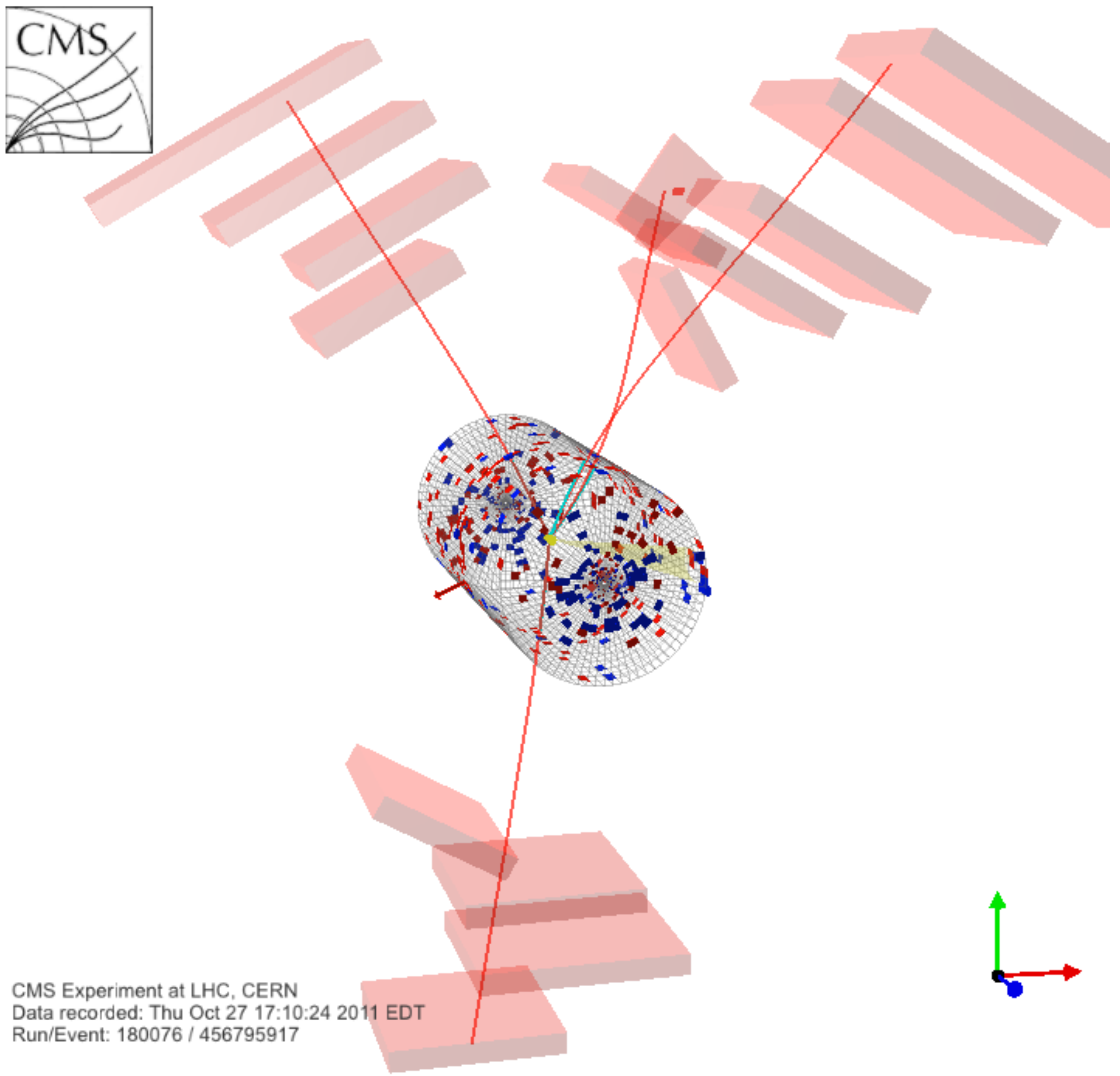


channel	$N_{observed}$	cross section (pb)
$\sigma_{WZ\to eee\nu}$	22	$0.086 \pm 0.022(stat) \pm 0.007(syst) \pm 0.005(lumi)$
$\sigma_{WZ\to ee\mu\nu}$	20	$0.060 \pm 0.017(stat) \pm 0.005(syst) \pm 0.004(lumi)$
$\sigma_{WZ\to \mu\mu e\nu}$	13	$0.053 \pm 0.018(stat) \pm 0.004(syst) \pm 0.003(lumi)$
$\sigma_{WZ\to \mu\mu\mu\nu}$	20	$0.060 \pm 0.016(stat) \pm 0.004(syst) \pm 0.004(lumi)$

$$\sigma(pp \to \mathrm{WZ} + X) = 17.0 \pm 2.4\ (\mathrm{stat.}) \pm 1.1\ (\mathrm{syst.}) \pm 1.0\ (\mathrm{lumi.})\ \mathrm{pb}.$$

Theory: 17.5 ± 0.6 pb (MCFM)

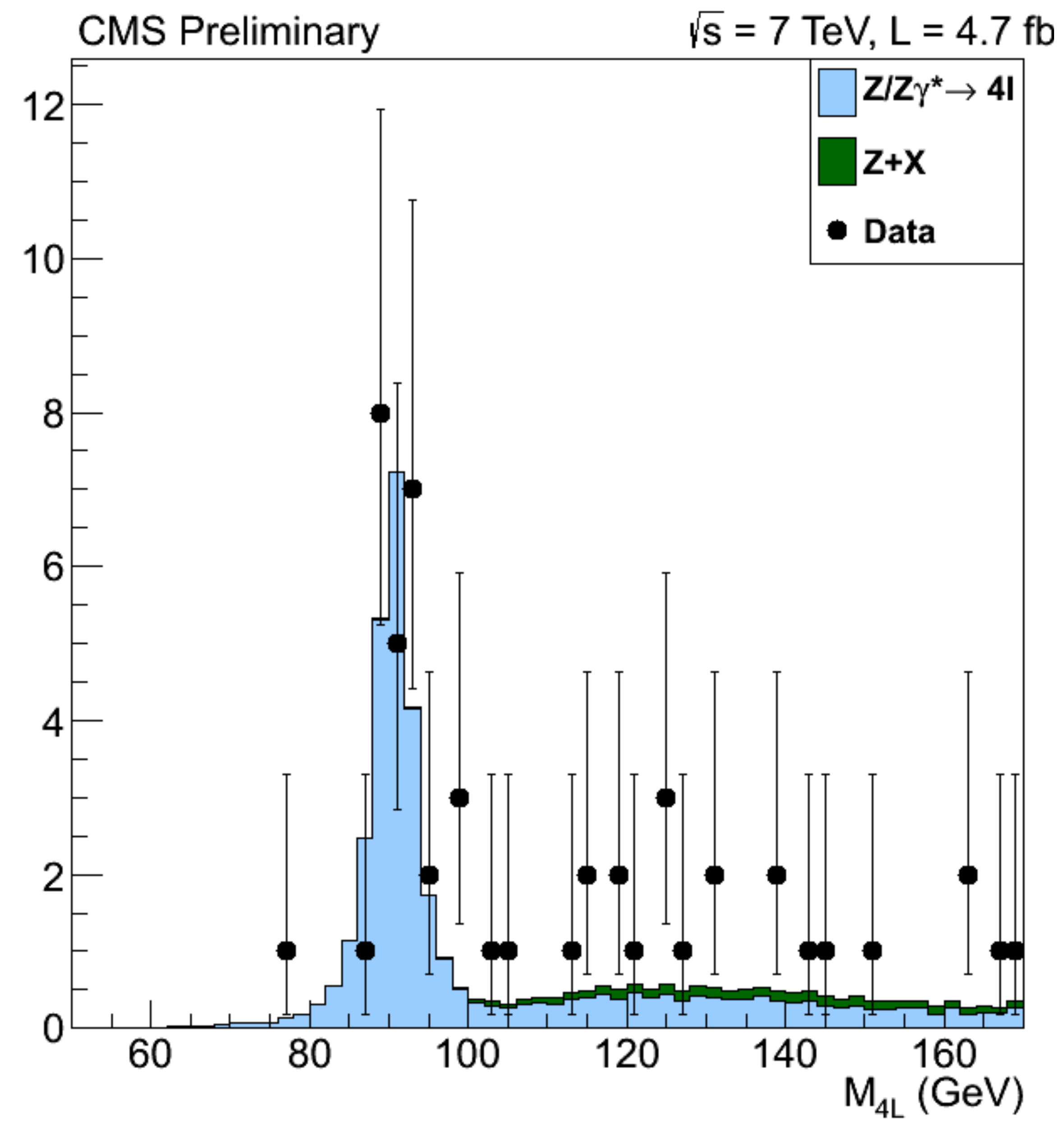




- First observation of $Z \rightarrow 4l$ peak at a hadron collider
- Key backgrounds:
  - $pp \rightarrow Z\gamma^* \rightarrow 4l$ (from MC)
  - Z+X (from Data)
- Define signal region as $80 < M_{4L} < 100$ GeV

$Z \rightarrow 4l$

Final state channels	$4e$	4μ	$2e2\mu$	4ℓ
Irreducible background ($pp \rightarrow Z\gamma^* \rightarrow 4\ell$)	0.04	0.16	0.08	0.3 ± 0.03
Other reducible backgrounds	0.01	0.01	0.05	0.1 ± 0.13
Expected signal ($pp \rightarrow Z \rightarrow 4\ell$)	3.1	12.3	9.2	24.6 ± 2.2
Total expected (MC)	3.2	12.5	9.3	25.0 ± 2.2
Observed events	2	14	10	26
Rate from the fit of the observed mass distribution		13.6	9.7	25.4

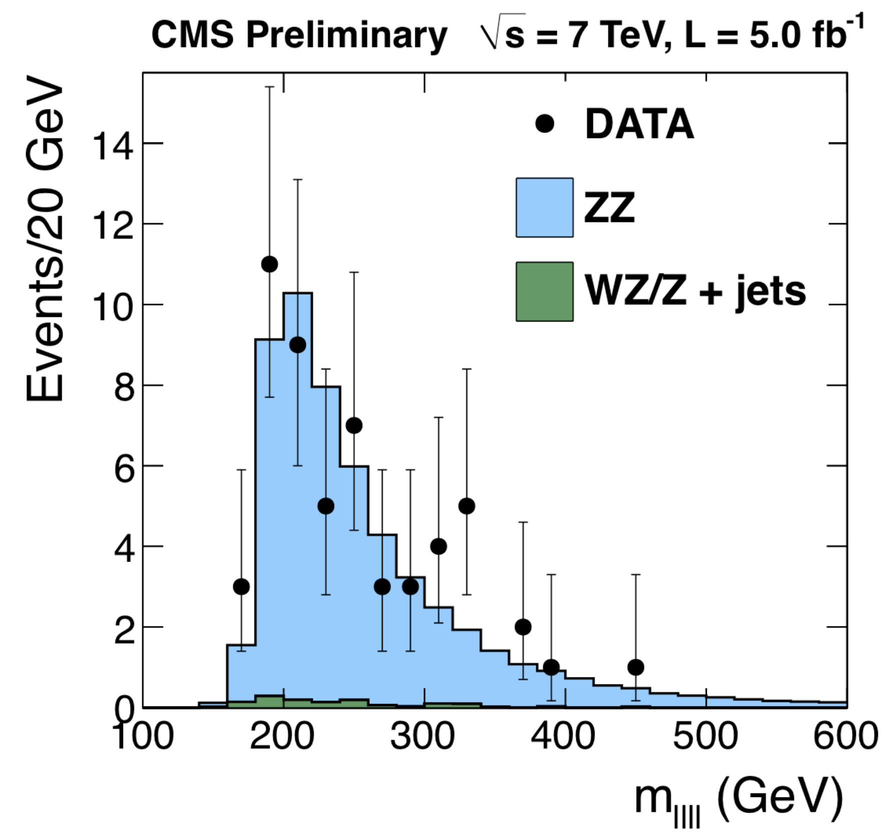


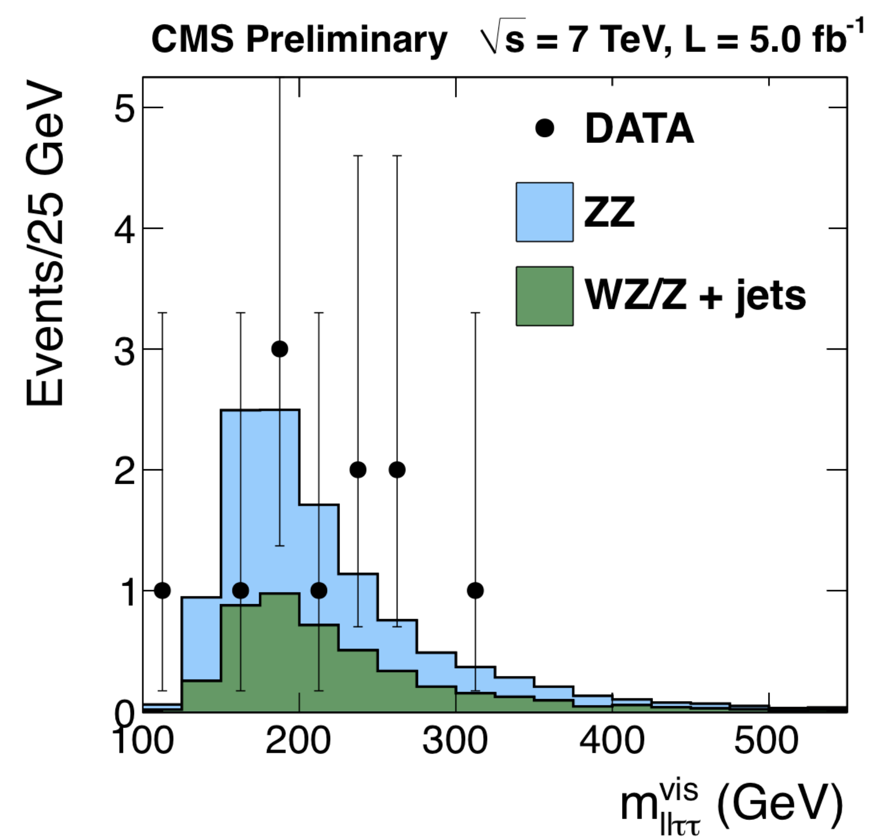
- 26 events observed, 24.6 expected signal, 0.4 expected background
- σ x BR($Z \rightarrow 4l$) = $125\,_{-23}^{+26}$ (stat.) $_{-6}^{+9}$ (syst.) $_{-5}^{+7}$ (lumi) fb

- Measured BR($Z \rightarrow 4l$) = $4.4\,_{-0.8}^{+1.0}$ (stat.) ±0.2 (syst.) x 10^{-6}
  - Theory: 4.45 x 10^{-6} (CalcHEP)

ZZ→4l Analysis Overview

- Key features:
  - ZZ→4l (l=e, μ) provides clean signature
    - Low background, high resolution ideal for Higgs physics
    - Beyond the Standard Model (ZZ decays of new particles, aTGCs)
  - 2l2τ states included in cross-section measurements (~10-15% additional yield)
- Signature: four leptons with $60 \leq M_{Z1}, M_{Z2} \leq 120$ ($30 \leq M_{vis} \leq 80$ for ττ legs)
- Background treatment:
  - Z+jets/WZ/ttbar, extracted from data via applying lepton fake rates to regions where one or both leptons fail selection criteria





$ZZ \rightarrow 4l$ 7 TeV Results

Decay channel	N_{ZZ}^{exp}	Background	Total expected	Observed
$\mu\mu\mu\mu$	$15.91 \pm 0.05 \pm 1.43$	$0.52 \pm 0.26 \pm 0.25$	$16.43 \pm 0.26 \pm 1.45$	14
eeee	$10.50 \pm 0.04 \pm 0.95$	$0.25 \pm 0.14 \pm 0.07$	$10.75 \pm 0.14 \pm 0.95$	9
$\mu\mu ee$	$26.74 \pm 0.10 \pm 2.41$	$0.58 \pm 0.18 \pm 0.23$	$27.32 \pm 0.17 \pm 2.41$	31
$\mu\mu\tau_h\tau_h$	$0.82 \pm 0.02 \pm 0.07$	$0.75 \pm 0.16 \pm 0.08$	$1.57 \pm 0.16 \pm 0.11$	0
$ee\tau_h\tau_h$	$0.75 \pm 0.01 \pm 0.07$	$0.76 \pm 0.16 \pm 0.05$	$1.51 \pm 0.16 \pm 0.09$	1
$ee\tau_e\tau_h$	$1.17 \pm 0.02 \pm 0.11$	$0.96 \pm 0.34 \pm 0.12$	$2.29 \pm 0.34 \pm 0.16$	3
$\mu\mu\tau_e\tau_h$	$1.15 \pm 0.02 \pm 0.10$	$0.35 \pm 0.34 \pm 0.11$	$1.60 \pm 0.34 \pm 0.15$	3
$\mu\mu\tau_\mu\tau_h$	$1.08 \pm 0.02 \pm 0.10$	$0.55 \pm 0.24 \pm 0.11$	$1.64 \pm 0.24 \pm 0.15$	2
$ee\tau_\mu\tau_h$	$0.94 \pm 0.02 \pm 0.08$	$0.22 \pm 0.14 \pm 0.04$	$1.17 \pm 0.14 \pm 0.06$	0
$ee\tau_e\tau_\mu$	$0.54 \pm 0.01 \pm 0.05$	$0.64 \pm 0.44 \pm 0.16$	$1.22 \pm 0.44 \pm 0.17$	0
$\mu\mu\tau_e\tau_\mu$	$0.60 \pm 0.01 \pm 0.05$	$0.14 \pm 0.30 \pm 0.10$	$0.74 \pm 0.30 \pm 0.11$	2

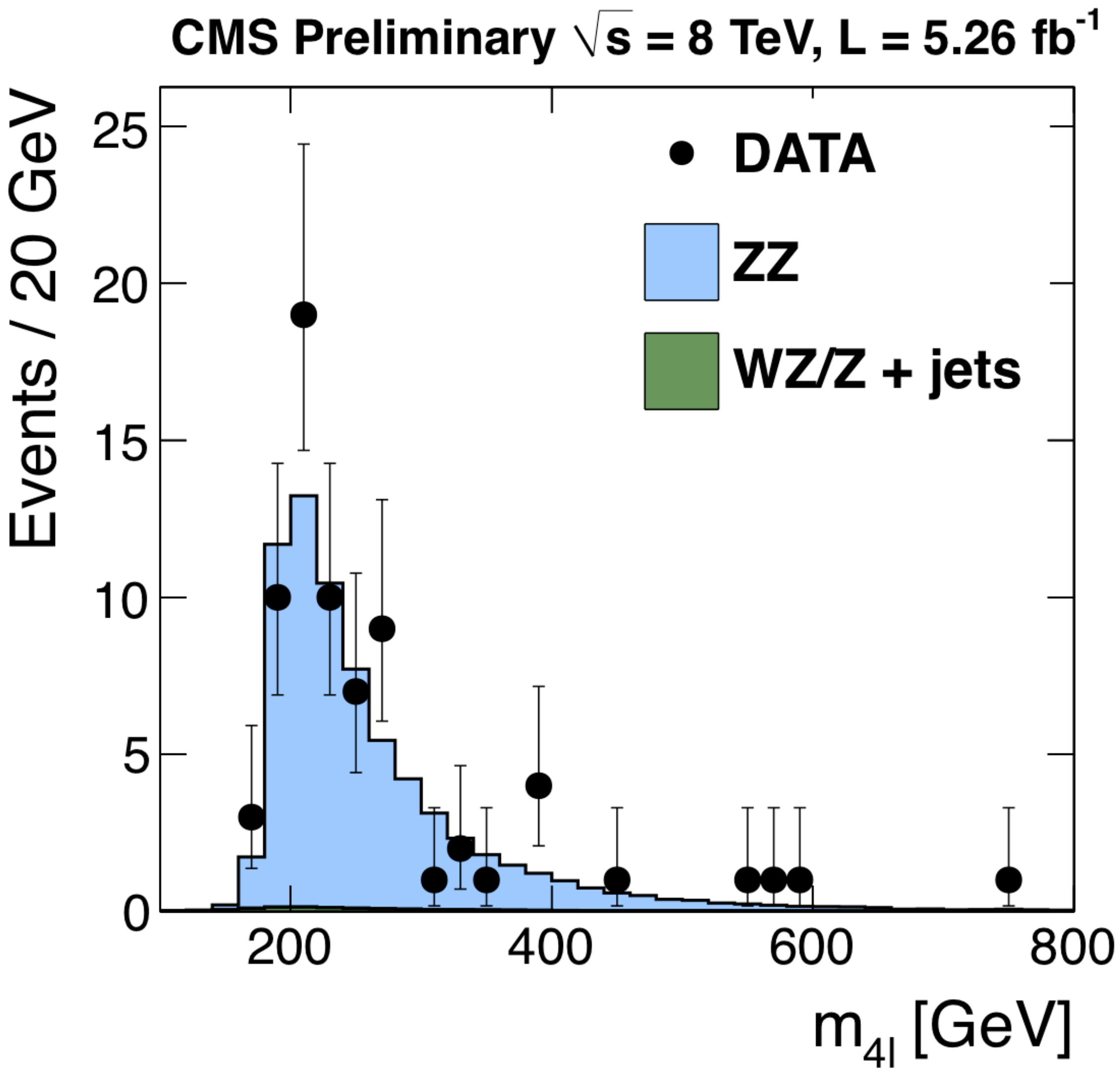
4l Total:
54 observed,
54.6 expected
(53.2+1.4)

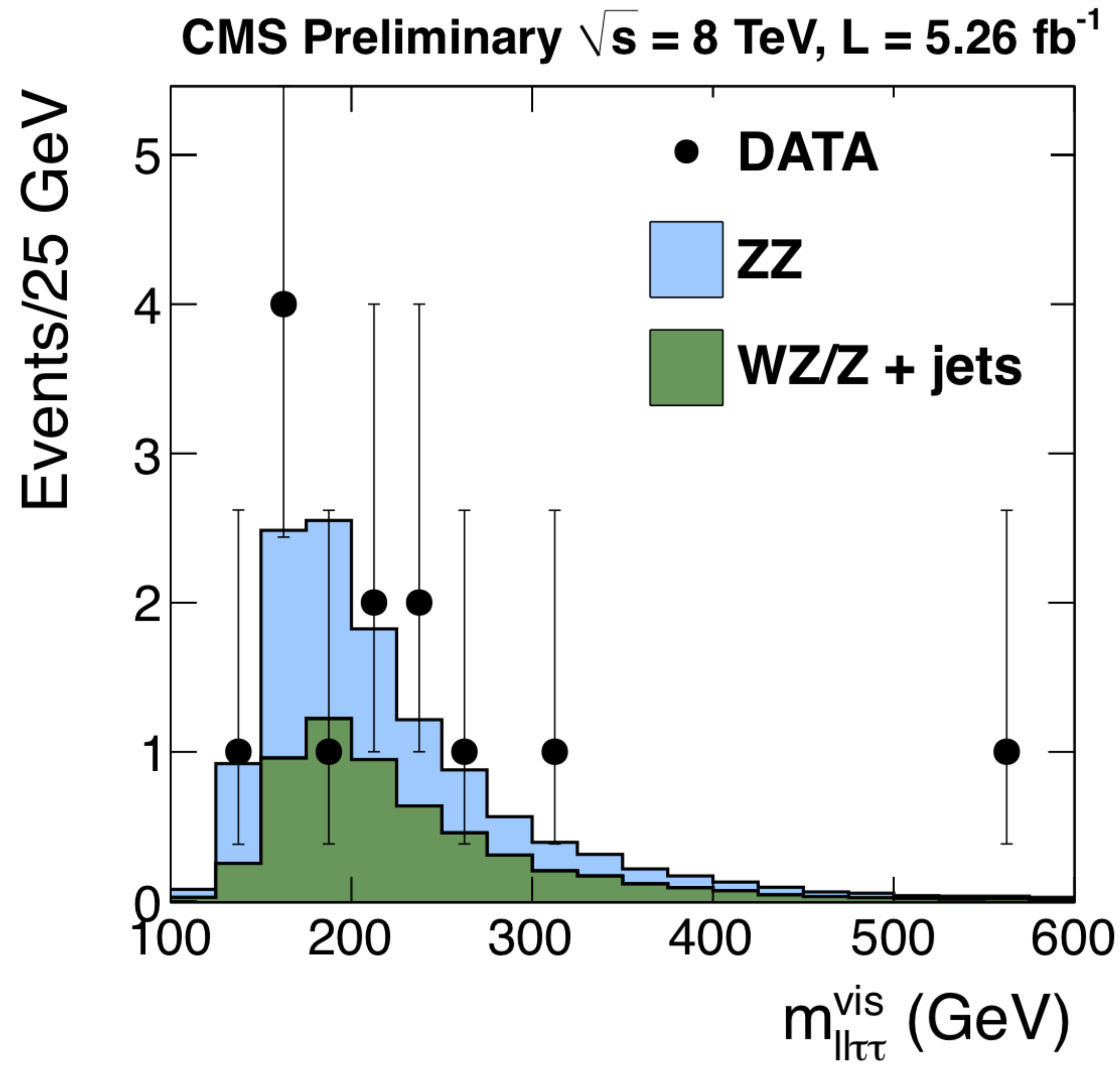
2l2τ Total:
11 observed,
11.5 expected
(7.1+4.4)

$$\sigma(pp \rightarrow ZZ) = 6.24^{+0.86}_{-0.80}(stat.)^{+0.41}_{-0.32}(sys.) \pm 0.14(lumi.) \text{ pb}$$

Theory: 6.3 ± 0.4 pb (MCFM)

ZZ→4l 8 TeV Results



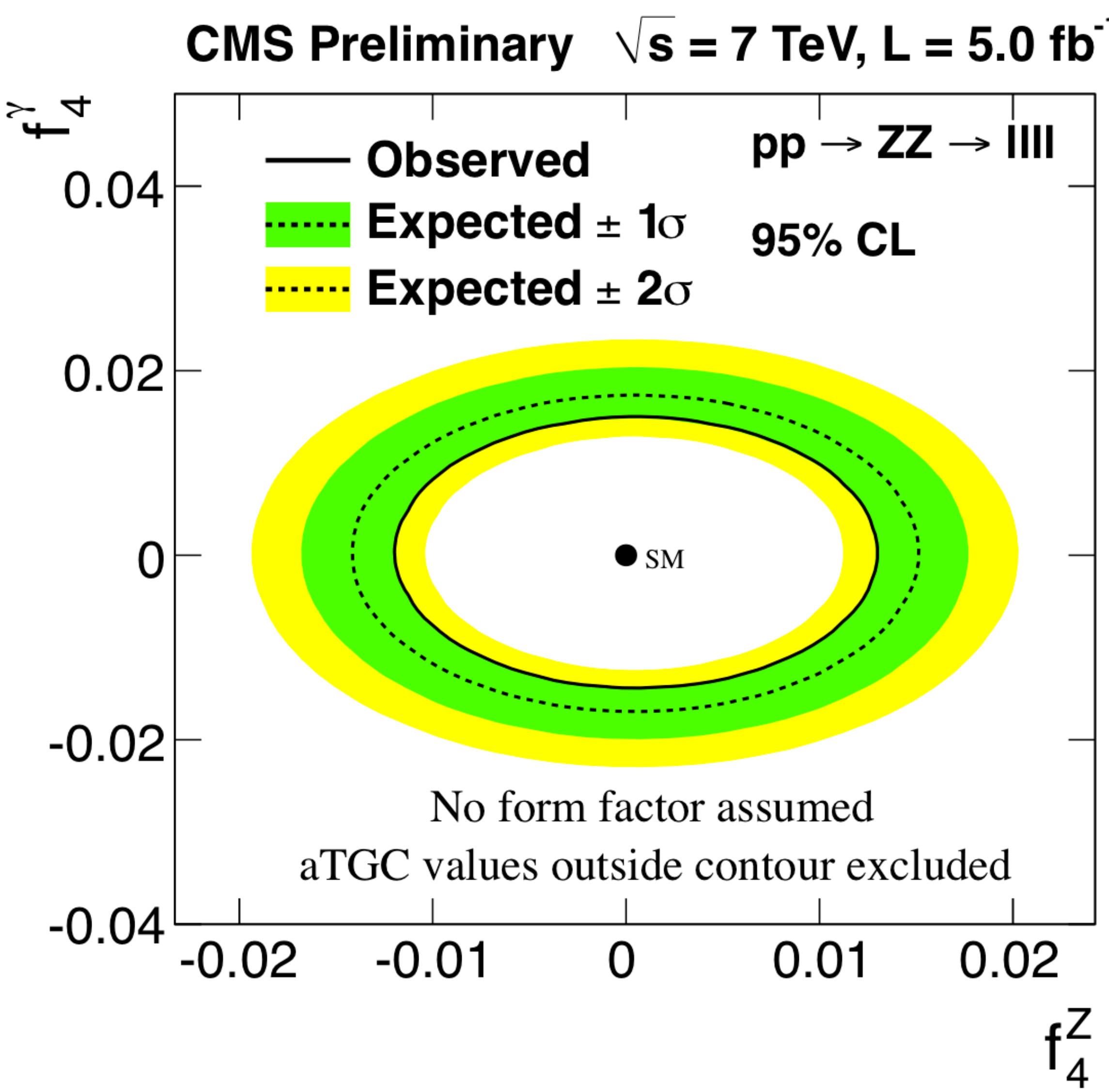


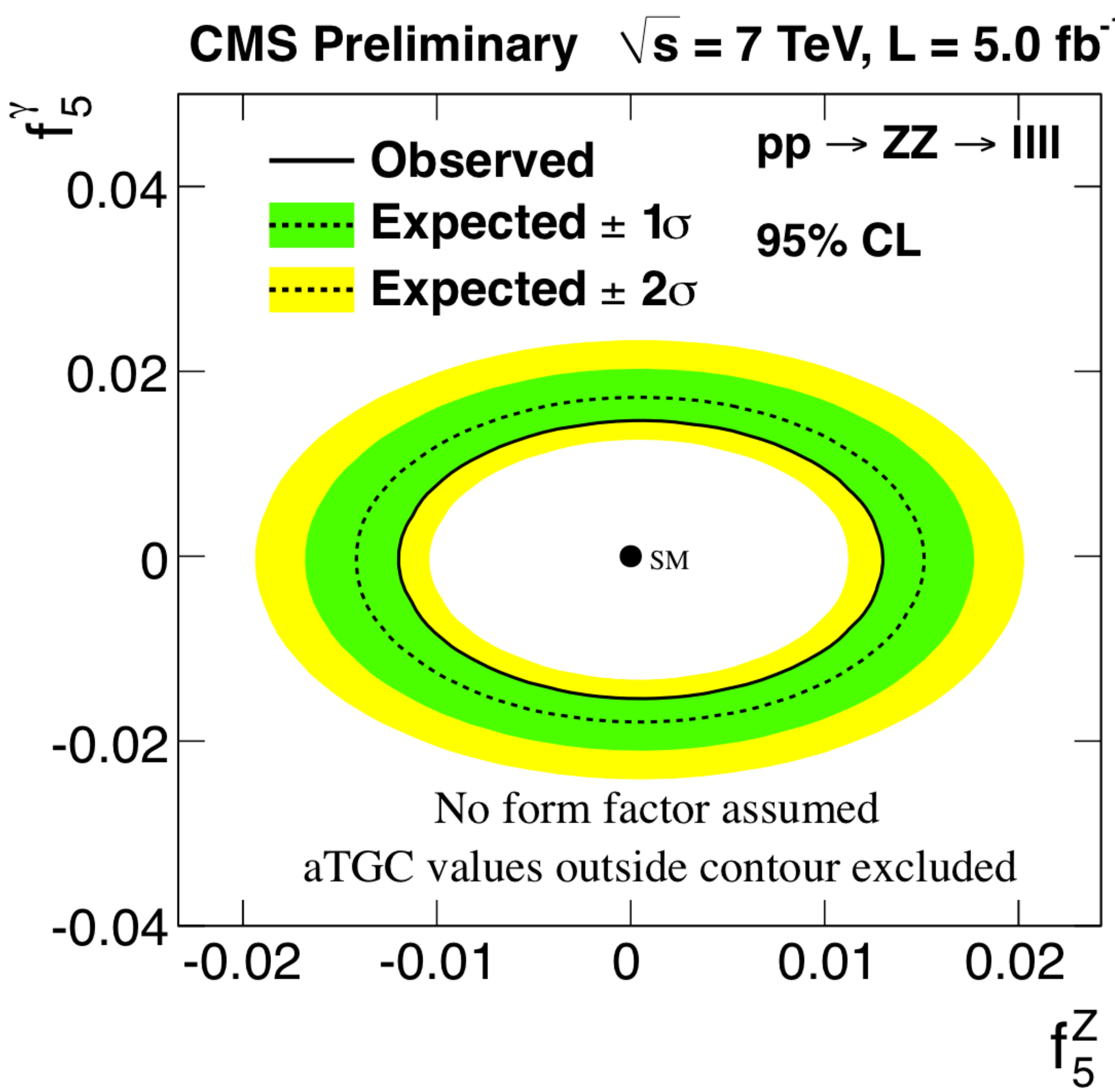
Channel	4e	4μ	$2e2\mu$	$2\ell 2\tau$
ZZ	11.6 ± 1.4	20.3 ± 2.2	32.4 ± 3.5	6.5 ± 0.8
Background	0.4 ± 0.2	0.4 ± 0.3	0.5 ± 0.4	5.6 ± 1.4
Total	12.0 ± 1.4	20.7 ± 2.2	32.9 ± 3.5	12.1 ± 1.6
Observed	14	19	38	13

- $\sigma(pp \to ZZ) = 8.4 \pm 1.0(\text{stat.}) \pm 0.7(\text{sys.}) \pm 0.4(\text{lumi.})$ pb

Theory: 7.7 ± 0.4 pb (MCFM)

- ZZZ/ZZγ vertex described with $f_4^{Z/\gamma}$ and $f_5^{Z/\gamma}$ couplings
- 4l invariant mass used as discriminating variable
- Limits set using CLs methodology





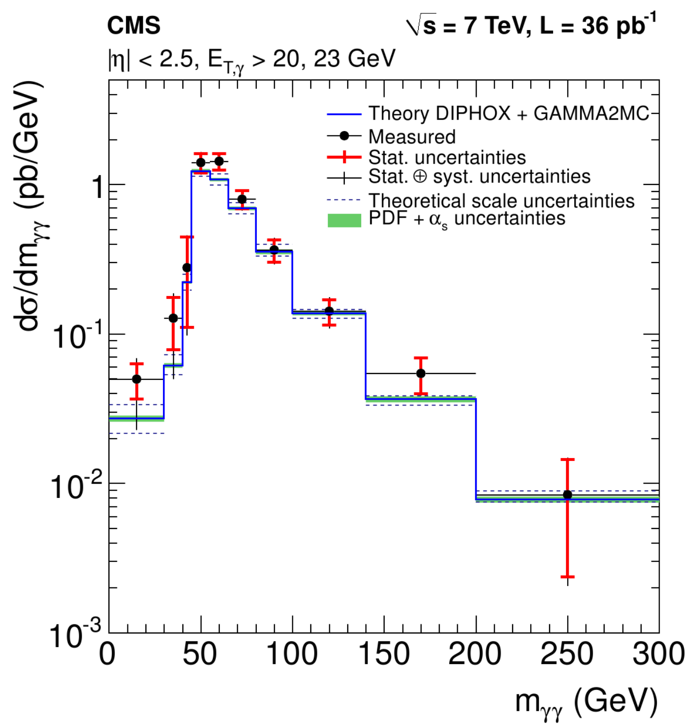
$-0.012 < f_4^Z < 0.013$

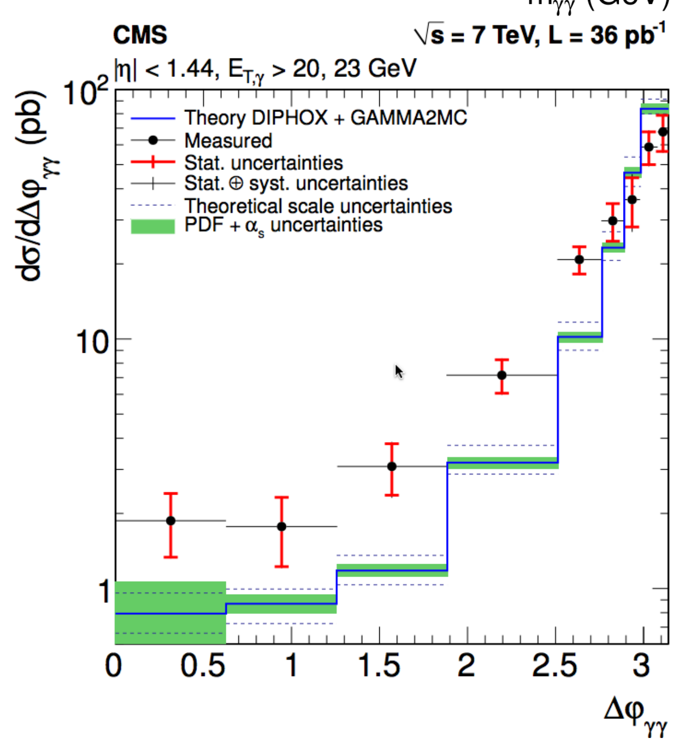
$-0.012 < f_5^Z < 0.013$

$-0.014 < f_4^\gamma < 0.014$

$-0.015 < f_5^\gamma < 0.015$

2010 Results, γγ and Vγ

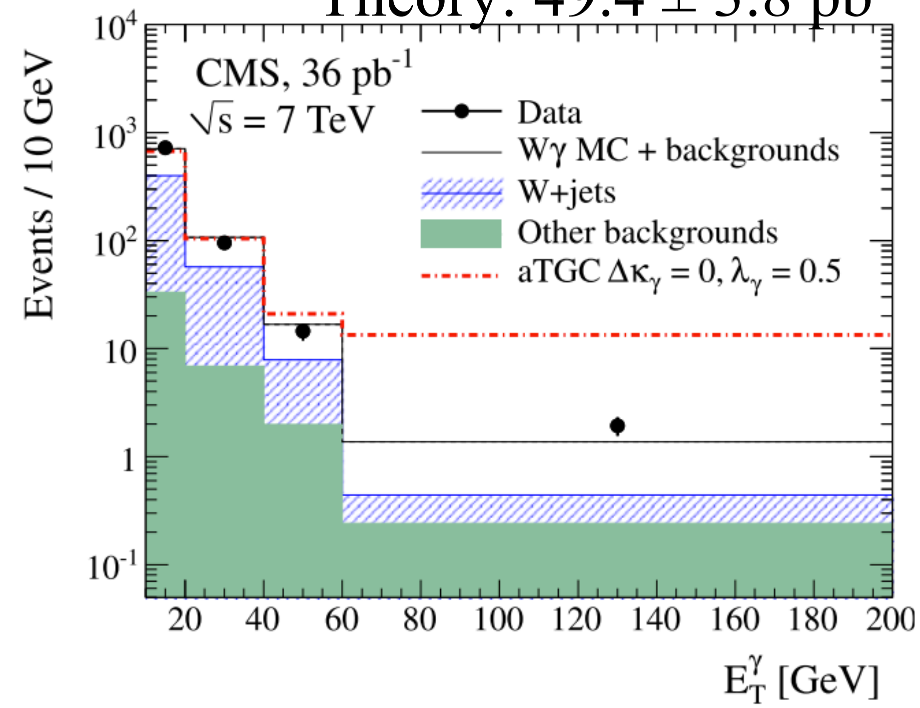


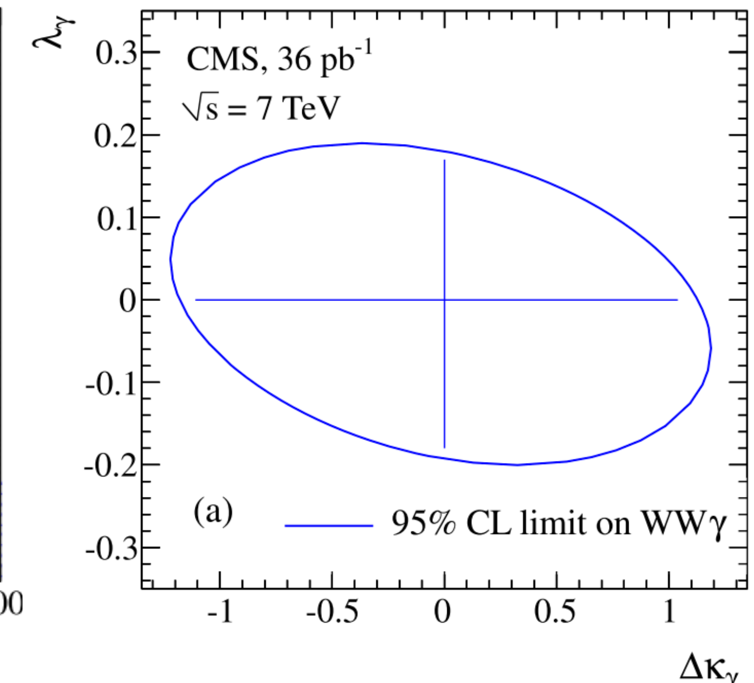


- Discrepancy observed in $\Delta\varphi_{\gamma\gamma} < 2.8$

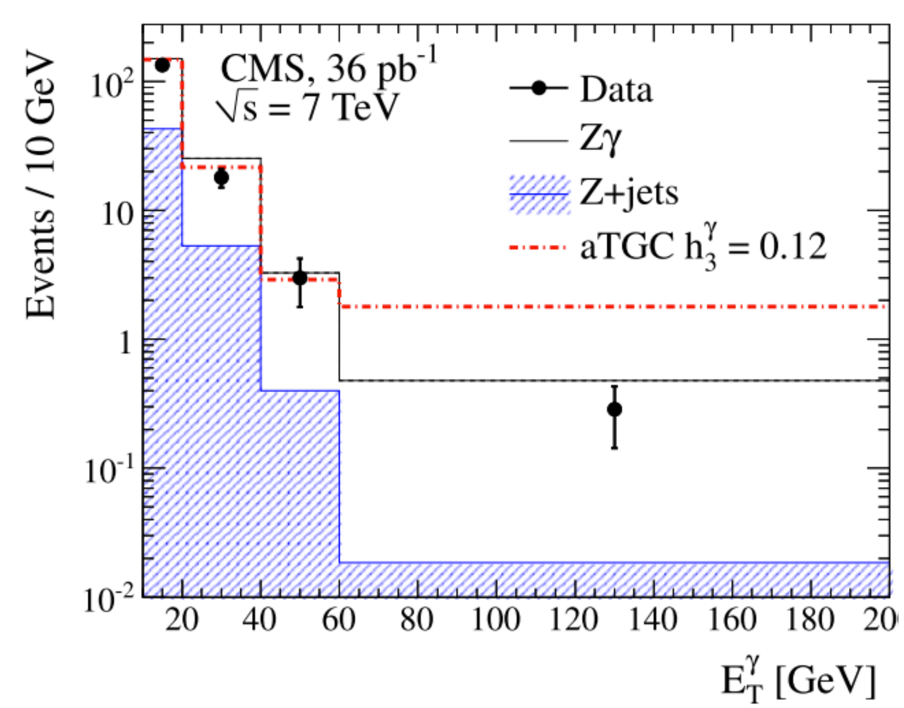
- $\sigma(pp \to W\gamma + X) \times B(W \to l\nu) = 56.3 \pm 7.4$ pb

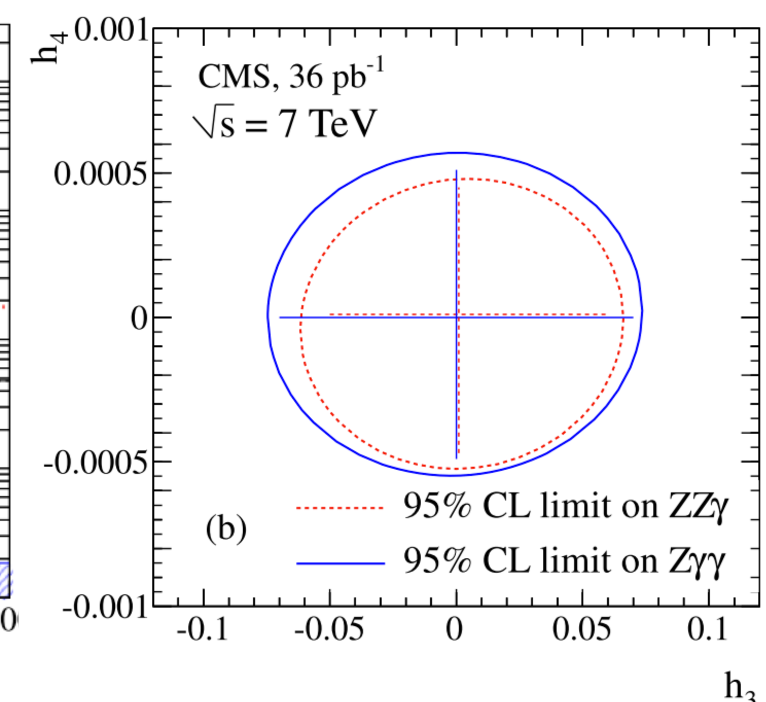
Theory: 49.4 ± 3.8 pb





- $\sigma(pp \to Z\gamma + X) \times B(Z \to ll) = 9.4 \pm 1.2$ pb
  - Theory: 9.6 ± 0.4 pb





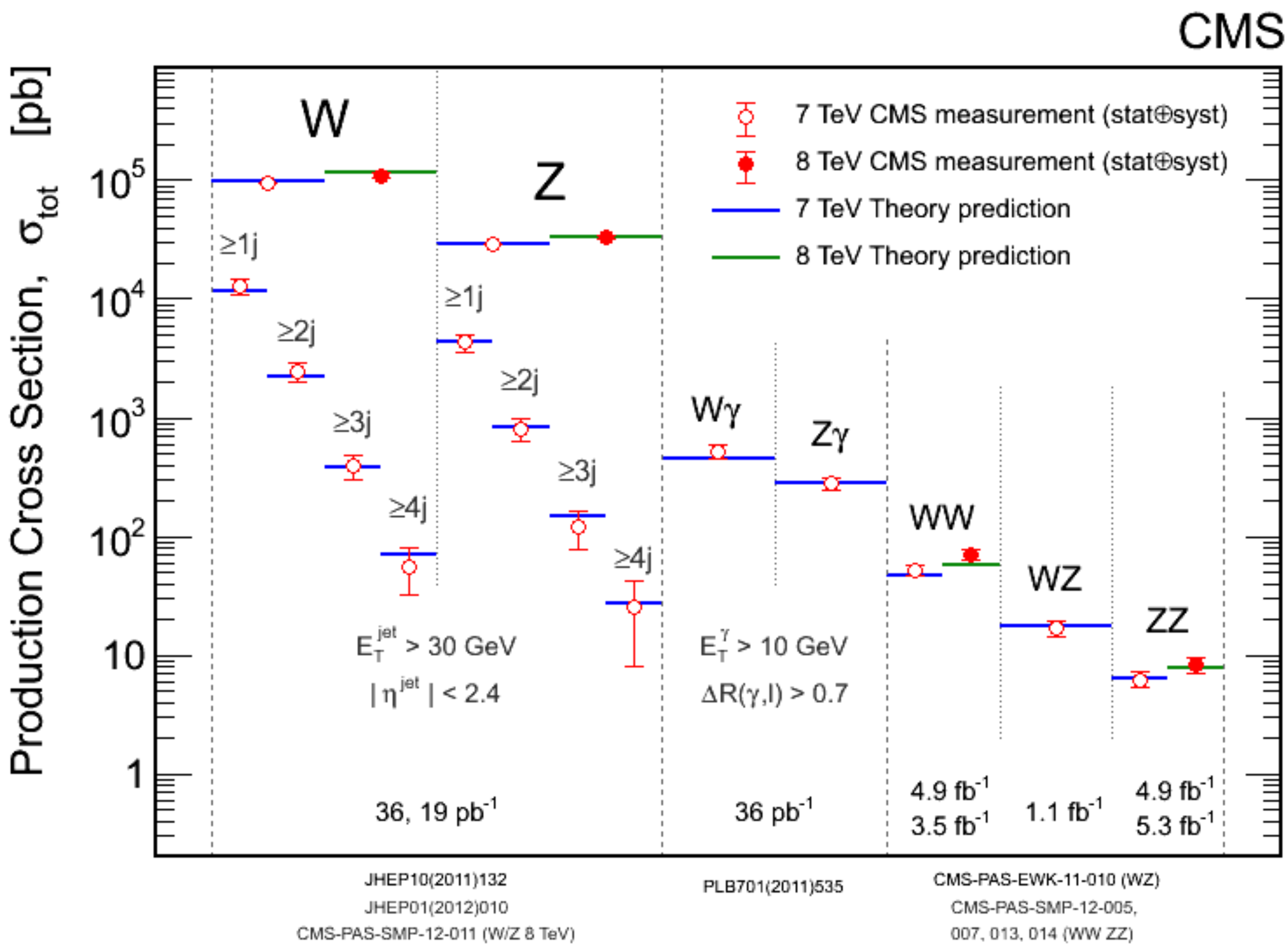
Conclusions

- Diboson production measurements at CMS indicate good agreement with Standard Model predictions

- aTGC limits have been produced in a handful of couplings, with sensitivity comparable to (or better than) current LEP and Tevatron limits

- New measurements and updates coming soon!

CMS Boson Measurement outlook

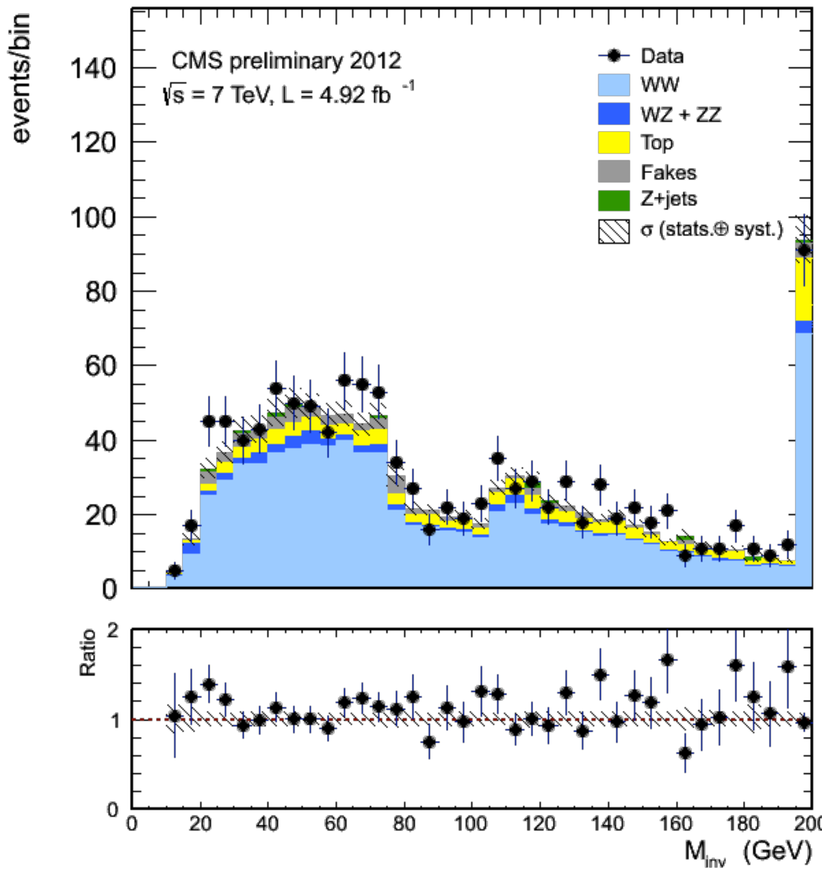


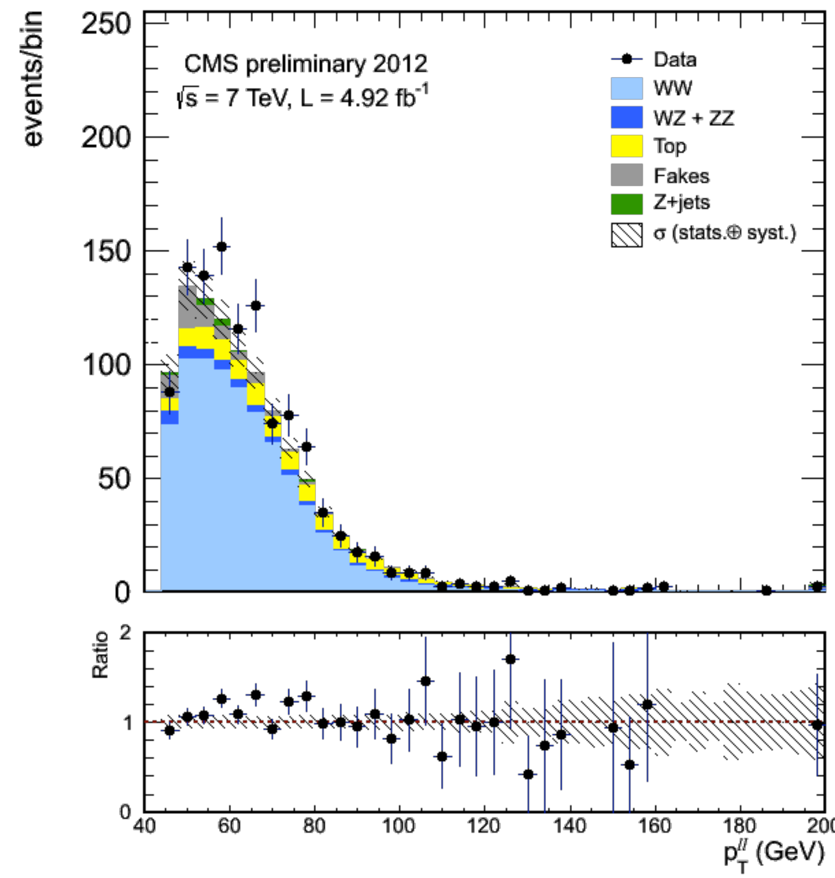
Backup

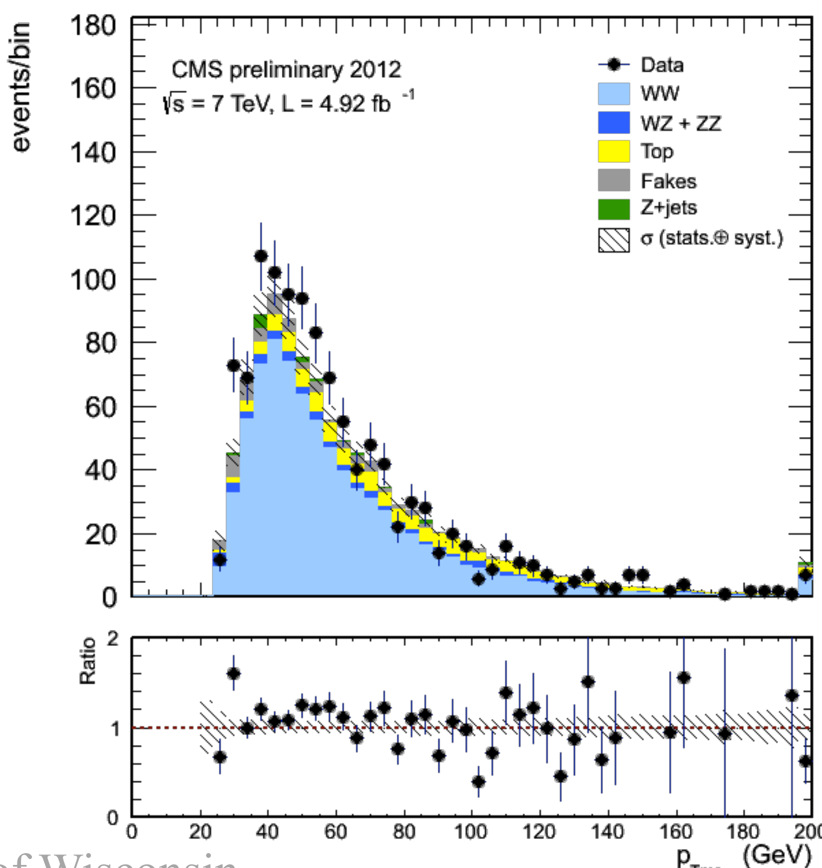
WW, 7 TeV Systematics

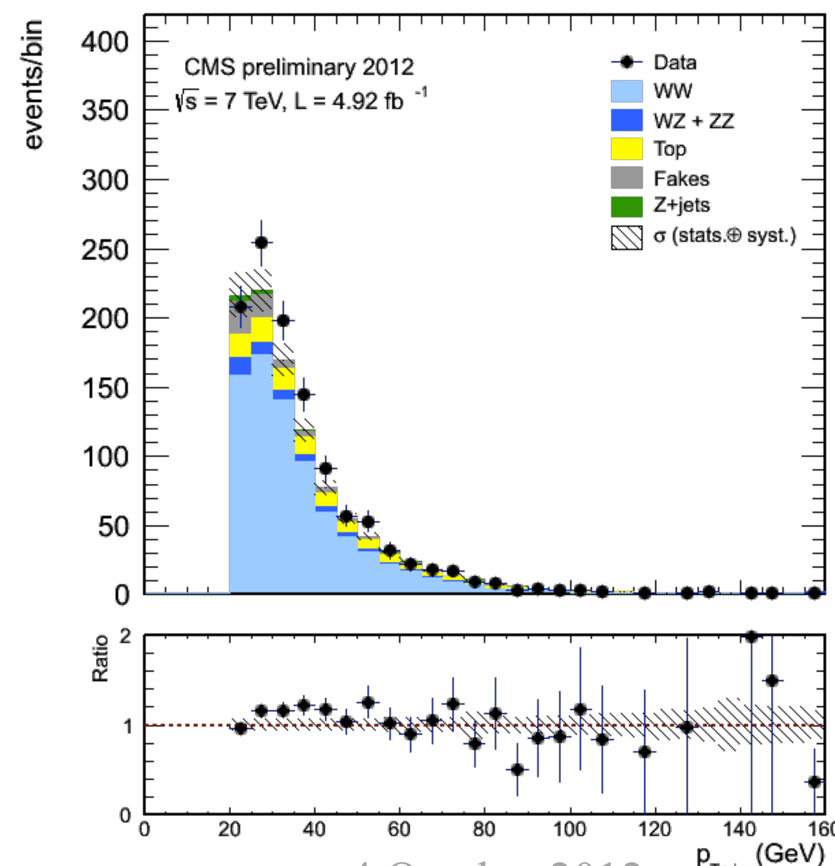
	$q\bar{q} \rightarrow W^+W^-$	$gg \rightarrow W^+W^-$	top	$W+$jets	WZ +ZZ	$Z/\gamma* \rightarrow \ell\ell$	$W+\gamma$	$W+\gamma^*$	$Z/\gamma* \rightarrow \tau\tau$
Luminosity	2.2	2.2	-	-	2.2	-	2.2	-	-
Trigger efficiency	1.5	1.5	-	-	1.5	-	1.5	-	-
Lepton id efficiency	2.0	2.0	-	-	2.0	-	2.0	-	-
Muon momentum scale	1.5	1.5	-	-	1.5	-	1.5	-	-
Electron energy scale	2.5	2.5	-	-	1.9	-	2.0	-	-
E_T^{miss} resolution	2.0	2.0	-	-	2.0	-	2.0	-	-
Jet veto efficiency	4.7	4.7	-	-	4.7	-	4.7	-	-
pile-up	2.3	2.3	-	-	2.3	-	2.3	-	-
top normalisation	-	-	18	-	-	-	-	-	-
$W+$jets normalisation	-	-	-	36.0	-	-	-	-	-
$Z/\gamma^* \rightarrow \ell^+\ell^-$ normalisation	-	-	-	-	-	50.0	-	-	-
$W+\gamma$ normalisation	-	-	-	-	-	-	30.0	-	-
$W+\gamma^*$ normalisation	-	-	-	-	-	-	-	30.0	-
$Z/\gamma^* \rightarrow \tau^+\tau^-$ normalisation	-	-	-	-	-	-	-	-	10.0
PDFs	2.3	0.8	-	-	5.9	-	-	-	-
Higher order corrections	1.5	30.0	-	-	3.3	-	-	-	-
Sample statistics	0.8	1.3	-	6.6	1.5	-	48.9	10.3	15.9

WW 7 TeV


CMS preliminary 2012
√s = 7 TeV, L = 4.92 fb⁻¹
Data
WW
WZ + ZZ
Top
Fakes
Z+jets
σ (stats.⊕ syst.)
events/bin
Ratio
M_inv (GeV)


CMS preliminary 2012
√s = 7 TeV, L = 4.92 fb⁻¹
Data
WW
WZ + ZZ
Top
Fakes
Z+jets
σ (stats.⊕ syst.)
events/bin
Ratio
p_T^ll (GeV)

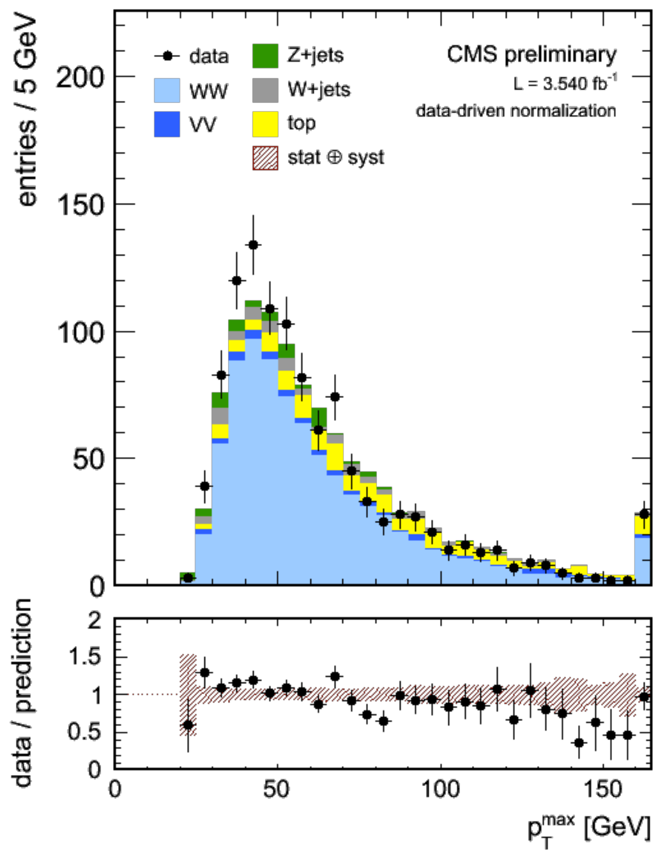

CMS preliminary 2012
√s = 7 TeV, L = 4.92 fb⁻¹
Data
WW
WZ + ZZ
Top
Fakes
Z+jets
σ (stats.⊕ syst.)
events/bin
Ratio
p_Tmax (GeV)


CMS preliminary 2012
√s = 7 TeV, L = 4.92 fb⁻¹
Data
WW
WZ + ZZ
Top
Fakes
Z+jets
σ (stats.⊕ syst.)
events/bin
Ratio
p_Tmin (GeV)

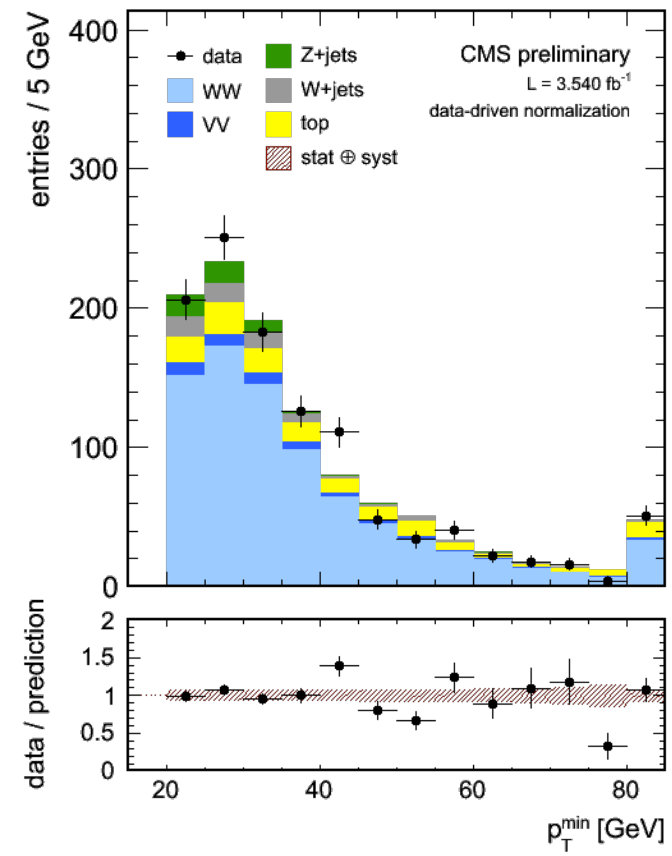
WW, 8 TeV Systematics

	$q\bar{q} \to WW$	$gg \to WW$	top	W+jets	$WZ + ZZ$	$Z/\gamma*$	$W+\gamma$	$W+\gamma^*$
Luminosity	5.0	5.0	-	-	5.0	-	5.0	-
Trigger efficiency	1.5	1.5	-	-	1.5	-	1.5	-
Lepton id efficiency	2.0	2.0	-	-	2.0	-	2.0	-
Muon momentum scale	1.5	1.5	-	-	1.5	-	1.5	-
Electron energy scale	2.5	2.5	-	-	1.9	-	2.0	-
E_T^{miss} resolution	2.0	2.0	-	-	2.0	-	2.0	-
Jet veto efficiency	4.7	4.7	-	-	4.7	-	4.7	-
pile-up	2.3	2.3	-	-	2.3	-	2.3	-
top normalisation	-	-	$9 \oplus 13$	-	-	-	-	-
W*jets* normalisation	-	-	-	$7 \oplus 36$	-	-	-	-
Z normalisation	-	-	-	-	-	$36 \oplus 20$	-	-
$W+\gamma$ normalisation	-	-	-	-	-	-	30	-
$W+\gamma^*$ normalisation	-	-	-	-	-	-	-	30
PDFs	2.3	0.8	-	-	5.9	-	-	-
Higher order corrections	1.5	30.0	-	-	3.3	-	-	-
Sample statistics	1.1	3.1	-	-	4.1	-	8.4	8.4

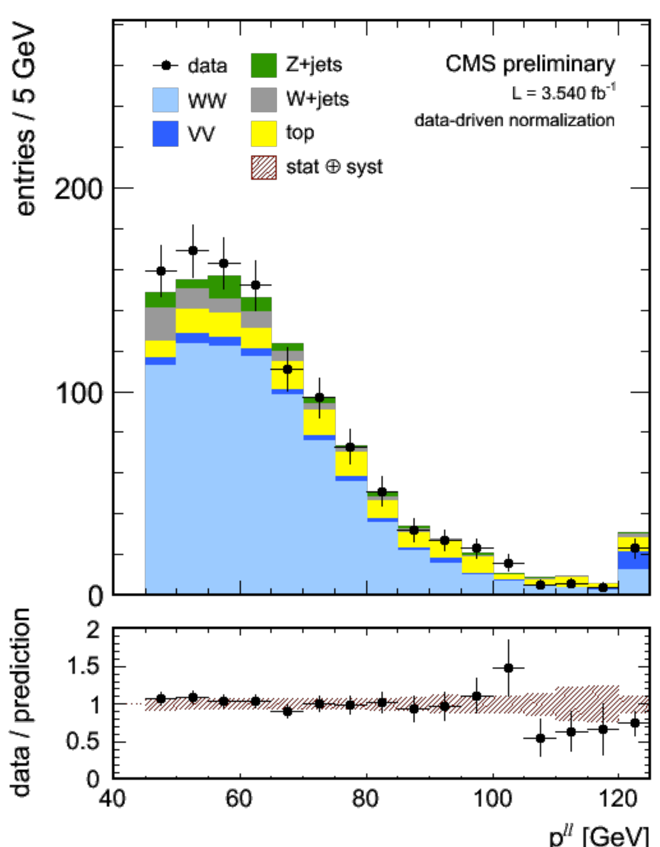
WW, 8 TeV



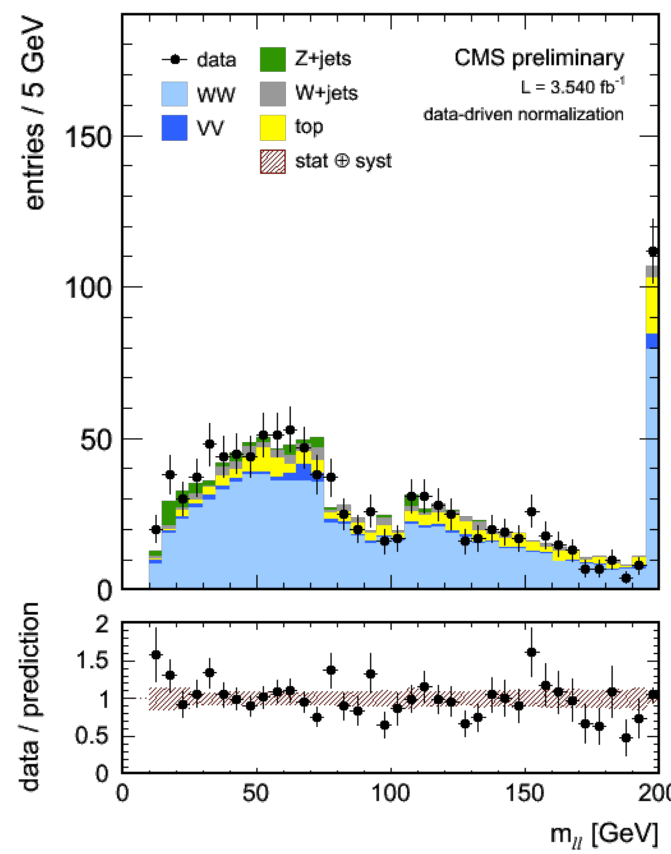
entries / 5 GeV
data
WW
VV
Z+jets
W+jets
top
stat ⊕ syst
CMS preliminary
L = 3.540 fb-1
data-driven normalization
data / prediction
p_T^max [GeV]



entries / 5 GeV
data
WW
VV
Z+jets
W+jets
top
stat ⊕ syst
CMS preliminary
L = 3.540 fb-1
data-driven normalization
data / prediction
p_T^min [GeV]



entries / 5 GeV
data
WW
VV
Z+jets
W+jets
top
stat ⊕ syst
CMS preliminary
L = 3.540 fb-1
data-driven normalization
data / prediction
p_T^ll [GeV]

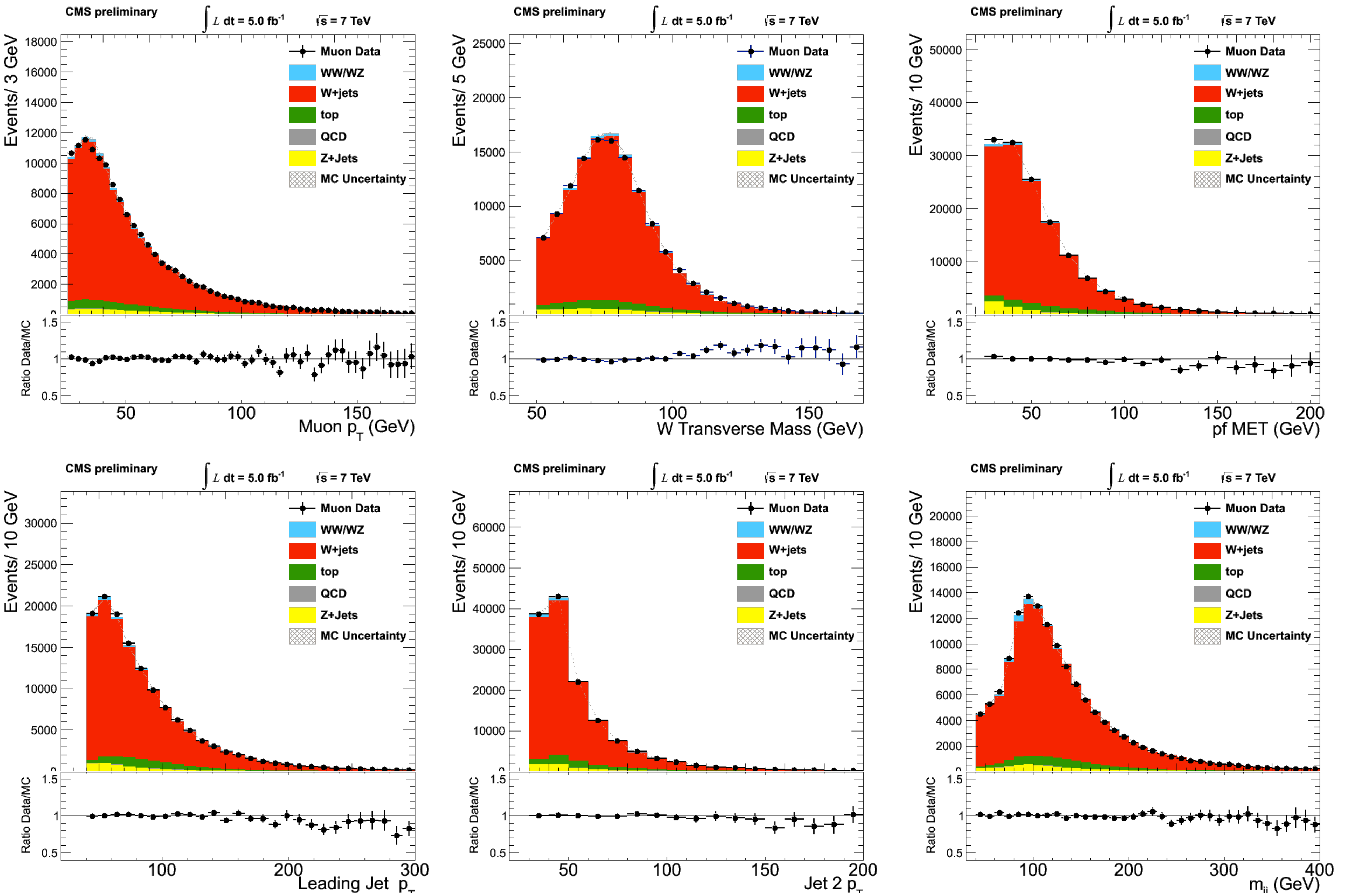


entries / 5 GeV
data
WW
VV
Z+jets
W+jets
top
stat ⊕ syst
CMS preliminary
L = 3.540 fb-1
data-driven normalization
data / prediction
m_ll [GeV]

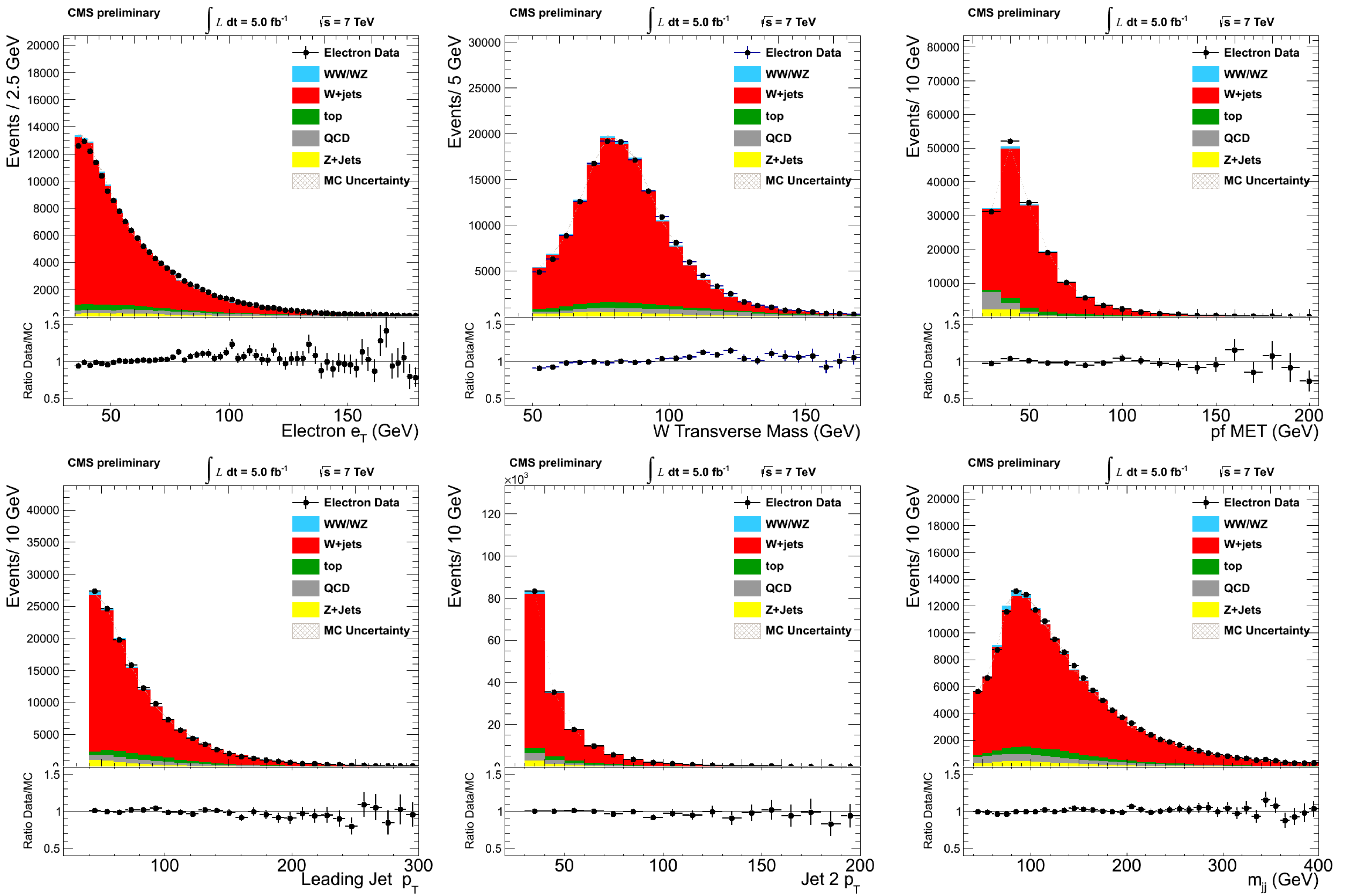
WW/WZ dijet, Systematics

- Systematic uncertainties:
  - Trigger Efficiency - 1%
  - Lepton Reconstruction and selection efficiency - 2%
  - Jet Energy scale - 0.6%
  - Missing Transverse Energy Resolution - 0.5%
  - Fit uncertainty - 0.2%
  - Luminosity Determination - 2.2%
  - Theory uncertainty on acceptance - 4%

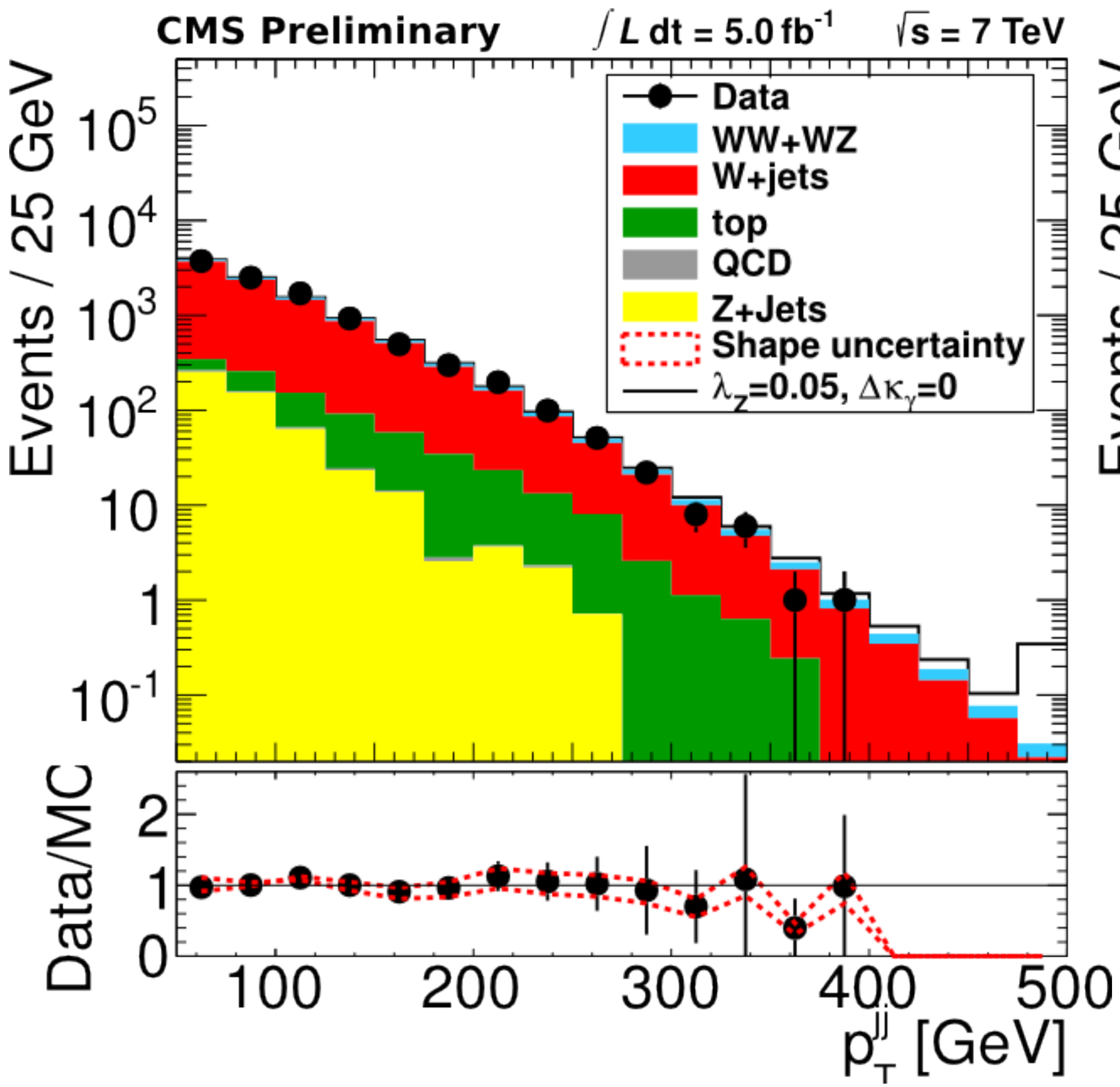
WW/WZ to Dijets, μ channel

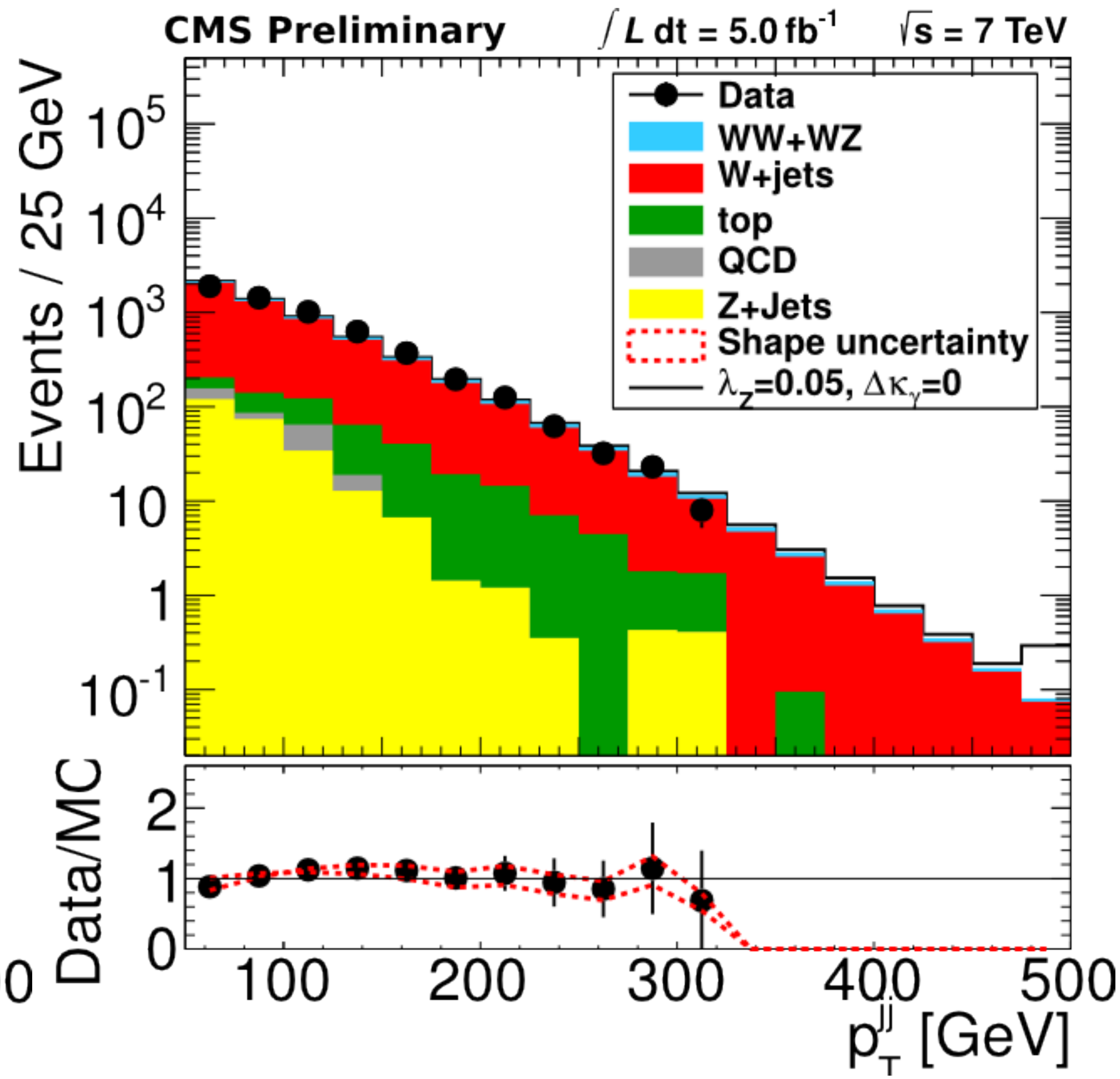


WW/WZ to Dijets, e channel



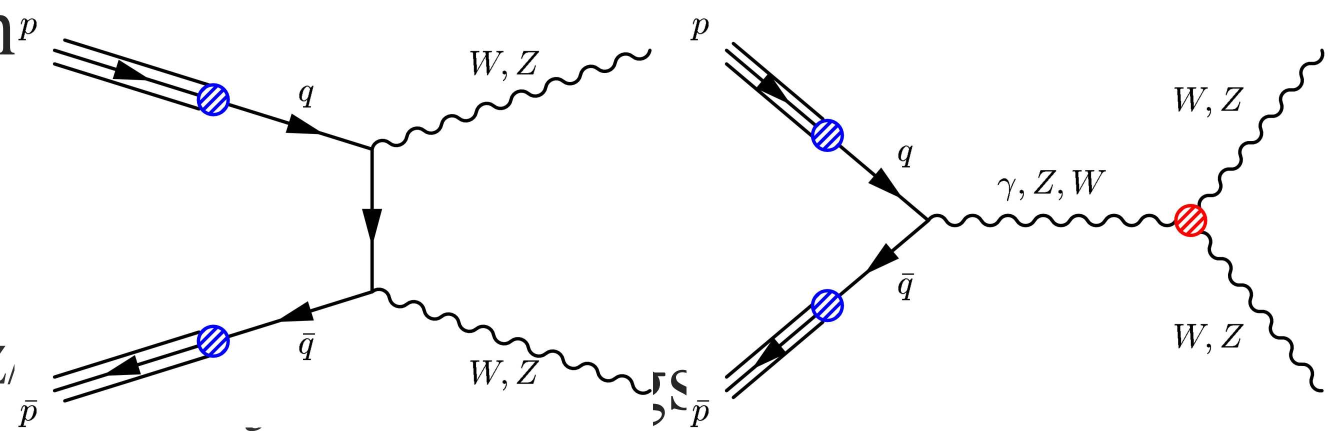
Manifestation of an aTGC signal, WW/WZ dijets





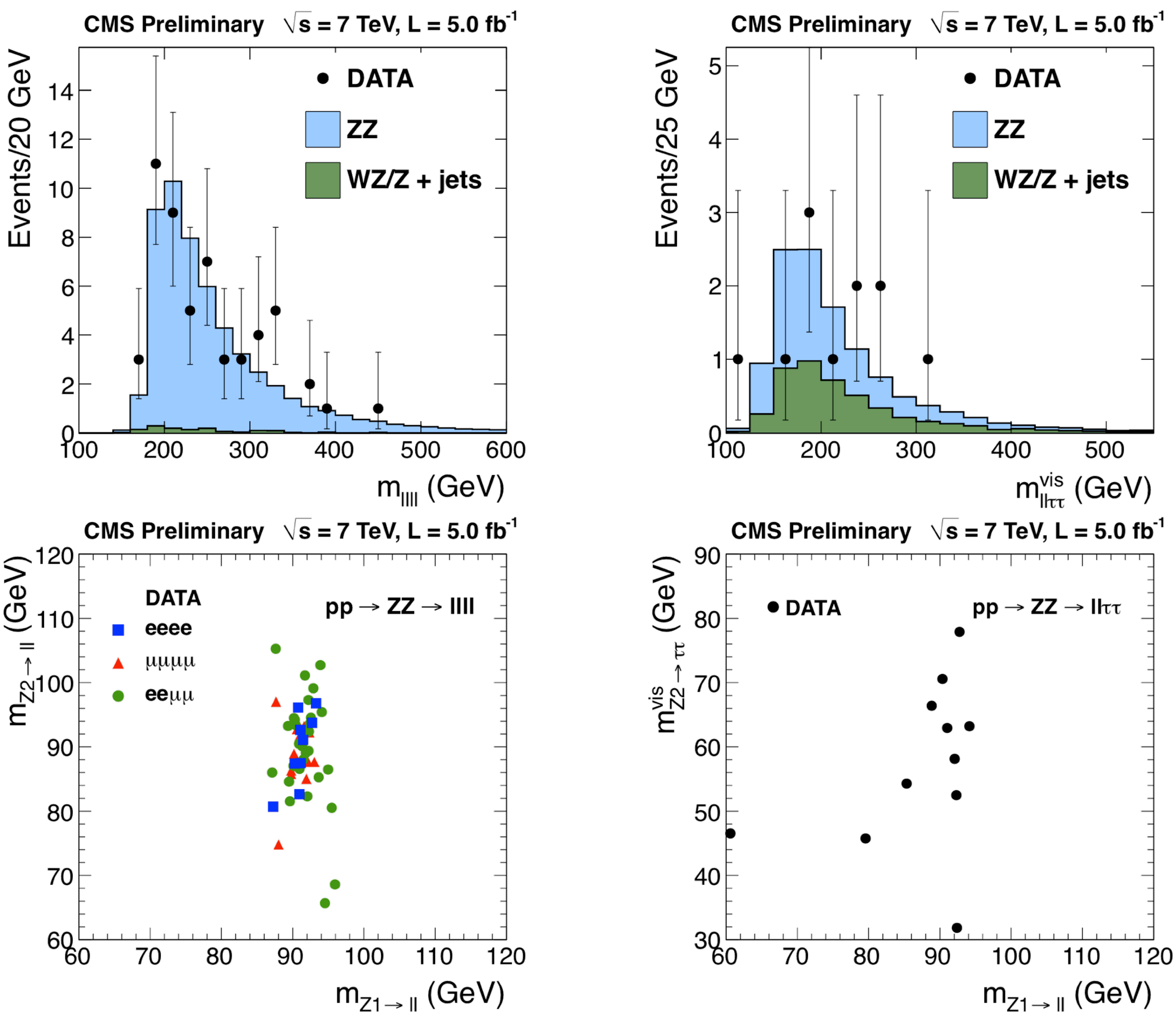
ZZZ/ZZγ aTGCs

- aTGCs motivation :
  - Neutral TGC (ZZZ/ZZγ) forbidden in SM (no s-channel at tree level)
  - A way to prospect new physics
  - ZZZ/ZZγ vertex described with $f_4^{Z/}$
  - Previous results:

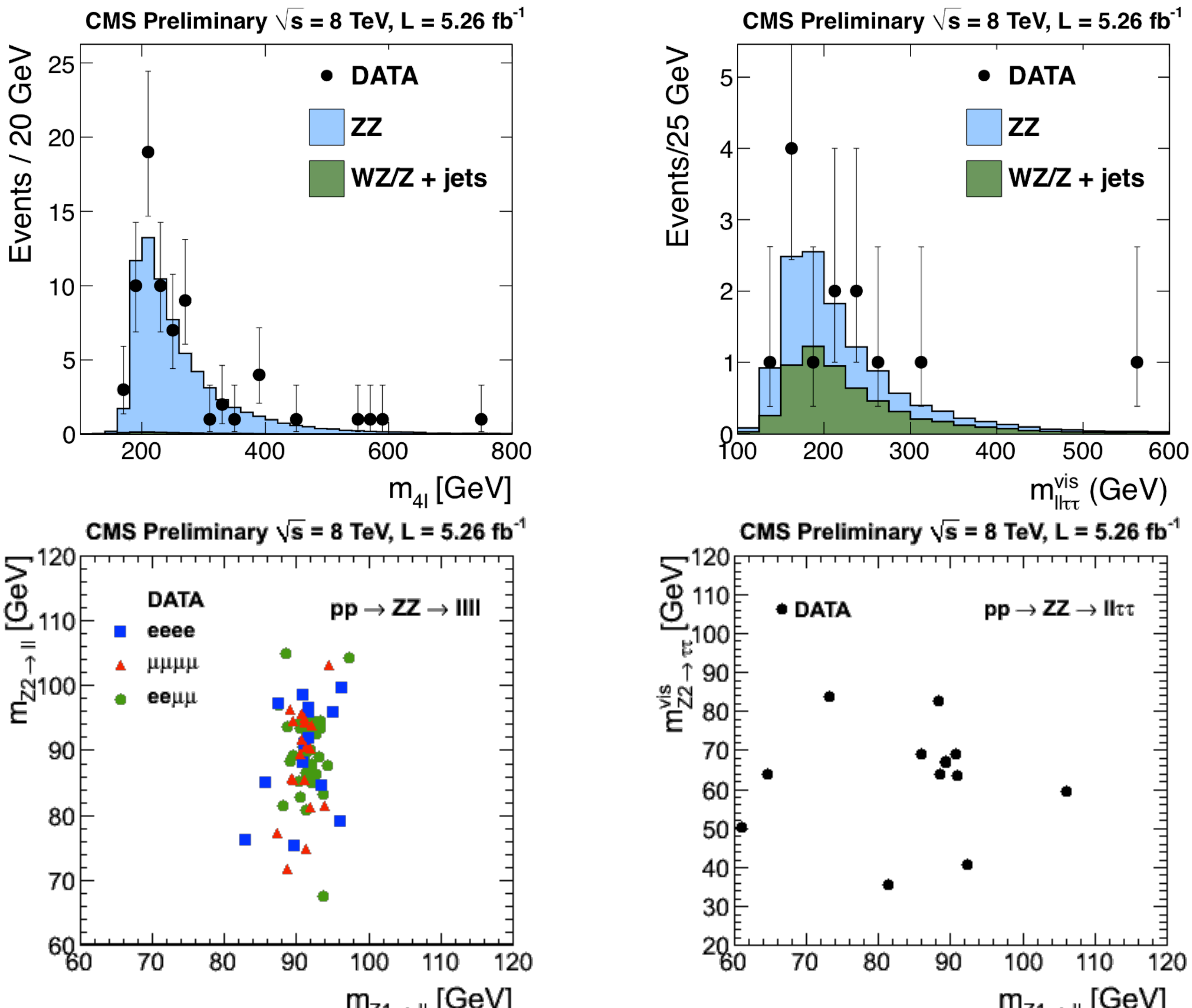


Experiment	f_4^Z	f_4^γ	f_5^Z	f_5^γ	Ref.	Comments
ALEPH	[-0.60;0.61]	[-0.40;0.36]	[-1.22;1.10]	[-0.81;0.79]	[23]	2D fit results
DELPHI	[-0.40;0.42]	[-0.23;0.25]	[-0.38;0.62]	[-0.52;0.58]	[24]	
L3	[-1.9;1.9]	[-1.1;1.2]	[-5.0;4.5]	[-3.0;2.9]	[27]	$\sqrt{s} = 189$ GeV only
OPAL	[-0.45;0.58]	[-0.32;0.33]	[-0.94;0.25]	[-0.71;0.59]	[26]	
LEP WG	[-0.30;0.30]	[-0.17;0.19]	[-0.34;0.38]	[-0.32;0.36]	[25]	LEP combination
CDF	[-0.12;0.12]	[-0.10;0.10]	[-0.13;0.12]	[-0.11;0.11]	[29]	Λ=1.2 TeV
D0	[-0.28;0.28]	[-0.26;0.26]	[-0.31;0.29]	[-0.20;0.28]	[28]	$\sim 1\ fb^{-1}$, Λ=1.2 TeV
ATLAS	[-0.12;0.12]	[-0.15;0.15]	[-0.13;0.13]	[-0.13;0.13]	[30]	$\sim 1\ fb^{-1}$, Λ=2 TeV
ATLAS	[-0.07;0.07]	[-0.08;0.08]	[-0.07;0.07]	[-0.08;0.08]	[30]	$\sim 1\ fb^{-1}$, Λ=inf

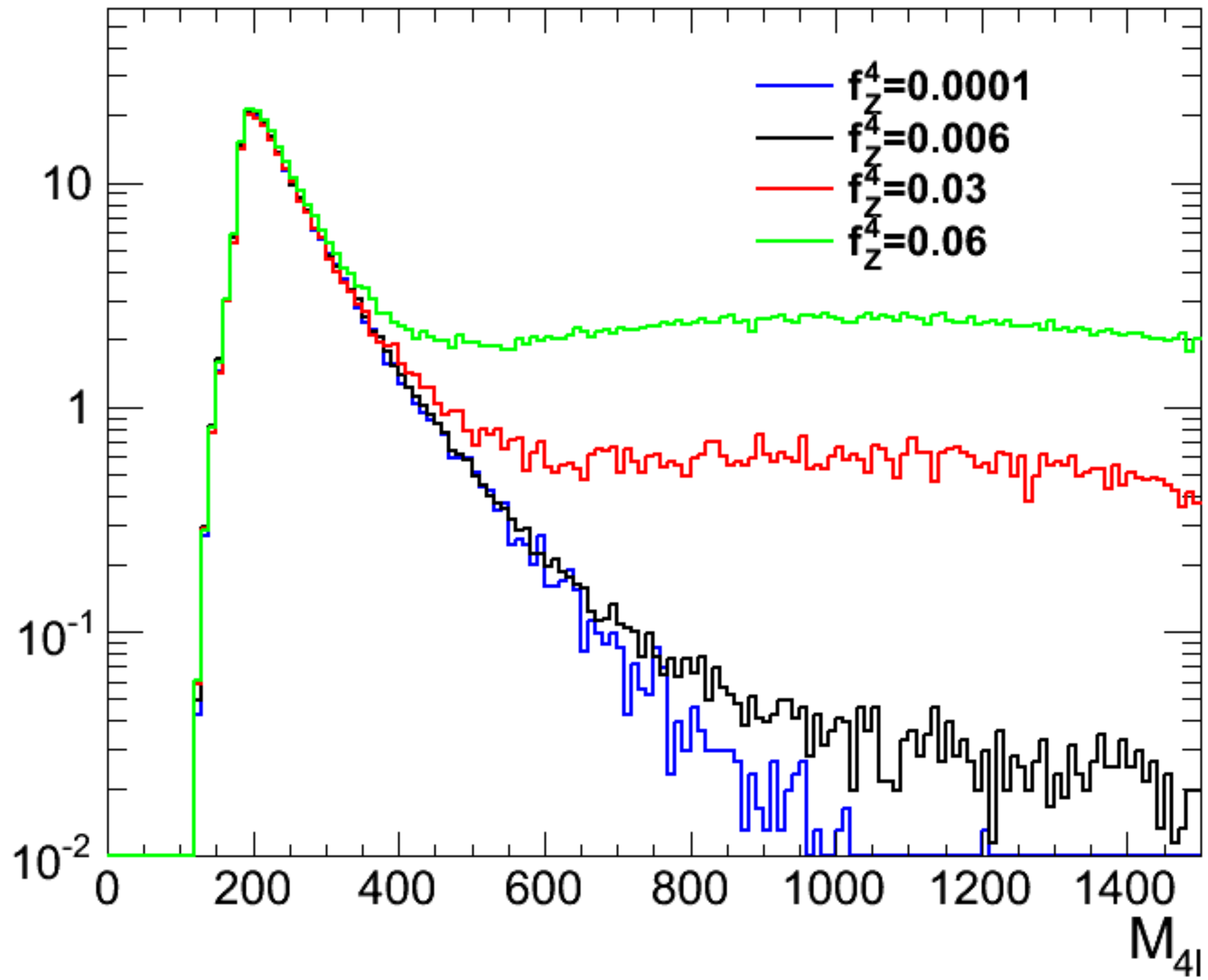
Invariant Mass Spectra, 7 TeV



Invariant Mass Spectra, 8 TeV

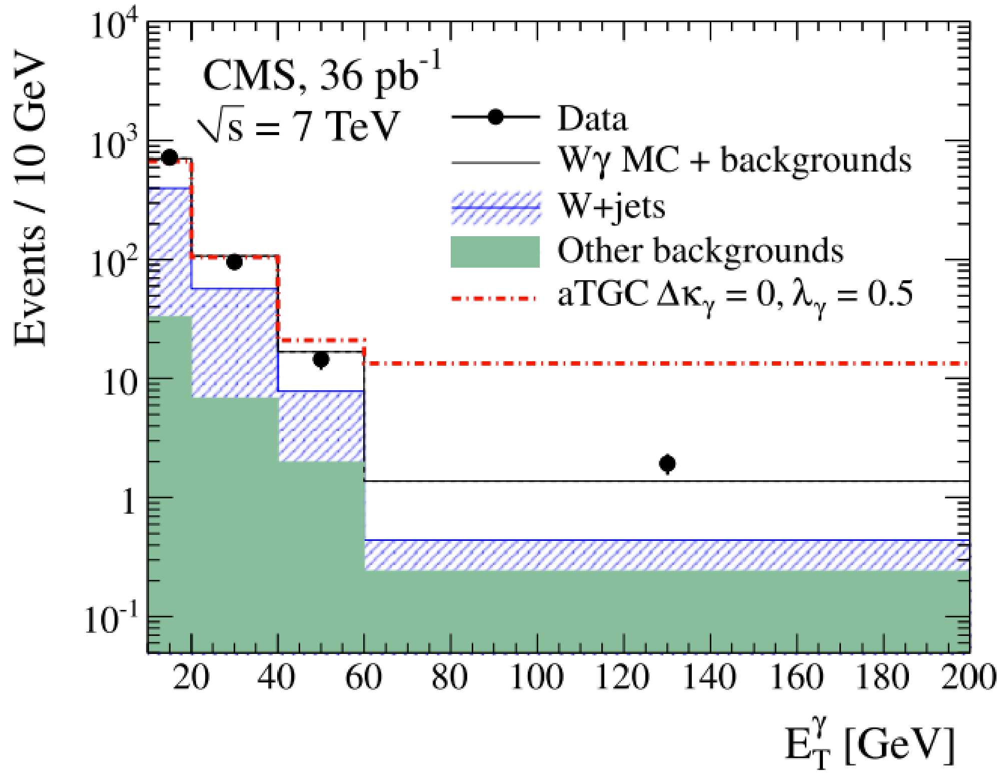


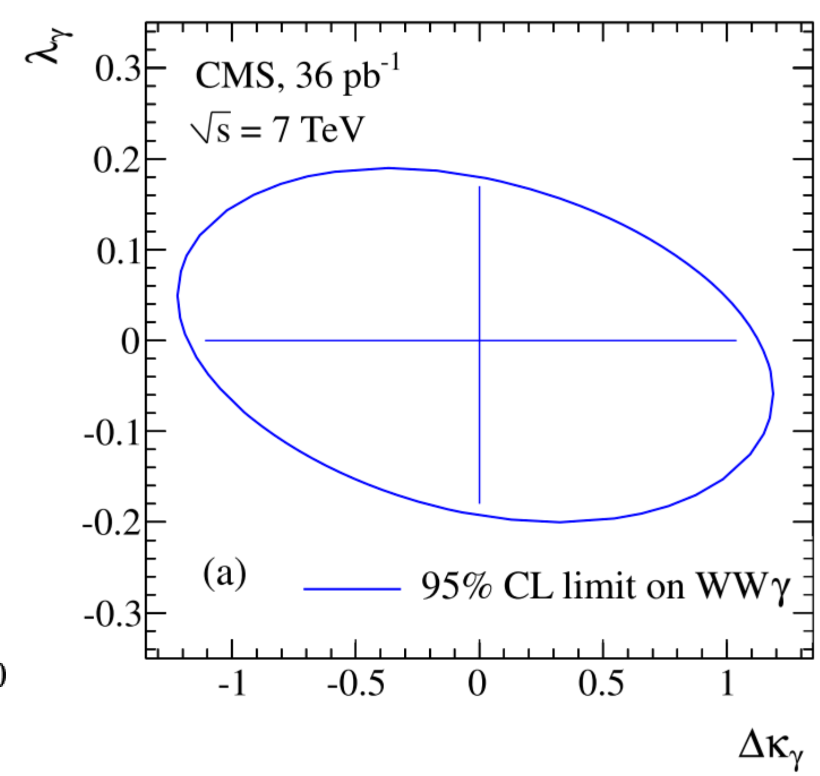
Manifestation of an aTGC signal, $ZZ \rightarrow 4l$



- Sensitivity to aTGCs is driven by long m_{4l} tails

- Wγ:
  - $\sigma(pp \rightarrow W\gamma + X) \times B(W \rightarrow l\nu) = 56.3 \pm 5.0(stat.) \pm 5.0(syst.) \pm 2.3(lumi.)$
  - Theory: 49.4 ± 3.8 pb





- Zγ:
  - $\sigma(pp \rightarrow Z\gamma + X) \times B(Z \rightarrow ll) = 9.4 \pm 1.0\ (stat.) \pm 0.6(syst.) \pm 0.4\ (lumi.)$ pb
  - Theory: 9.6 ± 0.4 pb