WW, WZ, and ZZ production at CMS

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Fermilab, CMS Collaboration

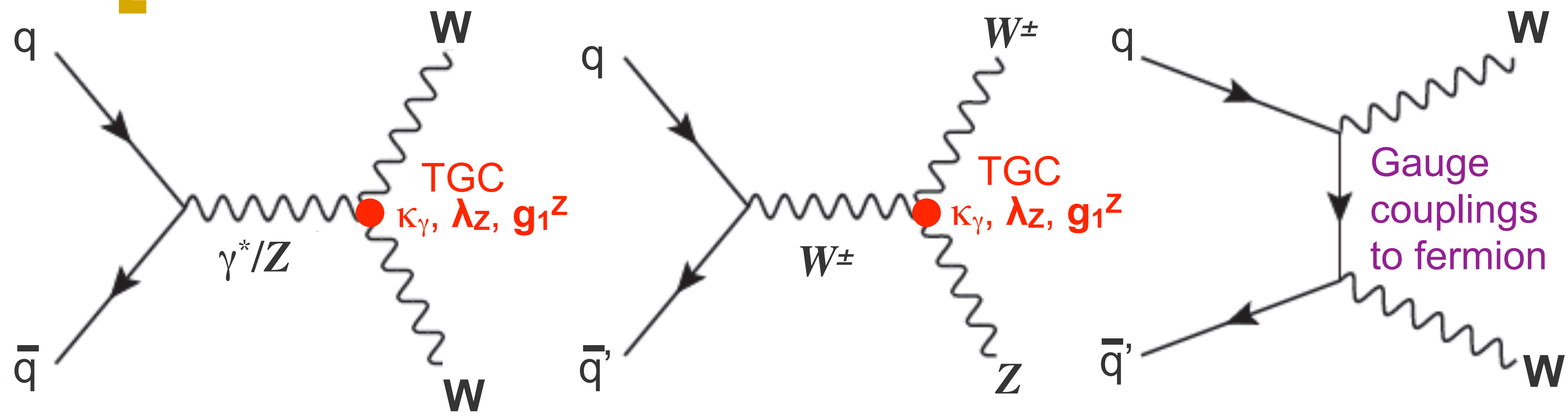
- WW cross section @7 & **8 TeV** **New !**
- WZ cross section @7 TeV
- First observation of Z→4l in pp collisions
- ZZ cross section @**7 & 8 TeV** **New !**

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

ICHEP 2012 at Melbourne, July 6, 2012

Diboson production at LHC

at Leading Order in α_S



s-channel WW

s-channel WZ

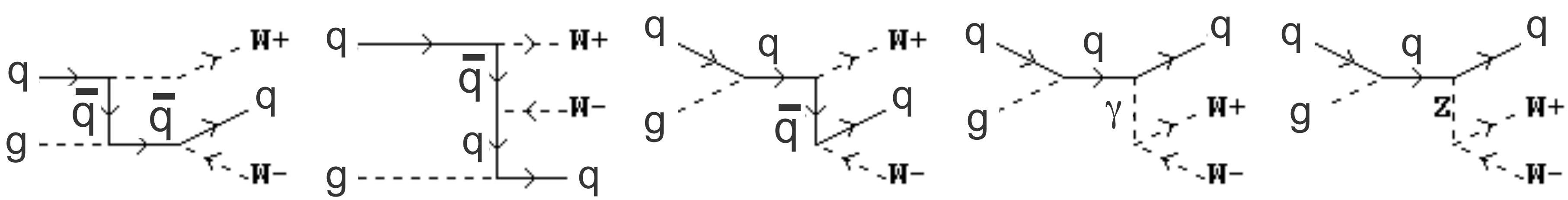
t-channel WW (similar diagrams for WZ, ZZ)

✦In SM, the s- and t-channel WW diagrams are divergent but their sum is not. Important milestone for LHC physics program.

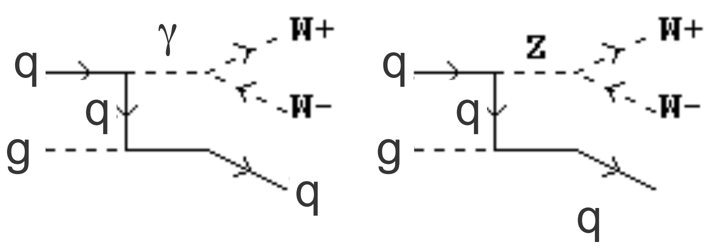
✦Allow test of triple−gauge couplings (TGC).

✦Background to Higgs.

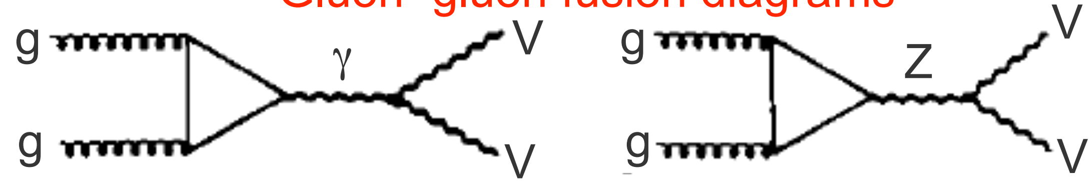
Significant contribution from NLO (≳50% of LO)

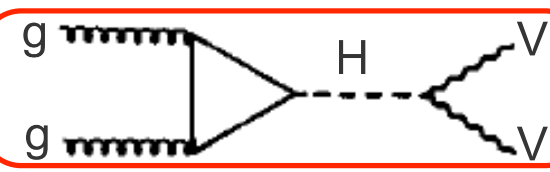


Quark−gluon diagrams



Gluon−gluon fusion diagrams





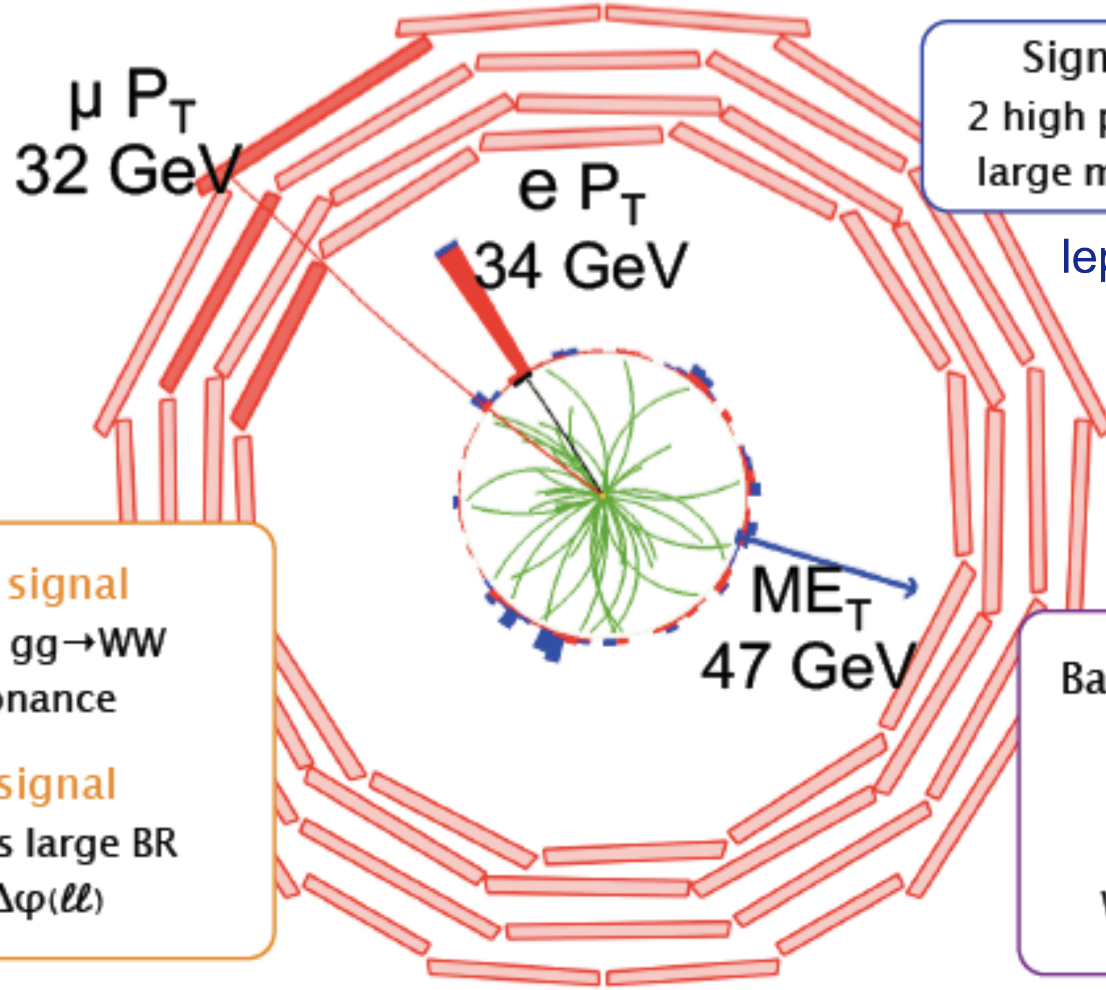
A tool for Higgs study

Box diagrams

Plus vector boson fusion diagrams

$WW \rightarrow 2\ell 2\nu$ cross section measurement

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12005



Signature:
2 high p_T leptons
large missing E_T

lepton p_T > 20 GeV
projected MET ⊥ to the closest lepton > 40 (20 for eμ) GeV

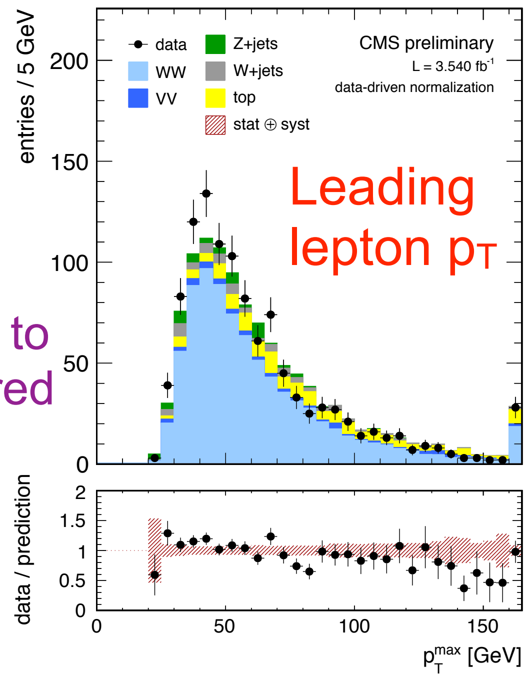
SM WW signal
$qq \rightarrow WW + gg \rightarrow WW$
no resonance

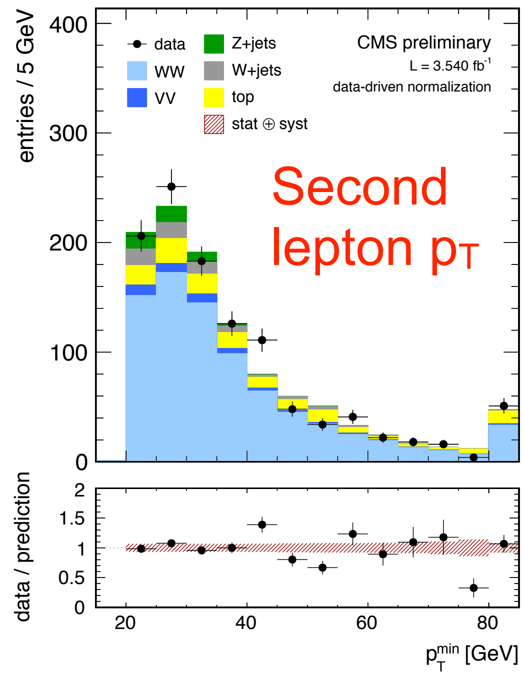
Higgs signal
$H \rightarrow WW$ has large BR
small $\Delta\varphi(\ell\ell)$

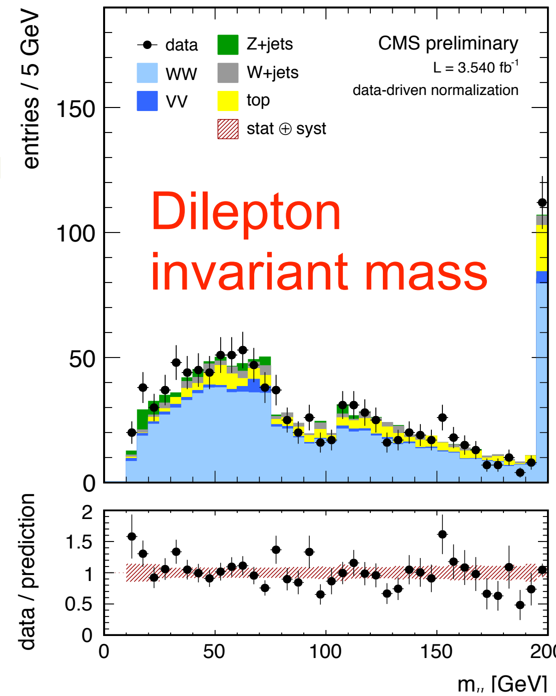
Backgrounds:
W+jet
Z/γ^*
top
$WZ/ZZ/W\gamma$

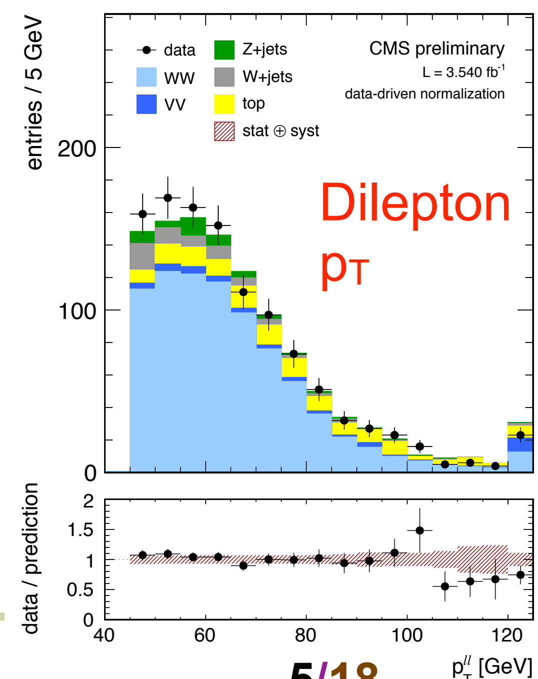
WW→2ℓ2ν: kinematics

WW cross section is normalized to the measured value









- ✦Drell-Yan reduced by MET requirement, and
  - $m_{\ell\ell}$ > 20 GeV, and veto 76 < $m_{\ell\ell}$ < 106 GeV
  - $\Delta\phi(\ell\ell$, jet) <165° to reduce Z+jets
- ✦W+jets, ttbar reduced by: central jet veto, b-veto
- ✦Z→ττ reduced using projected MET cut
- ✦Veto third lepton to reduce WW/WZ

WW→2ℓ2ν cross section at 7 TeV (5.0 fb^{-1})

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12005

S/B = 3.2

Signal efficiency averaged over all lepton flavors: 3.28 ± 0.02 (stat) ± 0.26 (sys) %

Cross section

$$\sigma \cdot BR = \frac{N_{signal}}{Acceptance \cdot Efficiency \cdot L}$$

BR(W→ℓν) from PDG: 0.1080 ± 0.0009

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

σ = 52.4 ± 2.0 (stat) ± 4.5 (sys) ± 1.2 (lum) pb

NLO prediction (MCFM): 47.0 ± 2.0 pb

Campbell, Ellis, Williams. JHEP 07 (2011), 018. arXiv:1105.0020.

Consistent with the NLO prediction

$WW \to 2\ell 2\nu$ cross section at 8 TeV ($3.54\ fb^{-1}$)

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12013

NLO prediction:

$$\sigma^{NLO}(gg \to W^+W^- + qq \to W^+W^-) = 57.25 \left(^{+2.35}_{-1.60}\right)\ pb$$

Campbell, Ellis, Williams. JHEP 07 (2011), 018. arXiv:1105.0020. MCFM.

Back-of-the-envelop calculation:

expect 57.3 pb x $3.54\ fb^{-1}$ x 3.2% ≈ 680 WW events

efficiency x acceptance x BR

S/B = 2.3

Expected & observed yields in $3.54\ fb^{-1}$ data

Sample	yield ± stat. ± syst.
$gg \to WW$	$43.3 \pm 1.0 \pm 13.4$
$qq \to WW$	$640.3 \pm 4.9 \pm 47.4$
$t\bar{t} + tW$	$129.7 \pm 12.7 \pm 19.3$
W + jets	$60.0 \pm 4.3 \pm 21.6$
WZ + ZZ	$27.4 \pm 0.5 \pm 2.9$
Z/γ^*	$46.4 \pm 16.6 \pm 8.7$
$W\gamma + W\gamma^*$	$29.2 \pm 6.5 \pm 9.3$
Total Background	$292.7 \pm 22.3 \pm 31.8$
Signal + Background	$976.3 \pm 22.9 \pm 63.9$
Data	1111

- $gg \to WW$ (included) contributes ~6%
- Higgs (125) can potentially contribute ~5%

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt8TeV

WW→2ℓ2ν at 8 TeV: systematics & results

Theoretical uncertainties

- PDF and QCD scale: 5%

includes jet veto uncertainty

Experimental measurements

- Luminosity: 4.4%
- Lepton efficiency, energy scale and resolution: 1-3%
- Jet energy scale: 2-3%
- Missing ET resolution: 2-3%

Need to improve

Background normalisation

- W+jets: ~35% + statistical
- Z/γ*: ~20%-100%
- Top: ~20% + statistical
- Z/γ*→ττ: up to 50%

Background components:

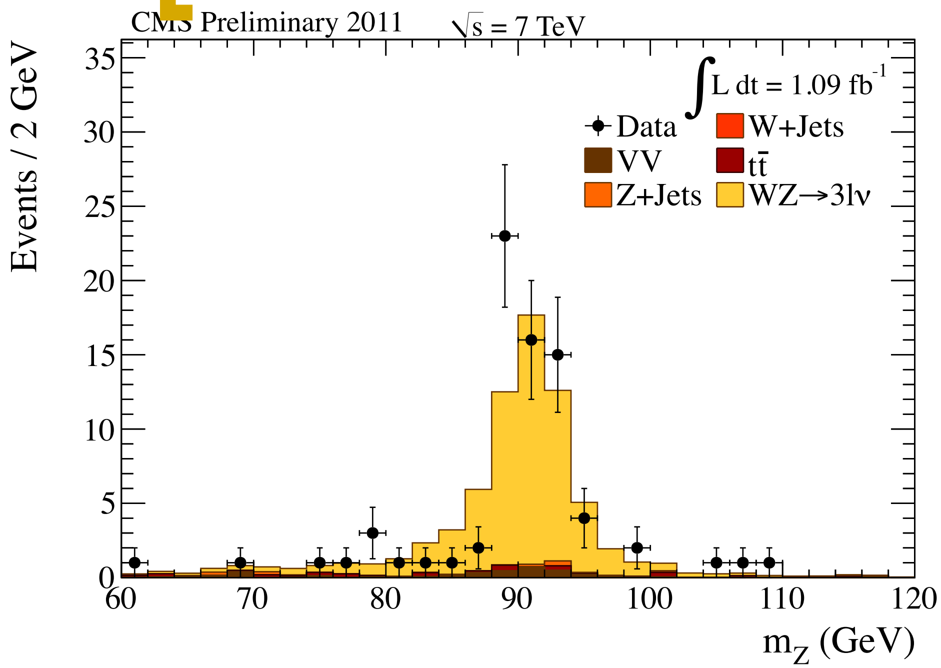
- Major Backgrounds (Data Driven)
  - QCD / W+jet
  - Top
  - Drell Yan
- Smaller backgrounds (*MC Simulation*)
  - Wγ
  - $Z \to \tau\tau$
  - non resonant WZ/ZZ

σ = 69.9 ± 2.8 (stat) ± 5.6 (sys) ± 3.1 (lum) pb

NLO prediction (MCFM): $57.25\,(^{+2.35}_{-1.60})$ pb

- **Already 4% statistical precision**
- **About 1.8σ higher than the NLO prediction**

WZ→3ℓν cross section at 7 TeV (1.1 fb^{-1})



http://cdsweb.cern.ch/record/1370067

(CMS PAS EWK-11-010)

- ✦Two isolated leptons: p_T > 20/10 GeV (e) or > 15 GeV (μ)
- ✦3rd lepton p_T > 20, MET>30 GeV
- ✦60 < $m_{\ell\ell}$ < 120 GeV; veto 2nd Z
- ✦Acceptance x efficiency = 19−25% for the four channels

Tiny background:

- •ttbar & Z+jets from data
- •Zγ and ZZ from MC

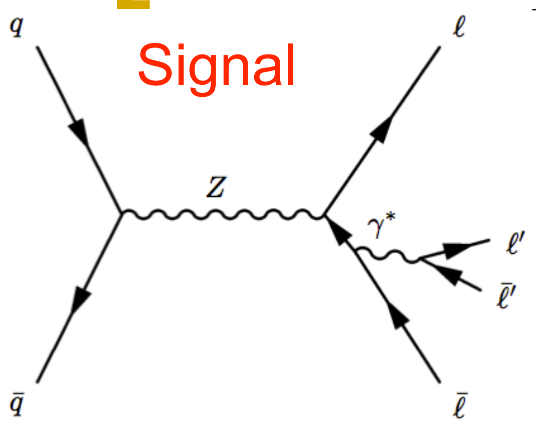
Main systematics: bkg estimation, efficiency, acceptance/theory.

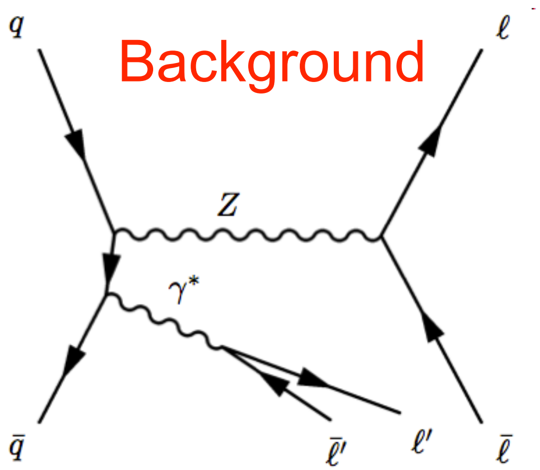
channel	$N_{observed}$	cross section (pb) x BR
$\sigma_{WZ\to eee\nu}$	22	$0.086 \pm 0.022(stat) \pm 0.007(syst) \pm 0.005(lumi)$
$\sigma_{WZ\to ee\mu\nu}$	20	$0.060 \pm 0.017(stat) \pm 0.005(syst) \pm 0.004(lumi)$
$\sigma_{WZ\to \mu\mu e\nu}$	13	$0.053 \pm 0.018(stat) \pm 0.004(syst) \pm 0.003(lumi)$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

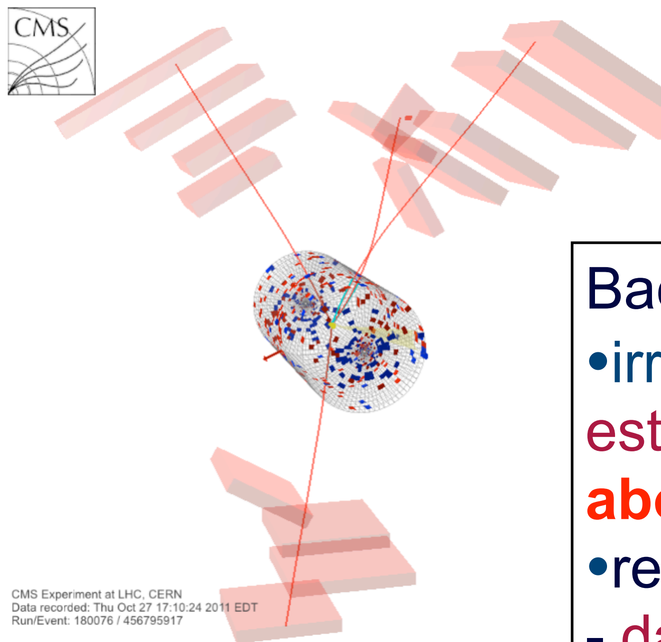
σ = 17.0 ± 2.4 (stat) ± 1.1 (sys) ± 1.0 (lum) pb

NLO: 17.5 ± 0.6 pb (MCFM, using real width bosons, PDF is CTEQ6L, error is PDF uncertainty)

First observation of $Z \to 4\ell$ in pp collisions







https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12009

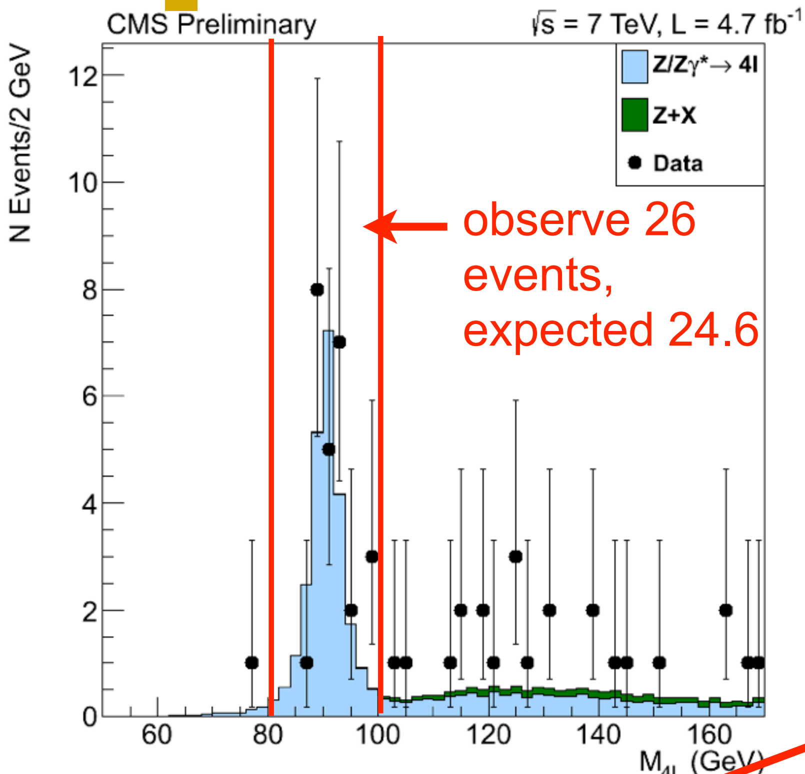
Backgrounds:

- irreducible $Z\gamma^* \to 4l$ - estimated using MC, **about 1% of the signal**
- reducible backgrounds - data-driven, **about 0.3% of signal**

calcHEP LO

Requirement	Quantity of interest	$4e$	4μ	$2e2\mu$	4ℓ
$m_{\ell\ell} > 4$ GeV	partial width, Γ_i (keV)	2.95	2.95	5.21	11.12
	branching fractions, Γ_i/Γ_{tot}	$1.18 \cdot 10^{-6}$	$1.18 \cdot 10^{-6}$	$2.09 \cdot 10^{-6}$	$4.45 \cdot 10^{-6}$
	relative fractions, $f_i = \Gamma_i/\Gamma_{4\ell}$	0.2655	0.2655	0.4690	

Z→4ℓ: the branching fraction measurement



Analyze 4ℓ invariant mass peak

- **production cross section x branching fraction**

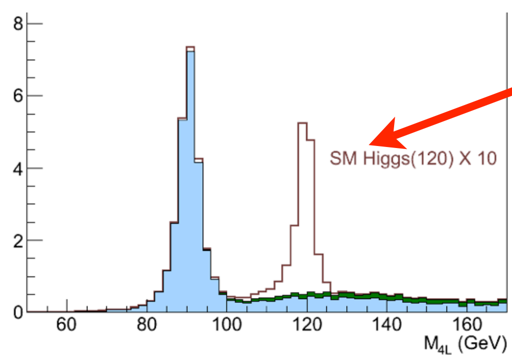
$$\sigma \times BR(Z \to 4\ell) = 125^{+26}_{-23}(\text{stat})^{+9}_{-6}(\text{syst})^{+7}_{-5}(\text{lumi})\ \text{fb}$$

- **branching fraction BR(Z→4ℓ)**

$$BR(Z \to 4l) = [4.41^{+0.96}_{-0.83}(stat) \pm 0.23(sys)] \times 10^{-6}$$

Efficiency x acceptance in the range 2.5−7.5%

Mass peak arising from Z→4ℓ decays is a standard candle for the Higgs boson search in the H→ZZ→4ℓ decay

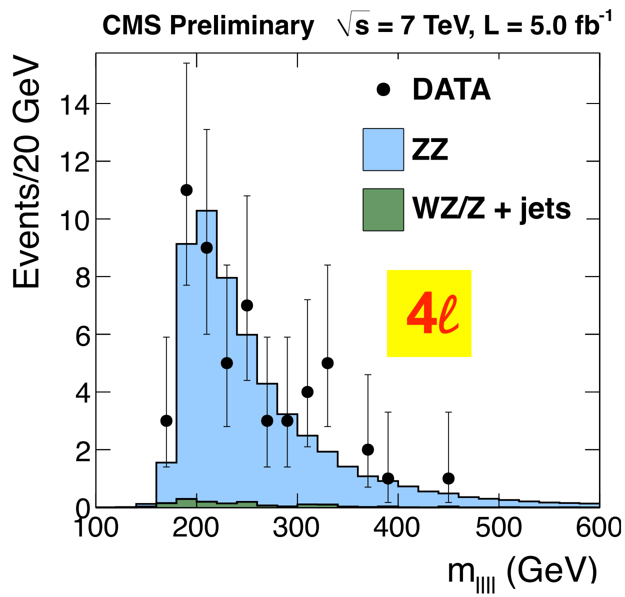


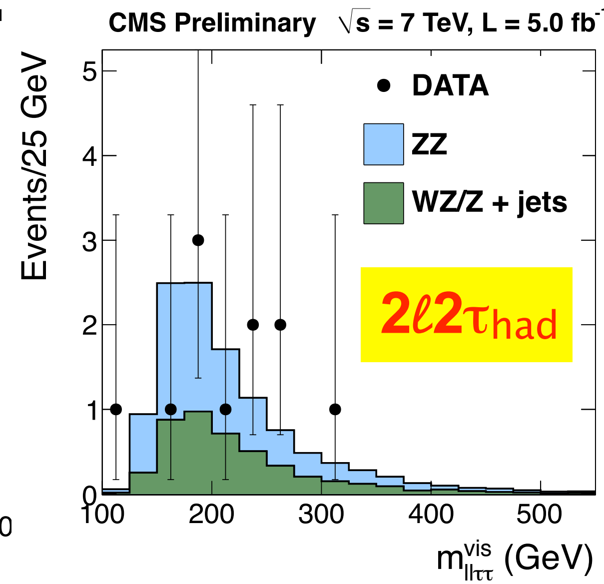
Final state channels	$4e$	4μ	$2e2\mu$	4ℓ
Irreducible background ($pp \to Z\gamma^* \to 4\ell$)	0.04	0.16	0.08	0.3 ± 0.03
Other reducible backgrounds	0.01	0.01	0.05	0.1 ± 0.13
Expected signal ($pp \to Z \to 4\ell$)	3.1	12.3	9.2	24.6 ± 2.2
Total expected (MC)	3.2	12.5	9.3	25.0 ± 2.2
Observed events	2	14	10	26
Rate from the fit of the observed mass distribution	2.1	13.6	9.7	25.4

ZZ→4ℓ cross section at 7 TeV (5.0 fb^{-1})

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12007

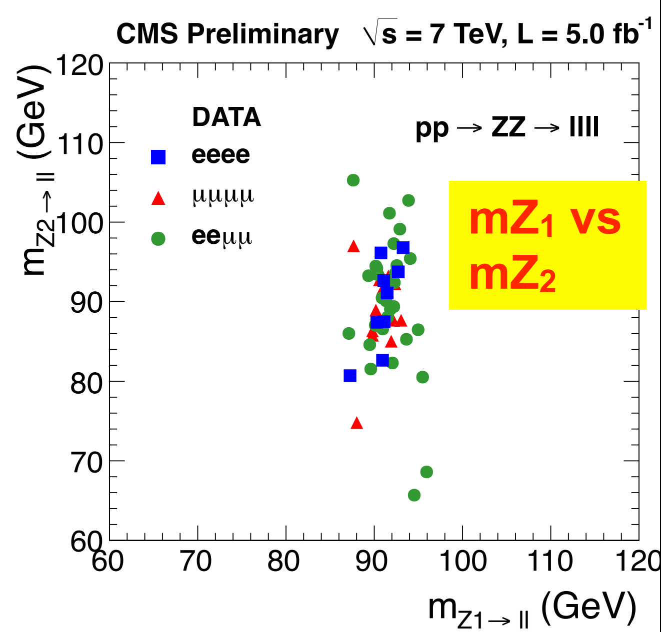
8 final states: eeee, eeμμ, μμμμ, eeeτ, eeμτ, eeττ, eeeμ, μμeτ, μμμτ, μμττ, μμeμ





Event reconstruction

- ✦objects: Isolated leptons: e $p_T>7$, $|\eta|<2.5$; μ $p_T>5$, $|\eta|<2.4$; τ_{had} $p_T>10$, $|\eta|<2.3$
- ✦Kinematics: (Z_1 has daughters with higher average p_T)
  - •60 GeV < mZ_1, mZ_2 < 120 GeV (30 GeV < m_{vis} Z_2 < 80 GeV for $\ell\tau_{had}$)
  - •Z_1 lepton p_T > 20/10 GeV; Z_2 lepton $p_T>5$ (μ), >7 (e) in $\ell\ell$; >10 in eμ, >20 GeV on τ_{had}



Expected and observed signal yields

NLO prediction: MCFM 6.0
(NLO for qq→ZZ and LO for gg→ZZ, MSTW 2008 PDF)

$\sigma(pp \to ZZ) =$ **6.3 ± 0.4 pb**

Back-of-the-envelop calculation:

expect 6 pb x 5 fb^{-1} x 0.2% ≈ 60 ZZ→4ℓ events

- Very little background for ZZ→4ℓ (2−4%)
- Even for ZZ→2ℓ2τ, S/B ≧ 1
- Background: QCD, W/Z+jets, WZ+jets
- Estimated from data: by reconstructing control samples where one or two lepton(s) fail the isolation/identification criteria

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)

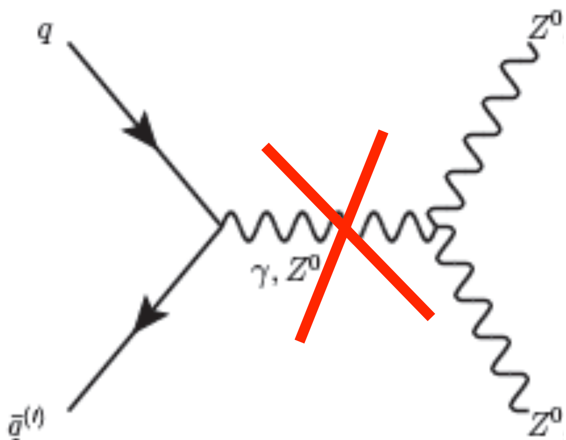
Cross section result and anomalous couplings

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

NLO (MCFM): 6.3 ± 0.4 pb

The measurement is consistent with the NLO prediction

Anomalous triple gauge couplings

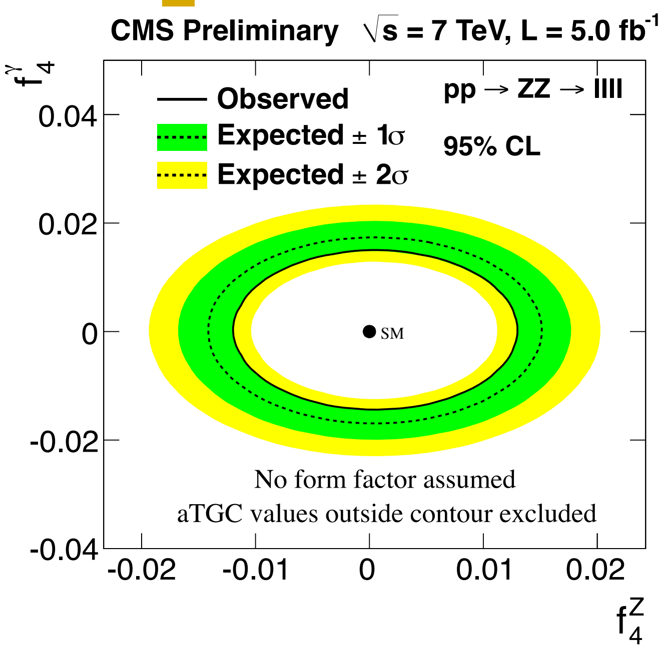


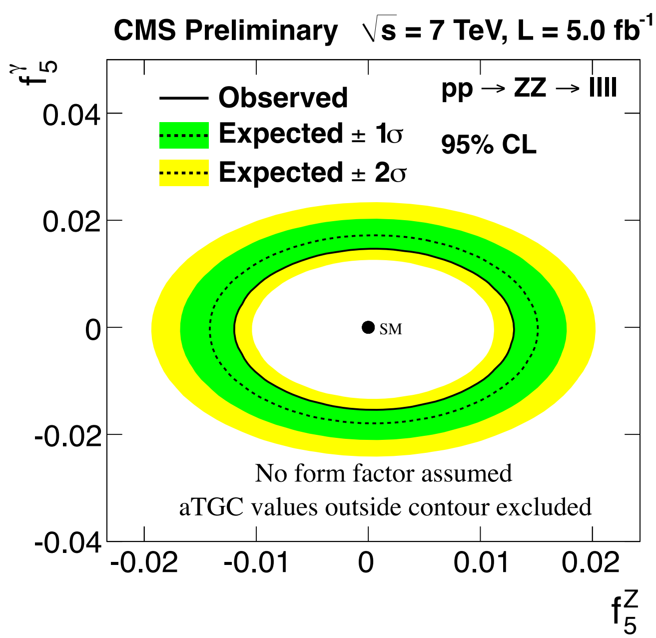
- Neutral triple gauge coupling (ZZZ /ZZγ) forbidden in SM (no s-channel at tree level)
  - -A way to look for prospective new physics
  - -Can enhance ZZ cross section
- ZZZ/ZZγ vertex described with $f_4^{Z/\gamma}$ and $f_5^{Z/\gamma}$ couplings in the TGC Lagrangian assuming gauge invariance and CP symmetry

Methodology

- SHERPA is currently the only generator that models ZZZ/ZZγ couplings
  - -LO only, but SM at tree level + 1 parton agree well with NLO (POWHEG)
- m_{4l} chosen as discriminating variable, more sensitive than leading Z p_T
- Independent approach (reweighing POWHEG) give consistent results

Limits on anomalous triple gauge couplings





Use no form factors, i.e., $\Lambda = \infty$

$-0.012 < f_4^Z < 0.013$

$-0.012 < f_5^Z < 0.013$

$-0.014 < f_4^\gamma < 0.014$

$-0.015 < f_5^\gamma < 0.015$

at 95% CL, the strongest limit to-date

Experiment	f_4^Z	f_4^γ	f_5^Z	f_5^γ	Comment
LEP WG	[-0.30;0.30]	[-0.17;0.19]	[-0.34;0.38]	[-0.32;0.36]	LEP combination
CDF	[-0.12;0.12]	[-0.10;0.10]	[-0.13;0.12]	[-0.11;0.11]	Λ=1.2 TeV
D0	[-0.28;0.28]	[-0.26;0.26]	[-0.31;0.29]	[-0.20;0.28]	$\sim$ 1 fb^{-1}, Λ=1.2 TeV
ATLAS	[-0.12;0.12]	[-0.15;0.15]	[-0.13;0.13]	[-0.13;0.13]	$\sim$ 1 fb^{-1}, Λ=2 TeV
ATLAS	[-0.07;0.07]	[-0.08;0.08]	[-0.07;0.07]	[-0.08;0.08]	$\sim$ 1 fb^{-1}, Λ=inf

CMS & ATLAS limits are much more constraining than LEP & Tevatron

ZZ→4ℓ cross section at 8 TeV (5.3 fb^{-1})

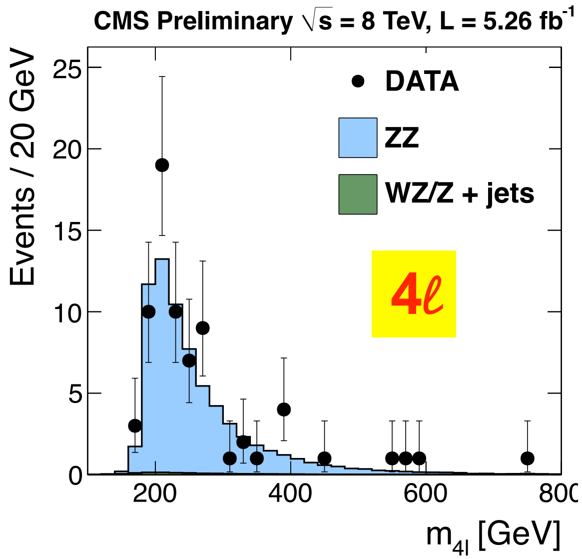
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12014

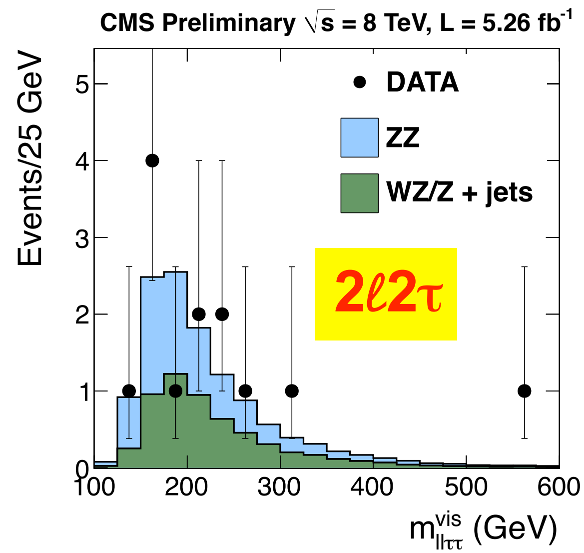
NLO prediction: MCFM

$$\sigma(pp \to ZZ) = 7.8 \pm 0.6\,\text{pb}$$

Back-of-the-envelop calculation:

expect 7.8 pb x 5.3 fb^{-1} x 0.2% ≈ 83 ZZ events





Channel	ZZ expected	Backgr-d	Observed
4e	11.6	0.4	14
4mu	20.3	0.4	19
2e2mu	32.4	0.5	38
Total	→	65.6	71
2l2tau	6.5	5.6	13
4l+2l2tau	→	77.7	84

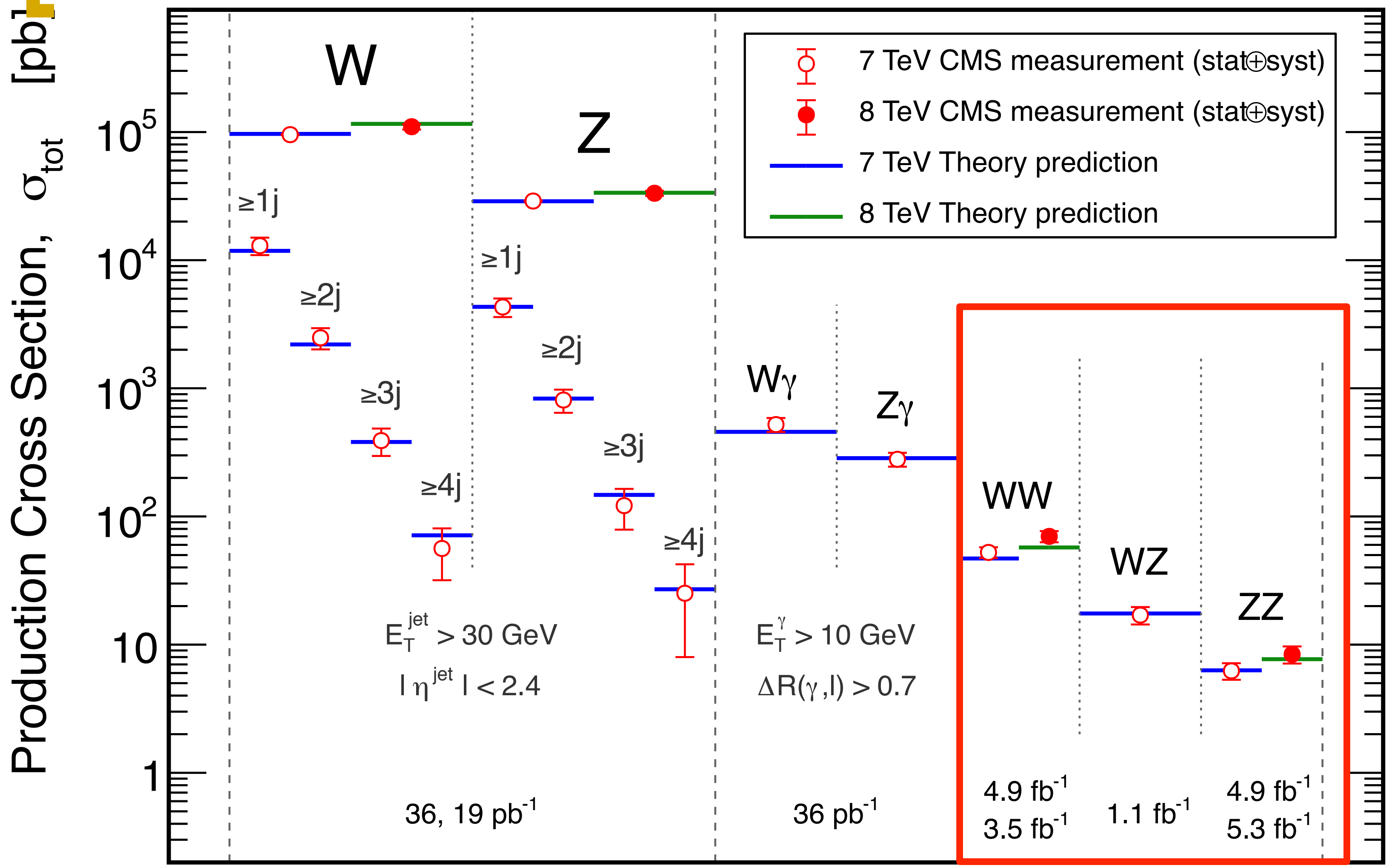
σ = 8.4 ± 1.0 (stat) ± 0.7 (sys) ± 0.4 (lum) pb

NLO (MCFM 6.0): 7.7 ± 0.4 pb

(NLO for qq→ZZ and LO for gg→ZZ, MSTW 2008 PDF)

The measurement is consistent with the NLO prediction

Summary of electroweak physics: July 2012



JHEP10(2011)132
JHEP01(2012)010
CMS-PAS-SMP-12-011 (W/Z 8 TeV)

PLB701(2011)535

CMS-PAS-EWK-11-010 (WZ)
CMS-PAS-SMP-12-005,
007, 013, 014 (WW ZZ)

Summary

☑ The precision of diboson (WW, WZ, ZZ) inclusive measurements in pp collisions is now approaching a few percent accuracy level (dominated by PDF & luminosity)

- All results show good agreement with the SM predictions
- Becoming feasible to study diboson differential distributions and diboson+jets production

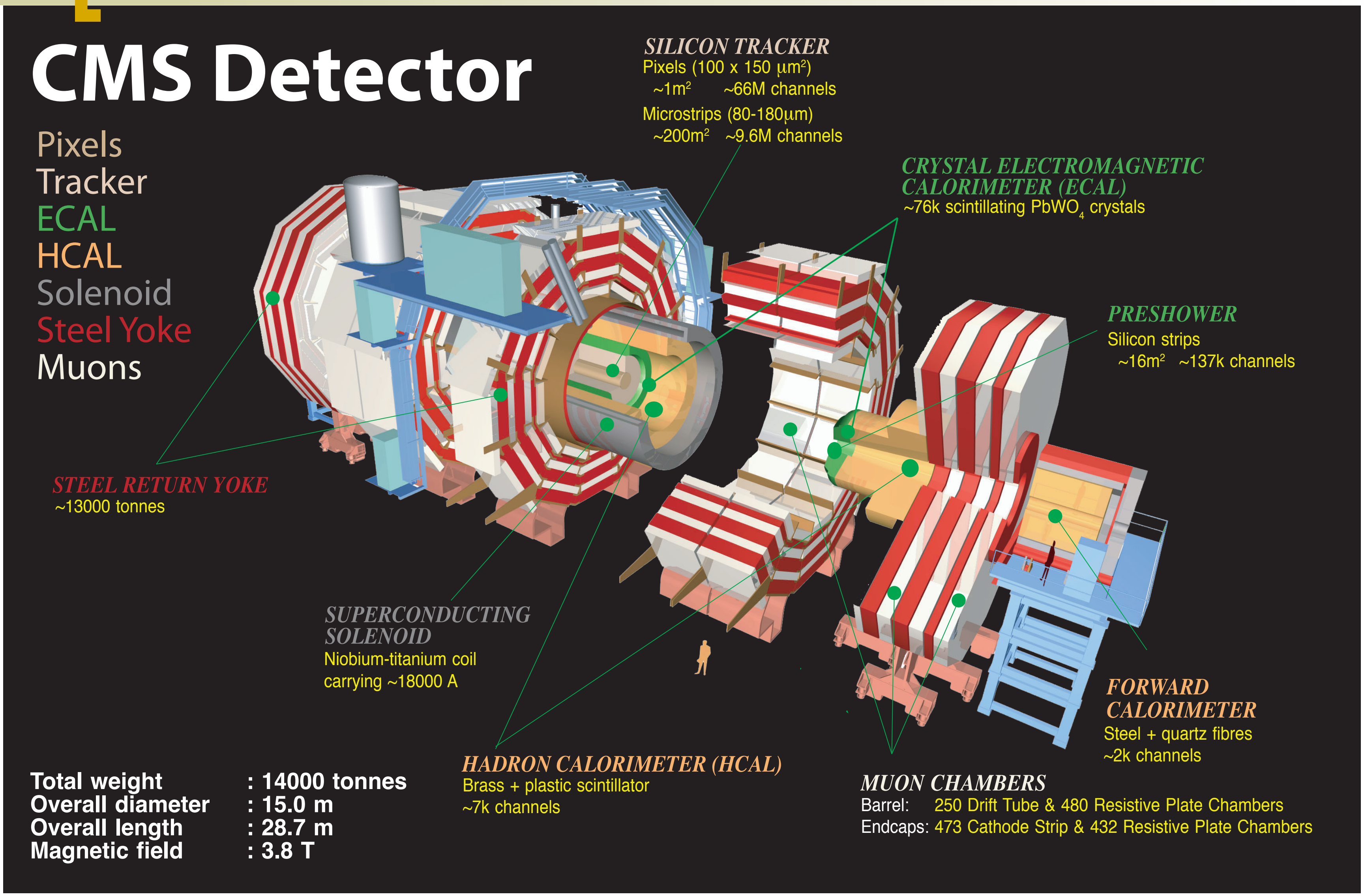
☑ First observation & BR measurement of $Z \rightarrow 4\ell$ @ pp collider

- Important standard candle for $H \rightarrow ZZ \rightarrow 4\ell$

☑ More golden opportunities and new exciting results with increasing integrated luminosity

BACKUP SLIDES

Understanding CMS detector



ZZ: anomalous TGC references (I)

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]	~ 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]	~ 1 fb^{-1}, Λ=2 TeV
ATLAS	[-0.07;0.07]	[-0.08;0.08]	[-0.07;0.07]	[-0.08;0.08]	[30]	~ 1 fb^{-1}, Λ=inf

[23] ALEPH Collaboration *JHEP* **0904** (2009) 124, doi:10.1088/1126-6708/2009/04/124.

[24] DELPHI Collaboration *Eur. Phys. J. C* **51** (2007) 525, doi:10.1140/epjc/10052-007-0345-0.

[25] LEP EWK Working Group Collaboration, "A combination of preliminary electroweak measurements and constraints on the standard model", arXiv:06.12034 [hep-ex].

ZZ: anomalous TGC references (II)

[26] OPAL Collaboration *Eur. Phys. J. C* **32** (2003) 303, doi:10.1140/epjc/s2003-01467-x.

[27] L3 Collaboration *Phys. Lett. B* **436** (1999) 187.

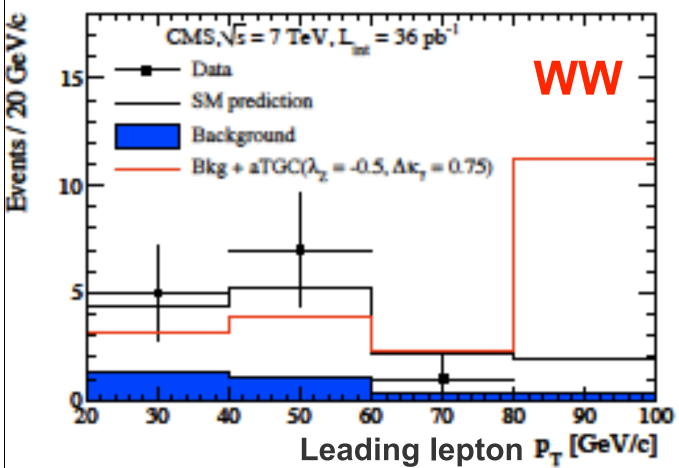
[28] D0 Collaboration *Phys. Rev. Lett.* **100** (2008) 131801.

[29] A. f. t. C. Robson and D. collaborations, "Diboson Physic at Tevatron", arXiv:1201.4771v1 [hep-ex].

[30] ATLAS Collaboration, "Measurement of the ZZ production cross section and limits on anomalous neutral triple gauge couplings in proton-proton collisions at sqrts = 7 TeV with the ATLAS detector", *Phys. Rev. Lett.* **108** (2012) 041804, arXiv:1110.5016 [hep-ex].

Limits on anomalous TGC from 36 pb^{-1} data

Limit set using p_T of the γ or leading lepton (MCFM/Sherpa/ Bour for aTGC)

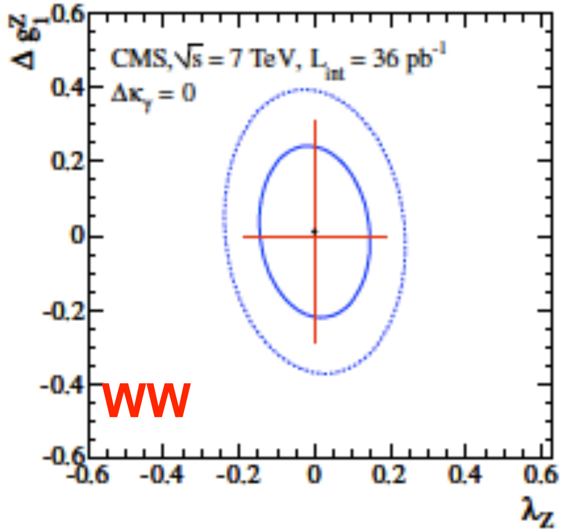


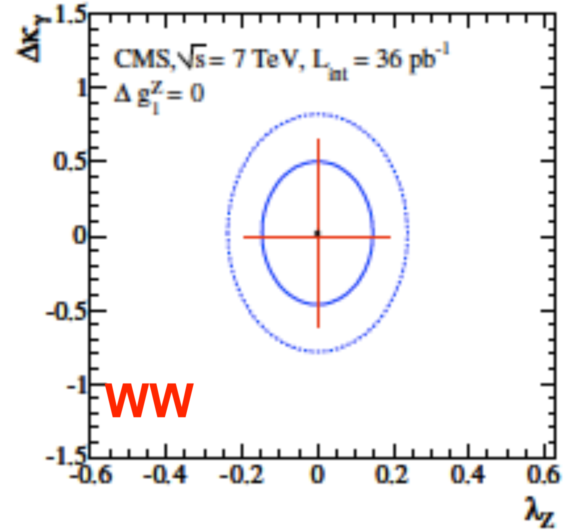
λ_Z	Δg_1^Z	$\Delta\kappa_\gamma$
$[-0.19, 0.19]$	$[-0.29, 0.31]$	$[-0.61, 0.65]$

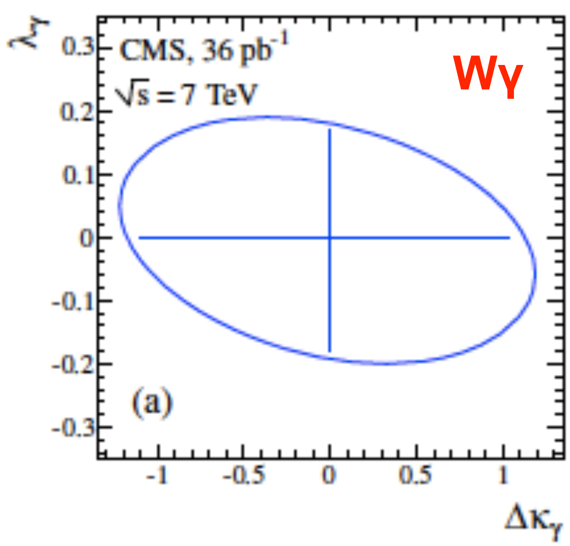
$WW\gamma$	$ZZ\gamma$
$-1.11 < \Delta\kappa_\gamma < 1.04$	$-0.05 < h_3 < 0.06$
$-0.18 < \lambda_\gamma < 0.17$	$-0.0005 < h_4 < 0.0005$

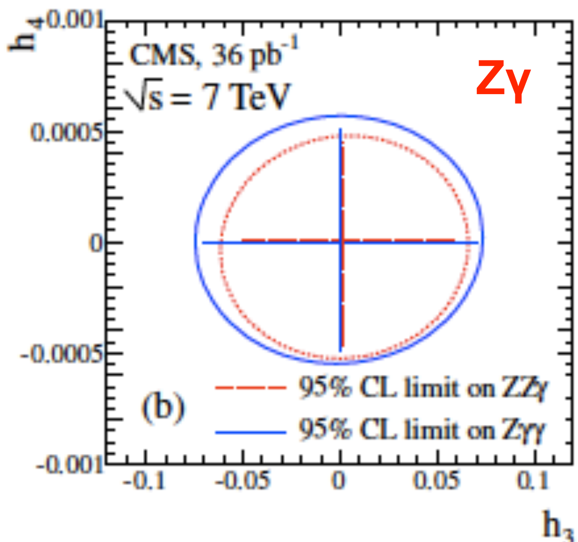
Similar sensitivity to Tevatron results presented in :

- Phys. Rev. Lett. 104 (2010) 201801
- Phys. Rev. Lett. 103 (2009) 191801









Z→4ℓ: signal background interference