Search for
New Physics in Diboson Events at CMS

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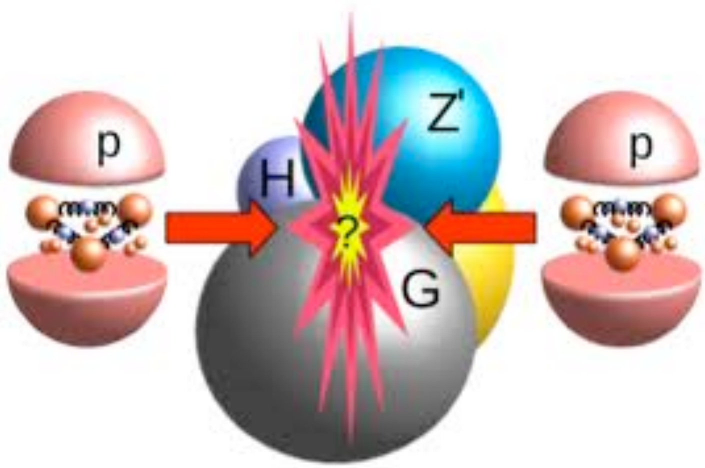
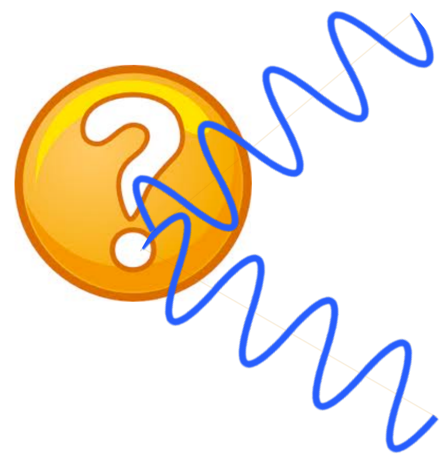
Fermilab, CMS Collaboration





Fermilab Wine & Cheese seminar, September 7, 2012

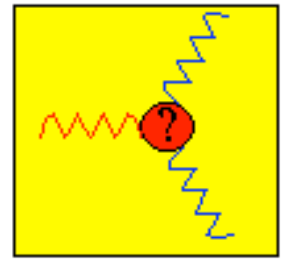
Outline

- Introduction
  - -Production rate, topology, new physics signatures
  - -CMS detector, calibration, trigger
- Standard candles
  - -Measurement of cross sections for WW, WZ, ZZ
- New physics searches
  - -Anomalous gauge couplings
  - -Bump hunt in diboson-like topology
  - -Specific models: techni-ρ/π, W', Z', RS graviton
- Summary

Introduction

What is so interesting about dibosons ?

A non-Abelian gauge theory will exhibit gauge boson self-interactions



✦In the case of the EWK theory they could be
-trilinear ($WW\gamma$, WWZ) or
-quartic ($WW\gamma\gamma$, $WZW\gamma$, $WWZZ$, $WWWW$)

✦Some electric charge conserving possibilities are forbidden at tree level
-ZZZ, $ZZ\gamma$, $Z\gamma\gamma$, $\gamma\gamma\gamma$,
-$ZZZZ$, $ZZZ\gamma$, $ZZ\gamma\gamma$, $Z\gamma\gamma\gamma$, $\gamma\gamma\gamma\gamma$

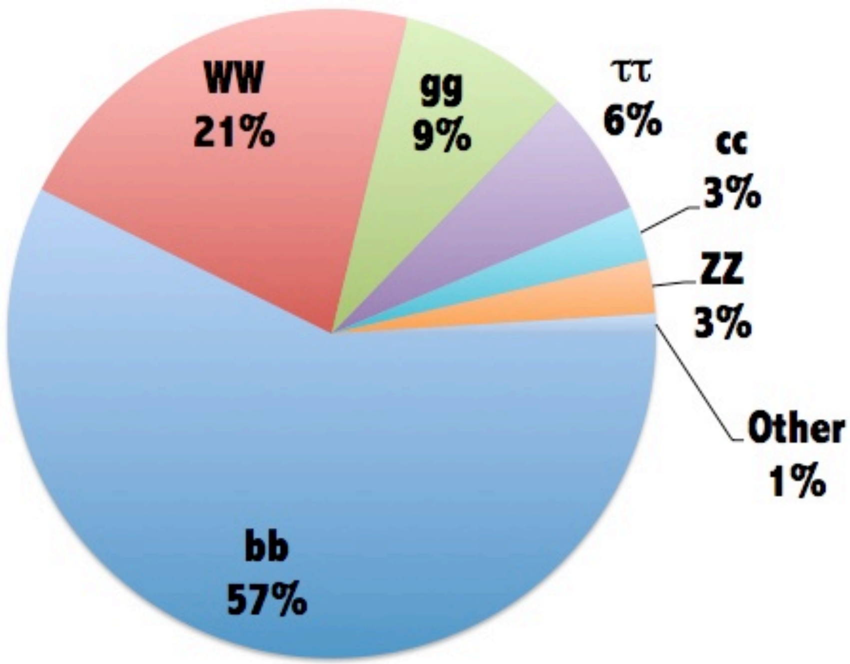
✦Observations of anomalous couplings would be an indication of new physics

What is so interesting about dibosons ?

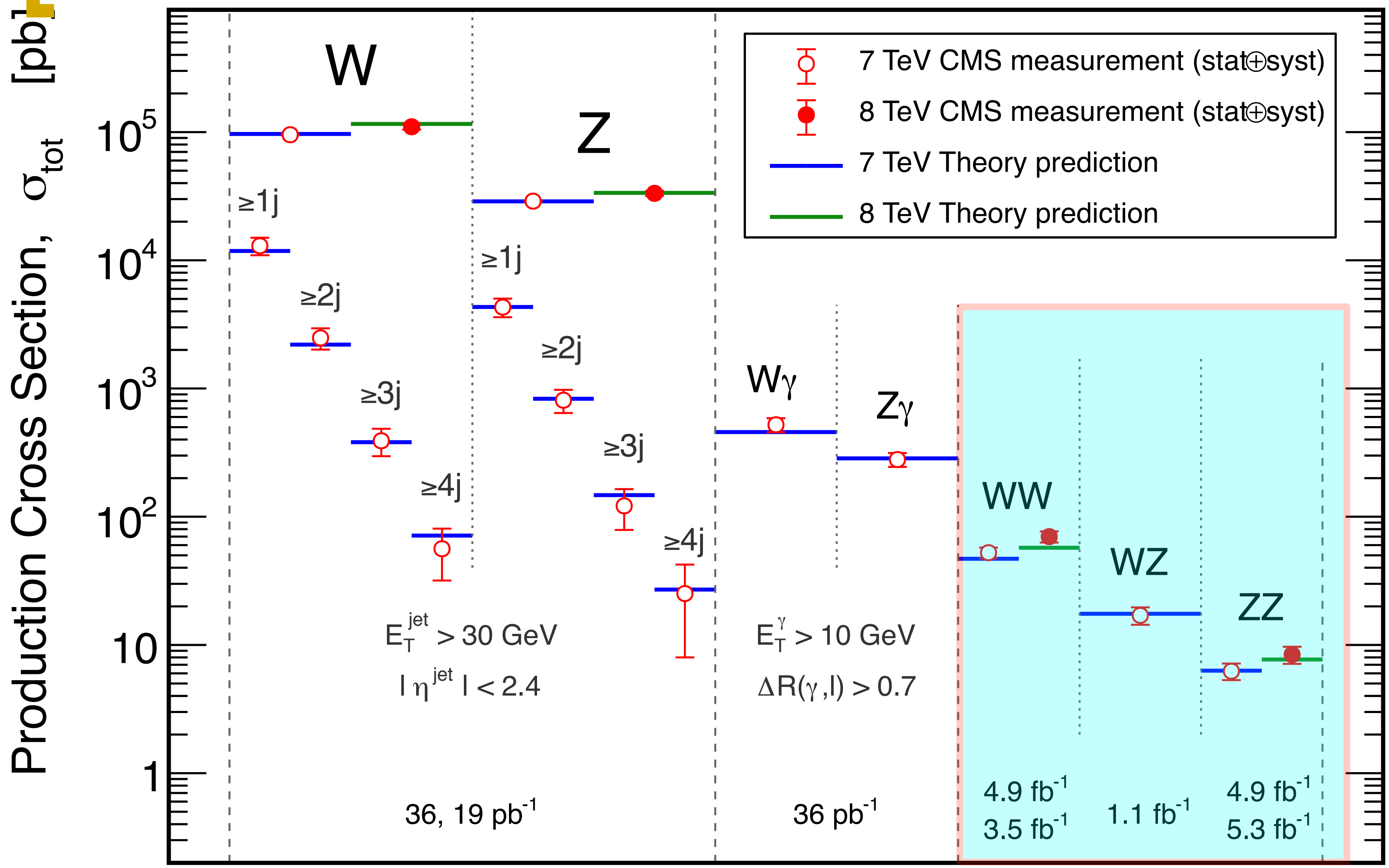
✦Higgs has a diboson branching fraction of 25%, although one or both boson can be significantly off-shell

-SM diboson is often the most significant background

-Need to measure them precisely in order to be able to constrain Higgs couplings



Rather small production rate: pb/fb processes!

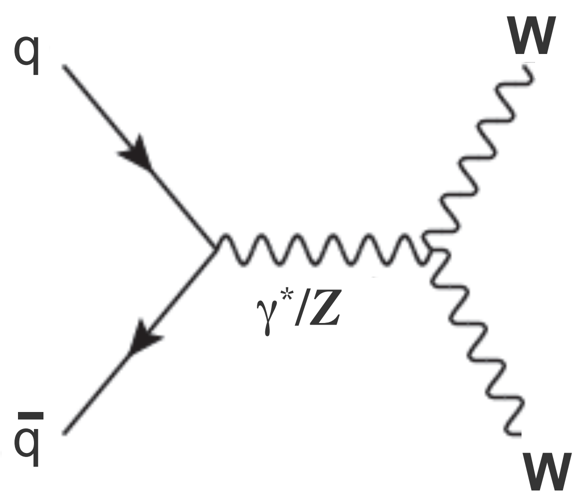


JHEP10(2011)132
JHEP01(2012)010
CMS-PAS-SMP-12-011 (W/Z 8 TeV)

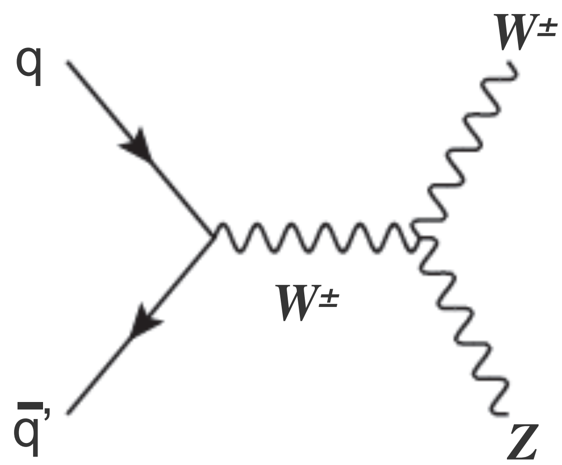
PLB701(2011)535

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

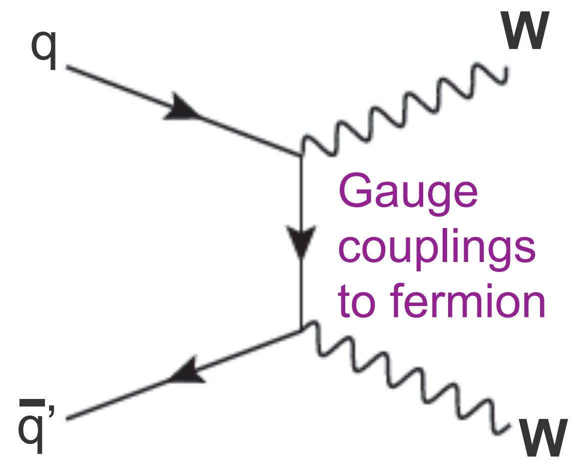
Diboson production at the Leading Order in α_S



s-channel WW



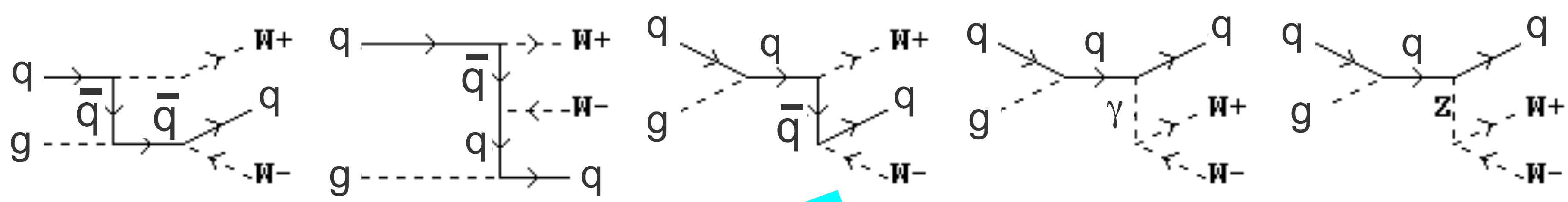
s-channel WZ



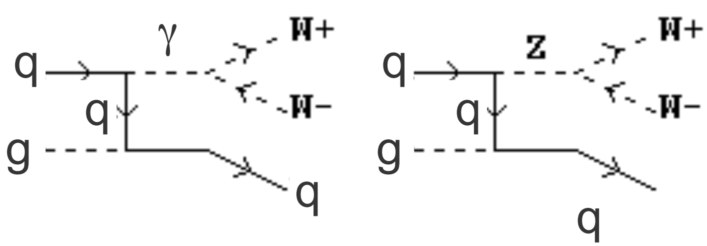
t-channel WW (similar diagrams for WZ, ZZ)

- The s- and t-channel WW diagrams are divergent but their sum is not
- At tree level, ZZ production only via the t-channel diagram

Significant contribution from NLO (≳50% of LO)

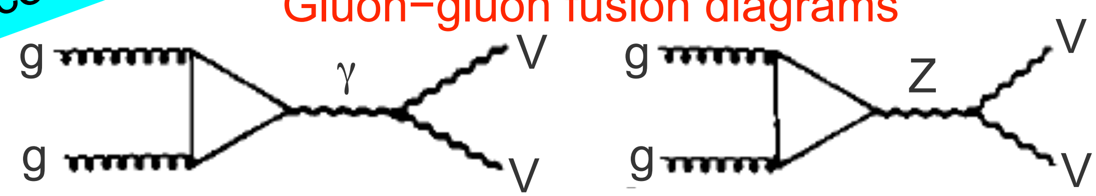


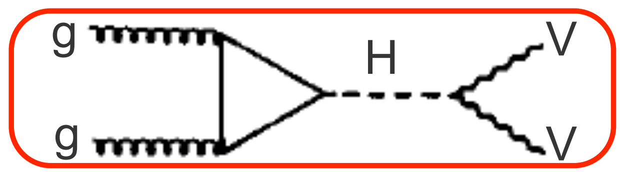
Quark−gluon diagrams



~6% gg contribution

Gluon−gluon fusion diagrams





H(125) can contribute up to 5% for WW*

Box diagrams

Plus vector boson fusion diagrams

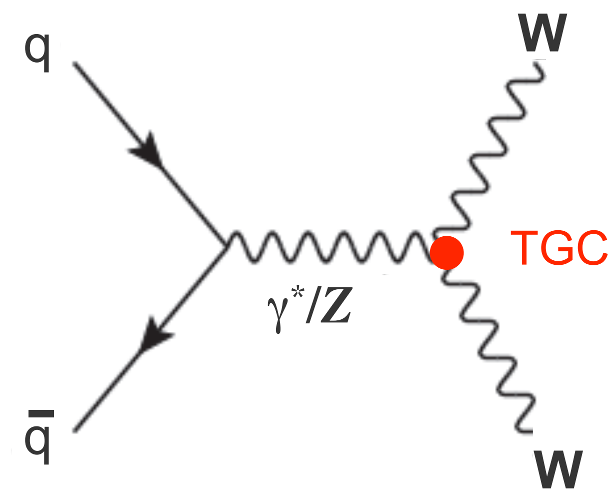
Kinds of new physics to probe I

Couplings at the TGC vertex can probe physics beyond the currently accessible mass range at the LHC

- New physics at very high energy scale (say O(10 TeV)) can produce anomalous couplings

- The Feynman diagrams same as in the SM, but different couplings

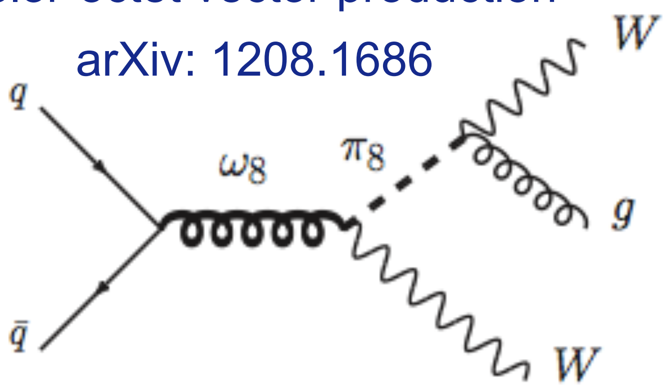
- Signature: measured cross section > the SM prediction, but mostly at high invariant mass (or high p_T tails)



Kinds of new physics to probe II

Color-octet vector production

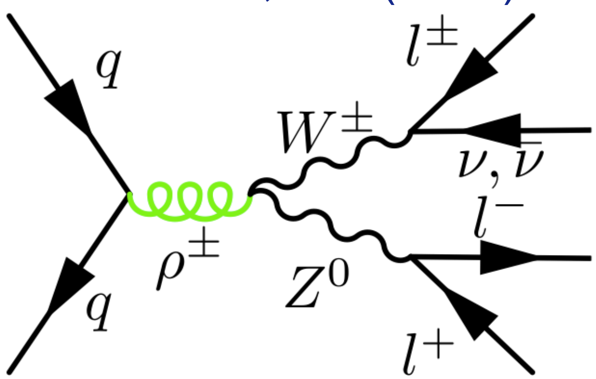
arXiv: 1208.1686

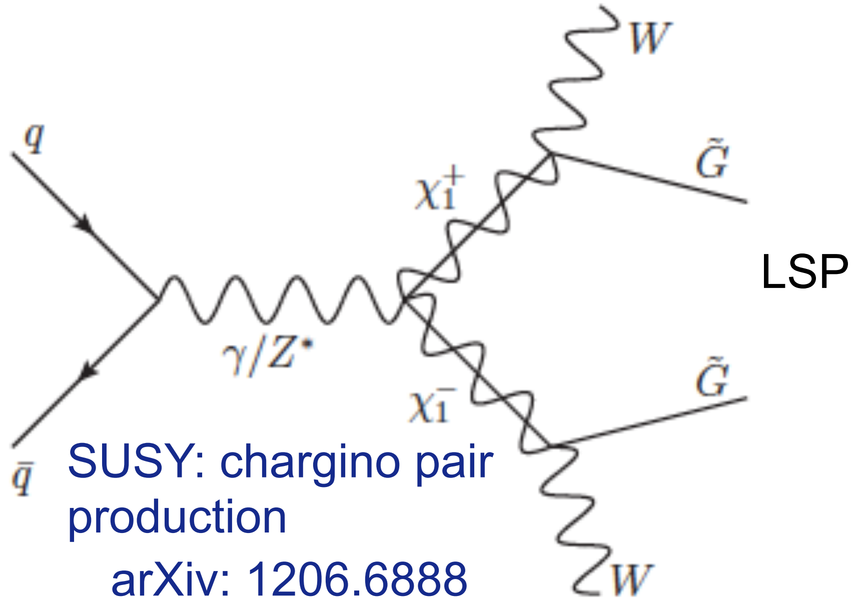


New physics can enhance diboson production rate. Few example models are shown here.

- Signature: measured cross section > the SM prediction

Low scale technicolor
Lane and Eichten, Phys. Lett. B222, 274 (1989)





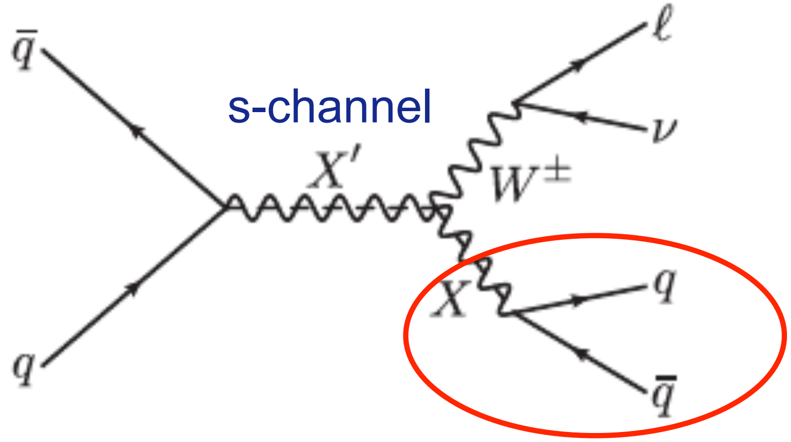
SUSY: chargino pair production
arXiv: 1206.6888

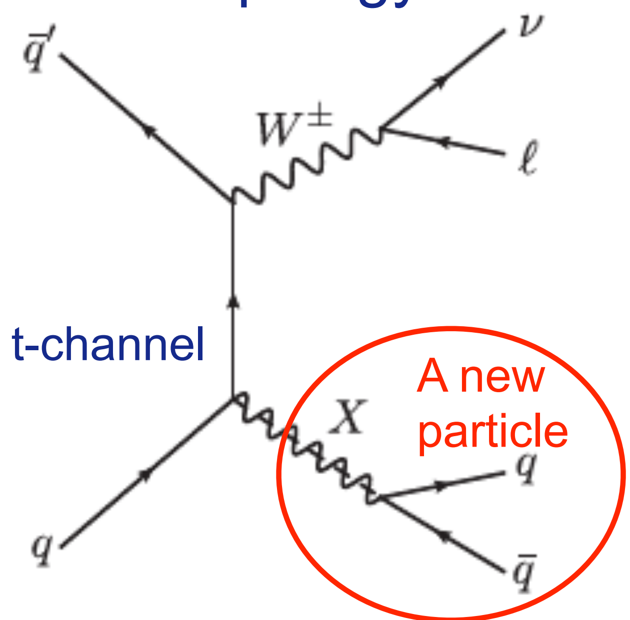
Kinds of new physics to probe III

New physics can show up in “diboson-like” topology.

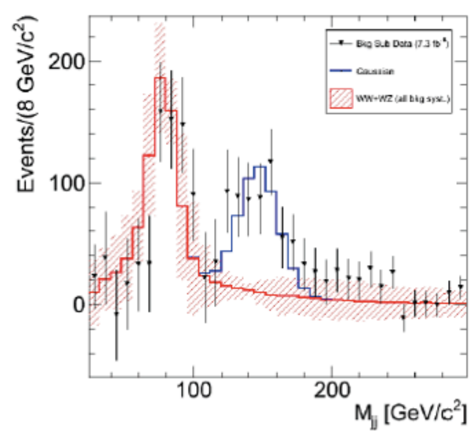
Buckley, Hooper, Kopp, Martin, Neil; arXiv: 1107.5799

Models:
technicolor,
Z’, W’, RS
graviton





•Signature: mass bump

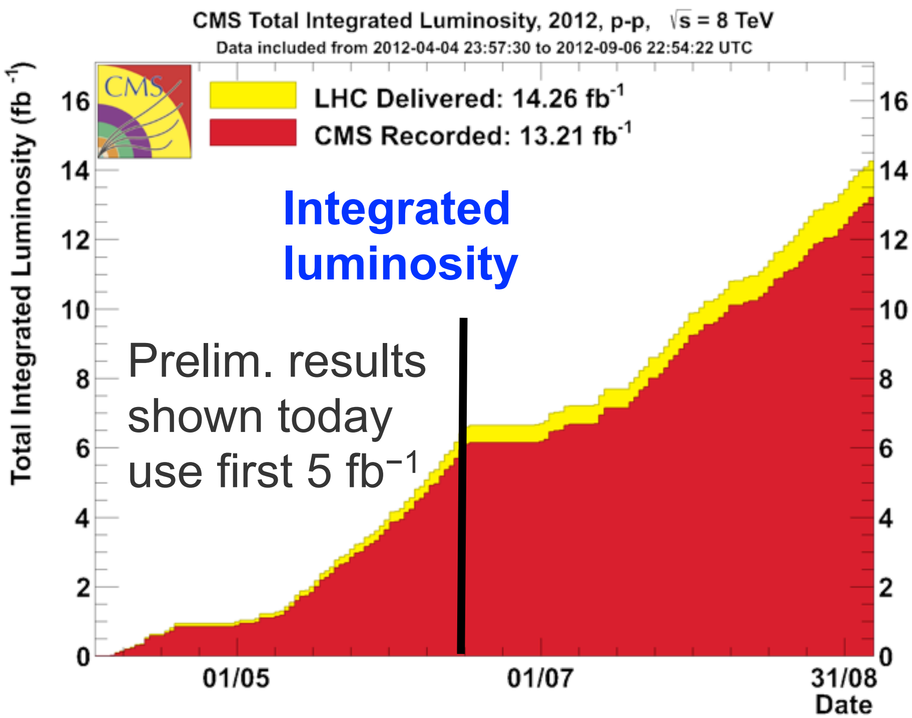


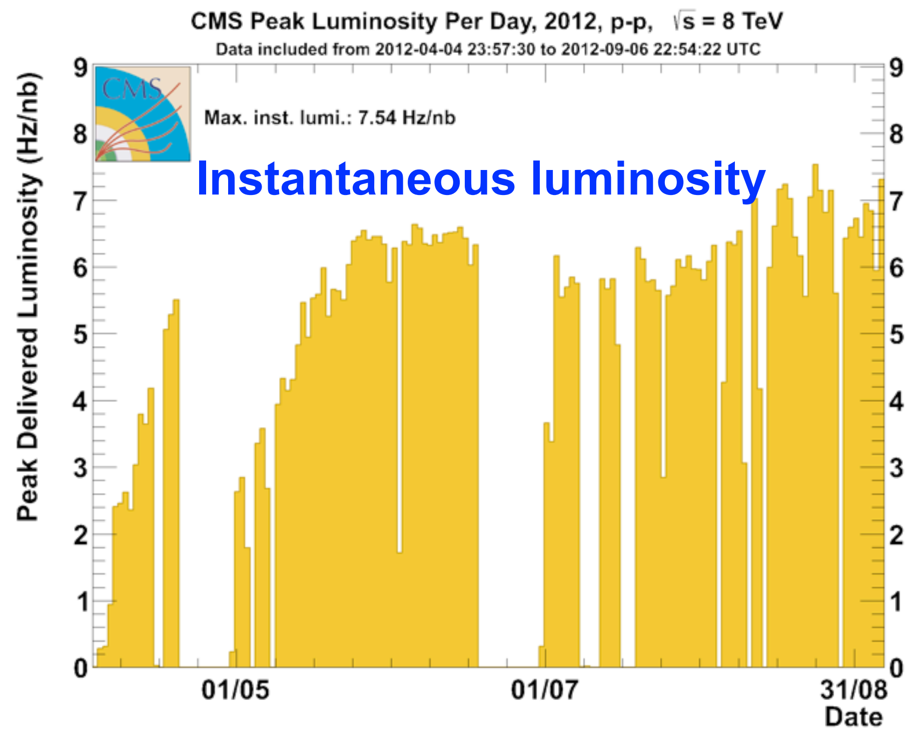
dijet invariant mass in W+ 2jet events at CDF

Data sample, Detector

- Data sample
- CMS detector
- Triggers
- Pileup
- Calibration

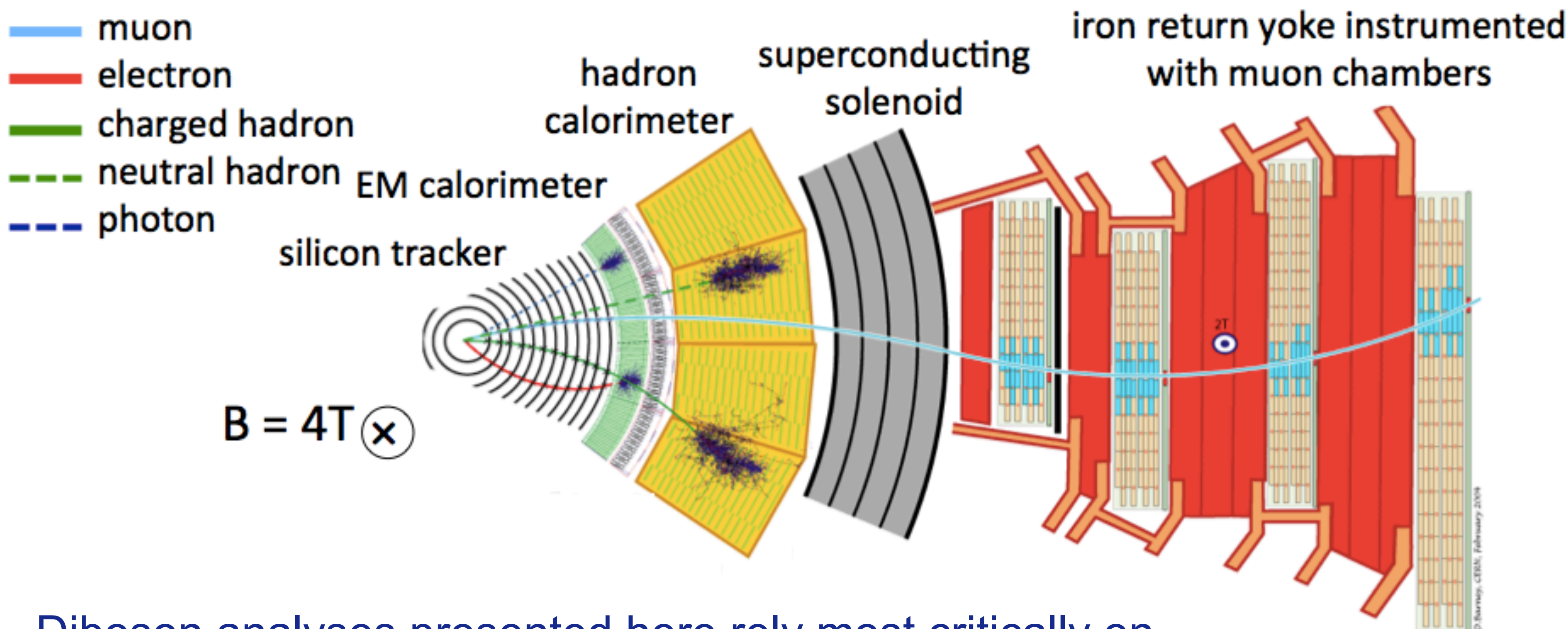
LHC data





- On target for 30 fb^{-1} by the end of 8 TeV run this year
- Routinely record 6−7 Hz/nb (i.e., 6−7 x 10^{33} $cm^{-2}s^{-1}$)

CMS detector



Diboson analyses presented here rely most critically on

- **electrons**: tracks matched to clusters in EM calorimeter
- **muons**: minimum ionizing tracks, penetrate deep into muon system
- **jets / H_T**: constructed with combined tracking + calo info
- **MET**: constructed with combined tracking + calo info, hermetic detector

Triggers

✦All analyses shown here use single or di-lepton triggers

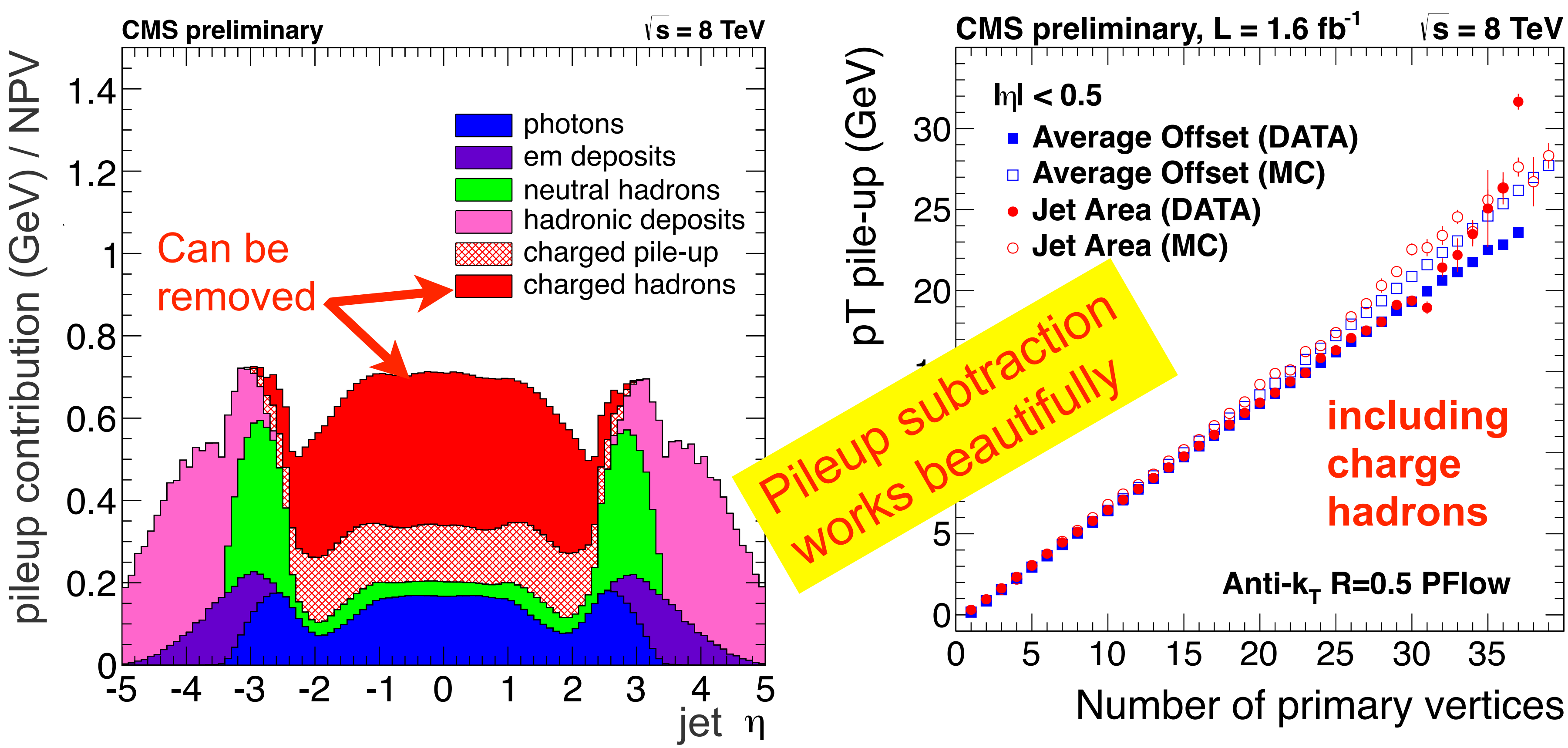
✦ Typical single lepton triggers require
- •one isolated lepton
- •threshold: 24 GeV for muon, 27 GeV for electron
- •MET > 20 GeV in case of electron

✦Typical dilepton triggers require
- •two leptons, at least one isolated
- •each with threshold that varies between 5−20 GeV

✦Offline analysis-level thresholds are higher than that in trigger. Simulation is corrected for trigger & selection efficiency.

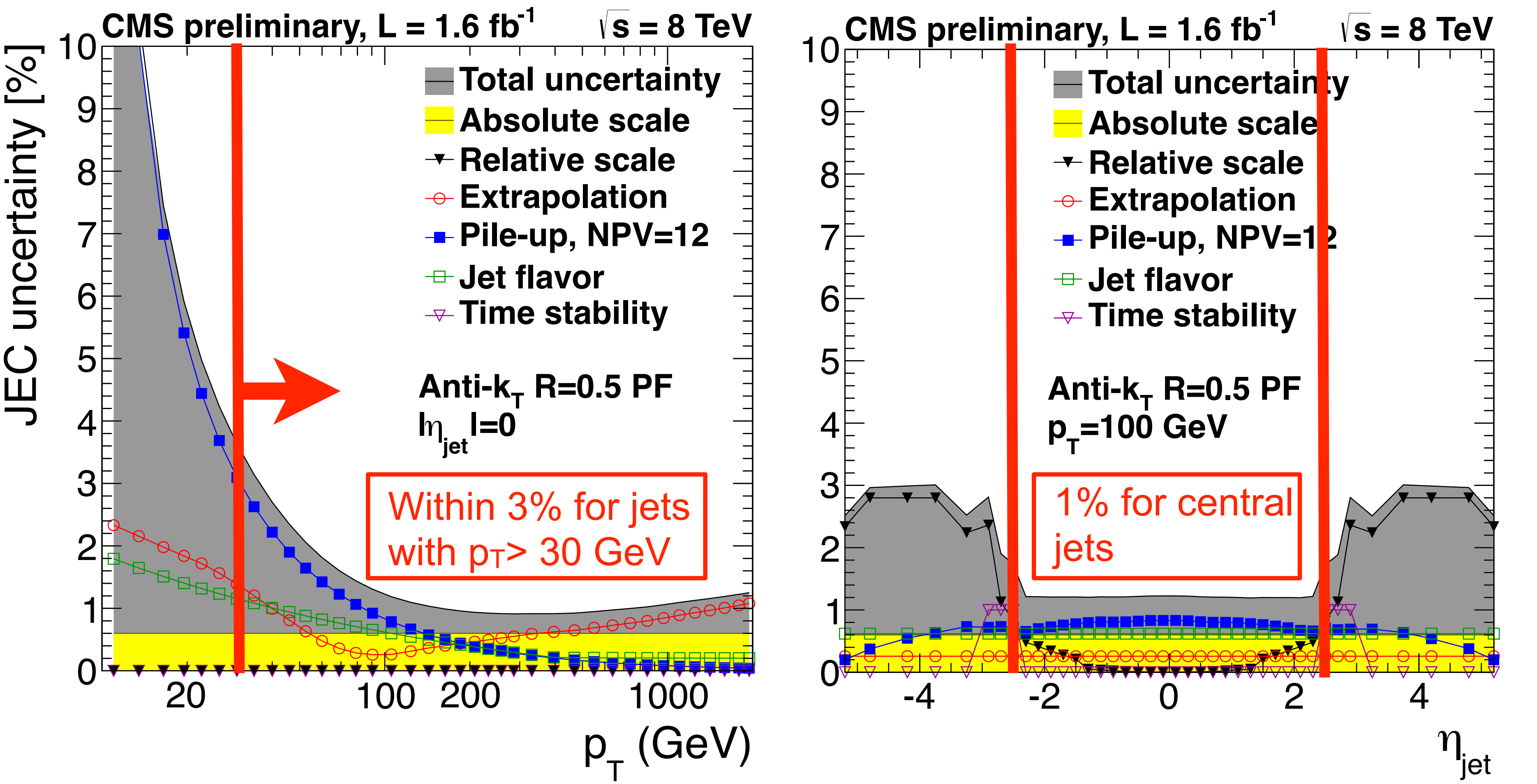
Dealing with pileup: subtract its contribution

✦ Pileup affects jet energy, MET, and lepton isolation
- Example: pileup contribution to jet p_T per primary vertex.
- Measure in data using several methods. Get consistent results.



Good understanding of detector performance

- ✦ An example: jet energy scale
  - Well calibrated

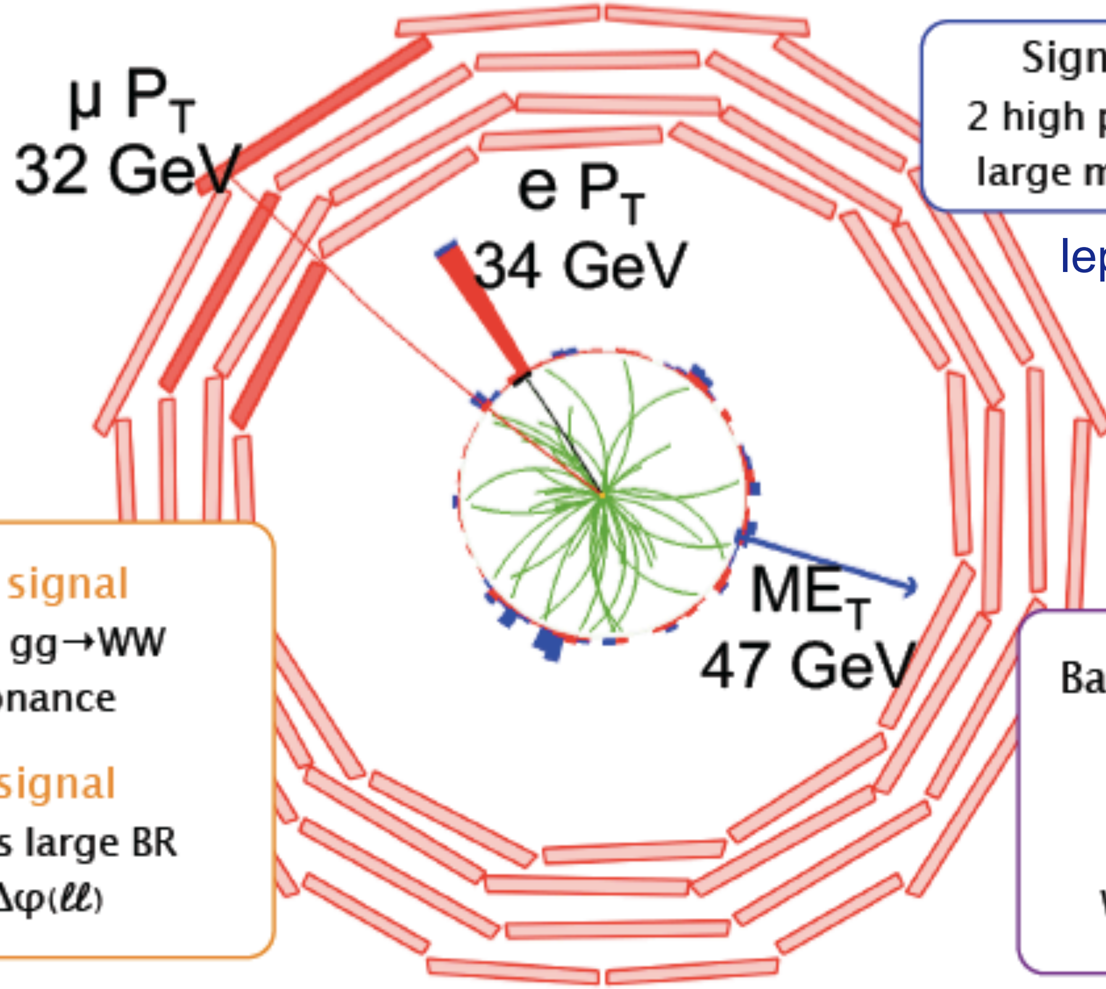


Diboson production rate measurements

- WW in purely leptonic final state (at 7 and 8 TeV)
- WW+WZ semi-leptonic (at 7 TeV)
- WZ leptonic (at 7 TeV)
- ZZ leptonic (at 7 and 8 TeV)

WW→2ℓ2ν measurements

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→WW + gg→WW
no resonance

Higgs signal
H→WW has large BR
small Δφ(ℓℓ)

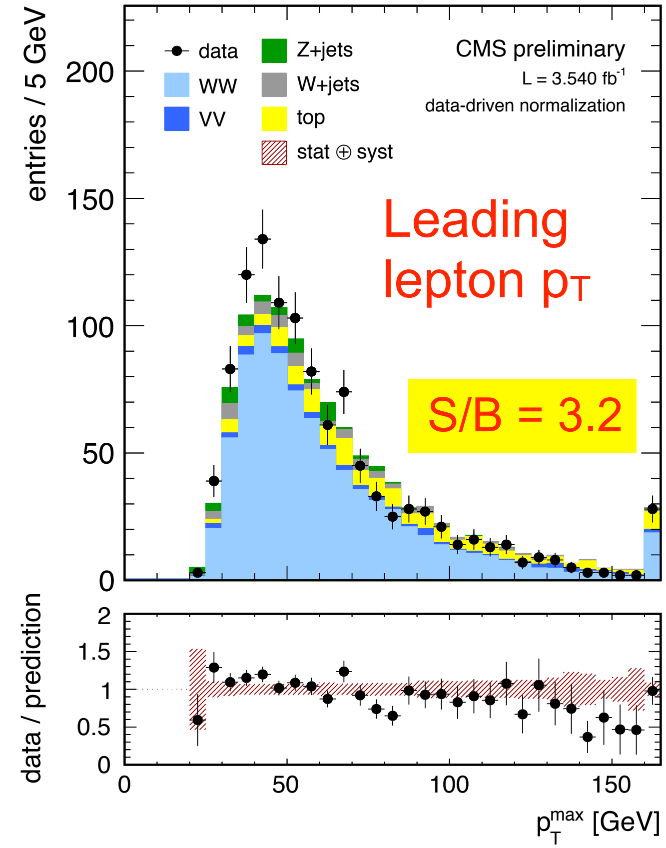
Backgrounds:
W+jet
Z/γ*
top
WZ/ZZ/Wγ

WW→2ℓ2ν cross section at 7 TeV

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

Signal and background yields

Sample	Yield ± stat. ± syst.
$gg \to W^+W^-$	$46.0 \pm 0.6 \pm 14.2$
$q\bar{q} \to W^+W^-$	$750.9 \pm 4.1 \pm 53.1$
Total Background	$247.1 \pm 14.6 \pm 29.5$
Signal + Background	$1044.0 \pm 15.2 \pm 62.4$
Data	1134



Cross section measurement

σ = 52.4 ± 2.0 (stat) ± 4.5 (sys) ± 1.2 (lum) pb
NLO prediction (MCFM): 47.0 ± 2.0 pb

☑ Consistent with NLO

Campbell, Ellis, Williams. JHEP 07 (2011), 018.

WW→2ℓ2ν cross section at 8 TeV

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

Signal and background yields

Sample	yield ± stat. ± syst.
gg→WW	$43.3 \pm 1.0 \pm 13.4$
qq→WW	$640.3 \pm 4.9 \pm 47.4$
Total Background	$292.7 \pm 22.3 \pm 31.8$
Signal + Background	$976.3 \pm 22.9 \pm 63.9$
Data	1111

σ = 69.9 ± 2.8 (stat) ± 5.6 (sys) ± 3.1 (lum) pb
NLO prediction (MCFM): 57.3 ± 2.0 pb

1.8σ above NLO prediction

Could be a conspiracy of syst bias & upward fluctuation, but has generated some buzz ...

Charginos Hiding In Plain Sight

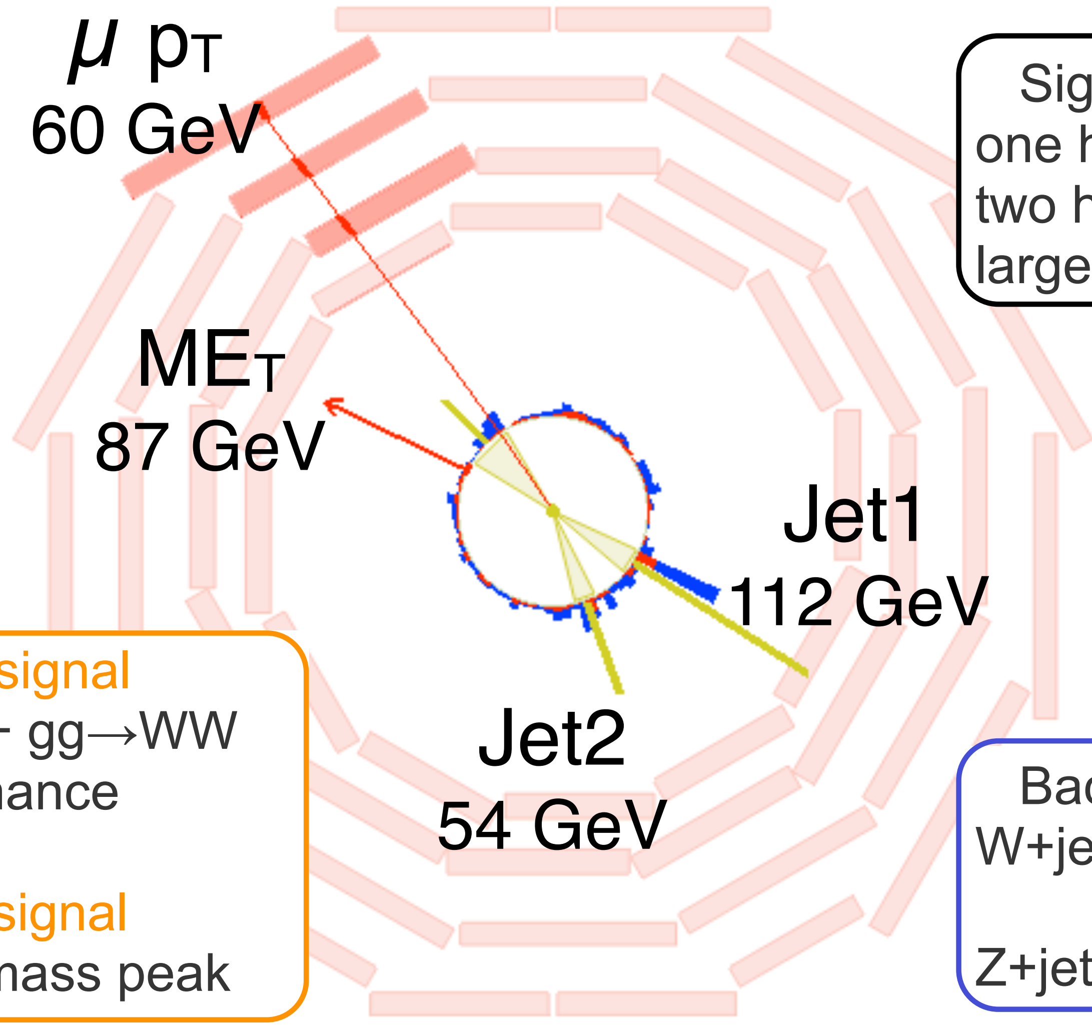
David Curtin,[1] Prerit Jaiswal,[1,2] and Patrick Meade[1]

arXiv:1206.6888v2

4% stat precision. Main systematics:
Theory (PDF & jet veto) 5%
Luminosity 4.4%.

WW/WZ→$\ell\nu$qq measurements

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12015



Signature:
one high p_T lepton
two high pT jets
large missing E_T

Lepton p_T > 25 GeV
(35 GeV for ele)
ME_T > 25 (30) GeV
Jet p_T > 35 GeV
$\Delta\eta$(Jet1, Jet2) < 1.5

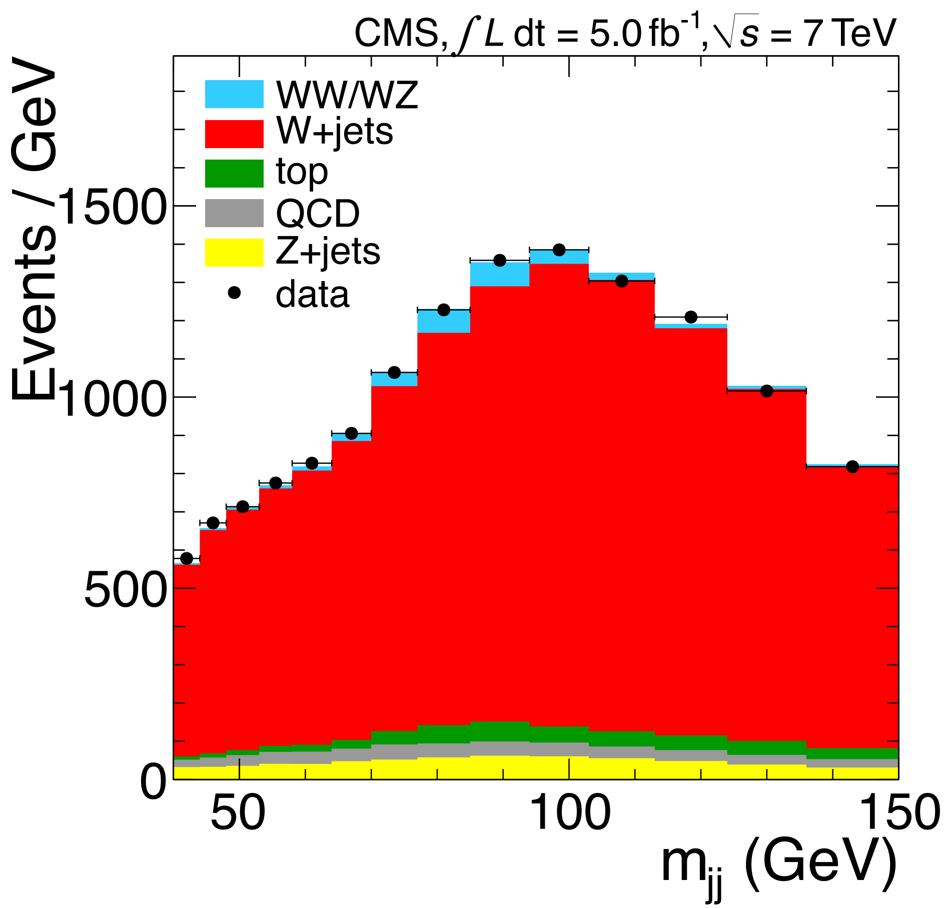
SM WW signal
qq→WW + gg→WW
no resonance

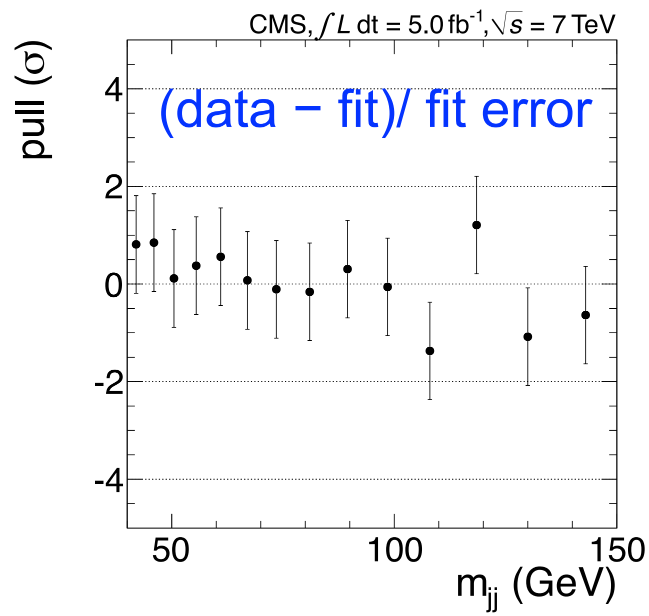
H→WW signal
resonant mass peak

Background:
W+jets (dominant)
top
Z+jets, multijet

WW+WZ→$\ell\nu$qq cross section at 7 TeV

Jet resolution doesn't allow to cleanly separate WW from WZ, so get admixture of the two. Fit the dijet mass spectrum.





Large background. The main thrust of the analysis is to model this well & control systematics.

WW+WZ→$\ell\nu$qq: signal extraction fit

Diboson contribution floated completely. QCD constrained using data. Other backgrounds constrained using (N)NLO predictions.

Process		Muon channel		Electron channel
Diboson (WW+WZ)	NLO prediction = 1697	1899 ± 389	NLO = 867	783 ± 302
W plus jets		67384 ± 586		31644 ± 850
$t\bar{t}$		1662 ± 117		946 ± 67
Single top		650 ± 33		308 ± 17
Drell-Yan plus jets (Z+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}

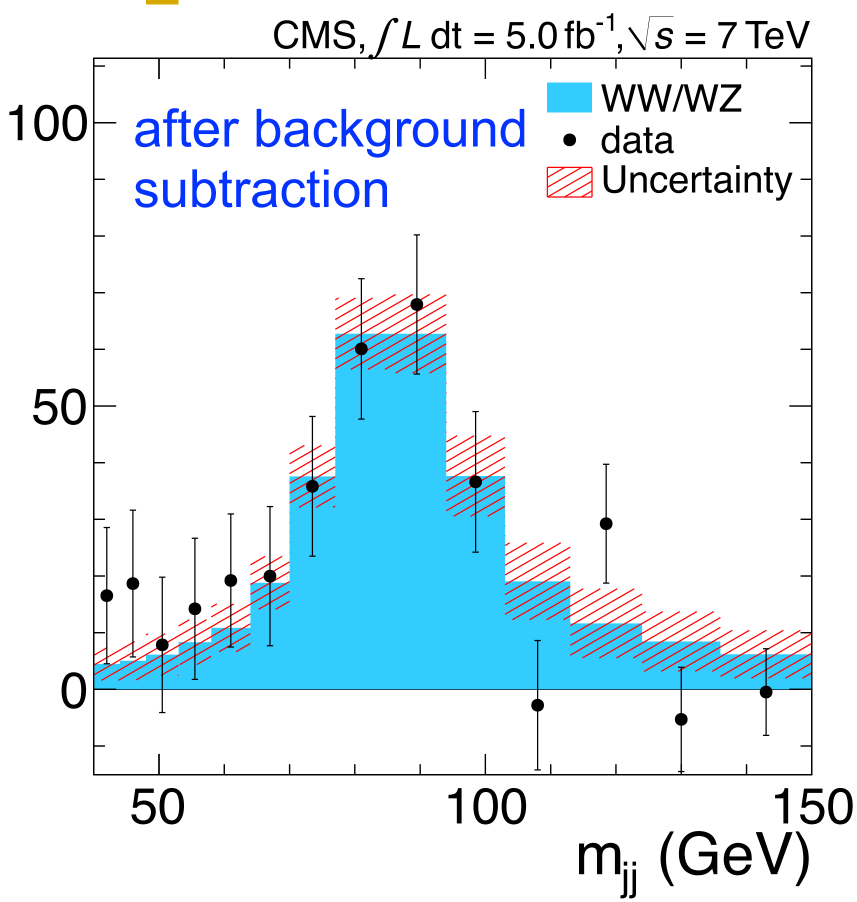
W+jets shape uncertainty

Needed to float factorization/renorm & ME-PS matching scales to get good modeling of data

$$\mathcal{F}_{\mathrm{W+jets}} = \alpha \, \mathcal{F}_{\mathrm{W+jets}}(\mu_0^2, q'^2) + \beta \cdot \mathcal{F}_{\mathrm{W+jets}}(\mu'^2, q_0^2) + (1-\alpha-\beta) \cdot \mathcal{F}_{\mathrm{W+jets}}(\mu_0^2, q_0^2),$$

- α (scale ↑ or ↓) and β (matching ↑ or ↓) consistent between e/μ data
- Data prefer smaller value for ME-PS matching threshold than 20 GeV

WW+WZ→ℓνqq cross section at 7 TeV



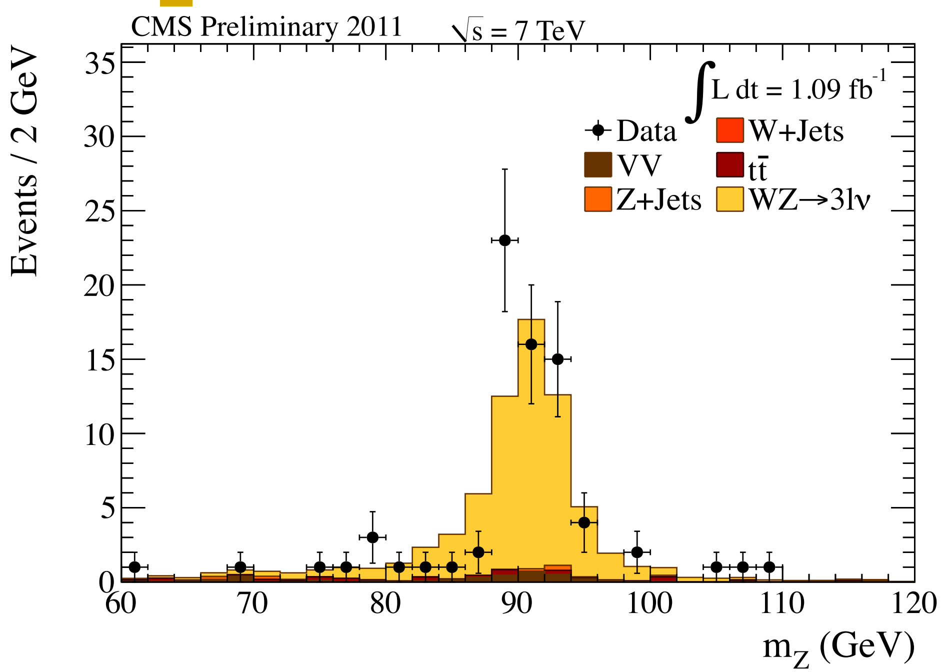
#diboson = 2682 ± 339(stat) ± 357(syst), NLO prediction = 2564

- The first observation of diboson in semi-leptonic channel at LHC.

σ = 68.9 ± 8.7 (stat) ± 9.7 (sys) ± 1.5 (lum) pb
NLO prediction (MCFM): 65.6 ± 2.2 pb

☑ Consistent with NLO

WZ→ℓℓℓ'ν cross section at 7 TeV



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

- Two iso ℓ: $p_T > 20/15$ GeV (e/μ)
- 3rd lepton $p_T > 20$, $ME_T > 30$ GeV
- $60 < m_{\ell\ell} < 120$ GeV; veto 2nd Z

Tiny background

Channel	$N_{observed}$
eee	22
$ee\mu$	20
$\mu\mu e$	13
$\mu\mu\mu$	20

σ = 17.0 ± 2.4 (stat) ± 1.1 (sys) ± 1.0 (lum) pb
NLO prediction (MCFM): 17.5 ± 0.6 pb

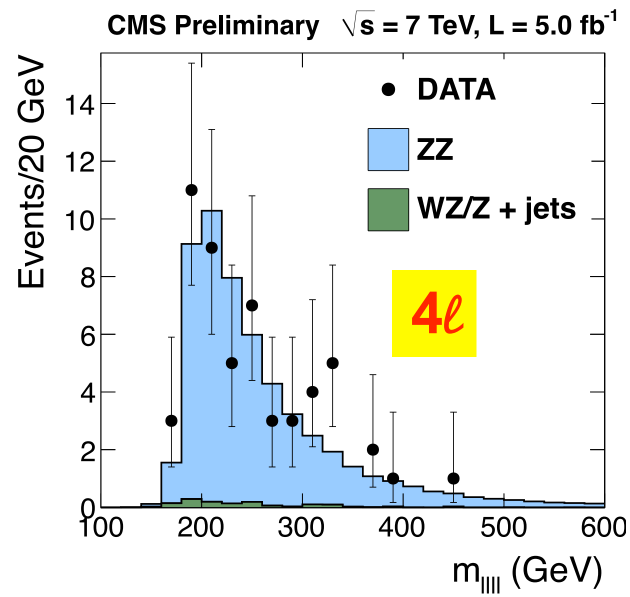
MCFM, real-width bosons, CTEQ6L, PDF uncertainty

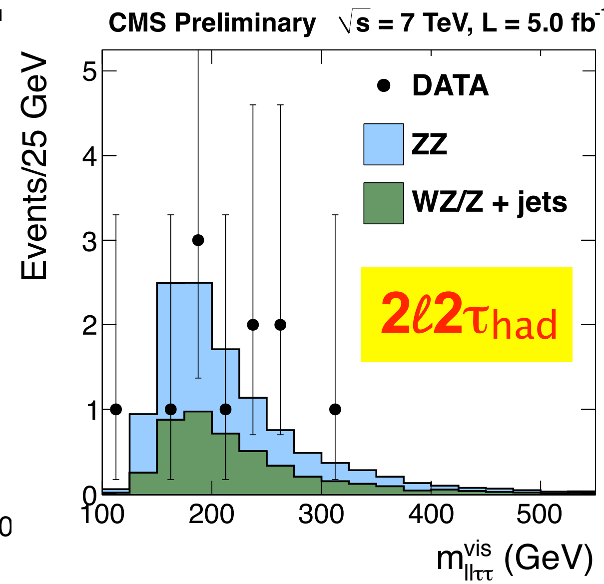
☑ Consistent with NLO

ZZ→4ℓ cross section at 7 TeV

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

- Lepton p_T: e >7 GeV, μ >5 GeV, τ_{had} >10 GeV
- $60 < m_Z < 120$ GeV ($30 < m_{vis} < 80$ for $\ell\tau_{had}$)





Channel	ZZ expected	Backgr-d	Observed
4e	10.5	0.5	9
4mu	15.9	0.2	14
2e2mu	26.7	0.6	31
Total	→	54.4	54
2l2tau	7.0	4.4	11
4l+2l2tau	→	65.8	65

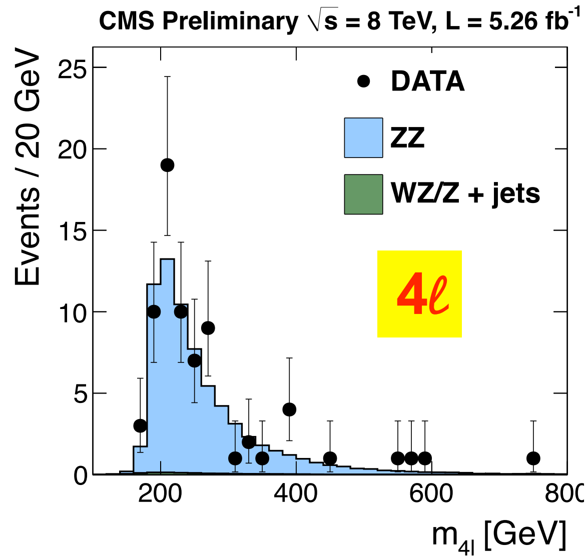
σ = 6.2 ± 0.9 (stat) ± 0.4 (sys) ± 0.1 (lum) pb
NLO prediction (MCFM): 6.3 ± 0.4 pb

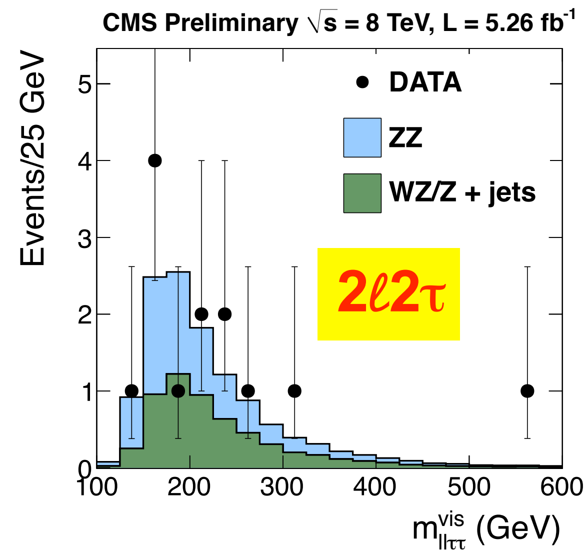
MCFM 6.0. NLO qq→ZZ + LO gg→ZZ, MSTW 2008)

☑ Consistent with NLO

ZZ→4ℓ cross section at 8 TeV

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



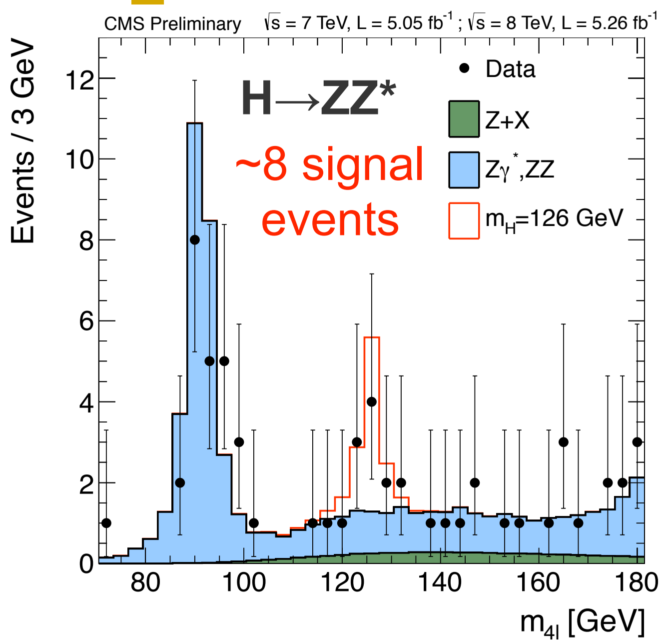


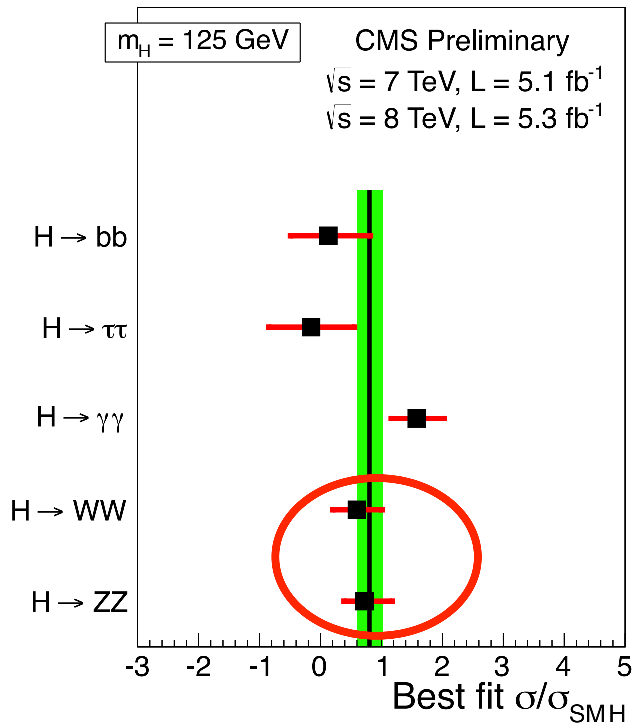
Channel	ZZ expected	Backgr-d	Observed
4e	11.6	0.4	14
4mu	20.3	0.4	19
2e2mu	32.4	0.5	38
Total		65.6	71
2l2tau	6.5	5.6	13
4l+2l2tau		77.7	84

σ = 8.4 ± 1.0 (stat) ± 0.7 (sys) ± 0.4 (lum) pb
NLO (MCFM 6.0): 7.7 ± 0.4 pb

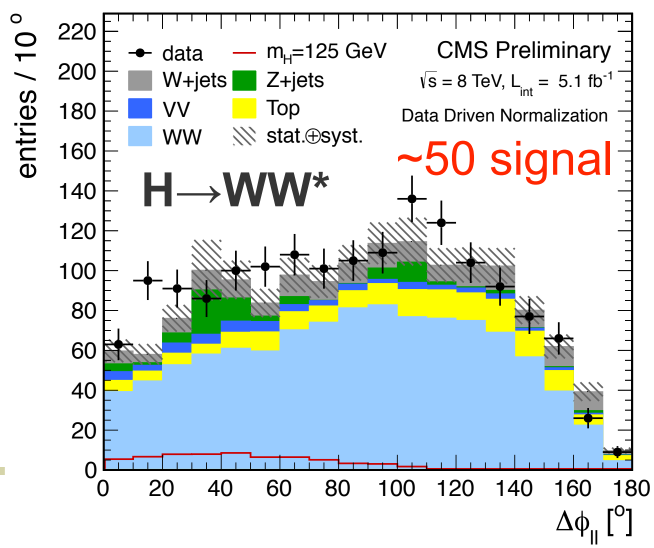
☑ Consistent with NLO

Diboson and Higgs





The observed Higgs-like boson has couplings to W & Z compatible with the SM Higgs expectation.



In order to measure Higgs couplings precisely (or to constrain/discover NP) we need to measure diboson precisely.

Anomalous triple gauge boson couplings

- Anomalous coupling in WW/WZ
- Anomalous coupling in ZZ

Anomalous couplings in WW/WZ production

5 independent couplings remain after assuming basic symmetry

$$\mathcal{L}_{anom} = ig_{WWZ}\left[\Delta g_1^Z\left(W^*_{\mu\nu}W^\mu Z^\nu - W_{\mu\nu}W^{*\mu}Z^\nu\right) + \Delta\kappa^Z W^*_\mu W_\nu Z^{\mu\nu} + \frac{\lambda^Z}{M_W^2}W^*_{\rho\mu}W^\mu_\nu Z^{\nu\rho}\right] + ig_{WW\gamma}\left[\Delta\kappa^\gamma W^*_\mu W_\nu \gamma^{\mu\nu} + \frac{\lambda^\gamma}{M_W^2}W^*_{\rho\mu}W^\mu_\nu \gamma^{\nu\rho}\right],$$

Equal coupling parametrization $\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \cdot tan^2\theta_w$ and $\lambda_Z = \lambda_\gamma = \lambda$

Further assume that $\Delta g_1^Z = 0$ (SM), leaves two parameters: λ_Z , $\Delta\kappa_\gamma$

Previous measurements

World average: LEP combination

Coupling	Particle Data Group Fit
Λ_γ	$0.028^{+0.020}_{-0.021}$
Λ_Z	$\boxed{0.088^{+0.060}_{-0.057}}$
Δg_1^Z	$0.016^{+0.022}_{-0.019}$
$\Delta\kappa_\gamma$	$\boxed{0.027^{+0.044}_{-0.045}}$
$\Delta\kappa_Z$	$0.026^{+0.059}_{-0.056}$

Λ_Z: [-0.026, 0.208] @ 95% CL

$\Delta\kappa_\gamma$: [-0.063, 0.115] @ 95% CL

Tevatron (D0) brand-new result arXiv:1208.5458

λ_Z: [-0.039, 0.042] @ 95% CL

$\Delta\kappa_\gamma$: [-0.049, 0.124] @ 95% CL

Note: assumes form factor Λ = 2 TeV

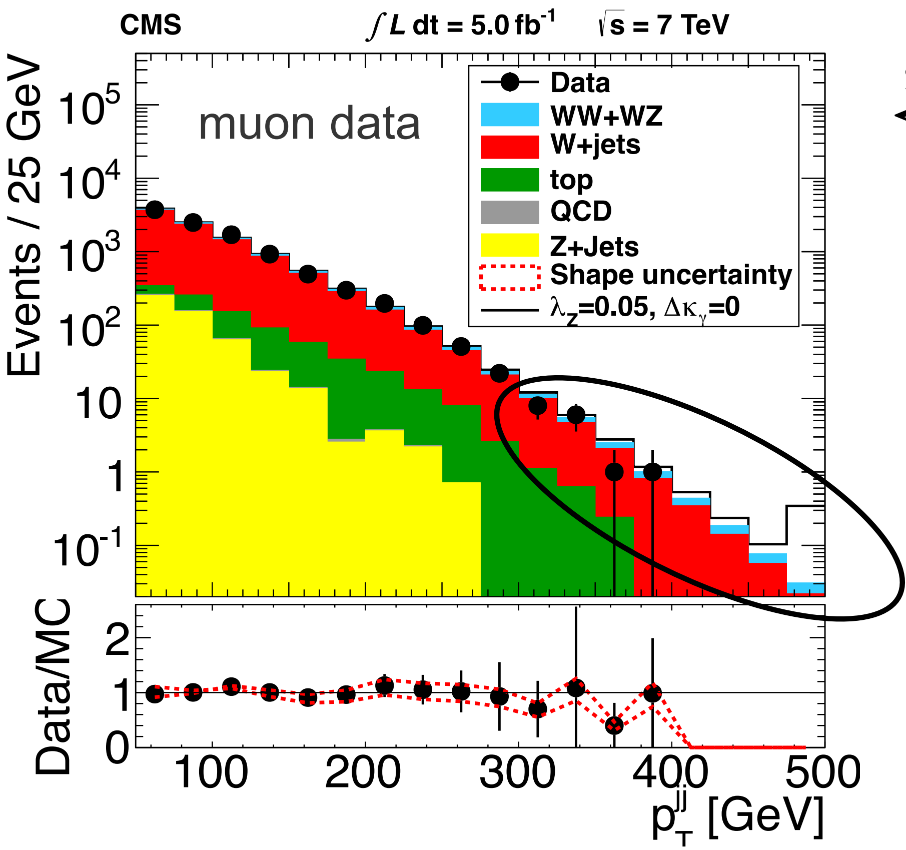
LHC

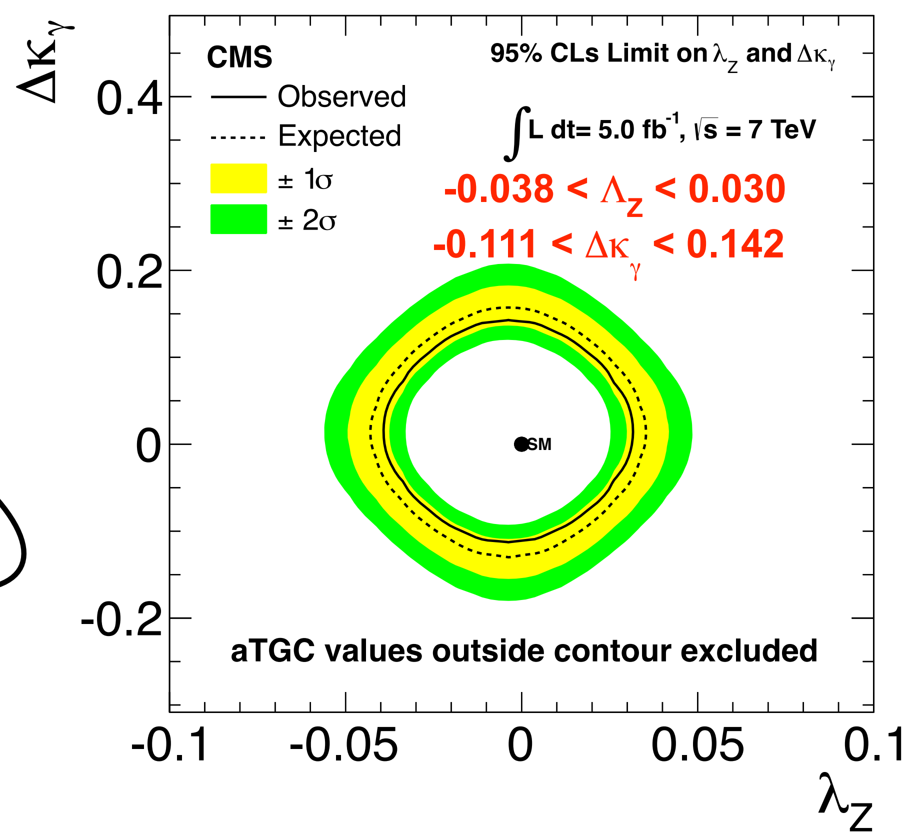
Coupling	CMS 35 pb^{-1} ($WW \to \ell^+\nu\ell^-\bar{\nu}$)	ATLAS 1 fb^{-1} ($WW \to \ell^+\nu\ell^-\bar{\nu}$)
Λ_Z	[-0.19,0.19] at 95% C.L.	[-0.079,0.77] at 95% C.L.
$\Delta\kappa_\gamma$	[-0.61,0.65] at 95% C.L.	[-0.071,0.071] at 95% C.L.
Δg_1^Z	[-0.29,0.31] at 95% C.L.	[-0.052,0.082] at 95% C.L.

LEP combination limits are still the most precise

Limits from WW/WZ→ℓνqq measurement

Use dijet (hadronic W) p_T as the observable

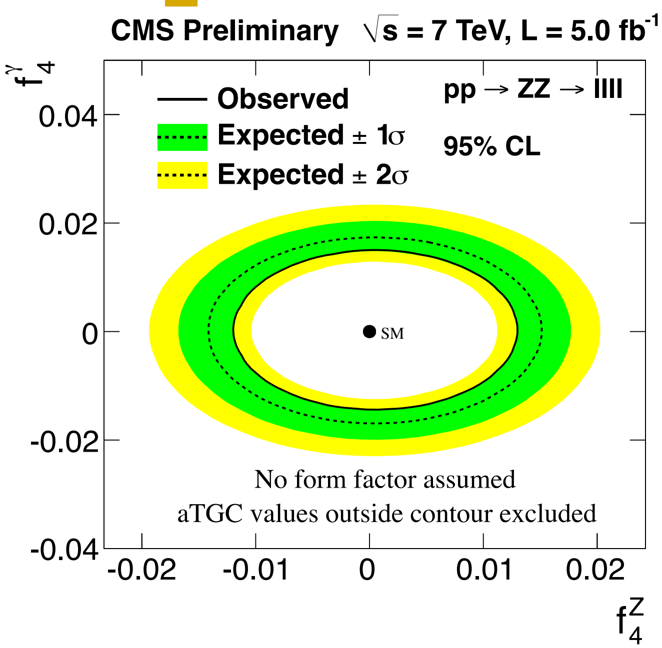


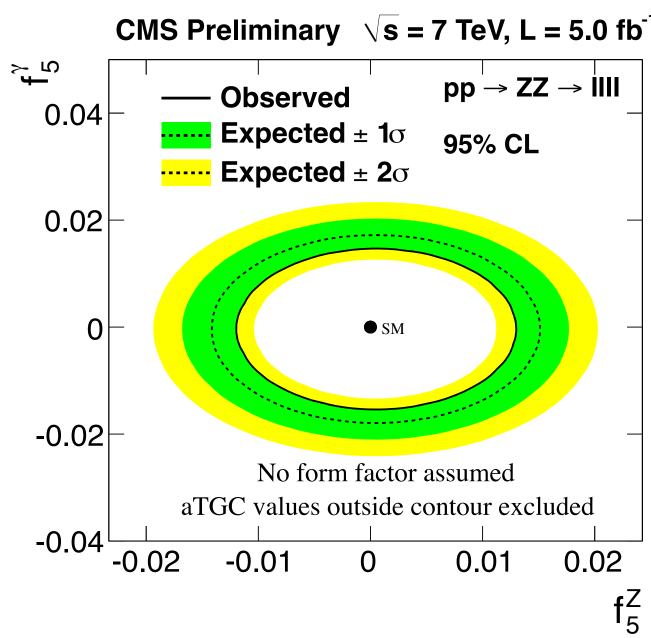


Anomalous coupling shows up in high p_T tails. Model using MCFM.

Competitive to the world average (LEP combination). Will surpass with 8 TeV data.

Limits on anomalous couplings in ZZ





Observable m_{4l}. Constrain parameters that would allow ZZZ, ZZγ, Zγγ, γγγ couplings.

$$-0.012 < f_4^Z < 0.013$$
$$-0.012 < f_5^Z < 0.013$$
$$-0.014 < f_4^\gamma < 0.014$$
$$-0.015 < f_5^\gamma < 0.015$$

At 95% CL, the strongest limit to-date
Use no form factors, i.e., $\Lambda = \infty$

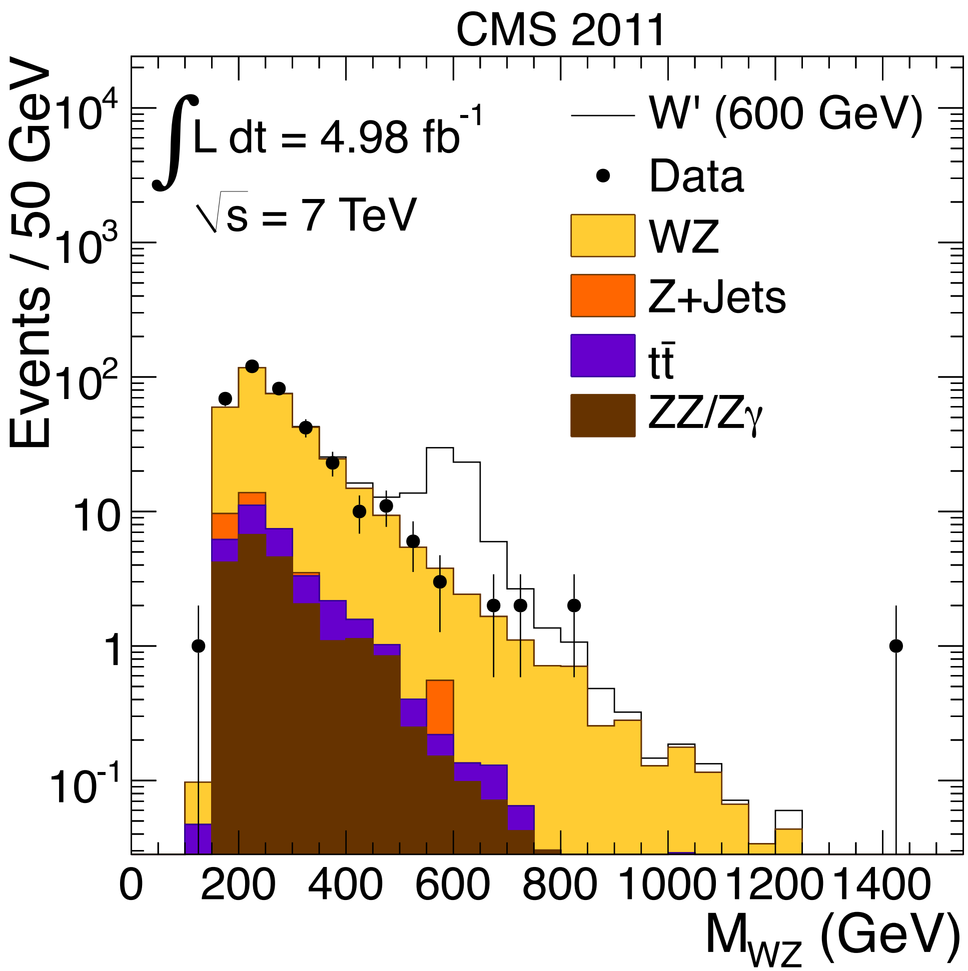
Experiment	f_4^Z	f_4^γ	f_5^Z	f_5^γ	Comment
LEP WG	[-0.30;0.30]	[-0.17;0.19]	[-0.34;0.38]	[-0.32;0.36]	LEP combination
ATLAS	[-0.07;0.07]	[-0.08;0.08]	[-0.07;0.07]	[-0.08;0.08]	~ 1 fb^{-1}, Λ=inf

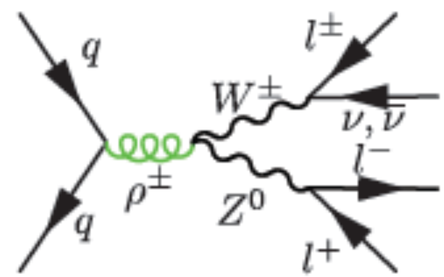
CMS limits are an order of magnitude more constraining than LEP.

Technicolor, Z', RS graviton, ...

Search for $\rho_{TC} \to WZ$ and $W' \to WZ$ ($\to \ell\ell'\nu$)

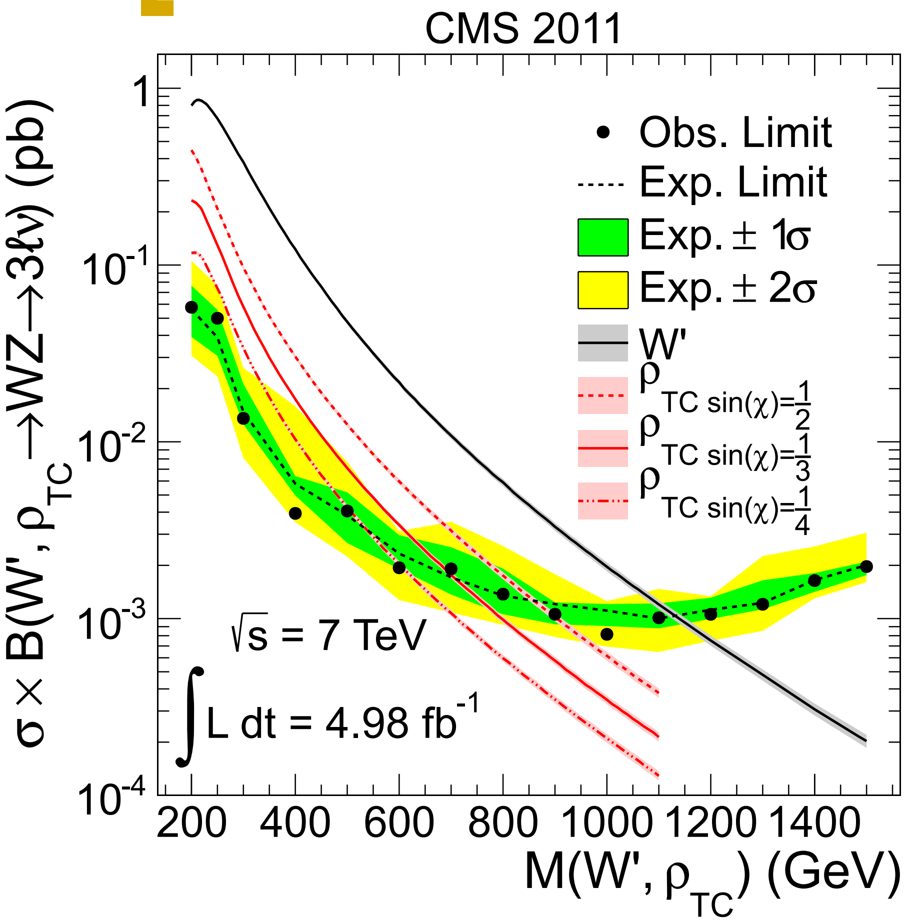
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11041

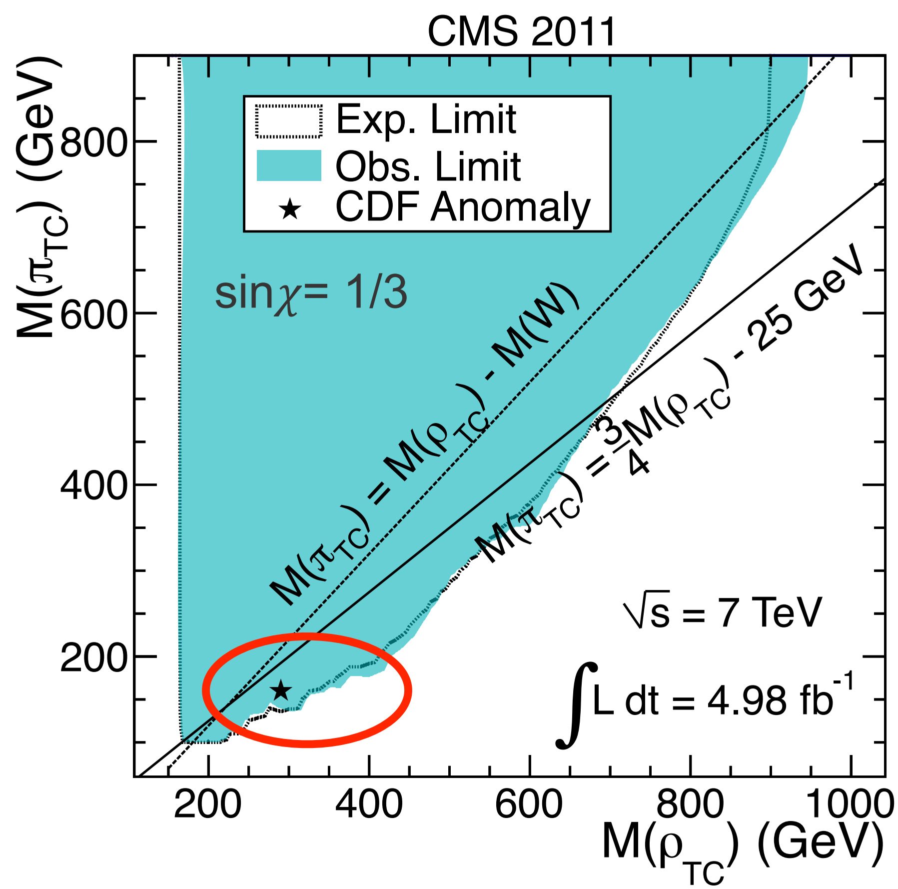




- Event selection same as in WZ cross section analysis
- Smoothly falling spectrum, no interesting structure
- Set limit

Limits on W', technicolor ρ_{TC}



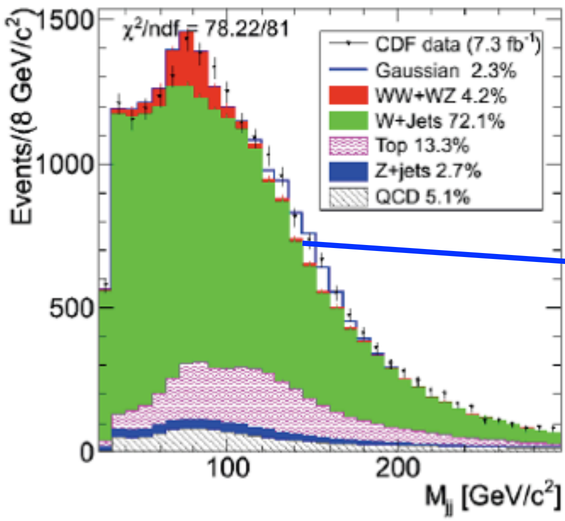


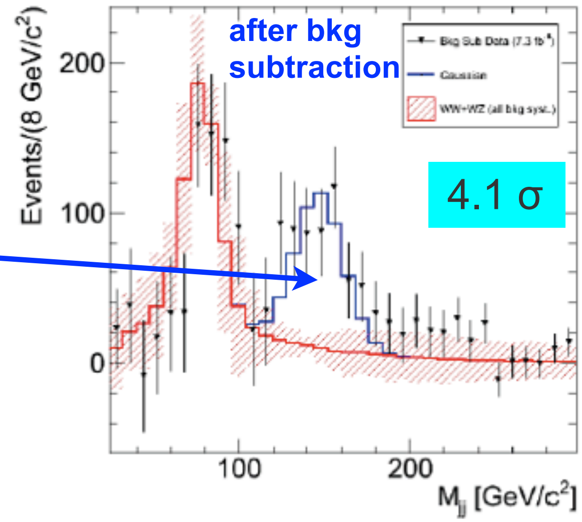
CDF anomaly: (ρ_{TC} =290, π_{TC} =160)

Exclude W' up to mass 1143 GeV at 95% CL

Exclude low scale techni-color interpretation of CDF anomaly

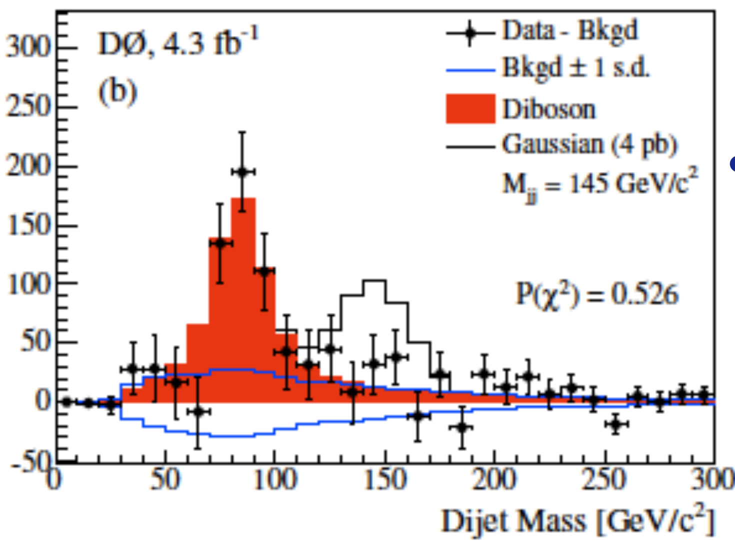
Search for NP in W+2jet: how it all started





arXiv: 1101.6079, PRL 106:171801 (2011)

- CDF W+jj data show an excess in m_{jj} spectrum near 150 GeV, width = 15 GeV (≈ jet reso.)
- production rate 4 pb



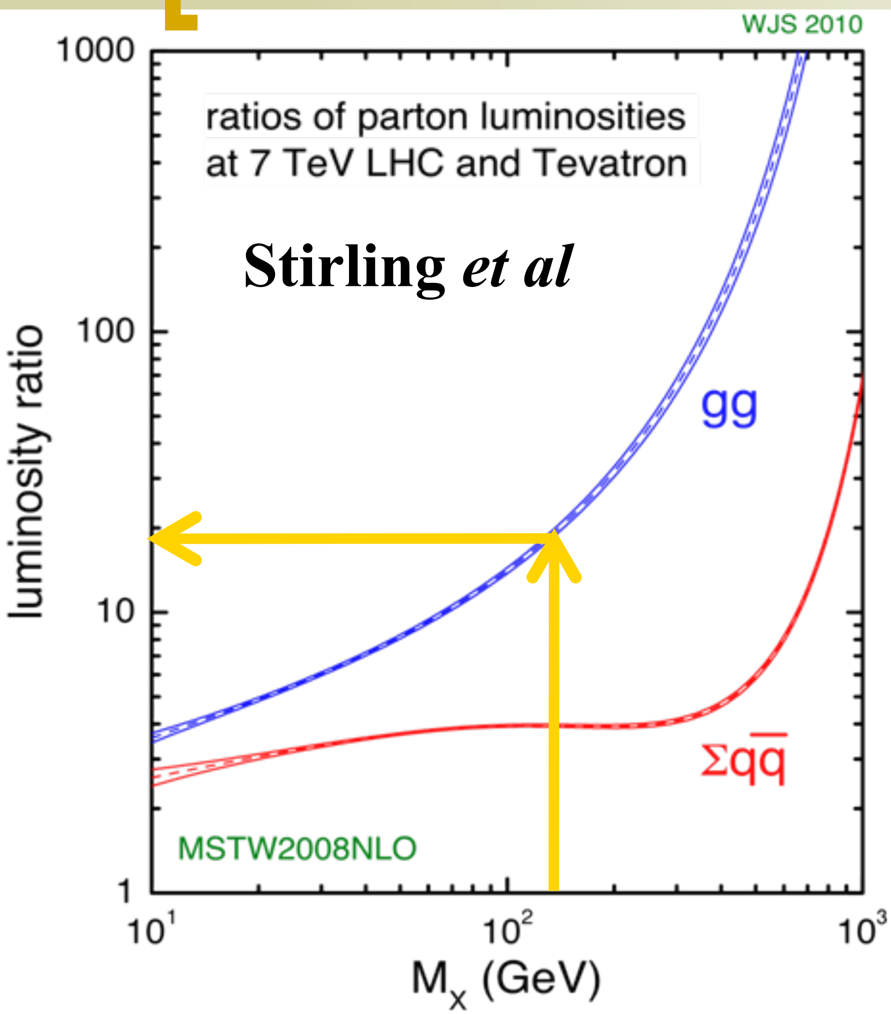
arXiv: 1106.1921, PRL 107:011804 (2011)

- D∅ data such excess @99.9999% CL

<u>Need for similar analysis at LHC</u>

- If it is new physics it should appear at LHC
- If not, still need to understand the SM processes in this important topology

Difficulty to reconstruct qq signal at LHC

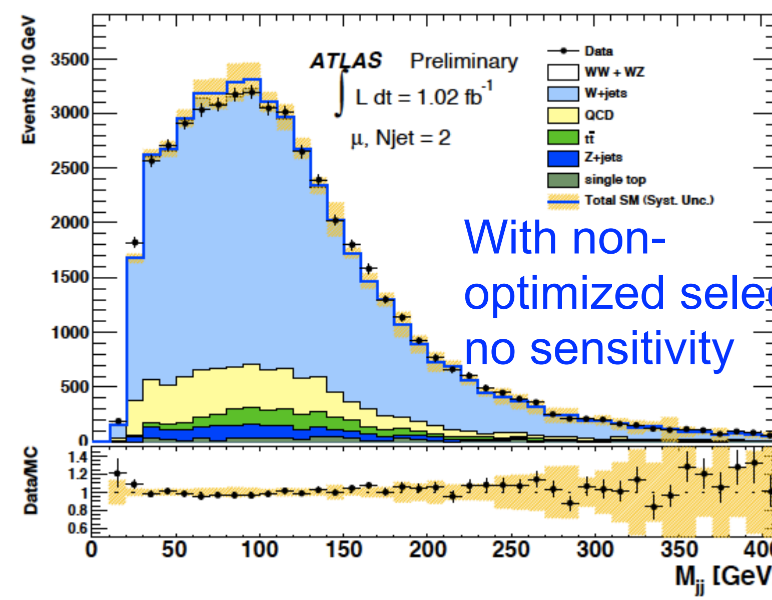


Need stronger cuts

$q\bar{q}$ → WW, WZ cross section at 7 TeV is **~ 3.5 times** that at 2 TeV

Major backgrounds are W/Z+jets, single top & $t\bar{t}$, QCD multi-jet etc. which rise **by factor 10** due to rise in qg and gg cross sections

⇒ Small signal, worse S/N



With non-optimized selection no sensitivity

CMS analysis: what are the differences

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11017

(submitted to PRL)

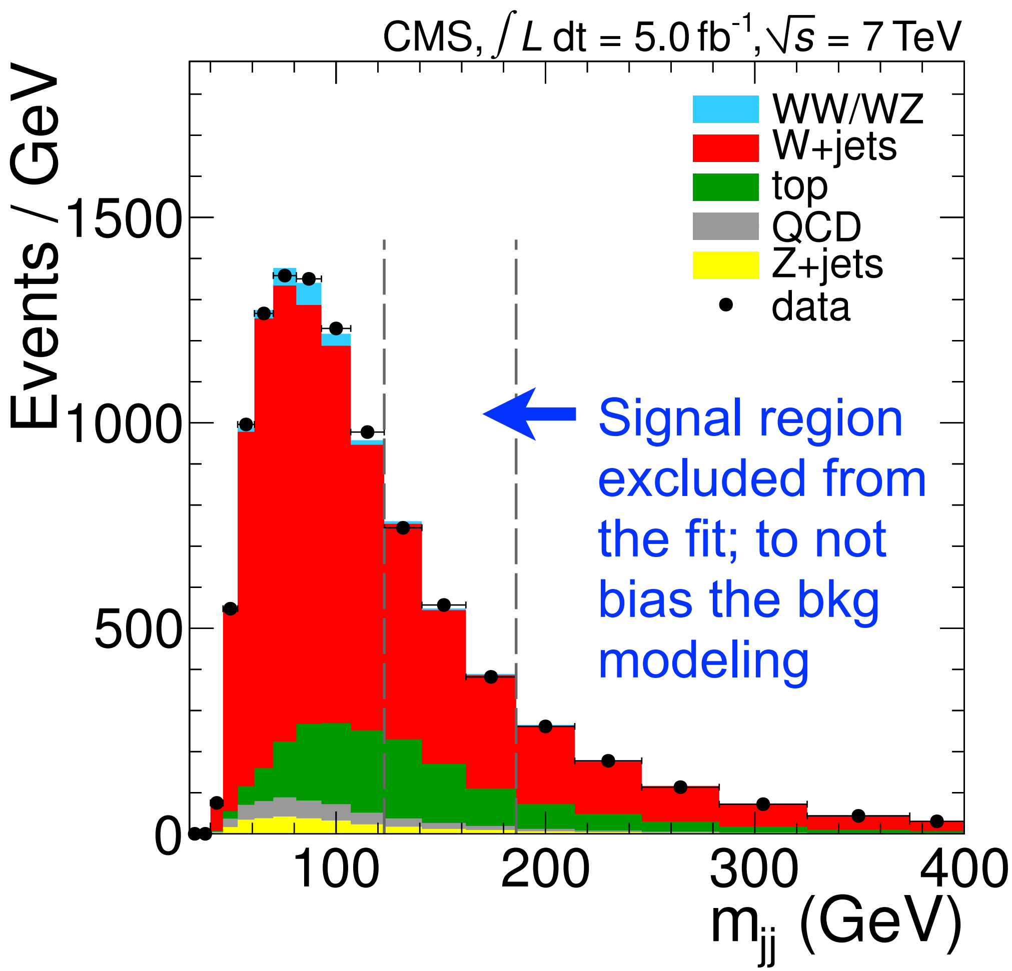
$W \to \ell\nu$ selection	Jet selection	
	$p_T^{j1} > 40\,\text{GeV}$	vs 30 GeV at CDF
$p_T^{\mu(e)} > 25\ (35)\,\text{GeV}$	$\|\vec{p}_T^{\,j1} + \vec{p}_T^{\,j2}\| > 45\,\text{GeV}$	vs 40 GeV
$\not{E}_T^{\mu(e)} > 25\ (30)\,\text{GeV}$	$\|\Delta\eta(j1, j2)\| < 1.2$	vs no cut
$M_T > 50\,\text{GeV}$	$0.3 < p_T^{j2}/m_{jj} < 0.7$	vs no cut

These are not real differences. Due to trigger constraints have higher lepton and MET threshold.

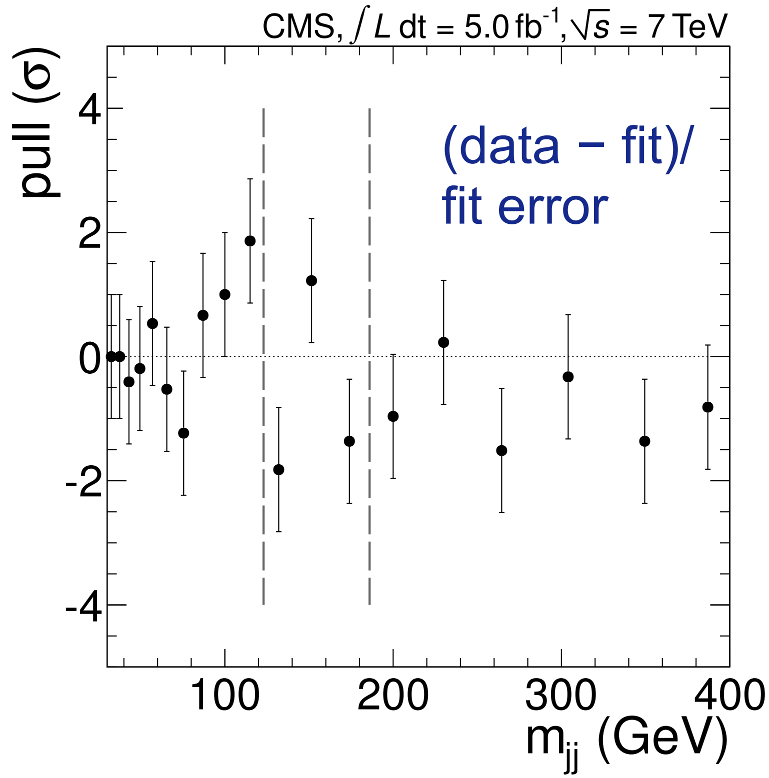
Also analyze 3-jet events

- Higher leading jet p_T helps in beating down the background
- Higher boost, smaller $\Delta\eta$, and Jacobian cut for dijet system
- Improve S/B for all resonant signal (diboson, TC, Z', WH)

Modeling of dijet mass spectrum



Signal region excluded from the fit; to not bias the bkg modeling



(data − fit)/ fit error

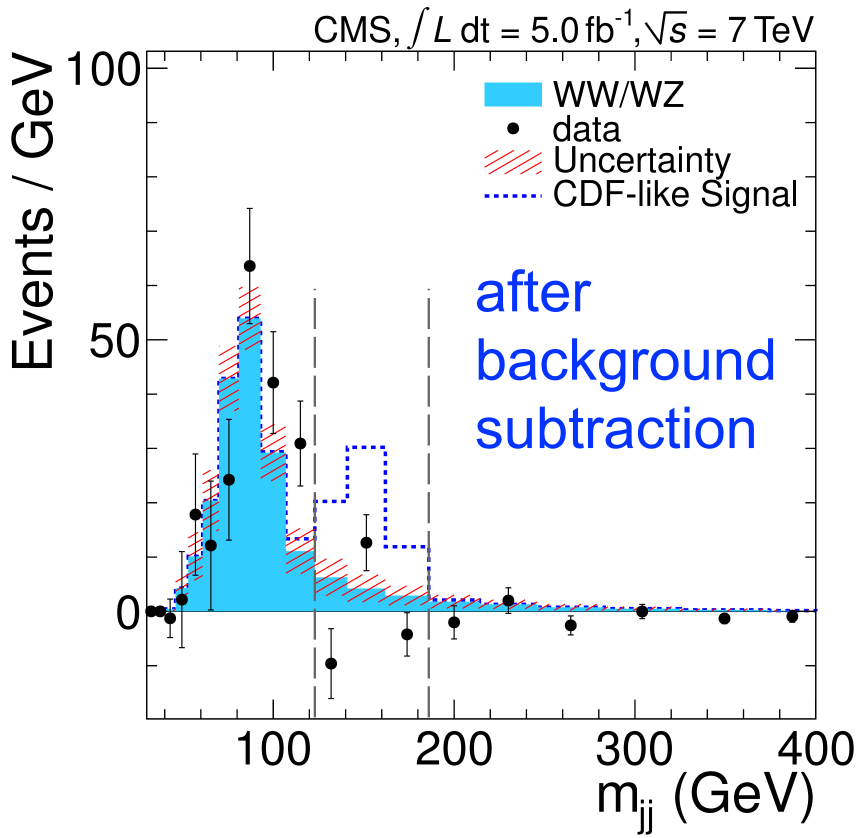
Good modeling of data. Same procedure as in semi-leptonic WW+WZ analysis is used.

Full fit results

	muons		electrons	
Process	2-jet	3-jet	2-jet	3-jet
W plus jets	58919 ± 530	13069 ± 366	29787 ± 1153	8397 ± 292
Dibosons	1236 ± 114	333 ± 32	685 ± 65	184 ± 18
$t\bar{t}$	4570 ± 307	9049 ± 382	2556 ± 174	4265 ± 253
Single-top	1765 ± 87	1001 ± 50	916 ± 46	521 ± 26
Drell–Yan plus jets	1837 ± 79	561 ± 24	1061 ± 46	364 ± 16
Multijet (QCD)	29 ± 284	0 ± 90	3944 ± 1133	324 ± 160
Fit χ^2 probability	0.454	0.729	0.969	0.991
Total from fit	68294 ± 307	24013 ± 193	38949 ± 228	14055 ± 143
Data	67900	24046	38973	14145

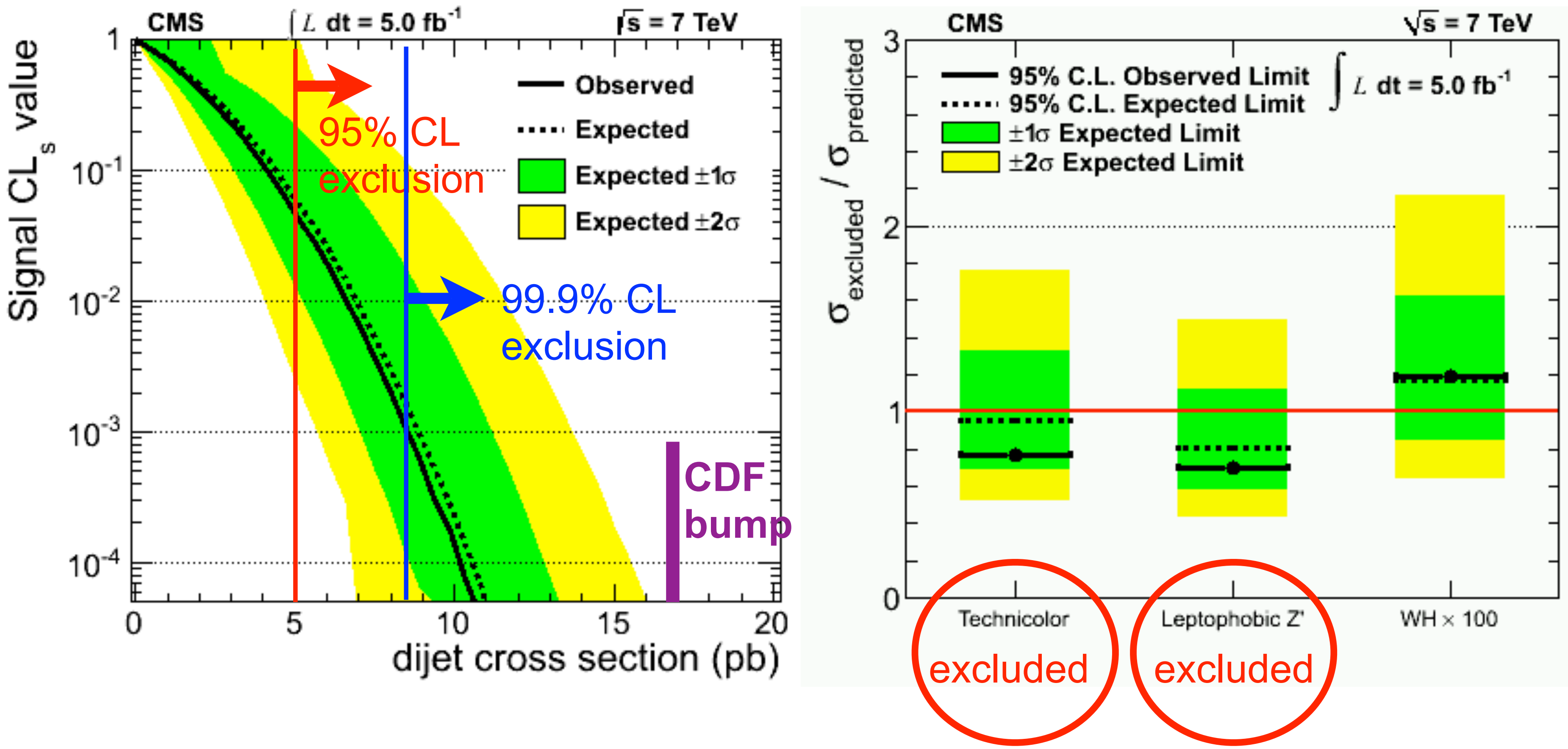
Modeling of SM background

In the signal region $123 < m_{jj} < 186\,\text{GeV}$ (excluded from the fit)				
Total predicted	14511 ± 125	7739 ± 95	7944 ± 92	4347 ± 70
Data	14050	7751	8023	4438



- No excess found in the signal/test region

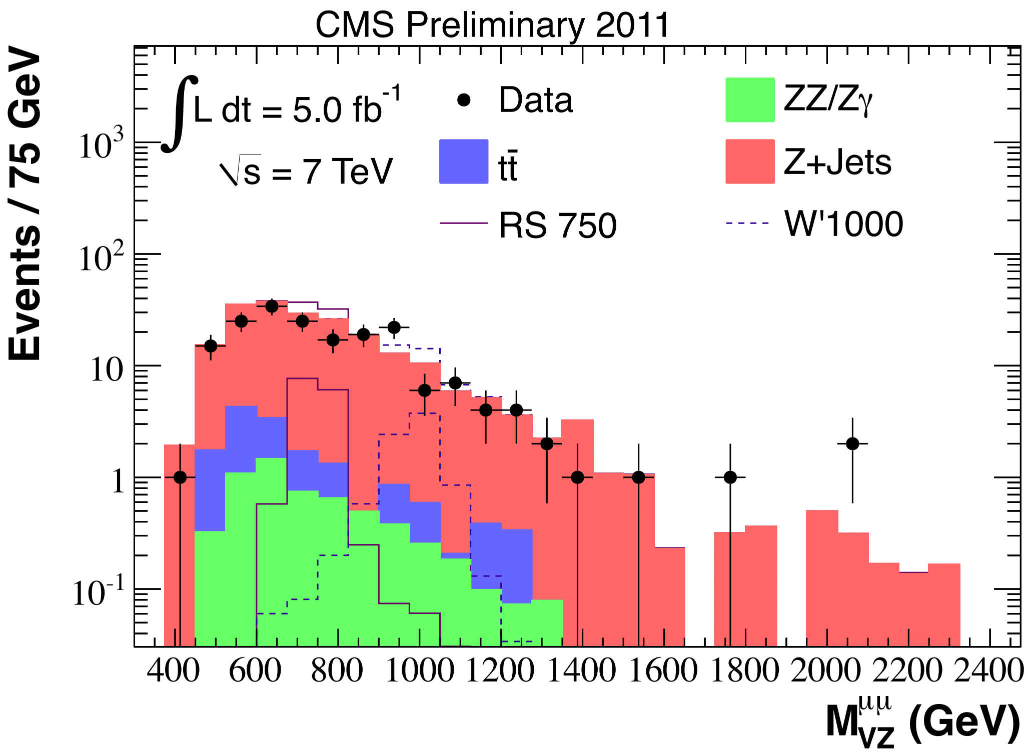
Limits



- Exclude CDF anomaly with very high confidence level
- Exclude low scale technicolor and Z' models

Search for W' & RS graviton in VZ→ℓℓ+j (boosted)

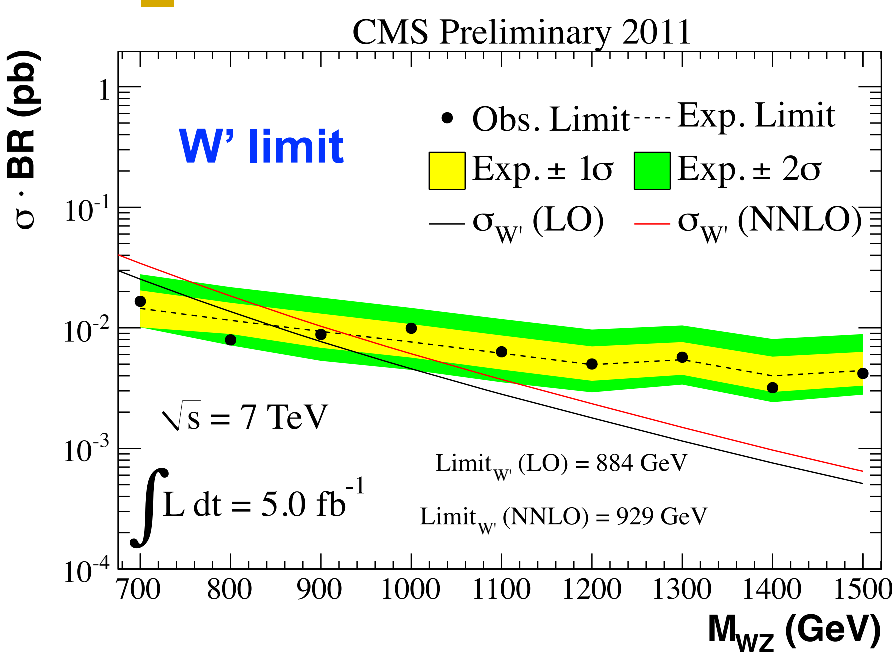
http://cdsweb.cern.ch/record/1444879

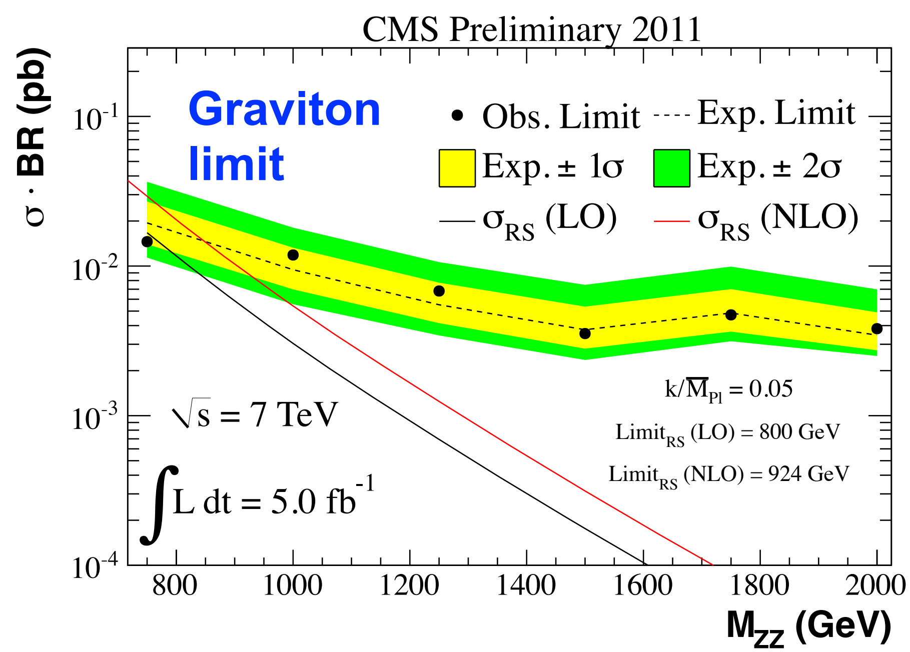


Smoothly falling spectrum. Set limit.

- ✦Search for W'→WZ and G →WZ where one Z decays laptonically
- ✦The other boson (W or Z) decays hadronically into a single (merged) jet
  - -anti-kT 0.7 jet
  - -highly boosted: p_T > 250 GeV
- ✦Plot invariant mass of the VZ system.

Limits on W' & RS graviton





At 95% CL we exclude

- Sequential W' bosons with masses < 700−929 GeV
- RS graviton with k/M_{Pl} =0.05 and masses < 700−924 GeV

The first results from LHC on VZ searches using boosted massive jet.

Summary I

- ☑ Measure diboson production rates with a few % accuracy
  - Cross sections for WW, WZ, ZZ
  - First measurement of WW+WZ production in semi-leptonic final state
  - Consistent with state-of-the-art MC and NLO predictions

- ☑ Focus now on new physics that can appear in these events
  - Set stringent limits on anomalous gauge boson couplings
  - ZZ anomalous TGC limits 10x more constraining than LEP
  - WW, WZ limits are approaching LEP-level sensitivity

Summary II

- Analyzed the W+jj data
  - No evidence for any bump at 150 GeV
  - Exclude nominal technicolor and Z' interpretations of CDF anomaly
  - The conclusion is also supported by WZ data
- Perform bump hunt in diboson topology
  - Exclude large parameter space for low scale technicolor
  - First search at LHC in WZ & ZZ events using boosted massive jet
  - Exclude large mass ranges for W', Z', and RS graviton

BACKUP SLIDES

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.

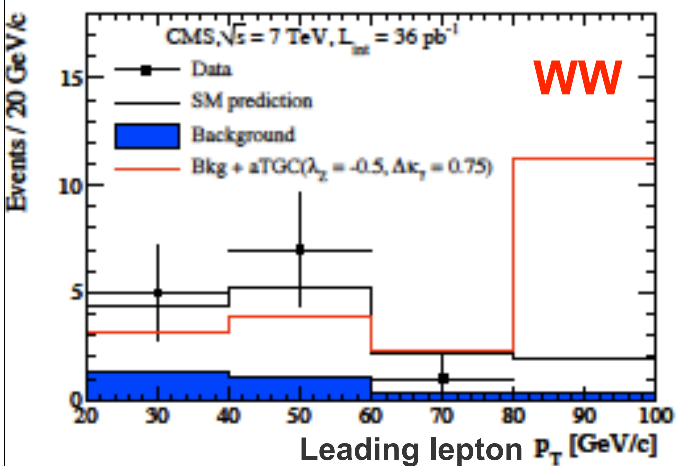
[28] D0 Collaboration *Phys. Rev. Lett.* **100** (2008) 131801.

[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)

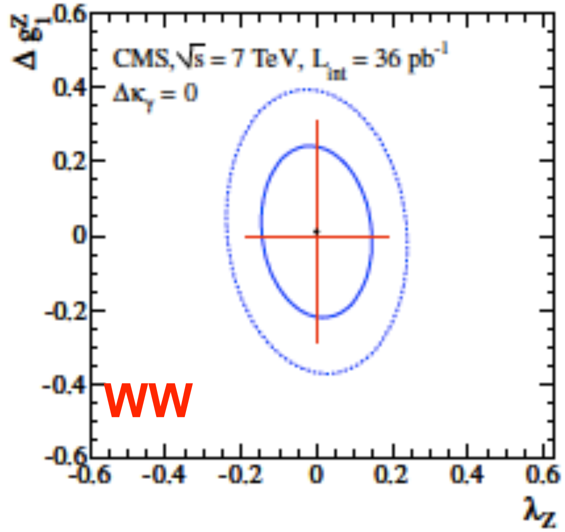


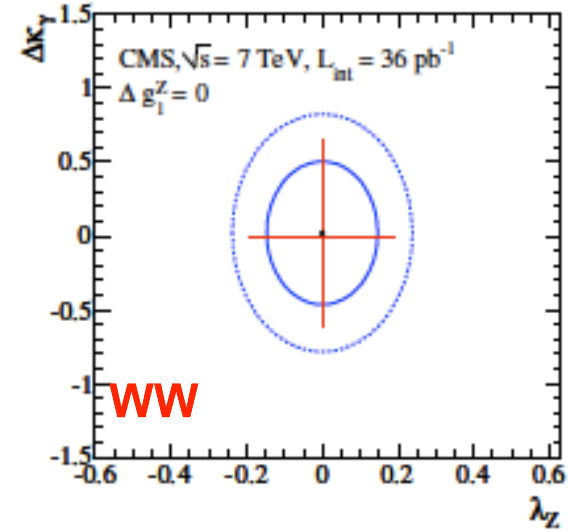
λ_Z	Δg_1^Z	$\Delta\kappa_\gamma$
$[-0.19, 0.19]$	$[-0.29, 0.31]$	$[-0.61, 0.65]$

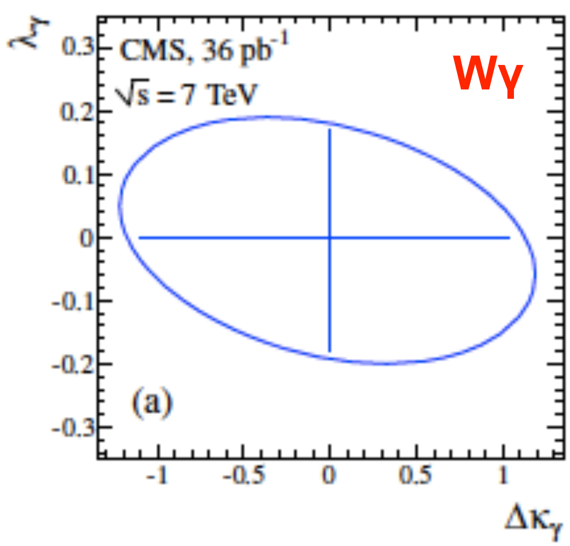
WWγ	ZZγ
$-1.11 < \Delta\kappa_\gamma < 1.04$	$-0.05 < h_3 < 0.06$
$-0.18 < \lambda_\gamma < 0.17$	$-0.0005 < h_4 < 0.0005$

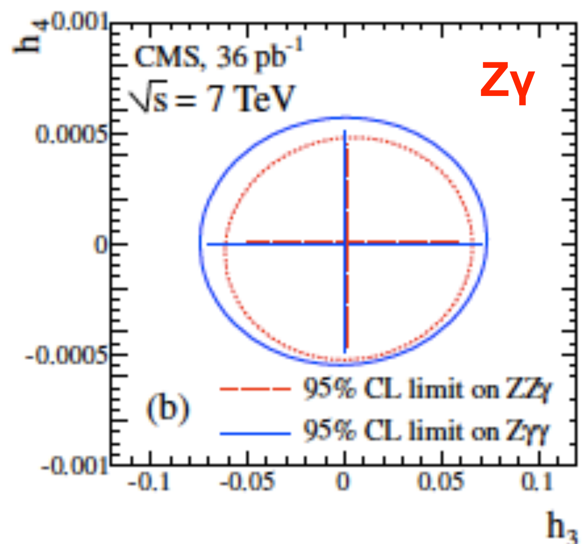
Similar sensitivity to Tevatron results presented in :

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









$WW \rightarrow 2\ell 2\nu$ 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
- $Z/\gamma^* \rightarrow \tau\tau$: up to 50%

Background components:

- Major Backgrounds — Data Driven
  - QCD / W+jet
  - Top
  - Drell Yan
- Smaller backgrounds — *MC Simulation*
  - $W\gamma$
  - $Z \rightarrow \tau\tau$
  - non resonant WZ/ZZ

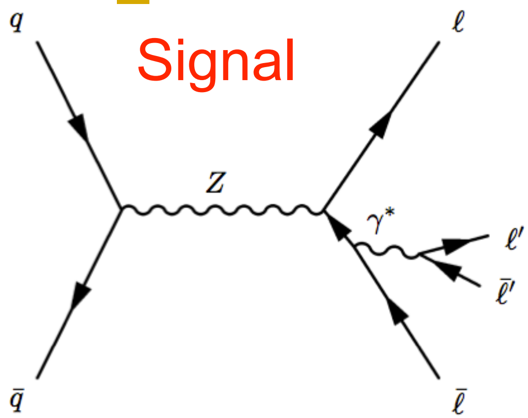
σ = 69.9 ± 2.8 (stat) ± 5.6 (sys) ± 3.1 (lum) pb

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

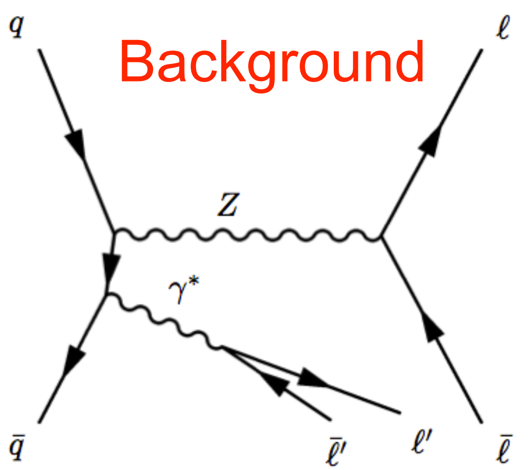
- **Already 4% statistical precision**
- **About 1.8σ higher than the NLO prediction**

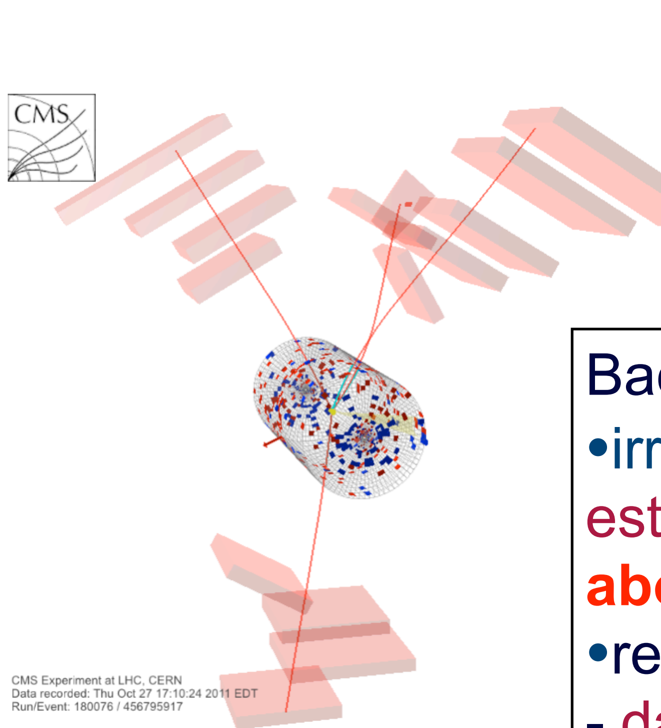
First observation of Z→4ℓ in pp collisions

Signal



Background





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

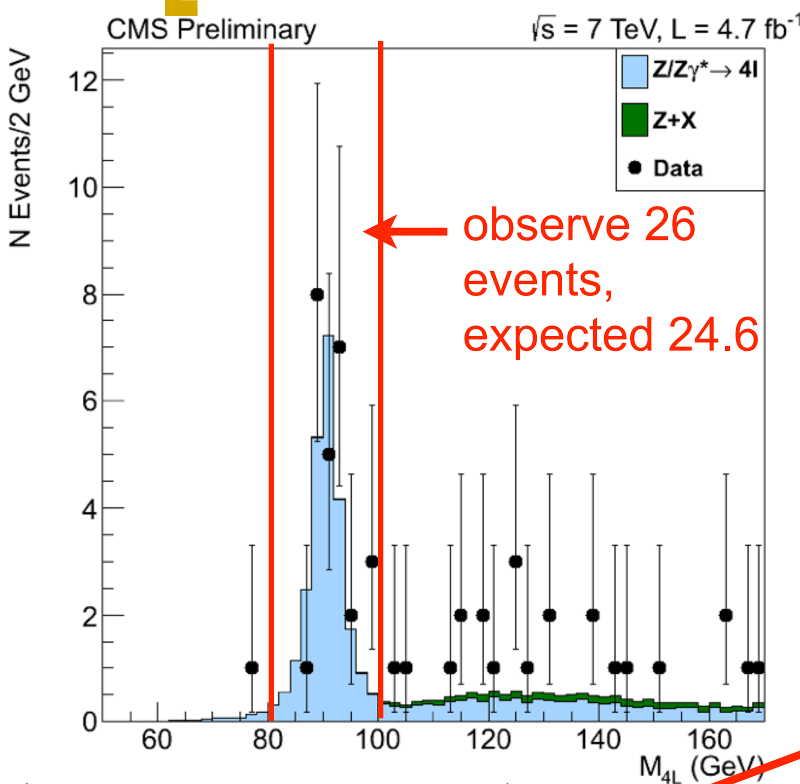
Backgrounds:

- irreducible $Z\gamma^* \rightarrow 4l$ - 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
$m_{\ell\ell} > 4\,\mathrm{GeV}$	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

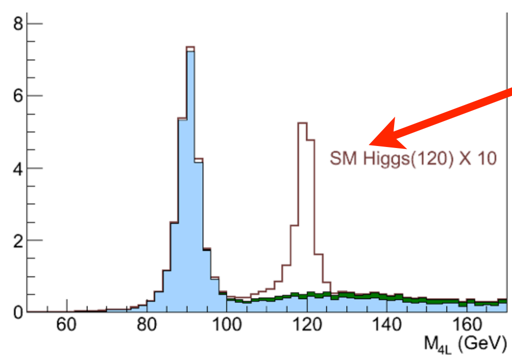
$$\sigma \times BR(Z \to 4\ell) = 125^{+26}_{-23}(\mathrm{stat})^{+9}_{-6}(\mathrm{syst})^{+7}_{-5}(\mathrm{lumi})\ \mathrm{fb}$$

•branching fraction BR(Z→4ℓ)

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

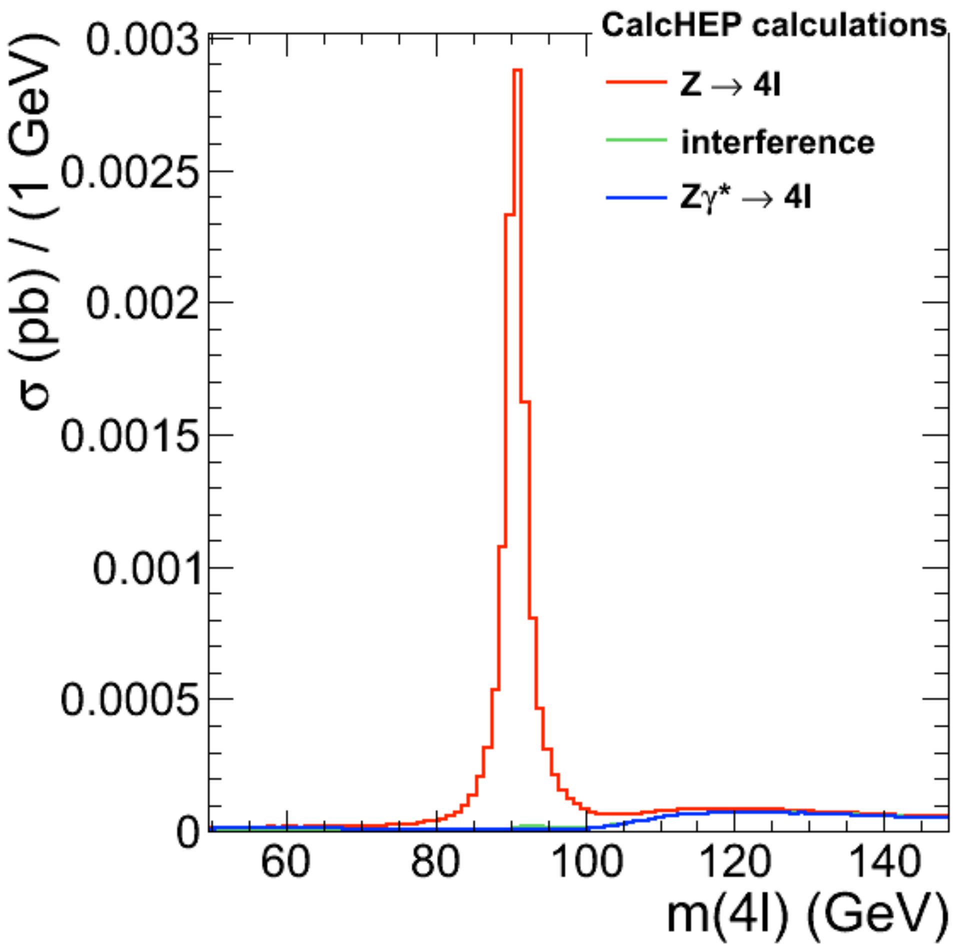
Efficiency x acceptance in the range 2.5−7.5%

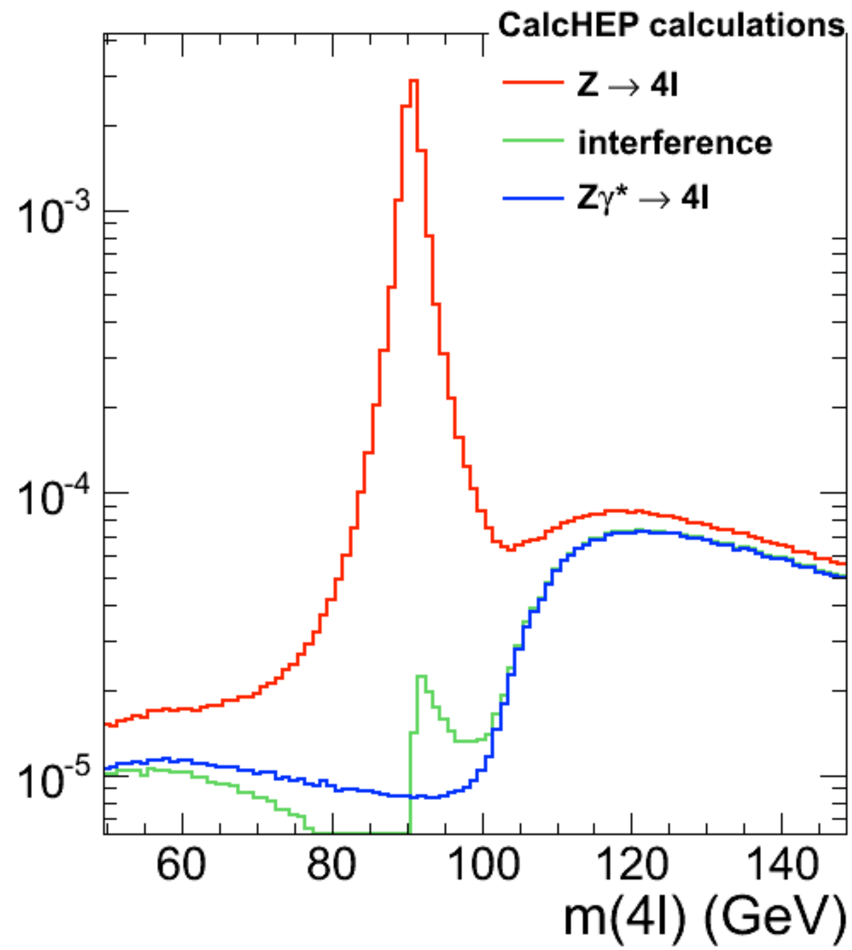
Mass peak arising from Z→4ℓ decays is a standard candle for the Higgs boson search in the H→ZZ→4ℓ decay



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

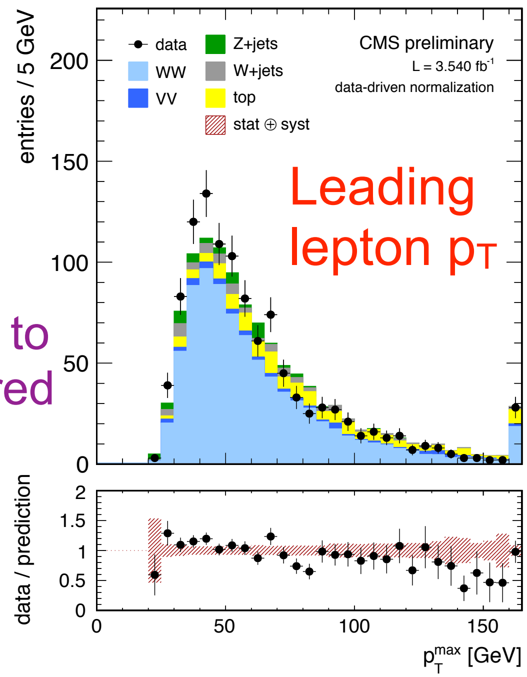
Z→4ℓ: signal background interference

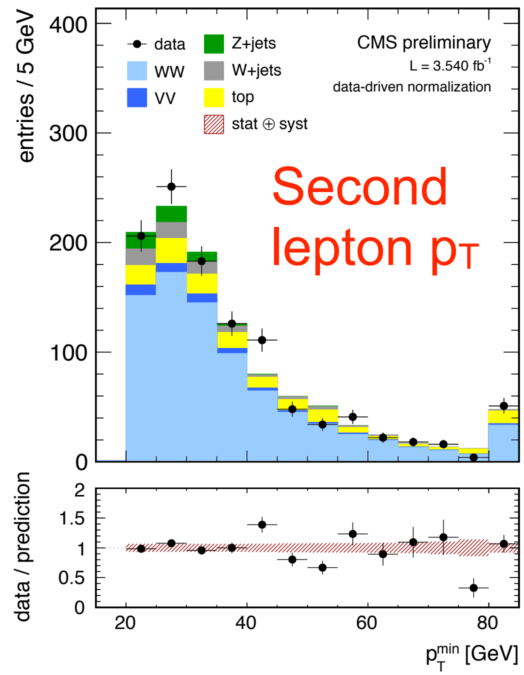


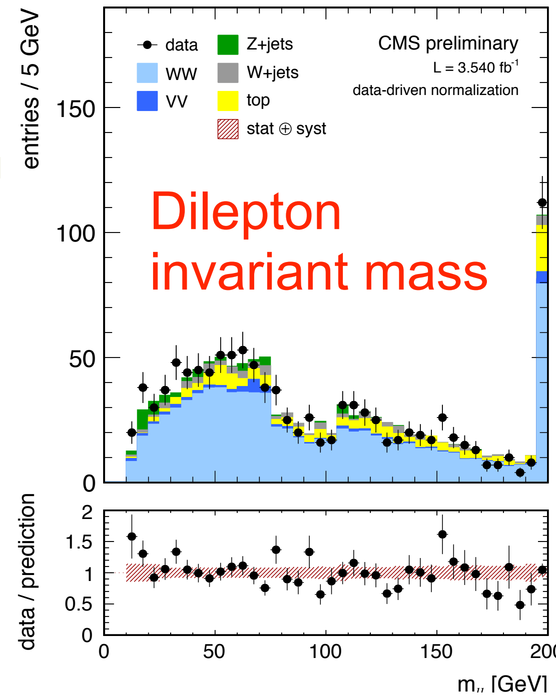


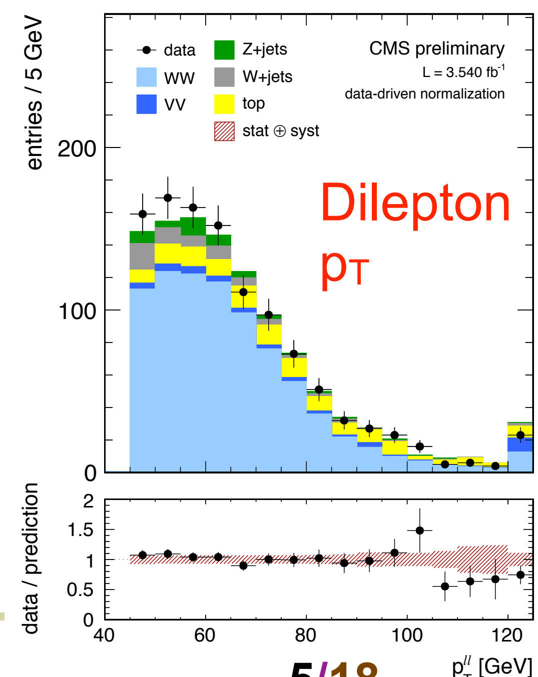
WW→2ℓ2ν: kinematics

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→$2\ell 2\nu$ 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

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

BR(W→$\ell\nu$) 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

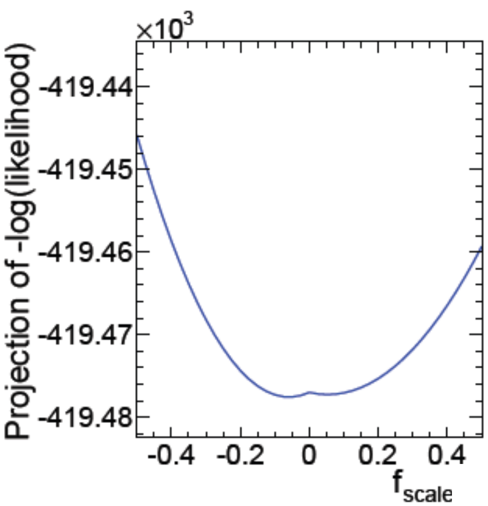
WW+WZ→$\ell\nu$qq: understanding W+jets bkg

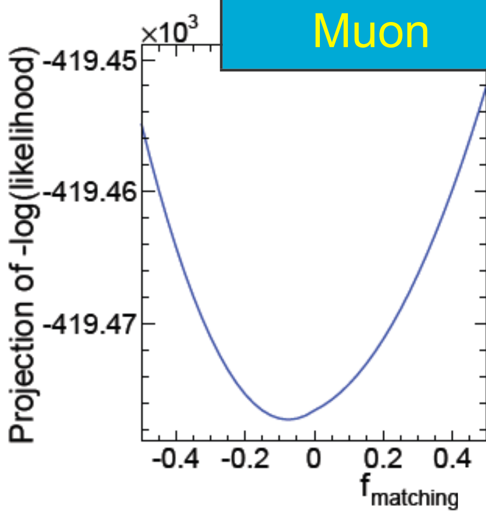
Process		Muon channel		Electron channel
Diboson (WW+WZ)	NLO prediction = 1697	1899 ± 389	NLO = 867	783 ± 302
W plus jets		67384 ± 586		31644 ± 850
$t\bar{t}$		1662 ± 117		946 ± 67
Single top		650 ± 33		308 ± 17
Drell-Yan plus jets (Z+jets)		3609 ± 155		1408 ± 64
Multijet (QCD)		296 ± 317		4195 ± 867
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}

W+jets shape uncertainty

$$\mathcal{F}_{\mathrm{W+jets}} = \alpha \cdot \mathcal{F}_{\mathrm{W+jets}}(\mu_0^2, q'^2) + \beta \cdot \mathcal{F}_{\mathrm{W+jets}}(\mu'^2, q_0^2) + (1-\alpha-\beta) \cdot \mathcal{F}_{\mathrm{W+jets}}(\mu_0^2, q_0^2).$$

	α (fSU)	β (fMU)
Electron	-0.003 ± 0.074	-0.136 ± 0.081
Muon	0.053 ± 0.078	-0.075 ± 0.065

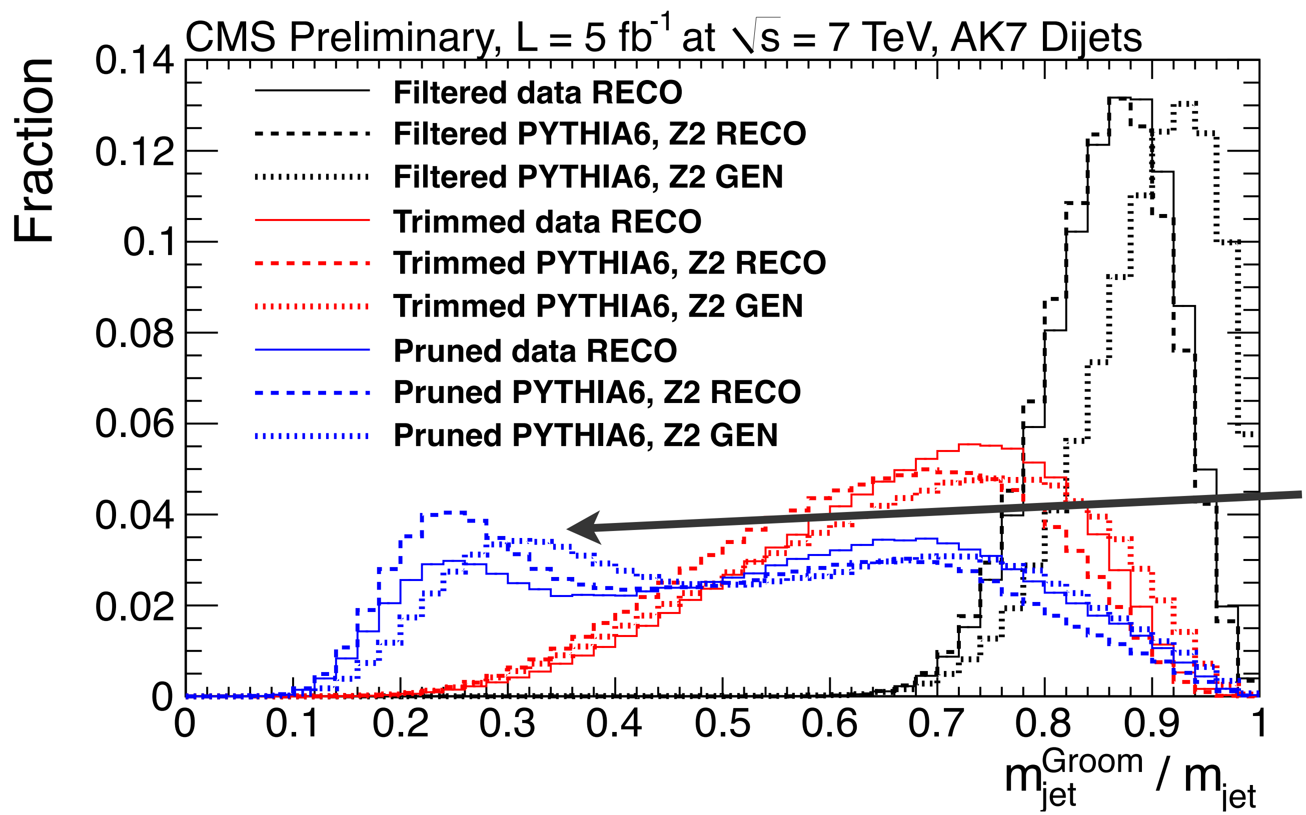




Factorization/renormalization scale and ME-PS matching scale vary in the fit.

- α (scale ↑ or ↓ fraction) and β (matching ↑ or ↓ fraction) are consistent b/w electron and muon data
- NLL versus α and β is well-behaved

Peep inside the merged jet, use grooming



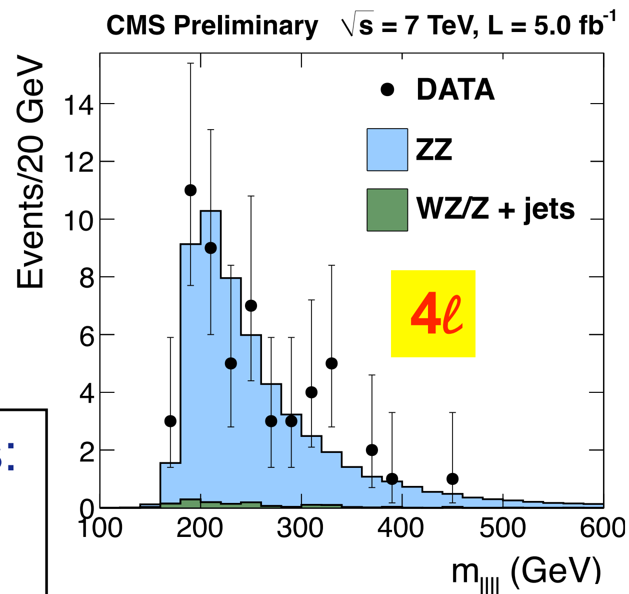
Pruning is the most aggressive, filtering is the least aggressive

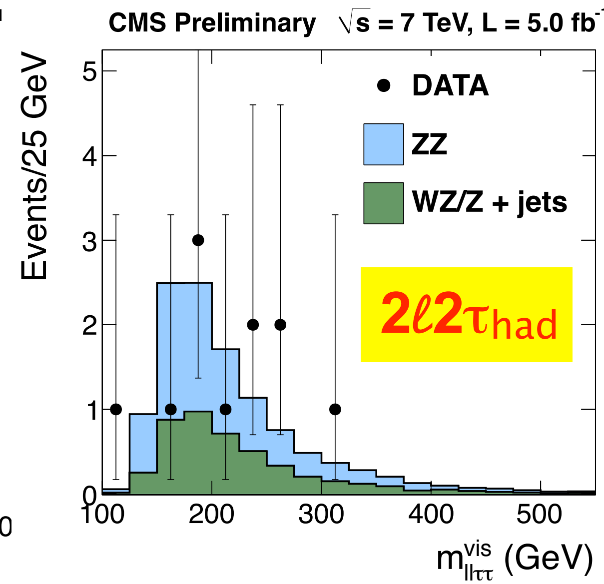
bimodal structure provides good separation for qq signal

Comparison of grooming algorithms at particle level (GEN), reconstructed simulation (RECO) and data

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

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

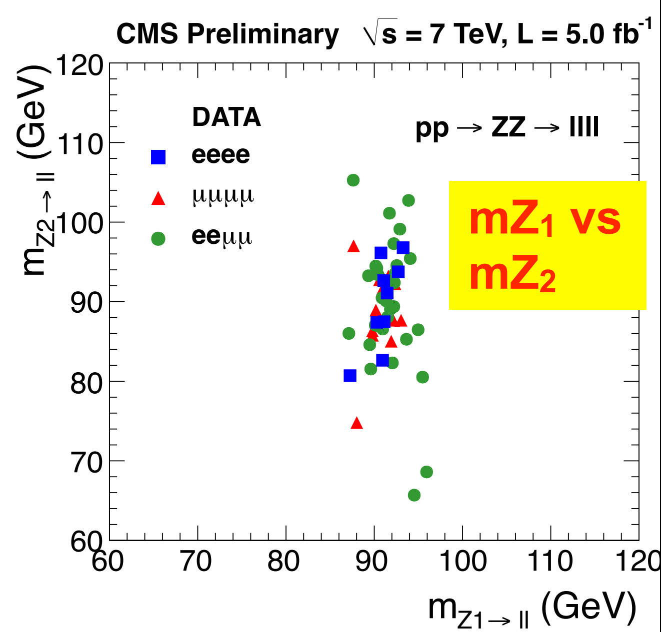




Event reconstruction

- ✦objects: Isolated leptons: e p_T>7, |η|<2.5; μ p_T>5, |η|<2.4; τ_{had} p_T>10, |η|<2.3
- ✦Kinematics:
  - •60 < m_Z < 120 GeV (30 < m_{vis} < 80 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}

(Z_1 has daughters with higher average p_T)



Expected and observed signal yields

- Very little background for $ZZ \to 4\ell$ (2−4%)
  - Even for $ZZ \to 2\ell 2\tau$, S/B ≧ 1
  - Background: QCD, W/Z+jets, WZ+jets

Estimated from data control samples where 1or 2 lepton(s) fail iso/id

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, 55 expected

$2\ell 2\tau$ Total: 11 observed, 12 expected

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

☑ Consistent with NLO

NLO prediction: **6.3 ± 0.4 pb** MCFM 6.0 (NLO for qq→ZZ and LO for gg→ZZ, MSTW 2008 PDF)

Current Limits

Table 21: Current limits on anomalous couplings. The world best limits are based on a fit of LEP measurements. The LHC and Tevatron results are shown for comparison.

LEP

Coupling	Particle Data Group Fit
Λ_γ	$0.028^{+0.020}_{-0.021}$
Λ_Z	$\boxed{0.088^{+0.060}_{-0.057}}$
Δg_1^Z	$0.016^{+0.022}_{-0.019}$
$\Delta\kappa_\gamma$	$\boxed{0.027^{+0.044}_{-0.045}}$
$\Delta\kappa_Z$	$0.026^{+0.059}_{-0.056}$

[-0.026, 0.208] @ 95% CL

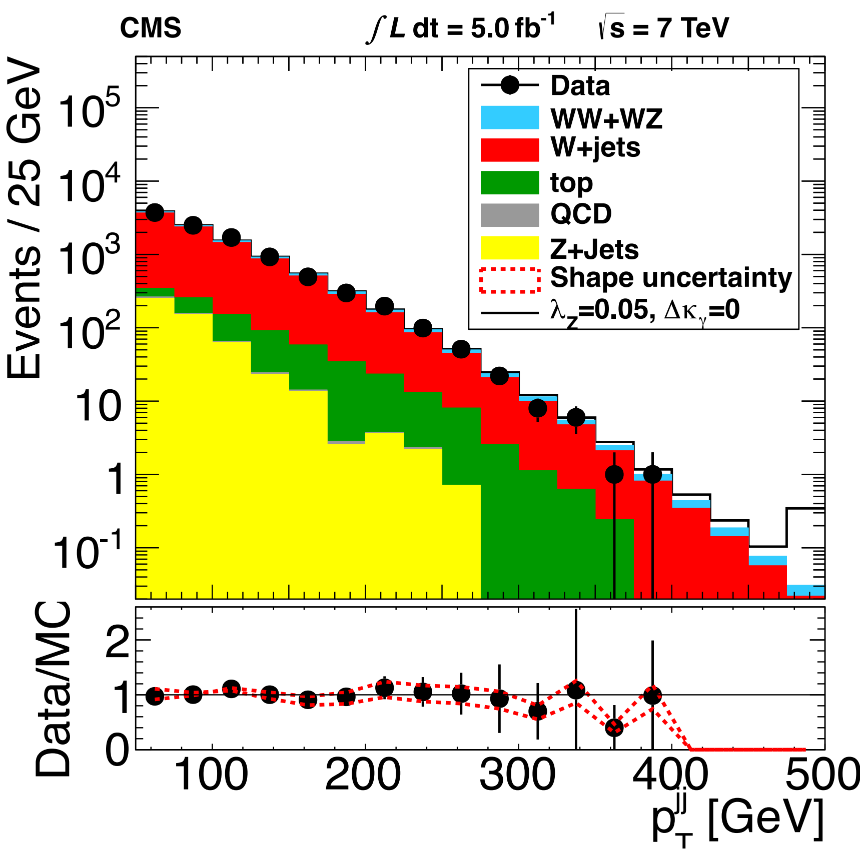
[-0.063, 0.115] @ 95% CL

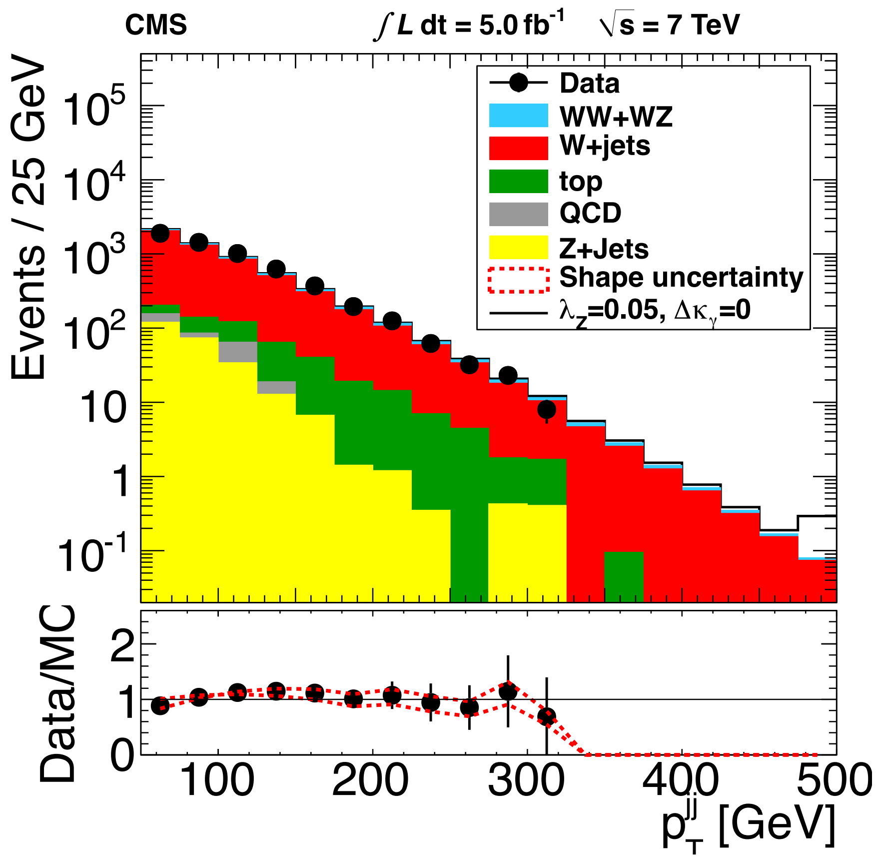
Coupling	Tevatron (WW +WZ $\to \ell\nu$2jet)	Tevatron (WW $\to \ell^+\nu\ell^-\overline{\nu}$)
$\Lambda = \Lambda_\gamma = \Lambda_Z$	[-0.10,0.11] at 95% C.L.	[-0.14,0.18] at 95% C.L.
$\Delta\kappa_\gamma$	[-0.44,0.55] at 95% C.L.	[-0.54,0.83] at 95% C.L.
Δg_1^Z	[-0.12,0.20] at 95% C.L.	[-0.14,0.30] at 95% C.L.

Coupling	CMS 35 pb^{-1} (WW $\to \ell^+\nu\ell^-\overline{\nu}$)	ATLAS 1 fb^{-1} (WW $\to \ell^+\nu\ell^-\overline{\nu}$)
Λ_Z	[-0.19,0.19] at 95% C.L.	[-0.079,0.77] at 95% C.L.
$\Delta\kappa_\gamma$	[-0.61,0.65] at 95% C.L.	[-0.071,0.071] at 95% C.L.
Δg_1^Z	[-0.29,0.31] at 95% C.L.	[-0.052,0.082] at 95% C.L.

Limits from WW/WZ→ℓνqq measurement

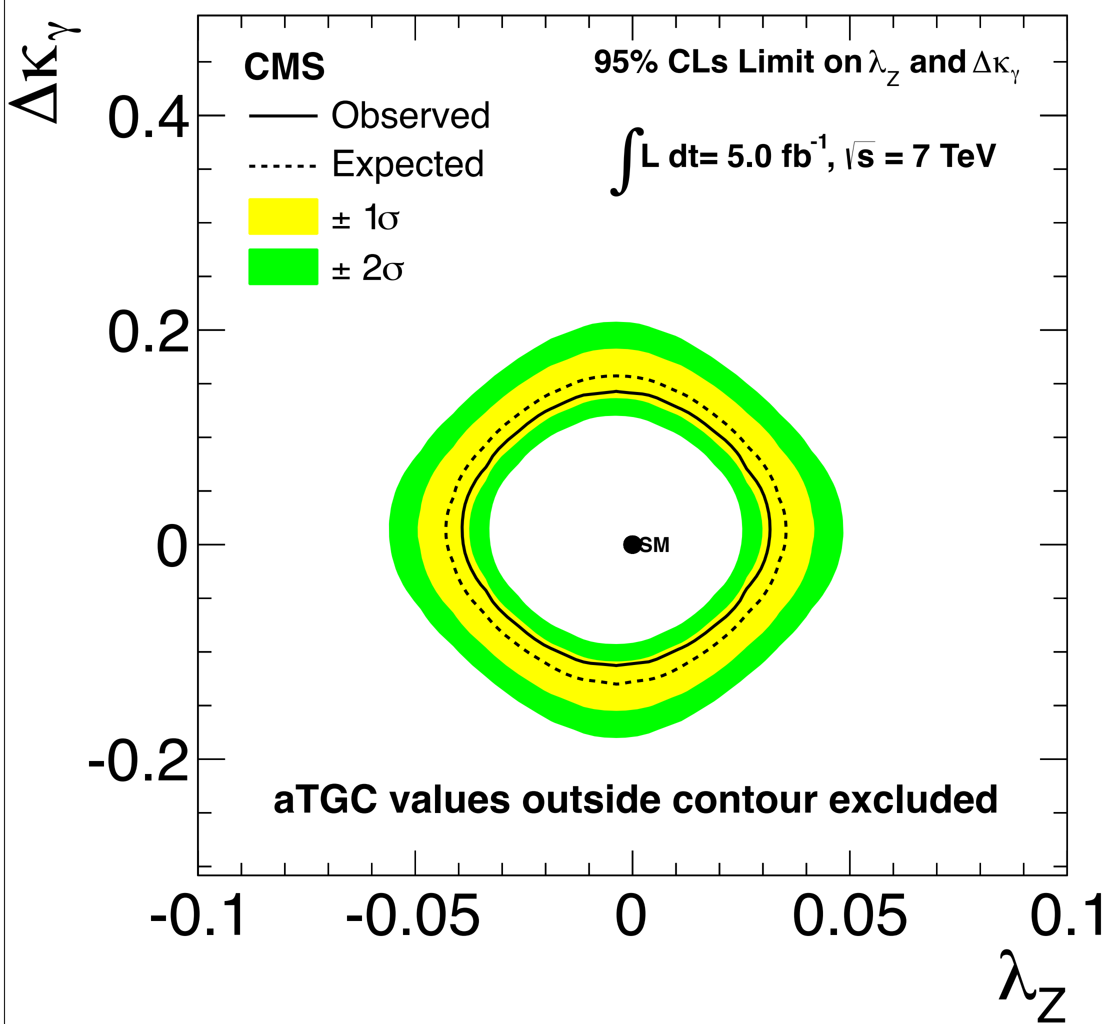
Use dijet (hadronic W) p_T as the observable





Anomalous coupling shows up in high p_T tails.
aTGC modeled using MCFM (re-weight Pythia).

Final Limits



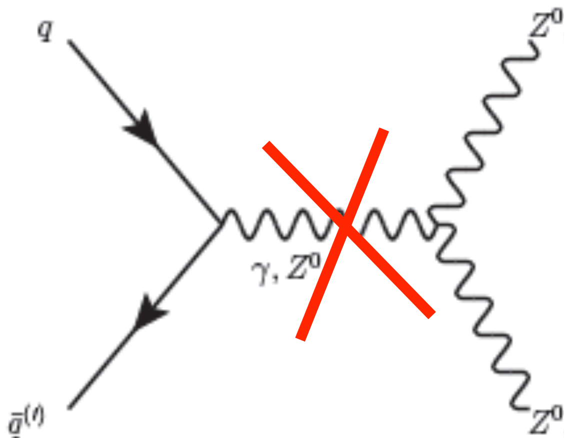
$-0.038 < \Lambda_Z < 0.030$, (assuming $\Delta\kappa_\gamma = 0$)

$-0.111 < \Delta\kappa_\gamma < 0.142$ (assuming $\Lambda_Z = 0$)

These are competitive to the current world average (LEP combination, all channels).

With 8 TeV data we will surpass LEP combined limits in this channel alone.

Anomalous couplings in ZZ production



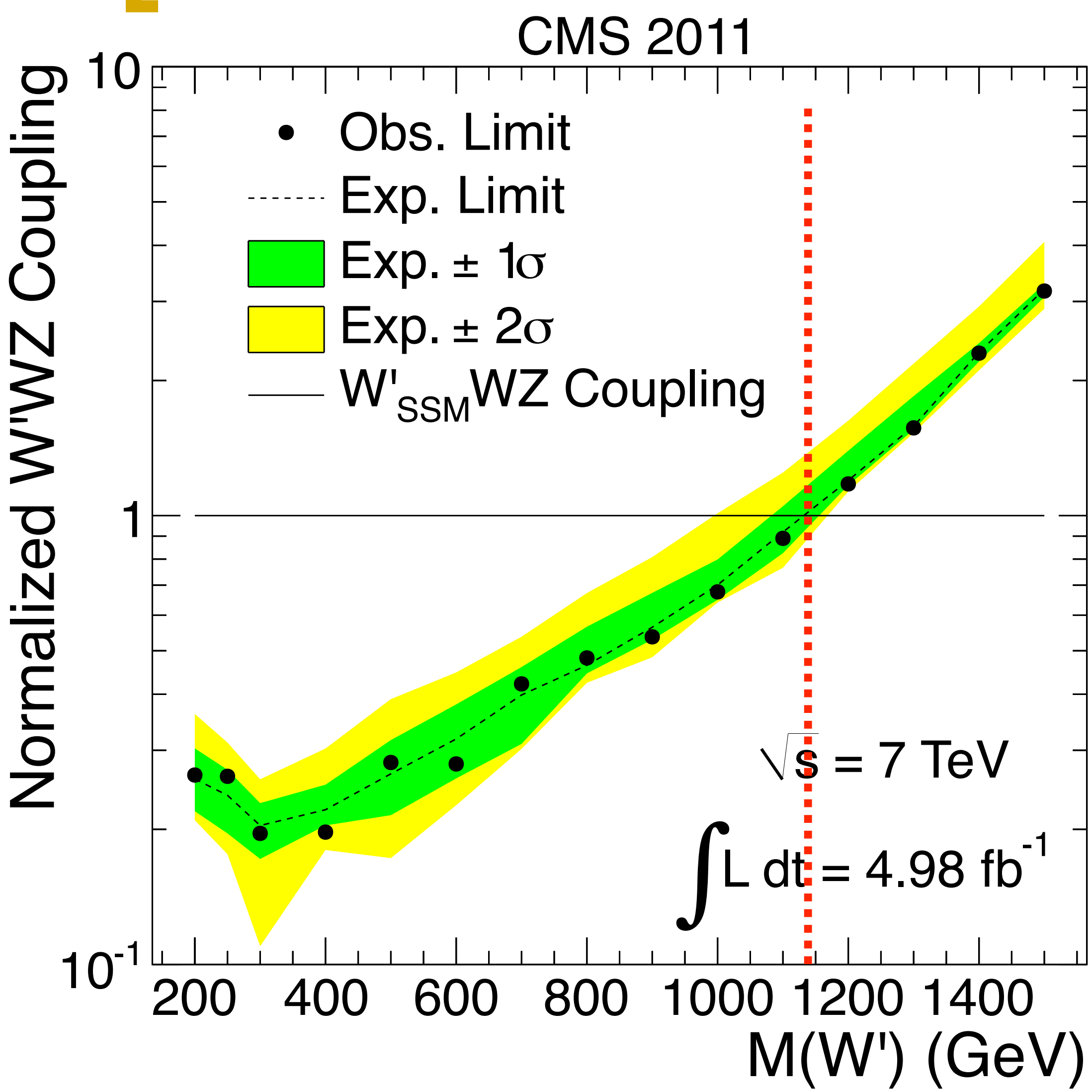
- Neutral triple gauge coupling (ZZZ /ZZγ) forbidden in SM (no s-channel at tree level)
  - -A way to look for prospective new physics
  - -Can enhance ZZ cross section

- ZZZ/ZZγ vertex described with $f_4^{Z/\gamma}$ and $f_5^{Z/\gamma}$ couplings in the TGC Lagrangian

Methodology

- SHERPA currently the only generator to model ZZZ/ZZγ couplings
  - -LO only, but SM at tree level + 1 parton agree well with NLO (POWHEG)
- use $m_{4\ell}$ as discriminating variable, more sensitive than leading Z p_T

Limit on a sequential SM-like W'



Exclude W' up to mass 1143 GeV at 95% CL

In $W' \to \ell\nu$ channel exclude up to mass ~2.6 TeV

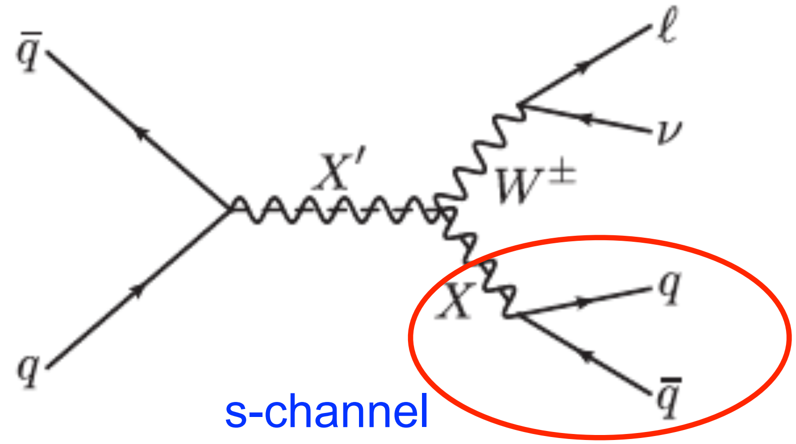
arXiv:1204.4764

In $W' \to td$ channel exclude up to mass 840 GeV

arXiv:1206.3921

Search for NP in W+2jet e.g. $\rho_T \to W(\to l\nu)\ \pi_T(\to jj)$

Buckley, Hooper, Kopp, Martin, and Neil; arXiv: 1107.5799

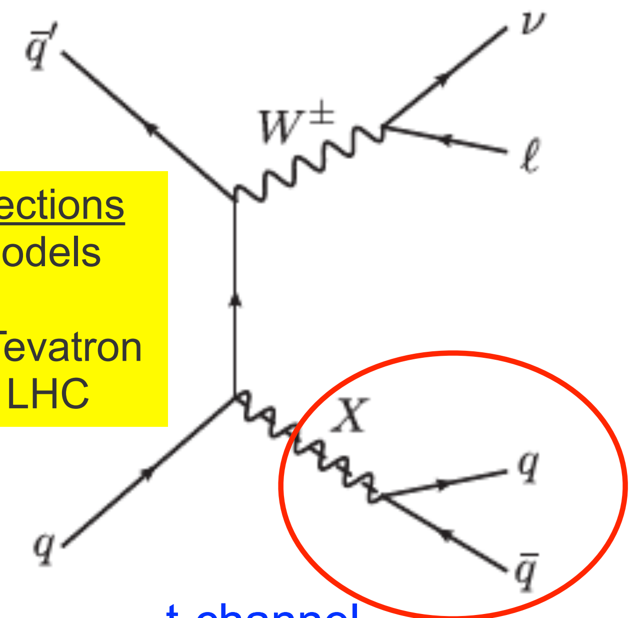


s-channel

In low-scale technicolor (LSTC) models, could originate from events in which a ~300 GeV neutral (charged) technirho, ρ_T, is produced and then decays to a $W^{\pm}$ and a ~150 GeV charged (neutral) technipion, π_T, which decays to jets (some fraction of which can be b-jets, depending on the CKM-like angles in the technicolor sector).

<u>Total cross sections</u>
for various models

~ 1−3 pb at Tevatron
~ 5−10 pb at LHC

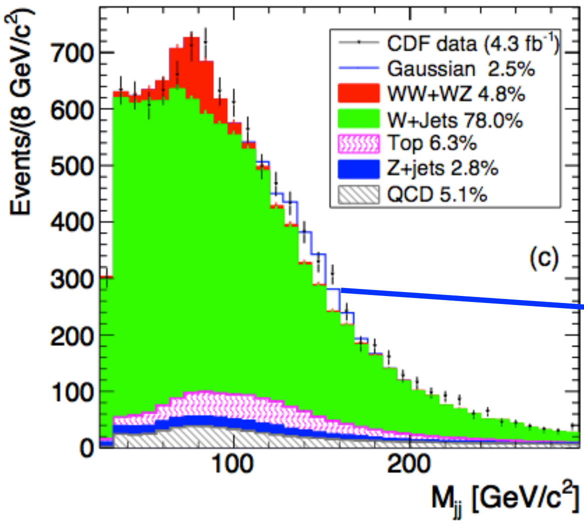


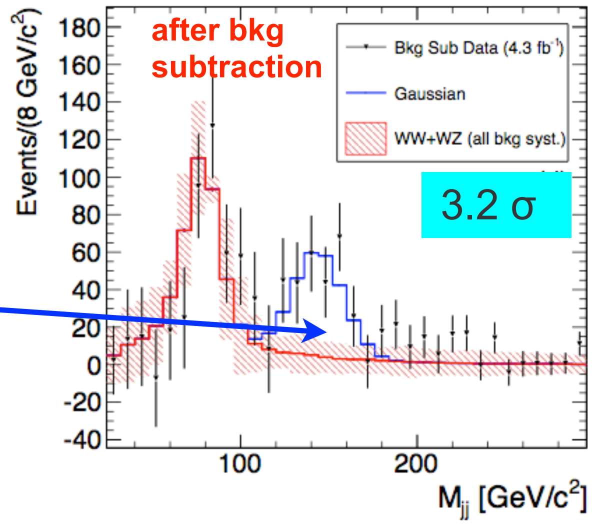
t-channel

X in this case can be either a scalar or a vector boson.

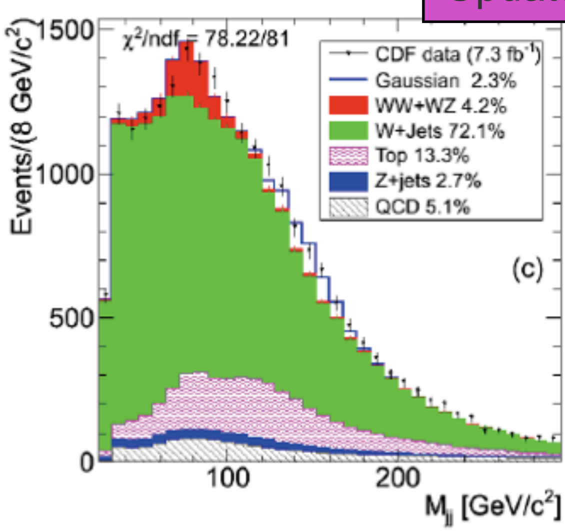
In Pythia “straw-man” implementation, $\pi_T^{\pm}$ and π_T^0 decay to heavy flavor quarks with BR 80−90%, but cannot decay to gluon. $\pi_T^{0'}$ decays to heavy flavor with BR ~50% and decays to gluon pair with BR ~50%. The mixing is such that $\pi_T^{0'}$ component is small.

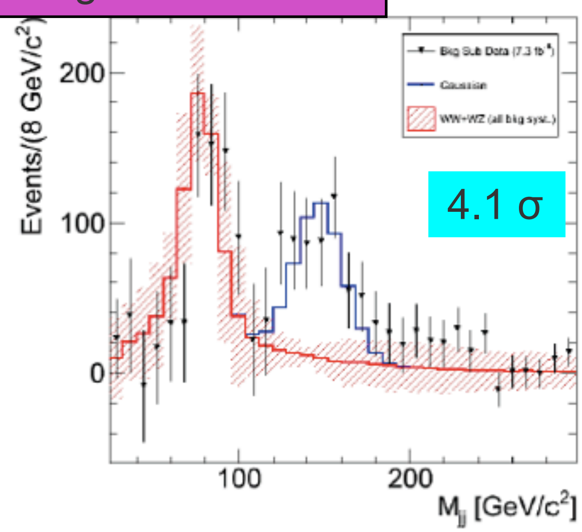
Thing that started it all: CDF saw anomaly in M_{jj}





Update using 7.3 fb^{-1} data





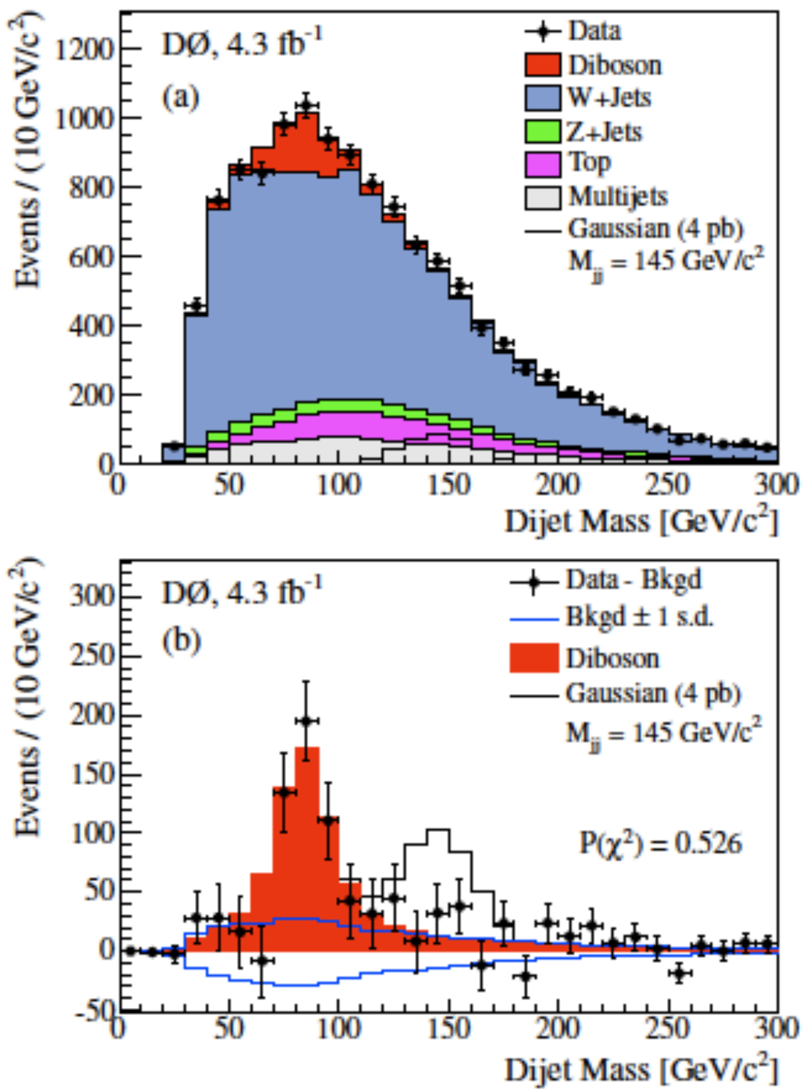
- ✦W+jj data doesn't have the featureless falloff of dijet mass spectrum
- ✦CDF finds an excess of 253 events, peaked at 145 GeV, width = 15 GeV
- ✦Significance 3.2σ, prod cross section 4 pb

arXiv: 1101.6079, Phys. Rev. Lett. 106:171801 (2011)

http://www-cdf.fnal.gov/physics/ewk/2011/wjj/

Significance has been growing with more data ! Statistical significance is not in doubt, but understanding of background modeling and jet calibration is.

D∅ doesn't confirm this anomaly



arXiv: 1106.1921, Phys. Rev. Lett. 107:011804 (2011)

✦W+jj data from D∅ DOES show the featureless falloff of dijet mass spectrum in the range 110−170 GeV

✦ D∅ doesn't find any excess peaked at 145 GeV

✦Excludes production cross section 4 pb at 99.9999% CL and 1.9 pb at 95% CL

✦D∅ data is fully consistent with the Standard Model W+jets and diboson production in this region

See details at:

http://www-d0.fnal.gov/Run2Physics/WWW/results/final/HIGGS/H11B/

Critical to understand what is going on here

The differences between the results of CDF and DØ are highly unlikely to arise from statistical fluctuations, leaving only underlying systematic issues or actual new physics as possible resolutions.

Case 1: It is New Physics (classic upward /downward fluctuations in two expts)

- Will show up in other places. Need to analyze:
  - other channels (Z+jj, γ+jj),
  - disjoint sub-samples (2-jet events vs 3-jet events) which have different S/B
  - signal-enhanced data (e.g., require the two jets to be close in rapidity, etc.)

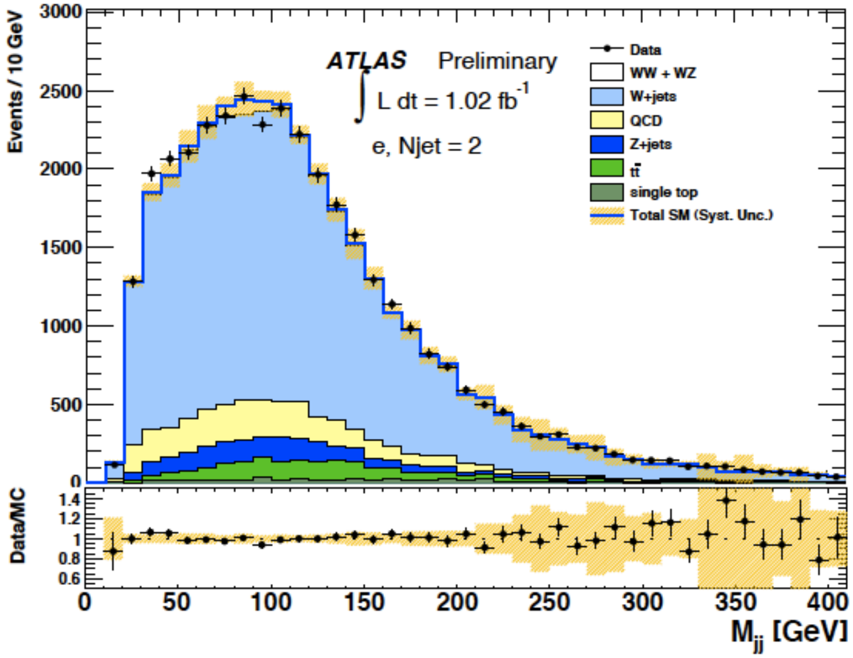
- Perform similar analysis at LHC:
  - Need to optimize carefully because of much smaller S/B (see next slide).
  - Cannot work with "loose" selection, but do not want to throw away signal.

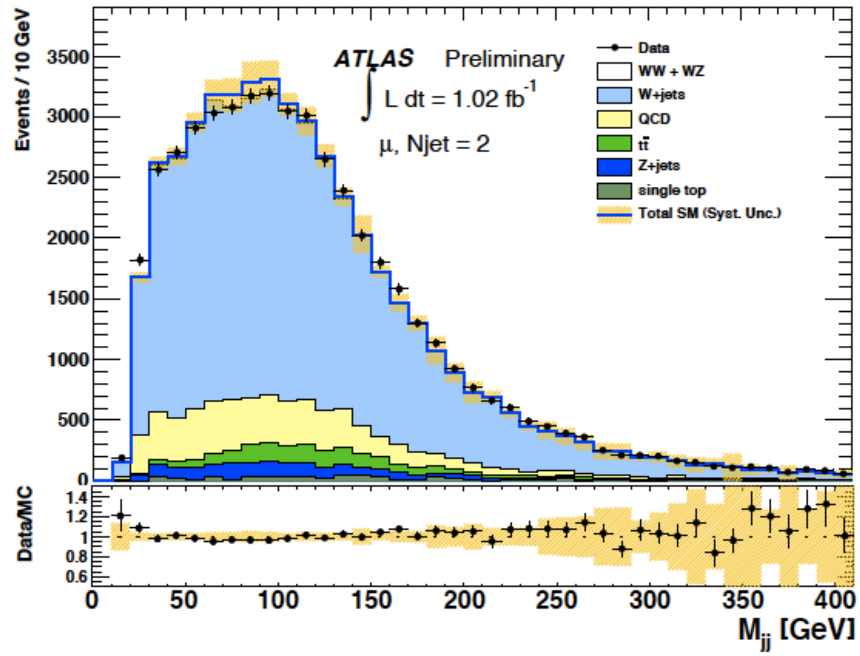
Case 2: CDF excess is caused by some subtle mis-modeling of the Standard Model backgrounds, or instrumental (mis-)calibration effect

- It is possible that the same error could propagate to the LHC experiments. Or in other analysis channels with similar final states.

Life is hard if looking for qqbar signal at LHC

ATLAS result shown in EPS





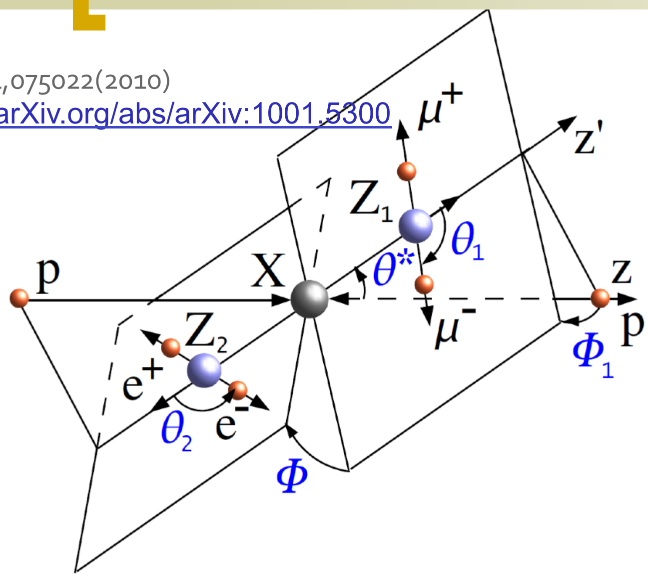
- Get swamped by W+jets
- **See no diboson peak**, nothing other than W+jets: S/B →0
- Large syst uncertainty

Clearly much worse than Tevatron experiments

Need to improve selection criteria to the ones more appropriate for LHC conditions. At the minimum should be able to see diboson peak. CMS is analyzing data carefully. With ~2−5 fb^{-1} we expect to observe or exclude CDF anomaly.

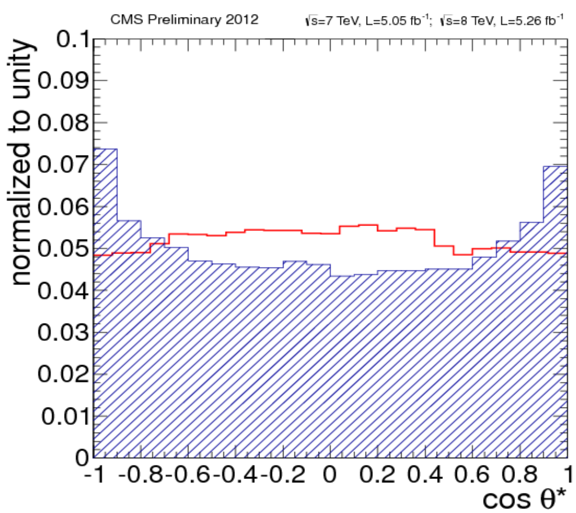
Spin-parity determination: angular analysis

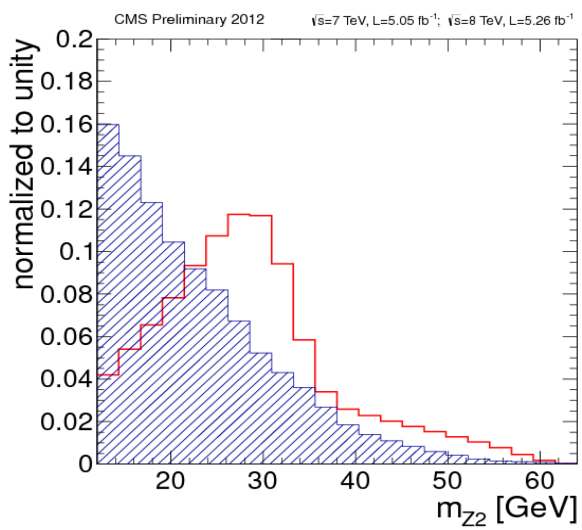
PRD81,075022(2010)
http://arXiv.org/abs/arXiv:1001.5300

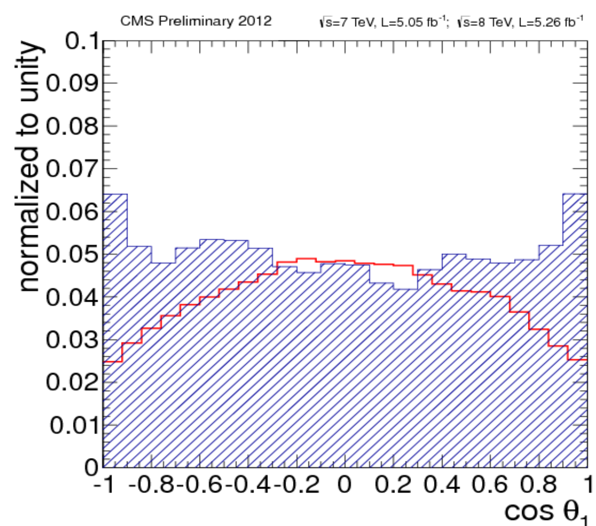


Matrix Element Likelihood Analysis:
uses kinematic inputs for
signal to background discrimination
$\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$





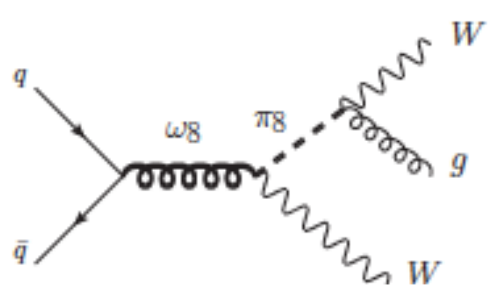


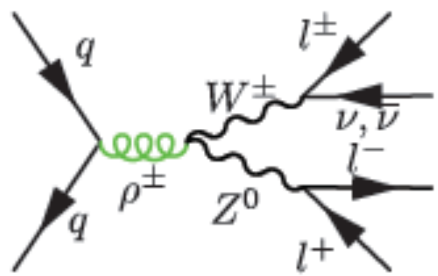
Kinds of new physics to probe in diboson events

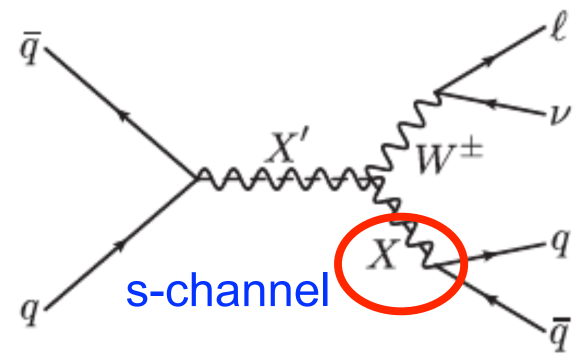
1. Anomalous couplings at the TGC vertex: can probe physics beyond the currently accessible mass range at the LHC

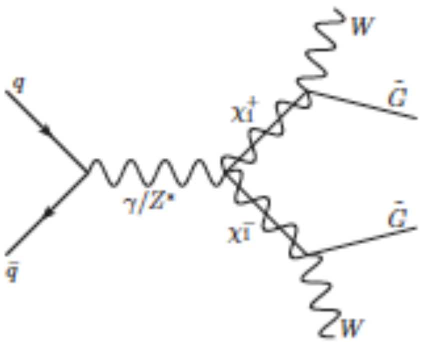
2. Enhancement in diboson production rate from new physics

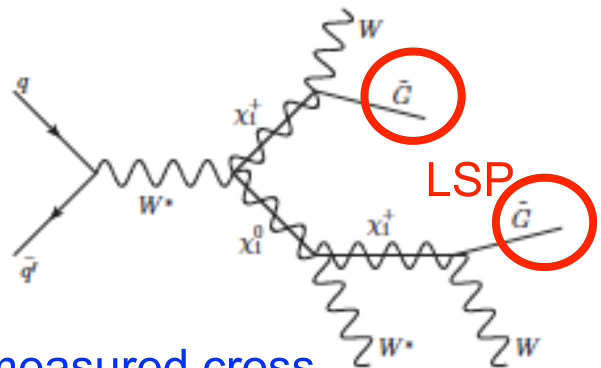
or pure bump hunt in diboson-like topology

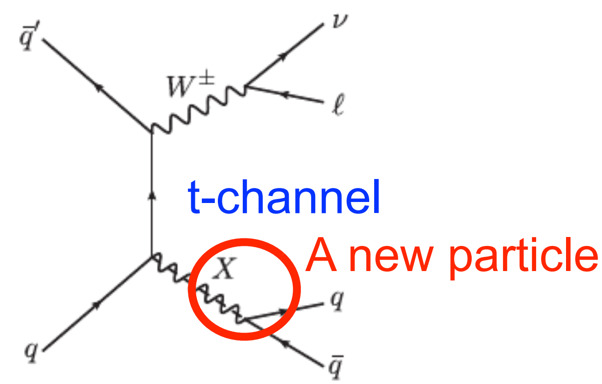












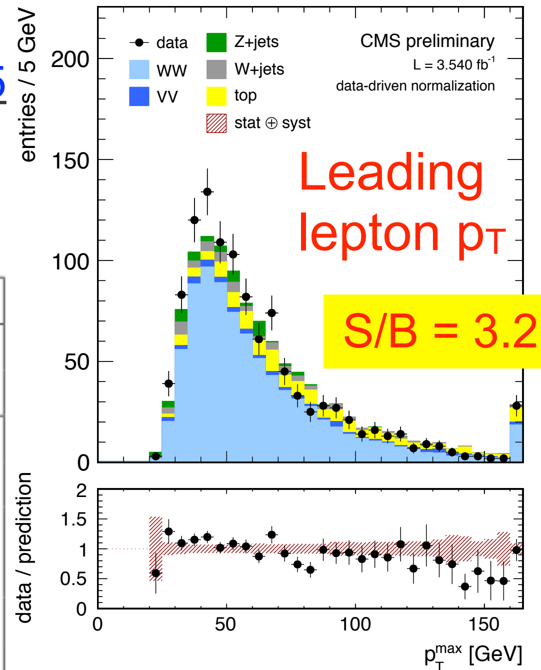
In these scenarios the measured cross section will be > the SM prediction

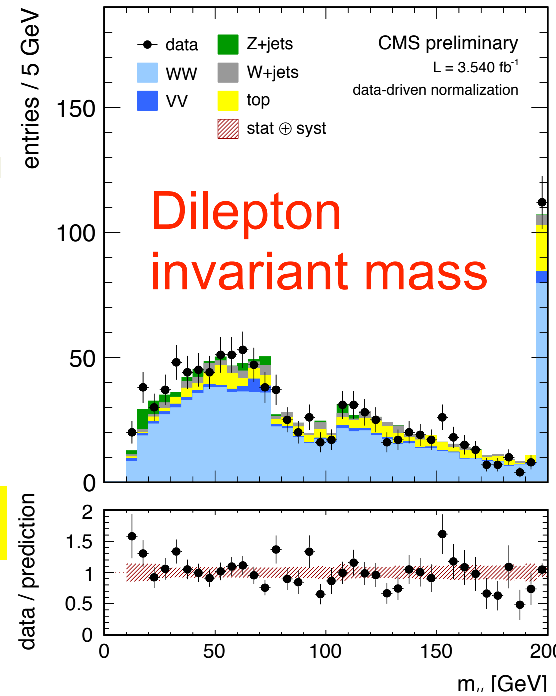
Cross section at 7 TeV (5.0 fb^{-1})

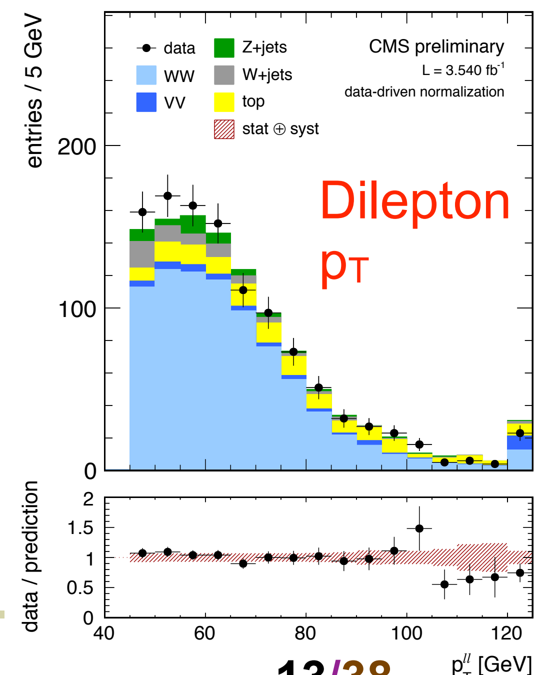
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12005

WW cross section is normalized to the measured value

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







☑ Consistent with NLO

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.

WW→2ℓ2ν cross section at 8 TeV

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

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

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

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

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

Main systematics: Theory (PDF & jet veto) 5%, luminosity 4.4%

Measured cross section

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

Already 4% stat precision

1.8σ above NLO prediction

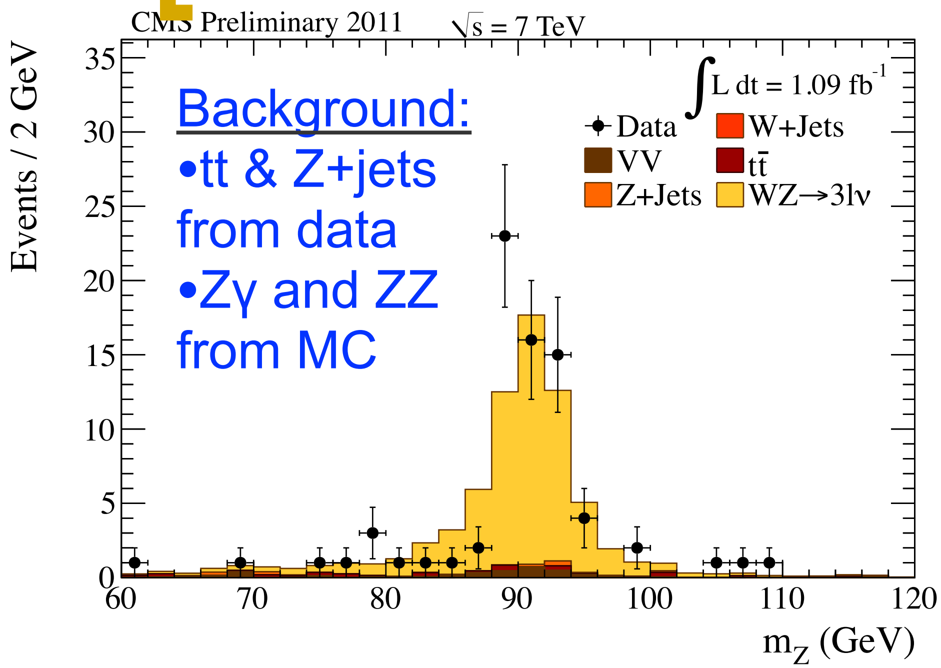
Likely an upward fluctuation, but has generated some buzz ..., e.g.,

Charginos Hiding In Plain Sight

David Curtin,[1] Prerit Jaiswal,[1,2] and Patrick Meade[1]

arXiv:1206.6888v2

WZ→$\ell\ell\ell'\nu$ cross section at 7 TeV (1.1 fb^{-1})



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

(CMS PAS EWK-11-010)

- ✦Two iso ℓ: p_T > 20/15 GeV (e/μ)
- ✦3rd lepton p_T > 20, ME_T>30 GeV
- ✦60 < $m_{\ell\ell}$ < 120 GeV; veto 2nd Z
- ✦Accept. x efficiency = 19−25%

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

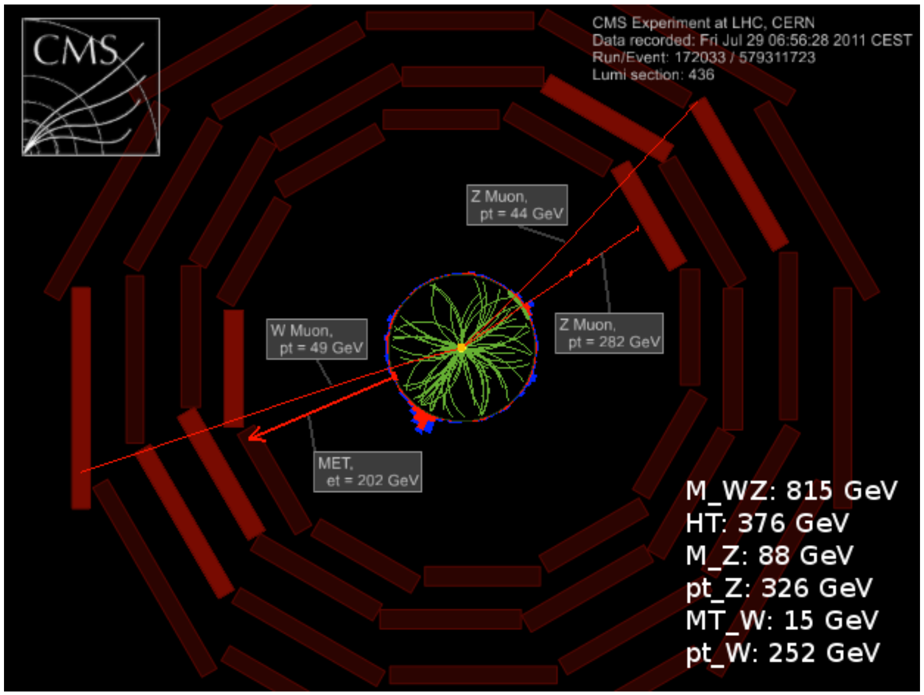
Channel	$A \cdot \epsilon$	$N_{observed}$
eee	0.193 ± 0.003	22
$ee\mu$	0.234 ± 0.003	20
$\mu\mu e$	0.190 ± 0.003	13
$\mu\mu\mu$	0.249 ± 0.003	20

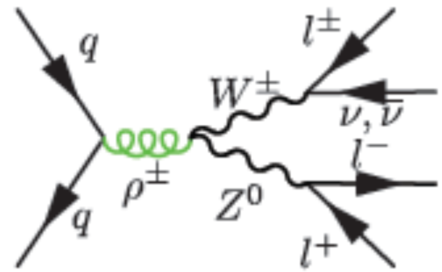
σ = 17.0 ± 2.4 (stat) ± 1.1 (sys) ± 1.0 (lum) pb

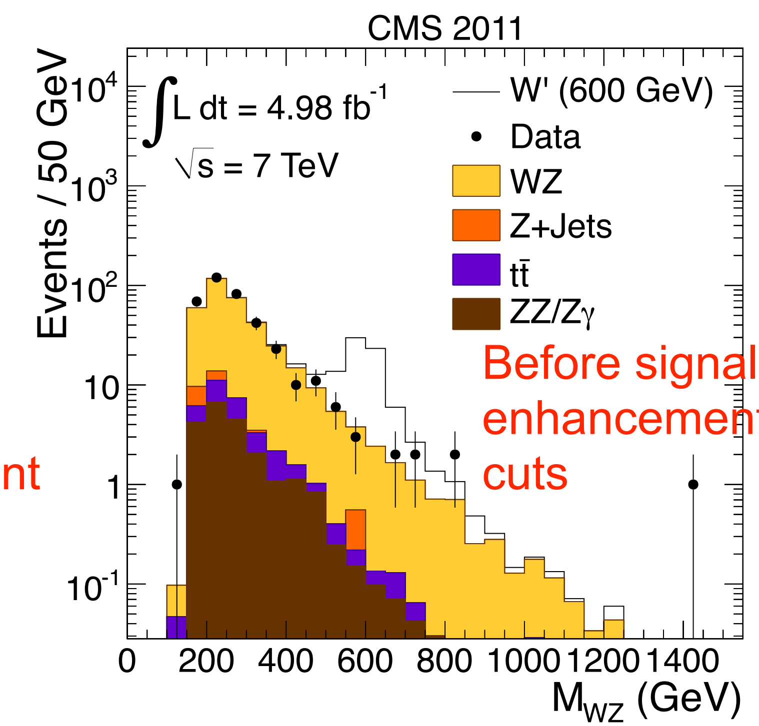
NLO: 17.5 ± 0.6 pb (MCFM, real-width bosons, CTEQ6L, error is PDF uncertainty)

Search for ρ_{TC} and $W' \to WZ \to \ell\ell\ell'\nu$

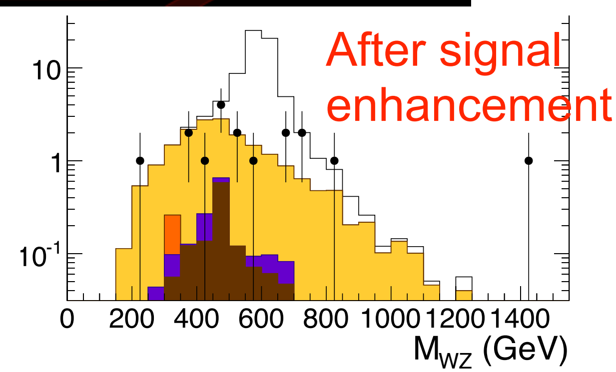
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11041







Event selection same as in WZ cross section analysis



CMS analysis

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11017

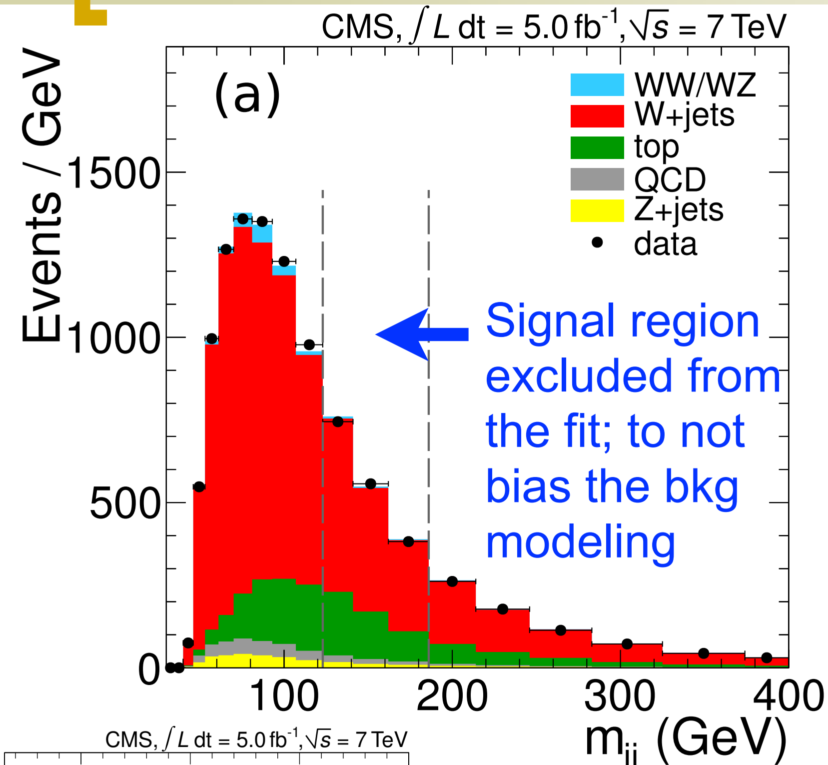
(submitted to PRL)

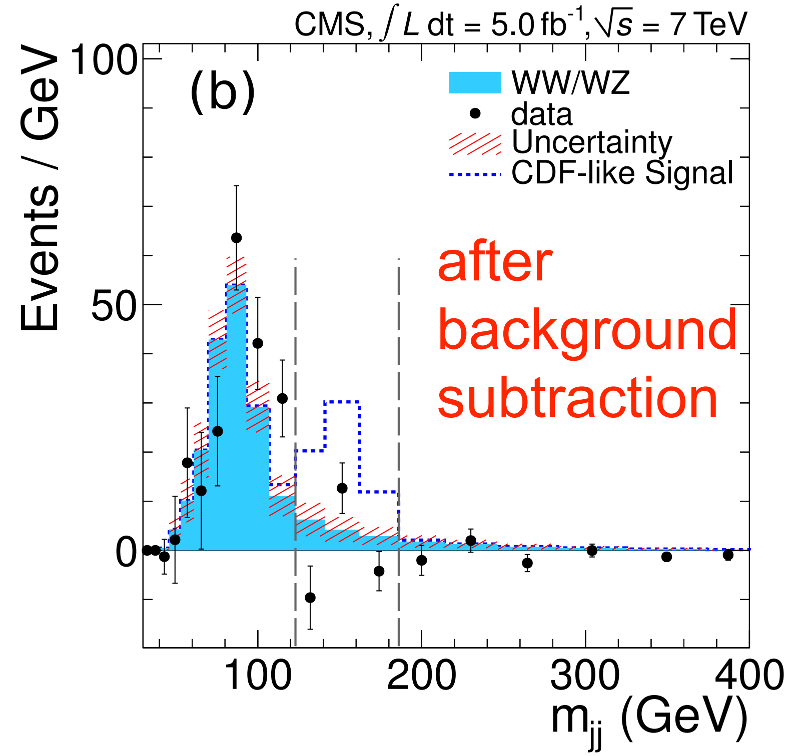
$W \to \ell\nu$ selection	Jet selection
Single-lepton trigger	$p_T^{j1} > 40\,\mathrm{GeV}$
Lepton identification and isolation	$p_T^{j2}, p_T^{j3} > 30\,\mathrm{GeV}$
$p_T^{\mu(e)} > 25\ (35)\ \mathrm{GeV}$	$\lVert \vec{p}_T^{\,j1} + \vec{p}_T^{\,j2} \rVert > 45\,\mathrm{GeV}$
$\not\!\!E_T^{\mu(e)} > 25\ (30)\ \mathrm{GeV}$	$\lvert\Delta\eta(j1, j2)\rvert < 1.2$
$M_T > 50\,\mathrm{GeV}$	$\Delta\phi(\not\!\!E_T, \mathrm{j1}) > 0.4$
Exclude events with > 1 lepton	$0.3 < p_T^{j2}/m_{jj} < 0.7$

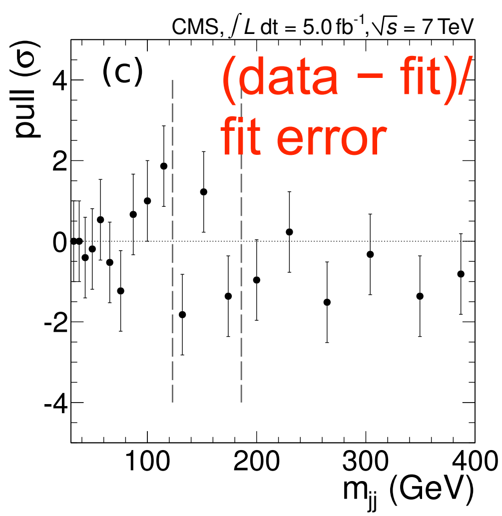
Efficiency x Acceptance for a few typical models

		$\varepsilon\mathcal{A}$			
		muons		electrons	
Signal model	$\sigma \times \mathcal{B}$ (pb)	2-jet	3-jet	2-jet	3-jet
Technicolor	7.4	0.065	0.020	0.039	0.011
Z'	8.1	0.070	0.023	0.042	0.014
WH	0.059	0.060	0.019	0.038	0.013

Modeling of SM background



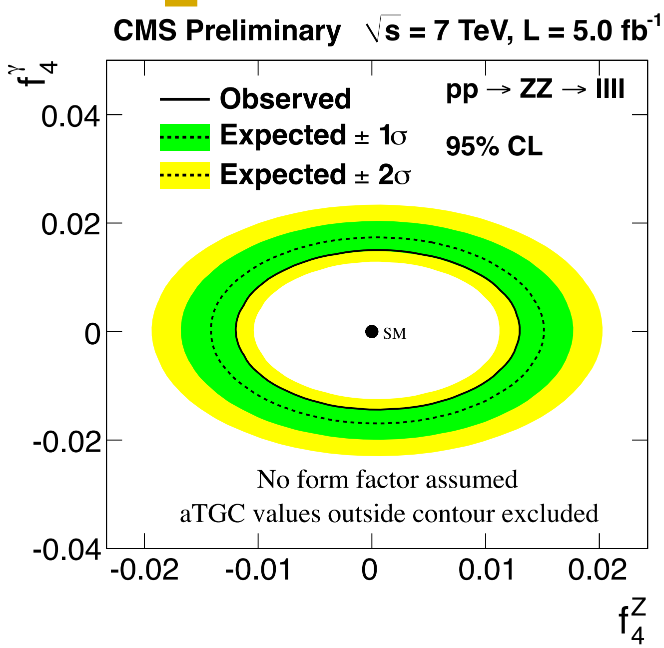


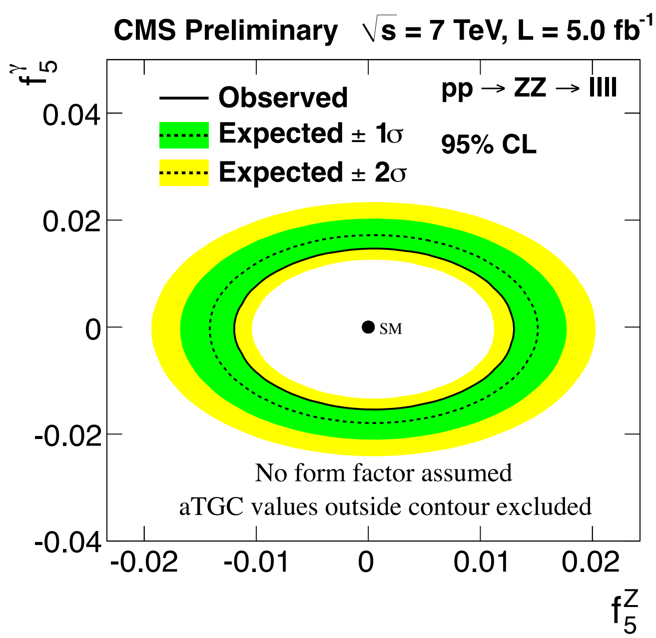


Process	Shape	Constraint on normalization
W plus jets	MC/data	Unconstrained
Diboson (WW+WZ)	MC	61.2 pb ±10% (NLO) [24]
$t\bar{t}$	MC	163 pb ±7% (NLO) [25]
Single-top	MC	84.9 pb ±5% (NNLL) [26–28]
Drell–Yan plus jets	MC	3.05 nb ±4.3% (NNLO) [29]
Multijet (QCD)	data	$E\!\!\!/_T$ fit (described in text)

(see slide 17)

Limits on anomalous triple gauge couplings





No form factors, i.e., $\Lambda = \infty$

$$-0.012 < f_4^Z < 0.013$$
$$-0.012 < f_5^Z < 0.013$$
$$-0.014 < f_4^\gamma < 0.014$$
$$-0.015 < f_5^\gamma < 0.015$$

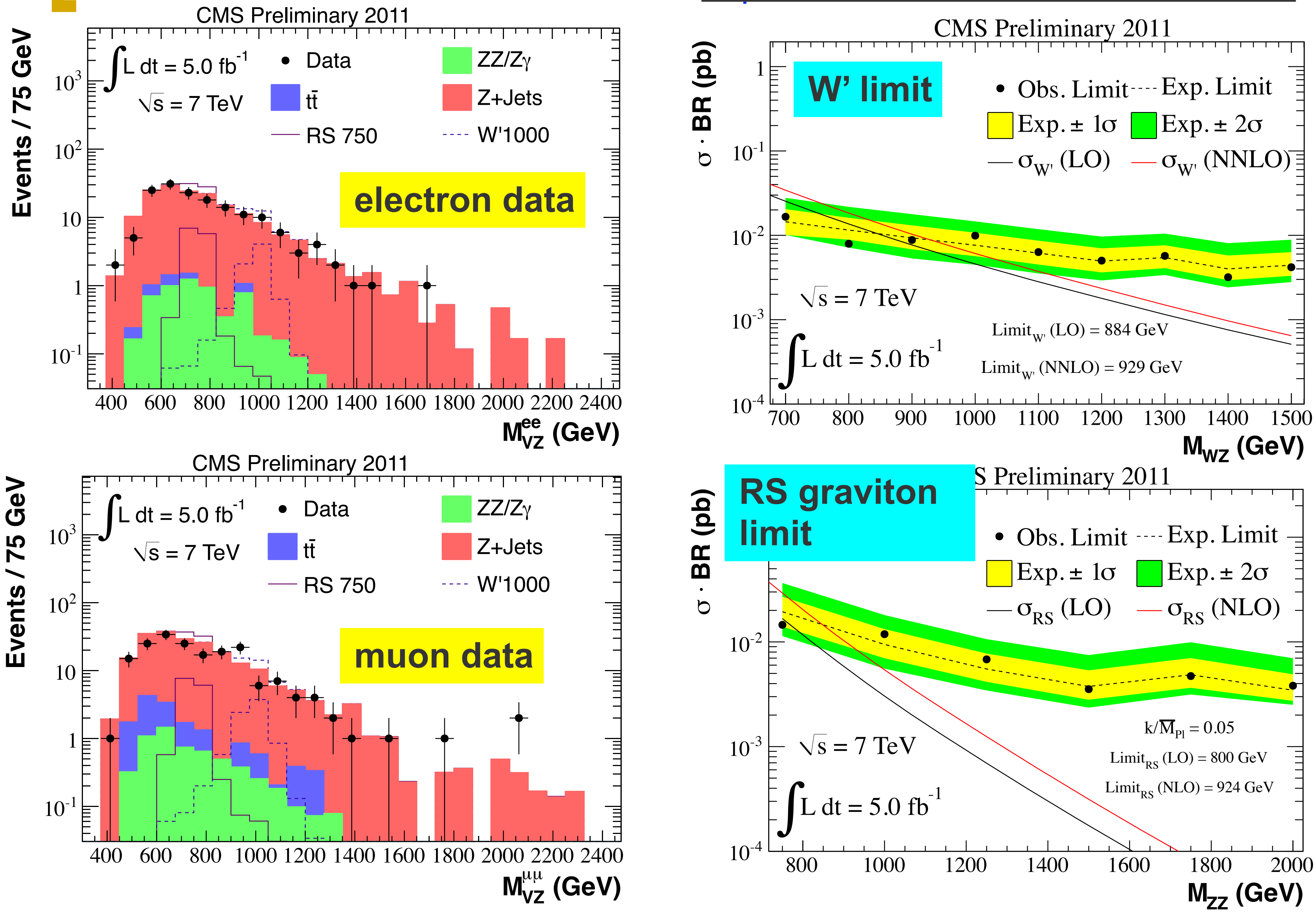
at 95% CL, the strongest limit to-date

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]	~ 1 fb^{-1}, Λ=1.2 TeV
ATLAS	[-0.12;0.12]	[-0.15;0.15]	[-0.13;0.13]	[-0.13;0.13]	~ 1 fb^{-1}, Λ=2 TeV
ATLAS	[-0.07;0.07]	[-0.08;0.08]	[-0.07;0.07]	[-0.08;0.08]	~ 1 fb^{-1}, Λ=inf

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

Search for W' & RS graviton in VZ→ℓℓ+j (boosted)

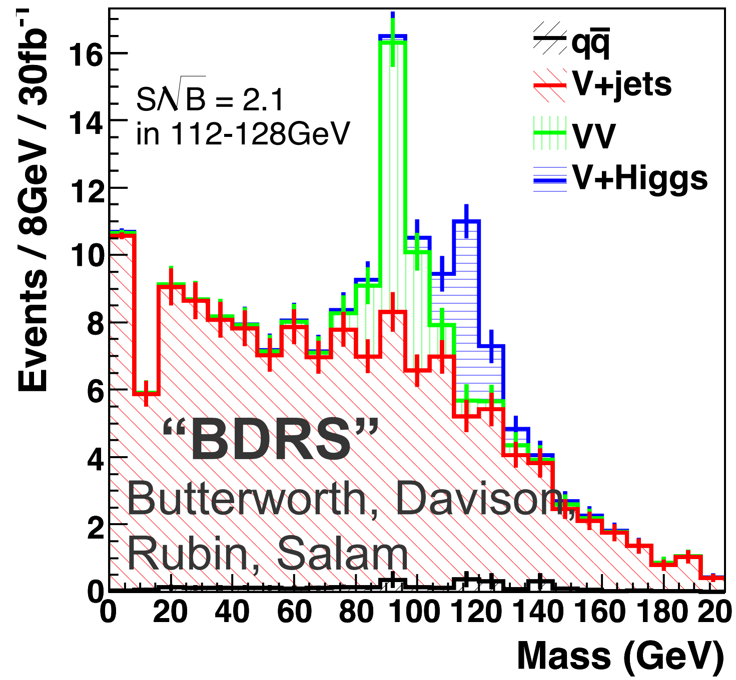
http://cdsweb.cern.ch/record/1444879



Future prospects: NP in boosted W/Z/Higgs

This is what we aim to do

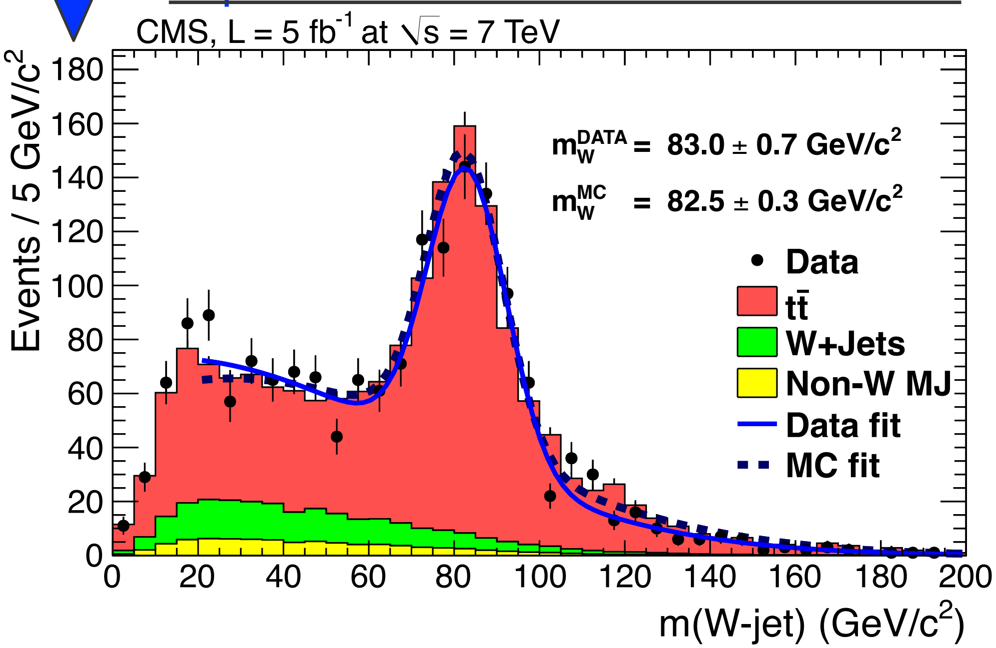
Reconstruct hadronic decays of boosted Higgs, W/Z, top



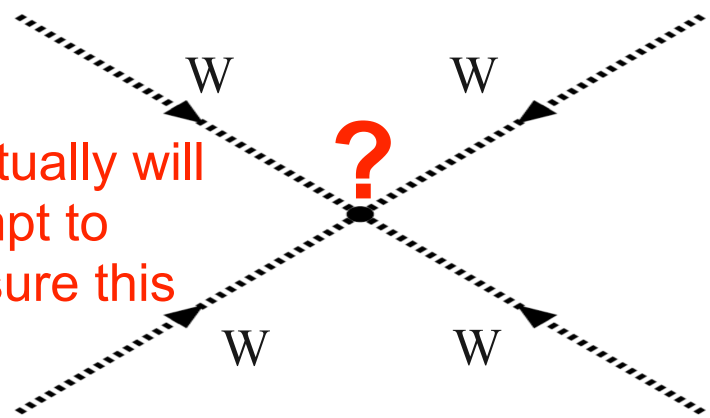
arXiv: 0802.2470

Started with hadronic W in boosted top events

http://cdsweb.cern.ch/record/1370237



Eventually will attempt to measure this



Summary

- Diboson measurements are approaching a few % accuracy
  - Measure production rates for WW, WZ, ZZ
  - Important for Higgs coupling to W and Z via H→WW, ZZ
  - And to b via WH(→bb). WZ (→bb) a good control sample
- Focus now on new physics that can appear in these events
  - Techni-color particles, Z', RS graviton, ...
  - More on the way...
- With 25 fb^{-1} we will be able to probe EWSB in more detail
  - Using modern tools like jet substructure
  - Will be possible to probe $W_L W_L$ scattering, weakly-produced resonances, ...