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W^+W^- differential cross-section

Measurement with the CMS detector at $\sqrt{s} = 8\,\text{TeV}$

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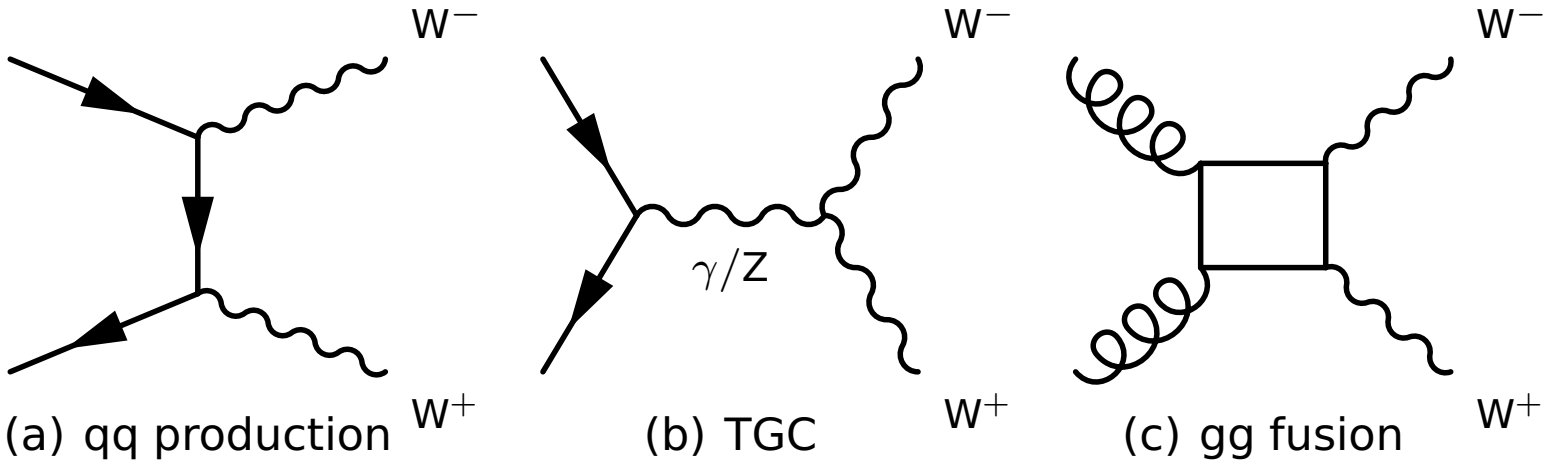
based on the publication in arXiv:1507.03268

08/27/2015

Outline

Introduction

Introduction



- measuring the WW production cross section

  → using the WW → $2\ell 2\nu$ decay channel (clean selection)

  → Signature: two leptons and large missing E_T

  → important irreducible background for H→WW

- this process is testing EWK and QCD and Higgs sector

  → sensitive to soft gluons in initial state, triple gauge coupling

The CMS Experiment

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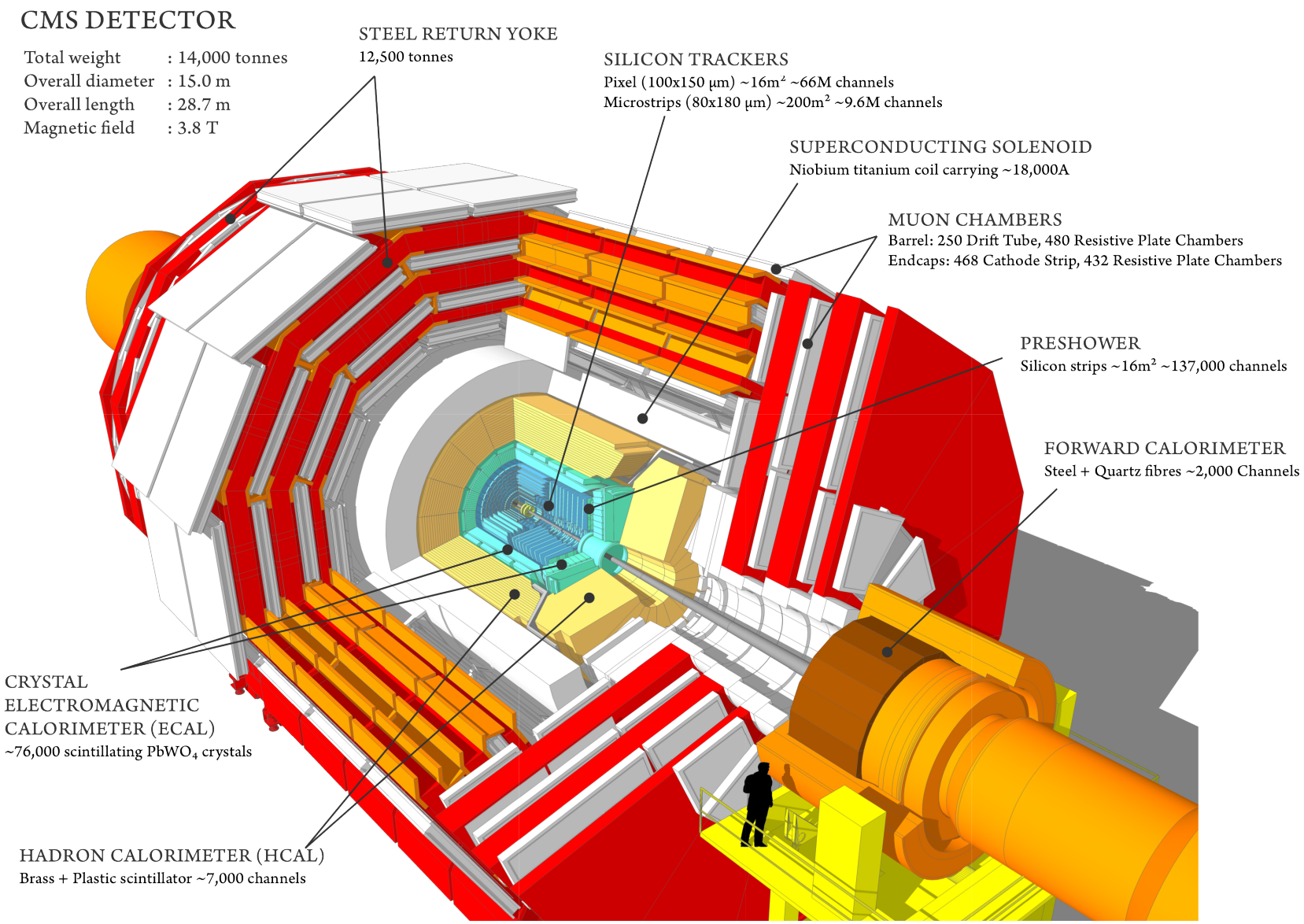
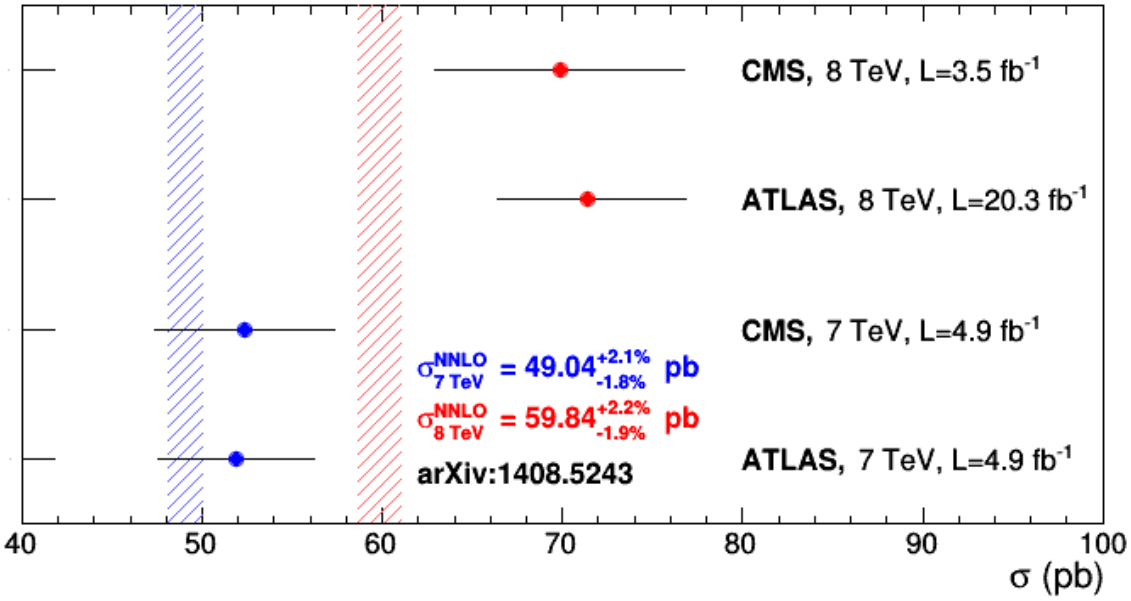


History & Current Status



- WW cross-section measurements received attention

  → inclusive measurements by ATLAS and CMS a bit above the theory prediction

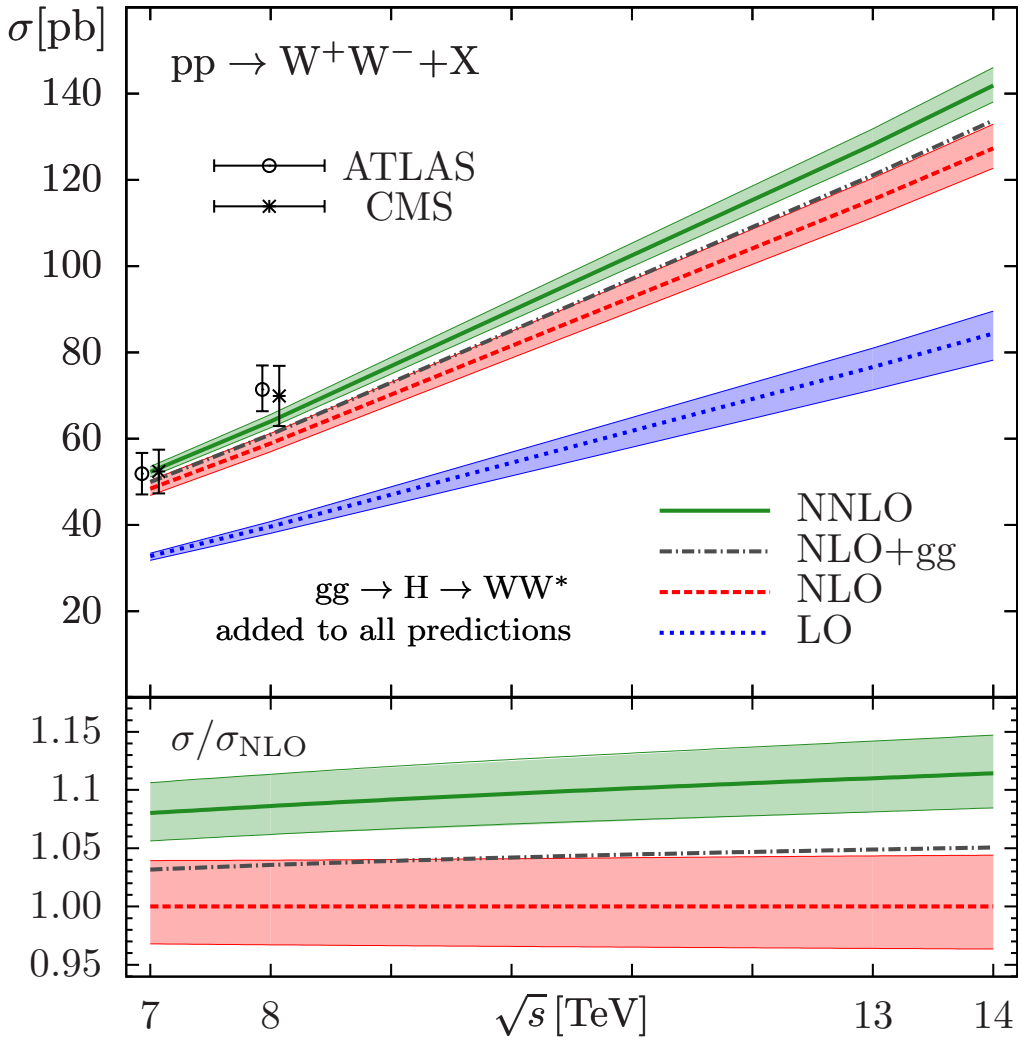
  → important background for the H→WW channel + testing the gauge structure of the SM

- Also, there is a recent CDF paper on WW production

  → arXiv:1505.00801v1: $\sigma_{WW}^{meas} = 14.0^{+1.6}_{-1.4}$ pb, with an NLO SM prediction of 11.3/11.7 $\pm \sim$ 1 pb

History & Current Status

- recent advancements in theory calculations



Source: arXiv:1408.5243

$\sqrt{s}$ [TeV]	**NLO** [pb]	**NNLO** [pb]
7	$45.16^{+3.7\%}_{-2.9\%}$	$49.04^{+2.1\%}_{-1.8\%}$
8	$54.77^{+3.7\%}_{-2.9\%}$	$59.84^{+2.2\%}_{-1.9\%}$
13	$106.0^{+4.1\%}_{-3.2\%}$	$118.7^{+2.5\%}_{-2.5\%}$
14	$116.7^{+4.1\%}_{-3.3\%}$	$131.3^{+2.6\%}_{-2.2\%}$

Results from CMS

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$\sqrt{s}$ [TeV]	$\int \mathcal{L}$ [fb^{-1}]	σ_{WW}^{meas} [pb]	σ_{WW}^{NNLO} [pb]
7	4.9	$52.4 \pm 2.0\,(\text{stat.}) \pm 4.5\,(\text{syst.}) \pm 1.2\,(\text{lumi.})$ pb	$49.04^{+2.1\%}_{-1.8\%}$
8	3.5	$69.9 \pm 2.8\,(\text{stat.}) \pm 5.6\,(\text{syst.}) \pm 3.1\,(\text{lumi.})$ pb	$59.84^{+2.2\%}_{-1.9\%}$
8	19.365	$60.2 \pm 0.9\,(\text{stat.}) \pm 4.5\,(\text{syst.}) \pm 1.6\,(\text{lumi.})$ pb	$59.84^{+2.2\%}_{-1.9\%}$

Differences to previous CMS analysis

- also measuring/publishing the fiducial cross-section
- checking differential distributions
- using the full luminosity
- multiple other improvements

  $\rightarrow$ e.g. recomputation of PDF and QCD scale unertainties, making use of embedded data samples, etc.

Analysis Details

Cuts (1/2)

Signal

Looking at the fully leptonic final state we require two leptons (within acceptance cuts) and missing E_T as we have real MET coming from the neutrinos.

Selection optimized to enhance S/B ratio

- tight lepton ID/isolation

  $\rightarrow$ to reject W+jets background (where the jet fakes a lepton)

- Z-mass window cut and MVA for off-peak contributions

  $\rightarrow$ to reject DY$\rightarrow \ell\ell$ background (fake missing E_T)

- top veto based on b-tagging, soft-muon-tagging

  $\rightarrow$ to reject ttbar and tW contributions (very important in 1-jet bin

- third lepton veto

  $\rightarrow$ to reject WZ events

Cuts (2/2)

- analysis performed in 4 exclusive categories

  $\rightarrow$ splitted in DF/SF and 0/1 jet (jet $|\eta| < 4.7$ and jet $p_T \geq 30$ GeV)

Variable	**Different Flavour**	**Same Flavour**
$q_{\ell_1} \cdot q_{\ell_2}$	< 0	< 0
p_T [GeV]	> 20	> 20
min proj. E_T^{miss}	> 20	> 20
DYMVA	–	> 0.88 (0jet), > 0.84 (1jet)
$\lvert m_{\ell\ell} - m_Z \rvert$ [GeV]	–	15
$p_{T,\ell\ell}$ [GeV]	> 30	> 45
$m_{\ell\ell}$ [GeV]	> 12	> 12
add. leptons ($p_T > 10$ GeV)	veto	veto
top-quark veto	applied	applied

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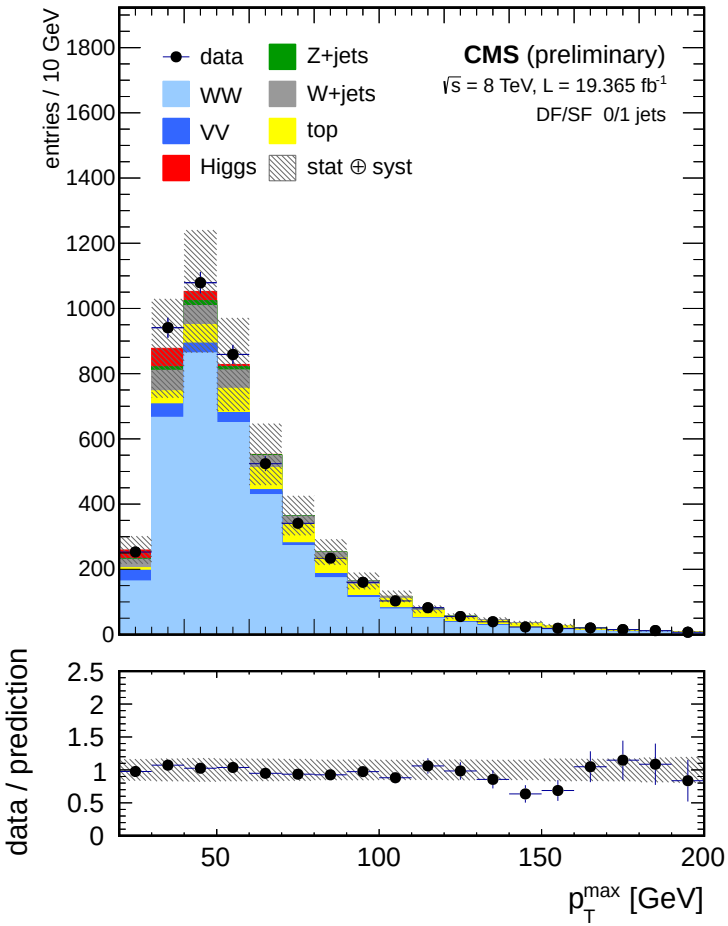
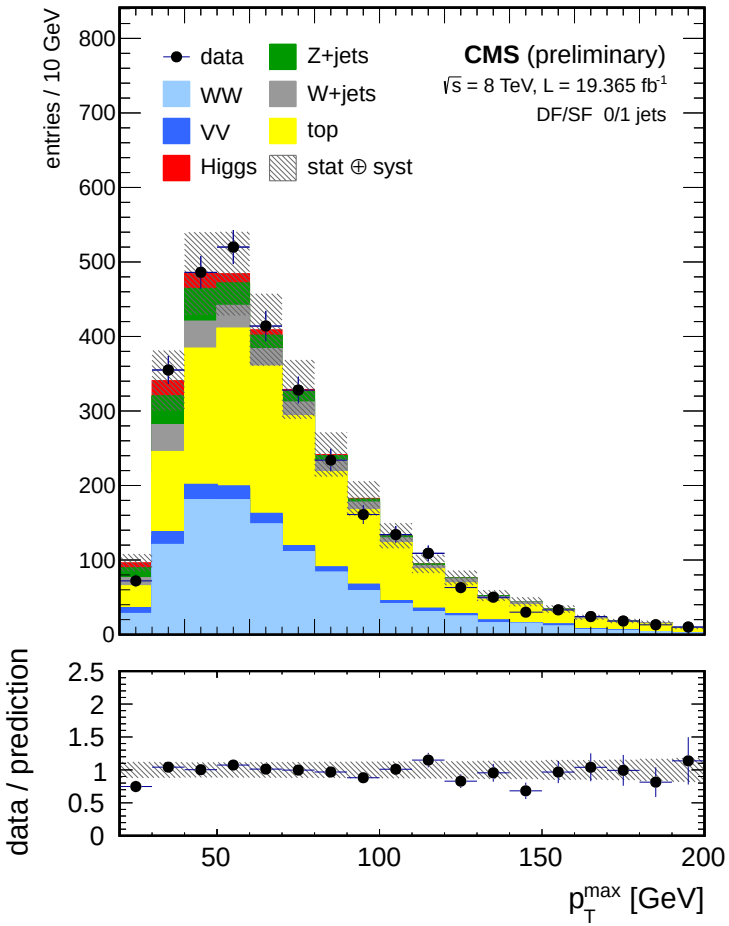
Leading lepton transverse momentum – $p_{T,\text{leading}}$

DF, 0-jet



DF, 1-jet



WW Fiducial Cross Section

- measurement is dominated by the 0-jet DF category
- the main source of systematic uncertainty is the modelling of the signal efficiency

  → especially in connection with the jet veto efficiency
- reporting the production cross section in fiducial regions

  → chosen to be very close to the event selection (including the jet veto)

  → fiducial volume definitions should be reproducable by theorists

  → report values for different jet veto thresholds to communicate modeling of the jet veto efficiency
- lower systematic uncertainties compared to extrapolating to the full phase space

  → systematic uncertainty on the lepton efficiencies is very small

WW Fiducial Cross Section

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Fiducial Volume Definition

- jets at particle level clustered with the anti-k_T algorithm
- two e (μ) with $|\eta| < 2.5$ (2.4) and $p_T > 20$ GeV

Results for different jet vetos in the 0 jet bin

p_T^{jet} threshold [GeV]	$\sigma_{fiducial}$ measured [pb]	$\sigma_{fiducial}^{NLO}$ predicted [pb]
20	0.223 ± 0.004 (stat.) ± 0.013 (exp.) ± 0.007 (th.) ± 0.006 (lum.)	0.228 ± 0.001 (stat.)
25	0.253 ± 0.005 (stat.) ± 0.014 (exp.) ± 0.008 (th.) ± 0.007 (lum.)	0.254 ± 0.001 (stat.)
30 (*)	0.273 ± 0.005 (stat.) ± 0.015 (exp.) ± 0.009 (th.) ± 0.007 (lum.)	0.274 ± 0.001 (stat.)

(*) used in later analysis steps

Differential Cross Section

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- differential cross section as function of leading lepton p_T, dilepton p_T , invariant mass $m_{\ell\ell}$, and opening angle between leptons $\Delta\varphi_{\ell\ell}$
- same fiducial region as before (jet veto at 30 Gev)

  $\rightarrow$ again including lepton acceptance: two e (μ) with $|\eta| < 2.5$ (2.4) and $p_T > 20$ GeV
- unfolding of "data – background" distributions

  $\rightarrow$ top and W+jets backgrounds estimated from data, other background from MC

  $\rightarrow$ jet smearing on signal applied
- response matrix is determined from POWHEG after reweighting the $p_{T,WW}$

  $\rightarrow$ tested to be independet of the Monte Carlo used to derive the response matrix
- SVD unfolding is used as a default method

Differential Distributions

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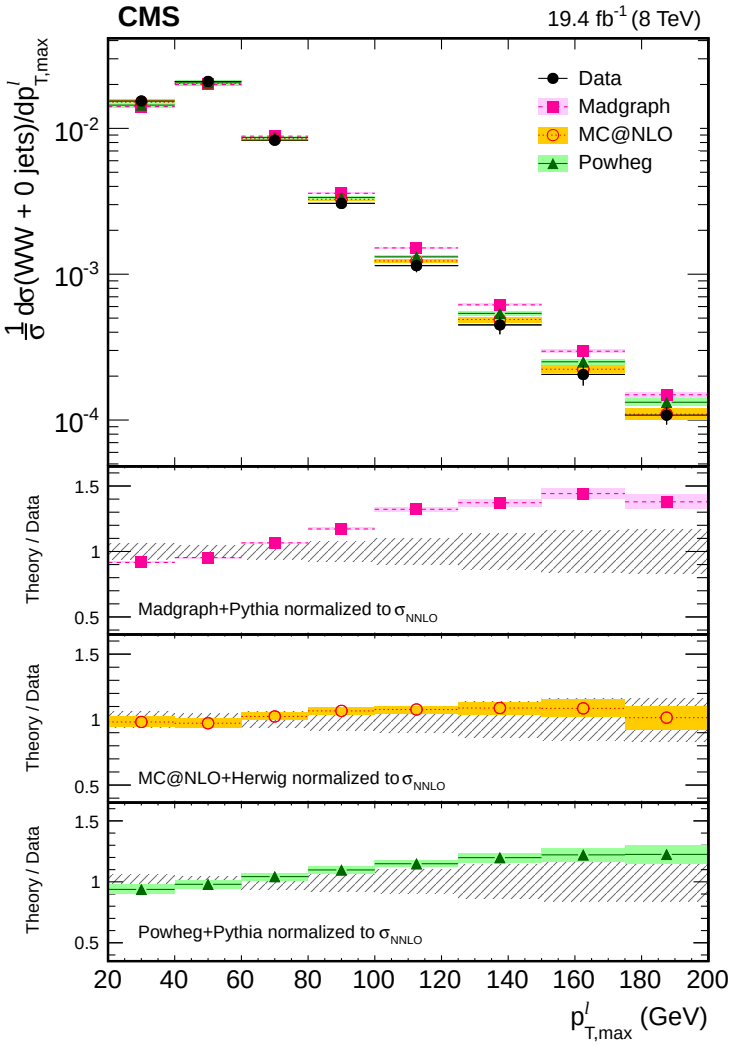
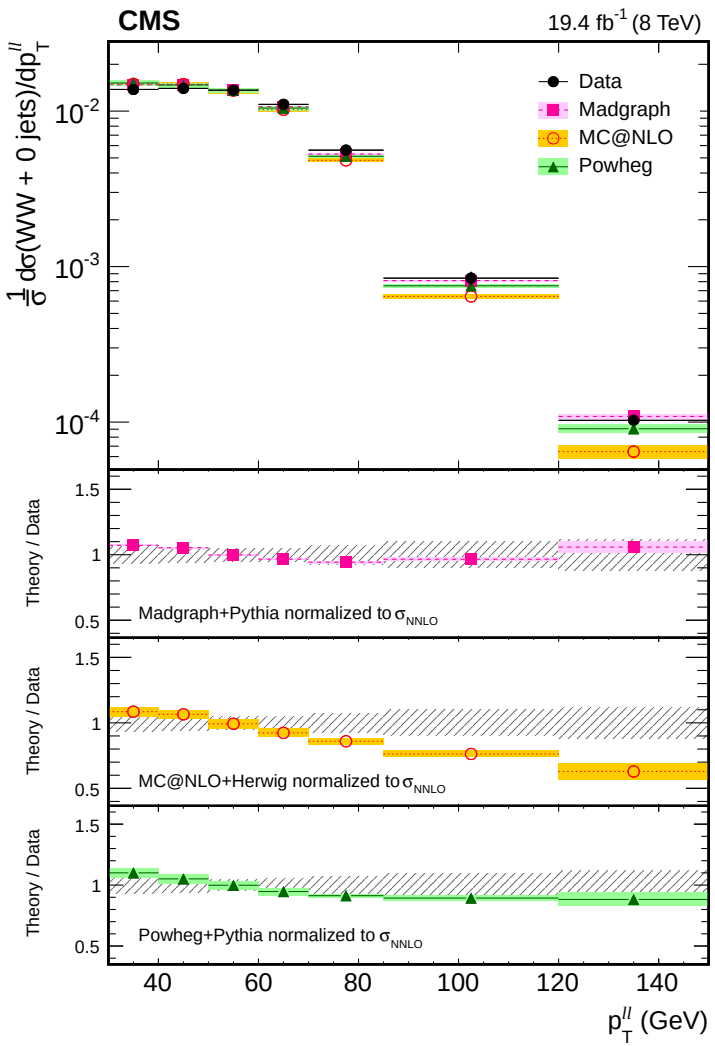
leading lepton p_T



dilepton $p_{T,\ell\ell}$



Differential Distributions

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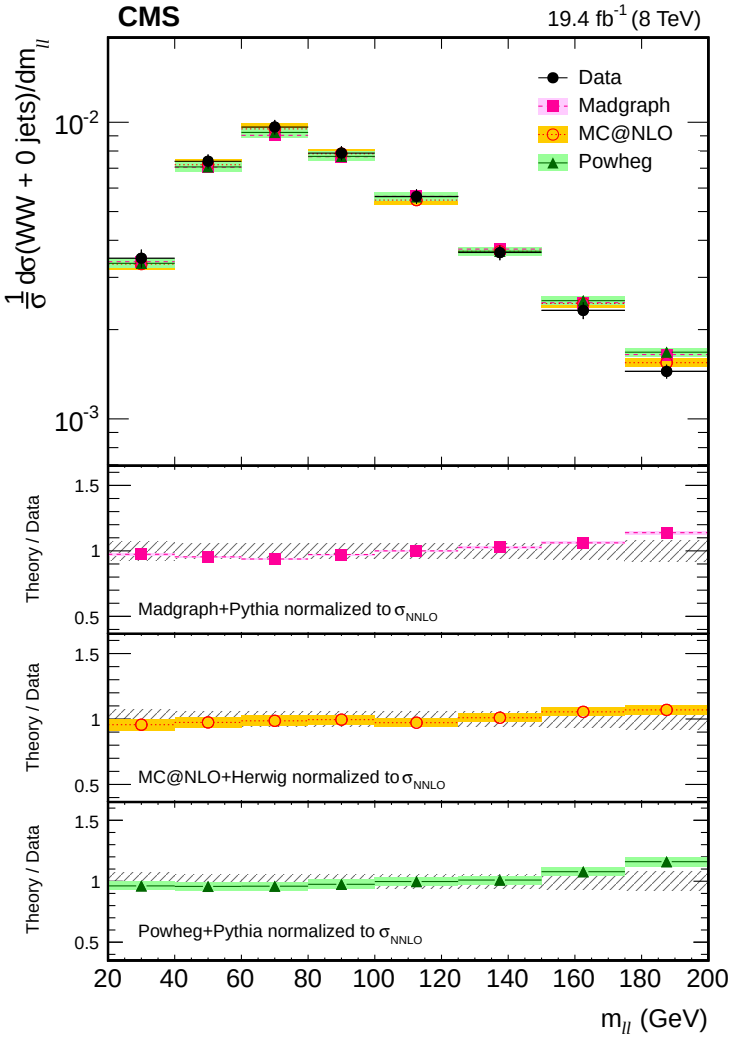
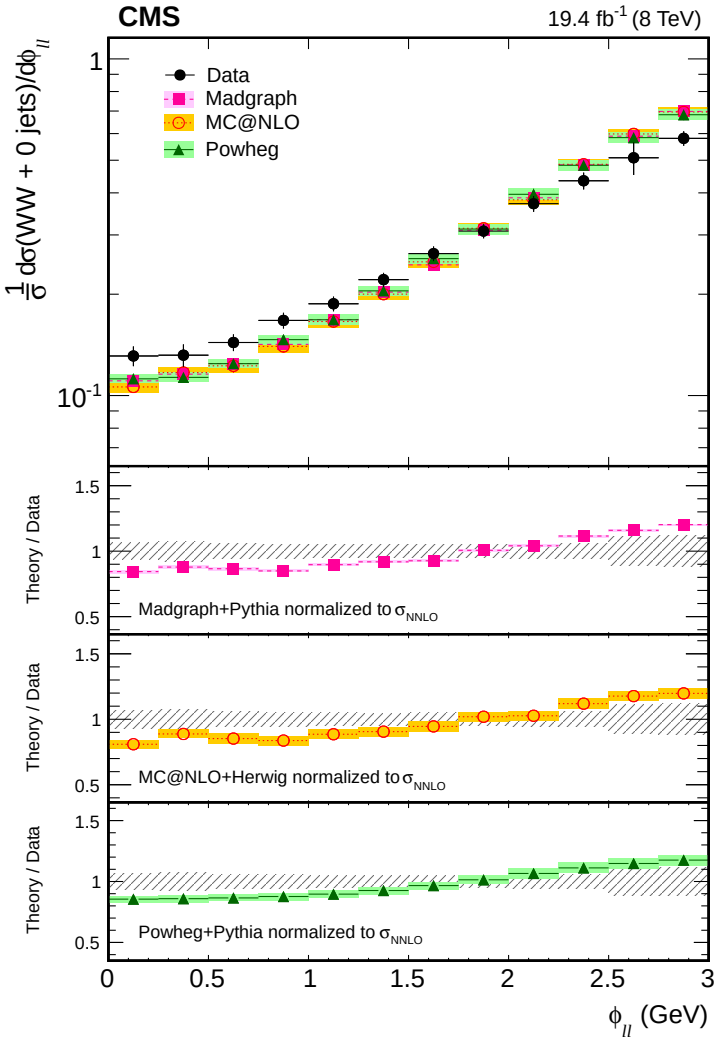
dilepton mass $m_{\ell\ell}$



opening angle $\Delta\varphi_{\ell\ell}$



Inclusive Analysis

The inclusive cross section is determined as

$$\sigma_{WW} = \frac{N_{\text{data}} - N_{\text{bkg}}}{\mathcal{L} \cdot \varepsilon \cdot (3 \cdot \mathcal{B}(\mathrm{W} \to \ell\nu))^2}$$

where ε is the signal efficiency, including

- detector geometrical acceptance
- selection and trigger efficiencies

Signal Efficiencies per Category

Event category		Signal efficiency [%]
0-jet category	Different-flavor	$3.01 \pm 0.22\,(\text{syst.}) \pm 0.02\,(\text{stat.})$
	Same-flavor	$1.21 \pm 0.09\,(\text{syst.}) \pm 0.01\,(\text{stat.})$
1-jet category	Different-flavor	$0.96 \pm 0.11\,(\text{syst.}) \pm 0.01\,(\text{stat.})$
	Same-flavor	$0.34 \pm 0.04\,(\text{syst.}) \pm 0.01\,(\text{stat.})$

Inclusive Analysis

Production Cross Section per Category

Event category		WW production cross section [pb]
0-jet category	Different-flavor	$59.9 \pm 1.1\,(\text{stat.}) \pm 4.9\,(\text{syst.}) \pm 1.6\,(\text{lum.})$
	Same-flavor	$64.6 \pm 2.1\,(\text{stat.}) \pm 6.4\,(\text{syst.}) \pm 1.7\,(\text{lum.})$
1-jet category	Different-flavor	$59.8 \pm 2.8\,(\text{stat.}) \pm 8.8\,(\text{syst.}) \pm 1.6\,(\text{lum.})$
	Same-flavor	$65.8 \pm 5.5\,(\text{stat.}) \pm 11.4\,(\text{syst.}) \pm 1.7\,(\text{lum.})$

Combination

The categories are then combined using a profile likelihood fit; this yields (theory: $\sigma_{\text{WW}}^{\text{NNLO}} = 59.8^{+1.3}_{-1.1}$ pb)

$$\sigma_{\text{WW}} = 60.1 \pm 0.9\,(\text{stat.}) \pm 4.5\,(\text{syst.}) \pm 1.6\,(\text{lumi.})\,\text{pb}$$

Inclusive Analysis

Source	Uncertainty (%)
Statistical uncertainty	1.5
Luminosity	2.6
Lepton efficiency	3.8
Lepton momentum scale	0.5
missing E_T resolution	0.7
Jet energy scale	1.7
tt+tW normalization	2.2
W+jets normalization	1.3
DY$\rightarrow \ell\ell$ normalization	0.6
DY$\rightarrow \tau\tau$ normalization	0.2
Wγ normalization	0.3
Wγ^* normalization	0.4
VV normalization	3.0
$H \rightarrow$WW normalization	0.8
Jet counting theory model	4.3
PDFs	1.2
MC statistics	0.9
Total uncertainty	7.9

- Total uncertainty around **8%**
- Result limited by systematics

$\rightarrow$ jet counting: $\sim$ 4.3%

$\rightarrow$ lepton efficiencies $\sim$ 3.8%

$\rightarrow$ background normalization

$\rightarrow$ luminosity $\sim$ 2.6%

Conclusion

Conclusion

- presented an updated measurement of the WW cross-section at $\sqrt{s} = 8\,\text{TeV}$ with the CMS detector
- inclusive result compatible with latest NNLO theory predictions ($\sigma_{\text{WW}}^{\text{NNLO}} = 59.8^{+1.3}_{-1.1}\,\text{pb}$)

$$\sigma_{\text{WW}}^{\text{measured}} = 60.1 \pm 0.9\,(\text{stat.}) \pm 4.5\,(\text{syst.}) \pm 1.6\,(\text{lumi.})\,\text{pb}$$

- measurement is currently limited by systematics
- fiducial results and differential distributions agree with MC predictions within the uncertainties
- looking forward to have a measurement at 13 TeV

Backup

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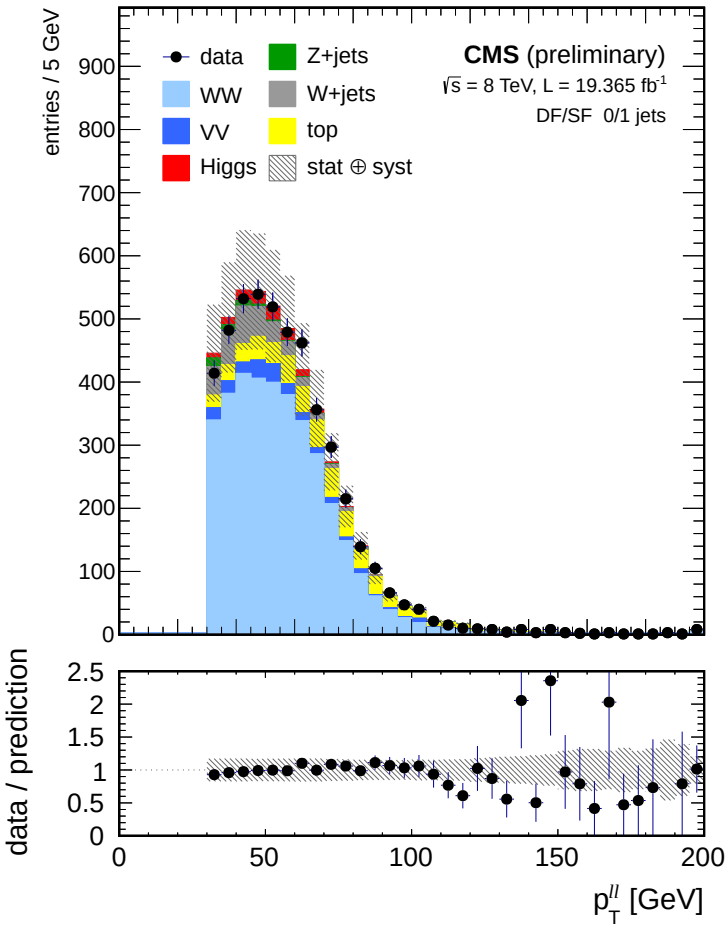
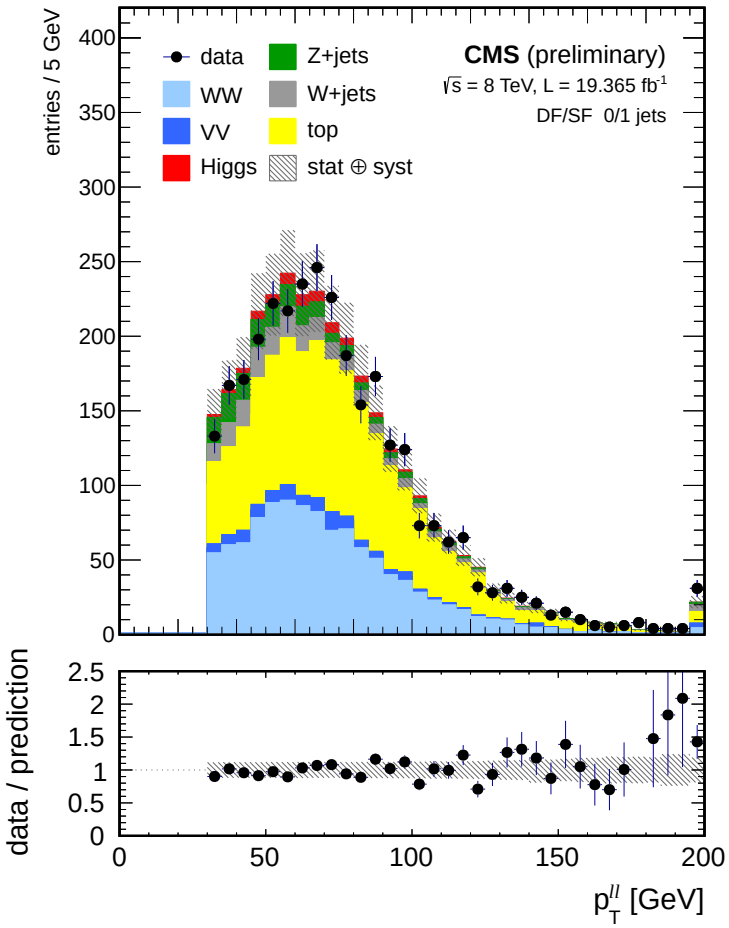
Dilepton transverse momentum – $p_{T,\ell\ell}$

DF, 0-jet



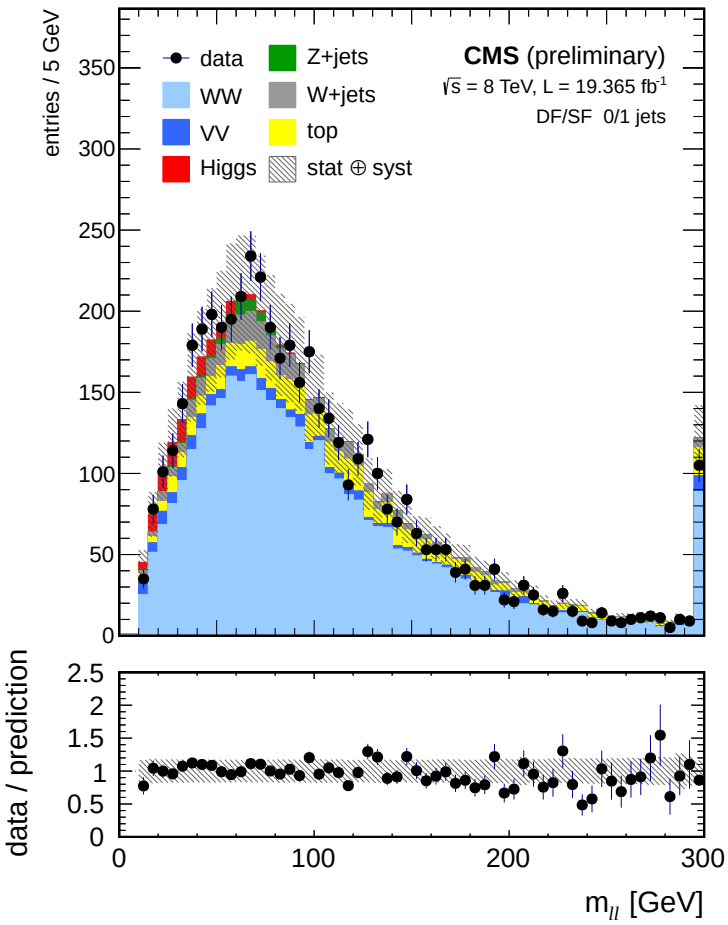
DF, 1-jet



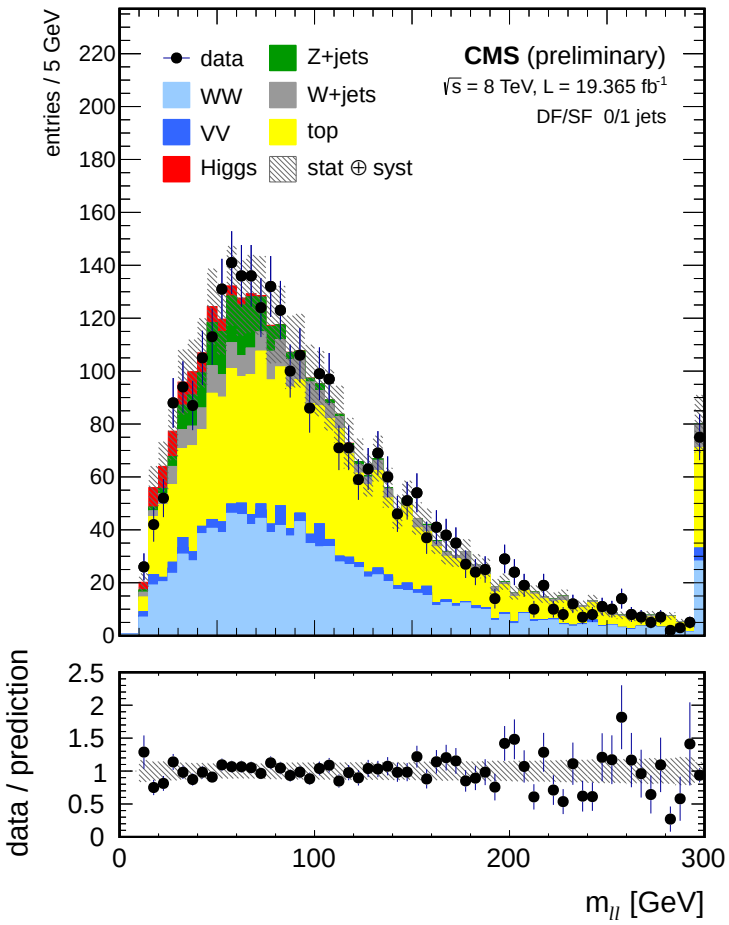
Kinematic Distributions

Dilepton mass – $m_{\ell\ell}$

DF, 0-jet



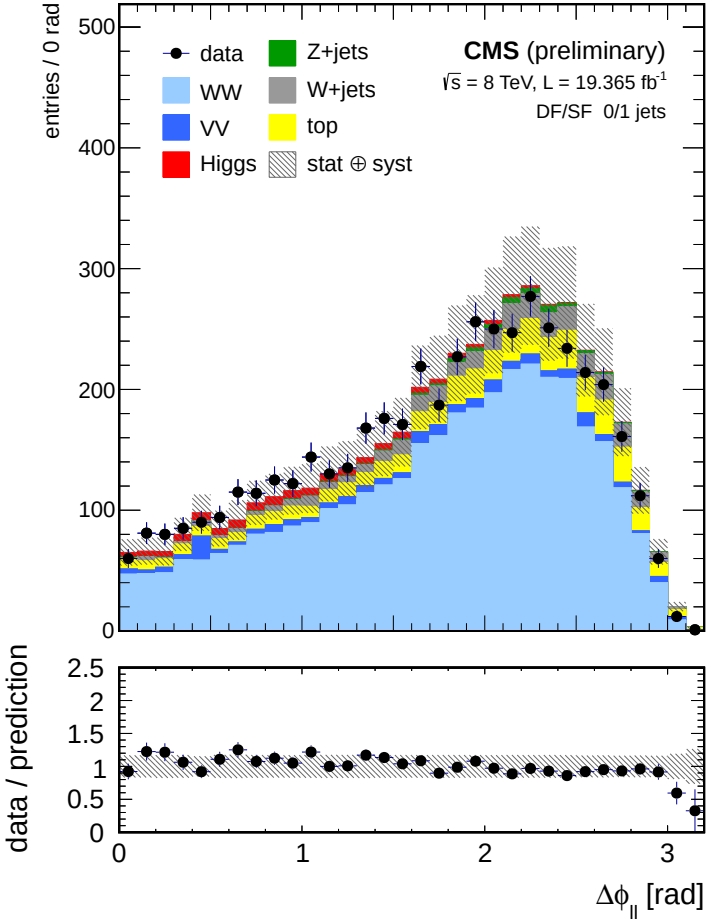
DF, 1-jet



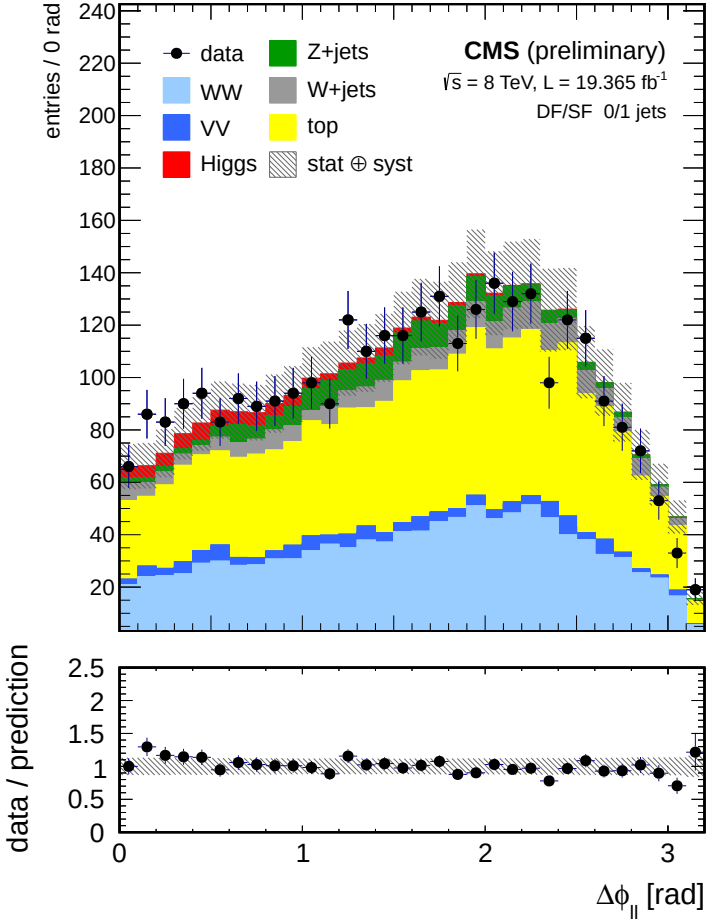
Kinematic Distributions

Dilepton opening angle – $\Delta\varphi_{\ell\ell}$

DF, 0-jet



DF, 1-jet



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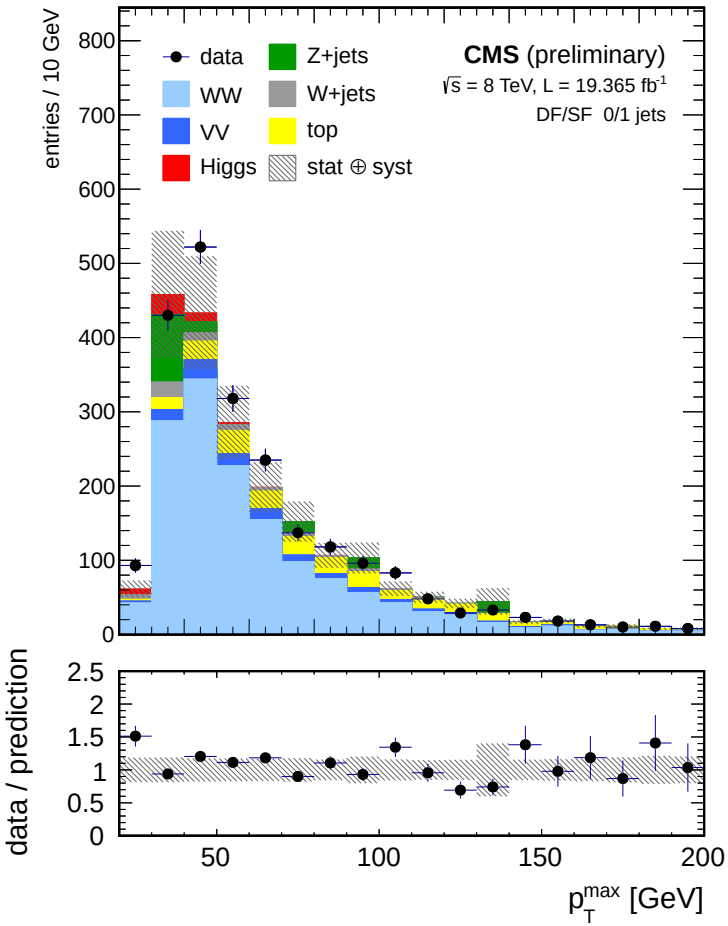
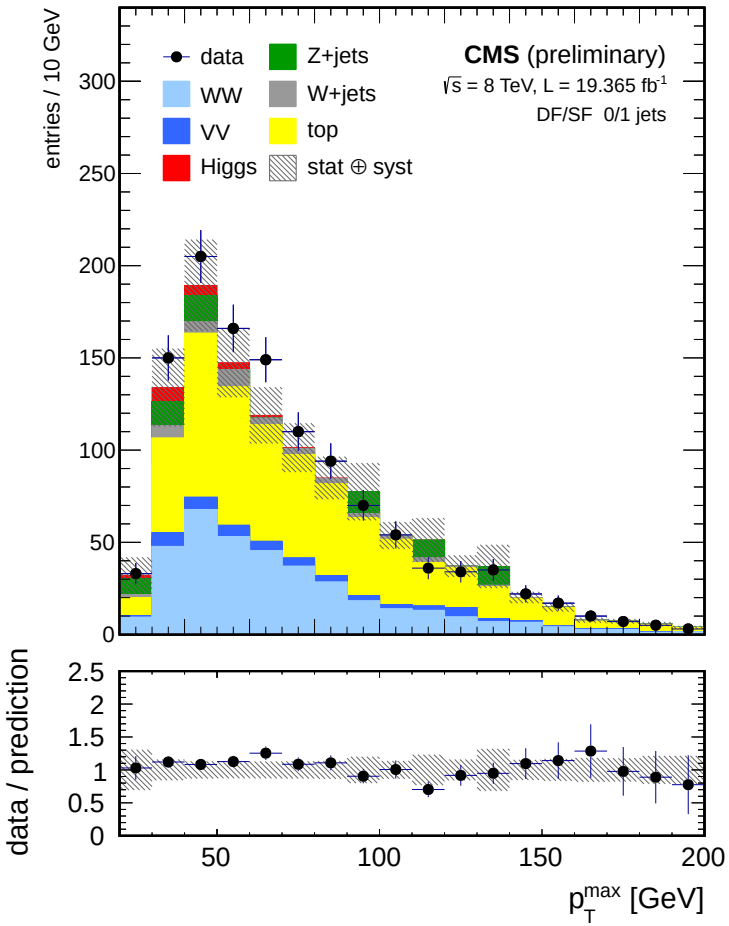
Leading lepton transverse momentum – $p_{T,\text{leading}}$

SF, 0-jet



SF, 1-jet



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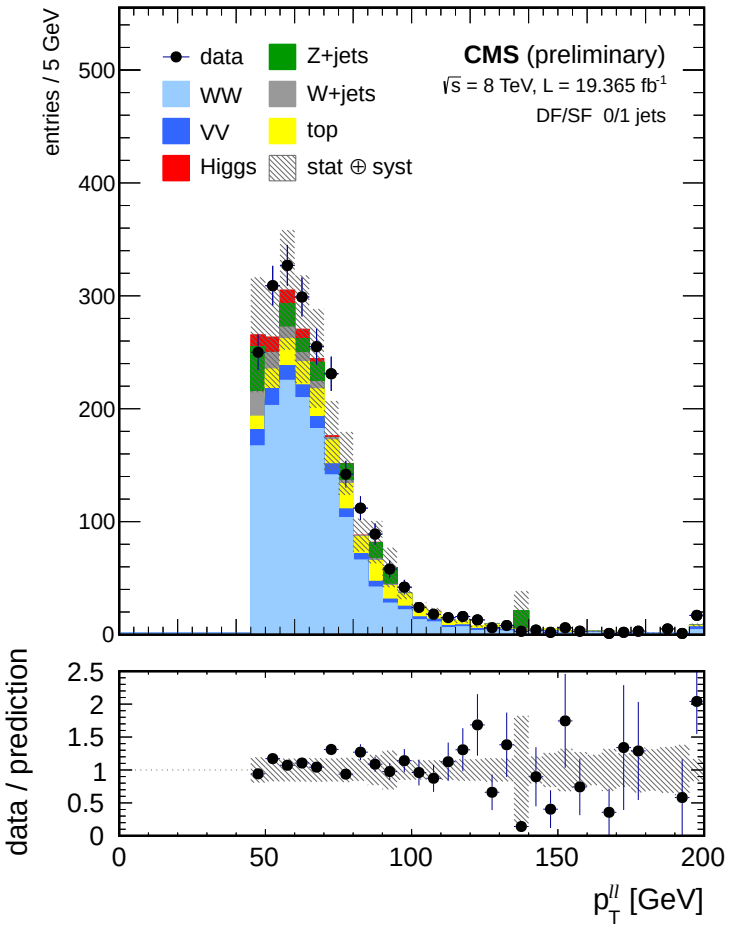
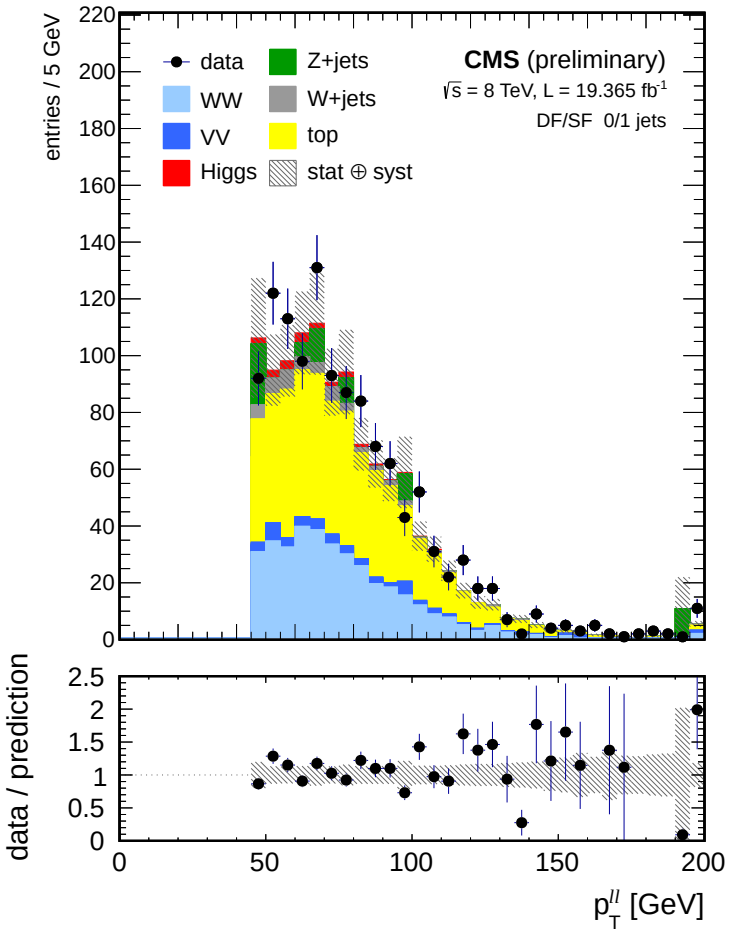
Dilepton transverse momentum – $p_{T,\ell\ell}$

SF, 0-jet



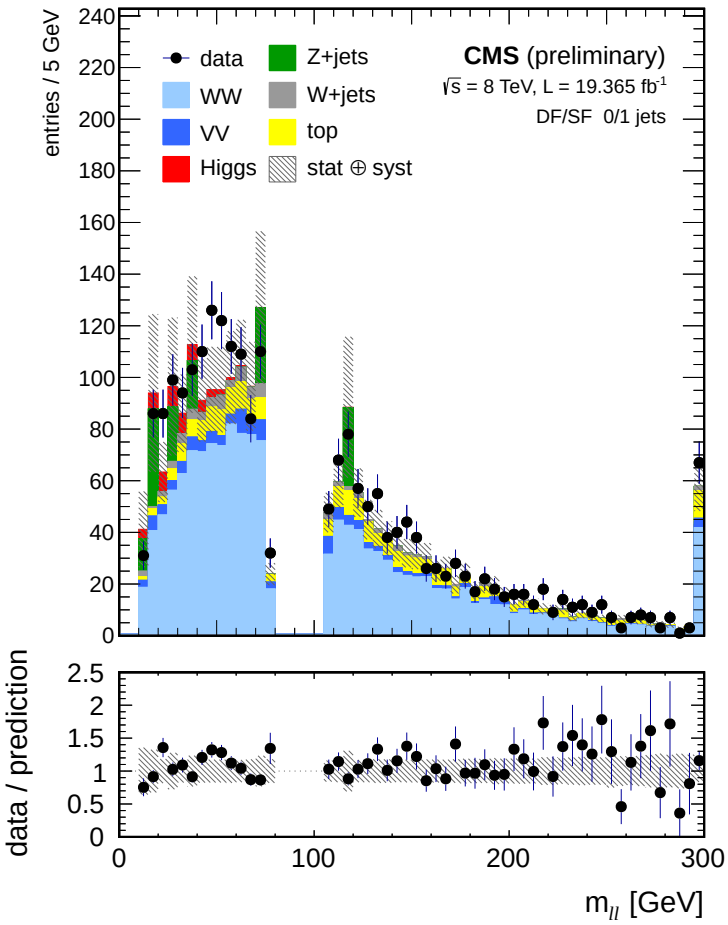
SF, 1-jet



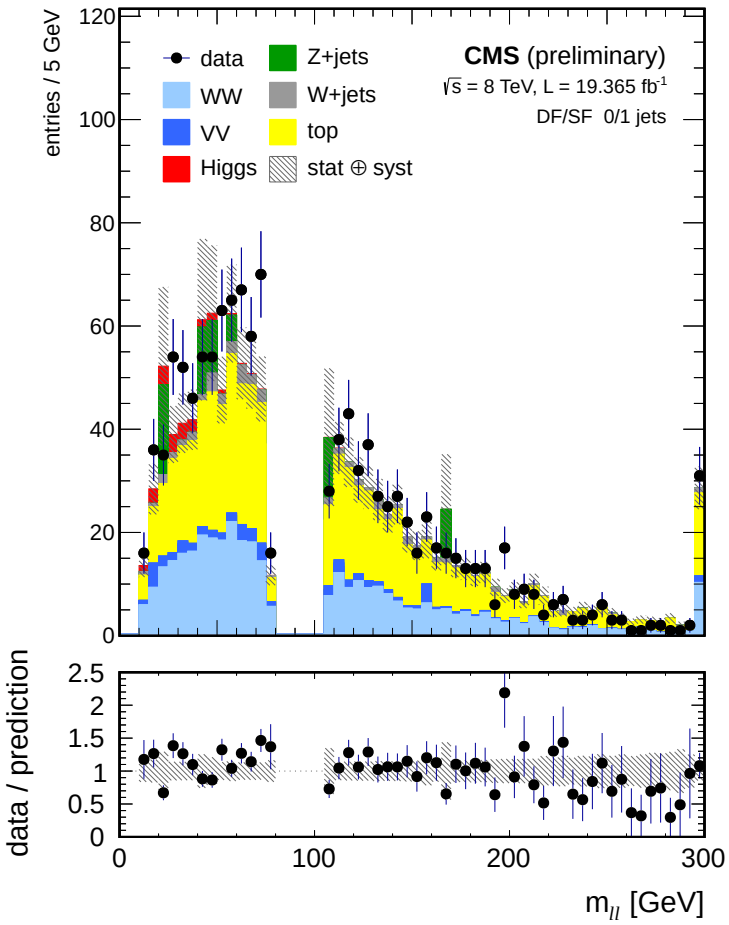
Kinematic Distributions

Dilepton mass – $m_{\ell\ell}$

SF, 0-jet



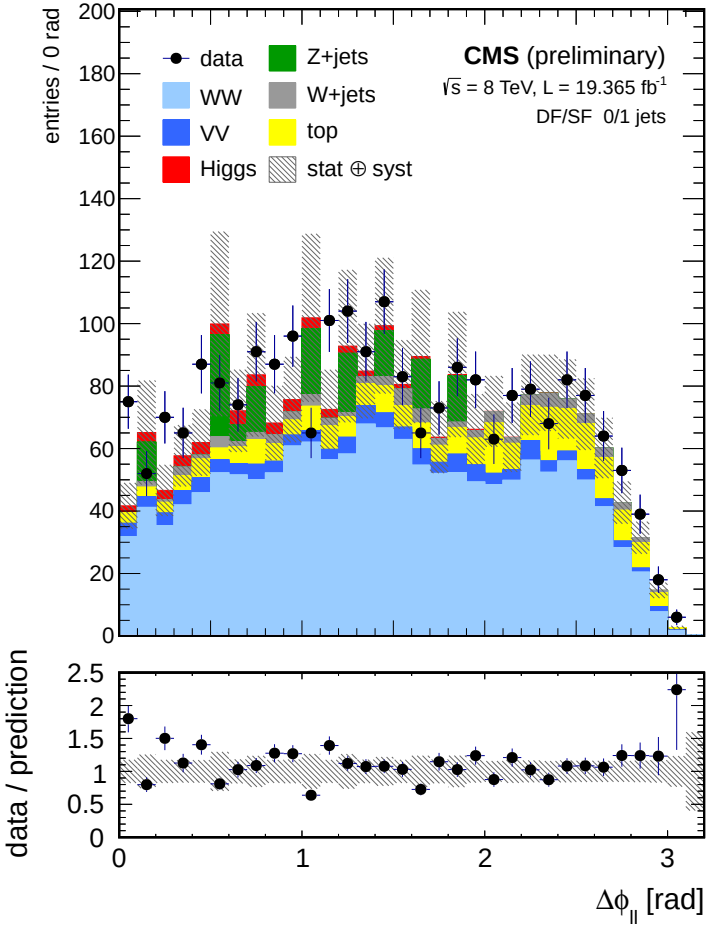
SF, 1-jet



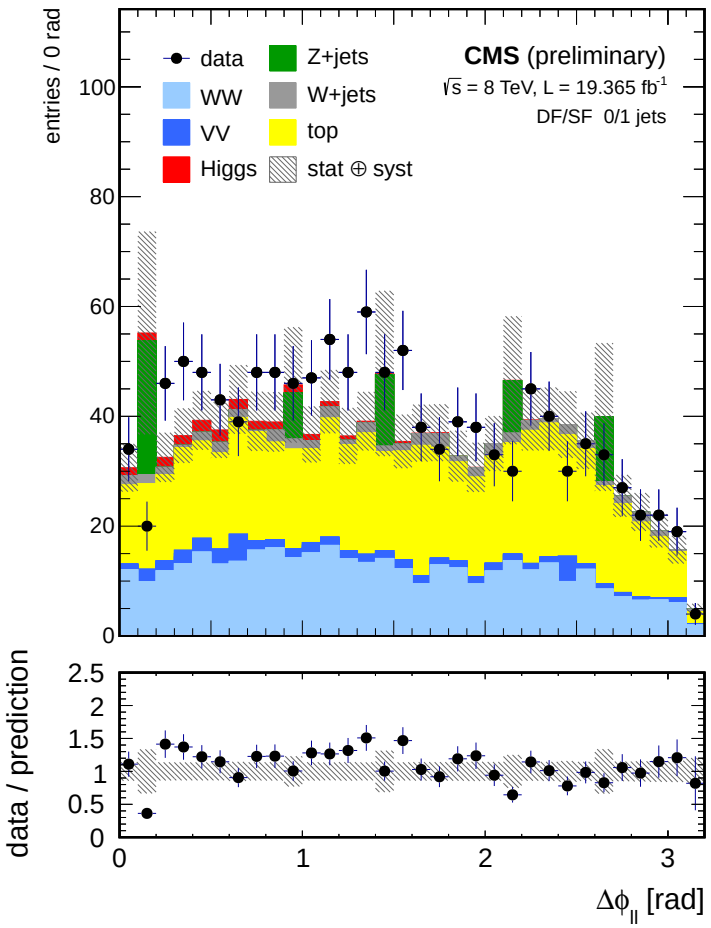
Kinematic Distributions

Dilepton opening angle – $\Delta\varphi_{\ell\ell}$

SF, 0-jet



SF, 1-jet



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Systematic Uncertainties

	qq $\to$ WW	gg $\to$ WW	ttbar + tW	W+jets	WZ +ZZ	Zγ $\to \ell\ell$	Wγ	Wγ^*	Zγ $\to \tau\tau$	Higgs
Luminosity	2.6	2.6	–	–	2.6	–	2.6	–	2.6	2.6
Lepton efficiency	3.5	3.5	–	–	3.5	–	3.5	–	–	3.5
Lepton momentum scale	1.0	1.0	–	–	1.0	–	1.0	–	–	1.0
MET resolution	2.0	2.0	–	–	2.0	–	2.0	–	–	2.0
Jet energy scale	2.0	2.0	–	–	3.0	–	2.0	–	–	3.0
ttbar+tW normalization	–	–	13-3	–	–	–	–	–	–	–
W+jets normalization	–	–	–	36	–	–	–	–	–	–
DYll normalization	–	–	–	–	–	30	–	–	–	–
DYtt normalization	–	–	–	–	–	–	–	–	10	–
Wγ normalization	–	–	–	–	–	–	30	–	–	–
Wγ^* normalization	–	–	–	–	–	–	–	40	–	–
Underlying event	3.5	3.5	–	–	–	–	–	40	–	–
PDFs	1.3	0.8	–	–	4.0	–	4.0	4.0	–	8.0
Higher-order corrections	3.8-9.2	30	–	–	5.0	–	–	–	–	18-28

aTGC Limits

Effective Field Theory

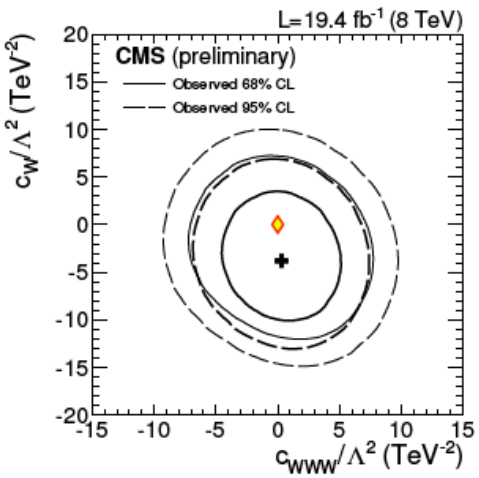
- if scale is large new physics can be described by an effective field theory
- there are six different dim-6 operators; where the following three are C- and P-conserving

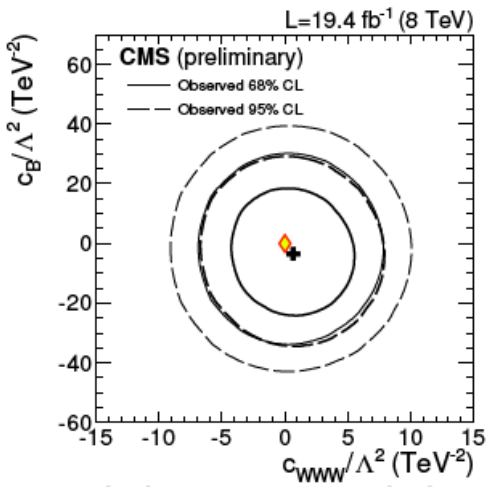
$$\mathcal{O}_{WWW} = \frac{c_{WWW}}{\Lambda^2}\mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}],$$
$$\mathcal{O}_{W} = \frac{c_{W}}{\Lambda^2}(D^{\mu}\Phi)^{\dagger}W_{\mu\nu}(D^{\nu}\Phi),$$
$$\mathcal{O}_{B} = \frac{c_{B}}{\Lambda^2}(D^{\mu}\Phi)^{\dagger}B_{\mu\nu}(D^{\nu}\Phi),$$

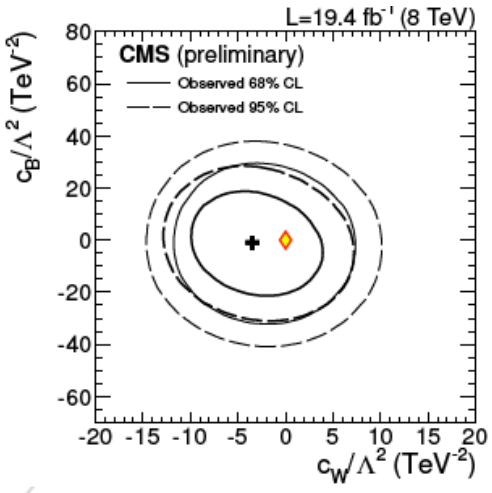
- only 0 jet category is considered
- using the $m_{\ell\ell}$ distribution

aTGC Limits

68% and 95% CL contours for the three 2D cases







95% CL allowing only one coupling constant to vary

- $-5.73 < c_{WWW}/\Lambda^2 < 5.95\ \text{TeV}^{-2}$
- $-11.38 < c_W/\Lambda^2 < 5.39\ \text{TeV}^{-2}$
- $-29.17 < c_B/\Lambda^2 < 23.90\ \text{TeV}^{-2}$