Measurement of the WW and WZ production cross sections in CMS

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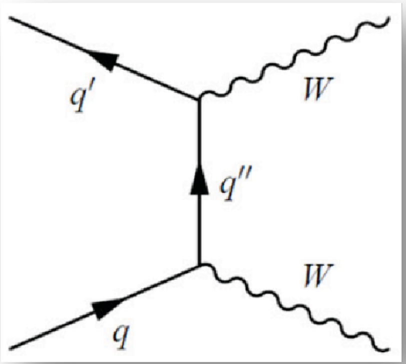
Outline

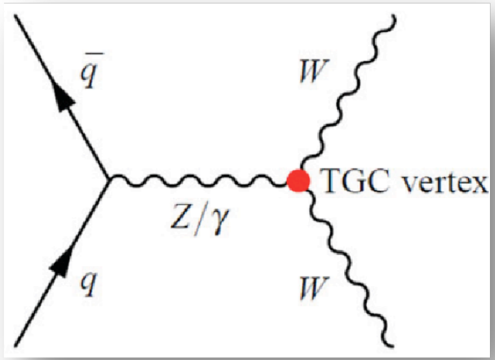
- WW production at LHC
- WW event selection
- WW cross section measurement
- Sources of systematic uncertainties
- WW normalized differential cross section
- Search for aTGC
- WZ event selection
- WZ cross section measurement
- Summary

W$^+$W$^-$ production

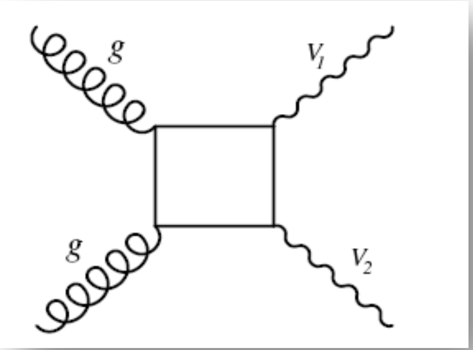
qq→WW LO diagram
t-channel



qq→WW LO diagram
s-channel



gg→WW NLO diagram
(~3 % contribution)

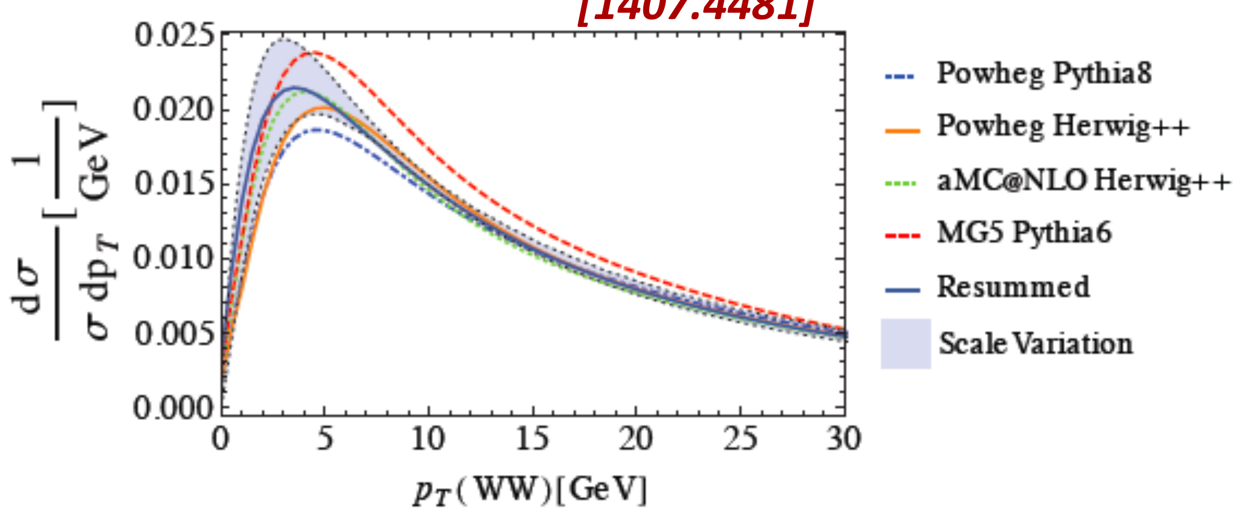


- Cross section available at NNLO QCD *[1408.5243]*
  - **~ 7% higher wrt NLO**
  - The **gg → H → WW is considered as background** (only 3% of expected signal yields)
- W$^+$W$^-$ production cross section larger than W$^\pm$Z and ZZ production
- Irreducible background to new physics searches and Higgs analyses
- Sensitive to new physics: probe the presence of aTGC

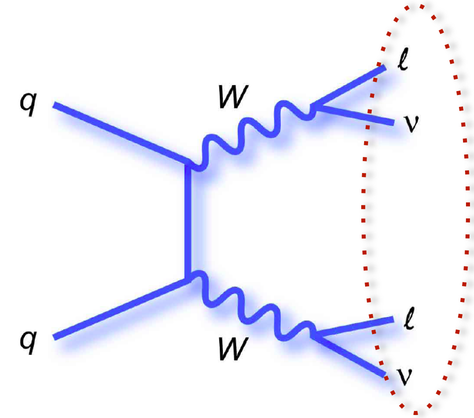
Higher order corrections

- Lots of theoretical interest in previous discrepancy, particularly wrt jet-veto efficiency *[1407.4481] [1407.4537]*
- **The 0-jet (or 1-jet bin) veto applied** in this analysis makes the kinematical distributions particularly sensitive to higher-order QCD corrections
  - We reweight p_T(WW) of the qq → WW MC to a NLO+NNLL p_T resummation calculation → **correlated with jet veto**
  - Compare to latest NNLO cross-section

[1407.4481]



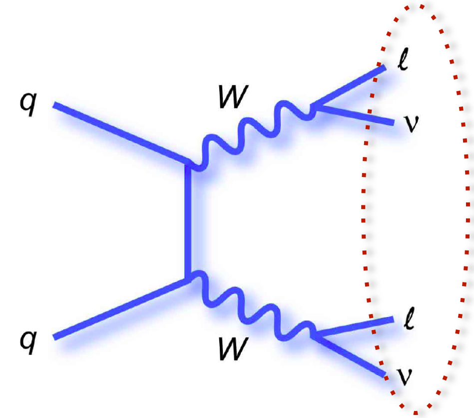
Event selection



- Data: 19.4 fb^{-1} at 8 TeV
- The **fully-leptonic (ee/μμ/eμ)** final state
  - 2 leptons with $P_T > 20$ GeV and $|\eta| < 2.4$ (2.5) for μ (e)
  - real MET from the neutrinos
- **Selection optimized to enhance ratio signal / background**
  - Tight lepton ID/Isolation

W→lν + jets (jet→fake lepton)

Event selection



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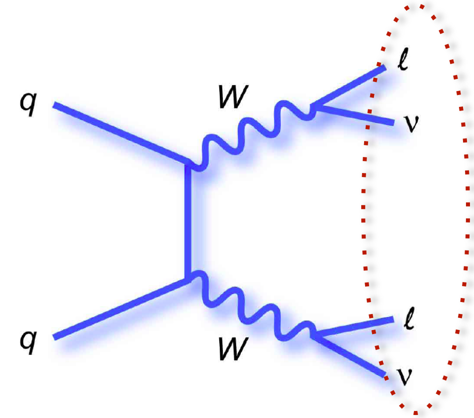
    Z→ll + jets (fake MET)

Event selection



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  - Apply top-veto based on jet b-tagging and soft muon tagging — **tW and ttbar production**

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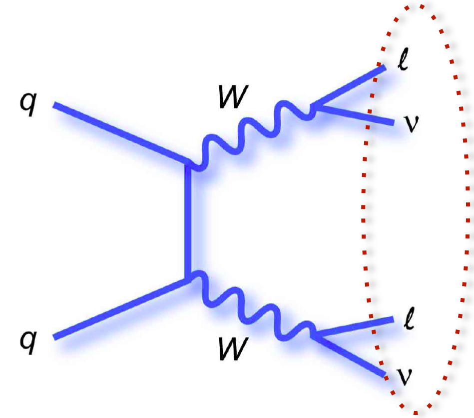
Event selection



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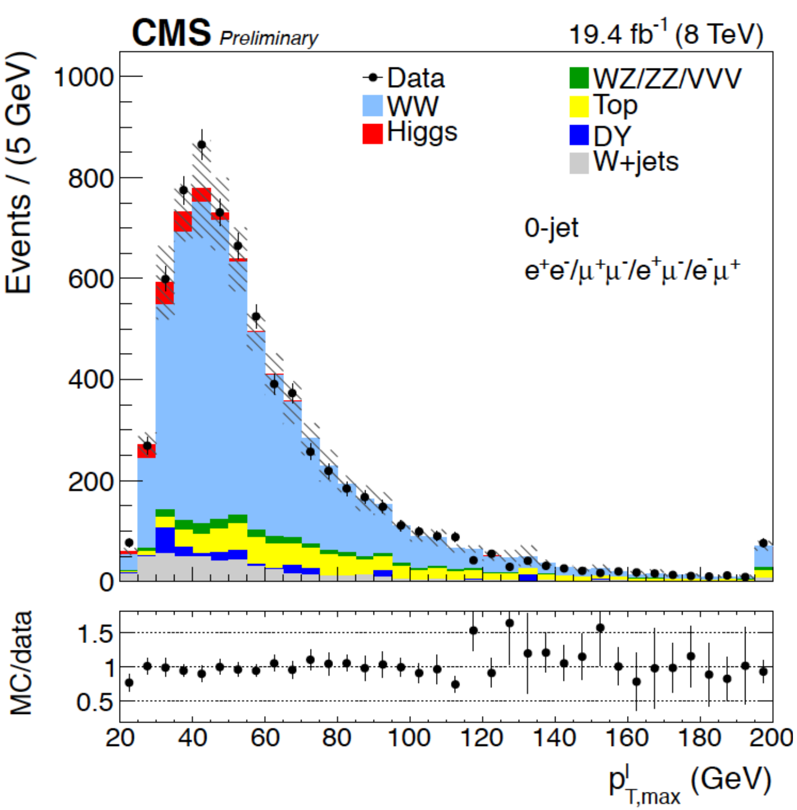
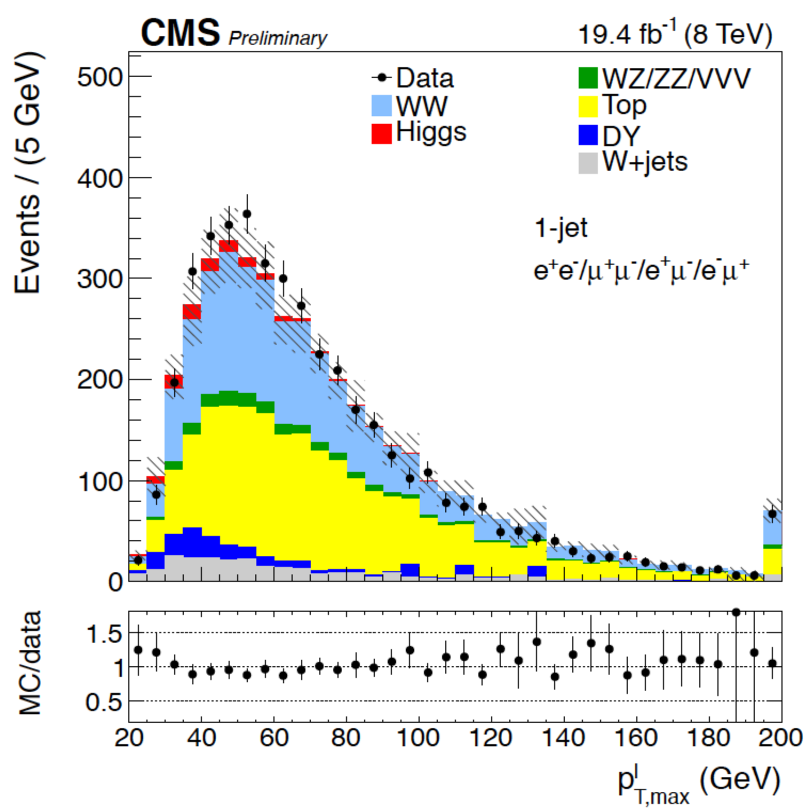
  - Apply top-veto based on jet b-tagging and soft muon tagging — **tW and ttbar production**
  - Reject events with a third lepton passing identification requirements — **WZ**

WW selected events

The events are analyzed in four exclusive categories

- Separated between different- and same-flavor leptons
- Separated between events with 0 or 1 reconstructed jet with $E_T > 30$ GeV





WW production cross section

$$\sigma_{W^+W^-} = \frac{N_{data} - N_{bkg}}{\mathcal{L} \cdot \epsilon \cdot (3 \cdot \mathcal{B}(W \to \ell\overline{\nu}))^2}$$

- $N_{data} - N_{bkg}$
- $\mathcal{L}$ = luminosity, 19.4 fb^{-1}
- ε = signal efficiency
- $\mathcal{B}$ (W→lv) = branching ratio to leptons , 10.80 ± 0.09%

Results per channel

Event category		W^+W^- production cross section (pb.)
0-jet category	Different-flavor	$59.7 \pm 1.1\,(\text{stat.}) \pm 3.3\,(\text{exp.}) \pm 3.5\,(\text{th.}) \pm 1.6\,(\text{lum.})$
	Same-flavor	$64.3 \pm 2.1\,(\text{stat.}) \pm 4.6\,(\text{exp.}) \pm 4.3\,(\text{th.}) \pm 1.7\,(\text{lum.})$
1-jet category	Different-flavor	$59.1 \pm 2.8\,(\text{stat.}) \pm 6.0\,(\text{exp.}) \pm 6.2\,(\text{th.}) \pm 1.6\,(\text{lum.})$
	Same-flavor	$65.1 \pm 5.5\,(\text{stat.}) \pm 8.3\,(\text{exp.}) \pm 8.0\,(\text{th.}) \pm 1.7\,(\text{lum.})$

Combined by performing a profile likelihood fit

$$\sigma_{W^+W^-} = 60.1 \pm 0.9\,(\text{stat.}) \pm 3.2\,(\text{exp.}) \pm 3.1\,(\text{th.}) \pm 1.6\,(\text{lum.})\,\text{pb}.$$

- The result is below one standard deviation of the NNLO theoretical prediction of $59.8^{+1.3}_{-1.1}$ pb

Sources of uncertainties

Source	Uncertainty (%)
Statistical uncertainty	1.5
Luminosity	2.6
Lepton efficiency	3.8
Lepton momentum scale	0.5
E_T^{miss} resolution	0.7
Jet energy scale	1.7
$t\bar{t}$+tW normalization	2.2
W + jets normalization	1.3
$Z/\gamma^* \rightarrow \ell^+\ell^-$ normalization	0.6
$Z/\gamma^* \rightarrow \tau^+\tau^-$ 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 ~8%
- Systematics limited result
- Main uncertainties
  - 4.3% jet counting
  - 3.8% lepton efficiency
  - 2.6% luminosity

WW fiducial phase space

- Measure "fiducial" cross section to minimize the dependence on theoretical prediction, especially that related to the requirement on the **number of reconstructed and identified jets**
- Two WW fiducial phase spaces

① **No jets** with $|\eta| < 4.7$ and a given minimum jet p_T

② **No jets** with $|\eta| < 4.7$ and a given minimum jet p_T **and prompt leptons** with pT > 20 GeV and $|\eta| < 2.5$

- Prompt leptons before final state radiation
- Leptons from τ decay not considered

WW fiducial cross section

Measured in the eμ and 0-jet category

Results in fiducial phase space ①

p_T^{jet} threshold (GeV)	σ_{0jet} measured (pb)	σ_{0jet} predicted (pb)
20	$36.2 \pm 0.6\,(\text{stat.}) \pm 2.1\,(\text{exp.}) \pm 1.1\,(\text{th.}) \pm 0.9\,(\text{lum.})$	$36.7 \pm 0.1\,(\text{stat.})$
25	$40.8 \pm 0.7\,(\text{stat.}) \pm 2.3\,(\text{exp.}) \pm 1.3\,(\text{th.}) \pm 1.1\,(\text{lum.})$	$40.9 \pm 0.1\,(\text{stat.})$
30	$44.0 \pm 0.7\,(\text{stat.}) \pm 2.5\,(\text{exp.}) \pm 1.4\,(\text{th.}) \pm 1.1\,(\text{lum.})$	$43.9 \pm 0.1\,(\text{stat.})$

- For a jet p_T > 30 GeV: 1.6% (stat) 5.7% (exp) 3.2% (th)

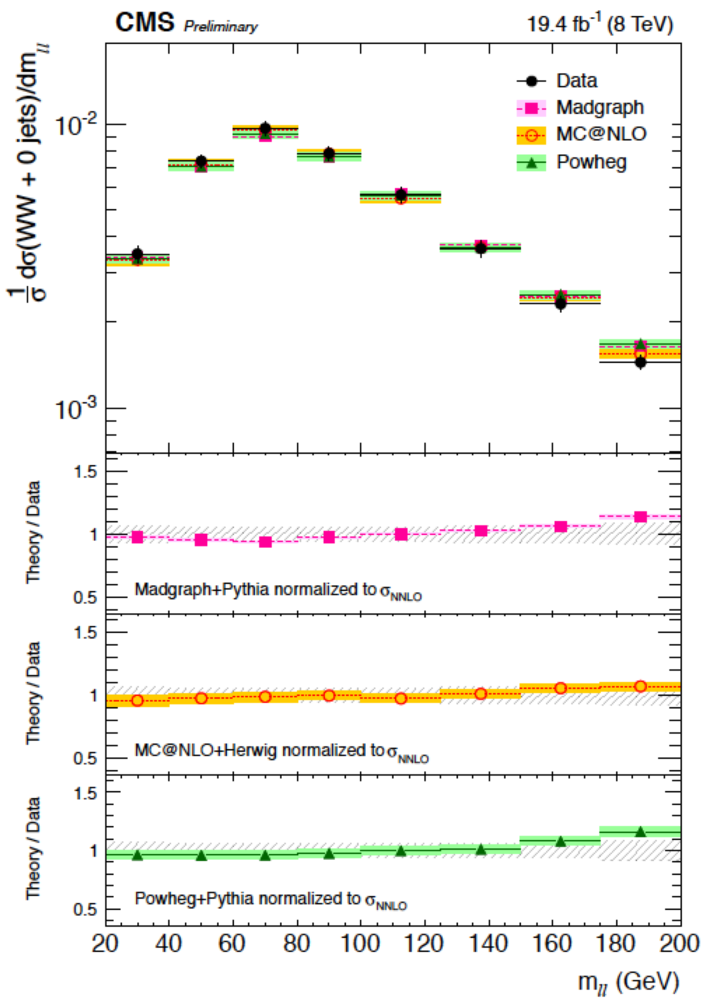
Results in fiducial phase space ②

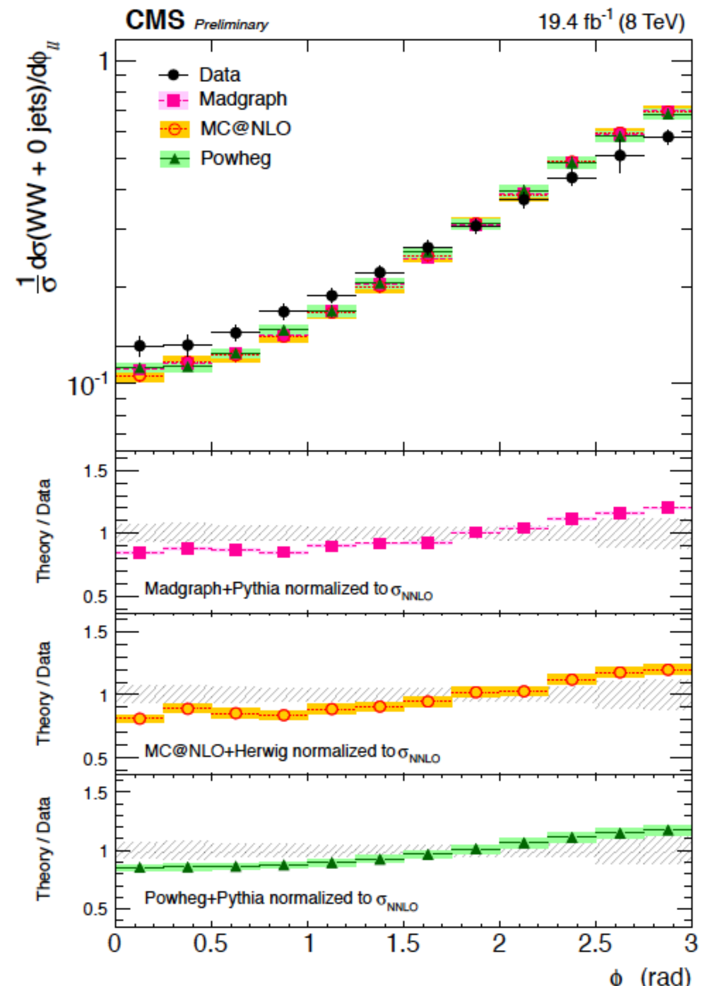
p_T^{jet} threshold (GeV)	$\sigma_{0jet,W\to\ell\nu}$ measured (pb)	$\sigma_{0jet,W\to\ell\nu}$ predicted (pb)
20	$0.223 \pm 0.004\,(\text{stat.}) \pm 0.013\,(\text{exp.}) \pm 0.007\,(\text{th.}) \pm 0.006\,(\text{lum.})$	$0.228 \pm 0.001\,(\text{stat.})$
25	$0.253 \pm 0.005\,(\text{stat.}) \pm 0.014\,(\text{exp.}) \pm 0.008\,(\text{th.}) \pm 0.007\,(\text{lum.})$	$0.254 \pm 0.001\,(\text{stat.})$
30	$0.273 \pm 0.005\,(\text{stat.}) \pm 0.015\,(\text{exp.}) \pm 0.009\,(\text{th.}) \pm 0.007\,(\text{lum.})$	$0.274 \pm 0.001\,(\text{stat.})$

- For a jet p_T > 30 GeV: 1.8% (stat) 5.6% (exp) 3.2% (th)

WW normalized differential cross section

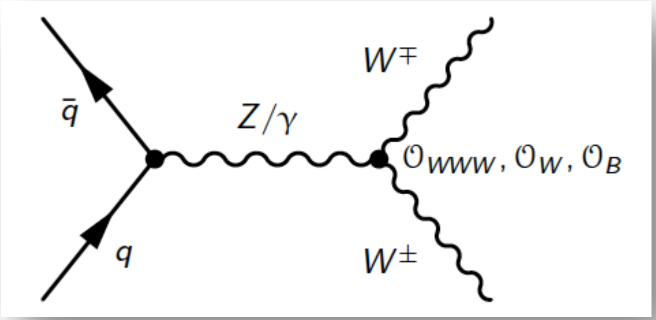
- Measured in the eμ and 0-jet category. **Fiducial phase space ②**
- Data-background unfolded (SVD method), **tested to be independent of the MC used (Powheg, Madgraph, MC@NLO)**

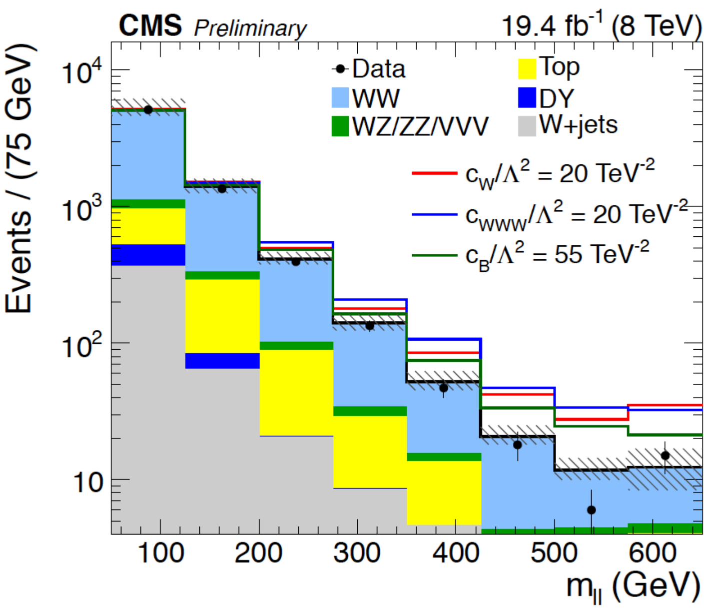




Anomalous triple gauge couplings

- Use only the 0-jet bin
- Look for TGC deviations from the SM
- If the scale of New Physics is large enough, it can be described by an **Effective Field Theory**
- Six different EWK **dimension-six operators generate aTGC and Higgs anomalous couplings**



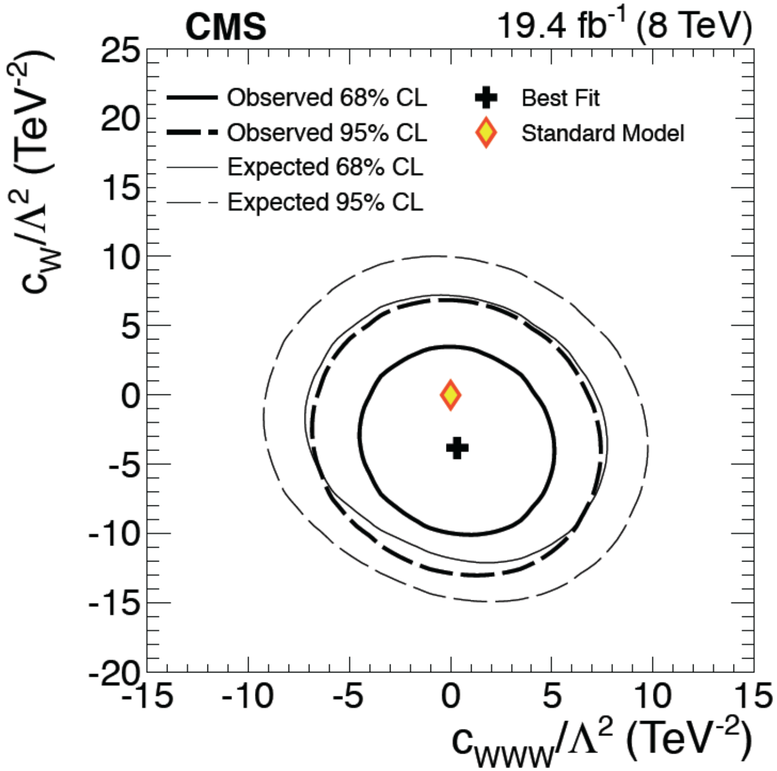


Anomalous triple gauge couplings

There are 3 **C- and P-conserving** dimension-six operators that generate aTGC

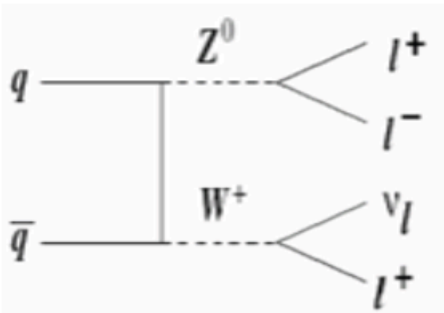
$$\mathcal{O}_{WWW} = \frac{c_{WWW}}{\Lambda^2}\mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}],$$
$$\mathcal{O}_{W} = \frac{c_{W}}{\Lambda^2}(D^{\mu}\Phi)^{\dagger}W_{\mu\nu}(D^{\nu}\Phi),$$
$$\mathcal{O}_{B} = \frac{c_{B}}{\Lambda^2}(D^{\mu}\Phi)^{\dagger}B_{\mu\nu}(D^{\nu}\Phi)$$

Performed 2D and 1D likelihood profiles

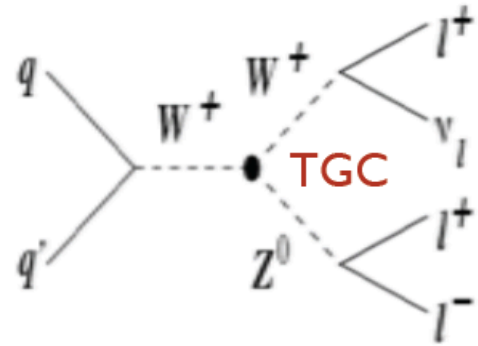


Coupling constant	This result (TeV^{-2})	This result 95% interval (TeV^{-2})	World average (TeV^{-2})
c_{WWW}/Λ^2	$0.1^{+3.2}_{-3.2}$	$[-5.7, 5.9]$	-5.5 ± 4.8 (from λ_γ)
c_{W}/Λ^2	$-3.6^{+5.0}_{-4.5}$	$[-11.4, 5.4]$	$-3.9^{+3.9}_{-4.8}$ (from g_1^Z)
c_{B}/Λ^2	$-3.2^{+15.0}_{-14.5}$	$[-29.2, 23.9]$	$-1.7^{+13.6}_{-13.9}$ (from κ_γ and g_1^Z)

WZ Production at the LHC

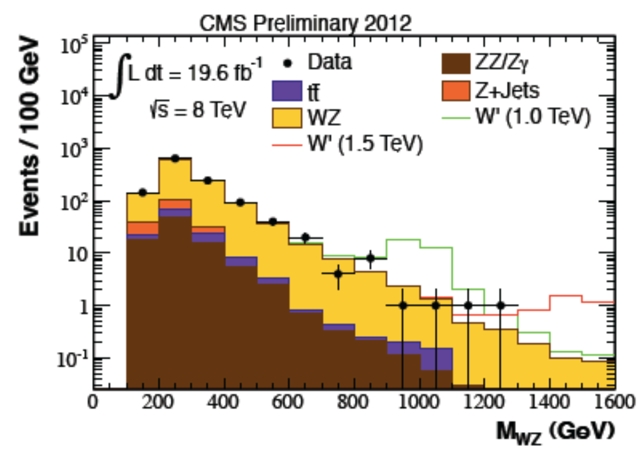


Processes for WZ Production at LO



- One of the diboson processes that has non-zero TGC contribution in SM
- The "ideal" diboson process:
  - Cross section relatively large
  - Small background
- Background to Higgs Physics and many searches: W', SUSY, Technicolor, …
- Sensitive to WWZ aTGCs

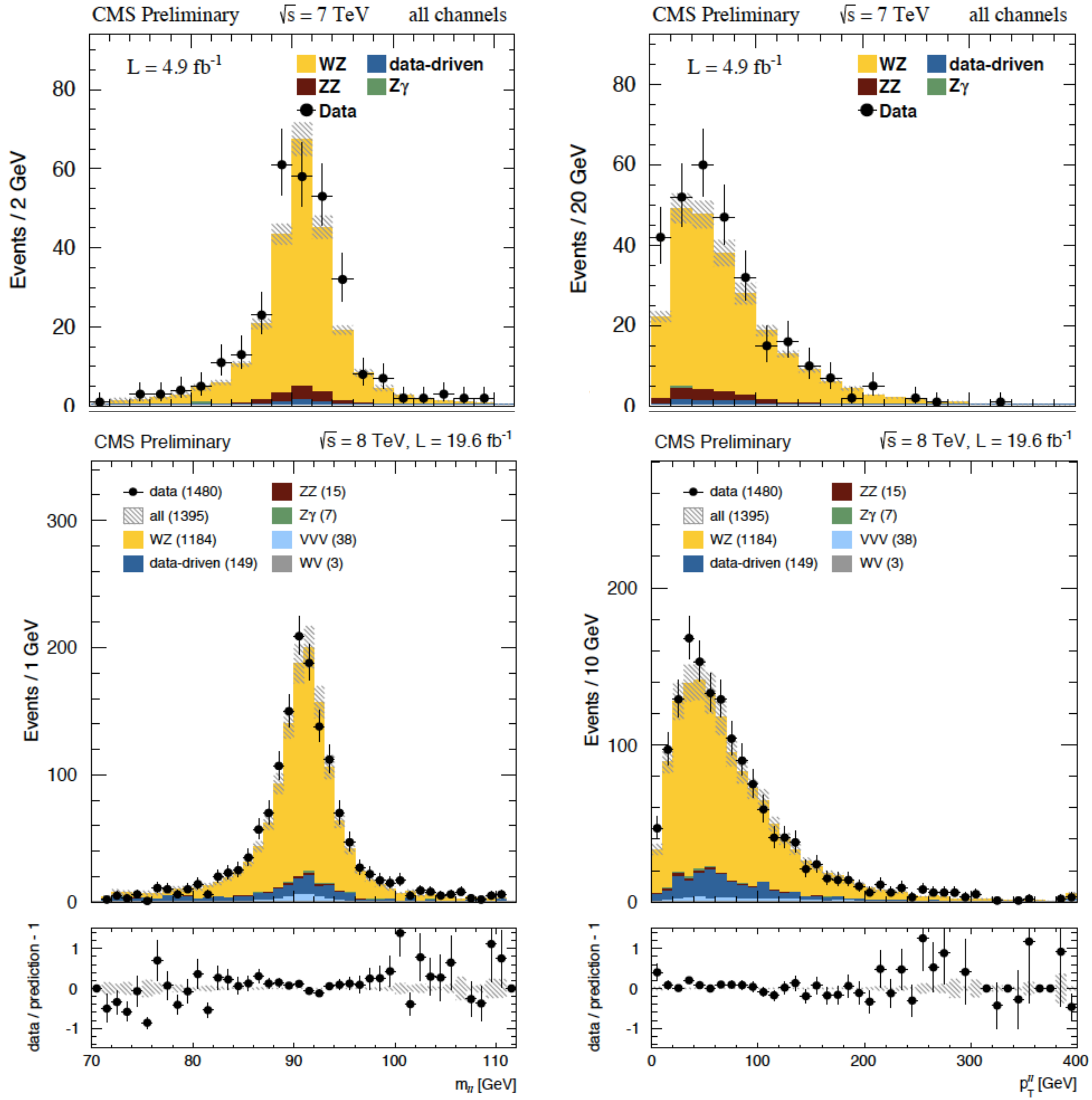
Search example:
W'→WZ Search
EXO-12-025



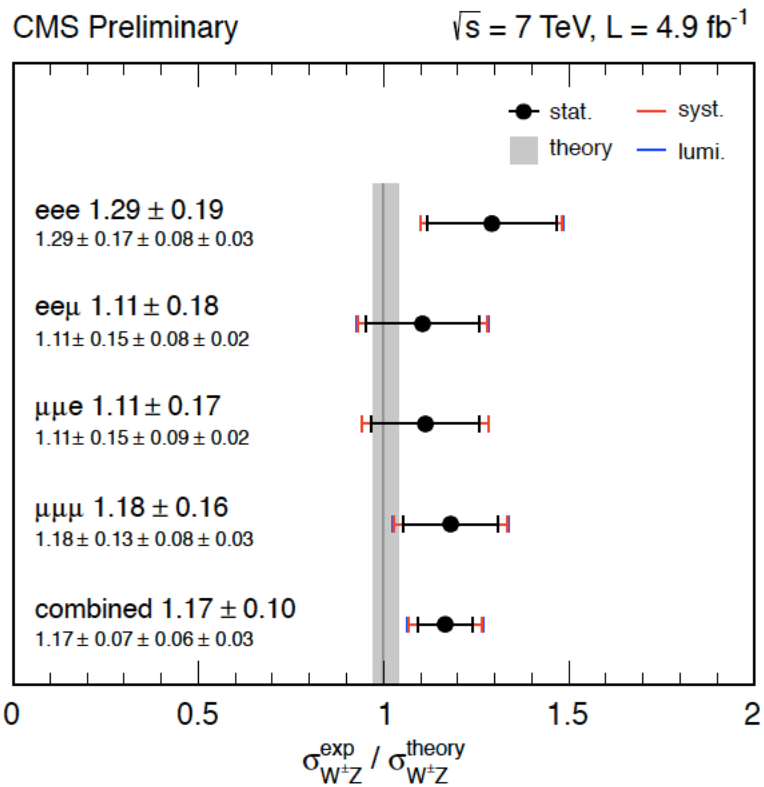
WZ event selection

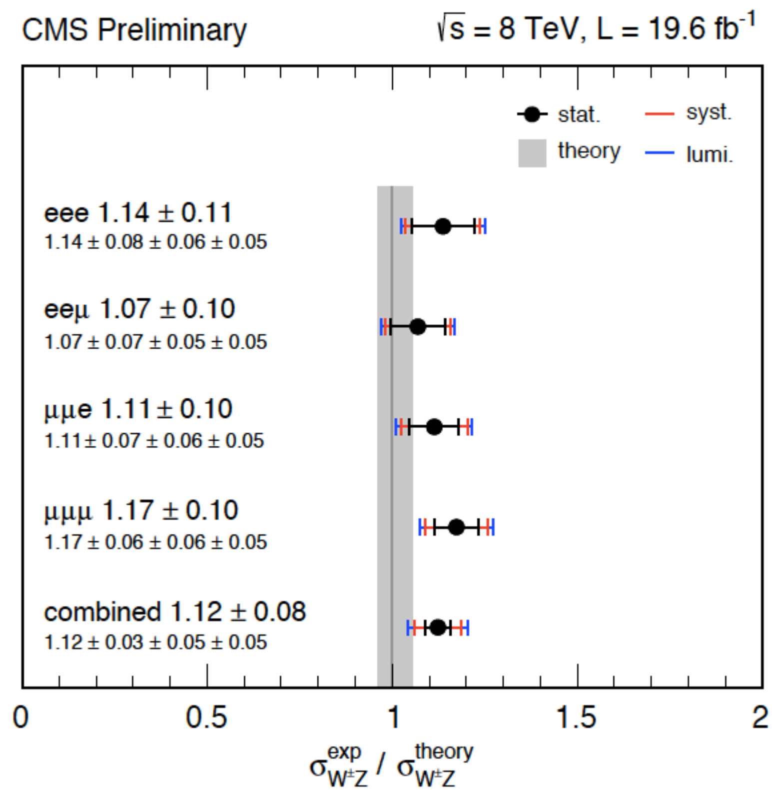
- Full 7 and 8 TeV luminosities
- Select **fully-leptonic (eee/eeμ/eμμ/μμμ)** final states
  - Z candidate = 2 opposite-charge same flavor leptons
  - W candidate = one lepton + MET > 30 GeV
- **Selection optimized to enhance S/B ratio**
  - ZZ is an irreducible background. Veto events with > 3 leptons
  - Instrumental backgrounds due to mis-identified particles or leptons not decaying from W/Z
    - Mainly Z+jets and top
    - Require tight lepton isolation, Z mass window and large MET
- **Analysis is signal dominated**

- Excellent S/B
- Good data description



WZ results





	$\sigma^{meas.}_{CMS}$ [pb]	$\sigma^{theo.}_{NLO}$ [pb] (MCFM, MSTW08 pdf sets)
7 TeV	$20.8 \pm 1.3(\text{stat.}) \pm 1.1(\text{syst.}) \pm 0.5(\text{lumi.})$	$17.8^{+0.7}_{-0.5}$
8 TeV	$24.7 \pm 0.8(\text{stat.}) \pm 1.1(\text{syst.}) \pm 1.1(\text{lumi.})$	$22.0^{+1.2}_{-0.8}$

- Statistical errors dominates 7 TeV measurement
- Main systematic uncertainty source coming from background estimation ($\simeq$ 6 %)
- Cross section measured slightly above the NLO predictions

Summary

- Inclusive WW production cross section measurement at 8 TeV **in agreement with the NNLO SM prediction**

- Inclusive WZ production cross section measurements at 7 and 8 TeV consistent with the NLO expectation

- **No evidence for anomalous WWZ and WWγ** triple gauge-boson couplings has been found

- Further information at **SMP-14-016** and **SMP-12-006** documents


BACKUP

WZ systematics

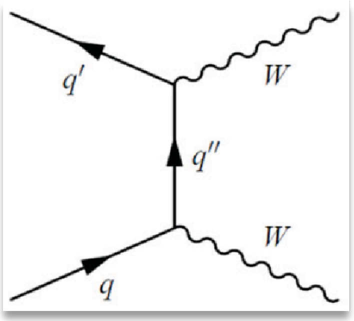
- Statistics dominated at both 7 and 8 TeV
- MET and data-driven backgrounds are the largest systematics

Table 1: Summary of systematic uncertainties, in units of percent, in the WZ cross section measurement at 7 TeV and 8 TeV.

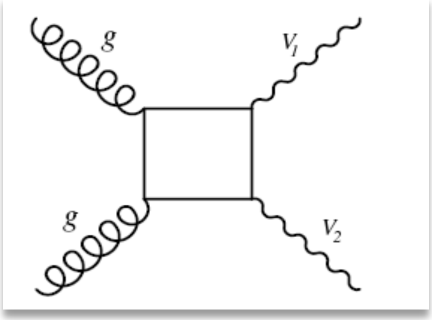
	7 TeV					8 TeV				
source	input	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$	input	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$
QCD scale	1.3	1.3	1.3	1.3	1.3	1.6	1.6	1.6	1.6	1.6
PDFs	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
lepton and trigger efficiency	–	2.9	2.7	2.0	1.4	1	1.8	1.8	1.8	1.8
$E_{\mathrm{T}}^{\mathrm{miss}}$	–	3.7	3.4	4.3	3.7	1.5 (μ), 2.5 (e), 5 (jets)	2.9	2.9	3.5	3.1
muon momentum scale	1	–	0.60	0.43	1.06	0.2	0.0	0.4	0.9	1.1
electron energy scale	2 (EB), 5 (EE)	1.9	0.75	1.2	–	$f(p_{\mathrm{T}},\eta)$	0.8	0.6	0.1	0.0
pile-up	5	0.27	0.50	1.00	0.64	–	0.8	1.1	0.6	0.9
ZZ cross section	14	0.50	0.92	0.62	0.85	15	0.2	0.2	0.2	0.2
Zγ cross section	7	0	0	0.04	0	15	0.2	0.0	0.2	0.0
data-driven	–	2.7	6.5	6.3	6.0	–	2.7	1.9	2.7	2.6
backgrounds	–	0.2	0.2	0.9	0.2	–	0.8	1.2	1.1	1.0
statistical	–	13.5	13.9	13.1	11.0	–	7.3	6.8	6.0	5.0
systematic	–	6.1	7.8	8.1	7.2	–	4.7	4.4	5.1	4.7
luminosity	2.2	2.2	2.2	2.2	2.2	4.4	4.4	4.4	4.4	4.4

WW signal samples

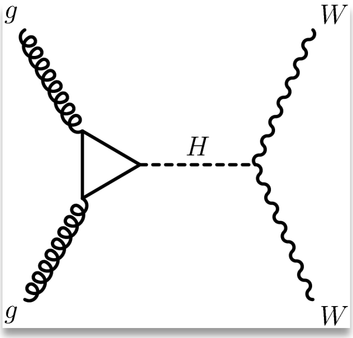
- The **qq → WW** is generated with **POWHEG**
  - For comparison also we used **MADGRAPH** and **MC@NLO**



- The **gg → WW** is generated using the **GG2VV.**



- The **gg → H → WW** is generated with **POWHEG**
  - Considered as <u>background</u> (only 3% of expected signal yields



- Set of **PDF**: CTEQ6L for LO generators and CT10 for NLO generators
- All generators interfaced with **PYTHIA**

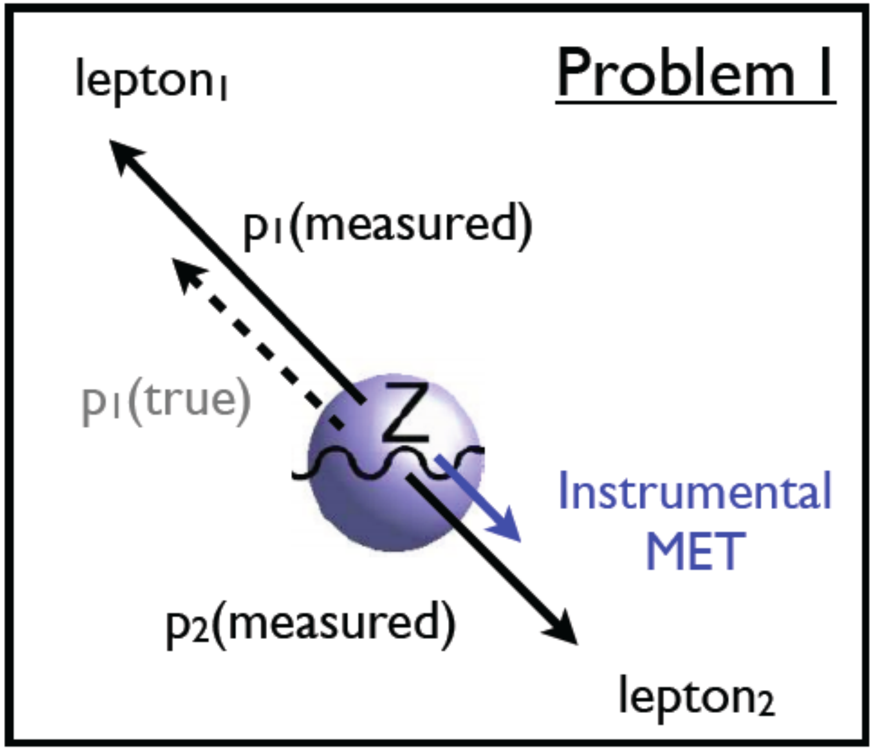
MET Definition for H → WW → lνlν Selection

- If the momentum of a lepton from Z decay is mis-measured
  - Invariant mass is also mis-measured
    - Event passes Z veto
  - Instrumental MET is generated
    - Event passes MET selection
- To reduce instrumental MET
  - Define a "Projected MET"
    - The MET component perpendicular to the lepton with the smallest ΔΦ(MET, l)
  - Projected MET also reduces background from DY→ττ

Projected MET Definition

$$\Delta\phi_{min} = min(\Delta\phi(\ell_1, E_{\mathrm{T}}^{\mathrm{miss}}), \Delta\phi(\ell_2, E_{\mathrm{T}}^{\mathrm{miss}}))$$

$$= \begin{cases} E_{\mathrm{T}}^{\mathrm{miss}} & \text{if } \Delta\phi_{min} > \frac{\pi}{2}, \\ E_{\mathrm{T}}^{\mathrm{miss}} \sin(\Delta\phi_{min}) & \text{if } \Delta\phi_{min} < \frac{\pi}{2} \end{cases}$$

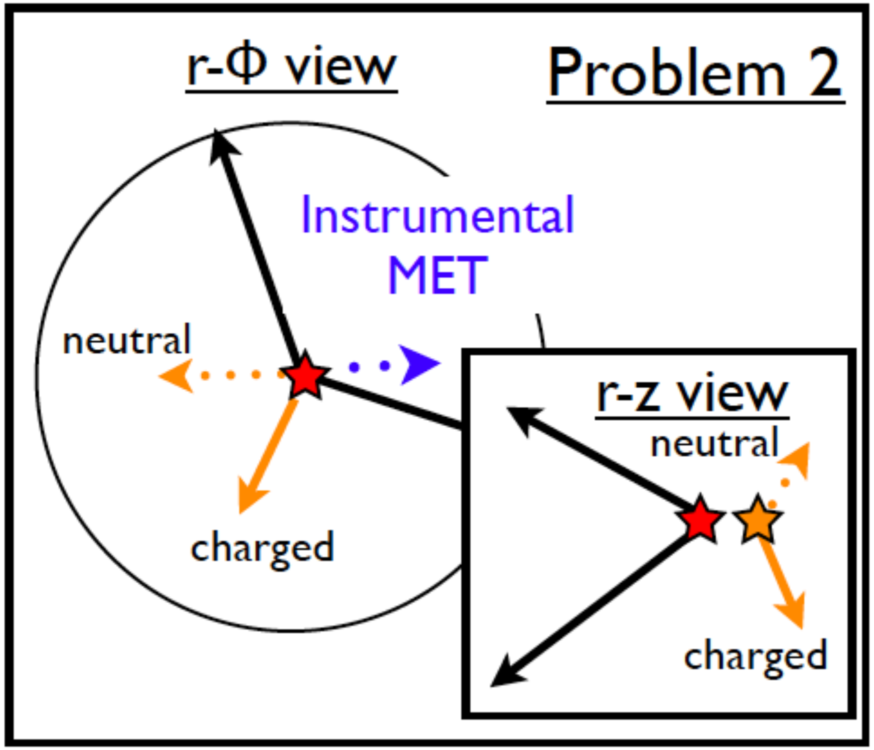


MET Definition for H → WW → lνlν Selection

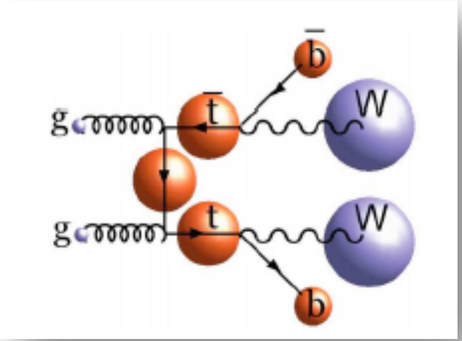
- Multiple proton-proton interactions per bunch crossing can produce instrumental MET
- Select events by taking the minimum of two different estimators of MET
  - Projected MET
  - Projected Track MET
- Track MET definition
  - Negative vector sum of tracks
    - $|Z_{track} - Z_{PV}| < 0.1$ cm
- The two estimators are more correlated for real MET than instrumental MET

Min MET Definition

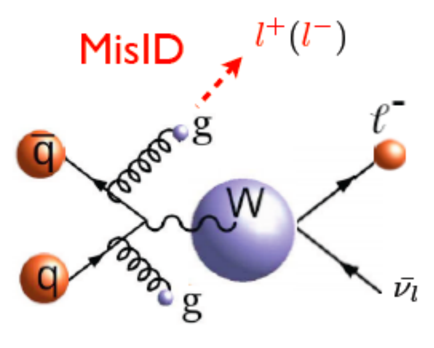
$$\mathrm{MinMET} = min(\mathrm{pMET}, \mathrm{pTrackMet})$$



Data-driven backgrounds

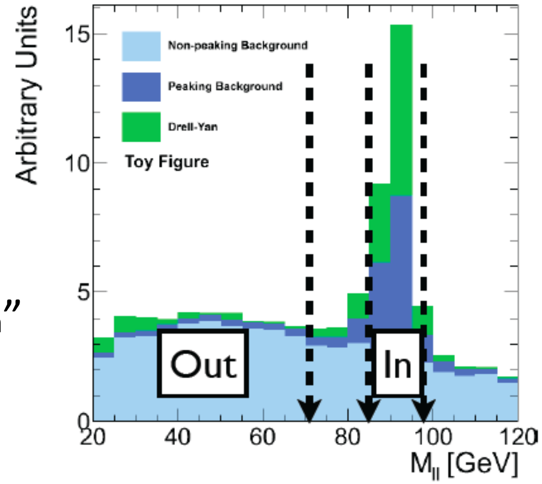


- **Top background (ttbar and tW) (syst. 2.2%)**
  - Jet veto efficiency applied to MC events to obtain normalization determined from a data control sample with inverted top veto.



- **W+jets background (syst. 1.3%)**
  - normalization and shape estimated from dilepton control region enriched in misidentified leptons.
  - Matrix method, using a (η, pT)-dependent fake rate measured with a QCD control sample.

- **Z+jets background (syst. 1%):**
  - Extrapolate to get the residual yield in the signal region using the expected ratio "$R_{out/in}$" w.r.t the Z mass window



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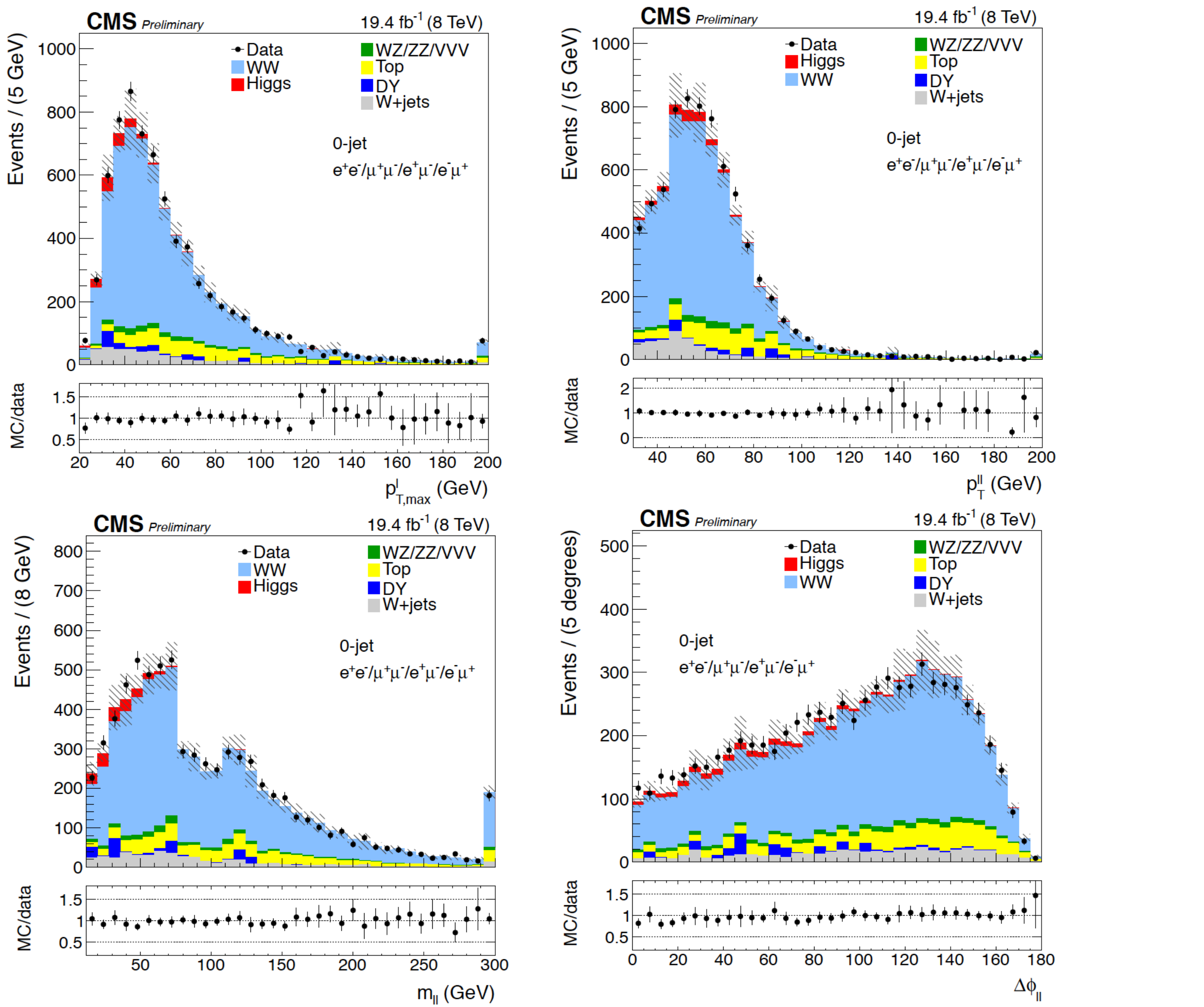
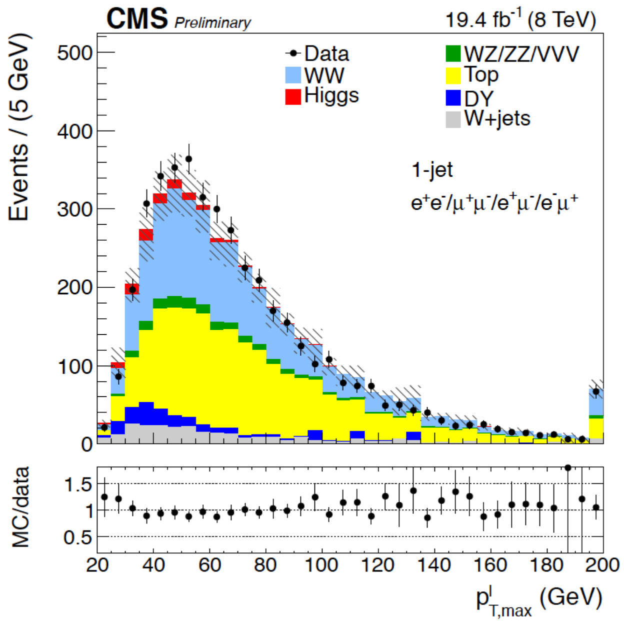
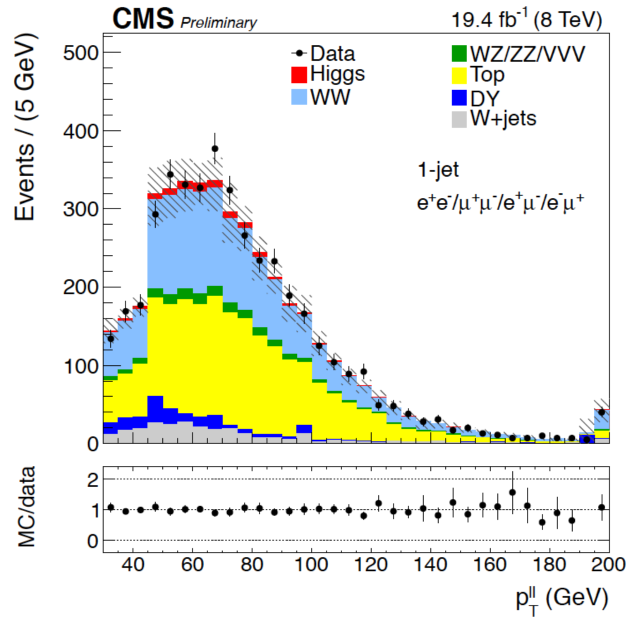
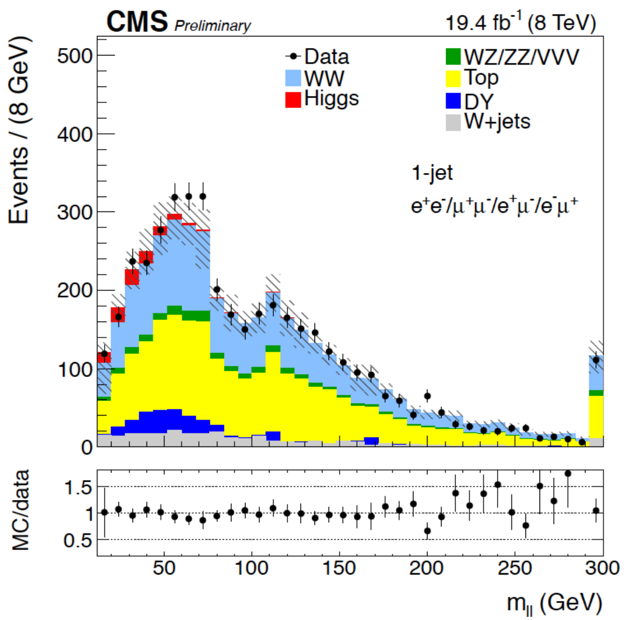
Results: 0-jets bin

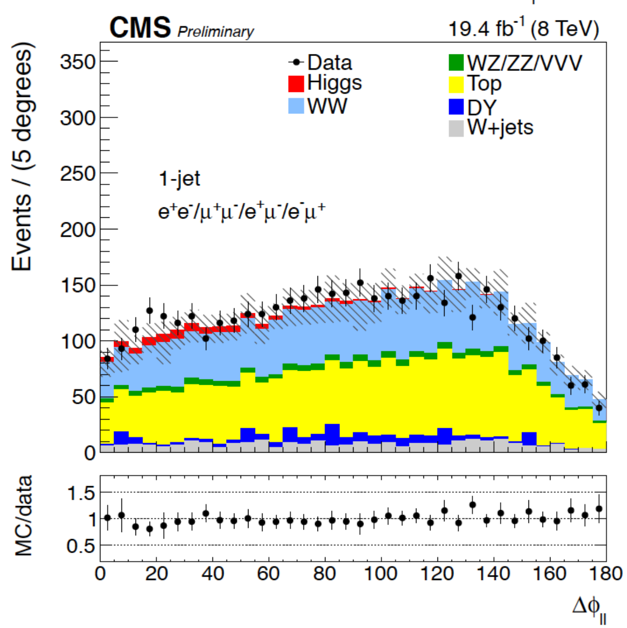


Results: 1-jets bin





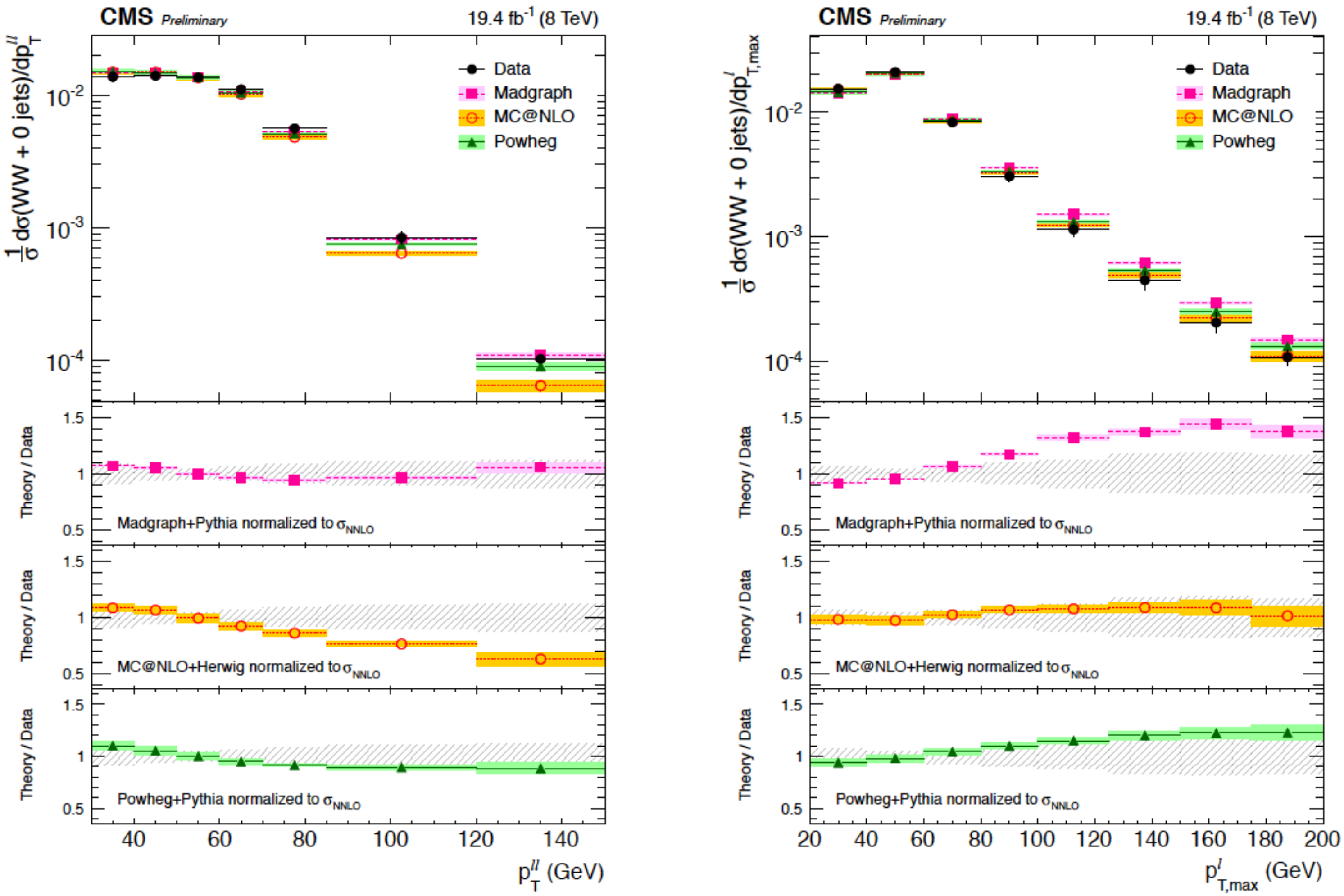




WW event yields

Process	0-jet category		1-jet category	
	Different-flavor	Same-flavor	Different-flavor	Same-flavor
$qq \to W^+W^-$	3516 ± 271	1390 ± 109	1113 ± 137	386 ± 49
$gg \to W^+W^-$	162 ± 50	91 ± 28	62 ± 19	27 ± 9
W^+W^-	3678 ± 276	1481 ± 113	1174 ± 139	413 ± 50
$ZZ + WZ$	84 ± 10	89 ± 11	86 ± 4	42 ± 2
VVV	33 ± 17	17 ± 9	28 ± 14	14 ± 7
Top-quark	522 ± 83	248 ± 26	1398 ± 156	562 ± 128
$Z/\gamma^* \to \ell^+\ell^-$	38 ± 4	141 ± 63	136 ± 14	65 ± 33
$W\gamma^*$	54 ± 22	12 ± 5	18 ± 8	3 ± 2
$W\gamma$	54 ± 20	20 ± 8	36 ± 14	9 ± 6
$W + \text{jets}(e)$	189 ± 68	46 ± 17	114 ± 41	16 ± 6
$W + \text{jets}(\mu)$	81 ± 40	19 ± 9	63 ± 30	17 ± 8
Higgs	125 ± 25	53 ± 11	75 ± 22	22 ± 7
Total bkg.	1179 ± 123	643 ± 73	1954 ± 168	749 ± 133
W^+W^- + Total bkg.	4857 ± 302	2124 ± 134	3128 ± 217	1162 ± 142
Data	4847	2233	3114	1198

WW normalized differential cross section



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WW particle level definition (1/2)

- Fiducial and differential WW cross sections at **Particle Level** only (not at Parton Level)
- **Particle Level definition:**
  - stable particles from full ME+parton shower generators. **WW results just before Final State Radiation (FSR).**
  - without any simulation of the interaction of these particles with the detector components or any additional proton-proton interactions.
- **Definition of jets** at particle level:
  - define with anti-k_t algorithm, with R= 0.5, built from stable truth particles: electrons, muons, taus and neutrinos are removed from the collection of gen-particles.

WW particle level definition (2/2)

- **Definition of leptons** at particle level:
  - No isolation condition is imposed
  - Leptons just after W decay before FSR (BORN leptons)
  - Parent of the lepton require to be a W boson
  - Taus considered as background: electrons and muons from tau decays are not considered as part of the signal

- **Further cuts in the event:**
  - Defined with hard jet veto in particle levels: **No jets** with $|\eta| <$ 4.7 and a given maximum jet p_T (nominal value in the analysis is jet $p_T > 30$ GeV)
  - Selected **only eμ events** with leptons=electron/muon are defined as before, and fulfilling:
    - pT > 20 GeV and $|\eta| < 2.5$