Hot topic: Measurement of W^+W^- production cross section in CMS at 8 TeV

Alicia Calderón
Instituto de Física de Cantabria, CSIC-UC
On behalf of the CMS collaboration

SM@LHC: Standard Model at LHC
April 23, 2015

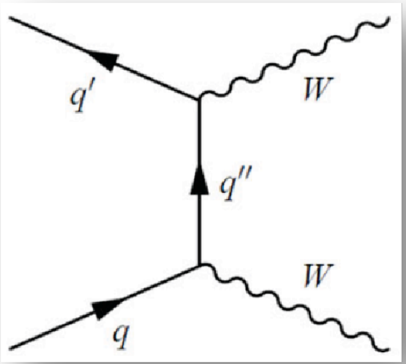
Outline

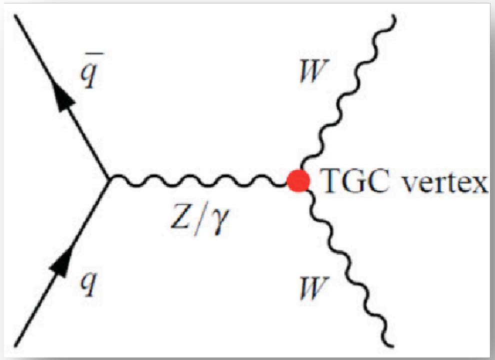
- WW production at LHC
- Analysis WW event selection
- WW production cross section measurement
- Sources of systematic uncertainties
- WW fiducial and normalized differential cross section measurements
- Search for Anomalous Trilinear Gauge Couplings (ATGCs)
- Summary

W$^+$W$^-$ production

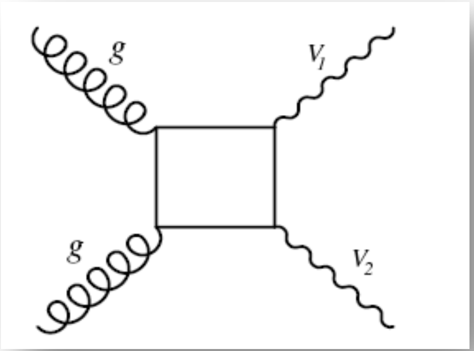
- **qq→WW LO diagrams:**

t-channel **s-channel**





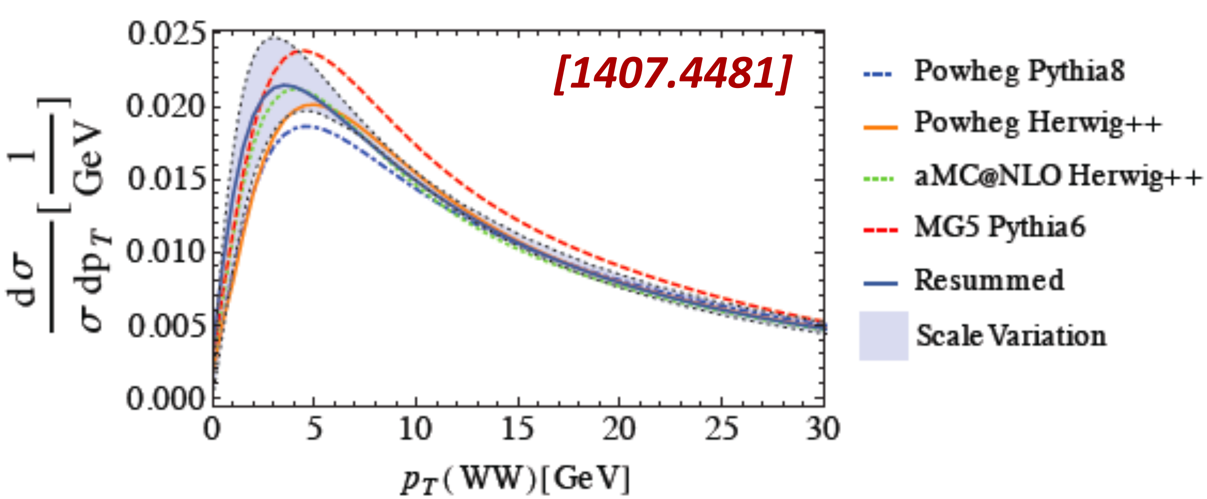
- **gg→WW NLO diagram (~3 % contribution)**



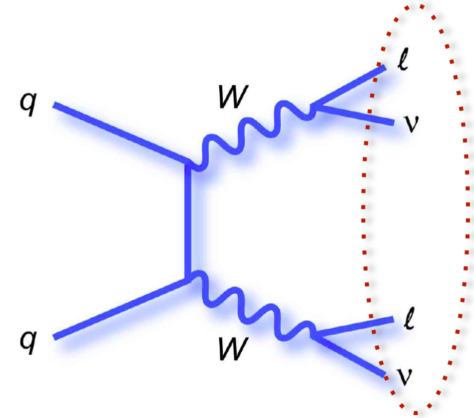
- **Cross section available at NNLO QCD *[1408.5243]***
  - **~ 7% higher wrt NLO**
  - The **gg → H → WW is considered as background** (only 3% of expected signal yields)
- W$^+$W$^-$ production cross section larger than W$^\pm$Z and ZZ production.
- Crucial to check the gauge structure of the Standard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

Higher order corrections

- Lots of theoretical interest in previous discrepancy, particularly w.r.t. 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.
  - Improve modelling of gluon resummation, by reweight $p_T(WW)$ of the qq → WW MC to a NLO+NNLL p_T resummation calculation → **correlated with jet veto**
    - ~ 3.5% effect on the 0-jet cross section.
  - the resummation scale also provides a convenient handle to determine the acceptance uncertainty



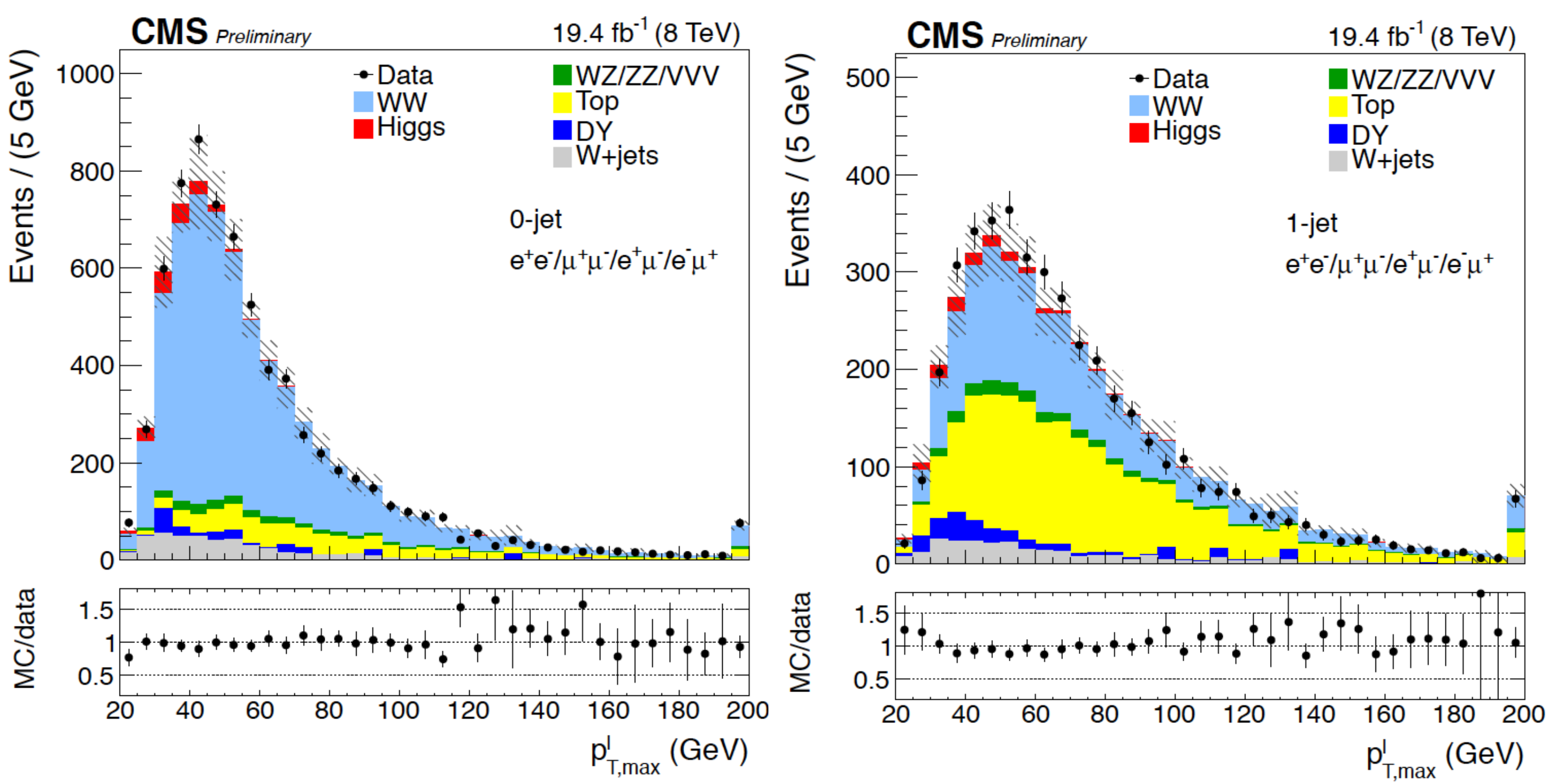
Event selection



- 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)**
  - Events outside Z mass window
  - min(proj. MET, proj. Track MET) > 20 GeV
  - Dedicated MVA to further reduce off-peak contribution — **Z→ll + jets (fake MET)**
  - 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 backg.**

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 p_T > 30 GeV and $|\eta| < 4.7$



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
- 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
$Z/\gamma^* \to \ell^+\ell^-$ normalization	0.6
$Z/\gamma^* \to \tau^+\tau^-$ normalization	0.2
$W\gamma$ normalization	0.3
$W\gamma^*$ normalization	0.4
VV normalization	3.0
$H \to$ WW normalization	0.8
Jet counting theory model	4.3
PDFs	1.2
MC statistics	0.9
Total uncertainty	7.9

- **Total uncertainty ~ 8%**
- **Systematic limited** result dominated by:
  - the jet counting ~ 4.3%
  - Lepton efficiencies ~ 3.8%
  - Background normalization from data
  - Luminosity ~ 2.6%

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 space requirements:

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

② **No jets** with $|\eta| < 4.7$ and a given maximum 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

- The 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 ± 0.6 (stat.) ± 2.1 (exp.) ± 1.1 (th.) ± 0.9 (lum.)	36.7 ± 0.1 (stat.)
25	40.8 ± 0.7 (stat.) ± 2.3 (exp.) ± 1.3 (th.) ± 1.1 (lum.)	40.9 ± 0.1 (stat.)
30	44.0 ± 0.7 (stat.) ± 2.5 (exp.) ± 1.4 (th.) ± 1.1 (lum.)	43.9 ± 0.1 (stat.)

  - For a jet p_T > 30 GeV: 1.6% (stat) 5.7% (exp.) 3.2% (th.) 2.6%(lumi.)

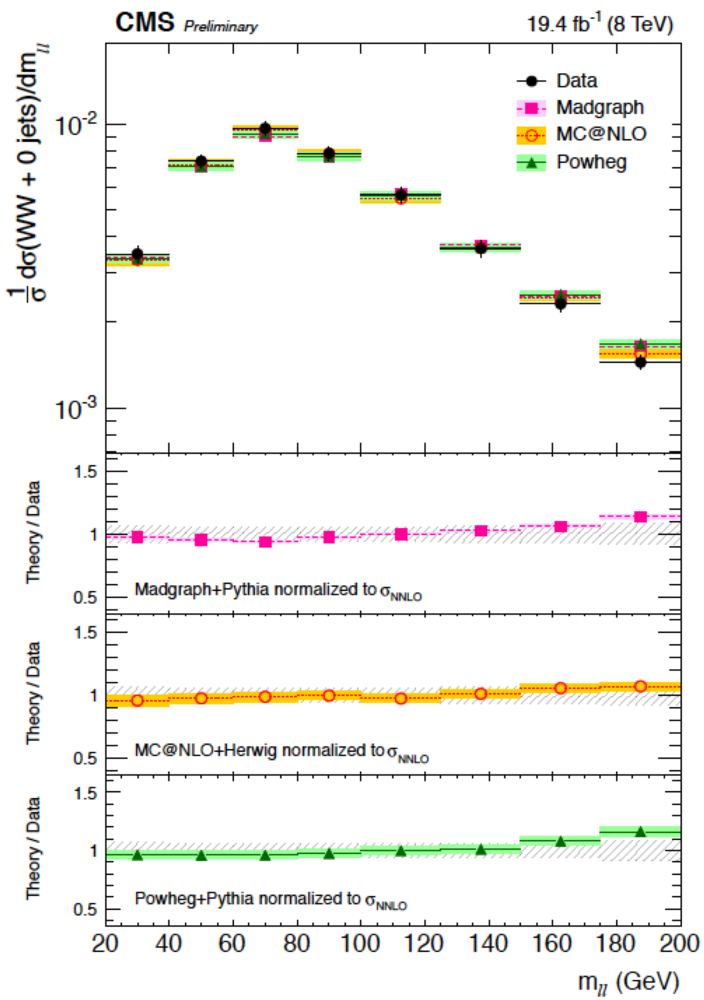
- **Results in fiducial phase space ②**

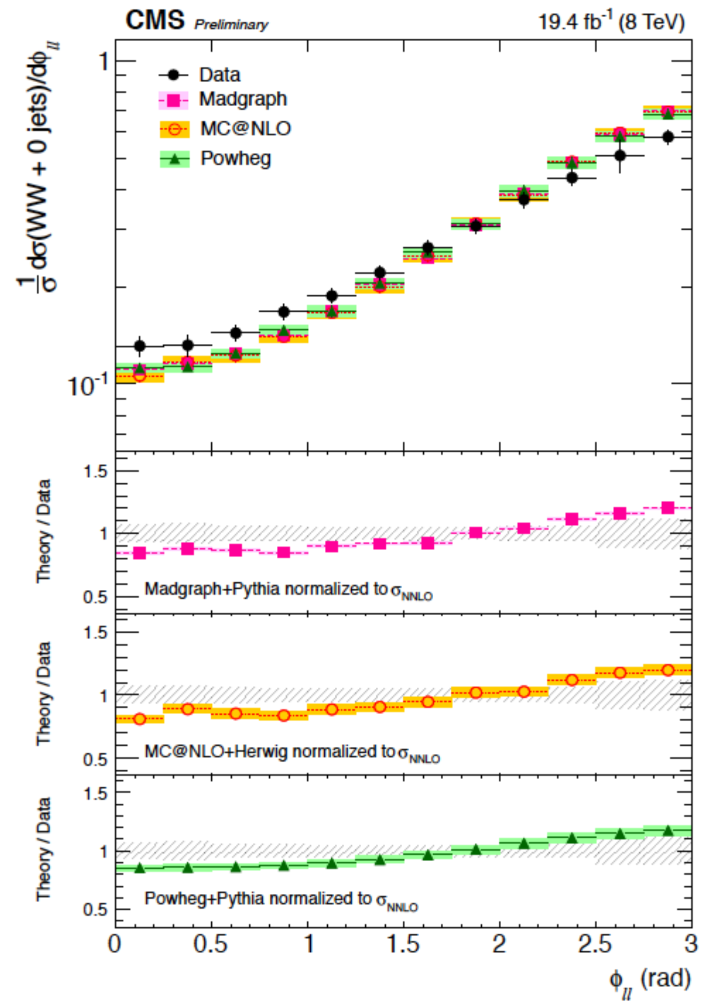
p_T^{jet} threshold (GeV)	$\sigma_{0jet,W\to\ell\nu}$ measured (pb)	$\sigma_{0jet,W\to\ell\nu}$ predicted (pb)
20	0.223 ± 0.004 (stat.) ± 0.013 (exp.) ± 0.007 (th.) ± 0.006 (lum.)	0.228 ± 0.001 (stat.)
25	0.253 ± 0.005 (stat.) ± 0.014 (exp.) ± 0.008 (th.) ± 0.007 (lum.)	0.254 ± 0.001 (stat.)
30	0.273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

  - For a jet p_T > 30 GeV: 1.8% (stat) 5.6% (exp.) 3.2% (th.) 2.6%(lumi.)

WW normalized differential cross section

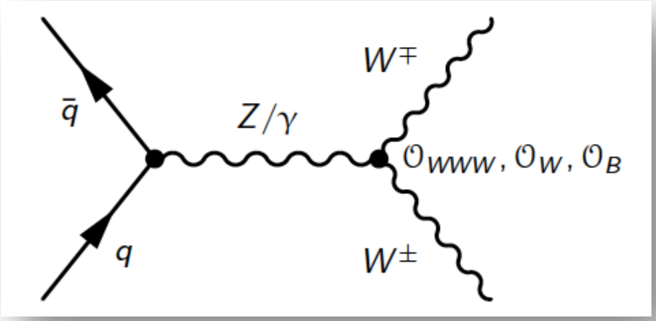
- Measured in the eμ and 0-jet category. **Fiducial phase space ②**
- Data-background unfolded (SVD method), **tested to be independent of the MC used (Powheg, Madgraph, MC@NLO)**

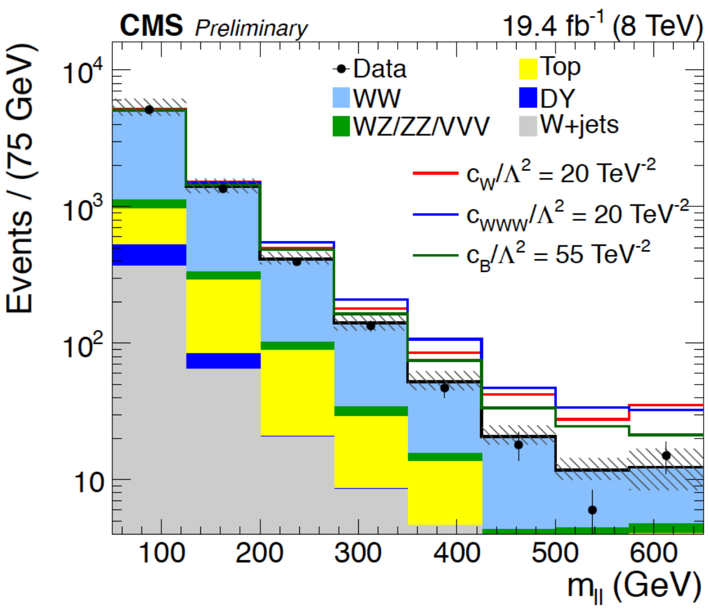




Anomalous triple gauge couplings

- Look for deviations in triple-gauge-boson couplings from SM: use only the 0-jet bin
- A model-independent way of describing high-energy new physics
  - If the scale of New Physics is large, it can be described by an **Effective Field Theory (EFT)**
  - Six different EWK **dimension-six operators generate ATGC and Higgs anomalous couplings, at three level**
- Use m_{ll} distribution.
  - Signal includes qqWW, ggWW and ggH



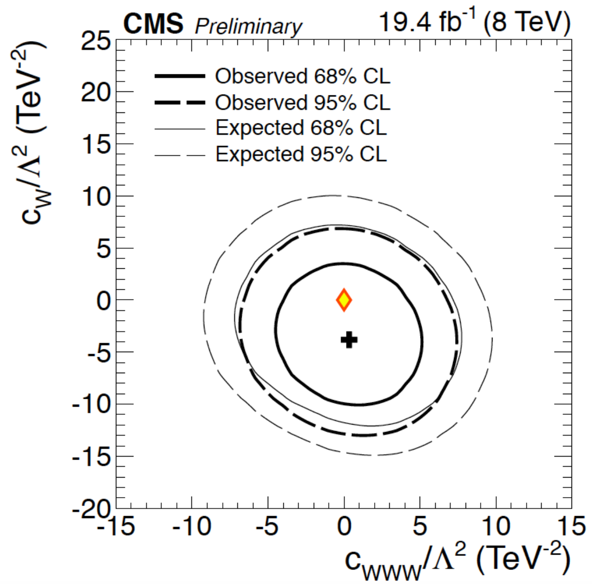


Anomalous triple gauge couplings

- Consider models with with **C- and P-conserving** operators

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

- **Poisson ΔNLL scans** over each parameter space, profiling over systematic uncertainty nuisance parameters.



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)

Summary

- Inclusive W^+W^- production cross section measurement at 8 TeV and luminosity 19.4 fb-1 is now **in agreement with the NNLO SM prediction** of $59.8^{+1.3}_{-1.1}$ pb

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

- We have achieved overall **better understanding of the jet-veto efficiency** + better estimation of associated theoretical uncertainties.

- We also have measured W^+W^- **cross section in a fiducial phase** space reducing theory uncertainties and **normalized differential cross section** as function of lepton kinematics.

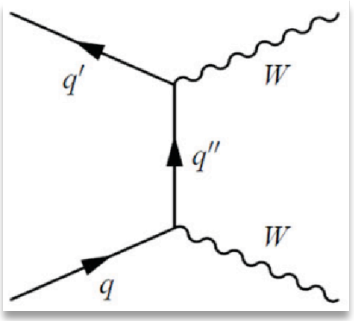
- **No evidence for anomalous WWZ and WWγ** triple gauge-boson couplings is found

- Further information under: **CMS PAS SMP-14-016**

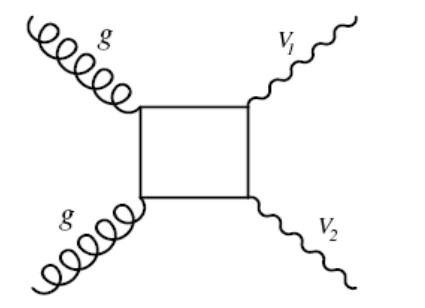

BACKUP

Signal samples

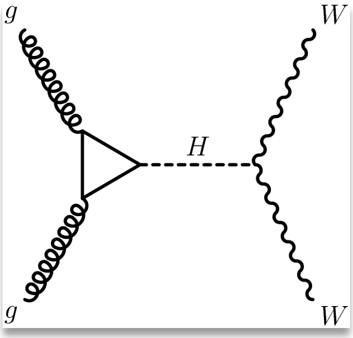
- The **qq → WW** is generated with **POWHEG**
  - For comparison also we used **MADGRAPH** and **MC@NLO**



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



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



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

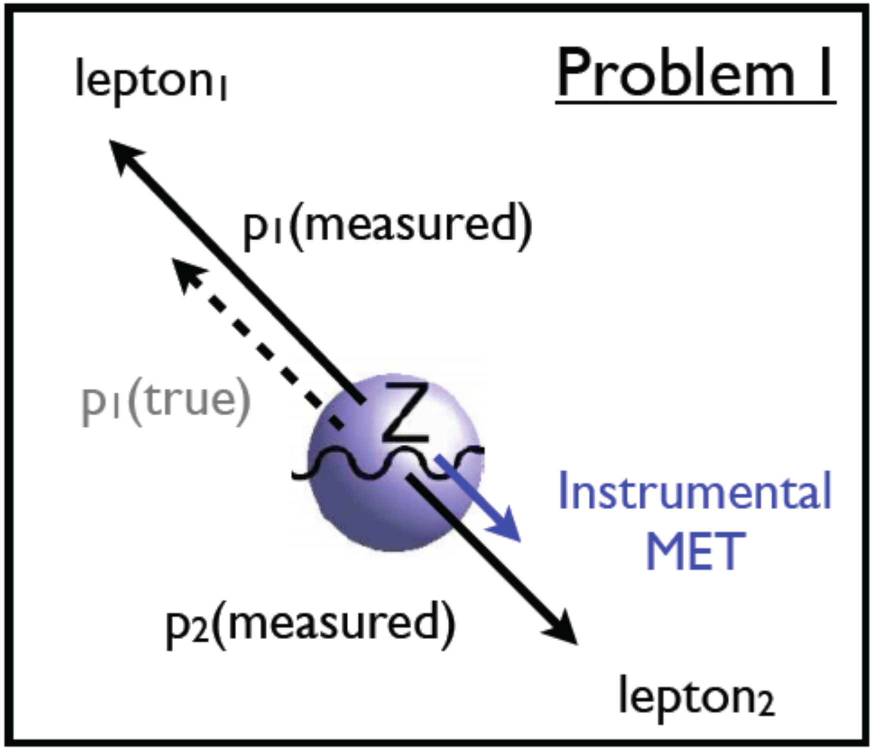
MET Definition for H → WW → lνlν Selection

- 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

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

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

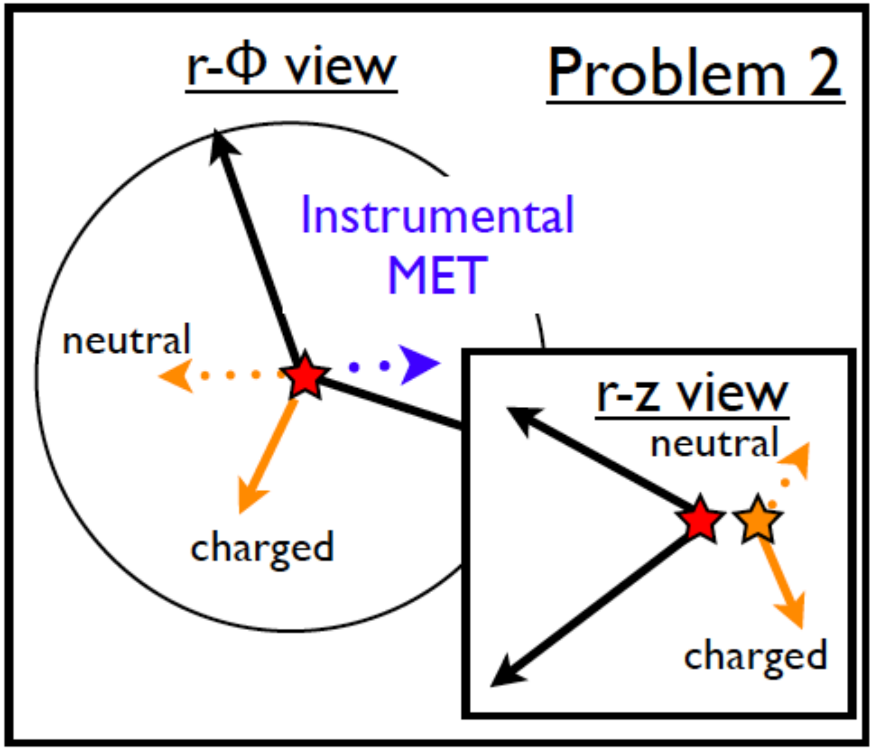


MET Definition for H → WW → lνlν Selection

- 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

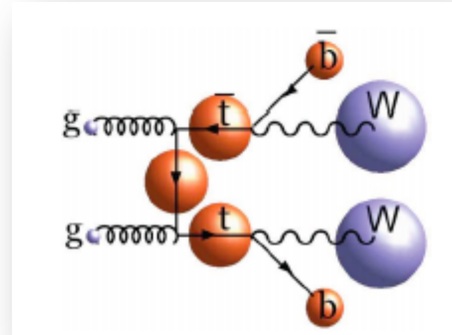
Min MET Definition

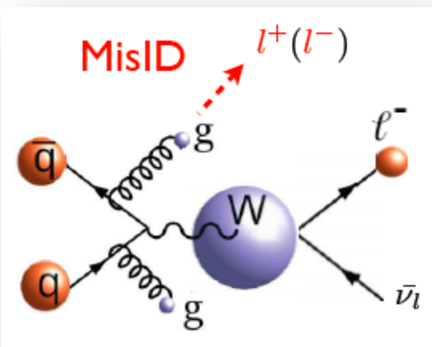
$$\mathrm{MinMET} = min(\mathrm{pMET}, \mathrm{pTrackMet})$$



Data-driven backgrounds

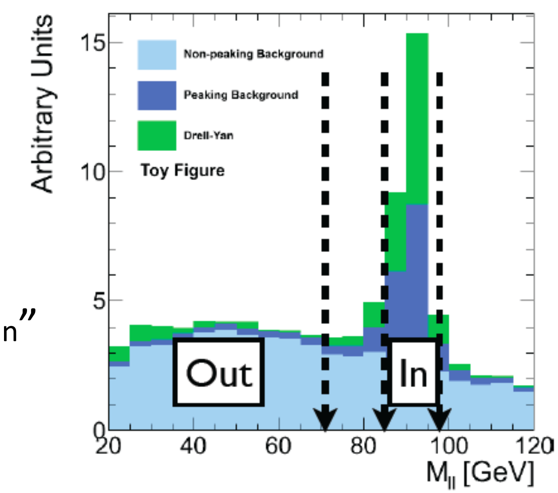
- **Top background (ttbar and tW) (syst. 2.2%)**
  - Jet veto efficiency applied to MC events to obtain normalization determined from a data control sample with inverted top veto.



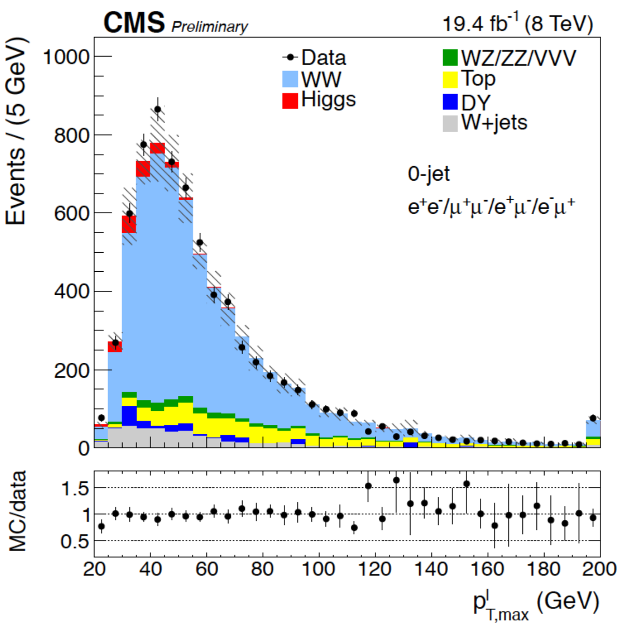


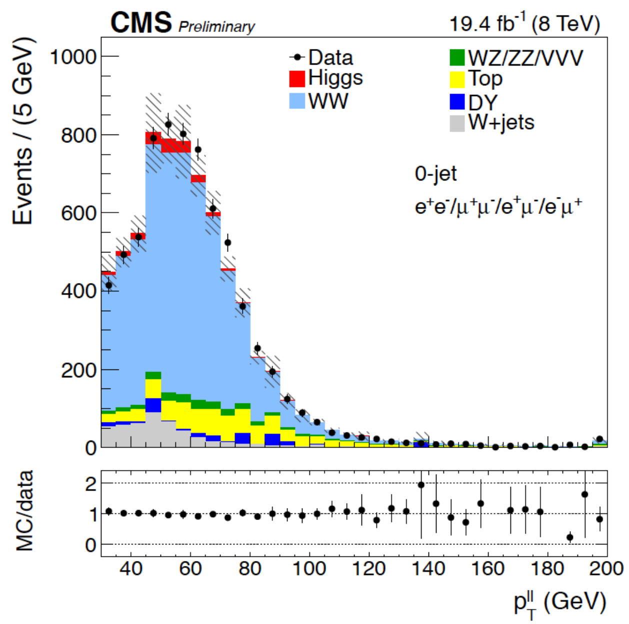
- **W+jets background (syst. 1.3%)**
  - normalization and shape estimated from dilepton control region enriched in misidentified leptons.
  - Matrix method, using a (η, pT)-dependent fake rate measured with a QCD control sample.

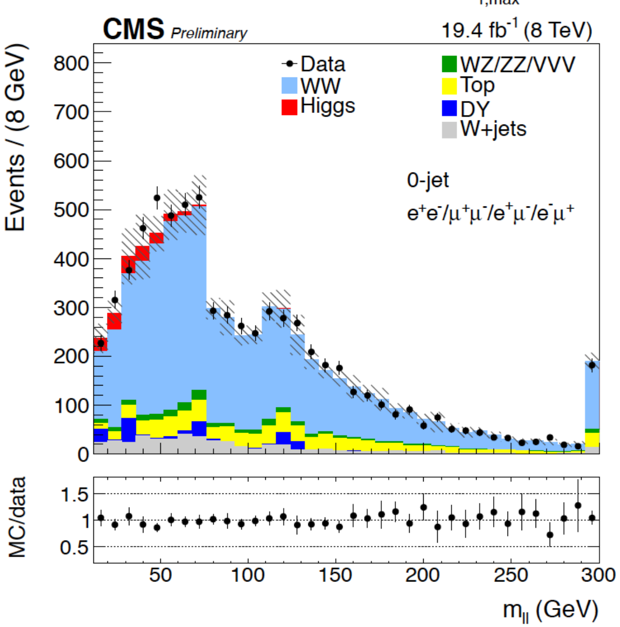
- **Z+jets background (syst. 1%):**
  - Extrapolate to get the residual yield in the signal region using the expected ratio "$R_{out/in}$" w.r.t the Z mass window

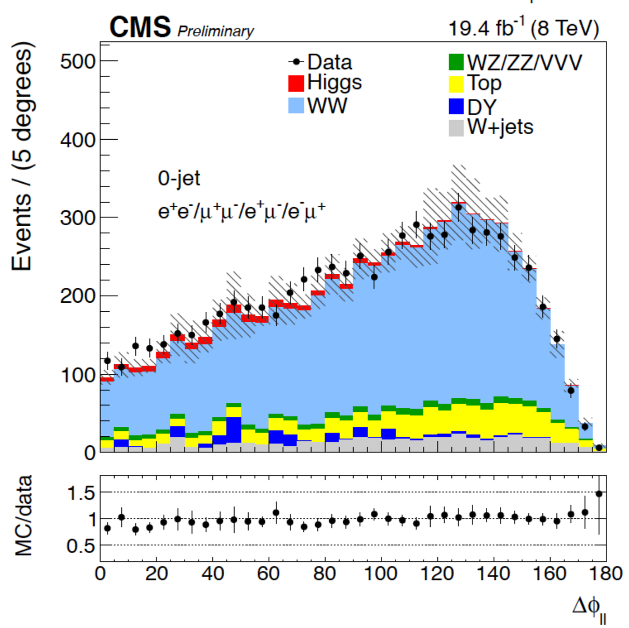


Results: 0-jets bin

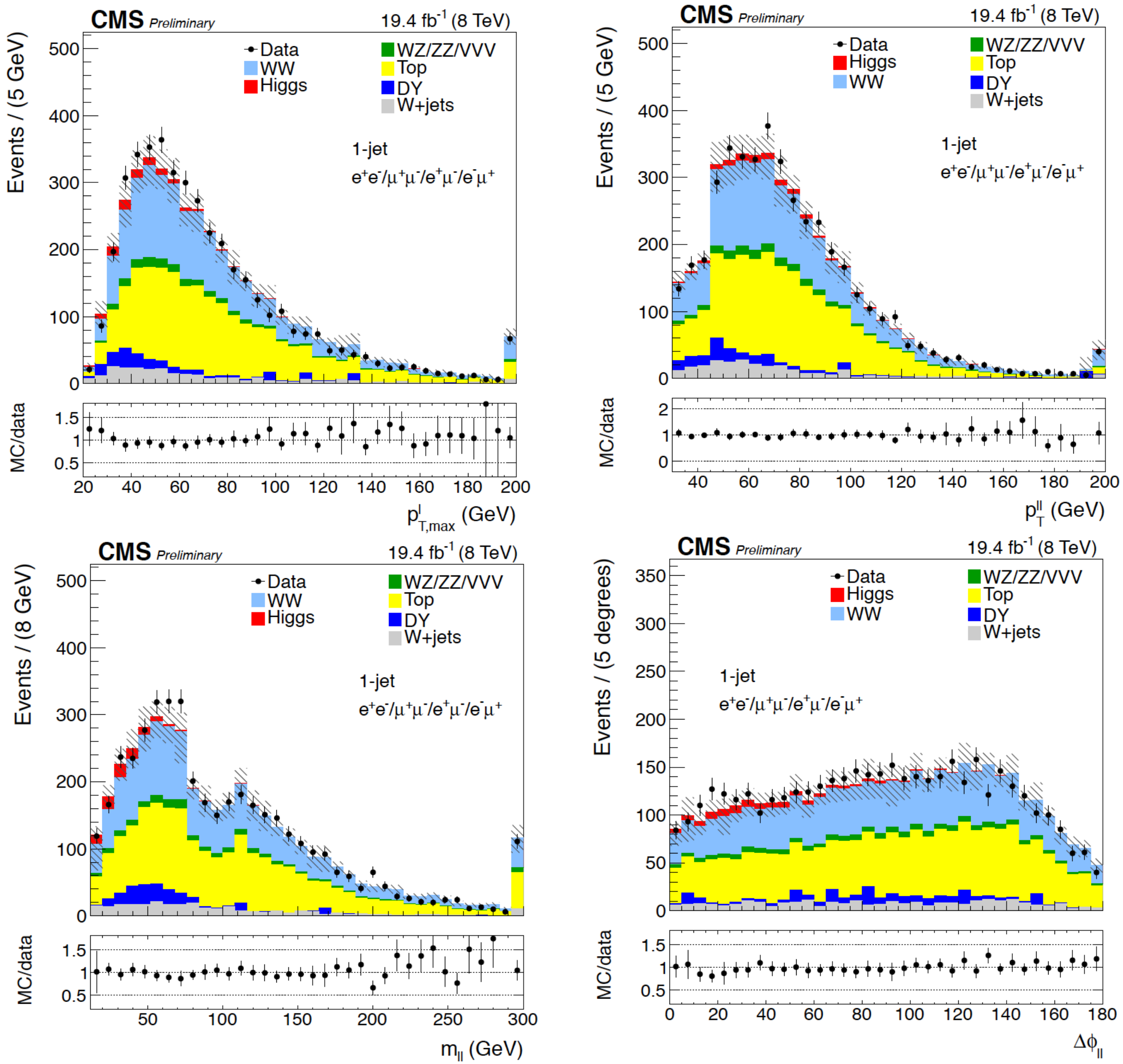








Results: 1-jets bin



Event yields

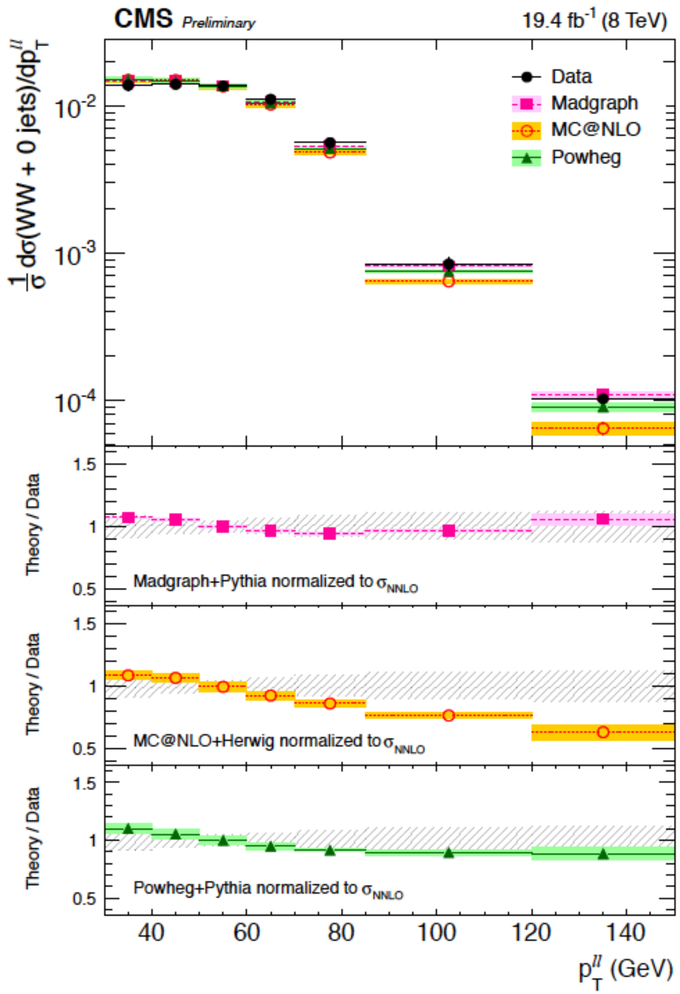
Process	0-jet category Different-flavor	0-jet category Same-flavor	1-jet category Different-flavor	1-jet category Same-flavor
$qq \to W^+W^-$	3516 ± 271	1390 ± 109	1113 ± 137	386 ± 49
$gg \to W^+W^-$	162 ± 50	91 ± 28	62 ± 19	27 ± 9
W^+W^-	3678 ± 276	1481 ± 113	1174 ± 139	413 ± 50
$ZZ + WZ$	84 ± 10	89 ± 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

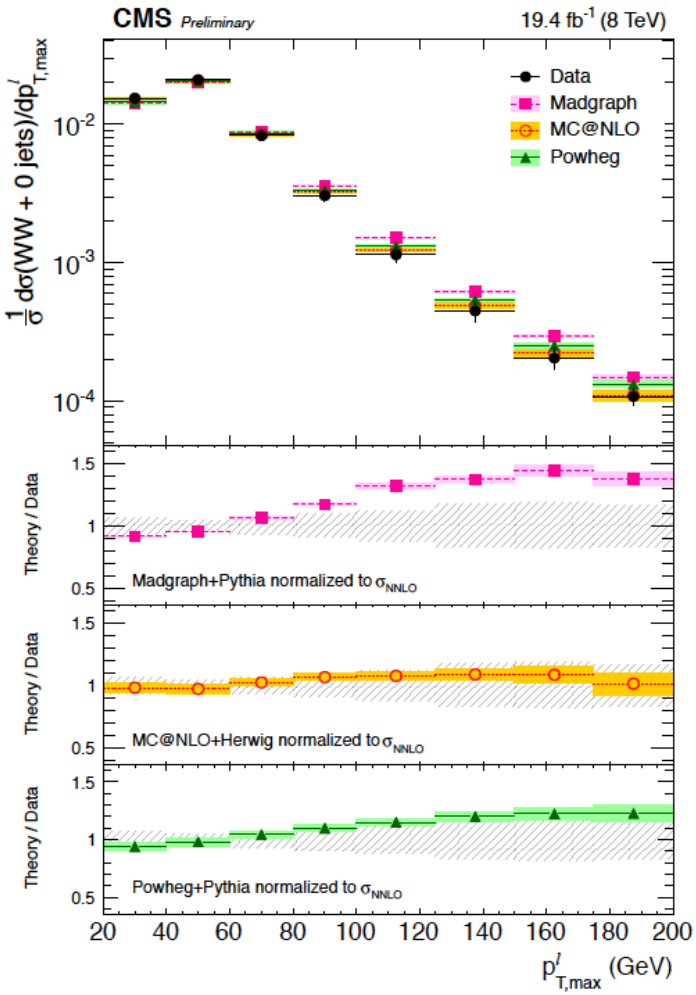
Systematics

- **PDF + α_s**: PDF4LHC prescription, ~ 1.3%(0.8%) for qqWW (ggWW)
- **Higher order corrections *[1407.4481]***
  - reweight Powheg by varying resummation scale at NLO+NNLL by half and twice the nominal value: 2.8%(6.9%) for 0-jet (1-jet)
  - renormalization by half and twice the nominal: 2.5%(6.3%) for 0-jet (1-jet)

  → Same order systematic on the final signal efficiency obtained from Stewart-Tackmann recipe [1107.2117]
- **UE+PS:**
  - three different showering tunes of the UE (CMS tune Z2*, ATLAS tune AUET2, new Tune 64 Z2*-Lep CMS) and two different PS (pythia and herwig). 3.5%

WW normalized differential cross section





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 <u>before</u> 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 $|\eta| < 2.5$