Measurement of the WW cross-section in the 2l2ν final state

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On behalf of the CMS Collaboration
IV Jornadas CPAN
Granada, 26-28 November 2012

- Introduction
- Selection
- Efficiency Measurements
- Background Estimation
- Systematics
- Results
- Conclusions

Introduction: Theory – WW Production

- Test of the Standard Model at the highest energies ever

$\sqrt{s}$ (TeV)	$\sigma_{\rm LO}$ WW (pb)	$\sigma_{\rm NLO}$ WW (pb)
7	29.51	47.04 pb $\binom{+4.3\%}{-3.2\%}$
8	35.56	57.25 pb $\binom{+4.1\%}{-2.8\%}$
10	48.07	78.80 pb $\binom{+3.6\%}{-2.5\%}$
14	74.48	124.31 pb $\binom{+2.8\%}{-2.0\%}$

[*]

- Measurement of the self-interaction boson coupling (TGC) could be a candle of new physics

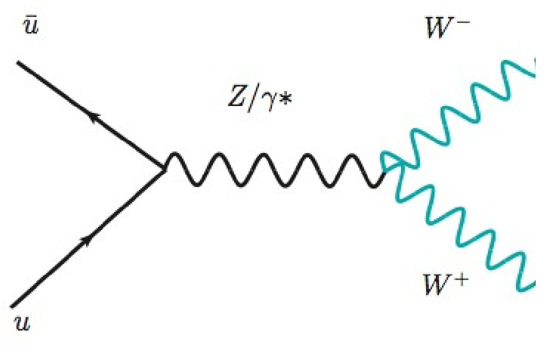
$$\mathcal{L}_{WWV} = ig_{WWV}\ g_1^V(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + k_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2}W^{+\nu}_\mu W^{-\rho}_\nu V^\mu_\rho)$$

- This process is a background for several analysis
    - Precision measurements in the SM (top, Electroweak)
    - Higgs (H → WW), SUSY and other New Physics searches

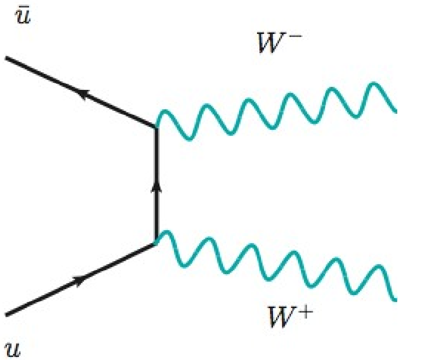
[*] J. M. Campbell, R. K. Ellis and C.Williams,``Vector boson pair production at the LHC,'' JHEP 1107, 018 (2011)

Introduction: Theory – WW Production

- WW Process: production modes
  - Quark – antiquark annihilation: $q\overline{q} \rightarrow WW$ (97 %)



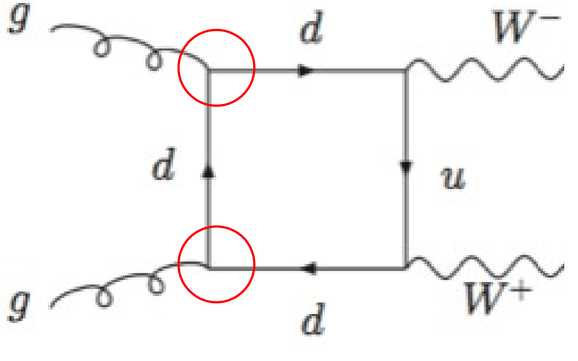
s – channel

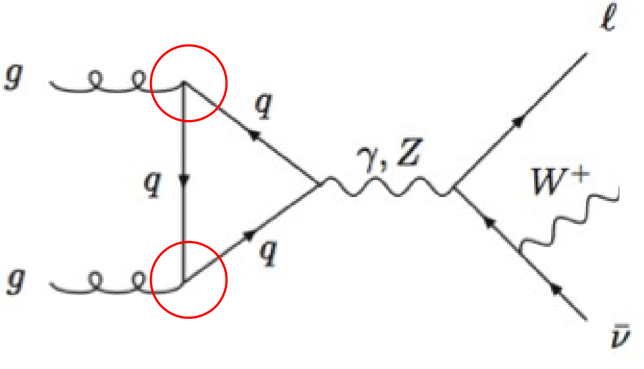


t – channel

  - Gluon – gluon fusion: $gg \rightarrow WW$ (3 %)

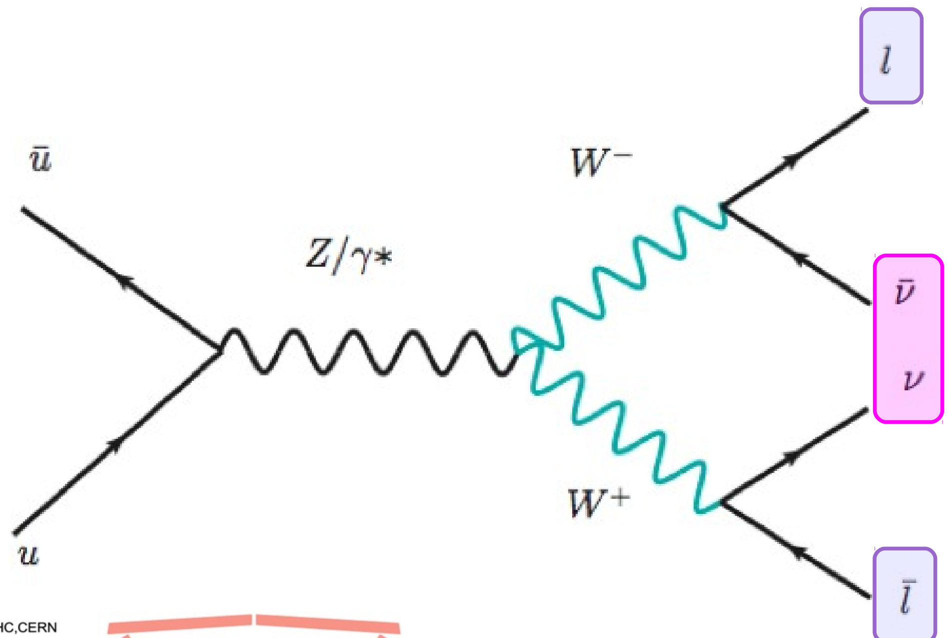
Suppressed by two powers of α_S





Introduction: Signal

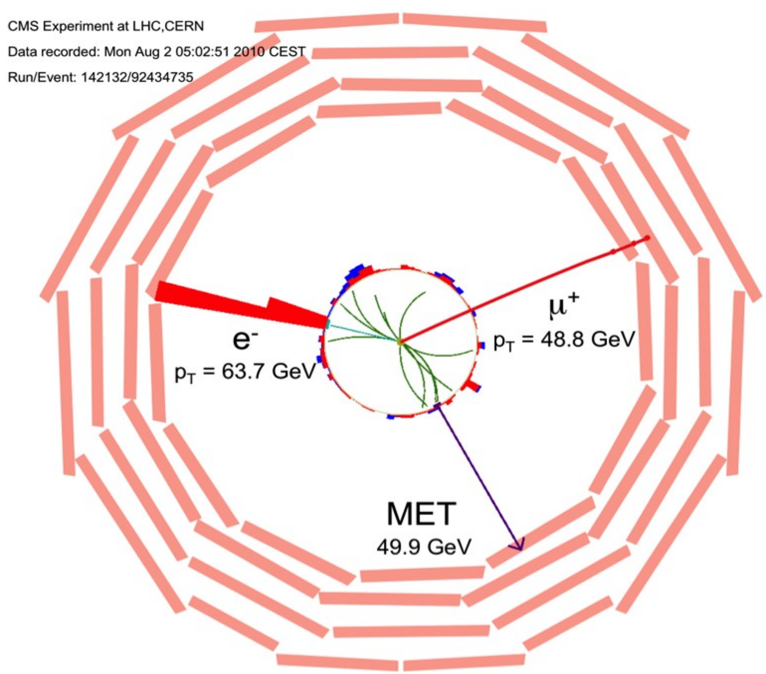
- Experimental Signature for WW → *ll*νν. BR (W → *l*ν) = 0.1080



2 hight pT leptons with opposite sign

Large missing transverse energy MET because of undetected neutrinos

No hard jet activity



- Major backgrounds:
  - Drell-Yan, ttbar, tW, W+jets, W+γ*
  - Estimated from control regions on Data
- Others (WZ/ZZ, Wγ) from MC

Selection

- Inclusive cross section estimated as:

$$\sigma_{WW} = \frac{N_{Data} - N_{bkg}}{\mathcal{L}_{int} \cdot \epsilon \cdot (3 \cdot BR(W \to \ell\bar{\nu}))^2}$$

N_{data}: Data yield
N_{bkg}: Expected Background
L_{int}: Integrated luminosity
ε: signal efficiency
BR: $W \to l\nu$ branching ratio

- We need to extract the number of signal events, $N_{signal} = N_{data} - N_{bkg}$
- Try to be as pure as possible, maximal background rejection
- Optimized **selection** to increase signal significance
- Four leptonic final states (channels) studied

total	=	μμ	+	μe	+	eμ	+	ee

Selection

Only 2 high p_T (20 GeV) isolated leptons with opposite sign — Reduce diboson WZ and ZZ and W+jets and QCD

Reject events consistent with Z boson mass for SF channels — Reduce Drell–Yan and peaking WZ / ZZ

Require high missing transverse energy, MET — Reduce Drell–Yan

Veto events with high p_T jets (30 GeV)
Veto events with soft muon or low p_T jets b-tagged — Reduce top quark backgrounds: ttbar and single top, tW

Kinematical cuts i.e. on $p_T(ll)$ — Reduce remaining Drell-Yan and W+jets

SF : Same flavour final state (mm, ee)
OF: Opposite flavour final state (me, em)

Signal Efficiency

$$\sigma_{\mathrm{WW}} = \frac{\mathrm{N_{Data}} - \mathrm{N_{bkg}}}{\mathcal{L}_{\mathrm{int}} \cdot \epsilon \cdot (3 \cdot \mathrm{BR}(\mathrm{W} \to \ell\bar{\nu}))^2}$$

- We need to measure correctly the efficiency for signal selection
  - Estimated from Monte Carlo simulation
  - Correct lepton efficiencies on MC with data measurements with scale factors (identification) or weights (trigger) – Tag & Probe with Z boson
  - Estimate also the scale factor the central jet veto (CJV) efficiency

$$\epsilon = A \cdot \epsilon_{\mathrm{trigger}} \cdot \epsilon_{\ell 1\ \mathrm{ID+Iso}} \cdot \epsilon_{\ell 2\ \mathrm{ID+Iso}} \cdot \epsilon_{\mathrm{CJV}} \cdot \epsilon_{\mathrm{other\ cuts}}$$

$$\epsilon = A \cdot \mathrm{w_{trigger}} \cdot (\mathrm{w_{eff\ell 1}} \cdot \epsilon_{\ell 1\ \mathrm{ID+Iso}}) \cdot (\mathrm{w_{eff\ell 2}} \cdot \epsilon_{\ell 2\ \mathrm{ID+Iso}}) \cdot (\mathrm{sf_{CJV}} \cdot \epsilon_{\mathrm{CJV}}) \cdot \epsilon_{\mathrm{other\ cuts}}$$

Background estimation

$$\sigma_{WW} = \frac{N_{Data} - N_{bkg}}{\mathcal{L}_{int} \cdot \epsilon \cdot (3 \cdot BR(W \to \ell\bar{\nu}))^2}$$

- Precise measurement of the backgrounds
  - Top processes: ttbar and single-top (tW)
  - Drell-Yan (ee and μμ final state)
  - W+jets
  - W+γ*

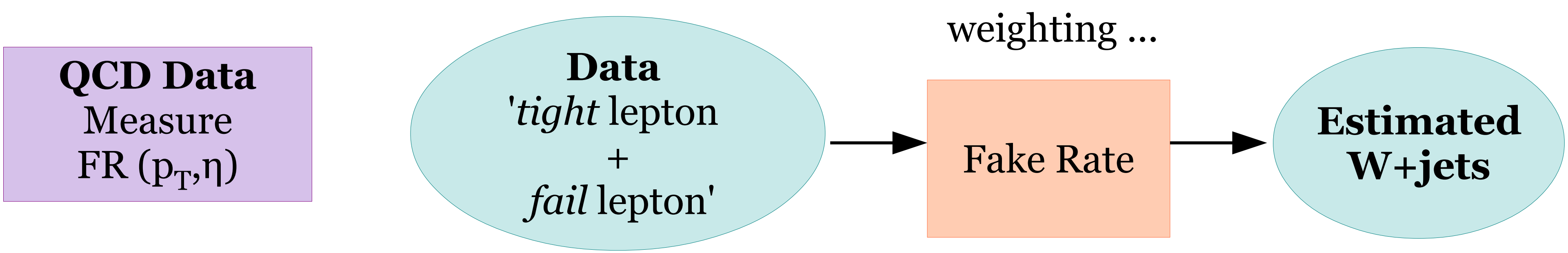
  Estimated from Control Regions on Data
  (Data Driven Methods)

  - WZ and ZZ
  - W+γ
  - Drell-Yan (ττ final state)

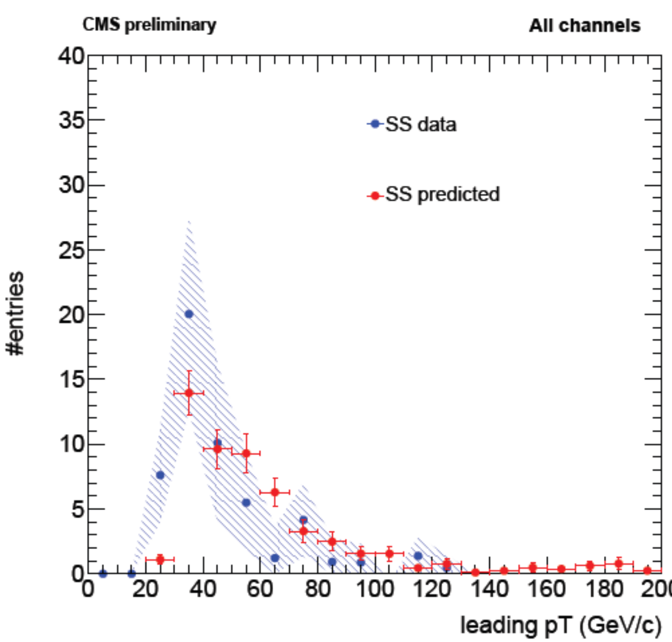
  Estimated from Monte Carlo simulation

Background estimation: W+jets

- Fake Rate (FR) method
  - Measure, in a QCD data enriched sample, the probability (FR) for a loose lepton object to pass the tight requirements used in the selection
  - Background estimation derived by weighting events in a '*tight+fail*' sample



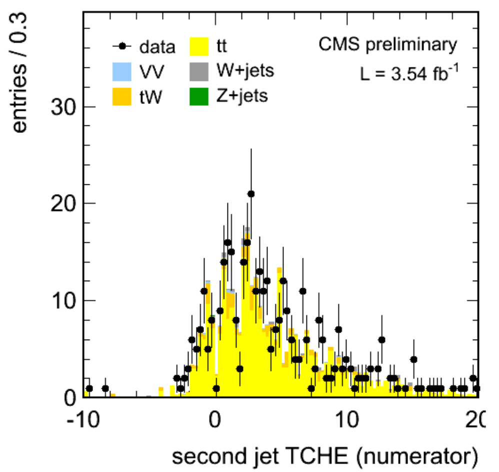
- Systematic error 36%
  - Differences in jet composition in the QCD-enriched control region sample and the W+jets in the analysis sample
  - Closure Test on Same Sign Data events

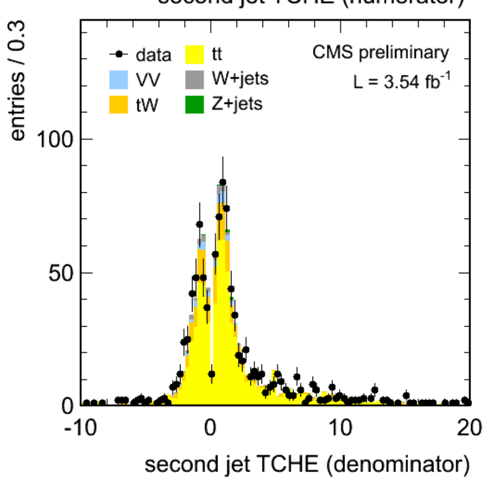


Background estimation: Top processes

- Top reduction: apply soft muon veto and low p_T jet top-tagging → tag a soft jet
- Measure the efficiency to tag a soft jet on Data and estimate the final top veto efficiency in the WW region
- Extrapolate from a control region in Data, enriched in tt/tW,

  by inverting the veto





Data top enriched
Measure top tagging efficiency
ε_{tag}

↓

Estimate efficiency for tagging top events
ε_{top}

Data
Control region
Top tagged events

↓ weighting ...

$$\frac{\varepsilon_{top}}{1-\varepsilon_{top}}$$

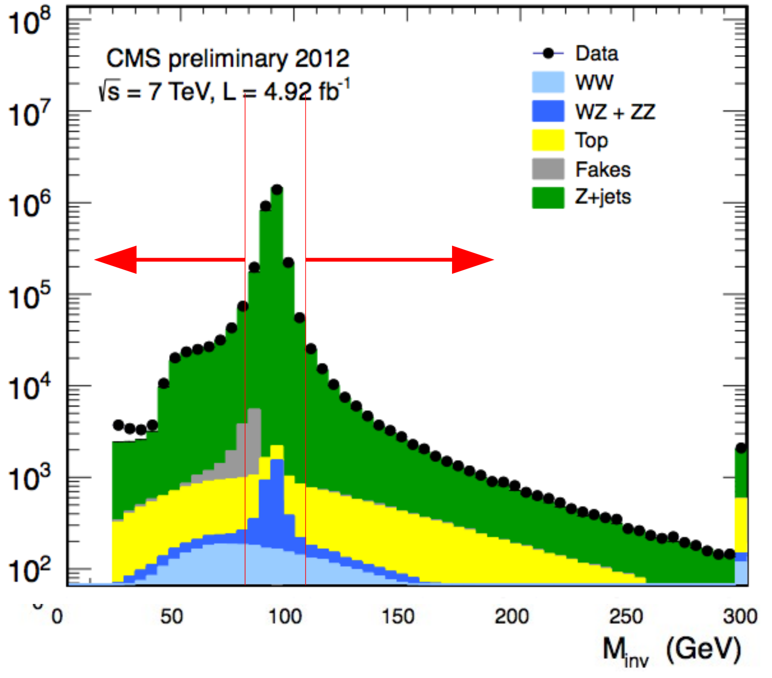
↓

Estimated top events

- Systematic error 18%
  - Top tagging efficiency
  - tt/tW cross-section
  - Control region statistics

Background estimation: Drell-Yan

- Estimate Drell-Yan contribution from a signal-free region (based on m_Z)



- Estimate the ratio of Drell-Yan events outside/inside the Z mass region

$$R_{\mathrm{MC}}^{\mathrm{out/in}} \equiv \frac{N_{DY}^{\mathrm{control,MC}}}{N_{DY}^{\mathrm{signal,MC}}}$$

- Count the number of events on data inside that region corrected for:
  - ZZ/WZ (real MET, MC predicted)
  - non-peaking backgrounds as $N_{e\mu}$ data events k corrected:

$$k_{SF} = \frac{1}{2} \cdot \left(\sqrt{\frac{N_{\mathrm{ee}}^{\mathrm{control}}}{N_{\mu\mu}^{\mathrm{control}}}} + \sqrt{\frac{N_{\mu\mu}^{\mathrm{control}}}{N_{\mathrm{ee}}^{\mathrm{control}}}} \right)$$

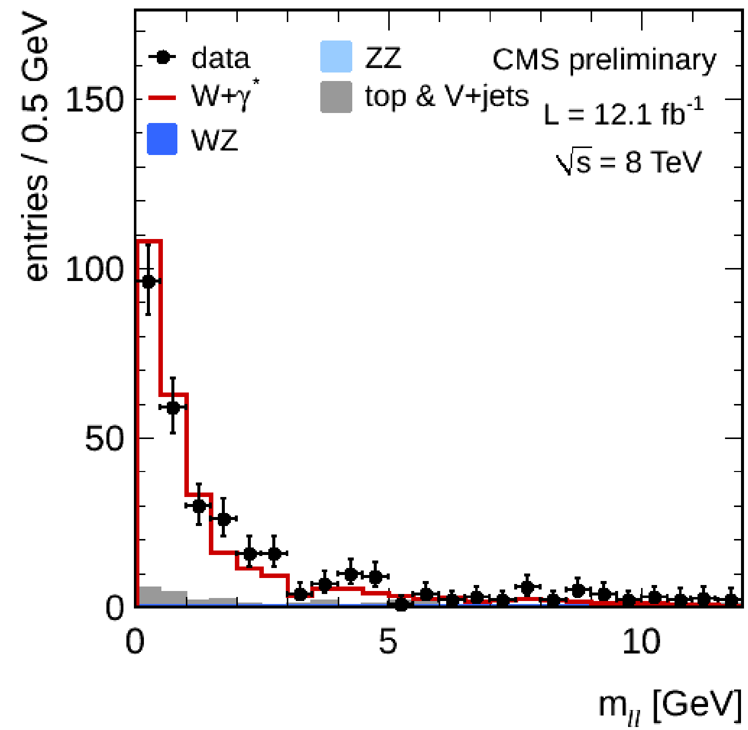
- Extrapolate to the signal region

$$N_{DY}^{\mathrm{signal,data}} = \left(N_{\ell\ell}^{\mathrm{control,data}} - k \cdot N_{\mathrm{e}\mu}^{\mathrm{control,data}} - N_{\mathrm{ZV}}^{\mathrm{control,MC}} \right) \cdot R_{\mathrm{MC}}^{\mathrm{out/in}}$$

- Systematic error 50%
  - Rout/in estimation
  - Control region sample statistics

Background estimation: Others

- $W+\gamma^*$: Use a data driven method to estimate the k-factor to correct for the NLO cross-section
  - Select a pure $W+\gamma^*$ region (dedicated cuts to reject backgrounds)
  - Using the $l^{\pm}\mu^{+}\mu^{-}$ final state a k-factor of 1.5 for the cross section is found, when comparing SS and OS number of events on Data



- WZ and ZZ backgrounds are estimated directly from MC simulation

- The Drell-Yan → ττ is also estimated from MC
  - Cross-check result on Data using the embedding method
  - Take kinematics from well reconstructed Z(μμ) events in data
  - Replace muons with taus from simulation and repeat reco

Systematic uncertainties

- As shown, several sources of systematics considered
  - Experimental: order of the few percent (momentum scale, MET resolution, etc …)
  - Theoretical: PDF and higher order corrections (few percent for qq production)
  - Major source for WW efficiency is the jet veto uncertainty
  - Data Driven methods: from 18 % for Top to 50% for Drell-Yan
  - Luminosity: 4.4% @ 8 TeV (2.2% @ 7 TeV)

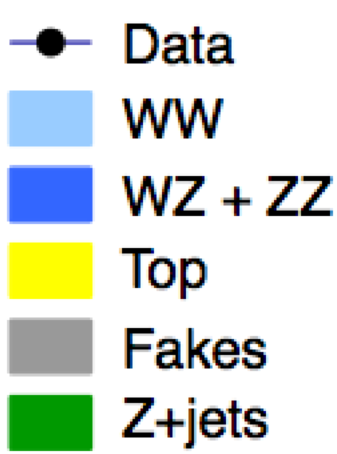
	$q\bar{q} \to W^+W^-$	$gg \to W^+W^-$	top	$W+$jets	WZ +ZZ	$Z/\gamma* \to \ell\ell$	$W+\gamma$	$W+\gamma^*$	$Z/\gamma* \to \tau\tau$
Luminosity	2.2	2.2	-	-	2.2	-	2.2	-	-
Trigger efficiency	1.5	1.5	-	-	1.5	-	1.5	-	-
Lepton id efficiency	2.0	2.0	-	-	2.0	-	2.0	-	-
Muon momentum scale	1.5	1.5	-	-	1.5	-	1.5	-	-
Electron energy scale	2.5	2.5	-	-	1.9	-	2.0	-	-
E_T^{miss} resolution	2.0	2.0	-	-	2.0	-	2.0	-	-
Jet veto efficiency	4.7	4.7	-	-	4.7	-	4.7	-	-
pile-up	2.3	2.3	-	-	2.3	-	2.3	-	-
top normalisation	-	-	18	-	-	-	-	-	-
$W+$jets normalisation	-	-	-	36.0	-	-	-	-	-
$Z/\gamma^* \to \ell^+\ell^-$ normalisation	-	-	-	-	-	50.0	-	-	-
$W+\gamma$ normalisation	-	-	-	-	-	-	30.0	-	-
$W+\gamma^*$ normalisation	-	-	-	-	-	-	-	30.0	-
$Z/\gamma^* \to \tau^+\tau^-$ normalisation	-	-	-	-	-	-	-	-	10.0
PDFs	2.3	0.8	-	-	5.9	-	-	-	-
Higher order corrections	1.5	30.0	-	-	3.3	-	-	-	-

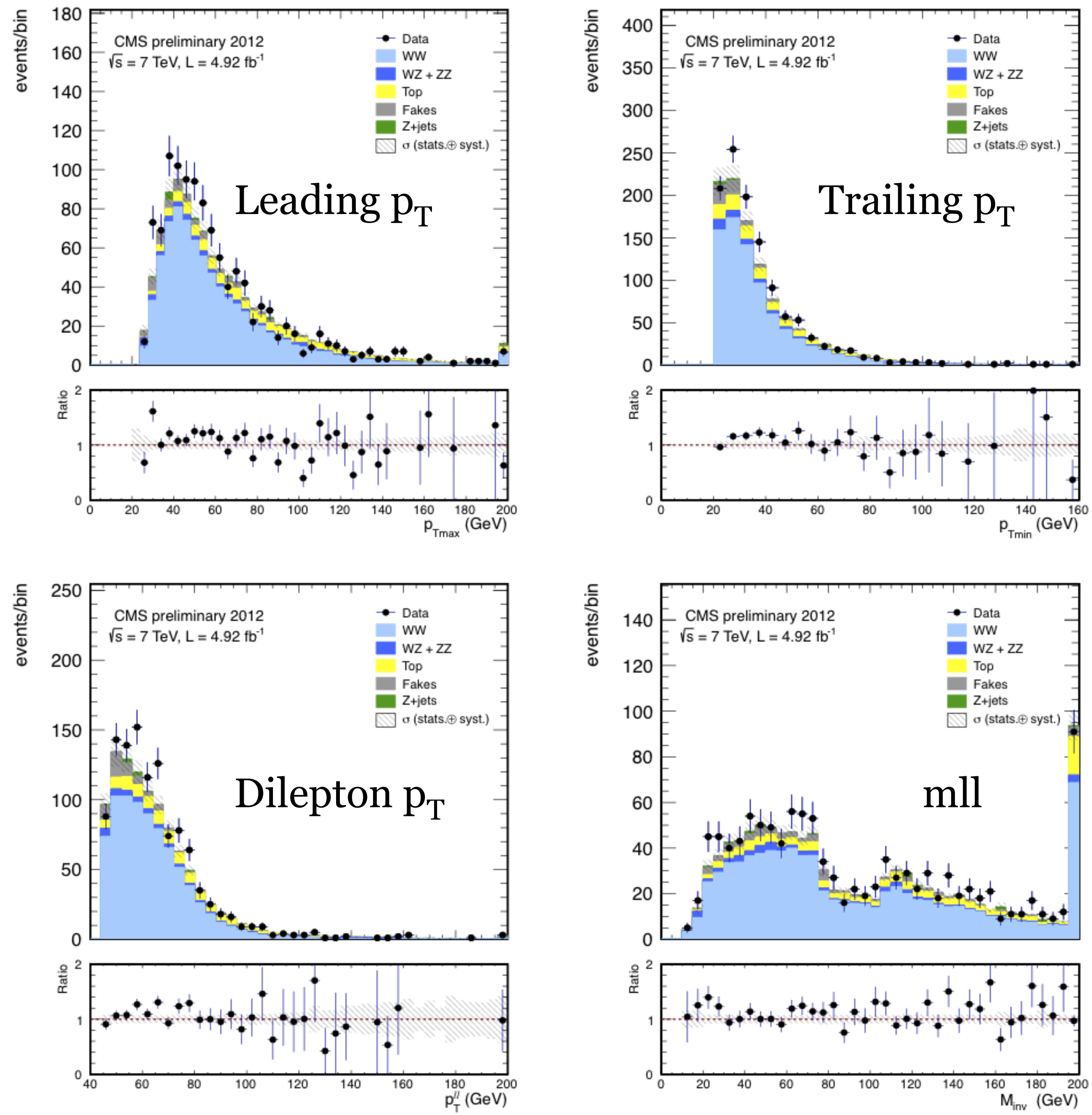
given in %

Results – WW 2011 @ 7 TeV

Distributions after signal selection for 4.92 /fb for the inclusive final state

Backgrounds scaled by control regions on data estimations

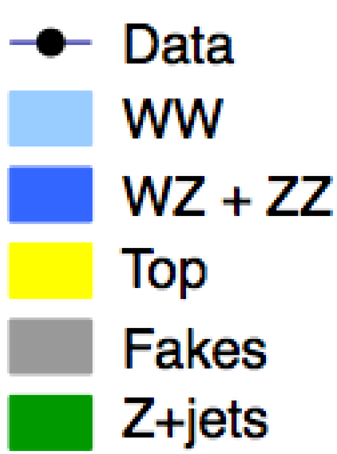


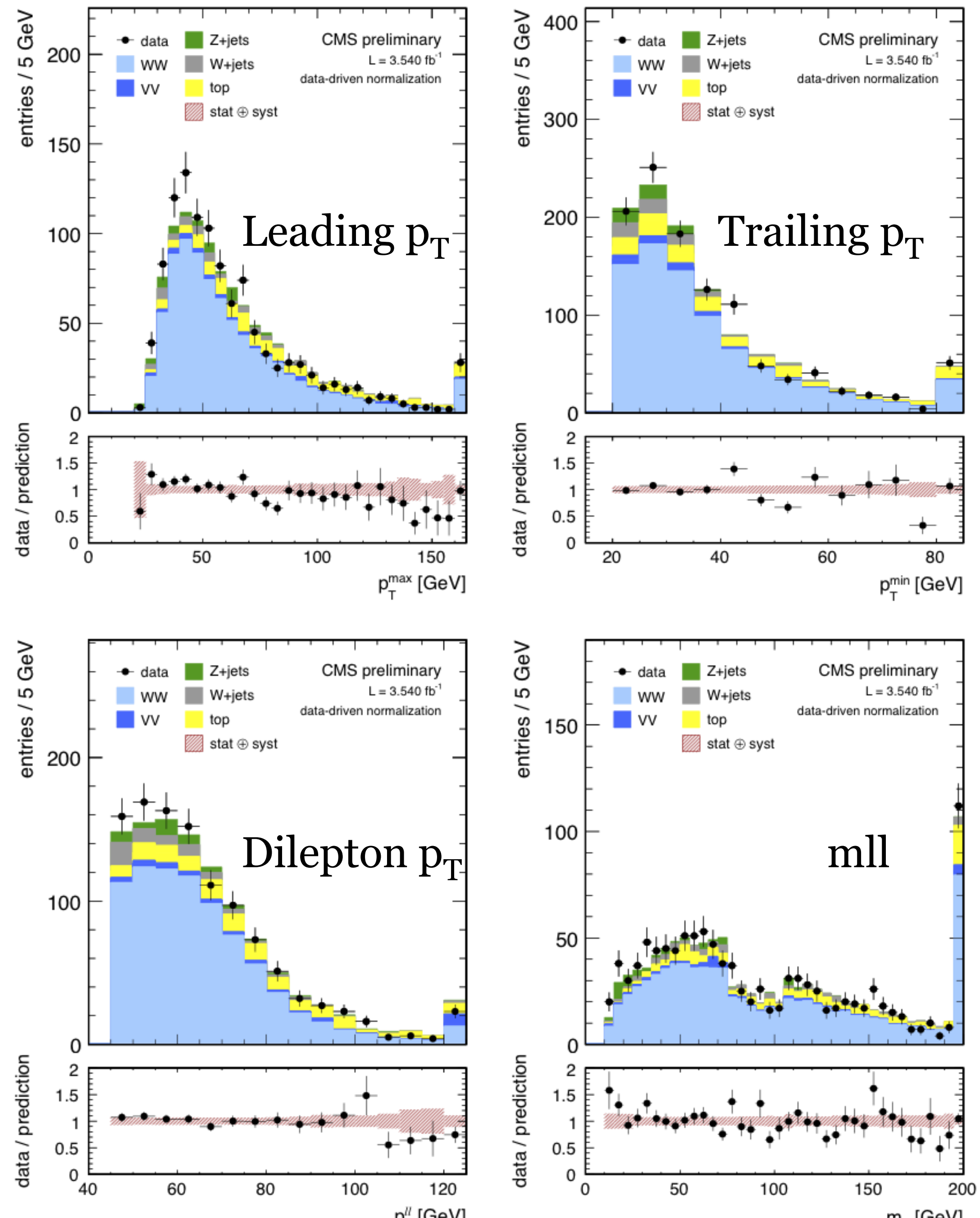


Results – WW 2012 @ 8 TeV

Distributions after signal selection for 3.54 /fb for the inclusive final state

Backgrounds scaled by control regions on data estimations





Results

Results for 7 TeV with 4.92 /fb

Sample	Yield ± stat. ± syst.
$gg \rightarrow W^+W^-$	$46.0 \pm 0.6 \pm 14.2$
$q\bar{q} \rightarrow W^+W^-$	$750.9 \pm 4.1 \pm 53.1$
$t\bar{t}$ +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^*	$11.0 \pm 5.1 \pm 2.6$
$W+\gamma$	$18.8 \pm 2.8 \pm 4.7$
$Z/\gamma^* \rightarrow \tau\tau$	$0.0 \pm 1.0 \pm 0.1$
Total Background	$247.1 \pm 14.6 \pm 29.5$
Signal + Background	$1044.0 \pm 15.2 \pm 62.4$
Data	1134

52.4 ± 2.0 (stat.) ± 4.5 (syst.) ± 1.2 (lumi.) pb

Theoretical: $\sigma_{NLO} = 47.0 \pm 2.0$ pb [*]

Results for 8 TeV with 3.54 /fb

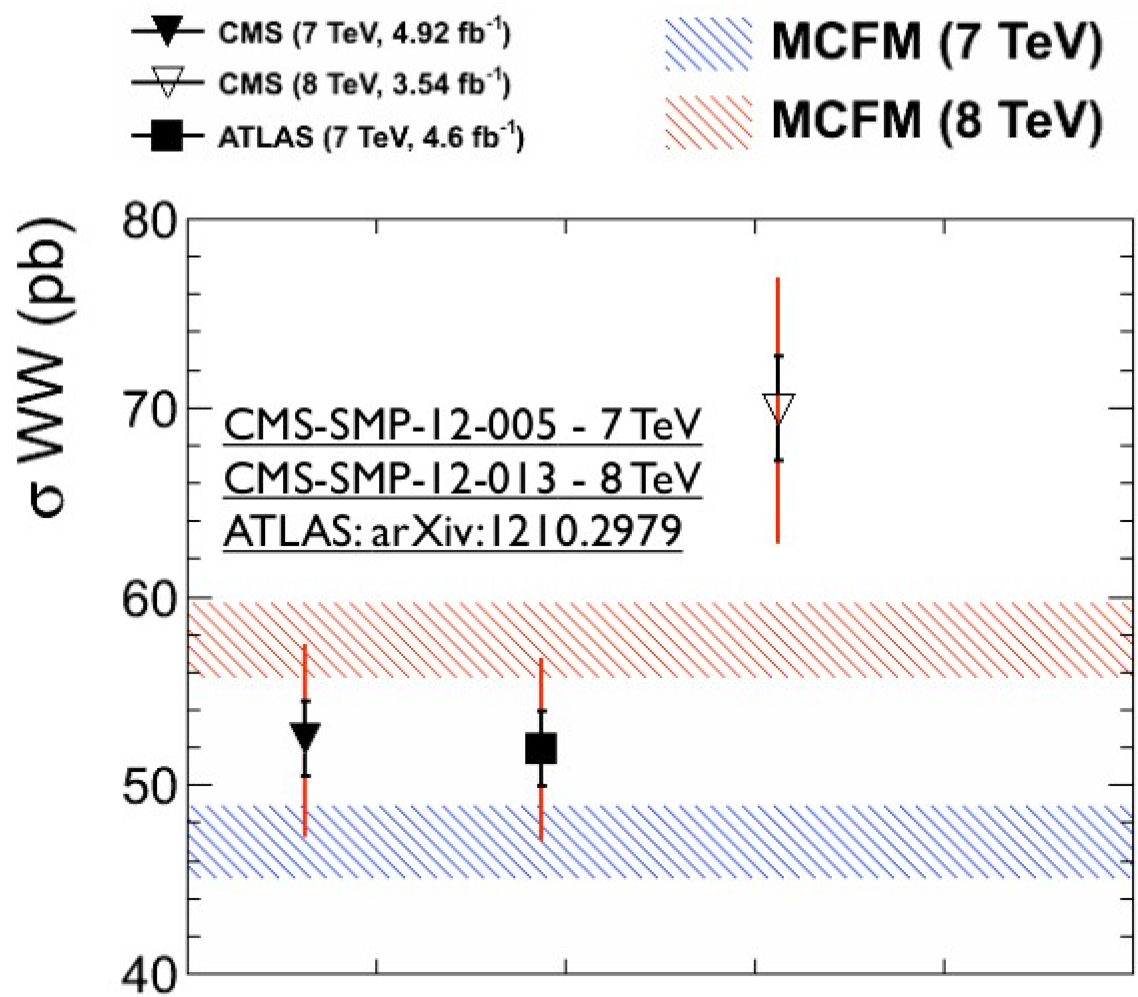
sample	yield ± stat. ± syst.
$gg \rightarrow WW$	$43.3 \pm 1.0 \pm 13.4$
$qq \rightarrow WW$	$640.3 \pm 4.9 \pm 47.4$
$t\bar{t}$ + tW	$131.6 \pm 12.7 \pm 19.5$
W + jets	$60.0 \pm 4.3 \pm 21.6$
WZ + ZZ	$27.4 \pm 0.5 \pm 2.9$
Z/γ^*	$42.5 \pm 6.0 \pm 9.9$
$W\gamma + W\gamma^*$	$13.6 \pm 2.4 \pm 4.3$
total background	$275.2 \pm 14.9 \pm 31.2$
signal + background	$958.8 \pm 15.7 \pm 58.3$
data	1111 ± 33

69.9 ± 2.8 (stat.) ± 5.6 (syst.) ± 3.1 (lumi.) pb

Theoretical: $\sigma_{NLO} = 57.3\,^{+2.0}_{-1.6}$ pb [*]

[*] J. M. Campbell, R. K. Ellis and C.Williams, ``Vector boson pair production at the LHC,'' JHEP 1107, 018 (2011)

Results – CMS & ATLAS



D. Evans @ HCP2012

- Both CMS and ATLAS observe an excess above theoretical prediction
    - Difference between 8 TeV result and theory value is (22 ± 13)%

Results – CMS & ATLAS

❑ **Results** (CERN-PH-EP-2012-242, CMS PAS SMP-12-005, CMS PAS SMP-12-013)

	$\int L$ (fb^{-1})	$\sigma(pp \to WW) \times B$ (pb)	SM NLO
ATLAS 7TeV	4.6	$51.9 \pm 2.0(stat.) \pm 3.9(syst.) \pm 2.0(\text{lumi.})$	$44.7^{+2.1}_{-1.9}$
CMS 7TeV	4.9	$52.4 \pm 2.0(stat.) \pm 4.5(syst.) \pm 1.2(\text{lumi.})$	–
CMS 8TeV	3.5	$69.9 \pm 2.8(stat.) \pm 5.6(syst.) \pm 3.1(\text{lumi.})$	$57.3^{+2.4}_{-1.6}$

1.5-2σ off

❑ **Systematics (~8%)**

– **Jet Veto efficiency (major), lepton, $E_{T,Rel}^{miss}$, lumi**

2012/11/14 Wednesday Y. WU @ HCP2012 10

A proposal for BSM interpretations of this discrepancy:

chargino production and leptonic decay

Feigl, Rzehak, Zeppenfeld, arXiv:1205.3468

M.L. Mangano @ HCP2012

- Understanding these excess from SM will rely on
  - Proving that the SM predictions are accurate
  - Increase the statistics and reduce the systematics
- Missing some WW contributions at higher order?
  - Double-parton-scattering, Diffraction, γγproduction …
- Missing backgrounds?
  - Could be introducing the observed bias

Conclusions

- The cross section for the WW process was measured in the fully leptonic final state for the full 2011 dataset at a center of mass energy of 7 TeV and for the first 3.54 /fb 2012 data at 8 TeV

σ_{WW} = 52.4 ± 2.0 (stat.) ± 4.5 (syst.) ± 1.2 (lumi.) pb — **CMS-SMP-12-005**

σ_{WW} = 69.9 ± 2.8 (stat.) ± 5.6 (syst.) ± 3.1 (lumi.) pb — **CMS-SMP-12-013**

- The value for 7 TeV is 1-σ deviated from the theoretical prediction of 47±2.0 pb
- For 8 TeV, more than 1-σ deviated from the prediction of $57.3^{+2.0}_{-1.6}$ pb
- Need to understand these excess: ongoing

- Benchmark analysis for the Higgs searches in the H → WW channel
  - Fully understanding of the main irreducible background
  - Validity of the methods

Back-up slides

Results – CMS & ATLAS

- Understanding whether indeed these are departures from the SM will rely on
  - proving that the SM (~QCD) predictions are accurate
  - increasing statistics
  - reducing systematics
- Improving QCD predictions requires better theoretical calculations, but needs data to be validated --- else you won't believe the predictions!
- Efforts to improve SM predictions will pay off regardless of whether the current discrepancies are confirmed or not!
- For example, the precision Higgs physics programme will require better QCD modeling:
  - The discovery did not rely on MCs, but the measurements will.

M.L. Mangano @ HCP2012

Signal Efficiency: Jet Veto

- We measured the jet veto efficiency on Data events and compare with MC
- Select a clean Z sample
  - Do not apply MET cuts
  - Look at the Z boson mass window
- Jet veto efficiency for signal on Data events
  - $\varepsilon_{WW} = \varepsilon_{WW}^{MC} (\varepsilon_Z^{data}/\varepsilon_Z^{MC})$
- Scale factor found to be near to one
  - Assign a systematic on the measurement

Signal Efficiency: Jet Veto Systematics

- Jet veto efficiency: $\varepsilon_{WW} = \varepsilon_{WW}^{MC} (\varepsilon_Z^{data}/\varepsilon_Z^{MC})$

- We studied the theoretical uncertainty from the ratio $\varepsilon_{WW}^{MC}/\varepsilon_Z^{MC}$
    - Vary the normalization (μR) and factorization (μF) scales by 0.5 and 2 times nominal
    - Take ratio of maximum WW and minimum Z and vice versa wrt nominal

- The systematic for jet veto efficiency

  is 4.6% for 30 GeV jets based on MCFM