Measurement of the W^+W^- Production Cross Section and Differential Cross Sections with Jets in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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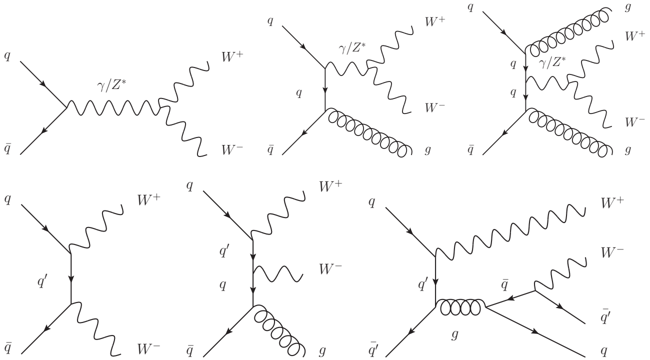
on behalf of the CDF Collaboration

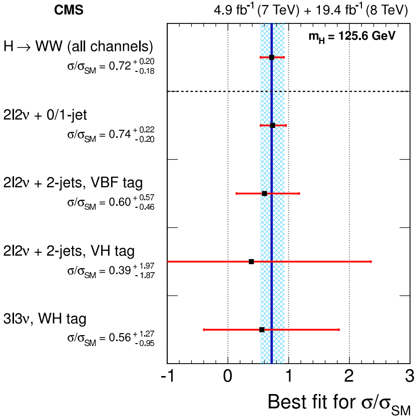
37th International Conference on High Energy Physics
Valencia, Spain, July 2-9, 2014

Motivation

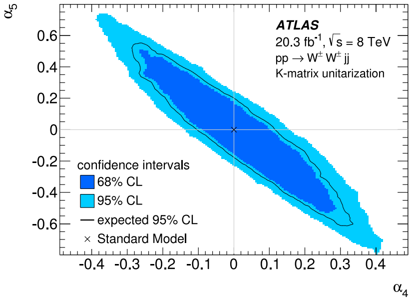


- *WW* production is a test of the electroweak sector
- Never before extended to include associated jet properties
- First differential measurement of the WW cross section
- Uniquely possible at the Tevatron due to lesser $t\bar{t}$ background

Motivation



JHEP01 (2014) 096



arXiv:1405.6241[hep-ex]

ATLAS Vector Boson Scattering ($W^{\pm}W^{\pm}jj$)

- Precision measurement of Higgs boson production and decay rates
  - Requires understanding of WW background in jet bins
- Vector Boson Scattering - sensitive to new physics in electroweak symmetry breaking
  - Requires understanding of $VV + 2$ jets QCD production

WW Measurements

$\sqrt{s}$	Experiment	Luminosity	Cross Section	Prediction	Jet Info
1.96 TeV	D0[1]	1.1fb^{-1}	11.5 ± 2.2 pb	12.7 ± 0.7 pb	Inclusive
	CDF[2]	3.6fb^{-1}	$12.1^{+1.8}_{-1.6}$ pb	11.7 ± 0.7 pb	Veto $E_T > 15$ GeV
7 TeV	ATLAS[3]	4.6fb^{-1}	51.9 ± 4.8 pb	44.4 ± 2.8 pb	Veto $p_T > 25$ GeV
	CMS[4]	4.9fb^{-1}	52.4 ± 5.1 pb	47.0 ± 2.0 pb	Veto $E_T > 30$ GeV
8 TeV	CMS[5]	3.5fb^{-1}	69.9 ± 7.0 pb	$57.3^{+2.3}_{-1.6}$ pb	Veto $p_T > 30$ GeV
	ATLAS(new)[6]	20.3fb^{-1}	$71.4^{+5.6}_{-5.0}$ pb	$58.7^{+3.0}_{-2.7}$ pb	Veto $p_T > 25$ GeV

- Previous W^+W^- measurements
- Inclusive or jet veto
- Consistent with predictions at the $\sim 2\sigma$ level

[1] PRL 103 191801 (2009)
[2] PRL 104 201801 (2010)
[3] PRD 87 112001 (2013)
[4] Eur. Phys. J C73 (2013) 2610
[5] Phys. Lett. B 721 (2013)
[6] ATLAS-CONF-2014-033

Event Selection

- Leptonic W's, loose kinematic selection
- Two oppositely charged leptons
  - Single high $E_T(p_T)$ electron or muon trigger
  - Multiple non-overlapping lepton categories
  - Isolation requirement to reduce misidentified objects
  - Additional requirements to reduce Drell-Yan and $W\gamma$
- Two neutrinos

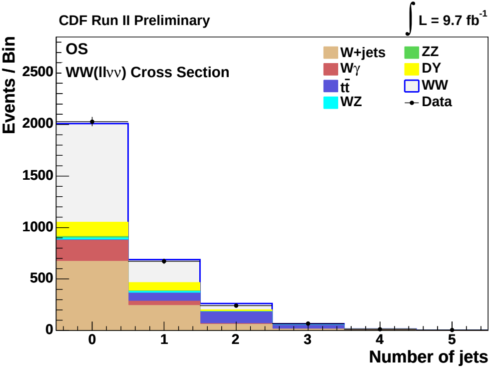
$$\not{E}_{T,rel} \equiv \begin{cases} \not{E}_T & \text{if}\Delta\phi(\vec{\not{E}}_T, lepton, jet) > \frac{\pi}{2} \\ \not{E}_T sin(\Delta\phi(\vec{\not{E}}_T, lepton, jet) & \text{if}\Delta\phi(\vec{\not{E}}_T, lepton, jet) < \frac{\pi}{2} \end{cases}$$

  - Reduces significance of $\not{E}_T$ aligned with mismeasured object
- Jets ($E_T > 15$ GeV, $|\eta| < 2.5$)
  - 0 Jet
  - 1 Jet - further separated:
    - ⋆ $15 < E_T < 25$ GeV
    - ⋆ $25 < E_T < 45$ GeV
    - ⋆ $E_T > 45$ GeV
  - 2 or more jets: b-tag veto

Signal and Background Modeling

- Irreducible
  - $WZ, ZZ, t\bar{t}$
  - Simulated with Pythia
- False $\not{E}_T$
  - Drell-Yan
  - Simulated with Pythia and Alpgen
- Misidentified particle
  - $W\gamma$ - simulated with Baur MC, data driven scaling
  - W+jets - data driven method

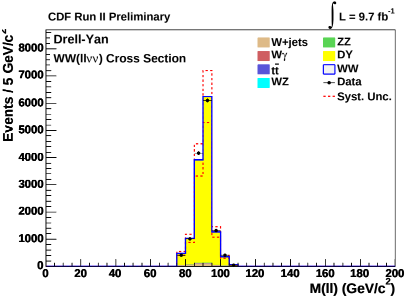
- WW Signal simulated with Alpgen, verified with MC@NLO

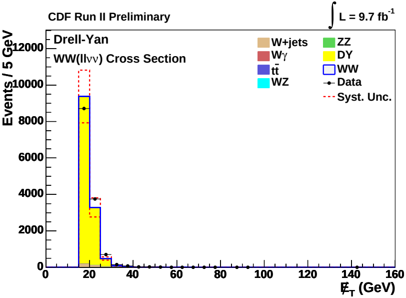


- Best fit to data

Control Region - Drell-Yan

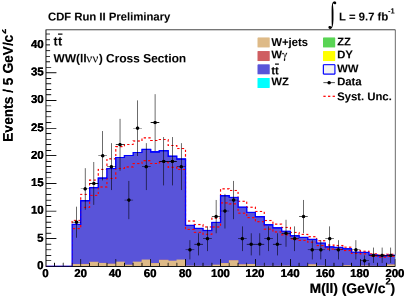
- Invariant mass of lepton pair near Z mass
- No $e\mu$ events
  - Unlikely to be Z
- Relax $\not{E}_{T,rel}$ requirement
  - No neutrinos

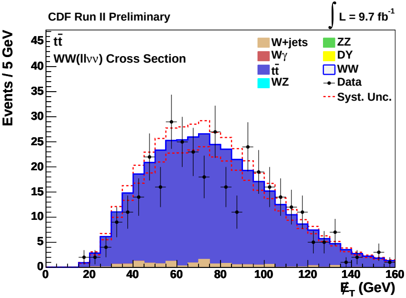




Control Region - $t\bar{t}$

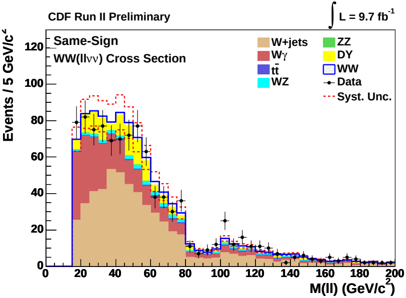
- Two or more jets
- One or more jets b-tagged
- Identical kinematic selection to two or more jets signal region

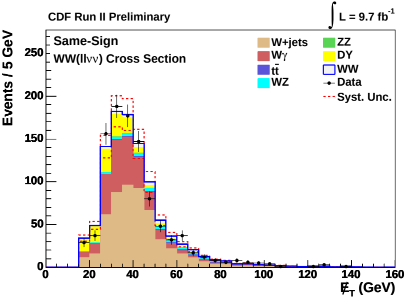




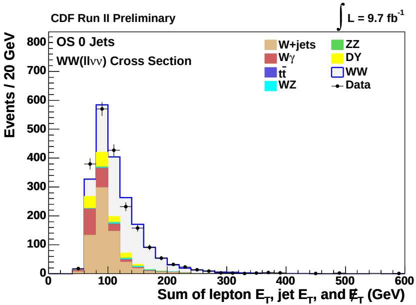
Control Region - Same Charge

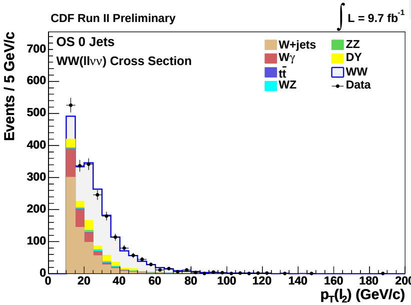
- Same charge leptons
- Tests modeling of misidentified objects
  - Enhances W+jets, $W\gamma$
- Identical kinematic selection to signal region



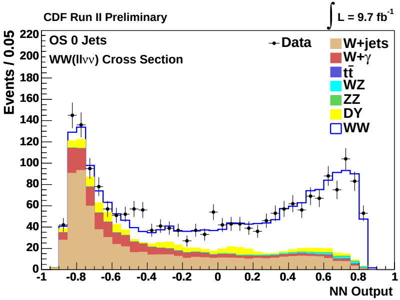


Neural Network - Zero Jets

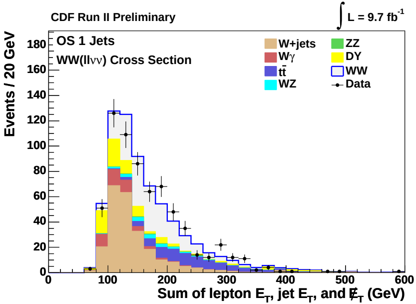


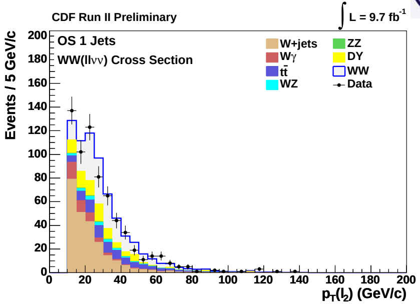


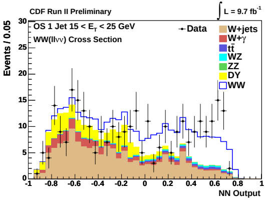
- Leading kinematic inputs:
  - Scalar sum E_T: WW energetic
  - $p_T(l_2)$: lower for j/γ misidentification

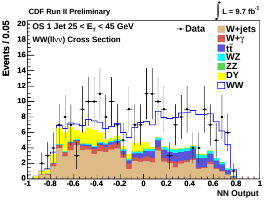


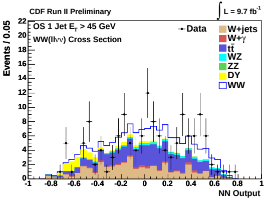
Neural Network - One Jet





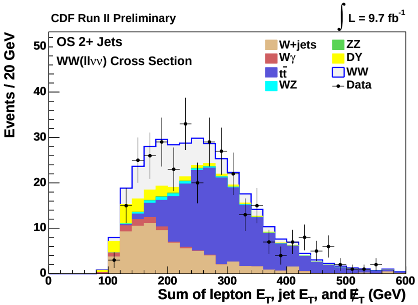


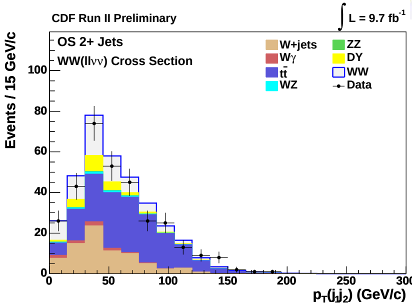




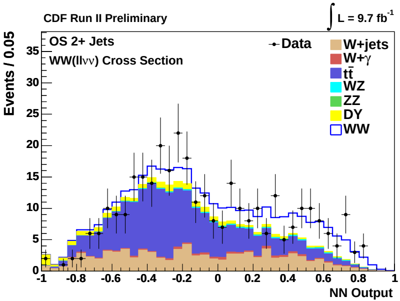
- Same leading kinematic inputs
- Separate template by jet E_T

Neural Network - Two or More Jets





- Leading kinematic inputs
  - Scalar sum E_T: $t\bar{t}$ even more energetic
  - $p_T(j_1 j_2)$: higher for $t\bar{t}$



Systematics

WW(ll$\nu\nu$) Cross Section — CDF Run II Preliminary — $\int L = 9.7\ \mathrm{fb}^{-1}$

Uncertainty Source	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jet
Cross Section	6.0%	6.0%	6.0%	4.3%*			
Acceptance							
$\not{E}_T$ Modeling					(19.0-26.0%*)		
Higher-order Diagrams		10.0%	10.0%			10.0%*	
$t\bar{t}$ QCD				2.7%			
Conversion Modeling						6.8%	
Scale	(23.7†-3.8%)						
PDF Modeling	(0.8-1.8%)						
Jet Energy Scale	(21.5†-4.7%)	(13.2†-6.4%)	(13.3†-3.5%)	(12.9†-26.8%)	(28.7†-10.2%)	(22.0†-3.5%)	
$b-$tag veto				(0.0-3.9%)			
Lepton ID Efficiencies	3.8%	3.8%	3.8%	3.8%	3.8%		
Trigger Efficiencies	2.0%	2.0%	2.0%	2.0%	2.0%		
Jet Fake Rate							(17.2-19.0%)
Luminosity	5.9%	5.9%	5.9%	5.9%	5.9%		

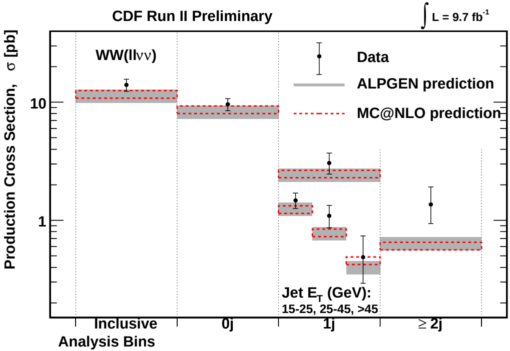
* indicates uncorrelated systematic. † indicates anticorrelated systematic.

- Dominant systematics
  - Fake Rate
  - $\not{E}_T$ Modeling
  - Parton Showering Scale
  - Jet Energy Scale

Determination of the Cross Section

- Neural net output templates separated by jet multiplicity and $\not{E}_T$
- Each bin fit simultaneously
  - Maximum likelihood method
  - Systematics - nuisance parameters with Gaussian constraint
  - Signal normalization - freely floating
- Cross section extracted from normalization
- Result unfolded
  - Jet distributions affected by detection/reconstruction
  - Cluster jets at hadronic level and compare to fully reconstructed
  - Correct via iterative Bayesian method
- Compared to Alpgen (LO with N hard jets) and MC@NLO (NLO)

Results



WW($ll\nu\nu$) Cross Section — CDF Run II Preliminary — $\int L = 9.7\ \text{fb}^{-1}$

Jet Bin	σ(pb) Measured	Uncertainty(pb) Stat.	Syst.	Lumi.	σ(pb) Alpgen	MC@NLO
Inclusive	14.0	± 0.6	$^{+1.6}_{-1.3}$	± 0.8	11.3 ± 1.4	11.7 ± 0.9
0 Jets	9.6	± 0.4	$^{+1.1}_{-0.9}$	± 0.6	8.2 ± 1.0	8.6 ± 0.6
1 Jet Inclusive	3.05	± 0.46	$^{+0.48}_{-0.32}$	± 0.18	2.43 ± 0.31	2.47 ± 0.18
1 jet, $15 < E_T < 25$ GeV	1.47	± 0.17	$^{+0.15}_{-0.11}$	± 0.09	1.26 ± 0.16	1.18 ± 0.09
1 jet, $25 < E_T < 45$ GeV	1.09	± 0.18	$^{+0.17}_{-0.12}$	± 0.06	0.77 ± 0.10	0.79 ± 0.06
1 jet, $E_T > 45$ GeV	0.49	± 0.15	$^{+0.20}_{-0.11}$	± 0.03	0.40 ± 0.05	0.46 ± 0.03
2 or More jets	1.36	± 0.30	$^{+0.46}_{-0.29}$	± 0.08	0.64 ± 0.08	0.61 ± 0.05

Conclusion

- Measurement of the differential cross section for WW production as a function of jet energy and multiplicity
  - Loose kinematic selection
  - Multivariate discriminant
  - Binned maximum likelihood fit
- Unfolded result found to be consistent with the Standard Model prediction
- Lesser $t\bar{t}$ background makes this uniquely possible at the Tevatron
- This is the most precise measurement of the WW cross section at a $p\bar{p}$ collider, and the first jet-differential cross section measurement in a massive diboson state

More information: http://www-cdf.fnal.gov/physics/ewk/2014/WWjets/ and CDF Public Note 11098