Measurement of the W^+W^- Production Cross Section and Search for Anomalous $WW\gamma$ and WWZ Couplings in pp Collisions at $\sqrt{s}$ = 1.96 TeV

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PRL Draft: CDF Note 9902

Paper Details

- Supporting Documentation
  - See godparent webpage:

www-cdf.fnal.gov/internal/physics/godparents/sigmaWW_3_6fb/

  - Main analysis notes:
    - WW Cross Section: CDF 9723
    - WW Triple Gauge Couplings: CDF 9785
  - Related Higgs to WW 3.6/fb analysis note: CDF 9685
  - PRL Draft: CDF 9902
- Many thanks to godparents
  - Mark Neubauer (chair), Corrinne Mills, Aurore Savoy Navarro
- ... and all who read the drafts, especially:
  - Geneva, Berkeley, Cantabria, SPRG, Pasha Murat, Andy Beretvas

WW TGC Measurement

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WW cross section (the HWW group)

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History of the WW Cross Section at CDF

- First evidence for WW production in dilepton channel by CDF (1997) using 108 pb^{-1} (5 WW candidates):

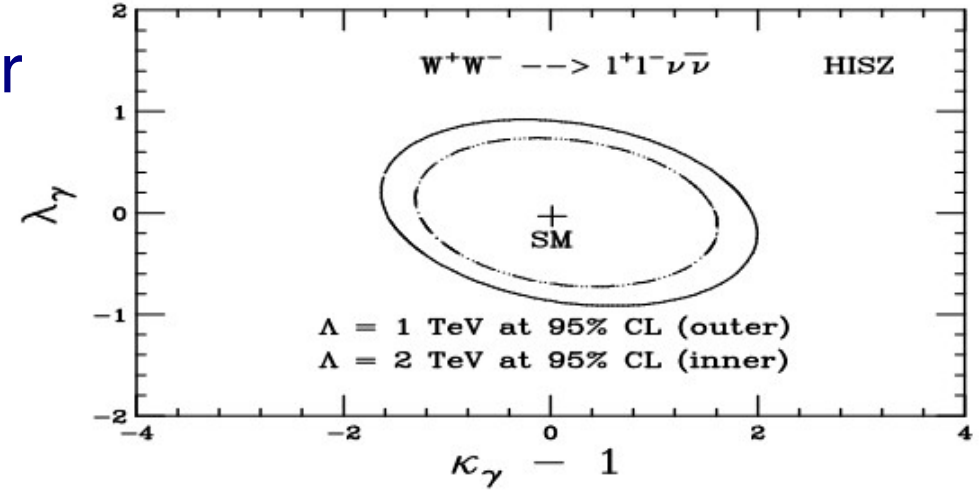
$$\sigma(\bar{p}p \to W^+W^-) = 10.2^{+6.3}_{-5.1}\ (\text{stat}) \pm 1.6\ (\text{syst})\ \text{pb}$$

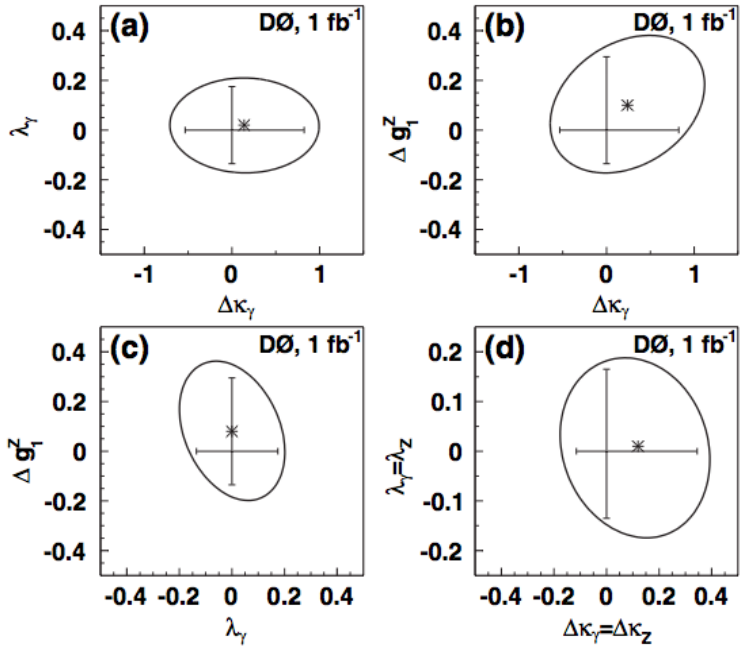
- CDF Run II WW cross section published with 184 pb^{-1}
  - Dilepton: $14.6^{+5.8}_{-5.1}(\text{stat})\ ^{+1.8}_{-3.0}(\text{syst}) \pm 0.9\ (\text{lumi})\ \text{pb}$
  - Lepton+Track: $24.4 \pm 6.9(\text{stat})\ ^{+5.2}_{-5.7}(\text{syst}) \pm 1.5\ (\text{lumi})\ \text{pb}$
- Unpublished CDF measurement with 825 pb^{-1}
  - Dilepton: $13.6 \pm 2.3(\text{stat}) \pm 1.6(\text{syst}) \pm 1.2\ (\text{lumi})\ \text{pb}$
- Recent D0 published measurement with 1 fb^{-1}:

$$\sigma(p\bar{p} \to WW) = 11.5 \pm 2.1\ (\text{stat} + \text{syst}) \pm 0.7\ (\text{lumi})\ \text{pb}$$

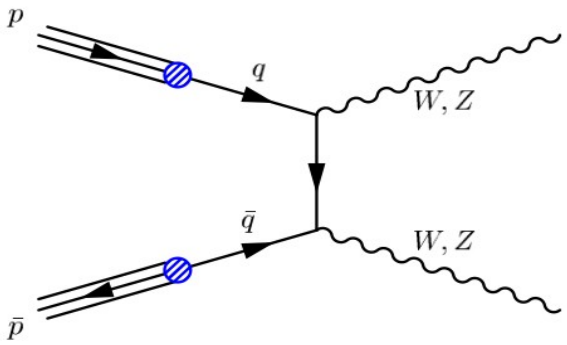
History of the WW TGC at CDF

- Run I WW evidence paper also set limits on anomalous couplings
  - Limits were not investigated in Run II paper
  - Not investigated in 825 pb^{-1} analysis either
- D0 published limits with WW cross section, 1 fb^{-1}:
- Now have a chance to update CDF search for anomalous TGC

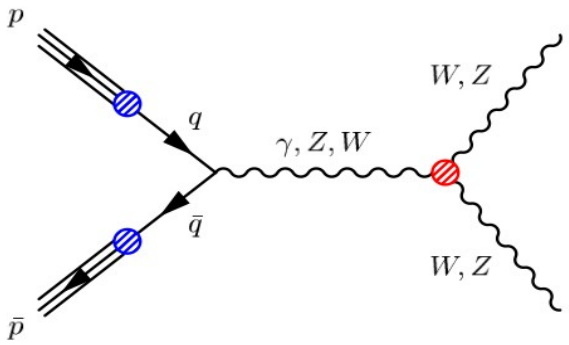




Motivation



(a) t-channel



(b) s-channel, involving triple gauge boson coupling

- Measure WW cross section using same selection and matrix element technique as Higgs to WW search
  - Demonstrate good understanding of backgrounds
  - Validation of analysis technique for Higgs search
- Update search for WWγ and WWZ anomalous couplings
  - Same event selection as WW cross section
  - TGCs sensitive to low-energy manifestations of new physics from a higher mass-scale

Event Selection (both analyses)

- Select dilepton events in 3.6 fb^{-1}
  - Two opposite charge leptons (e or μ)
    - Lepton selection (most use Joint Physics definitions):
      - TCE, PHX, CMUP, CMX, CMIOCES, CMIOPES, CrkTrk
    - $p_T(l_1) > 20$, $p_T(l_2) > 10$ GeV/c
  - Require **no** reconstructed jets ($|\eta| < 2.5$ and $E_T > 15$ GeV)
  - Dilepton mass $M_{ll} > 16$ GeV/c^2
  - Special $\not\!\!E_T$ cuts suppress Drell-Yan with mismeasured leptons:

$$\not\!\!E_{T,rel} > 25 \text{ GeV } (ee, \mu\mu) \text{ or } \not\!\!E_{T,rel} > 15 \ (e\mu), \text{ where}$$

$$\not\!\!E_{T,rel} \equiv \left\{ \begin{array}{ll} \not\!\!E_T & \text{if } \Delta\phi(\not\!\!E_T, \ell) > \frac{\pi}{2} \\ \not\!\!E_T \sin\Delta\phi(\not\!\!E_T, \ell) & \text{if } \Delta\phi(\not\!\!E_T, \ell) \leq \frac{\pi}{2} \end{array} \right\}$$

Event Selection, continued

- Use the following standard triggers
  - CENTRAL_ELECTRON_18, MUON_CMUP_18, MUON_CMX_18, MET_PEM
  - One lepton required to confirm trigger
  - Apply appropriate pre-scaling
  - Require candidates to be in appropriate good run list
- Signal and background modeling:
  - WW modeled by MC@NLO
  - Wγ modeled by Baur generator
  - W+1-jet uses data-driven estimate of fake leptons
    - Select identified leptons (numerator) and “fakeable objects” (denominator) in jet-triggered data samples
  - Remaining backgrounds modeled by Pythia (WZ, ZZ, tt, Drell-Yan)

Expected Sample Composition

- Use control regions to check background modeling
  - Drell-Yan region: test lepton SF, triggers, lumi accounting
  - Same sign region: test fake lepton contributions
  - Low $\not\!\!E_T$ significance: test effects of mismeasured energy
  - All regions show good data-MC agreement
- Also show good modeling of lepton p_T (necessary for TGC analysis)
- Expected events: Table 1 in PRL

Process	Events
Z/γ^* (Drell-Yan)	79.8 ± 18.4
WZ	13.8 ± 1.9
$W\gamma$	91.7 ± 24.8
W + 1-jet	112.7 ± 31.2
ZZ	20.7 ± 2.8
$t\bar{t}$	1.3 ± 0.2
Total Background	320.0 ± 46.8
W^+W^-	317.6 ± 43.8
Total Expected	637.6 ± 73.0
Data	654

Matrix Elements

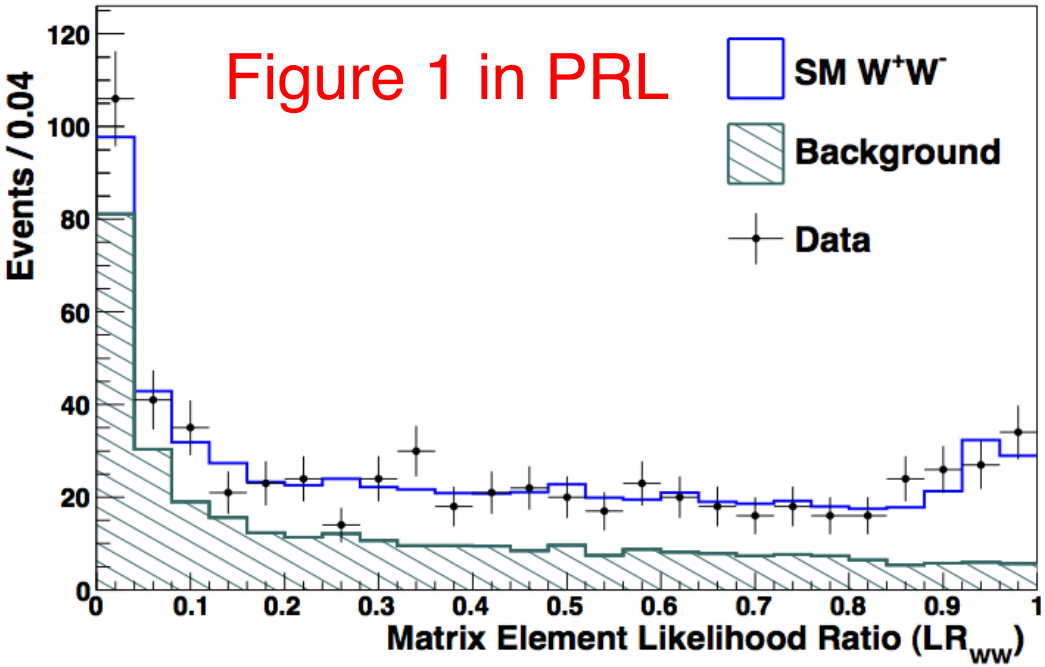
$$P(\vec{x}_{obs}) = \frac{1}{\langle\sigma\rangle} \int \frac{d\sigma_{th}(\vec{y})}{d\vec{y}}\, \varepsilon(\vec{y})\, G(\vec{x}_{obs}, \vec{y})\, d\vec{y}$$

- Event probability density, with:

$\vec{x}_{obs}$	Observed leptons and $\not\!\!E_T$
$\vec{y}$	True lepton 4-vectors (l, ν)
σ_{th}	Leading order theoretical cross-section
$\varepsilon(\vec{y})$	Efficiency & acceptance
$G(\vec{x}_{obs}, \vec{y})$	Resolution effects
$1/\langle\sigma\rangle$	Normalization

$$LR_m = \frac{P_m(\vec{x}_{obs})}{P_m(\vec{x}_{obs}) + \sum_i k_i P_i(\vec{x}_{obs})}$$

- Calculate 4 probabilities:
  - WW, ZZ, Wγ, W+1-jet
- Construct Likelihood Ratio LR_{WW}



WW Cross Section Results

- Perform binned maximum likelihood fit to LR_{WW}
  - Formed from Poisson probabilities of observing n_i events in the *i*-th bin when μ_i are expected
  - Systematics included as Gaussian constraints
  - Likelihood maximized using MINUIT
- Fit for normalization parameter α_{WW} to extract WW cross section:

$$\sigma(p\bar{p} \rightarrow W^+W^- + X) = 12.1 \pm 0.9\ (\text{stat})\ ^{+1.6}_{-1.4}\ (\text{syst})\ \text{pb}$$

- Good agreement with previous results and recent theoretical prediction: $\sigma^{NLO}(p\bar{p} \rightarrow W^+W^-) = 11.7 \pm 0.7\ \text{pb}$
- Improvement over recent D0 measurement
  - Reduced uncertainty to < 15%!

Systematics

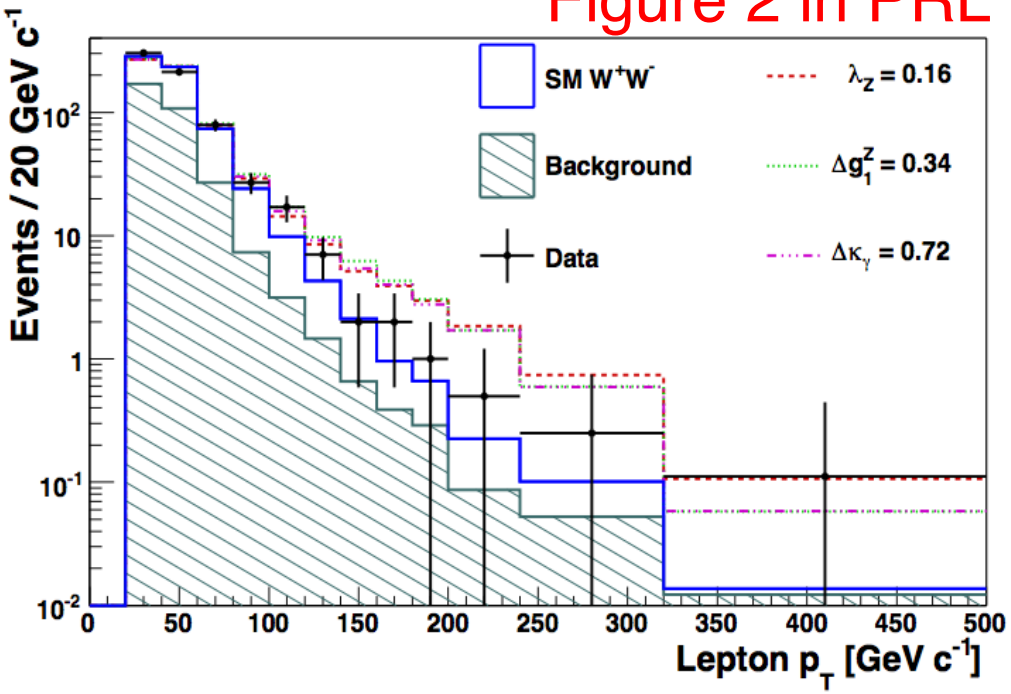
- Same uncertainties as for Higgs to WW analysis
  - Compare WW Pythia sample to WW MC@NLO to estimate effects due to higher-order diagrams
  - PDF uncertainties assessed using 20 CTEQ PDFs
  - W+1-jet: uncertainty on jet being identified as a lepton

Uncertainty Source	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jet
Cross Section		*6.0%*	*6.0%*	10.0%	5.0%	10.0%	
Acceptance							
PDF Model	*1.9%*	*2.7%*	*2.7%*	*2.1%*	*4.1%*	*2.2%*	
Higher-order Diagrams	*5.0%*	*10.0%*	*10.0%*	10.0%		*10.0%*	
Jet Modeling	2.0%				21.0%	4.0%	
Conversion Modeling						20.0%	
Jet Fake Rates							27.7%
MC Run Dependence	*3.8%*			*1.0%*		*5.0%*	
Lepton ID Efficiencies	*2.0%*	*1.7%*	*2.0%*	*2.0%*	*1.9%*	*1.4%*	
Trigger Efficiencies	*2.1%*	*2.1%*	*2.1%*	*2.0%*	*3.4%*	*7.0%*	
Luminosity	*5.9%*	*5.9%*	*5.9%*	*5.9%*	*5.9%*	*5.9%*	

TGC Analysis Technique

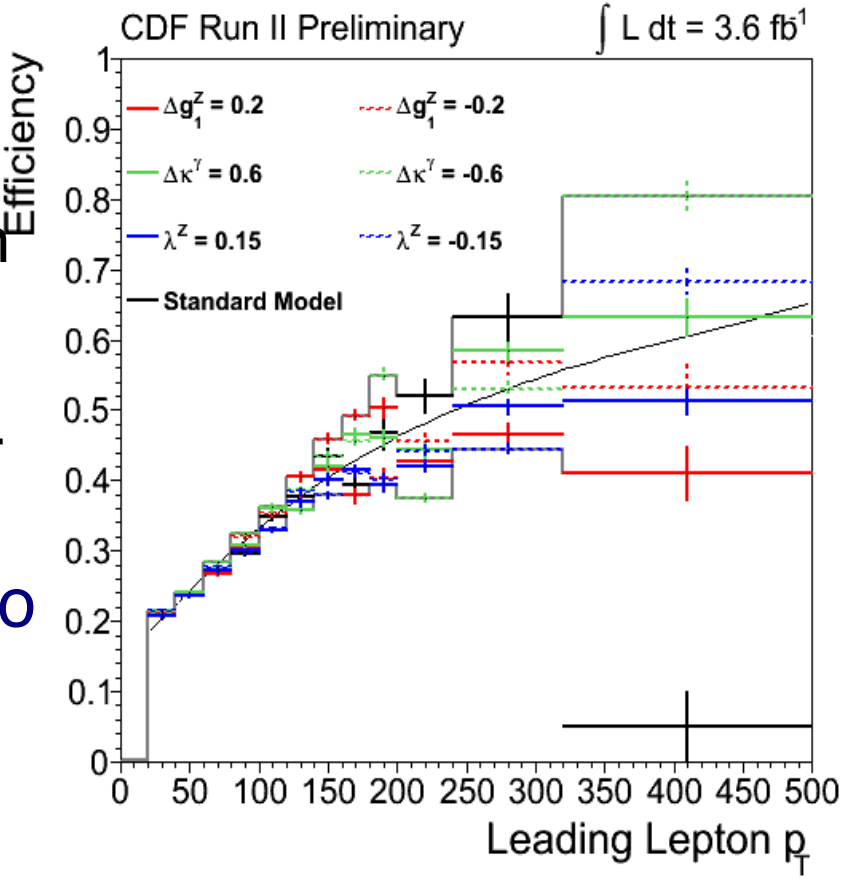
- Six coupling parameters condensed into 3 (λ_z, g_1^z, κ_γ) using $SU(2)_L \otimes U(1)_Y$ conserving constraints
  - Called the HISZ scheme after the authors
  - In the SM, $\lambda_z = 0$ and $g_1^z = \kappa_\gamma = 1$ ($\Delta g_1^z = g_1^z - 1$, $\Delta\kappa_\gamma = \kappa_\gamma - 1$)
  - Non-SM, parameters are a function of $\sqrt{s}$
- Leading lepton p_T sensitive to couplings
- Coupling values shown here correspond to D0 limits
- TGC samples generated with MCFM

Figure 2 in PRL



Universal Efficiency Curve

- To set limits, compute 1D binned likelihood fits $\mathcal{L}(\lambda_z)$, $\mathcal{L}(\Delta g_1^z)$, and $\mathcal{L}(\Delta\kappa_\gamma)$ of the data to the model
- For this, need to generate MC for each point in TGC space
  - CPU-intensive to process each all the way through simulation
  - Instead: fully simulate 6 samples (2 for each parameter near the previous limits)
- Apply p_T dependent efficiency to generator-level p_T distributions
- Variation taken as systematic



Anomalous TGC Results

- Calculate limits for 2 values of Λ (the cut-off scale for new physics, needed to preserve unitarity)
- Set 95% CL limits where
  - $(-2 \ln \mathcal{L}) - (-2 \ln \mathcal{L}_{min}) = (1.96)^2$
  - Apply systematics in the direction that reduces sensitivity

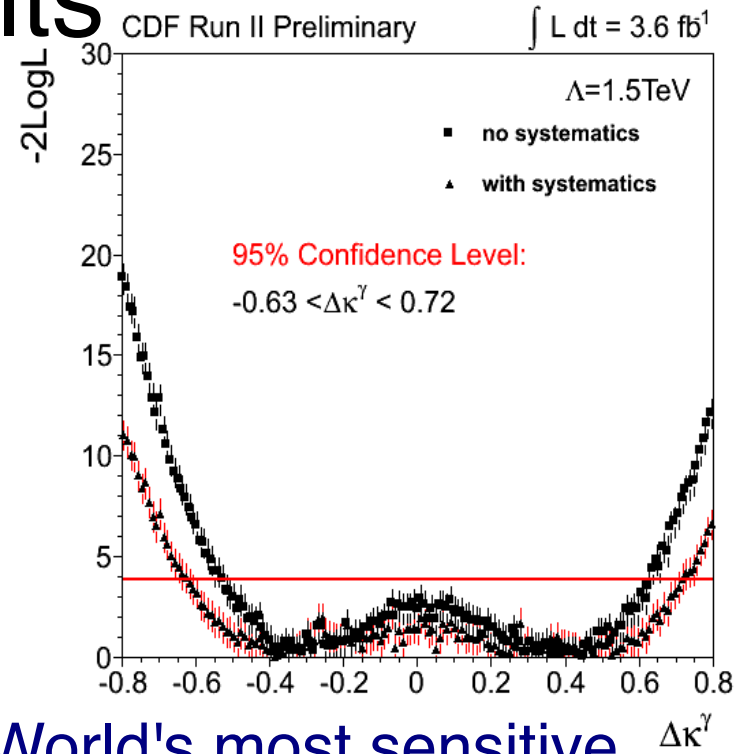


Table 2 in PRL

	Λ (TeV)	λ_Z	Δg_1^Z	$\Delta\kappa_\gamma$
Expected	1.5	(-0.05,0.07)	(-0.09,0.17)	(-0.23,0.31)
Observed	1.5	(-0.16,0.16)	(-0.24,0.34)	(-0.63,0.72)
Expected	2.0	(-0.05,0.06)	(-0.08,0.15)	(-0.20,0.27)
Observed	2.0	(-0.14,0.15)	(-0.22,0.30)	(-0.57,0.65)

- World's most sensitive expected limits
- Observed are higher due to fluctuation of events in tail of p_T distribution
  - Consistent with statistical fluctuation

Summary

- Updated measurement of WW production cross section and limits on anomalous WWγ and WWZ triple gauge couplings with 3.6 fb^{-1}
  - World's best measurement of WW cross section
    - Measurement comes from Higgs to WW search
    - First published update from CDF since 184 pb^{-1}
  - Most sensitive expected limits on aTGC
    - Observed limits comparable to current best limits
    - First update from CDF Run II
- Ready for submission to PRL
  - Thanks again to godparents and reading institutions for helpful comments!