Dibosons at the Tevatron
for CDF and DØ

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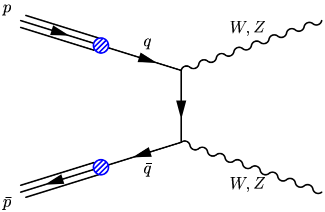
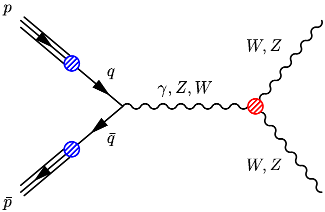
Moriond QCD, March 12th, 2008

Physics Motivation



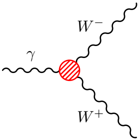
t-channel
Fermion to Boson Couplings

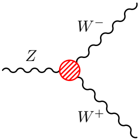


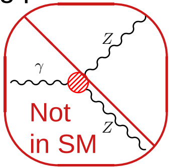
s-channel
Boson to Boson Couplings

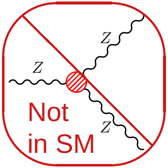
The Group Structure is a Key Ingredient to Electroweak Symmetry Breaking: $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{em}$

- Relationships between the masses and couplings of the W and Z
- Triple and quartic gauge coupling predictions





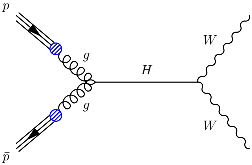




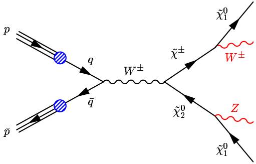
Physics Motivation (continued)

Could get contributions from new physics & Similar topologies to interesting searches

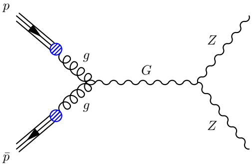
- "New Physics": Higgs (also *WH* and *ZH*)



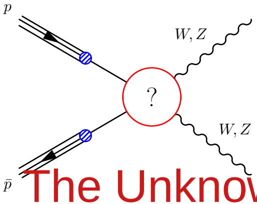
- Possible New Physics: e.g SUSY



- Possible New Physics: e.g Randall-Sundrum Graviton

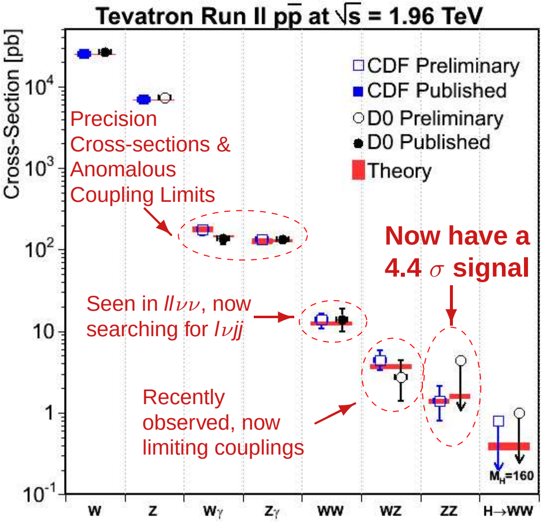


- Possible New Physics



The Unknown

Experimental Status Overview



What's in 1 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV?

$\approx$ 5,000,000 $W \to l\nu$

$\approx$ 500,000 $Z \to ll$

$\approx$ 32000 $W\gamma \to l\nu\gamma$

$\approx$ 8000 $Z\gamma \to ll\gamma$

$\approx$ 550 $WW \to ll\nu\nu$

$\approx$ 3700 $WW \to l\nu jj$

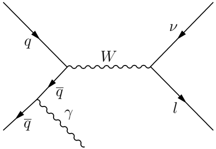
$\approx$ 50 $WZ \to llll$

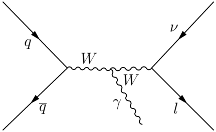
$\approx$ 6 $ZZ \to llll$

where l=e or μ

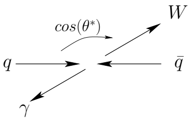
Analyses presented in this talk use 1-2 fb^{-1}

$W\gamma \to l\nu\gamma$ @ DØ : Radiation Amplitude Zero (RAZ)



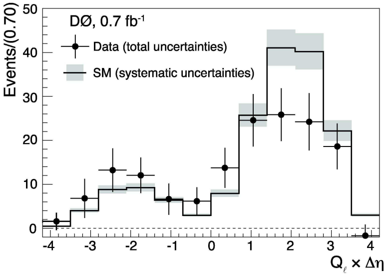


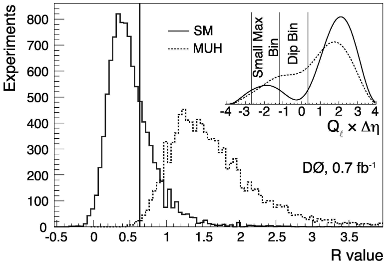
- Photons radiated from the quark and *W* lines interfer destructively
- Classical cancellation at tree-level
- Sensitive to the $WW\gamma$ vertex



Zero is at $+\frac{1}{3}$ for $u\bar{d} \to W^+\gamma$ and $-\frac{1}{3}$ for $d\bar{u} \to W^-\gamma$

No measurement of p_z of ν, use $Q_l \times (\eta_\gamma - \eta_l)$





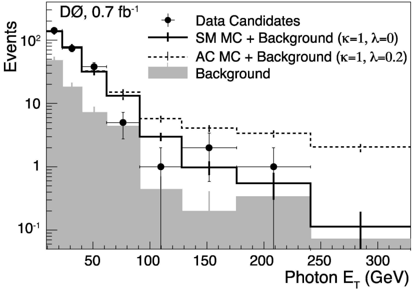
P-value = 0.45% $\Rightarrow$ No dip hyphothesis ruled out at 2.6σ

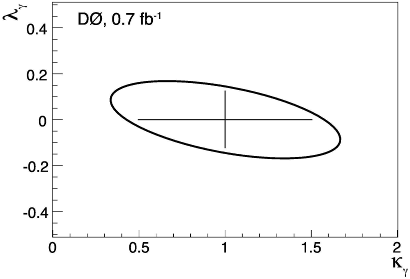
Parameterize deviations in the $WW\gamma$ vertex as $\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{aTGC}$

$$\mathcal{L}_{aTGC}/ig_{WW\gamma} = \Delta\kappa_\gamma W^*_\mu W_\nu F^{\mu\nu} + \frac{\lambda_\gamma}{M_W^2} W^*_{\rho\mu} W^\mu_\nu F^{\nu\rho}$$

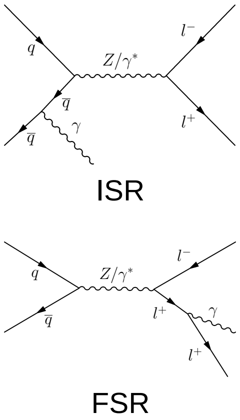
- λ_γ and $\Delta\kappa_\gamma$ are zero in the SM ($\kappa_\gamma = 1 + \Delta\kappa_\gamma$)

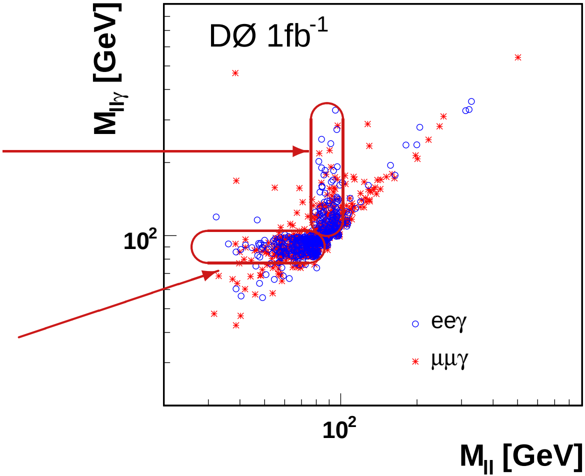
DØ (0.7 fb^{-1})
0.49 < κ_γ < 1.51
-0.12 < λ_γ < 0.13





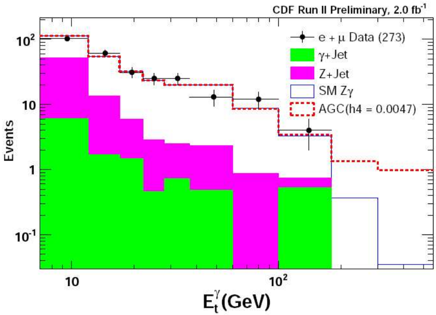
$Z\gamma$ Samples

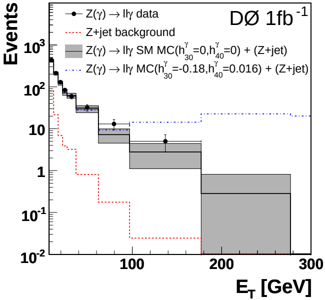




Experiment	Measured Cross-Section	NLO Prediction
DØ	$4.9 \pm 0.3(stat. + syst) \pm 0.3(lumi.)$	4.7 ± 0.2 pb
CDF (ISR)	$1.2 \pm 0.1(stat.) \pm 0.2(syst.) \pm 0.1(lumi.)$	1.2 ± 0.1 pb
CDF (FSR)	$3.4 \pm 0.2(stat.) \pm 0.2(syst.) \pm 0.2(lumi.)$	3.3 ± 0.3 pb

$Z\gamma$ Anomalous Coupling Limits





Experiment Luminosity	CDF 1.1 fb^{-1} e + 2.0 fb^{-1} μ	DØ 1.1 fb^{-1} e & μ
h_3^γ	[-0.084,0.084]	[-0.085,0.084]
h_4^γ	[-0.0047,0.0047]	[-0.0053,0.0054]
h_3^Z	[-0.083,0.083]	[-0.083,0.082]
h_4^Z	[-0.0047,0.0047]	[-0.0053,0.0054]

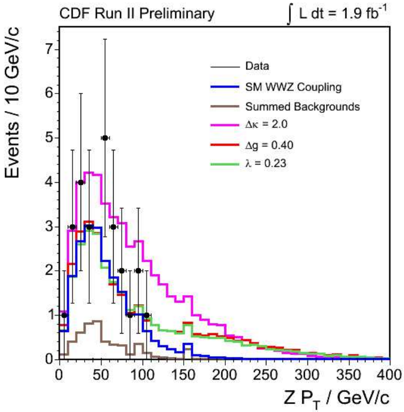
WZ Samples

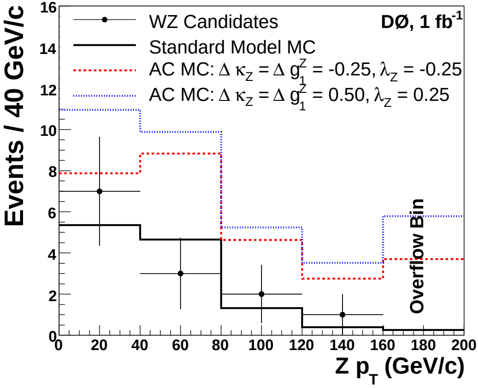
- DØ First Evidence: Summer 2006 ($760 - 860\ pb^{-1}$)
  - Observed 12 evts → 3.3σ evidence
  - 7.5 ± 1.2 signal and 3.6 ± 0.2 background
  - $\sigma(WZ) = 4.0^{+1.9}_{-1.5}\ pb$ [NLO $\sigma(WZ) = 3.7 \pm 0.3\ pb$]
- CDF First Observation: Fall 2006 (1.1 fb^{-1})
  - Observed 16 evts → 5.9σ signal
- CDF Update 1.9 fb^{-1}

Source	Expected ± Stat ± Syst ± Lumi
Z+jets	$2.45 \pm 0.48 \pm 0.48 \pm 0.00$
ZZ	$1.09 \pm 0.01 \pm 0.12 \pm 0.07$
$Z\gamma$	$1.03 \pm 0.06 \pm 0.35 \pm 0.06$
$t\bar{t}$	$0.17 \pm 0.01 \pm 0.03 \pm 0.01$
WZ	$16.45 \pm 0.03 \pm 1.74 \pm 0.99$
Total	$21.19 \pm 0.48 \pm 2.20 \pm 1.12$
Observed	**25**

$$\sigma(WZ) = 4.4^{+1.3}_{-1.0}(stat.) \pm 0.2(syst.) \pm 0.3(lumi.)\text{pb}$$

WZ Anomalous Coupling Limits

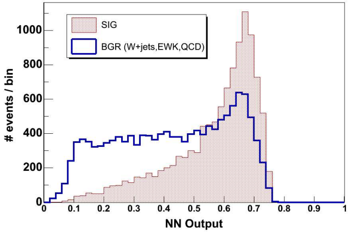




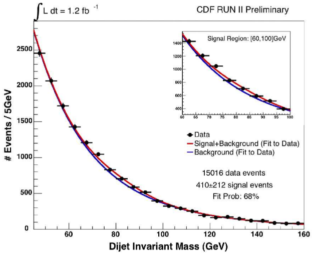
CDF (1.9 fb^{-1})	DØ (1.1 fb^{-1})
$-0.13 < \lambda_Z < 0.14$	$-0.17 < \lambda_Z < 0.21$
$-0.15 < \Delta g_Z < 0.24$	$-0.14 < \Delta g_Z < 0.34$
$-0.82 < \Delta\kappa_Z < 1.27$	$-0.12 < \Delta\kappa_Z = \Delta g_Z < 0.29$

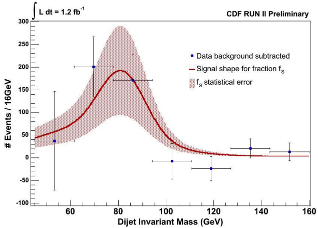
$WW/WZ \to l\nu jj$ @ CDF: A semi-hadronic channel

- Experimentally challenging
  - 5-10 $\times$ more signal
  - 1000 $\times$ more background
- Similar final state to $WH \to l\nu bb$
- Fit m_{jj} distribution



m_{jj}-Unbiased Neural Net





N_{Signal}	410 $\pm$ 212(stat) $\pm$ 107(sys) events
Observed	$\sigma \times \mathcal{B}$ = 1.47 $\pm$ 0.77(stat) $\pm$ 0.38(sys) pb
95% Limit	$\sigma \times \mathcal{B}$ < 2.88 pb
NLO prediction	$\sigma \times \mathcal{B}$ = 2.09 $\pm$ 0.14 pb

ZZ at DØ : Search and anomalous coupling limits

Selection & Search: 4 leptons $\rightarrow$ Very low rate, very low background

- $eeee$, $ee\mu\mu$, & $\mu\mu\mu\mu$ channels
- m_{ll} > 30 GeV/c^2 includes $ZZ/Z\gamma^*$ interference
- Dominant backgrounds
  - Z+jets where two jets are misidentified as leptons
  - $Z\gamma$+jets where the γ and a jet are misidentified as leptons

	$eeee$	$ee\mu\mu$	$\mu\mu\mu\mu$	Total
ZZ Sig	0.44$\pm$0.03	0.81$\pm$0.09	0.46$\pm$ 0.05	1.71$\pm$0.15
Bkg	0.080$\pm$0.021	0.013$\pm$0.004	0.033$\pm$0.006	0.13$\pm$0.03
Observe	**0**	**1**	**0**	**1**

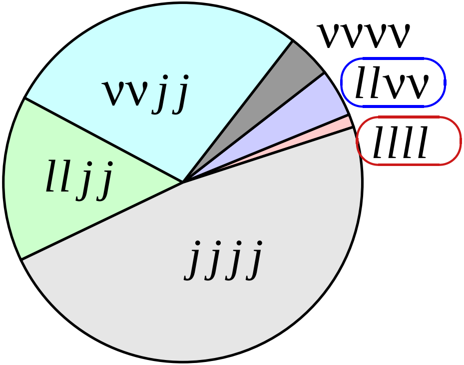
$\sigma(ZZ) < 4.4$ pb compared to 1.6 pb NLO prediction

Anomalous Coupling Limits

- Limit region to m_{ll} > 50 GeV/c^2 for $\mu\mu$ and m_{ll} > 70 GeV/c^2 for ee
- Use yields (all zero) to limit anomalous couplings

$$-0.28 < f_{40}^{Z} < 0.28$$
$$-0.31 < f_{50}^{Z} < 0.29$$
$$-0.26 < f_{40}^{\gamma} < 0.26$$
$$-0.30 < f_{50}^{\gamma} < 0.28$$

CDF ZZ: Two modes instead of one



pie chart includes τs as leptons

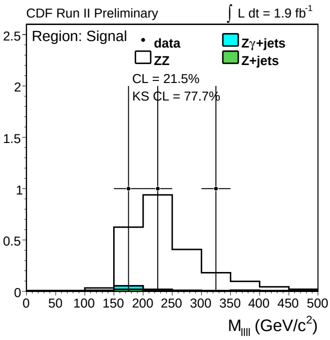
- Very small cross-section $\sigma(p\bar{p} \rightarrow ZZ) = 1.4\ pb$
- Only using e or μ leptons

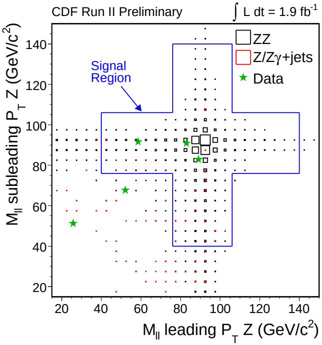
- Two viable modes
- $ZZ \rightarrow 4$ leptons
  - Very clean
  - Very small BR: $(2 \times 0.033)^2 = 0.0044$
- $ZZ \rightarrow ll\nu\nu$
  - 6 times larger BR: $2 \times 0.2 \times (2 \times 0.033) = 0.026$
  - Several significant backgrounds *WW*,*WZ*,Drell-Yan
  - Use Matrix Elements to discriminate signal and background
- The strategy is to combine this into one result

CDF ZZ: The $ZZ \to llll$ Channel

2 $\mu\mu\mu\mu$ Candidates

1 *eeee* Candidate





Category	Candidates without a a trackless electron	Candidates with a a trackless electron
ZZ	$1.990 \pm 0.013 \pm 0.210$	$0.278 \pm 0.005 \pm 0.029$
Z+jets/$Z\gamma$+jets	$0.014^{+0.010}_{-0.007} \pm 0.003$	$0.082^{+0.089}_{-0.060} \pm 0.016$
Total	$2.004^{+0.016}_{-0.015} \pm 0.210$	$0.360^{+0.089}_{-0.060} \pm 0.033$
Observed	**2**	**1**

Backgrounds are measured in 100ths of an event

CDF ZZ: The $ZZ \to ll\nu\nu$ Channel

Looking for 13 $ZZ \to ll\nu\nu$ events in a sample of $\approx$ 250 $ll\nu\nu$ candidates

Use the **full kinematic information**

$$P(\vec{x}_{obs}) = \frac{1}{<\sigma>} \int \frac{d\sigma_{th}(\vec{y})}{d\vec{y}} \epsilon(\vec{y}) G(\vec{x}_{obs}, \vec{y}) d\vec{y}$$

What we measure

$\vec{x}_{obs}$	observed "leptons" and $\vec{\not{E}}_T$

Theory at leading order

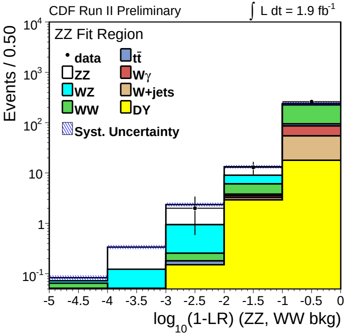
$\sigma_{th}(\vec{y})$	leading order calculation of the cross-section
$\vec{y}$	true lepton four-vectors (including neutrinos)

Detector Effects

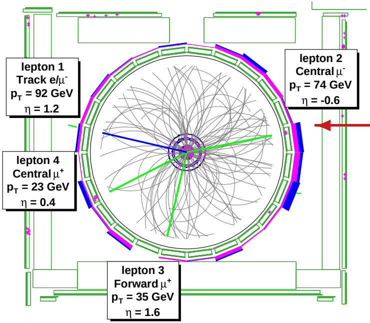
$\epsilon(\vec{y})$	total event efficiency $\times$ acceptance
$G(\vec{x}_{obs}, \vec{y})$	resolution effects

$$LR \equiv \frac{P_{ZZ}}{P_{ZZ} + P_{WW}}$$

- Plot $log_{10}(1 - LR)$ to avoid binning away "Golden Events"

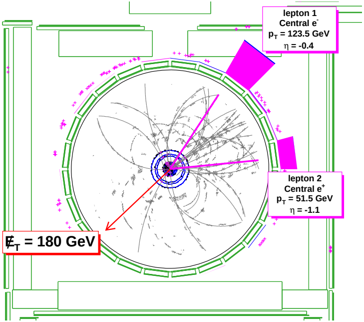


CDF ZZ: Combined $ZZ \to ll\nu\nu$ and $ZZ \to llll$



$\mu\mu\mu\mu$ Candidate

$ee\nu\nu$ Candidate



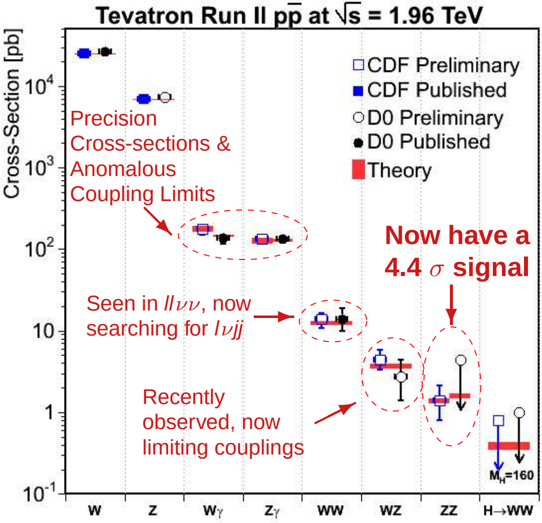
Combined Results

		$ll\nu\nu$	4 lepton	Combined
Significance	P-Value	0.12	1.1×10^{-5}	5.1×10^{-6}
	Significance	$1.2\ \sigma$	$4.2\ \sigma$	$4.4\ \sigma$

Measured Cross-Section $1.4^{+0.7}_{-0.6}(stat.+syst.)$ pb (NLO prediction is 1.4 pb)

50/50 chance of seeing 5σ, Observe a $4.4\ \sigma$ signal for ZZ

Summary



Highlights

- Progress in all modes
- Radiation Amplitude Zero in $W\gamma$
- Increasing *WZ* Samples
- 4.4 σ signal for *ZZ*