WW & *WZ* Dibosons at the Tevatron

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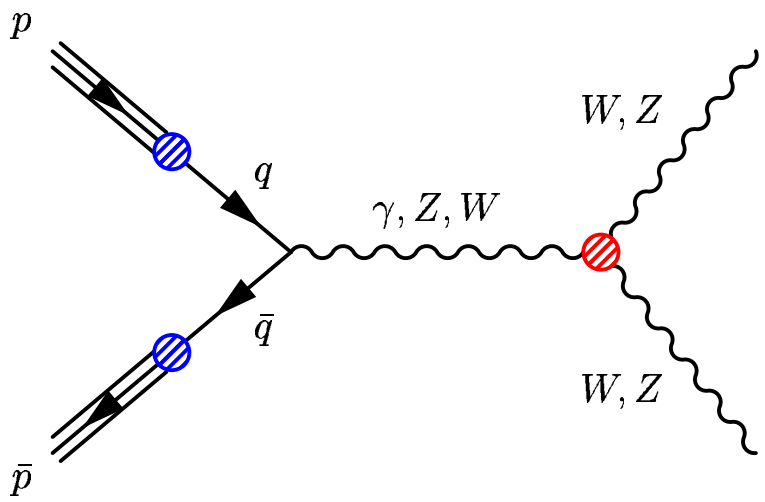
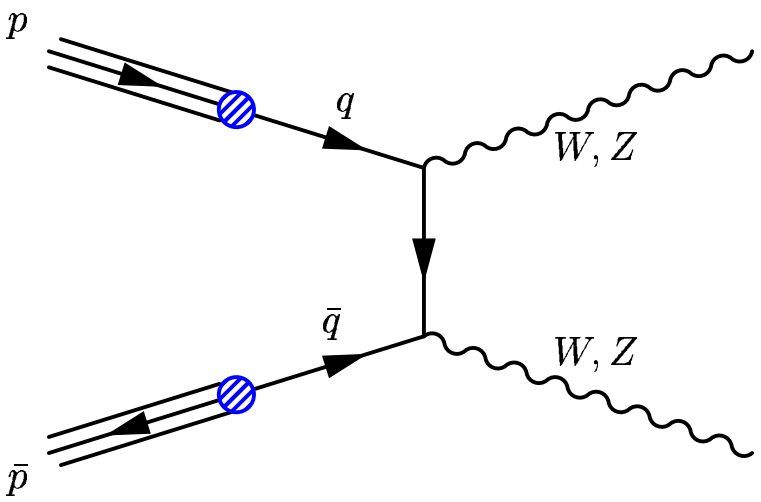
Diboson Production in $\sqrt{s} = 1.96$ TeV $p\bar{p}$ Collisions



s-channel

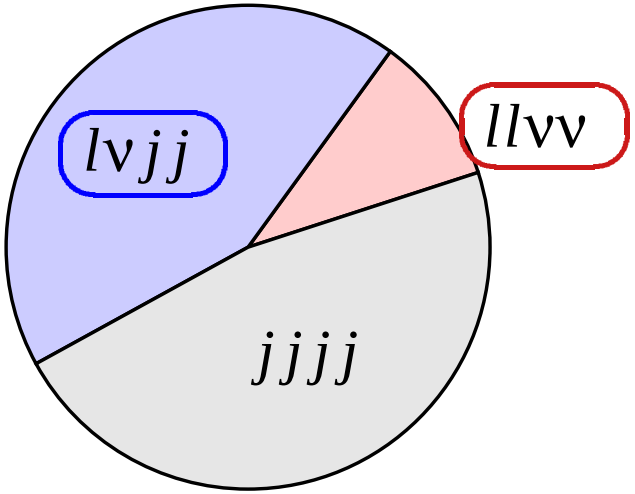


t-channel

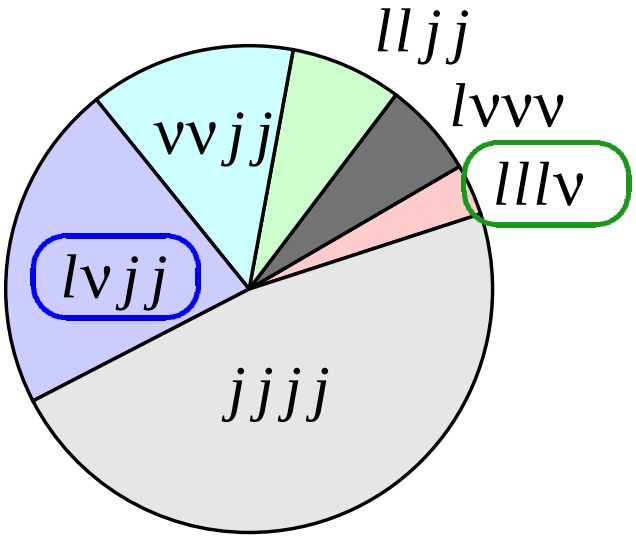
Physic Motivation

- Dibosons are a unique probe of the triple gauge couplings
  - Measure the couplings between γ, W, and Z
  - Couplings can depend on the q^2 of the boson pair
    - Tevatron has the highest q^2 currently available
  - Anomalous couplings can effect cross-sections and kinematics
- $gg \to H \to WW^*$ may be hiding in the WW samples

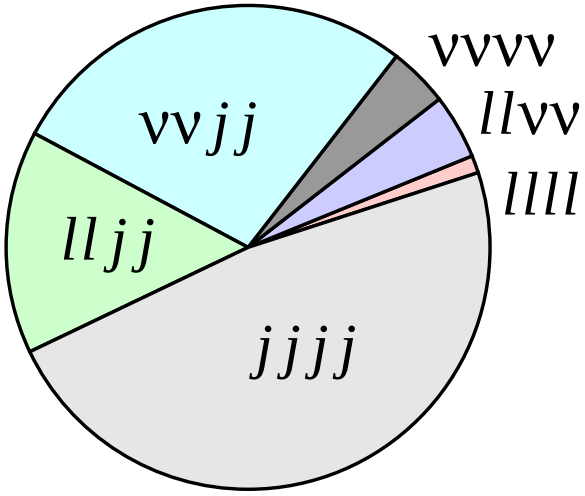
In this talk



$\sigma(p\overline{p} \to WW) = 12.4\ pb$



$\sigma(p\overline{p} \to WZ) = 3.7\ pb$



$\sigma(p\overline{p} \to ZZ) = 1.4\ pb$

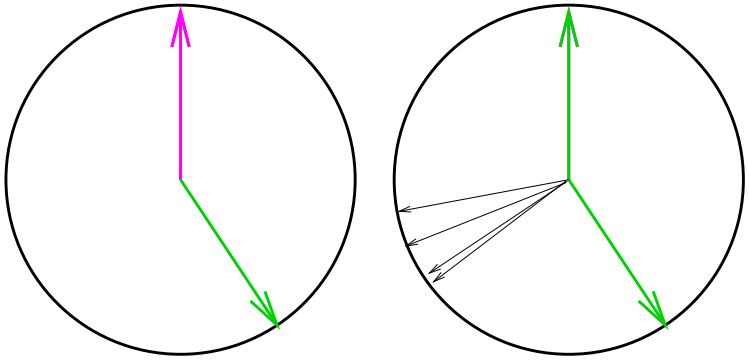
- $WW \to ll\nu\nu$
- $WW + WZ \to l\nu jj$
- $WZ \to lll\nu$
- ZZ, not ready yet
  - both experiments are working on it

$WW \to ll\nu\nu$: A CDF Event

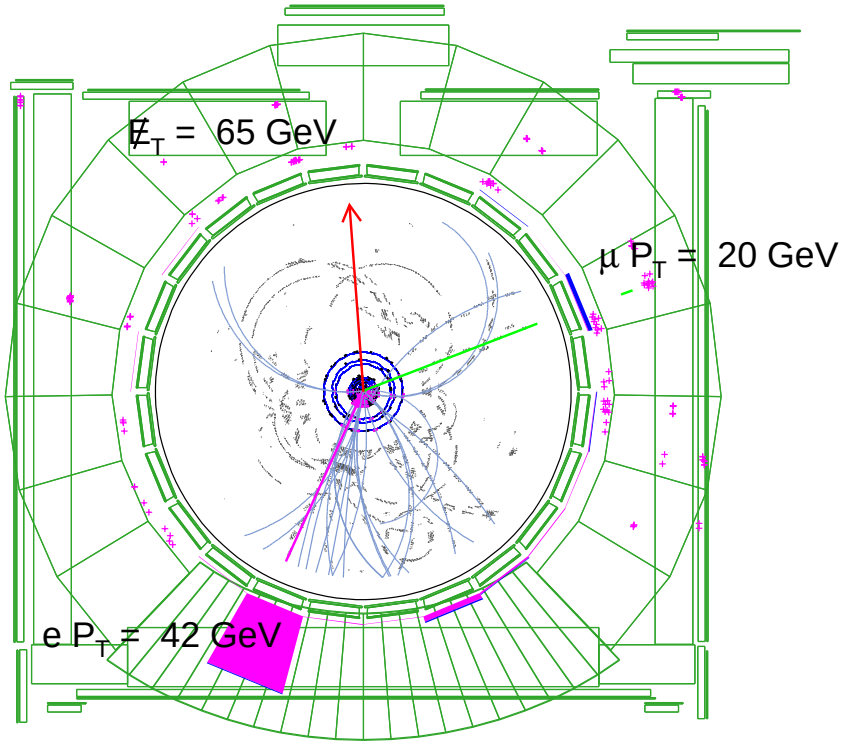
Neutrinos show up as missing transverse energy $\not\!\!E_T$

WW will produce $e\mu$ events, while Drell-Yan is only ee and $\mu\mu$

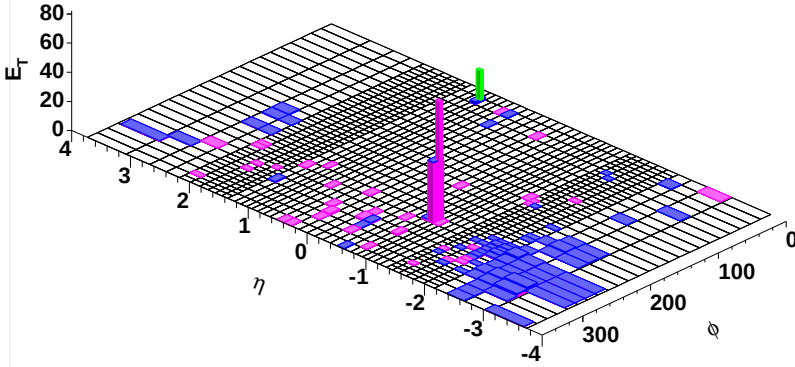
Event Topology Cartoons



WW Drell-Yan



Beam's Eye View of CDF



Calorimeter Unrolled

$WW \to ll\nu\nu$

Selection Outline (example CDF, DØ similar)

- Identify 2 leptons (e or μ)
- Drell-Yan ($q\bar{q} \to \gamma^*/Z \to ll$) is $\mathcal{O}(10^5)$ times bigger
  - Suppress with missing transverse energy $\not{E}_T > 25$ GeV
  - Special *clean up cuts* on $\not{E}_T$
- Suppress $t\bar{t} \to W^+W^-b\bar{b}$: no jets $E_T > 15$ GeV and $|\eta| < 2.5$

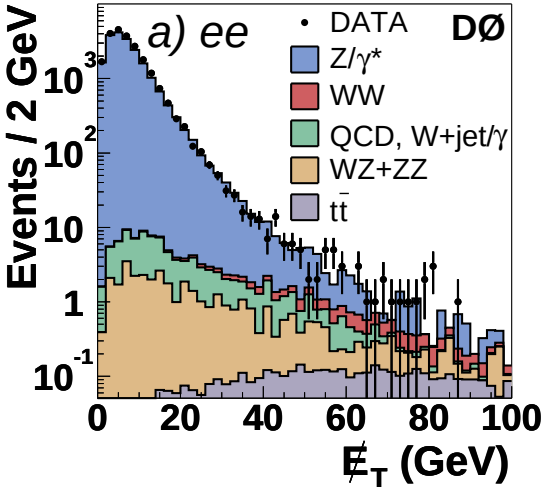
CDF Preliminary with $825 pb^{-1}$

Contribution	Expected Events
SM WW	$52.4 \pm 0.1 \pm 4.3$
Drell-Yan	$11.8 \pm 0.8 \pm 3.1$
W+jets	$11.0 \pm 0.5 \pm 3.2$
$WZ + ZZ$	$7.9 \pm 0.0 \pm 0.8$
$W\gamma$	$6.8 \pm 0.2 \pm 1.4$
$t\bar{t}$	$0.2 \pm 0.0 \pm 0.0$
Sum Bkg	$37.8 \pm 0.9 \pm 4.7$
Total Expected	$90.2 \pm 0.9 \pm 6.4$
Data	95

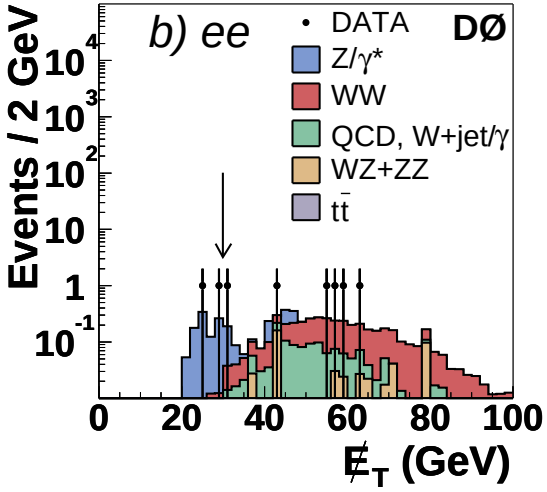
DØ ($224 - 252\ pb^{-1}$):

25 evts with bkg of 8.1 ± 0.6(stat) ± 0.6(sys) ± 0.5(lumi)

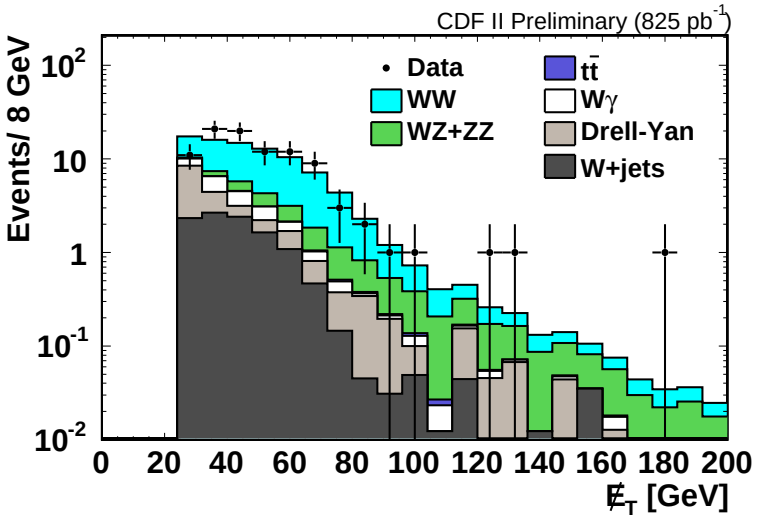
$WW \to ll\nu\nu$



DØ before other cuts



DØ after other cuts



DØ (224 – 252 pb^{-1})

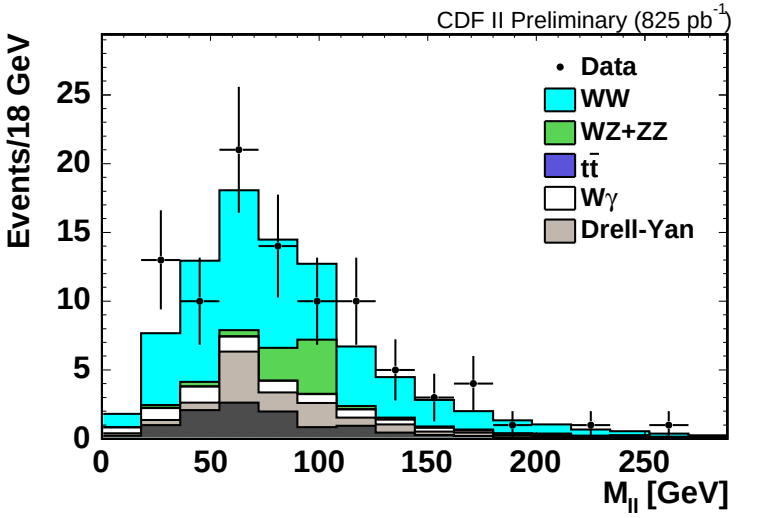
$$\sigma = 13.8^{+4.3}_{-3.8}(stat)^{+1.2}_{-0.9}(sys) \pm 0.9(lum)\ pb$$

CDF (825 pb^{-1})

$$\sigma = 13.6 \pm 2.3(stat) \pm 1.6(sys) \pm 1.2(lum)\ pb$$

NLO Theory: Campbell,Ellis

$$\sigma^{WW}_{NLO} = 12.4 \pm 0.8\ pb$$



CDF with 825 pb^{-1}

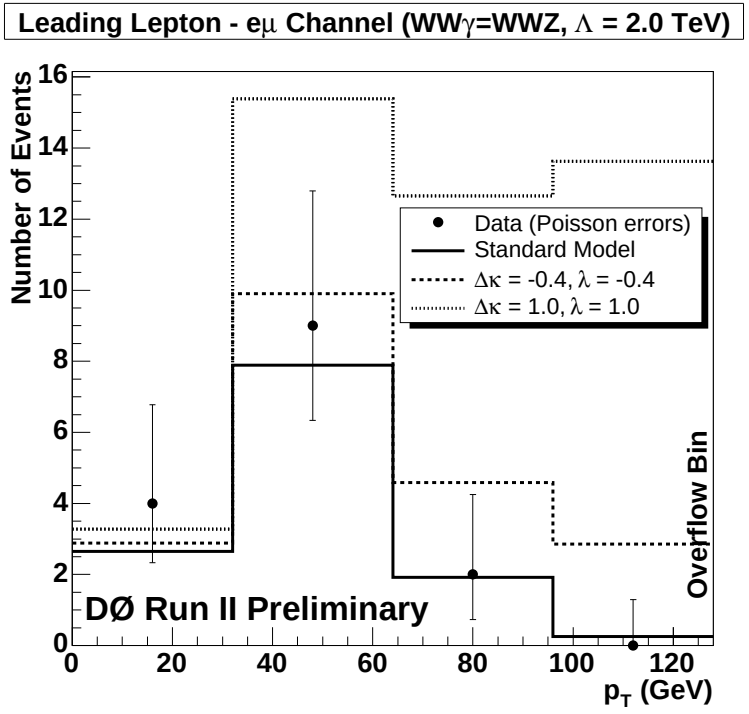
$WW \to ll\nu\nu$: DØ Extraction of Coupling limits

- General extension of SM Lagrangian

$$\begin{aligned}\mathcal{L}_{WWV} &= ig_1^V(W_{\mu\nu}W^\mu V^\nu - W_\mu V_\nu W^{\mu\nu}) \\ &+ i\kappa_V W_\mu W_\nu V^{\mu\nu} + \frac{i\lambda_V}{M_W^2} W_{\lambda\mu} W^\mu_\nu V^{\nu\lambda}\end{aligned}$$

- In Standard Model: $\kappa_\gamma = \kappa_Z = g_1^Z = 1$ and $\lambda_Z = \lambda_\gamma = 0$

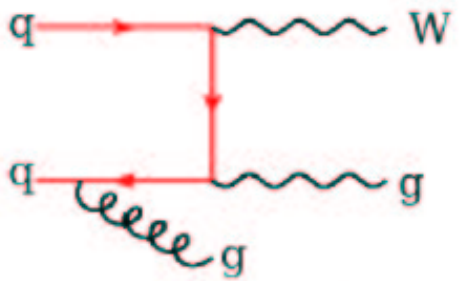
- Couplings parameters $\kappa_\gamma, \lambda_\gamma, \kappa_Z, \lambda_Z, g_1^Z$ are functions of $\hat{s}$
  - DØ uses standard parameterization $\alpha(\hat{s}) = \alpha_0/(1+\hat{s}/(2TeV)^2)^2$
- Use several different schemes to reduce 5 parameters to 2 $\Delta\kappa$ and λ
- Fit the leading lepton p_T spectrum
- Equal Coupling Scheme: $-0.32 < \Delta\kappa < 0.45$, $-0.29 < \lambda < 0.30$



DØ ($224 - 252\ pb^{-1}$)

$WW + WZ \rightarrow l\nu jj$ at CDF

WW/WZ TGC diagram



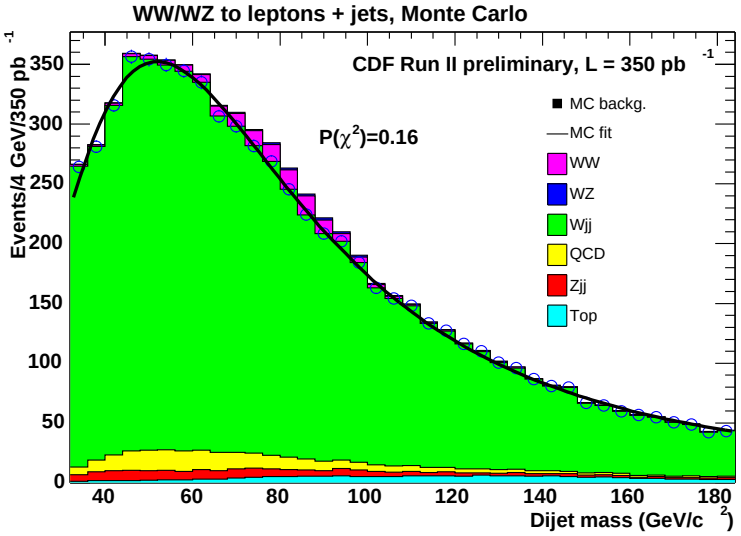
Example W+2j diagram

- $\approx 4\times$ larger BR $WW \rightarrow ll\nu\nu$
- $\approx 10\times$ larger BR $WZ \rightarrow lll\nu$
- Large background from W+jets (need to understand W+jets)
  - falls at high p_T where anomalous couplings can enhance signal

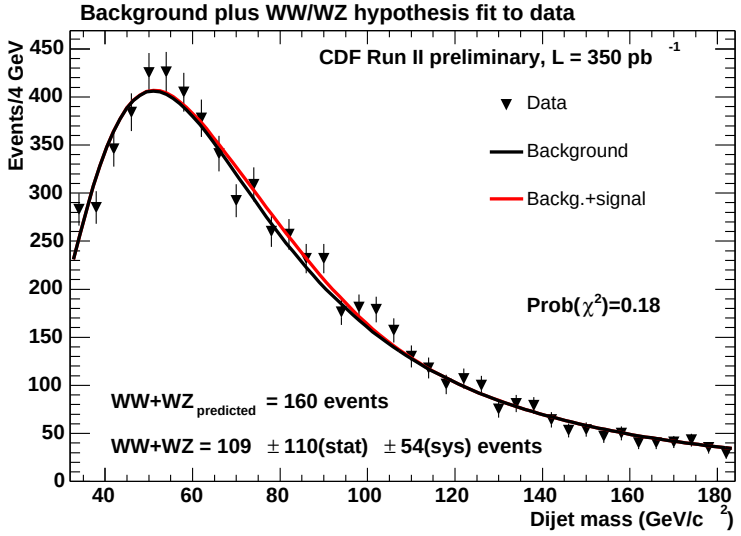
Selection Outline

- 1 lepton (p_T>25 GeV), $\not{E}_T$ > 25 GeV
- $\geq$2 jets (p_T > 15 GeV)

$\sigma(WW + WZ) < 36\ pb$ @95% CL

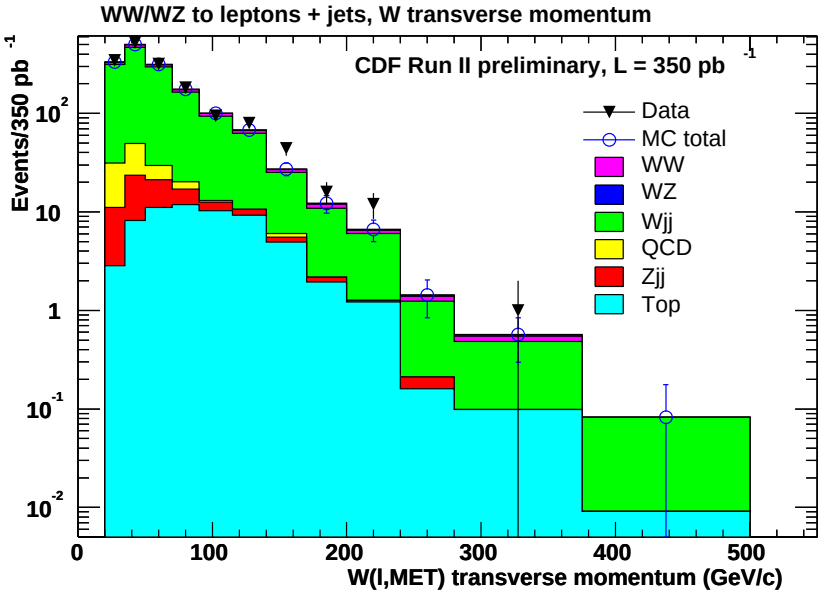


Monte Carlo



Data

$WW + WZ \to l\nu jj$: Anomalous Couplings at CDF



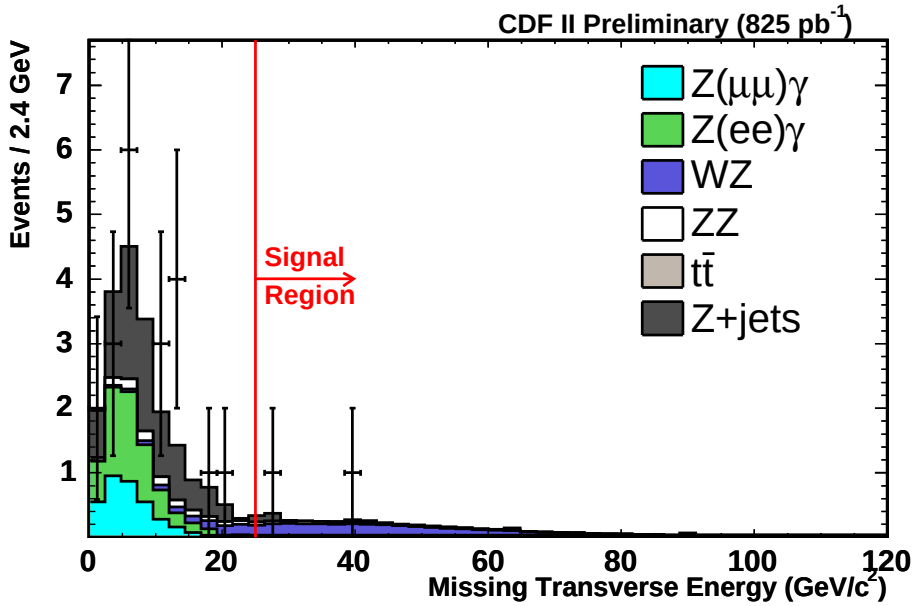
$W(l, \not{E}_T)\ p_T$

- Select dijet mass $56 < m_{jj} < 112$ GeV peak region
- Minimize likelihood for $W(l, \not{E}_T)\ p_T$ distribution
  - Anomalous couplings tend to enhance the rate at high p_T
- Results ($\Delta\kappa = \lambda = 0$ in the Standard Model)

$$-0.51 < \Delta\kappa < 0.44 \qquad\qquad -0.28 < \lambda < 0.28$$

- Coupling constants are order unity in SM

$WZ \to lll\nu$



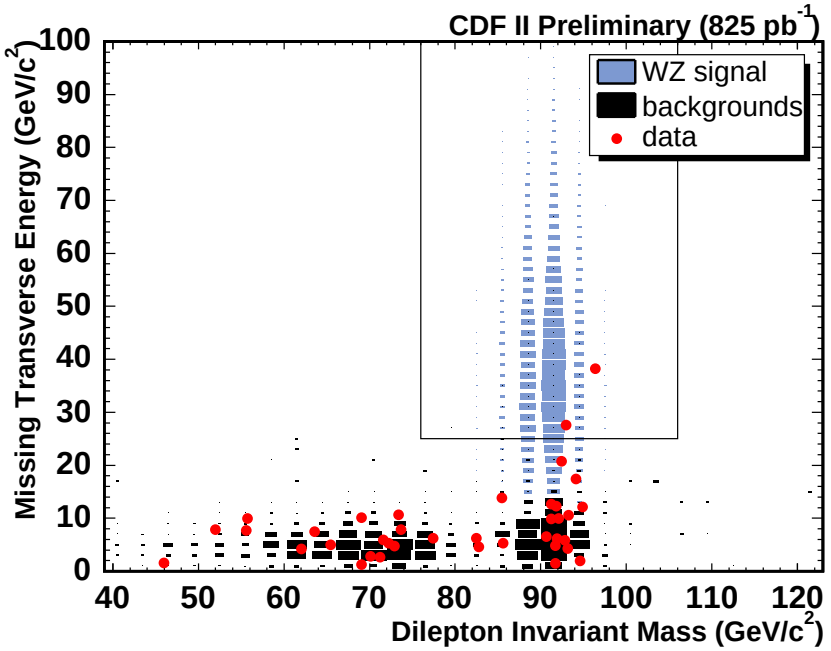
- Total acceptance scales as approximately lepton acceptance cubed (DØ $A \times \epsilon \approx 0.16 - 0.21$)
- Both experiments have optimized the selections for efficiency and acceptance

Selection Outline

- 3 leptons (e or μ)
  - CDF: leading lepton: p_T>20 GeV, others:p_T>10 GeV
  - DØ : p_T>15 GeV for all leptons
- 1 same-flavor opposite sign lepton pair in Z-mass window
- Main background: Z+jets and $Z\gamma$ suppressed with $\not{E}_T$ requirement

$WZ \to lll\nu$: CDF Limit

Mode	Expected $\pm$ stat. $\pm$ syst.
WZ	$3.72 \pm 0.02 \pm 0.15$
ZZ	$0.50 \pm 0.01 \pm 0.05$
$Z\gamma$	$0.03 \pm 0.01 \pm 0.01$
$t\bar{t}$	$0.05 \pm 0.01 \pm 0.01$
Z+jets	$0.34 \pm 0.07\ ^{+0.15}_{-0.09}$
Bkg Sum	$0.92 \pm 0.07\ ^{+0.16}_{-0.10}$
Exp Yield	$4.64 \pm 0.07\ ^{+0.22}_{-0.18}$
Data	**2**



CDF (825 pb^{-1})

Limit

$\sigma(WZ) < 6.3\ pb$ @ 95% CL

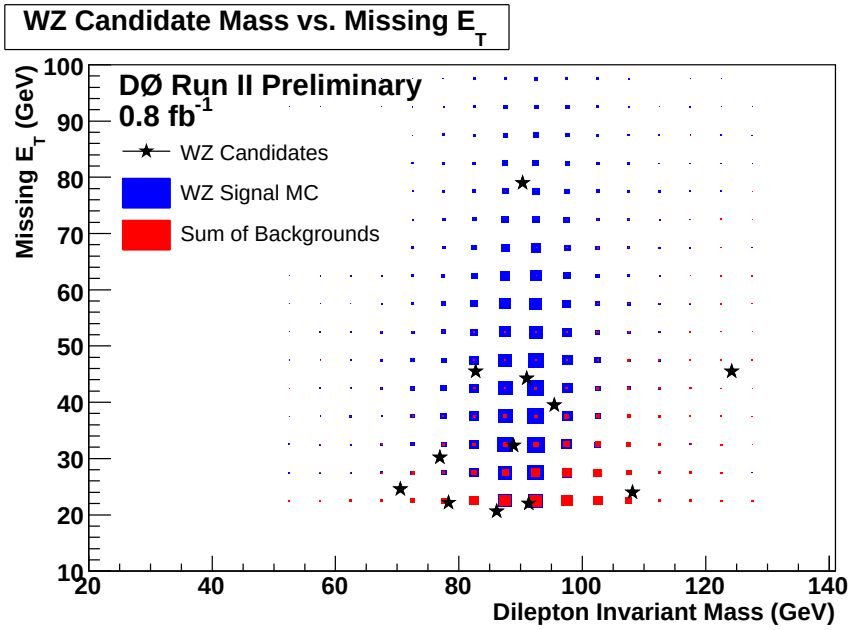
NLO Theory: Campbell,Ellis

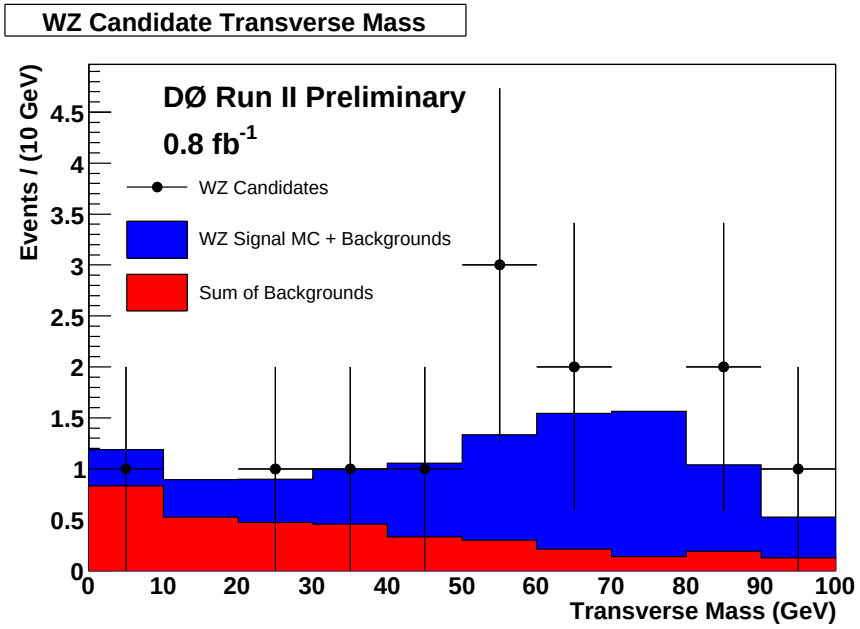
NLO $\sigma(WZ) = 3.7 \pm 0.1\ pb$

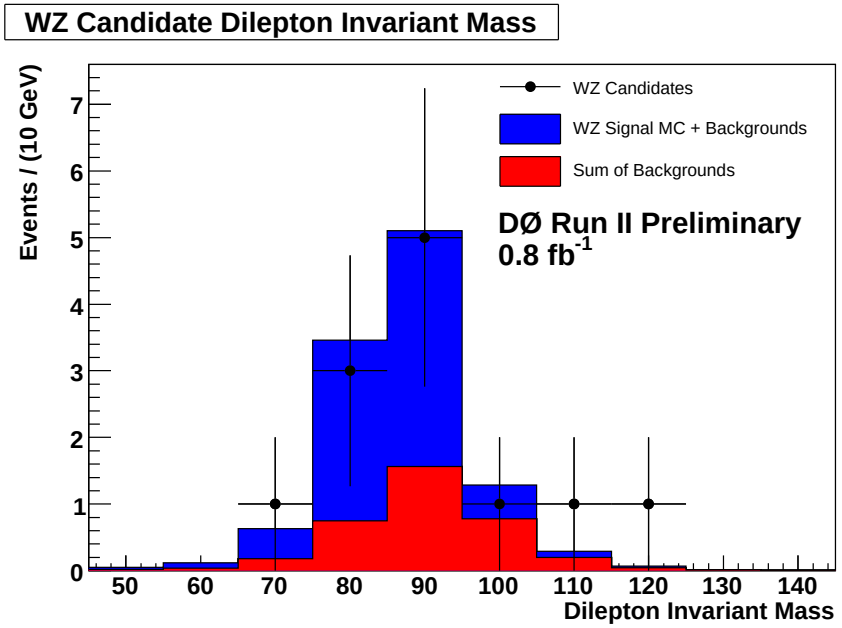
- observed 2 evts
- expected 3.7 ± 0.3 signal and 0.9 ± 0.2 background
- probability of observed given expectation 15%

$WZ \to lll\nu$: DØ , First Evidence

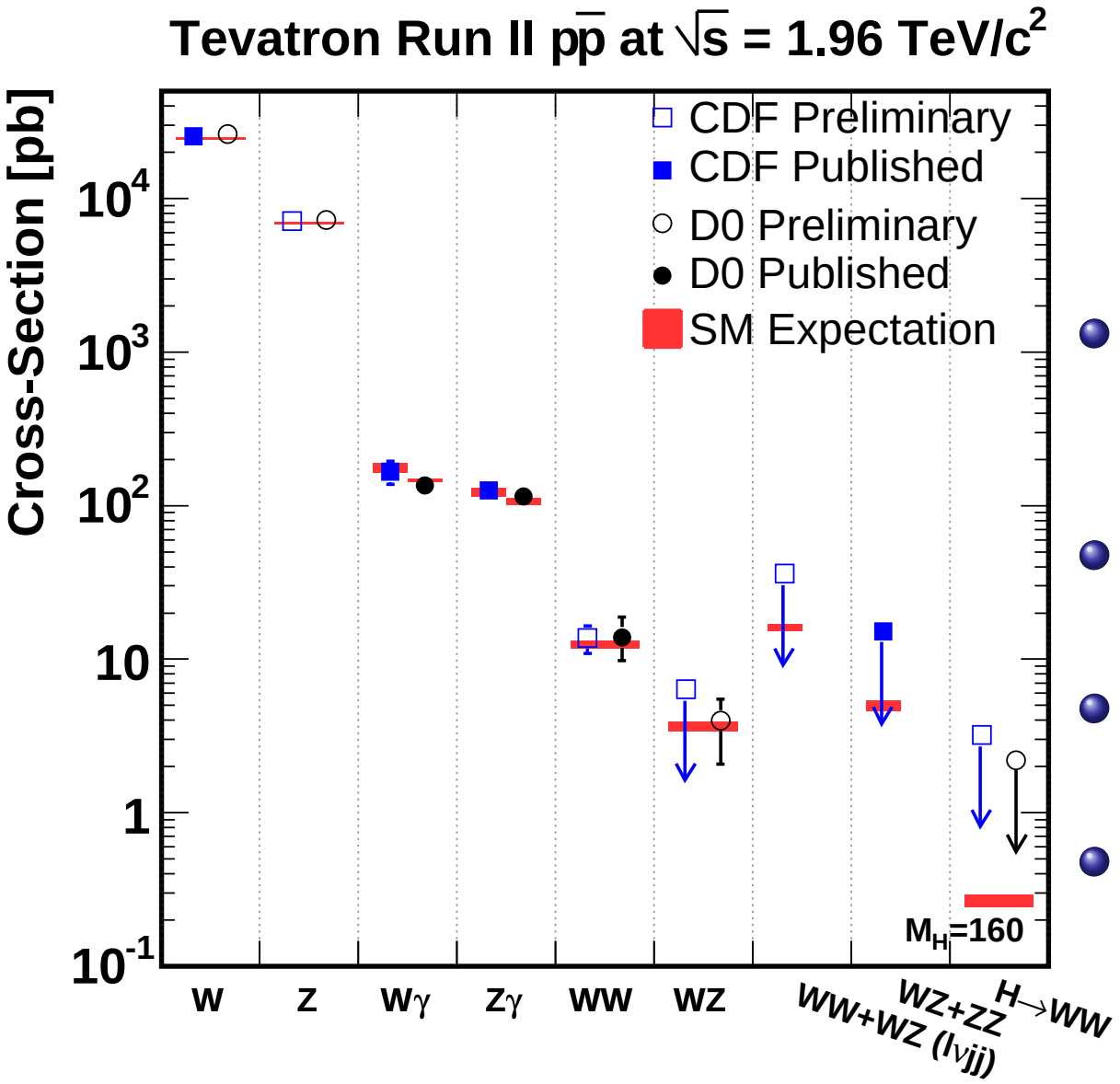
- $760 - 860\ pb^{-1}$ of data
- Observed 12 evts!
- Expected 7.5 ± 1.2 signal and 3.6 ± 0.2 background
- 3.3σ evidence
- $\sigma(WZ) = 3.98^{+1.91}_{-1.53}\ pb$
  - NLO $\sigma(WZ) = 3.7 \pm 0.1\ pb$







Summary



- Measuring Triple Gauge Couplings at high-q^2
- Significant samples WW being collected
- First Evidence for $p\bar{p} \to WZ$ production
- $p\bar{p} \to ZZ$ is next!