WZ Anomalous Couplings and *ZZ* at CDF

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Fermilab Wine & Cheese
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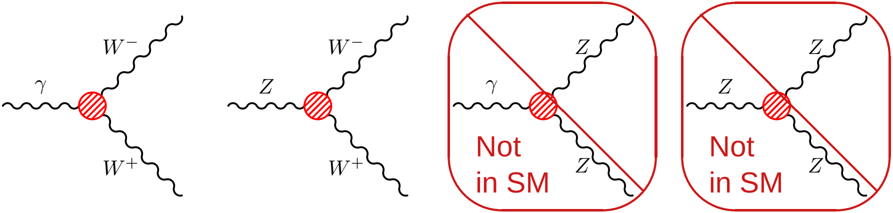
Outline

- Diboson Motivation
- The CDF WZ Sample
- Limits on Anomalous WWZ Couplings
- Measurement of the ZZ Cross-section

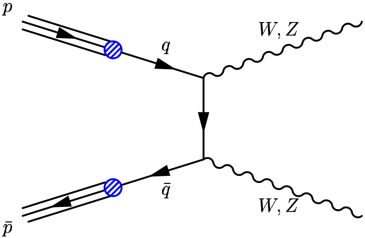
The Group Structure is a Key Ingredient to Electroweak Symmetry Breaking

- $SU(2)_L \otimes U(1)_Y \to U(1)_{em}$
- Relationships between the masses and couplings of the W and Z
- Triple and quartic gauge coupling predictions

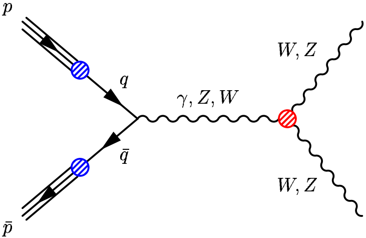


Measuring How Bosons Couple to Each Other

Diagrams Contributing to Diboson Production



t-channel



s-channel

- Boson to Fermion Couplings
- Tested extensively in
  - nuclear β-decay
  - μ, τ decay
  - Strange, charmed, and bottom decay
  - W/Z production and decay

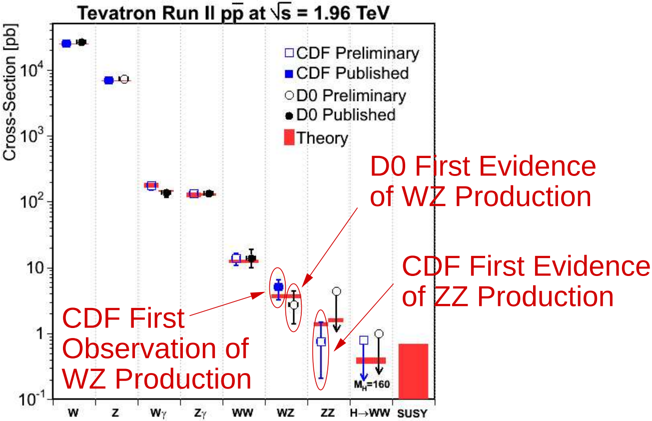
Highest energies are at Tevatron

- Boson to Boson Couplings:
- Indirect tests ($\approx$ low energy):
  - $(g-2)_\mu$, $b \to s\gamma$
  - Atomic parity violation
  - Precision Z measurements
- Direct tests in Dibosons
  - WW and ZZ at LEP
  - WZ isolates WWZ vertex

Demonstrate and Push Sensitivity

Finding very small multilepton signals

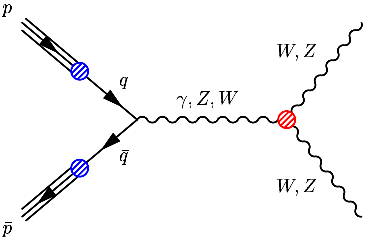
Now sensitive to pair producing heavy electroweak particles



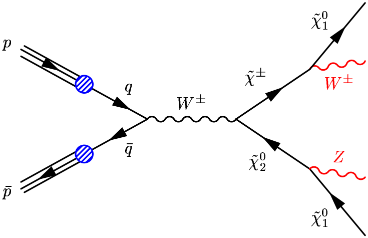
Recently Rapid Progress in Finding New Final States

Heavy Diboson Motivation Summary

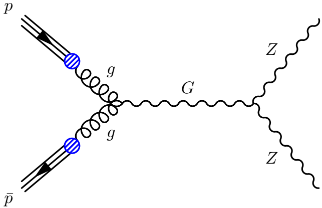
- Access to the Gauge Boson Self-Couplings



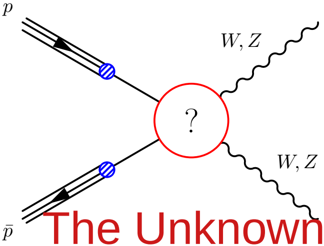
- Possible New Physics: e.g SUSY



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



- Possible New Physics

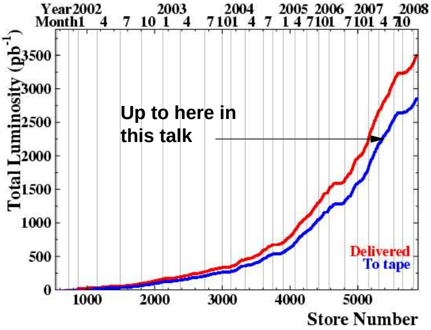


The Unknown

The CDF Experiment

The Tevatron provides $p\bar{p}$ collisions at $\sqrt{s}$ =1.96 TeV

- 1.9 fb^{-1} used in this talk
  - Data up to Apr 1, 2007
- > 2.5 fb^{-1} on tape
  - Inclusion of this data is well underway

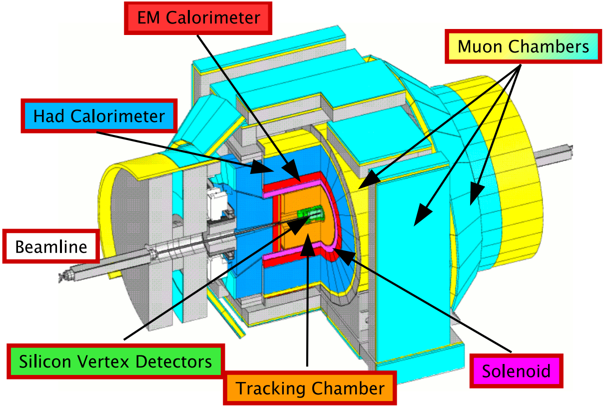


Produced in 1.9 fb^{-1}

$\approx$	10,000,000	$W \to l\nu$
$\approx$	1,000	$WW \to ll\nu\nu$
$\approx$	12	$ZZ \to llll$

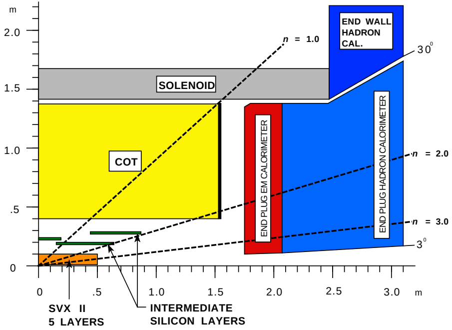
where l=e or μ

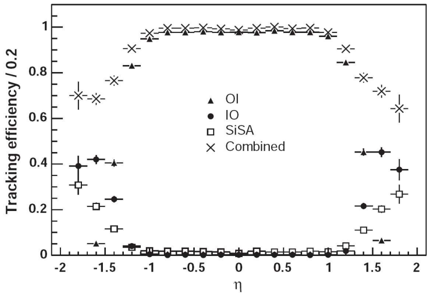
The CDF Detector



- Segmented sampling calorimeters
- Shower maximum detectors
  - Shower shape measurement
  - Central: gas-based
  - Forward: scintillator
- Muon Chambers
  - CMU & CMP ($|\eta| < 0.6$)
  - CMX ($0.6 < |\eta| < 1.0$)

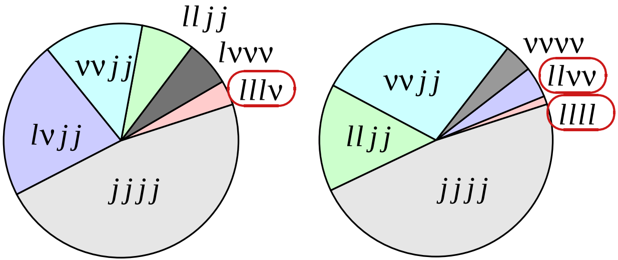
The CDF Tracking





- Silicon coverage out to $|\eta| < 2.0$
- Drift layers crossed decreases from 100% at $|\eta| < 1$ to 0 at $|\eta| < 2$
- Central tracking $|\eta| < 1$: efficiency $\approx$ 100% (Outside-In=OI)
- Silicon-seed tracks (Inside-Out=IO)
  - Increase high η tracking efficiency
- Forward electrons use shower seeded tracks (Phoenix tracks)

Choosing a Decay Mode to Use



WZ *ZZ*

Fully Leptonic

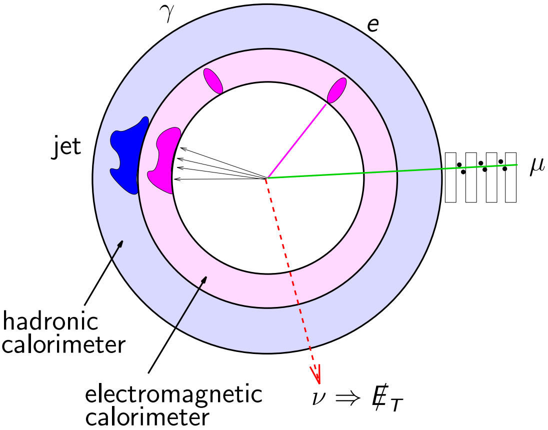
- Small branching fractions
- Low backgrounds
- Controllable backgrounds

Semileptonic

- $\approx 5 - 10\times$ branching fractions
- $\approx 1000\times$ backgrounds
- Complicated detector and nonperturbative physics in backgrounds

Finding electrons, muons, and neutrinos

- $\approx$ 1000 times more jets than leptons!
  - hadronic fluctuations
  - decay in flight
  - heavy flavor
  - fakes either e or μ
- $W\gamma$ and $Z\gamma$ still 100 times bigger
  - photons convert to e^+e^- in material

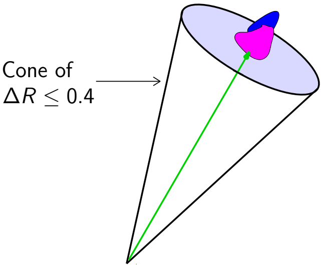


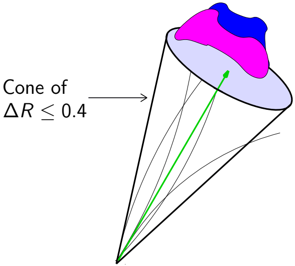
- $\not\!\!E_T$: Measure neutrinos with transverse momentum balance
  - "Missing Transverse Energy"
  - EM and hadronic components measured in calorimeters
  - Corrected for muons

Technique Overview: Isolation

Powerful handle to separate leptons from boson decay from the products of hadronic processes

Boosted Cone: $\Delta R \equiv \sqrt{\Delta\phi^2 + \Delta\eta^2}$





Real Leptons from Boson Decay

- Electrons from converted photons from diboson decays also isolated

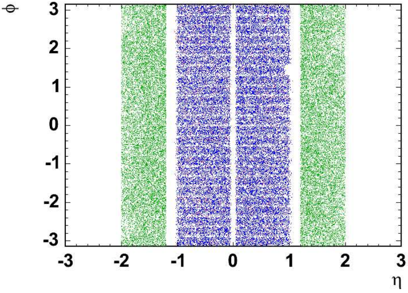
Fake or *Real* Leptons in Jet

- Real leptons in jets from flavor decay (π, K, D, B,...) and photon conversions

Cut: non-lepton related energy <10% of the lepton energy in the cone

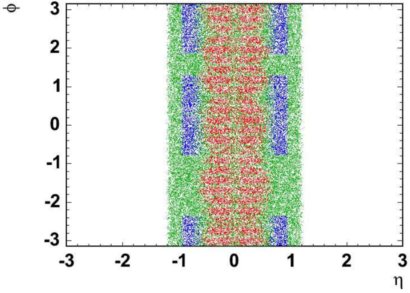
Extended Lepton Acceptance

Lepton Types used in Typical CDF Analyses



Standard Electron Id

- Central Electron
- Forward Electron



Standard Muon Id

- μ chambers CMUP and CMX
- Minimum Ionizing Tracks

Increase acceptance by...

- Use nearly every track and electromagnetic shower found
- Use as much information as possible for each candidate

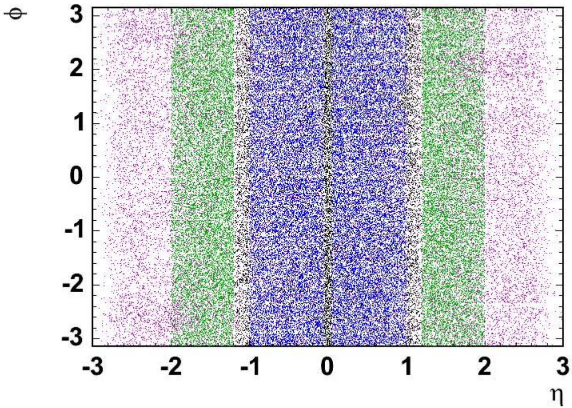
Increasing Electron Acceptance

Central Electrons

- Fiducial to central shower max

Forward Electrons

- Fiducial to forward shower max
- With or without a silicon-base track



Isolated Tracks

- If not fiducial to a shower max detector

All fiducial EM showers used, Tracks fill in calorimeter gaps

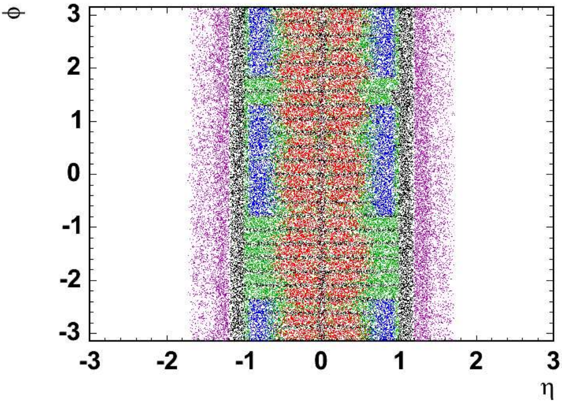
Increasing Muon Acceptance

Two sets of central muons chambers

- CMUP ($|\eta| < 0.6$)
- CMX ($0.6 < |\eta| < 1.0$)

Minimum ionizing tracks

- Fiducial to central calorimeter
- Fiducial to forward calorimeter



Isolated Tracks

- If not fiducial to a shower max detector

All tracks with drift chamber hits used including very forward tracks

The CDF WZ Sample

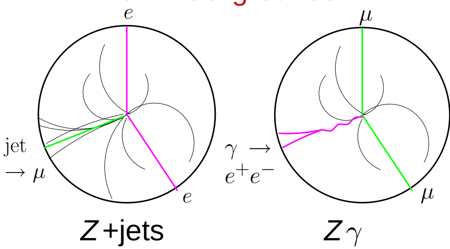
- Define selection for candidate events
- Construct a model of the signals and backgrounds
- Test the model
- Look at the results

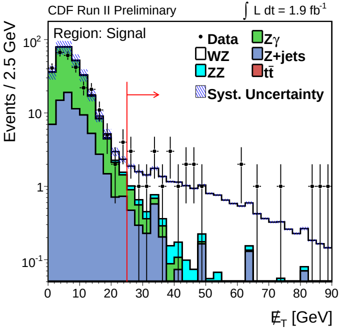
First observation of WZ was published with 1.1 fb^{-1}
Now extending to anomalous coupling limits with 1.9 fb^{-1}

Event Selection for $WZ \rightarrow lll\nu$

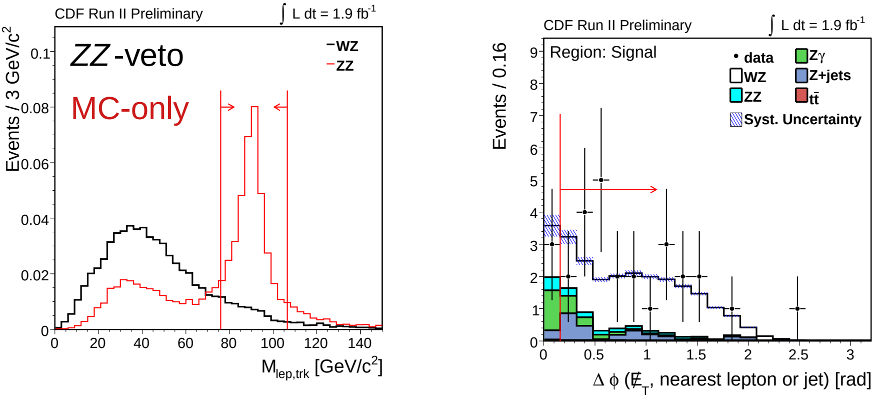
- 3 leptons from types just shown
  - one: $p_T > 20$ GeV for triggering
  - two more with $p_T > 10$ GeV
- 4 Different Triggers: Two central μ, Central *e*, Forward *e* + $\not\!\!E_T$
- Missing transverse energy $\not\!\!E_T$>25 GeV
  - Indicates presence of neutrino
- One pair of same-flavor opposite-sign leptons consistent with Z-mass
  - $76 < m_{ll} < 106$ GeV
  - Tracks without calorimeter information can be either flavor
  - Showers without tracks can be either charge

Main Backgrounds





Event Selection for $WZ \rightarrow lll\nu$



- ZZ veto: No tracks with $p_T > 8$ GeV in event make a Z-mass with any of the 3 leptons
- min $\Delta\phi(\not{E}_T, l \text{ or jet})$)>0.16
  - Assures quality of $\not{E}_T$
- Selection optimized using independent background samples

Signal and Background Modeling

Monte Carlo Derived Contributions

- WZ, ZZ, $Z\gamma$(special generator), $t\bar{t}$: Pythia + GEANT
- Corrected with measured lepton id efficiency & γ-conversion rate

Data Derived Estimate of Z+jets Background

- Measure the rate jets are misidentified as leptons in multi-jet QCD data
  - not many real leptons in jet data
  - Assumes jets in multi-jet events are the same as in Z+jets
  - Select jets where this is more likely to be true $\rightarrow$ "denominator"

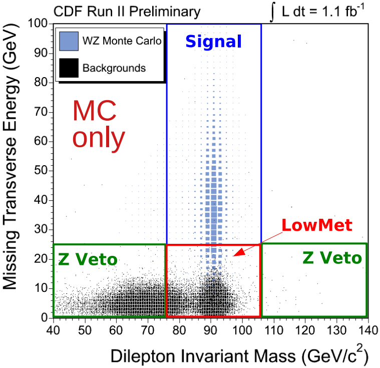
1. Calculate in the jet data

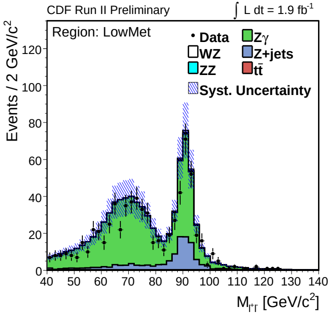
$$\text{Fake Rate} = \frac{\#\text{Identified Leptons}}{\#\text{Denominator Objects}}$$

2. Correct for W and Z contamination using Monte Carlo
3. Scale data Z+"denominator object" events by measured fake rate

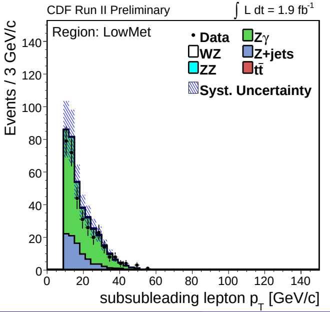
Control Regions: Testing the Sample Modeling

- Low $\not\!\!E_T$ tests background modeling
  - Z-veto region mostly $Z\gamma$
  - LowMet in Z-mass region 50/50 $Z\gamma$ and Z+jets



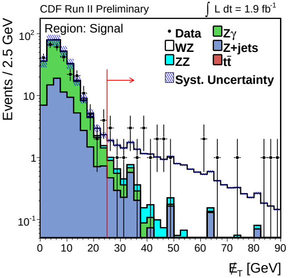


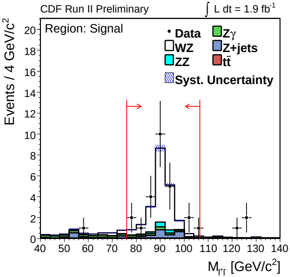
m_{ll} in Both Regions

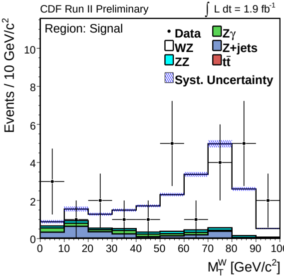


Lowest p_T lepton in Z-mass Region

WZ Signal Region







- First Observation with 16 events in 1.1 fb^{-1}
  - 5.9 σ significance using likelihood with 2 $\not\!\!E_T$ bins
  - PRL 98, 161801 (2007)

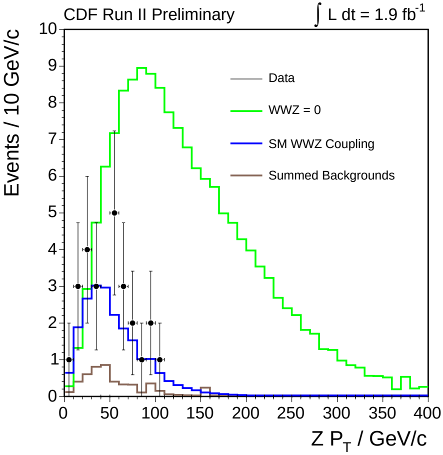
Source	Expected ± Stat ± Syst ± Lumi
Z+jets	2.45 ± 0.48 ± 0.48 ± 0.00
ZZ	1.09 ± 0.01 ± 0.12 ± 0.07
$Z\gamma$	1.03 ± 0.06 ± 0.35 ± 0.06
$t\bar{t}$	0.17 ± 0.01 ± 0.03 ± 0.01
WZ	16.45 ± 0.03 ± 1.74 ± 0.99
Total	21.19 ± 0.48 ± 2.20 ± 1.12
Observed	**25**

Updated to 1.9 fb^{-1}:

$$\sigma(WZ) = 4.4^{+1.3}_{-1.0}(stat.) \pm 0.2(syst.) \pm 0.3(lumi.)\text{pb}\ [\sigma(WZ)_{NLO} = 3.7\text{pb}]$$

Limits on Anomalous *WWZ* Couplinigs

- If there were no *WWZ* vertex we would see it in the cross-section
- This section is about making quantative limits on anomalous *WWZ* couplings using our *WZ* sample

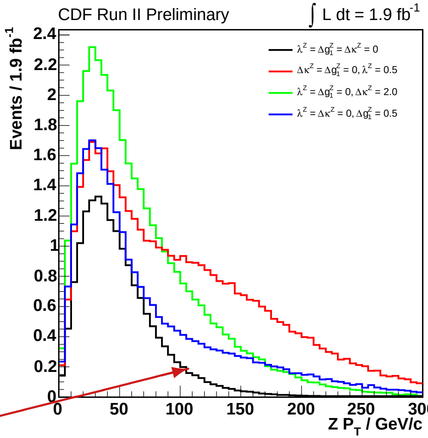


Parameterizing the *WWZ* Vertex

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

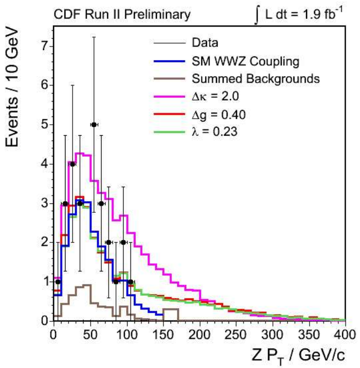
$$\begin{aligned} \mathcal{L}_{aTGC}/ig_{WWZ} &= \Delta g(W^*_{\mu\nu}W^{\mu}Z^{\nu}W_{\mu\nu}W^{*\mu}Z^{\nu}) \\ &+ \Delta\kappa W^*_{\mu}W_{\nu}Z^{\mu\nu} + \frac{\lambda}{M_W^2}W^*_{\rho\mu}W^{\mu}_{\nu}Z^{\nu\rho} \end{aligned}$$

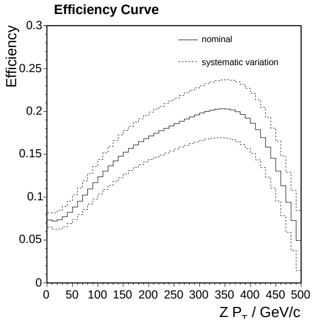
- λ, Δg, and $\Delta\kappa$ are zero in the SM
- Effect of anomalous couplings grow with $M_{WZ} \equiv \hat{s}$
- Use Z p_T as a measure of $\hat{s}$



Standard Model

Likelihood Construction





Efficiency curve applied

$$\mathcal{L} = \prod_i \frac{\mu_i^{N_i} e^{-\mu_i}}{N_i!}$$

where

- N_i is observed yield in bin i
- μ_i is the prediction for the bin

$$\mu_i = S_i(\lambda, \Delta g, \Delta\kappa) + bkg_i$$

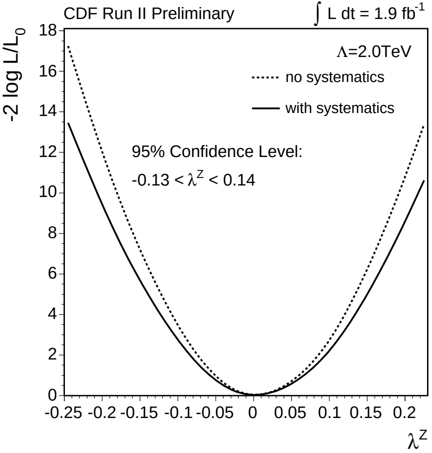
- S_i is the signal expected for a given set of couplings calculated at NLO with MCFM

Limits Extracted from Likelihood

- Effects of couplings get too large at high $\hat{s}$
  - Introduce form-factor to turn off coupling at high $\hat{s}$

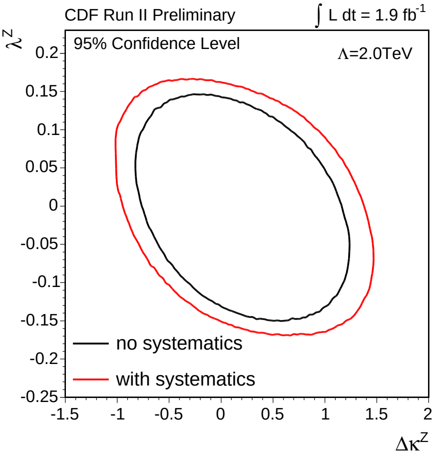
$$\frac{1}{(1+\hat{s}/\Lambda^2)^2}$$

- Limits extracted from $-2\Delta \log \mathcal{L}$
- Systematics
  - Dependence of efficiency on couplings
  - Zero-width Z approximation
  - NLO effects
  - Background modeling
  - Luminosity
  - Signal Acceptance



WWZ Coupling Limits

2d limits with the third parameter fixed to SM value



Example 2-d Limit

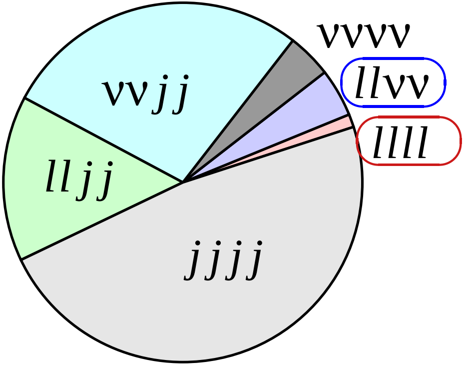
1d limits with the other two parameters fixed to SM value (zero)

CDF (1.9 fb^{-1})	DØ (1 fb^{-1})
$-0.13 < \lambda < 0.14$	$-0.17 < \lambda < 0.21$
$-0.15 < \Delta g < 0.24$	$-0.14 < \Delta g < 0.34$
$-0.82 < \Delta\kappa < 1.27$	

- DØ made different assumptions for $\Delta\kappa$ so limits are not comparable

The Search for *ZZ* Production

Two modes are better than one



pie chart includes τs as leptons

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

- Two viable modes
- $ZZ \to$ 4 leptons
  - Very clean
  - Very small BR: $(2 \times 0.033)^2 = 0.0044$
- $ZZ \to ll\nu\nu$
  - 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

The $ZZ \rightarrow llll$ Channel

Selection

- 4 leptons from the same types used for WZ
  - one with $p_T > 20$ GeV for triggering
  - three more with $p_T > 10$ GeV
- 3 Triggers: Two central muon and central electron
- 1 lepton pair: $76 < m_{ll} < 106$ GeV
- 1 lepton pair: $40 < m_{ll} < 140$ GeV

Dominant backgrounds

- Z+jets where two jets are misidentified as leptons
- $Z\gamma$+jets where the γ and a jet are misidentified as leptons
- Trackless electrons have a much higher background than other lepton types
- $\Rightarrow$ divide into two channels with and without trackless electrons

Backgrounds are measured in 100ths of an event

The $ZZ \to llll$ Background Modeling

Z+jets and $Z\gamma$+jets modeled like the Z+jets background in WZ...

- Measure, in multi-jet data, the rate $p(d)$ a lepton-like jet (d=“denominator”), d, is identified as a lepton
- Apply in a sample of 3 leptons + denominator in data

$$\text{Background} = \sum_{3l+d \text{ in data}} p(d)$$

- Includes where one of the 3 identified leptons was actually a γ

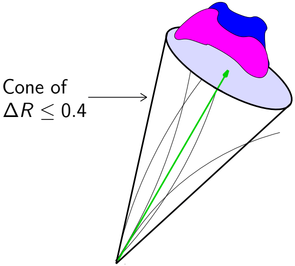
The $ZZ \rightarrow llll$ Background Modeling

Subtleties: Estimating 100ths of an event is hard

1. Double counting of Z+jets (two fakes) due to combinatorics
   - Corrected with 2 identified leptons + 2 denominator sample
2. Very small number of $3l + d$ actually contaminated by ZZ

   $\Rightarrow$ redefine d with an anti-isolation cut to suppress real leptons

   Require >20% non-lepton related E_T in cone

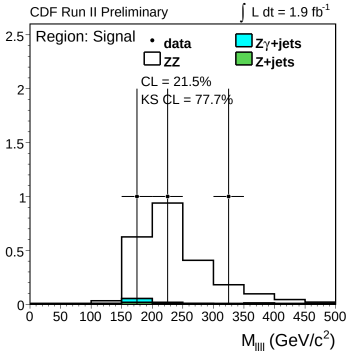


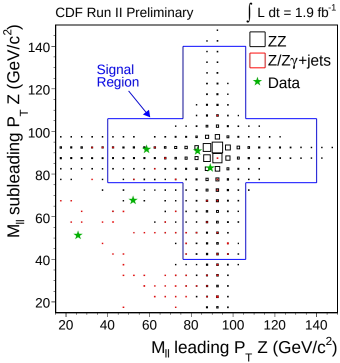
3. Very small number of $3l + d$ means poor sampling of the fake rate space
   - Estimate background and it's variance using a set of possible $3l + d$ distributions that are consistent with those observed

The $ZZ \rightarrow llll$ Yields

Two 4-muon candidates

One 4-electron candidate

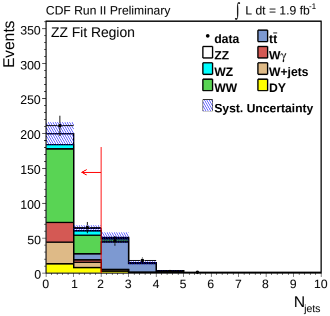




Category	Candidates without a a trackless electron	Candidates with a a trackless electron
ZZ	$1.990 \pm 0.013 \pm 0.210$	$0.278 \pm 0.005 \pm 0.029$
Z+jets/$Z\gamma$+jets	$0.014^{+0.010}_{-0.007} \pm 0.003$	$0.082^{+0.089}_{-0.060} \pm 0.016$
Total	$2.004^{+0.016}_{-0.015} \pm 0.210$	$0.360^{+0.089}_{-0.060}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

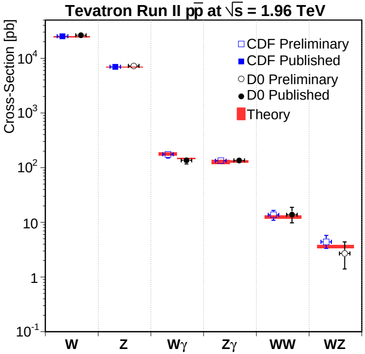
Event Selection for $ZZ \to ll\nu\nu$

- Same as WZ, but with one less lepton
  - Throw out loosest lepton categories
  - Add extra isolation cut
- 2d cut for $\not{E}_T$ not along lepton directions
- $N_{\text{jets}} < 2$ to get rid of $t\bar{t}$

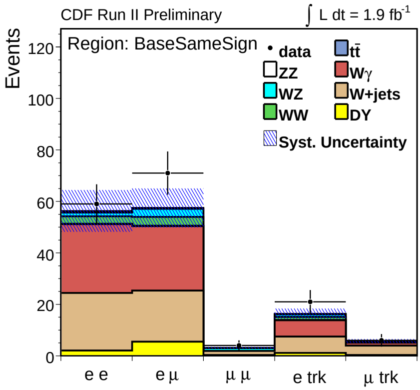


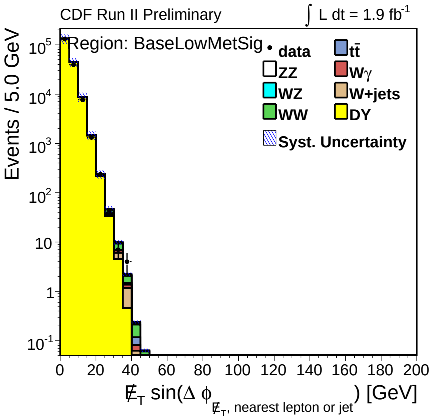
- With added cut on hadronic activity: $\frac{\not{E}_T}{\sqrt{\sum E_T}} > 2.5\ GeV^{\frac{1}{2}}$, because of larger sensitivity to Z + fake $\not{E}_T$ backgrounds
- Only ee and $\mu\mu$ channels are used (No flavor changing neutral currents)

Everything in this plot is a back-ground plus $t\bar{t} \to WWb\bar{b}$



Control Regions

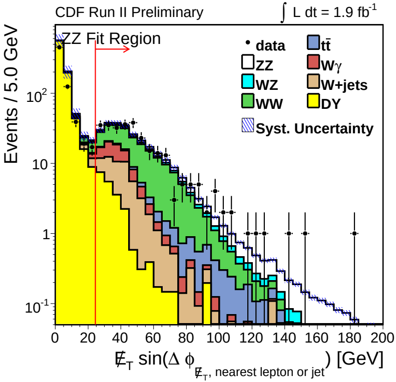


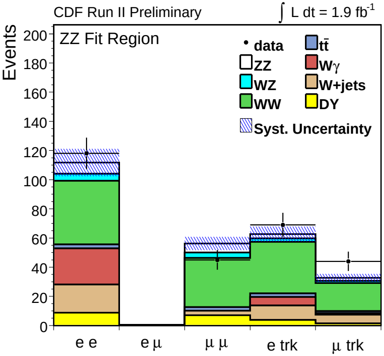


- Same event selection but with same-sign leptons
- Tests model of jet or γ misidentified as leptons
  - Both components have 25% systematics

- Events with lots of hadronic activity
- Worse $\not\!\!E_T$ resolution $\Rightarrow$ mostly Drell-Yan
- Tests $\not\!\!E_T$ modeling

$WW \rightarrow ll\nu\nu$ and $ZZ \rightarrow ll\nu\nu$





	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jets	Total	Data
$e\ e$	43.7	4.8	5.4	2.7	8.7	24.8	19.3	109 $\pm$10	118
$\mu\ \mu$	33.7	3.7	4.4	2.4	7.0	0.0	2.7	54 $\pm$ 5	45
e trk	35.3	2.3	2.2	2.4	3.8	5.9	9.9	62 $\pm$ 5	69
μ trk	19.2	1.5	1.5	1.4	1.5	1.1	5.2	31 $\pm$ 3	44
Total	131.8	12.3	13.5	9.0	21.1	31.7	37.1	256 $\pm$21	276

The Matrix Element Calculation

Event-by-event probability density using the **full kinematic information**

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

Theory at leading order

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

What we measure

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

Detector Effects

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

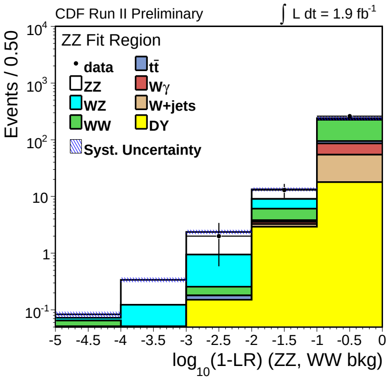
- Integration over missing neutrino information
- Same implementation as is used for CDF $H \rightarrow WW$ analysis

$ZZ \rightarrow ll\nu\nu$ with Matrix Elements

Contruct Likelihood Ratio

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

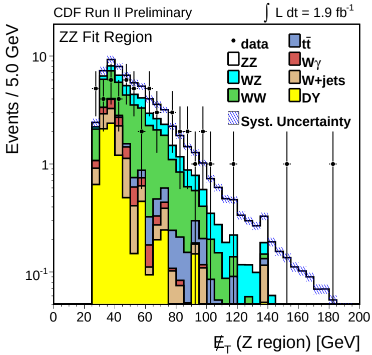
- Plot $log_{10}(1 - LR)$ to avoid binning away “Golden Events”
- Most of phase-space has too much background

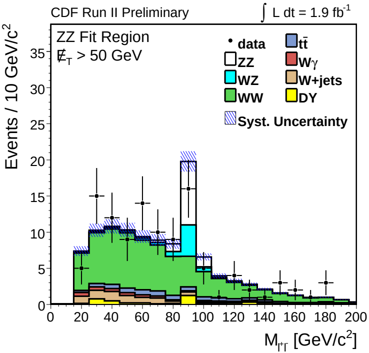


Using the Calculated Probabilities: 1-D histogram

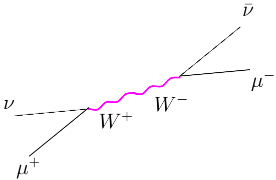
- Models don’t have to be perfect
- Don’t have to model everything
  - Small, difficult to model backgrounds: Drell-Yan
  - Next-to-leading order effects...

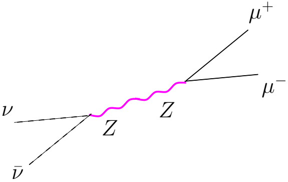
$ZZ \to ll\nu\nu$ with Matrix Elements





Most of the sensitivity comes from high $\not{E}_T$



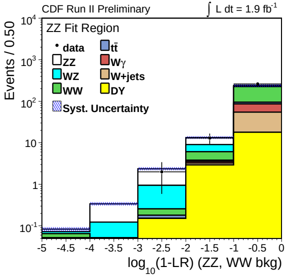


At large M_{WW} $\nu + \bar{\nu}$ p_T cancel

At large M_{ZZ} $\nu + \bar{\nu}$ p_T add together

ZZ Statistical Procedure

Likihood constructed out of these inputs



Channel	Observed	Background
without trackless e	2	$0.014^{+0.010}_{-0.007} \pm 0.003$
with trackless e	1	$0.082^{+0.089}_{-0.060} \pm 0.016$

2 yields for the two four lepton channels

- Test Statistic = Likelihood Ratio
  - ZZ floating = test hypothesis (value $\rightarrow$ cross-section)
  - ZZ fixed to zero = null hypothesis

$$ts = (-2\ln\mathcal{L}_{ZZ\ free}) - (-2\ln\mathcal{L}_{ZZ\ fixed})$$

- 10 million pseudo experiments (bin statistics & systematics varied)

$$\text{p-value} = \frac{\#\text{ of background experiments with larger } ts \text{ than data}}{\#\text{ pseudo-experiments generated}}$$

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

Probability of Observing a Signal

Significance	$ll\nu\nu$	4 lepton	combined
2σ	0.55	0.82	0.87
3σ	0.33	0.67	0.75
5σ	0.06	0.34	0.50

$\Rightarrow$ 50/50 chance of seeing 5σ

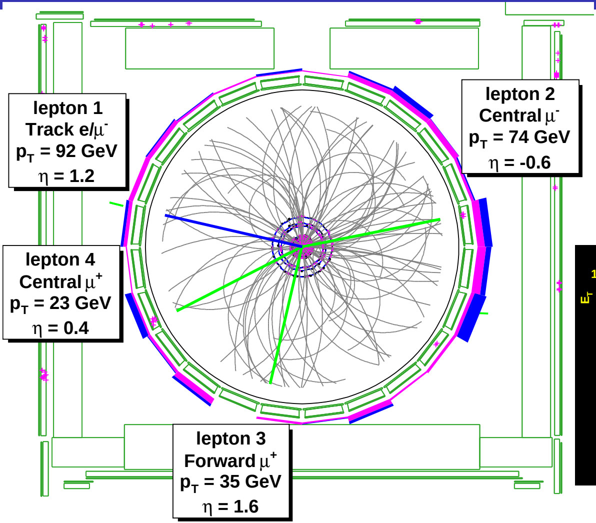
Combined Results

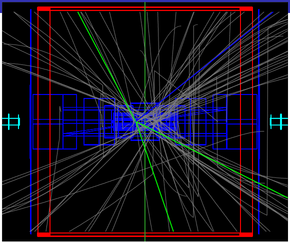
		$ll\nu\nu$	4 lepton	Combined
Significance	P-Value	0.12	1.1×10^{-5}	5.1×10^{-6}
	Significance	$1.2\ \sigma$	$4.2\ \sigma$	$4.4\ \sigma$

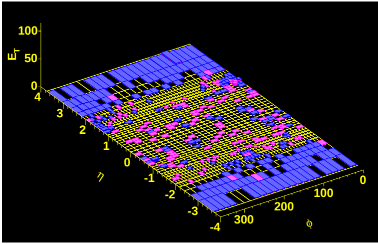
Measured Cross-Section $1.4^{+0.7}_{-0.6}(stat. + syst.)$ pb (NLO prediction is 1.4 pb)

Observe a $4.4\ \sigma$ signal for *ZZ*

A *ZZ* to 4 Muon Candidate





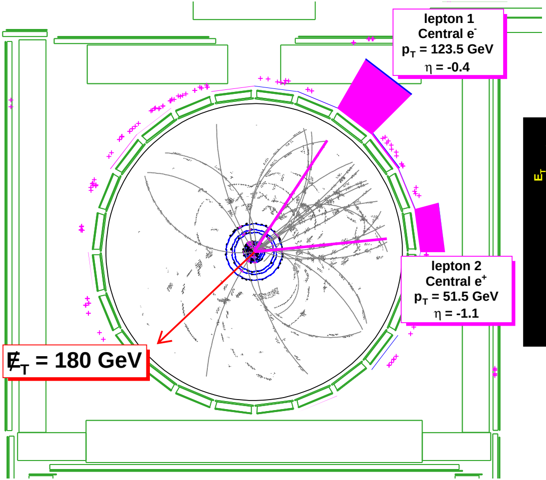


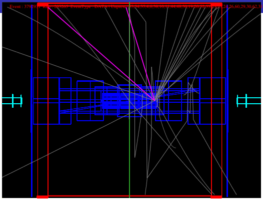
m_{ll1}=90.92 GeV $\quad |\not{E}_T|$=8.7 GeV

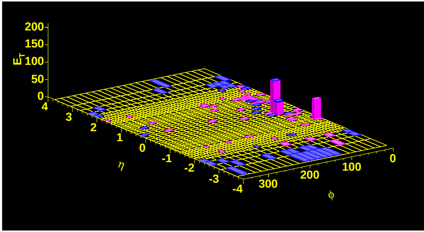
m_{ll2}=83.03 GeV $\quad N_{jets}$ = 0

M_{llll}=312.4 GeV/c^2

Most likely $ZZ \rightarrow ll\nu\nu$ event







Run=203265 Event=3792931

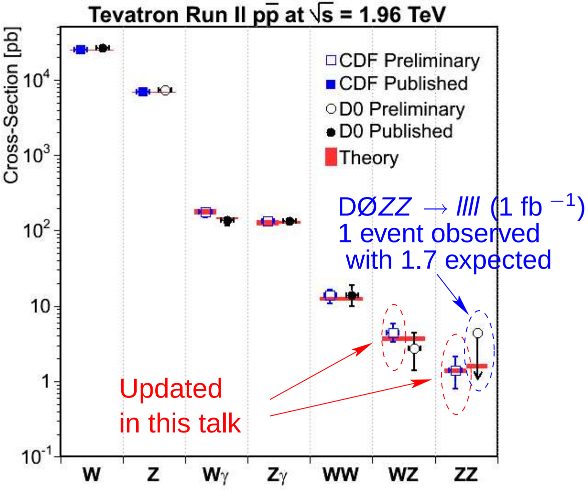
m_{12}=91.22 GeV

$|\not{E}_T|$=180.5 GeV

Type	p_T	η	ϕ
Central *e*	123.5	-0.4	1.0
Central *e*	51.5	-1.1	0.1

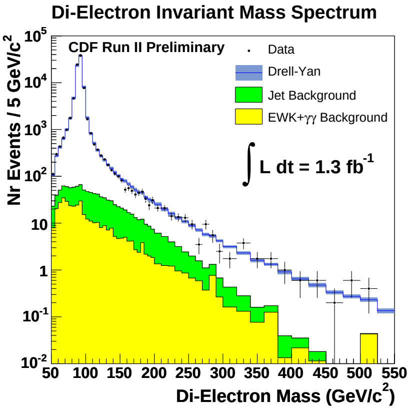
Now pair producing electroweak bosons in significant numbers

- *WZ* Production
  - Now updated to 1.9 fb^{-1}
  - Yield is now 25 events
- Exploiting *WZ* Sample: Limits on anomalous *WWZ*
- 4.4 σ Signal for *ZZ* Production
  - Combined *llll* and $ll\nu\nu$
  - Sumbitted to PRL (arXiv:0801.4806 [hep-ex])

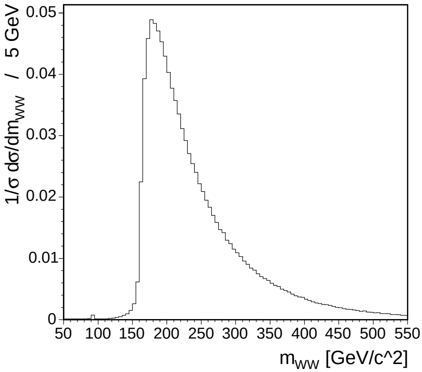


Backup

The Energy Scale at the Tevatron

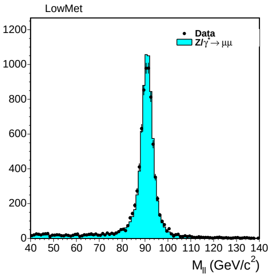


$p\bar{p} \to eeX$ Data

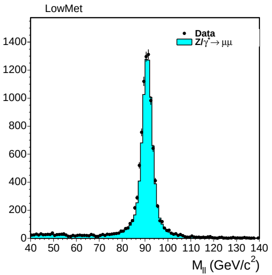


$p\bar{p} \to WWX$ Monte Carlo

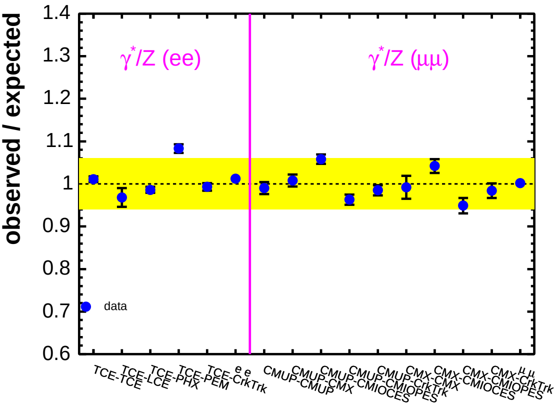
Check the Selections using the Z-peak



Central μ+Track in Crack



Central μ+Forward μ



All the triggerable lepton pairs

- Efficiencies measured in data using Z-decays
- Monte Carlo corrected

Backup: *WZ* Results

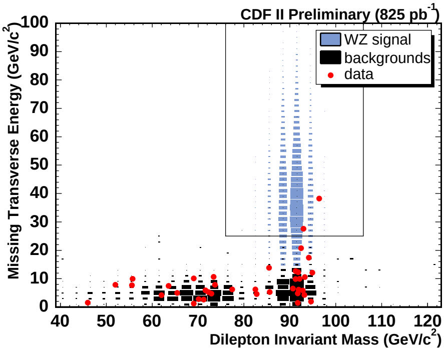
Previous CDF Results

Basic $WZ \to lll\nu$ Signature

- 3 leptons
- 2 leptons make a Z-mass
- Missing Transverse Energy

Main Backgrounds

- Z+jets and $Z\gamma$ with jet or γ misidentified as a lepton
- ZZ and $t\bar{t}$



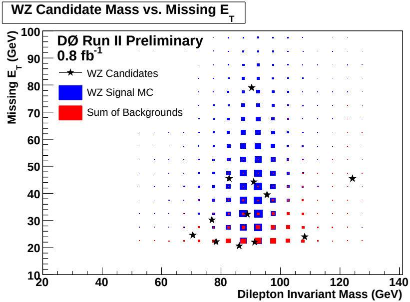
Previous CDF Results

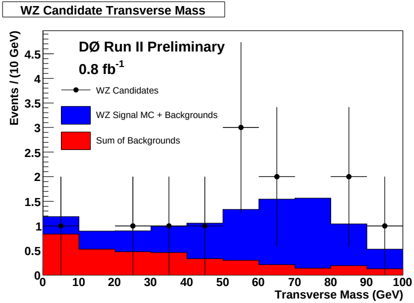
- Expected: 3.7 ± 0.3 signal and 0.9 ± 0.2 background
- Observed: 2 events (probability to observe ≤ 2 : 15%)

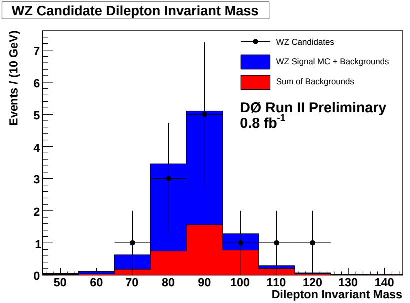
$\sigma(WZ) < 6.3$ *pb* @ 95% CL
NLO Theory: $\sigma(WZ) = 3.7 \pm 0.3$ *pb* (Campbell,Ellis)

$WZ \rightarrow lll\nu$: 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
- $\sigma(WZ) = 4.0^{+1.9}_{-1.5}\ pb$
  - NLO $\sigma(WZ) = 3.7 \pm 0.3\ pb$







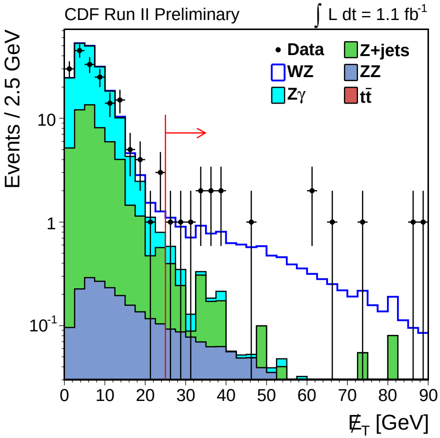
Determining the Significance

- Use 2 bins in $\not\!\!E_T$
  - $25 < \not\!\!E_T < 45$ GeV and $\not\!\!E_T > 45$ GeV
- Find most likely yield...

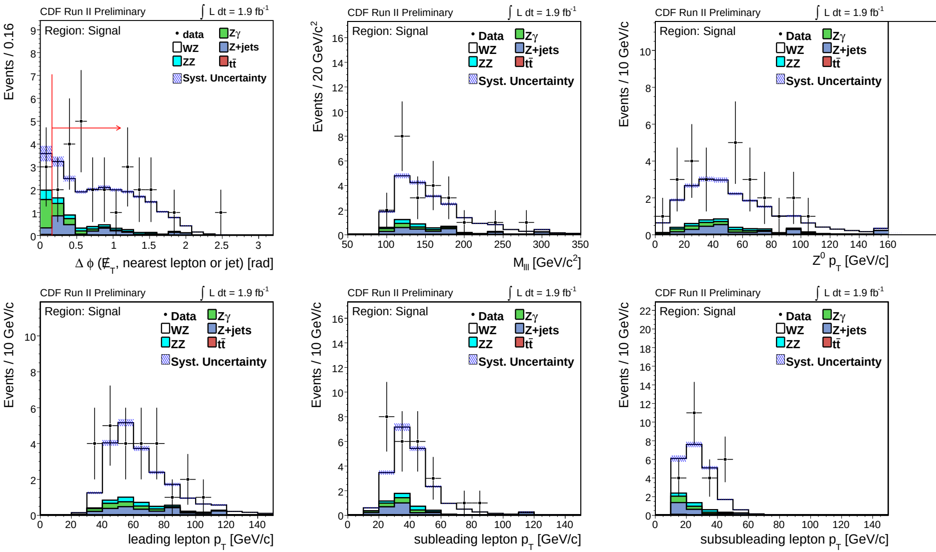
$$\Delta \ln \mathcal{L} = \ln \mathcal{L}_{N_{\text{signal}}=0} - \ln \mathcal{L}_{\text{best fit}}$$

- Bins were optimized *a priori* for expected significance
- Do 1 *billion* background only pseudo-experiments
  - Only 2 less likely to be background than our signal

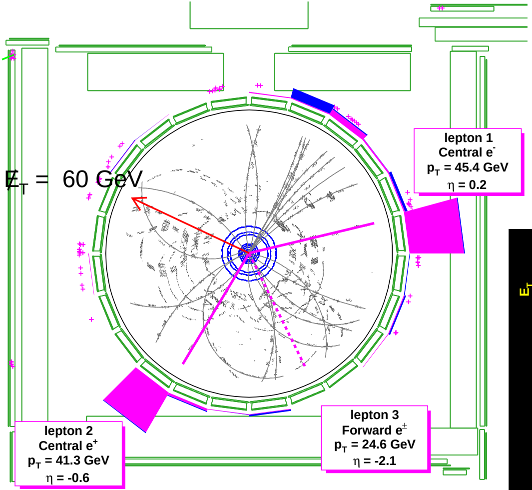
Significance is 5.9 σ

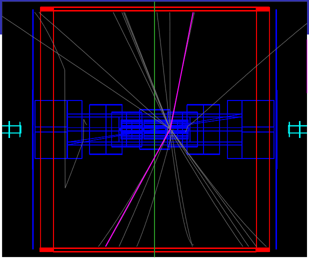


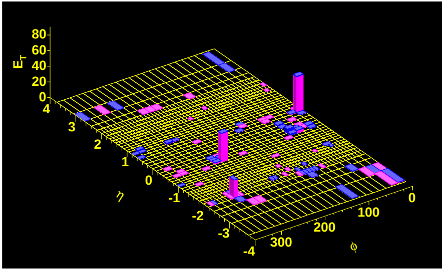
More *WZ* Distributions



Sample *eee* Event





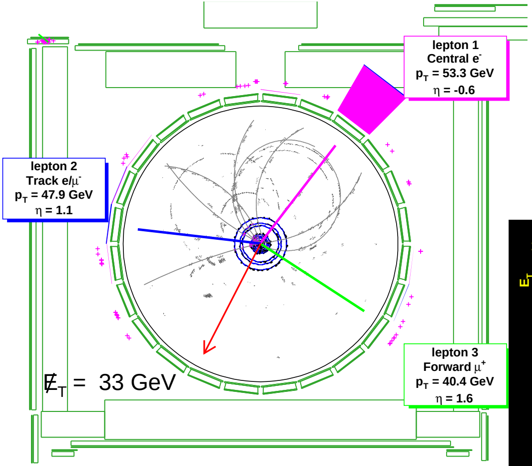


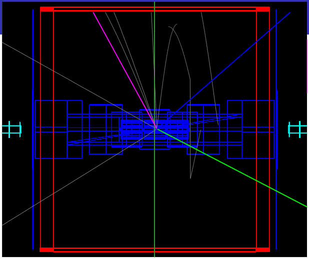
m_{12}=87.91 GeV
m_{13}=104.37 GeV
m_{23}=59.62 GeV

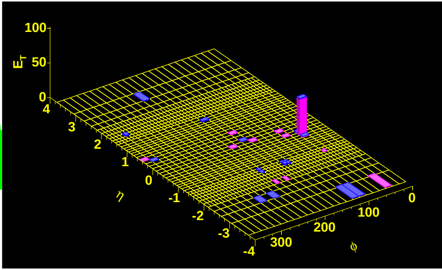
$|\not\!\!E_T|$=60.5 GeV
$\Delta\phi(\not\!\!E_T, \text{lepton}, \text{jet})$=1.5

Type	p_T	η	ϕ
Central *e*	45.4	0.2	0.2
Central *e*	41.3	-0.6	-2.1
Forward *e*	24.6	-2.1	-1.1

Sample $e\mu\mu$ Event







m_{12}=131.15 GeV

m_{13}=136.36 GeV

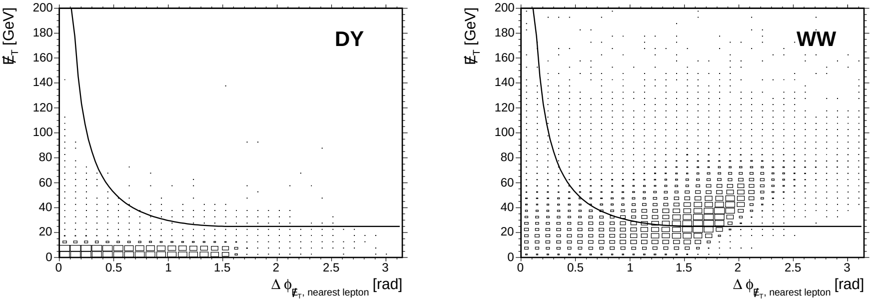
m_{23}=88.09 GeV

$|\not\!\!E_T|$=32.8 GeV

$\Delta\phi(\not\!\!E_T, \text{lepton}, \text{jet})$=1.2

Type	p_T	η	ϕ
Central e	53.3	-0.6	0.9
Track e/μ	47.9	1.1	3.0
Forward μ	40.4	1.6	-0.6

2-d $\not\!\!E_T$ and $\min \Delta\phi(\not\!\!E_T, l \text{ or jet})$ Cut



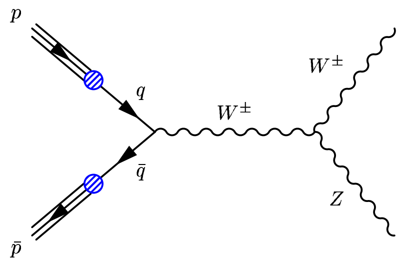
$$\not\!\!E_{T\,rel} \equiv \begin{cases} \not\!\!E_T & \text{if } \min \Delta\phi(\not\!\!E_T, l \text{ or jet}) > \frac{\pi}{2} \\ \underbrace{\not\!\!E_T \sin(\min \Delta\phi(\not\!\!E_T, l \text{ or jet}))}_{\text{least } \not E_T \text{ transverse to a lepton or jet}} & \text{if } \min \Delta\phi(\not\!\!E_T, l \text{ or jet}) < \frac{\pi}{2} \end{cases}$$

$ll\nu\nu$ Systematics

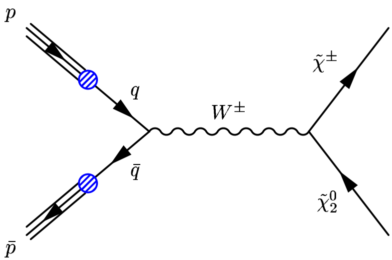
	Fractional Uncertainty (%)						
	WW	*WZ*	*ZZ*	$t\bar{t}$	DY	$W\gamma$	*W*+jets
$\not\!\!E_T$ Modeling	1.0	1.0	1.0	1.0	20.0	1.0	-
Conversions	-	-	-	-	-	20.0	-
NLO Acceptance	6.9	10.0	10.0	10.0	5.0	10.0	-
Cross-section	10.0	10.0	10.0	15.0	5.0	10.0	-
PDF Uncertainty	1.9	2.7	2.7	2.1	4.1	2.2	-
LepId $\pm 1\sigma$	1.4	1.4	1.4	1.4	1.4	1.0	-
Trigger Eff	2.5	2.2	2.1	2.5	3.4	6.1	-
Fake Rate	-	-	-	-	-	-	19.8
Total	12.6	14.7	14.7	18.4	21.9	25.4	19.8

- *WW* NLO acceptance: MC@NLO vs Pythia (LO with parton shower model)
- Conversion-veto efficiency measured in data
- $\not\!\!E_T$ Modeling from the high $\not\!\!E_T$, high hadronic activity modeling
- PDF using standardized procedures from CTEQ
- Fake rates from variations of the fake probability sample

WZ: The SUSY Golden Mode's Mirror Image

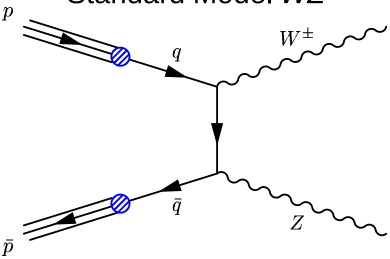


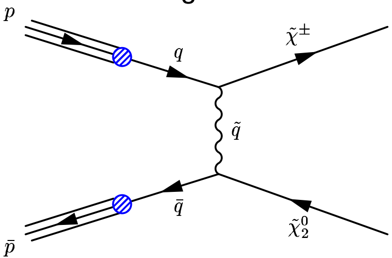
Standard Model *WZ*



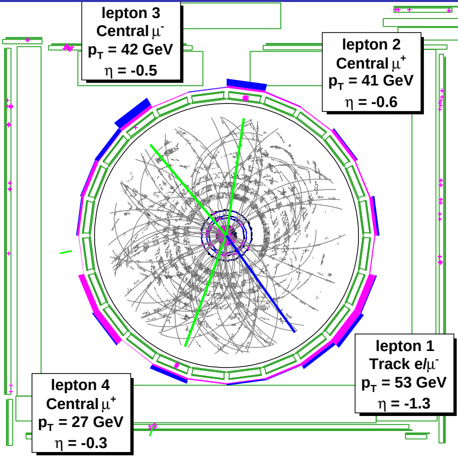
SUSY Chargino-Neutralino

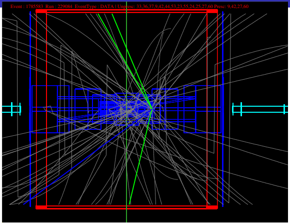
SUSY Mirror

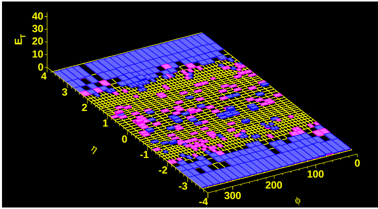




The other ZZ to 4 Muon Candidate







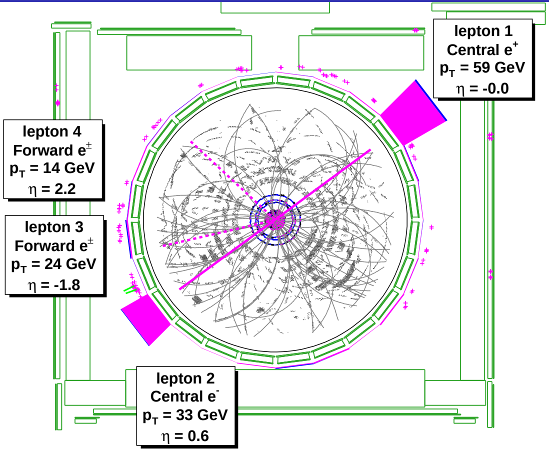
Run=229084 Event=1785583

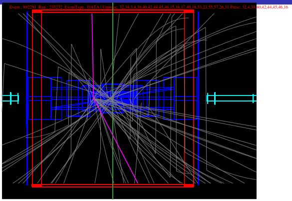
m_{ll1}=91.53 GeV $\quad |\not{E}_T|$=0.8 GeV

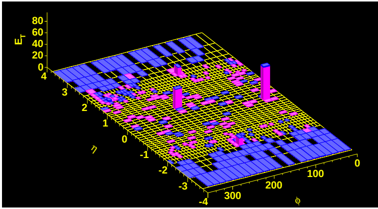
m_{ll2}=58.94 GeV $\quad N_{jets}$ = 0

M_{llll}=174.5 GeV/c^2

The *ZZ* to 4 Electron Candidate







Run=235232 Event=892291

m_{ll1}=89.06 GeV $\quad$ $|\not{E}_T|$=2.1 GeV

m_{ll2}=82.82 GeV $\quad$ N_{jets} = 0

M_{llll}=230.6 GeV/c^2