Dibosons at the Energy Frontier

Finding Heavy Dibosons and the Search for $H \rightarrow WW$ at CDF

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Outline

- Introduction
  - Lightning Review of Electroweak
  - Diboson and Multilepton Motivation
- Hadron Collisions and the CDF Experiment
- Improvements in Multilepton Technique at CDF
- First Observation of WZ Production
- Search for Higgs Decaying to WW using Matrix Element Probability Calculations
- First Measurement of ZZ at a Hadron Collider

The Story of a Broken Symmetry

- The Proton and the Neutron are *almost* the same except for charge

$$\begin{pmatrix} p \\ n \end{pmatrix}$$

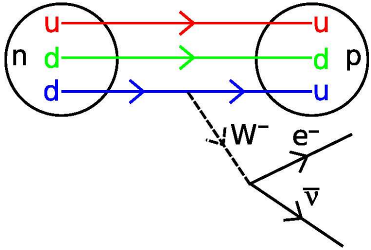
	Mass	Spin	EM Charge
Proton	938.27 MeV/c^2	$\frac{1}{2}$	+1
Neutron	939.56 MeV/c^2	$\frac{1}{2}$	0

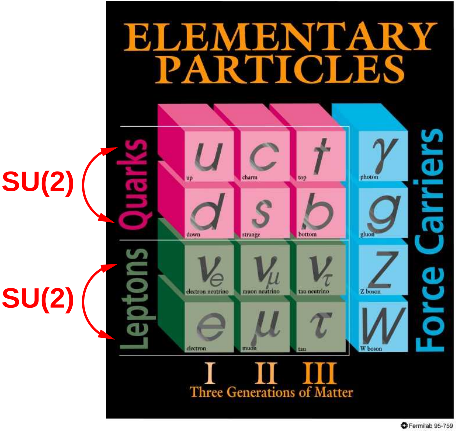
- There is a symmetry between them
  - But it's a "broken" symmetry
- Weak nuclear interactions, e.g. "β-decay", can transform one to the other

The Standard Model of particle physics says:

There is an electroweak symmetry and it's broken by the Higgs.

...okay, it's not quite that simple



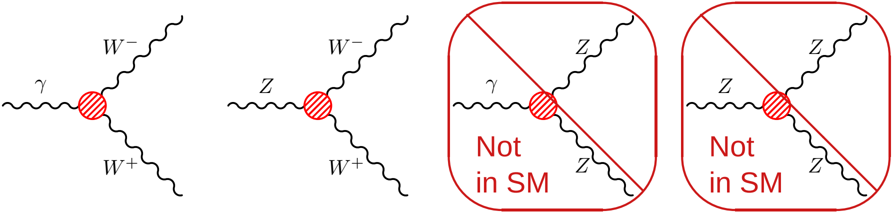


- Proton and Neutron are not fundamental particles
- Same strong, QCD, couplings hides the size of the symmetry is broken
  - Most of the mass is of *p* and *n* are in gluons and "sea" quarks (non-valence)
- Larger symmetry $SU(2)_L \otimes U(1)_Y$ is broken, but $U(1)_{em}$, the electromagnetic guage, symmetry is left

The Ingredients of Electroweak Symmetry Breaking

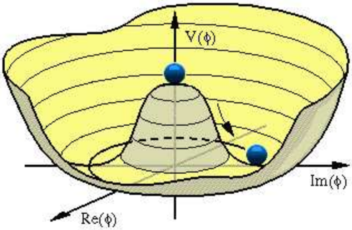
The Group Structure: $SU(2)_L \otimes U(1)_Y$

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



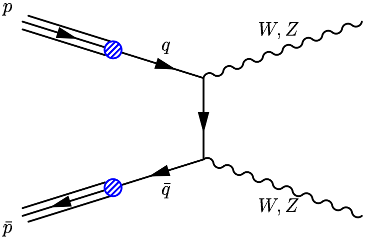
The Agent of Electroweak Symmetry Breaking: Higgs

- Single scalar Higgs is Occam's razor
- Indirect limits $m_H < \sim 180$ GeV/c^2
- Direct limits $m_H > 114$ GeV/c^2
- $H \rightarrow WW$ covers a lot of this range

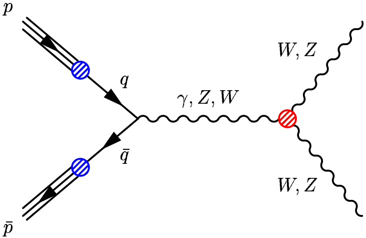


Measuring How Bosons Couple to Each Other

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

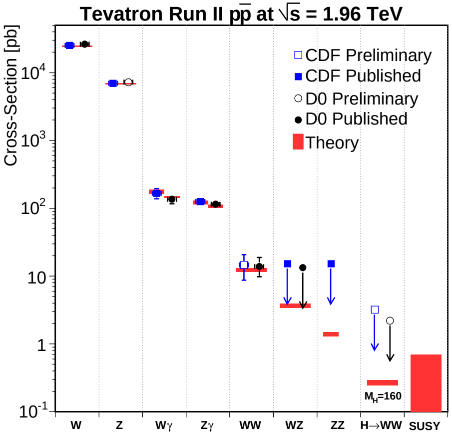
Highest energies are at Tevatron

- 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

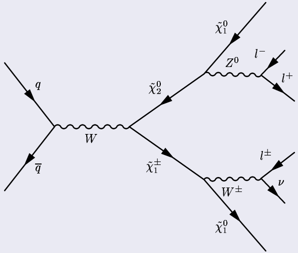
Now sensitive to pair producing heavy electroweak particles



Diboson Status as of February 2006

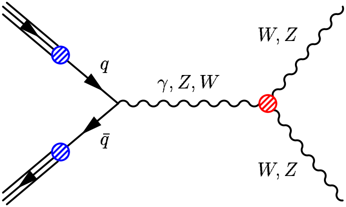
Example

- Search for WZ in 3 leptons + a not easily detected neutrino
- 3 leptons + neutrino + two not easily detected neutralinos

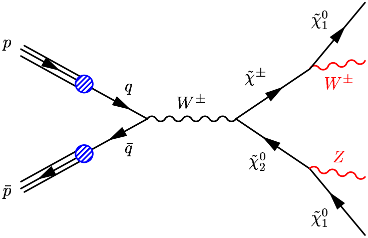


SUSY Golden Mode

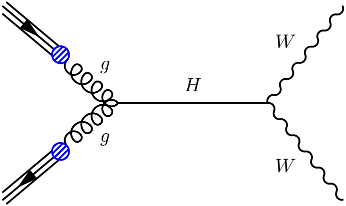
- Access to the Gauge Boson Self-Couplings



- Possible New Physics



- Searching for the Higgs



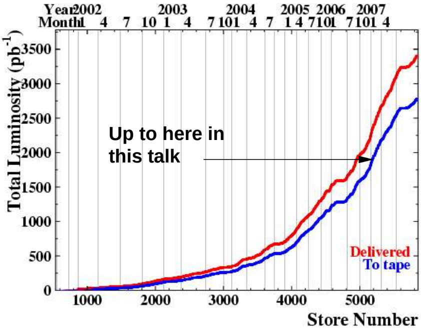
Topics selected for this talk

- *WZ* production
- Search for $H \rightarrow WW$
- *ZZ* production

The Experiment

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

- 1.9 fb^{-1} used in this talk
- > 2.5 fb^{-1} on tape
- estimates are $\approx$ 3.5 fb^{-1} for Summer 08
- Could be as much as 5-6 fb^{-1} in 2009



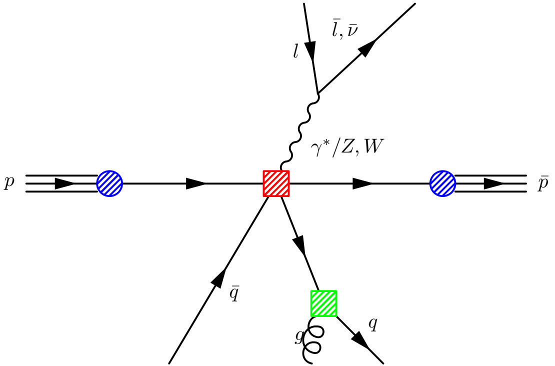
Produced in 1.9 fb^{-1}

$\approx$	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

Hadron Collisions are Complicated

- Electroweak Physics and Perturbative QCD
- Nonperturbative QCD
  - Lots of different topologies and effects



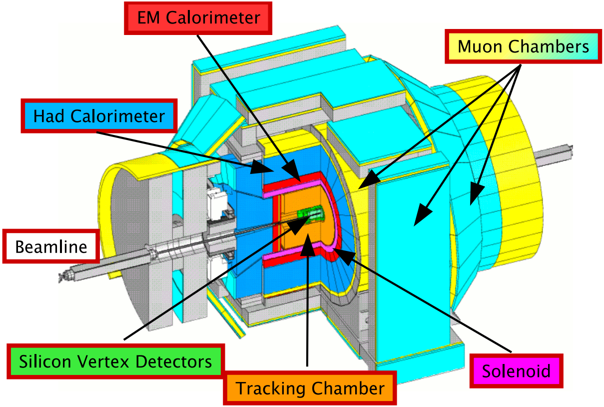
- Parton Distribution Functions $\equiv$ Structure of the Proton
  - All the events are "boosted" along the beam line:

$$\eta = -log(tan(\theta/2))$$

$\eta = 0$	: Transverse to beam
$\eta \to \infty$	: Parallel to beam

  - θ is the angle of the particle relative to the beam line
  - For massless particles differences in η invariant under z-boost

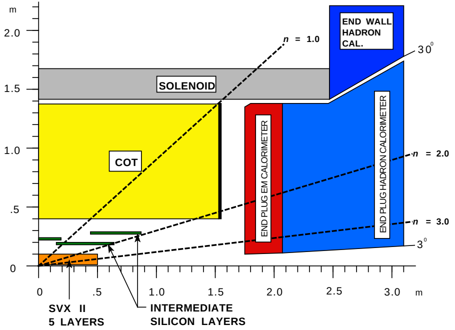
The CDF Detector

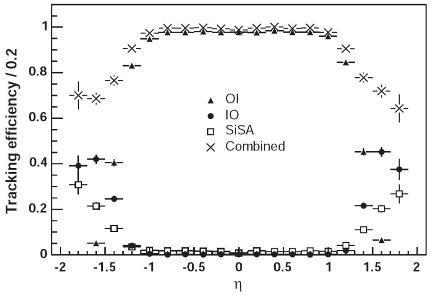


- Segmented sampling calorimeters
- Shower maximum detectors
  - Shower shape measurement
  - Central: gas-based
  - Forward: scintillator

- Muon Chambers
  - CMU & CMP ($|\eta| < 0.6$)
  - CMX ($0.6 < |\eta| < 1.0$)

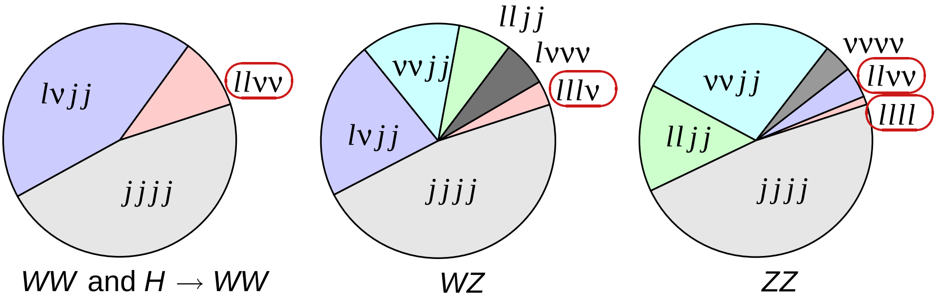
The CDF Tracking





- 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

Choosing a Decay Mode to Use



Fully Leptonic

- Small branching fractions
- Low backgrounds
- Controllable backgrounds

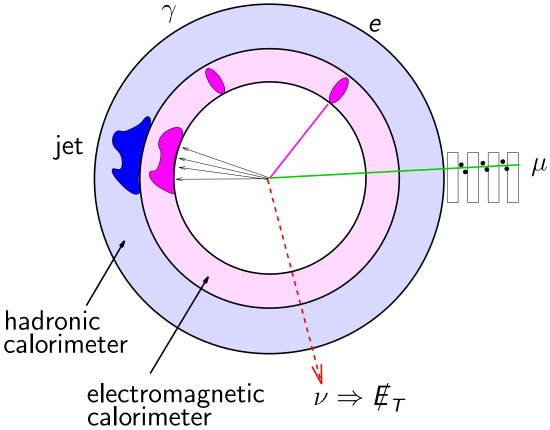
Semileptonic

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

Technique Overview

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

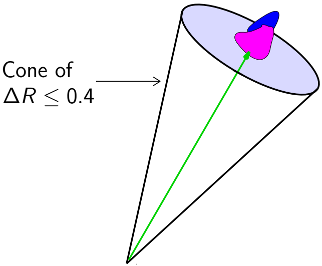


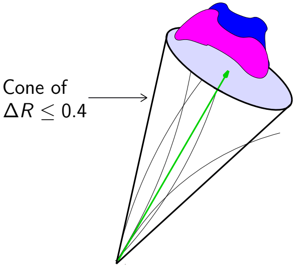
- $\not\!\!E_T$: Measure neutrinos with transverse momentum balance
  - "Missing Transverse Energy"
  - EM and hadronic components measured in calorimeters
  - Corrected for muons

Technique Overview: Isolation

Powerful handle to separated leptons from boson decay from fake or real leptons from hadronic processes

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





Real Leptons from Boson Decay

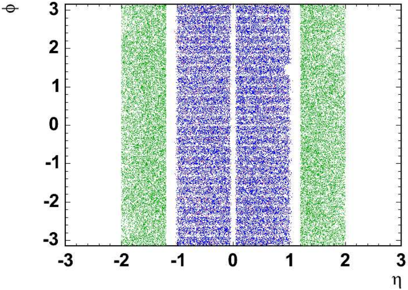
- Electrons from converted photons from diboson decays also isolated

Fake or *Real* Leptons in Jet

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

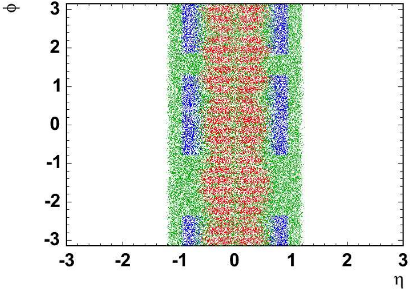
Cut: non-lepton related energy $<$10% of the lepton energy in the cone

The Starting Point
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

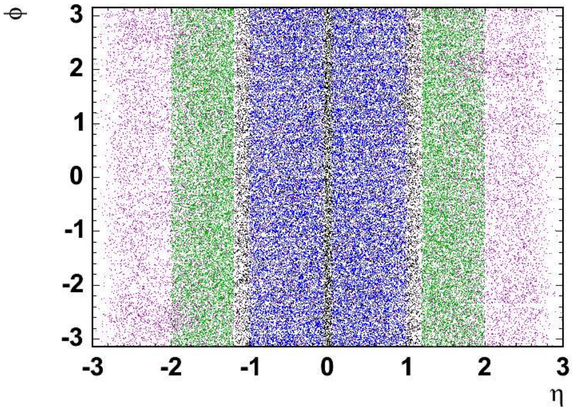
Increasing Electron Acceptance

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 electromagnetic showers used, Tracks fill in fiducial edges

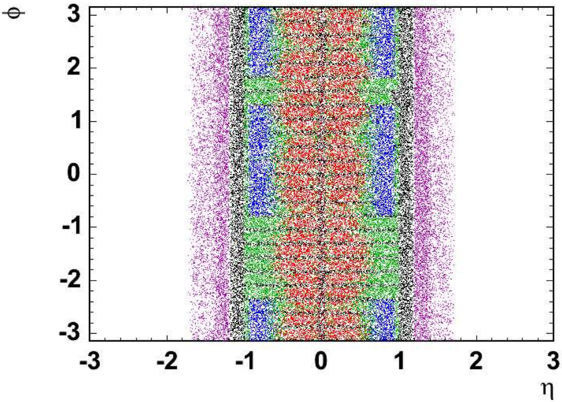
Increasing Muon Acceptance

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

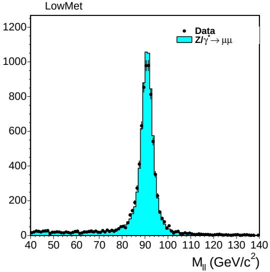


Isolated Tracks

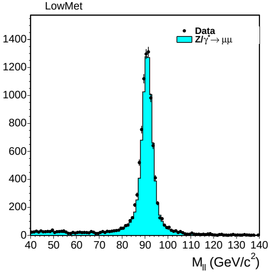
- If not fiducial to a shower max detector

All tracks with drift chamber hits used including very forward tracks

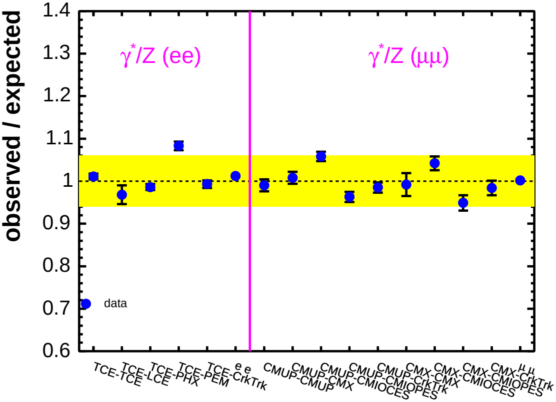
Check the Selections using the Z-peak



Central μ+Track in Crack



Central μ+Forward μ



All the triggerable lepton pairs

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

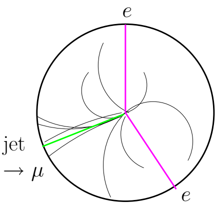
First Observation of WZ Production

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

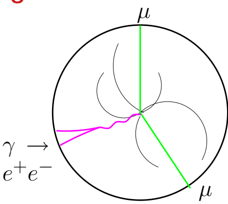
Event Selection for $WZ \rightarrow lll\nu$

- 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

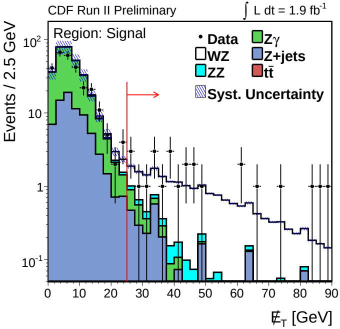
Main Backgrounds



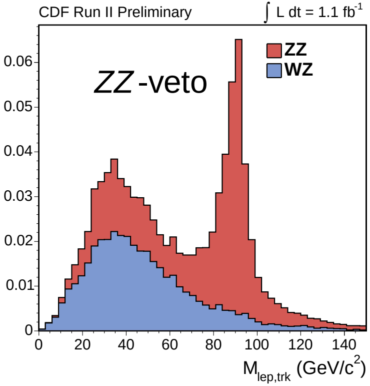
Z+jets

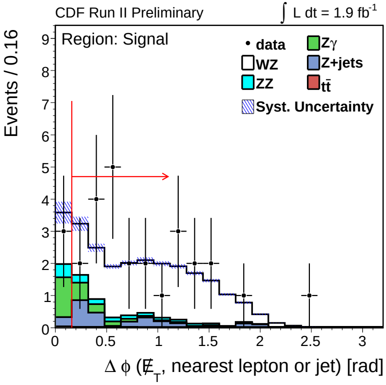


$Z\gamma$



Event Selection for $WZ \to lll\nu$





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

Signal and Background Modeling

Monte Carlo Derived Contributions

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

Data Derived Estimate of Z+jets Background

- Measure 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 → "denominator"

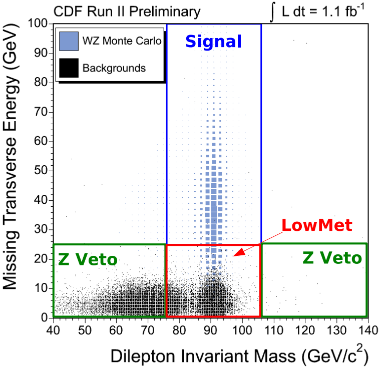
1. Calculate in the jet data

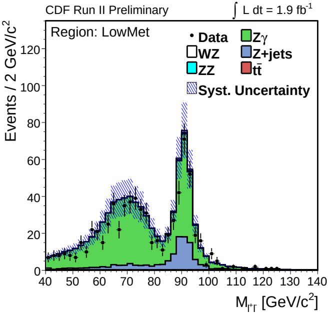
$$\text{Fake Rate} = \frac{\#\text{Identified Leptons}}{\#\text{Denominator Objects}}$$

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

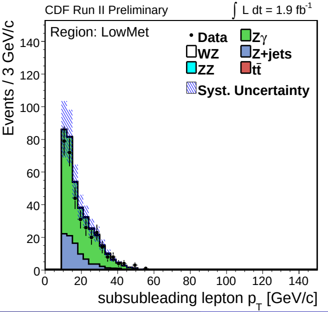
Control Regions: Testing the Sample Modeling

- 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



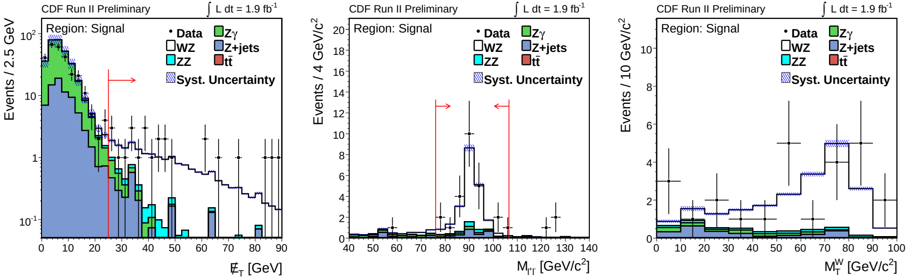


m_{ll} in Both Regions



Lowest p_T lepton in Z-mass Region

WZ Signal Region



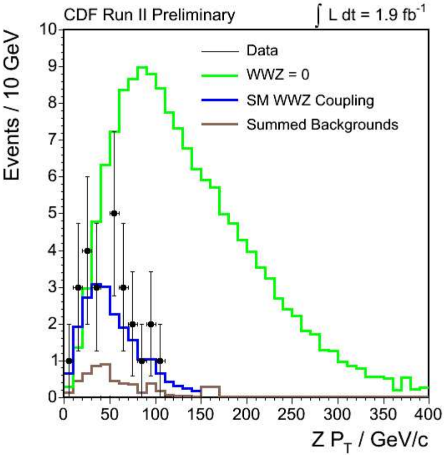
- First Observation with 16 events in 1.1 fb^{-1}
  - 5.9 σ significance using likelihood with 2 $\not{E}_T$ bins
  - PRL 98, 161801 (2007)

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}:

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

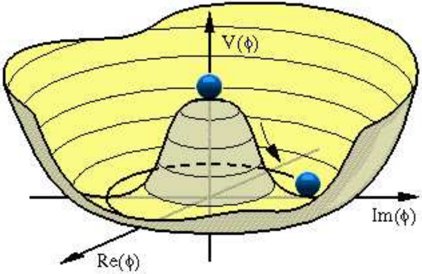
WZ: Sensitivity to *WWZ* vertex



- No time to discuss this in this talk
- See Fermilab Wine and Cheese on February 1st

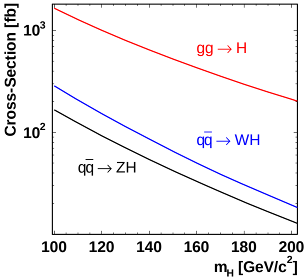
Search for a Higgs Decaying to WW^*

- Overview of Experimental Issues
- Sample Selection
- Event Probability Calculations
- The Result
- The Future of $H \to WW^*$



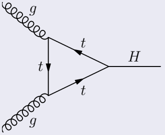
The problem

- Things that couple strongly to the Higgs have large masses
- Things with large masses decay (subject to quantum numbers)
- We can only collide long-lived particles

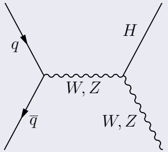


Some of the possible solutions...

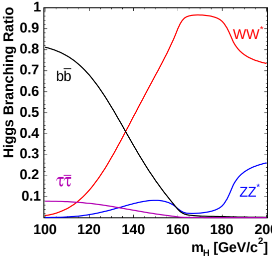
Produced the Higgs via heavy quark loops $gg \to H$



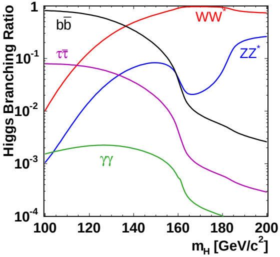
Produced the Higgs via in association with W or Z



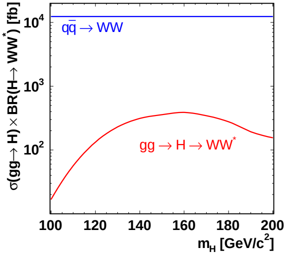
Decay Modes



BR Linear Scale



BR Log Scale



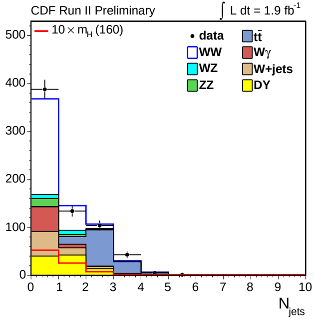
BR × X-sec Product

- Again the Higgs couples to heavy stuff which decays...
- $H \rightarrow b\bar{b}$ has huge QCD backgrounds
  - Only via in associated production
- $H \rightarrow WW^*$ is under the $q\bar{q} \rightarrow WW^*$

The Higgs is underneath the needle in the haystack

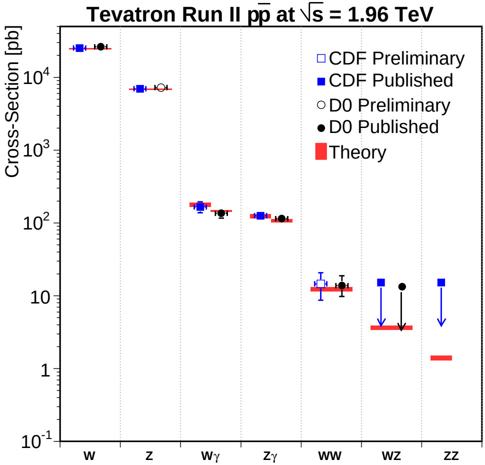
Event Selection for $(H \rightarrow) WW \rightarrow l l \nu \nu$

- 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
- $N_{\rm jets} < 2$ to get rid of $t\bar{t}$

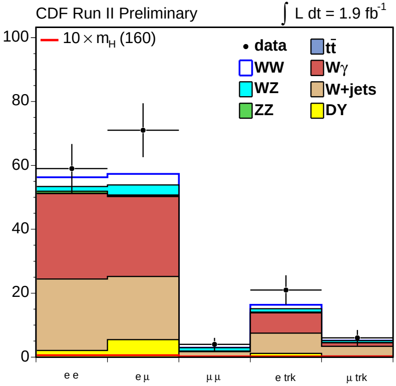


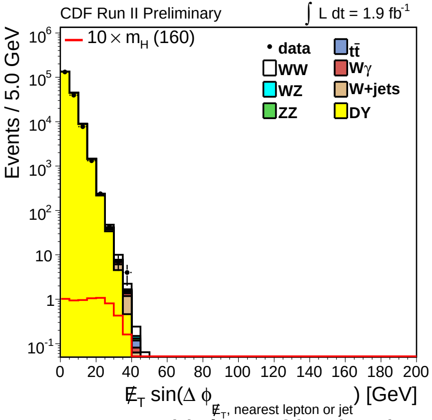
Everything in this plot is a background !

plus $t\bar{t} \rightarrow WWb\bar{b}$!



Controls Regions

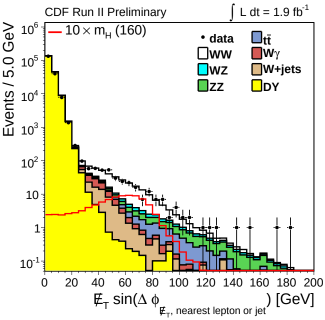


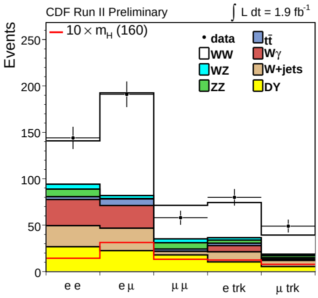


- Same event selection but with same-sign leptons
- Tests model of jet or γ misidentified as leptons
  - Both component 25% systematics

- 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 $H \rightarrow WW \rightarrow ll\nu\nu$





WW	251.0
WZ	16.9
ZZ	20.9
$t\bar{t}$	16.8
DY	82.2
$W\gamma$	58.5
W+jets	66.6
Total	512.9
Data	**522**

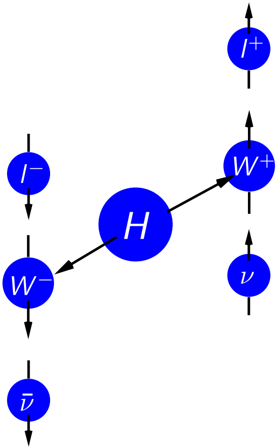
Predicted Higgs Yields

Higgs Mass (GeV)									
110	120	130	140	150	160	170	180	190	200
0.4	1.3	3.0	4.8	6.4	7.8	7.6	6.2	4.4	3.5

Telling $H \to WW^*$ from the $q\bar{q} \to WW$ Continuum

The Handles

- Parity violation makes W-decay an excellent spin analyzer
  - Higgs is scalar $\Rightarrow$ charged leptons go $\approx$ same direction
  - t-channel WW: Ws $\approx$ polarized along the beam direction
- At low masses one W is off-shell
  - One lepton is lower energy
- gg vs $q\bar{q}$
  - Fragmentation
  - WW system z-momentum
  - Not well enough understood yet
  - Recently CDF measured: $\frac{\sigma(gg \to t\bar{t})}{\sigma(p\bar{p} \to t\bar{t})}$



How do we exploit it all?

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
- Photons and jets additional factor = fraction detected as leptons
- Modeled modes: WW, ZZ, $Wp \rightarrow W +$ fake, $W\gamma \rightarrow We_{conv}$

Likelihood Ratio Discriminant

Using the Calculated Probabilities

$$LR = \frac{P_{Higgs}(M_H)}{P_{Higgs}(M_H) + \sum_i f_{\mathrm{bkg,i}} P_{\mathrm{bkg,i}}}$$

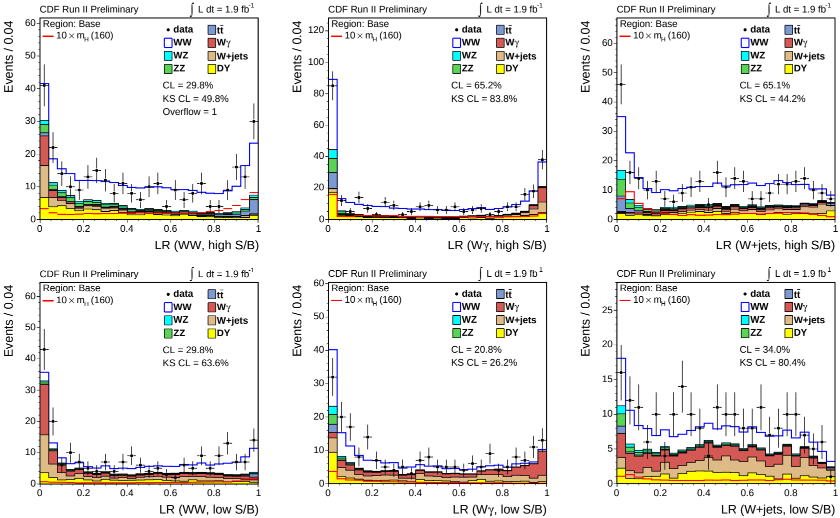
- Fit using a 1-d histogram
- Models don't have to be perfect
- Don't have to model everything
  - Small difficult to model backgrounds: Drell-Yan
  - Next-to-leading order effects...

First a cross-check ...

Treat Backgrounds as Signal in Likelihood Ratio

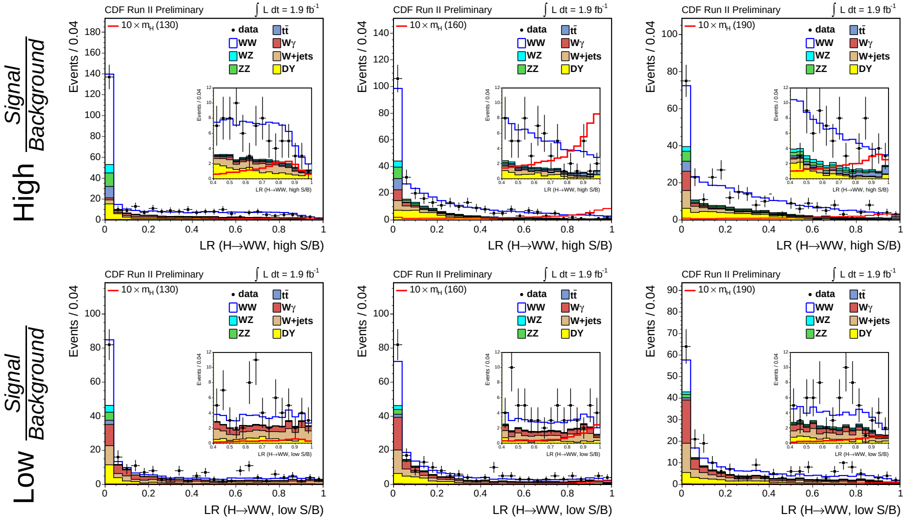
High $\frac{Signal}{Background}$

Low $\frac{Signal}{Background}$



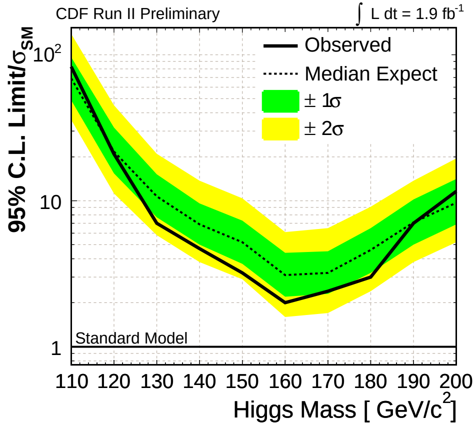
$$\frac{P_{WW}}{P_{WW}+\sum_i f_{\mathrm{bkg,i}}P_{\mathrm{bkg,i}}} \qquad \frac{P_{W\gamma}}{P_{W\gamma}+\sum_i f_{\mathrm{bkg,i}}P_{\mathrm{bkg,i}}} \qquad \frac{P_{W+\mathrm{jets}}}{P_{W+\mathrm{jets}}+\sum_i f_{\mathrm{bkg,i}}P_{\mathrm{bkg,i}}}$$

Likelihood Ratio Discriminant



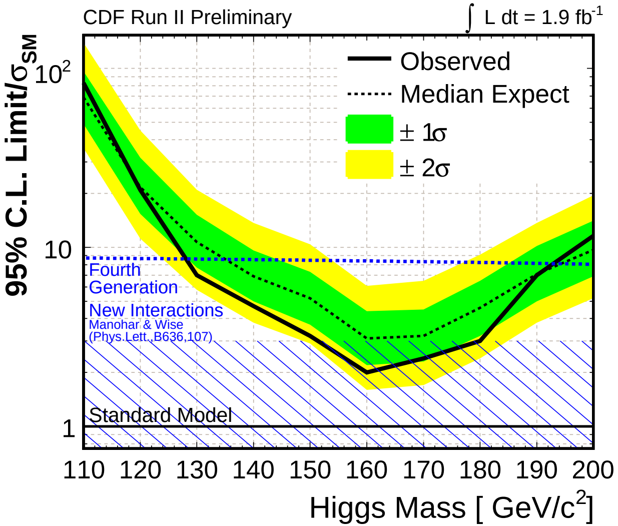
m_H =130 GeV m_H =160 GeV m_H =190 GeV

The Limits



$M_H (GeV/c^2)$	110	120	130	140	150	160	170	180	190	200
$\sigma_{NNLL}(pb)$	0.06	0.13	0.23	0.31	0.36	0.39	0.34	0.28	0.19	0.16
$median(pb)$	3.9	2.9	2.5	2.2	1.8	1.2	1.1	1.3	1.4	1.6
$Observed(pb)$	4.7	2.8	1.6	1.5	1.1	0.8	0.8	0.8	1.4	1.8
Expected/σ_{NNLL}	68.8	21.9	10.7	7.0	5.0	3.1	3.2	4.7	7.0	10.0
Observed/σ_{NNLL}	81.9	20.6	7.0	4.7	3.2	2.0	2.4	3.0	7.0	11.7

The Standard Model is not the Only Model

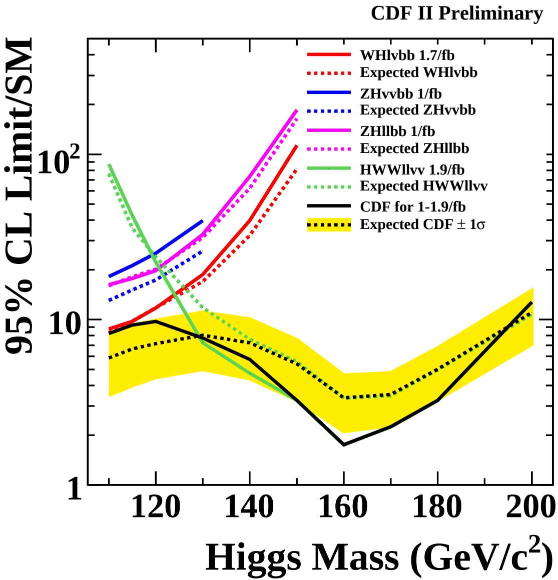


New particles or interactions enter through the loop in the *ggH* coupling

Result with Rest of the Tevatron SM Higgs Program

Single best limit above $m_H \approx 125$ GeV

Better than the combination of all $H \to b\bar{b}$ above $m_H \approx 130$ GeV



The Future of $H \to WW^*$

Personal Perspective

At the Tevatron:

- 2-3 $\times$ more data (5-6 fb) + Combination with DØ
- Add τ leptons, lower p_T cuts, reducible backgrounds
- $\Rightarrow$ with in a factor of 1-2 of the SM

At the LHC

	Tevatron $\sqrt{s}$ = 1.96 TeV	LHC $\sqrt{s}$ = 14 TeV	Ratio	Authors
$H \to WW^*$	0.4 pb	26.4 pb	$\approx$60	Catani, et al.
$q\overline{q} \to WW$	13.5 pb	127 pb	$\approx$9.4	Campbell & Ellis

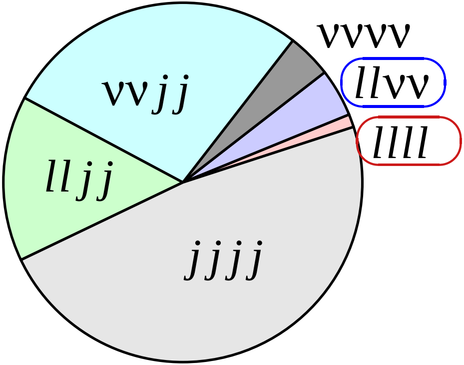
$\Rightarrow$ 1 fb of LHC data is worth 20 fb of Tevatron data ($m_H = 160$ GeV/c^2)

Why do the Tevatron?

- Enhancements are possible, and we may rule out some SM range
- Learn the technique in the real world
- We are already constraining deviations in the *WW* model a factor of 2-3 times smaller than the effect of $H \to WW^*$ at LHC

First Measurement of ZZ Production at a Hadron Collider

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

The $ZZ \to llll$ Background Modeling

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

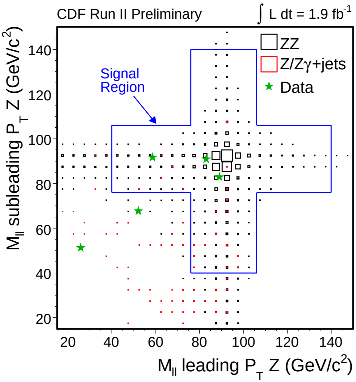
- Measure, in multi-jet data, the rate $p(j_l)$ a lepton-like jet ("denominator"), j_l, is identified as a lepton
- Apply in a sample of 3 leptons + j_l in data

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

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

Subtleties

1. Double counting of Z+jets (two fakes) due to combinatorics
2. Very small number of $3l + j_l$ actually contaminated by ZZ
   - $\Rightarrow$ redefine j_l with an anti-isolation cut to suppress real leptons
3. Very small number of $3l + j_l$ means poor sampling of $p(j_l)$ space
   - Estimate background/variance using a set of possible expected $p(j_l)$ distributions consistent with those observed



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**

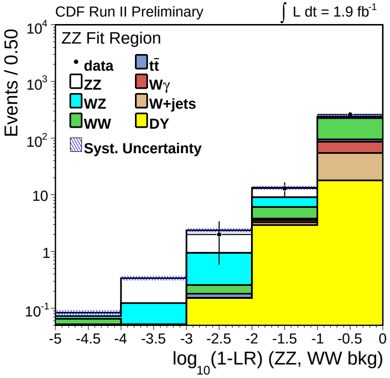
$ZZ \rightarrow ll\nu\nu$ with Matrix Elements

- Same selection as used for $H \rightarrow WW$
  - 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)

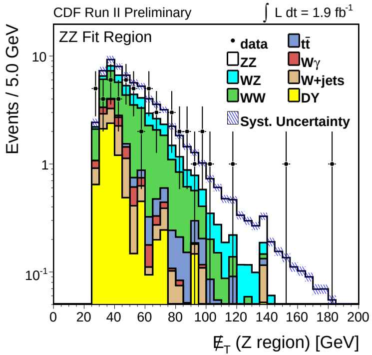
- Same Matrix Element calculation as used for $H \rightarrow WW$

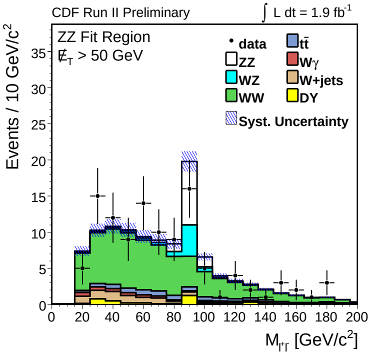
$$LR \equiv \frac{P_{ZZ}}{P_{ZZ} + P_{WW}}$$

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

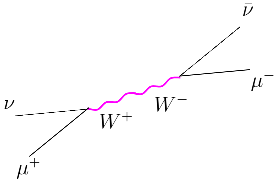


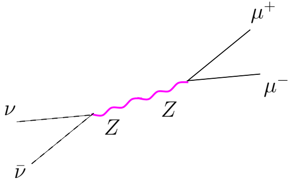
$ZZ \to ll\nu\nu$ with Matrix Elements





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

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

Combined Results

Significance

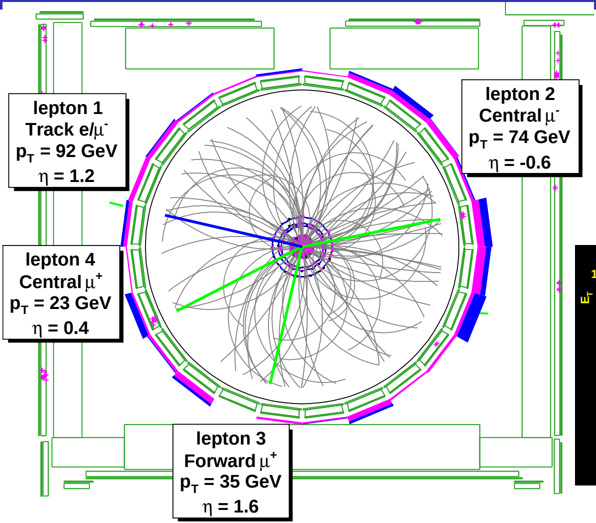
	$ll\nu\nu$	4 lepton	Combined
P-Value	0.12	1.1×10^{-5}	5.1×10^{-6}
Significance	1.2 σ	4.2 σ	4.4 σ

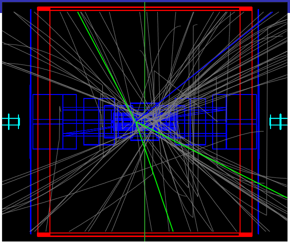
Measured Cross-Section

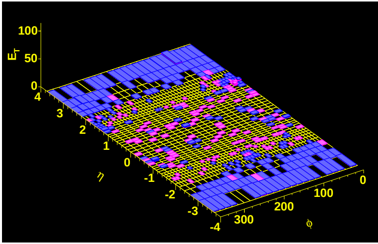
$1.4^{+0.7}_{-0.6}(stat. + syst.)$ pb (NLO prediction is 1.4 pb)

4.4 σ signal for ZZ!

A ZZ to 4 Muon Candidate





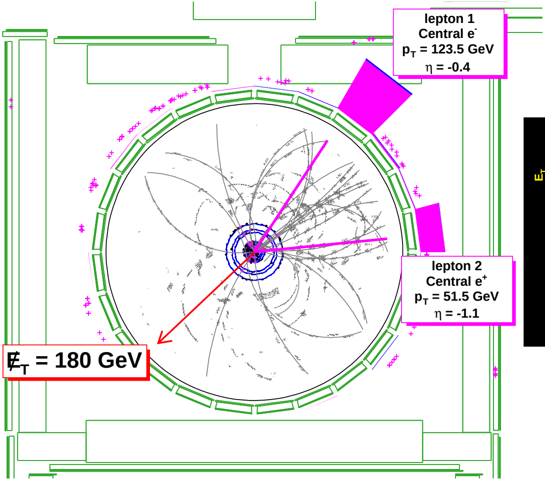


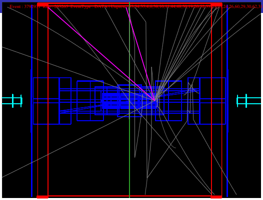
m_{ll1}=90.92 GeV $|\not\!\!E_T|$=8.7 GeV

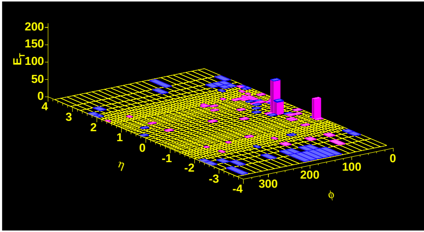
m_{ll2}=83.03 GeV N_{jets} = 0

M_{llll}=312.4 GeV/c^2

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







Run=203265 Event=3792931

m_{12}=91.22 GeV

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

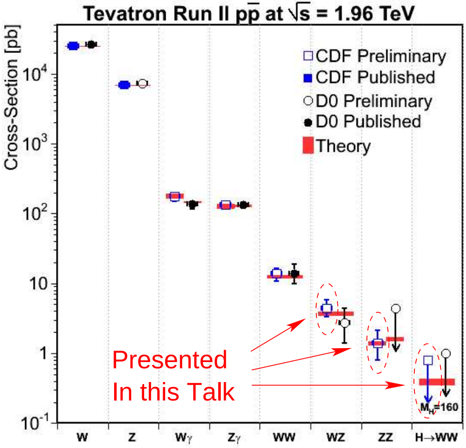
Type	p_T	η	ϕ
Central *e*	123.5	-0.4	1.0
Central *e*	51.5	-1.1	0.1

Summary

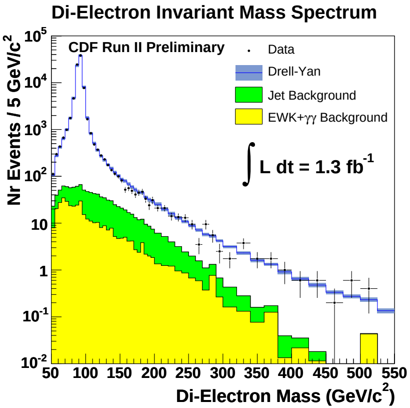
A Comprehensive Approach to Heavy Diboson Decaying Leptons

- First Observation of *WZ* Production
  - 16 events is 5.9 σ signal with 1.1 fb^{-1}
  - Now updated to 25 events
- 4.4 σ Signal for *ZZ* Production
  - Combined *llll* and $ll\nu\nu$
- Higgs $\rightarrow$ *WW* Limits Closing in on the SM
  - Ruling out real possibilities of enhancements on the way

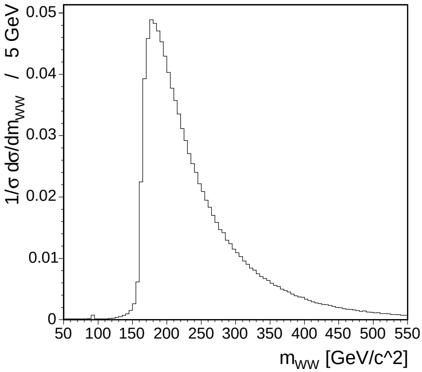
Now pair producing electroweak bosons in significant numbers



The Energy Scale at the Tevatron



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

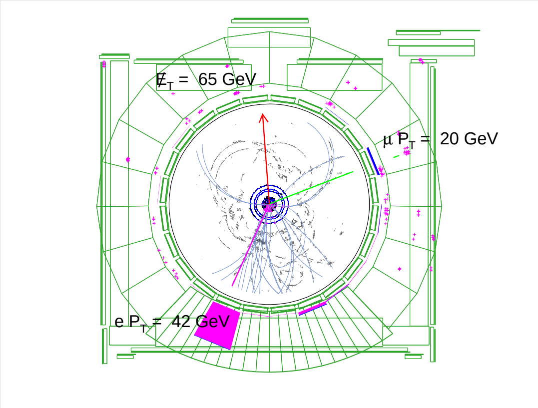


$p\bar{p} \to WWX$ Monte Carlo

$\not{E}_T$ Example: Finding $(H \to)WW \to ll\nu\nu$

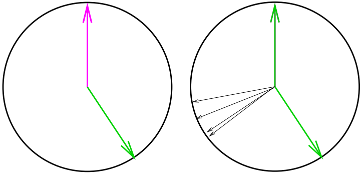
Neutrinos show up as missing transverse energy $\not{E}_T$

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

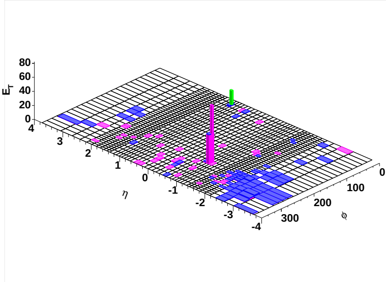


Beam's Eye View of CDF

Event Topology Cartoons



WW Drell-Yan



Calorimeter Unrolled

Backup: WZ Results

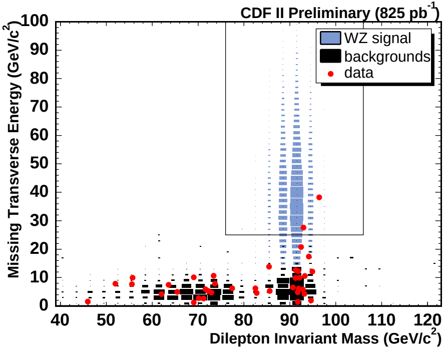
Previous CDF Results

Basic $WZ \rightarrow lll\nu$ 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

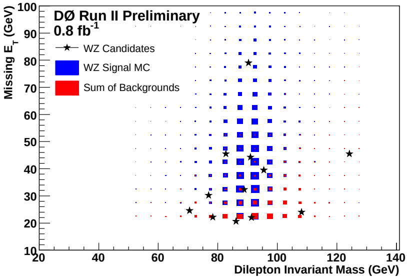
- Expected: 3.7 ± 0.3 signal and 0.9 ± 0.2 background
- Observed: 2 events (probability to observe ≤ 2 : 15%)

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

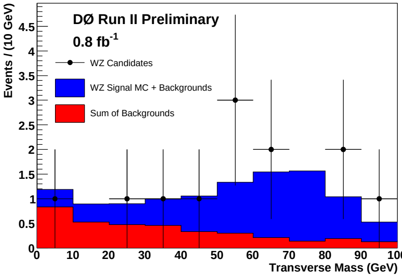
$WZ \rightarrow lll\nu$: DØ , First Evidence

- $760 - 860\ pb^{-1}$ 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 $\sigma(WZ) = 3.7 \pm 0.3\ pb$

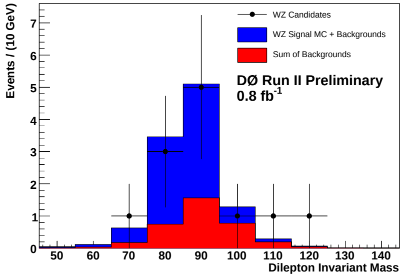
WZ Candidate Mass vs. Missing E_T



WZ Candidate Transverse Mass



WZ Candidate Dilepton Invariant Mass



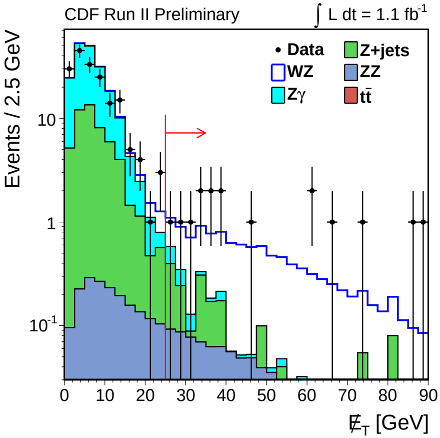
Determining the Signifi cance

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

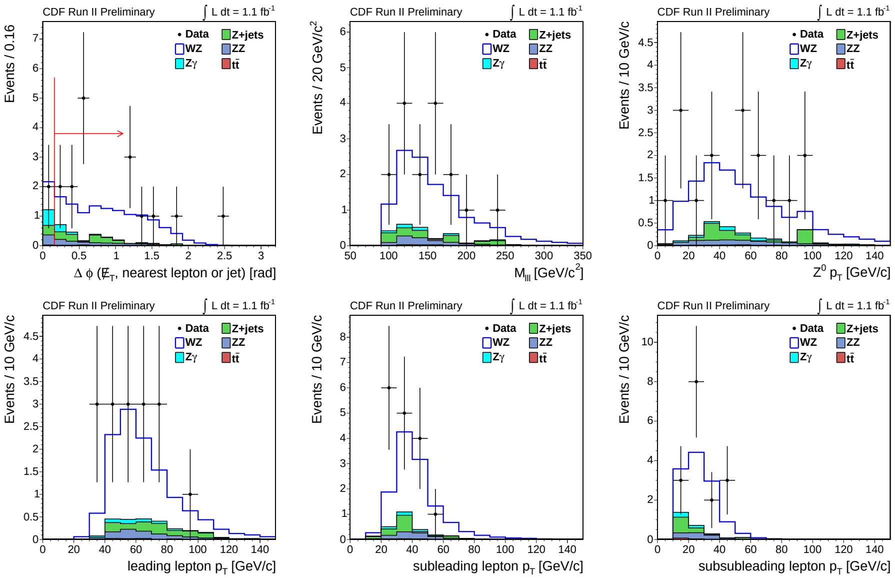
$$\Delta \ln \mathcal{L} = \ln \mathcal{L}_{N_{\text{signal}}=0} - \ln \mathcal{L}_{\text{best fit}}$$

- 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

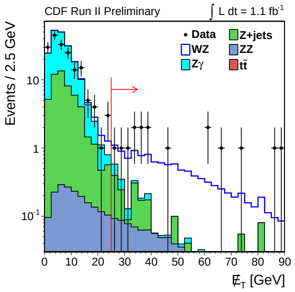
Signifi cance is 5.9 σ

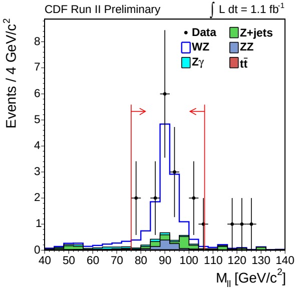


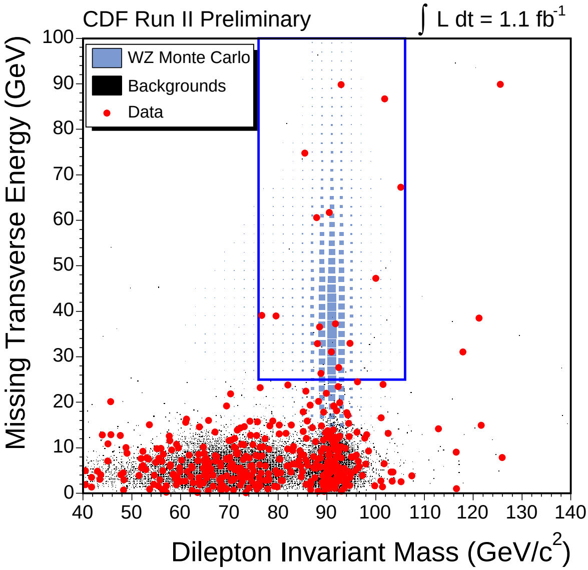
More *WZ* Distributions



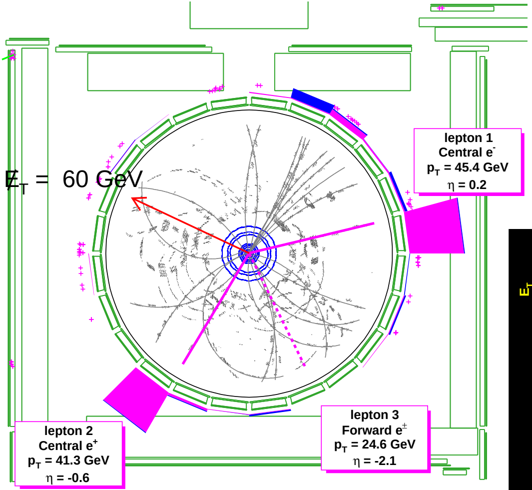
The WZ 2-d plot

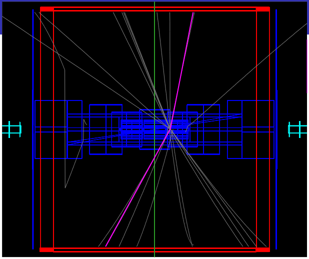


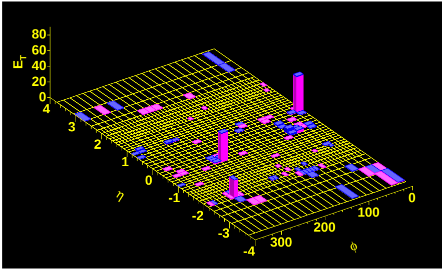




Sample *eee* Event







m_{12}=87.91 GeV

m_{13}=104.37 GeV

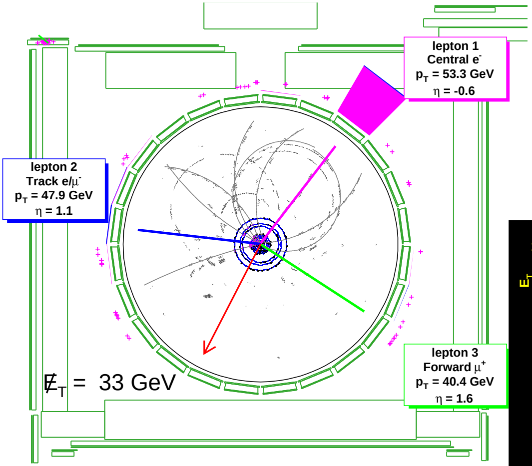
m_{23}=59.62 GeV

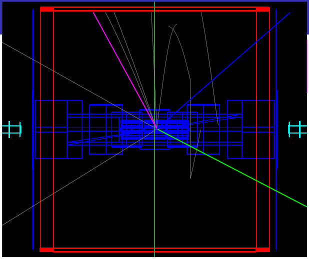
$|\not{E}_T|$=60.5 GeV

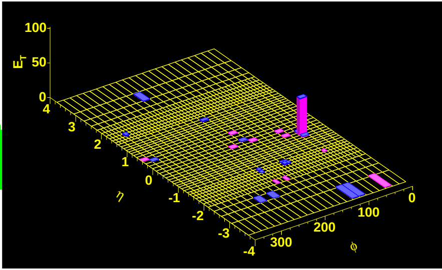
$\Delta\phi(\not{E}_T, \mathrm{lepton}, \mathrm{jet})$=1.5

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

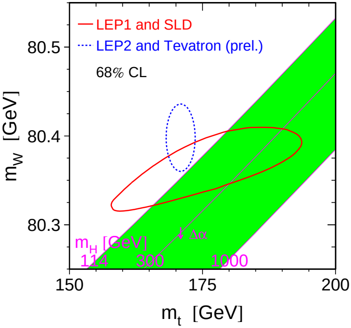
m_{23}=88.09 GeV

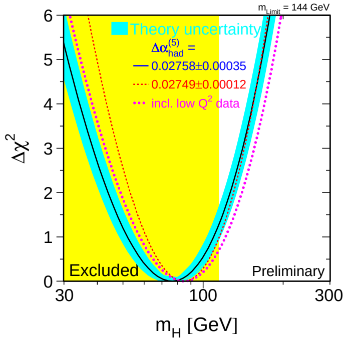
$|\not\!\!E_T|$=32.8 GeV

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

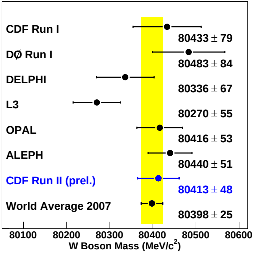
Type	p_T	η	ϕ
Central e	53.3	-0.6	0.9
Track e/μ	47.9	1.1	3.0
Forward μ	40.4	1.6	-0.6

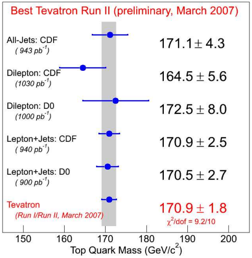
Backup: Higgs



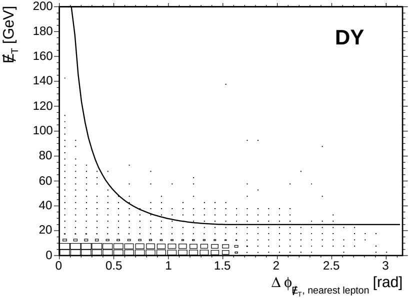


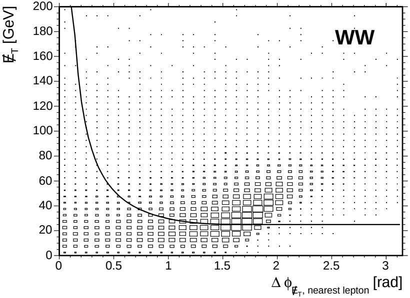
- Includes latest m_W from CDF and m_t from both CDF and DØ





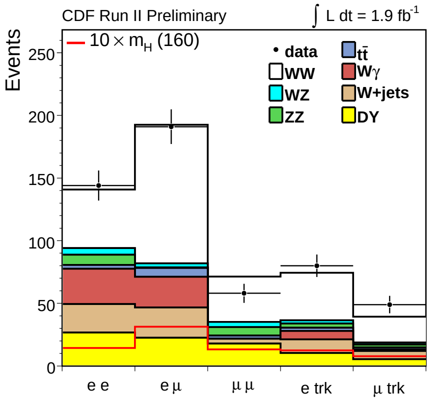
2-d $\not\!\!E_T$ and min $\Delta\phi(\not\!\!E_T, l \text{ or jet})$ Cut





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

$ll\nu\nu$ Yields



Flavor	*WW*	*WZ*	*ZZ*	$t\bar{t}$	DY	$W\gamma$	*W*+jets	Total	Data
e e	46.6	5.3	8.2	2.9	26.6	27.2	22.8	139.5	144
$e\ \mu$	110.1	3.2	0.5	7.0	22.5	23.8	24.1	191.1	191
$\mu\ \mu$	36.0	4.1	6.7	2.7	17.6	0.0	3.1	70.1	58
e trk	37.8	2.6	3.3	2.6	10.3	6.5	10.9	73.9	80

$ll\nu\nu$ Systematics

	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jets	Higgs
$\not\!\!E_T$ Modeling	1.0	1.0	1.0	1.0	20.0	1.0	-	1.0
Conversions	-	-	-	-	-	20.0	-	-
NLO Acceptance	5.5	10.0	10.0	10.0	5.0	10.0	-	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	-	2.2
LepId $\pm 1\sigma$	1.5	1.4	1.3	1.5	1.5	1.2	-	1.5
Trigger Eff	2.1	2.1	2.1	2.0	3.4	7.0	-	3.3
Total	11.9	14.7	14.6	18.4	21.9	25.6	22.5	10.9

- 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

ZZ Statistical Procedure

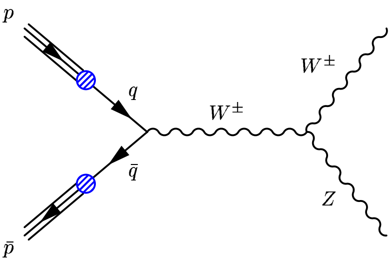
- Inputs
  - 1-d histogram of $ll\not\!\!E_T$ LR with background model
  - 2 1-bin histograms for the two four lepton channels
    - Statistical error and systematics errors included with expected correlations
- Test Statistic = Likelihood Ratio
  - All contributions floating with Gaussian constraints determined by the systematics
  - ZZ floating = test hypothesis (value $\rightarrow$ cross-section)
  - ZZ fixed to zero = null hypothesis

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

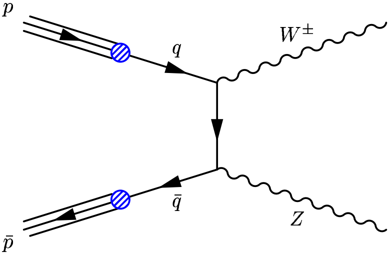
- 10 million pseudo experiments
  - Bin statistics and systematics varied

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

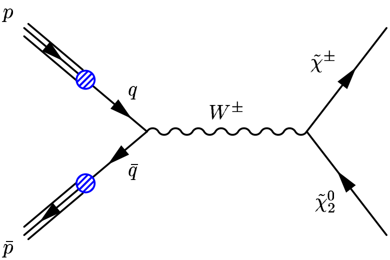
WZ: The SUSY Golden Mode's Mirror Image



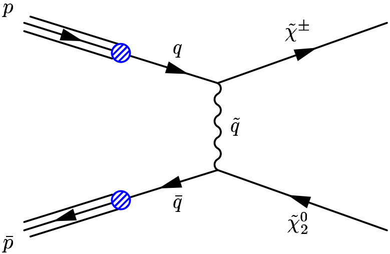
Standard Model *WZ*

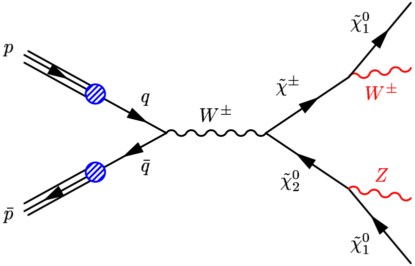


SUSY Mirror



SUSY Chargino-Neutralino





SUSY decaying on-shell *WZ*

There is always the unknown