Measurement of WW/WZ cross section in lepton-neutrino + jets final state at CDF

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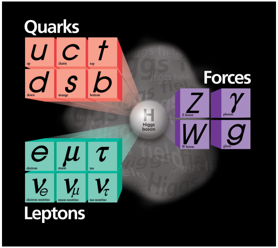
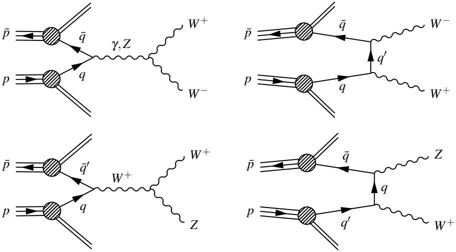
Why studying Diboson?

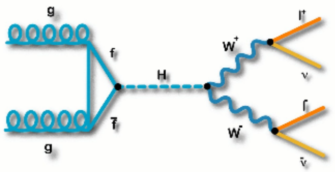




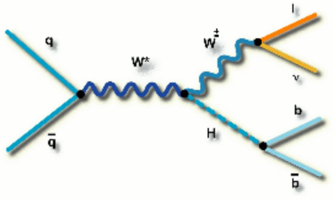
- Measurements of electroweak vector boson production are an important test of the Standard Model.
- They are a reality check on path to finding mutilepton and semileptonic final states with very small $\sigma \times BR$.
- s-channel probes triple gauge couplings (TGC)
  1. Sensitive to new physics: ZZZ, $ZZ\gamma$, $Z\gamma\gamma$ absent in SM
- Cross sections can be enhanced by new physics(Higgs, SUSY, ...)

Motivation: Higgs searches

- $H \to WW$ is the dominant decay mode for a high mass Higgs ($m_H > 135$ GeV/c^2)
  - Drives current exclusion limits
  - Direct diboson production is the single most important background



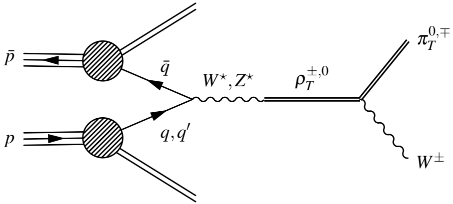
- $WH \to \ell\nu b\bar{b}$ is a promising search mode for low mass Higgs ($m_H < 135$ GeV/c^2)
  - Similar topology/final state to WW/WZ$\to \ell\nu q\bar{q}$
  - Similar challenges $\to$ S/B WH 1.2% WW/WZ 2.9%



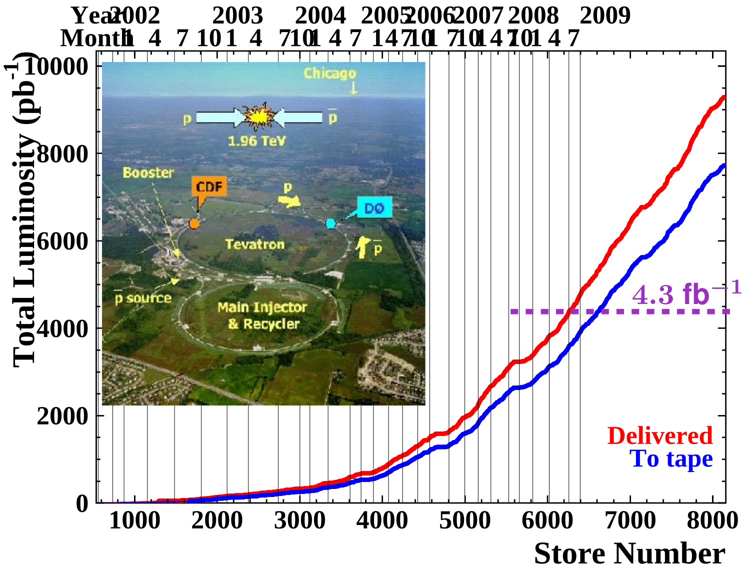
WW/WZ$\to \ell\nu q\bar{q}$ is a proving ground for Higgs search

Motivation: physics beyond the SM

- Measurements involving associated production of W and jets gives us strong foundation also for searches for physics beyond the SM.
- SM Higgs, in fact, is not the only solution to the electroweak symmetry breaking
- One of the golden mode to test the MSSM Higgs sector is the channel Wϕ (neutral Higgs bosons) in which the ϕ decays in $b\bar{b}$.
- Also Technicolor predicts that the same signature would be shared by processes like $\rho_T \to W\pi_T$. The signal process in the semileptonic final state is expected to show resonant peaks in both the dijet and W+2 jets mass spectra.

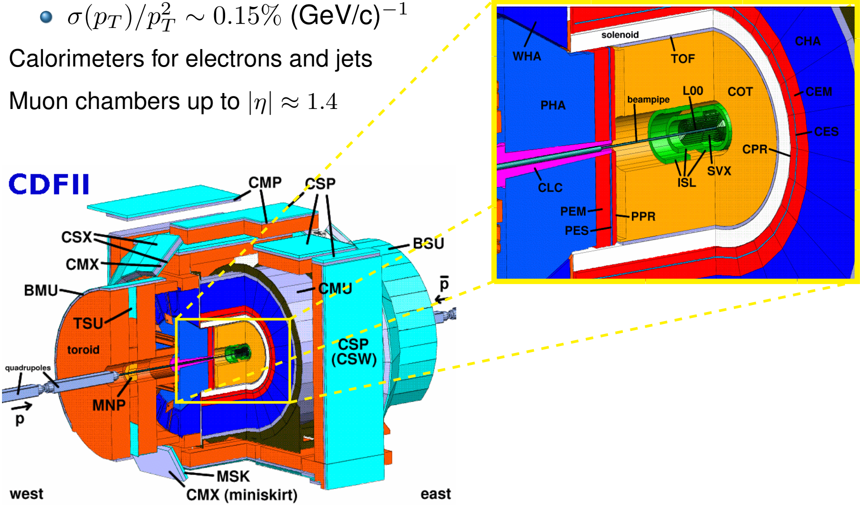


Collected data until Summer 2010 shutdown:



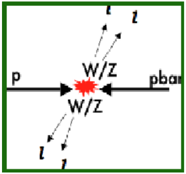
Important CDF II features

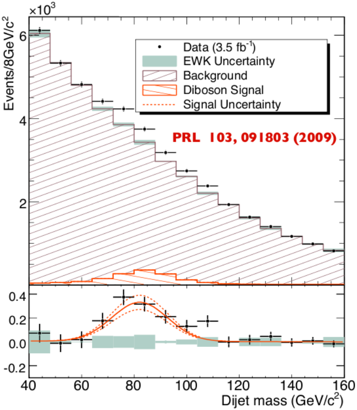
- Silicon detectors (L00+SVX+ISL) and central drift chamber (COT) in 1.4 T magnetic field
  - I.P. resolution $\sim 40\ \mu$m
  - $\sigma(p_T)/p_T^2 \sim 0.15\%$ (GeV/c)$^{-1}$
- Calorimeters for electrons and jets
- Muon chambers up to $|\eta| \approx 1.4$

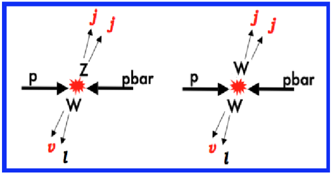


Diboson final states

- WW, WZ and ZZ production have already been studied in leptonic final states both at LEP and Tevatron
  - Clean Yields but low BR
- Semi-leptonic modes suffer from large background:
  - WW, WZ, ZZ observed in $\not{E}_T$ + jets mode at CDF in 2009
  - leptons + jets final state → DØ showed evidence in 2008.

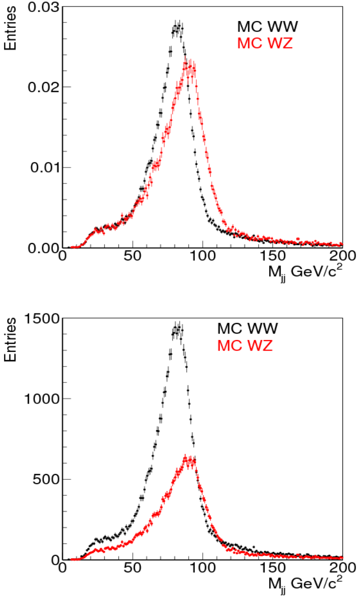




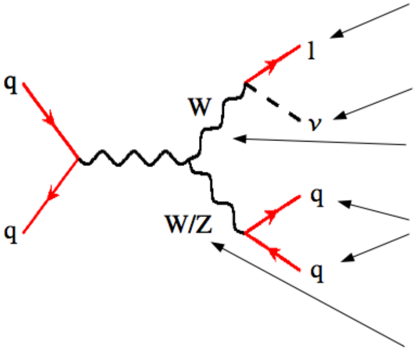


$WW/WZ \to \ell\nu + jets$ final state

- We treat events from WW and WZ as indistinguishable signals
- Largely due to insufficient dijet mass resolution: 10 GeV difference in mass
- Cascade decays of heavy quarks in $Z \to b\bar{b}$ contain neutrinos, thus reducing reconstructed dijet mass in these events. Final mass difference: ~7 GeV
- Consider relative efficiency:
  1. $\sigma(WW(WZ) \to \ell\nu + jets) \times BR \sim 3.5(0.5)$ pb



Strategy



- Trigger on the charged lepton
- Require missing transverse energy
- Get a sample of inclusive W
- Look for at least two jets and form the invariant masse
- Fit the expected W/Z and background dijet mass shape to data to extract the diboson fraction

Backgrounds

- $W \to \ell\nu$ + jets ($l = e, \mu, \tau$):
  - same signature as signal with a much higher cross section (2066 pb)
  - $\sim$ 80% of the sample
- $Z \to ll$ + jets ($l = e, \mu, \tau$):
  - where one of the two leptons escapes detection and produces $\not\!\!E_T$
  - cross section 187 pb
- $t\bar{t}$ + single top:
  - final state similar to signal with at least one real W and two jets.
  - $\sigma(t\bar{t})$ = 7.5 pb and σ(single top) = 2.9 pb (assuming a mass of 172.5 GeV/c^2)
- QCD Multijet:
  - events without a real high pT lepton
  - e.g a three-jet event in which one jet passes all lepton cuts and, simultaneously, the energies are so badly measured that a large $\not\!\!E_T$ is reported.
  - probability for a jet to mimic a lepton is very small, but QCD processes have very large cross sections
  - estimated from data using orthogonal selection

High p_T Electron and Muon selection

- Start from a sample trigger with a high p_T electron or muon (CEM $|\eta| < 1.0$, CMUP $|\eta| < 0.6$, CMX $0.6 < |\eta| < 1.0$)

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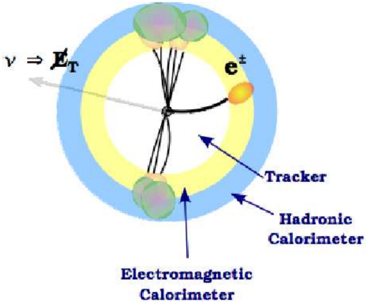
- Electrons
  1. Require calorimeter showers consistent with electromagnetic interactions
  2. Calorimeter energy is clustered in cones of radius $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.4$
  3. Require that 90% of energy is deposited in the EM calorimeter



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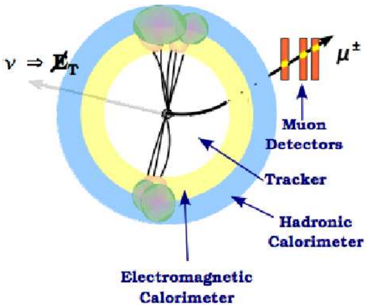
  1. Require high quality track
  2. Good matching between the track and the hit in the muon chambers
  3. Calorimeter deposit compatible with MIP



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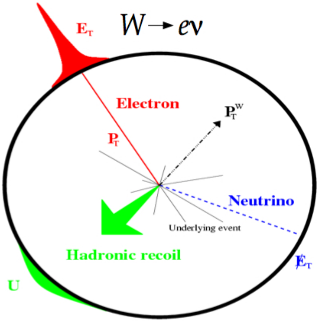
- Selecting electrons and muon with $E_T(p_T) > 20$ GeV/c^2 (GeV/c) and $|\eta| < 1.2$.
- Both are required to be isolated to reject leptons from semi-leptonic decays of heavy flavor hadrons and leptons faked by hadrons.

$W \to \ell\nu$

- Once we have a good lepton, we want events consistent with $W \to \ell\nu$ decay
- Undetected neutrino manifests as an imbalance in transverse momentum: "missing" transverse energy

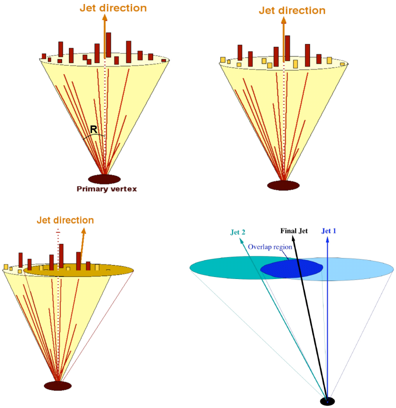
$$\vec{\not{E}}_T = -\sum_i \vec{E}_T^i$$

- To reduce multijet backgrounds, we require $\not{E}_T > 25$ GeV and $M_T^W > 30$ GeV.
- Veto events with two leptons whose invariant mass is in the Z window
- Veto on cosmic events and conversions.



Jet reconstruction

- The algorithm used for the Jet Reconstruction is JETCLU:
  1. Finds the seed towers with $E_T > 1GeV$
  2. Looks for adjacent towers in a cone $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$
  3. The E_T weighted centroid is then formed and if this equals the one of the previous iteration, the cone is considered stable.
  4. If the shared energy between two clusters is more than 75% towers assigned to the closest cluster.



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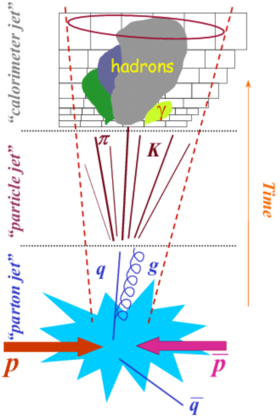
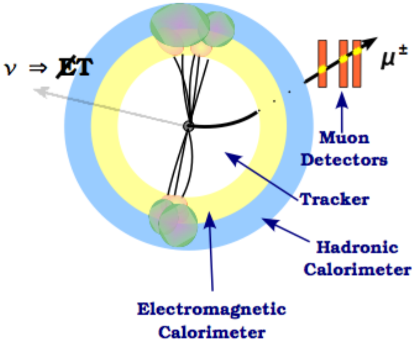
  4. If the shared energy between two clusters is more than 75% towers assigned to the closest cluster.
- The four-momentum assigned to a jet suffers for both detector inaccuracies and reconstruction algorithm imperfections.
- Correct for the response inhomogeneity in η, contributions from multiple interactions, the non-linearity of the calorimeter response



$W/Z \to q\bar{q}$

- Quark jets arising from W/Z$\to q\bar{q}$ decays are very energetic and relatively central
- Cluster energy in cones of $\Delta R < 0.4$
- Calorimeter signature must be inconsistent with electron signatures
- No veto on number of jets to increase acceptance.
- Select jet with $E_T > 20$ GeV and $|\eta| < 2.4$



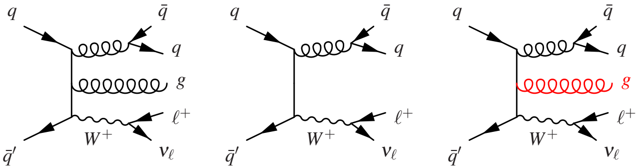
Modeling of background

- Most of the backgrounds modeled using Monte Carlo simulation
  1. WW/WZ simulated using PYTHIA
  2. $W + jets$ simulated using ALPGEN with the showering from PYTHIA
  3. $Z + jets$ simulated using ALPGEN with the showering from PYTHIA
  4. $t\bar{t}$ production simulated using PYTHIA with a top mass of 172.5
  5. Single top production simulated with MADEVENT + PYTHIA
  6. QCD modeled using data.

Process	σ **(pb)**
WW/WZ inclusive	15.9 ± 0.9
$Z \to e, \mu, \tau$+jets	787 ± 85
$t\bar{t}$	7.5 ± 0.83
single top	2.86 ± 0.36
W+jets	data
QCD multijet	data

Alpgen+Pythia

- While simulating W/Z + N-jets, we need to get the inclusive cross section and the relative cross section for exclusive N-jets
- We simulate by pairing Alpgen (LO matrix elements) and Pythia (parton showers)
  1. Matrix Elements: Fixed order. Gives an accurate description of the hard process. Needed for N-jet description
  2. Parton showers: Needed for a realistic description of the final state in the detector
- Combine them using MLM scheme to avoid double counting.
- Cluster the showered partons into cone jets. Keep events only if each jet is matched to just one parton



Monte Carlo Corrections

Need to take into account efficiency, reconstruction, resolution differences between data and MC:

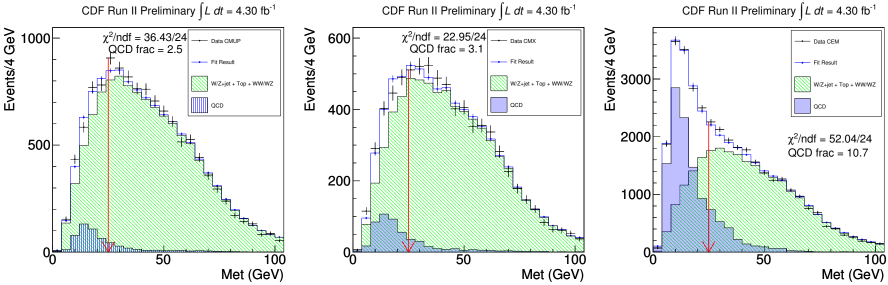
- Trigger Efficiencies: Data must pass the trigger to be selected $\rightarrow$ apply these efficiencies to the MC
- Lepton Energy Scale, Energy Resolution, and Identification: MC does not do a perfect job of modeling detector response to leptons $\rightarrow$ correct energies and apply data/MC scale factors
- Luminosity Profile: not the same as for the data $\rightarrow$ reweight as a function of number of vertices

Modeled using data sidebands

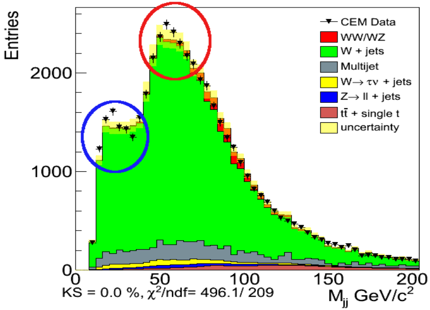
- “Non isolated muons”:
  - Using non-isolated events, events which pass all selection criteria except the requirement of lepton isolation.
  - Based on the rationale that non-isolated events are typically leptons contained in jets, and jets that contain energetic leptons are more likely to pass lepton identification cuts.
- “AntiElectrons”:
  - Some non-kinematic cuts for the electron (EHAD/EM ...) are used to reject fake electrons.
  - Model is constructed of events which fail at least two of the non-kinematic cuts but pass all the kinematic cuts of the electron.

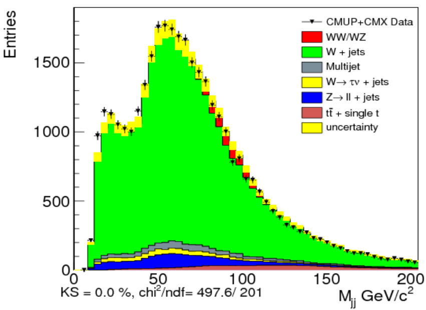
QCD estimation

- QCD multijet events are characterized by low $\not\!\!E_T$, so $\not\!\!E_T$ distribution is completely different from $W + jets$
- Best solution $\rightarrow$ Fit the $\not\!\!E_T$ distribution on data
- Extract the fraction of QCD and knowing all the others contributions can extract also a preliminary $W + jets$ normalization (left completely free in the final fit)
- Systematic associated with the normalization estimated using different models (25%)



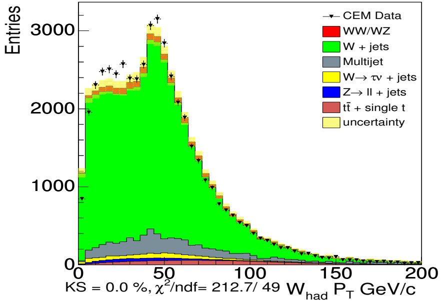
Dijet mass shape I

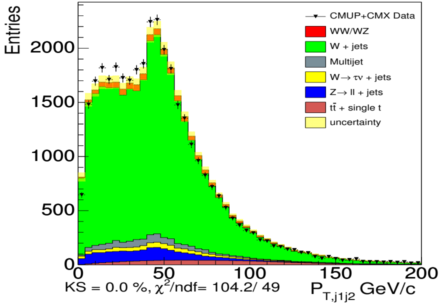




- With all the ingredients can look at the M_{jj}
- The E_T threshold on the jets gives rise to two peaks:
  - At $M_{jj} \sim$ 20 GeV for almost collinear jets where the invariant mass is minimum and the combined dijet $P_{T,jj}$ is maximum
  - The second one is at M_{jj} ∼40 GeV, for back to back jets ($\Delta\phi \sim \pi$), where the invariant mass is maximum.

Dijet mass shape II

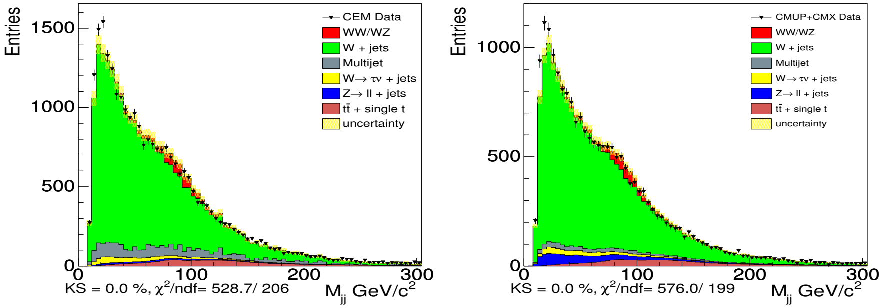




Two possible solutions:

- Cut lower in jet E_T $\rightarrow$ Kinematic region not well modeled
- Cut on the dijet $p_T > 40$ GeV/c (that also shows mismodeling in the low p_T region):
  1. Loose $\sim$ 40 % of the signal

Dijet mass shape II

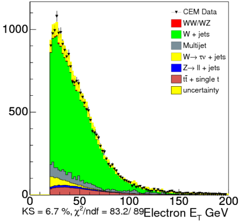


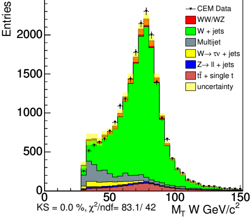
Two possible solutions:

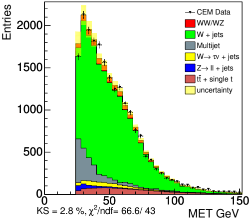
- Cut lower in jet E_T $\rightarrow$ Kinematic region not well modeled
- Cut on the dijet $p_T > 40$ GeV/c (that also shows mismodeling in the low p_T region):
  1. Loose $\sim$ 40 % of the signal
  2. Get a smooth distribution where the diboson is well separated from the $W + jets$

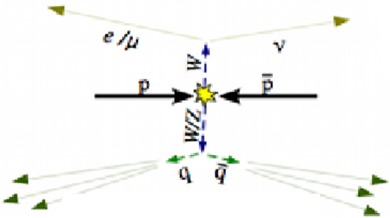
Sample Composition

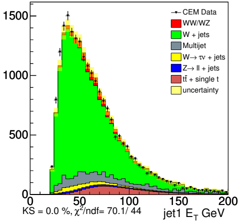
CDF Run II Preliminary L_{int}= 4.30 fb^{-1}

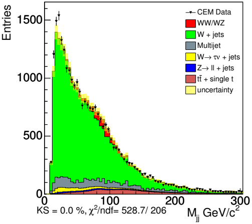


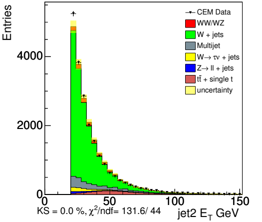




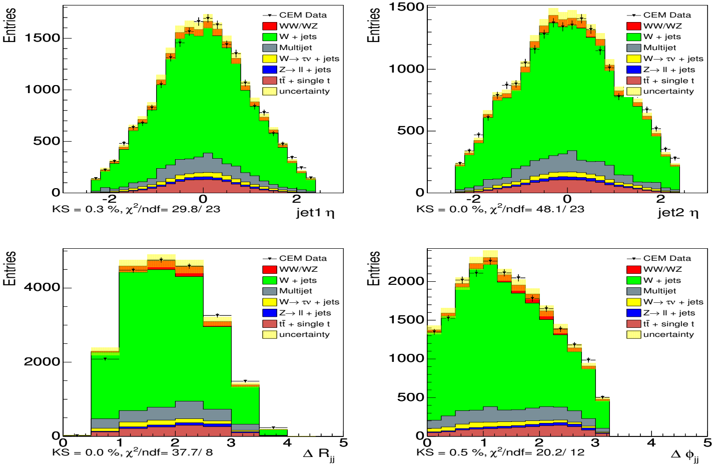






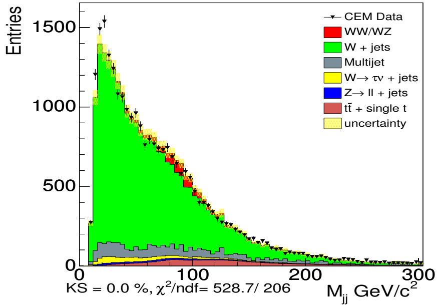


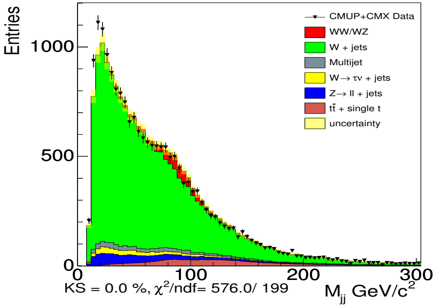
Angular modeling



- Angular distributions fairly well modeled
- Energy distributions show some mismodeling → systematic on $W + jets$ shape

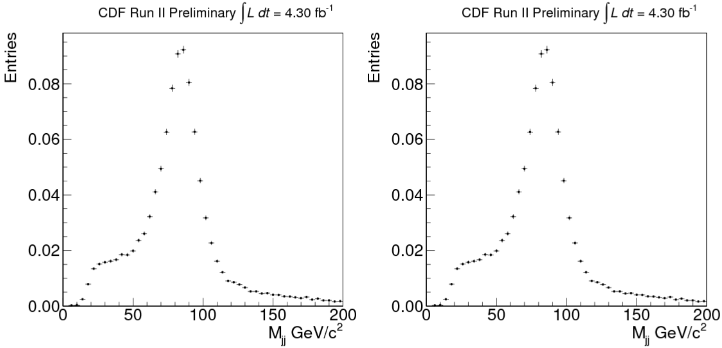
Fit to M_{jj} distribution





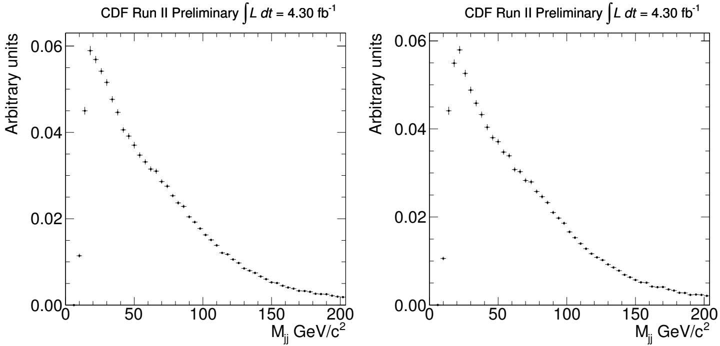
- Fit separately electrons and muons since they have different background contributions.
- Binned fit to the mjj shape taking as templates the histograms:
  1. Signal (WW and WZ)
  2. $W + jets \longrightarrow$ completely free in the fit
  3. QCD $\longrightarrow$ gaussian constraint to the value found in the $\not{E}_T$ fit with 25% width.
  4. Top+single top: constrained to the measured cross section
  5. $Z + jets$: constrained to the measured cross section

Templates



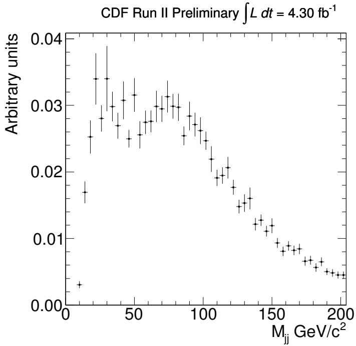
- Diboson

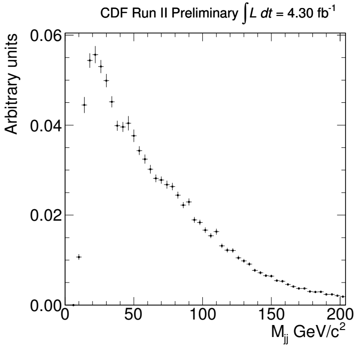
Templates



- Diboson
- $W + jets$

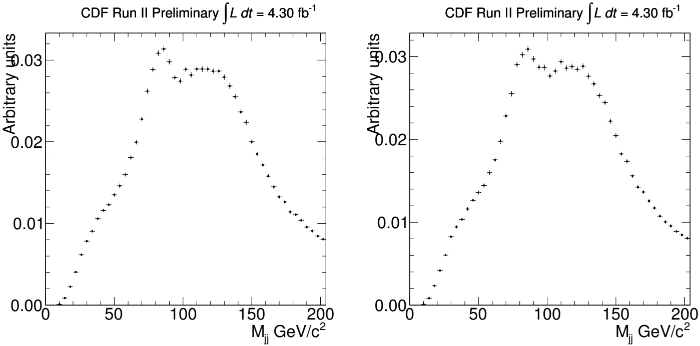
Templates





- Diboson
- $W + jets$
- $Z + jets$

Templates

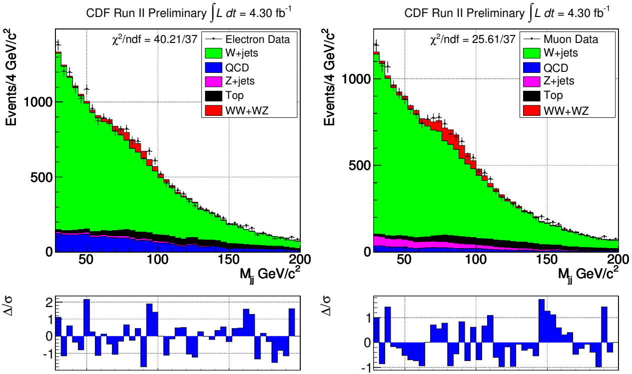


- Diboson
- $W + jets$
- $Z + jets$
- top+single top

Results

- Perform the fit on data after checking for no bias

Sample	CEM	CMUP + CMX
W +jets	18010 ± 531	16673 ± 482
Z+jets	353 ± 42	966 ± 115
diboson	739 ± 43	645 ± 37
top + single top	1324 ± 134	1149 ± 115
QCD	2375 ± 594	532 ± 133
Total Prediction	22801 ± 810	19965 ± 527
Observed Events	22204 ± 149	19738 ± 141



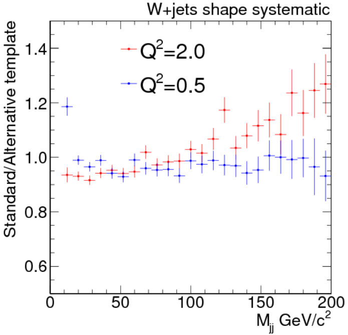
Systematic summary

- Consider two classes of systematics:
  1. systematics affecting signal extraction
  2. systematics affecting signal cross-section
- Evaluated generating statistical trials with the varied templates and fitting with the standard ones.

Affected Quantity	Source	Uncertainty (%)	
		Electrons	Muons
Number of Signal Events	QCD shape	± 4.5	± 3.9
	Q^2	± 6.2	± 6.1
	JES	± 6.3	± 5.1
	JER	± 2.9	± 1.4
	Total	$\mathbf{\pm 10.3}$	$\mathbf{\pm 9.0}$
Cross Section	Lepton Acceptance	± 2.0	± 2.0
	ISR	± 1.8	± 1.4
	FSR	± 0.7	± 2.6
	PDFs	± 2.0	± 2.0
	Luminosity	± 6.0	± 6.0
	Total	$\mathbf{\pm 12.4}$	$\mathbf{\pm 11.6}$

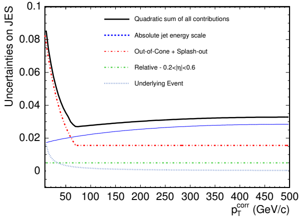
Shape systematic: $W + jets$

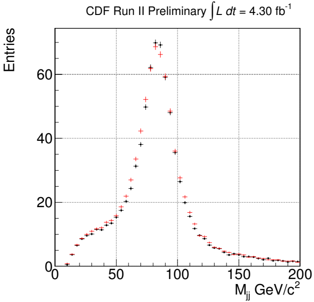
- Alpgen MC depends on a number of parameters:
  1. Factorization and normalization scale $Q^2 = M_W^2 + \sum p_T^2$ which can be varied by a constant factor
  2. k_T Scale Factor: Alpgen's scale factor for α_s at each decay vertex.
  3. Parton matching cluster p_T threshold: the minimum p_T for jet clusters that are used for matching procedure.
  4. Parton matching clustering radius size: the size of the jet cone used when creating jet clusters for matching procedure $\rightarrow$ Alpgen authors recommend using the generator level cut.
- The only significant effect is given by the Q^2
- Double and halve it to obtain alternative templates



Other shape systematics

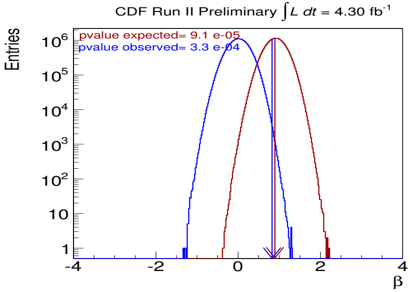
- Measurement is dominated by the Jet Energy Scale:
  1. Parameterized as a function of p_T
  2. The uncertainty on each correction is derived by comparison of the data to MC or by comparison of different MC generators.
  3. Even if the agreement between the data and the MC in the fit supports that the JES (that would induce a shift in the diboson template) is well calibrated, we still include a systematic error coming from this source.
  4. Apply to all MC modeled processes at the same time
- Jet energy resolution on diboson template: the MC description of the jet resolution is compared to the resolution in data in γ+jet and dijet events.
- QCD shape systematic evaluated using different models

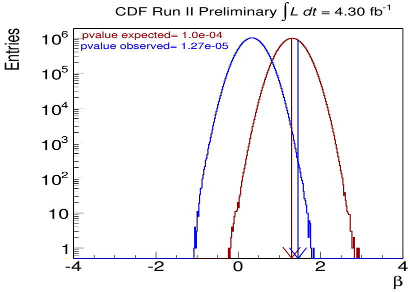


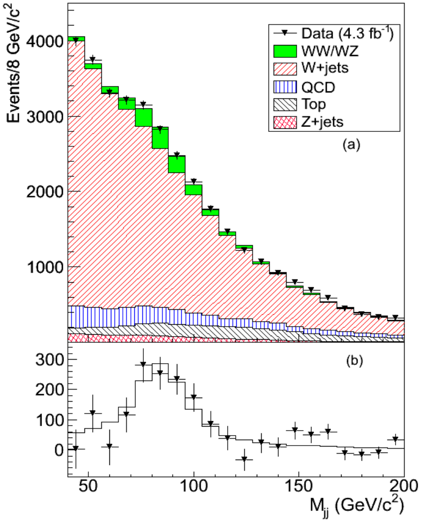


Significance estimation

- To quantify the significance of the signal we define as test statistic, the ratio, β, between the expected and the observed numbers of events.
- To take into account the systematic uncertainties we use a method called *supremum p-value* that maximizes the p-value with respect to all the combinations of systematics.
- We generate one set of pseudo-experiments with a variation of the fit templates according to some of the systematic sources.
- This is done for all possible combinations. For each set we evaluate the corresponding p-value. The worst case is taken.
- The combined p-value is 8.56×10^{-8} that corresponds to 5.24σ found where 5.09σ was expected







We estimate 1582 ± 275(stat.) $\pm\ 107$(syst.) events of $WW + WZ \to \ell\nu +$ jets.

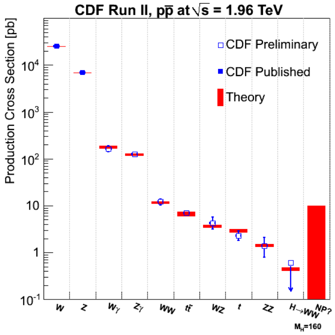
The resulting cross section is

$\sigma(WW/WZ) = 18.1 \pm 3.3$(stat.)$\pm 2.5$(syst.) pb

that is in agreement with SM expectation $(15.9 \pm 0.9$ pb).

Conclusion

- Measured the cross section of WW/WZ $\rightarrow l\nu$ +jets
  - PRL published on march 2010: Phys. Rev. Lett. 104, 101801 (2010)
  - Observation in lepton+jets final state.
  - http://www-cdf.fnal.gov/physics/ewk/2010/WW_WZ/index.html



- Opens the way to diboson studies with jets
- Error on cross section dominated by the statistical uncertainty
  - Tevatron will deliver 10 fb^{-1} by the end of 2011 and eventually 16 fb^{-1}
- Getting closer to Higgs sensitivity

Backup

Electron Trigger

- Level 1:
  - an energy deposit of a minimum 8 GeV in the calorimeter tower;
  - $E_{\text{HAD}}/E_{\text{EM}}$ is required to be less than 0.125 to reject hadronic particles;
  - a track with $p_T > 8.34$ GeV/c found by the XFT is required to point to the tower.
- Level 2:
  - a calorimeter cluster is formed by adding adjacent towers with $E_T > 7.5$ GeV to the “seed” tower found at Level 1;
  - for the cluster, the requirements are $E_T > 16$ GeV and $E_{\text{HAD}}/E_{\text{EM}} < 0.125$;
  - the Level 1 XFT requirement is confirmed.
- Level 3:
  - an EM object with $E_T >$ 18 GeV and $E_{\text{HAD}}/E_{\text{EM}} < 0.125$ (confirmed);
  - a fully reconstructed three-dimensional COT track with $p_T >$ 9 GeV/c is required to point to the cluster.

Muon trigger

- Level 1:
  - hits in one or more layers of the CMU or CMX chambers are found;
  - for the CMU/CMP trigger, 3 or 4 additional hits in the CMP are required to be consistent with hits in the CMU;
  - an XFT track with $p_T > 4.09$ GeV/c (8.34 GeV/c) is demanded to match in the $r - \phi$ plane the hits found in the CMU/CMP (CMX);
- Level 2:
  - a COT reconstructed track in the transverse plane with $p_T > 14.77$ GeV/c;
- Level 3:
  - a fully reconstructed three-dimensional COT track with $p_T >$ 18 GeV/c is required to match a track reconstructed in the muon chambers.

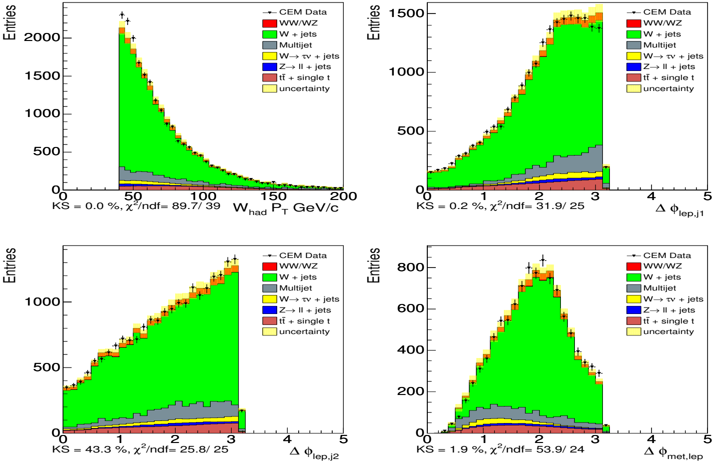
Lepton Selection

Variable	Requirement
Fiduciality	Detected in the active region of the CES/CEM
Track $\|Z_0\|$	≤ 60 cm
E_T	> 20 GeV
p_T	> 10 GeV/c
COT Axial segments	≥ 3 with ≥ 5 hits each
COT Stereo segments	≥ 2 with ≥ 5 hits each
E/p	≤ 2 (unless $p_t \geq 50$ GeV/c)
$E_{\text{HAD}}/E_{\text{EM}}$	$\leq 0.055 + 0.00043 \cdot E$
L_{shr}	< 0.2
Iso/E_T	≤ 0.1
Signed ΔX_{CES}	$-3 \leq q\Delta X_{\text{CES}} \leq 1.5$
$\|\Delta z_{\text{CES}}\|$	< 3 cm
χ^2_{CES}	≤ 10

Lepton Selection

Variable	Requirement
p_T	> 20 GeV/c
Iso/p_T	≤ 0.1
$\lvert z_0 \rvert$	≤ 60 cm
E_{EM}	$\leq 2 + \max\left[0, (p - 100) \cdot 0.0115\right]$
E_{HAD}	$\leq 6 + \max\left[0, (p - 100) \cdot 0.028\right]$
COT Axial segments	≥ 3 with ≥ 5 hits each
COT Stereo segments	≥ 2 with ≥ 5 hits each
$\lvert d_0 \rvert$ for tracks w/ Si hits	< 0.2 cm
$\lvert d_0 \rvert$ for tracks w/o Si hits	< 0.02 cm
ρ_{COT} for CMX muons	> 140
χ^2_{COT}	< 2.3
$\lvert \Delta X_{\text{CMU}} \rvert$	≤ 7 cm
$\lvert \Delta X_{\text{CMP}} \rvert$	≤ 5 cm
$\lvert \Delta X_{\text{CMX}} \rvert$	≤ 6 cm
CMU Fiduciality	$x < x_{\text{fid}}$, $z < z_{\text{fid}}$
CMP Fiduciality	$x < x_{\text{fid}}$, $z < z_{\text{fid}} - 3$ cm
CMX Fiduciality	$x < x_{\text{fid}}$, $z < z_{\text{fid}} - 3$ cm

Alpgen modeling



- Angular distributions fairly well modeled