Diboson Production at DØ

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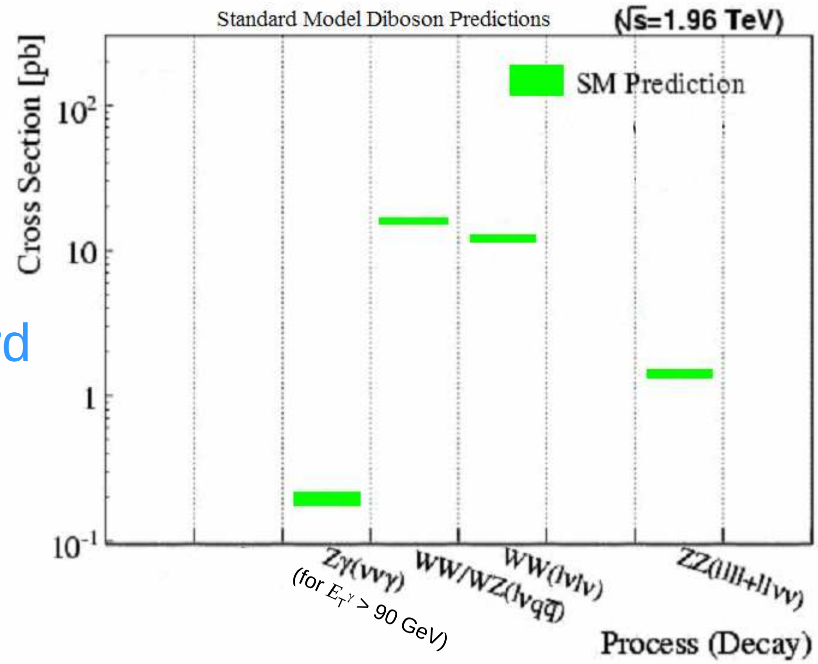
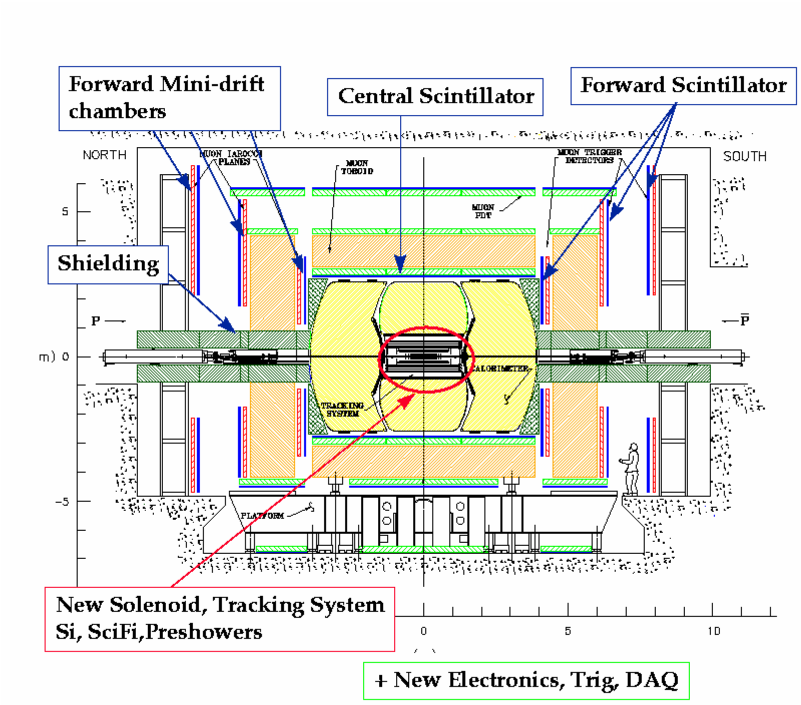
Diboson Physics at DØ

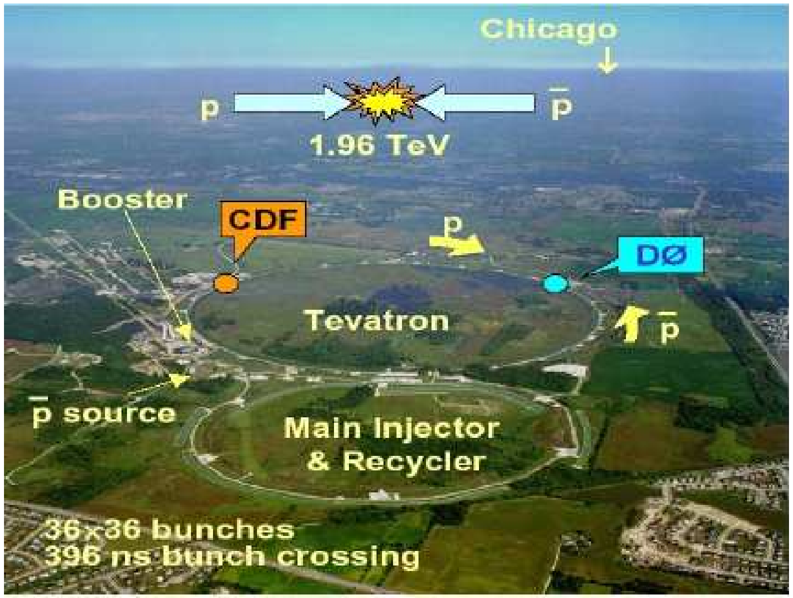
- Diboson processes have low cross sections
  - Provide natural series of goals for detector sensitivity
  - Probe fundamental details of standard model EW sector directly
  - Search at Tevatron explores higher energies than LEP and provides access to some channels (e.g., *WZ*) not available there
  - New physics would be reflected in increased cross sections

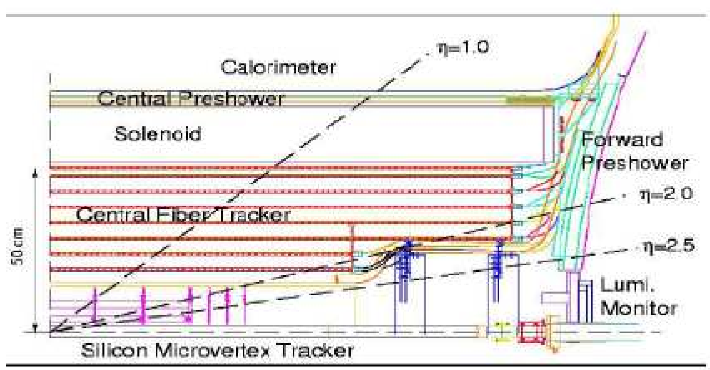


- Motivated by Higgs and SUSY searches
  - Share same or similar final states
    - Vital to understand diboson background
  - Share similar analysis techniques that can be used at the LHC

The DØ Detector







- Silicon micro-strip vertex detector
- Scintillating fiber tracker
- 2 T solenoid magnet
- Uranium Liquid Argon calorimeter
- 1.8 T toroid magnet
- Wire tracking / scintillation counter muon detector
- $|\eta|$ coverage:
  - electrons < 3.2
  - muons < 2.0

$ZZ \rightarrow llll$

- Selected events from 1.7 fb^{-1} of Run IIb data
  - Four isolated leptons

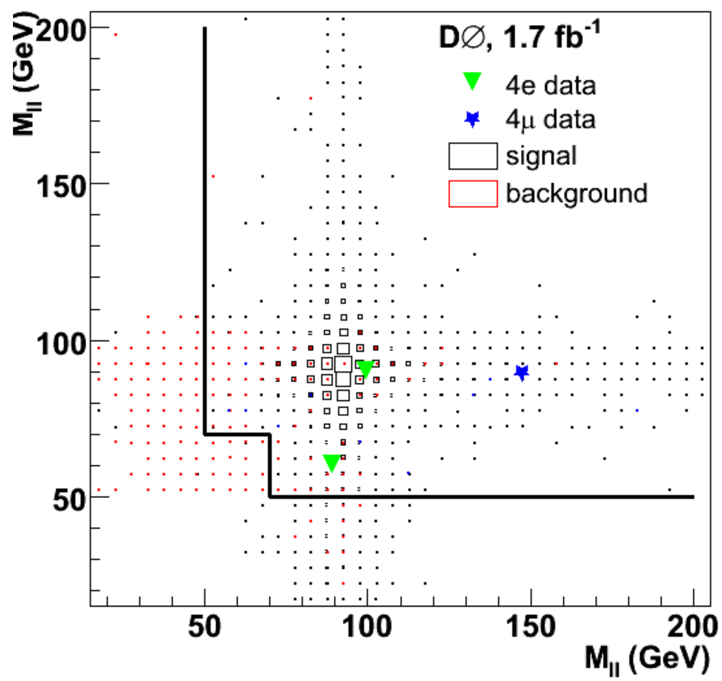
    4e channel: Four electrons with $p_T^1 > 30$, $p_T^2 > 25$, $p_T^{3,4} > 15$ GeV sorted by number of electrons with $|\eta| < 1.1$ (at least two)

    4μ channel: Four muons with $p_T^1 > 30$, $p_T^2 > 25$, $p_T^{3,4} > 15$ GeV

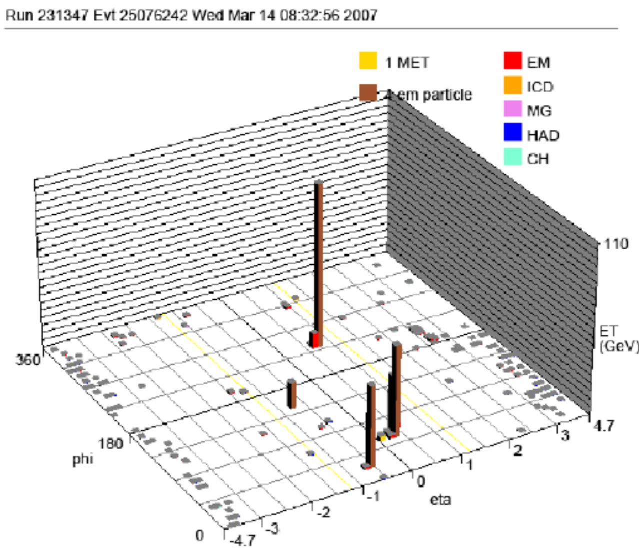
    2e2μ channel: Two electrons and two muons with $p_T^1 > 25$, $p_T^2 > 15$ GeV sorted by number of electrons with $|\eta| < 1.1$
  - Consistent with coming from a pair of Z bosons

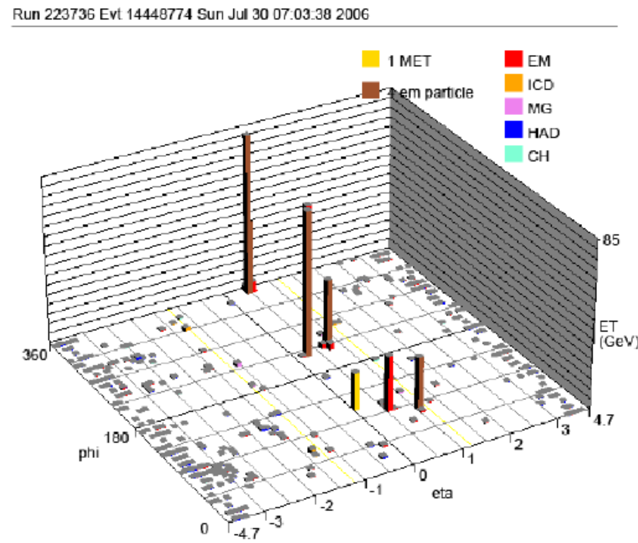
    Dilepton mass $M_{ll}^t > 70$, $M_{ll}^l > 50$ GeV

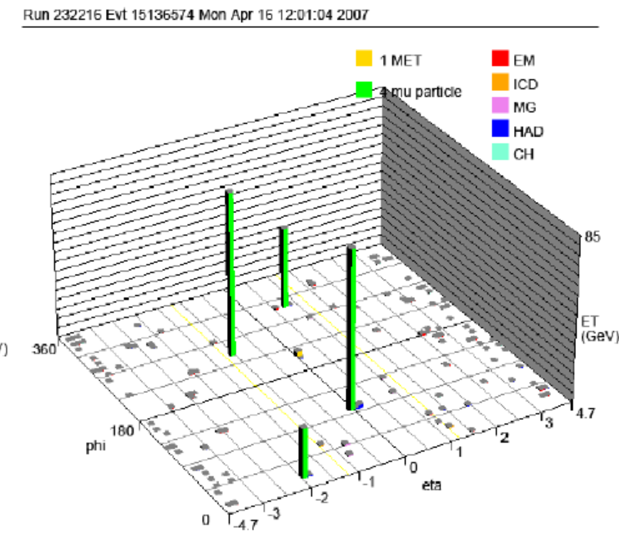
    (one combo of opposite-charge, like flavor lepton pairings)
- Clean Signature
  - No other SM background with 4 leptons
  - Small number of expected events means understanding background is important
  - Small $Z(\gamma)$+jets background
    - Jets reconstructed as leptons
    - Varies depending upon number of electrons in central calorimeter
- Predicted background: $0.14^{+0.03}_{-0.02}$
- Predicted signal: 1.89 ± 0.08
- Observe 3 candidate events

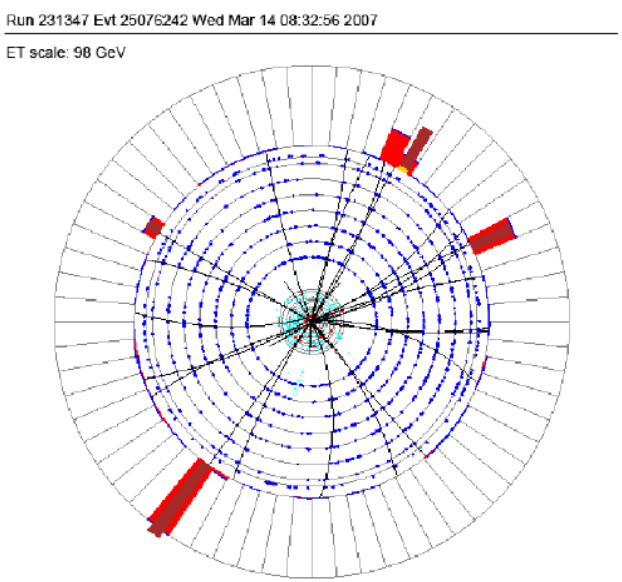


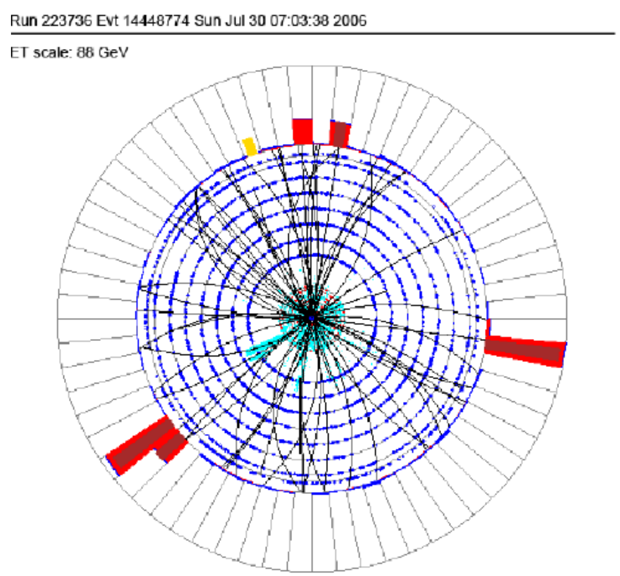
$ZZ \rightarrow llll$

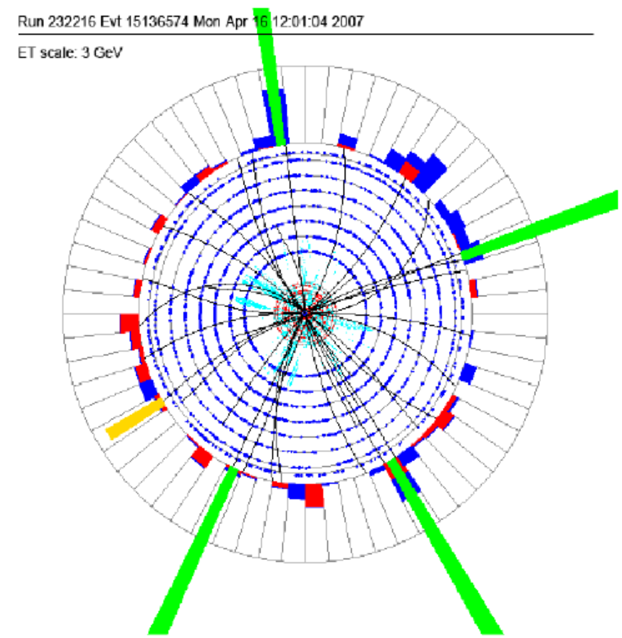












$ZZ \rightarrow llll + ll\nu\nu$

- Results
  - Likelihood of background fluctuating to give the observed yield (p-value) is 4.3×10^{-8} corresponding to 5.3σ (3.7σ expected)
    - Observation
  - Measured cross section:

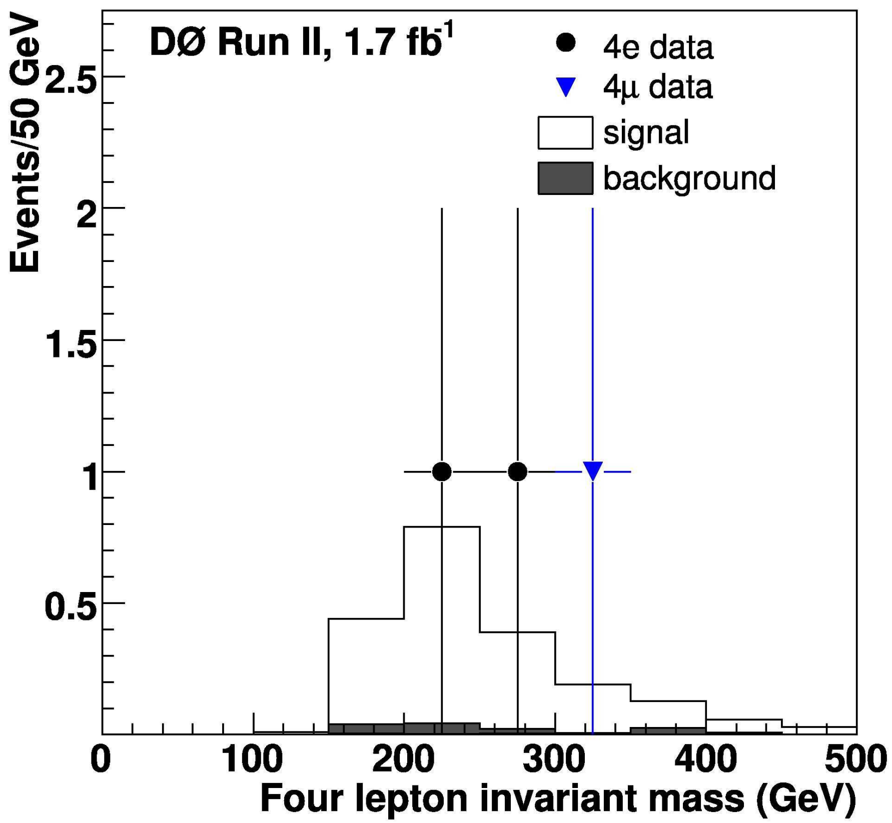
$$1.75^{+1.27}_{-0.86}\ (\text{stat.}) \pm 0.13\ (\text{syst.})\ \text{pb}$$

- Combined with previous $ZZ \rightarrow llll$ analysis (1 fb^{-1} Run IIa) and $ZZ \rightarrow ll\nu\nu$ (2.7 fb^{-1})
  - p-value of 6.2×10^{-9} corresponding to 5.7σ (4.8σ expected)
  - Measured cross section:

$$1.60 \pm 0.63\ (\text{stat.})^{+0.16}_{-0.17}\ (\text{syst.})\ \text{pb}$$

  - Agrees with earlier CDF result

PRL 101, 171803 (2008)



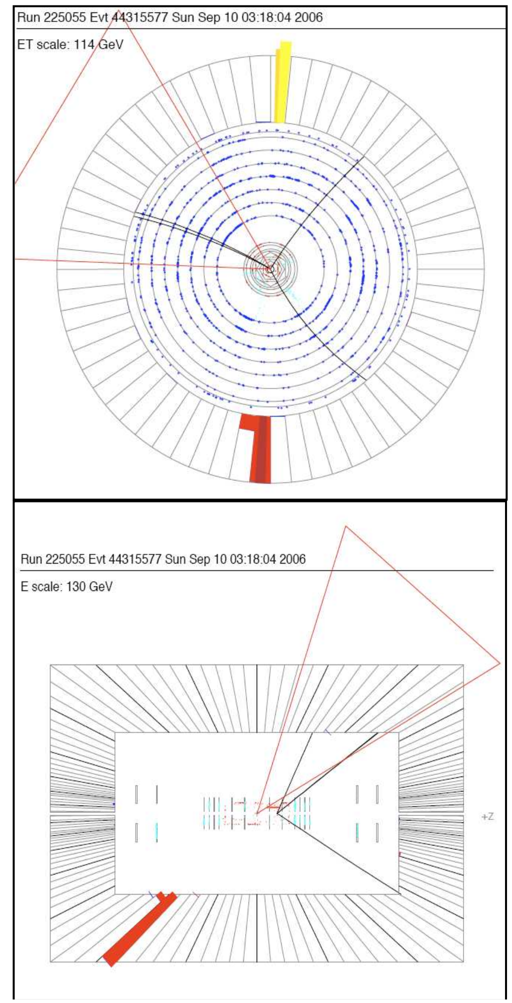
SM NLO: $\sigma(ZZ) = 1.4 \pm 0.1$ pb

J. M. Campbell and R. K. Ellis, Phys. Rev. D **60**, 113006 (1999).

$Z\gamma \rightarrow \nu\nu\gamma$

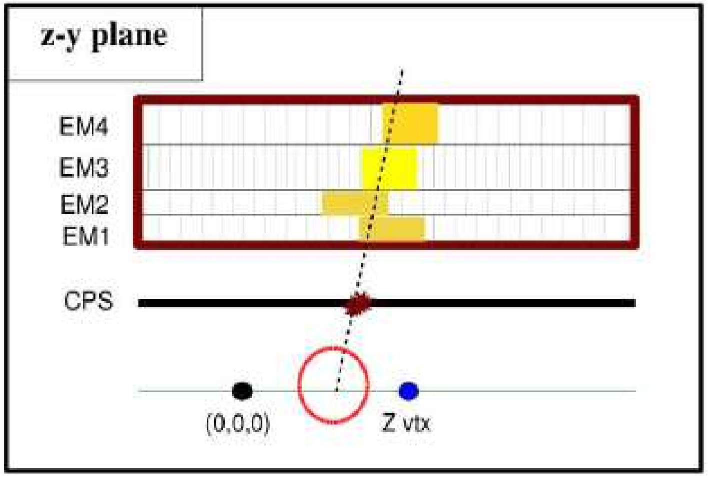
- Selected events from 3.6 fb^{-1} of Run II data
  - Single high E_T photon with p_T > 90 GeV and $|\eta|$ < 1.1
  - Large missing transverse energy mE_T > 70 GeV
    - Suppresses multijet background

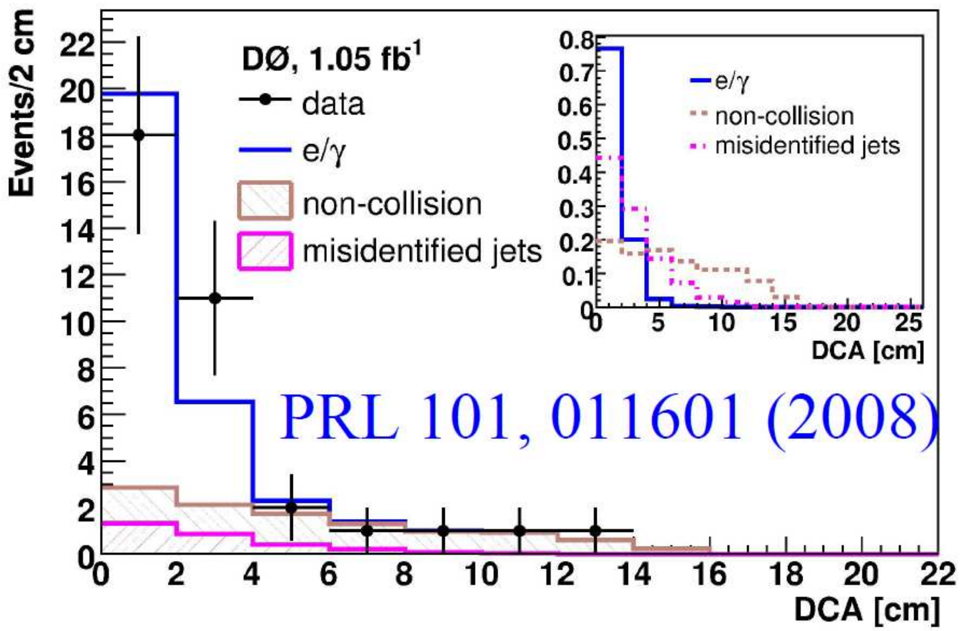
- Reduce backgrounds
  - Mis-measured mE_T
    - Reject events with jets with p_T > 15 GeV
  - $W \rightarrow l\nu$ and $Z \rightarrow ll$
    - Veto muons
    - Veto Isolated tracks
    - Veto additional EM objects with p_T > 15 GeV

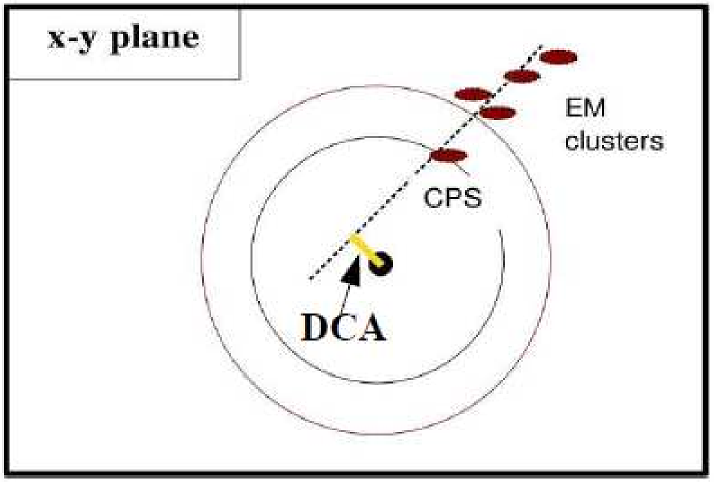


✸ Reduce backgrounds

- Non-collision background (*e.g.*, muon from halo or cosmics undergoing bremsstrahlung)
  - Pointing algorithm (assume EM shower initiated by photons)
    - → require $|z_{em} - z_{vtx}| < 10$ cm
    - → require DCA < 4 cm



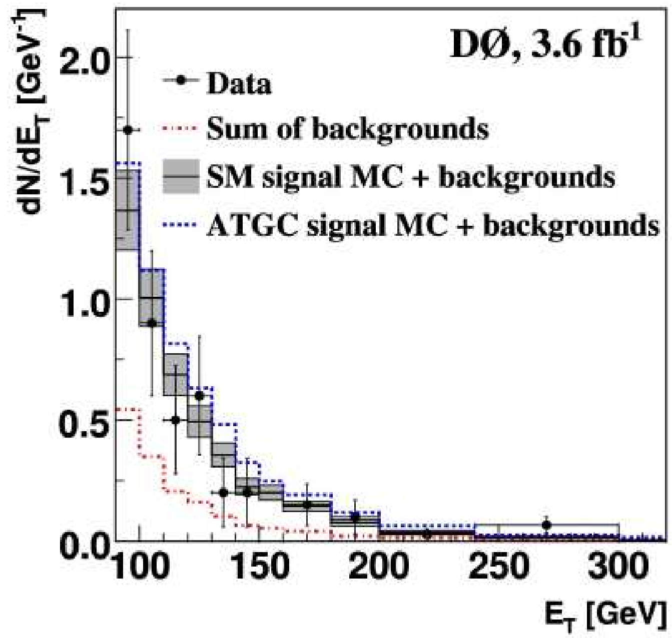




$Z\gamma \rightarrow \nu\nu\gamma$

- Predicted background: 17.3 ± 2.4
- Predicted Signal: 33.7 ± 3.4
- Observe 51 candidate events

PRL 102, 201802 (2009)



- Results
  - Measured cross section (for E_T^γ > 90 GeV)

    $\sigma(Z\gamma)\cdot BR(Z\rightarrow\nu\nu) = 32.9 \pm 9(\text{stat+syst}) \pm 2(\text{lumi})$ fb
  - p-value of 3.1 $\times 10^{-7}$ corresponding to significance of 5.1σ
    - First Tevatron observation in this channel

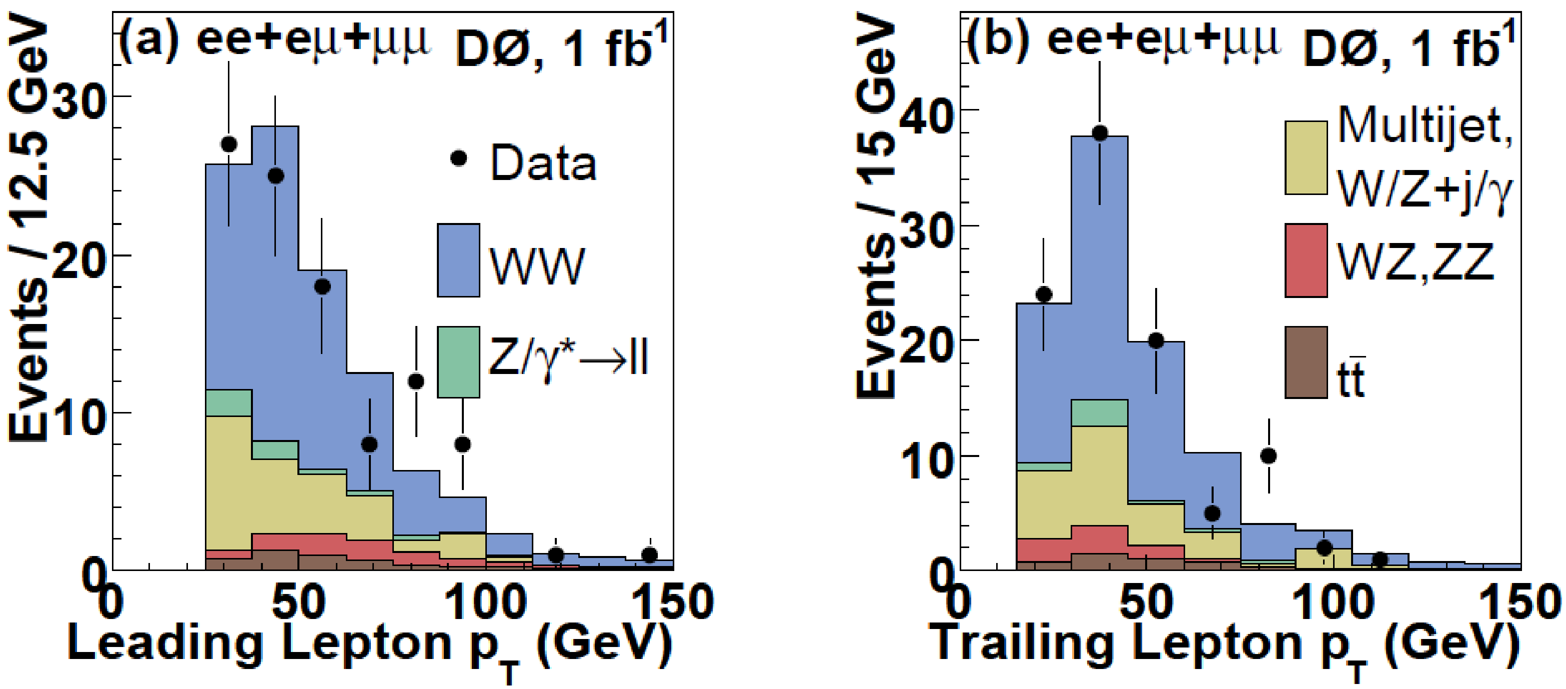
SM NLO: $\sigma(Z\gamma)\cdot BR(Z\rightarrow\nu\nu) = 39 \pm 4$ fb

(for E_T^γ > 90 GeV)

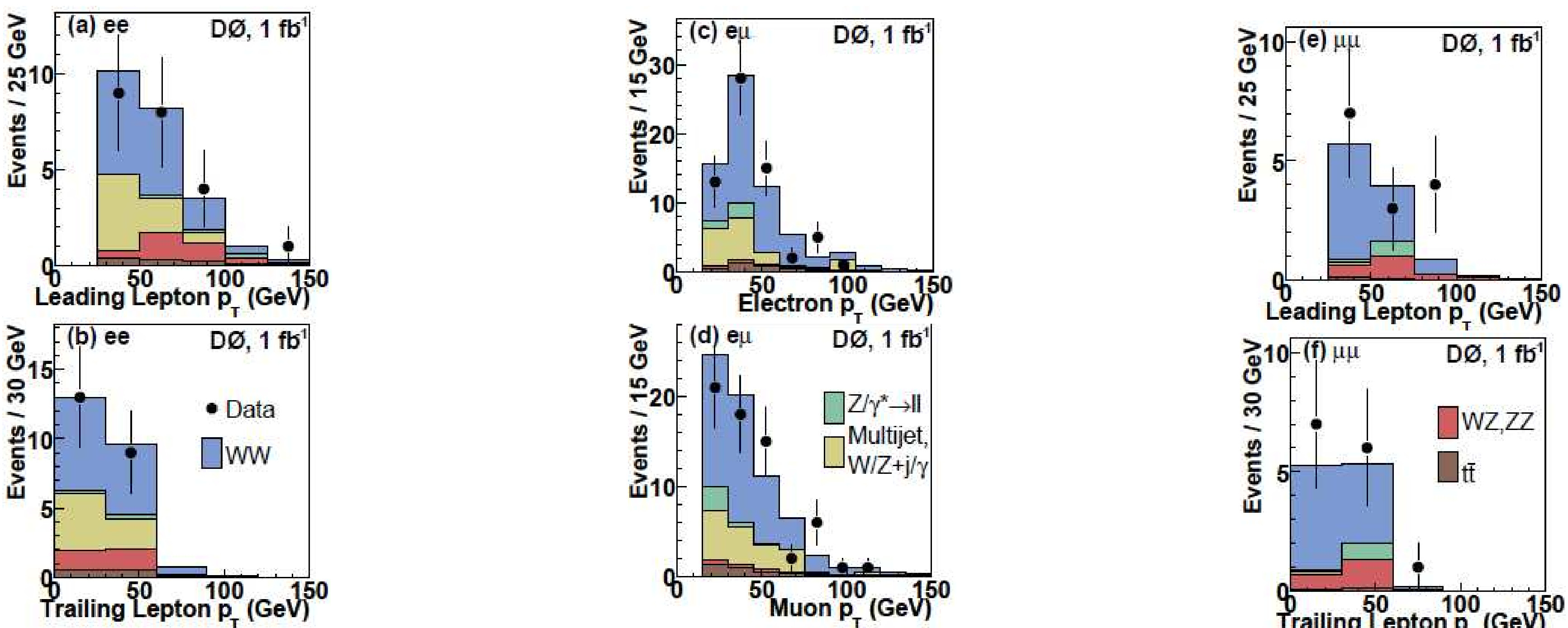
U. Baur, T. Han, and J. Ohnemus, Phys. Rev. D 57, 2823 (1998).

$WW \rightarrow l\nu l\nu$

- Selected events from 1 fb^{-1} of Run II data
  - Two isolated leptons from same vertex
    - ee, $e\mu$ or $\mu\mu$ of opposite charge
      - →At least one electron in central calorimeter
    - Leading lepton p_T^1 > 25 GeV
    - Trailing lepton p_T^2 > 15 GeV



- Reduce backgrounds
  - $Z \to ll$
    - Removed by optimized mE_T cuts for each channel
      $\to$ m$E_T^{ee} > 45$, m$E_T^{e\mu} > 20$, m$E_T^{\mu\mu} > 35$ GeV
    - Further refined by invariant mass requirement in ee channel, and azimuthal angle requirements in $e\mu$ and $\mu\mu$ channels
  - $t\bar{t}$ and W+jets
    - Require balanced event in $q_T = |\vec{p}_T^{\,1} + \vec{p}_T^{\,2} + \vec{\text{m}E}_T|$:
      $q_T^{ee} < 20$, $q_T^{e\mu} < 25$, $q_T^{\mu\mu} < 16$ GeV



$WW \rightarrow l\nu l\nu$

✸ Results

Process	ee	$e\mu$	$\mu\mu$
Signal	12.38 ± 0.62	44.43 ± 0.86	7.89 ± 0.35
Background	11.08 ± 1.80	24.21 ± 3.78	2.91 ± 0.46
Total expected	23.46 ± 1.90	68.64 ± 3.88	10.79 ± 0.58
Data	22	64	14

- Measured cross section (combined from individual channel results using the best linear unbiased estimator method):

$$\sigma(WW) = 11.5 \pm 2.1(\text{stat+syst}) \pm 0.7(\text{lumi})\ \text{pb}$$

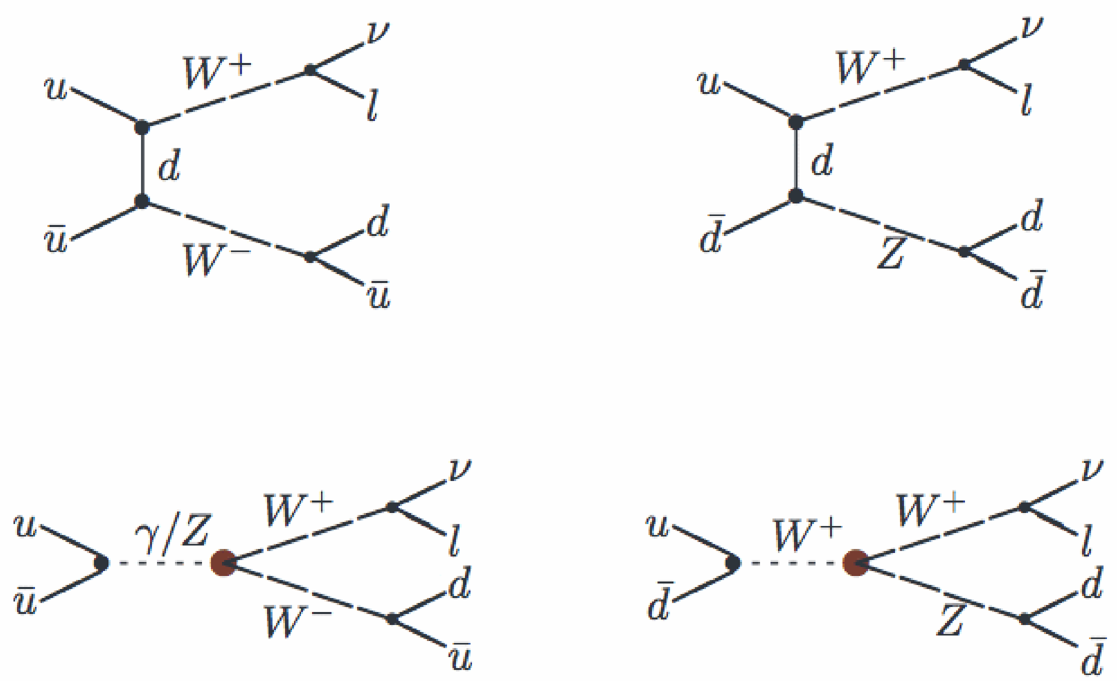
SM NLO: $\sigma(WW) = 12.0 \pm 0.7$ pb

J. M. Campbell and R. K. Ellis, Phys. Rev. D **60**, 113006 (1999).

arXiv: 0904.0673; submitted to PRL

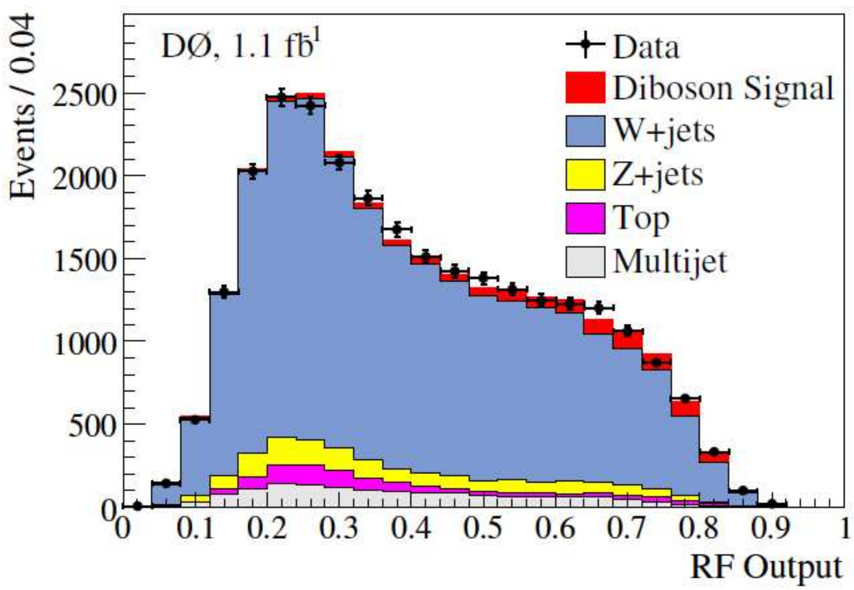
$WW/WZ \rightarrow l\nu jj$

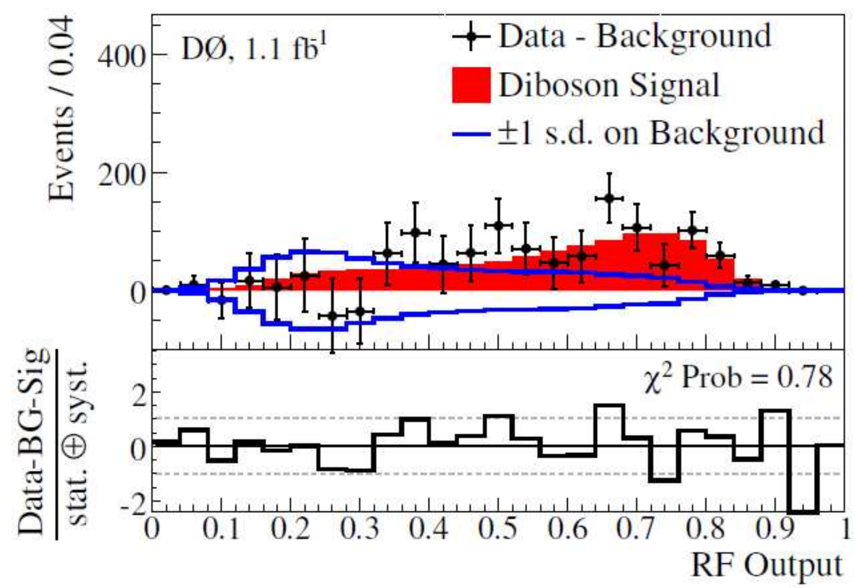
- Selected events from 1.1 fb^{-1} of Run II data
  - One isolated lepton with p_T > 20 GeV and $|\eta|$ < 1.1 (2.0) for electrons (muons)
  - mE_T > 20 GeV
  - Two jets with p_T^1 > 30, p_T^2 > 20 GeV and $|\eta|$ < 2.5



$WW/WZ \rightarrow l\nu jj$

- Reduce backgrounds
  - Multijet backgrounds
    - "Transverse" *W* mass > 35 GeV
  - *W*+jets (*Z*+jets, top)
    - "Random Forest" multivariate discriminant





$WW/WZ \rightarrow l\nu jj$

✸ Results

- p-value of 5.4×10^{-6} corresponding to significance of 4.4σ (3.6σ expected)

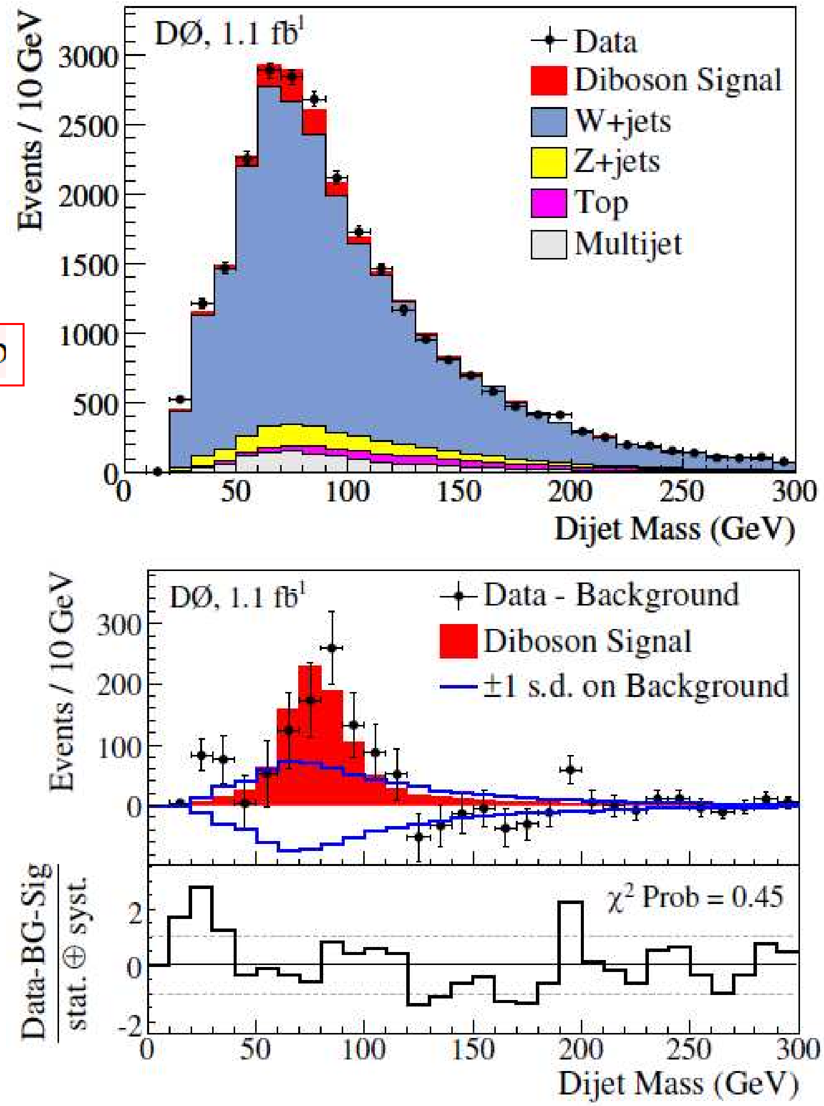
- Measured cross section

$$\sigma(WW+WZ) = 20.2 \pm 4.4(\text{stat+syst}) \pm 1.2(\text{lumi})\ \text{pb}$$

SM NLO: $\sigma(WW+WZ) = 16.1 \pm 0.9$ pb

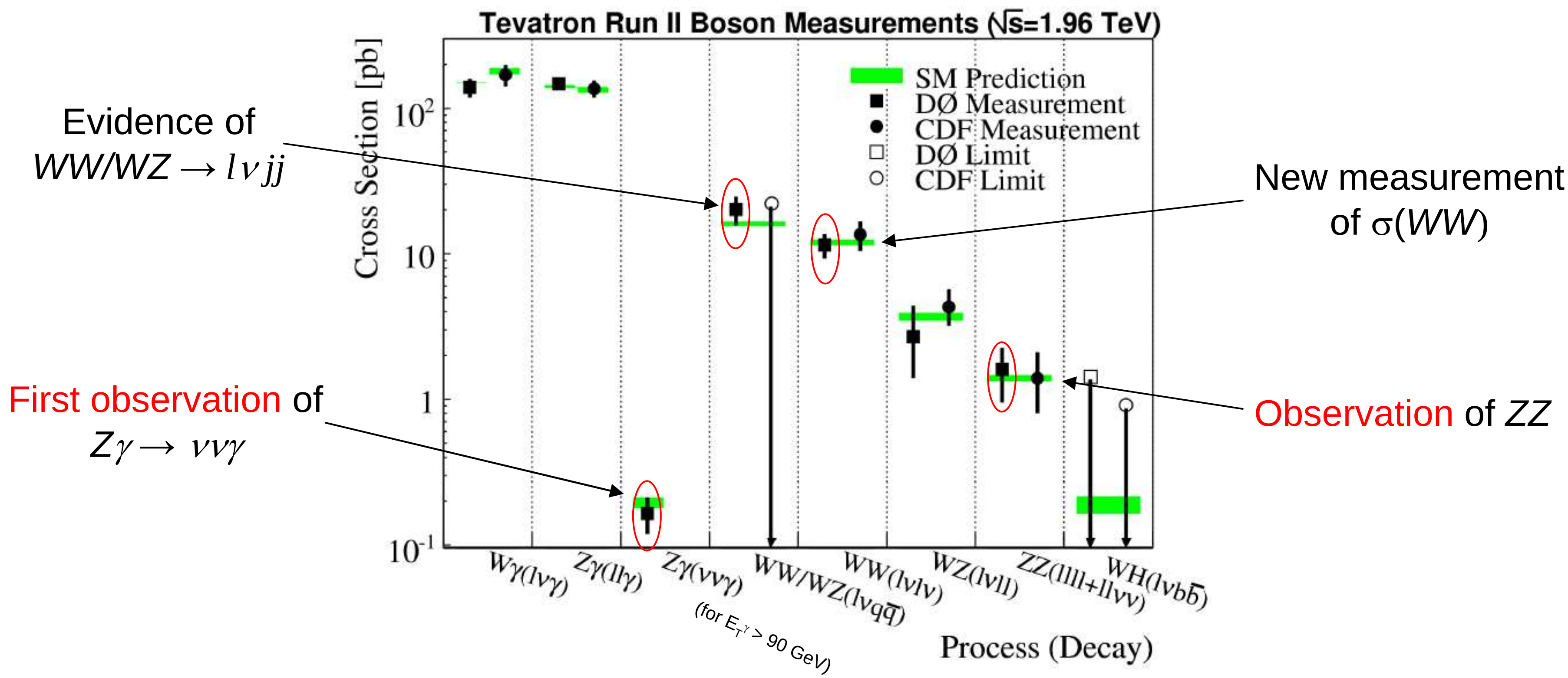
J. M. Campbell and R. K. Ellis, Phys. Rev. D **60**, 113006 (1999).

PRL 102, 161801 (2009)



Conclusions

- So far, everything agrees with the standard model:



- Now have over 6 fb^{-1} of reconstructed data
  - Stay tuned for more diboson physics to come from DØ

Backup

Calculation of Significance

- Performed using a semi-frequentist approach
  - Assume data is drawn randomly from a Poisson parent distribution
- Input is the information in channels (binned)
  - *s* is expected signal, *b* is expected background, *d* is data
  - Generate pseudo-experiments via random Poisson with mean value from expected *b* and *s*+*b*
  - Systematic uncertainties treated using a Bayesian model
    - Treated as Gaussian-distributed, randomly sampled for each pseudo-experiment
    - Nominal background prediction varied according to smeared values of systematics, changing the mean of the random Poisson with each pseudo-experiment
- Use a negative log-likelihood ratio (LLR) test statistic:

$$LLR(\vec{s},\vec{b},\vec{d}) = \sum_{i=0}^{N_{bins}} s_i - d_i \ln(1+\frac{s_i}{b_i})$$

ZZ Results

Subchannel	$4e_{2C}$	$4e_{3C}$	$4e_{4C}$	4μ	$2\mu 2e_{0C}$	$2\mu 2e_{1C}$	$2\mu 2e_{2C}$
Luminosity (fb^{-1})	1.75 ± 0.11	1.75 ± 0.11	1.75 ± 0.11	1.68 ± 0.10	1.68 ± 0.10	1.68 ± 0.10	1.68 ± 0.10
Signal	0.084 ± 0.008	0.173 ± 0.015	0.140 ± 0.012	0.534 ± 0.043	$0.058^{+0.007}_{-0.006}$	0.352 ± 0.040	$0.553^{+0.045}_{-0.044}$
$Z(\gamma)$+jets	$0.030^{+0.009}_{-0.008}$	$0.018^{+0.008}_{-0.007}$	$0.002^{+0.002}_{-0.001}$	0.0003 ± 0.0001	$0.03^{+0.02}_{-0.01}$	0.05 ± 0.01	$0.008^{+0.004}_{-0.003}$
$t\bar{t}$	–	–	–	–	$0.0012^{+0.0016}_{-0.0009}$	0.005 ± 0.002	$0.0007^{+0.0009}_{-0.0005}$
Observed events	0	0	2	1	0	0	0

Candidate					
$4e$ candidate 1		e_1^+	e_2^+	e_3^-	e_4^-
	p_T (GeV)	107	59	52	16
	η	0.66	0.25	-0.64	-0.85
	ϕ	4.10	1.08	0.46	2.62
	$M_{\ell\ell}$ (GeV)	$e_1^+ e_4^-$ 89 ± 3		$e_2^+ e_3^-$ 61 ± 2	
$4e$ candidate 2		e_1^+	e_2^+	e_3^-	e_4^-
	p_T (GeV)	83	75	35	26
	η	0.64	0.40	0.85	1.17
	ϕ	6.16	3.80	3.83	1.40
	$M_{\ell\ell}$ (GeV)	$e_1^+ e_3^-$ 99 ± 3		$e_2^+ e_4^-$ 90 ± 4	
4μ candidate		μ_1^+	μ_2^-	μ_3^-	μ_4^+
	p_T (GeV)	115	77	42	24
	η	0.04	-1.01	0.77	-1.93
	ϕ	1.69	4.26	5.29	0.36
	$M_{\ell\ell}$ (GeV)	$\mu_1^+ \mu_3^-$ 148^{+32}_{-18}		$\mu_2^- \mu_4^+$ 90^{+12}_{-8}	