Diboson Production At D0

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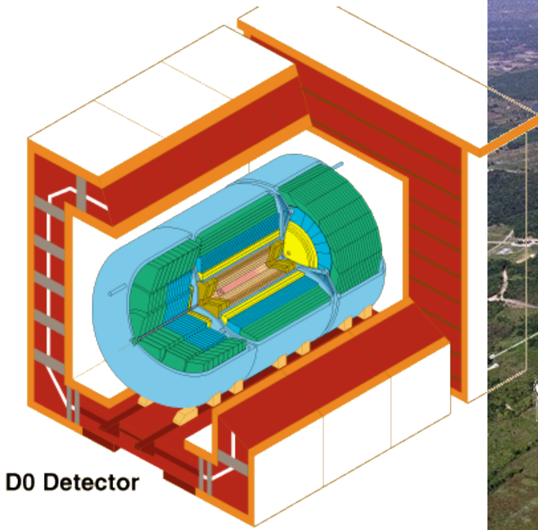
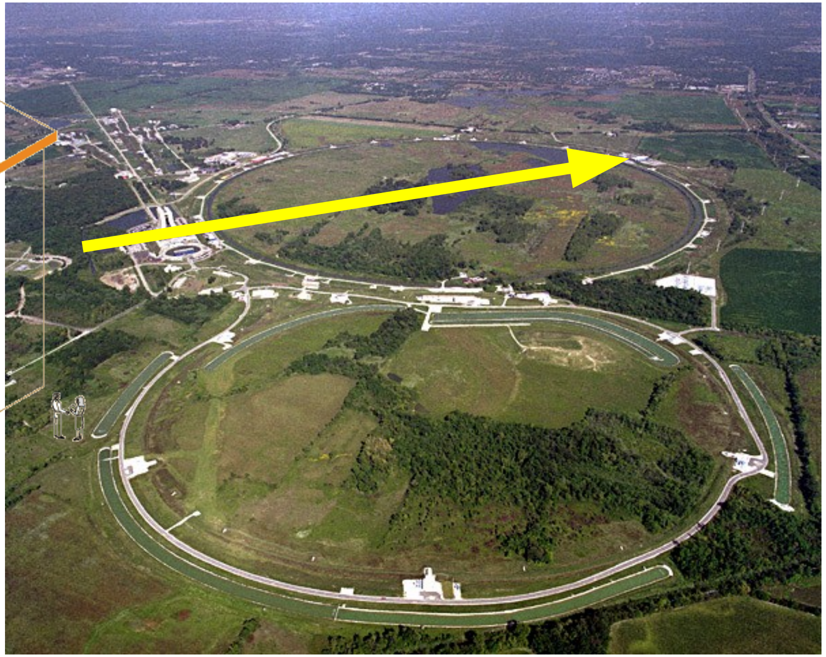
Introduction

- Most recent Diboson measurements from D0 experiment at Fermilab's Tevatron Collider
  - $ZZ \rightarrow llll$
  - $Z\gamma \rightarrow \nu\nu\gamma$
  - $WW+WZ \rightarrow l\nu qq$
  - $WW \rightarrow l\nu l\nu$
  - WV Combination ($V = \gamma, Z, W$)

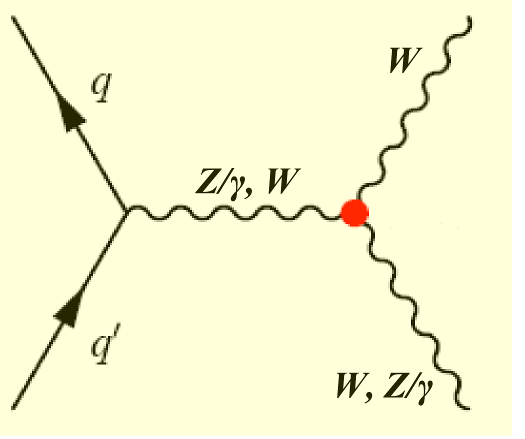




- Diboson production at D0
  - The Tevatron is a vector boson factory
    - Able to deliver more than 50 pb^{-1}/week: ~600 ***WW***, ~200 ***WZ***, and ~100 ***ZZ*** events!
  - Hadonic environment not as clean as LEP, but
    - Access to diboson processes not available at LEP (***WZ*** and ***Wγ***)
    - Able to probe higher energies

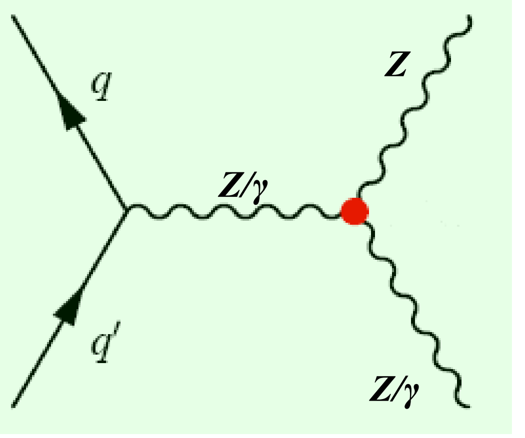
Introduction

- Probe of new physics above some higher energy scale Λ_{NP}
  - Could result in anomalous trilinear gauge-boson couplings (TGCs)
    - Affects cross sections and event kinematics
    - Anomalous TGCs could give clues to the mechanism for electroweak symmetry breaking
  - SM is the low energy limit of a more general theory



γWW and ZWW TGCs

Probed by WW, WZ, and $W\gamma$ production
General Lagrangian has 14 TGC parameters
Assume EM gauge invariance and C and P conservation
⇒ 5 TGC parameters: $g_1^Z, \kappa_\gamma, \kappa_Z, \lambda_\gamma, \lambda_Z$



γZZ and $\gamma\gamma Z$ TGCs

Probed by ZZ and $Z\gamma$ production
General Lagrangian has 8 TGC parameters
Assume CP conservation
⇒ 4 TGC parameters: $h_3^\gamma, h_3^Z, h_4^\gamma, h_4^Z$

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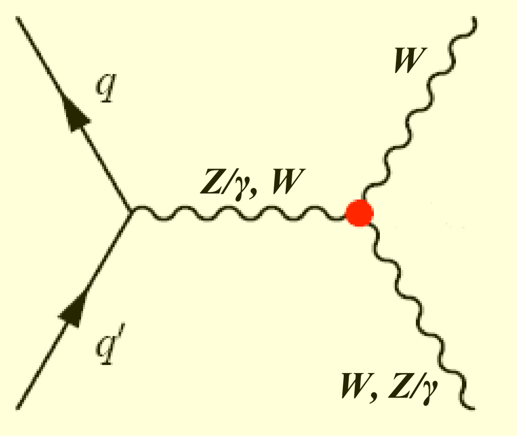
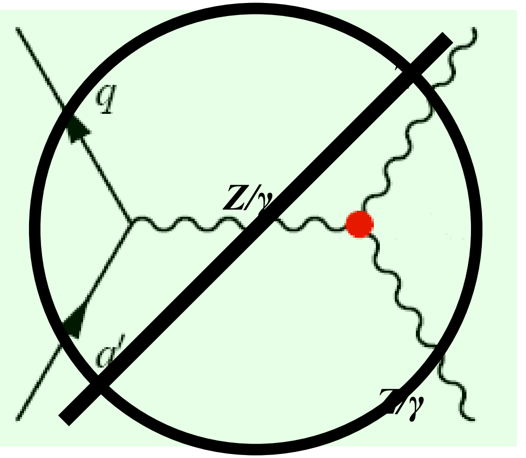
    - Affects cross sections and event kinematics
    - Anomalous TGCs could give clues to the mechanism for electroweak symmetry breaking
  - In the SM:

$$\lambda_\gamma = \lambda_Z = 0 \text{ and } g_1^Z = \kappa_\gamma = \kappa_Z = 1 \Rightarrow \Delta\kappa_V \equiv \kappa_V - 1, \quad \Delta g_1^V \equiv g_1^V - 1$$

$$h_3^\gamma = h_3^Z = h_4^\gamma = h_4^Z = 0$$

$\Delta\kappa$, Δg, λ, or $h \neq 0$ $\Rightarrow$ anomalous TGCs





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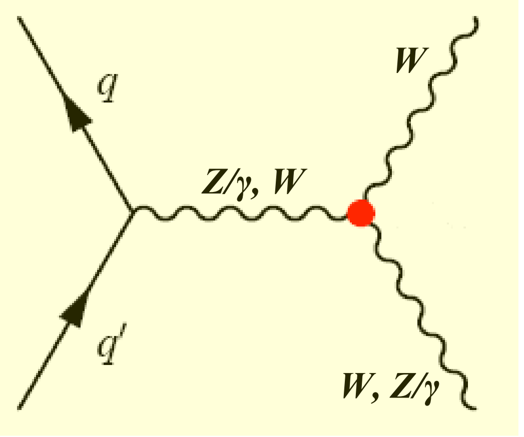
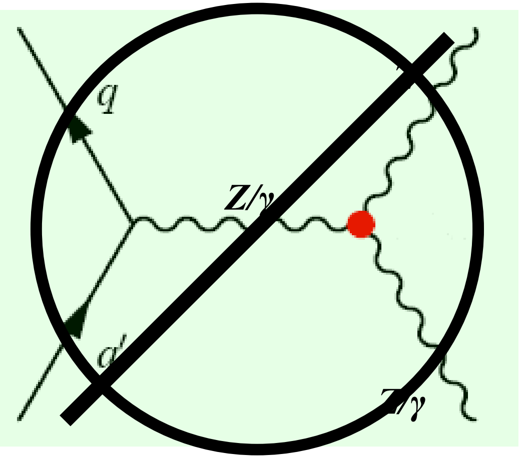


- Higgs and SUSY motivations
  - Same or similar final states
    - Vital to understand (often significant) diboson backgrounds
      - *E.g.*, high mass Higgs exclusion dominated by $H \rightarrow WW$
  - Many common analysis techniques
    - Diboson measurements provide proving ground for techniques use in searches



$ZZ \rightarrow \ell\ell\ell\ell$

(PRL 101, 171803 (2008))

- Selected events in 1.7 fb^{-1} of Run II data
  - Four isolated leptons

4e channel: Four electrons with $p_T > 30, 25, 15, 15$ GeV
4μ channel: Four muons with $p_T > 30, 25, 15, 15$ GeV
2e2μ channel: Two electrons and two muons with $p_T > 25, 15$ GeV

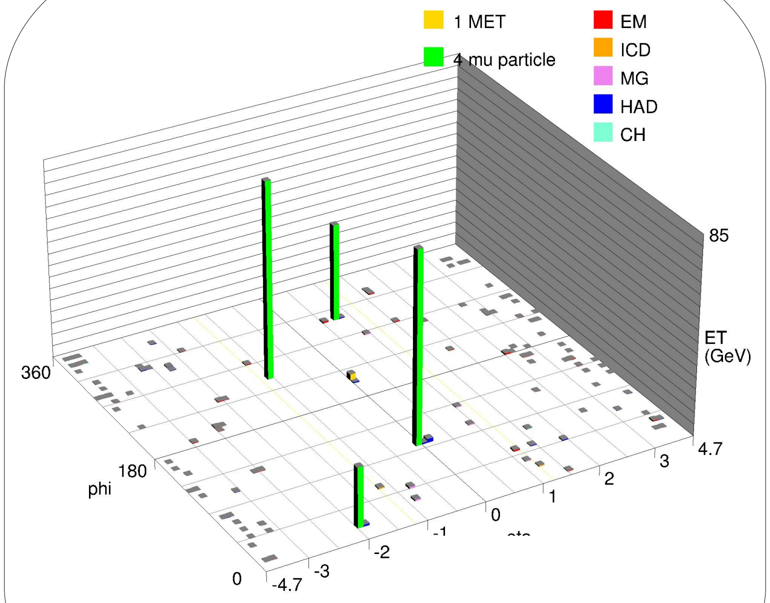
  - That came from a pair for *Z* bosons

Dilepton mass $M_{ll} > 70, 50$ GeV
(one combo of opposite-charge, like-flavor lepton pairings)

- Very clean signature
  - No SM background with four high p_T leptons!
  - Small Z(γ)+jets background
    - Jets reconstructed as leptons

- Predicted background: $0.14^{+0.03}_{-0.02}$
- Predicted signal: 1.89 ± 0.08

$\Rightarrow$ Observe 3 candidate events



4μ candidate event

$ZZ \rightarrow llll$

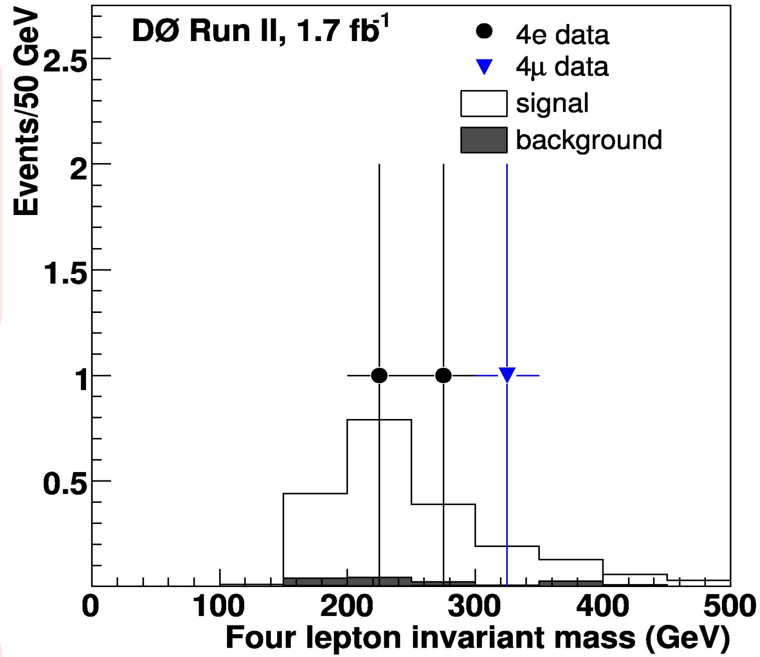
(PRL 101, 171803 (2008))

- Production results

Measured cross section:
$\sigma(ZZ) = 1.75^{+1.27}_{-0.86}(\text{stat}) \pm 0.13(\text{syst})$ pb
Expected significance: 3.7σ
Observed significance: 5.3σ ⇒ First Tevatron observation!

- Combined with previous $ZZ \rightarrow llll$ (1 fb^{-1}) analysis and $ZZ \rightarrow ll\nu\nu$ (2.7fb^{-1})

Measured cross section:
$\sigma(ZZ) = 1.60 \pm 0.63(\text{stat})\ ^{+0.16}_{-0.17}(\text{syst})$ pb
Expected significance: 4.8σ
Observed significance: 5.7σ

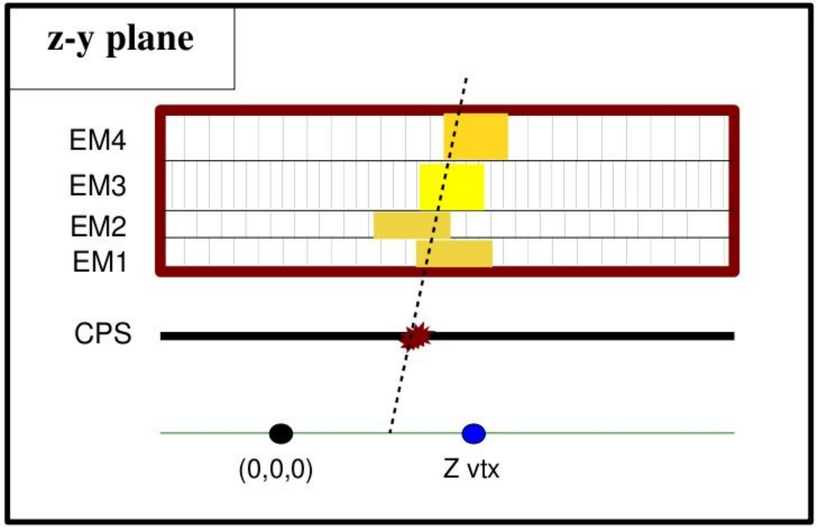


SM NLO: $\sigma(ZZ) = 1.4 \pm 0.1$ pb

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

- Selected events in 3.6 fb^{-1} of Run II data
  - Single high energy photon with $E_T > 90$ GeV
  - Large missing transverse energy $\not{E}_T > 70$ GeV

- Reduce backgrounds:
  - $W \rightarrow l\nu$ and $Z \rightarrow ll$ background
    - Veto muons, addit'l EM objects, isolated tracks
  - Non-collision backgrounds (*e.g.*, bremsstrahlung from beam halo)
    - Pointing algorithm: require $|z_{EM} - z_{vtx}| < 10$ cm
  - Mis-measured $\not{E}_T$
    - Require no jets ($p_T > 15$ GeV)



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

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

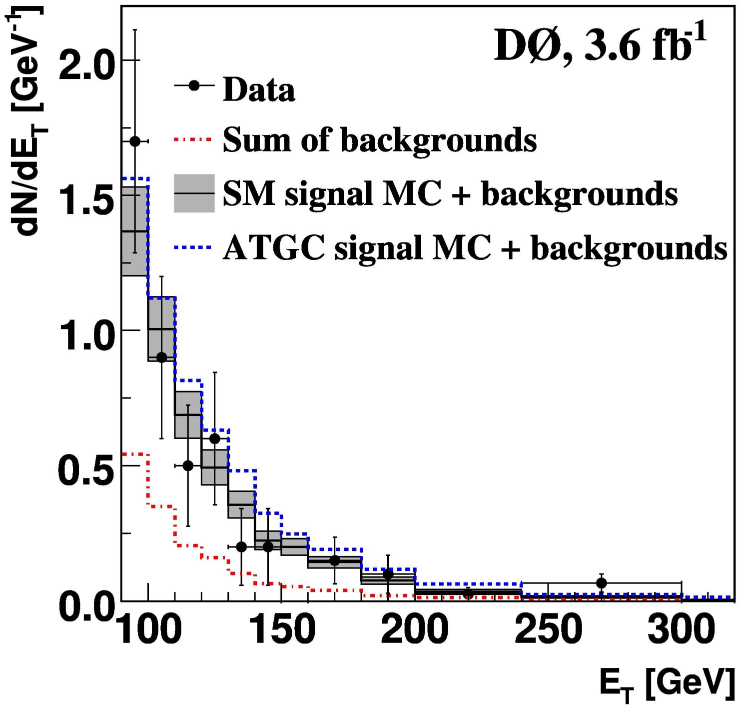
(PRL 102, 201802 (2009))

- Production results

SM NLO: $\sigma(Z\gamma\ ;\ E_T^{\gamma} > 90\ \text{GeV})\cdot BR(Z\rightarrow\nu\nu) = 39 \pm 4$ fb

Measured cross section:
$\sigma(Z\gamma\ ;\ E_T^{\gamma} > 90\ \text{GeV})\cdot BR(Z\rightarrow\nu\nu) = 32.9 \pm 9(\text{stat+syst}) \pm 2(\text{lumi})$ fb

Observed significance: 5.1σ ⇒ First Tevatron observation!



- 95% limits on anomalous γZZ and $\gamma\gamma Z$ TGCs
  - Use photon E_T spectrum
    - Highly sensitive to anomalous TGCs

$|h_3^{\gamma}| < 0.036 \quad |h_3^{Z}| < 0.0019$
$|h_4^{\gamma}| < 0.035 \quad |h_4^{Z}| < 0.0019$

(Λ_{NP}=1.5 TeV)

  - Combine with $Z\gamma\rightarrow ee\gamma$ and $Z\gamma\rightarrow\mu\mu\gamma$

$|h_3^{\gamma}| < 0.033 \quad |h_3^{Z}| < 0.0017$
$|h_4^{\gamma}| < 0.033 \quad |h_4^{Z}| < 0.0017$

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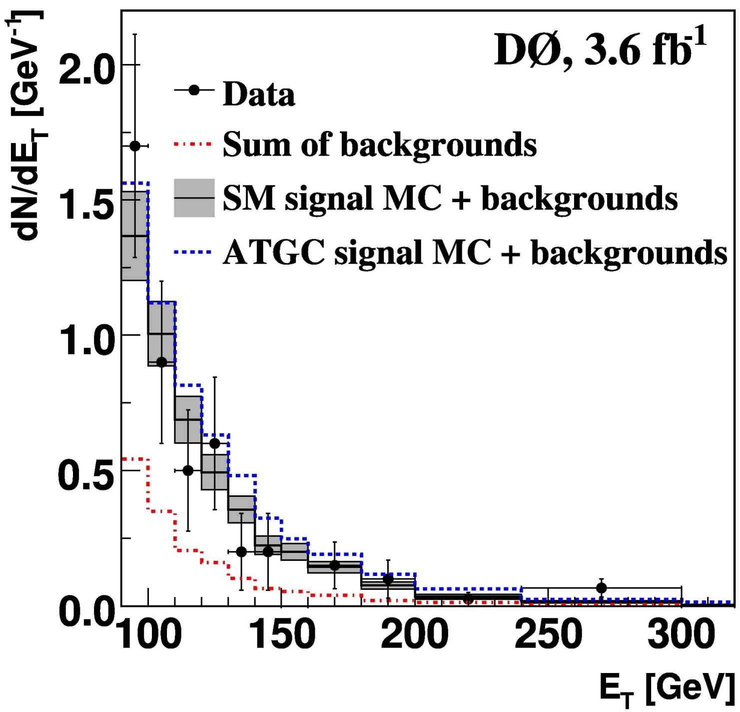

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World best!

$WW/WZ \to l\nu qq$ (PRL 102, 161801 (2009))

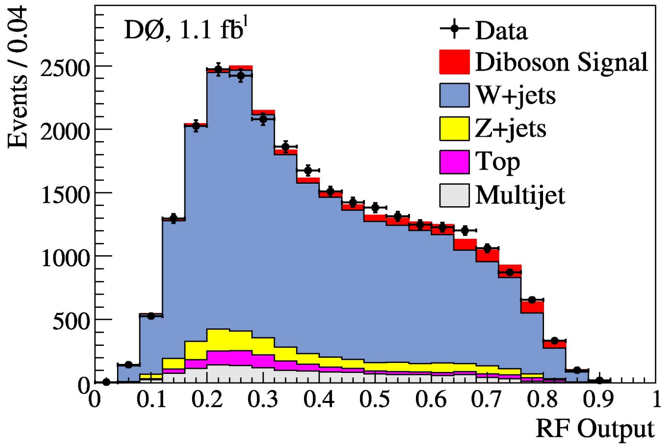
- Selected events in 1.1 fb^{-1} of Run II data
  - One isolated lepton with $p_T > 20$ GeV
  - Missing transverse energy $\not{E}_T > 20$ GeV
  - Two jets with $p_T > 30, 20$ GeV
  - Reduce backgrounds:
    - Multijet backgrounds
      - "Transverse" W mass > 35 GeV
    - ***W***+jets (***Z***+jets, top)
      - "Random Forest" multivariate discriminant
      - Fit to determine cross section
- Production results

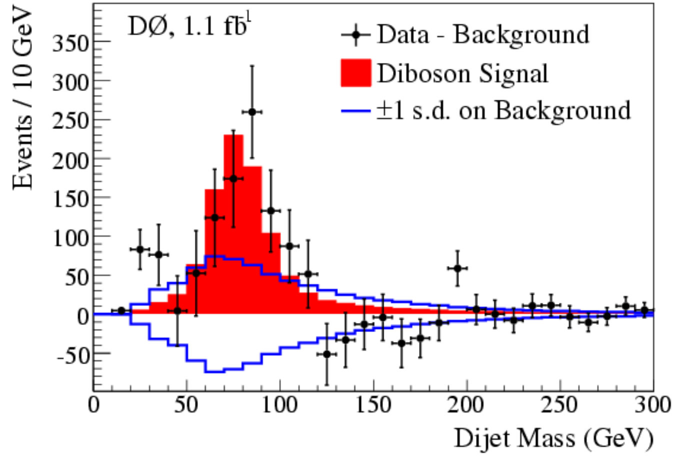
Measured cross section:

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

Expected significance: 3.7σ

Observed significance: 5.3σ ⇒ First Tevatron evidence!





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

$WW/WZ \to l\nu qq$ (preliminary)

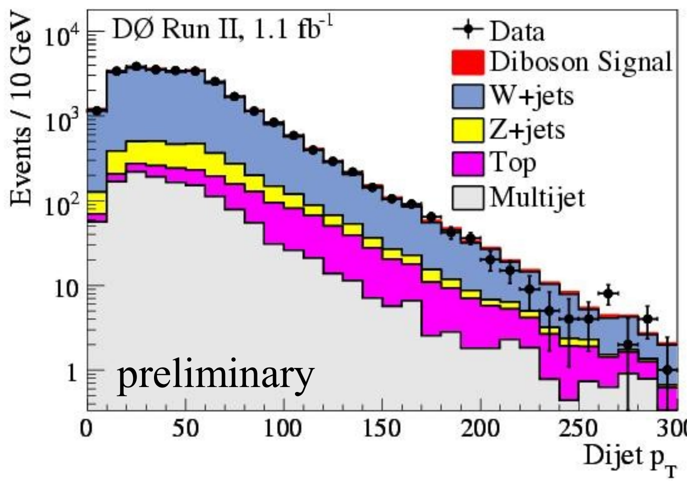
- 95% limits on γWW and ZWW TGCs
  - Use p_T of dijet system
  - Requiring SU(2)xU(1) symmetry (a.k.a. LEP parameterization):

$$\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \cdot \tan^2\theta_W \text{ and } \lambda_\gamma = \lambda_Z$$

⇒ Three independent parameters

$$-0.44 < \Delta\kappa_\gamma < 0.55$$
$$-0.10 < \lambda < 0.11$$
$$-0.12 < \Delta g_1^Z < 0.20$$

(Λ_{NP}=2 TeV)

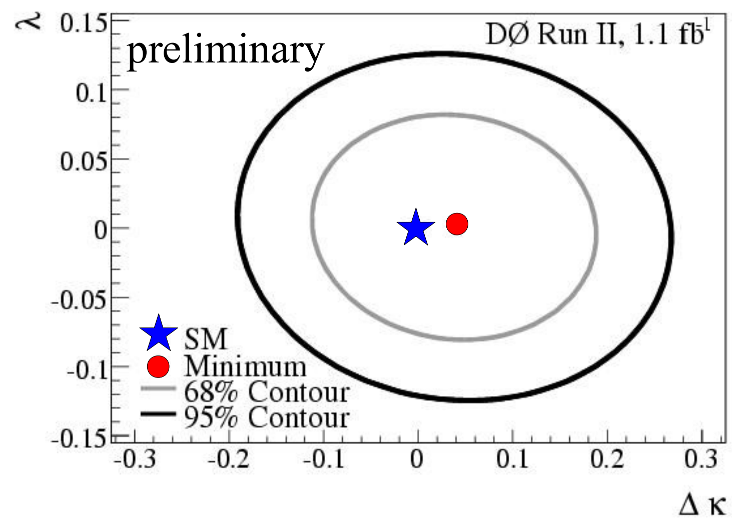


  - Equal couplings scenario (a.k.a. $\gamma WW = ZWW$)

$$\Delta\kappa_Z = \Delta\kappa_\gamma, \ \Delta g_1^Z = \Delta g_1^\gamma = 1, \text{ and } \lambda_\gamma = \lambda_Z$$

⇒ Two independent parameters

$$-0.16 < \Delta\kappa < 0.23$$
$$-0.11 < \lambda < 0.11$$

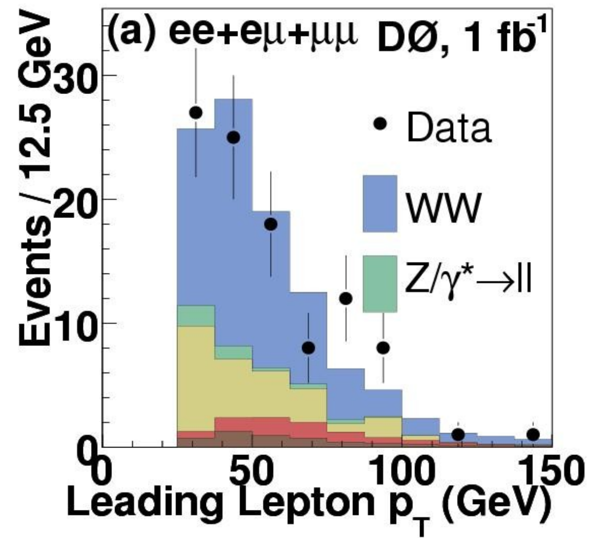


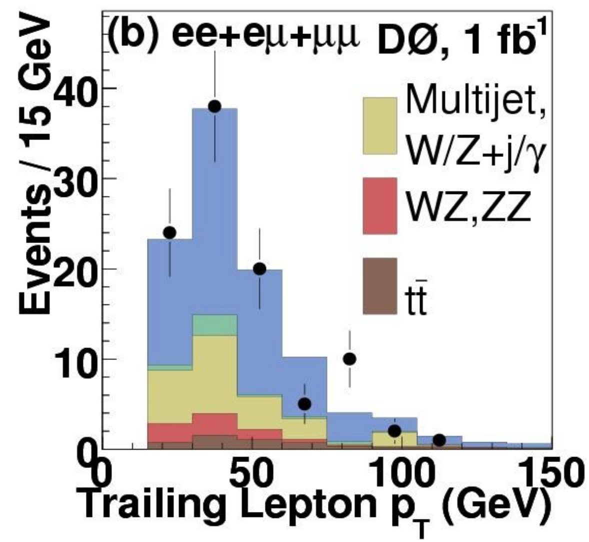
$WW \rightarrow l\nu l\nu$

(arXiv.org:0904.0673)

- Selected events in 1 fb^{-1} of Run II data
  - Two isolated leptons
    - ***ee***, ***eμ***, or ***μμ*** of opposite charge
    - Leading lepton pT > 25 GeV
    - Trailing lepton pT > 15 GeV
  - Reduce backgrounds:
    - ***Z→ll*** backgrounds
      - Optimized $\not\!E_T$ cuts for each channel
    - ***tt*** and ***W***+jets
      - Require balanced event
        - $|p_T^{l1} + p_T^{l2} + \not\!E_T| < 20(ee), 25(e\mu), 16(\mu\mu)$

Process	*ee*	*eμ*	*μμ*
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





$WW \to l\nu l\nu$

(arXiv.org:0904.0673)

- Production results

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

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

- 95% limits on γWW and ZWW TGCs
  - Use 2-dimensional distribution of lepton p_Ts
  - Requiring SU(2)xU(1) symmetry:

$\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \cdot \tan^2\theta_W$ and $\lambda_\gamma = \lambda_Z$

$-0.54 < \Delta\kappa_\gamma < 0.83$
$-0.14 < \lambda < 0.18$
$-0.14 < \Delta g_1^Z < 0.30$

(Λ_{NP}=2 TeV)

  - Equal couplings:

$\Delta\kappa_Z = \Delta\kappa_\gamma,\ \Delta g_1^Z = \Delta g_1^\gamma = 1,$ and $\lambda_\gamma = \lambda_Z$

$-0.12 < \Delta\kappa < 0.35$
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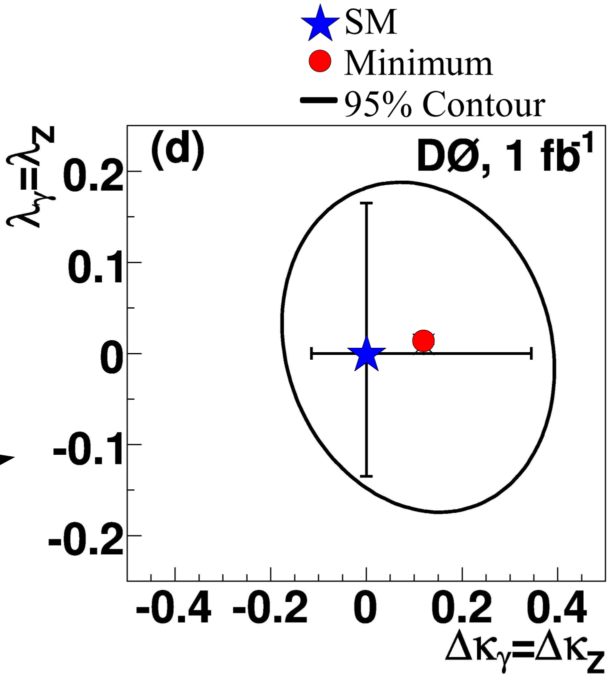
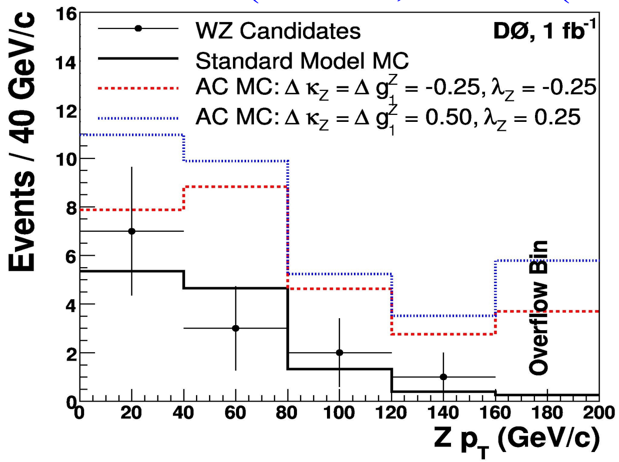


WV Combination

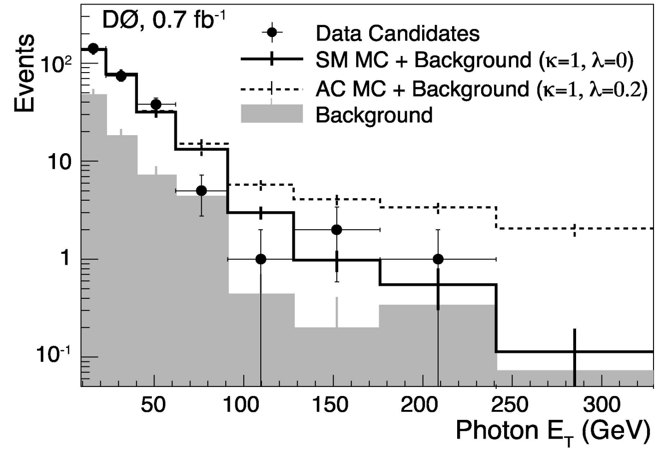
(preliminary)

- Combination of four analyses with ~1 fb^{-1}

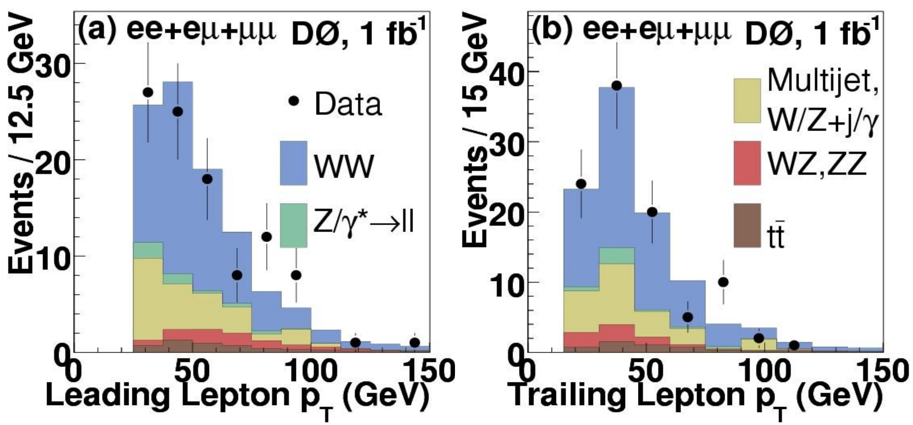
WZ→lνll (PRD 76, 111104 (2007))



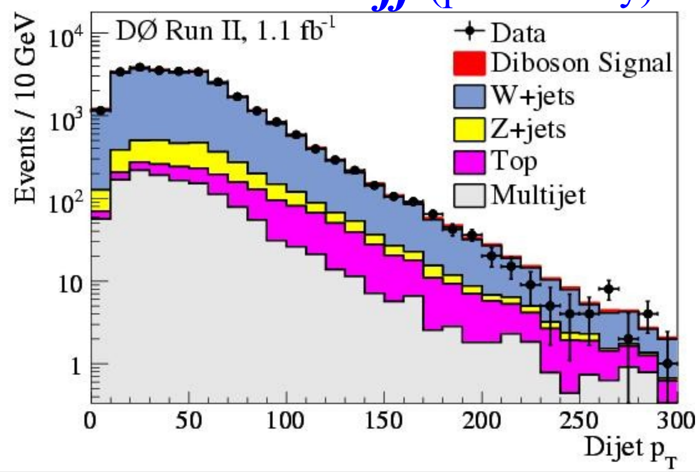
Wγ→lνγ (PRL 100, 241805 (2008))



WW→lνlν (arXiv.org:0904.0673)



WW+WZ→lνjj (preliminary)



WV Combination (preliminary)

- Combination of four analyses with ~1 fb^{-1}
- 95% limits on γWW and ZWW TGCs (Λ_{NP}=2 TeV)
  - Requiring SU(2)xU(1) symmetry:

    $\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \cdot \tan^2\theta_W$ and $\lambda_\gamma = \lambda_Z$

    $-0.29 < \Delta\kappa_\gamma < 0.38$

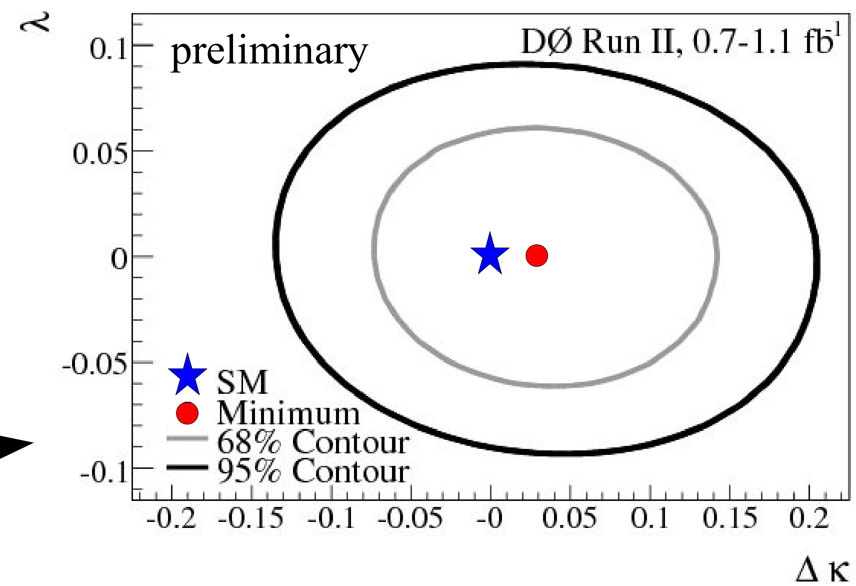
    $-0.08 < \lambda < 0.08$

    $-0.07 < \Delta g_1^Z < 0.16$
  - Equal couplings:

    $\Delta\kappa_Z = \Delta\kappa_\gamma,\ \Delta g_1^Z = \Delta g_1^\gamma = 1,$ and $\lambda_\gamma = \lambda_Z$

    $-0.11 < \Delta\kappa < 0.18$

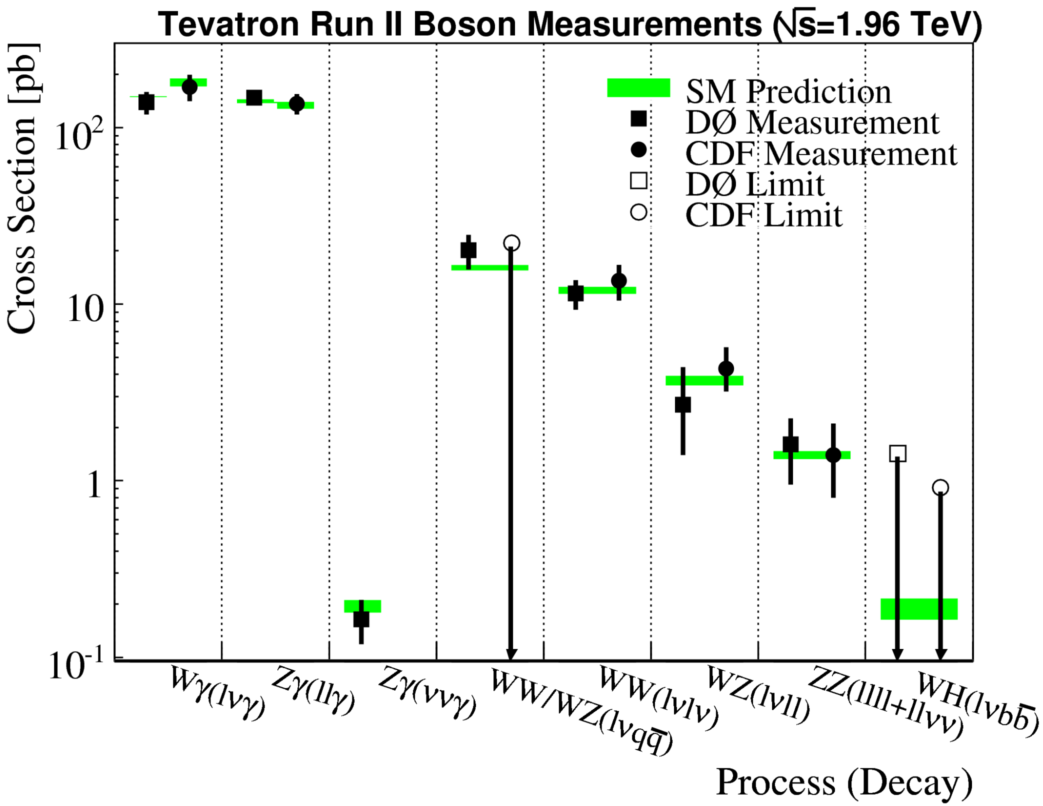
    $-0.08 < \lambda < 0.08$



⇒ Approaching sensitivity of the LEP2 experiments

Conclusions

- So far everything agree with the Standard Model
- Many of the measurements are firsts or bests from a hadron collider



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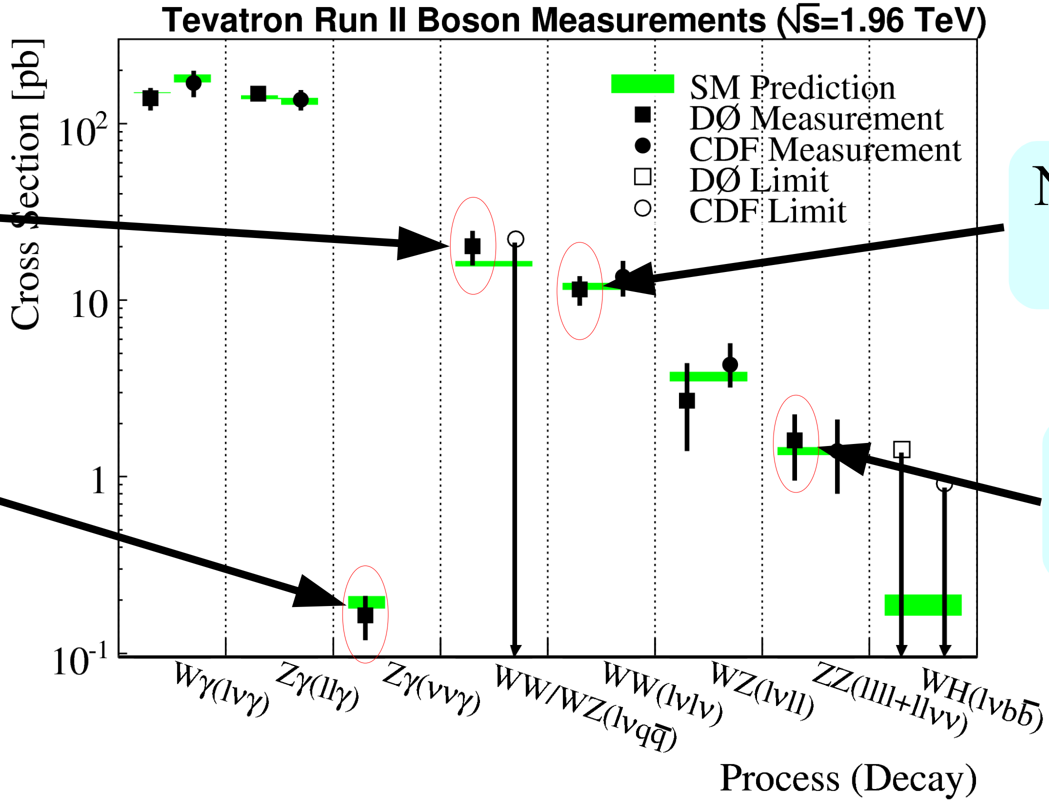
First evidence of ***WW+WZ→lνqq***

First observation of ***Zγ→ννγ***

New measurement of σ(***WW***)

First observation of ***ZZ***



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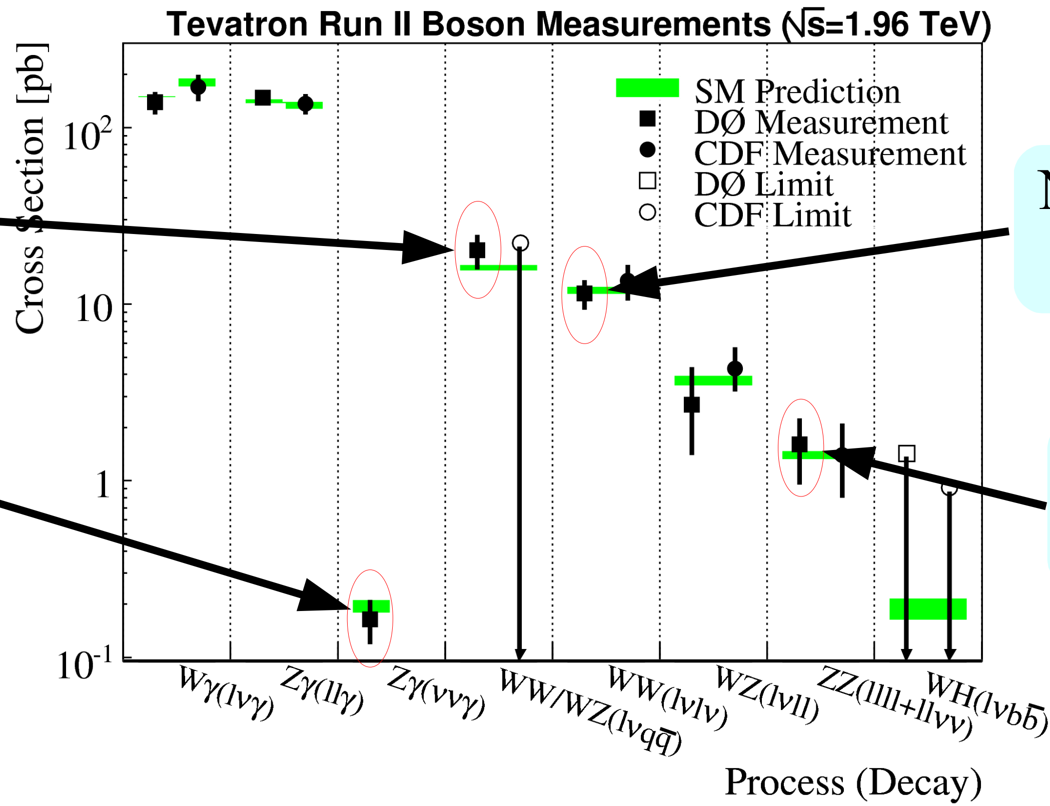


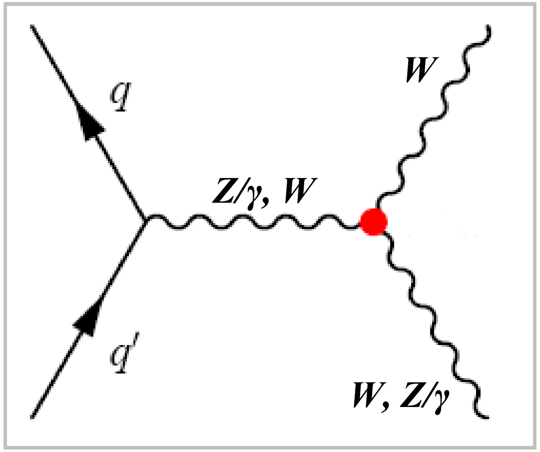
New measurement of σ(***WW***)

First observation of ***ZZ***

- And we now have over 6 fb^{-1} of reconstructed data
  ⇒ The future is bright for Diboson physics at D0!

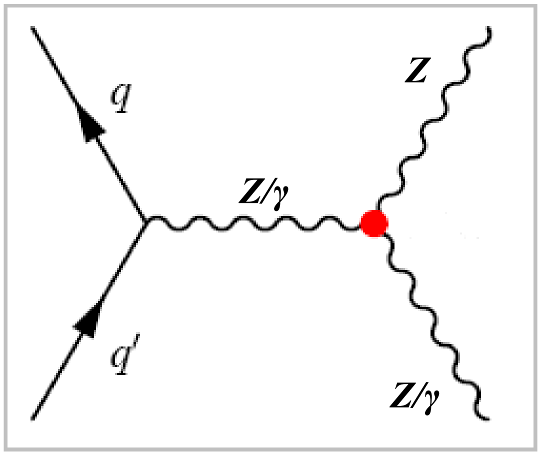
thank you

Anomalous Couplings



- ***ZWW*** **and** ***γWW*** **couplings**
  - General Lorentz invariant Lagrangian has 14 couplings

$$\frac{L_{WWV}}{g_{WWV}} = i g_1^V (W^*_{\mu\nu} W^{\mu} V^{\nu} - W^*_{\mu} V_{\nu} W^{\mu\nu}) + i \kappa_V W^*_{\mu} W_{\nu} V^{\mu\nu} + i \frac{\lambda_V}{M_W^2} W^*_{\lambda\mu} W^{\mu}_{\nu} V^{\nu\lambda}$$
$$- g_4^V W^*_{\mu} W_{\nu} \left(\partial^{\mu} V^{\nu} + \partial^{\nu} V^{\mu}\right) + g_5^V \varepsilon^{\mu\nu\lambda\rho} \left(W^*_{\mu} \partial_{\lambda} W_{\nu} - \partial_{\lambda} W^*_{\mu} W_{\nu}\right) V_{\rho}$$
$$+ i \tilde{\kappa}_V W^*_{\mu} W_{\nu} \tilde{V}^{\mu\nu} + i \frac{\tilde{\lambda}_V}{M_W^2} W^*_{\lambda\mu} W^{\mu}_{\nu} \tilde{V}^{\nu\lambda}$$



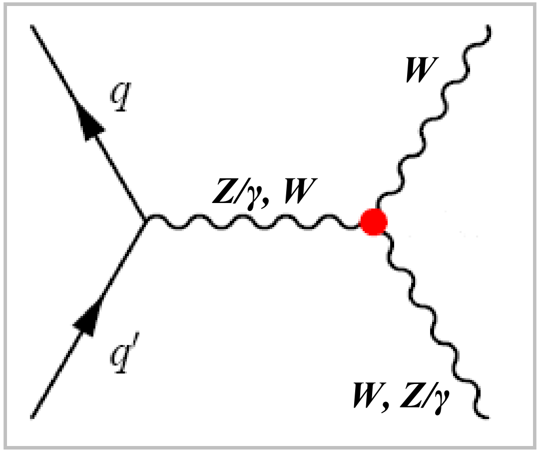
- ***γZZ*** **and** ***γγZ*** **couplings:**
  - General Lorentz invariant Lagrangian has 8 couplings

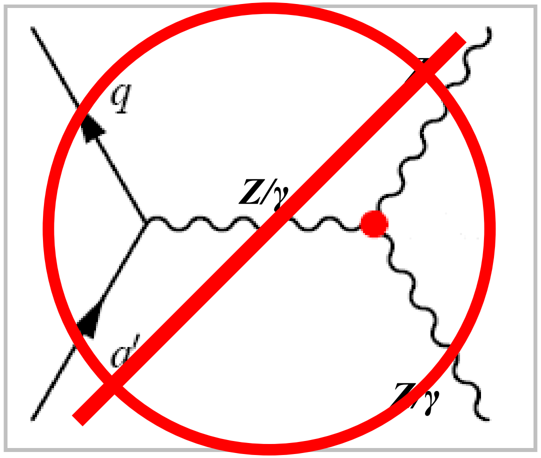
$$L_{\gamma Z V} = -ie\left[\left(h_1^V F^{\mu\nu} + h_3^V \tilde{F}^{\mu\nu}\right) Z_{\mu} \frac{\left(\Box + m_V^2\right)}{M_Z^2} V_{\nu} + \left(h_2^V F^{\mu\nu} + h_4^V \tilde{F}^{\mu\nu}\right) Z^{\alpha} \frac{\left(\Box + m_V^2\right)}{M_Z^4} \partial_{\alpha} \partial_{\mu} V_{\nu}\right]$$

  - C and P conserving: $g_1^{\gamma}, g_1^{Z}, \kappa_{\gamma}, \kappa_Z, \lambda_{\gamma}, \lambda_Z$
  - C and P violating, but CP conserving: $g_5^Z, h_3^{\gamma}, h_3^Z, h_4^{\gamma}, h_4^Z$
  - CP violating: $g_4^{\gamma}, g_4^Z, \tilde{\kappa}_{\gamma}, \tilde{\kappa}_Z, \tilde{\lambda}_{\gamma}, \tilde{\lambda}_Z, h_1^{\gamma}, h_1^Z, h_2^{\gamma}, h_2^Z$

SM: $g_1^{\gamma} = g_1^Z = \kappa_{\gamma} = \kappa_Z = 1$ and all others are zero

Anomalous Couplings





- ***ZWW*** and ***γWW*** couplings
  - In the SM:
    - *γWW* and *ZWW* TGCs
      - $g_1^Z = \kappa_\gamma = \kappa_Z = 1$ and $\lambda_\gamma = \lambda_Z = 0$
    - No *γZZ* and *γγZ* TGCs
      - $h_3^\gamma = h_3^Z = h_4^\gamma = h_4^Z = 0$
  - Measure deviations from SM
    - $\Delta\kappa_V \equiv \kappa_V - 1, \quad \Delta g_1^V \equiv g_1^V - 1$
    - $\Delta\lambda_V = \lambda_V, \quad \Delta h_3^V = h_3^V, \quad \Delta h_4^V = h_4^V$
    - $\Delta x \neq 0 \Rightarrow$ anomalous TGC

$ZZ \rightarrow llll$

- Three candidate events

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}	