Measurements of the Trilinear Gauge Boson Couplings from Diboson Production at DØ

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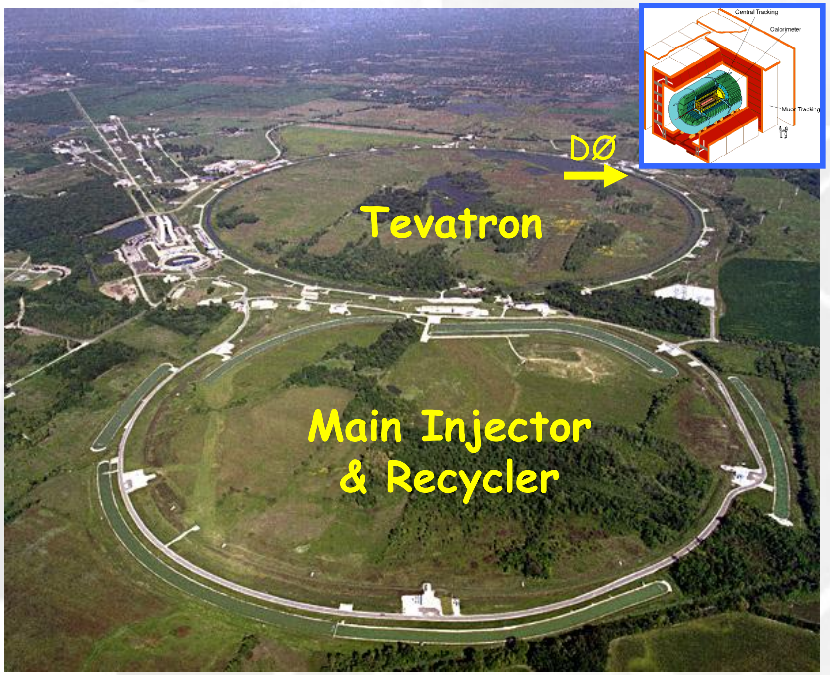
For the DØ Collaboration

DPF 2009, July 27-31, Detroit

Introduction

- Tevatron = vector boson factory

  $p\bar{p}$ collisions @ $\sqrt{s} = 1.96$ TeV



Luminosity ≈ 50/pb recorded per week:
~ $1.2 \cdot 10^6$ Ws, ~ $3.5 \cdot 10^5$ Zs, ~ 620 WW,
~ 190 WZ, ~ 70 ZZ, ~ 800 W/Zγ (inclus.)

- Run II data:
  2002 – present
  Recorded luminosity: 6.1/fb

- Recent (new 2009) results from DØ studies related to gauge boson couplings in diboson production:
  - **Zγ→ννγ final states**
  - **WW→lνlν final states**
  - **WW/WZ→lνjj final states**
  - **Combined study of γWW/ZWW couplings**

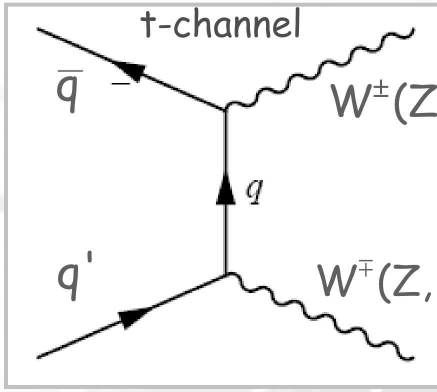
http://www-d0.fnal.gov/Run2Physics/WWW/results/ew.htm

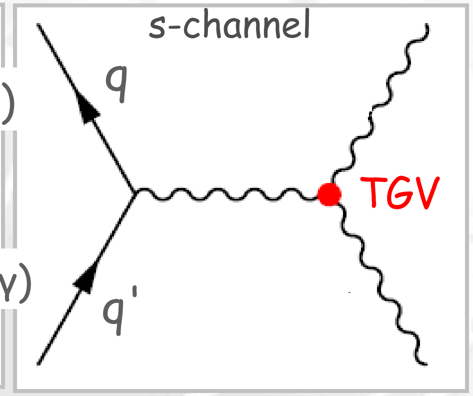
Trilinear Gauge Boson Couplings (TGCs)

- **Test of the SM, Search for New Physics (low energy effects)**

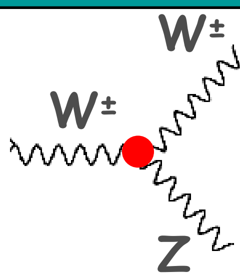
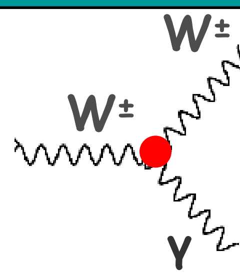
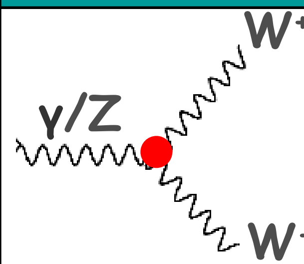
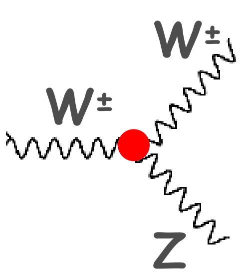
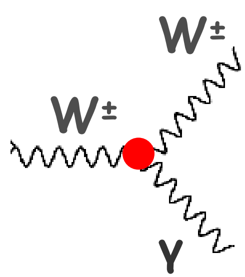
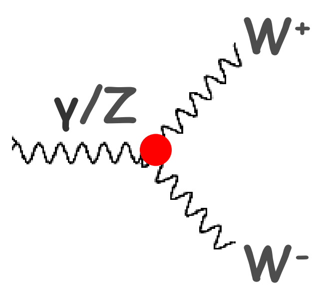
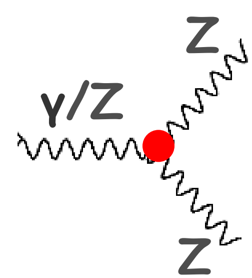
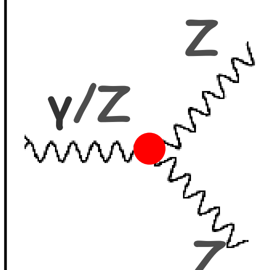
  Measurements: Cross Sections, Gauge Boson Couplings (TGCs)

t – channel dominates total cross section





s – channel sensitive to TGCs due to the existence of TG boson vertex (TGV)

Final State	WZ	Wγ	WW	ZZ	Zγ
SM				Highly suppressed in the SM	
Non-SM					

Trilinear Gauge Boson Couplings (TGCs)

- Effective Lagrangian for **neutral** TGCs (ZZγ/Zγγ):

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

CP conserving → $h_{3,4}^V$ couplings (V = γ, Z) $\Rightarrow h_3^\gamma, h_3^Z, h_4^\gamma, h_4^Z$

- Effective Lagrangian for **charged** TGCs (WWγ/WWZ):

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

If we assume:
EM gauge inv. ($g_1^\gamma = 1$), C and P conserving ⇒ 5 couplings: $\Rightarrow \kappa_\gamma, \kappa_Z, \lambda_\gamma, \lambda_Z, g_1^Z$

SM :

$$g_1^Z = \kappa_V = 1, \quad \lambda_V = h_{3,4}^V = 0$$

SM Deviations :

$$\Delta g_1^Z = g_1^Z - 1, \quad \Delta\kappa_V = \kappa_V - 1$$
$$\Delta\lambda_V = \lambda_V - 0, \quad \Delta h_{3,4}^V = h_{3,4}^V - 0$$

$\Delta \neq 0$

ANOMALOUS COUPLINGS

Trilinear Gauge Boson Couplings (TGCs)

- Helicity amplitudes grow with energy $\hat{s}$ $\Rightarrow$ Unitarity violation
  Form factor:

$$\Delta\alpha(\hat{s}) = \frac{\Delta\alpha_0}{\left(1+\hat{s}/\Lambda_{NP}^2\right)^n}$$

$\Delta\alpha_0$ ← Low-energy approximation of coupling

Λ_{NP} ← New physics scale

$\hat{s}$: (partonic) center-of-mass energy

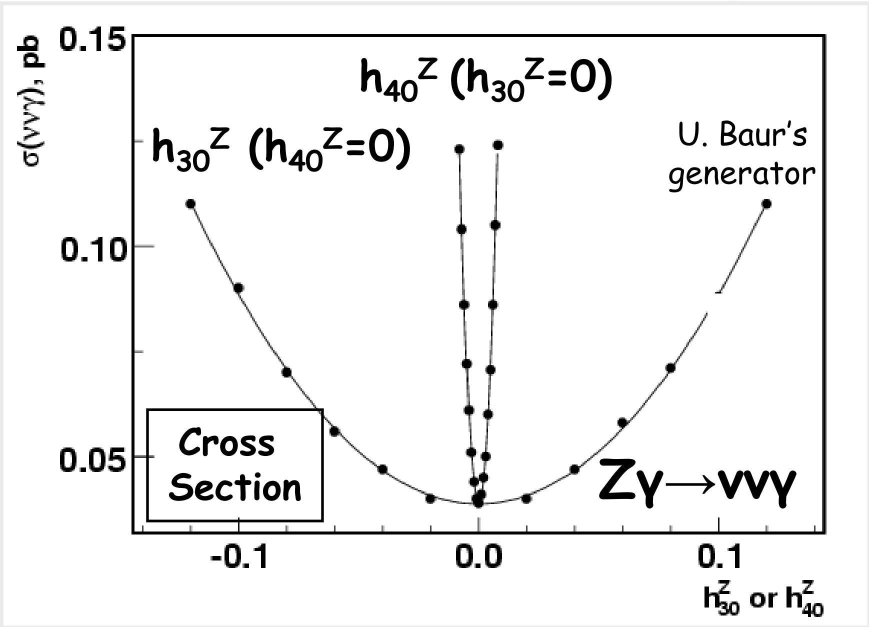
n=2 for WW,WZ
n=3,4 for Zγ

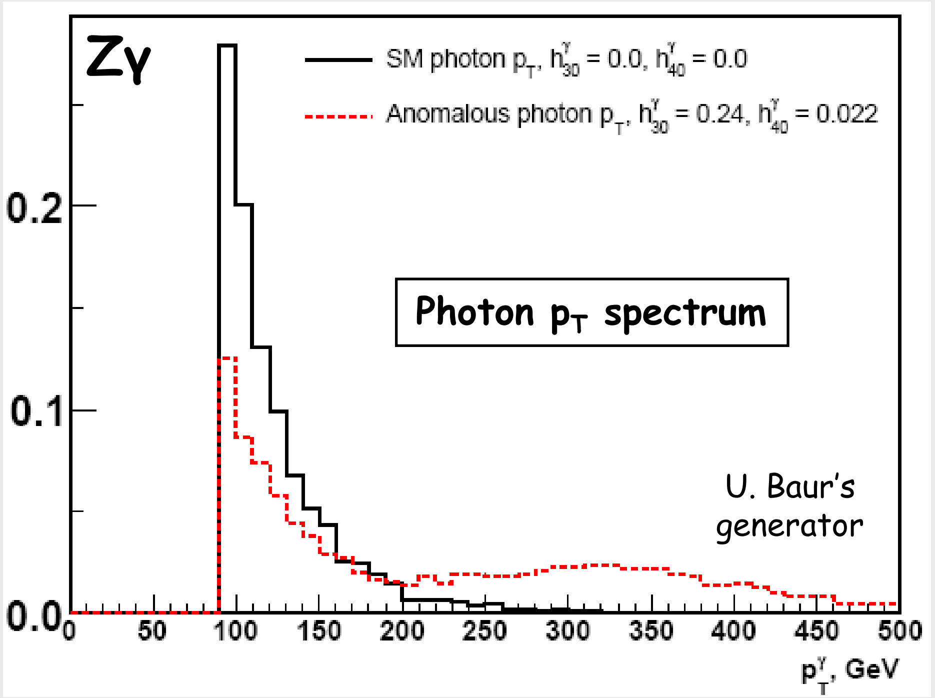
Form factor: conservative estimate based on the lowest possible scale for the new physics

Observables Sensitive to Anomalous TGCs

- **Example: neutral TGCs**

U. Baur and E. Berger, Phys. Rev. D 47, 4889 (1993)
U. Baur, T. Han, and J. Ohnemus, Phys. Rev. D 57, 2823 (1998)





Cross sections as a function of anomalous couplings in Zγ production; Different couplings ⇒ different sensitivities

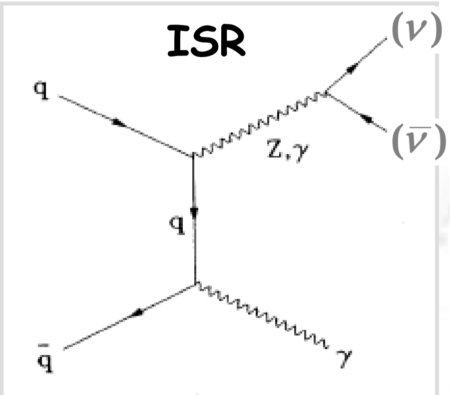
Deviation from the SM prediction as a function of anomalous TGCs – enhanced high p_T production

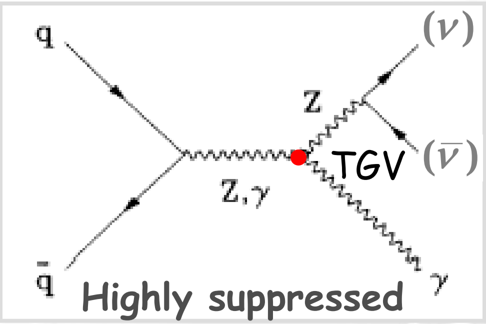
Disagreement with the SM expectation would indicate New Physics

(Neutral) TGCs in Zγ→ννγ events

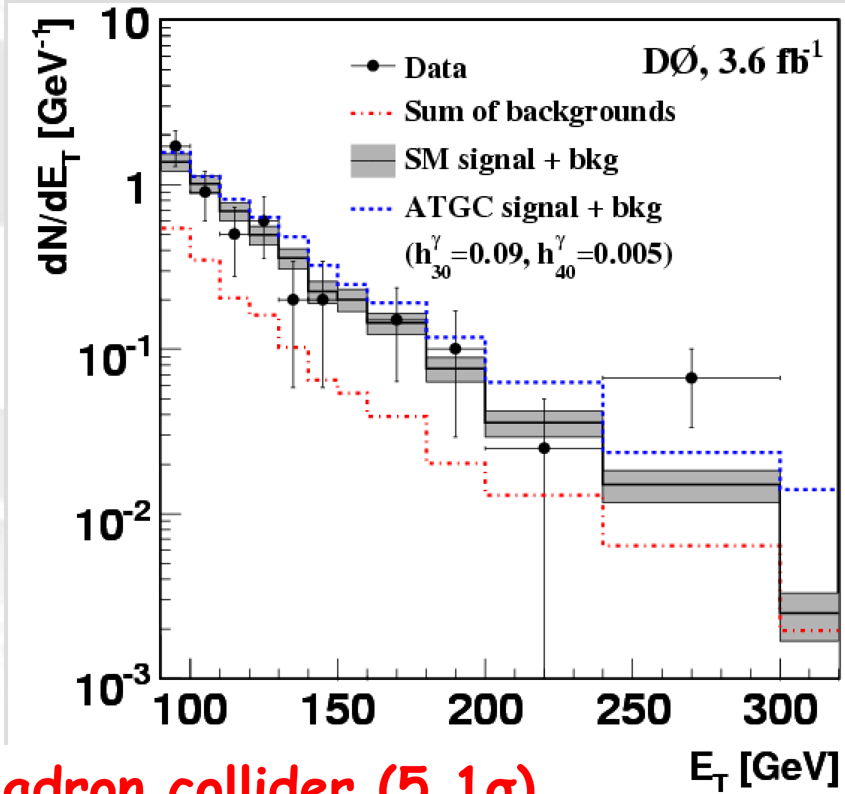
Phys. Rev. Lett. 102 201802 (2009)

Tree-level diagrams for Zγ→ννγ production





- No FSR diagram
- BR(Z→νν) ≈ 20%
- s-channel contains γ/ZZγ vertex
  ⇒ h_i^V couplings (V=γ,Z)



Event Signature: Photon + MET

Zγ→ννγ candidates (3.6/fb of data):

($E_T^γ$>90 GeV, MET>70 GeV)

Data: 51

Expected Signal: $33.7 \pm 3.4_{(stat)}$

Expected Background: $17.3 \pm 2.4_{(stat)}$

$$\sigma^{theo}_{Z\gamma\to\nu\nu\gamma} = 39 \pm 4 \text{ fb}$$

$$\sigma^{Meas}_{Z\gamma\to\nu\nu\gamma} = 32 \pm 9\,(\text{stat}+\text{syst}) \pm 2\,(\text{lumi}) \text{ fb}$$

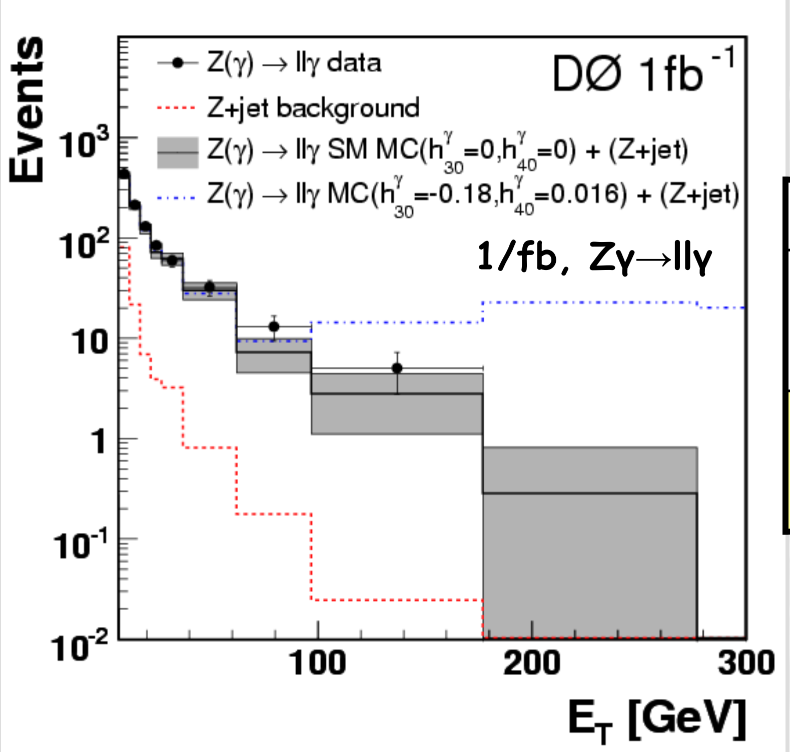
➡ **First observation of Zγ→ννγ at a hadron collider (5.1σ)**

(Neutral) TGCs in $Z\gamma \to \nu\nu\gamma$ events

Photon E_T spectrum used to set the limits on TGCs, $h_{30,40}^{\gamma,Z}$

- **Signal MC predictions (with anomalous TGCs):** Baur's generator
- **Binned Likelihood Method:** likelihood values from the Data/MC fits fitted with 2-par function in each photon E_T bin:

$$F(\Delta h_{30}, \Delta h_{40}) = c_1 + c_2 \Delta h_{30} + c_3 \Delta h_{40} + c_4 \Delta h_{30}^2 + c_5 \Delta h_{40}^2 + c_6 \Delta h_{30} \Delta h_{40}$$



1-parameter 95% CL limits on $h_{30,40}^{\gamma,Z}$ (Λ_{NP} = 1.5 TeV):

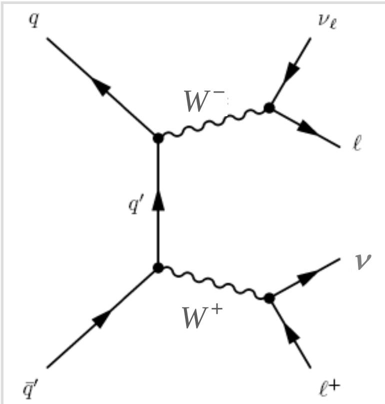
	h^γ (h^Z = 0)	h^Z (h^γ = 0)
$Z\gamma \to \nu\nu\gamma$ 3.6/fb	$\lvert h_{30}\rvert < 0.036$	$\lvert h_{30}\rvert < 0.035$
	$\lvert h_{40}\rvert < 0.0019$	$\lvert h_{40}\rvert < 0.0019$
$ll\gamma + \nu\nu\gamma$ (1+3.6)/fb	$\lvert h_{30}\rvert < 0.033$	
	$\lvert h_{40}\rvert < 0.0017$	

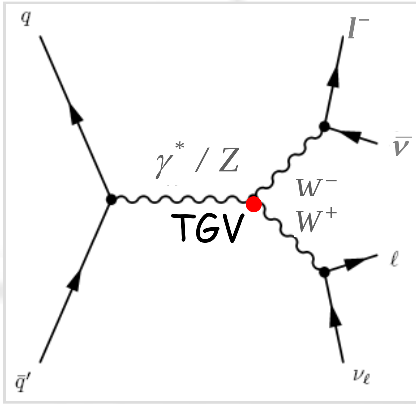
The most stringent limits on h_{30}^γ, h_{30}^Z and h_{40}^γ

(Charged) TGCs in WW→lνlν events

arXiv.org:0904.0673

Tree-level diagrams for WW→lνlν production





- BR(W→lν;W→lν) ≈ 10%
- Interference between ZWW and γWW vertices ⇒ sensitive to κ_Z, λ_Z κ_γ, λ_γ, g_1^Z

Event Signature: 2 leptons$^{(\pm)}$+MET

WW→lνlν candidates (μe,ee,μμ) (1/fb of data):

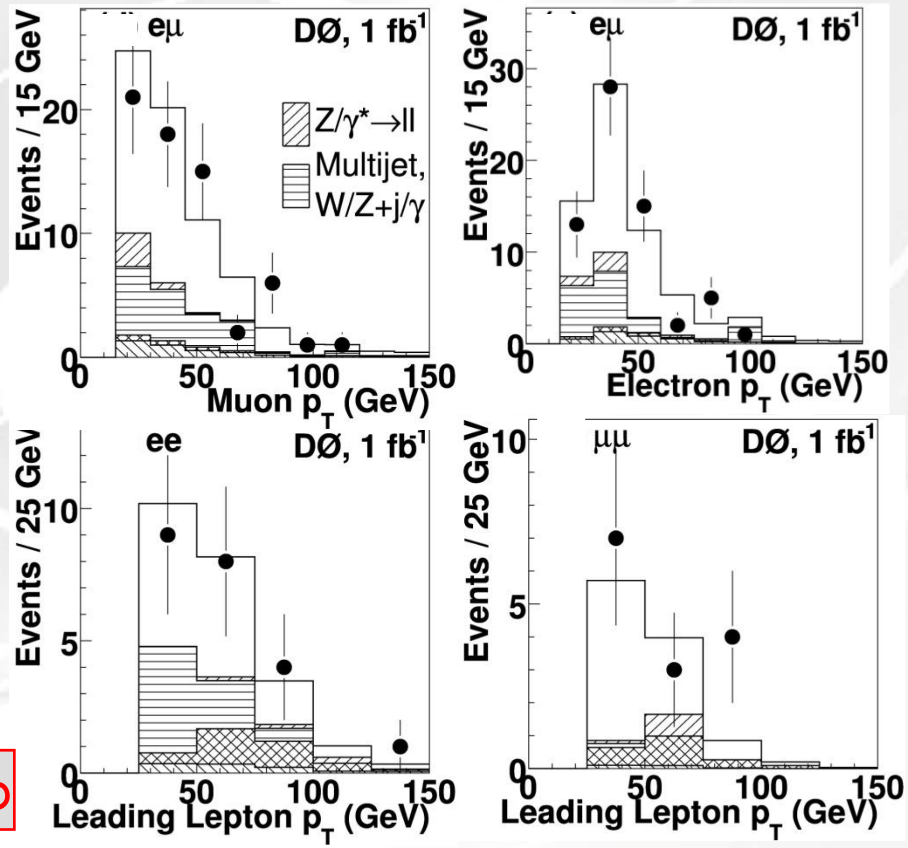
Data: 100

Expected Signal: $64.7 \pm 1.1_{(stat)}$

Expected Background: $38.2 \pm 4.0_{(stat)}$

$$\sigma_{WW}^{theo} = 12.4 \pm 0.8\ \text{pb}$$

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



(Charged) TGCs in WW→lvlv events

- Use measured lepton p_T's to set constraints on ZWW/γWW TGCs
- Considers two different relations between the TGCs:
  1. **Equal γWW and ZWW couplings** (equality of γ/Z couplings)

     $$\Delta\kappa_\gamma = \Delta\kappa_Z,\ \Delta\lambda_\gamma = \Delta\lambda_Z,\ \text{EM invariance}: \Delta g_1^\gamma = \Delta g_1^Z = 0$$

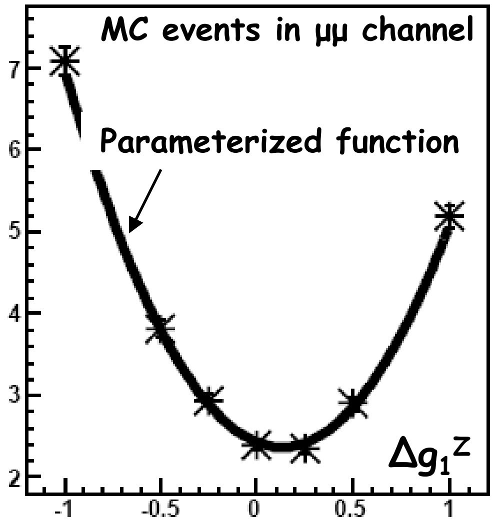
  2. **LEP parameterization** (light Higgs boson existence, preserve $SU(2)_L \times U(1)_Y$ gauge invariance)

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

- MC predictions (with anomalous TGCs): Hagiwara-Zeppenfeld-Woodside generator (HZW)

  K. Hagiwara, J. Woodside, and D. Zeppenfeld, Phys. Rev. D 41, 2113 (1990)

  3-par function for each 2D lepton p_T bin (interpolation between generated anomalous TGC points) ⇒ prediction for any TGC value



- Likelihood MC/Data fit in bin-by-bin basis:

1D 95% CL limits on $\Delta\kappa_\gamma$, $\Delta\lambda_\gamma$ and Δg_1^Z with Λ_{NP}=2TeV:

$SU(2)_L \times U(1)_Y$	$\gamma WW = ZWW$
$-0.54 < \Delta\kappa_\gamma < 0.83$	$-0.12 < \Delta\kappa < 0.35$
$-0.14 < \Delta\lambda_\gamma < 0.18$	$-0.14 < \Delta\lambda < 0.18$
$-0.14 < \Delta g_1^Z < 0.30$	

Complementary to LEP results

(Charged) TGCs in WW/WZ→lvjj events

arXiv.org:0907.4398
Submitted to PRD

Tree-level diagrams are the same as for WW→lvlv

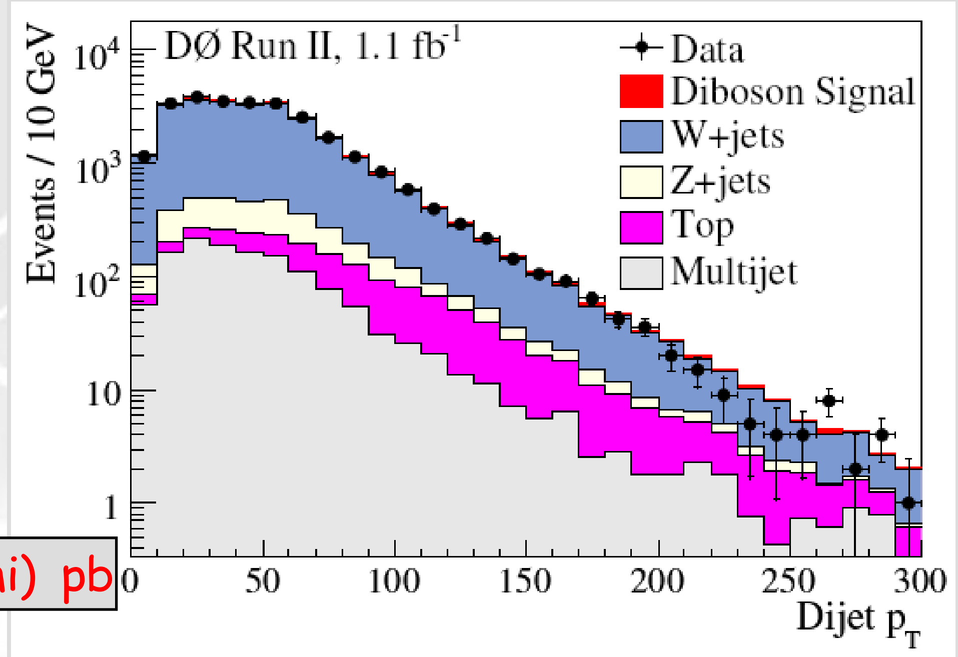
- Indistinguishable signals (insufficient W/Z→jj resolution)
- Larger BR than for leptonic modes:
  - WW(WZ) → (e+μ)vjj branching ratio: ~28.5 (14.2)%
  - WW(WZ) → (e+μ)vjj $\sigma^{theo}\times$BR: ~3.5 (0.5) pb
- Huge background: ~ 86% W+jets, ~ 3% WW+WZ, tt-bar !
- Interference between ZWW and γWW couplings ⇒ sensitive to κ_Z, λ_Z κ_γ, λ_γ and g_1^Z

WW/WZ→lvjj candidates (μ/evjj) (1.1/fb of data):

Data: 26865

Expected Signal: $773 \pm 4_{(stat)}$

Expected Bkg: $25867 \pm 120_{(stat)}$



$$\sigma^{theo}_{WW+WZ} = 16.1 \pm 0.9 \text{ pb}$$

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

Phys. Rev. Lett. 102, 161801 (2009)

➧ **First evidence of WW/WZ→lvjj at a hadron collider (4.4σ)**

(Charged) TGCs in WW/WZ→lvjj events

- **Use dijet p_T distribution to set constraints on ZWW/γWW TGCs**
- **Considers SU(2)xU(1) and γWW=ZWW relations between the TGCs**
- **MC predictions with (anomalous TGCs): Reweighting Method**

Quadratic dependence of the differential cross-section on anomalous TGCs

$$d\sigma = const \cdot |M|^2 dX = const \cdot |M|^2_{SM} \frac{|M|^2}{|M|^2_{SM}} dX$$

$$R = \frac{|M|^2}{|M|^2_{SM}} = \left[1 + A(X)\Delta\kappa + B(X)\Delta\kappa^2 + C(X)\Delta\lambda + D(X)\Delta\lambda^2 + E(X)\Delta\kappa\Delta\lambda + \ldots\right]$$

X - variable sensitive to anomalous TGCs **(W/Z boson p_T)**
A(X), B(X), C(X), D(X), E(X) are **reweighting coefficients** (SM: = 0)
R(TGC;X) – **weight R**, matrix elements ratio per event

K. Hagiwara, J. Woodside, and D. Zeppenfeld, Phys. Rev. D 41, 2113 (1990)

- **HZW generator to describe effects of anomalous TGCs**

Reweight PYTHIA p_T distribution to various HZW models (with *R*, in the reconstructed dijet p_T bin and sum all weighted events in that bin) to explore the parameter space

- **1D and 2D fit:** Poisson χ^2 for each point in TGC space between Data and MC prediction … and we look at the $\Delta\chi^2$ from the minimum to set limits

(Charged) TGCs in WW/WZ→lvjj events

Most probable TGC values as measured from 1D MC fit to Data with their errors at 68% CL:

Λ_{NP} = 2TeV	κ_γ	$\lambda = \lambda_\gamma = \lambda_Z$	g_1^Z
$SU(2)_L \times U(1)_Y$	$1.07^{+0.26}_{-0.29}$	$0.00^{+0.06}_{-0.06}$	$1.04^{+0.09}_{-0.09}$
$\gamma WW = ZWW$	$1.04^{+0.11}_{-0.11}$	$0.00^{+0.06}_{-0.06}$	-

The 95% CL limits from 1D MC fit to Data compared to other DØ analyses:

	Λ_{NP} = 2TeV	$\Delta\kappa_\gamma$	$\lambda = \lambda_\gamma = \lambda_Z$	Δg_1^Z
$SU(2)_L \times U(1)_Y$	WZ→lvll (1/fb)	-	$-0.17 < \lambda < 0.21$	$-0.14 < \Delta g_1^Z < 0.34$
	Wγ→lvγ (0.7/fb)	$-0.51 < \Delta\kappa_\gamma < 0.51$	$-0.12 < \lambda < 0.13$	-
	WW→lvlv (1/fb))	$-0.54 < \Delta\kappa_\gamma < 0.83$	$-0.14 < \lambda < 0.18$	$-0.14 < \Delta g_1^Z < 0.30$
	WW/WZ→lvjj (1.1/fb)	$-0.44 < \Delta\kappa_\gamma < 0.55$	$-0.10 < \lambda < 0.11$	$-0.12 < \Delta g_1^Z < 0.20$
γWW=ZWW	WZ→lvll (1/fb)	-	$-0.17 < \lambda < 0.21$	-
	Wγ→lvγ (0.7/fb)	-	$-0.12 < \lambda < 0.13$	-
	WW→lvlv (1/fb)	$-0.12 < \Delta\kappa < 0.35$	$-0.14 < \lambda < 0.18$	-
	WW/WZ→lvjj (1.1/fb)	$-0.16 < \Delta\kappa < 0.23$	$-0.11 < \lambda < 0.11$	-

Combined Measurement of γWW/ZWW TGCs

arXiv.org:0907.4952
Submitted to PRD-RC

!!! First TGCs combined study for RunII
High statistics ~1/fb !!!

- Measurement of charged TGCs: $\kappa_\gamma, \kappa_Z, \lambda_\gamma, \lambda_Z, g_1^Z$

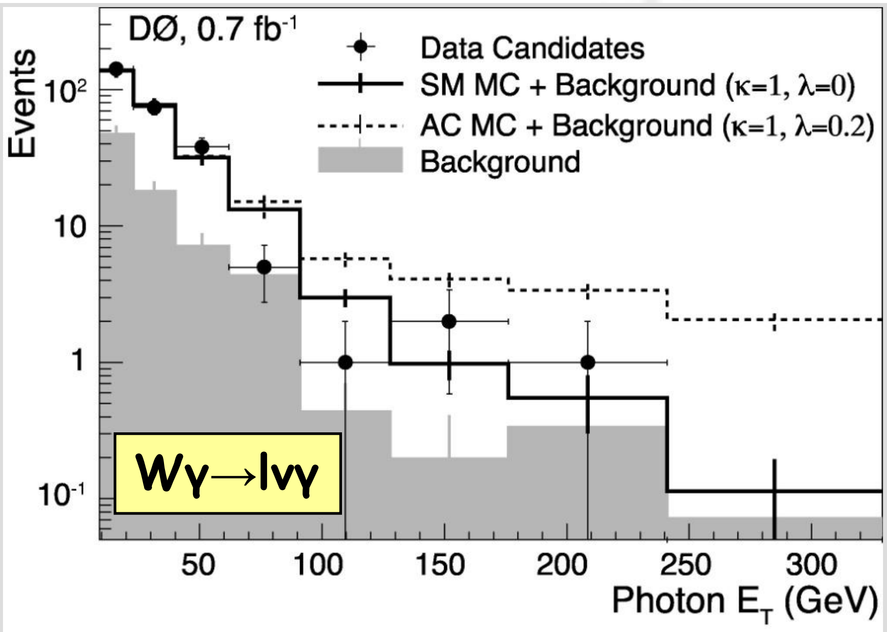
Combined final states:

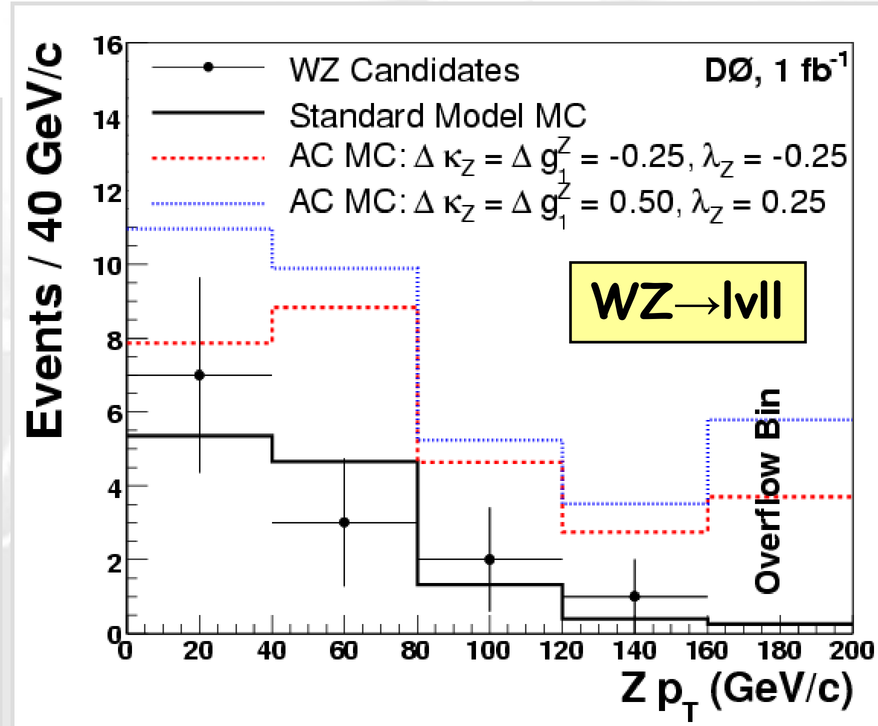
$WW \to l\nu l\nu$	1/fb	Lepton p_T distributions
$WZ \to lll\nu$	1/fb	Z_{ll} p_T distribution ← Phys. Rev. D 76 111104 (2007)
$W\gamma \to l\nu\gamma$	0.7/fb	Photon E_T distribution ← Phys. Rev. Lett. 100 241805 (2008)
$WW/WZ \to l\nu jj$	1.1/fb	Dijet p_T distribution

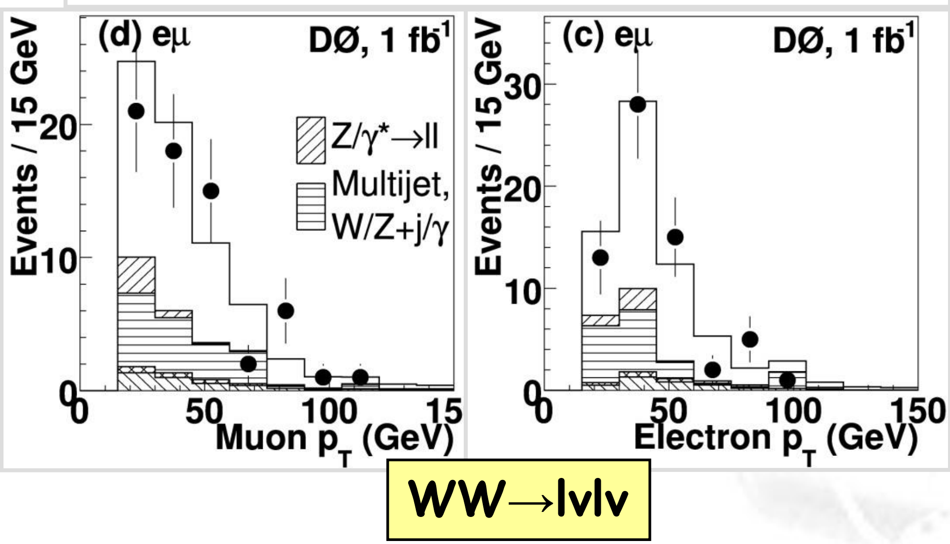
- SU(2)xU(1) and γWW=ZWW relations between the TGCs considered
- Λ_{NP} = 2TeV

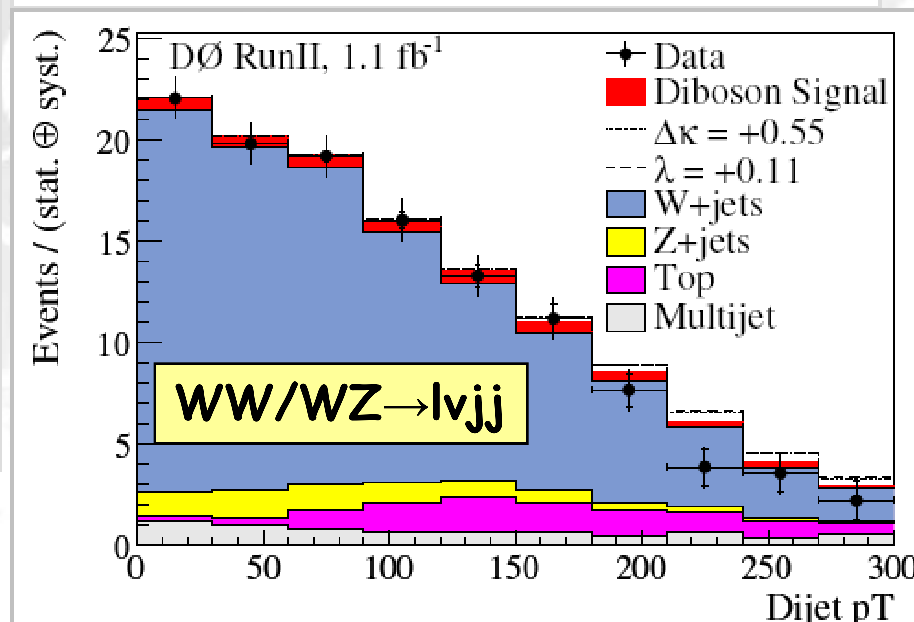
✘ Extraction of the W boson magnetic dipole moment
$\mu_W = e/2M_W(1+\kappa+\lambda)$

✘ Extraction of the W boson electric quadrupole moment
$q_W = -e/M_W^2(\kappa_\gamma-\lambda_\gamma)$


DØ, 0.7 fb-1
Data Candidates
SM MC + Background (κ=1, λ=0)
AC MC + Background (κ=1, λ=0.2)
Background
Events
Photon E_T (GeV)
Wγ→lνγ


WZ Candidates
DØ, 1 fb-1
Standard Model MC
AC MC: Δ κ_Z = Δ g_1^Z = -0.25, λ_Z = -0.25
AC MC: Δ κ_Z = Δ g_1^Z = 0.50, λ_Z = 0.25
WZ→lνll
Overflow Bin
Events / 40 GeV/c
Z p_T (GeV/c)


(d) eμ
DØ, 1 fb-1
Z/γ*→ll
Multijet,
W/Z+j/γ
Events / 15 GeV
Muon p_T (GeV)
(c) eμ
DØ, 1 fb-1
Events / 15 GeV
Electron p_T (GeV)
WW→lνlν


DØ RunII, 1.1 fb-1
Data
Diboson Signal
Δκ = +0.55
λ = +0.11
W+jets
Z+jets
Top
Multijet
Events / (stat. ⊕ syst.)
Dijet pT
WW/WZ→lνjj

Combined Measurement of γWW/ZWW TGCs

Most probable TGC values as measured from 1D MC fit to Data, 68% and 95% CL limits (Λ_{NP}=2TeV):

$SU(2)_L \otimes U(1)_Y$-constraint Results			
Parameter	Minimum	68% C.L.	95% C.L.
$\Delta\kappa_\gamma$	0.07	$-0.13, 0.23$	$-0.29, 0.38$
Δg_1^Z	0.05	$-0.01, 0.11$	$-0.07, 0.16$
λ	0.00	$-0.04, 0.05$	$-0.08, 0.08$
Equal Coupling Results			
Parameter	Minimum	68% C.L.	95% C.L.
$\Delta\kappa$	0.03	$-0.04, 0.11$	$-0.11, 0.18$
λ	0.00	$-0.05, 0.05$	$-0.08, 0.08$

68% CL (SU(2)xU(1), g_1^Z=1):

$$\mu_W = 2.02^{+0.08}_{-0.09}\,(e/2M_W)$$

$$q_W = -1.00 \pm 0.09\,(e/M_W^2)$$

- ~25% improvement in sensitivity relative to individual DØ analyses
- Most stringent limits on γ/ZWW couplings measured from hadronic collisions to date
- Most stringent (published soon) results of μ_W and q_W to date

Summary

- TGC studies useful in search for New Physics
- All DØ results (cross sections/gauge boson couplings) are in the agreement with the SM
- The world's tightest limits on TGCs h_{30}^{γ}, h_{30}^{Z} and h_{40}^{γ}
- Combined TGC results with high statistics for the first time (RunII, ~1/fb)
  $W\gamma \rightarrow l\nu\gamma$ + $WW \rightarrow l\nu l\nu$ + $WZ \rightarrow l\nu ll$ + $WW/WZ \rightarrow l\nu jj$
- Most stringent limits on γ/ZWW couplings measured from hadronic collisions to date
  - close to LEP2 individual results in λ; 2x g_1^Z; 2-3x $\Delta\kappa_\gamma$
  - with expected ~10/fb data at DØ ~ sensitivity of LEP2 individual
- The best results on μ_W and q_W to date

Still statistically limited but can be improved with incoming data ⇒ competitive results are in front of us !