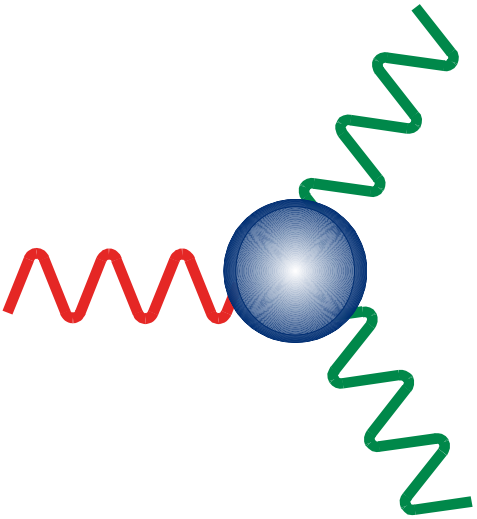
Measurement of Trilinear Gauge Boson Couplings



T. Yasuda
Northeastern University

Outline

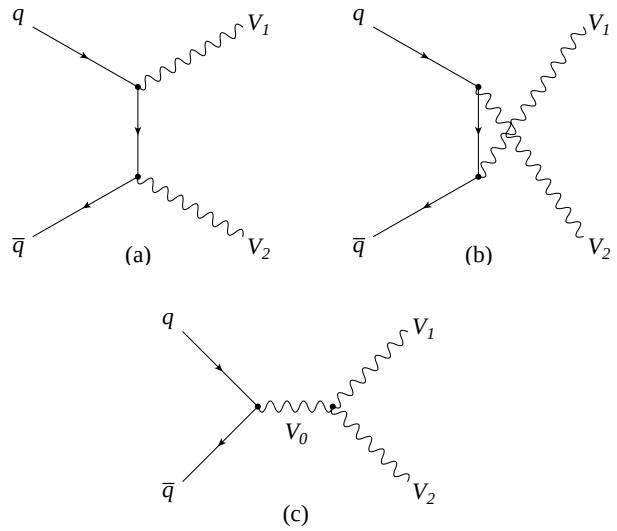
- Introduction
- Experimental Methods
- Measurements on WWV couplings
  - $W\gamma$
  - $WW \rightarrow$ dilepton
  - $WW/WZ \rightarrow l\nu jj$
  - $WZ \rightarrow$ trilepton
- Measurements on $Z\gamma V$ couplings
  - $Z\gamma \rightarrow ee\gamma$, $\mu\mu\gamma$
  - $Z\gamma \rightarrow \nu\nu\gamma$
- Future prospects
- Summary

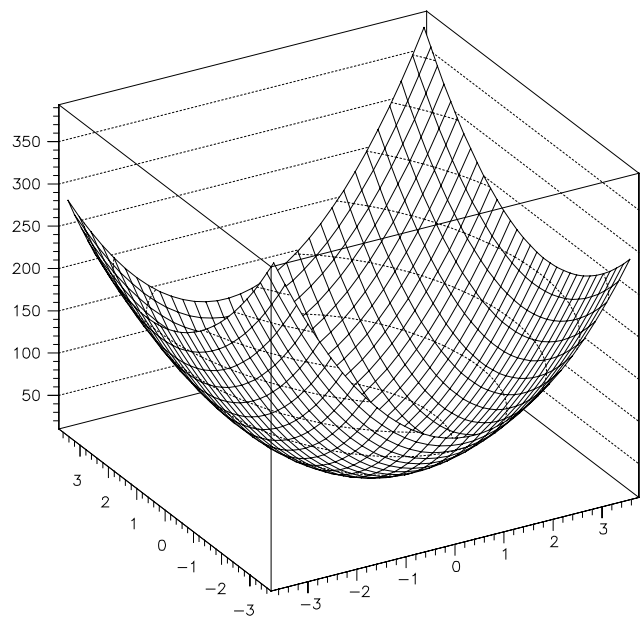
Trilinear Gauge Boson couplings

- Trilinear gauge boson couplings
  - Direct consequence of the non-Abelian SU(2)xU(1) gauge symmetry of the Standard Model
  - Important for the renormalizability of the SM
- Measurement of the couplings using gauge boson pair final states
  - Crucial direct test of the Standard Model
- Deviations from the Standard Model
  - Signal for new physics

Trilinear Gauge Boson couplings

- Study of Trilinear Gauge Boson Couplings
  ⇒ Study of Gauge Boson pair final states
  - Wγ
  - WW
  - WZ
  - Zγ
  - ZZ
- Signature of anomalous couplings
  - A dramatic increase in cross sections at large s
  - A dramatic increase in cross sections for high p_T gauge bosons





WWV(V=γ or Z) Couplings

- Lorentz invariant effective Lagrangian

$$
\begin{aligned}
i\mathcal{L}_{WWV} &= g_{WWV}[g_1^V V^\mu (W^-_{\mu\nu}W^{+\nu} - W^+_{\mu\nu}W^{-\nu}) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} \\
&+ \frac{\lambda_V}{m_W^2} V^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu} + i g_5^V \epsilon_{\mu\nu\rho\sigma}((\partial^\rho W^{-\mu})W^{+\nu} - W^{-\mu}(\partial^\rho W^{+\nu}))V^\sigma \\
&+ i g_4^V W^-_\mu W^+_\nu (\partial^\mu V^\nu - \partial^\nu V^\mu) \\
&+ \frac{\tilde{\kappa}_V}{2} W^-_\mu W^+_\nu \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} + \frac{\tilde{\lambda}_V}{2m_W^2} W^-_{\rho\mu} W^{+\mu}_\nu \epsilon^{\nu\rho\alpha\beta} V_{\alpha\beta}
\end{aligned}
$$

where $V = \gamma$ or Z, $W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$, and $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$.

- Assuming C, P and CP invariance
  $\Rightarrow g_4^V = g_5^V = \kappa_V = \lambda_V = 0$

- EM gauge invariance
  $\Rightarrow g_1^\gamma = 1$
  $\Rightarrow$ 5 couplings: λ_γ, κ_γ, g_1^Z, λ_Z, κ_Z

- Standard Model at tree level
  $g_1^V = 1$, $\Delta\kappa_V = \kappa_V - 1 = 0$, $\lambda_V = \lambda_V = \kappa_V = g_4^V = g_5^V = 0$
  where V=Z or γ

- Anomalous couplings with a cutoff scale Λ
  $\lambda(s) = \lambda/(1+s/\Lambda^2)^2$ and $\Delta\kappa(s) = \Delta\kappa/(1+s/\Lambda^2)^2$

SU(2)xU(1) gauge invariance

- Z-fermion couplings agree with SM prediction at 10^{-3} level (LEP 1 and SLC).
  - e.g. $g_V^l = -0.0377 \pm 0.0007$, $g_A^l = -0.5008 \pm 0.0008$

- SU(2)xU(1) gauge structure must underly any model of anomalous TGCs.

- Effective lagrangian can be made SU(2)xU(1) invariant with an addition of a light Higgs doublet (linear realization)
  $\Rightarrow g_1^Z = \kappa_Z + \tan^2\theta_W(\kappa_\gamma - 1)$, $\lambda_\gamma = \lambda_Z$

WWV(V=γ or Z) Couplings (Tevatron)

- Assumptions to reduce the number of couplings
  - WWγ and WWZ couplings are equal
    $\Rightarrow g_1^{\gamma} = g_1^{Z} = 1$, $\Delta\kappa_{\gamma} = \Delta\kappa_Z$ and $\lambda_{\gamma} = \lambda_Z$
  - HISZ: SU(2)xU(1) gauge invariance with a Higgs doublet ($g_1^Z = \kappa_Z + \tan^2\theta_W(\kappa_{\gamma} - 1)$, $\lambda_Z = \lambda_{\gamma}$)
    + an additional constraint $\Delta g_1^Z = \Delta\kappa_{\gamma}/2 \cos^2\theta_W$
    $\Rightarrow \Delta\kappa_Z = \Delta\kappa_{\gamma}(1 - \tan^2\theta_W)/2$, $\lambda_Z = \lambda_{\gamma}$, and
    $\Delta g_1^Z = \Delta\kappa_{\gamma}/2 \cos^2\theta_W$
  - SM WWγ couplings
  - SM WWZ couplings

WWV(V=γ or Z) Couplings (LEP)

- SU(2)xU(1) gauge invariance with a Higgs doublet
  $\Rightarrow g_1^Z = \kappa_Z + \tan^2\theta_W(\kappa_\gamma - 1)$, $\lambda_\gamma = \lambda_Z$
  $\Rightarrow$ three independent parameters: $\alpha_{B\phi}$, $\alpha_{W\phi}$ and α_W
  $\alpha_{B\phi} \equiv \Delta\kappa_\gamma - \Delta g_1^Z \cos^2\theta_W$, $\alpha_{W\phi} \equiv \Delta g_1^Z \cos^2\theta_W$
  and $\alpha_W \equiv \lambda_\gamma = \lambda_Z$
  - Extra constraint in HISZ corresponds to $\alpha_{B\phi} = \alpha_{W\phi}$

WWV Couplings (V=γ or Z) (Tevatron + LEP working group)

- SU(2)xU(1) gauge invariance with a Higgs doublet
  $\Rightarrow g_1^Z = \kappa_Z + \tan^2\theta_W(\kappa_\gamma - 1)$, $\lambda_\gamma = \lambda_Z$
  $\Rightarrow$ three independent parameters: λ_γ, $\Delta\kappa_\gamma$ and Δg_1^Z

Note: limits on λ_γ = limits on α_W when $\Delta\kappa_\gamma = \Delta g_1^Z = 0$
limits on $\Delta\kappa_\gamma$ = limits on $\alpha_{B\phi}$ when $\lambda_\gamma = \Delta g_1^Z = 0$

$Z\gamma V$ ($V=\gamma$ or Z) Couplings

- General couplings
  - h_3^V, h_4^V (CP-conserving); h_1^V, h_2^V (CP-violating)
- Standard Model
  - $h_i^V = 0$ ($i = 1\ldots4$)
- Anomalous couplings with a cutoff scale Λ
  - $h_i^V(s) = h_{i0}^V/(1+s/\Lambda^2)^n$ where n=3 for i=1,3 and n=4 for i=2,4

Anomalous couplings and Physical quantities

- Static moments of W

$$
\begin{aligned}
\mu_W &= \frac{e}{2m_W}(1+\kappa_\gamma+\lambda_\gamma) \\
d_W &= \frac{e}{2m_W}(\tilde{\kappa}_\gamma+\tilde{\lambda}_\gamma) \\
Q_W^e &= -\frac{e}{m_W^2}(\kappa_\gamma-\lambda_\gamma) \\
Q_W^m &= -\frac{e}{m_W^2}(\tilde{\kappa}_\gamma-\tilde{\lambda}_\gamma)
\end{aligned}
$$

- Transition moments of Z

$$
\begin{aligned}
\mu_Z &= \frac{-e}{\sqrt{2}m_Z}\frac{E_\gamma^2}{m_Z^2}(h_1^Z-h_2^Z) \\
d_Z &= \frac{-e}{\sqrt{2}m_Z}\frac{E_\gamma^2}{m_Z^2}(h_3^Z-h_4^Z) \\
Q_Z^e &= \frac{2\sqrt{10}e}{m_Z^2}h_1^Z \\
Q_Z^m &= \frac{2\sqrt{10}e}{m_Z^2}h_3^Z
\end{aligned}
$$

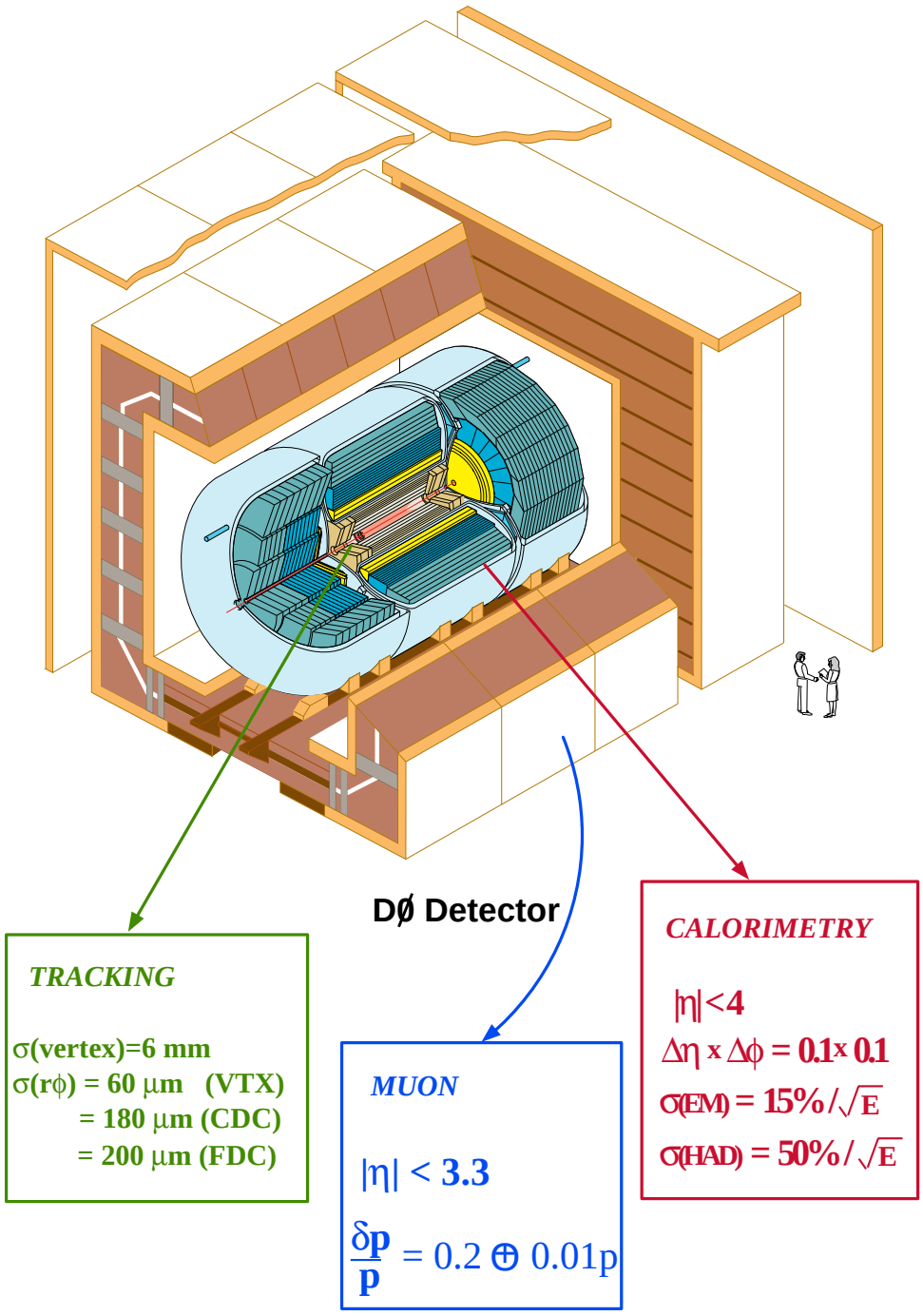
Indirect bounds on couplings

- Indirect upper bounds on couplings from precision measurements

  J. Ellison and J. Wudka hep-ph/9804322

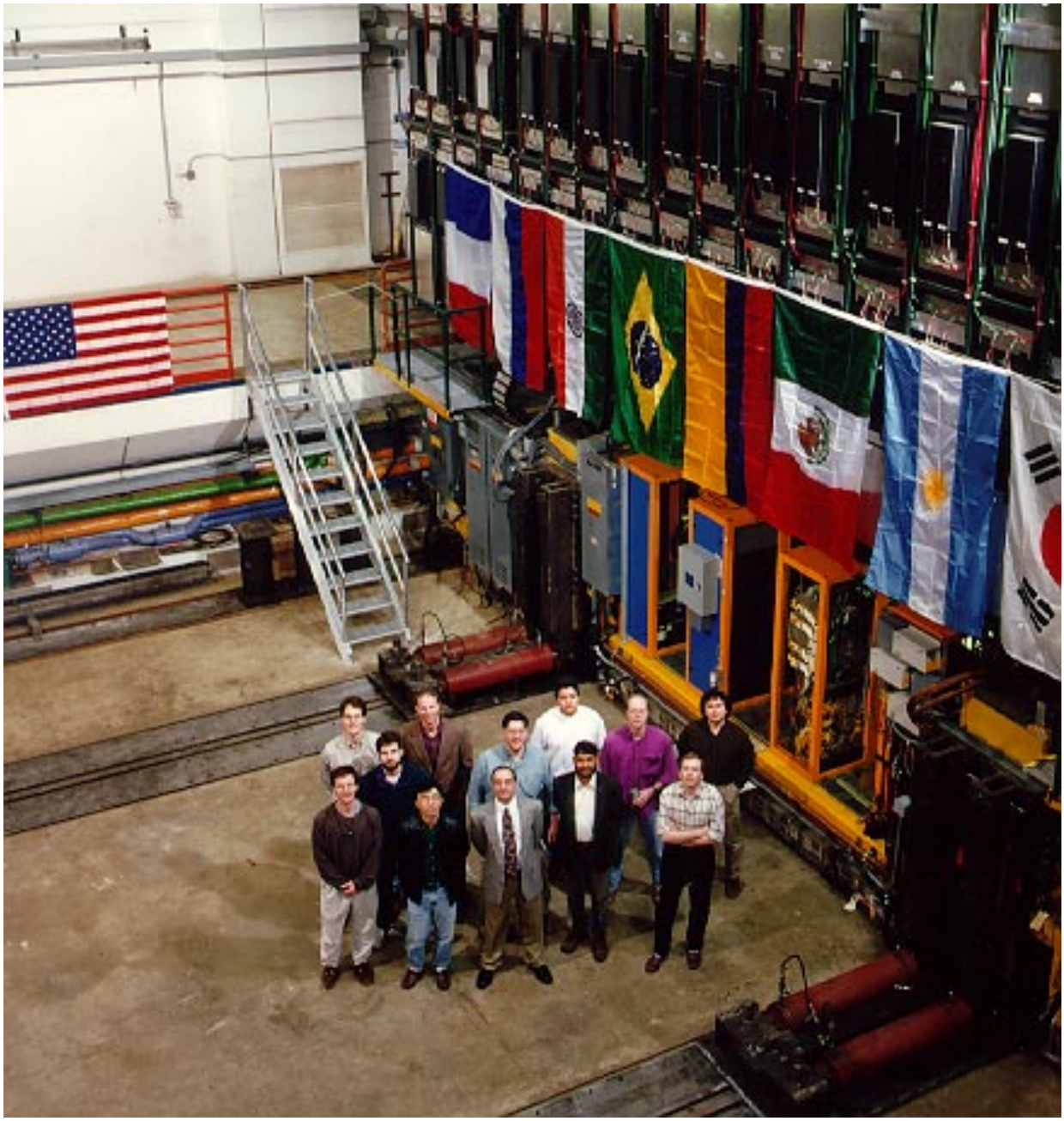
	Oblique params.	$(g\text{-}2)_\mu$	d_n	d_e	$b\to s\gamma$	*Atomic parity viol.*	$K_L\to\mu\mu$
$\lvert\Delta\kappa_\gamma\rvert$	0.05	1	-	-	2	1	1
$\lvert\Delta\kappa_Z\rvert$	0.4	-	-	-	-	0.12	-
$\lvert\lambda_\gamma\rvert$	0.2	2	-	-	7	0.13	-
$\lvert\lambda_Z\rvert$	0.2	-	-	-	-	0.13	-
$\lvert\kappa_\gamma\rvert$	-	-	-	0.14	0.4	-	-
$\lvert\kappa_Z\rvert$	-	-	-	0.04	-	-	-
$\lvert\lambda_\gamma\rvert$	-	-	0.00025	-	1.3	-	-
$\lvert g_4^Z\rvert$	-	-	-	0.80	-	-	-
$\lvert h_3^\gamma\rvert$	-	4.5	-	-	-	-	-

D0 detector


DØ Detector
TRACKING
σ(vertex)=6 mm
σ(rφ) = 60 μm (VTX)
= 180 μm (CDC)
= 200 μm (FDC)
MUON
|η| < 3.3
δp/p = 0.2 ⊕ 0.01p
CALORIMETRY
|η|<4
Δη x Δφ = 0.1x 0.1
σ(EM) = 15%/√E
σ(HAD) = 50%/√E

D0 Collaboration

Diboson Group



Experimental Methods

- Selection of Gauge Boson pair events
  - In all analysis channels ($W\gamma$, $WW \rightarrow$dilepton, $WW/WZ \rightarrow l\nu jj, lljj$, $WZ \rightarrow$trilepton and $Z\gamma$), at least one gauge boson is identified via leptonic decay mode.
    - A W boson is identified by a high E_T electron or muon and a large missing E_T in the event.
    - A Z boson is identified by two high E_T electrons or muons, or a large missing E_T ($Z \rightarrow \nu\nu$ decay)in the event.
  - The second gauge boson is:
    - a photon ($W\gamma$, $Z\gamma$)
    - a W boson or a Z boson decaying leptonically ($WW \rightarrow$dilepton, $WZ \rightarrow$ trilepton)
    - a W boson or a Z boson decaying hadronically($WW/WZ \rightarrow l\nu jj, lljj$)

Experimental Methods

- Backgrounds to Gauge Boson pair final states
  The amount of background is manageable for all channels except WW/WZ $\rightarrow l\nu jj, lljj$.
  - Jet(s) detected as a photon or a lepton (e or μ)
    - W+jets events with a jet faking a photon ($W\gamma$), or an electron (WW $\rightarrow$dilepton)
    - QCD multijet events with a jet faking an electron or accompanied by a muon (WW/WZ $\rightarrow l\nu jj, lljj$)
    - Z+jets events with a jet faking a photon ($Z\gamma$)
  - Other sources of background:
    - $Z\gamma$ with an electron or a muon undetected ($W\gamma$)
    - ttbar production
    - $Z\rightarrow\tau\tau$,
    - $W\gamma$ with γ misidentified as electron (WW $\rightarrow$ dilepton)
    - W+jets (WW/WZ $\rightarrow l\nu jj, lljj$)

* Probabilities of a jet faking an electron or a photon = 10^{-3} ~10^{-4}.

$\sigma_W \cdot B(W\rightarrow e\nu) = 2.5$ nb

$\sigma_Z \cdot B(Z\rightarrow ee) = 0.2$ nb

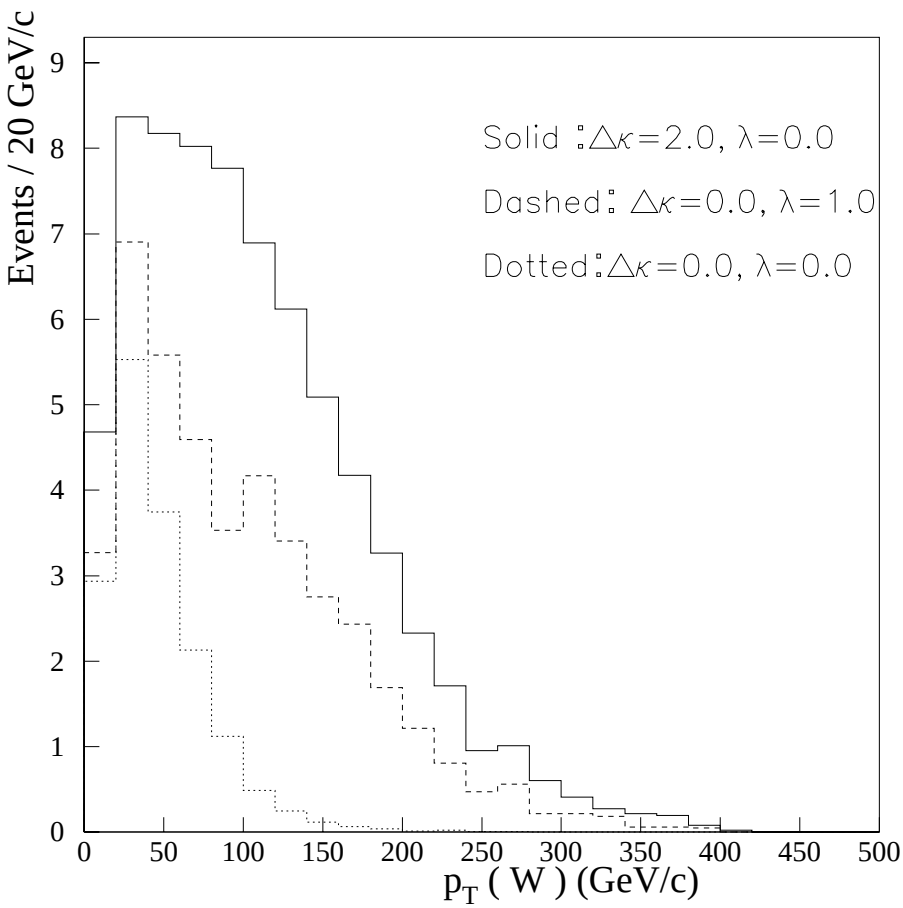
$\sigma_{W\gamma} \cdot B(W\rightarrow e\nu) = 12.5$ pb

$\sigma_{WW} = 10$ pb

$\sigma_{WZ} = 2.5$ pb

Experimental Methods

- Measurement of anomalous couplings
  - Maximum likelihood fit to the p_T spectrum of one of final state Gauge Bosons (p_T^{γ} in $W\gamma$ and $Z\gamma$, p_T^{W} in $WW/WZ \rightarrow l\nu jj$)
  - Maximum likelihood fit to the p_T spectra of final state leptons ($WW \rightarrow$ dilepton)



Experimental Methods

The probability P_i for observing N_i events in a given bin:

$$P_i = \frac{(b_i + n_i)^{N_i}}{N_i!} e^{-(b_i+n_i)}, n_i = \mathcal{L}\epsilon\sigma_i(\lambda, \Delta\kappa)$$

b_i : estimated background

n_i : expected signal

$\mathcal{L}$: integrated luminosity

ϵ : detection efficiency

σ_i : theoretical crosssection

The joint probability for all the kinematical bins:

$$P = \prod_{i=1}^{N_{bin}} P_i$$

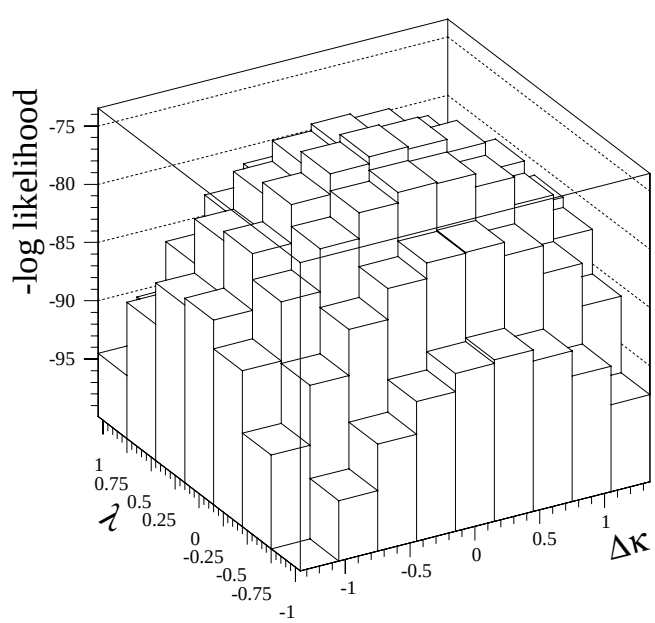
The posterior probability:

$$P'(\lambda, \Delta\kappa) = \frac{\int \mathcal{G}_{f_n} df_n \int \mathcal{G}_{f_b} df_b \prod_{i=1}^{N_{bin}} \frac{e^{-(f_n n_i(\lambda,\Delta\kappa)+f_b b_i)}(f_n n_i(\lambda,\Delta\kappa)+f_b b_i)^{N_i}}{N_i!} p(\lambda, \Delta\kappa)}{\int \mathcal{G}_{f_n} df_n \int \mathcal{G}_{f_b} df_b \sum_{\lambda,\Delta\kappa} p(\lambda, \Delta\kappa)}$$

$p(\lambda, \Delta\kappa)$: prior on λ and κ

f_n and f_b : norm. factors

$\mathcal{G}_{f_n}$ and $\mathcal{G}_{f_b}$: Gaussian prior



Wγ→eνγ, μνγ

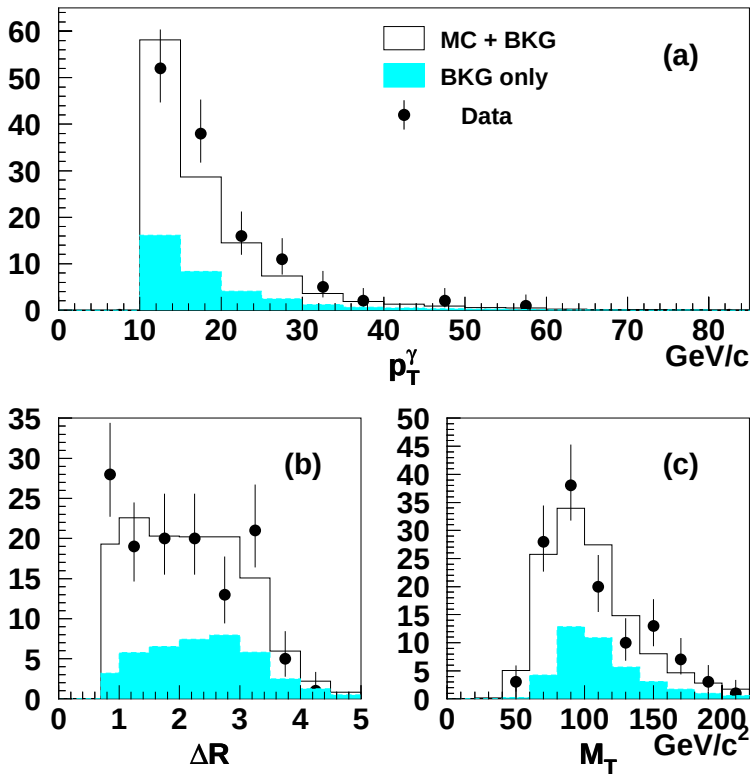
- Event Selection

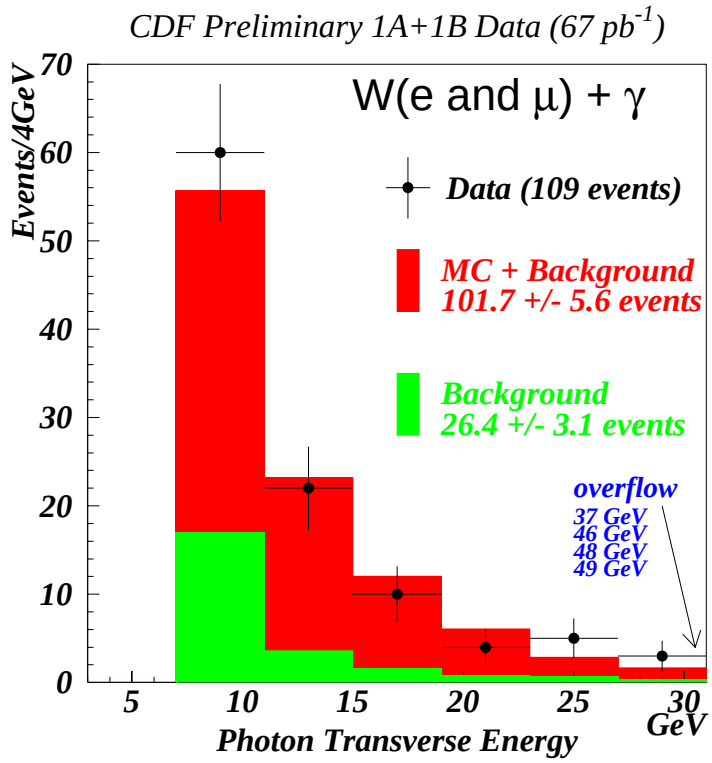
DØ ($\int \mathcal{L}dt = 89.1$ pb^{-1})		CDF ($\int \mathcal{L}dt \sim 67$ pb^{-1})	
$e\nu\gamma$	$\mu\nu\gamma$	$e\nu\gamma$	$\mu\nu\gamma$
$\lvert\eta_e\rvert < 1.1$	$\lvert\eta_\mu\rvert < 1.7$ (1a)	$\lvert\eta_e\rvert < 1.1$	$\lvert\eta_\mu\rvert < 0.6$
$1.5 < \lvert\eta_e\rvert < 2.5$	$\lvert\eta_\mu\rvert < 1.0$ (1b)		
$E_T^e > 25$ GeV	$p_T^\mu > 15$ GeV/c	$E_T^e > 20$ GeV	$p_T^\mu > 20$ GeV/c
$\not{E}_T > 25$ GeV	$\not{E}_T > 15$ GeV	$\not{E}_T > 20$ GeV	$\not{E}_T > 20$ GeV
$E_T^\gamma > 10$ GeV		$E_T^\gamma > 7$ GeV	
$\Delta R_{\ell\gamma} > 0.7$		$\Delta R_{\ell\gamma} > 0.7$	
$\lvert\eta^\gamma\rvert < 1.1, 1.5 < \lvert\eta^\gamma\rvert < 2.5$		$\lvert\eta^\gamma\rvert < 1.1$	

- Major Backgrounds
  - W+jets with a jet faking a photon
  - Zγ with one lepton undetected

- Results

	DØ ($\int \mathcal{L}dt = 89.1$ pb^{-1})		CDF ($\int \mathcal{L}dt \sim 67$ pb^{-1})	
	$e\nu\gamma$	$\mu\nu\gamma$	$e\nu\gamma$	$\mu\nu\gamma$
N_{data}	57	70	75	34
N_{BG}	15.2 ± 2.5	27.7 ± 4.7	16.1 ± 2.4	10.3 ± 1.2
N_{Signal}	41.8 ± 8.9	42.3 ± 9.7	58.9 ± 9.4	23.7 ± 6.0
$\sigma \cdot$ BR	$11.3^{+1.7}_{-1.5} \pm 1.4 \pm 0.6$ pb		$20.7 \pm 2.9 \pm 0.7$ pb	
$\sigma \cdot$ BR(SM)	12.5 ± 1.0 pb		18.6 ± 2.9 pb	

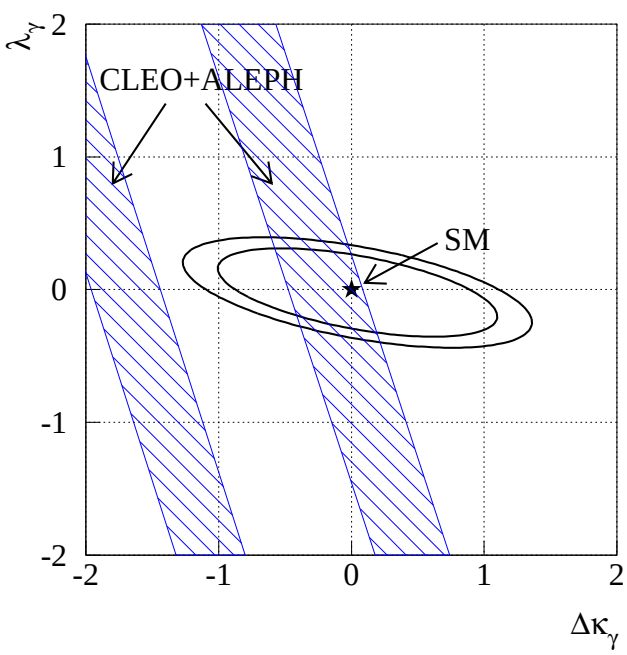

MC + BKG
BKG only
Data
(a)
p_T^γ
GeV/c
(b)
ΔR
(c)
M_T
GeV/c^2

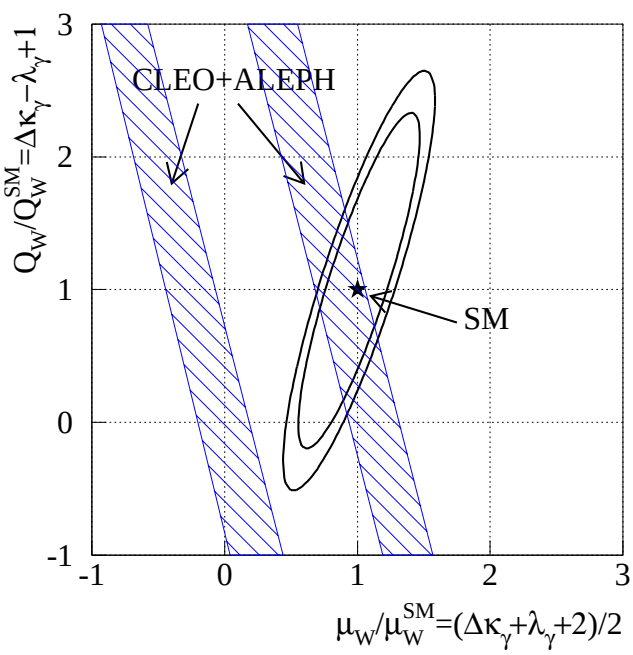

CDF Preliminary 1A+1B Data (67 pb^{-1})
W(e and μ) + γ
Data (109 events)
MC + Background
101.7 +/- 5.6 events
Background
26.4 +/- 3.1 events
overflow
37 GeV
46 GeV
48 GeV
49 GeV
Events/4GeV
Photon Transverse Energy
GeV

Limits on anomalous WWγ couplings

$\Lambda = 1.5\ TeV$	$\lambda_\gamma = 0$	$\Delta\kappa_\gamma = 0$
D0	$-0.93 < \Delta\kappa_\gamma < 0.94$	$-0.31 < \lambda_\gamma < 0.29$
CDF (preliminary)	$-1.8 < \Delta\kappa_\gamma < 2.0$	$-0.7 < \lambda_\gamma < 0.6$

D0 limits on λ_γ is the tightest single channel limit to date.





WW → dilepton

- Event Selection

	ee	$e\mu$	$\mu\mu$
DØ	$E_T^{e1} > 25$ GeV $E_T^{e2} > 20$ GeV $\not{E}_T > 25$ GeV $\lvert m_{ee} - m_Z \rvert < 15$ GeV/c^2	$E_T^{e} > 25$ GeV $p_T^{\mu} > 15$ GeV $\not{E}_T{}^{\text{cal}} > 25$ GeV $\not{E}_T > 20$ GeV	$p_T^{\mu 1} > 25$ GeV/c $p_T^{\mu 2} > 20$ GeV/c $\not{E}_T{}^{\eta} > 30$ GeV
	$20^\circ < \Delta\phi < 160^\circ$ for $\not{E}_T < 50$ GeV	$20^\circ < \Delta\phi < 160^\circ$ for $\not{E}_T < 50$ GeV	$\Delta\phi(\not{E}_T, p_T^{\mu 1}) < 160^\circ$
	$\lvert \vec{E}_T^{Had} \rvert < 40$ GeV		
CDF	$E_T^{e} > 20$ GeV $\not{E}_T > 25$ GeV $75 < m_{ee} < 105$ GeV/c^2	$E_T^{e} > 20$ GeV $p_T^{\mu} > 20$ GeV/c $\not{E}_T > 25$ GeV	$p_T^{\mu} > 20$ GeV/c $\not{E}_T > 25$ GeV $75 < m_{\mu\mu} < 105$ GeV/c^2
	$\Delta\phi(\not{E}_T, \ell) > 20^\circ$ for $\not{E}_T < 50$ GeV 0-jet with $E_T^{j} > 10$ GeV		

- Major Background
  - Drell-Yan (Z, γ)
  - tt
  - Wγ with a γ misidentified as an e (D0)
  - Z → ττ
  - W+jets with a jet misidentified as an e or μ

$$\vec{E}_T^{Had} = -(\vec{E}_T^{\ell 1} + \vec{E}_T^{\ell 2} + \vec{\not{E}_T})$$

WW → dilepton

- Detection Efficiencies

	ee	eμ	μμ
D0	6.5 ±0.4%	6.0 ±0.6%	1.9 ±0.2%
CDF	6.9 ±0.8%	8.9 ±1.1%	5.4 ±0.7%

- Results

	D0 ($\int$Ldt=96.6 pb $^{-1}$)	CDF ($\int$Ldt=108 pb $^{-1}$)
N_{data}	5	5
N_{BG}	3.3±0.4	1.2±0.3
N_{SM}	2.10±0.15	3.5±1.2

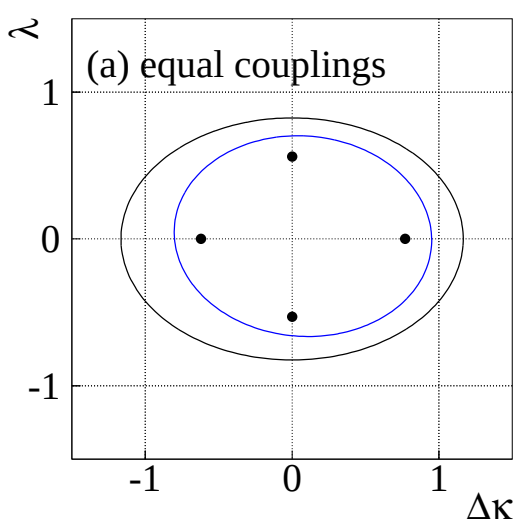
- Measurement of WW production cross section (CDF)

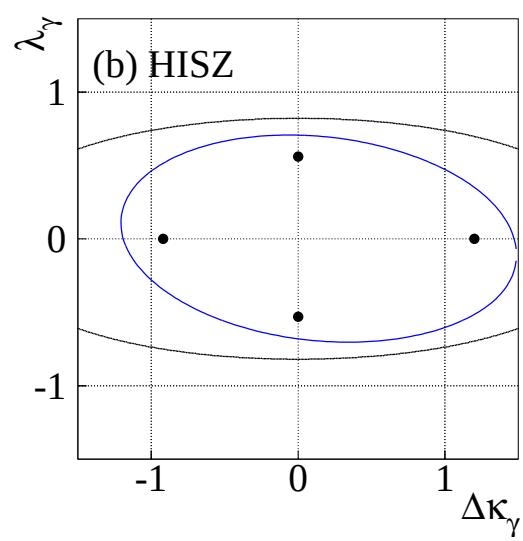
$$\sigma(\bar{p}p \to W^+W^-) = 10.2^{+6.3}_{-5.1}\ (\text{stat}) \pm 1.6\ (\text{syst})\ \text{pb}$$
$$\sigma(\bar{p}p \to W^+W^-)_{SM} = 9.5\ \text{pb}$$

WW → dilepton

- Limits on WWγ and WWZ couplings (D0)
  - A binned maximum likelihood fit to E_T of two leptons in the event
  - Competitive limits to WW/WZ semileptonic modes

	Λ = 1.5 TeV
$\lambda_\gamma=\lambda_Z$ ($\Delta\kappa_\gamma=\Delta\kappa_Z=0$)	-0.53, 0.56
$\Delta\kappa_\gamma=\Delta\kappa_Z$($\lambda_\gamma=\lambda_Z=0$)	-0.62, 0.77
λ_γ (HISZ) ($\Delta\kappa_\gamma=0$)	-0.53, 0.56
$\Delta\kappa_\gamma$(HISZ) ($\lambda_\gamma=0$)	-0.92, 1.20





WW/WZ → lνjj,lljj

- Event Selection

DØ ($\int \mathcal{L}dt = 96.0$ pb^{-1})	DØ ($\int \mathcal{L}dt = 80.7$ pb^{-1})	CDF ($\int \mathcal{L}dt = 110$ pb^{-1})
$e\nu jj$	$\mu\nu jj$	$e\nu jj, \mu\nu jj, eejj, \mu\mu jj$
$E_T^e > 25$ GeV	$p_T^\mu > 20$ GeV/c	$p_T^{e,\mu} > 20$ GeV/c
$\not\!\!E_T > 25$ GeV	$\not\!\!E_T > 20$ GeV	$\not\!\!E_T > 20$ GeV
$M_T^{e\nu} > 40$ GeV/c^2	$M_T^{\mu\nu} > 40$ GeV/c^2	$M_T^{e\nu,\mu\nu} > 40$ GeV/c^2
		or $70 < M_{ee,\mu\mu} < 110$ GeV/c^2
≥ 2 jets with $E_T^j > 20$ GeV		≥ 2 jets with $E_T^j > 30$ GeV
(cone size = 0.5)		(cone size = 0.4)
$50 < M_{jj} < 110$ GeV/c^2		$60 < M_{jj} < 110$ GeV/c^2
		$p_T^{jj} > 200$ GeV

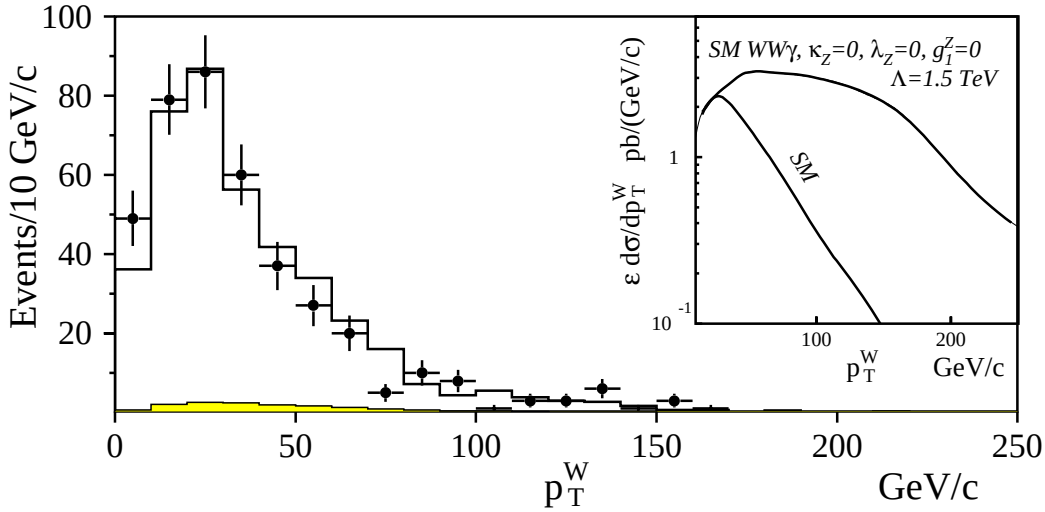
- Results

DØ	$e\nu jj$	$\mu\nu jj$
Luminosity	96.0 pb^{-1}	80.7 pb^{-1}
Backgrounds		
$W+ \geq 2$ jets	341.7 ± 38.3	117.1 ± 23.9
Multijet	116.5 ± 12.6	104.7 ± 19.3
others	4.6 ± 1.3	2.7 ± 1.2
Total	462.8 ± 40.4	224.5 ± 30.7
Data	483	224
SM $WW + WZ$ prediction	20.7 ± 3.1	$4.5^{+0.6}_{-0.8}$

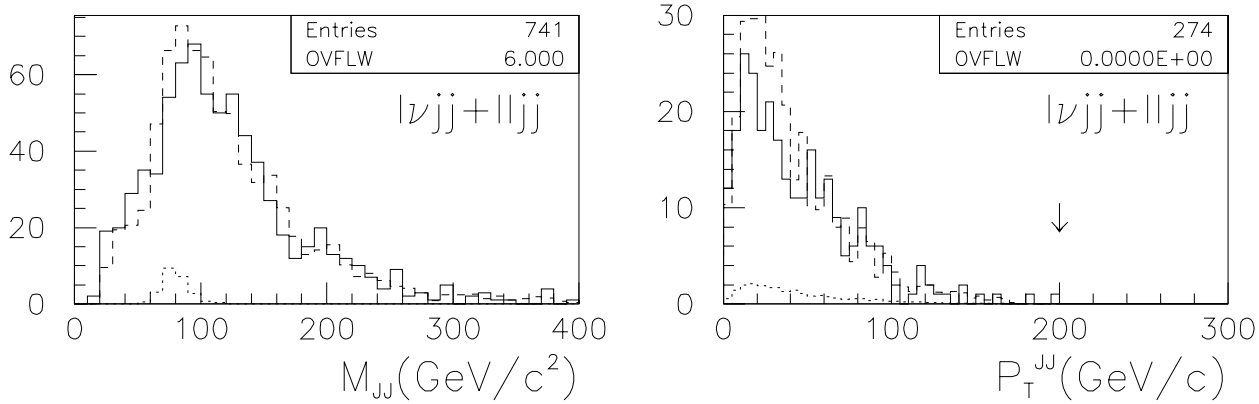
CDF (110 pb^{-1})	$\ell\nu jj$	$\ell\ell jj$
Before M_{jj} cut	294	47
After M_{jj} cut	0	0

Methods to set limits on anomalous couplings

- D0: A binned maximum likelihood fit to p_T^W spectrum



- CDF: Limits on the cross section from a high p_T^W cut where no background exists



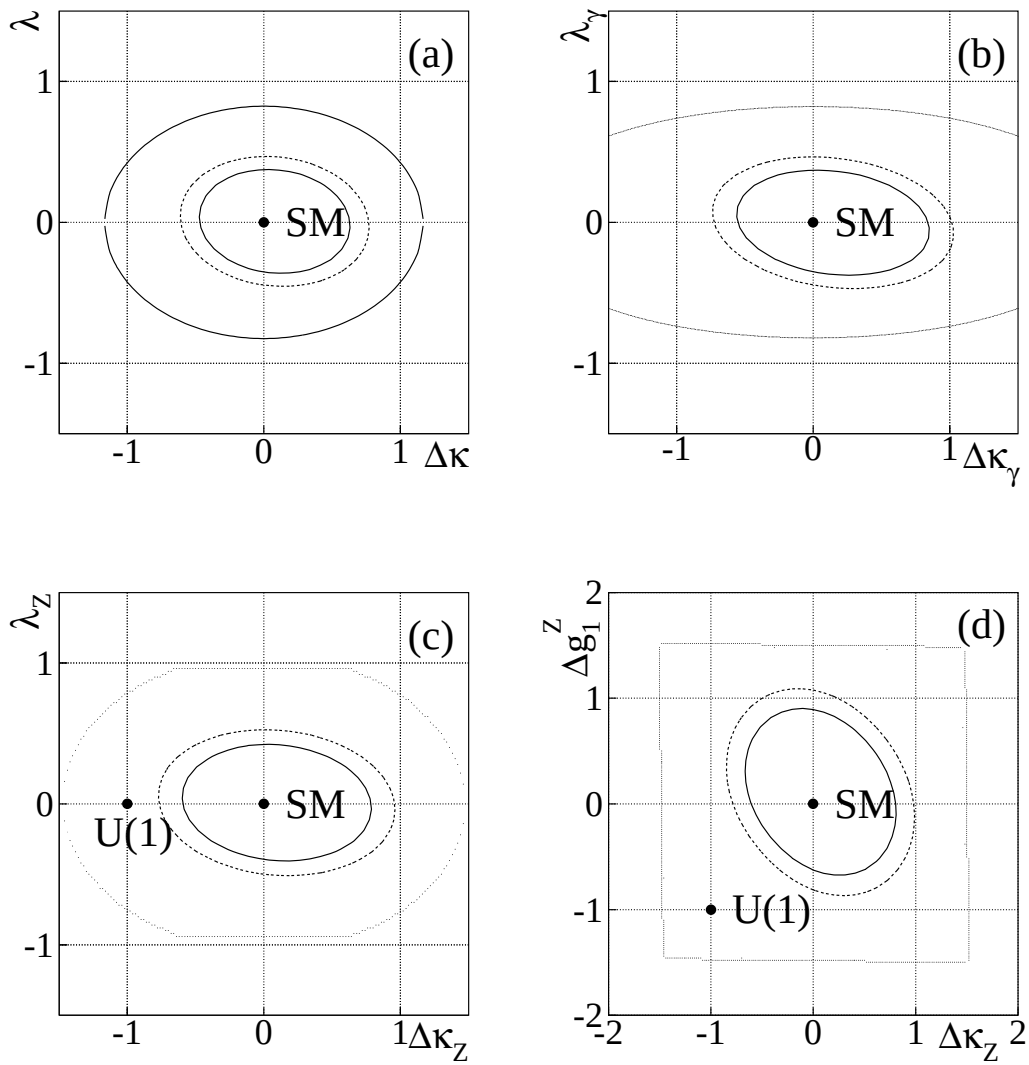
WW/WZ → lνjj,lljj

	DØ $e\nu jj$		DØ $\mu\nu jj$	
Couplings \Λ(TeV)	1.5	2.0	1.5	2.0
$\lambda_\gamma = \lambda_Z$	-0.36, 0.39	-0.33, 0.36	-0.44, 0.46	-0.42, 0.44
$\Delta\kappa_\gamma = \Delta\kappa_Z$	-0.47, 0.63	-0.43, 0.59	-0.60, 0.78	-0.58, 0.73
λ_γ HISZ	-0.36, 0.38	-0.34, 0.36	-0.44, 0.46	-0.42, 0.44
$\Delta\kappa_\gamma$ HISZ	-0.56, 0.85	-0.53, 0.78	-0.71, 0.99	-0.67, 0.95
λ_Z(SM $WW\gamma$)	-0.40, 0.43	-0.37, 0.40	-0.48, 0.51	-0.46, 0.48
$\Delta\kappa_Z$(SM $WW\gamma$)	-0.60, 0.79	-0.54, 0.72	-0.74, 0.91	0.69, 0.86
Δg_1^Z(SM $WW\gamma$)	-0.64, 0.89	-0.60, 0.81	-0.77, 0.99	-0.73, 0.94

	CDF	
Couplings \Λ(TeV)	1.0	2.0
$\lambda_\gamma = \lambda_Z$	-0.51, 0.51	-0.35, 0.32
$\Delta\kappa_\gamma = \Delta\kappa_Z$	-0.67, 0.85	-0.49, 0.54
λ_γ HISZ	-0.51, 0.52	-0.34, 0.33
$\Delta\kappa_\gamma$ HISZ	-0.83, 1.02	-0.61, 0.67
λ_Z(SM $WW\gamma$)	-0.60, 0.58	-0.37, 0.40
$\Delta\kappa_Z$(SM $WW\gamma$)	-0.95, 1.01	0.58, 0.68
Δg_1^Z(SM $WW\gamma$)	-0.91, 1.05	-0.61, 0.68

- U(1) point in the WWZ couplings plane is excluded at 99% CL.

WW/WZ → lνjj,lljj



(a) $\Delta\kappa \equiv \Delta\kappa_\gamma = \Delta\kappa_Z, \lambda \equiv \lambda_\gamma = \lambda_Z$
(b) HISZ relations are used.
(c) SM $WW\gamma$ couplings are assumed.
(d) SM $WW\gamma$ couplings are assumed.

WZ→trilepton (D0) (Preliminary)

- Event Selection

$eee\nu$	$ee\mu\nu$
$E_T^{e1} > 25$ GeV	$E_T^{e1} > 25$ GeV
$E_T^{e2} > 25$ GeV	$E_T^{e2} > 25$ GeV
$E_T^{e3} > 10$ GeV	$p_T^{\mu} > 15$ GeV/c
$\not{E}_T > 15$ GeV	$\not{E}_T > 15$ GeV
$81 < m_{i,j} < 101$ GeV	
$m_T(k, \not{E}_T) > 30$ GeV	

- Results

	$eee\nu$	$ee\mu\nu$
Luminosity (pb^{-1})	92.3 ± 4.9	
Backgrounds	$0.38 \pm 0.07 \pm 0.12$	$0.118 \pm 0.018 \pm 0.035$
SM prdiction	$0.146 \pm 0.002 \pm 0.011$	$0.099 \pm 0.001 \pm 0.008$
Data	1	0

- Limits

Λ=1.0 TeV

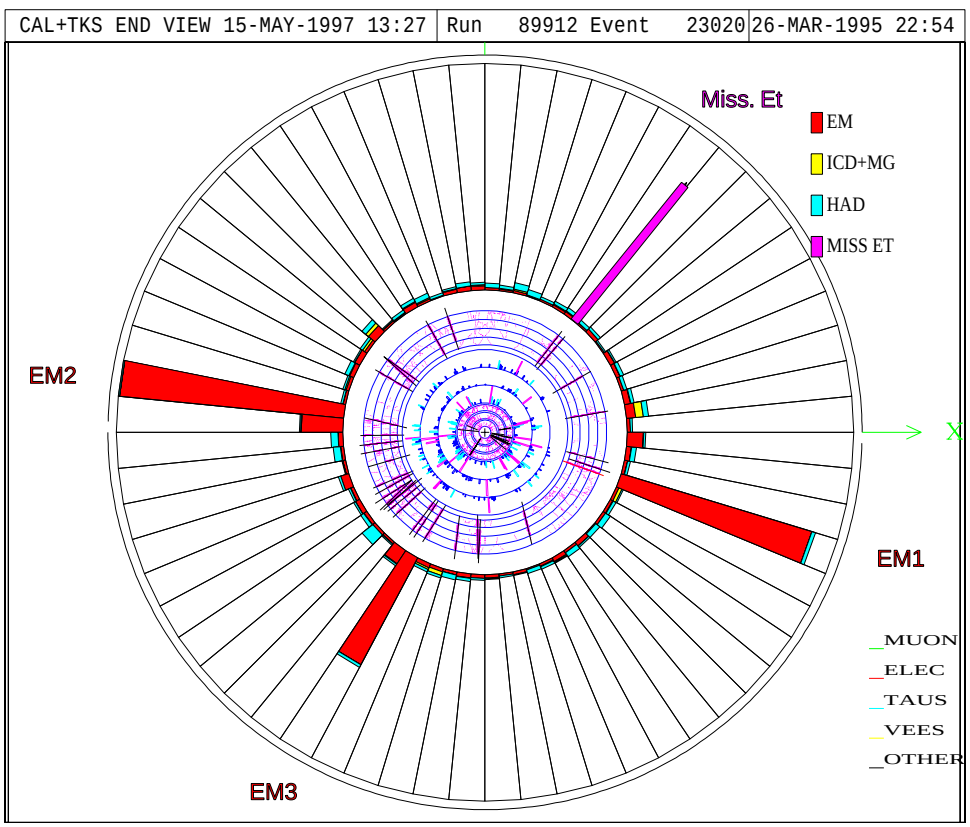
$|\Delta g_1^Z|<1.63$ for $\lambda_Z=0$

$|\lambda_Z|<1.42$ for $\Delta g_1^Z=0$

WZ→trilepton (D0) (Preliminary)

- Candidate

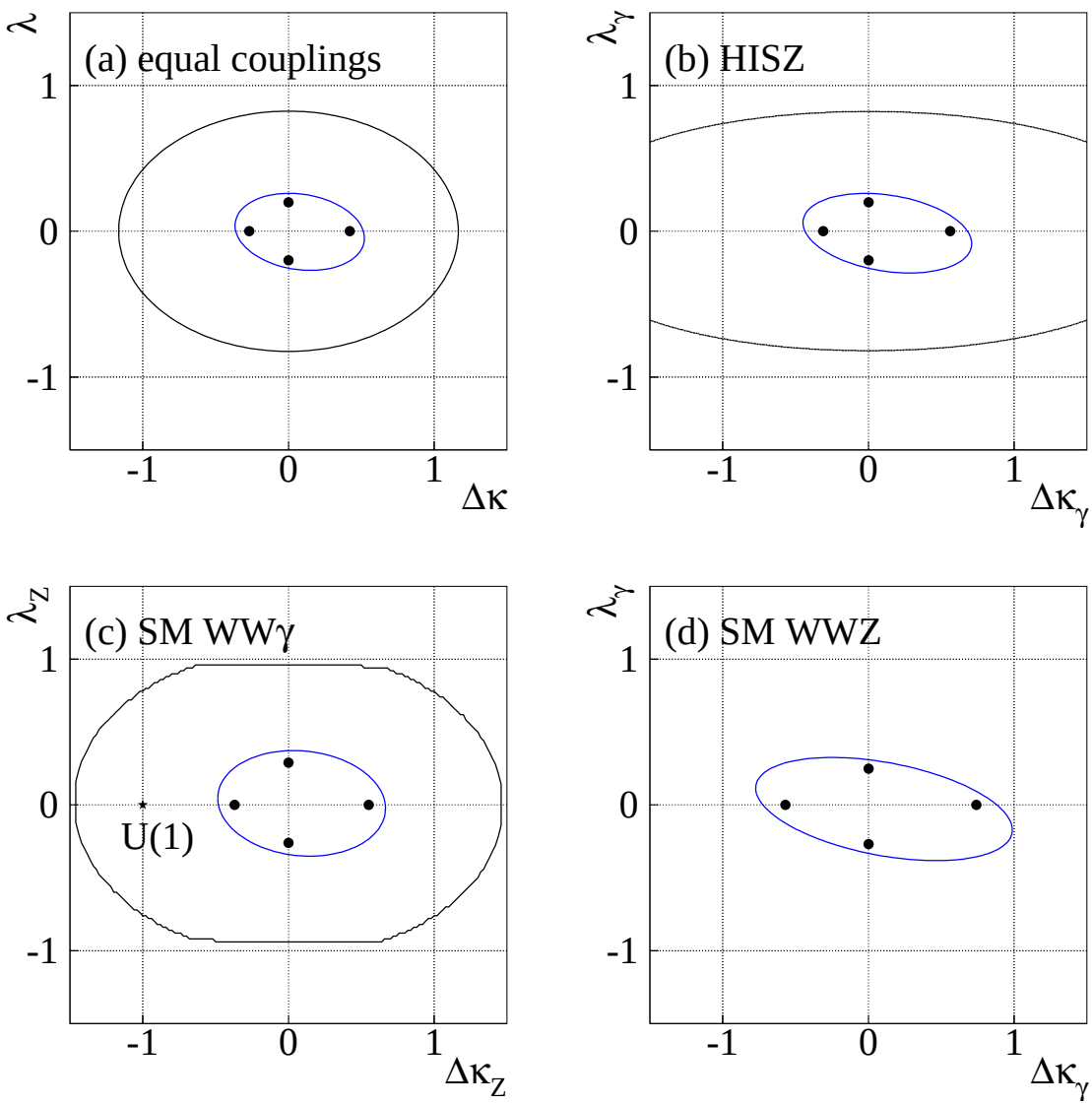
	$E_T(GeV)$	η	ϕ
e_1	54.5	0.11	5.94
e_2	50.9	-0.62	3.04
e_3	37.7	1.37	4.14
MET	46.2		1.29



$M_T(2)$=74.7 GeV M_{13}=93.6 GeV

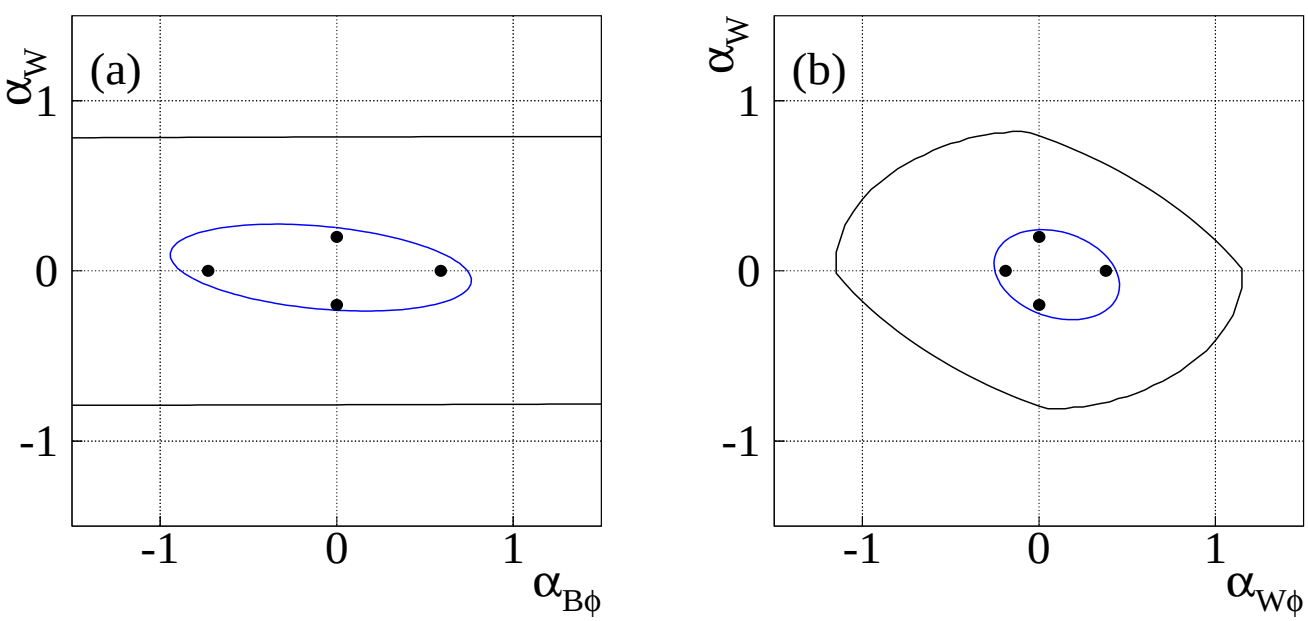
Limits on WWγ/WWZ couplings from combined fit (D0)

- Simultaneous fit to photon E_T of Wγ data samples, $p_T^{l\nu}$ of WW/WZ→lνjj data samples, and lepton E_T of WW → dilepton data samples.
- Correlated uncertainties such as the integrated luminosities and theoretical predictions are properly taken into account.

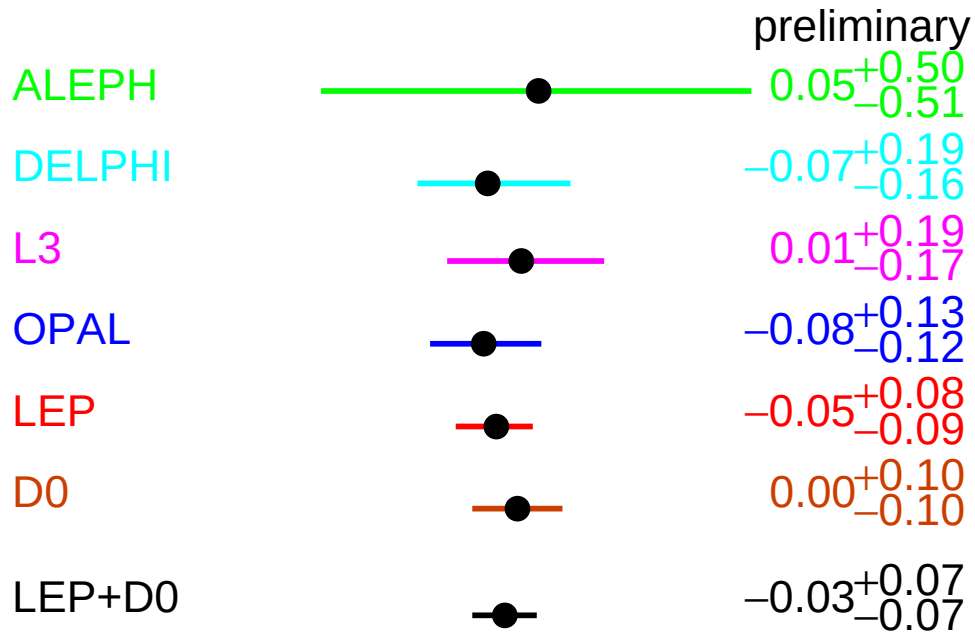


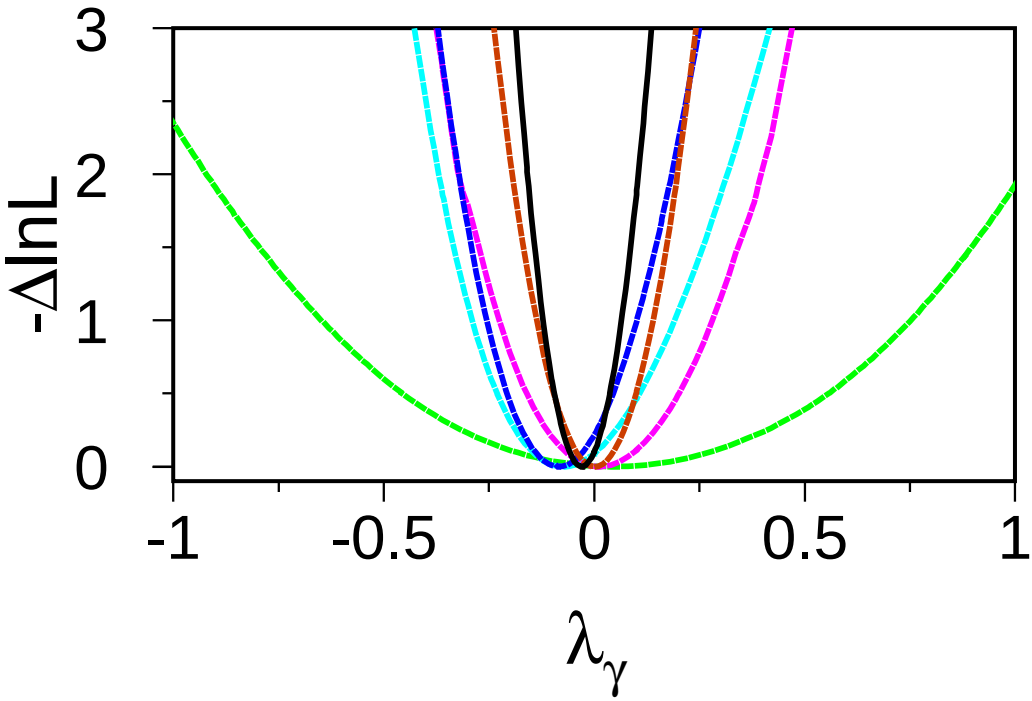
Λ	1.5 TeV	2.0 TeV
$\lambda_\gamma = \lambda_Z$ $(\Delta\kappa_\gamma = \Delta\kappa_Z = 0)$	$-0.20,\ 0.20$	$-0.18,\ 0.19$
$\Delta\kappa_\gamma = \Delta\kappa_Z$ $(\lambda_\gamma = \lambda_Z = 0)$	$-0.27,\ 0.42$	$-0.25,\ 0.39$
λ_γ(HISZ) $(\Delta\kappa_\gamma = 0)$	$-0.20,\ 0.20$	$-0.18,\ 0.19$
$\Delta\kappa_\gamma$(HISZ) $(\lambda_\gamma = 0)$	$-0.31,\ 0.56$	$-0.29,\ 0.53$
λ_Z(SM $WW\gamma$) $(\Delta\kappa_Z = \Delta g_1^Z = 0)$	$-0.26,\ 0.29$	$-0.24,\ 0.27$
$\Delta\kappa_Z$(SM $WW\gamma$) $(\lambda_Z = \Delta g_1^Z = 0)$	$-0.37,\ 0.55$	$-0.34,\ 0.51$
Δg_1^Z(SM $WW\gamma$) $(\lambda_Z = \Delta\kappa_Z = 0)$	$-0.39,\ 0.62$	$-0.37,\ 0.57$
λ_γ(SM WWZ) $(\Delta\kappa_\gamma = 0)$	$-0.27,\ 0.25$	$-0.25,\ 0.24$
$\Delta\kappa_\gamma$(SM WWZ) $(\lambda_\gamma = 0)$	$-0.57,\ 0.74$	$-0.54,\ 0.69$

Λ	1.5 TeV	2.0 TeV	OPAL
$\alpha_{B\phi}$ $(\alpha_{W\phi} = \alpha_W = 0)$	$-0.73,\ 0.59$	$-0.67,\ 0.56$	$-1.6,\ 2.7$
$\alpha_{W\phi}$ $(\alpha_{B\phi} = \alpha_W = 0)$	$-0.19,\ 0.38$	$-0.18,\ 0.36$	$-0.55,\ 0.64$
α_W $(\alpha_{B\phi} = \alpha_{W\phi} = 0)$	$-0.20,\ 0.20$	$-0.18,\ 0.19$	$-0.78,\ 1.19$
Δg_1^Z $(\alpha_{B\phi} = \alpha_W = 0)$	$-0.25,\ 0.49$	$-0.23,\ 0.47$	$-0.75,\ 0.77$



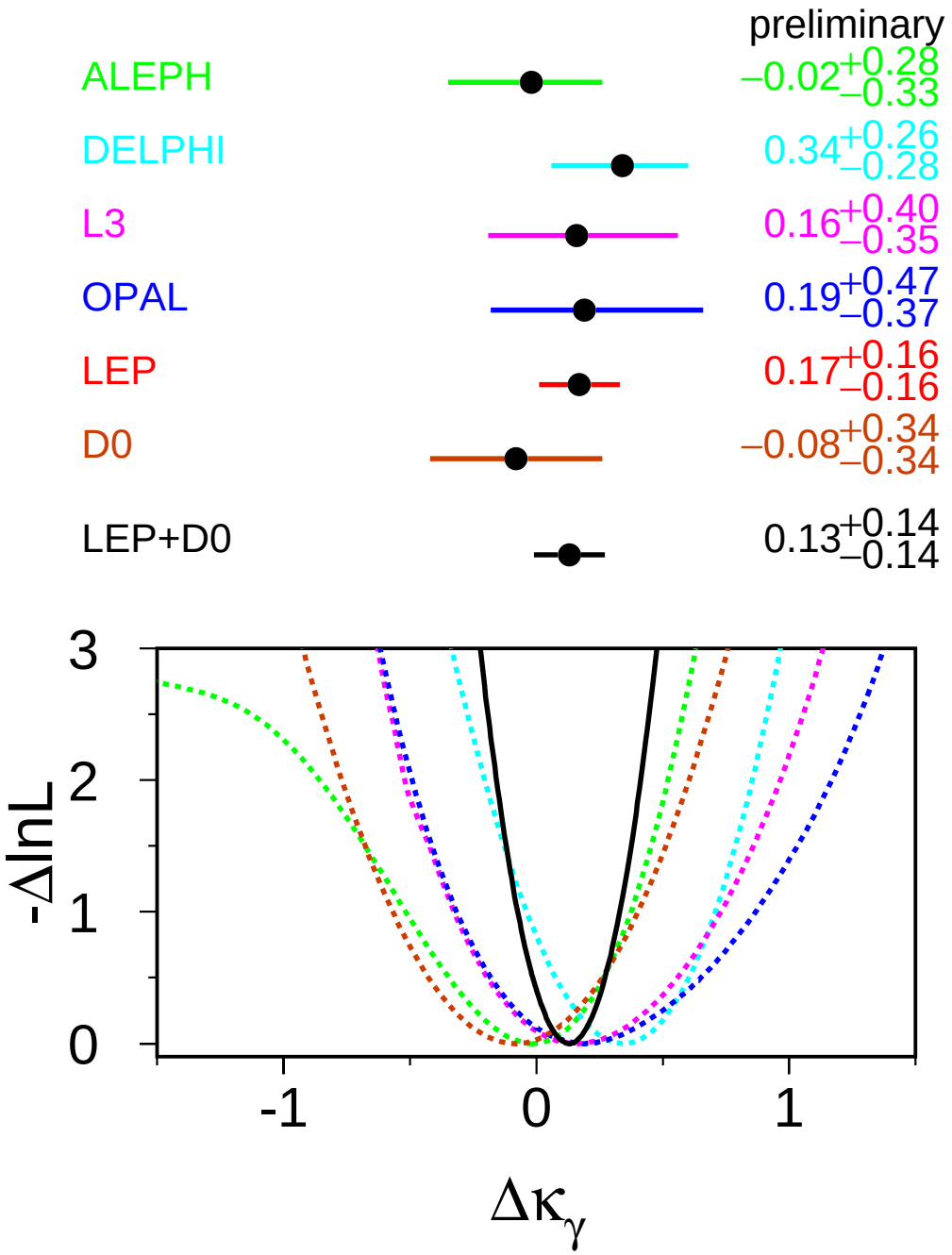
D0 + LEP combined limits





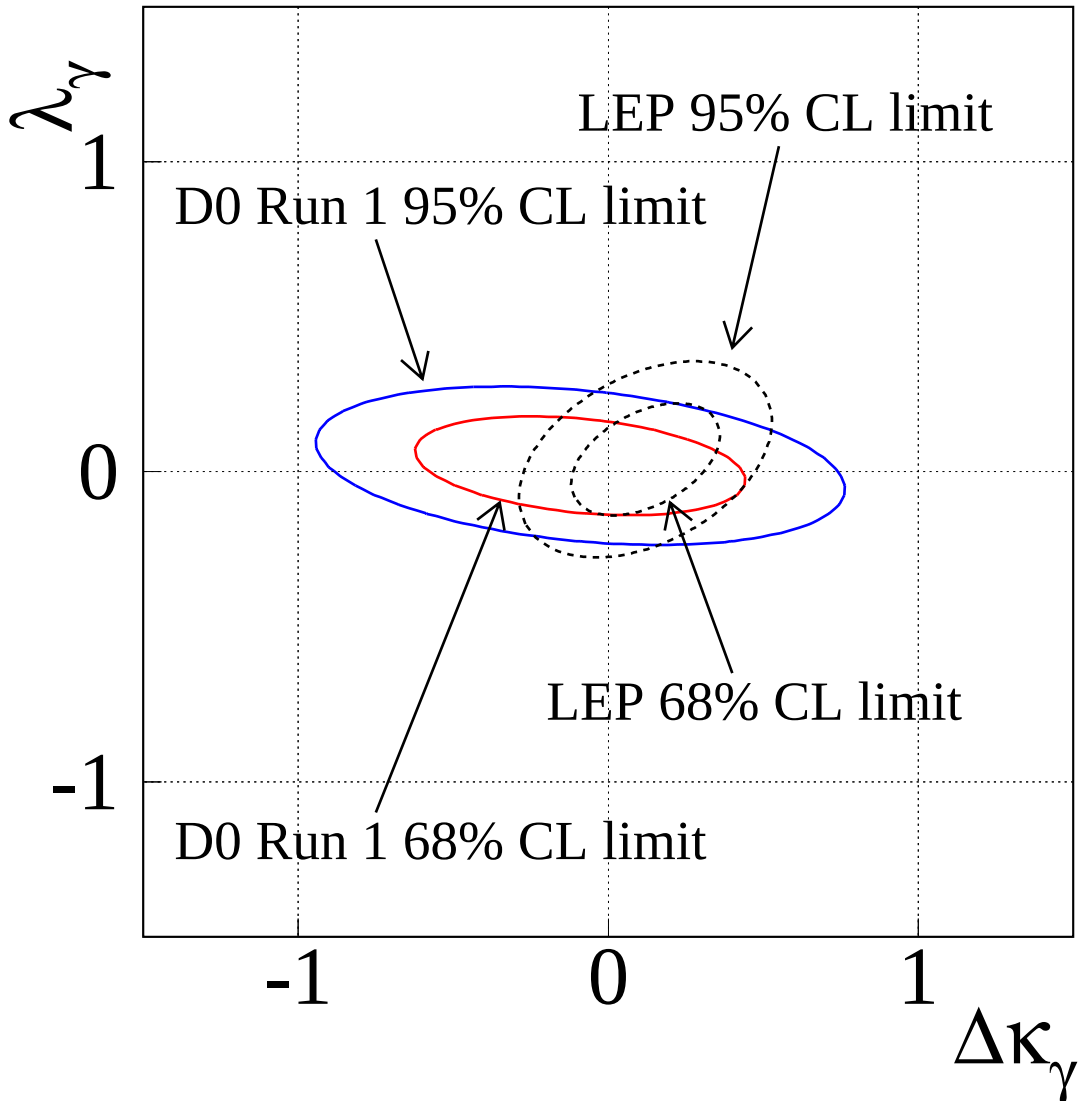
One σ (68% CL) errors are quoted in this plot.

D0 + LEP combined limits



One σ (68% CL) errors are quoted in this plot.

D0 - LEP comparison



Zγ→eeγ, μμγ

- Event Selection

DØ ($\int \mathcal{L}dt = 103$ pb^{-1})	
$ee\gamma$	$\mu\mu\gamma$
$\lvert\eta_e\rvert < 1.1$, $1.5 < \lvert\eta_e\rvert < 2.5$	$\lvert\eta_\mu\rvert < 1.0(2.4)$ (Run 1b)
$E_T^e > 20$ GeV	$p_T^{\mu 1} > 15$ GeV/c
	$p_T^{\mu 2} > 8(10)$ GeV/c (Run 1b)
$E_T^\gamma > 10$ GeV	
$\Delta R_{\ell\gamma} > 0.7$	
$\lvert\eta^\gamma\rvert < 1.1, 1.5 < \lvert\eta^\gamma\rvert < 2.5$	

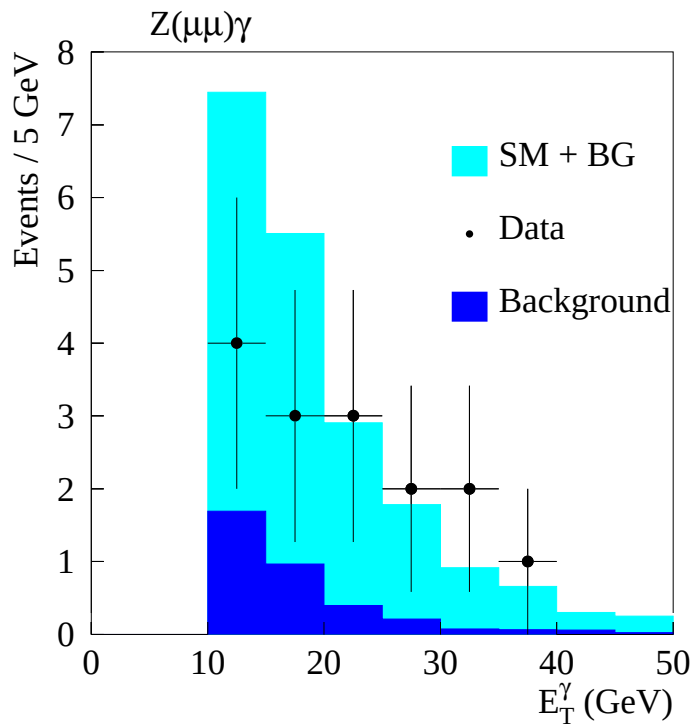
CDF ($\int \mathcal{L}dt \sim 67$ pb^{-1})	
$ee\gamma$	$\mu\mu\gamma$
$\lvert\eta_{e1}\rvert < 1.1$, $\lvert\eta_{e2}\rvert < 4.2$	$\lvert\eta_{\mu 1}\rvert < 0.6$, $\lvert\eta_{\mu 2}\rvert < 1.2$
$E_T^{e1} > 20$ GeV	$p_T^{\mu 1,2} > 20$ GeV/c
$E_T^{e2} > 20, 15, 10$ GeV	
$E_T^\gamma > 7$ GeV	
$\Delta R_{\ell\gamma} > 0.7$	
$\lvert\eta^\gamma\rvert < 1.1$	

- Major background sources
  - Z+jets with a jet faking a photon
  - multijet and direct photon + jets

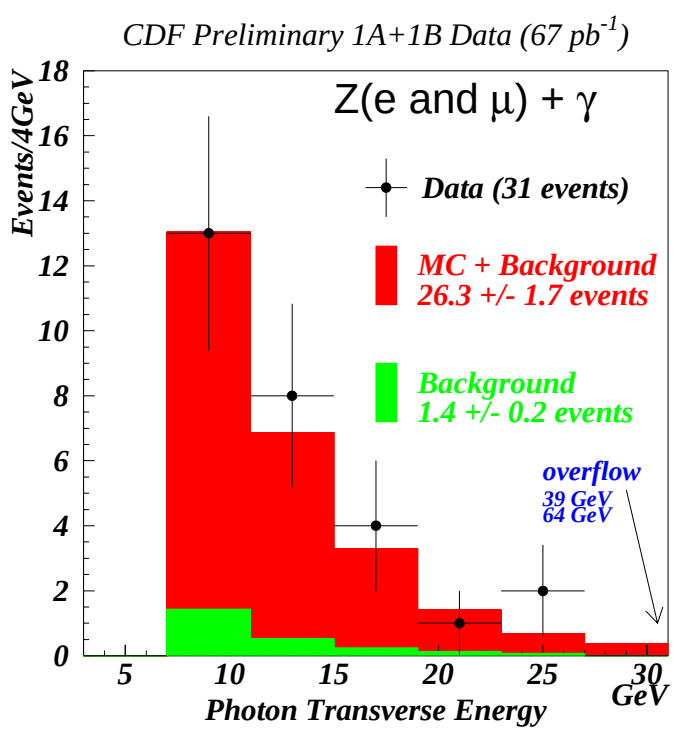
Zγ→eeγ, μμγ

- Results

	DØ ($\int \mathcal{L}dt = 103$ pb^{-1})	
	$ee\gamma$	$\mu\mu\gamma$
N_{data}	18	17
N_{BG}	2.2 ± 0.5	3.7 ± 0.7
N_{Signal}	15.8 ± 4.3	13.3 ± 4.2

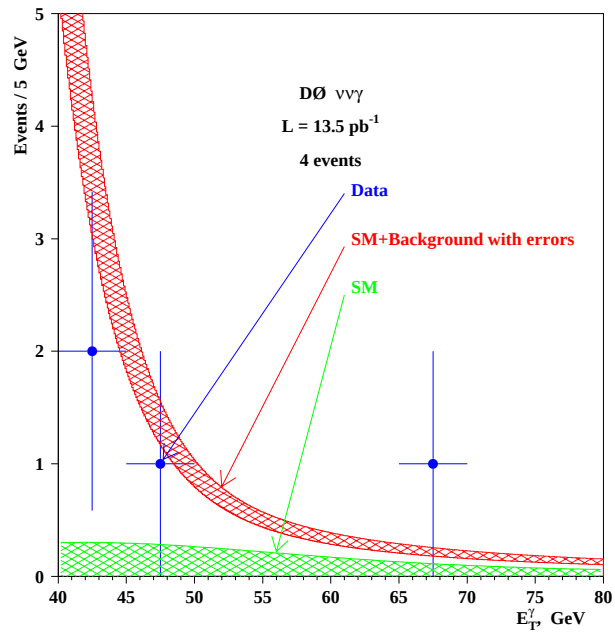


	CDF ($\int \mathcal{L}dt \sim 67$ pb^{-1})	
	$ee\gamma$	$\mu\mu\gamma$
N_{data}	18	13
N_{BG}	0.9 ± 0.3	0.5 ± 0.1
N_{Signal}	17.1 ± 5.7	12.5 ± 3.6



$Z\gamma \rightarrow \nu\nu\gamma$ (D0)

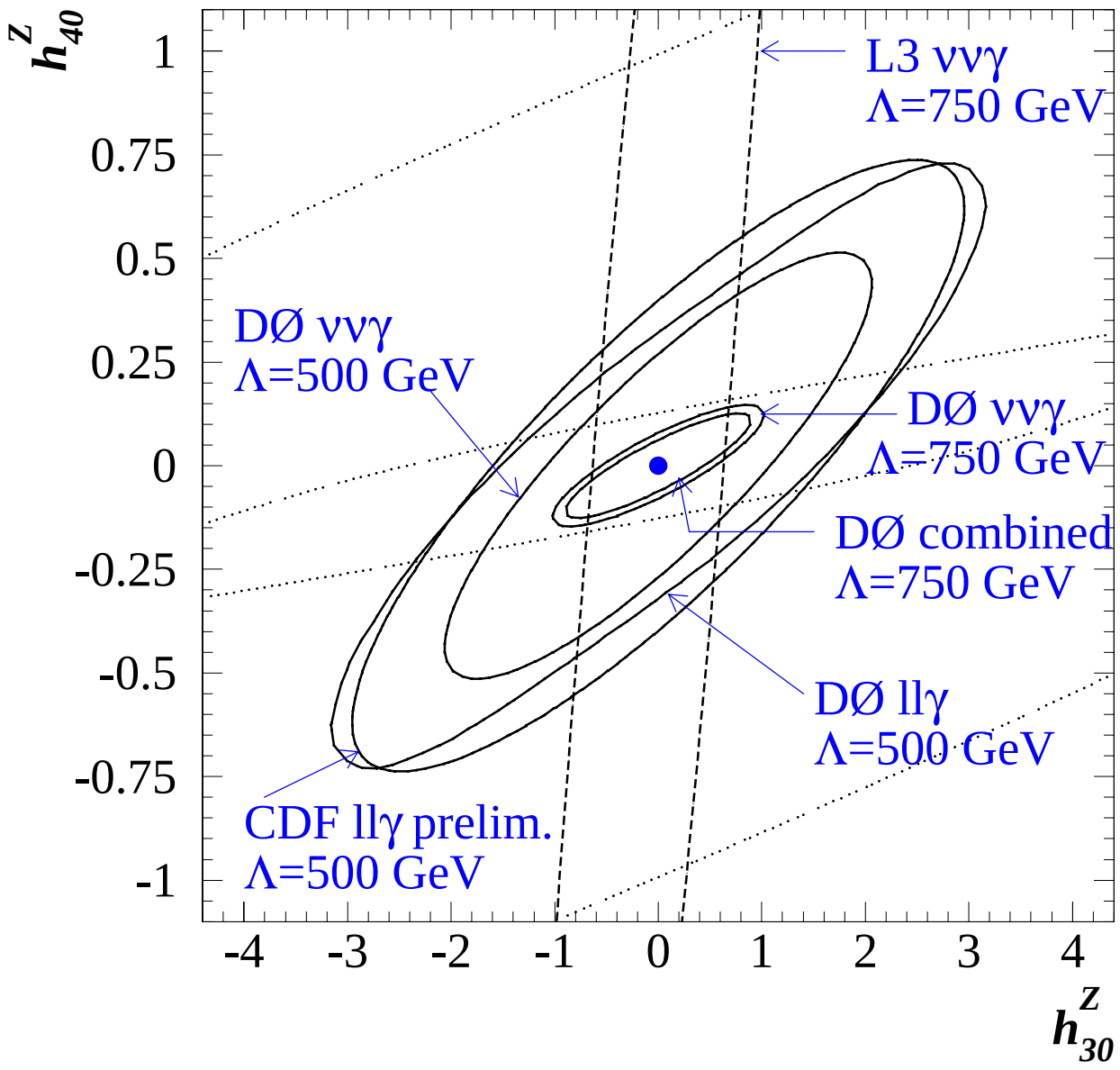
- Advantages over $ee\gamma$, $\mu\mu\gamma$
  - A higher branching ratio
    20 % vs 3.4 + 3.4 %
  - No radiative contributions
- Event selection
  - missing $E_T > 40$ GeV
  - $E_T^{\gamma} > 40$ GeV
    $|\eta_\gamma| < 1.1$
    or $1.5 < |\eta_\gamma| < 2.5$



- Backgrounds
  - Bremsstrahlung from cosmic or beam halo muons
  - $W \rightarrow e\nu \rightarrow$ "γ"ν

D0 1a ($\int Ldt$ = 13.5 pb $^{-1}$)	
$N_{candidate}$	4
Muon background	1.8±0.6
$W \rightarrow e\nu$ background	4.0±0.8
$jj+j\gamma$ background	<0.6
Total	5.8±1.0
N_{SM}	1.8±0.2

Zγ Limit contours



Summary of ZZγ and Zγγ couplings measurements

- D0 limits
  - Run 1a eeγ, μμγ, ννγ + Run 1b eeγ, μμγ
  - Cutoff scale: Λ = 0.75 TeV

	Limits
$\lvert h_{30}^{\gamma}\rvert$	<0.37
$\lvert h_{30}^{Z}\rvert$	<0.36
$\lvert h_{40}^{\gamma}\rvert$	<0.05
$\lvert h_{40}^{Z}\rvert$	<0.05

- CDF limits
  - Run 1a+1b eeγ, μμγ
  - Cutoff scale: Λ = 0.5 TeV

	Limits
$\lvert h_{30}^{\gamma}\rvert$	<1.6
$\lvert h_{30}^{Z}\rvert$	<1.6
$\lvert h_{40}^{\gamma}\rvert$	<0.4
$\lvert h_{40}^{Z}\rvert$	<0.4

What should we expect?

- SM Loop Correction in units of 10^{-3}
  - Argyres et al., hep-ph/9603362

m_ϕ	100 GeV	300 GeV
λ_γ	-0.7	-0.6
$\Delta\kappa_\gamma$	-3.7	-4.7
λ_Z	-0.7	-0.6
$\Delta\kappa_Z$	-5.4	-2.9

- MSSM Loop Correction in units of 10^{-3}
  - Argyres et al., hep-ph/9603362

$A_0,m_0,M_{1/2}$	300,300,80 GeV		300,300,300 GeV		0,0,300 GeV	
	$\mu > 0$	$\mu < 0$	$\mu > 0$	$\mu < 0$	$\mu > 0$	$\mu < 0$
λ_γ	-1.2	-0.4	-0.7	-0.7	-0.7	-0.7
$\Delta\kappa_\gamma$	-3.9	-4.2	-3.8	-3.9	-3.9	-3.9
λ_Z	+0.5	+1.5	-0.4	-0.5	-0.4	-0.4
$\Delta\kappa_Z$	-6.4	-6.7	+6.0	-5.0	-5.1	-5.0

- Estimated limits in Run II

	λ	$\Delta\kappa$	h_{30}^V	h_{40}^V
100 pb^{-1}	0.2	0.4	0.4	0.05
1 fb^{-1}	0.06	0.12	0.12	0.02
10 fb^{-1}	0.02	0.04	0.04	0.005

What should we expect?

- SM Higgs boson production at Tevatron
  LEP direct + indirect limits on SM Higgs mass
  $80 < m_\phi < 250$ GeV
  $\sigma \cdot Br(pp \rightarrow \phi \rightarrow WW) \approx 0.1$ pb for $m_\phi = 190$ GeV
  $\Rightarrow$ 100 times smaller than the SM WW production

- Expected numbers of events in Run II

	SM WW		**$\phi \rightarrow$WW**	
	lνjj	lνl'ν'	lνjj	lνl'ν'
1 fb^{-1}	140	40	1.4	0.4
10 fb^{-1}	1400	400	14	4

  – If we get 30 fb^{-1}, 3-5 σ signal observation is possible.
    Tao Han and Ren-Jie Zhang, hep-ph/9807424

Summary

- Measurement of trilinear gauge boson couplings, using gauge boson pair production processes, is a crucial test of the Standard Model.

- In all of the processes studied ($W\gamma$, WW, WZ, $Z\gamma$), observations are consistent with the SM prediction.

- Tevatron and LEP experiments are complementary in probing the trilinear gauge boson couplings; different final states and at different CM energies.

- Run II will be an excellent opportunity to nail down trilinear gauge boson couplings.