Diboson Production at the Tevatron

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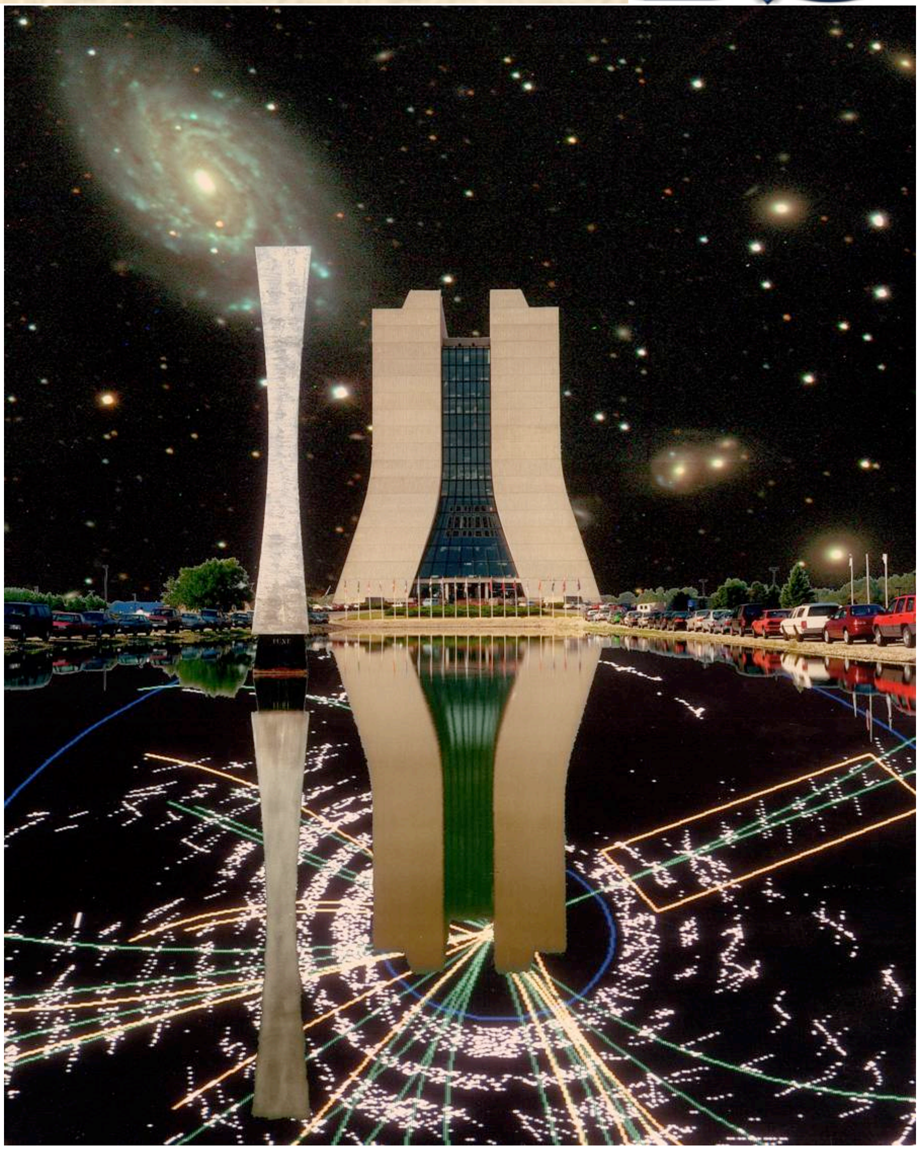
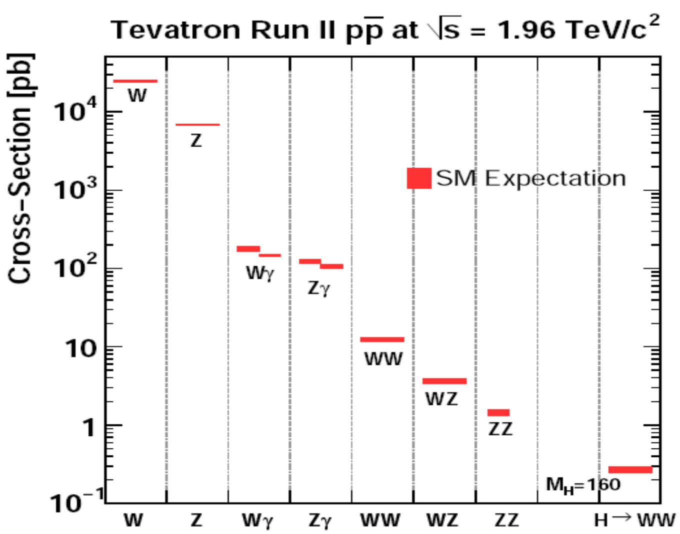


Introduction

- **Tevatron diboson program:** **measure production cross sections, study kinematics and probe gauge boson self-interactions.**
- **Diboson production is one of the least tested areas of the SM.**
- **Triple gauge vertices are difficult to access with other than diboson production processes. They are expected to be sensitive to physics beyond the SM.**
- **Tevatron complementary to LEP:** **explores higher energies and different combinations of couplings.**
- **Even in the SM, diboson production is an important process to understand:** **it shares many characteristics and is a background to Higgs and SUSY.**



What's in 1 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV?

$\approx$ 5,000,000 $W \to l\nu$
$\approx$ 500,000 $Z \to ll$
$\approx$ 32000 $W\gamma \to l\nu\gamma$
$\approx$ 8000 $Z\gamma \to ll\gamma$
$\approx$ 3700 $WW \to l\nu jj$
$\approx$ 550 $WW \to ll\nu\nu$
$\approx$ 50 $WZ \to lll\nu$
$\approx$ 6 $ZZ \to llll$
where l=e or μ

Introduction

- **Excursions from the SM can be described via effective Lagrangian:**

$$L_{WWV}/g_{WWV} = g_V^1 (W^+_{\mu\nu} W^{\mu} V^{\nu} - W^+_{\mu} V_{\nu} W^{\mu\nu}) + \kappa_V W^+_{\mu} W_{\nu} V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W^+_{\lambda\mu} W^{\mu}_{\nu} V^{\nu\lambda}$$

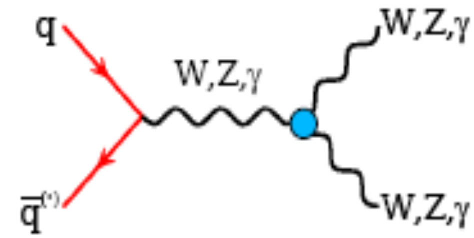
where $V = Z, \gamma$

In SM: $g_V^1 = \kappa_V = 1, \quad \lambda_V = 0$

- **Anomalous Triple Gauge Copuling's (TGC) increase production cross sections, particularly at high values of the boson E_T ($W / Z / \gamma$).**

- **Unitarity violation avoided by introducing a form-factor scale Λ, modifying the anomalous coupling at high energy:**

$$\lambda(\hat{s}) = \frac{\lambda}{(1 + \hat{s}/\Lambda^2)^n}$$



$q\bar{q}' \to W^{(*)} \to W\gamma$: $WW\gamma$ only

$q\bar{q}' \to W^{(*)} \to WZ$: WWZ only

$q\bar{q} \to Z/\gamma^{(*)} \to WW$: $WW\gamma, WWZ$

$q\bar{q} \to Z/\gamma^{(*)} \to Z\gamma$: $ZZ\gamma, Z\gamma\gamma$

$q\bar{q} \to Z/\gamma^{(*)} \to ZZ$: $ZZ\gamma, ZZZ$

Absent in SM

- **Two types of effective Lagrangians with:**

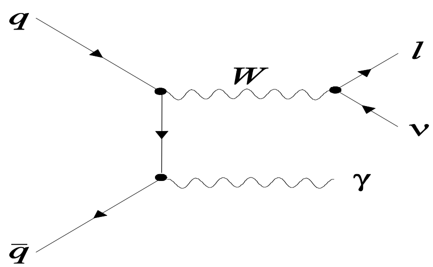
on-shell Zγ ($Z\gamma Z^*, Z\gamma\gamma^*$)		**on-shell ZZ ($ZZZ^*, ZZ\gamma^*$)**
h_{10}^V, h_{20}^V	**(CP violating)**	f_{40}^V
h_{30}^V, h_{40}^V	**(CP conserving)**	f_{50}^V

SM predicts all to be 0

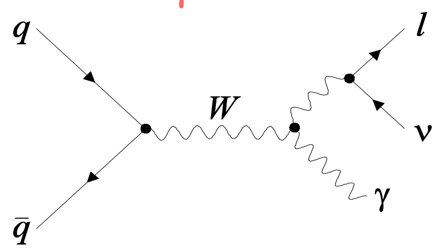
Wγ analysis at DØ

- **Three main diagrams for Wγ production at the Tevatron:**

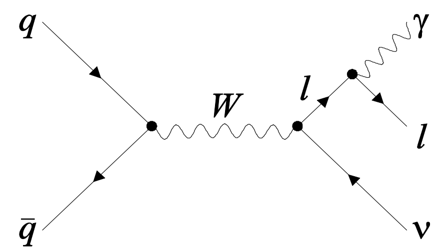
Initial State Radiation



WWγ Vertex



Final State Radiation

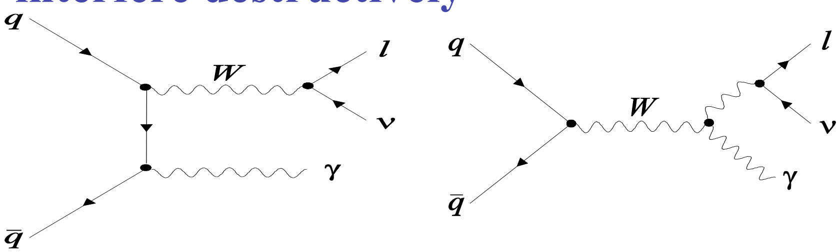


- **Deviation from the SM prediction would be a sign of new physics**
  - **Particularly at high p_T region of photon**
  - **Sensitive to WWγ coupling**
  - **Interference of photons radiated from quark and W lines yield a peculiar experimental feature**
- **Basic W$\gamma \rightarrow l\,\upsilon\,\gamma$ event selection ($l = e, \mu$):**
  - **High p_T electron or muon and high E_T^{miss}**
  - **E_T^{γ} > 9 GeV either in Central (|η|<1.1) or Endacp (1.5 < |η|<2.5) calorimeter**
  - **dR(l,γ) > 0.7**
  - **$M_T(l\upsilon\gamma)$ > 110 (120) GeV**

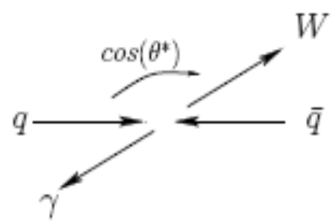
  } **To reduce FSR contribution**
- **Main background processes:** **W+jets, "*l*eX"– events with *l* and e faking γ, W(→τ υ)γ, Zγ.**

Wγ analysis: Radiation Amplitude Zero

- **Photons radiated from quark and W lines interfere destructively**

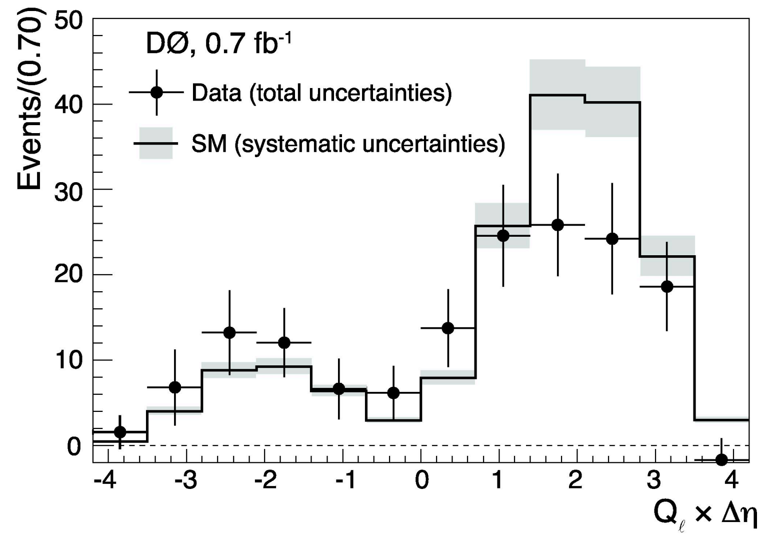


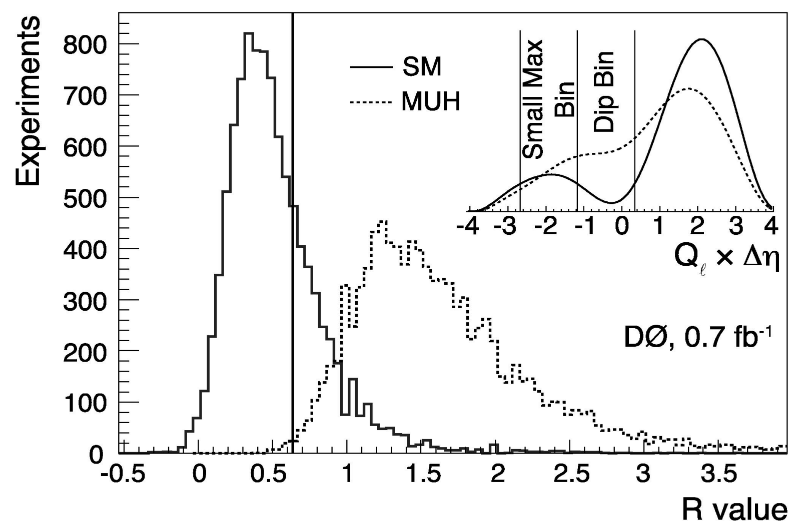
- **Zero amplitude at**
  - **$\cos\theta^* = +1/3$ for u dbar $\rightarrow W^+\gamma$**
  - **$\cos\theta^* = -1/3$ for d ubar $\rightarrow W^-\gamma$**



- **No measurement of p_z of ν: use $Q_l \times (\eta_\gamma - \eta_l)$ to observe "dip" in the distribution**
- **Non-SM coupling may fill the "dip"**

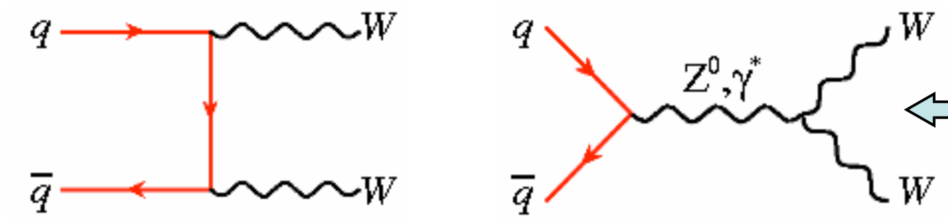
- **DØ: No dip hypothesis ruled out at 2.6 σ level ⇒ constitutes first indication for radiation-amplitude zero in *Wγ*.**





PRL 100, 241805 (2008)

WW→$l\nu l\nu$ production



Sensitive to WWZ / WWγ couplings

- **Dilepton channel provides cleanest signature:** ee, μμ or eμ accompanied by missing E_T
- **Main background processes:** W+j/γ, dijet, Drell-Yan, top pairs, WZ, ZZ
- **Theory prediction for production cross section is 12.0-13.5 pb** *(J. Ohnemus, PRD 50, 1931 (1994); J.M. Campbell and R.K. Ellis, PRD 60, 113006 (1999))* — **accessible at Tevatron Run II already with a couple of 100 pb^{-1}.**

- **Cross section measurements**
  - **DØ, $L \approx 1\ fb^{-1}$**, arXiv.org:0904.0673

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

  - **CDF, $L \approx 3.6\ fb^{-1}$, preliminary**

    $$\sigma = 12.1 \pm 0.9(\text{stat})^{+1.6}_{-1.4}(\text{sys})\ \text{pb}$$

WW $\rightarrow l\nu l\nu$ production: probing WWZ and WWγ couplings

- Use p_T spectra of leptons to probe WWZ and WWγ couplings:
  - Non-SM TGC enhances cross-section at high p_T.

- Test various assumptions for WWZ and WWγ coupling relations:
  - equal couplings $\Delta\kappa_Z = \Delta\kappa_\gamma,\ \Delta g_1^Z = \Delta g_1^\gamma = 1,$ and $\lambda_\gamma = \lambda_Z$

$-0.12 < |\Delta\kappa| < 0.35$
$-0.14 < |\lambda| < 0.18$

(Λ_{NP}=2 TeV)

  - HISZ parametrization: imposes SU(2)×U(1) symmetry on the coupling parameters

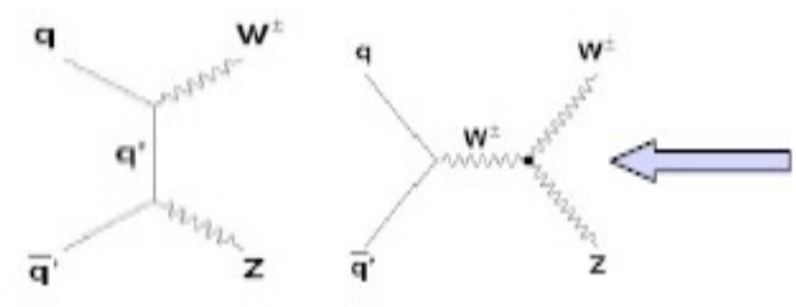
DØ

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

CDF

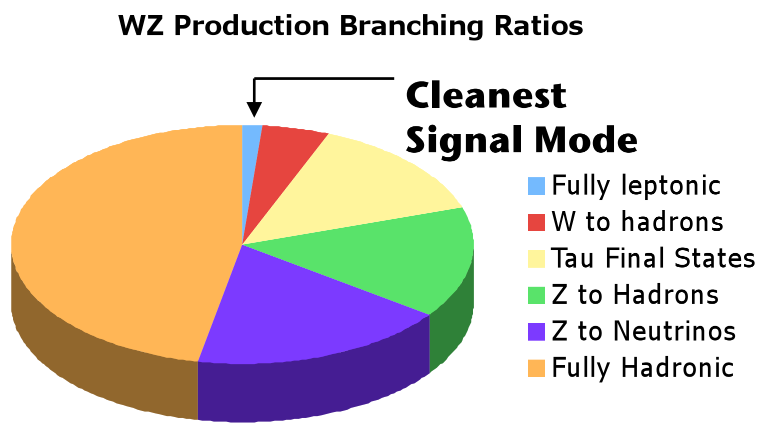
$-0.57 < |\Delta\kappa_\gamma| < 0.65$
$-0.14 < |\lambda| < 0.15$
$-0.22 < |\Delta g_1^Z| < 0.30$

WZ → $lll\nu$ production



- **Sensitive to WWZ coupling only**
  (WW is sensitive to both WWZ and WWγ).
- **WZ production is unavailable at e^+e^- colliders.**

- **Search for WZ production in 3 leptons (eee,eeμ, eμμ, μμμ) + missing E_T**
- **Distinct, but rare signature:**
  - **σ(ppbar→WZ) = 3.7 ± 0.1 pb**
  - **Branching fraction ~1.5%**
- **Background processes: Z+jet(s), ZZ, Zγ, ttbar production**

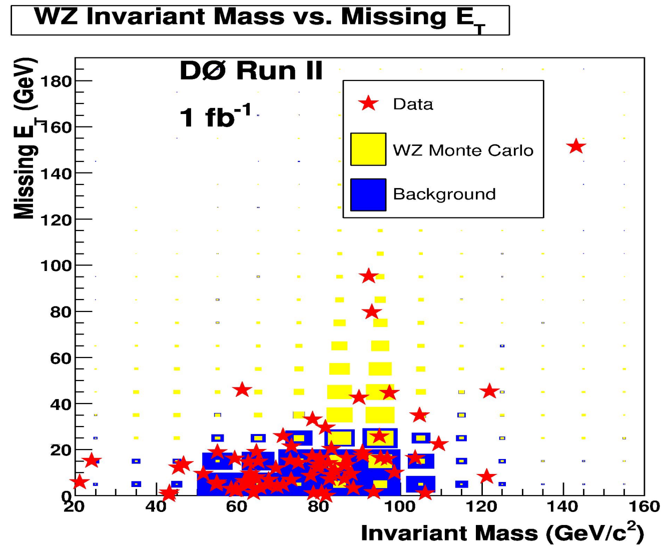


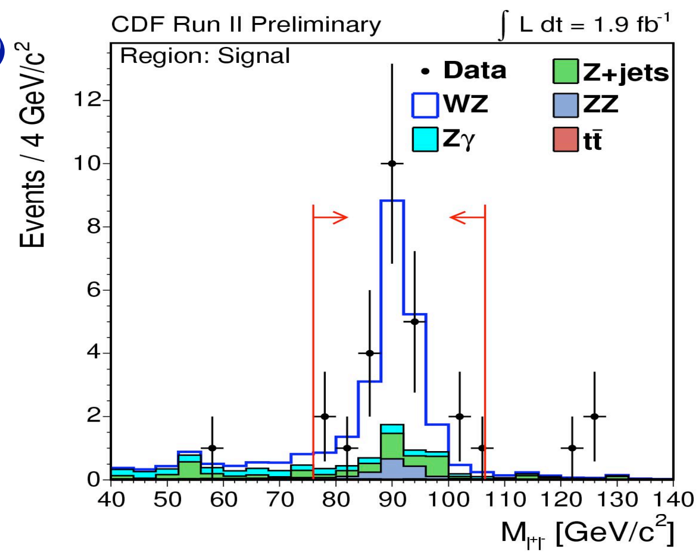
WZ → *lllν* production

- First evidence at > 3 σ in summer 2006 with ~ 0.8 fb^{-1} at DØ
- First observation at > 5 σ in fall 2006 with ~1.1 fb^{-1} at CDF (*PRL 98, 161801 (2007)*)
- Cross section measurements
  - DØ, $L = 1.0\ fb^{-1}$:
    - Events observed 13
    - Expected background 4.5 ± 0.6
    - Expected signal 9.2 ± 1.0
    - $\sigma(WZ) = 2.7^{+1.7}_{-1.3}$ pb *PRD 76, 111104(R) (2007)*
  - CDF, $L = 1.9\ fb^{-1}$:
    - Events observed 25
    - Expected background 4.7±1.5
    - Expected signal 16.5±2.0

$$\sigma(WZ) = 4.3^{+1.3}_{-1.0}(\text{stat}) \pm 0.2(\text{syst}) \pm 0.3(\text{lumi})\ \text{pb}$$

NLO prediction: $\sigma(WZ) = 3.7 \pm 0.3$ pb

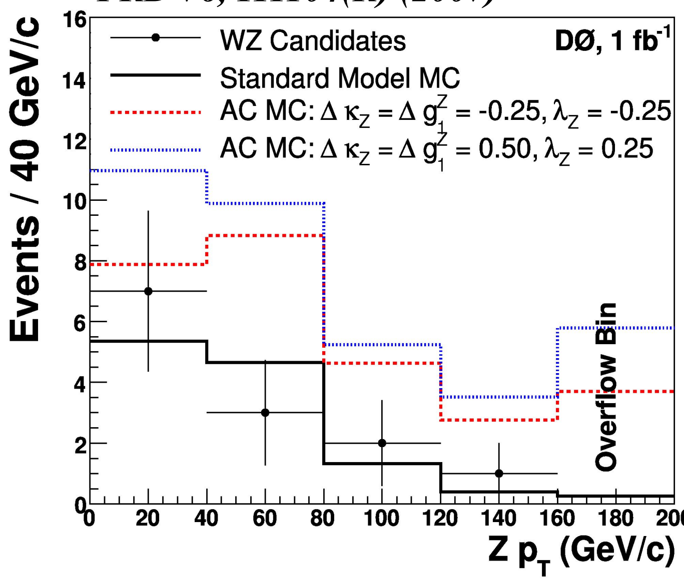


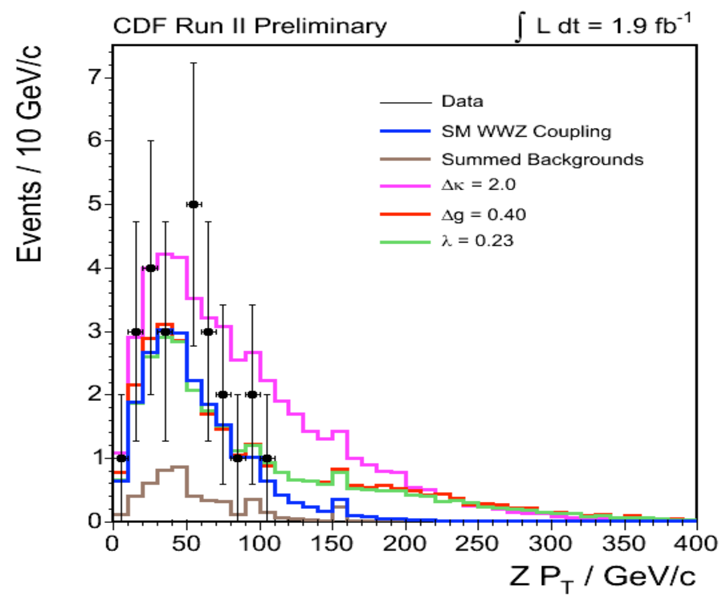


WZ → *lll*ν production: probing WWZ coupling

- Non-SM WWZ coupling enhances cross section at high values of Z p_T

PRD 76, 111104(R) (2007)





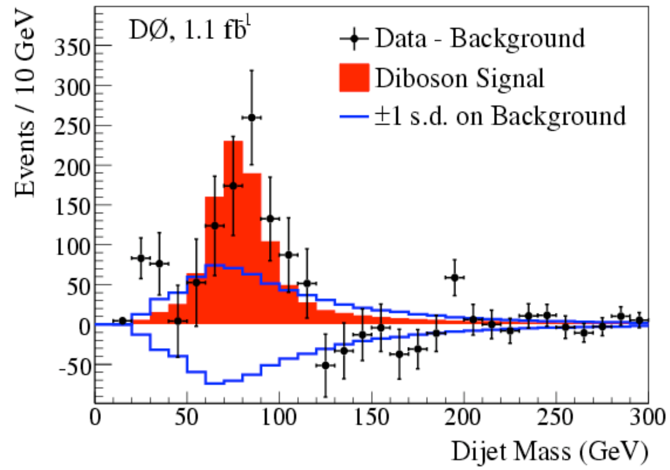
95% C.L. limits for Λ=2 TeV

DØ published, 1.1 fb^{-1}	CDF preliminary, 1.9 fb^{-1}
$-0.17 < \lambda_Z < 0.21$	$-0.13 < \lambda_Z < 0.14$
$-0.14 < \Delta g_Z < 0.34$	$-0.13 < \Delta g_Z < 0.23$
$-0.12 < \Delta\kappa_Z = \Delta g_Z < 0.29$	$-0.76 < \Delta\kappa_Z < 1.18$

WW/WZ→lνjj production

- Combined analysis of WW→*l*νjj and WZ→*l*νjj channels
- Final state similar to WH→lνbb
- Experimentally challenging:
  - 5-10 × more data than in leptonic channels
  - 1000 × more background: W+jets, Z+jets, QCD multijet, ttbar.
- Select events with
  - High p_T electron or muon
  - High missing E_T and $M_T(l, E_T^{miss})$
  - ≥ 2 jets
- S/B < 1% after selection
  - Use multivariate discriminant
  - Look for "bump" in M(jj) distribution

PRL 102, 161801 (2009))



- Observed significance
  - 4.4σ at D0 ⇒ First evidence
  - 5.4σ at CDF ⇒ First observation

- Cross section measurements

D0 (1.1 fb^{-1}) $\sigma(WW+WZ) = 20.2 \pm 4.4(stat+syst) \pm 1.2(lumi)pb$

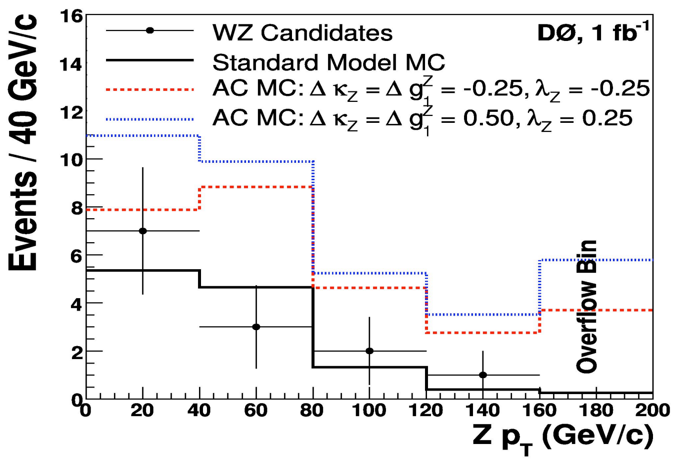
CDF (2.7 fb^{-1}) $\sigma(WW+WZ) = 17.7 \pm 3.1(stat) \pm 2.4(sys)pb$

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

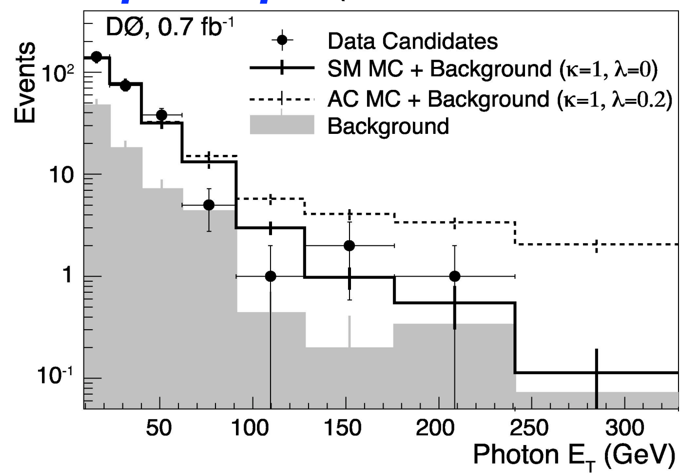
WV Combination

- **Combination of four DØ analysis with ~ 1fb^{-1}**

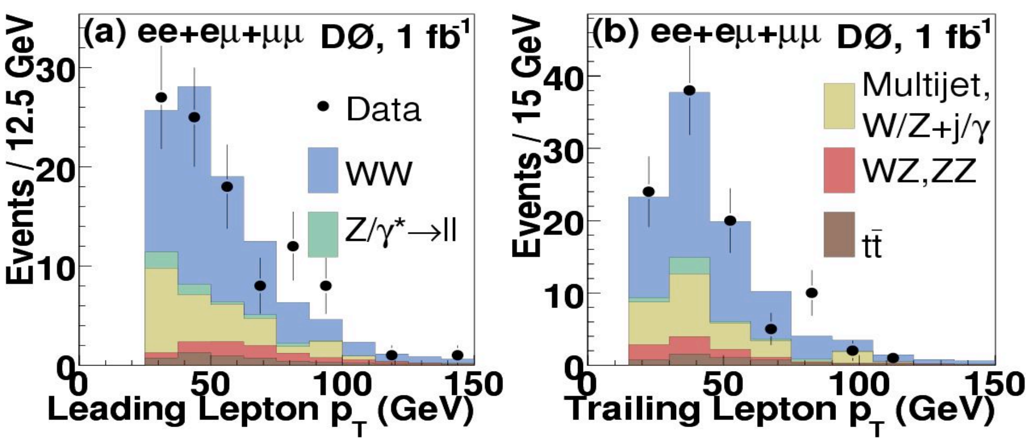
WZ→lνll (PRD 76, 111104 (2007))



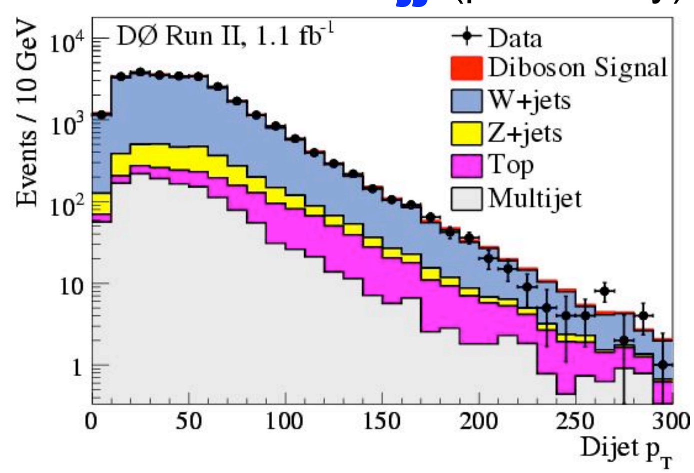
Wγ→lνγ (PRL 100, 241805 (2008))



WW→lνlν (arXiv.org:0904.0673)



WW+WZ→lνjj (preliminary)



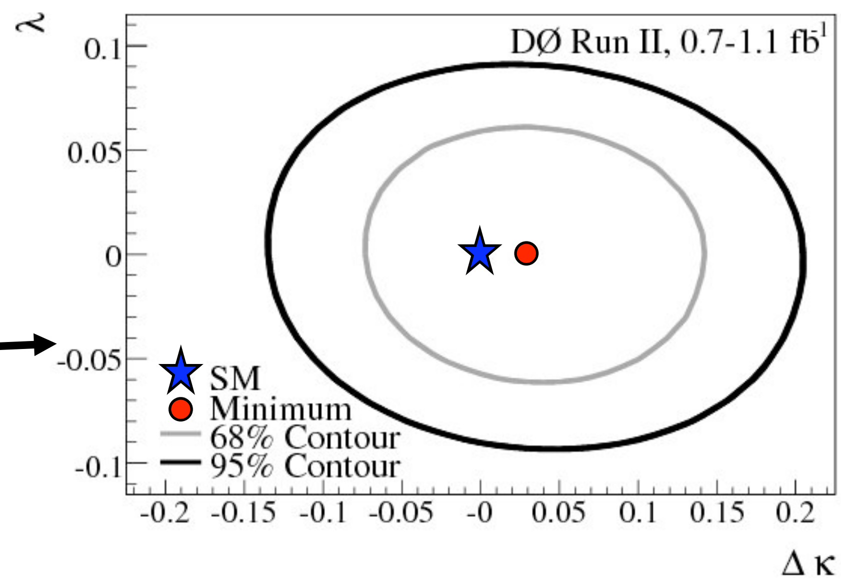
WV Combination

- Combination of four DØ analysis with ~ $1fb^{-1}$
- 95% CL limits on γWW and ZWW TGCs under various assumptions
  - Requiring SU(2)xU(1) symmetry
    $\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \cdot \tan^2\theta_W$ and $\lambda_\gamma = \lambda_Z$

(Λ_{NP}=2 TeV)

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

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

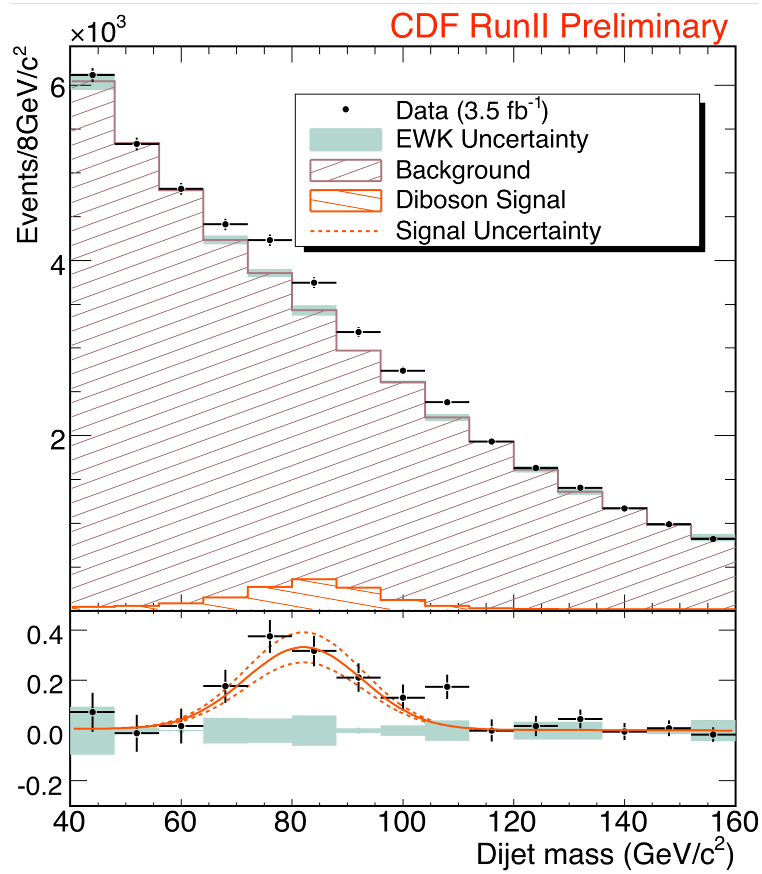


$-0.12 < |\Delta\kappa| < 0.35$
$-0.14 < |\lambda| < 0.18$

- Approaching sensitivity to LEP experimets

VV → MET+jets channel

- **Combined analysis of ZZ→ννjj, ZW→ννjj/*l*νjj and WW→*l*νjj channels**
- **Challenging**
  - **difficult to trigger – benefits from L2 met/cal trigger upgrade at CDF**
  - **large background from W/Z+jets, ttbar and QCD multijet.**
- **Select events with**
  - **High missing E_T^{miss} and E_T^{miss} significance**
  - **$\Delta\phi(E_T^{miss}, \text{jet}) > 0.4$**
  - **=2 jets**
  - **Small $\Delta\phi(E_T^{miss}, \text{trk}E_T^{miss})$**
- **Cross section extracted using unbinned extended maximum Lhood fit of di-jet mass:**



$$\sigma(WW + WZ + ZZ) = 18.0 \pm 2.8(\text{stat}) \pm 2.4(\text{sys}) \pm 1.1(\text{lumi})\text{pb}$$

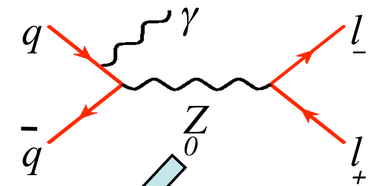
arXiv.org:0905.4717

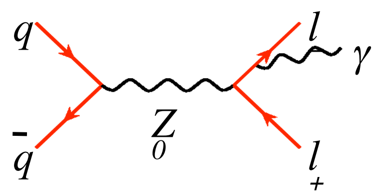
SM prediction = 16.8 ± 0.5 pb (MCFM+CTEQ6M)

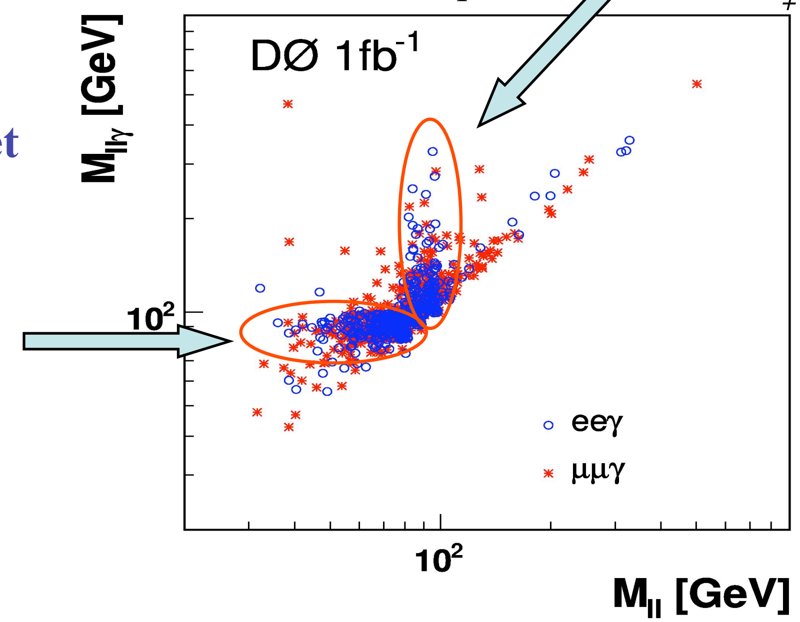
- **Observed significance = 5.3σ** ⇒ First Tevatron observation!

Z γ analysis

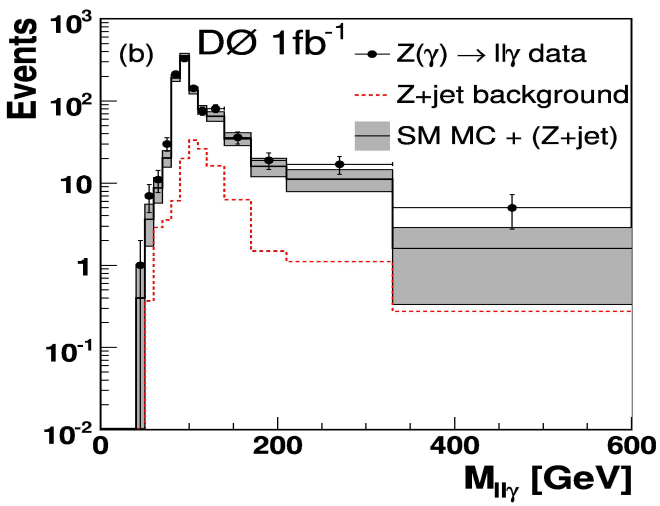
- **Basic $Z\gamma \rightarrow ll\,\gamma$ (l=e,μ) events selection:**
  - Pair of high p_T electrons or muons
  - M(ll) > 30 GeV
  - Photon with $E_T^{\gamma} > 7$ GeV and $dR_{l\gamma} > 0.7$
- **Main background process Z(→ee/μμ)+jet production**







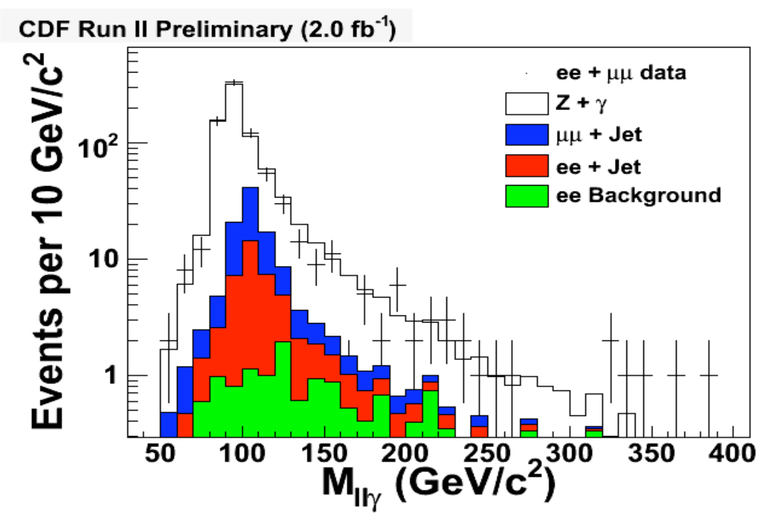
PLB 653, 378 (2007)

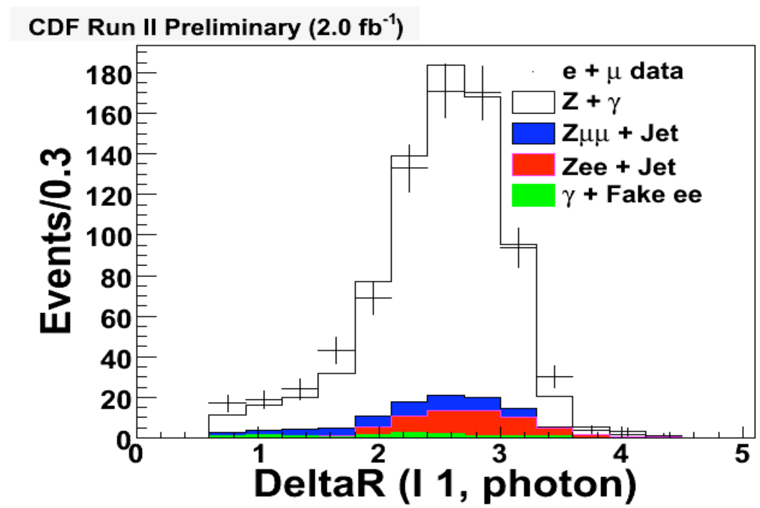


- **Cross section:**
  - DØ measurement $\sigma \times BR(Z\gamma \rightarrow ll\gamma) = 4.96 \pm 0.42\,pb$
  - NLO theory $\sigma \times BR(Z\gamma \rightarrow ll\gamma) = 4.74 \pm 0.22\,pb$

Z γ analysis

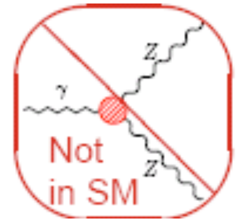
- **CDF: separate measurements for ISR and FSR processes:**
  - ISR enriched sample by applying M ($l\,l\,\gamma$) > 100 GeV
    - Measured $\sigma \times BR(Z\gamma \rightarrow ll\gamma) = 1.2 \pm 0.1(stat.) \pm 0.2(syst.) \pm 0.1(lumi)$ pb
    - NLO theory $\sigma \times BR(Z\gamma \rightarrow ll\gamma) = 1.2 \pm 0.1$ pb
  - FSR enriched applying M ($l\,l\,\gamma$) < 100 GeV
    - Measured $\sigma \times BR(Z\gamma \rightarrow ll\gamma) = 3.4 \pm 0.2(stat.) \pm 0.2(syst.) \pm 0.2(lumi)$ pb
    - NLO theory $\sigma \times BR(Z\gamma \rightarrow ll\gamma) = 3.3 \pm 0.3$ pb

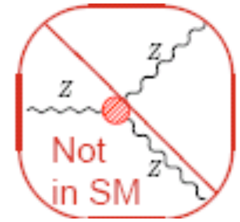


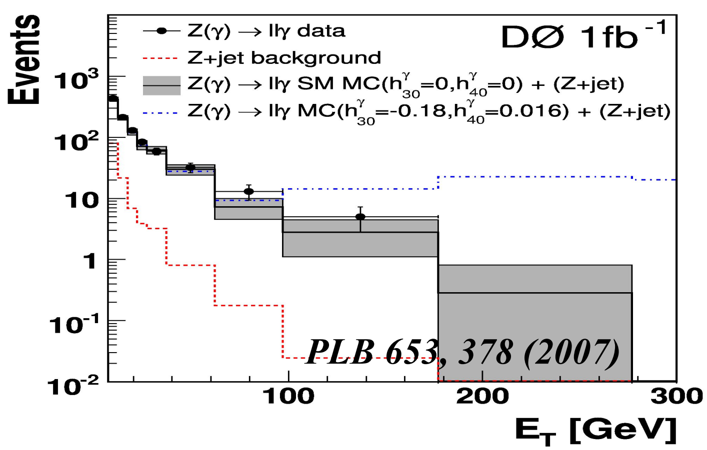


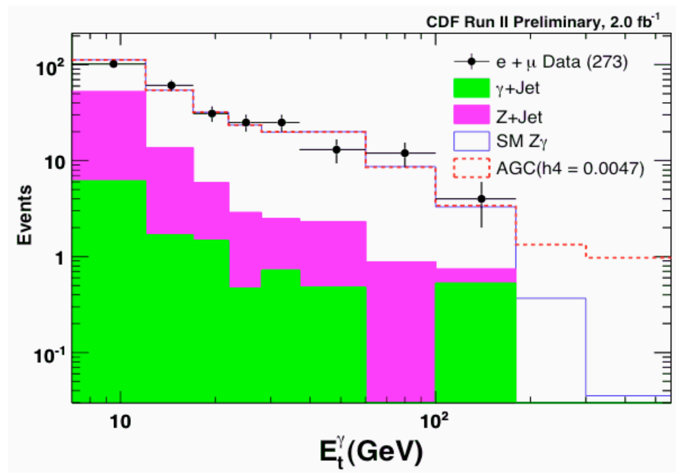
Z γ analysis: probing ZγZ and Zγγ couplings

- No ZγZ and Zγγ vertices in SM
- Non-SM ZγZ and Zγγ TGCs enhance production cross section
  - Particularly at high p_T region of photon
  - Probes $h^Z_{3,4}$ and $h^\gamma_{3,4}$ parameters (both zero in SM)









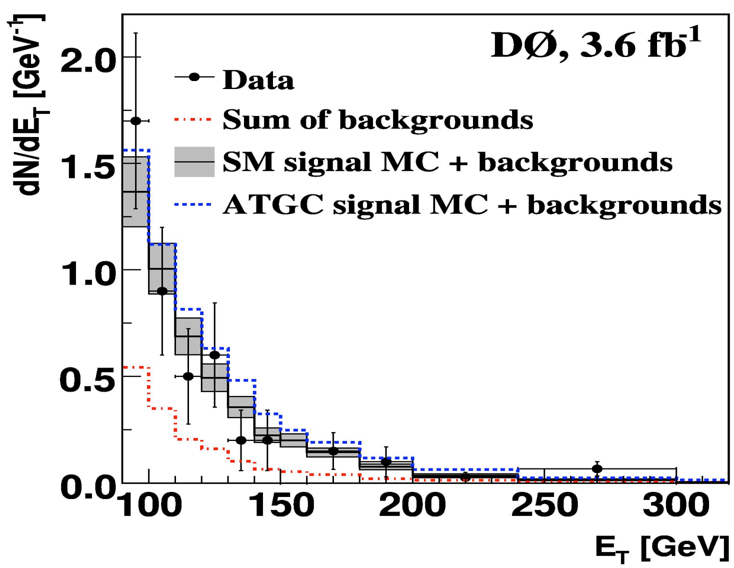
95% C.L. limits for Λ=2 TeV

	DØ published ~1 fb^{-1}	CDF preliminary 1.1fb^{-1} e, 2.0 fb^{-1} μ	LEP-II 2003
h^γ_3 h^γ_4	[-0.085, 0.084] [-0.0053, 0.0054]	[-0.084, 0.084] [-0.0047, 0.0047]	[-0.049, -0.008] [-0.002, 0.034]
h^Z_3 h^Z_4	[-0.083, 0.082] [-0.0053, 0.0054]	[-0.083, 0.083] [-0.0047, 0.0047]	[-0.20, 0.07] [-0.05, 0.12]

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

- **Final state includes**
  - **Energetic photon with $E_T > 90$ GeV and large missing $E_T > 70$ GeV**
- **Background: W→lν and Z→ll productions, beam halo, mis-measured missing E_T**
- **Expected events from**
  - **background: 17.3 ± 2.4**
  - **signal: 33.7 ± 3.4**
- **Observed: 51**
- **Significance of observation 5.1 σ – First Tevatron observation**
- **Measurement** $\sigma(Z\gamma, E_T^{\gamma} > 90\text{GeV}) \times BR(Z \rightarrow \nu\nu) = 31.9 \pm 9(\text{stat}+\text{sys}) \pm 2(\text{lumi})$ fb

SM NLO prediction = 39 ± 4 fb



- **Combined 95 % CL limits on γZZ and γγZ TGCs from Zγ→ννγ / eeγ / μμγ channels**

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

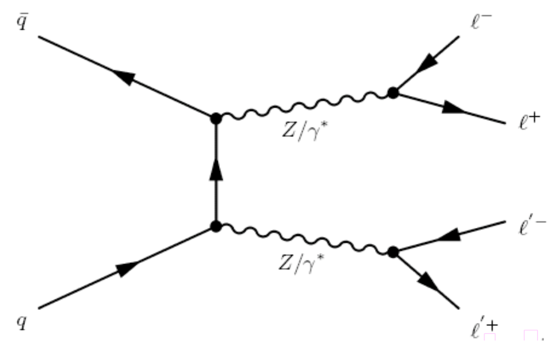
(Λ_{NP}=1.5 TeV)

Most restrictive limits so far

ZZ production

- **Very small production cross section:**

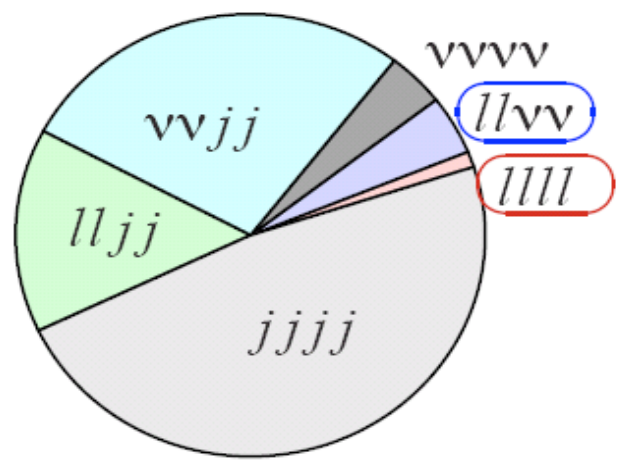
$$\sigma(p\bar{p} \rightarrow ZZ) = 1.4 - 1.6 \text{ pb}$$



- **Two main decay modes studied at the Tevatron**

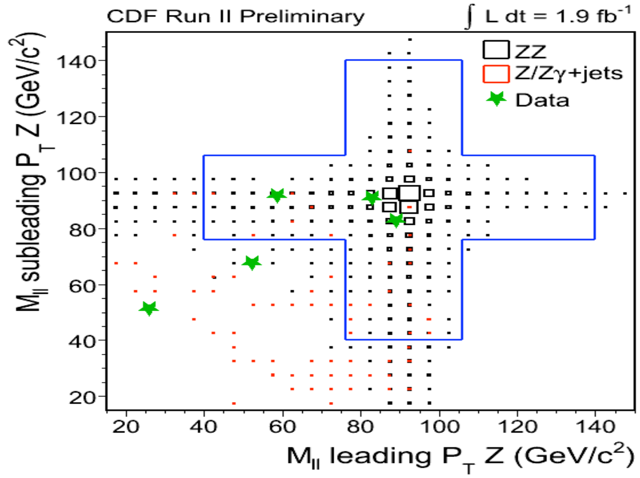
  - **$ZZ \rightarrow 4l$, with $l=e,\mu$**
    - **Very clean: low background contamination from Z/γ+jets and ttbar processes.**
    - **Small BR =$(2 \times 0.033)^2 = 0.0044$**

  - **$ZZ \rightarrow ll\nu\nu$, with $l = e, \mu$**
    - **Several significant background processes: WW, Z+jets, WZ, Drell-Yan productions**
    - **6 times larger BR =$2 \times 0.2 \times (2\times0.033)=0.026$**
    - **Use multivariate approach to discriminate between signal and background:**
      - **Matrix Element method by CDF**
      - **Likelihood method by DØ**



ZZ at CDF

- $Z \rightarrow 4l$ channel
  - Split 4e, 4mu and 2e2mu channels into 7 exclusive categories depending whether a lepton has a track and/or is identified explicitly.
  - One pair of leptons with M(ll) in [76 GeV – 106 GeV]; other pair with M(ll) in [40 GeV -140 GeV].



- $Z \rightarrow ll\nu\nu$ channel
  - Select events with ee/μμ + large E_T^{mis}. Veto central jets to suppress ttbar bkgd
  - Observe 276 events in the pre-selected sample
  - expect only 14 ± 2 signal events
  - Use full kinematic information (Matrix Method) to extract the signal

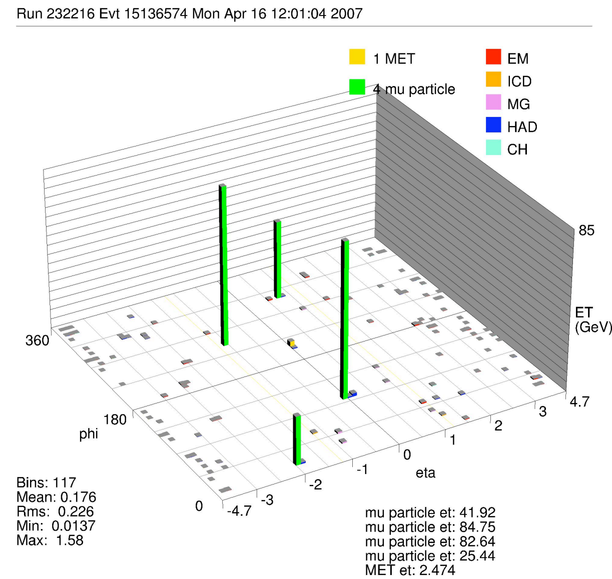
- Combine $ZZ \rightarrow 4l$ and $ZZ \rightarrow 2l2\nu$ channels: 4.4 σ significance
- Cross-section measurement $\sigma(ZZ) = 1.4^{+0.7}_{-0.6}(\text{stat} + \text{sys})$ pb

PRL 100, 201801 (2008)

σ(ZZ)=1.4±0.1 pb predicted by NLO

ZZ at DØ

- **$Z \rightarrow 4l$ channel:**
  - **Split 4mu, 2e2mu, 4e channels into 7 exclusive categories depending on the number of electrons in CC ($|\eta|<1.1$) region.**
  - **Dilepton mass M(ll) > 70, 50 GeV**
  - **Predicted background: $0.14^{+0.03}_{-0.02}$**
  - **Predicted signal: 1.89 ± 0.08**
  - **Observe 3 candidate events (one 4mu, two 4e)**



4μ candidate event

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

$$\sigma(ZZ) = 1.60 \pm 0.63(\text{stat})^{+0.16}_{-0.17}(\text{sys})\ \text{pb}$$

$\sigma(ZZ)=1.4\pm0.1$ pb predicted by NLO

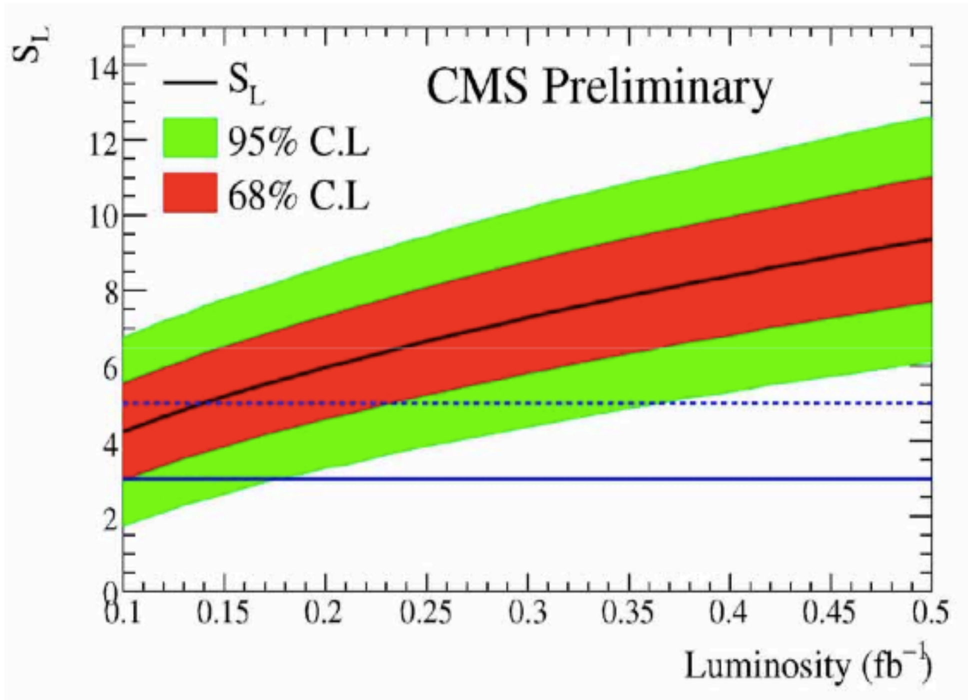
- **Expected significance: 4.8σ**
- **Observed significance: 5.7σ – first Tevatron Observation**

PRL 101, 171803 (2008)

Prospects at LHC

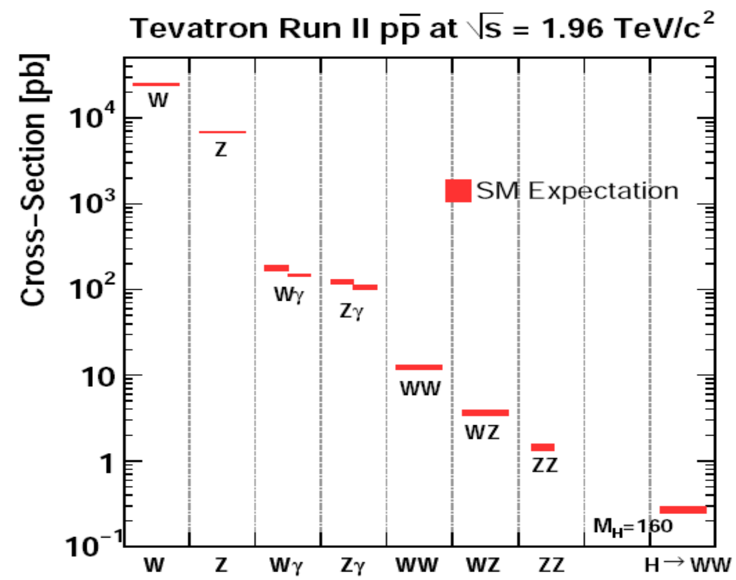
- At LHC, diboson cross sections can be measured at low luminosity
  - σ (WW) = 110 pb
  - σ (WZ) = 49 pb
  - σ (ZZ) = 15 pb
- WWZ, WWγ, ZZZ, and ZZγ TGCs will be probed
  - Expect to reach better accuracy than at LEP2
- With high luminosity, polarization measurements in ZZ and WZ events are feasible

WZ production



Summary

- Tevatron experiments are exploring radically new territories:
  - Observation of diboson processes not accessible previously
  - Testing various triple gauge boson couplings with increasingly higher precisions
  - Probing peculiar features predicted by the Standard Model
  - Extending studies beyond leptonic final states
  - So far … Standard Model wins again



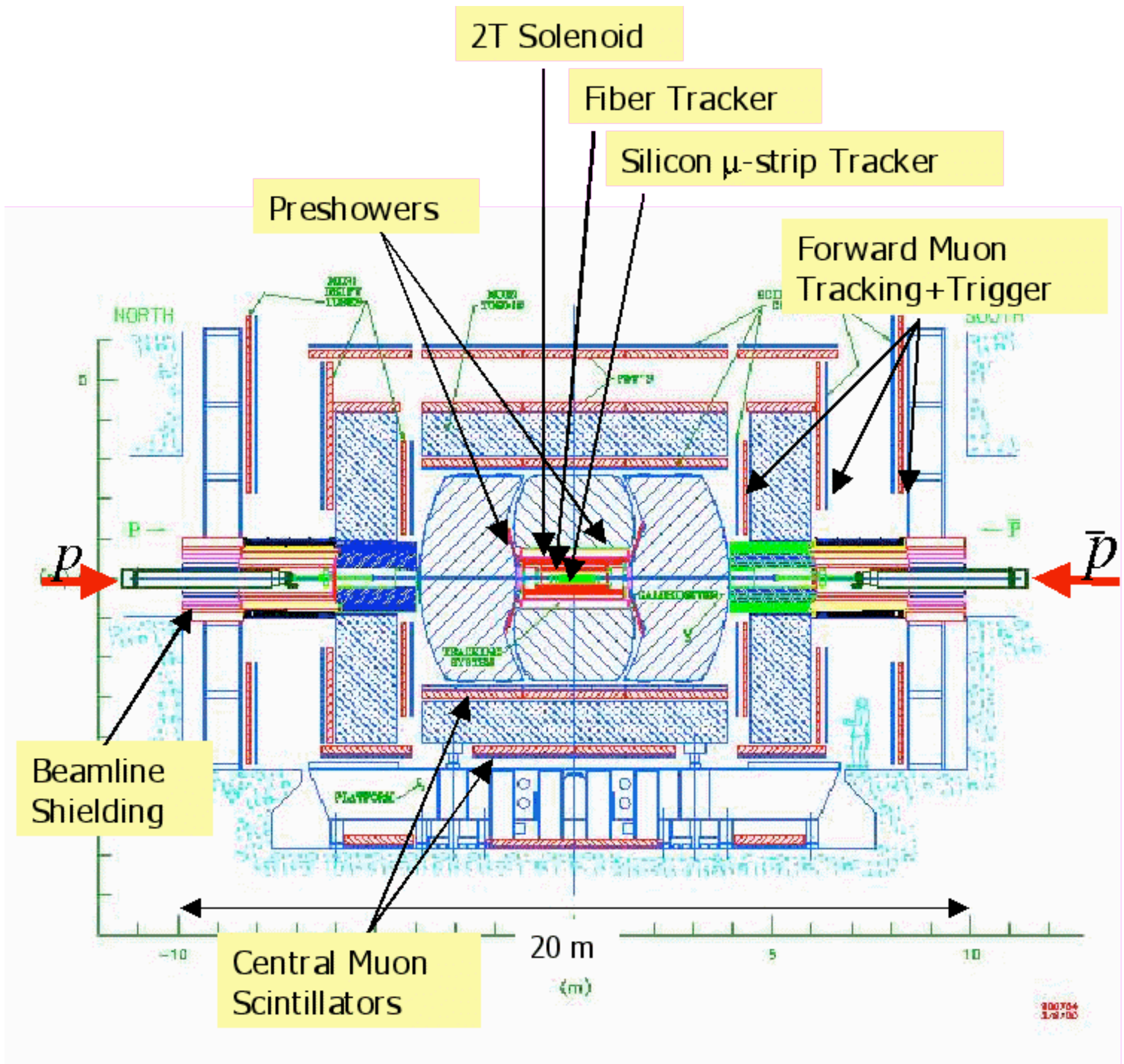
note: this is σ, not $\sigma \times$ BR

- Even more exciting times ahead
  - Presented results based on up to 0.7-3.6 fb^{-1}
  - Tevatron experiments have recorded more 6 fb^{-1} of data. More to come
    - entering precision diboson physics era

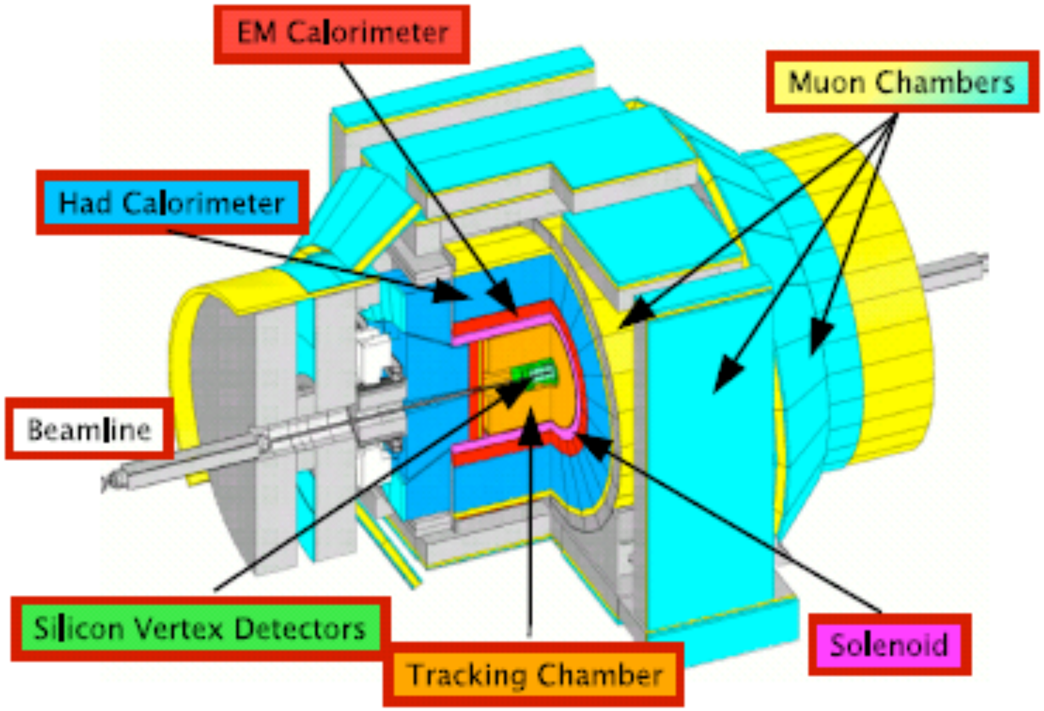
Backup slides

DØ Detector

- Silicon detector and scintillating fiber tracker in 2.0 T solenoidal field
  - Coverage up to $|\eta| = 2.5$
- Liquid Argon/Uranium calorimeters
  - Central and two forward calorimeters
  - Stable, uniform response, radiation hard
  - Hermetic with coverage up to $|\eta| = 4.2$
- Muon System
  - Coverage up to $|\eta| = 2.0$
  - Three layers of scintillators and drift tubes
  - Central and Forward
  - A layer – inside 1.8T toroid magnet
  - Shielding reduces backgrounds by 50-100 x
- Three Level Trigger
  - L1/L2/L3 ~ 1800/1000/50 Hz



CDF Detector



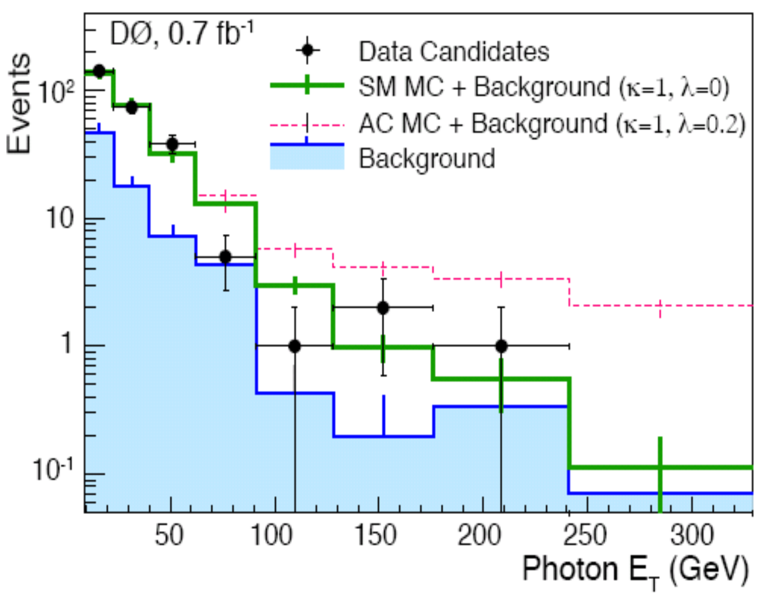
- Segmented sampling calorimeters
- Shower maximum detectors
  - Shower shape measurement
  - Central: gas-based
  - Forward: scintillator
- Muon Chambers
  - CMU & CMP ($|\eta| < 0.6$)
  - CMX ($0.6 < |\eta| < 1.0$)

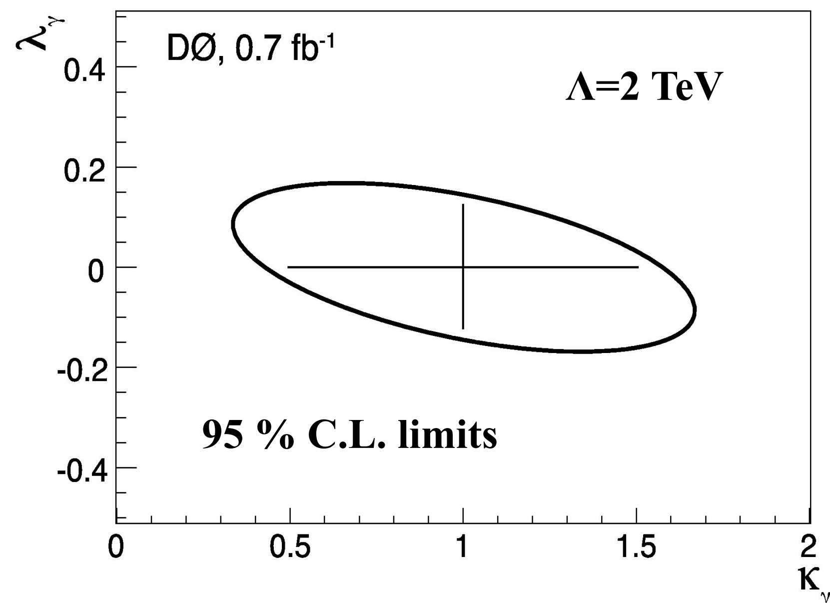
Wγ analysis: probing WWγ coupling

- **Non-SM WWγ TGC enhances production cross section**
  - **Particularly at high p_T region of photon**
  - **Probes Δk_γ and λ_γ parameters (both zero in SM)**

DØ (0.7 fb-1), Λ=2TeV	LEP, $\hat{s} \approx 2M_W$
$-0.49 < \Delta\kappa_\gamma < 0.51$	$-0.105 < \Delta\kappa_\gamma < 0.069$
$-0.12 < \lambda_\gamma < 0.13$	$-0.059 < \lambda_\gamma < 0.026$

arXiv:0803.0030v1





ZZ→4*l* at DØ

- **Three channels considered: eeee,eeμμ and μμμμ**
  - **M (*ll*) > 30 GeV, includes ZZ/Zγ* interference**
  - **Background from**
    - **Z+jets where two jets are mis-identified as leptons**
    - **Zγ+jets where the γ and a jet are misidentified as leptons**
    - **ttbar → lνb + lνbbar with b/bbar decaying semileptonically**

$1\ fb^{-1}$	eeee	eeμμ	μμμμ	Total
ZZ Sig	0.44±0.03	0.81±0.09	0.46± 0.05	1.71±0.15
Bkg	0.080±0.021	0.013±0.004	0.033±0.006	0.13±0.03
Observe	**0**	**1**	**0**	**1**

- **95% C.L. limit on cross section:** $\sigma(ZZ) < 4.4pb$

The NLO theory calculations: $\sigma(ZZ) = 1.6 \pm 0.3pb$

- **Anomalous Couplings:**
  - **Limit region to M(*ll*) > 50 (70) GeV for ee (μμ)**
  - **Use event yields (all zero) to limit anomalous couplings**

95% C.L. limits for Λ=1.2 TeV

$-0.28 < f_{40}^{Z} < 0.28$

$-0.31 < f_{50}^{Z} < 0.29$

$-0.26 < f_{40}^{\gamma} < 0.26$

$-0.30 < f_{50}^{\gamma} < 0.28$

Phys. Rev. Lett. 100, 131801 (2008)