Rencontres de Moriond
Electroweak Interactions and Unified Theories

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Diboson Production at the Tevatron

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For CDF and DØ Collaboration

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  - Cross section measurement
  - Triple Gauge Boson Couplings
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- Zγ production
  - Cross section measurement
  - Triple Gauge Boson Couplings
- ZZ production
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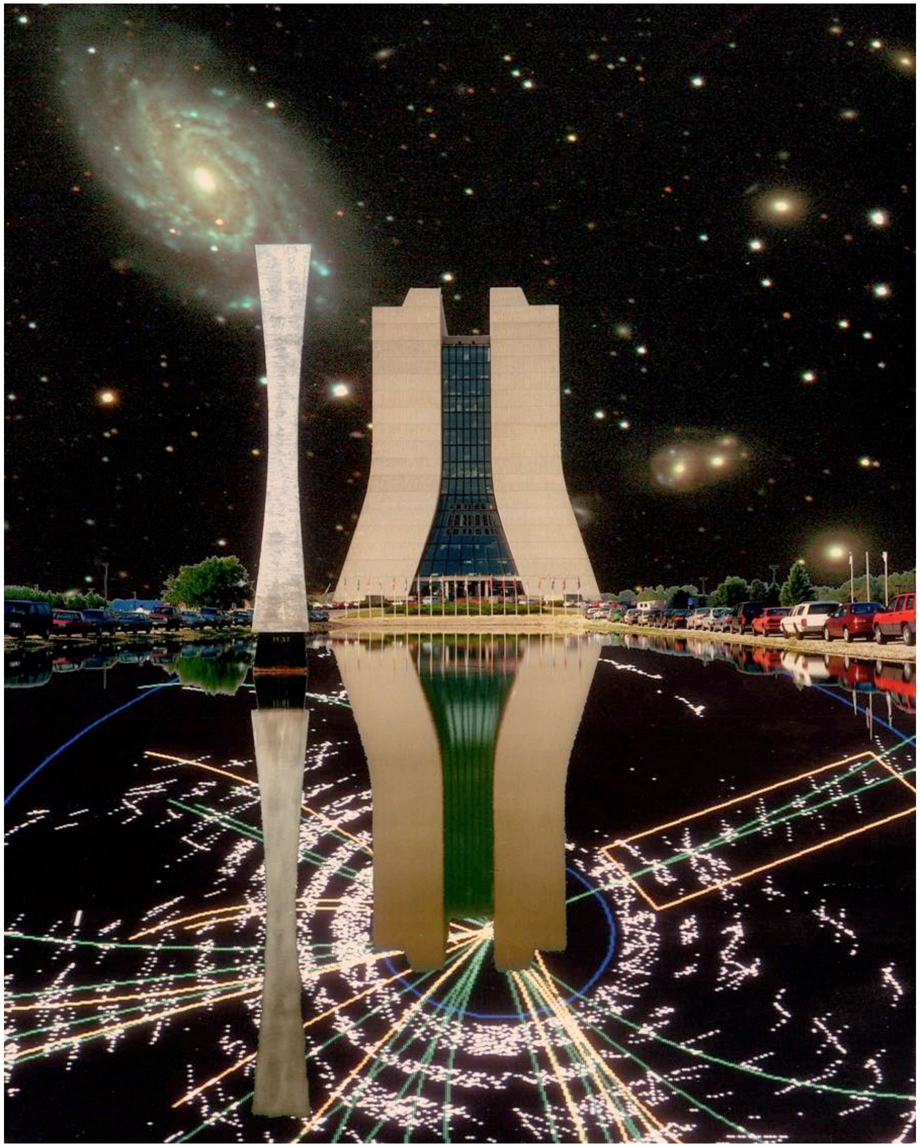
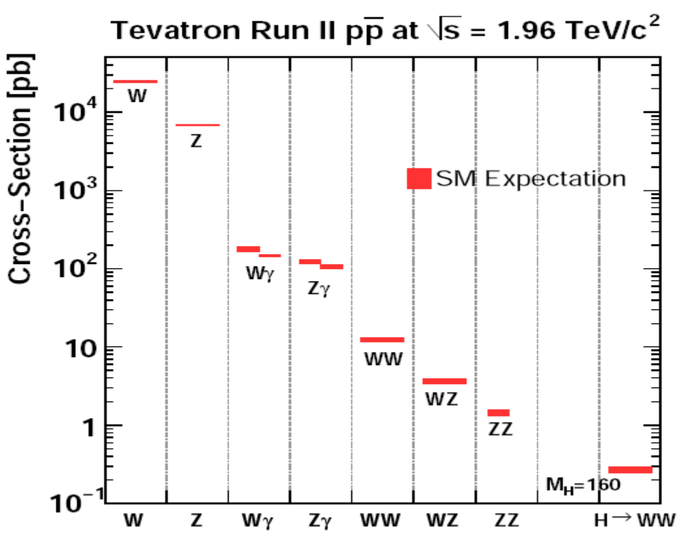
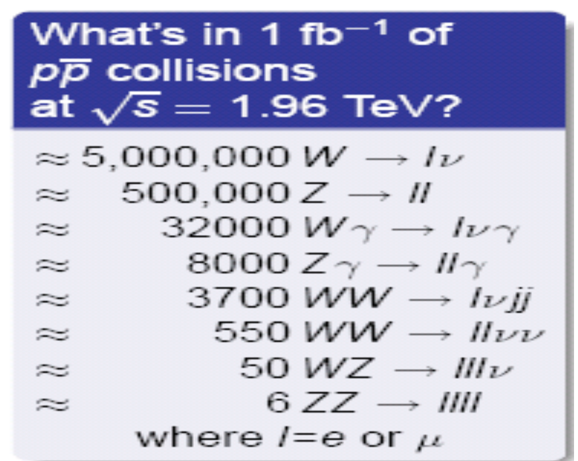
- Summary



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 sensitive to physics beyond the SM.**
- **Tevatron complementary to LEP:** explores higher energies and different combinations of couplings.
- **In the SM, diboson productions are important to understand:** they shares many characteristics and present backgrounds to Higgs and SUSY.





Introduction

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

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

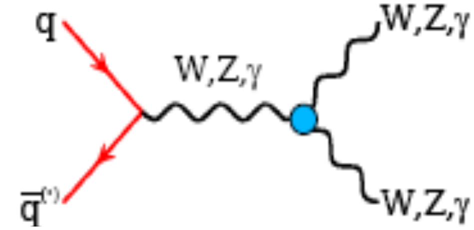
where V = Z,γ

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

- **Anomalous Triple Gauge Coupling'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:**

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



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

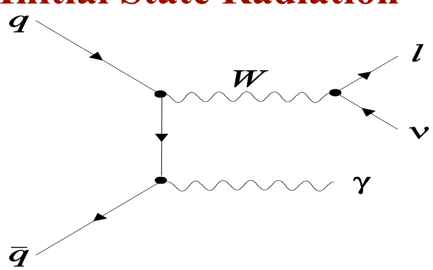
on-shell Zγ ($Z\gamma Z^*, Z\gamma\gamma^*$)		on-shell ZZ ($ZZZ^*, ZZ\gamma^*$)
h_{10}^V, h_{20}^V	(CP violating)	f_{40}^V
h_{30}^V, h_{40}^V	(CP conserving)	f_{50}^V

SM predicts all to be 0

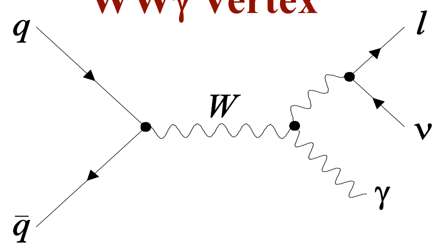
$W\gamma \rightarrow l\nu\gamma$ analysis at DØ

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

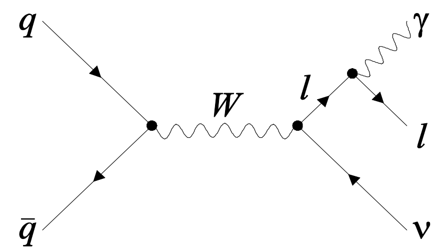
Initial State Radiation



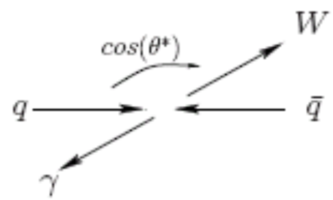
WWγ Vertex



Final State Radiation

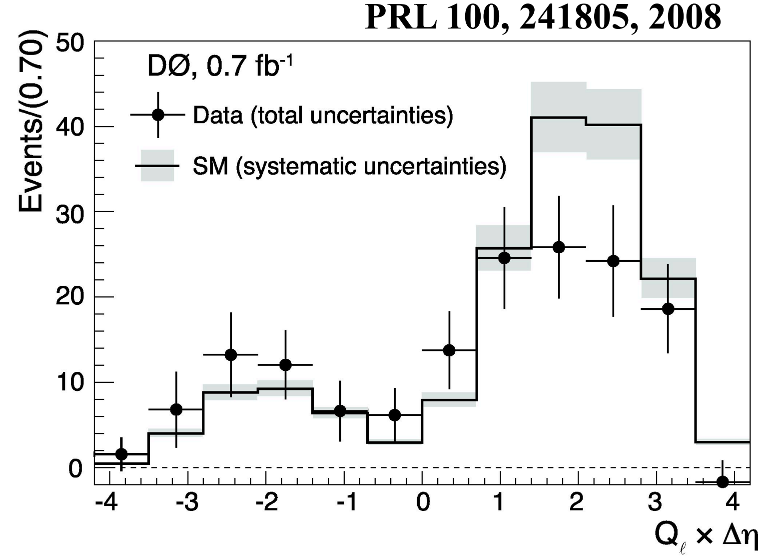


- **Photons radiated from quark and W lines interfere destructively.**
  - **Zero amplitude at**
    - **$\cos\theta^* = +1/3$ for u dbar $\rightarrow W^+\gamma$**
    - **$\cos\theta^* = -1/3$ for d ubar $\rightarrow W^-\gamma$**



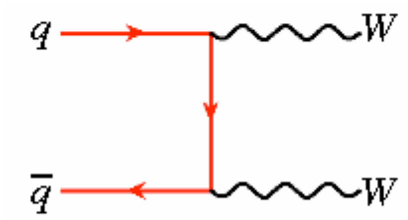
  - **No measurement of p_z of ν: use $Q_l \times (\eta_\gamma - \eta_l)$ to observe "dip" in the distribution**
  - **Non-SM coupling may fill the "dip"**

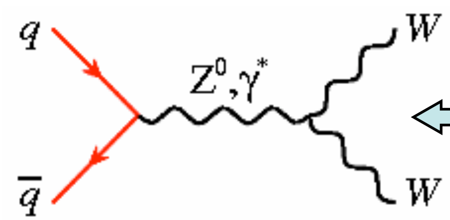
PRL 100, 241805, 2008



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

WW→*ll*νν production





Sensitive to WWZ / WWγ couplings

- **Dilepton channel provides cleanest signature:** ee, μμ or eμ and missing E_T
- **Signature similar to H→WW→*ll*νν production**
- **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:** accessible at Tevatron Run II already with a *O*(100) pb^{-1}.

- **Cross section measurements**

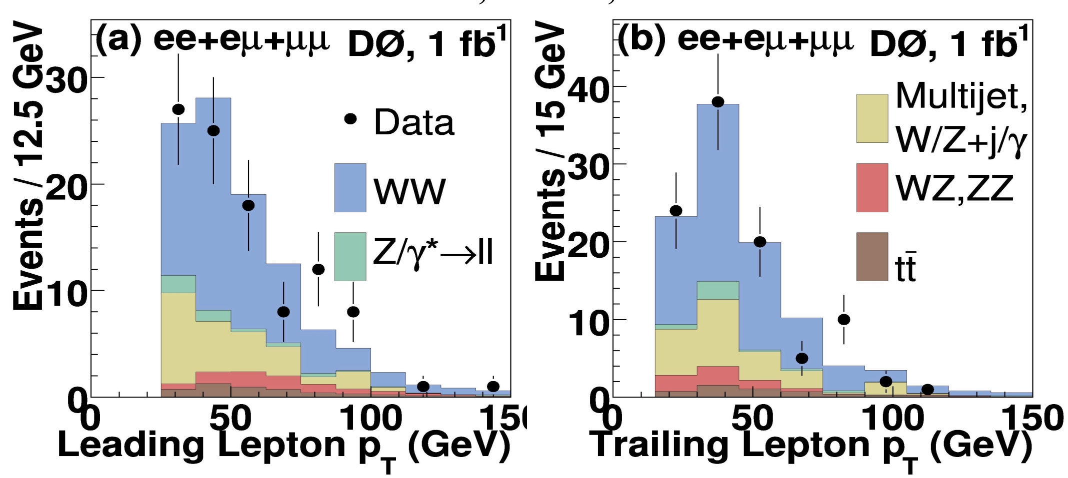
DØ (L_{int}= 1 fb^{-1})

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

CDF (L_{int}=3.6 fb^{-1}) arXiv:0912.4500

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

PRL 103, 191801, 2009



$WW \rightarrow ll\nu\nu$ production: probing WWZ and $WW\gamma$ couplings

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

- **Study various scenarios for WWZ and WWγ coupling relations, and different values of Λ.**

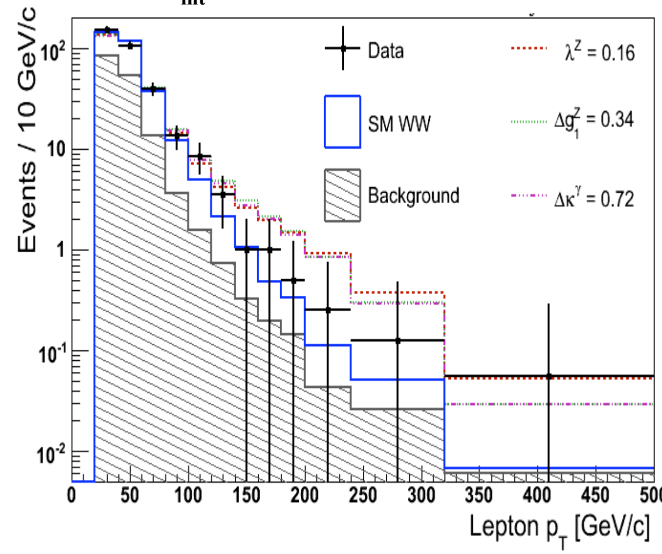
- **95 % C.L. limits on TGC's (Λ= 2 TeV):**
  - ➢ **Assuming equal couplings:** $\kappa_Z = \kappa_\gamma,\ g_1^Z = g_1^\gamma = 1$, and $\lambda_\gamma = \lambda_Z$

DØ

$-0.12 < \Delta\kappa < 0.35$

$-0.14 < \lambda < 0.18$

CDF L_{int}=3.6 fb^{-1} arXiv:0912.4500



  - ➢ **Respecting $SU(2)_L \times U(1)_Y$ symmetry:** $\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_W$ and $\lambda_\gamma = \lambda_Z$

DØ

$-0.54 < \Delta\kappa_\gamma < 0.83$

$-0.14 < \lambda < 0.18$

$-0.14 < \Delta g_1^Z < 0.30$

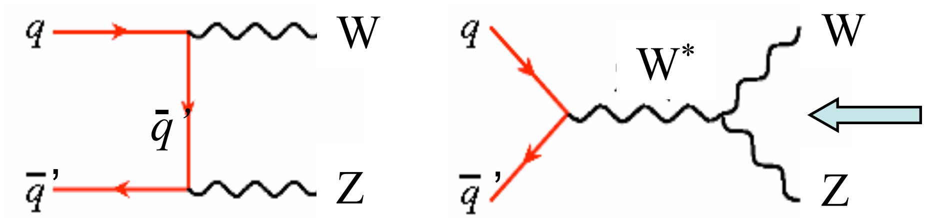
CDF

$-0.57 < \Delta\kappa_\gamma < 0.65$

$-0.14 < \lambda < 0.15$

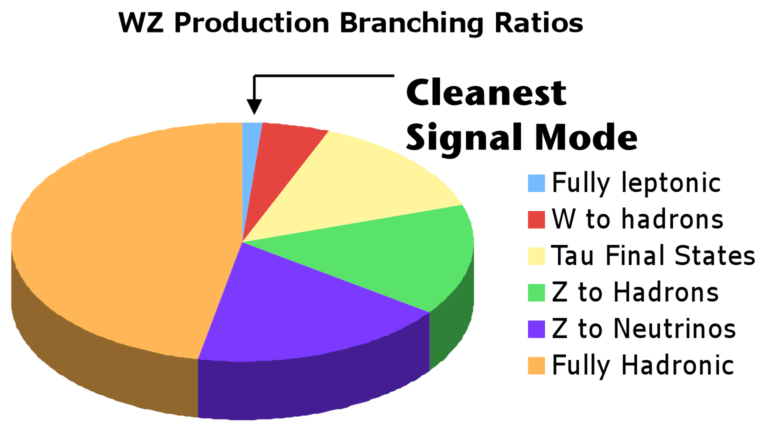
$-0.22 < \Delta g_1^Z < 0.30$

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 ± 0.3 pb
  - Branching fraction ~1.5%
- Background processes: Z+jet(s), ZZ, Zγ, ttbar production



WZ → $lll\nu$ production and anomalous couplings

- **Cross section measurements**
  - DØ (L_{int} = 1 fb^{-1}):

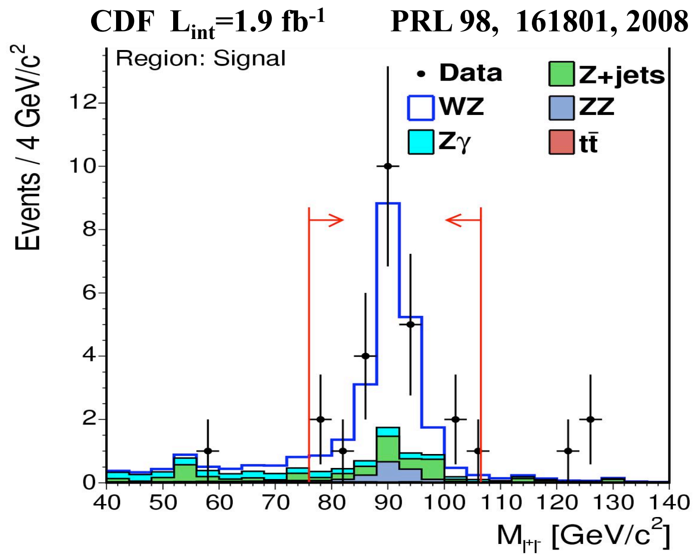
    $$\sigma(WZ) = 2.7^{+1.7}_{-1.3}\ \text{pb}$$

  - CDF (L_{int} = 1.9 fb^{-1}):

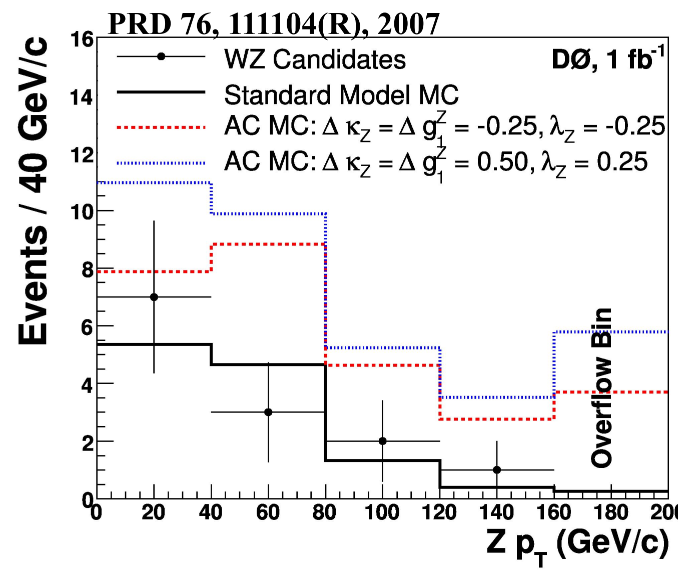
    $$\sigma(WZ) = 4.3^{+1.3}_{-1.0}(\text{stat}) \pm 0.2(\text{syst}) \pm 0.3(\text{lumi})\ \text{pb}$$

NLO prediction:

$$\sigma(WZ) = 3.7 \pm 0.3\ \text{pb}$$



- **Probing TGCs:** Non-SM WWZ coupling enhances cross section at high values of Z p_T



95% C.L. limits for Λ=2 TeV

DØ published, 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→$l\nu$jj production

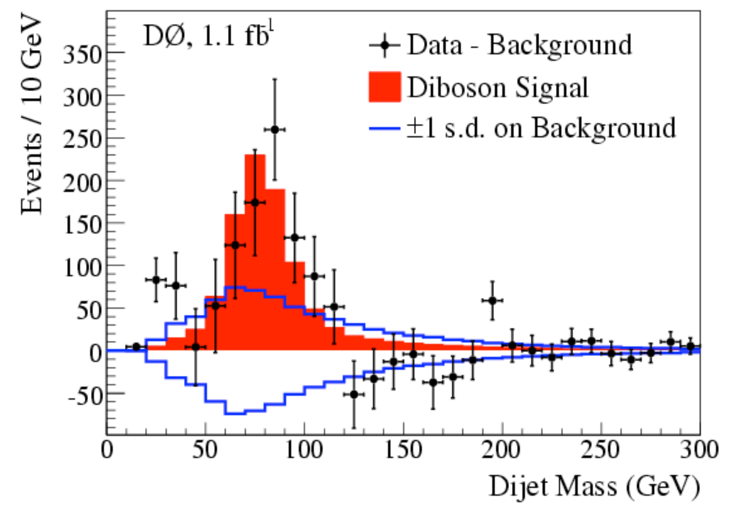
- Combined analysis of WW→$l\nu$jj and WZ→$l\nu$jj channels
- Final state similar to WH→$l\nu$bb
- Experimentally challenging:
  - 5-10 × more data than in leptonic channels
  - 1000 × more background: W/Z+jets, QCD, ttbar
- Select events with
  - High-p_T e/μ, large E_T^{miss} and $M_T(l, E_T^{miss})$
  - ≥ 2 jets
- S/B < 1% after selection
  - Use multivariate discriminant (Lhood, ME)
  - Look for "bump" in M(jj) distribution
- Cross section measurements
  - D0 (L_{int}=1.1 fb^{-1}) – evidence at 4.4σ significance

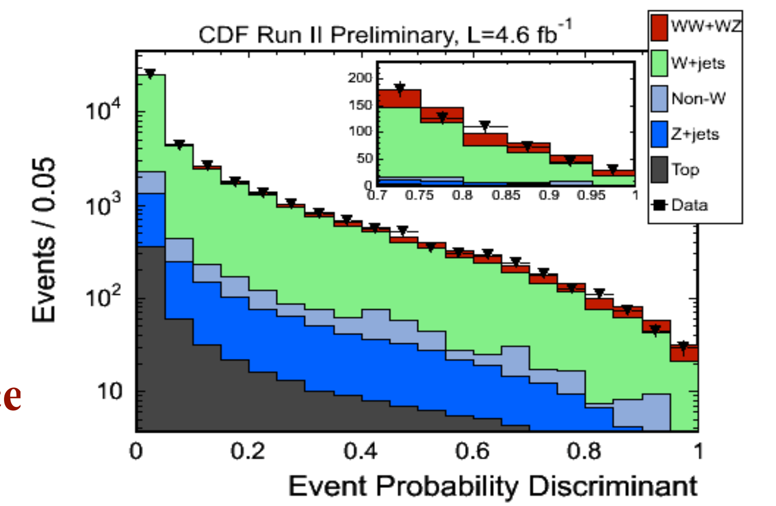
    $\sigma(WW + WZ) = 20.2 \pm 4.5$ pb
  - CDF (L_{int}=4.6 fb^{-1}) – observation at 5.4σ significance

    $\sigma(WW + WZ) = 16.5^{+3.3}_{-3.0}$ pb
  - SM NLO calculation

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

PRL 102, 161801, 2009





VV → MET+jets analysis at CDF

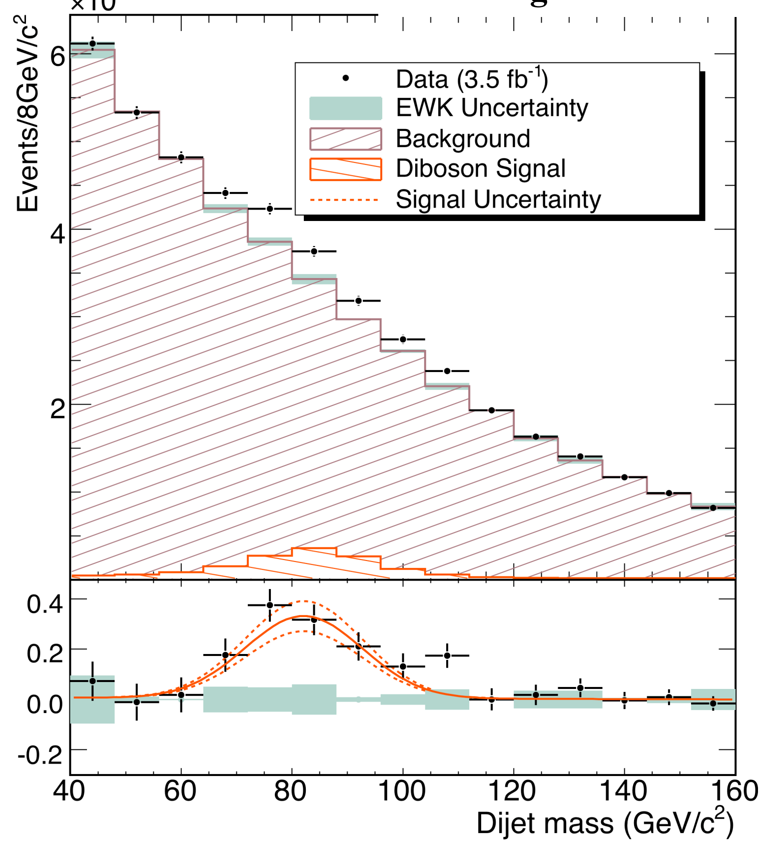
- **Combined analysis of ZZ→ννjj, ZW→ννjj/*l*νjj and WW→*l*νjj channels**
- **Final state similar to WH→*l*νbb**
- **Challenging**
  - **difficult to trigger – benefits from L2 met/cal trigger upgrade at CDF**
  - **large background from W/Z+jets, ttbar and QCD multijet.**
- **Select events with**
 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

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

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

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

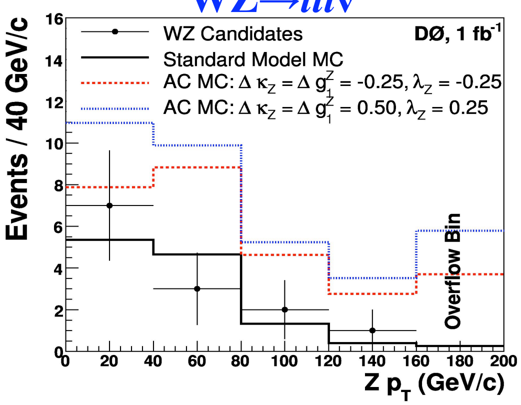
arXiv.org:0905.4717



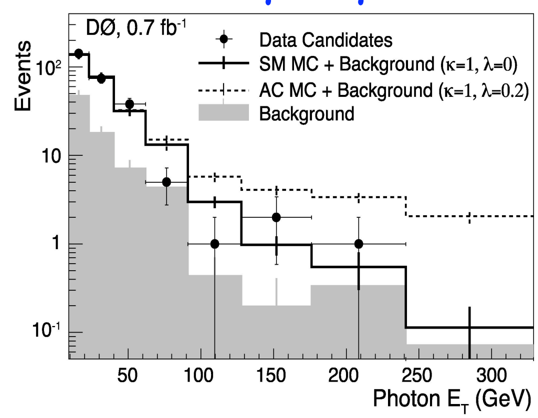
WV Combination at DØ

- Combination of four DØ analyses to probe TGCs and W magnetic dipole (μ_W) and electric quadrupole (q_W) moments.

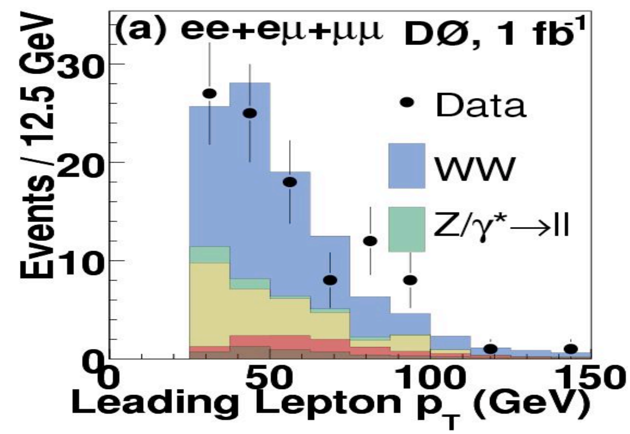
$WZ \rightarrow lll\nu$



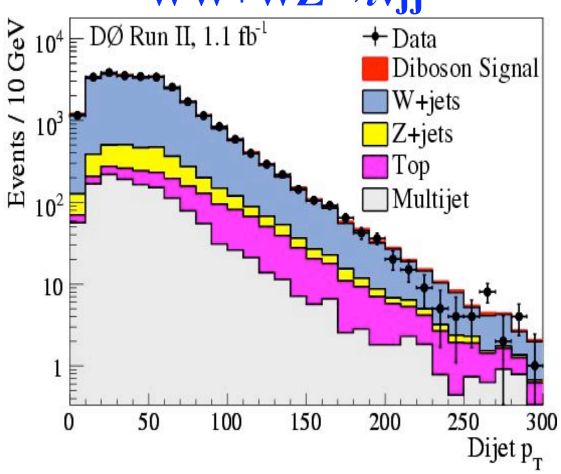
$W\gamma \rightarrow l\nu\gamma$



$WW \rightarrow ll\nu\nu$



$WW+WZ \rightarrow l\nu jj$



- **95% C.L. limits** (Λ=2 TeV)

Imposing $SU(2)_L \times U(1)_Y$

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

$-0.08 < \lambda < 0.08$

$-0.07 < \Delta g_1^Z < 0.16$

$1.86 < \mu_W < 2.16$

$-1.16 < q_W < -0.84$

Assuming equal couplings

$-0.11 < \Delta\kappa < 0.18$

$-0.08 < \lambda < 0.08$

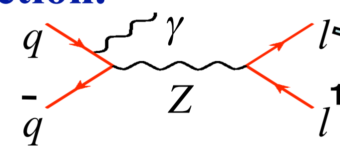
$1.86 < \mu_W < 2.15$

$-1.16 < q_W < -0.87$

- Approaching sensitivity of individual LEP experiments

$Z\gamma \rightarrow ll\,\gamma$ analysis

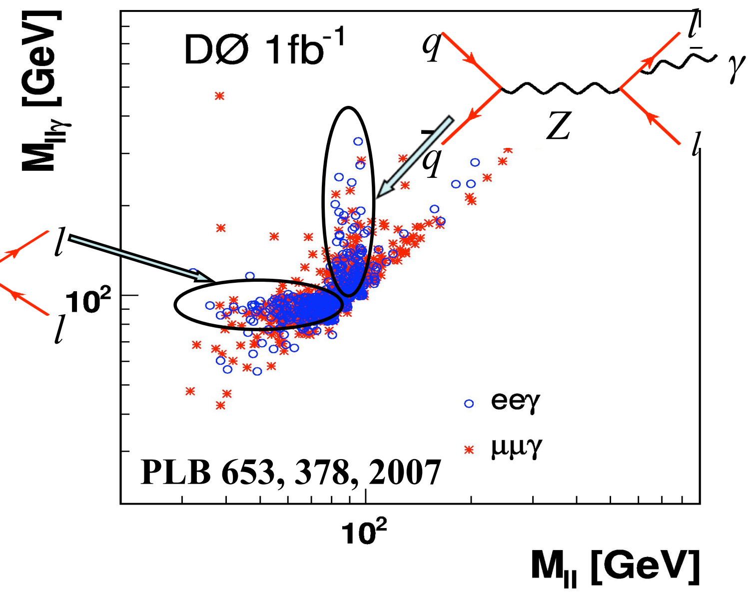
- **Basic $Z\gamma \rightarrow ll\,\gamma$ (l=e,μ) events selection:**
  - Pair of high-p_T e's or μ's; High M(ll) > 30/40 GeV
  - Photon with $E_T^{\gamma} > 7$ GeV and $dR_{l\gamma} > 0.7$
- **Main background Z(→ee/μμ)+jet production.**



- **DØ (L_{int}=1 fb^{-1}) measurement**

$$\sigma \times BR(Z\gamma \rightarrow ll\gamma) = 4.96 \pm 0.30\ (stat. + syst.) \pm 0.30(lumi)\ pb$$

❑ NLO theory $\sigma \times BR(Z\gamma \rightarrow ll\gamma) = 4.74 \pm 0.22\,pb$



- **CDF (L_{int}=1.1 /2.0 fb^{-1}): also separate measurements for ISR and FSR processes**
  - ➢ **ISR enriched sample, M ($l\,l\,\gamma$) > 100 GeV**

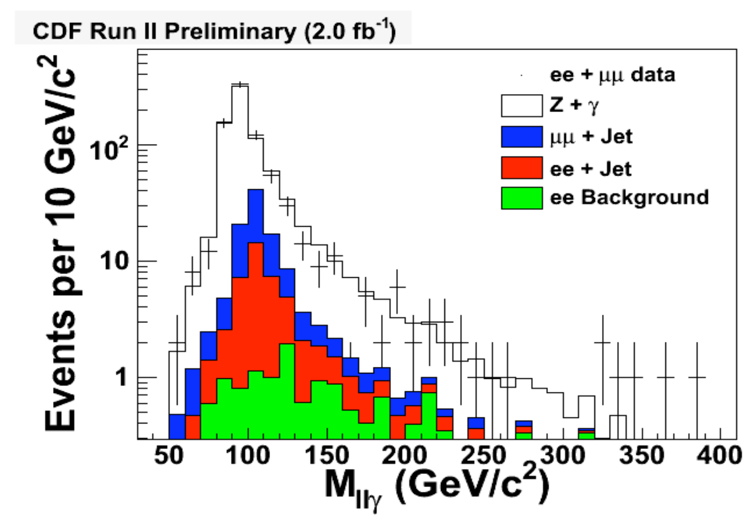
$$\sigma \times BR(Z\gamma \rightarrow ll\gamma) = 1.2 \pm 0.1(stat.) \pm 0.2(syst.) \pm 0.1(lumi)\ \ pb$$

❑ NLO theory $\sigma \times BR(Z\gamma \rightarrow ll\gamma) = 1.2 \pm 0.1\ \ pb$

  - ➢ **FSR enriched sample M ($l\,l\,\gamma$) < 100 GeV**

$$\sigma \times BR(Z\gamma \rightarrow ll\gamma) = 3.4 \pm 0.2(stat.) \pm 0.2(syst.) \pm 0.2(lumi)\ \ pb$$

❑ NLO theory $\sigma \times BR(Z\gamma \rightarrow ll\gamma) = 3.3 \pm 0.3\ \ pb$



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

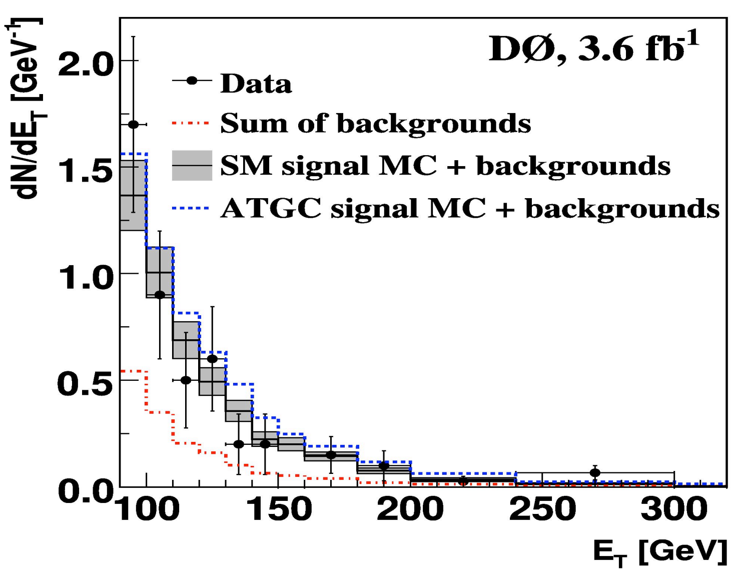
- **Final state includes**
  - Energetic photon (e.g. $E_T > 90$ GeV) and large missing E_T (e.g. > 70 GeV)
- **Background:** $W\rightarrow l\nu$ and $Z\rightarrow ll$ productions, beam halo, mis-measured missing E_T
- **DØ (L_{int}=3.6 fb^{-1}) measurement**

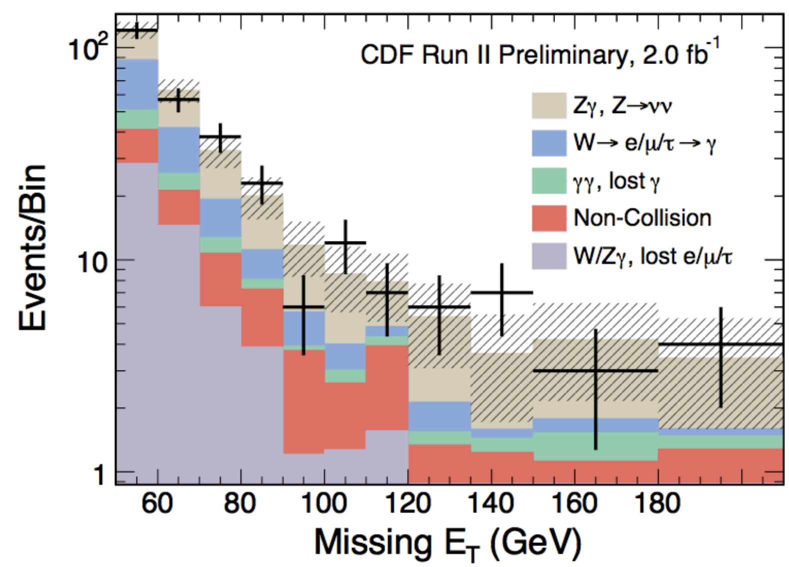
$$\sigma(Z\gamma,\ E_T^{\gamma} > 90\text{GeV}) \times BR(Z \rightarrow \nu\nu) = 31.9 \pm 9(\text{stat}+\text{sys}) \pm 2(\text{lumi})\ \text{fb}$$

SM NLO prediction = 39 ± 4 fb

- **Significance of observation** 5.1 σ – First Tevatron observation

PRL 102, 201802 (2009)





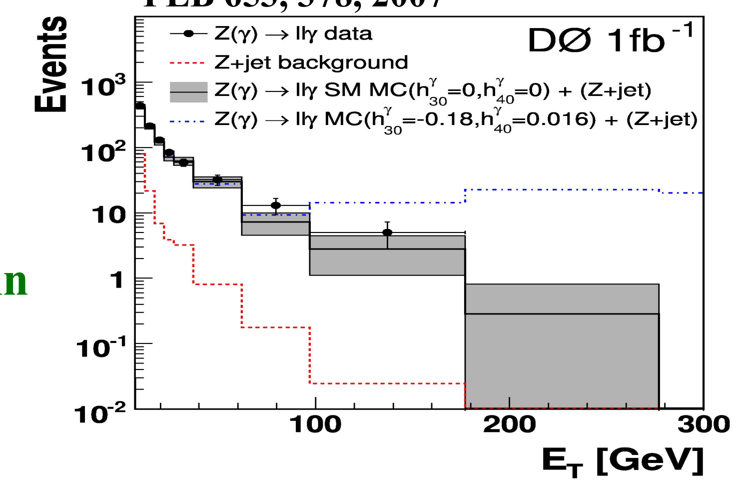
Z γ analysis: probing ZγZ and Zγγ couplings

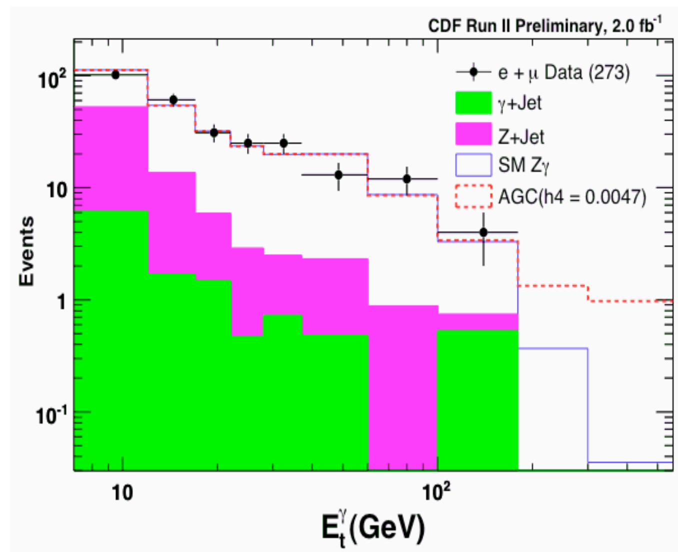
- No ZγZ and Zγγ vertices in SM
- Non-SM ZγZ and Zγγ TGCs enhance production cross section
  - ➢ Particularly at high-p_T region of photon
  - ➢ Probes $h^Z_{30,40}$ and $h^\gamma_{30,40}$ parameters (both zero in SM)
- Combined 95 % C.L. limits on γZZ and γγZ TGCs from Zγ→ννγ / eeγ / μμγ channels.

	DØ published 1 fb^{-1} ee/μμ, 3.6 fb^{-1} νν Λ=1.5 TeV	CDF preliminary 1.1 fb^{-1} ee, 2.0 fb^{-1} μμ/νν Λ=1.2 TeV
h^γ_{30}	[-0.033, 0.033]	[-0.051, 0.051]
h^γ_{40}	[-0.0017, 0.0017]	[-0.0034, 0.0034]
h^Z_{30}	[-0.033, 0.033]	[-0.050, 0.050]
h^Z_{40}	[-0.0017, 0.0017]	[-0.0034, 0.0034]

- Some of the most restrictive limits so far.

PLB 653, 378, 2007

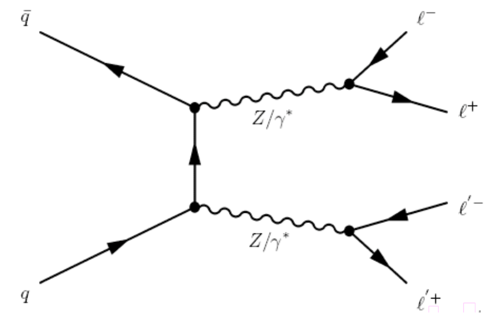




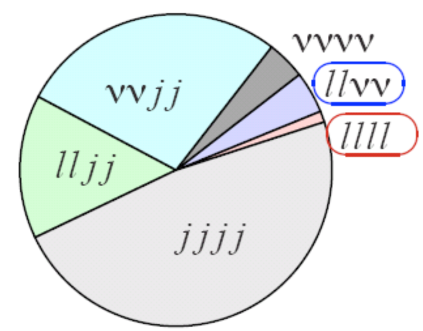
ZZ production

- **Very small production cross section:**

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



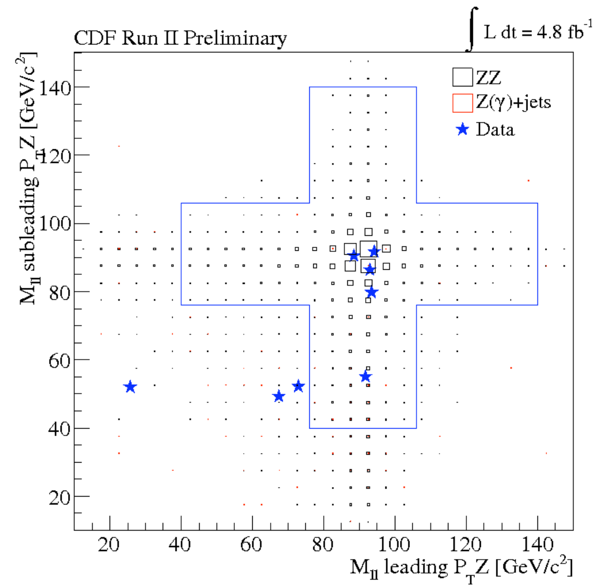
- **Two main decay modes studied at the Tevatron**
  - **ZZ → 4l, with l=e,μ**
    - **Four high-pT isolated leptons;**
    - **On-shell Z boson requirements:**
      - **CDF: $M_1(ll)$ = [76 –106 GeV], $M_2(ll)$ = [40 -140 GeV].**
      - **DØ: $M_1(ll) > 70$ GeV, $M_2(ll) > 50$ GeV**
    - **Low background from Z/γ+jets and ttbar.**
    - **Small BR $=(2 \times 0.033)^2 = 0.0044$**



  - **ZZ → llνν, with l = e, μ**
    - **Events with ee/μμ + large E_t^{mis}.**
    - **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 production

- **Z→4l channel**
  - **Split 4e, 4μ and 2e2μ channels into exclusive categories depending whether a lepton has a track and/or is identified explicitly.**
  - **DØ (L_{int}=2.7 fb^{-1}): 3 candidates observed**
    - **5.7σ stat. significance – first Tevatron Observation**
  - **CDF (L_{int} = 4.8 fb^{-1}): 5 candidates observed**



- **Cross section measurements**
  - **DØ combined channels, L_{int}=2.7 fb^{-1} (PRL 101, 17803, 2008):**

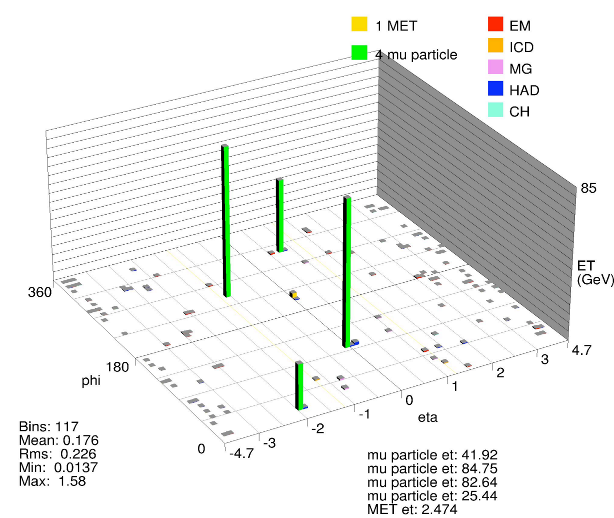
$$\sigma(ZZ) = 1.60 \pm 0.63(\text{stat})^{+0.16}_{-0.17}(\text{sys})\ \text{pb}$$

  - **CDF Z→4l L_{int}=4.8 fb^{-1} (preliminary):**

$$\sigma(ZZ) = 1.56^{+0.80}_{-0.63}(\text{stat}) \pm 0.25(\text{sys})\ \text{pb}$$

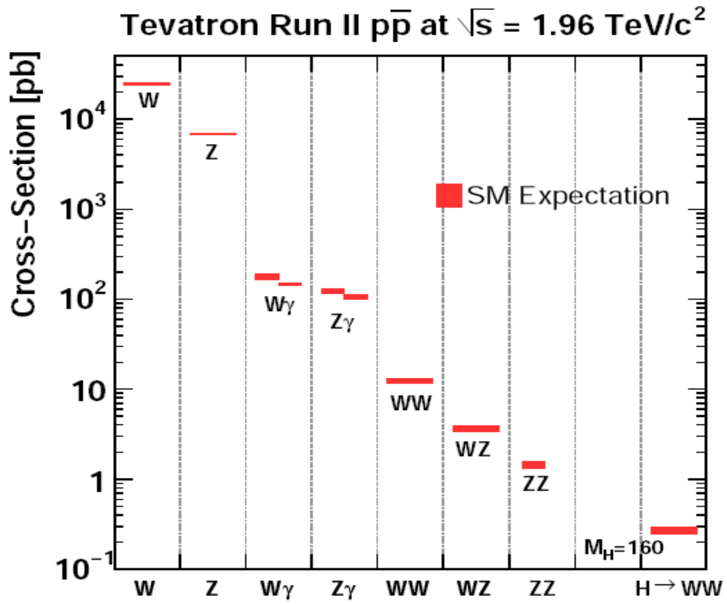
σ(ZZ)=1.4±0.1 pb predicted by NLO

DØ: 4μ candidate event



Summary

- Very rich diboson program at the Tevatron:
  - First time observations of diboson processes not accessible previously.
  - Important benchmarks for the Higgs searches.
  - Testing various triple gauge boson couplings with increasingly higher precisions.
  - Probing peculiar features predicted by the Standard Model.
  - Extending studies beyond leptonic final states.



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

- With only fraction of data analyzed and ×1.5 more luminosity expected from the accelerator, more precise diboson measurements from Tevatron in the near future.