HCP 2008 May 27 - 31, 2008

Diboson Production at the Tevatron

Ia Iashvili

University at Buffalo
The State University of New York

For the CDF and DØ Collaborations

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- ZZ production
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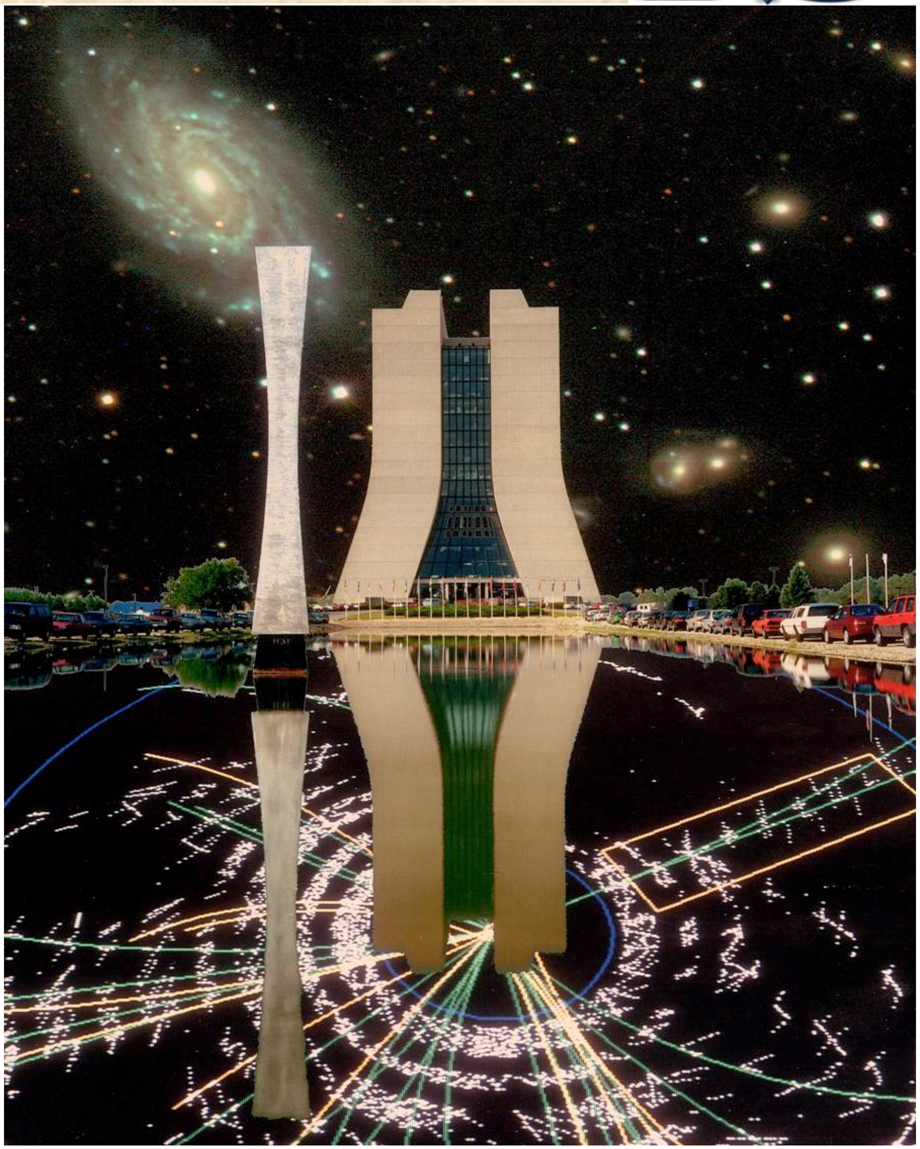
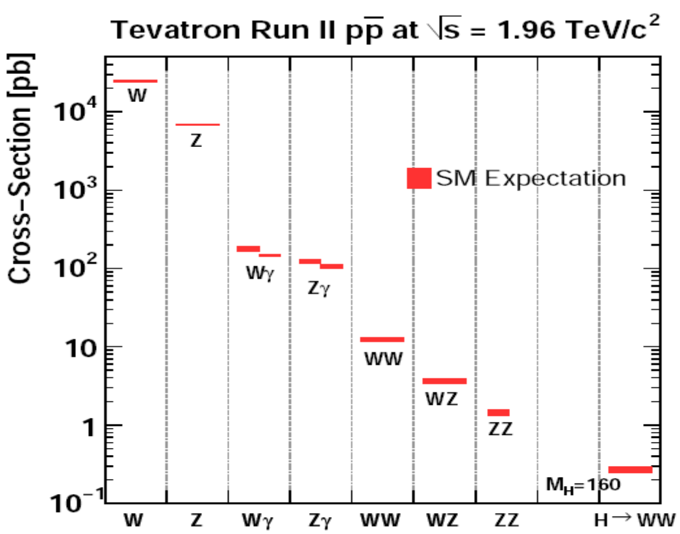


Introduction

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

Introduction

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

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

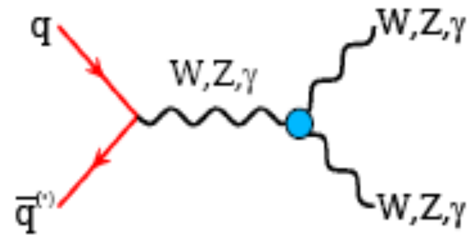
where $V = Z, \gamma$

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:

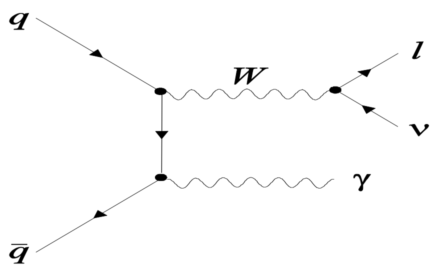
on-shell Zγ ($Z\gamma Z^*, Z\gamma\gamma^*$)		on-shell ZZ ($ZZZ^*, ZZ\gamma^*$)
h_{10}^V, h_{20}^V	(CP violating)	f_{40}^V
h_{30}^V, h_{40}^V	(CP conserving)	f_{50}^V

SM predicts all to be 0

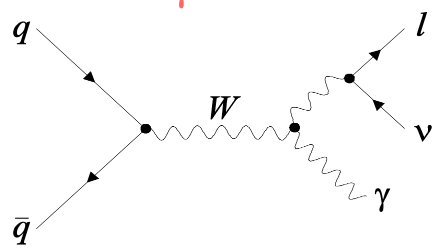
Wγ analysis at DØ

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

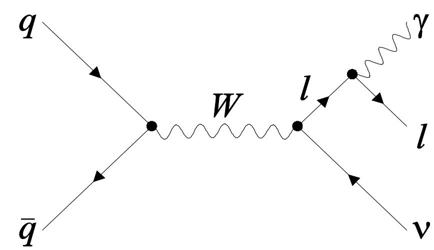
Initial State Radiation



WWγ Vertex



Final State Radiation

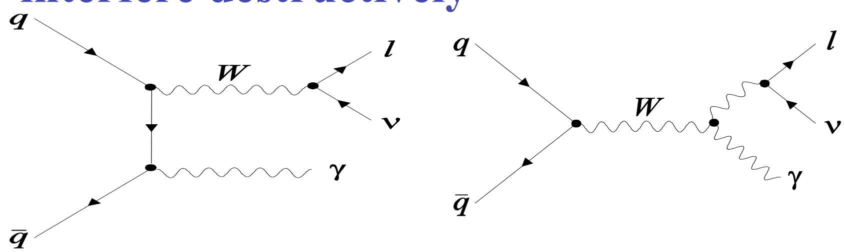


- **Deviation from the SM prediction would be a sign of new physics**
  - **Particularly at high p_T region of photon**
  - **Sensitive to WWγ coupling**
  - **Interference of photons radiated from quark and W lines yield a peculiar experimental feature**
- **Basic W$\gamma \rightarrow l\ \upsilon\ \gamma$ 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**

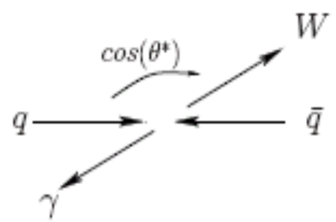
  } **To reduce FSR contribution**
- **Main background processes:** **W+jets, "*l*eX"– events with *l* and e faking γ, W(→τ υ)γ, Zγ.**

Wγ analysis: Radiation Amplitude Zero

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

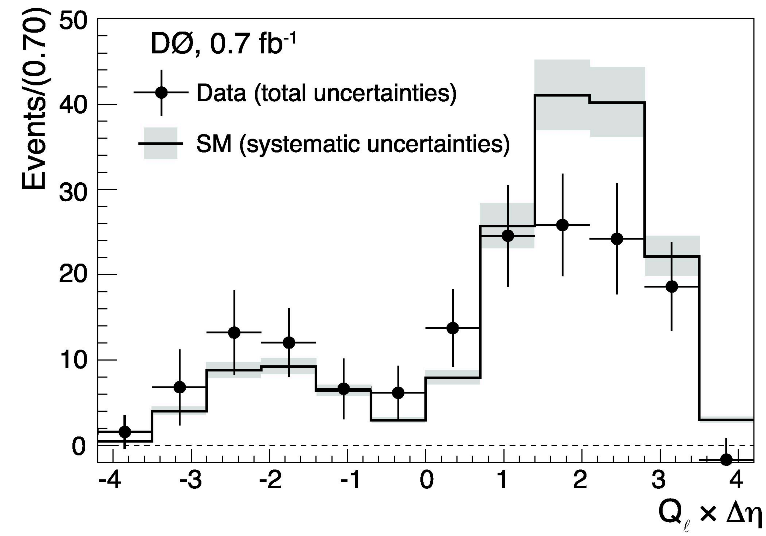


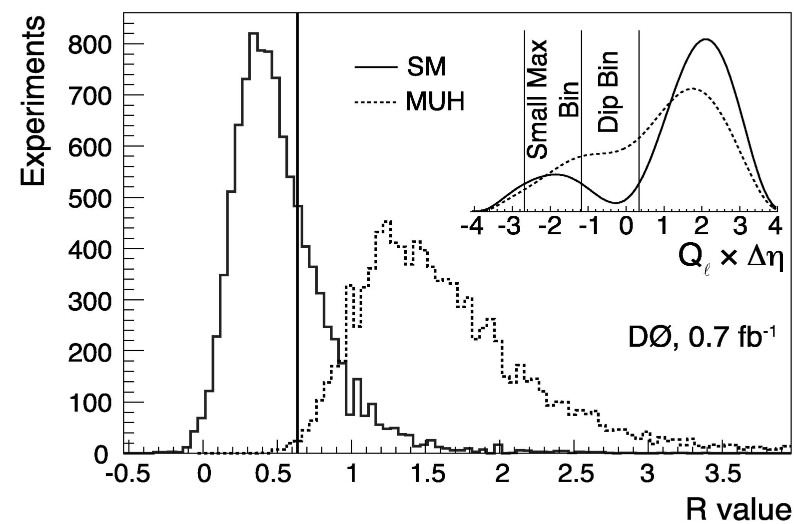
  - **Zero amplitude at**
    - **$\cos\theta^* = +1/3$ for u dbar $\rightarrow W^+\gamma$**
    - **$\cos\theta^* = -1/3$ for d ubar $\rightarrow W^-\gamma$**



  - **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*.**



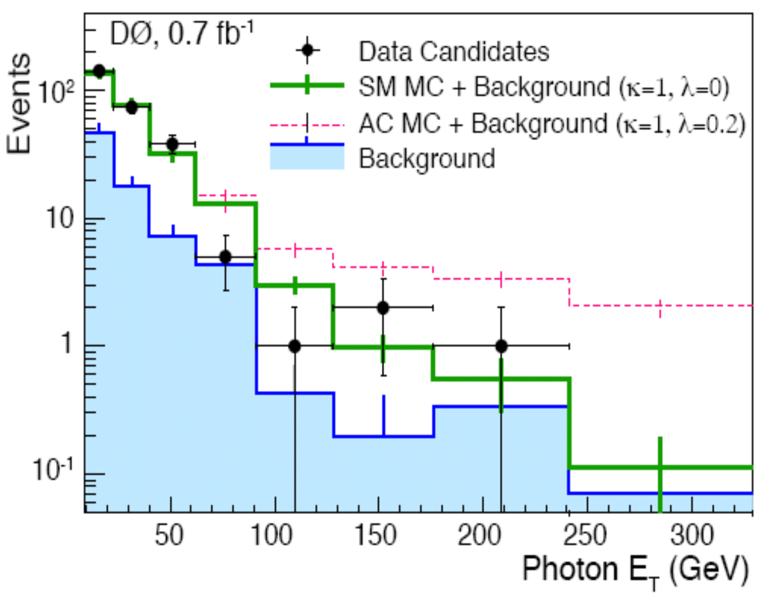


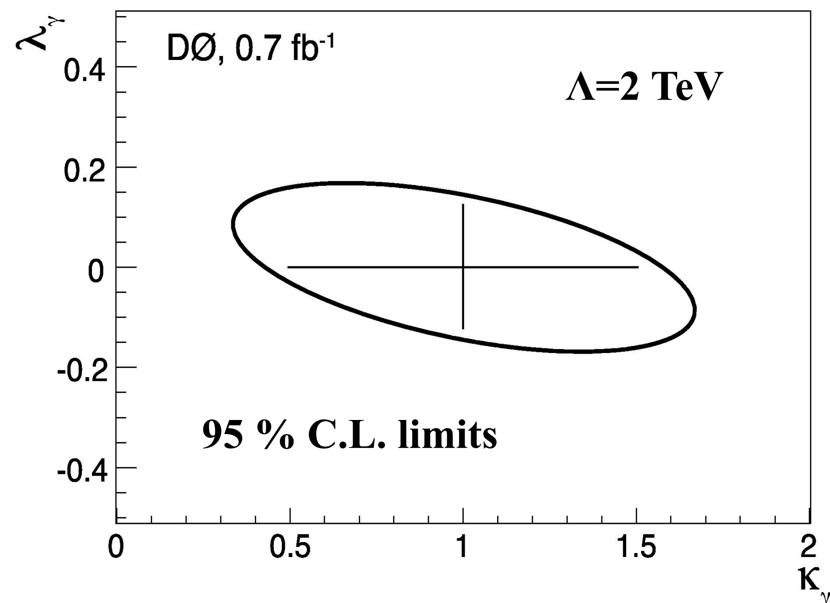
Wγ analysis: probing WWγ coupling

- **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)**

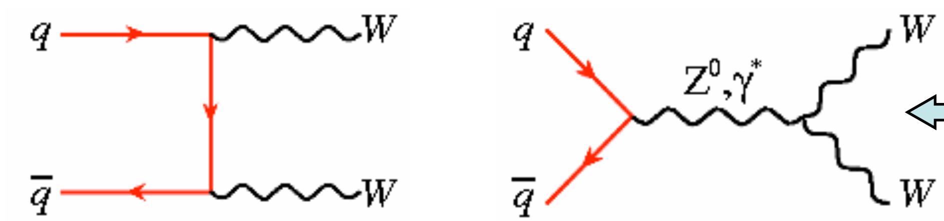
DØ (0.7 fb-1), Λ=2TeV	LEP, $\hat{s} \approx 2M_W$
$-0.49 < \Delta\kappa_\gamma < 0.51$	$-0.105 < \Delta\kappa_\gamma < 0.069$
$-0.12 < \lambda_\gamma < 0.13$	$-0.059 < \lambda_\gamma < 0.026$

arXiv:0803.0030v1, Accepted by PRL





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, $L \approx 240\ pb^{-1}$,** ***PRL 94, 151801 (2005)***

$$\sigma = 13.8^{+4.3}_{-3.8}(\text{stat})^{+1.2}_{-0.9}(\text{sys}) \pm 0.9(\text{lumi})\ \text{pb}$$

  - **CDF, $L \approx 825\ pb^{-1}$, preliminary**

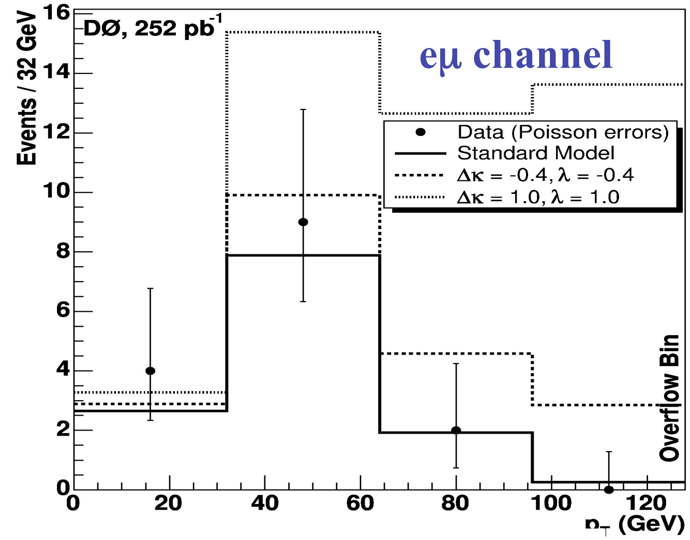
$$\sigma = 13.6 \pm 2.3(\text{stat}) \pm 1.6(\text{sys}) \pm 1.2(\text{lumi})\ \text{pb}$$

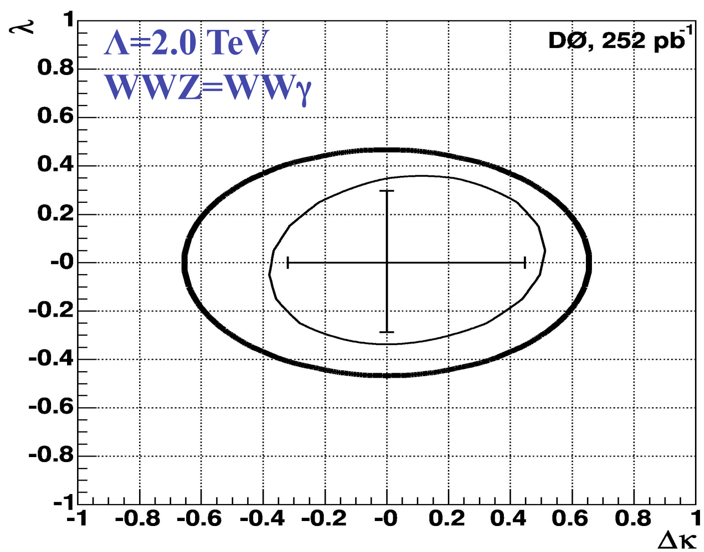
Previous results with $L = 200\ pb^{-1}$ in ***PRL 94, 211801 (2005)***

WW →*lνlν* 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:
  - WWZ coupling = WWγ coupling
  - HISZ parametrization: imposes SU(2)×U(1) symmetry on the coupling parameters
  - Fix WWZ (WWγ) coupling to the SM value

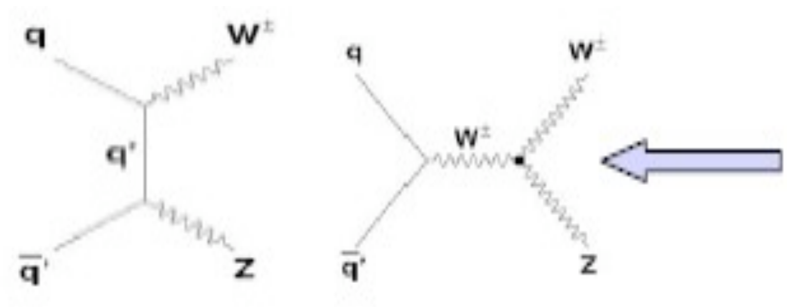
PRD 74 (057101), 2006





Coupling		95% C.L. Limits	Λ (TeV)
$WW\gamma = WWZ$	λ	$-0.31, 0.33$	1.5
	$\Delta\kappa$	$-0.36, 0.47$	
$WW\gamma = WWZ$	λ	$-0.29, 0.30$	2.0
	$\Delta\kappa$	$-0.32, 0.45$	
HISZ	λ	$-0.34, 0.35$	1.5
	$\Delta\kappa_\gamma$	$-0.57, 0.75$	
SM $WW\gamma$	λ_Z	$-0.39, 0.39$	2.0
	$\Delta\kappa_Z$	$-0.45, 0.55$	
SM WWZ	λ_γ	$-0.97, 1.04$	1.0
	$\Delta\kappa_\gamma$	$-1.05, 1.29$	

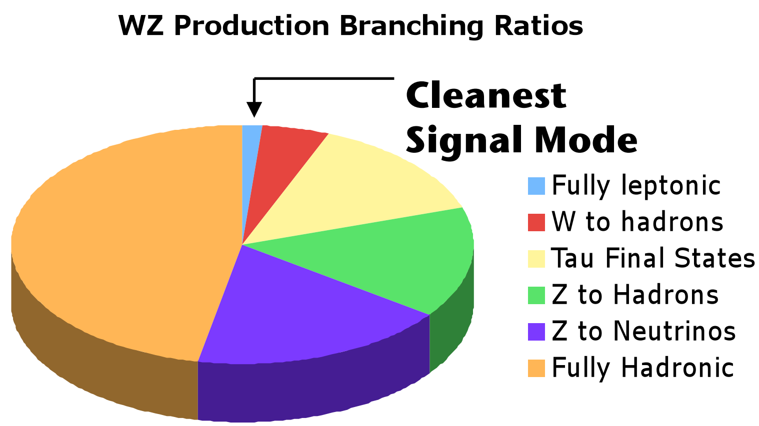
WZ → *lllν* production



- **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}:**

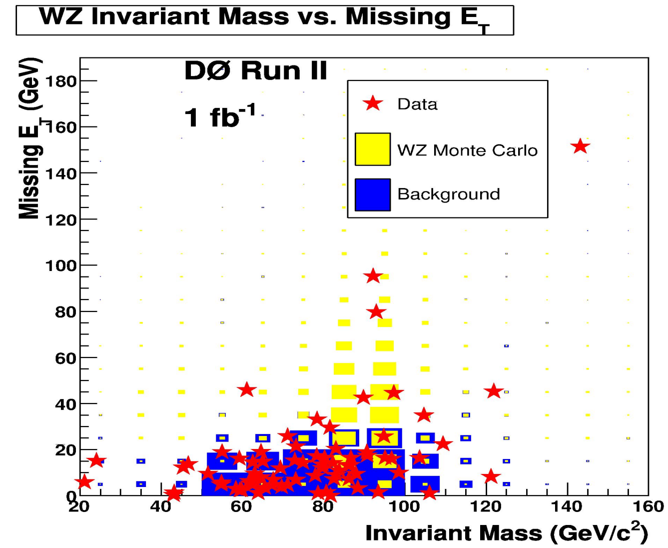
    Events observed 25

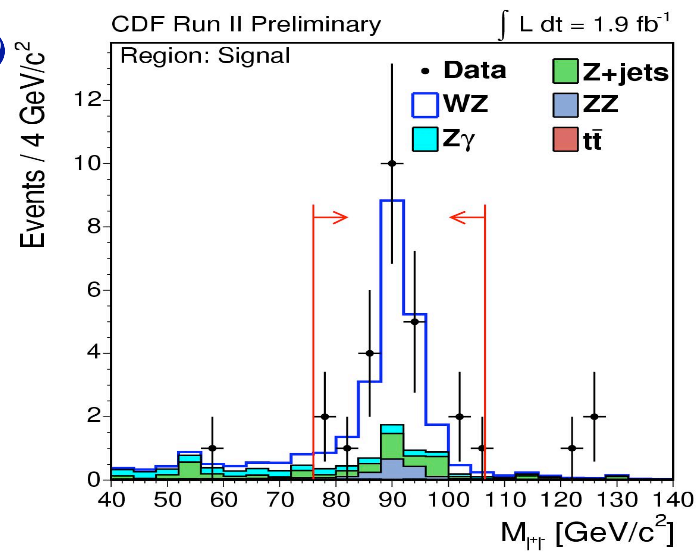
    Expected background 4.7±1.5

    Expected signal 16.5±2.0

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

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

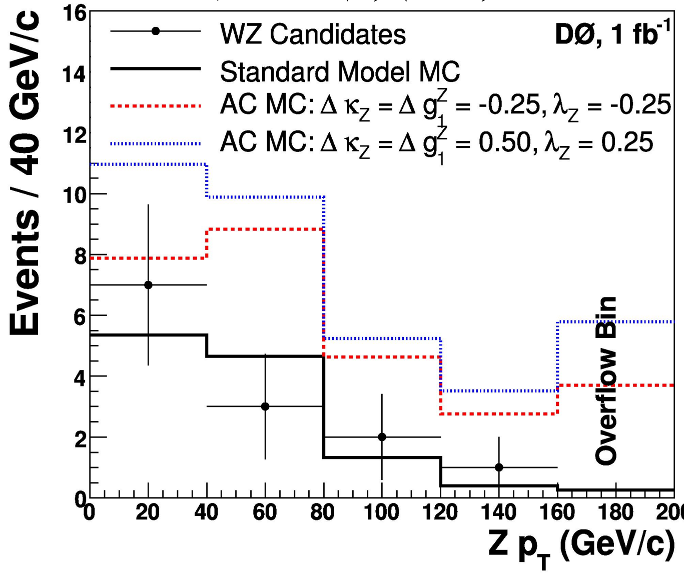


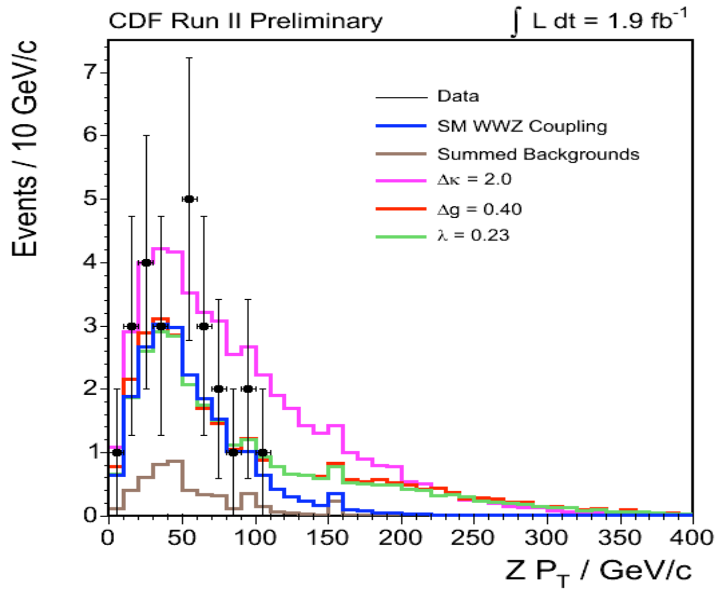


WZ → $ll\nu$ production: probing WWZ coupling

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

PRD 76, 111104(R) (2007)



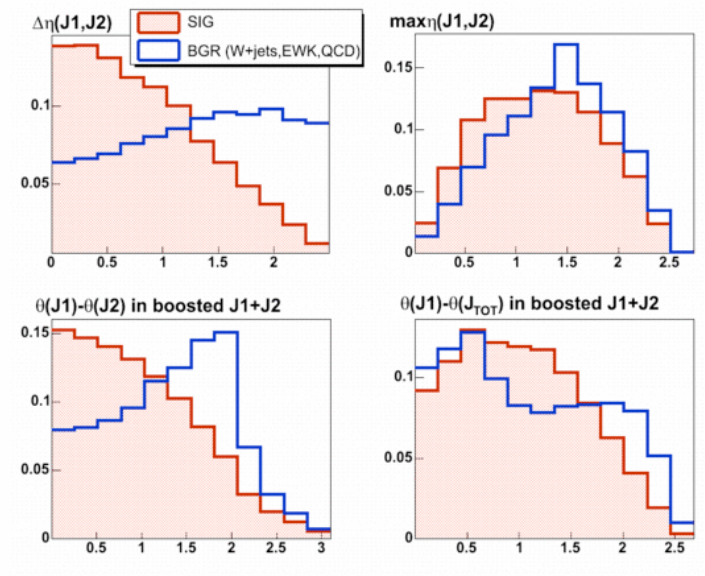


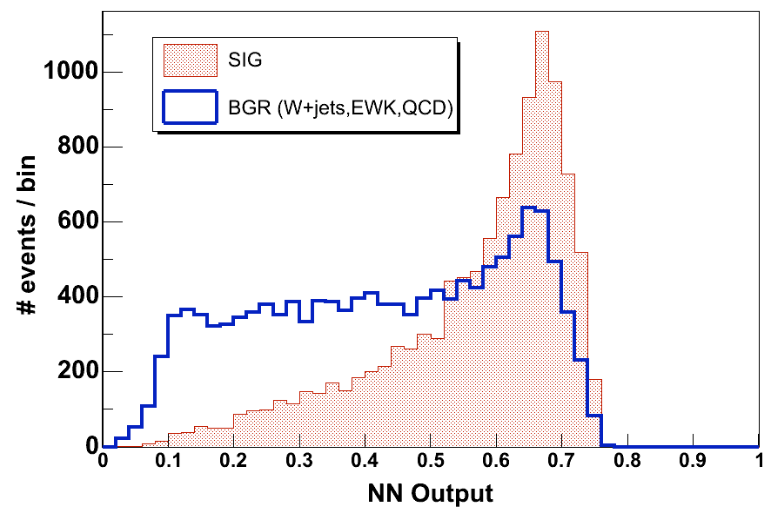
95% C.L. limits for Λ=2 TeV

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 at CDF

- 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
  - Hih p_T electron or muon
  - High missing E_T
  - High $M_T(l, E_T^{miss})$
  - ≥ 2 jets
- S/B < 1% after selection
  - Apply NN to suppress background
  - For NN input only use variables non-correlated with M(jj)
  - Look for "bump" in M(jj) distribution





WW/WZ→lνjj at CDF

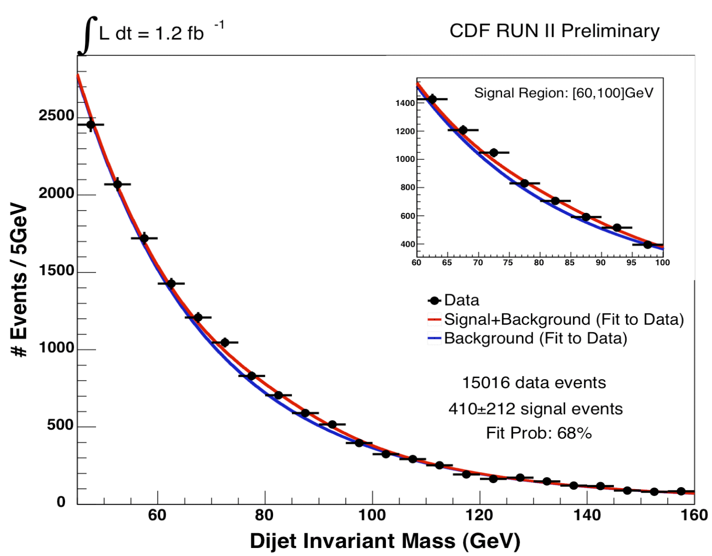
- Signal is extracted by fitting M(jj) distribution
  - Signal shape from MC
  - Background shape from MC+data

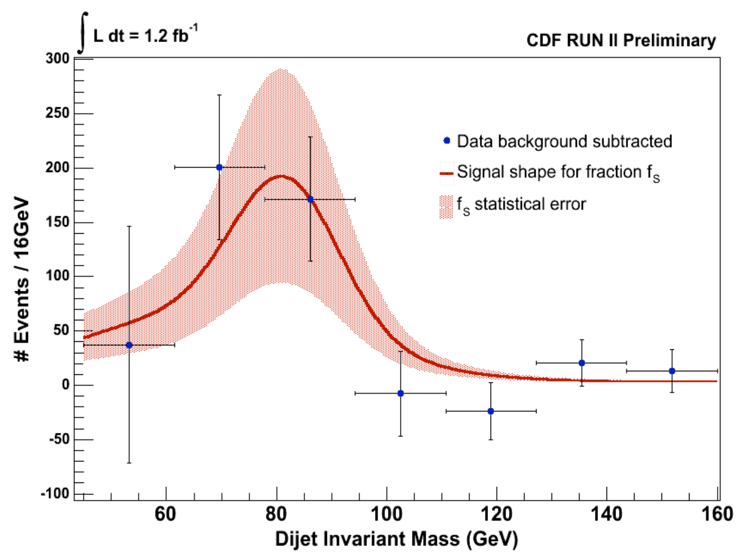
$$Nsignal = 410 \pm 212(stat) \pm 107(syst)$$

Measured cross section $\sigma \times \mathrm{Br} = 1.47 \pm 0.77(\mathrm{stat}) \pm 0.38(\mathrm{sys})\mathrm{pb}$

95% C.L. upper limit $\sigma \times \mathrm{Br} < 2.88\ \mathrm{pb}$

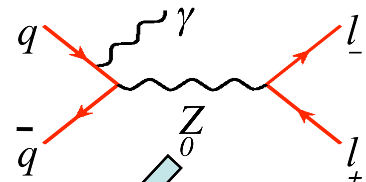
Theory calculation $\sigma \times \mathrm{Br} = 2.09 \pm 0.14\mathrm{pb}$



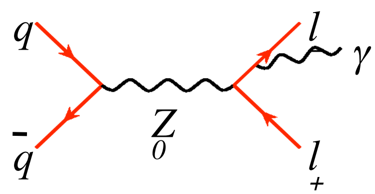


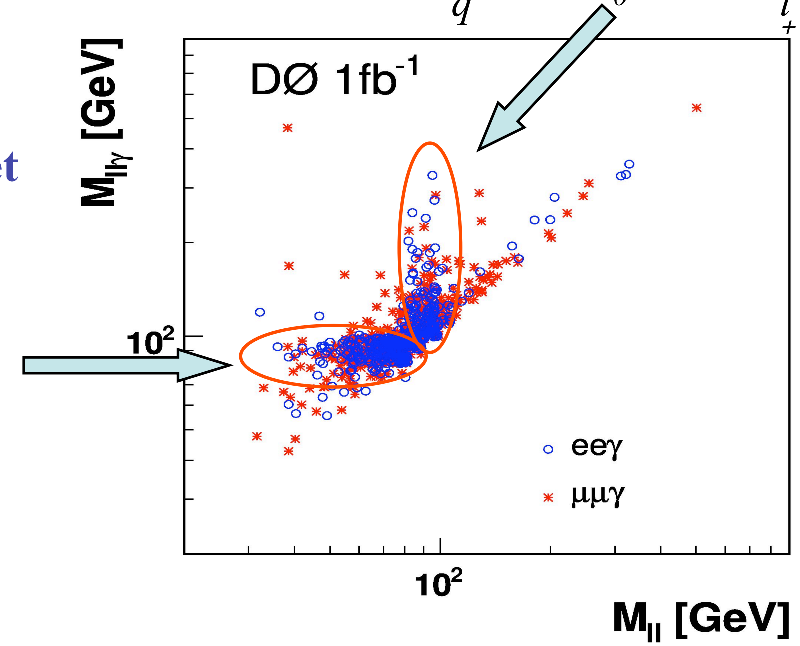
Z γ analysis

- **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 $dR_{l\gamma} > 0.7$

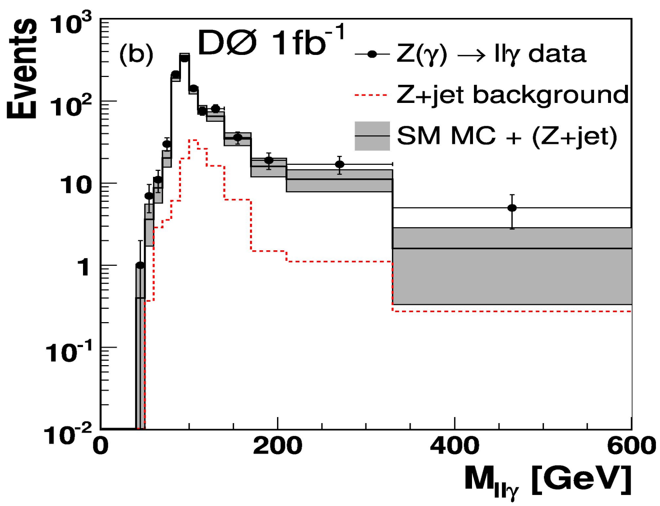


- **Main background process Z(→ee/μμ)+jet production**





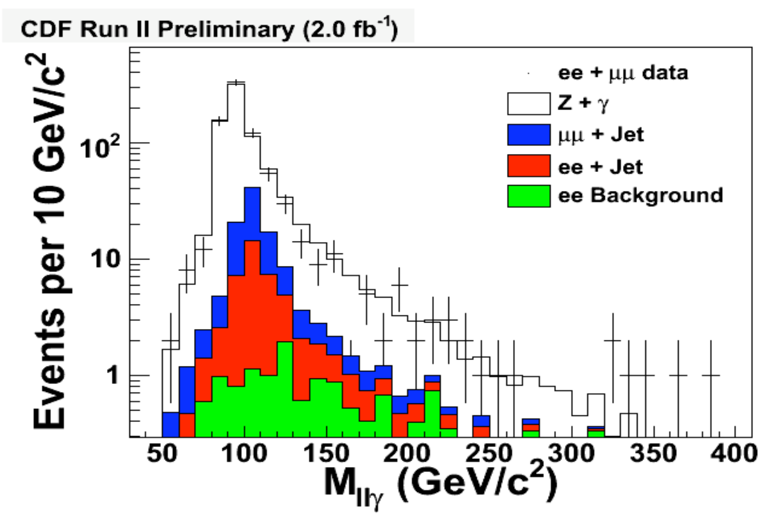
PLB 653, 378 (2007)

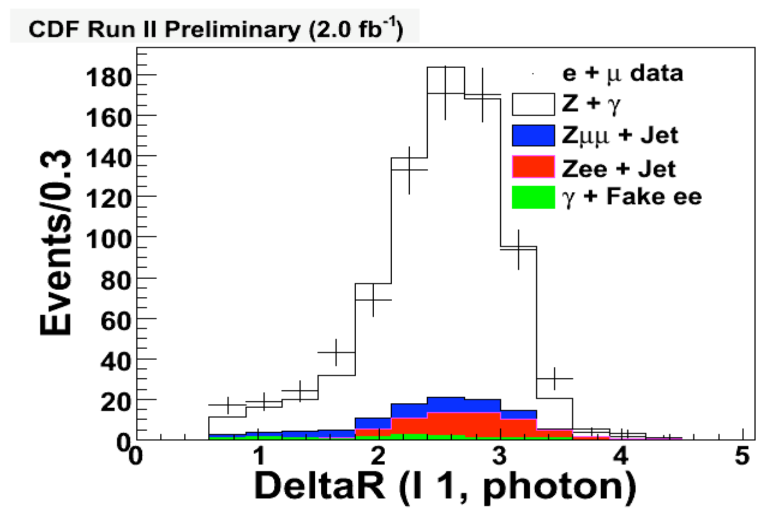


- **Cross section:**
  - DØ measurement $\sigma \times BR(Z\gamma \rightarrow ll\gamma) = 4.96 \pm 0.42\,\text{pb}$
  - NLO theory $\sigma \times BR(Z\gamma \rightarrow ll\gamma) = 4.74 \pm 0.22\,\text{pb}$

Z γ analysis

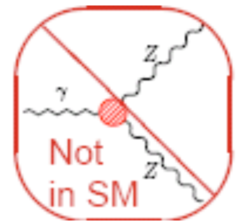
- **CDF:** separate measurements for ISR and FSR processes:
  - ISR enriched sample by applying M ($l\,l\,\gamma$) > 100 GeV
    - Measured $\sigma \times BR(Z\gamma \to ll\gamma) = 1.2 \pm 0.1(stat.) \pm 0.2(syst.) \pm 0.1(lumi)\ \ pb$
    - NLO theory $\sigma \times BR(Z\gamma \to ll\gamma) = 1.2 \pm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

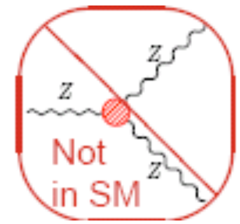


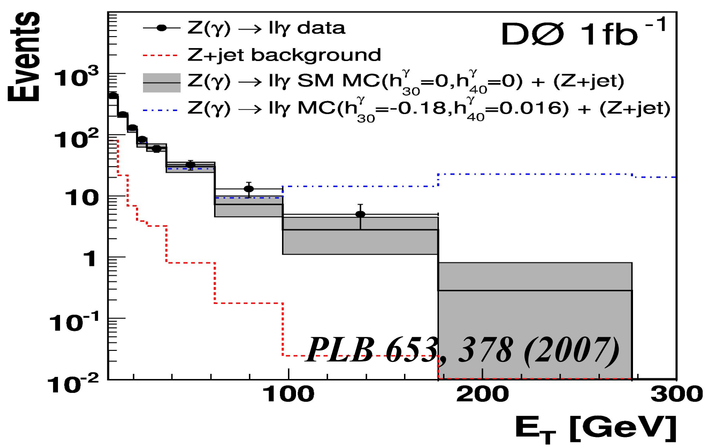


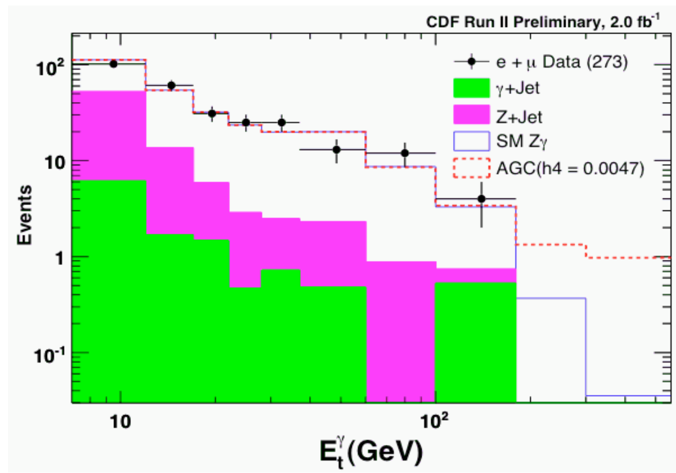
Z γ analysis: probing ZγZ and Zγγ couplings

- 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_3^γ	[-0.085, 0.084]	[-0.084, 0.084]	[-0.049, -0.008]
h_4^γ	[-0.0053, 0.0054]	[-0.0047, 0.0047]	[-0.002, 0.034]
h_3^Z	[-0.083, 0.082]	[-0.083, 0.083]	[-0.20, 0.07]
h_4^Z	[-0.0053, 0.0054]	[-0.0047, 0.0047]	[-0.05, 0.12]

ZZ production

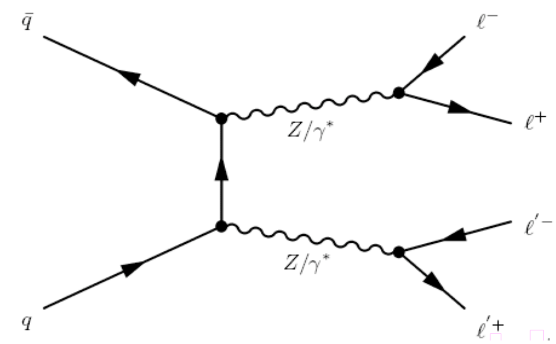
- **Very small production cross section:**

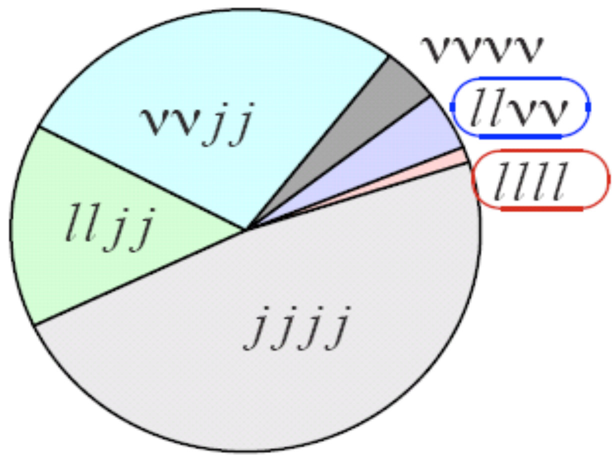
$$\sigma(p\bar{p} \rightarrow ZZ) = 1.4 - 1.6 \text{ pb}$$

- **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**

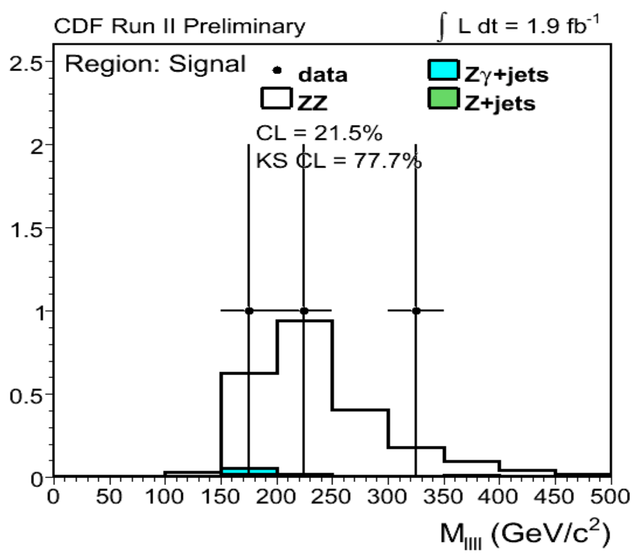


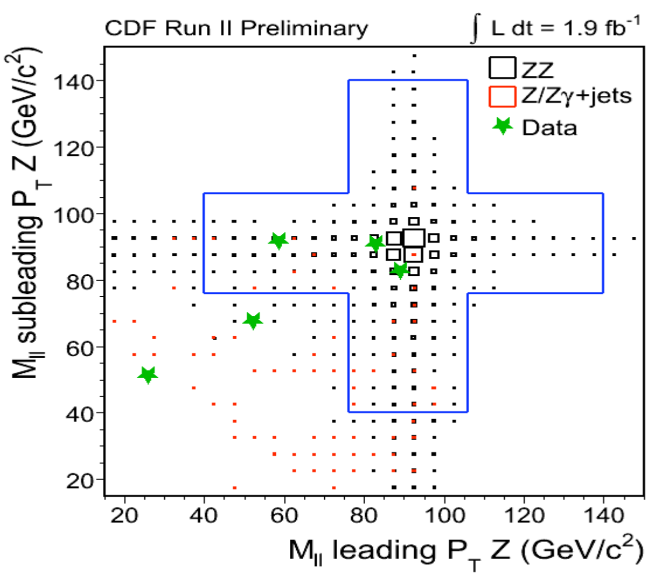


ZZ→4*l* at CDF

- **Z→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]; the other pair with M(ll) in [40 GeV -140 GeV].**

$1\ fb^{-1}$ Category	Candidates without a a trackless electron	Candidates with a a trackless electron
ZZ	$1.990 \pm 0.013 \pm 0.210$	$0.278 \pm 0.005 \pm 0.029$
Z+jets/$Z\gamma$+jets	$0.014^{+0.010}_{-0.007} \pm 0.003$	$0.082^{+0.089}_{-0.060} \pm 0.016$
Total	$2.004^{+0.016}_{-0.015} \pm 0.210$	$0.360^{+0.089}_{-0.060} \pm 0.033$
Observed	**2**	**1**





ZZ→$ll\nu\nu$ at CDF

- **Select events with ee/μμ + large missing E_T.**
Veto on central jets to suppress ttbar contribution
  - **Observe 276 events in the pre-selected sample**
  - **expect only 14 ± 2 signal events**

- Use the full kinematic information

$$P(\vec{x}_{obs}) = \frac{1}{<\sigma>} \int \frac{d\sigma_{th}(\vec{y})}{d\vec{y}} \epsilon(\vec{y}) G(\vec{x}_{obs}, \vec{y}) d\vec{y}$$

What we measure

$\vec{x}_{obs}$ observed "leptons" and $\vec{E}_T$

Theory at leading order

$\sigma_{th}(\vec{y})$ leading order calculation of the cross-section

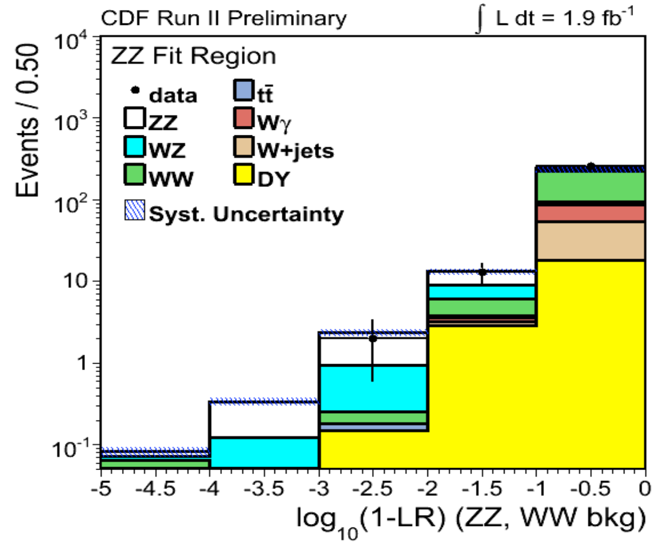
$\vec{y}$ true lepton four-vectors (including neutrinos)

Detector Effects

$\epsilon(\vec{y})$ total event efficiency $\times$ acceptance

$G(\vec{x}_{obs}, \vec{y})$ resolution effects

$$LR \equiv \frac{P_{ZZ}}{P_{ZZ} + P_{WW}}$$



- **Combine ZZ→4l and ZZ→2l2ν channels:**
50% chance to observe 5σ effect

Observed Results

P-Value	0.12	1.1×10^{-5}	5.1×10^{-6}
Significance	1.2 σ	4.2 σ	4.4 σ

- **Cross-section measurement**

$$\sigma(ZZ) = 1.4^{+0.7}_{-0.6}(\text{stat} + \text{sys})\ \text{pb}$$

σ(ZZ)=1.4 pb predicted by NLO

arXiv:0801.4806v1, submitted to PRL

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	ee$\mu\mu$	$\mu\mu\mu\mu$	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:** $\sigma(ZZ) < 4.4\text{pb}$

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

- **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

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

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

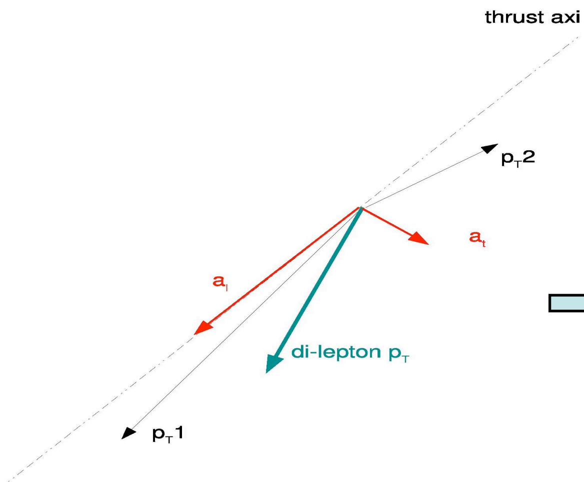
$-0.26 < f_{40}^{\gamma} < 0.26$

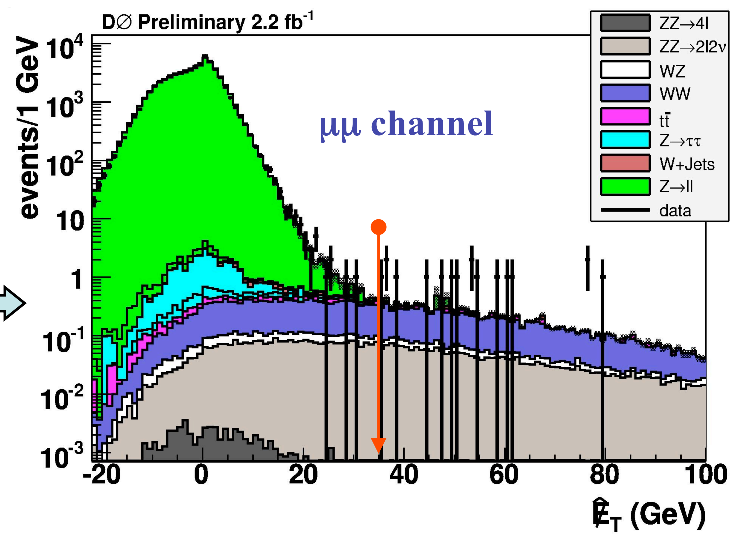
$-0.30 < f_{50}^{\gamma} < 0.28$

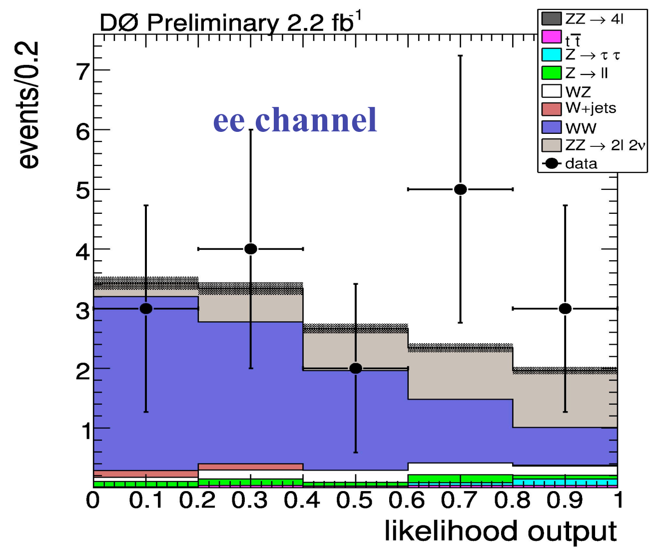
Phys. Rev. Lett. 100, 131801 (2008)

ZZ→$ll\nu\nu$ at DØ

- Select ee/μμ events with M(ll) consistent with M_Z. Veto central jets to suppress ttbar background.
- Find a variable sensitive to mis-measurements of the lepton p_T and the hadronic recoil ⇒ cause of missing E_T in Z(→ee/μμ) background events.
- Combine several variables in a likelihood discriminant





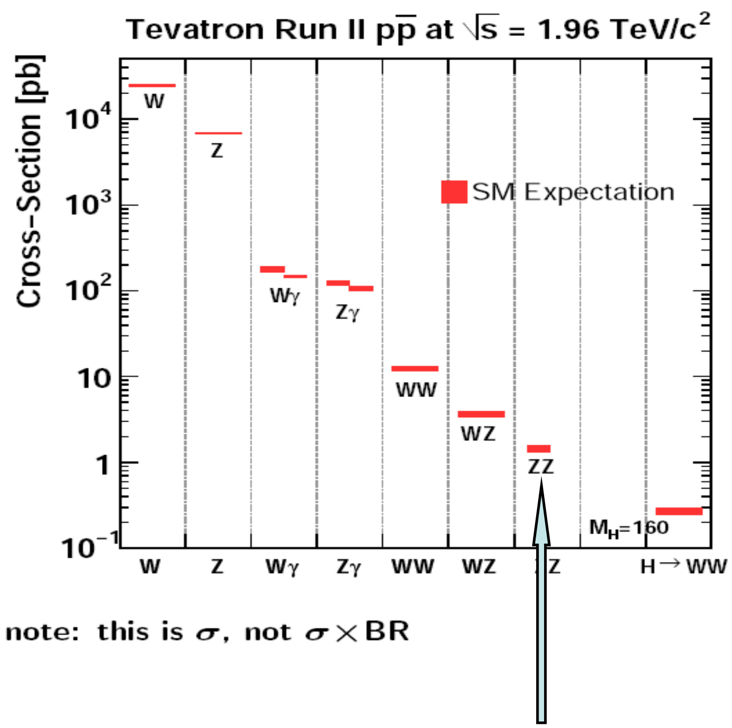


- Significance
  - Expected = 1.8 σ
  - Observed = 2.4 σ
- Cross section $\sigma(p\bar{p} \to ZZ) = 2.1 \pm 1.1(stat.) \pm 0.4(sys.)$ pb

The NLO theory: $\sigma(ZZ) = 1.6 \pm 0.1$pb

Summary

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

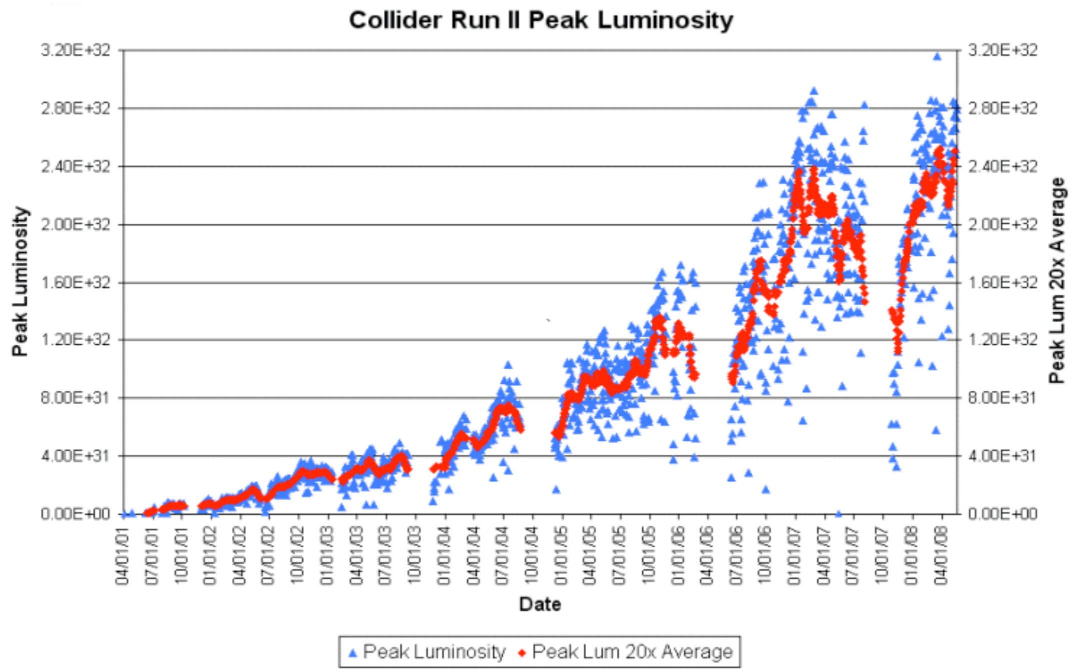


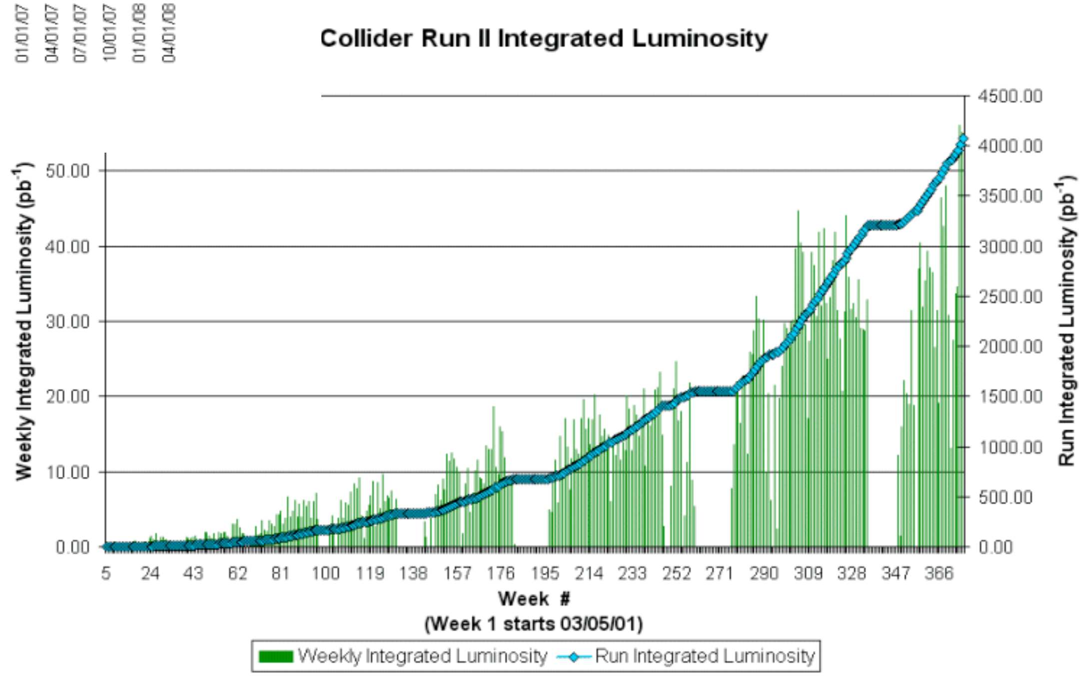
- Even more exciting times ahead
  - Presented results based on 0.2 - 2 fb^{-1}
  - Tevatron experiments have just celebrated delivery of 4 fb^{-1} of data. More data to come.

Already here

Backup slides

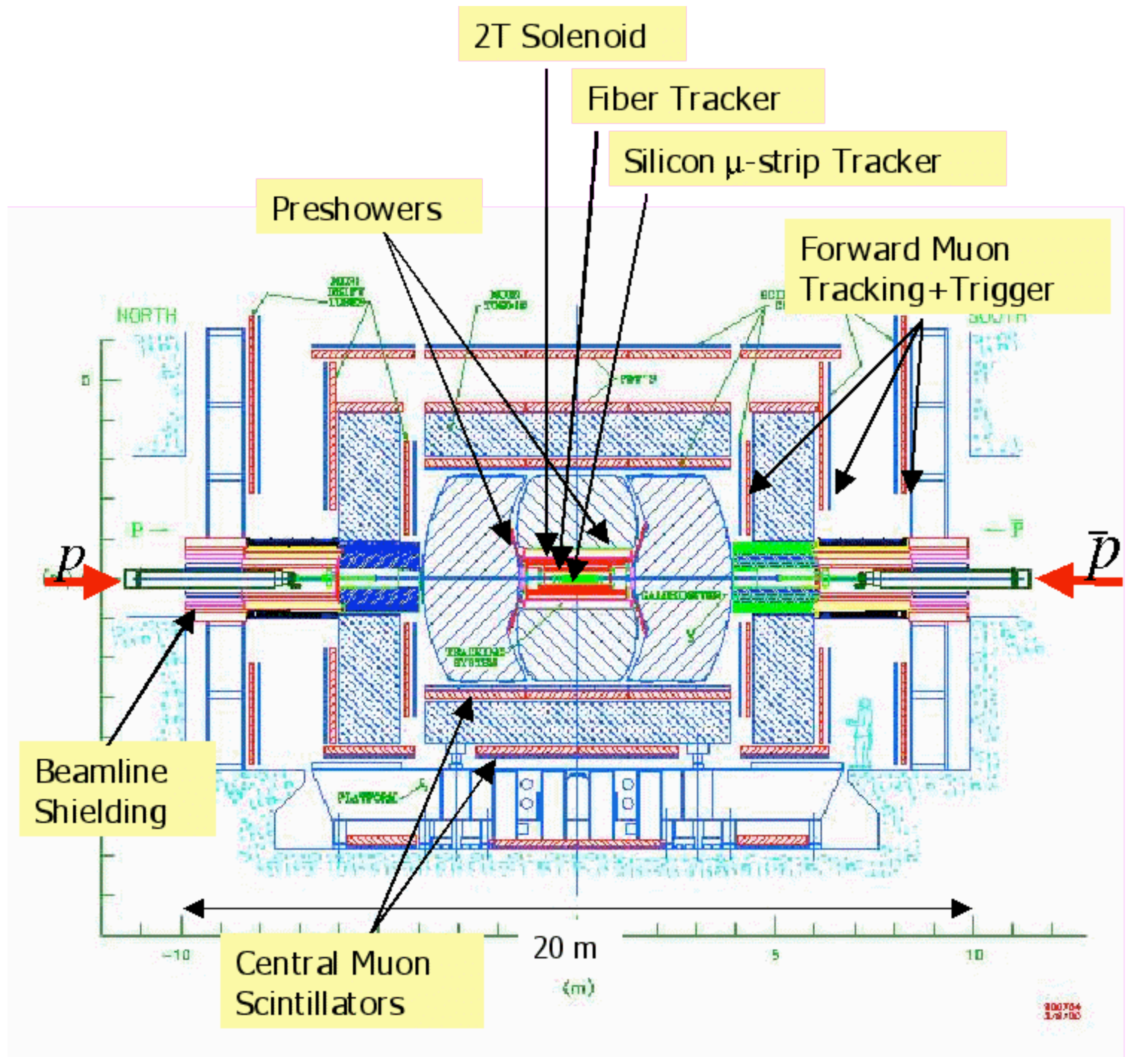
Tevatron


Collider Run II Peak Luminosity
Peak Luminosity
Peak Lum 20x Average
Date
Peak Luminosity
Peak Lum 20x Average

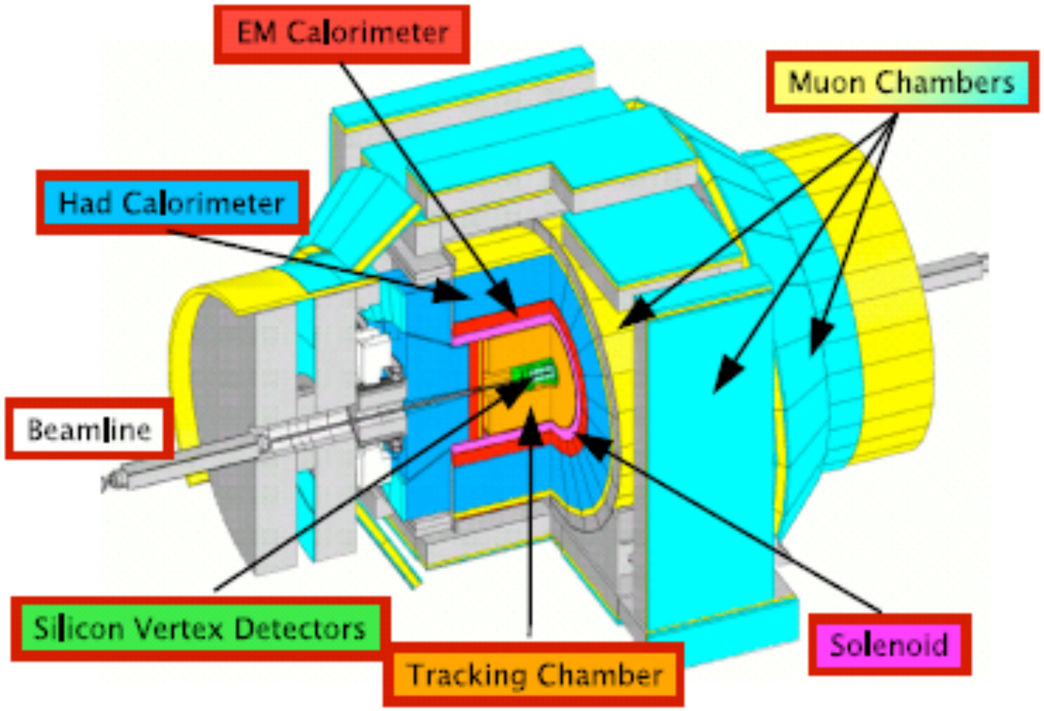

Collider Run II Integrated Luminosity
Weekly Integrated Luminosity (pb-1)
Run Integrated Luminosity (pb-1)
Week #
(Week 1 starts 03/05/01)
Weekly Integrated Luminosity
Run Integrated Luminosity

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 ($0.6 < |\eta| < 1.0$)