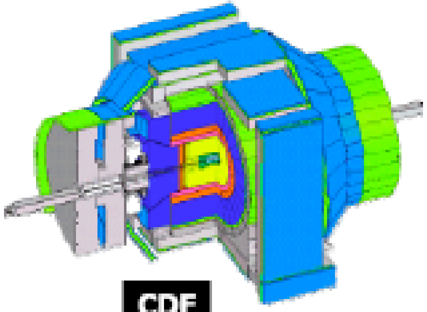
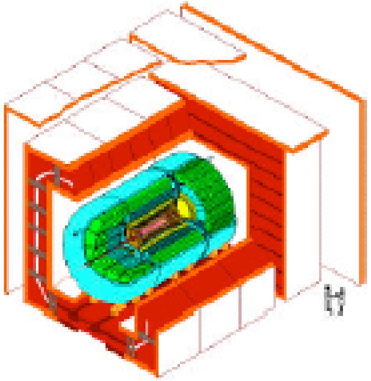
Diboson Physics
at the Tevatron





Hadron Collider Physics
July 5, 2005

Al Goshaw , Duke University
for the CDF and DØ Collaborations

The DZero Collaboration

- 19 Countries
- 86 institutions
- ~620 physicists

AZ U. of Arizona
CA U. of California, Berkeley
U. of California, Riverside
Cal. State U., Fresno
Lawrence Berkeley Nat. Lab.
FL Florida State U.
IL Fermilab
U. of Illinois, Chicago
Northern Illinois U.
Northwestern U.
IN Indiana U.
U. of Notre Dame
IA Iowa State U.
KS U. of Kansas
Kansas State U.
LA Louisiana Tech U.
MD U. of Maryland
MA Boston U.
Northeastern U.
MI U. of Michigan
Michigan State U.
MS U. of Mississippi
NE U. of Nebraska
NJ Princeton U.
NY Columbia U.
U. of Rochester
SUNY, Stony Brook
Brookhaven Nat. Lab.
OK Langston U.
U. of Oklahoma
RI Brown U.
TX Southern Methodist U.
U. of Texas at Arlington
Rice U.
VA U. of Virginia
WA U. of Washington

U. de Buenos Aires

LAFEX, CBPF, Rio de Janeiro
State U. do Rio de Janeiro
State U. Paulista, São Paulo

U. of Alberta
McGill U.
Simon Fraser U.
York U.

IHEP, Beijing

U. de los Andes, Bogotá

Charles U., Prague
Czech Tech. U., Prague
Academy of Sciences, Prague

LPC, Clermont-Ferrand
ISN, IN2P3, Grenoble
CPPM, IN2P3, Marseille
LAL, IN2P3, Orsay
LPNHE, IN2P3, Paris
DAPNIA/SPP, CEA, Saclay
IReS, Strasbourg
IPN, IN2P3, Villeurbanne

U. San Francisco de Quito

The DØ Collaboration

U. of Aachen
Bonn U.
U. of Freiburg
U. of Mainz
Ludwig-Maximilians U., Munich
U. of Wuppertal

Panjab U. Chandigarh
Delhi U., Delhi
Tata Institute, Mumbai

University College, Dublin

KDL, Korea U., Seoul

CINVESTAV, Mexico City

FOM-NIKHEF, Amsterdam
U. of Amsterdam / NIKHEF
U. of Nijmegen / NIKHEF

JINR, Dubna
ITEP, Moscow
Moscow State U.
IHEP, Protvino
PNPI, St. Petersburg

Lund U.
RIT, Stockholm
Stockholm U.
Uppsala U.

Lancaster U.
Imperial College, London
U. of Manchester

HCIP, Hochiminh City

Ann Heinson, UC Riverside

The CDF Collaboration

Russia
JINR, Dubna
ITEP, Moscow

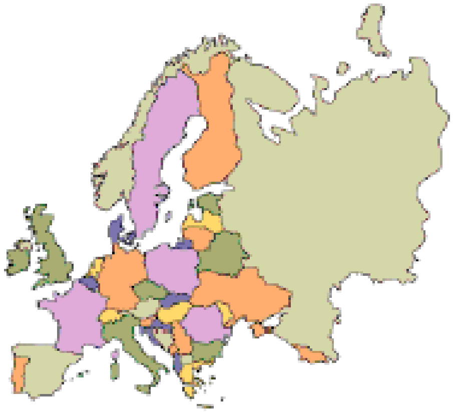
Germany
Univ. Karlsruhe

Switzerland
Univ. of Geneva

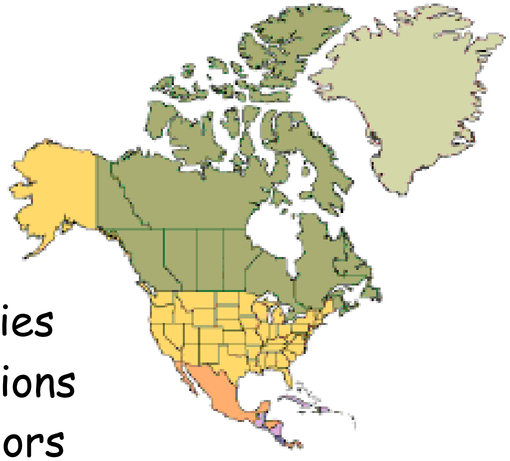
UK
Glasgow Univ.
Univ. of Liverpool
Univ. of Oxford
Univ. College London

Italy
Univ. of Bologna,INFN
Frascati, INFN
Univ. di Padova,
Pisa, INFN
Univ. di Roma I,INFN
INFN-Trieste
Univ. di Udine

Spain
Univ. of Cantabria
IFAE Barcelona
IFAE Valencea

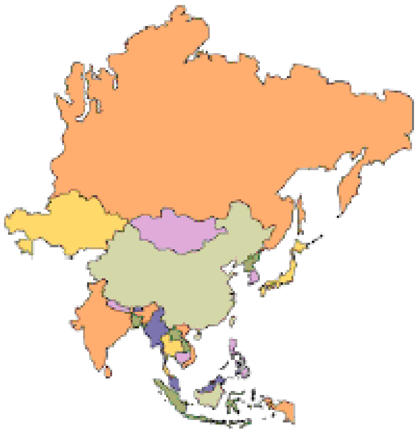


- 12 countries
- 62 institutions
- ~700 authors



Canada
McGill Univ.
Univ. of Toronto

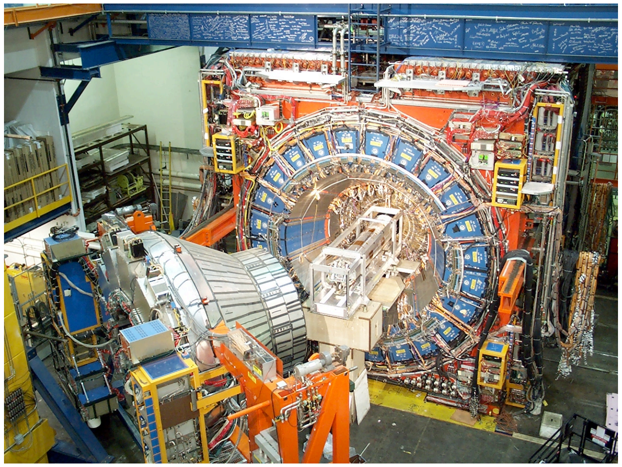
USA
Argonne National Laboratory,IL
Brandeis Univ.,MS
Univ. of Chicago,IL
Davis UC,CA
Duke Univ.,NC
FNAL,IL
Univ. of Florida,FL
Harvard Univ.,MA
Univ. of Illinois,IL
The Johns Hopkins Univ.,MD
LBNL,CA
MIT,MA
Michigan State Univ.,MI
Univ. of Michigan,MI
Univ. of New Mexico,NM
The Ohio State Univ.,OH
Univ. of Pennsylvania,PA
Univ. of Pittsburgh,PA
Purdue Univ.,IN
Univ. of Rochester,NY
Rockefeller Univ.,NY
Rutgers Univ.,NJ
Texas A&M Univ.,TX
Texas Tech Univ.,TX
Tufts Univ.,MA
UCLA,CA
Univ. of Wisconsin,WI
Yale Univ.,CT



Korea
KHCL

Japan
Hiroshima Univ.
KEK
Osaka City Univ.
Univ. of Tsukuba
Waseda Univ., Tokyo

Taiwan
Academia Sinica,
Taipei



Outline

- Introduction
- Survey of recent measurements
  - W($l\nu$) γ
  - W Z studies using leptonic decays
  - WW and WZ studies using leptonic and hadronic decays
  - Z($l\ l$) γ
- Summary and outlook

Introduction

Boson production at the Tevatron

- The CDF and DØ collaborations are completing the first round of Run II studies of γ, W, Z and H production.

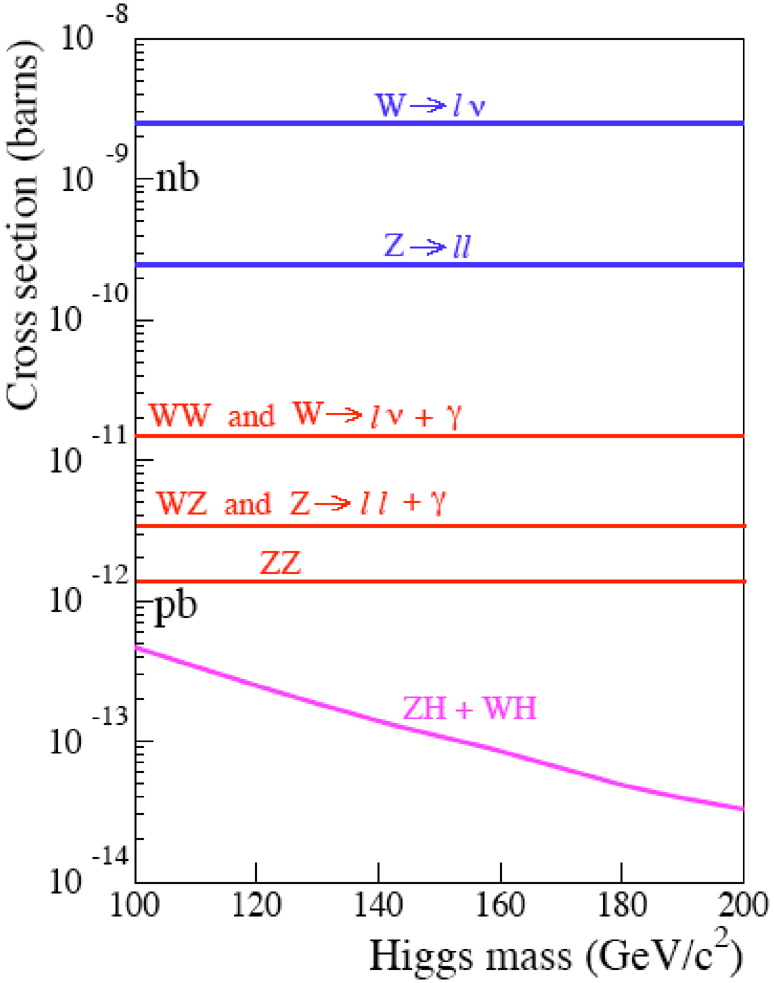
- Inclusive W and Z bosons
  - W/Z production and decay properties (Serban Protopopescu's talk)
  - W mass and width (Mark Lancaster's talk)

- Vector boson pair production (this talk)

γ γ	W W
W γ	W Z
Z γ	Z Z

- Higgs boson searches (Anna Goussiou talk)
  - WH, ZH, H->W*W, SUSY Higgs

p p̄ production cross sections of W and Z bosons at $\sqrt{s}$ = 1.96 TeV



High statistics W/Z inclusive

Lower statistics di-bosons

$E_T(\gamma) > 10$ GeV $\Delta R(l\gamma) > 0.7$

Limits on H production

Di-boson physics at the Tevatron

- The study of di-boson production provides a rich source of electroweak Standard Model tests, is sensitive to new physics signatures, and opens a window into the challenges faced in searches for the Higgs boson.

- The CDF and DØ experiments have completed the first analysis phase
  - Results reported here are based upon 200-400 pb^{-1} of data.
  - Goal is to update with ~ 1 fb^{-1} of data by winter conferences 2006
  - Ultimate sensitivity based upon 4-8 fb^{-1}
  - And then continuation at the LHC …

- There are separate talks on electron, photon and muon identification at CDF and DØ, and I will not dwell on details here
  - Electron/photon ID at the Tevatron (Greg Veramendi's talk)
  - Muon ID at the Tevatron (Jeff Temple's talk)

Approach to di-boson studies

- 1. Compare di-boson (Wγ, Zγ, WW, WZ, ZZ) production properties to Standard Model predictions and measure agreement/deviations.

- 2. Use anomalous coupling parameters as the metric for evaluating the sensitivity to new physics. This assumes the new physics appears as deviations of the W and Z boson from Standard Model point particles.

  There are of course other sources of new physics that would appear in di-boson production -- perhaps the most likely sources of a discovery.

- 3. Use the advantage of having both $q\bar{q}$ and $q\bar{q}'$ collisions to separate out specific triple gauge couplings where possible:

$q\bar{q}'$ -> W* -> W γ	WWγ coupling only	
$q\bar{q}'$ -> W* -> W Z	WWZ coupling only	
$q\bar{q}$ -> Z/γ -> W W	mix of WWγ and WWZ couplings	
$q\bar{q}$ -> Z/γ -> Z γ	mix of ZZγ and Zγγ couplings	absent in SM
$q\bar{q}$ -> Z/γ -> Z Z	mix of ZZγ and ZZZ couplings	

Approach to di-boson studies

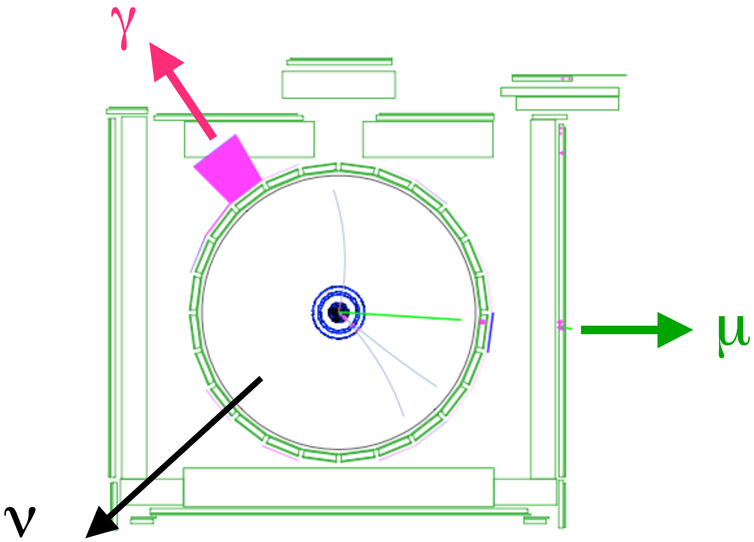
- 4. For the triple gauge coupling studies use (primarily) leptonic decays of the W and Z:
  - $W\gamma \rightarrow l\nu\gamma$
  - $Z\gamma \rightarrow l^+ l^- \gamma$
  - $W^+ W^- \rightarrow l^+ \nu\ l^- \nu$
  - $WZ \rightarrow l' \nu\ l^+ l^-$
  - $ZZ \rightarrow l^+ l^- l'^+ l'^-$ and $l^+ l^- \nu\nu$
  - where l = e or μ

- 5. Extend measurements to W/Z hadronic decay channels
  - Specific channels: W/Z(jet-jet) + γ and W/Z(jet-jet) + W($l\nu$)
  - Useful for calibration/improvement of di-jet mass resolution
  - Similar to searches for Higgs boson in W/Z H($b\bar{b}$) searches

Wγ studies using p $\bar{p}$ -> l ν γ + x

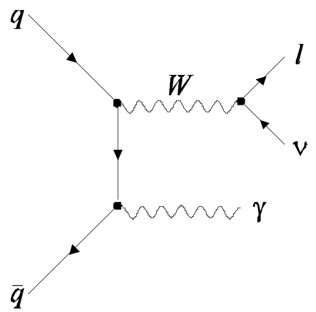
WWγ coupling

CDF
p $\bar{p}$ -> μ ν γ + x
candidate

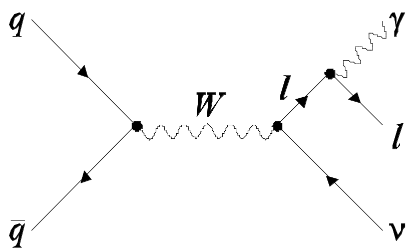


$p\,\bar{p}$ -> $l\,\nu\,\gamma$ + x Production

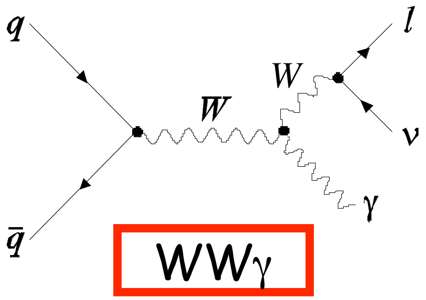
- The $l\,\nu\,\gamma$ final states have contributions from quark and lepton bremsstrahlung processes and the direct production $W\gamma$ -> $l\,\nu\,\gamma$



initial state radiation



final state radiation



triple gauge coupling

- The first two diagrams involve W boson coupling only to fermions, and are assumed to be described by the Standard Model .
- The third diagram depends on the $WW\gamma$ coupling
- Therefore the production $p\,\bar{p}$ -> $l\,\nu\,\gamma$ + x is a measure of this coupling

$p\,\bar{p} \to l\,\nu\,\gamma + X$ Production

- Under the assumption of Lorentz and electromagnetic gauge invariance, for massless fermions, the $WW\gamma$ coupling can be described in terms of four parameters.

- The effective Lagrangian is [Baur and Berger PRD 41, 1476 (1990)]

$$\begin{aligned}\mathcal{L}_{WW\gamma} = -ie\,[(&W^{\dagger}_{\mu\nu}\,W^{\mu}\,A^{\nu} - W^{\dagger}_{\mu}\,A_{\nu}\,W^{\mu\nu}\,)\\ &+ \kappa_{\gamma}\,W^{\dagger}_{\mu}\,W_{\nu}\,F^{\mu\nu} + \lambda_{\gamma}/M_W^{2}\,W^{\dagger}_{\lambda\mu}\,W^{\mu}{}_{\nu}\,F^{\nu\lambda}\\ &+ \text{ 2 more CP violating terms}\end{aligned}$$

Strong constraints from limits on the neutron's electric dipole moment

- The magnetic dipole and electric quadrapole moments of the W boson are given by:

$$\mu_W = (1 + \kappa_{\gamma} + \lambda_{\gamma})e/2M_W \quad \text{and} \quad Q_W = -(\kappa_{\gamma} - \lambda_{\gamma})e/M_W^{2}$$

- In the SM at tree level $\Delta\kappa_{\gamma} = \kappa_{\gamma} - 1 = \lambda_{\gamma} = 0$. Estimates of loop corrections are small: $|\Delta\kappa_{\gamma}| = 0.008$ and $|\lambda_{\gamma}| = 0.002$.

$p\bar{p} \to l \nu \gamma + X$ Production

- Destructive interference of the TGC diagram with the initial state bremsstrahlung process suppresses the $l \nu \gamma$ cross section. For $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV the SM expectations are:

  inclusive W and Z boson production: $\sigma[W(l\nu)] / \sigma[Z(ll)] \sim 10.7$

  while for $E_T(\gamma) > 10$ (100) GeV, $\Delta R(l\gamma) > 0.7$ $\sigma[l\nu\gamma] / \sigma[ll\gamma] \sim 4.3$ (1.5)

- Radiation amplitude zeros also occur when $\eta(\gamma) - \eta(l^+) \sim -0.3$.

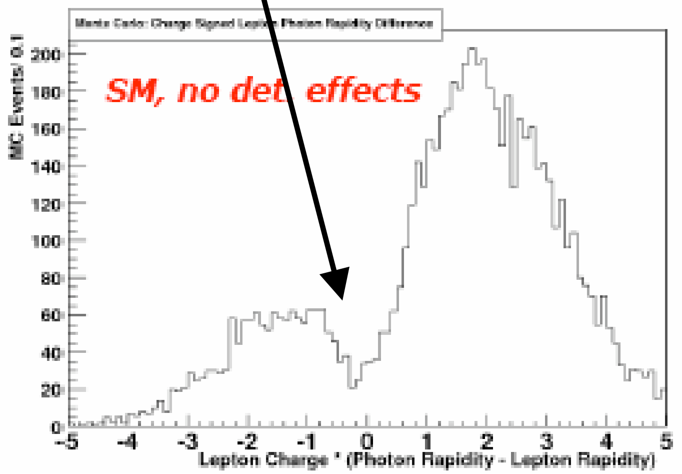
  [see Baur, Errede, + Landsberg, PRD 50, 1917 (1994)]

Deviations from these SM predictions can be expressed in terms of:

$$\Delta\kappa_\gamma = \Delta\kappa_{o\gamma} / (1 + s/\Lambda^2)^2$$

$$\lambda_\gamma = \lambda_{o\gamma} / (1 + s/\Lambda^2)^2$$

where Λ is the scale of the new physics and $\sqrt{s}$ is the $W\gamma$ invariant mass.



Data selection for $l\ \nu\ \gamma$ events

- Events triggered on high E_T/P_T central electron/muon
- Selection of leptons similar to inclusive W/Z measurements

	charged leptons	neutrinos	$l\nu$ transverse mass GeV/c^2
electron channels	$E_T > 25$ GeV	$\not{E}_T > 25$ GeV	30 - 120 (CDF) 40 -> (DØ)
muon channels	$P_T > 20$GeV/c	$\not{E}_T > 20$ GeV	30 - 120 (CDF) None (DØ)

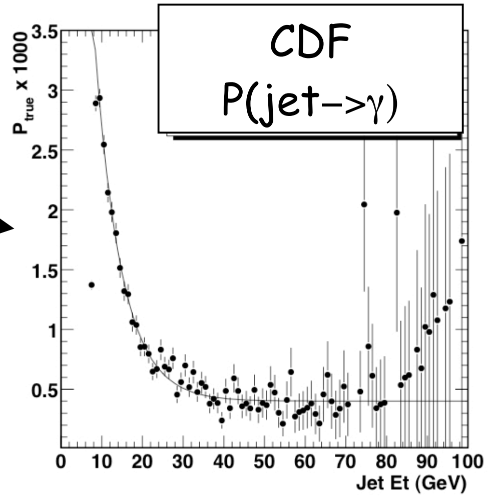
- Selection of photons
  - central: $|\eta| < \sim 1.0$ photon
  - energy: $E_T > 7 - 8$ GeV
  - isolated: $\Delta R(l\ \gamma) > 0.7$

Integrated Luminosity 130-200 pb^{-1}

Backgrounds in $l\ \nu\ \gamma$ events

- Backgrounds are dominated by W($l\ \nu$)+jets and Z/γ($l\ l$)+jets with jet -> fake photon
  - Use jet-triggered data samples to measure the fake rates
  - Correct for real photon content (γ+jet events) in jet data
  - Apply this to jets in W/Z+jet data

P(jet-> fake γ) ~ 3×10^{-3} (E_T ~ 10 GeV)
~ 4×10^{-4} (E_T > 50 GeV)



- Other backgrounds determined from SM generators
  - Cross-talk between Z($l\ l$)γ and W($l\ \nu$)γ channels
  - Feed-down from W -> $\tau\ \nu$ decays

backg. source	e ν γ	μ ν γ
W + jets	59.5±18.1	27.6±7.5
$\tau\ \nu\ \gamma$	1.5±0.2	2.3±0.2
$l\ l\ \gamma$	6.3±0.3	17.4±1.0
total backg.	67.3±18.1	47.3±7.6
data	195	128

CDF Data

S/B ~ 1.8

Signal acceptance (A) and efficiency (ε) for $l\ \nu\ \gamma$

- Electron and muon ID efficiencies are evaluated from data using Z -> ee and $\mu\mu$ decays.
- Photon ID efficiencies are determined from a combination of data (use electrons as proxies for photons) and GEANT-based detector simulations.
- Geometric acceptances determined from SM event generators and detector simulations.
  - Correct for W-> $l\ \nu$ decay phase space
  - Quote cross sections for $E_T(\gamma) > 8$ GeV and $\Delta R(l\ \gamma) > 0.7$

	$e\nu\gamma$	$\mu\nu\gamma$
background	60.8±4.1	71.3±5.2
data	112	161
A x ε	0.023±0.001	0.044±0.002

DØ Data

A x ε
~ 2 - 4%

Comparison of $p\bar{p} \to l\,\nu\,\gamma + X$ to Standard Model predictions

$\sigma(p\bar{p} \to l\,\nu\,\gamma + X)$ at $\sqrt{s} = 1.96$ TeV with $\Delta R(l\,\gamma) > 0.7$

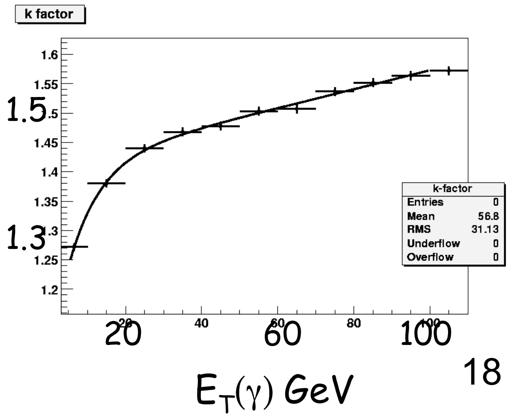
	N_{data} $(e + \mu)$	$\sigma(l\,\nu\,\gamma)$ exp.	$\sigma(l\,\nu\,\gamma)$ SM theory	$E_T(\gamma)$ cut
CDF	323	18.1±3.1	19.3±1.4	> 7 GeV
DØ	273	14.8±2.1	16.0±0.4	> 8 GeV

Measured cross sections:

- Systematic and statistical errors ~ equal plus 6% luminosity error
- Systematic errors dominated by jet -> photon fake rate

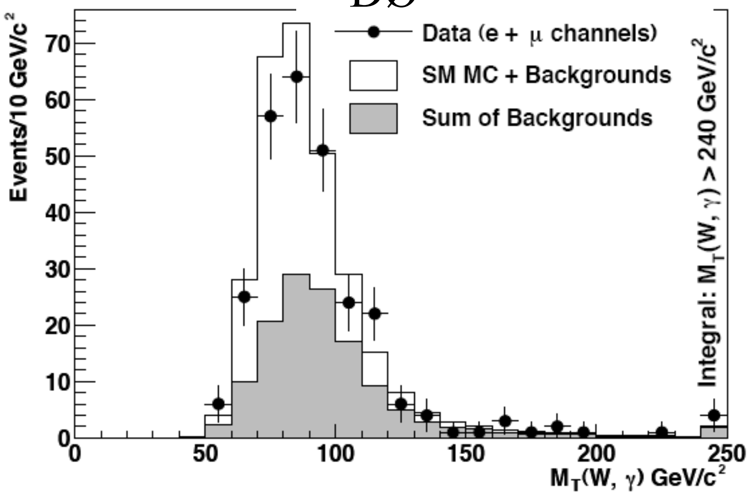
Standard Model cross section predictions:

- Use LO matrix elements
  [Baur + Berger, PRD 47, 4889 (1993)]
- Correct for NLO k-factor
  [Baur, Han, +Ohnemus PRD57, 2823 (1998)

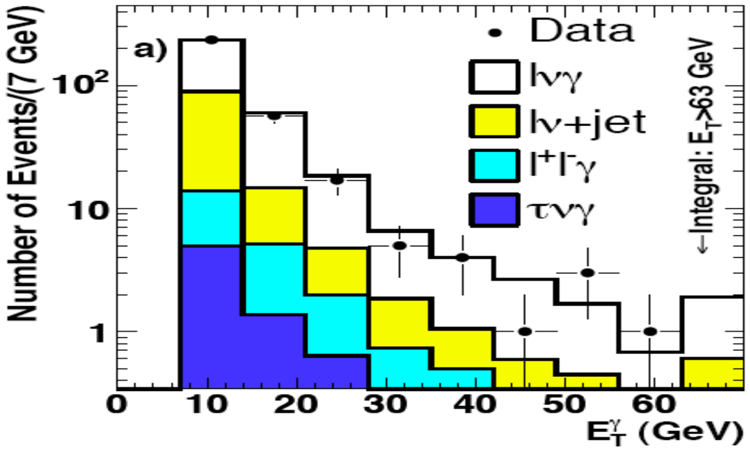


Comparison of $l\ \nu\ \gamma$ signal to Standard Model predictions

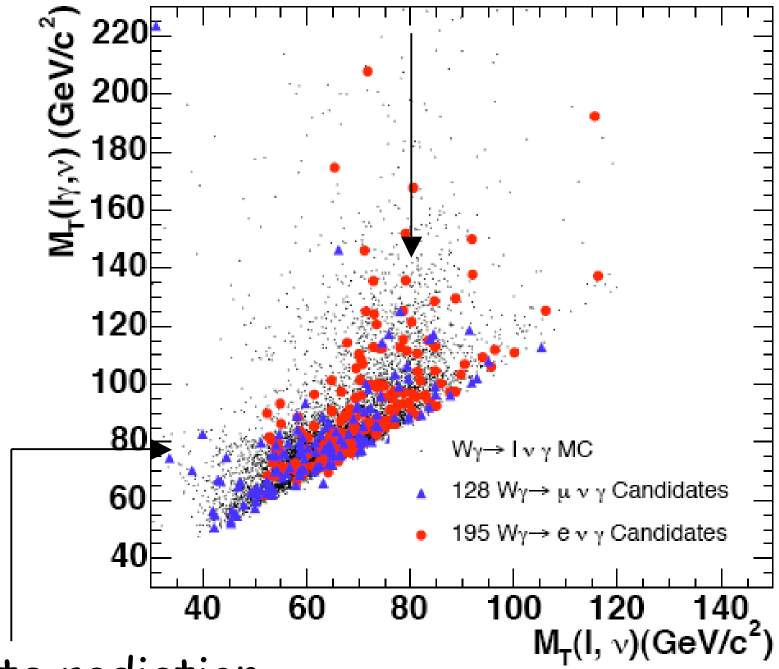
DØ



CDF



W + γ CDF

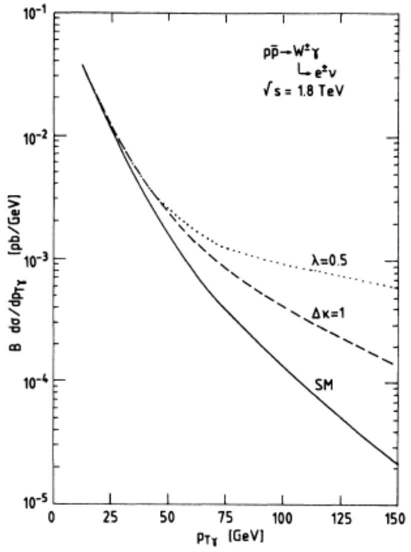


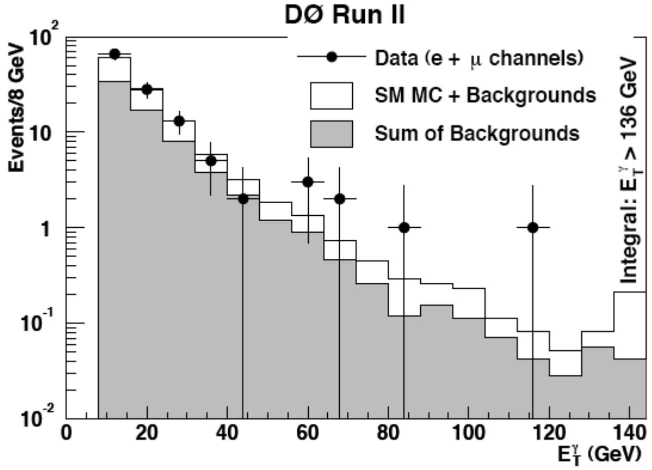
final state radiation

PRL 94, 040803 (2005) CDF

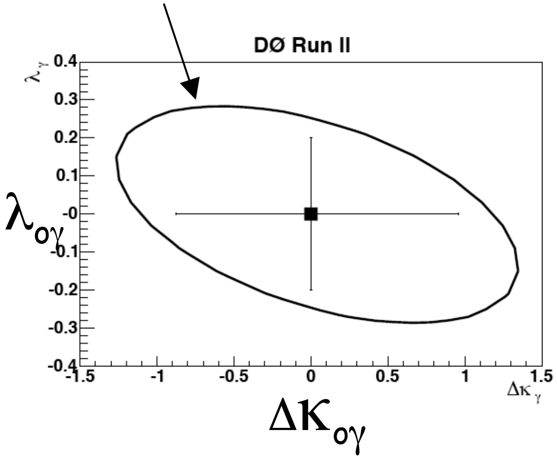
Using $l\ \nu\ \gamma$ events to put limits on WWγ couplings (DØ)

- Non-zero $\Delta\kappa_\gamma$ or λ_γ lead to enhancement of high E_T photons above the SM prediction.
- Suppress event with FSR by selecting events with $M_T(l\ \nu\ \gamma) > 90$ GeV/c^2
- Use binned-likelihood fitting $E_T(\gamma)$ on $\Delta\kappa_{o\gamma}$ vs $\lambda_{o\gamma}$ grid





2D 95% C.L.



1D 95% C.L.

$-0.88 < \Delta\kappa_{o\gamma} < 0.96$

$-0.20 < \lambda_{o\gamma} < 0.20$

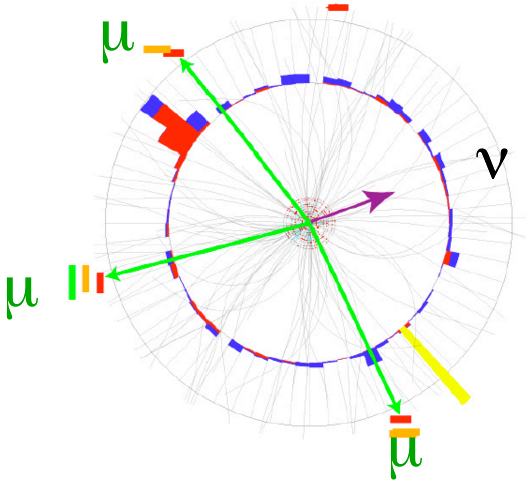
$\Lambda = 2$ TeV

PRD 71, 091108(2005) DØ

WZ studies
using $p\bar{p} \rightarrow l'\nu\, l^+ l^- + x$

WWZ coupling

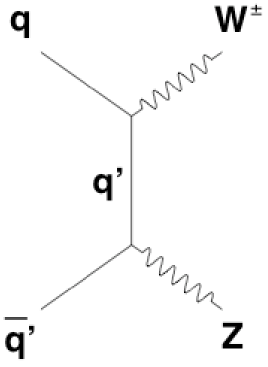
DØ
$p\bar{p} \rightarrow \mu\, \nu\, \mu\, \mu + x$
candidate

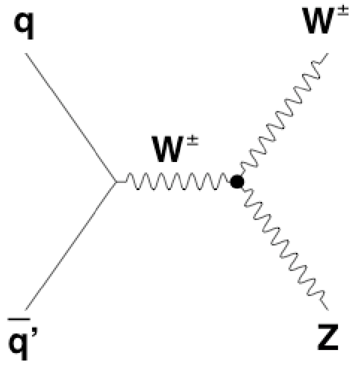


$p\,\bar{p}$ -> WZ + X Production

- The next logical step in unraveling the di-boson anamalous couplings is to measure WZ production. This isolates the WWZ vertex.

destructive interference causes WZ cross section suppression





WWZ

- Under the same assumptions* made for the WWγ coupling the effective Lagrangian is [Haigwara, Peccii and Zeppenfeld, NP B282 253 (1987)]:

$$\mathcal{L}_{WWZ} = -ie \cot\theta_W \,[\, g_1^z \,(W_{\mu\nu} W^\mu Z^\nu - W_\mu Z_\nu W^{\mu\nu}\,)$$

$$+ \kappa_z \;W_\mu W_\nu Z^{\mu\nu} + \;\lambda_z / M_W^2 \;\; W_{\lambda\mu} W^\mu{}_\nu Z^{\nu\lambda}$$

* in addition to dropping CP violating terms, excude a term which conserves CP but violates both C and P.

- In the SM at tree level $g_1^z = \kappa_z = 1$ and = $\lambda_z = 0$.

Data selection for WZ events

- The SM expectation for $p\bar{p} \rightarrow W Z + x$ at $\sqrt{s} = 1.96$ TeV is ~ 4.0 pb
- But the branching ratios reduce the usable signal:

WZ decay channel	Fraction %
$q\bar{q}'q\bar{q} + q\bar{q}\nu\nu$	61.1
$q\bar{q}\ l\nu$	22.4
$q\bar{q}'\ ll$	6.9
$l\ \nu\nu\nu$	6.4
$l\ \nu\ ll$	3.2

← buried in QCD jets

← useful (see below)

← buried in inclusive W/Z

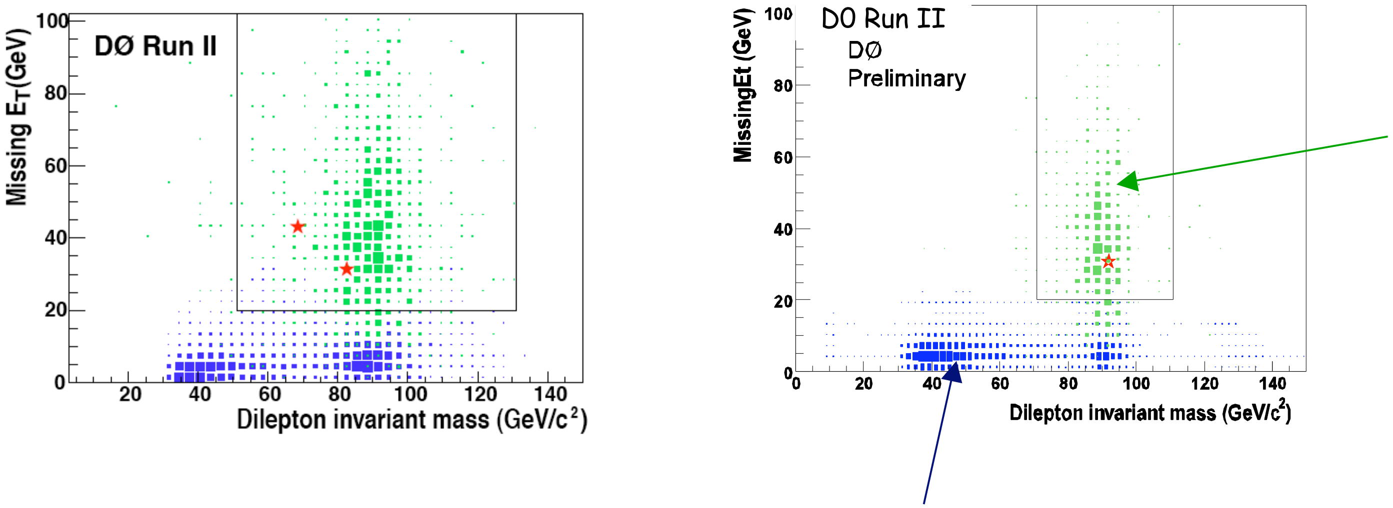
← cleanest channel

- Restricting l = e or μ , the total branching ratio for $p\bar{p} \rightarrow l'\nu l^+ l^- + x$ ~ 1.4%.
- Acceptance x efficiency varying from 10 to 15% (without BR's)
  - Particle ID efficiencies use $Z \rightarrow ee/\mu\mu$ data
  - Acceptance use PYTHIA event generator plus detector simulations

Data selection for $l' \nu \, l^+ l^-$ events

two 3-μ events

one 3- e event



signal simulation

background simulation

- Backgrounds with S/B ~ 3-4
  - Dominated by jet -> fake lepton in W/Z + jet/γ events (from data)
  - Feed through from WW, ZZ, $t\bar{t}$ determined from SM event generators plus detector simulations.

Comparison of WZ (and ZZ) to Standard Model predictions using all leptonic decays

$\sigma[p\bar{p} \to WZ\ (ZZ) + x]$ at $\sqrt{s}$ = 1.96 TeV corrected for W/Z branching ratios

	N_{data}	$N_{backgrond}$	SM theory cross section (pb)	Experimental cross section (pb)	95% C.L.
CDF(WZ+ZZ)	3	1.02 ± 0.24	5.0 ± 0.4	4.3 +5.0 - 2.6	< 15.2 pb
DØ (WZ)	3	0.71 ± 0.08	3.65 ± 0.26	4.5 +5.1 - 3.3	< 13.3 pb

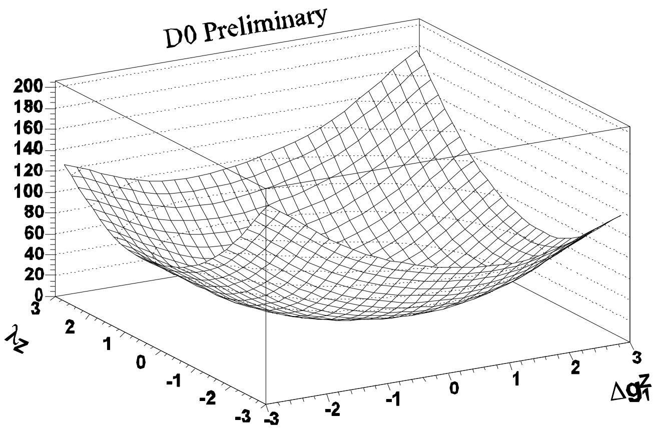
- SM theory predictions at NLO with MCFM
- Experimental details can be found at:
  - DØ hep-ex/0504019 (Submitted to PRL)
  - CDF PRD 71, 091105 (2005)

Integrated Luminosity
~ 300 pb^{-1} (DØ)
~ 200 pb^{-1} (CDF)

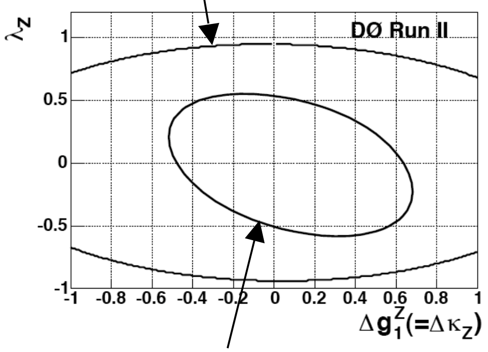
- Bottom line: consistent with the SM

Using $l'\nu\ l^+ l^-$ events to put limits on WWZ couplings (DØ)

- Non-zero Δg_1^z , $\Delta\kappa_Z$ or λ_z lead to enhancement of high Et W/Z above the SM prediction. Here $\Delta g_1^z = g_1^z - 1$ and $\Delta\kappa_Z = \kappa_Z - 1$.
- Hold one anamolous coupling parameter at zero and form a 2D grid of predictions versus the other two [Hagiwara,Woodside,Zeppenfeld LO generator].
- Use dipole form factors as for $W\gamma$ analysis:



Unitarity bound



2D 95% C.L.

1D 95% C.L.

$-0.49 < \Delta g_{01}^z < 0.66$

$-0.48 < \lambda_{oz} < 0.48$

$\Delta\kappa_{oz}$ no limit

Λ = 1.5 TeV

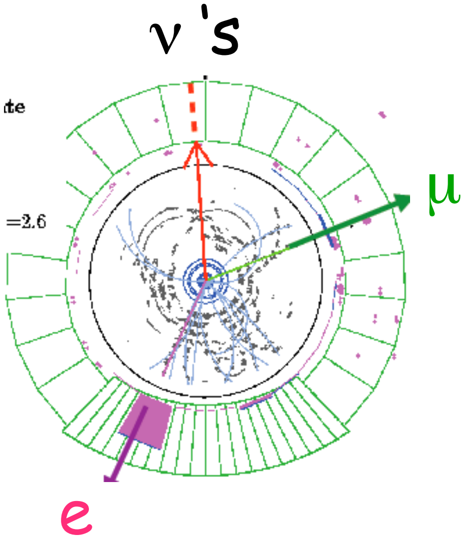
$W^+ W^-$ studies using $p \bar{p} \to l^+ \nu \, l'^- \nu + x$ and $p \bar{p} \to l \nu \; q \bar{q} + x$

Mix of $WW\gamma$,WWZ couplings

CDF

$p \bar{p} \to \mu \nu e \nu + x$

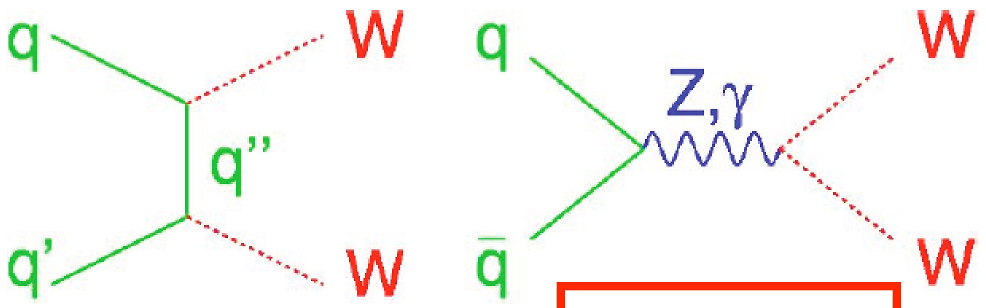
candidate



$p\,\bar{p}$ -> $W^+ W^-$ + x Production

- The WWγ (WWZ) couplings introduce the parameters discussed above [Haigwara, Woodside and Zeppenfeld, PRD 41, 2113 (1990)]:

destructive interference causes WW cross section suppression



WWZ and WWγ

- The SM expectation for $p\,\bar{p}$ - > W W +X at $\sqrt{s}$ = 1.96 TeV is ~ 12.4 pb
- To date CDF and DØ have used channels.:
  - $l\,\nu\,l'\,\nu$ with l , l' = e or μ

    BR ~ 4.6% small BR, good S/B
  - q q' $l\,\nu$ with l = e or μ

    BR ~ 29% good BR, poor S/B

WW	Fraction %
qq' q q'	46.2%
q q' $l\,\nu$	43.5%
$l\,\nu\,l'\,\nu$	10.3%

Comparison of W^+W^- to Standard Model predictions using $l^+ \nu\, l'^- \nu$ decays

- Measurement of $p\bar{p}$ -> $W^+ W^-$ +X at $\sqrt{s}$ = 1.96 TeV with BR corrections

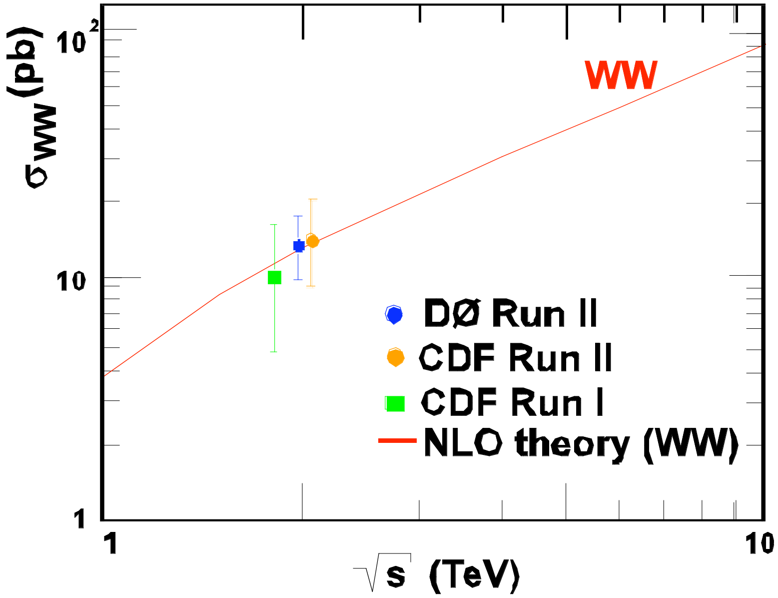
$$\sigma(WW) = 13.8^{+4.3}_{-3.8}(stat.)^{+1.2}_{-0.9}(sys.) \pm 0.9(lum.)\ \mathrm{pb}$$

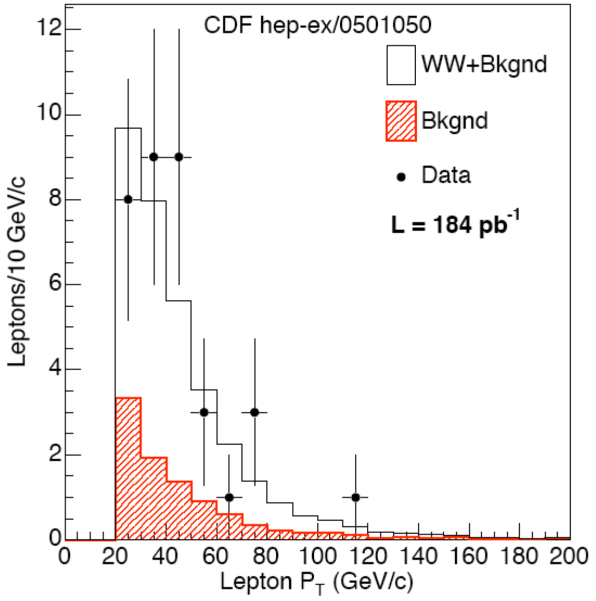
DØ Run II: PRL 94, 151801 (2005)

$$\sigma(WW) = 14.6^{+5.8}_{-5.1}(stat.)^{+1.8}_{-3.0}(sys.) \pm 0.9(lum.)\ \mathrm{pb}$$

CDF Run II: PRL 94, 211801 (2005)

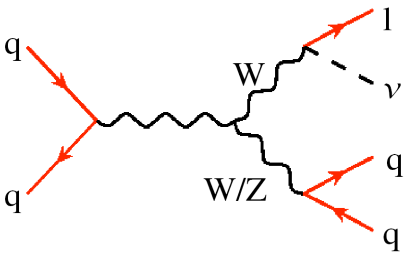
SM σ(WW) = 12.4 ± 0.8 pb





W^+W^- and W Z studies using $l\,\nu$ $q\,\bar{q}$ decays

- The channel $p\,\bar{p} \to W(l\,\nu) + W/Z\,(q\,\bar{q})$ has been studied by CDF
  - Advantages: larger branching ratio
  - Disadvantages: much higher backgrounds
  - BUT anomalous signals appear at high E_T of the W where backgrounds lower



- W + jet jet QCD background is constrained by fitting to dijet mass spectrum around M_W plus M_Z peak.

- Fit to data:

  $N_{data} = 66 \pm 78 \pm 34$ events

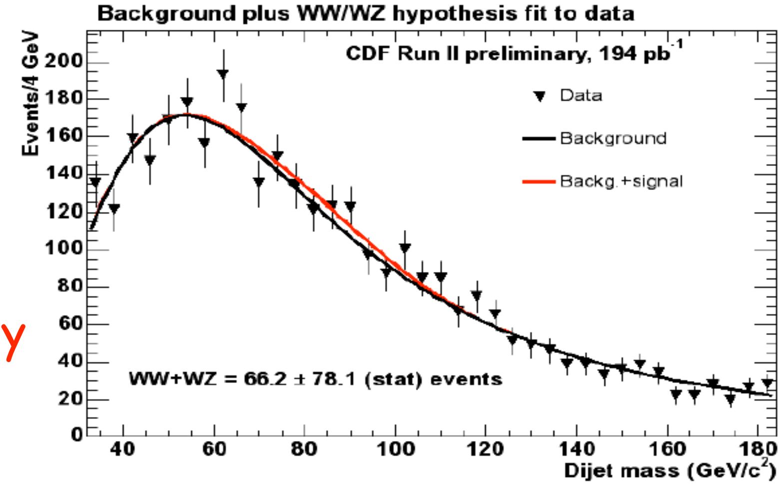
  $\sigma_{data}(WW + WZ) < 40$ pb

- With the SM expectation

  $N_{SM} \sim 91$ events

  $\sigma_{SM}(WW + WZ) = 16.5$ pb

CDF Preliminary

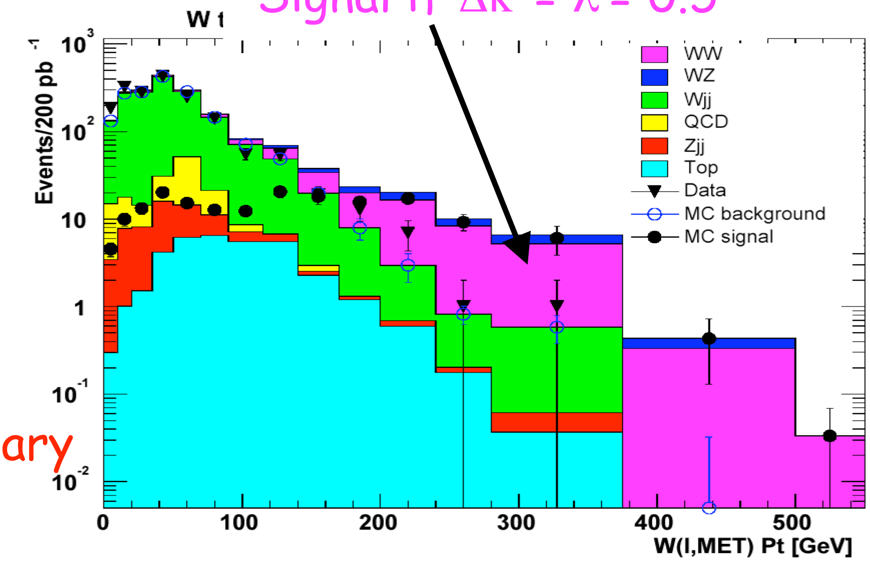


W^+W^- and W Z studies using $l\,\nu$ $q\,\bar{q}$ decays

- Fits to anomalous couplings require assumptions here since 5 parameters contribute to WW plus WZ production: Δg_1^Z , $\Delta\kappa_Z$, λ_Z, $\Delta\kappa_\gamma$, and λ_γ
- Assume $\Delta g_{01}^Z = 0$ and let $\Delta\kappa_o = \Delta\kappa_{oZ} = \Delta\kappa_{o\gamma}$ and $\lambda_o = \lambda_{oZ} = \lambda_{o\gamma}$
- The P_T of the $W(l\,\nu)$ is found to be the most sensitive distribution since anomalous VV pairs are produced at high P_T .
- Limits set:

$$-0.42 < \Delta\kappa_o < +0.58$$
$$-0.32 < \lambda_o < +0.35$$

Signal if $\Delta\kappa = \lambda = 0.5$

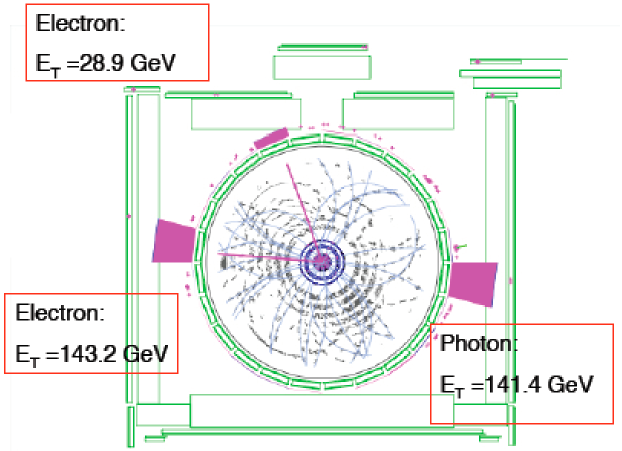


CDF Preliminary

Zγ studies
using $p\,\bar{p}$ -> $l^+ l^- \gamma + x$

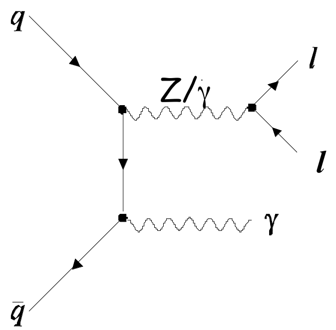
ZZγ and Z$\gamma\gamma$ couplings

CDF
$p\,\bar{p}$ -> $e^+ e^- \gamma + x$
candidate

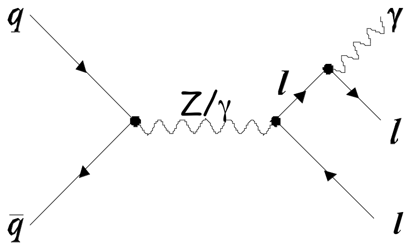


p p̄ -> $l^+ l^- \gamma$ + x Production

- Within the confines of the SM as the ZZγ and Zγγ couplings are zero at tree level.

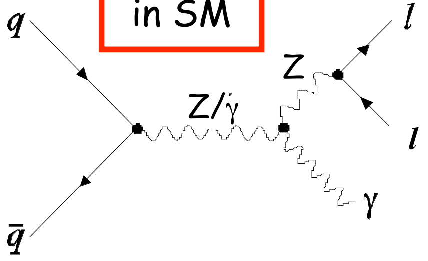


initial state radiation



final state radiation

Absent in SM



triple gauge coupling

- Therefore beyond the SM affects appear as deviations from bremsstrahlung radiation.
- Under the assumptions of Lorentz and electromagnetic gauge invariance, the anomalous coupling parameters in this case are:

$h_i^V = h_{io}^V / (1 + s/\Lambda^2)^n$ where V = s-channel γ or Z

$\sqrt{s}$ = Zγ invariant mass

i = 1,2 (CP violating), 3,4 (CP conserving)

==> 8 parameters [see e.g. Baur and Berger PRD 47, 4889 (1993)]

Data selection for $l^+ l^- \gamma$ events

- Events triggered on high E_T/P_T central electron/muon. The offline lepton and photon cuts are similar to those for Wγ events (see page 14).
- DØ selects events with $M(l^+ l^-) > 30$ GeV/c^2, CDF 40 - 130 GeV/c^2
- The only significant source of Background is Z + jet events with a jet faking a photon (see p 16).

backg. source	e e γ	$\mu\ \mu\ \gamma$
Z + jets	23.6±2.3	22.4±3.0
data	138	152

~ 300 pb^{-1} (DØ)
S/B ~ 6

backg. source	e e γ	$\mu\ \mu\ \gamma$
Z + jets	2.8±0.9	2.1±0.6
data	36	35

~ 200 pb^{-1} (CDF)
S/B ~ 15

Comparison of $l^+ l^- \gamma$ signals to Standard Model predictions

$\sigma(p\bar{p} \to l\,l\,\gamma + X)$ with $\Delta R(l\,\gamma) > 0.7$

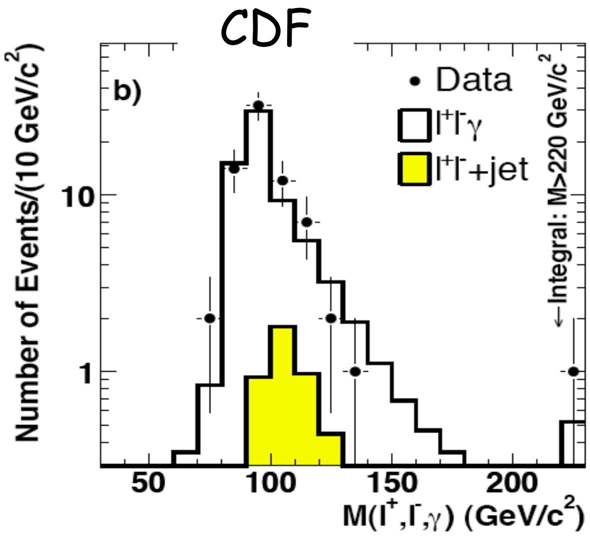
	N_{data} $(e + \mu)$	$\sigma(l\,l\,\gamma)$ exp.	$\sigma(l\,l\,\gamma)$ theory	$E_T(\gamma)$ GeV	$M(l\,l)$ GeV/c^2
CDF	71	4.6 ± 0.6	4.5 ± 0.3	> 7	> 40
DØ	290	4.2 ± 0.5	3.9 ± 0.2	> 8	> 30

CDF PRL 94, 041803 (2005)

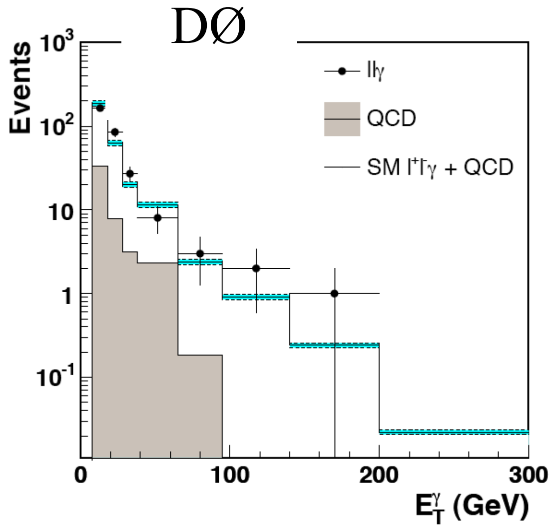
DØ hep-ex/0502036 (submitted to PRL)

Comparison of $l^+ l^- \gamma$ signal to Standard Model predictions

CDF



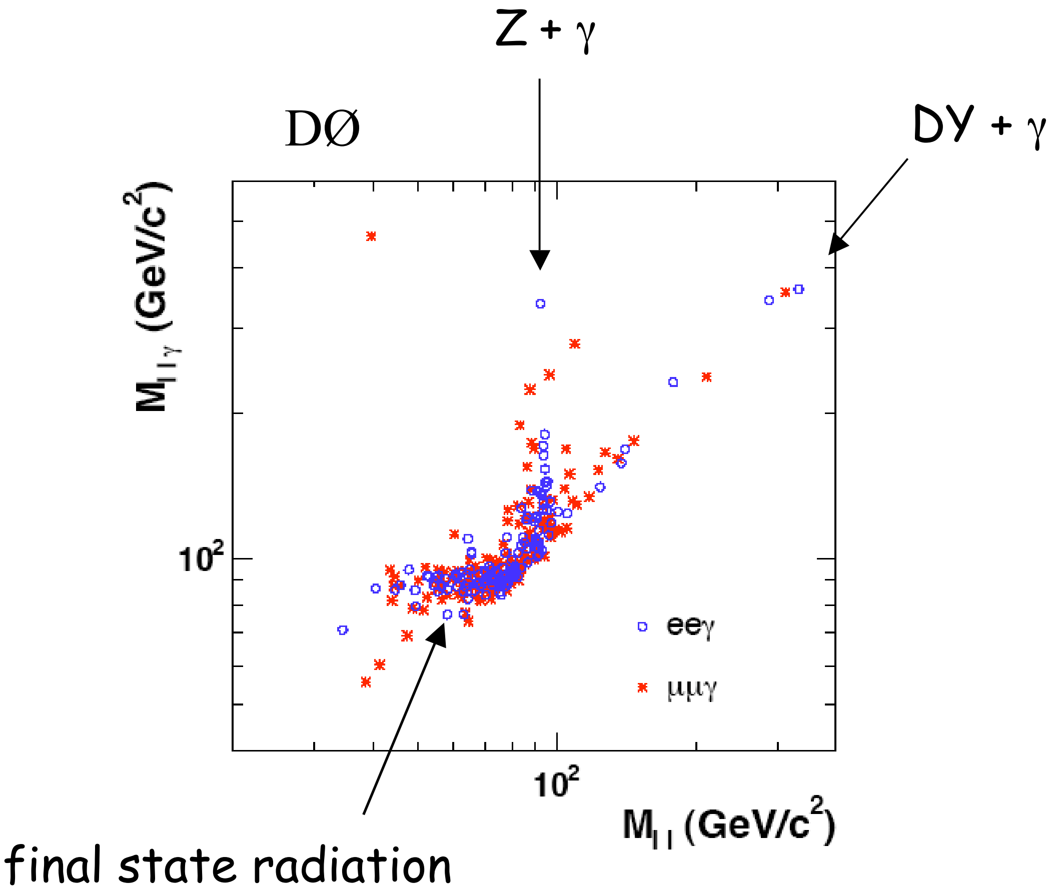
DØ



Z + γ

DØ

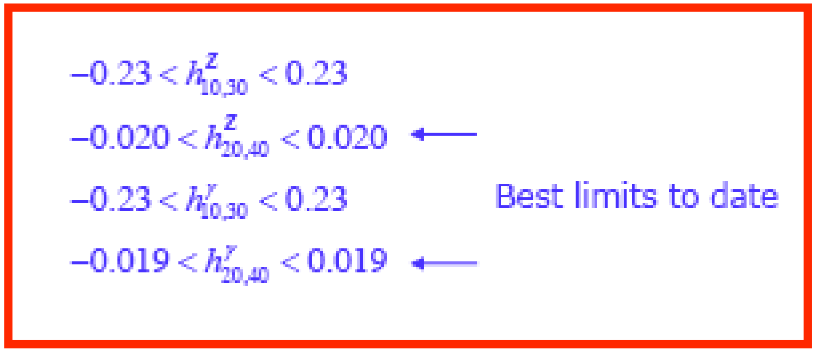
DY + γ



final state radiation

Using $l^+ l^- \gamma$ events to put limits on $ZZ\gamma$ and $Z\gamma\gamma$ couplings (DØ)

- No deviations from SM predictions, but very clean data samples can be used to put limits on anomalous couplings.
- Form factors imposed to preserve unitarity with n= 3 for i = 1,3 and n = 4 for i = 2,4 (see form on page 31).
- Use binned-likelihood fitting to $E_T(\gamma)$ on 2D grid of (h_{10}^V vs h_{20}^V) and (h_{30}^V vs h_{40}^V). Set 95% C/L. for Λ = 1 TeV. (D0 PRL and hep-ex/0502036).



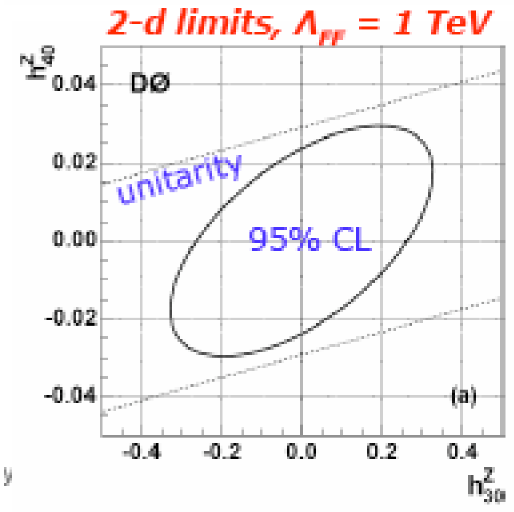
$-0.23 < h^Z_{10,30} < 0.23$

$-0.020 < h^Z_{20,40} < 0.020$ ←

$-0.23 < h^\gamma_{10,30} < 0.23$

$-0.019 < h^\gamma_{20,40} < 0.019$ ←

Best limits to date



Summary and Outlook

SUMMARY: Comparison to SM predictions

Tevatron Run II
p p at $\sqrt{s}$ = 1.96 TeV
200-400 pb^{-1}

Channel (l =e,μ)	$(\sigma_{data} - \sigma_{SM})/\sigma_{SM}$
W γ [$l\, \nu\, \gamma$]	-0.06 ± 0.16 CDF
	-0.06 ± 0.16 DØ
Z γ [$l\, l\, \gamma$]	+0.02 ± 0.13 CDF
	+0.08 ± 0.13 DØ
WW [$l\, \nu\, l\, \nu$]	+0.17 ± 0.42 CDF
	+0.10 ± 0.32 DØ
cross section limits	σ_{data} (95% C.L.)/ σ_{SM}
WZ [$l\, \nu\, l\, l$]	3.3 DØ
WZ + WW [$l\, \nu$ qq]	2.4 CDF
ZW + ZZ [$l\, l\, (l\, \nu$ or $\nu\, \nu)$]	3.0 CDF

All rates and
kinematic distributions
are consistent with
SM predictions

(table uses nominal SM predictions with no theory uncertainties)

SUMMARY: Limits on anomalous couplings

Analyses just starting on individual channels

Coupling	limits at 95% CL	Energy scale Λ
$WW\gamma$	$-0.88 < \Delta\kappa_{o\gamma} < 0.96$	2 TeV
	$-0.20 < \lambda_{o\gamma} < 0.20$	
WWZ	$-0.49 < \Delta g_{01}^{z} < 0.66$	1.5 TeV
	$-0.48 < \lambda_{oz} < 0.48$	
$ZZ\gamma$	$\lvert h^{\gamma}_{10,30}\rvert < 0.23$	1 TeV
	$\lvert h^{\gamma}_{20,40}\rvert < 0.019$	
ZZZ	$\lvert h^{z}_{10,30}\rvert < 0.23$	1 TeV
	$\lvert h^{z}_{10,30}\rvert < 0.020$	
WWZ and $WW\gamma$	$-0.42 < \Delta\kappa_{o} < 0.58$	1.5 TeV
	$-0.32 < \lambda_{o} < 0.35$	

In future will combine channels and CDF+D0 measurements

SUMMARY: Physics beyond the SM

- New physics sources (anomalous couplings, new fermions or gauge bosons) contribute to the high P_T tails of W/Z/γ production.
- At high P_T most sources of background (jets faking photons and leptons) fall rapidly.
- Therefore the sensitivity to new physics is almost entirely statistics driven.
- The Tevatron is ramping up according to its design plan, and the CDF and DØ detectors are operating with good efficiency.
- The data sets presented here represent 2-10% of the potential of the Tevatron.
- We hope to set more than limits …

Backup Slides

Searches for W/Z-> q $\bar{q}$ using W/Z γ events

Searches for $p \bar{p} \to W/Z(q \bar{q}) + \gamma$
Motivation

- New physics searches using dijets depend critically on a good understanding of the jet-jet invariant mass resolution.

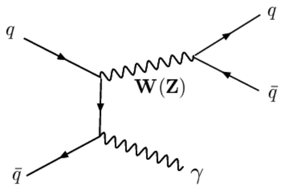
- One calibration source is $W/Z \to q \bar{q} \to$ jet jet

- This requires a trigger that does not bias the W/Z mass peak, and allows low mass side bands for background subtraction.

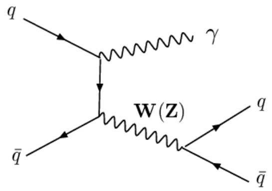
- Using diboson events of the type $W/Z(q \bar{q})\, \gamma$ and $W/Z(q \bar{q})\, W(l\, \nu)$ allows a trigger selection based upon the a high Et photon or lepton, and provides an unbiased look at the jet-jet spectrum for extraction of $W/Z \to q \bar{q}$.

- Also, the $W/Z(q \bar{q})\, W(l\, \nu)$ channels are very similar to those used for Higgs searches in $H(b \bar{b})\, W(l\, \nu)$ and provide a SM calibration line.

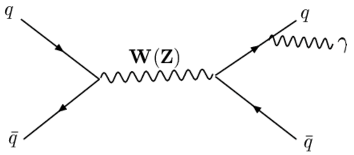
W/Z($q\bar{q}$) signal in W/Zγ events



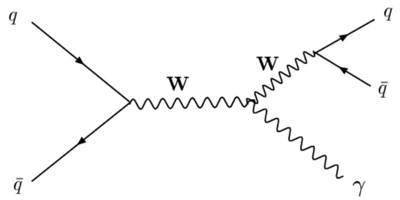
t – channel



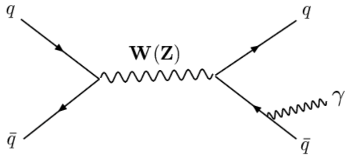
u – channel

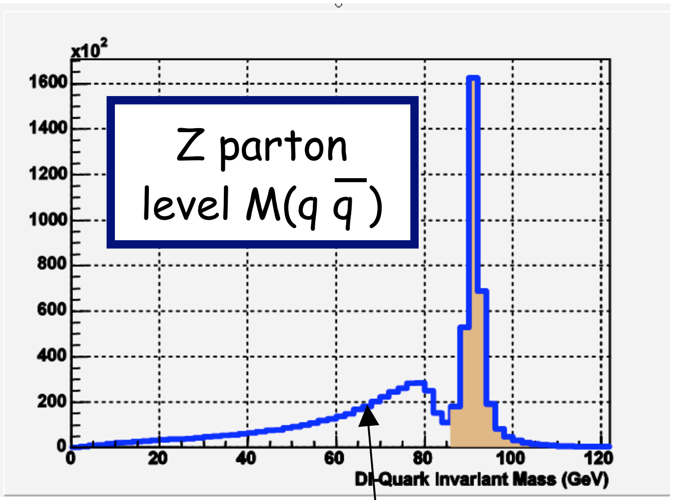


Inner Bremsstrahlung



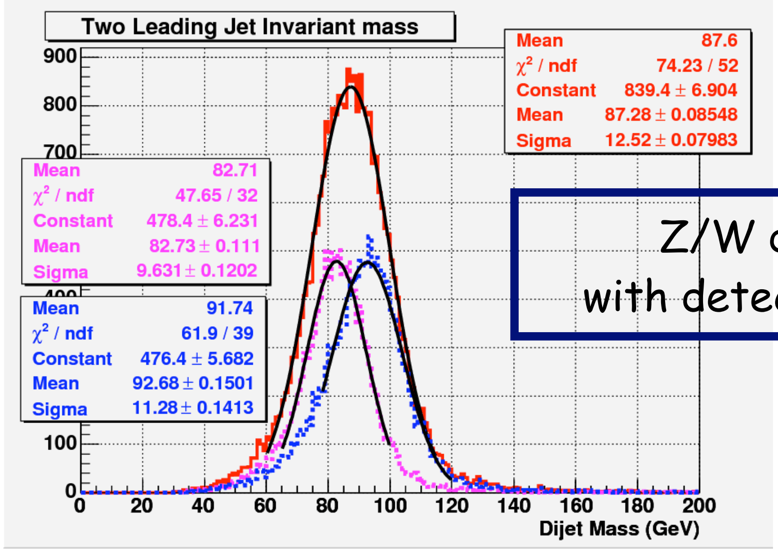
s – channel





Z parton level M($q\bar{q}$)

Radiative tail

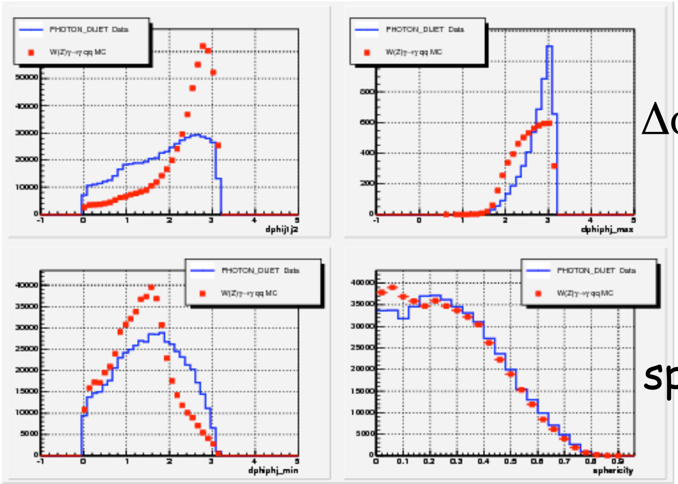


Z/W di-jet mass with detector resolution

Neural net used for S/B separation

Studied 19 discriminating variable

Found best 10 for maximizing S/ √b



$\Delta\phi(j_1\text{-}j_2)$

W/Z γ signal

γ dijet data

$\Delta\phi(j_1-\gamma)$

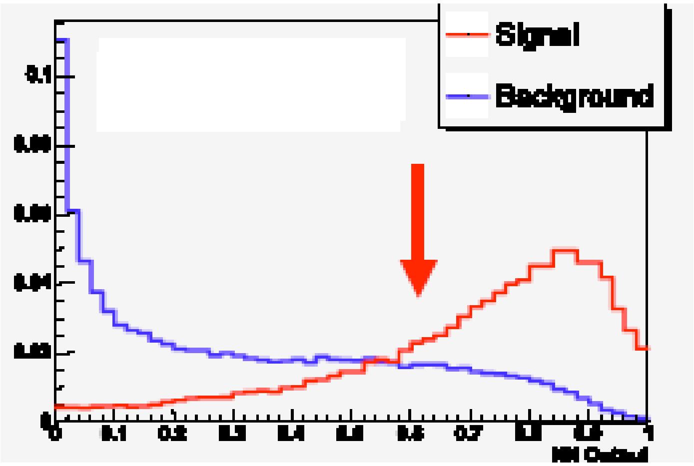
$\Delta\phi(j_2-\gamma)$

sphericity

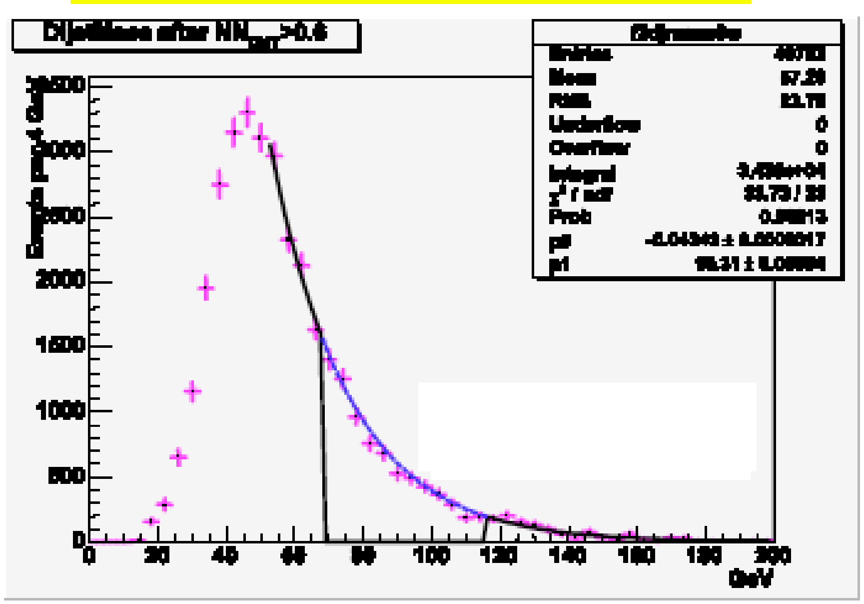
ΔM= 72-110 GeV

S/√B = 2.17

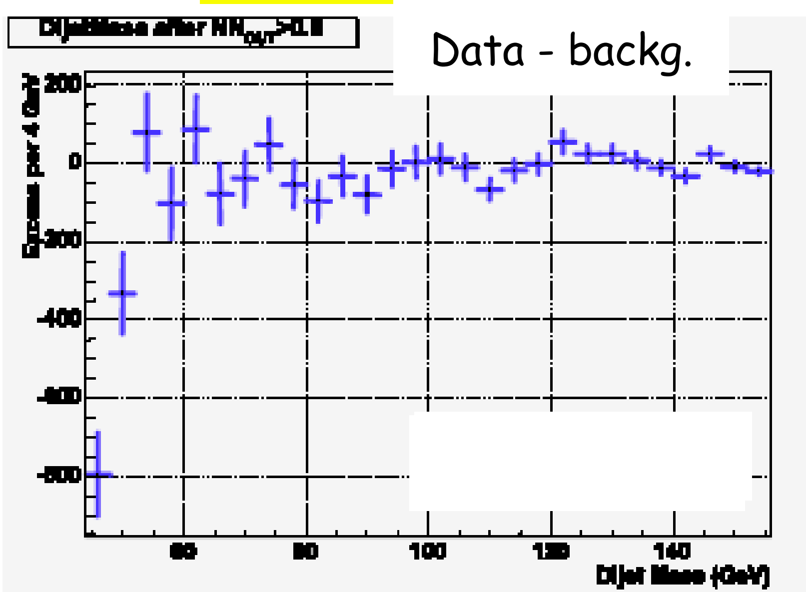
CDF Preliminary



No W/Zγ signal seen with 182 pb^{-1} of data



dijet mass GeV/c²



Data - backg.

dijet mass GeV/c²

CDF Preliminary

$$\sigma_{W(Z)\gamma} = \sigma(p\bar{p} \to W\gamma) \times \mathfrak{B}(W \to q\bar{q}) + \sigma(p\bar{p} \to Z\gamma) \times \mathfrak{B}(Z \to q\bar{q})$$
$$< 54 \quad \text{pb} \qquad \text{at } 95\% \text{ CL}$$

(SM prediction 20.5 pb)