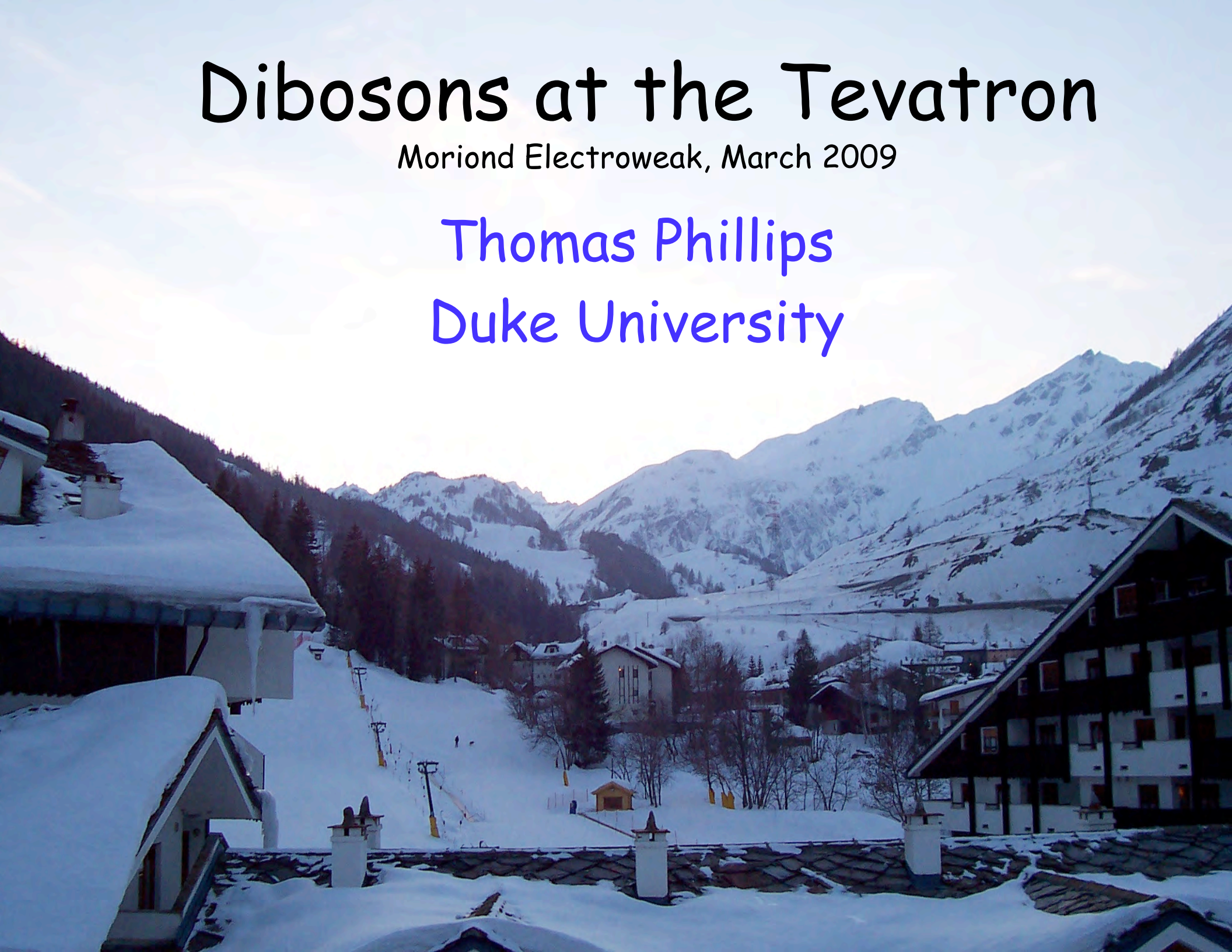
Dibosons at the Tevatron

Moriond Electroweak, March 2009

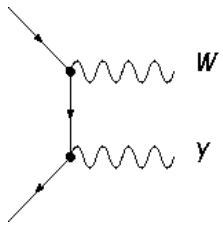
Thomas Phillips
Duke University

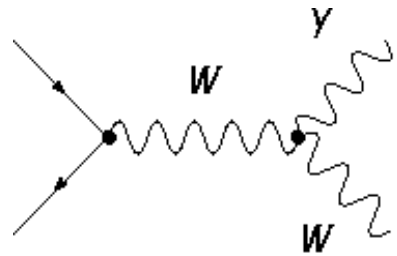


Standard Model Dibosons

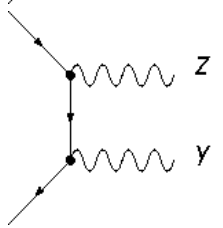
Diboson Final State

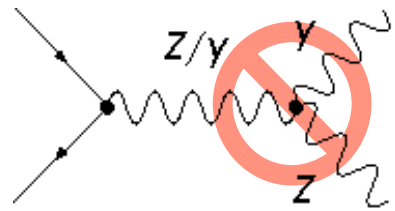
Wγ



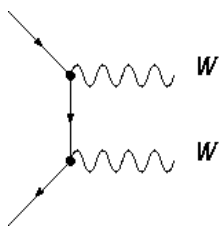


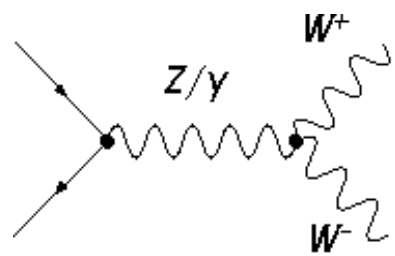
Zγ



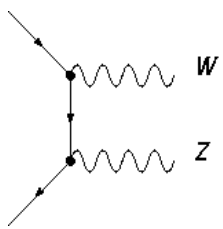


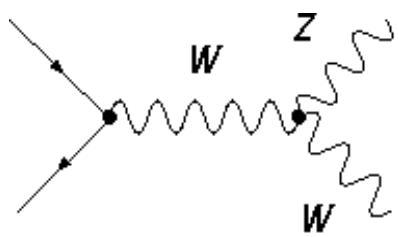
WW



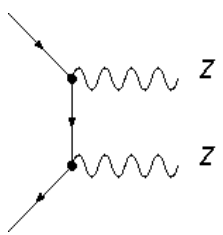


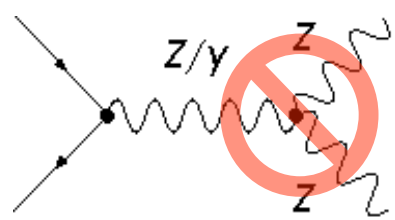
WZ





ZZ

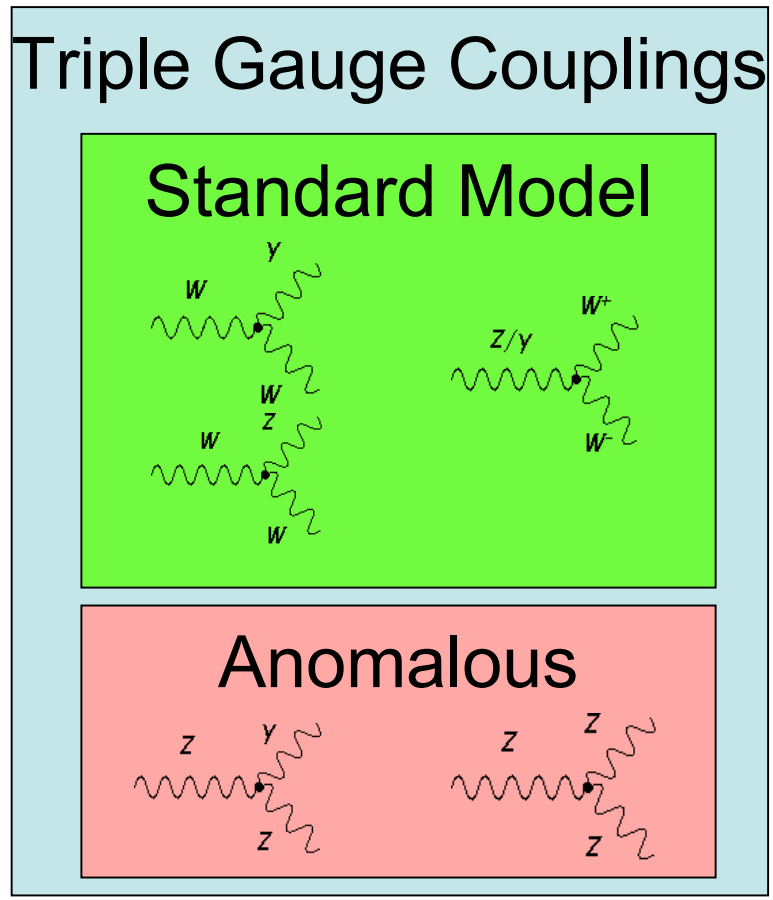




SM Tests:

1) Test SM production predictions
2) Look for "anomalous couplings"

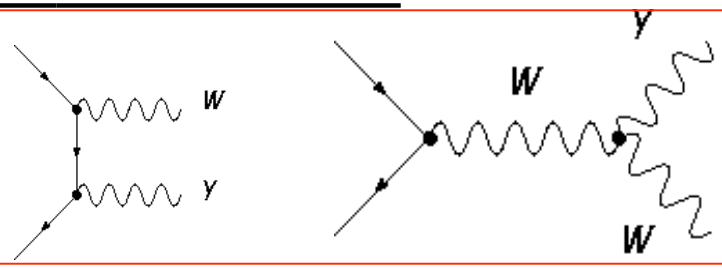
Cross sections similar to Higgs



Wγ Production

Diboson Final State

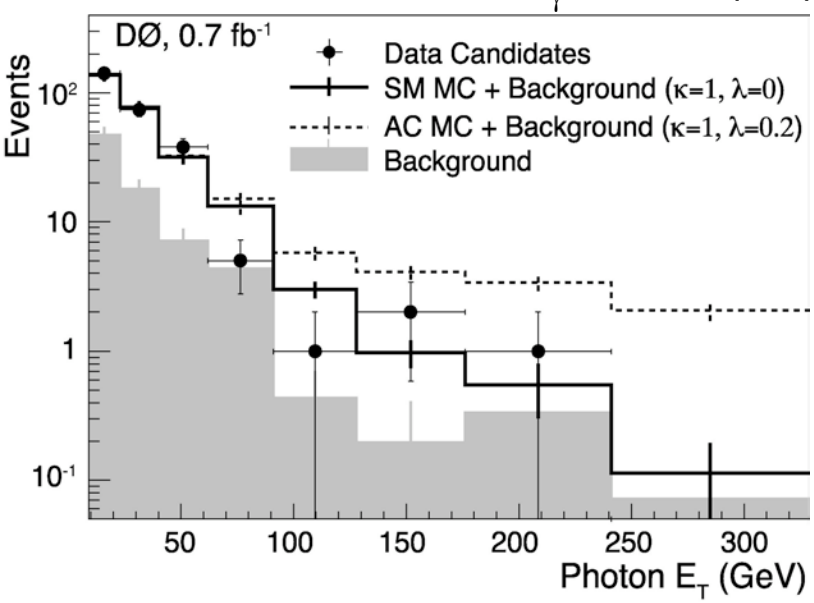
Wγ



SM Tests:

Look for "anomalous couplings"

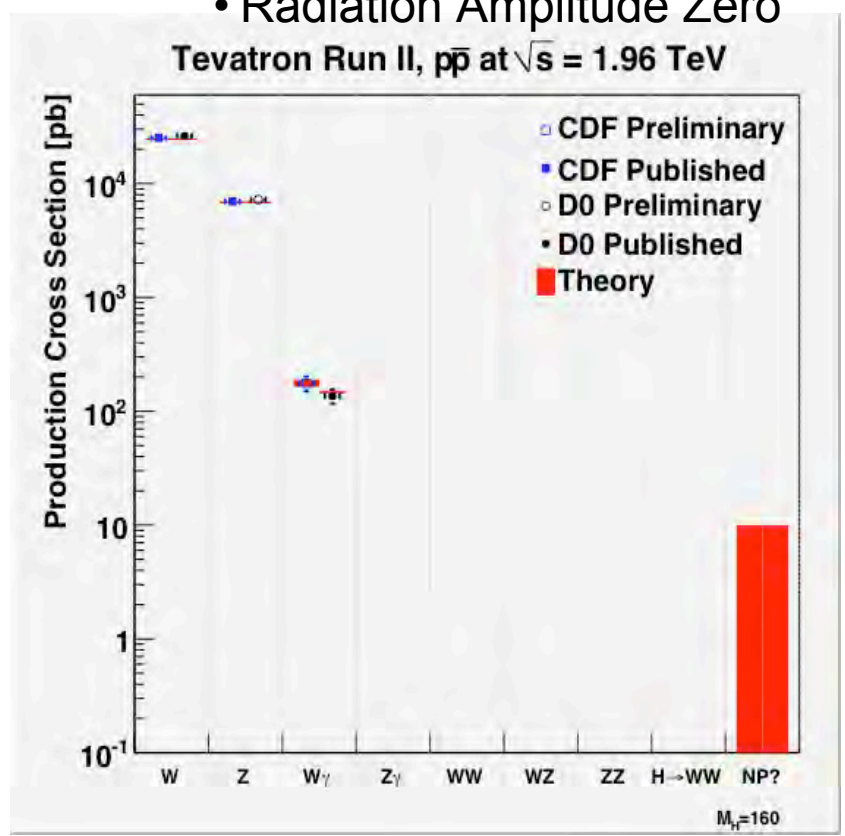
- CP-conserving effective Lagrangian non-SM parameters: K_γ and Λ_γ
- $\Delta K_\gamma = 1 - K_\gamma = 0$ & $\Lambda_\gamma = 0$ in SM
  - $0.49 < K_\gamma < 1.51$ (D0)
  - $-0.12 < \Lambda_\gamma < 0.13$ (D0)



SM Tests:

Test SM production predictions

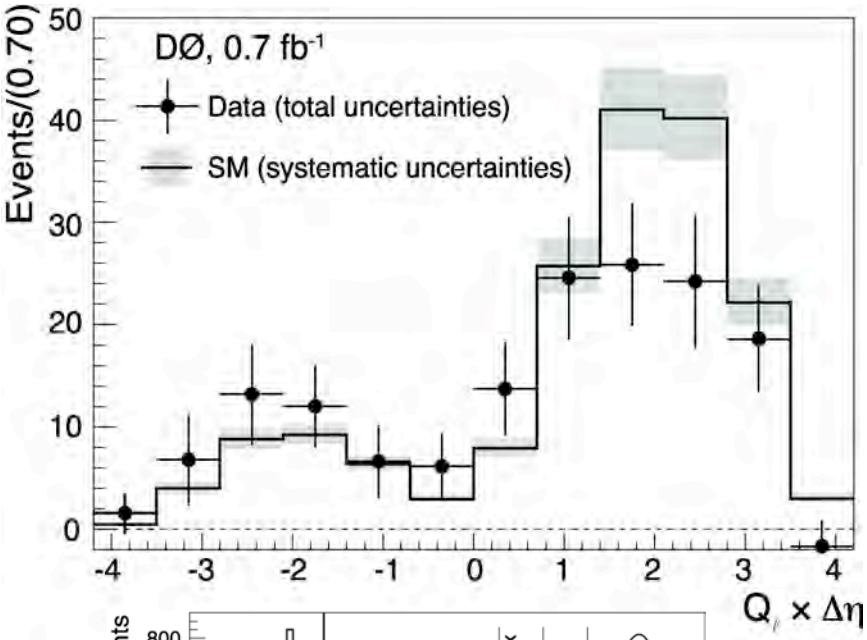
- Cross sections ($\Delta R_{l\gamma} > 0.7$)
  - $\sigma(E_T\gamma > 7$ GeV) = 18.0 ± 2.8 pb (CDF)
    - SM: 19.3 ± 1.4 pb
  - $\sigma(E_T\gamma > 8$ GeV) = 14.8 ± 2.1 pb (D0)
    - SM: 16.0 ± 0.4 pb
- Radiation Amplitude Zero

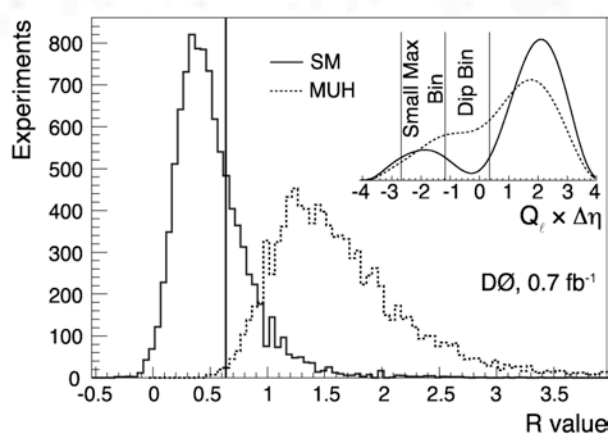


Wγ Production

Radiation amplitude 0

- ➔predicted in 1979
- ➔observed by D0 in 2008





PRL 43, 746(1979)

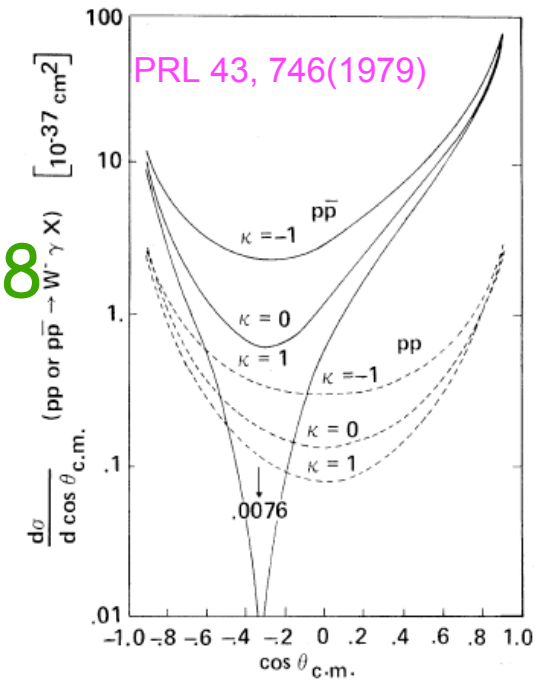
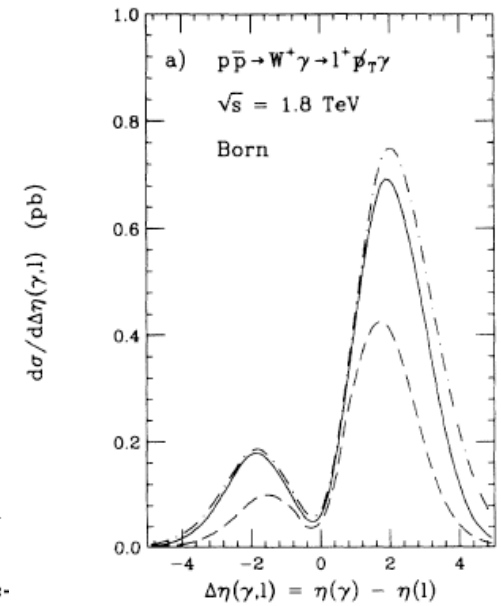


FIG. 3. The differential cross section for $pp \to W^-\gamma X$ and $p\bar{p} \to W^-\gamma X$, with a photon energy cut $E_\gamma > 30$ GeV. $\theta_{c.m.}$ is the angle between the W^- and the proton direction in the $W^-\gamma$ c.m. frame. $\sqrt{S} = 540$ GeV and $M_W = 85$ GeV/c^2.

PRD 50, 1917(1994)

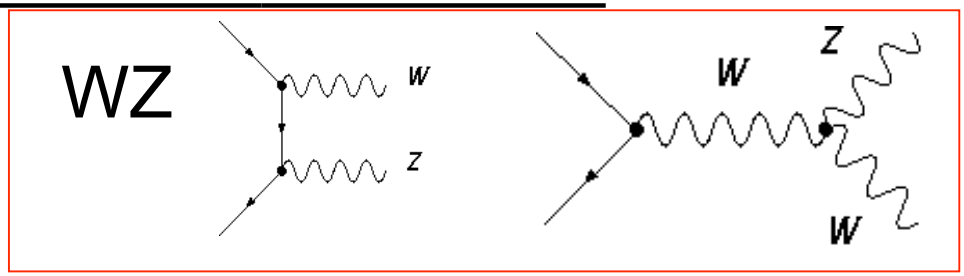


$$p_T(\gamma) > 5 \text{ GeV}, \quad |\eta(\gamma)| < 3,$$
$$p_T(\ell) > 20 \text{ GeV}, \quad |\eta(\ell)| < 3.5,$$
$$\not{p}_T > 20 \text{ GeV}, \quad \Delta R(\gamma, \ell) > 0.7.$$

Dashed: $p_T(\gamma) > 10$ GeV
Dash-dotted: no $p_T(\ell)$ or MEt cuts

WZ Production

Diboson Final State



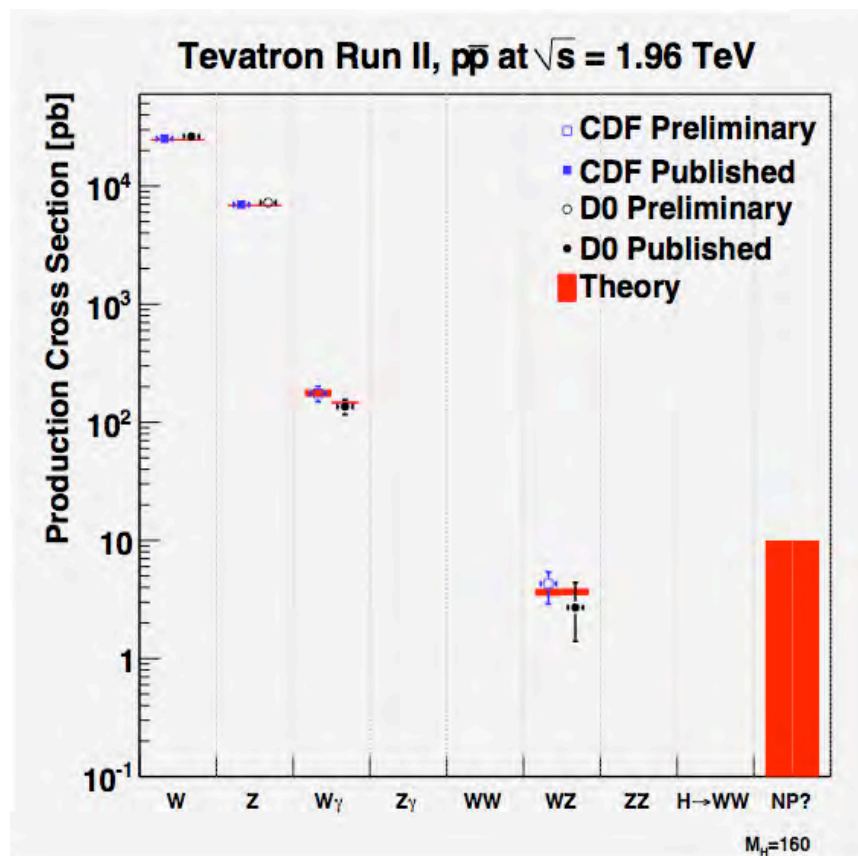
SM Tests:

Look for "anomalous couplings"

- effective Lagrangian non-SM parameters: Δg, $\Delta K_{\gamma,Z}$ and $\lambda_{\gamma,Z}$
- $\Delta K_{\gamma,Z} = K_{\gamma,Z} - 1 = 0$ & $\Delta g = \lambda_{\gamma,Z} = 0$ in SM
- at scale Λ = 2 TeV
  - $-0.12 < \Delta K_Z (= \Delta g_1^Z) < 0.29$ (D0)
  - $-0.17 < \lambda_Z < 0.21$ (D0)
  - $-0.13 < \lambda < 0.14$ (CDF)
  - $-0.76 < \Delta K < 1.18$ (CDF)
  - $-0.13 < \Delta g < 0.23$ (CDF)

SM Tests:

1) Test SM production predictions
   - Cross sections
     - $\sigma = 4.3 \pm 1.4 \pm 1.1$ pb (CDF)
       - SM: 3.65 ± 0.25 pb
     - $\sigma = 2.7 + 1.7 - 1.3$ pb (D0)
       - SM: 3.68 ± 0.25 pb



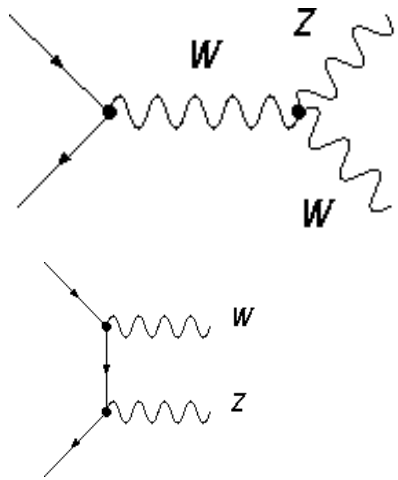
WZ Couplings

CDF uses Z P_T of WZ events to test WWZ coupling

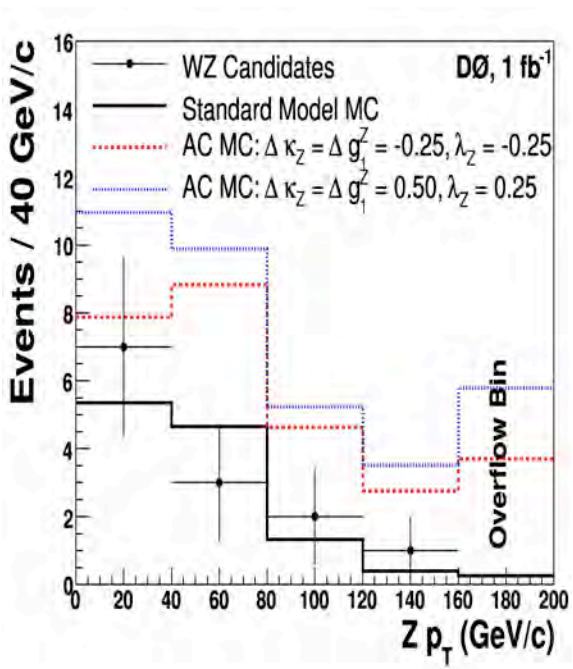
- ➔ Parameterize WWZ coupling $\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{aTGC}$

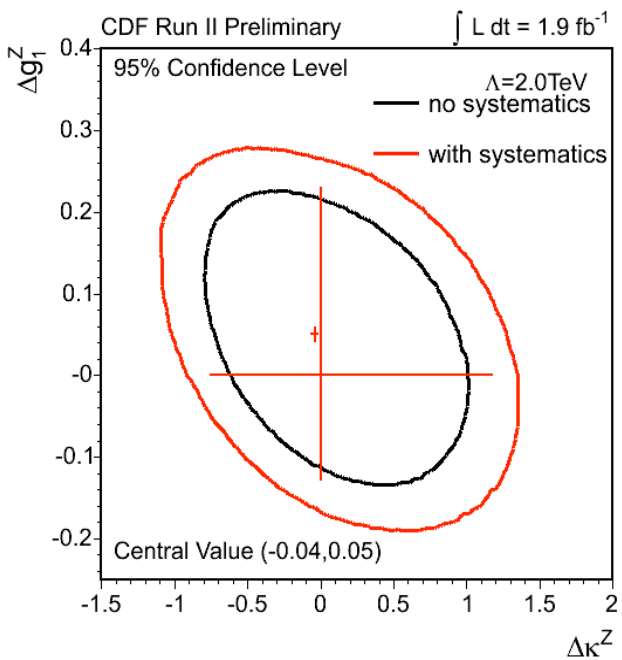
$$\mathcal{L}_{aTGC}/ig_{WWZ} = \Delta g(W^*_{\mu\nu}W^{\mu}Z^{\nu} - W_{\mu\nu}W^{*\mu}Z^{\nu}) + \Delta\kappa W^*_{\mu}W_{\nu}Z^{\mu\nu} + \frac{\lambda}{M_W^2}W^*_{\rho\mu}W^{\mu}_{\nu}Z^{\nu\rho}$$

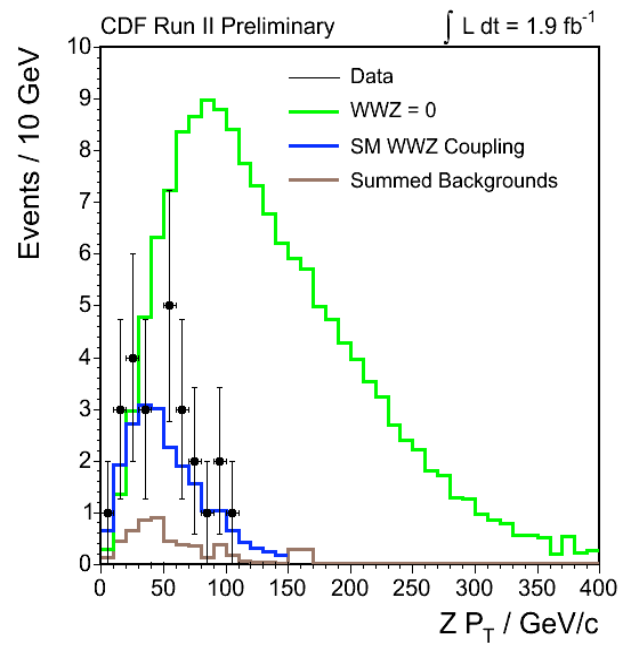
- ➔ $\Delta g = \Delta\kappa = \lambda = 0$ in the Standard Model



- ➢ Would see $\mathcal{L}_{SM}$=0 in cross section
- ➢ Anomalous coupling limits from Z P_T distribution

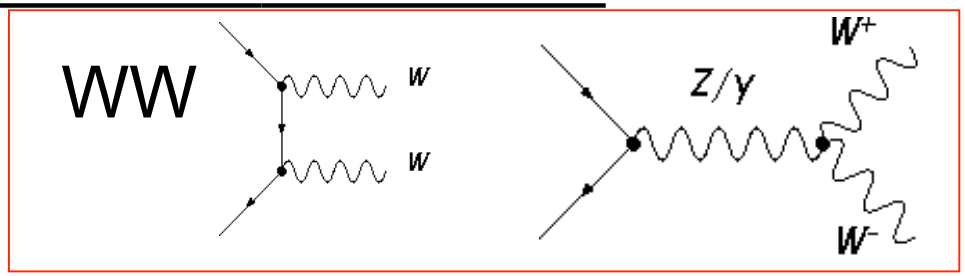






WW Production

Diboson Final State



SM Tests:

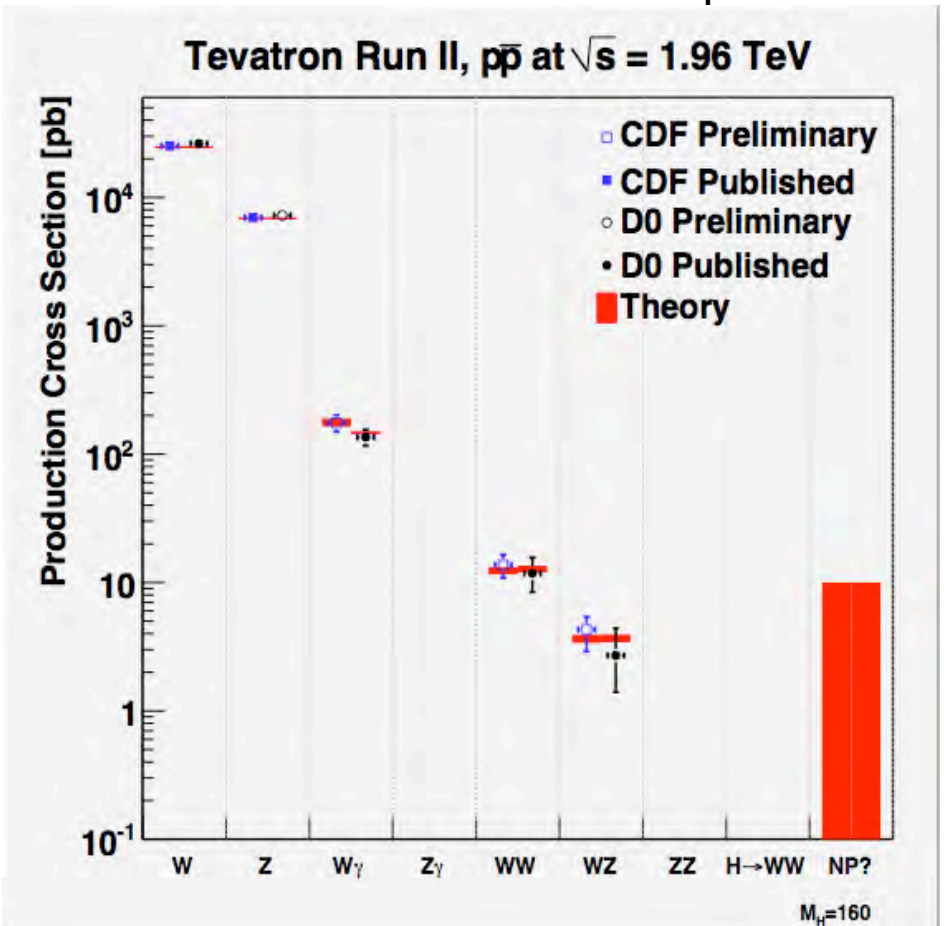
Look for "anomalous couplings"

- CP-conserving effective Lagrangian non-SM parameters: $K_{\gamma,Z}$ and $\Lambda_{\gamma,Z}$
- $\Delta K_{\gamma,Z} = K_{\gamma,Z} - 1 = 0$ & $\Lambda_{\gamma,Z} = 0$ in SM
  - $-0.32 < \Delta K_{\gamma,Z} < 0.45$ (D0)
  - $-0.12 < \Lambda_{\gamma,Z} < 0.13$ (D0)

SM Tests:

Test SM production predictions

- Cross sections
  - $\sigma = 13.6 \pm 2.3 \pm 1.6 \pm 1.2$ pb (CDF)
    - SM: 12.4 ± 0.8 pb
  - $\sigma = 11.8\ ^{+3.7}_{-3.2}\ ^{+1.0}_{-0.8} \pm 0.7$ pb (D0)
    - SM: 12.0 to 13.5 pb



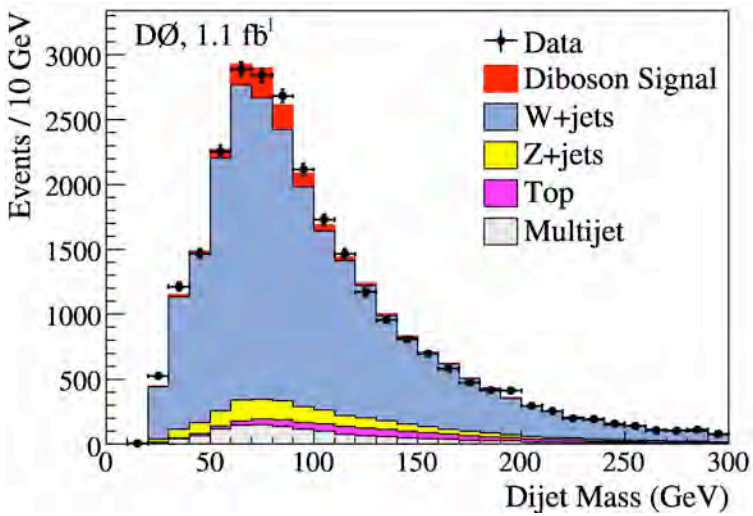
WW & WZ -> lν + jets

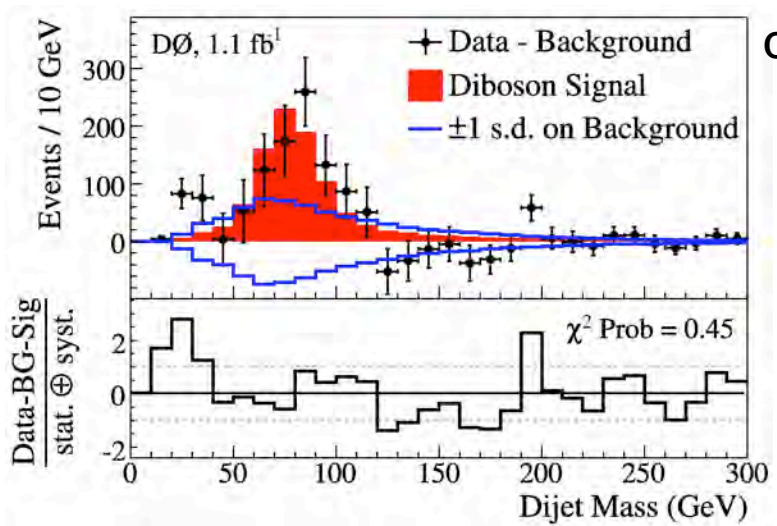
Search for lν + 2 or more jets

E_T > 20 GeV ME_T > 25 GeV M_T > 30 GeV/c^2 (CDF)
E_T > 20 GeV ME_T > 20 GeV M_T > 35 GeV/c^2 (D0)

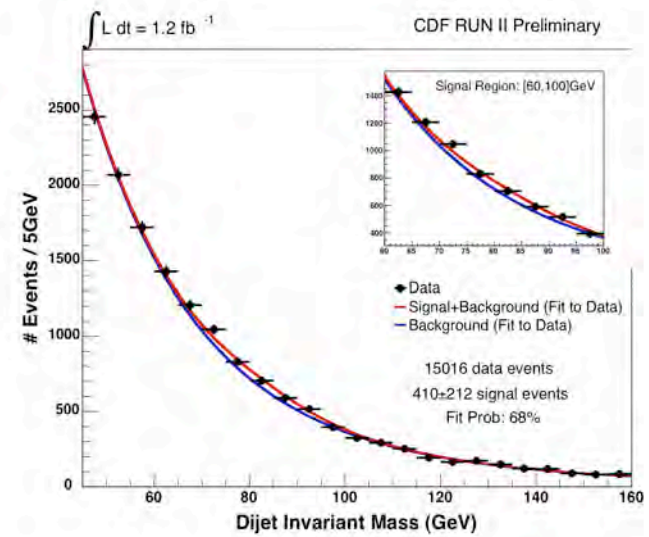
Use neural net or Random Forrest to enhance W/Z->2 jets

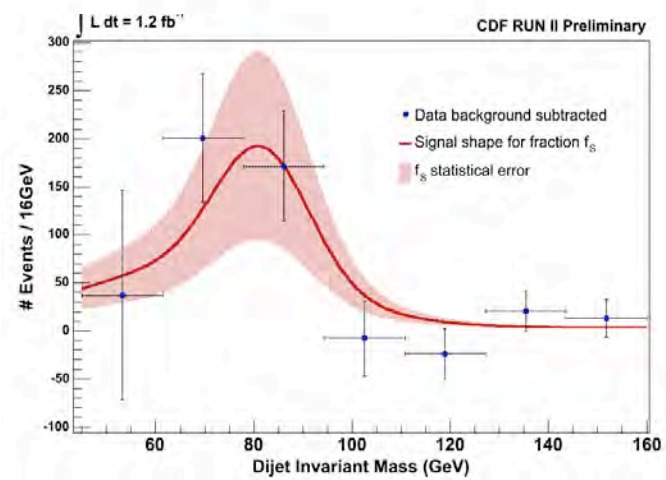
Fit for signal & background





D0:
σ(WV) = 20.2 ± 4.5 pb
σ = 16.1 ± 0.9 pb (SM)

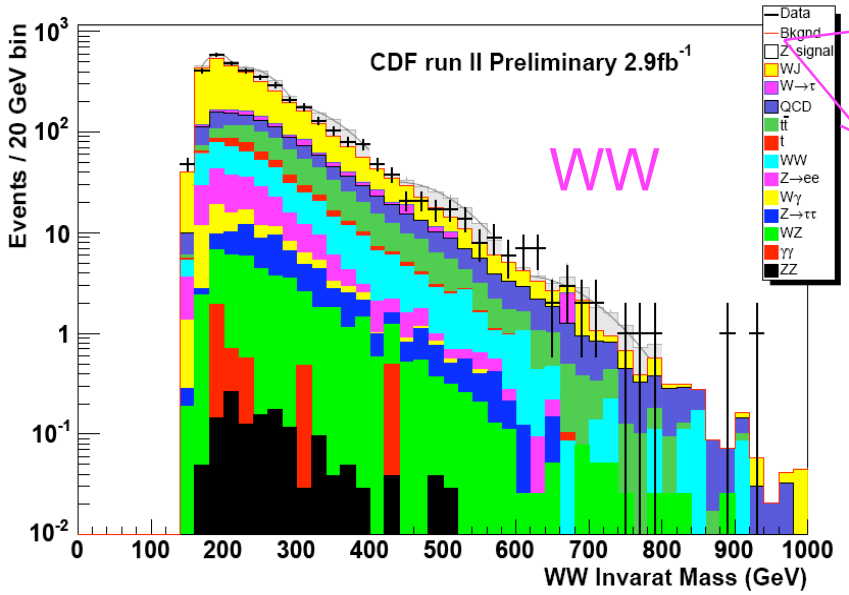


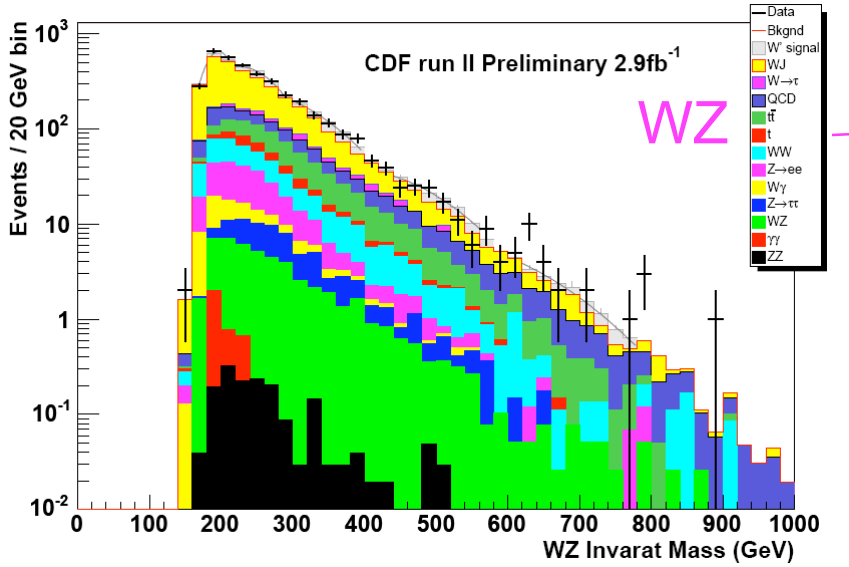


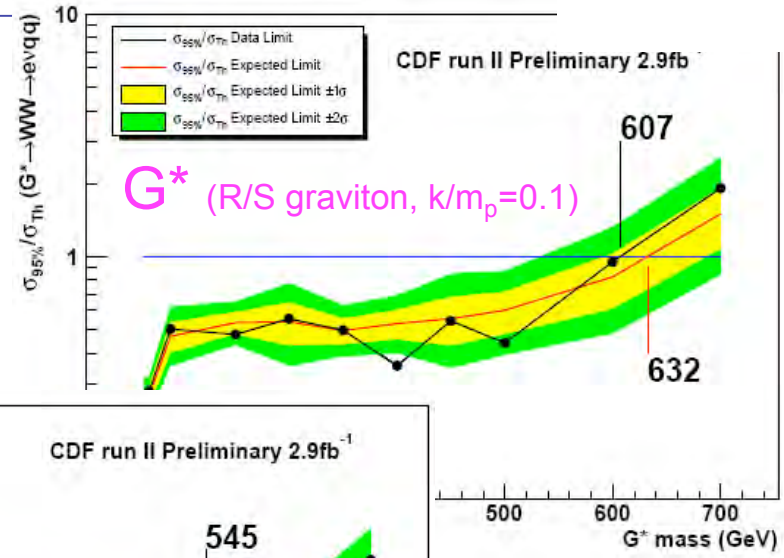
CDF:
N_{Signal} = 410 ± 212(stat) ± 107(sys)
σ × Br = 1.47 ± 0.77(stat) ± 0.38(sys) pb
σ × Br < 2.88 pb (95% C.L.)

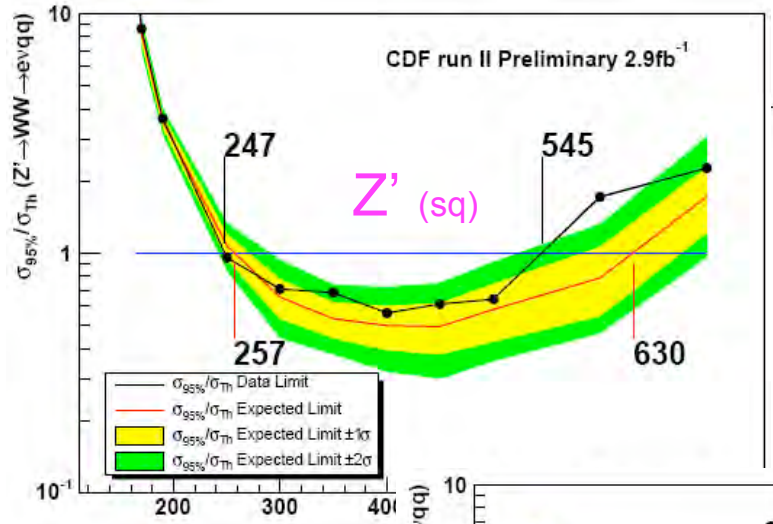
Search for Diboson Resonances

Combine e + $\not{E}_t$ to W, and, jet+jet to W or Z, then, combine WW or WZ for new particles.



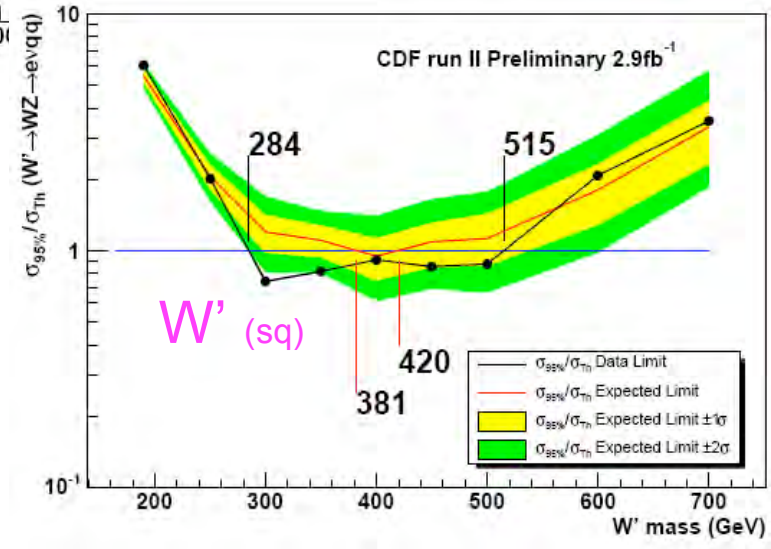






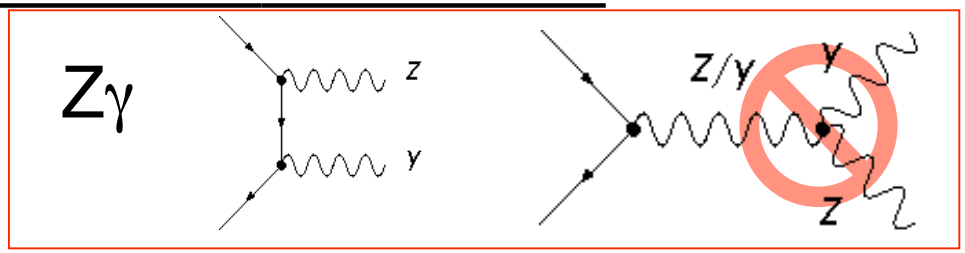
Cross section limit ratio

$\sigma_{95\%CL}/\sigma_{theory}$



Zγ Production

Diboson Final State



SM Tests:

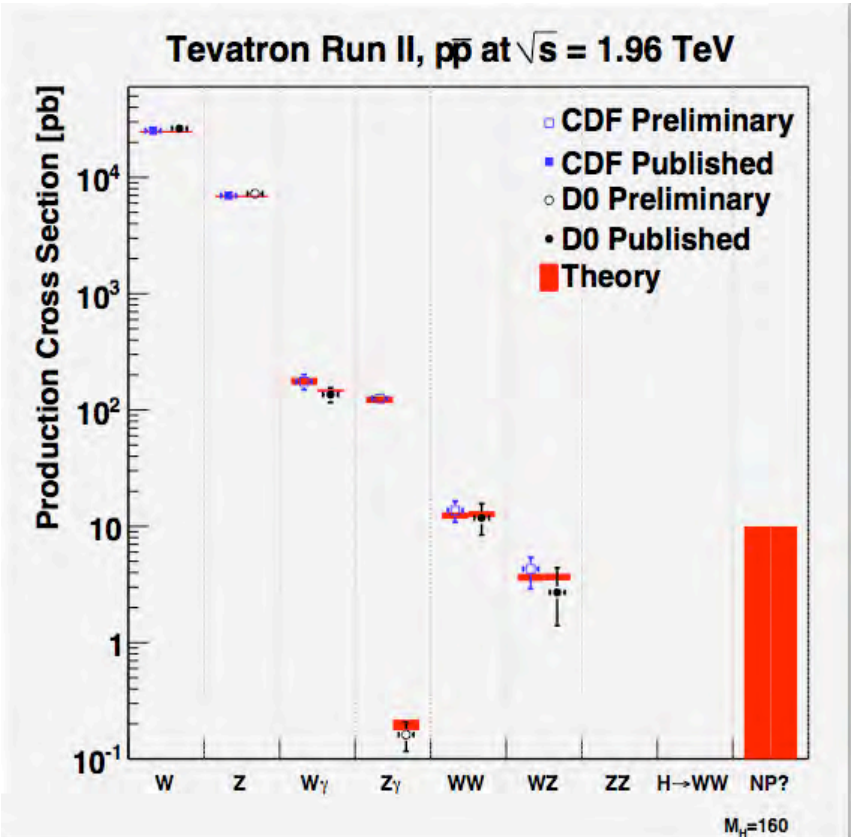
Look for "anomalous couplings"

- effective Lagrangian non-SM parameters: $h^{\gamma,Z}_{30}$ and $h^{\gamma,Z}_{40}$
- 0 in SM
  - $|h^{\gamma,Z}_{30}| < 0.033$ (D0, Λ=1.5 TeV)
  - $|h^{\gamma,Z}_{40}| < 0.0017$ (D0 , Λ=1.5 TeV)
  - $|h^{Z}_{30}| < 0.083$ (CDF, Λ=1.2 TeV)
  - $|h^{\gamma}_{30}| < 0.084$ (CDF, Λ=1.2 TeV)
  - $|h^{\gamma,Z}_{40}| < 0.0047$ (CDF, Λ=1.2 TeV)

SM Tests:

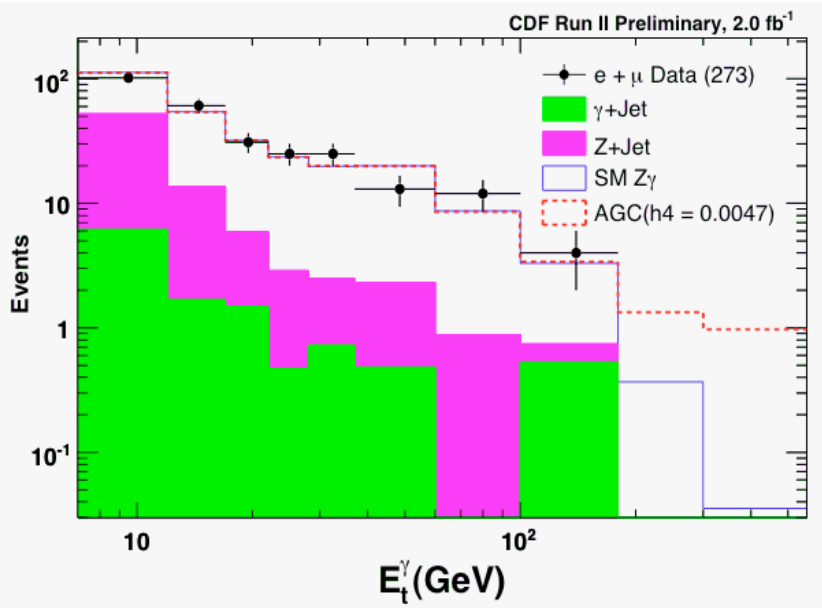
Test SM production predictions

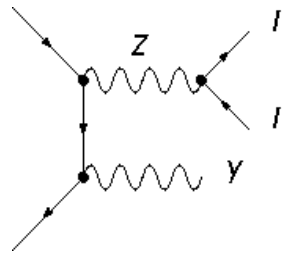
- Cross sections ($\Delta R_{l\gamma} > 0.7$)
  - $\sigma(E_T\gamma > 7$ GeV) = 4.6 ± 0.5 pb (CDF)
    - SM: 4.5 ± 0.4 pb
  - $\sigma(E_T\gamma > 90$ GeV) = 32 ± 9 ± 2 fb (D0)
    - SM: 39 ± 4 fb



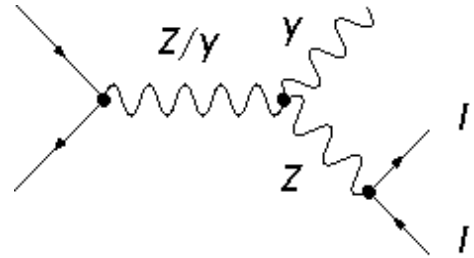
Zγ Production

Anomalous couplings look like ISR events, but have more events at higher photon Et.

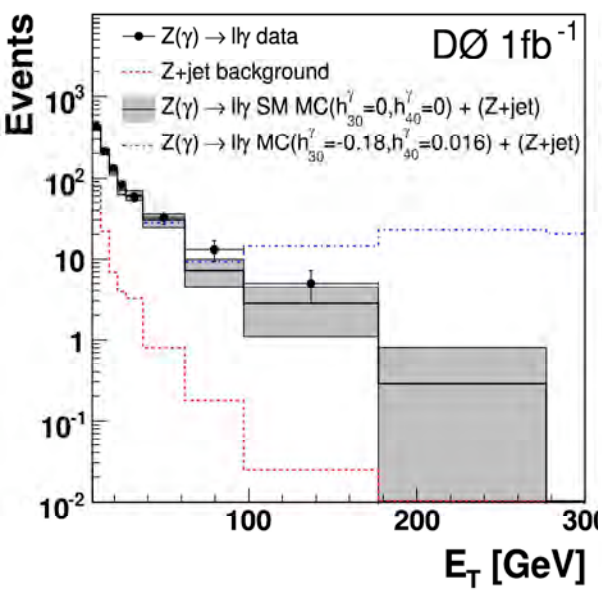


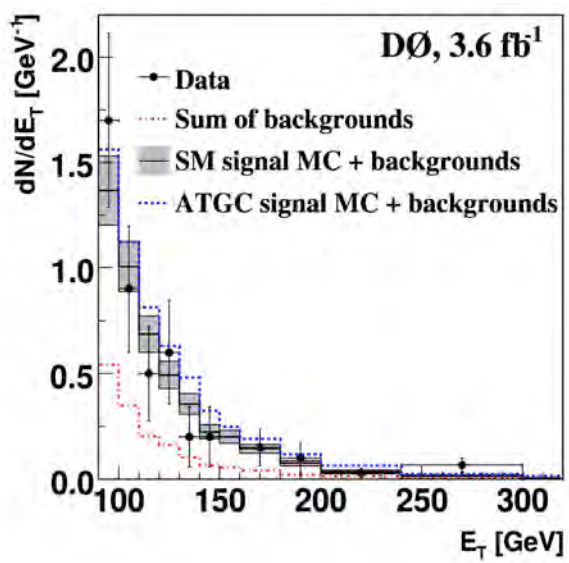


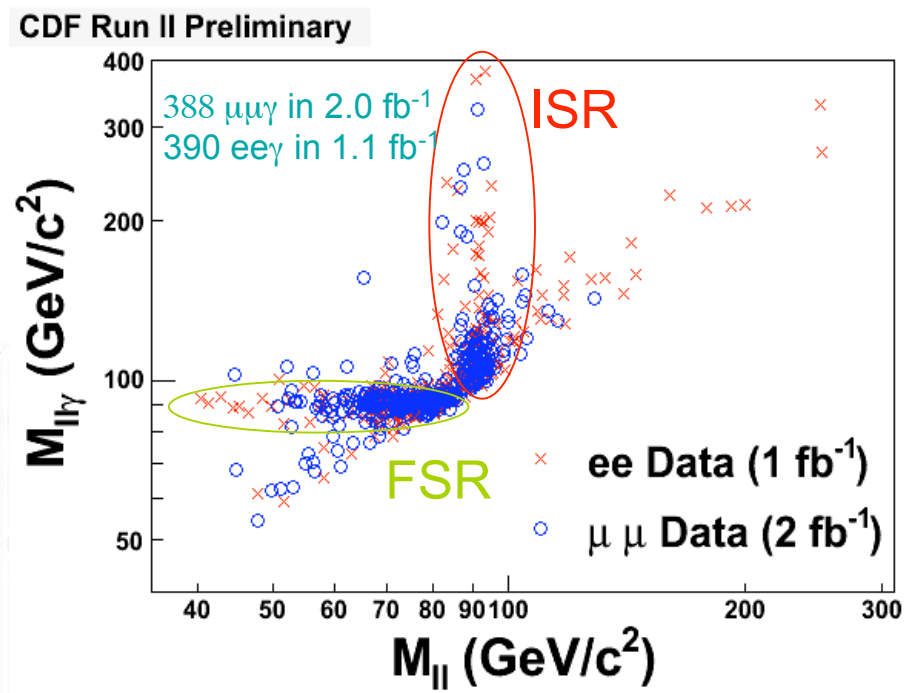
ISR ($M_{\ell\ell}$~M_Z)

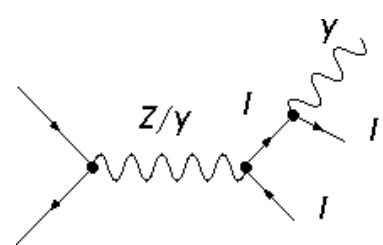


Anomalous Coupling ($M_{\ell\ell}$~M_Z) like ISR





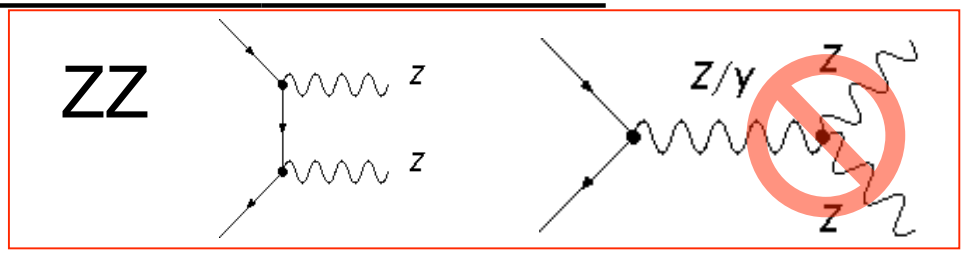




FSR ($M_{\ell\ell\gamma}$ ~M_Z)

ZZ Production

Diboson Final State



SM Tests:

Look for "anomalous couplings"

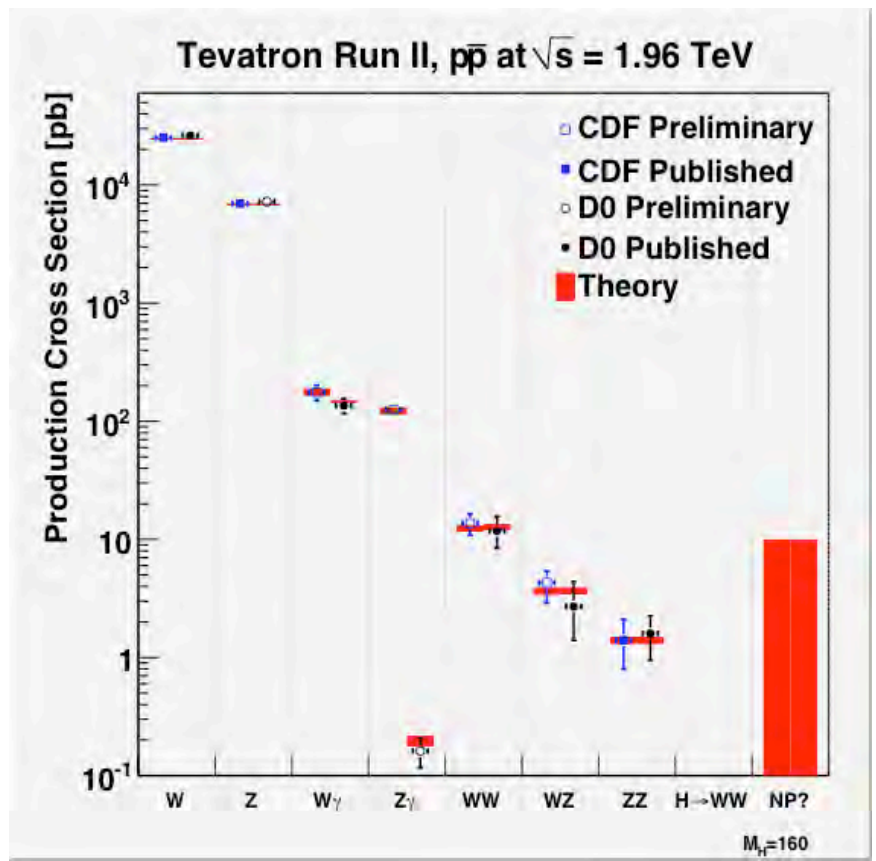
- effective Lagrangian non-SM parameters: $h^{\gamma,Z}_5$ and $h^{\gamma,Z}_4$
- 0 in SM
  - $-0.26 < f^{\gamma}_4 < 0.26$ (D0)
  - $-0.28 < f^{Z}_4 < 0.28$ (D0)
  - $-0.30 < f^{\gamma}_5 < 0.28$ (D0)
  - $-0.31 < f^{Z}_5 < 0.29$ (D0)

  - $-0.10 < f^{\gamma}_4 < 0.10$ (CDF)
  - $-0.12 < f^{Z}_4 < 0.12$ (CDF)
  - $-0.11 < f^{\gamma}_5 < 0.11$ (CDF)
  - $-0.13 < f^{Z}_5 < 0.12$ (CDF)

SM Tests:

Test SM production predictions

- Cross sections)
  - $\sigma = 1.4 + 0.7 - 0.6$ pb (CDF)
    - SM: 1.4 ± 0.1 pb
  - $\sigma = 1.6 \pm 0.7$ pb (D0)
    - SM: 1.4 ± 0.1 pb



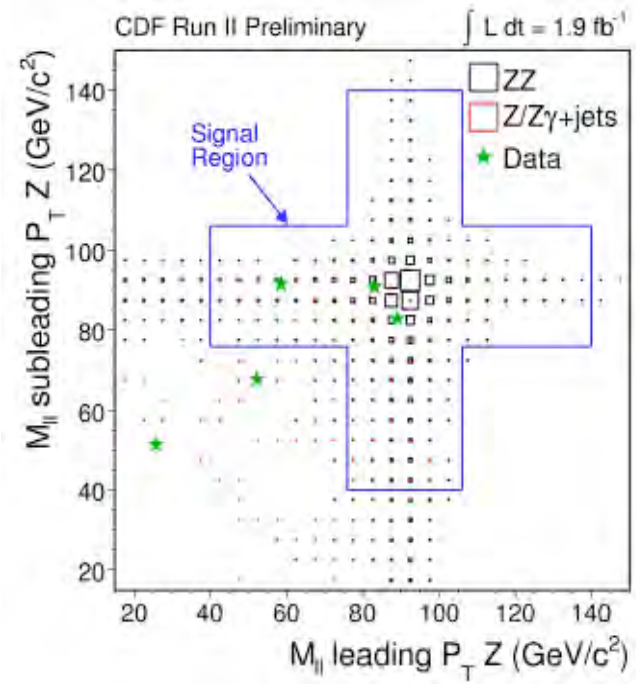
ZZ Production

CDF Results

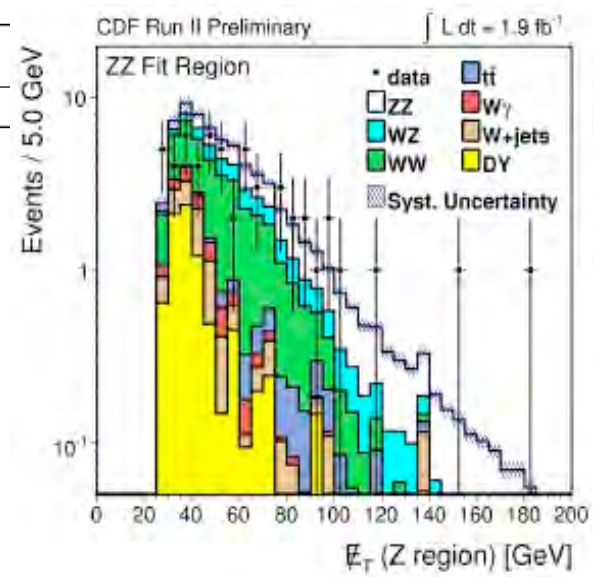
- Search for 4 leptons or 2 leptons + 2 ν
  - → 4 leptons (eeee, ee$\mu\mu$, $\mu\mu\mu\mu$)

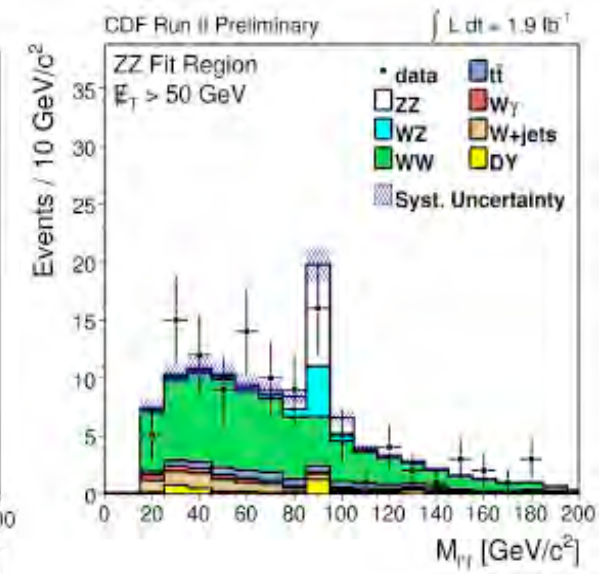
Category	Candidates without a a trackless electron	Candidates with a a trackless electron
ZZ	$1.990 \pm 0.013 \pm 0.210$	$0.278 \pm 0.005 \pm 0.029$
Z+jets/$Z\gamma$+jets	$0.014^{+0.010}_{-0.007} \pm 0.003$	$0.082^{+0.089}_{-0.060} \pm 0.016$
Total	$2.004^{+0.016}_{-0.015} \pm 0.210$	$0.360^{+0.089}_{-0.060}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

  - → ll$\nu\nu$
    - many backgrounds
      - WW->ll$\nu\nu$
    - use as much kinematic information as possible
      - use matrix elements



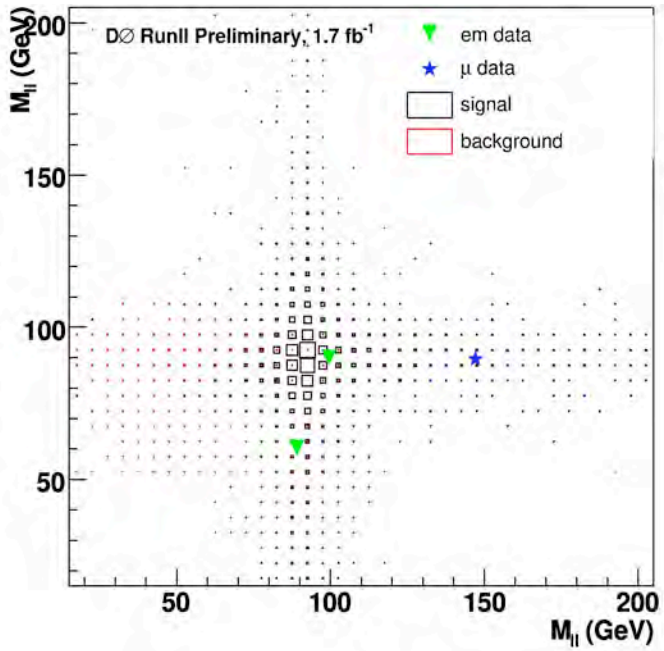
3 events in signal box:
- two 4-μ
- one 4-e





ZZ Production

- DO Results
- 4 leptons
  - ➔(eeee, eeμμ, μμμμ)



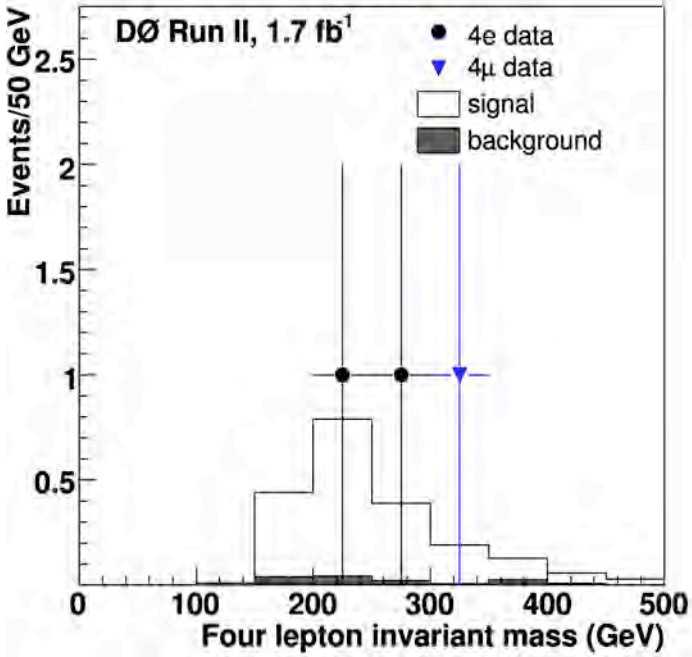
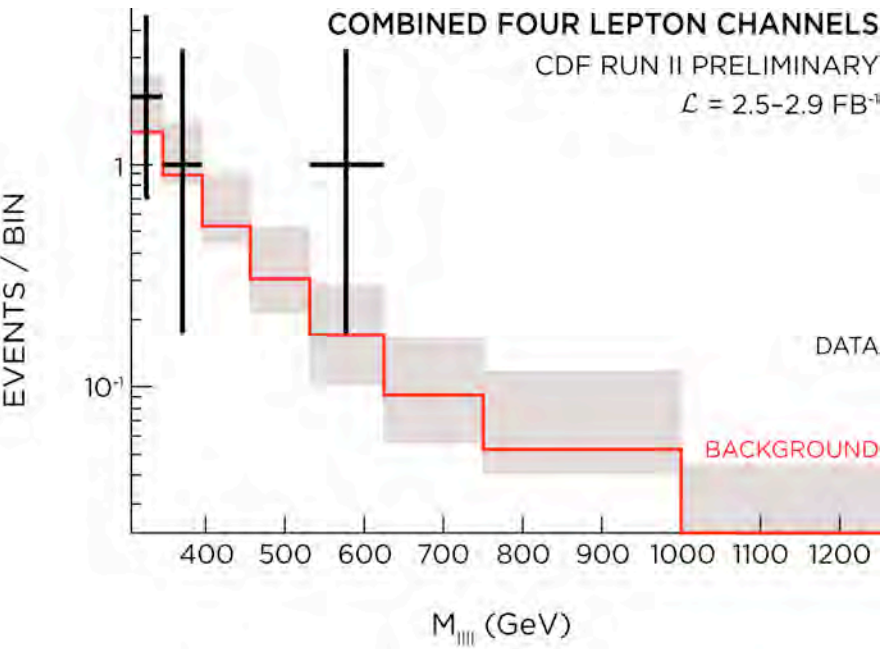


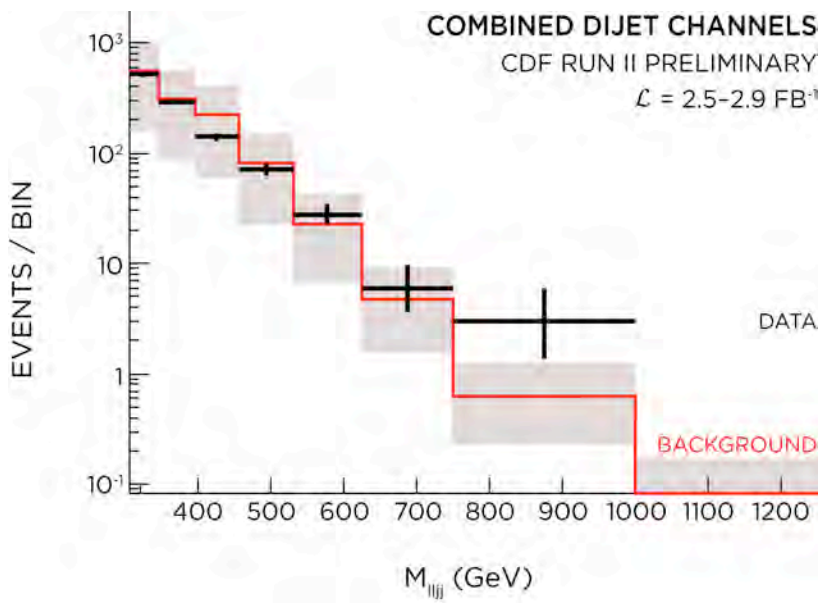
TABLE I. The integrated luminosity, expected number of signal (Z/γ^* Z/γ^*) and background events [$t\bar{t}$ and $Z(\gamma)$ + jets which includes all $W/Z/\gamma$ + jets contributions], and the number of observed candidates in the seven $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ subchannels. Uncertainties reflect statistical and systematic contributions added in quadrature.

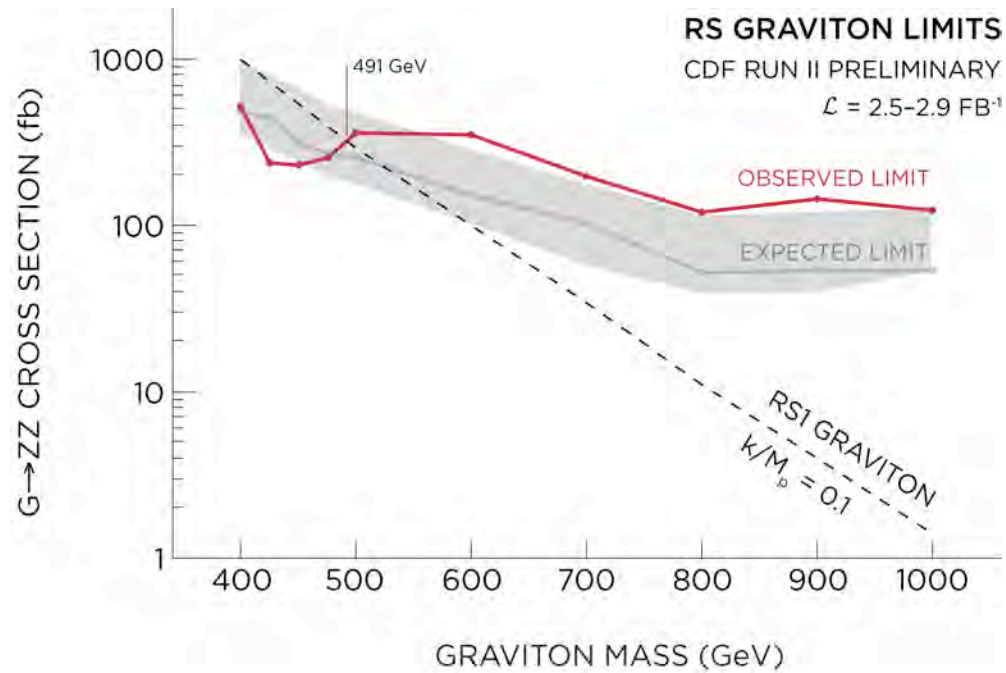
Subchannel	$4e_{2C}$	$4e_{3C}$	$4e_{4C}$	4μ	$2\mu 2e_{0C}$	$2\mu 2e_{1C}$	$2\mu 2e_{2C}$
Luminosity (fb^{-1})	1.75 ± 0.11	1.75 ± 0.11	1.75 ± 0.11	1.68 ± 0.10	1.68 ± 0.10	1.68 ± 0.10	1.68 ± 0.10
Signal	0.084 ± 0.008	0.173 ± 0.015	0.140 ± 0.012	0.534 ± 0.043	$0.058^{+0.007}_{-0.006}$	0.352 ± 0.040	$0.553^{+0.045}_{-0.044}$
$Z(\gamma)$ + jets	$0.030^{+0.009}_{-0.008}$	$0.018^{+0.008}_{-0.007}$	$0.002^{+0.002}_{-0.001}$	0.0003 ± 0.0001	$0.03^{+0.02}_{-0.01}$	0.05 ± 0.01	$0.008^{+0.004}_{-0.003}$
$t\bar{t}$	...	...	...	...	$0.0012^{+0.0016}_{-0.0009}$	0.005 ± 0.002	$0.0007^{+0.0009}_{-0.0005}$
Observed events	0	0	2	1	0	0	0

Search for ZZ Resonances

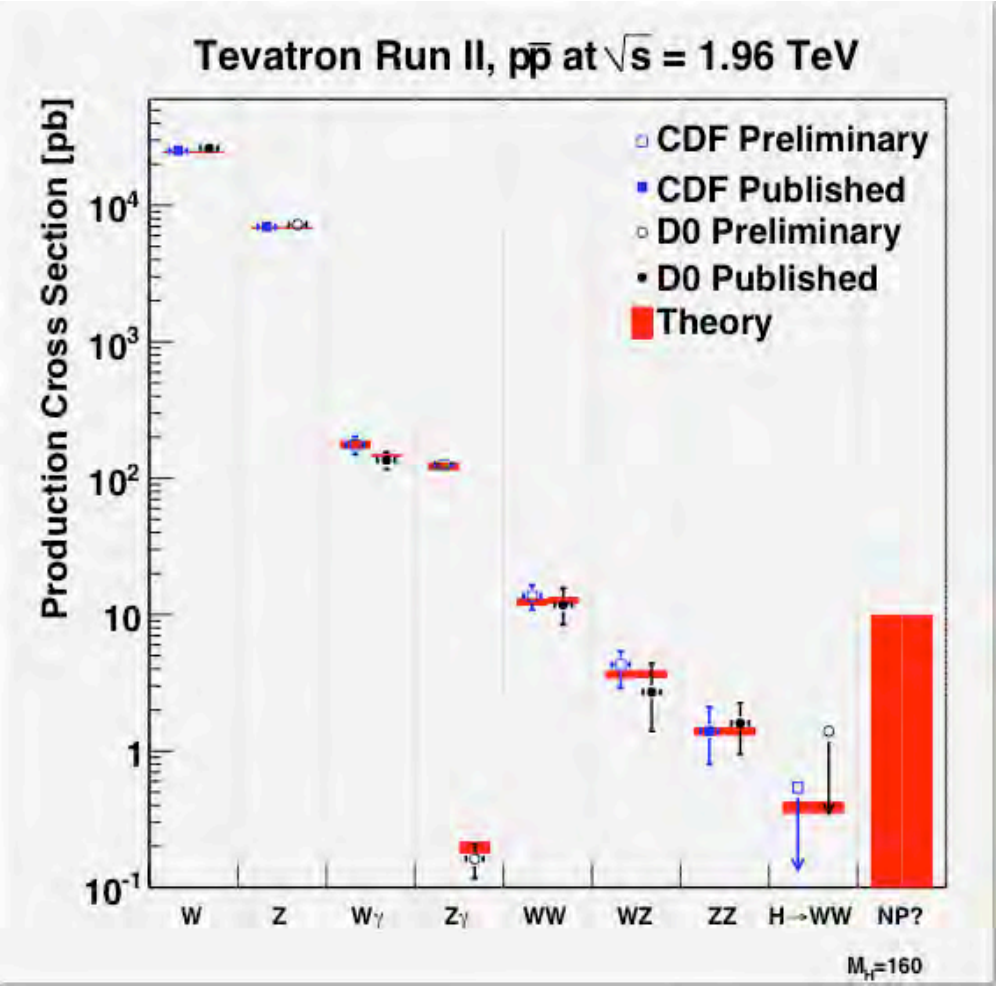
4 leptons or ll+2jet for ZZ
significantly expanded lepton acceptance







Summary



Diboson production is well described by the Standard Model!

- All modes have been seen
- Cross sections match SM
- Couplings look like SM
  - ➔ Limits on Anomalous Couplings
- No resonant diboson production is observed

Now seeing processes with cross sections similar to Higgs!