Diboson Physics at the Tevatron

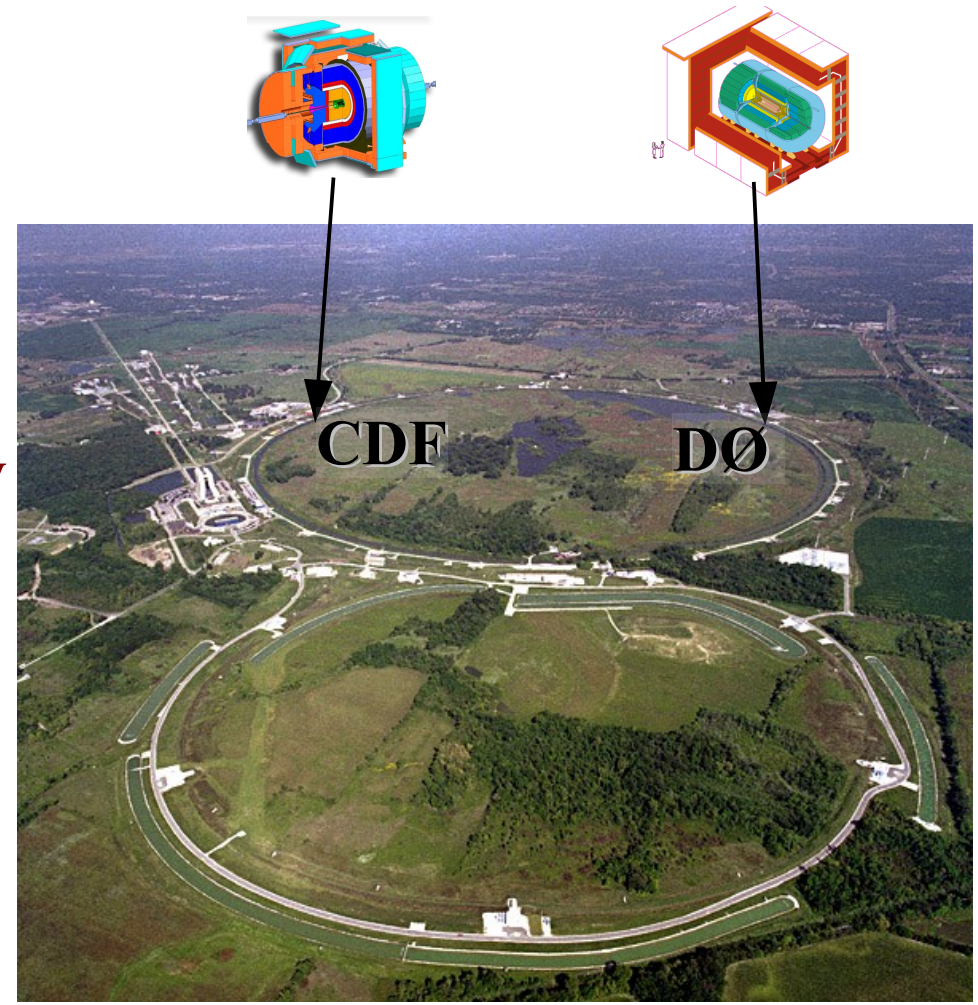
Joseph Haley – Northeastern U.
for the CDF and DØ Collaborations

April 14, 2011

DIS 2011
XIX International Workshop
on Deep-Inelastic Scattering
and Related Subjects

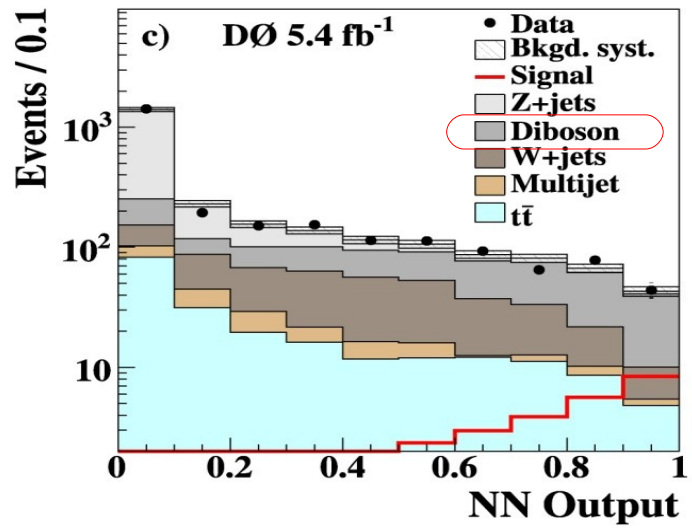
Tevatron

- Most recent Diboson measurements from the CDF and DØ experiments
  - $W\gamma \rightarrow l\nu\gamma$
  - $Z\gamma \rightarrow ll\gamma$
  - $WZ \rightarrow l\nu ll$
  - $ZZ \rightarrow llll, ll\nu\nu$
  - $WZ+ZZ \rightarrow l\nu bb/\nu\nu bb$
- Tevatron is a vector boson factory
  - Delivering ~50 pb^{-1}/week
    - ~600 *WW*, ~200 *WZ*, ~100 *ZZ*
  - Access to charged final states (not possible at LEP)
    - $W\gamma \rightarrow l\nu\gamma$, $WZ \rightarrow l\nu ll$, $l\nu qq$

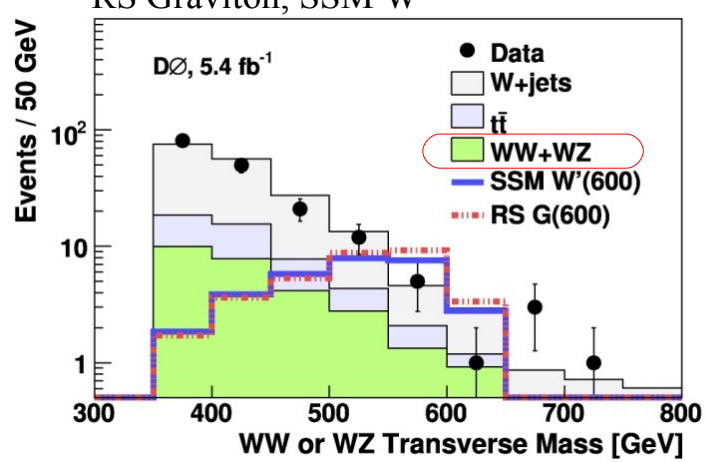


Motivation for Diboson Physics

- Higgs and BSM motivations
  - Same or similar final states
    - Must understand diboson backgrounds
      - High mass Higgs exclusion dominated by $H \rightarrow WW$
      - Searches for Beyond the SM resonance
  - Common analysis techniques
    - Diboson measurements provide proving ground for techniques used in searches

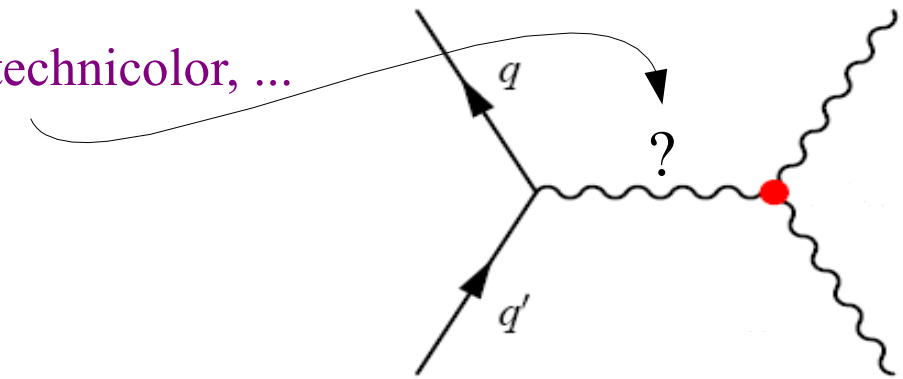


RS Graviton, SSM W'



Motivation for Diboson Physics

- Probe of new physics above some higher energy scale Λ_{NP}
  - For example, a new heavy gauge boson predicted by many extension to the SM
    - SUSY, technicolor, ...



  - Would appear as anomalous trilinear gauge-boson couplings (TGCs)
    - Affects cross sections and event kinematics
    - Anomalous TGCs could give clues to the mechanism for electroweak symmetry breaking

Motivation for Diboson Physics

- Probe of new physics above some higher energy scale Λ_{NP}
  - SM is the low energy limit of a more general theory

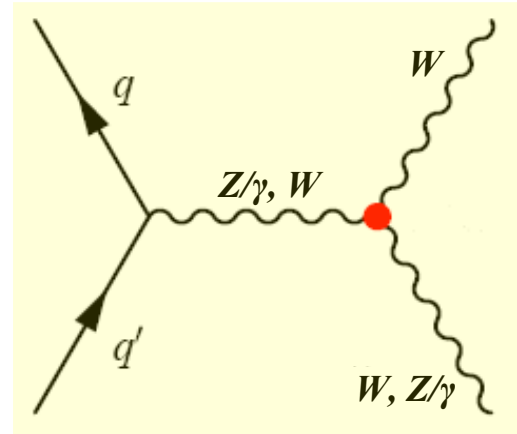
▸ γWW and ZWW TGCs

General Lagrangian has 14 TGC parameters

Assume EM gauge invariance and C and P conservation

$\Rightarrow g_1^Z,\ \kappa_\gamma,\ \kappa_Z \quad \equiv 1$ in the SM

$\Rightarrow \lambda_\gamma,\ \lambda_Z \quad \equiv 0$ in the SM

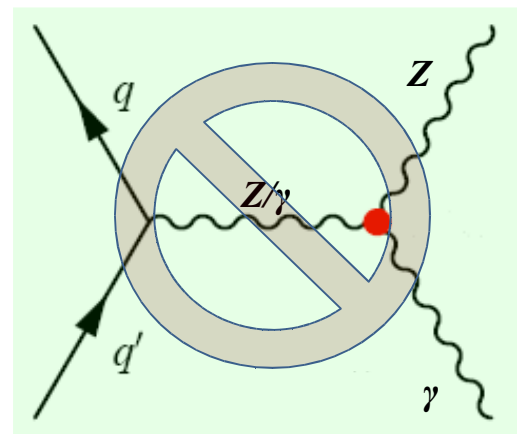


▸ γZZ and $\gamma\gamma Z$ TGCs

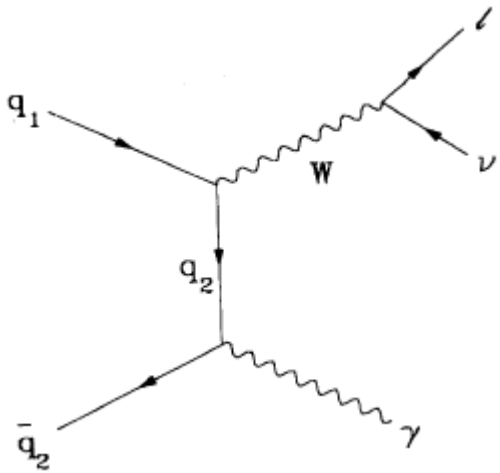
General Lagrangian has 8 TGC parameters

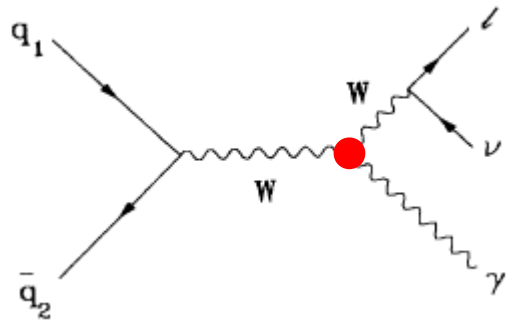
Assume CP conservation

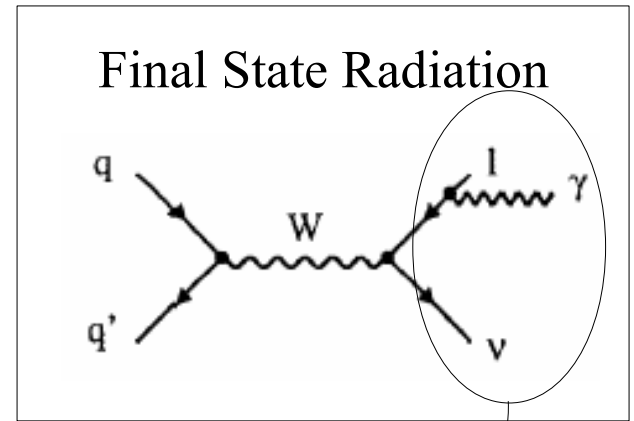
$\Rightarrow h_3^\gamma,\ h_3^Z,\ h_4^\gamma,\ h_4^Z \quad \equiv 0$ in the SM

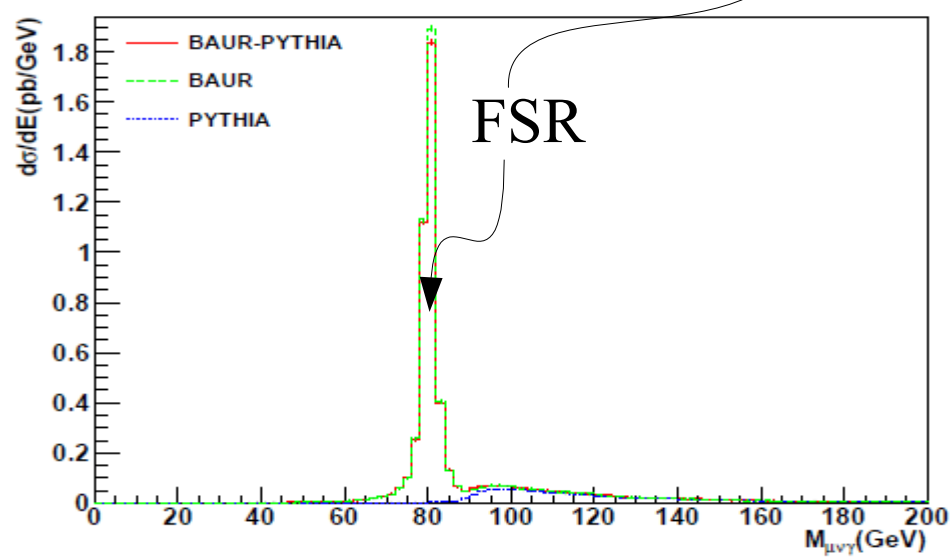


$W\gamma$ Production







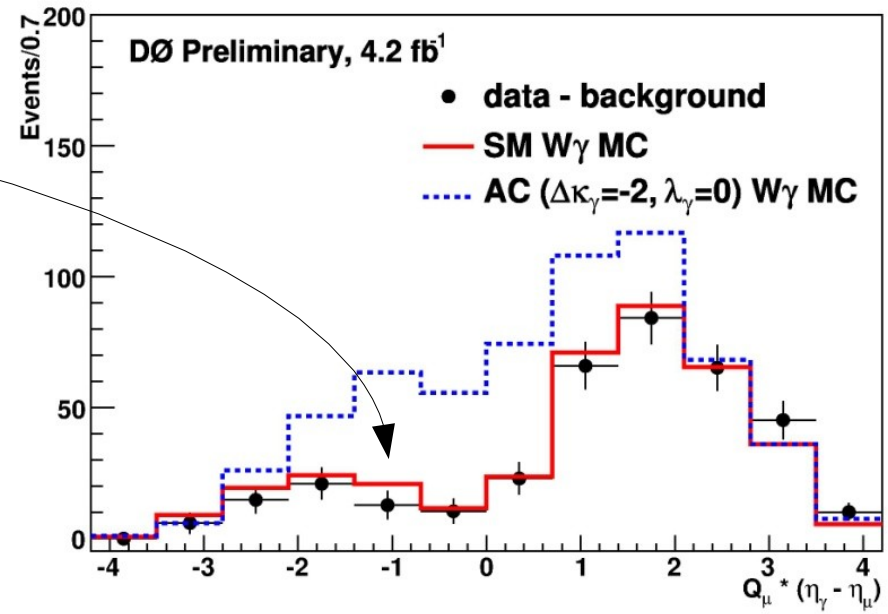


- $\sigma_{NLO} = 16.0 \pm 0.4$ pb
  - $p_T(\gamma) > 8$ GeV, $\Delta R(\gamma, l) > 0.7$
- Use 3-body mass $M_{l\nu\gamma}$ to distinguish Final State Radiation
- γWW vertex $\Rightarrow \kappa_\gamma$ and λ_γ

$W\gamma$ Cross Section

Preliminary

- Unique test of the SM: Radiation amplitude zero
  - Destructive interference between tree-level diagrams
  - ⇒ Dip in sign(l) × | η(γ) – η(l) |
    - In agreement with SM



- Cross section measurement
  - 4.2 fb^{-1} of data
  - High p_T μ, high p_T γ, and $\not{E}_T$
    - 492 $W\gamma$ candidates
    - Expected signal: 376 ± 42
    - Expected background: 134 ± 9
      - ~100 from W+jets

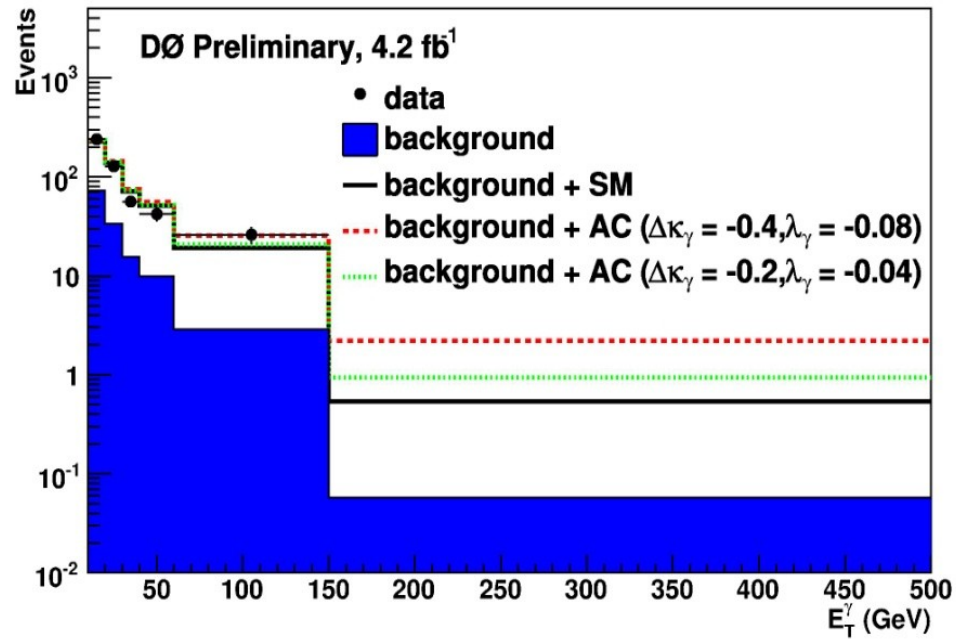
σ (pp → Wγ) = 15.2 ± 1.6 (stat+syst) pb

σ_{NLO} = 16.0 ± 0.4 pb

Wγ TGCs

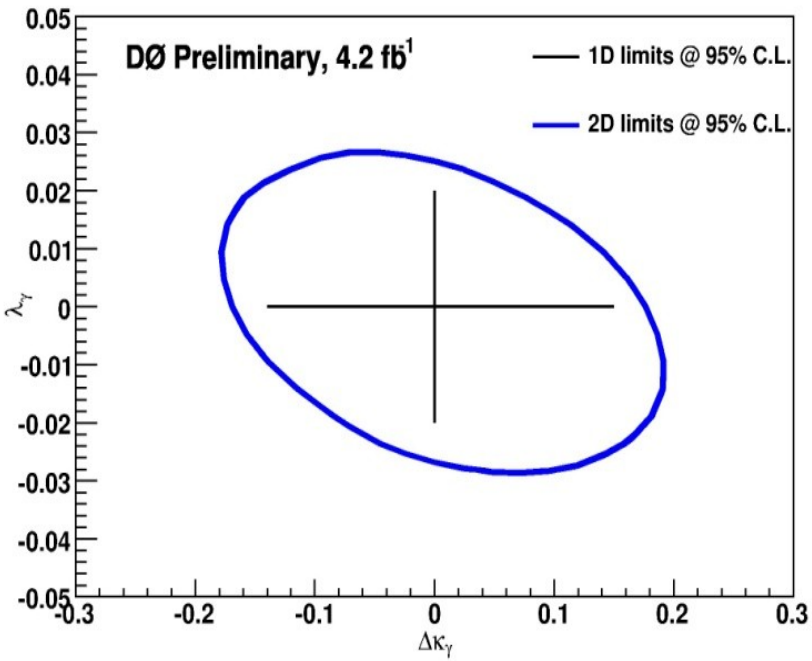
Preliminary

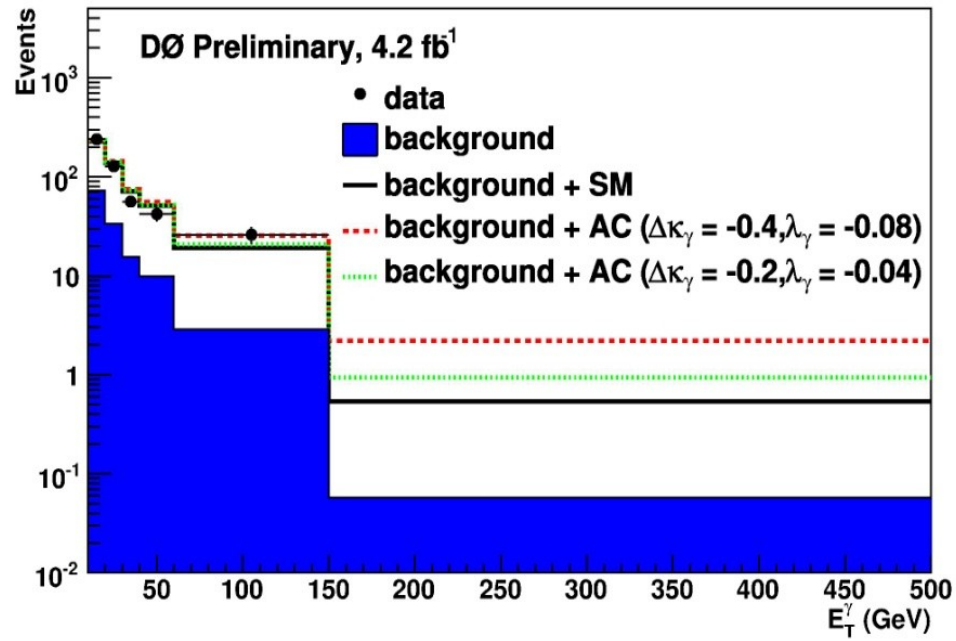
- Photon E_T spectrum sensitive to anomalous TGCs



Wγ TGCs

- Photon E_T spectrum sensitive to anomalous TGCs
  - Set 95% CL limits on anomalous TGCs (Λ_{NP} = 2 TeV)
    - 2D limits:



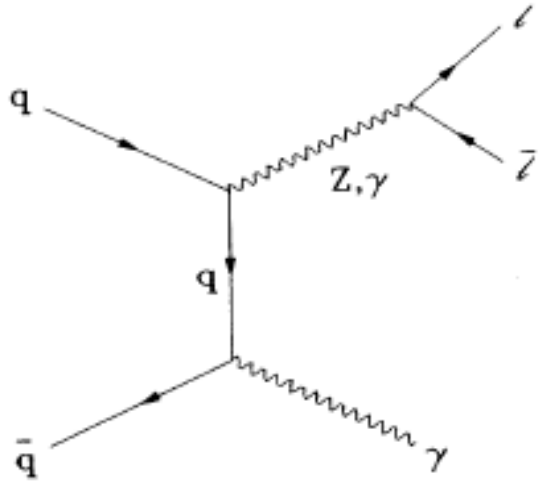


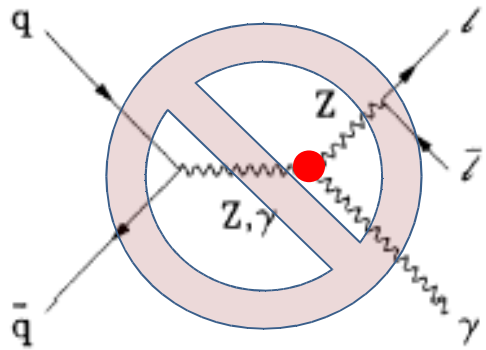
- 1D limits: Vary one coupling at a time

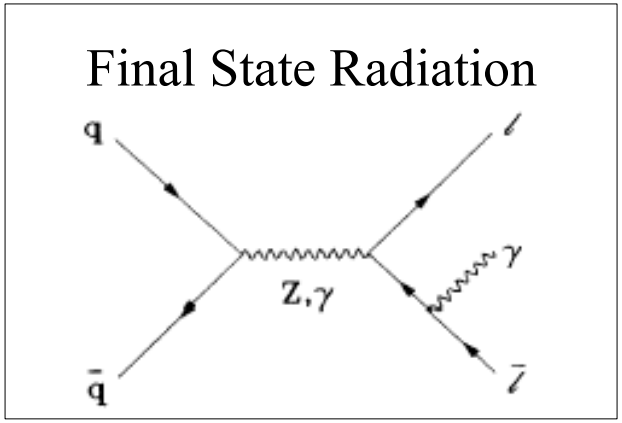
$$-0.14 < \Delta\kappa_\gamma < 0.15$$

$$-0.02 < \lambda_\gamma < 0.03$$

Zγ Production





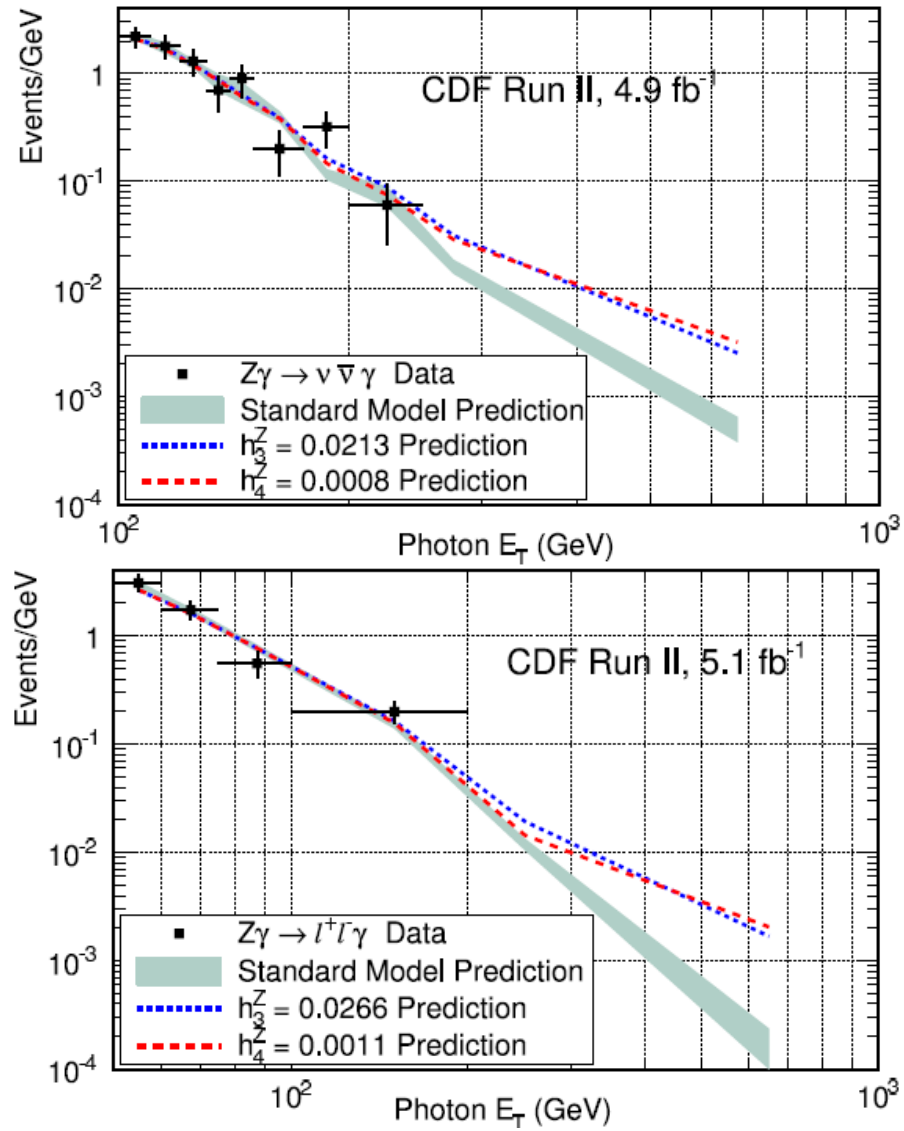


- No s-channel in the SM
- $Z\gamma\gamma$ and $ZZ\gamma$ vertices ⇒ h_3^{γ}, h_3^{Z}, h_4^{γ}, h_4^{Z}

$Z\gamma$ TGCs

arXiv:1103.2990 [hep-ex]

- Photon E_T spectra sensitive to TGCs
  - Combination of two selections
    - $Z\gamma \rightarrow ll\gamma$: 5.1 fb^{-1}, $E_T(\gamma) > 50$ GeV
    - $Z\gamma \rightarrow \nu\nu\gamma$: 4.9 fb^{-1}, $E_T(\gamma) > 100$ GeV
  - Observe 176 candidate events
    - Expected signal: 140 ± 9
    - Small background (mostly cosmic μ)



$Z\gamma$ TGCs

arXiv:1103.2990 [hep-ex]

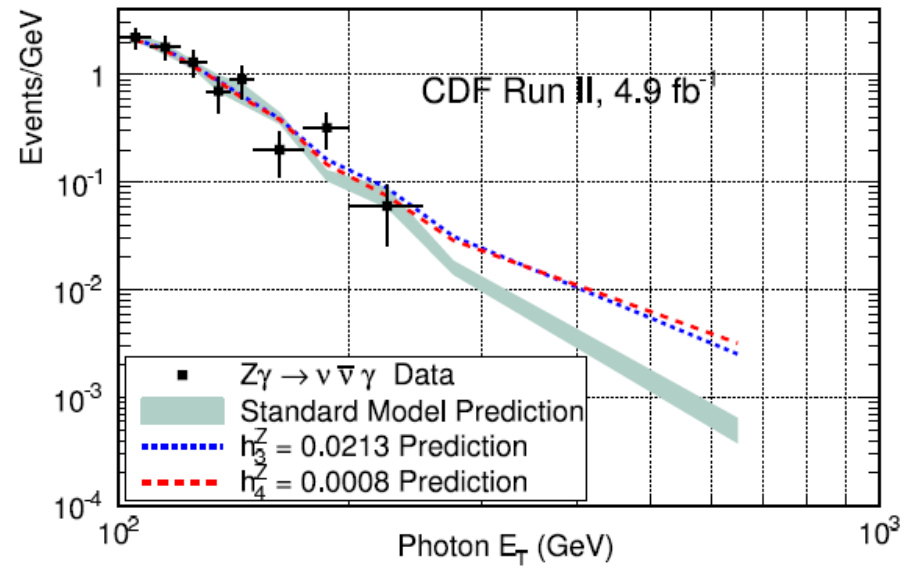
- Photon E_T spectra sensitive to TGCs
  - Combination of two selections
    - $Z\gamma \to ll\gamma$: 5.1 fb^{-1}, $E_T(\gamma) > 50$ GeV
    - $Z\gamma \to \nu\nu\gamma$: 4.9 fb^{-1}, $E_T(\gamma) > 100$ GeV
  - Observe 176 candidate events
    - Expected signal: 140 ± 9
    - Small background (mostly cosmic μ)
  - Set 95% CL limits (Λ_{NP} = 1.5 TeV)

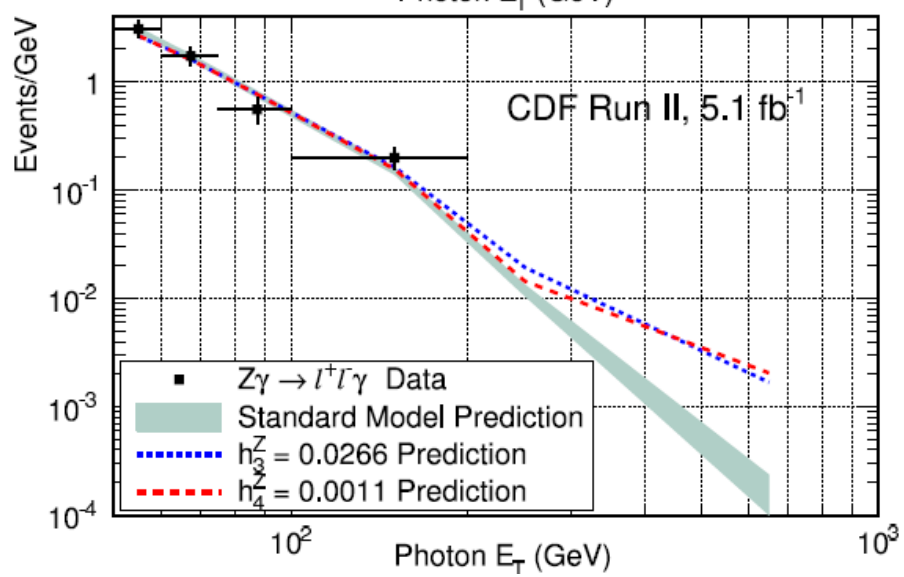
$$-0.017 < h_3^Z < 0.016$$

$$-0.017 < h_3^\gamma < 0.016$$

$$-0.0006 < h_4^Z < -0.0005$$

$$-0.0006 < h_4^\gamma < -0.0006$$





$Z\gamma$ TGCs

arXiv:1103.2990 [hep-ex]

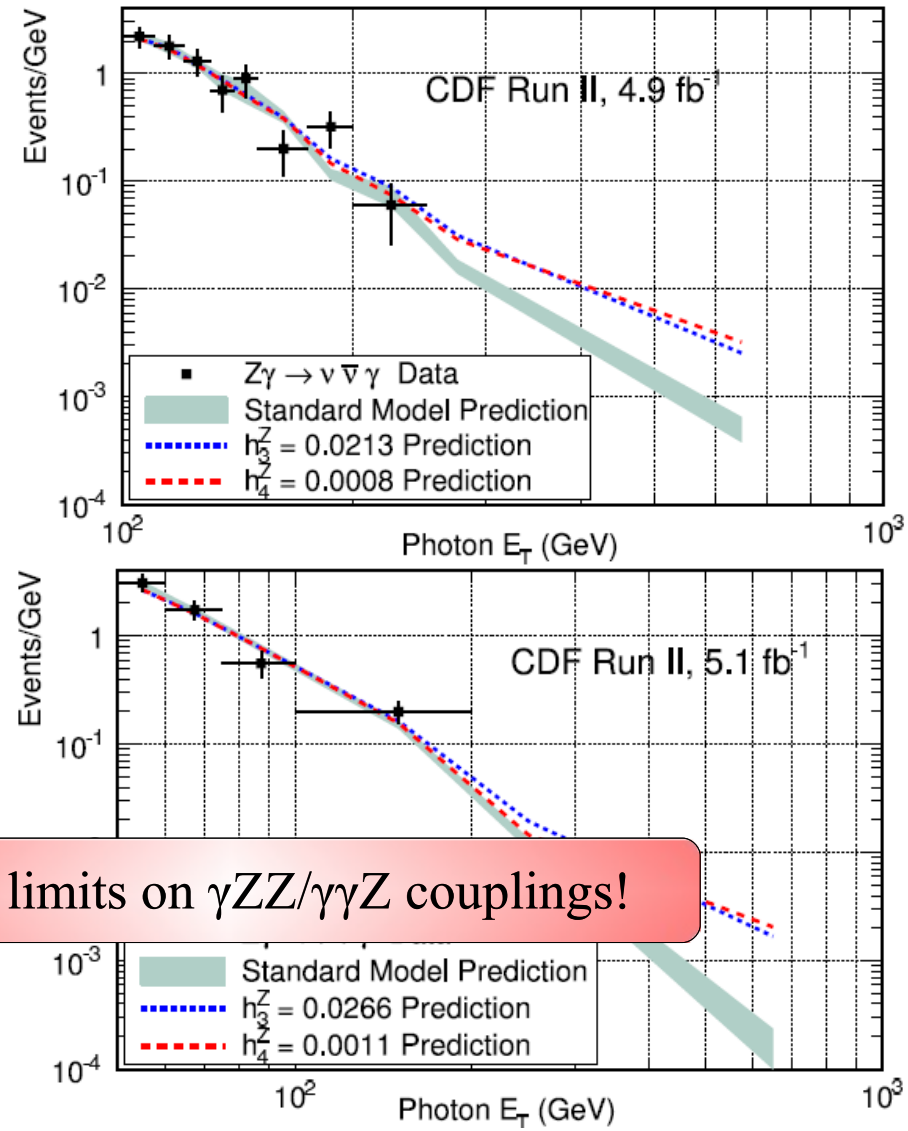
- Photon E_T spectra sensitive to TGCs
  - Combination of two selections
    - $Z\gamma \rightarrow ll\gamma$: 5.1 fb^{-1}, $E_T(\gamma) > 50$ GeV
    - $Z\gamma \rightarrow \nu\nu\gamma$: 4.9 fb^{-1}, $E_T(\gamma) > 100$ GeV
  - Observe 176 candidate events
    - Expected signal: 140 ± 9
    - Small background (mostly cosmic μ)
  - Set 95% CL limits (Λ_{NP} = 1.5 TeV)

$$-0.017 < h_3^Z < 0.016$$

$$-0.017 < h_3^\gamma < 0.016$$

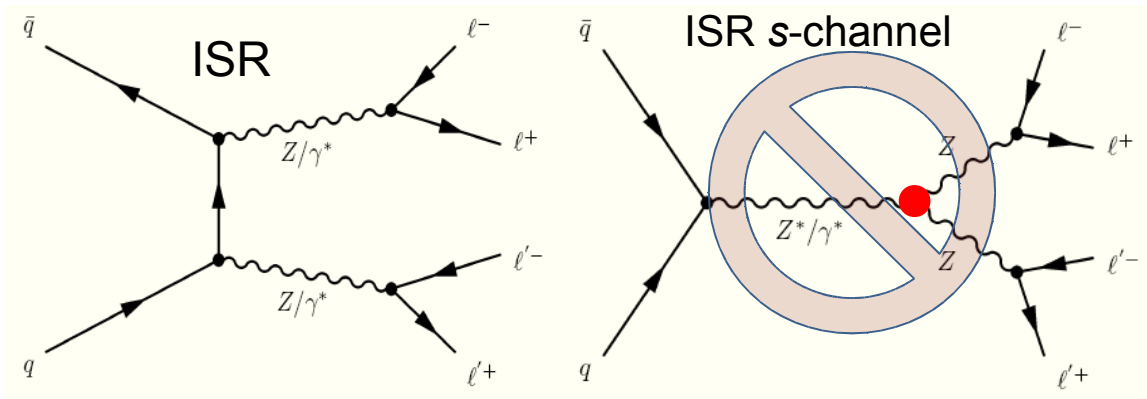
$$-0.0006 < h_4^Z < -0.0005$$

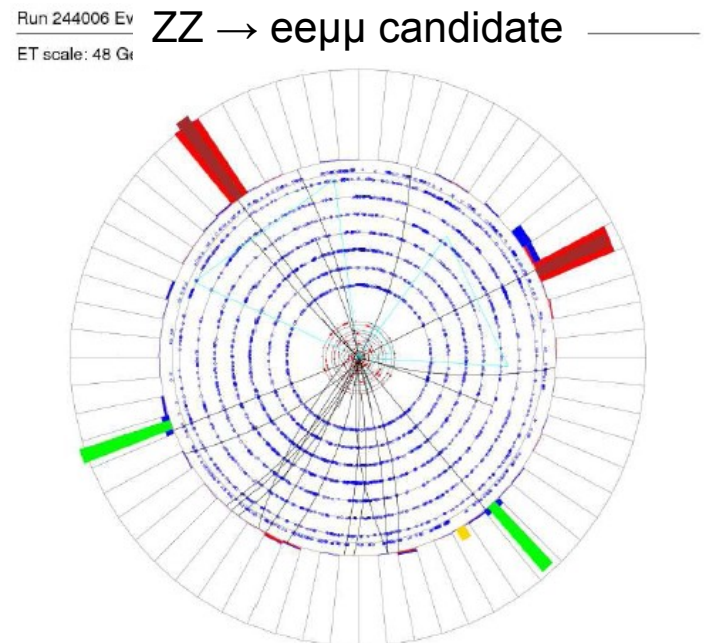
$$-0.0006 < h_4^\gamma < -0.0006$$



Tightest limits on $\gamma ZZ/\gamma\gamma Z$ couplings!

ZZ Production





- Most recently observed diboson process at the Tevatron
- $\sigma_{NLO} = 1.4 \pm 0.1$ pb
- Very clean four lepton final state

ZZ Cross Section

Preliminary

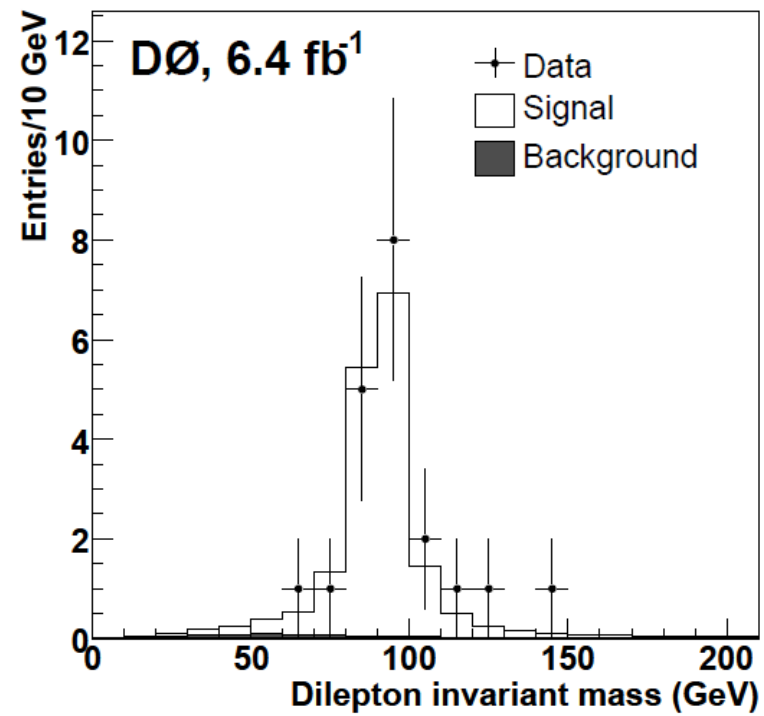
- 6.4 fb^{-1} of data
  - Four high p_T charged leptons (*eeee, eeμμ, μμμμ*)
    - Dilepton masses > 70 GeV and 50 GeV
      - ⇒ Very clean
    - 10 *ZZ* candidates
    - Expected signal: 8.7 ± 1.2
    - Expected background: 0.4 ± 0.1 (Z+jets)

$$\sigma_{(p\bar{p}\to ZZ)} = 1.33^{+0.50}_{-0.40}\,(\text{stat}) \pm 0.15\,(\text{syst}+\text{lumi})\ \text{pb}$$

⇒ 6-σ significance!

$\sigma_{NLO} = 1.4 \pm 0.1$ pb

preliminary

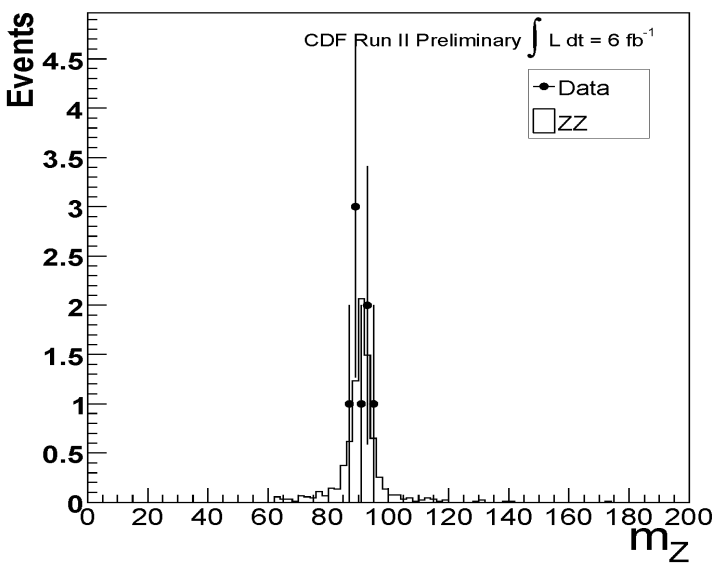


ZZ Cross Section

Preliminary

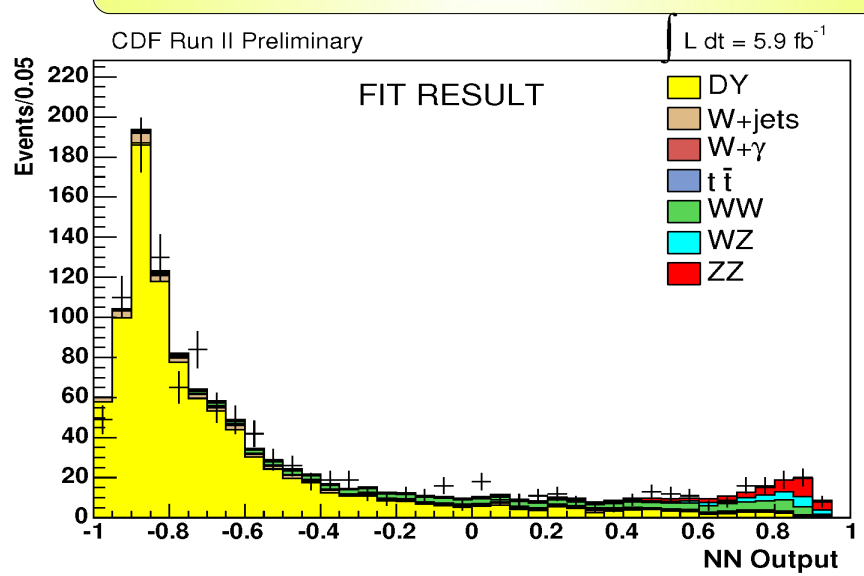
- 6 fb^{-1} of data
  - Four high p_T lepton
    - 4 *ZZ* candidates
    - Expected background: < 0.01 !

$$\frac{\sigma(p\bar{p} \to ZZ)}{\sigma(p\bar{p} \to Z)} = [2.3^{+1.5}_{-0.9}\,(\text{stat}) \pm 0.3\,(\text{syst})] \times 10^{-4}$$



- 5.9 fb^{-1} of data
  - Two high p_T leptons + $\not{E}_T$
    - Background dominated: *Z*+jets
    - 1162 *ZZ* candicates
    - Expected signal: 50 ± 6
    - Expected background: 1113 ± 158

$$\sigma_{(p\bar{p} \to ZZ)} = 1.7^{+1.2}_{-0.7}\,(\text{stat}) \pm 0.2\,(\text{syst})\ \text{pb}$$



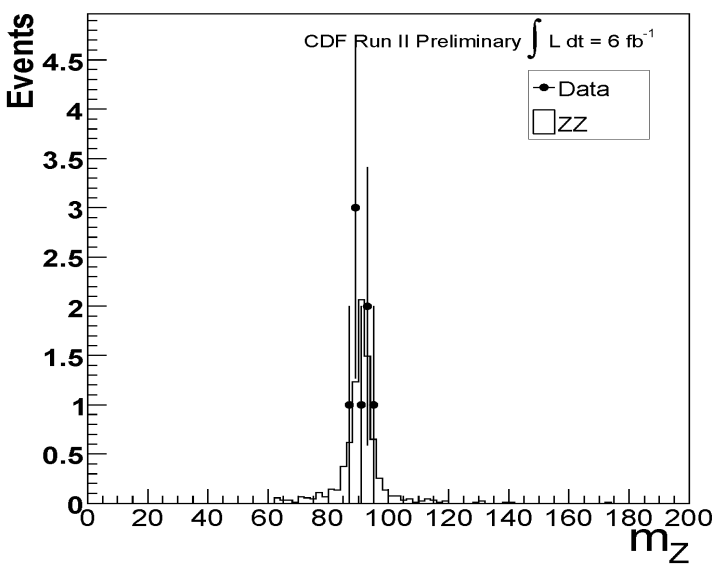
ZZ Cross Section

Preliminary

- 6 fb^{-1} of data
  - Four high p_T lepton
    - 4 *ZZ* candidates
    - Expected background: < 0.01 !

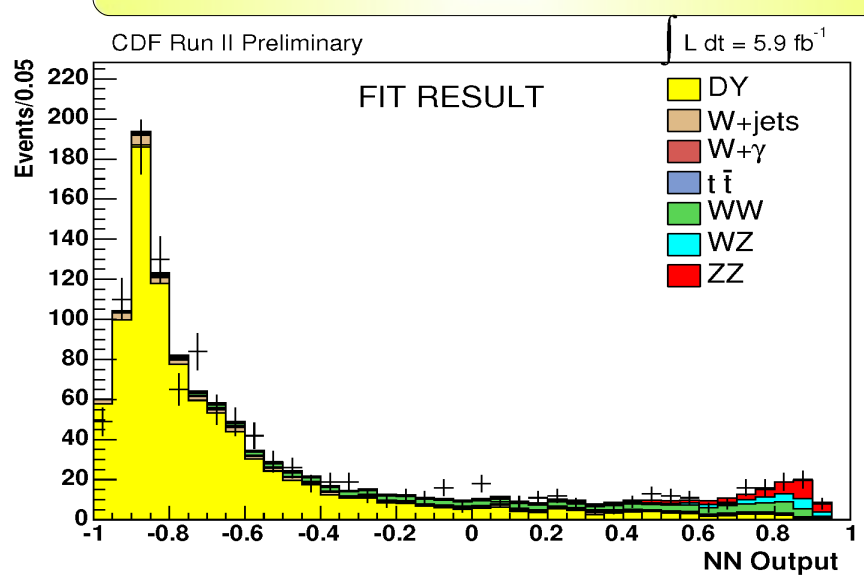
$$\sigma_{(p\bar{p}\to ZZ)} = 1.45^{+0.45}_{-0.42}\,(\text{stat})\,^{+0.41}_{-0.30}\,(\text{syst})\ \text{pb}$$

$$\sigma_{NLO} = 1.4 \pm 0.1\ \text{pb}$$



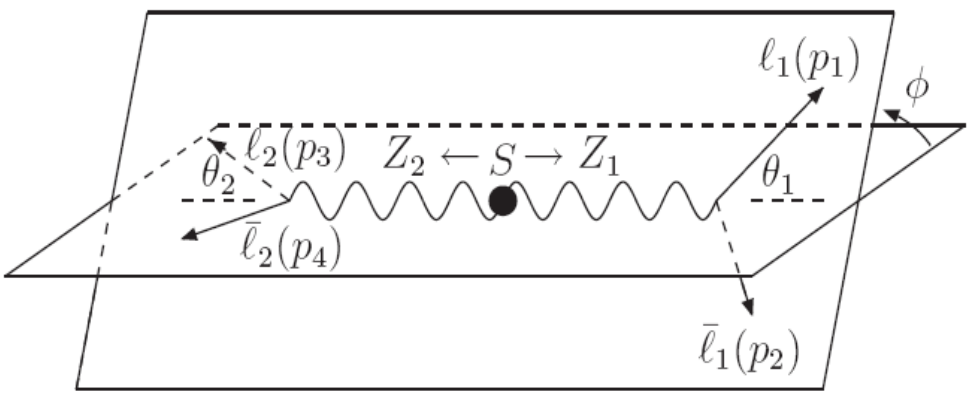
- 5.9 fb^{-1} of data
  - Two high p_T leptons + $\not{E}_T$
    - Background dominated: *Z*+jets
    - 1162 *ZZ* candicates
    - Expected signal: 50 ± 6
    - Expected background: 1113 ± 158

$$\sigma_{(p\bar{p}\to ZZ)} = 1.7^{+1.2}_{-0.7}\,(\text{stat}) \pm 0.2\,(\text{syst})\ \text{pb}$$

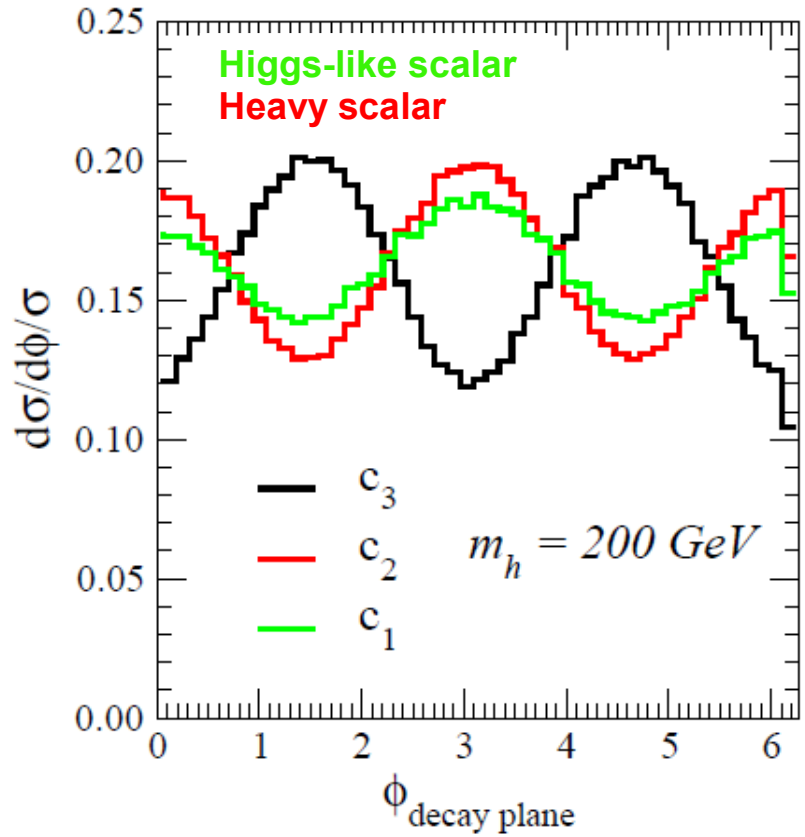


ZZ Kinematics

- Azimuthal angle between Z decay planes can distinguish different Scalar models
  - Higgs-like, CP violating/conserving scalar



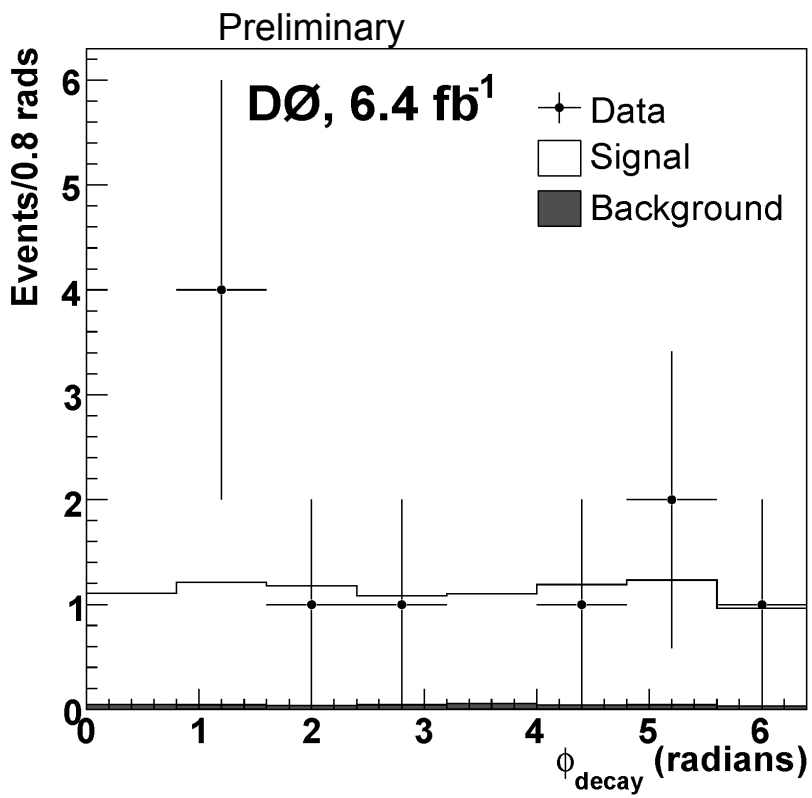
Q-H. Cao, C.B. Jackson, W-Y. Keung, I. Low, J. Shu, PRD 81, 015010 (2010)



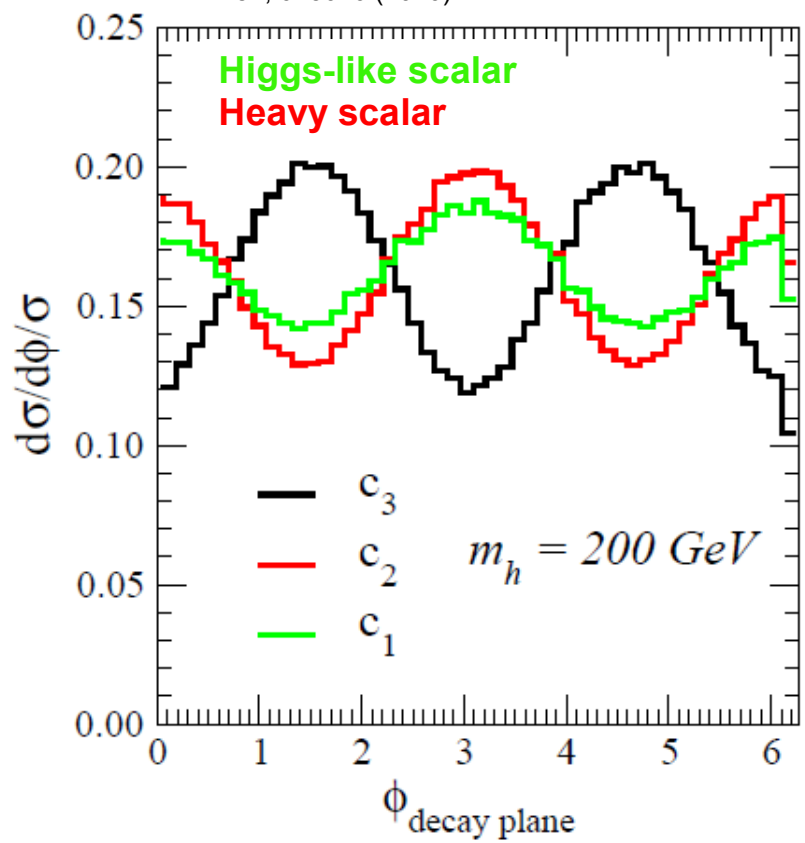
ZZ Kinematics

Preliminary

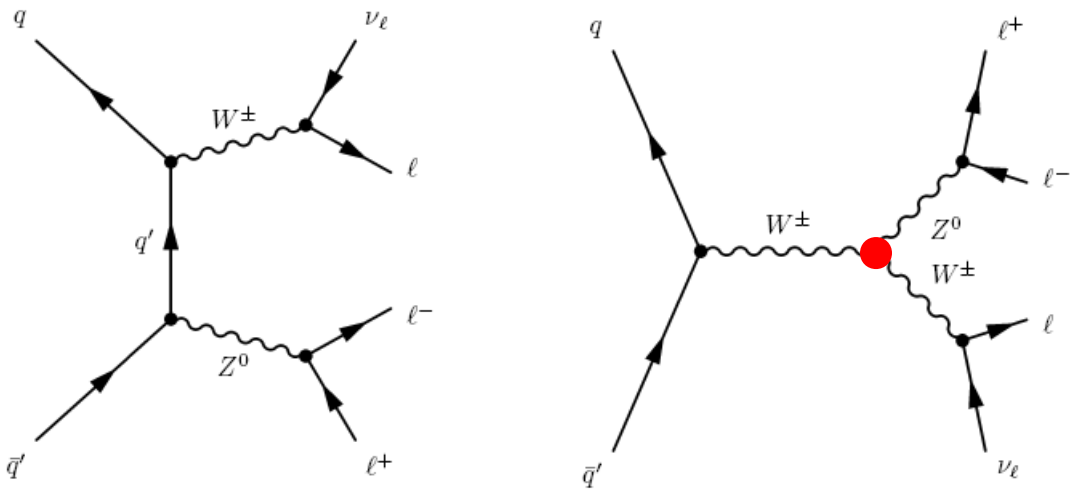
- Azimuthal angle between *Z* decay planes can distinguish different Scalar models
  - Higgs-like, CP violating/conserving scalar



Q-H. Cao, C.B. Jackson, W-Y. Keung, I. Low, J. Shu, PRD 81, 015010 (2010)



WZ Production



- $\sigma_{NLO} = 3.5 \pm 0.3$ pb
- Not directly accessible at LEP
- No SM backgrounds with three leptons and $\not{E}_T$
  - Small background from $ZZ \rightarrow lll$, Z+jets, tt
- WWZ vertex $\Rightarrow$ κ_Z , λ_Z , g_1^Z

WZ Cross Section

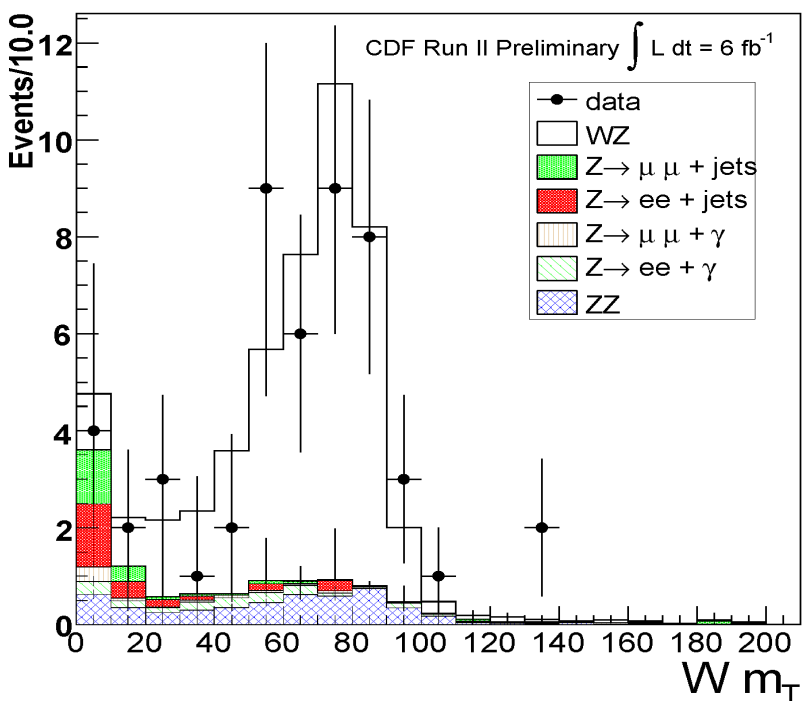
Preliminary

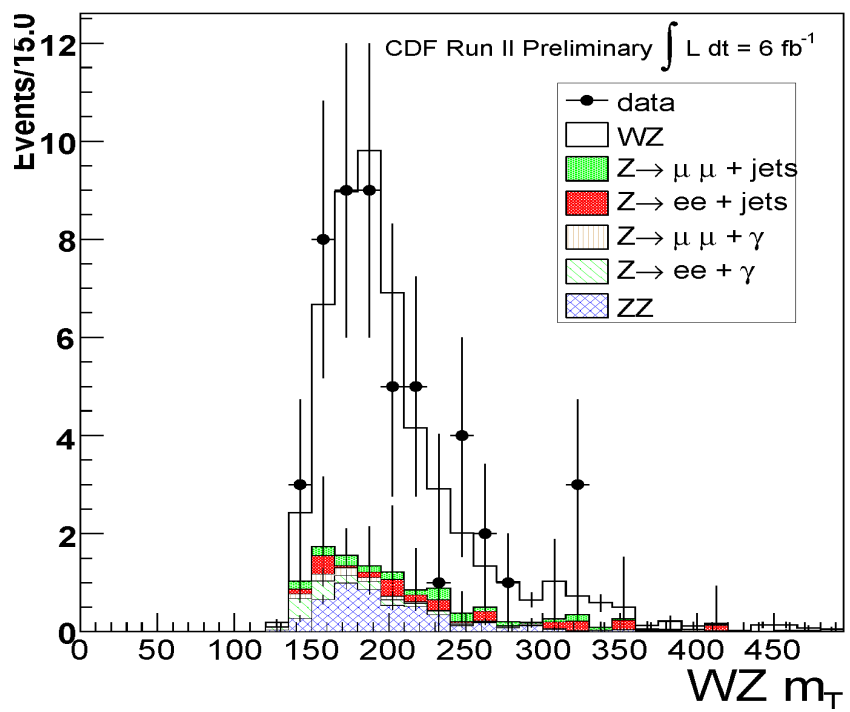
- 6 fb^{-1} of data
  - Three high p_T lepton + large $\not{E}_T$
    - 50 *WZ* candidates
    - Expected background: 11 ± 1

$$\sigma\frac{(p\bar{p}\to WZ)}{\sigma(p\bar{p}\to Z)}=[5.5\pm0.9]\times10^{-4}$$

$$\sigma(p\bar{p}\to WZ)=4.1\pm0.6(\text{stat})\pm0.4(\text{syst})\ \text{pb}$$

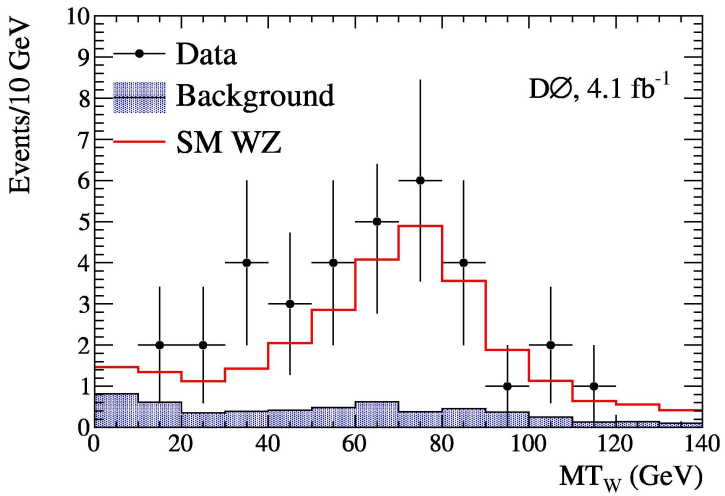
$\sigma_{NLO} = 3.5 \pm 0.4$ pb

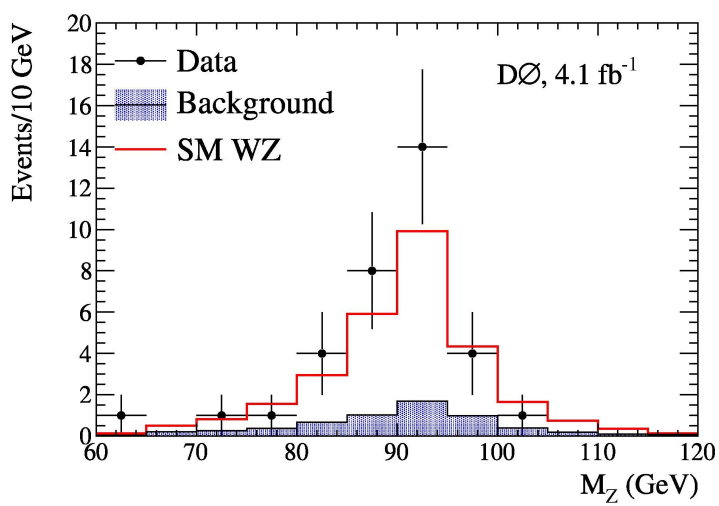




WZ Cross Section

PLB 695, 67 (2011)





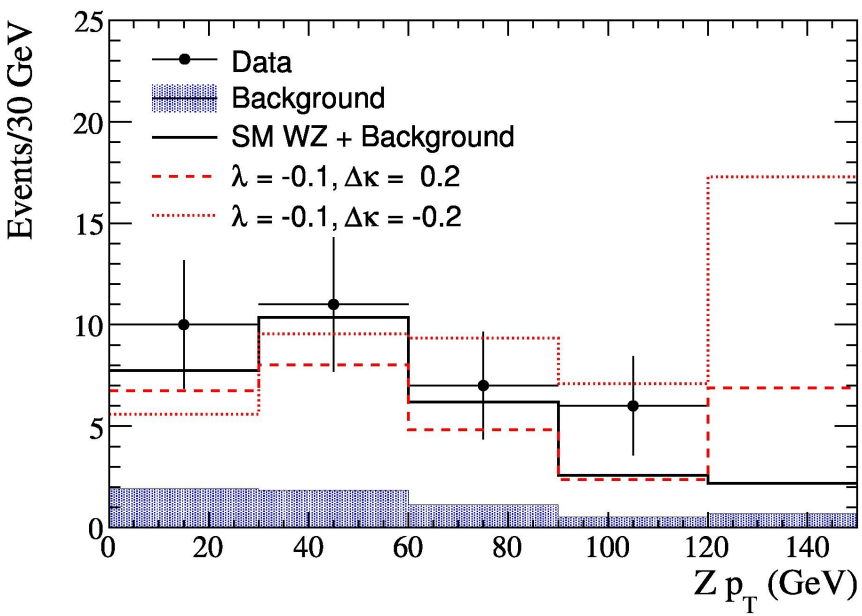
- 4.1 fb^{-1} of data
  - Three high p_T leptons + large $\not{E}_T$
    - 34 *WZ* candidate events
    - Predicted signal: 23.3 ± 1.5
    - Predicted background: 6.03 ± 0.57

$$\sigma(WZ) = 3.90^{+1.09}_{-0.90}\ \text{pb}$$

$\sigma_{NLO} = 3.5 \pm 0.4$ pb

WZ Cross Section

PLB 695, 67 (2011)



- 4.1 fb^{-1} of data
  - Three high p_T leptons + large $\not{E}_T$
    - 34 *WZ* candidate events
    - Predicted signal: 23.3 ± 1.5
    - Predicted background: 6.03 ± 0.57

$$\sigma(WZ) = 3.90^{+1.09}_{-0.90}\ \text{pb}$$

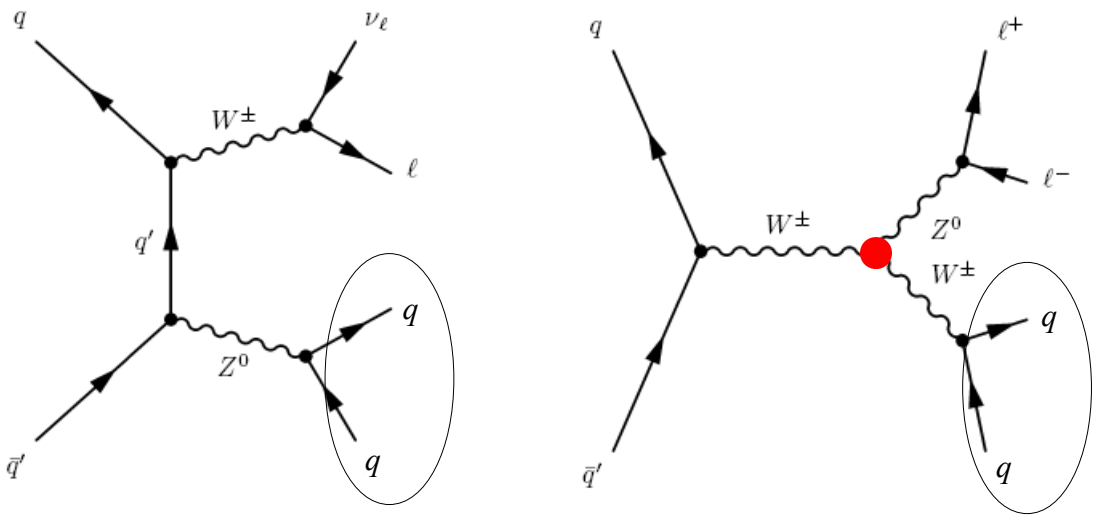
$\sigma_{NLO} = 3.5 \pm 0.4$ pb

- Boson p_T sensitive to anomalous TGCs
  - Set 95% CL limits on anomalous TGCs (Λ_{NP} = 2 TeV)

-0.075	<	λ_Z	<	0.093
-0.053	<	Δg_1^Z	<	0.156
-0.376	<	$\Delta\kappa_Z$	<	0.686

Tightest limits on WWZ couplings from direct measurement!

VV with Hadronic Decays

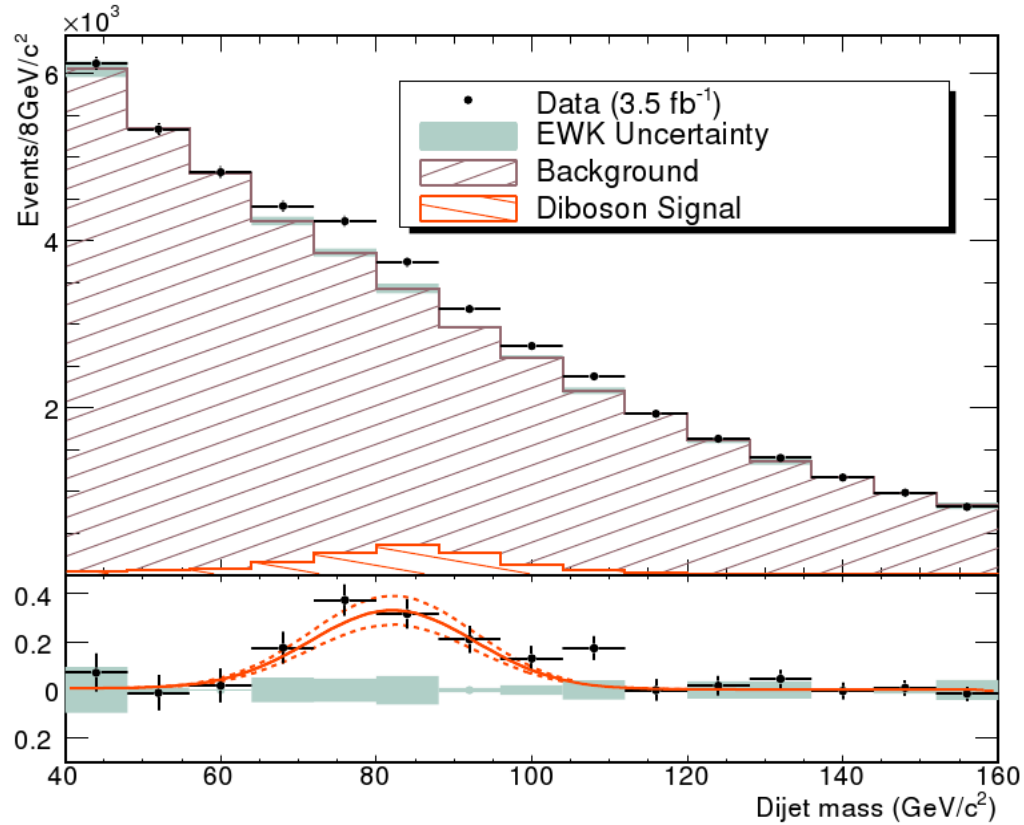


- $\sigma_{NLO}(WZ+ZZ) = 4.9 \pm 0.3$ pb
- Larger hadronic branching ratios
- Much larger background contamination
  - *W/Z*+jets: same final states, orders of magnitude larger cross sections

VV with b-Tagging

PRL 103, 091803 (2009)

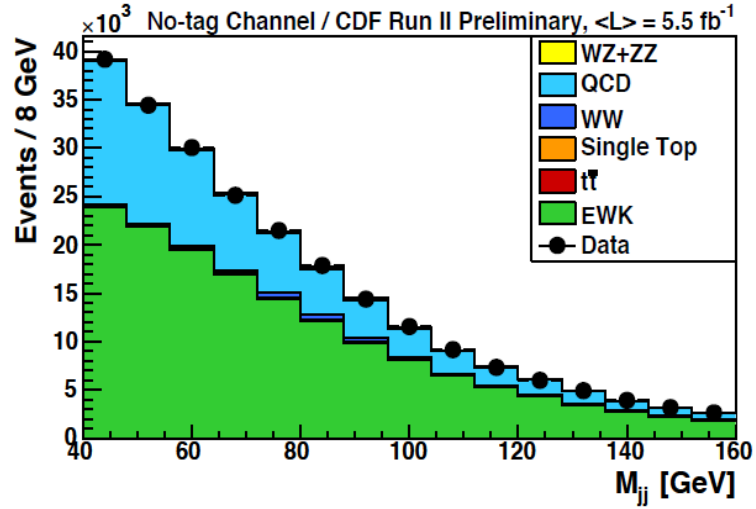
- 2009: observed $VV \rightarrow \not{E}_T$ + jets final states
  - *WW→lvqq, WZ→lvqq/qqvv, ZZ→vvqq/qqvv*

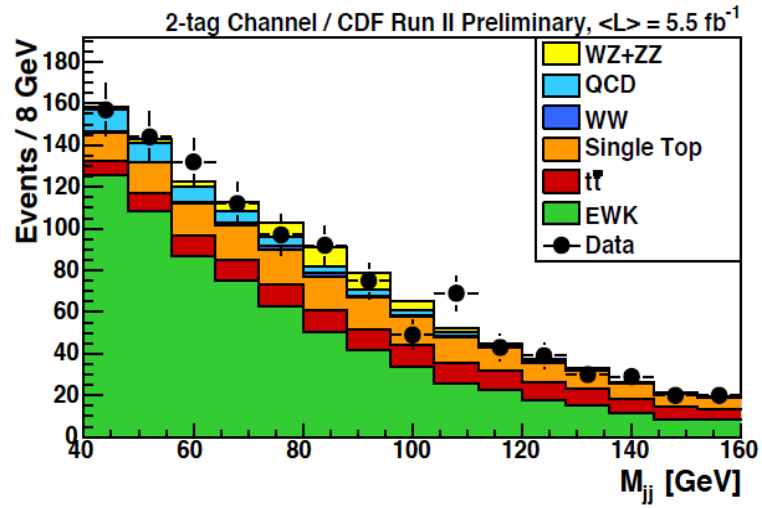


VV with b-Tagging

Preliminary

- 2009: observed $VV \rightarrow \not{E}_T$ + jets final states
  - *WW→lvqq, WZ→lvqq/qqvv, ZZ→vvqq/qqvv*
- Now apply b-tagging (5.5 fb^{-1})
  - Try to separate out *WZ→lvbb, ZZ→vvbb*
    - Same analysis tools as low mass Higgs searches
    - Fit *WZ+ZZ* cross section
      - *WW* is constrained to prediction
      - *W/Z*+jet normalization free to fit





CDF Run II Preliminary, $\int L = 5.5$ fb^{-1}

Process(es)	Fit # events (no-tag)	Fit # events (2-tag)
EWK	153300 ± 3000	694 ± 48
TOP	1700 ± 140	$313\ ^{+24}_{-26}$
QCD	72300 ± 2800	54.6 ± 7.3
WW	2720 ± 190	$8.3\ ^{+1.8}_{-1.9}$
WZ/ZZ	1160 ± 620	39.9 ± 20
Data:	231232	1108

VV with b-Tagging

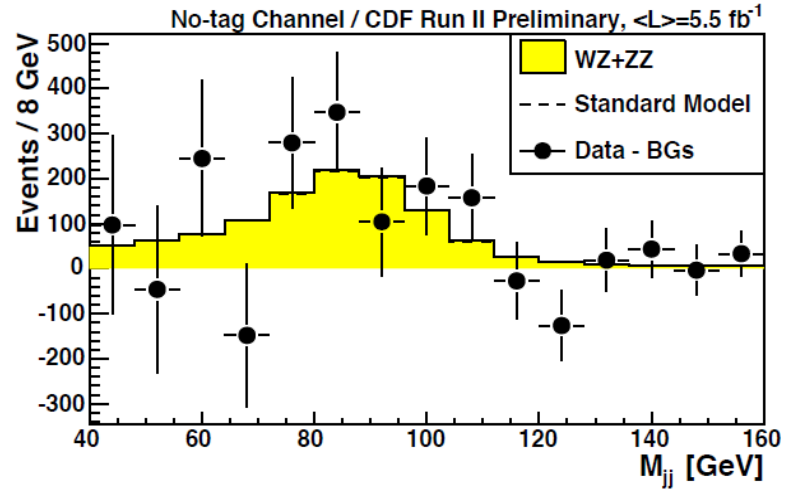
Preliminary

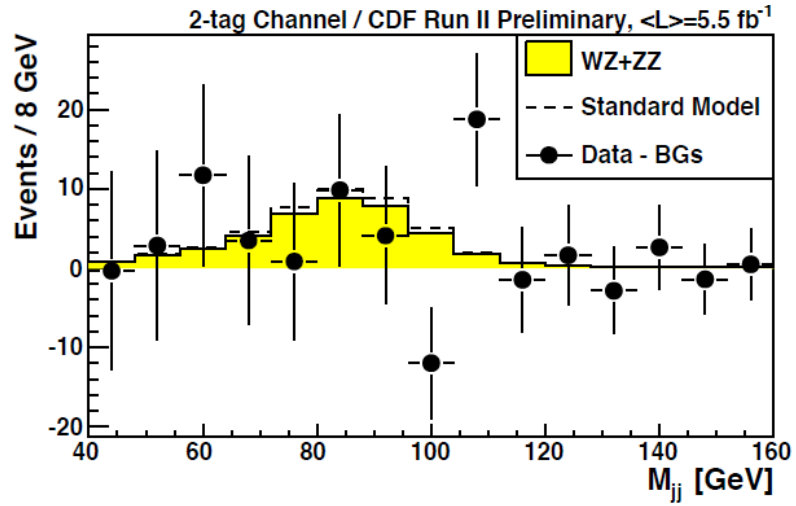
- 2009: observed $VV \rightarrow \not{E}_T$ + jets final states
  - *WW→lvqq, WZ→lvqq/qqvv, ZZ→vvqq/qqvv*
- Now apply b-tagging (5.5 fb^{-1})
  - Try to separate out *WZ→lvbb, ZZ→vvbb*
    - Same analysis tools as low mass Higgs searches
    - Fit *WZ+ZZ* cross section
      - *WW* is constrained to prediction
      - *W/Z*+jet normalization free to fit

$$\sigma\,(pp \rightarrow WZ+ZZ) = 5.0^{+3.6}_{-2.5}\ pb$$

$$\sigma\,(pp \rightarrow WZ+ZZ) < 13\ pb\ @\ 95\%\ CL$$

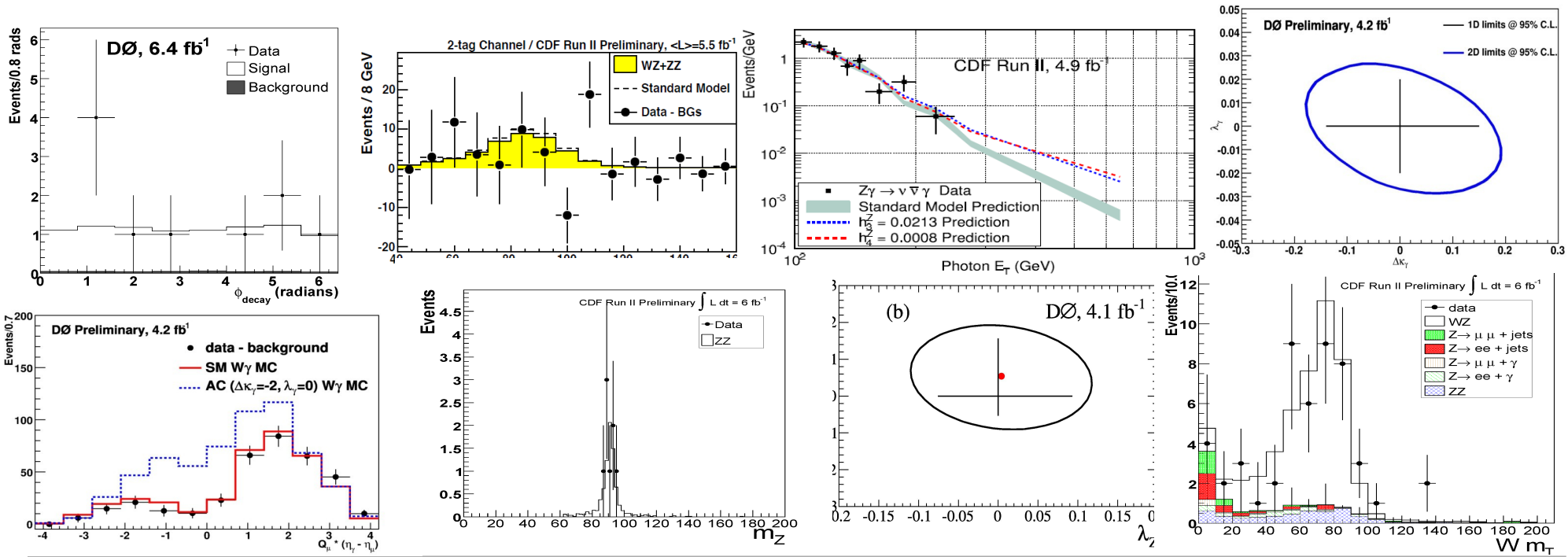
$$\sigma_{NLO} = 4.9 \pm 0.4\ pb$$





Conclusions

- 4 – 6 fb^{-1} of RunII Tevatron data analyzed by each experiment
- Measuring very small cross sections
- Setting some of the tightest limits on anomalous TGCs
- Most results statistics limited
- Expect ~2 × more data before the Tevatron shuts off



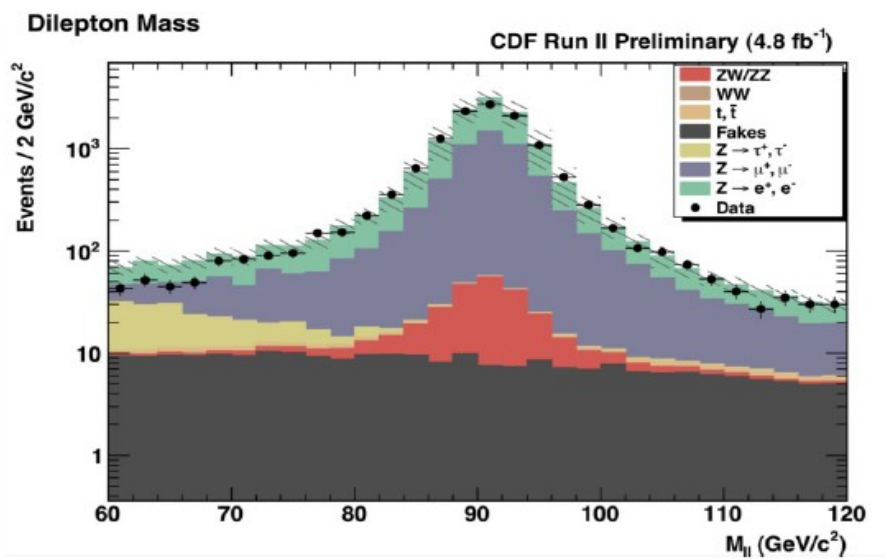
thank you

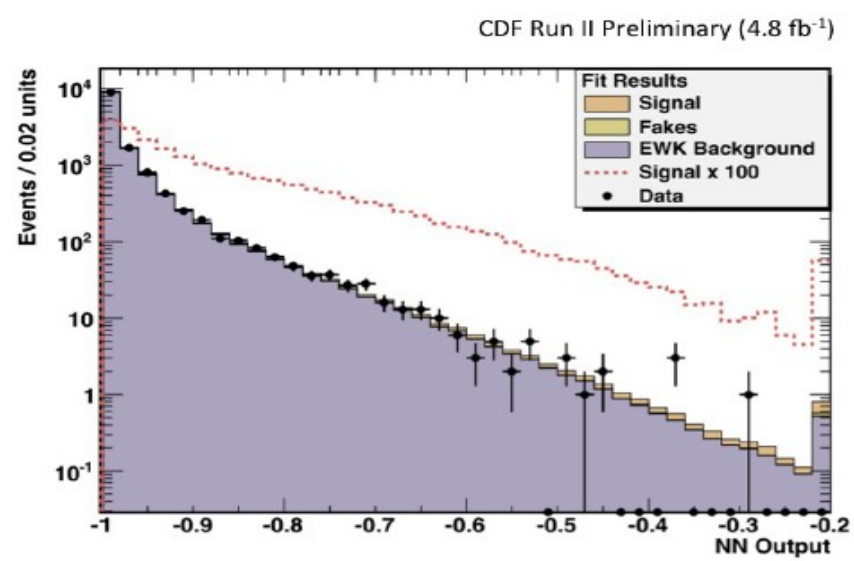
$WZ+ZZ \rightarrow qqll$

Preliminary

- 4.8 fb^{-1} of data
  - Two high pT leptons, two high pT jets, and low ET
    - Expected signal ~202 events
    - Expected background ~13000 events : Dominated by Z+jets
  - Use an artificial Neural Network to identify signal like events
    - Includes variables to separate quark and gluon jets

  ⇒ Significance ~1 standard deviation above background

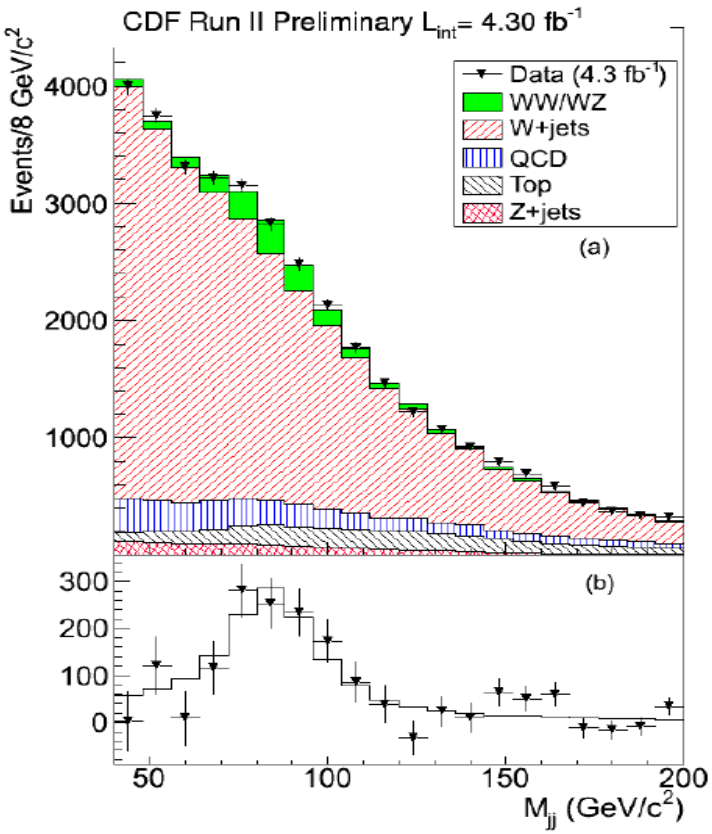




CDF Dijet Mass Excess

arXiv:1104.0699 [hep-ex]

Cross sections measurement



- Use a fit to dijet mass to extrapolate the WW/WZ contribution
- We estimate 1582 ± 275(stat.) $\pm$ 107(syst.) events for a significance of 5.2σ.
- The resulting cross section is

  $\sigma(WW/WZ) = 18.1 \pm 3.3$(stat.)$\pm 2.5$(syst.) pb

  that is in agreement with SM expectation (15.9 ± 0.9 pb).

CDF Dijet Mass Excess

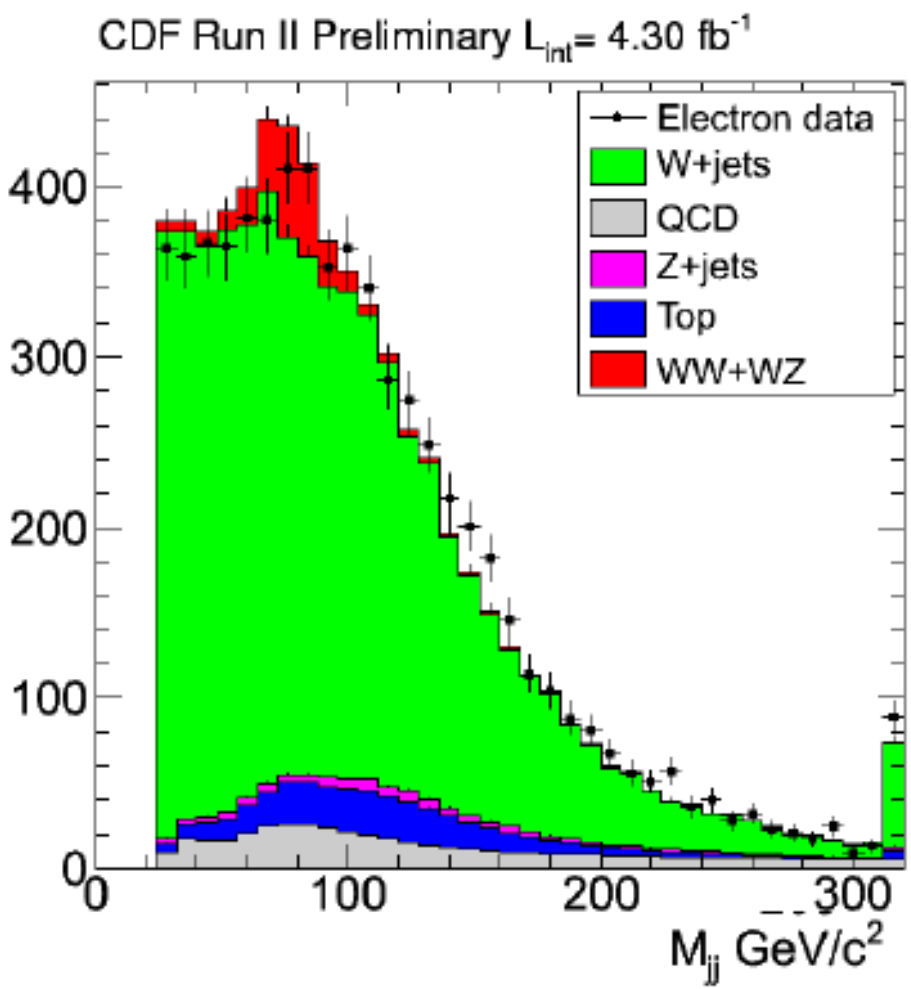
arXiv:1104.0699 [hep-ex]

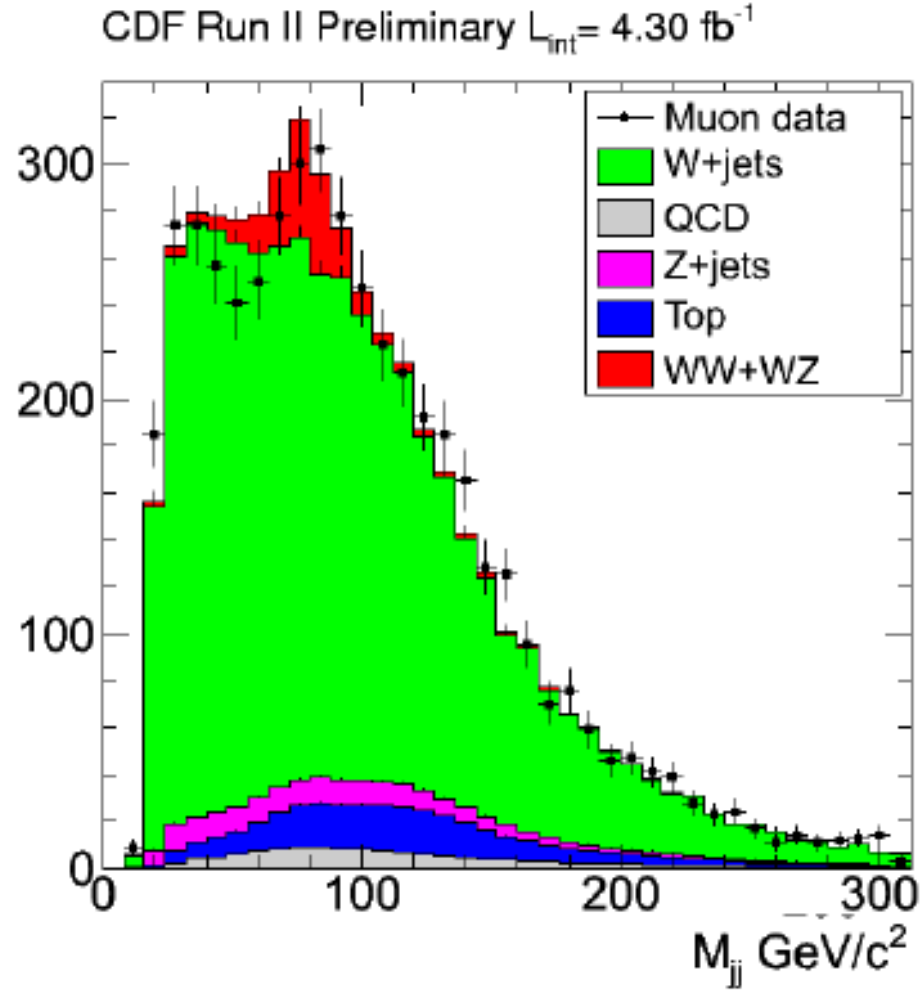
Moving to different kinematical region

- Using exactly the same kinematical cuts as the diboson analysis but:
- We require both jets to have $E_T > 30$ GeV
  1. Energetic jets are measured with better accuracy.
  2. Modeling in this region is expected to be more accurate
  3. A possible heavier particle would be characterized by more energetic jets
- Sample modeling using same processes with different relative contribution
- All cuts chosen "a priori"

CDF Dijet Mass Excess

arXiv:1104.0699 [hep-ex]



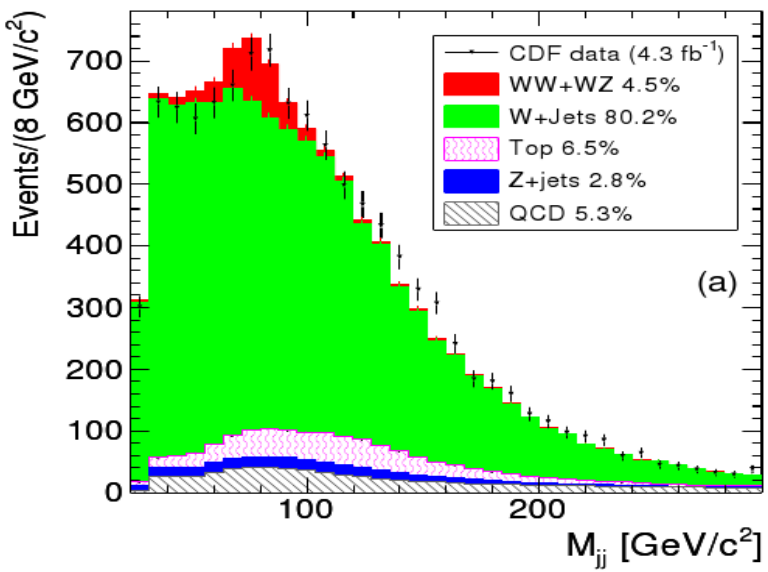


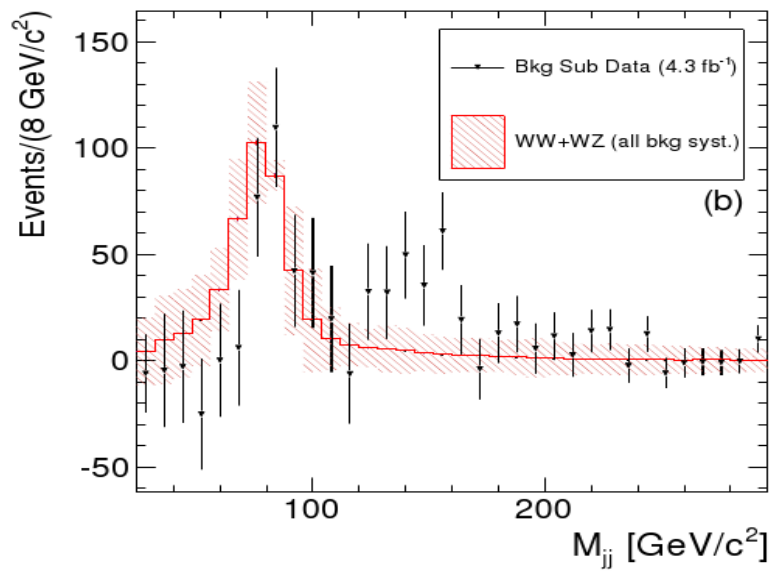
CDF Dijet Mass Excess

arXiv:1104.0699 [hep-ex]

Fitting procedure

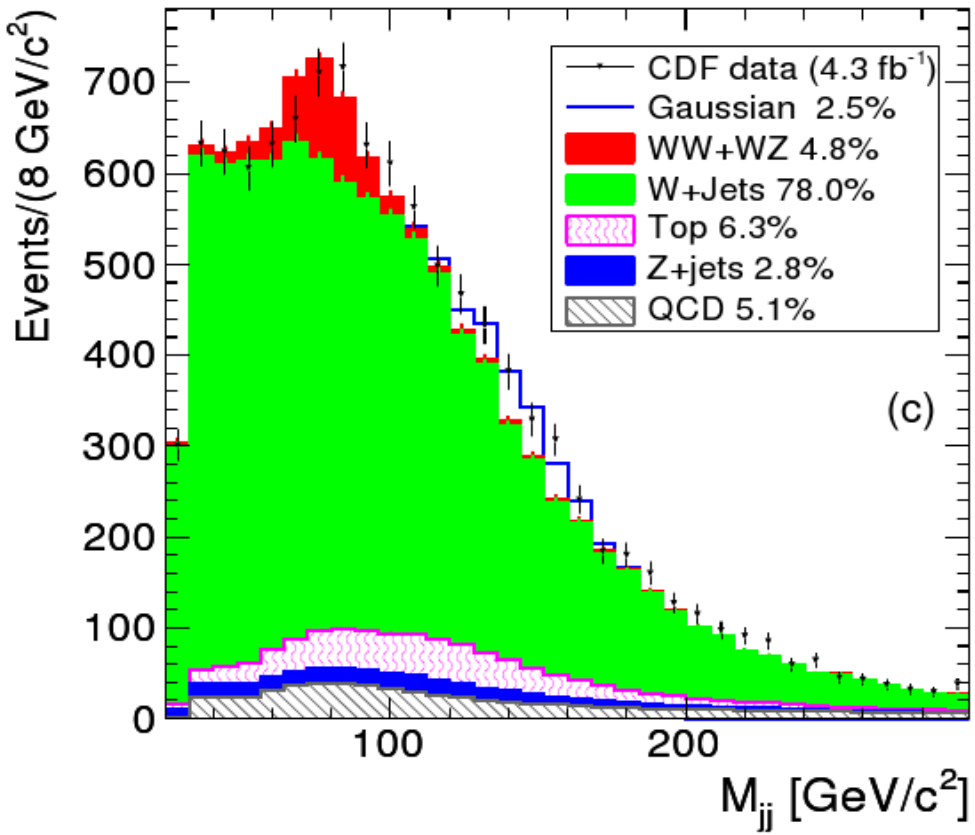
- Combined χ^2 fit to the dijet mass distribution in electron and muon samples.
- 5 templates:
  1. W + jets (uncostrained, normalization determined from the fit)
  2. QCD (normalization constrained to its fraction with 25 % error)
  3. Z + jets (normalization constrained to the measured cross section)
  4. top & single top (normalization constrained to the theoretical cross section)
  5. WW/WZ (normalization constrained to the theoretical cross section)

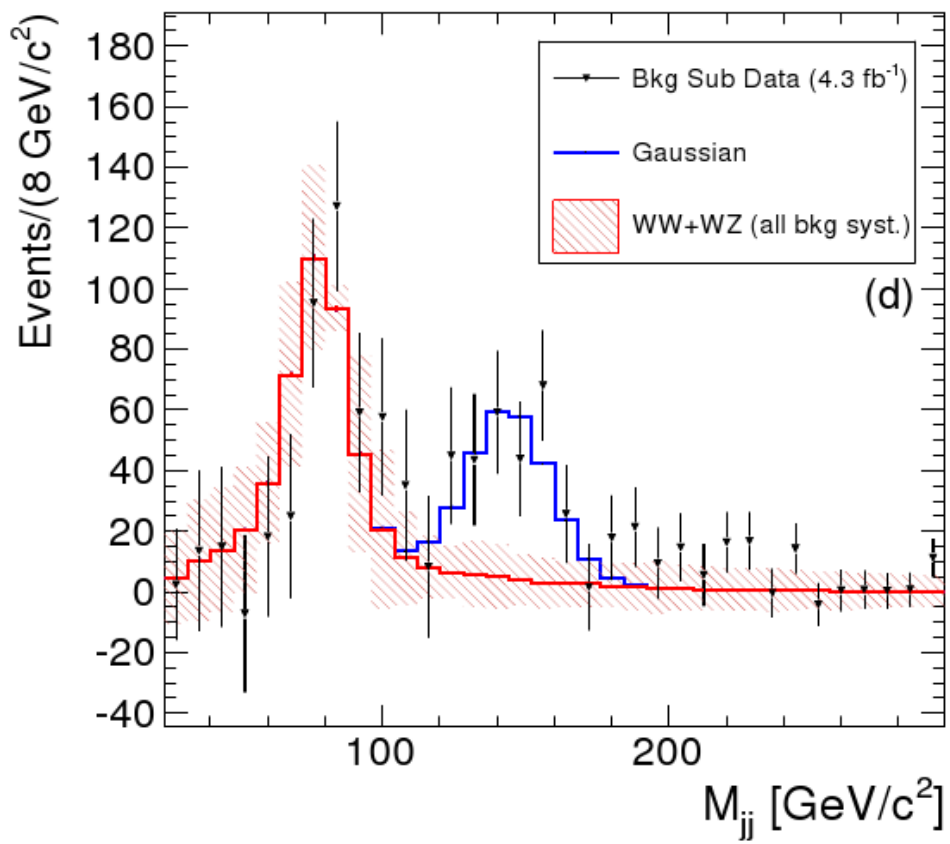




CDF Dijet Mass Excess

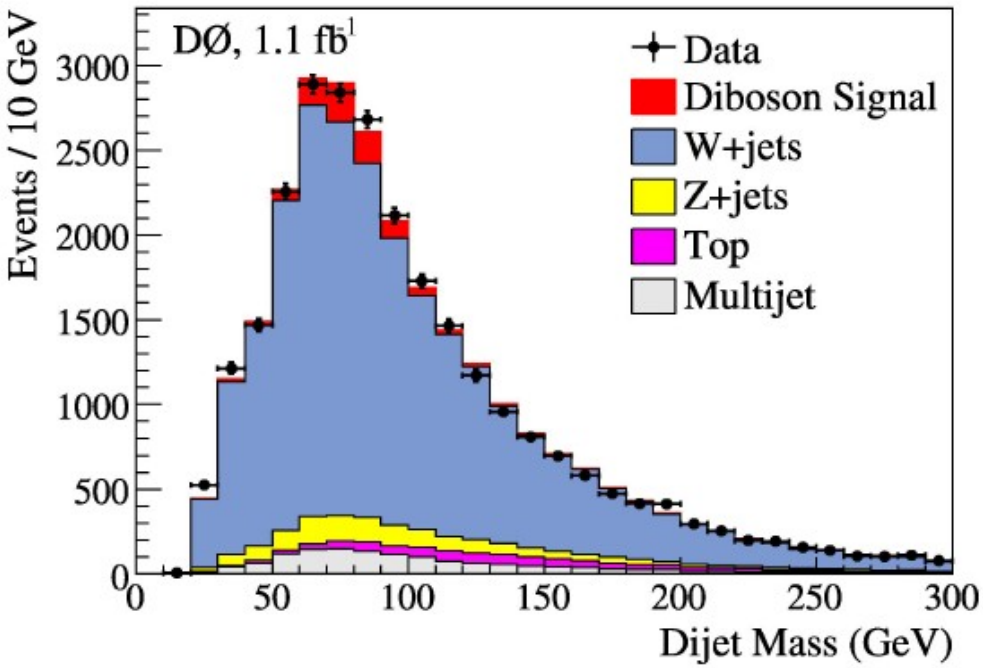
arXiv:1104.0699 [hep-ex]

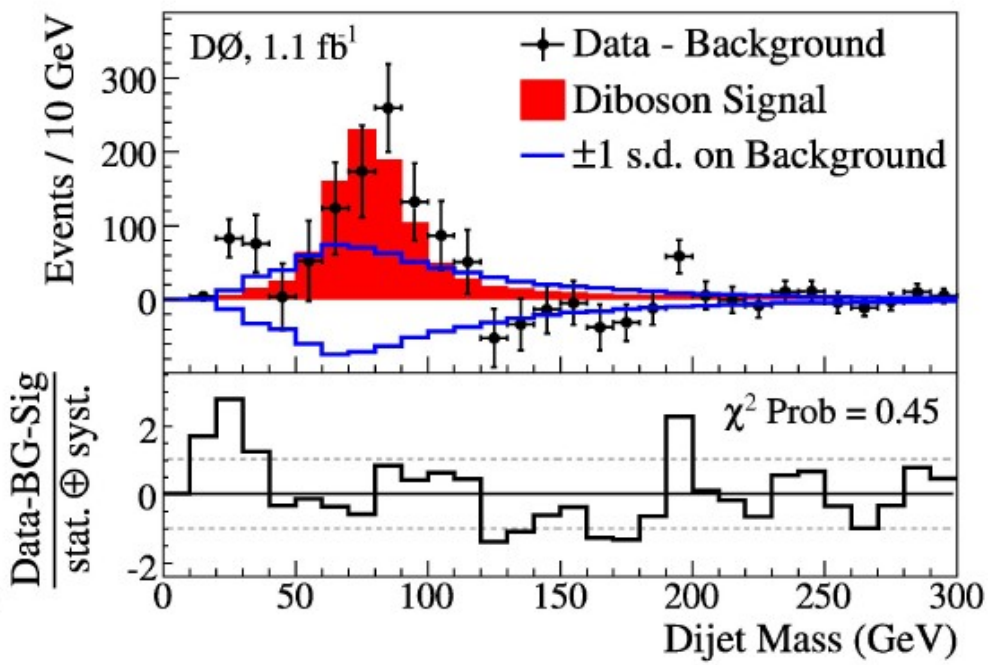




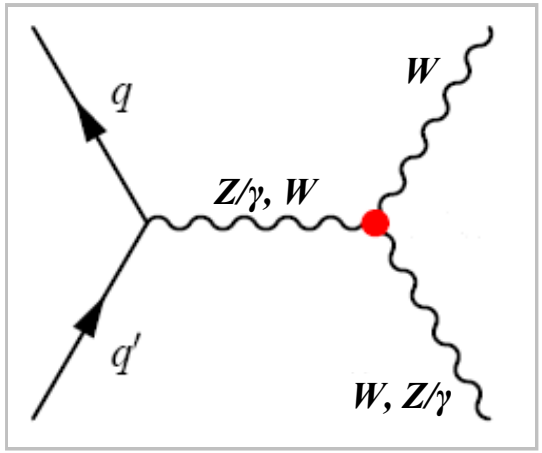
DZero lνqq Measurement

PRL 102, 161801 (2009)



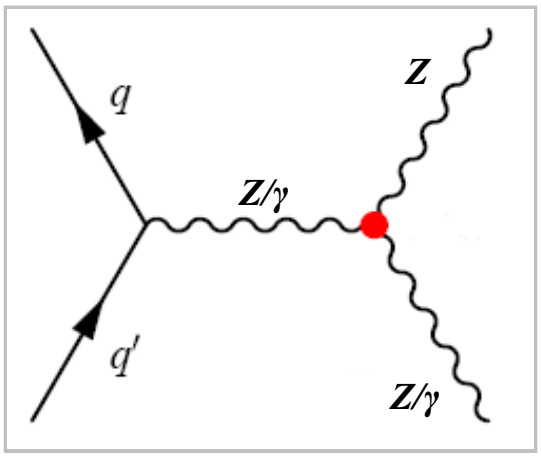


Anomalous Couplings



- ***ZWW*** and ***γWW*** couplings
  - General Lorentz invariant Lagrangian has 14 couplings

$$\frac{L_{WWV}}{g_{WWV}} = i\boxed{g_1^V}\left(W^*_{\mu\nu}W^{\mu}V^{\nu} - W^*_{\mu}V_{\nu}W^{\mu\nu}\right) + i\boxed{\kappa_V}W^*_{\mu}W_{\nu}V^{\mu\nu} + i\frac{\boxed{\lambda_V}}{M_W^2}W^*_{\lambda\mu}W^{\mu}_{\nu}V^{\nu\lambda}$$
$$- \boxed{g_5^V}W^*_{\mu}W_{\nu}\left(\partial^{\mu}V^{\nu} + \partial^{\nu}V^{\mu}\right) + \boxed{g_4^V}\varepsilon^{\mu\nu\rho\lambda}\left(W^*_{\mu}\partial_{\lambda}W_{\nu} - \partial_{\lambda}W^*_{\mu}W_{\nu}\right)V_{\rho}$$
$$+ i\boxed{\tilde{k}_V}W^*_{\mu}W_{\nu}\tilde{V}^{\mu\nu} + i\frac{\boxed{\tilde{\lambda}_V}}{M_W^2}W^*_{\lambda\mu}W^{\mu}_{\nu}\tilde{V}^{\nu\lambda}$$



- C and P conserving: $g_1^{\gamma}, g_1^{Z}, \kappa_{\gamma}, \kappa_Z, \lambda_{\gamma}, \lambda_Z$
- C and P violating, but CP conserving: g_5^{Z}
- CP violating: $g_4^{Z}, g_4^{Z}, k_{\gamma}, k_Z, \lambda_{\gamma}, \lambda_Z$

SM: $g_1^{\gamma} = g_1^{Z} = \kappa_{\gamma} = \kappa_Z = 1$
and all others are zero

$\Lambda_{\mathcal{NP}}$

Any new physics that causes anomalous TGCs must respect unitarity. However, anomalous TGCs in the SM violate unitarity at high energies. Thus, a dipole form factor:

$$a(s) = \frac{a_0}{\left(1 - \frac{s}{\Lambda^2_{NP}}\right)^2}$$

is used to regulate this behavior. Λ_{NP} can be interpreted as the energy at which the new physics turns on.