Diboson production cross sections at the Tevatron

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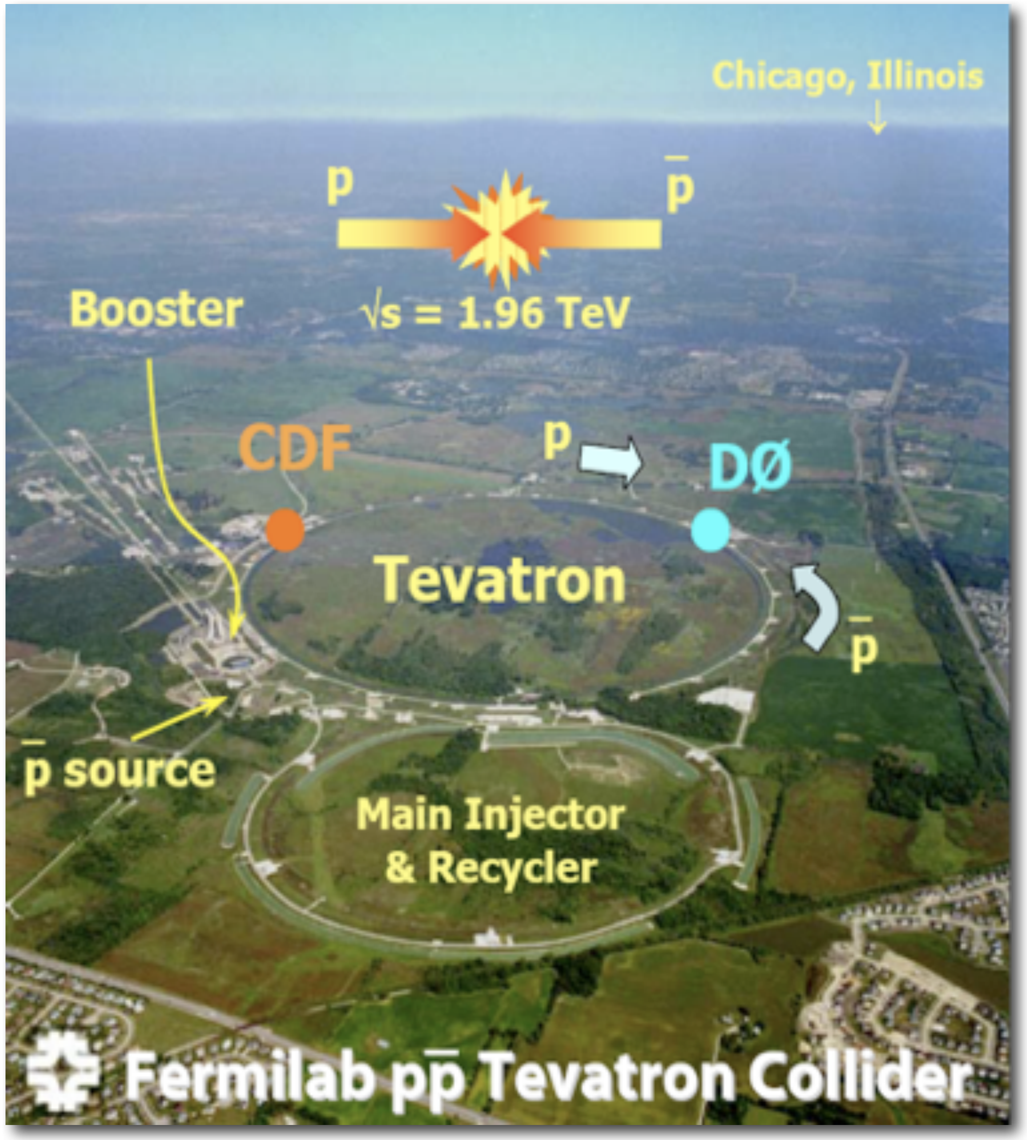
Tevatron

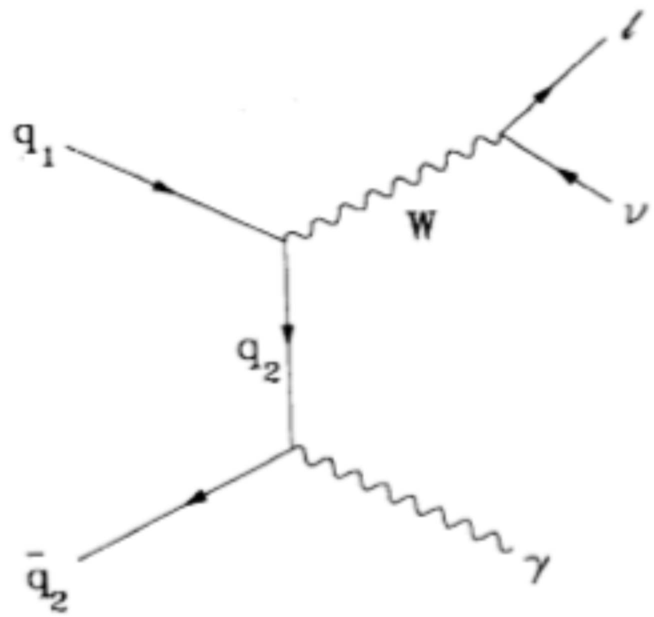
- Most recent Diboson measurements from the CDF and DØ experiments
  - Wγ→lvγ
  - Zγ→llγ
  - WZ → lvll
  - ZZ → llll, llvv
  - WZ+ZZ → lvbb/vvbb
- Tevatron is a vector boson factory
  - Delivering ~50 pb^{-1}/week
    - ~600 WW, ~200 WZ, ~100 ZZ
  - Access to charged final states (not possible at LEP)
    - Wγ→lvγ, WZ→lvll, lvqq

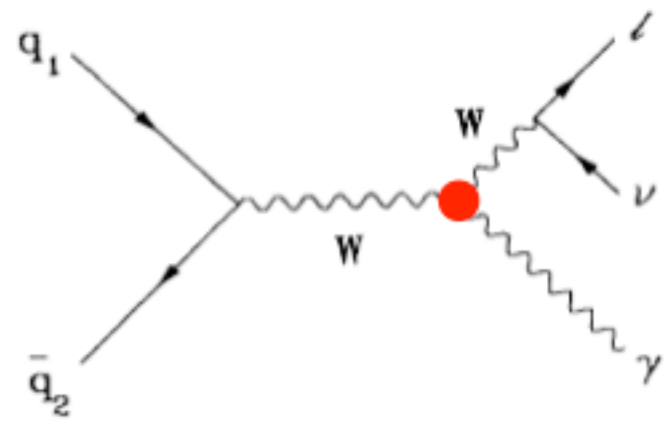


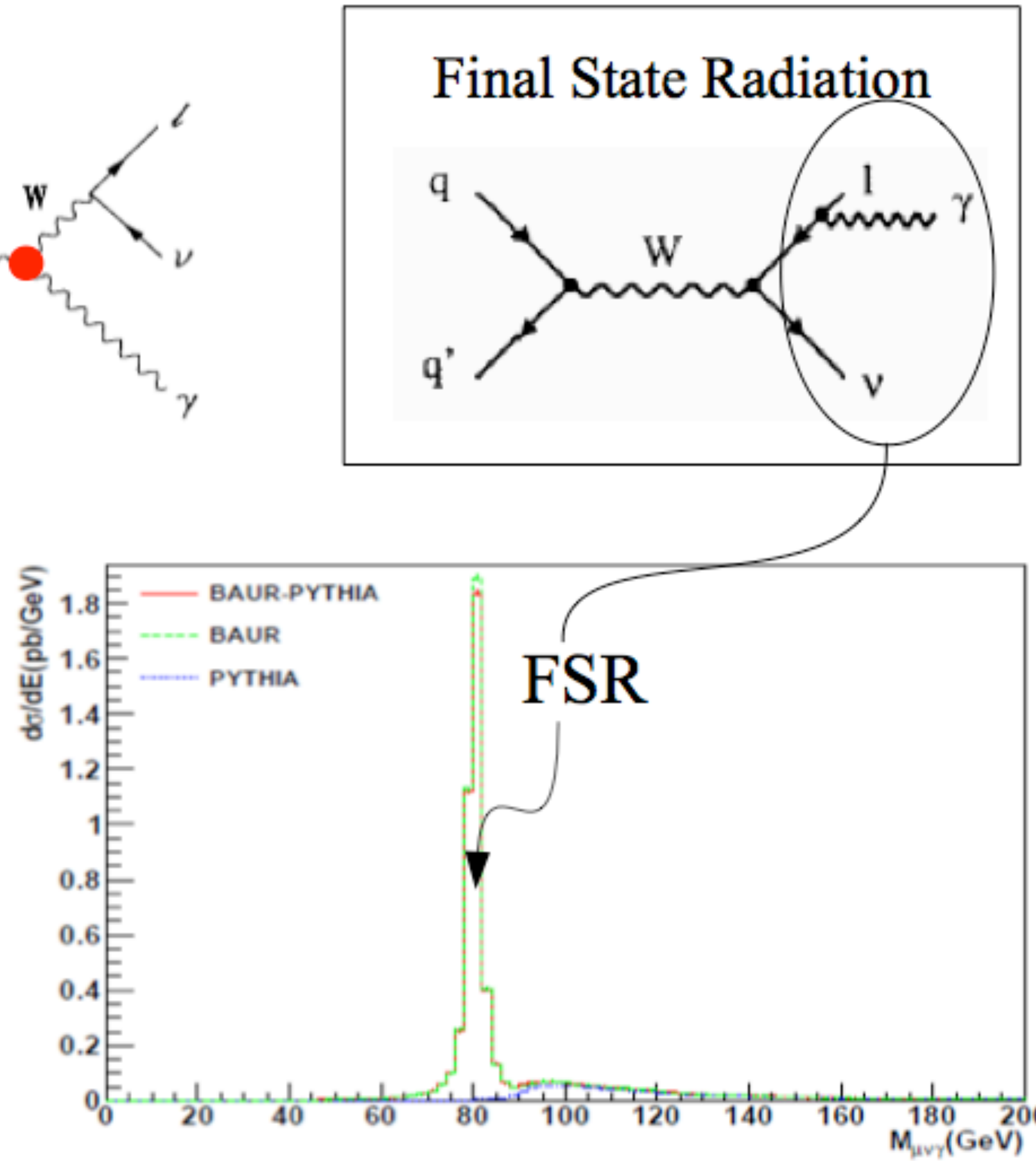
Motivations for Diboson Physics

- Test of Standard Model
  - SM provides precise predictions of Diboson production cross sections
- New physics can enhance Diboson production
  - Enhancement of triple gauge couplings (TGCs)
  - Resonances decaying to pairs of bosons
- Measurement of SM Diboson Production is important step in hunt for Higgs boson
  - H → WW / H → ZZ: Higgs can decay to Dibosons
  - Associated WH / ZH production: also same final states

Wγ Production



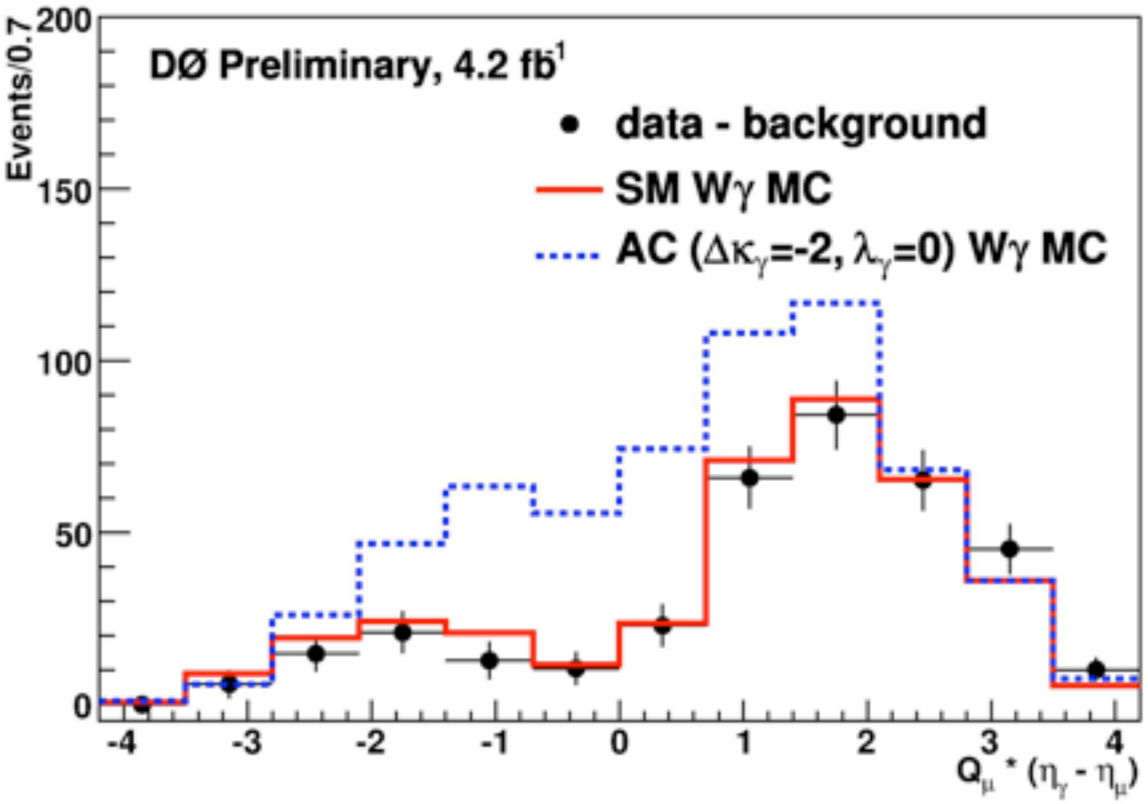




- σ_{NLO}=16.0 ± 0.4pb
  - pT(γ) > 8 GeV, ΔR(γ,l) > 0.7
- Use 3-body mass $M_{l\nu\gamma}$ to distinguish Final State Radiation
- γWW vertex ⇒ κ_γ and λ_γ

Wγ Cross Section (DØ)

- 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 $p_T\mu$, high $p_T\gamma$, and MET
    - 492 Wγ candidates
    - Expected signal: 376 ± 42
    - Expected background: 134 ± 9
      - ~100 from W+jets



$$\sigma(p\bar{p} \to W\gamma) = (15.2 \pm 1.6(\mathrm{stat} + \mathrm{syst}))\ \mathrm{pb}$$

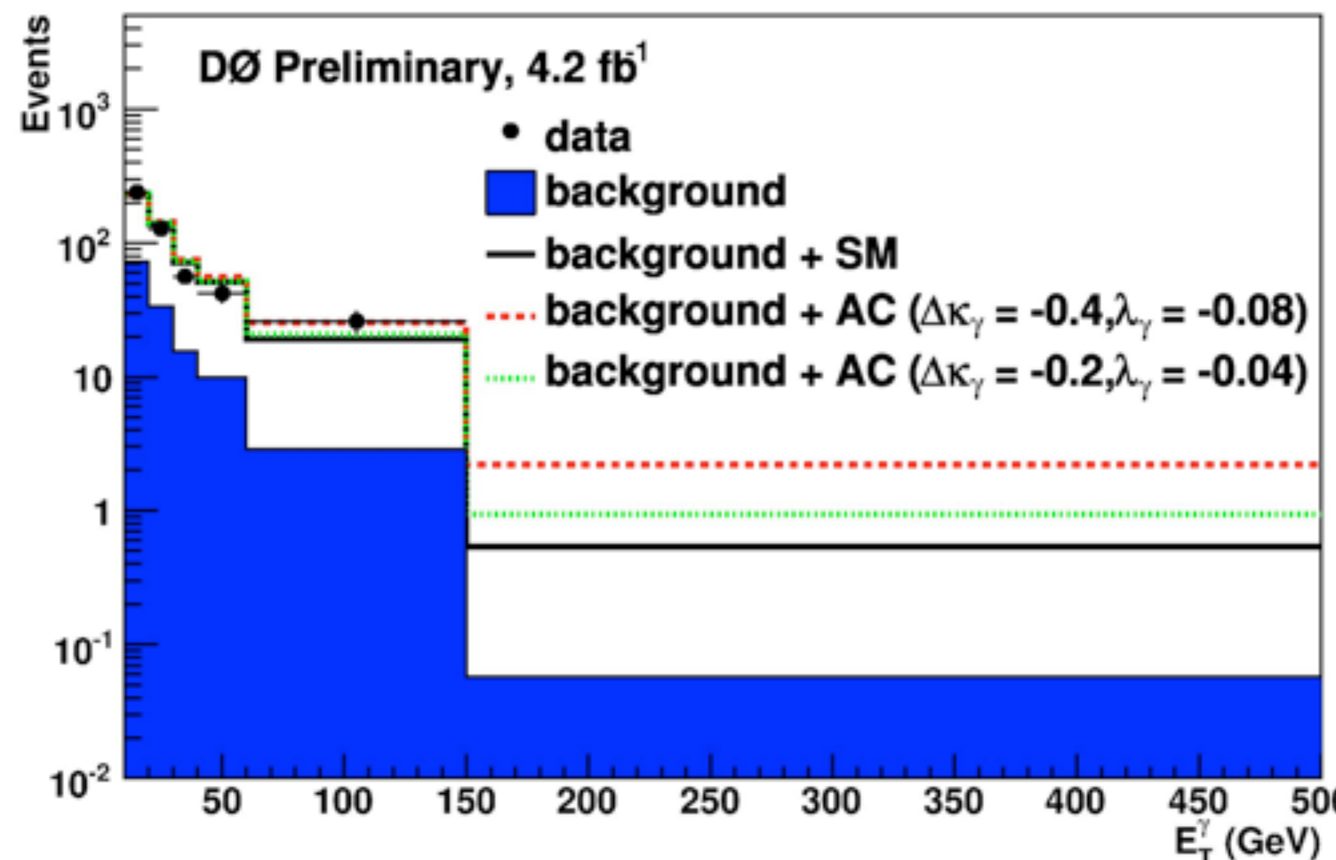
$$\sigma_{NLO} = (16.0 \pm 0.4)\ \mathrm{pb}$$

Wγ TGCs (DØ)

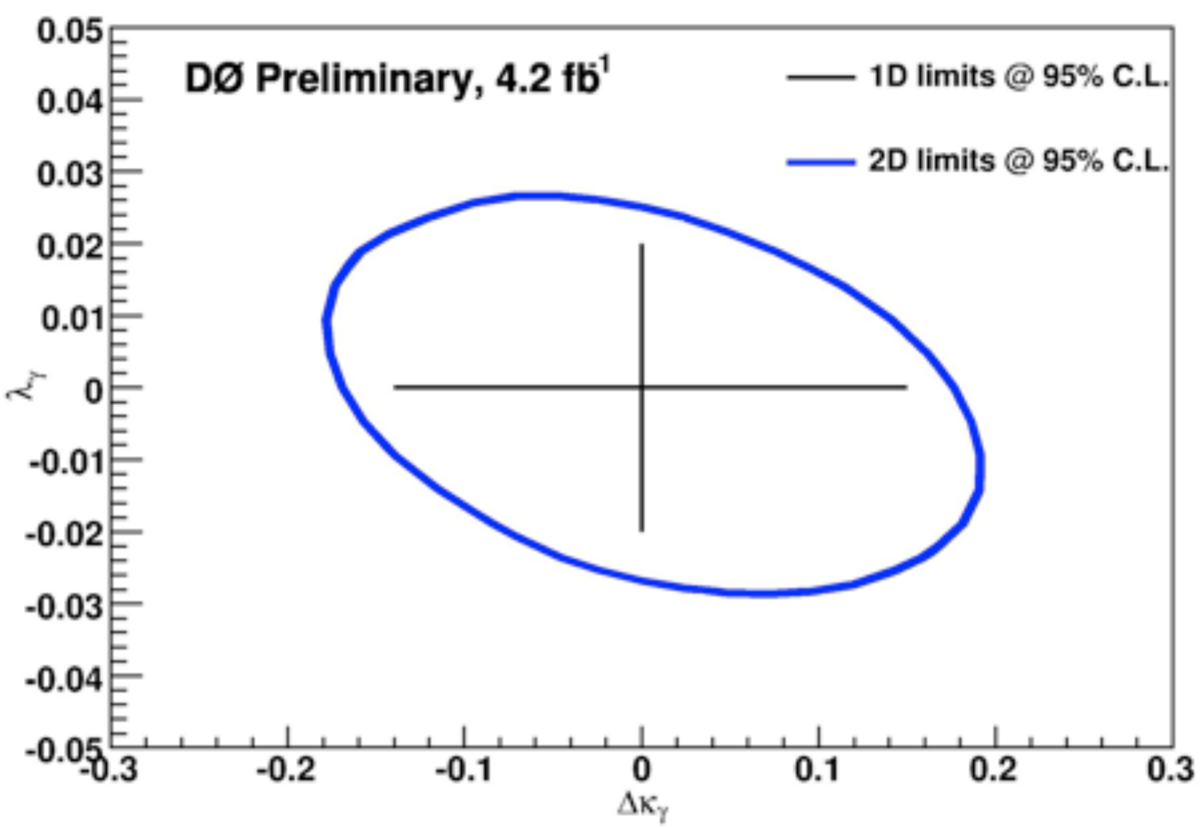
- Photon ET spectrum sensitive to anomalous TGCs
  - Set 95% CL limits on anomalous TGCs (Λ_{NP} = 2 TeV)

1D Limits:

$-0.14 < \Delta\kappa_\gamma < 0.15$
$-0.02 < \lambda_\gamma < 0.02$



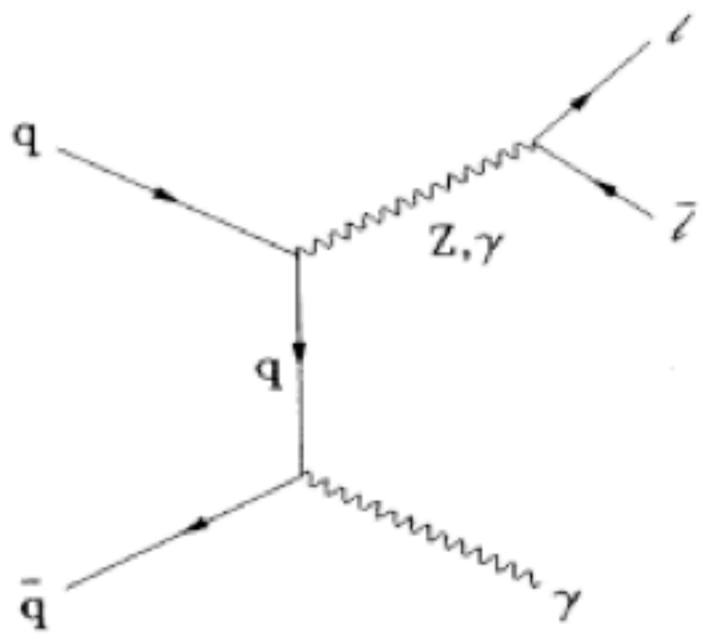
2D Limits:

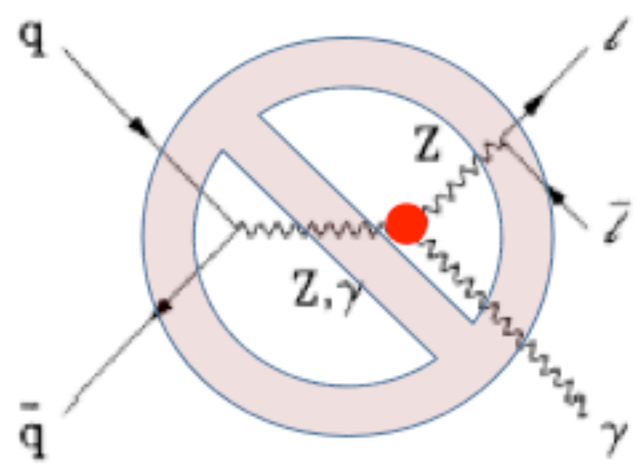


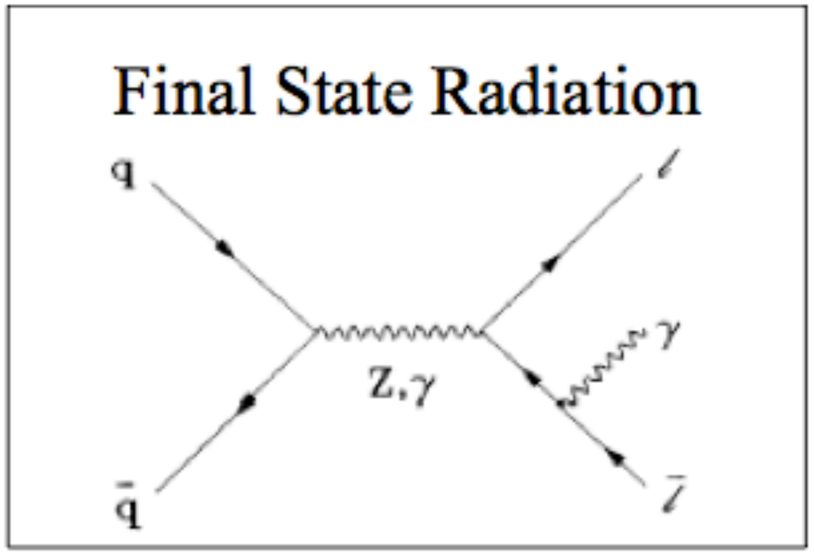
68% Limits

ALEPH	$-0.1 < \Delta\kappa_\gamma < 0.029$	$-0.043 < \lambda_\gamma < 0.014$
L3	$-0.049 < \Delta\kappa_\gamma < 0.095$	$-0.062 < \lambda_\gamma < 0.019$
OPAL	$-0.1 < \Delta\kappa_\gamma < 0.018$	$-0.097 < \lambda_\gamma < -0.024$
LEP2 combined	$-0.072 < \Delta\kappa_\gamma < 0.017$	$-0.049 < \lambda_\gamma < 0.008$
DØ 4.2 fb^{-1}	$-0.07 < \Delta\kappa_\gamma < 0.07$	$-0.012 < \lambda_\gamma < 0.011$

Zγ Production







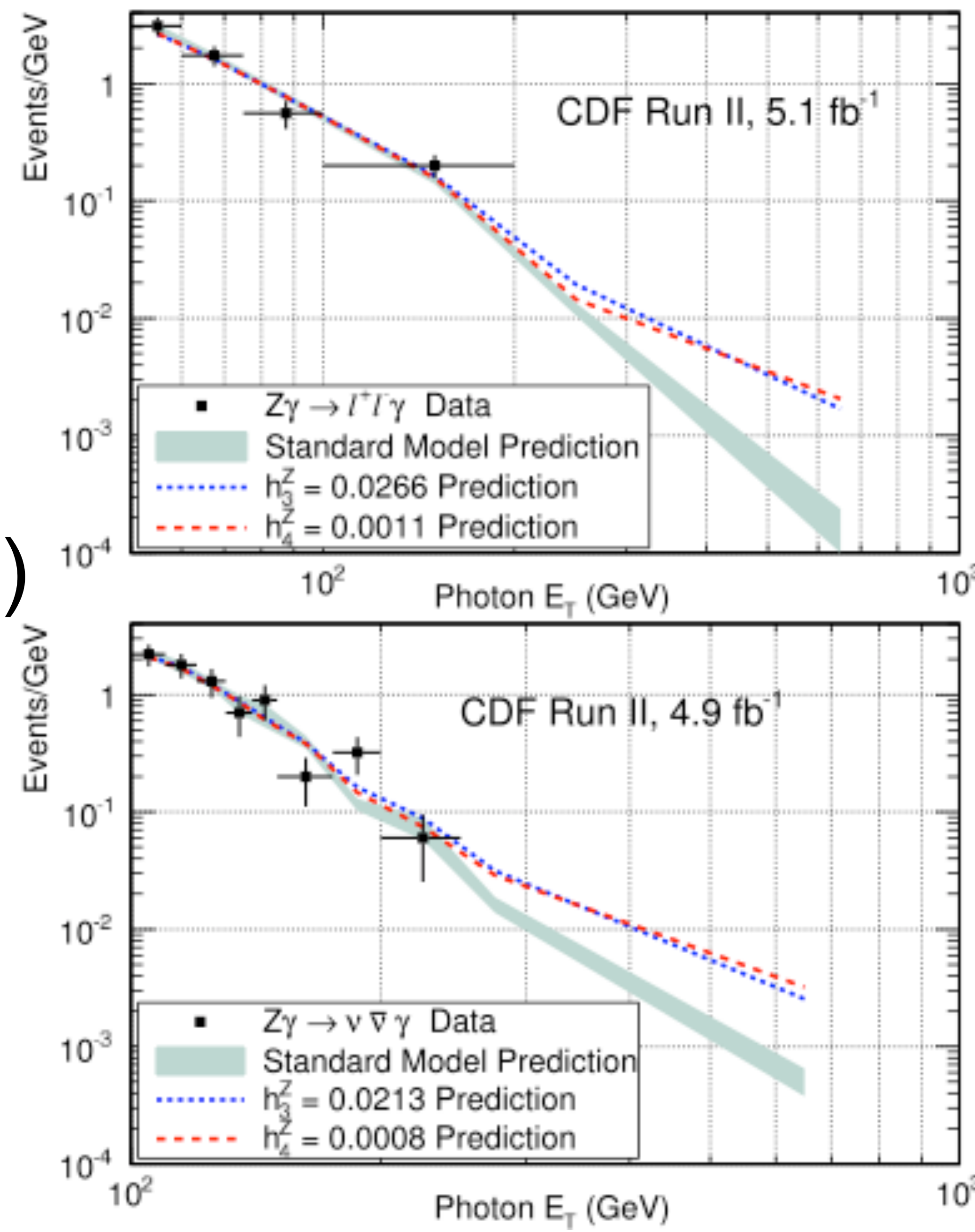
- No s-channel at the tree-level
- Zγγ and ZZγ vertices ⇒ h_3^γ, h_3^Z, h_4^γ, h_4^Z

Zγ Production (CDF)

- Photon ET spectra sensitive to TGCs
  - Combination of two selections
    - Zγ→llγ : 5.1 fb^{-1}, ET(γ) > 50 GeV
    - Zγ→ννγ : 4.9 fb^{-1}, ET(γ) > 100 GeV
  - Observe176 candidate events
  - Expected signal: 140 ± 9
  - Small background (mostly cosmic μ)
- Set 95% CL limits

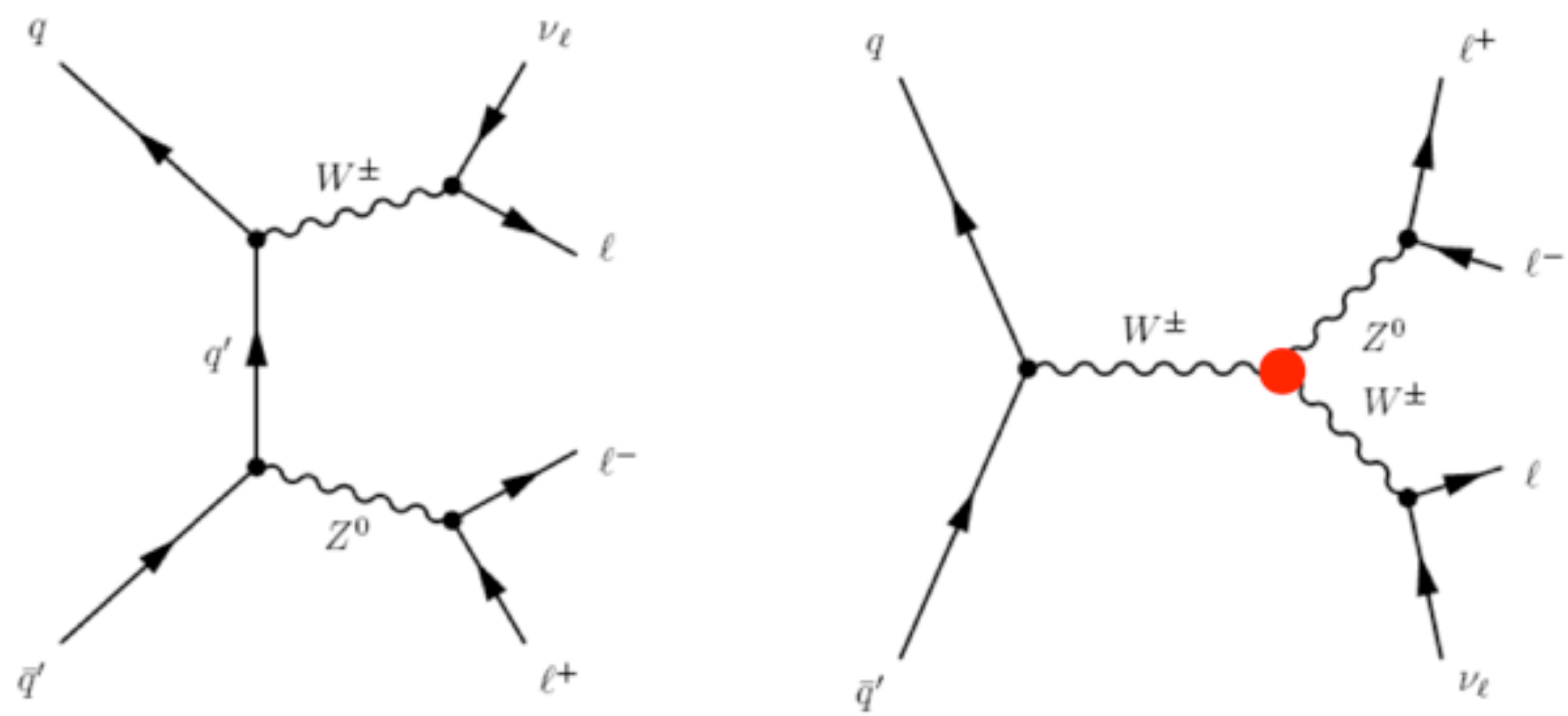
Parameter	$(\Lambda = 1.2$ TeV$)$	$(\Lambda = 1.5$ TeV$)$
h_3^Z	$-0.018, 0.020$	$-0.017, 0.016$
h_4^Z	$-0.0009, 0.0009$	$-0.0006, 0.0005$
h_3^γ	$-0.021, 0.021$	$-0.017, 0.016$
h_4^γ	$-0.0009, 0.0010$	$-0.0006, 0.0006$

Tightest limits on γZZ/γγZ couplings



arXiv:1103.2990 [hep-ex]

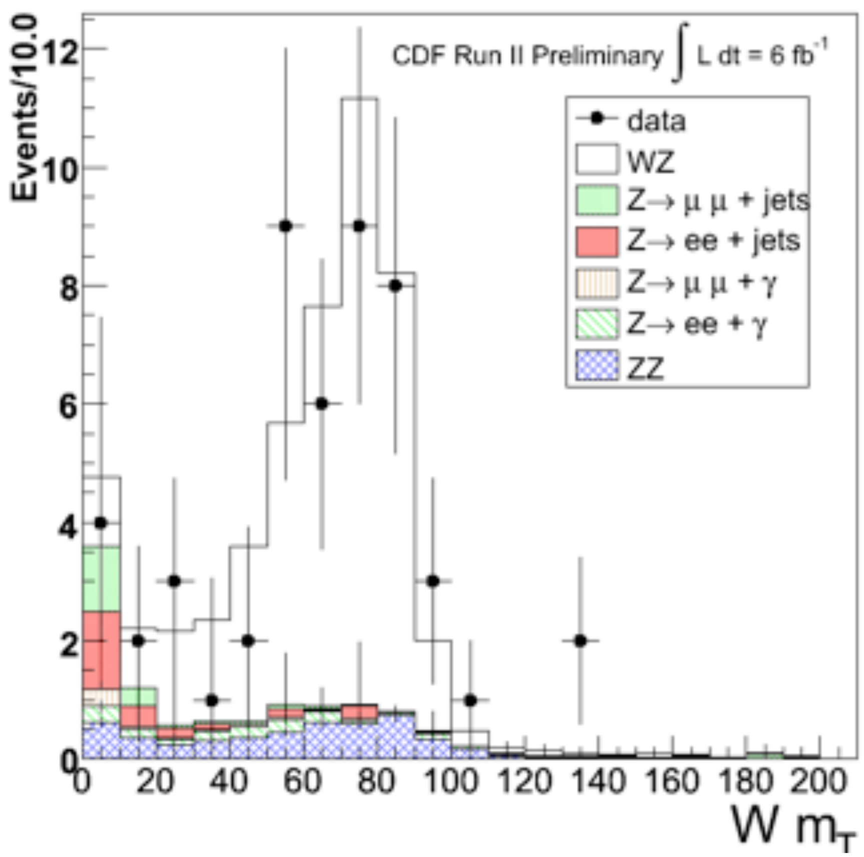
WZ Production

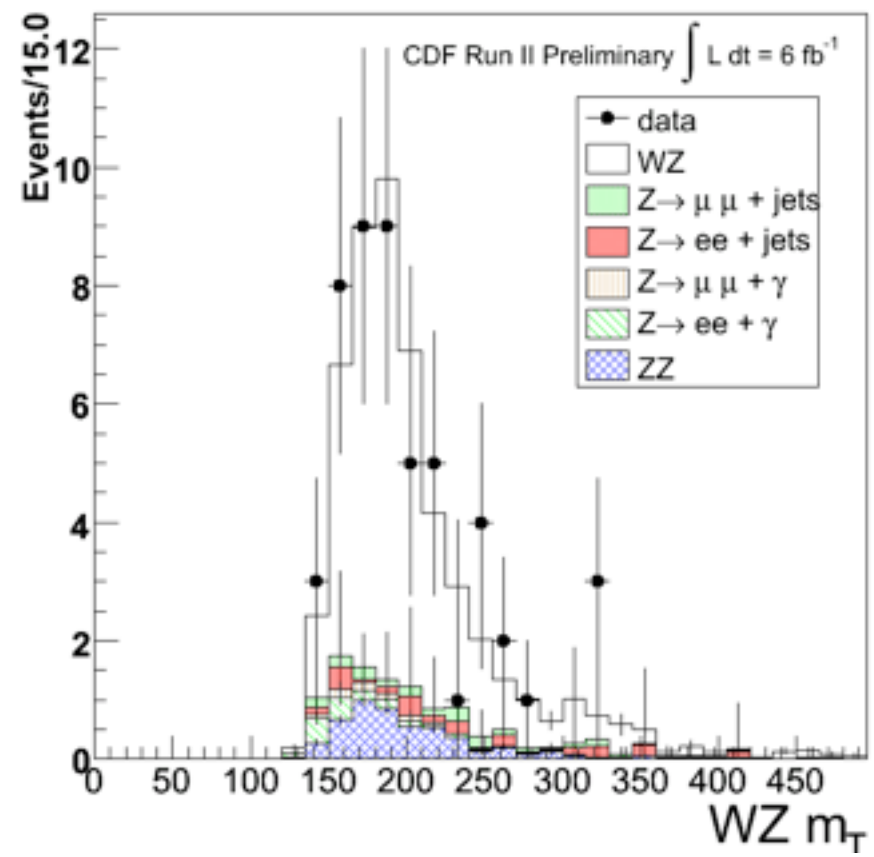


- σ_{NLO}= 3.5 ± 0.3 pb
- Not directly accessible at LEP
- No SM backgrounds with three leptons and MET
  - Small background from ZZ→llll, Z+jets, tt
- WWZ vertex ⇒ κ_Z ,λ_Z ,g_1^Z

WZ → lνll (CDF)

- Signature: three isolated, high-pT leptons with MET
- Build Z from two opposite-sign, same-flavor leptons, require invariant mass to be close to Z mass



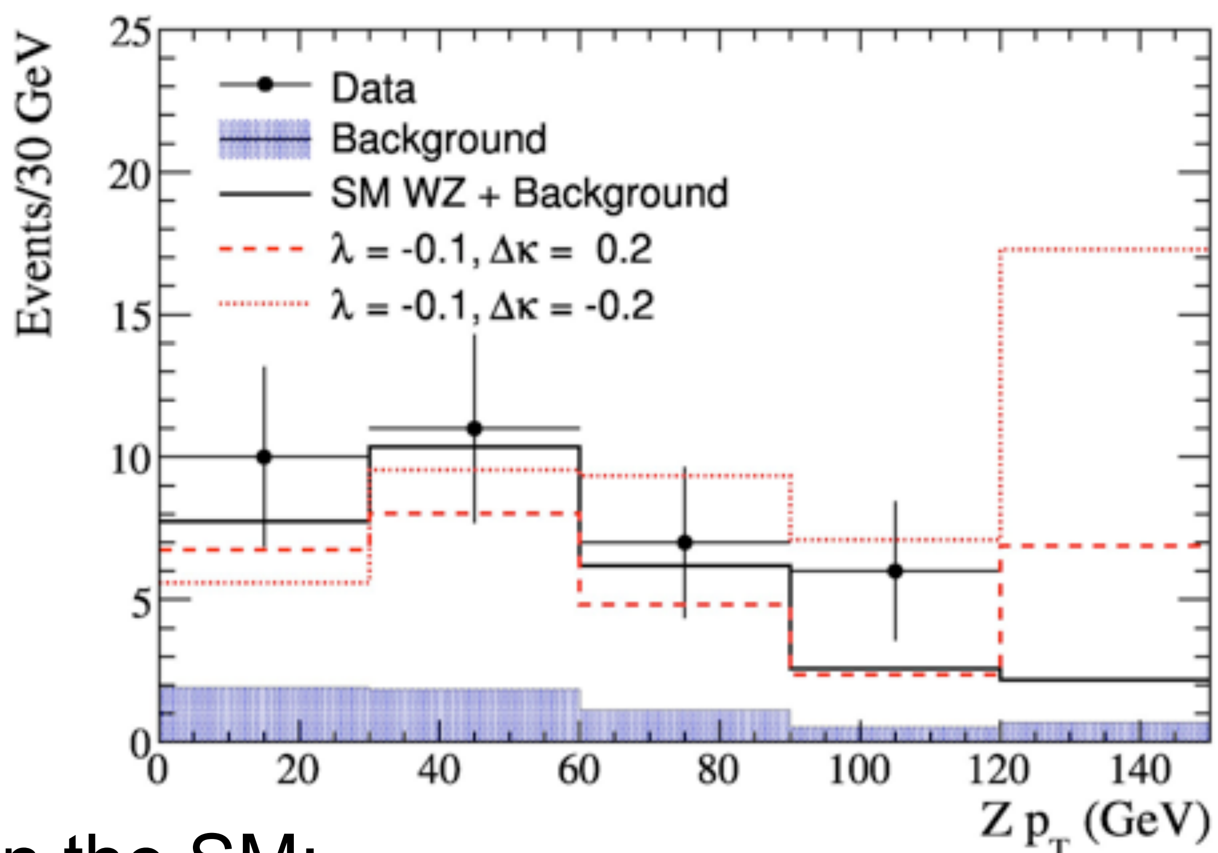


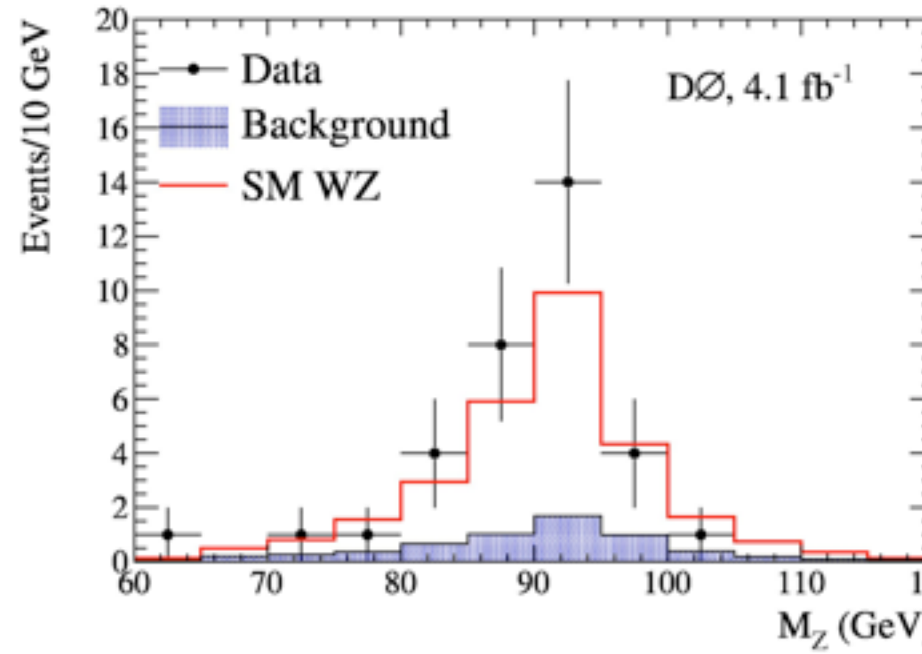
- In 6 fb^{-1}, ~50 signal and ~11 BG events

$$\frac{\sigma(p\bar{p}\to WZ)}{\sigma(p\bar{p}\to Z)} = (5.5 \pm 0.9) \times 10^{-4} \qquad \sigma(p\bar{p} \to WZ) = (4.1 \pm 0.7)\ \mathrm{pb}$$

WZ → lνll (DØ)

- In 4.1 fb^{-1}, expect ~23 signal and ~6 BG events, observe 34, $\sigma(WZ) = 3.90^{+1.06}_{-0.90}$ pb
- Use pT of Z boson to set limit on aTGCs: best limit from direct measurement of WWZ vertex





In the SM:

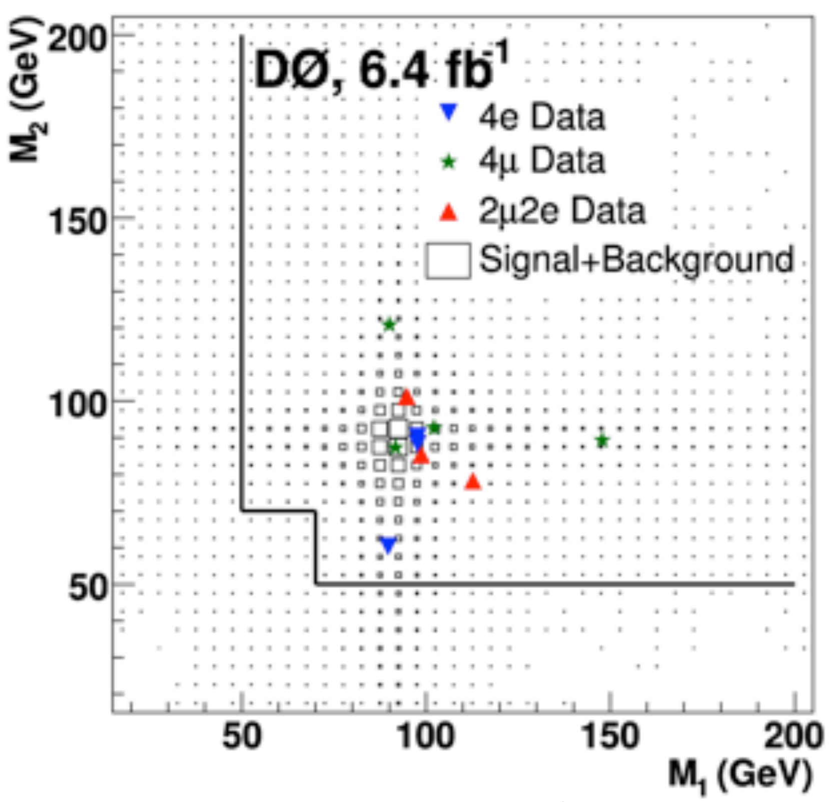
g_1^Z, κ_γ, $\kappa_Z \equiv 1$ and λ_γ, $\lambda_Z \equiv 0$

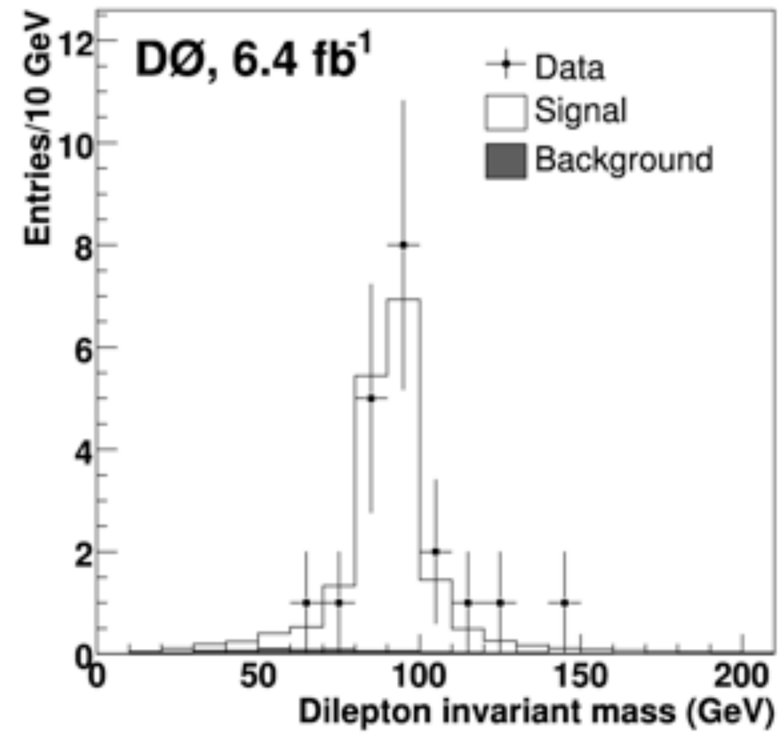
Coupling relation	95% C.L. Limit
$\Delta g_1^Z = \Delta\kappa_Z = 0$	$-0.075 < \lambda_Z < 0.093$
$\lambda_Z = \Delta\kappa_Z = 0$	$-0.053 < \Delta g_1^Z < 0.156$
$\lambda_Z = \Delta g_1^Z = 0$	$-0.376 < \Delta\kappa_Z < 0.686$
$\Delta\kappa_Z = 0$ (HISZ)	$-0.075 < \lambda_Z < 0.093$
$\lambda_Z = 0$ (HISZ)	$-0.027 < \Delta\kappa_Z < 0.080$

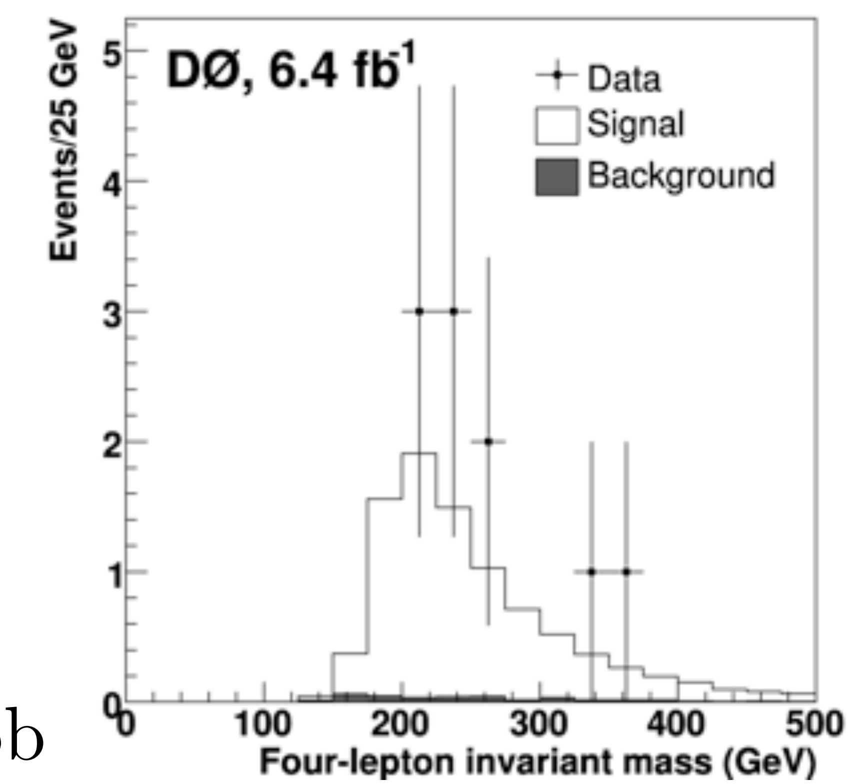
PLB 695, 23 (2011)

ZZ → llll (DØ)

- Two pairs of opposite-sign, same flavor leptons → very clean signature
- First observation of ZZ in 2008 with three four-lepton events
- Now in 6.4 fb^{-1}
  - Expect ~9 signal events, ~0.4 BG events
  - Observe 10 events





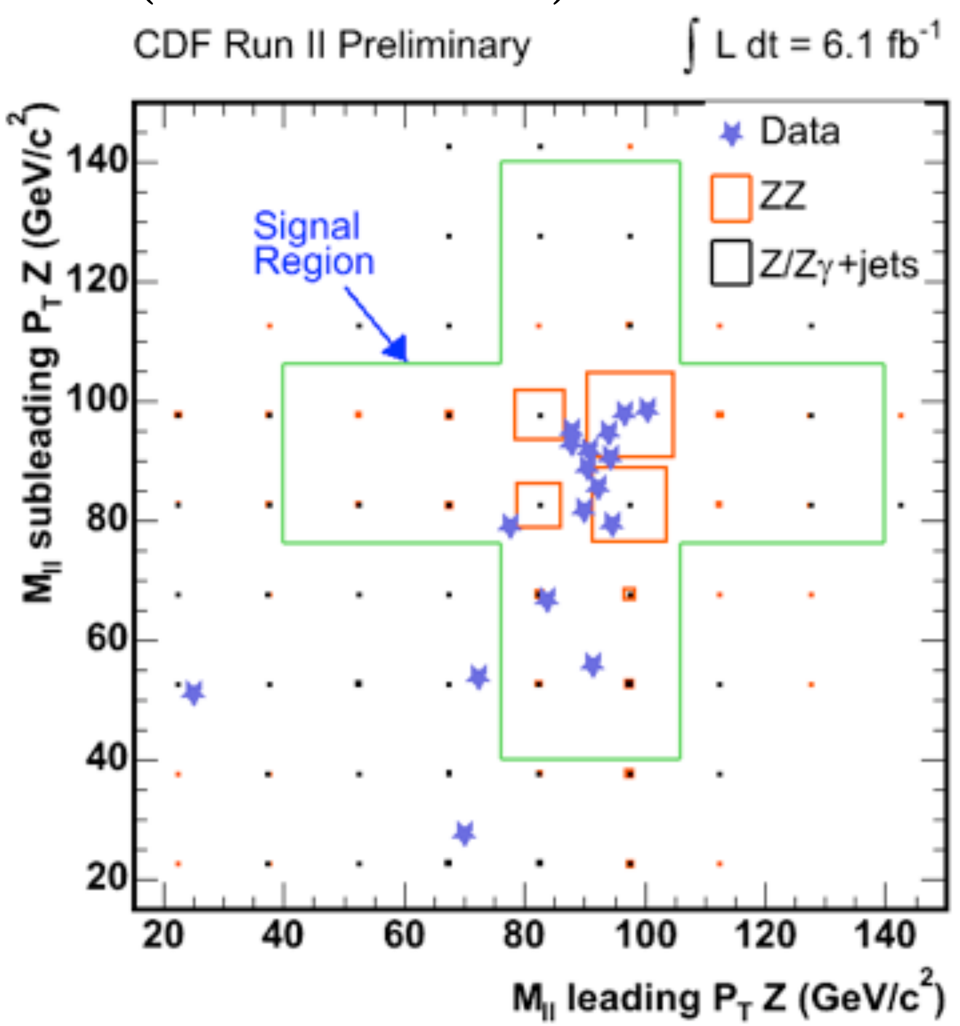


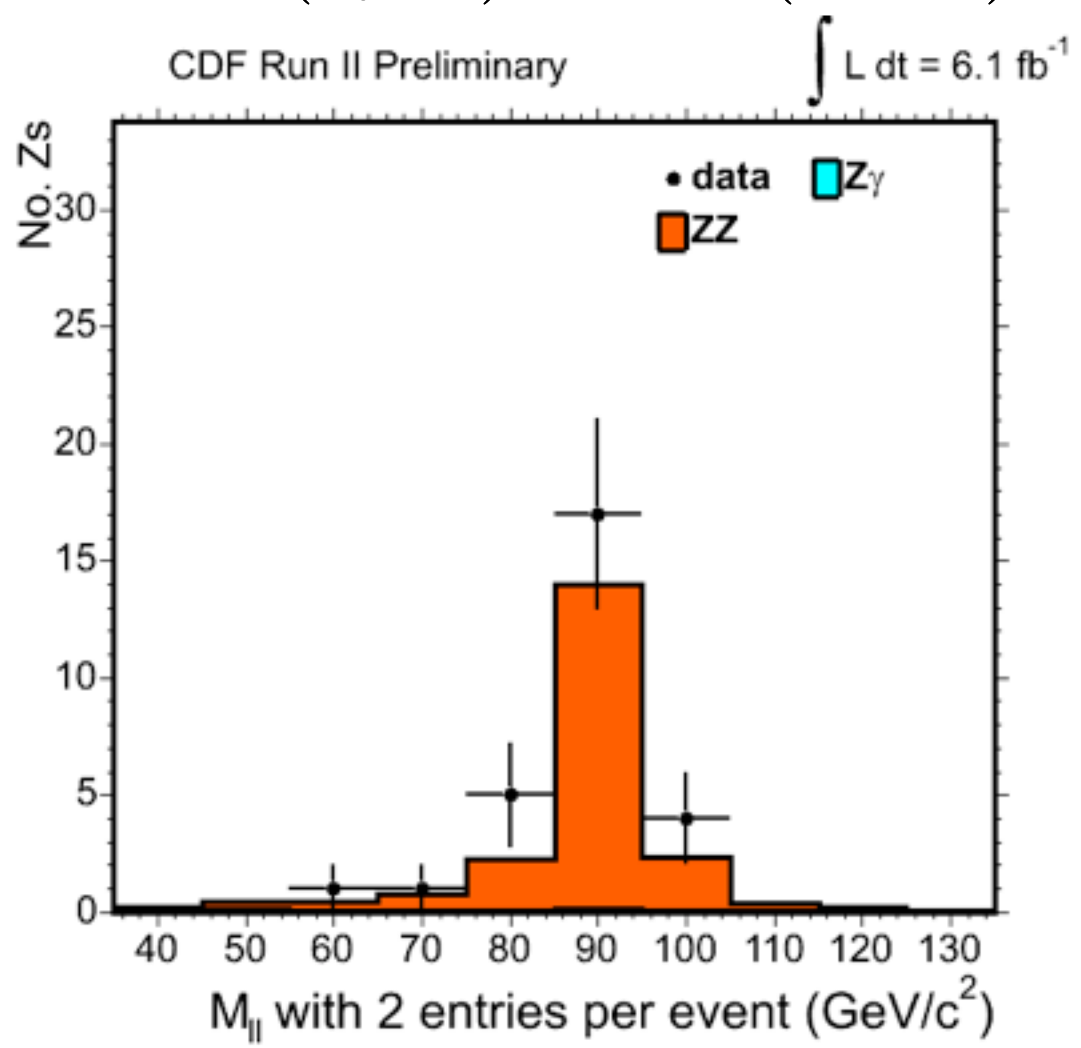
$$\sigma(p\bar{p} \to ZZ) = 1.26^{+0.47}_{-0.37}(\text{stat}) \pm 0.14(\text{syst})\ \text{pb}$$

Submitted to Phys. Rev. D
arXiv:1104.3078v1

ZZ → llll (CDF)

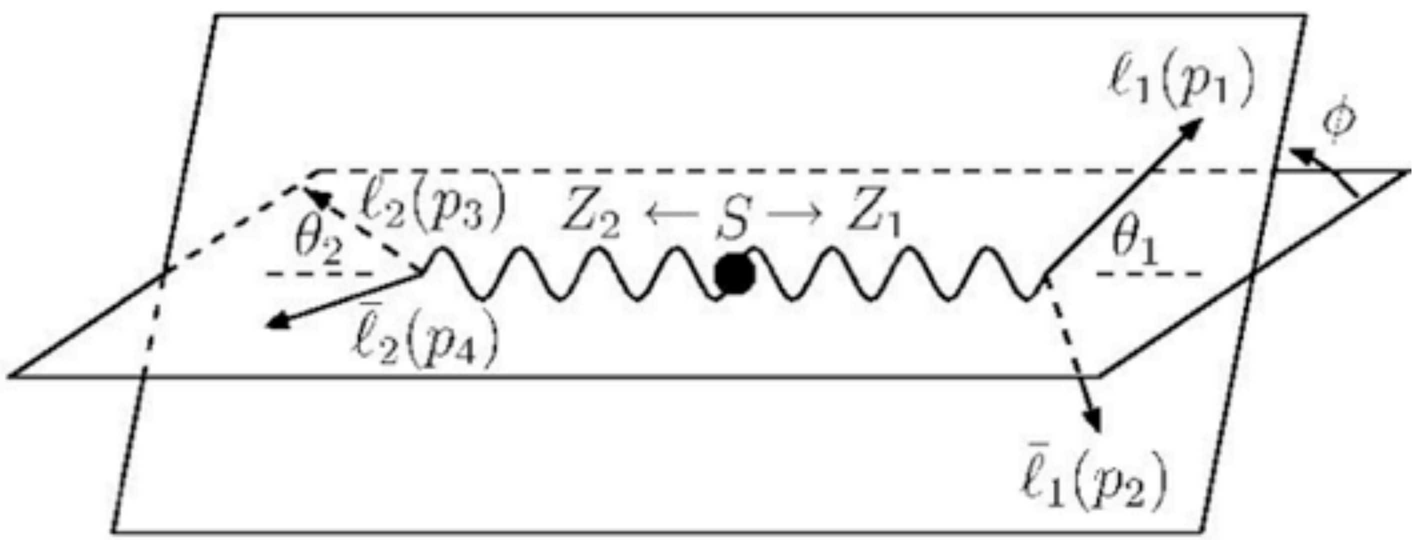
- In 6.1 fb^{-1}, expect ~10 signal events ~0.26 BG events
- Observe 14 events
- $\sigma(p\bar{p} \to ZZ) = 2 \pm 29\%(\mathrm{stat}) \pm 16\%(\mathrm{syst}) \pm 6\%(\mathrm{lumi})\ \mathrm{pb}$



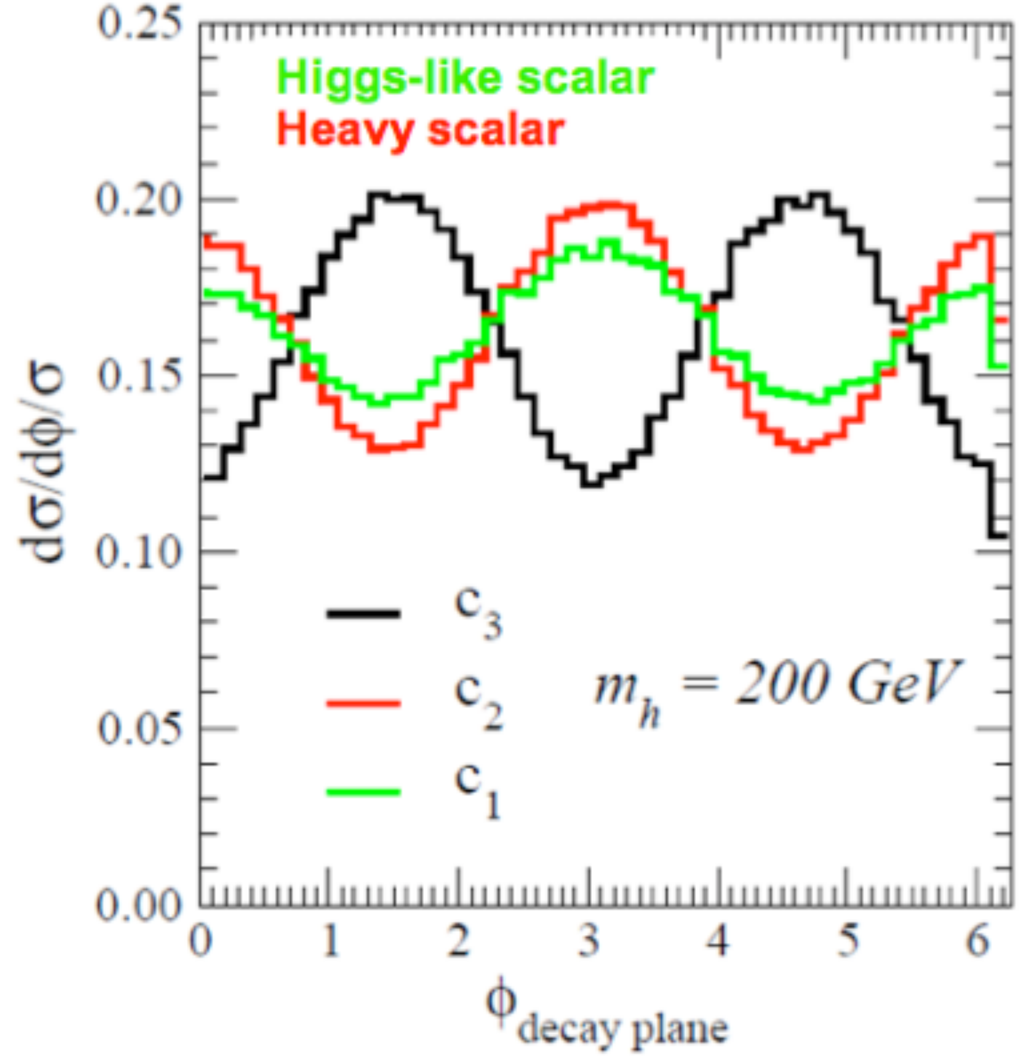


ZZ Kinematics

- 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)



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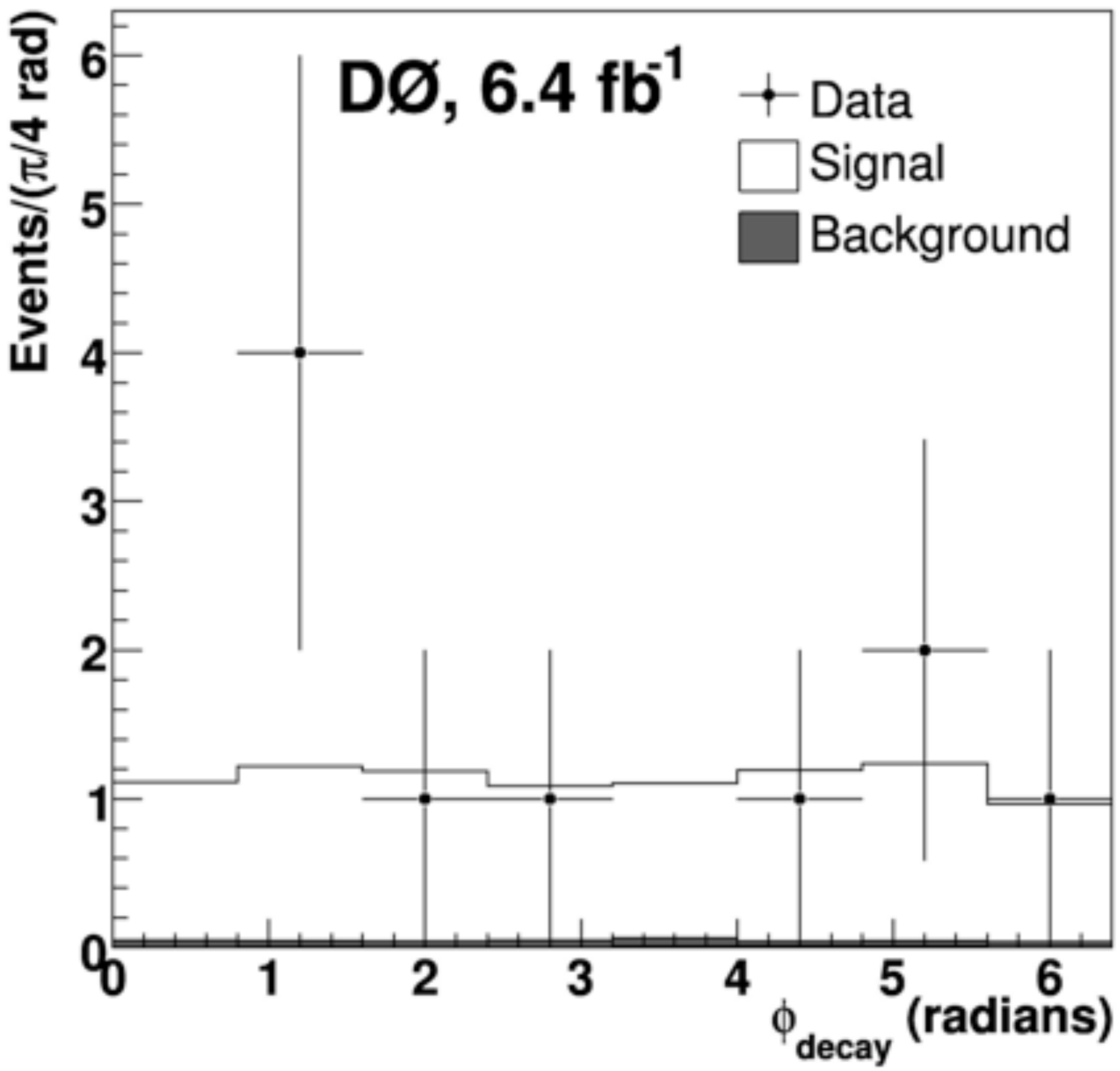

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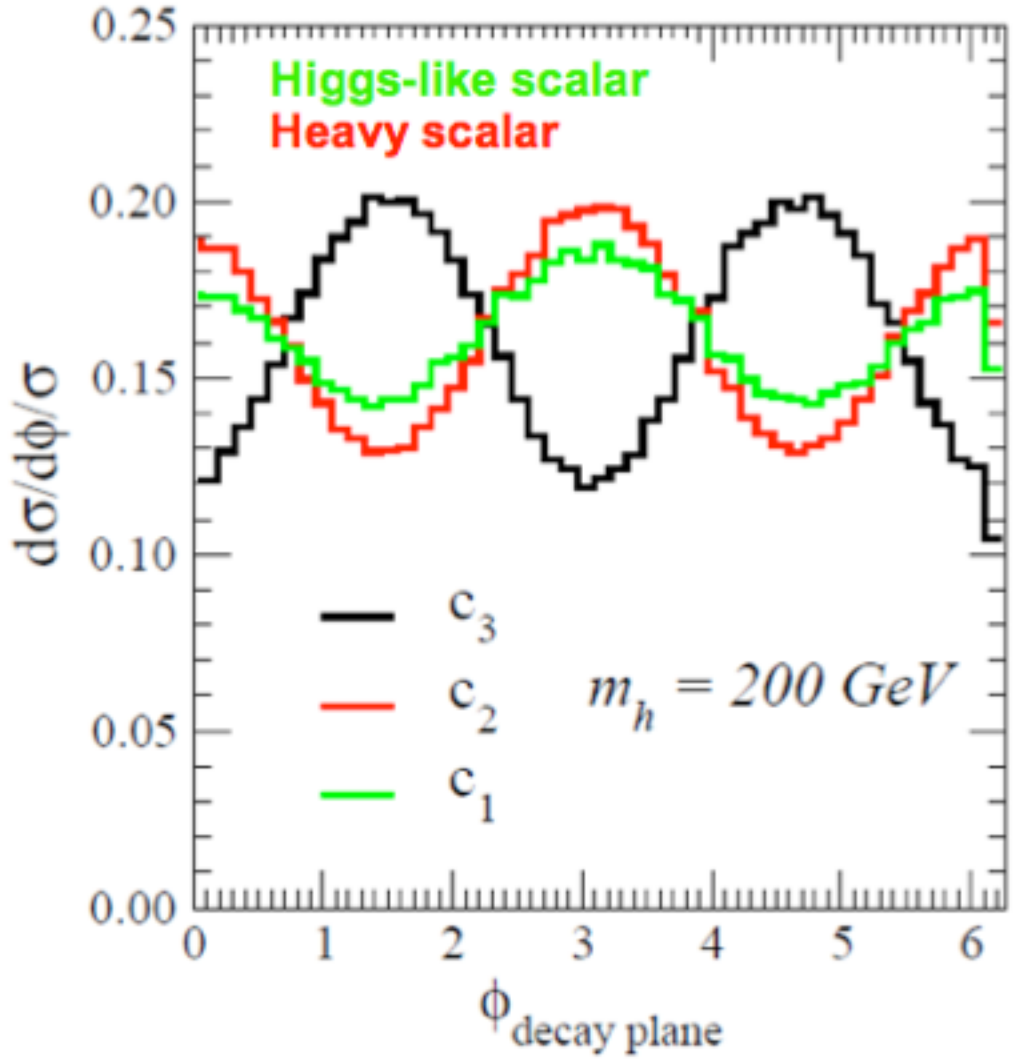
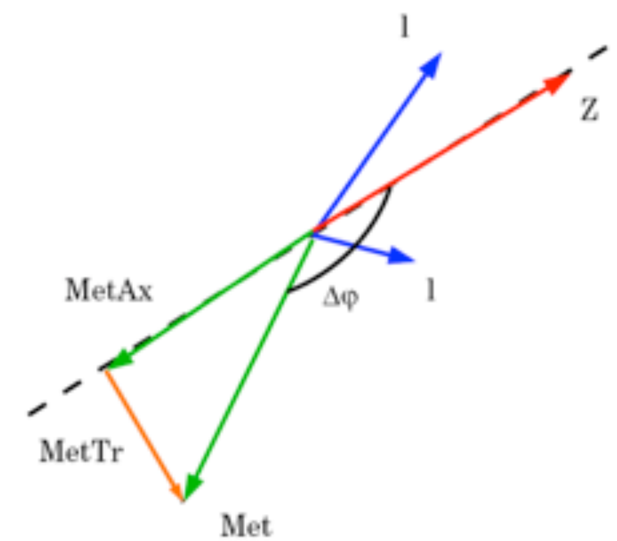
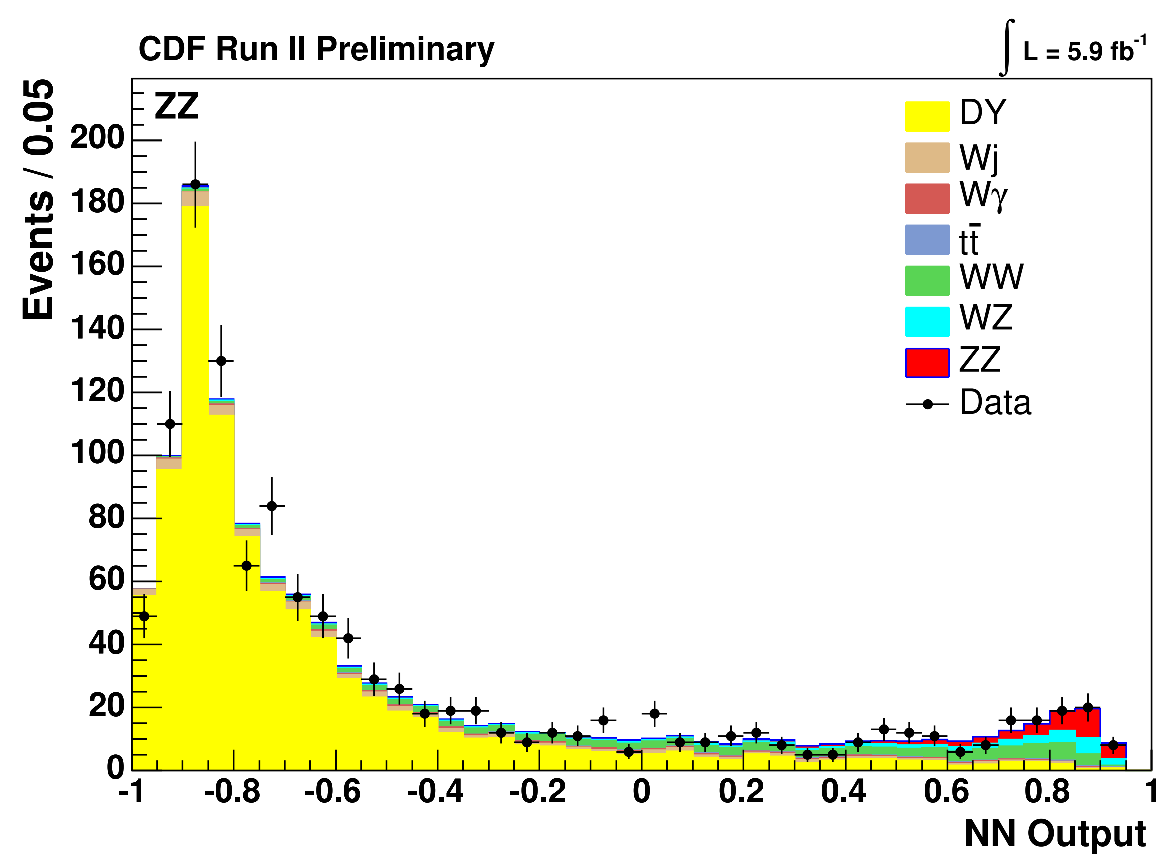


ZZ → llνν (CDF)

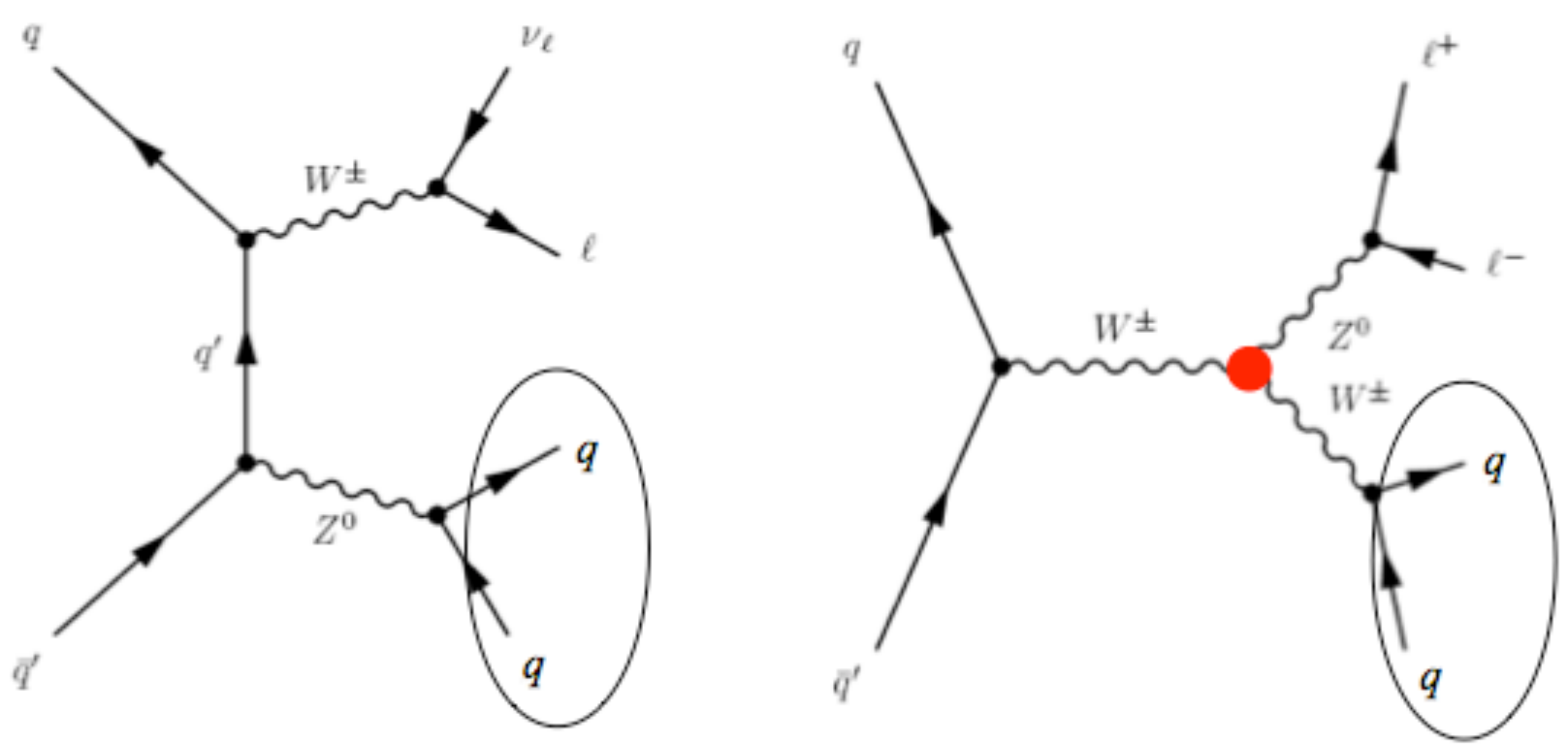
- Z → l+l- plus high MET
  - Not as clean as Z → llll: background from Drell-Yan production
- To reduce D-Y background, require MET to be back-to-back with Z boson in transverse plane
- 5.9 fb^{-1}
  - Expect ~50 signal events
  - Expect ~1100 BG events
  - Observe 1162 events
- Use neural network to separate signal and background





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

VV with Hadronic Decays

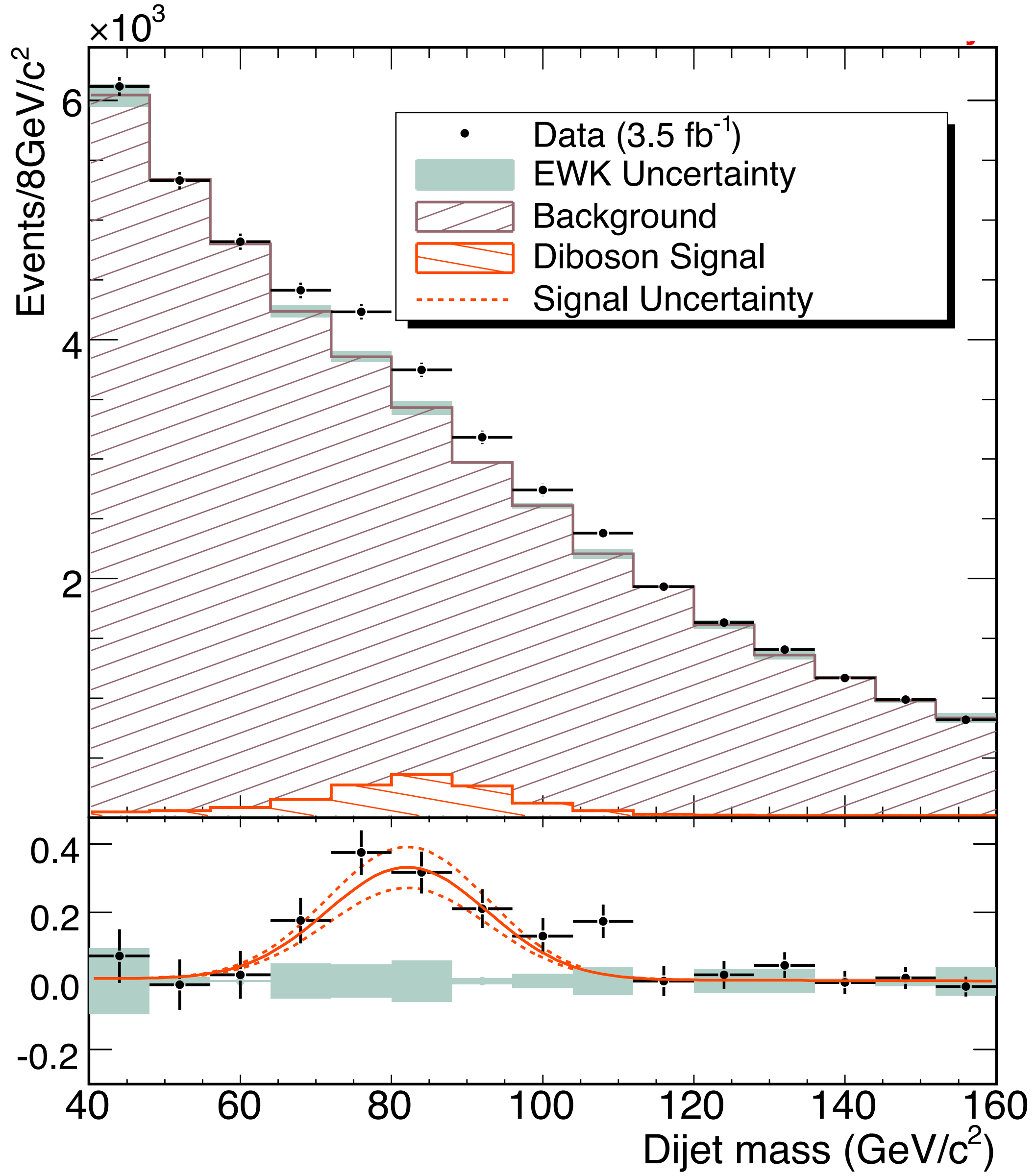


- $\sigma_{NLO}(WZ+ZZ) = 4.9 \pm 0.3$ pb
- Larger hadronic branching ratios
- Much larger background contamination
  - W/Z+jets: same final states, orders of magnitude larger cross sections

VV with Hadronic Decays

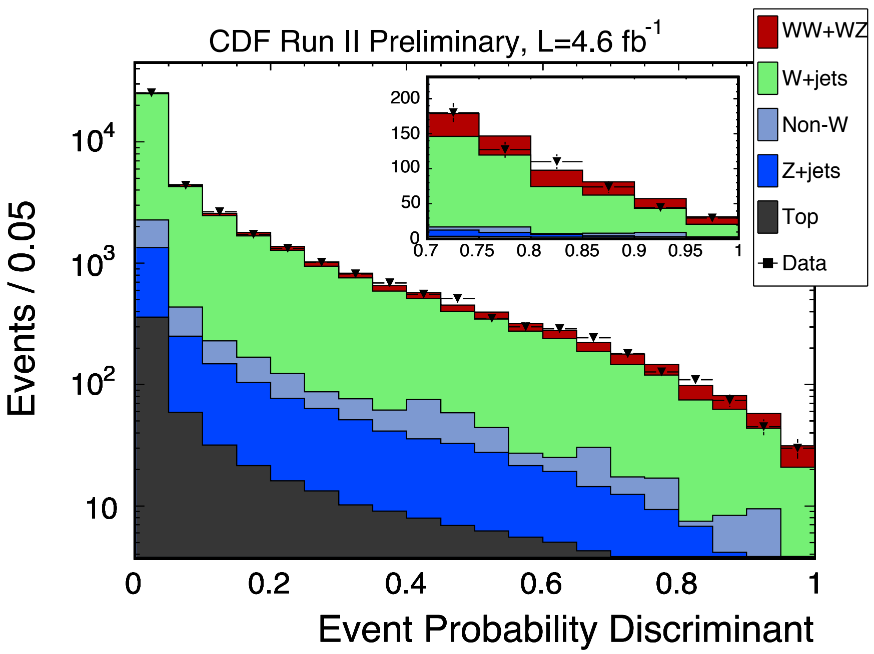
- 2009: observed VV → MET + jets final states
  - WW→lvqq, WZ→lvqq/qqvv, ZZ→vvqq/qqvv

PRL 103, 091803 (2009)

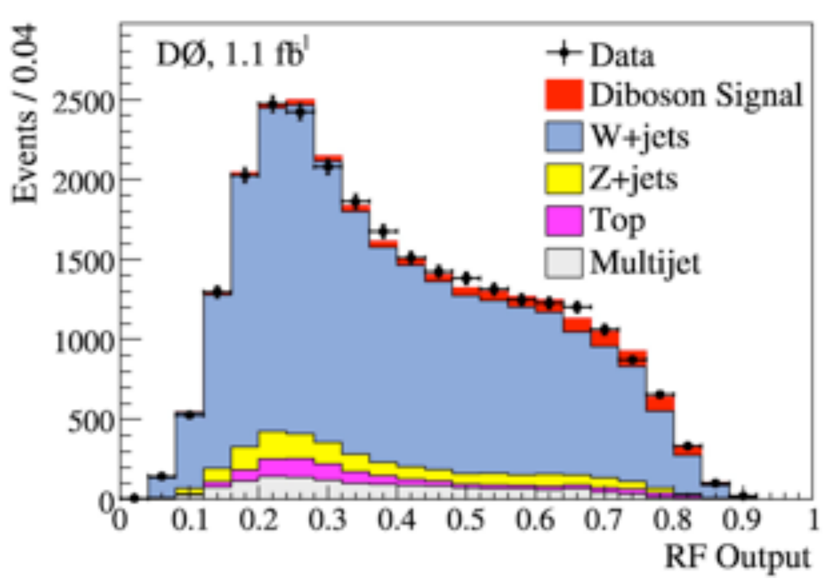


WW+WZ → lvjj

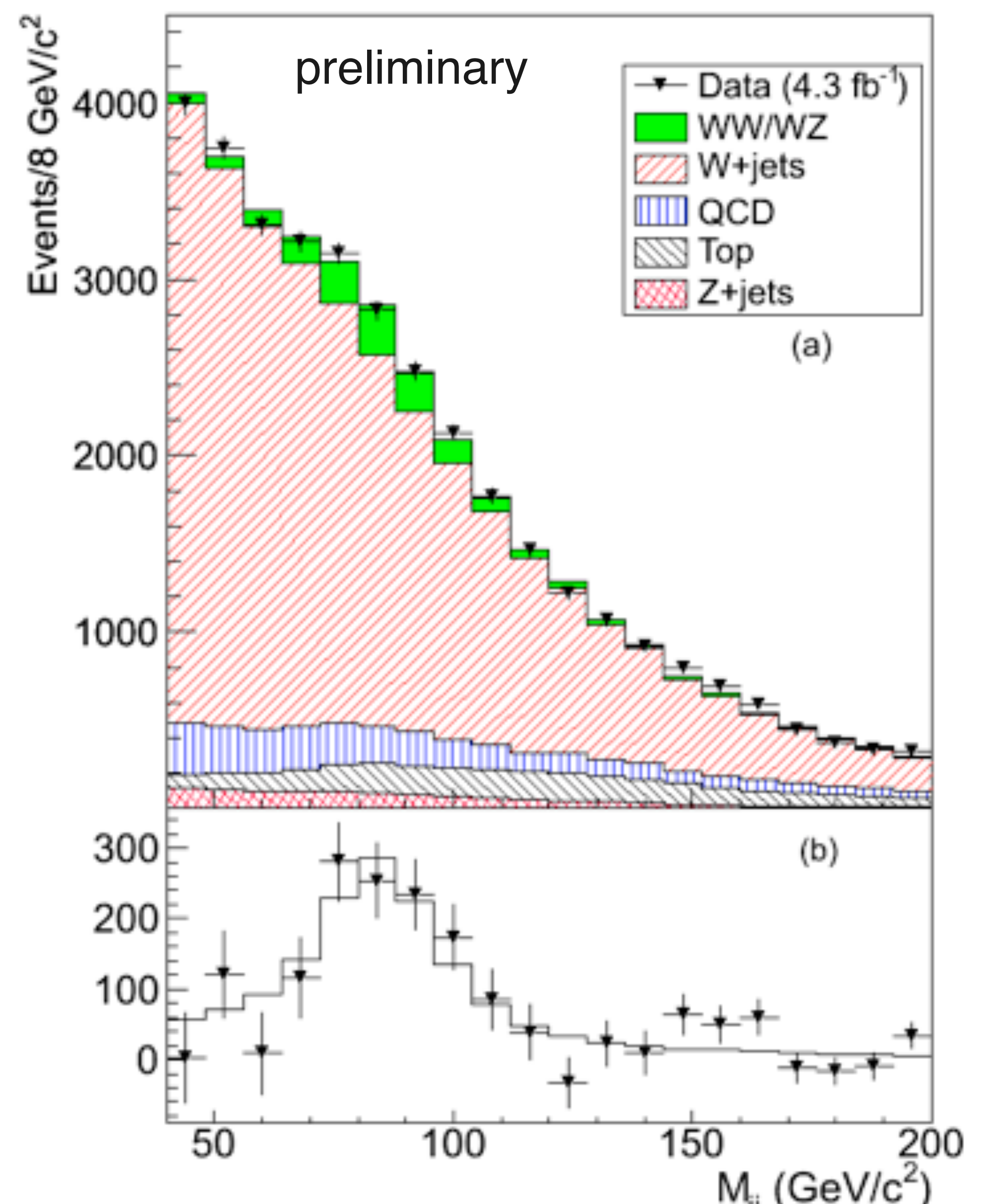
- One trigger lepton, two jets and MET → large W+jets background
- Challenge is to separate signal and BG; model BG well



CDF matrix element:
σ(WW+WZ) = 17.4 ± 3.3 pb
PRD 82, 112001 (2010)



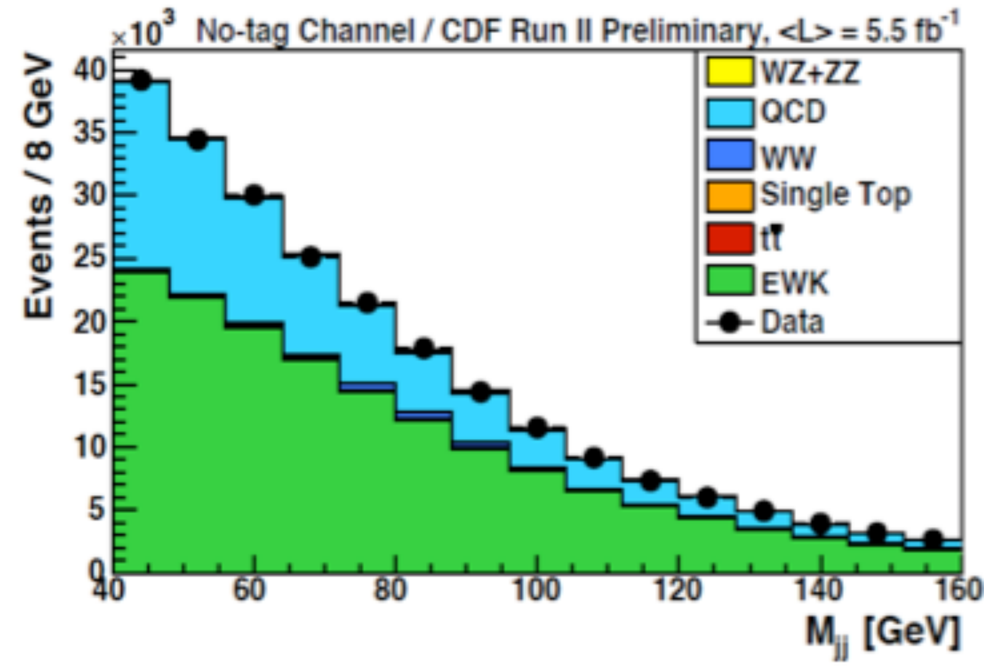
D0 random forest:
σ(WW+WZ) = 20.2 ± 4.5 pb
PRL 102, 161801 (2009)

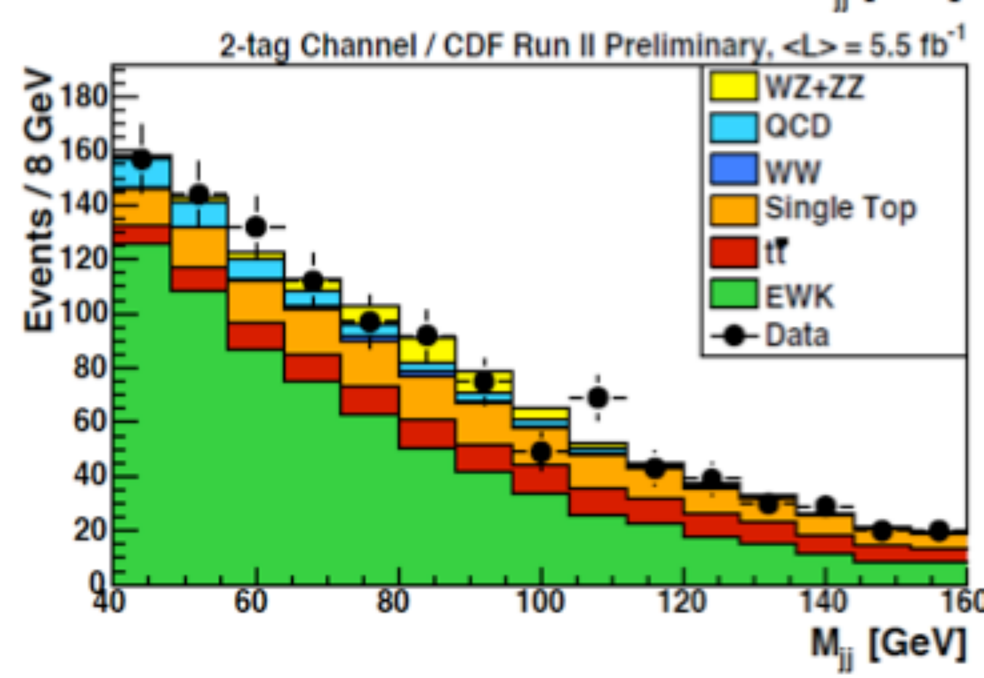


CDF dijet mass: σ(WW+WZ) = 18.1 ± 4.1 pb

VV with b-Tagging

- Now apply b-tagging (5.5 fb^{-1})
  - Try to separate out $WZ \to l\nu bb$, $ZZ \to \nu\nu bb$
    - 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





$\sigma_{NLO} = 4.9 \pm 0.3$ pb

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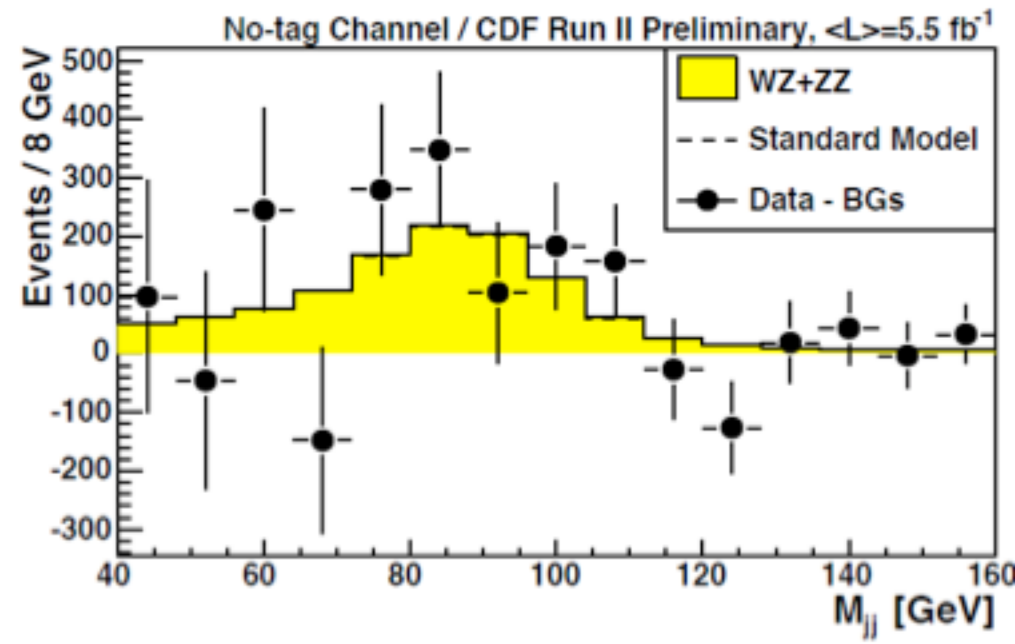
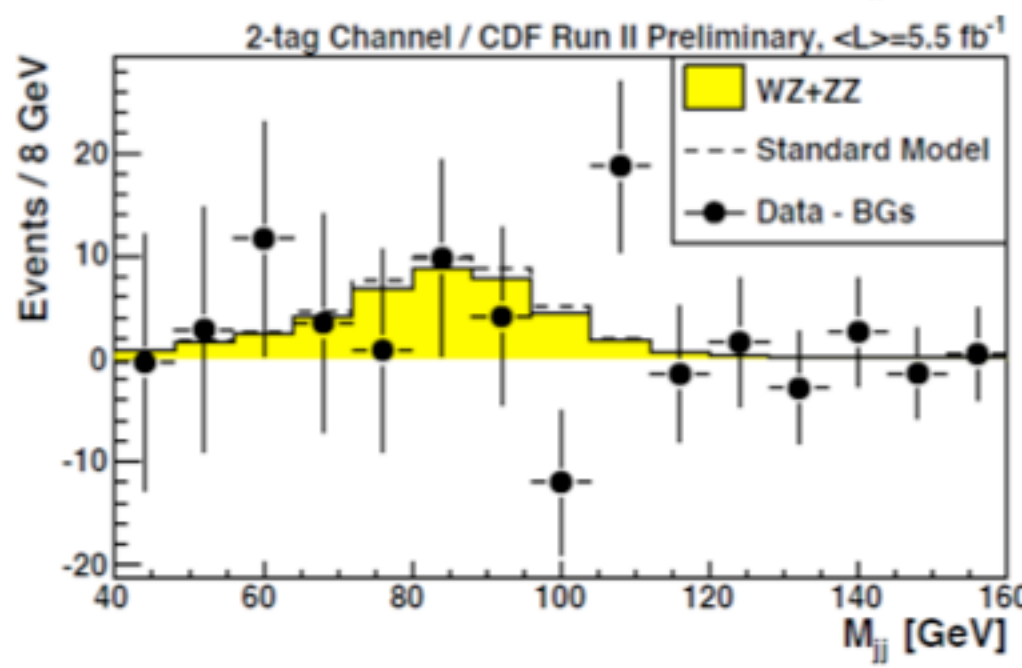


$$\sigma(p\bar{p} \to WZ + ZZ) = 5.0^{+3.6}_{-2.5}\ \text{pb}$$

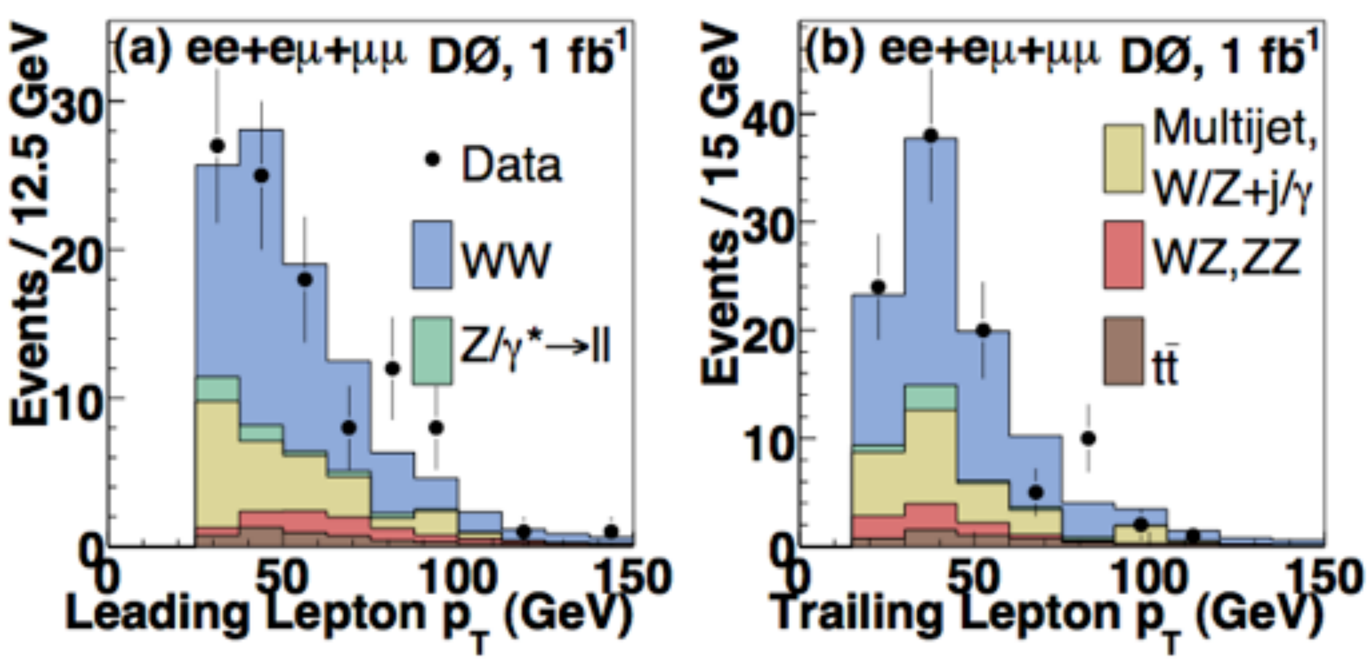


$$\sigma(p\bar{p} \to WZ + ZZ) < 13\ \text{pb at } 95\%\ \text{CL}$$

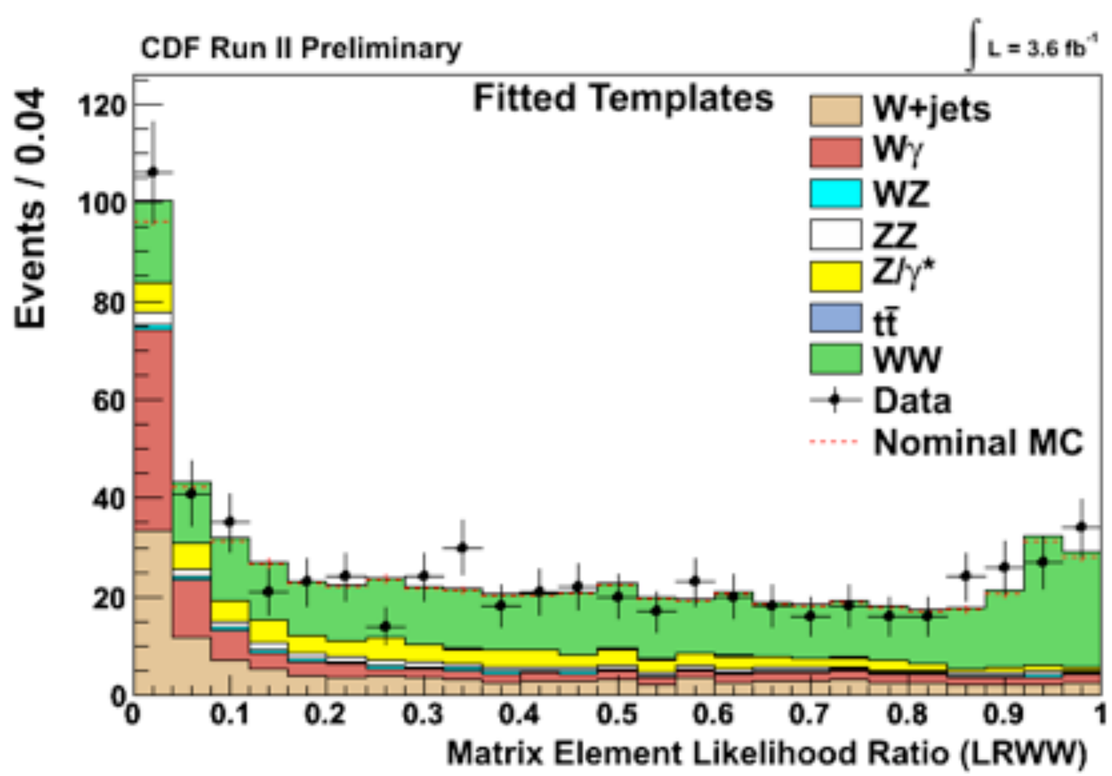
$\sigma_{NLO} = 4.9 \pm 0.3$ pb

WW → lνlν

- Signature: two opposite-sign, isolated, high-pT leptons and
- large MET Major BGs from Drell-Yan, Wγ, W+jets
- D0: count events, combine ee, eμ and μμ channels
  - ~65 signal, ~40 BG events in 1 fb^{-1}
  - σ(WW)= 11.5±2.2 pb
- CDF: matrix element probabilities to separate signal and BG
  - ~300 signal, ~300 BG events (3.6 fb^{-1})
  - σ(WW)= 12.1±1.8 pb



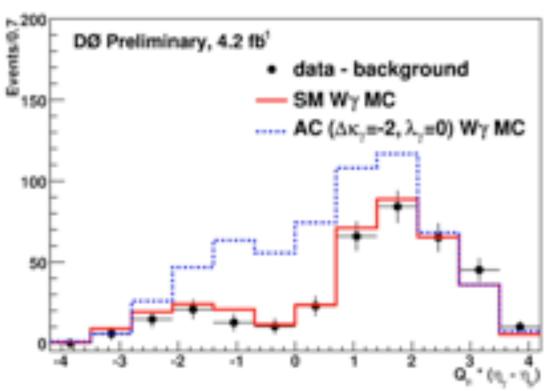
PRL 103, 191801 (2009)

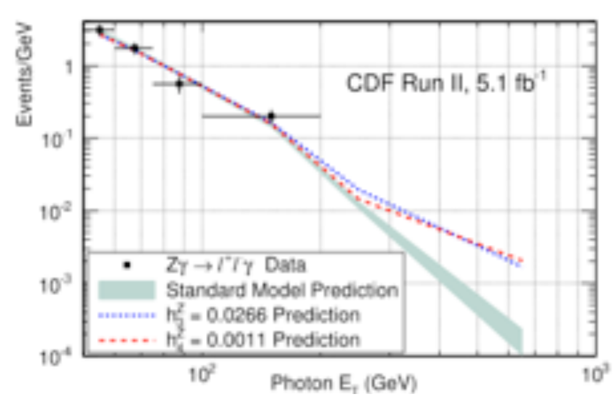


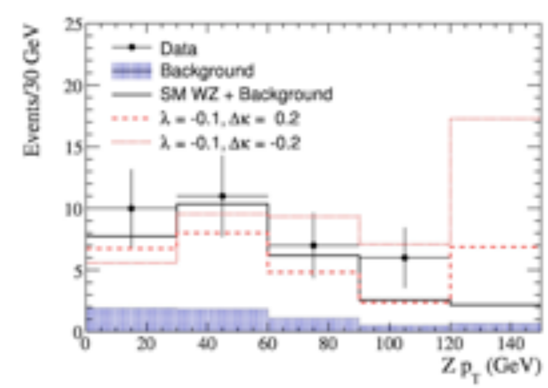
PRL 104, 201801 (2010)

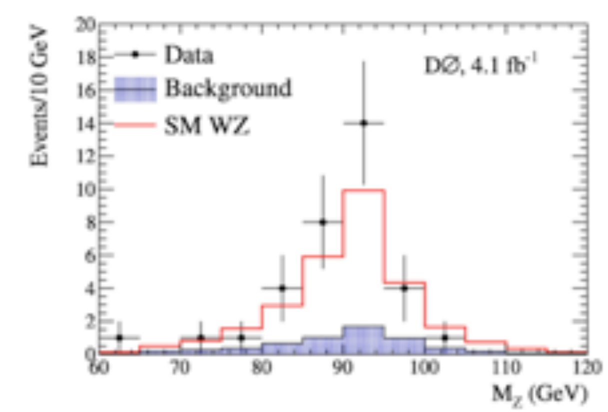
Conclusions

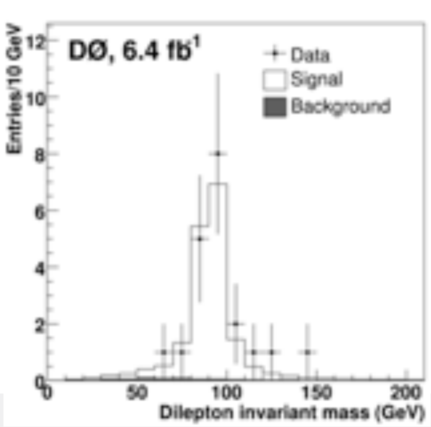
- 4 – 6 fb^{-1} of RunII Tevatron data analyzed by each experiment
- Measuring very small cross sections
- Setting some of the tightest limits on anomalous TGCs
- Most results are still statistics limited
- Expect ~2 × more data before the Tevatron shuts off

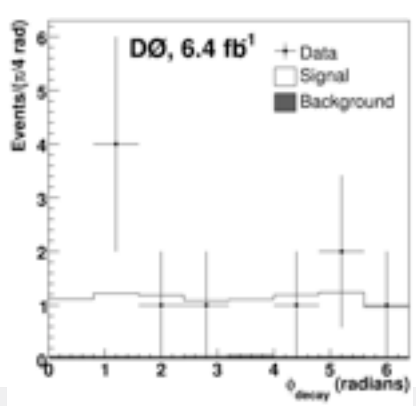


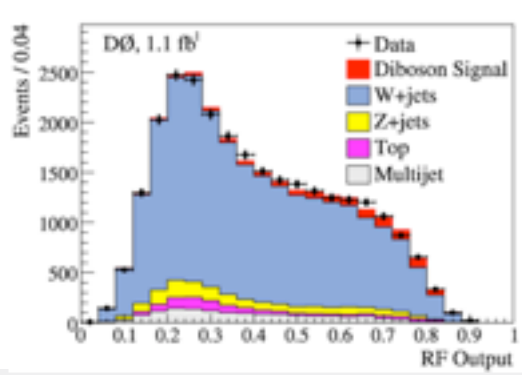


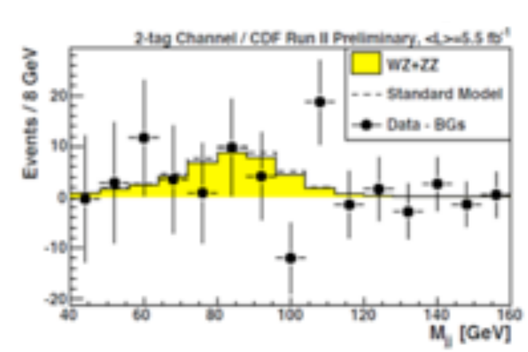


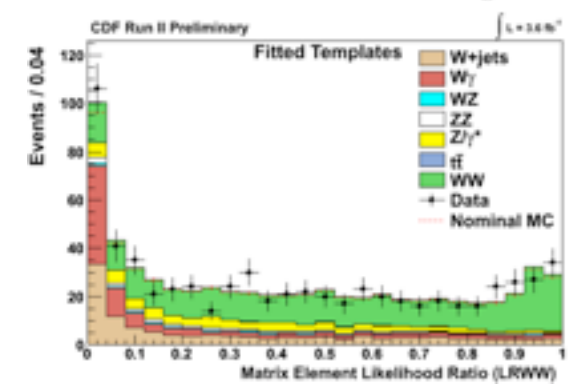


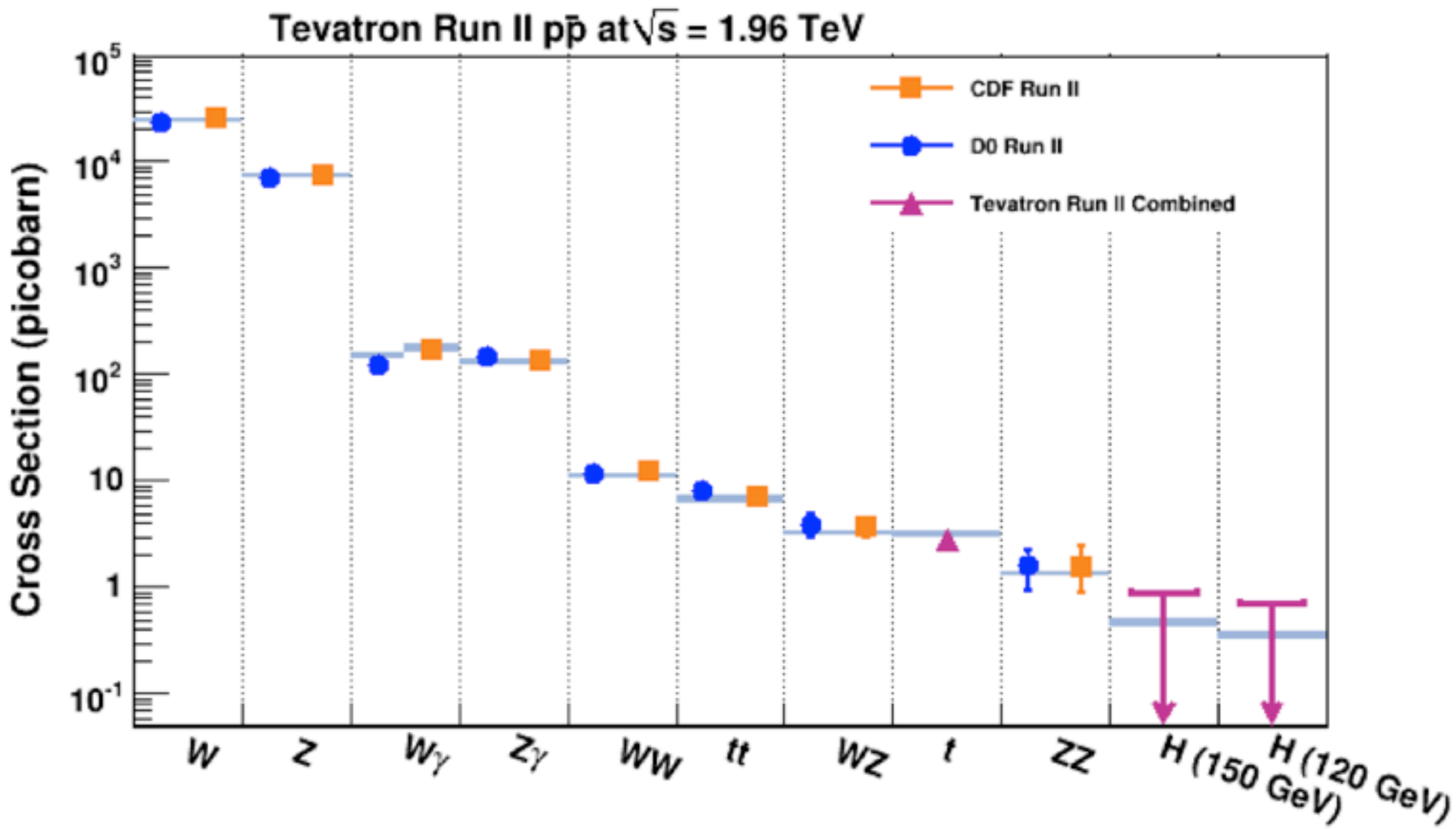











Tevatron Run II pp̄ at √s = 1.96 TeV
Cross Section (picobarn)
10^5
10^4
10^3
10^2
10
1
10^-1
CDF Run II
D0 Run II
Tevatron Run II Combined
W
Z
Wγ
Zγ
WW
tt
WZ
t
ZZ
H (150 GeV)
H (120 GeV)

Backup starts right here….

Motivation for Diboson Physics

- Probe of new physics at 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

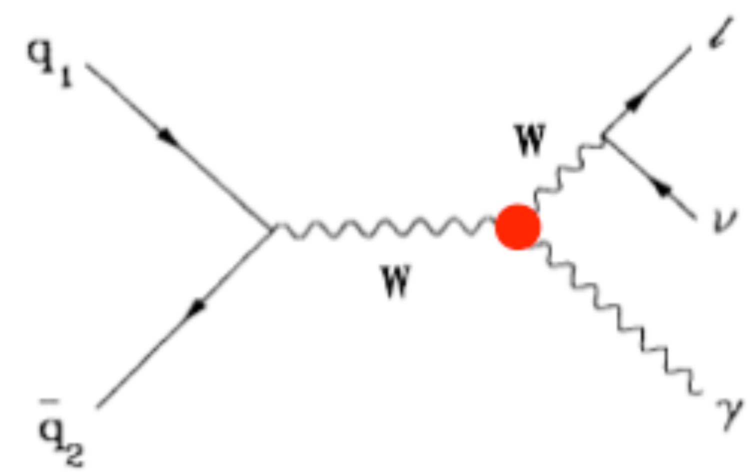
      $\Rightarrow g_1^Z, \kappa_\gamma, \kappa_Z \equiv 1$ in the SM

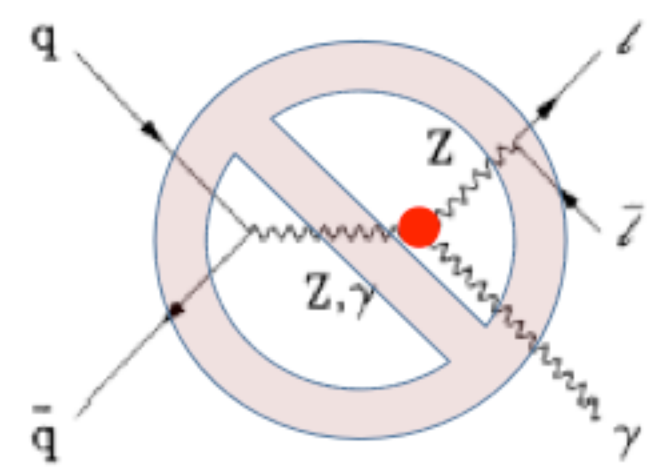
      $\Rightarrow \lambda_\gamma, \lambda_Z \equiv 0$ in the SM
    - γZZ and $\gamma\gamma Z$ TGCs

      General Lagrangian has 8 TGC parameters

      Assume CP conservation

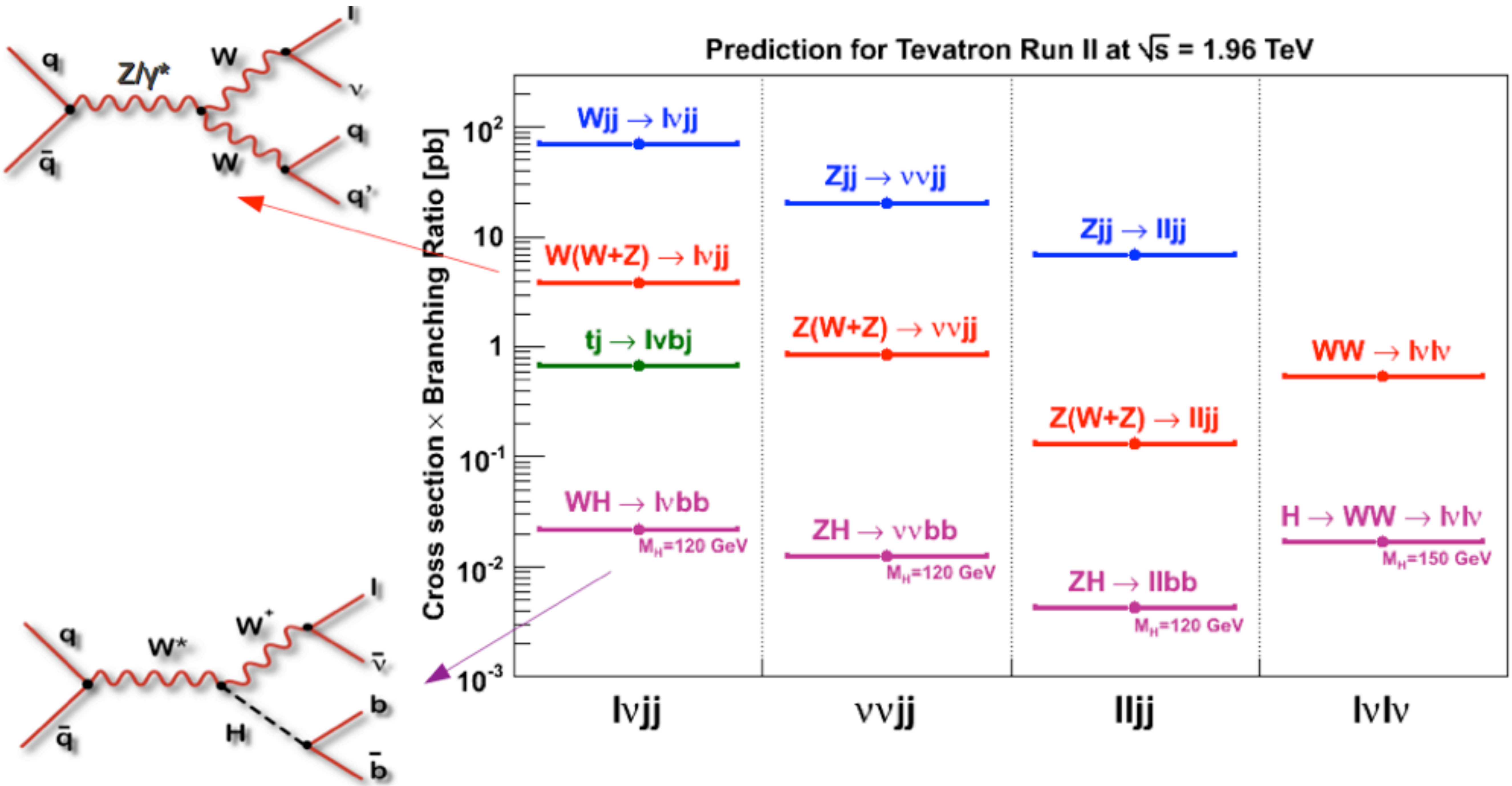
      $\Rightarrow h_3^\gamma, h_3^Z, h_4^\gamma, h_4^Z \equiv 0$ in the SM



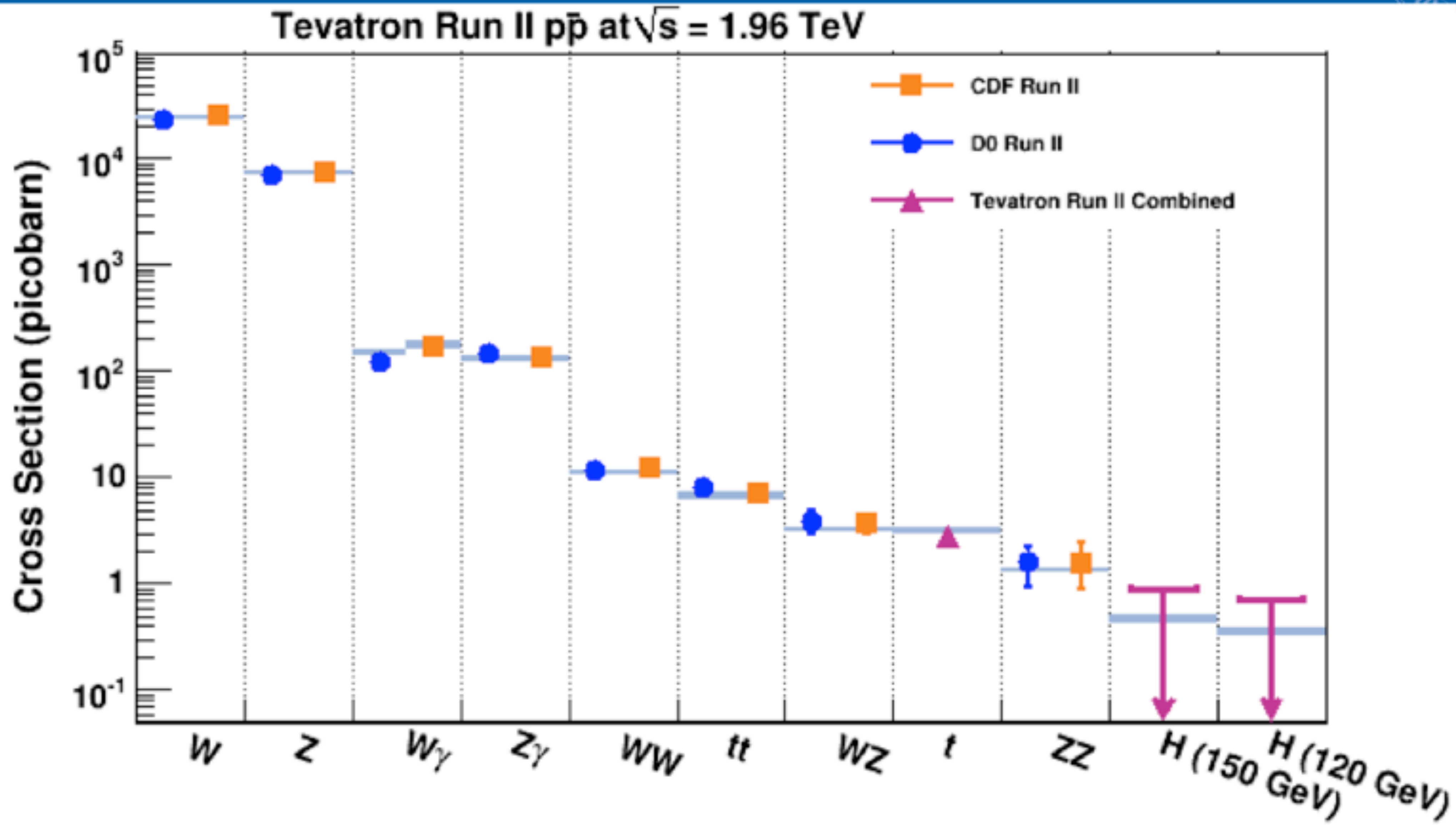


Dibosons and the Higgs

- Sensitive Higgs search channels at the Tevatron:



Diboson production cross sections



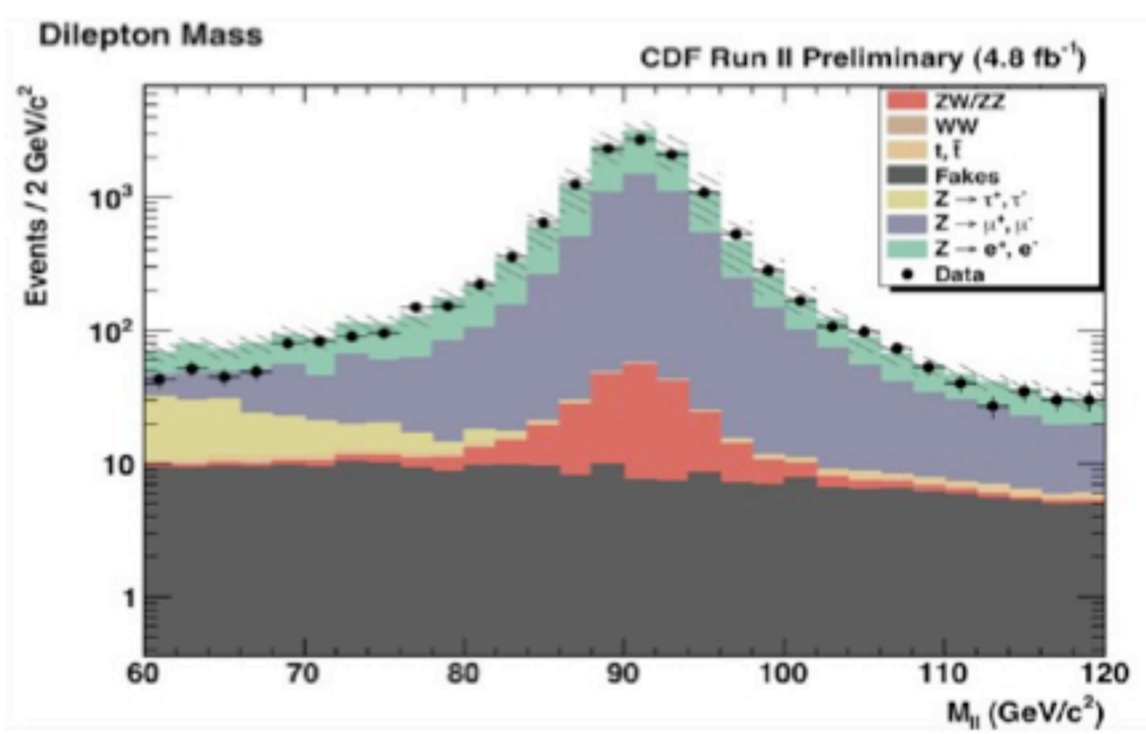
Process	DØ Measurement [pb]	CDF Measurement [pb]	NLO Prediction [pb]
WW	11.5 ± 2.2	$12.1^{+1.8}_{-1.7}$	11.7 ± 0.8
WZ	$3.90^{+1.06}_{-0.90}$	4.1 ± 0.7	3.5 ± 0.3
ZZ	$1.35^{+0.52}_{-0.43}$	$1.56^{+0.84}_{-0.68}$	1.4 ± 0.1

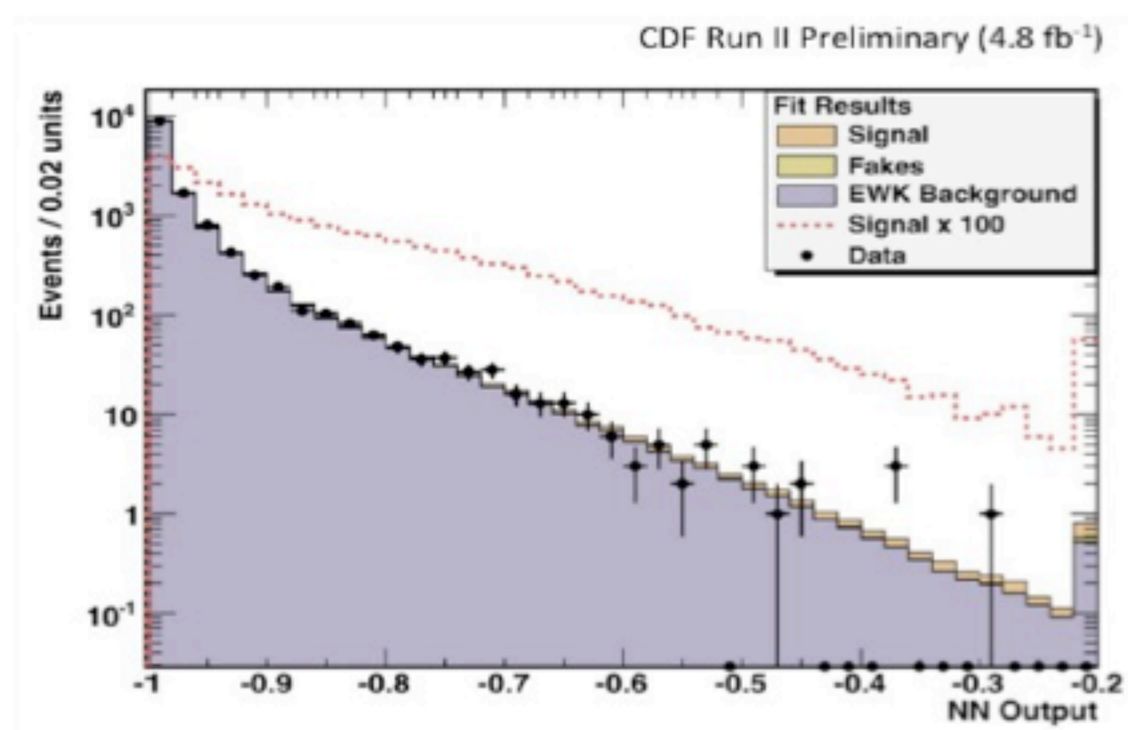
- Different measurements use different integrated luminosities, between 1 and 6 fb^{-1}

WZ+ZZ →qqll

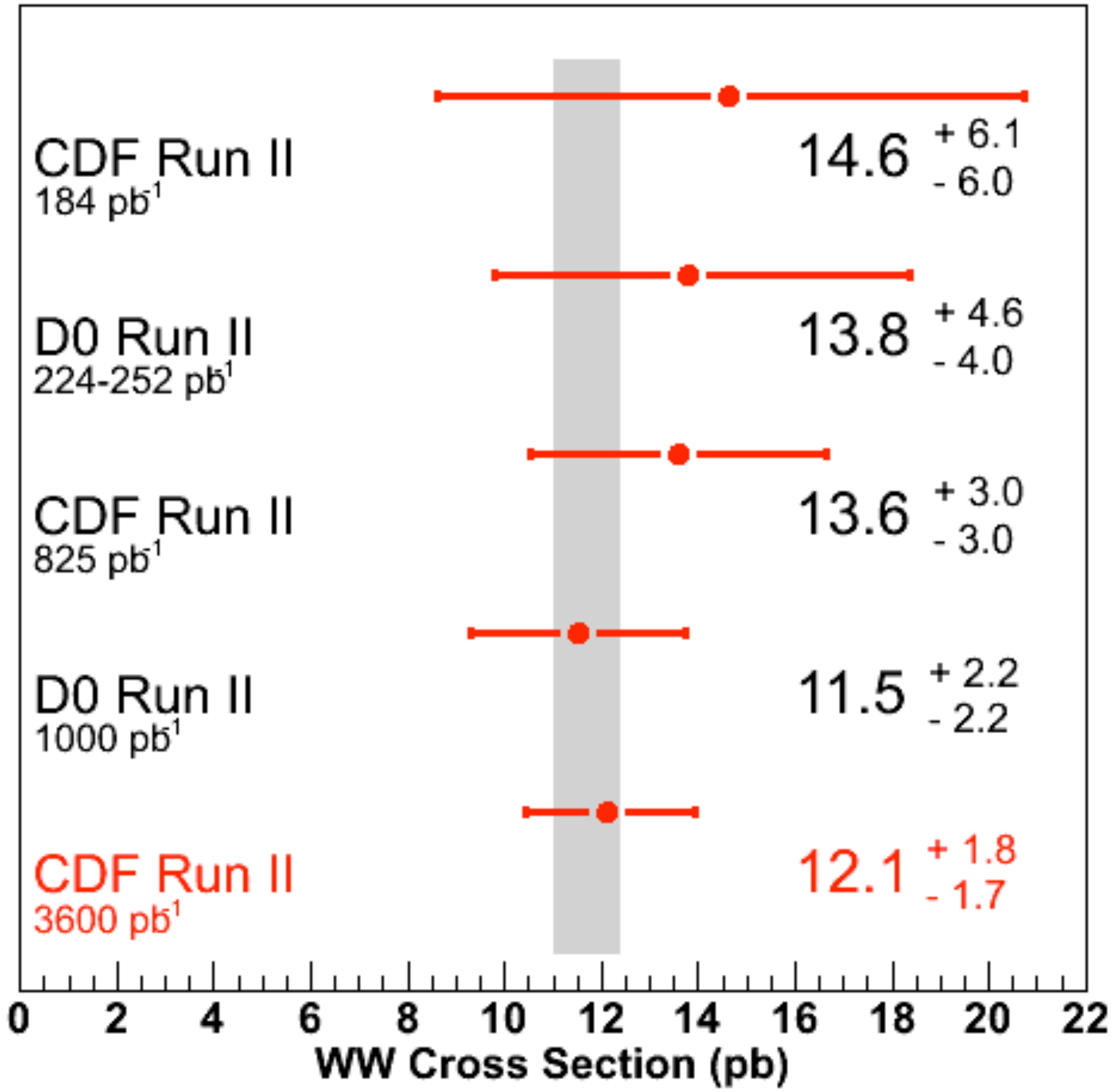
- 4.8 fb-1 of data
  - Two high pT leptons, two high pT jets, and low MET
    - Expected signal ~202 events
    - Expected background ~13000 events: Dominated by Z+jets
- Use an artificial Neural Network to identify signal like events
- Includes variables to separate quark and gluon jets

⇒ Significance ~1 standard deviation above background





WW → lνlν



CDF Run II
184 pb-1
14.6 + 6.1 - 6.0
D0 Run II
224-252 pb-1
13.8 + 4.6 - 4.0
CDF Run II
825 pb-1
13.6 + 3.0 - 3.0
D0 Run II
1000 pb-1
11.5 + 2.2 - 2.2
CDF Run II
3600 pb-1
12.1 + 1.8 - 1.7
0 2 4 6 8 10 12 14 16 18 20 22
WW Cross Section (pb)

CDF Dijet Mass Excess

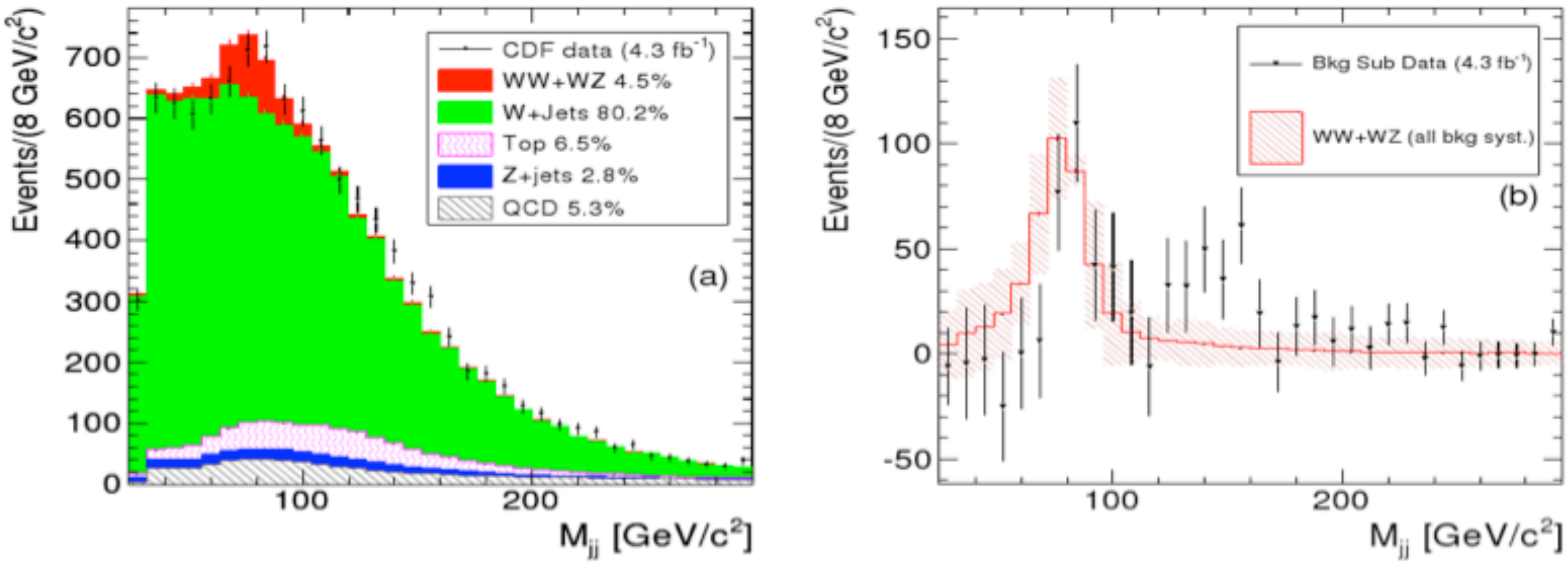
Moving to different kinematical region

- 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

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)



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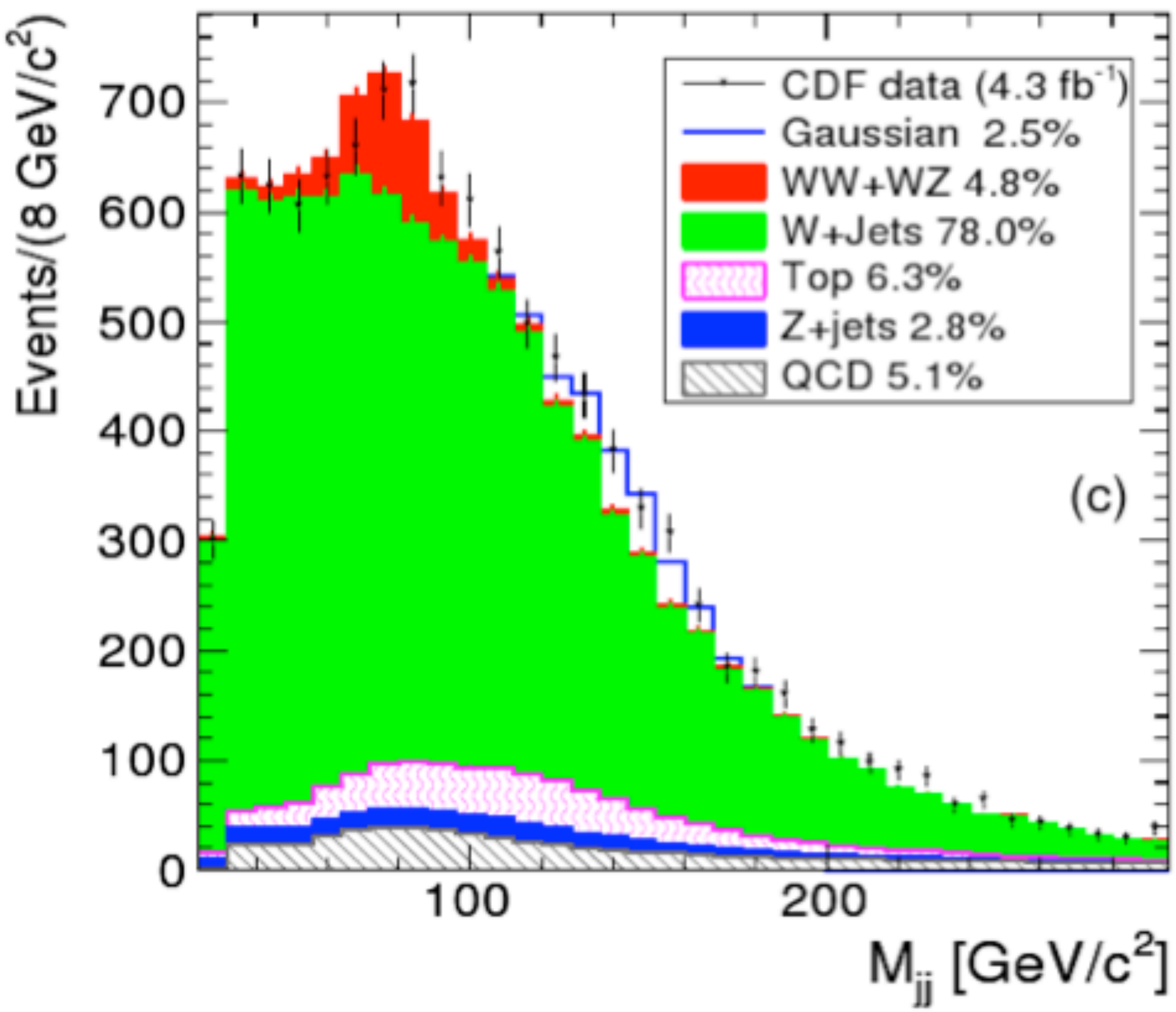
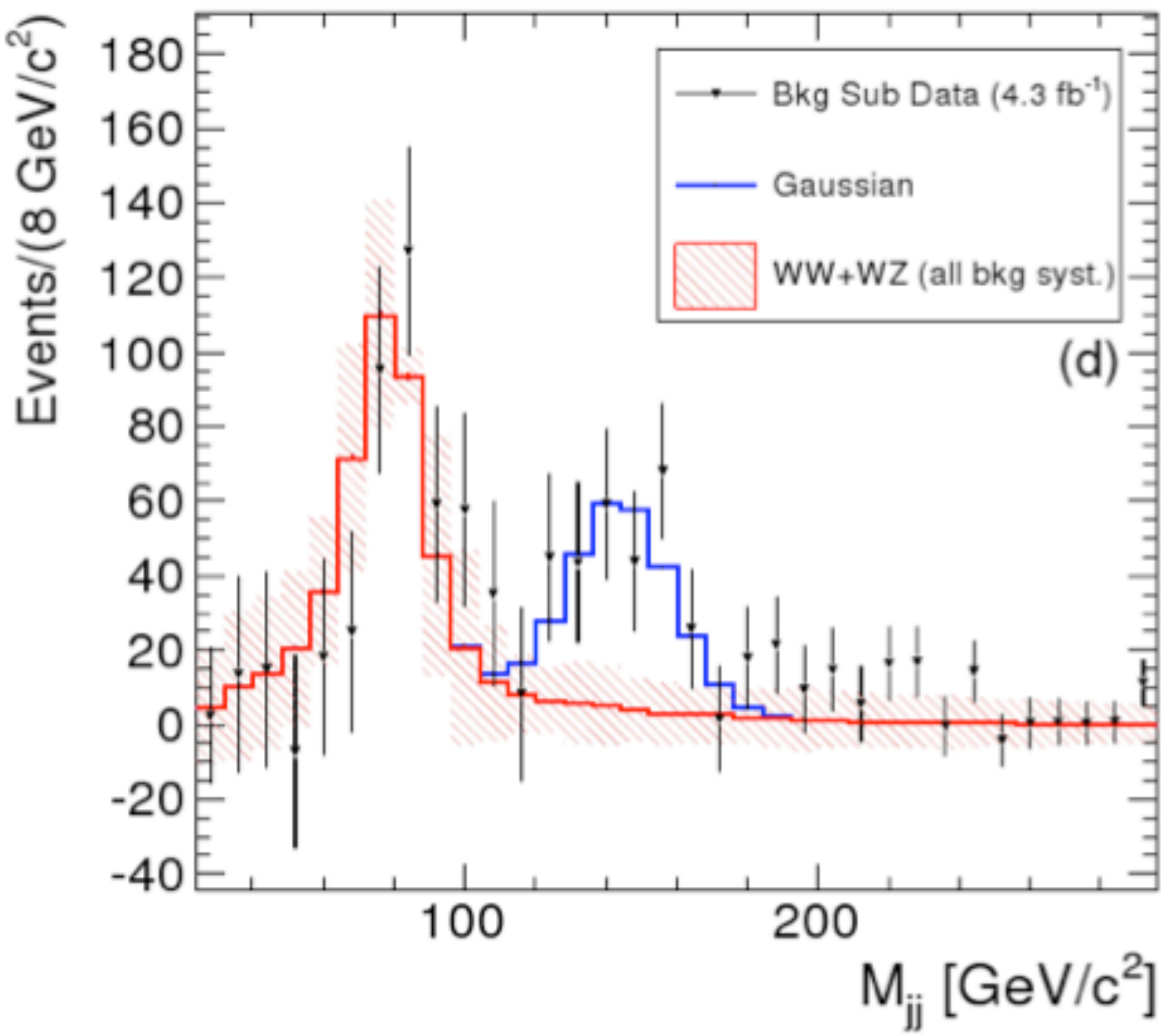
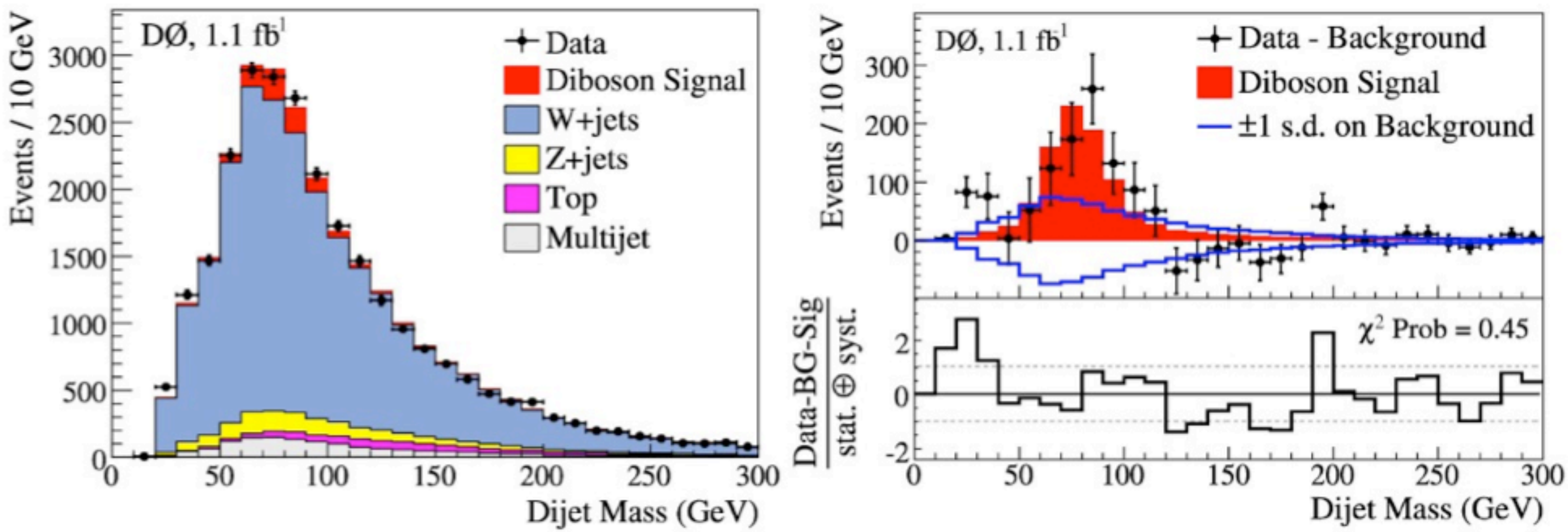
CDF Dijet Mass Excess





arXiv:1104.0699 [hep-ex]

DZero lνqq Measurement



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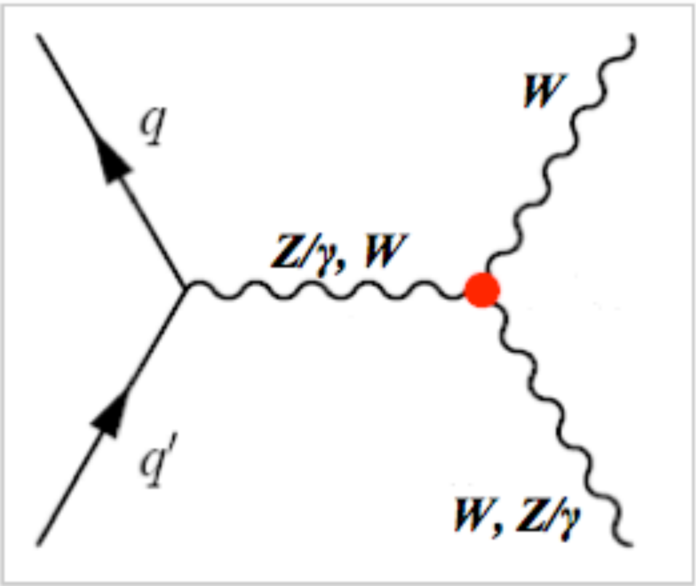
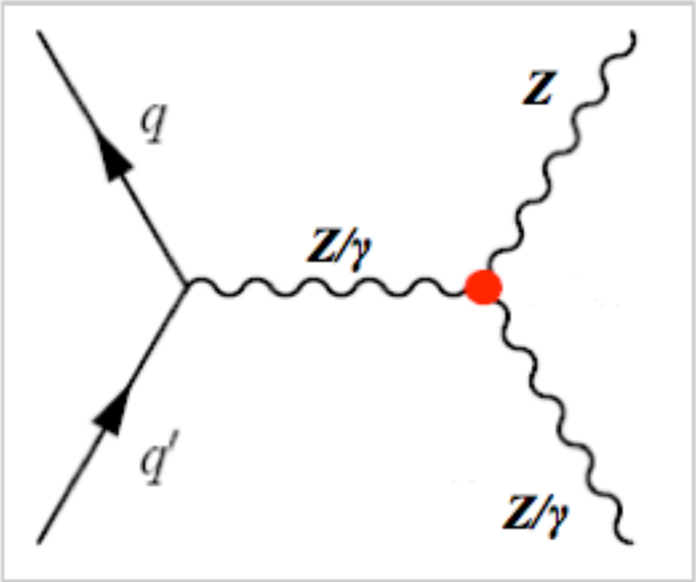
Anomalous Couplings





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

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

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

- 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: $g_4^{Z}, g_4^{Z}, k_{\gamma}, k_{Z}, \lambda_{\gamma}, \lambda_{Z}$

Λ_{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.

Fermilab

Tevatron Facts:
- RunII since 2002
- 36 x 36 bunches
- Average initial luminosity: $>350 \times 10^{30}\ cm^{-2}\ s^{-1}$
- $>50\ pb^{-1}$ per week