Electroweak Measurements from DØ

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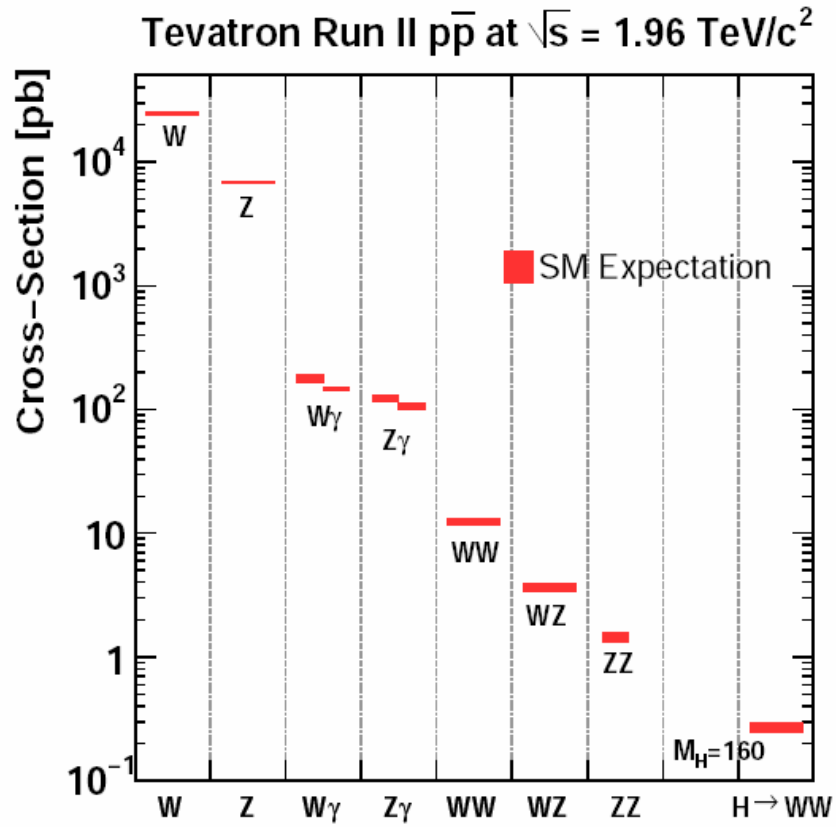
Diboson Physics at the Tevatron

- Measure production cross sections
- Probe gauge boson self-interactions
  - Consequence of non-Abelian nature of $SU(2)_L \otimes U(1)_Y$
  - One of the least tested areas of the SM
- Sensitive to new physics in trilinear gauge couplings (TGC)
  - Tevatron complementary to LEP
  - Explores higher center-of-mass energy than LEP
  - Different combinations of couplings
- Backgrounds to numerous channels:
  - Higgs; SUSY; $t\bar{t}$



note: this is σ, not $\sigma \times BR$

Anomalous Couplings

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

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

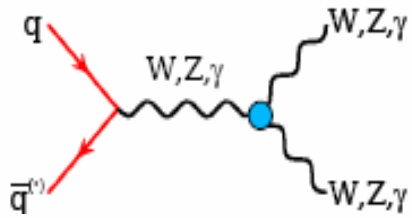
where $V = Z,\ \gamma$

In SM: $g_V^1 = \kappa_V = 1, \quad \lambda_V = 0$

$(\Delta\kappa = \kappa - 1) \qquad (\Delta g^1 = g^1 - 1)$

- Cross section increases especially for High E_T bosons (*W/Z/γ*).
- Unitarity Violation avoided by introducing a form-factor scale Λ, modifying the anomalous coupling at high energy:

$$\lambda(\hat{s}) = \frac{\lambda}{(1+\hat{s}/\Lambda^2)^n}$$ (Not an issue at LEP)



$q\bar{q}' \to W^{(*)}$	$\to W\gamma$:	$WW\gamma$ only
$q\bar{q}' \to W^{(*)}$	$\to WZ$:	WWZ only
$q\bar{q} \to Z/\gamma^{(*)}$	$\to WW$:	$WW\gamma, WWZ$
$q\bar{q} \to Z/\gamma^{(*)}$	$\to Z\gamma$:	$ZZ\gamma, Z\gamma\gamma$
$q\bar{q} \to Z/\gamma^{(*)}$	$\to ZZ$:	$ZZ\gamma, ZZZ$

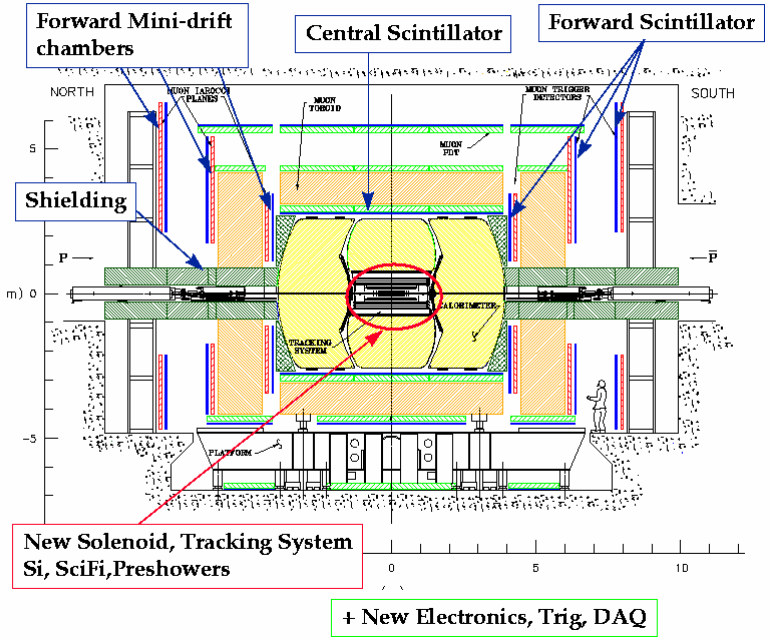
Absent in SM

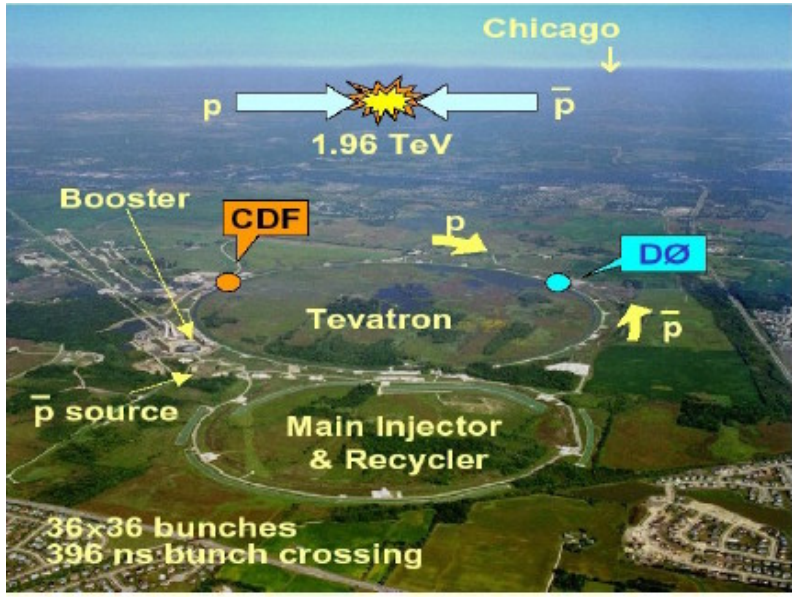
Two types of effective Lagrangians with:

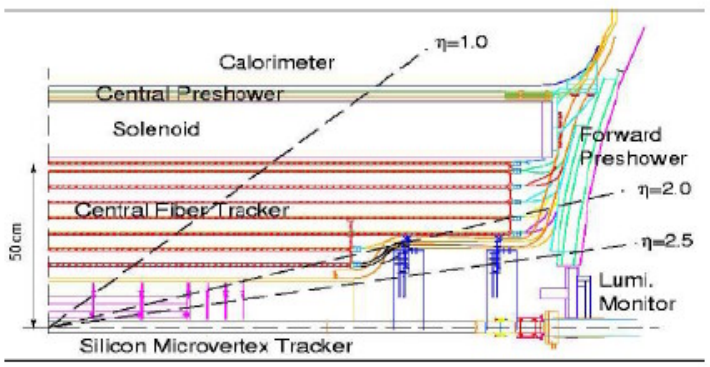
on-shell Zγ ($Z\gamma Z^*, Z\gamma\gamma^*$)		on-shell ZZ ($ZZZ^*, ZZ\gamma^*$)
h_{10}^V, h_{20}^V	(CP violating)	f_{40}^V
h_{30}^V, h_{40}^V	(CP conserving)	f_{50}^V

SM predicts all to be 0

The DØ Detector



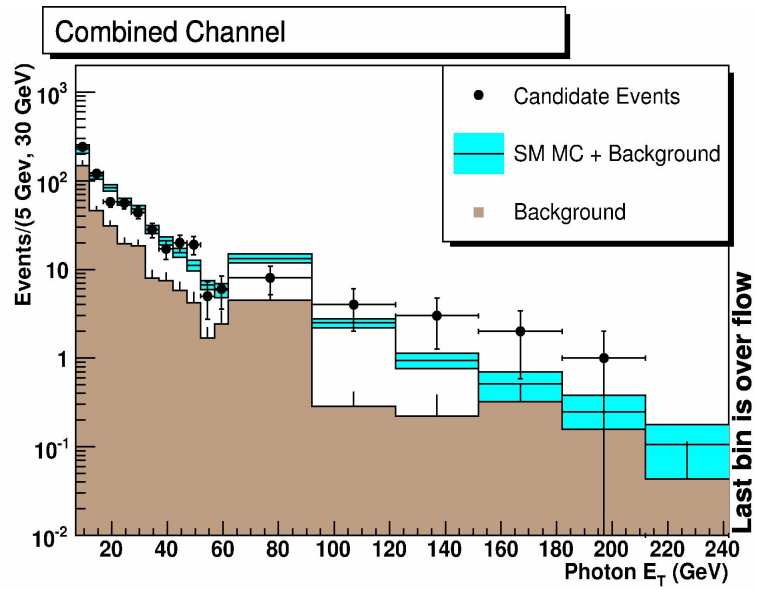




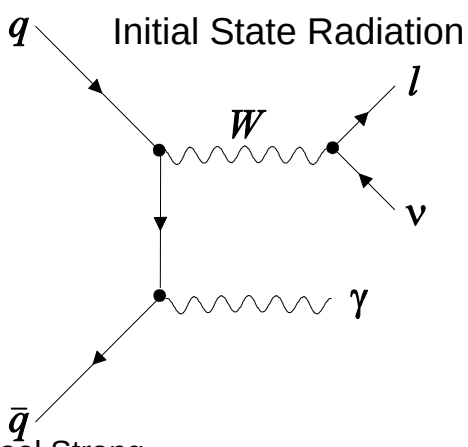
- Silicon micro-strip vertex detector
- Scintillating fiber tracker
- 2 T solenoid magnet
- Uranium Liquid Argon calorimeter
- 1.8 T toroid magnet
- Wire tracking / scintillation counter muon detector
- $|\eta|$ coverage:
  - electrons < 3.2
  - muons < 2.0

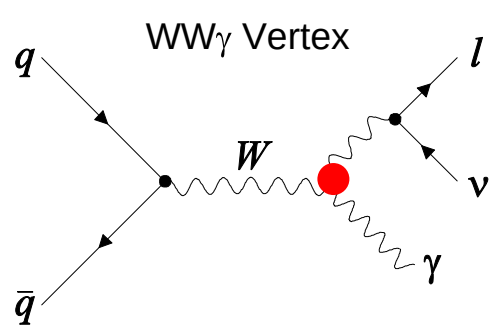
$W\gamma$ Production

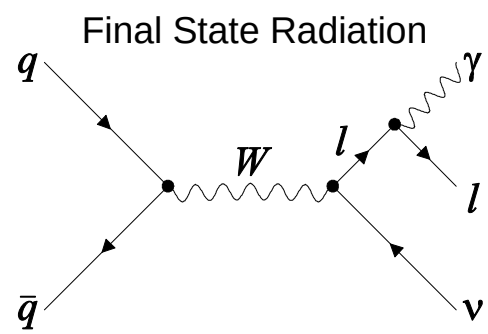
- Deviation from the SM prediction would be sign of new physics
  - Particularly high p_T photons
- Measure $W\gamma \rightarrow l\nu\gamma$ with $E_T^{\gamma} > 7$ GeV, $\Delta R_{l\gamma} > 0.7$, $M_T(l\nu\gamma) > 90$ GeV (reduce FSR) (l is electron or muon)
- Preliminary measured cross sections:
  - Electron: $\sigma \times \mathrm{BR}(W\gamma \rightarrow e\nu\gamma) = 3.12 \pm 0.42$ pb
  - Muon: $\sigma \times \mathrm{BR}(W\gamma \rightarrow \mu\upsilon\gamma) = 3.21 \pm 0.52$ pb
  - Theory: $\sigma \times \mathrm{BR}(W\gamma \rightarrow l\nu\gamma) = 3.21 \pm 0.08$ pb
- Sensitive to $WW\gamma$ coupling



Preliminary Results

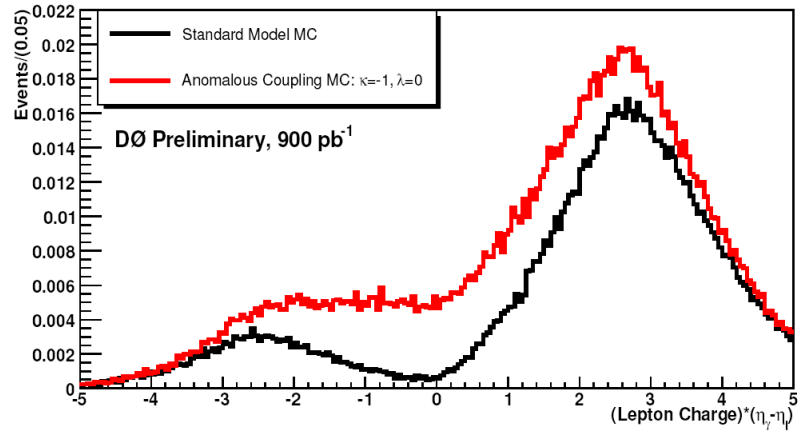




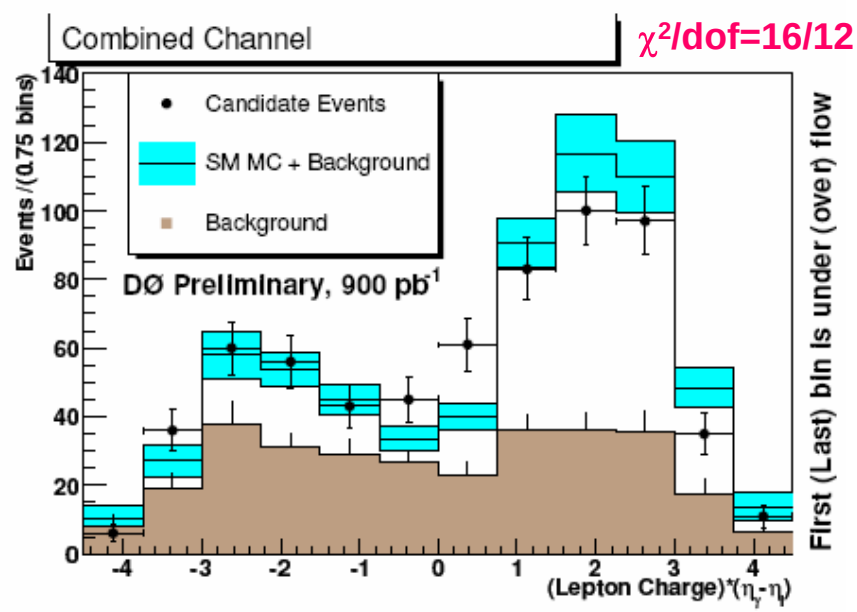


$W\gamma$: Radiation Amplitude Zero

- Radiation amplitude zero: caused by the interference among the tree-level diagrams at $\cos(\theta^*) = \pm 1/3$
  - θ^* is the angle between the W and the direction of the incoming quark
- Can't measure θ^* directly because of ν in final state
- Can measure charge-sign photon-lepton rapidity difference $Q \times [\eta(\gamma) - \eta(l)]$
- Anomalous coupling may fill dip

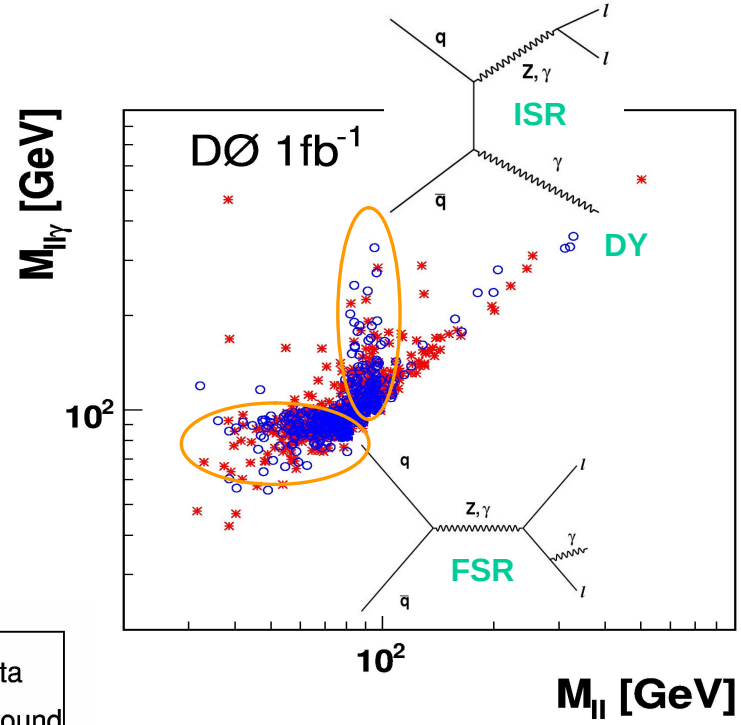


- Use of Dip Test of Unimodality gives the probability of the dip in the 80-90% range
- Measurement constitutes first indication for radiation-amplitude zero in $W\gamma$

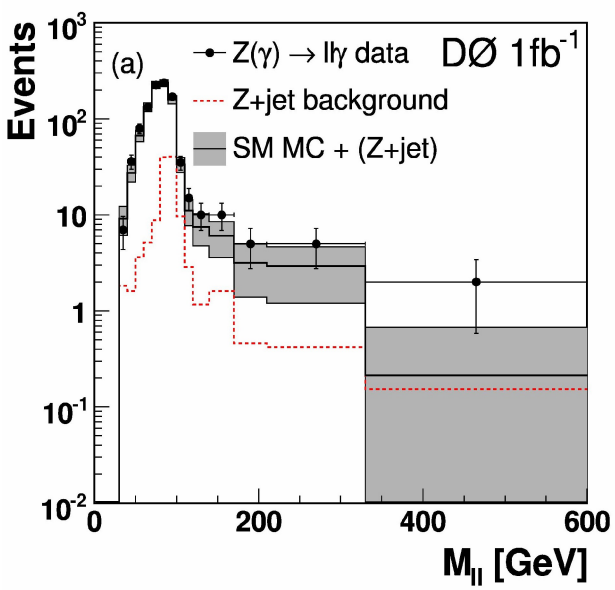


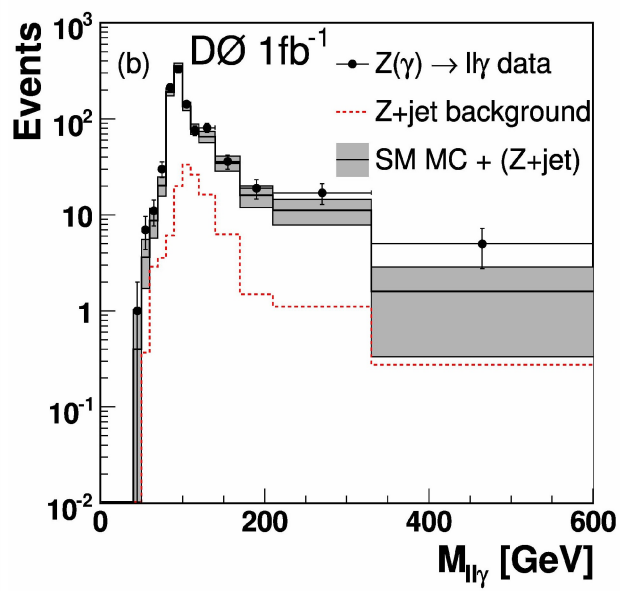
$Z\gamma$ Production

- Measure $Z\gamma \rightarrow ll\gamma$ with $E_T^{\gamma} > 7$ GeV, $\Delta R_{l\gamma} > 0.7$, $M(ll) > 30$ GeV (l is electron or muon)
- Observe 968 candidates (combined) with 116 ± 13 background
- Cross section:
  - Measured $\sigma \times \mathrm{BR}(Z\gamma \rightarrow ll\gamma) = 4.96 \pm 0.42$ pb
  - Theory $\sigma \times \mathrm{BR}(Z\gamma \rightarrow ll\gamma) = 4.74 \pm 0.22$ pb



PLB 653, 378 (2007)





Most precise cross section measurement of this channel at a hadron collider

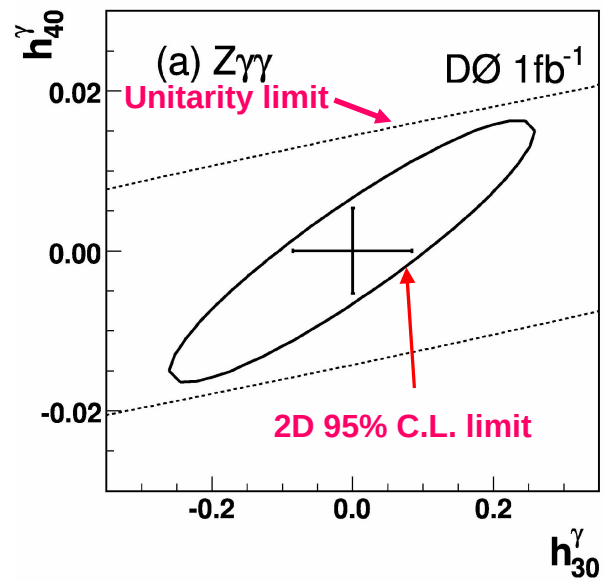
Limits on anomalous $Z\gamma Z^*$ and $Z\gamma\gamma^*$ couplings

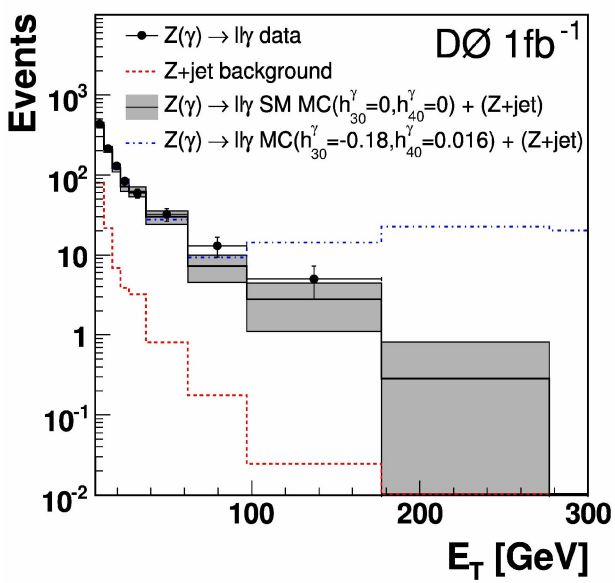
- $Z\gamma$ sensitive to two couplings
  - Various SM extensions predict large values of the trilinear couplings of $ZZ\gamma$ and $Z\gamma\gamma$
- Use photon E_T spectrum to probe anomalous couplings for Λ = 1.2 TeV. 95% C.L. limits:

$$-0.085 < h_{30}^{\gamma} < 0.084, \quad -0.0053 < h_{40}^{\gamma} < 0.0054$$

$$-0.083 < h_{30}^{Z} < 0.082, \quad -0.0053 < h_{40}^{Z} < 0.0054$$

- New limits represent a significant improvement over previous results. The limits on h_{40}^{V} are the most stringent to date





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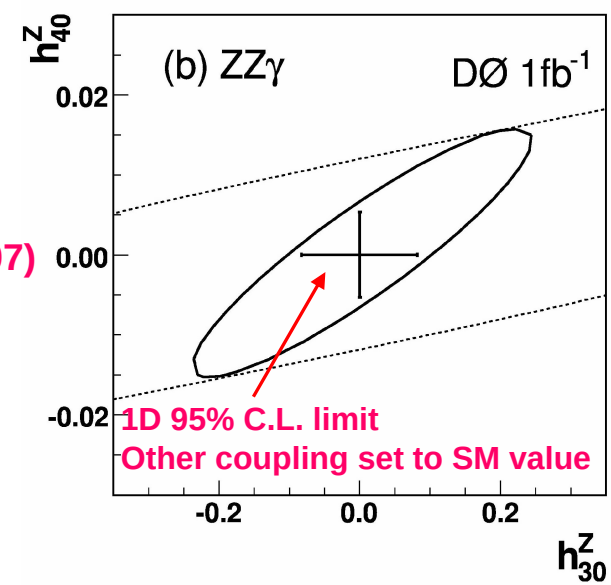
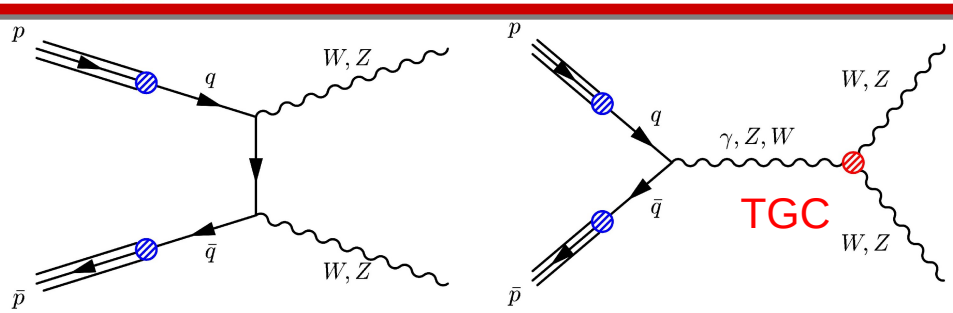
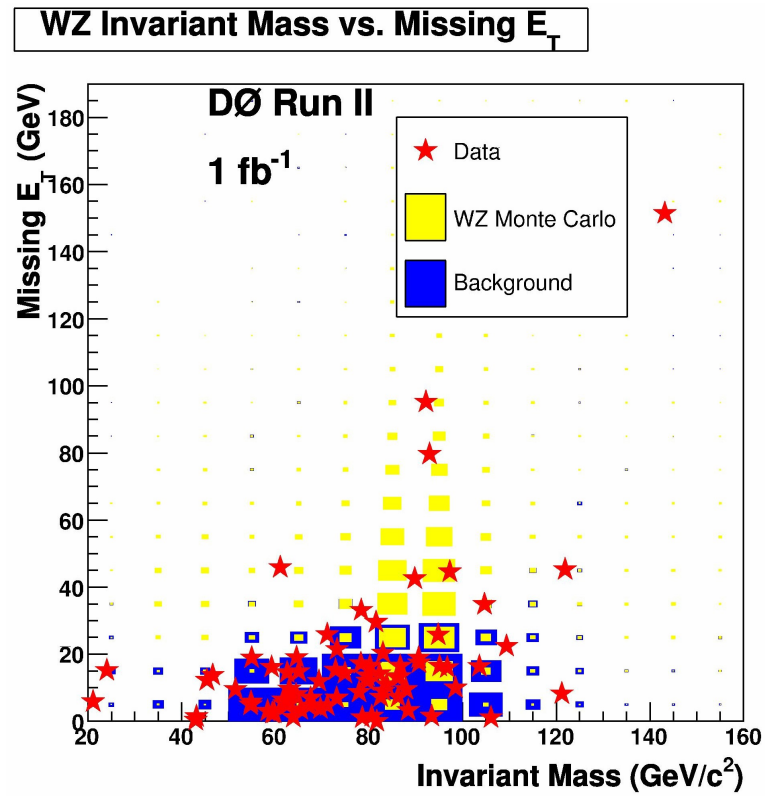


WZ Production





PRD 76, 111104(R) (2007)

- Analysis performed in four channels:
  - *eee / eeμ / μμe / μμμ* plus missing energy
  - Cross section is calculated by combining likelihoods from each channel with candidates determined by:
    - Z→ee mass in range 71-111 GeV
    - Z→μμ mass range 50-130 GeV
    - Missing Et > 20 GeV
- Results:
  - Observe 13 candidate events
    - Expected background of 4.5 ± 0.6
    - SM predicts 9.2 ± 1.0
  - Probability of expected background to fluctuate to 13 events is 1.2×10^{-3}
    - significance of 3.0σ
  - Measured cross section of $\sigma(WZ) = 2.7^{+1.7}_{-1.3}$ pb
    - Theory predicts $\sigma(WZ) = 3.68 \pm 0.35$ pb

Limits on anomalous *WWZ* couplings

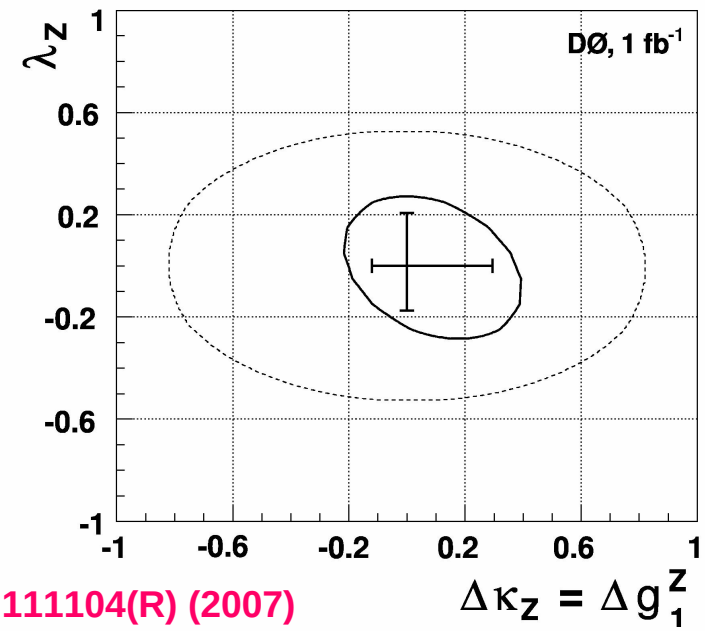
- Use the measured cross section and Z p_T distribution to probe anomalous couplings for Λ = 2 TeV. 95% C.L. limits are:

$$-0.17 < \lambda_Z < 0.21 \;\; (\Delta\kappa_Z = 0)$$

  - Assuming $\Delta g_1^Z = \Delta\kappa_Z$:

$$-0.12 < \Delta\kappa_Z < 0.29 \;\; (\lambda_Z = 0)$$

- These are most restrictive limits to date



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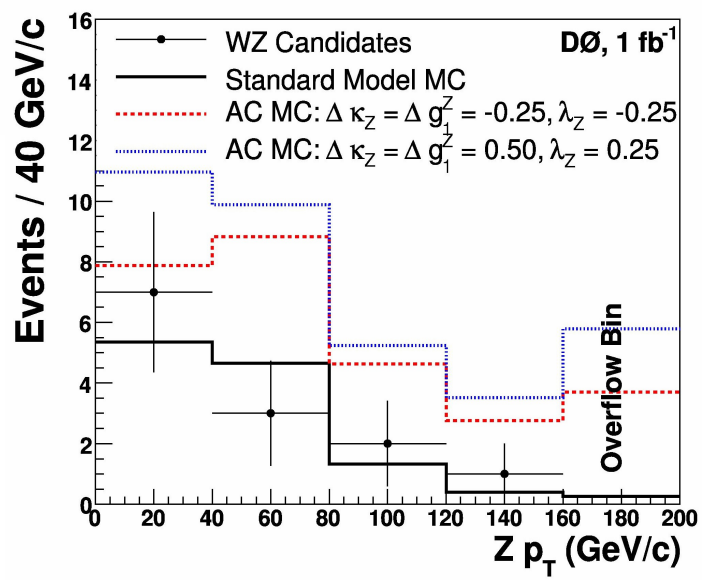
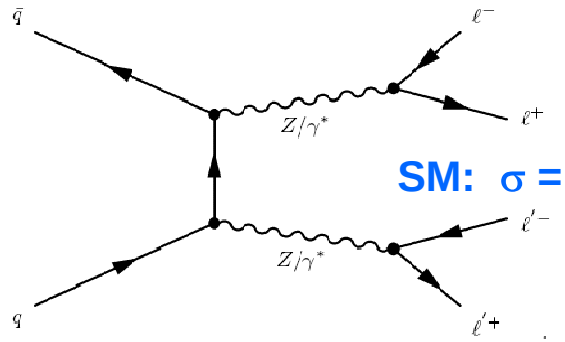


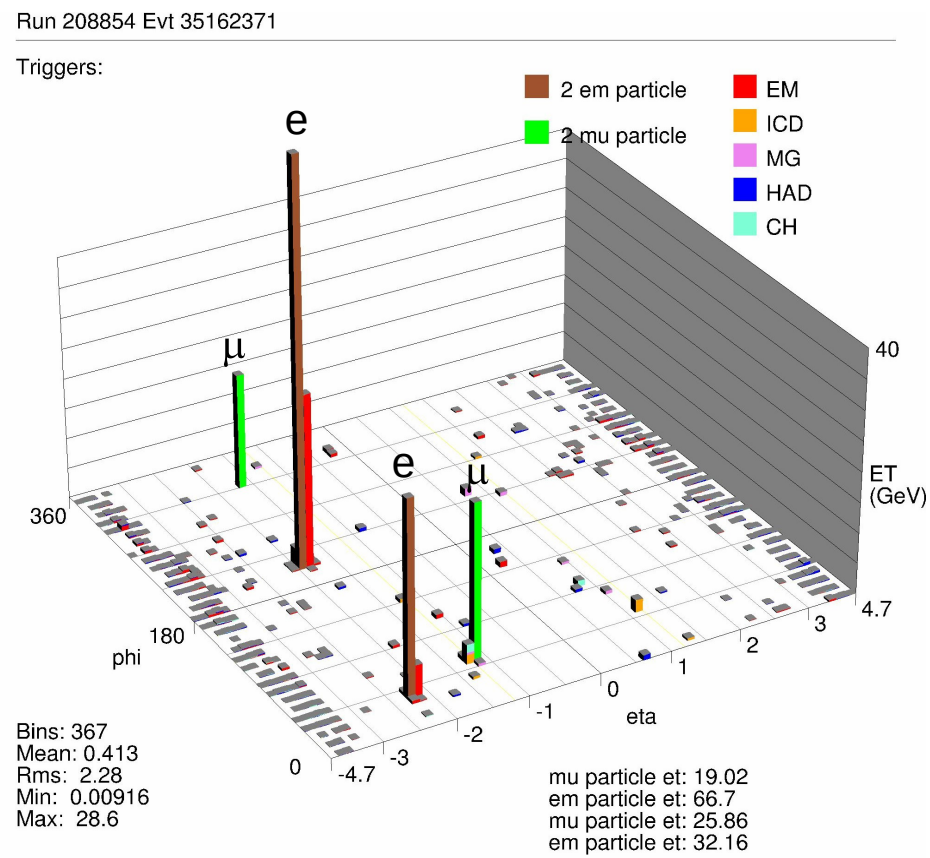
ZZ Production

- No self coupling of Z bosons in SM
- t-channel production:



SM: $\sigma = 1.6 \pm 0.1$ pb

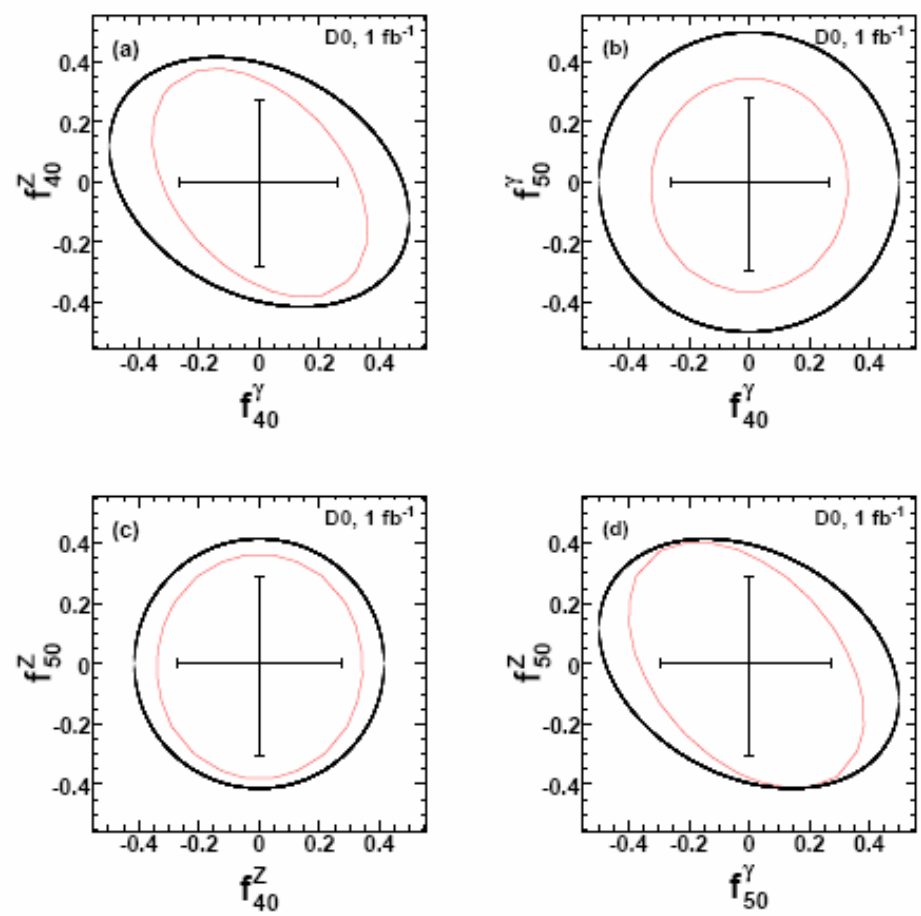
- ZZ → electons and muons
  - Cross section drops to 7.2 fb
- Observe one $ee\mu\mu$ candidate in 1 fb^{-1} of data
  - Expected background of 0.13 ± 0.03 events
  - SM predicts 1.71 ± 0.15 events
- Set upper limit of $\sigma(ZZ/Z\gamma^*) < 4.4$ pb at 95% CL



Submitted to PRL arXiv: 0712.0599

Limits on anomalous ZZZ^* and $ZZ\gamma^*$ couplings

- ZZ channel sensitive to two couplings
- 95% CL limits on anomalous couplings for Λ = 1.2 TeV
  - $-0.28 < f_{40}^{Z} < 0.28$
  - $-0.31 < f_{50}^{Z} < 0.29$
  - $-0.26 < f_{40}^{\gamma} < 0.26$
  - $-0.30 < f_{50}^{\gamma} < 0.28$
- First bounds on these limits from Tevatron
- f_{40}^{Z}, f_{50}^{Z}, f_{50}^{γ} are most restrictive to date



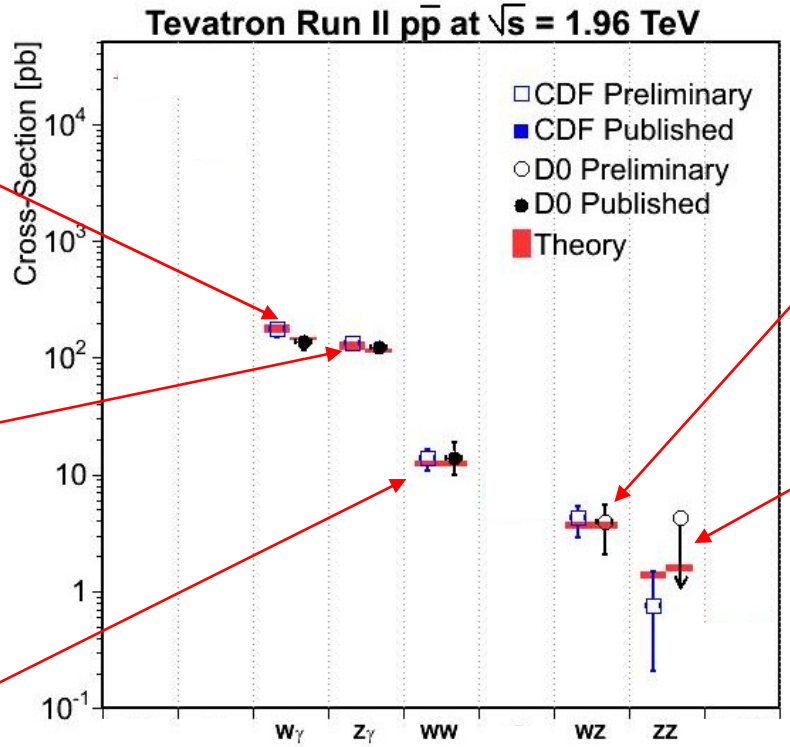
Submitted to PRL arXiv: 0712.0599

Summary

Wγ
Preliminary cross section
Indication of radiation amplitude zero

Zγ
Cross section measured
Limits on ZZγ and Zγγ couplings

WW
Cross section measured
PRL 94, 151801 (2005)



WZ
First observation
Limits on WWZ couplings

ZZ
Cross section limit
Limits on ZZZ and ZZγ* couplings

- Initial results with Tevatron Run II data
- Newer results with up to 3 times the data and refined analyses coming soon