Di-boson production and limits on triple gauge boson couplings at the Tevatron

ICHEP, July 2010

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For the CDF & D0 Collaborations

Standard Model Dibosons

Diboson Final State

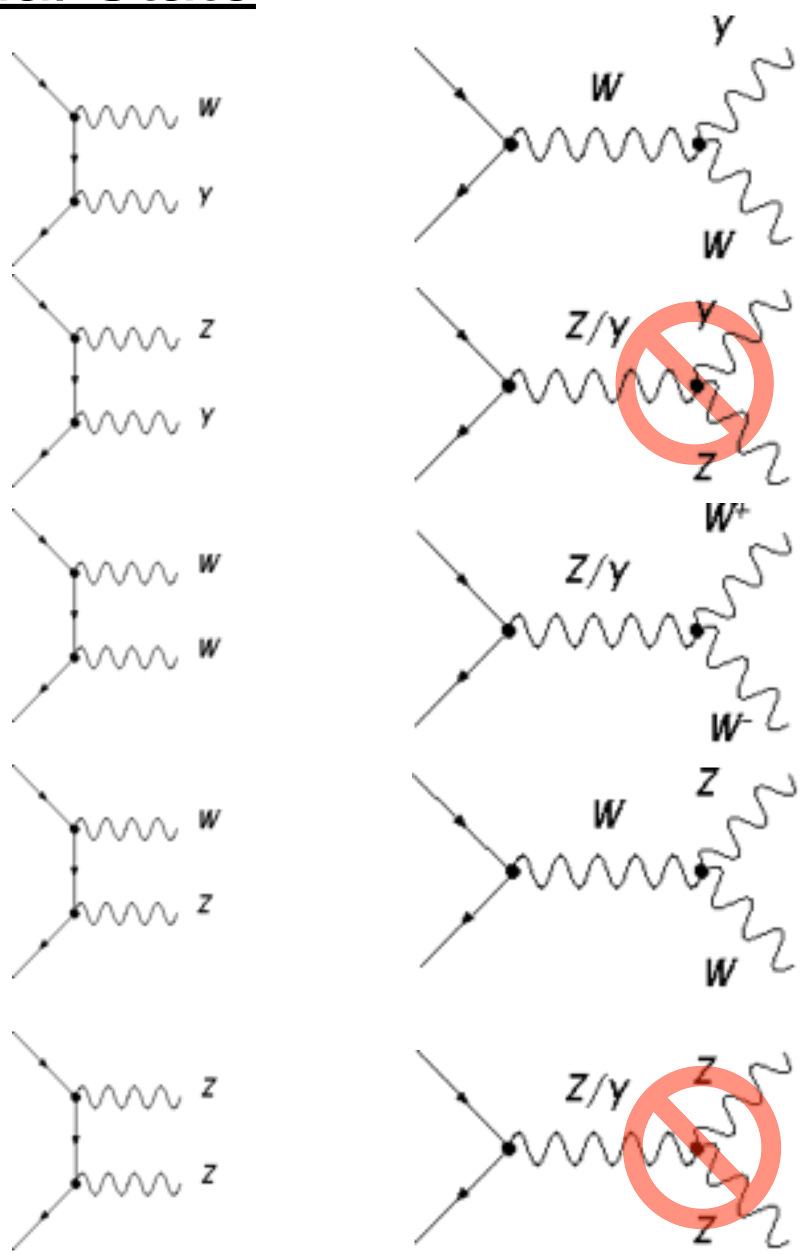
Wγ

Zγ

WW

WZ

ZZ



SM Tests:

1) Test SM production predictions
2) Look for "anomalous couplings"
   Sensitive to compositeness, new particles,...

Triple Gauge Couplings

Standard Model

Anomalous

Standard Model Dibosons

Diboson Final State

Wγ

Zγ

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WZ

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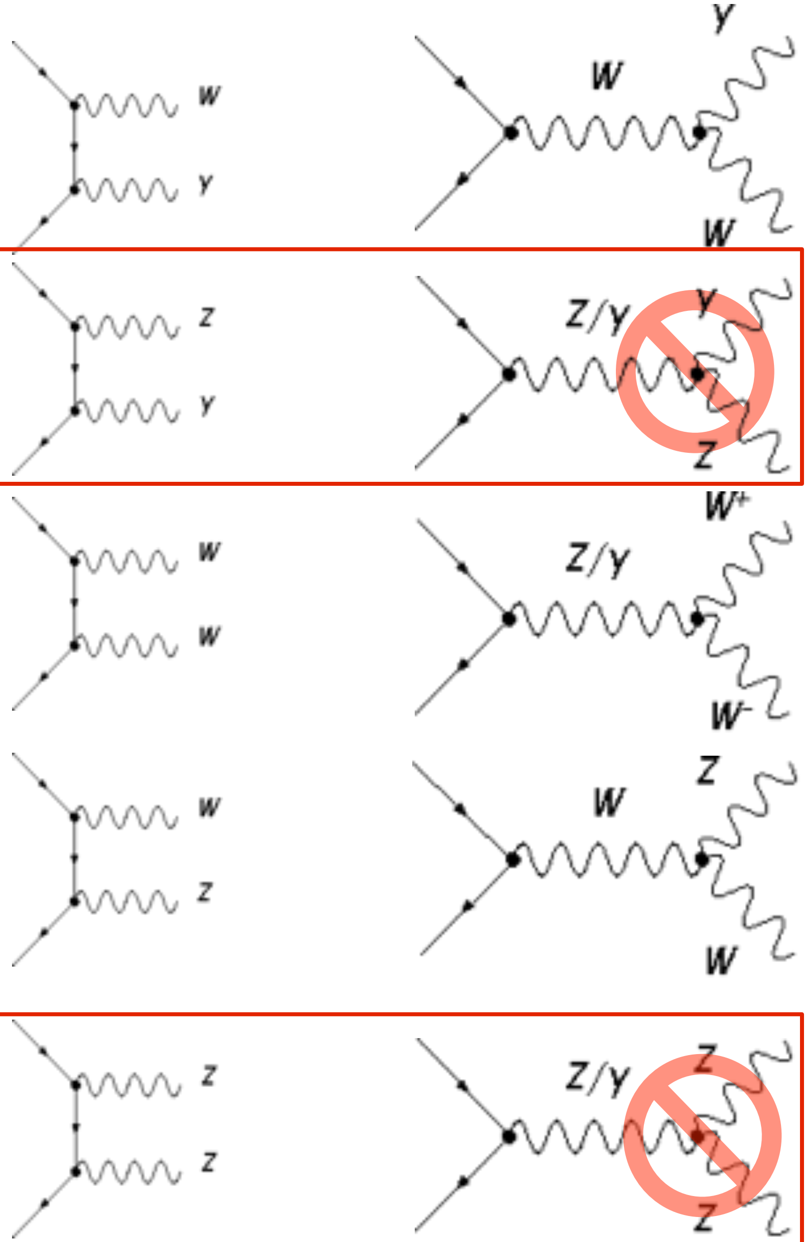

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Triple Gauge Couplings

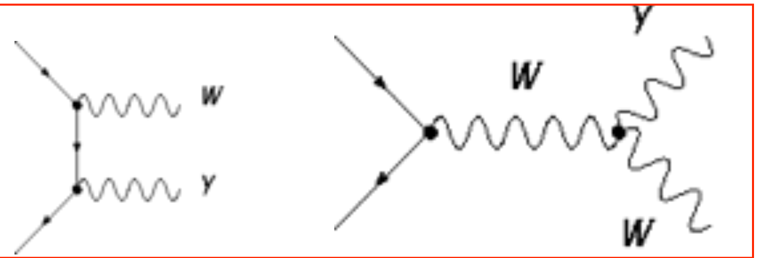
Standard Model

Anomalous

Wγ Production

Diboson Final State

Wγ



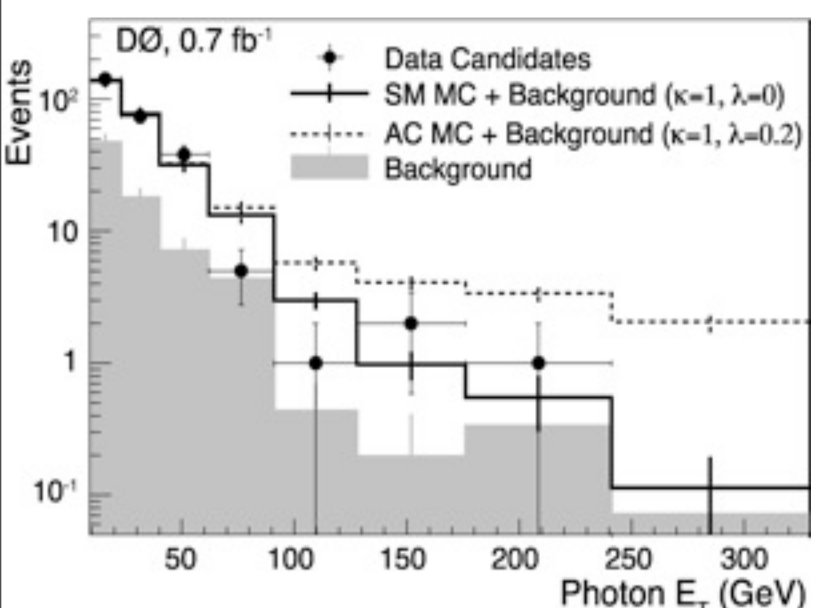
Look for "anomalous couplings"

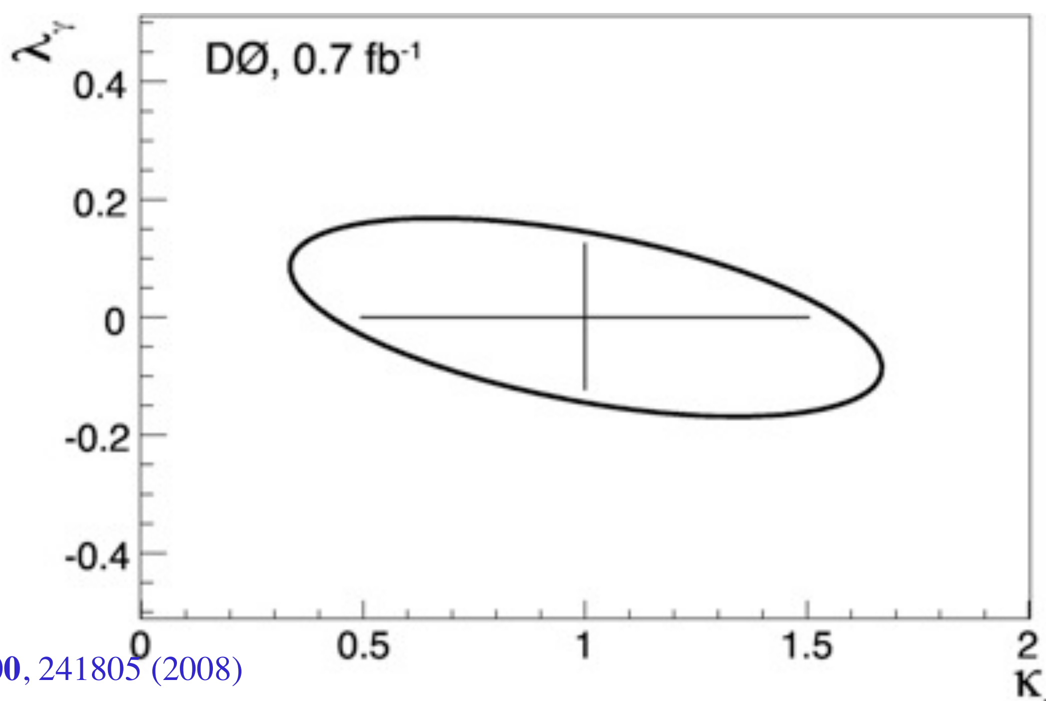
- CP-conserving effective Lagrangian parameters: K_γ and λ_γ
- $\Delta K_\gamma = 1 - K_\gamma = 0$ & $\lambda_\gamma = 0$ in SM
  - $0.49 < K_\gamma < 1.51$ (D0)
  - $-0.12 < \lambda_\gamma < 0.13$ (D0)

SM Tests:

Test SM production predictions

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





PRL **100**, 241805 (2008)

Wγ Production

Radiation amplitude 0

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

PRL 43, 746(1979)

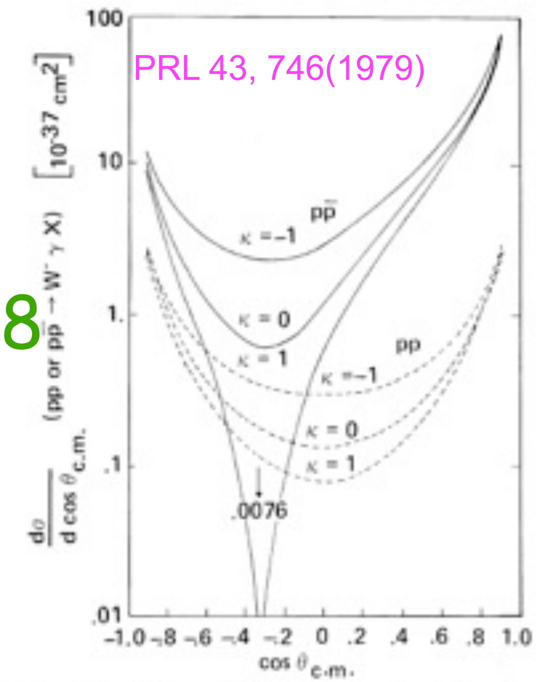
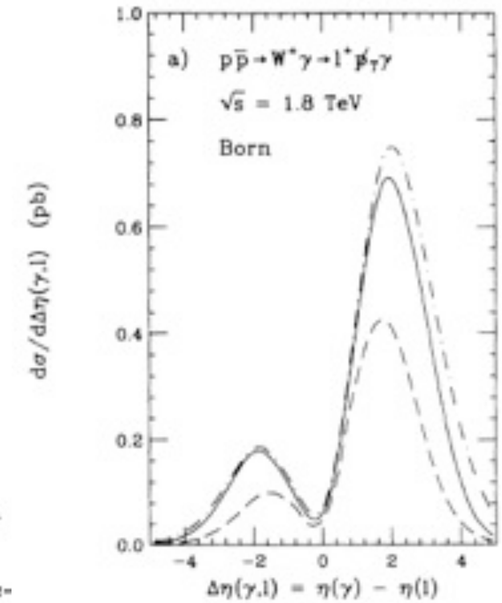


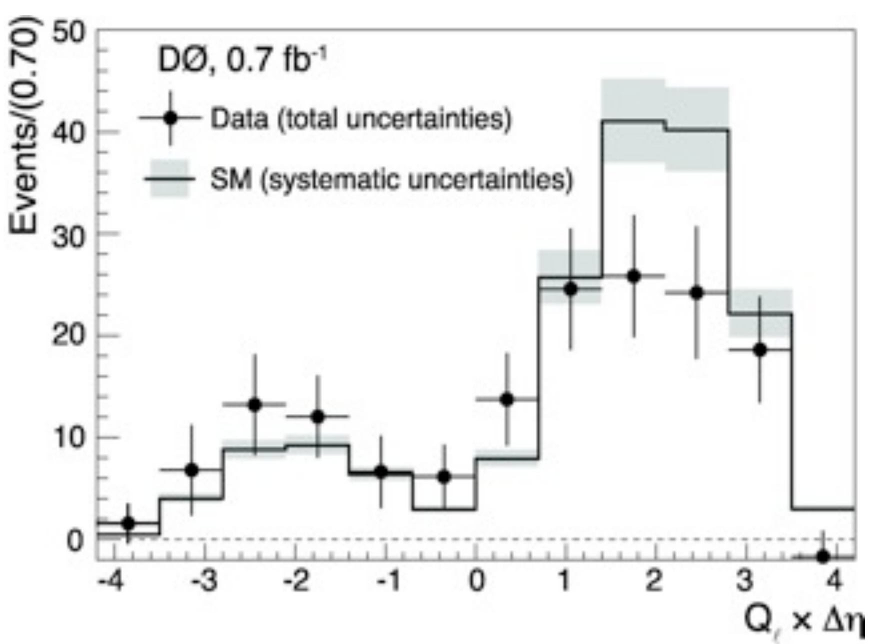
FIG. 3. The differential cross section for $pp \to W^{-}\gamma X$ and $p\bar{p} \to W^{-}\gamma X$, with a photon energy cut $E_\gamma > 30$ GeV. $\theta_{c.m.}$ is the angle between the W^- and the proton direction in the $W^-\gamma$ c.m. frame. $\sqrt{S} = 540$ GeV and $M_W = 85$ GeV/c^2.

PRD 50, 1917(1994)



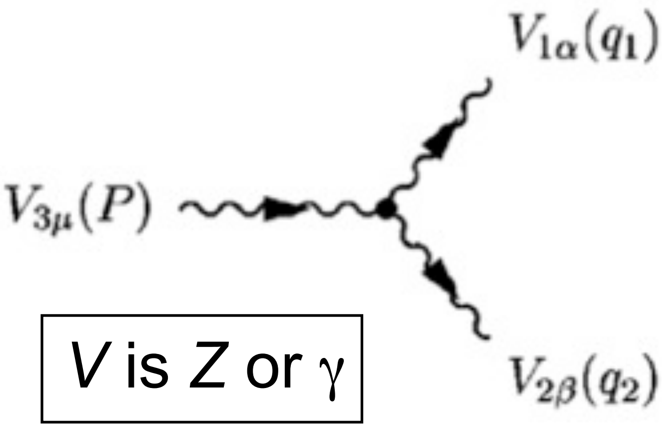
$$p_T(\gamma) > 5 \text{ GeV}, \quad |\eta(\gamma)| < 3,$$
$$p_T(\ell) > 20 \text{ GeV}, \quad |\eta(\ell)| < 3.5,$$
$$\not{p}_T > 20 \text{ GeV}, \quad \Delta R(\gamma,\ell) > 0.7.$$

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



PRL **100**, 241805

Generalized Zγ Couplings



$$= ie\,\Gamma^{\alpha,\beta,\mu}_{V_1V_2V_3}(q_1,q_2,P)$$

V is *Z* or γ

Form factor Λ:

$$h_i^V(\hat{s}) = \frac{h_{i0}^V}{(1+\frac{\hat{s}}{\Lambda})^n}$$

Parameterization from G.J. Gounaris *et al.* PRD 62, 073012.

$$\Gamma^{\alpha\beta\mu}_{Z\gamma V}(q_1,q_2,P) = \frac{i(s-m_V^2)}{m_Z^2}\{h_1^V(q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}) + \frac{h_2^V}{m_Z^2}P^\alpha[(Pq_2)g^{\mu\beta} - q_2^\mu P^\beta]$$
$$-h_3^V\epsilon^{\mu\alpha\beta\rho}q_{2\rho} - \frac{h_4^V}{m_Z^2}P^\alpha\epsilon^{\mu\beta\rho\sigma}P_\rho q_{2\sigma}\},$$

- CP Violating:
  - ➔ h_1^V and h_2^V
- CP Conserving:
  - ➔ h_3^V and h_4^V

Physical Quantities

Z dipole moments:

$$\mu_Z = \frac{-e}{\sqrt{2}m_Z}\frac{E_\gamma^2}{m_Z^2}(h_1^Z - h_2^Z)$$

$$d_Z = \frac{-e}{\sqrt{2}m_Z}\frac{E_\gamma^2}{m_Z^2}(h_3^Z - h_4^Z)$$

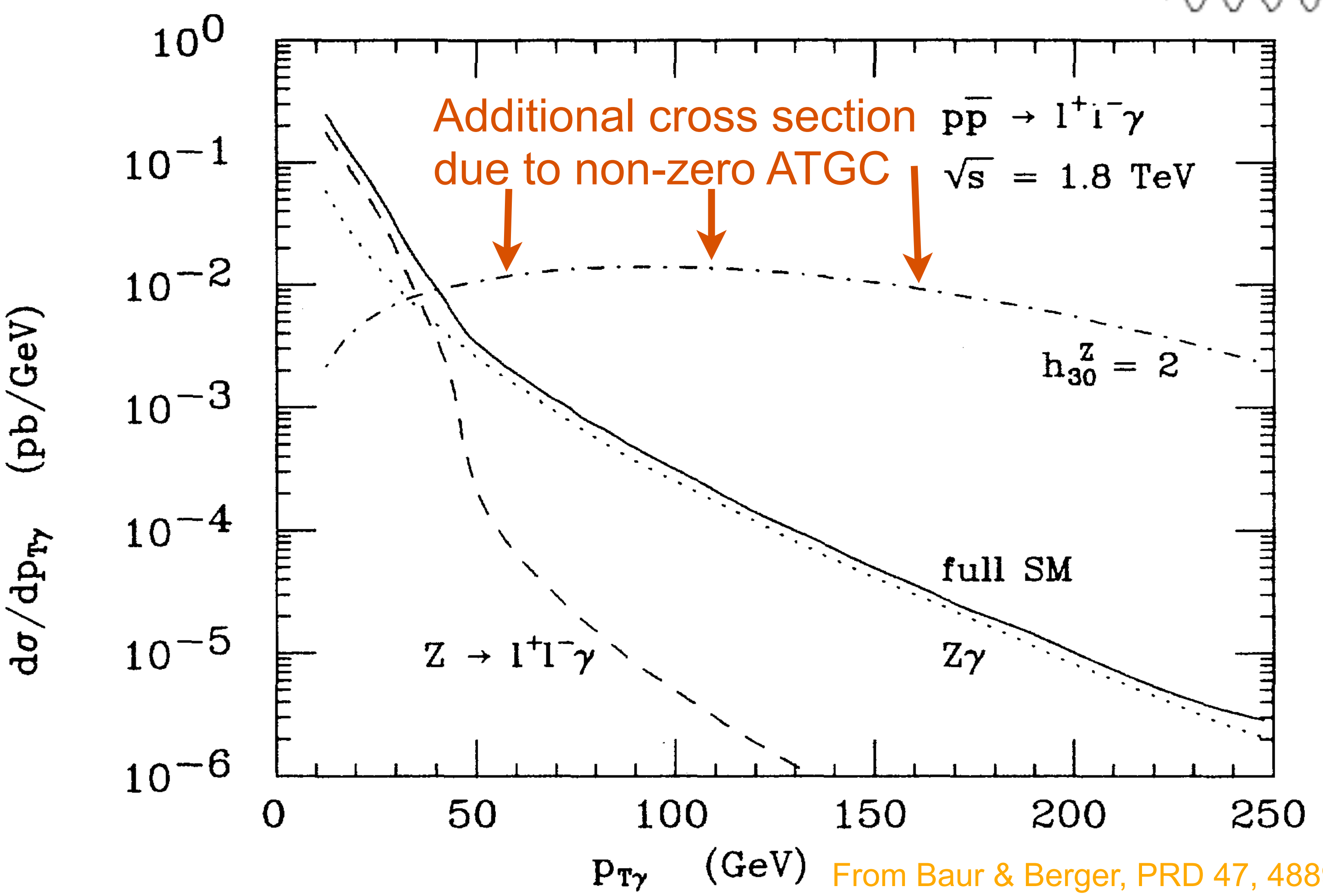
Z quadrupole moments:

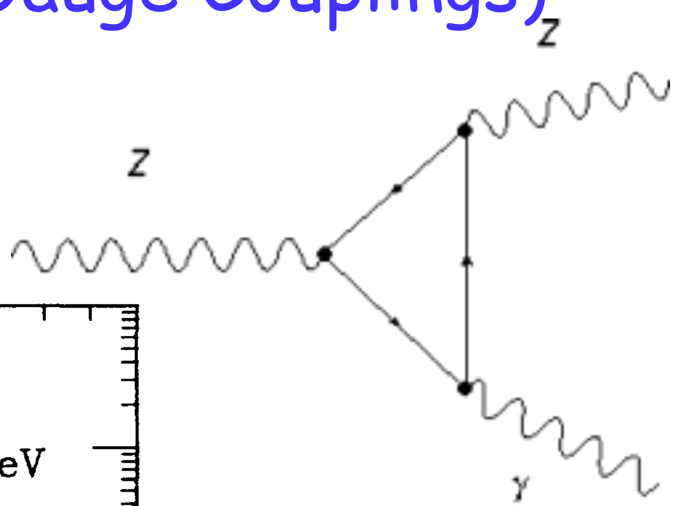
$$Q_Z^e = \frac{2\sqrt{10}e}{m_Z^2}h_1^Z$$

$$Q_Z^m = \frac{2\sqrt{10}e}{m_Z^2}h_3^Z$$

Anomalous Couplings

- Non-zero ATGC (Anomalous Triple-Gauge Couplings)
  - ➔ increase $Z\gamma$ cross section
  - ➔ stiffen $E_{T\gamma}$ distribution

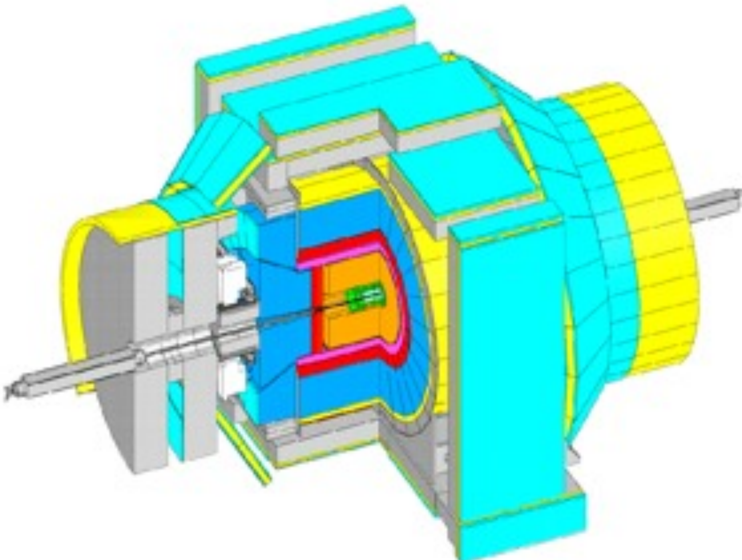




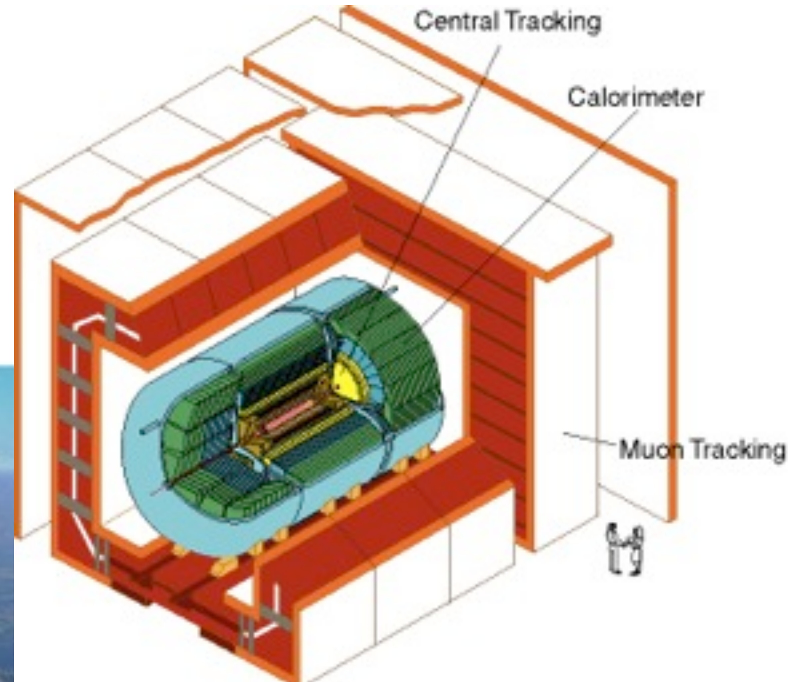
Anomalous Coupling due to a new particle

From Baur & Berger, PRD 47, 4889 (1993).

Tevatron Experiments



CDF



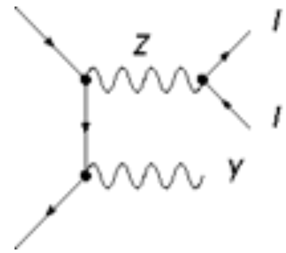
D0

$Z\gamma$ Production

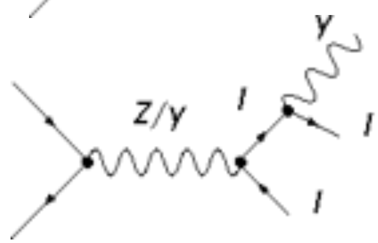
- Search for $Z\gamma$ with $Z \to e^+e^-$, $\mu^+\mu^-$, $\nu\bar{\nu}$
- SM $Z\gamma$ production:
  - ➔ Initial-state radiation (ISR)
  - ➔ Final-state radiation (FSR)
- No direct Z-γ coupling in Standard Model
  - ➔ Anomalous coupling produce excess events at high $E_{T\gamma}$

$l^+l^-\gamma$: Low backgrounds

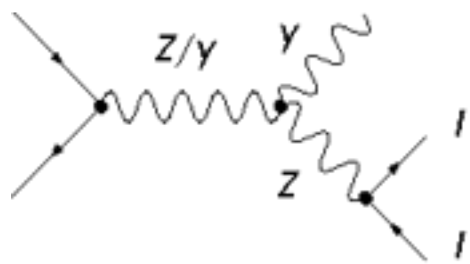
$\nu\bar{\nu}\gamma$: higher branching fraction



ISR ($M_{ll} \sim M_Z$)



FSR ($M_{ll\gamma} \sim M_Z$)

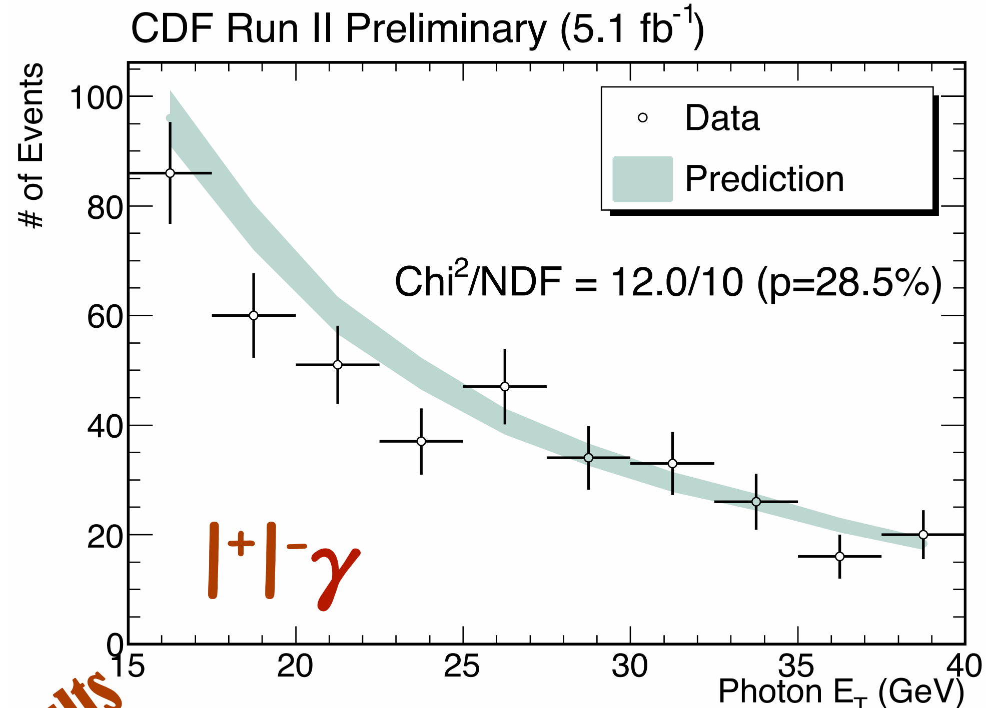


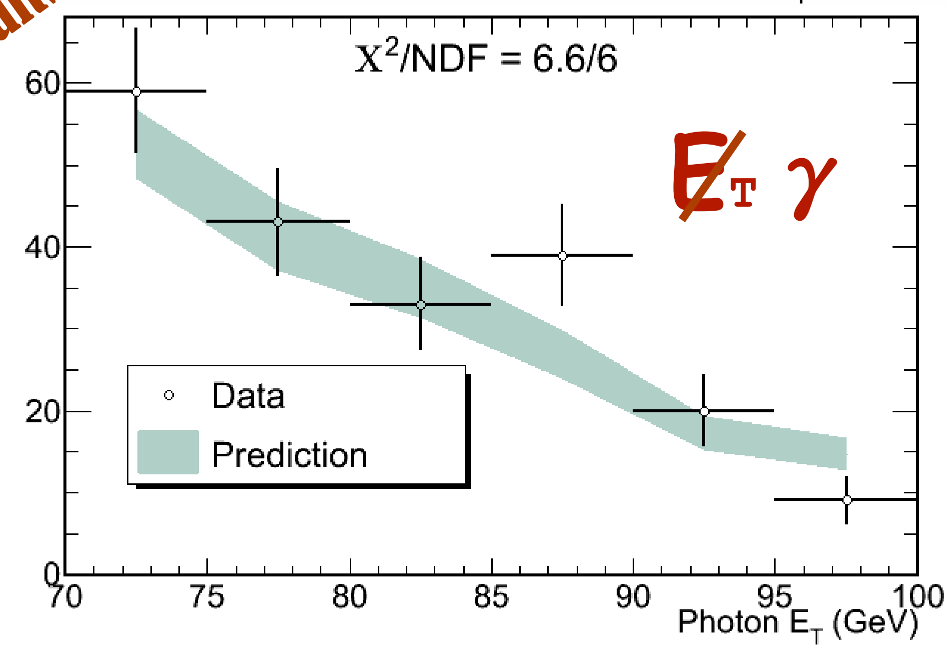
Anomalous Coupling ($M_{ll} \sim M_Z$)

Zγ Analysis

- Select Z-> l^+l^-
  - ➔ Standard lepton selection
    - $Et_1 > 20$ GeV, $Et_2 > 10$ GeV
  - ➔ $76 < M_{ll} < 106$ GeV/c^2
  - ➔ then look for standard γ
- Select $Z\gamma \to \nu\nu\gamma$
  - ➔ γ ; $\not{E}_T > 50$ GeV
  - ➔ no jets or high-Et tracks
- Anomalous Couplings produce excess high-Et γ
  - ➔ use low-Et photons for control regions
  - ➔ look for ATGC in high-Et γ

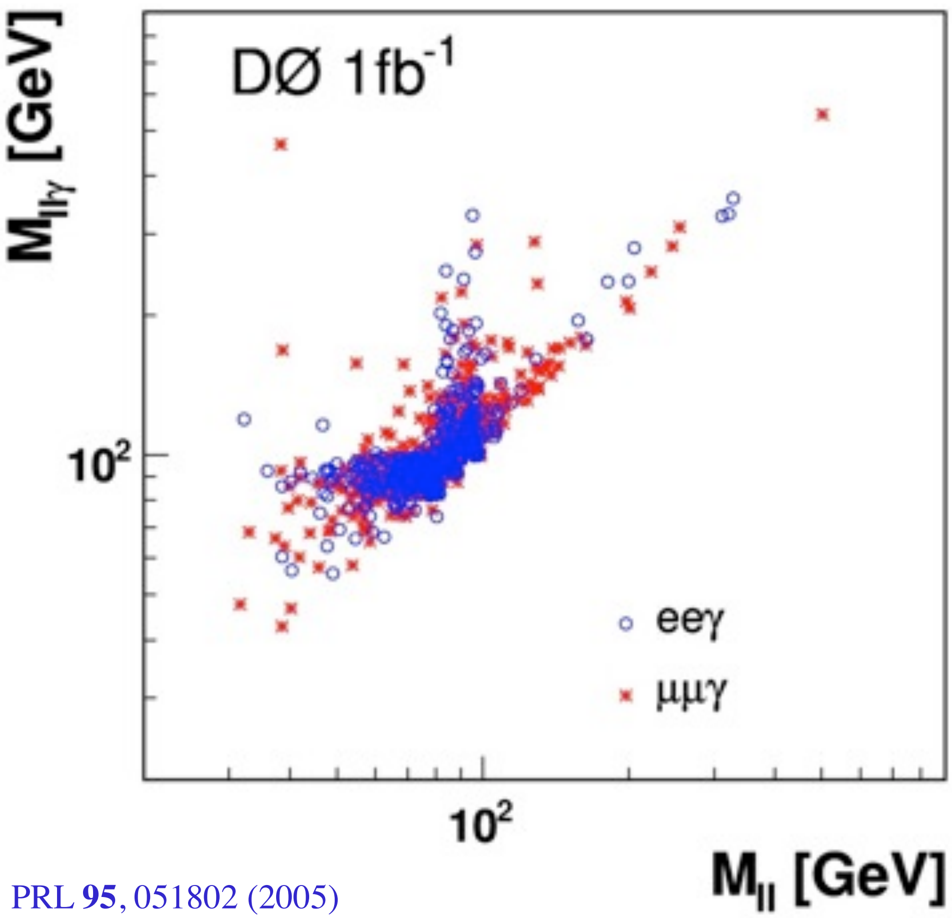
New Results





$Z\gamma$ Invariant Mass

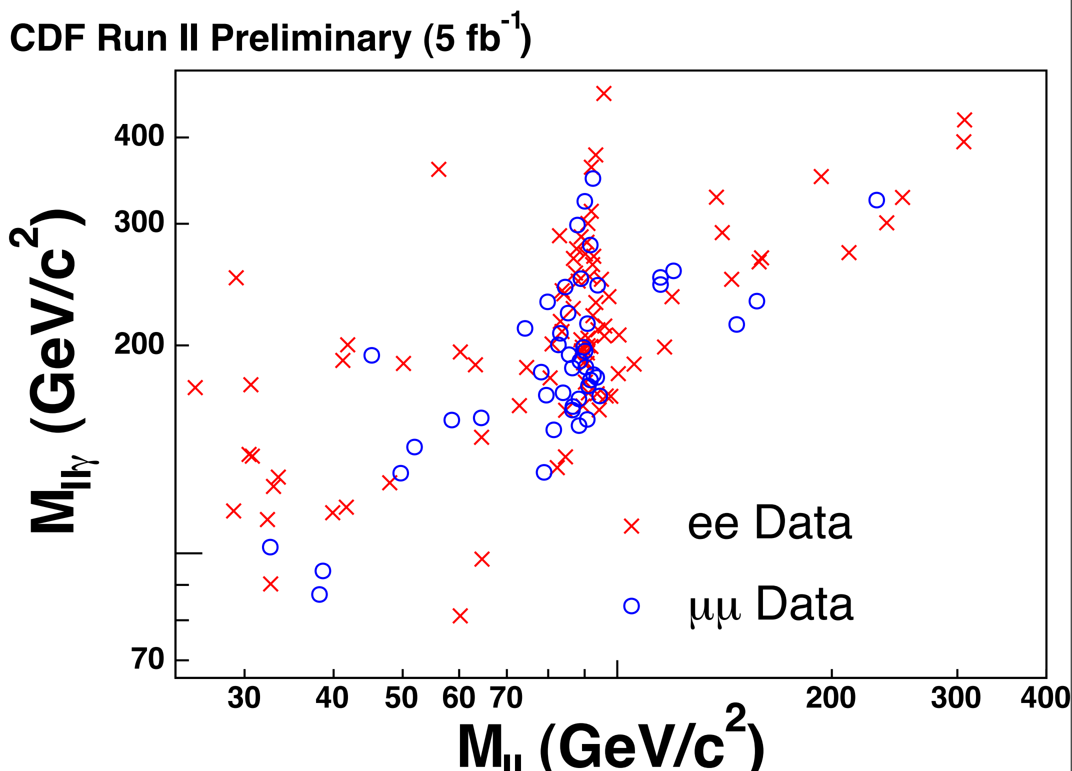
$E_{T\gamma}$ > 7 GeV
ISR (M_{ll}~M_Z) &
FSR ($M_{ll\gamma}$~M_Z) Clearly visible



PRL **95**, 051802 (2005)

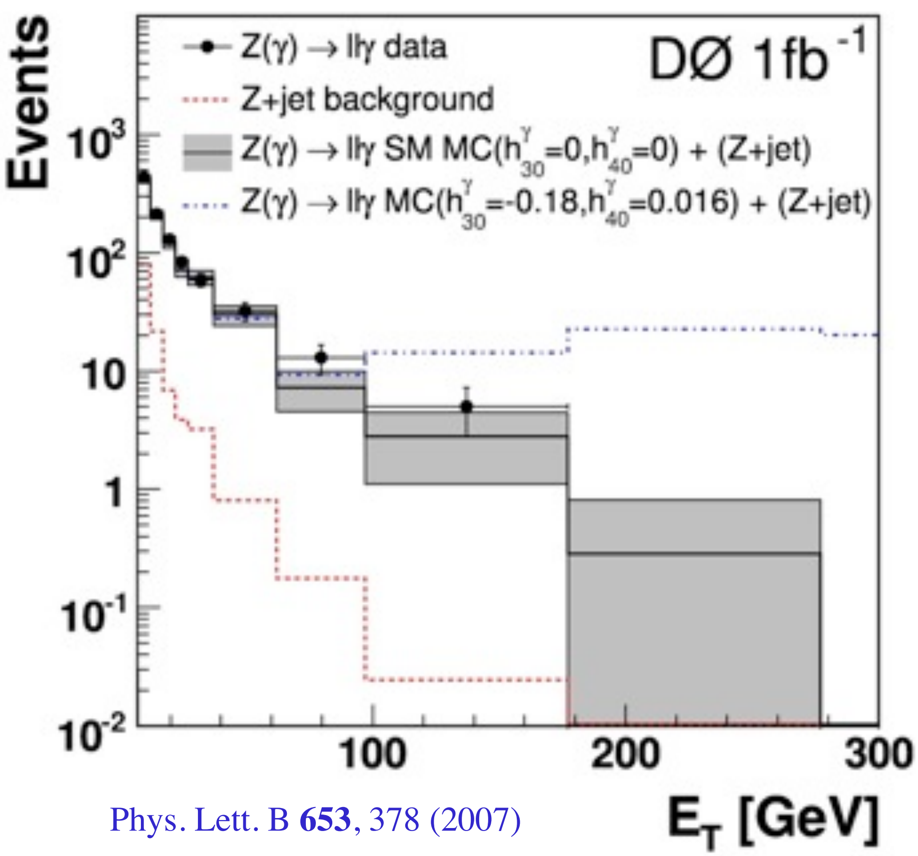
New Results

$E_{T\gamma}$ > 50 GeV
(removes FSR)

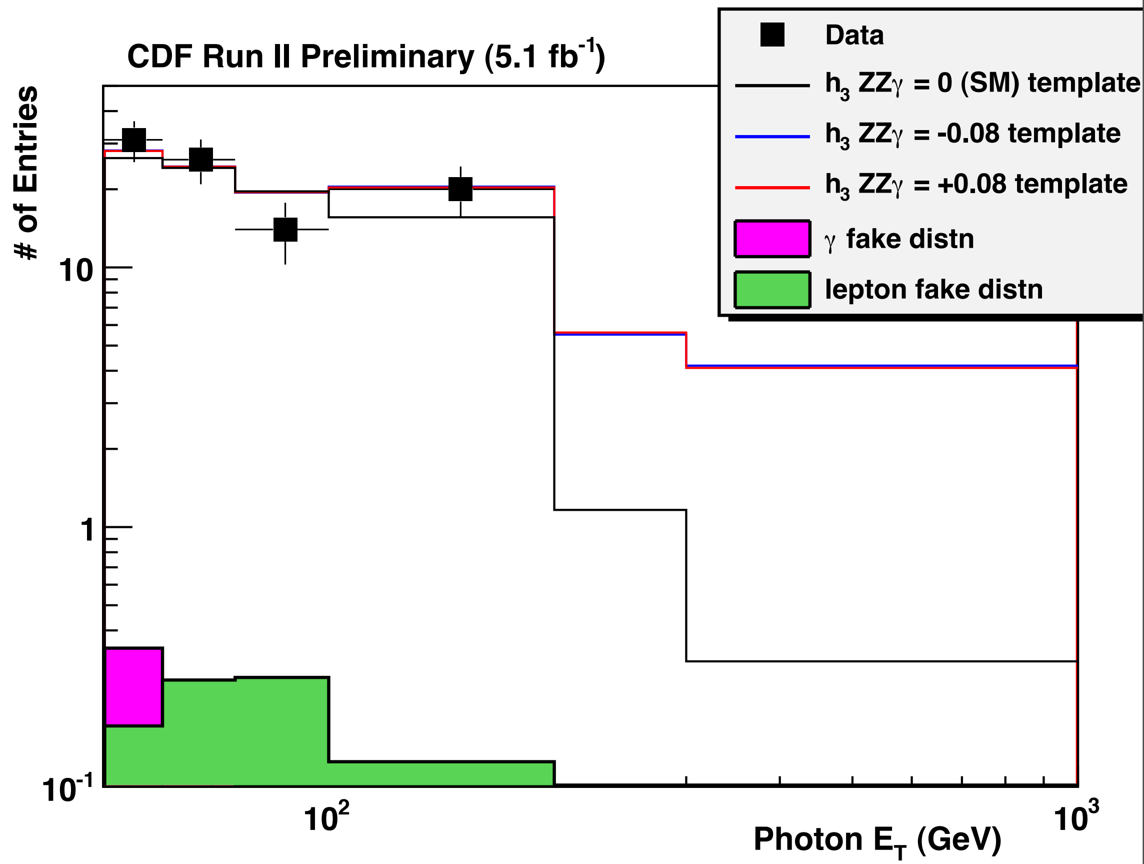


ATGC Signal Region

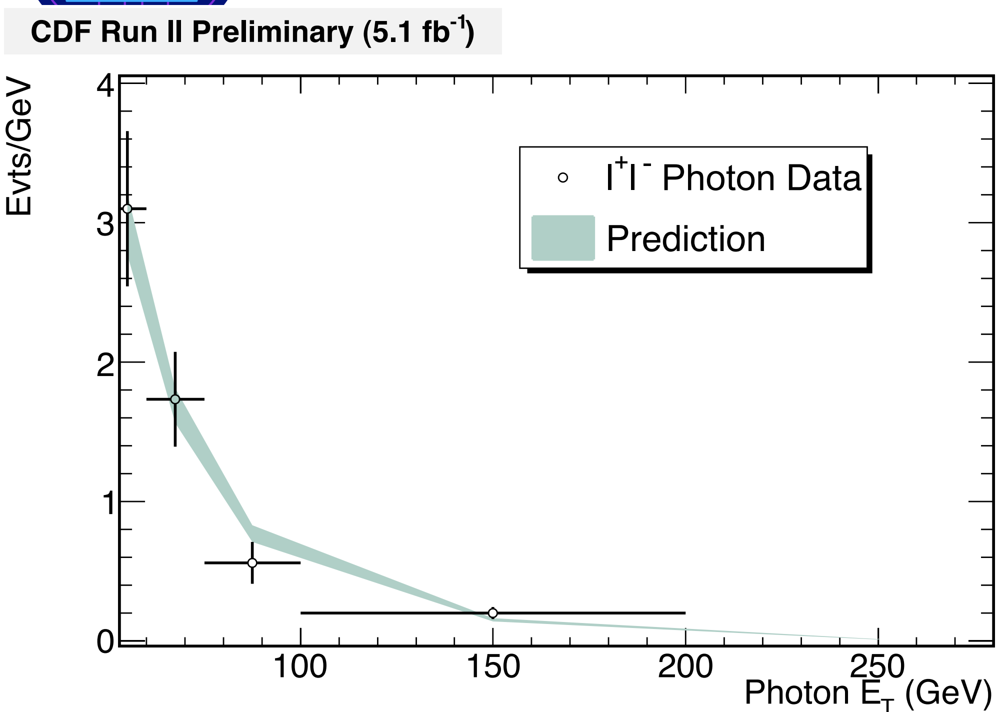
- Use MC to generate Etγ templates
  - ➔ function of Anomalous Triple-Gauge Couplings
  - ➔ use to look for & set limit on ATGC's

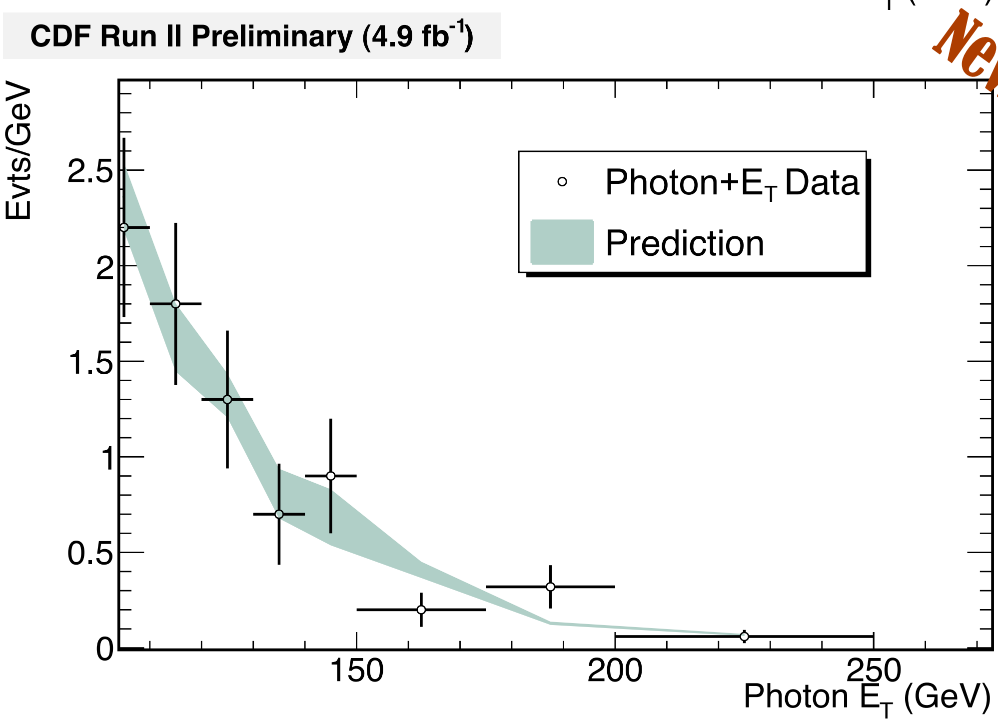


Phys. Lett. B **653**, 378 (2007)



Zγ Data

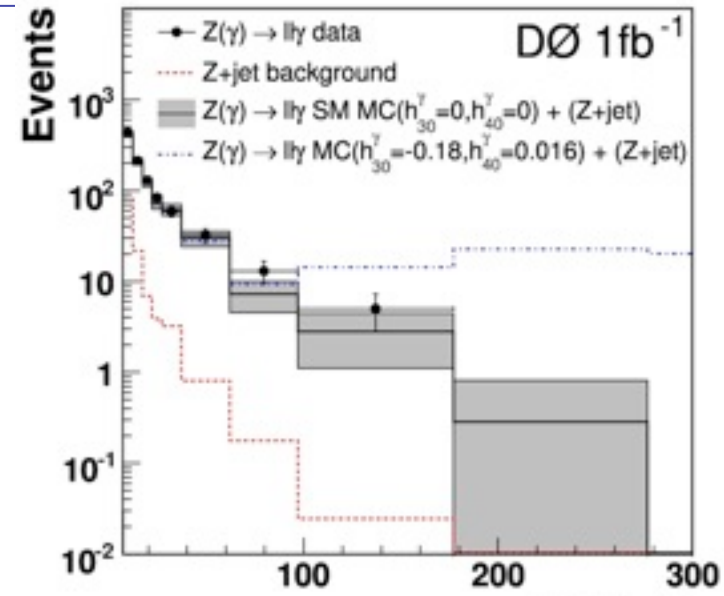




New Results

$l^+l^-\gamma$

$\not{E}_T\ \gamma$



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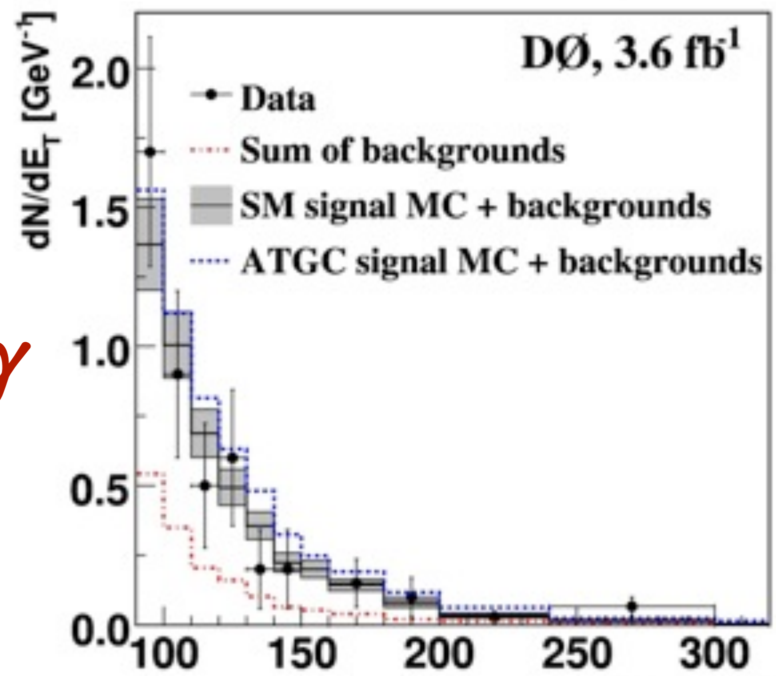


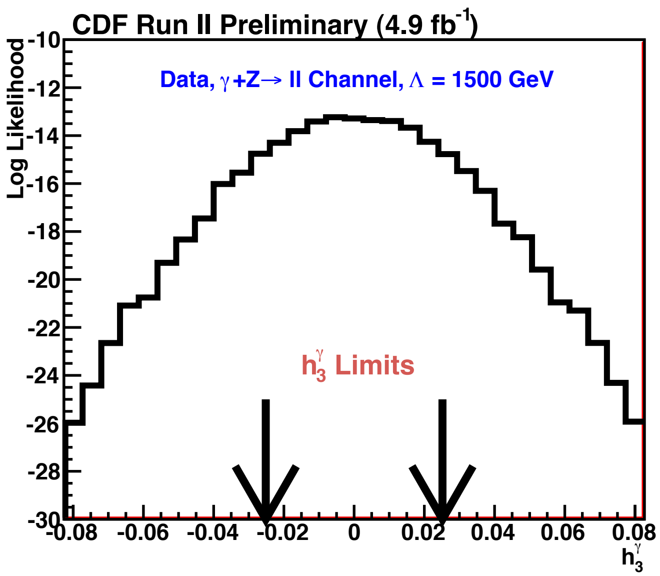
PRL **102**, 201802 (2009)

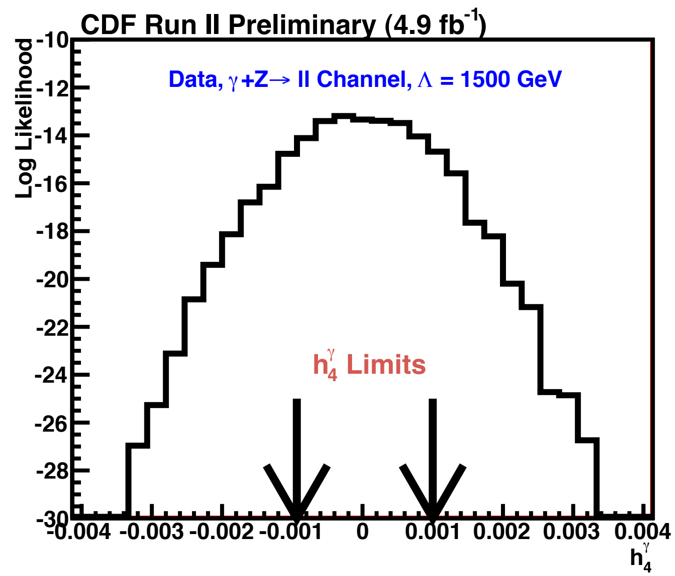
ATGC Limits (Λ=1.5 TeV)

New Results

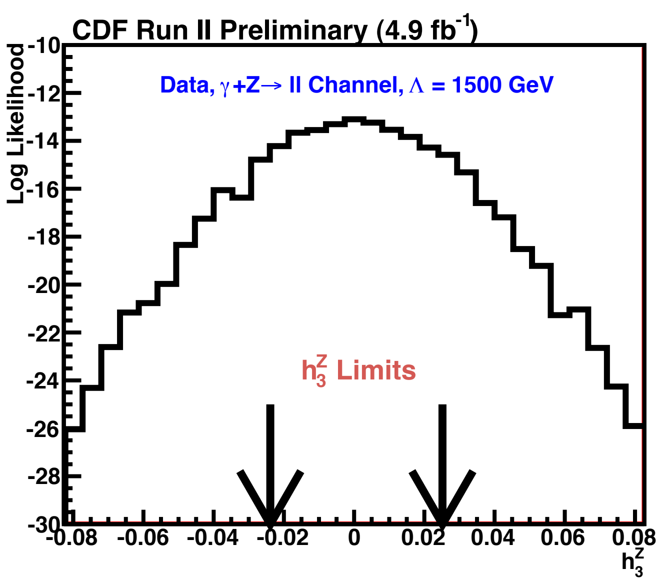
h_3 | h_4

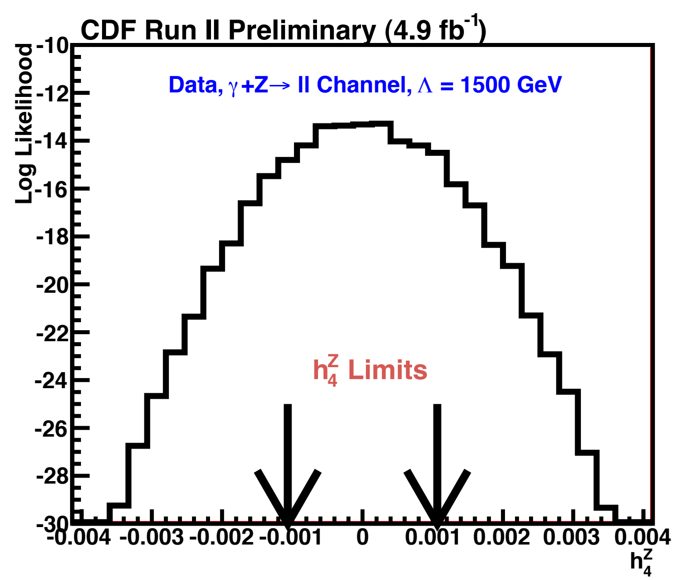
γ





Z





$Z\gamma$ Anomalous Coupling Limits

Existing limits:

PRL **102**, 201802 (2009)

- $|h^{\gamma,Z}_3| < 0.033$ (D0, Λ=1.5 TeV)
- $|h^{\gamma,Z}_4| < 0.0017$ (D0 , Λ=1.5 TeV)

Includes 1 fb $^{-1}$ e, μ, and 3.6 fb $^{-1}$ ν

Includes 1 fb $^{-1}$ e and 2 fb $^{-1}$ μ

add 2 fb^{-1} ν

arXiv:1004.1140v1

- $|h^{Z}_3| < 0.083$ (CDF, Λ=1.2 TeV) < 0.050
- $|h^{\gamma}_3| < 0.084$ (CDF, Λ=1.2 TeV) < 0.051
- $|h^{\gamma,Z}_4| < 0.0047$ (CDF, Λ=1.2 TeV) < 0.0034

New CDF limits: Includes 5fb^{-1} e, μ, ν

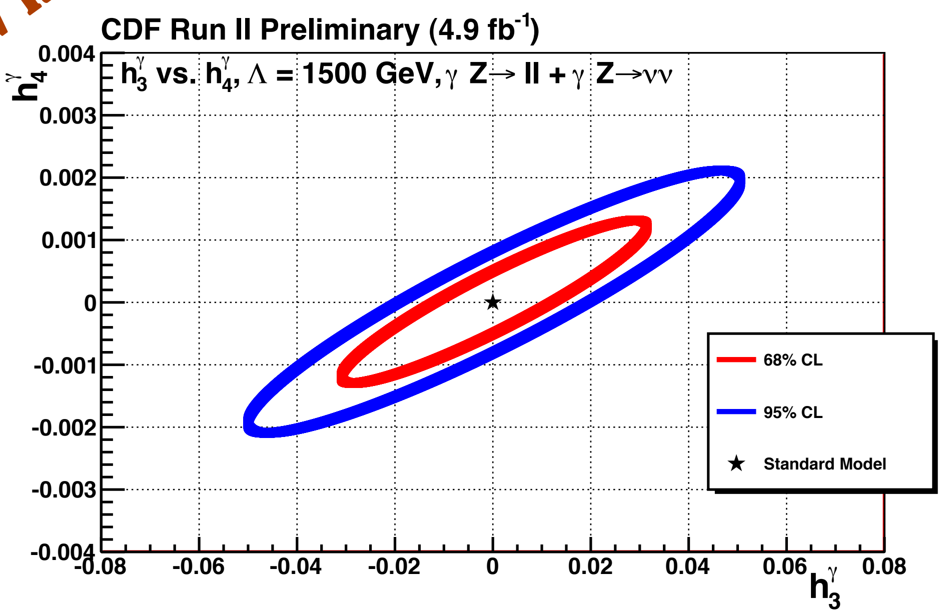
	Λ=1.2 TeV	Λ=1.5 TeV
h^{γ}_3	(-0.022, 0.021)	(-0.017, 0.016)
h^{γ}_4	(-0.0009, 0.0010)	(-0.0006, 0.0006)
h^{Z}_3	(-0.018, 0.020)	(-0.017, 0.016)
h^{Z}_4	(-0.0009, 0.0009)	(-0.0006, 0.0005)

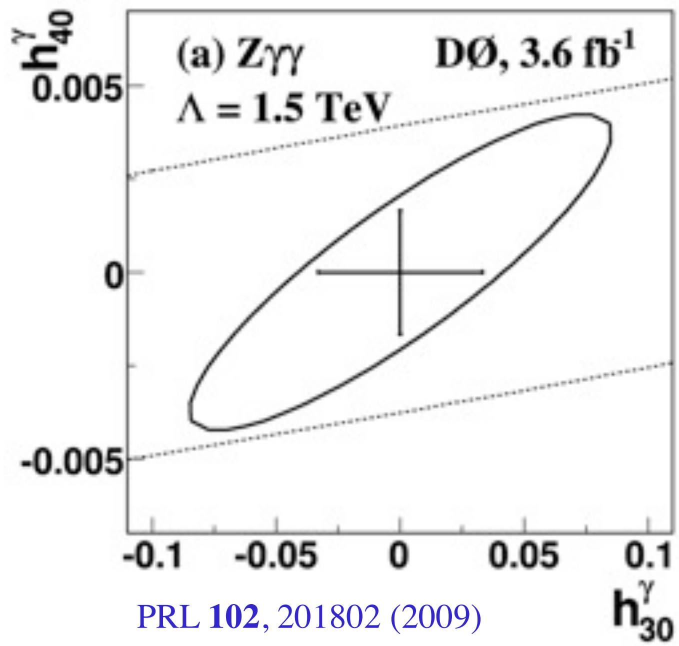
2D ATGC Limits (Λ=1.5 TeV)

New Results

Λ = 1.5 TeV

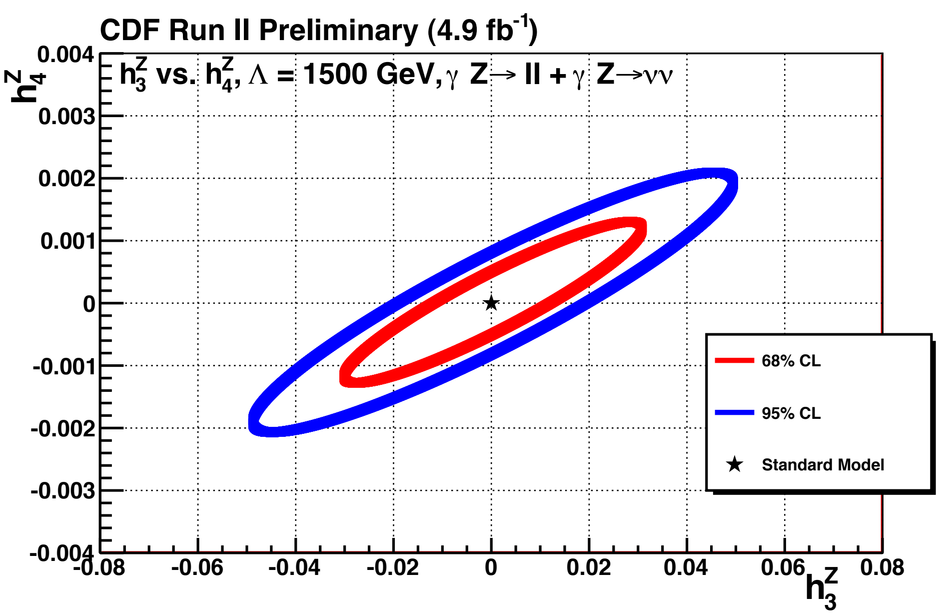
γ

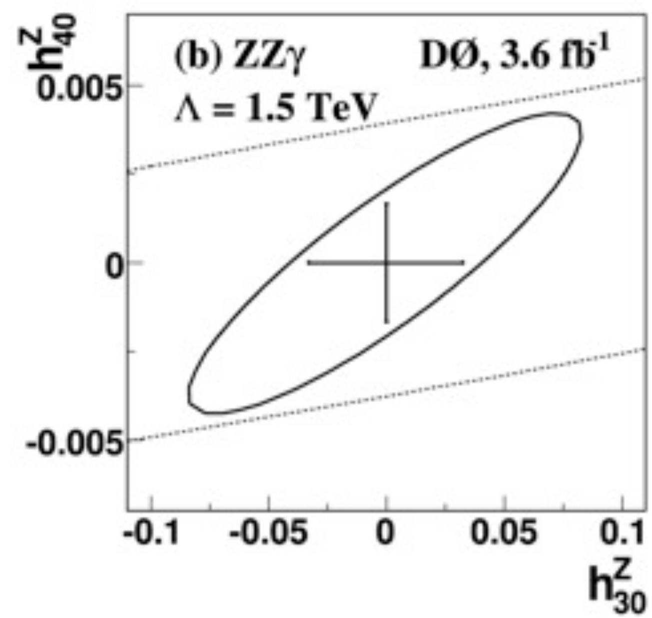




PRL **102**, 201802 (2009)

Z

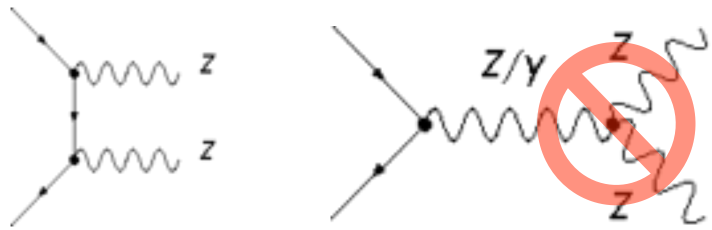


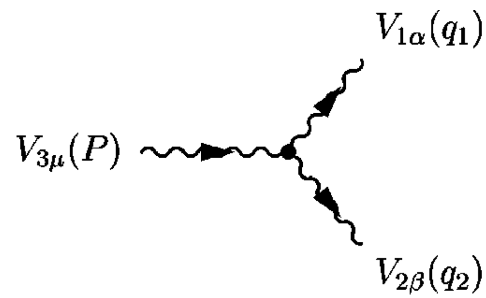


ZZ Production

Diboson Final State

ZZ





$= ie\ \Gamma^{\alpha,\beta,\mu}_{V_1 V_2 V_3}(q_1, q_2, P)$

- ZZ cross section is small
  - ➔ ZZ-> eeee, ee$\mu\mu$, $\mu\mu\mu\mu$
    - low backgrounds
    - small branching fraction
  - ➔ ZZ -> l^+l^-jj or $l^+l^-\nu\nu$
    - larger branching fractions
    - significant backgrounds

Parameterization from G.J. Gounaris *et al.* PRD 62, 073012.

$$\Gamma^{\alpha\beta\mu}_{ZZV}(q_1, q_2, P) = \frac{i(s - m_V^2)}{m_Z^2}[f_4^V(P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}) - f_5^V \epsilon^{\mu\alpha\beta\rho}(q_1 - q_2)_\rho],$$

$f^{\gamma,Z}_5$ and $f^{\gamma,Z}_4$ 0 in SM

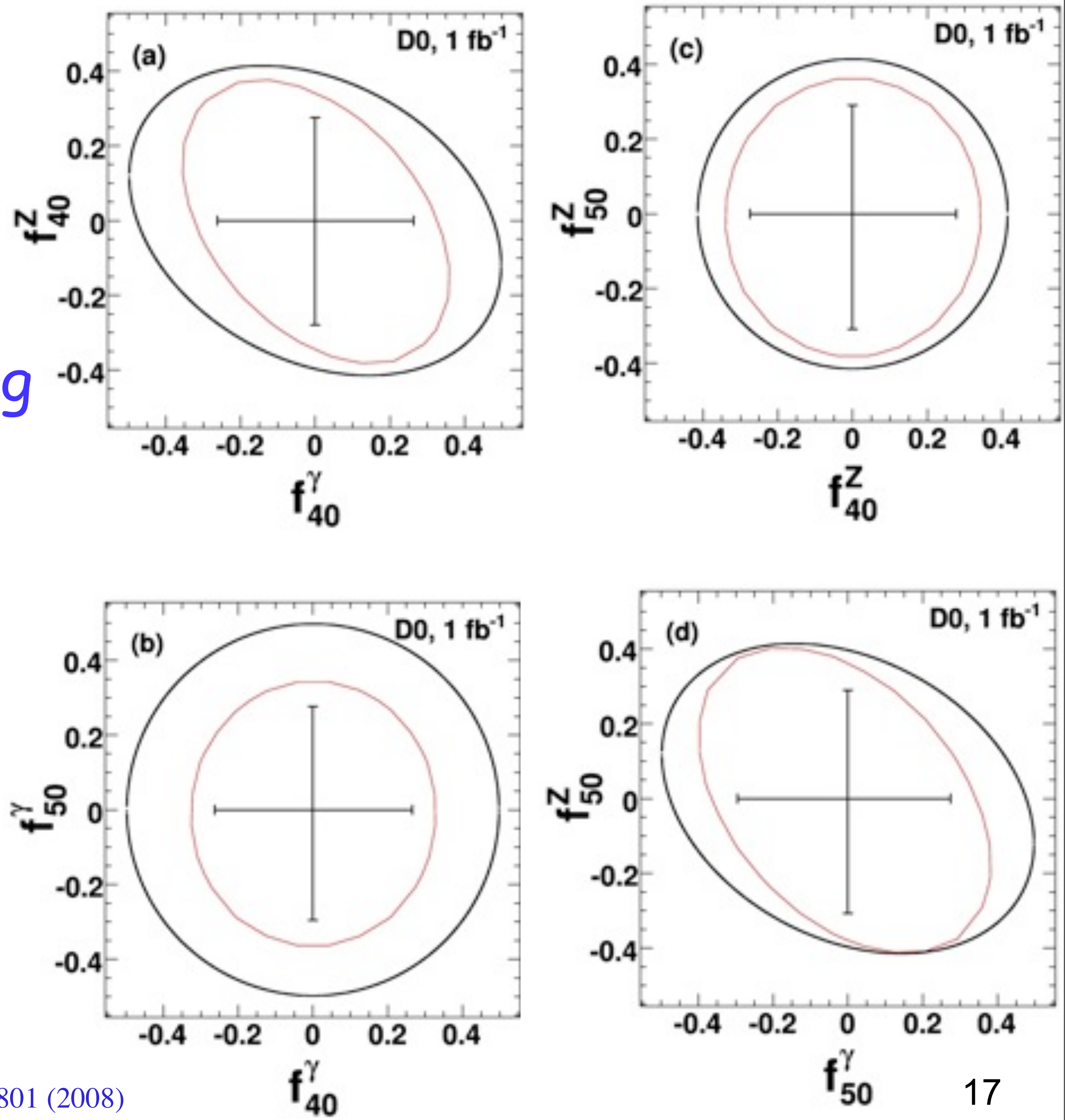
ZZ ATGC Limits (1/fb)

- D0 Results
- 4 leptons
  - → (eeee, eeμμ, μμμμ)
- 1 event, 0.13 ± 0.03 bkg

anomalous couplings limits:

- effective Lagrangian non-SM parameters: $f^{\gamma,Z}_5$ and $f^{\gamma,Z}_4$
- 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)

Λ = 1.2 TeV



PRL **100**, 131801 (2008)

ZZ ATGC Limits (1.9/fb)

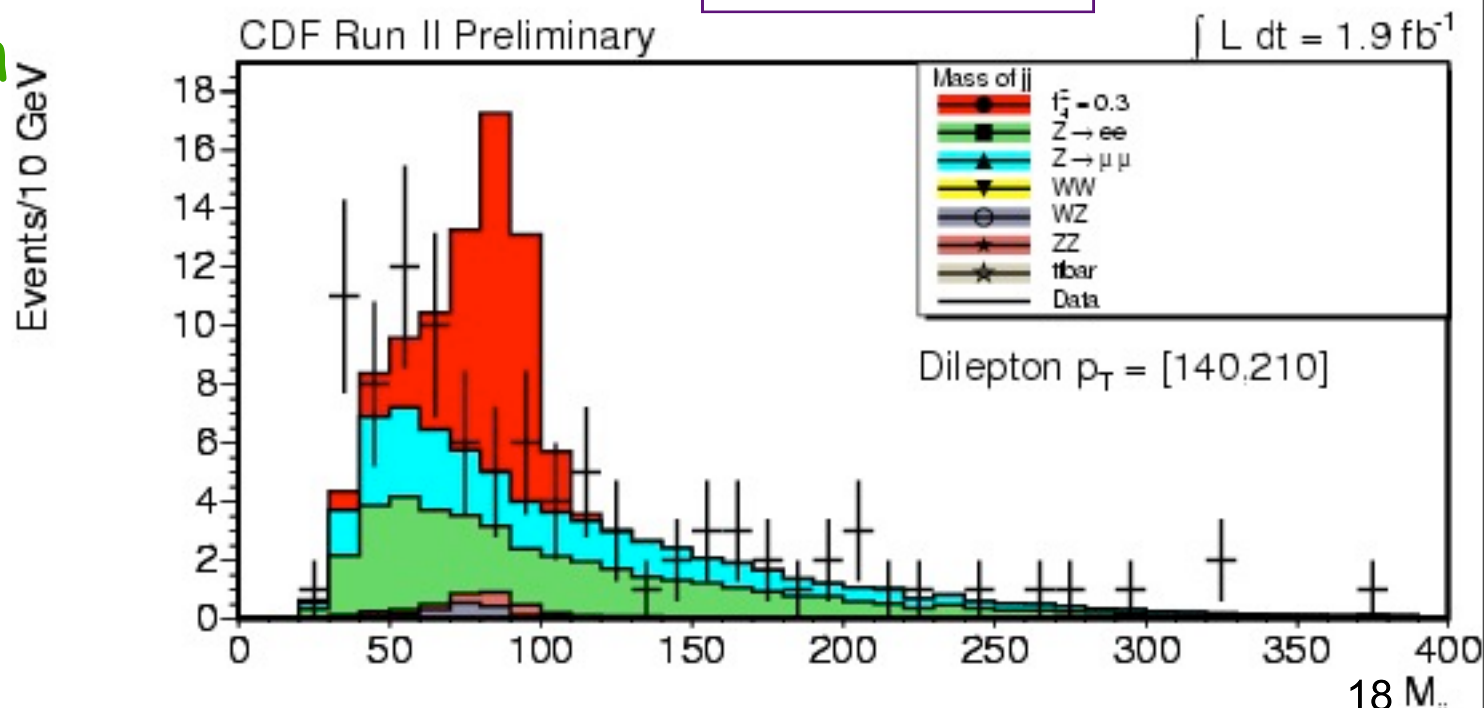
CDF Results

- Search for 2 leptons and 2 jets
  - ➔ sort results by P_{Tll}
  - ➔ Search for excess Z->jj cross section

Anomalous couplings Limits:

- effective Lagrangian non-SM parameters: $f^{\gamma,Z}_5$ and $f^{\gamma,Z}_4$
- 0 in SM
  - $-0.10 < f^{\gamma}_4 < 0.10$ (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)

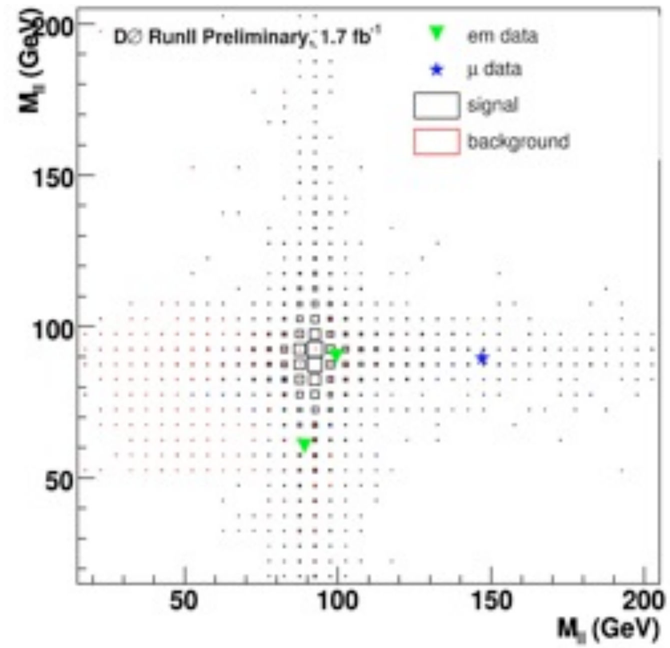
$\Lambda = 1.2$ TeV

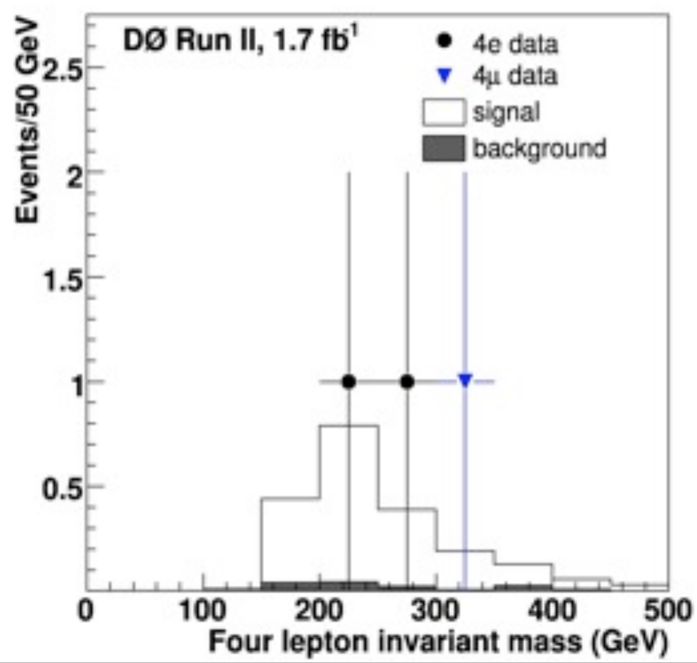


ZZ Production (1.7/fb)

- D0 Results
- 4 leptons
  - → (eeee, ee$\mu\mu$, $\mu\mu\mu\mu$)
- 3 events, $0.14^{+0.03}_{-0.02}$ bkg
  - → 5.3 σ observation
- Combine with ZZ->$l^+l^- \nu\ \nu$
  - → 5.7 σ observation
  - → σ(ZZ)=1.60 ±$0.63^{+0.16}_{-0.17}$ pb

σ(ZZ)=1.4 ±0.1 pb (SM)



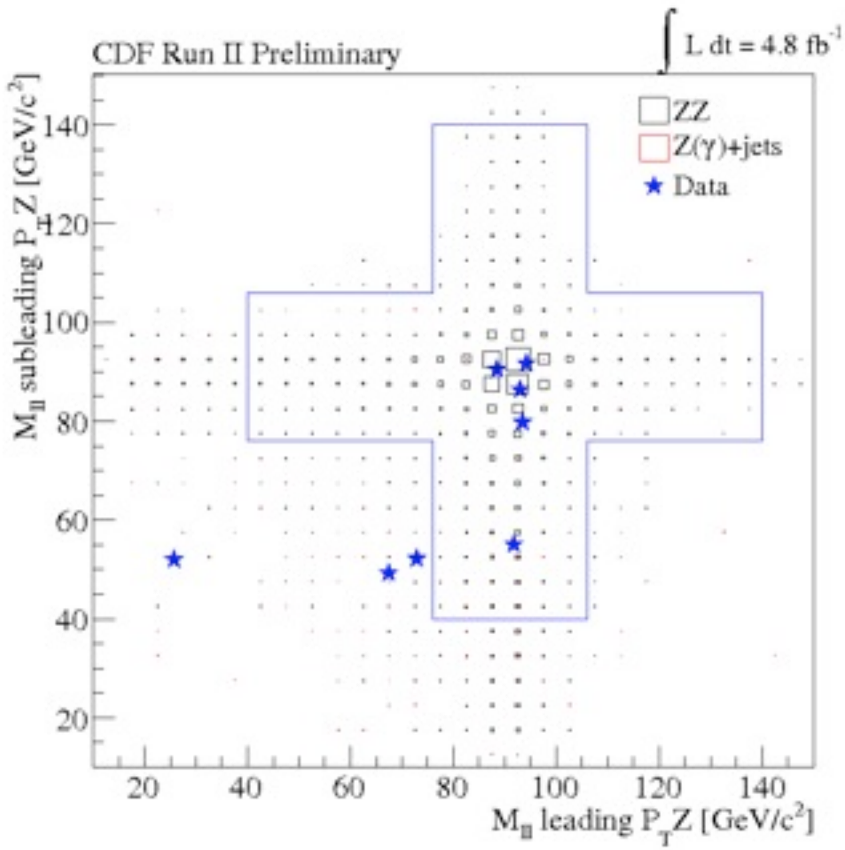


PRL **101**, 171803 (2008)

ZZ Production (4.8/fb)

CDF Results

- Search for 4 leptons or 2 leptons + 2 ν
  - ➔4 leptons (eeee, ee$\mu\mu$, $\mu\mu\mu\mu$)
    - clean, but small branching fraction
    - increase acceptance wherever possible
  - ➔5.7 σ observation
  - ➔ $\sigma(ZZ)=1.56\ ^{+0.80}_{-0.63} \pm 0.25$ pb



5 events in signal box:
- three 4-μ
- two ee $\mu\mu$

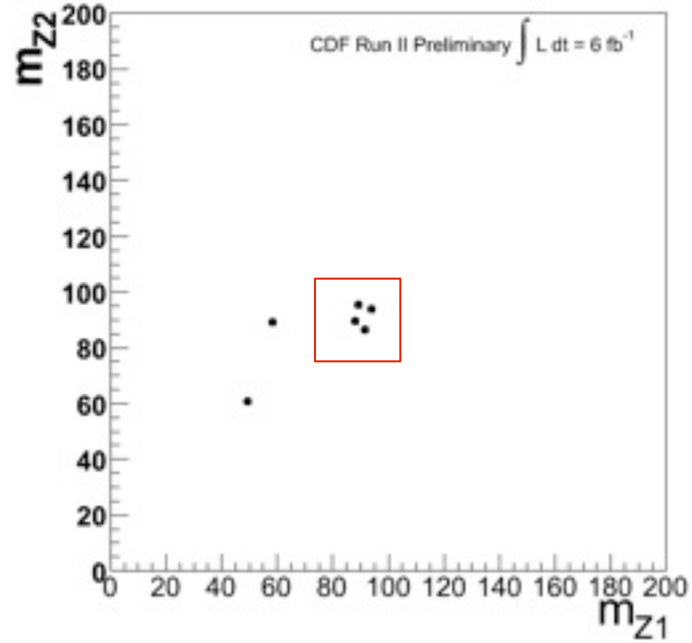
$\sigma(ZZ)=1.4 \pm 0.1$ pb (SM)

ZZ Production (6/fb)

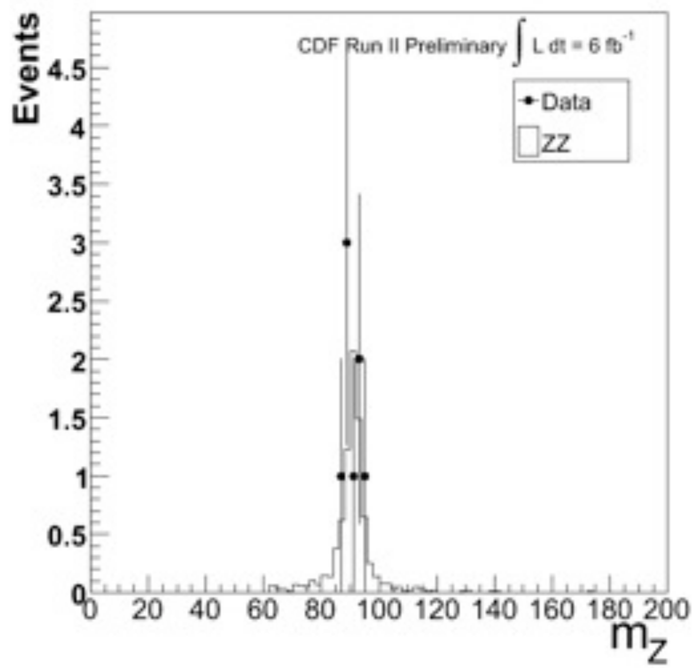
New Results

CDF Results

- Search for 4 leptons
  - 4 leptons (eeee, $ee\mu\mu$, $\mu\mu\mu\mu$)
    - clean, but small branching fraction
    - $76 < M_{ll} < 106$ GeV
    - $M_{llll} < 300$ GeV
      - will look for ZZ resonance above this
  - Normalize to $\sigma(Z)$
    - $\sigma(ZZ) = 1.7^{+1.2}_{-0.7} \pm 0.2$ pb
  - Could be used for new ATGC limits



4 events (3 new) in signal box:
- one 4-μ
- two $ee\mu\mu$
- one 4-e



Summary

Diboson production is well described by the Standard Model!

- All modes have been seen, including ZZ
- Couplings look like SM!

	Λ=1.2 TeV	Λ=1.5 TeV
h^{γ}_{3}	(-0.022, 0.021)	(-0.017, 0.016)
h^{γ}_{4}	(-0.0009, 0.0010)	(-0.0006, 0.0006)
h^{Z}_{3}	(-0.018, 0.020)	(-0.017, 0.016)
h^{Z}_{4}	(-0.0009, 0.0009)	(-0.0006, 0.0005)
f^{γ}_{4}	(-0.10, 0.10)	
f^{γ}_{5}	(-0.11, 0.11)	
f^{Z}_{4}	(-0.12, 0.12)	
f^{Z}_{5}	(-0.13, 0.12)	

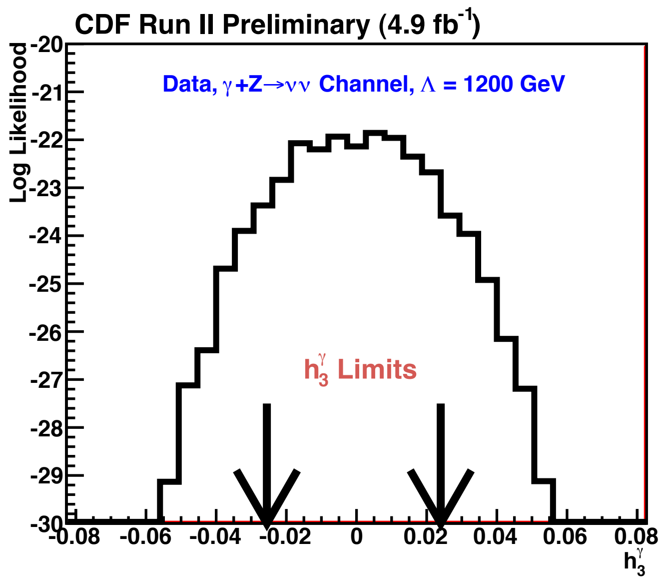
Backup

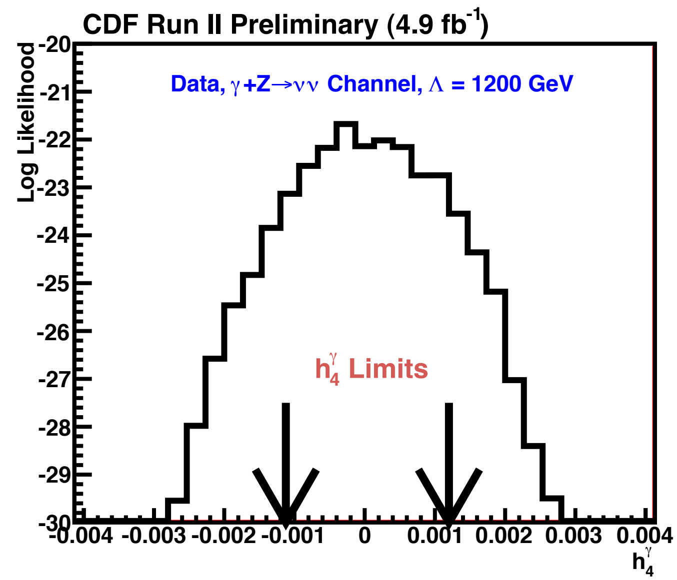
CDF ATGC Limits (Λ=1.2 TeV)

New Results

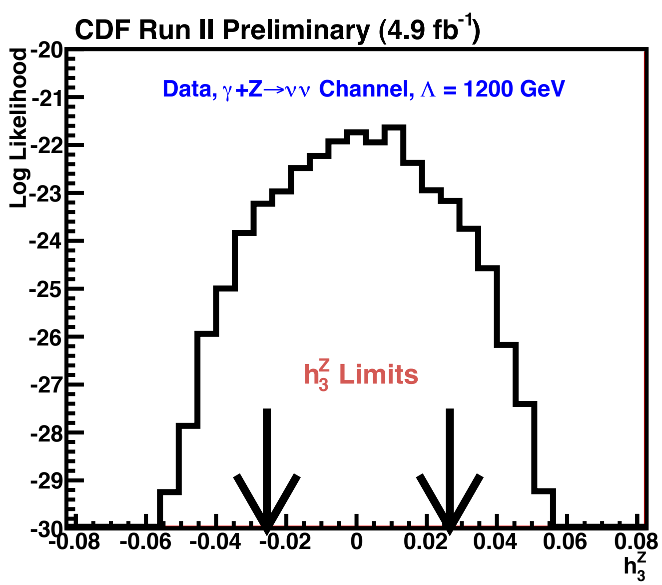
h_3 | h_4

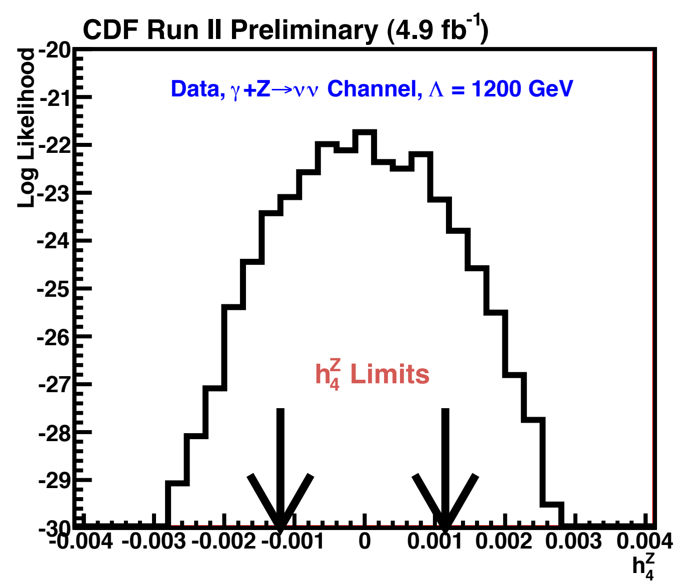
γ





Z



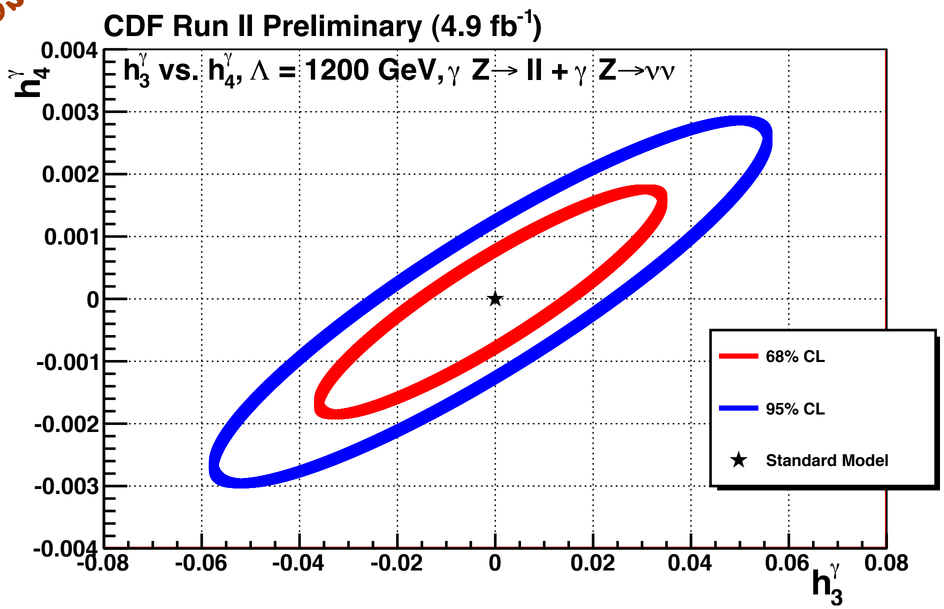


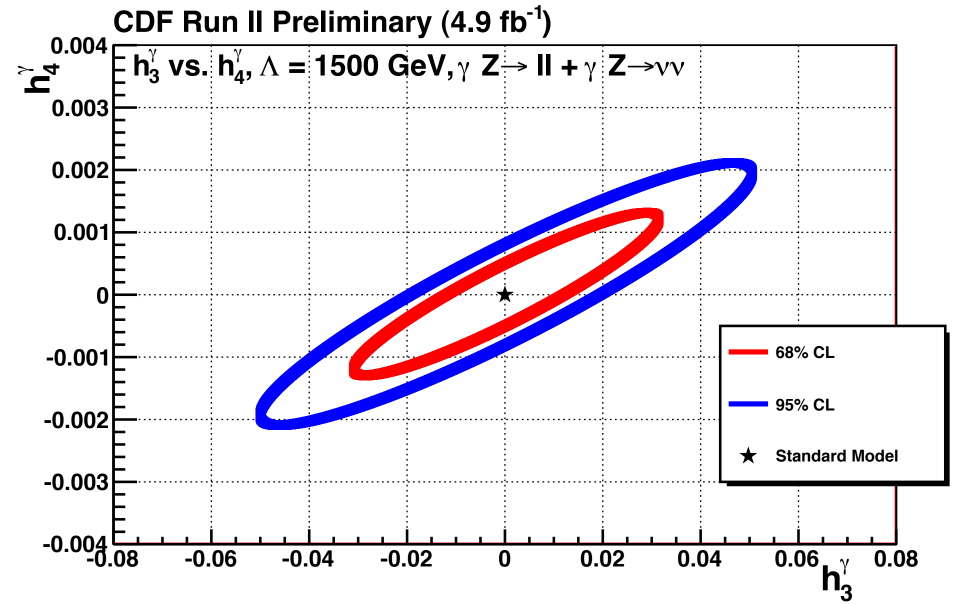
CDF 2D ATGC Limits

New Results

Λ = 1.2 TeV | Λ = 1.5 TeV

γ





Z