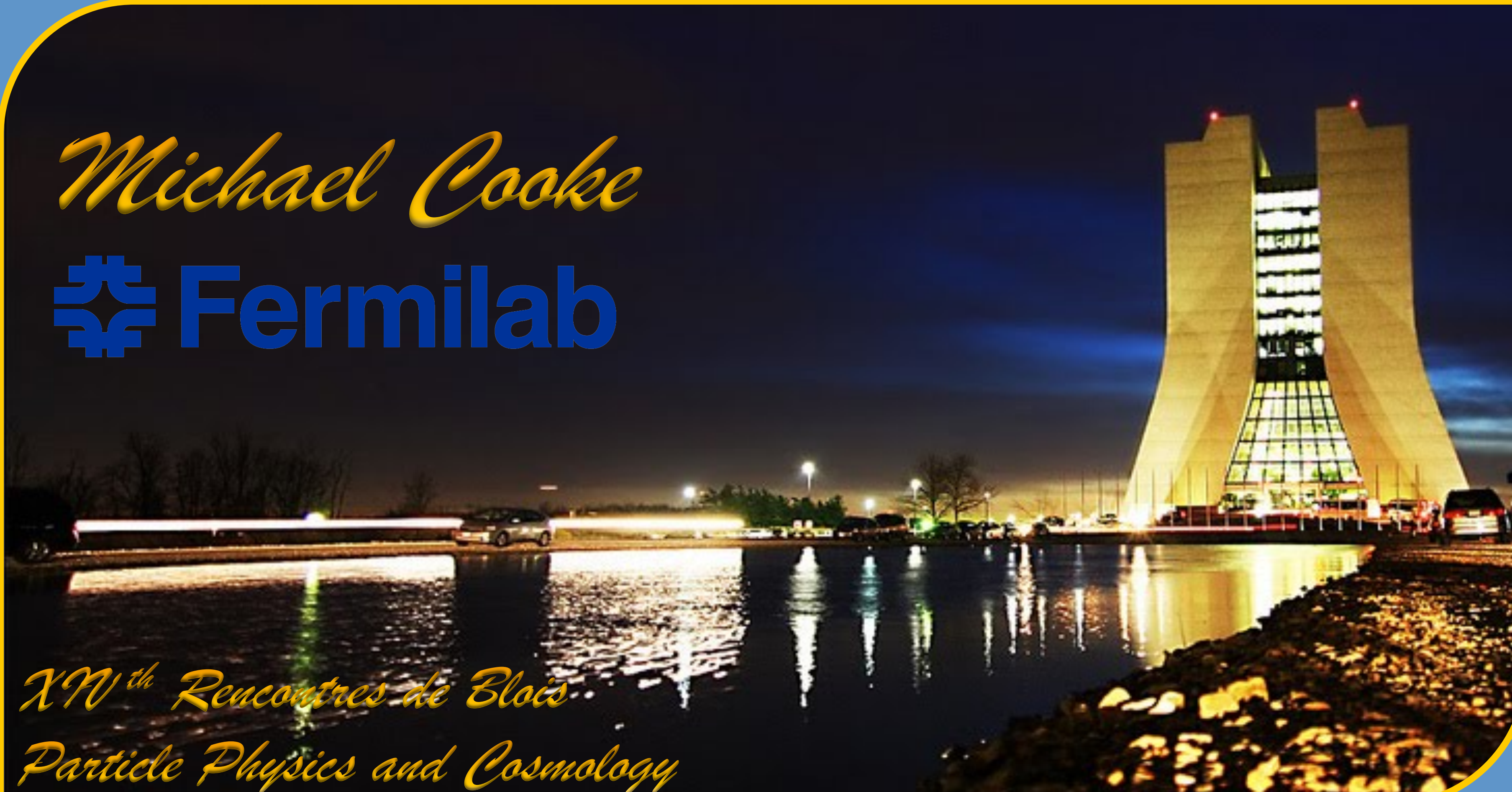
Diboson Production
at the Tevatron

CDF DØ



Michael Cooke

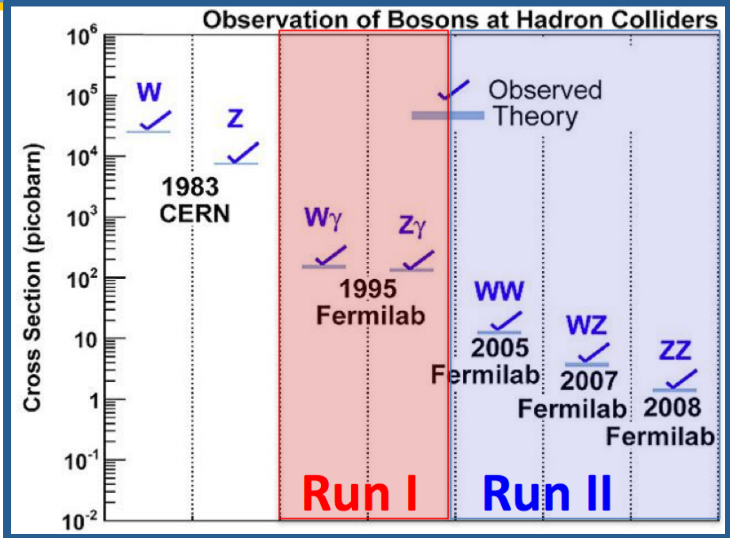
Fermilab

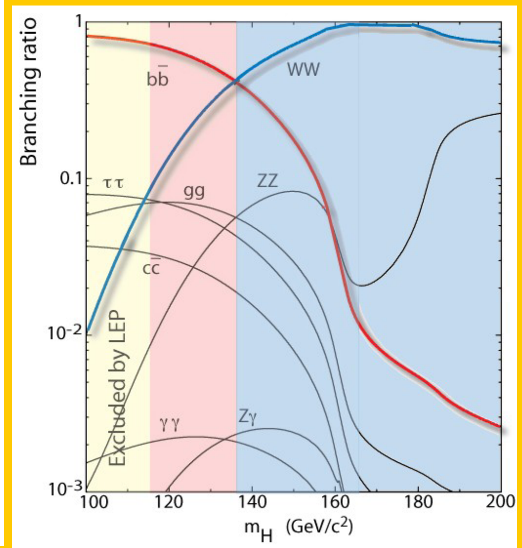
XIV th Rencontres de Blois

Particle Physics and Cosmology

Motivation

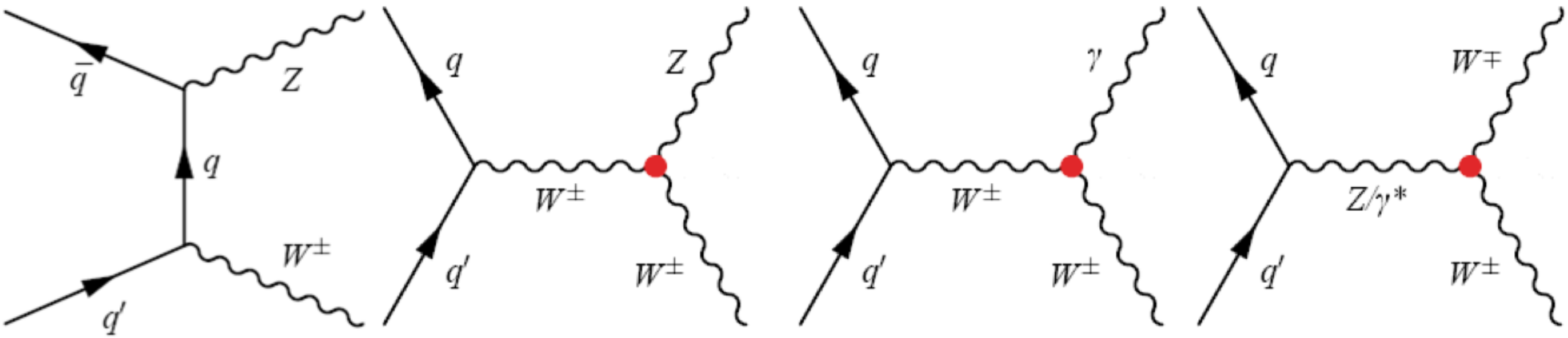
- Precision test of standard model predictions
- Probe for new physics
  - Anomalous values of triple gauge boson couplings
- Direct window to SM Higgs
  - *H→WW, ZZ, Zγ*
  - Validate the tools and methods used in search for Higgs boson





Triple Gauge Couplings

- SM has two charged TG vertices: *WWZ* & *WWγ*



- With EM gauge invariance and C and P cons., most general Lorentz inv. Lagrangian is:

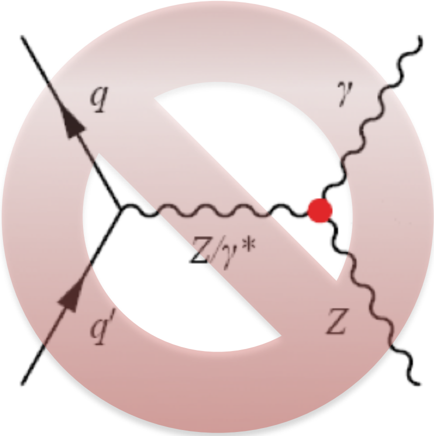
$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = i\, g_1^V \left(W^\dagger_{\mu\nu} W^\mu - W^{\dagger\mu} W_{\mu\nu} \right) V^\nu + i\, \kappa_V\, W^\dagger_\mu W_\nu V^{\mu\nu} + i \frac{\lambda_V}{M_W^2} W^{\dagger\,\nu}_{\mu} W_\nu{}^\rho V_\rho{}^\mu$$

...where $V = \gamma$ or Z, $g_{WW\gamma} = -e$, $g_{WWZ} = -e \cot\theta_W$, and $g_1^\gamma = 1$

In SM:
$\lambda_V = 0$
$g_1{}^V = \kappa_V = 1$
$(\Delta\kappa \equiv \kappa - 1)$

Neutral TGCs & Form Factors

- No $Z\gamma\gamma/ZZ\gamma$ vertices in the SM
  - Most general Lagrangian has CP-odd and CP-even terms



$$\frac{L_{\gamma ZV}}{-ie} = (h_1^V F^{\mu\nu} + h_3^V \tilde{F}^{\mu\nu}) Z_\mu \frac{\Box + m_V^2}{M_Z^2} V_\nu + (h_2^V F^{\mu\nu} + h_4^V \tilde{F}^{\mu\nu}) Z^\alpha \frac{\Box + m_V^2}{M_Z^4} \partial_\alpha \partial_\mu V_\nu$$

...where $F^{\mu\nu}$ is the photon field, "~" denotes antisymmetry, $\Box = \partial^2/\partial t^2 - \nabla^2$

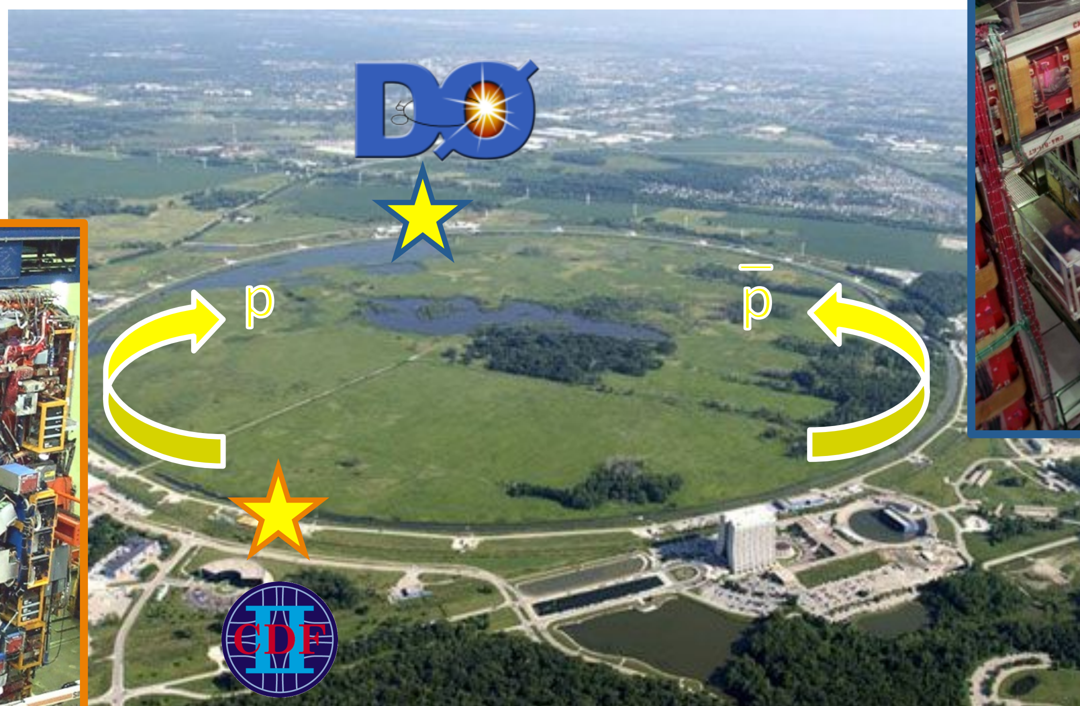
- Anomalous TGCs introduced as form factors

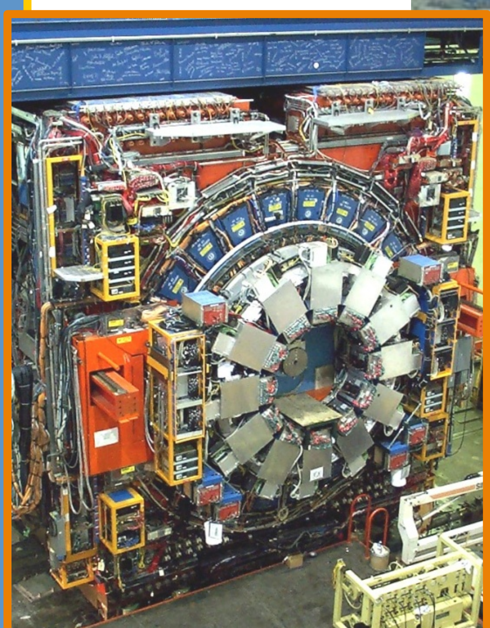
$$A(\hat{s}) = \frac{A_0}{(1+\hat{s}/\Lambda^2)^n}$$

$n = 2$ for κ_V, λ_V, g_1^Z
$n = 3$ for h_1^V, h_3^V
$n = 4$ for h_2^V, h_4^V

Making Dibosons at Fermilab

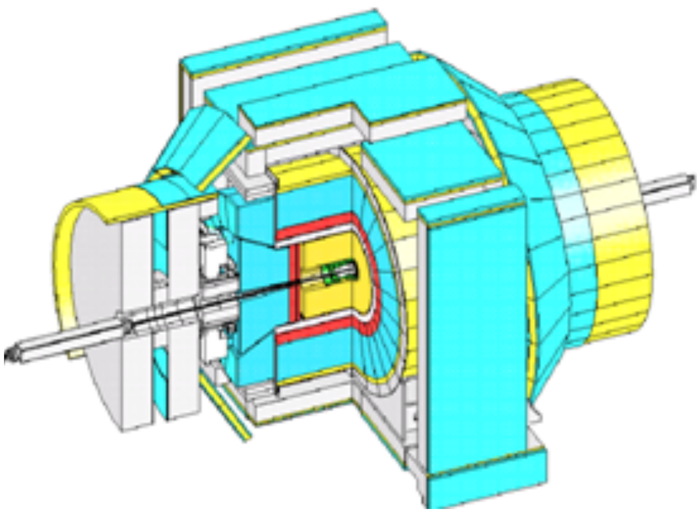
The Tevatron produced $p\bar{p}$ collisions at CM energy ($\sqrt{s}$) 1.96 TeV



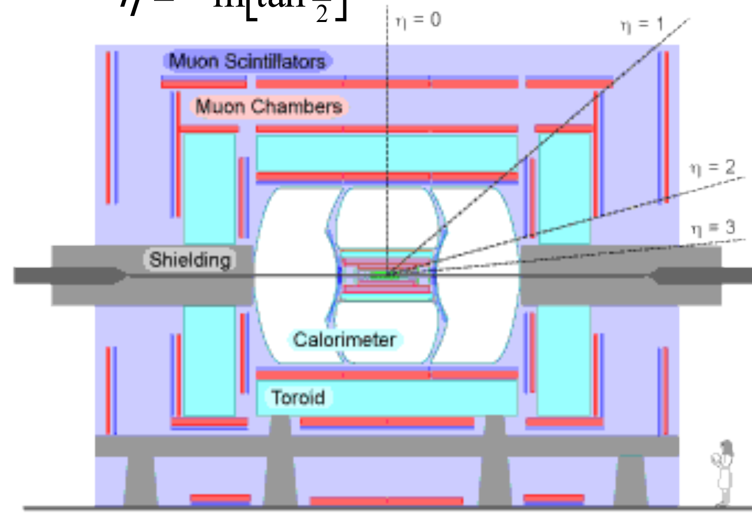


Total delivered luminosity ≈ 12 fb^{-1}

The CDF and DØ Detectors



$$\eta = -\ln\left[\tan\frac{\theta}{2}\right]$$



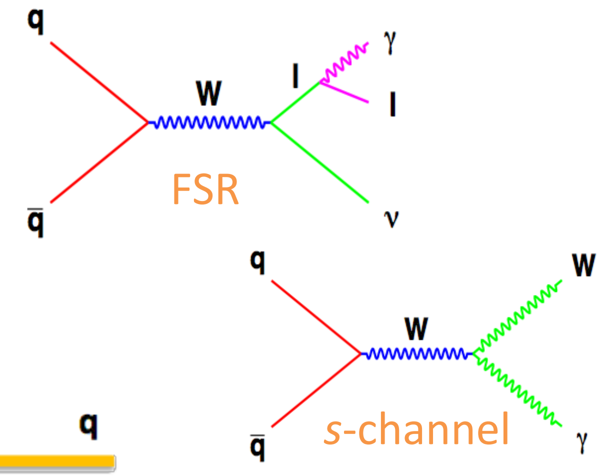
- Silicon vertex detector
- Wire drift chamber tracking
- Pb/Fe-scintillator calorimetery
- Muon chambers

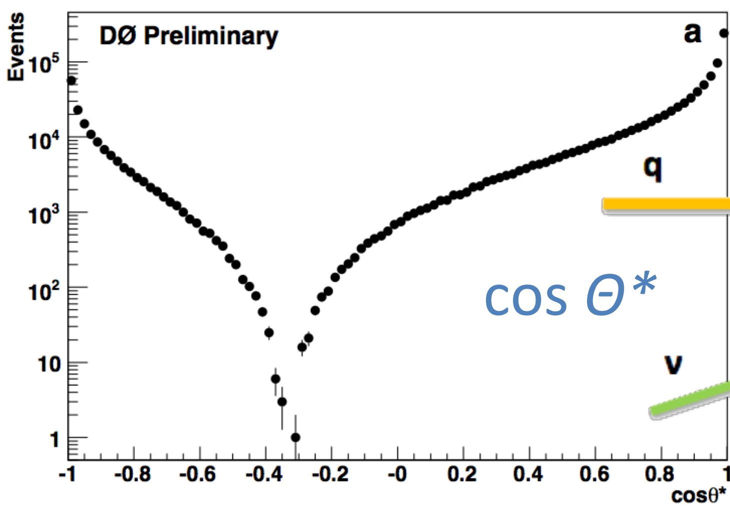
- Silicon vertex detector
- Scintillating fiber tracking
- LAr-U calorimeter
- Muon chambers

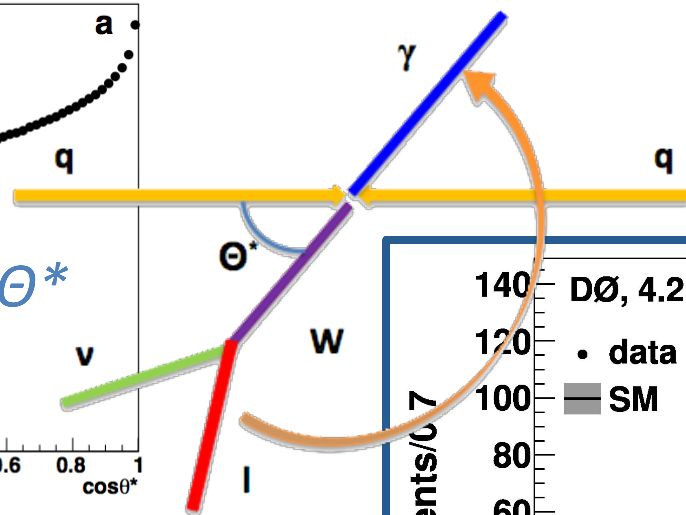
PRL 107, 241803(2011), 4.2 fb^{-1}

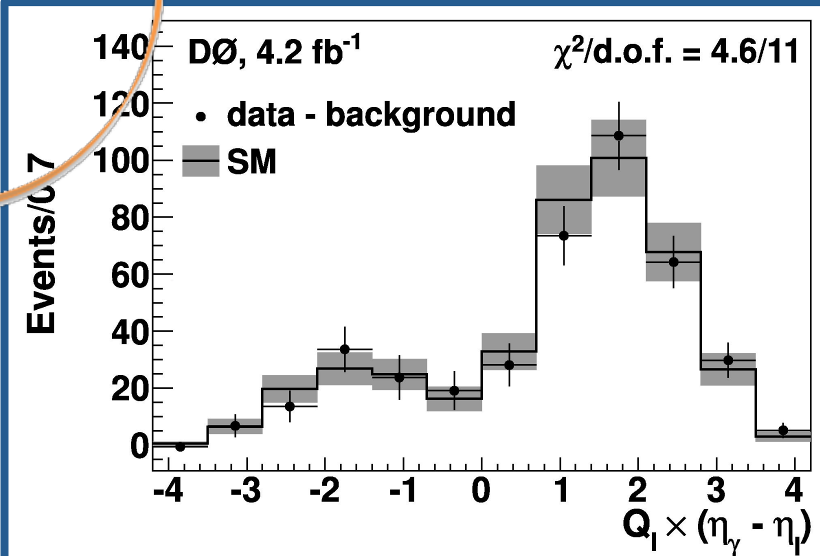
$W\gamma \longrightarrow \ell\nu\gamma$ Production

- Event selection suppresses FSR
  - 3-body M_T > 110 GeV, $\Delta R_{\ell\gamma}$ > 0.7









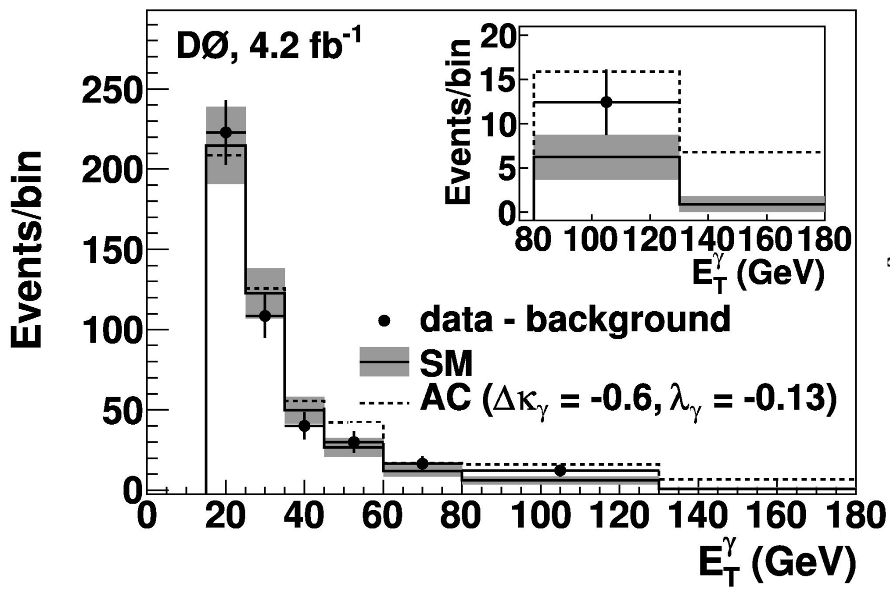
SM: (p_T^γ > 15, ΔR > 0.7): σ = 7.6 ± 0.2 pb

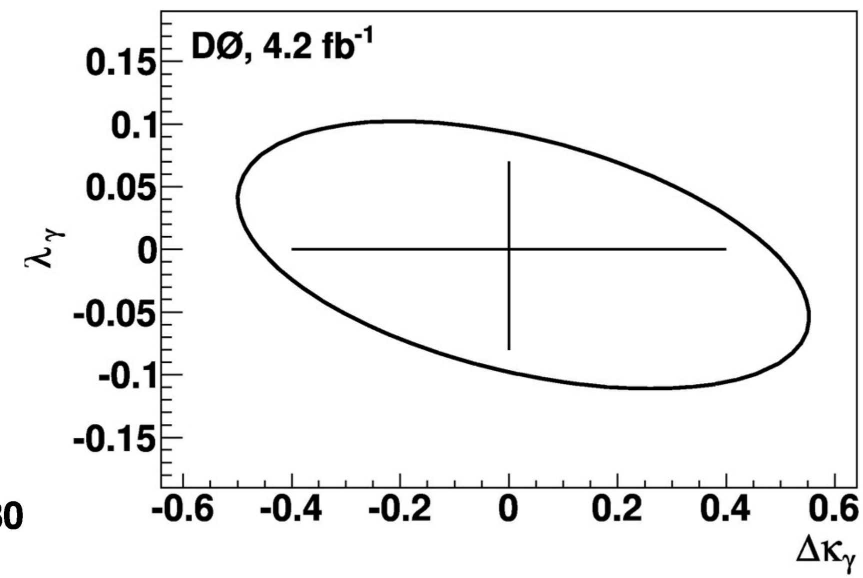
Obs: σ = 7.6 ± 0.4 (stat) ± 0.6 (syst) pb

PRL 107, 241803(2011), 4.2 fb^{-1}

Anomalous *WWγ* TGCs

- Limits set using E_T^{γ} spectrum (Λ = 2 TeV)



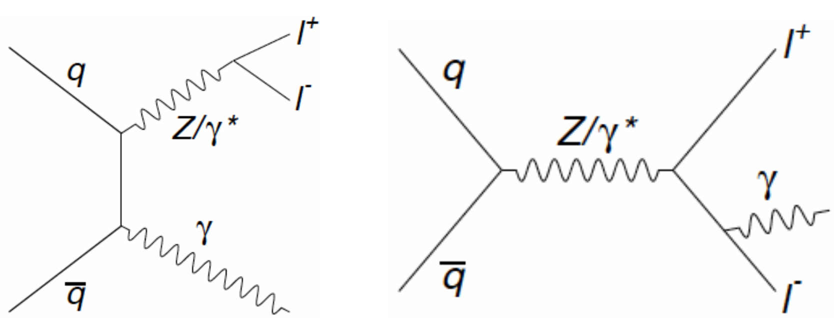


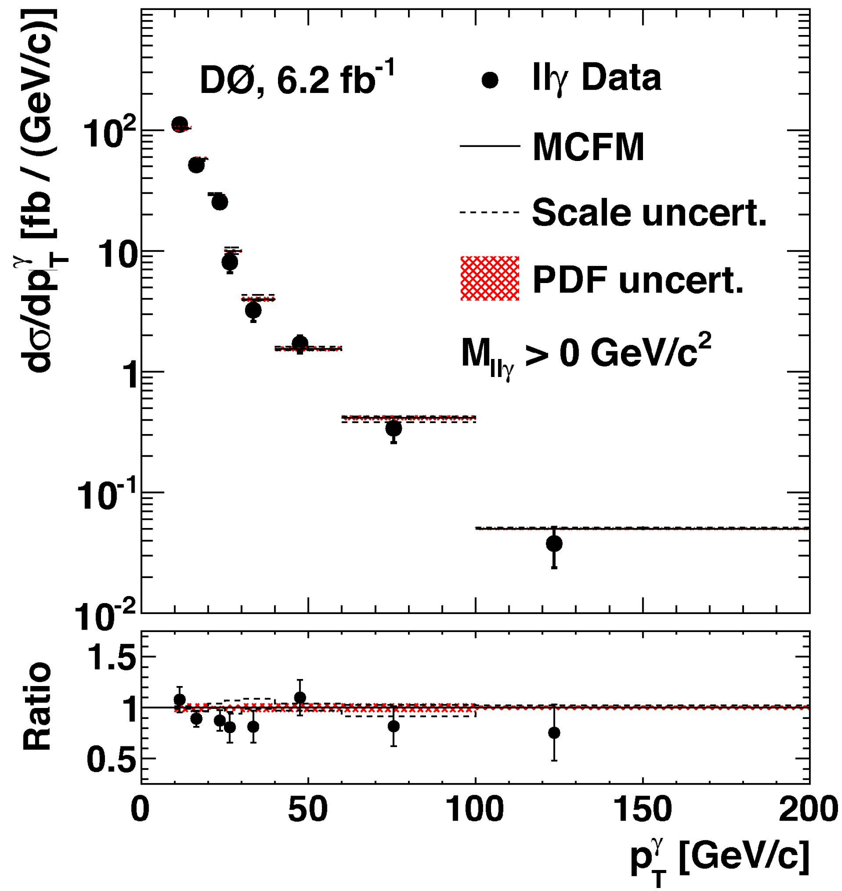
95% C.L. Limits: **$-0.4 < \Delta\kappa_\gamma < 0.4$ $-0.08 < \lambda_\gamma < 0.07$**

PRD 85, 052001 (2012), 6.2 fb^{-1}

$Z\gamma \longrightarrow \ell\ell\gamma$ Production

- High p_T lepton pair + γ
  - $M_{\ell\ell} > 60$ GeV, γ $E_T > 10$ GeV
  - FSR reduced with $\Delta R_{\ell\gamma} > 0.7$
    - Separated 3-body $M > 110$ GeV





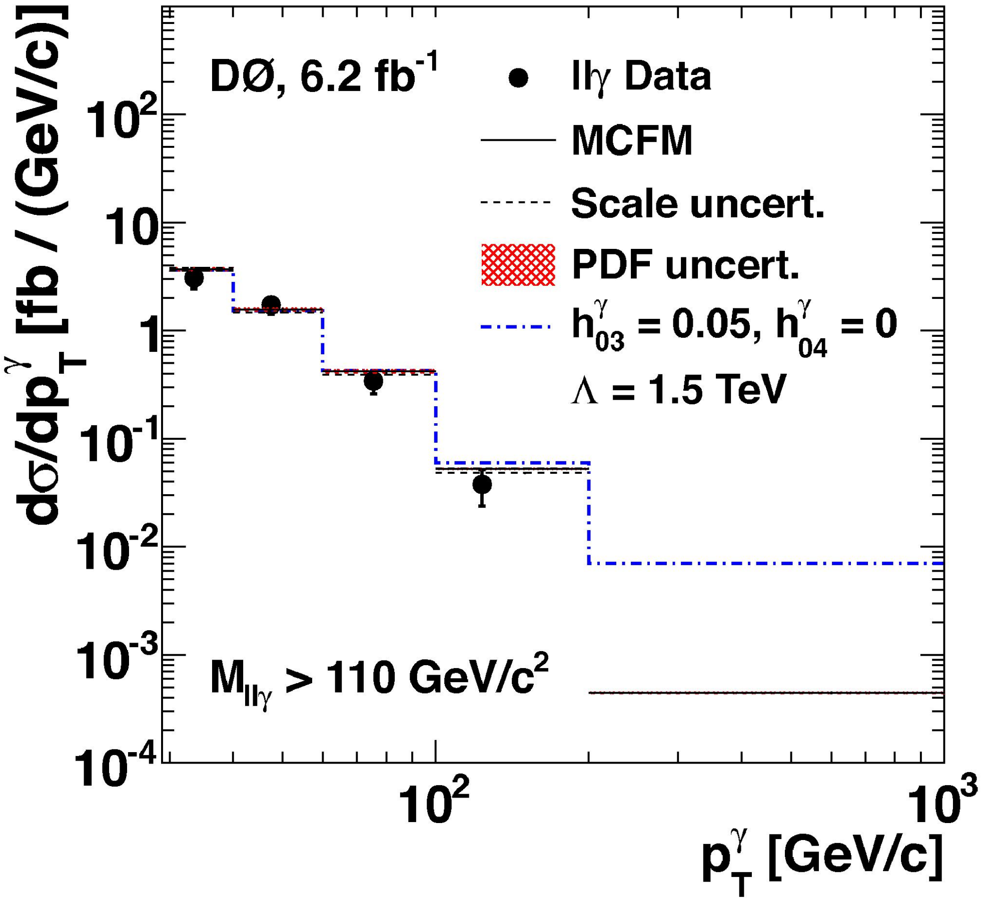
SM: $\sigma = 1096 \pm 34$ (PDF) $^{+2}_{-4}$ (scale) fb
($M_{\ell\ell\gamma} > 110$) $\sigma = 294 \pm 10$ (PDF) $^{+1}_{-2}$ (scale) fb

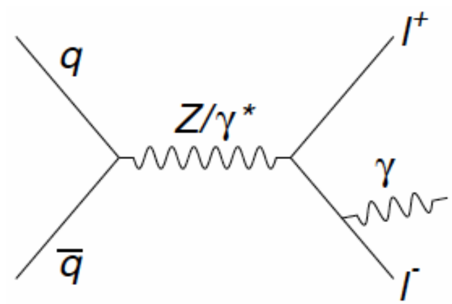
Obs: $\sigma = 1089 \pm 40$ (stat) ± 65 (syst) fb
($M_{\ell\ell\gamma} > 110$) $\sigma = 288 \pm 15$ (stat) ± 11 (syst) fb

PRD 85, 052001 (2012), 6.2 fb^{-1}

$Z\gamma \longrightarrow \ell\ell\gamma$ TGCs

TGC limits from $d\sigma/dp_T^{\gamma}$ for $M_{\ell\ell\gamma}$ > 110 GeV

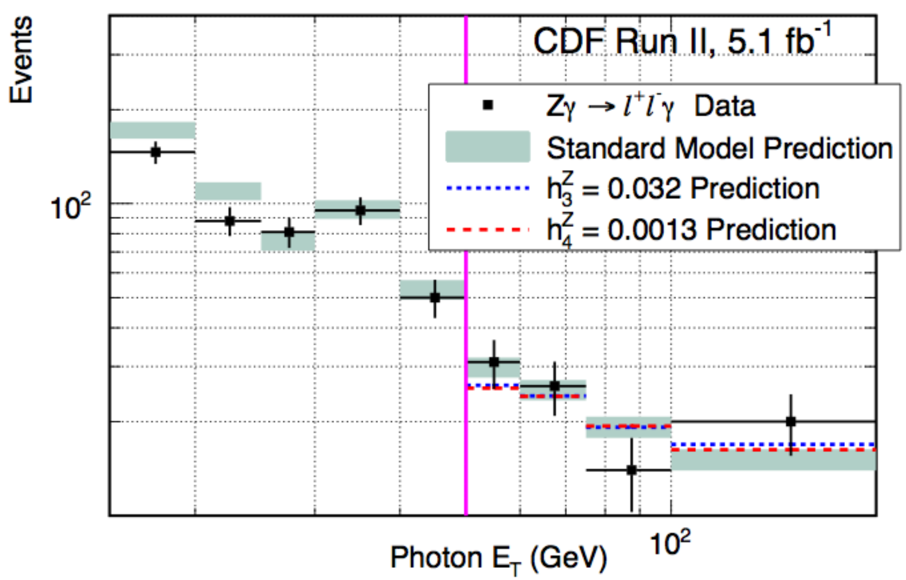


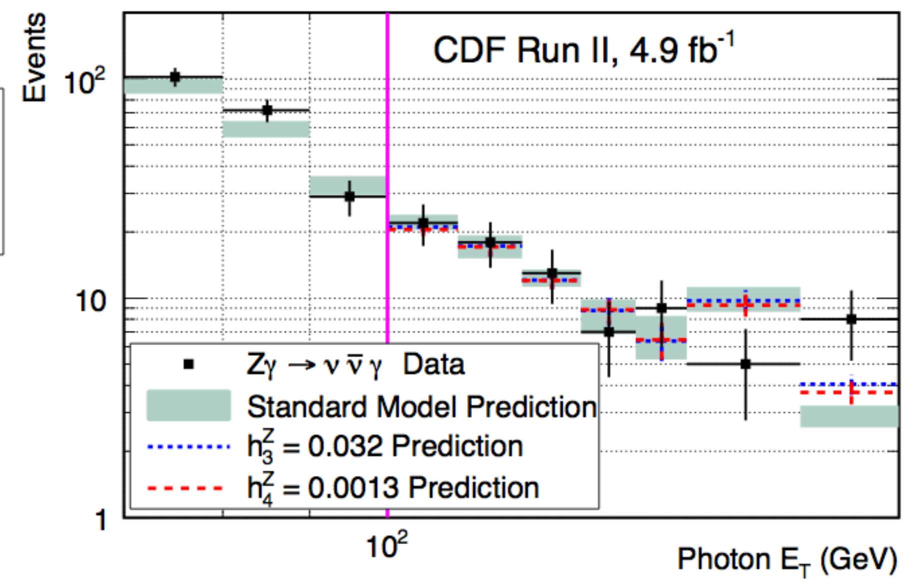


	$\ell\ell\gamma$ 6.2 fb^{-1} $\Lambda = 1.5$ TeV	$\ell\ell\gamma$ 7.2 fb^{-1} $\nu\nu\gamma$ 3.6 fb^{-1} $\Lambda = 1.5$ TeV
$\lvert h_{03}^{Z}\rvert <$	0.041	0.026
$\lvert h_{04}^{Z}\rvert <$	0.0023	0.0013
$\lvert h_{03}^{\gamma}\rvert <$	0.044	0.027
$\lvert h_{04}^{\gamma}\rvert <$	0.0023	0.0014

$Z\gamma \rightarrow \ell\ell\gamma$, $\nu\nu\gamma$ TGCs

- Combine high p_T lepton pair + γ and MET+γ



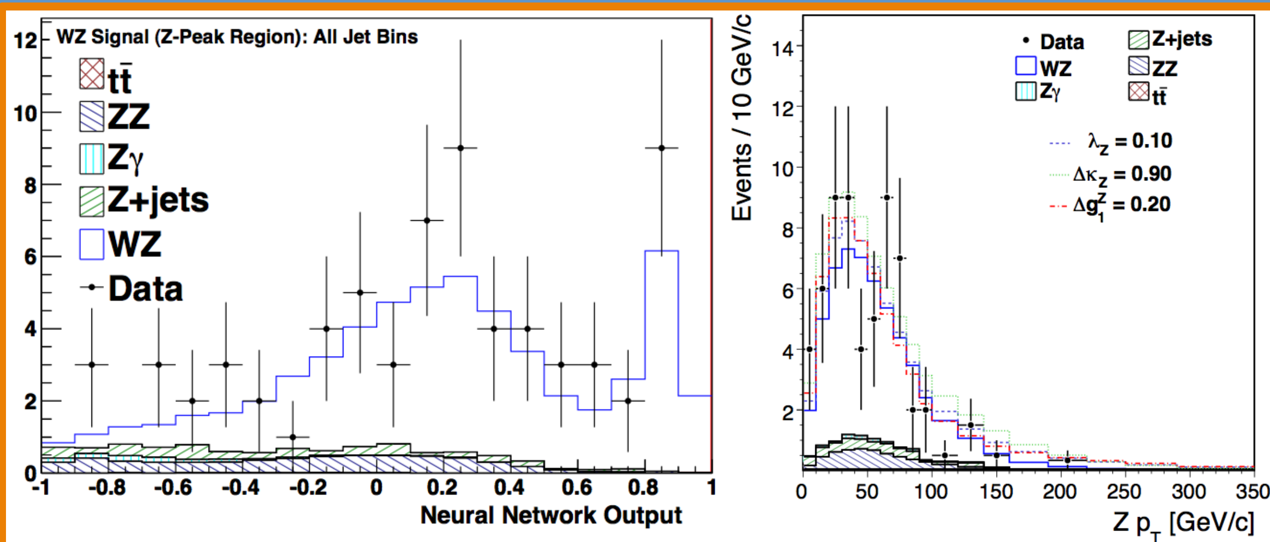


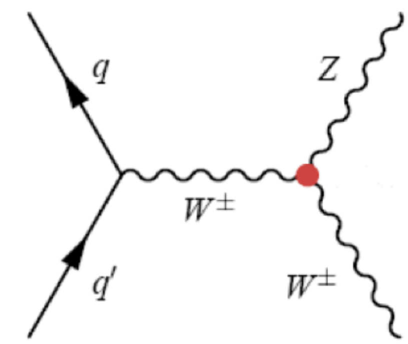
Parameter	$\Lambda = 1.5$ TeV
h_3^Z	$-0.020, 0.021$
h_4^Z	$-0.0009, 0.0009$
h_3^γ	$-0.022, 0.020$
h_4^γ	$-0.0008, 0.0008$

Dibosons at the Tevatron

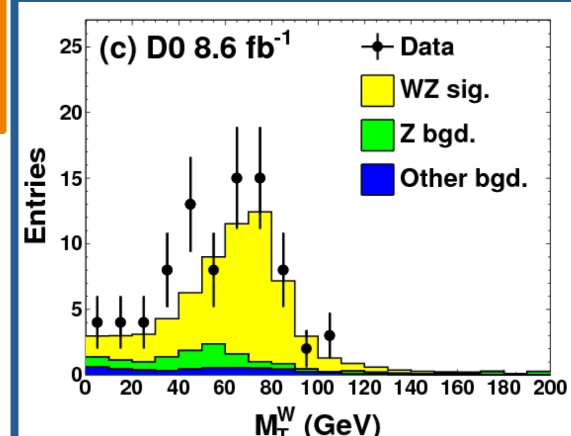
Sub. PRL [arXiv:1202.6629], 7.1 fb^{-1} Acc. PRD [arXiv:1201.5652], 8.6 fb^{-1}

$WZ \longrightarrow \ell'\nu\ell\ell$ Production





	Λ (TeV)	λ_Z	Δg_1^Z	$\Delta\kappa_Z$
Expected	1.5	(−0.11, 0.12)	(−0.12, 0.23)	(−0.58, 0.94)
Observed	1.5	(−0.09, 0.11)	(−0.09, 0.22)	(−0.42, 0.99)
Expected	2.0	(−0.10, 0.10)	(−0.11, 0.20)	(−0.53, 0.86)
Observed	2.0	(−0.08, 0.10)	(−0.08, 0.20)	(−0.39, 0.90)



SM: $\sigma = 3.46 \pm 0.21$ pb

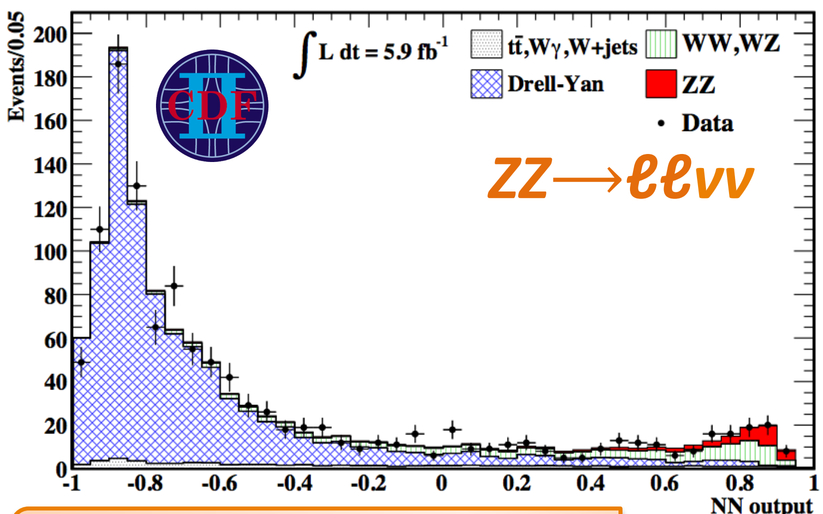
Obs: $\sigma = 3.9\ ^{+0.8}_{-0.7}$ (stat+syst) pb

Obs: $\sigma = 4.5\ ^{+0.6}_{-0.7}$ (stat+syst) pb

PRL 108 (2012) 101801, 6.1 fb^{-1} Acc. by PRD [arXiv:1201.5652], 8.6 fb^{-1}

$ZZ \longrightarrow 4\ell$, $\ell\ell\nu\nu$ Production

- *4ℓ:* Optimize for best acceptance & efficiency
- *ννℓℓ:* MET reconstruction critical

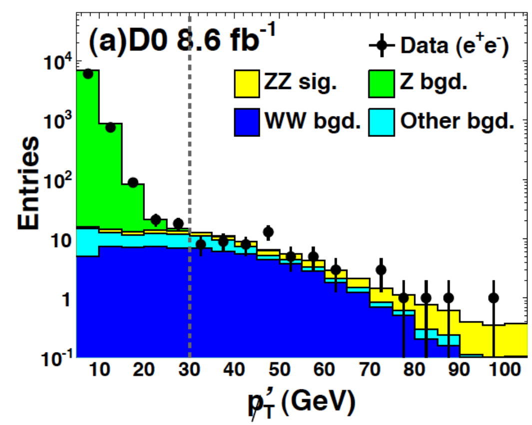


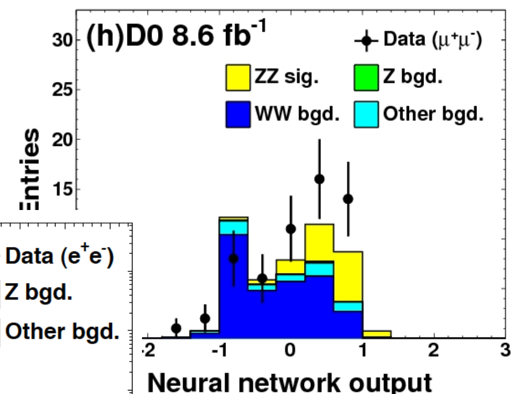
SM: σ = 1.40 ± 0.10 pb

Combination of $ZZ \longrightarrow 4\ell$, $\ell\ell\nu\nu$ channels:

Obs: $\sigma = 1.64\,^{+0.44}_{-0.38}$ (stat+syst) pb

ZZ⟶eeνν





ZZ⟶μμνν

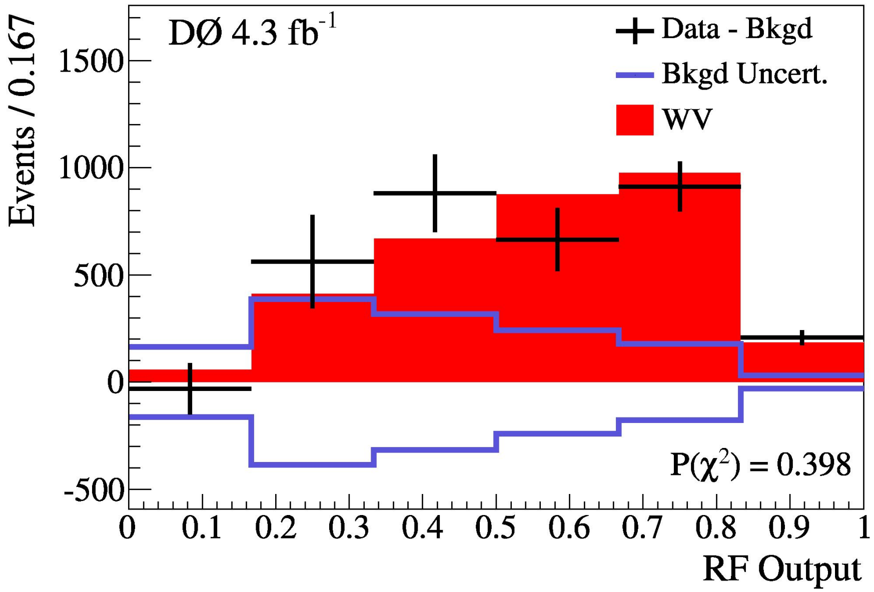
Combined with previous DØ 6.4 fb^{-1} $ZZ \longrightarrow 4\ell$:

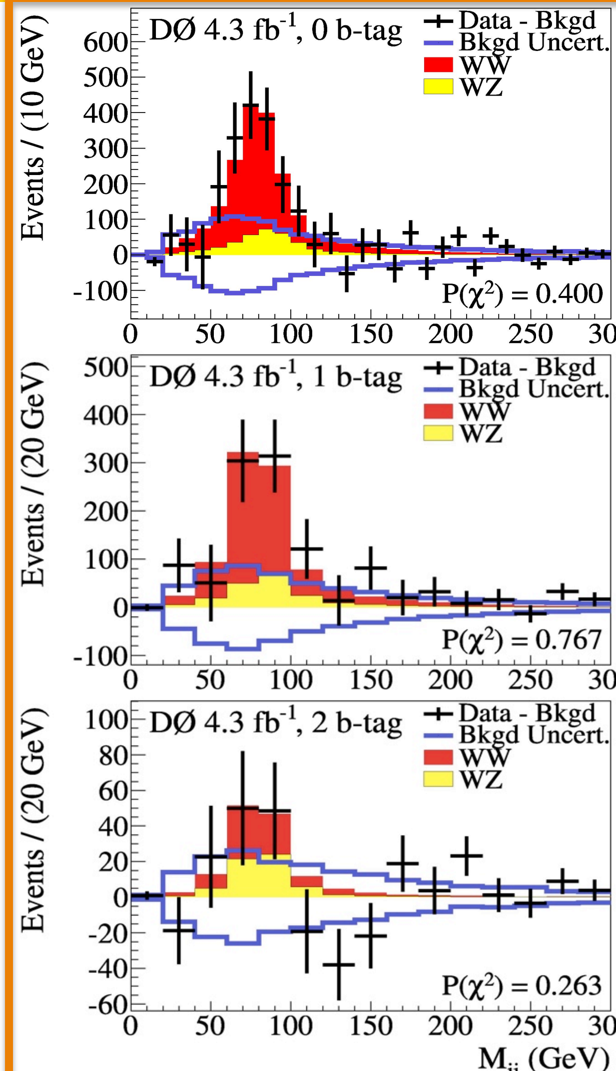
Obs: $\sigma = 1.44\,^{+0.35}_{-0.34}$ (stat+syst) pb

PRL 108, 181803 (2012), 4.3 fb^{-1}

WW/WZ⟶ℓν + (HF) jets

Signal ratio changes in tag bins





Obs: RF σ_{WW+WZ} = 19.6 $^{+3.2}_{-3.0}$ (stat+syst) pb

M_{jj} σ_{WW+WZ} = 18.3 $^{+3.8}_{-3.6}$ (stat+syst) pb

SM: σ_{WW} = 11.7 ± 0.8 pb

σ_{WZ} = 3.5 ± 0.3 pb

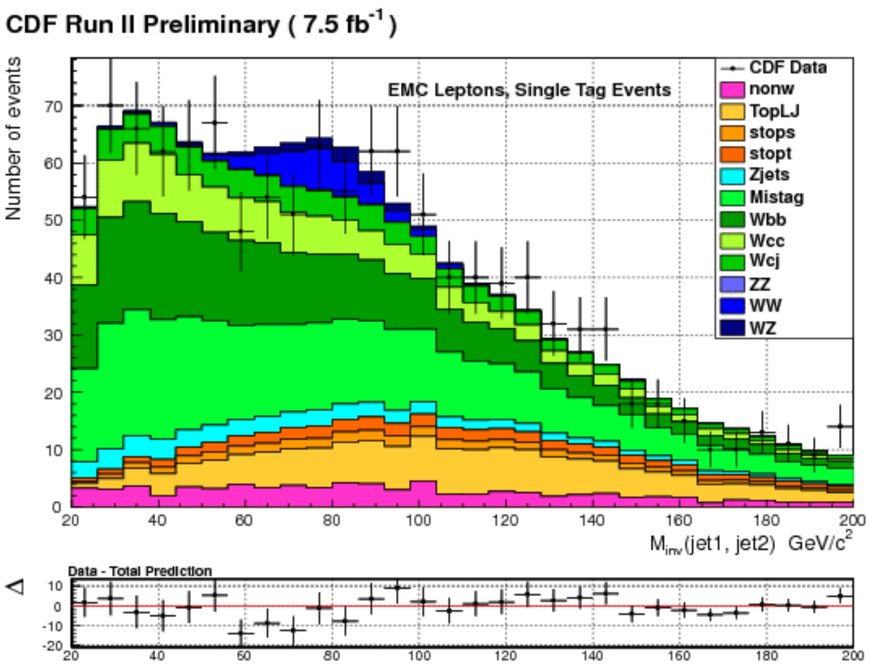
σ_{WW} = 15.9 $^{+3.7}_{-3.2}$ (st+sy) pb

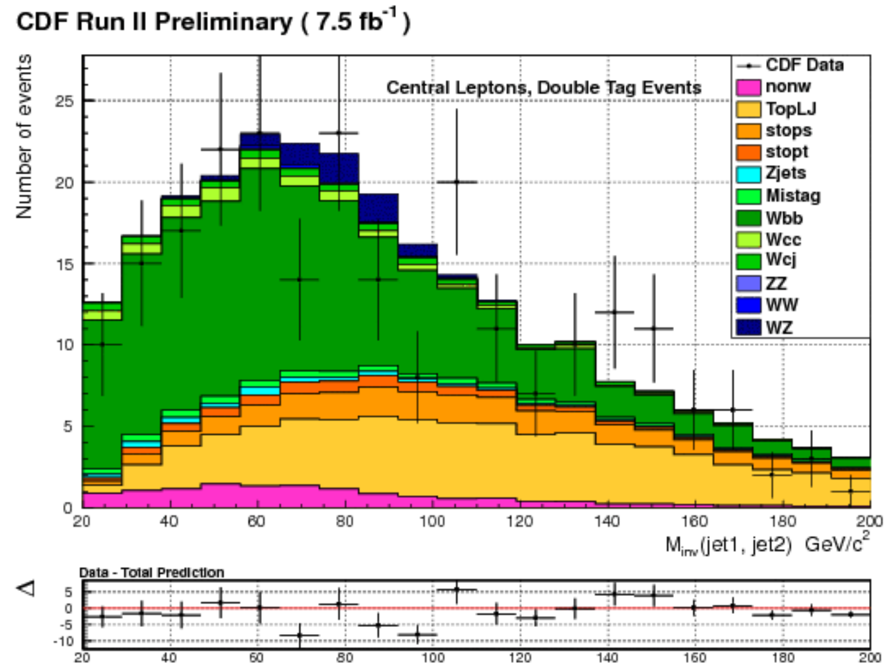
σ_{WZ} = 3.3 $^{+4.1}_{-3.3}$ (st+sy) pb

CDF Note 10598, 7.5 fb^{-1}

WW/WZ⟶ℓν + (HF) jets

- Lepton *η*, 1/2 *b*-tags divide into 4 channels
  - M_{jj} used to fit for signal



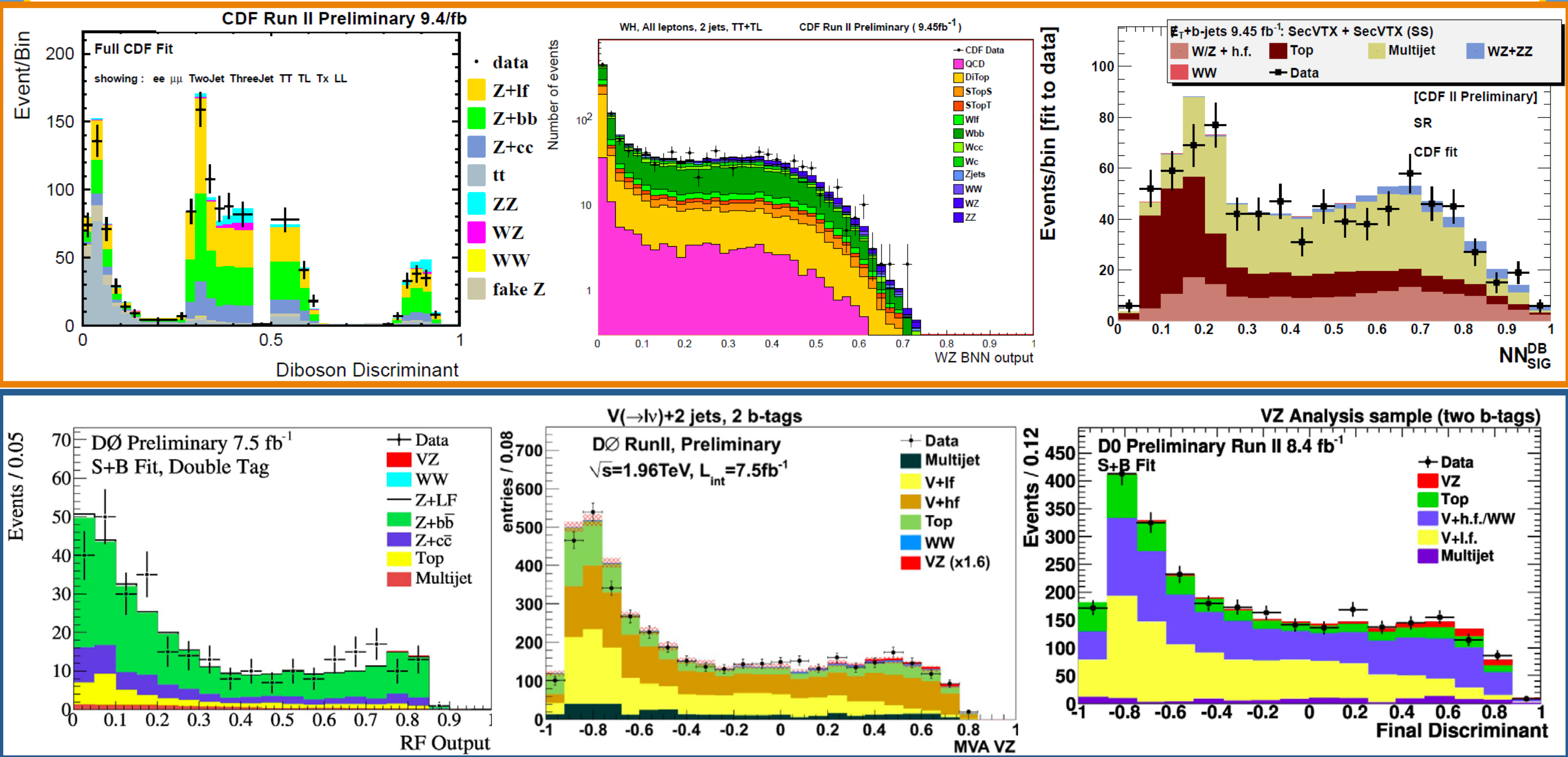


Obs: $\sigma_{WW+WZ} = 1.09^{+0.26}_{-0.40}$ (stat+syst) $\times\ \sigma_{SM}$

FERMILAB-CONF-12-063-E, 7.5-9.5 fb^{-1}

WZ/ZZ⟶ℓℓ/ℓν/νν + (HF) jets

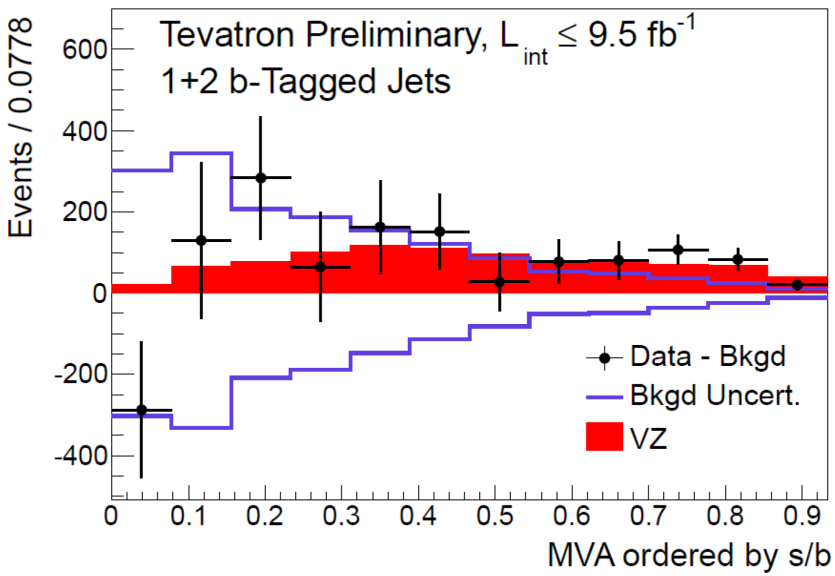
- Retrain Higgs search channels on diboson signal

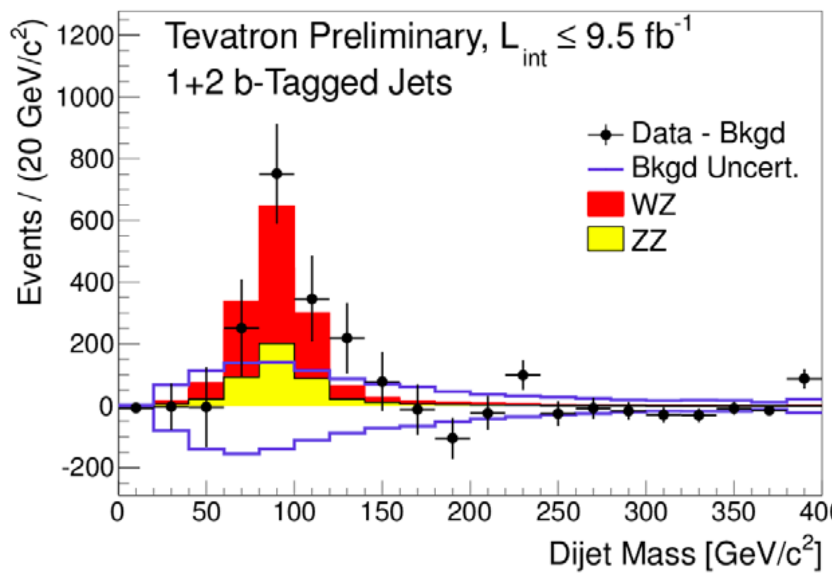


FERMILAB-CONF-12-063-E, 7.5-9.5 fb^{-1}

$WZ/ZZ \longrightarrow \ell\ell/\ell\nu/\nu\nu$ + (HF) jets

Validate Higgs analyses in diboson sector





SM: σ_{WZ+ZZ} = 4.4 ± 0.3 pb

CDF σ_{WZ+ZZ} = 4.1 $^{+1.4}_{-1.3}$ (stat+syst) pb 3.2σ

DØ σ_{WZ+ZZ} = 1.13 ± 0.36 (st+sy) × σ_{SM} 3.3σ

Tevatron σ_{WZ+ZZ} = 4.47 ± 0.64 (stat) $^{+0.73}_{-0.72}$ (syst) pb *4.6σ*

Summary

- Up to 9.4 fb^{-1} used to measure diboson production and study TGCs
  - No deviation from SM in observations
- Analyses in challenging final states set a firm foundation for the Tevatron program
  - Advanced techniques help observe difficult final states, including $WW/WZ \rightarrow \ell\nu + (HF)$ *jets*
  - Evidence of $WZ/ZZ \rightarrow \ell\ell/\ell\nu/\nu\nu + (HF)$ *jets* demonstrates our sensitivity to small signals

Diboson Production

at the Tevatron

CDF II DØ

Thank you!

Michael Cooke

Fermilab