Diboson Production at the Tevatron

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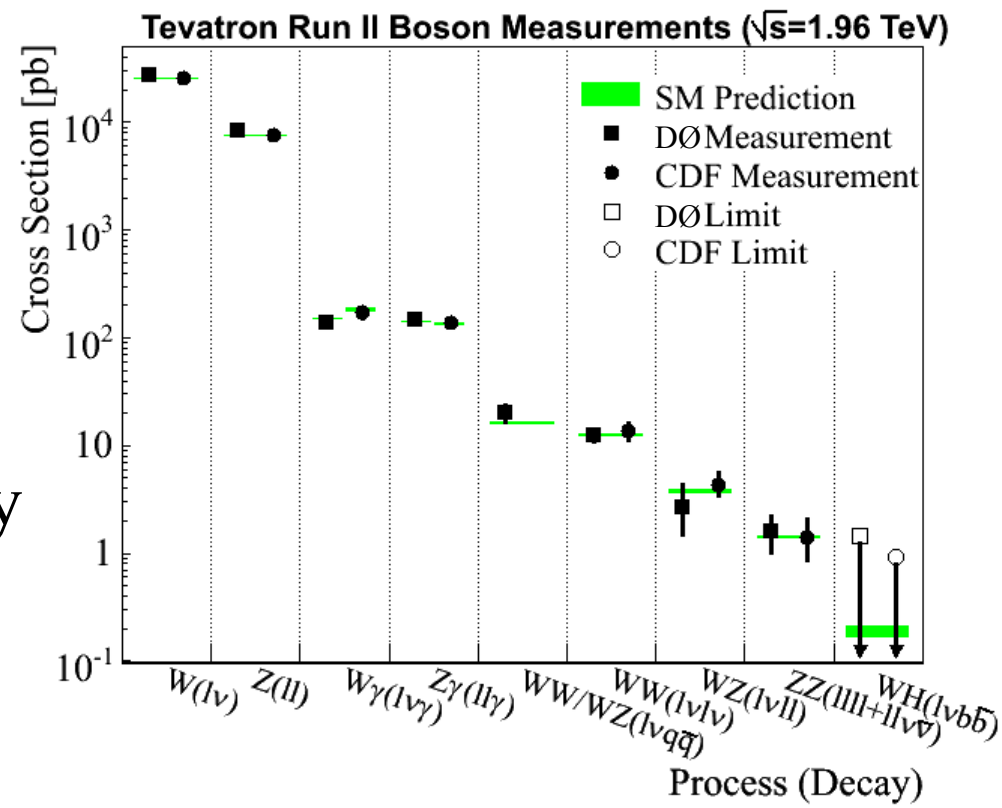
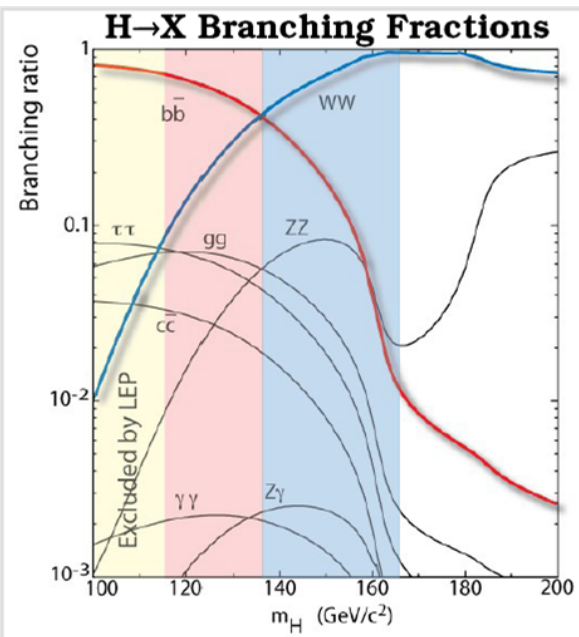
on behalf of the CDF and DØ Collaborations

DIS 2009, April 28th, Madrid, Spain

Diboson Physics

- Diboson processes have low cross sections
  - Provide natural series of goals for detector sensitivity
  - Probe fundamental details of the SM EW sector directly

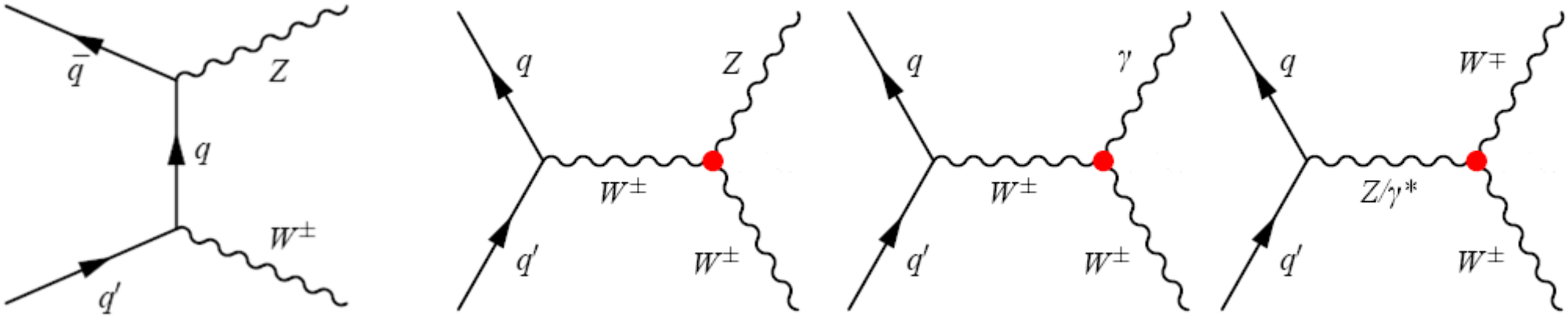




- Direct window to SM Higgs decay
  - Higgs can decay directly into *WW*, *ZZ*, *Zγ*
  - Associated *WH*, *ZH* production

Search for Anomalous Couplings

- SM includes two triple gauge-boson verticies
  - Contribute directly to $W\gamma$, WW, WZ production



- Assuming EM gauge invariance and C and P conservation, the most general Lorentz invariant effective Lagrangian for triple gauge couplings is:

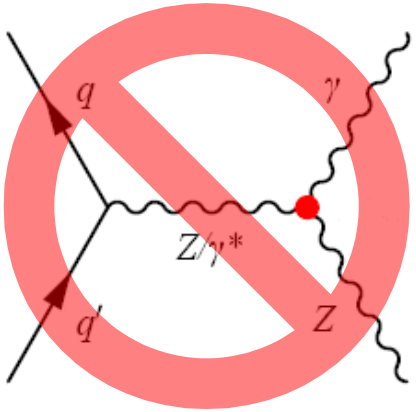
$$\frac{L_{WWV}}{g_{WWV}} = i\boxed{g_1^V}\left(W^{\dagger}_{\mu\nu}W^{\mu}V^{\nu} - W^{\dagger}_{\mu}V_{\nu}W^{\mu\nu}\right) + i\boxed{\kappa_V}W^{\dagger}_{\mu}W_{\nu}V^{\mu\nu} + i\frac{\boxed{\lambda_V}}{M_W^2}W^{\dagger}_{\lambda\mu}W^{\mu}_{\nu}V^{\nu\lambda}$$

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

- In SM: $g_1^V = \kappa_V = 1$, $\lambda_V = 0$

Search for Anomalous Couplings

- Equivalent triple-gauge boson vertex does not exist in SM for $Z\gamma\gamma/ZZ\gamma$
  - Can probe for this anomalous tree-level diagram in $Z\gamma$ production
  - Most general Lagrangian has CP-odd and CP-even couplings



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

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

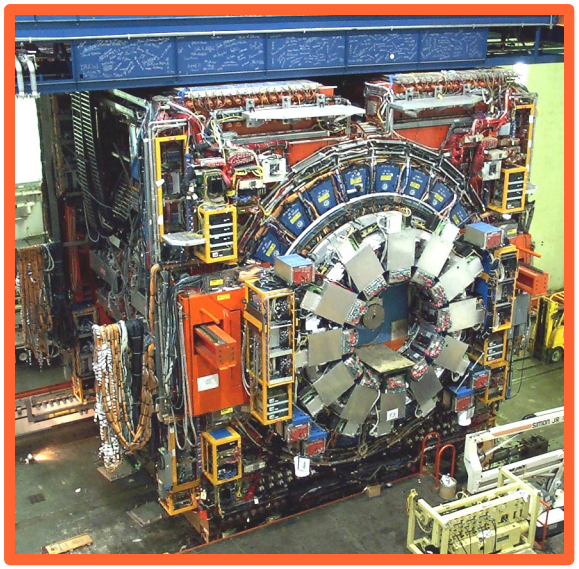
- To preserve partial-wave unitarity and avoid divergent cross-sections, TGCs are introduced as form factors:
  - Limits set in terms of A_0
  - Λ sets scale of new physics

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

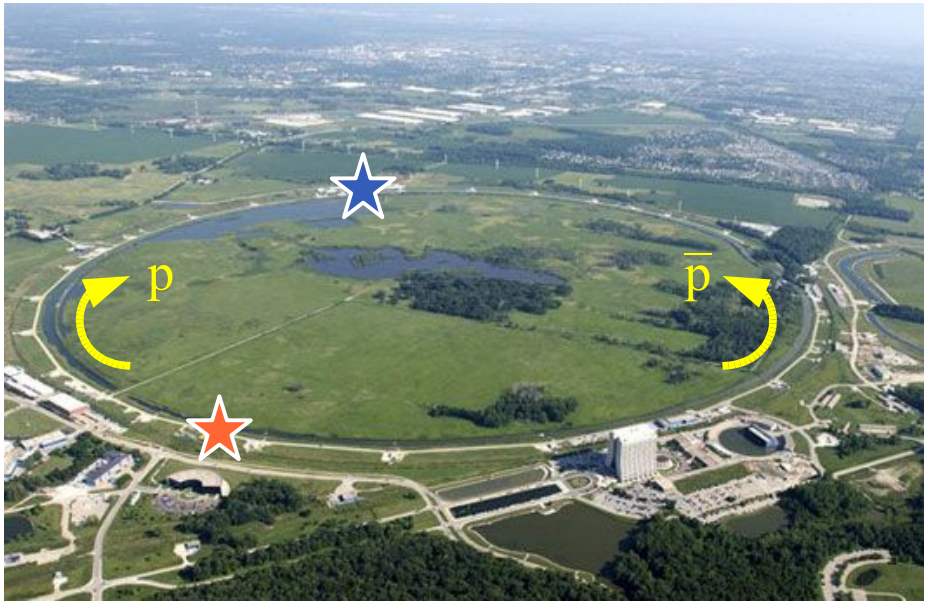
  - n = 2 for κ_V, λ_V, g_1^Z
  - n = 3 for h_1^V, h_3^V
  - n = 4 for h_2^V, h_4^V

Creating Dibosons at Fermilab

- Tevatron produces $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV
  - CDF and DØ detectors measure the created particles

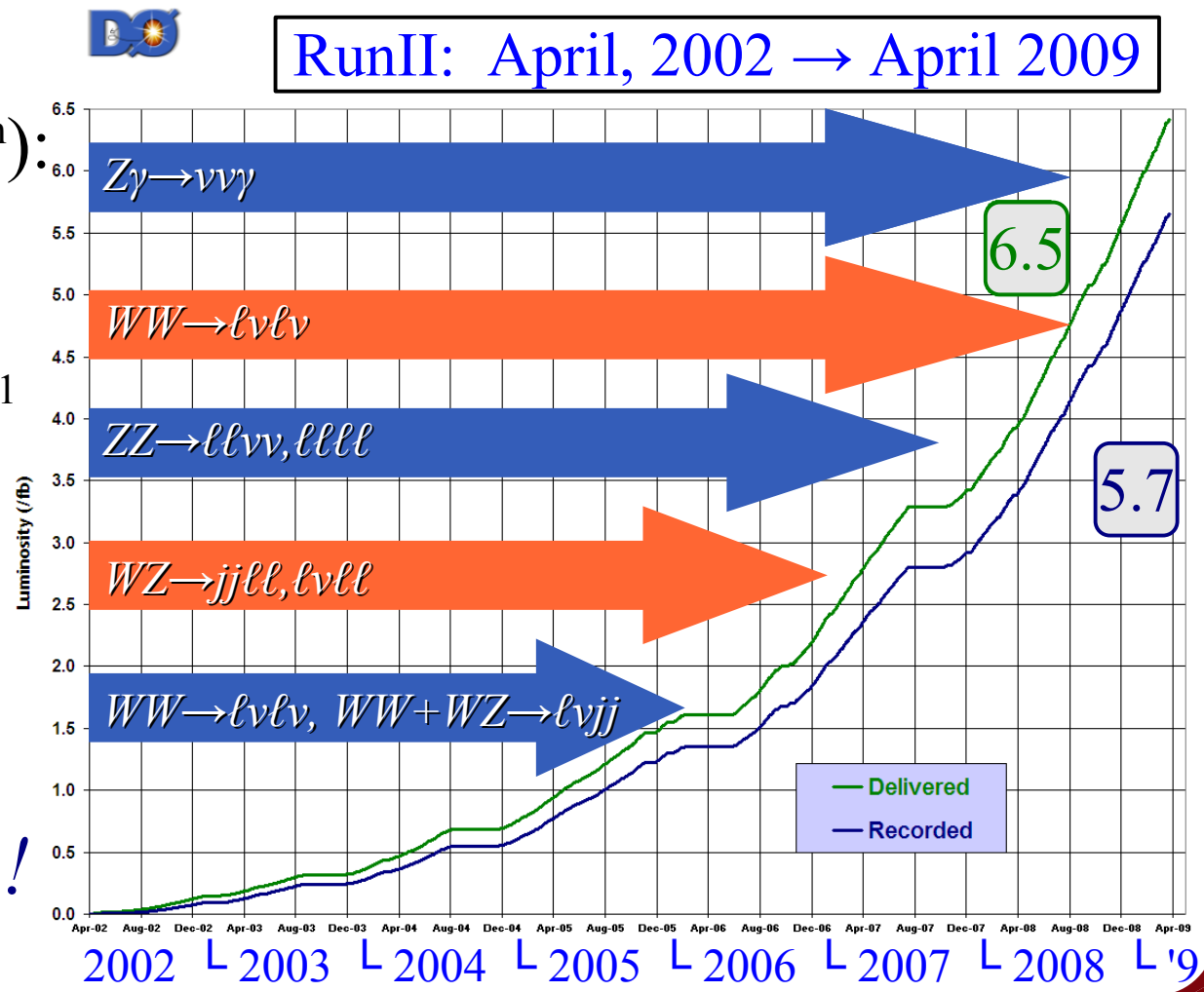


36-on-36 particle bunches
with 396 ns spacing
1.7 million collisions per second

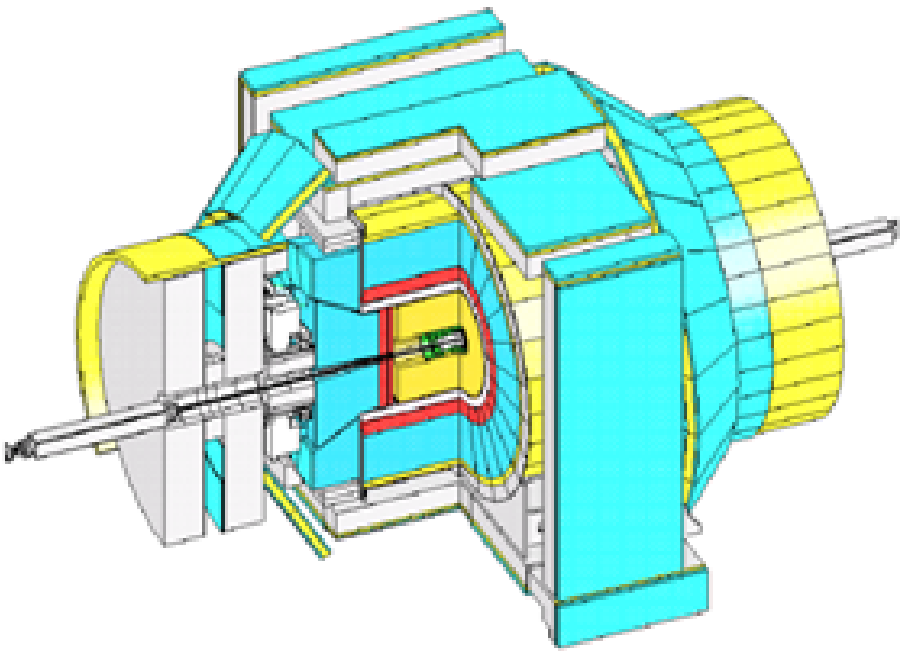


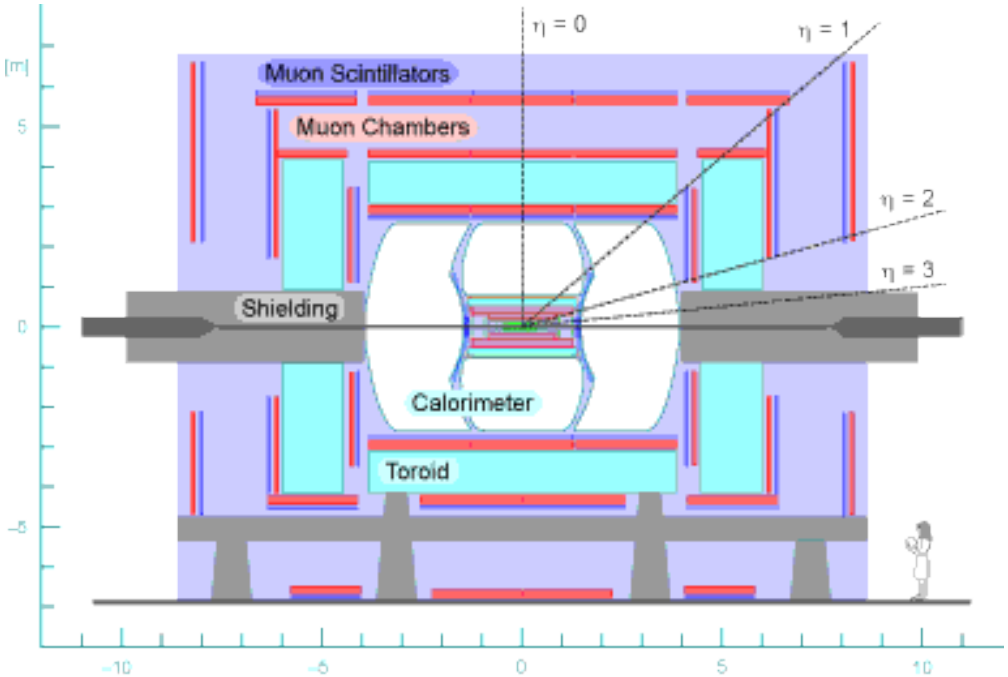
Tevatron Performance

- Tevatron has delivered 6.5 fb^{-1} of integrated luminosity to each experiment so far in RunII!
  - Record weekly int. lumi. (April 13th–20th): 73.1 pb^{-1}
  - 1992-95 (RunI) int. luminosity: ~110 pb^{-1}
  - Results presented today correspond to 1.0–3.6 fb^{-1}
- *Thank you, Accelerator Division!*



The CDF and DØ Detectors





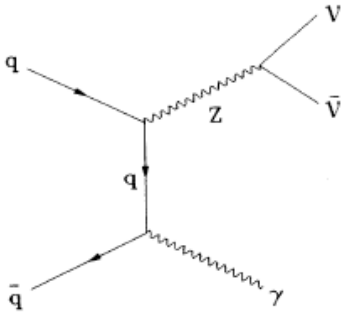
- Silicon vertex detector
- Wire drift chamber tracking
- Pb/Fe-scintillator calorimetry
- Muon chambers

- Silicon vertex detector
- Scintillating fiber tracking
- LAr-U compensating cal.
- Muon chambers

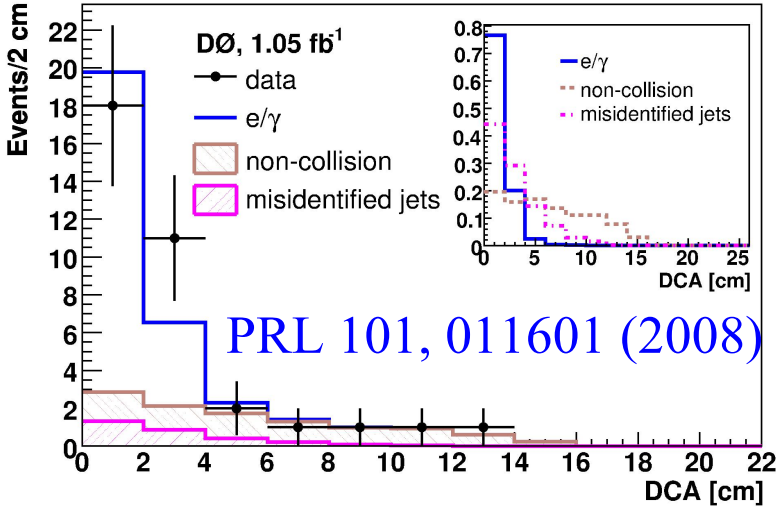
$Z\gamma \rightarrow \nu\nu\gamma$

arXiv [0902.2157]
Submitted to PRL
3.6 fb^{-1}

- Only ISR diagram contributes to $Z\gamma \rightarrow \nu\nu\gamma$ at tree level
  - SM NLO $\sigma_{Z\gamma}^{[E_T^\gamma > 90\ \mathrm{GeV}]} = 39 \pm 4$ fb; selection:
    - Missing $E_T > 70$ GeV
    - Central calorimeter γ candidate with $E_T > 90$ GeV
      - Use EM shower pointing to confirm vertex & estimate backgrounds
    - Veto on: Jet or 2nd EM object with $E_T > 15$ GeV; muons; iso. tracks



	Number of events
$W \rightarrow e\nu$	$9.67 \pm 0.30(\mathrm{stat.}) \pm 0.48(\mathrm{syst.})$
non-collision	$5.33 \pm 0.39(\mathrm{stat.}) \pm 1.91(\mathrm{syst.})$
W/Z + jet	$1.37 \pm 0.26(\mathrm{stat.}) \pm 0.91(\mathrm{syst.})$
$W\gamma$	$0.90 \pm 0.07(\mathrm{stat.}) \pm 0.12(\mathrm{syst.})$
Total background	$17.3 \pm 0.6(\mathrm{stat.}) \pm 2.3(\mathrm{syst.})$
$N_{\nu\bar{\nu}\gamma}^{\mathrm{SM}}$	33.7 ± 3.4
N_{obs}	51



PRL 101, 011601 (2008)

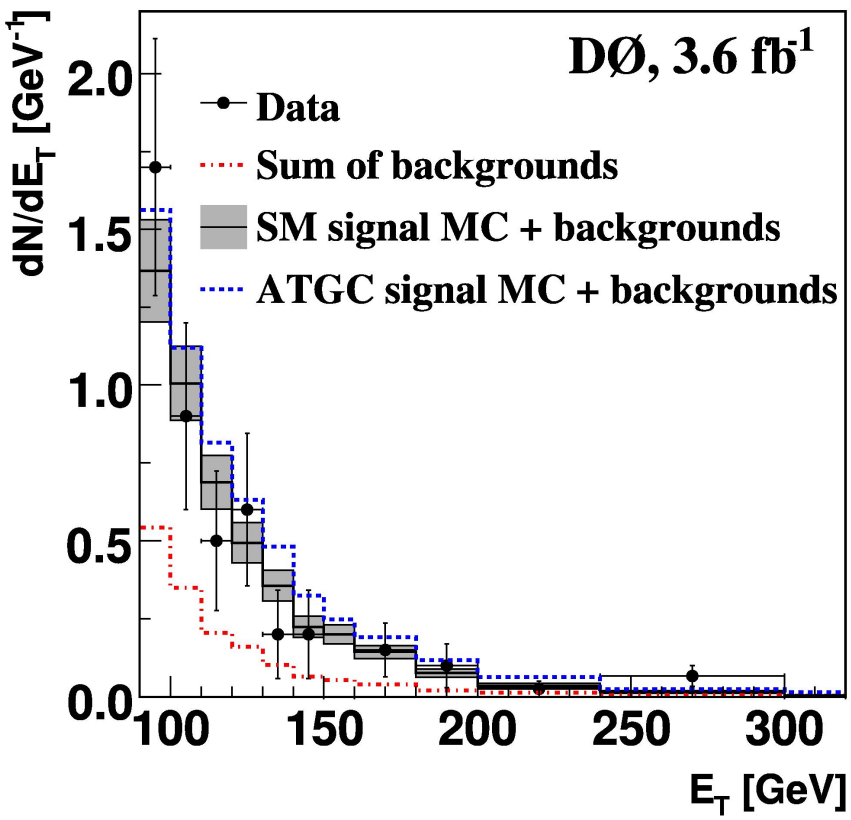
- OBSERVATION (5.1σ): $[E_T^\gamma > 90\ \mathrm{GeV}]$

$\sigma_{Z\gamma} = 32 \pm 9$ (stat+syst) ± 2 (lumi) fb

$Z\gamma \rightarrow \nu\nu\gamma$: ATCGs

arXiv [0902.2157]
Submitted to PRL
3.6 fb^{-1}

- Photon E_T spectrum used to examine anomalous TGCs
  - No distinction between CP-even/odd couplings ($h_{1,2}^V$ vs $h_{3,4}^V$)
  - Combined with DØ $Z\gamma \rightarrow \ell\ell\gamma$ [PLB 653, 378 (2007); 1.1 fb^{-1}]



$|h_{30}^\gamma| < 0.033$ $|h_{40}^\gamma| < 0.0017$
$|h_{30}^Z| < 0.033$ $|h_{40}^Z| < 0.0017$

- Tightest limits from hadronic collider!
  - 3× improvement vs $Z\gamma \rightarrow \ell\ell\gamma$
  - All but h_{30}^γ improve upon LEP2

$WW \to \ell\nu\ell\nu$

arXiv [0904.0673]
Submitted to PRL
1.0 fb^{-1}

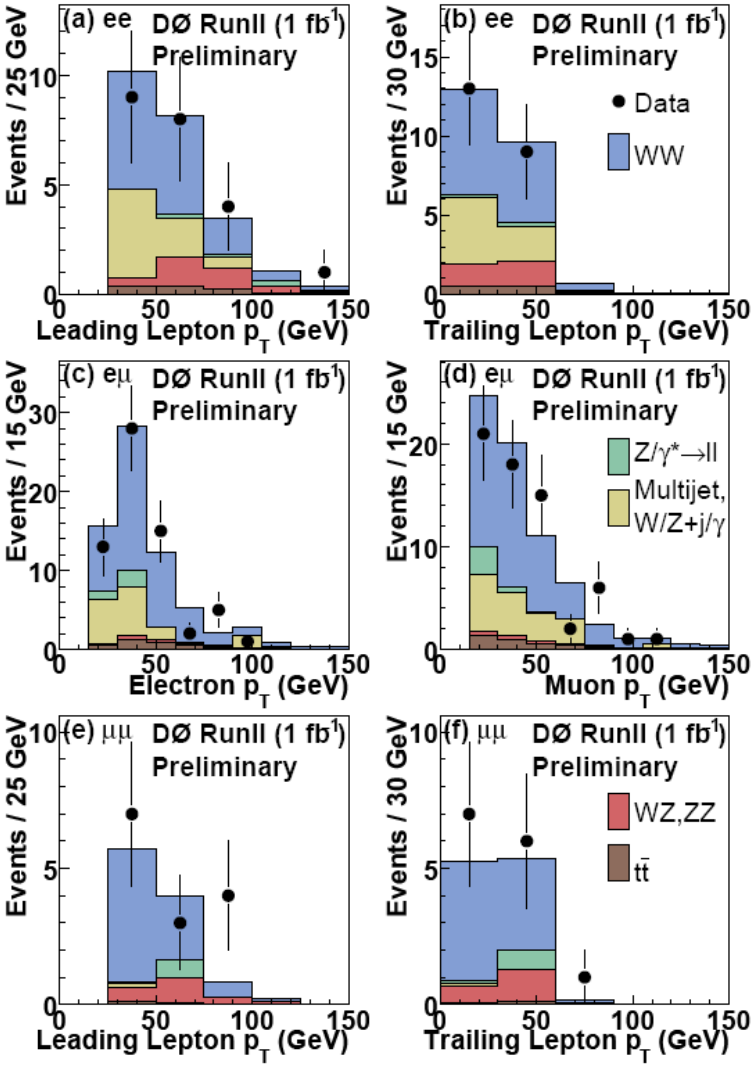
Individual channel cuts optimized for σ_{WW} measurement

- SM NLO $\sigma_{WW} = 12.4 \pm 0.7$ pb:
  - Lepton $p_T > 25$, 15 GeV
  - $\not{E}_T > 45$ (ee), 20 ($e\mu$), 35 ($\mu\mu$) GeV
  - Maximum p_T^{WW} cut suppresses Z and $t\bar{t}$

$WW \to \ell\ell'$	10.98 ± 0.59	39.25 ± 0.81	7.18 ± 0.34
$WW \to \ell\tau/\tau\tau \to \ell\ell'$	1.40 ± 0.20	5.18 ± 0.29	0.71 ± 0.10
Total expected	23.46 ± 1.90	68.64 ± 3.88	10.79 ± 0.58
Data	22	64	14

$\sigma_{WW} = 11.5 \pm 2.1$ (stat+syst) ± 0.7 (lumi) pb

Most precise at hadronic collider when submitted Apr. 3rd!



TGC limits based on lepton p_T:

$\Lambda = 2$ TeV
LEP: $-0.54 < \Delta\kappa_\gamma < 0.83$, $-0.14 < \lambda < 0.19$, $-0.14 < \Delta g_1^Z < 0.30$
EQUAL: $-0.12 < \Delta\kappa_\gamma = \Delta\kappa_Z < 0.35$, $-0.14 < \lambda_\gamma = \lambda_Z < 0.19$

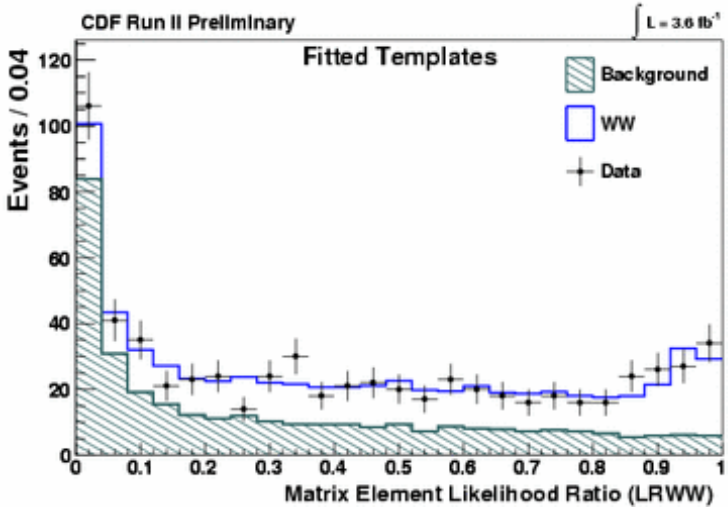
$WW \rightarrow \ell\nu\ell\nu$

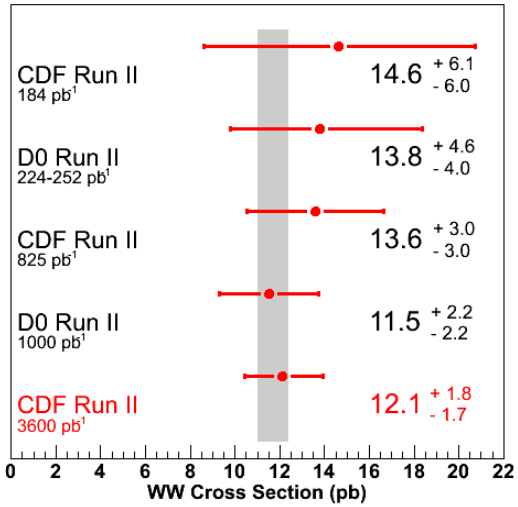
Preliminiary
3.6 fb^{-1}

- Matrix element based likelihood ratio analysis
  - SM NLO $\sigma_{WW} = 12.4 \pm 0.7$ pb:
    - Event kinematics are used to assign a probability based on LO ME cross section calculation for the *WW*, *ZZ*, *Wγ* and *W+jet* processes

CDF Run II Preliminary $\int \mathcal{L} = 3.6\ \mathrm{fb}^{-1}$

Process	Events		
Z/γ^*	79.8	$\pm$	18.4
WZ	13.8	$\pm$	1.9
$W\gamma$	91.7	$\pm$	24.8
W+jets	112.7	$\pm$	31.2
ZZ	20.7	$\pm$	2.8
$t\bar{t}$	1.3	$\pm$	0.2
Total Background	320.1	$\pm$	46.8
WW	317.6	$\pm$	54.1
Signal+Background	637.6	$\pm$	79.6
Data	**654**		





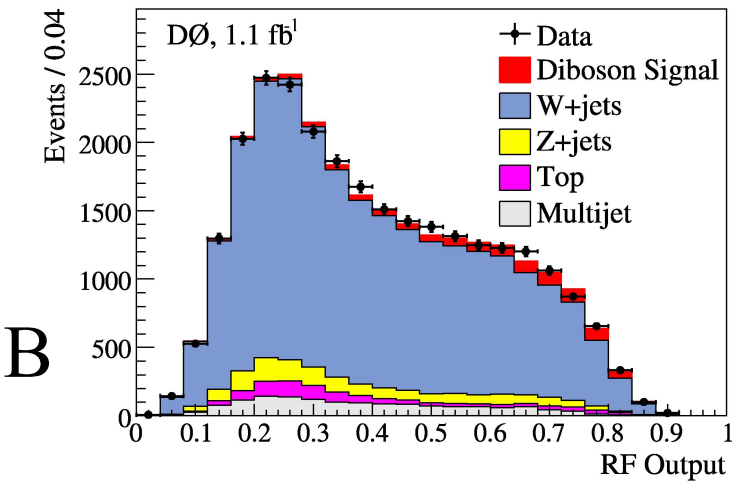
$$\sigma_{WW} = 12.1 \pm 0.9\ (\mathrm{stat})\ ^{+1.6}_{-1.4}\ (\mathrm{syst})\ \mathrm{pb}$$

Public note made available on April 20th,
currently most precise measurement at hadronic collider!

$WW+WZ \rightarrow \ell\nu jj$

arXiv [0810.3873]
Accepted by PRL
1.1 fb^{-1}

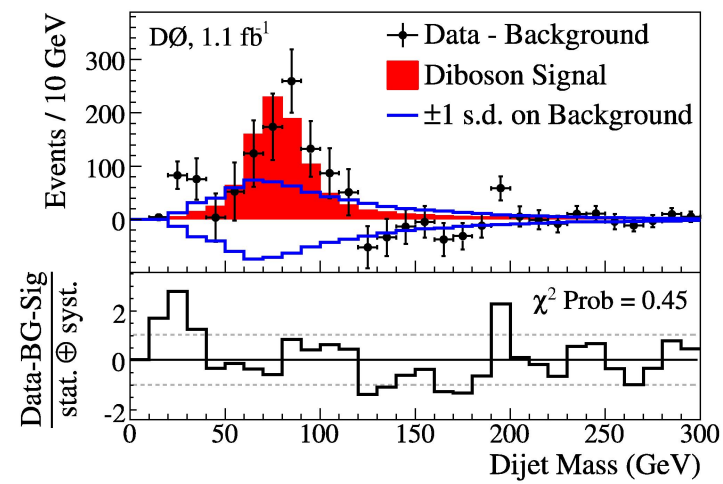
- Multivariate discriminant separates WW/WZ from $W+j$
  - SM NLO $\sigma_{WW+WZ} = 16.1 \pm 0.9$ pb; selection:
    - e/μ $p_T > 20$ GeV; Missing $E_T > 20$ GeV
    - 2+ jets with $p_T > 30, 20$ GeV
    - Transverse W mass > 35 GeV
  - Random Forest discriminates S from B
    - Average over many decision trees



- Fit to RF output determines signal
  - RF fit p-value = 5.4×10^{-6} (4.4σ)

σ_{WW+WZ} = 20.2 ± 2.5 (stat) ± 3.6 (syst) ± 1.2 (lumi) pb

First EVIDENCE in this channel at hadronic collider!

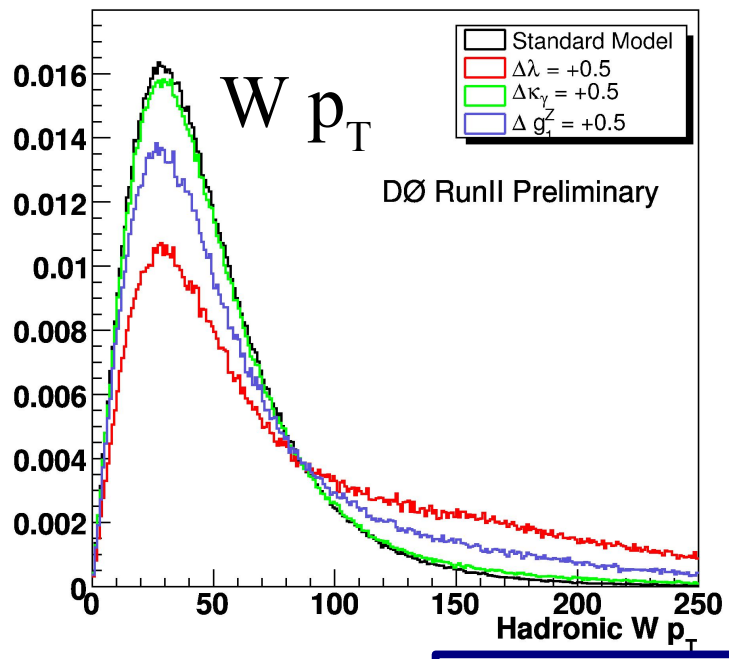


$WW+WZ \rightarrow \ell\nu jj$: ATCGs

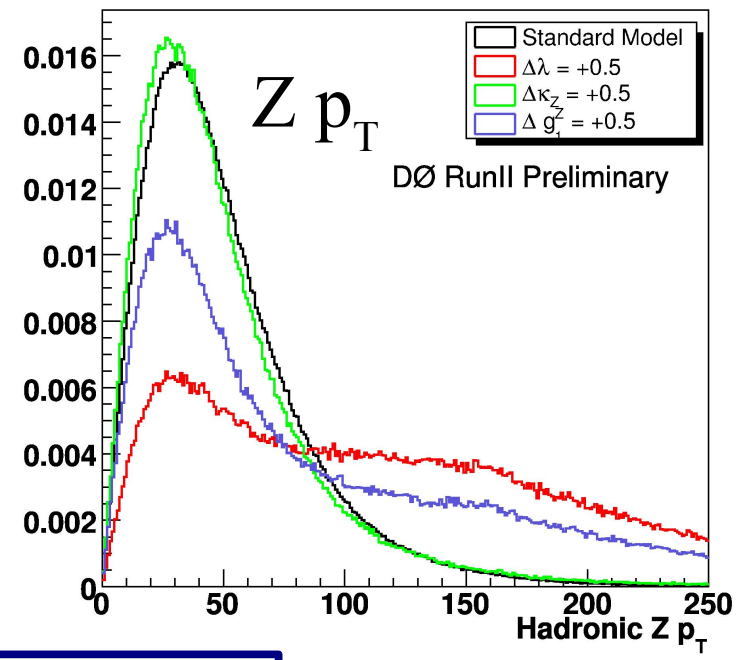
Preliminary
1.1 fb^{-1}

- Dijet mass spectrum used to examine anomalous TGCs
  - Smallest allowed range of values at 95% C.L. from Tevatron

W p_T distributions (generator level)



Z p_T distributions (generator level)



- LEP Constraints conserve $SU(2)_L \otimes U(1)_Y$ symmetry
- Specifically, $\lambda_\gamma = \lambda_Z$ and $\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan\theta_W$

LEP Compatible, $\Lambda = 2$ TeV
$-0.12 < \Delta g_1^Z < 0.20$
$-0.44 < \Delta\kappa_Z < 0.55$
$-0.10 < \lambda_Z < 0.11$

Equal Couplings, $\Lambda = 2$ TeV
$-0.16 < \Delta\kappa_\gamma = \Delta\kappa_Z < 0.23$
$-0.11 < \lambda_\gamma = \lambda_Z < 0.11$

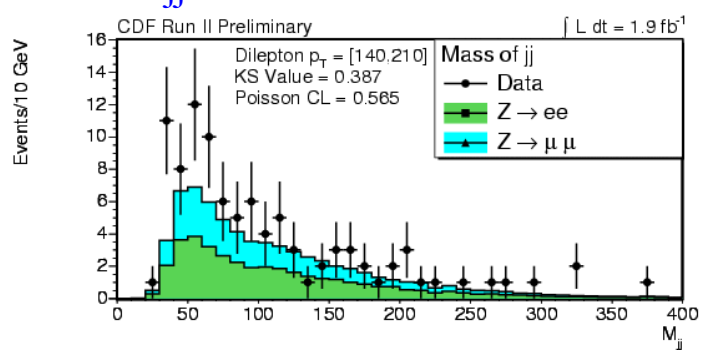
$WZ \rightarrow jj\ell\ell$

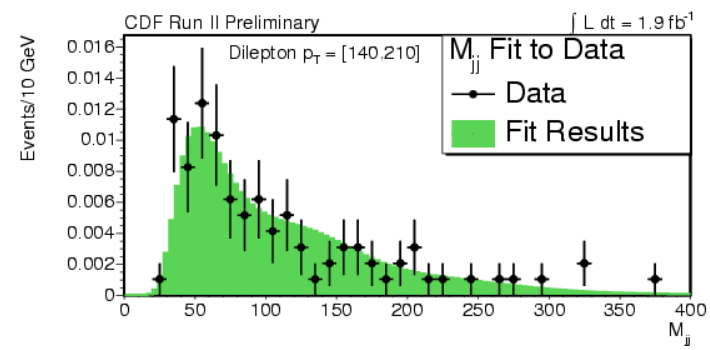
Preliminary
1.9 fb^{-1}

- Three bins in Z boson p_T used to study σ_{WZ} and ATGCs
  - [105-140] GeV: Control bin
    - Dominated by high p_T Drell-Yan, used to test modeling
  - [140-210] GeV: Medium and [210+] GeV: High
    - Used to perform m_{jj} fits to set limits on σ_{WZ} and ATGCs

Medium p_T Bin

channel	Total	Data
e e	30.0	34
$\mu\ \mu$	23.8	36
e trk	8.5	17
μ trk	8.3	10
Total	71.4 ± 0.5	97





High p_T Bin

channel	Total	Data
e e	4.0	5
$\mu\ \mu$	3.4	4
e trk	1.2	2
μ trk	1.2	1
Total	9.74 ± 0.178	12

95% C.L. σ_{WZ} Limits:
Medium Bin: 234 fb
High Bin: 135 fb

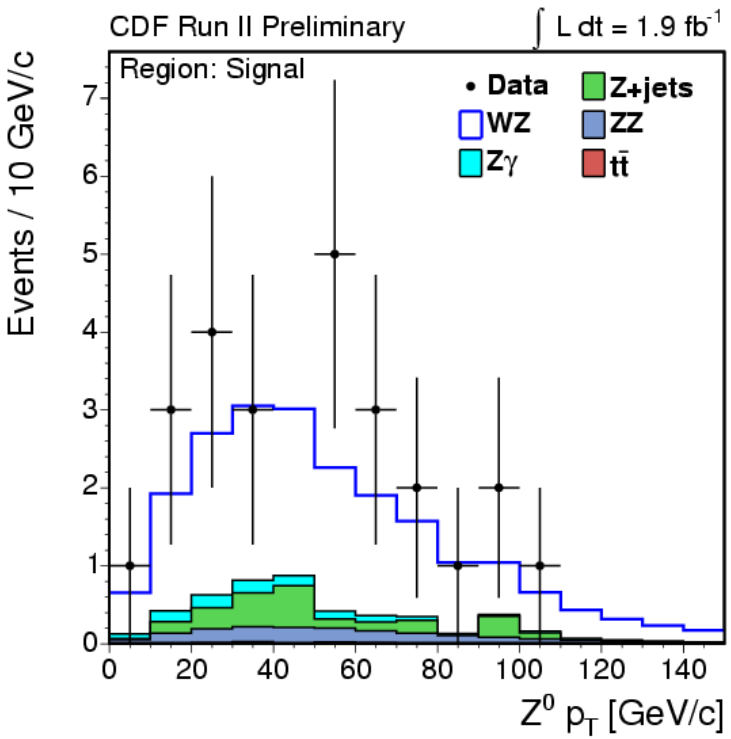
$\Lambda = 1.5$ TeV:
$-0.22 < \Delta g_1^Z < 0.32$
$-1.09 < \Delta\kappa_Z < 1.40$
$-0.18 < \lambda_Z < 0.18$

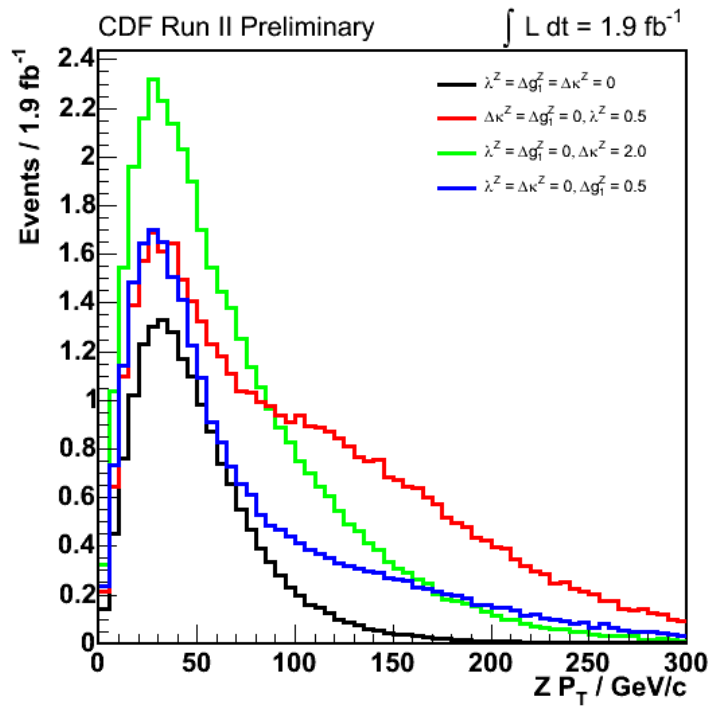
$\Lambda = 2.0$ TeV:
$-0.20 < \Delta g_1^Z < 0.29$
$-1.01 < \Delta\kappa_Z < 1.27$
$-0.16 < \lambda_Z < 0.17$

$WZ \to \ell\nu\ell\ell$: ATGCs

Preliminary
1.9 fb^{-1}

- Z boson p_T spectrum used to set 95% C.L. limits on anomalous TGCs
  - Extends PRL 98, 161801 (2007), using 25 observed events





$\Lambda = 1.5$ TeV:
$-0.14 < \Delta g_1^Z < 0.25$
$-0.81 < \Delta\kappa_Z < 1.29$
$-0.14 < \lambda_Z < 0.15$

$\Lambda = 2.0$ TeV:
$-0.13 < \Delta g_1^Z < 0.23$
$-0.76 < \Delta\kappa_Z < 1.18$
$-0.13 < \lambda_Z < 0.14$

$ZZ \to \ell\ell\nu\nu$

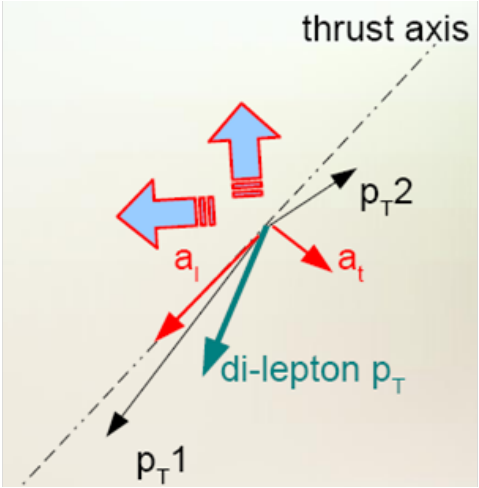
Phys. Rev. D 78, 072002 (2008)
2.7 fb^{-1}

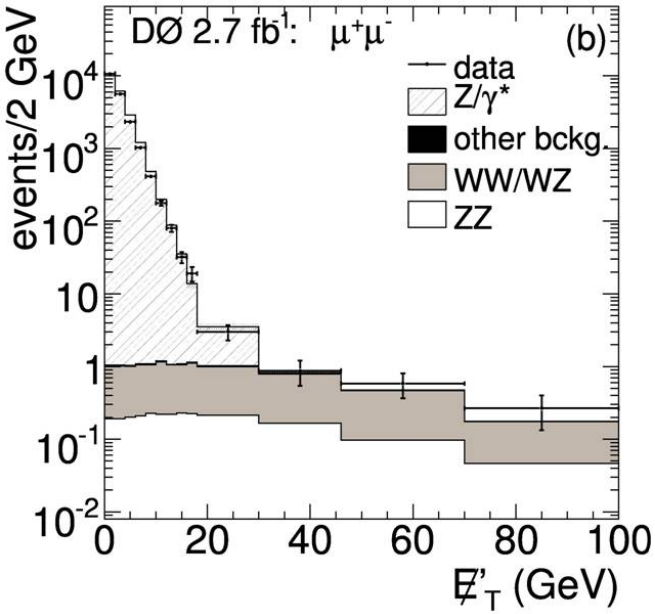
- Getting a good handle on Missing E_T is critical!
  - SM NLO $\sigma_{ZZ} = 1.4 \pm 0.1$ pb; selection:
    - Select *ee/μμ* events with lepton $p_T > 15$ GeV
    - Veto extra EM clus. (5 GeV), muons, iso. tracks, > 2 jets (10 GeV)
  - Create "corrected E_T" discriminant
    - Minimize effect of mismeasured jets/μ

$$\hat{\not{E}}_T = \sqrt{\hat{\not{E}}_l^2 + (1.5\,\hat{\not{E}}_t)^2} - \delta_{LeptonTrks} - \delta_{JetTrks}$$

  - Expect 7.4 *ZZ*, 26.5±0.5 bkgd; 43 data
- LLR p-value = 4.2×10^{-3} (2.6σ):

σ_{ZZ} = 2.01 ± 0.93 (stat) ± 0.29 (syst) pb

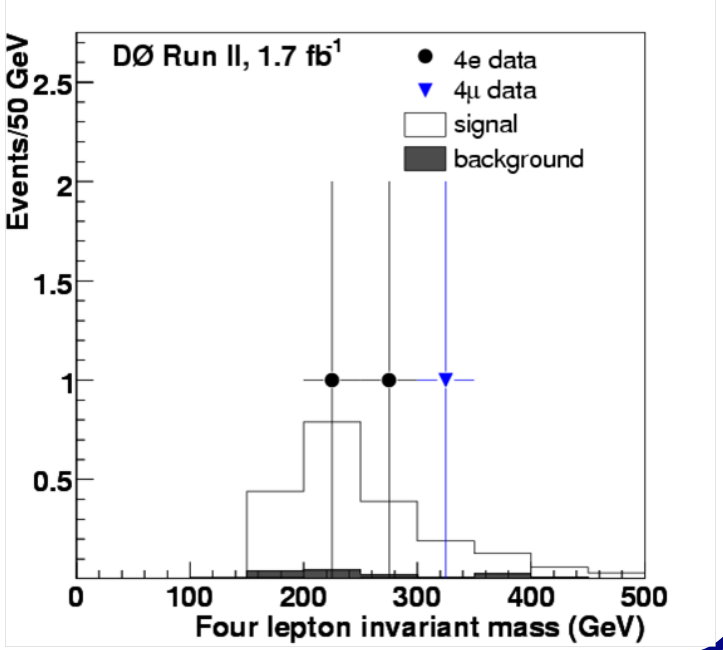




$ZZ \rightarrow \ell\ell\ell\ell$

Phys. Rev. Lett. 101, 171803 (2008) 1.7 fb^{-1}

- Analysis focused on optimization of lepton selection
  - SM NLO $\sigma_{ZZ} = 1.4 \pm 0.1$ pb; selection:
    - Study *eeee*, *eeμμ*, *μμμμ* channels, with tighter cuts on lepton p_T, lepton isolation and dilepton mass than previous DØ analysis
      - $4e/4\mu$ require $p_T > 30, 25, 15, 15$ GeV (*eeμμ* 25, 15); all > 15 GeV before
      - Dilepton mass pairs > 70, 50 GeV vs. > 30, 30 GeV in previous analysis
- Comparison to previous 1 fb^{-1} analysis (no data overlap):
  - 1 fb^{-1}: expect 1.71 ± 0.15 *ZZ*, 0.13 ± 0.03 bkgd; observed 1 event
  - 1.7 fb^{-1}: expect 1.89 ± 0.08 *ZZ*, 0.14 ± 0.03 bkgd; observed 3 events



ZZ Combination

Phys. Rev. Lett. 101, 171803 (2008) 2.7 fb^{-1}

- 1.7 fb^{-1} $ZZ \rightarrow \ell\ell\ell\ell$ observations: p-value 4.3×10^{-8} (5.3σ)
  - $\sigma_{ZZ} = 1.75\ ^{+1.27}_{-0.86}$ (stat) $\pm$ 0.13 (syst) pb
- Three analyses combined into final σ_{ZZ} measurement:
  - Non-overlapping 1.0 fb^{-1} and 1.7 fb^{-1} $ZZ \rightarrow \ell\ell\ell\ell$
    - 1.0 fb^{-1}: Phys. Rev. Lett. 100, 131801 (2008)
  - Complimentary 2.7 fb^{-1} $ZZ \rightarrow \ell\ell\nu\nu$
    - Phys. Rev. D 78, 072002 (2008)
  - Combined p-value = 6.2×10^{-9} (5.7σ)

    $\sigma_{ZZ} = 1.60 \pm 0.63$ (stat) $^{+0.16}_{-0.17}$ (syst) pb
- First OBSERVATION of ZZ at hadronic collider!
  - CDF: 1.4 $^{+0.7}_{-0.6}$ (stat+syst) pb (4.4 σ) [PRL 100, 201801 (2008)]

Summary

- Diboson production results are in agreement with SM
  - Cross section measurements remain consistent with SM
  - No evidence of anomalous triple gauge-boson couplings
- Recently, the Tevatron has provided:
  - EVIDENCE for $WW+WZ \rightarrow \ell\nu jj$ (4.4σ)
  - OBSERVATION of $Z\gamma \rightarrow \nu\nu\gamma$ (5.1σ)
  - OBSERVATION of ZZ production (5.7σ)
  - MOST PRECISE $WW \rightarrow \ell\nu\ell\nu$ cross section at hadronic collider
    - *...twice in April!*
  - MOST STRINGENT LIMITS on h_{30}^{Z}, h_{40}^{γ}, h_{40}^{Z}
  - INCREASINGLY STRINGENT LIMITS on κ_V, λ_V, g_1^{Z} from hadronic collisions