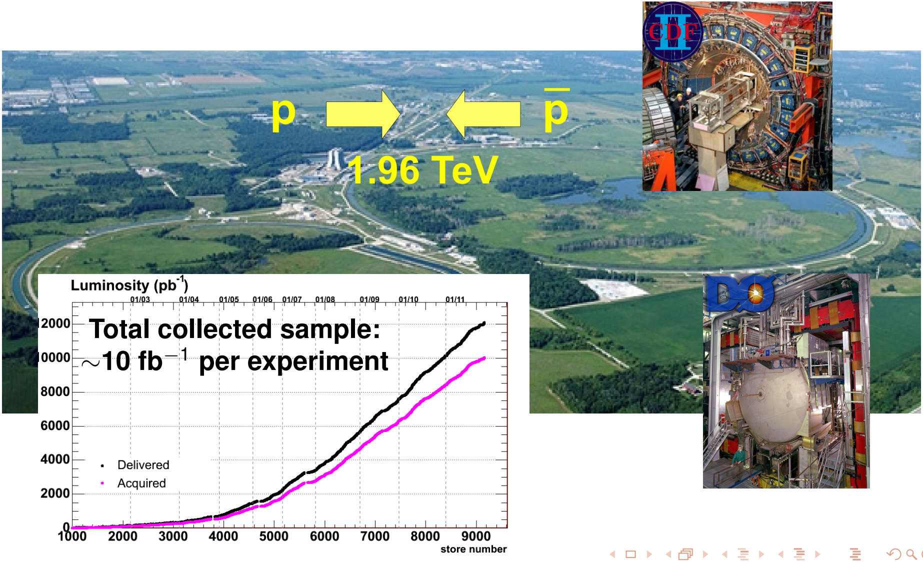
Diboson Physics at the Tevatron

M. Bauce

on behalf of CDF and D0 collaborations

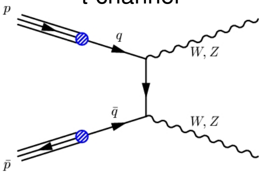
Rencontres de Moriond EW 2013

Tevatron, CDF and D0

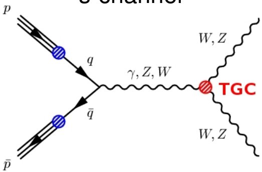


Physics motivation

t-channel



s-channel



Absent at LEP

$q\bar{q}' \to W^{(*)} \to W\gamma : \boxed{WW\gamma \text{ only}}$

$q\bar{q}' \to W^{(*)} \to WZ : \boxed{WWZ \text{ only}}$

$q\bar{q} \to Z/\gamma^{(*)} \to WW : WW\gamma, WWZ$

$q\bar{q} \to Z/\gamma^{(*)} \to Z\gamma : \boxed{ZZ\gamma, Z\gamma\gamma}$

$q\bar{q} \to Z/\gamma^{(*)} \to ZZ : \boxed{ZZ\gamma, ZZZ}$

Absent in SM

- Dibosons are sensitive to Trilinear Gauge Couplings (TGC): ZZZ, Z$Z\gamma$, $Z\gamma\gamma$ not present in SM
- New physics will enhance/suppress diboson production cross sections
- Significant background for several searches:

  SM scalar, gravitons, other resonances

At the Tevatron ($\sqrt{s}$= 1.96 TeV)

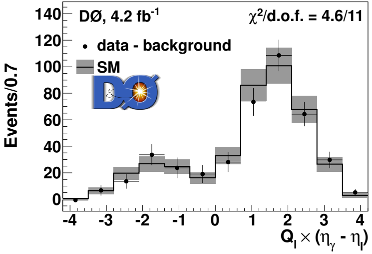
Process	Cross section
W($\to \ell\nu$)γ	7.6 ± 0.2 pb†
Z($\to \ell\ell$)γ	4.5 ± 0.4 pb†
WW	11.7 ± 0.7 pb†
WZ	3.46 ± 0.2 pb†
ZZ	1.4 ± 0.1 pb†

† MCFM,MSTW08

$W\gamma$

Interference between tree level diagrams at specific $W-q$ angles in the $W\gamma$ rest-frame. (Sensitive to BSM signatures)

Expected a dip in the $Q_\ell \times (\eta_\gamma - \eta_\ell)$ distribution at -1/3 for $W\gamma$ events.



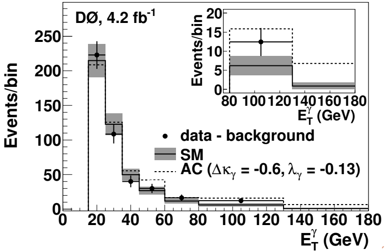
Measured **cross section**

$\sigma_{W\gamma} \times \mathcal{BR}(W \to \ell\nu)$ = 7.6 $\pm$ 0.4$_{(stat.)}$ $\pm$ 0.6$_{(syst.)}$ pb

$(\sigma \times \mathcal{BR})^{NLO}_{SM}$ = 7.6 $\pm$ 0.2 pb (MCFM, MSTW08)

95% C.L. **limits on anomalous TGC** (Λ_{NP} = 2 TeV) from the E_T^γ spectrum

- -0.4 $< \Delta k_\gamma <$ 0.4
- -0.08 $< \lambda_\gamma <$ 0.07



PRL 107, 241803 (2011)

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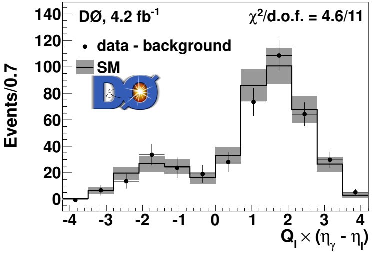

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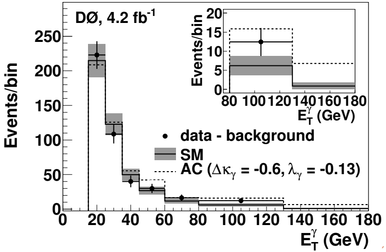

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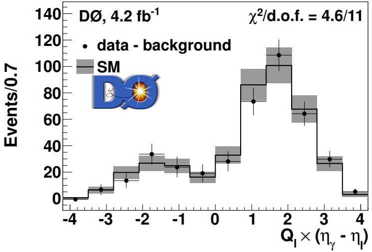

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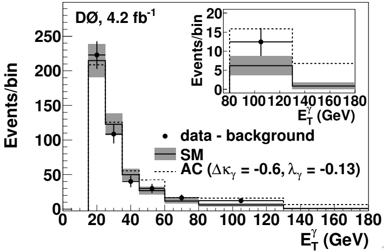


PRL 107, 241803 (2011)

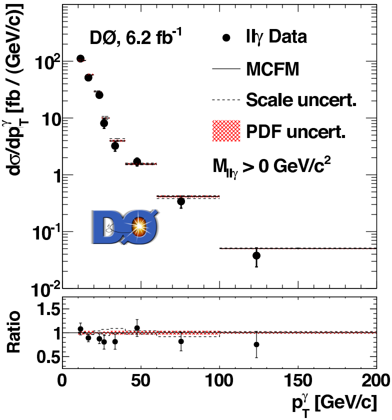
$Z\gamma$

No $ZZ\gamma$, $Z\gamma\gamma$ vertices expected in SM:
limits from E_T^γ spectrum on h_3^Z, h_4^Z, h_3^γ, h_4^γ

D0 **cross section measurement**

$\sigma(Z\gamma \to \ell\ell\gamma)$ = 1.09$\pm$0.04(*stat.*)$\pm$0.06(*syst.*) pb

$\sigma(Z\gamma \to \ell\ell\gamma)^{NLO}_{SM}$ = 1.10 $\pm$ 0.03 pb (*MCFM, MSTW08*)



TCG limits: considered decay modes:

- CDF: $Z\gamma \to \ell\ell\gamma$, $Z\gamma \to \nu\nu\gamma$
- D0: $Z\gamma \to \ell\ell\gamma$

95% C.L. limits for Λ = 1.5 TeV:

Parameter	CDF	D0
h_3^Z	-0.020, 0.021	-0.026, 0.026
h_4^Z	-0.0009, 0.0009	-0.0013, 0.0013
h_3^γ	-0.022, 0.020	-0.027, 0.027
h_4^γ	-0.0008, 0.0008	-0.0014, 0.0014

PRL 107, 051802 (2011) *PRD 85, 052001 (2012)*

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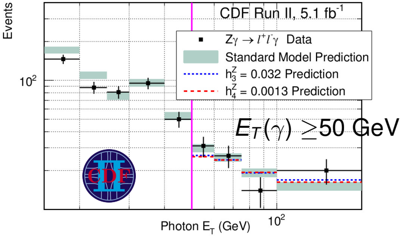

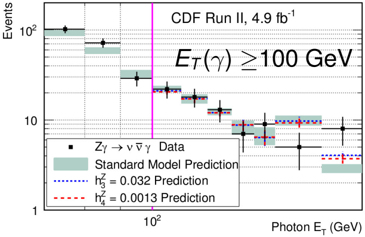

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$$\sigma(Z\gamma \to \ell\ell\gamma)_{SM}^{NLO} = 1.10 \pm 0.03 \text{ pb} \text{ (MCFM, MSTW08)}$$

TCG limits: considered decay modes:

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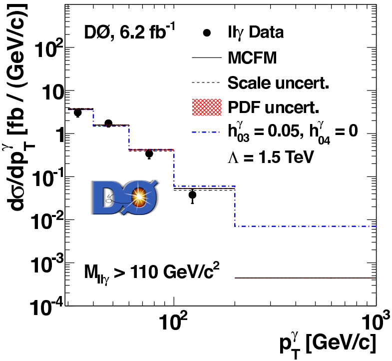
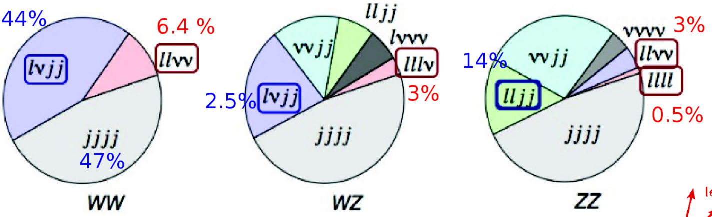


PRL 107, 051802 (2011)   PRD 85, 052001 (2012)

Heavy diboson final states

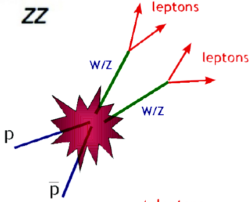


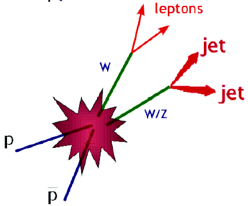
Leptonic Decay Modes: 0.5% - 6.4%

- Small branching ratio
- Clean signature in the detector

Semi-leptonic Decay Modes: 2.5% - 44%

- Larger branching ratio
- Better analysis techniques needed



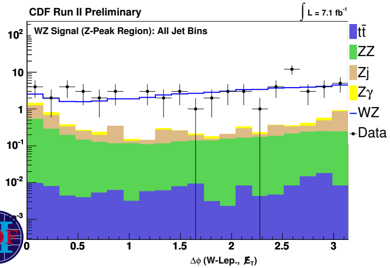


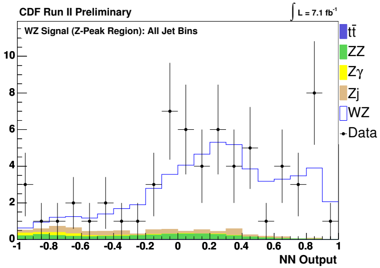
$WZ \rightarrow \ell\nu\ell'\ell'$

- Select events with:
  - Exactly three leptons: $p_T(\ell_1) > 20$ GeV/c, $p_T(\ell_{2,3}) > 10$ GeV/c
  - A pair of same flavor, opposite charge leptons with $76 < m_{\ell\ell} < 106$ GeV/c^2
  - $\not{E}_T > 25$ GeV
- Exploit a Neural Network to separate the signal from background and measure the cross section from the NN output
- limit on aTGC from $p_T(Z)$ distribution

$$\sigma(WZ) = 3.9^{+0.6}_{-0.5}(stat.)^{+0.6}_{-0.4}(syst.)\text{ pb} \qquad (\sigma_{SM} = 3.46 \pm 0.21\text{ pb})$$

MCFM, MSTW08 — zero width approx.





PRD 86, 031104 (2012)

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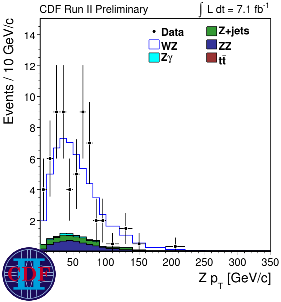
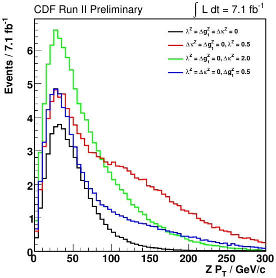




95% C.L. limits	
Parameter	Λ_{NP} = 2 TeV
λ_Z	-0.09, 0.11
Δg_1^Z	-0.08, 0.20
Δk_Z	-0.39, 0.90

PRD 86, 031104 (2012)

$WZ \to \ell\nu\ell'\ell'$

D0 strategy similar to CDF:

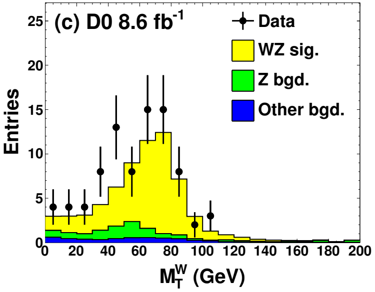
- ► cross section from a fit to $m_T(W)$.

$$\sigma(WZ) = 4.50 \pm 0.61(stat.)^{+0.16}_{-0.25}(syst.)\text{ pb}$$

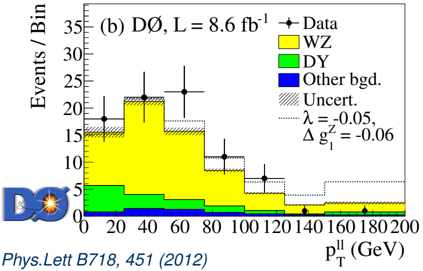
$$(\sigma_{SM} = 3.21 \pm 0.19\text{ pb})$$

$$(MCFM,\ MSTW08 - m_{\ell\ell} \in [60, 120]\ GeV/c^2)$$

PRD 85, 112005 (2012)



- ► Anomalous TGC limits from $p_T(\ell\ell)$ spectrum



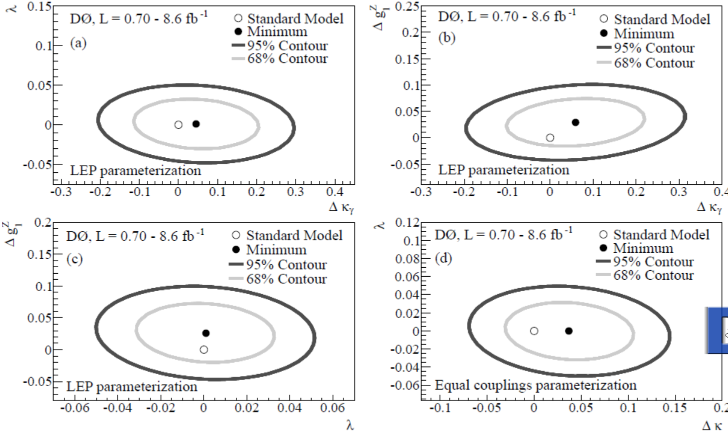
	95% C.L. limits
Parameter	Λ_{NP} = 2 TeV
λ^Z	-0.077, 0.089
Δg_1^Z	-0.055, 0.117

Phys.Lett B718, 451 (2012)

D0 combination of different diboson analyses:

$WZ \to \ell\nu\ell'\ell'$	8.6 fb^{-1}
$W\gamma \to \ell\nu\gamma$	4.9 fb^{-1}
$WW \to \ell\nu\ell'\nu$	1.0 fb^{-1}
$WW + WZ \to \ell\nu jj$	4.3 + 1.1 fb^{-1}

Most stringent aTGC limits at hadron collider



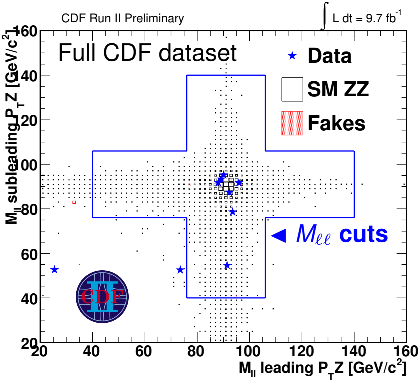
$ZZ \to \ell\ell\ell'\ell'$

Clean signature, small unphysical background.
Complete reconstruction of ZZ topology.

Select events with 4 leptons:

- $e^+e^-e^+e^-$, $\mu^+\mu^-\mu^+\mu^-$, $e^+e^-\mu^+\mu^-$
- $p_T(\ell_1) \geq$20 GeV/c, $p_T(\ell) \geq$10 GeV/c
- $M_{\ell\ell,1} \in [76,106]$ GeV/c^2, $M_{\ell\ell,2} \in [40,140]$ GeV/c^2

Main background coming from jet misidentification in $Z(\gamma)$+jets events.



Process	$\int \mathcal{L} = 9.7$ fb^{-1} candidate events
ZZ	9.59 $\pm$ 1.55
$Z(\gamma)$+jets	0.06 $\pm$ 0.03
Total Expected	9.65 $\pm$ 1.55
Data	7

$ZZ \to \ell\ell\ell'\ell'$ Signal Region

Measured cross section

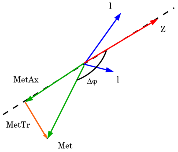
$$\sigma = 1.02^{+0.43}_{-0.34}(\text{stat.})^{+0.11}_{-0.07}(\text{syst.})\ \text{pb}$$

$$(\sigma^{NLO}_{ZZ} = 1.4 \pm 0.1\ \text{pb})$$

(*MCFM*, *MSTW*08)

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

- Two same flavor opposite charge leptons: $p_T(\ell_1) \geq 20$ GeV/c, $p_T(\ell_2) \geq 10$ GeV/c
- $76 \leq M_{\ell\ell} \leq 106$ GeV/c^2
- No jets with $\Delta\phi(j, Z) \geq \pi/2$
- $\not{E}_T^{Ax} \equiv -\not{E}_T \cdot \cos\Delta\phi(\not{E}_T, Z) \geq 30$ GeV

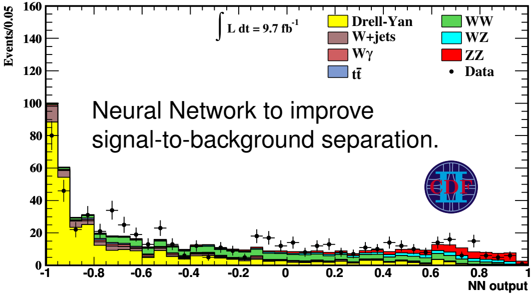


$\int \mathcal{L} = 9.7\ \text{fb}^{-1}$

Process	candidate events		
DY	317	$\pm$	51.3
$t\bar{t}$	11.9	$\pm$	2.2
W+jets	69.5	$\pm$	18.5
$W\gamma$	17.3	$\pm$	2.2
WW	114	$\pm$	10.6
WZ	37.5	$\pm$	5.3
Total Background	567	$\pm$	24.4
ZZ	63	$\pm$	11
Data	618		

$ZZ \rightarrow \ell\ell\nu\nu$ Signal Region

Full CDF dataset



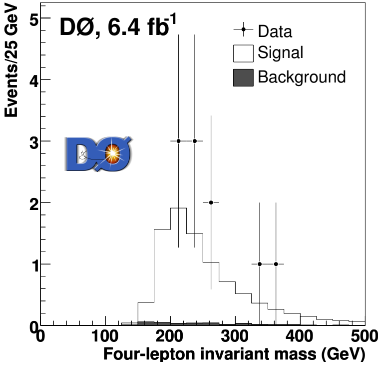
Measured cross section

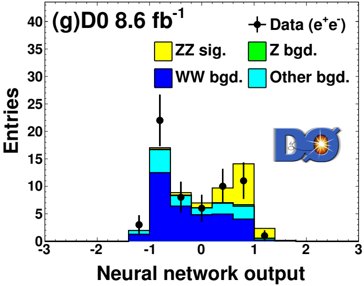
$$\sigma(ZZ) = 1.48^{+0.34}_{-0.31}(stat.) \pm 0.17\ \text{pb}$$

$$(\sigma_{ZZ}^{NLO} = 1.4 \pm 0.1\ \text{pb})$$

(*MCFM*, *MSTW08*)

- $ZZ \to \ell\ell\ell'\ell'$ 10 events in 6.4 fb^{-1}, counting exp.
- $ZZ \to \ell\ell\nu\nu$ Tight background rejection, Neural Network discriminant





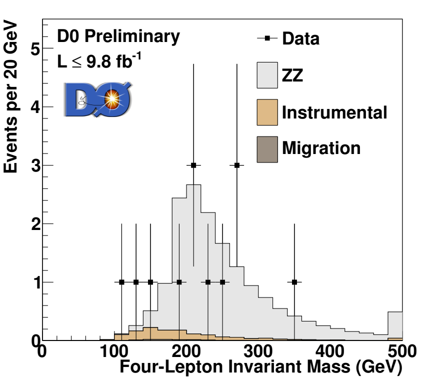
Combination of the two decay modes

$$\sigma(p\bar{p} \to ZZ) = 1.44^{+0.31}_{-0.28}(stat.)^{+0.17}_{-0.19} \text{ pb}$$

PRD 85, 112005 (2012)

Last Night Call - Very preliminar

D0 update of $ZZ \to \ell\ell\ell'\ell'$ to the full dataset
(loosened requirements, increased lepton acceptance)



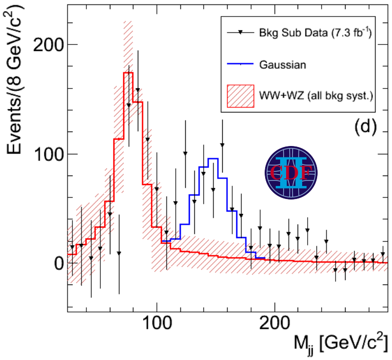
Process	$\int \mathcal{L} < 9.8$ fb^{-1} candidate events
ZZ	15.3 ± 1.9
$Z(\gamma)$+jets	$1.5^{+0.2}_{-0.3}$
Tot. Exp.	16.8 ± 1.9
Data	13

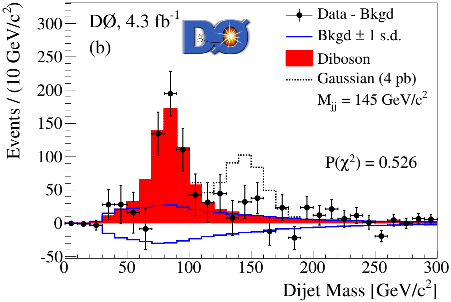
$$\sigma(ZZ) = 1.05^{+0.37}_{-0.30}(stat.)^{+0.14}_{-0.12}(syst.) \pm 0.06(lum.)\ \text{pb}$$

$WW/WZ \to \ell\nu jj$

Semileptonic diboson decays are more challenging:
need to extract small signal from a background dominated sample.

- ***W*+jj background modeling need particular care**:
  - earlier CDF analysis saw an excess in the M_{jj} spectrum
  - corresponding analysis from D0 didn't confirm that





No such excess reported by LHC experiments

$WW/WZ \to \ell\nu jj$

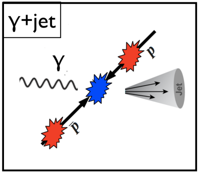
Semileptonic diboson decays are more challenging:
need to extract small signal from a background dominated sample.

- Further investigation at CDF (past 2 years)

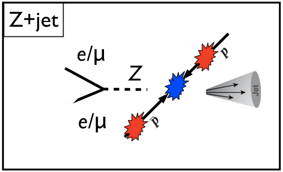
- selection based on dijet topology
- calibrate detector response:
  Z+jet, γ+jet balancing
- model fake lepton background

Obtained a really good modeling of the W/Z+jet background:

- Sensitivity to semileptonic final states
- **Good modeling** of background processes for SM Scalar searches at low masses



Different quark/gluon jet fraction



Soon documented on a PRD

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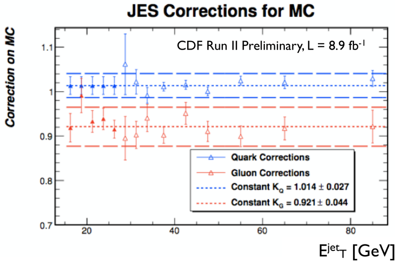


Different energy corrections applied to quark/gluon

Soon documented on a PRD

$WW/WZ \to \ell\nu jj$

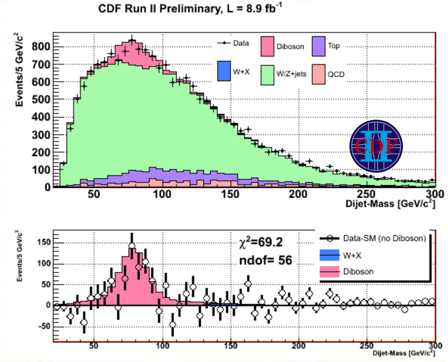
Semileptonic diboson decays are more challenging:
need to extract small signal from a background dominated sample.

- Further investigation at CDF (past 2 years)

- selection based on dijet topology
- calibrate detector response: Z+jet, γ+jet balancing
- model fake lepton background

Obtained a really good modeling of the W/Z+jet background:

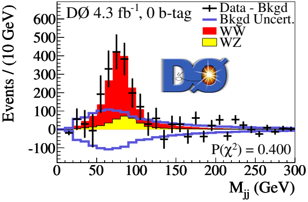
- Sensitivity to semileptonic final states
- **Good modeling** of background processes for SM Scalar searches at low masses



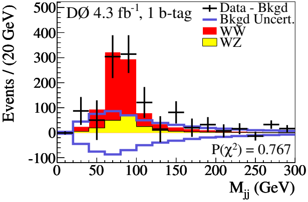
Soon documented on a PRD

$WW/WZ \to \ell\nu + jj(/b\bar{b})$

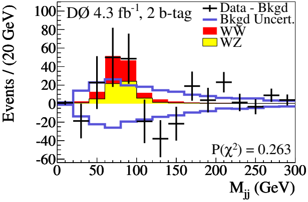
No b-tag



1 b-tag



2+ b-tag



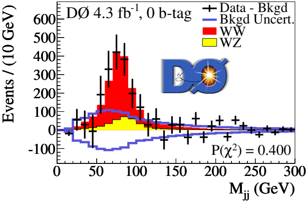
Identify heavy-flavor jets (b-tagging)
Combined fit to M_{jj} distribution in 0,1,2+ tagged jet sample:

$$\sigma(WW + WZ) = 19.6^{+3.2}_{-3.0} \text{ pb}$$

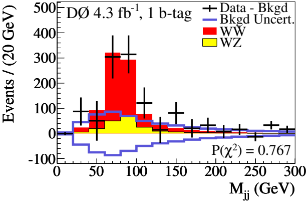
($\sigma(WZ) = 6.5 \pm 3.1$ pb when fixing σ_{WW} to SM)

PRL 108, 181803 (2012)

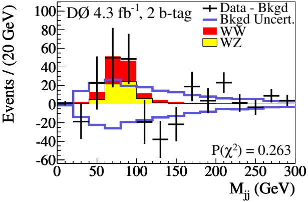
No *b*-tag



1 *b*-tag



2+ *b*-tag

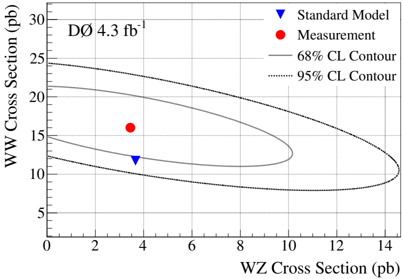


Simultaneous fit of the two processes measures:

$$\sigma(WW) = 15.9^{+3.7}_{-3.2}\ \text{pb}$$

$$\sigma(WZ) = 3.3^{+4.1}_{-3.3}\ \text{pb}$$

consistent with the SM prediction



PRL 108, 181803 (2012)

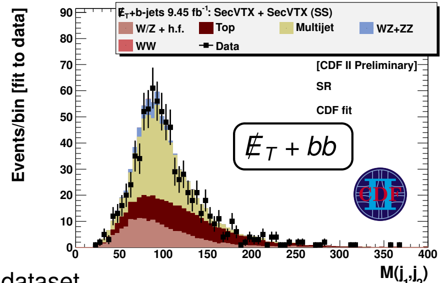
Dibosons in heavy-flavor jets final states

VZ production with $b\bar{b}$ in the final state.
Combine different decay modes:

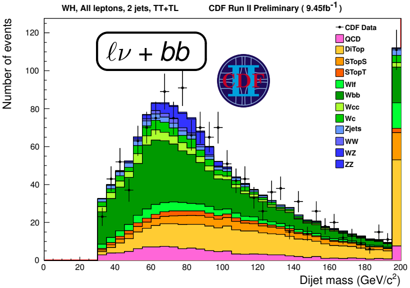
- $VZ \rightarrow \nu\nu b\bar{b}$ CDF Note 10798
- $VZ \rightarrow \ell\nu b\bar{b}$ CDF Note 10796
- $VZ \rightarrow \ell\ell b\bar{b}$ CDF Note 10799

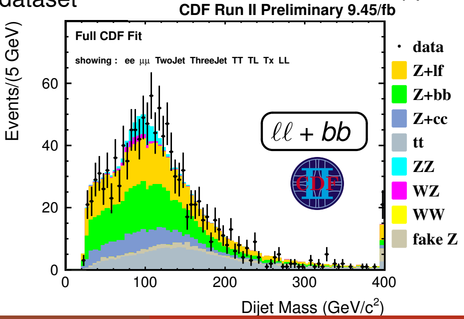
$$\sigma(WZ+ZZ) = 4.08^{+1.38}_{-1.26}\ \text{pb}$$

$$\sigma^{NLO}_{WZ+ZZ} = 4.4 \pm 0.3\ \text{pb}$$



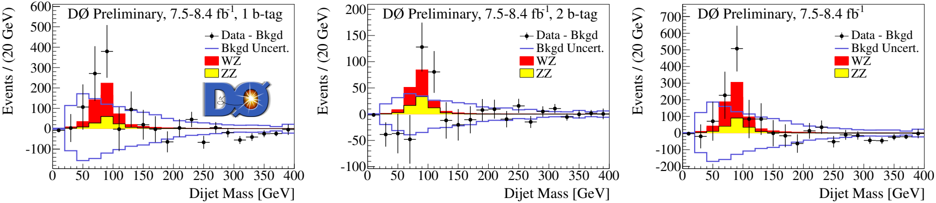
Full CDF dataset





Dibosons in heavy-flavor jets final states

D0 combines $\not\!\!E_T + b\bar{b}$, $\ell\nu + b\bar{b}$, $\ell\ell + b\bar{b}$ analysis **exploiting MVA distributions**.



- Fixing WZ/ZZ ratio to SM:

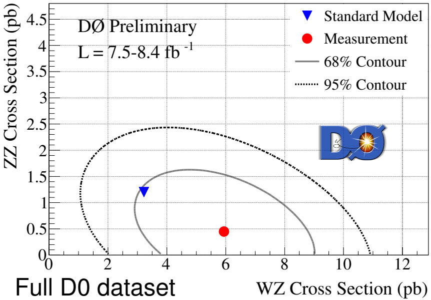
$$\sigma(WZ+ZZ) = 5.0 \pm 1.0(stat.)^{+1.3}_{-1.2}(syst.)\ \text{pb}$$

$$(\sigma(WZ+ZZ)^{NLO}_{SM} = 4.4 \pm 0.3\ \text{pb})$$

- Simultaneous fit of *WZ* and *ZZ* cross sections:

$$\sigma(WZ) = 5.9 \pm 1.4(stat.) \pm 0.7(syst.)\ \text{pb}$$

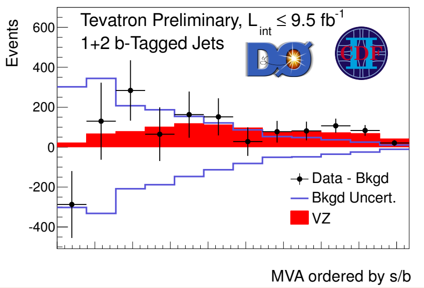
$$\sigma(ZZ) = 0.45 \pm 0.61(stat.) \pm 1.2(syst.)\ \text{pb}$$



Full D0 dataset

arXiv:1204.4496v1 (2012)

CDF and D0 diboson heavy-flavor final states combination (exploit MVA information)



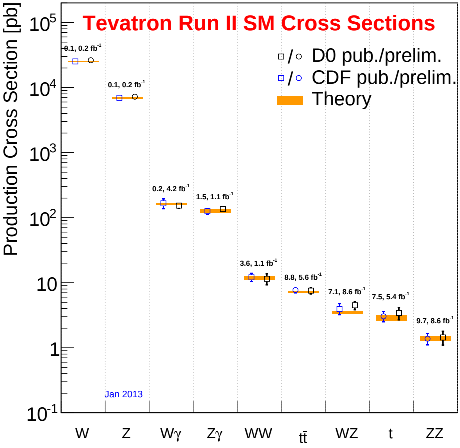
$$\sigma(WZ + ZZ) = 4.47 \pm 0.64(stat.) \pm 0.72(syst.)\ \text{pb}$$

observed with 4.6 s.d.

arXiv:1203.3782 (2012)

arXiv:1204.4496v1 (2012)

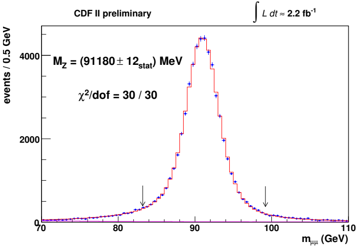
Summary & Conclusions

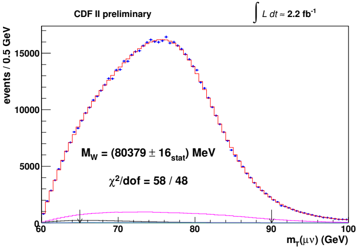


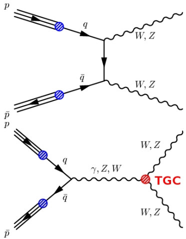
- Diboson production measured exploiting up to the full available dataset
- Sensitive to several semi-leptonic final states
  - Validation for SM/exotic searches
- Investigation of the anomalous TGC:
  - no deviation seen from the SM prediction
- CDF and D0 finalization and combination in progress to set the best EWK measurements at the Tevatron

Acknowledgments

- Leptons:
  - High-p_T leptons $>$10-15 GeV/c, maximized detector acceptance $|\eta|$ $<$1.5(μ), $<$2.1(e)
  - Calorimeter and track isolation exploited
  - Collect data with high-p_T lepton trigger
- Photons:
  - $E_T(\gamma) \geq$15 GeV in the acceptance ($|\eta|$ $<$2.5)
  - Calorimeter based isolation
- Jets:
  - $E_T \geq$10(15) GeV in the acceptance ($|\eta|$ $<$2.4)
  - Calorimeter based isolation, associated track reconstruction
- $Z \to \ell^+\ell^-$ selection:
  - Same flavor and opposite charge lepton pair
  - $m_{\ell\ell}$ within 15 GeV/c^2 from the PDG Z mass
- $W \to \ell\nu$ selection:
  - One isolated lepton
  - Significant $\not\!\!E_T$ (cuts starting from 20 GeV)
  - large W transverse mass, $m_T(W)$ (cut starting from 20 GeV)







$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = i\,[g_1^V(W^{\dagger}_{\mu\nu}W^{\mu}V^{\nu} - W_{\mu\nu}W^{\dagger\mu}V^{\nu}) + k^V W^{\dagger}_{\mu}W_{\nu}V^{\mu\nu} + \frac{\lambda^V}{m_W^2}W^{\dagger}_{\rho\mu}W^{\mu}_{\nu}V^{\nu\rho}]$$

$$\mathcal{L} = \frac{e}{M_Z^2}\left[f_4^V(\delta_\mu V^{\mu\beta})Z_\alpha(\delta^\alpha Z_\beta) + f_5^V(\delta^\sigma V_{\sigma\mu})Z^{\mu\beta}Z_\beta\right]$$

EM gauge invariance and C and P conservation:

▶ 5 independent TGC for WW g_1^Z, k_Z, k_γ, λ_Z, λ_γ

- $W\gamma$ sensitive to k_γ, λ_γ
- WZ sensitive to g_1^Z, k_Z, λ_Z

$$a(s) = \frac{a_0}{(1+\frac{s}{\Lambda^2})^2}$$

Standard Model: g_1^Z=k_Z=k_γ=1 so consider Δg_1^Z, Δk_Z, Δk_γ
λ_Z=λ_γ=0

LEP parametrization

$$\Delta k_Z = \Delta g_1^Z - \Delta k_\gamma \cdot \tan^2\theta_W$$

$$\lambda_Z = \lambda_\gamma = \lambda$$

$Z\gamma Z$ vertex: $Z\gamma$ sensitive to h_3^Z, h_3^γ, h_4^Z, h_4^γ
$ZZ\gamma$ vertex: ZZ sensitive to f_4^Z, f_4^γ, f_5^Z, f_5^γ all zero in SM

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