Diboson Results from the Tevatron

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on behalf of the CDF and D0 Collaborations

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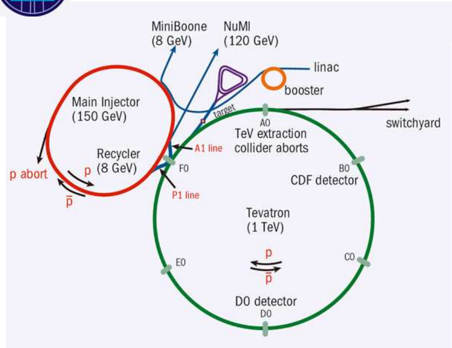
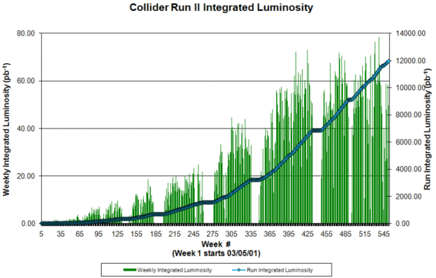
Outline

- Massive diboson cross sections
  - $ZZ \rightarrow lll'l', ll\nu\nu$
  - $WZ \rightarrow lll\nu$
  - $WW \rightarrow ll\nu\nu$
  - Tevatron diboson cross sections
- Anomalous gauge coupling limits
  - $WZ \rightarrow lll\nu$
  - $WZ \rightarrow l\nu jj$
  - $WW \rightarrow ll\nu\nu$
  - Tevatron anomalous trilinear gauge coupling limits
  - $WW\gamma\gamma$ coupling limits

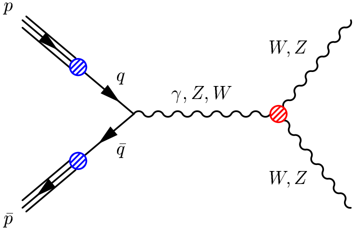
The Tevatron

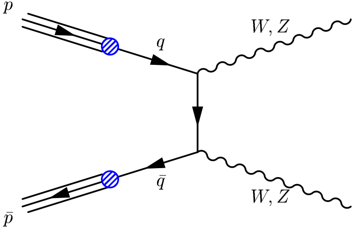




- 1987-2011
- 6.9 km ring
- $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV
- Peak luminosity $4 \times 10^{32} cm^{-2} s^{-1}$
- Two experiments: D0 and CDF
- Integrated luminosity $\sim 10\text{fb}^{-1}$
  - $\sim 8,000$ $WW \to ll\nu\nu$ events
  - ~ 300 $ZZ \to lll'l' / ll\nu\nu$ events

Physics Motivation





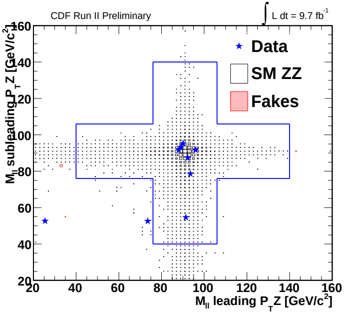
- Massive diboson production is an important test of standard model predictions

Process	σ (pb)
WW	11.7 ± 0.7
WZ	3.5 ± 0.2
ZZ	1.4 ± 0.1

- Dibosons are sensitive to trilinear and quartic gauge couplings
- New physics could appear as deviations from predicted diboson cross sections
- Background to Higgs analyses and new physics searches

$ZZ \rightarrow ll l' l'$

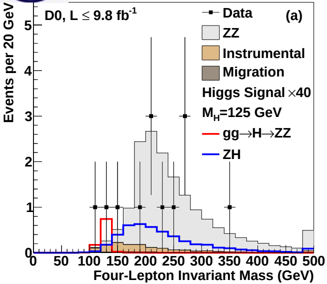
- Final states: $eeee$, $ee\mu\mu$, $\mu\mu\mu\mu$
- Small cross section
- Very clean final state
- ZZ production is a background for $ZH \rightarrow Zb\bar{b}$, $H \rightarrow ZZ$



- D0:
- 4 l with $p_T > 15$ GeV
- $M_{ll} > 30$ GeV for both pairs
- OS pairs for muons
- All $eeee$ pairs considered with no charge requirement

- CDF:
- 4 l with $p_T(l_{1(i)}) > 20(10)$ GeV
- Minimize $|M_{ll} - M_Z|$ for both pairs: $76 < M_{ll,1} < 106$ GeV, $41 < M_{ll,2} < 141$ GeV
- All leptons OS same flavor pairs

$ZZ \to \ell\ell\ell'\ell'$ Analysis and Result



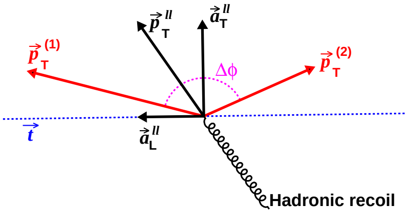
Process	Yield(CDF)	Yield(D0)
ZZ	9.59 ± 1.55	15.31 ± 1.84
Bkg.	0.06 ± 0.03	1.48 ± 0.31
Data	7	13

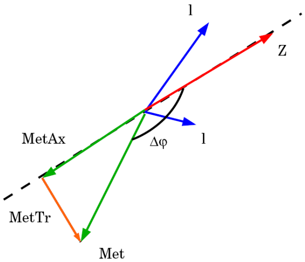
- Instrumental background: Z/γ^* with two additional misidentified jets/photons
- Fake rate from jet-trigger events
- Applied to 2/3 lepton + jets events
- D0: Looser acceptance, separate lepton categories

	$\sigma(p\bar{p} \to ZZ)$ (pb) $(\ell\ell\ell'\ell')$
CDF	$0.99^{+0.45}_{-0.35}(\mathrm{stat})^{+0.11}_{-0.07}(\mathrm{syst})$
D0	$1.05^{+0.37}_{-0.30}(\mathrm{stat})^{+0.14}_{-0.12}(\mathrm{syst}) \pm 0.06(\mathrm{lumi})$
MCFM	1.4 ± 0.1

CDF: PRD 89, 112001 (2014); D0: PRD 88, 032008 (2013)

$ZZ \rightarrow ll\nu\nu$ Selection

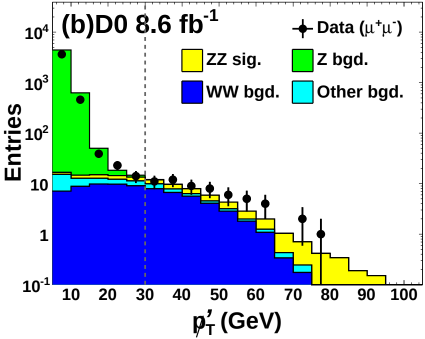


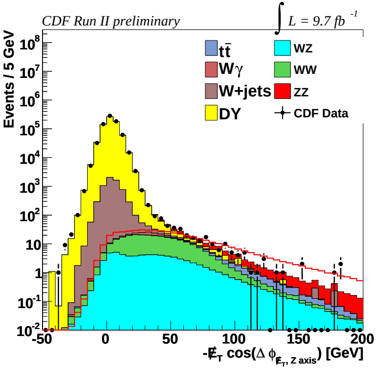


- D0: Two OS l of $p_T > 15$ GeV or $p_T(l_{1(2)}) > 20(10)$ GeV
- $60 < m_{ll} < 120$ GeV
- ≤ 2 jets with $E_T > 15$ GeV
- No additional isolated jets/EM clusters/μs/τs
- $\not{p}_T > 30$ GeV, $\not{a}_T > 5$ GeV

- Similar CDF selection:
- $\not{E}_T^{Ax} \equiv -\not{E}_T \cos\Delta\phi(\hat{\not{E}}_T, \hat{p}_T^Z) \geq 30$ GeV
- $\not{E}_T/\sqrt{(}E_T) > 3.0$ GeV$^{1/2}$
- $76 < m_{ll} < 106$ GeV
- No jets with $\Delta\phi(j, Z) \geq \pi/2$

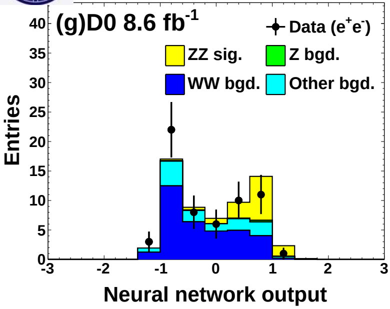
$ZZ \rightarrow ll\nu\nu$ Analysis

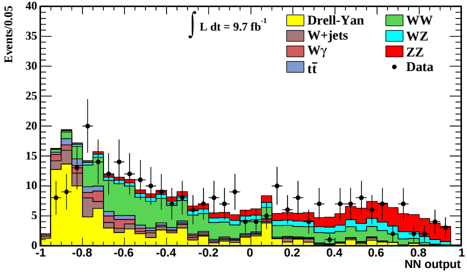




- DY and WW validated in $m_{ll}/\not{E}_T^{Ax}$ and $e-\mu$ control regions
- Modeling: Pythia
- D0: reweight p_T^{ll} according to RESBOS(DY), POWHEG(VV)
- CDF: MC@NLO(WW), Baur($W\gamma$)
- W+jets: data-driven
- Neural networks based on kinematic inputs to enhance separation of signal and background

$ZZ \to ll\nu\nu$ Result and Combination





	$\sigma(p\bar{p} \to ZZ)$ (pb) ($ll\nu\nu$)
CDF	$1.18^{+0.32}_{-0.31}(\text{stat})^{+0.22}_{-0.17}(\text{syst})$
MCFM	1.4 ± 0.1
D0[a]	$1.64 \pm 0.44(\text{stat})^{+0.13}_{-0.15}(\text{syst})$
MCFM[a]	1.3 ± 0.1

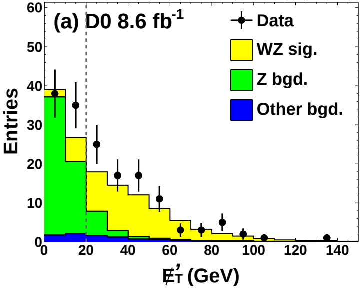
[a] For $60 < m_{ll} < 120$ GeV

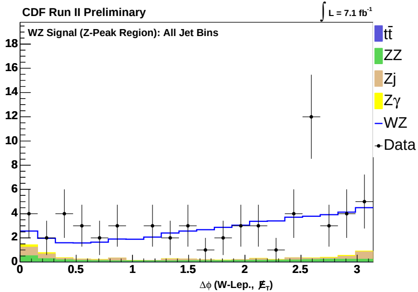
Combination of decay modes:

	$\sigma(p\bar{p} \to ZZ)$ (pb)
CDF	$1.04^{+0.32}_{-0.25}(\text{stat+syst})$
D0	$1.32^{+0.32}_{-0.28}(\text{stat+syst})$

CDF: PRD 89, 112001 (2014); D0: PRD 85, 112005 (2012)

$WZ \to lll\nu$ Selection

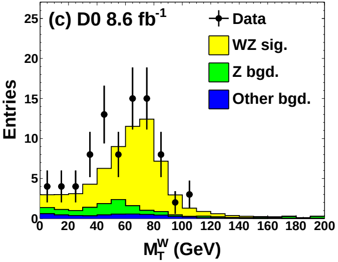


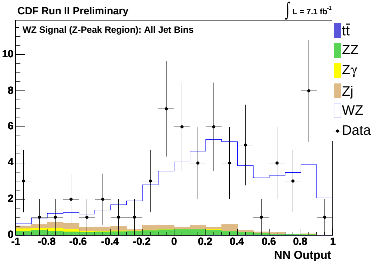


- D0:
- Exactly three l (one OS) of $p_T > 15$ GeV or $p_T(l_{1,2,3}) > 20, 15, 10$ GeV
- $60 < m_{ll} < 120$
- $\not\!E_T' > 20 GeV$
- $|m_{3l} - m_Z| > |m_{ll} - m_Z|$

- CDF:
- Exactly three l (one OS) of $p_T(l_{1,i}) > 20, 10$ GeV
- $\not\!E_T > 25$ GeV
- $76 < m_{ll} < 106$

$WZ \to lll\nu$ Analysis





- Minimal background in signal region: ZZ, $Z + jets$
- D0: fit to m_T^W
- CDF: neural network trained on kinematics and lepton types

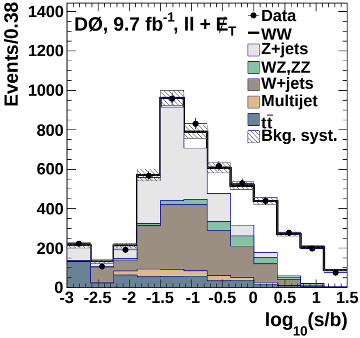
	$\sigma(p\bar{p} \to WZ)$ (pb) ($lll\nu$)
CDF	$3.93^{+0.60}_{-0.53}(\mathrm{stat})^{+0.59}_{-0.46}(\mathrm{syst})$
MCFM	3.50 ± 0.21
D0[a]	$4.50 \pm 0.61(\mathrm{stat})^{+0.16}_{-0.25}(\mathrm{syst})$
MCFM[a]	3.21 ± 0.19

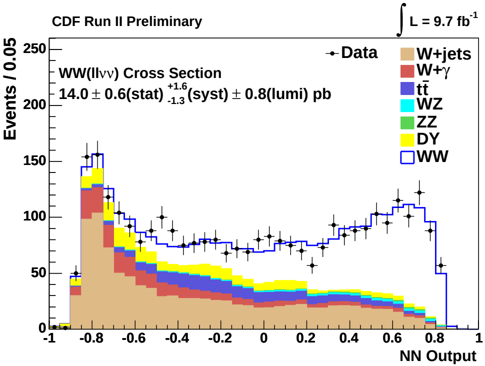
- TGC limits shown below

CDF: PRD 86 031104 (2012);
D0: PRD 85 112005 (2012)

[a]For $60 < m_{ll} < 120$ GeV

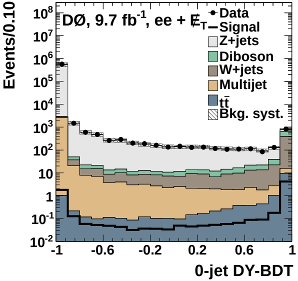
$WW \to l l \nu \nu$

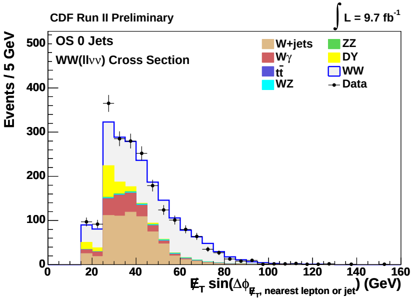




- Highest-statistics massive diboson process
- Multiple significant backgrounds
- Background to - and extension of - $H \to WW$ analyses

$WW \rightarrow l l \nu \nu$ Selection

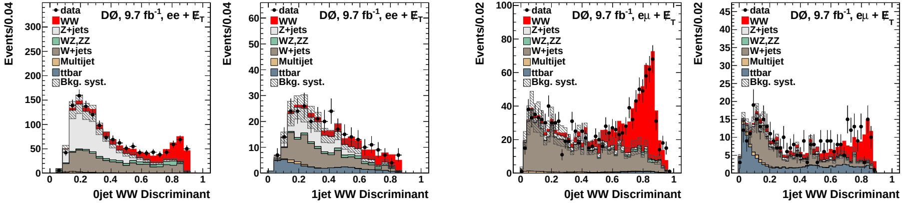




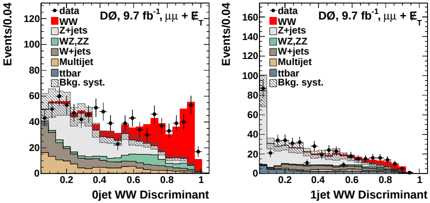
- D0:
- $p_T^{l_{1(2)}} > 15(10)$ GeV
  - $ee/\mu\mu$:
  - $m_{ll} > 15$ GeV
  - Cut on anti-DY BDT
  - $e-\mu$:
  - $p_T^{l_{e(\mu)}} > 15(10)$ GeV
  - Cut on $M_T(l, \not\!\!E_T)$, M_{T_2}

- CDF:
- $E_T(p_T)^{l_{1(2)}} > 20(10)$ GeV
- $E_T(p_T)_{l_2} > 10$ GeV
- Cut-based DY rejection
  - Veto $80 < m_{ll} < 99$
  - Require $\not\!\!E_T$ transverse to nearby object
  - Relaxed for $e-\mu$

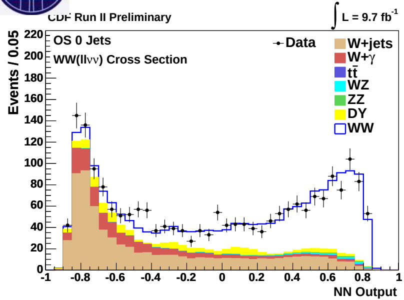
$WW \rightarrow ll\nu\nu$ Analysis - D0

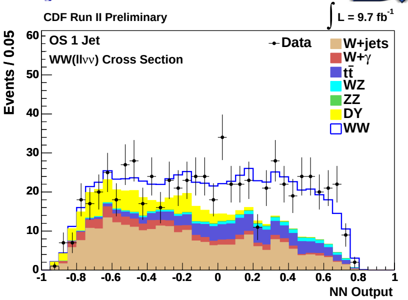


- Modeling: Pythia(VV), Alpgen ($t\bar{t}$, V+jets), data-driven (multijet)
- Second set of BDT's trained to discriminate *WW*
- Additional variables: lepton quality, *b*-tagging
- Trained separately for *ee*, $e\mu$, $\mu\mu$, and for 0 and 1 jet events

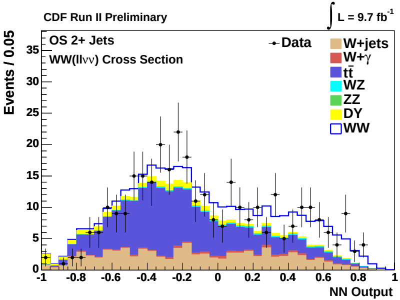


$WW \rightarrow ll\nu\nu$ Analysis - CDF

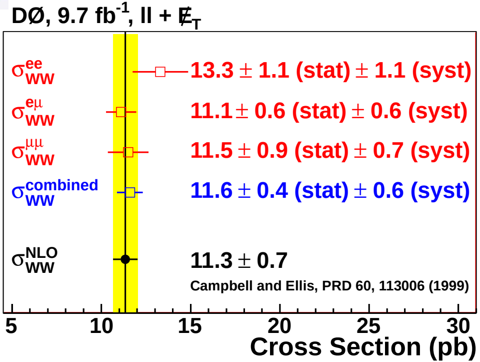




- Modeling: Pythia($t\bar{t}$, DY, VZ), Alpgen(DY+jets, WW), Baur($W\gamma$), data-driven(W+jets)
- Neural networks: 0, 1, 2+jets
- 1-jet region binned by $E_T(j_1)$
- Veto events with 2+jets, $1 + b$-tags



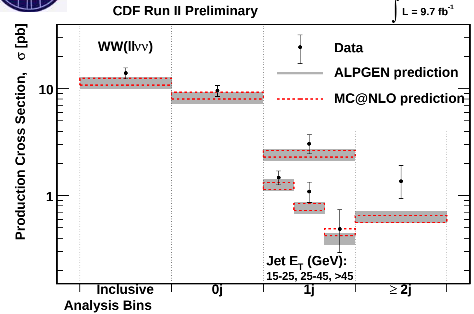
$WW \to \ell\ell\nu\nu$ Result



- D0 observed $\sigma(p\bar{p} \to WW) = 11.6 \pm 0.4(\mathrm{stat}) \pm 0.6(\mathrm{syst})$
- Expected(MCFM) $\sigma(p\bar{p} \to WW) = 11.3 \pm 0.7$
- Measured precision equivalent to NLO theory

D0: PRD 88 052006 (2013)

$WW \rightarrow l l \nu\nu$ Result



- Differential cross section
- Unfolded to hadronic level
- Alpgen: fixed order
- MC@NLO: next-to-leading order

WW($ll\nu\nu$) Cross Section — CDF Run II Preliminary — $\int L = 9.7\ \text{fb}^{-1}$

Jet Bin	σ(pb) Measured	Uncertainty(pb) Stat.	Syst.	Lumi.	σ(pb) Alpgen	MC@NLO
Inclusive	14.0	± 0.6	$^{+1.2}_{-1.0}$	± 0.8	11.3 ± 1.4	11.7 ± 0.9
0 Jets	9.57	± 0.40	$^{+0.82}_{-0.68}$	± 0.56	8.24 ± 1.04	8.62 ± 0.63
1 Jet Inclusive	3.04	± 0.46	$^{+0.48}_{-0.32}$	± 0.18	2.43 ± 0.31	2.47 ± 0.18
1 jet, $15 < E_T < 25$ GeV	1.47	± 0.17	$^{+0.13}_{-0.09}$	± 0.09	1.26 ± 0.16	1.18 ± 0.09
1 jet, $25 < E_T < 45$ GeV	1.09	± 0.18	$^{+0.14}_{-0.11}$	± 0.06	0.77 ± 0.10	0.79 ± 0.06
1 jet, $E_T > 45$ GeV	0.48	± 0.15	$^{+0.19}_{-0.11}$	± 0.03	0.40 ± 0.05	0.46 ± 0.03
2 or More jets	1.35	± 0.30	$^{+0.45}_{-0.28}$	± 0.08	0.64 ± 0.08	0.61 ± 0.05

CDF: PRD coming soon

Diboson Cross Sections Summary

Process	σ_{CDF}(pb)	σ_{D0}(pb)	Prediction(pb)	Data(fb^{-1})
WW	14.0 ± 1.6	11.6 ± 0.7	11.7 ± 0.7	9.7
WZ	3.9 ± 0.8	-	3.5 ± 0.2	7.1
WZ[1]	-	4.5 ± 0.6	3.2 ± 0.2	8.6
ZZ	1.0 ± 0.3	1.3 ± 0.3	1.4 ± 0.1	9.7,8.6-9.8

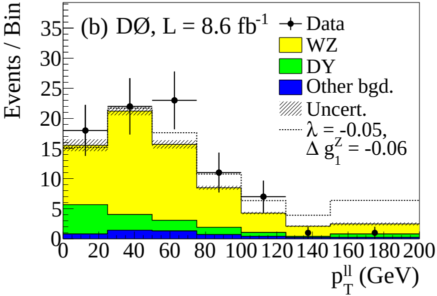
- Leptonic final states
- *WW* and *ZZ* measurements exploit full dataset
- Consistent with Standard Model predictions

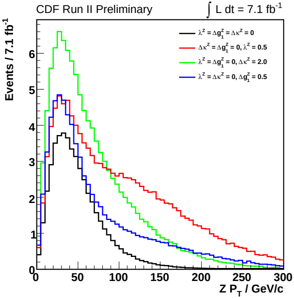
	CDF					
Process	Obs. σ(pb)	Exp. σ(pb)	$E_T(\gamma)$ (GeV)	$\lvert\eta_\gamma\rvert$	$\Delta R_{\gamma,l/\gamma}$	Data(fb^{-1})
$\gamma\gamma$	12.3 ± 3.5	11.6 ± 0.3	17,15	1	0.4	9.5
$W(\rightarrow l\nu)\gamma$	18.0 ± 2.8	19.3 ± 1.4	7	1.1	0.7	1.1
$Z(\rightarrow ll)\gamma$	4.6 ± 0.5	4.5 ± 0.3	7	1.1	0.7	1.1-2.0
	D0					
Process	Obs. σ(pb)	Exp. σ(pb)	$E_T(\gamma)$ (GeV)	$\lvert\eta_\gamma\rvert$	$\Delta R_{\gamma,l/\gamma}$	Data(fb^{-1})
$\gamma\gamma$	9.4 ± 0.4	7.9	18,17	0.9	0.4	8.5
$W(\rightarrow l\nu)\gamma$	7.6 ± 0.7	7.6 ± 0.2	15	2.5	0.4	4.2
$Z(\rightarrow ll)\gamma$	1.1 ± 0.1	1.1	10	1.1	0.4	6.5

Additional references in backup

[1] $60 < m_{ll} < 120$ GeV

$WZ \rightarrow lll\nu$ aTGC Limits





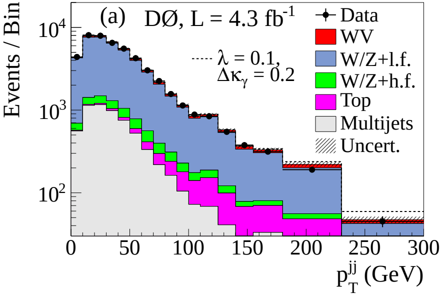
- aTGCs would increase production cross section at high p_T^V
- Events reweighted according to aTGC simulation
- Fit to p_T^{ll} distribution
- D0: Combination limit described below

aTGC limits from $WZ \rightarrow lll\nu$ ($\Lambda = 2$ TeV)

LEP Parameterization	$\Delta\kappa_Z$	λ	Δg_1^Z
D0	-	$(-0.077, 0.089)$	$(-0.055, 0.117)$
CDF	(-0.39,0.90)	(-0.08,0.10)	(-0.08,0.20)

$WW + WZ \to l\nu jj$

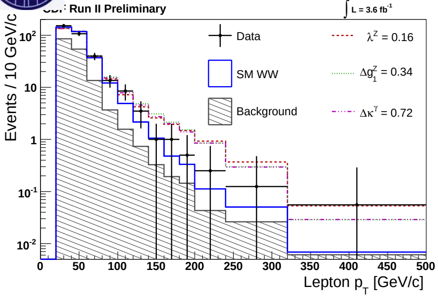
- D0:
- Single $e(\mu)$ with $p_T > 15(20)$ GeV
- $\not\!\!E_T > 20$ GeV
- 2 or 3 jets with $p_T > 20$ GeV
- $55 < m_{jj} < 110$ GeV
- $M_T^{l\nu} > 40 - 0.5\not\!\!E_T$

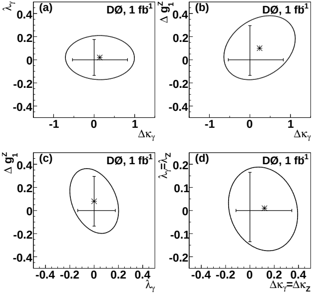


- Reweight p_T^{jj} distribution to account for aTGCs
- Fit SM and aTGC to data
- CDF: Ongoing work on $l\nu jj$ in backup

D0 $WW/WZ \to l\nu jj$	
$\Delta\kappa_\gamma$	(-0.27,0.37)
λ	(-0.075,0.080)
Δg_1^Z	(-0.071,0.137)

$WW \rightarrow ll\nu\nu$ aTGC Limits



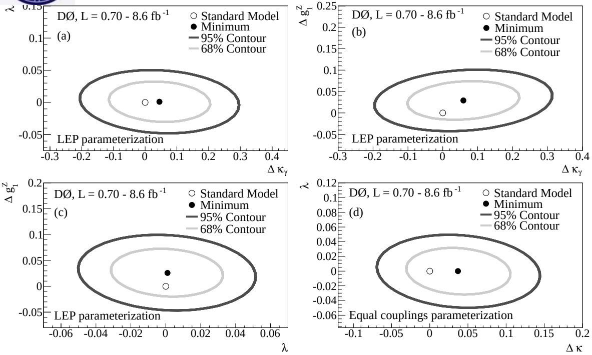


- Previous WW analyses $(1.1 - 3.6\mathrm{fb}^{-1})$
- Limits set by lepton p_T likelihood
- Additional eff. $\times$ accept. uncertainty as a function of $p_T(l)$
- D0: 2D, combination

aTGC limits from $WW \rightarrow ll\nu\nu$ ($\Lambda = 2$ TeV)

	$\Delta\kappa_\gamma$	λ	Δg_1^Z
D0	(-0.54,0.83)	(-0.14,0.18)	(-0.14,0.30)
CDF	(-0.57,0.65)	(-0.14,0.15)	(-0.22,0.30)

Trilinear Gauge Coupling Limits



- D0 combination
- $WZ \to lll\nu$ (8.6 fb^{-1})
- $WW + WZ \to l\nu jj$ (4.3 + 1.1 fb^{-1})
- $W\gamma \to l\nu\gamma$ (4.9 fb^{-1})
- $WW \to ll\nu\nu$ (1 fb^{-1})
- p_T^{ll}, p_T^{jj}, E_T^{γ}, p_T^{ll} distributions reweighted for effects of aTGCs
- SM and aTGC fit to data simultaneously in all samples

$WWZ/WW\gamma$ aTGC limits ($\Lambda = 2$ TeV)

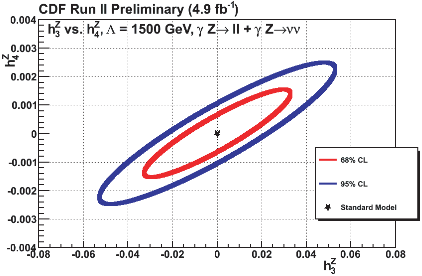
$WW,WZ,W\gamma$	λ	Δg_1^Z	$\Delta\kappa_Z$	$\Delta\kappa_\gamma$
D0 Comb.(8.6 fb^{-1})	(-0.036,0.044)	(-0.034,0.084)	-	(-0.158,0.255)
CDF WW(3.6 fb^{-1})	(-0.14,0.15)	(-0.22,0.30)	-	(-0.57,0.65)
CDF WZ(7.1 fb^{-1})	(-0.08,0.10)	(-0.08,0.20)	(-0.39,0.90)	-

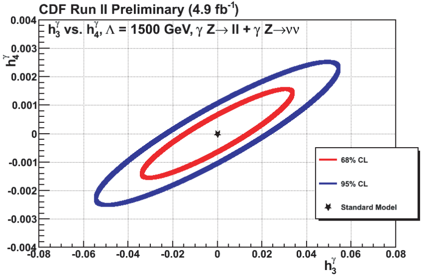
D0 $WW/WZ/ZZ$ combination comparable to LHC limits

CDF WW: PRL 104, 201801 (2010); CDF WZ: PRD 86, 081104 (2012);

D0 Comb.: Phys.Lett B718, 451 (2012)

Trilinear Gauge Coupling Limits





$ZZ\gamma/Z\gamma\gamma$ aTGC limits ($\Lambda = 1.5$ TeV)

$Z\gamma$	H_{03}^Z	H_{04}^Z	H_{03}^γ	H_{04}^γ
D0(6.2 fb^{-1})	(-0.026,0.026)	(-0.0013,0.0013)	(-0.027,0.027)	(-0.0014,0.0014)
CDF(5 fb^{-1})	(-0.020,0.021)	(-0.0009,0.0009)	(-0.022,0.020)	(-0.0008,0.0008)

$ZZ\gamma/ZZZ$ aTGC limits ($\Lambda = 1.2$ TeV)

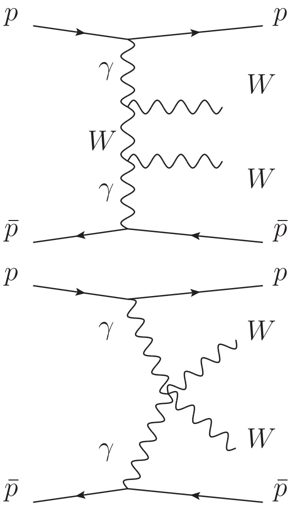
ZZ	f_{04}^Z	f_{05}^Z	f_{04}^γ	f_{05}^γ
D0(1 fb^{-1})	(-0.28,0.28)	(-0.31,0.29)	(-0.26,0.26)	(-0.30,0.28)
CDF(1.9 fb^{-1})	(-0.12,0.12)	(-0.13,0.12)	(-0.10,0.10)	(-0.11,0.11)

CDF $Z\gamma$: PRL 107 051802 (2011); D0 $Z\gamma$: PRD 85, 052001 (2012);

D0 ZZ: PRL 100, 131801 (2008)

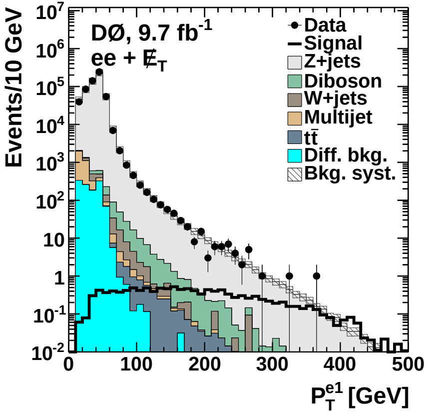
$\gamma\gamma \rightarrow WW$

- $WW\gamma\gamma$ Quartic Gauge Coupling (QGC) allowed in Standard Model
- $p\bar{p} \rightarrow p\bar{p}WW$
- Small cross section in Standard Model: 3 fb - 0.1 events expected after selection
- Sensitive to anomalous QGCs described by a_0^W, a_C^W
- Similar effects expected from a_0^W, a_C^W



$\gamma\gamma \to WW$ Selection

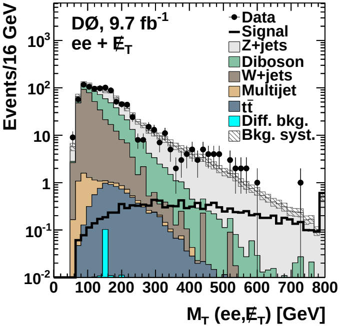
- Two OS electrons
- $p_T^{e1} > 15$ GeV, $p_T^{e2} > 10$ GV, $M_{ee} > 15$ GeV
- At least one in central cal., other in central or end
- Central jet veto ($p_T > 20$ GeV, $|\eta| < 2.4$) to require EWK scattering topology
- Dominant background: Z+jets

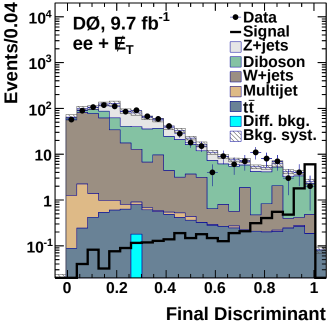


Signal: $a_0^W/\Lambda^2 = 5 \times 10^{-4}$ GeV^{-2}, no form factor

$WW\gamma\gamma$ Analysis

- Selection BDT against Z/γ^*+jets based on kinematics - most significant input: $(M_T(ee, \not{E}_T))$

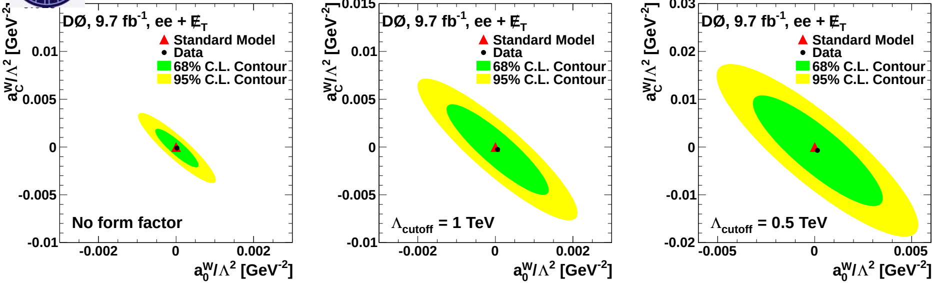




Signal: $a_0^W/\Lambda^2 = 5 \times 10^{-4}$ GeV^{-2}, no form factor

- Dominant backgrounds after selection: W/Z+jets, diboson
- Second BDT for aQGC signal also uses electron reconstruction quality

$WW\gamma\gamma$: aQGC Limits



$|a_0^W/\Lambda^2|$

Cutoff	Expected upper limit [GeV^{-2}]	Observed upper limit [GeV^{-2}]
No form factor	0.00043	0.00043
$\Lambda = 1$ TeV	0.00092	0.00089
$\Lambda = 0.5$ TeV	0.0025	0.0025

$|a_C^W/\Lambda^2|$

Cutoff	Expected upper limit [GeV^{-2}]	Observed upper limit [GeV^{-2}]
No form factor	0.0016	0.0015
$\Lambda = 1$ TeV	0.0033	0.0033
$\Lambda = 0.5$ TeV	0.0090	0.0092

D0: PRD 88, 012005 (2013)

Conclusion

- Massive diboson production: test of Standard Model predictions
- All SM diboson cross sections have been measured, making use of up to the full CDF and D0 datasets
- Experimental precision equal to NLO theoretical predictions reached in high statistics diboson modes
- Limits have been set on aTGC's and $WW\gamma\gamma$ coupling
- $WW/WZ/W\gamma$ combination limits comparable to LHC
- All results are consistent with the Standard Model

Backup

$ZZ \to 4l$ Systematics

CDF

Syst	%
Higher Order	2.5
PDF	2.7
Luminosity	5.9
Lepton ID	3.6
Drell-Yan	50

D0

Syst	%
Trigger eff.	1
CC/EC e ID	3.7
ICR E ID	6
μ ID	3.2
Instrum. Bkg.	10-50
$t\bar{t}$	20
PDF	2.5
$\sigma(ZZ)$	7.1
ZZ p_T	1-7
$ZZ_{migr.}$ p_T	40
Scale	2

$ZZ \rightarrow ll\nu\nu$ NN inputs

- CDF NN Inputs
- $p_T(l_1)$
- $\not{E}_T^{sig}$
- m_{ll}
- $p_T(ll)$
- $\Delta\phi(ll)$
- N_{jets}
- $\Delta\phi(\vec{\not{E}}_T, \vec{\not{p}}_T)$

- D0 NN Inputs
- $p_T(l_1)$
- $p_T(l_2)$
- $\not{E}_T$
- $\cos\theta^*_\eta$ - CM scattering angle
- $\Delta\phi(l_1, ll)$
- $(m_{ll} - m_Z)/\sigma(m_{ll})$

$ZZ \to ll\nu\nu$ CDF Systematics

Source	ZZ	WW	WZ	$t\bar{t}$	DY	$W\gamma$	$W+$jets
Theoretical cross section		6	6	10		10	
Run-dependence modeling				10			
PDF modeling	2.7	1.9	2.7	2.1		2.2	
Higher-order amplitudes	5		5	10		5	
Luminosity	5.9	5.9	5.9	5.9		5.9	
Photon conversion modeling						10	
Jet-energy scale	2.0	1.6	3.4	5.3		2.0	
Jet-to-lepton misidentification rate							16
Lepton identification efficiency	3	3	3	3			
Trigger efficiency	2	2	2	2			
DY normalization					10.2		
DY mismodeling					✓		

$ZZ \to ll\nu\nu$ D0 Systematics

	N_{bgd}	$A_{\ell\ell}$	A_{sig}	$A_{\ell\ell}/A_{\text{sig}}$	σ_{sig}
L_{inst} profile	1.5	4.5	5.2	0.7	1.8
Vertex z profile	1.0	1.3	0.7	0.6	2.5
$Z/\gamma^* p_T$	0.0	0.0	0.0	0.0	0.6
Diboson p_T	2.6	0.0	1.8	1.8	3.7
Jet energy scale	1.1	0.8	1.5	0.8	1.8
Jet energy resol.	0.9	0.1	0.1	0.0	1.8
IC jet treatment	0.2	0.2	0.4	0.2	0.6
Jet reconstr.	0.5	0.3	0.0	0.2	0.0
Trkjet reconst.	1.5	0.0	1.1	1.2	3.1
Electron p_T scale	0.4	0.0	0.0	0.0	0.6
Electron p_T resol.	1.0	0.1	0.5	0.4	1.8
Electron p_T tails	1.0	0.0	0.6	0.6	1.2
Muon p_T scale	0.1	0.0	0.0	0.0	0.0
Muon p_T resol.	0.5	0.1	0.5	0.5	0.6
Muon p_T tails	0.1	0.1	0.5	0.4	0.6
Lepton eff. vs p_T	0.0	0.0	0.0	0.0	0.6
Lepton eff. vs η	0.0	0.0	0.0	0.0	0.6
W+jets model.	1.9	0.0	0.0	0.0	0.6
$W\gamma$ model.	3.9	0.0	0.0	0.0	1.8
Systematic	6.0	4.8	6.0	2.6	7.1
Statistical	–	–	–	–	27.0
Stat. $\oplus$ syst.	6.0	4.8	6.0	2.6	27.9

$WZ \rightarrow lll\nu$ CDF Systematics

Syst	%
Lumi	6
PDF	2.1-2.7
HO	10
σ	5-7
γ misID	20
Fake Rate	25
Lep ID	2
Trigger	5.4
Jet modeling	1.2

$WZ \to l l l \nu$ D0 Systematics

	N_{bgd}	$A_{\ell\ell}$	A_{sig}	$A_{\ell\ell}/A_{sig}$	σ_{sig}
L_{inst} profile	4.0	2.4	3.3	0.9	0.2
Vertex z profile	1.6	1.3	0.9	0.4	0.7
$Z/\gamma^* p_T$	0.0	0.0	0.0	0.0	0.2
Diboson p_T	0.1	0.0	0.4	0.4	0.2
Jet energy scale	6.0	0.1	0.3	0.2	1.3
Jet energy resol.	2.2	0.0	0.0	0.0	0.2
IC jet treatment	1.1	0.0	0.0	0.0	0.2
Electron p_T scale	0.3	0.0	0.1	0.1	0.2
Electron p_T resol.	1.0	0.1	0.0	0.0	0.2
Electron p_T tails	0.1	0.0	0.3	0.4	0.2
Muon p_T scale	0.1	0.0	0.1	0.1	0.2
Muon p_T resol.	0.9	0.1	0.1	0.0	0.2
Muon p_T tails	1.0	0.2	0.4	0.2	0.2
Track reconstr.	0.1	0.7	1.1	0.3	0.7
Muon reconstr.	0.2	0.3	0.5	0.2	0.2
Electron reconstr.	0.2	0.2	0.2	0.0	0.2
Z/γ^*+jets model.	17.7	0.0	0.0	0.0	2.5
Systematic	19.4	2.9	3.7	1.2	3.1
Statistical	–	–	–	–	13.2
Stat. $\oplus$ syst.	19.4	2.9	3.7	1.2	13.6

$WZ \rightarrow lll\nu$ CDF NN Inputs

- Only most significant inputs:
- $\not{E}_T$
- $\Delta\phi(W, \vec{\not{E}}_T)$
- ΣE_T
- Lepton flavor combination

$WW \to ll\nu\nu$ CDF Systematics

WW(ll$\nu\nu$) Cross Section — CDF Run II Preliminary — $\int L = 9.7\ \mathrm{fb}^{-1}$

Uncertainty Source	*WW*	*WZ*	*ZZ*	$t\bar{t}$	*DY*	$W\gamma$	W+jet
Cross Section		6.0%	6.0%	4.3%*	(0 − 5.0%*)		
Acceptance							
$\not\!\!E_T$ Modeling					(19.0-26.0%*)		
Higher-order Diagrams		10.0%	10.0%			10.0%*	
$t\bar{t}$ QCD				2.7%			
Conversion Modeling						6.8%	
Scale	(23.7†-3.8%)						
PDF Modeling	(0.8-1.8%)						
Jet Energy Scale	(21.5†-4.7%)	(13.2†-6.4%)	(13.3†-3.5%)	(12.9†-26.8%)	(28.7†-10.2%)	(22.0†-3.5%)	
$b-$tag veto				(0.0-3.9%)			
Lepton ID Efficiencies	3.8%	3.8%	3.8%	3.8%	(0 − 3.8%)		
Trigger Efficiencies	2.0%	2.0%	2.0%	2.0%	(0 − 2.0%)		
Jet Fake Rate							(17.2-19.0%)
Luminosity	5.9%	5.9%	5.9%	5.9%	(0 − 5.9%)		

* indicates uncorrelated systematic. † indicates anticorrelated systematic.

$WW \to ll\nu\nu$ D0 Systematics

D0	
Syst	%
σ	4-7
Multijet	30
W+jets	15-30
Z+jets	2-15
$\not\!\!E_T$ Modeling	5-19
Shape	
JES	4
Jet Res.	0.5
Jet ID	2
Jet Vtx.	2
b−tag	¡2
W+jets Model	10-30
$p_T(V)$ Model	¡1

$WW \to ll\nu\nu$ CDF NN Inputs

- 0 Jets:
- SumEtLeptonsMet
- $p_T(l_2)$
- LRWW
- m_{ll}
- $\Delta\phi(l,l)$
- M_t(ll,$\not{E}_T$)
- $p_T(l_1)$
- $E(l_1)$
- $\Delta R(l,l)$

- 1 Jet:
- SumEtLeptonsMet
- $p_T(l_2)$
- $\not{E}_{T,rel}$
- $E(l_1)$
- $\Delta R(l,l)$
- M_t(ll,$\not{E}_T$)
- $p_T(l_1)$
- m_{ll}

- 2+jets:
- SumEtLeptonsMet
- $p_T(j1+j2)$
- $\not{E}_{T,rel}$
- $p_T(l_2)$
- $\not{E}_T^{sig}$
- Aplanarity
- $\Delta R(l,l)$
- SumEtLeptonsJets
- $\cos(\Delta\phi(l,l)_{CM})$
- $\Delta\phi(ll,\not{E}_T)$
- SumEtJetsMet
- m_{ll}
- $p_T(l_1)$

$WW \to ll\nu\nu$ D0 BDT Inputs

The following input variables are used for the DY-BDT:

(i) lepton p_T

(ii) invariant mass of the leptons, $M_{\ell_1\ell_2}$

(iii) azimuthal opening angle between the two leptons, $\Delta\phi(\ell_1, \ell_2)$

(iv) separation in η, ϕ space between the two leptons, $\Delta R(\ell_1, \ell_2) = \sqrt{(\eta_{\ell_1} - \eta_{\ell_2})^2 + (\phi_{\ell_1} - \phi_{\ell_2})^2}$

(v) minimal transverse mass, $M_T^{\min}$

(vi) extended transverse mass, M_{T2}

(vii) missing transverse energy, $\not{E}_T$

(viii) smallest and largest of the azimuthal angles, $\Delta\phi$ between the $\not{E}_T$ and either lepton

(ix) transverse mass of the $\not{E}_T$ and the dilepton pair, $M_T(\ell_1\ell_2, \not{E}_T)$

(x) special missing transverse energy, $\not{E}_T^{\text{special}}$, defined for object ζ, which corresponds to either the nearest lepton or jet in the event relative to the direction of the $\vec{\not{E}}_T$:

$$\not{E}_T^{\text{special}} = \begin{cases} \not{E}_T, & \text{if } \Delta\phi(\not{E}_T, \zeta) > \pi/2 \\ \not{E}_T \times \sin[\Delta\phi(\not{E}_T, \zeta)], & \text{otherwise} \end{cases}$$

(xi) jet p_T

(xii) scaled missing transverse energy defined as

$$\not{E}_T^{\text{scaled}} = \frac{\not{E}_T}{\sqrt{\sum_{\text{jets}} [\Delta E^{\text{jet}} \cdot \sin\theta^{\text{jet}} \cdot \cos\Delta\phi(\text{jet}, \not{E}_T)]^2}},$$

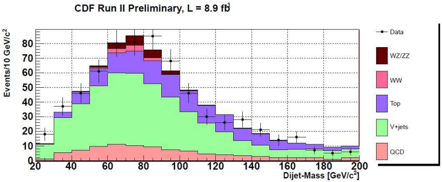
where ΔE^{jet} is a measure of jet energy resolution and is proportional to $\sqrt{E^{\text{jet}}}$; the fluctuation in the measurement of jet energy in the transverse plane can be approximated by the quantity $\Delta E^{\text{jet}} \cdot \sin\theta^{\text{jet}}$ [6]

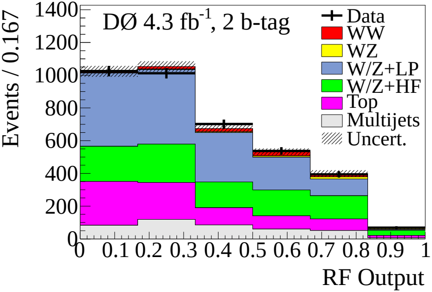
(xiii) azimuthal angle between the $\not{E}_T$ and the jets, $\Delta\phi(\not{E}_T, \text{jet})$

(xiv) absolute value of the pseudorapidity difference between the jets, $|\Delta\eta(j_1, j_2)|$, where j_1 and j_2 are the two highest-p_T jets in the event

(xv) invariant mass of the two jets, $M(j_1, j_2)$.

$WZ/ZZ \to l\nu jj$





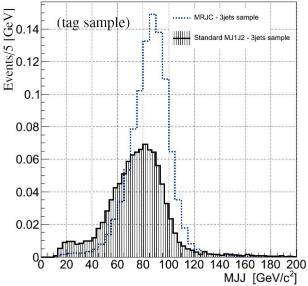
- Same topology as $WH \to b\bar{b}$
- Small production cross section
- Substantial backgrounds
- $\not{E}_T > 20$ GeV
- $M_T^{l\nu} > 40 - 0.5\not{E}_T$
- Random forest classifier
- Similar CDF analysis:
- 2 jets, fit to M_{jj}

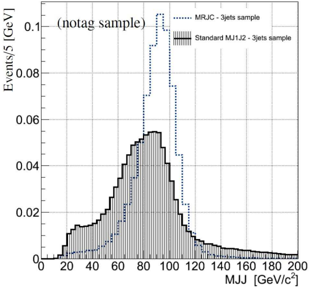
- Single $e(\mu)$, $p_T > 15(20)$ GeV
- 2-3 jets, $p_T > 20$ GeV
- Separated by NN b-tags

	$\sigma(p\bar{p} \to WZ)$ (pb) (l
CDF$(WZ + ZZ)$	$5.1^{+3.6}_{-2.5}$
D0	$3.3^{+4.1}_{-3.0}$
MCFM	3.5 ± 0.3

$WZ/ZZ \to l\nu jj(j)$

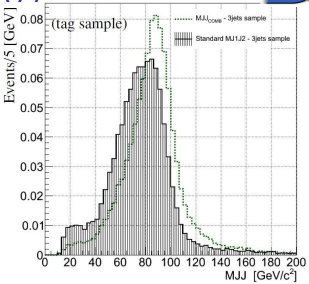
- Including a 3^{rd} jet improves acceptance by 1/3
- Exactly three jets, $E_T(j_1, j_2, j_3) > 25, 15, 15$ GeV
- $M_T^W > 10(30)$ GeV for $\mu(e)$
- $\not{E}_T - \text{significance} \geq 1.8$ to suppress multijet QCD
- Resolution of $M(j_1, j, 2)$ degraded by third jet

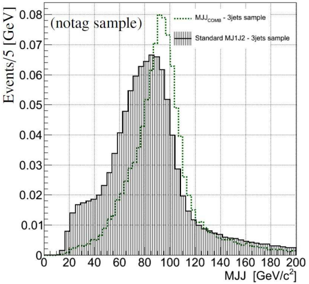




$WZ/ZZ \to l\nu jj(j)$

- Jets ordered by bness(tag) or E_T(notag)
- Train four neural networks to select each correct jet combination
- MJJ_{COMB}=($J_1 + J_2$, $J_1 + J_2 + J_3$, $J_1 + J_3$, $J_2 + J_3$)
- Apply successive cuts to each distribution to select MJJ_{COMB}
- Including 3-jet events with this technique improves expected p-value to extract WZ/ZZ signal from 0.75σ to 1.05σ





CDF: Nucl. Instrum. Meth. A738 (2014)

Additional References

CDF $\gamma\gamma$: PRL 110, 101801 (2013)
D0 $\gamma\gamma$: Phys.Lett B725, 6 (2013)
D0 $W\gamma$: PRL 107, 241803 (2011)
CDF $Z\gamma$: PRL 107, 051802 (2011)
D0 $Z\gamma$: PRD 85, 052001 (2012)