Di-Boson Production Cross Section at the Tevatron

Moriond QCD and High Energy Interactions 2012

Jesús Vizán
on behalf of the CDF and D0 collaborations

UCL (Université catholique de Louvain)

Outline

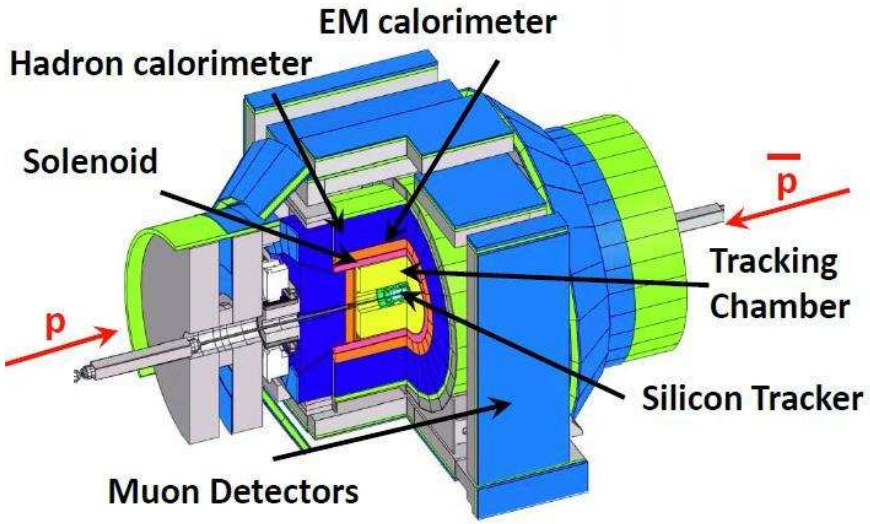
- Motivation for diboson studies
- Diboson production at Tevatron
- Milestones on diboson studies at Tevatron
- ***New Tevatron result***
  - D0/CDF Combined WZ/ZZ search in final states with b-tagged jets
- Summary

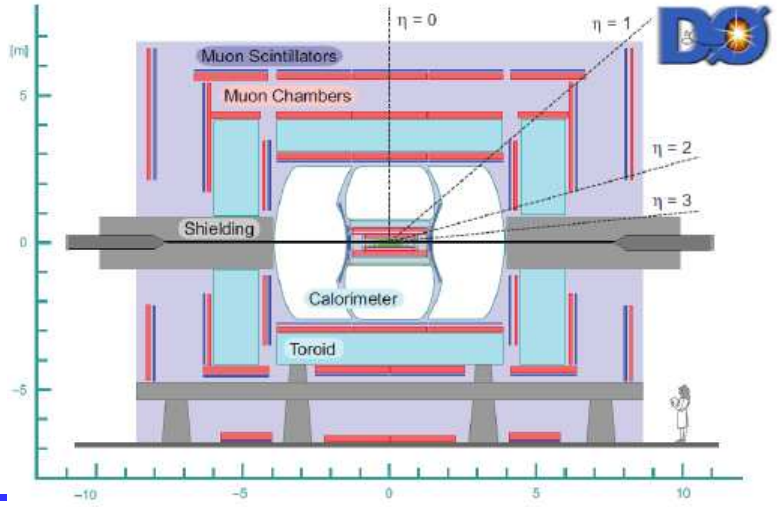
Motivation

- Diboson production represents an important test of the EWK sector of the SM
  - Sensitive to anomalous gauge boson couplings
  - New particles in extensions of the SM
- Important background to top, Higgs, SUSY
- ***Proving ground for combined Tevatron search for low mass Higgs (H→bb modes)***

Experimental Environment

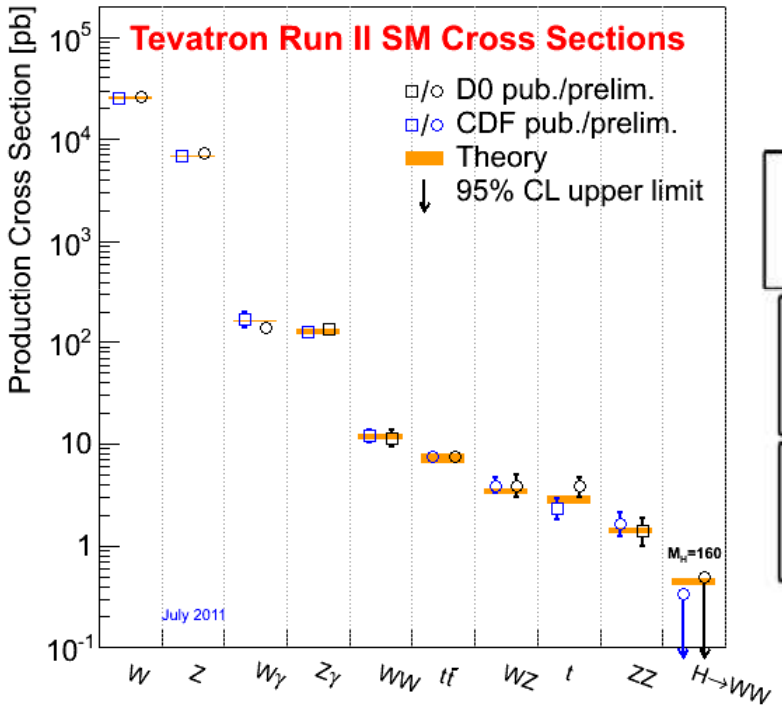
- Tevatron: proton-antiproton collisions at $\sqrt{s}$=1.96TeV
- Using full dataset (up to ***~10*** fb^{-1})
  - ~12 fb^{-1} delivered





Diboson Production at Tevatron

- WW, WZ, and ZZ production are among the smallest standard model cross sections



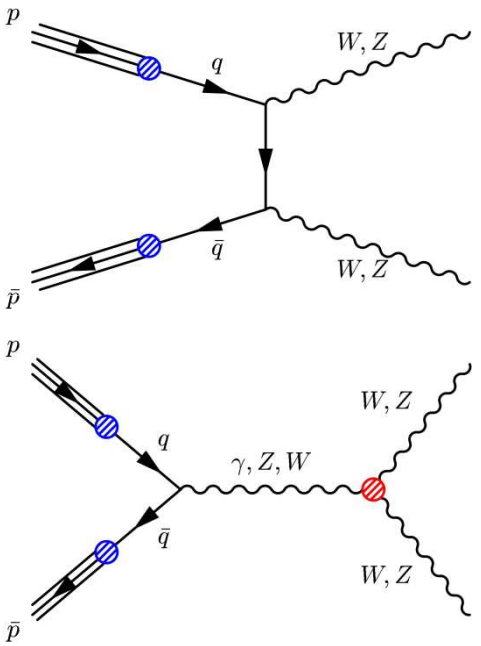
Extremely rare processes:

$\sigma_{p\bar{p}\to W^+W^-}$ 11.34 ± 0.7 pb

$\sigma_{p\bar{p}\to W^\pm Z^0}$ 3.22 ± 0.2 pb

$\sigma_{p\bar{p}\to Z^0Z^0}$ 1.2 ± 0.07 pb

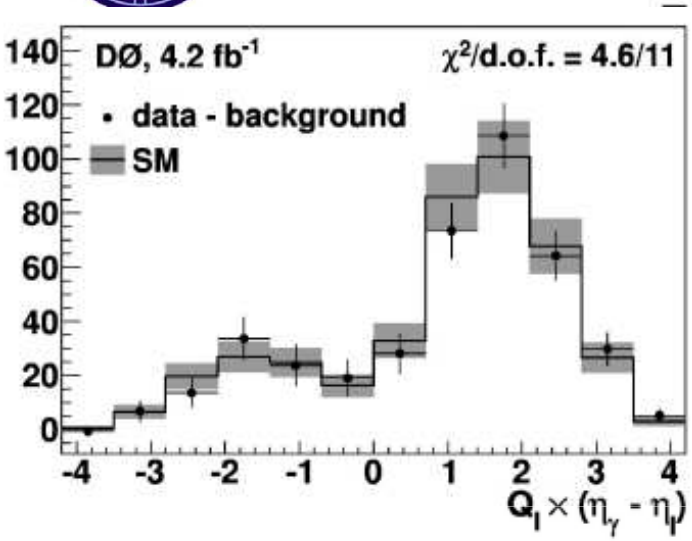
arXiv:1107.5518



- TeVatron experiments already observed all modes

Diboson at the Tevatron: W/Z + γ

Wγ→lν γ



➢ PRL 107, 241803 (2011)

➢ $Q_l(\eta_\gamma-\eta_l)$ in agreement with SM

$$-0.4 < \Delta\kappa_\gamma < 0.4, -0.08 < \lambda_\gamma < 0.07$$

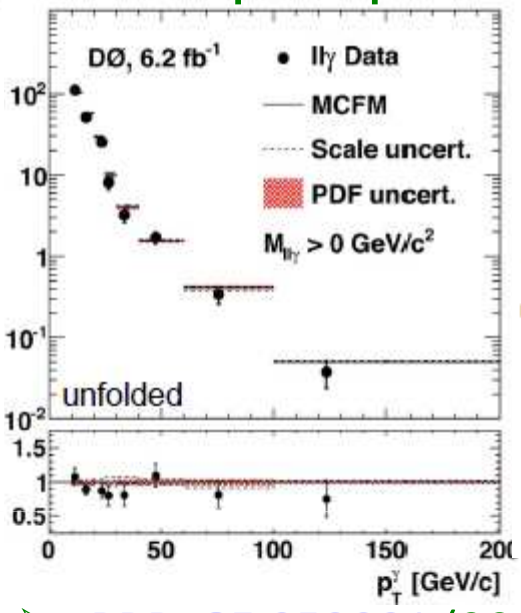
➢ ***95% C.L. TGC limits for Λ = 2 TeV***

$$\sigma_{W\gamma} \times BR(W \to l\nu) = 7.6 \pm 0.4(\text{stat}) \pm 0.6(\text{syst})\ \text{pb}$$

SM@NLO $\sigma(W\gamma)\times BR(W\to l\nu) = 7.6 \pm 0.2$ pb

E_T^γ>15GeV, $\Delta R^{l\gamma}$>0.7

Zγ →llγ



➢ PRD **85** 052001 (2012)

$$\sigma_{Z\gamma} \times BR(Z \to ll) = 1089 \pm 40(\text{stat}) \pm 65(\text{syst})\ \text{fb}$$

SM@NLO $\sigma(Z\gamma)\times BR(Z\to ll) = 1096 \pm 34$ fb

$M_{ll\gamma}$ > 110 GeV (FSR removal):

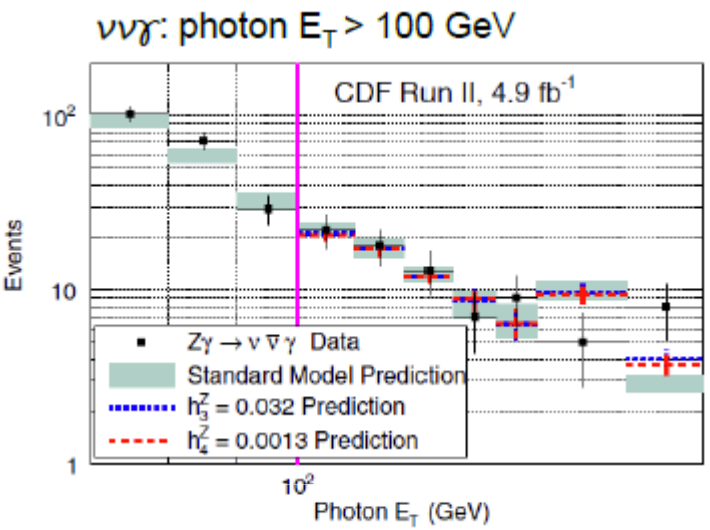
$$\sigma_{Z\gamma} \times BR(Z \to ll) = 288 \pm 15(\text{stat}) \pm 11(\text{syst})\ \text{fb}$$

SM@NLO $\sigma(Z\gamma)\times BR(Z\to ll) = 294 \pm 10$ fb

P_T^γ>10GeV, $\Delta R^{l\gamma}$>0.7,$|\eta^\gamma|$<1

➢diff. cross section ($d\sigma/dp_T^\gamma$) in agreement with SM

Zγ →llγ , νγγ



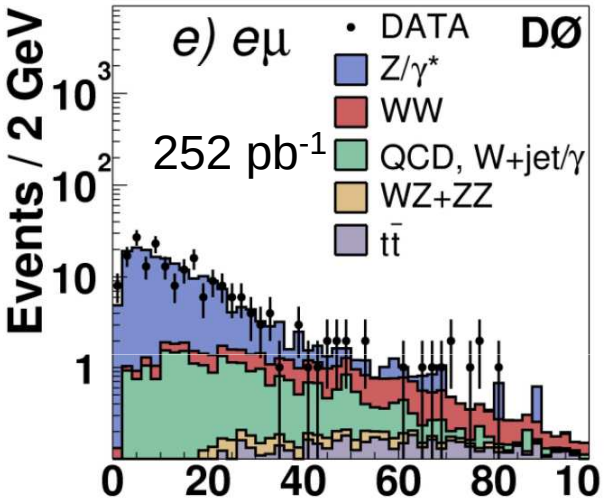
➢ PRL **107**, 051802 (2011)

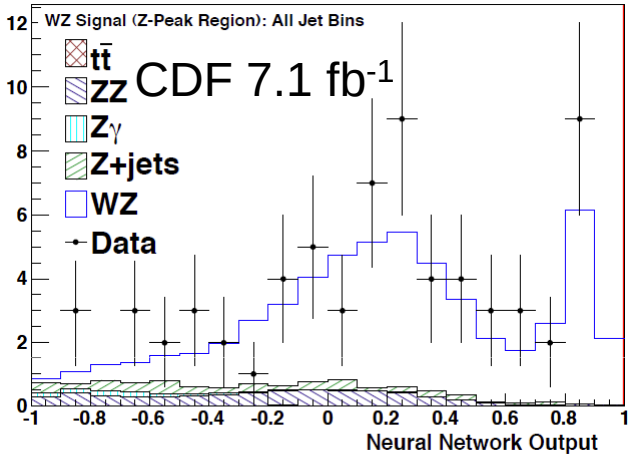
Parameter	(Λ = 1.5 TeV)
h_3^Z	−0.020, 0.021
h_4^Z	−0.0009, 0.0009
h_3^γ	−0.022, 0.020
h_4^γ	−0.0008, 0.0008

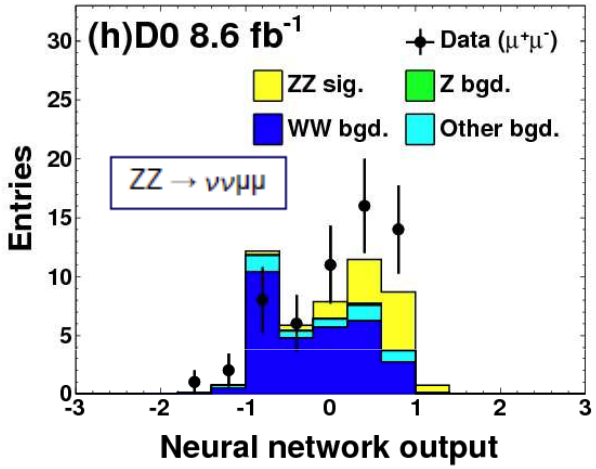
➢ ***95% C.L. TGC limits for these final states***

Diboson at the Tevatron: dilepton states

- Observation first in fully leptonic final states







- WW→lνlν
- PRL **94**, 151801 (2005)

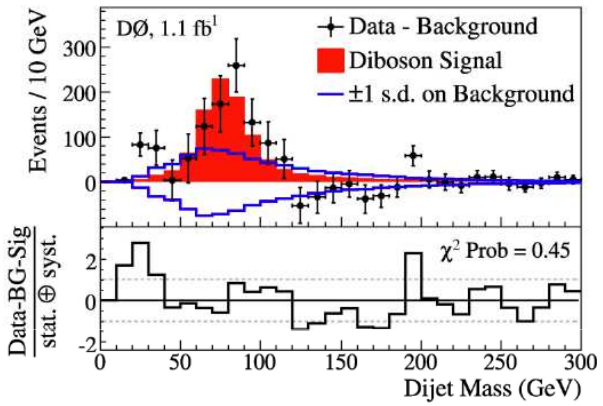
- WZ→lνll
- Submitted to PRL
- $\sigma(WZ)=3.9^{+0.8}_{-0.7}$ pb
- Set TGZ limits (HISZ scheme)

- ZZ→llll, νν̄ll
- arXiv:1112.2978 [hep-ex]
- $\sigma(ZZ)=1.44^{+0.35}_{-0.34}$ pb

Diboson at Tevatron: semileptonic states

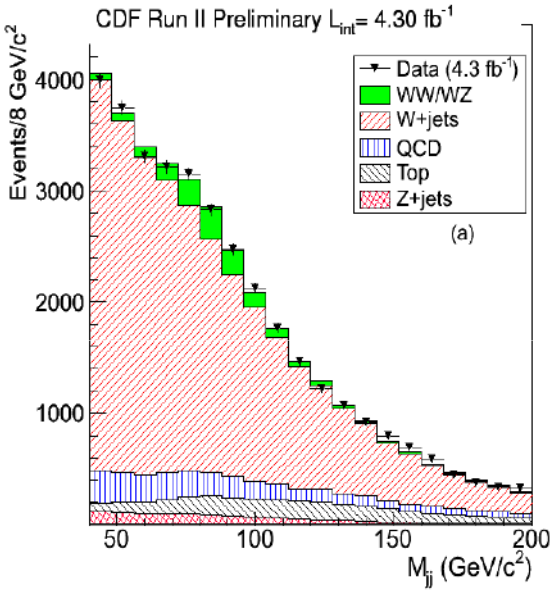
- Difficult to separate WW/WZ due to dijet mass resolution

D0 1.1 fb^{-1}

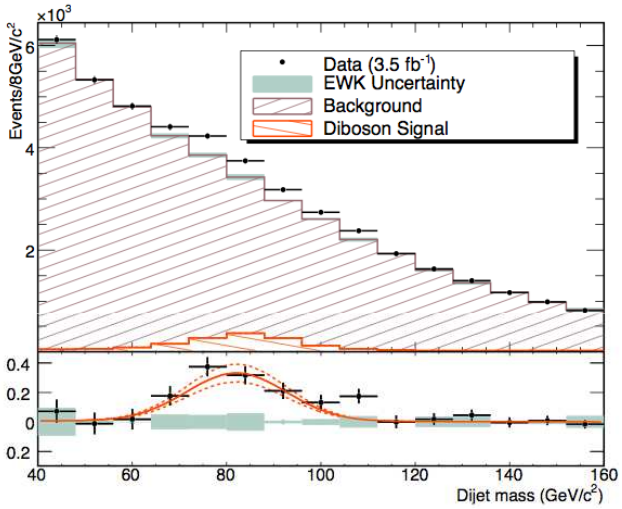


Phys. Rev. Lett. **102**, 161801 (2009) PI

CDF 4.3 fb^{-1}



CDF 3.5 fb^{-1}



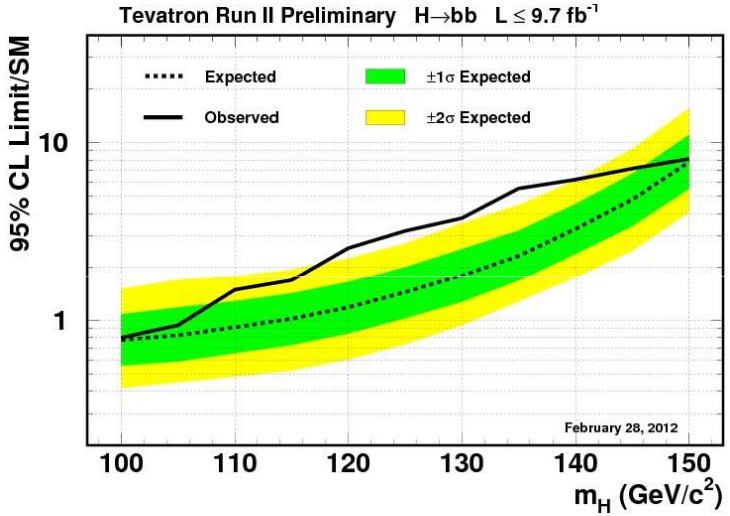
- WW/WZ→lνjj
- PRL **102**, 161801 (2009) evidence

- WW/WZ→lνjj
- PRL **104**, 101801 (2010) observation

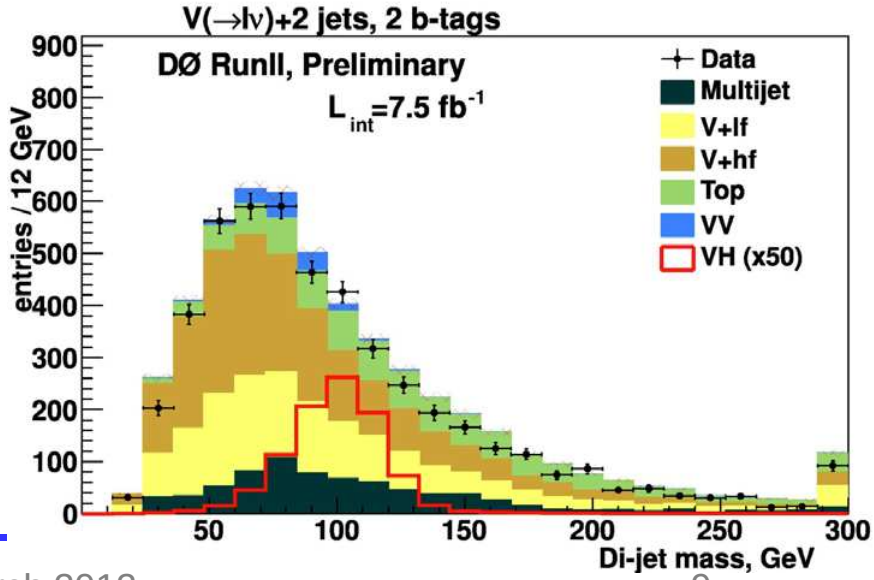
- WW/WZ/ZZ→ννjj
- PRL **103**, 091803 (2009) observation

WZ/ZZ with heavy flavor jets

- Next step as probing ground for H→bb searches
  - WZ/ZZ →llbb, lvbb, vvbb same final states as most important channels for low-mass Higgs searches at Tevatron (WH/ZH)



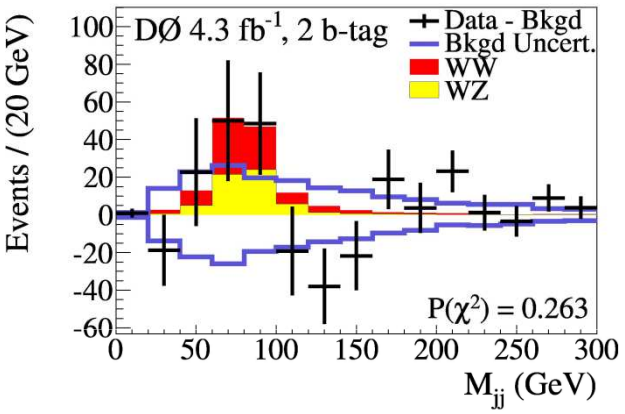
Final State	(W/Z)*H (115 GeV)*	(W/Z)*Z*
lvbb	**27 fb**	**105 fb**
llbb	**5 fb**	**24 fb**
vvbb	**15 fb**	**73 fb**

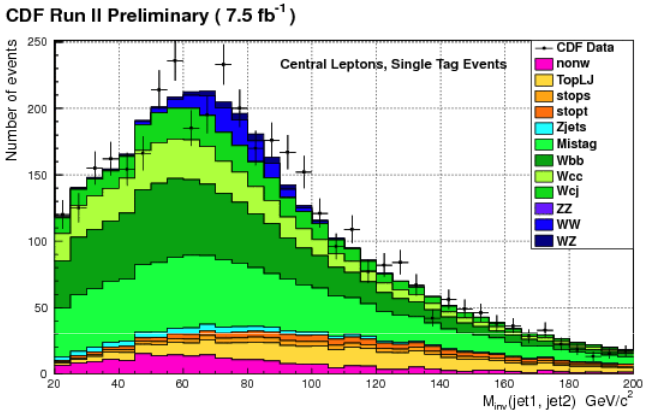


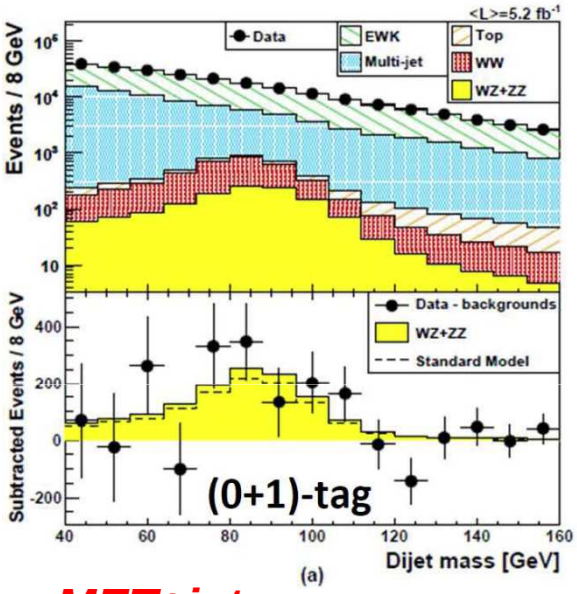
- WZ/WZ ~ 4-5 times larger cross section than WH/ZH
- WZ/ZZ harder to distinguish from large irreducible background (WW…)

Diboson with heavy flavor jets

- Application of b-tagging key to separate WW from WZ/ZZ
  - Fix WW/WZ ratio to SM, Fit for WZ/ZZ







- ***lν+jets***
- 0, 1, 2-tag channels
- arXiv:1112.0536 (submitted to PRL)
- ***2.2 (1.2)*** σ observed (expected) significance

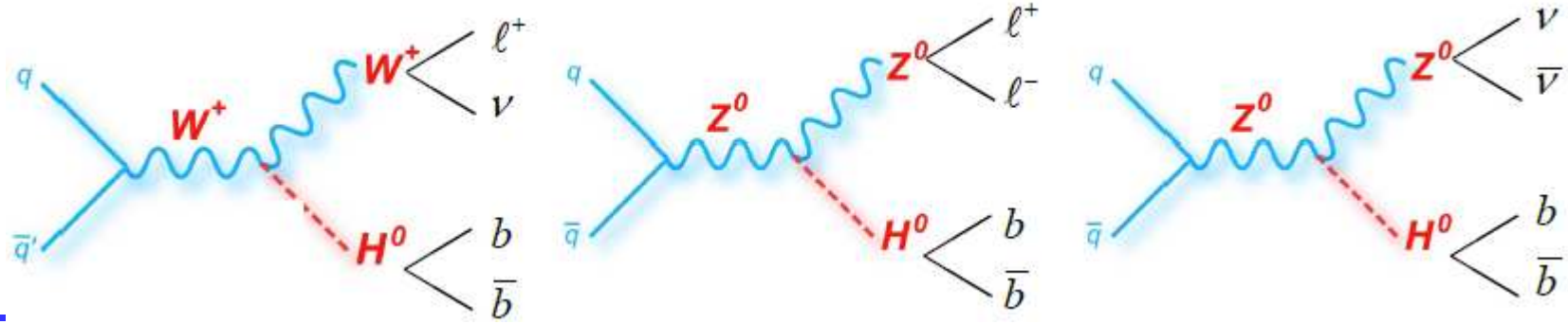
- ***lν+jets***
- 1, 2-tag channels
- Measure $1.1^{+0.26}_{-0.40}$ ***X SM*** cross section
- ***1.08 σ observed***
- ***Evidence*** when WW contribution is included
- 1 tag important (W→cs)

- ***MET+jets***
- 0, 1, 2-tag channels
- Measure $1.1^{+0.7}_{-0.6}$ ***X SM*** cross section
- ***1.9(1.7)*** σ observed (expected) significance

Diboson with heavy flavor jets

❑ *Another further step*

- ➢ Replicate Higgs-low-mass analyses (see Tevatron combination by Daniela) to search for WZ/ZZ
- ➢ 3 main low mass final states: lvbb, llbb, vvbb
- ➢ ***NEW Tevatron*** combination
- ➢ Require at least 1 b-tagged jet
- ➢ Train multivariate discriminants as for Higgs searches
- ➢ Some signal contribution from (W→cs, Z→cc)

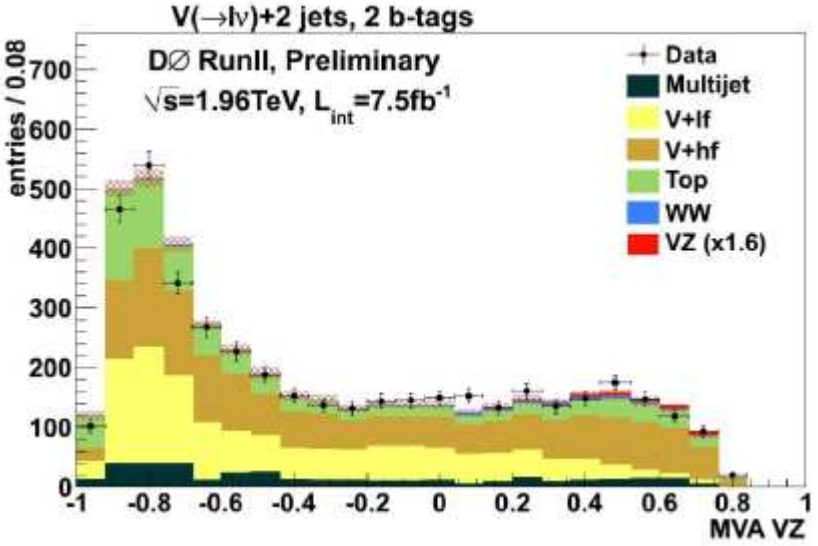


WZ→lνbb

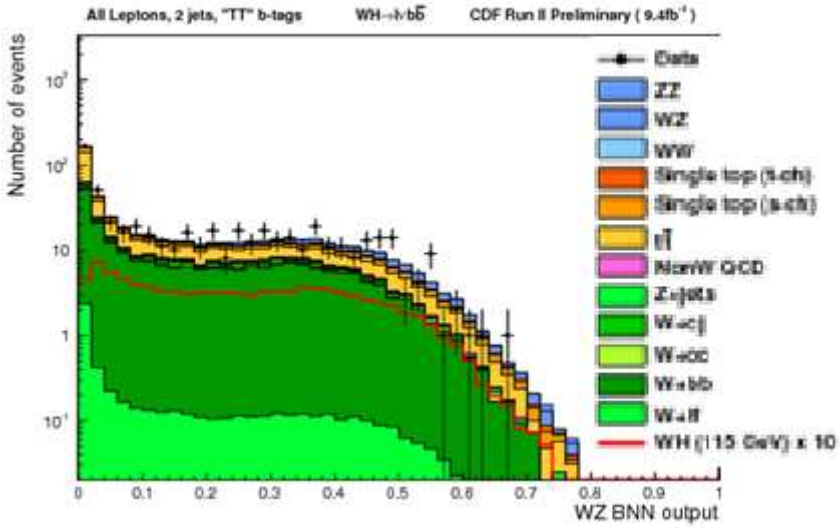
$\sigma(VZ)_{SM}$= 4.42 pb

- Highest cross section
- High PT muon/electron + 2 or 3 jets + MET
- QCD rejected by use of multivariate techniques

- ***D0*** (***7.5 fb^{-1}***): ***MVA***
- b-Id output used as input of MVA
- ***σ(VZ)=7.2±2.03(stat)±2.74(syst) pb***
- ***2.2 σ*** significance, ***1.4 σ*** expected



- ***CDF*** (***9.4 fb^{-1}***): ***Bayesian Neural Network*** discriminant
- Sensitivity improved by use of new NN tagger (HOBIT)
- ***$\sigma(VZ)=7.78^{+2.47}_{-2.25}$ pb***



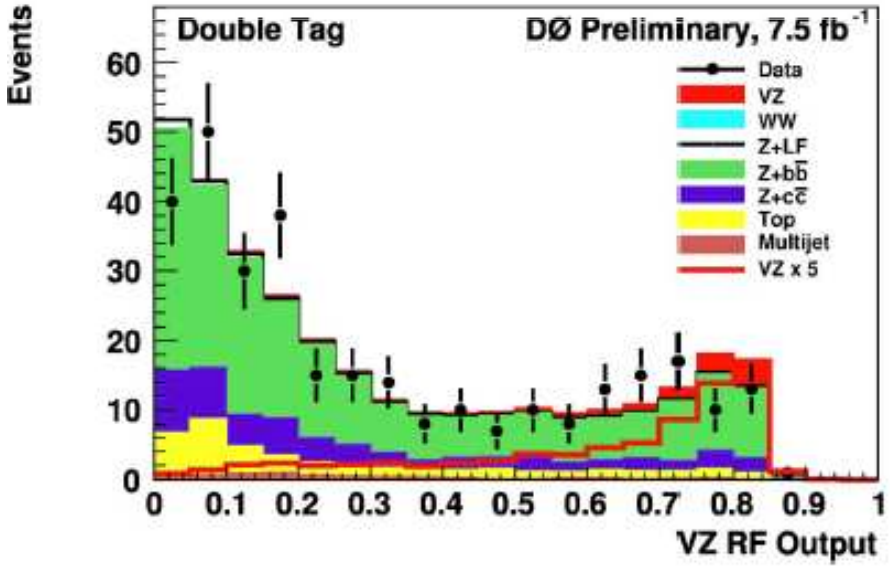
ZZ→llbb

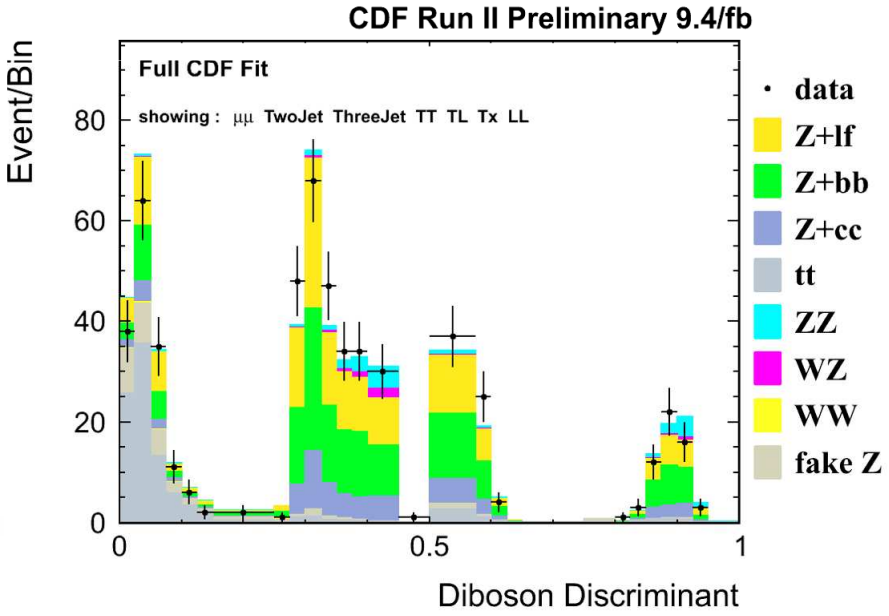
$\sigma(VZ)_{SM}$= 4.42 pb

- Lowest background, worse statistics
- 2 High PT muon/electrons + 2 or 3 jets
- Fully reconstructed final state: allows to improve Mjj resolution

- **D0** (*7.5 fb^{-1}*): ***Random Forest***
- ***σ(VZ)=0.4 ± 2.8 pb***
- ***0.2 σ*** significance, ***1.5 σ*** expected

- **CDF** (*9.4 fb^{-1}*): ***Combine 4 different NN***
- ***σ(VZ)=0.79$^{+1.68}_{-0.70}$ pb***



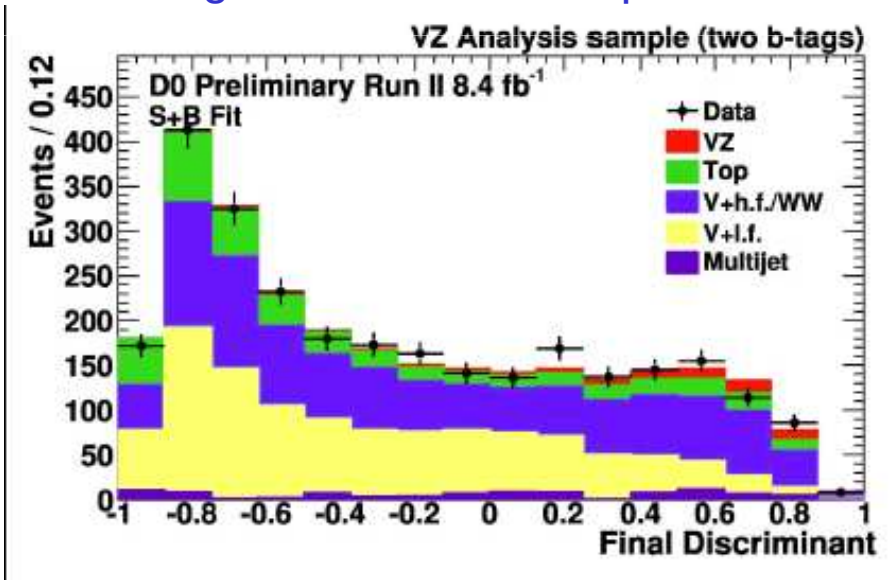


ZZ→ννbb

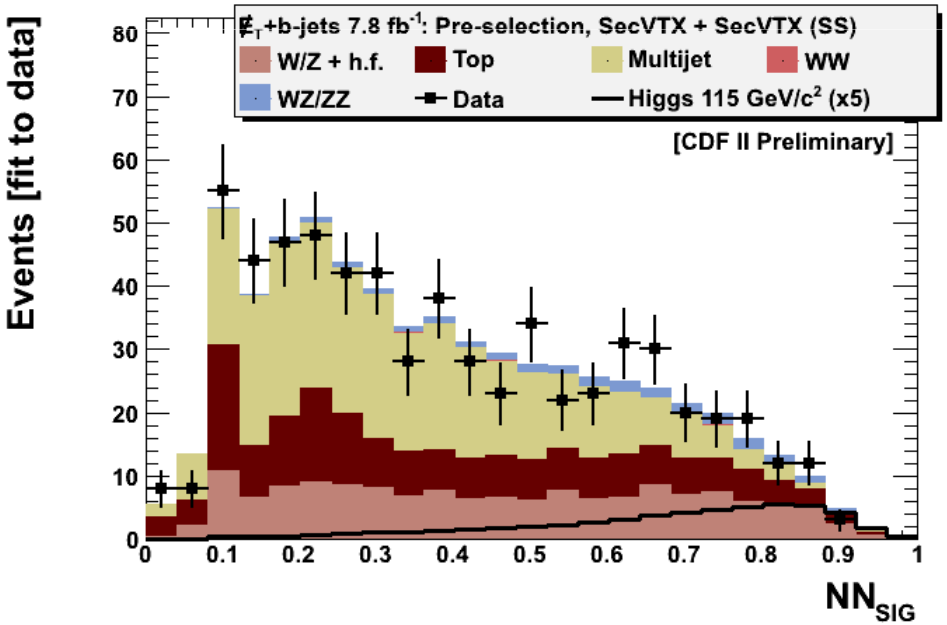
$\sigma(VZ)_{SM}$= 4.42 pb

- Large MET + lepton veto + at least 2 jets
- Sensitive to WZ→lνbb with a missed lepton
- Large MET provides large background rejection

- **D0** (*8.4fb^{-1}*): ***multijet DT + Final Boosted Decision Tree***
- Include b-ID ouput as part of BDT
- ***σ(VZ)=6.9±1.3(stat)±1.8(syst) pb***
- ***2.8 σ*** significance, ***1.9 σ*** expected

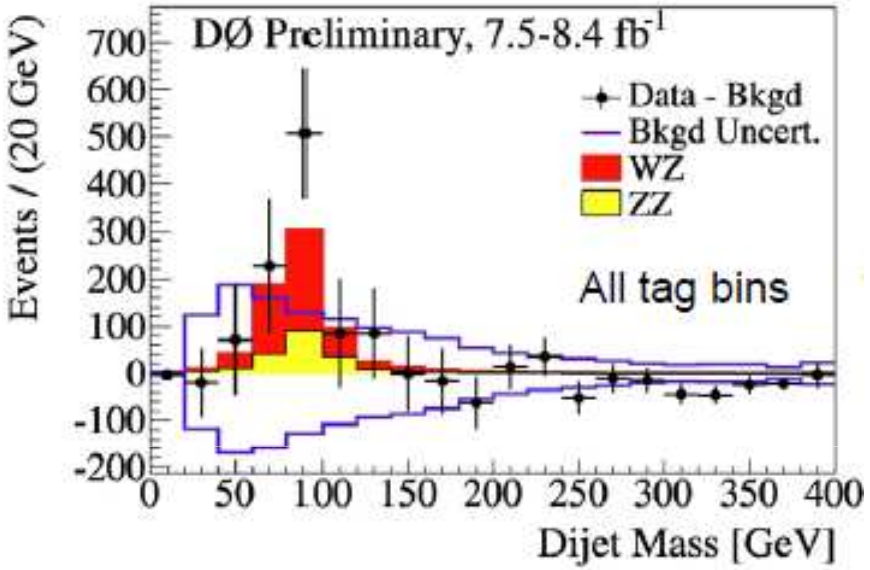


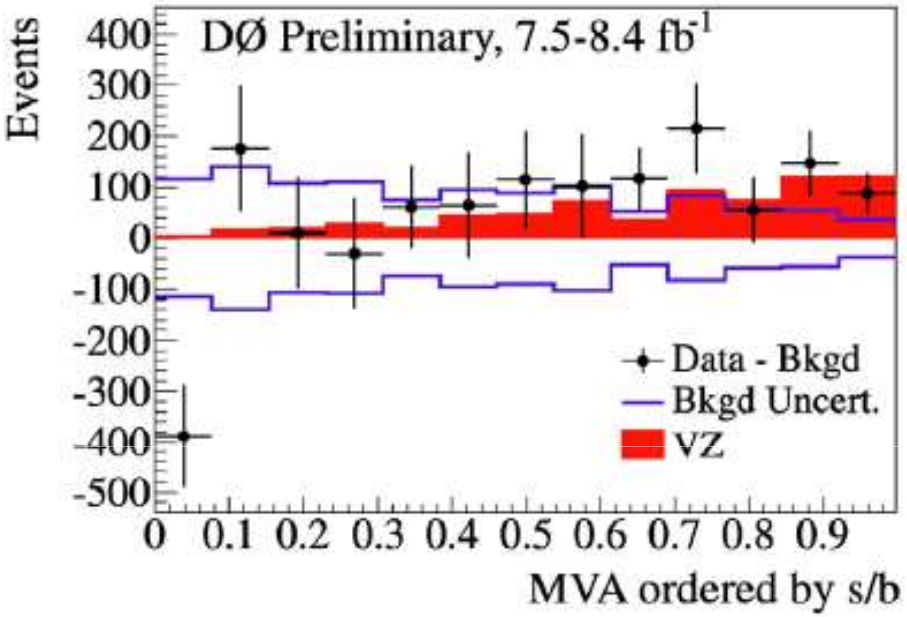
- **CDF** (*9.4 fb^{-1}*): ***multijet artificial NN + Multilayer perceptron***
- 2 or 3 jets
- ***σ(VZ)=2.47$^{+2.07}_{-1.90}$ pb***
- Does not make use of HOBIT yet ***yet***



D0 Combination

$\sigma(VZ)_{SM}$= 4.42 pb



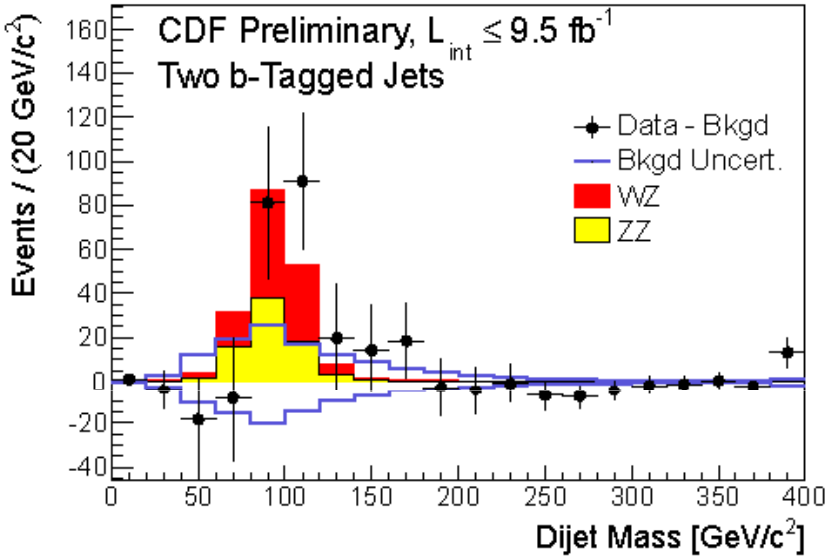


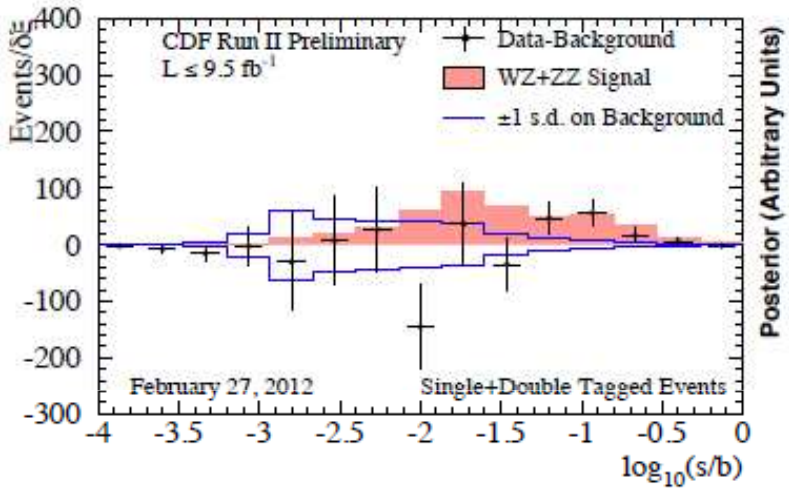
- D0 Note 6260
- ***σ(VZ)=5.0±1.6 pb***
- Evidence with ***3.3σ***, (***2.9 σ*** expected)

CDF Combination

$\sigma(VZ)_{SM}$= 4.42 pb

NEW



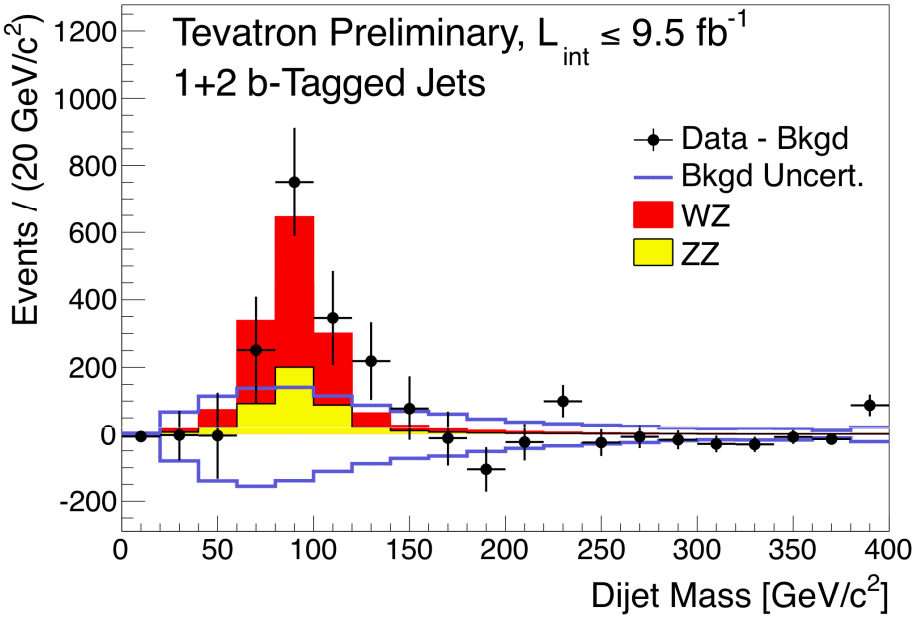


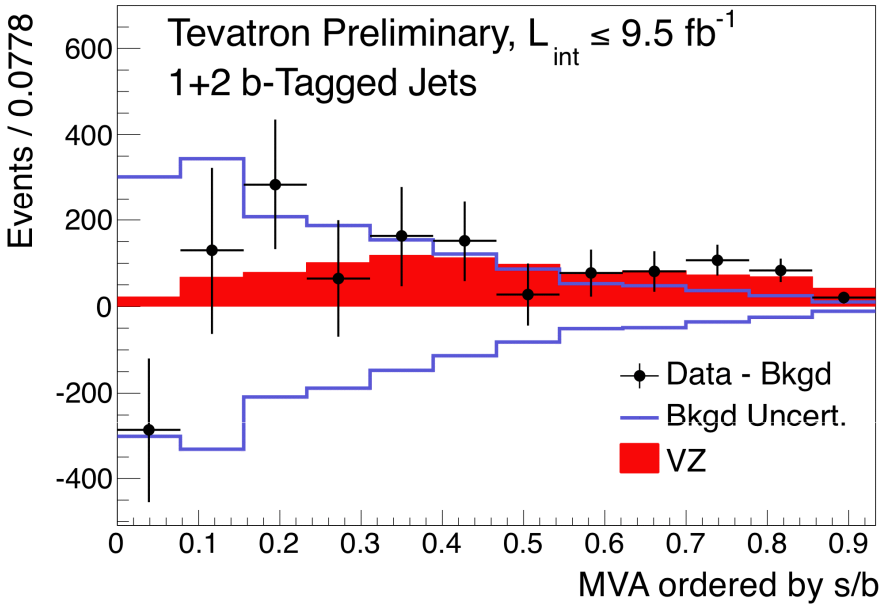
- CDF Note 10805
- ***σ(VZ)=4.08$^{+1.38}_{-1.26}$ pb***
- Compatible with the SM prediction

Tevatron Combination

$\sigma(VZ)_{SM}$= 4.42 pb

NEW





- ***σ(VZ)=4.47 ± 0.64 ± 0.73 pb***
- Compatible with the SM prediction
- Evidence with ***4.6σ***
- FERMILAB-CONF-12-063-E

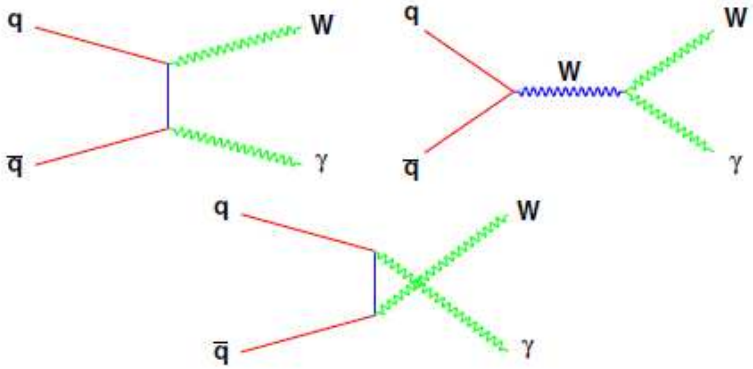
Summary

- Tevatron sensitive to diboson WW/WZ/ZZ
- Even in some of the most challenging decay modes
- Like final states with b-tagged jets
  - New Tevatron combination (WW as background)
  - $\sigma(VZ)=4.47\pm0.64(stat.)^{+0.73}_{-0.72}(syst.)$ pb
  - *4.6 σ evidence for WZ/ZZ with HF jets*
    - *Validates Tevatron Higgs searches in VH (H→bb) channels*
  - Compatible with SM expectations

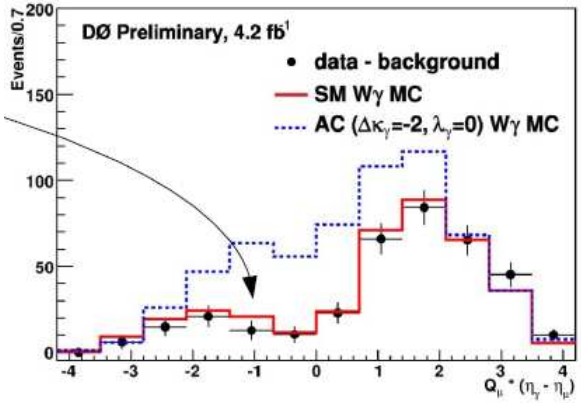
BACK-UP

$W\gamma \rightarrow l\nu\,\gamma$ PRL 107, 241803 (2011)

- Probe of new physics above some higher energy scale Λ_{NP}



Tree-level interferences between these amplitudes produces a zero at a certain θ* (W,incoming q) in the Wγ rest frame→ dip at ~ -1/3 for $Q_l\,(\eta_\gamma-\eta_l)$



- Cross section measurement
  - 4.2 fb^{-1} of data
  - High p_T μ, high p_T γ, and $\not\!\!E_T$
    - 492 $W\gamma$ candidates
    - Expected signal: 376 ± 42
    - Expected background: 134 ± 9
      - ~100 from W+jets

	$e\nu\gamma$ channel	$\mu\nu\gamma$ channel
W + jet	33.9 ± 3.7	64.6 ± 6.8
leX	1.1 ± 0.6	2.1 ± 0.7
$Z\gamma \rightarrow ll\gamma$	1.8 ± 0.3	17.6 ± 1.9
$W\gamma \rightarrow \tau\nu\gamma$	2.3 ± 0.3	5.4 ± 0.6
Total background	39.1 ± 3.8	89.7 ± 7.2
SM $W\gamma$ prediction	150.9 ± 13.8	282.1 ± 25.4
Data	196	363

$$\sigma\,(pp \rightarrow W\gamma) = 15.2 \pm 1.6\ (stat+syst)\ pb$$

$$\sigma_{NLO} = 16.0 \pm 0.4\ pb$$

Wγ→lνγ (D0)

PRL 107, 241803 (2011)

- Probe of new physics above some higher energy scale Λ_{NP}

γWW and ZWW TGCs

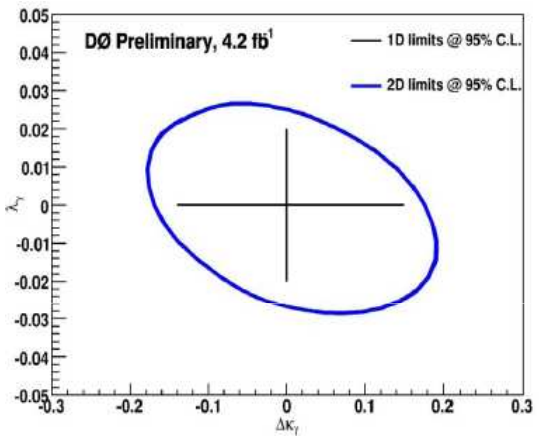
General Lagrangian has 14 TGC parameters

Assume EM gauge invariance and C and P conservation

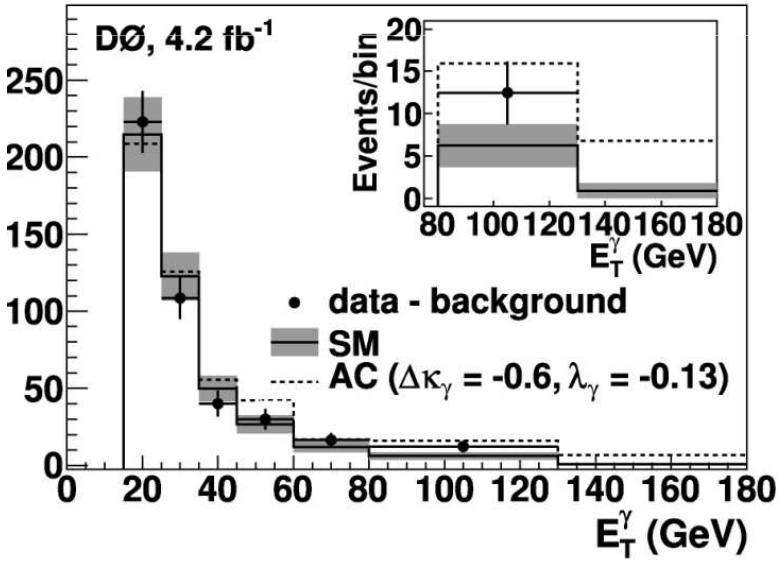
$\Rightarrow g_1^Z, \kappa_\gamma, \kappa_Z \equiv 1$ in the SM

$\Rightarrow \lambda_\gamma, \lambda_Z \equiv 0$ in the SM

Set 95% CL limits on anomalous TGCs (Λ_{NP} = 2 TeV)



Photon E_T spectrum sensitive to anomalous TGCs



1D limits: Vary one coupling at a time

$-0.14 < \Delta\kappa_\gamma < 0.15$

$-0.02 < \lambda_\gamma < 0.03$

Zγ →llγ (D0) ➢ PRD 85 052001 (2012)

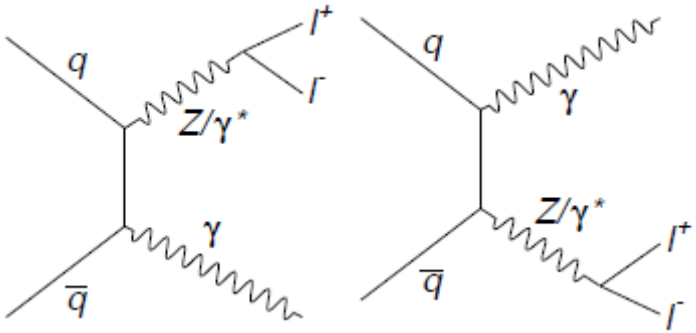
- Probe of new physics above some higher energy scale Λ_{NP}

γZZ and $\gamma\gamma Z$ TGCs

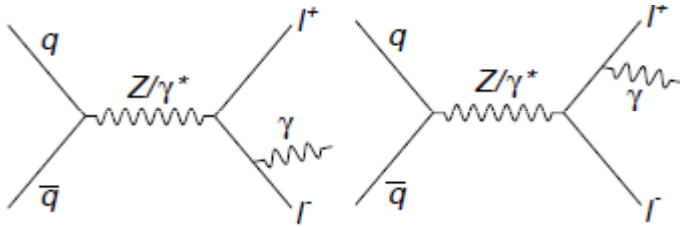
General Lagrangian has 8 TGC parameters

Assume CP conservation

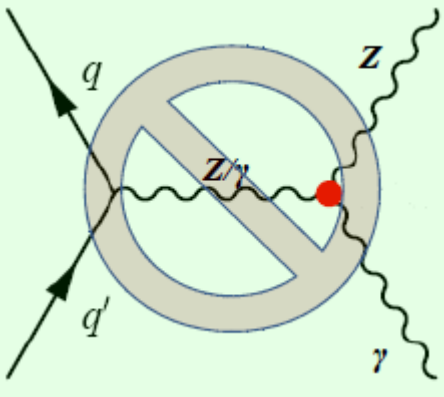
$\Rightarrow h_3^\gamma,\ h_3^Z,\ h_4^\gamma,\ h_4^Z \equiv 0$ in the SM



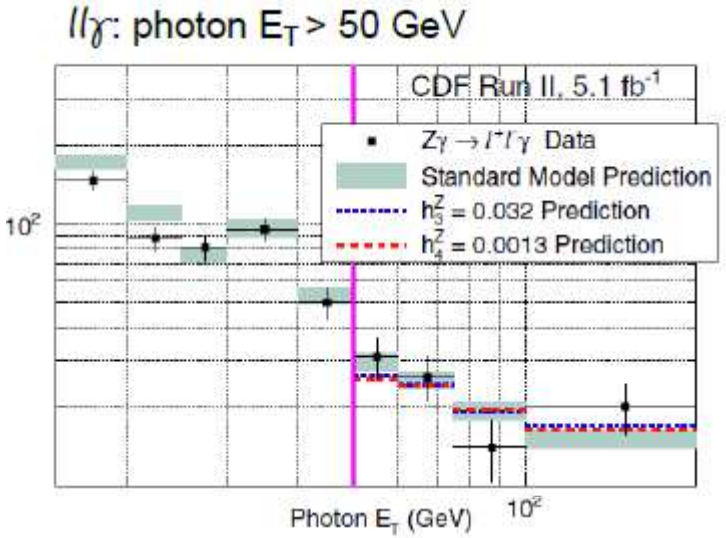
prompt **ISR**

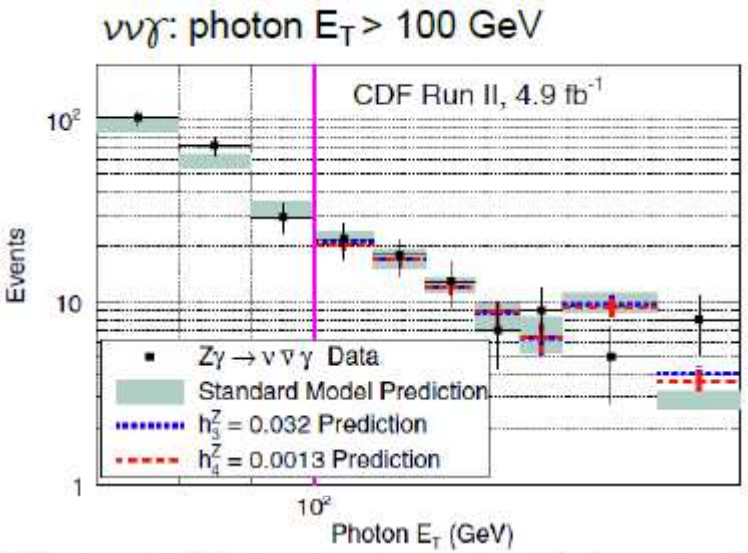


FSR



Zγ →llγ, νγγ (CDF)





PRL 107, 051802 (2011)

Parameter	(Λ = 1.2 TeV)	(Λ = 1.5 TeV)
h_3^Z	−0.024, 0.027	−0.020, 0.021
h_4^Z	−0.0013, 0.0013	−0.0009, 0.0009
h_3^γ	−0.026, 0.026	−0.022, 0.020
h_4^γ	−0.0012, 0.0013	−0.0008, 0.0008

- Photon E_T spectra sensitive to TGCs
- Combination of two selections
  - $Z\gamma \to ll\gamma$: 5.1 fb^{-1}, $E_T(\gamma) > 50$ GeV
  - $Z\gamma \to \nu\nu\gamma$: 4.9 fb^{-1}, $E_T(\gamma) > 100$ GeV
- Observe 176 candidate events
  - Expected signal: 140 ± 9
  - Small background (mostly cosmic μ)

WZ →lllγ (CDF)

Event selection:

- Exactly three leptons (1st with $p_T > 20$ GeV and 2nd, 3rd with $p_T > 10$ GeV), $\not\!\!E_T > 25GeV$
- Z-selection, a pair of same flavor, opposite charge leptons with $76 < m_{ll} < 106$ GeV
- ZZ biggest background → Trilepton + track rejection to remove events with a 2nd Z-boson.

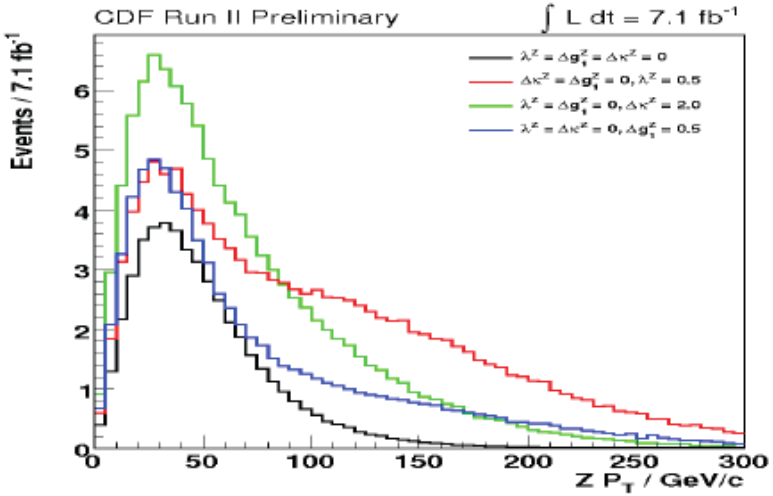
A neural network to separate S from B → Templates are fitted to data using a binned maximum likelihood fit.

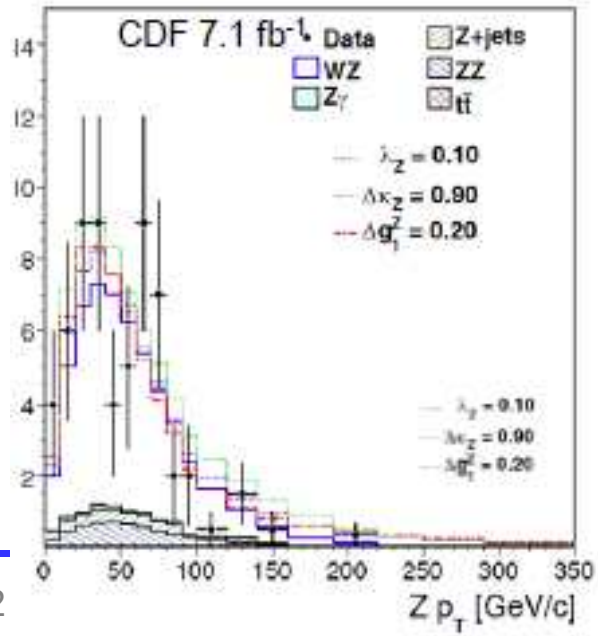
Extract from Z p_T distribution also TGC limits → HISZ scheme= 3 parameters

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

95% CL limits on TGCs (Z p_T spectrum)

	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)





WZ →lllγ (D0)

Do not restrict the offline event selection to events satisfying specific trigger conditions → analyse all recorded data in order to maximise the event yields

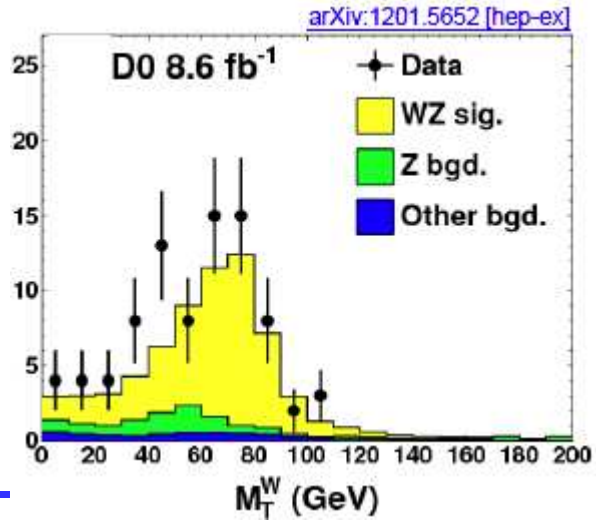
Event selection:

- Exactly three leptons: 1st with $p_T > 20$ (15) GeV and 2nd, 3rd with $p_T > 15$ (10) GeV
- Z-selection, a pair of same flavour, opposite charge leptons with $60 < m_{ll} < 120$ GeV

Likelihood fit to the M_T to extract cross section

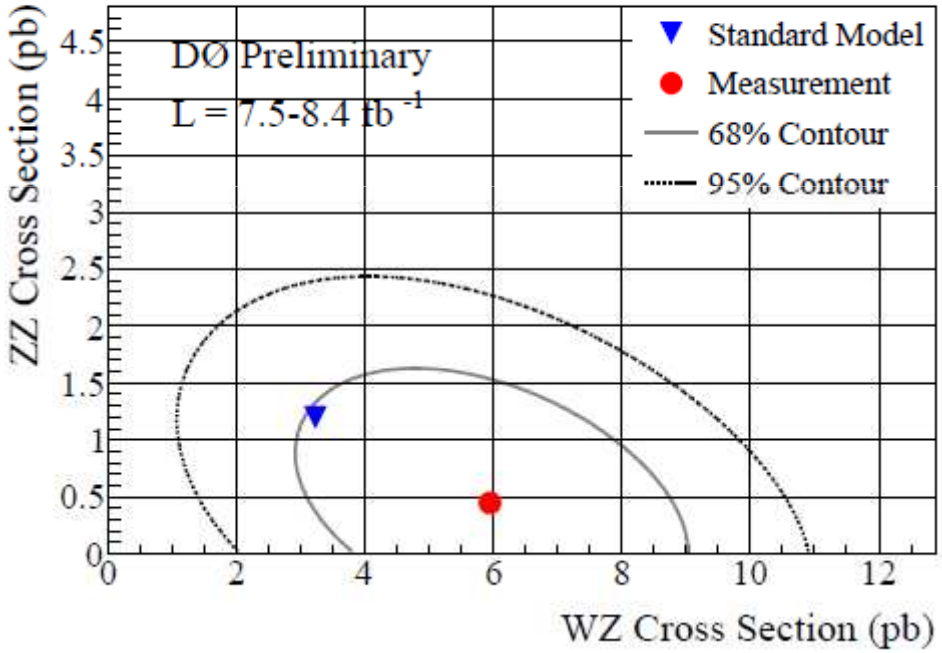
Total cross section uncertainty reduced by taking the ratio to $Z \to \ell\ell$ and then multiplying to theory

$$\sigma(WZ) = 4.50 \pm 0.61(stat.)^{+0.16}_{-0.25}(syst.)\ pb\ (SM\ = 3.46 \pm 0.21)pb$$



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

SM@NLO: σ = 3.21 ± 0.19 pb
($60 < M_{ll} < 120$ GeV)

D0 Combo

- Maximum likelihood fit of the signal and background distributions to the data