Diboson Physics at the Tevatron

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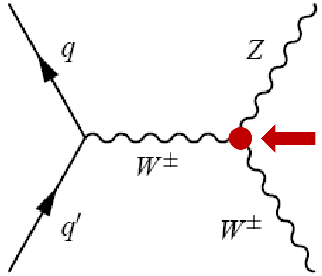
For the CDF and DØ Collaborations

The XLVIIth Rencontres de Moriond EW, March 8, 2012

Motivation for Diboson Studies



Probe of the EWSB mechanism

- Test of the SM
- Indirect searches for New Physics

Cross sections, Kinematic distributions, Trilinear Gauge Boson Couplings (TGCs)

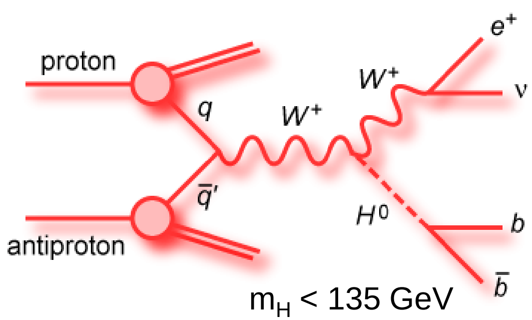
Important background to:

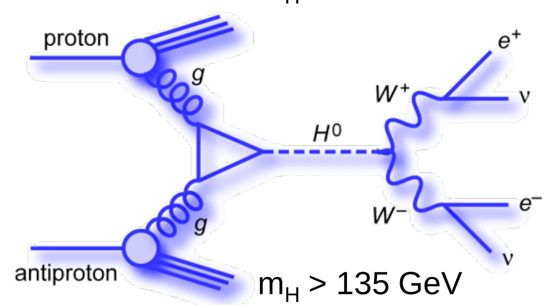
- Top
- Higgs
- Beyond the SM

Good understanding is highly valuable

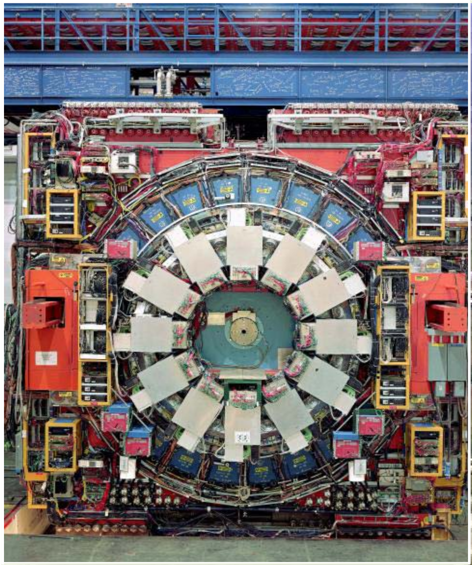
Proving ground for analysis techniques and statistical treatment used in the Tevatron **Higgs searches**

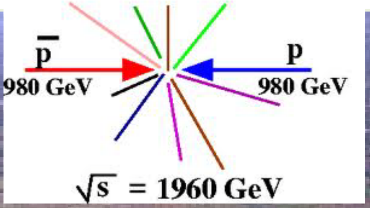
Complementary to Higgs production
(same final states/challenges)





Tevatron Experiments (CDF & DØ)





- Silicon Tracker
- Central Outer Tracker
- Solenoid
- Calorimeter
- Muon Detectors

- Silicon Tracker
- Central Fiber Tracker
- Solenoid
- Calorimeter
- Muon System

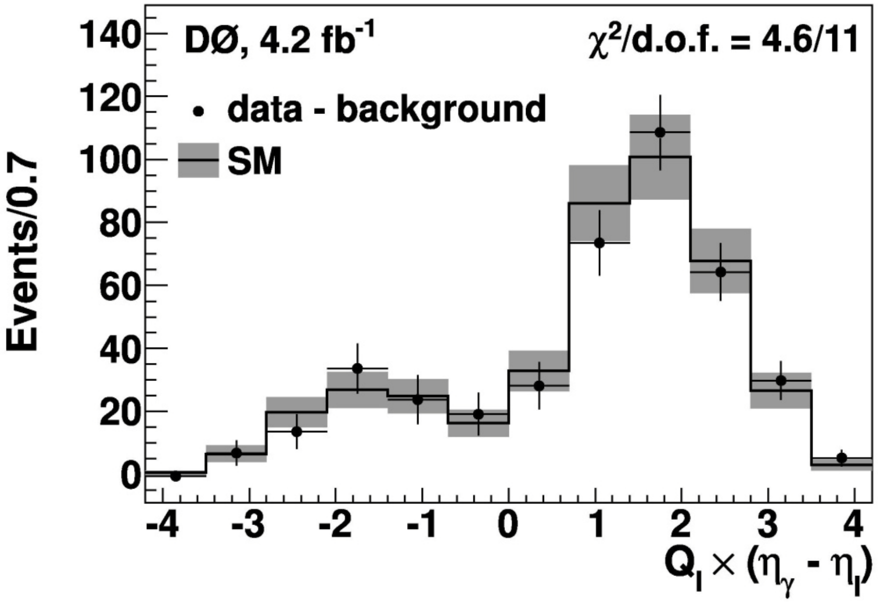
- Multipurpose detectors
- Luminosity: ~10 fb^{-1}

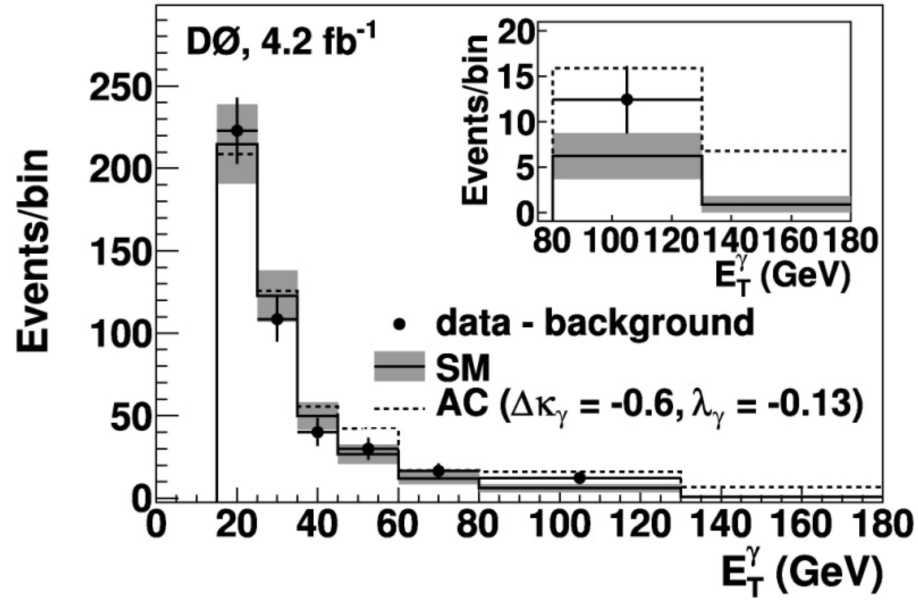
$W\gamma \to l\nu\gamma$ Production

Radiation amplitude zero, cross section, limits on TGCs

- High p_T (isolated) muon/electron and photon, missing transverse energy (MET)

PRL 107, 241803 (2011)





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

$$\text{SM@NLO}: \sigma = 7.6 \pm 0.2\,\text{pb}$$

(photon E_T > 15 GeV, $dR_{(l\gamma)}$ > 0.7)

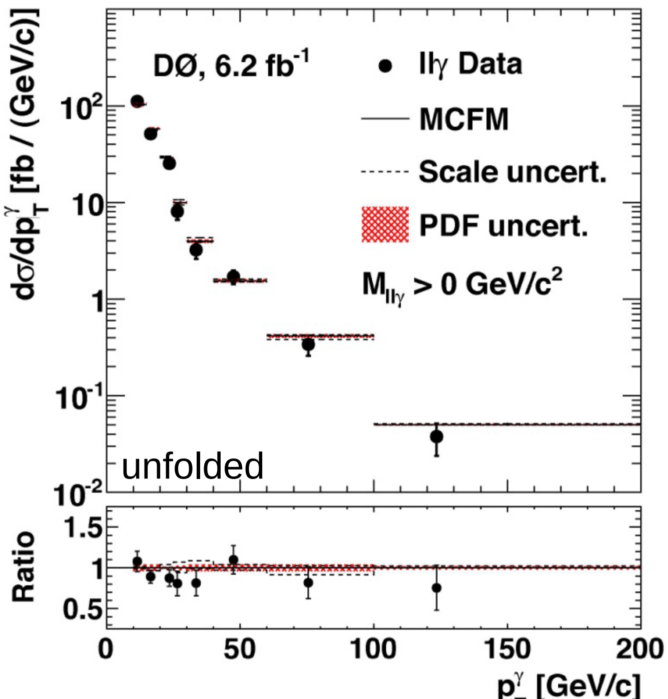
95% CL limits on TGCs:

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

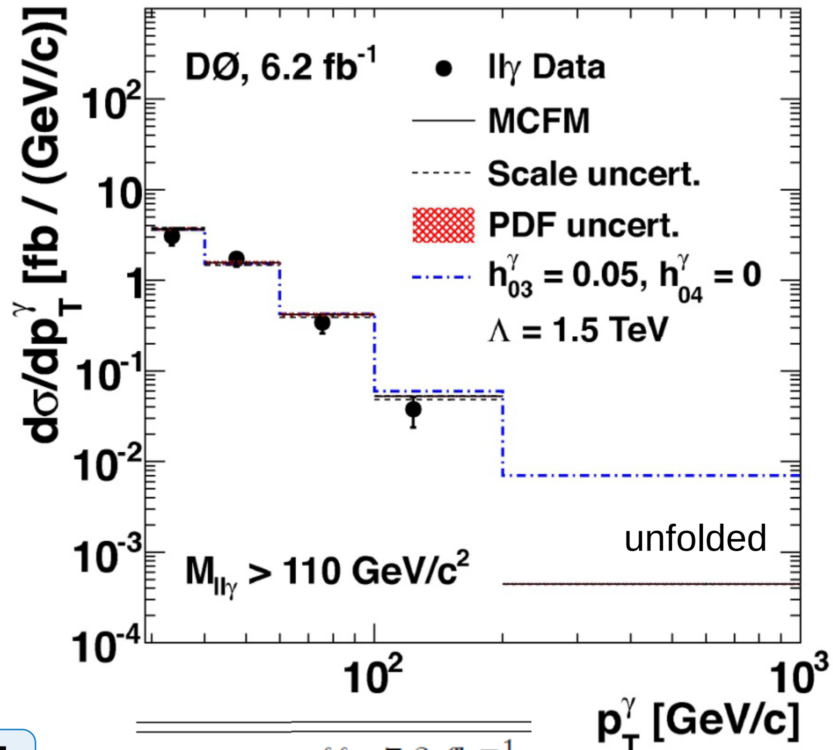
$Z\gamma \to ll\gamma$ Production

Cross section, differential cross section ($d\sigma/dp_T^\gamma$), limits on TGCs

- Two high p_T (isolated) muons/electrons and photon



Accepted by PRD (2012)



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

$SM@NLO: \sigma = 1096 \pm 34$ fb

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

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

$SM@NLO: \sigma = 294 \pm 10$ fb

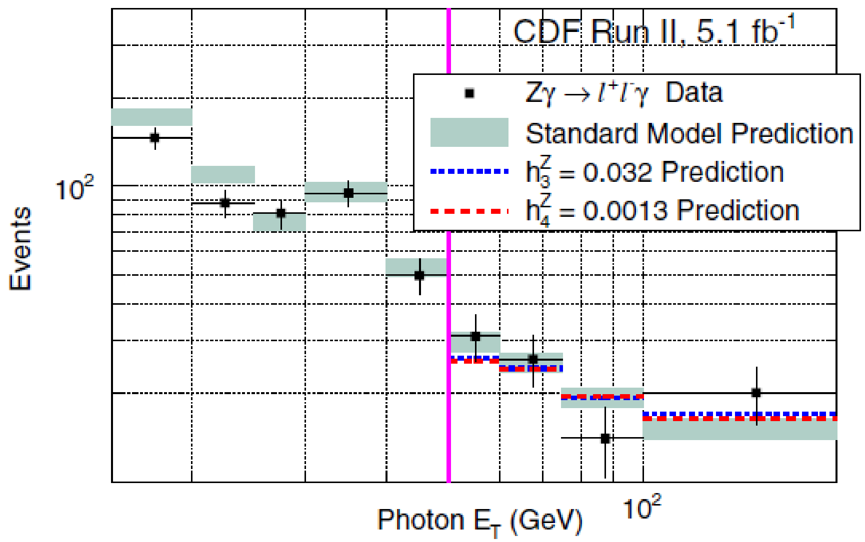
	$\ell\ell\gamma$ 7.2 fb^{-1} $\nu\nu\gamma$ 3.6 fb^{-1} $\Lambda = 1.5$ TeV
$\lvert h_{03}^Z \rvert <$	0.026
$\lvert h_{04}^Z \rvert <$	0.0013
$\lvert h_{03}^\gamma \rvert <$	0.027
$\lvert h_{04}^\gamma \rvert <$	0.0014

95% CL limits on TGCs

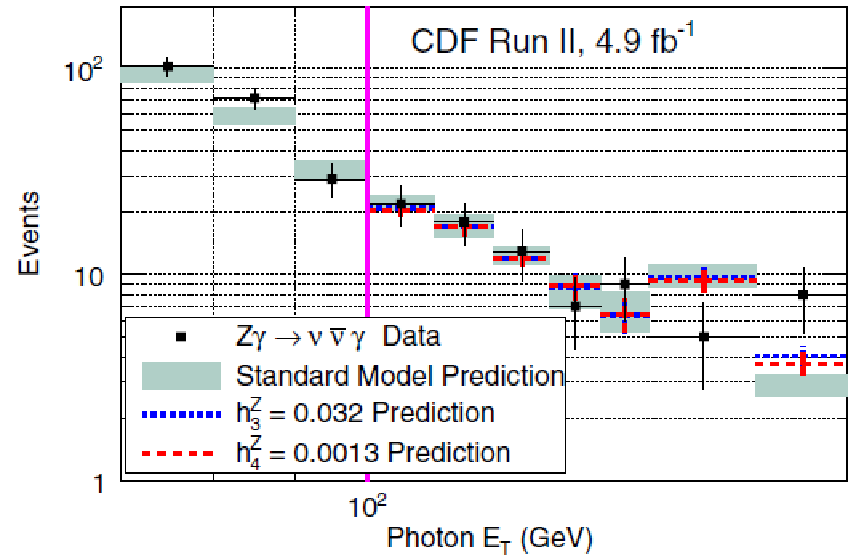
$Z\gamma \to ll\gamma, \nu\nu\gamma$ Production

Limits on TGCs

$ll\gamma$: photon $E_T > 50$ GeV



$\nu\nu\gamma$: photon $E_T > 100$ GeV



PRL 107, 051802 (2011)

Parameter	($\Lambda = 1.2$ TeV)	($\Lambda = 1.5$ 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	$-0.0012, 0.0013$	$-0.0008, 0.0008$

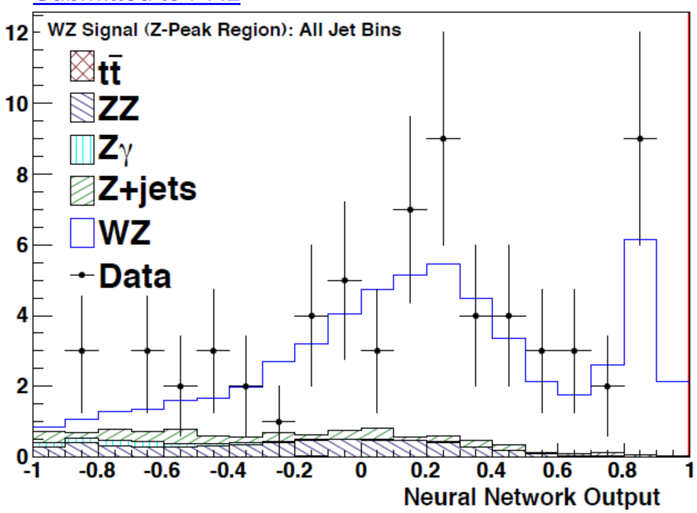
WZ → lνll Production

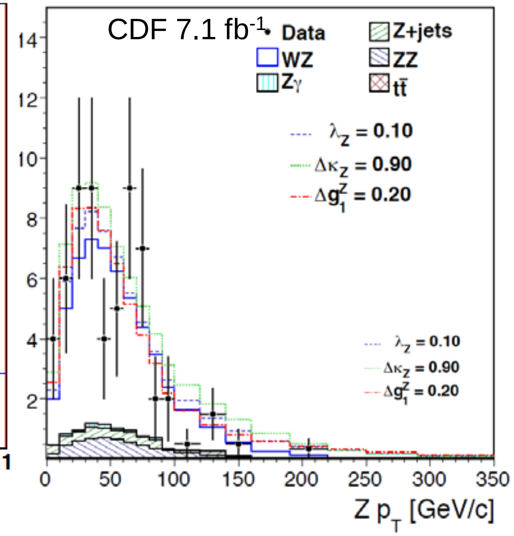
Cross section for the WZ production using fully leptonic final states

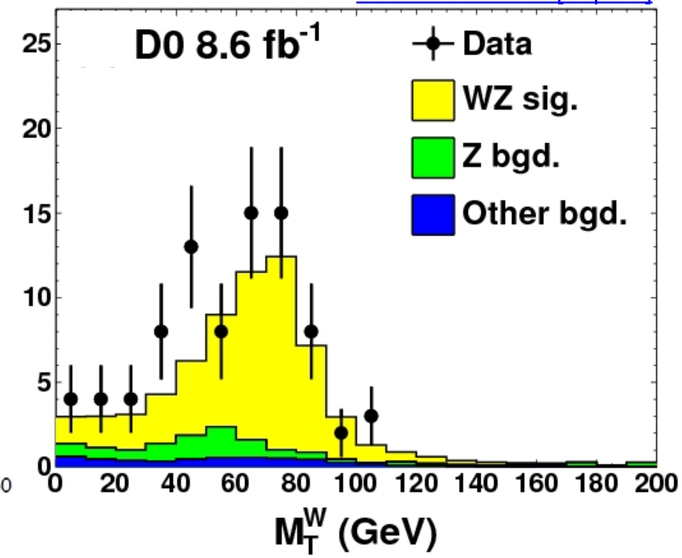
- Three high p_T (isolated) leptons (μμμ, eee, eeμ, μμe), MET

Submitted to PRL

arXiv:1201.5652 [hep-ex]







$$\boldsymbol{\sigma}_{WZ} = \mathbf{3.9^{+0.8}_{-0.7}(stat + syst)\,pb}$$

SM@NLO: σ = 3.46 ± 0.21 pb

$$\boldsymbol{\sigma}_{WZ} = \mathbf{4.5^{+0.6}_{-0.7}(stat + syst)\,pb}$$

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

95% CL limits on TGCs (Z p_T spectrum)

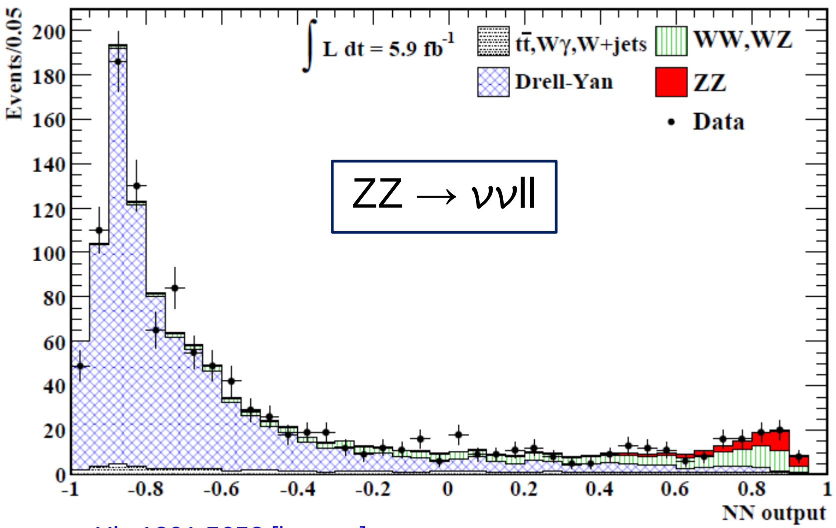
	Λ (TeV)	λ_Z	Δg_1^Z	$\Delta\kappa_Z$
Expected	1.5	(−0.11, 0.12)	(−0.12, 0.23)	(−0.58, 0.94)
Observed	1.5	(−0.09, 0.11)	(−0.09, 0.22)	(−0.42, 0.99)
Expected	2.0	(−0.10, 0.10)	(−0.11, 0.20)	(−0.53, 0.86)
Observed	2.0	(−0.08, 0.10)	(−0.08, 0.20)	(−0.39, 0.90)

ZZ → llll, ννll Production

Cross section for the ZZ production using fully leptonic final states

- Four high p_T leptons (μμμμ, eeee, eeμμ)
- Challenge in *ννll* final states: MET reconstruction

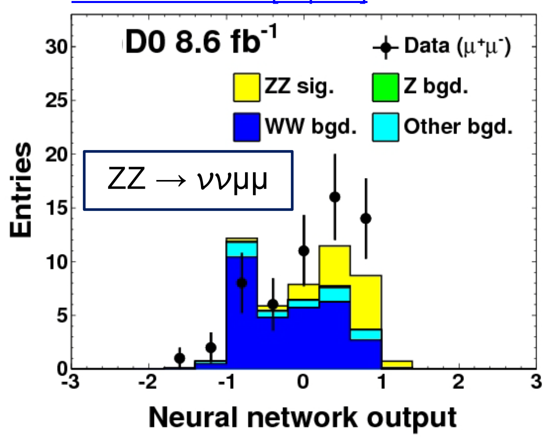
arXiv:1112.2978 [hep-ex]

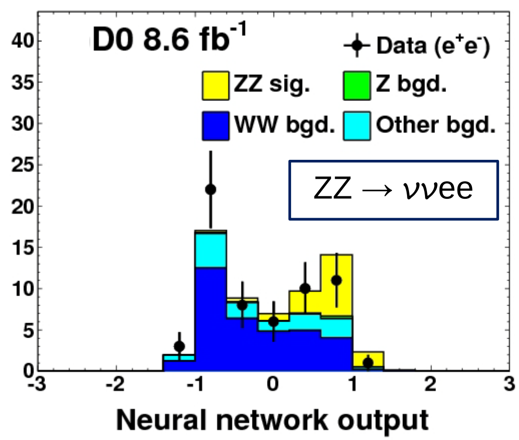


Combined llll (6.1 fb^{-1})+ννll (5.9 fb^{-1}):

$$\boldsymbol{\sigma}_{ZZ} = \mathbf{1.64^{+0.44}_{-0.38}(stat + syst)\,pb}$$

arXiv:1201.5652 [hep-ex]





Combined llll (6.4 fb^{-1})+ννll (8.6 fb^{-1}):

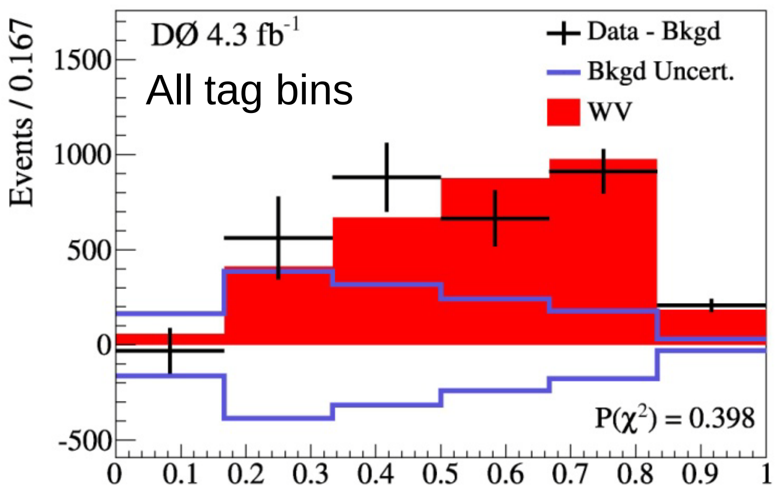
$$\boldsymbol{\sigma}_{ZZ} = \mathbf{1.44^{+0.35}_{-0.34}(stat + syst)\,pb}$$

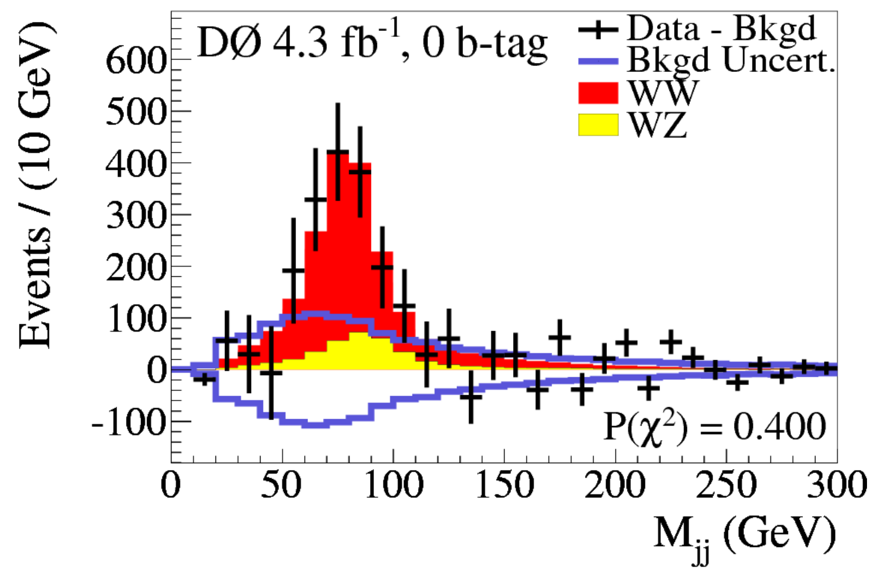
SM@NLO: σ = 1.40 ± 0.10 pb

WW and WZ with Heavy Flavor jets

Cross sections for WW/WZ production in lν+HF final states (b-tagging)

- High p_T muon/electron + MET + 2 or 3 jets
- b-tagging to isolate heavy flavor (HF) jets contribution
- S/B separation: Random Forest (RF)
- MC/data fit to the RF output and M_{JJ} distributions
- Cross sections measured in 0, 1, 2 b-tag channels (W→cs, Z→cc part of signal)





arXiv:1112.0536v1 [hep-ex]

$$\sigma^{RF}_{(WW+WZ)} = 19.6^{+3.2}_{-3.0}(\text{stat}+\text{syst})\,\text{pb}\;(7.9\sigma)$$

$$\sigma^{Mjj}_{(WW+WZ)} = 18.3^{+3.8}_{-3.6}(\text{stat}+\text{syst})\,\text{pb}\;(5.6\sigma)$$

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

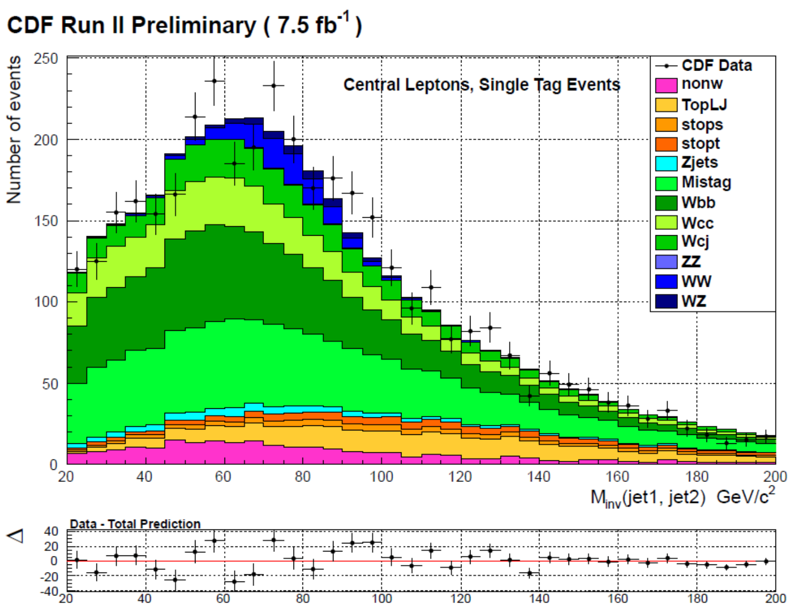
$$\sigma^{RF}_{(WZ)} = 3.3^{+4.1}_{-3.3}(\text{stat}+\text{syst})\,\text{pb}$$

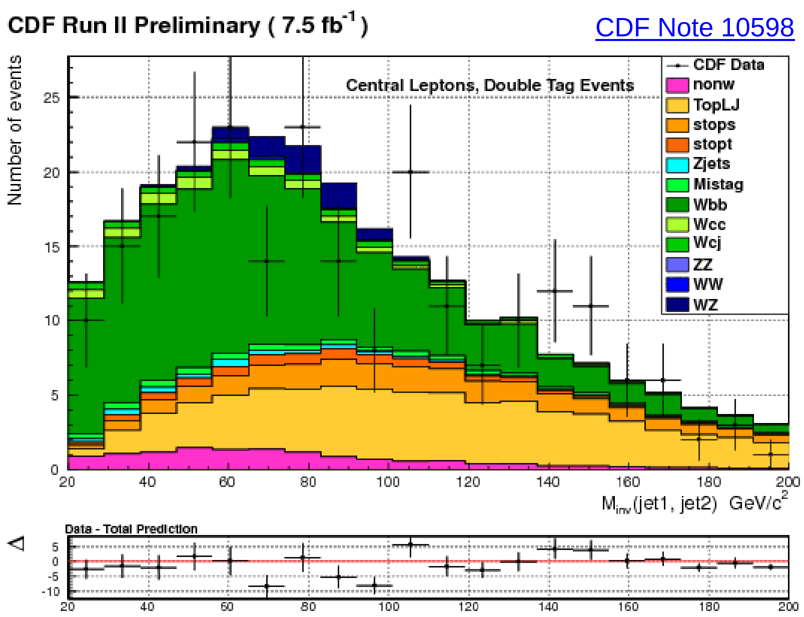
$$\text{SM@NLO}: \sigma(WW) = 11.7 \pm 0.8\,\text{pb},\;\; \sigma(WZ) = 3.5 \pm 0.3\,\text{pb}$$

Cross section for WW+WZ production in $l\nu$+HF final states (b-tagging)

- High p_T muon/electron + MET + exactly 2 jets
- Four independent channels based on: lepton quality, detector coverage, number of b-tagged jets
- MC/data fit to the M_{JJ} distribution
- Cross section measured in 1 and 2 b-tag channels (W→cs, Z→cc part of signal)

In 1-tag: WW ~74% of the signal
In 2-tag: WZ ~88% of the signal





CDF Note 10598

$$\sigma^{Mjj}_{(WW+WZ)} = 1.1^{+0.3}_{-0.4} \times \sigma_{SM} \; (3.0\sigma)$$

WZ and ZZ with Heavy Flavor jets

Validation of the low mass Higgs searches at the Tevatron

- By converting low mass Higgs analyses into diboson analyses
  WH/ZH ⇒ **lνbb**, **llbb**, **$\nu\nu$bb** ⇐ WZ/ZZ
- Measure the WZ+ZZ cross sections in heavy flavor final states

  Event selection as in CDF/DØ low mass Higgs analyses

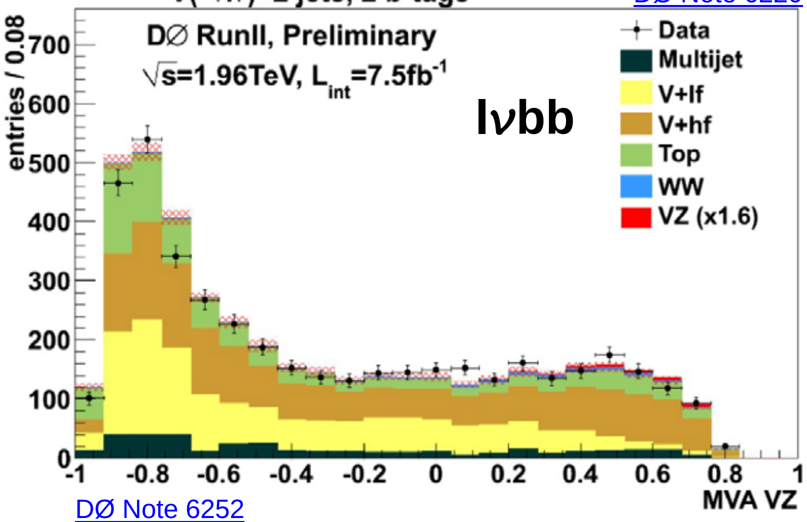
  - Events with 1 and 2 b-tagged jets
    - 1 b-tag: W→sc, Z→cc, Z→bb similar contributions to the signal
    - 2 b-tag: Z→bb dominates in the signal
  - Final MVA discriminant: MC template fit to data
    - WZ+ZZ normalization is a free parameter
    - WW constrained to the SM

The observation of (W/Z)(Z→bb), using the same techniques as for the Higgs searches, is validation for Higgs searches at the Tevatron

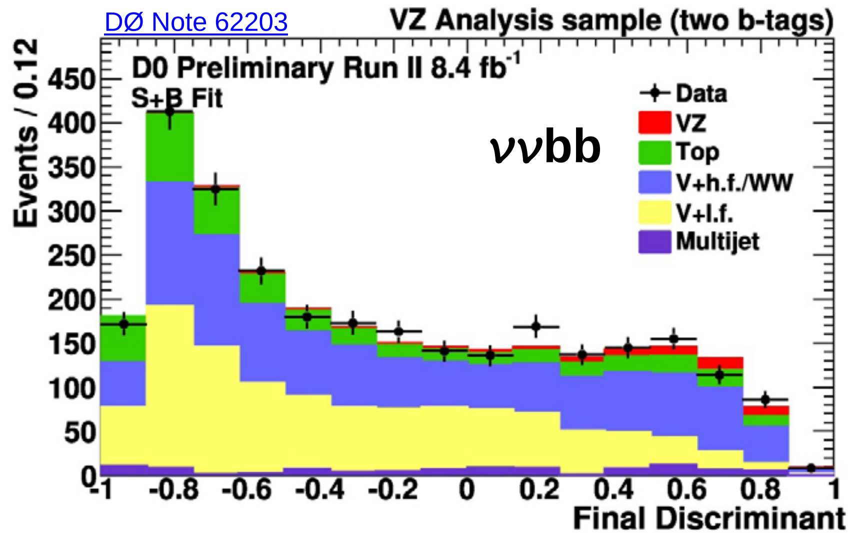
WZ and ZZ with Heavy Flavor jets

Individual DØ final discriminats for WZ+ZZ (7.5 - 8.4 fb^{-1})

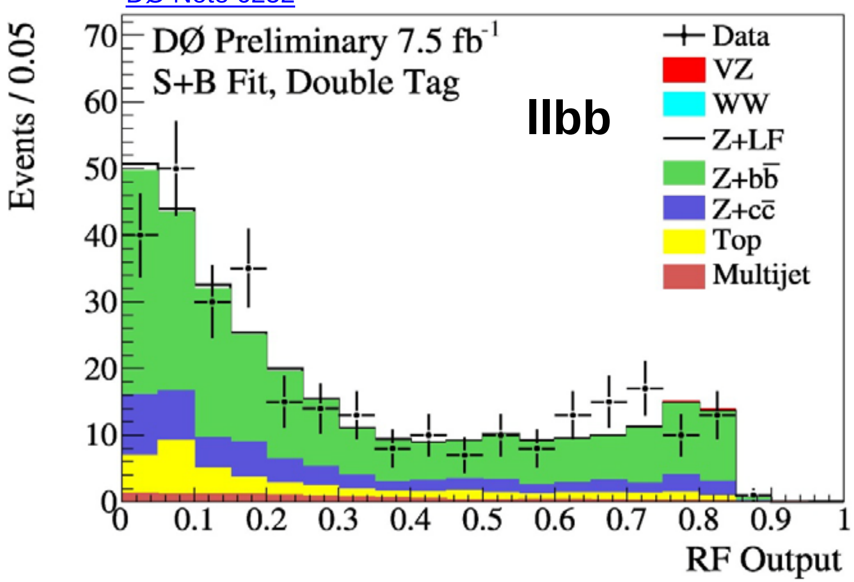
DØ Note 6220



DØ Note 62203



DØ Note 6252



lνbb: $\sigma^{BDT}_{(WZ+ZZ)} = (1.6 \pm 0.8) \times \sigma_{SM}$

$(2.2\sigma;\ \text{exp.}\ 1.4\sigma)$

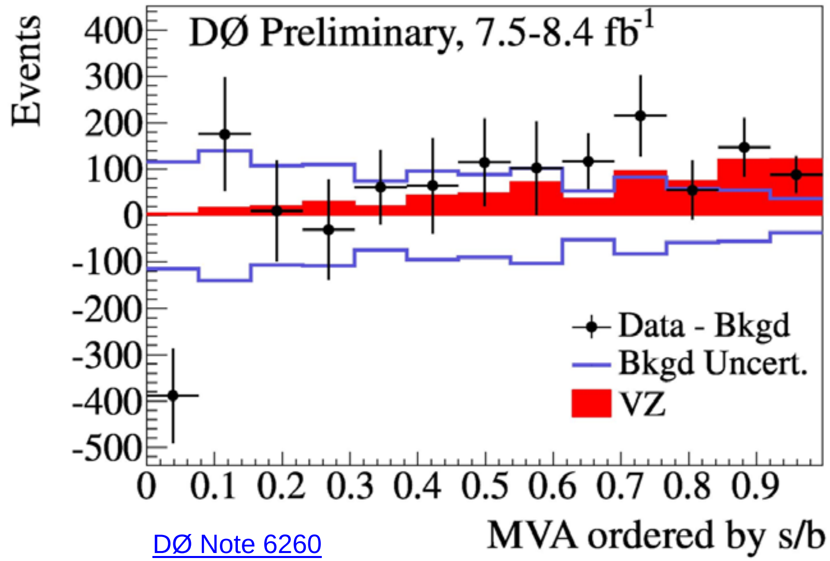
llbb: $\sigma^{RF}_{(WZ+ZZ)} = (0.1 \pm 0.6) \times \sigma_{SM}$

$(0.1\sigma;\ \text{exp.}\ 1.5\sigma)$

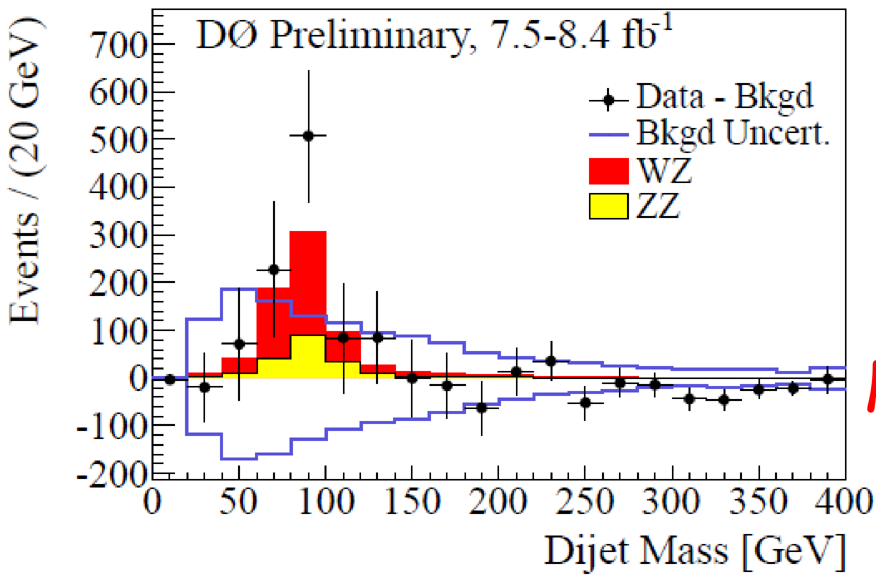
ννbb: $\sigma^{BDT}_{(WZ+ZZ)} = (1.5 \pm 0.5) \times \sigma_{SM}$

$(2.8\sigma;\ \text{exp.}\ 1.5\sigma)$

WZ+ZZ Combination @ DØ



DØ Note 6260



WZ and ZZ with HF jets

The bins of the individual final discriminants have been grouped according to s/b, and summed in a single distribution

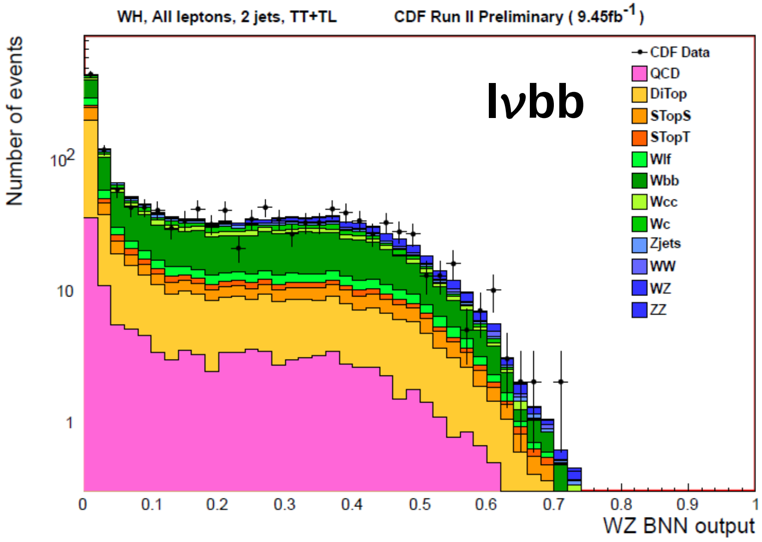
$$\boldsymbol{\sigma}^{\mathrm{MVA}}_{(WZ+ZZ)} = \mathbf{(1.13 \pm 0.36)} \times \boldsymbol{\sigma}_{\mathrm{SM}} \; (3.3\sigma)$$

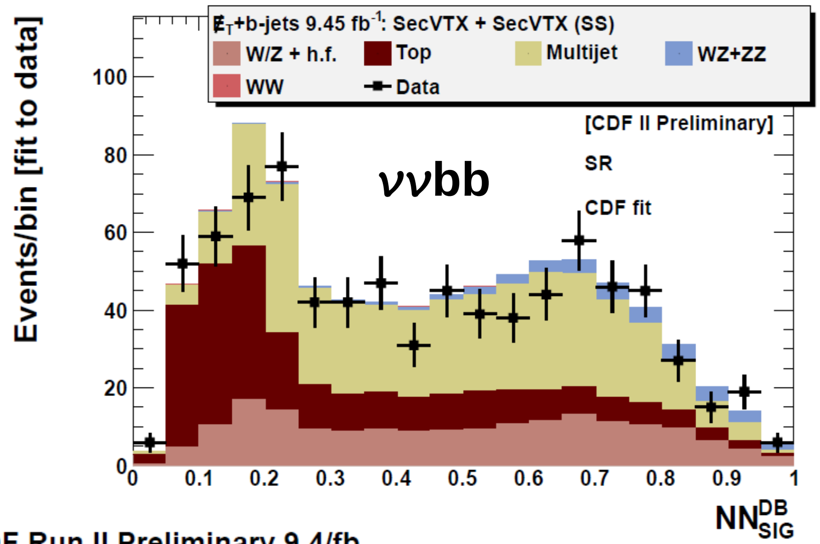
(expected: 2.9σ)

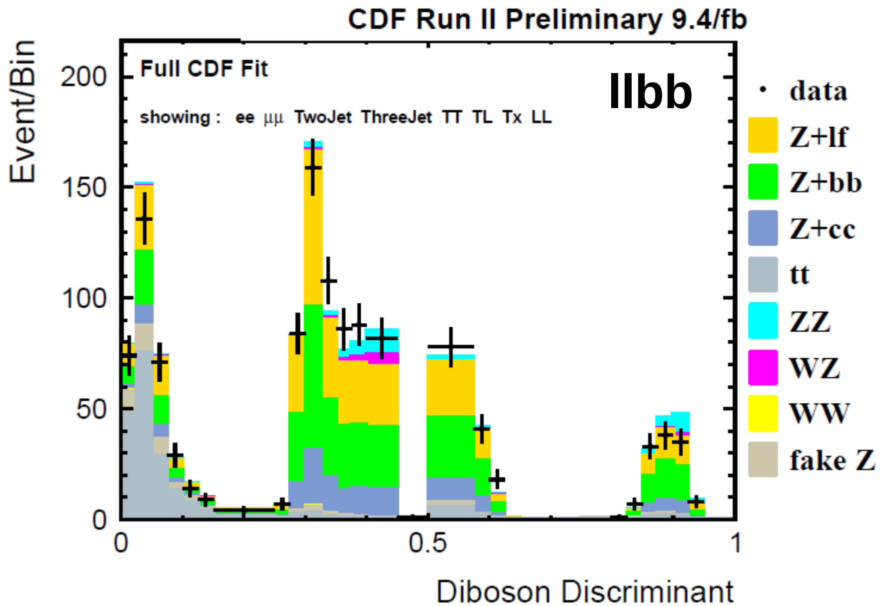
3.3σ Evidence for WZ+ZZ production with heavy flavor jets

WZ and ZZ with Heavy Flavor jets

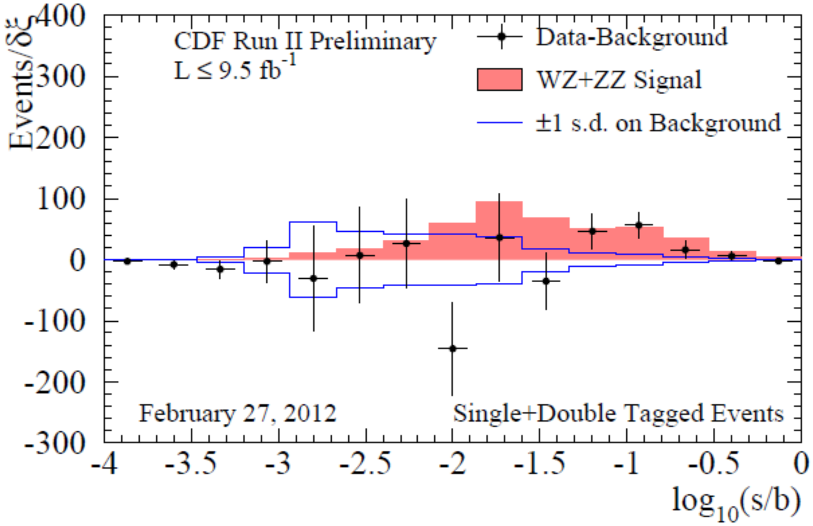
Individual CDF final discriminants for WZ+ZZ (9.4 fb^{-1})



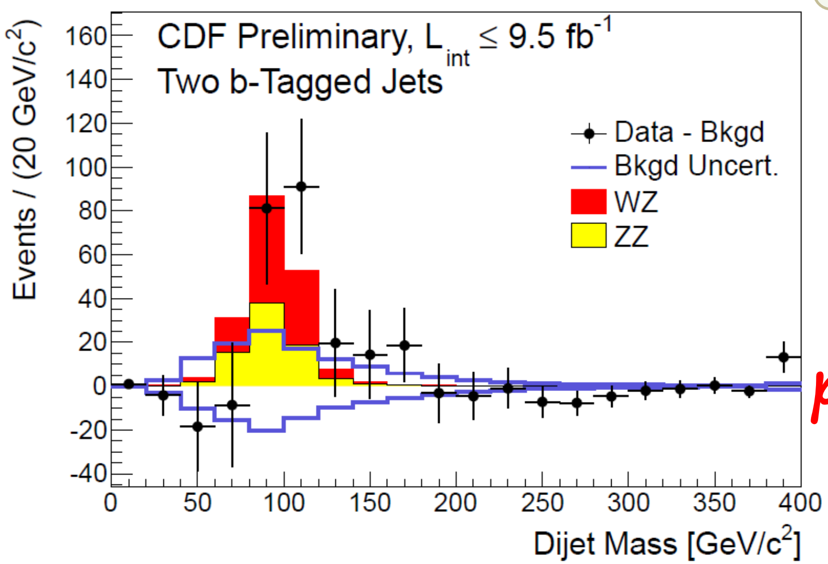




WZ+ZZ Combination @ CDF



CDF Note 10805



WZ and ZZ with HF jets

The bins of the individual final discriminants have been grouped according to s/b, and summed in a single distribution

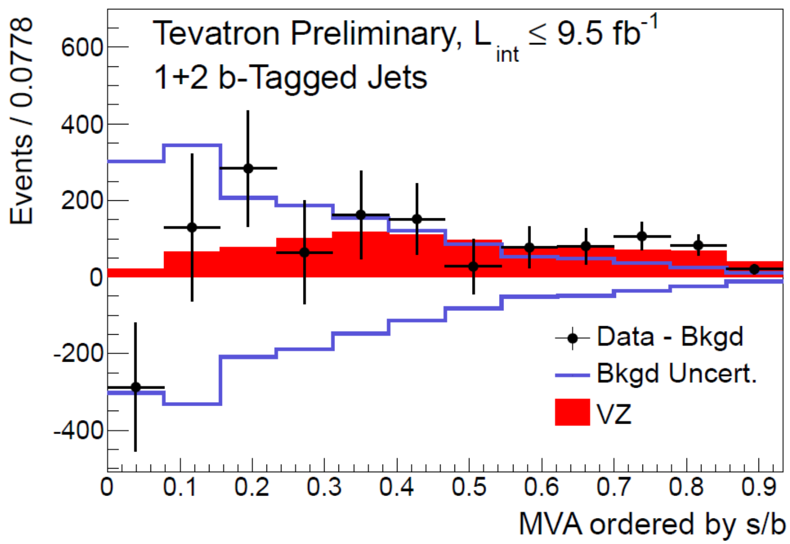
$$\sigma^{MVA}_{(WZ+ZZ)} = \mathbf{4.1^{+1.4}_{-1.3}\,(stat+syst)\,pb}\ (3.2\sigma)$$

$$\mathrm{SM@NLO}: \sigma(WZ+ZZ) = 4.4 \pm 0.3\,\mathrm{pb}$$

3.2σ Evidence for WZ+ZZ production with heavy flavor jets

WZ and ZZ with HF jets (7.5 - 9.4 fb^{-1})

Correlations between CDF/DØ uncertainties taken into account



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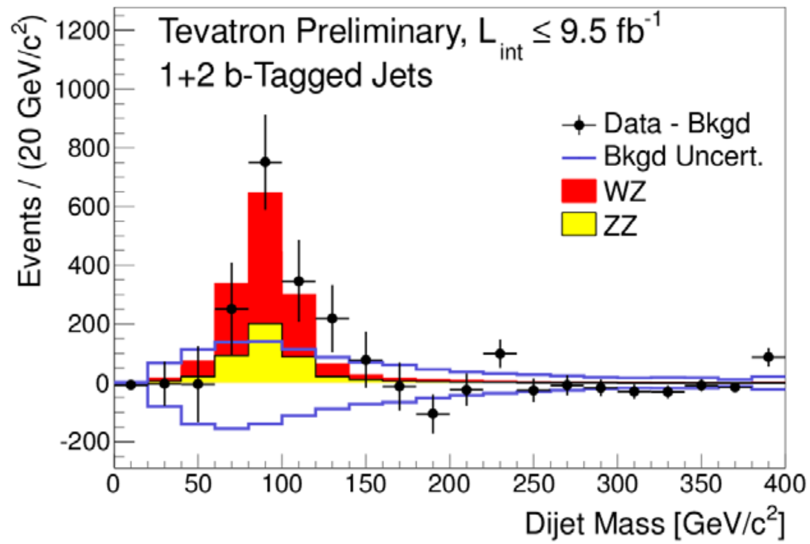


$$\sigma^{MVA}_{(WZ+ZZ)} = \mathbf{4.47 \pm 0.64(stat)^{+0.73}_{-0.72}\,(syst)\,pb}\ (4.6\sigma)$$

$$\text{SM@NLO}: \sigma(WZ + ZZ) = 4.4 \pm 0.3\,\text{pb}$$

4.6σ Evidence for WZ+ZZ production with heavy flavor jets

SUMMARY

- **Tevatron diboson results are in agreement with the SM**
- **Diboson production**

  Well-studied in challenging final states

  Observation of the WW+WZ production with jets in final state
- **Importance for Higgs searches**

  Same data/methodologies as in low mass Higgs searches

  Validation of the general strategy in the low mass Higgs searches

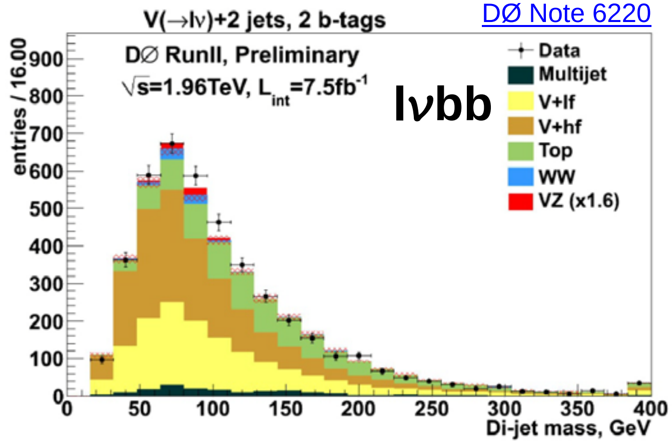
Evidence for WZ+ZZ production with HF jets demonstrates a capability to measure the cross section of the same order of magnitude as that expected for associated Higgs production

BACKUP SLIDES

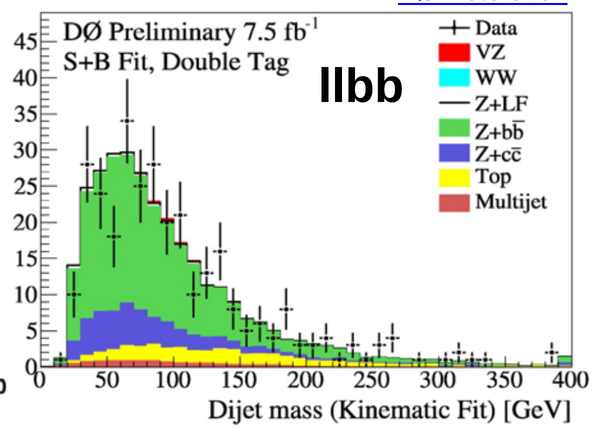
WZ and ZZ with Heavy Flavor jets

Individual DØ final dijet mass distributions (7.5 - 8.4 fb^{-1})

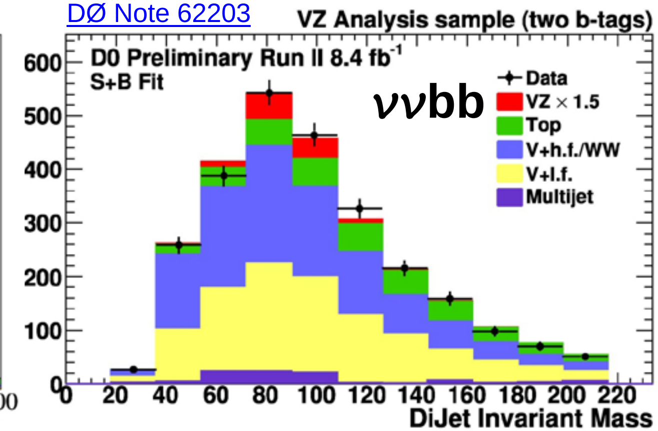
DØ Note 6220



DØ Note 6252



DØ Note 62203



Individual CDF dijet mass distributions (9.4 fb^{-1})