SUSY 2011 Conference - FNAL

WW / WZ / ZZ Diboson Production at the Tevatron

Kyle J. Knoepfel

Fermi National Accelerator Laboratory

On behalf of the CDF and DO Collaborations

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Getting to Higgs Territory

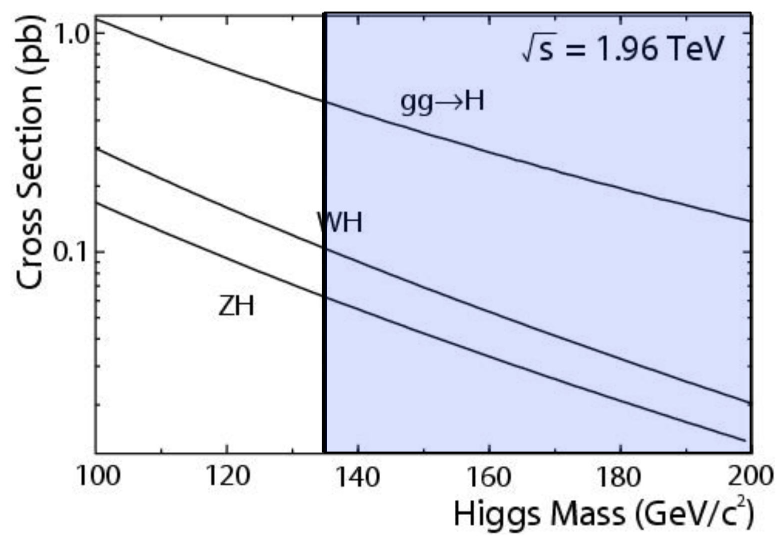
- Higgs production cross-sections are very small
  - (0.01 to 1) pb
- Look in production modes/ decay channels with highest statistics
- Naïve Search Channels:
  - Low-mass Higgs (m_H < 135 GeV)

$$gg \to H \to b\bar{b}$$

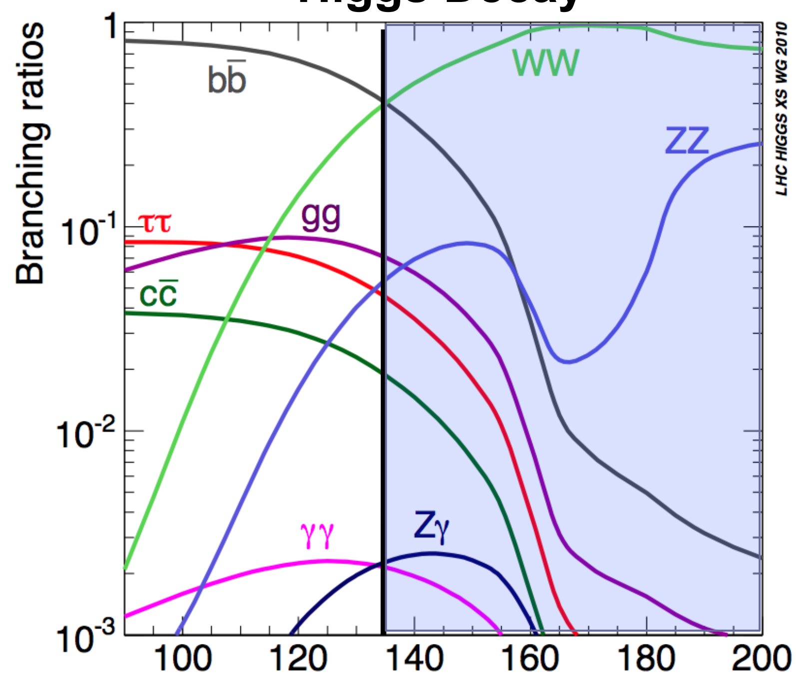
  - High-mass Higgs (m_H > 135 GeV)

$$gg \to H \to W^+W^-$$

Higgs Production



Higgs Decay



Getting to Higgs Territory

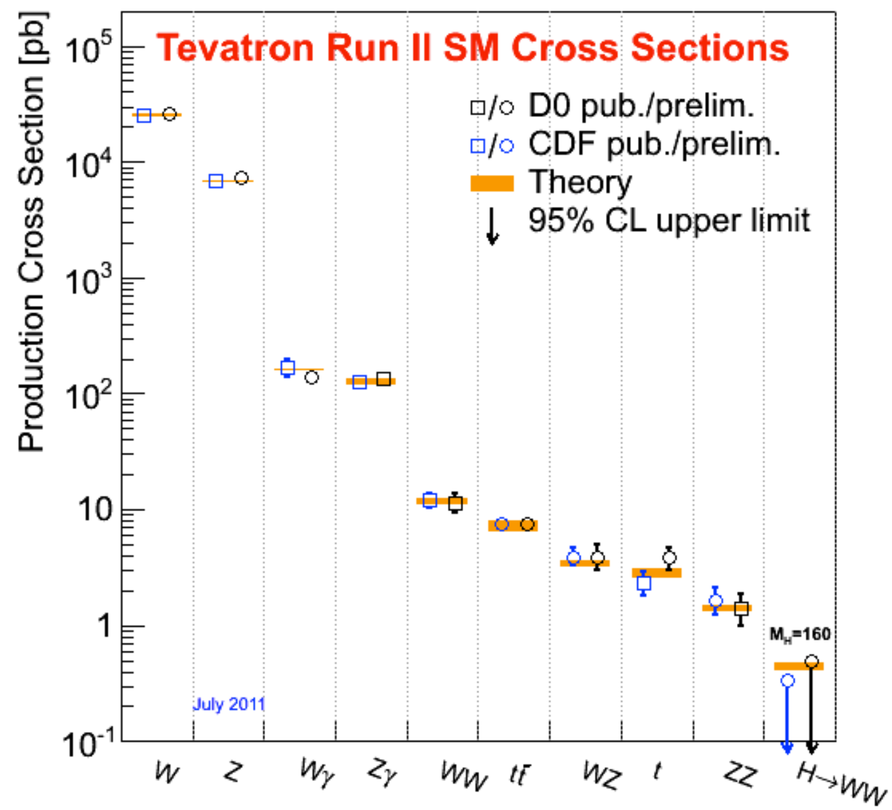
- In reality…
  - Large multijet QCD backgrounds make $gg \to H \to b\bar{b}$ searches unfeasible at low Higgs mass
  - Search for low-mass Higgs with associated production:

$$p\bar{p} \to VH \to X + b\bar{b}$$

  - Small cross-sections!

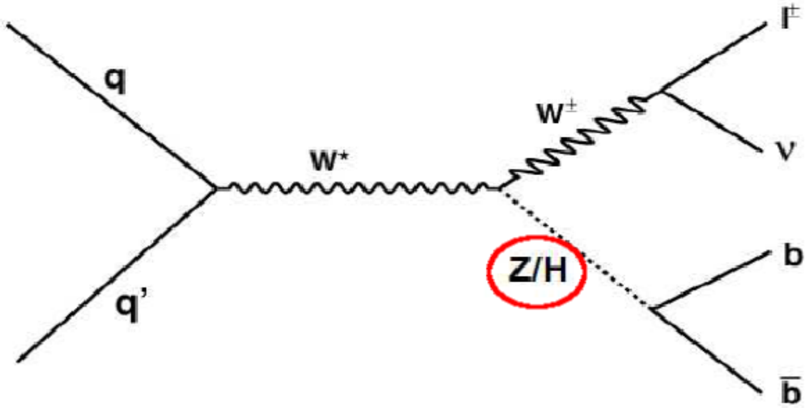
- To validate Higgs search procedures, search for known SM-processes with "comparably"-small production cross sections:

Diboson Production!



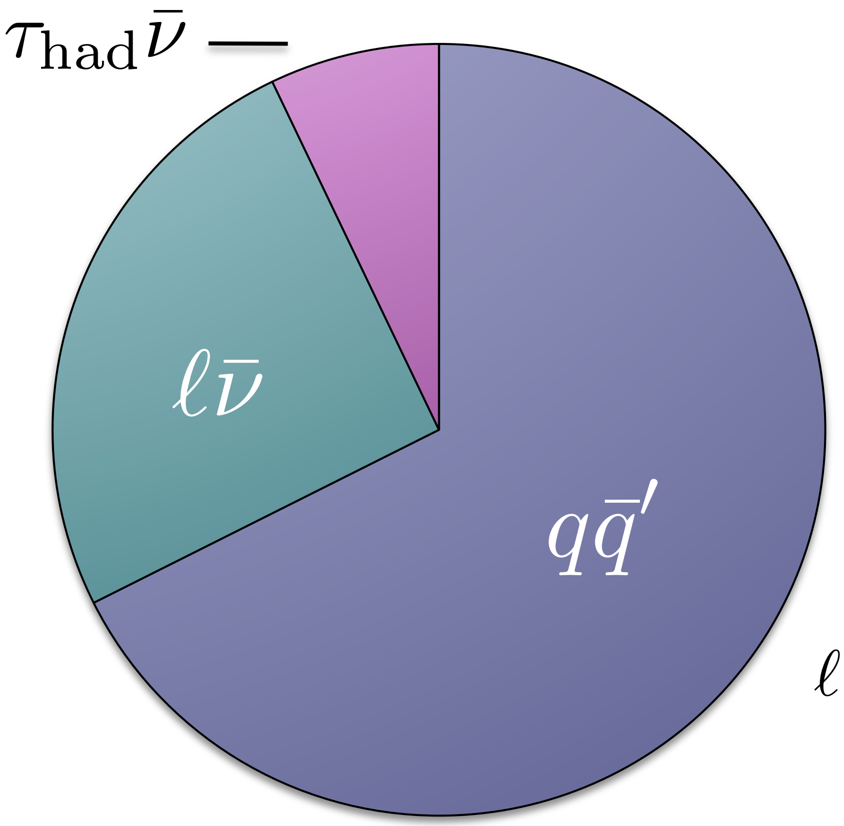
Diboson vs. Higgs Analyses

- Feynman diagrams are topologically equivalent

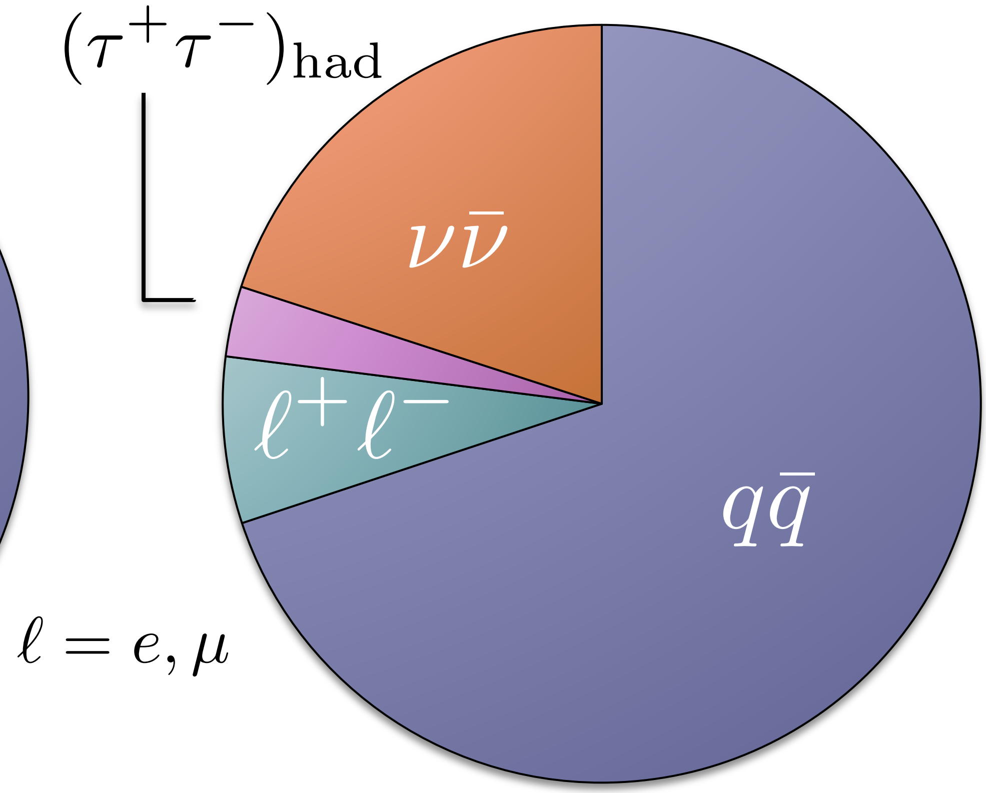


- Same final states, and therefore same analysis strategy, modulo different definitions of signal.
  - Retraining signal/background discriminants

W-Boson Decays

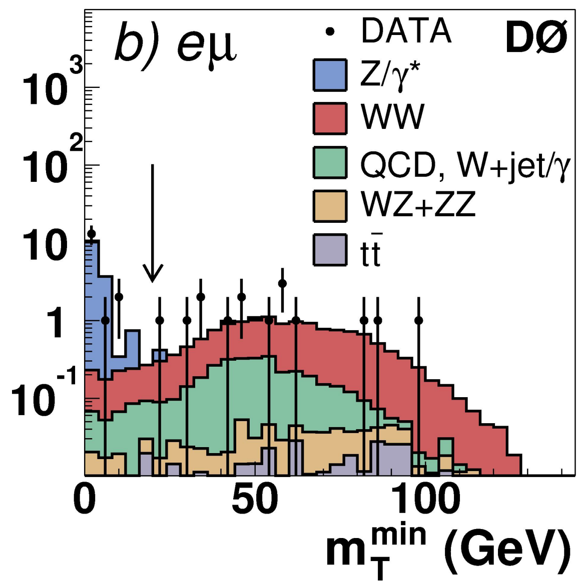


Z-Boson Decays



- Dominant decay modes are to jets, limited energy resolution
- Start with leptonic decay modes, benefit from precise energy determinations from trackers and electromagnetic calorimeters

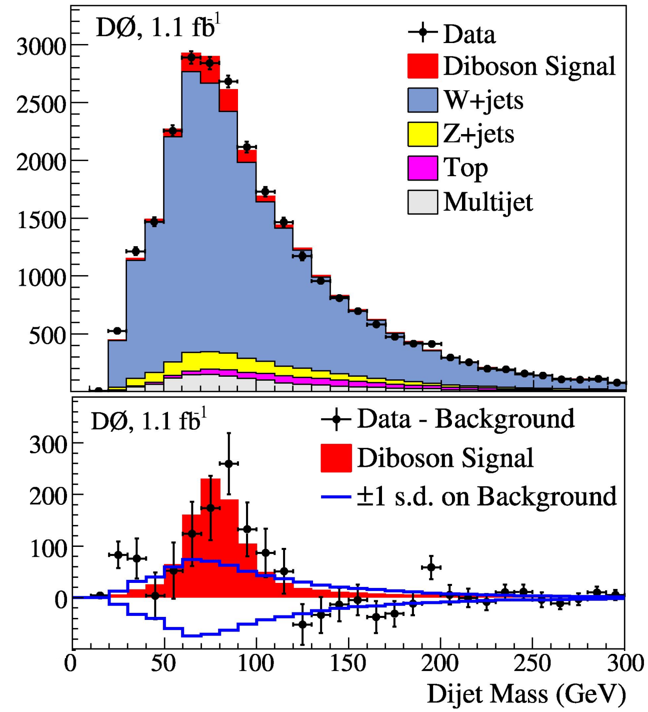
Previous Diboson Searches



- First observation of diboson production in lepton channels (2005)
- WW production in 2 Leptons plus Missing Energy

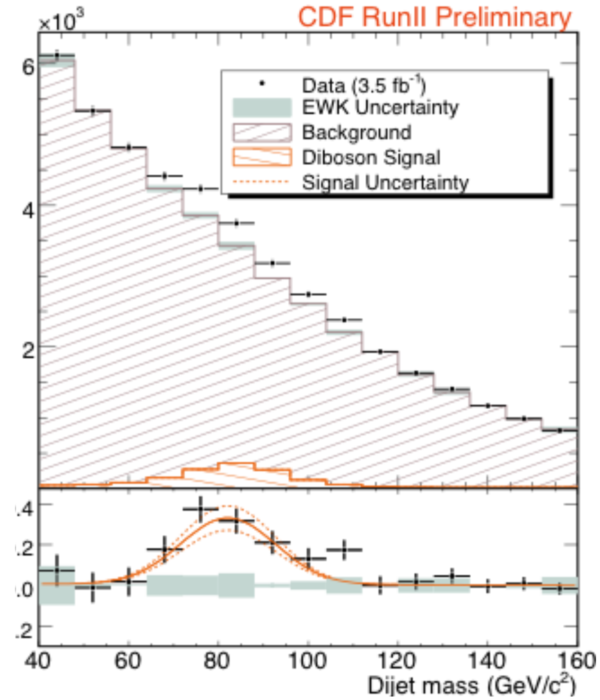
D0: PRL **94** 151801 (2005)

CDF: PRL **94** 211801 (2005)



- D0 Analysis:
  1.1 fb^{-1} (2009)
- First evidence of WW/ WZ production in 2 jets + 1 lepton:
  4.4σ

D0: PRL **102** 161801 (2009)



- CDF Analysis:
  3.5 fb^{-1} (2009)
- First observation of WW/WZ/ZZ production in 2 jets + MET:
  5.3σ

CDF: PRL **103** 091803 (2009)

Getting Closer to the Higgs

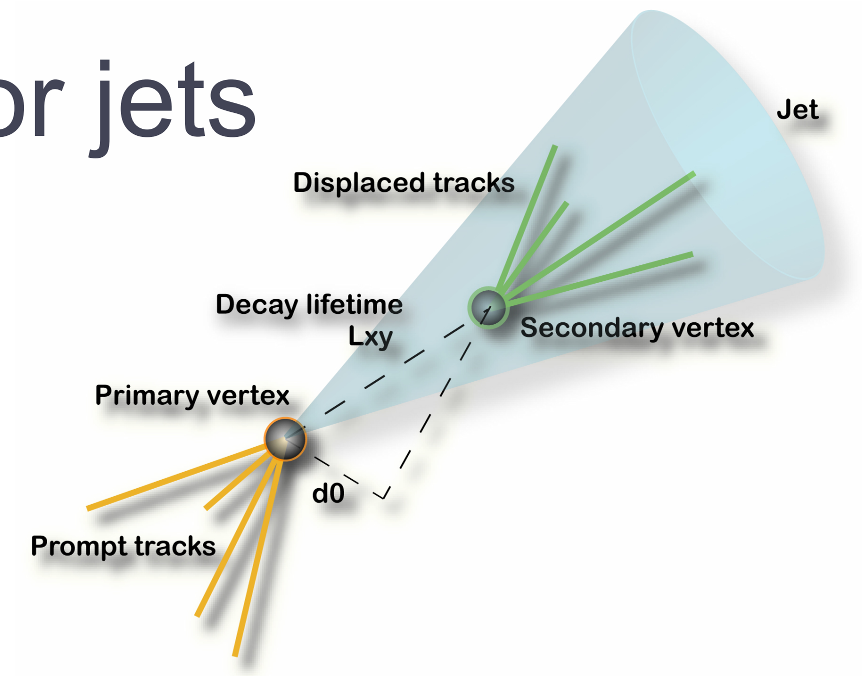
- Diboson production observed in hadronic final states
- Look for diboson production in final states with two *heavy-flavor* (H.F.) jets
- Discussed today—diboson final states with the following reconstructed objects:

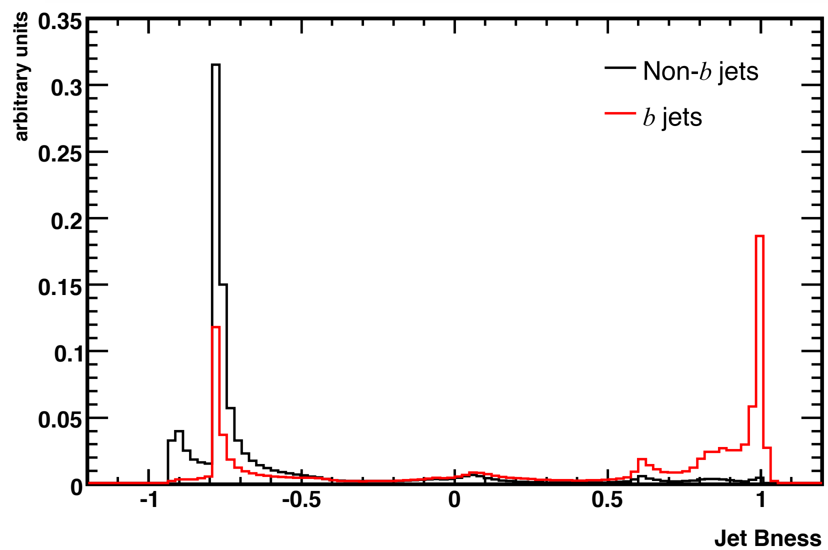
H.F. Jets	Leptons	Missing E?	Analogous Higgs Process
2	2	No	$ZH \to \ell\ell + b\bar{b}$
2	1	Yes	$WH \to \ell\nu + b\bar{b}$
2	0	Yes	$ZH \to \nu\bar{\nu} + b\bar{b}$

Tagging heavy-flavor jets

- Both collaborations use algorithms to identify *b(c)*-jets.
  - Neural networks
  - Decision trees

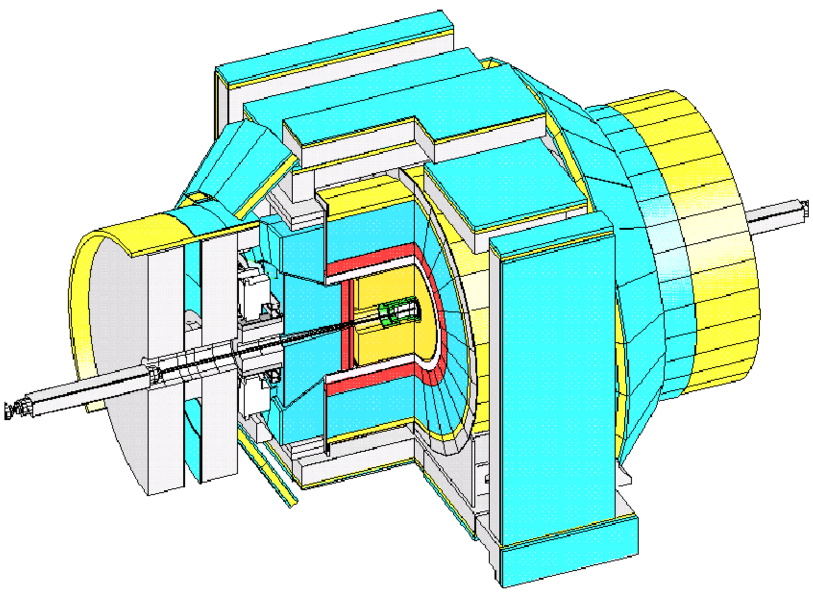
- Use variables which depend on longer lifetimes and heavier masses of *B(D)*-hadrons
  - Displaced vertex (L_{xy}, d_0)
  - Jet lifetime
  - Jet mass
  - Distribution of tracks within the jet cone
  - etc.

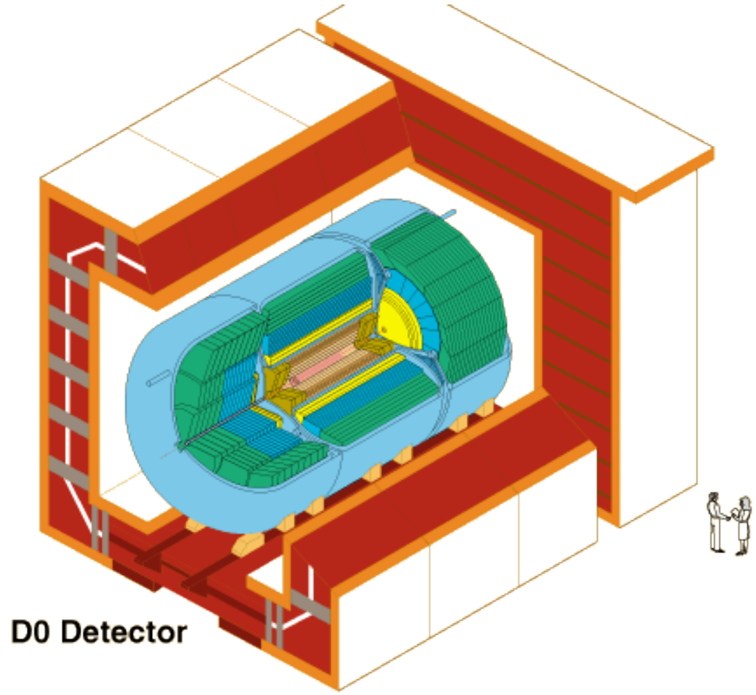




Detectors

- Center-of-Mass Energy: 1.96 TeV
- 11.7 fb^{-1} delivered to both experiments





- CDF II Detector
  - Collected Lumi: ~9.7 fb^{-1}
  - Analyzed Lumi: ≤ 7.5 fb^{-1}
- D0 Detector
  - Collected Lumi: ~10.5 fb^{-1}
  - Analyzed Lumi: ≤ 8.4 fb^{-1}

2 Jets + 2 Leptons + No Missing Energy

Final States:

$$WZ \to q\bar{q}' + \ell\ell$$
$$ZZ \to q\bar{q} + \ell\ell$$

Benefit: Can completely reconstruct the *Z*

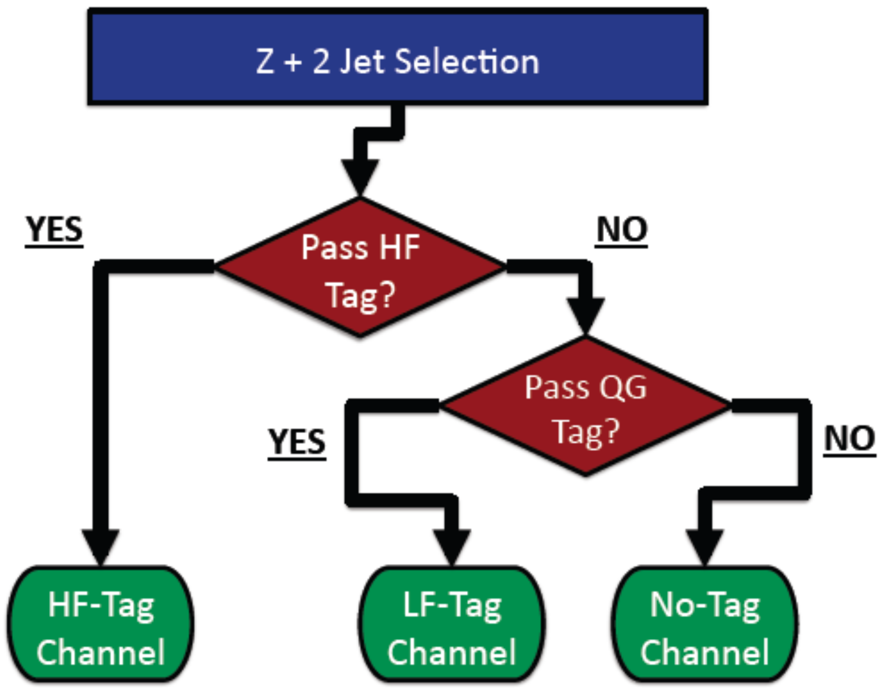
Downside: Small *Z-to-leptons* branching ratio (~7%)

(*b*-) jets + 2 Leptons (6.6 fb^{-1})

- Selection criteria
  - Lepton P_T > 20 GeV/c
  - 76 < m_Z < 106 GeV/c^2
  - 2 Jet E_T > 20 GeV
  - Jet |η| < 2.0
  - Small MET
  - etc.

- Energy Adjustments
  - Electrons: Z+0 jets
    - Z-peak matches in MC and data
  - Jets: Z+1 jets
    - Gluon- and quark-like jets treated differently in MC

- Analysis performed in three channels
  - HF-Tag channel
  - LF-Tag channel
  - No-Tag channel



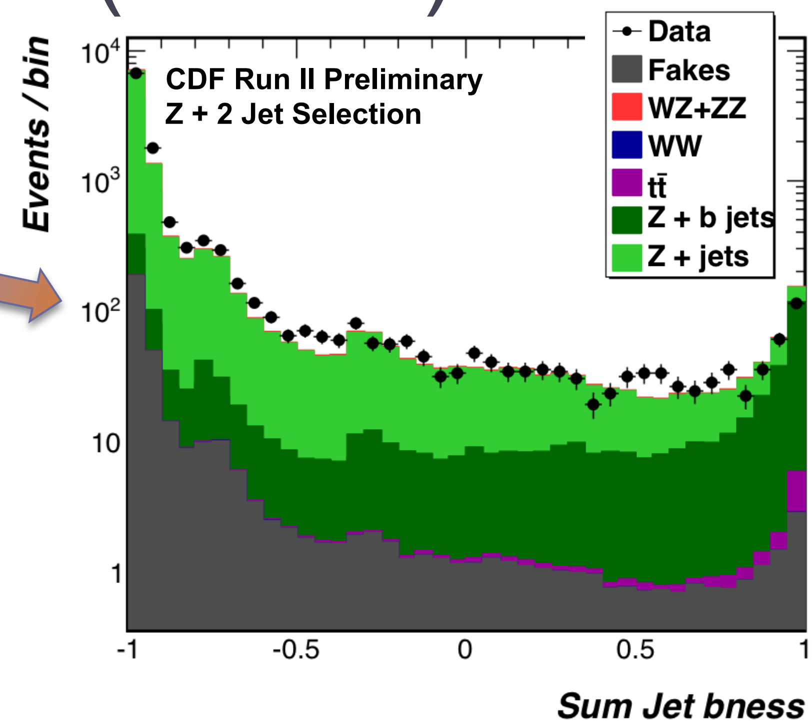
(*b*-) jets + 2 Leptons (6.6 fb^{-1})

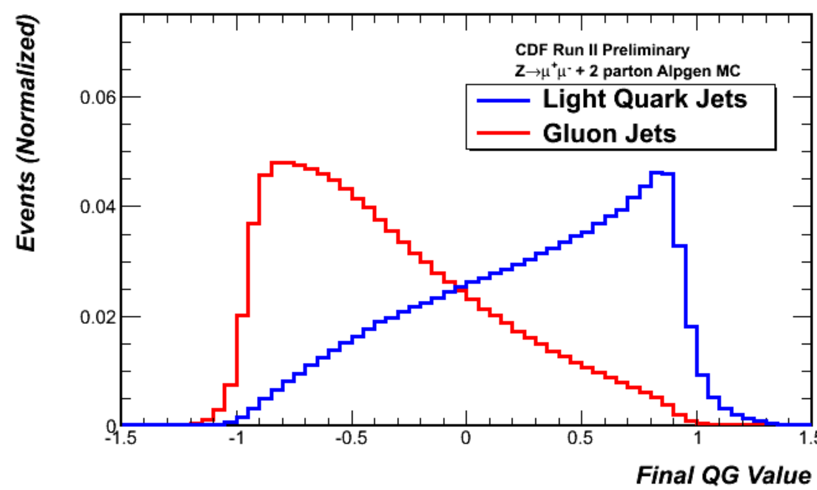
- HF-tagged event based on *b*ness (NN):
  - Track p_T
  - Track rapidities
  - Impact parameters
  - etc.

    (arXiv:1108.4738)

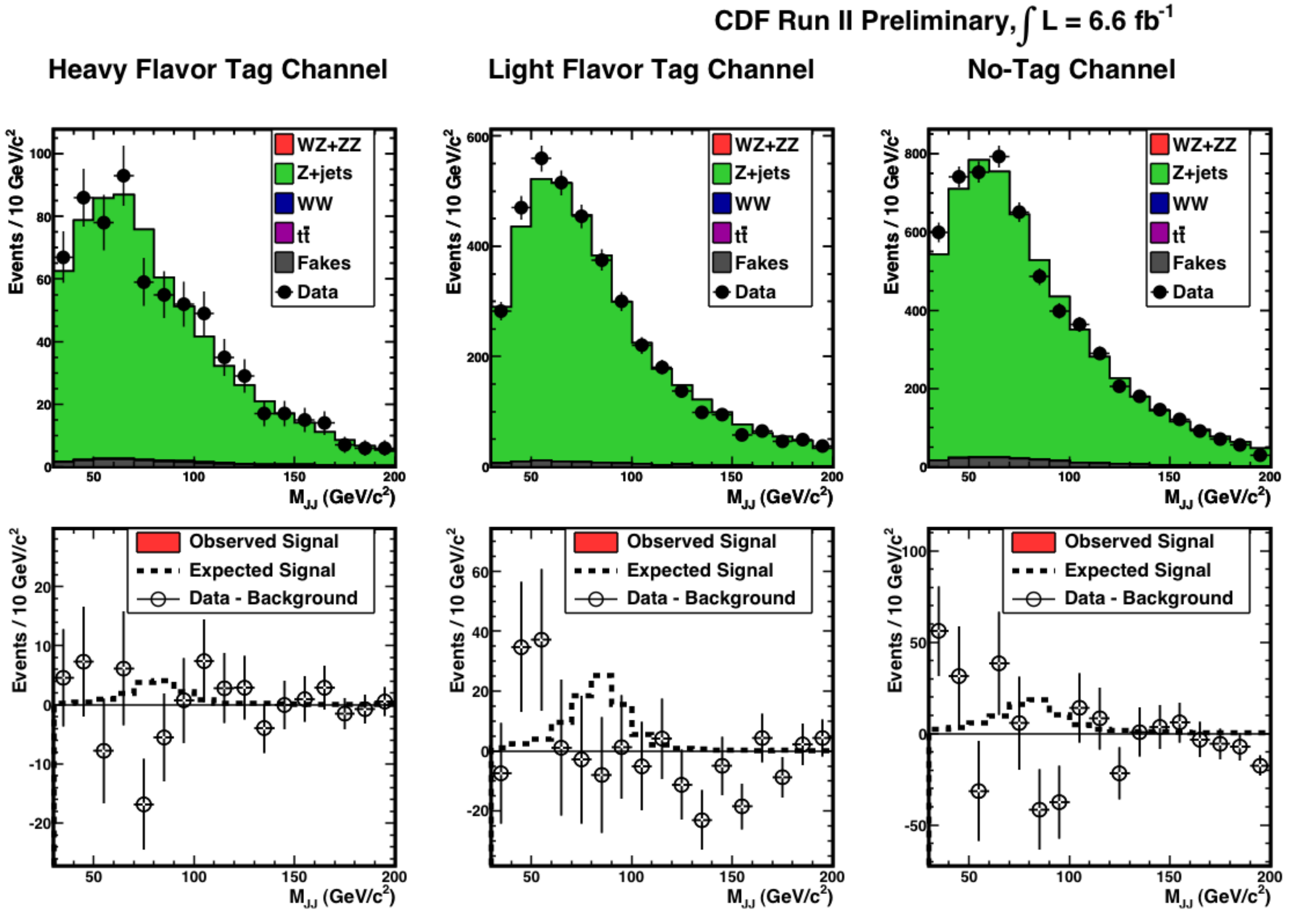
- LF-tagged event based on quark-gluon discriminant:
  - Track/tower distributions within jet
  - No. of tracks/towers
  - Jet η
  - Jet E_T
  - etc.

- No-tagged event fails both of these criteria





(b-) jets + 2 Leptons (6.6 fb^{-1})



Combined Result:

$$\sigma(p\bar{p} \rightarrow WZ, ZZ) < 1.3 \times \sigma_{\rm SM} \quad @\ 95\%\ \mathrm{CL}$$

Close to SM diboson production sensitivity in this channel.

2 Jets + 1 Lepton + Missing Energy

Final States:

$$WW \to \ell\nu + q\bar{q}' \qquad WZ \to q\bar{q}' + \ell\ell$$
$$WZ \to \ell\nu + q\bar{q} \qquad ZZ \to q\bar{q} + \ell\ell$$

Benefit: Large branching ratio to hadronic final states

Downside: Backgrounds from multi-jet QCD

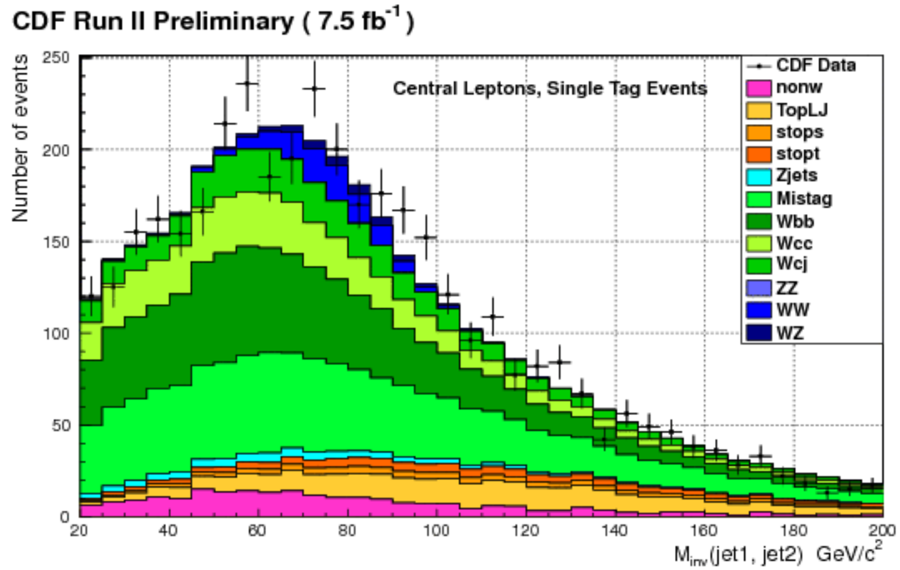
b/c-Jets + 1 Lepton + MET (7.5 fb^{-1})

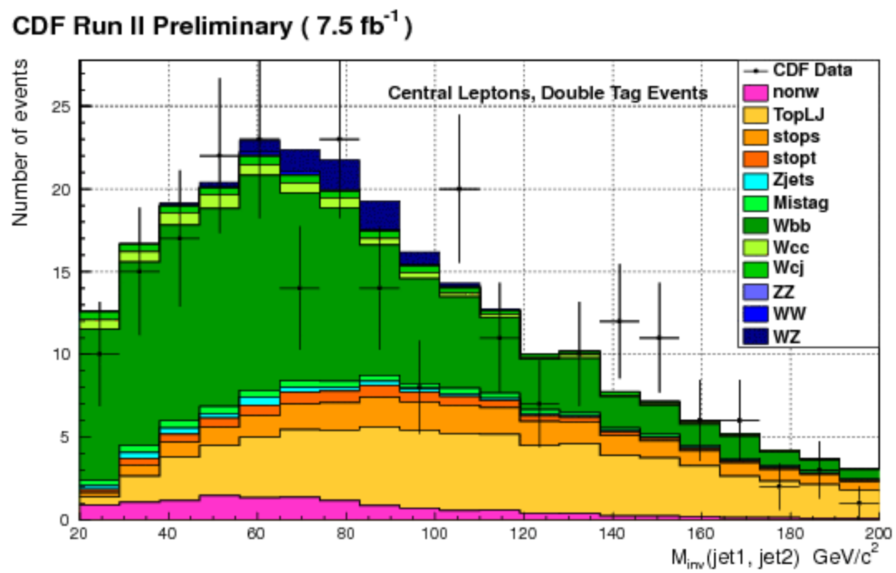
- Selection criteria (e.g.)
  - Missing E_T > 20 GeV
  - Lepton E/P_T > 20 GeV
  - 2 Jet E_T > 20 GeV
- Results determined from two regions
  - Only 1 HF-tag
  - Only 2 HF-tags
- Fake-W backgrounds suppressed by support vector machine (SVM) algorithm (e.g.):
  - Lepton P_T
  - MET
  - Electron-MET Angle
  - Jet 2 E_T
  - Significance of MET
- Remaining backgrounds
  - Fake-W
  - W + non-resonant b-jets
  - W + Mis-tagged Jets
  - Electroweak

b/c-Jets + 1 Lepton + MET (7.5 fb^{-1})

Fit Results

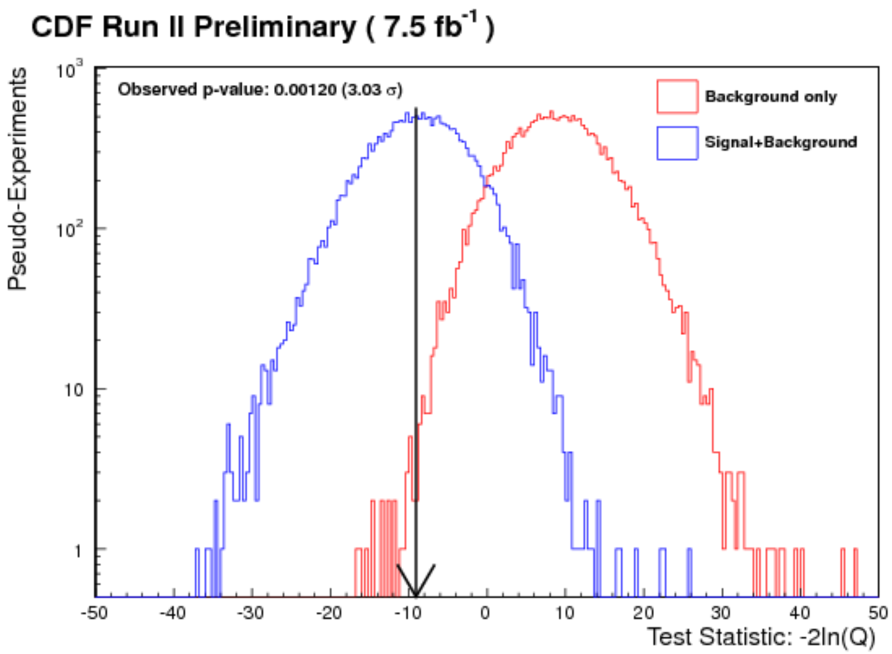
	1 HF-Tag	2 HF-Tags
Pretag Data	137456	137456
$t\bar{t}$	538 ± 53	109.7 ± 15.8
Single Top s	133 ± 12	35.6 ± 5.0
Single Top t	178 ± 21	10.8 ± 1.7
WW	160 ± 22	1.3 ± 0.3
WZ	54.7 ± 5.9	9.6 ± 1.4
ZZ	2.4 ± 0.2	0.43 ± 0.06
Z+jets	163 ± 21.1	7.2 ± 1.0
W + $b\bar{b}$	1444 ± 579	192 ± 78
W + $c\bar{c}$	747 ± 301	11.0 ± 4.5
W + cj	569 ± 229	8.3 ± 3.4
MIstag	323.3 ± 129	7.8 ± 1.6
Non-W	1416 ± 146	12.8 ± 6.1
Prediction	5729 ± 1132	406.9 ± 89.5
Observed	5486	366
WW/WZ	214.8 ± 24.4	10.9 ± 1.5

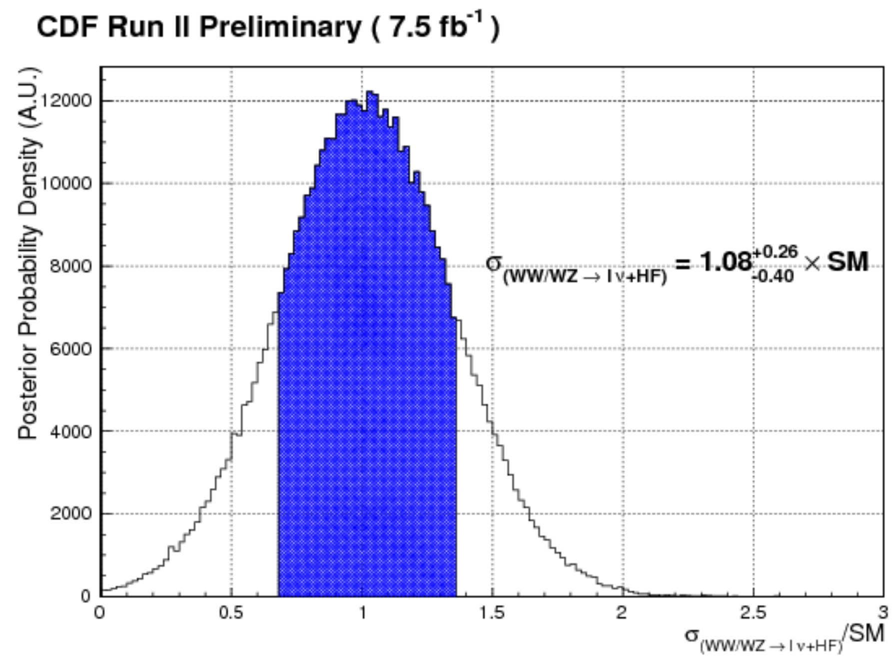




b/c-Jets + 1 Lepton + MET (7.5 fb^{-1})

- Significance of result determined with by log-likelihood ratio (-2 ln Q) test: 3.03σ (obs.) 3.02σ (exp.)





$$\sigma(p\bar{p} \to WW, WZ) = 1.08^{+0.26}_{-0.40} \times \sigma_{\rm SM}$$

2 Jets + 0 Leptons + Missing Energy

Final States:

$$WZ \to q\bar{q}' + \nu\bar{\nu}$$
$$ZZ \to q\bar{q} + \nu\bar{\nu}$$

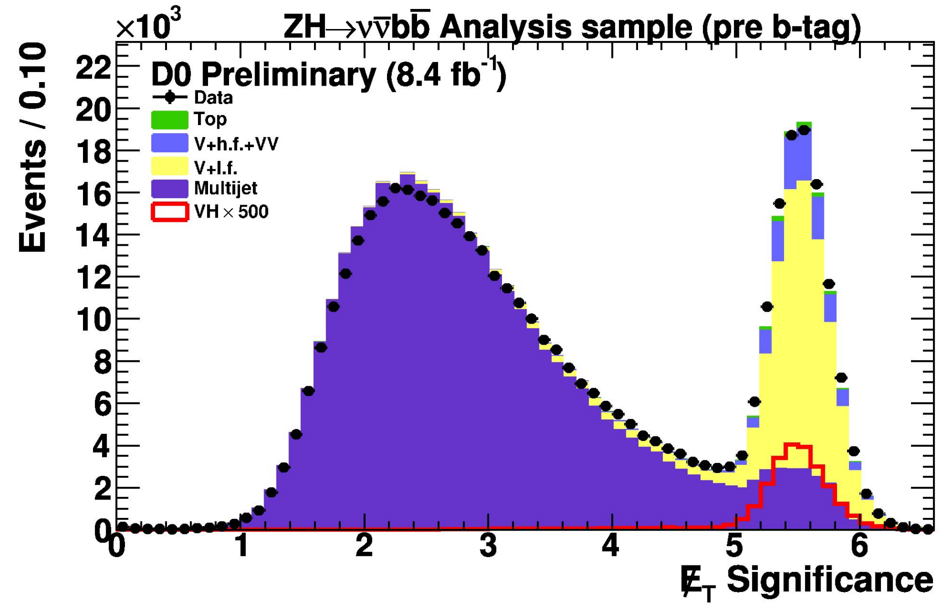
$$WW \to \ell\nu + q\bar{q}'$$
$$WZ \to \ell\nu + q\bar{q}$$

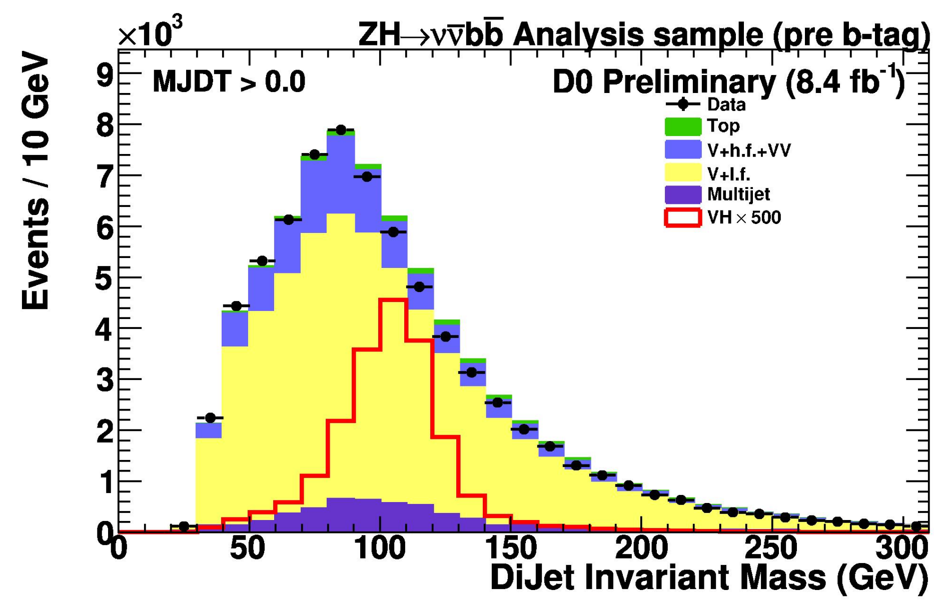
Benefits: Large branching ratio to hadronic final states
Large-ish *Z-to-neutrinos* branching ratio (20%)

Downside: Very large backgrounds from multi-jet QCD

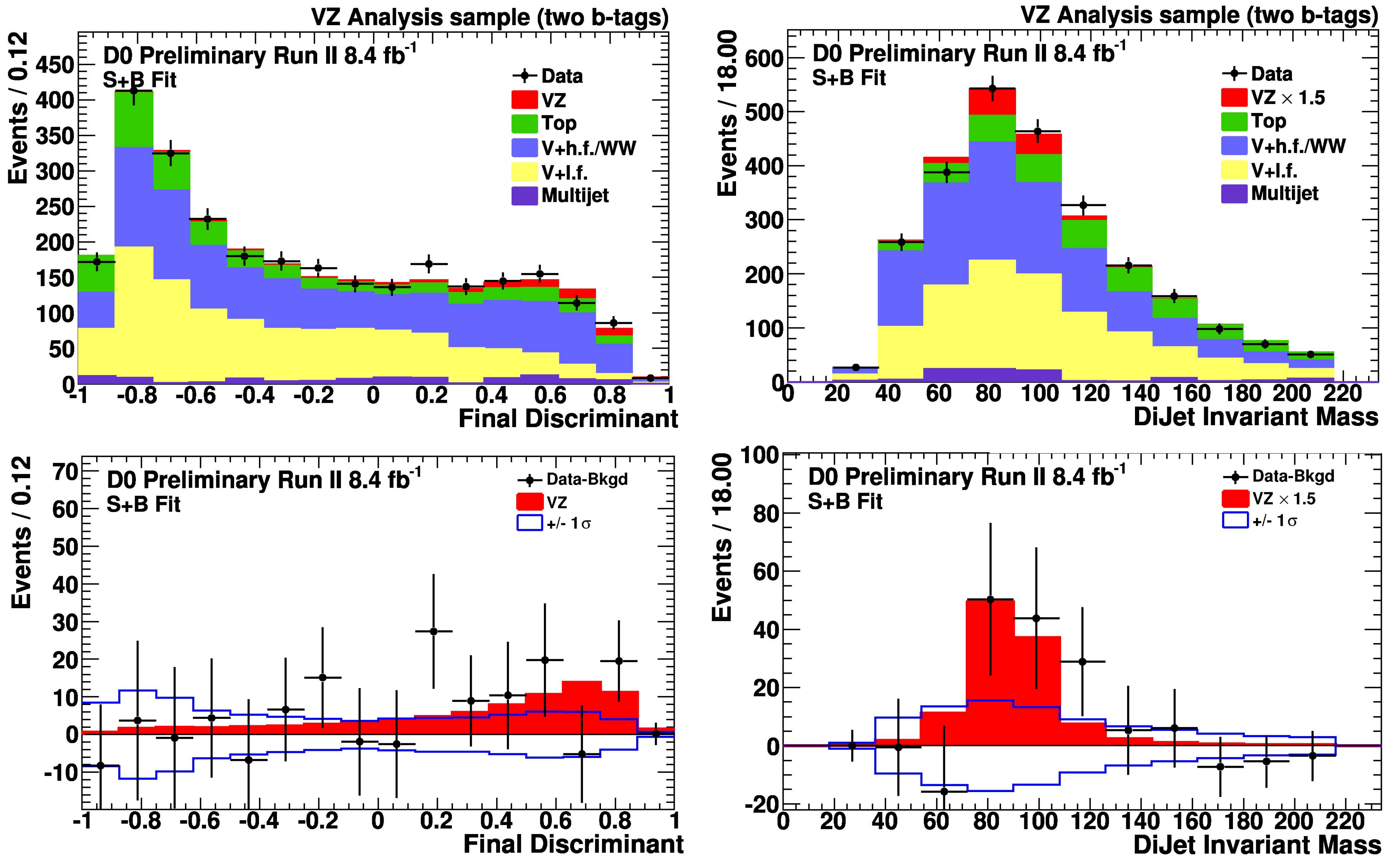
Missing Energy + *b*-jets (8.4 fb^{-1})

- QCD backgrounds suppressed with selection criteria:
  - Missing E_T > 30 GeV
  - MET-Jet Angle > 23 degrees
  - Jet1-Jet2 Angle < 165 degrees
  - MET significance > 5
- Boosted Decision Tree used to identify *b*-jets
- Boosted Decision Trees used to suppress
  - QCD multi-jet backgrounds (MJDT)
  - Remaining SM backgrounds
- Analysis performed in 1- and 2-*b*-tagged channels

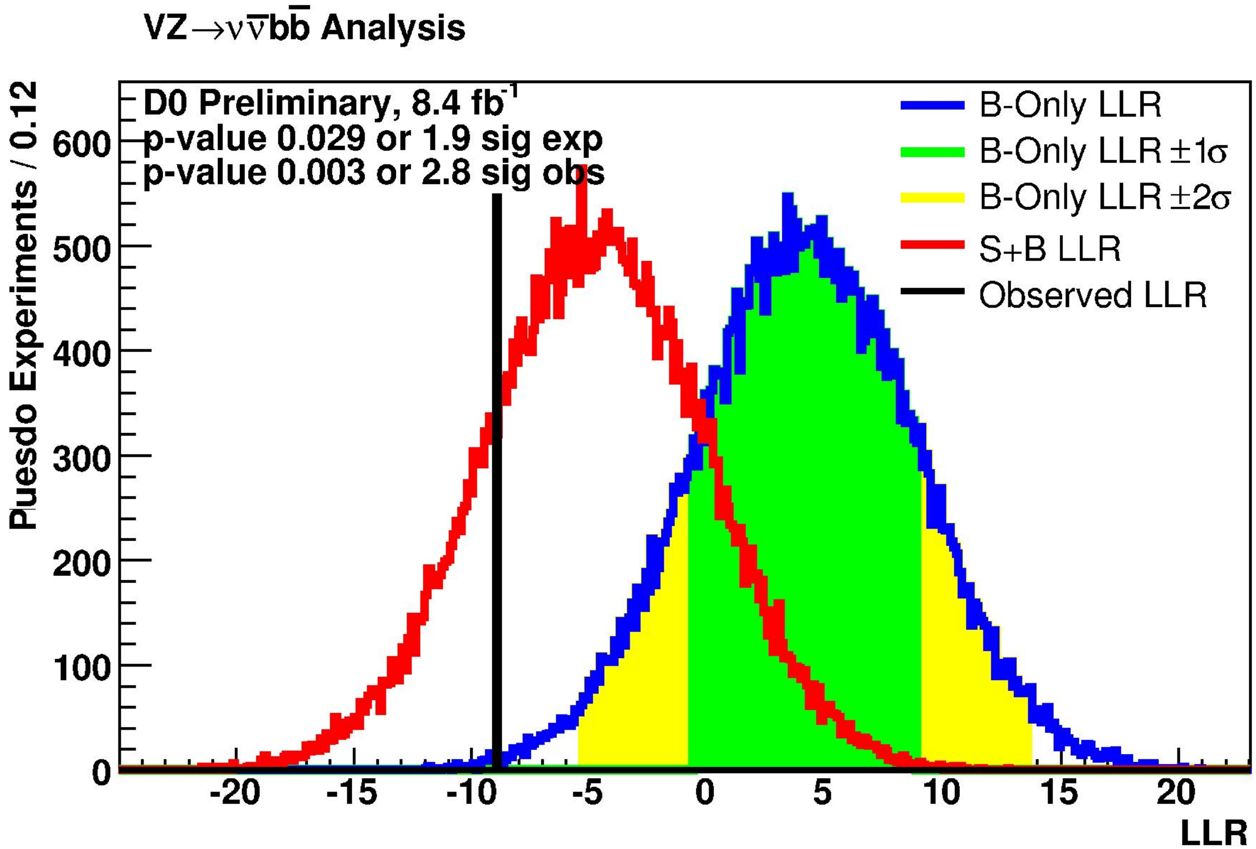




Missing Energy + *b*-jets (8.4 fb^{-1})



Missing Energy + *b*-jets (8.4 fb^{-1})



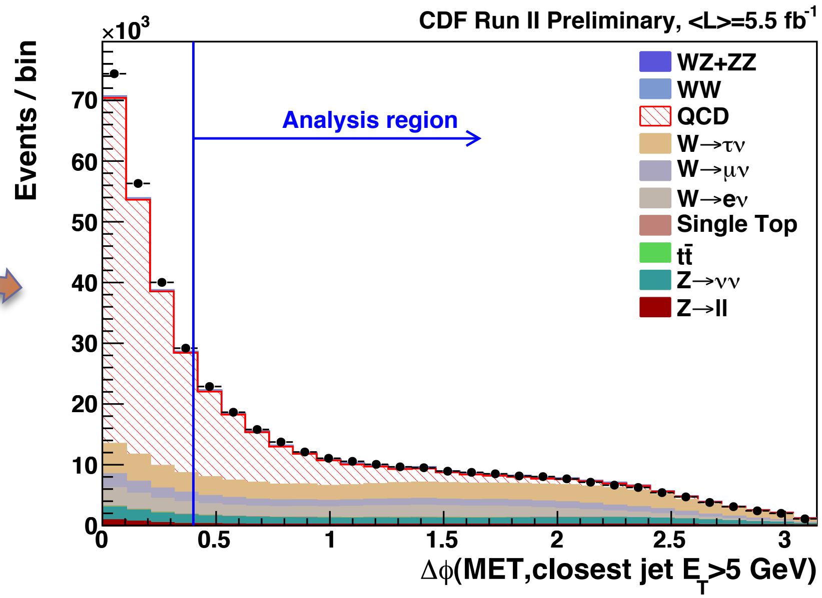
$$\sigma(p\bar{p} \to WZ, ZZ) = \begin{cases} 6.9 \pm 1.3 \pm 1.8 \text{ pb} \\ 1.5 \times \sigma_{\rm SM} \end{cases}$$

Significance: 2.8σ (obs.) 1.9σ (exp.)

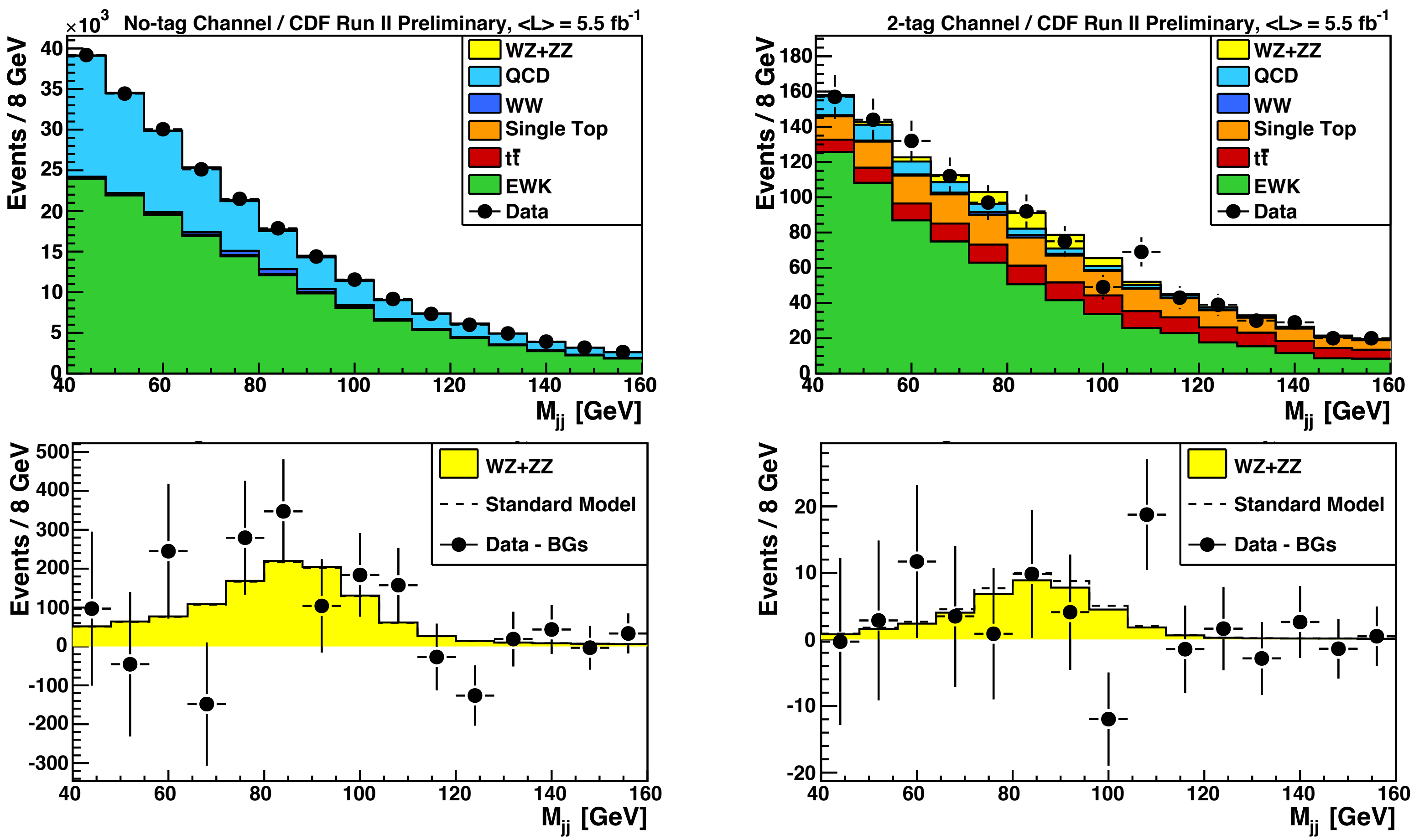
Missing Energy + (*b*-) jets (5.5 fb^{-1})

- CDF analysis performed with *at most* one identified lepton (e or μ)
- QCD backgrounds suppressed by:
  - Missing E_T > 50 GeV
  - MET-Jet Azimuthal Angle > 0.4

  (avoids instrumental MET)
- *b*-jets identified with *b*ness variable
- Remaining QCD multijet background measured in data control region
- Analysis performed in *b*-tagged and untagged samples
  - Results determined from simultaneous fit to both samples



Missing Energy + (*b*-) jets (5.5 fb^{-1})



- Combined Result:

$$\sigma(p\bar{p} \to WZ, ZZ) = 5.0^{+3.6}_{-2.5}\ \text{pb}$$
$$\sigma(p\bar{p} \to WZ, ZZ) < 13\ \text{pb @ 95\% CL}$$

Conclusions

- Diboson production is a rare process with cross-sections near the Higgs production level

- Increased sensitivity to diboson production with new analyses, and close to evidence in *b*-tagged jets

  - WW, WZ production: CDF (HF-jets) 3.0σ
  - WZ, ZZ production: D0 (*b*-jets) 2.8σ

- Significances will increase with more luminosity, refined analysis techniques

- D0 + CDF combination planned for individual WZ and ZZ cross-section measurements with *b*-jets.

Thank you.

Public Webpages

- D0
  - http://www-d0.fnal.gov/Run2Physics/WWW/results/final/EW/E08H/
- CDF
  - http://www-cdf.fnal.gov/physics/new/hdg/Results_files/results/wzllbb_071911/Diboson_public_6.6fb.html
  - http://www-cdf.fnal.gov/physics/new/hdg/Results_files/results/wzlnubb_071911/
  - http://www-cdf.fnal.gov/physics/new/hdg/Results_files/results/wzzz_sep10/METBB_dibosons/Dibosons_METJJ_2.html

Back-up Slides

Some definitions

MET	Missing Transverse Energy
"tagged"	Jet identified as a *b*-jet
HF	Heavy Flavor
LF	Light Flavor
NN	Neural Network