# Recent WW, WZ and ZZ Results from the Tevatron

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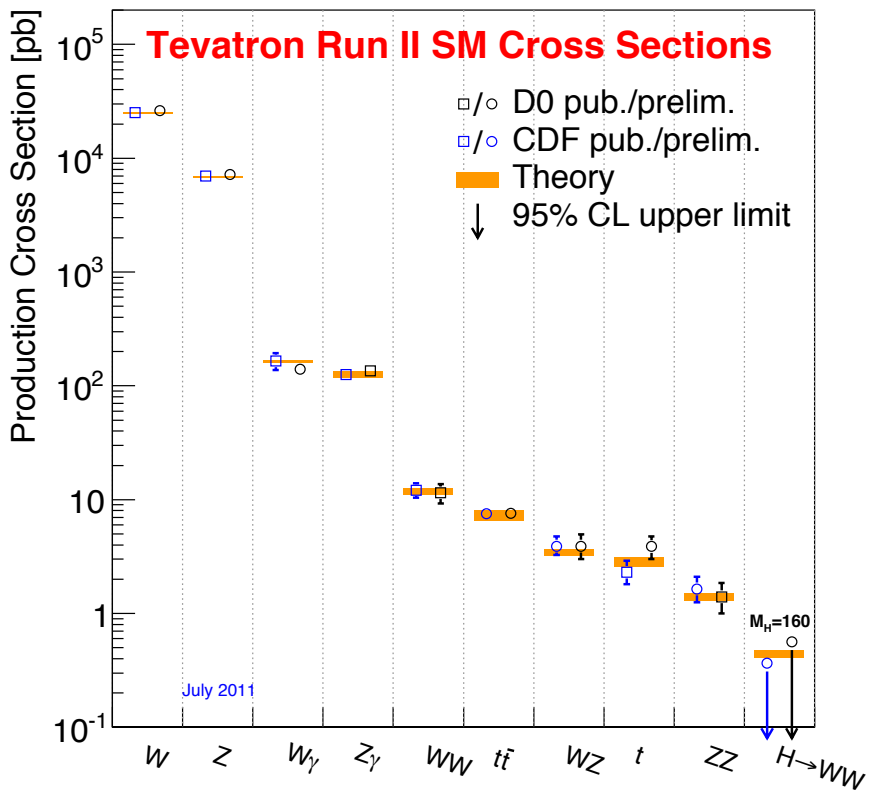
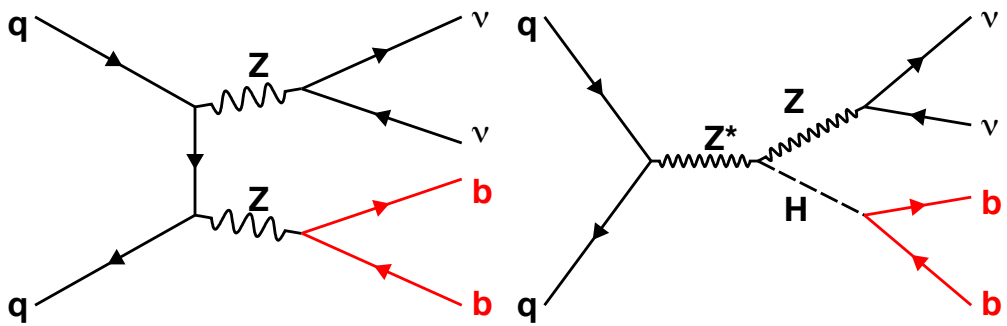
# Diboson introduction

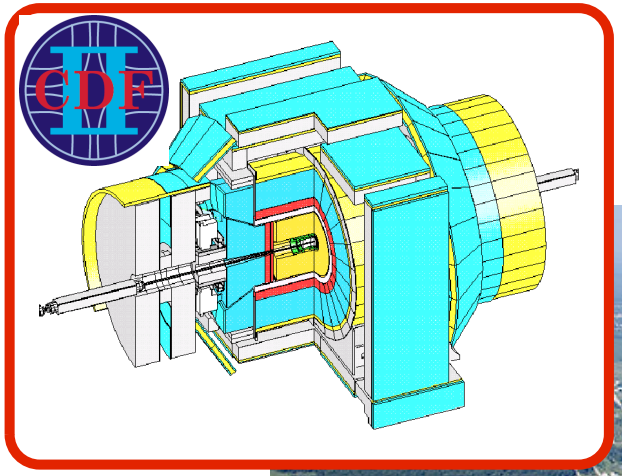
- Important test of EW sector of standard model.
- Significant backgrounds in searches for the SM Higgs.
- WW, WZ, and ZZ have all been observed at the Tevatron.
  - Start to explore more challenging final states...
- Following analyses will be presented:
  - **WZ → lνll**
  - **WV → lνjj** (V = W or Z)
  - **VZ** with **heavy flavour** jets.

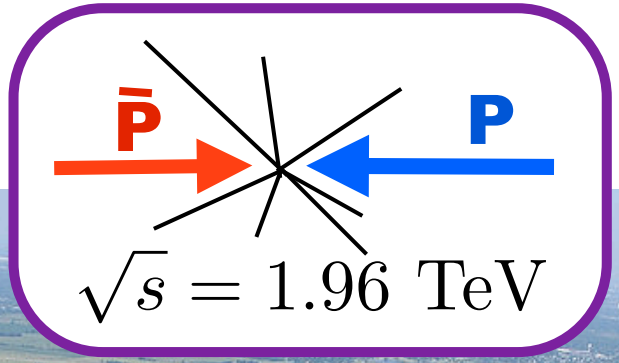


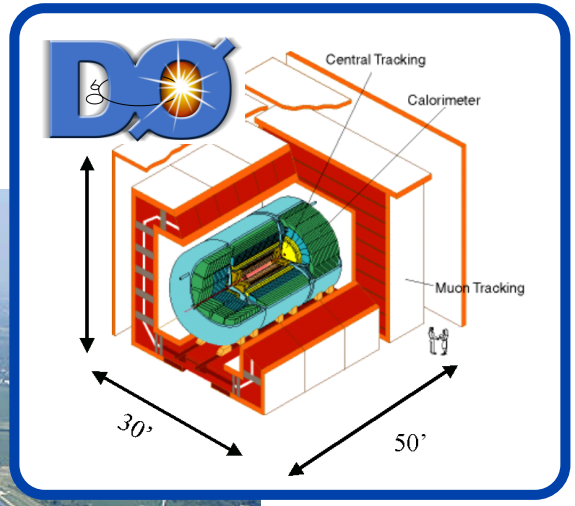

Backgrounds to SM Higgs searches

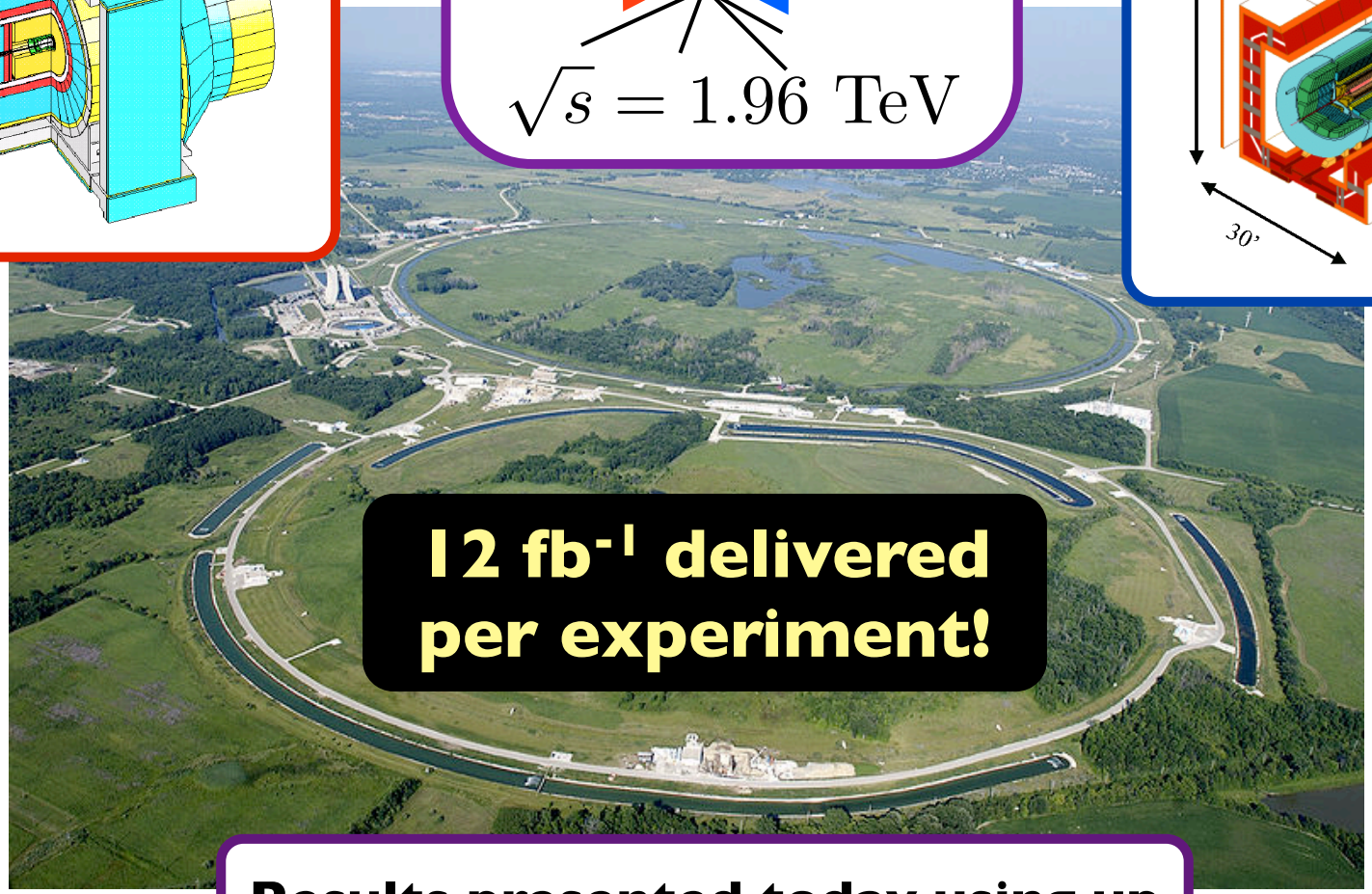


# The Tevatron, CDF and D0



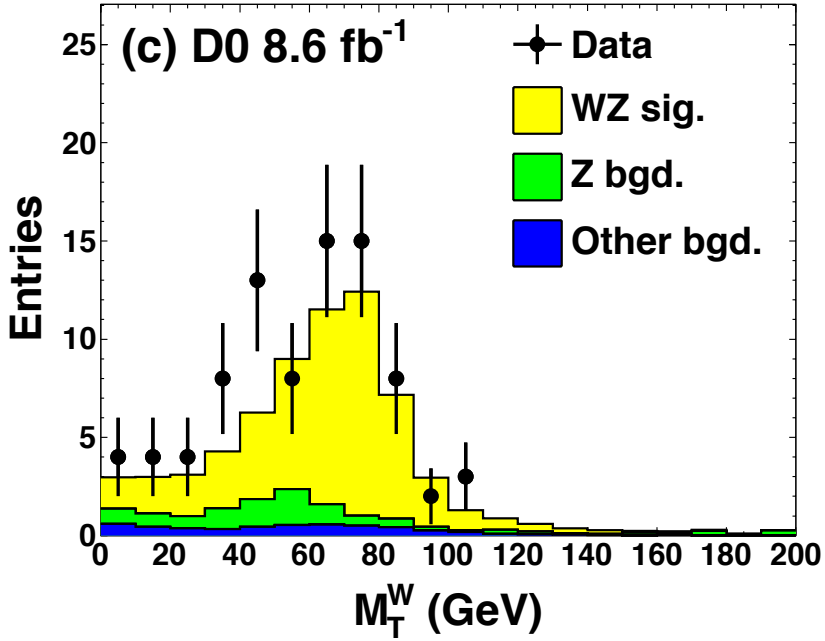
**12 fb$^{-1}$ delivered per experiment!**

**Results presented today using up to 9.5 fb$^{-1}$ of data!**

# WZ → lνll (D0)

arXiv:1201.5625v1, Submitted to PRD, Jan 2012.

- Select events with three high $p_T$ isolated electrons/muons and missing transverse energy.
- Measure cross section as ratio of WZ relative to Z
  - Significant cancellation in systematic uncertainties (e.g. lepton reconstruction efficiencies)
  - Use NNLO prediction* of Z cross section. Known to ≈ 3%, compared to ≈ 6% for measured luminosity.




$$\sigma_{WZ} = 4.5^{+0.6}_{-0.7}\ \text{pb}$$

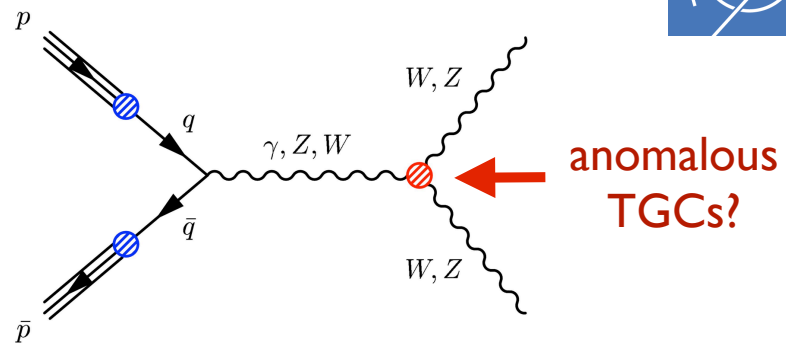
$$\sigma_{WZ}^{\text{NLO}} = 3.2 \pm 0.2\ \text{pb}$$

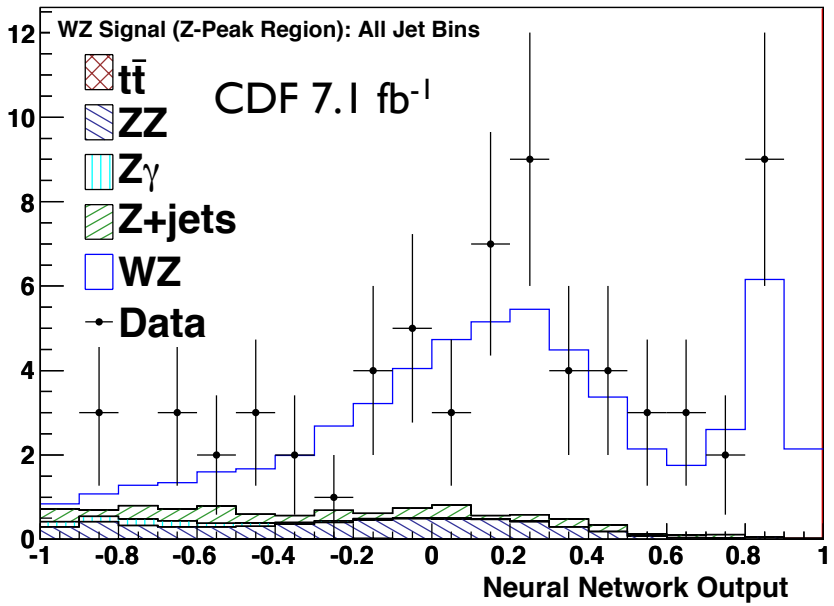
Measured cross section in agreement with but a little less than 2 σ higher than the SM prediction.

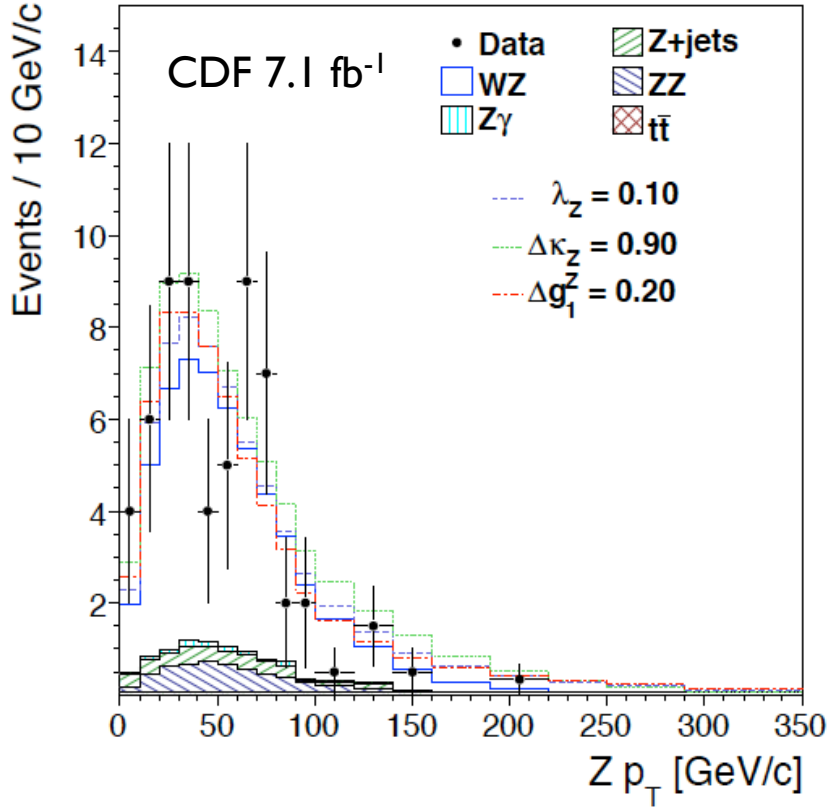
*R. Hamberg, W.L. van Neerven, T. Matsuura, Nucl. Phys. B 359 343 (1991).
WZ cross section uses MCFM, J.M. Campbell, R.K. Ellis, PRD 60 113006 (1999), with MSTW2008 NLO PDF, A. Martin et al., EPJC 63 189–285 (2009)

# WZ → lνll (CDF)

- Use neural network to extract signal cross section.
  - Use measured luminosity.




$$\sigma_{WZ} = 3.9^{+0.8}_{-0.7}\ \text{pb}$$

$$\sigma_{WZ}^{\text{NLO}} = 3.5 \pm 0.3\ \text{pb}$$

*different Z/γ* mass window to D0

95% C.L.

| | $\Lambda$ (TeV) | $\lambda_Z$ | $\Delta g_1^Z$ | $\Delta\kappa_Z$ |
|---|---|---|---|---|
| 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) |

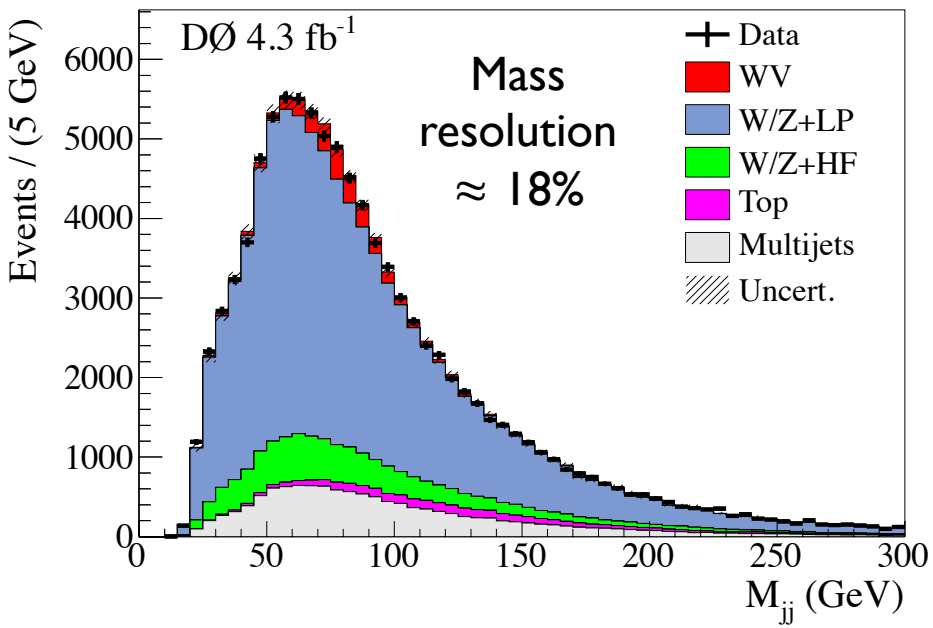
arXiv:1202.6629v1, Submitted to PRL, Feb 2012.

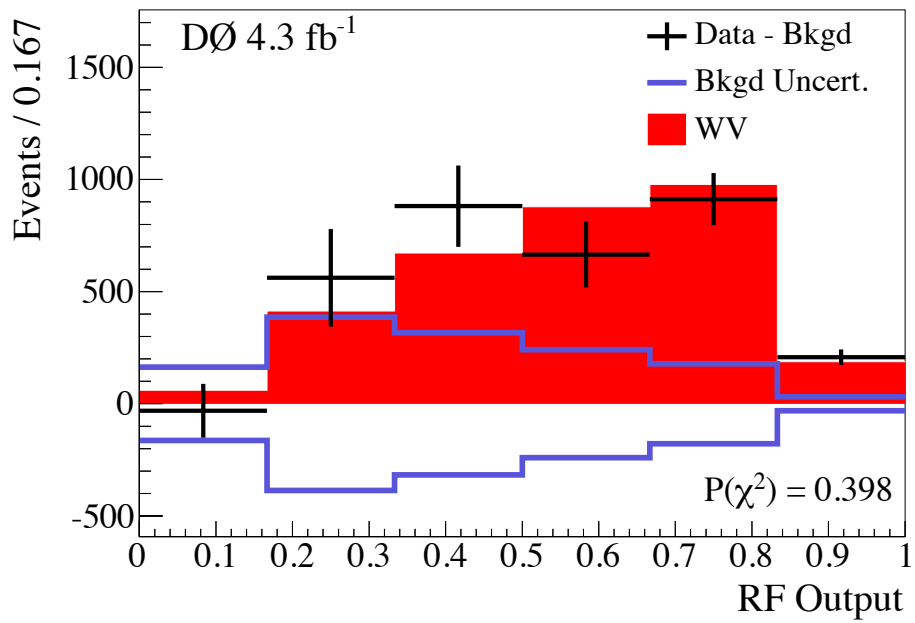
# WW/WZ → lνjj (D0)

- High $p_T$ electron or muon, missing $E_T$, and 2 or 3 jets
- Cannot resolve WW from WZ based on the dijet mass
  - Measure the combined cross section (assuming the SM ratio of WW vs WZ).

$$\sigma(WW + WZ) = 19.6 \pm 3.2 \text{ pb}$$

$$\sigma_{WW}^{\text{NLO}} = 11.7 \pm 0.8 \text{ pb} \quad \sigma_{WZ}^{\text{NLO}} = 3.5 \pm 0.3 \text{ pb}$$

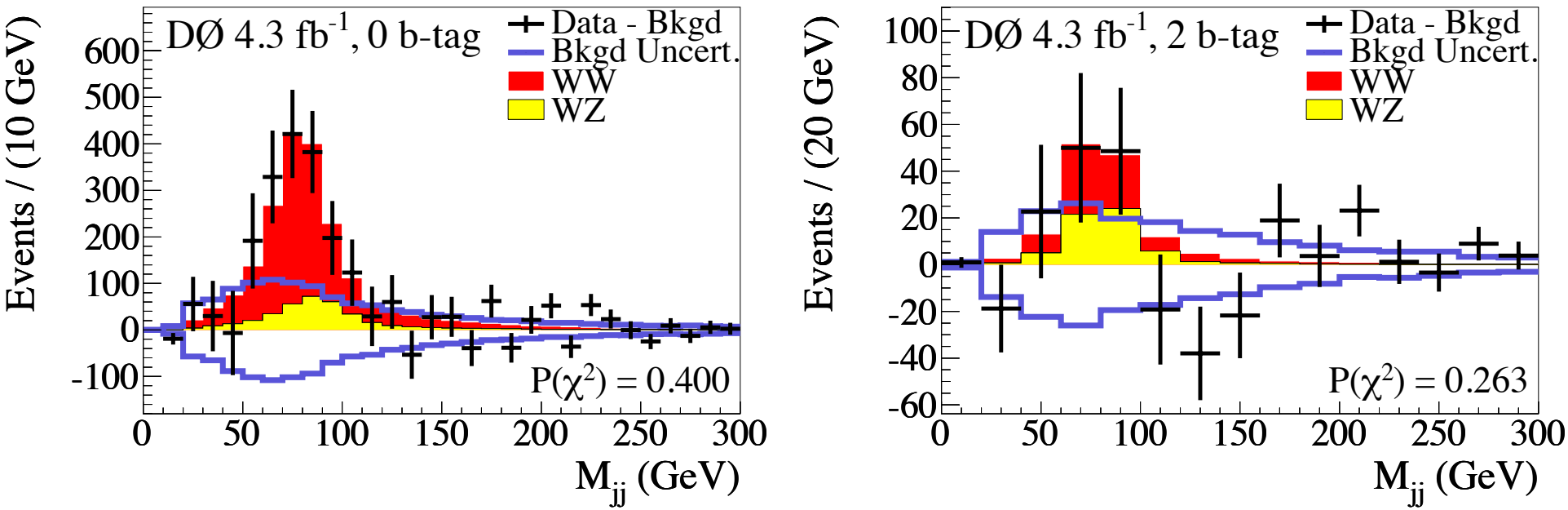



arXiv:1112.0536v1, Dec 2012, Accepted by PRL.

# WW/WZ → lνjj (D0)

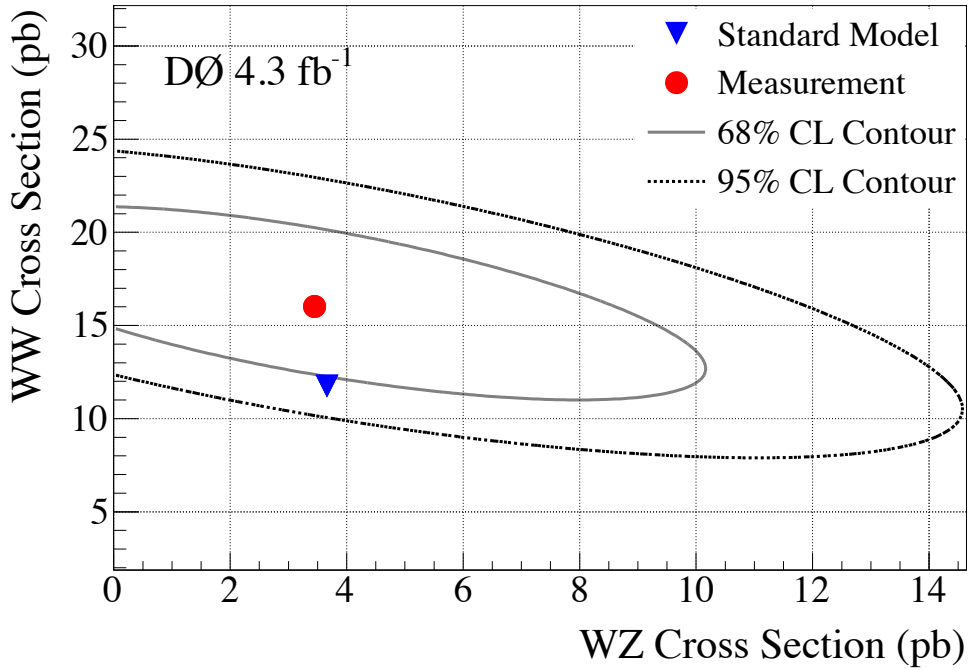
- Cannot resolve Z → jj from W → jj?
- **B-tagging** enhances the fraction of **WZ** (i.e., due to Z → bb, Z → cc decays).




arXiv:1112.0536v1, Dec 2012, Accepted by PRL.

# WW/WZ → lνjj (D0)

- With the addition of B-tagging information, we can resolve WW and WZ.




$$\sigma(WW) = 15.9^{+3.7}_{-3.2}\ \text{pb}$$
$$\sigma(WZ) = 3.3^{+4.1}_{-3.3}\ \text{pb}$$

$$\sigma^{\text{NLO}}_{WZ} = 3.5 \pm 0.3\ \text{pb}$$
$$\sigma^{\text{NLO}}_{WW} = 11.7 \pm 0.8\ \text{pb}$$

- Also extract σ(WZ) after constraining σ(WW) to the SM value.
  - σ(WZ) = 6.5 ± 0.9(stat) ± 3.0(syst) pb, with 2.2σ(1.2σ) observed(expected) significance.

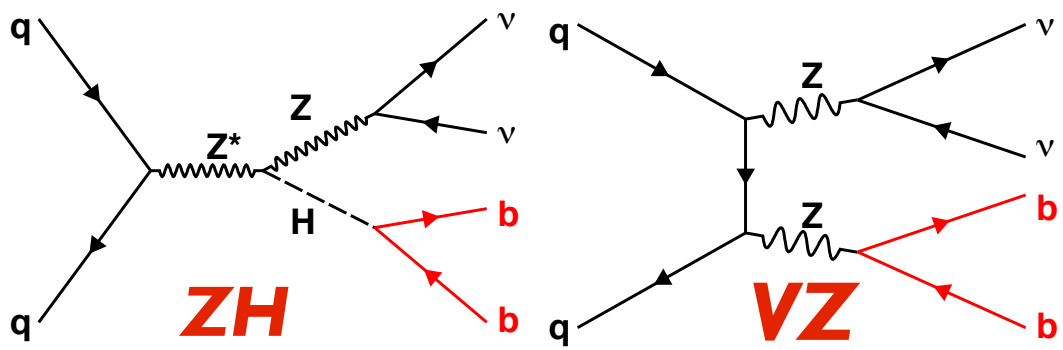
arXiv:1112.0536v1, Dec 2012, Accepted by PRL.

# Dibosons with heavy flavour jets

See Higgs talk by Kyle Knoepfel

- Main low mass Higgs search channels involve VH with H → bb.
  - Three main final states: **ννbb, lνbb, llbb.**
- Significant background from VZ with **Z → HF**.
- Recast the Higgs searches as VZ cross section measurements.
  - Validation of the methods used in the Higgs searches (e.g. background modeling).
  - Demonstrate sensitivity to processes with cross sections at the same order of magnitude, and in the same final states.

E.g. **ννbb:**

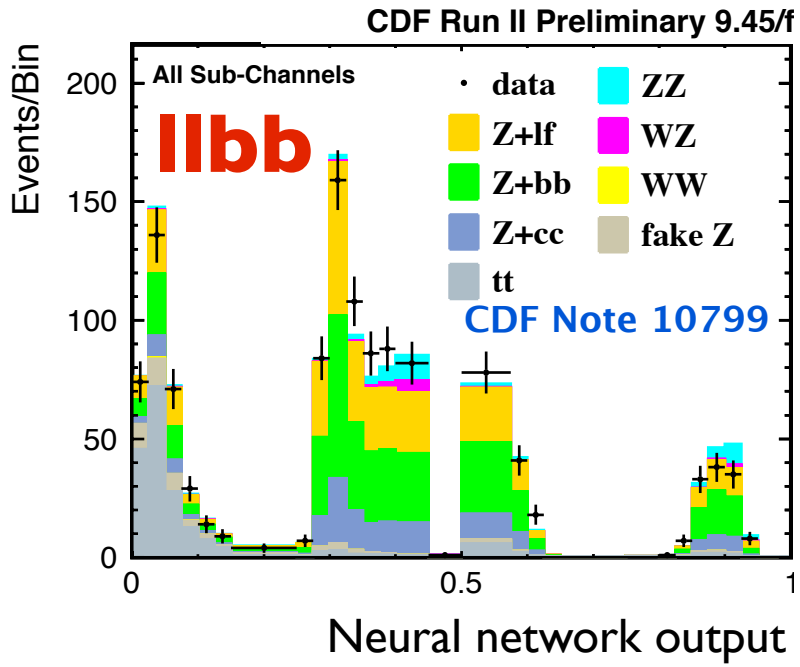


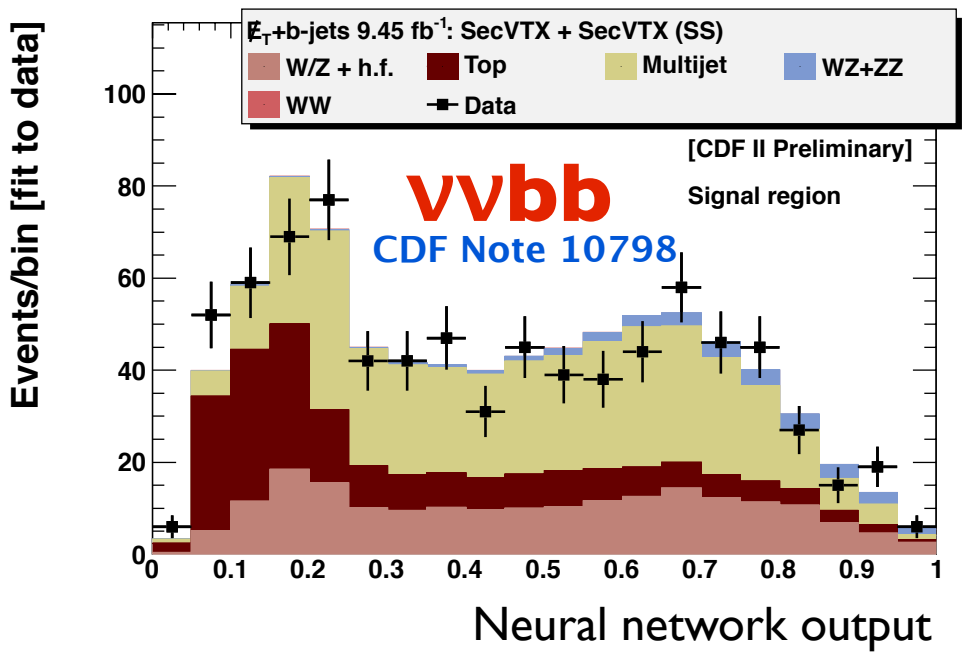

Cross section times branching fractions (to bb)

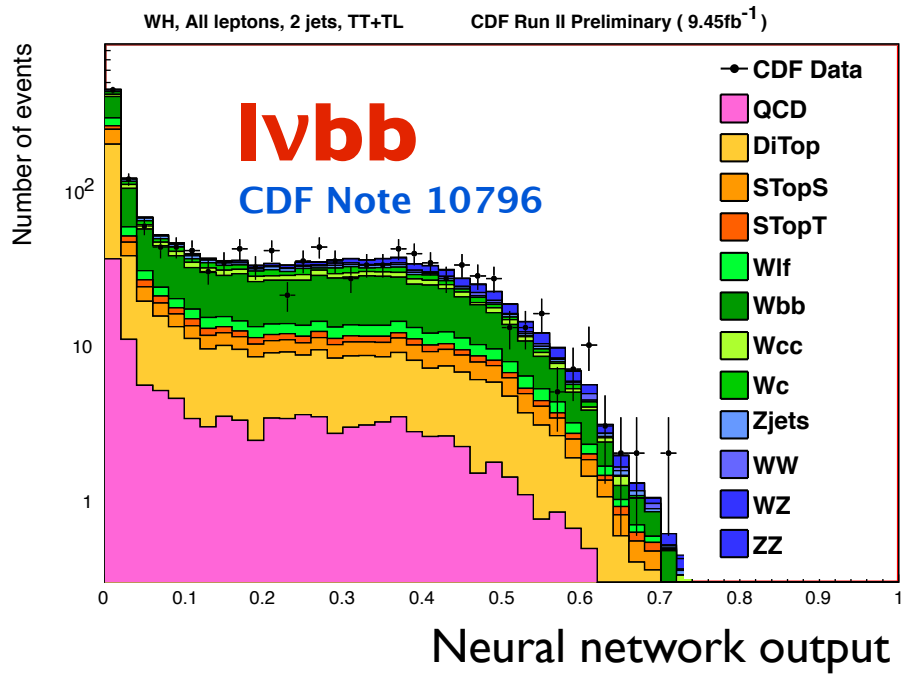
| Final state | VH | VZ |
|---|---|---|
| lνbb | 27 fb | 105 fb |
| llbb | 5 fb | 24 fb |
| ννbb | 15 fb | 73 fb |

# CDF Inputs

- All channels use **9.5 fb$^{-1}$** of data.
- Retrain the multivariate discriminants to treat VZ as signal rather than VH.



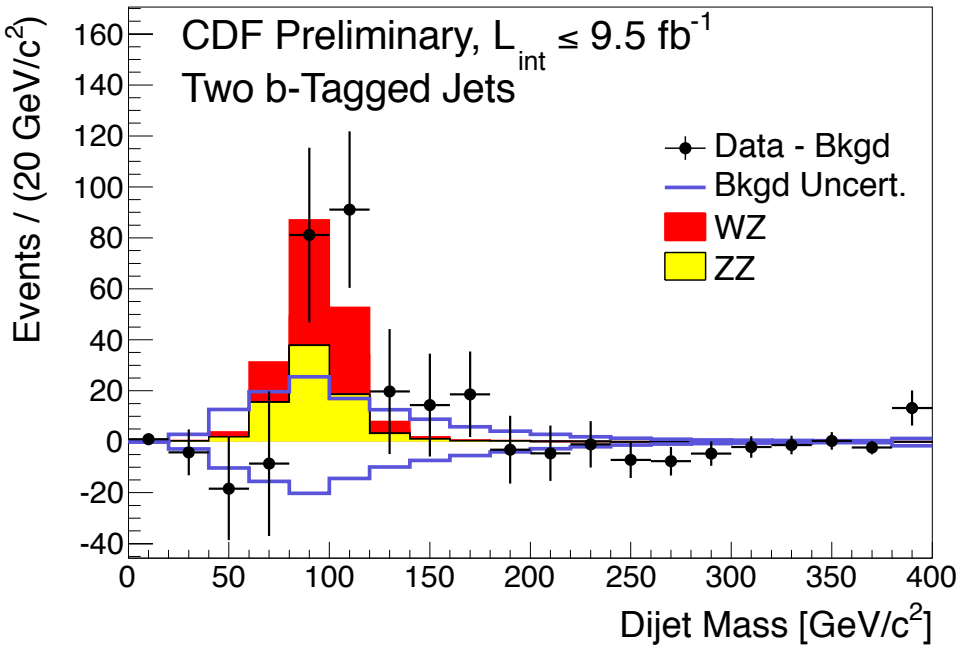



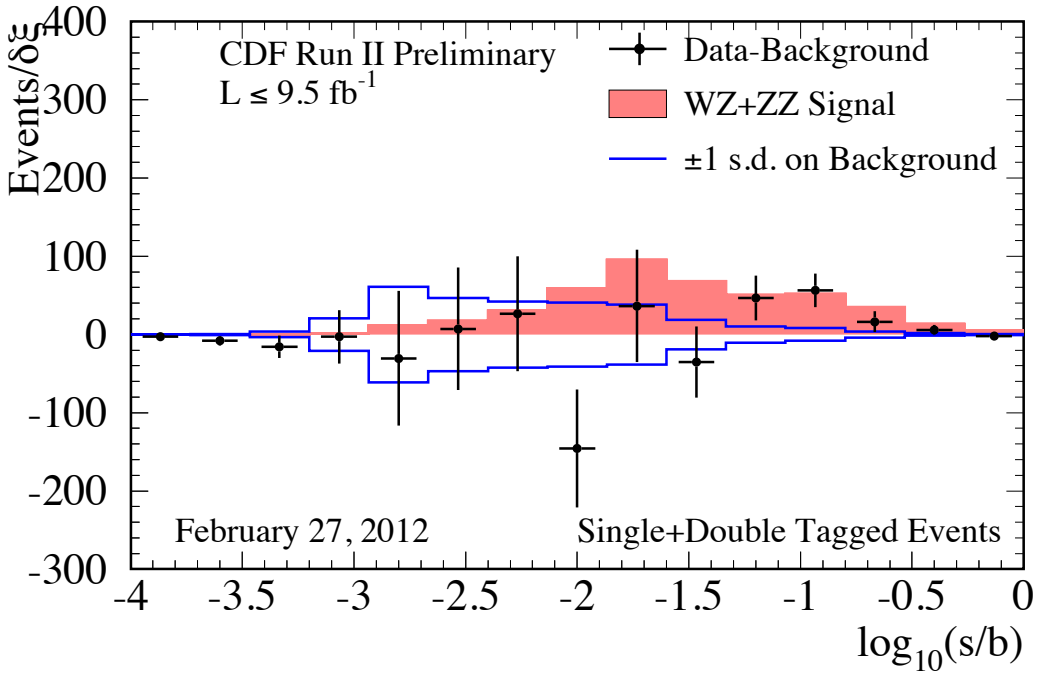
# CDF Combination

- Group bins from the different channels according to expected s/b.
- **Evidence** for VZ signal with **3.2σ** significance.

$$\sigma(ZZ + WZ) = 4.1^{+1.4}_{-1.3}\ \text{pb}$$

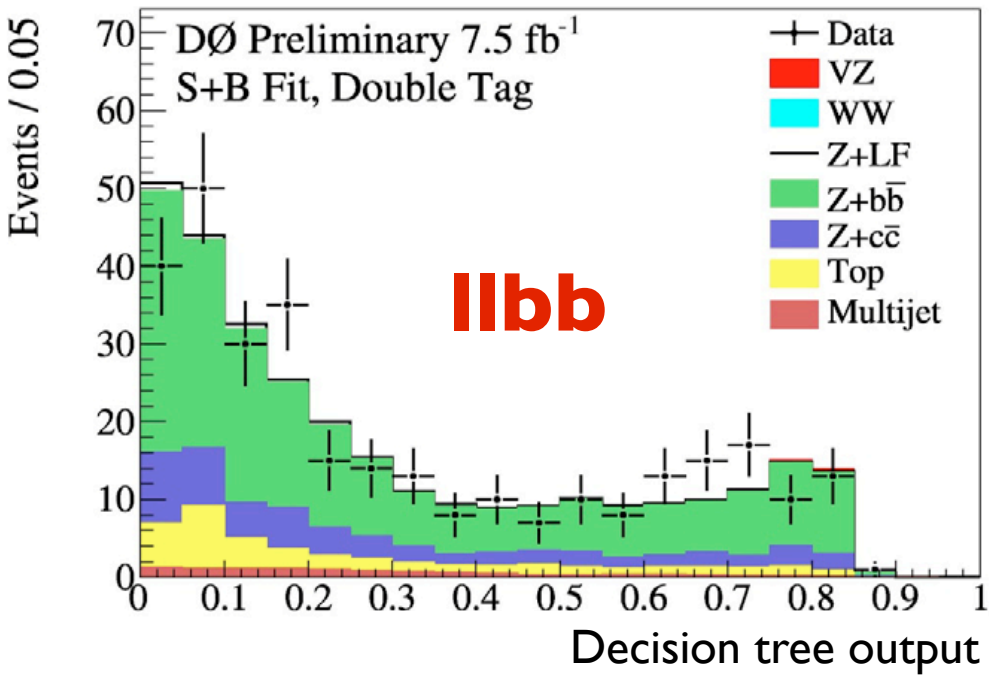
$$\sigma^{\text{NLO}}(ZZ + WZ) = 4.3 \pm 0.3\ \text{pb}$$

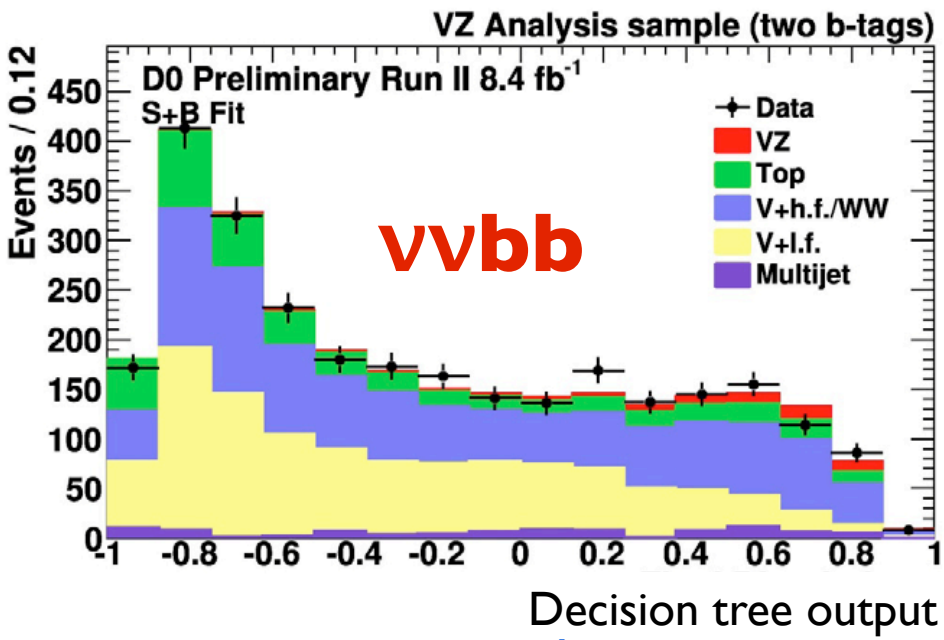


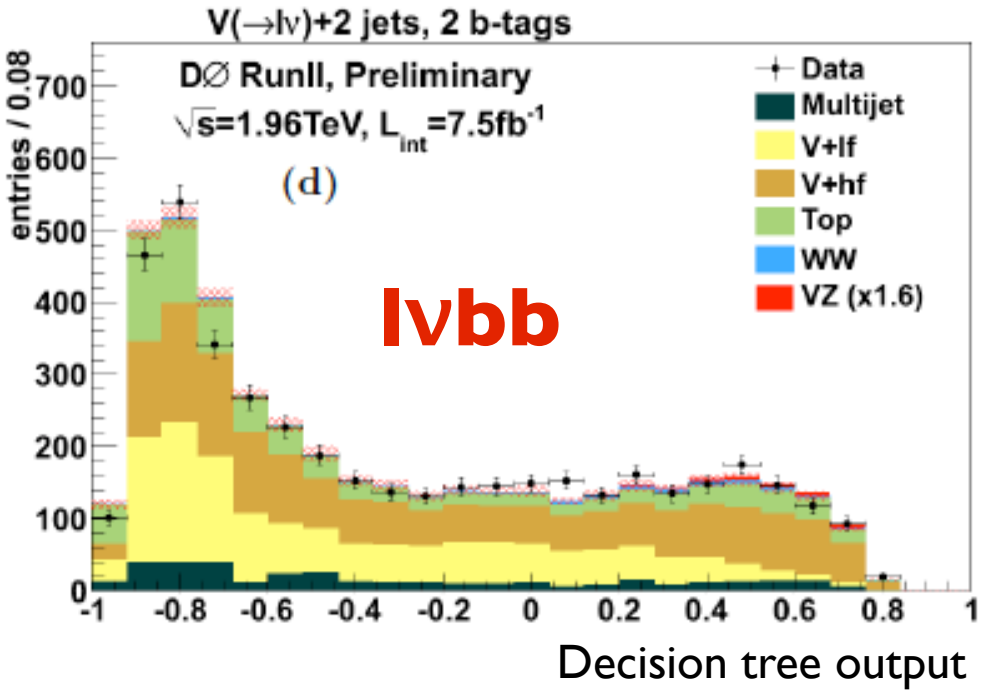



# D0 Inputs

- Individual inputs to D0 analysis (7.5-8.4 $fb^{-1}$)



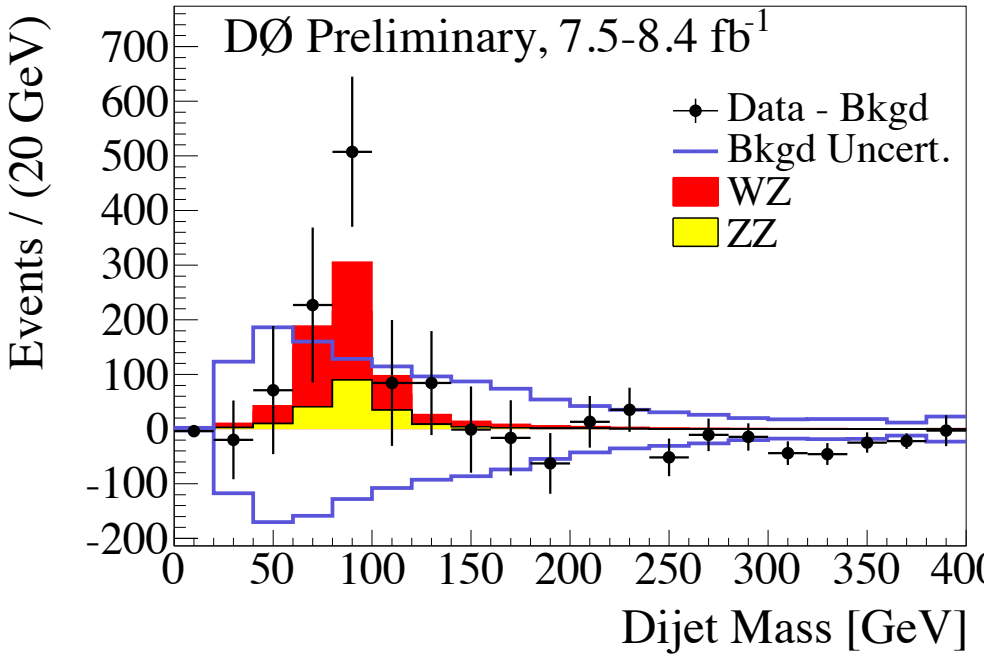

DØ Note 6260-CONF, November 2012

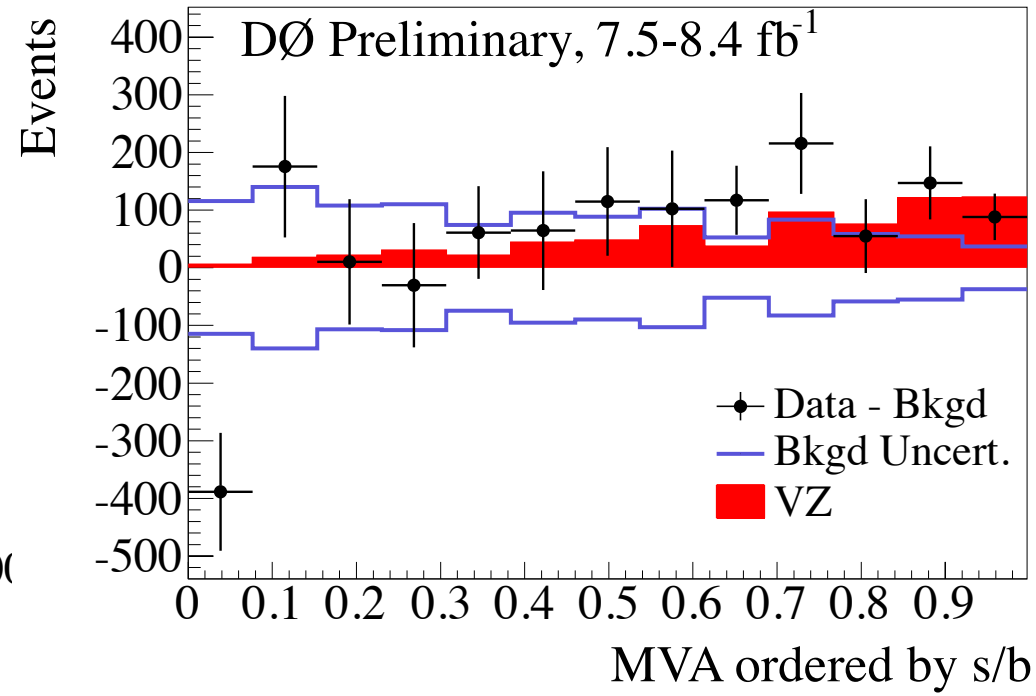
# D0 Combination

- Group bins from the different channels according to expected s/b.
- **Evidence** for VZ signal with **3.3σ** significance (2.9σ expected).

$$\sigma(ZZ + WZ) = 4.5 \pm 1.6 \text{ pb}$$

$$\sigma^{\text{NLO}}(ZZ + WZ) = 4.3 \pm 0.3 \text{ pb}$$



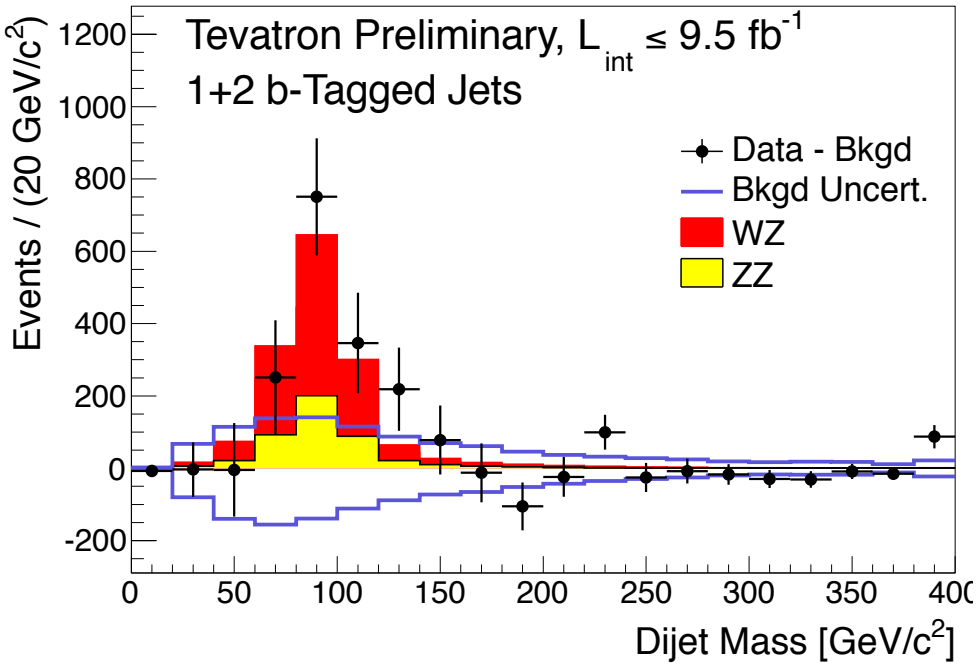

DØ Note 6260-CONF, November 2012

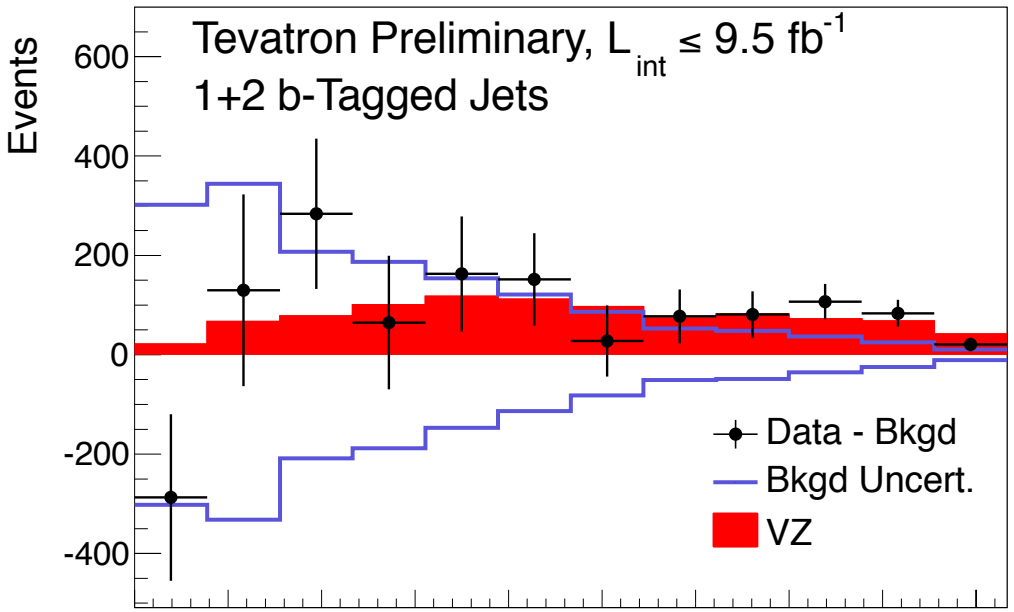
# Tevatron Combination

- **4.6σ evidence** for VZ with **heavy flavour**

$$\sigma(ZZ + WZ) = 4.47 \pm 0.64(\text{stat}) \pm 0.73(\text{syst})\ \text{pb}$$

$$\sigma^{\text{NLO}}(ZZ + WZ) = 4.3 \pm 0.3\ \text{pb}$$




MVA ordered by s/b

arXiv:1203.3774v1 [hep-ex], March 2012.

# Conclusions

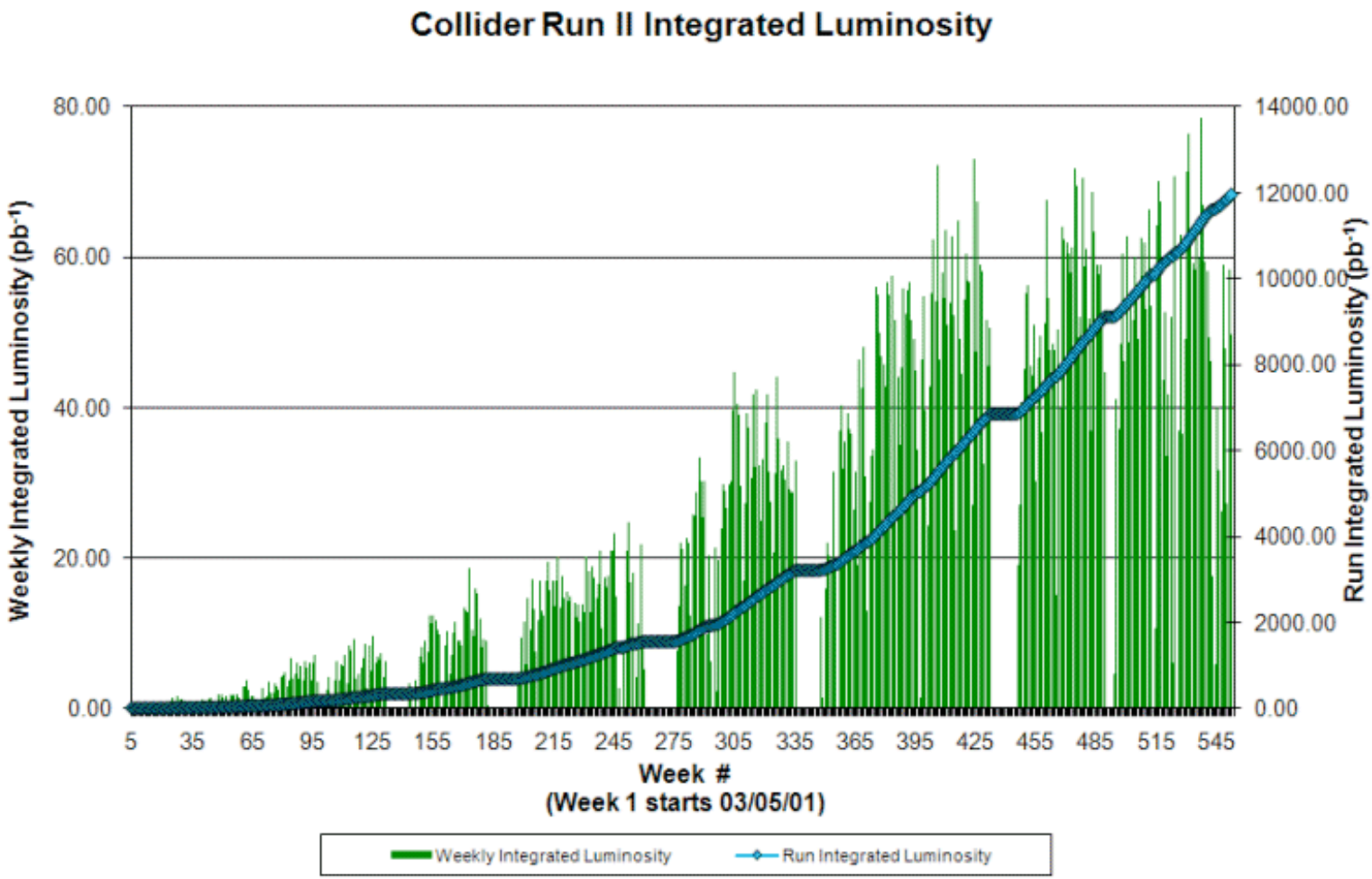
V = W or Z

- Many new diboson results, and no deviations from SM predictions.
- Precise cross section measurements with WZ → lνll
  - Stringent limits on anomalous triple gauge couplings.
- Precise measurement of WV cross section in WV → lνjj
  - Separate measurements of σ(WW) and σ(WZ).
- 4.6σ evidence for VZ with heavy flavour jets
  - Tevatron combination using the same methods as in the low mass Higgs (→bb) searches.
  - Good validation of the low mass Higgs searches.

# Backup Slides

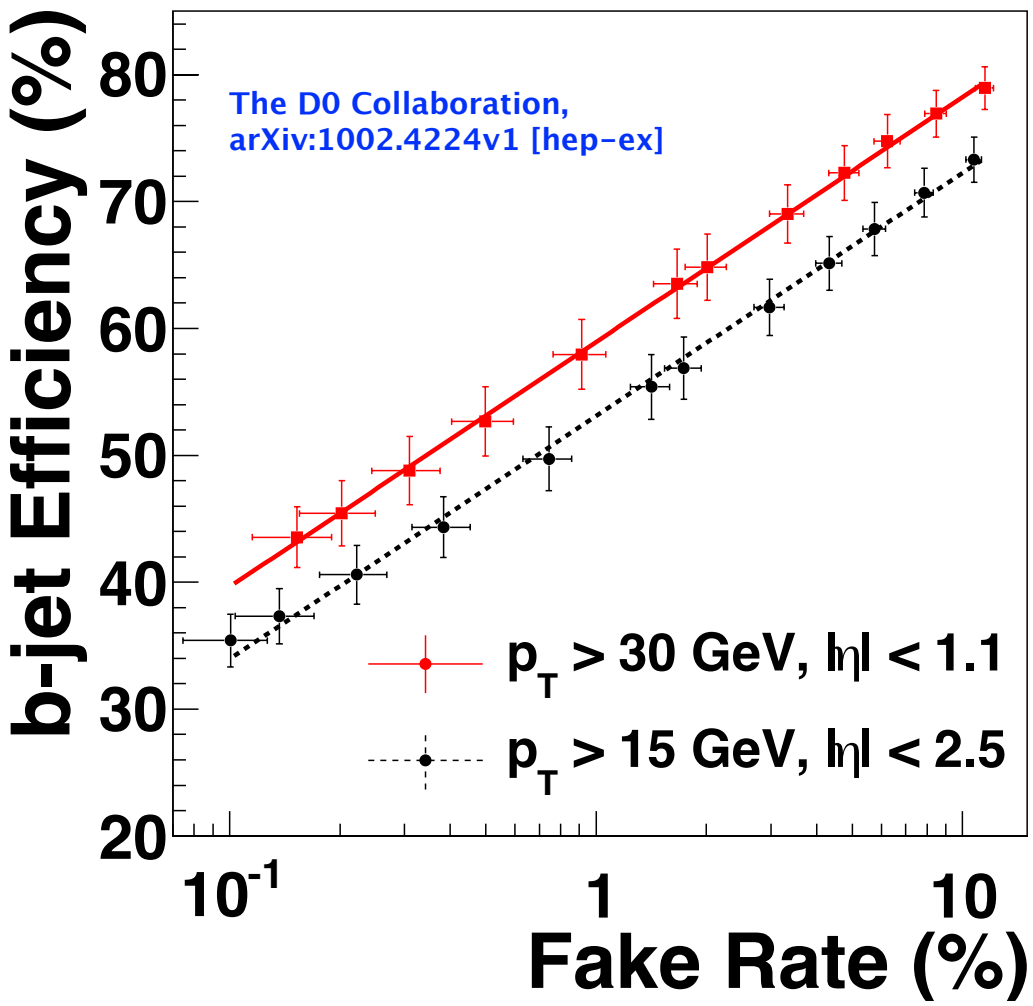
# Tevatron luminosity

- Final delivered luminosity ≈ 12 $fb^{-1}$ per experiment



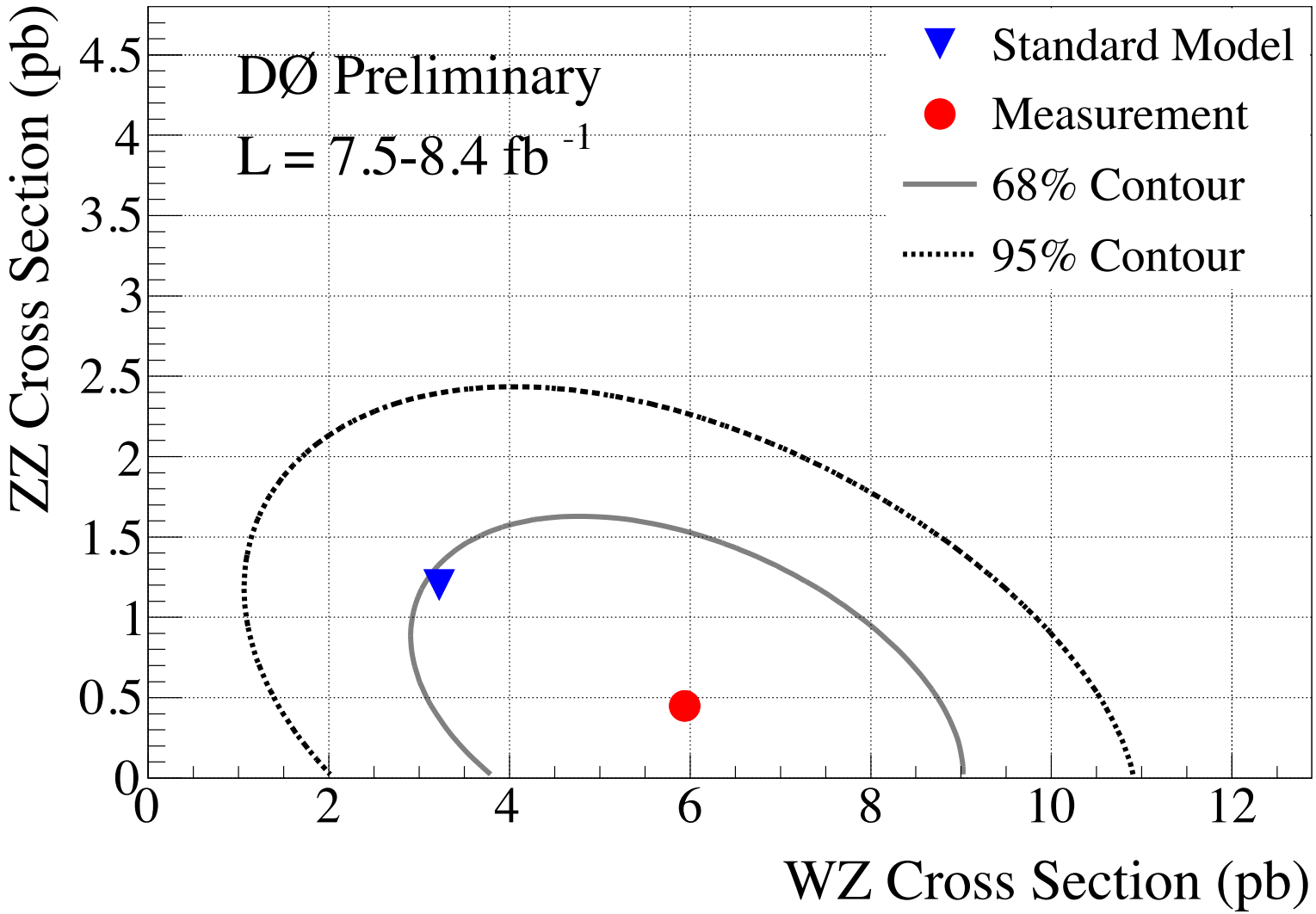
# B-tagging at D0

- Neural network based B tagger.



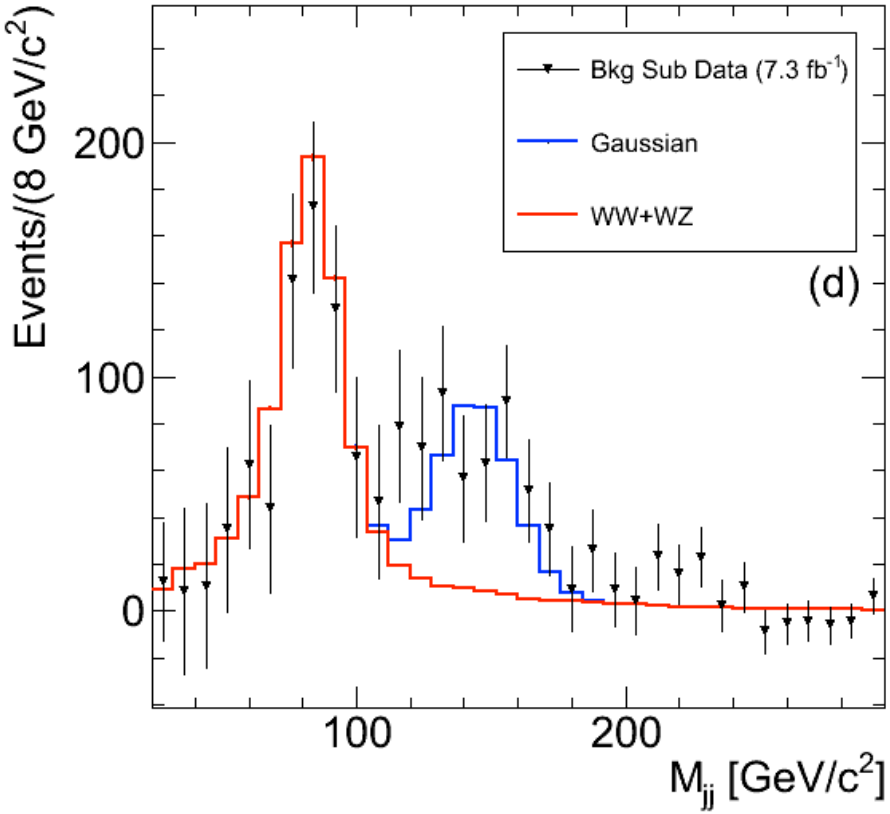
# Simultaneous σ(WZ) and σ(ZZ)

- Another result extracted from the D0 analysis:

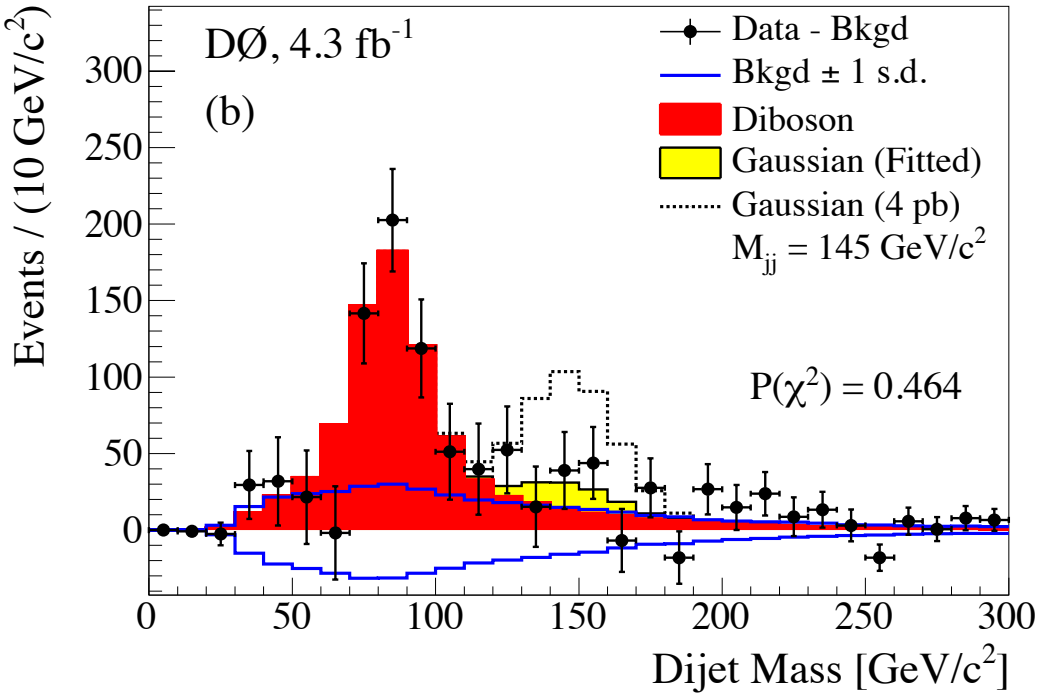



DØ Note 6260-CONF, November 2012

# W+2 jet anomaly?

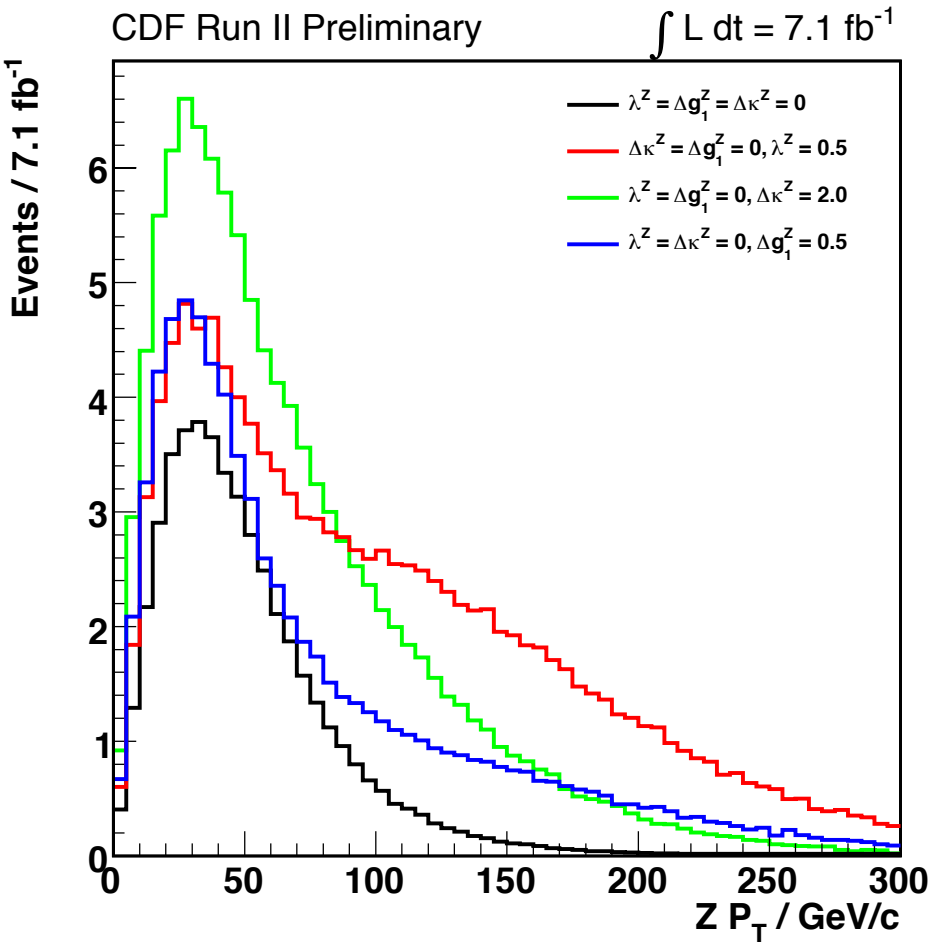


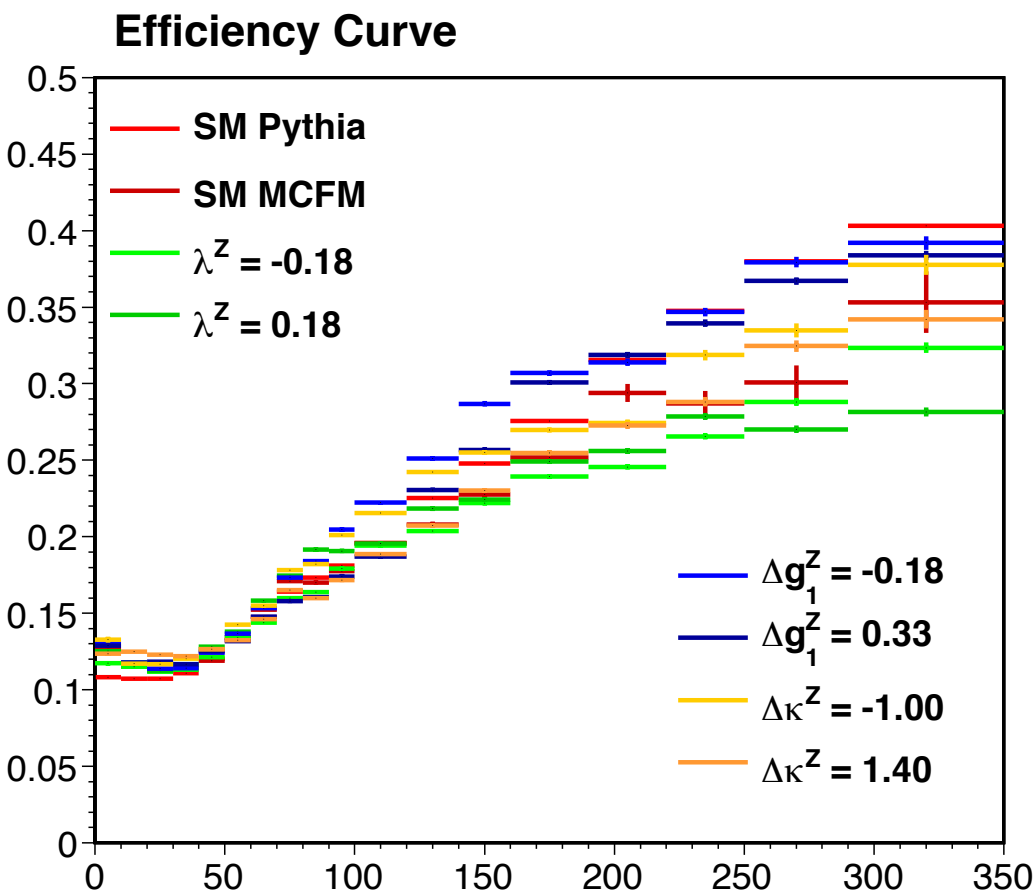

Phys.Rev.Lett.107:011804,2011



# CDF WWZ aTGGs

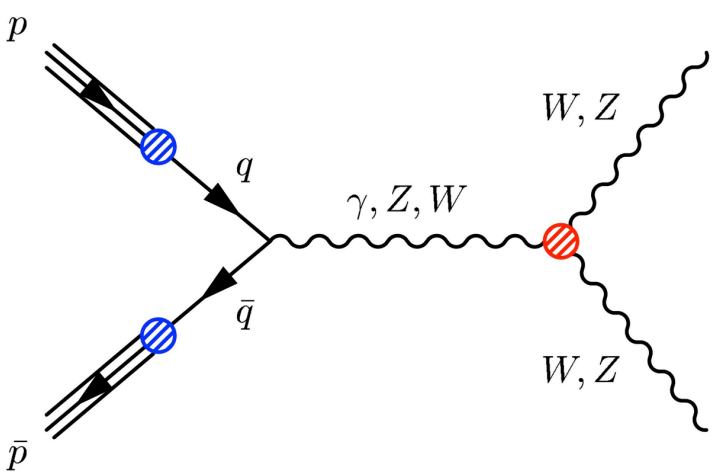
- Set limits using shape and normalization of Z $p_T$ distribution in WZ events.

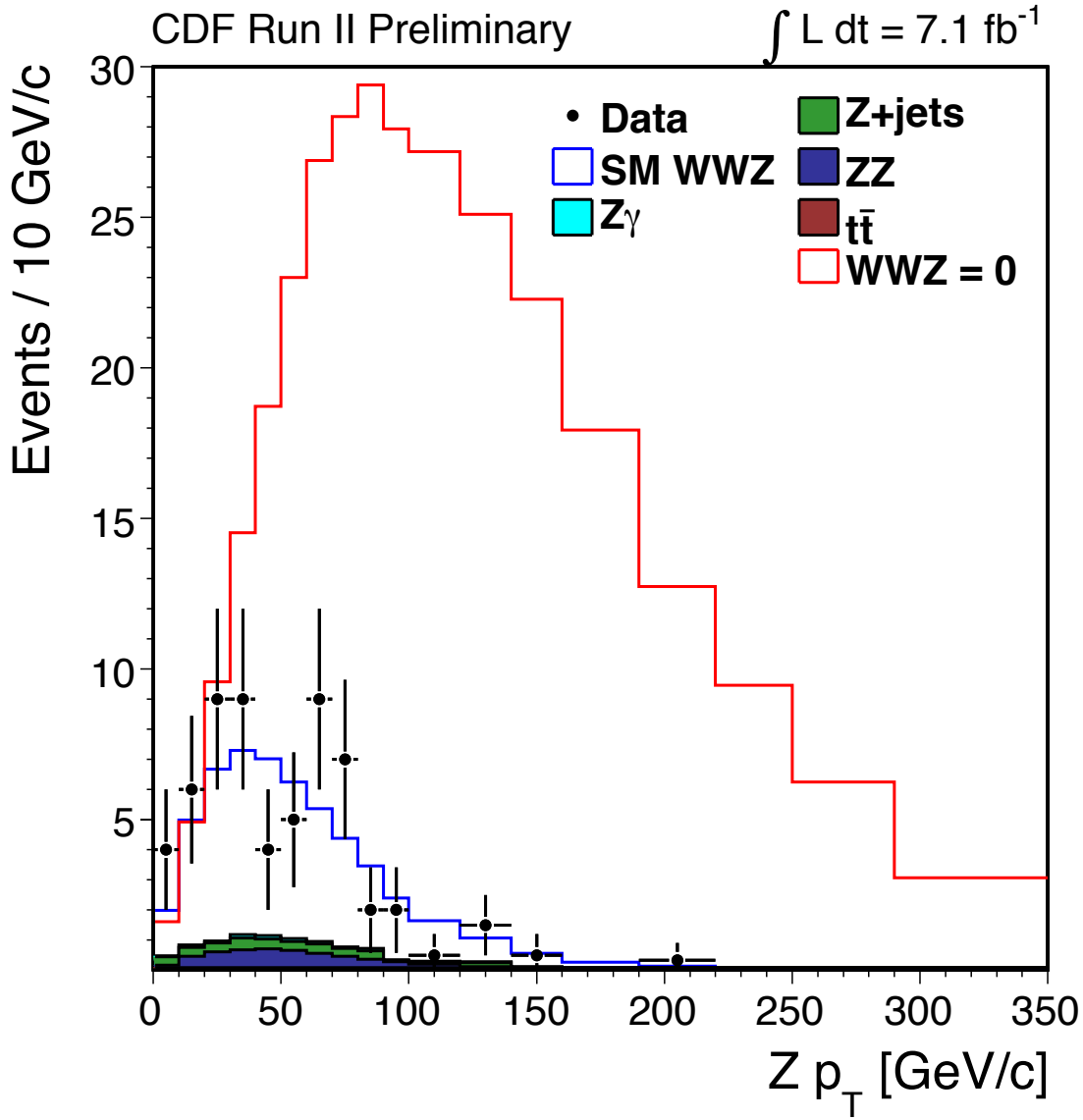


# CDF WWZ aTGGs

## Unitarity conserved by form factor



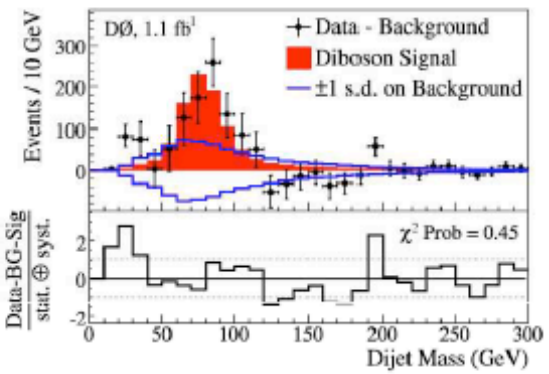




K. Hagiwara, R.D. Peccei, D. Zeppenfeld, and K. Hikasa, Nucl. Phys. B 282, 253 (1987).

# Dibosons with semileptonics

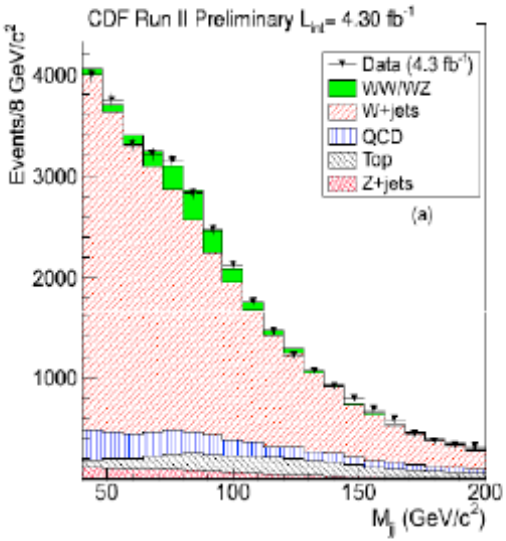
- Difficult to separate WW/WZ due to dijet mass resolution

D0 1.1 fb$^{-1}$

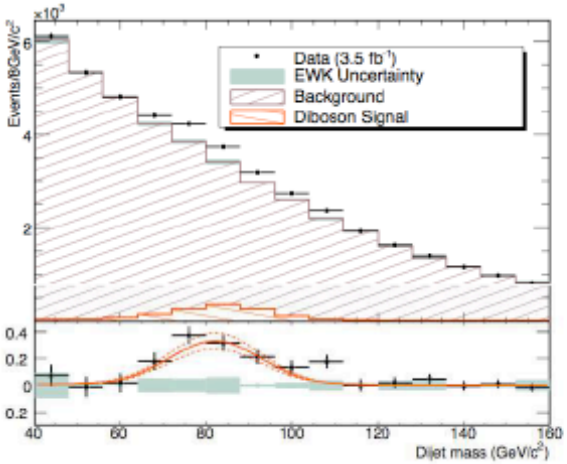



Phys. Rev. Lett. **102**, 161801 (2009) Ph

CDF 4.3 fb$^{-1}$




CDF 3.5 fb$^{-1}$

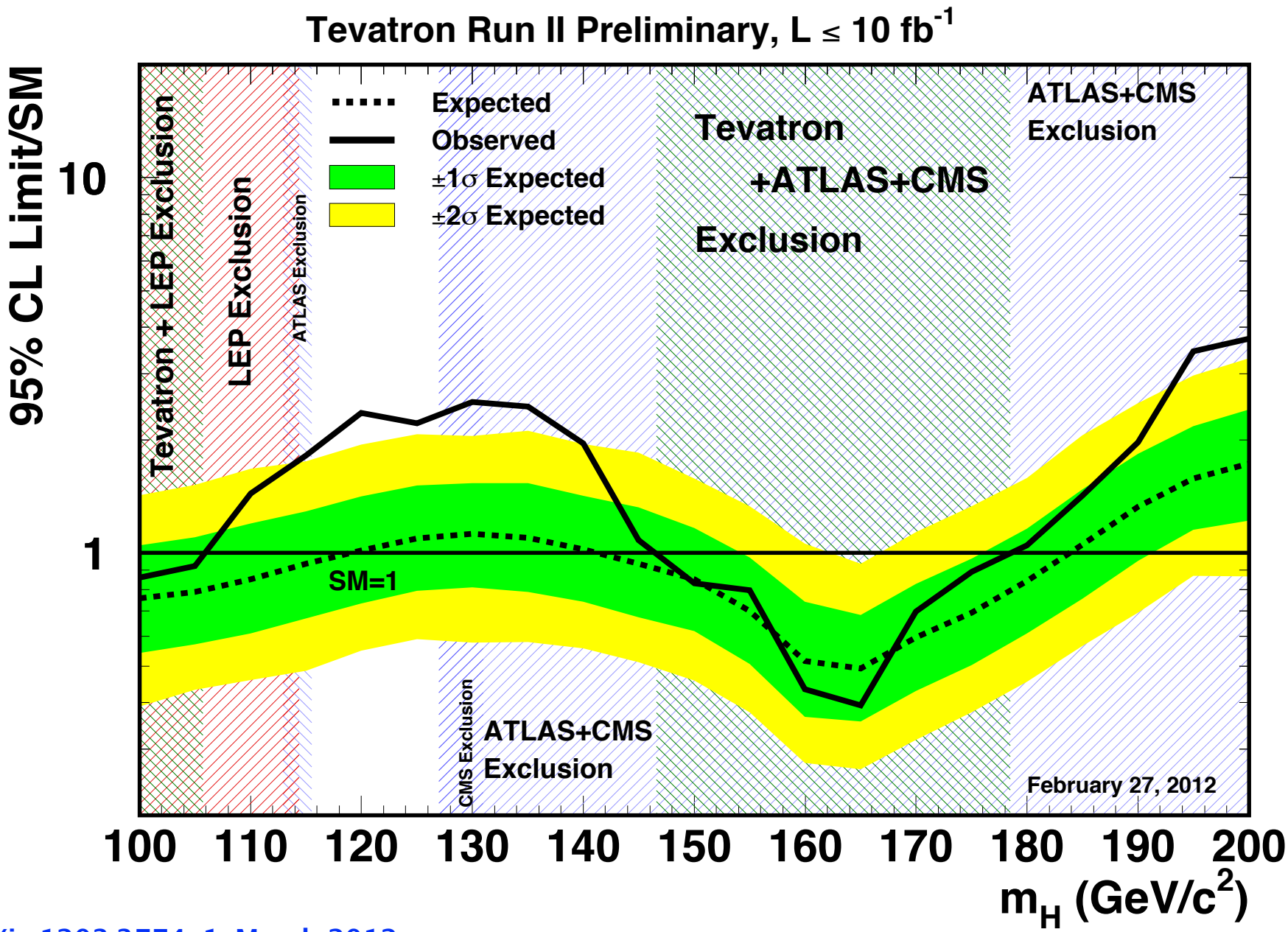



- WW/WZ→lνjj
- PRL **102**, 161801 (2009) evidence

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

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

# Tevatron Higgs combination




arXiv:1203.3774v1, March 2012.