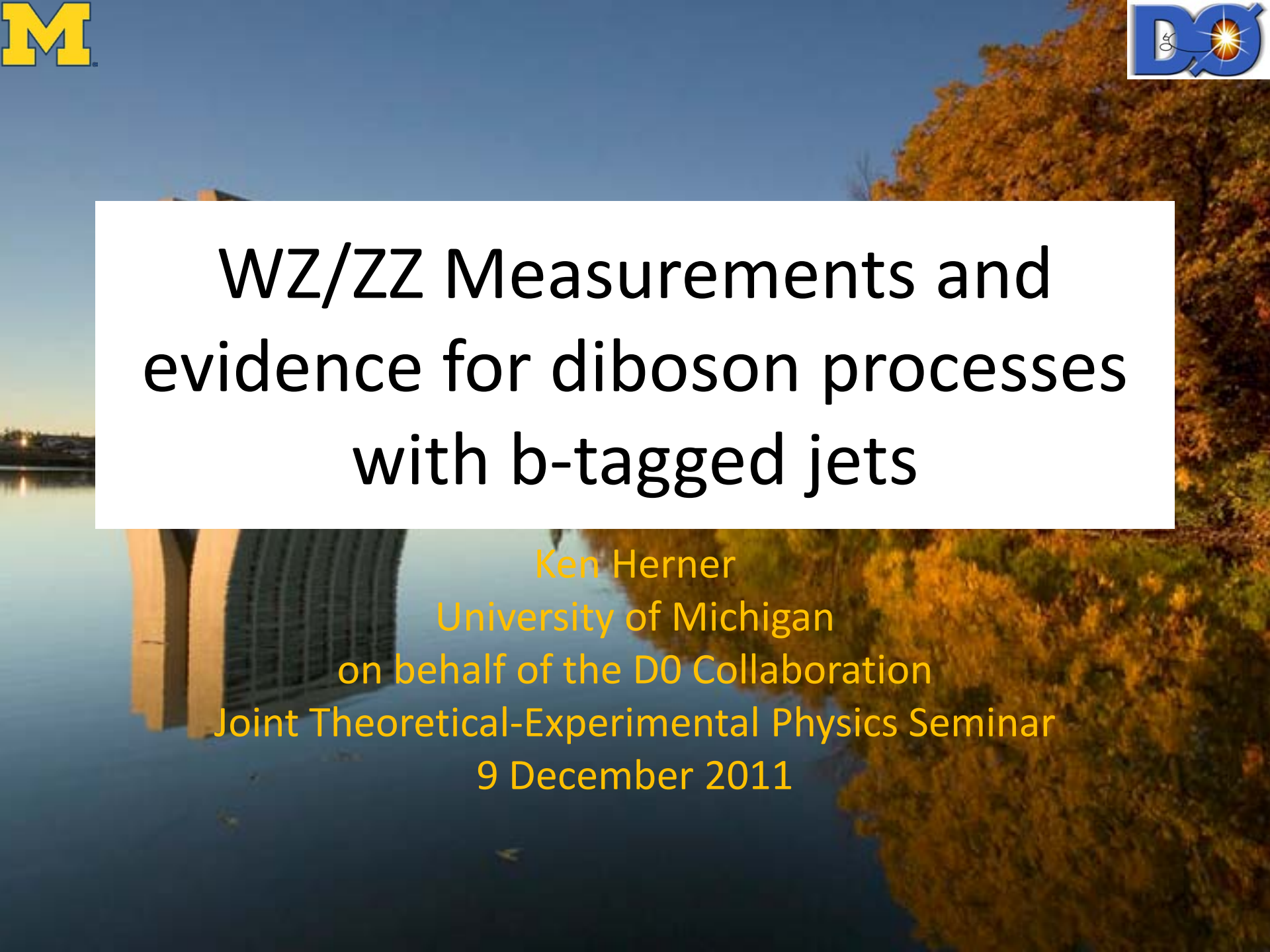


WZ/ZZ Measurements and evidence for diboson processes with b-tagged jets

Ken Herner
University of Michigan
on behalf of the D0 Collaboration

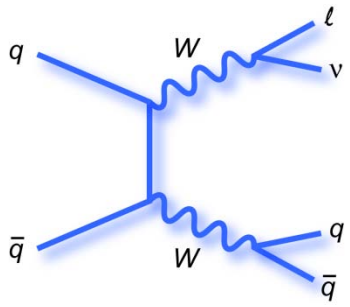
Joint Theoretical-Experimental Physics Seminar
9 December 2011

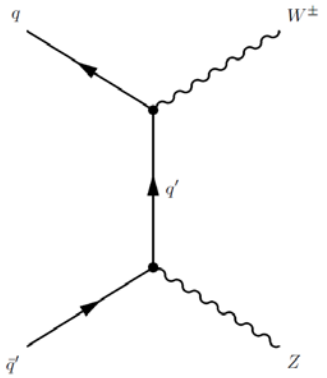
Outline

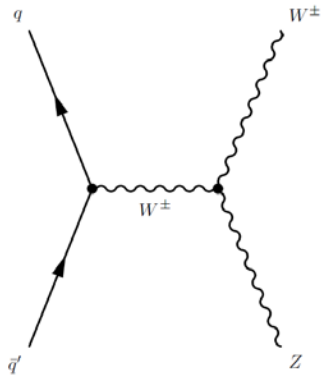
- Motivation for diboson studies
- Diboson production at the Tevatron
- D0 Standard Model Higgs Boson ($H \rightarrow b\bar{b}$) searches
- Diboson production, Higgs-style
- Results

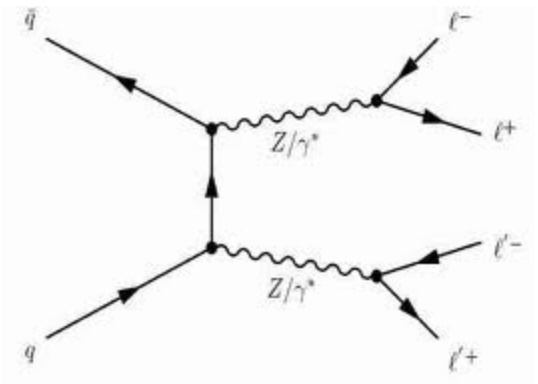
Diboson Production

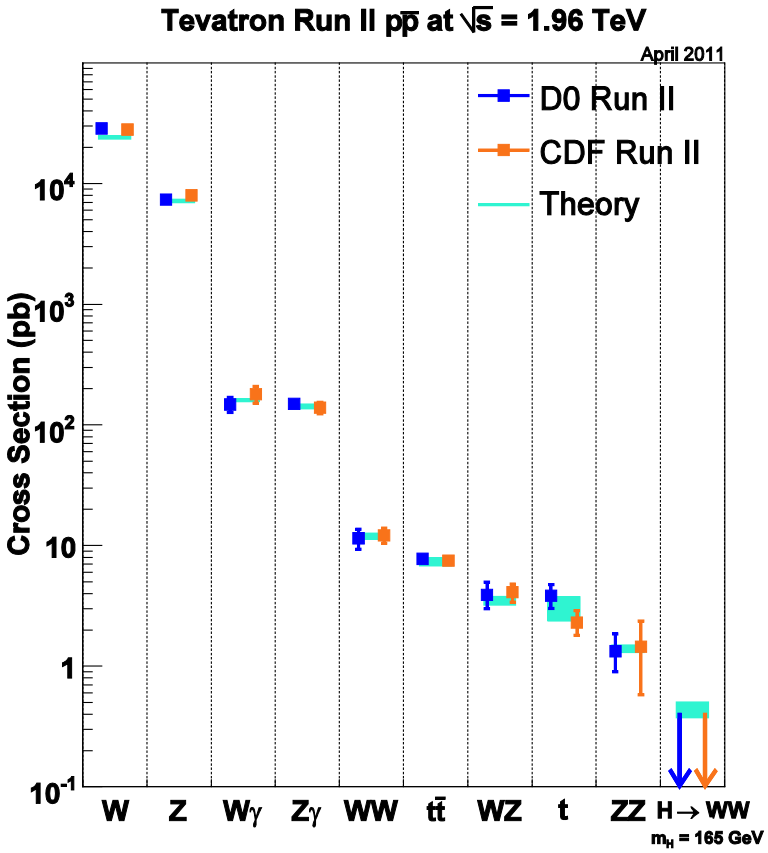
- WW, WZ, and ZZ production are among the smallest Standard Model (SM) cross sections (aside from Higgs...)
- All three have been observed at the Tevatron





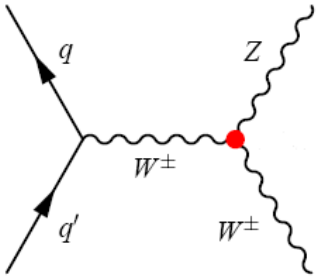




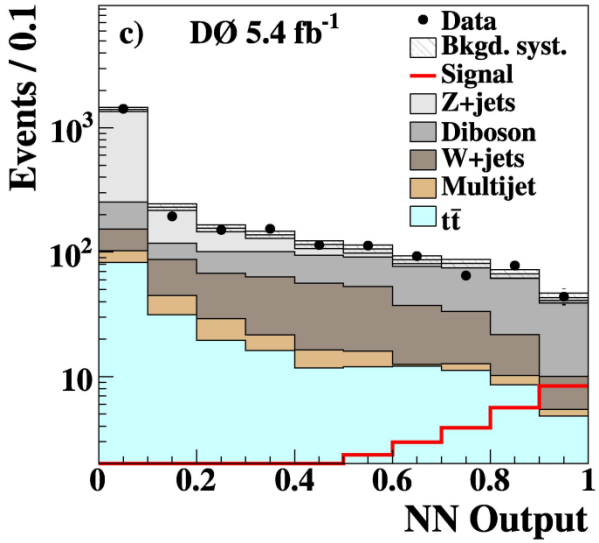


Diboson Motivations

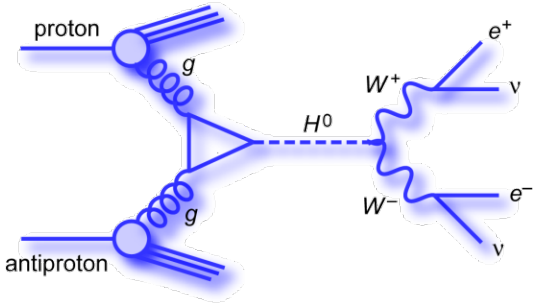
Probe of the Electroweak Symmetry Breaking mechanism
SM tests
Indirect searches for New Physics
(cross sections, kinematic distributions, gauge boson couplings)

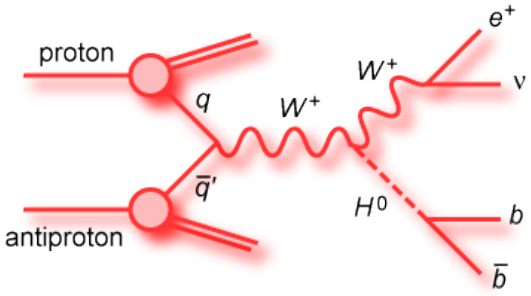


Important background to Top, Higgs, SUSY
Good understanding is highly valuable



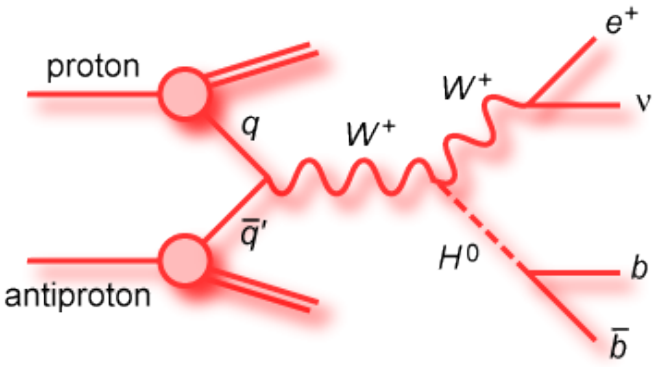
Proving ground for analysis techniques
and statistical treatment used in the Tevatron
Higgs searches, especially low-mass searches

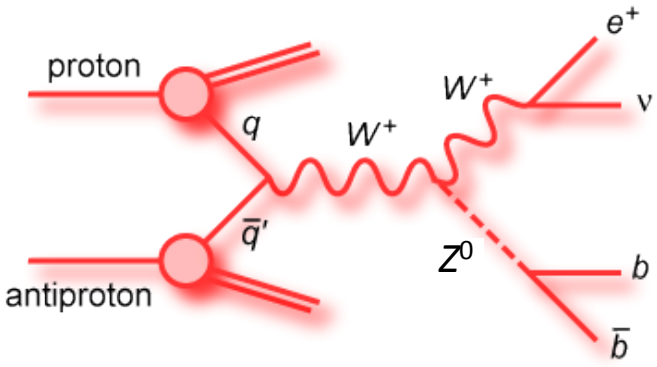




Our main motivation in this talk

WZ/ZZ as Higgs benchmark





For (W/Z)H with mH = 115 GeV:

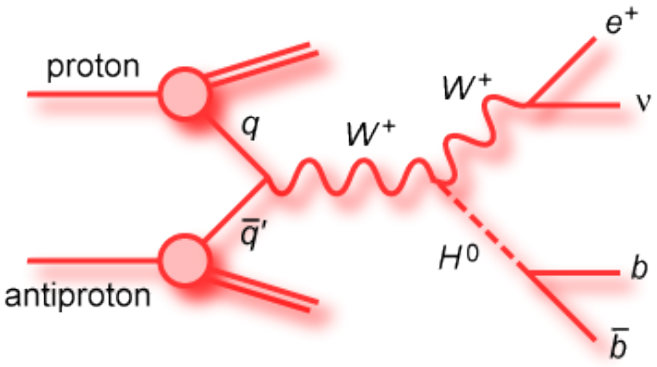
WH → lνbb:	27 fb	(l=e,μ)
ZH → llbb:	5 fb	(ll=ee,μμ)
ZH → ννbb:	15 fb	
Total:	46 fb	

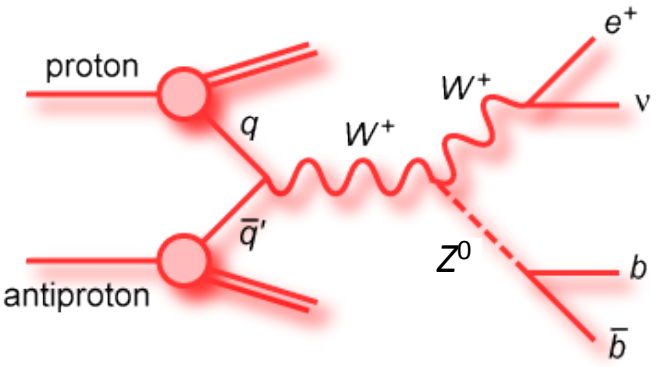
For (W/Z)Z:

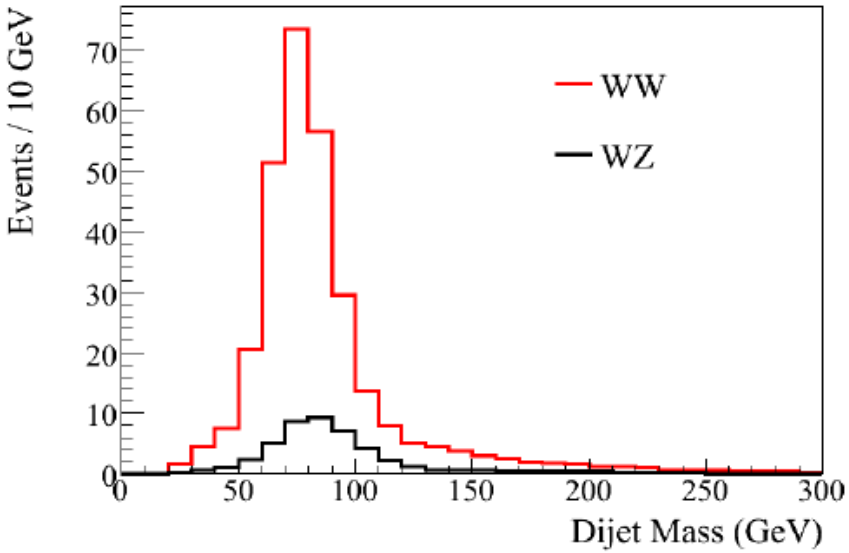
WZ → lνbb:	105 fb	(l=e,μ)
ZZ → llbb :	24 fb	(ll=ee,μμ)
ZZ → ννbb:	73 fb	
Total:	202 fb	

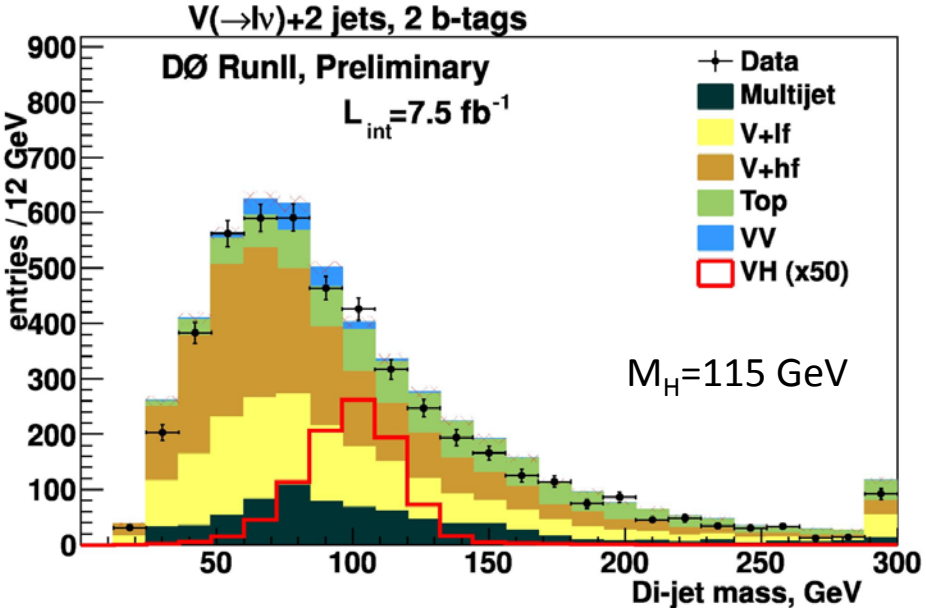
- WZ and ZZ (with Z→$b\bar{b}$): same final states as WH/ZH
  - 4-5 times larger cross section
  - But wait a minute...

WZ/ZZ as Higgs benchmark









Higgs somewhat easier to see than WZ+ZZ (VZ) – we do have handles!

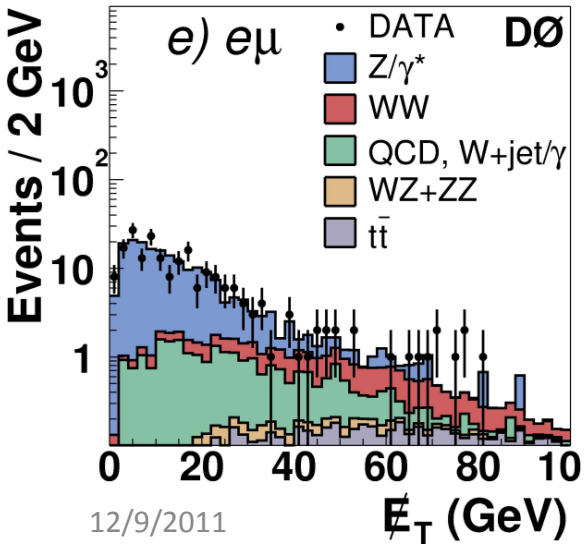
Observing VZ production with Z→bb is the ultimate benchmark!

Dibosons at the Tevatron

- Studies began in Run I (no observations; limits set)
- Observation first in fully leptonic final states: WW→lνlν, WZ→lνll, ZZ→llll
- Clean detector signatures: 2-4 leptons (e,μ), also have large missing transverse energy (MET)

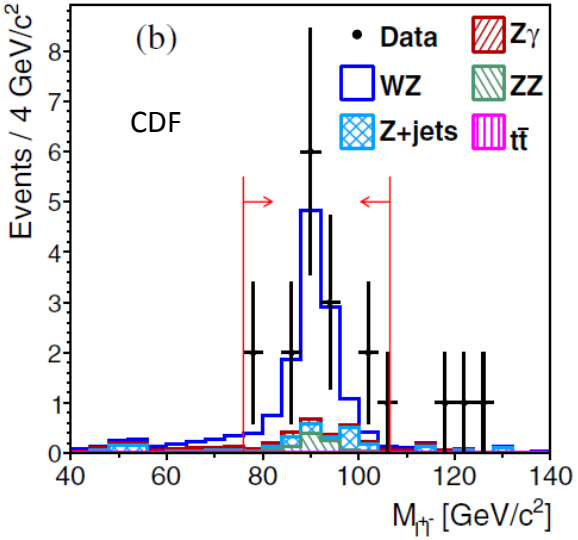
WW

Phys. Rev. Lett. **94** , 151801 (2005)



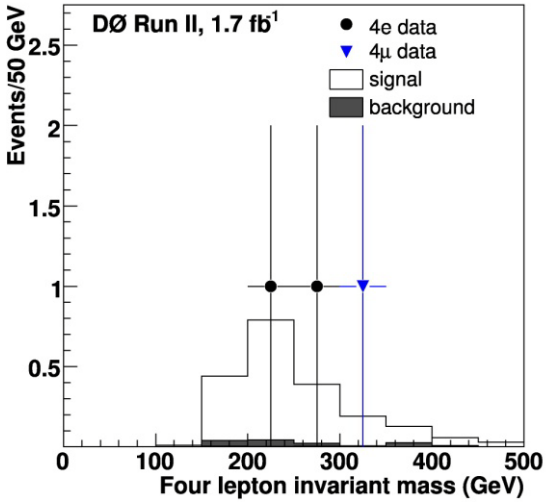
WZ

Phys. Rev. Lett. **98**, 161801 (2007)



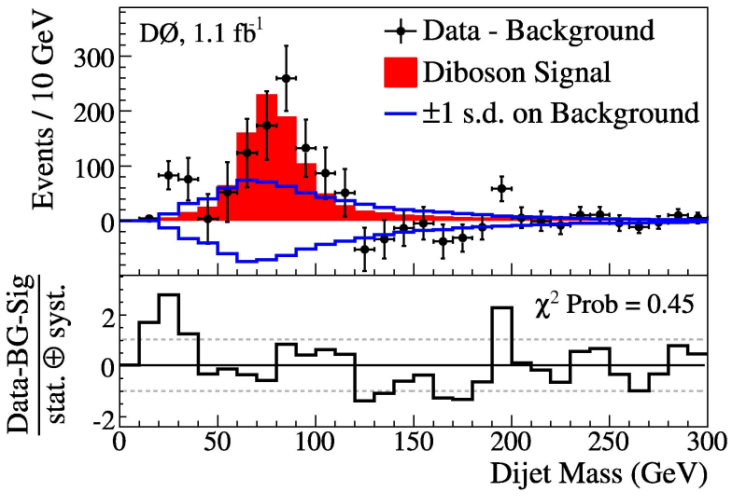
ZZ

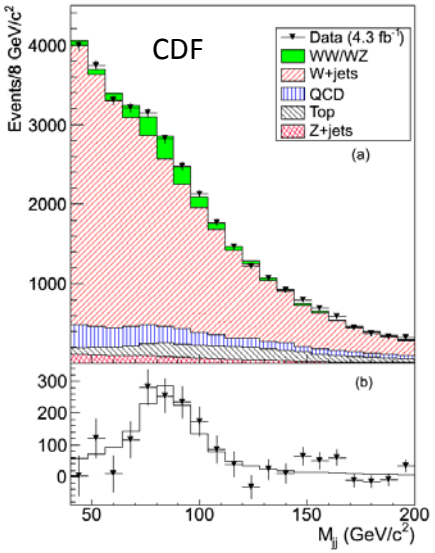
Phys. Rev. Lett. **101**, 171803 (2008)

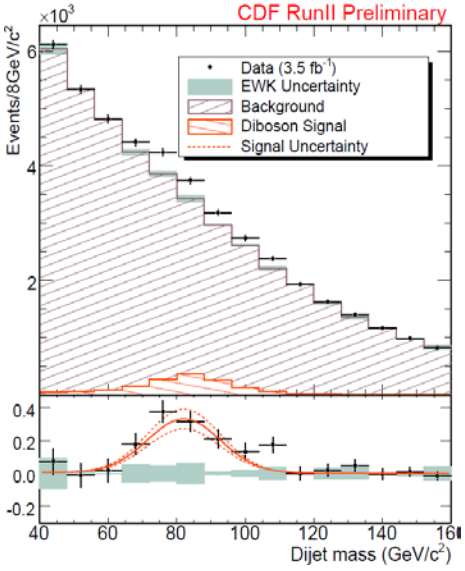


Dibosons in semileptonic states

- Possible final states: lvjj, lljj, vvjj
  - Detector Signatures: lepton+MET+jets, dilepton+jets, MET+jets
- lepton+MET+jets: D0 Evidence (2009), CDF observation (2010)
- MET + jets: CDF observation (2009)
- Cannot separate WW and WZ due to dijet mass resolution







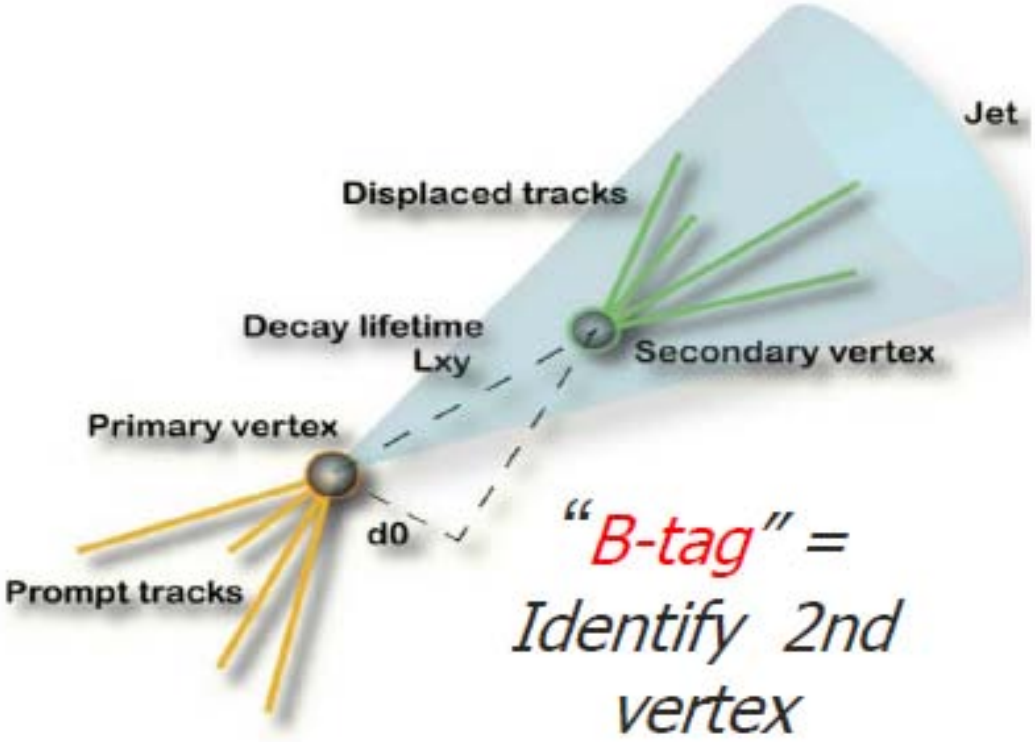
Phys. Rev. Lett. **102**, 161801 (2009) Phys.Rev.Lett. **104**, 101801 (2010) Phys. Rev. Lett. **103**, 091803 (2009)

Separating WW and VZ

- Some handles for discrimination
  - Dijet mass difference? Nope
  - Apply b-tagging to enhance WZ component
  - $B(Z \rightarrow b\bar{b}) \approx 15\%$
- With b-tagging, some care is required
  - Must strike a balance between high statistics and contamination from samples without b-jet, e.g. $W \rightarrow c\bar{s}$
  - Also contributions from $Z \rightarrow c\bar{c}$

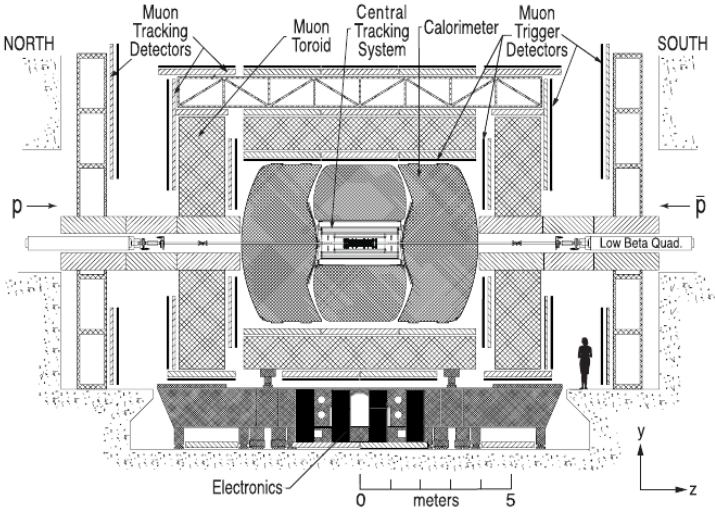
b-tagging at D0

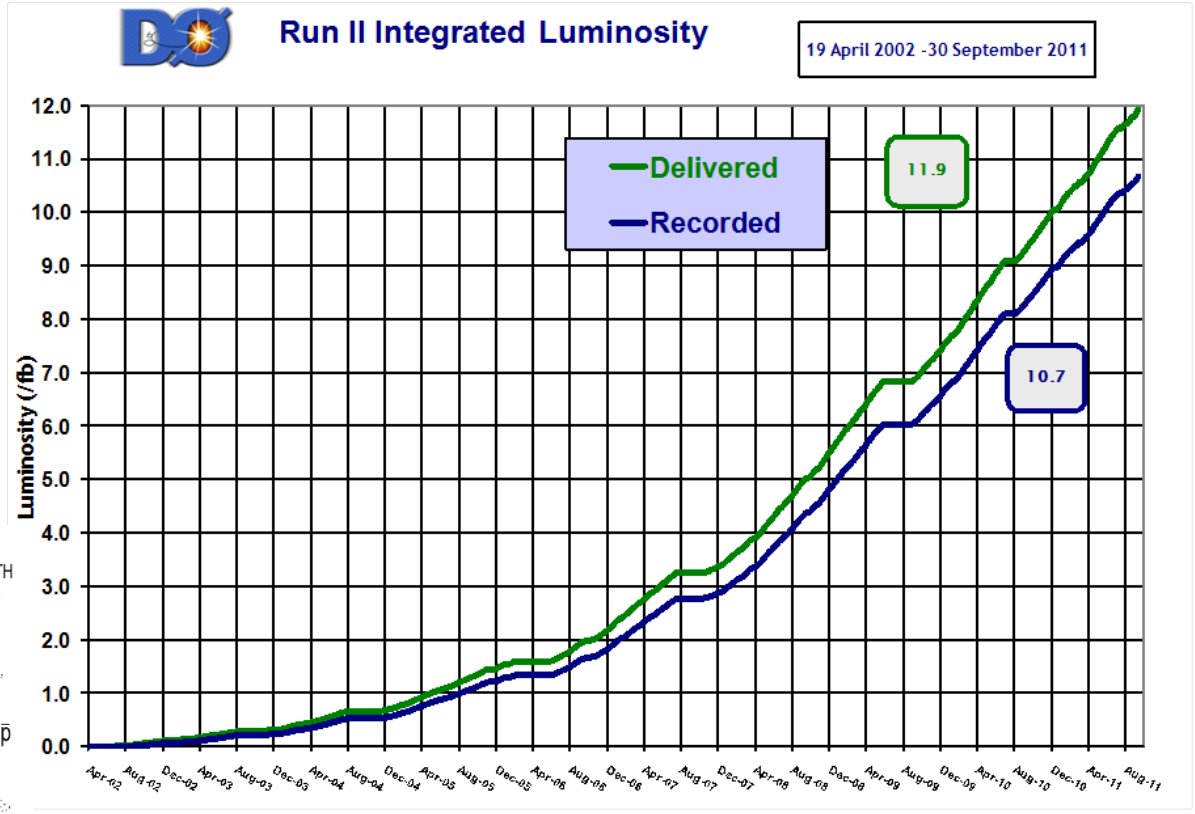
- *B*-hadrons travel millimeters before decay
  - Displaced vertex at decay position
  - Multivariate b-tagger with jet and track variables, impact parameter
  - Typically 50-60% efficient for 0.5-1.5% fake rate



The Tevatron and D0

- **Thanks to the Accelerator Division for their remarkable efforts over the past decade!**

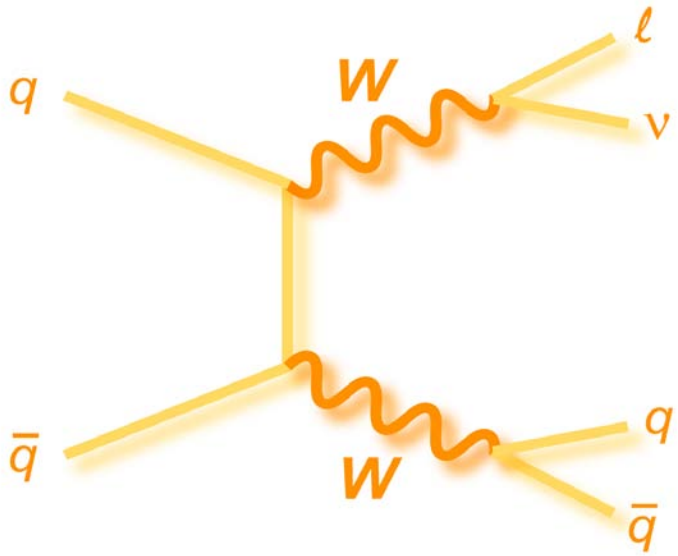


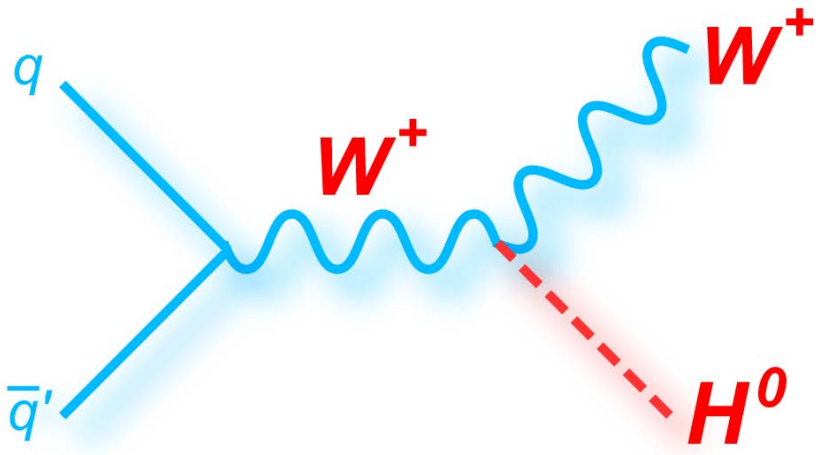


Today's Analyses: 4.3-8.4 fb-1

Signal and Background modeling

- Higgs and diboson: PYTHIA
- Top pair, W+jets, Z+jets: ALPGEN+PYTHIA
- Single top: COMPHEP+PYTHIA
- Multijet backgrounds: analysis-dependent, generally data-driven
-





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- Multijet backgrounds: analysis-dependent, generally data-driven
- TEVNPHWG cross sections for diboson processes:

$$\sigma(W^+W^-) = 11.34^{+0.56}_{-0.49}(\text{scale})^{+0.35}_{-0.28}(\text{PDF})\ \text{pb}$$

$$\sigma(W^\pm Z^0) = 3.22^{+0.20}_{-0.17}(\text{scale})^{+0.11}_{-0.08}(\text{PDF})\ \text{pb}$$

$$\sigma(Z^0Z^0) = 1.20^{+0.05}_{-0.04}(\text{scale})^{+0.04}_{-0.03}(\text{PDF})\ \text{pb}$$

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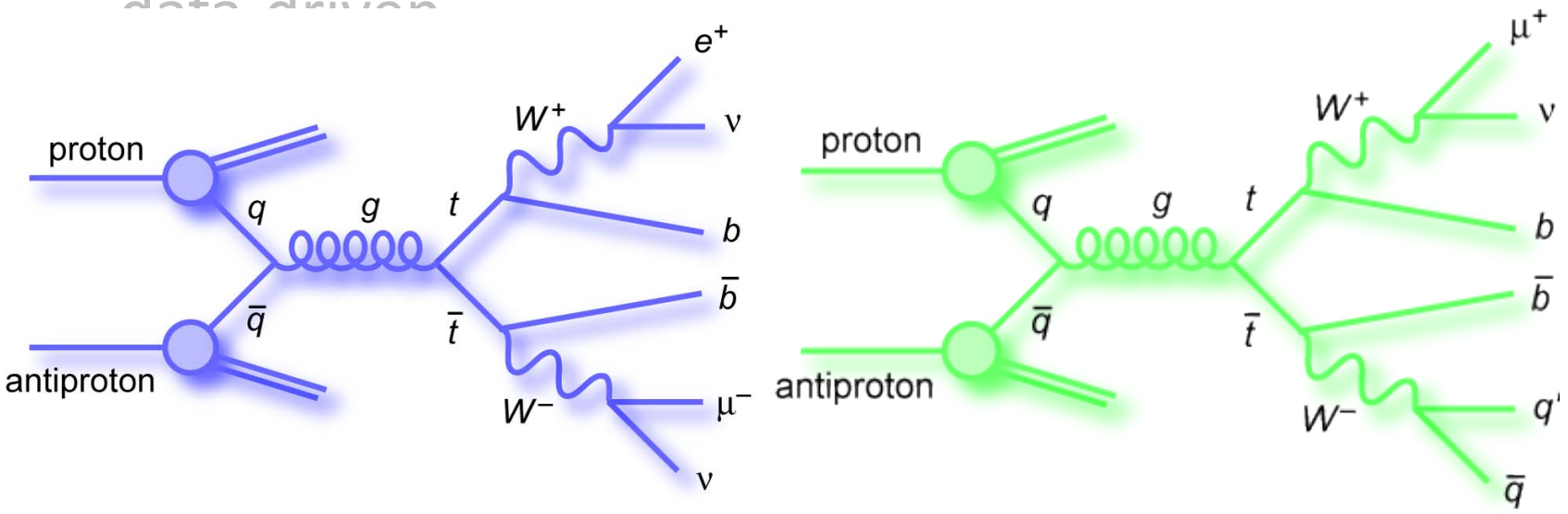

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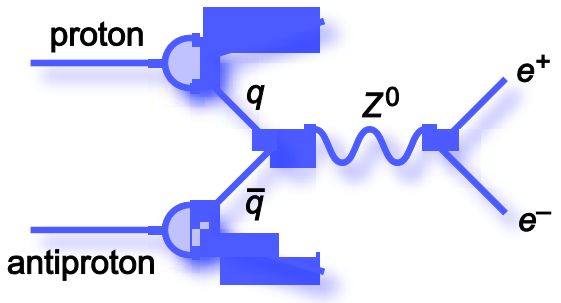

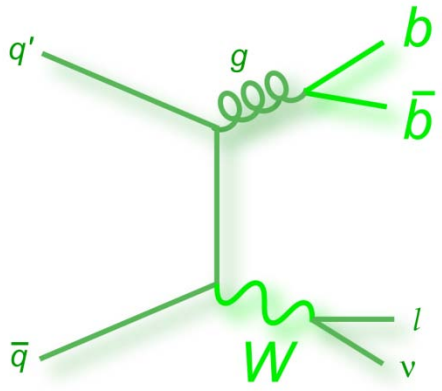

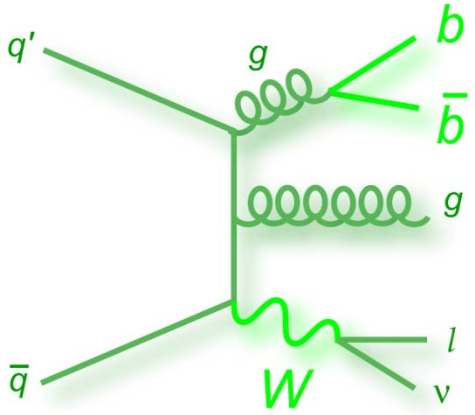

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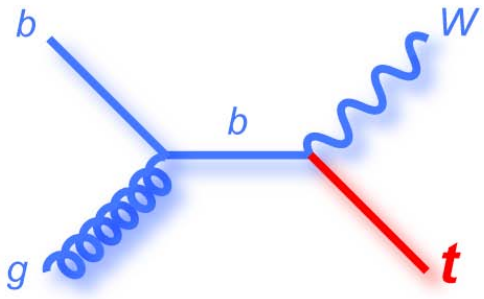

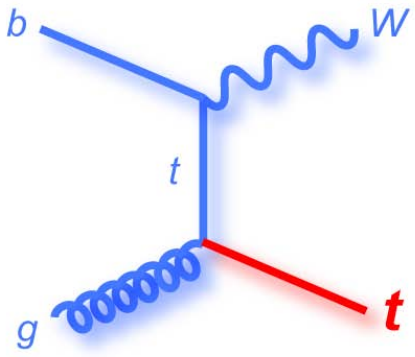

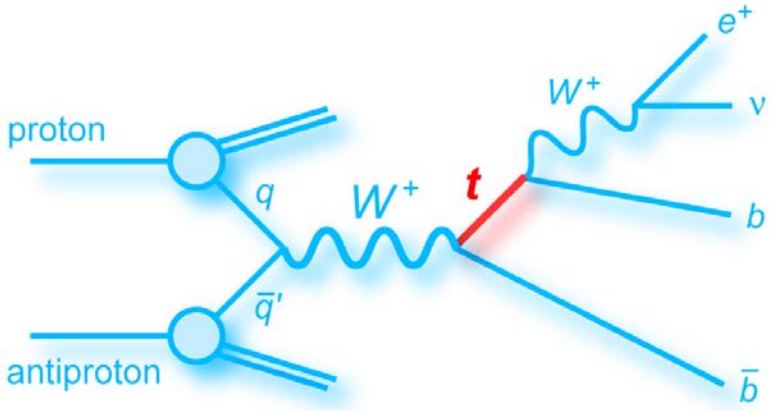

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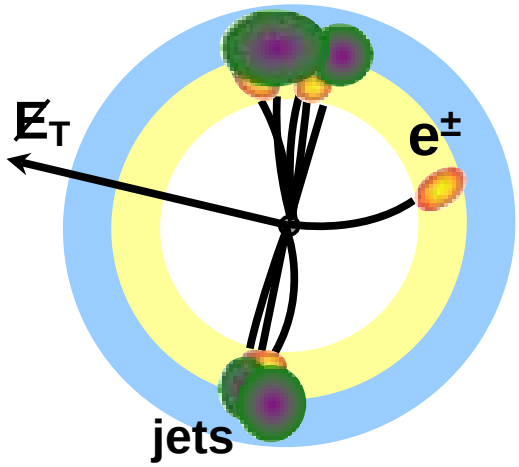
WW/WZ with heavy flavor jets

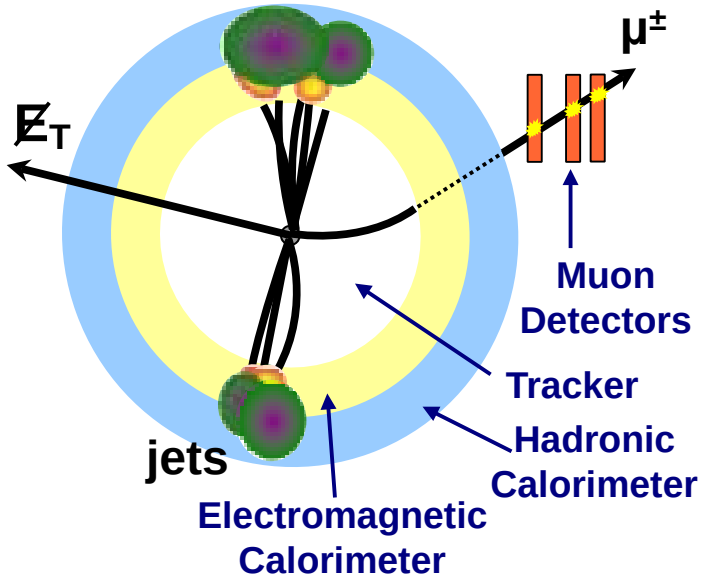
- New D0 Result, 4.3 fb^{-1}

arXiv:1112.0536

SUBMITTED TO PRL

- Event selection: isolated e(μ) with pT > 15(20) GeV, 2 or 3 jets with pT > 20 GeV, Missing transverse energy (MET) > 20, reject events with second lepton





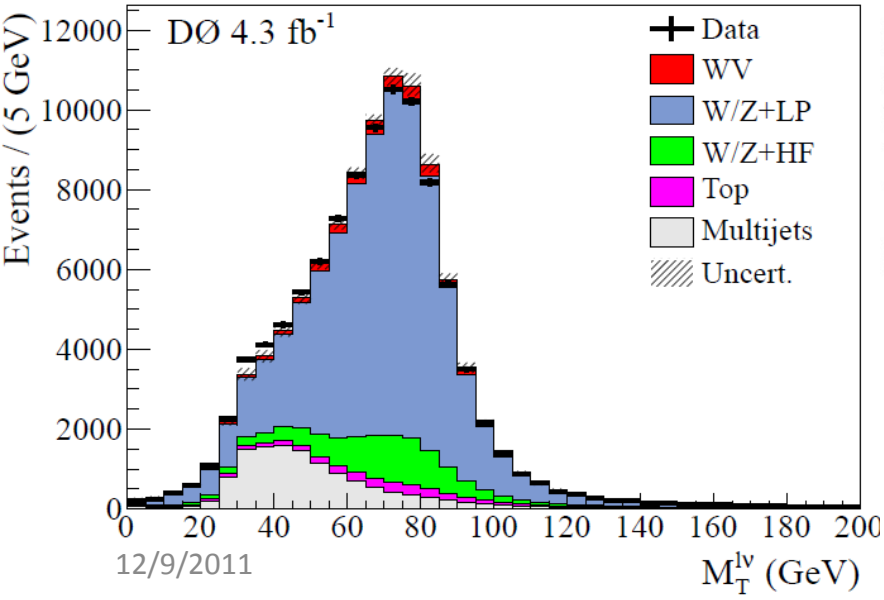
WW/WZ with heavy flavor jets

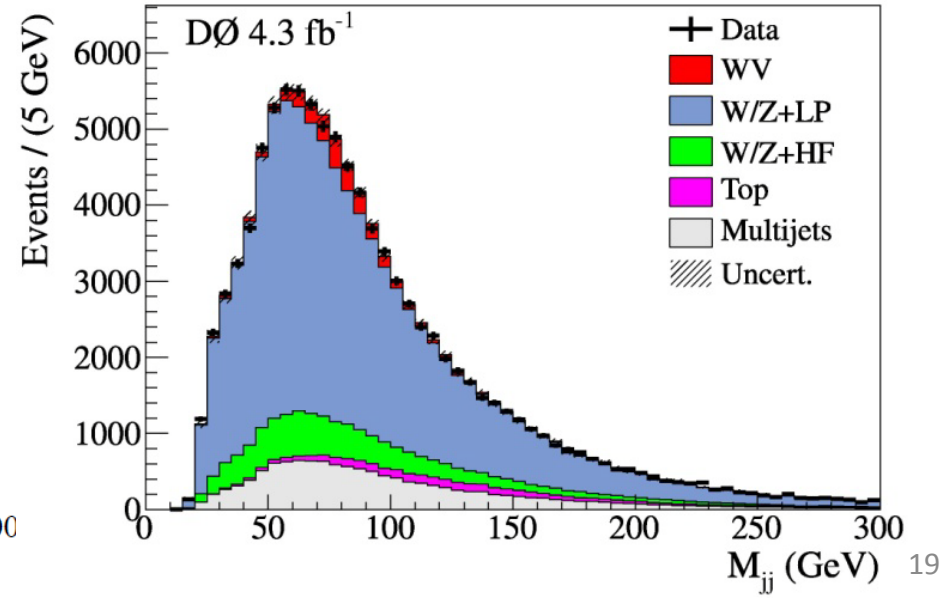
- New D0 Result, 4.3 fb^{-1}

arXiv:1112.0536

SUBMITTED TO PRL

- Event selection: isolated e or μ, 2 or 3 jets, Missing transverse energy (MET), reject events with second lepton
- Triggers: electron and electron+jet (e channel), inclusive mix of muon, muon+jet, MET+jet, multijet triggers (μ channel)
- Multijet background estimated from data in control samples w/non-isolated leptons

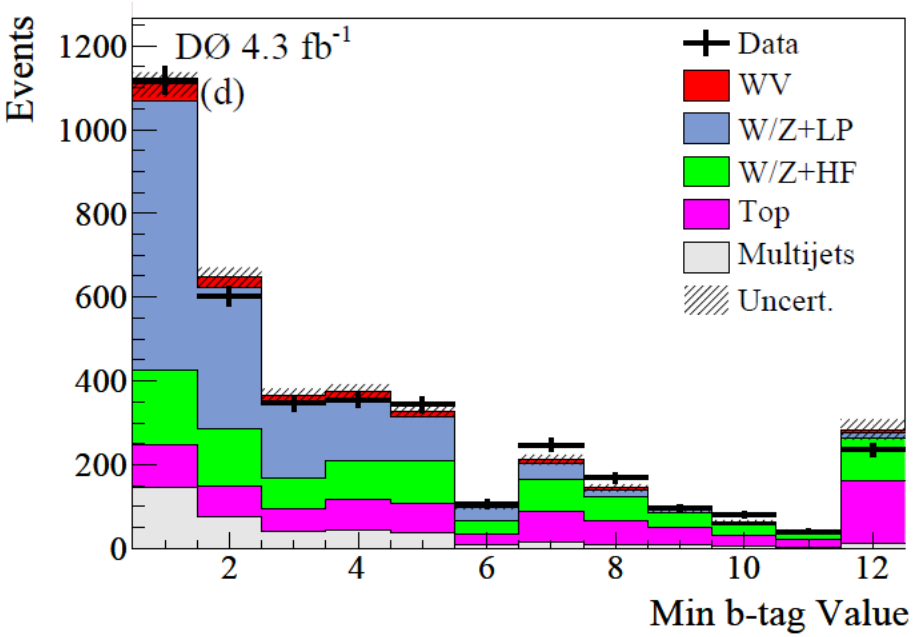


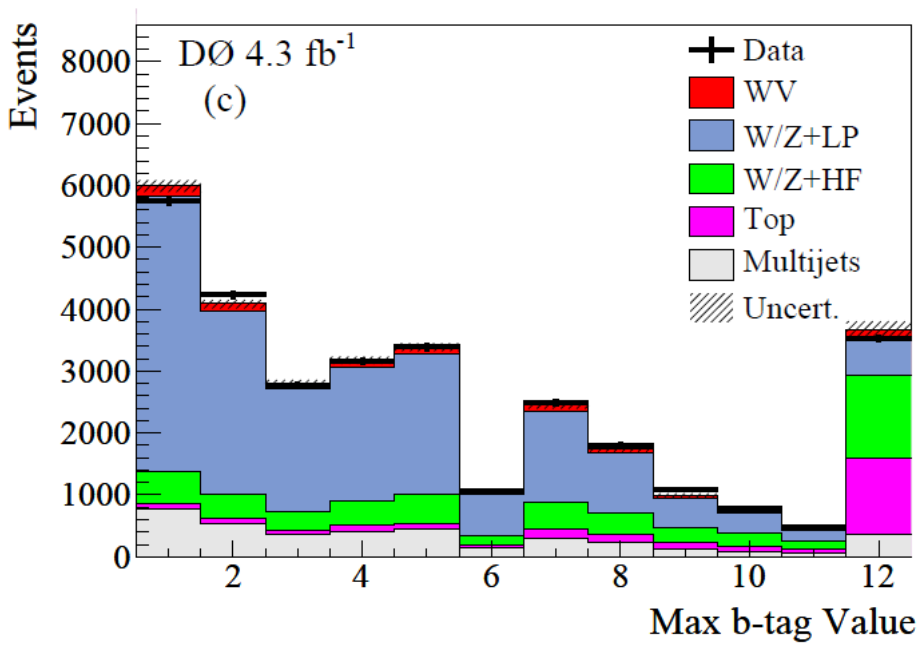


Applying b-tagging

- This analysis: make loosest possible b-tagging cut, place events into three categories
  - no jets passing cut (0-tag)
  - exactly one jet passing cut (1-tag)
  - two or more jets passing cut (2-tag)

Increasing heavy flavor fraction



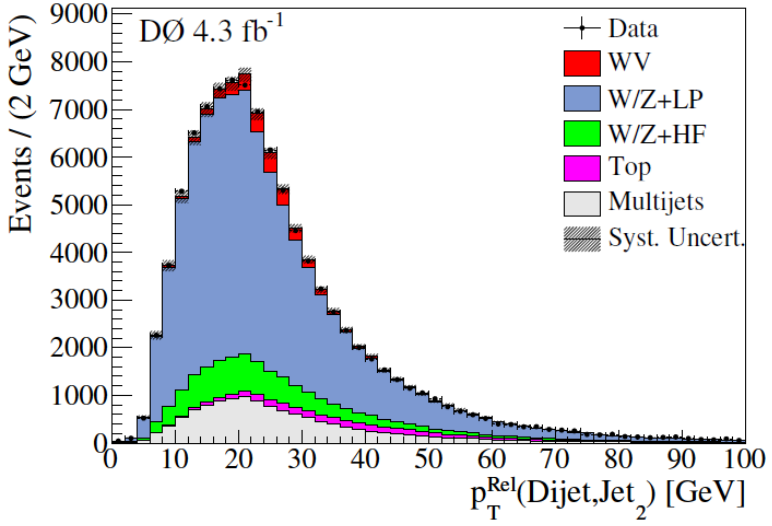


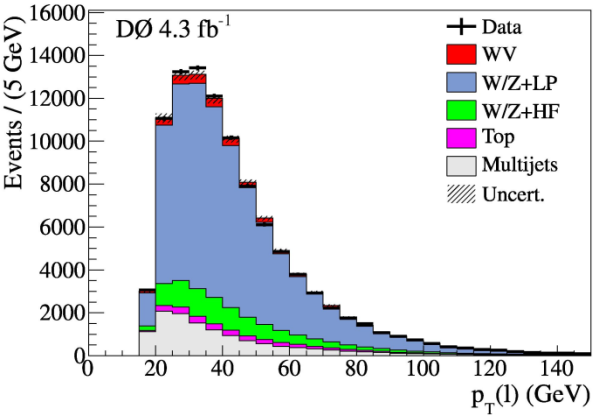
Multivariate Techniques

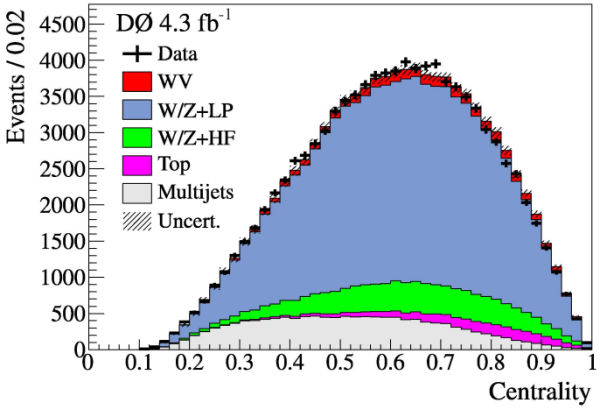
Create Random Forest (RF) for further signal-background discrimination

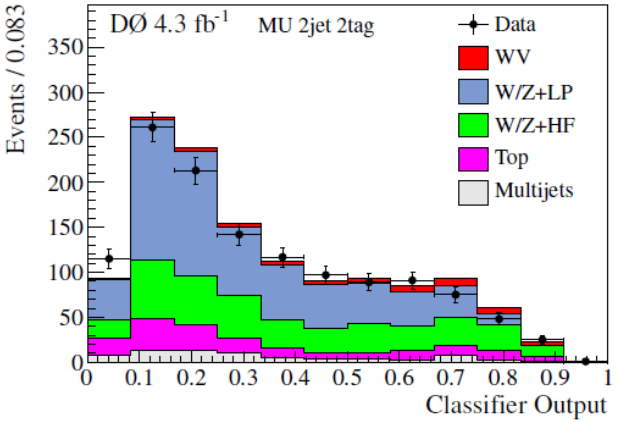
Input: 15 well described variables to separate signal from background (min. and max. b-tag NN output as an input, etc. in backup slides)

- **0-tag**: trained with all dibosons as signal
- **1-tag**: trained with WZ+ZZ as signal
- **2-tag**: trained with WZ+ZZ as signal









Systematic Uncertainties

- Both shape and normalization
- Leading uncertainties: jet energy scale/ID, b-tagging, background cross sections
  - Jet energy scale: changes shape of differential distributions, events can migrate between jet bins
  - b-tagging: affects classification (1-tag vs. 2-tag, etc.), final discriminant shapes
  - Background cross sections affect only normalization of that background
- Low mass Higgs analyses have very similar uncertainties, but relative importance varies from channel to channel

Leading systematics	Signal	W+jets	Z+jets	Top
Jet energy Scale	2-4%	6-8%	4-12%	2-3%
b-tagging	1-5%	1-4%	1-5%	8-10%
Jet energy resolution	2-4%	3-12%	4-10%	1-2%
Cross section	7%	6-20%	6-20%	10%
Luminosity	6.1%	6.1%	6.1%	6.1%

Cross Section Fit

- Perform a fit to data in the Random Forest or Dijet Mass Distributions by minimizing a Poisson χ^2 function with respect to variations in the systematic uncertainties

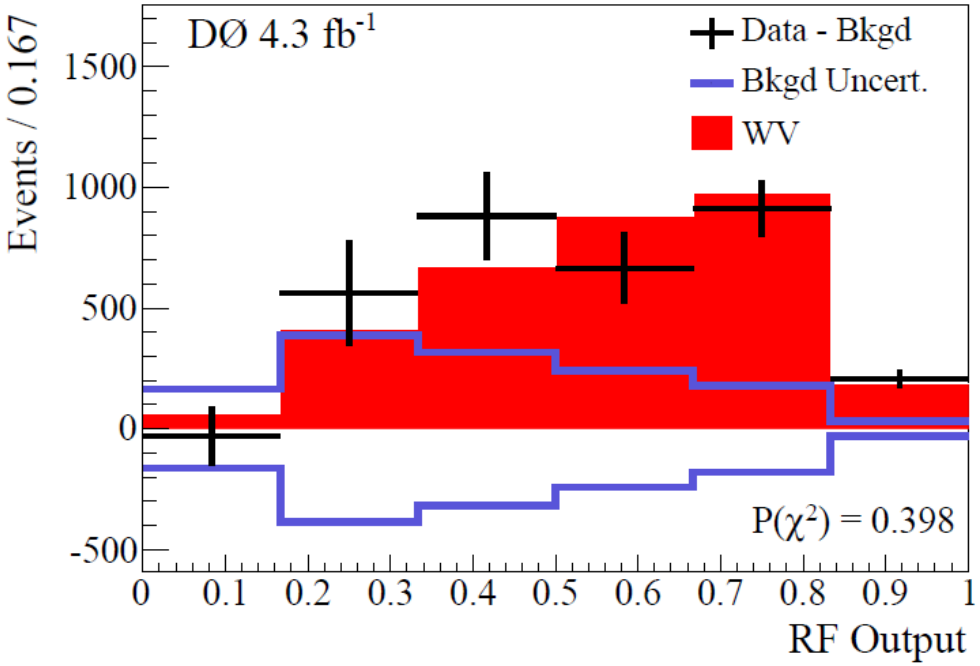
(simultaneous fit of the electron and muon distributions in the 0, 1, and 2-tag sub-channels, and 2- and 3- jet bins)

- W+jets and diboson (WW+WZ) normalizations are free parameters

Yields from the RF fit

	Electron channel	Muon channel
Diboson signal	1725 ± 84	1465 ± 67
W/Z+light-flavor jets	37232 ± 1033	33516 ± 709
W/Z+heavy-flavor jets	5371 ± 608	4854 ± 490
$t\bar{t}$ and single top	1746 ± 127	1214 ± 86
Multijet	10630 ± 1007	1982 ± 384
Total predicted	56704 ± 635	43031 ± 531
Data	56698	43044

ZZ contribution to VV ≈ 1.5%



Cross section fit result

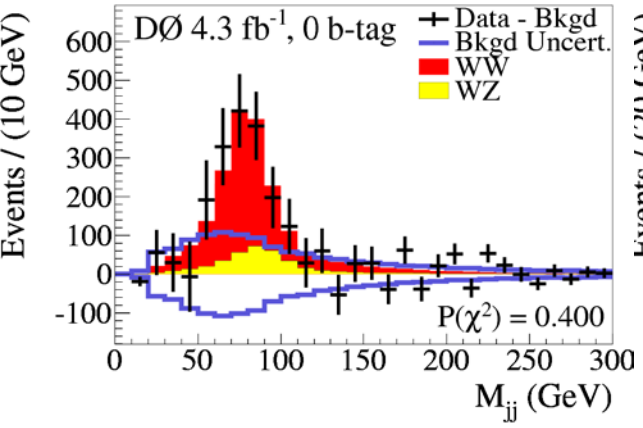
- Measures $\sigma(WV) = 19.6^{+3.2}_{-3.0}$ pb

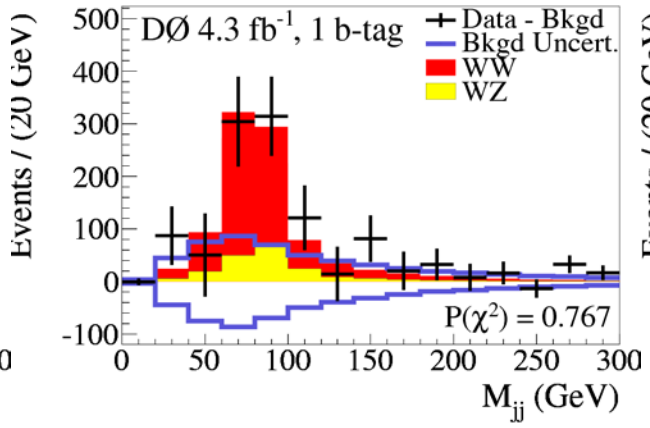
  → $\sigma(WV)_{SM} = 14.6$ pb

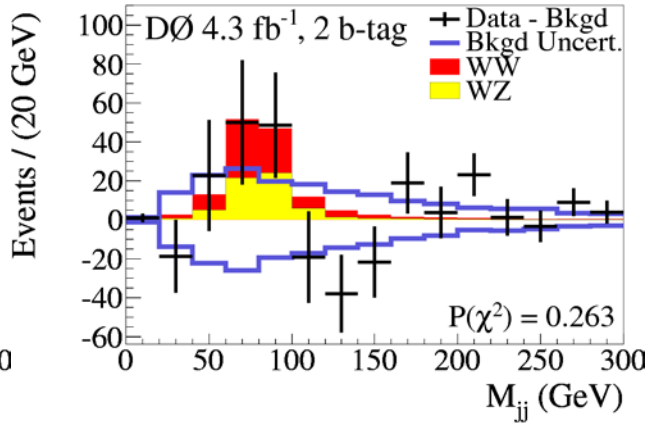
- Simultaneous fit of WW and WZ:

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

$\sigma(W^+W^-)_{SM} = 11.34$ pb $\qquad$ $\sigma(W^{\pm}Z^0)_{SM} = 3.22$ pb







Simultaneous WW/WZ fit

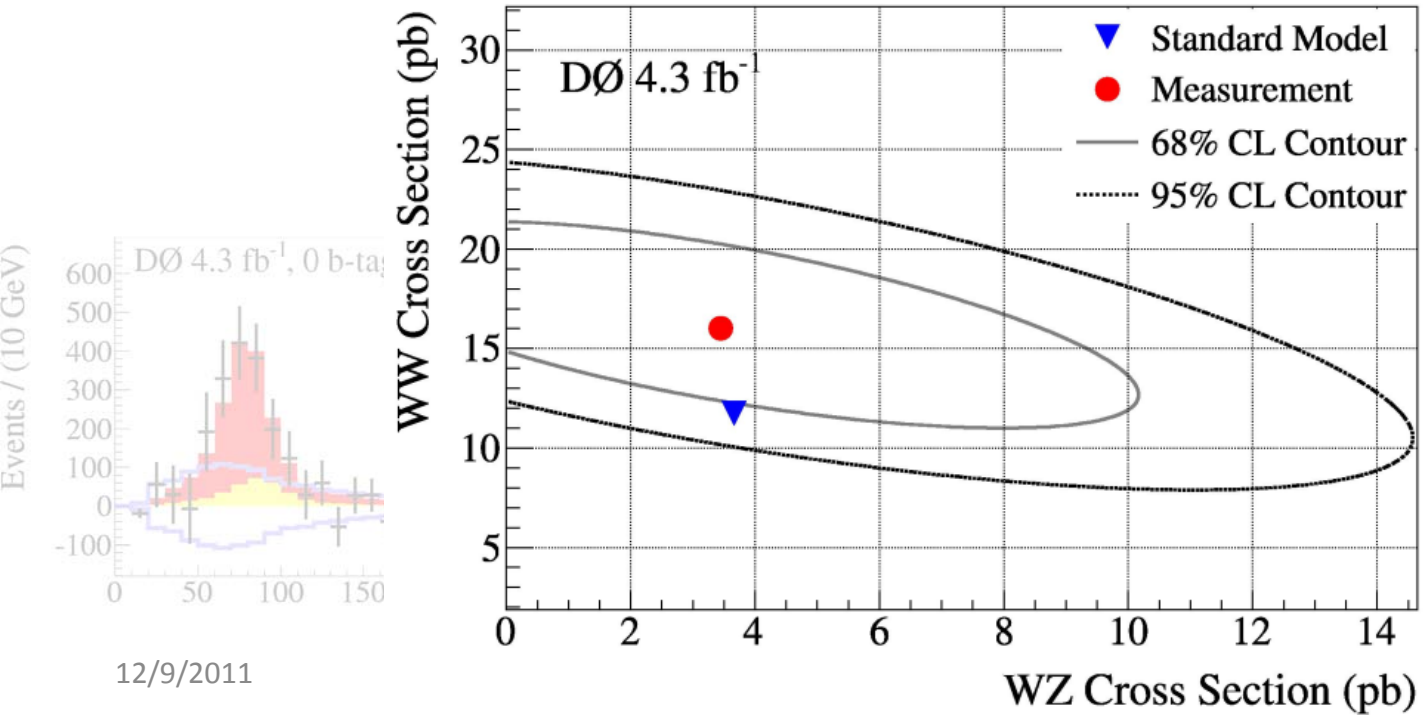
- Measures $\sigma(WV) = 19.6^{+3.2}_{-3.0}$ pb

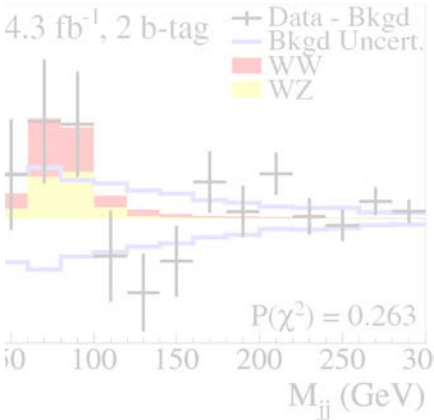
  → $\sigma(WV)_{SM} = 14.6$ pb

- Simultaneous fit of WW and WZ:

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

$\sigma(W^+W^-)_{SM} = 11.34$ pb $\quad$ $\sigma(W^{\pm}Z^0)_{SM} = 3.22$ pb



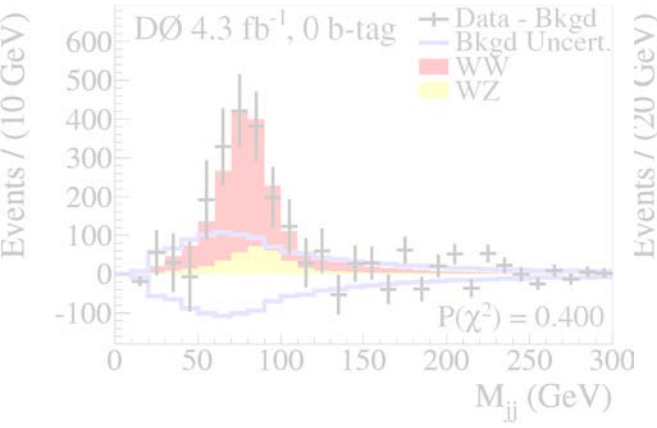


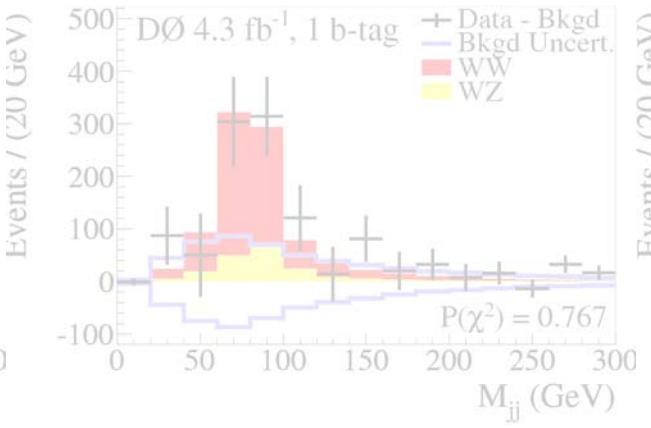
WW/WZ with heavy flavor jets

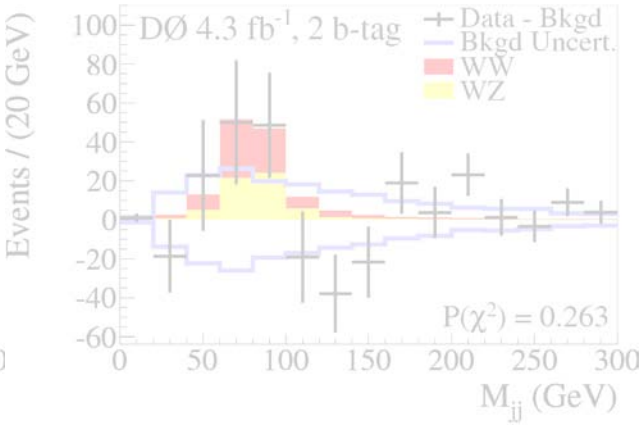
- Fix WW to SM and fit WZ cross section:

$$\sigma(WZ) = 6.5 \pm 0.9(\text{stat.}) \pm 3.0(\text{syst.})\ \text{pb}$$

2.2 (1.2)σ Observed (Expected) significance

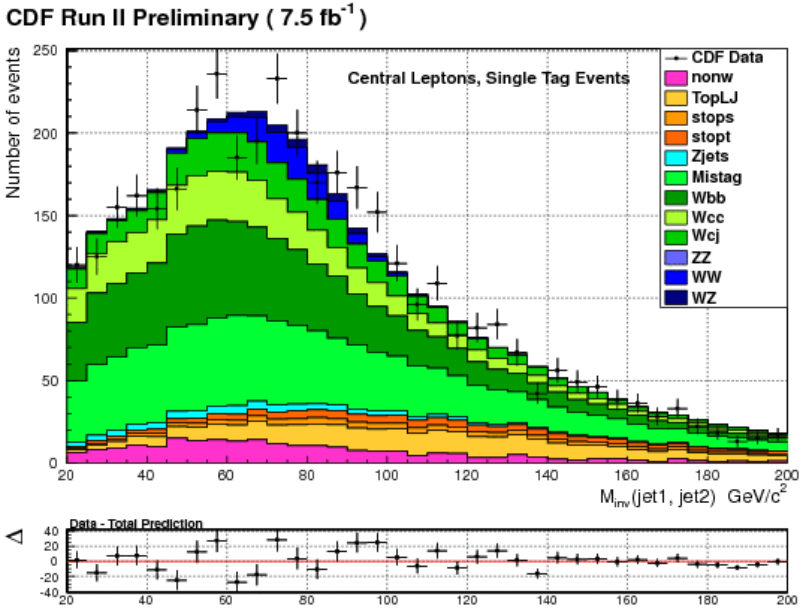


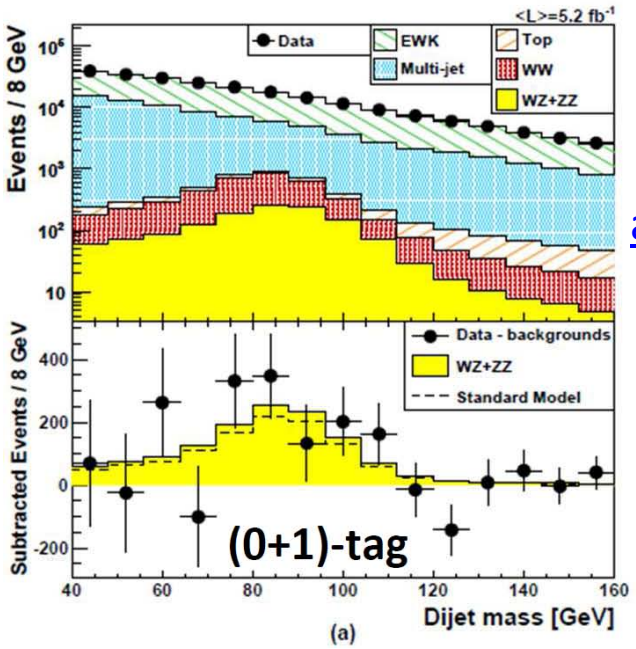




More Dibosons with b-tagging

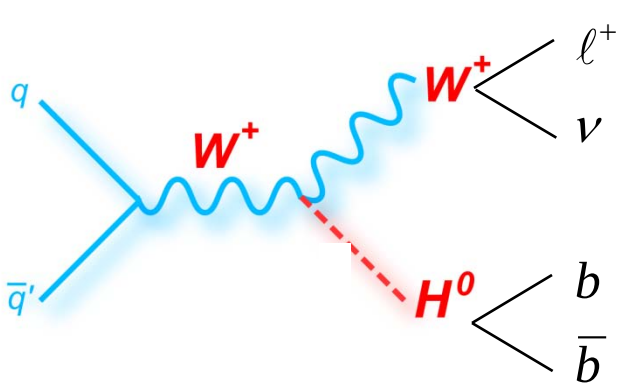
- CDF result in the lvjj final state
  - 1-tag and 2-tag channels
  - Fix WW/WZ ratio to SM value, fit with dijet mass
  - Measure 1.1 x SM cross section
  - Main contribution still from WW→lvcs
- CDF results in MET+jets final state, 0,1,2-tag channels
  - allow up to 1 lepton
  - Measure $1.1\ ^{+0.7}_{-0.6}$ times SM WZ+ZZ cross section
  - Significance: 1.9σ observed, 1.7σ expected

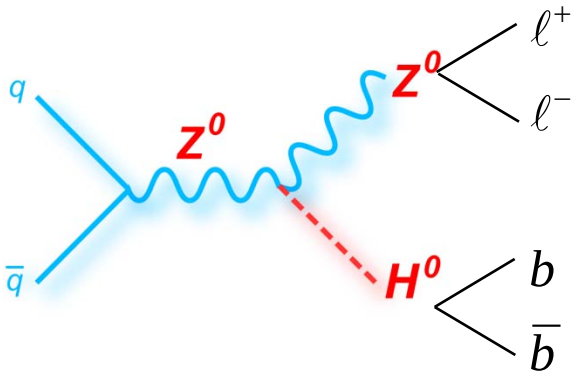


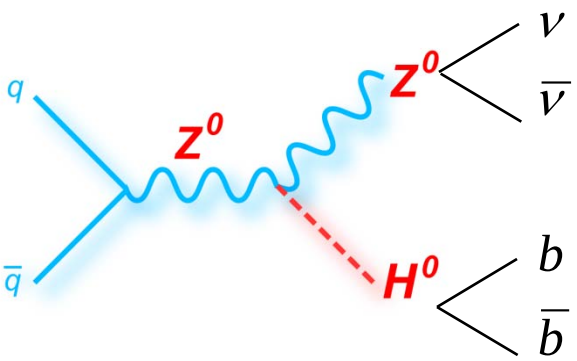


arXiv:1108.2060

D0 low-mass Higgs Searches

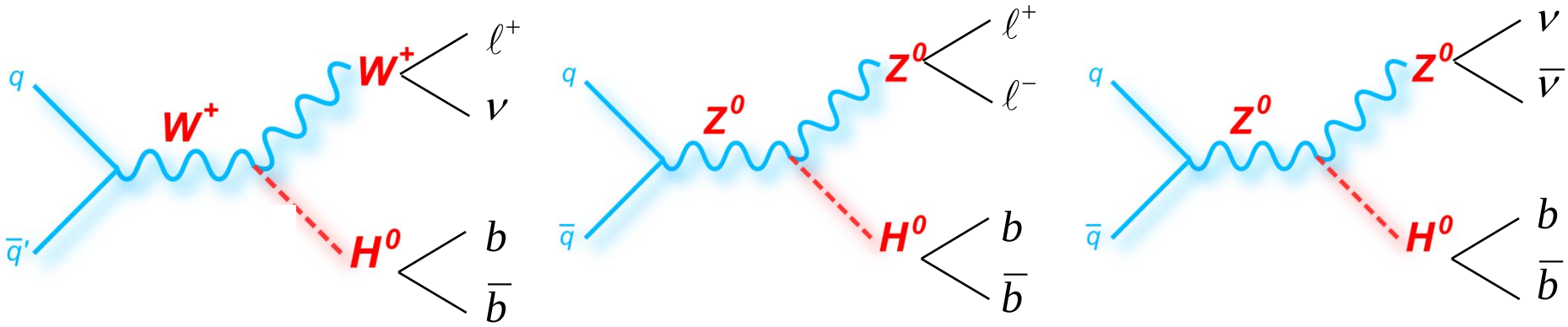






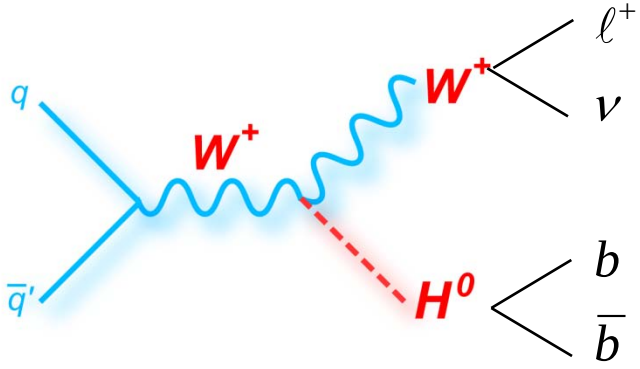
D0 low-mass Higgs Searches

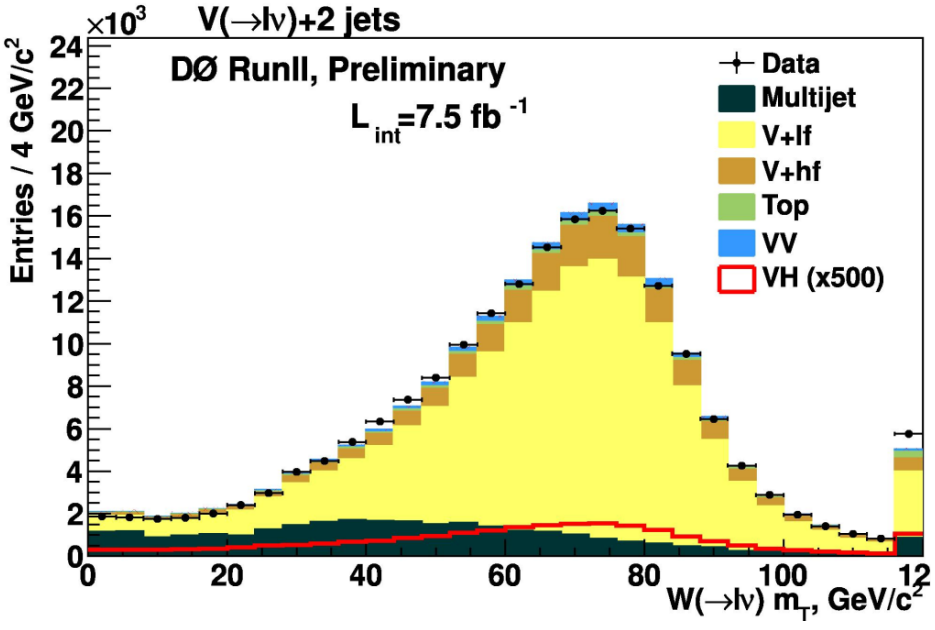
- 3 analyses: lvbb, llbb, vvbb
- General strategy:
  - V+jets preselection (lepton + MET+jets, dilepton, large MET + jets)
  - Multijet background modeling and rejection
  - apply b-tagging (split into 1-tag and 2-tag channels; improves purity and increases sensitivity)
  - identify variables with good signal-background separation, train multivariate technique with them
  - Orthogonality maintained through appropriate lepton vetoes

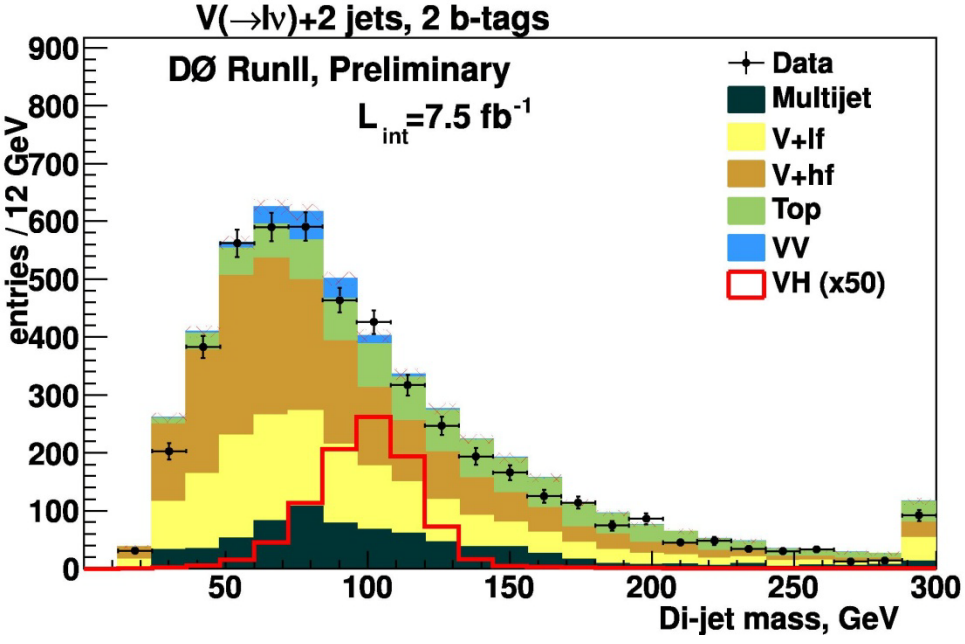


WH→lνbb

- Highest cross section with accessible final state for low-mass searches
- Signature: one isolated lepton(e,μ), missing transverse momentum (MET), and 2 jets
- Selection very similar to aforementioned WW/WZ analysis
  - Multijet rejected with dedicated multivariate discriminant in the electron channel

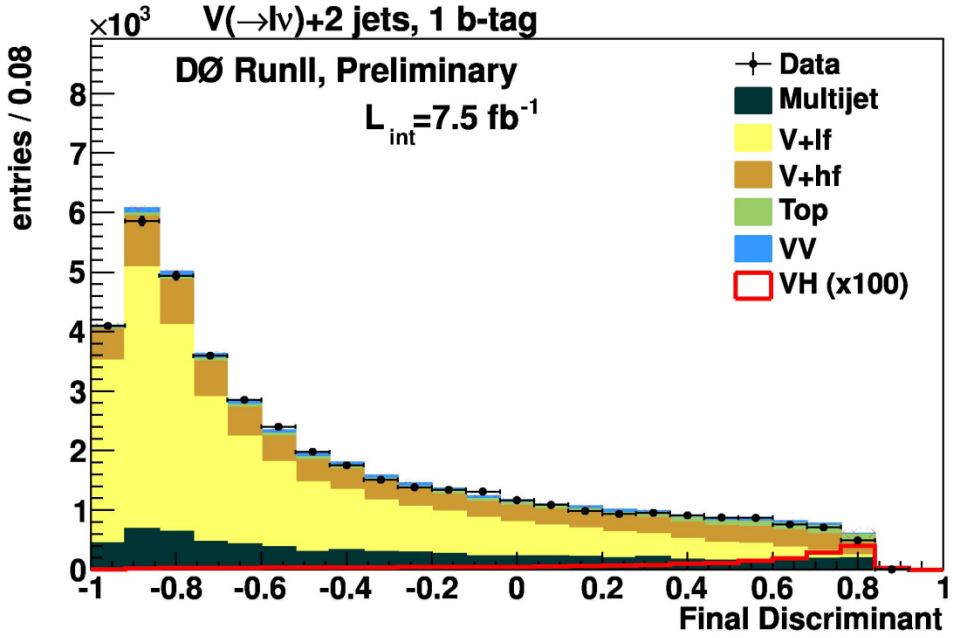


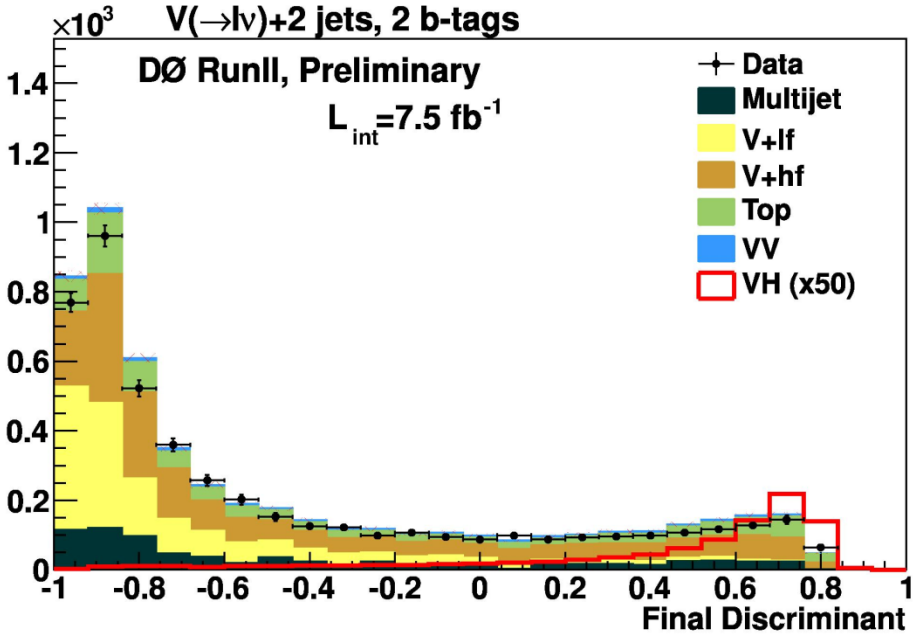




WH→lνbb

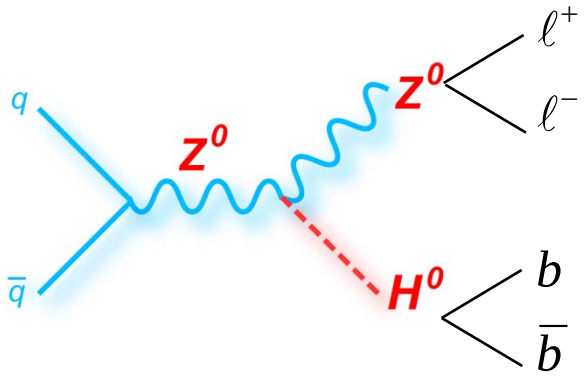
- Boosted Decision Tree (BDT) as Final Discriminant
- Include b-ID output information as input to BDT

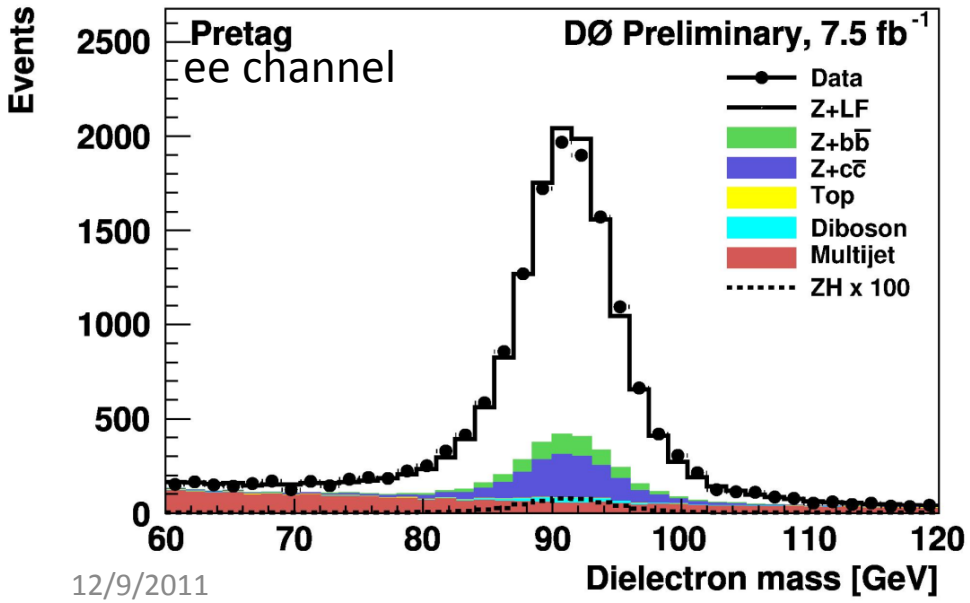


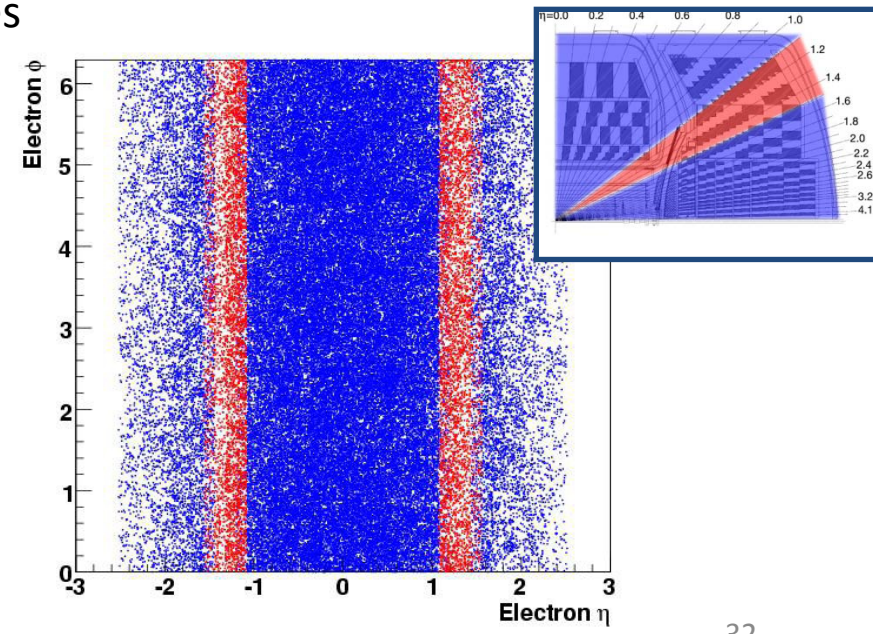


ZH→llbb

- Event selection: two isolated leptons consistent with the Z mass, two or three jets, trigger with lepton, lepton+jet, multijet, dilepton triggers
- Special selections to recover leptons that pass through gaps in detector coverage
- Leading backgrounds: Z+jet, multijet
- Normalize simulation to the Z-peak in data before applying b-tagging
  - Removes 6% integrated luminosity uncertainty!
  - Constrains lepton identification uncertainties



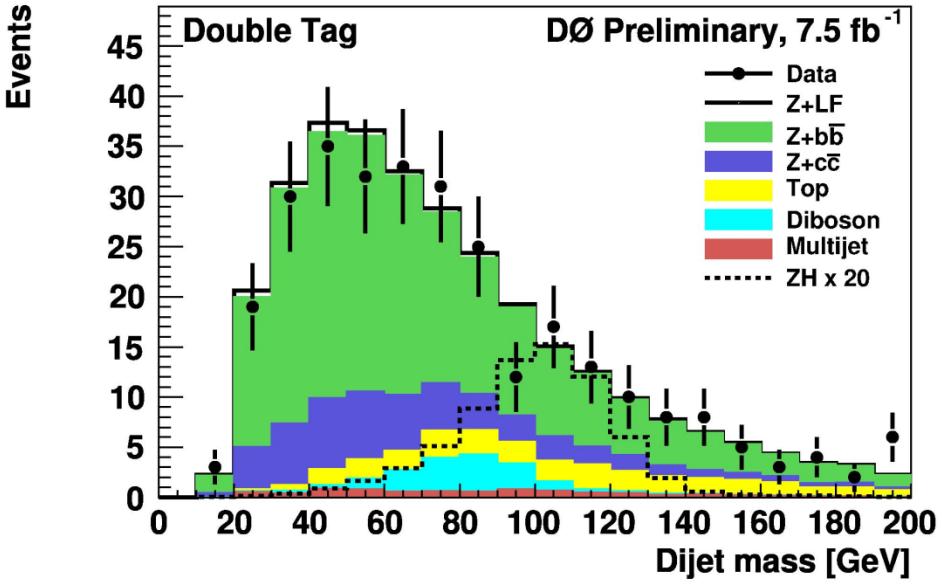




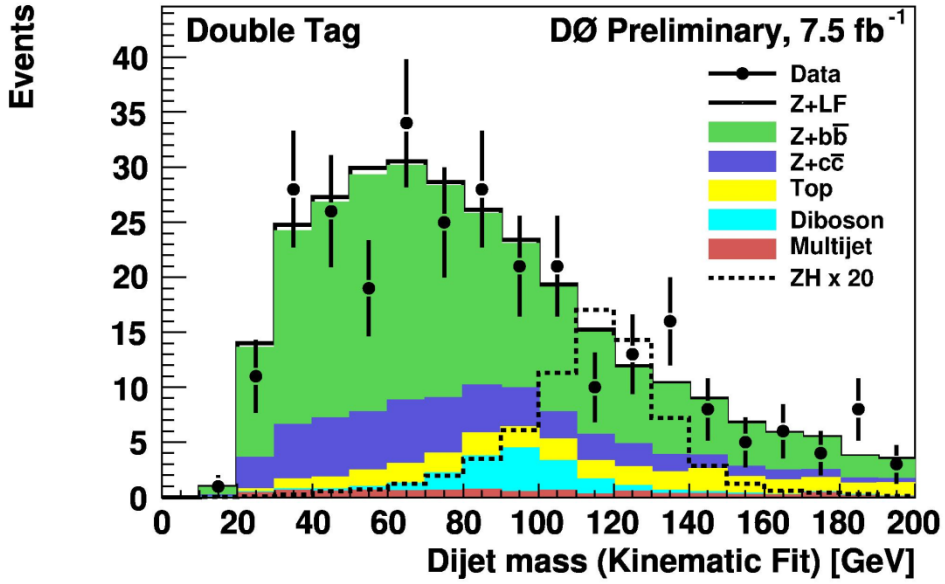
ZH→llbb

- Fully reconstructed final state allows for kinematic fitting
  - Adjust jets/leptons with likelihood fit to constrain M_{ll} to mass/width of the Z, and total p_T of the lljj system to be consistent with ZH spectrum

Before Fit

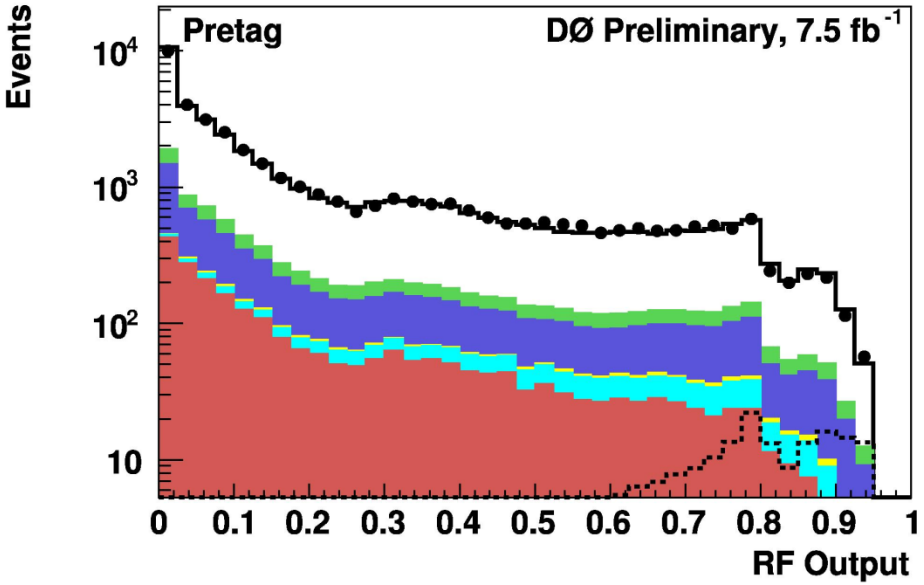


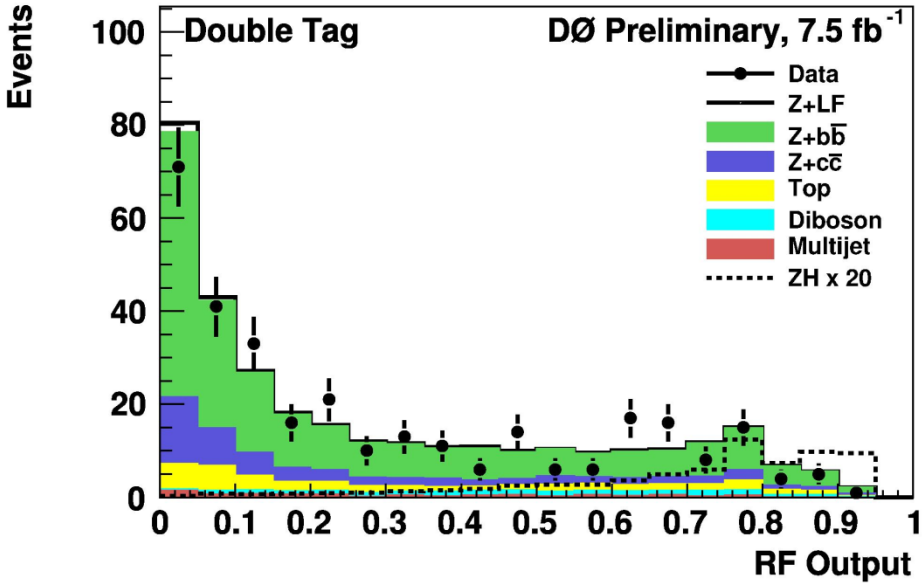
After Fit



ZH→llbb

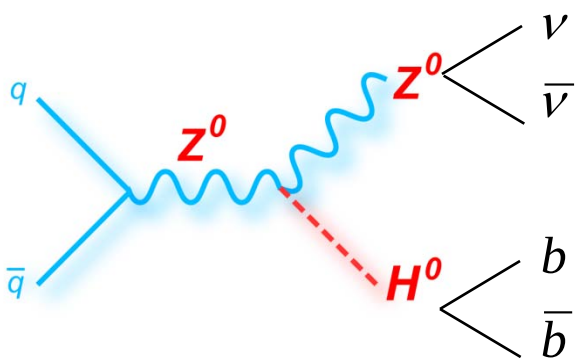
- Fully reconstructed final state allows for kinematic fitting
  - Adjust jets/leptons with likelihood fit to constrain M_{ll} to mass/width of the Z, and total p_T of the lljj system to be consistent with ZH spectrum
- Apply b-tagging (somewhat tighter than WH)
- Train a multivariate discriminant (Random Forest)

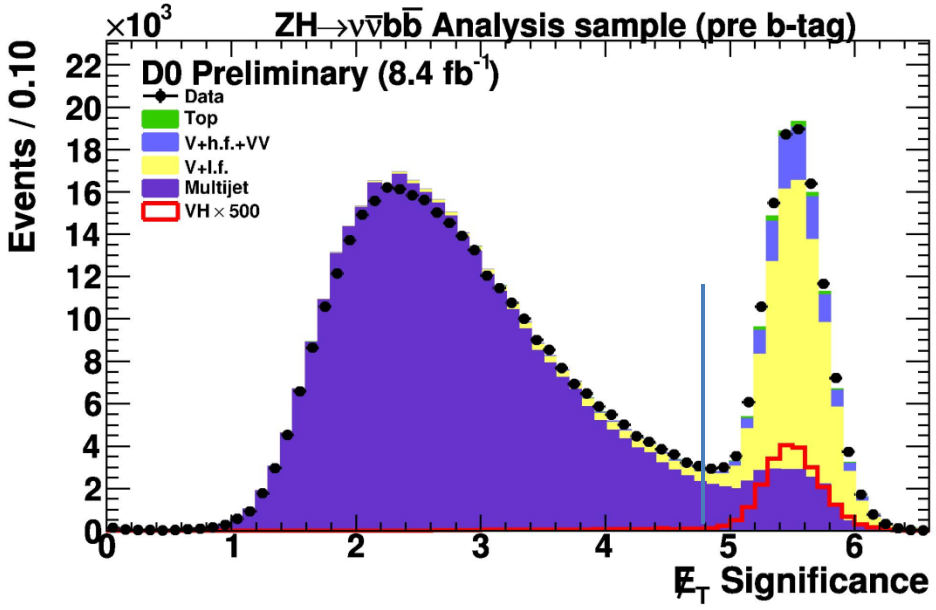




ZH→ννbb

- Larger *Z* branching ratio, but large backgrounds (Z+jet, multijet)
- Basic event selection: 2 jets (not back-to-back in transverse plane), large MET > 40 GeV
- Trigger with MET + jet triggers
- MET significance provides strong background rejection

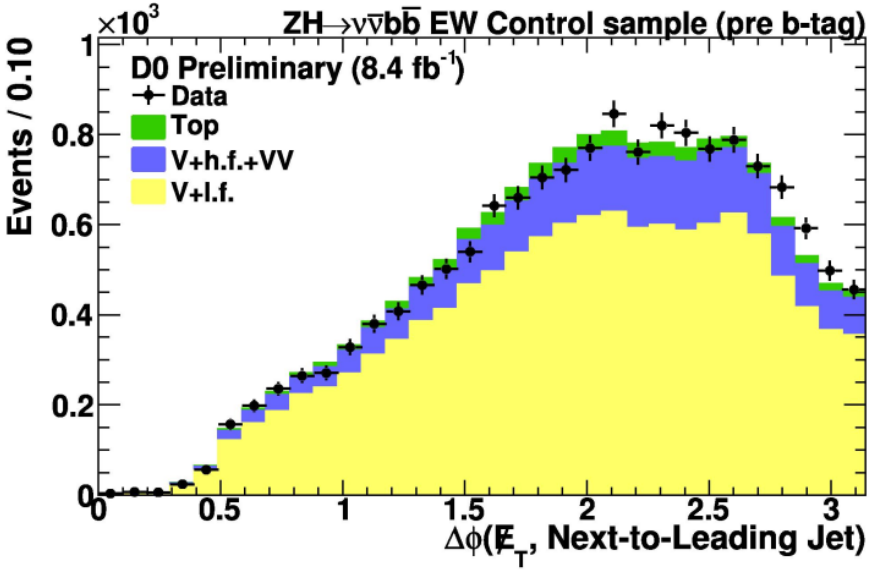


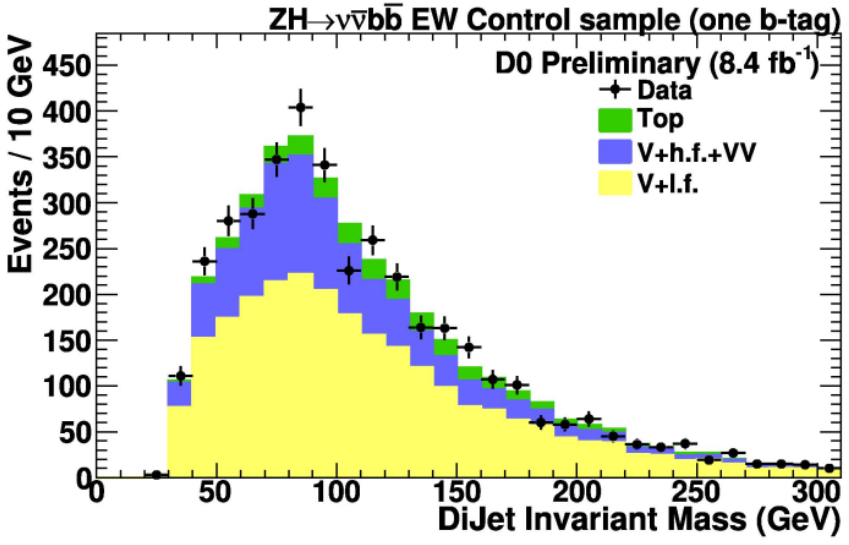


Control samples created to study and validate electroweak and multijet background modeling

ZH→ννbb

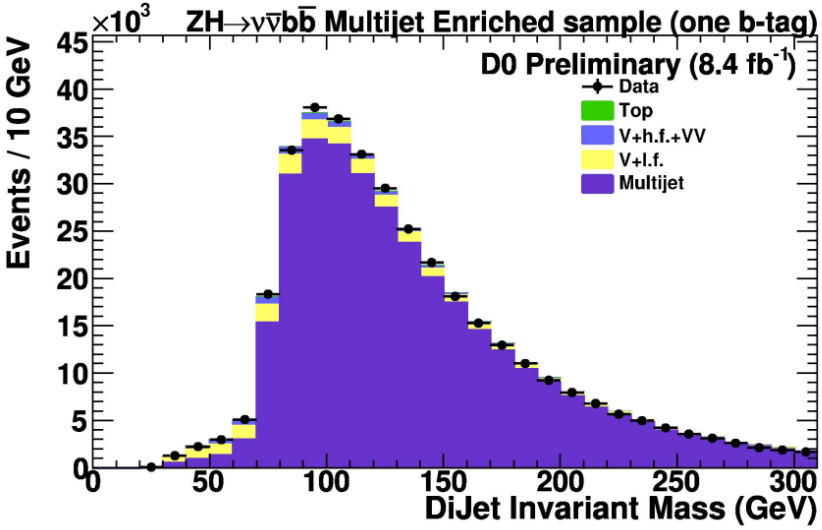
- Electroweak control sample: require isolated muon, muon-MET transverse mass consistent with W boson
- Use for verification of EW sample modeling, derivation of reweighting function ($\Delta\eta$ between jets) for Alpgen samples (based on Sherpa)

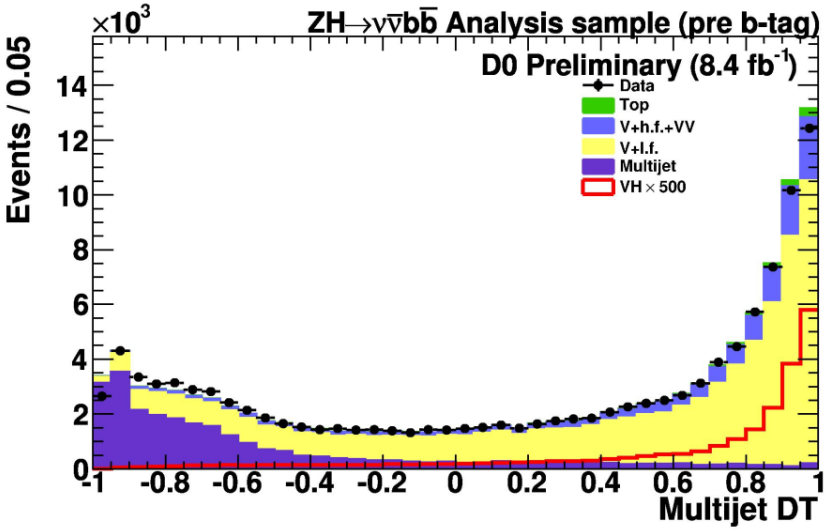




ZH→ννbb

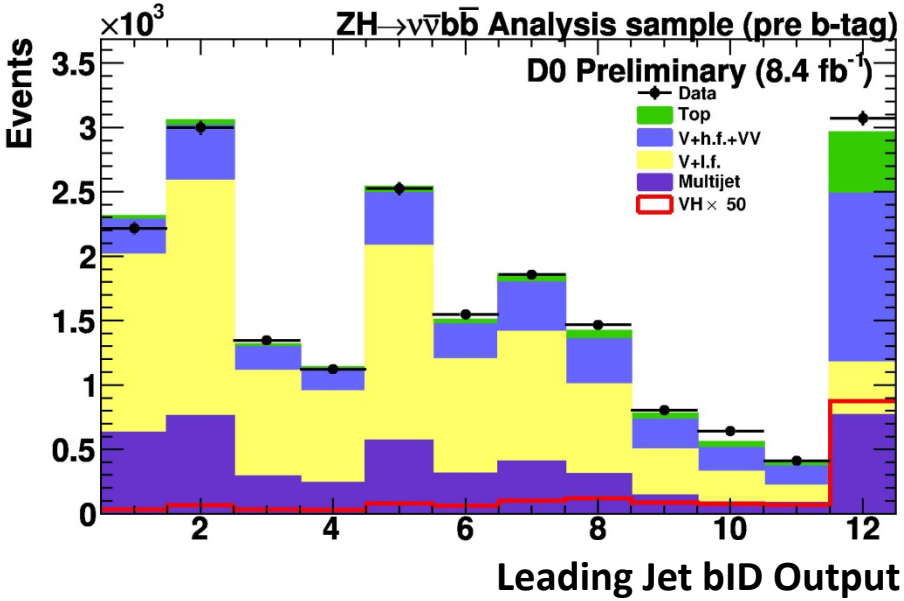
- Multijet samples: Modeling and validation regions
- Used for checking multijet modeling in main analysis sample
- Train Decision Tree (DT) against multijet background

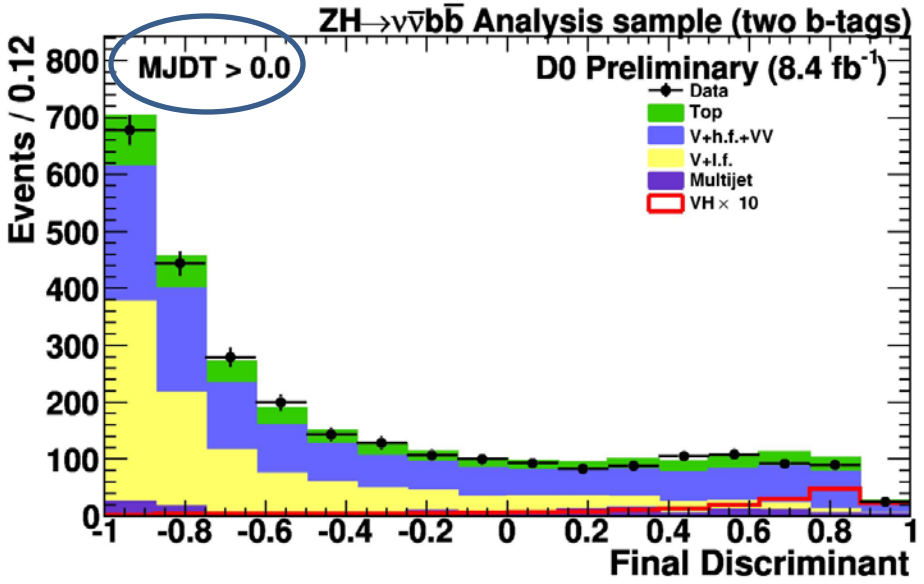




ZH→ννbb

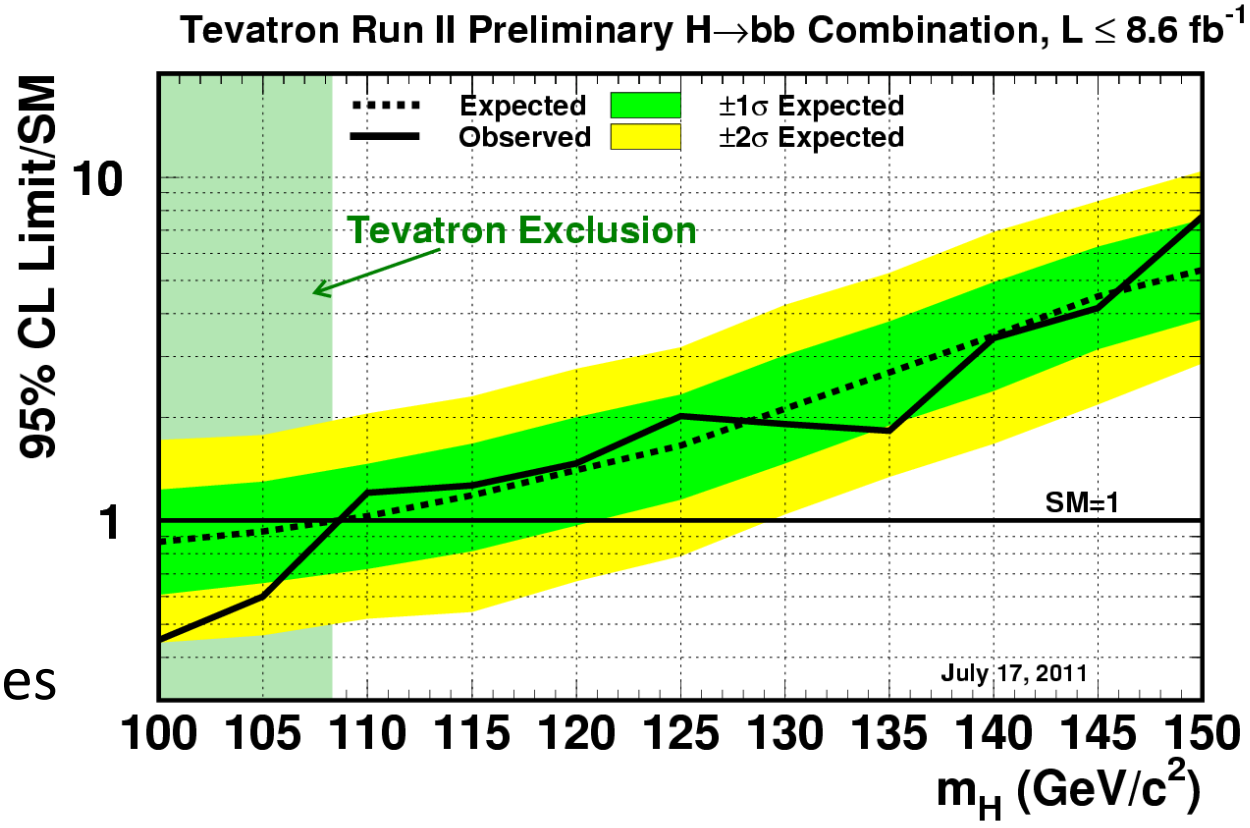
- Create final "analysis" sample
  - cut on multijet DT, feed surviving events to Final BDT Discriminant
  - Also include b-ID output as input variable to Final Dsicriminant
- Separate training for 1 and 2 tag channels and each Higgs mass point (also in lvbb and llbb)





Summer 2011 Higgs combination

- All analyses part of Summer 2011 Tevatron Combination first shown at EPS



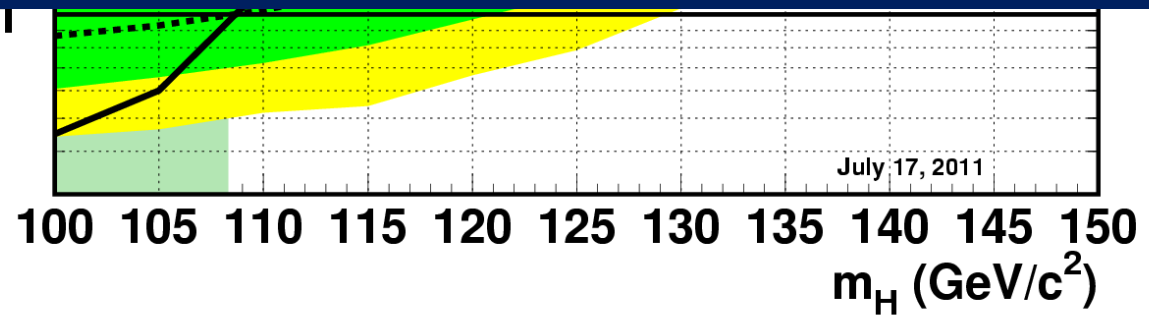
CDF + D0
bbar searches

Summer 2011 Higgs combination

- All analyses part of Summer 2011 Tevatron Combination first shown at EPS

Very close to saying something very interesting at low mass!
It's a good idea to validate the searches just presented by showing the methods can work elsewhere...

CDF + D0
bbar searches



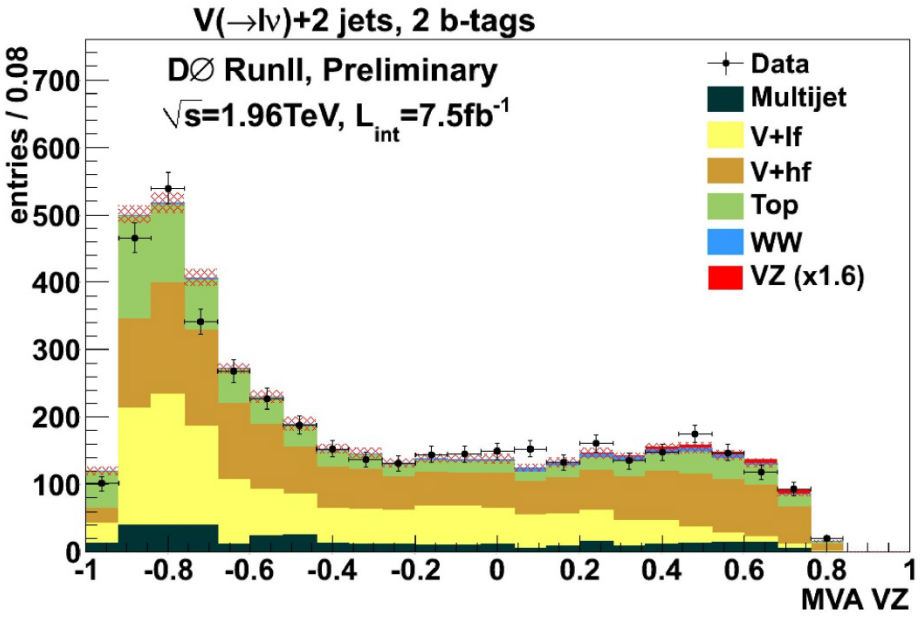
General benchmark procedure

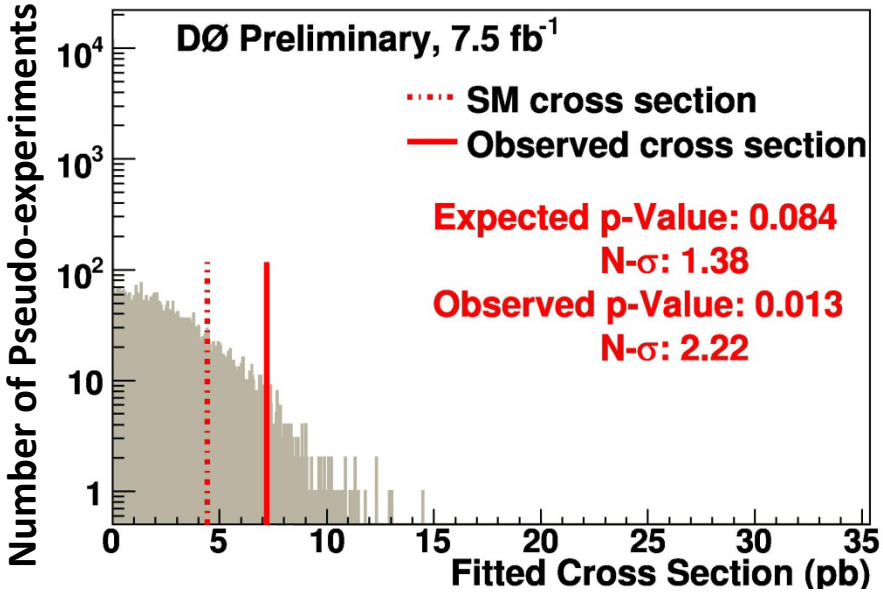
- We should also validate the Higgs search ***methods***, not just our ability to see something in the final state
- Start with the low-mass Higgs analyses
- Create a version with WZ/ZZ as signal, WW as background
  - Minimal changes from the WH/ZH analysis, NOT a separate effort
- Perform WZ+ZZ cross section measurement in the same way as the D0 WW+WZ analysis; use pseudo-experiments for significance

Diboson lvbb

- Use 7.5 fb^{-1} of RunIIb data
- Train new MVA with WZ/ZZ as signals: same variables and training parameters as WH search
- Measure $\sigma(VZ)$ = 7.2 ± 2.03 (stat.) ± 2.74 (syst.) pb
- 1.4σ Expected, 2.2σ Observed significance

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





Diboson lvbb

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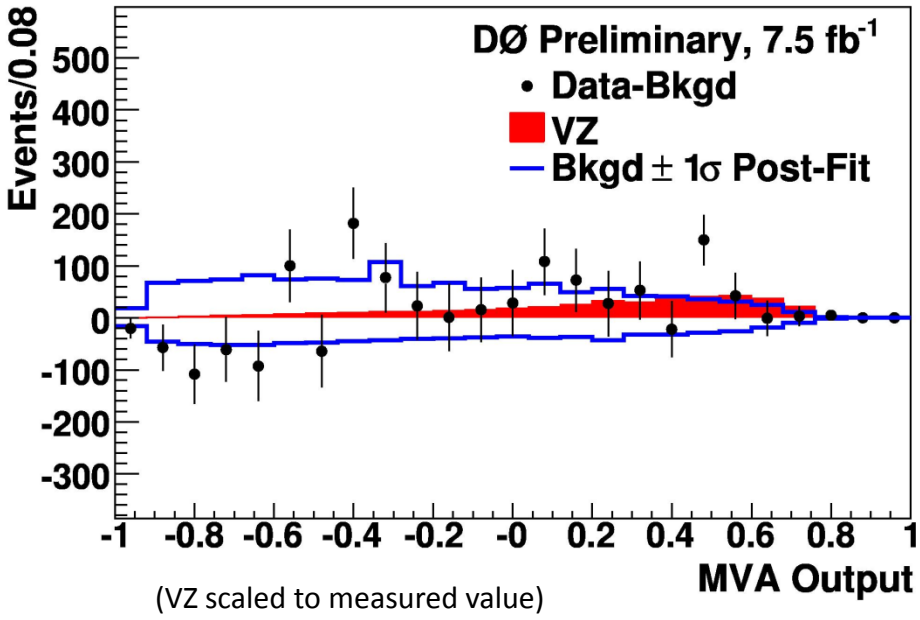
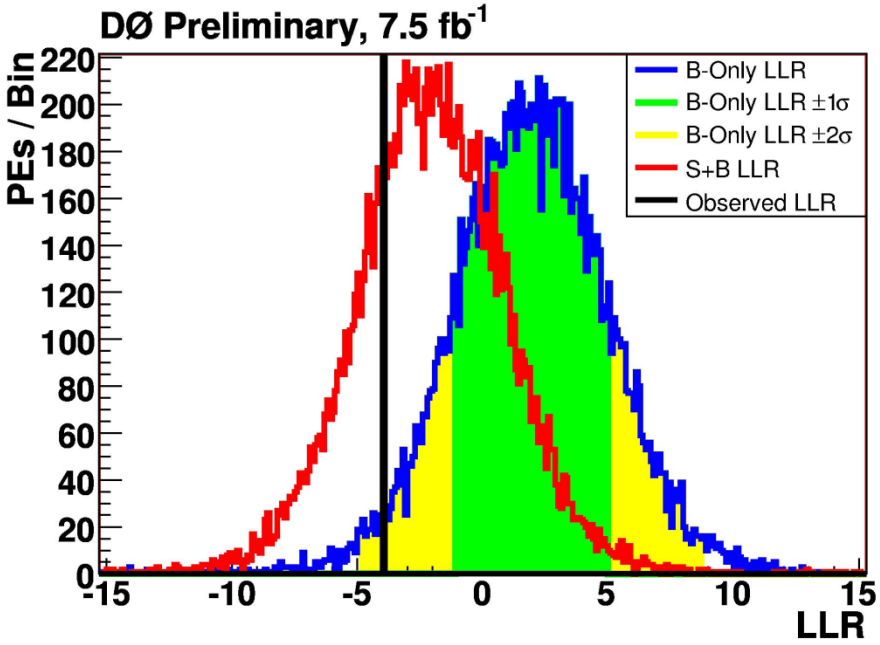
- 1.4σ Expected, 2.2σ Observed significance

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



(VZ scaled to measured value)



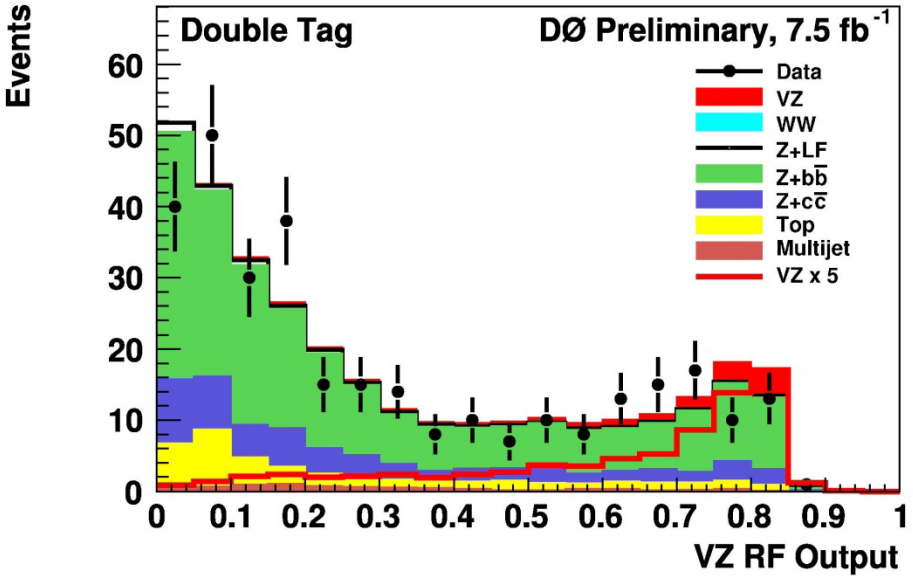
LLR= Log-likelihood ratio

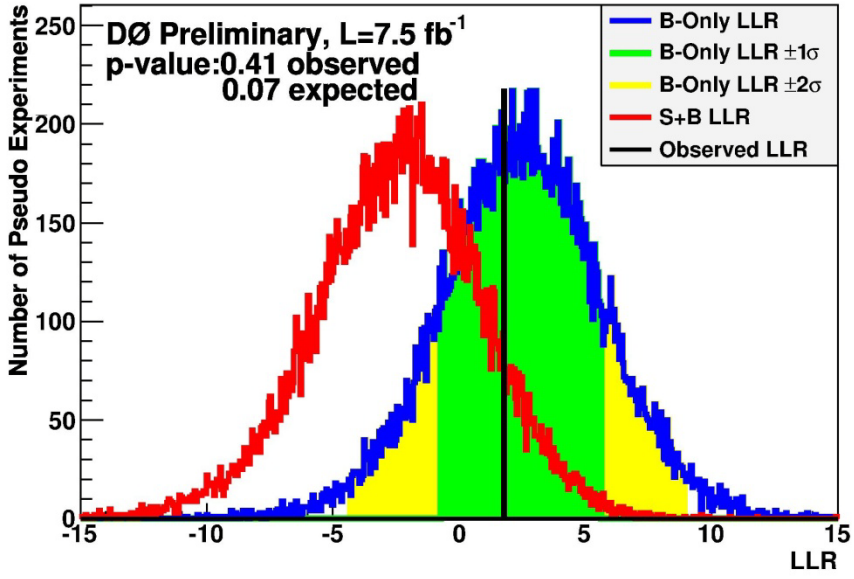
B-Only LLR and S+B LLR from PEs

Diboson llbb

- Also uses 7.5 fb^{-1} of RunIIb data, same procedures as ZH search
- Observed value consistent with SM at ~1.5 s.d.
- Measures $\sigma(VZ) = 0.4 \pm 2.8$ pb

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





Diboson llbb

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- Observed value consistent with SM at ~1.5 s.d.
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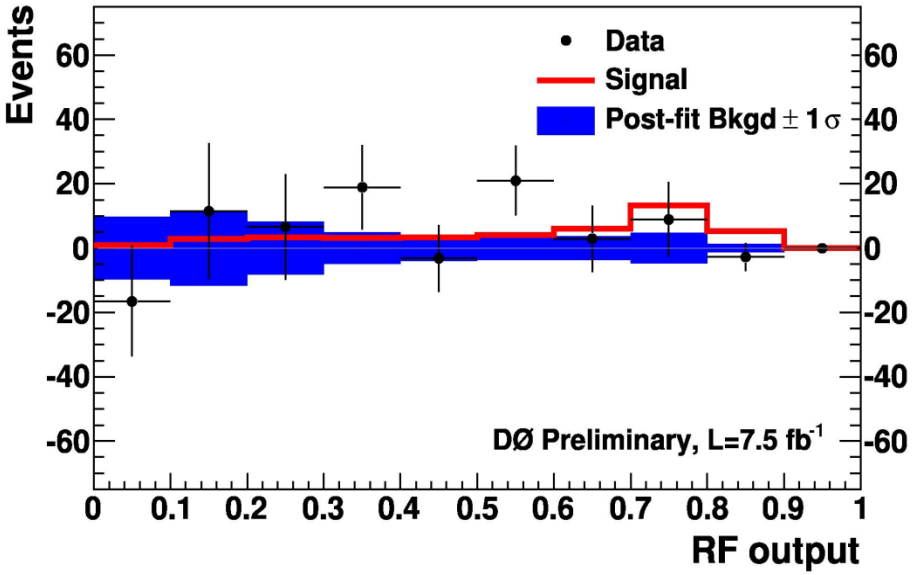
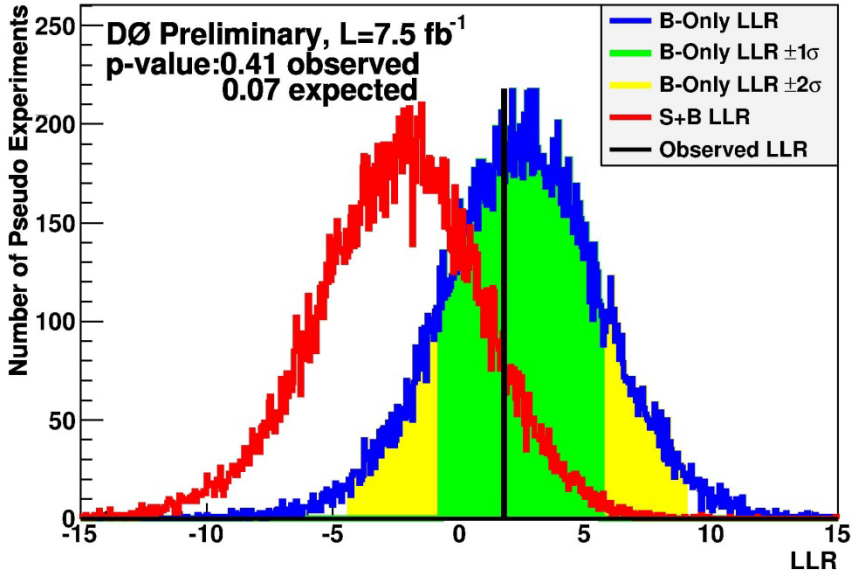
$\sigma(VZ)_{SM} = 4.42$ pb

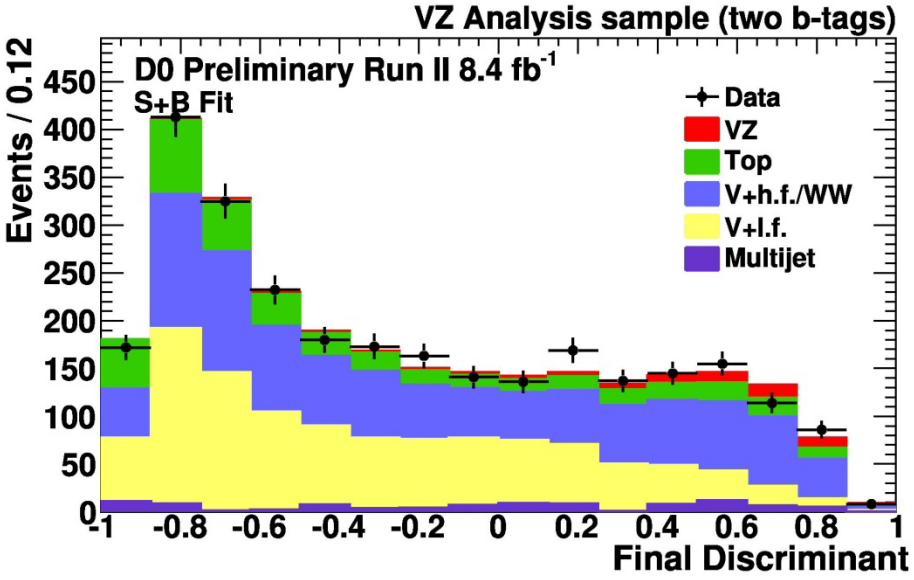


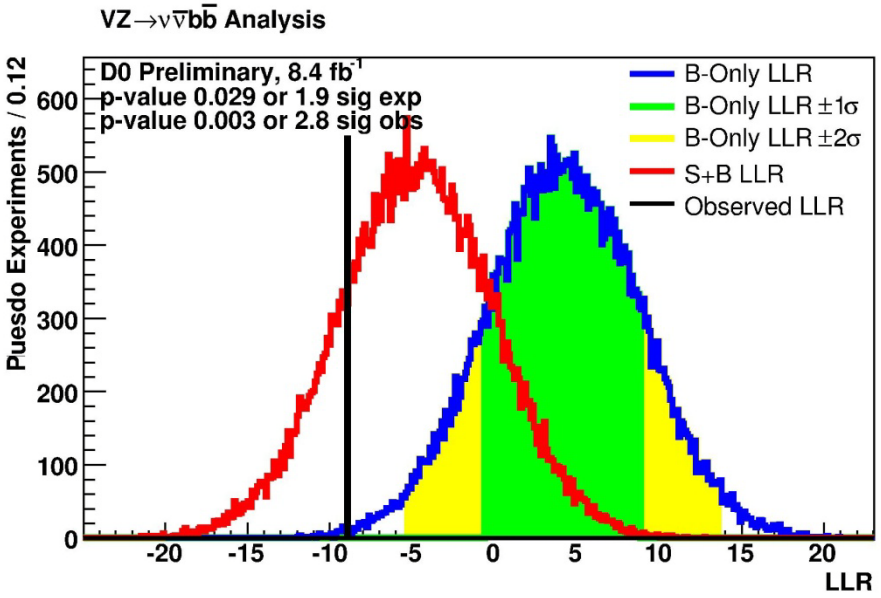


Diboson vvbb

- 8.4 fb^{-1} of RunII data
- Sensitive to WZ→lvbb with missed lepton
- Measure $\sigma(VZ) = 6.9 \pm 1.3(stat.) \pm 1.8(syst.)$ pb
  - 2.8σ significance, 1.9σ expected

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

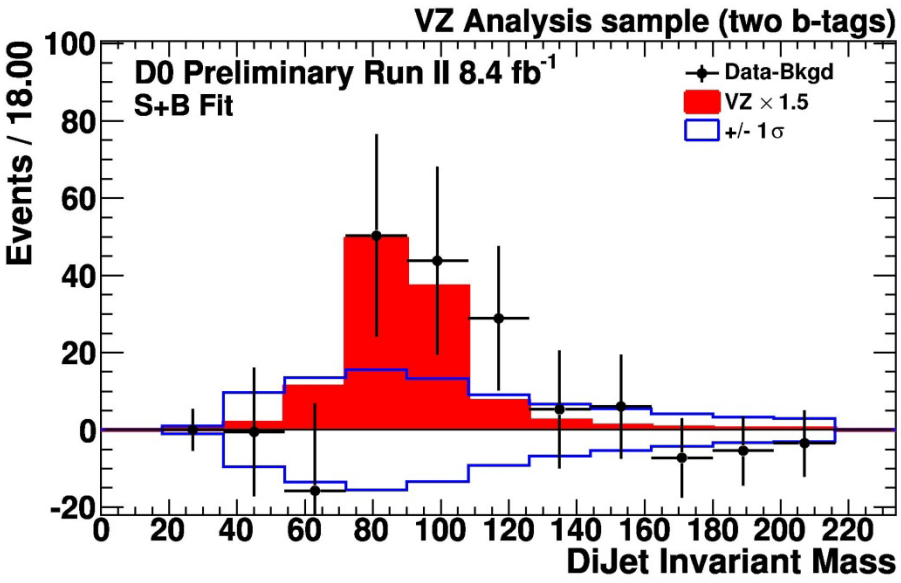


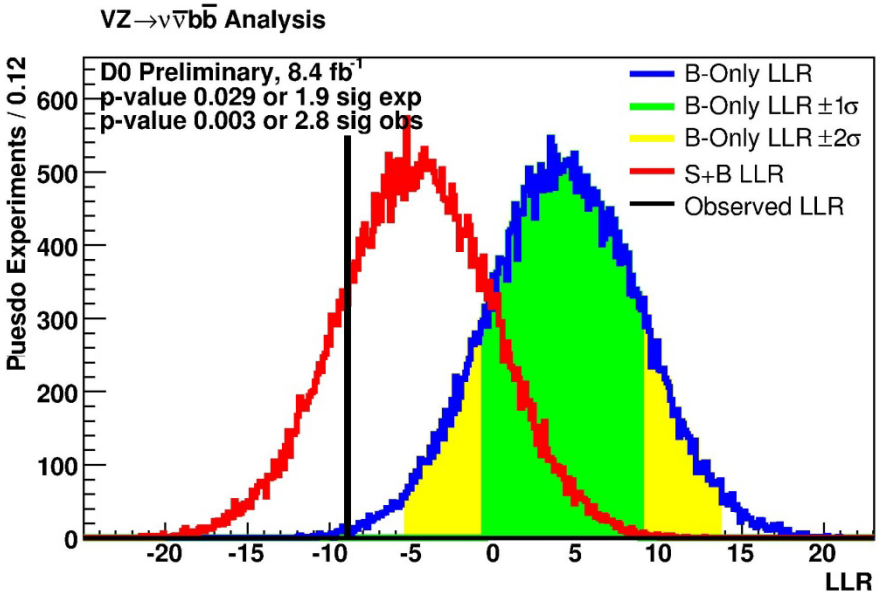


Diboson vvbb

- 8.4 fb^{-1} of RunII data
- Sensitive to WZ→lvbb with missed lepton
- Measure $\sigma(VZ) = 6.9 \pm 1.3(\text{stat.}) \pm 1.8(\text{syst.})$ pb
  - 2.8σ significance, 1.9σ expected

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





S+B Fit from MVA applied to dijet mass

D0 Diboson Combination

- Combine lvbb, llbb, and vvbb analyses
- Maintain proper correlations among channels

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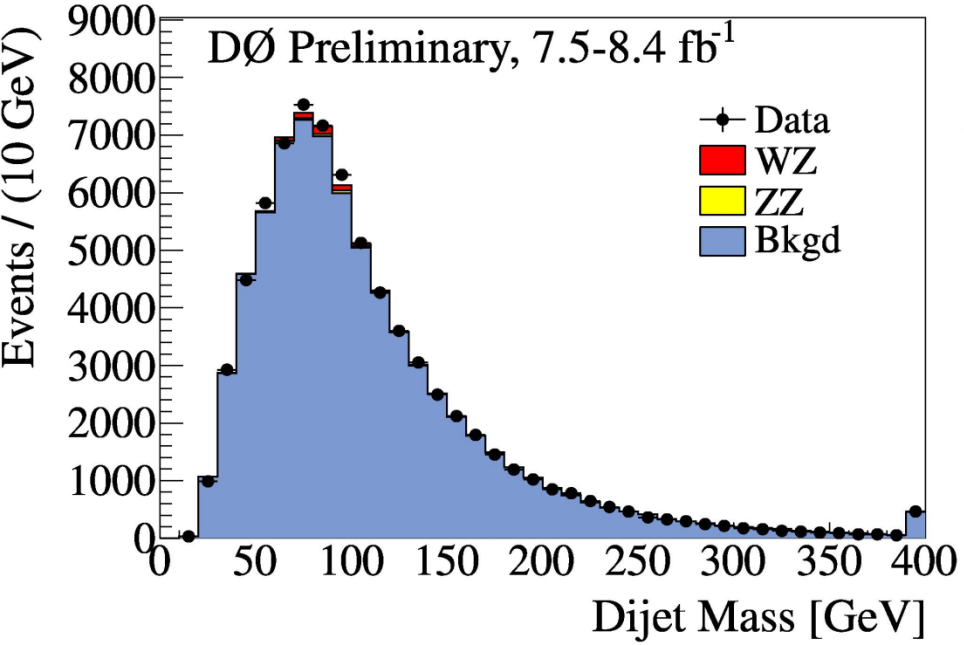
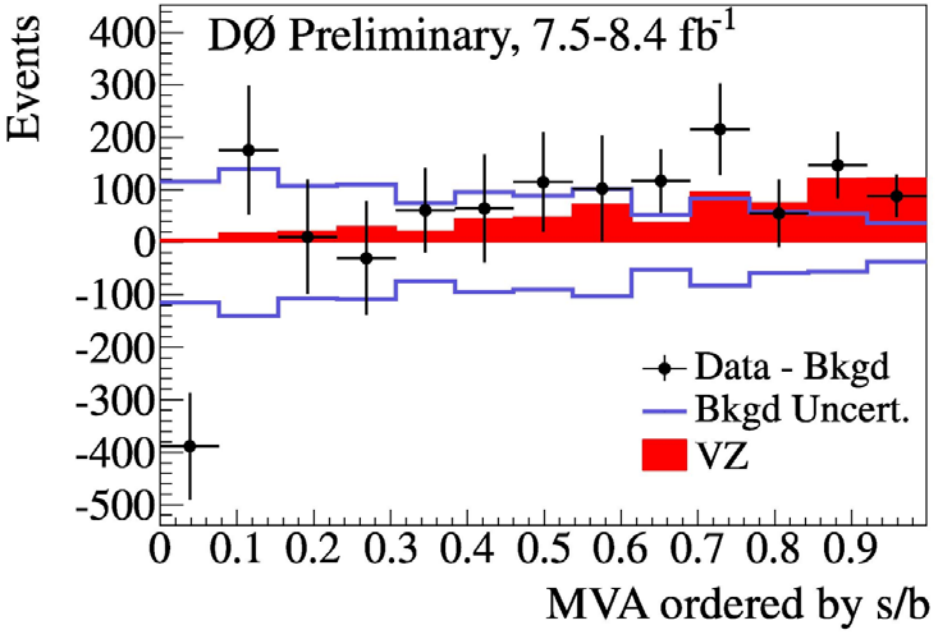
Combined dijet mass for lvbb, llbb, vvbb

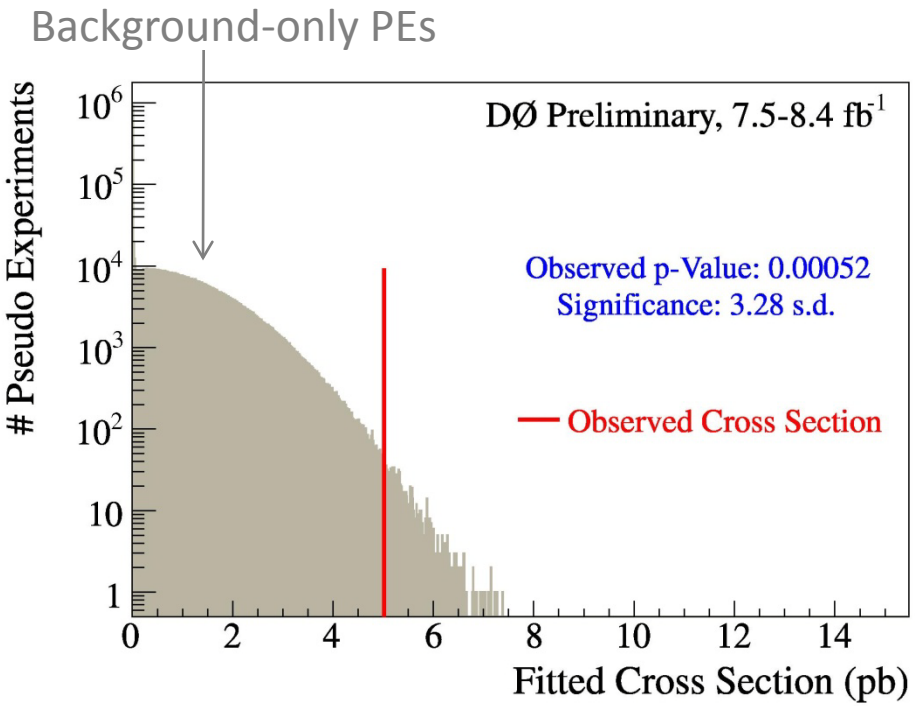


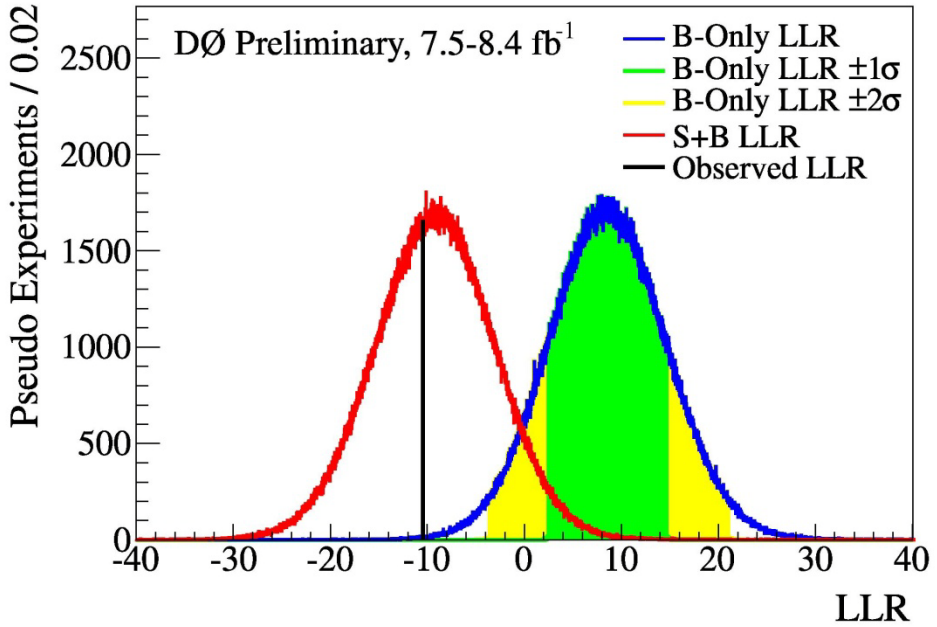


D0 Diboson Combination

- Combine lvbb, llbb, and vvbb analyses
- Measure $\sigma(VZ) = 5.0 \pm 1.0\ (\text{stat.})^{+1.3}_{-1.2}\ (\text{syst.})$ pb
- **Evidence with 3.3σ significance, 2.9σ expected**

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





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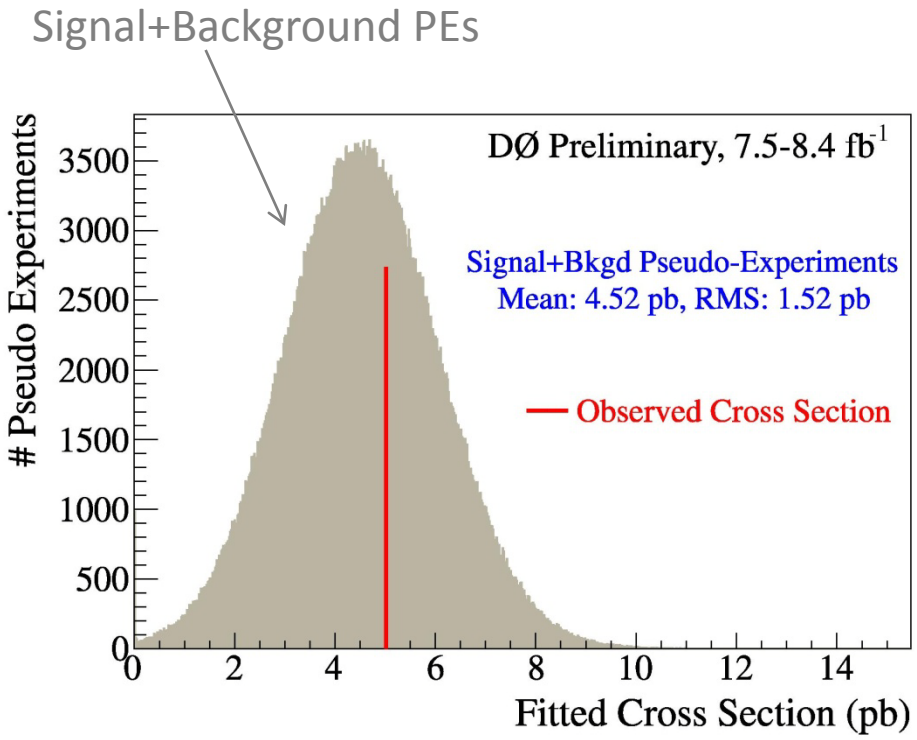
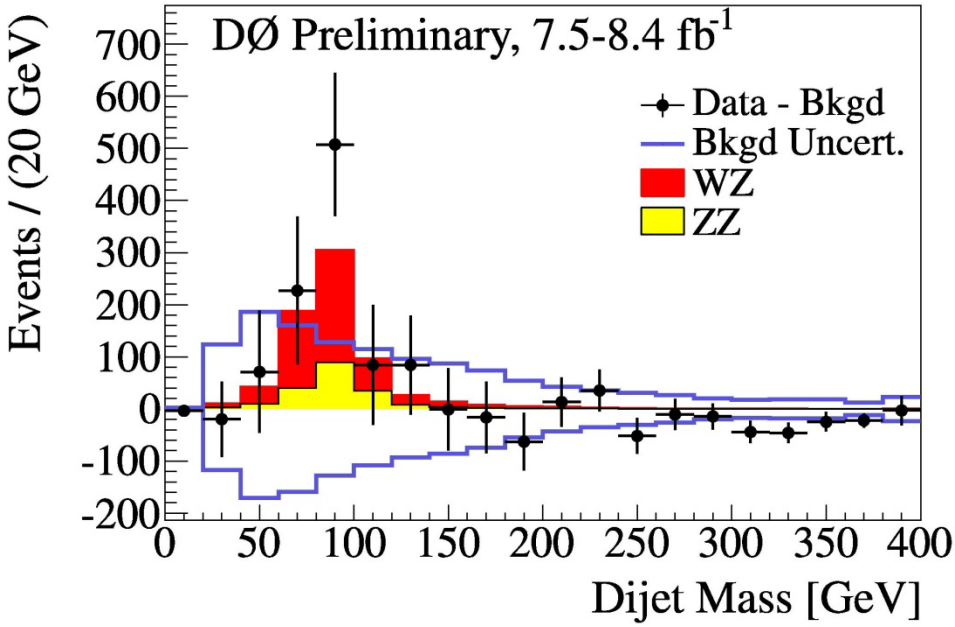


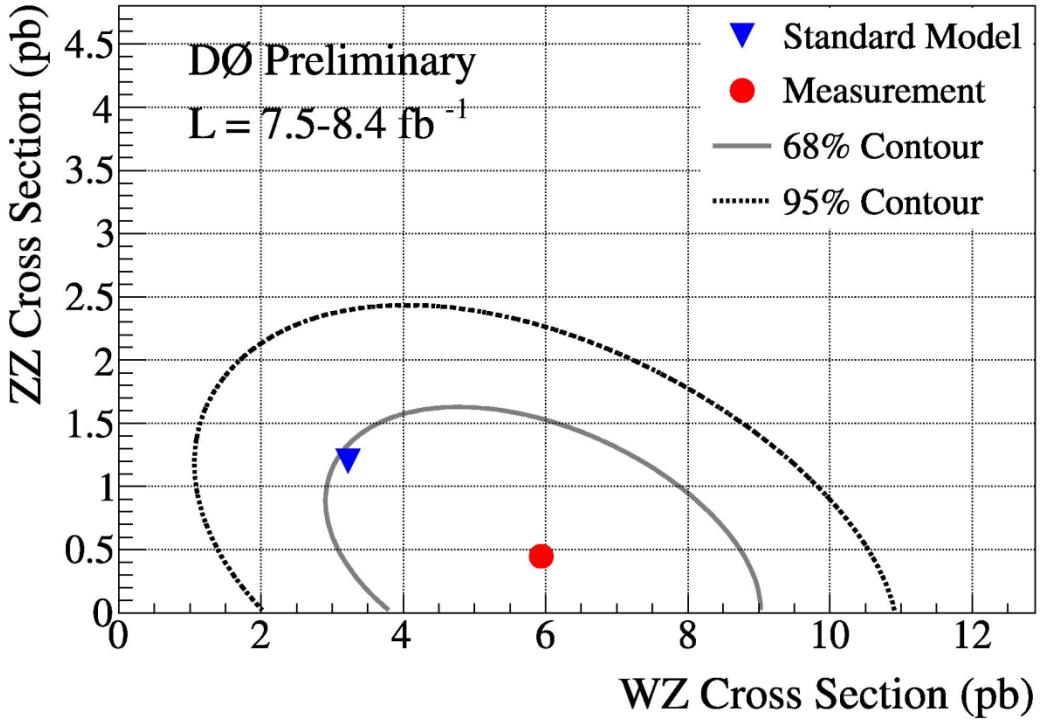


2-D cross section fit

- Allow WZ and ZZ contributions to float separately
- Result consistent with SM at ≈1 sigma

$$\sigma(WZ) = 5.9 \pm 1.4\,(\text{stat.}) \pm 0.7\,(\text{syst.})\ \text{pb}$$

$$\sigma(ZZ) = 0.45 \pm 0.61\,(\text{stat.}) \pm 1.2\,(\text{syst.})\ \text{pb}$$



$\sigma(WZ)_{SM}$= 3.22 pb
$\sigma(ZZ)_{SM}$= 1.20 pb

Summary and Prospects

- Diboson production well-studied at the Tevatron in ever-more challenging final states
- D0 has evidence for VZ production in final states with b-tagged jets, agrees well with Standard Model prediction
- Analyses use same datasets/methodologies as low-mass Higgs searches
- Major benchmark for the low-mass Higgs program and validation of the general strategy
- Expect to update at Moriond with full Run II dataset (9.7 fb^{-1})
  - Expect to combine with similar analyses from CDF (now in preparation)
  - With full dataset from both experiments, should be very close to observation!