Searches for WZ and ZZ Diboson Production in Final States with Jets and Charged Leptons or Missing Transverse Energy at CDF

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on behalf of the CDF Collaboration

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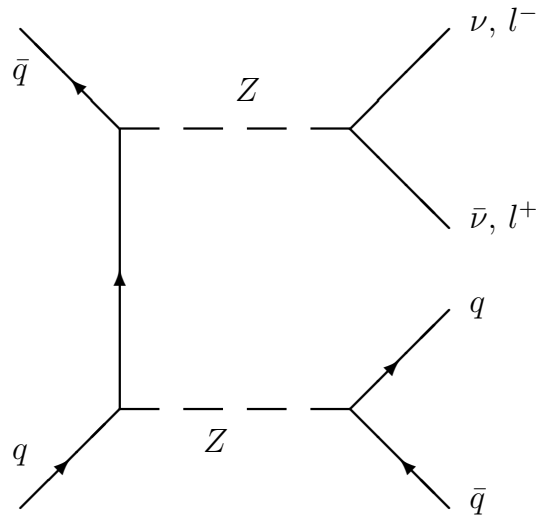
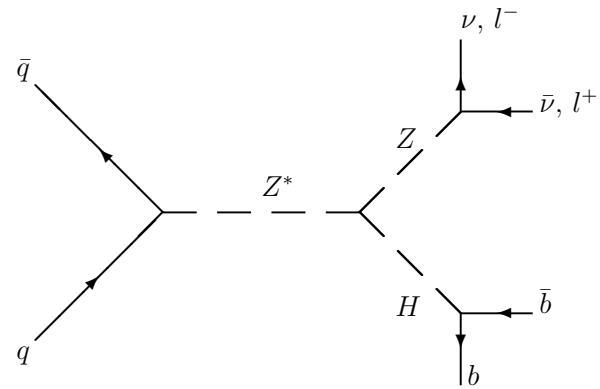
Motivation

- Semi-hadronic diboson decays important step to Higgs
  - Share similar final state for $m_H < 135$ GeV/c^2
  - Testing ground for new tools
- Previous observations all involve WW
  - Larger σ
  - Large W→l,ν branching ratio
- In this talk
  - ***WZ/ZZ → lν,νν + qq*** : MET (Missing transverse energy) + jets
    - *b* tagging to separate from WW
  - ***ZW/ZZ → l^+l^- + qq/qq'*** : Charged leptons + jets
    - New quark-gluon discriminant to combat large Z + (gluon) jets background



ZZ Production



ZH Production

Process	Cross Section (pb)
WW	11.70 ± 0.7
WZ	3.60 ± 0.3
ZZ	1.49 ± 0.2

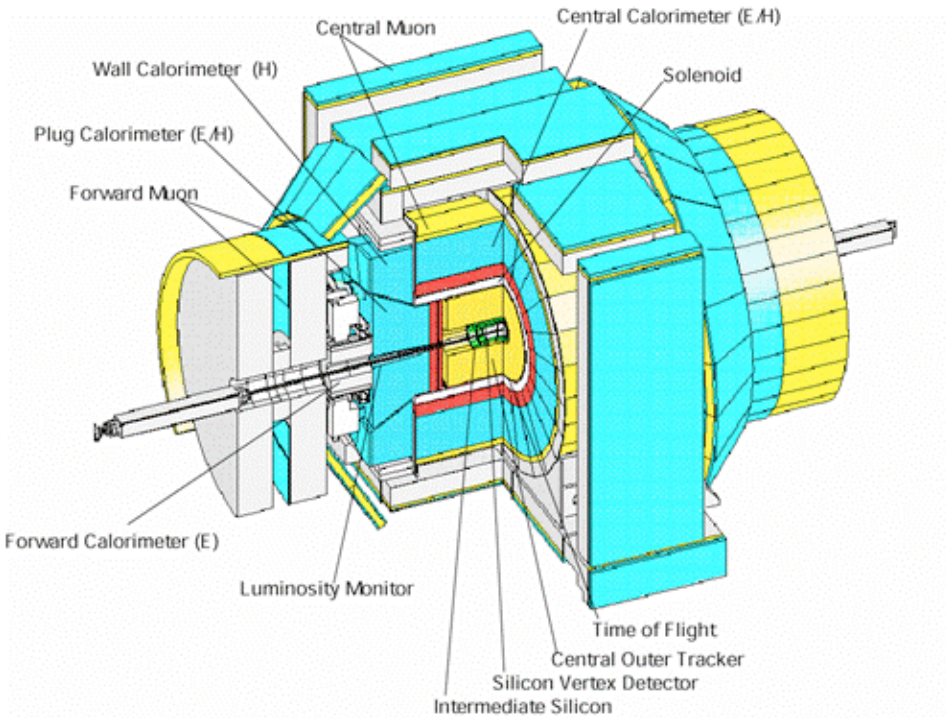
Previous Tevatron WZ/ZZ Measurements

Process	SM σ (pb)	Decay Channel	σ (pb)	∫L (Year Pub.)	Exp.
WZ	3.6	$l\nu$, l^+l^-	$3.89^{+1.07}_{-0.90}$	4.1 fb^{-1} (2010)	D0
			$3.9^{+0.8}_{-0.7}$	**7.1 fb^{-1} (2011)**	**CDF**
ZZ	1.5	l^+l^-, l^+l^-	**$1.26^{+0.49}_{-0.40}$**	**6.4 fb^{-1} (2011)**	**D0**
			2.18 ± 0.49	**6.1 fb^{-1} (2011)**	**CDF**
		l^+l^-, $\nu\nu$	2.01 ± 0.97	2.7 fb^{-1} (2008)	D0
			$1.45^{+0.60}_{-0.51}$	5.9 fb^{-1} (2010)	CDF
WZ	**3.6**	**$l\nu$,jj & l^+l^-,jj**	**?**		
ZZ	**1.5**	**$\nu\nu$,jj & l^+l^-,jj**	**?**		

Other New Tevatron Measurements

Process	Experiment	URL
Wγ	D0	http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/EW/E36/
Zγ	CDF	http://www-cdf.fnal.gov/physics/ewk/2011/zgamma/Zgamma5invfb/index.html
W + jj	D0	http://www-d0.fnal.gov/Run2Physics/WWW/results/final/HIGGS/H11B/
	CDF	http://www-cdf.fnal.gov/physics/ewk/2011/wjj/7_3.html
WW/WZ → lν + h.f.	CDF	http://www-cdf.fnal.gov/physics/new/hdg/Results_files/results/wzlnubb_071911/

About the Tevatron and CDF



- Fermilab Tevatron
  - Collide p-pbar at $\sqrt{s}$ = 1.96 TeV
  - 11.6 fb^{-1} delivered to experiments
- Collider Detector at Fermilab (CDF)
  - Silicon detectors and "outer" drift chamber for particle tracking
  - Electromagnetic and hadronic calorimeters
  - Muon systems outside calorimeters

Event Selection

MET + Jets

- Data from MET triggers
  - MET > 50 GeV
  - Quality cuts to reduce "fake" MET from multijet production
  - Determine trigger efficiency from $Z \rightarrow \mu^+\mu^-$ sample

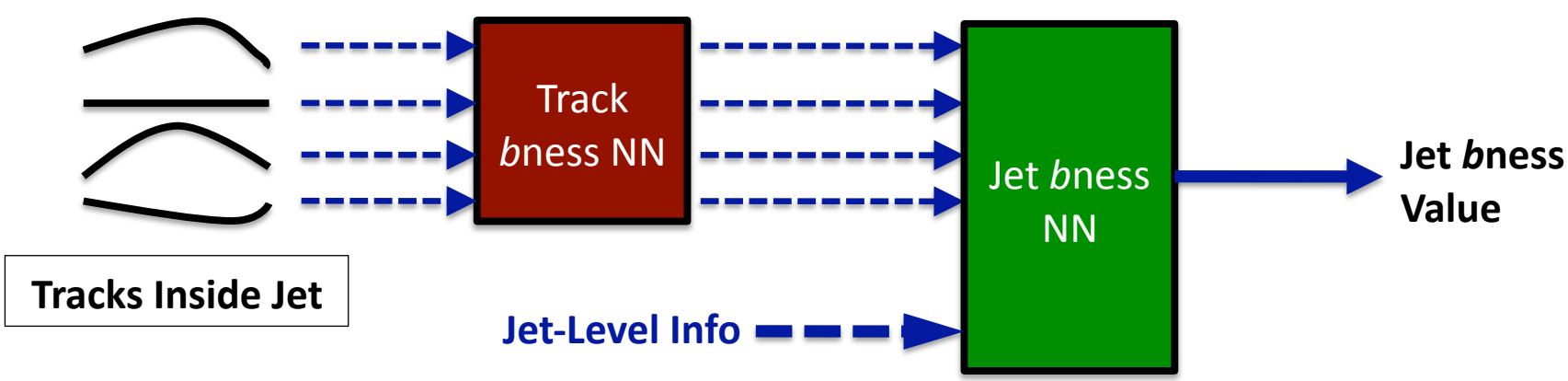
$e^+e^-, \mu^+\mu^-$ + Jets

- Data from high-p_T lepton triggers
  - Leptons' p_T > 20 GeV/c
  - 76 GeV/c^2 < Dilepton Mass < 106 GeV/c^2
  - Determine trigger efficiency by comparing data and MC in Z + 1 jet sample

- Two (or more) jets
  - Jets' E_T > 20 GeV, $|\eta|$ < 2.0
  - **Fit to Dijet Mass to extract Diboson signal**

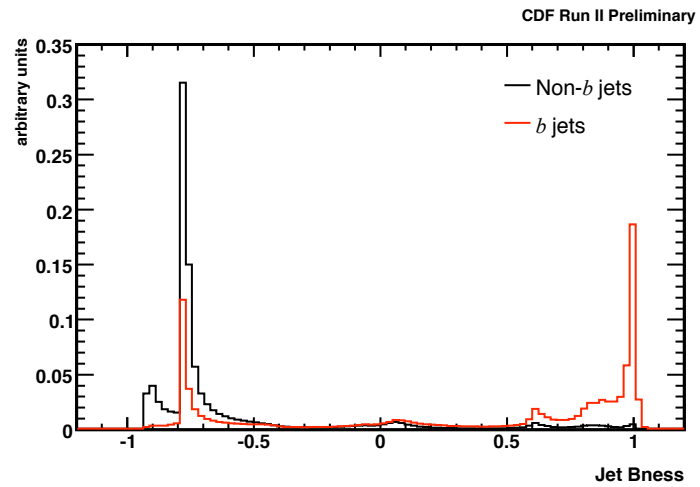
Artificial Neural-Network Based Jet *b*ness Tagger

- Multivariate algorithm to separate *b* jets from non-*b* jets
  - Long *B* hadron lifetimes
  - Large *B* hadron mass compared to decay products
- Focus on properties of individual tracks
  - Train NN to assign "track *b*ness" to each track in a jet
    - Consider d_0, z_0, p_T, *rapidity* and p_T w.r.t. jet axis ($p_\perp$)
  - Combine with jet-level information to assign overall "jet *b*ness"
    - Decay length in xy-plane (L_{xy}), existence of K_S *or* μ's in jet

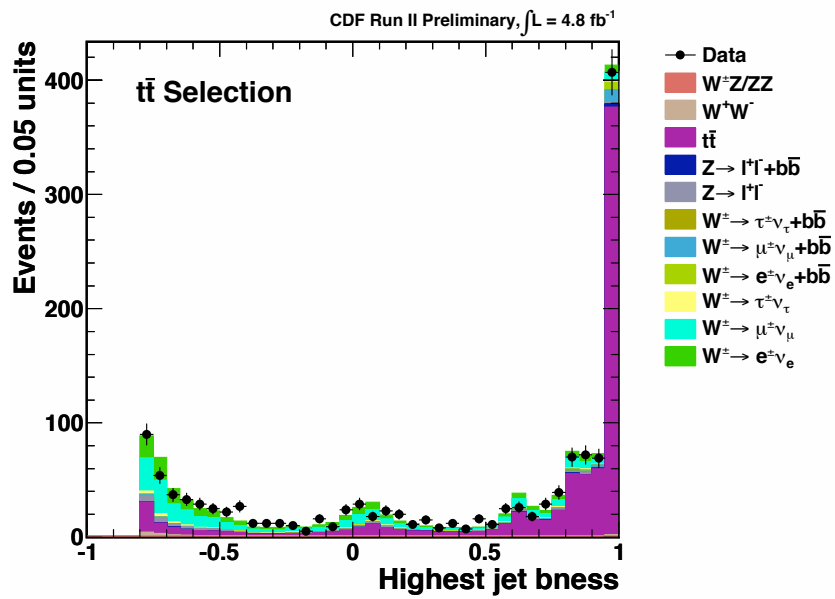


Jet *b*ness Tagger

- Train using ZZ Pythia MC
  - Jets from Z→*bb* decays for *b* jet samples
  - Jets from Z→*qq* (no b's present) for non-*b* samples

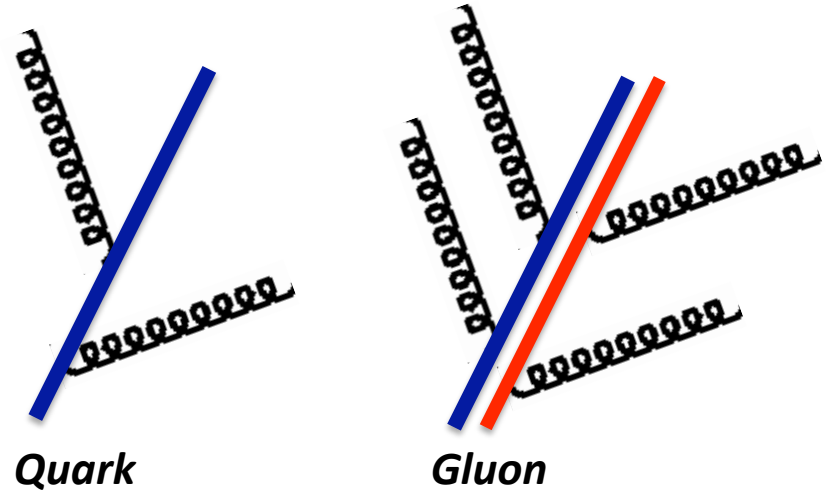


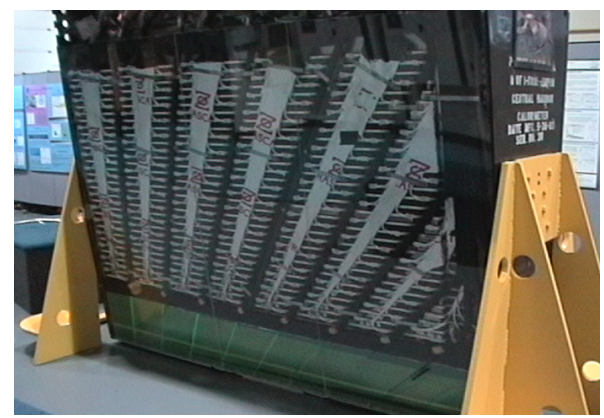
- "Tag": Place cut on minimum *b*ness value for jets
  - Optimize cut location
  - Calculate efficiency of cut in data from *b*-rich *tt* selection
  - Get mistag rate from Z or W + jets samples
  - Correct MC efficiency/mistag rate to match data



Artificial Neural-Network Based Jet Quark-Gluon Discriminant

- WZ/ZZ signal is entirely quark jets
  - W/Z + jets background has significant gluon contribution
- ***Gluon jets more spatially spread than quark jets***
  - Gluons have more color charge than quarks
- Construct distribution of distances between pairs of towers and tracks in a jet
  - $\Delta R = [\ (\Delta\eta)^2 + (\Delta\phi)^2\ ]^{1/2}$
  - Weight towers/tracks by their energy/momentum content

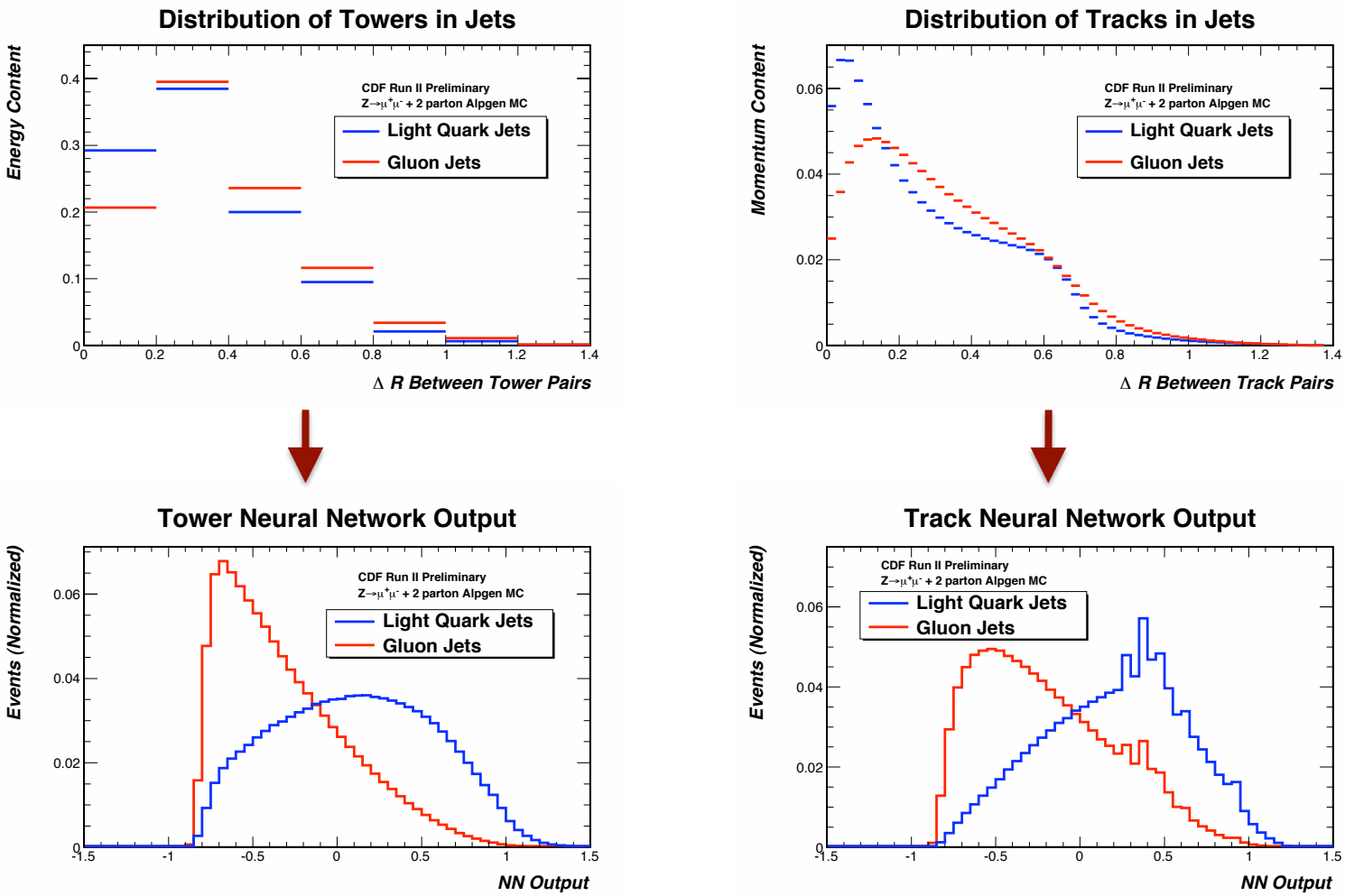




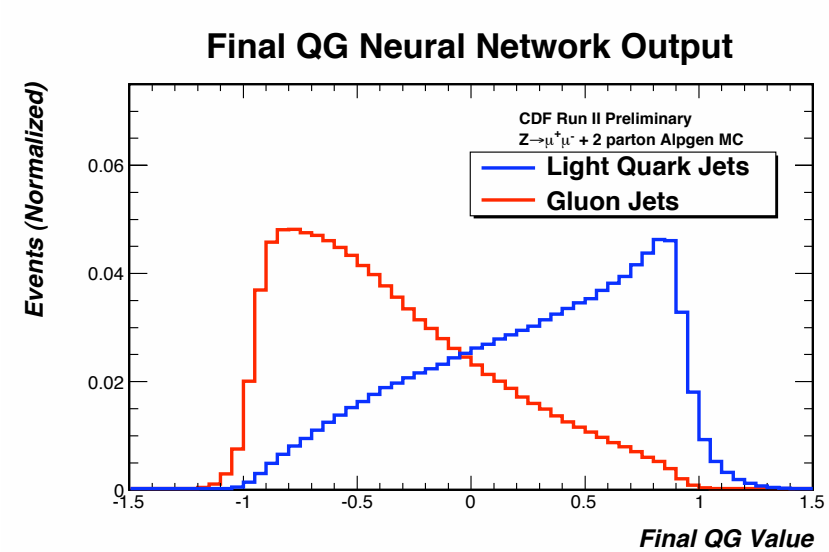
A wedge of the CDF central calorimeter. Towers' size ~ 0.1 in η and 15° in φ.

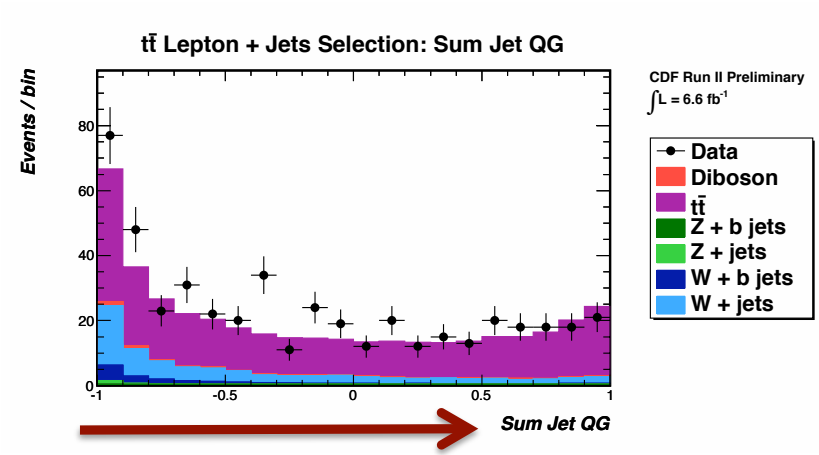
Jet QG Discriminant

- Content in bins of ΔR are inputs into NN discriminant
  - Separate NNs for tower and track distributions



Jet QG Discriminant





More Quark-Like

- Use third neural network to combine tower and track information, and other relevant jet variables
  - Tower and Track NN values
  - Ratios of Energy and Momentum in Cone 0.4 to 0.7 around jet
  - Jet EM Fraction
  - Number of Tracks and Towers in jet
  - Jet E_T, η
    - Gluon distribution normalized to match quarks
  - Number of interaction vertices
- Calibrate MC response by comparing data and MC in W + 1 jet selection region
- Determine efficiency of cut on QG value
  - *tt → Wb, Wb → lvb, qq'b* for quark-jet signal
  - *W* + jets for background-like regions

Backgrounds To Diboson Searches: W/Z + Jets

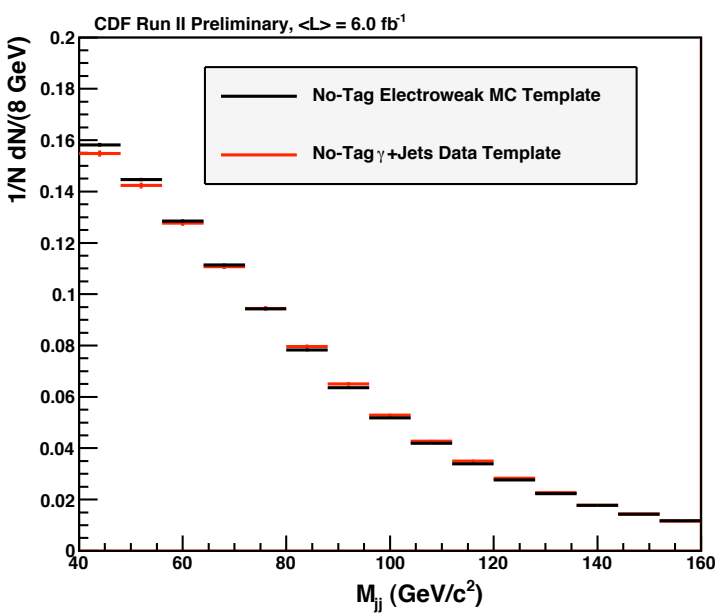
- Dominant background for both analyses
- Two different approaches

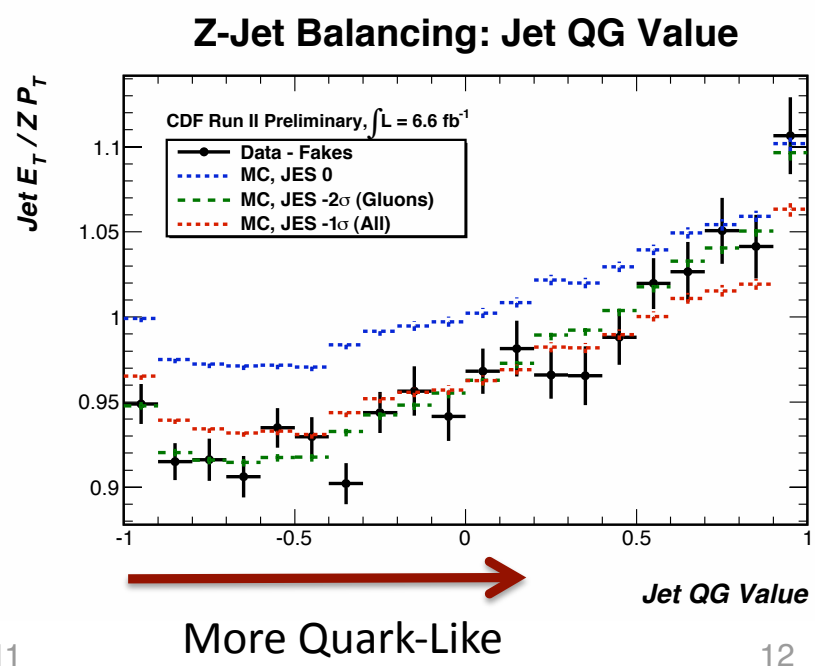
MET + Jets:

Photon + 2 jet data used to correct MC modeling of dijet mass

Charged Leptons + Jets:

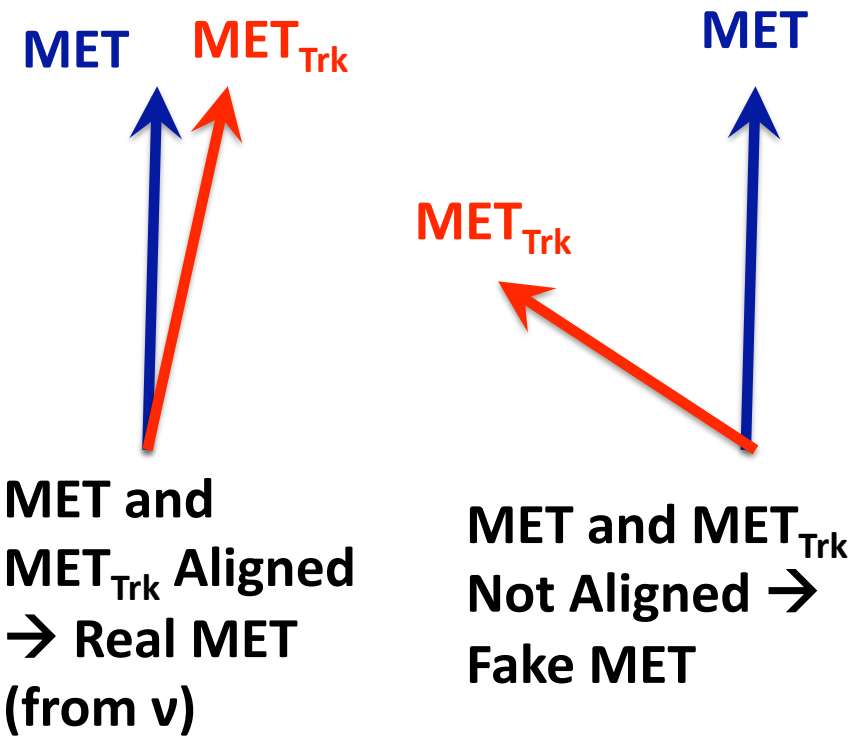
Use MC, but scale JES of gluon jets down based on Z + 1 jet balancing studies





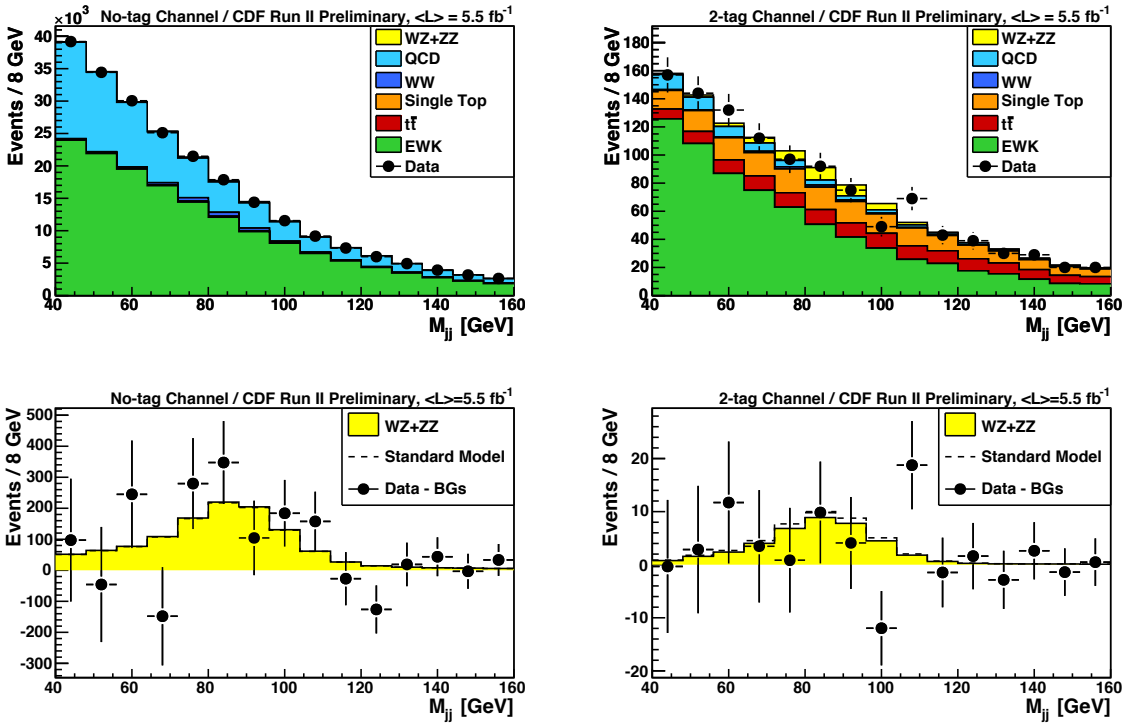
Backgrounds To Diboson Searches: Jets Faking Charged Leptons/Neutrinos

- MET + Jets:
  - Multijet production with mismeasured jet energies can fake MET
  - To model…
    - Construct missing P_T from tracks (MET_{Trk})
    - $\Delta\phi(MET, MET_{Trk}) > 1$ → "QCD-Enhanced" region



- Lepton + Jets
  - W + 1 jet faking a lepton may pass dilepton cuts
    - Use like-sign objects to model muon fakes
    - Calculate probability of jet to fake electron from jet triggered data

MET + Jets Results



- Perform χ^2 fit to dijet mass in two channels
  - Heavy-flavor enriched "2-tag" region
  - Remaining events in "no-tag" region
- Best fit: $N_{WZ/ZZ}$ ~ SM prediction
- Use Feldman-Cousins method to extract sensitivity

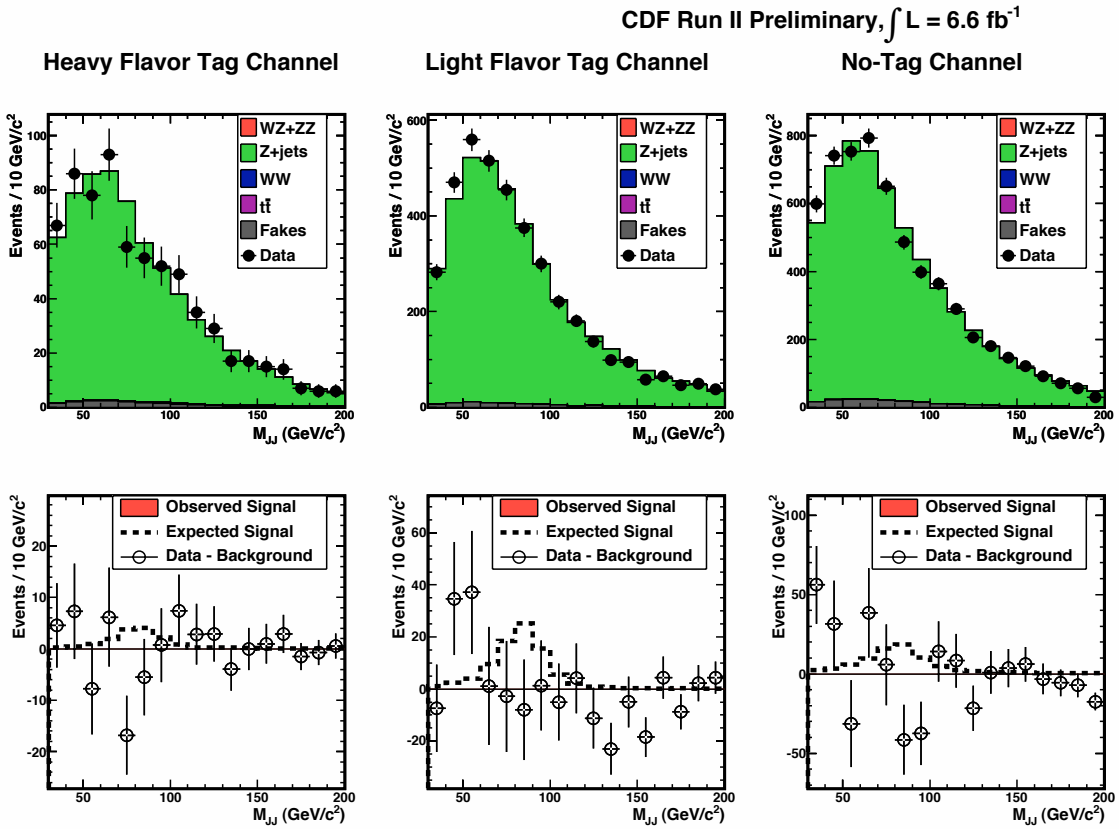
CDF Run II Preliminary, $\int L = 5.5$ fb^{-1}

Process(es)	Fit N_{events} (no-tag)	Fit N_{events} (2-tag)
EWK	153300 ± 3000	694 ± 48
$t\bar{t}$ and single t	1700 ± 140	$313\ ^{+24}_{-26}$
QCD	72300 ± 2800	54.6 ± 7.3
WW	2720 ± 190	$8.3\ ^{+1.8}_{-1.9}$
WZ/ZZ	1160 ± 620	39.9 ± 20

$\sigma_{WZ/ZZ} = 5.0^{+3.6}_{-2.5}$ **pb**

< 13 pb at 95% CL

Charged Leptons + Jets Results



CDF Run II Preliminary, $\int L = 6.6\ fb^{-1}$

Process	N_{events} (HF Tag)	N_{events} (LF Tag)	N_{events} (No Tag)
Z + jets	660^{+170}_{-150}	3900^{+920}_{-800}	5800^{+1300}_{-1800}
$t\bar{t}$	$4.26^{+0.56}_{-0.59}$	$0.86^{+0.19}_{-0.23}$	$2.51^{+0.42}_{-0.36}$
WW	0.025 ± 0.002	$0.26^{+0.07}_{-0.04}$	$0.56^{+0.07}_{-0.19}$
Fakes	18.3 ± 4.7	80 ± 21	190 ± 49
WZ/ZZ	$0^{+3.3}_{at\ limit}$	$0^{+17}_{at\ limit}$	$0^{+16}_{at\ limit}$
Data	685 ± 26	3942 ± 63	5976 ± 77

$WZ/ZZ \rightarrow l^+l^-jj$ Search

- Perform χ^2 fit to dijet mass in three channels
  - Heavy-flavor tag region using jet *b*ness
  - Light-flavor tag region using jet QG
  - Remaining events in no-tag region
- Best Fit: $N_{WZ/ZZ} = 0$
- Use Feldman-Cousins method to get limit
  - σ_{SM} consistent with no observed signal

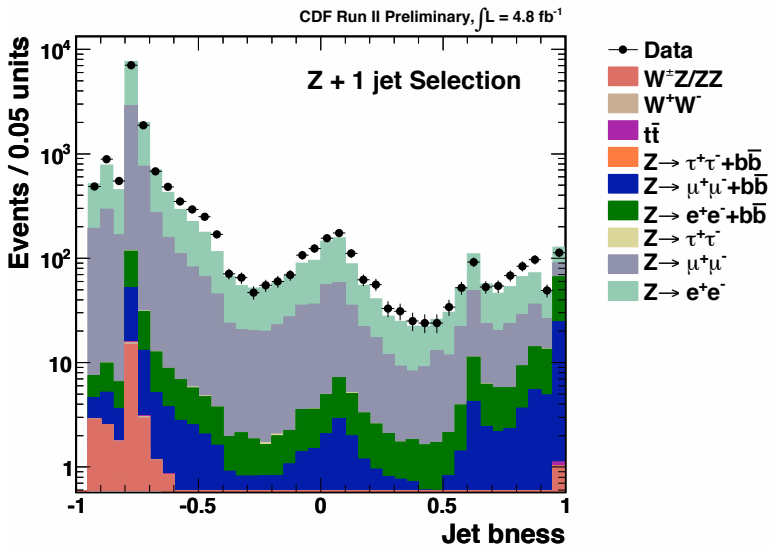
$\sigma_{WZ/ZZ}$ < 1.3 x σ_{SM} (Exp: 2.3)
< 6.6 pb at 95% CL

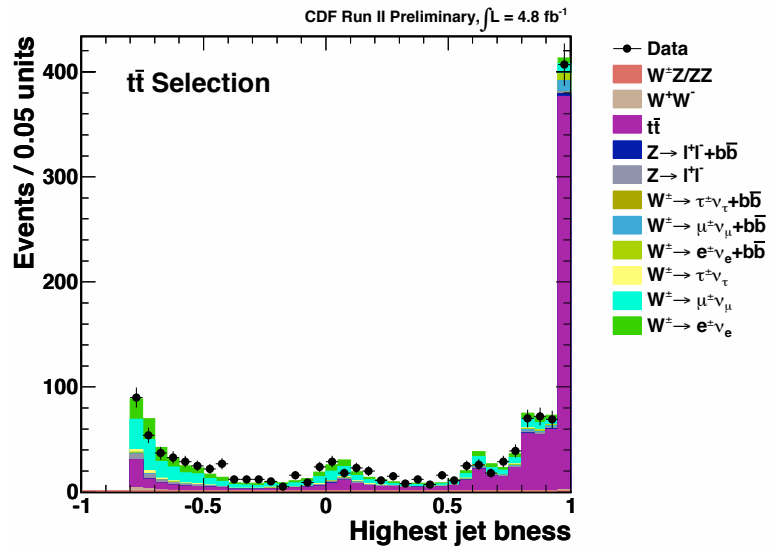
Conclusions

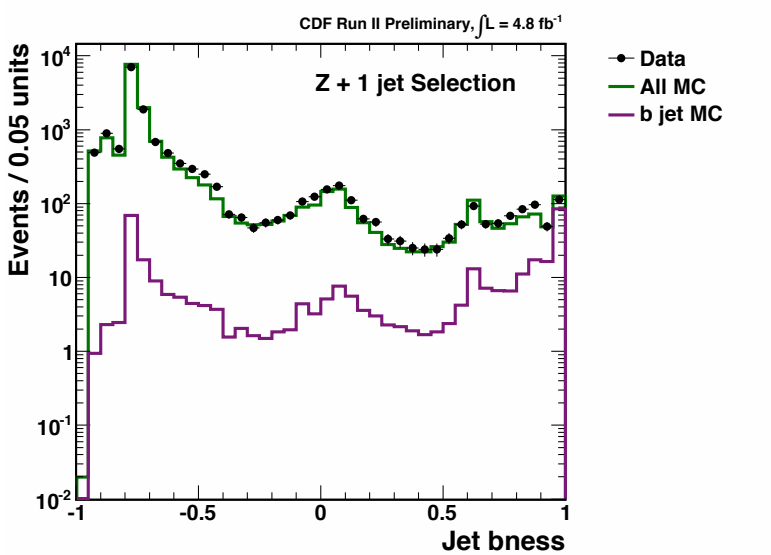
- Have conducted searches for WZ/ZZ production in semi-hadronic final states
  - Similar final state to Higgs searches with $m_H < 135$ GeV/c^2
- Using new multivariate algorithms to increase sensitivity
  - Jet *b*ness tagger picks out heavy-flavor jets
  - Jet QG discriminant separates light-flavor quark jets from gluon jets
- Extract signal through fit to dijet mass distribution
  - **MET + jets: $\sigma_{WZ/ZZ} < 13$ pb at 95% CL** (5.5 fb^{-1})
  - **Charged leptons + jets: $\sigma_{WZ/ZZ} < 6.6$ pb at 95% CL** (6.6 fb^{-1})
    - Standard model: $\sigma_{WZ/ZZ} = 5.1$ pb
- Looking ahead
  - Further studies of W/Z + jets modeling using jet QG value
    - Reduce systematic uncertainties on modeling
  - Implement new tools in Higgs searches

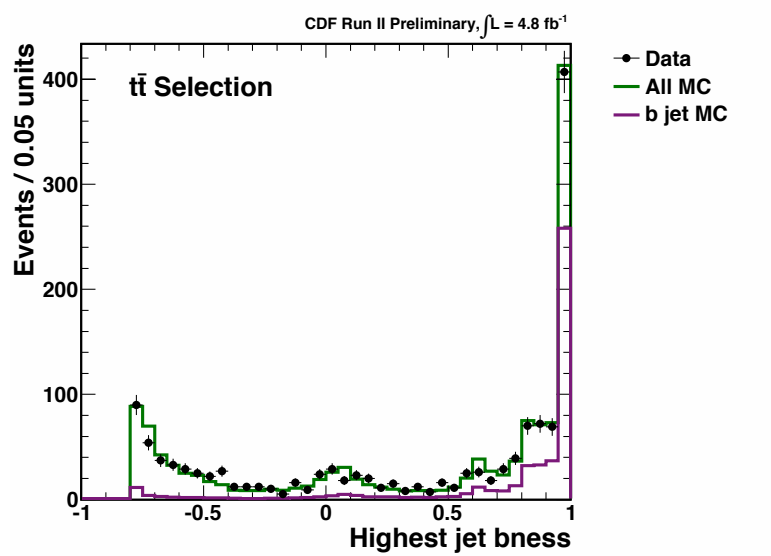
BACKUP SLIDES

Jet *b*ness Tagger: Efficiency and Mistag Rates

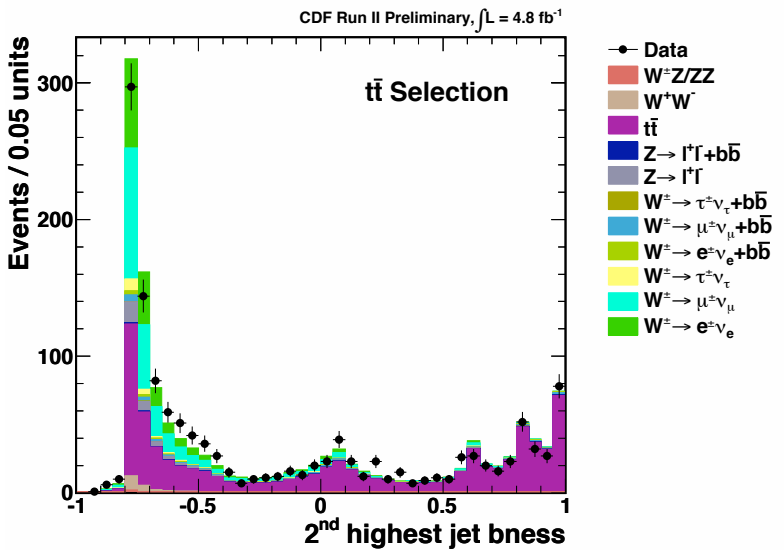


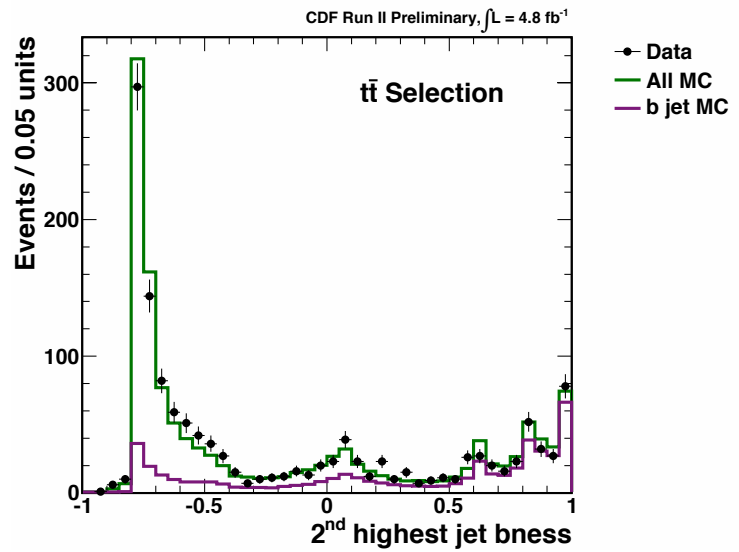




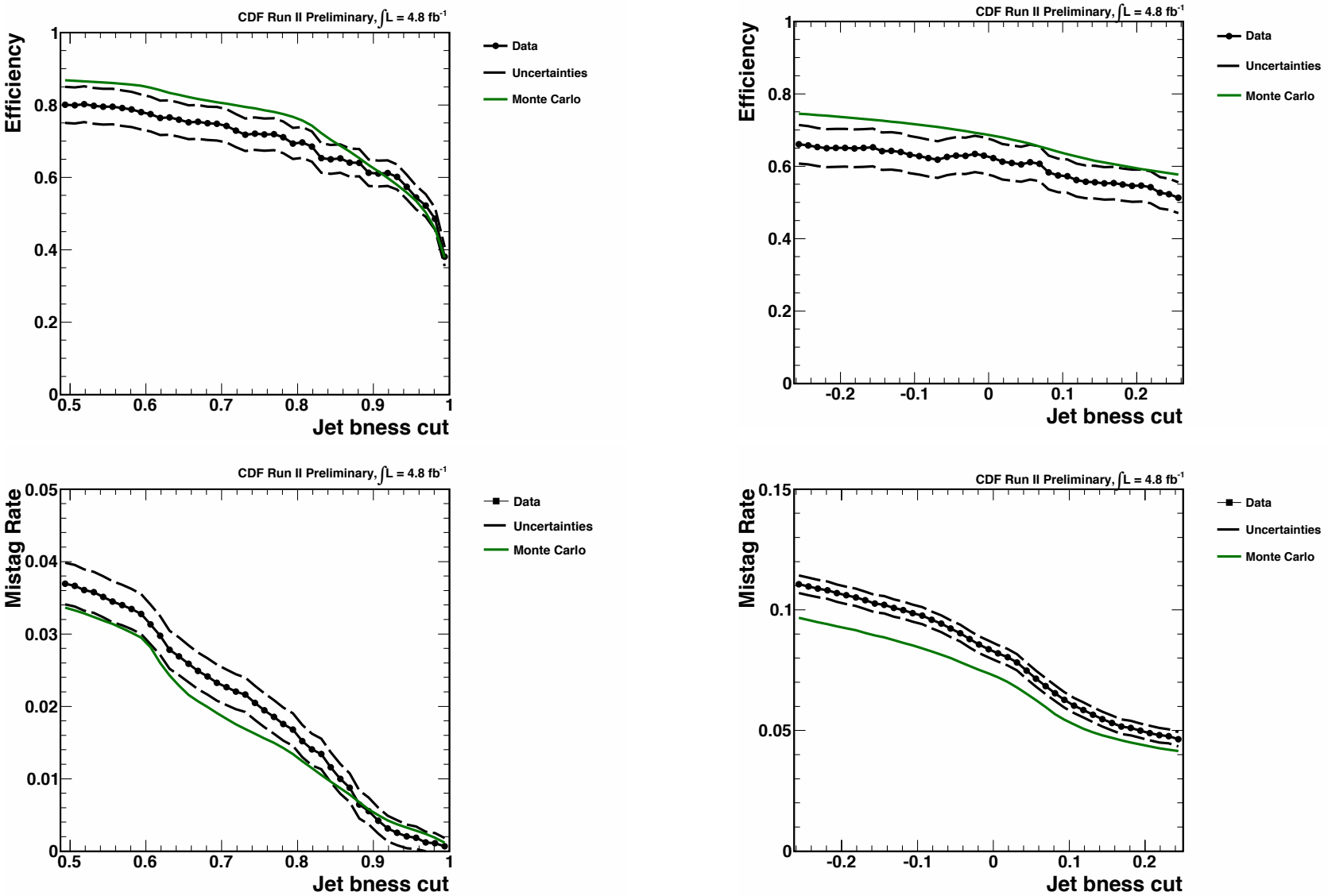


Jet *b*ness Tagger: Efficiency and Mistag Rates

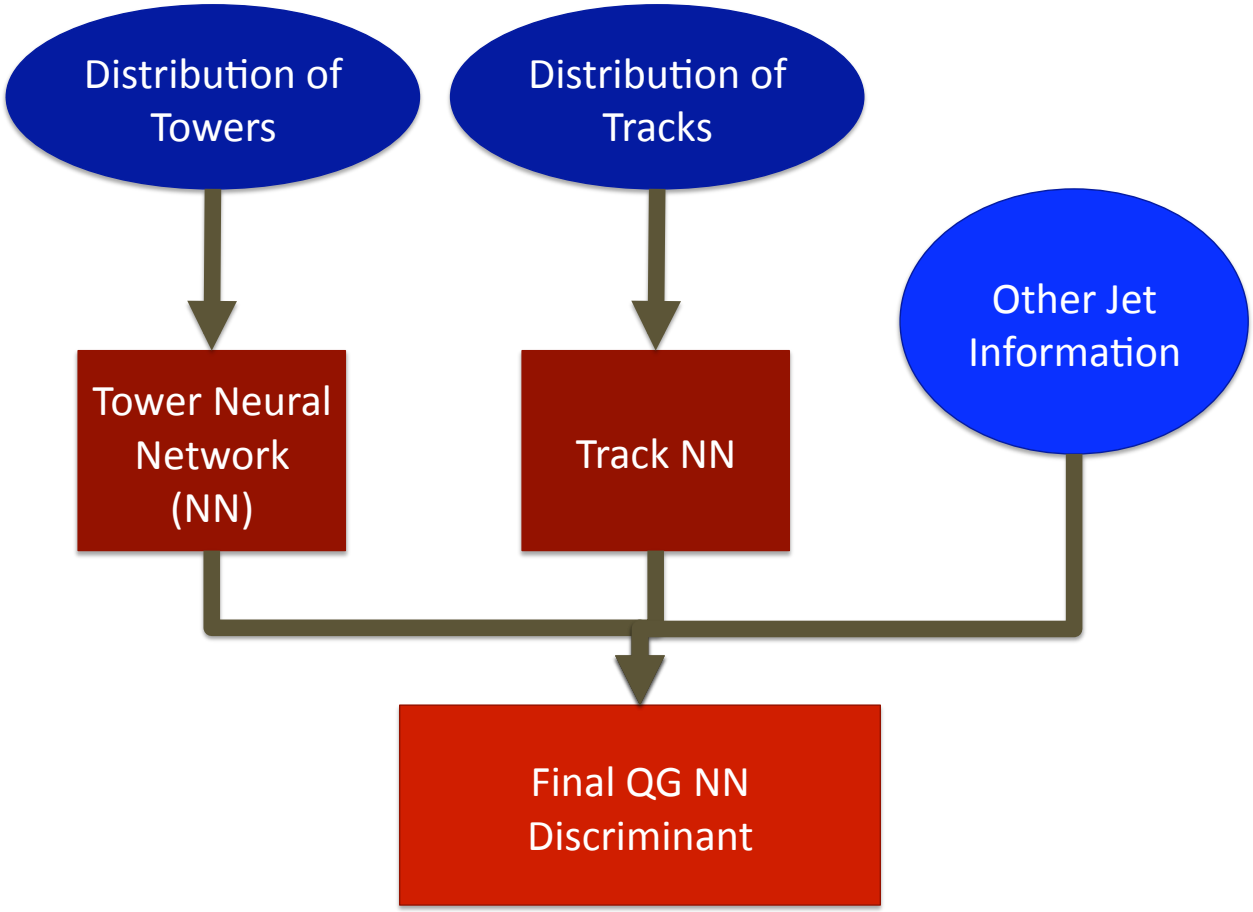




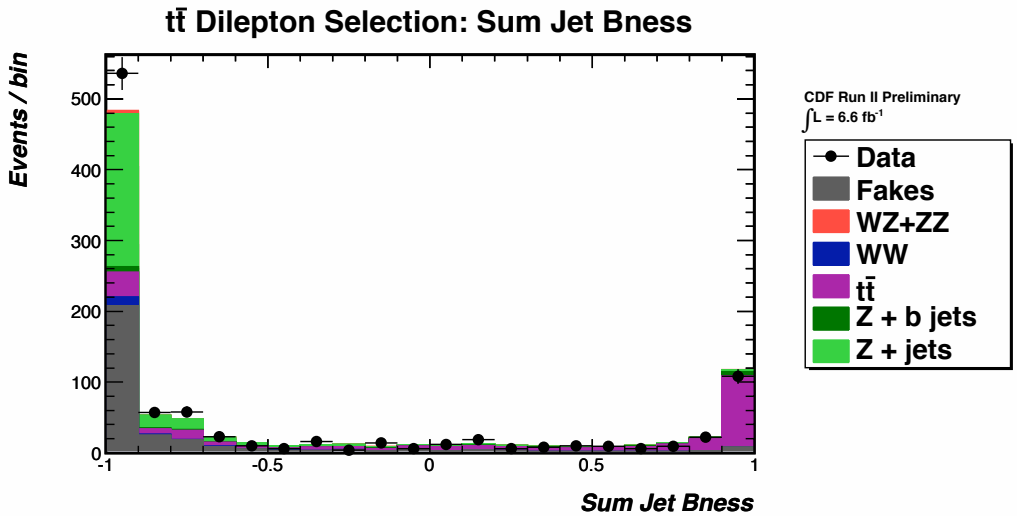
Jet *b*ness Tagger: Efficiency and Mistag Rates

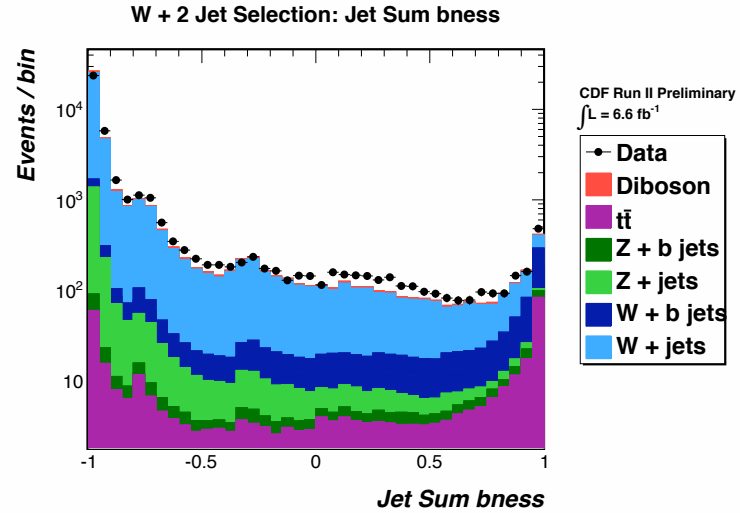


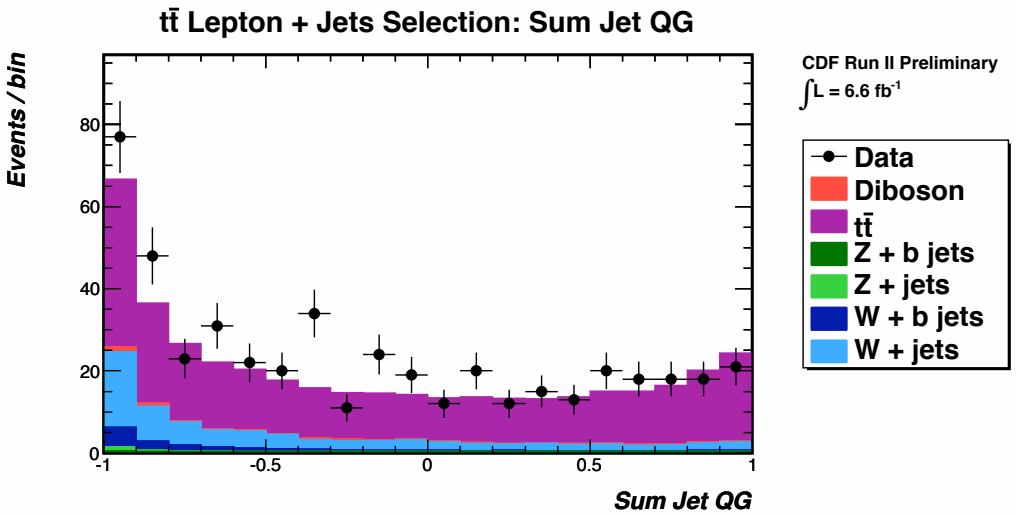
Jet QG Discriminant: Flow Chart

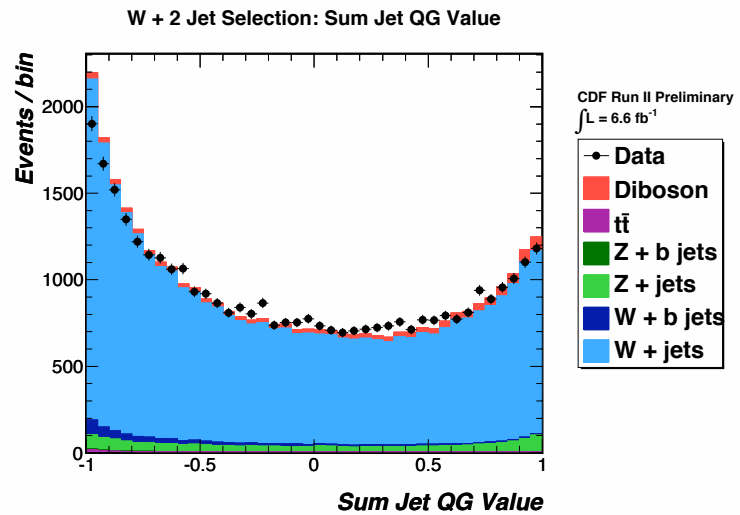


Jet QG Discriminant: Efficiency/Mistag Rates

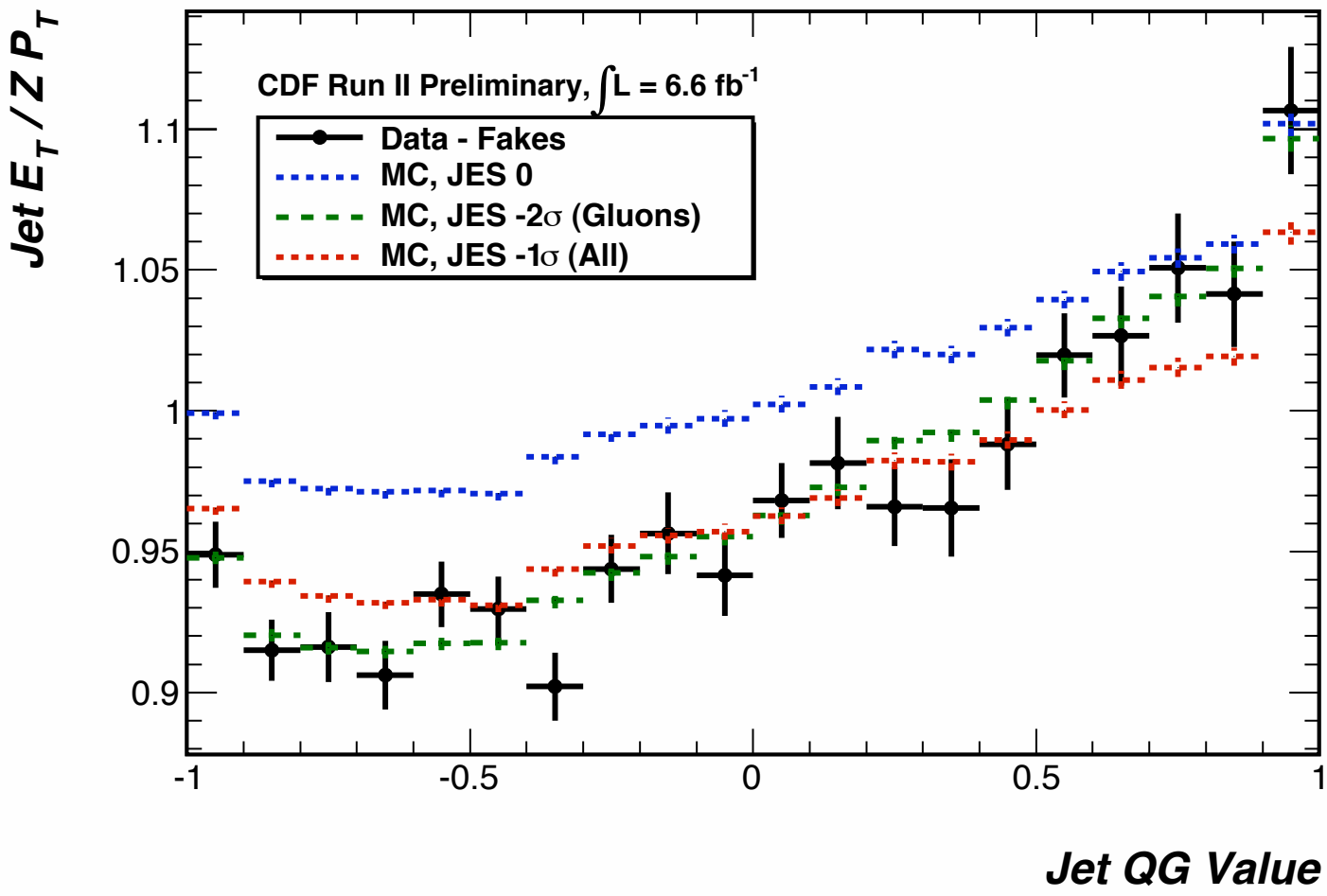




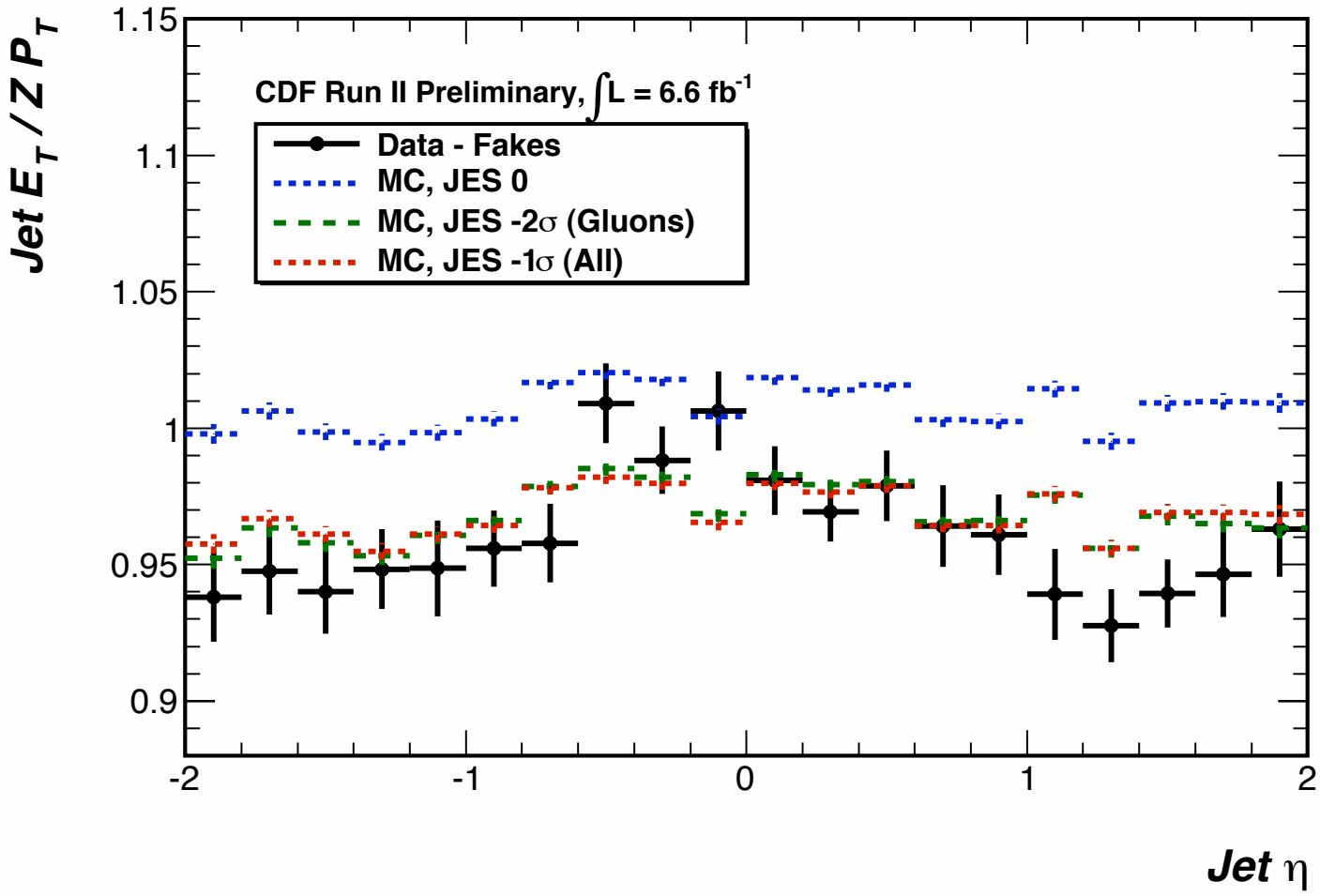




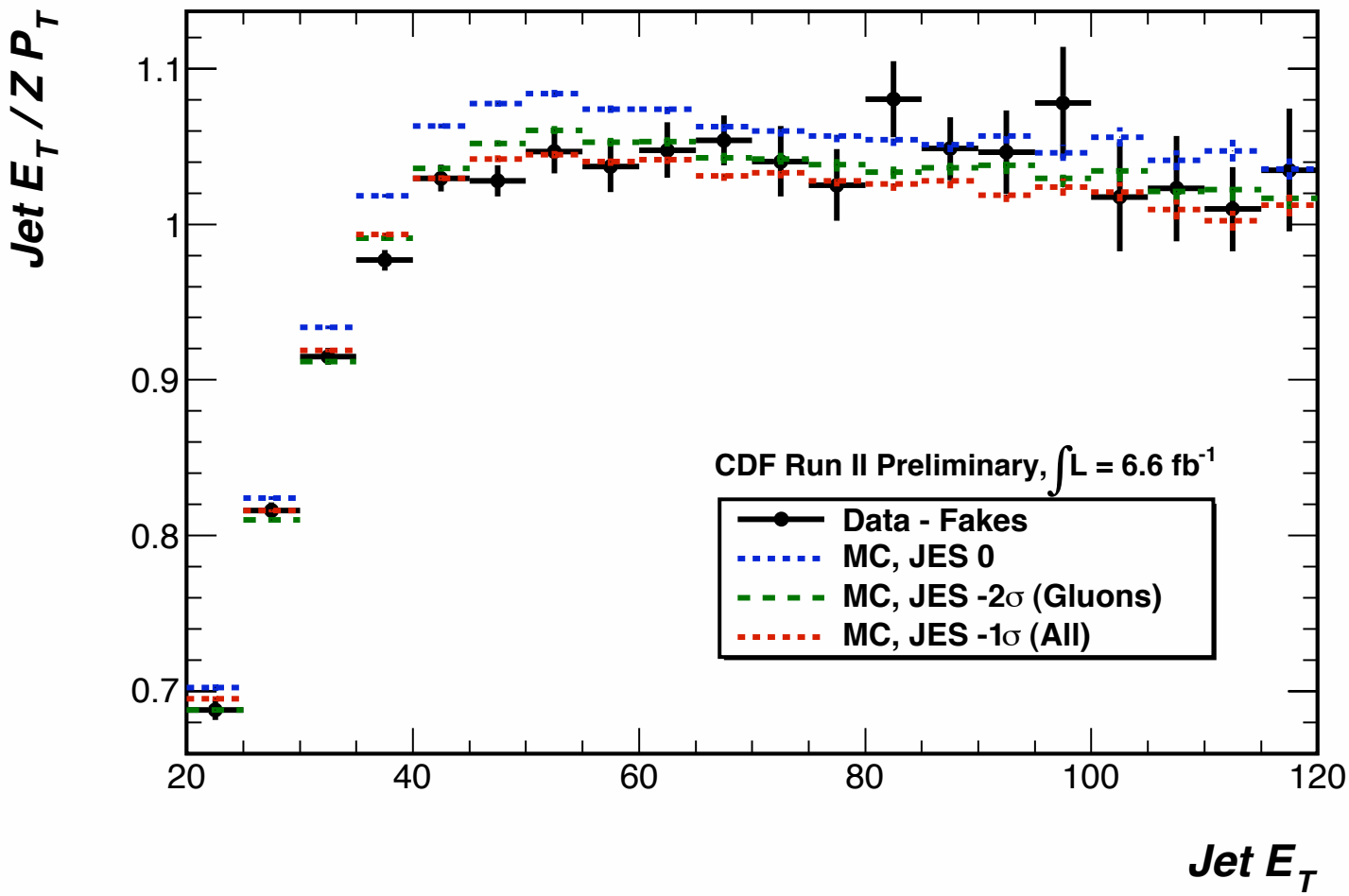
Z-Jet Balancing: Jet QG Value



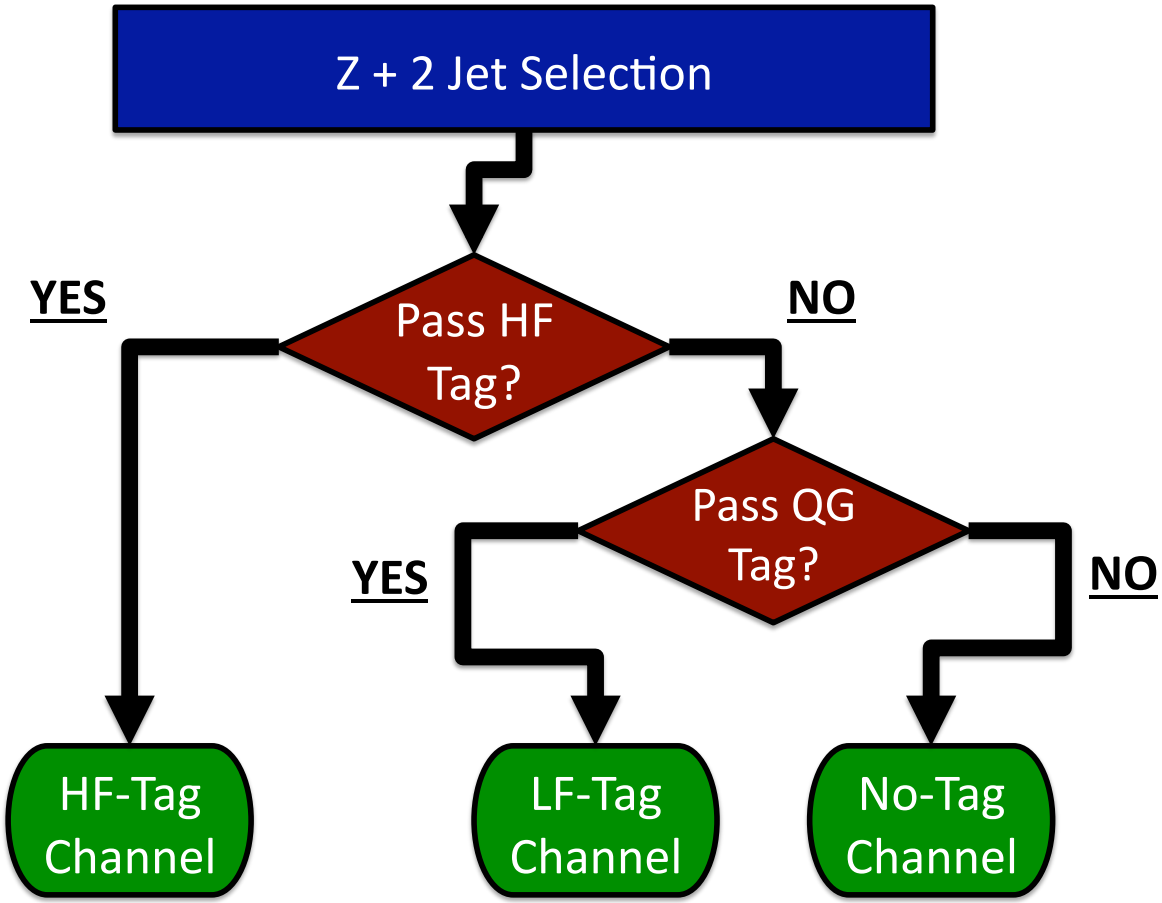
Z-Jet Balancing: Jet η



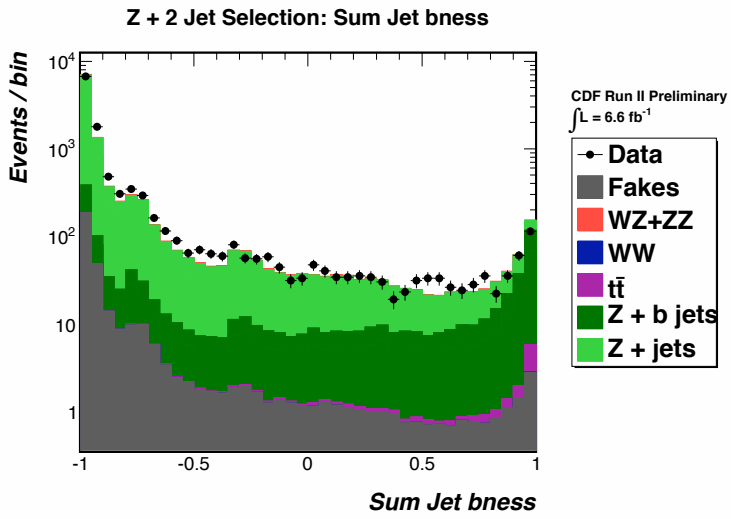
Z-Jet Balancing: Jet E_T

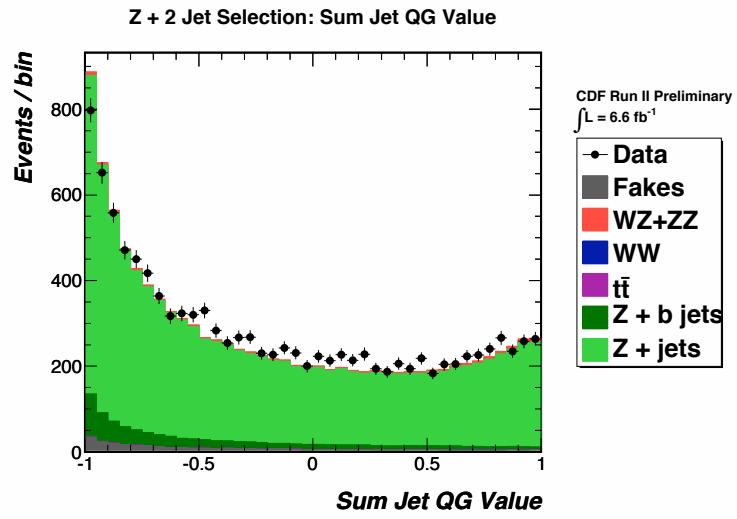


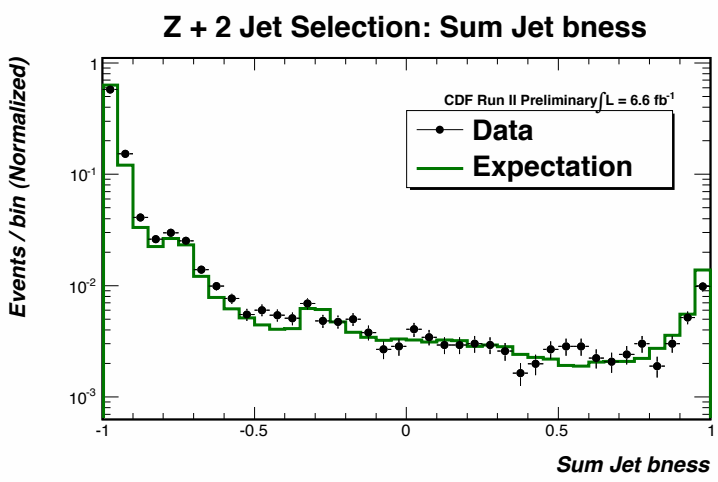
Flow Chart for Analysis

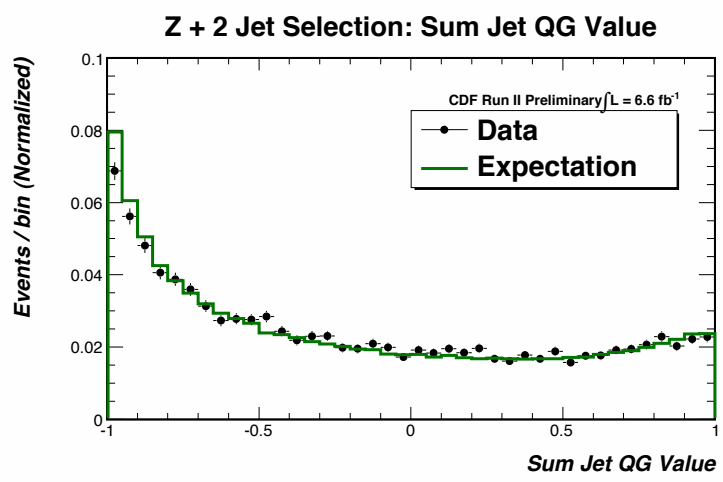


Z + 2 Jet Selection: Tagging Variables









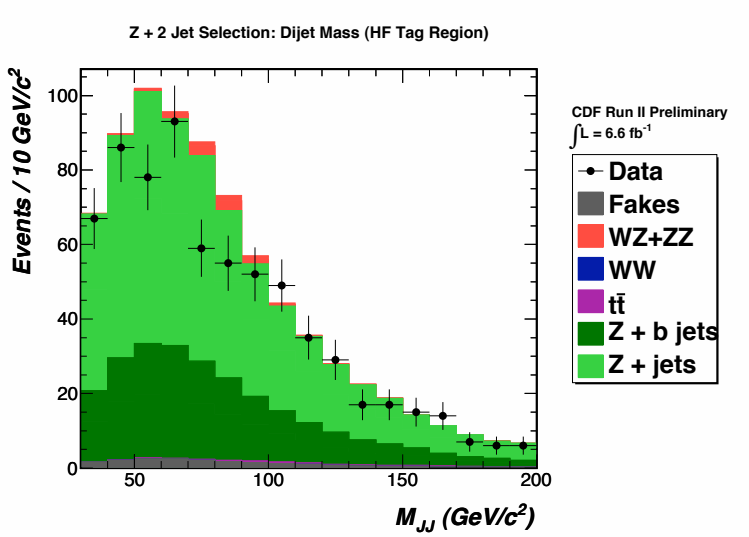
Charged Leptons + Jets: Expected Events

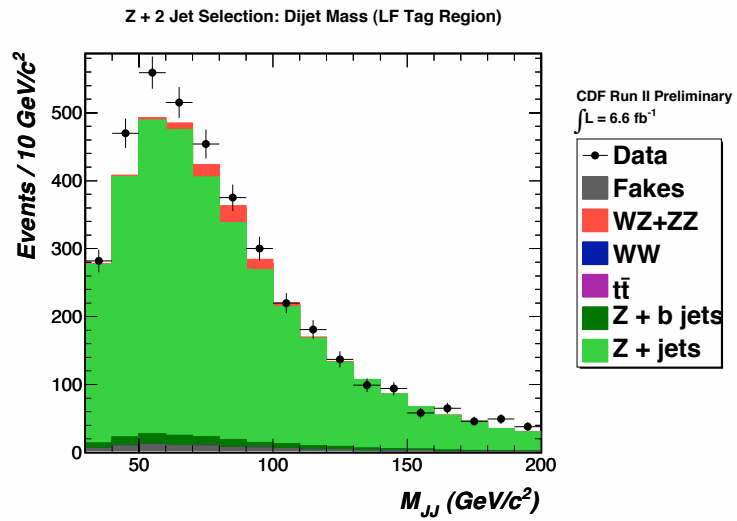
CDF Run II Preliminary, $\int L = 6.6\ fb^{-1}$

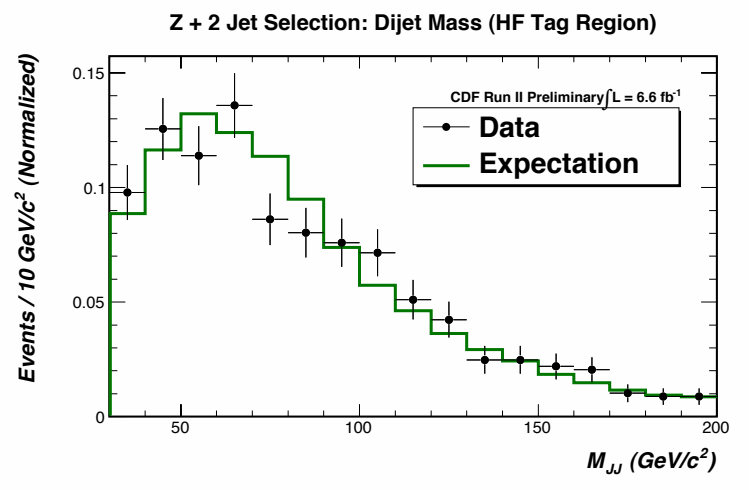
Process	N_{events} (HF Tag)	N_{events} (LF Tag)	N_{events} (No Tag)
Z + jets	730 ± 120	3510^{+550}_{-630}	5490^{+970}_{-1120}
$t\bar{t}$	$4.26^{+0.56}_{-0.59}$	$0.86^{+0.19}_{-0.23}$	$2.51^{+0.42}_{-0.36}$
WW	0.025 ± 0.002	$0.26^{+0.07}_{-0.04}$	$0.56^{+0.07}_{-0.19}$
Fakes	18.9 ± 4.7	82 ± 21	196 ± 49
Total Background	760^{+120}_{-130}	3600^{+550}_{-620}	5690^{+970}_{-1120}
WZ/ZZ	$15.9^{+2.0}_{-2.1}$	$87.2^{+9.7}_{-9.4}$	$80.3^{+9.6}_{-9.2}$
Total Predicted	770^{+120}_{-130}	3690^{+560}_{-630}	5770^{+980}_{-1120}
Data	685 ± 26	3942 ± 63	5976 ± 77

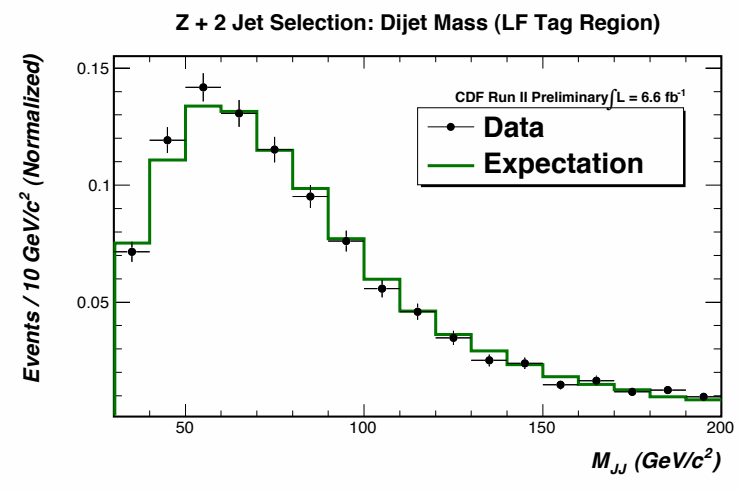
$WZ/ZZ \rightarrow l^+l^-jj$ *Search*

Z + 2 Jet Selection: Dijet Mass Fit Templates

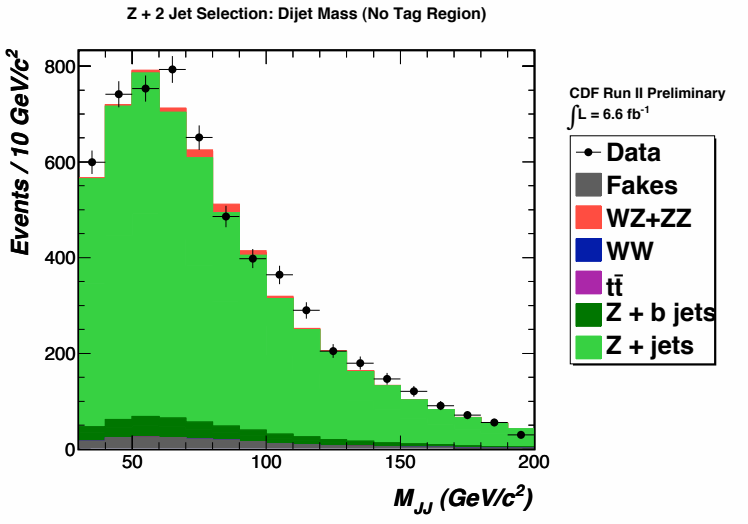


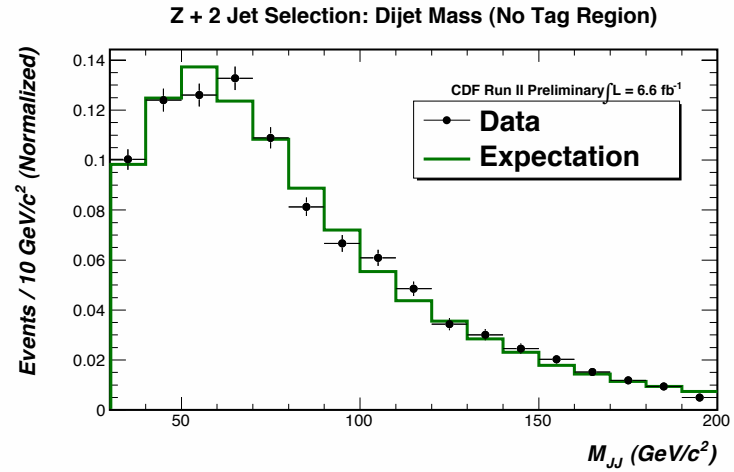






Z + 2 Jet Selection: Dijet Mass Fit Templates



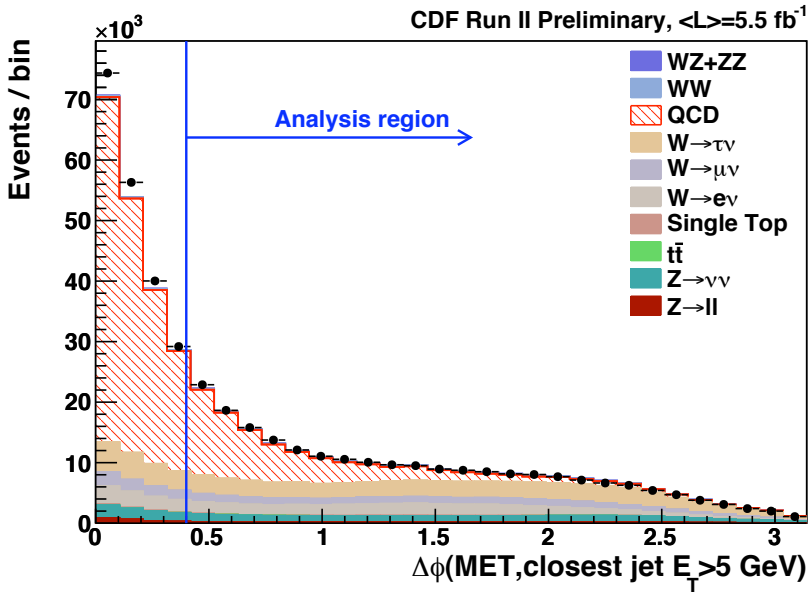


Remaining Backgrounds

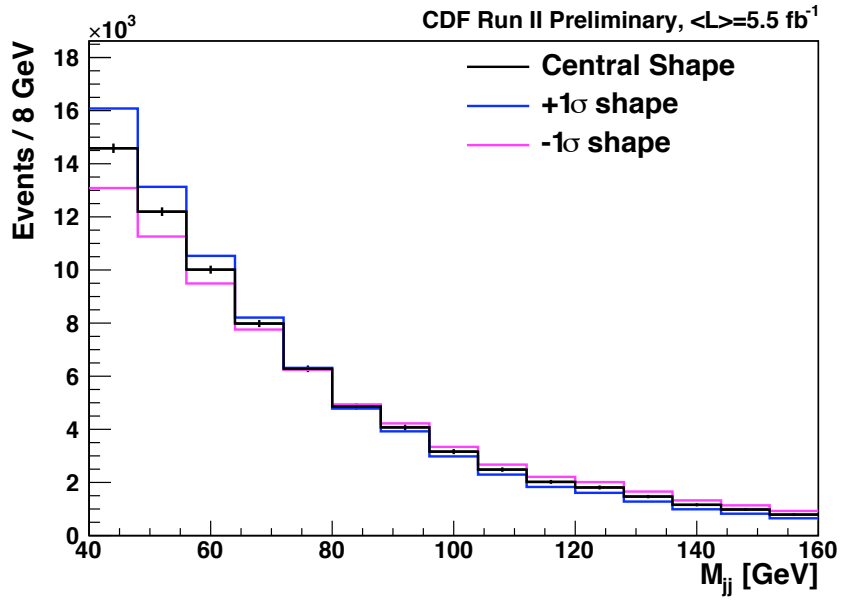
- Backgrounds
  - Top quark production
    - Add cuts to reduce top-pair production background
      - MET + jets: cuts on jet and lepton multiplicty
      - Leptons + jets: Require MET < 25 GeV
  - WW diboson production (MET + jets)
    - Indistinguishable from signal (WZ/ZZ) from dijet mass
    - Use *b* tagging to pick out events with Z→*bb*

MET + Jets: Multijet Production Modeling

MET Quality Cuts in
MET + Jets Analysis



QCD dijet mass distribution in
MET + Jets Analysis



Systematic Uncertainties: Charged Leptons + Jets

CDF Run II Preliminary, $\int L = 6.6\ fb^{-1}$

	Normalization	JES	b-tag	QG-Tag	Q^2
Z + jets					
HF Tag Region	—	±12%	+10%,-8.3%	—	Shape Only
LF Tag Region	—	+14%,-16%	-0.5%,+0.4%	+1.0%,-1.9%	Shape Only
No Tag Region	—	+16%,-19%	-1.0%,+0.9%	-0.6%,1.2%	Shape Only
$t\bar{t}$					
HF Tag Region	±6.45%	+0.4%,-0.1%	+8.9%,-9.8%	—	—
LF Tag Region	±6.45%	+0.3%,-0.4%	-17%,+16%	+11%,-19%	—
No Tag Region	±6.45%	+4.4%,-2.4%	-9.5%,+11%	-3.8%,6.6%	—
WW					
HF Tag Region	±6%	—	—	—	—
LF Tag Region	±6%	+12%,-9.4%	—	+20%,-0%	—
No Tag Region	±6%	+32%,-8.4%	—	-9.6%,-0%	—
Signal					
HF Tag Region	—	+4.2%,-4.3%	+9.7%,-10%	—	—
LF Tag Region	—	+5.5%,-4.4%	-0.7%,+0.6%	+6.3%,-6.6%	—
No Tag Region	—	+6.0%,-5.4%	-1.2%,+1.4%	-6.9%,+7.2%	—
Fakes (All Regions)	±25%				

$WZ/ZZ \to l^+l^-jj$ *Search*

Systematic Uncertainties: Charged Leptons + Jets

CDF Run II Preliminary, $\int L = 6.6\ fb^{-1}$

Acceptance Uncertainty	
Lepton Energy Scale	$\pm 0.7\%$
Lepton Energy Resolution	$\pm 0.14\%$
Trigger/Lepton Reconstruction Efficiency	$\pm 2.2\%$
Jet Resolution	$\pm 2.5\%$
ISR/FSR	$\pm 1.2\%$
PDF	$\pm\ 2\%$
Luminosity	$\pm 6\%$

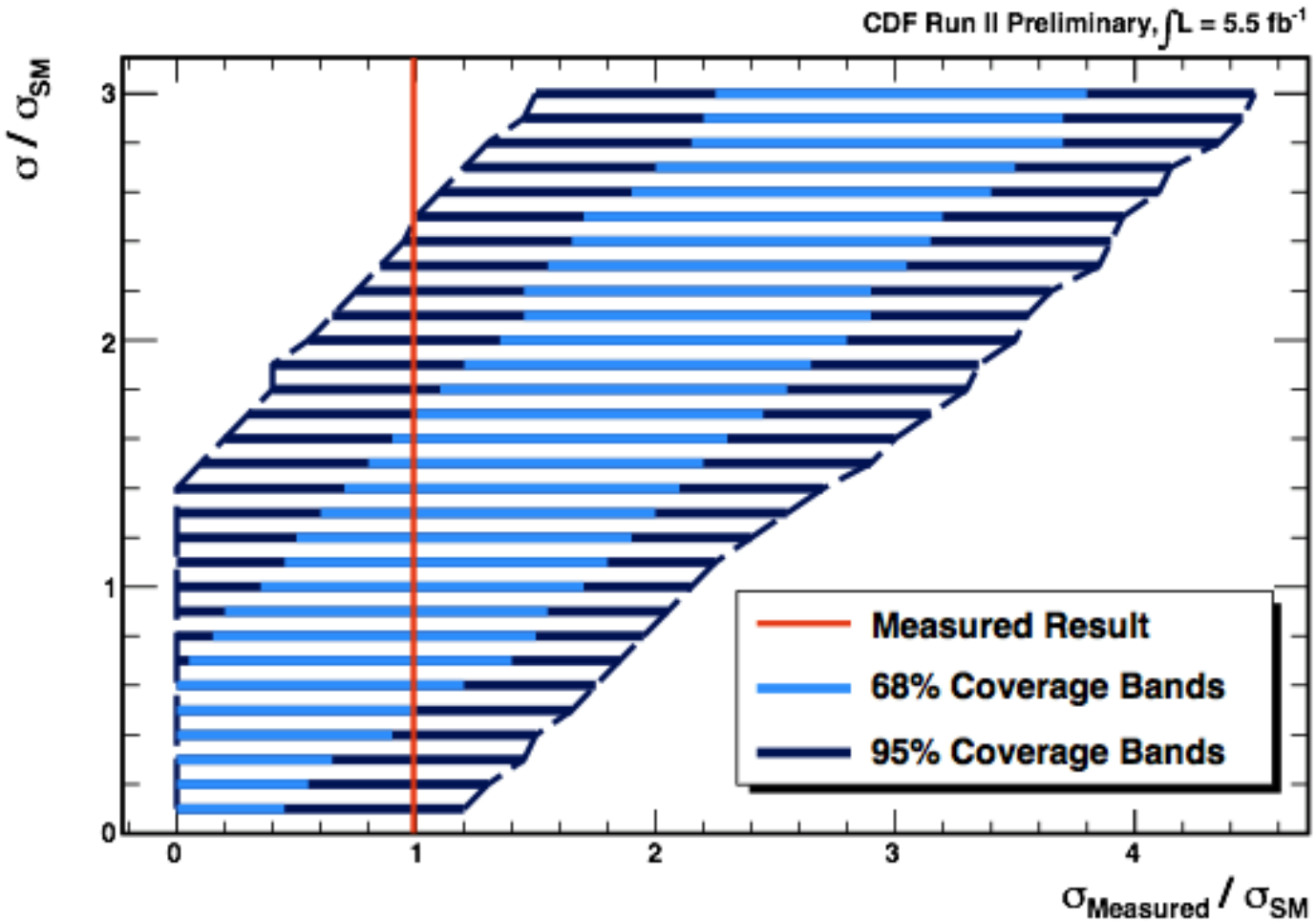
$WZ/ZZ \rightarrow l^+l^-jj$ *Search*

Systematic Uncertainties: MET + Jets

CDF Run II Preliminary

Systematic	channel	WZ/ZZ	WW	$t\bar{t}$ & single t	EWK	QCD
Cross Section (Norm.)	no-tag		$\pm$ 6%	$\pm$ 7.9%		$\pm$ 7%
	2-tag		$\pm$ 6%	$\pm$ 6.9%		$\pm$ 13.5%
EWK Shape	both				✓	
QCD Shape	both					✓
JES Shape/Rate	no-tag	yes/$\pm$ 7.1%	yes/$\pm$ 7.6%	no/$\pm$ 3.7%		
	2-tag	yes/$\pm$ 6.9%	yes/$\pm$ 7.6%	no/$\pm$ 3.2%		
$b$ness cuts (up)	no-tag	+0.46%	+0.08%	+2.3%		
	2-tag	−13.2%	−23.9%	−12.1%		
$b$ness cuts (down)	no-tag	−0.51%	−0.08%	−2.7%		
	2-tag	+14.4%	+25.8%	+14.5%		
Acceptance						
JER		$\pm$ 0.7%	$\pm$ 0.7%	$\pm$ 0.7%		
$\not{E}_T$ Model		$\pm$ 1.0%	$\pm$ 1.0%	$\pm$ 1.0%		
ISR/FSR		$\pm$ 2.5%	$\pm$ 2.5%	$\pm$ 2.5%		
PDF		$\pm$ 2%	$\pm$ 2%	$\pm$ 2%		
Lumi/Trigger e		$\pm$ 6.4%	$\pm$ 6.4%	$\pm$ 6.4%		

Feldman-Cousins Bands for MET+ Jets



Feldman-Cousins Bands for Charged Leptons + Jets