Update on the di-jet mass spectrum in W+2 jet events at CDF

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on behalf of the CDF collaboration

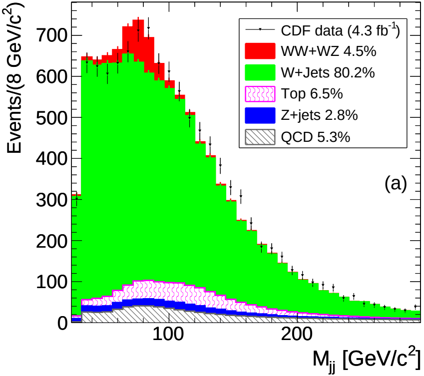
Tuesday 23rd of July 2013

CERN-EP Seminar

Introduction

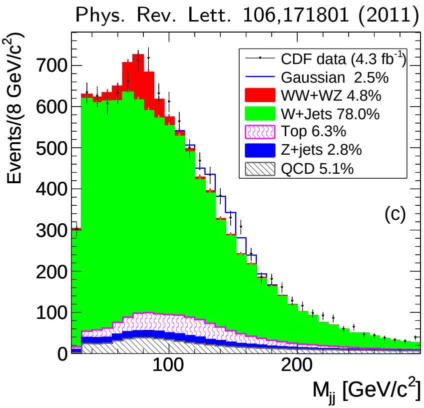
- In 2011, CDF reported an excess of events around a dijet mass of 145 GeV/c^2 using 4.3 fb^{-1} of data

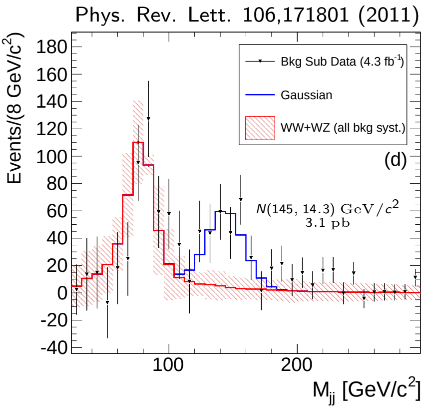
Phys. Rev. Lett. 106,171801 (2011)



Introduction

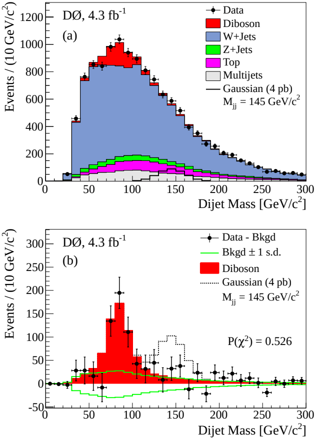
- In 2011, CDF reported an excess of events around a dijet mass of 145 GeV/c^2 using 4.3 fb^{-1} of data
- "*One possible way to interpret this disagreement is an excess in the* 120 – 160 GeV/c^2 *range*" with a 3.2σ significance





Cross-checks by other experiments

Phys. Rev. Lett. 107, 011804 (2011)



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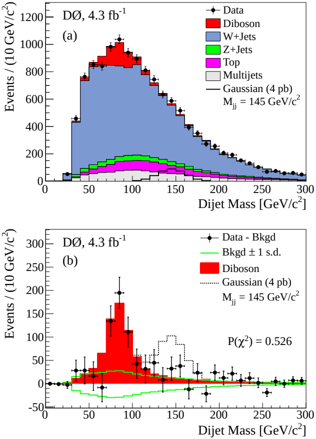
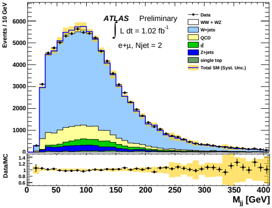
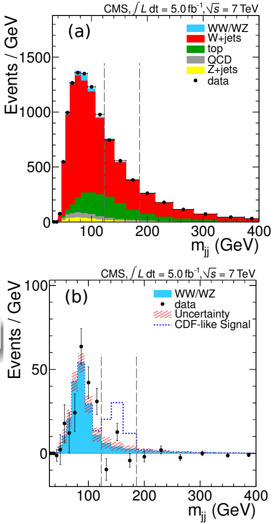


ATLAS-CONF-2011-097



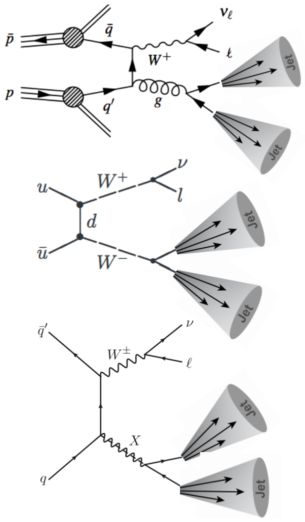
Phys.Rev. Lett. 109, 251801 (2012)



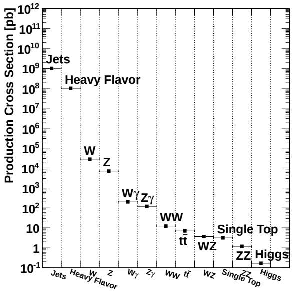
What is going on?

Excess not confirmed by other collider experiments

Motivation – Why it matters



- W (and Z) production in association with jets is a **fundamental test of the Standard Model**
- These processes are **dominant backgrounds** to diboson, single-top, SM Higgs, etc.
- As a consequence, they also need to be understood to study **physics beyond the SM**



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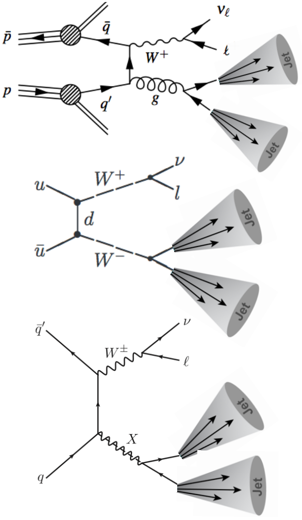

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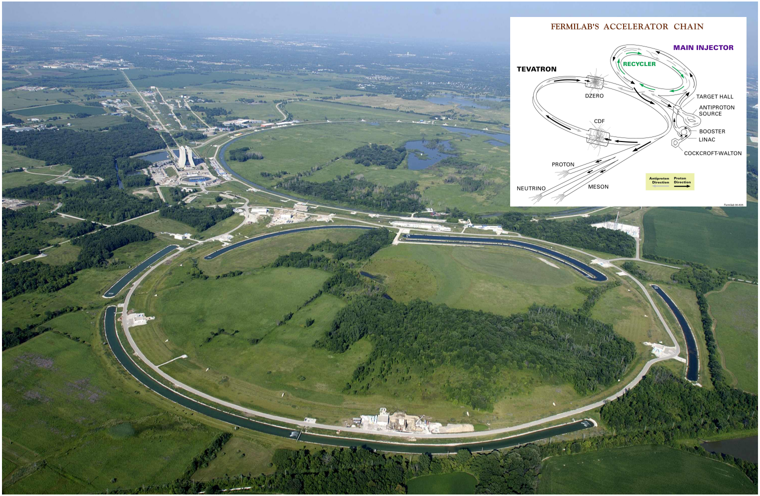
Also, CDF needs to study this signature to understand where the discrepancy comes from, and how it affects CDF physics results!

Outline

- Experimental Apparatus
- Update of previous result using full CDF-II data set
- Studies in orthogonal samples
- Updated results
- Discussion of impact on CDF analyses

The Tevatron (1983 - 2011)

A proton-antiproton collider with a center of mass energy of 1.96 TeV.

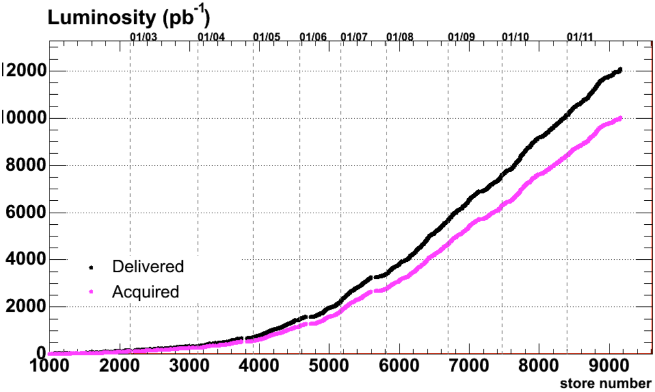


The Tevatron (1983 - 2011)

The CDF experiment.

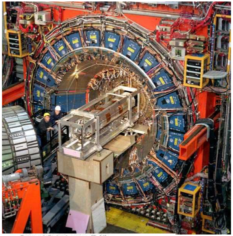
The Tevatron (1983 - 2011)

The Tevatron and CDF performed well in delivering and acquiring quality data.



Many thanks to all the people who made this possible!

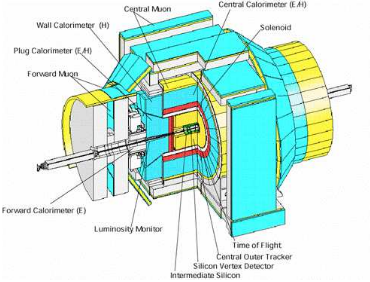
The CDF II detector



- A well-understood multi-purpose detector;
- Relatively compact: 10m×10m×15m;
- Basic detection sub-systems: two tackers, a calorimeter, and muon chambers;

The CDF sub-detectors

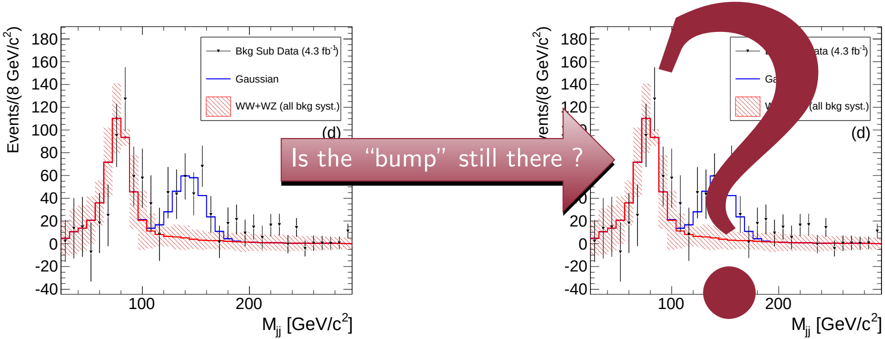
Silicon Detector:	Precision vertex detection and heavy flavor tagging up to $\|\eta\| \sim 2$;
Drift chambers:	Charged particle p_T measurement up to $\|\eta\| \sim 1.5$;
Calorimeters:	Electromagnetic and hadronic, with 4π coverage up to $\|\eta\| \sim 3.5$;
Muon chambers:	Muon identification up to $\|\eta\| \sim 1.5$;



Coverage is not very good compared to LHC experiments.

Di-jet resonance analysis with full CDF-II data set

- The original analysis used 4.3 fb^{-1} of data
- The complete dataset is over two times larger!
- Re-did the analysis to check for this effect

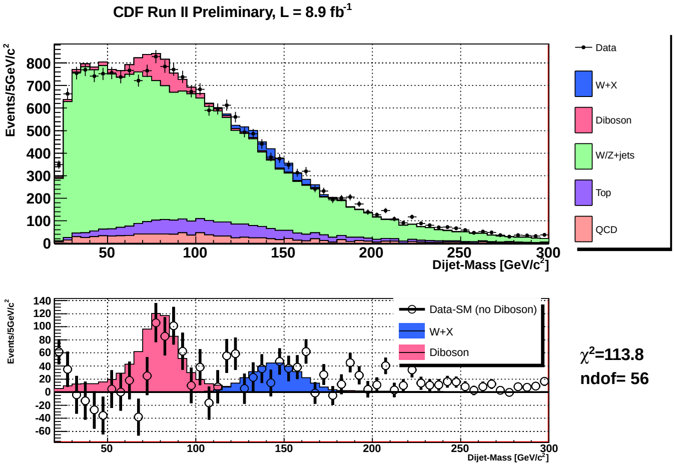


Event Selection

Let us recall the event selection:

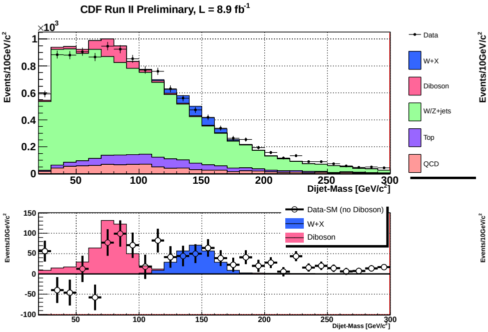
- Dijet selection:
  - Two jets (j_1, j_2) with $E_T^j > 30$ GeV and $|\eta| < 2.4$ $(E_T^{j_1} > E_T^{j_2})$
  - No additional jet with those requirements
- W selection:
  - One lepton with $|\eta| < 1.0$ and $E_T > 20$ GeV $[e]$ or $p_T > 20$ GeV$/c$ $[\mu]$
    Online selection: resp. $E_T > 18$ GeV and $p_T > 18$ GeV$/c$
    Electrons: calorimeter showers consistent with EM interactions $(E_{EM}/E > 0.9)$
    Muons: high quality track with good matching to hit in the muon chambers
  - $\not{E}_T > 25$ GeV and $m_T^W > 30$ GeV$/c^2$
- Requirements to remove multi-jet background:
  - $p_T^{jj} > 40$ GeV$/c$, $|\Delta\eta(j_1, j_2)| < 2.5$ and $\Delta\phi(\not{E}_T, j_1) > 0.4$

Analysis with full CDF-II data set – Outcome

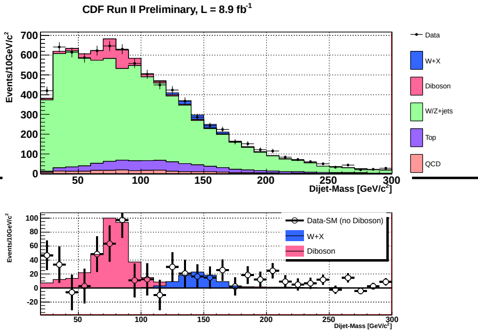


The effect is further enhanced.

Analysis with full CDF-II data set – Outcome



[Electron sample]



[Muon sample]

Similar effect in both e and μ
Electrons particularly affected!

State of affairs

- Effect reported by CDF (using 4.3 fb^{-1}) is not seen by other experiments
- Effect still there after re-analysis using full CDF data set (over 2x bigger)

What's going on ? What did we miss ?

Internal cross-checks in orthogonal samples

- $\not{E}_T$-dijet channel: sensitive to missed leptons from W decays
- $\ell\ell$-jet channel: cleaner sample, probing potential ZX production

Using orthogonal channels (different analysis techniques) for hints on what's going on!

Two jets and large $\not\!\!E_T$

Data set: 9.1fb^{-1} of data collected by CDF-II (final set)

Event selection

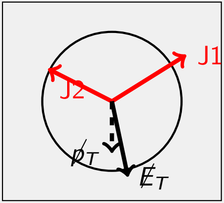
- Orthogonal to $\ell\nu jj$: explicit **veto** of identified electrons or muons
- $\not\!\!E_T > 50$ GeV
- 2 or 3 jets: $E_T^{j_1} > 35$ GeV, $E_T^{j_2} > 25$ GeV, $E_T^{j_3} > 15$ GeV with $|\eta^{j_i}| < 2.0$
  - For good tracker coverage, we require that either j_1 or j_2 have $|\eta^{j_i}| < 0.9$
  - For good separation, we demand $\Delta R(j_1, j_2) > 1$
  - The third jet allows selecting hadronic τ decays
- Cleanup cuts: cosmic rejection, halo removal, etc. (applied to data only)

At this point, QCD multi-jet production is by far the largest background

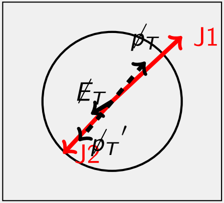
QCD multi-jet background rejection

- Defining $\not{p}_T = |-\sum_{\text{tr}} \vec{p_T}|$, we require $\Delta\phi(\not{E}_T, \not{p}_T) < \pi/2$ [arXiv:1205.4470]

$ZZ \to \nu\nu jj$



QCD $b\bar{b}$



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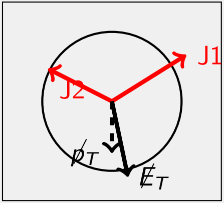

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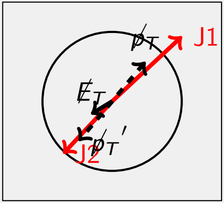
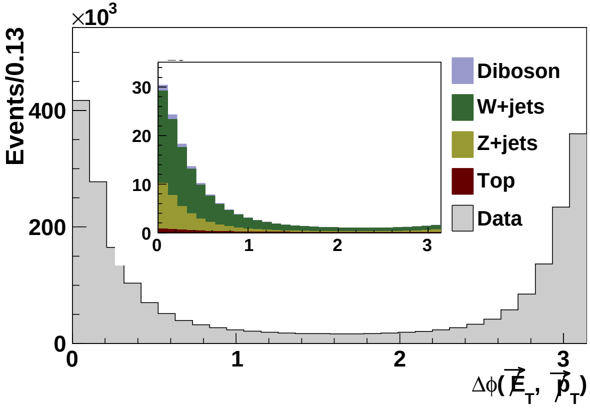




Events with $\Delta\phi(\not{E}_T, \not{p}_T) > \pi/2$ are used to model QCD multi-jet production

Process modeling

Process	Modeling	Cross-section (pb)
WW	PYTHIA	12.4 ± 1.4
WZ	PYTHIA	3.7 ± 0.4
ZZ	PYTHIA	3.6 ± 0.4
$t\bar{t}$	PYTHIA	7.04 ± 0.46
Single top s-channel	MADEVENT+PYTHIA	1.05 ± 0.17
Single top t-channel	MADEVENT+PYTHIA	2.12 ± 0.32
W/Z+jets	ALPGEN+PYTHIA	$\not\!\!E_T$ fit
QCD multi-jet	data-driven	$\not\!\!E_T$ fit

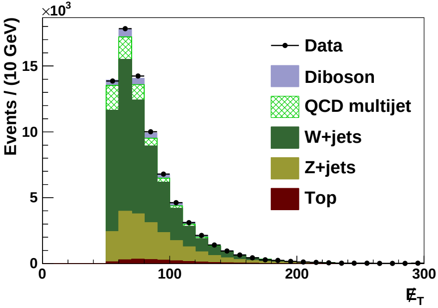
More on the $\not\!\!E_T$ fit

- $\not\!\!E_T$ shape distribution distinguishes W/Z+jets from QCD multi-jet well
- Diboson, single top, and top pair fixed to theoretical predictions
- QCD multi-jet and W/Z+jets free to float (correlating W+jets and Z+jets)
- Outcome: k-Factor of 1.21 (± 19% for Z+jets, ± 30% for W+jets)

Additional selections

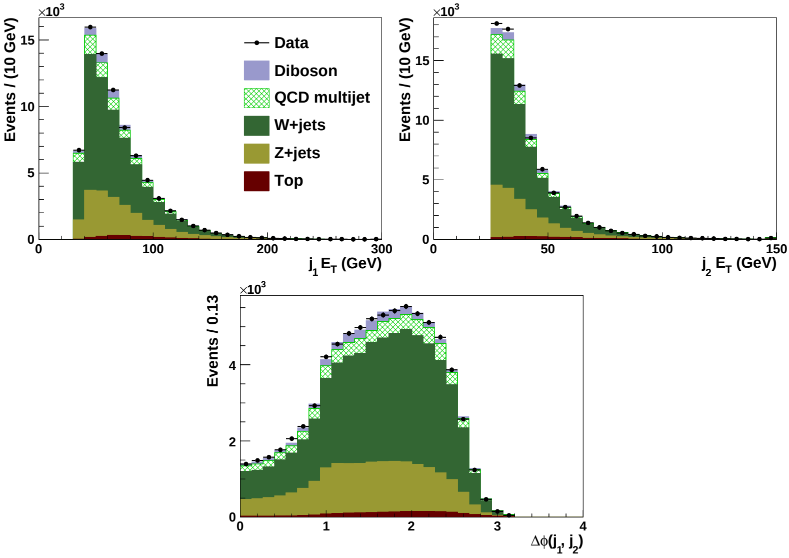
1. Reject mis-measured jets: $\Delta\phi(\not{E}_T, j_i) > 0.8$
2. Keep events where $\not{E}_T$ is significant: $\not{E}_T / \sqrt{\sum E_T} > 3.5\ \mathrm{GeV}^{1/2}$
3. Reject events with low $\not{p}_T$ by requiring $\not{p}_T > 20\ \mathrm{GeV}/c$
4. Matched "jet" and "calo" $\not{E}_T$: $\not{H}_T / \not{E}_T < 1.2$, with $\not{H}_T \equiv \left| -\sum_{\mathrm{jets}} \vec{E}_T^{j} \right|$

These cuts reject 99% of the QCD multi-jet events

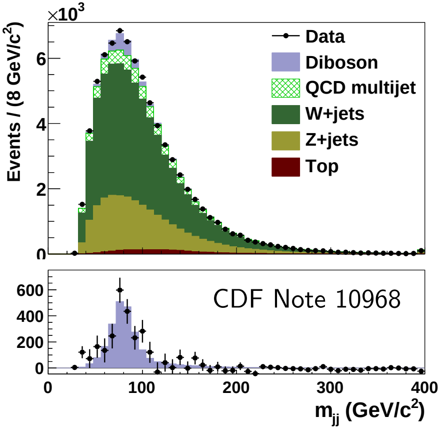


Process	Yield		
WW	1850	±	165
WZ	674	±	61
ZZ	378	±	34
Top	2037	±	189
W+jets	46176	±	14188
Z+jets	19713	±	6057
QCD multijet	6276	±	1193
Total expected	77104	±	21887
Data	77149		

Excellent model agreement with data



Diboson cross-section measurement ($VV = WW, WZ, ZZ$)



- Fitting the m_{jj} distribution, VV floating
- Flat, non-negative prior probability for $\sigma(VV)$
- Unit Gaussian priors for nuisance parameters

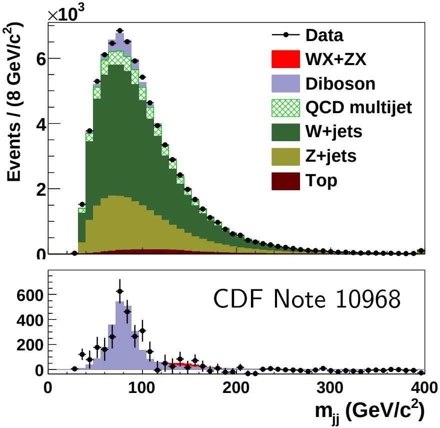
Systematic	Rate (%)
QCD normalization*	19
Background cross-sections	6.5-30
JES*	1.4-12.9
$\mathcal{L}$	5
PDF	2
Lepton veto	2
Trigger efficiency	2
Q^2 scale*	shape only

* indicates a shape systematic

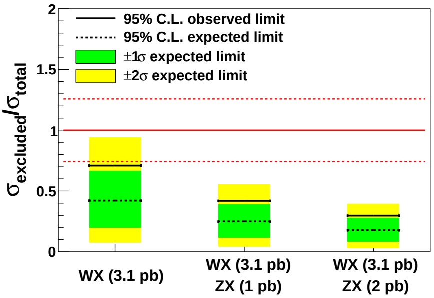
$\sigma(p\bar{p} \to VV) = 13.8^{+3.0}_{-2.7}$ pb ; SM prediction: $\sigma(p\bar{p} \to VV) = 16.8 \pm 1.0$ pb

γ^* and Z contributions restricted to $[40, 140]$ GeV$/c^2$ mass range

Limits on $W + X$ and $Z + X$ production



- VV cross-section floating within $\pm 6\%$
- Adding $N(145, 14.4)\ \mathrm{GeV}/c^2$
- Considering three scenarios



Excluding $W + X$ at the level of the excess in Phys. Rev. Lett. 106,171801 (2011) at 95% C.L.

Another orthogonal cross-check

Two jets and two charged leptons

Measurement of $\sigma(ZZ + ZW \rightarrow \ell\ell jj)$

Data set: 8.9 fb^{-1} of data collected by CDF-II (final set)

Event selection:

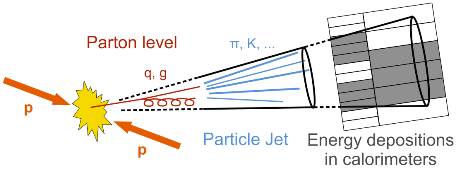
- Orthogonal to $\ell\nu jj$: requiring two charged leptons (sensitive to $Z + jj$)
  - $p_T^\ell > 20\ \mathrm{GeV}/c$
  - $76 < m_{\ell\ell} < 106\ \mathrm{GeV}/c^2$
- Two jets with $E_T^j > 25\ \mathrm{GeV}$, $|\eta^j| < 2.0$, and $\Delta R(l, j) > 0.4$
  - Well separated: $\Delta R(j_1, j_2) > 0.7$
- Small missing transverse energy: $\not{E}_T > 20\ \mathrm{GeV}$

Analysis technique:

- Uses 3 flavor channels: heavy-flavor, light-flavor, and “un-tagged”
- Introducing ANN to separate quark jets form gluon jets (from $Z \rightarrow \ell\ell$)

Jet Energy Scale (JES)

- The jets are mostly reconstructed using the JetClu algorithm ($R = 0.4$)
- The jet energies measured by the calorimeter require **corrections** to match tower-cluster energies to parton-level energies
- The default CDF corrections include various effects: non-linear response, pile-up, η corrections, etc.
- These corrections are derived from γ**-jet balancing**



Jet Energy Scale (JES)

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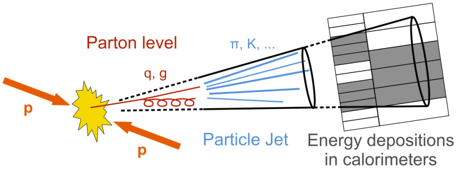
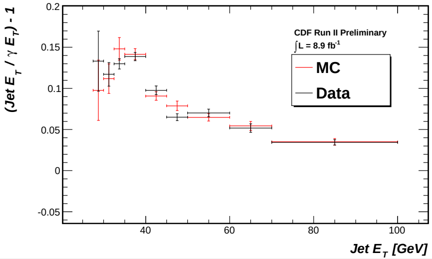


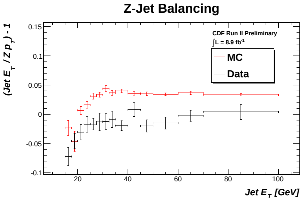
CDF Note 10864 **γ-Jet Balancing**



Good agreement between Data and MC

Jet Energy Scale (JES) in Z+jet events

- Studying JES in $Z \to \ell\ell + 1$ jet events possible due to large dataset
- It turns out that the standard corrections do not work very well (esp. in MC)



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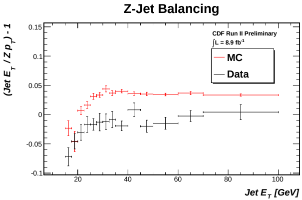
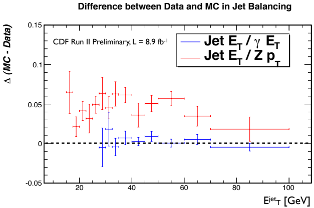
- In particular, there is a **discrepancy between data and MC**





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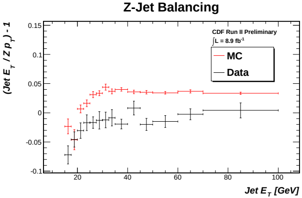
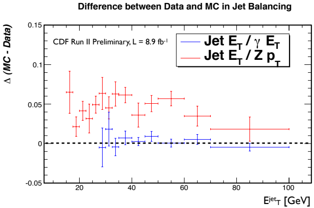
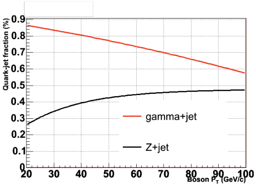
- Studying JES in $Z \to \ell\ell + 1$ jet events possible due to large dataset
- It turns out that the standard corrections do not work very well (esp. in MC)
- In particular, there is a **discrepancy between data and MC**
- The effect is due to the different quark/gluon fraction in these samples

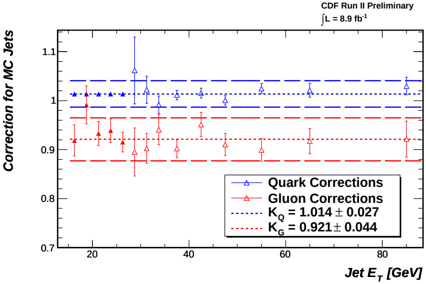






Standard CDF JES corrections not applicable to gluon jets!

Additional JES correction for quak/gluon jet content



CDF Run II Preliminary

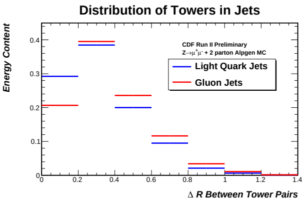
		Quark jets	Gluon jets
JES Correction		1.014	0.921
Uncertainty	Fit/Statistics	0.020	0.025
	$F_Q^{Z-\text{jet}}$	0.006	0.021
	$F_Q^{\gamma-\text{jet}}$	0.018	0.027
	Low E_T Extrapolation		0.004
	N_{vert} difference	0.002	0.012
	Total	± 0.027	∓ 0.044

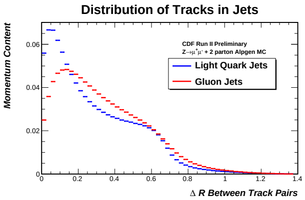
Derived for JETCLU ($R = 0.4$) and MC showered with *Pythia*

No corrections applied to data

ANN to separate quark jets form gluon jets

- Quark/Gluon separation by looking
  1. at the distribution of energy in calorimeter towers
  2. at the distribution of momenta in reconstructed charged-particle tracks
- Two networks: NN_{Towers} and NN_{Track}





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  1. at the distribution of energy in calorimeter towers
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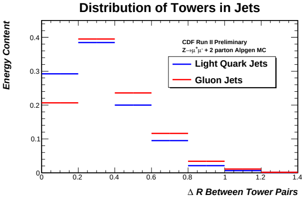
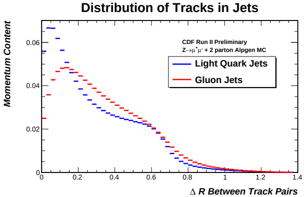
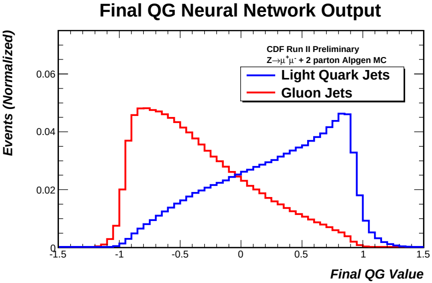
- Two networks: NN_{Towers} and NN_{Track}
- Two networks combined into a QG NN output



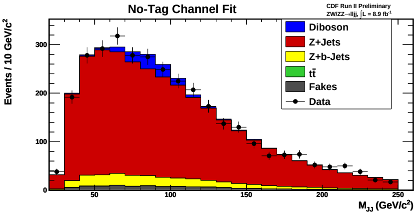




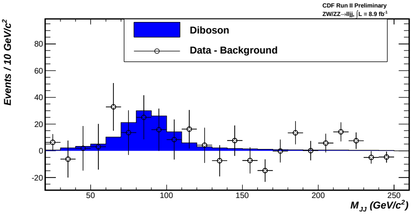
Useful for quark-gluon JES studies!

More in CDF Note 10864

$ZZ + ZW \to \ell\ell jj$ – Results



No "bump" here either!



CDF Run II Preliminary

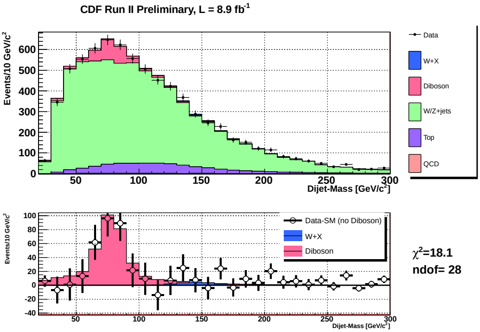
$ZW/ZZ \to \ell\ell jj$, High dijet p_T, $\int L = 8.9$ fb^{-1}

	Events
Z + jets	$3\,016 \pm 382$
$Z + b$ jets	267 ± 111
$t\bar{t}$	4.8 ± 0.5
Misidentified Leptons	102 ± 51
Diboson $(ZW + ZZ)$	129 ± 13
Total Predicted Events	$3\,517 \pm 430$
Data Events	3 349

More in CDF Note 10864

Main analysis result: $\sigma(ZW + ZZ) = 2.5^{+2.0}_{-1.0}$ pb **(SM ~ 5.08 pb)**

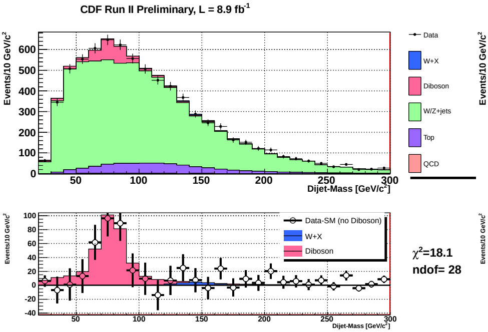
Effect of qg JES corrections on m_{jj} in $\ell\nu jj$ events



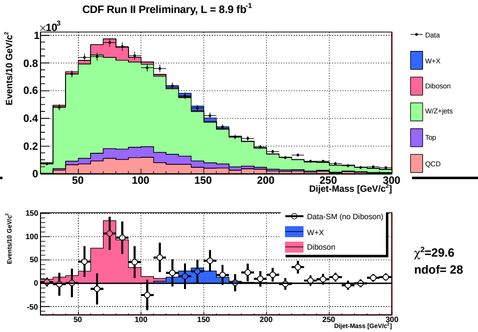
[Muon sample]

Effect has disappeared from μ sample

Effect of qg JES corrections on m_{jj} in $\ell\nu jj$ events



[Muon sample]



[Electron sample]

Effect has disappeared from μ sample
Electrons still affected!

There's still something missing!

What's different between the e and μ samples ?

Let's take a closer look!

Background estimation

Process	Shapes	Rate constraint
Diboson	PYTHIA	Theory ($\pm$6%)
$t\bar{t}$	PYTHIA	7.65 ± 0.42 pb
single-top	MADEVENT+PYTHIA	Theory ($\pm$6%)
W/Z+jets	ALPGEN+PYTHIA	None
Multi-jet background	data-driven	

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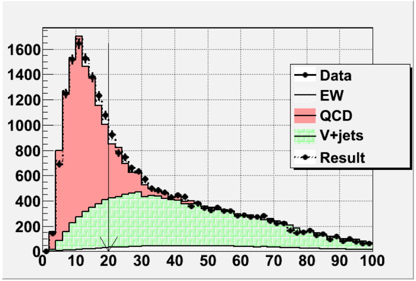
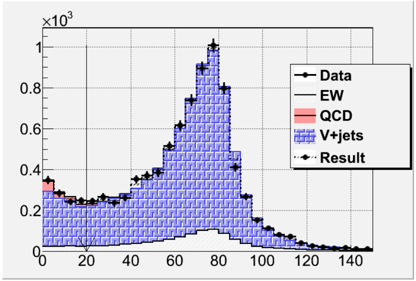
W/Z+jets	Alpgen+Pythia	None
Multi-jet background	data-driven	





- Proportion of QCD in background is estimated by fitting the $\not{E}_T$ distribution
- Very different composition between the e and μ samples

Background estimation

Process	Shapes	Rate constraint
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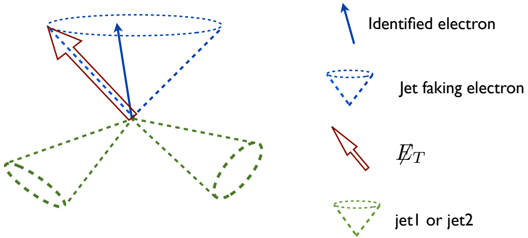
$t\bar{t}$	PYTHIA	7.65 ± 0.42 pb
single-top	MADEVENT+PYTHIA	Theory (±6%)
W/Z+jets	ALPGEN+PYTHIA	None
Multi-jet background	data-driven	

Most obvious answer is fake lepton background!

- Negligible for the μ sample
- Sizeable for the electron sample

QCD multi-jet background

- 3-jet QCD events can fake the signal when one jets is identified as an electron
- The $\not{E}_T$ arises form mis-measurements in the calorimeter



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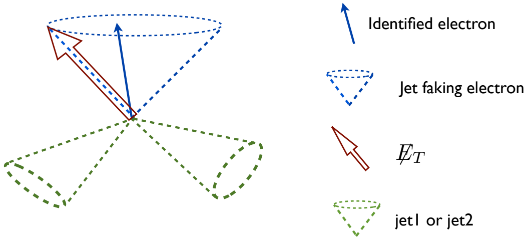
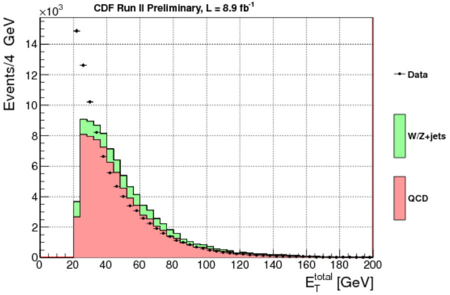


Fake lepton model from non-electron sample

- Uses same kinematics, but reverses electron-ID (e.g. requiring $E_{EM}/E < 0.9$)
- Electron has larger E_{EM}/E than non-electron, affecting the online efficiency

Correcting for online efficiency

- Using a **control region** where the effects are magnified
- Consists in events with $\not{E}_T < 20$ GeV or $m_T^W < 30$ GeV$/c^2$
- Orthogonal to the signal region, and with about 85% of QCD background



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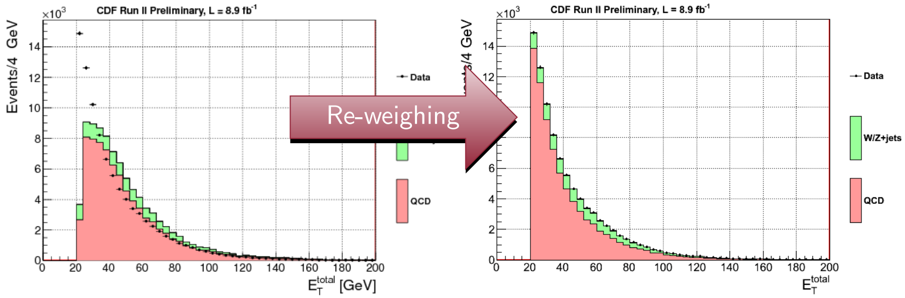
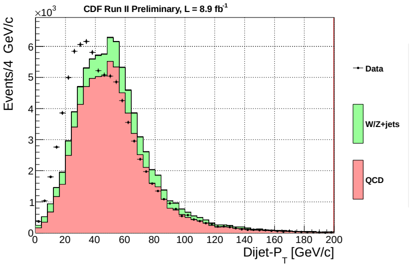
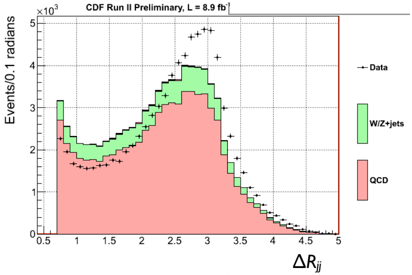


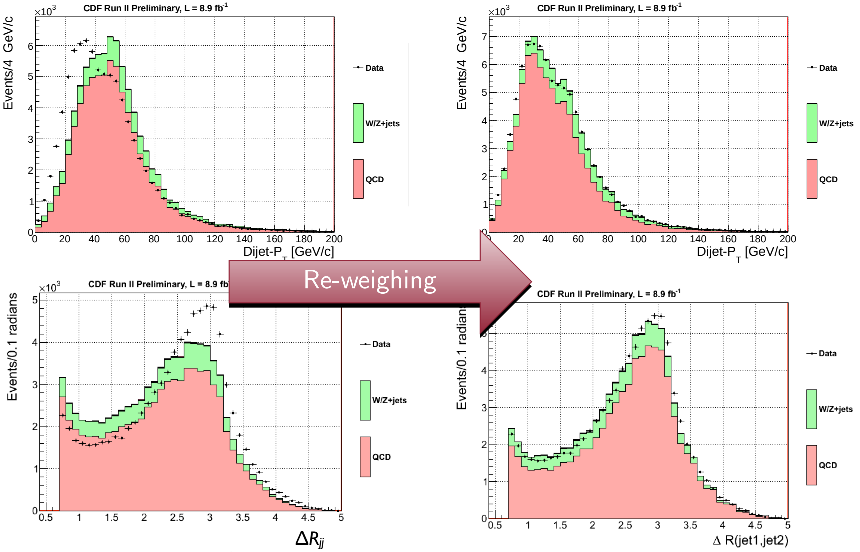
- The efficiency of the online selection (trigger) is much lower for non-electrons
- After reweighing, we check the effect on other kinematic variables

Cross-checks in multi-jet-enriched (control) region





Cross-checks in multi-jet-enriched (control) region



Effect on m_{jj} (in signal region)

- So far, so good. But how is the m_{jj} distribution in the signal region affected ?

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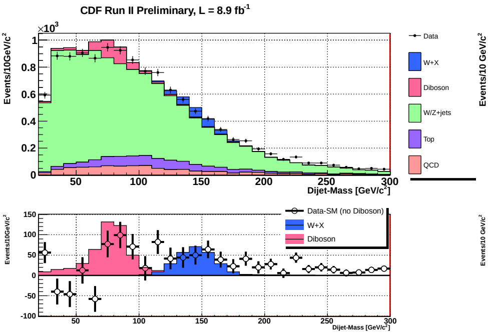
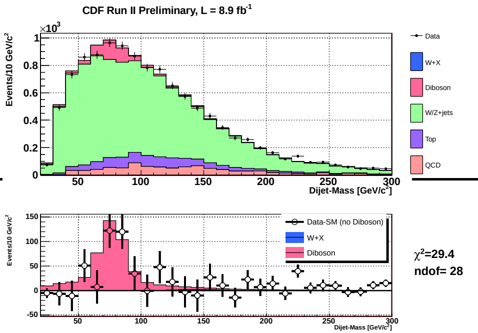


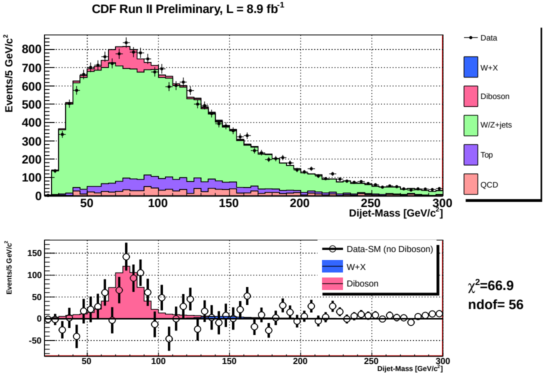
[Before re-weighing]



[After re-weighing]

Effect has totally disappeared!

Final word on m_{jj} in $\ell\nu jj$ from CDF



Systematic	Uncertain
QCD normalization	15
Background cross-sections	5.5 -
$\mathcal{L}$	6
ISR/FSR	2.5
PDF	2.2
Q-JES	2.7
G-JES*	4.8
JER	0.7
Trigger efficiency	2.2

* 100% anti-correlated to Q-JES

New upper limit: $\sigma(WX) < 0.9$ pb at 95% C.L. (was 3.1 pb)

As expected, this was not new physics

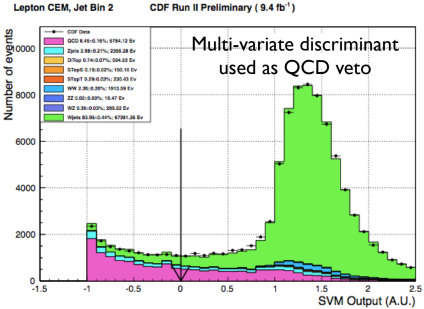
Excellent agreement with the Standard Model

Impact on CDF physics results

Non-negligible effects uncovered; how do they affect other CDF results ?

SM Higgs

- Quark/Gluon JES effects already included in latest result.
- Effect of QCD model fix is negligible
  - Applies only to 1 out of the 3 main analyses
  - Effect was partially accounted for
  - QCD fraction is about $\sim 2\%$ (tight QCD veto)

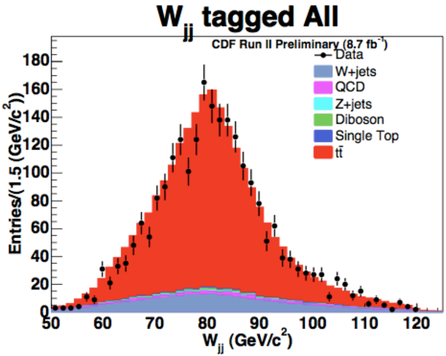


Impact on CDF physics results

Non-negligible effects uncovered; how do they affect other CDF results ?

Top physics

- Checked: no effect from quark/gluon JES found
  - Top pair sample gluon-free to high extent
- Effect of QCD model fix is negligible ($\sim 5\%$ QCD)



Impact on CDF physics results

Non-negligible effects uncovered; how do they affect other CDF results ?

QCD measurements

- Cross-section analyses use MIDPOINT ($R = 0.7$) or ANTIKT jets
- These are less sensitive to soft radiation
- $\Delta\mathrm{JES}(\mathrm{MC} - \mathrm{Data})$ within standard uncertainty for JETCLU ($R = 0.7$) jets

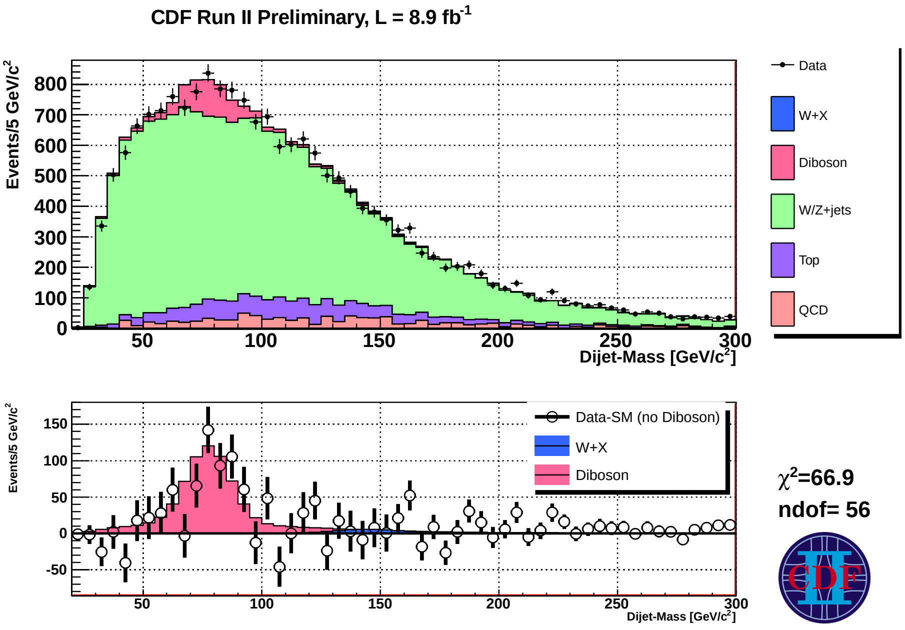
Many cross-check performed.
No significant impact on CDF analyses!

Summary

- Discrepancy reported in 2011 using 4.3 fb^{-1} of data is **now understood**
- That's good, because no other experiment confirmed it
- Big effort (~2 years) by the CDF collaboration to reach this point!
- **Composite effect:** JES for quark- and gluon-jets and electron fakes model
- These effects affect have **no significant impact on other CDF results**
- Derived new upper limit: $\sigma(WX) < 0.9$ pb at 95% C.L. (was 3.1 pb)
- Several cross-checks performed in $\not{E}_T + jj$ and $\ell\ell + jj$ signatures
- All details to be **published in PRD** soon
  - Already available as a CDF Note: `http://www-cdf.fnal.gov/physics/new/hdg/Results_files/results/w2jet_130222/DijetMassSpectra.pdf`

No new physics

Thank You!



CDF Run II Preliminary, L = 8.9 fb-1
Events/5 GeV/c2
Dijet-Mass [GeV/c2]
Data
W+X
Diboson
W/Z+jets
Top
QCD
Data-SM (no Diboson)
W+X
Diboson
χ2=66.9
ndof= 56
CDF