Study of the Dijet Invariant Mass in W + 2 jet events by the DØ Collaboration

Jadranka Sekaric for the DØ Collaboration (University of Kansas)

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How did it all begin …

Measurement of the WW/WZ cross section in the $l\nu jj$ final states

Significant excess of events in the dijet mass distribution at $M_{JJ} \sim 145$ GeV (3.2$\sigma$)

- Excess modeled with a Gaussian with a width expected from the dijet mass resolution
- Efficiency from MC WH with $m_H@150$ GeV→lνbb
- If a new particle X, with BR($X\to jj$) = 1: $\sigma(pp\to WX) \approx 4$ pb

Results from the CDF Experiment (I)

PRL 106, 171801 (2011)
Significant excess of events in the dijet mass distribution at $M_{JJ} \sim 145$ GeV (4.3$\sigma$)
Do the DØ data show a similar excess at $M_{JJ} \sim 145$ GeV?

- Same event selection as in the CDF analysis
- Detailed treatment of systematic uncertainties

- Fit SM processes to data
  - Is there an excess of events similar to that in CDF data?

- Include a model “a la CDF” for $WX \rightarrow \ell vjj$ in the fit
  - How large excess do the DØ data support?

Cross checks with signal-injected data
The DØ Collaboration

86 institutions, ~500 collaborators
The DØ Experiment (Fermilab, US)

- Integrated Luminosity
  Recorded by DØ: 10.3 fb\(^{-1}\)
- Peak Luminosity
  \(4.2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}\)

Multipurpose detector operates with efficiency > 90%
The DØ Detector

Pseudorapidity: $\eta = -\ln \left( \tan \frac{\theta}{2} \right)$

Calorimeters
- Electromagnetic (EM)
- Fine Hadronic (FH)
- Coarse Hadronic (CH)

Tracking Detectors
- Silicon Microstrip Vertex Detector
- Central Fiber Tracker

2T Solenoid Magnet

1.8T Toroid Magnet

Electromagnetic (EM) Fine Hadronic (FH) Coarse Hadronic (CH)

Muon Scintillators

Muon Chambers

Preshower detectors

Shielding

Calorimeter

Toroid

Scintillating tiles

Drift tubes

3 Layer Muon System

Electronics, Trigger, DAQ

Preshower detectors

1.8T Toroid Magnet

2T Solenoid Magnet

[Diagram showing the layout of the DØ detector with various sub-components and their positions]
Event Selection

$W(\rightarrow l\nu) + 2$ jets from 4.3 fb$^{-1}$ DØ data, single lepton and lepton + jets triggers

Electrons
- $p_T \geq 20$ GeV, $|\eta| \leq 1.0$
- Isolated in calorimeter/tracker
- Good EM shower shape
- Match to a track

Muons
- $p_T \geq 20$ GeV, $|\eta| \leq 1.0$
- Isolated in calorimeter/tracker
- Hits in muon system (3 layers)
- Match to a track

Global Selection

Missing $E_T$ (MET) $\geq 25$ GeV, $M_T(W\rightarrow l\nu) \geq 30$ GeV

$M_T(W\rightarrow l\nu) < 200$ GeV (in the muon channel)

Veto events with more than 1 charged lepton
Event Selection

W(→lν) + 2 jets from 4.3 fb⁻¹ DØ data, single lepton and lepton + jets triggers

Jets
• Cone algorithm with radius R = 0.5
• Energy deposition in the calorimeter in transverse and longitudinal directions is consistent with hadronic jet
• At least two tracks originating from the primary interaction point
• Two jets with p_T ≥ 30 GeV (we do not veto events with extra jets with p_T < 30 GeV)
• Jet |η_J| < 2.5, |Δη_{JJ}| < 2.5, p_T(JJ) ≥ 40 GeV, Δφ(leading jet, MET) > 0.4
W(→lν) + 2 jets from 4.3 fb⁻¹ DØ data, single lepton and lepton + jets triggers

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- Jet $|\eta_J| < 2.5$, $|\Delta\eta_{JJ}| < 2.5$, $p_T(JJ) \geq 40$ GeV, $\Delta\phi$(leading jet, MET) > 0.4

### Standard Jet Energy Scale
Measured in photon+jet and dijet events
*(quark dominated)*
Correct the jet energy back to the particle-level for:
- detector energy response
- out-of-cone showering
- additional $p\bar{p}$ interaction (pileup, ZB/MB)
W(\rightarrow l\nu) + 2 jets from 4.3 fb^{-1} DØ data, single lepton and lepton + jets triggers

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Additional Jet Energy Calibration
(relative data/MC corrections)

Measured in $Z$+jet events (for MC: Alpgen) 

*(gluon dominated)*

Correct $p_T$ imbalance and energy resolution for:

- soft out-of-cone radiation
- different quark/gluon sample composition

(applied to Alpgen $W$+jet sample)
Modeling of SM processes

<table>
<thead>
<tr>
<th>Event Source</th>
<th>Generator</th>
<th>$\sigma$(SM) / $\sigma$(WW) = 12.4 pb</th>
</tr>
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<tbody>
<tr>
<td>WW</td>
<td>Pythia</td>
<td>1.0 NLO</td>
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<tr>
<td>WZ</td>
<td>Pythia</td>
<td>0.3 NLO</td>
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<td>Pythia</td>
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<tr>
<td>W+light flavor jets</td>
<td>Alpgen</td>
<td>800 from FIT</td>
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<td>W+heavy flavor jets</td>
<td>Alpgen</td>
<td>30 from FIT</td>
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<tr>
<td>Z+light flavor jets</td>
<td>Alpgen</td>
<td>30 NNLO</td>
</tr>
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<td>Z+heavy flavor jets</td>
<td>Alpgen</td>
<td>1 NNLO</td>
</tr>
<tr>
<td>Double-Top</td>
<td>Alpgen</td>
<td>0.6 NNLO</td>
</tr>
<tr>
<td>Single-Top</td>
<td>Comphep</td>
<td>0.2 NNLO</td>
</tr>
</tbody>
</table>

**Multijet Background**
(jet misidentified as a lepton)

- Estimated from (multijet enriched) data
  - Muon channel: Reverse muon isolation cuts
  - Electron channel: Loose electron quality criteria
- Corrected for contributions already accounted for by MC
- Normalization: template fit of $M_T(W \rightarrow l\nu)$
Modeling of SM processes

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**Standard MC Corrections**
(to account for differences from data)

- Reconstruction and Identification efficiencies of leptons/jets
- Trigger selection
- Z boson \( \rho_T \) modeling
Modeling of $V+\text{jets}$ processes ($V = W, Z$)

- $W+\text{jets}$ is the dominant background. Important to understand/model properly.
- Different generators, different predictions.

- In analyses with looser jet $p_T$ cuts ($WH\rightarrow l\nu b\bar{b}$), discrepancies of this type have been seen. ⇒ data-driven corrections (+ uncertainties) to model $\Delta R_{JJ}$, $\eta_J$, $W p_T$ distributions.

Plot courtesy of Adam Martin
Modeling of $V$+jets processes

(V = W, Z)

- W+jets is the dominant background
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- In analyses with looser jet $p_T$ cuts (WH→lνbb) discrepancies of this type have been seen
  ⇒ data-driven corrections (+ uncertainties) to model $\Delta R_{JJ}$, $\eta_{J}$, $W$ $p_T$ distributions

- In this analysis
  (higher jet $p_T$ cuts reduce discrepancies)
  ⇒ no data-driven corrections

1. Include uncertainties due to modeling of Alpgen variables $\Delta R_{JJ}$, $\eta_{J}$, $W$ $p_T$
Modeling of V+jets processes 

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1. Include uncertainties due to modeling of Alpgen variables
   $\Delta R_{JJ}$, $\eta_J$, $W$ $p_T$

We do not apply these corrections when comparing to the CDF result
Modeling of $V$+jets processes

$(V = W, Z)$

- $W$+jets is the dominant background
  Important to understand/model properly
- Different generators, different predictions

- In analyses with looser jet $p_T$ cuts ($WH \rightarrow l\nu bb$) discrepancies of this type have been seen
  $\Rightarrow$ data-driven corrections (+ uncertainties) to model $\Delta R_{JJ}$, $\eta_J$, $W p_T$ distributions

1. Include uncertainties due to modeling of Alpgen variables $\Delta R_{JJ}$, $\eta_J$, $W p_T$

We perform a cross check with these corrections applied
2. Include uncertainties due to tuning of Alpgen parameters

- Parton-jet matching parameters ($p_T$, $\Delta R$)
- Parton shower model and underlying event (tunes)
- Renormalization/factorization scales

Change MLM jet $p_T$ matching threshold by 2.5 GeV

Pythia vs. Herwig

Change renormalization scale by 20%
### Systematic Uncertainties

**Normalization (flat) and/or Differential (shape) of the dijet mass distribution**

max. deviation in the shape/normalization of the dijet mass distribution after ±1σ parameter changes

given in [%]

<table>
<thead>
<tr>
<th>Source of systematic uncertainty</th>
<th>Diboson signal</th>
<th>W+jets</th>
<th>Z+jets</th>
<th>Top</th>
<th>Multijet</th>
<th>Nature</th>
<th>Δσ (pb)</th>
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<tbody>
<tr>
<td>Trigger/Lepton ID efficiency</td>
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<td>±2</td>
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<td>Jet energy resolution</td>
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<td>Jet vertex confirmation</td>
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<td>Multijet shape, electron channel</td>
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<td>Parton distribution function</td>
<td>±1</td>
<td>±5</td>
<td>±4</td>
<td>±3</td>
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<tr>
<td>Unclustered Energy correction</td>
<td>±&lt;1</td>
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<td>±3</td>
<td>±&lt;1</td>
<td>D</td>
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<td><strong>ALPGEN η and ΔR(jet1, jet2) corrections</strong></td>
<td>±&lt;1</td>
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<td>D</td>
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<td><strong>ALPGEN W pt corrections</strong></td>
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<td>D</td>
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<td>D</td>
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<td>Renormalization and factorization scales</td>
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<td><strong>ALPGEN parton-jet matching parameters</strong></td>
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Correlated if common for electron and muon channels, but mutually independent
Study of the dijet mass distribution in the DØ data

Fit SM contributions to data
⇒ Is there an excess of events similar to that in CDF data?

Include a model “a la CDF” for WX→lνjj in the fit
⇒ How large excess do the DØ data support?
Fit of SM contributions to data

- Best fit of all SM contributions to the data using the dijet mass distribution, minimizing Poisson $\chi^2$ function (ratio of Poisson likelihoods + prior information on the systematic uncertainties)

\[
\chi^2(\theta, S(\theta_k), B(\theta_k); D) = 2 \sum_{i=0}^{N_{\text{bins}}} (B_i + S_i - D_i) \frac{D_i \ln \left( \frac{B_i + S_i}{D_i} \right)}{D_i} + \sum_{k=0}^{N_{\text{syst}}} \theta_k^2
\]

- SM contributions fluctuate within systematic uncertainties (constrained by Gaussian priors)
- Normalization for any process can be treated as a free parameter (Gaussian constraint removed from the sum)

\( D \): observed number of events
\( S(\theta_k) \): predicted number of signal events
\( B(\theta_k) \): predicted number of background events
\( \theta_k \): number of s.d. systematic “k” has been pulled away from nominal

\( N_{\text{bins}} \): number of bins
\( N_{\text{syst}} \): number of systematic uncertainties

Gaussian constraint on systematic
Reconstructed $W\rightarrow \ell\nu$ distributions after fitting the SM contributions to the data
Normalizations for dibosons and $W+$jets are free parameters
Reconstructed jet distributions after fitting the SM contributions to the data.

Normalizations for dibosons and W+jets are free parameters.
The dijet mass distribution after fitting the SM contributions to the data (normalizations for dibosons and $W+$jets are free parameters)

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<td>Total predicted</td>
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<tr>
<td>Data</td>
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Without Alpgen Modeling Corrections

DØ, 4.3 fb$^{-1}$

$e + \mu$

Data  
- Diboson
- $W+$Jets
- $Z+$Jets
- Top
- Multijets

Gaussian (4 pb) $M_{jj} = 145 \text{ GeV/c}^2$
Fit of SM contributions to data

The dijet mass distribution after fitting the SM contributions to the data (normalizations for dibosons and W+jets are free parameters)

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Without Alpgen Modeling Corrections

The DØ data are consistent with the SM prediction
The dijet mass distribution after fitting the SM contributions to the data (normalizations for dibosons and W+jets are free parameters)

With Alpgen Modeling Corrections

The DØ data are consistent with the SM prediction
Study of the dijet mass distribution in the DØ data

Fit SM contributions to data
⇒ Is there an excess of events similar to that in CDF data?

Include a model “a la CDF” for WX→lνjj in the fit
⇒ How large excess do the DØ data support?
Modeling of an Excess

- Gaussian distribution in dijet mass with a width $\sigma_{\text{excess}}$ determined by the DØ experimental resolution

  \[
  \text{For } M_{\text{JJ}}^{\text{excess}} = 145 \text{ GeV} \\
  \sigma_w, M_W \text{ from } WW \rightarrow l\nu jj \text{ sample}
  \]

- Efficiency for WX estimated with WH→lνbb sample ($m_H@150$ GeV)
- Assumption BR$(X \rightarrow jj) = 1$

\[
\sigma_{\text{excess}} = \sigma_w \sqrt{\frac{M_{\text{JJ}}^{\text{excess}}}{M_W}} = 15.7 \text{ GeV}
\]
Modeling of an Excess

- Gaussian distribution in dijet mass with a width $\sigma_{\text{excess}}$ determined by the DØ experimental resolution

  For $M_{\text{excess}}^{jj} = 145$ GeV
  $\sigma_W, M_W$ from $WW \rightarrow l\nu jj$ sample

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  \sigma_{\text{excess}} = \sigma_W \sqrt{\frac{M_{\text{excess}}^{jj}}{M_W}} = 15.7 \text{ GeV}
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- Efficiency for WX estimated with $WH \rightarrow l\nu bb$ sample ($m_H@150$ GeV)
- Assumption $\text{BR}(X \rightarrow jj) = 1$

- **Systematic uncertainties** (normalization and shape)
  - Luminosity, lepton identification, jet identification (3%)
  - Jet Energy Scale: shifting the mean of Gaussian by 1.5% and 3% change in rate
  - Jet Resolution: changing a width by 3% and 0.7% change in rate
Modeling of an Excess

- Gaussian distribution in dijet mass with a width $\sigma_{\text{excess}}$ determined by the DØ experimental resolution

  \[
  \text{For } M_{jj}^{\text{excess}} = 145 \text{ GeV} \\
  \sigma_w, M_W \text{ from } WW \to l\nu jj \text{ sample}
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- Efficiency for WX estimated with WH$\to l\nu bb$ sample ($m_H@150$ GeV)

- Assumption $\text{BR}(X \to jj) = 1$

- Fit $\text{SM contributions} + WX$ to data
  (normalizations for dibosons, W+jets, WX are free parameters)
Modeling of an Excess

- Gaussian distribution in dijet mass with a width $\sigma_{\text{excess}}$ determined by the DØ experimental resolution

\[ M_{\text{excess}}^{\text{JJ}} = 145 \text{ GeV} \]
\[ \sigma_{\text{W}}, M_{\text{W}} \text{ from WW} \rightarrow l\nu jj \text{ sample} \]

\[ \sigma_{\text{excess}} = \sigma_{\text{W}} \sqrt{\frac{M_{\text{excess}}^{\text{JJ}}}{M_{\text{W}}}} = 15.7 \text{ GeV} \]

- Efficiency for WX estimated with WH$\rightarrow l\nu bb$ sample ($m_H @ 150$ GeV)
- Assumption BR($X \rightarrow jj$) = 1
- Fit SM contributions + WX to data (normalizations for dibosons, $W$+jets, WX are free parameters)
Gaussian distribution in dijet mass with a width $\sigma_{\text{excess}}$ determined by the DØ experimental resolution

For $M_{\text{JJ}}^{\text{excess}} = 145$ GeV

$\sigma_W, M_W$ from $WW \rightarrow l\nu jj$ sample

$\sigma_{\text{excess}} = \sigma_W \sqrt{\frac{M_{\text{JJ}}^{\text{excess}}}{M_W}} = 15.7$ GeV

Efficiency for WX estimated with $WH \rightarrow l\nu bb$ sample ($m_H@150$ GeV)

Assumption $\text{BR}(X \rightarrow jj) = 1$

Fit $\text{SM contributions} + WX$ to data
(normalizations for dibosons, $W+\text{jets}$, $WX$ are free parameters)

Fitted data is consistent with no excess
Modeling of an Excess

- Gaussian distribution in dijet mass with a width $\sigma_{\text{excess}}$ determined by the DØ experimental resolution

$$\text{For } M_{\text{JJ}}^{\text{excess}} = 145 \text{ GeV}$$

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  (normalizations for dibosons, W+jets, WX are free parameters)

1. **Measured cross section:**
(normalizations for WW+WZ, W+jets, WX float)

$$\sigma(WX) \times B(X \rightarrow jj) = 0.82^{+0.83}_{-0.82} \text{ pb}$$

**Fitted cross section consistent with zero!**
Modeling of an Excess

- Gaussian distribution in dijet mass with a width $\sigma_{\text{excess}}$ determined by the DØ experimental resolution

For $M_{\text{excess}}^{\text{JJ}} = 145$ GeV

$\sigma_{\text{W}}, M_{\text{W}}$ from $WW\rightarrow l\nu jj$ sample

$\sigma_{\text{excess}} = \sigma_{\text{W}} \sqrt{\frac{M_{\text{excess}}^{\text{JJ}}}{M_{\text{W}}}} = 15.7$ GeV

- Efficiency for WX estimated with $WH\rightarrow l\nu bb$ sample ($m_{H}@150$ GeV)

- Assumption $\text{BR}(X\rightarrow jj) = 1$

- Fit $\text{SM contributions}+WX$ to data

  (normalizations for dibosons, $W+jets$, WX are free parameters)

1. Measured cross section:
   (normalizations for $WW+WZ$, $W+jets$, WX float)

   $\sigma(WX) \times B(X \rightarrow jj) = 0.82^{+0.83}_{-0.82}$ pb

2. Measured cross section:
   (normalizations for $W+jets$, WX float, a la CDF)

   $\sigma(WX) \times B(X \rightarrow jj) = 0.42^{+0.76}_{-0.42}$ pb

Fitted cross sections consistent with zero!
Poisson Negative Log-Likelihood Ratio, LLR (statistical test)
Test Signal+Background (S+B) and Background-only (B) hypotheses

\[
LLR = -2 \ln \left( \frac{L(D; S+B, \theta_k)}{L(D; B, \theta_k)} \right) = \chi^2(D; S+B, \theta_k) - \chi^2(D; B, \theta_k)
\]

⇒ generate pseudo-experiments from Poisson fluctuations of S+B and B hypotheses allowing statistical and systematic fluctuations (\(\theta_k\), Gaussian distributed)

How the LLR probability distributions for each hypothesis compare to the observed LLR?

CL\(_S\) method (1 - CL\(_S\) = 1 - CL\(_{S+B}\)/CL\(_B\))
Cross section upper limit for which the 1 - CL\(_S\) value is 0.95 (95% CL)
(5% chance to get observed outcome if S+B hypothesis were true)
Setting the Limits on WX

LLR for data, S+B and B hypotheses, along with 1 s.d. and 2 s.d. fluctuations of the background

95% CL upper limits on WX→lνjj (for CDF model)

★1.9 pb @ M_{JJ} = 145 GeV
Setting the Limits on WX

LLR for data, S+B and B hypotheses, along with 1 s.d. and 2 s.d. fluctuations of the background.

Without Alpgen Modeling Corrections

95% CL upper limits on WX→lνjj (for CDF model)

1.9 pb @ M_{JJ} = 145 GeV

With Alpgen Modeling Corrections

1.5 pb @ M_{JJ} = 145 GeV
The DØ data are not consistent with the excess seen by CDF
Cross checks with signal-injected data
If a resonance of $\sim 4$ pb is present would we be able to see it?

- Build the test data: “data + WX→ℓνjj” (model at 145 GeV)
- Fit all **SM contributions** to test data using the dijet mass distribution
- **Without** Alpgen Modeling Corrections

**Test Data Study**

- Dijet Mass [GeV/c^2]
- Events / (10 GeV/c^2)

**e + μ**

**Without** Alpgen Modeling Corrections

**Test Data Study**

- Dijet Mass [GeV/c^2]
- Events / (10 GeV/c^2)

**Poor agreement**

- $P(\chi^2) = 0.010$

**Without** Alpgen Modeling Corrections
If a resonance of \(\sim 4 \text{ pb}\) is present would we be able to see it?

- Build the test data: “data + WX→\(l\nu jj\)” (model at 145 GeV)
- Fit all **SM contributions** + WX to test data using the dijet mass distribution
- Normalizations for dibosons, W+jets and WX are free parameters

**Test Data Study**

- Events / (10 GeV/c^2)
- Dijet Mass [GeV/c^2]
- \(e+\mu\)

**Test Data Study**

- Events / (10 GeV/c^2)
- Dijet Mass [GeV/c^2]
- \(e+\mu\)

- Fake Data
- Gaussian (Fitted)
- Diboson
- W+jets
- Z+jets
- Top
- Multijets
- Gaussian (4 pb)
- Gaussian (4 pb) \(M_{jj} = 145 \text{ GeV/c^2}\)

\(P(\chi^2) = 0.542\)

**Without Alpgen Modeling Corrections**
If a resonance of ~4 pb were present in our data, we would certainly see it.
Search for the resonance @ $M_{JJ} = 145$ GeV in $W+2$ jet events using the same event selection

We studied extensively the dijet mass distribution

DØ data are consistent with the SM prediction

For an excess (resonance) at 145 GeV:

- data exclude cross sections larger than 1.9 pb at 95% CL
- cross section of 4 pb excluded at 4.3σ

result published in [PRL 107, 011804 (2011)]