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

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(University of Kansas)

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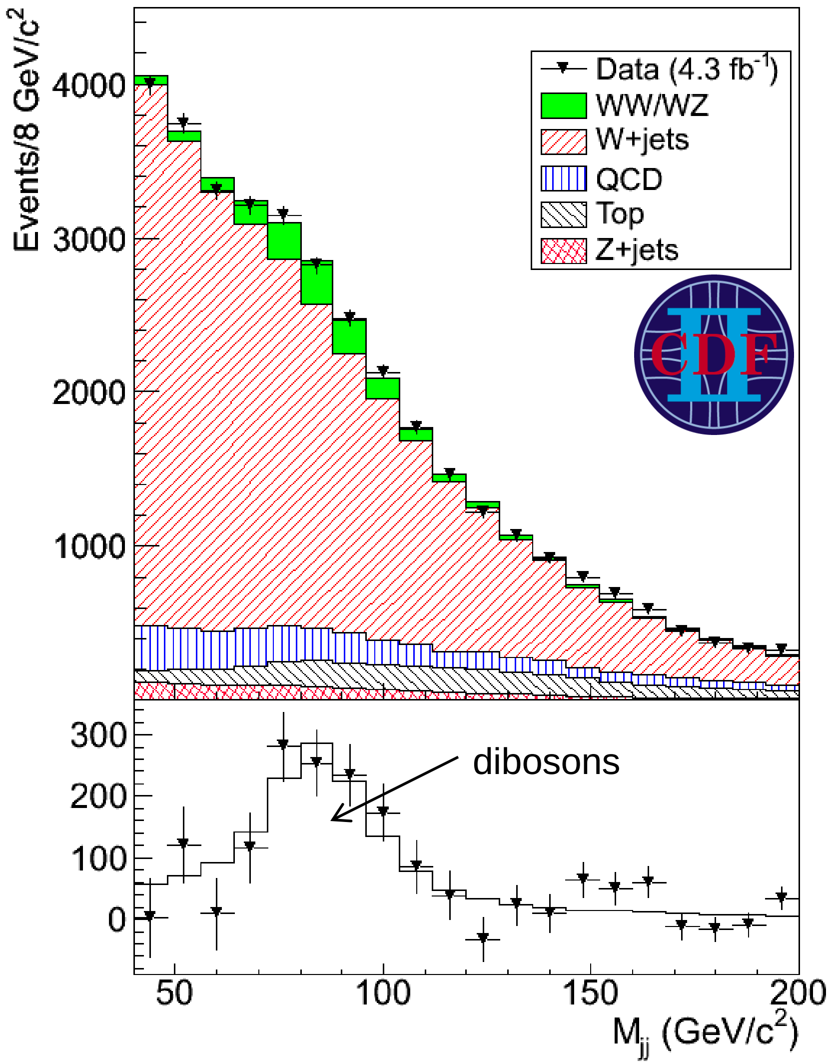
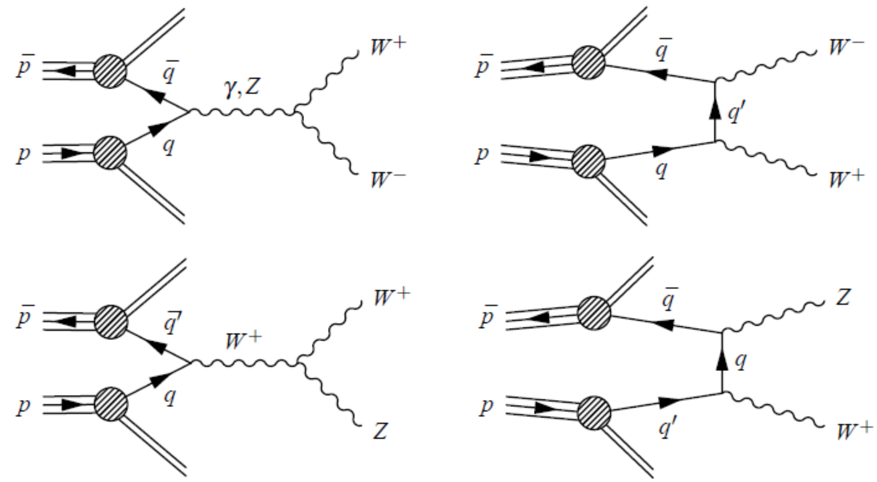
How did it all begin …

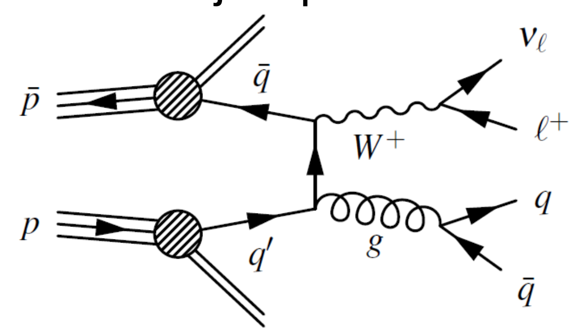
Measurement of the WW/WZ cross section in the lνjj final states



Diboson production



W+jets production



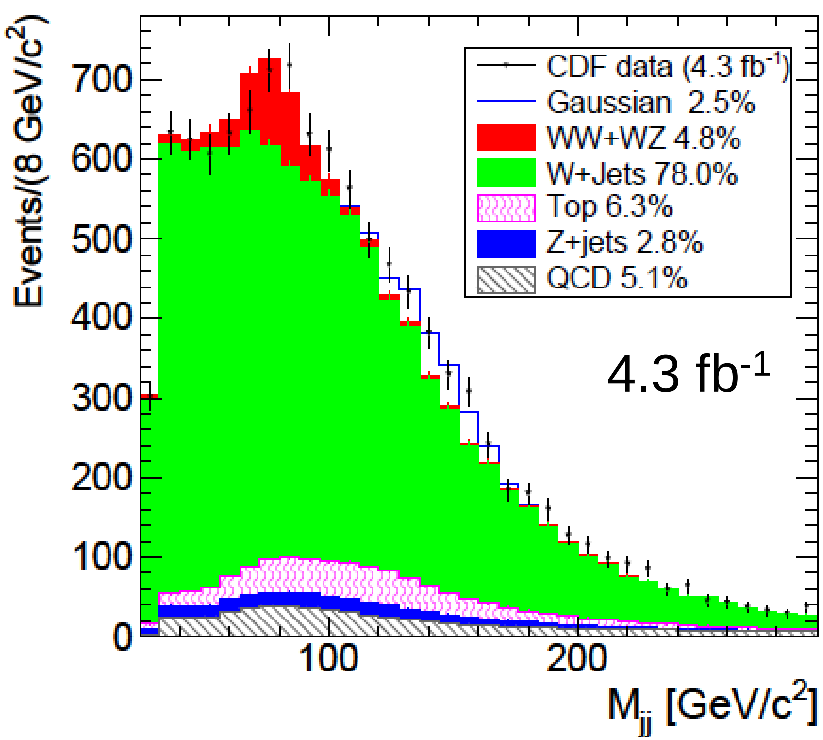
http://www-cdf.fnal.gov/physics/ewk/2010/WW_WZ/index.html

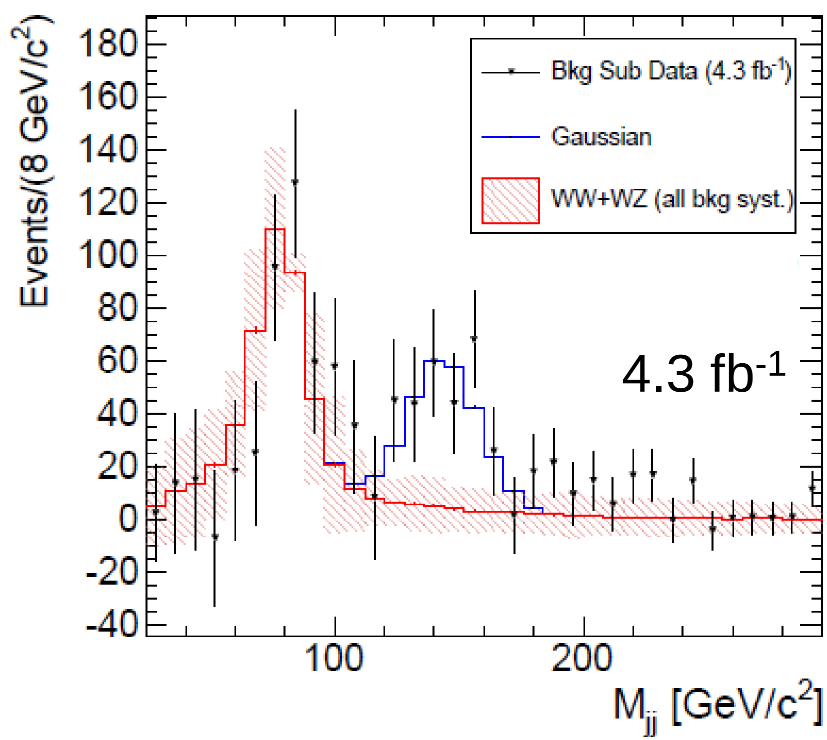
Results from the CDF Experiment (I)

Significant excess of events in the dijet mass distribution at M_{JJ} ~145 GeV (3.2σ)

- 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→jj) = 1: **σ(pp→WX) ≈ 4 pb**

PRL 106, 171801 (2011)

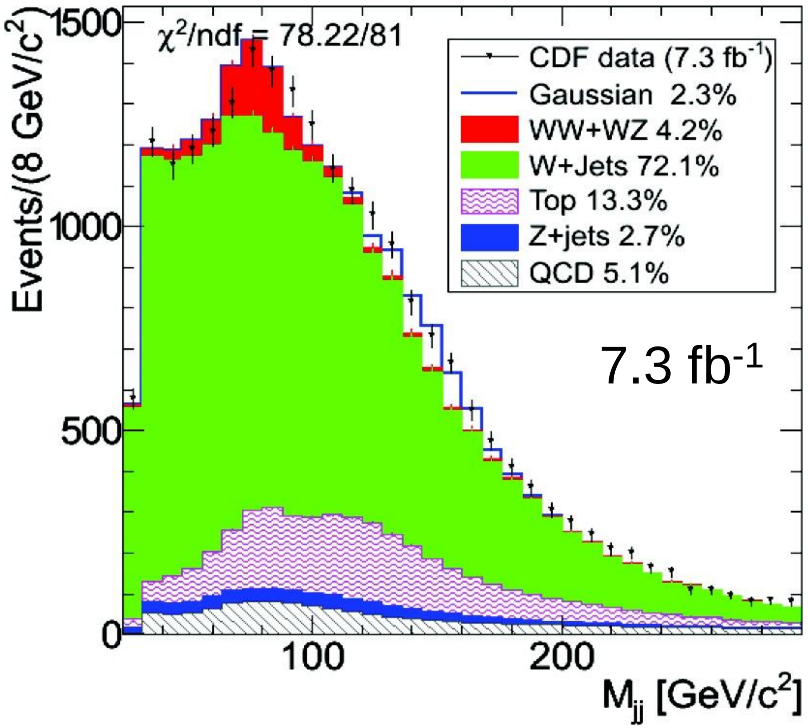


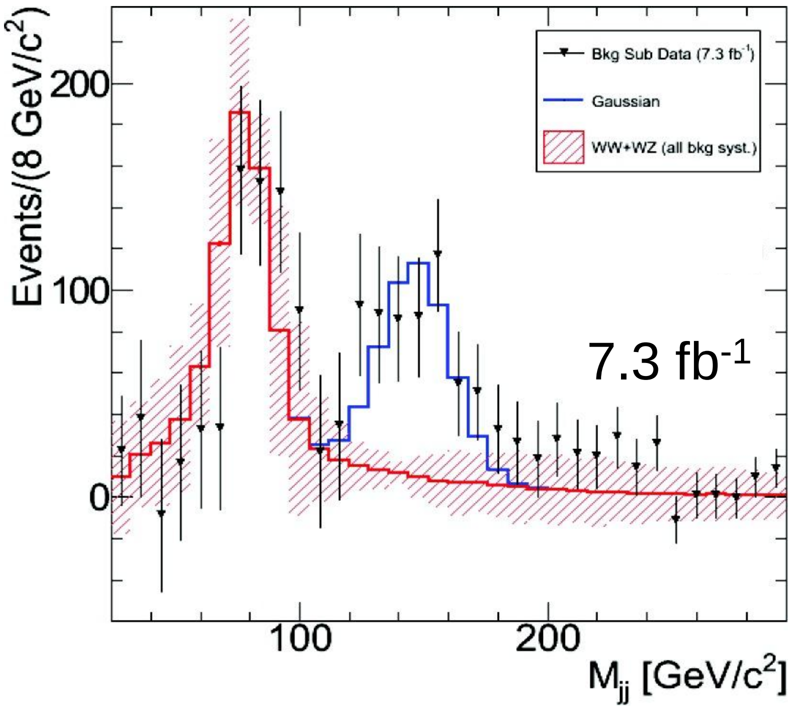


Results from the CDF Experiment (II)

Significant excess of events in the dijet mass distribution at M_{JJ} ~145 GeV (4.3σ)

www-cdf.fnal.gov/physics/ewk/2011/wjj/7_3.html





Analysis at the DØ Experiment

Do the DØ data show a similar excess at M_{JJ} ~145 GeV?

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

- Fit SM processes to data

$\Rightarrow$ Is there an excess of events similar to that in CDF data?

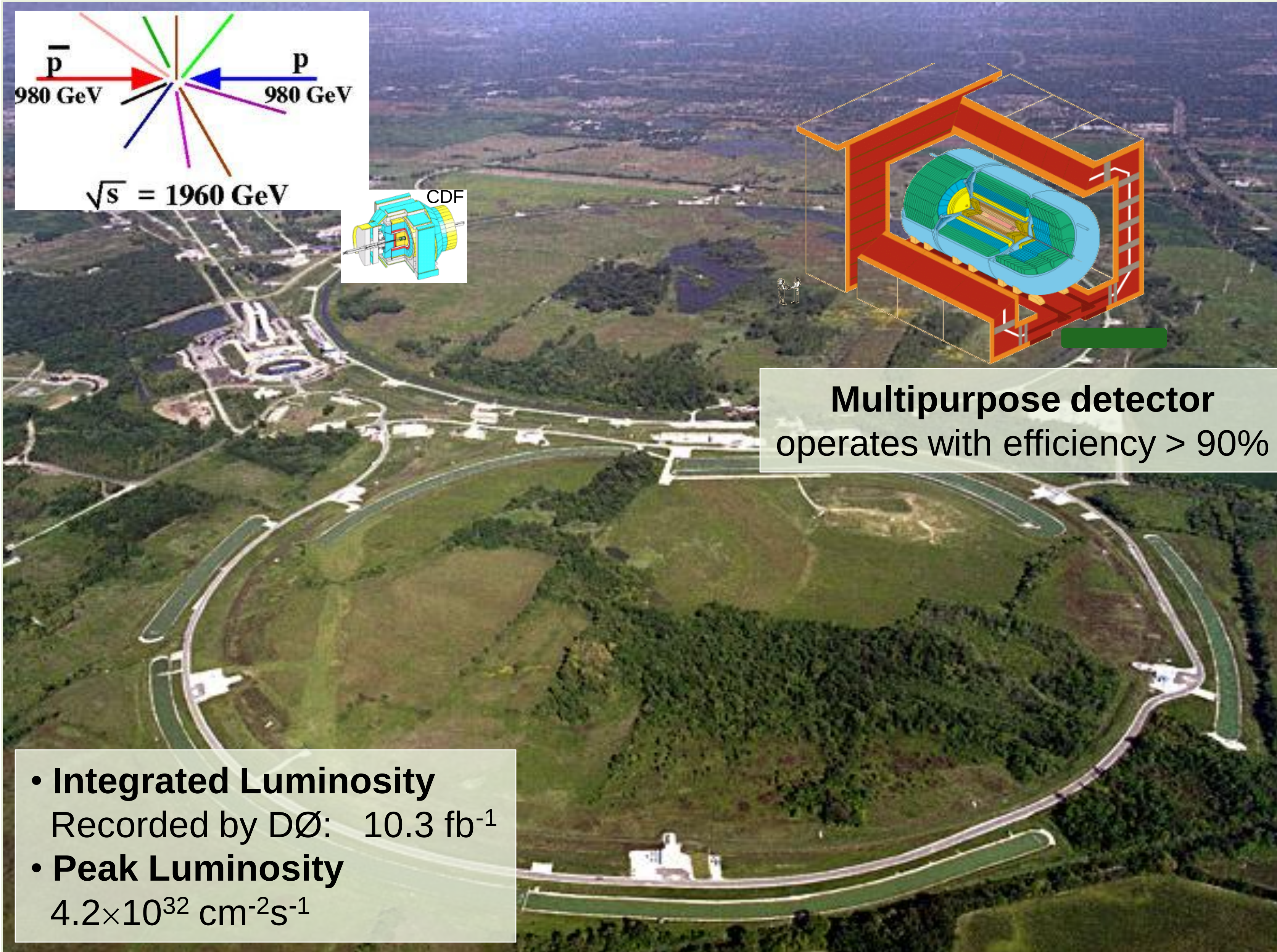
- Include a model “a la CDF” for $WX \rightarrow l\nu jj$ in the fit

$\Rightarrow$ How large excess do the DØ data support?

Cross checks with signal-injected data

The DØ Collaboration

The DØ Experiment (Fermilab, US)



Multipurpose detector
operates with efficiency > 90%

- **Integrated Luminosity**
  Recorded by DØ: $10.3\ fb^{-1}$
- **Peak Luminosity**
  $4.2\times10^{32}\ cm^{-2}s^{-1}$

The DØ Detector

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

Calorimeters

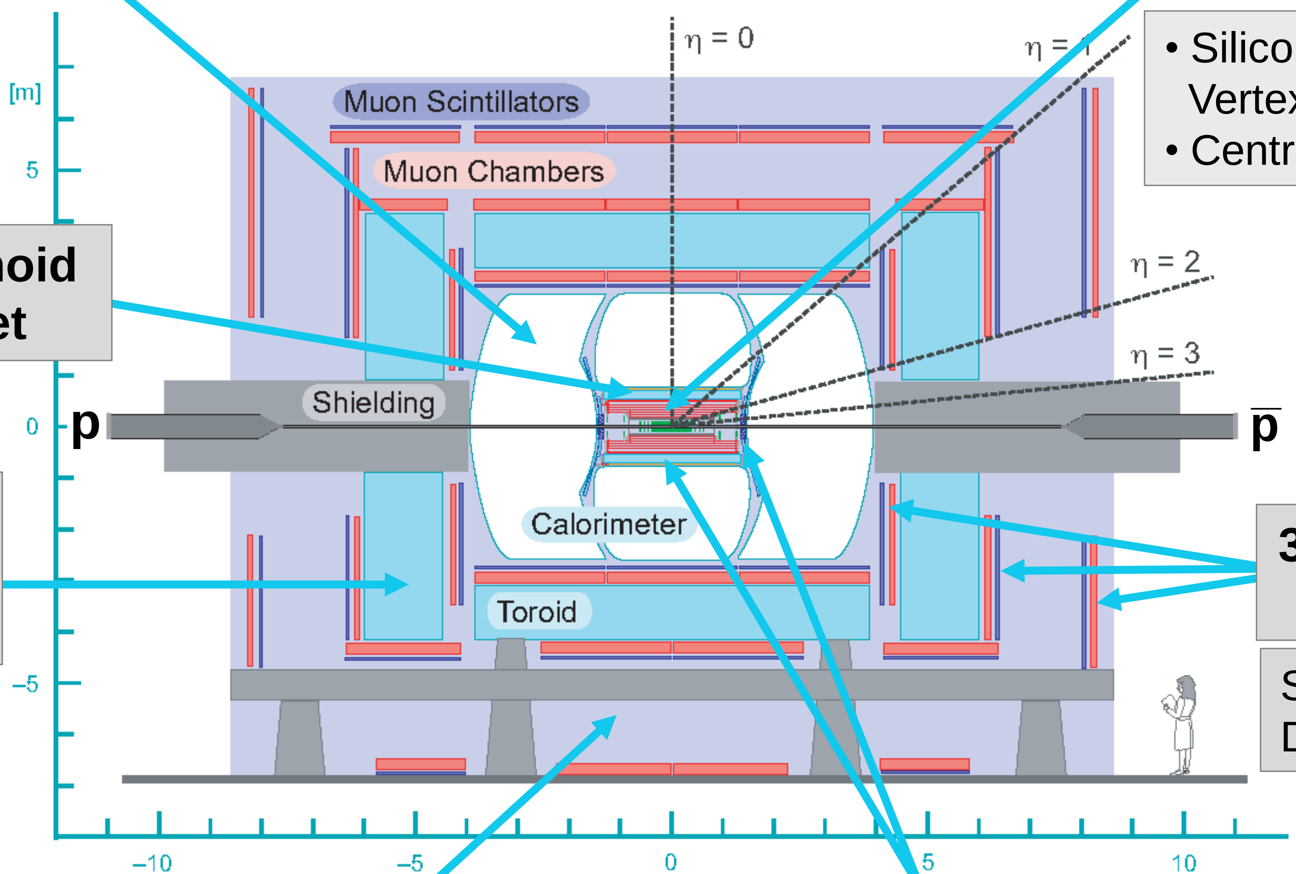
Electromagnetic (EM)
Fine Hadronic (FH)
Coarse Hadronic (CH)

Tracking Detectors

- Silicon Microstrip Vertex Detector
- Central Fiber Tracker

2T Solenoid Magnet

1.8T Toroid Magnet



3 Layer Muon System

Scintillating tiles
Drift tubes

Electronics, Trigger, DAQ

Preshower detectors

Event Selection

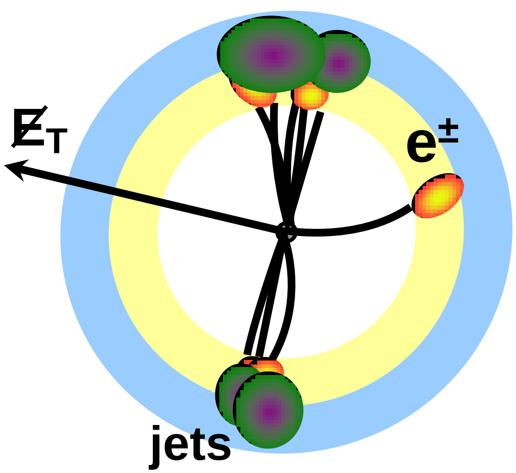
$W(\rightarrow l\nu)$ + 2 jets from 4.3 fb^{-1} DØ data, single lepton and lepton + jets triggers

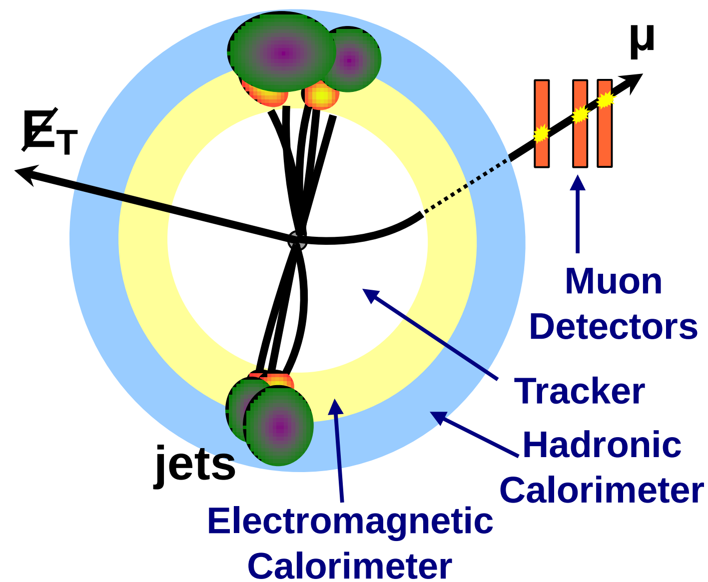
Electrons

- $p_T \geq 20$ 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

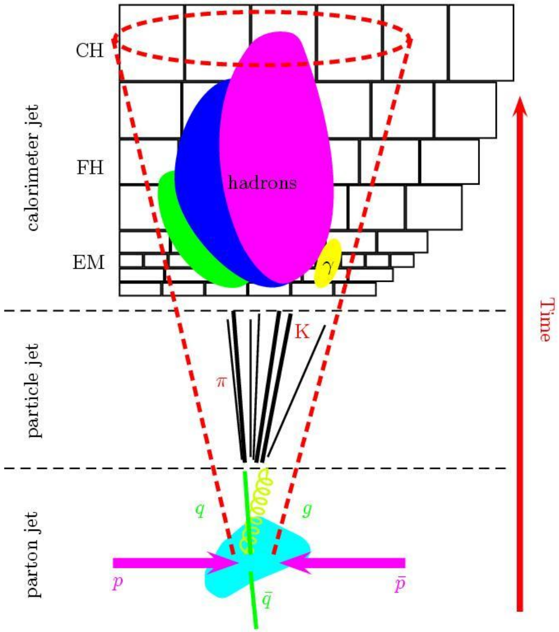
Missing E_T (MET) ≥ 25 GeV, $M_T(W\rightarrow l\nu) \geq 30$ GeV
$M_T(W\rightarrow l\nu) < 200$ GeV (in the muon channel)
Veto events with more than 1 charged lepton

Event Selection

W($\rightarrow l\nu$) + 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 $p_T \geq 30$ GeV (we do not veto events with extra jets with $p_T < 30$ GeV)
- Jet $|\eta_J| < 2.5$, $|\Delta\eta_{JJ}| < 2.5$, $p_T(JJ) \geq 40$ GeV, $\Delta\phi$(leading jet, MET) > 0.4



Event Selection

W(→lν) + 2 jets from 4.3 fb^{-1} DØ data, single lepton and lepton + jets triggers

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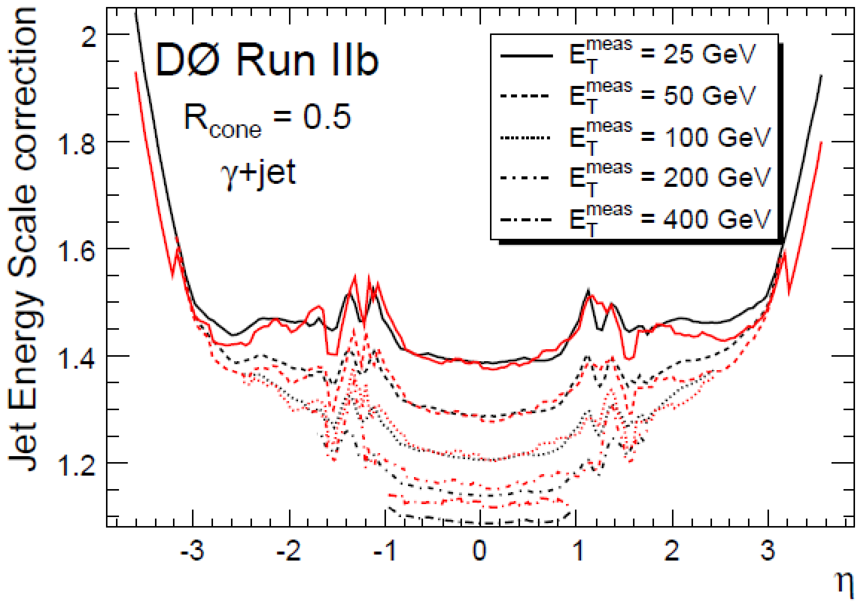
Standard Jet Energy Scale

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)



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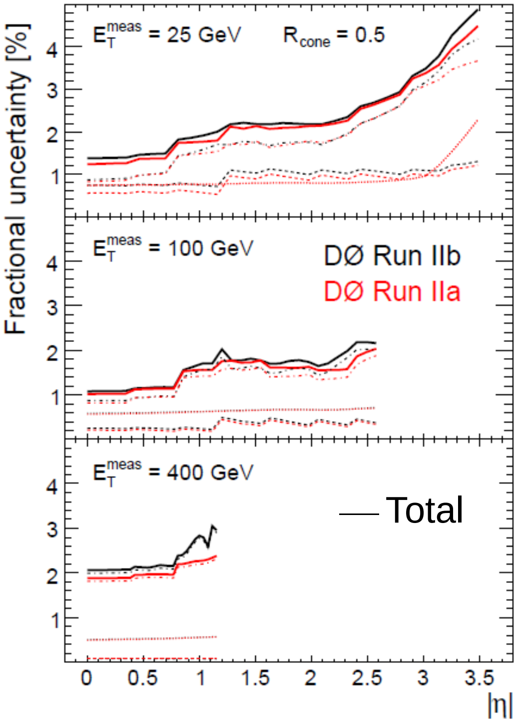

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Additional Jet Energy Calibration
(relative data/MC corrections)

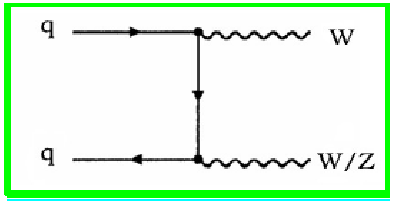
Measured in Z+jet events (for MC: Alpgen)
(*gluon dominated*)

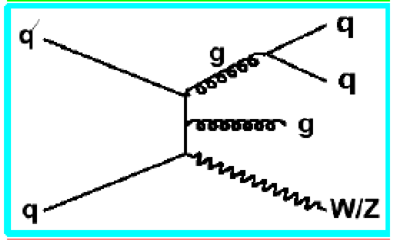
Correct p_T imbalance and energy resolution for:

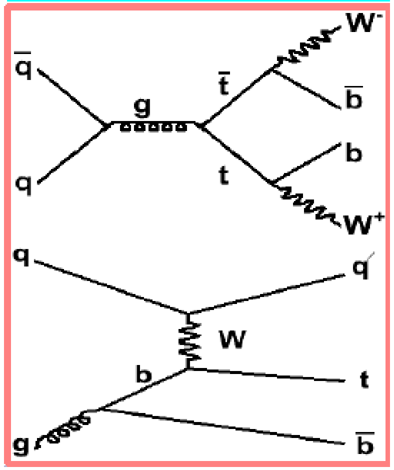
- soft out-of-cone radiation
- different quark/gluon sample composition (applied to Alpgen W+jet sample)

Modeling of SM processes

Event Source	Generator		$\sigma(SM)$ / $\sigma(WW)$ = 12.4 pb	
WW	Pythia		1.0	NLO
WZ	Pythia		0.3	NLO
ZZ	Pythia		0.1	NLO
W+light flavor jets	Alpgen	+ Pythia	800	from FIT
W+heavy flavor jets	Alpgen	+ Pythia	30	from FIT
Z+light flavor jets	Alpgen	+ Pythia	30	NNLO
Z+heavy flavor jets	Alpgen	+ Pythia	1	NNLO
Double-Top	Alpgen	+ Pythia	0.6	NNLO
Single-Top	Comphep	+ Pythia	0.2	NNLO







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 $M_T(W\rightarrow l\nu)$

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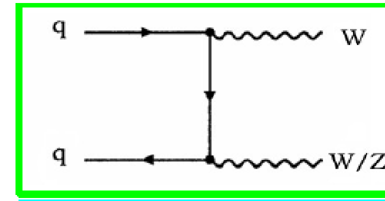
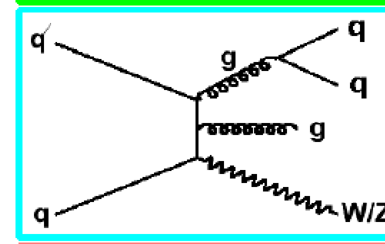
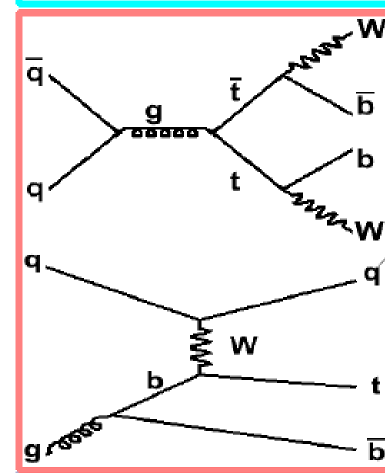






Standard MC Corrections

(to account for differences from data)

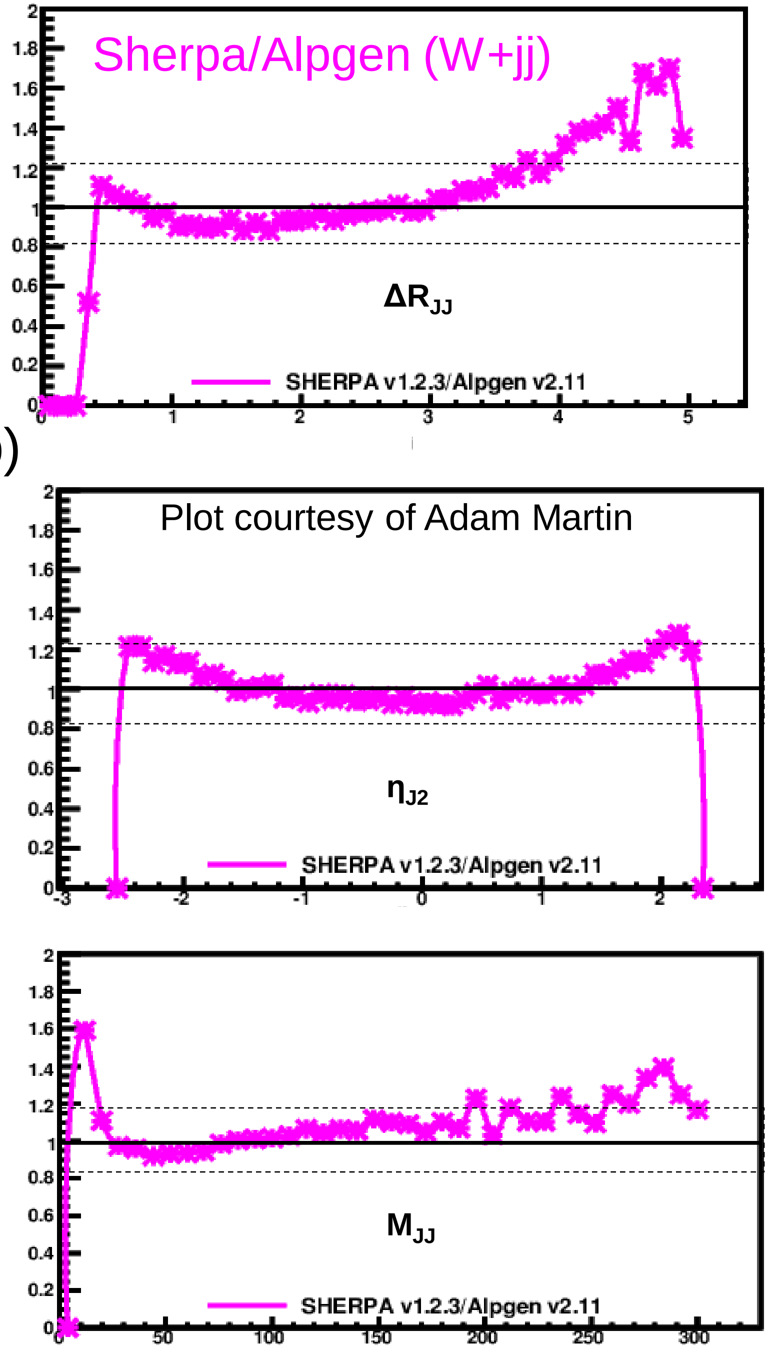
- Reconstruction and Identification efficiencies of leptons/jets
- Trigger selection
- Z boson p_T modeling

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 **ΔR_{JJ}, η_J, W p_T** distributions



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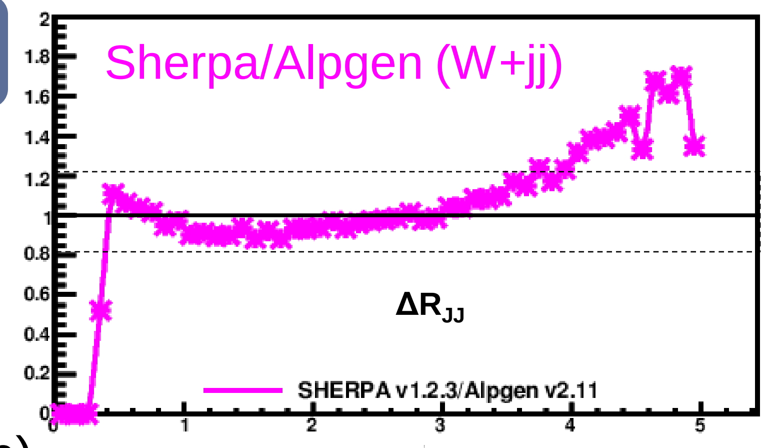
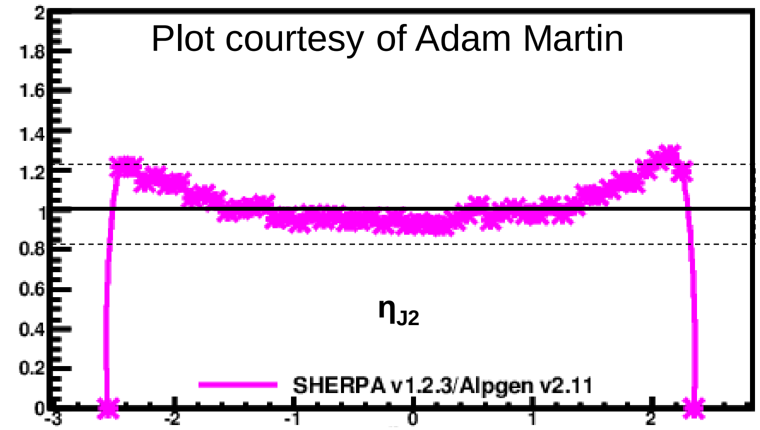


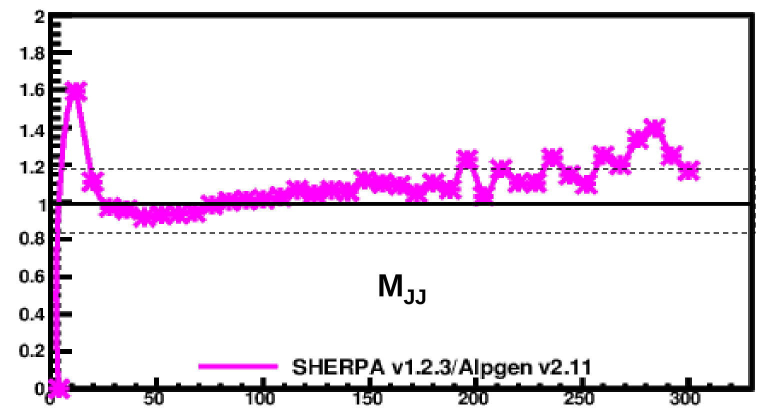
- In analyses with looser jet p_T cuts ($WH \rightarrow l\nu bb$) discrepancies of this type have been seen
  $\Rightarrow$ data-driven corrections (+ uncertainties) to model $\mathbf{\Delta R_{JJ}}$, $\mathbf{\eta_J}$, **W** $\mathbf{p_T}$ distributions



- In this analysis
  (higher jet p_T cuts reduce discrepancies)

  $\Rightarrow$ **no data-driven corrections**

  1. **Include uncertainties due to modeling of Alpgen variables ΔR_{JJ}, η_J, W p_T**



Modeling of V+jets processes

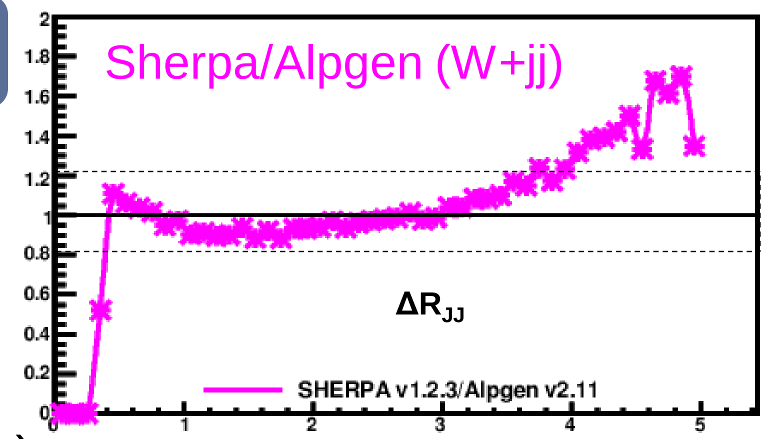
(V = W, Z)

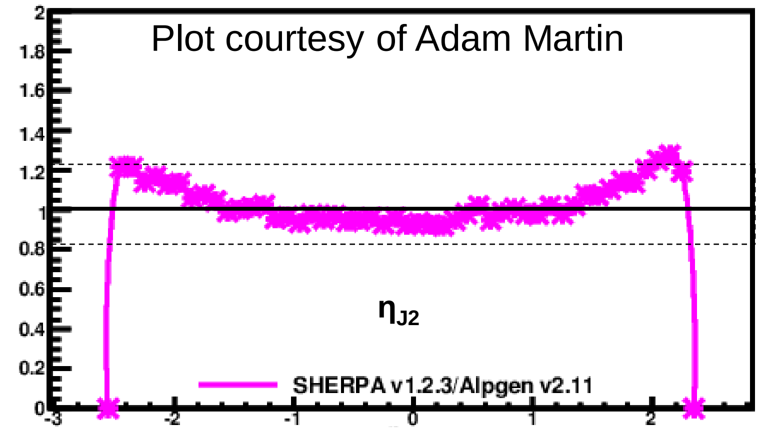
- W+jets is the dominant background
  Important to understand/model properly
- Different generators, different predictions

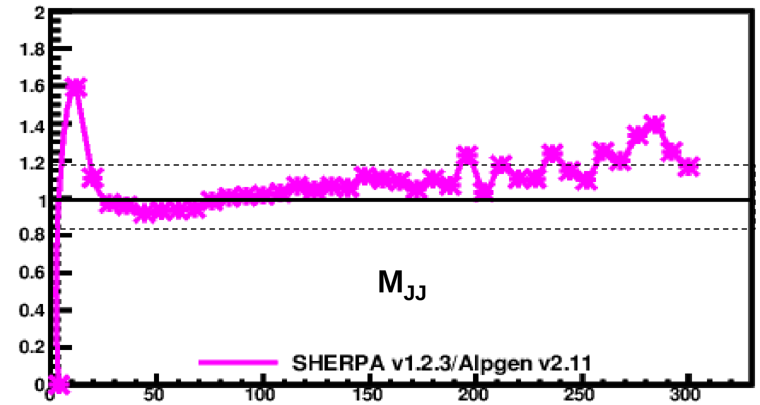
- In analyses with looser jet p_T cuts (WH→lνbb) discrepancies of this type have been seen
  ⇒ data-driven corrections (+ uncertainties)
  to model **ΔR_{JJ}, η_J, W p_T** distributions

- In this analysis
  (higher jet p_T cuts reduce discrepancies)
  ⇒ **no data-driven corrections**
  1. **Include uncertainties due to modeling of Alpgen variables ΔR_{JJ}, η_J, W p_T**

We do not apply these corrections when comparing to the CDF result





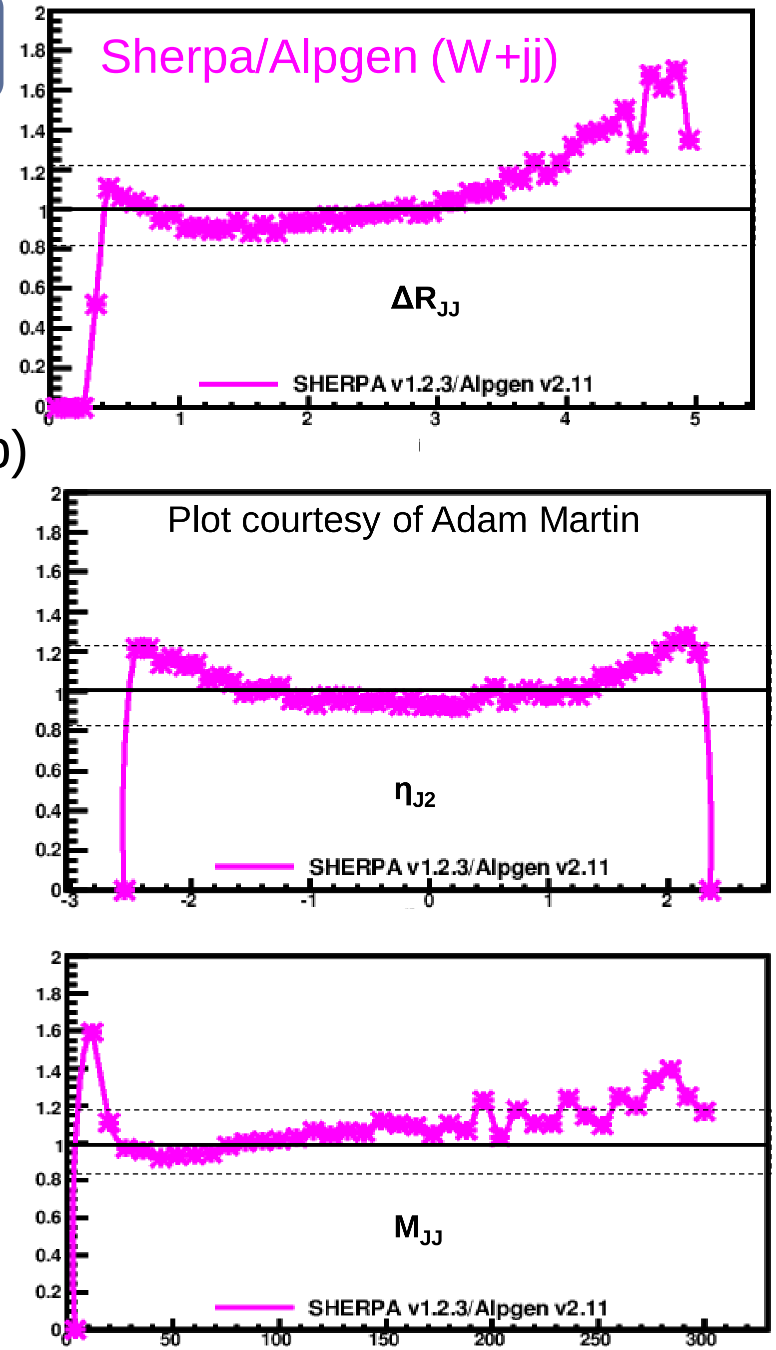


Modeling of V+jets processes

(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 $\mathbf{\Delta R_{JJ}}$, $\mathbf{\eta_J}$, **W** $\mathbf{p_T}$ distributions



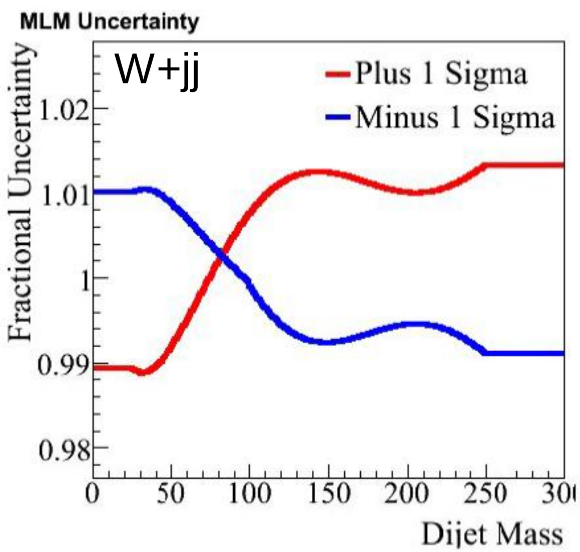
1. Include uncertainties due to modeling of Alpgen variables $\mathbf{\Delta R_{JJ}}$, $\mathbf{\eta_J}$, W $\mathbf{p_T}$

We perform a cross check with these corrections applied

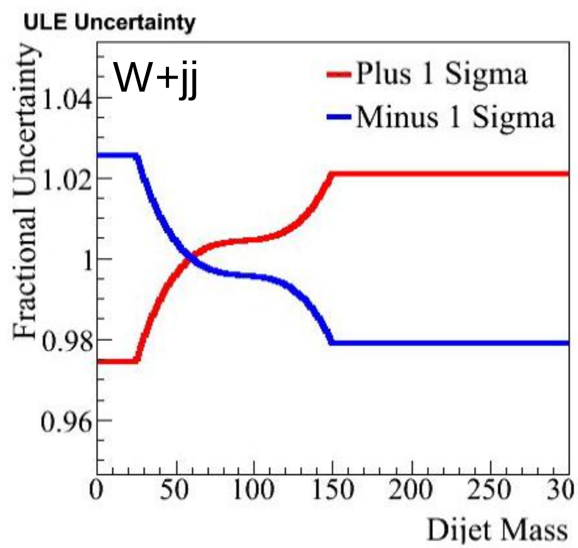
Modeling of V+jets processes

2. Include uncertainties due to tuning of Alpgen parameters

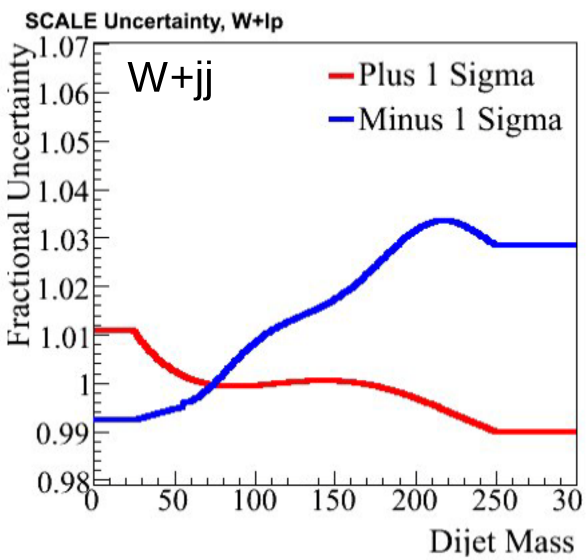
- Parton-jet matching parameters (p_T, ΔR)
- Parton shower model and underlying event (tunes)
- Renormalization/factorization scales



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 **D**ifferential (shape) of the dijet mass distribution

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

given in [%]

Source of systematic uncertainty	Diboson signal	W+jets	Z+jets	Top	Multijet	Nature	$\Delta\sigma$ (pb)
Trigger/Lepton ID efficiency	±5	±5	±5	±5		N	
Trigger correction, muon channel	±5	±5	±5	±5		D	
Jet identification	±1	±1	±2	±1		N D	
Jet energy scale	±10	±5	±7	±5		N D	
Jet energy resolution	±6	±1	±3	±6		N D	
Jet vertex confirmation	±3	±3	±4	±1		N D	
Luminosity	±6.1	±6.1	±6.1	±6.1		N	
Cross section	±7	±6.3	±6.3	±10		N	
V+hf cross section		±20	±20			N	
Multijet normalization					±20	N	
Multijet shape, electron channel					±1	D	
Multijet shape, muon channel					±10	D	
Diboson modeling	±8					D	
Parton distribution function	±1	±5	±4	±3		D	
Unclustered Energy correction	$\pm<1$	±3	±3	$\pm<1$		D	
ALPGEN η and $\Delta R(jet1, jet2)$ corrections		$\pm<1$	$\pm<1$			D	
ALPGEN W p_T corrections		$\pm<1$				D	
ALPGEN correction Diboson bias	±1	±1	±1	±1		D	
Renormalization and factorization scales		±1	±1			D	
ALPGEN parton-jet matching parameters		±1	±1			D	
Parton shower and Underlying event correction		±2	±2			D	

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 $WX \rightarrow l\nu jj$ 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 χ^2 function (ratio of Poisson likelihoods+prior information on the systematic uncertainties)

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

Gaussian constraint on systematic

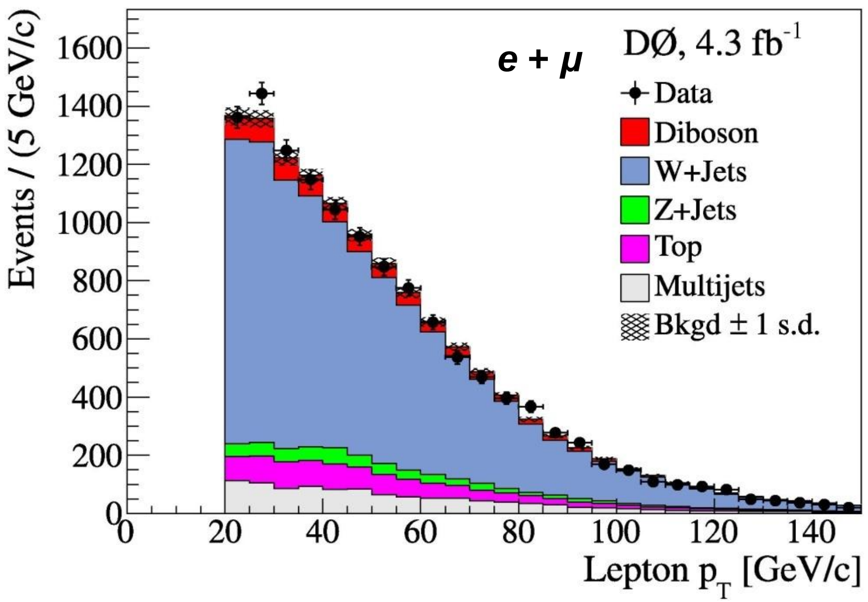
D:	observed number of events
$S(\theta_k)$:	predicted number of signal events
$B(\theta_k)$:	predicted number of background events
θ_k:	number of s.d. systematic "k" has been pulled away from nominal

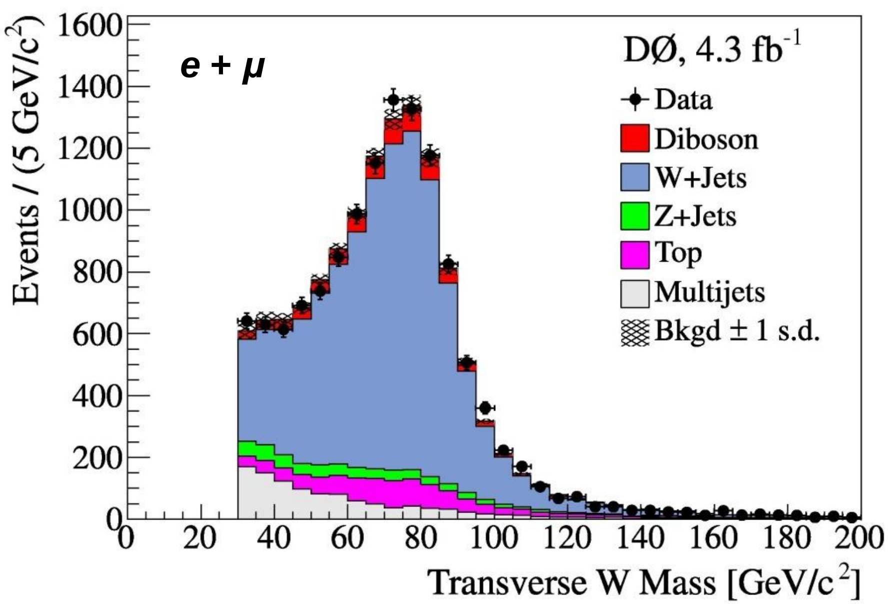
- SM contributions fluctuate within systematic uncertainties (constrained by Gaussian priors)
- Normalization for any process can be treated as a free parameter (Gaussian constraint removed from the sum)

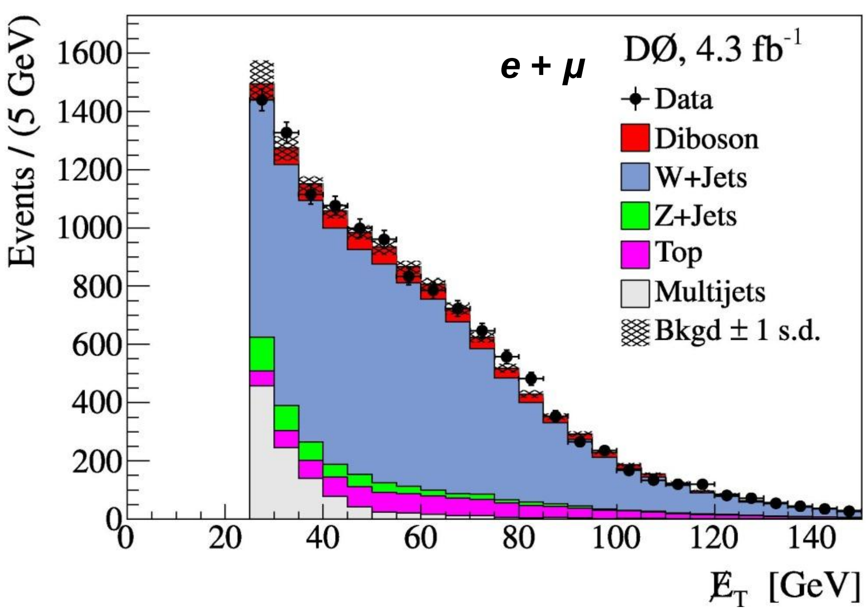
Fit of SM contributions to data

Reconstructed **W→lν** distributions after fitting the SM contributions to the data

Normalizations for dibosons and W+jets are free parameters







Fit of SM contributions to data

Reconstructed **jet** distributions after fitting the SM contributions to the data
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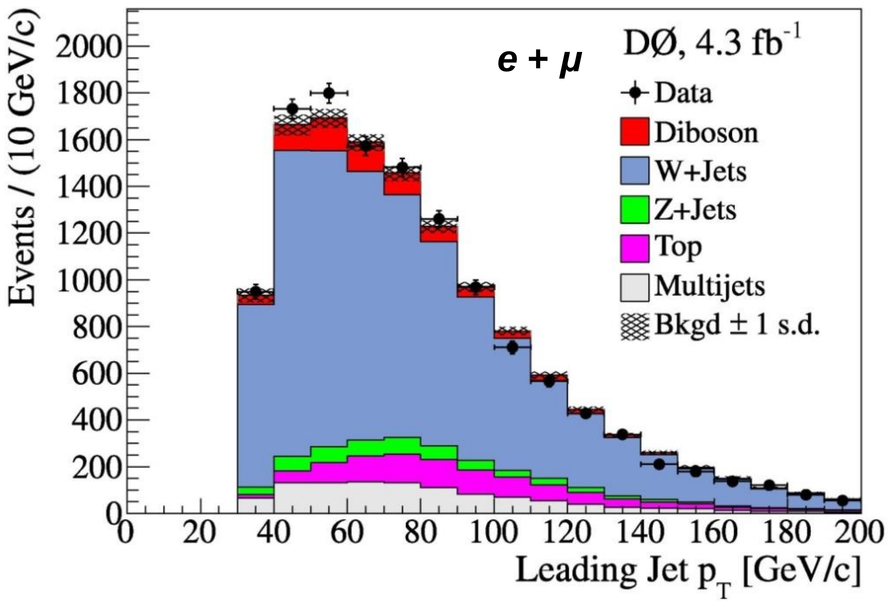
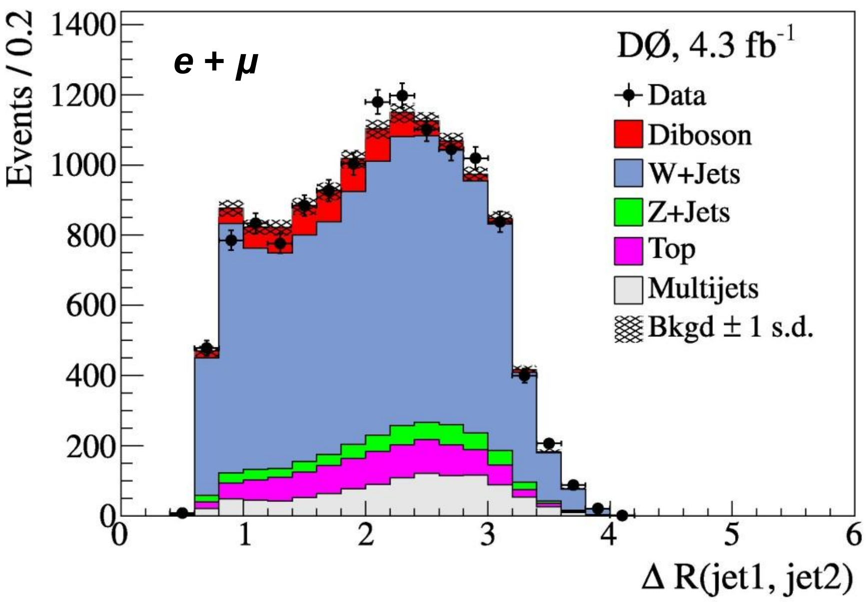
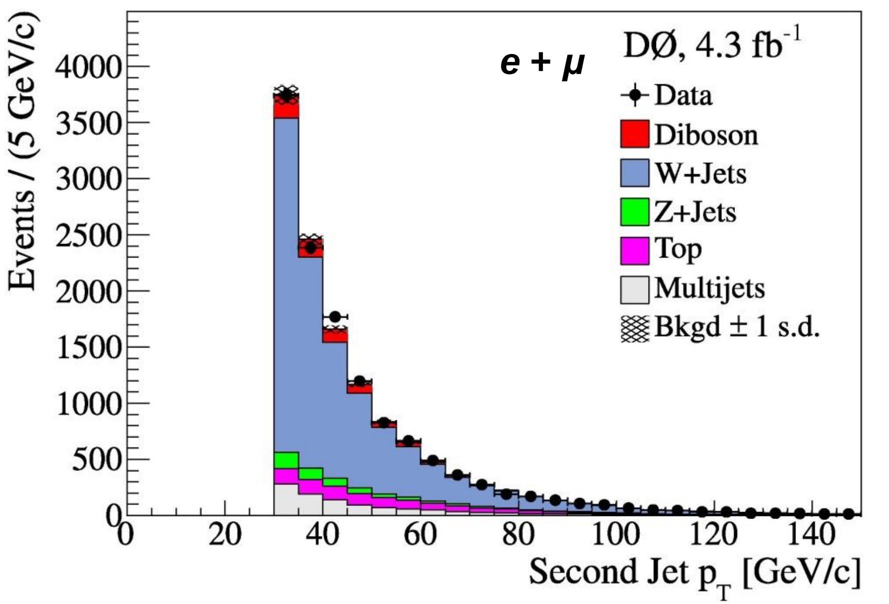




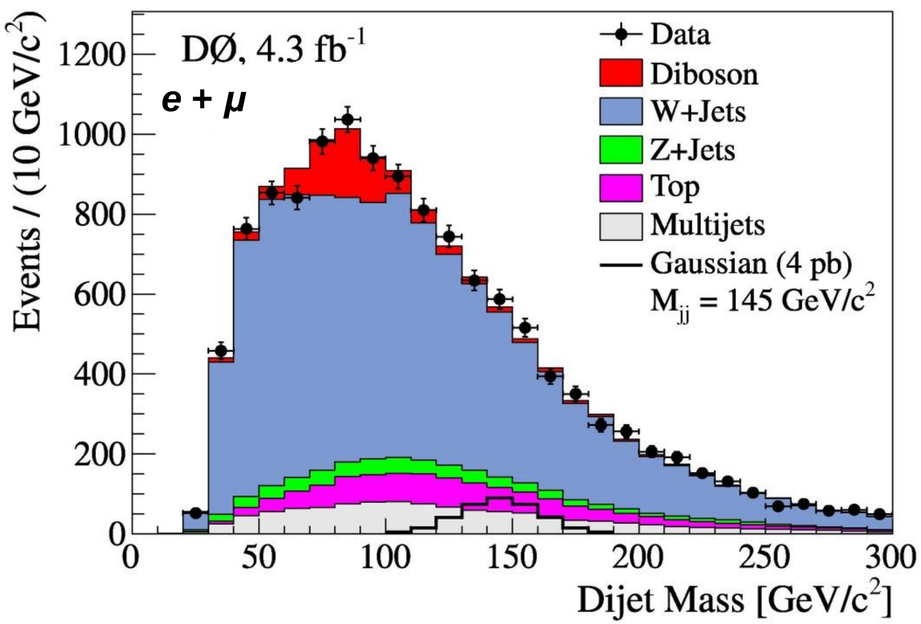


Fit of SM contributions to data

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

Without Alpgen Modeling Corrections

	Electron channel	Muon channel
Dibosons	434 ± 38	304 ± 25
W+jets	5620 ± 500	3850 ± 290
Z+jets	180 ± 42	350 ± 60
$t\bar{t}$ + single top	600 ± 69	363 ± 39
Multijet	932 ± 230	151 ± 69
Total predicted	7770 ± 170	5020 ± 130
Data	7763	5026

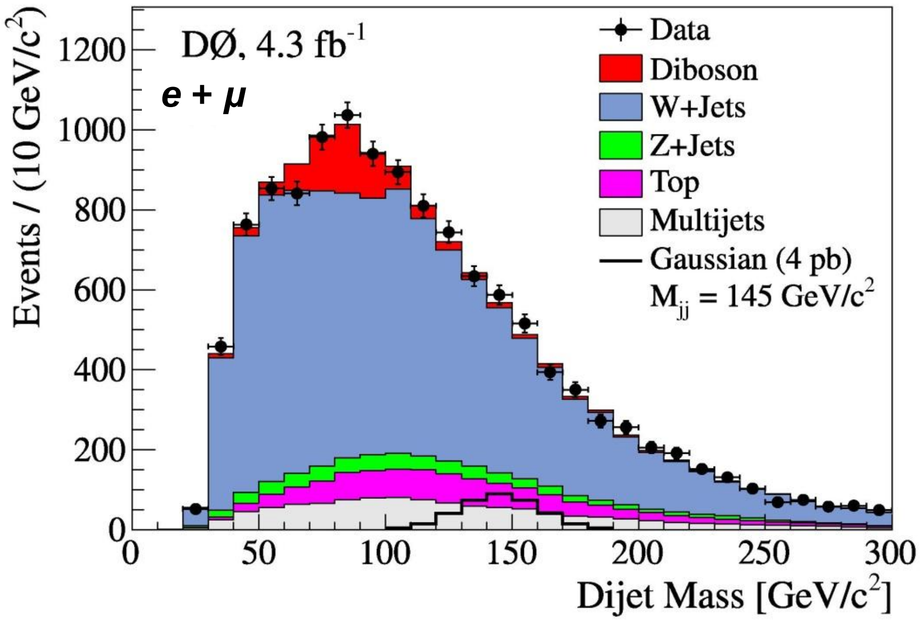


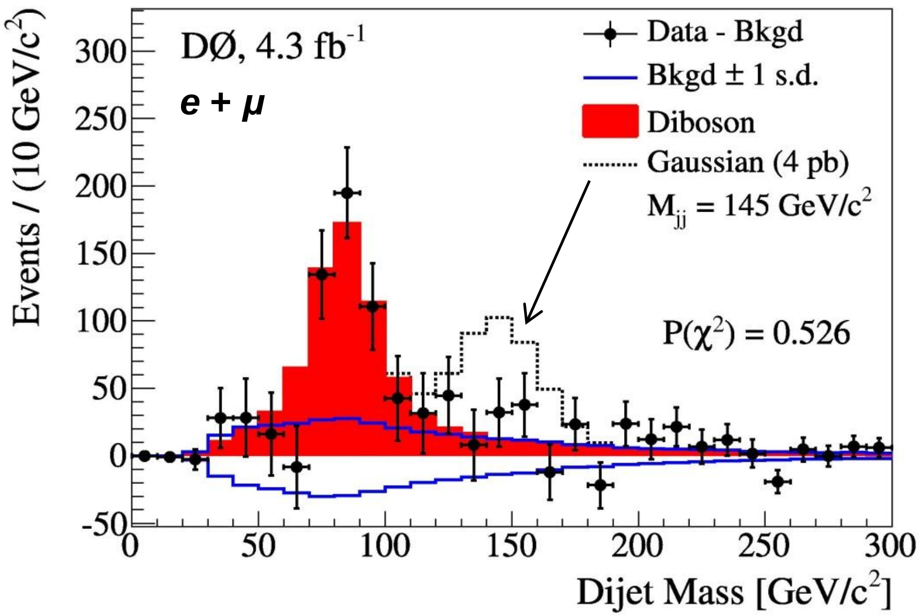
Fit of SM contributions to data

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

Without Alpgen Modeling Corrections

	Electron channel	Muon channel
Dibosons	434 ± 38	304 ± 25
W+jets	5620 ± 500	3850 ± 290
Z+jets	180 ± 42	350 ± 60
$t\bar{t}$ + single top	600 ± 69	363 ± 39
Multijet	932 ± 230	151 ± 69
Total predicted	7770 ± 170	5020 ± 130
Data	7763	5026



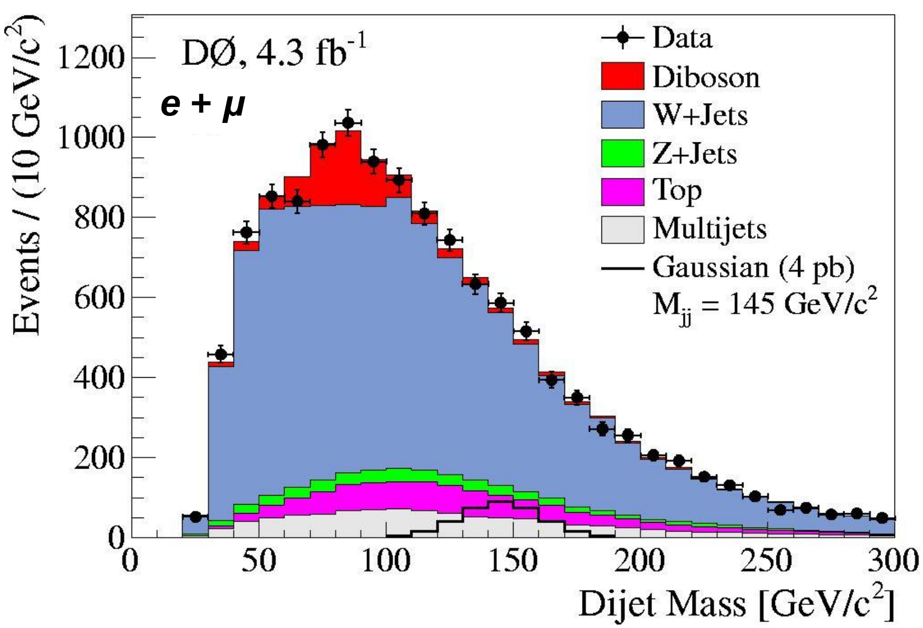


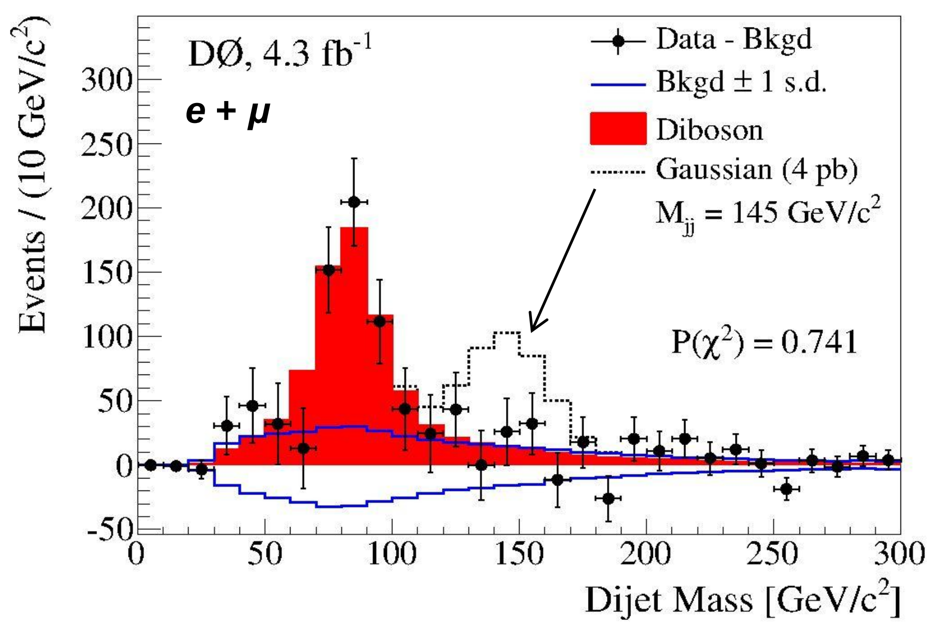
The DØ data are consistent with the SM prediction

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)

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

$\Rightarrow$ Is there an excess of events similar to that in CDF data?

Include a model "a la CDF" for WX$\rightarrow$lνjj in the fit

$\Rightarrow$ How large excess do the DØ data support?

Modeling of an Excess

- Gaussian distribution in dijet mass with a width σ_{excess} determined by the DØ experimental resolution

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

σ_W, M_W from WW→lνjj sample

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

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

Modeling of an Excess

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- Efficiency for WX estimated with WH→lνbb sample (m_H@150 GeV)
- Assumption BR(X→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 σ_{excess} determined by the DØ experimental resolution

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

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- Efficiency for WX estimated with WH→lνbb sample (m_H@150 GeV)
- Assumption BR(X→jj) = 1
- Fit ***SM contributions+WX*** to data (normalizations for dibosons, W+jets, WX are free parameters)

Modeling of an Excess

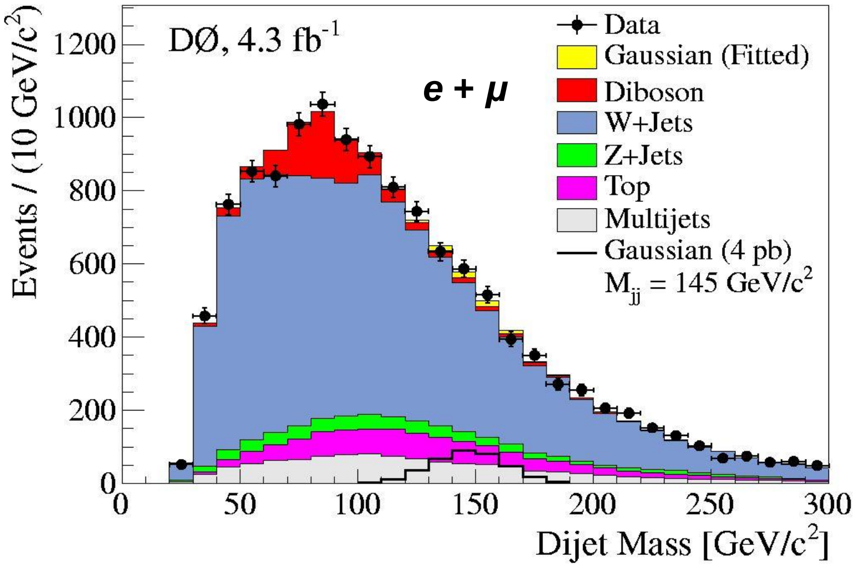
- Gaussian distribution in dijet mass with a width σ_{excess} determined by the DØ experimental resolution

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

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

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

- 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)



Modeling of an Excess

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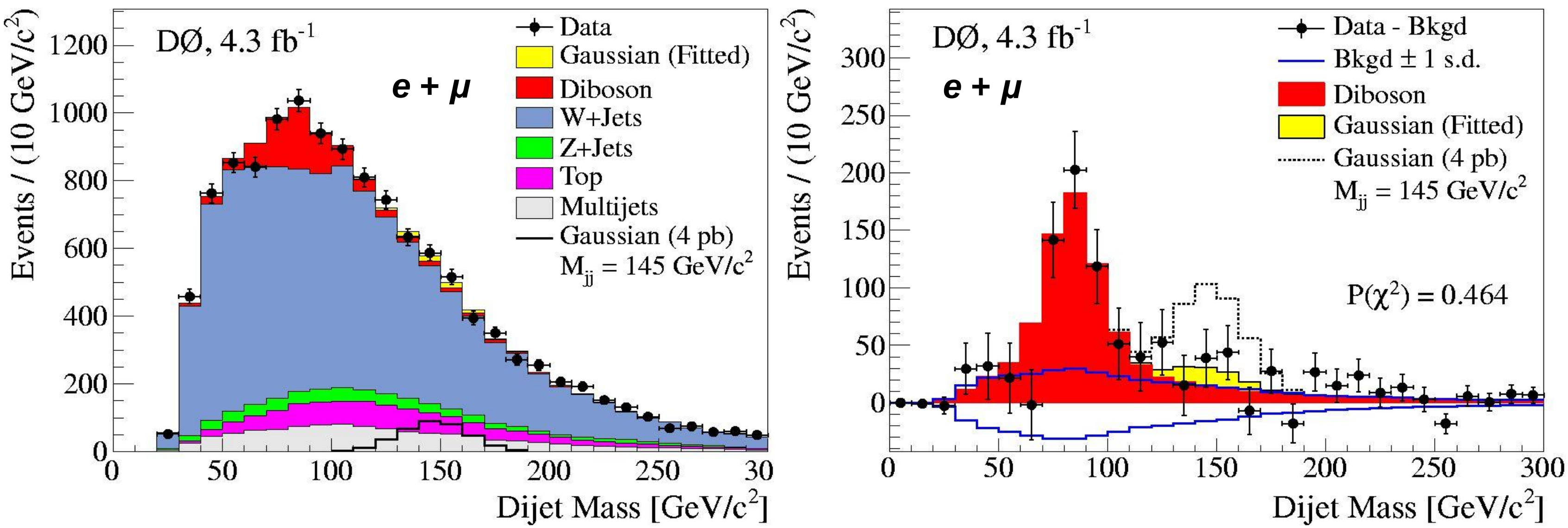

Fitted data is consistent with no excess

Modeling of an Excess

- Gaussian distribution in dijet mass with a width σ_{excess} determined by the DØ experimental resolution

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

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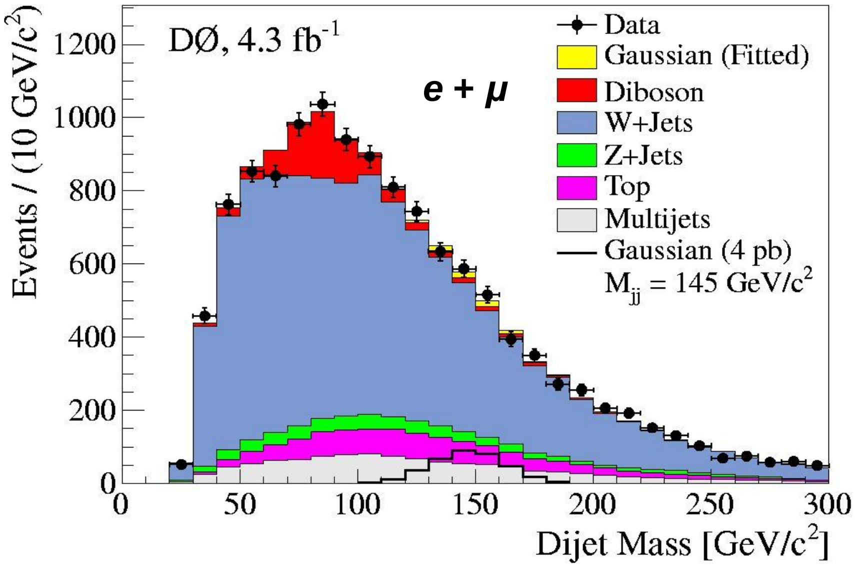


1. Measured cross section:

(normalizations for WW+WZ, W+jets, WX float)

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

Fitted cross section consistent with zero!

Modeling of an Excess

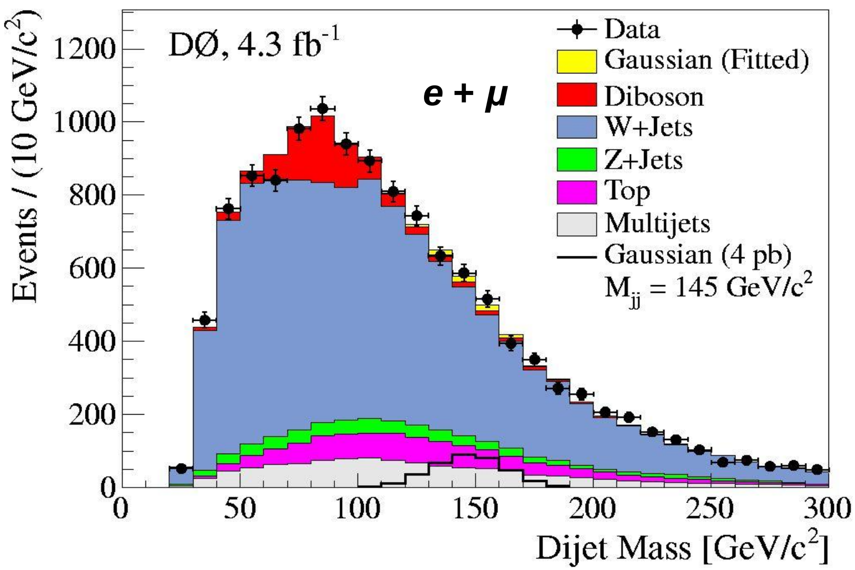
- Gaussian distribution in dijet mass with a width σ_{excess} determined by the DØ experimental resolution

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

σ_W, M_W from WW→lνjj sample

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

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

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

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

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

Fitted cross sections consistent with zero!

Setting the Limits on WX

- **Poisson Negative Log-Likelihood Ratio, LLR** (statistical test)
  Test Signal+Background (S+B) and Background-only (B) hypotheses

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

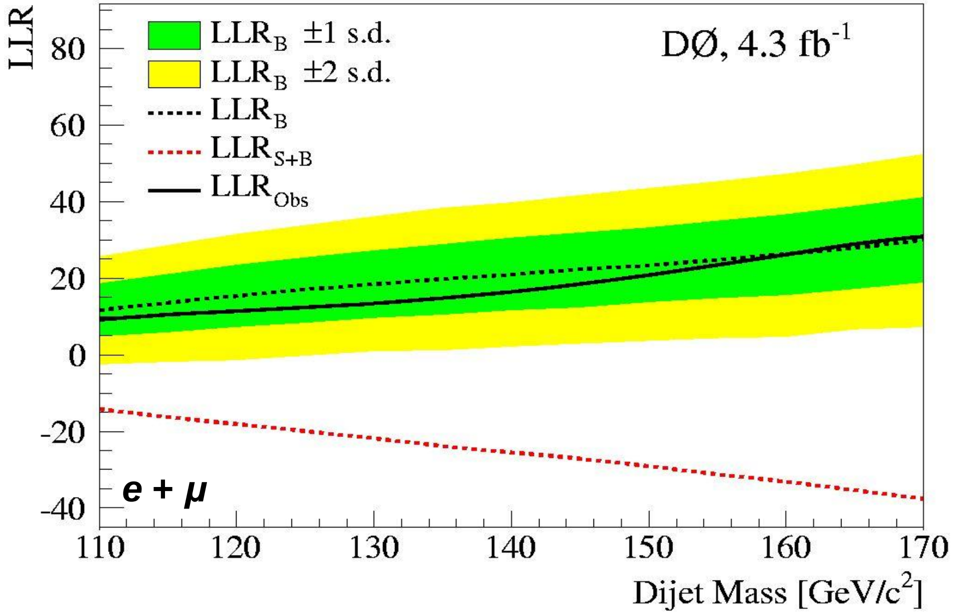
D: observed # of ev.
S: predicted # of signal ev.
B: predicted # of bkg ev.

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

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

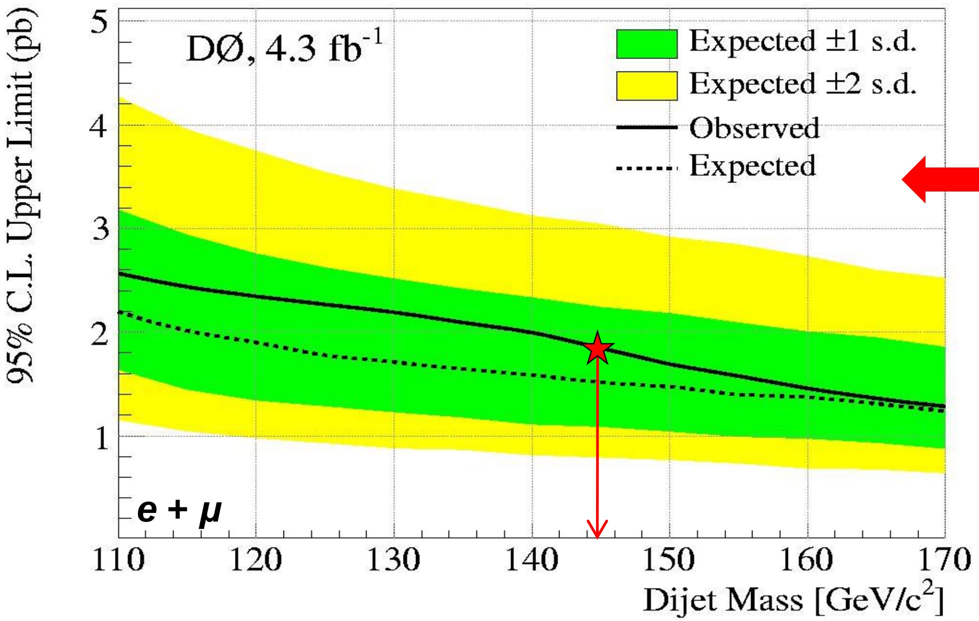
- **CL_S method** ($1- CL_S = 1- CL_{S+B}/CL_B$)
  Cross section upper limit for which the $1- CL_s$ value is 0.95 (95% CL)
  (5% chance to get observed outcome if S+B hypothesis were true)

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

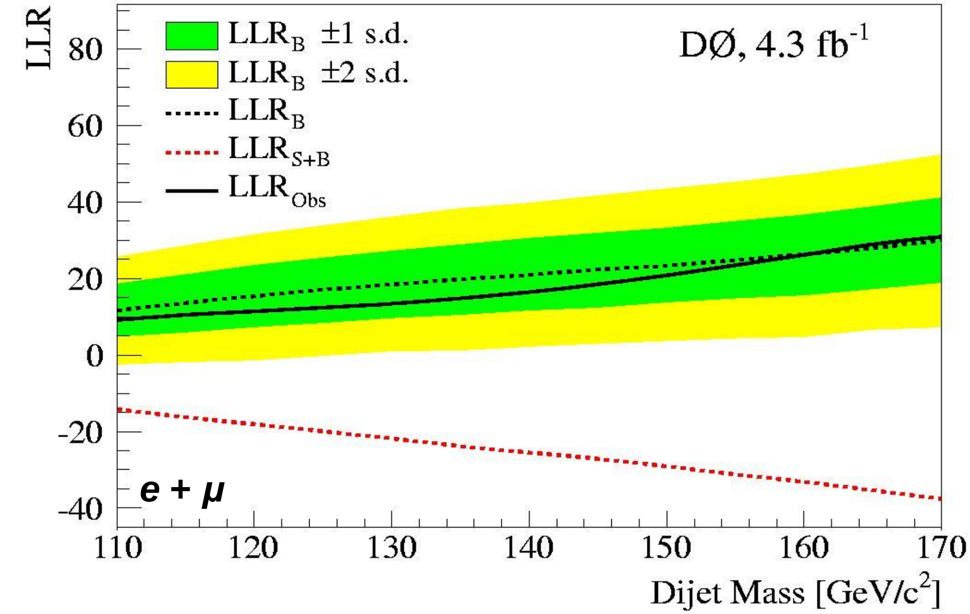
Without
Alpgen Modeling Corrections



95% CL upper limits on $WX \to l\nu jj$
(for CDF model)

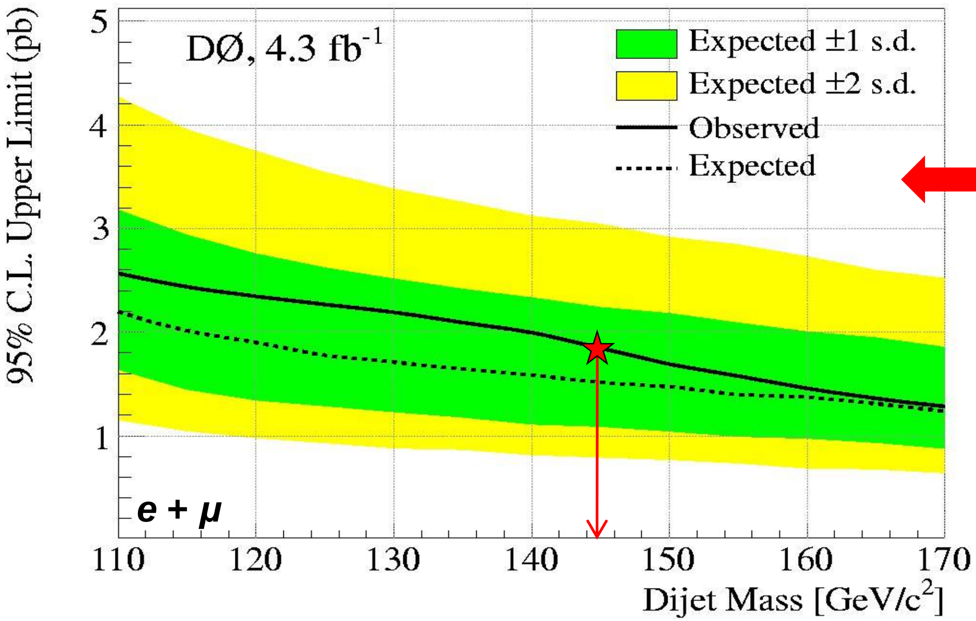
★**1.9 pb @ M_{JJ} = 145 GeV**

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)

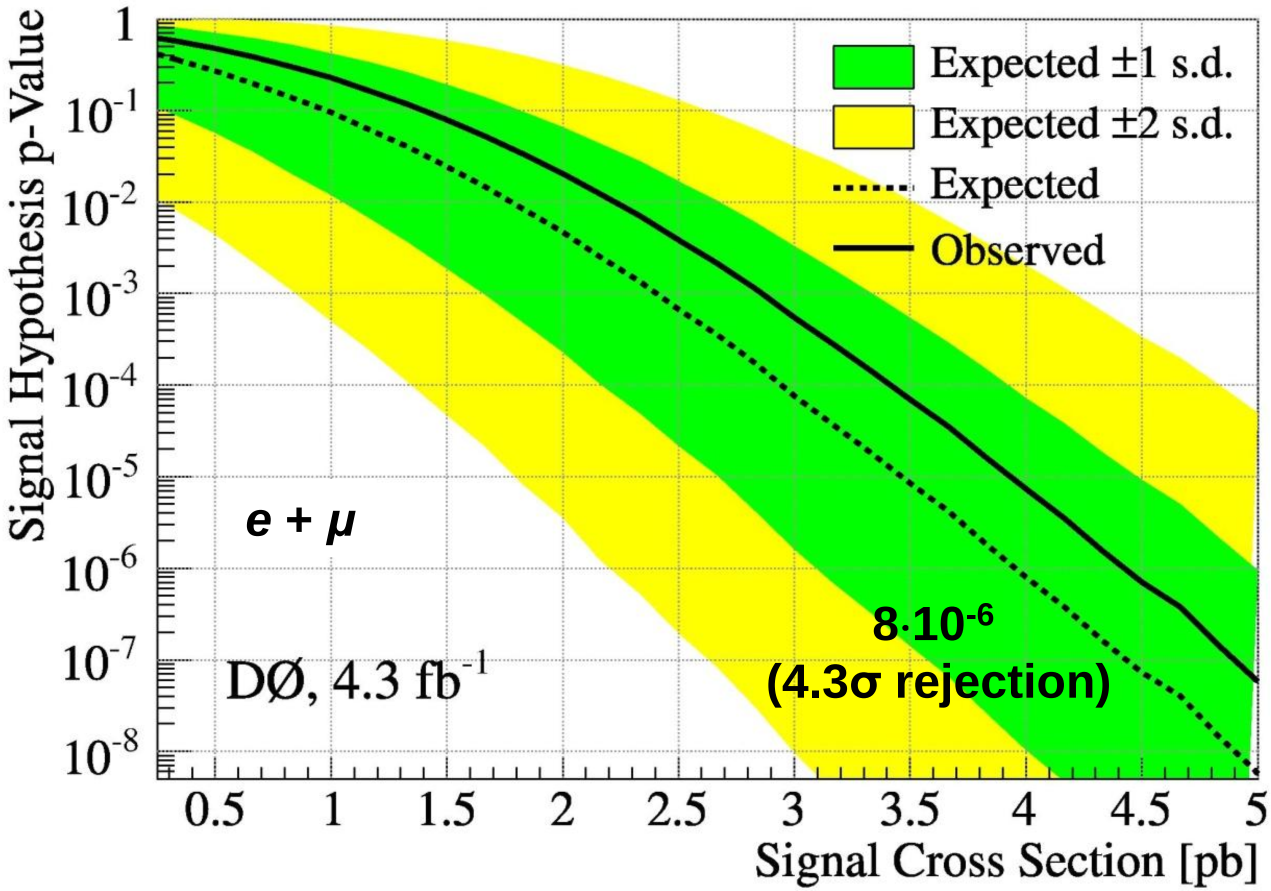
★**1.9 pb @ M_{JJ} = 145 GeV**

With
Alpgen Modeling Corrections

1.5 pb @ M_{JJ} = 145 GeV

Setting the Limits on WX

- Probability for S+B hypothesis to be true as a function of a cross section (for the CDF model of an excess at M_{JJ} = 145 GeV)
- Cross section of 4 pb excluded at 4.3σ



Without Alpgen Modeling Corrections

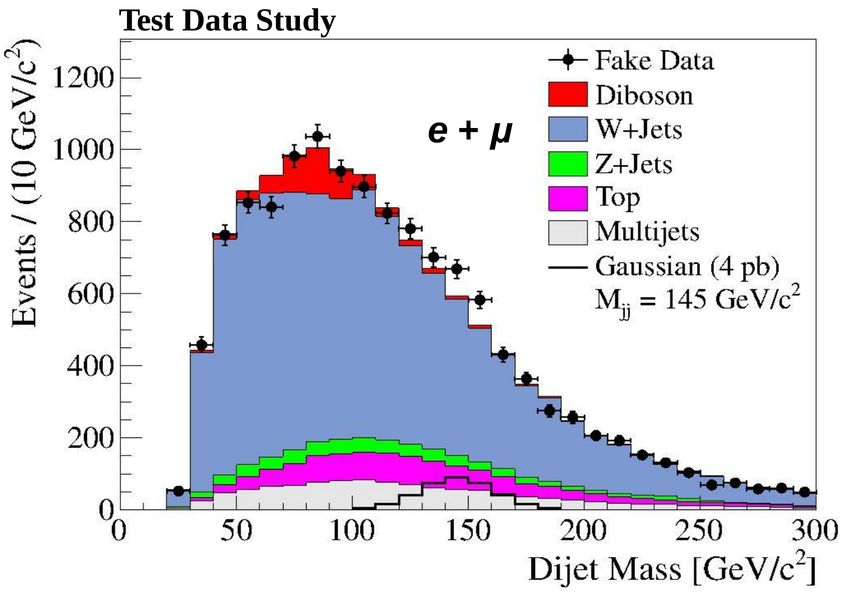
The DØ data are not consistent with the excess seen by CDF

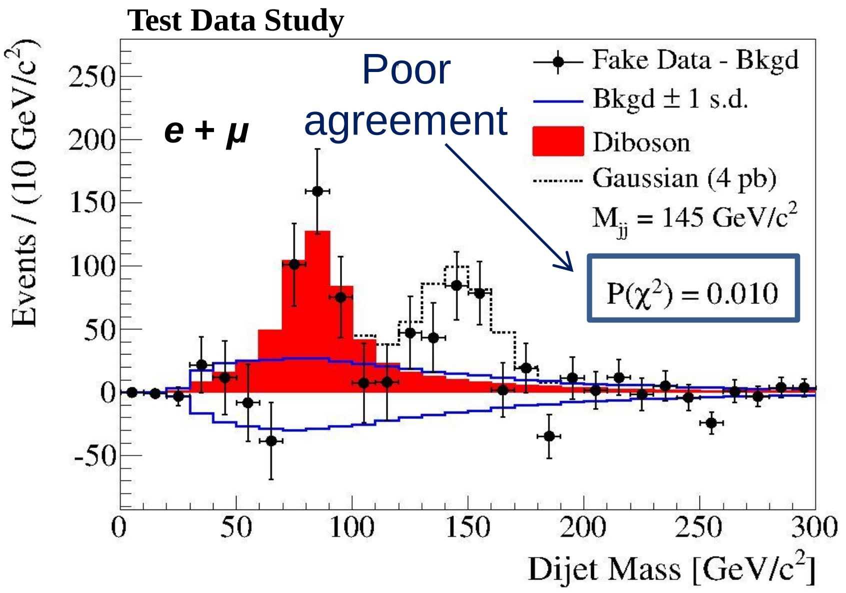
Cross checks with signal-injected data

Signal Injection

If a resonance of ~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
- Normalizations for dibosons and W+jets are free parameters



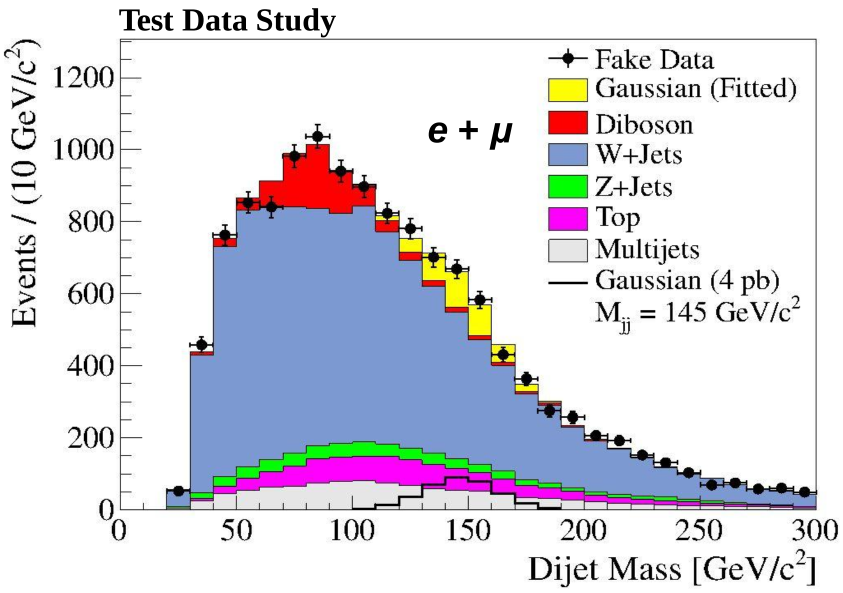


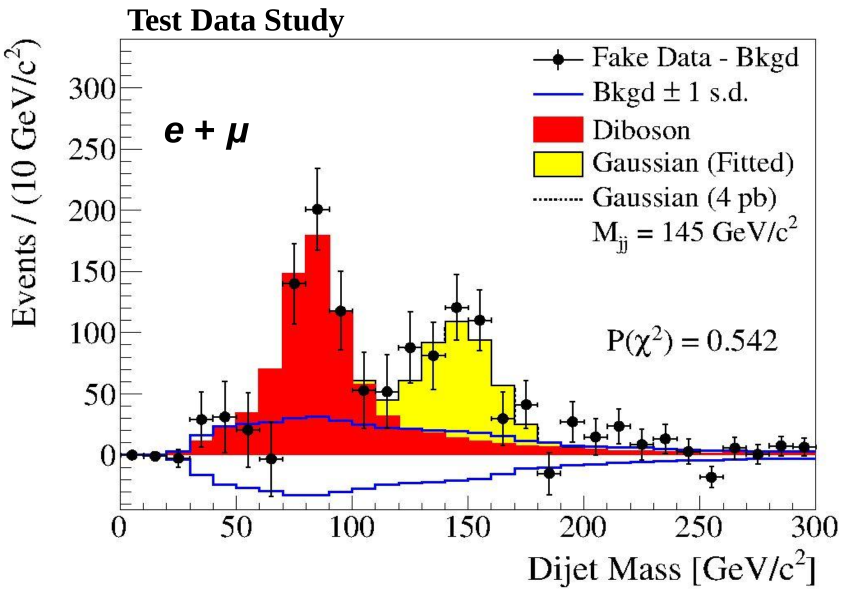
Without
Alpgen Modeling Corrections

Signal Injection

If a resonance of ~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+WX** to test data using the dijet mass distribution
- Normalizations for dibosons, W+jets and WX are free parameters

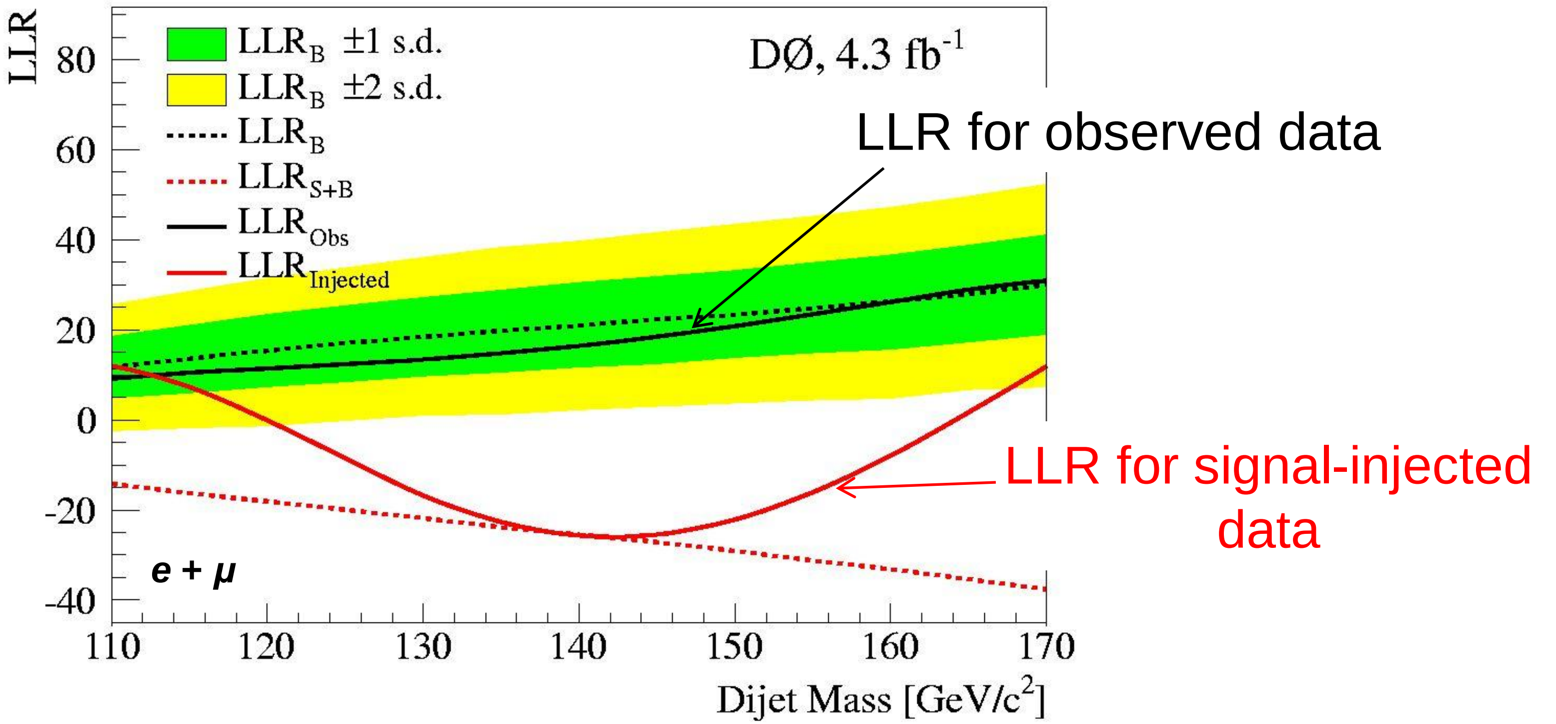




Without
Alpgen Modeling Corrections

Signal Injection

If a resonance of ~4 pb were present in our data, we would certainly see it

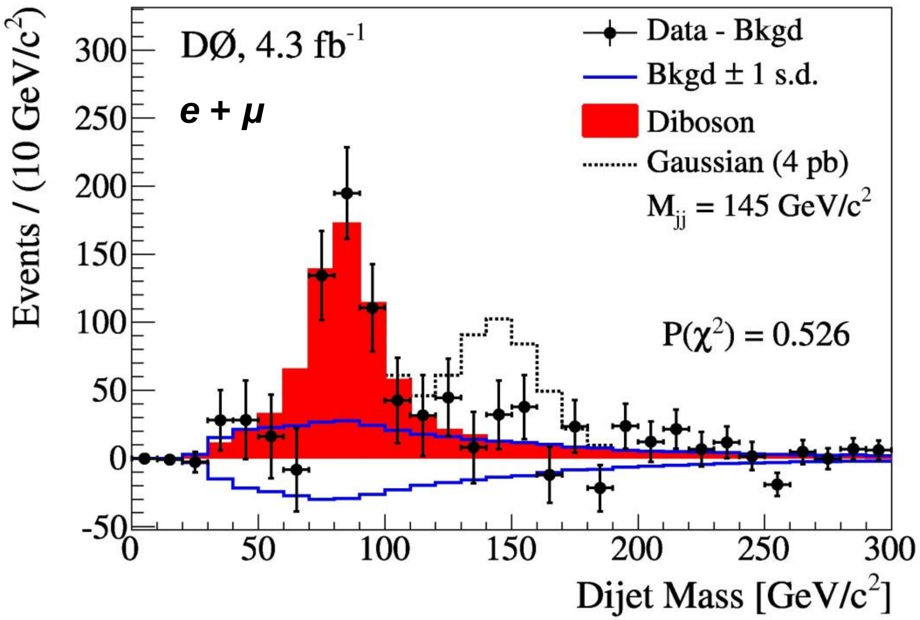


Without
Alpgen Modeling Corrections

Summary & Conclusions

- 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)