

# W/Z + Jets Results from the Tevatron



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## Outline

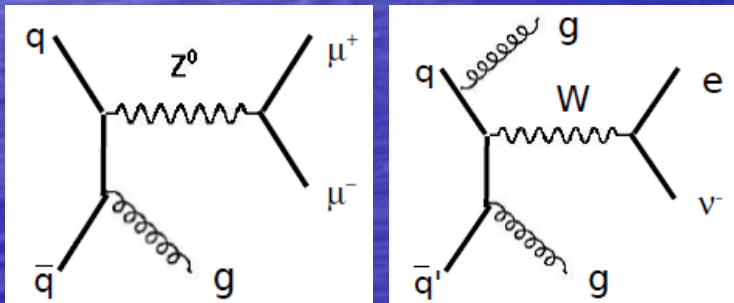
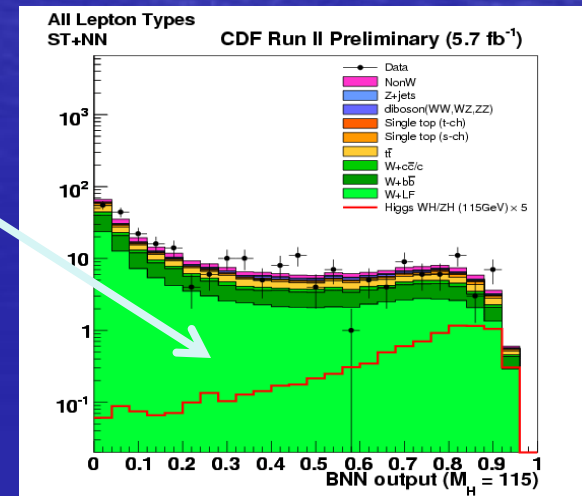
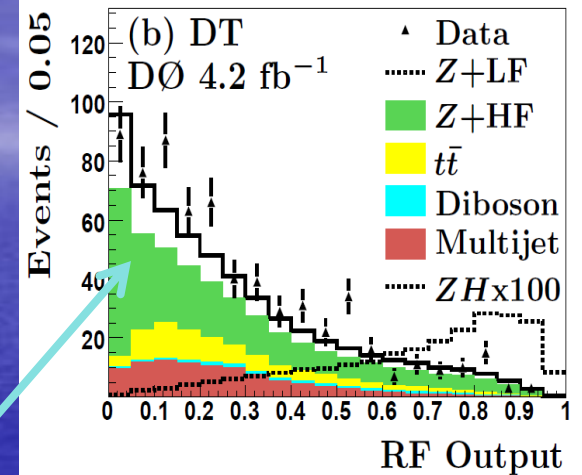
- Motivation
- Measurements
  - V+Jets
  - V+ HF Jets
- Summary & Outlook

Standard Model Benchmarks at the Tevatron and LHC  
Fermilab, Nov 19-20, 2010

# Why study W/Z + Jets production?

hep-ex/1008.3564

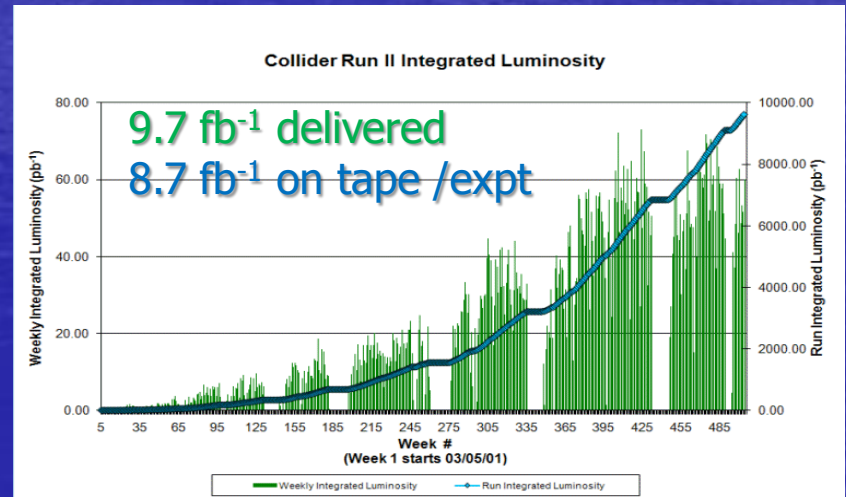
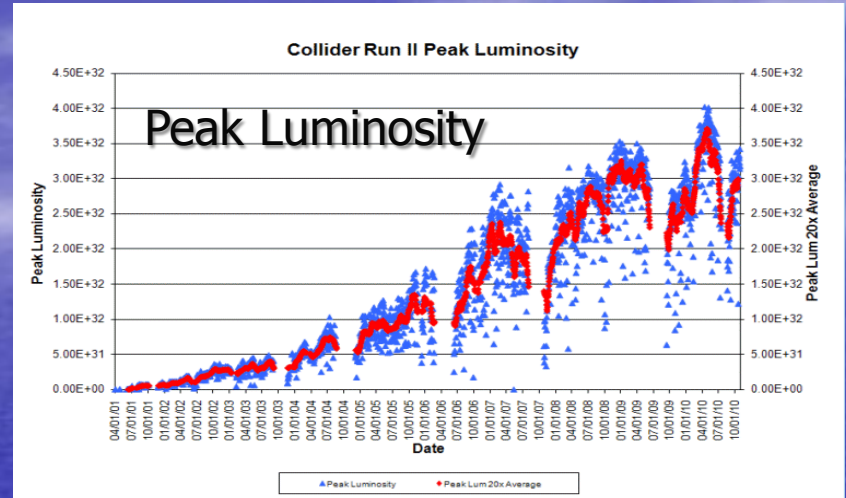
- **Test of pQCD in multijet environment**
  - Presence of W/Z ensure high  $Q^2$ : pQCD
  - Clean environment: leptonic final state provides clean signature, low BG
  - High statistics allows precision tests
- **Test of MC Models**
  - Key sample to validate available MC tools using experimental data
- **W/Z+HF production sensitive to HF PDFs**
- **Significant irreducible background**
  - Studies of Top production & properties
  - SM Higgs search : WH & ZH channels
  - BSM searches (SUSY in MET+jets)



$\sigma(Z^0 \rightarrow l^+l^-) \sim 250 \text{ pb}$   
 $\sigma(W^\pm \rightarrow l\nu) \sim 2700 \text{ pb}$   
 $\Rightarrow$  Millions of W's;  
 100's k Z's per  $\text{fb}^{-1}$

# The Tevatron Collider at Fermilab

- $p\bar{p}$  collisions @  $\sqrt{s} = 1.96$  TeV
  - 36 bunches, 396 ns
- Excellent performance
  - Peak lumi :  $3.5 \text{ E}32 \text{ cm}^{-2}\text{s}^{-1}$
  - $\int \text{Ldt} / \text{week} \sim 50 \text{ pb}^{-1}$
- Both expts performing well :  $\sim 90\%$  data taking efficiency



Thanks to the Accelerator Division!

Expect  $\sim 2.5 \text{ fb}^{-1}$  delivered in FY11  
Results presented based on  $1 - 6 \text{ fb}^{-1}$



# CDF & DØ Run II Detectors



- Multi-purpose detectors with broad particle identification capabilities

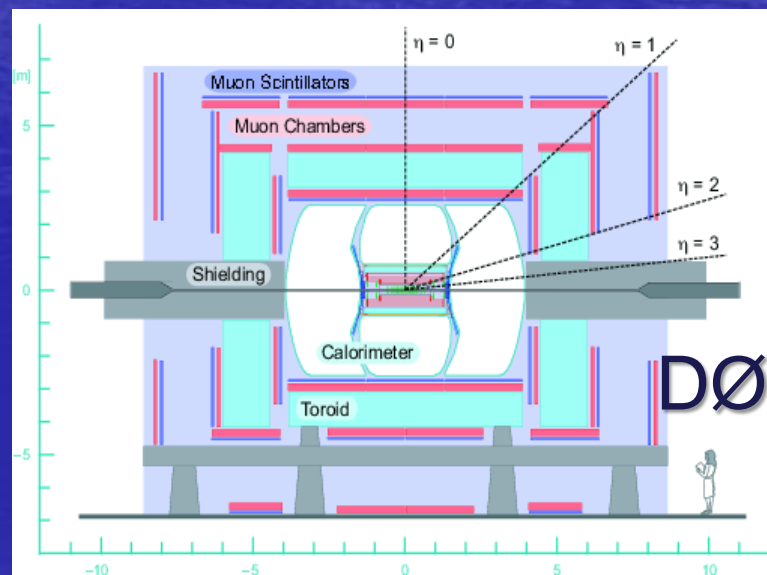
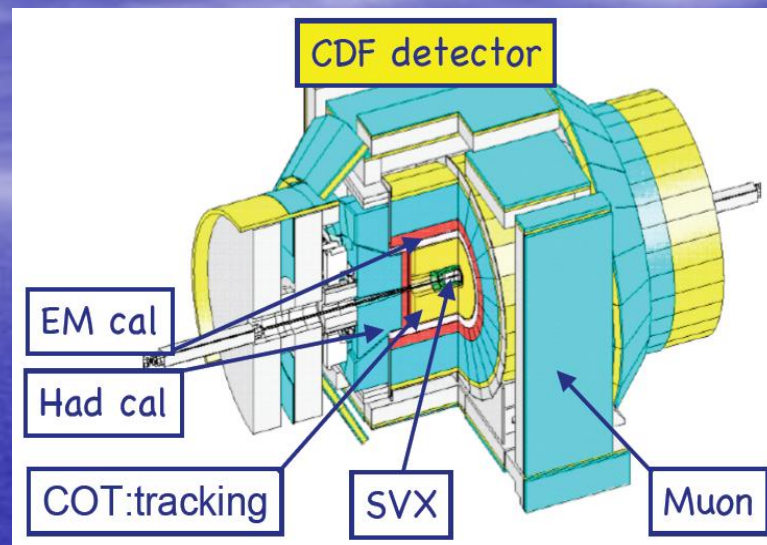
- **Common features**

- Tracking in magnetic field with silicon vertexing
- EM and Hadron calorimeters
- Muon systems

- **Competitive advantages**

- **CDF** : better track momentum resolution & displaced track trigger at Level 1
- **DØ** : finer calorimeter segmentation, and forward muon system

Performing well making use of all detectors capabilities

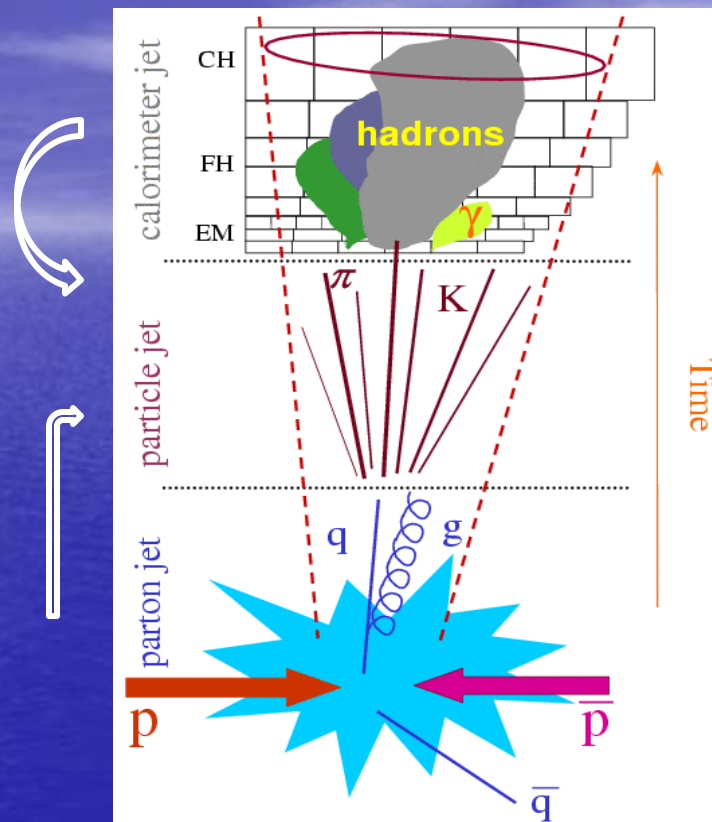


**W** →  $l\nu$  and **Z** →  $l^+l^-$  decays are easily identified with little background.

**Z** - two high  $p_T$  electrons or muons  
 - clean signal  
 - BG : fake leptons, semi-leptonic decays, di-boson production

**W** - high  $p_T$  lepton + Missing  $E_T$   
 - higher statistics, also higher BG  
 - BG : QCD (fake lepton),  $W \rightarrow \tau\nu$ , Top, diboson,  $Z \rightarrow ll$

- Jets are identified using midpoint cone algorithm.
- Jets are full corrected for the instrumental effects back to the particle level jets for comparison with the theory predictions.



**Theory predictions at parton level** : Need corrections for non-pQCD effects (hadronization and UE); derived from simulation

# Comparison to NLO QCD & MC Models

- pQCD calculations

- NLO calculations mostly available for lower jet multiplicities

Z+2 jets (+3 jets) at NLO (LO) evaluated with MCFM

W+3 jets (+4 jets) at NLO now available in MCFM

- Monte Carlo Simulation Tools

- LO matrix elements + PS modeling

PYTHIA v6.420

- Tune Perugia ( $p_T$  ordered showers)
- Tune QW ( $Q^2$  ordered showers)

HERWIG v6.510 +JIMMY v4.31

- HO matrix elements matched with PS

- ALPGEN v2.13+PYTHIA v6.420
- ALPGEN v2.13+HERWIG v6.510
- Sherpa 1.1.3

Data fully corrected for instrumental effects  $\Rightarrow$  can be directly used for testing & improving MC models and any future calculations /models.



# Many Tevatron Run II Results



## V + Jets

|  |                           |                          |
|--|---------------------------|--------------------------|
| Z/ $\gamma^*$ ( $\rightarrow\mu\mu$ )+jets | CDF/6.0 fb <sup>-1</sup>  | Preliminary              |
| Z/ $\gamma^*$ ( $\rightarrow ee$ )+jets    | CDF/2.5 fb <sup>-1</sup>  | Preliminary              |
| Z/ $\gamma^*$ +1 jet pT balance            | CDF/4.6 fb <sup>-1</sup>  | NIMA 662, 698 (2010)     |
| Z/ $\gamma^*$ ( $\rightarrow\mu\mu$ )+jets | D0/1.0 fb <sup>-1</sup>   | PLB 682, 370 (2010)      |
| Z/ $\gamma^*$ ( $\rightarrow ee$ )+jets    | D0/1.0 fb <sup>-1</sup>   | PLB 678, 45 (2009)       |
| Z/ $\gamma^*$ ( $\rightarrow ee$ )+jets    | CDF/1.7 fb <sup>-1</sup>  | PRL 100, 102001 (2008)   |
| W( $\rightarrow l\nu$ )+jets               | CDF/0.32 fb <sup>-1</sup> | PRD 77, 011108(R) (2008) |
| Z/ $\gamma^*$ ( $\rightarrow\mu\mu$ )+jets | D0/1.0 fb <sup>-1</sup>   | PLB 669, 278 (2008)      |
| Z/ $\gamma^*$ ( $\rightarrow ee$ )+jets    | D0/0.4 fb <sup>-1</sup>   | PLB 658, 112 (2008)      |

## V + Heavy Flavor Jets

|                       |                           |                        |
|-----------------------|---------------------------|------------------------|
| W+charm               | CDF/4.3 fb <sup>-1</sup>  | Preliminary            |
| Z+b/Z+jets            | D0/4.2 fb <sup>-1</sup>   | hep-ex/1010.6203       |
| W+bottom              | CDF/1.9 fb <sup>-1</sup>  | PRL 104, 131801 (2010) |
| Z/ $\gamma^*$ +bottom | CDF/2.0 fb <sup>-1</sup>  | PRD 79, 052008 (2009)  |
| W+charm               | CDF/1.8 fb <sup>-1</sup>  | PRL 100, 091803 (2008) |
| W+c/W+jets            | D0/1.0 fb <sup>-1</sup>   | PLB 666, 23 (2008)     |
| Z/ $\gamma^*$ +bottom | CDF/0.33 fb <sup>-1</sup> | PRD 74, 032008 (2006)  |
| Z+b/Z+jets            | D0/0.18 fb <sup>-1</sup>  | PRL 94, 161801 (2005)  |

Will concentrate on recent results

# $Z/\gamma^* \rightarrow \mu^+ \mu^- + \geq 1 \text{ Jet}$



$\mathcal{L} = 6 \text{ fb}^{-1}$

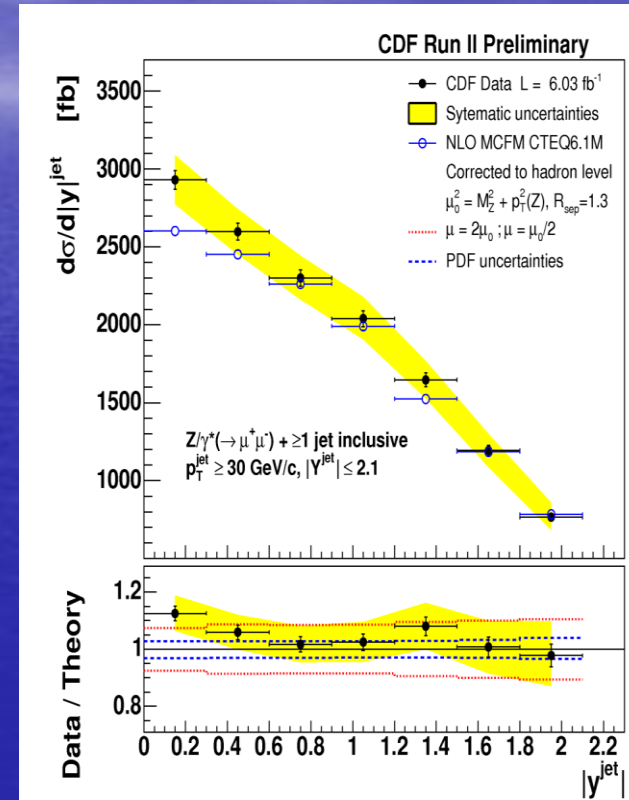
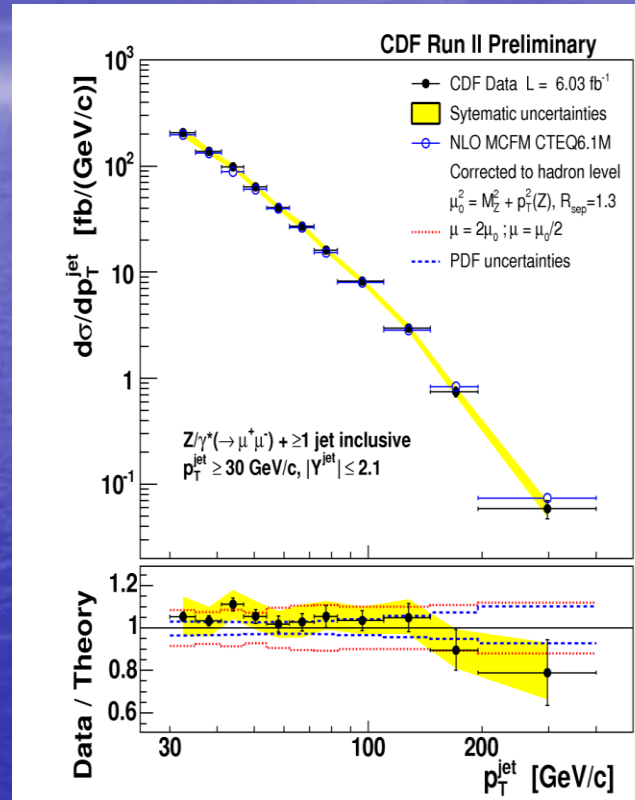
Inclusive jet diff. cross sections in  $p_T^{\text{jet}}$  and  $y^{\text{jet}}$

## Kinematic selection

- Two central  $\mu$ 's
- $p_T^\mu > 25 \text{ GeV}$ ,  $|\eta| < 1.0$
- $66 < M_{\mu\mu} < 106 \text{ GeV}$
- $\geq 1 \text{ jet}$ ,  $R = 0.7$
- $p_T^{\text{jet}} > 30 \text{ GeV}$ ,  $|y^{\text{jet}}| < 2.1$

## Events :

Data : 13200  
 Background : 6%  
 QCD Multijet, W+jets  
 $Z_\gamma$  (dominant),  $t\bar{t}$ ,  
 Diboson,  $Z \rightarrow \tau\tau$



Measured cross sections are corrected back to particle level. Compared to MCFM NLO prediction including non-pQCD effects. Data is well described.



# $Z/\gamma^* \rightarrow \mu^+ \mu^- + \geq 2 \text{ Jets}$



$\mathcal{L} = 6 \text{ fb}^{-1}$

Inclusive jet diff. cross sections in  $p_T^{\text{jet}}$  and  $y^{\text{jet}}$

Events :

Data : 1500

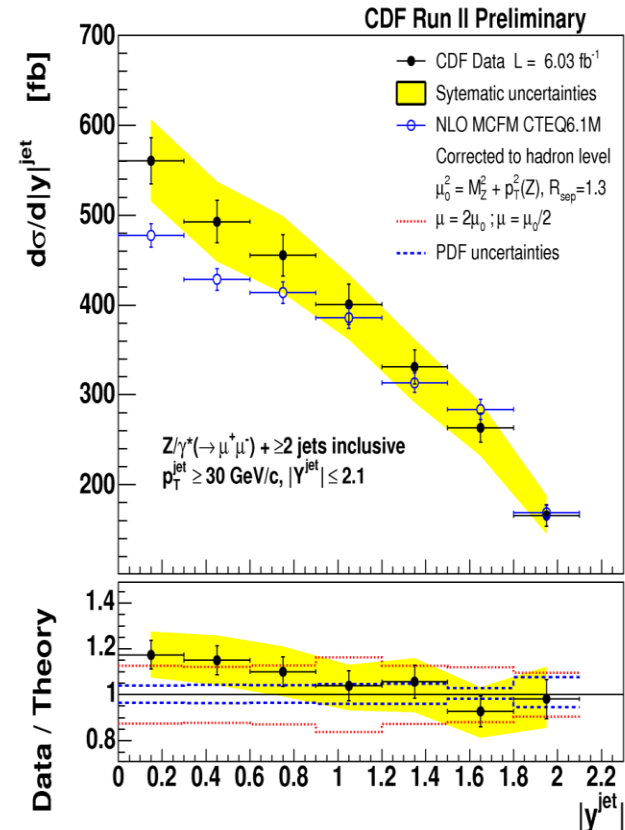
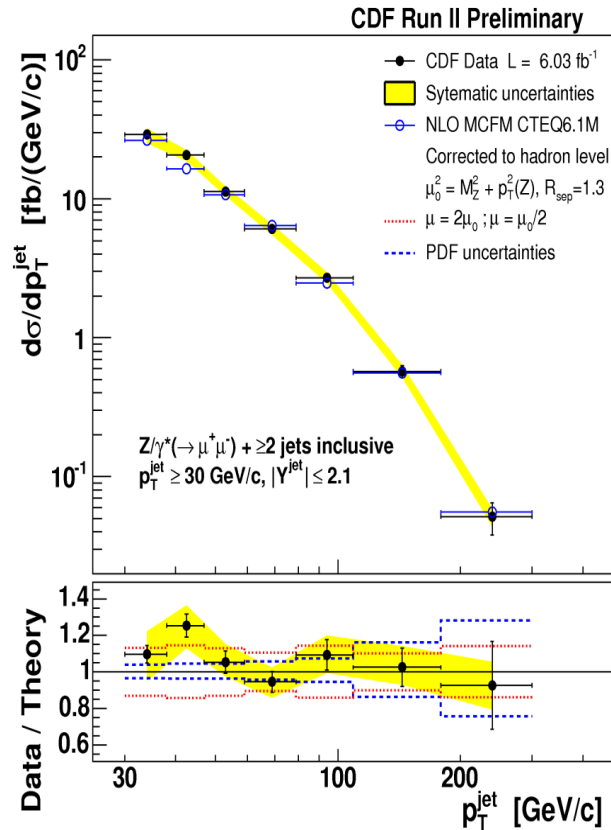
Background : 9%

NLO MCFM :

CTEQ6.1 PDF

$\mu_0^2 = M_Z^2 + p_T^2(Z)$

Non-pert. Corr. for fragmentation and UE estimated from Pythia -Tune A



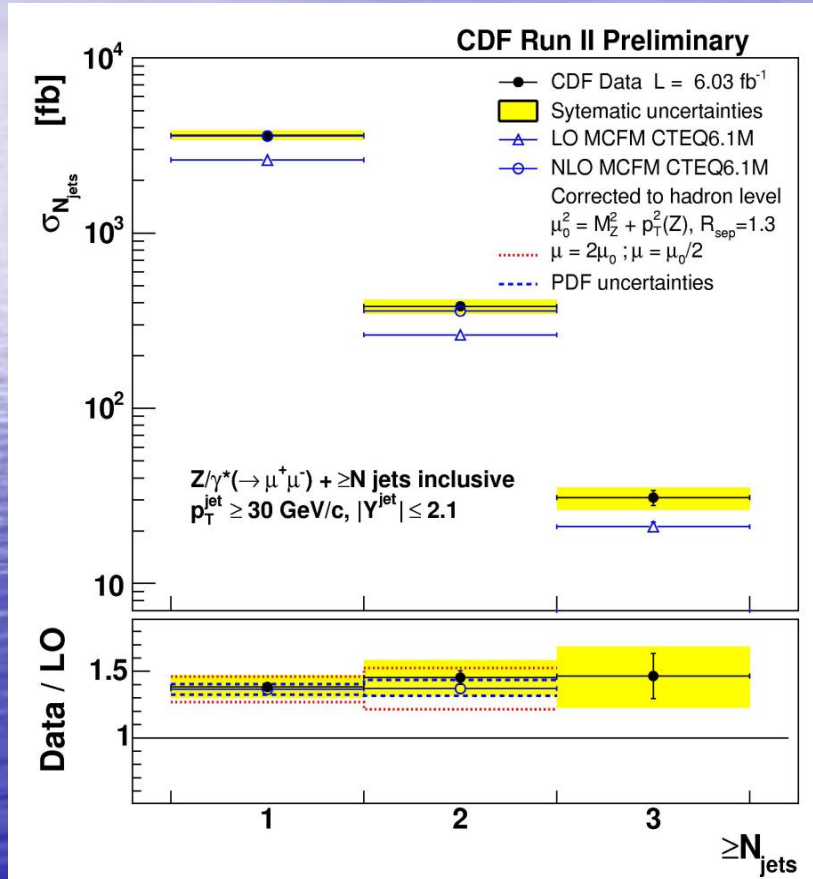
Measurements are well described by MCFM NLO

# $Z/\gamma^* \rightarrow \mu^+ \mu^- + \geq 1 \text{ Jet}$



$\mathcal{L} = 6 \text{ fb}^{-1}$

Total incl. cross sections in  
incl. jet multiplicities



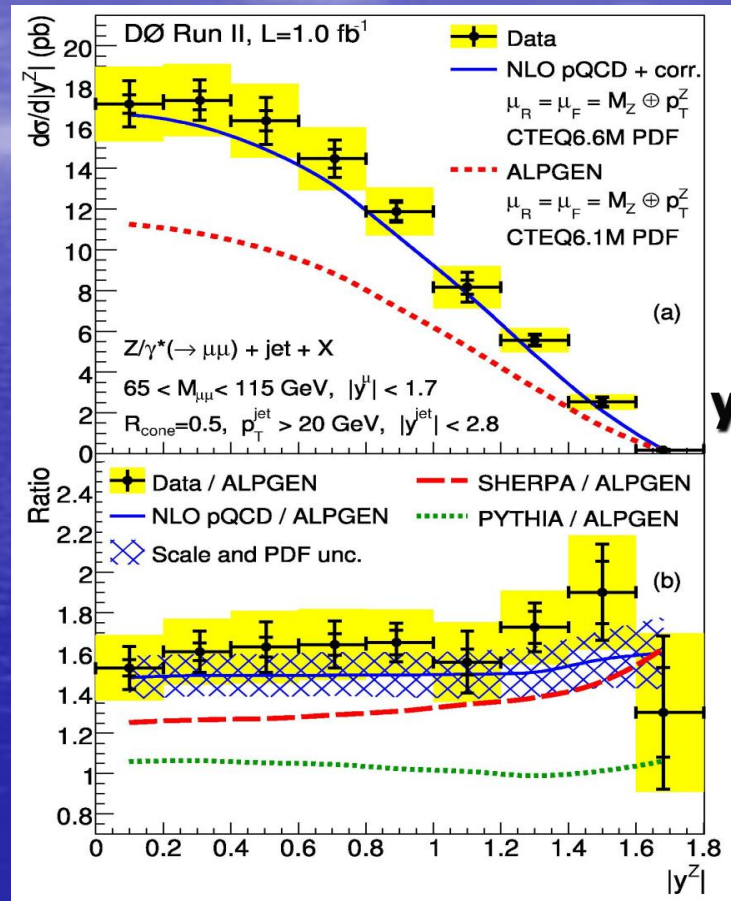
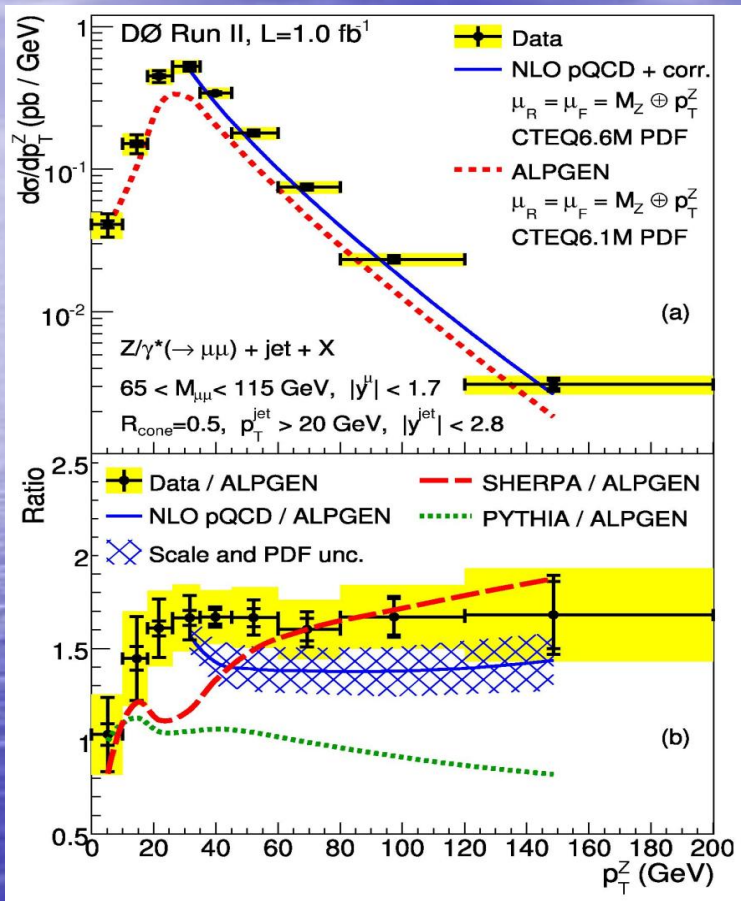
- Good agreement between data & NLO prediction in  $\geq 1, \geq 2$  jet bins
- For  $N_{\text{jet}} \geq 3$ , only LO calculation available
- Systematic uncertainties : 5–15%, JES dominant
- Data suggest a ratio to LO of  $\sim 1.4$
- 130 (10) events in  $Z + \geq 3$  ( $Z + \geq 4$ ) jets bin

# $Z/\gamma^* \rightarrow \mu^+ \mu^- + \text{Jet}(s)$



$\mathcal{L} = 1 \text{ fb}^{-1}$

Differential cross sections in  $p_T$  and  $y$  of the Z boson



ALPGEN describes shape well except at low  $p_T^Z$   
 All generators show significant normalization differences to the data

MCFM NLO better describes data except at low  $p_T^Z$ , where non-pert. Processes dominate

# $Z/\gamma^* \rightarrow e^+e^- + \geq 2 \text{ Jets}$



$\mathcal{L} = 1 \text{ fb}^{-1}$

Measured diff. cross sections normalized to incl.  $\sigma(Z)$  binned in  $p_T$  of  $n$ th jet :  $Z + \geq n \text{ jets}, n=1-3$

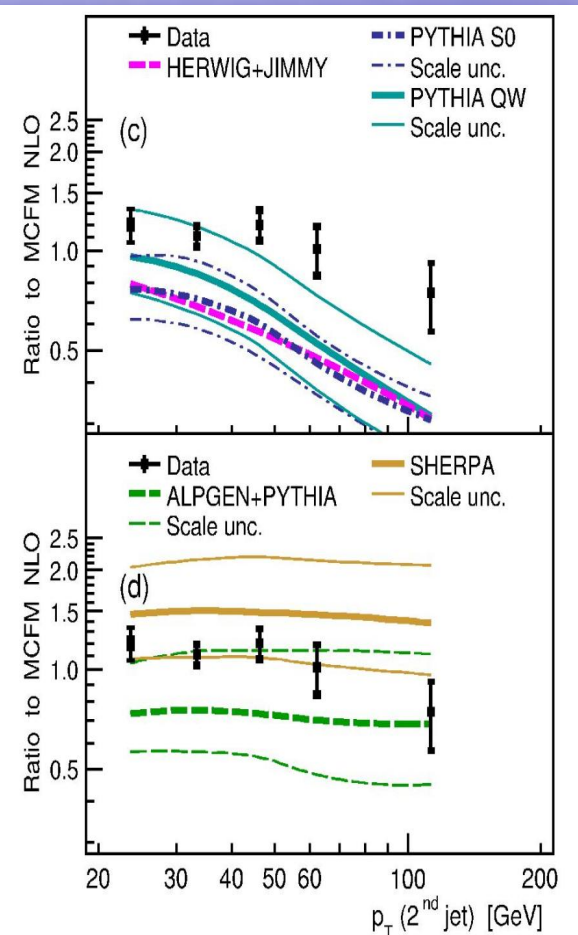
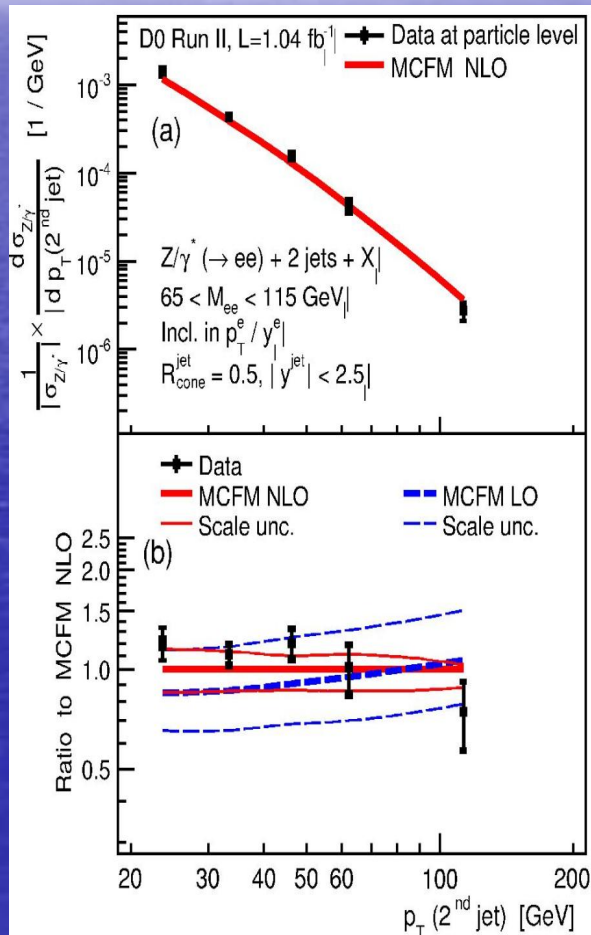
$Z + \geq 2 \text{ jet}, 2^{\text{nd}} \text{ jet } p_T$

MCFM NLO significant improvement over LO  
NLO describes data

Event generators  
HERWIG, PYTHIA :  
normalization and  
shape differences

ALPGEN+PYTHIA and  
SHERPA predict shape  
reasonably well.  
Normalizations can be  
made to agree by  
adjusting the scale.

Uncertainties on MC  
predictions large!



# Z/ $\gamma^*$ + Jet(s) Angular Correlations



$\mathcal{L} = 1 \text{ fb}^{-1}$

PLB 682, 370 (2010)

First measurements of angular correlations between Z and leading jet

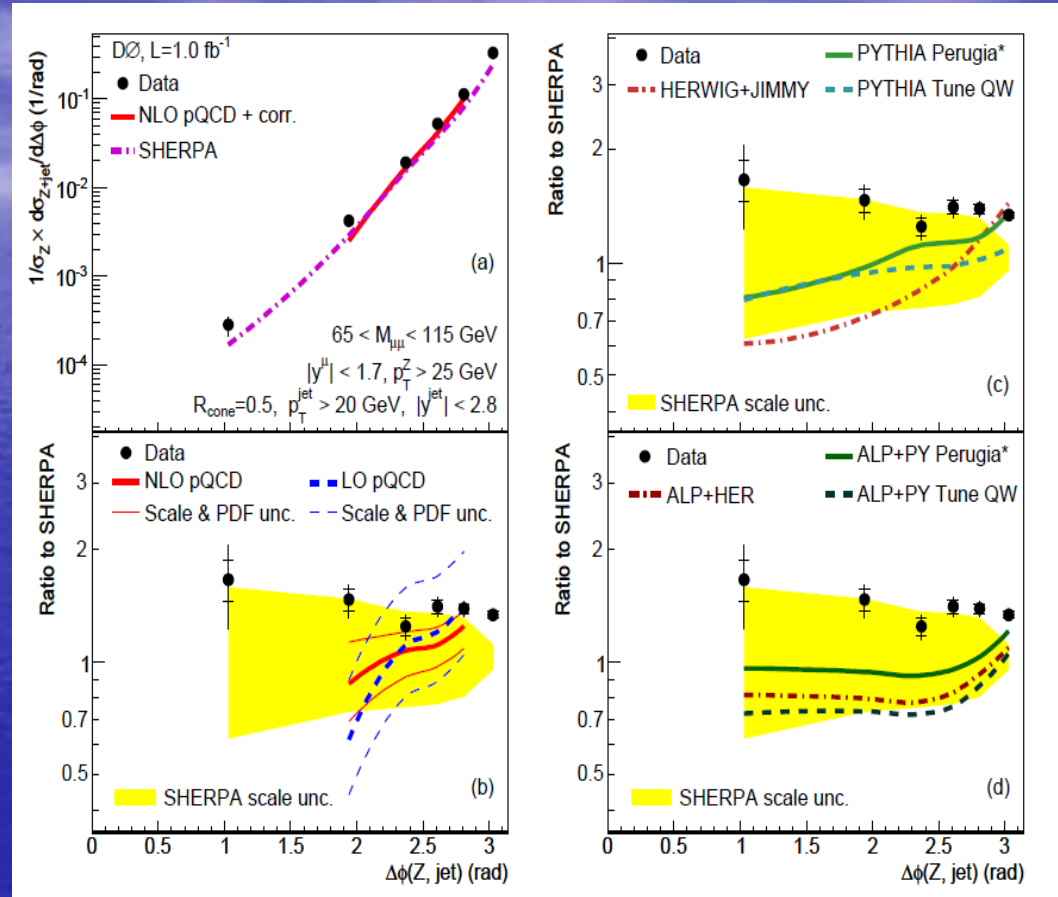
$$\Delta\phi(Z, \text{jet}), \Delta y(Z, \text{jet})$$

$$y_{\text{boost}} = 1/2(y_Z + y_{\text{jet}})$$

Sensitive to QCD radiation :  
Test of PS model assumptions.

The diff. cross-sections are normalized to incl.  $\sigma(Z)$   
 $p_T^Z > 25 \text{ GeV}$  (avoid soft effects)  
 Small  $\Delta\phi(Z, \text{jet})$  excluded from MCFM due to importance of non pert. effects.

Reasonable agreement between data and NLO.  
 Sherpa best describes the shape, but not normalization.



Event generators tend to have normalization and shape differences. ALPGEN+PYTHIA (Perugia) improves description.

# Z + Jet $p_T$ balance



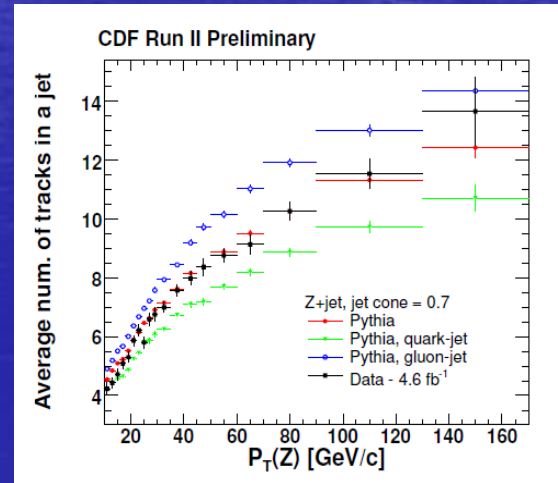
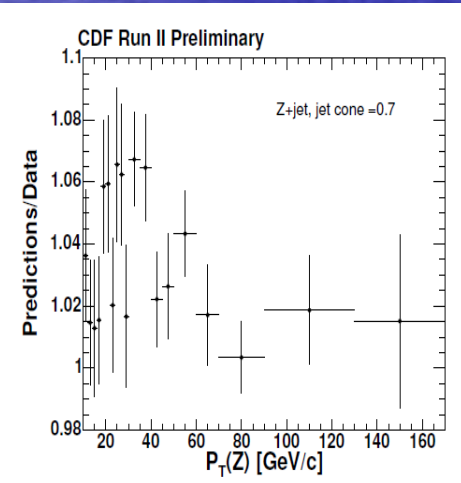
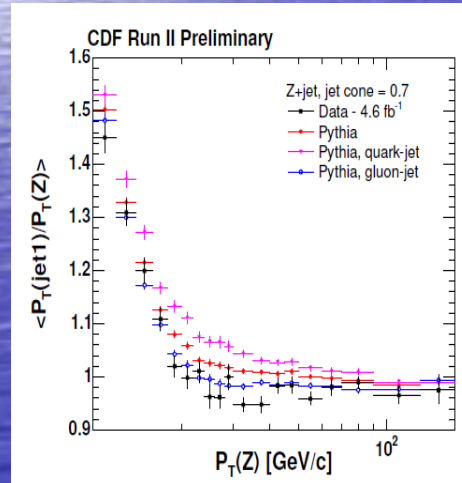
$\mathcal{L} = 4.6 \text{ fb}^{-1}$

Select Z + 1 jet events, back-to-back  
 $p_T^j > 18 \text{ GeV}$ ,  $80 < M_{ll} < 100 \text{ GeV}$   
 Leading jet  $p_T^{\text{jet}} > 8 \text{ GeV}$ ,  $0.2 < |\eta| < 0.8$   
 $\Delta\phi(\text{Z, jet}) > 3.0 \text{ rad}$   
 $R = 0.4, 0.7, 1.0$

Study of  $p_T$  balance has been used to study and evaluate the impact of various theoretical uncertainties on the jet energy measurements.

- ME's and parton-jet matching; renorm. & fact. scales, PDFs, FSR parameters, MPI, single particle response, large-angle FSR

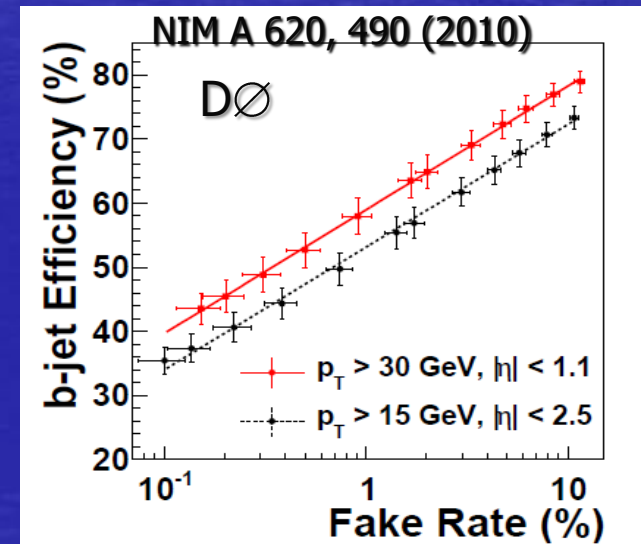
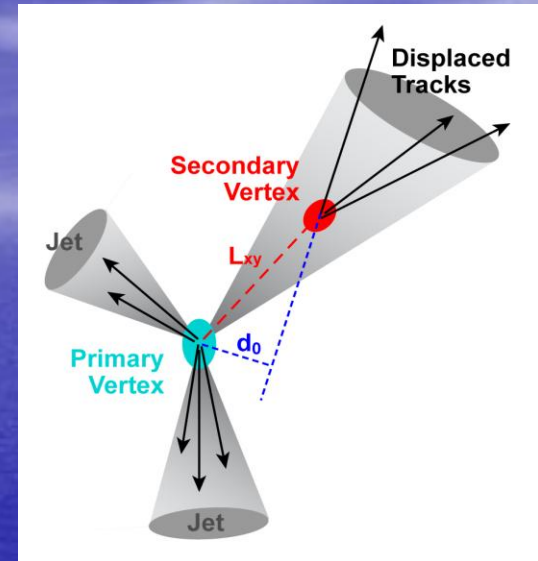
## Independent test of CDF JES



The uncertainty from mis-modeling of FSR at large angles is largest.

# Identifying b-jets

- Most common b-tagging technique exploits long lifetime of b-hadrons
  - Reconstruct secondary vertex from displaced tracks (not from primary vertex) inside jet
- CDF' : SecVtx tagging based on large transverse displacement ( $L_{xy}$ )
- D0 : NN based on combination of variables sensitive to presence of displaced tracks forming sec. vtx.



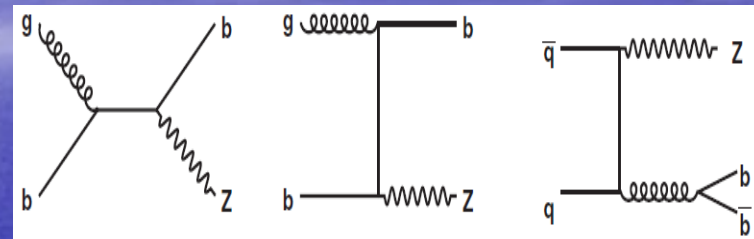
# Z + b-jets / Z + jets



$\mathcal{L} = 4.2 \text{ fb}^{-1}$

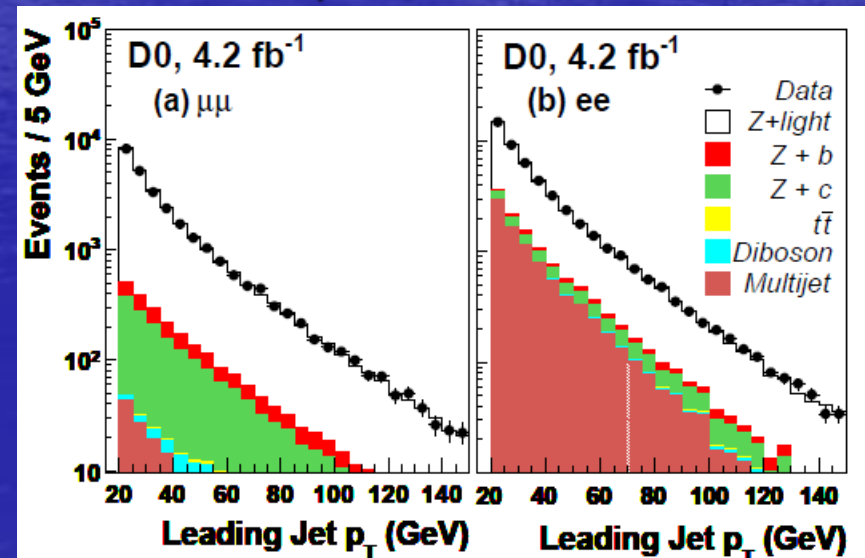
## Motivation

- Interesting test of pQCD predictions
- Important bkgd to SM Higgs search in  $ZH \rightarrow \nu\nu / ll \text{ } bb$  channel
- Sensitive to b-quark PDF
- Measurement of ratio benefits from cancellation of many systematics  $\Rightarrow$  precise comparison with theory



hep-ex/1010.6203

- Data :  $4.2 \text{ fb}^{-1}$
- Consider both e and  $\mu$  channels  
 $70 < M_{ll} < 110 \text{ GeV}$
- $Z + \geq 1 \text{ Jet}$   
 $R=0.5, p_T > 20 \text{ GeV}, |\eta| < 2.5$





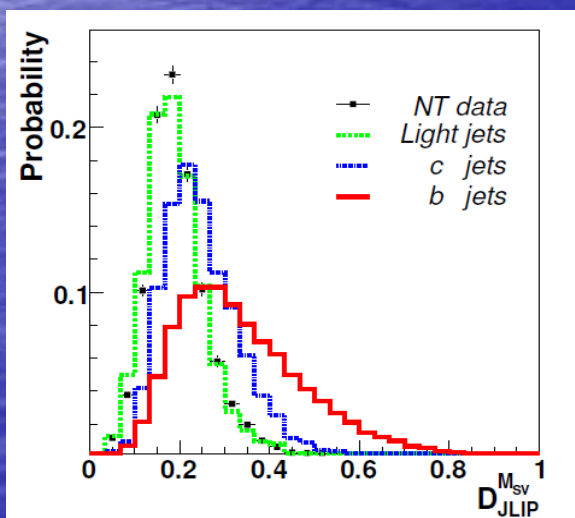
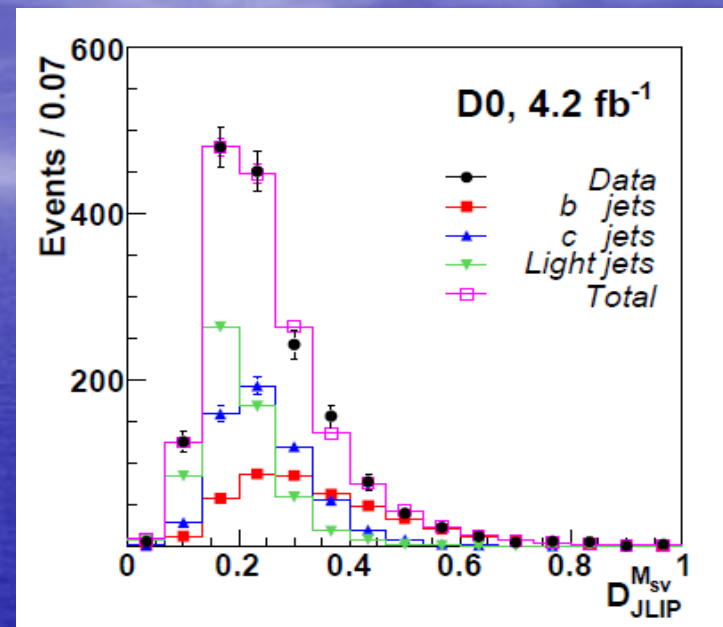
# Z + b-jets / Z + jets



$\mathcal{L} = 4.2 \text{ fb}^{-1}$

• **Strategy:**

- Select Z events with  $\geq 1$  b-tagged jet to enrich sample with heavy flavors
- Use a novel technique to distinguish b-flavored jets from charm and light flavored jets : construct a discriminant with  $M_{\text{svT}}$  and jet lifetime probability.
- Fit Data – Bkgd with templates of disc. to extract Z+b fraction



- Measured  $\sigma(Z+b)/\sigma(Z+jet)$  ratio  
 $= 0.0192 \pm 0.0022 \pm 0.0015$ 
  - Most precise to date
  - Good agreement with MCFM prediction :  $0.0185 \pm 0.0022$
  - CDF result :  $0.0208 \pm 0.0033 \pm 0.0034$

# Z + b-jets Production

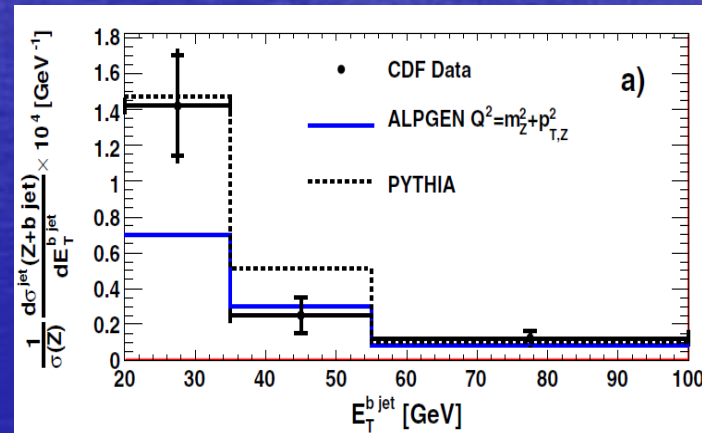
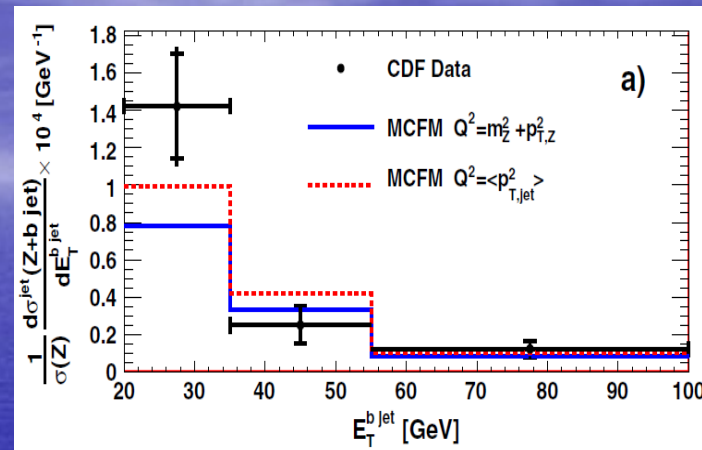
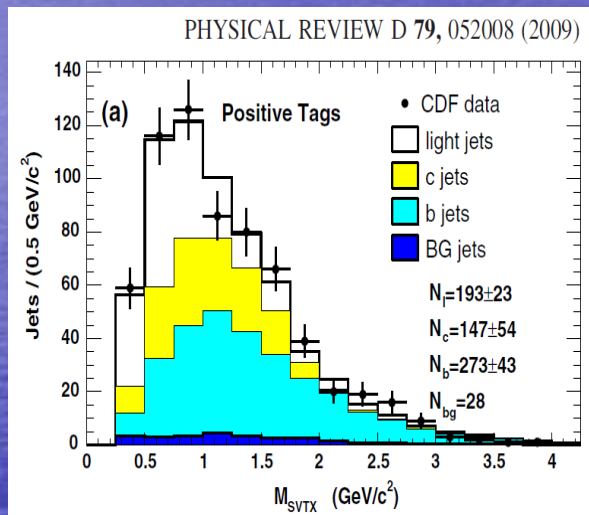


$\mathcal{L} = 2 \text{ fb}^{-1}$

- Utilize  $Z \rightarrow ee/\mu\mu$
- Jets :  $R = 0.7$ ,  $p_T > 20 \text{ GeV}$ ,  $|\eta| < 1.5$
- b-quark composition extracted from fit to sec. vtx. mass

$\sigma(Z+b)/\sigma(Z) = 0.336 \pm 0.053 \pm 0.041\%$

MCFM NLO : 0.28%  
 PYTHIA : 0.35%  
 ALPGEN : 0.21%



Measurements in agreement with predictions (large uncert. in both data & theory).

No complete NLO calculation for  $Z+bb \rightarrow$  large scale dependence

Slight underestimation by MCFM NLO at low  $E_T$   
 Pythia : good at low  $E_T$ , but, less so at higher  $E_T$   
 Large variations between ALPGEN & PYTHIA.

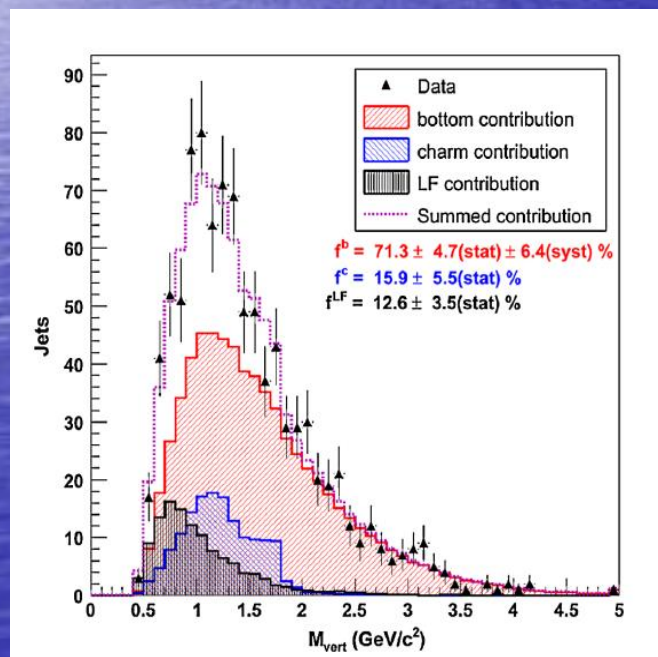
# W + b-jets Production


 $\mathcal{L} = 1.9 \text{ fb}^{-1}$ 

- $W \rightarrow l\nu$  ( $l=e,\mu$ ) selection  
 $p_T > 20 \text{ GeV}$ ,  $|\eta| < 1.1$ ,  $p_T^\nu > 25 \text{ GeV}$
- **Jets : 1 or 2 in final state**  
 $R = 0.4$ ,  $p_T > 20 \text{ GeV}$ ,  $|\eta| < 2.0$
- $\geq 1$  b-tagged jet, SecVtx algorithm
- **Determine W+b fraction** from fit to  $M_{\text{SVT}}$  with templates of b,c & light flavors.

- **Major backgrounds**  
 ttbar (40%), single top (30%)  
 Fake W (15%), WZ (5%)

$$\sigma_{W+bjets} \cdot Br = \frac{N_{b-tags} \cdot f^{bjets} - N_{bkg}^{bjets}}{L \times A \times \epsilon}$$



- **Measurement**  
 $\sigma \times BR = 2.74 \pm 0.27 \pm 0.42 \text{ pb}$   
 NLO MCFM :  $1.22 \pm 0.14 \text{ pb}$   
 Pythia :  $1.10 \text{ pb}$ , Alpgen :  $0.78 \text{ pb}$

**Measurement 2.5 – 3.5 x higher than MC & Theory predictions**  
 Need for improved theory : HO corrections, b-quark frag. model.

# W + Single c Production

- **Motivation**

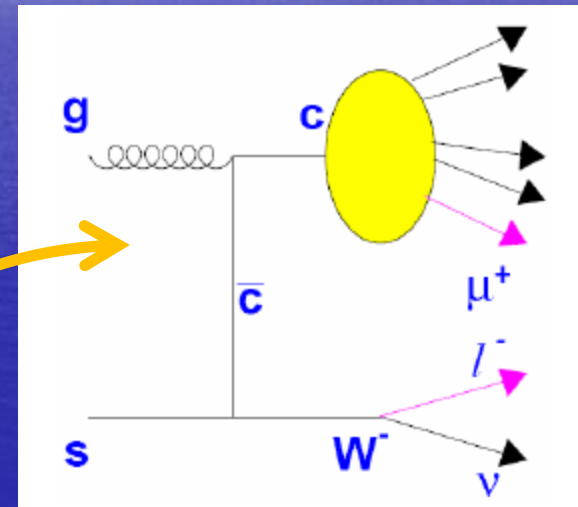
- Sensitive to s-quark PDF in proton
- Also to CKM matrix element  $V_{cs}$
- BG for single top, WH

- **Strategy**

- $W \rightarrow l\nu$  selected by high  $p_T$   $e/\mu + MET$
- Charm-jets are identified by soft lepton tagging (SLT) algorithm
- Exploit charge correlation between lepton from W decay and SLT lepton
- Wc events : OS
- Most of BG processes like Wcc give OS & SS almost equally
- Look for excess of  $N^{OS} - N^{SS}$

$gs \rightarrow W^+c$  ( $\sim 90\%$ )

$gd \rightarrow W^-c$  ( $\sim 10\%$ )



- **Main backgrounds**

- Fake W (QCD)
- W+light jets
- Drell-Yan

$$\sigma_{W+c} \times Br(W \rightarrow l\nu) = \frac{N_{measured}^{OS-SS} - N_{bkg}^{OS-SS}}{L \times A \times \epsilon}$$



# W + Single c Production

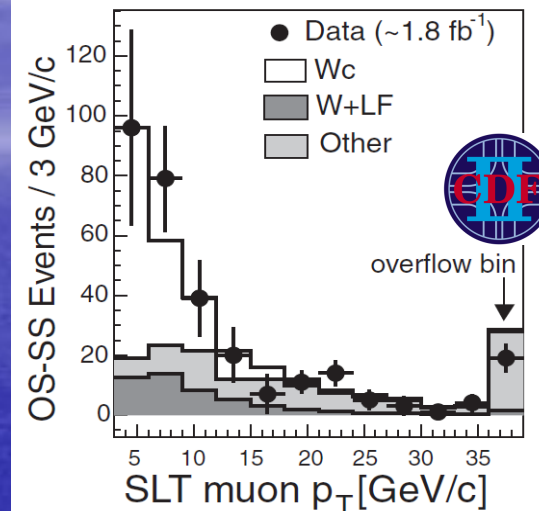
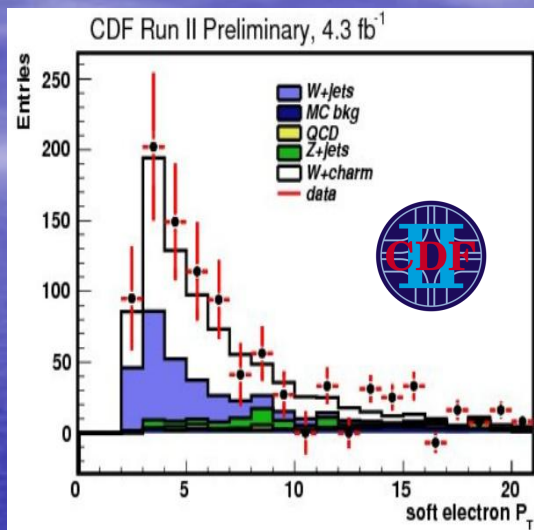


PRL 100, 091803 (2008)

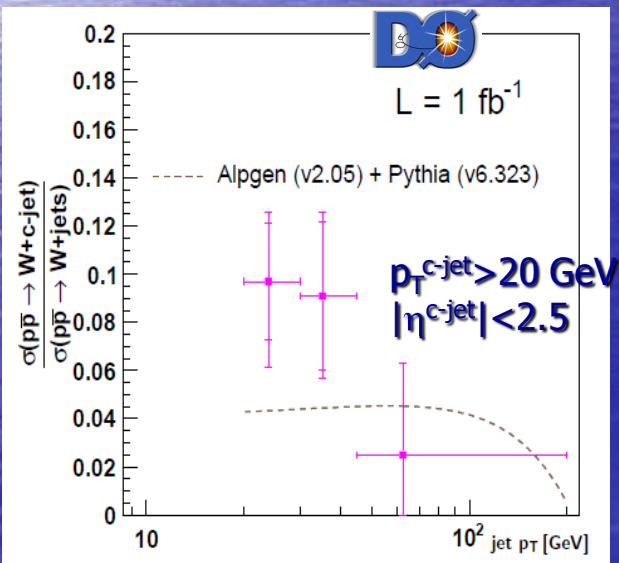
- 4.3 fb<sup>-1</sup> (SLTe)
   
p<sub>T</sub><sup>c-jet</sup> > 20 GeV, |η<sup>c-jet</sup>| < 1.5
   
σ × BR = 21.1 ± 7.1 ± 4.6 pb

- 1.8 fb<sup>-1</sup> (SLTμ)
   
σ × BR = 9.8 ± 2.8 ± 1.6 pb

NLO (MCFM) = 11.2 ± 2.2 pb



Data in reasonable agreement with NLO.



PLB 666, 23 (2008)

$$\frac{\sigma [W + c\text{-jet}]}{\sigma [W + jets]} = 0.074 \pm 0.019(\text{stat.})_{-0.014}^{+0.012}(\text{syst.})$$

ALPGEN : 0.044 ± 0.003

# Summary & Outlook

- Tevatron has a rich physics program to study various properties of vector boson + jets production
  - Many interesting results
  - Comparisons to ME+PS generators
  - First measurements for angular correlations
- Good understanding of these processes critical for SM Higgs and NP searches
- Generally, MCFM NLO QCD calculations describe data well. Measurements on  $W/Z+b$  jets indicate need for improvement.
- SHERPA gives the best description of angular distributions.
- More results with better statistics will become available soon.
- Tevatron would continue exploring these processes  
<http://www-cdf.fnal.gov/physics/new/qcd/QCD.html>  
<http://www-d0.fnal.gov/Run2Physics/qcd/>



# W/Z Candidates



## Production rates at Tevatron

$$\sigma(Z^0 \rightarrow l^+l^-) \sim 250 \text{ pb}$$

$$\sigma(W^\pm \rightarrow lv) \sim 2700 \text{ pb}$$

⇒ Millions of W's; 100's k Z's per fb<sup>-1</sup>

## Z → l<sup>+</sup>l<sup>-</sup> is a clean signal

Fully reconstruct Z with two leptons

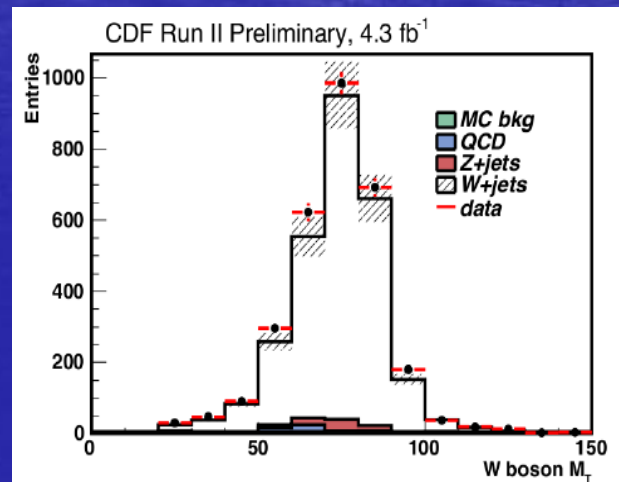
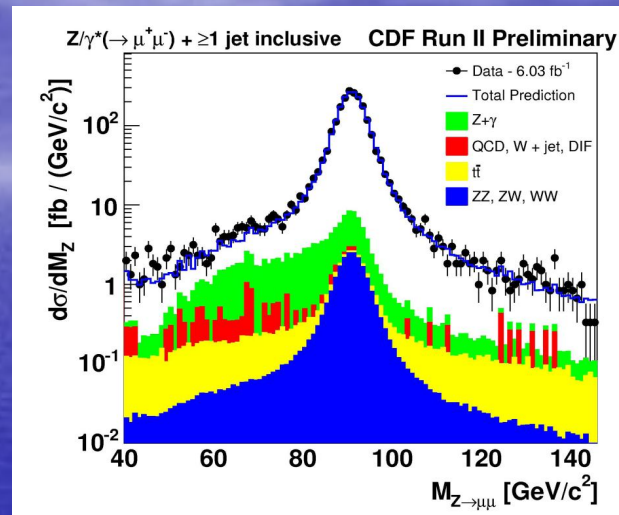
BG : fake leptons, semi-leptonic decays, di-boson production

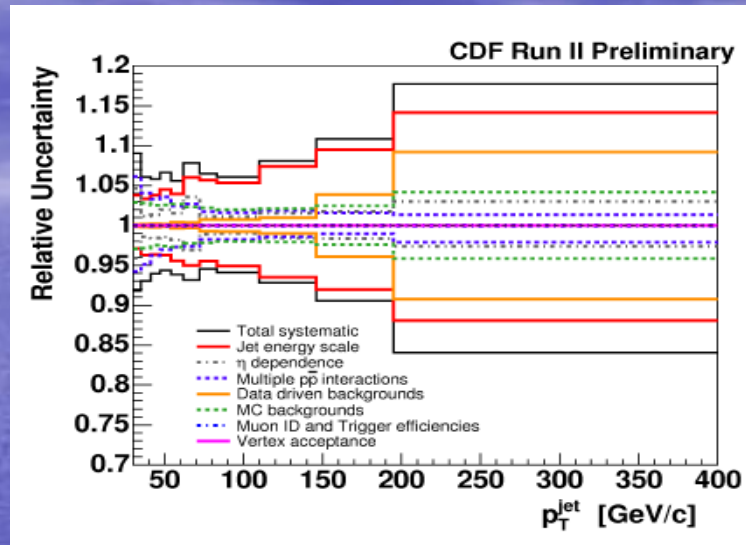
## W → lv

## Higher statistics, higher BG

Reconstruct lepton,  $\nu \Rightarrow$  missing E<sub>T</sub>

BG : QCD (fake lepton), W → τν, Top, diboson, Z → ll





**CDF II Preliminary**

| Backgrounds                                  | Estimated events in $6.03 \text{ fb}^{-1}$ |                                 |                                    |
|--|--|---------------------------------|------------------------------------|
|  | $Z + \geq 1 \text{ jet}$                   | $Z + \geq 2 \text{ jets}$       | $Z + \geq 3 \text{ jets}$          |
| $Z/\gamma^* \rightarrow \mu^+\mu^- + \gamma$ | $495.5 \pm 148.6$                          | $39.9 \pm 12.0$                 | $2.4 \pm 0.7$                      |
| $WW, ZZ, ZW$                                 | $134.3 \pm 40.3$                           | $48.9 \pm 14.7$                 | $4.9 \pm 1.5$                      |
| QCD, W+jets and DIF                          | $72 \pm 72$                                | $20 \pm 20$                     | $2.0 \pm 2.0$                      |
| tt production                                | $44.2 \pm 13.2$                            | $25.1 \pm 7.5$                  | $3.1 \pm 0.9$                      |
| $Z \rightarrow \tau^+\tau^- + \text{jets}$   | $3.6 \pm 1.1$                              | $1.7 \pm 0.5$                   | $0.0 \pm 0.0$                      |
| <b>Total Backgrounds</b>                     | <b><math>750 \pm 171</math></b>            | <b><math>136 \pm 29</math></b>  | <b><math>12.3 \pm 2.7</math></b>   |
| <b>Data</b>                                  | <b><math>13247 \pm 115</math></b>          | <b><math>1485 \pm 39</math></b> | <b><math>133.0 \pm 11.5</math></b> |



# Backup Slides

# CDF & D0 detectors

- CDF properties
- Silicon Tracker: large si+ Time of flight detectors
  - $|\eta| < 2$ , 90cm long,  $r_{L00} = 1.3 - 1.6$ cm
- Drift Chamber(COT)
  - 96 layers between 44 and 132cm
- Muon coverage
  - $|\eta| < 1.5$
  - Outer chambers: high purity muons
- Electron and general Calorimeter
  - $|\eta| < 2.8$

## Calorimeter

- CEM lead + scint 13.4%/√E<sub>e</sub> ⊕ 2%
- CHA steel + scint 75%/√E<sub>e</sub> ⊕ 3%

## Tracking

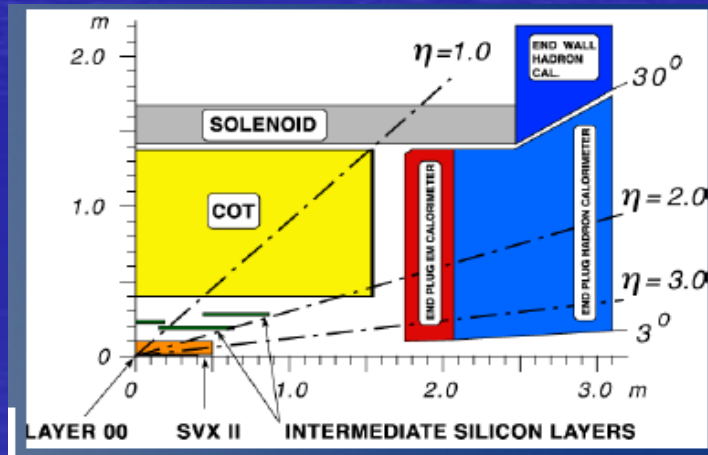
- $\sigma(d0) = 40\mu\text{m}$  (incl. 30 $\mu\text{m}$  beam)
- $\sigma(\text{pt})/\text{pt} = 0.15\%$  pt

• **Tracker** (Silicon Microstrips + Scintillating Fibers):  
covers  $|\eta| < 2.5$  inside 2 T superconducting solenoid

• **Calorimeter** (Sampling U/Liquid Ar):  
hermetic coverage:  $|\eta| < 4.2$

► Calorimeters ( $\rightarrow$  jets, e,  $\gamma$ ): Fine granularity and good energy resolution  
DØ:  $\Delta\eta \times \Delta\phi \sim 0.1 \times 0.1$   
CDF:  $\Delta\eta \times \Delta\phi \sim 0.1 \times 0.26$

• **Muon system** (Wire Chambers + Scintillators):  
covers  $|\eta| < 2$  before and after toroid



# Z/ $\gamma^*$ $\rightarrow$ $\mu^+\mu^-$ + Jets



Latest results with 6 fb<sup>-1</sup>

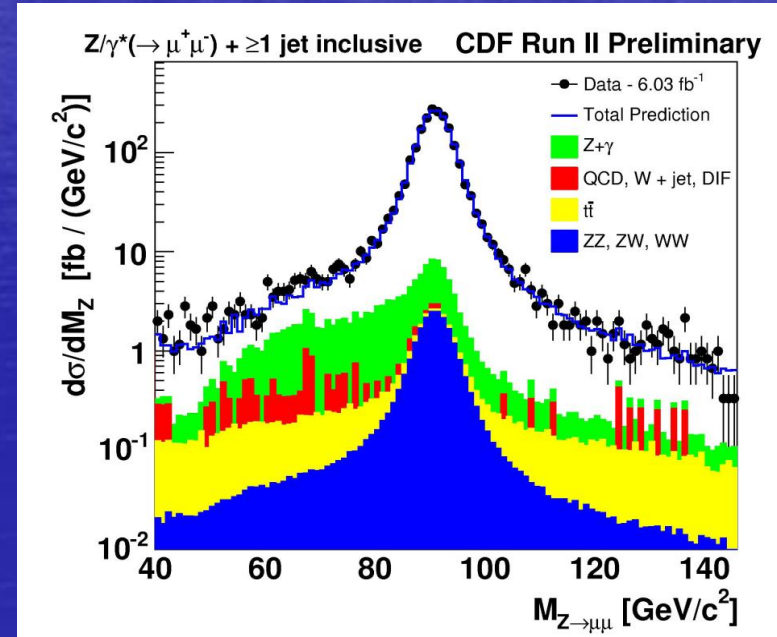
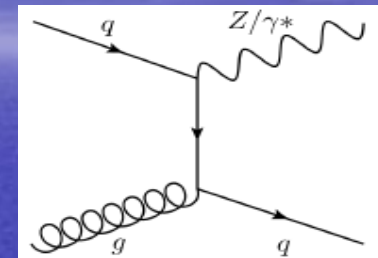
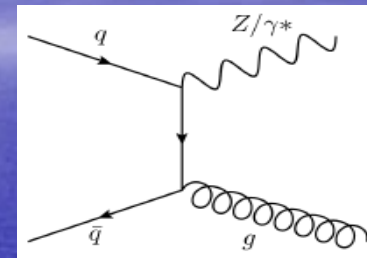
- Kinematic selection**

$p_T^\mu > 25$  GeV,  $|\eta| < 1.0$ ,  $66 < M_{\mu\mu} < 106$  GeV  
 $p_T^{\text{jet}} > 30$  GeV,  $|\gamma| < 2.1$ ,  $R = 0.7$

- Events** : 13000, 1500, 130 in Z+ $\geq 1$  jet,  $\geq 2$ ,  $\geq 3$  jet bins

- Backgrounds:**

QCD multi-jet, W+jets (data-driven)  
 $Z_\gamma$ , Top, Diboson, Z $\rightarrow\tau\tau$  (MC)  
 – Total BG 5-10%



CDF II Preliminary

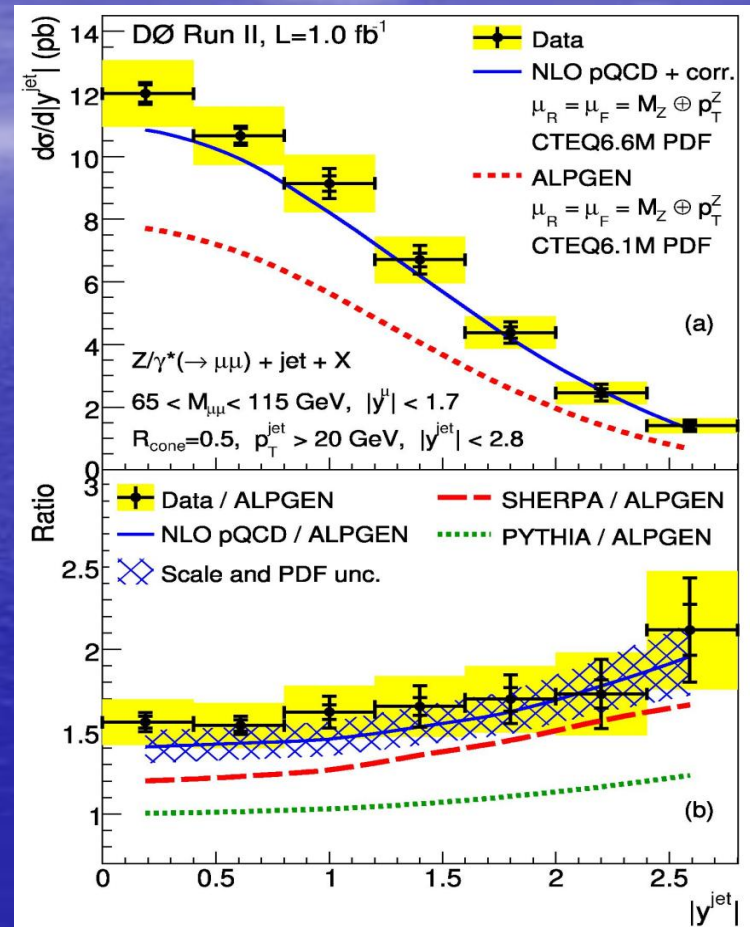
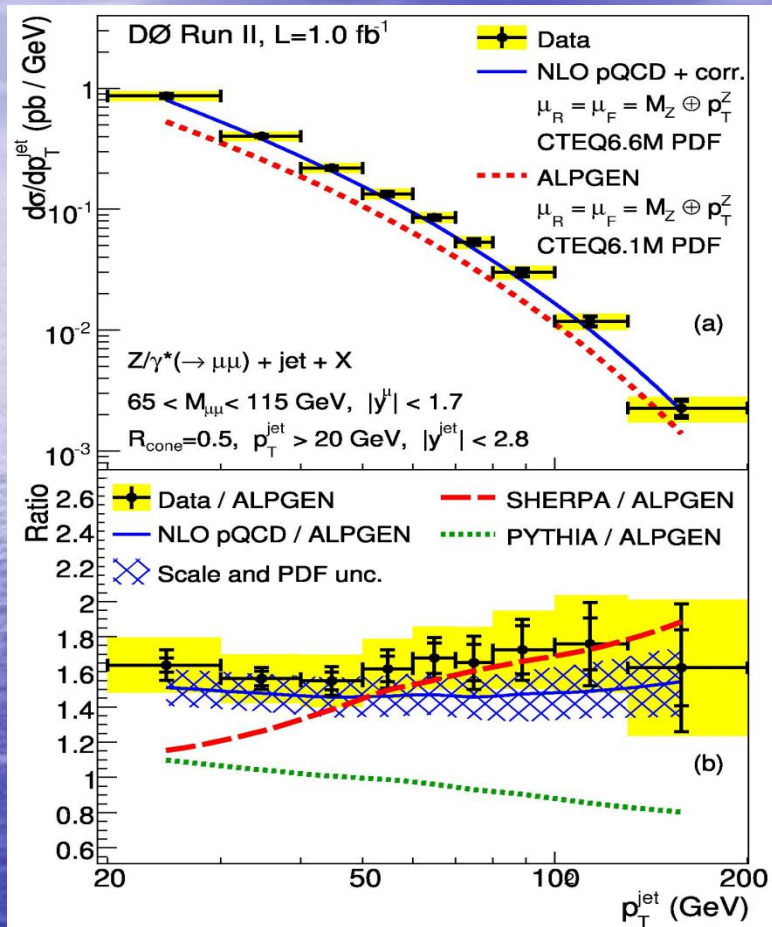
| Backgrounds                                       | Estimated events in 6.03 fb <sup>-1</sup> |                                 |                                    |
|---|---|---------------------------------|------------------------------------|
|   | Z + $\geq 1$ jet                          | Z + $\geq 2$ jets               | Z + $\geq 3$ jets                  |
| Z/ $\gamma^*$ $\rightarrow$ $\mu^+\mu^- + \gamma$ | 495.5 $\pm$ 148.6                         | 39.9 $\pm$ 12.0                 | 2.4 $\pm$ 0.7                      |
| WW, ZZ, ZW  | 134.3 $\pm$ 40.3                          | 48.9 $\pm$ 14.7                 | 4.9 $\pm$ 1.5                      |
| QCD, W+jets and DIF                               | 72 $\pm$ 72                               | 20 $\pm$ 20                     | 2.0 $\pm$ 2.0                      |
| tt production                                     | 44.2 $\pm$ 13.2                           | 25.1 $\pm$ 7.5                  | 3.1 $\pm$ 0.9                      |
| Z $\rightarrow$ $\tau^+\tau^-$ + jets             | 3.6 $\pm$ 1.1                             | 1.7 $\pm$ 0.5                   | 0.0 $\pm$ 0.0                      |
| <b>Total Backgrounds</b>                          | <b>750 <math>\pm</math> 171</b>           | <b>136 <math>\pm</math> 29</b>  | <b>12.3 <math>\pm</math> 2.7</b>   |
| <b>Data</b>                                       | <b>13247 <math>\pm</math> 115</b>         | <b>1485 <math>\pm</math> 39</b> | <b>133.0 <math>\pm</math> 11.5</b> |

# $Z/\gamma^* \rightarrow \mu^+ \mu^- + \text{Jet}(s)$



$\mathcal{L} = 1 \text{ fb}^{-1}$

Differential cross sections in  $p_T$  and  $y$  of the leading jet

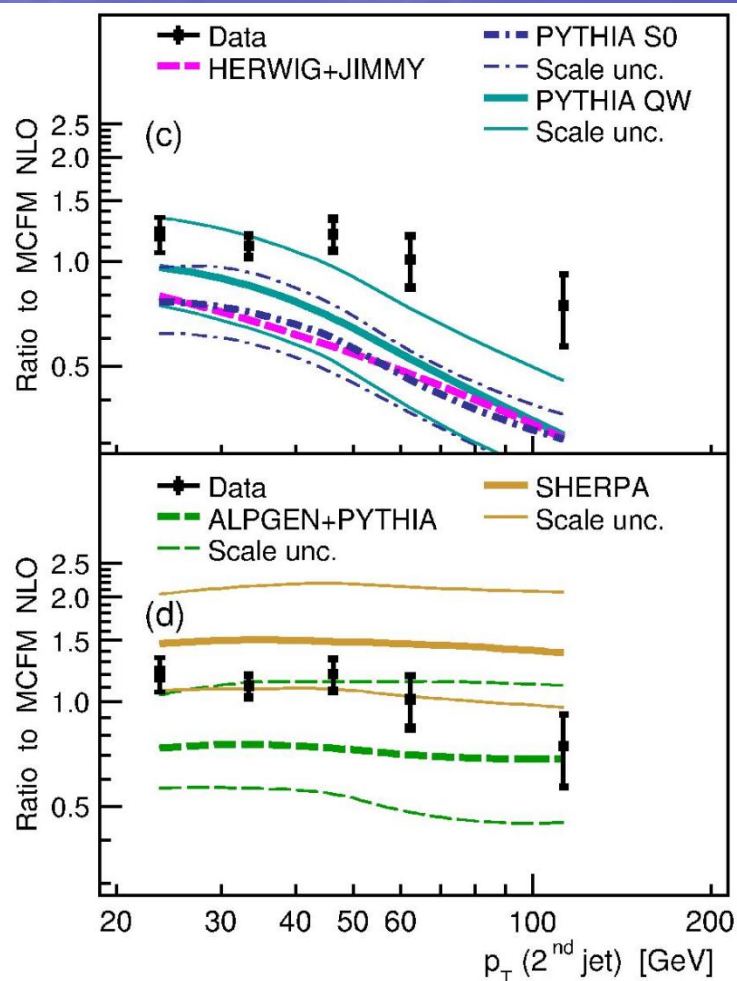
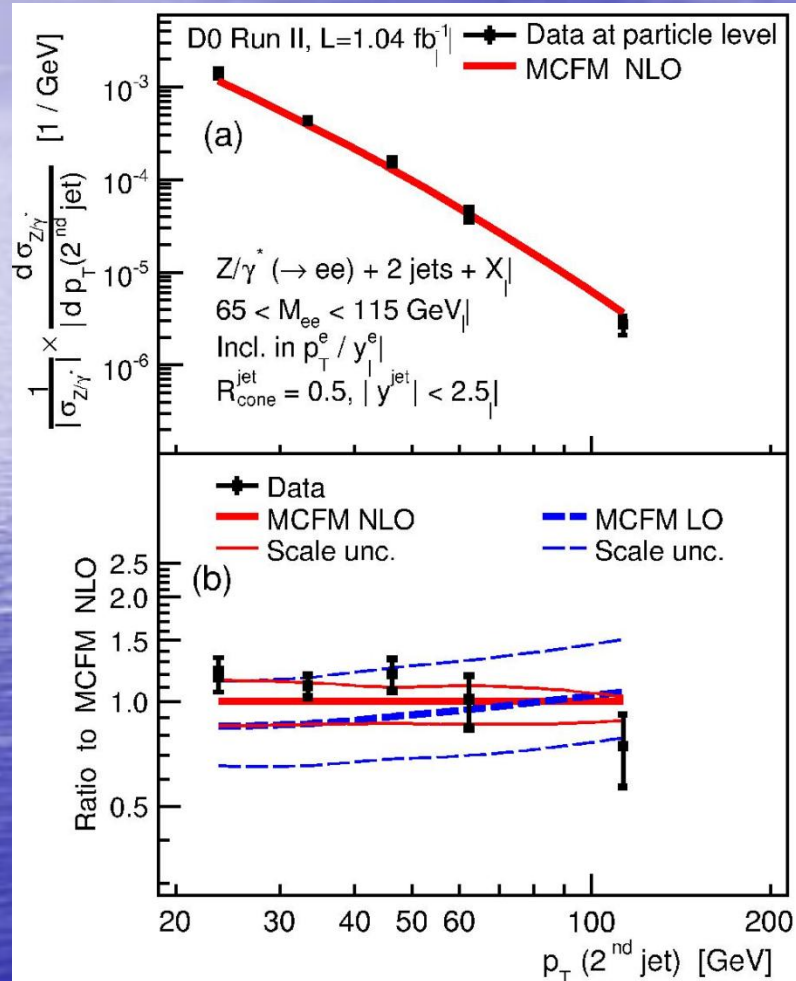


ALPGEN describes shape well.  
ALPGEN and PYTHIA below the data, SHERPA better

MCFM NLO better describes data

# $Z/\gamma^* \rightarrow e^+e^- + \geq 2 \text{ Jets}$

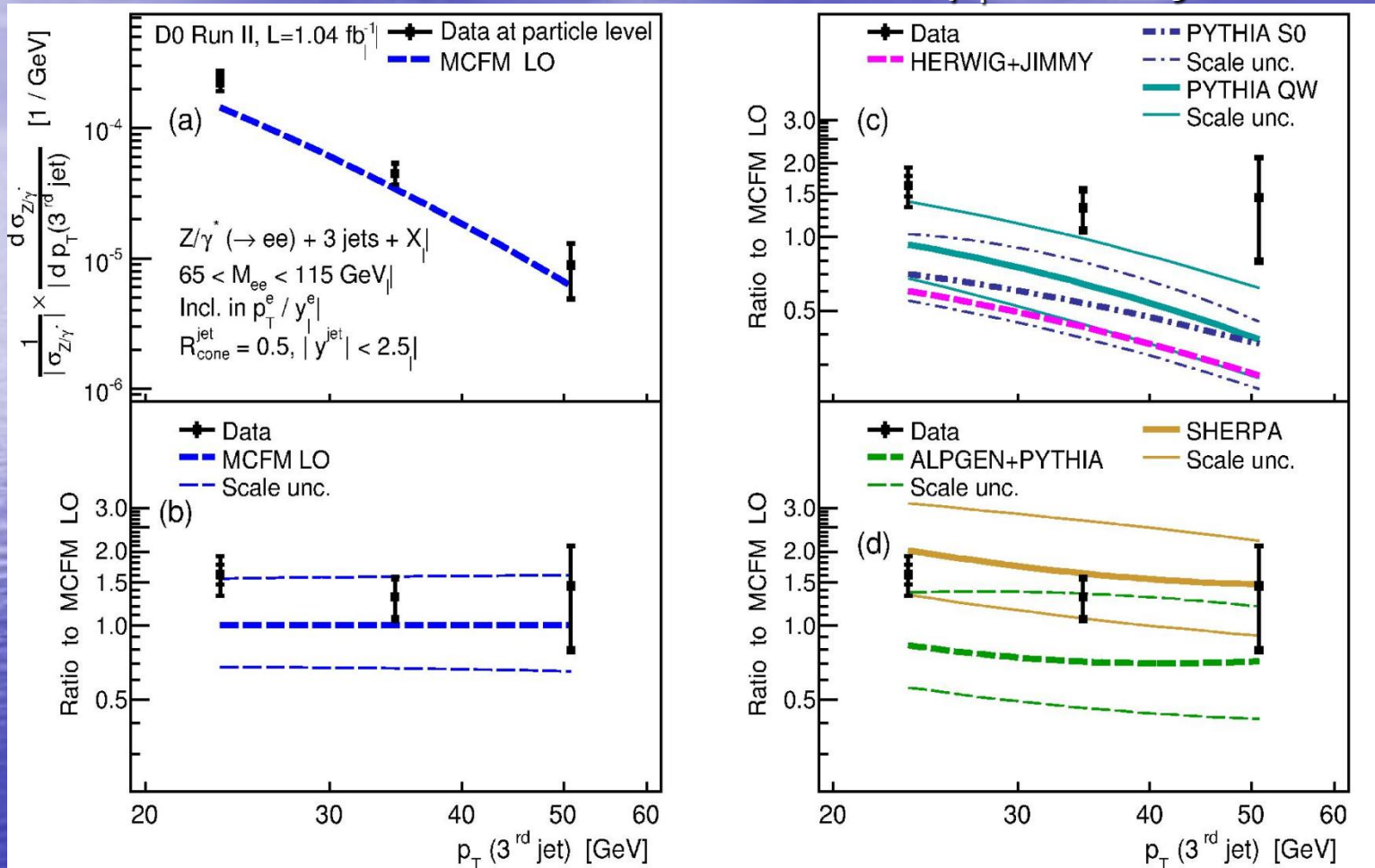
Normalized differential cross sections in  $p_T$  the 2<sup>nd</sup> jet



Data described well by MCFM NLO

# $Z/\gamma^* \rightarrow e^+e^- + \geq 3 \text{ Jets}$

Normalized differential cross sections in  $p_T$  the 3<sup>rd</sup> jet



**MCFM LO and Sherpa are preferred. Uncertainties in data and predictions due to scale variations are large.**

# Z/ $\gamma^*$ + Jet(s) Angular Correlations



PLB 682, 370 (2010)

$\mathcal{L} = 1 \text{ fb}^{-1}$

$Z p_T > 45 \text{ GeV}$

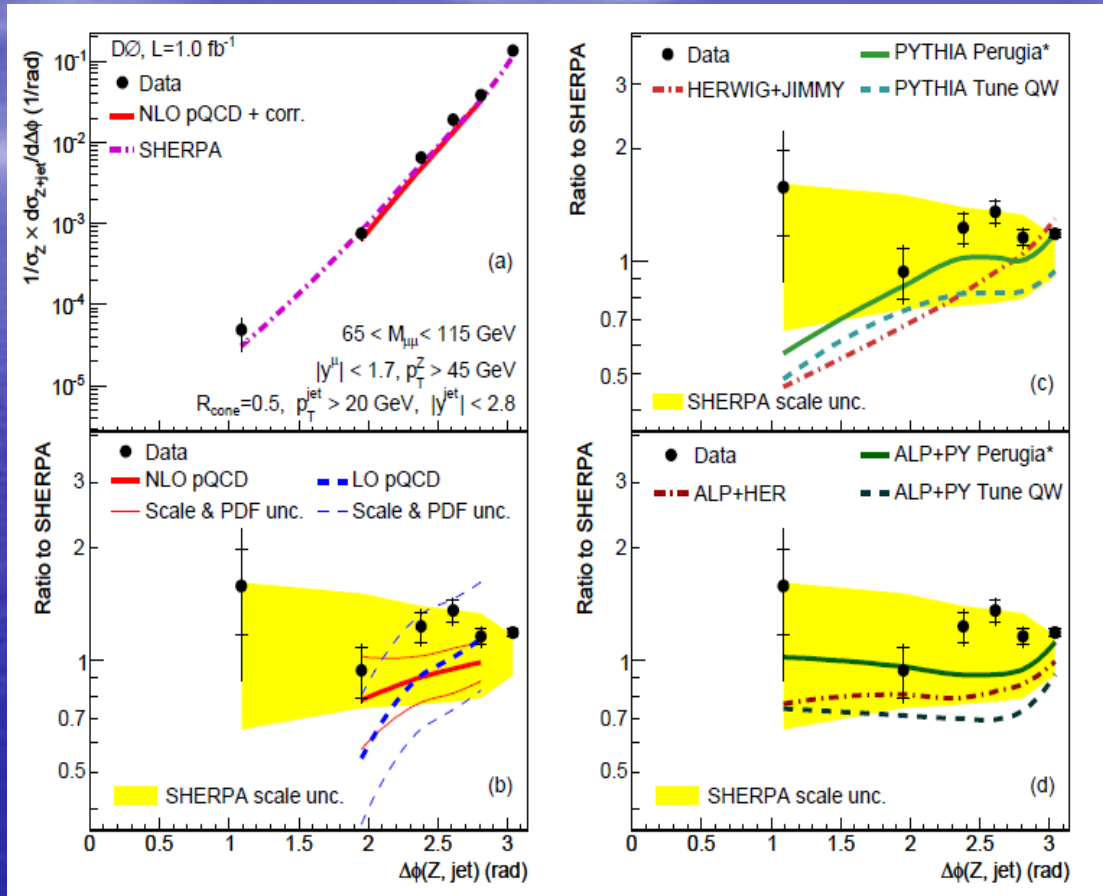
Reasonable agreement between data and NLO.  
NLO : improvement over LO

MC2M v5.6  
PDF's: MSTW2008  
 $\mu_r^2 = \mu_f^2 = M_Z^2 + p_{T,Z}^2$

Hadronisation and underlying event correction:  
PYTHIA 6.421, Tune QW, CTEQ6.1M

Event generators tend to have normalization and shape differences.

PYTHIA 6.421,  
HERWIG 6.510 + JIMMY 4.31  
ALPGEN 2.13,  
SHERPA 1.1.3,  
PDF's: CTEQ6.1M and MRST2007 (LO\*) for Perugia\*

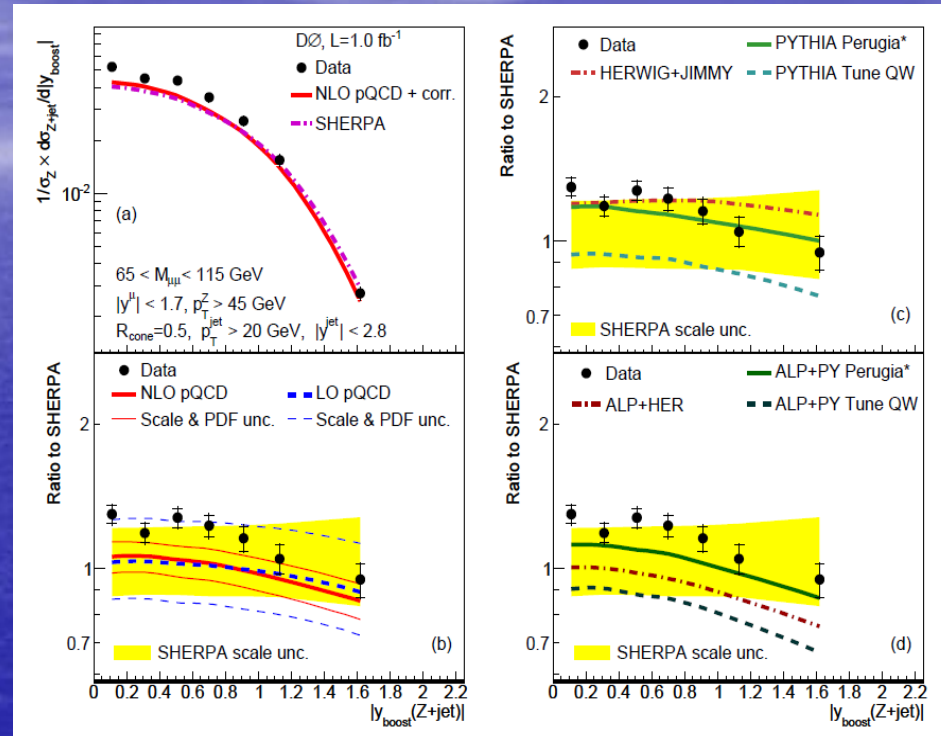
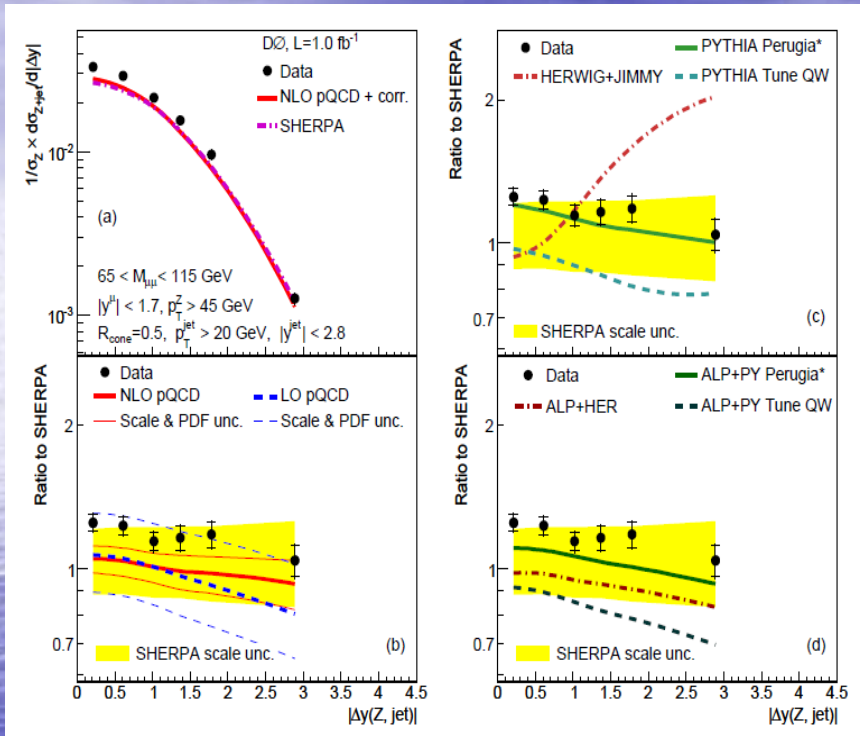


ALPGEN+PYTHIA (Perugia) improves description.  
Sherpa best describes the shape, not normalization.

# Z/ $\gamma^*$ + Jets Angular Variables

$Z p_T > 45 \text{ GeV}$

$Z p_T > 45 \text{ GeV}$



NLO, Sherpa describes the  $\Delta y$  shape.

All predictions describe  $y_{boost}$  shape.

$Z p_T > 25 \text{ GeV}$

$Z p_T > 45 \text{ GeV}$

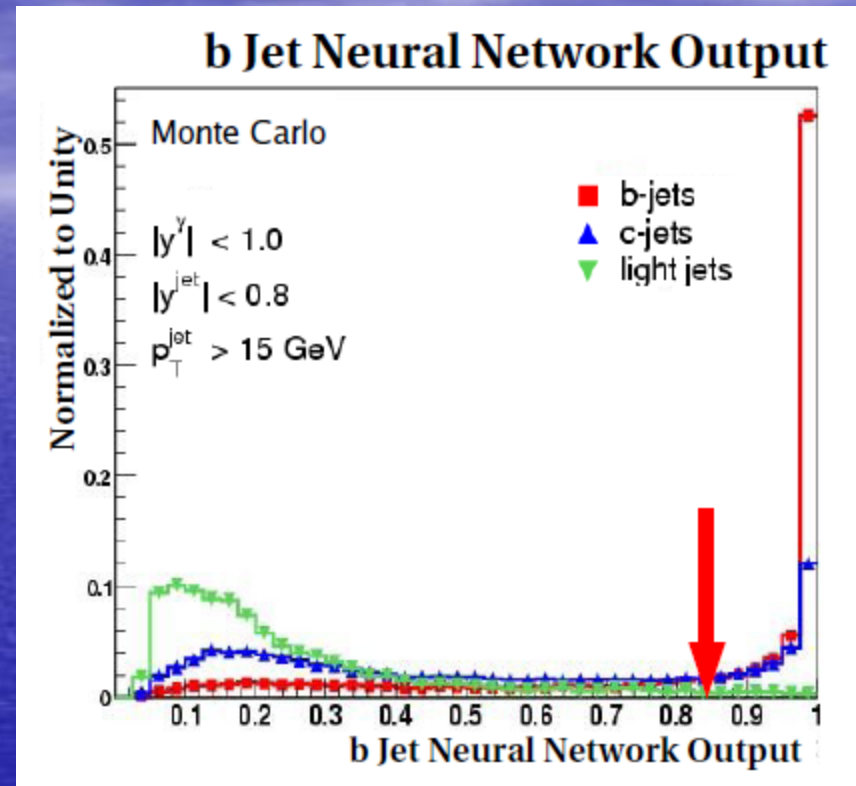
$\sigma_{Z+jet}/\sigma_Z = [122 \pm 2(\text{stat.}) \pm 4(\text{syst.})] \cdot 10^{-3}$   
 pQCD:  $[111 \pm 6(\text{scale}) \pm 2(\text{PDF})] \cdot 10^{-3}$  @NLO

$\sigma_{Z+jet}/\sigma_Z = [47 \pm 1(\text{stat.}) \pm 2(\text{syst.})] \cdot 10^{-3}$   
 pQCD:  $[40 \pm 3(\text{scale}) \pm 1(\text{PDF})] \cdot 10^{-3}$  @NLO



# Identifying Heavy Flavor Jets

- Light jets have a much higher production rate than heavy flavor jets
  - ~100:1 light jets to b jets
  - ~10:1 light jets to c jets
  - ~10:1 c jets to b jets
- But, heavy flavor jets can be distinguished due to **the long lifetimes of their mesons**
  - Average meson lifetimes
    - $\sim 1.5 \times 10^{-12}$  seconds (B mesons)
    - $\sim 0.8 \times 10^{-12}$  seconds (C mesons)
  - Decay *measurable distances* from the primary vertex
- The **secondary vertex**:
  - Contains valuable information to identify heavy flavor jets



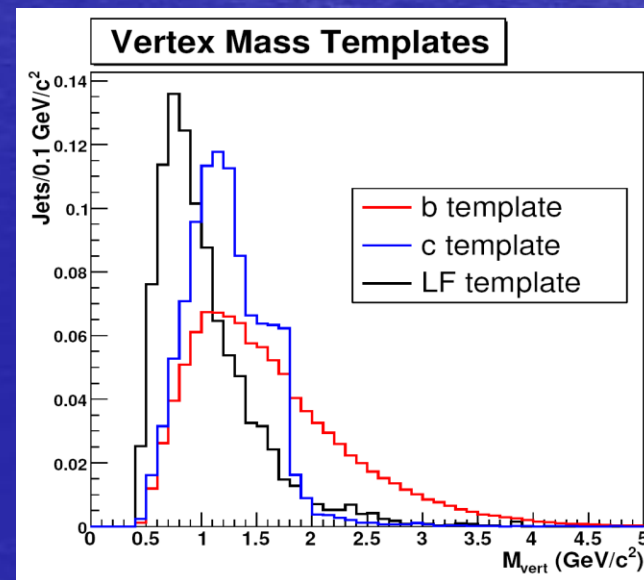
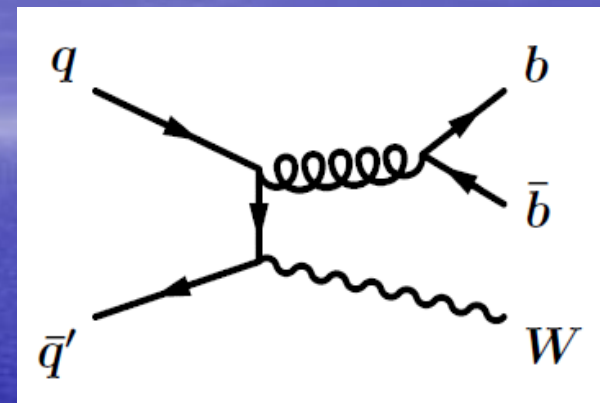
The inputs to the NN combine several characteristic quantities of the jet and associated tracks to provide a continuous output value between zero and one. The input variables are the number of reconstructed secondary vertices in the jet, the mass of the secondary vertex, the number of tracks used to reconstruct the secondary vertex, the two dimensional decay length significance of the secondary vertex in the plane transverse to the beam, a weighted combination of the tracks' transverse impact parameter significances, and the probability that a jet originates from the primary vertex, which is referred to as the JLIP probability. The NN output value tends toward one and zero for *b* jets and non-*b* jets, respectively.

# W + b-jets Production

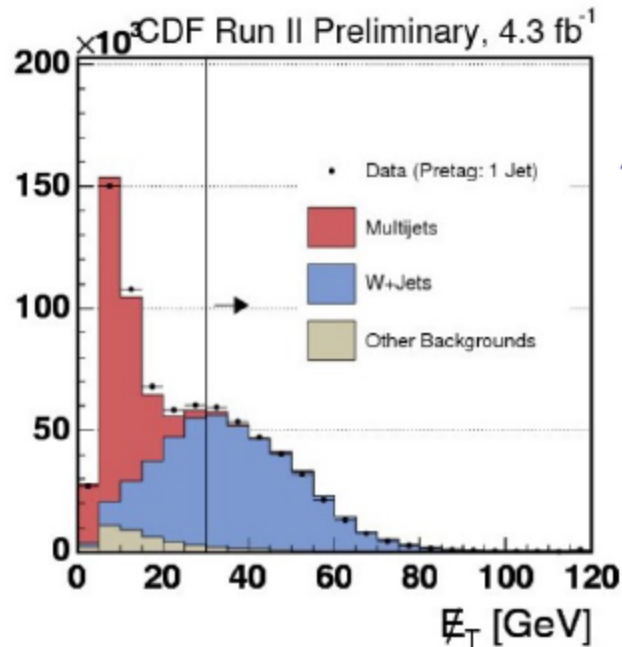


- **W → lν (l=e,μ) selection**
  - $p_T > 20$  GeV,  $|\eta| < 1.1$ ,  $p_T^{\nu} > 25$  GeV
- **Jets : 1 or 2 in final state (too much top in 3<sup>rd</sup> jet bin)**
  - $p_T > 20$  GeV,  $|\eta| < 2.0$ ,  $R = 0.4$
- **Determine W+b fraction**
  - SecVtx tagging to enrich sample with HF jets.
  - b-fraction obtained from fit to  $M_{SVT}$  with templates of b,c & light flavors.

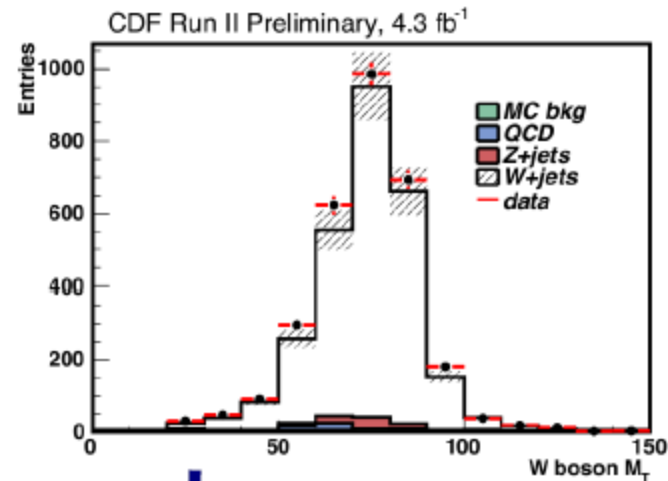
- **Major backgrounds**
  - ttbar (40%)
  - single top (30%)
  - Fake W (15%)
  - WZ (5%)



# W + charm background



QCD background is estimated by a fit to the MET spectrum



Background validation in OS+SS control region

Main backgrounds:

- Fake W (QCD)
- W + light jets
- Drell-Yan



## SM precision limits from $Z + 1$ jet $p_T$ balance ( $Z \rightarrow ee, \mu\mu$ )

- All sorts of possible sources of uncertainties are considered:  
(Effect (in %) on predicted mean of  $p_T(Z)$  balance)

| Source of uncertainty                    | jet cone = 0.4 | jet cone = 0.7 | jet cone = 1.0 |
|--|----------------|----------------|----------------|
| renormalization and factorization scales | +0.9 -0.0      | +0.9 -0.4      | +0.4 -0.4      |
| FSR parameters in PYTHIA                 | +0.4 -0.4      | +0.1 -0.1      | +0.1 -0.1      |
| ME's and parton-jet matching             | +0.8 -0.0      | +1.1 -0.0      | +0.8 -0.0      |
| single particle response                 | +2.5 -2.5      | +2.5 -2.5      | +2.5 -2.5      |
| multiple proton interactions             | +1.0 -0.0      | +1.2 -0.0      | +1.2 -0.0      |
| large-angle FSR, limitation of PS        | +0.0 -2.9      | +0.0 - 0.2     | +1.7 -0.0      |
| Estimate of the total variation          | +3.0 -3.8      | +3.1 -2.5      | +3.4 -2.5      |
| The observed discrepancy                 | +4.7           | +3.2           | +2.0           |

← Prediction  
Data

Only large angle-radiation (FSR) observed as sub-leading jets is able to explain discrepancy