Measurements of W/Z production in association with jets at D0

Ashish Kumar,
SUNY at Buffalo
(on behalf of the D0 Collaboration)

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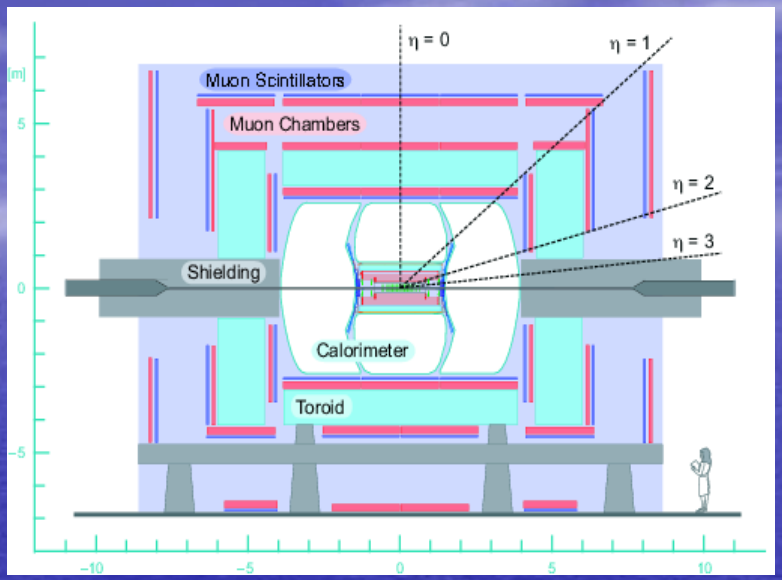
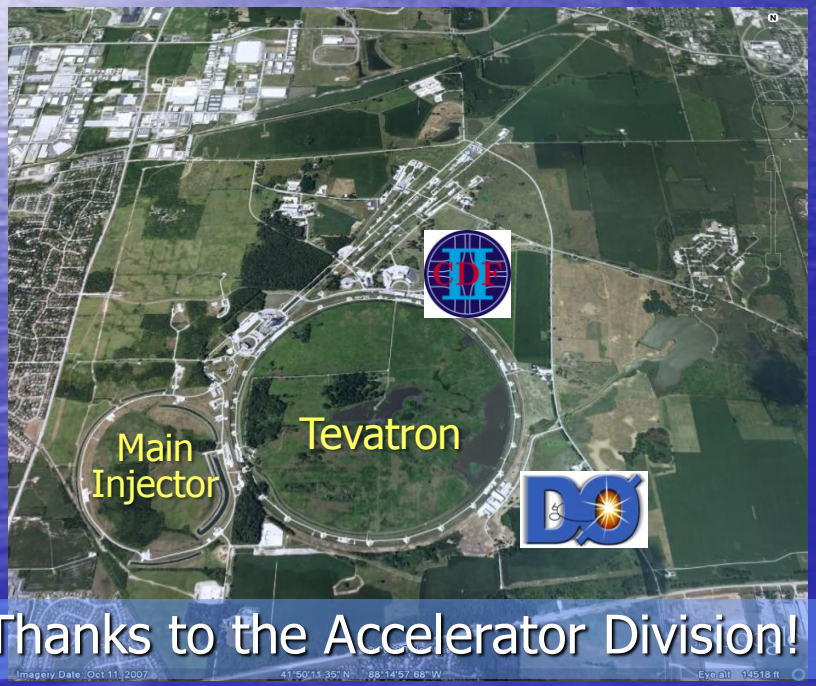
Outline

- Introduction
- Motivation
- Results
  - W + jets cross section
  - Z + jets cross section
  - Z + jets angular correlations
  - Z + Heavy Flavor Jets
- Summary

The DØ Experiment at the Fermilab Tevatron

- $p\bar{p}$ collisions @ $\sqrt{s}$ = 1.96 TeV
  - 36 bunches, 396 ns
- Excellent performance
  - Peak lumi : 4 E32 $cm^{-2}s^{-1}$
  - $\int Ldt$ /week ~ 70 pb^{-1}
- Delivered : 11.6 fb^{-1}
  Recorded : 10.4 fb^{-1}





Thanks to the Accelerator Division!

Tracker : silicon mictrostrips and scintillating fibers inside 2T

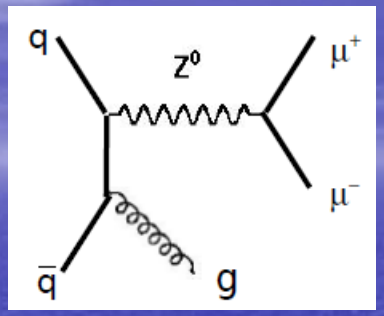
Calorimeter: Liquid Ar sampling & U absorber.

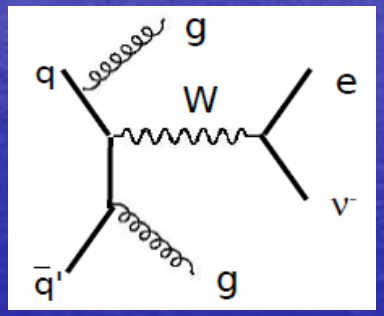
Wire tracking and scintillating muon system:

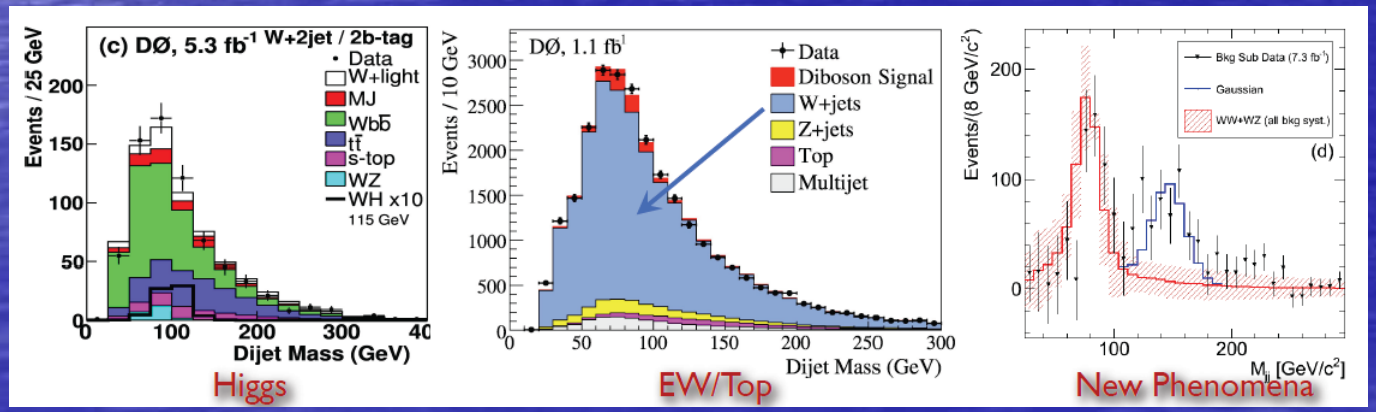
Results based on 1-4.2 fb^{-1} data.

Motivation

- 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
  - Searches for SM Higgs & New Phenomena

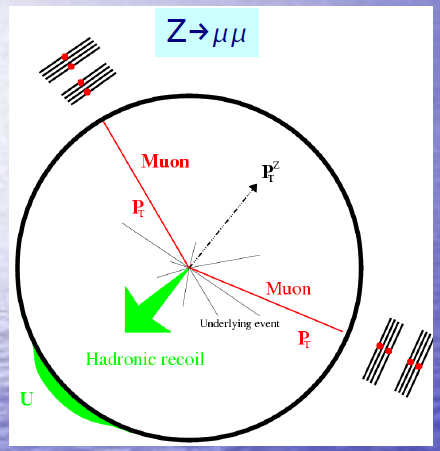






W/Z + Jets Production

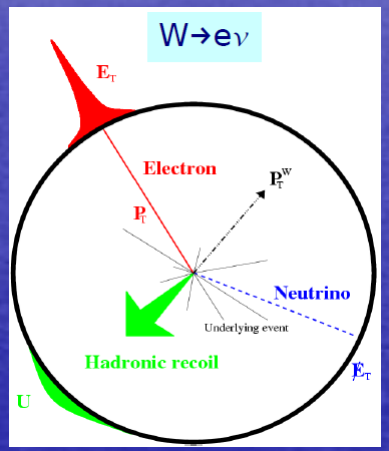
$\sigma(Z^0 \rightarrow l^+l^-) \sim 250$ pb $\sigma(W^{\pm} \rightarrow l\nu) \sim 2700$ pb $\Rightarrow$Millions of W's; 100's k Z's per fb^{-1}



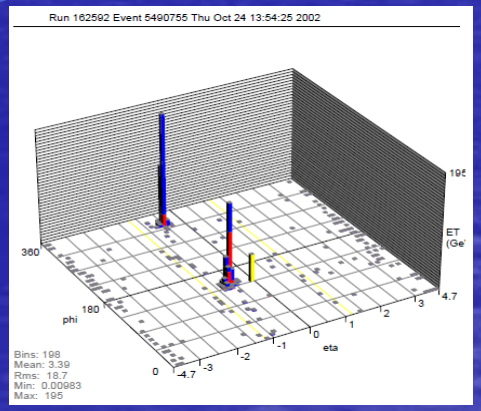
$W \rightarrow l\nu$ and $Z \rightarrow l^+l^-$ decays are easily identified with little background.

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 – use calorimeter towers as seeds.
- Jets are fully corrected for the instrumental effects.

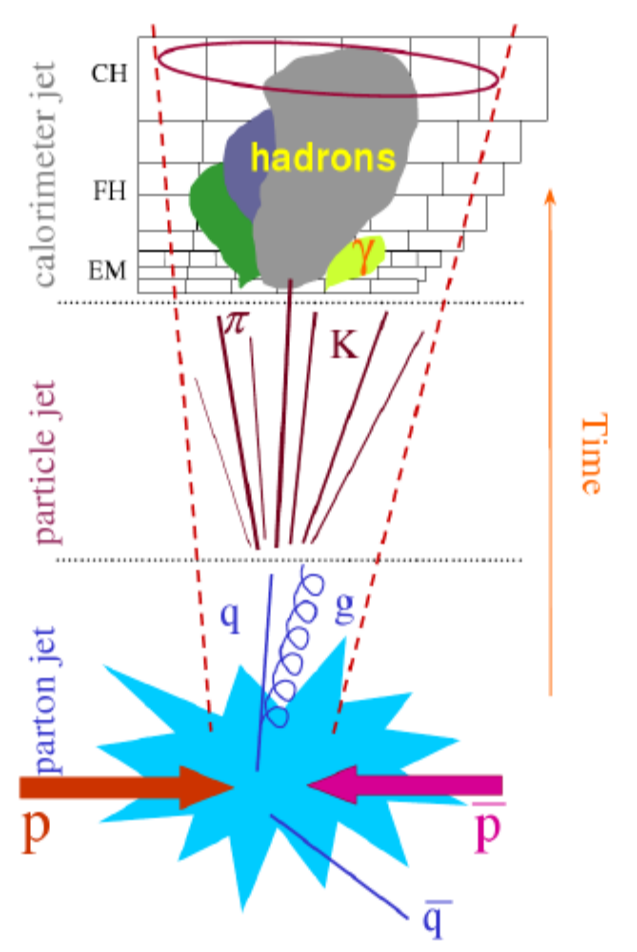


W/Z + Jets Measurements

Measurements are unfolded to particle level correcting for the effect of finite experimental resolution, detector response, acceptance and efficiencies.

Data – Theory comparison done at the particle level

Correct parton-level theory for non-perturbative effects (hadronization and underlying events) using parton shower Monte Carlo.



hep:ex/1106.1457

W(→eν)+ Jets

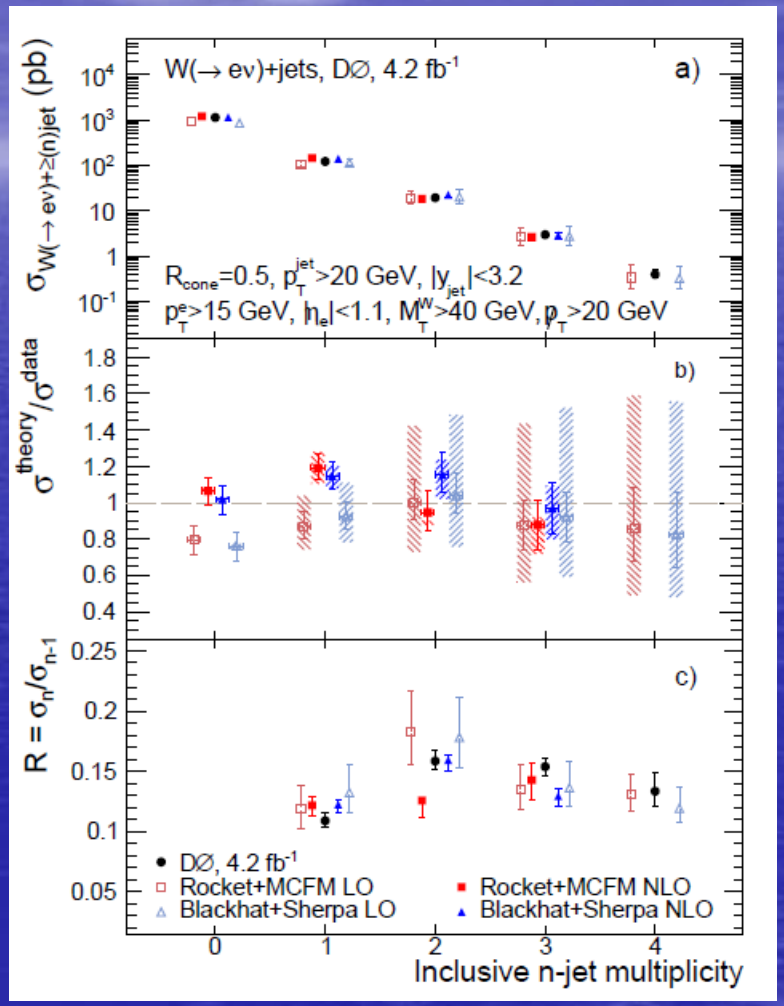
$\mathcal{L}$ = 4.2 fb^{-1}

- Precise measurement s of inclusive W(→eν)+n jet cross-sections (n=1 - 4)
  -- total incl. x-sections
  -- diff. x-sections vs nth jet p_T
- Considerably smaller uncertainties than previous measurements
- First detailed study of W+4j production

- Compared to two NLO calculations
  Blackhat + Sherpa, Rocket + MCFM

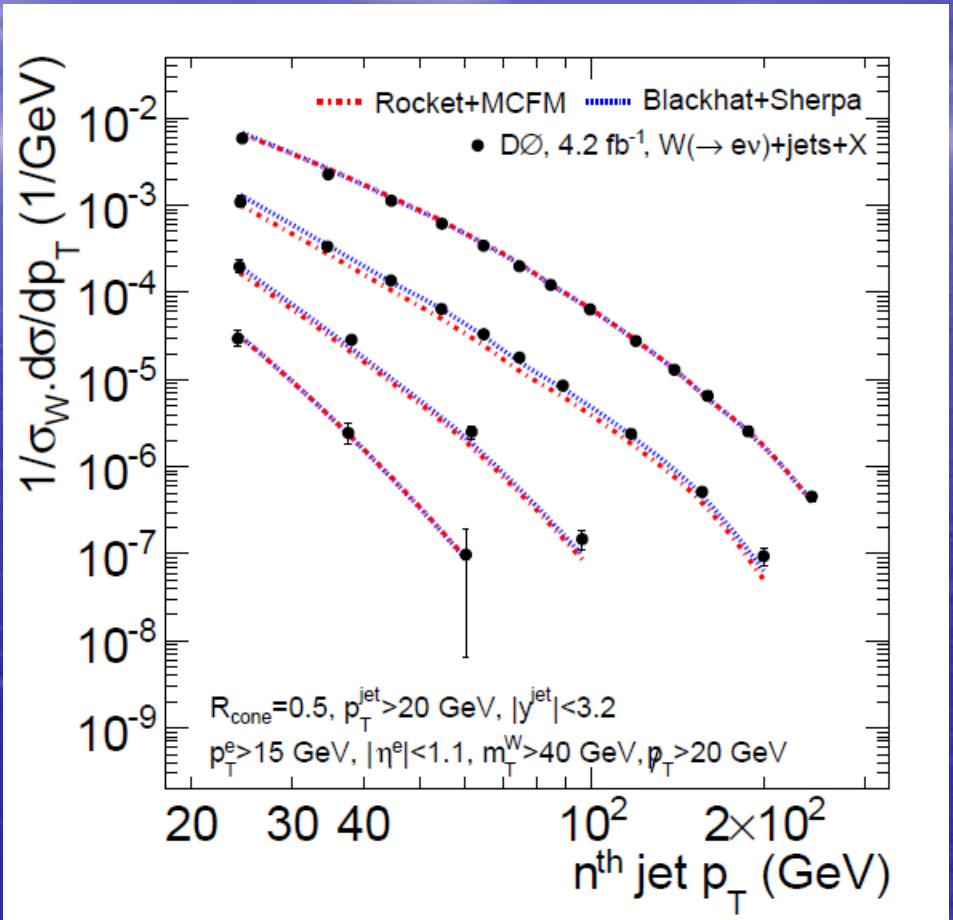
$\mu = \frac{1}{2} H_T$ $\mu = \sqrt{M_W^2 + (p_T^{jet})^2}$

- UE + hadronization particle level corrections derived from Sherpa
- Good agreement between data and theory except for 1-jet bin.



W(→eν)+ jets

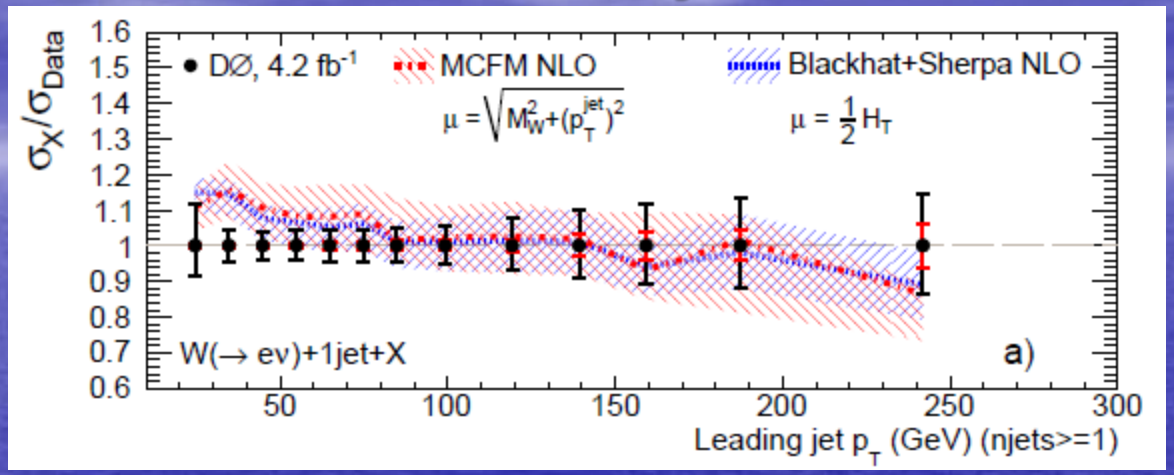
- Diff. x-sections normalized to inclusive W cross section
- Many uncertainties cancel in the ratio
- Measurement uncertainties of 4-14% (W+1j), 5-20% (W+2j), smaller than the theoretical predictions.
- Data agree well with NLO calculations except for certain regions of phase space where theory can be improved



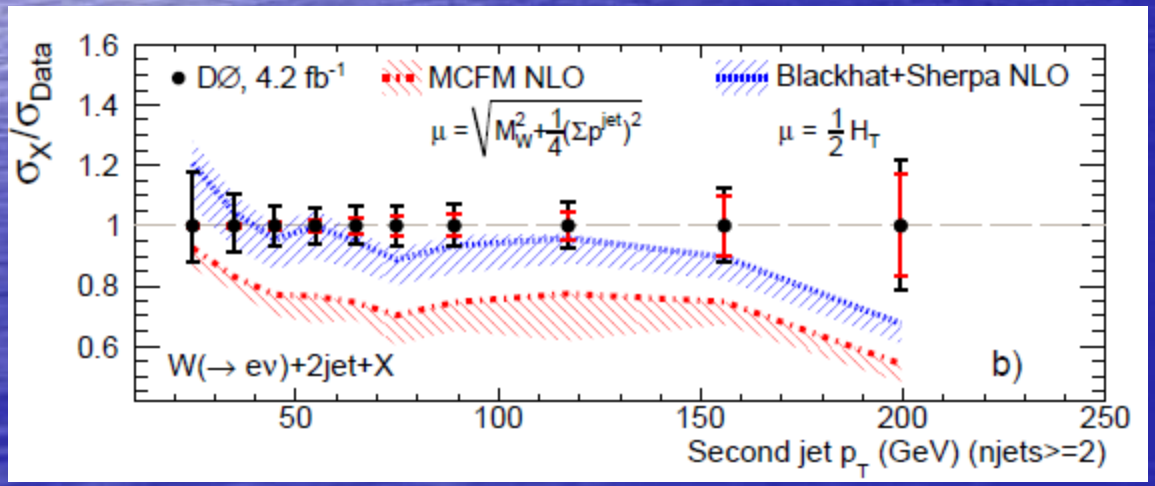
W(→eν)+ jets

Data agree well with NLO calculations

W+1j



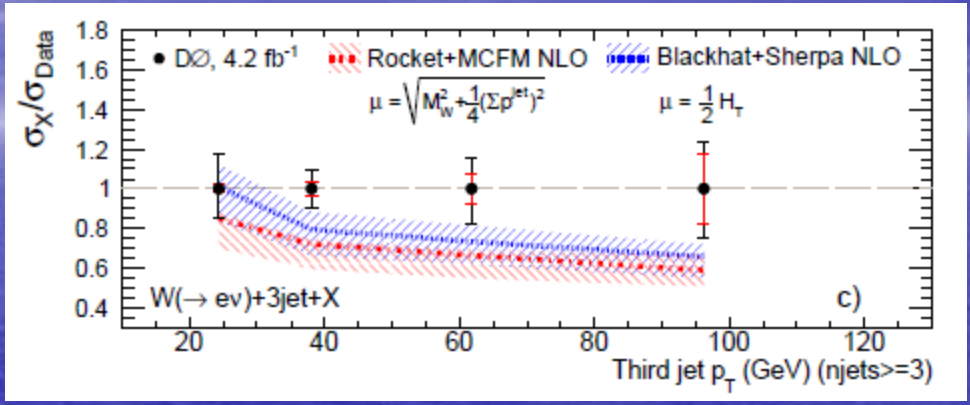
W+2j



MCFM significantly lower

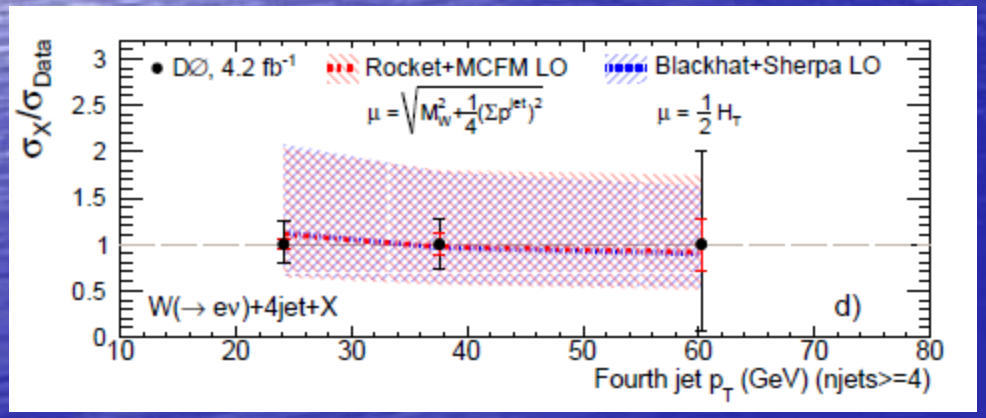
W(→eν)+ jets

W+3j



NLO predictions smaller but still consistent within uncertainties

W+4j



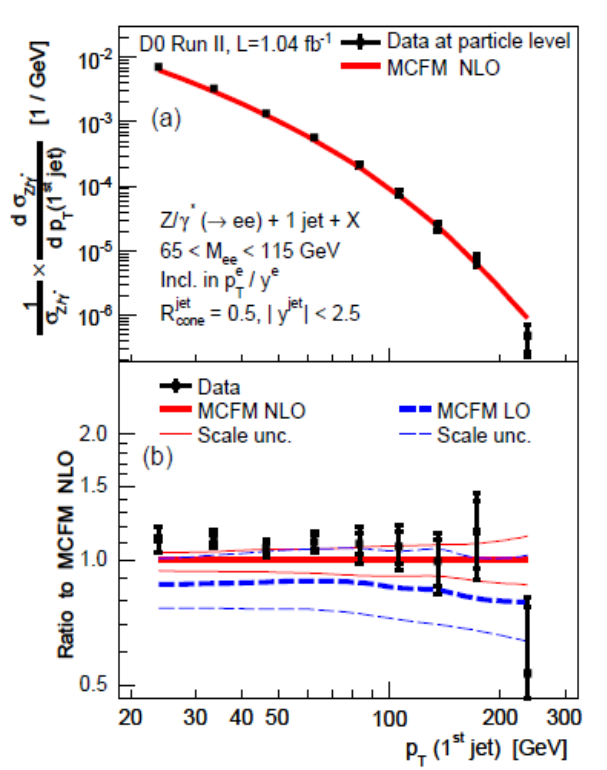
- Only LO available , need NLO calculation for Tevatron
- Good agreement but large uncertainties
- First differential cross section for W+4 jets

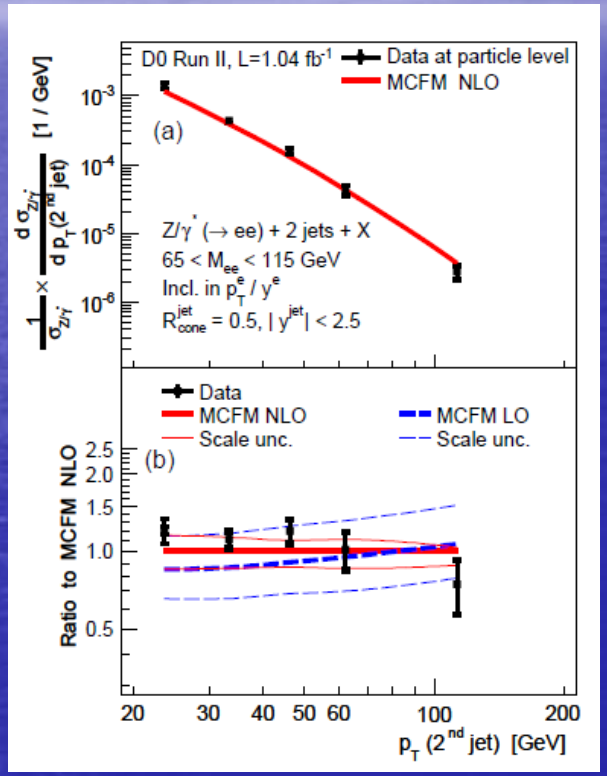
PLB 678, 45 (2009)

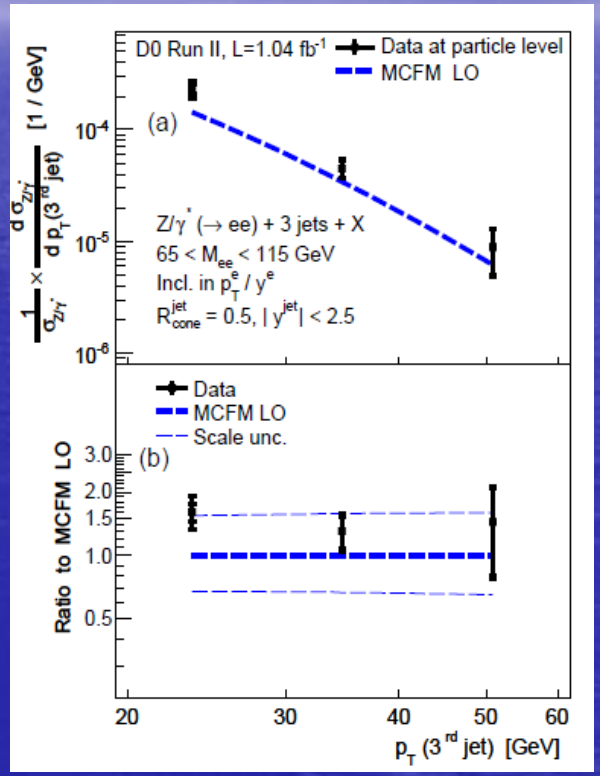
Z + Jets

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

Measure diff. x-sections normalized to incl. $\sigma(Z)$ binned in p_T of nth jet for Z+ ≥ n jets, n=1-3







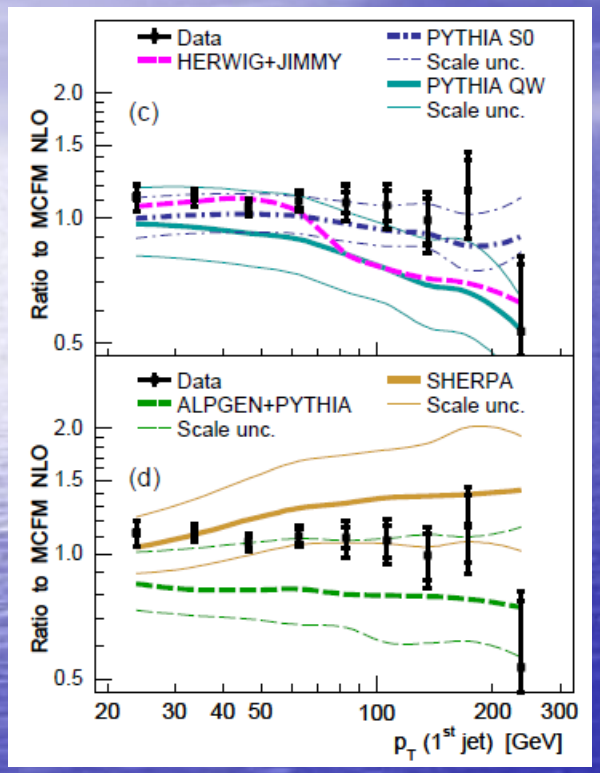
Data described well by MCFM predictions

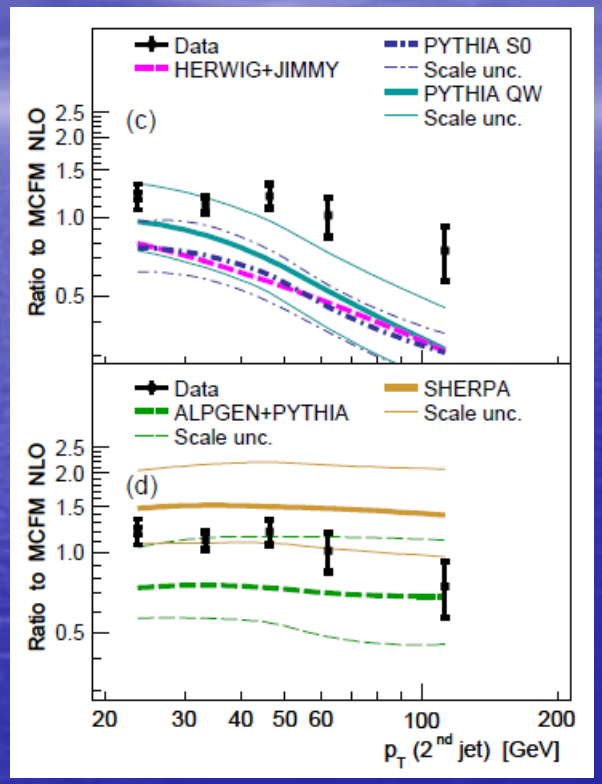
PLB 678, 45 (2009)

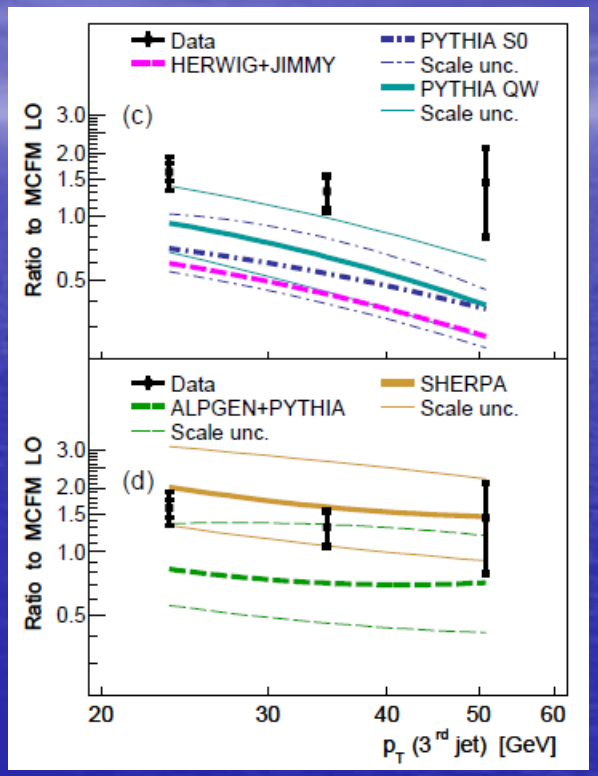
Z + Jets

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

Comparison with event generators exhibit normalization & shape differences







- Pythia (v6.325) with p_T ordered showering (S0) shows improved performance
- Alpgen (v2.13) + Pythia predicts lower rates but shapes described well
- Sherpa (v1.1.1) generally well described, some deviations for p_T>40 GeV
- Herwig (v6.510) + Jimmy (v.4.31)

Z+ Jets Angular Correlations

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

The diff. cross-sections are normalized to incl. $\sigma(Z)$

p_T^Z>25 GeV (avoid soft effects)

Small $\Delta\phi$(Z,jet) excluded from MCFM due to importance of non pert. effects.

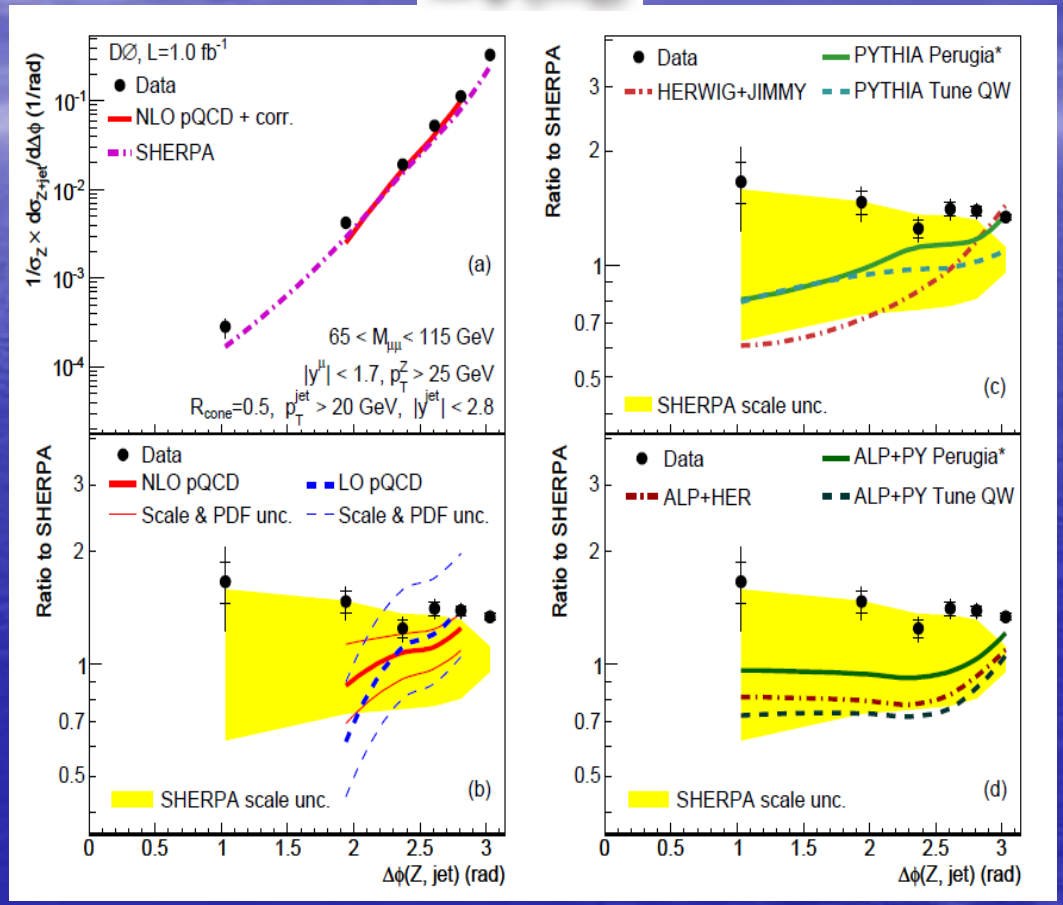
NLO predictions describe data reasonably well.

Event generators tend to have normalization and shape differences.

--Sherpa best describes the shape, but not normalization

-- Alpgen + Pythia (Perugia improves description

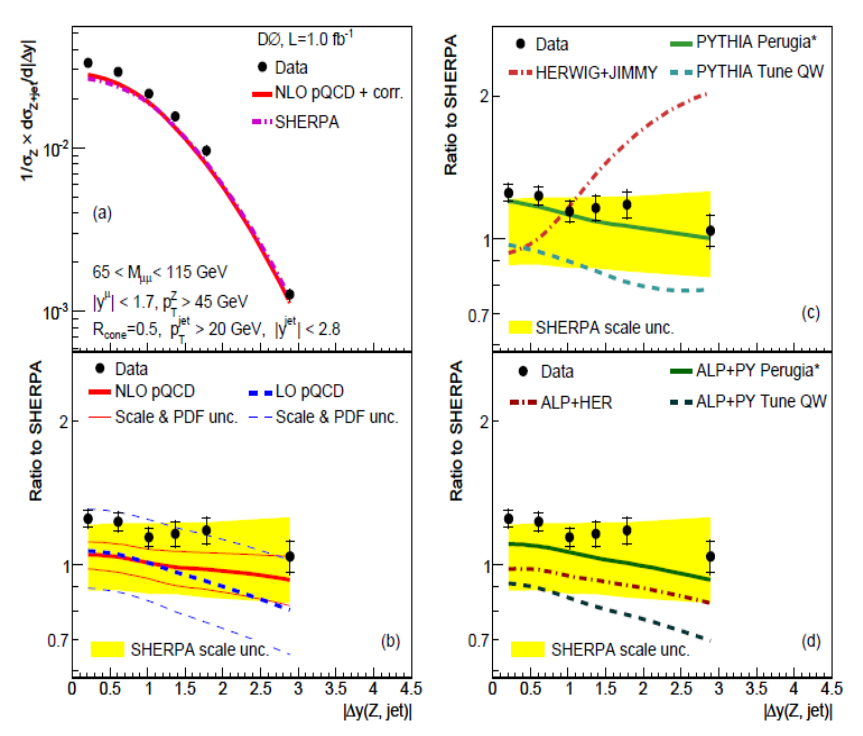
$\Delta\varphi(Z,j)$



Z/γ*+ Jets Angular Variables

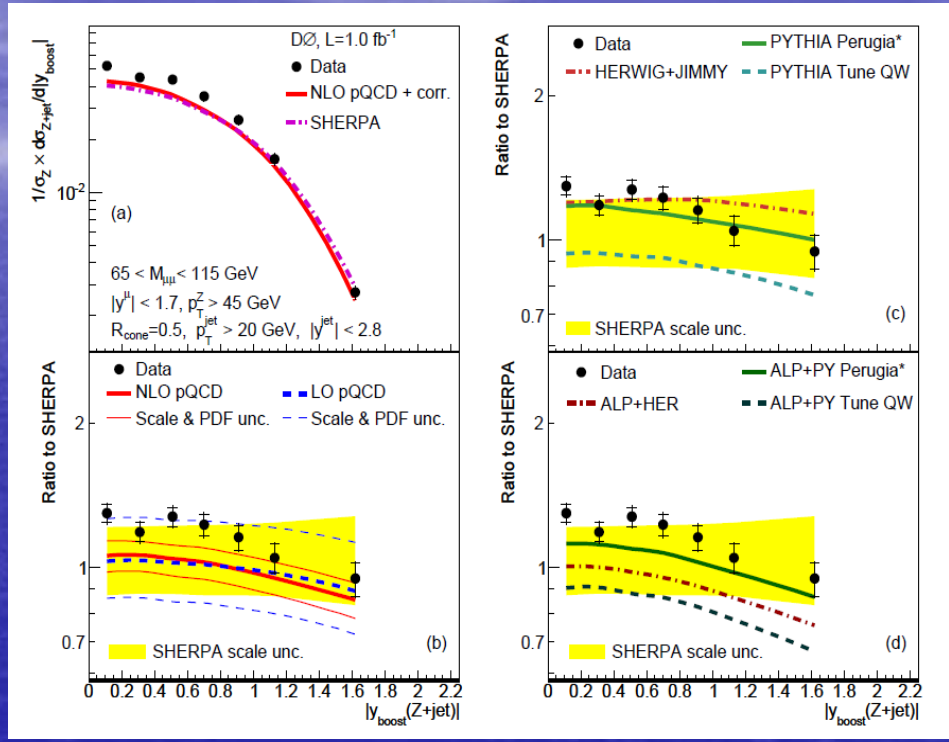
$\mathcal{L} = 1\ \mathrm{fb}^{-1}$

Z p_T > 45 GeV



NLO, Sherpa describes the Δy shape.

Z p_T > 45 GeV



All predictions describe y_{boost} shape.

Z p_T > 25 GeV

$\sigma_{Z+\mathrm{jet}}/\sigma_Z = [122 \pm 2(\mathrm{stat.}) \pm 4(\mathrm{syst.})] \cdot 10^{-3}$

pQCD: $[111 \pm 6(\mathrm{scale}) \pm 2(\mathrm{PDF})] \cdot 10^{-3}$ @NLO

Z p_T > 45 GeV

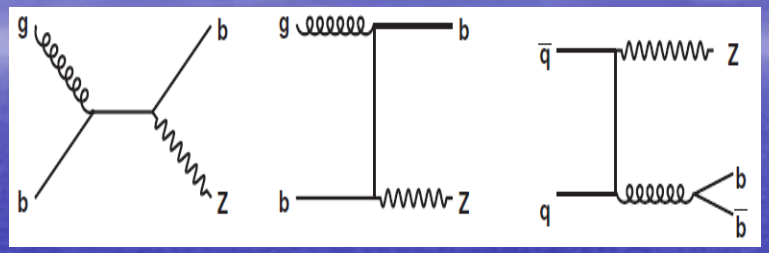
$\sigma_{Z+\mathrm{jet}}/\sigma_Z = [47 \pm 1(\mathrm{stat.}) \pm 2(\mathrm{syst.})] \cdot 10^{-3}$

pQCD: $[40 \pm 3(\mathrm{scale}) \pm 1(\mathrm{PDF})] \cdot 10^{-3}$ @NLO

Z + b-jets / Z + jets

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

- Motivation
  - Interesting test of pQCD predictions
  - Important bkgd to SM Higgs search in ZH→νν/ll bb channel
  - Sensitive to b-quark PDF
  - Measurement of ratio benefits from cancellation of many systematics ⇒ precise comparison with theory



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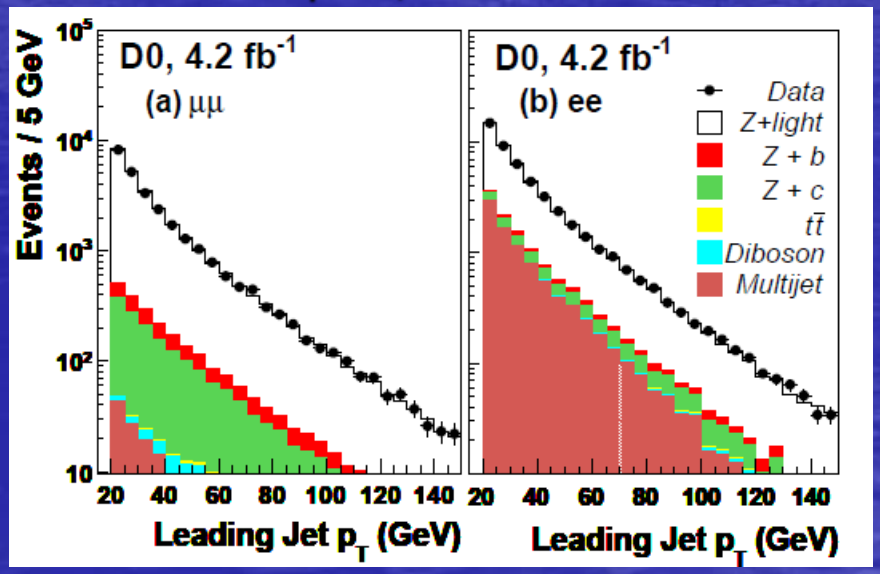


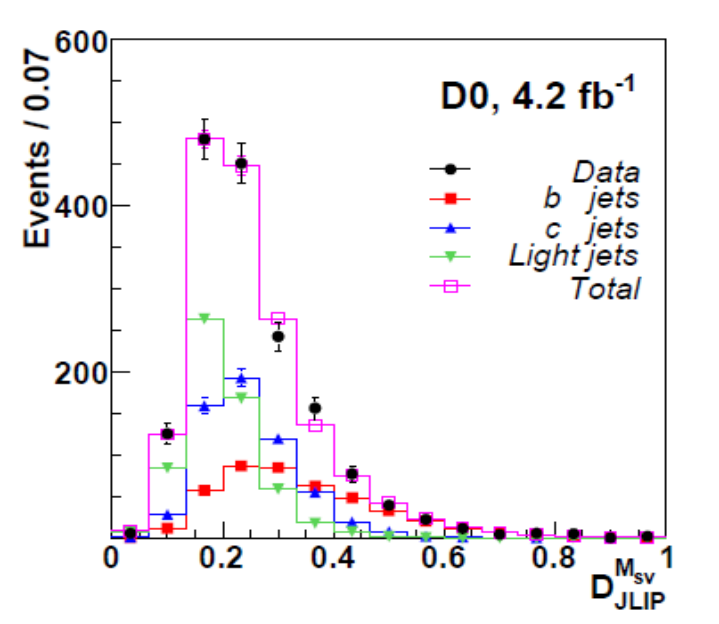
- Data : 4.2 fb^{-1}
- Consider both e and μ channels
  $70 < M_{ll} < 110$ GeV
- Z + ≥ 1 Jet
  R=0.5, p_T>20 GeV, |η|<2.5

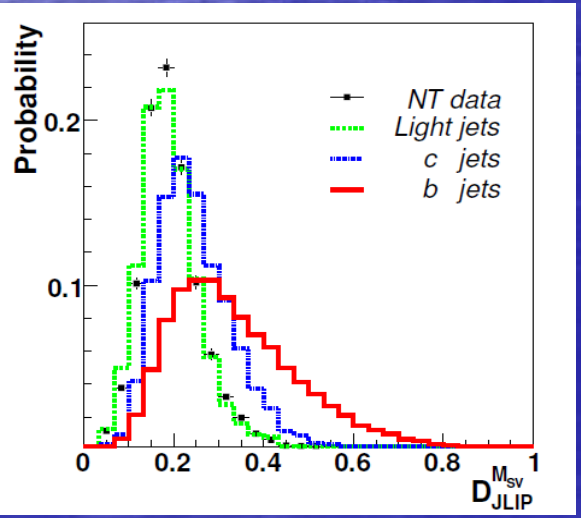
PRD 83, 031105 (2011)

Z + b-jets / Z + jets

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

- Strategy:
  Select Z events with ≥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_{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 ± 0.0022 ± 0.0015
  - Most precise to date
  - Good agreement with MCFM prediction : 0.0185 ± 0.0022
  - CDF result : 0.0208 ± 0.0033 ± 0.0034

Summary & Outlook

- Many interesting results focusing on vector boson + jets production
- Generally, NLO QCD calculations describe data well, but some discrepancies observed indicating need for improvement
- Experimental uncertainties either comparable or lower than theoretical uncertainties
- Good understanding of W/Z+jets processes critical for SM Higgs and NP searches
- More results with better statistics will become available soon.
- Tevatron would continue exploring these processes

http://www-d0.fnal.gov/Run2Physics/qcd/

Backup Slides

Z+ Jets Angular Correlations

PLB 682, 370 (2010)

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

First measurements of Z+jets cross sections as function of Angular correlations between Z and leading jet

$\Delta\phi$(Z, jet), Δy(Z, jet)

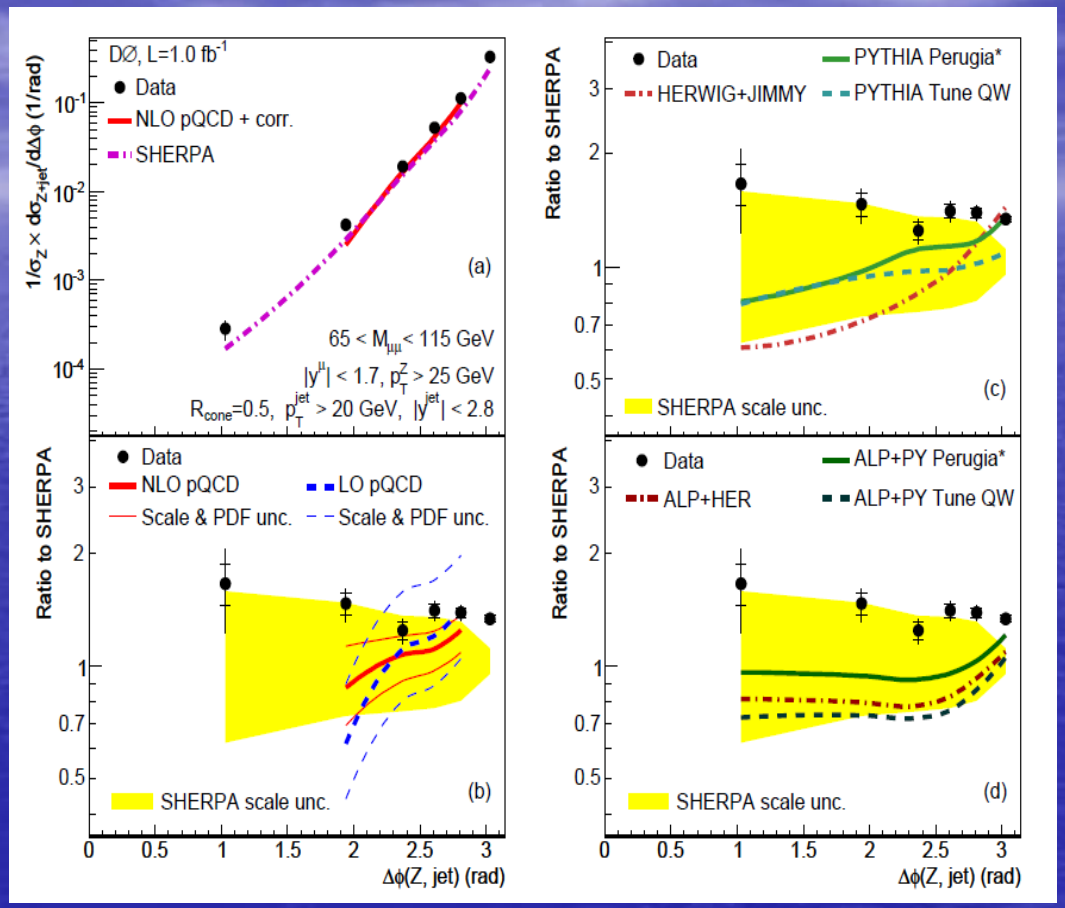
$y_{boost}=1/2(y_Z + y_{jet})$

Sensitive to QCD radiation : Test of PS model assumptions.

The diff. cross-sections are normalized to incl. σ(Z)

p_T^Z>25 GeV (avoid soft effects)

Small $\Delta\phi$(Z,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.

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

- 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.

Z/γ*+ Jet(s) Angular Correlations

PLB 682, 370 (2010)

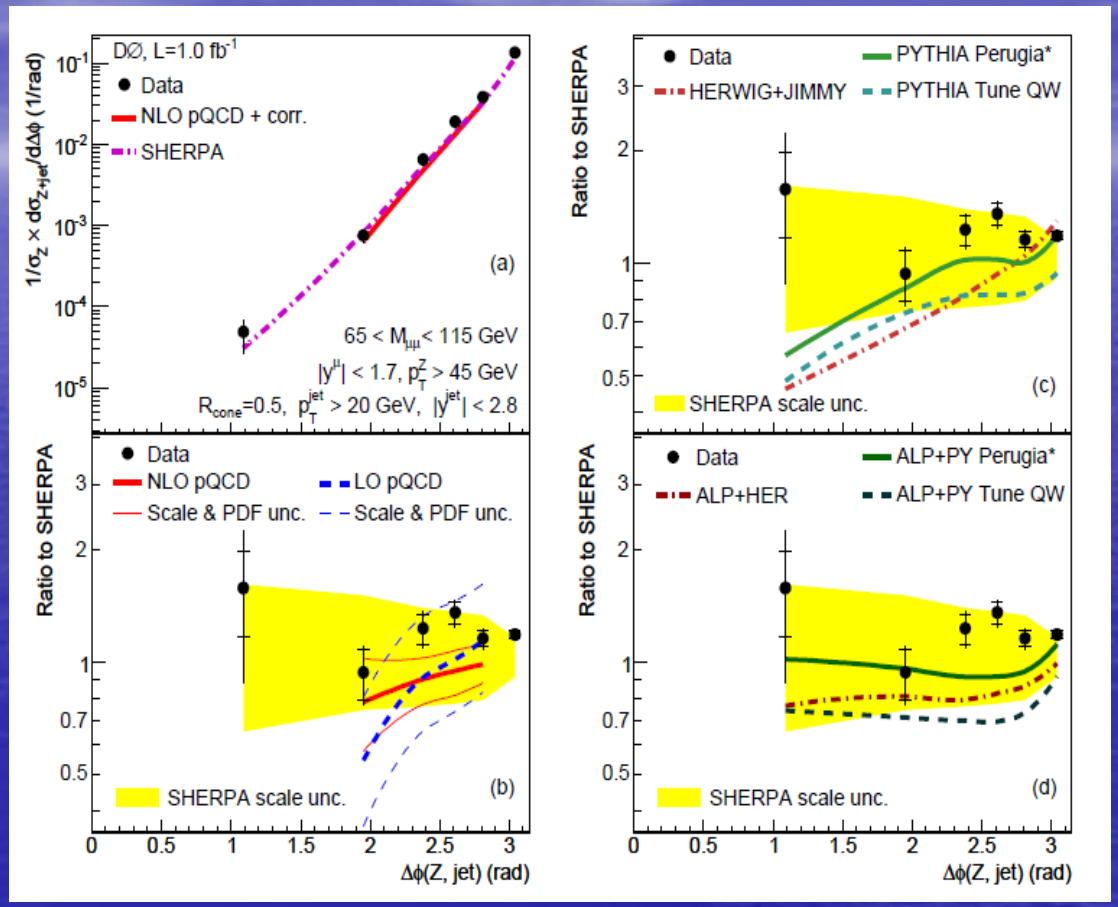
$\mathcal{L}$ = 1 fb^{-1}

Z p_T > 45 GeV

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

MCFM 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.

CDF & D0 detectors

- CDF properties
- Silicon Tracker: large si+ Time of flight detectors
  - $|\eta|<2$, 90cm long, r_{L00} =1.3 - 1.6cm
- 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 $13.4\%/\sqrt{E_t}\oplus 2\%$
- CHA steel + scint $75\%/\sqrt{E_t}\oplus 3\%$

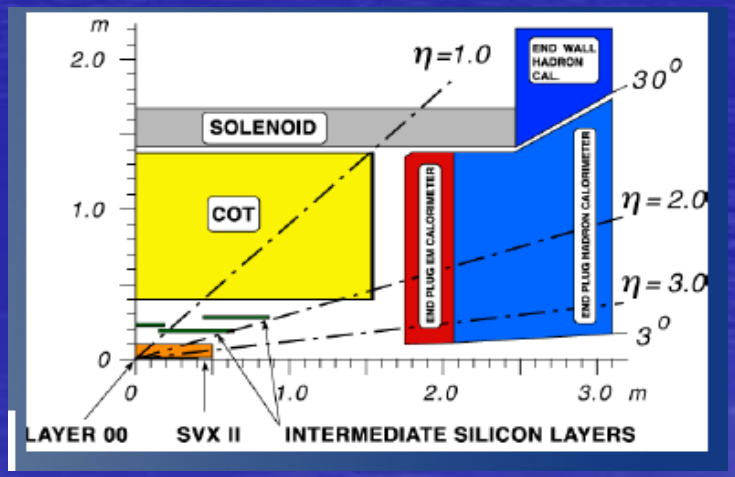
Tracking

- $\sigma(d0)$ = 40μm (incl. 30μm beam)
- $\sigma(pt)/pt$ = 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, γ): 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



Many Tevatron Run II Results

V + Jets

$Z/\gamma^*(\rightarrow\mu\mu)$+jets	D0/1.0 fb^{-1}	PLB 682, 370 (2010)
$Z/\gamma^*(\rightarrow ee)$+jets	D0/1.0 fb^{-1}	PLB 678, 45 (2009)
$Z/\gamma^*(\rightarrow\mu\mu)$+jets	D0/1.0 fb^{-1}	PLB 669, 278 (2008)
$Z/\gamma^*(\rightarrow ee)$+jets	D0/0.4 fb^{-1}	PLB 658, 112 (2008)

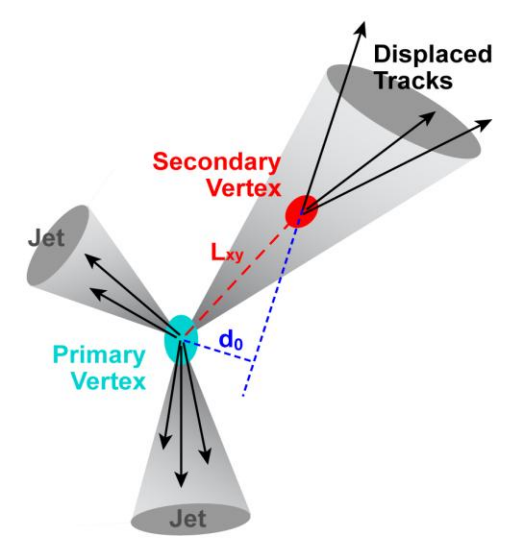
V + Heavy Flavor Jets

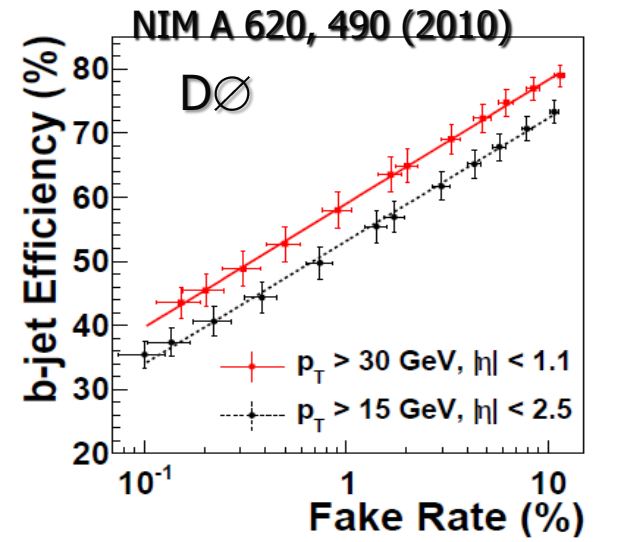
Z+b/Z+jets	D0/4.2 fb^{-1}	hep-ex/1010.6203
W+c/W+jets	D0/1.0 fb^{-1}	PLB 666, 23 (2008)
Z+b/Z+jets	D0/0.18 fb^{-1}	PRL 94, 161801 (2005)

Will concentrate on recent results

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
- D0 : NN based on combination of variables sensitive to presence of displaced tracks forming sec. vtx.



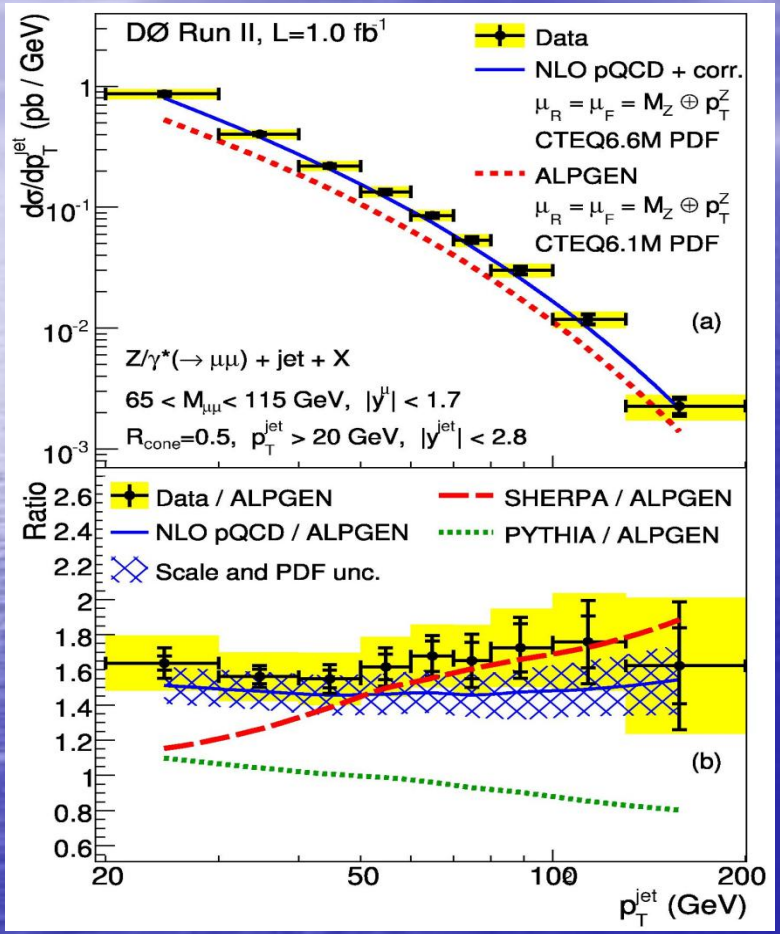


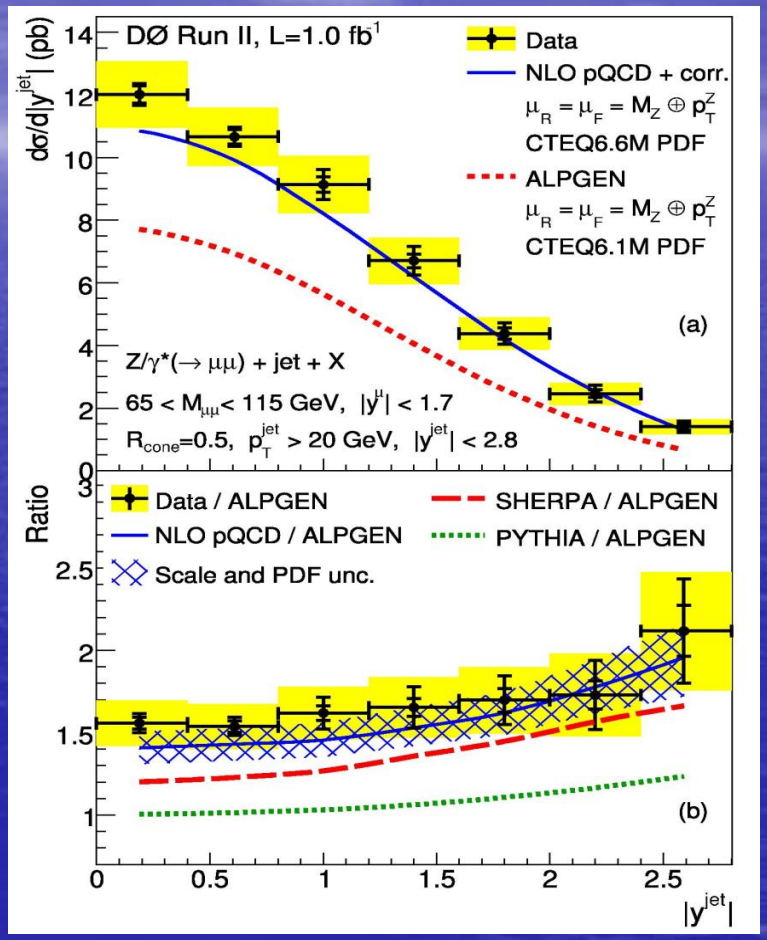
PLB 669, 278 (2008)

$Z/\gamma^* \rightarrow \mu^+\mu^- + Jet(s)$

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

Differential cross sections in p_T and y of the leading jet



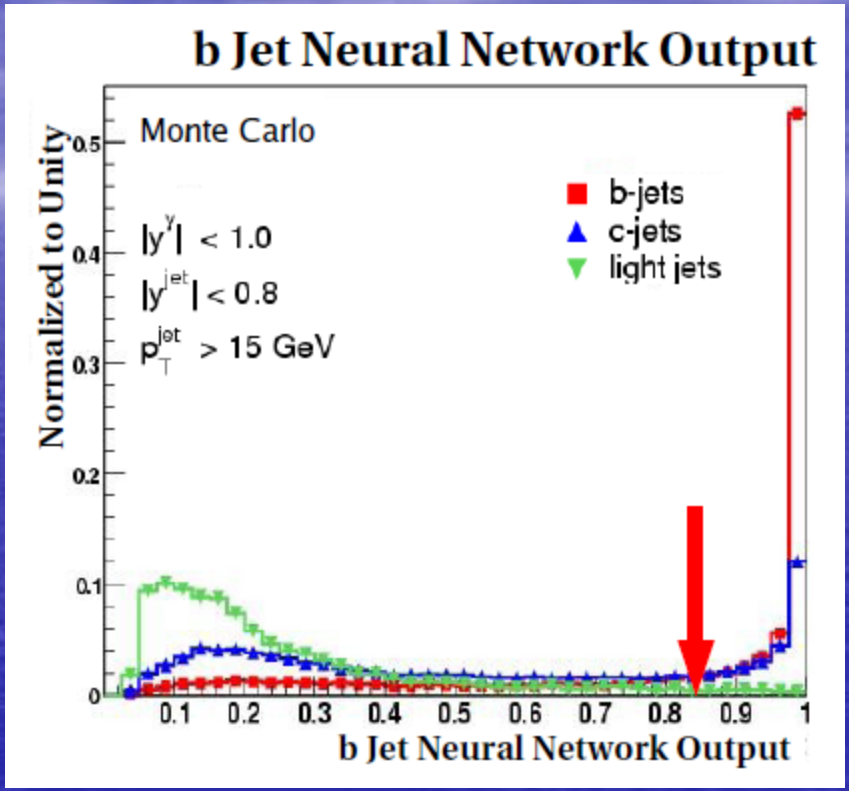


ALPGEN describes shape well.
ALPGEN and PYTHIA below the data, SHERPA better

MCFM NLO better describes data

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
    - ~1.5 x 10^{-12} seconds (B mesons)
    - ~0.8 x 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.

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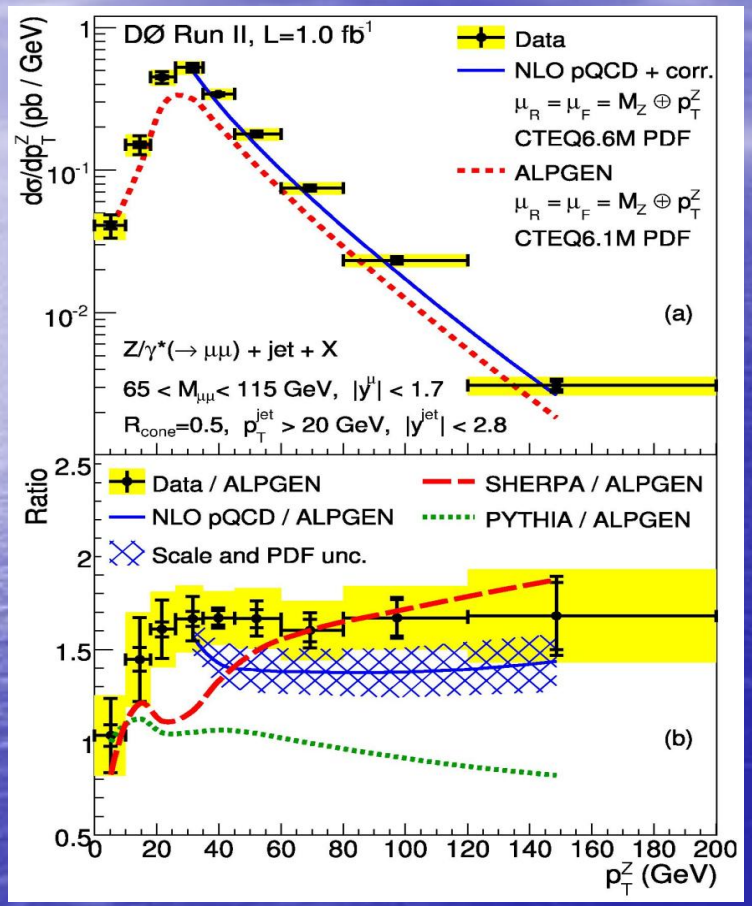
$Z/\gamma^* \rightarrow \mu^+\mu^- + Jet(s)$

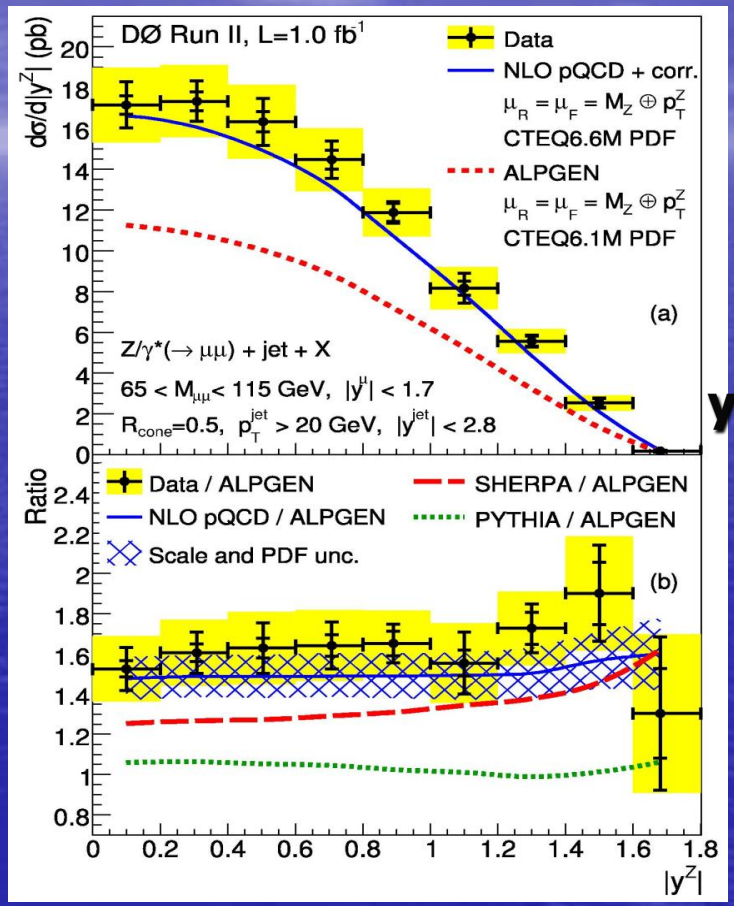
Differential cross sections in p_T and y of the Z boson

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

$p_T(Z)$



$y(Z)$



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