W/Z + Jets Results from the Tevatron

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Outline

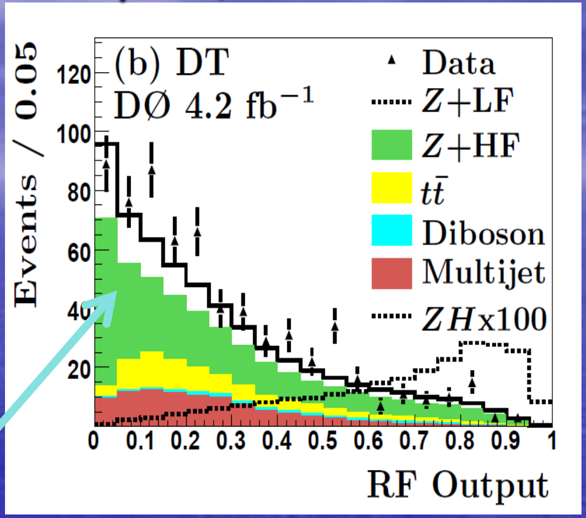
- Motivation
- Measurements
  - V+Jets
  - V+ HF Jets
- Summary & Outlook

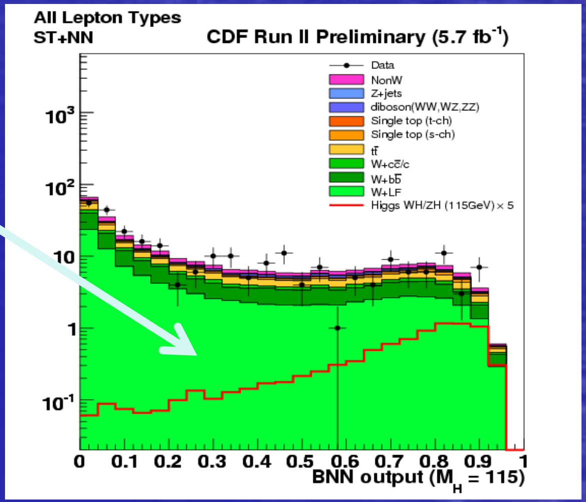
Standard Model Benchmarks at the Tevatron and LHC
Fermilab, Nov 19-20, 2010

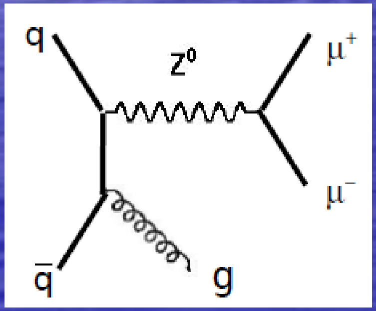
Why study W/Z + Jets production?

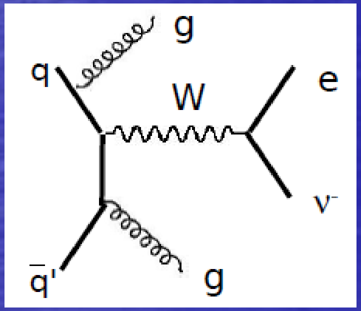
- Test of pQCD in multijet environment
  - Presence of W/Z ensure high Q^2: pQCD
  - Clean environment: leptonic final state provides clean signature, low BG
  - High statistics allows precision tests
- Test of MC Models
  - Key sample to validate available MC tools using experimental data
- W/Z+HF production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

hep-ex/1008.3564









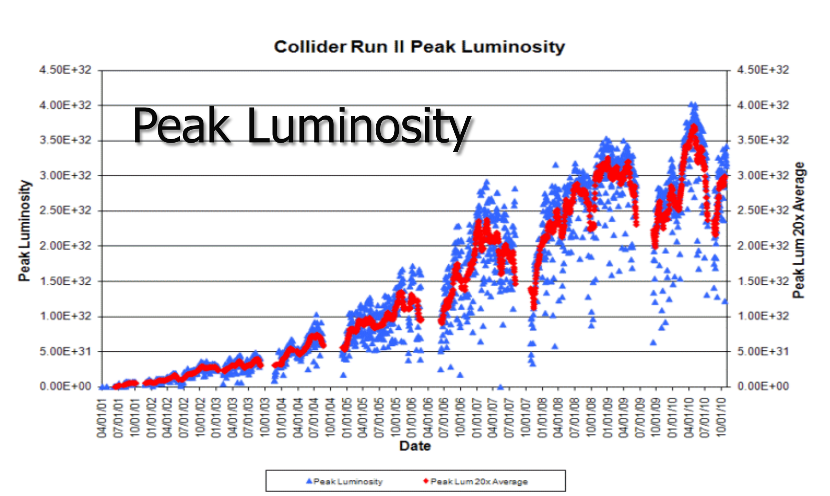
$\sigma(Z^0 \rightarrow l^+l^-) \sim 250$ pb

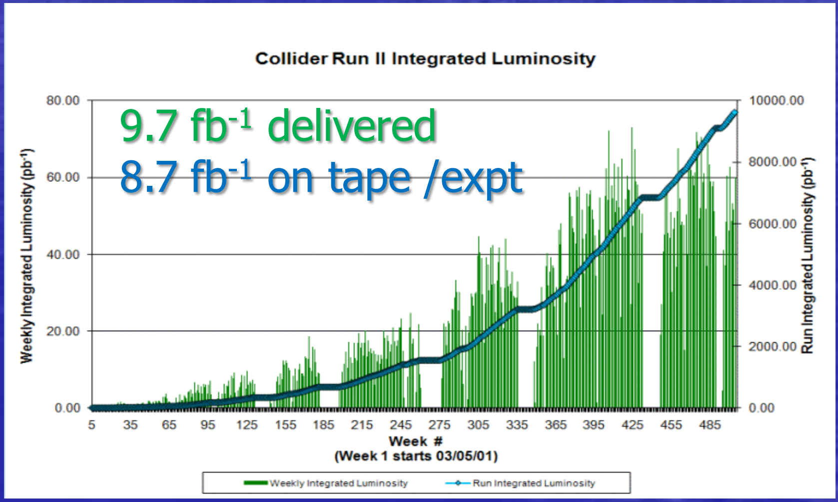
$\sigma(W^\pm \rightarrow l\nu) \sim 2700$ pb

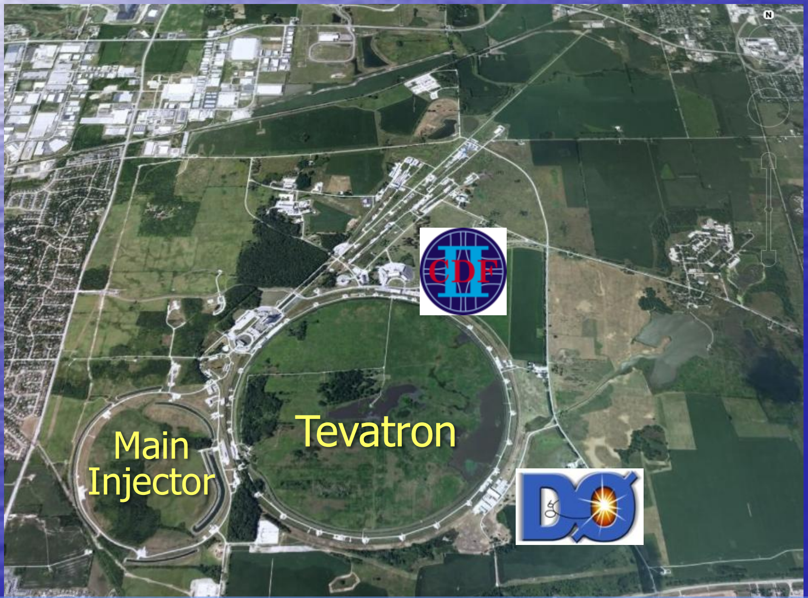
$\Rightarrow$Millions of W's; 100's k Z's per fb^{-1}

The Tevatron Collider at Fermilab

- $p\bar{p}$ collisions @ $\sqrt{s}$ = 1.96 TeV
  - 36 bunches, 396 ns
- Excellent performance
  - Peak lumi : 3.5 E32 $cm^{-2}s^{-1}$
  - $\int Ldt$ /week ~ 50 pb^{-1}
- Both expts performing well : ~90% data taking efficiency







Thanks to the Accelerator Division!

Expect ~2.5 fb-1 delivered in FY11

Results presented based on 1 – 6 fb^{-1}

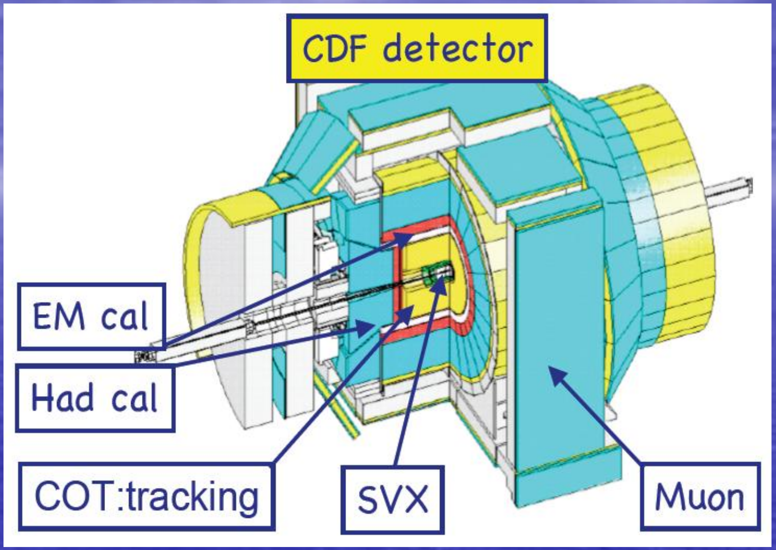
CDF & DØ Run II Detectors

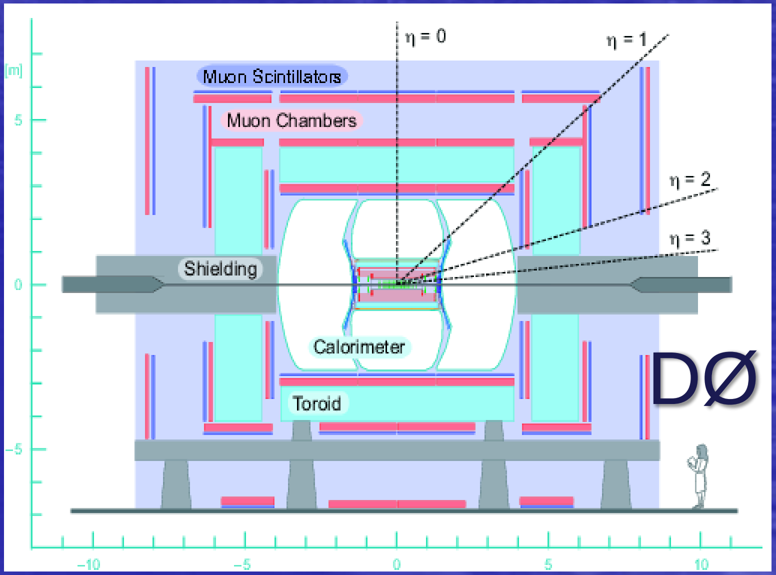
- Multi-purpose detectors with broad particle identification capabilities

- 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
  - **D0** : finer calorimeter segmentation, and forward muon system

Performing well making use of all detectors capabilities



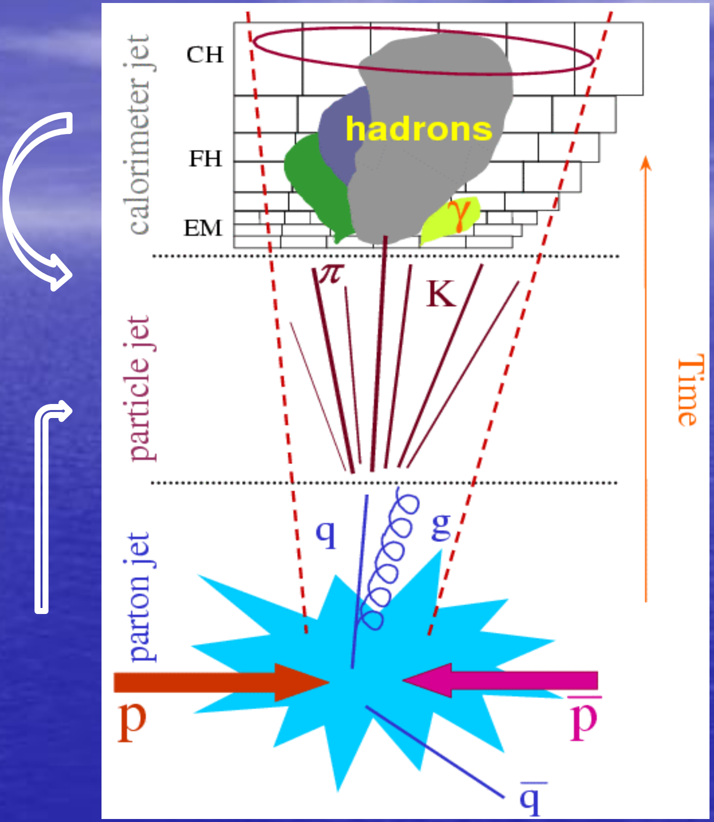


W/Z + Jets Selection

$W \to l\nu$ and $Z \to l^+l^-$ 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), $W \to \tau\nu$, Top, diboson, $Z \to ll$



- 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 ava

- 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 ⇒ can be directly used for testing & improving MC models and any future calculations /models.

Many Tevatron Run II Results

V + Jets

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

V + Heavy Flavor Jets

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

Will concentrate on recent results

$Z/\gamma^* \to \mu^+\mu^- + \geq 1$ Jet

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

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

Kinematic selection

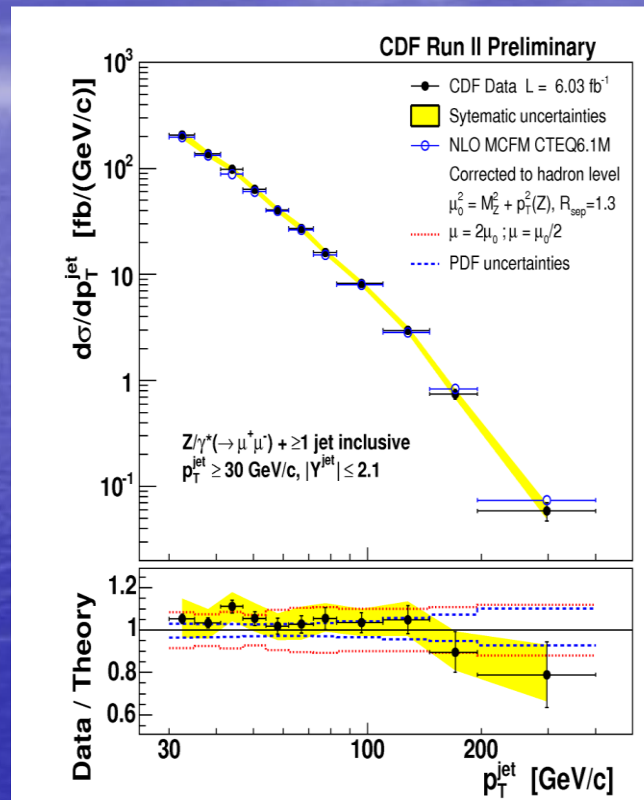
- Two central μ's

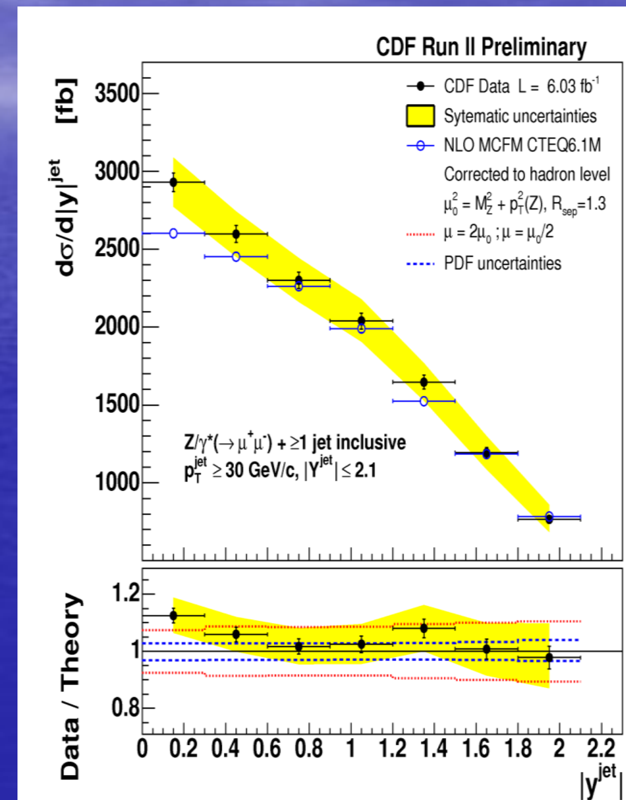
$p_T^{\mu} > 25$ GeV, $|\eta| < 1.0$

$66 < M_{\mu\mu} < 106$ GeV

- ≥1 jet, R = 0.7

$p_T^{jet} > 30$ GeV, $|y| < 2.1$





Events :

Data : 13200

Background : 6%

QCD Multijet, W+jets

Zγ (dominant), ttbar,

Diboson, $Z \to \tau\tau$

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

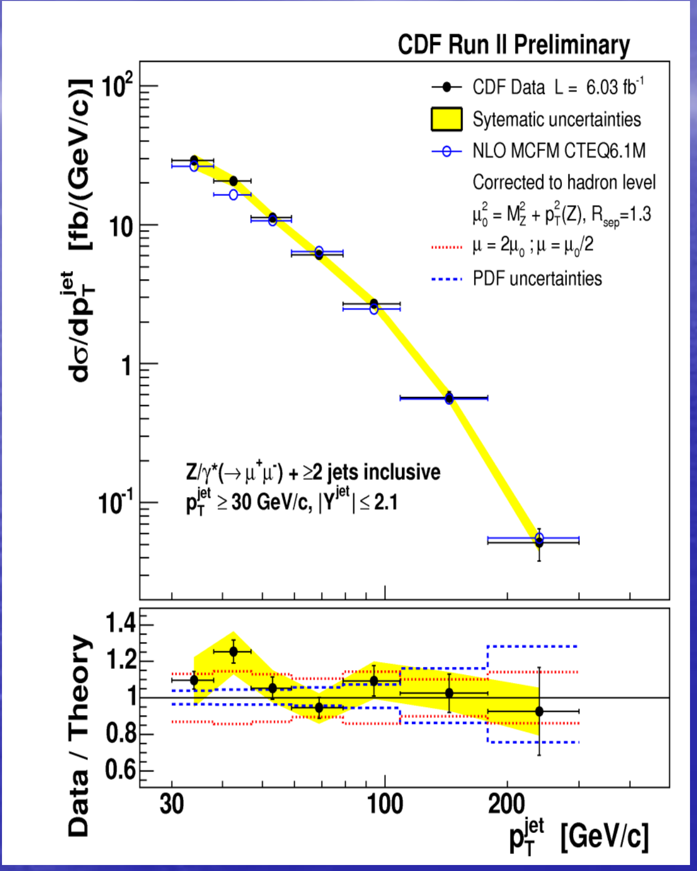
$Z/\gamma^* \rightarrow \mu^+\mu^- + \geq 2$ Jets

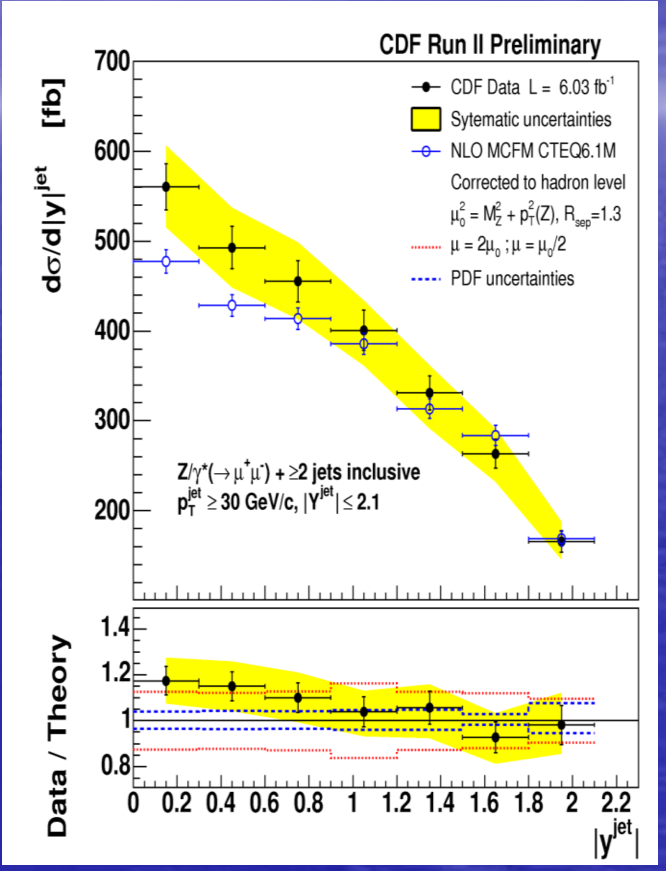
$\mathcal{L} = 6\ fb^{-1}$

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



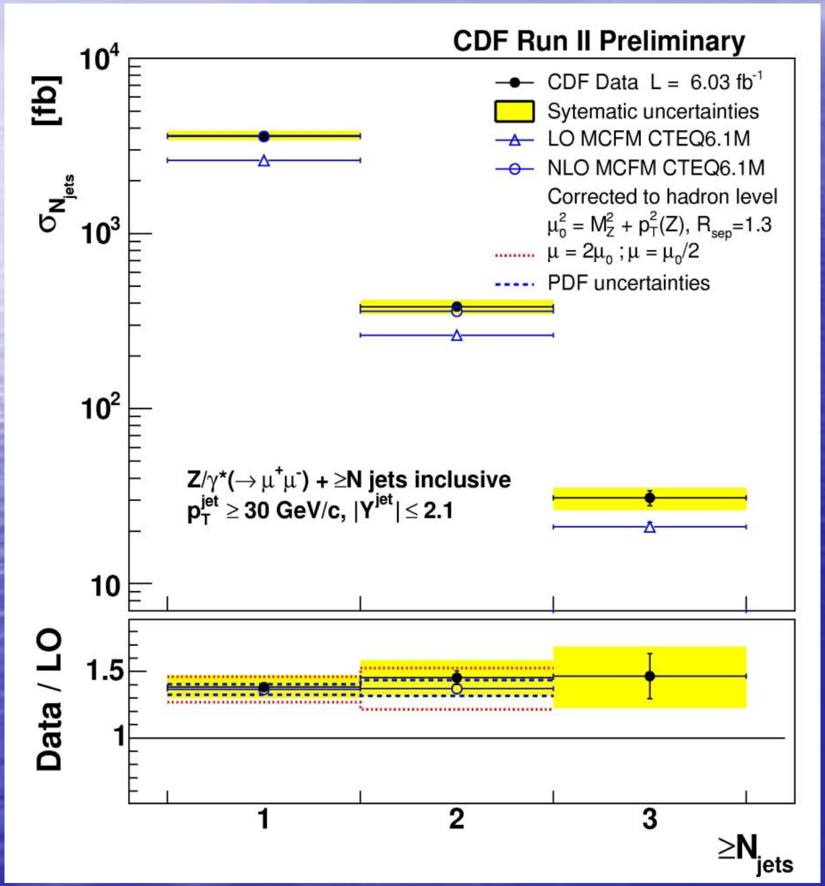


Measurements are well described by MCFM NLO

$Z/\gamma^* \rightarrow \mu^+\mu^- + \geq 1$ Jet

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

Total incl. cross sections in incl. jet multiplicities



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

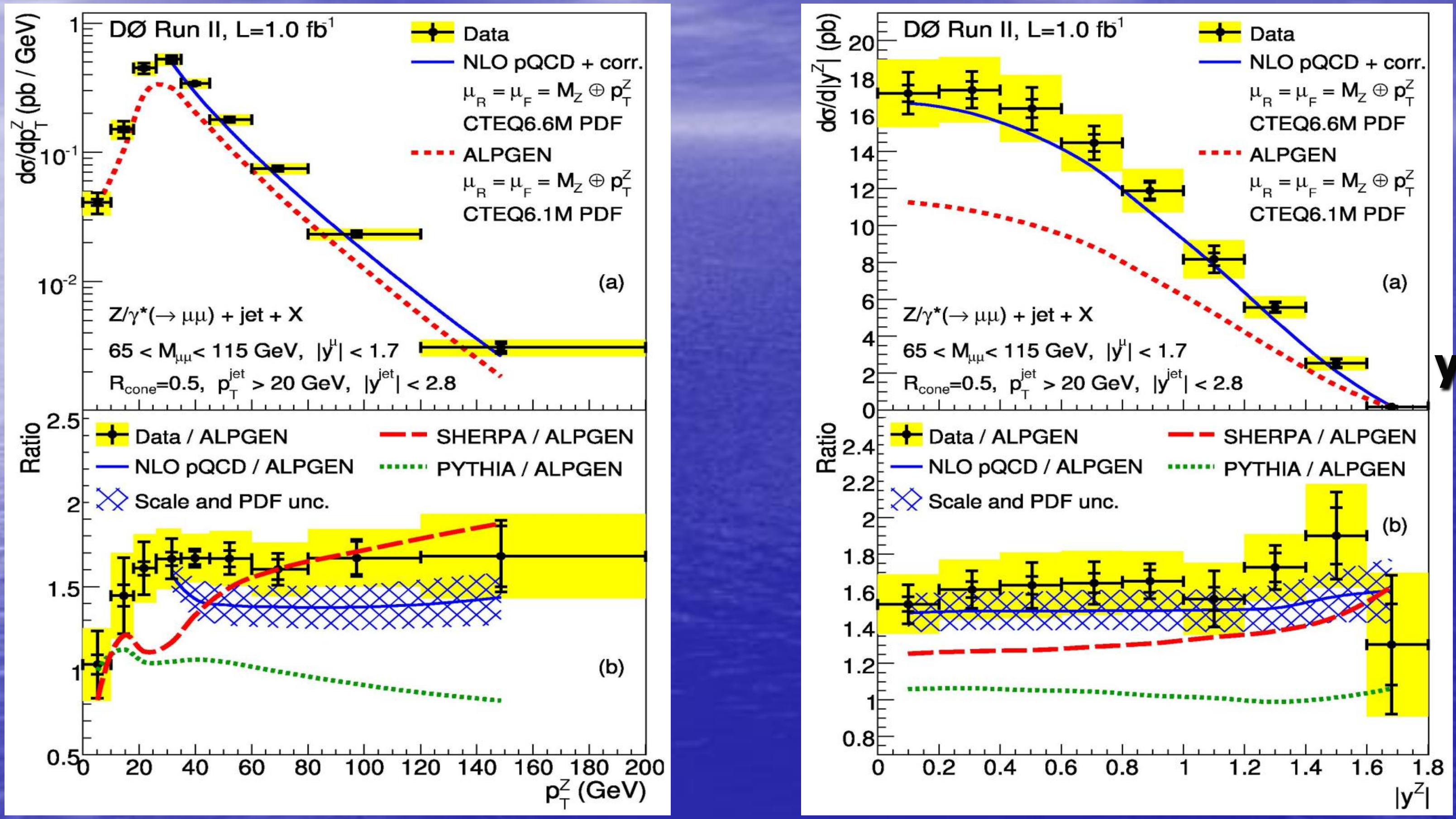
PLB 669, 278 (2008)

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

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

Differential cross sections in p_T and y of the Z boson

$p_T(Z)$



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

PLB 678, 45 (2009)

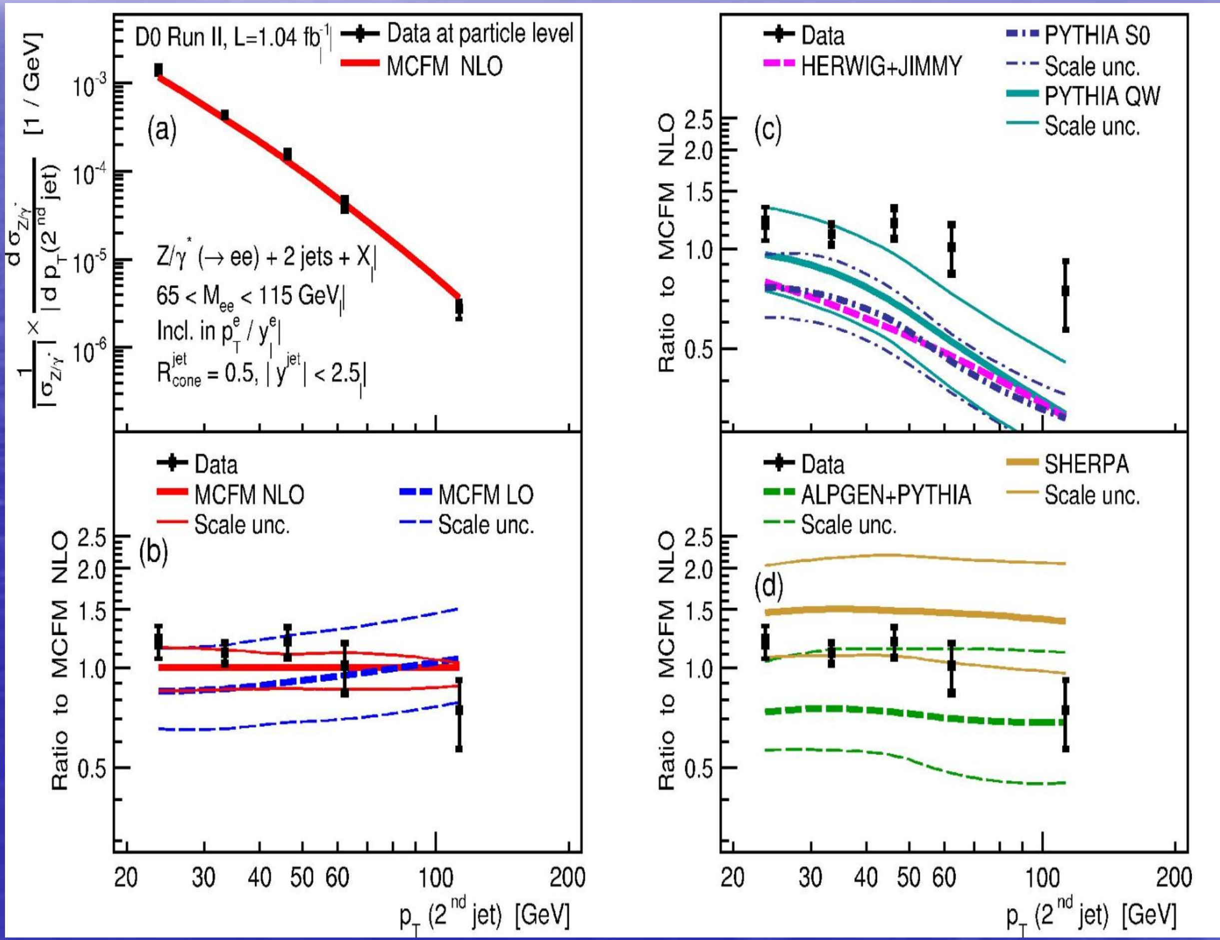
$Z/\gamma^* \rightarrow e^+e^- + \geq 2$ Jets

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

MCFM NLO significant improvement over LO
NLO describes data

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

Z + ≥ 2 jet, 2nd jet pT



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/γ*+ Jet(s) Angular Correlations

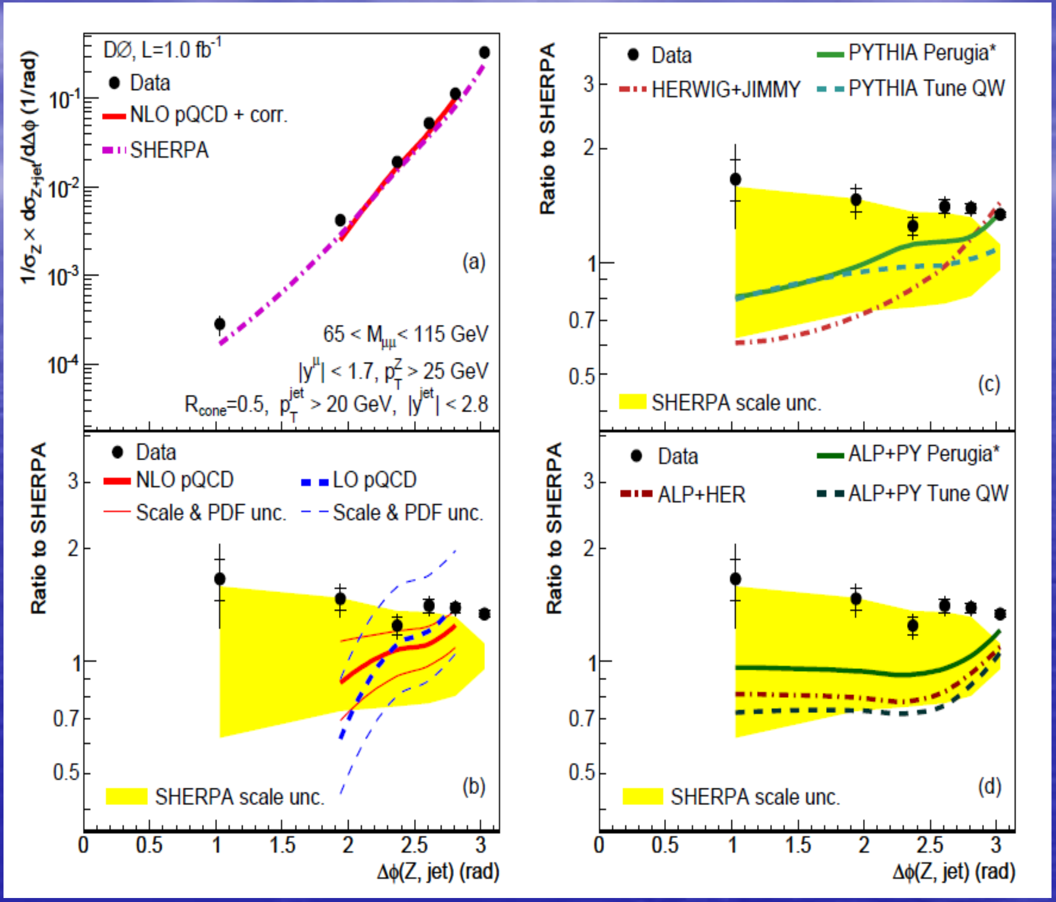
PLB 682, 370 (2010)

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

First measurements of angular correlations between Z and leading jet
$\Delta\phi(Z, jet)$, $\Delta y(Z, jet)$
$y_{boost}=1/2(y_Z + y_{jet})$
Sensitive to QCD radiation : Test of PS model assumptions.

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

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.

NIM A 662, 698 (2010)

Z + Jet p_T balance

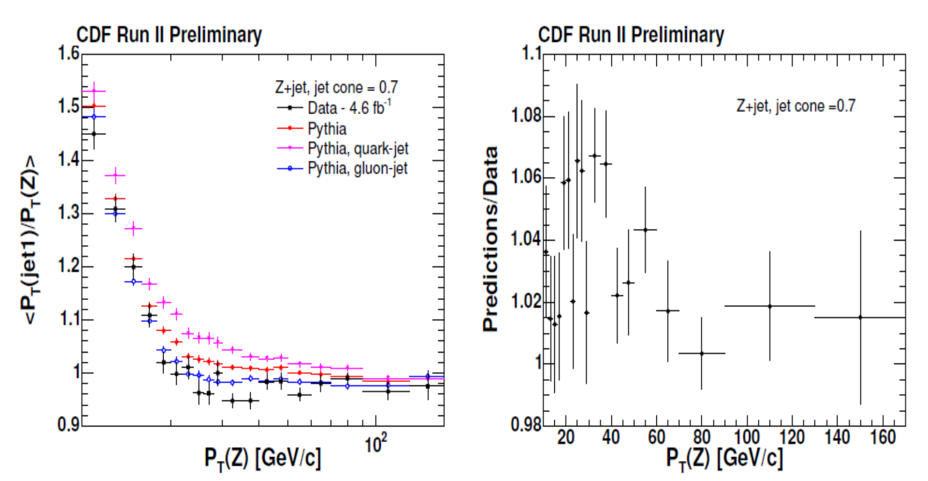
$\mathcal{L} = 4.6\ fb^{-1}$

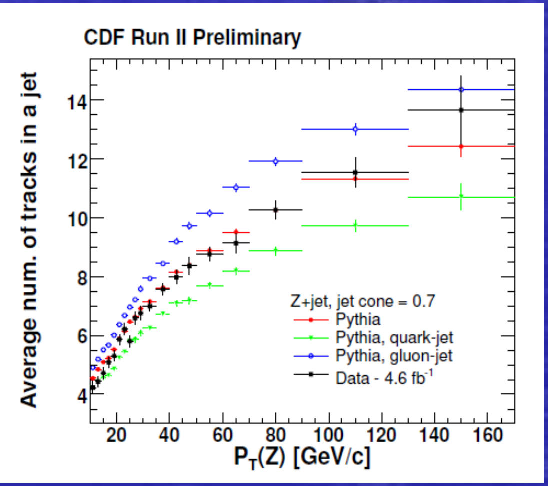
Select Z + 1 jet events, back-to-back
$p_T^l > 18$ GeV, $80 < M_{ll} < 100$ GeV
Leading jet $p_T^{jet} > 8$ GeV, $0.2 < |\eta| < 0.8$
$\Delta\phi$(Z, jet) > 3.0 rad
R = 0.4, 0.7, 1.0

Independent test of CDF JES

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

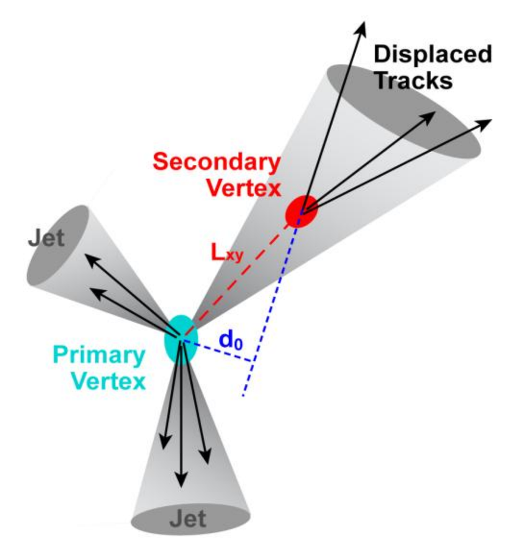




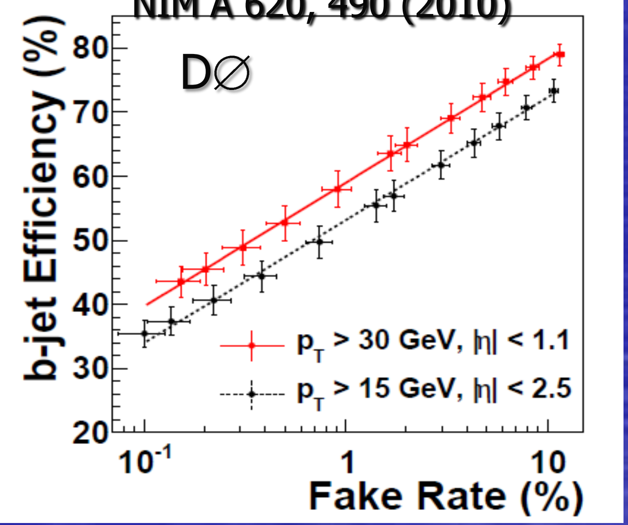
The uncertainty from mis-modeling of FSR at large angles is largest.

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.



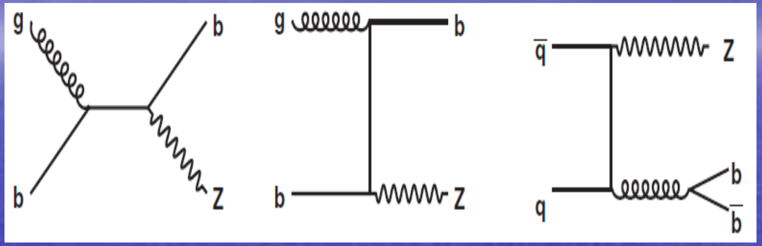
NIM A 620, 490 (2010)



Z + b-jets / Z + jets

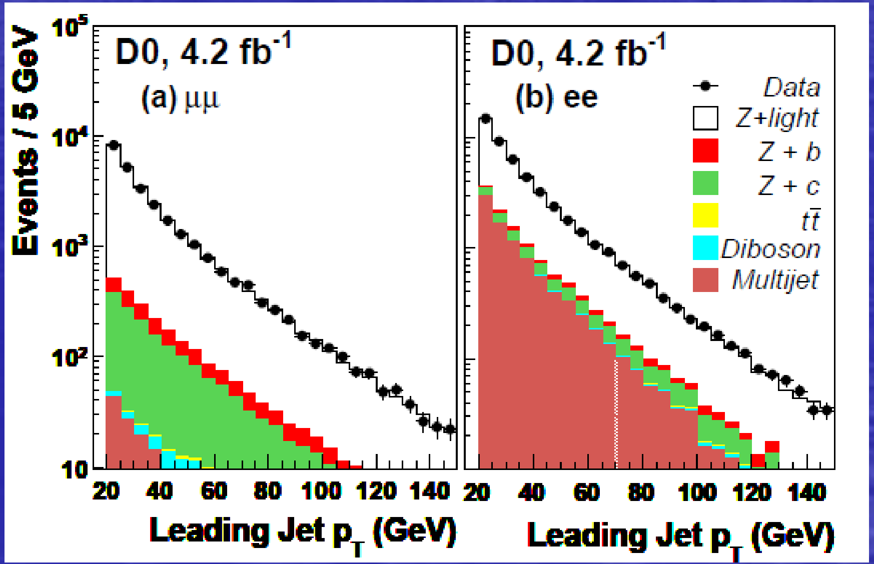
$\mathcal{L} = 4.2\ fb^{-1}$

- 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



- 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

hep-ex/1010.6203

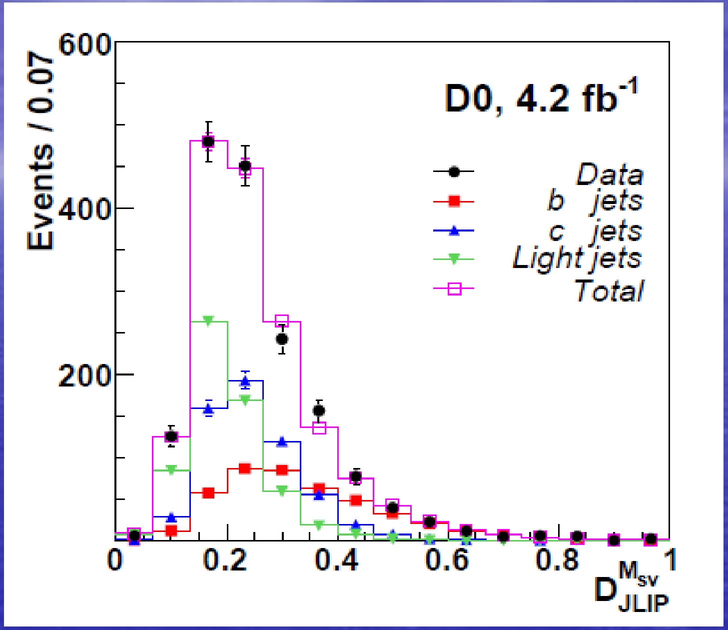


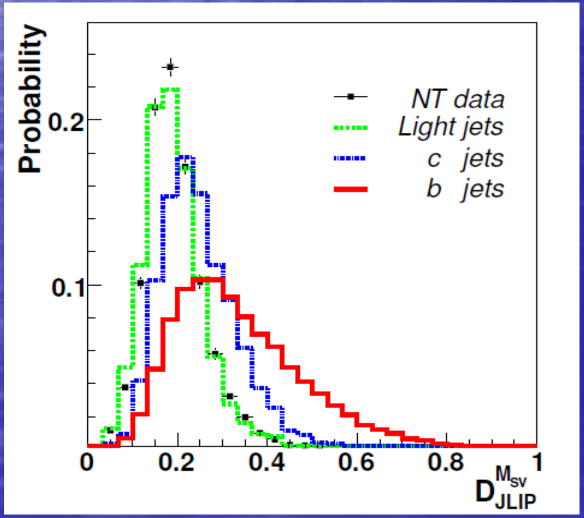
hep-ex/1010.6203

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 σ(Z+b)/σ(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

PRD 79, 052008 (2009)

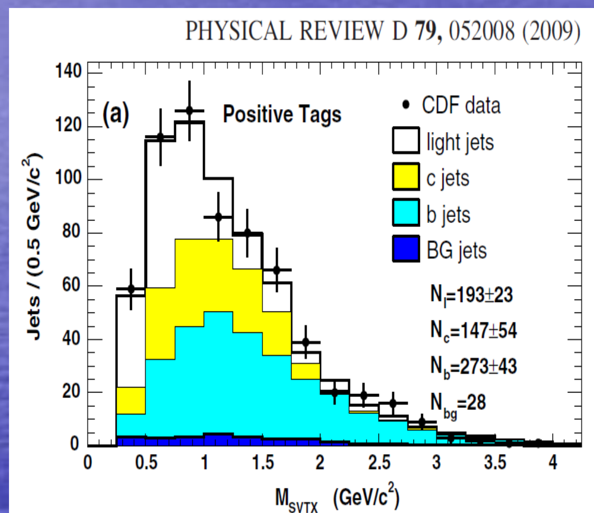
Z + b-jets Production

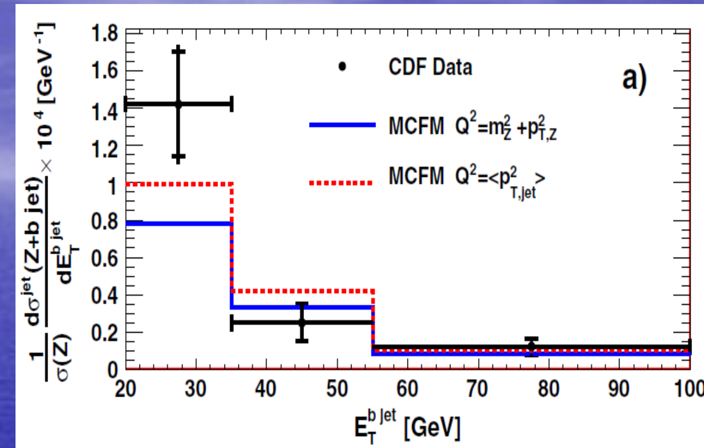
$\mathcal{L}$ = 2 fb^{-1}

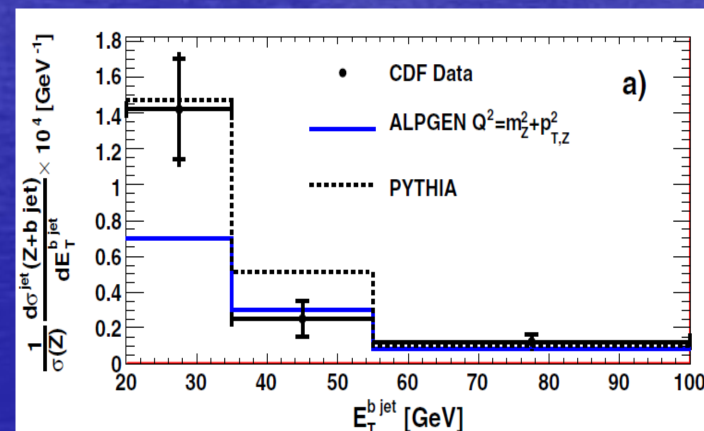
- Utilize $Z \rightarrow ee/\mu\mu$
- Jets : R = 0.7, p_T>20 GeV, $|\eta|$<1.5
- b-quark composition extracted from fit to sec. vtx. mass

$\sigma(Z+b)/\sigma(Z)$ = 0.336±0.053±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.

PRL 104, 131801 (2010)

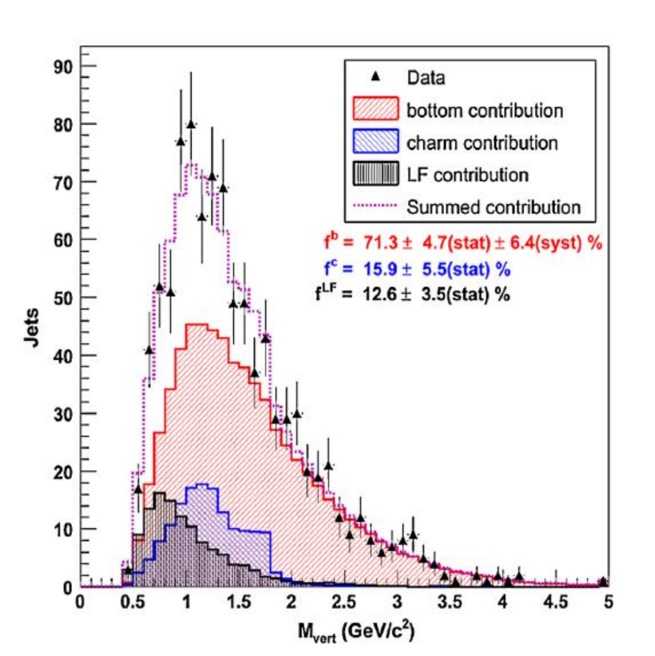
W + b-jets Production

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

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

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

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



- Measurement
  σxBR = 2.74 ± 0.27± 0.42 pb
  NLO : 1.22 ± 0.14 pb
  Pythia : 1.10 pb, Alpgen : 0.78 pb

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

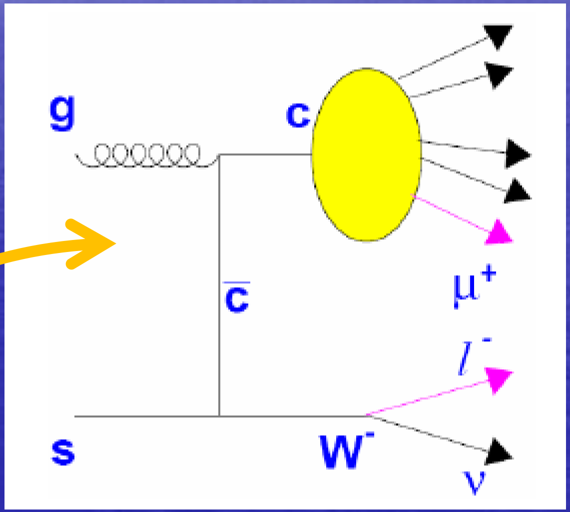
W + Single c Production

$gs \to W^- c$ (~90%)

$gd \to W c$ (~10%)

- Motivation
  - Sensitive to s-quark PDF in proton
  - Also to CKM matrix element V_{cs}
  - BG for single top, WH
- Strategy
  - $W \to l\nu$ selected by high p_T e/μ+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 $N^{OS} - N^{SS}$



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

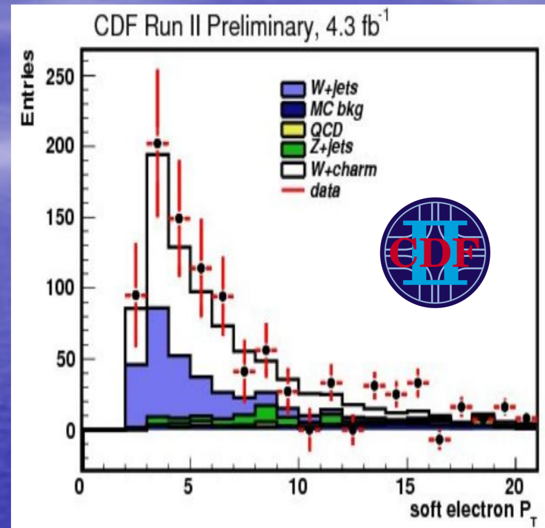
$$\sigma_{W+c} \times Br(W \to l\nu) = \frac{N^{OS-SS}_{measured} - N^{OS-SS}_{bkg}}{L \times A \times \varepsilon}$$

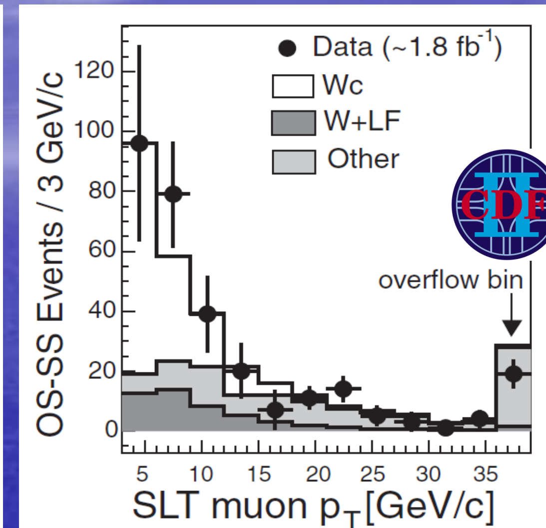
W + Single c Production

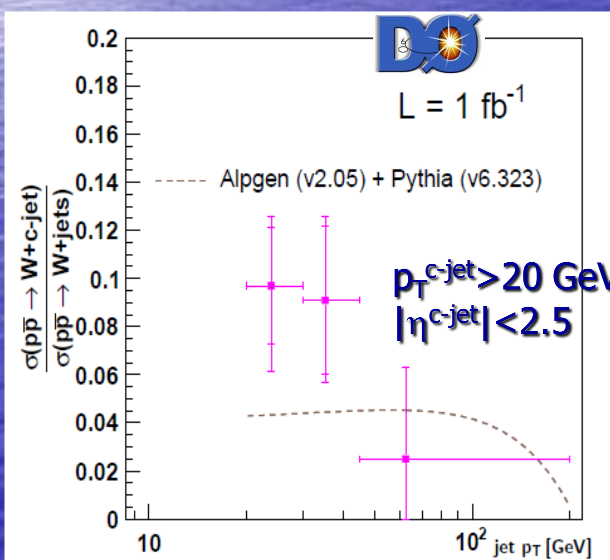
PRL 100, 091803 (2008)

- 4.3 fb^{-1} (SLTe)
  $p_T^{c\text{-jet}} > 20$ GeV, $|\eta^{c\text{-jet}}| < 1.5$
  σxBR = 21.1 ± 7.1± 4.6 pb
- 1.8 fb^{-1} (SLTμ)
  σxBR = 9.8 ± 2.8 ± 1.6 pb

NLO (MCFM) = 11.2 ± 2.2 pb







Data in reasonable agreement with NLO.

PLB 666, 23 (2008)

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

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/

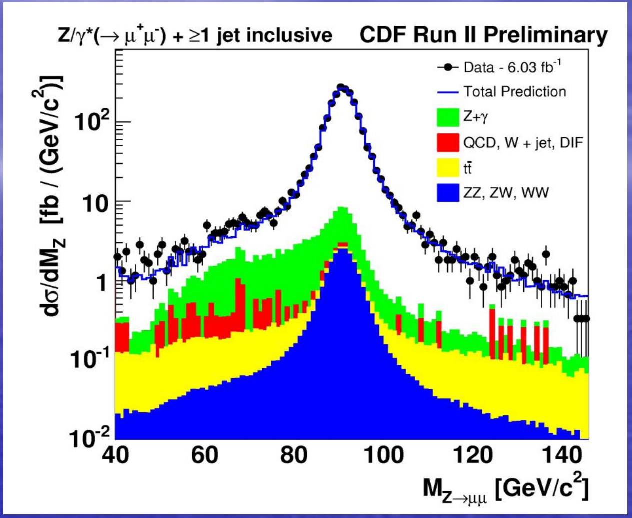
W/Z Candidates

Production rates at Tevatron

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

$\sigma(W^\pm \rightarrow l\nu) \sim 2700$ pb

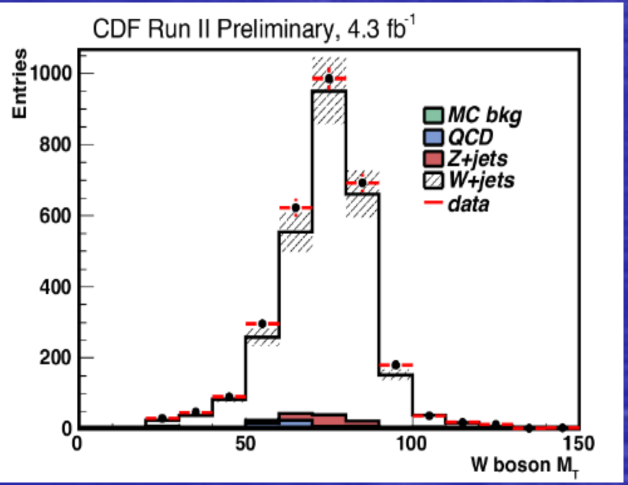
$\Rightarrow$Millions of W's; 100's k Z's per fb^{-1}



$Z \rightarrow l^+l^-$ is a clean signal

Fully reconstruct Z with two leptons

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

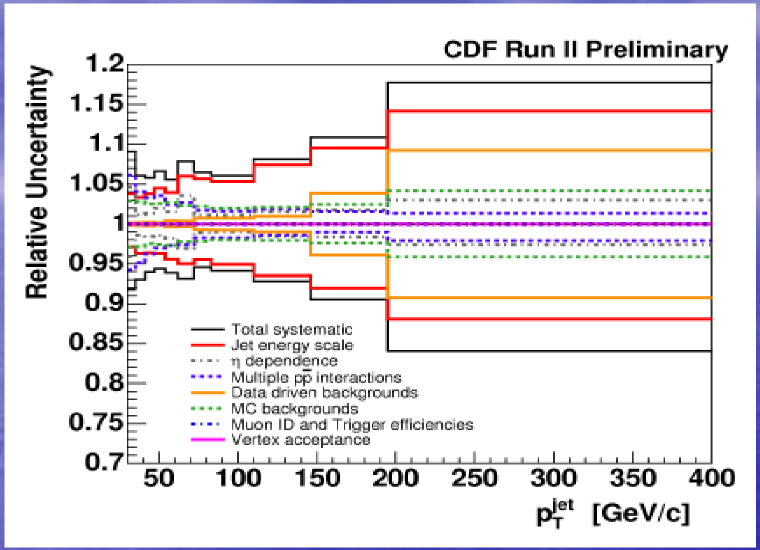


$W \rightarrow l\nu$

Higher statistics, higher BG

Reconstruct lepton, $\nu \Rightarrow$ missing E_T

BG : QCD (fake lepton), $W \rightarrow \tau\nu$, Top, diboson, $Z \rightarrow ll$



CDF II Preliminary

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

Backup Slides

CDF & D0 detectors

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

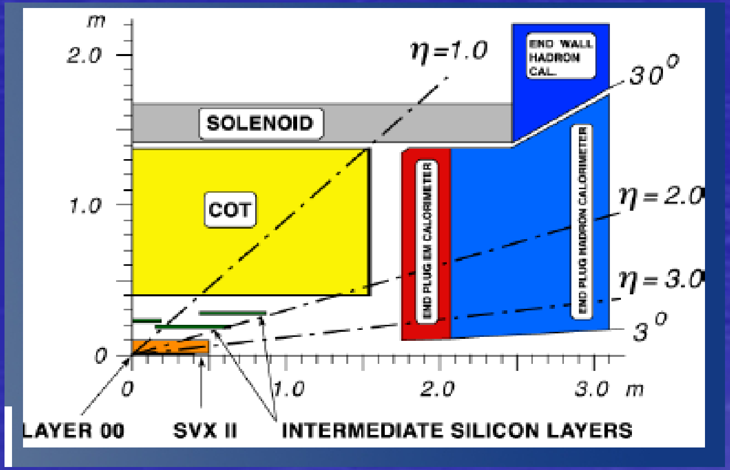
Calorimeter

- CEM lead + scint 13.4%/$\sqrt{E_t}\oplus$2%
- CHA steel + scint 75%/$\sqrt{E_t}\oplus$3%

Tracking

- σ(d0) = 40μm (incl. 30μm beam)
- σ(pt)/pt = 0.15 % pt

- Tracker (Silicon Microstrips + Scintillating Fibers): covers |η| < 2.5 inside 2 T superconducting solenoid
- Calorimeter (Sampling U/Liquid Ar): hermetic coverage: |η| < 4.2
- Calorimeters (→ 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 |η| < 2 before and after toroid



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

Latest results with 6 fb^{-1}

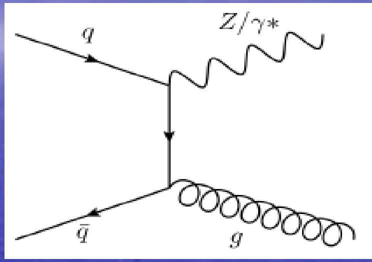
- Kinematic selection

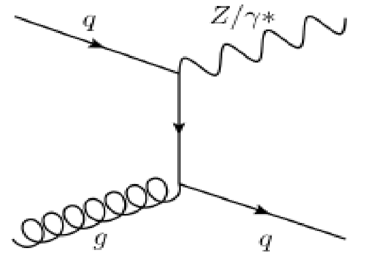
p_T^{μ} >25 GeV, $|\eta|$<1.0, 66<$M_{\mu\mu}$<106 GeV
p_T^{jet} >30 GeV, $|y|$<2.1, R = 0.7

- Events :13000, 1500, 130 in Z+≥1 jet, ≥2, ≥3 jet bins
- Backgrounds:

QCD multi-jet, W+jets (data-driven)
Zγ, Top, Diboson, Z→ττ (MC)

– Total BG 5-10%





CDF II Preliminary

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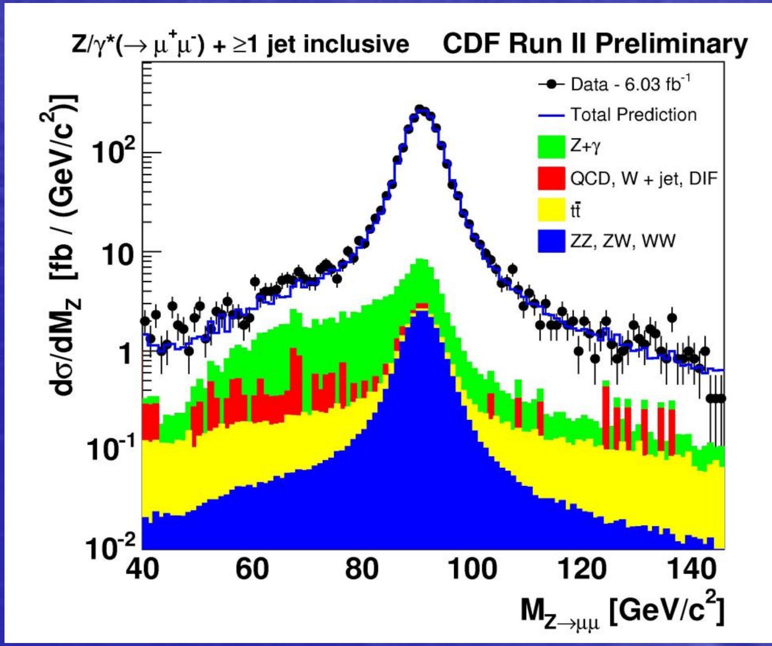
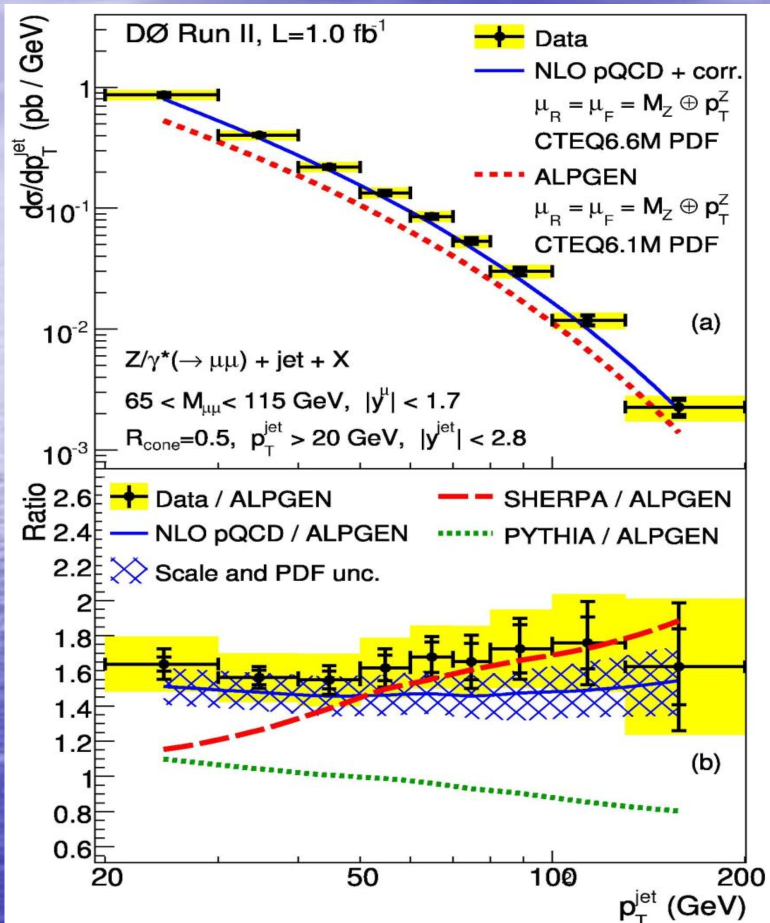


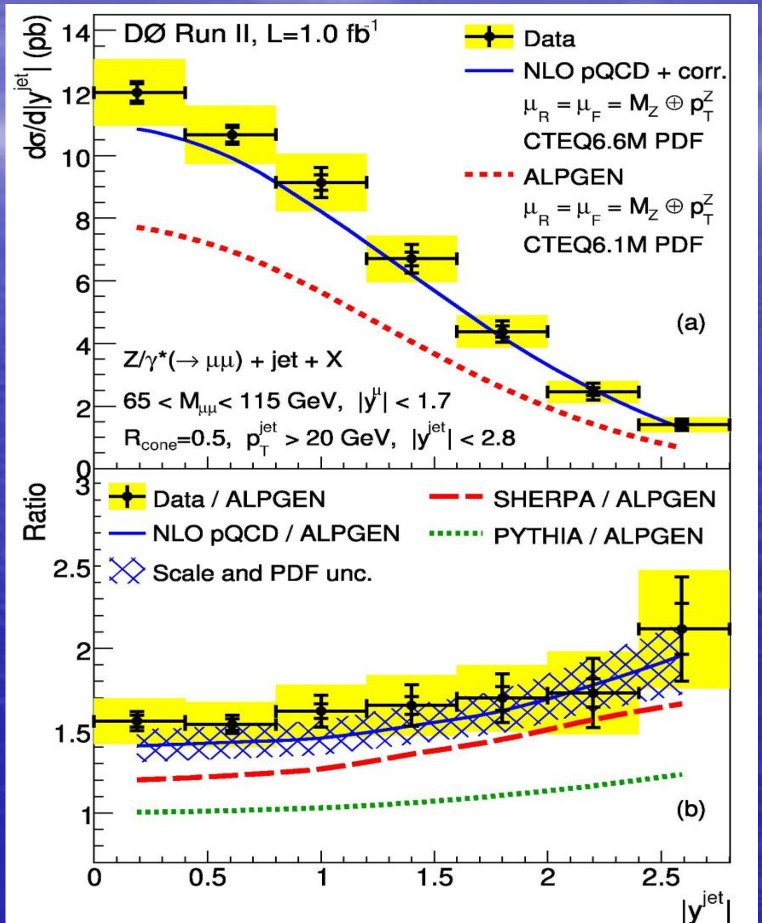
PLB 669, 278 (2008)

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

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

Differential cross sections in p_T and y of the leading jet



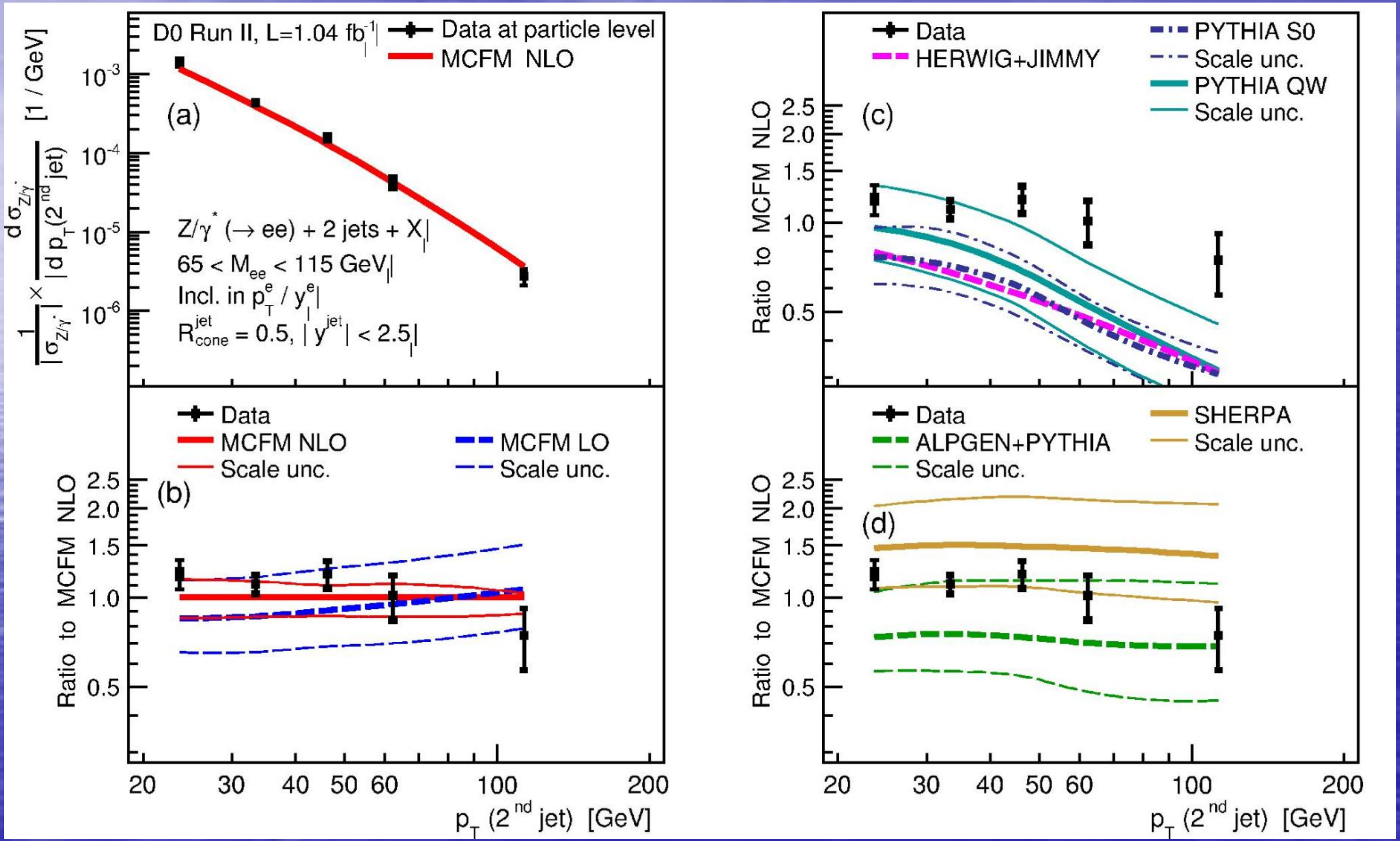


ALPGEN describes shape well.
ALPGEN and PYTHIA below the data, SHERPA better

MCFM NLO better describes data

$Z/\gamma^* \rightarrow e^+e^- + \geq 2$ Jets

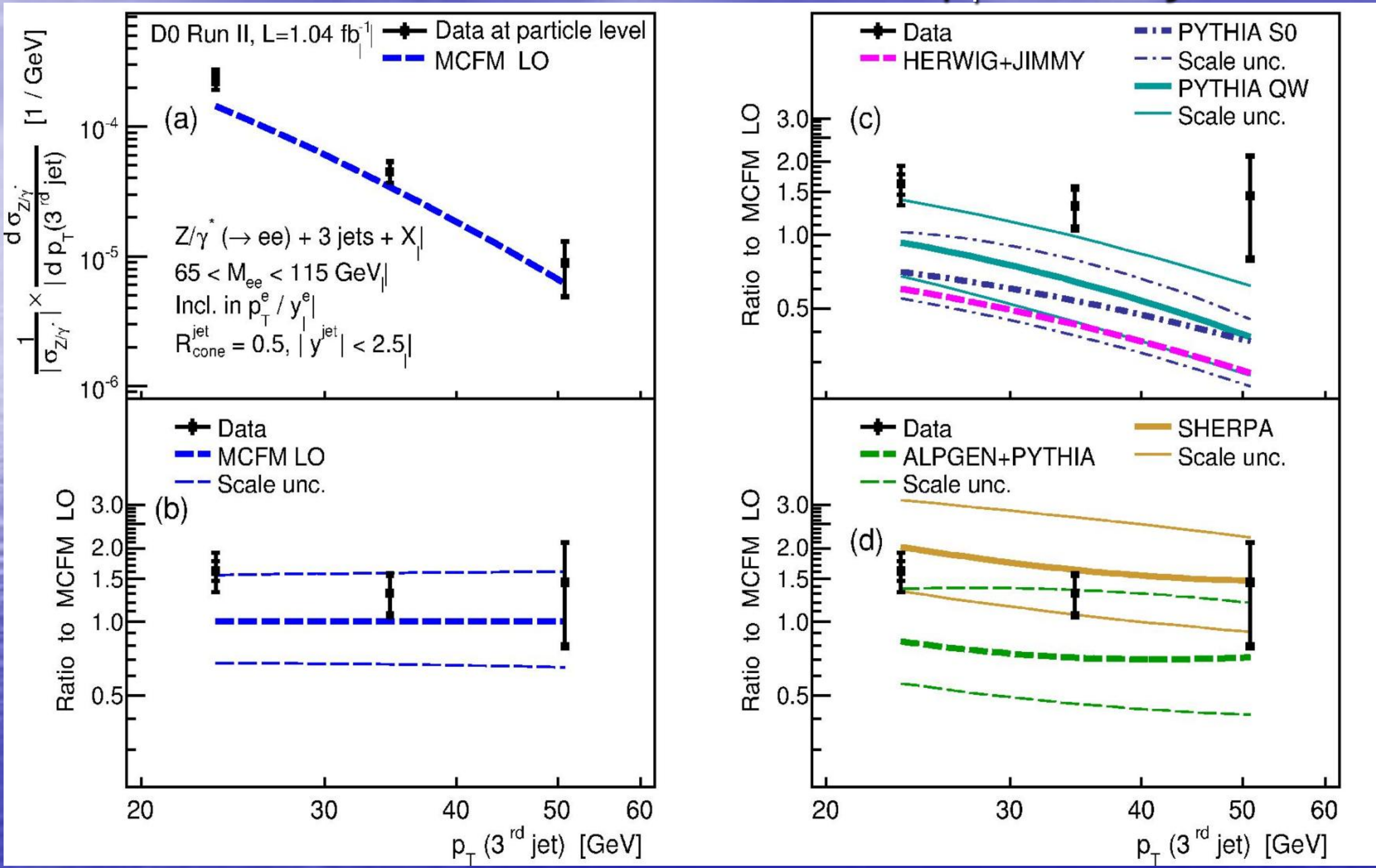
Normalized differential cross sections in p_T the 2[nd] jet



Data described well by MCFM NLO

$Z/\gamma^* \to e^+e^- + \geq 3$ Jets

Normalized differential cross sections in p_T the 3rd jet



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

Z/γ*+ Jet(s) Angular Correlations

PLB 682, 370 (2010)

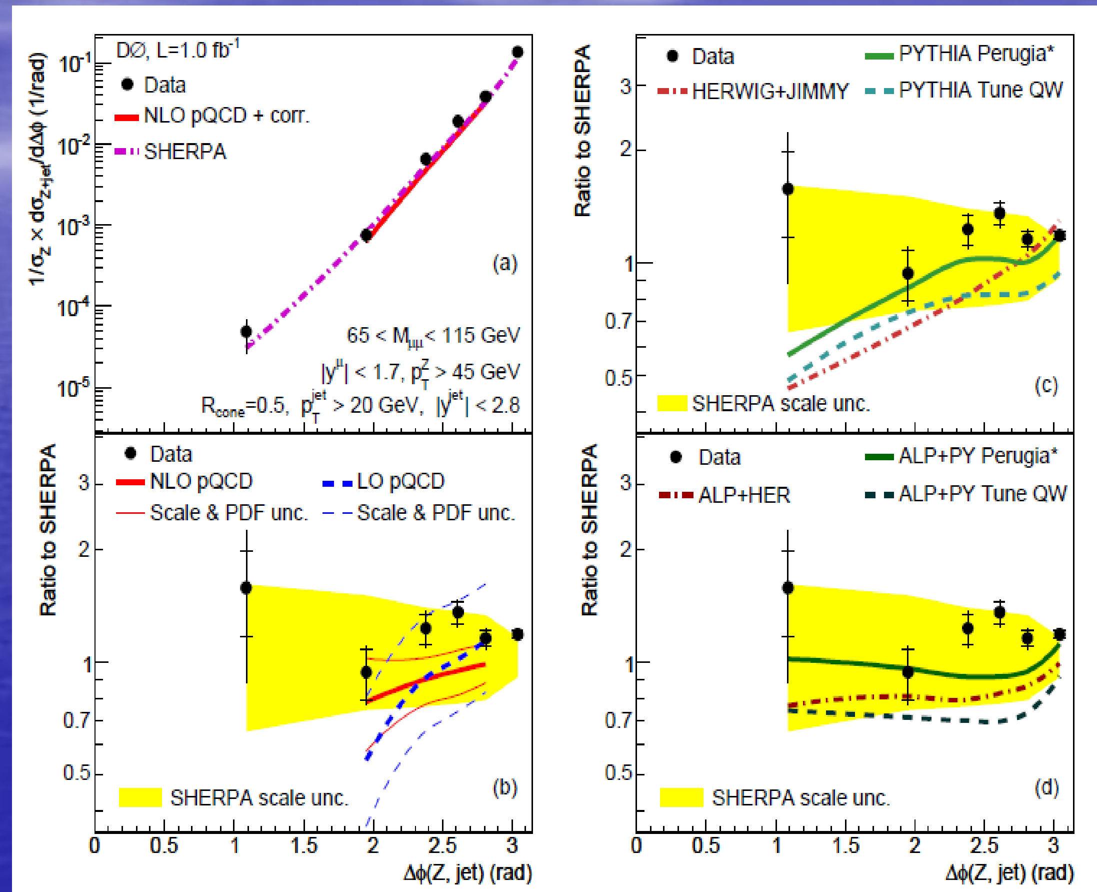
Z p_T > 45 GeV

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

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



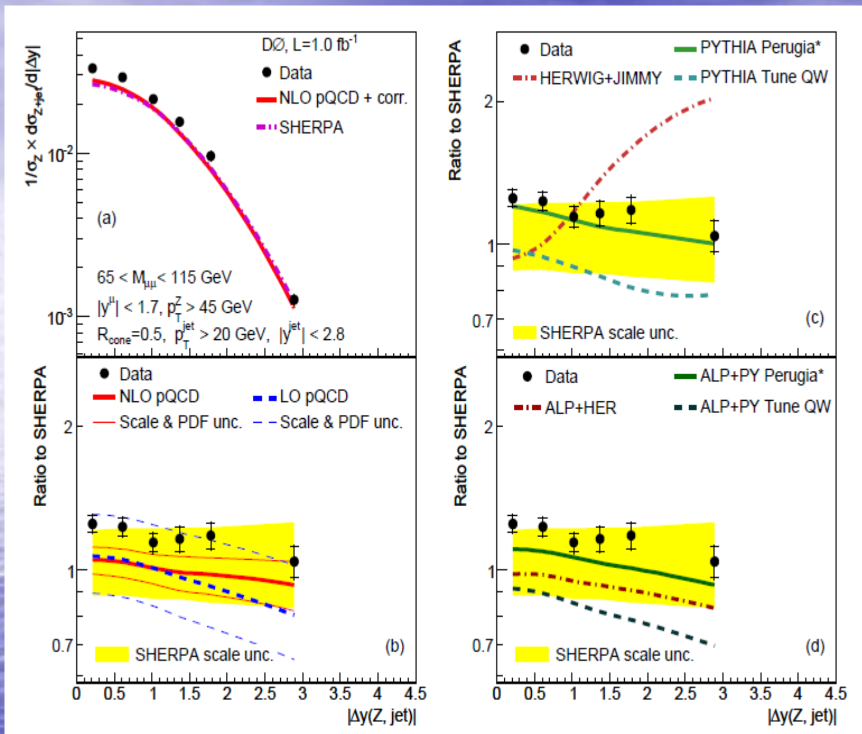
Event generators tend to have normalization and shape differences.

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.

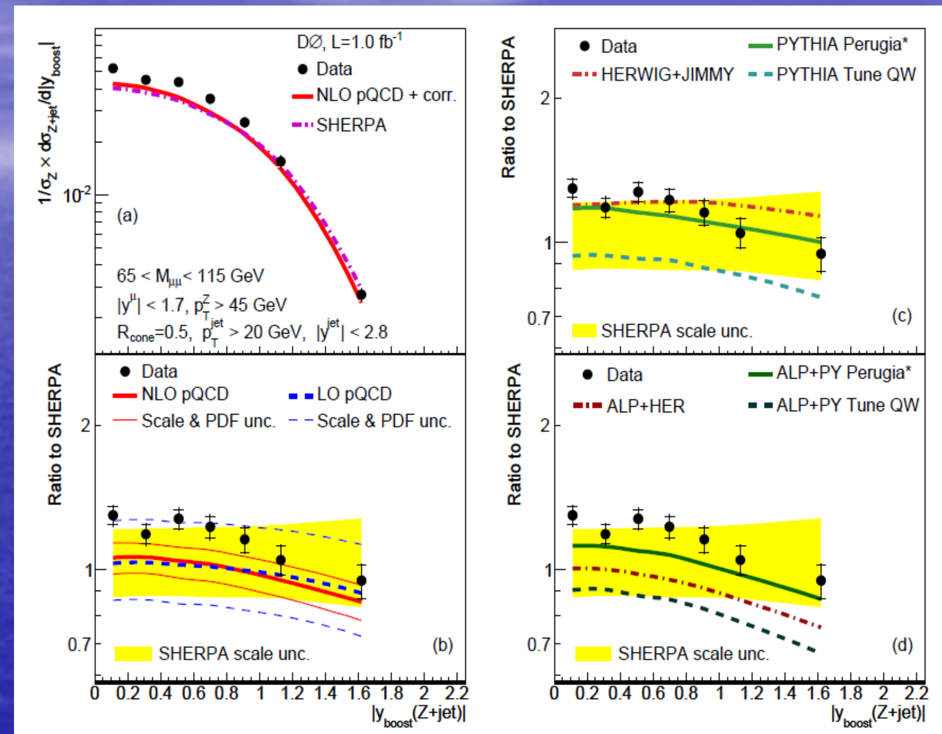
Z/γ*+ Jets Angular Variables

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

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

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

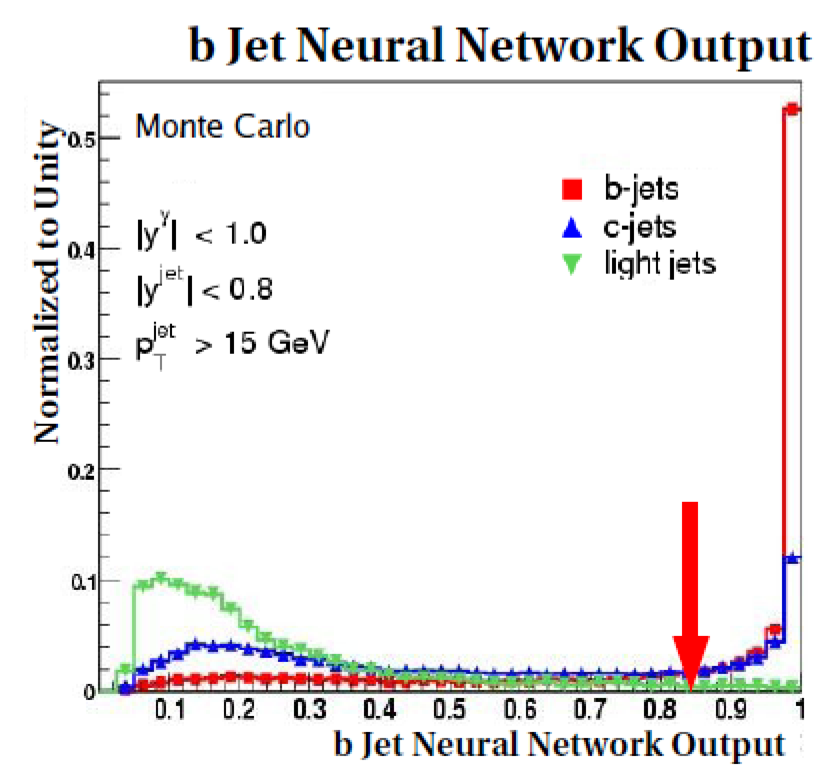
Z p_T > 45 GeV

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

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

Identifying Heavy Flavor Jets

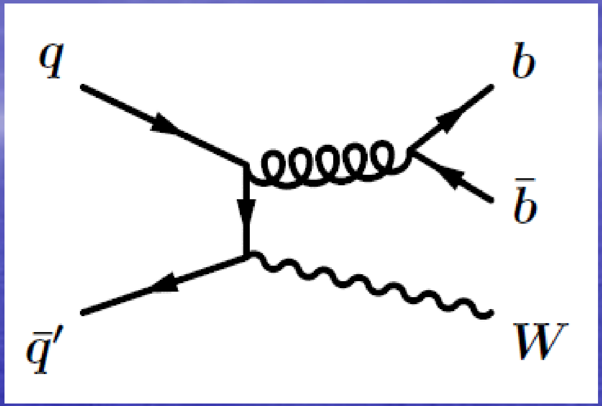
- Light jets have a much higher production rate than heavy flavor jets
  - ~100:1 light jets to b jets
  - ~10:1 light jets to c jets
  - ~10:1 c jets to b jets
- But, heavy flavor jets can be distinguished due to **the long lifetimes of their mesons**
  - Average meson lifetimes
    - ~1.5 x 10^{-12} 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



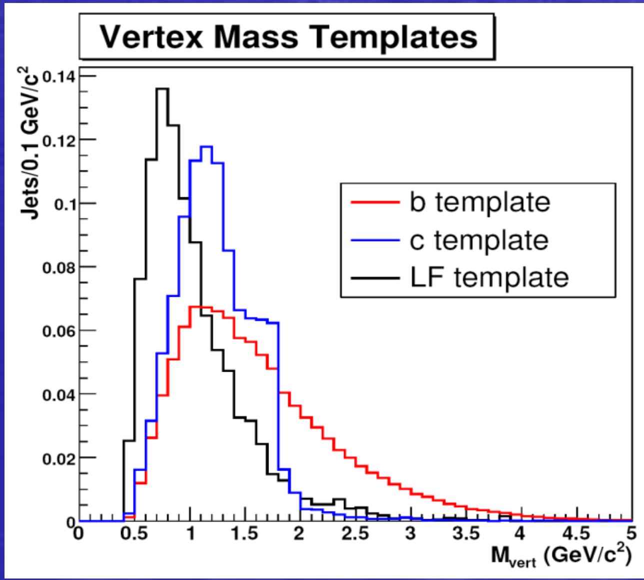
The inputs to the NN combine several characteristic quantities of the jet and associated tracks to provide a continuous output value between zero and one. The input variables are the number of reconstructed secondary vertices in the jet, the mass of the secondary vertex, the number of tracks used to 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.

W + b-jets Production

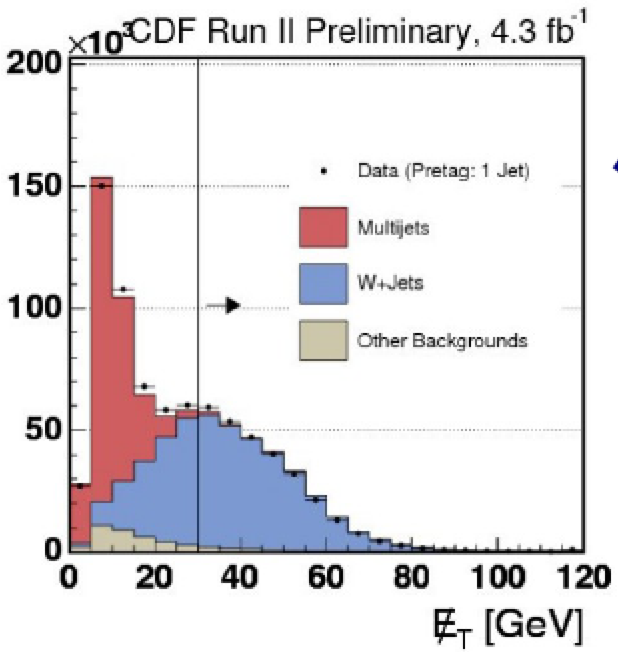
- $W \rightarrow l\nu$ ($l=e,\mu$) selection
  - $p_T>20$ GeV, $|\eta|<1.1$, $p_T^{\nu}>25$ GeV
- Jets : 1 or 2 in final state (too much top in 3rd jet bin)
  - $p_T>20$ GeV, $|\eta|<2.0$, R = 0.4
- Determine W+b fraction
  - SecVtx tagging to enrich sample with HF jets.
  - b-fraction obtained from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



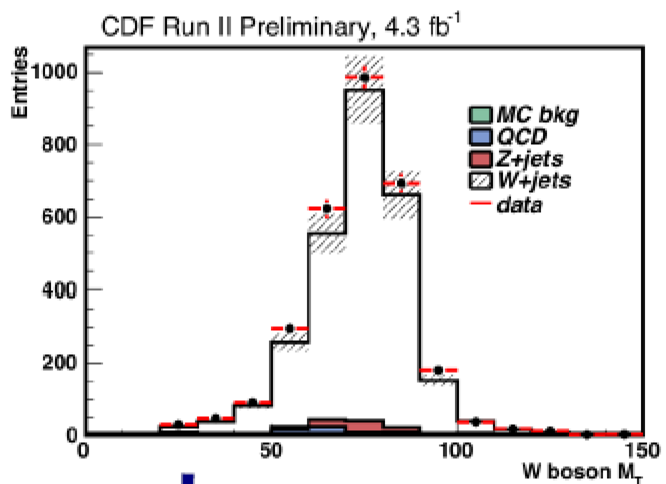
- Major backgrounds
  ttbar (40%)
  single top (30%)
  Fake W (15%)
  WZ (5%)



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

← $\frac{\text{Prediction}}{\text{Data}}$

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