Measurement of Cross Sections for W/Z/γ + b-jets and Inclusive b-jets Productions at the Tevatron

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Berkeley Workshop on Heavy Flavor Production at Hadron Colliders, Jan 14 – 16, 2013

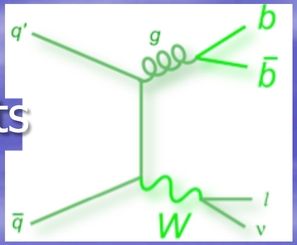
Outline

- Introduction
- Measurement Strategy
- W/Z + b-jet measurements
- Photon + b-jet measurements
- Incl. b-jet measurement
- Summary

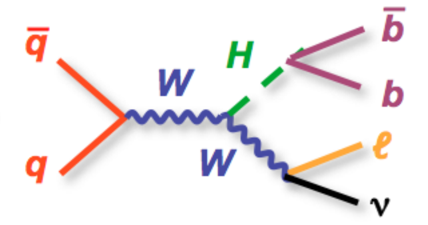
Motivation

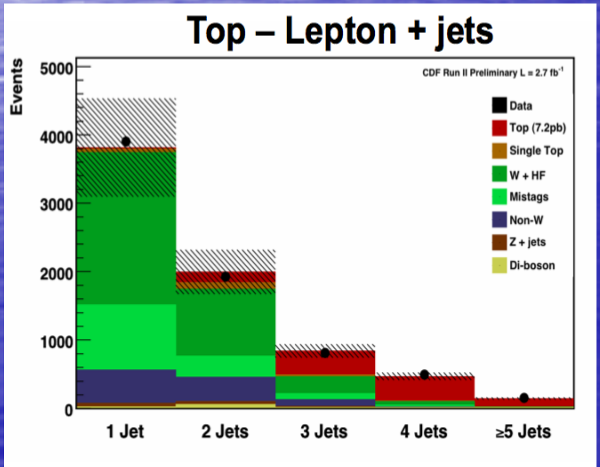
- Test of pQCD predictions at high Q^2
- Test of Monte carlo models
- Major background to various analyses and searches
  - -- Top quark properties
  - -- ZH(->bb), WH->bb)
  - -- BSM searches (e.g. sbottom)
  - (30-40% uncertainty in W/Z+HF processes)
- Sensitive to b-quark PDFs

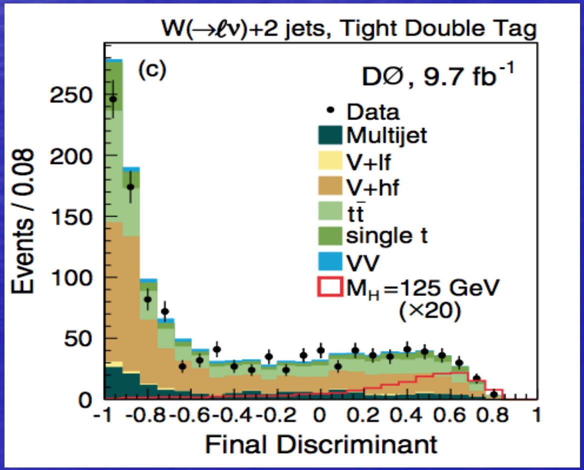
W + b-jets

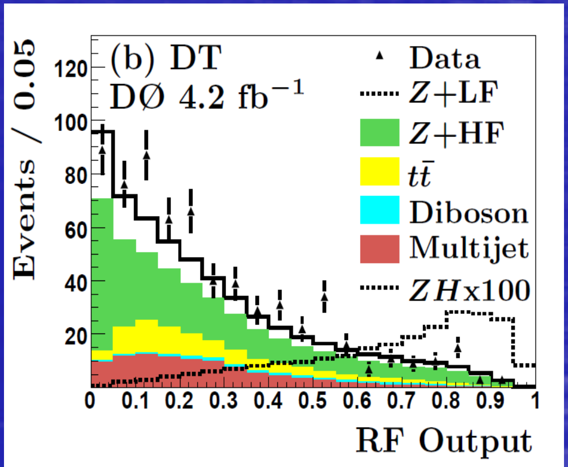


WH(->bb)





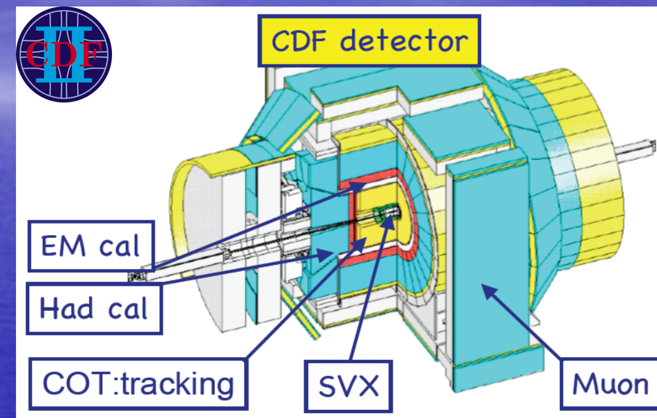


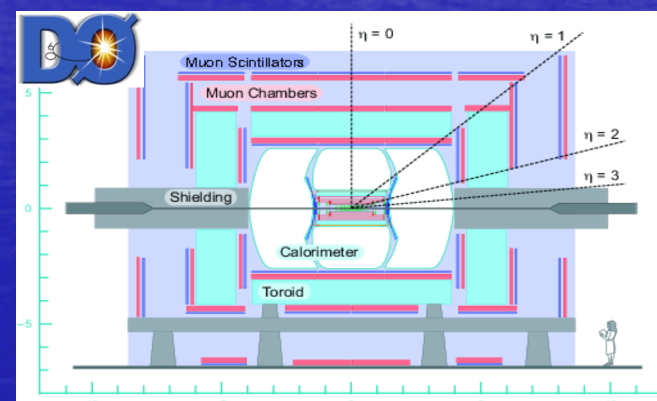


CDF & DØ Experiments

- $p\bar{p}$ collisions @ $\sqrt{s}$ = 1.96 TeV
- Excellent performance in Run II (March 2001 – Sept. 2011)
  - Delivered : 11.6 fb^{-1}
  - Recorded : 10.4 fb^{-1} per exp
- Latest results presented based on 6.2 – 9.7 fb^{-1}

Multi-purpose particle detectors





- Central tracking system
- Calorimeters
- Muon System

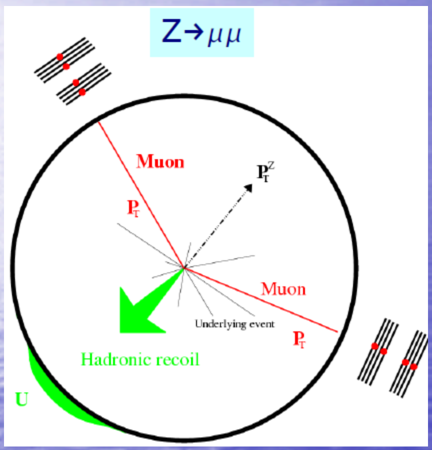
Tevatron Results

Z + b-jets	D0/9.7 fb^{-1}	hep-ex/1301.2233
	D0/4.2 fb^{-1}	PRD 83, 031105 (2011)
	D0/0.18 fb^{-1}	PRL 94, 161801 (2005)
	CDF/9.1 fb^{-1}	CDF Note 10594
	CDF/2.0 fb^{-1}	PRD 79, 052008 (2009)
	CDF/0.33 fb^{-1}	PRD 74, 032008 (2006)
W + b-jets	D0/6.2 fb^{-1}	hep-ex/1210.0627
	CDF/1.9 fb^{-1}	PRL 104, 131801 (2010)
γ + b-jets	D0/8.7 fb^{-1}	PLB 714, 32 (2012)
	D0/1.0 fb^{-1}	PLB 102, 192002 (2009)
	CDF/9.1 fb^{-1}	CDF Note 10818
	CDF/2.0 fb^{-1}	PRD 81, 052006 (2010)
Incl. b-jets	CDF/0.3 fb^{-1}	CDF Note 8418

Full set of results can be found on:

- http://www-d0.fnal.gov/Run2Physics/WWW/results/qcd.htm
- http://www-cdf.fnal.gov/physics/new/qcd/QCD.html

W/Z/γ + Jet Event Reconstruction

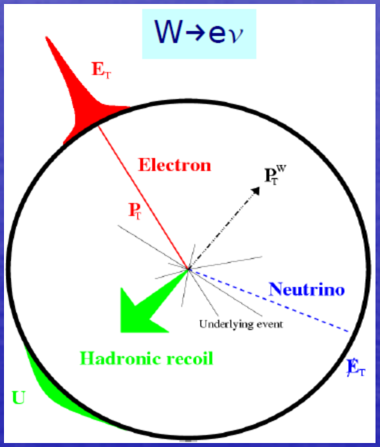


Clean signature with relatively low backgrounds – clean environment for the QCD measurements

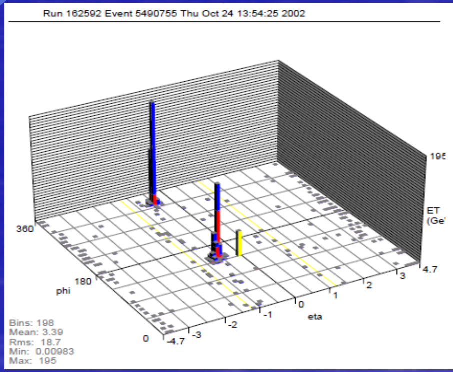
Z - two high p_T electrons or muons
- clean signal
- BG : fake leptons, semi-leptonic decays, di-boson production

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

γ - isolated EM cluster not matched to a track, significant background from jet mis-identication

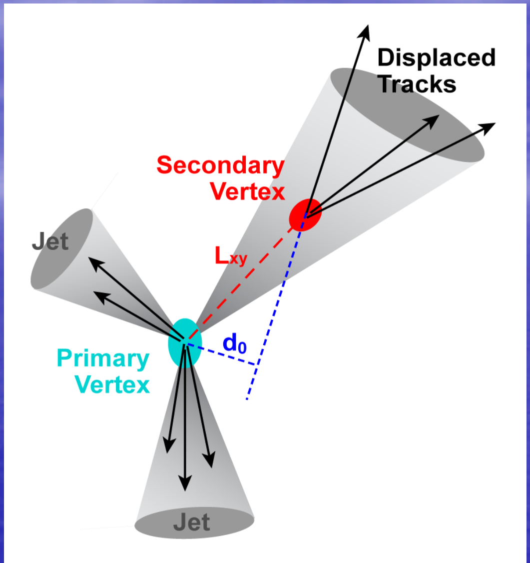


- Jets are reconstructed using midpoint cone algorithm – use calorimeter towers as seeds.
- Jets are fully corrected for the instrumental effects.

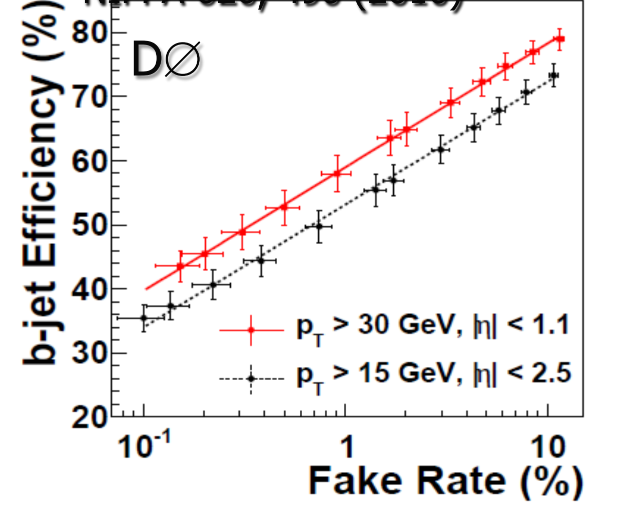


Identifying b-jets

- Long lifetime (~1.5 ps), $c\tau$ = 450 μm
  Large hadron mass – large IP of tracks
- b-tagging technique exploits longer lifetime of b-hadrons
- CDF uses secondary vertex tagger which is based on reconstruction of secondary vertex (SV) from displaced charged particle tracks (not coming from primary vertex) inside the jet
- D0 uses MVA based discriminant designed from combination of variables sensitive to presence of displaced tracks forming SV
  - Number of SV,
  - Invariant mass of tracks $\in$ SV
  - No. of tracks used to reconstruct SV
  - 2D decay length significance of SV
  - Weighted combination of transverse IP significances
  - Probability of jet tracks to originate from PV



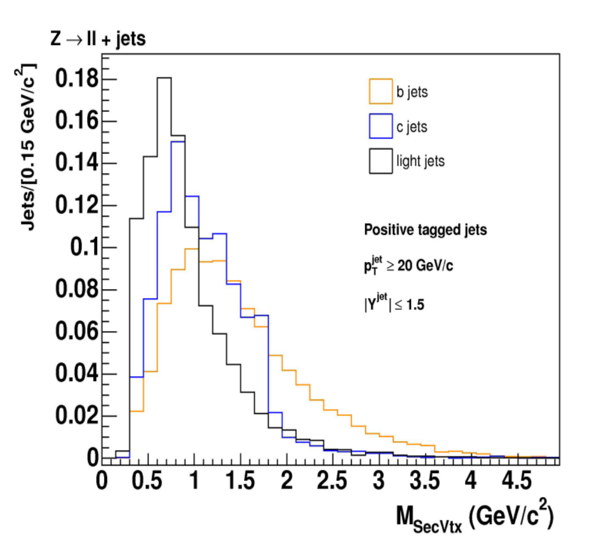
NIM A 620, 490 (2010)

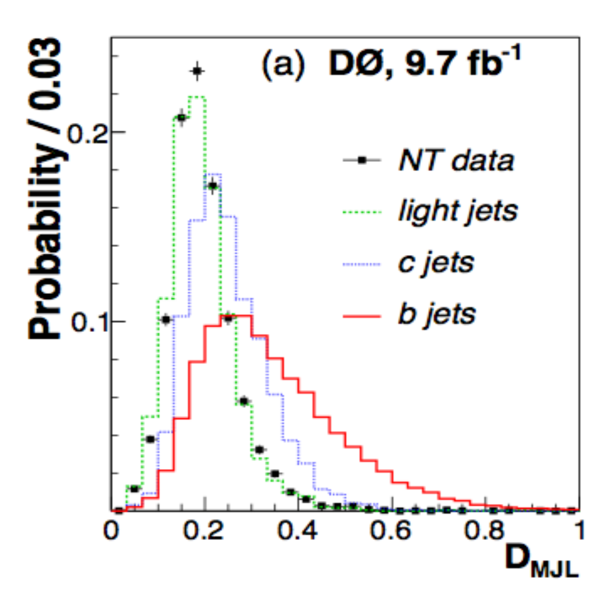


Measurement Strategy

- Select of V + jet candidates
- Two-step procedure for the determination of b-jet fraction
- Require ≥1 b-tagged jet to enrich sample with heavy flavors
- Extract the b-jet fraction in the tagged sample by template fit with a discriminant which distinguishes b-jets from charm and light jets
- M_{SecVtx} – invariant mass of all charged tracks attached with the Sec. Vtx. On average b-jets have larger values due to larger mass of b hadrons
- D_{MJL} – combination of M_{SecVtx} and jet lifetime impact parameter probability (JLIP) which measures overall probability of jet tracks to originate from primary vertex.

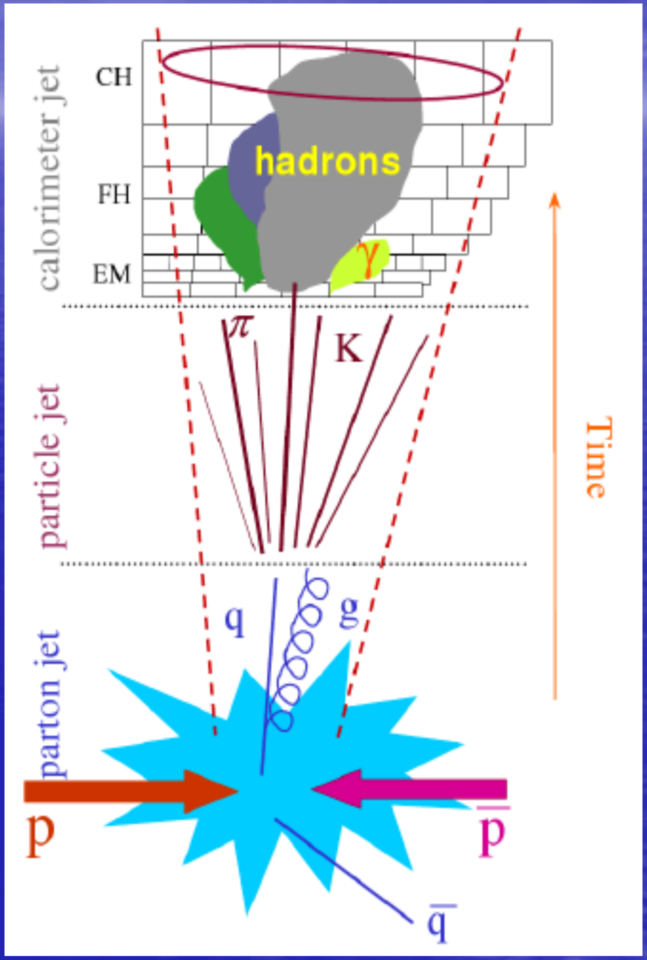
$$D_{\mathrm{MJL}} = 0.5 \times (M_{\mathrm{SV}}/5\ \mathrm{GeV} - \ln(\mathrm{JLIP})/20)$$





Comparison with Theory

- 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.



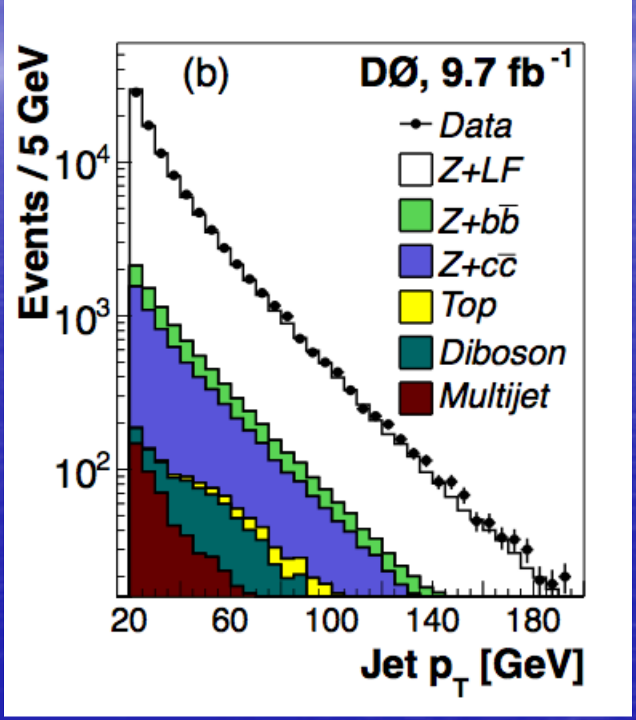
W/Z + b-jet measurements

hep-ex/1301.2233

Z + b-jets

$L = 9.7 fb^{-1}$

- Measurement of $\sigma(Z+b)/\sigma(Z+jet)$: cancellation of many systematic uncertainties
- Use full data set : $9.7\ fb^{-1}$
- Consider both e and μ channels
  $70 < M_{ll} < 110$ GeV
- Jets : R=0.5, p_T>20 GeV, |y|<2.5
- MET>60 GeV to suppress ttbar



Backgrounds
- Diboson and ttbar processes – determined from MC simulation and theory predictions
- Fake lepton : estimated from data using control samples

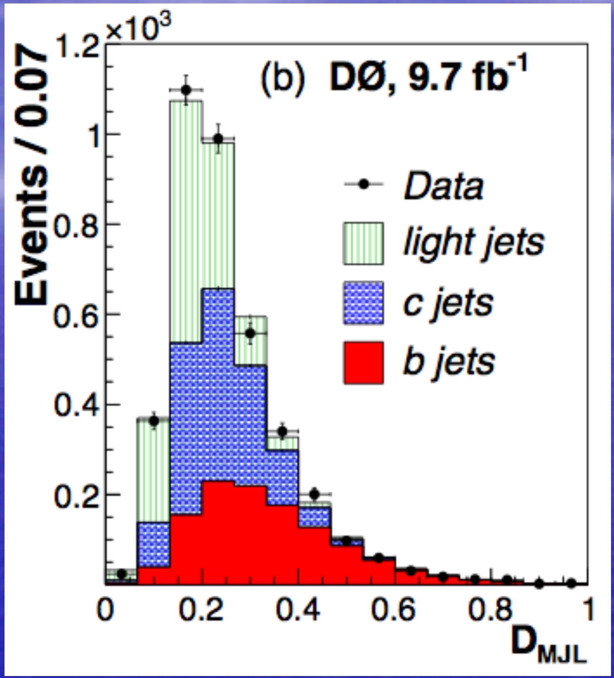
Z + b-jets

L = 9.7 fb^{-1}

b-jet identification

- Select Z events with ≥1 b-tagged jet
- Fit with the MJL discriminant templates of jet flavors to extract the Z+b-jet fraction. Non-Z+jet backgrounds are subtracted from data prior to the fit.

$$\frac{\sigma(Z+b\text{ jet})}{\sigma(Z+\text{jet})} = \frac{N\,f_b}{N_{\text{incl}}\,\epsilon^b_{tag}} \times \frac{\mathcal{A}_{\text{incl}}}{\mathcal{A}_b}$$



Data – Bgd = 3800 events
f_b = 0.30+/- 0.02

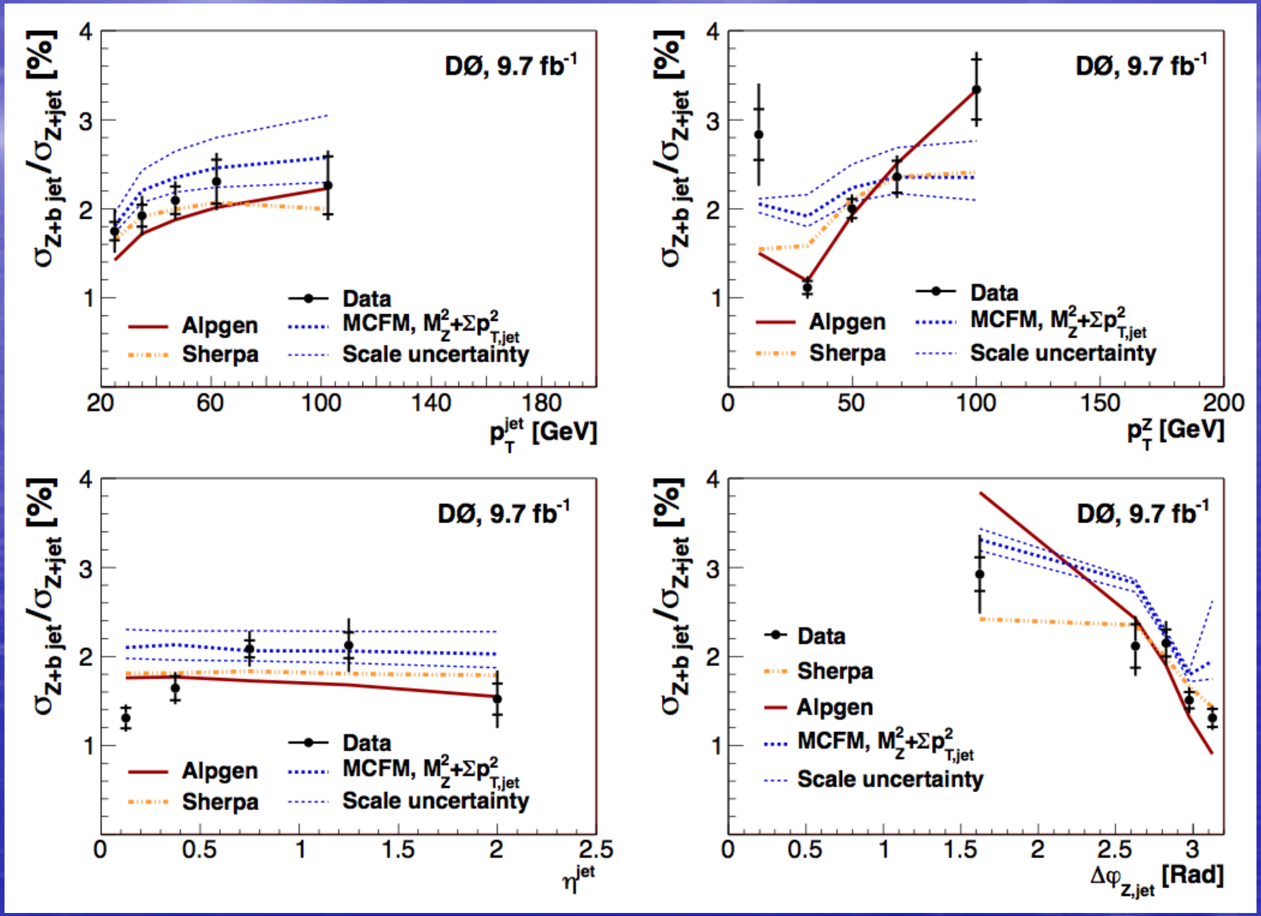
- σ(Z+b) /σ(Z+jet) = 2.02±0.14(stat.)±0.18 (syst.) %
- MCFM predictions, MSTW2008 PDFs 2.06% ($Q^2 = M_Z^2+\sum(p_T^{\text{jet}})^2$)
- Good agreement with MCFM prediction and consistent with previous measurements

Major systematic uncertainty from template shape, b-tagging efficiency and Jet energy scale

Z + b-jets

$L = 9.7 fb^{-1}$

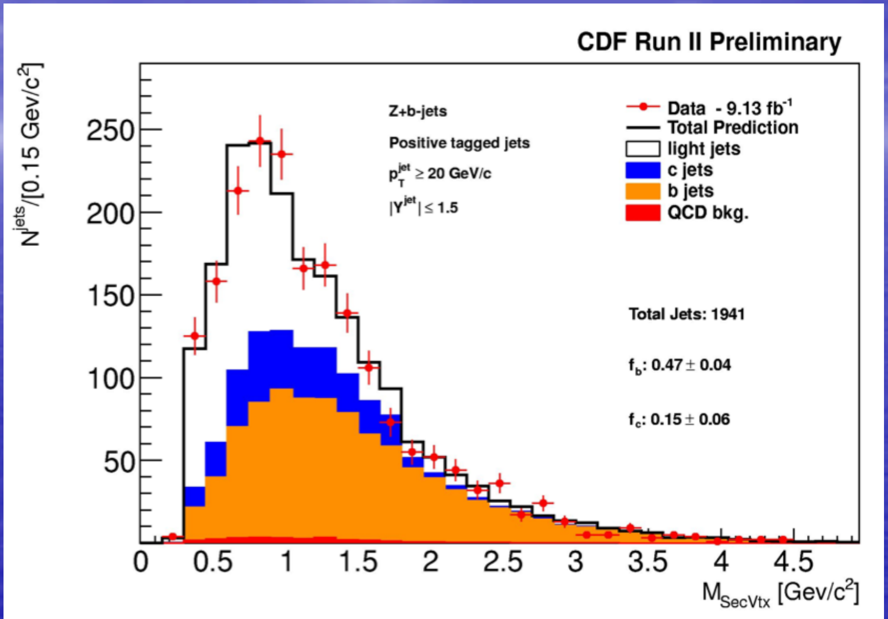
- Enlarged data sample allows measurement of the ratio σ(Z+b)/σ(Z+jet) differentially in bins of various kinematic Variables
- Measurements compared with predictions from NLO and MCs
- Except for jet p_T, none of the predictions fully describe the examined distributions.



Z + b-jets

$L = 9\ fb^{-1}$

- Measurement of $\sigma(Z+b)/\sigma(Z)$ and $\sigma(Z+b)/\sigma(Z+jet)$: many syst. uncert. cancel
- Use full data set and improved lepton identification
- $Z \rightarrow ee/\mu\mu$, $66<M_{ll}<116$ GeV
- Jets : R=0.7, $p_T>20$ GeV, $|y|<1.5$
- b-jet identification
  - Secondary Vertex tagger
  - Extract b composition from a fit to Sec Vtx Mass.



$$\frac{\sigma_{Z\_bjet}}{\sigma_Z} = 0.261 \pm 0.023^{stat} \pm 0.029^{syst}\%$$

$$\frac{\sigma_{Z\_bjet}}{\sigma_{Zjet}} = 2.08 \pm 0.18^{stat} \pm 0.27^{syst}\%$$

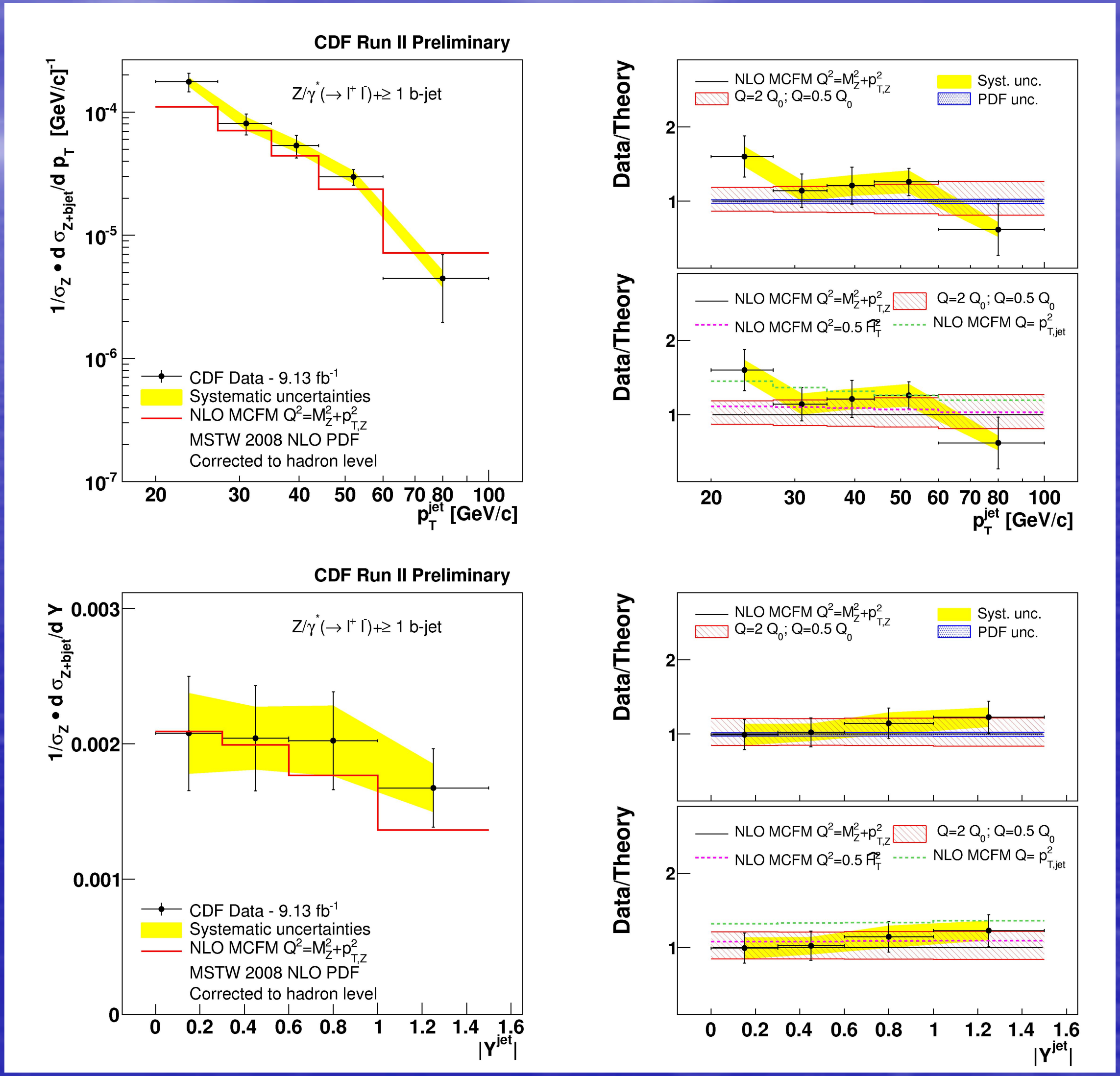
	$Q^2 = m_Z^2 + p_{T,Z}^2$	$Q^2 =< p_{T,jet}^2 >$
$\frac{\sigma_{Z\_bjet}}{\sigma_Z}$	0.23 %	0.29 %
$\frac{\sigma_{Z\_bjet}}{\sigma_{Zjet}}$	1.8 %	2.2%

- Results in agreement NLO calculation
- Main systematic uncertainty due to vertex mass template modeling
- Other sources : b-tagging efficiency, Jet energy scale, backgrounds etc.

Z + b-jets

L = 9 fb^{-1}

- Measure $\sigma(Z+b)/\sigma(Z)$ differentially in bins of jet p_T and rapidity
- Results statistically limited
- Compared with MCFM calculations with different scales and PDFs
- Good agreement with the predictions within uncertainties

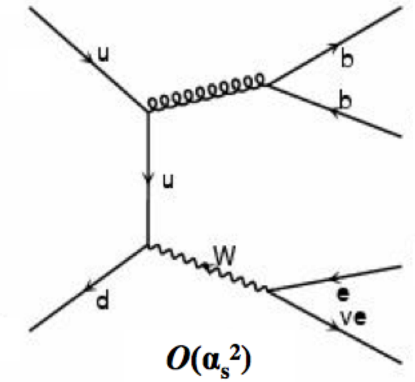


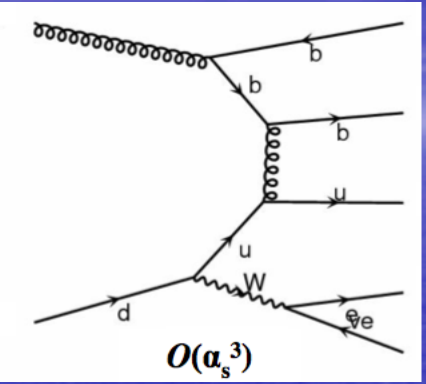
hep-ex/1210.0627

W + b-jets

$L = 6.2\ fb^{-1}$

- Measurement of W+b-jet cross section using 6.2 fb^{-1} of data
- Final states with W➔eν/μν
- Kinematic phase space
  $p_T^{e/\mu} > 20$ GeV, $p_T^{\nu} > 25$ GeV,
  $|\eta^{\mu}| < 1.7$
  $|\eta^{e}| < 1.1$ or $1.5 < |\eta^{e}| < 2.5$
- Jets (R=0.5): at least one jet
  $p_T > 20$ GeV, $|\eta| < 1.1$

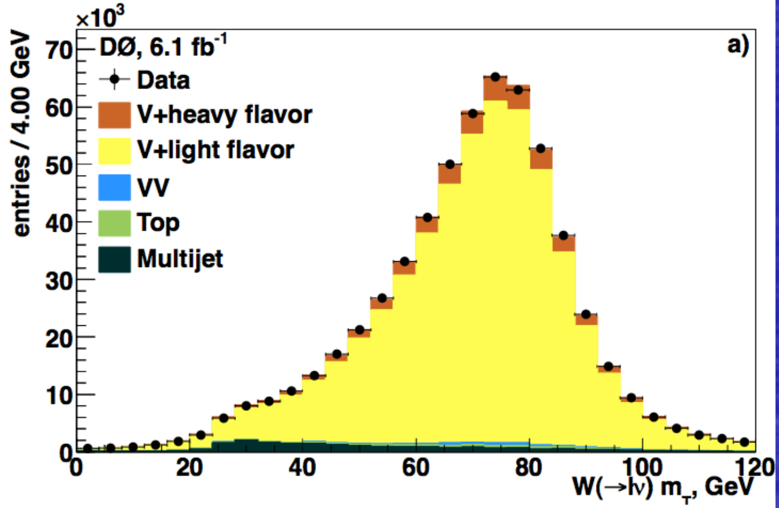




Major Backgrounds

- Single Top, Top pair and diboson production: estimated using simulation and theory calculations
- Multijets: estimated from data. Cut on W transverse mass to suppress MJ bgd.

$$40\ \text{GeV} + \tfrac{1}{2}\not{E}_T < M_T < 120\ \text{GeV}$$

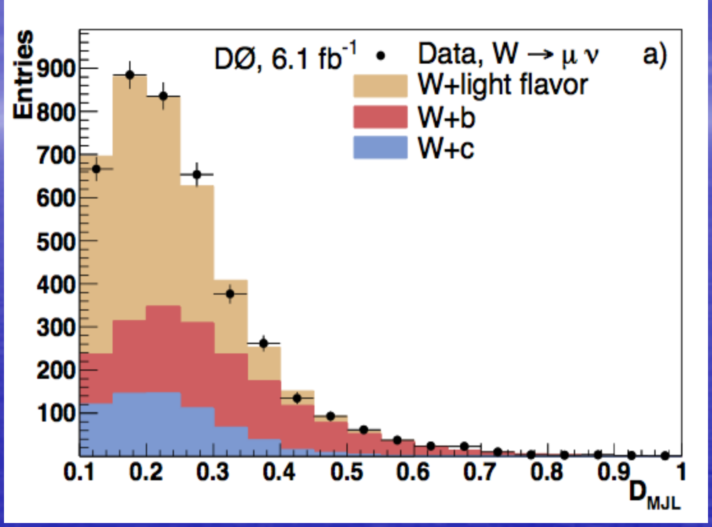


W + b-jets

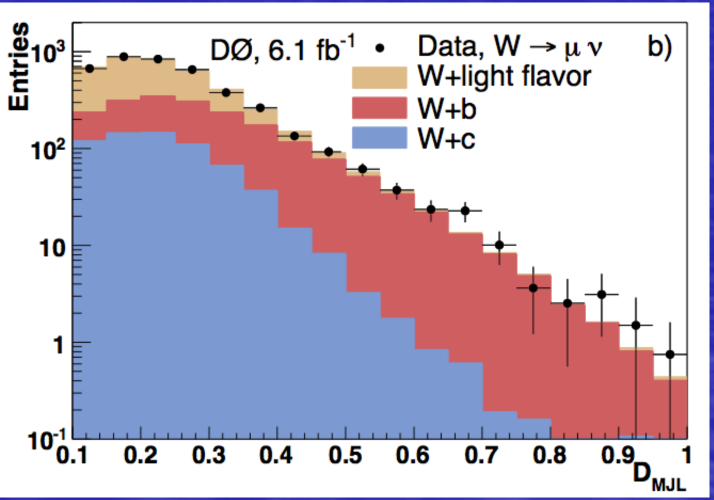
L = 6.2 fb^{-1}

b-jet fraction

- Select W candidates with ≥1 b-tagged jet to enrich sample with heavy flavors
- Use MJL discriminant (based on M_{SVT} and jet lifetime probability) to distinguish b-jets from c- and light jets
- Fit Data – Bkgd with templates of discriminant to extract W+b-jet fraction



	$W \to \mu\nu$		$W \to e\nu$	
Process	Events	Fraction	Events	Fraction
$W + b$	1306 ± 166	0.3 ± 0.04	1676 ± 212	0.27 ± 0.03
$W + c$	664 ± 97	0.1 ± 0.02	1096 ± 159	0.18 ± 0.03
$W +$ l.f.	2152 ± 265	0.5 ± 0.07	3479 ± 425	0.56 ± 0.07
Data−Bkgd	4127 ± 150		6255 ± 168	



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W + b-jets

L = 6.2 fb^{-1}

$$\sigma(W+b)\cdot\mathcal{B}(W\to\ell\nu)=\frac{N_{W+b}}{\mathcal{L}\cdot\mathcal{A}\cdot\epsilon}$$

W→eν

$$1.00 \pm 0.04\,(\text{stat.}) \pm 0.12\,(\text{syst.})\ \text{pb}$$

$$1.28\ ^{+0.40}_{-0.33}\ (\text{scale})\ \pm 0.06\ (\text{PDF})\ ^{+0.09}_{-0.05}\ (m_b)\ \text{pb}$$

W→μν

$$1.04 \pm 0.05\,(\text{stat.}) \pm 0.12\,(\text{syst.})\ \text{pb}$$

$$1.34\ ^{+0.40}_{-0.33}\ (\text{scale})\ \pm 0.06\ (\text{PDF})\ ^{+0.09}_{-0.05}\ (m_b)\ \text{pb}$$

MCFM predictions with CTEQ6M PDFs and scale of M_W+2m_b

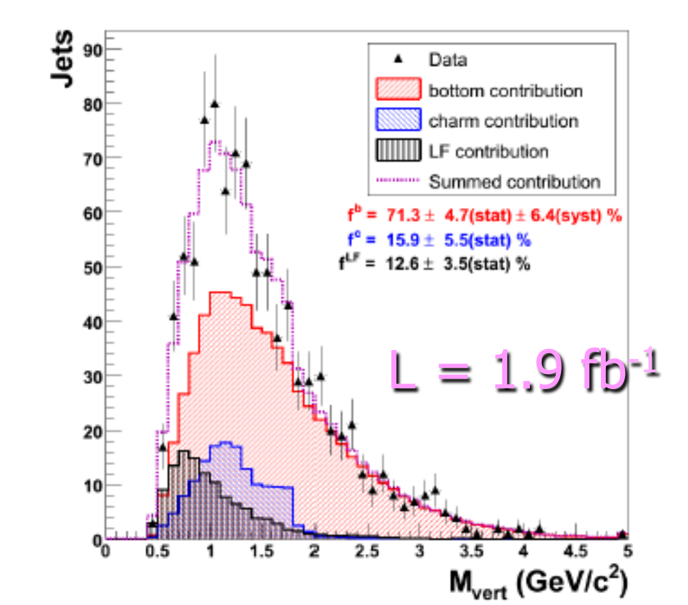
Results in agreement with NLO calculations

Major systematic uncertainties include template shape, luminosity, b-tagging, Jet energy scale and estimation of backgrounds

PRL 104, 131801 (2010)

W + b jets

- First measurement of the W+b-jet cross section
- $W \rightarrow l\nu$ ($l=e,\mu$) selection
  $p_T>20$ GeV, $|\eta|<1.1$, $p_T^{\nu}>25$ GeV
- Jets : 1 or 2 in final state
  R = 0.4, $p_T>20$ GeV, $|\eta|<1.5$
- ≥1 b-tagged jet, SecVtx algorithm
- Determine W+b fraction from fit to Vertex Mass distribution M_{vert}



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

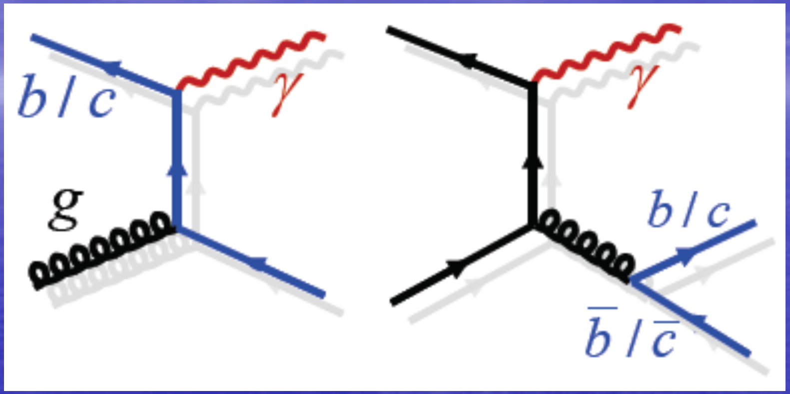
- Measurement
  σxBR = 2.74 ± 0.27± 0.42 pb
- Prediction
  NLO : 1.22 ± 0.14 pb
  (Campbell, Cordero, Reina)
  Pythia : 1.10 pb, Alpgen : 0.78 pb

→Measurement substantially higher

γ + b-jet measurements

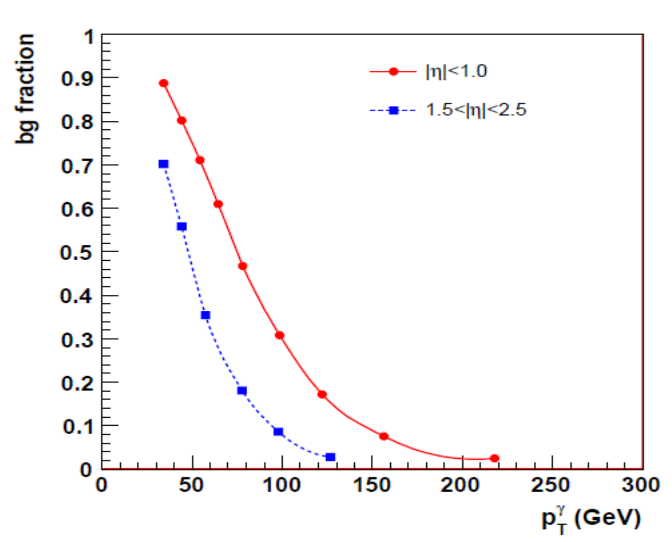
Photon + b-jets

- Produced predominantly through Compton scattering $gQ \rightarrow \gamma Q$ at low p_T^γ and through quark-antiquark annihilation with gluon splitting to heavy quarks $qq \rightarrow \gamma QQ$ at higher p_T^γ
  - ➢ Sensitive to b/c quark PDFs and rate of gluon splitting which have substantial uncertainties



- Additional LO+NLO diagrams from fragmentation are mostly suppressed by the photon isolation requirement

- Two background sources
  - ➢ Significant background from jet misidentified as a photon
  - ➢ Light flavor jets faking heavy flavor jets



PLB 714, 32 (2012)

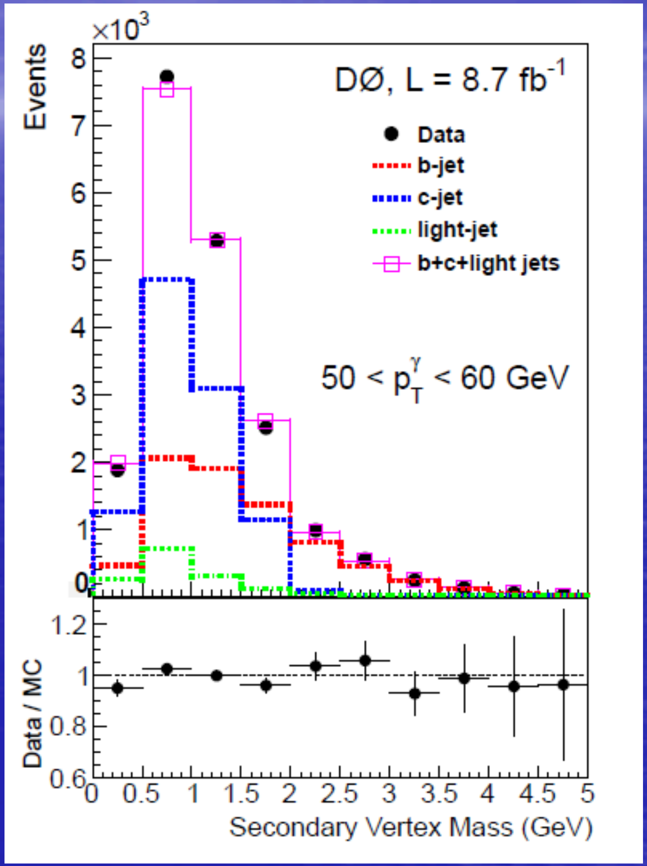
γ + b jets Cross Sections

L = 8.7 fb^{-1}

Measurements in extended kinematic region
$30 < p_T^\gamma < 300$ GeV @ $|y^\gamma| < 1.0$
$30 < p_T^\gamma < 200$ GeV @ $1.5 < |y^\gamma| < 2.5$

Probe the extended phase space x-Q^2
$9E+2 < Q^2 < 9E+4$, $0.01 < x < 0.4$ ($|y^\gamma| < 1.0$)
$9E+2 < Q^2 < 4E+4$, $0.007 < x < 0.4$ ($1.5 < |y^\gamma| < 2.5$)

- Select γ+jet events with $p_T^{jet} > 15$ GeV and $|y^{jet}| < 1.5$
- Enrich the sample with heavy flavor jets using tighter b-tagging requirement : select $\gamma + \geq 1$ b-tagged jet
- Determine faction of b-jets by fitting secondary vertex mass templates which provides discrimination of b-jets from its counterparts .



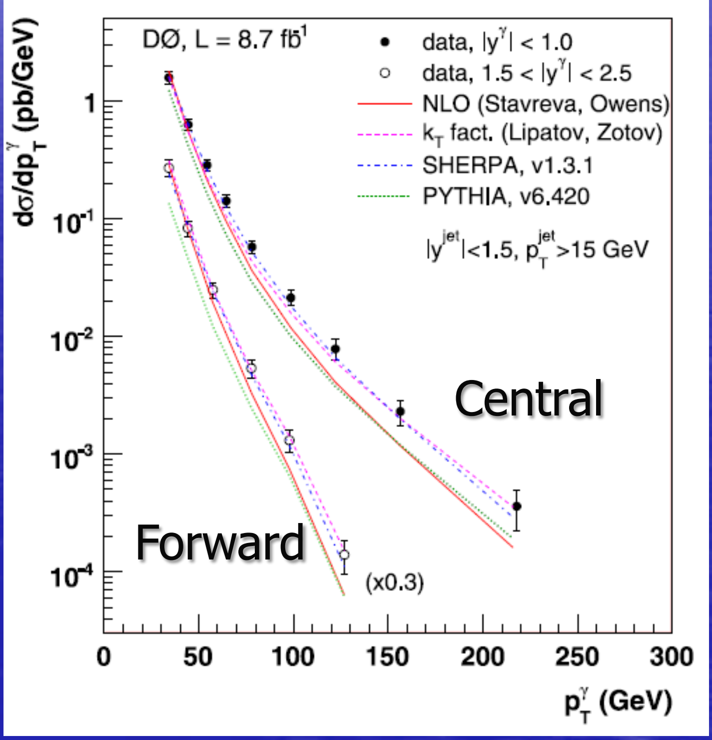
γ + b-jets Cross Sections

L = 8.7 fb^{-1}

$$\frac{d\sigma}{dp_T^\gamma} = \frac{N_{evt} \times f_\gamma \times f_b}{A \times \varepsilon \times L \times \Delta p_T^\gamma}$$

PLB 714, 32 (2012)

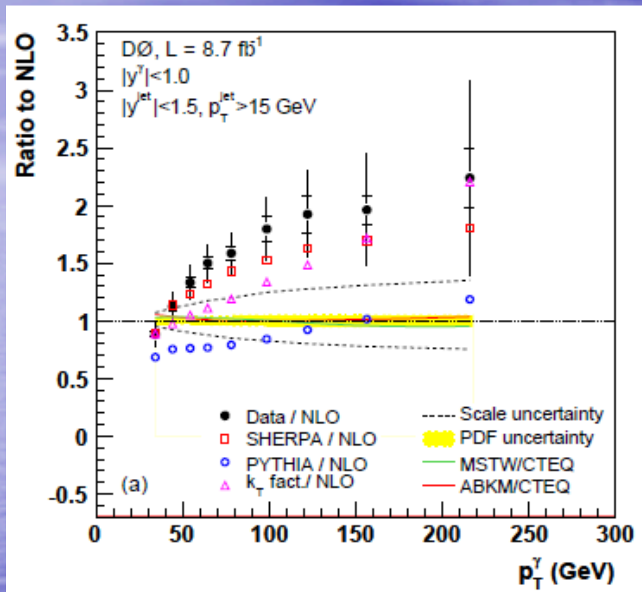
- Comparison with theory predictions
  - NLO, $\mu_{R,F,f} = p_T^\gamma$, CTEQ6.6M PDFs
  - Pythia : 2->2 MEs with gb->γb & qq->γg, with g->bb splitting in PS
  - SHERPA : Allows up to two extra hard partons in MEs in addition to b-quark. Accounts for further emissions via consistent combination with PS
  - k_T-factorization approach: Additional contributions to cross sections due to integ. over k_T^2 region, which accounts for diagrams with extra soft gluon radiation.

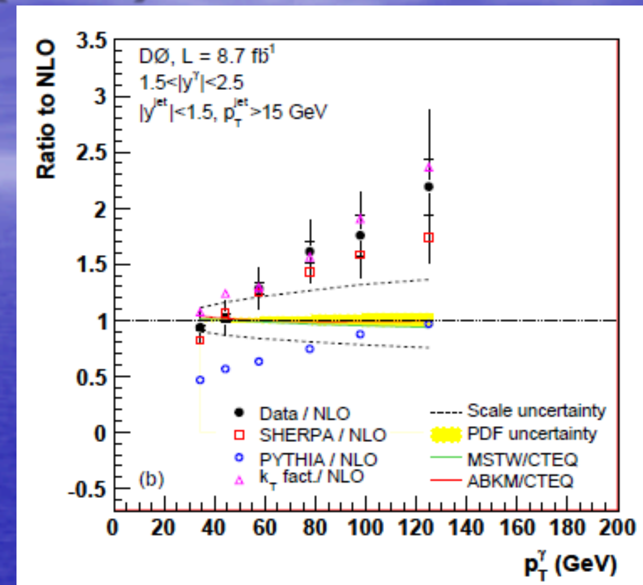


γ + b-jets Cross Sections

PLB 714, 32 (2012)

L = 8.7 fb^{-1}



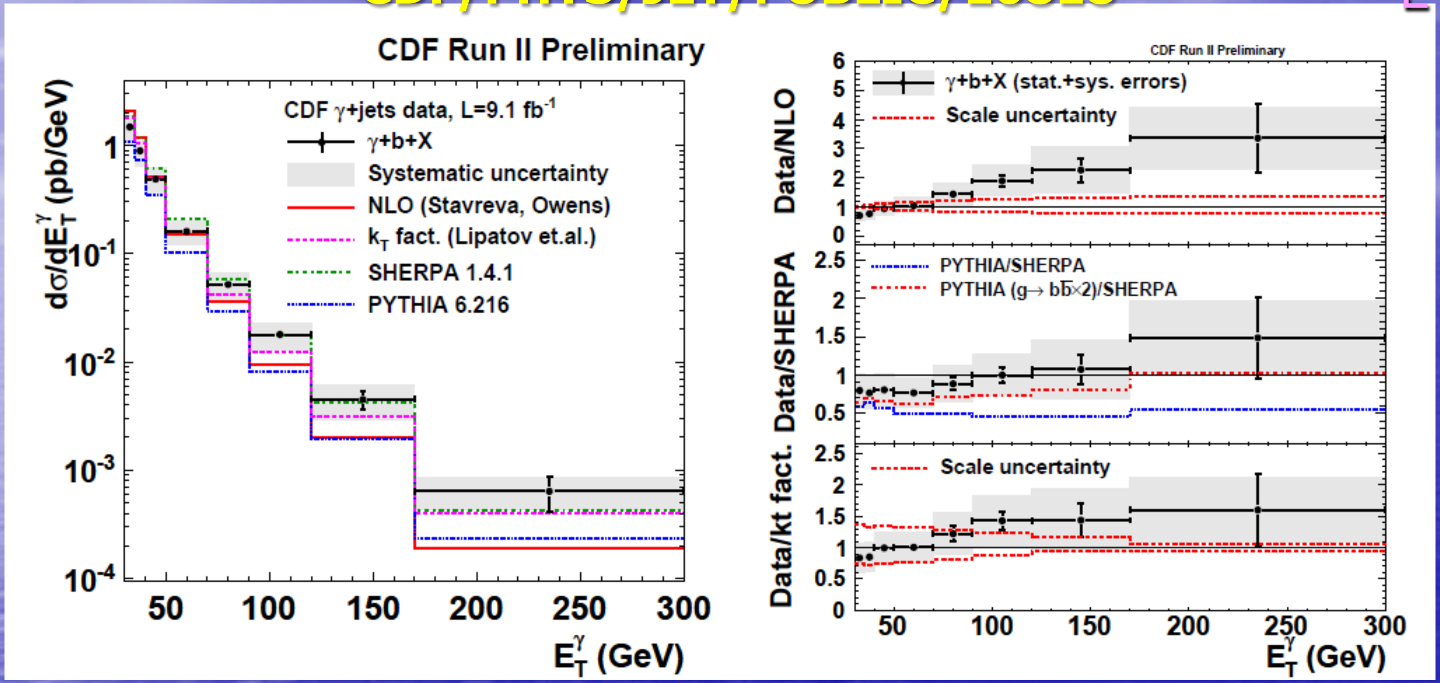


- NLO describes data within uncertainties at low p_T^{γ} <70 GeV
- Disagreements at higher p_T^{γ} : slopes differ for both central and forward photons
  - Need for higher order corrections at large p_T^{γ} dominated by annihilation process, and resummation of diagrams with additional gluon radiation.
- SHERPA and k_T-factorization approach provide better description

γ + b-jets Cross Sections

CDF/PHYS/JET/PUBLIC/10818

L = 9.1 fb^{-1}



- CDF's measurement in similar phase space, only for central photons
- NLO fails to describe data for E_T^{γ} >70 GeV
  - Need for higher order corrections at large p_T^{γ}
- Sherpa and k_T-factorization predictions describe data much better within theoretical and experimental uncertainties
- Pythia underestimates data in the entire kinematic region. Predictions with double the rate of g→bb agree better

Inclusive b-jet Cross Section measurement

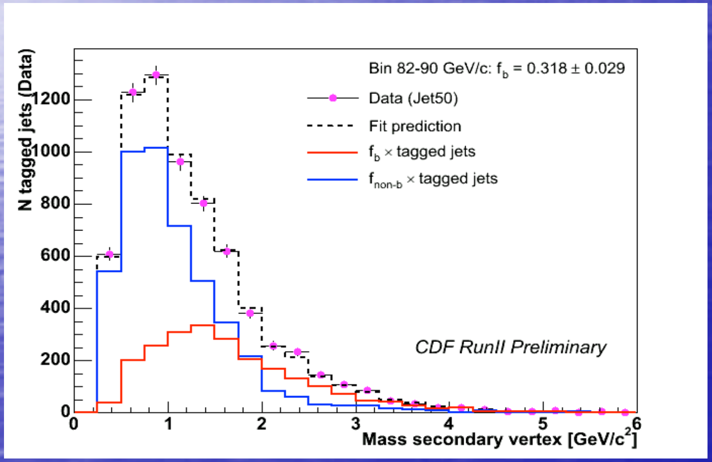
Inclusive b-jets Production

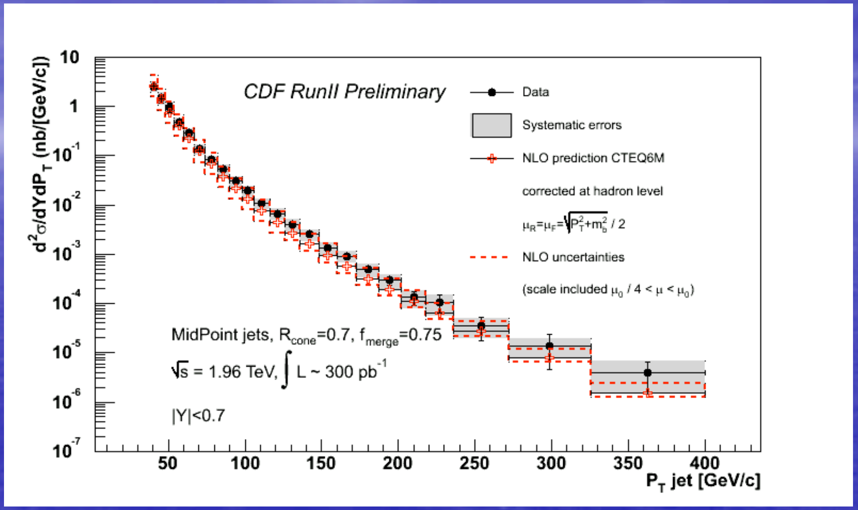
L = 300 pb^{-1}

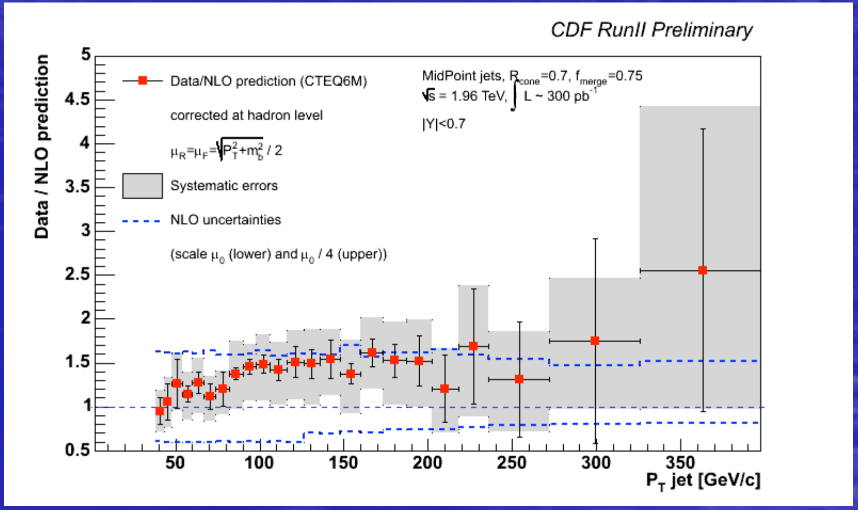
- ❑ Phase space

38<p_T <400 GeV, |y|<0.7

- ❑ Selection of b-tagged jets
- ❑ Extraction of b-jet fraction in each bin by maximum likelihood fit of the secondary vertex mass







- ❑ Results agree with NLO predictions within uncertainties
- ❑ Big scale uncertainties suggest the the importance of higher order calculations

Summary & Outlook

- Many interesting precise measurements focusing on vector boson + heavy 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 the study of Higgs and NP searches
- More results with better statistics will become available soon.

http://www-cdf.fnal.gov/physics/new/qcd/QCD.html

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

TABLE I: Results for the ratio $\sigma(Z + b\text{ jet})/\sigma(Z + \text{jet})$ in bins of p_T^{jet}, p_T^Z, η^{jet}, and $\Delta\varphi_{Z,\text{jet}}$. Bin centers, shown in parentheses, are chosen using the prescription found in Ref. [24].

p_T^{jet} [GeV]	N	$\frac{\sigma(Z+b\text{ jet})}{\sigma(Z+\text{jet})}$	Statistical Uncertainty	Systematic Uncertainty
20 – 30 (25)	1317	0.0175	0.0010	0.0022
30 – 40 (35)	858	0.0192	0.0012	0.0019
40 – 55 (47)	712	0.0210	0.0016	0.0015
55 – 70 (62)	369	0.0231	0.0025	0.0021
70 – 200 (102)	535	0.0226	0.0033	0.0022
p_T^Z [GeV]				
0 – 20 (12)	502	0.0283	0.0029	0.0050
20 – 40 (32)	1326	0.0112	0.0007	0.0010
40 – 60 (50)	998	0.0200	0.0011	0.0012
60 – 80 (68)	512	0.0236	0.0018	0.0016
80 – 200 (100)	453	0.0334	0.0034	0.0025
η^{jet}				
0 – 0.25 (0.13)	614	0.0131	0.0012	0.0010
0.25 – 0.5 (0.38)	639	0.0164	0.0014	0.0012
0.5 – 1.0 (0.75)	1180	0.0209	0.0010	0.0018
1.0 – 1.5 (1.25)	888	0.0213	0.0014	0.0027
1.5 – 2.5 (2.00)	477	0.0152	0.0017	0.0027
$\Delta\varphi_{Z,\text{jet}}$ [rad]				
0 – 2.5 (1.62)	833	0.0292	0.0019	0.0040
2.5 – 2.75 (2.63)	514	0.0212	0.0024	0.0023
2.75 – 2.9 (2.83)	596	0.0215	0.0015	0.0020
2.9 – 3.05 (2.98)	961	0.0151	0.0009	0.0012
3.05 – 3.2 (3.13)	895	0.0131	0.0010	0.0009

TABLE II: Systematic uncertainties for the ratio of differential cross sections.

Source of Systematic Uncertainty	Uncertainty [%]				
p_T^{jet} [GeV]	20 – 30	30 – 40	40 – 55	55 – 70	70 – 200
Jet Energy Scale, Resolution	10.7	7.4	4.3	4.9	2.6
Template Shape	5.7	4.9	5.1	6.3	6.8
b tagging	1.2	1.4	1.9	2.5	2.6
Acceptance	3.3	3.4	0.4	3.2	5.9
p_T^Z [GeV]	0 – 20	20 – 40	40 – 60	60 – 80	80 – 200
Jet Energy Scale, Resolution	16.4	5.7	2.0	0.8	1.5
Template Shape	6.1	4.8	5.1	6.2	6.4
b tagging	1.6	1.7	1.8	1.9	2.1
Acceptance	1.1	4.8	0.2	1.8	3.2
η^{jet}	0 – 0.25	0.25 – 0.5	0.5 – 1.0	1.0 – 1.5	1.5 – 2.5
Jet Energy Scale, Resolution	4.3	4.0	5.8	9.6	12.9
Template Shape	5.9	5.5	5.3	5.9	6.9
b tagging	1.3	1.3	1.4	1.5	5.7
Acceptance	1.5	2.2	2.7	5.1	8.6
$\Delta\varphi_{Z,\text{jet}}$ [rad]	0 – 2.5	2.5 – 2.75	2.75 – 2.9	2.9 – 3.05	3.05 – 3.2
Jet Energy Scale, Resolution	11.5	8.8	6.6	5.3	3.8
Template Shape	6.6	5.6	5.5	4.8	4.9
b tagging	1.7	1.8	2.0	2.0	1.9
Acceptance	3.1	2.5	2.2	1.9	1.8