Measurements of the Associated Production of a Vector Boson with Jets at D0

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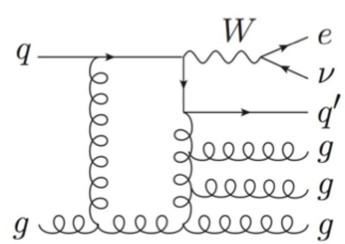
Outline

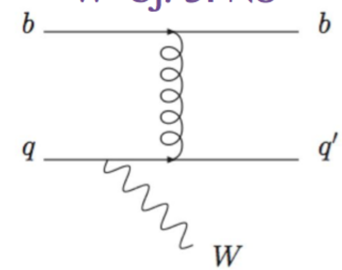
- Motivation
- The DØ Detector
- Measurement Strategy
- Results
  - W + jets
  - γ + jets
  - W + b jets
  - Z + b/c jets
  - γ + b/c jets
- Conclusions

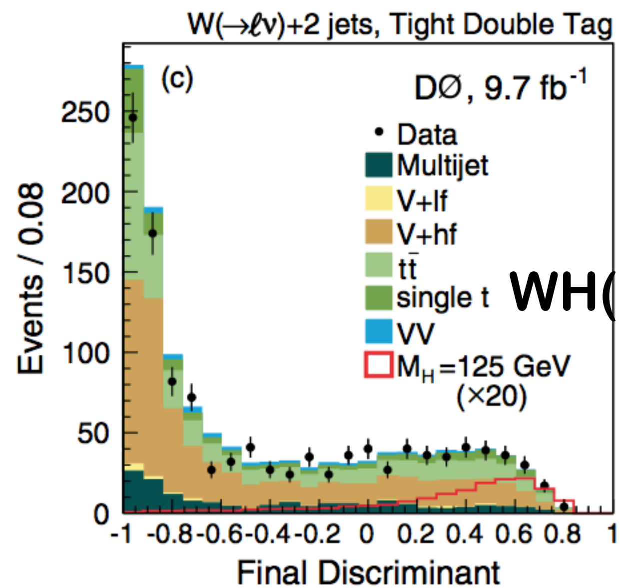
- Test of pQCD calculations
  - Recent high jet multiplicity calculations available
  - 5FNS and 4FNS schemes
  - Novel techniques: NLO + Parton Shower merging
- Validation of simulation models
  - Novel techniques for matching Matrix Elements with Parton Shower
- Sensitive to heavy flavor content of the proton
- Backgrounds for variety of precision SM measurements and searches for new physics
  - Top quark properties
  - Study of Higgs Boson
  - SUSY searches (e.g. sbottom)

W+4jets



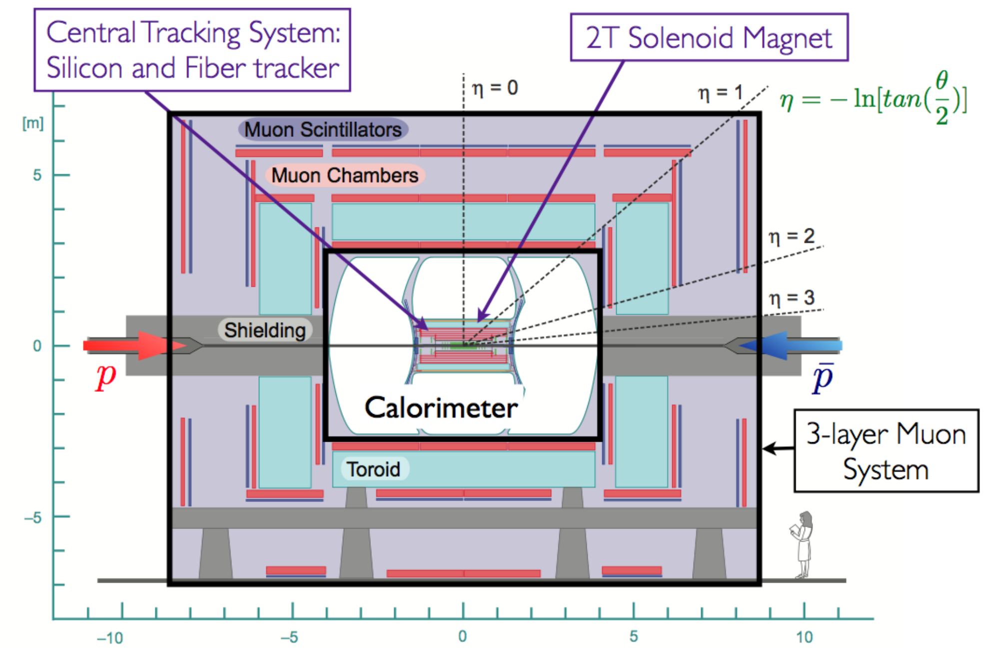
W+bj: 5FNS

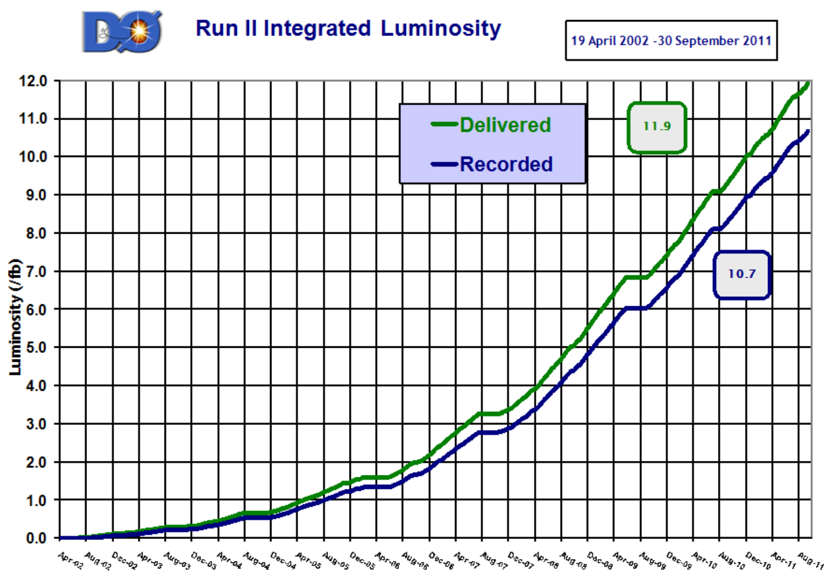




WH(➔bb)

Data Sample





- **Results presented based on proton-antiproton collision data at $\sqrt{s}$=1.96 TeV with integrated luminosity of 6.1 – 9.7 fb^{-1}**

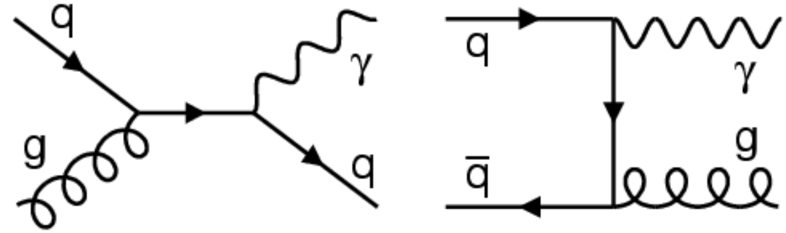
Recent Boson plus Jet Measurements by D0

γ + jet	8.7 fb-1	arXiv:1308.2708
W + jets	6.2 fb-1	arXiv:1302.6508
Z+b-jet	9.7 fb-1	PRD 87, 092010 (2013)
W+b-jet	6.1 fb-1	PLB 718, 1314 (2013)
γ +b-jet	8.7 fb-1	PLB 714, 32 (2012)
γ +c-jet	8.7 fb-1	PLB 719, 354 (2013)
Z+c-jet	9.7 fb-1	Preliminary

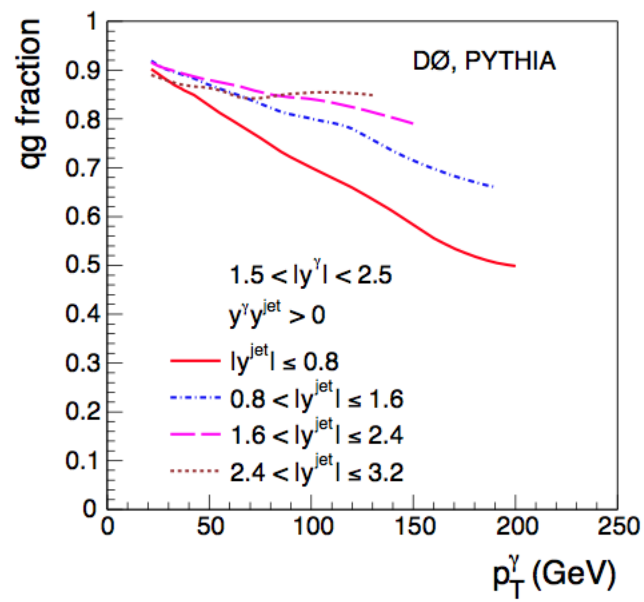
$p\bar{p} \rightarrow \gamma + \text{jet} + X$

arXiv:1308.2708

- **Measurement of** $d^3\sigma / dp_T^\gamma dy^\gamma dy^{jet}$ **for**
  - Central photons: $|y^\gamma| < 1.0$
  - Forward photons: $1.5 < |y^\gamma| < 2.5$
  - 4 jet rapidity intervals
    - $|y^{jet}| \leq 0.8$
    - $0.8 < |y^{jet}| \leq 1.6$
    - $1.6 < |y^{jet}| \leq 2.4$
    - $2.4 < |y^{jet}| \leq 3.2$
  - Configurations with same sign ($y^\gamma y^{jet} \geq 0$) and opposite sign ($y^\gamma y^{jet} < 0$) events



- **These regions probe different ranges of x and Q^2**
  - **varying contribution from gluon-initiated Compton process**
  - **different levels of fragmentation contribution**

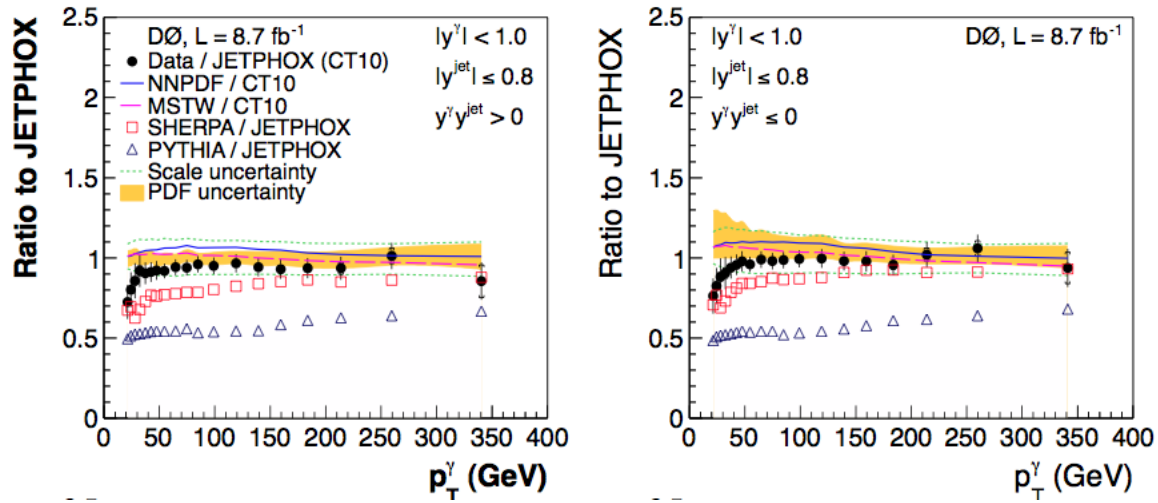


$p\bar{p} \rightarrow \gamma + \text{jet} + X$

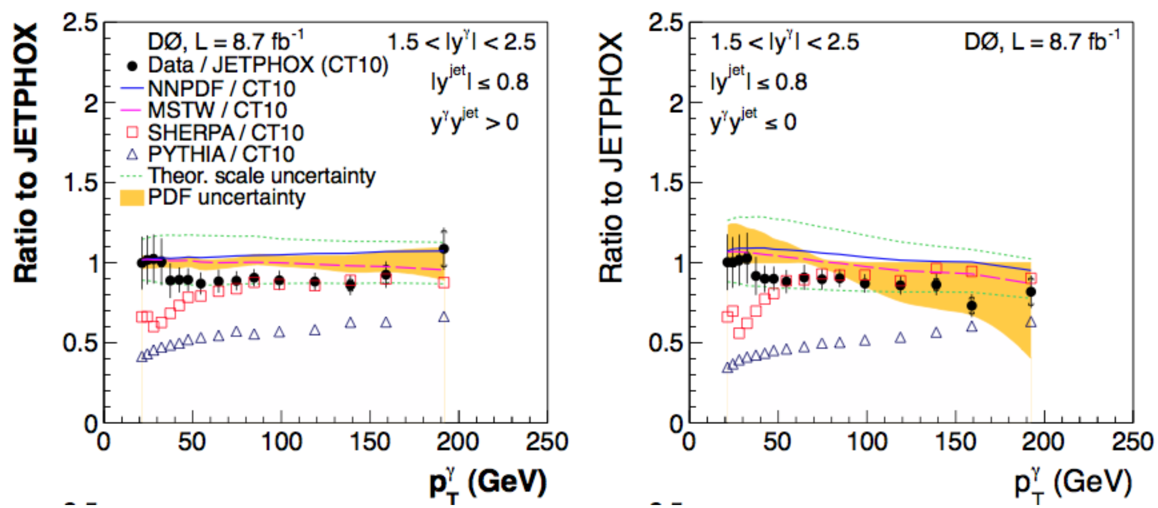
arXiv:1308.2708

- NLO predictions describe data in almost all rapidity regions with some exceptions
  - $p_T^{\gamma} < 40$ GeV for central photons
- Typical uncertainties similar or smaller than PDF + scale uncertainties

Central Photons



Forward Photons

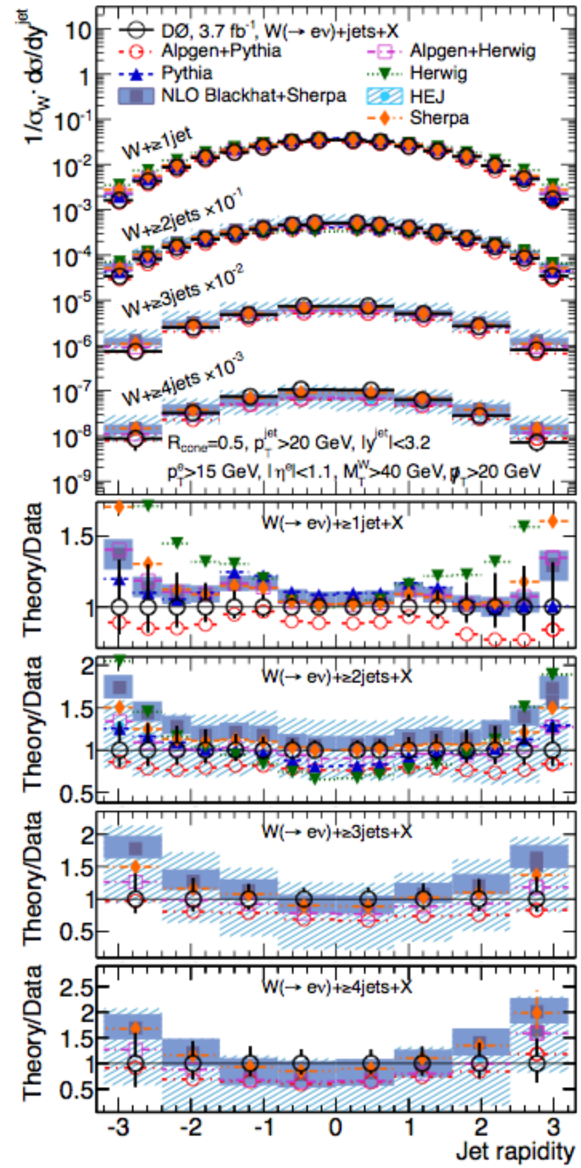


W + Jets Measurements

arXiv:1302.6508

- Comprehensive study of W+n-jet production (n=1 - 4)
  - Measurements of 40 observables
  - Uncertainties smaller or similar compared to theoretical ones
  - Comparison with recent NLO calculations and MCs (PS, ME+PS)
  - Validation of new theoretical approaches and MC tuning

- Measurement of the nth-jet rapidity distribution
  - Tests the modeling of parton emission
  - All predictions largely agree in shape at central rapidities



W+Jets Measurements

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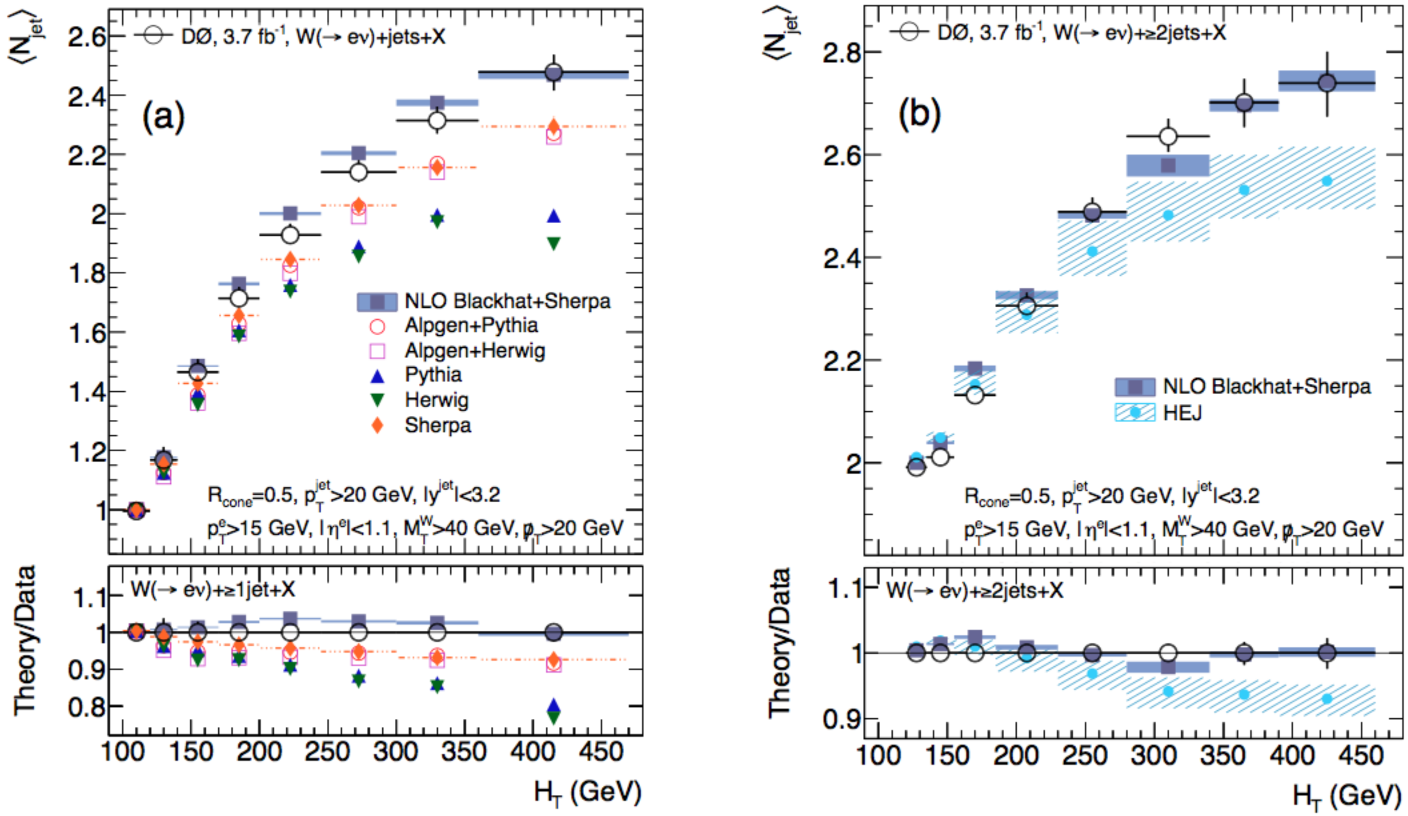
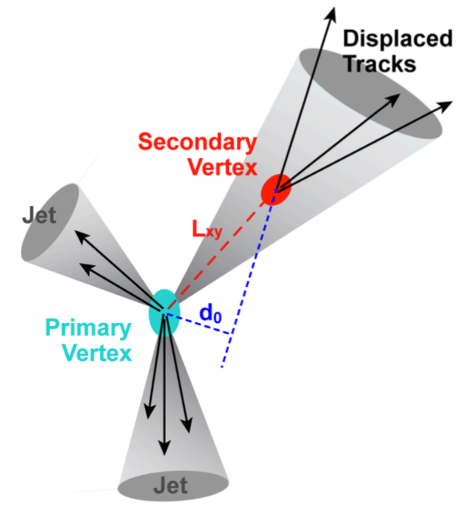
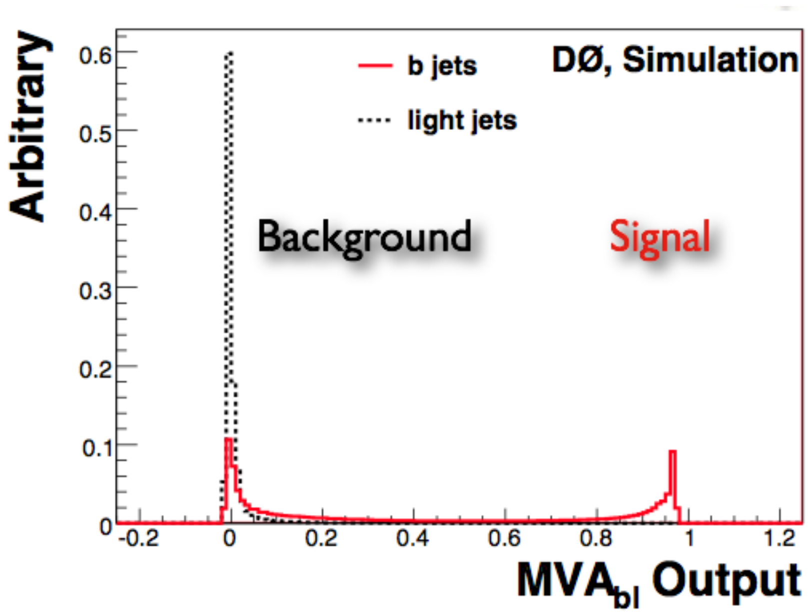


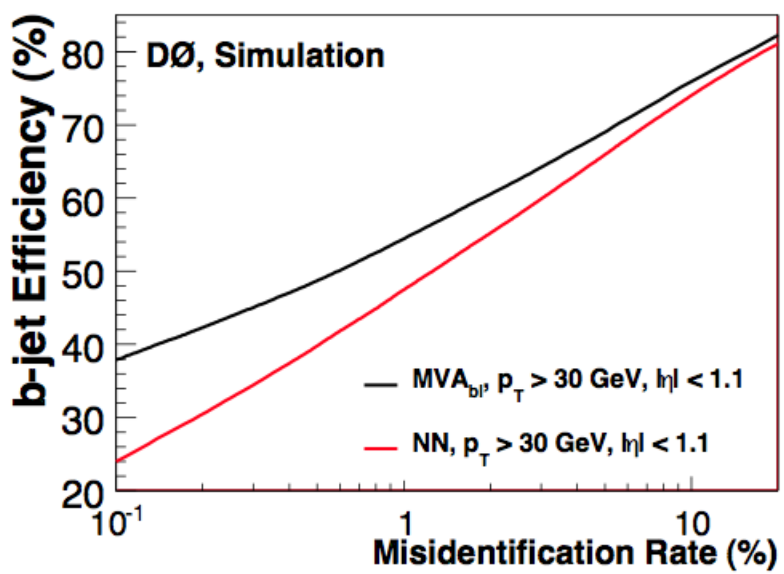
- Dependence of mean no of jets in an event on total transverse energy of the hard interaction tested for the first time
  - NLO describes <N_{jet}> spectrum over entire H_T range
  - Both PS and ME+PS underestimate amount of high p_T jet emission

Heavy Flavor (HF) Jet Tagging

- Long lifetime (~1 ps) of b/c hadrons resulting in displaced secondary vertex.
- Large hadron masses 2-5 GeV
  - Tracks displaced from primary vertex with large impact parameters
- HF tagging exploits characteristics of the tracks to create a discriminant
  - Typically 50-60% efficient for 0.5-1.5% fake rate





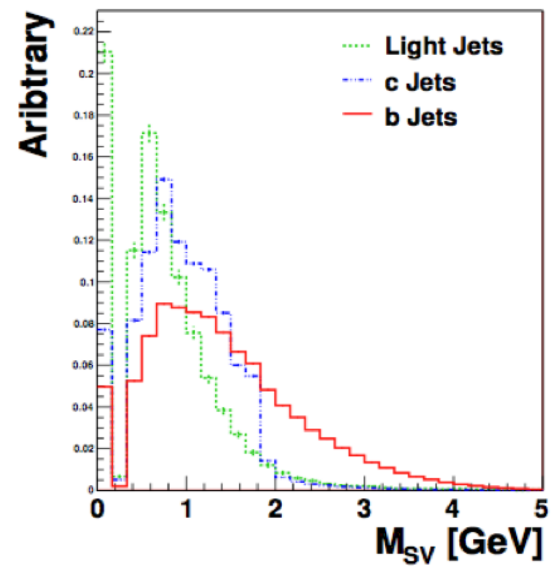


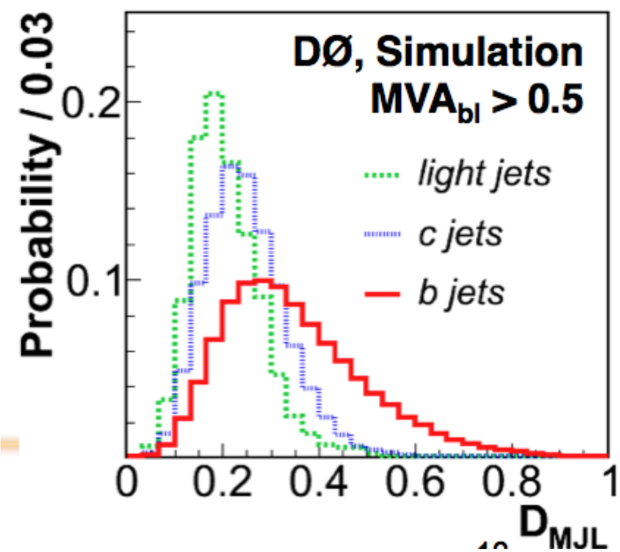
Estimation of Heavy Flavor Fraction

- The tagged sample still has some fraction of misidentified jets
- To further separate jets of different flavors, use a discriminant
  - M_{SVT} is invariant mass of tracks associated to secondary vertex
  - JLIP is jet lifetime impact parameter

$$D_{\mathrm{MJL}} = \frac{M_{\mathrm{svt}}/5 - ln(\mathrm{JLIP})/20}{2}$$

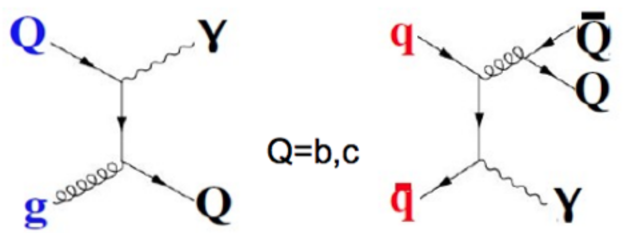
- Fit background subtracted data distribution with the templates to extract the jet flavor fractions
  - For c-jet fraction, fitting with three templates return large uncertainties
  - Fit data with b- and c-jet templates after subtracting the residual contribution of light jets



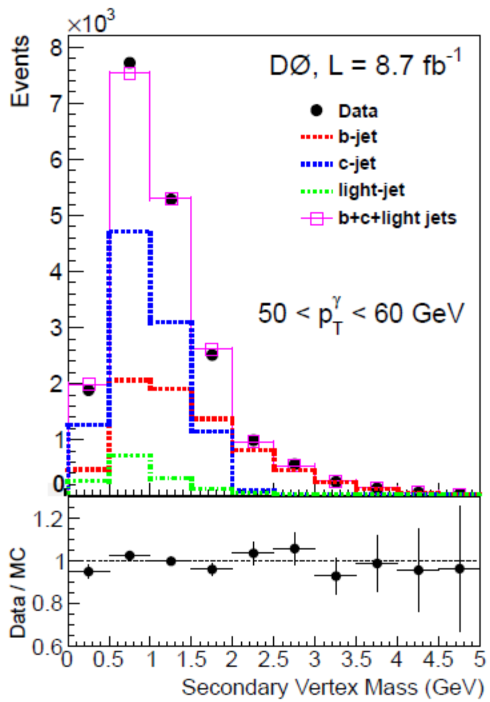


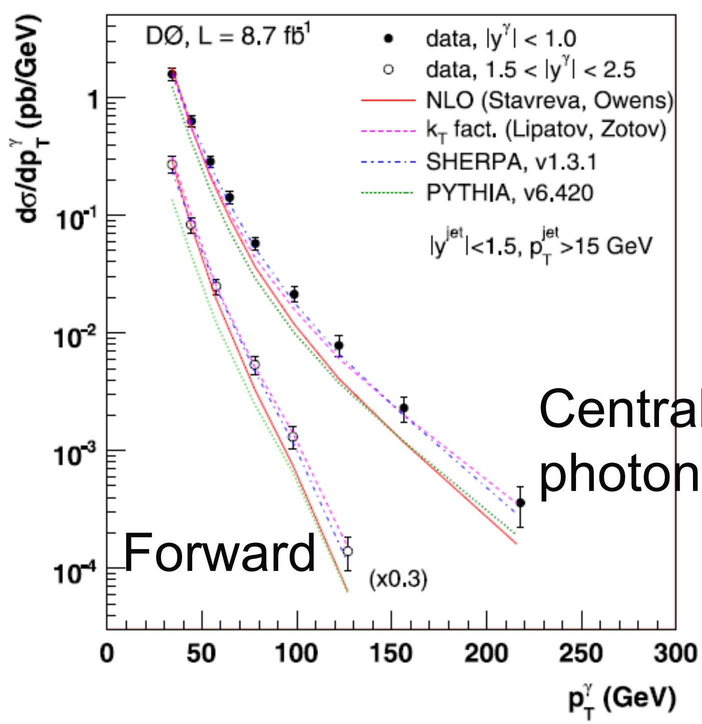
γ + b-jet(s)

PLB 714, 32 (2012)



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





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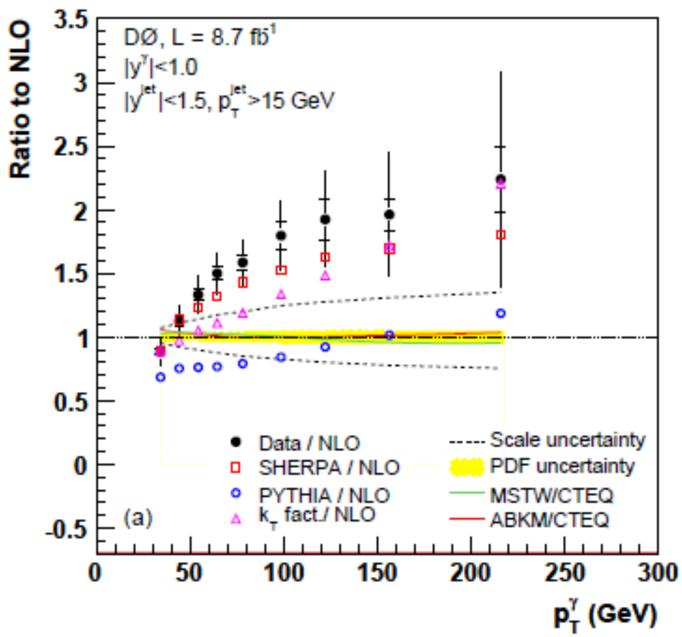
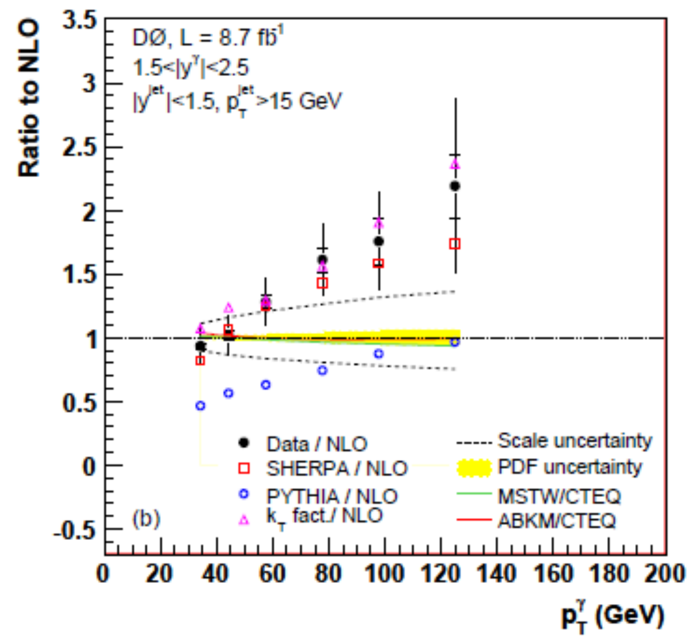


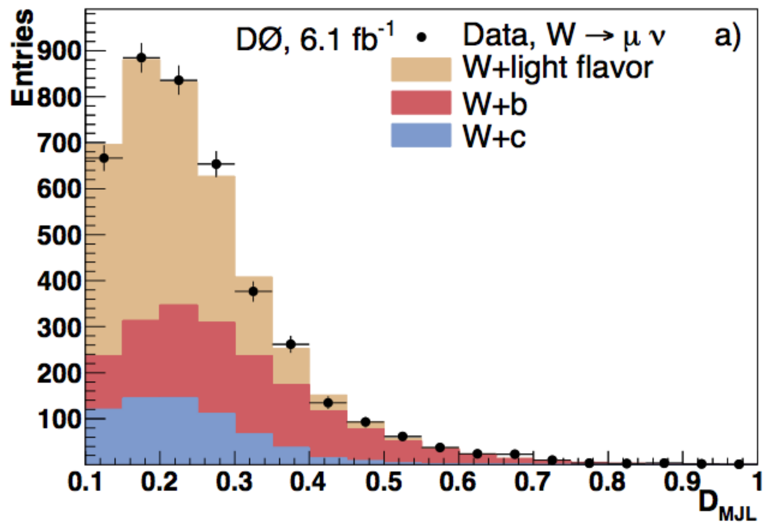


- **Reasonable description within uncertainties at low p_T^γ <70 GeV**
- **Disagreements (difference in slopes) at higher p_T^γ**
  - **Need for higher order corrections at large p_T^γ dominated by annihilation process, and resummation of diagrams with additional gluon radiation.**
- **Better description by SHERPA and k_T-factorization approach**

W + b-jet(s)

PLB 718, 1314 (2013)

- W(→lν) selection
  - Isolated lepton $p_T > 20$ GeV
  - Muon: $|\eta^{\mu}| < 1.7$
  - Electron: $|\eta^{e}| < 1.1$ or $1.5 < |\eta^{e}| < 2.5$
  - Missing $E_T > 25$ GeV
- Jet selection
  - ≥ 1 jet, R=0.5
  - $p_T > 20$ GeV, $|\eta| < 1.1$



	W→μν	W→eν
Data – Bkg	4127	6255
W+b frac.	0.30 ± 0.04	0.27 ± 0.03

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

$$= 1.05 \pm 0.03\,(\text{stat.}) \pm 0.12\,(\text{syst.})\ \text{pb}$$

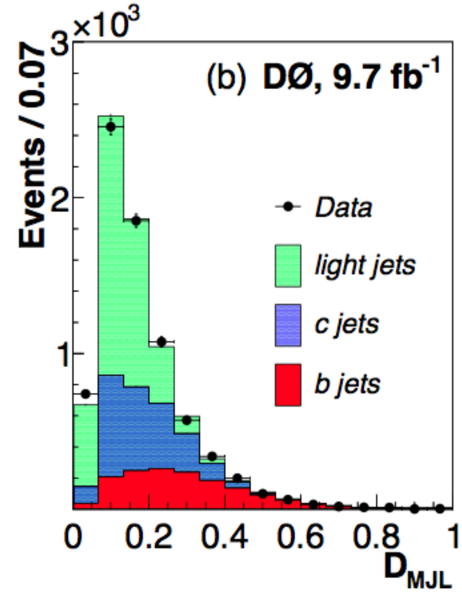
$$= 1.34^{+0.41}_{-0.34}\ (\text{MCFM NLO})$$

Measurement consistent with NLO prediction within uncertainties

$\sigma(Z+b) / \sigma(Z+\text{jets})$

Phys. Rev. D **87**, 092010 (2013)

- Z(→ee / $\mu\mu$) selection
  - Missing E_T < 60 GeV
- Jet selection
  - ≥ 1 jet
  - p_T > 20 GeV, $|\eta|$ < 2.5
- Measurement of ratio allows for precise comparison with theory



$$\frac{\sigma(Z+b\text{ jet})}{\sigma(Z+\text{jet})} = \frac{N_{fitted}\, f_b}{N_{Z+j}\, \varepsilon^b_{btag}} \times \frac{A_{incl}}{A_b}$$

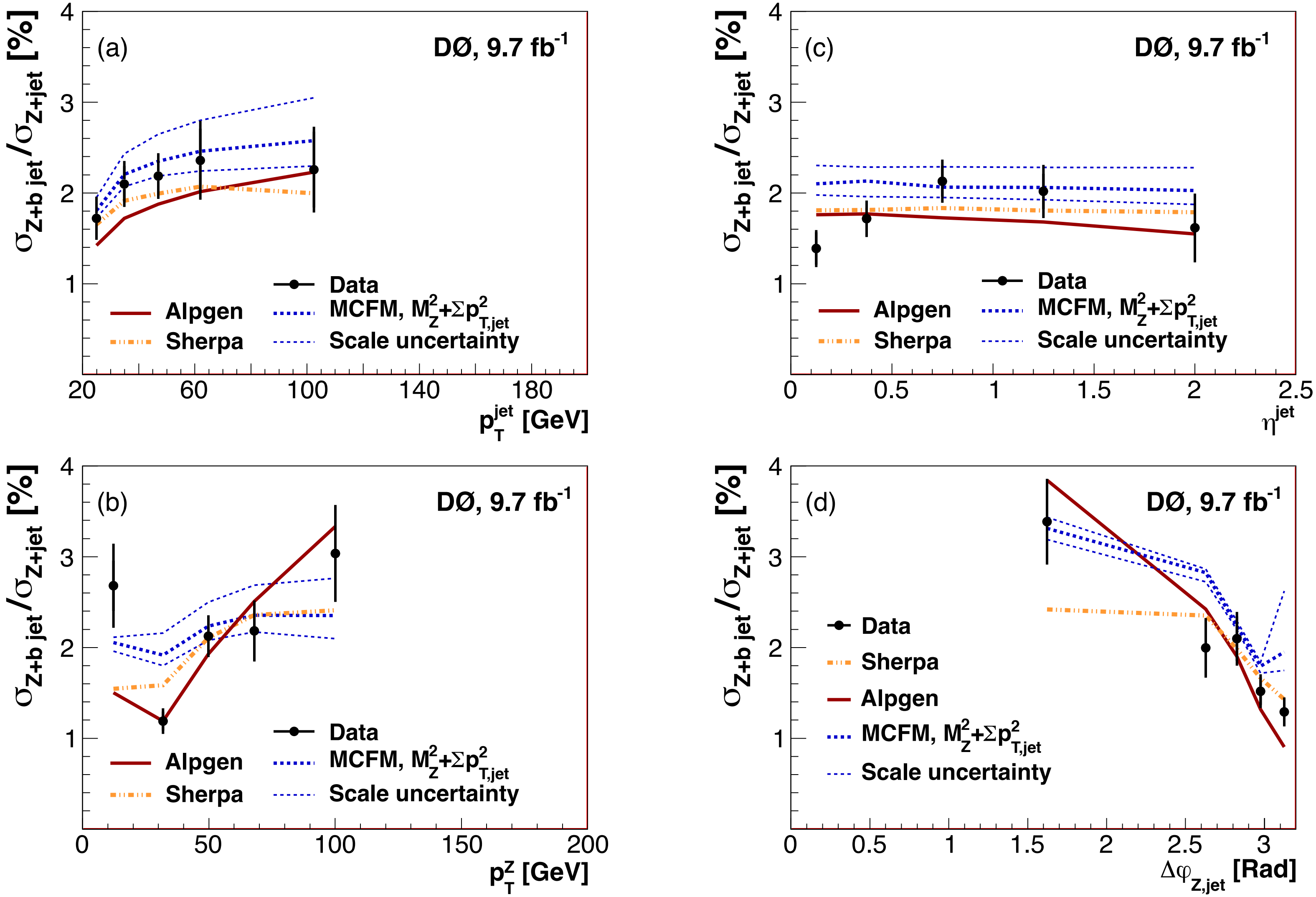
	Z→μμ	Z→ee
Data – Bkg	3,921	3,576
Z+b %	21.5 ± 1.6	19.8 ± 1.9

D0	0.0196 ± 0.0012 (stat.) ± 0.0013 (syst.)
CDF	0.0208 ± 0.0018 (stat) ± 0.0027 (syst.)

MCFM [MSTW2008, $M_Z^2+\Sigma(\text{jet } p_T)^2$] $0.0206^{+0.0022}_{-0.0013}$

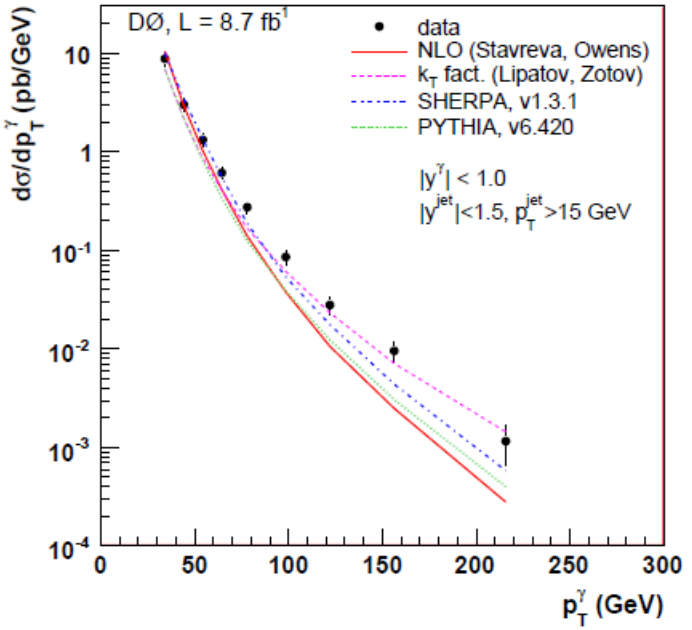
σ (Z+b jet) / σ (Z + jets)

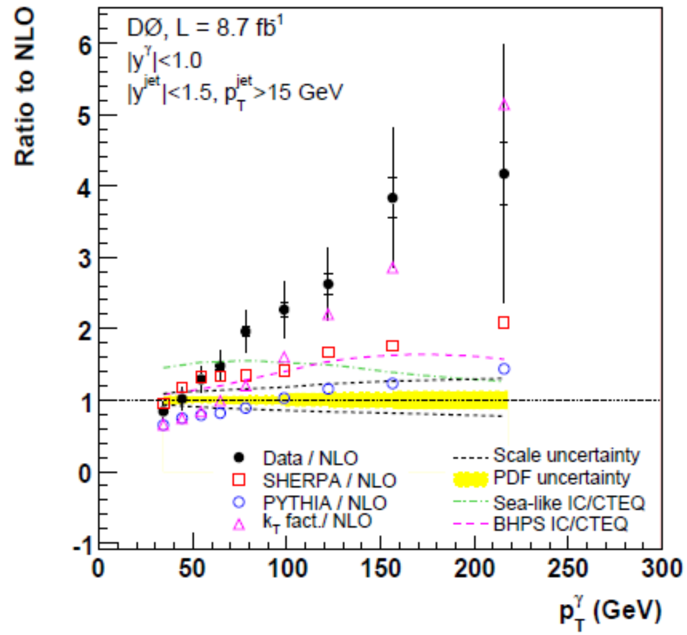
- First measurement of the ratio differentially as a function of kinematic observables Phys. Rev. D **87**, 092010 (2013)



γ + c-jet(s)

PLB 719, 354 (2013)



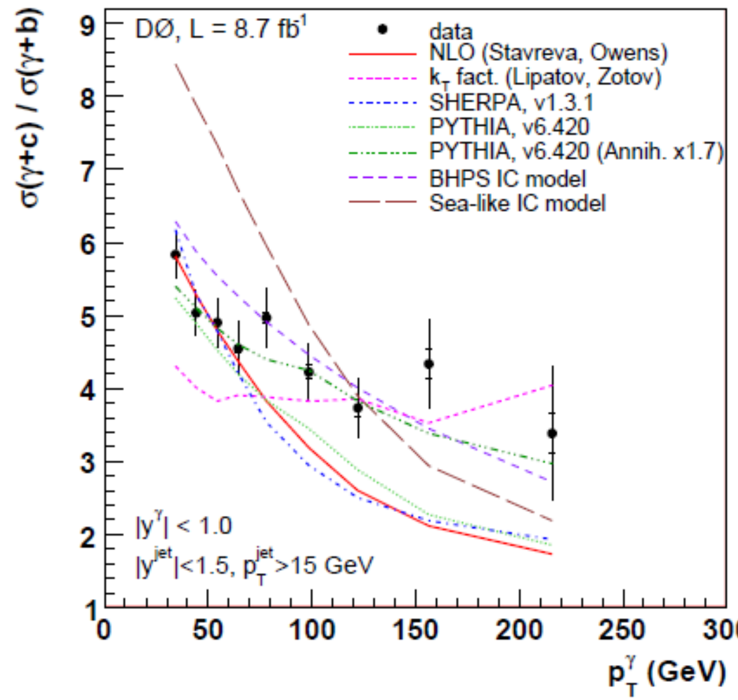


- **Reasonable description within uncertainties at low p_T^γ <70 GeV**
- **Systematic disagreement at higher p_T^γ**
  - **Need for HO corrections at large p_T^γ dominated by annihilation process, and resummation of diagrams with additional gluon radiation.**
- **Better description by SHERPA and k_T-factorization approach**

$\sigma(\gamma+c)/\sigma(\gamma+b)$

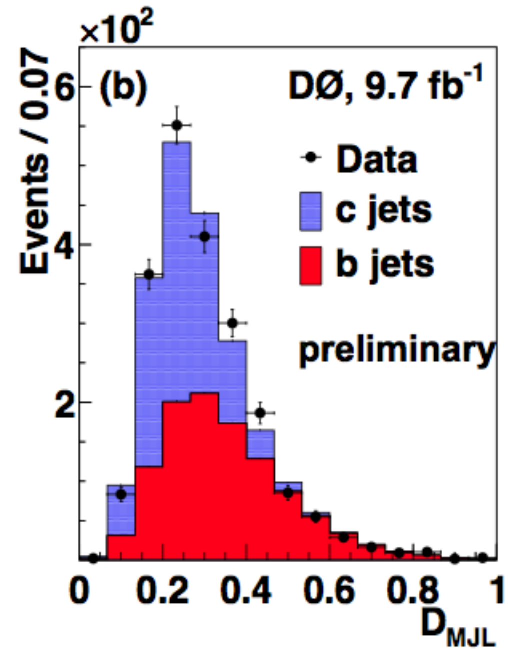
PLB 719, 354 (2013)

- Measurement of ratio allows more precise comparison with theory
  - Cancellation of many systematic uncertainties
- p_T^γ <70 GeV: Good agreement with NLO, PYTHIA and SHERPA, while k_T-factorization predicts smaller ratios
- p_T^γ >70 GeV: Data show systematically higher ratios
  - k_T-factorization tend to agree within uncertainties
  - BHPS model with small shift in normalization should provide better description
  - Predictions with larger $g \rightarrow cc$ rates (~1.7) also provide better description



$\sigma(Z + c) / \sigma(Z + \text{jets})$

- First measurement of the Z+c-jet production
- $Z(\to ee / \mu\mu)$ selection
- Jet selection
  - ≥ 1 jet, $p_T > 20$ GeV, $|\eta| < 2.5$



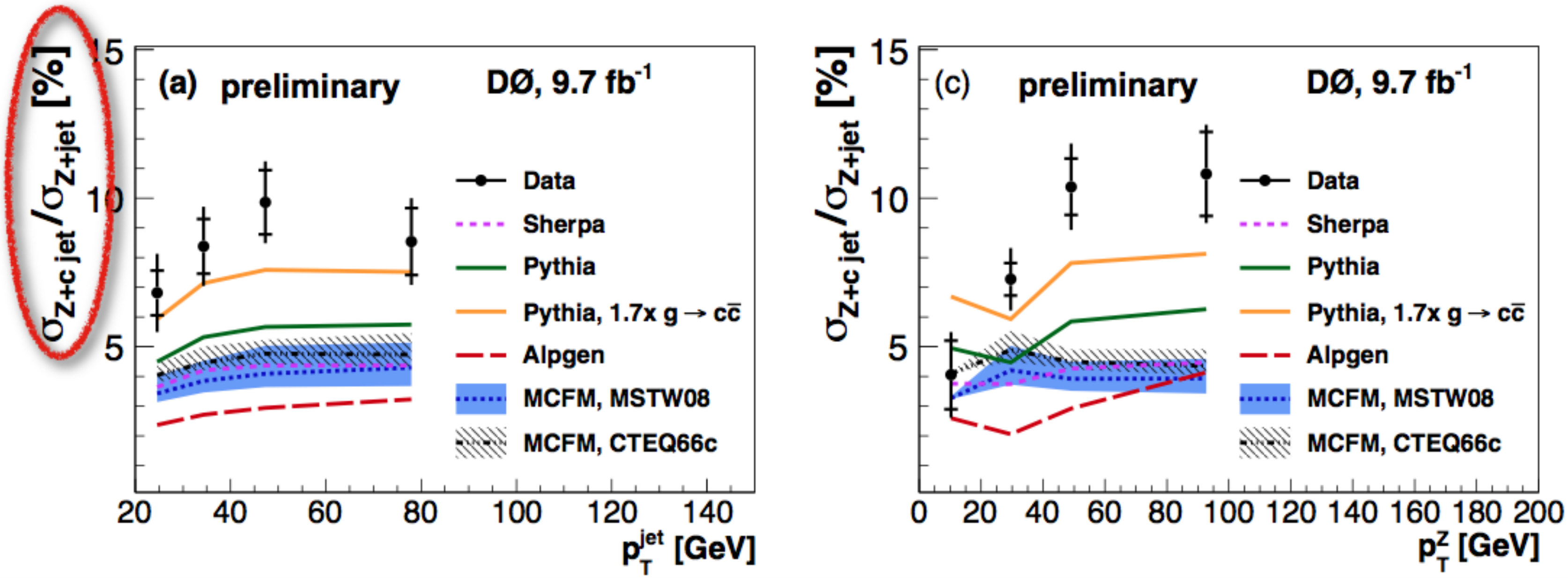
$$\frac{\sigma(Z + c\ \text{jet})}{\sigma(Z + \text{jet})} = \frac{N_{fitted}\ f_c}{N_{Z+j}^{presel}\ \epsilon_{tag}^c} \times \frac{\mathcal{A}_{incl}}{\mathcal{A}_c}$$

D0	0.0829 ± 0.0052 (stat.) ± 0.0089 (syst.)
MCFM [MSTW2008, $M_Z^2+\Sigma(\text{jet } p_T)^2$	$0.0368^{+0.0063}_{-0.0039}$
MCFM [IC model, CTEQ6.6c]	$0.0425^{+0.0048}_{-0.0029}$

For 9.7 fb^{-1}	ee + $\mu\mu$
Data-bkg	2125
Z+b jet	[51.4 ± 2.8] %
Z+c jet	[48.6 ± 2.8] %

Measurements significantly in excess of predictions

σ (Z+c jet) / σ (Z+jet) Dependence

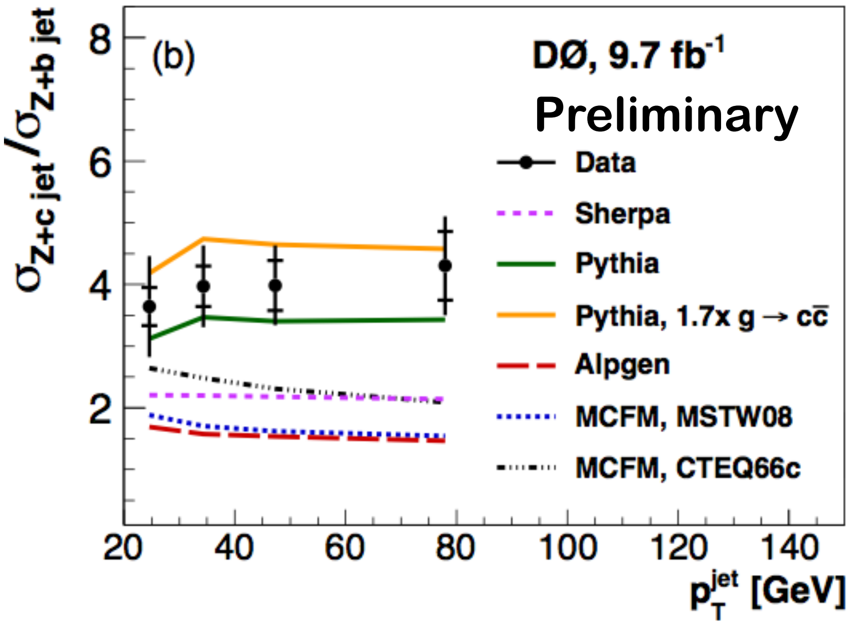


- **Measurements significantly in excess of predictions**
- **Predictions with enhanced g→cc rates provide better description**

σ (Z+c jet) / σ (Z+b-jet)

$$\frac{\sigma(Z + c \text{ jet})}{\sigma(Z + b \text{ jet})} = \frac{f_c\ \epsilon^b_{tag}}{f_b\ \epsilon^c_{tag}} \times \frac{\mathcal{A}_b}{\mathcal{A}_c}$$

- **Cancellation of many syst. uncert. in the ratio**
- **Allows for precise comparison with theory calculations**



D0	4.00 ± 0.21 (stat.) ± 0.58 (syst.)
MCFM [MSTW2008, $M_Z^2+\Sigma(\text{jet } p_T)^2$	1.64
MCFM [IC model, CTEQ6.6c]	2.23
ALPGEN	**1.57**
SHERPA	**2.19**

Measurements significantly in excess of predictions

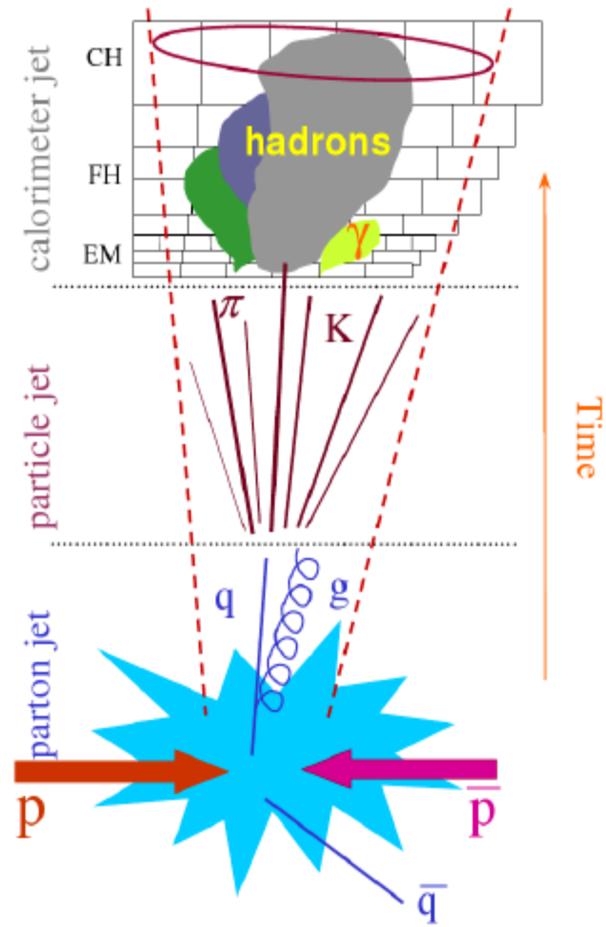
Conclusions

- Vector boson + heavy flavor jet production provides a good laboratory for precision tests of pQCD and probes the heavy flavor content of the proton
- Understanding of these processes key for the New Phenomena searches
- Many interesting results from the D0 experiment
  - Extend the previously probed phase space
  - Test various predictions from theory and simulation
  - Important feedback for the theory development & MC tuning
- Compressive study of W+njet and photon+jet production
- Many new measurements on vector boson plus heavy flavor jets
  - First measurement of Z+c-jet production
- More interesting measurements in the pipeline. Stay tuned.

Thank You!

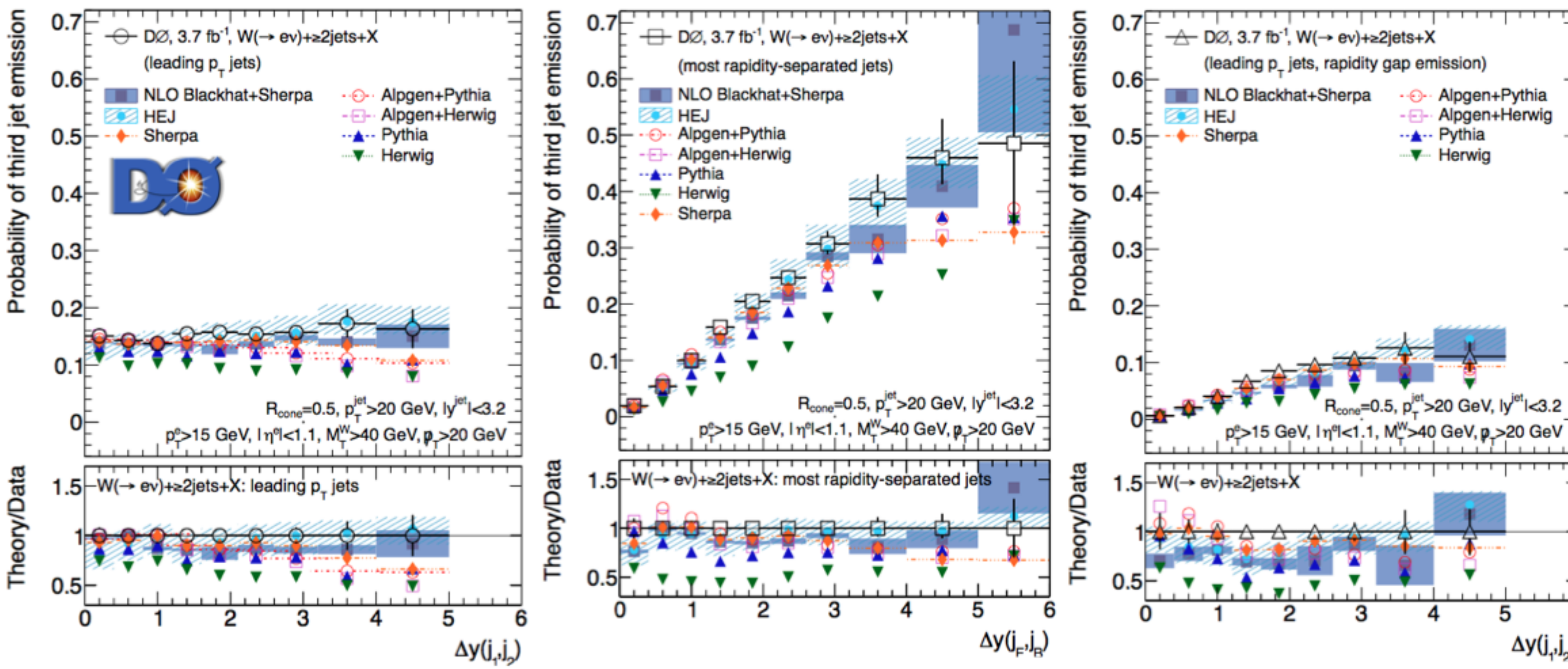
Jets

- Reconstruction
  - Hadronic shower
  - Iterative mid-point cone algorithm, R = 0.5
- Jet Energy Scale
  - Measured in γ+jet and Dijet events
  - Correct energy to particle level
  - Correct for detector response, out of cone showering, overlap with pile up energy
- Correct parton-level theory for non-perturbative effects (hadronization and Underlying events) using parton shower Monte Carlo



W+Jets Measurements

arXiv:1302.6508



- Measurement of the probability of emission of 3rd jet in the inclusive W+2jet events as a function of
  - Dijet rapidity separation of two highest p_T jets
  - Dijet rapidity separation of two most rapidity-separated jets
  - Dijet rapidity separation of two highest p_T jets and the 3rd jet is emitted into the rapidity interval defined by the two leading jets

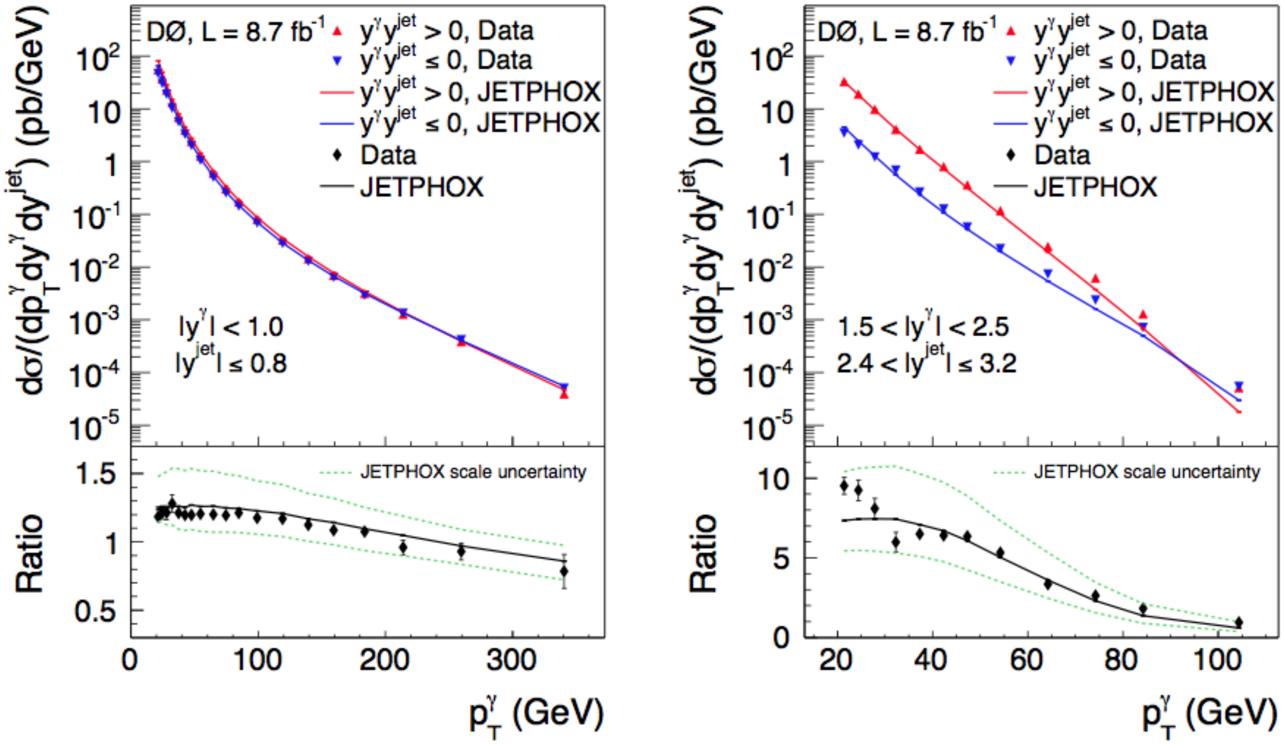


FIG. 8: (color online) Comparison of the same-sign to opposite-sign cross section ratios for events with a central central jet and those with a forward photon and very forward jet.