# Recent Results from the D0 Experiment on Heavy Particle Production with jets


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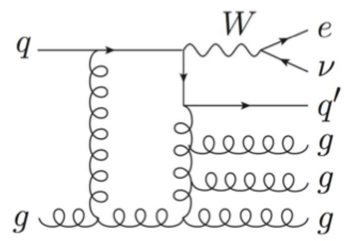
# Outline

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

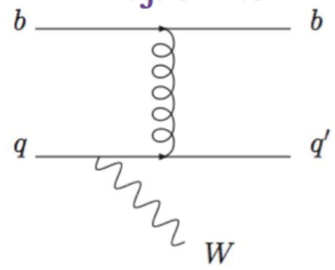
# Motivation

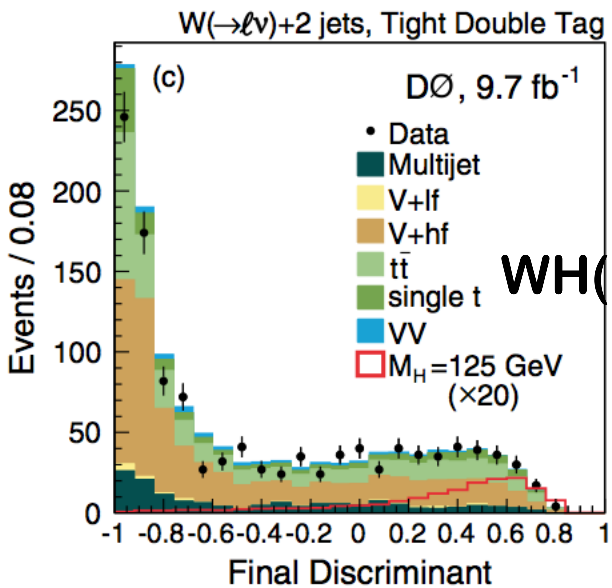
- Test of pQCD calculations
  - Recent high jet multiplicity calculations available
  - 5FNS and 4FNS schemes
  - Novel techniques: NLO + Parton Shower merging
- Validation of simulation models
  - Novel techniques for matching Matrix Elements with Parton Shower
- Sensitive to heavy flavor content of 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



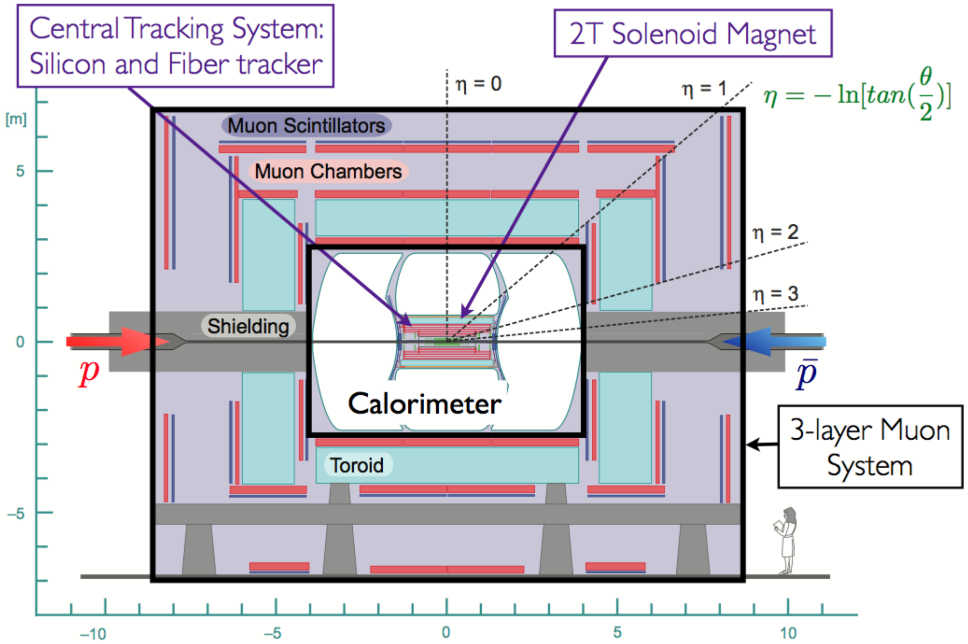

W+bj: 5FNS

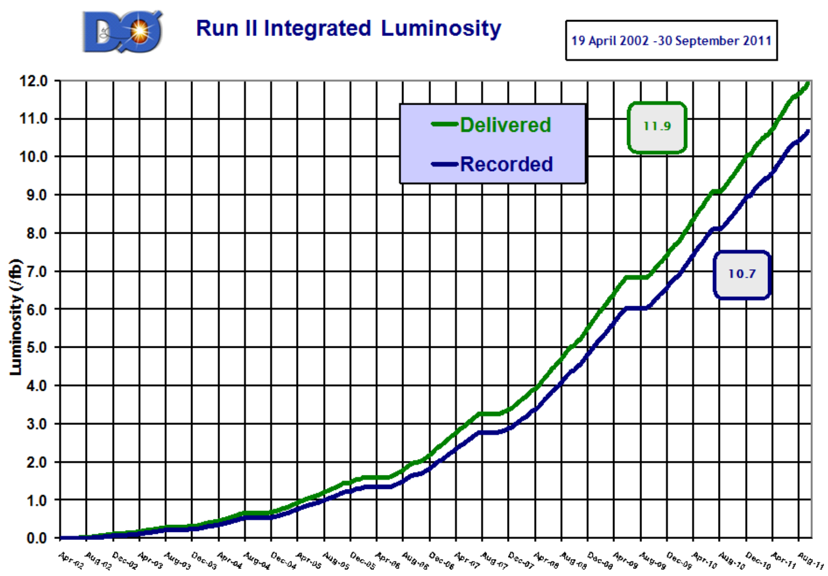



WH(➔bb)

# Data Sample




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

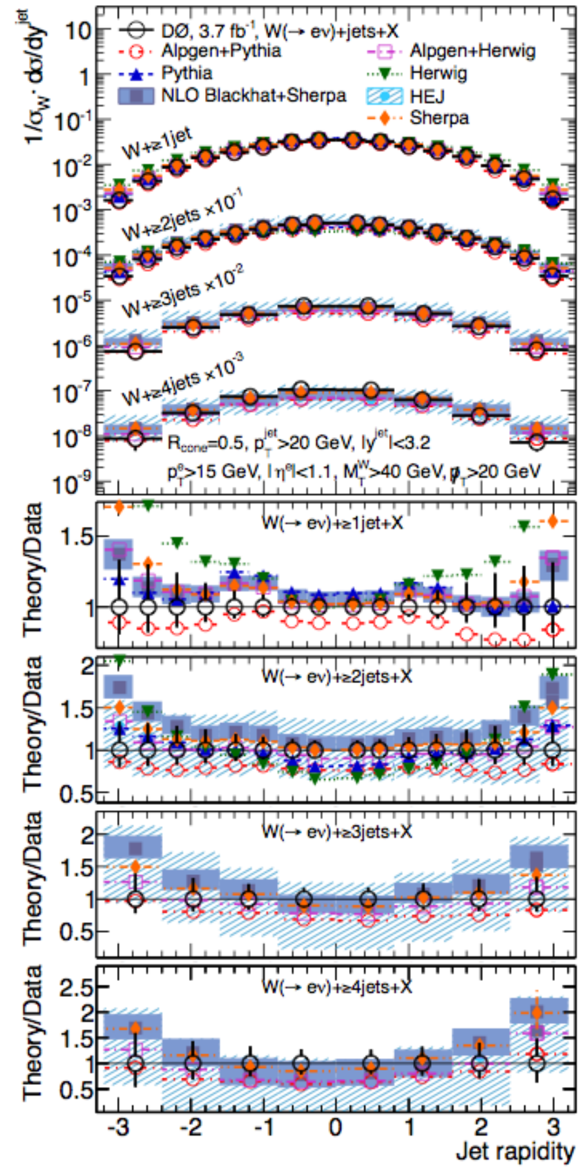
# Recent Boson + Jet Measurements from D0

| | | |
|---|---|---|
| $\gamma$ + jet | 8.7 fb-1 | arXiv:1308.2708 |
| W + jets | 6.2 fb-1 | arXiv:1302.6508 |
| $\gamma$ +b-jet | 8.7 fb-1 | PLB 714, 32 (2012) |
| Z+b-jet | 9.7 fb-1 | PRD 87, 092010 (2013) |
| W+b-jet | 6.1 fb-1 | PLB 718, 1314 (2013) |
| $\gamma$ +c-jet | 8.7 fb-1 | PLB 719, 354 (2013) |
| Z+c-jet | 9.7 fb-1 | arXiv:1308.4384 |

# arXiv:1302.6508

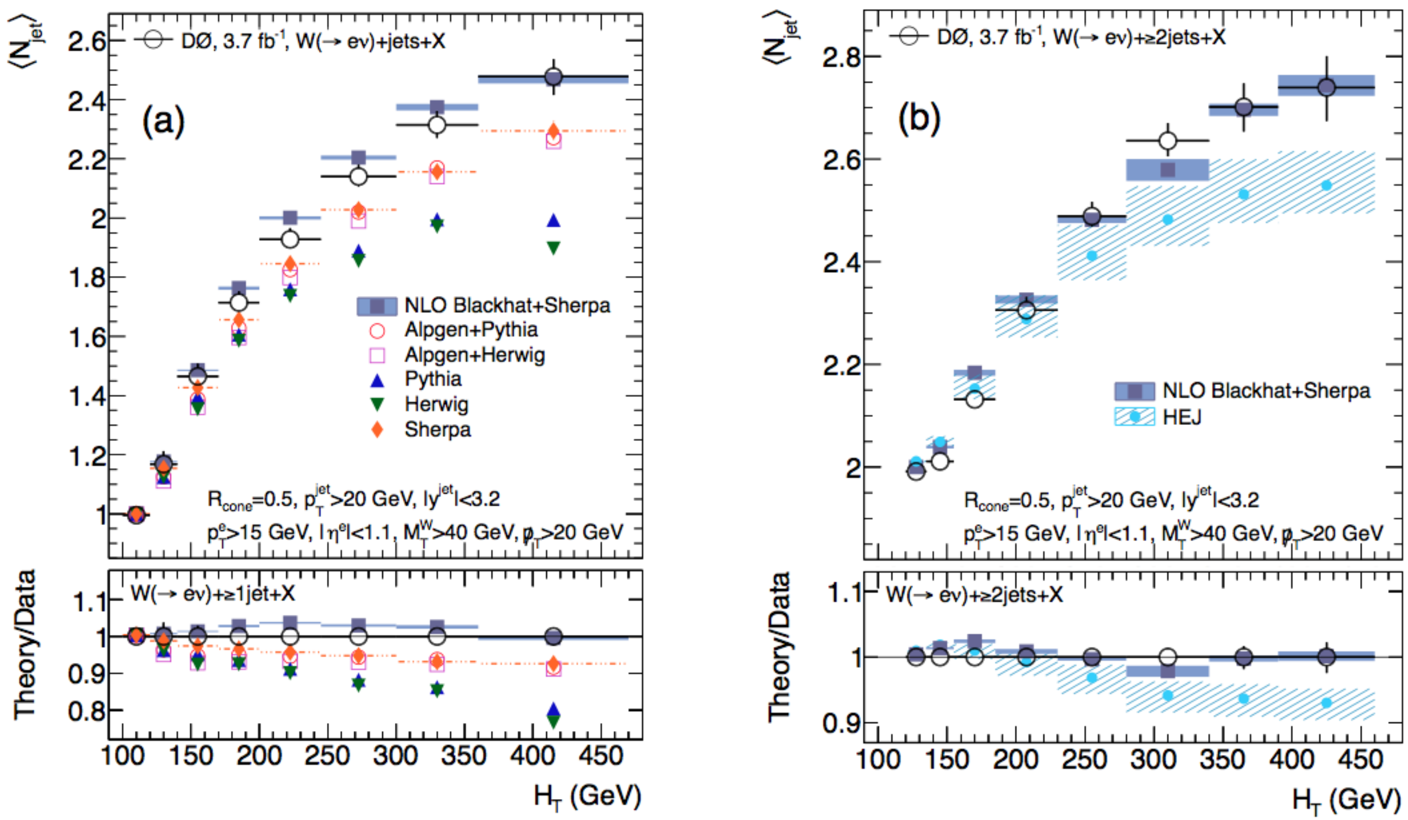
- Comprehensive study of W+n-jet production (n=1 - 4)
  - Measurements of 40 observables
  - Uncertainties smaller or similar compared to theoretical ones
  - Comparison with recent NLO calculations and MCs (PS, ME+PS)
  - Validation of new theoretical approaches and MC tuning

- 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

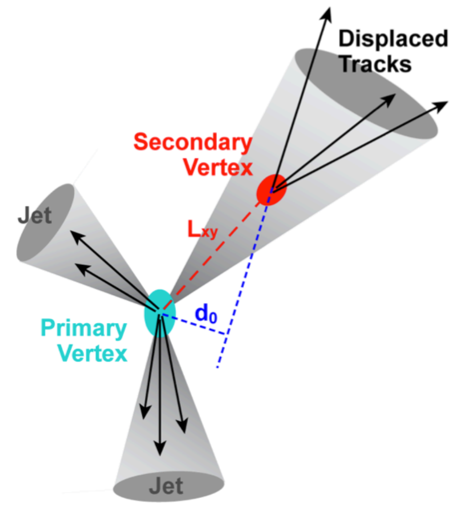
arXiv:1302.6508

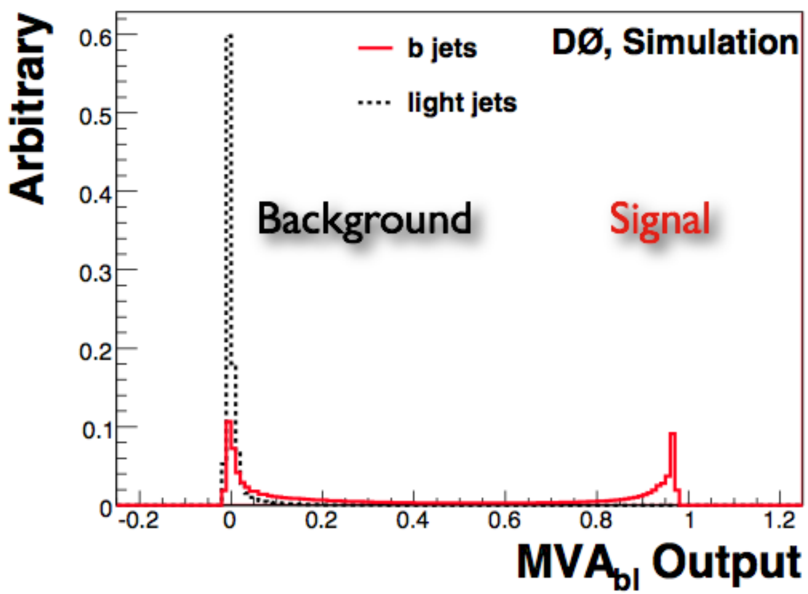


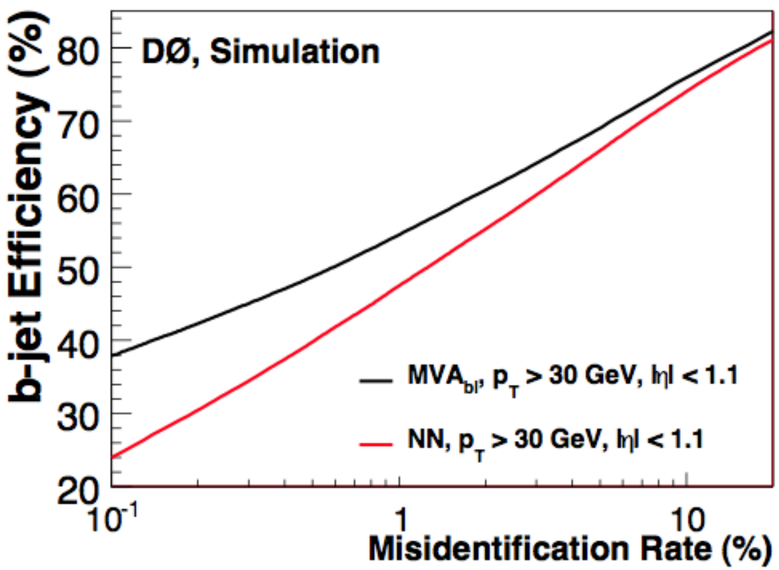

- Dependence of mean no of jets in an event on total transverse energy of the hard interaction tested for the first time
  - NLO describes $\langle N_{jet} \rangle$ spectrum over entire $H_T$ range
  - Both PS and ME+PS underestimate amount of high $p_T$ jet emission

# 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



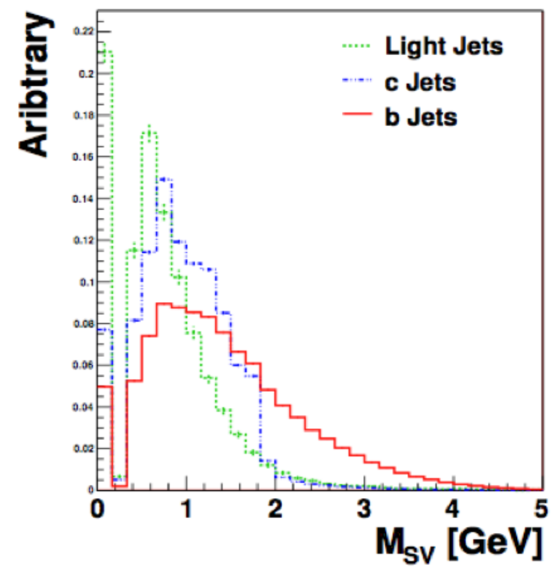



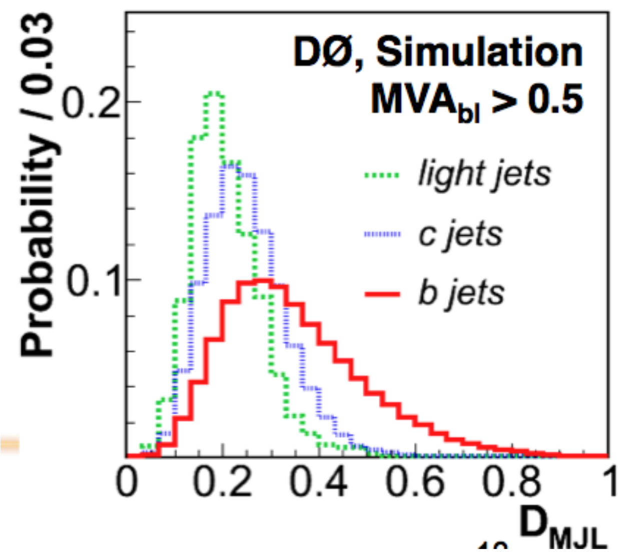
# Estimation of Heavy Flavor Fraction

- 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

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



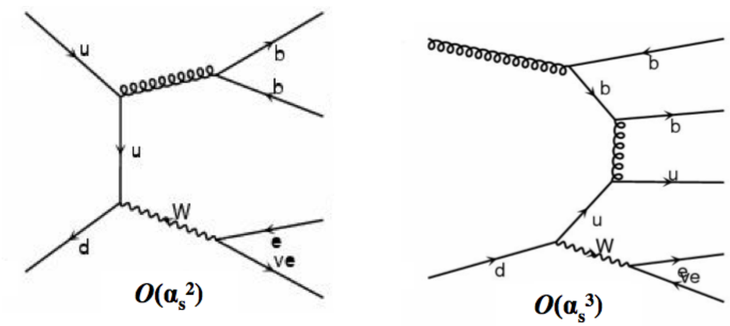

- Fit background subtracted data distribution with the templates to extract the jet flavor fractions
  - For c-jet fraction, fitting with three templates return large uncertainties
  - Fit data with b- and c-jet templates after subtracting the residual contribution of light jets

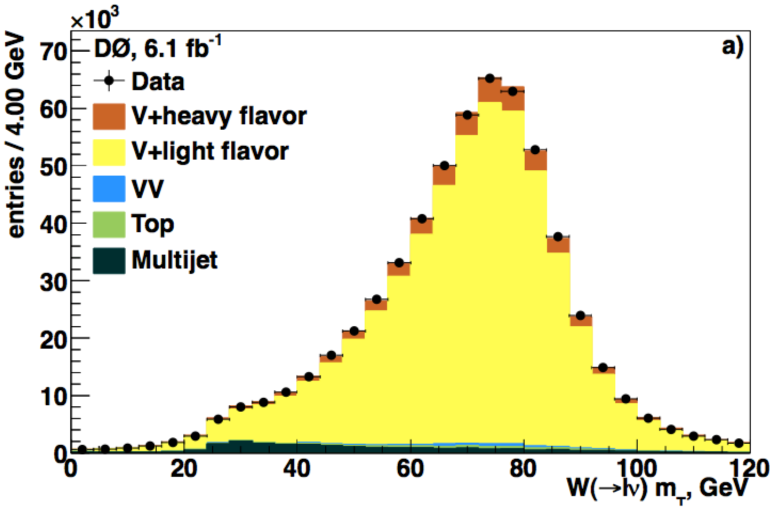


# W + b-jet(s)

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, $|\eta| < 1.1$
- Backgrounds
  - Single top, top pair and diboson production
  - Multi-jet production estimated from data

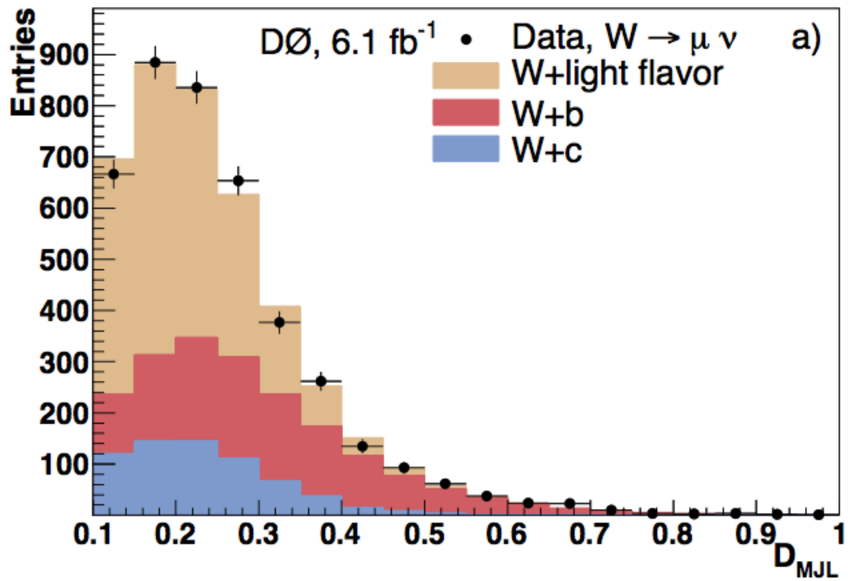


# W + b-jet(s)

PLB 718, 1314 (2013)

| | $W\to\mu\nu$ | $W\to e\nu$ |
|---|---|---|
| **Data – Bkg** | 4127 | 6255 |
| **W+b frac.** | 0.30 ± 0.04 | 0.27 ± 0.03 |




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

$$=1.05\pm0.03\,(\text{stat.})\pm0.12\,(\text{syst.})\text{ pb}$$

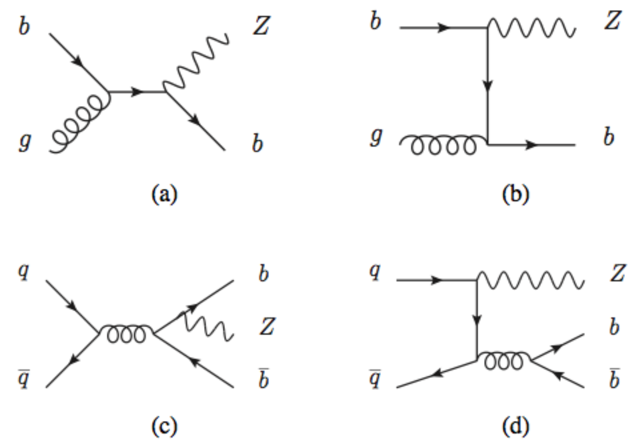
= 1.34 $^{+0.41}_{-0.34}$ pb (MCFM NLO)
= 1.21 pb (SHERPA)
= 1.54 pb (MADGRAPH)

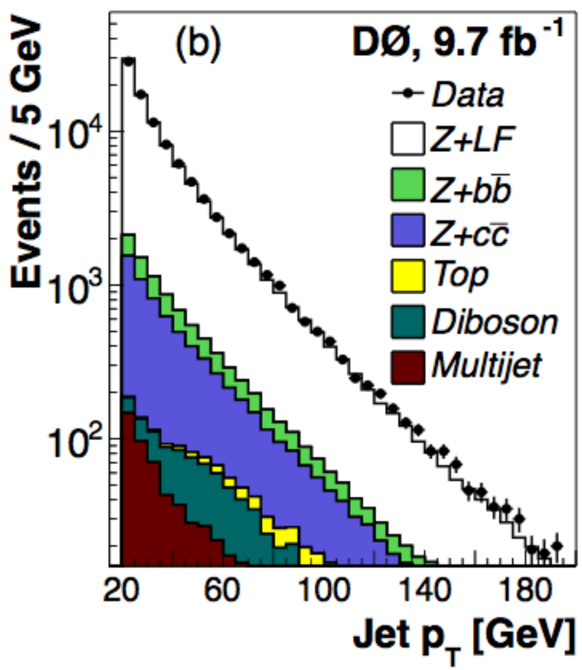
**Measurement consistent with NLO prediction within uncertainties**

# $\sigma(Z+b)/\sigma(Z+jets)$

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

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

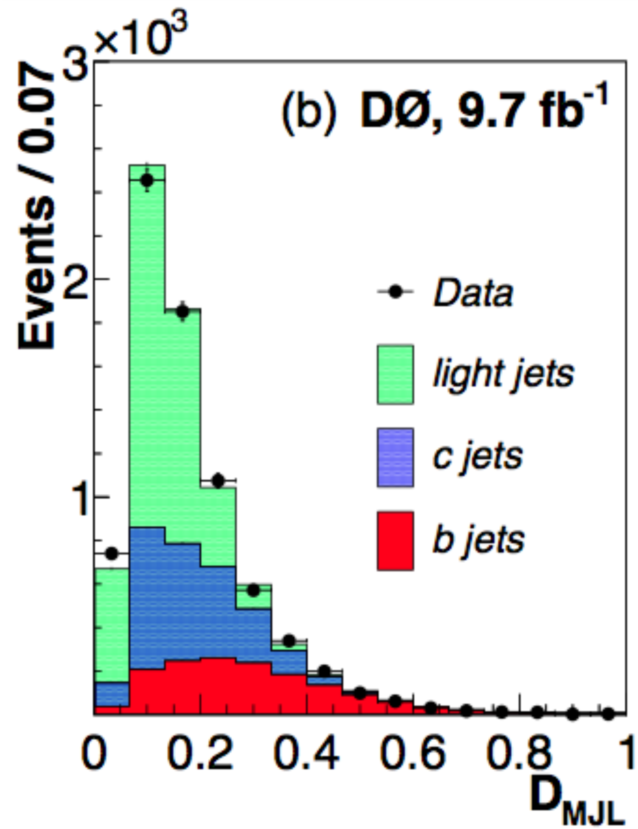


# $\sigma(Z+b) / \sigma(Z+\text{jets})$

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

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




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

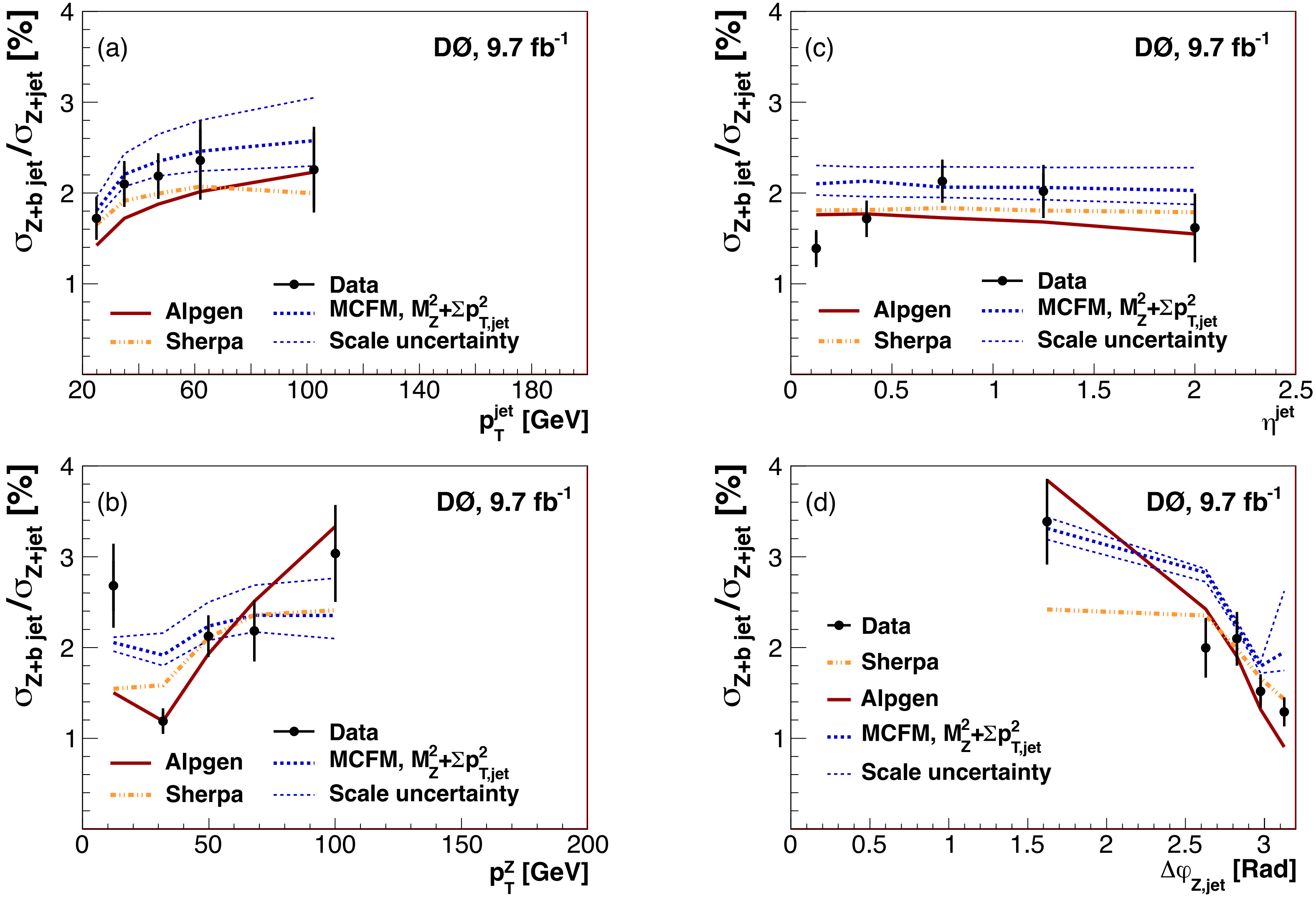
**D0** 0.0196 ± 0.0012 (stat.) ± 0.0013 (syst.)

**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)

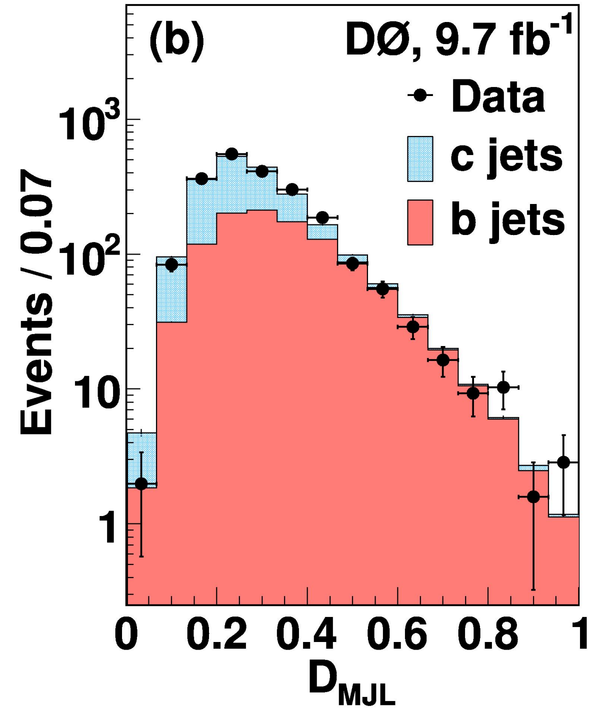
- **First measurement of the ratio differentially as a function of kinematic observables** Phys. Rev. D **87**, 092010 (2013)



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

arXiv:1308.4384

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




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

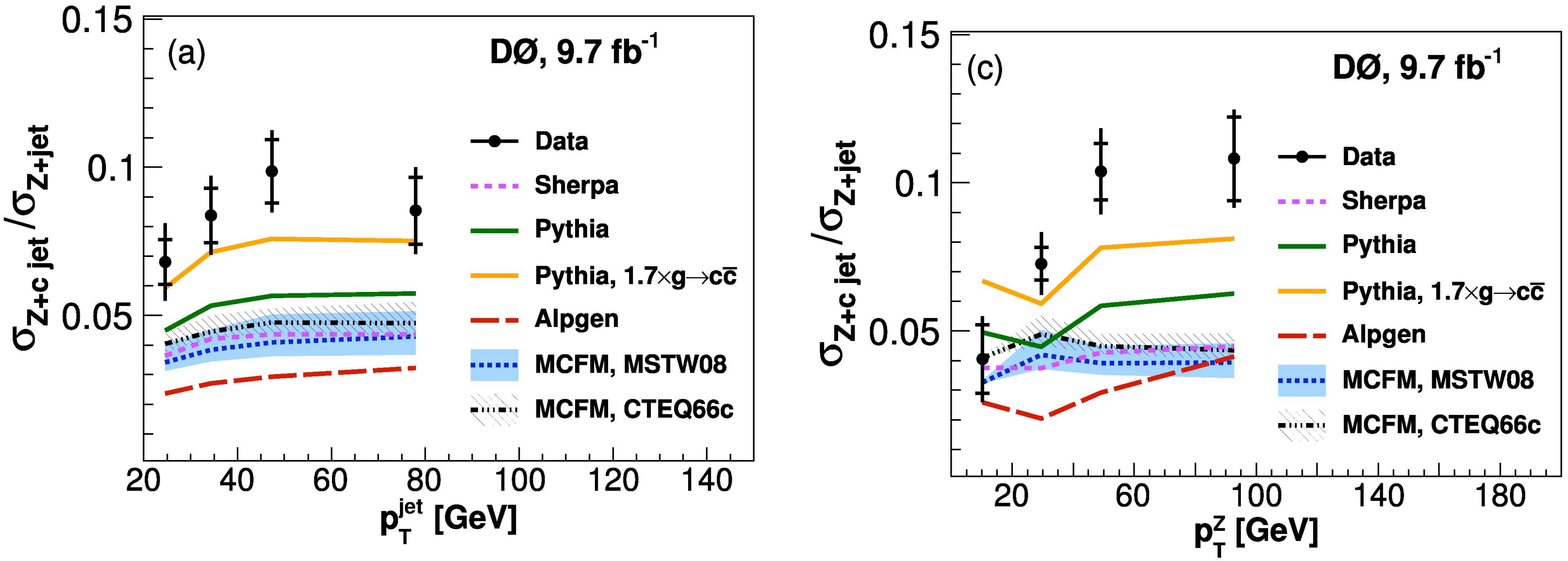
| For 9.7 fb$^{-1}$ | ee + $\mu\mu$ |
|---|---|
| Data-bkg | 2125 |
| Z+b jet | [51.4 ± 2.8] % |
| Z+c jet | [48.6 ± 2.8] % |

| | |
|---|---|
| **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] | $0.0425^{+0.0048}_{-0.0029}$ |

**Measurements significantly in excess of predictions**

# σ (Z+c jet) / σ (Z+jet) Dependence

arXiv:1308.4384




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

# $\sigma$ (Z+c jet) / $\sigma$ (Z+b-jet)

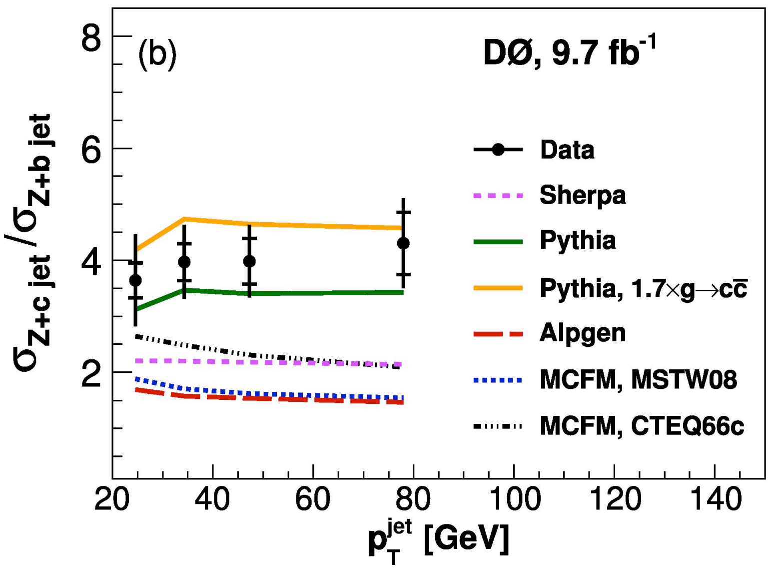
arXiv:1308.4384

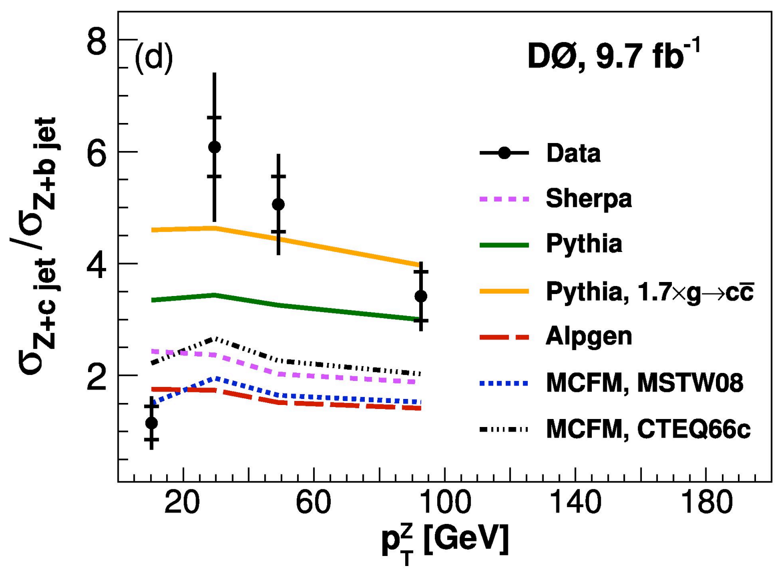
$$\frac{\sigma(Z+c\ \text{jet})}{\sigma(Z+b\ \text{jet})} = \frac{f_c\ \epsilon^b_{tag}}{f_b\ \epsilon^c_{tag}} \times \frac{\mathcal{A}_b}{\mathcal{A}_c}$$

- 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



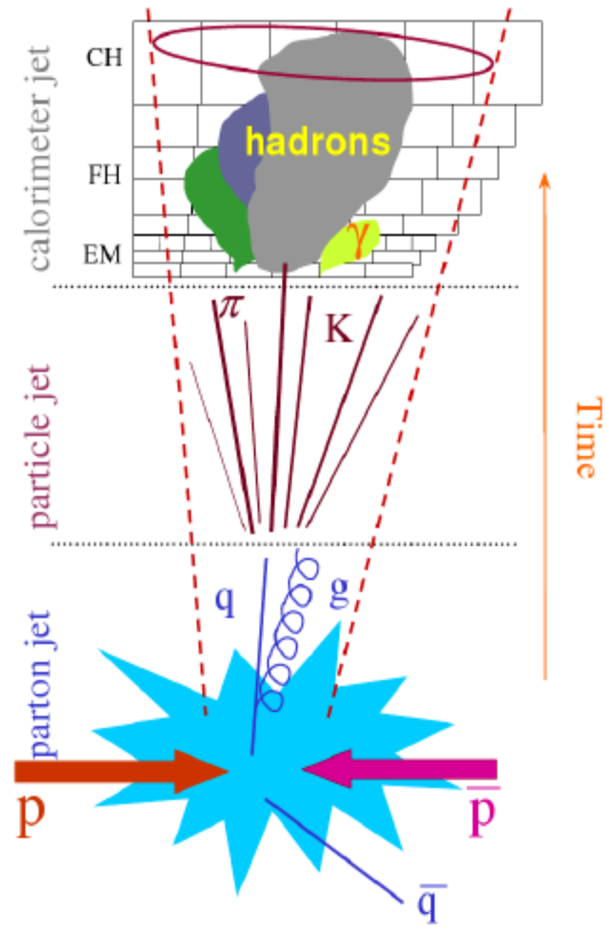
# Conclusions

- Vector boson + 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 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.

# Extra Slides

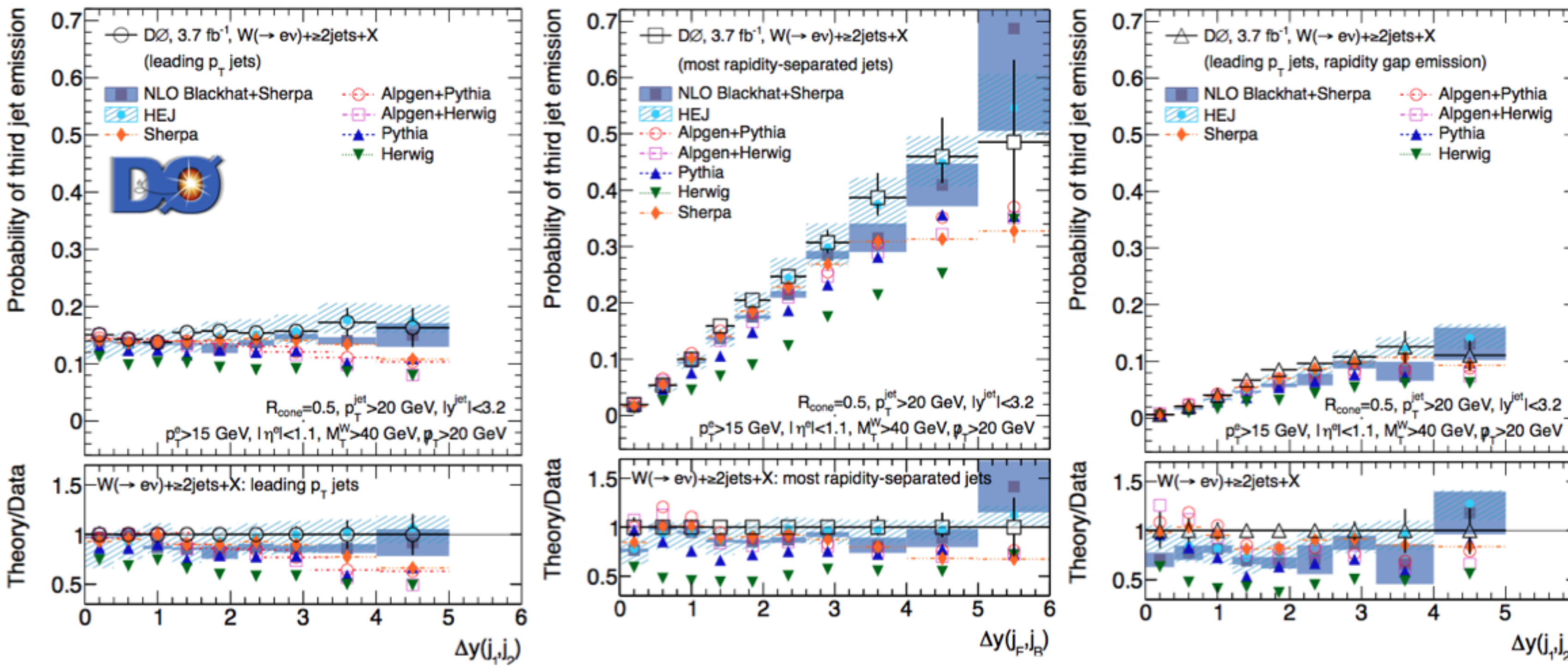
# Jets

- **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

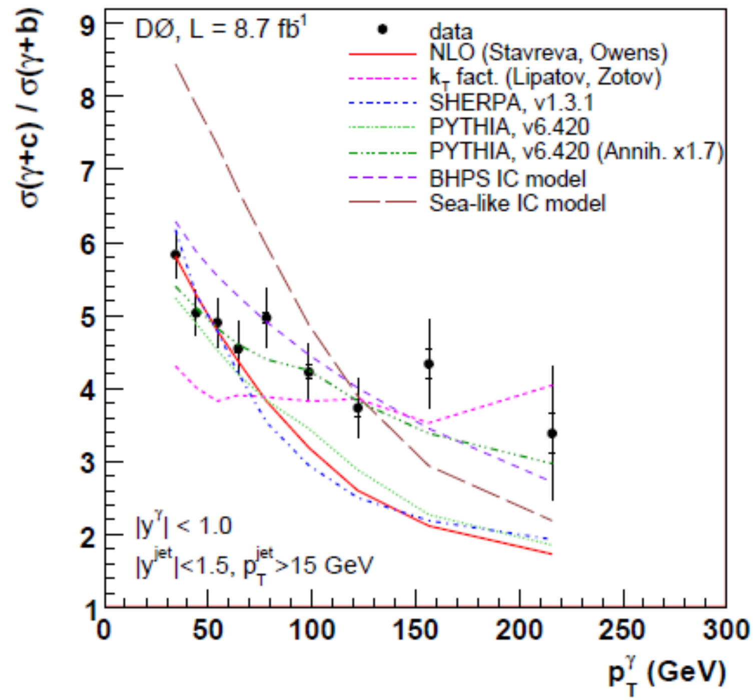



- Measurement of the probability of emission of 3rd jet in the inclusive W+2jet events as a function of
  - Dijet rapidity separation of two highest $p_T$ jets
  - Dijet rapidity separation of two most rapidity-separated jets
  - Dijet rapidity separation of two highest $p_T$ jets and the 3rd jet is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

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

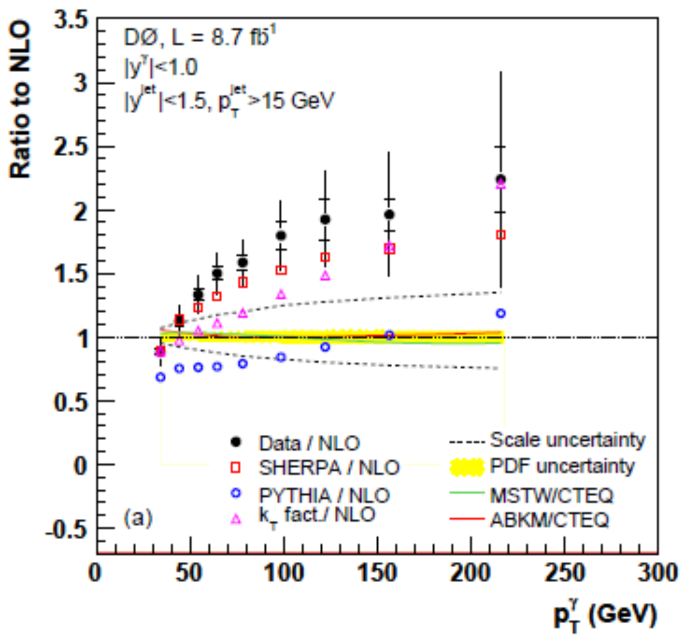
**PLB 719, 354 (2013)**

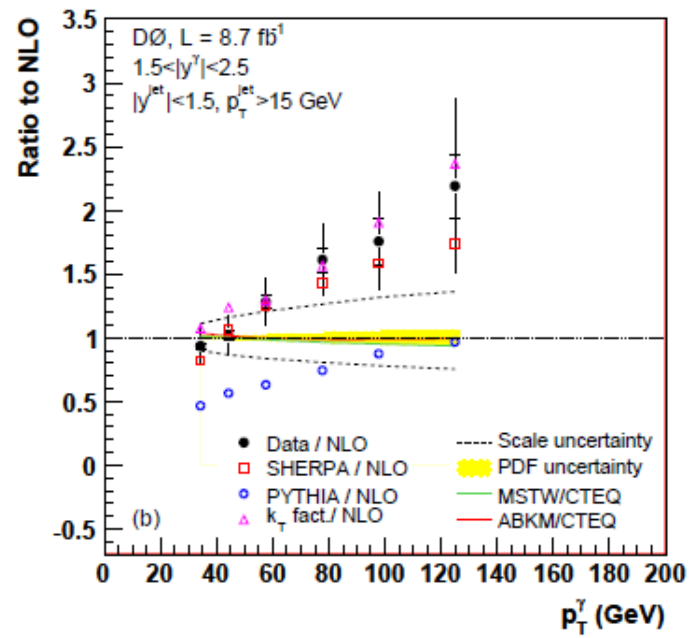
- Measurement of ratio allows more precise comparison with theory
  - Cancellation of many systematic uncertainties
- $p_T^\gamma$ <70 GeV: Good agreement with NLO, PYTHIA and SHERPA, while $k_T$-factorization predicts smaller ratios
- $p_T^\gamma$ >70 GeV: Data show systematically higher ratios
  -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



# $\gamma$ + b-jet(s)

**PLB 714, 32 (2012)**

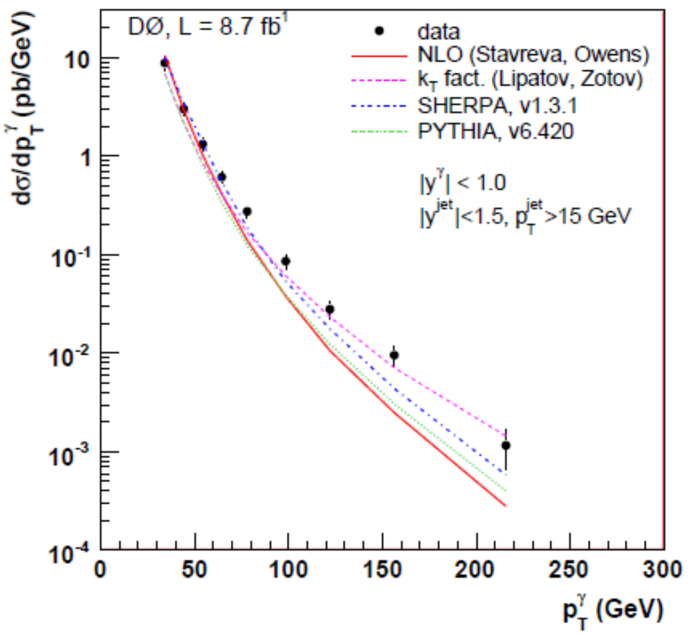


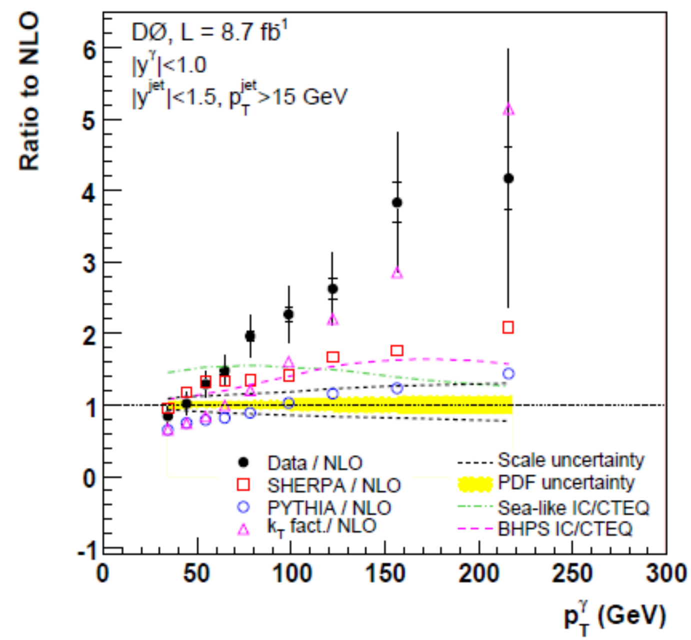




- **Reasonable description within uncertainties at low $p_T^\gamma$ <70 GeV**
- **Disagreements (difference in slopes) at higher $p_T^\gamma$**
  - **Need for higher order corrections at large $p_T^\gamma$ dominated by annihilation process, and resummation of diagrams with additional gluon radiation.**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

# $\gamma$ + c-jet(s)

**PLB 719, 354 (2013)**




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