Measurements of differential $W+\text{jets}$ production and $\alpha_s$ from multijet production

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pp collisions at $\sqrt{s}=1.96$ TeV
$\int L dt = 10.7$ fb$^{-1}$
W + jets Introduction

- Motivation
  - Tests of pQCD
  - A dominant background in SM process like $t\bar{t}$ production, Higgs
  - Background in non-SM processes
- Use $W \rightarrow e\nu$ channel. Same dataset as PLB 705, 200 (2011)
- Selection Criteria
  - Global: $|z_{\text{vtx}}| < 60$ cm
  - Electron: $p_T > 15$ GeV, $|\eta| < 1.1$, $\Delta R$ (between e and jet) $> 0.5$
  - Jet: $\geq 1$ jet, $E_T > 20$ GeV, $|y| < 3.2$
  - W: $E_T > 20$ GeV, $m_T(W) > 40$ GeV
- Backgrounds Considered: $Z$+jets, $t\bar{t}$, single top, diboson, multijet
- Theoretical Predictions:
  - Sherpa (ME matched to parton shower)
  - HEJ (all order resummation)
  - Blackhat (+Sherpa) NLO
- Data and theory compared at particle level
Cross section as a function of W boson $p_T$

$W$+jets cross section, $p_T(W)$

$1/\sigma_{W,\,dN/\!d^2p_T}^W$ (1/GeV)$^2$

$W$+1 jet
$W$+2 jets $\times 10^{-1}$
$W$+3 jets $\times 10^{-2}$
$W$+4 jets $\times 10^{-3}$

$R_{cone}=0.5$, $p_T^{jet}>20$ GeV, $|y^{jet}|<3.2$
$p_T^{W}>15$ GeV, $|\eta^W|<1.1$, $m^{W}>40$ GeV, $p_T>20$ GeV

$\geq 1$ Jet
$\geq 2$ Jets
$\geq 3$ Jets
$\geq 4$ Jets
Cross section as a function of dijet mass for two highest $p_T$ jets for $W+2$ jet and $W+3$ jet

Cross section as a function of dijet mass for two highest $p_T$ jets for $W+2$ jet and $W+3$ jet.
Cross section as a function of $n^{th}$ jet rapidity.

Some problems in high $\eta$ regions
Probability of emission of a 3rd jet in W+≥2 jet events as a function of rapidity separation

Three selection choices

☐ Two jets with the largest gap in rapidity
☐ Two leading $p_T$ jets
△ Two leading $p_T$ jets with 3rd jet in rapidity gap between them

Emission probability grows with gap size as expected.
W+jets, 3rd jet emission

Probability of emission of a 3rd jet in W+2 ≥ jet events as a function of rapidity separation

- Blackhat+Sherpa gives marginally the best fit.
- Some discrepancies in leading $p_T$ gap emission.
Measuring $\alpha_s$ from multijet events

Jet production in hadron collisions

Jet production in hadron collisions

Diagram showing the interaction between a proton and an antiproton, leading to the production of jets.
Measuring $\alpha_s$ from multijet events

Jet production in hadron collisions

Parton distribution functions (PDFs) of the hadrons
Measuring $\alpha_s$ from multijet events

Jet production in hadron collisions

Parton distribution functions (PDFs) of the hadrons

pQCD matrix elements
Measuring $\alpha_s$ from multijet events

Jet production in hadron collisions

Parton distribution functions (PDFs) of the hadrons

pQCD matrix elements

Strong coupling constant
\( \alpha_s(\mu_R) \): depends on \( \mu_R \) the renormalization scale

- Observables must be independent of \( \mu_R \)
- Renormalization Group Equation (RGE) relates \( \alpha_s(Q_0) \) at one scale \( Q_0 \) to \( \alpha_s(Q) \) at any other scale \( Q \)
- RGE predicts all \( \alpha_s(Q) \) curves which are possible
$\alpha_s$ and the RGE

- $\alpha_s(\mu_R)$: depends on $\mu_R$ the renormalization scale
- Observables must be independent of $\mu_R$
- Renormalization Group Equation (RGE) relates $\alpha_s(Q_0)$ at one scale $Q_0$ to $\alpha_s(Q)$ at any other scale $Q$
- RGE predicts all $\alpha_s(Q)$ curves which are possible

Agreement: label curves by $\alpha_s(\mu_R=M_Z)$
Not yet at scales > 208 GeV

S. Bethke, arXiv:0908.1135
"Test running over 40 < \text{E}_T < 440 \text{ GeV}"

"Test running up to \text{p}_T \rightarrow 600 \text{ GeV}"


B. Malaescu, P. Starovoitov, arXiv:1203.5416

From ATLAS inclusive jet cross section data
But analyses use PDFs for which DGLAP evolution is already done under assumption of running $\alpha_s(Q)$ according to the RGE

- RGE was already assumed
- Not an independent test

DGLAP: Dokshitzer–Gribov–Lipatov–Altarelli–Parisi


B. Malaescu, P. Starovoitov, arXiv:1203.5416

“Test running over 40 < $E_T$ < 440 GeV”

“Test running up to $p_T$ = 600 GeV”
$R_{\Delta R}$

average number of neighboring jets for jets from an inclusive jets sample

Depends on 3 variables:

- inclusive jet $p_T$
- distance $\Delta R$ to neighbor jet in $(\Delta \phi, \Delta y)$
- neighbor jet $p_{T-nbr}$ requirement
1. Start with central inclusive jet sample ($|y|<1$)
2. Loop over all inclusive jets
   For each inclusive jet: count No. of neighboring jets
   - in distance $\Delta R$ in $(\Delta \phi, \Delta y)$
   - with $p_{T_{nbr}} > p_{T_{min\,nbr}}$
3. Ratio: sum of all neighboring jets / total number of inclusive jets
   - average number of neighboring jets:
     \[ R_{\Delta R}(p_T, \Delta R, p_{T_{min\,nbr}}) \]
   • For $\Delta R < \pi$ only contributions from (at least) 3-jet events
   • Inclusive measurement using all jets
   • RGE dependence and systematic uncertainties mostly cancel out in the ratio
$R_{\Delta R} = \text{average number of neighboring jets per jet}$

here: for $\Delta R < \pi/2$

in this example all jets have same $(p_T, y)$

2 jets

no neighbors within $\Delta R$:

0 neighbors

3 jets

two jets have one neighbor each:

2 neighbors

4 jets

each of the four jets has one neighbor:

4 neighbors

if all events were like this

$R_{\Delta R} = 0$

$R_{\Delta R} = 2/3$

$R_{\Delta R} = 1$
$R_{\Delta R}$ results

- Average number of neighbor jets within $\Delta R$ of an inclusive jet
- $|y|<1$, $50<p_T<450$ GeV
- 4 different $p_T$-nbr-min requirements in 3 $\Delta R$ regions

dependence of $R_{\Delta R}$ on $(p_T, p_T$-nbr, $\Delta R)$ described by pQCD
\( R_{\Delta R} \) data/theory

- Good agreement for \( p_{T-nbr-min} = 50 \text{ GeV} \) and higher
- Not so good for requirement \( p_{T-nbr-min} = 30 \text{ GeV} \) (low \( p_T \) physics?)
Single data point:
Determine $\alpha_s$ from projection

Groups of data points:
Determine $\alpha_s$ by minimizing $\chi^2$ function

Both require a parameterization of the theory result vs. $\alpha_s$.

**Perturbative:**
- NLOJET++/fastNLO for 2-jet and 3-jet NLO calculation
- PDFs: MSTW2008NLO
- PDF uncertainty: MSTW 68% C.L. PDFs / CT10, NNPDFv2.1
- Central scale $\mu_R = \mu_F = \mu_0 = p_T$
- Scale uncertainty varying: $\mu_R, \mu_F$ in $(0.5, 2)\mu_0$ with $0.5 < (\mu_R/\mu_F) < 2$

**Non-Perturbative Corrections:** PYTHIA with different tunes
\( \alpha_s(p_T) \) results

- Use \( p_{T\text{nbr}} > 50, 70, 90 \) GeV (138 data points total)
- At each \( p_T \), combine all data points with different \( p_{T\text{nbr}} \) and \( \Delta R \) requirements
- Determine results for \( \alpha_s(p_T) \) at 12 \( p_T \) values

\( \rightarrow \alpha(p_T) \) results up to 400 GeV
\( \rightarrow \alpha_s(p_T) \) decreases with \( p_T \) as predicted by the RGE

Results agree with results from
\( \rightarrow \) ALEPH event shape data
\( \rightarrow \) Previous DØ results from inclusive jets

\[
\alpha_s(M_Z) = 0.1191^{+0.0048}_{-0.0071}
\]
Summary

- DØ continues to produce important QCD results
- W+jet distributions measured and compared with theory. Agreement is reasonable
- A new inclusive variable defined \((R_{\Delta R})\) for measuring \(\alpha_s\) from multi-jet events
- \[\alpha_s(M_Z) = 0.1191^{+0.0048}_{-0.0071}\]
- Demonstrates running of \(\alpha_s\) to 400 GeV
Published W+jets

\[ \frac{\sigma_X}{\sigma_{\text{Data}}} \]

- **DØ, 4.2 fb^{-1}**
- **MCFM NLO**
- **Blackhat+Sherpa NLO**

**a)** $W(\rightarrow e\nu)+1\text{jet}+X$ vs. Leading jet $p_T$ (GeV) (njets>=1)

**b)** $W(\rightarrow e\nu)+2\text{jet}+X$ vs. Second jet $p_T$ (GeV) (njets>=2)
Published $W+\text{jets}$

**Graph c)**

$\sigma_X/\sigma_{\text{Data}}$ vs. Third jet $p_T$ (GeV) (njets$\geq$3)

- **$D\emptyset, 4.2 \text{ fb}^{-1}$**
- **Rocket+MCFM NLO**
- **Blackhat+Sherpa NLO**

**Graph d)**

$\sigma_X/\sigma_{\text{Data}}$ vs. Fourth jet $p_T$ (GeV) (njets$\geq$4)

- **$D\emptyset, 4.2 \text{ fb}^{-1}$**
- **Rocket+MCFM LO**
- **Blackhat+Sherpa LO**
\( \alpha_s \) from inclusive jets

\[ \alpha_s(p_T) \text{ from inclusive jet cross section in hadron-induced processes} \]

\[ \alpha_s(M_Z) = 0.1161 \pm 0.0041 \pm 0.0048 \]

\( \text{(D\O\ combined fit)} \)

Phys. Rev. D 80, 111107 (2009),
Inclusive Jet Cross Section

\[ \frac{d^2 \sigma}{dp_T dy} (\text{pb/GeV}) \]

- \( |y| < 0.4 \) (x32)
- \( 0.4 < |y| < 0.8 \) (x16)
- \( 0.8 < |y| < 1.2 \) (x8)
- \( 1.2 < |y| < 1.6 \) (x4)
- \( 1.6 < |y| < 2.0 \) (x2)
- \( 2.0 < |y| < 2.4 \)

\[ \sqrt{s} = 1.96 \text{ TeV} \]
\[ L = 0.70 \text{ fb}^{-1} \]
\[ R_{\text{cone}} = 0.7 \]

- NLO pQCD
- +non-perturbative corrections

\[ \text{CTEQ6.5M} \quad \mu_R = \mu_F = p_T \]

Inclusive Jet Cross Section

DØ Run II \( R_{\text{cone}} = 0.7 \)

L = 0.70 fb\(^{-1} \)

NLO pQCD \( \mu_R = \mu_F = p_T \)
+ non-perturbative corrections

Data
Systematic uncertainty

\[ \frac{\text{data}}{\text{theory}} \]

\|y\| < 0.4

0.4 < |y| < 0.8

0.8 < |y| < 1.2

1.2 < |y| < 1.6

1.6 < |y| < 2.0

2.0 < |y| < 2.4

\( p_T \) (GeV)

NLO scale uncertainty

CTEQ6.5M with uncertainties

MRST2004