Vector boson + jet production at forward rapidities

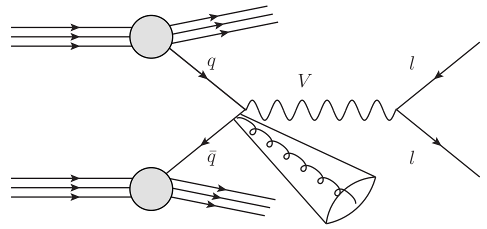
Duncan M. Walker

June 5, 2019

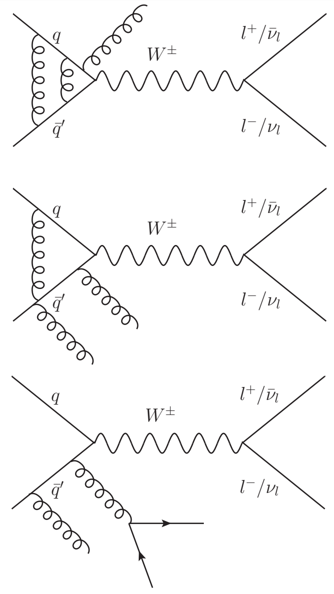
NNLOJET collaboration
IPPP, Durham University
31^{st} Rencontres de Blois

Motivation

- Precision test of pQCD
  ↪ Forward region challenging:
    ↪ Numerics, power corrections
- PDF constraints
  ↪ Large source of theory uncertainty
- Detector calibration
  ↪ jet energy scale
- BSM searches
  ↪ monojet



Antenna Subtraction @ NNLO

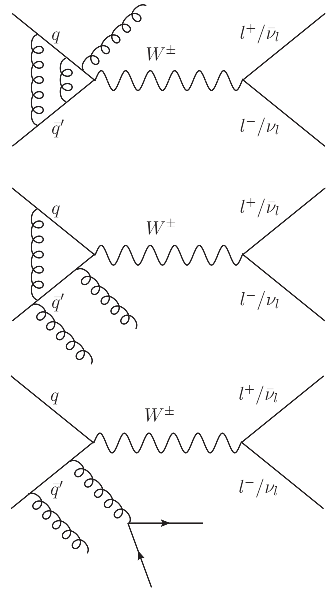


VV: $\int_{\Phi_{W+1}} d\sigma^{VV}_{NNLO} \rightarrow 1/\epsilon^4 \ldots 1/\epsilon$ poles

RV: $\int_{\Phi_{W+2}} d\sigma^{RV}_{NNLO} \rightarrow 1/\epsilon^2, 1/\epsilon$ poles
Single unresolved

RR: $\int_{\Phi_{W+3}} d\sigma^{RR}_{NNLO} \rightarrow$ Double unresolved
Single unresolved

Antenna Subtraction @ NNLO



VV: $\int_{\Phi_{W+1}} \left[d\sigma^{VV}_{NNLO} - d\sigma^{U}_{NNLO} \right]$
$\rightarrow$ finite

RV: $\int_{\Phi_{W+2}} \left[d\sigma^{RV}_{NNLO} - d\sigma^{T}_{NNLO} \right]$
$\rightarrow$ finite

RR: $\int_{\Phi_{W+3}} \left[d\sigma^{RR}_{NNLO} - d\sigma^{S}_{NNLO} \right]$
$\rightarrow$ finite

$\rightarrow \int d\sigma^{U}_{NNLO} + \int d\sigma^{T}_{NNLO} + \int d\sigma^{S}_{NNLO} = 0$

```
    _  ___  ____   ____     ____________
   / |/ / |/ / /  / __ \__ / / __/_  __/
  /    /    / /__/ /_/ / // / _/  / /
 /_/|_/_/|_/____/\____/\___/___/ /_/
```

X. Chen, J. Cruz-Martinez, J. Currie, R. Gauld, A. Gehrmann-De Ridder,
T. Gehrmann, E.W.N. Glover, M. Höfer, A. Huss, I. Majer, J. Mo,
T. Morgan, J. Niehues, J. Pires, DMW, J. Whitehead

Processes available with antenna subtraction (+ p2B, Q_T):

$pp \to V$	@NNLO	$pp \to H$	@N^{3}LO
$pp \to V + j$	@NNLO	$pp \to H + j$	@NNLO
$\hookrightarrow V \to ll, \quad V \in [W^{\pm}, Z/\gamma^*]$		$pp \to H + 2j$ (VBF)	@NNLO
$pp \to$ jets	@NNLO	$\hookrightarrow H \to \gamma\gamma,\ \tau\tau,\ V\gamma,\ VV$	
$\hookrightarrow$ inclusive, dijet		$pp \to VH$	@NNLO
$pp \to \gamma + j$	@NNLO	$\hookrightarrow H \to bb$	
$pp \to \gamma\gamma$	@NNLO	$e^+e^- \to 3j$	@NNLO
$ep \to 1j$ (NC, CC)	@N^{3}LO	$ep \to 2j$ (NC, CC)	@NNLO

Overview

Consider two sets of combined V + jet data:

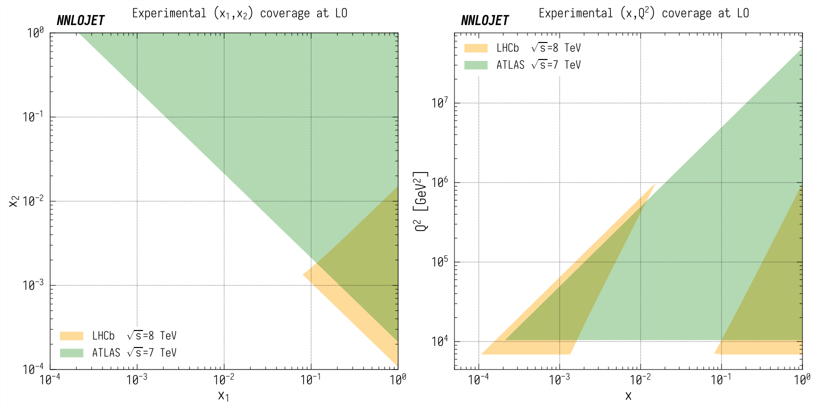
- **LHCb** $\sqrt{s} = 8$ TeV [hep-ex/1605.00951]
  - Separate Z, W^+ and W^- distributions
  - $W^\pm$ ratios/asymmetry
  - $\sim 2 < \eta < 4.5$
- **ATLAS** $\sqrt{s} = 7$ TeV
  - W + jet distributions [hep-ex/1409.8639]
  - Z + jet distributions [hep-ex/1304.7098]
  - W/Z ratios [hep-ex/1408.6510]
  - $\sim |\eta| < 4.4$

Idea: Use NNLOJET calculation to push NNLO V + jet to high η/y for the first time → PDFs at high Bjorken x, flavour sensitivity

Full results: hep-ph/1901.11041, EPJC XXXX

[A. Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover, A. Huss, DMW]

Kinematic Coverage [LO]



Allows us to probe forward regions ↔ high x_1, low x_2

$$x_{1,2} \geq \frac{1}{\sqrt{s}}(m_T^V e^{\pm y^V} + p_T^j e^{\pm y^j})$$

LHCb @ 8 TeV

LHCb Fiducial Region

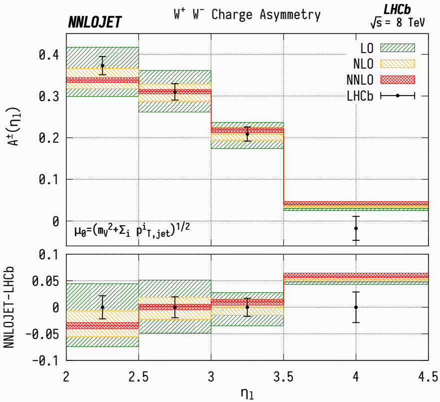
Overall selection:

$$p_T^{\text{jet}} > 20\ \text{GeV}, \qquad 2.2 < \eta^{\text{jet}} < 4.2, \qquad \Delta R_{\mu,\text{jet}} > 0.5,$$
$$p_T^{\mu} > 20\ \text{GeV}, \qquad 2 < y^{\mu} < 4.5$$

Process specific cuts:

$$W^{\pm}: \qquad p_T^{\mu+\text{jet}} > 20\ \text{GeV}$$
$$Z: \qquad 60\ \text{GeV} < m_{\mu\mu} < 120\ \text{GeV}$$

LHCb Charge Asymmetry $\left[\frac{\sigma_{W^+} - \sigma_{W^-}}{\sigma_{W^+} + \sigma_{W^-}}\right]$



Scale uncertainties:

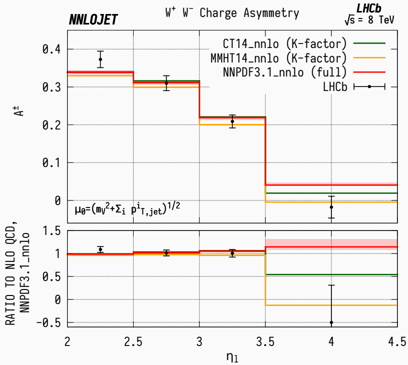
Decorrelate μ_R, μ_F between numerator/denominator by a maximum factor of 2 between any scale pair

→ 31pt variation

NNPDF3.1_nnlo @ $\alpha_S = 0.118$

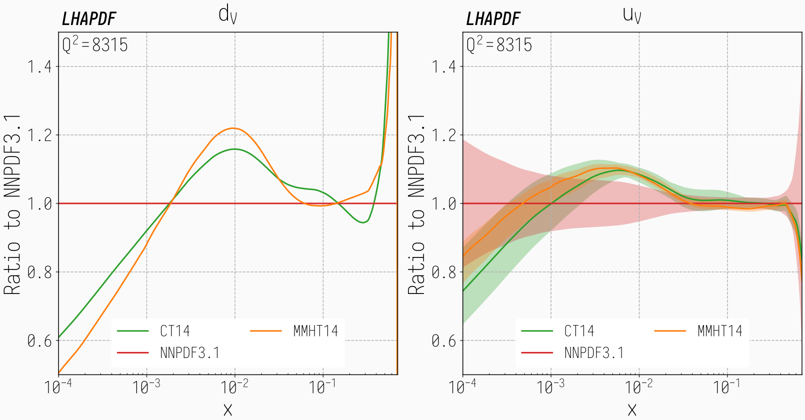
- Asymmetry probes $(u - d)$ valence quark PDFs
- Most forward bin: $x_1 \gtrsim 0.1$, $x_2 \gtrsim 5 \times 10^{-5}$
- Overshoot in asymmetry ↔ u overestimate, d underestimate

LHCb Charge Asymmetry $\left[\frac{\sigma_{W^+}-\sigma_{W^-}}{\sigma_{W^+}+\sigma_{W^-}}\right]$



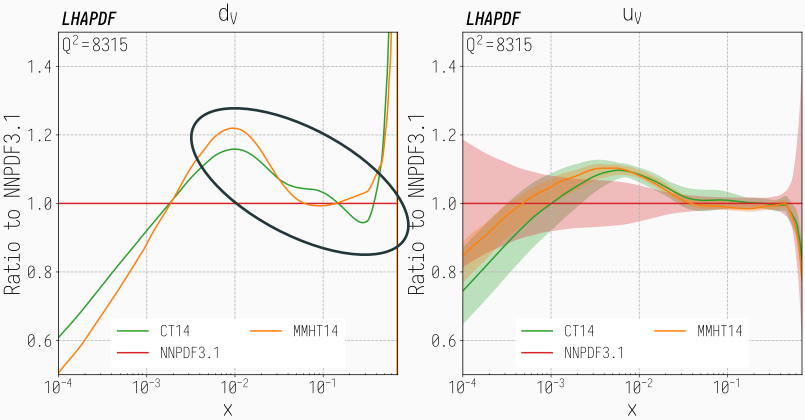
- NLO + k-factor reconstruction for PDF variation
- Large variation between PDF sets → sensitivity!

Valence Quark PDFs



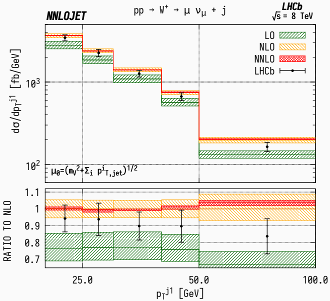
- At high-x, d valence contribution drives difference between PDF sets
- Current constraints on u/d primarily from DØ lepton charge asymmetry data + fixed target experiments

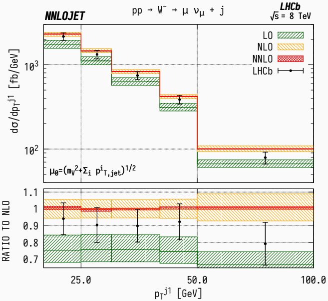
Valence Quark PDFs

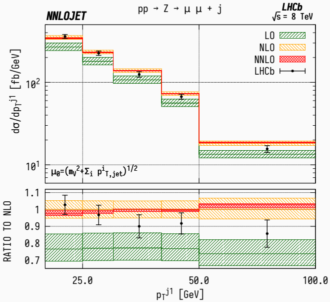


- At high-x, d valence contribution drives difference between PDF sets
- Current constraints on u/d primarily from DØ lepton charge asymmetry data + fixed target experiments

LHCb Jet p_T Distributions







Universal overestimate at high x

W(Z)J lowest bin:

$x_1 \gtrsim 0.04(0.08)$,

$x_2 \gtrsim 5 \times 10^{-5}(1 \times 10^{-4})$

W(Z)J highest bin:

$x_1 \gtrsim 0.08(0.11)$,

$x_2 \gtrsim 1.1 \times 10^{-4}(2 \times 10^{-2})$

ATLAS @ 7 TeV

ATLAS Fiducial Region

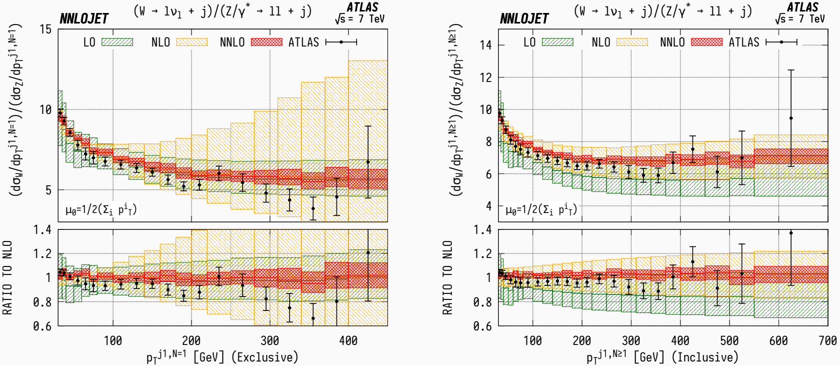
Overall selection:

$$
\begin{aligned}
{p_T}^{\text{jet}} &> 30\ \text{GeV}, \qquad |y^{\text{jet}}| < 4.4, \qquad \Delta R_{\mu,\text{jet}} > 0.5, \\
{p_T}^{l} &> 25\ \text{GeV}, \qquad |y^{l}| < 2.5
\end{aligned}
$$

Process specific cuts:

$$
\begin{aligned}
W^{\pm}: \quad & E_T^{\text{miss}} > 25\ \text{GeV} \\
& m_T^W > 40\ \text{GeV} \\
Z: \quad 60\ \text{GeV} < {} & m_{\mu\mu} < 116\ \text{GeV} \\
& \Delta R_{\ell} > 0.2
\end{aligned}
$$

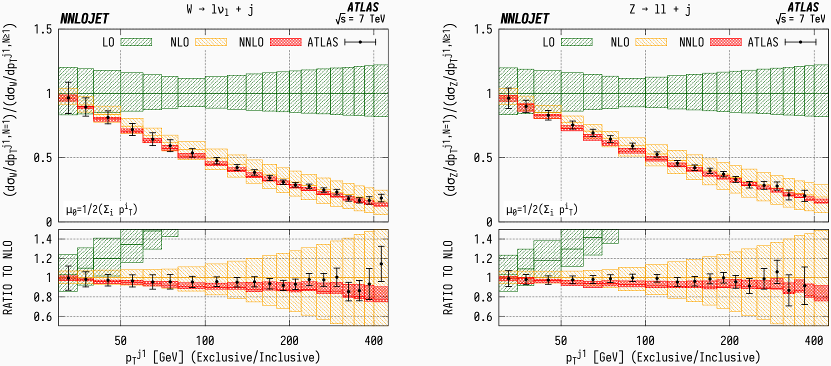
ATLAS Jet p_T Ratios



Global overestimate in both inclusive (right) and exclusive (left)

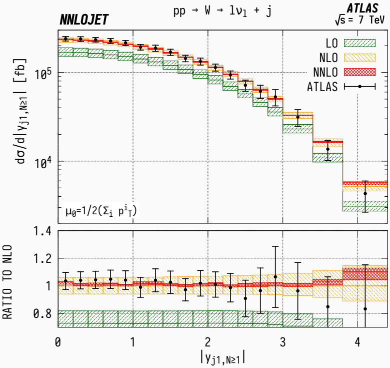
$$\frac{\sigma^{WJ}}{\sigma^{ZJ}} \sim \frac{ug + dg}{0.29ug + 0.37dg},$$ consistent with harder d quark distribution

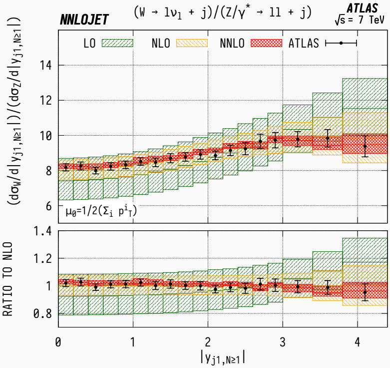
ATLAS Exclusive/Inclusive



- Quantify description of jet multiplicities > 1 using ratio $(N \geq 1)/(N = 1)$
- Reasonable agreement, capture dominant behaviours
- W, Z emission structure $\sim$ identical

ATLAS Jet Rapidity Distributions





- Forwardmost bin: $x_1 \gtrsim 0.19$, $x_2 \gtrsim 1.5 \times 10^{-4}$
- Combined $W^{\pm}$ $\rightarrow$ lose some flavour sensitivity

Conclusions

- Now able to access V + jet @ NNLO in forward ($\eta > 3$) regions
- Natural use is for inclusion of data in NNLO PDF fits to constrain high-x contributions
- Charge asymmetry $\rightarrow$ valence quark constraints
  $\rightarrow$ LHCb data is particularly sensitive to d valence distributions

Backup slides

Scale Variation Envelopes

Distributions:

$$d\sigma(\mu_F, \mu_R), \quad \frac{1}{2} \leq \mu/\mu' \leq 2, \quad \mu,\ \mu' \in [\mu_R, \mu_F]$$

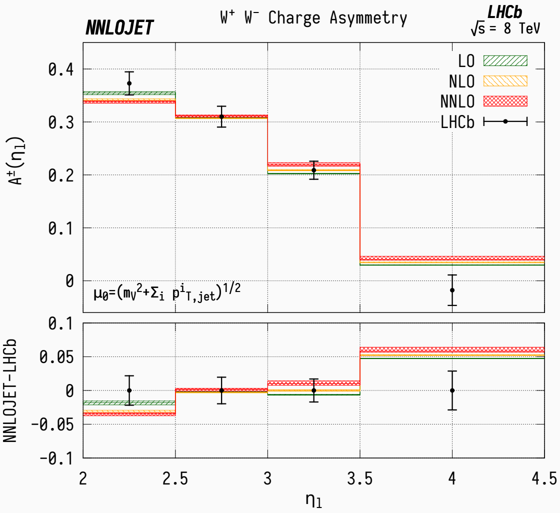
Ratios:

$$\frac{d\sigma^a(\mu_F, \mu_R)}{d\sigma^b(\tilde{\mu}_f, \tilde{\mu}_R)}, \quad \frac{1}{2} \leq \mu/\mu' \leq 2, \quad \mu,\ \mu' \in [\mu_R, \tilde{\mu}_R, \mu_F, \tilde{\mu}_F]$$

Asymmetries:

$$\frac{\left[d\sigma^{W^+} - d\sigma^{W^-}\right](\mu_F, \mu_R)}{\left[d\sigma^{W^+} + d\sigma^{W^-}\right](\tilde{\mu}_f, \tilde{\mu}_R)}, \quad \frac{1}{2} \leq \mu/\mu' \leq 2, \quad \mu,\ \mu' \in [\mu_R, \tilde{\mu}_R, \mu_F, \tilde{\mu}_F]$$

LHCb Charge Asymmetry $\left[\frac{\sigma_{W+}-\sigma_{W-}}{\sigma_{W+}+\sigma_{W-}}\right]$



Fully Correlated scale uncertainties