New physics opportunities in W+j at the LHC

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Particle Theory Seminar
Universität Würzburg, Germany

3rd of February 2022

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New opportunities for an old process

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Outline:

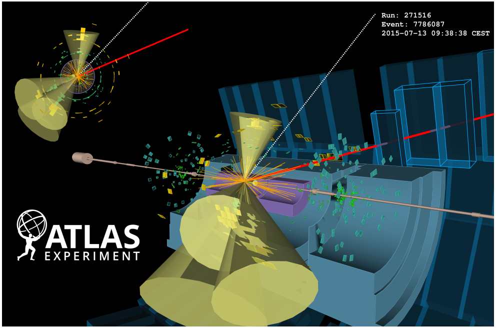
→ Predictions for ...

- Polarised $\mathrm{pp} \to \mathrm{W}^{\pm} + \mathrm{j}$
- $\mathrm{pp} \to \mathrm{W}^{\pm} + \mathrm{j}_c$

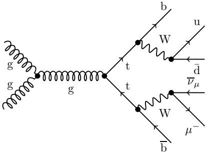
→ ... and why you want to compute them

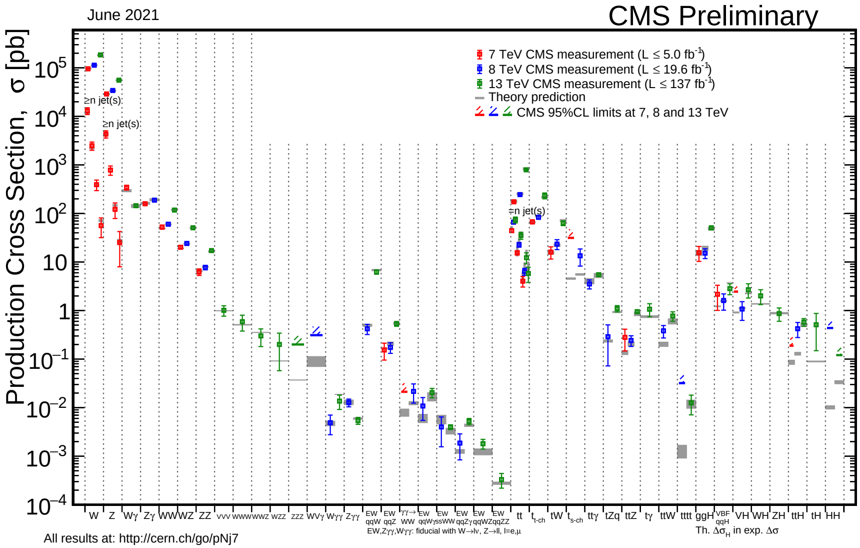
$\rightarrow$ Illustration of Giordano Bruno's philosophical ideas (XVIthcentury)

LHC: Great tool to probe fundamental interactions at high energies
$\rightarrow$ Cross talk between **experiment** and **theory**



$$\mathrm{pp} \to \mathrm{t}^\star\bar{\mathrm{t}}^\star \to (\mathrm{W}^\star \to \nu_\mu \mu^-)\,(\mathrm{W}^\star \to \mathrm{jj})\,\mathrm{b}\bar{\mathrm{b}}$$





→ Cross-sections measurements machine!

- Greatest achievement of the LHC so far:

Discovery of the Higgs boson

→ Great interest in measuring properties of the Higgs boson ...

... but there are also other interesting things

Tools

- Private Monte Carlo STRIPPER

  [Czakon, Heymes, Poncelet; 1005.0274, 1101.0642, 1408.2500]
- Tree level: AVH [Bury, van Hameren; 1503.08612]
- One-loop: OPENLOOP2 [Buccioni et al.; 1907.13071]
- Two-loop: [Gehrmann, Tancredi; 1112.1531]

  → using GINAC [Bauer, Frink, Kreckel], [Vollinga, Weinzierl; hep-ph/0410259]
- Complex-mass scheme [Denner et al.; hep-ph/9904472, hep-ph/0505042, hep-ph/0605312]
- PDF: LHAPDF [Buckley et al.; 1412.7420]

State of the art: W+j

- NLO QCD:

  [Giele et al.; hep-ph/9302225], [Arnold et al.; Nucl.Phys. B319 (1989) 37-71, Phys.Rev. D40 (1989) 912],

  [Campbell et al.; hep-ph/0202176, 0809.3003, 1107.3714]

- NNLO QCD:

  [Boughezal et al.; 1504.0213, 1602.06965], [Gehrmann-De Ridder et al.; 1901.11041]

- NLO EW:

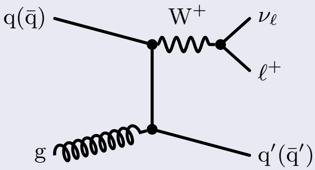
  [Kühn et al.; hep-ph/0703283, 0708.0476], [Hollik et al.; 0707.2553], [Denner et al.; 0906.1656]

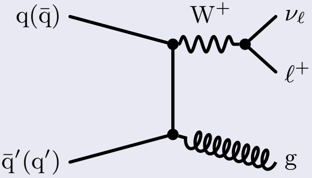
- Combinations of QCD and EW corrections:

  [Kallweit et al.; 1412.5157, 1511.08692], [Lindert et al.; 1511.08692], [Biederman, MP et al.; 1704.05783]

- NNLO QCD for polarised $\mathrm{pp} \to \mathrm{W}^{\pm} + \mathrm{j}$

LO process





- pp $\rightarrow \ell^{\pm} \overset{(-)}{\nu_\ell}$ j is the physical process
  $\rightarrow$ Not pp $\rightarrow$ W$^{\pm}$ j !

State of the art (polarised W+j)

- NLO QCD for polarised W-jet:

  [Bern et al.; 1103.5445] [Stirling, Vryonidou; 1204.6427]

- Interpretation of polarisation in terms of BSM:

  [Belyaev, Ross; 1303.3297]

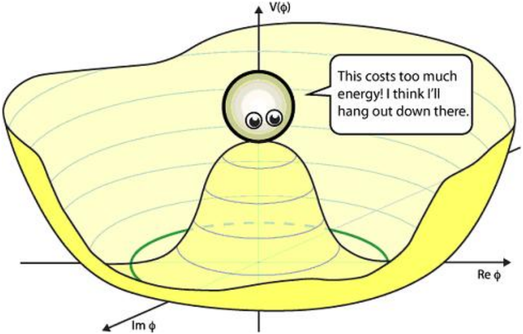
- Recent polarised predictions (diboson)
  - NLO QCD+EW: [Denner, Pelliccioli; 2006.14867, 2010.07149, 2107.06579], [Baglio, Le Duc; 1810.11034, 1910.13746]
  - NNLO QCD: [Poncelet, Popescu; 2102.13583]
  - Automation: [Buarque Franzosi, Mattelaer, Ruiz, Shil; 1912.01725]

→ This work:
[MP, Popescu, Poncelet; 2109.14336]:

NNLO QCD computation for polarised W+jet production

Motivation

- Polarisation related to EWSB
  $\rightarrow$ longitudinal polarisation
  "the Higgs mechanism is the conversion of Goldstone modes into the longitudinal polarisation mode of massive weak bosons" [Pellicciolli]
  $\rightarrow$ probe of new physics/extended Higgs sector



Introduction

Master formula

$$\mathcal{M}^{\mathrm{NWA}}(\mathrm{wj}) = \frac{1}{M_W \Gamma_W} \sum_{h\in\Lambda} \mathcal{M}_h(\mathrm{pp} \to \mathrm{Wj}) \cdot \Gamma_h \left(\mathrm{W} \to \ell^{\pm} \overset{(-)}{\nu_\ell}\right)$$

with $\Lambda = \{+1, -1, 0\}$

- transversely polarised amplitudes: $\Lambda = \mathrm{T} = \{+1, -1\}$
- longitudinally polarised amplitudes: $\Lambda = \mathrm{L} = \{0\}$
  - Unpolarised cross section: $|\mathcal{M}^{\mathrm{NWA}}|^2$
  - polarised cross sections:
    - $\sigma_{\mathrm{L}} \sim |\mathcal{M}_0|^2 \cdot |\Gamma_0|^2$
    - $\sigma_{\mathrm{T}} \sim |\mathcal{M}_{+1}|^2 \cdot |\Gamma_{+1}|^2 + |\mathcal{M}_{-1}|^2 \cdot |\Gamma_{-1}|^2$
  - polarised sum of cross sections: $\sigma_{\mathrm{pol.\ sum}} = \sigma_{\mathrm{L}} + \sigma_{\mathrm{T}}$
  - Polarisation fractions: $f_{\mathrm{L}} = \sigma_{\mathrm{L}}/\sigma_{\mathrm{pol.\ sum}}$, $f_{\mathrm{T}} = \sigma_{\mathrm{T}}/\sigma_{\mathrm{pol.\ sum}}$

“Measuring polarisation”

- No measurement of polarisation
  $\rightarrow$ extraction of parameters based on theory input

Several shortcomings

⚠ Polarisation only defined for on-shell bosons
⚠ Only the unpolarised prediction is physical

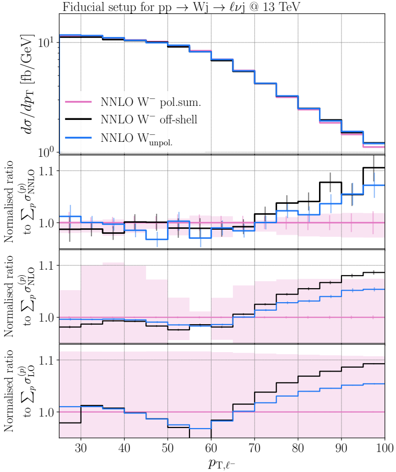
Set-up

Set-up taken from CMS analysis 13 TeV analysis [1707.05979]

$$|y_\mathrm{j}| < 2.4 \quad \text{and} \quad p_{\mathrm{T,j}} > 30\,\mathrm{GeV}$$

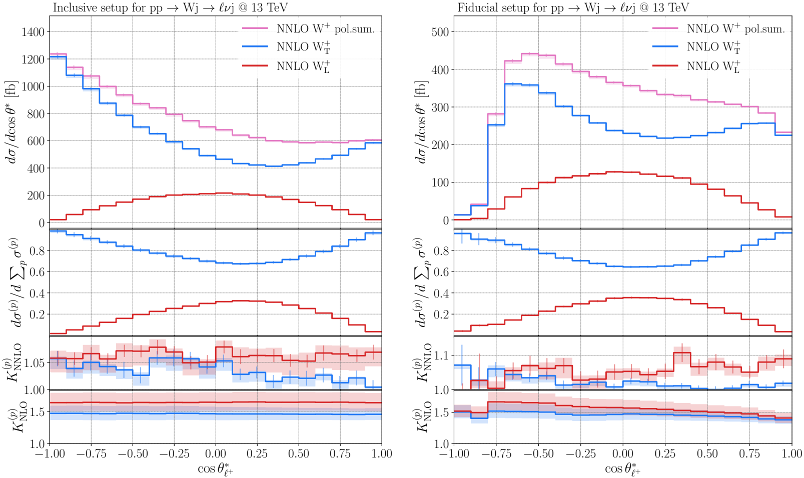
- Inclusive setup:
  Only jet requirement
- Fiducial setup:
  Jet requirement
  +
  $$\Delta R(\ell, j) > 0.4$$
  +
  $$p_{\mathrm{T},\ell} > 25\,\mathrm{GeV}, \qquad |\eta_\ell| < 2.5, \qquad M_\mathrm{T}(\mathrm{W}) > 50\,\mathrm{GeV}$$

Addressing shortcomings

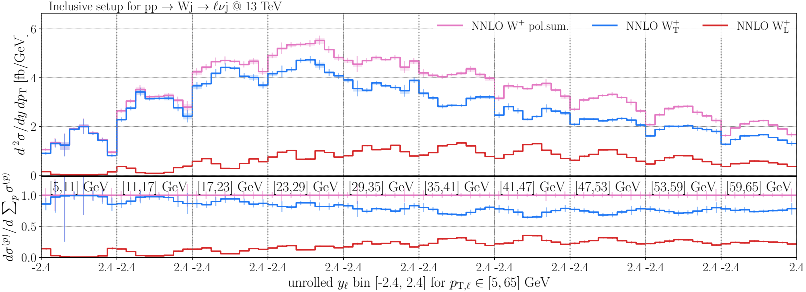


- Off-shell and interference effect up to 10%
  → dangerous regions for extraction of polarisation

W^+_T vs. W^+_L

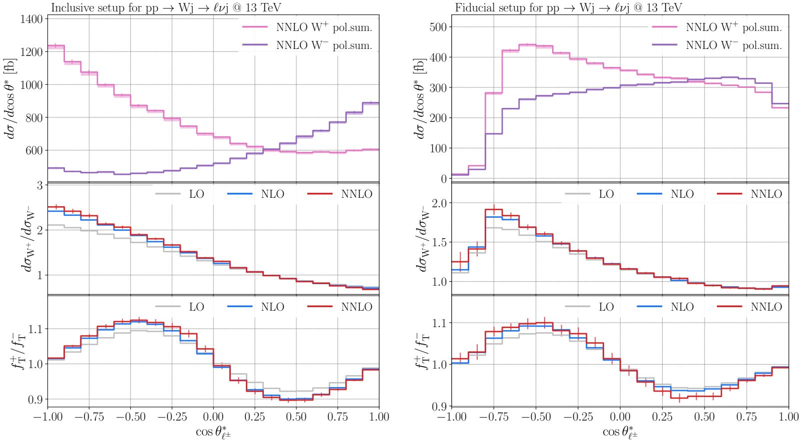


- W^+_T and W^+_L rather different
- Corrections are observable dependent
- Large effect of event selection



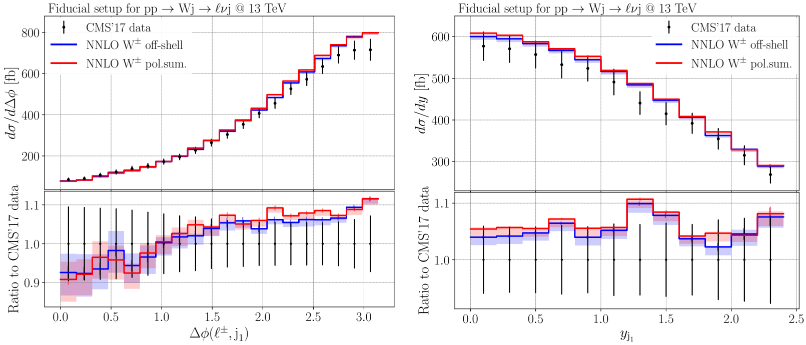
- 2D-information
- Usable in experimental analysis
  → CMS Drell-Yan at 13 TeV [2008.04174]

W^+ vs. W^-



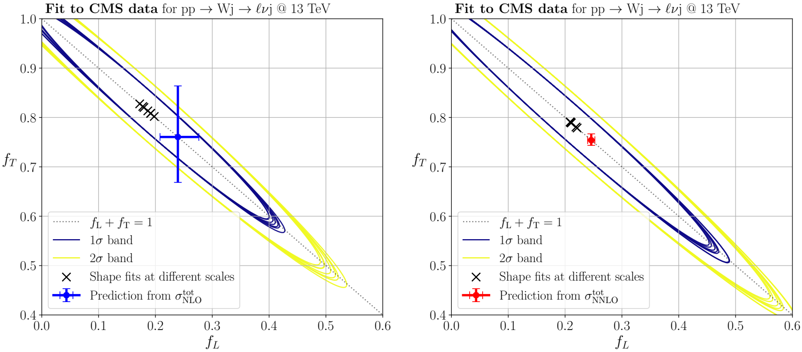
- W^+ and W^- rather different
- Ratios rather stable
- Interesting feature for $\cos\theta^*_{\ell\pm}$

Comparison against data



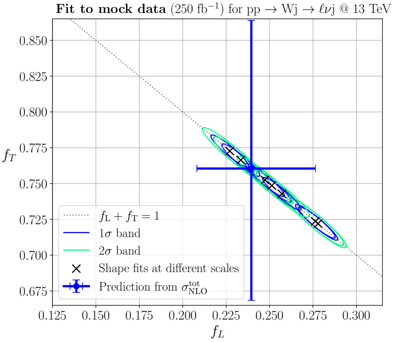
- Relatively good agreement between theory and data
- Off-shell and interference effects negligible

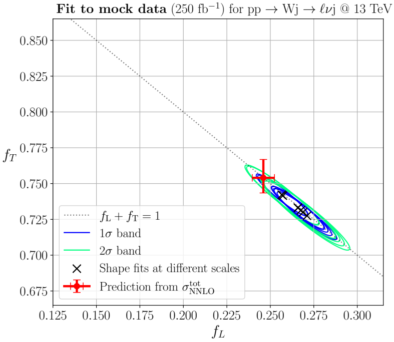
Fit to data



- Fits identical at NLO and NNLO
  → due to large experimental uncertainty

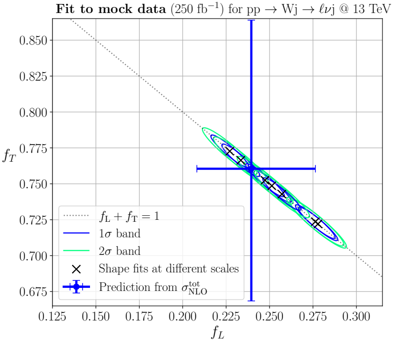
Fit to mock data

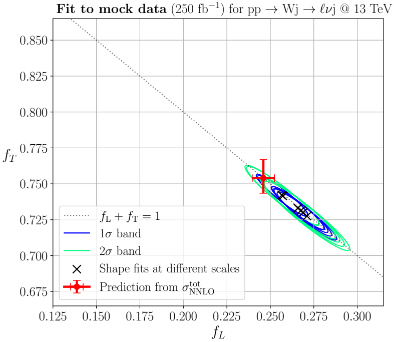




- Assume 250 fb^{-1} and the off-shell computation
- 1D fit
  → polar angle between the charged lepton and the hardest jet

Fit to mock data (II)





- 2D fit
  → rapidity and transverse momentum of charged lepton
- Missing correlation between two observables

Discussion

All theoretical ingredients ...
... but not enough

Open questions

- Should the two signatures be fitted separately or together?
- How should theoretical uncertainties be taken into account in the fit?
- How should one define the overall uncertainty on the fit of the polarisation fractions?

$\rightarrow$ Answers in collaboration with experimental collaborations

- NNLO QCD to $\mathrm{pp} \to \mathrm{W}^{\pm} + \mathrm{j_c}$

State of the art (W+c)

- NLO QCD for W+c-jet:

  [Giele, Keller, Laenen; hep-ph/9511449] [Stirling, Vryonidou; 1203.6781]

- NLO QCD+PS for W+c-jet:

  [Bevilacqua, Garzelli, Kardos, Toth; 2106.11261]

- Study of charm production in context of strange PDF:

  [Lai et al.; hep-ph/0702268], [Yalkun, Dulat; 1908.00026], [Faura et al.; 2009.00014]

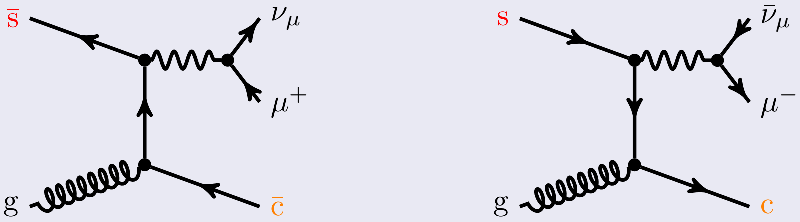
- NNLO QCD Z+b-jet

  [Gauld et al.; 2005.03016]

→ This work:
[Czakon, Mitov, MP, Poncelet; 2011.01011]:

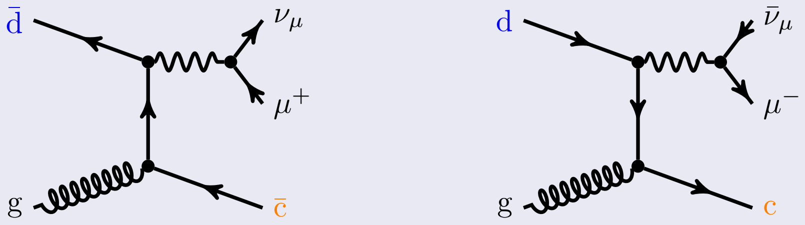
NNLO QCD computation for W+c-jet production

LO process (1)



- Direct link between W+c measurements and strange PDF
  $\rightarrow$ main motivation to be interested in this process
- Test of (perturbative) QCD
  $\rightarrow$ s-$\bar{s}$ asymmetry predicted at 3-loop in QCD
  [Catani, de Florian, Rodrigo, Vogelsang; hep-ph/0404240]
- Study of flavour jets
- ...

LO process (2)



- With non-diagonal CKM matrix ($V_{\mathrm{cd}} \neq 0$) ...
  ...more complicated interpretation in terms of strange PDF

LO process (3)

PDF set	V_{cd}	$\sigma_{W^+j_c}$ [pb]	$\sigma_{W^-j_c}$ [pb]	$R_{W^\pm j_c}$
NNPDF31 LO	$= 0$	9.8395(4)	10.4654(4)	0.94020(5)
	$\neq 0$	12.0725(4)	14.2624(5)	0.84646(4)
NNPDF31 NLO	$= 0$	22.593(2)	23.718(2)	0.95260(6)
	$\neq 0$	24.500(9)	27.29(1)	0.8977(5)
CT18 NLO	$= 0$	21.675(2)	21.675(2)	1.0000(1)
	$\neq 0$	23.477(9)	25.252(8)	0.9297(5)

$$R_{W^\pm j_c} = \frac{\sigma_{W^+j_c}}{\sigma_{W^-j_c}} \sim \left(|V_{cs}|^2\bar{s} + |V_{cd}|^2\bar{d}\right) / \left(|V_{cs}|^2 s + |V_{cd}|^2 d\right)$$

Inclusion of higher orders

$pp \to W^+ j_c$

Contrib.	LO	NLO	NNLO
$\bar{s}g$	✓	✓	✓
sg	X	X	✓
$s\bar{s}$	X	✓	✓
$\bar{s}\bar{s}$	X	✓	✓
$\bar{s}q$	X	✓	✓
qq'	X	✓	✓
gq	X	X	✓
gg	X	✓	✓

$pp \to W^- j_c$

Contrib.	LO	NLO	NNLO
$\bar{s}g$	X	X	✓
sg	✓	✓	✓
$s\bar{s}$	X	✓	✓
ss	X	✓	✓
sq	X	✓	✓
qq'	X	✓	✓
gq	X	X	✓
gg	X	✓	✓

$\rightarrow$ Higher-order corrections further complicates the picture

$\rightarrow$ Interpretation of W+c-jet is not trivial

Set up - [ATLAS; 1402.6263] @ 7 TeV

- Event selection

$$p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}, \qquad |\eta_\ell| < 2.5$$
$$p_{\mathrm{T,miss}} > 25\,\mathrm{GeV}, \qquad m_{\mathrm{T}}^{\mathrm{W}} > 40\,\mathrm{GeV}.$$

  One and only one flavoured c-jet with:

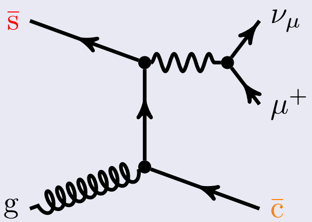
$$p_{\mathrm{T},\mathrm{j}_c} > 25\,\mathrm{GeV}, \qquad |\eta_{\mathrm{j}_c}| < 2.5.$$

- NNPDF31 sets with $\alpha_{\mathrm{s}} = 0.118$ [Ball et al.; 1706.00428]
- $\mu = \frac{1}{2}\left(E_{\mathrm{T},W} + p_{\mathrm{T},\mathrm{j_c}}\right)$ where $E_{\mathrm{T,W}} = \sqrt{M_{\mathrm{W}}^2 + (\vec{p}_{\mathrm{T},\ell} + \vec{p}_{\mathrm{T},\nu})^2}$
- flavour k_{T} algorithm with $R = 0.4$ [Banfi, Salam, Zanderighi; hep-ph/0601139]

Jet algorithm

- Beyond NLO, flavour jet algorithm is required
  $\rightarrow$ Otherwise not IR-safe definition of flavour jets
  $\rightarrow$ Large soft wide angle radiations are problematic
- flavour k_{T} algorithm with $R = 0.4$ [Banfi, Salam, Zanderighi; hep-ph/0601139]
  $\rightarrow$ Soft radiations are clustered first
  $\rightarrow$ rules:
  - $\mathsf{c} + \mathsf{c} = \mathsf{j}$ or $\mathsf{c} + \bar{\mathsf{c}} = \mathsf{j}$
  - $\mathsf{c} + \mathsf{c} + \bar{\mathsf{c}} = \mathsf{j}_{\mathrm{c}}$ or $\bar{\mathsf{c}} + \mathsf{c} + \bar{\mathsf{c}} = \mathsf{j}_{\mathrm{c}}$

Features of the computation



- NNLO QCD computation to $\mathrm{pp} \to \mu^+ \nu_\mu \mathrm{j_c}$ and $\mathrm{pp} \to \mu^- \bar{\nu}_\mu \mathrm{j_c}$
- 5-flavour scheme
- PDF uncertainty computed at NNLO using [Carrazza et al.; 1602.00005]
- $V_{\mathrm{cd}} \neq 0$ at LO when comparing against data

$V_{\rm cd} \neq 0$

Order	$\sigma_{\rm W^+j_c}$ [pb]	$\sigma_{\rm W^-j_c}$ [pb]	$R_{\rm W^\pm j_c} = \sigma_{\rm W^+j_c}/\sigma_{\rm W^-j_c}$
LO	$12.0725(4)^{+11.6\%}_{-12.9\%}$	$14.2624(5)^{+11.6\%}_{-10.9\%}$	$0.84646(4)^{+1.48\%}_{-2.22\%}$
NLO	$35.164(9)^{+8.0\%}_{-7.0\%}$	$37.096(9)^{+7.5\%}_{-6.7\%}$	$0.9479(3)^{+0.49\%}_{-0.36\%}$
NNLO	$38.6(1)^{+2.2\%\ +3.8\%({\rm PDF})}_{-3.2\%\ -3.8\%({\rm PDF})}$	$39.3(1)^{+1.8\%\ +3.9\%({\rm PDF})}_{-2.9\%\ -3.9\%({\rm PDF})}$	$0.983(5)^{+0.45\%\ +2.7\%({\rm PDF})}_{-0.37\%\ -2.7\%({\rm PDF})}$

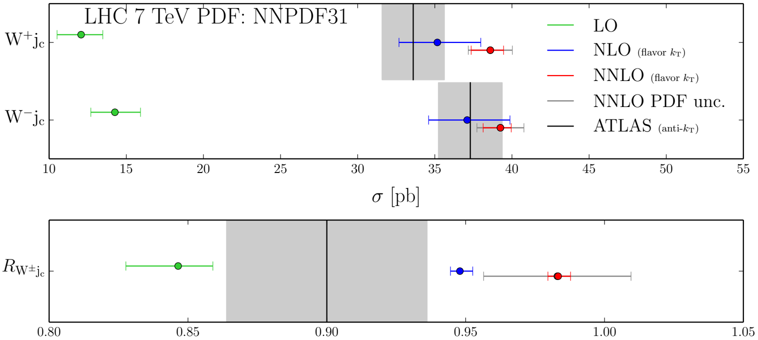
[Czakon, Mitov, MP, Poncelet; 2011.01011]

$$\sigma^{\rm ATLAS}_{\rm W^+j_c} = 33.6 \pm 0.9\,(\text{stat}) \pm 1.8\,(\text{syst})\,\text{pb}$$
$$\sigma^{\rm ATLAS}_{\rm W^-j_c} = 37.3 \pm 0.8\,(\text{stat}) \pm 1.9\,(\text{syst})\,\text{pb}$$

$$R^{\rm ATLAS}_{\rm W^\pm j_c} = 0.90 \pm 0.03\,(\text{stat}) \pm 0.02\,(\text{syst})$$

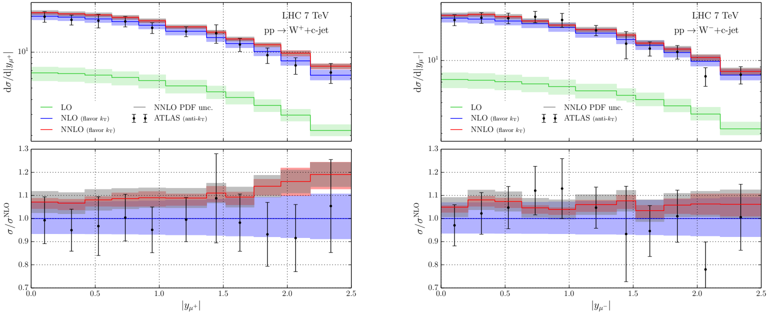
[ATLAS; 1402.6263]

Th. vs. Exp. - cross section (2)



- PDF uncertainty dominant over NNLO scale uncertainty
- NNLO QCD prediction tends to be larger for the + signature
  $\rightarrow$ Not statistically relevant

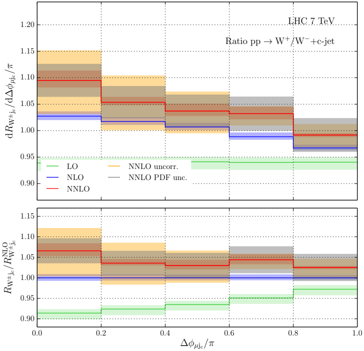
Th. vs. Exp. - Differential distribution

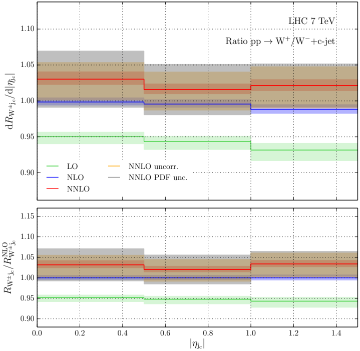


[Czakon, Mitov, MP, Poncelet; 2011.01011]

Similar picture as for the total cross section
→ General good agreement

Differential distributions - ratio





[Czakon, Mitov, MP, Poncelet; 2011.01011]

As for total cross section, PDF uncertainty are dominant in ratios
→ Uncorrelated scale uncertainty more conservative

Discussion

- Difference in the jet algorithms (flavoured k_{T} vs. anti-k_{T})
  $\rightarrow$ Estimated to be 12% in $\mathrm{Z}+\mathrm{b}$ [Gauld et al.; 2005.03016] ...
  ... but difficult to translate to $\mathrm{W}+\mathrm{c}$
- Lack of higher-order QCD corrections to the off-diagonal CKM matrix element $\sim$ few per cent
- Absence of EW corrections $\sim$ - few per cent
- PDF uncertainty
- Definition of the experimental measurement
  (D meson and not charm jet: OS - SS)

Summary

New computations for:

- W+c [Czakon, Mitov, MP, Poncelet; 2011.01011]
- Polarised W+j [MP, Poncelet, Popescu; 2109.14336]

- Decisive information for SM measurements
  $\rightarrow$ Precision programme at the LHC
- Crucial interplay between theory and experiment
  $\rightarrow$ Big impact on physics results

Thank you

BACK-UP