NNLO QCD predictions for W+c-jet production at the LHC

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→ Based on **arXiv:2011.01011**

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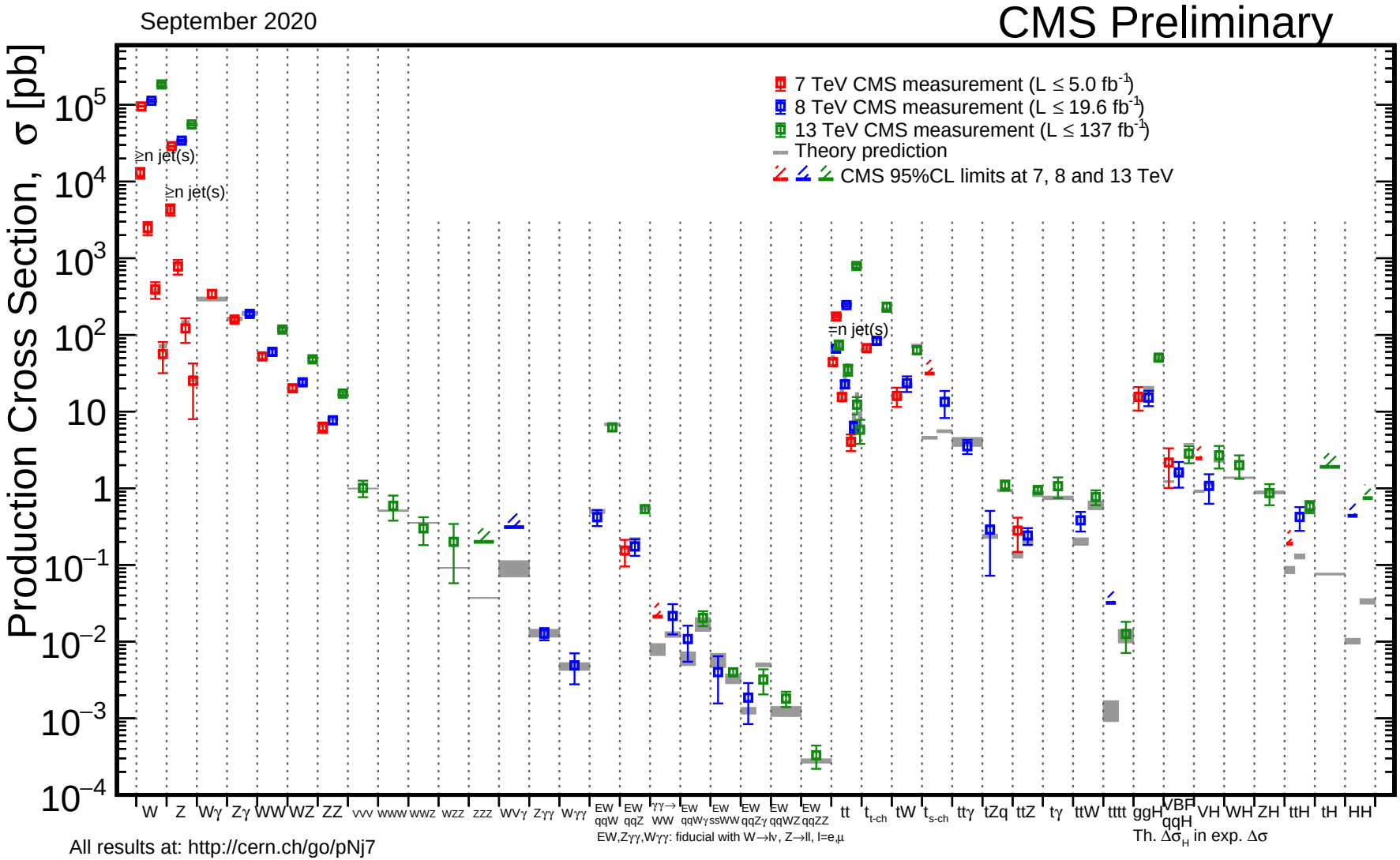
Outline:

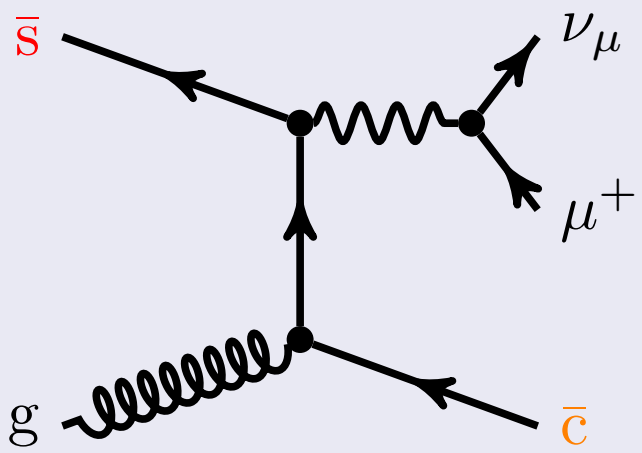
- What is W+c-jet ...
  ... and why you want to compute it

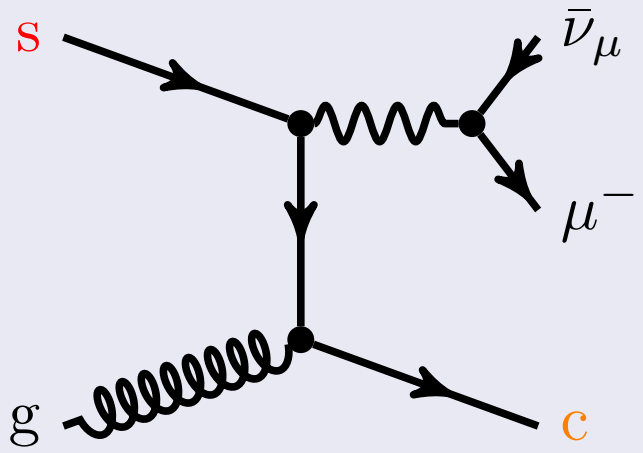
- NNLO QCD predictions to:
  → $pp \to \mu^+ \nu_\mu j_c$
  → $pp \to \mu^- \bar{\nu}_\mu j_c$



→ **LHC = cross-sections measurements machine!**

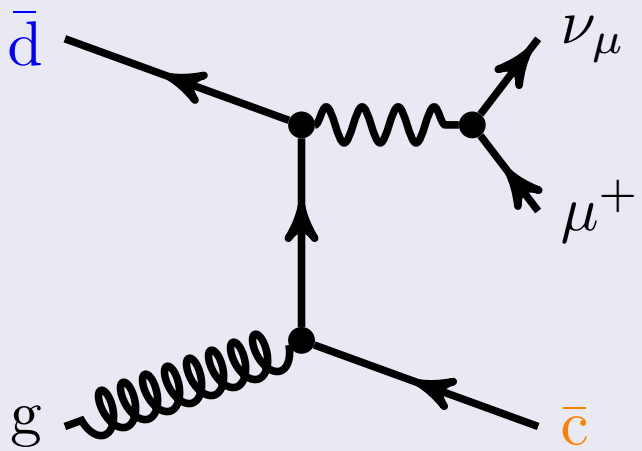
LO process (1)

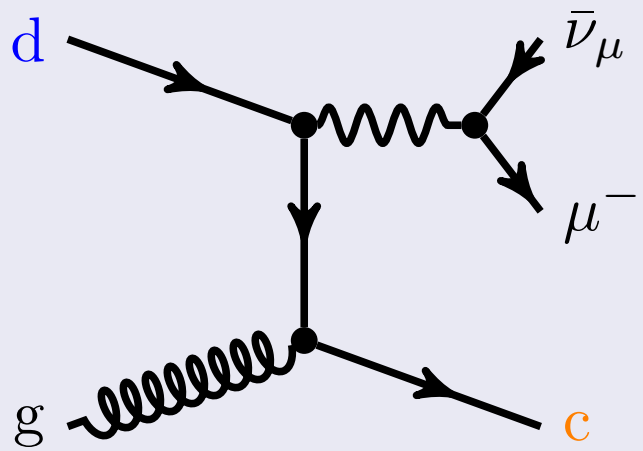




- Direct link between W+c measurements and strange PDF
  $\rightarrow$ main motivation to be interested in this process
- Test of (perturbative) QCD
- Study of flavour jets
- ...

LO process (2)





- With non-diagonal CKM matrix ($V_{cd} \neq 0$) ...
  ...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)

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

Inclusion of higher orders

$pp \to W^+ j_c$				$pp \to W^- j_c$			
Contrib.	LO	NLO	NNLO	Contrib.	LO	NLO	NNLO
$\bar{s}g$	✓	✓	✓	$\bar{s}g$	X	X	✓
sg	X	X	✓	sg	✓	✓	✓
$s\bar{s}$	X	✓	✓	$s\bar{s}$	X	✓	✓
$\bar{s}\bar{s}$	X	✓	✓	ss	X	✓	✓
$\bar{s}q$	X	✓	✓	sq	X	✓	✓
qq'	X	✓	✓	qq'	X	✓	✓
gq	X	X	✓	gq	X	X	✓
gg	X	✓	✓	gg	X	✓	✓

→ Higher-order corrections further complicates the picture
→ Interpretation of W+c-jet is not trivial

State of the art (W+j)

→ Extensive litterature

- 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], [Bern et al.; 1103.5445]
- 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]

State of the art (W+c)

- NLO QCD for W+c-jet: [Giele, Keller, Laenen; hep-ph/9511449] [Stirling, Vryonidou; 1203.6781]
- NNLO QCD for Z+b-jet: [Gauld et al.; 2005.03016]
- Study of charm production in context of strange PDF:

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

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

First NNLO QCD computation for W+c-jet production

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]

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:

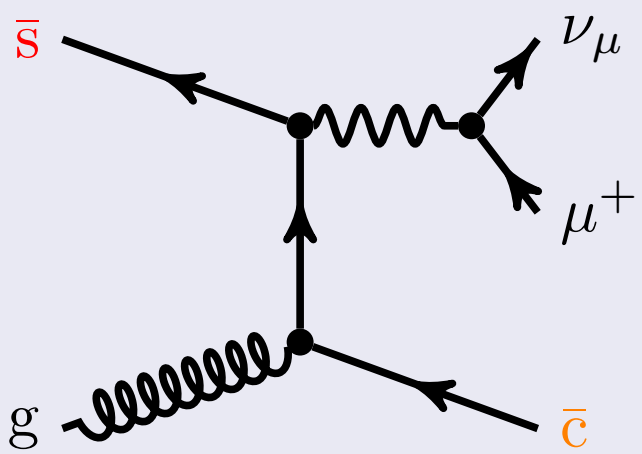
$$p_{\mathrm{T},\mathrm{j}_c} > 25\,\mathrm{GeV}, \qquad |\eta_{\mathrm{j}_c}| < 2.5.$$

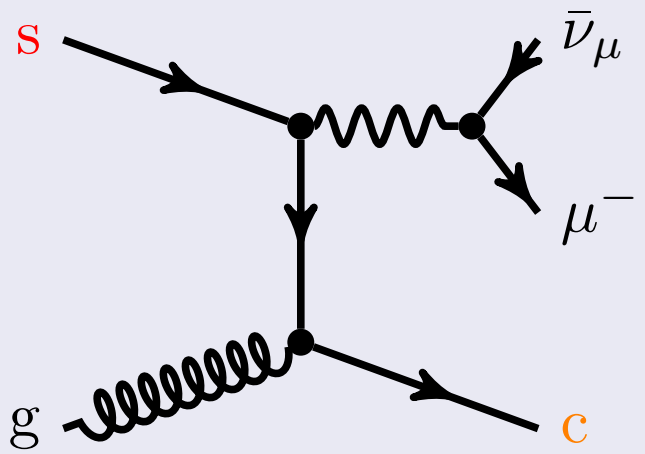
- NNPDF31 sets with $\alpha_s = 0.118$ [Ball et al.; 1706.00428] matching the corresponding orders
- $\mu = \frac{1}{2}\left(E_{\mathrm{T},W} + p_{\mathrm{T},\mathrm{j_c}}\right)$ where $E_{\mathrm{T,W}} = \sqrt{M_{\mathrm{W}}^2 + (\vec{p}_{\mathrm{T},\ell} + \vec{p}_{\mathrm{T},\nu})^2}$

Jet algorithm

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

Features of the computation





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

Th. vs. Exp. - cross section (1)

$V_{cd} \neq 0$

Order	$\sigma_{W^+j_c}$ [pb]	$\sigma_{W^-j_c}$ [pb]	$R_{W^\pm j_c} = \sigma_{W^+j_c}/\sigma_{W^-j_c}$
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	$38.6(1)^{+2.2\%\ +3.8\%(\mathrm{PDF})}_{-3.2\%\ -3.8\%(\mathrm{PDF})}$	$39.3(1)^{+1.8\%\ +3.9\%(\mathrm{PDF})}_{-2.9\%\ -3.9\%(\mathrm{PDF})}$	$0.983(5)^{+0.45\%\ +2.7\%(\mathrm{PDF})}_{-0.37\%\ -2.7\%(\mathrm{PDF})}$

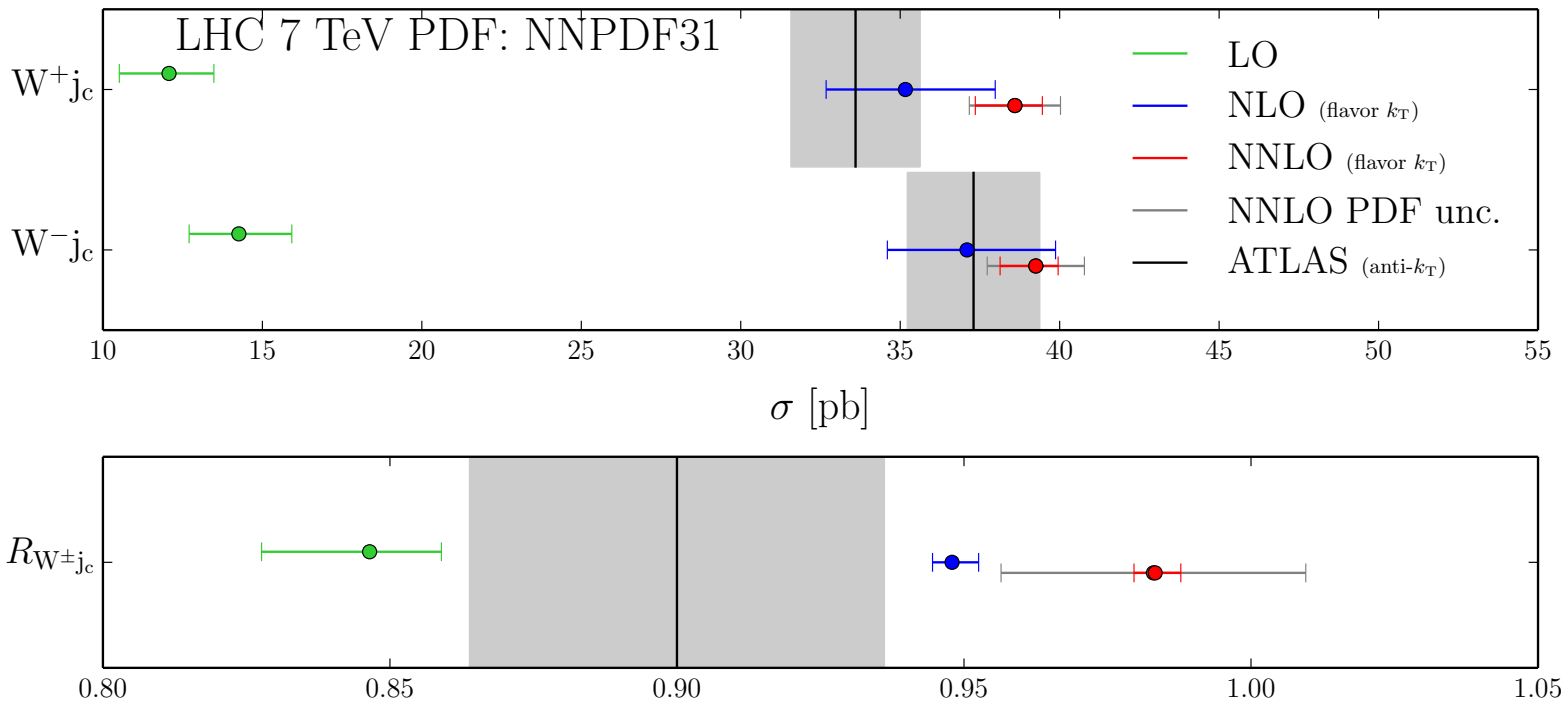
[Czakon, Mitov, MP, Poncelet; 2011.01011]

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

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

[ATLAS; 1402.6263]

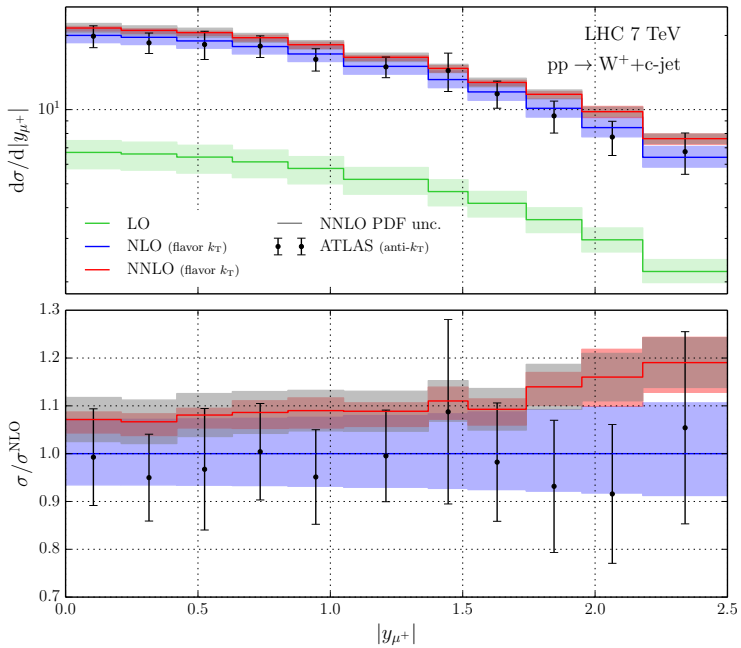
Th. vs. Exp. - cross section (3)

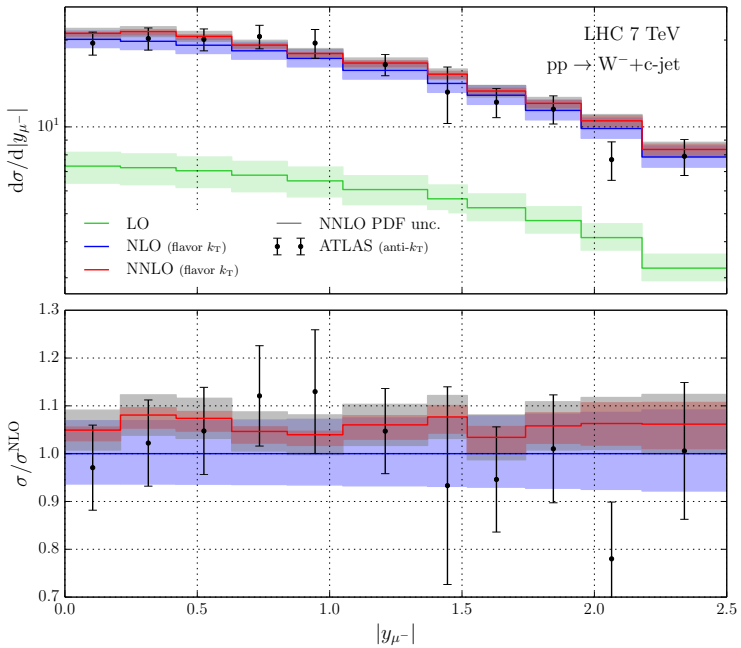


[Czakon, Mitov, MP, Poncelet; 2011.01011]

- 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 (3)





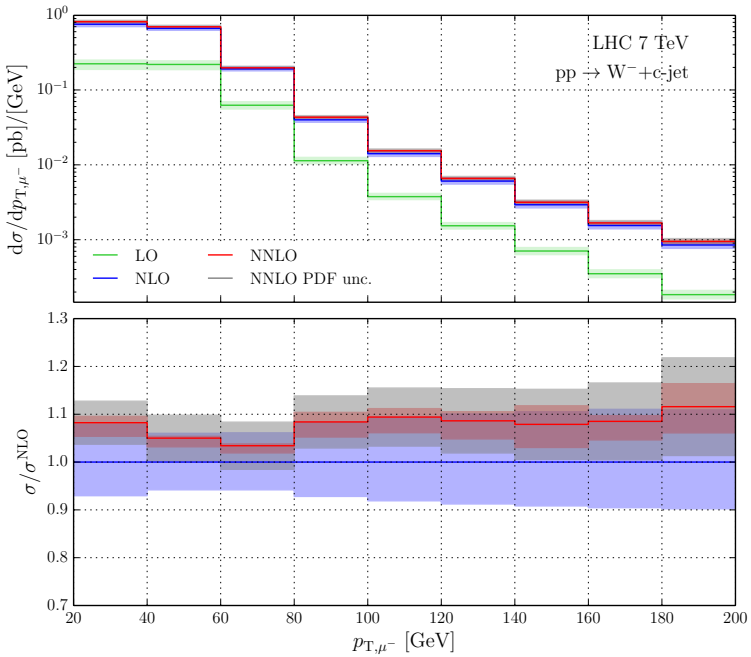
[Czakon, Mitov, MP, Poncelet; 2011.01011]

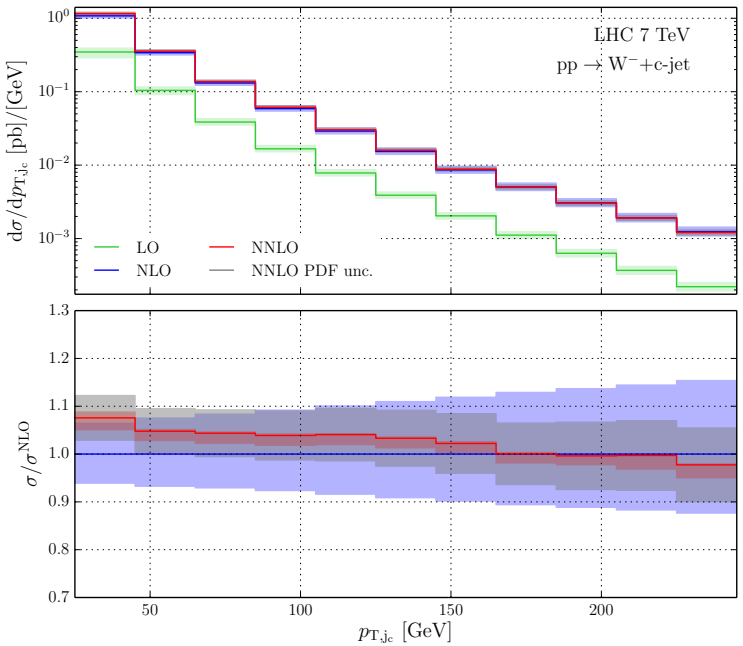
Similar picture as for the total cross section
→ General good agreement

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 $\mathrm{W} + \mathrm{c}$
  (See talk by Rhorry Gauld later)
- 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

Differential distributions - absolute

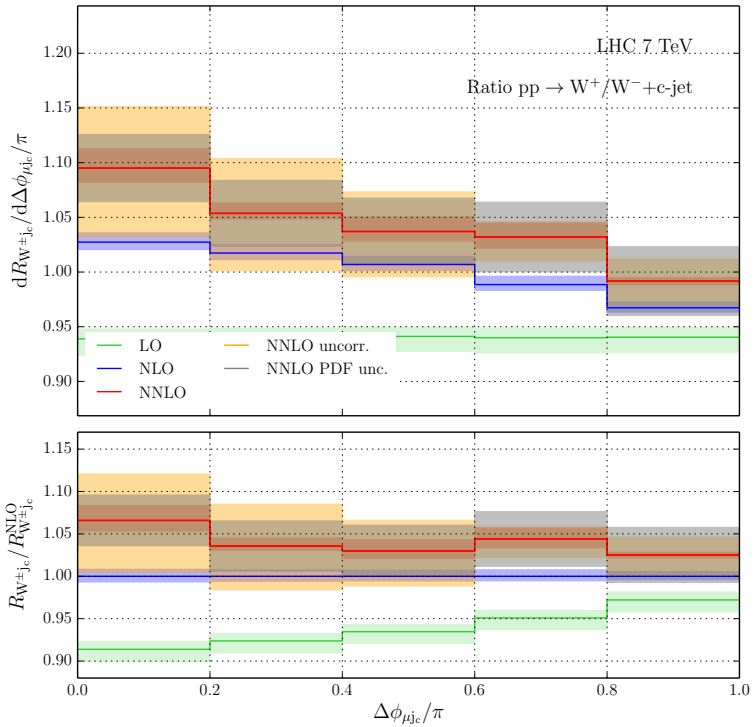


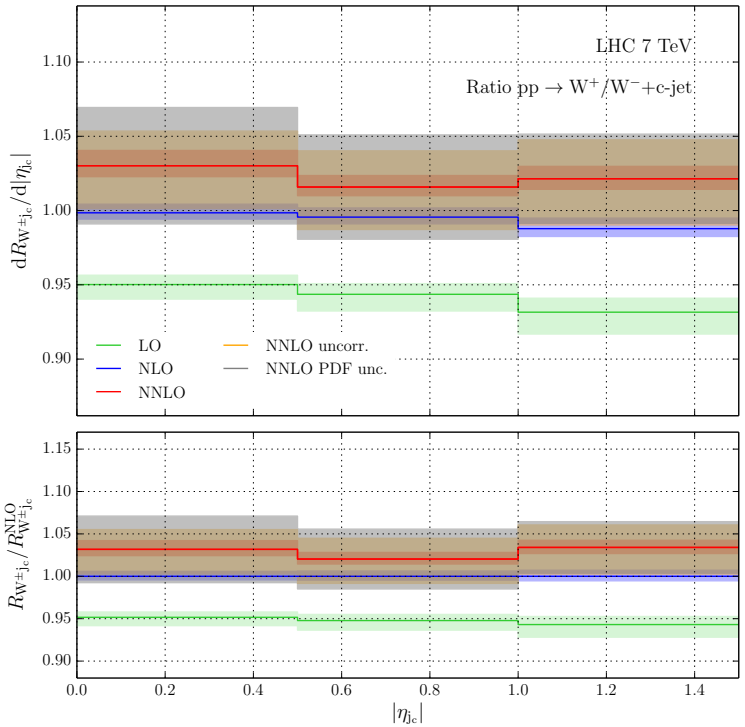


[Czakon, Mitov, MP, Poncelet; 2011.01011]

- Well behaved QCD corrections
- Many more distributions in back-up or article

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

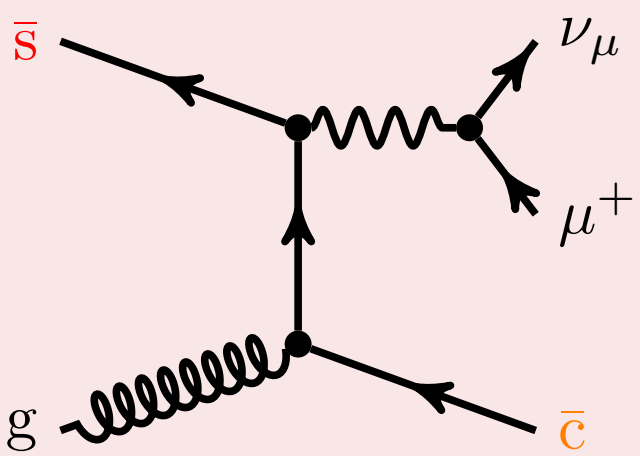
Summary

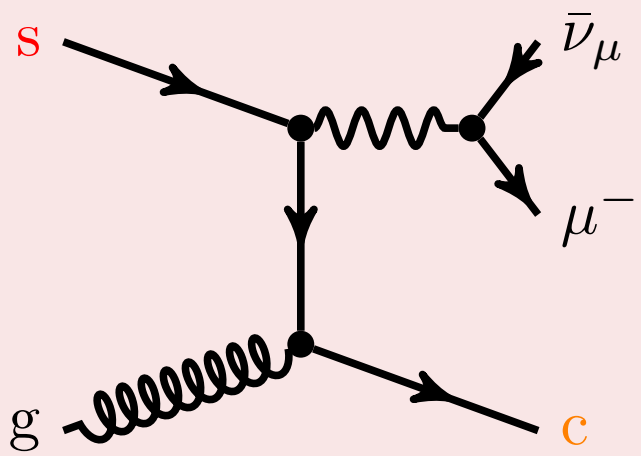
New computation for W+c-jet at NNLO QCD: **arXiv:2011.01011**

- NNLO QCD computation to pp $\to \mu^+\nu_\mu \mathrm{j_c}$ and pp $\to \mu^-\bar{\nu}_\mu \mathrm{j_c}$
  - $\to$ Significant QCD corrections
  - $\to$ Significant reduction of scale uncertainty
  - $\to$ PDF uncertainty is dominant
- Predictions compared to [ATLAS; 1402.6263] at 7 TeV
- Many more differential distributions available
- Computation of ratios

Outlook

- More precise comparison with experimental data
  $\rightarrow$ flavour jet definition
- Inclusion of missing theoretical effects
- ...

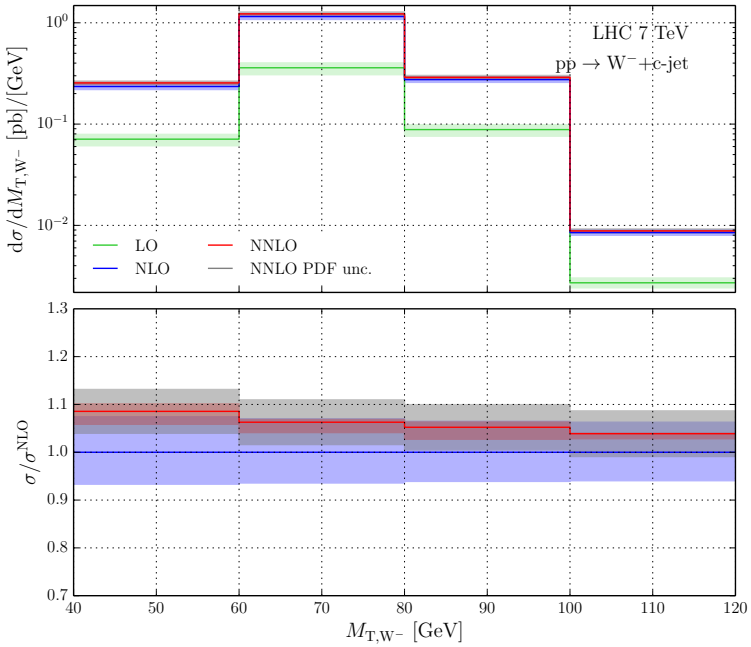


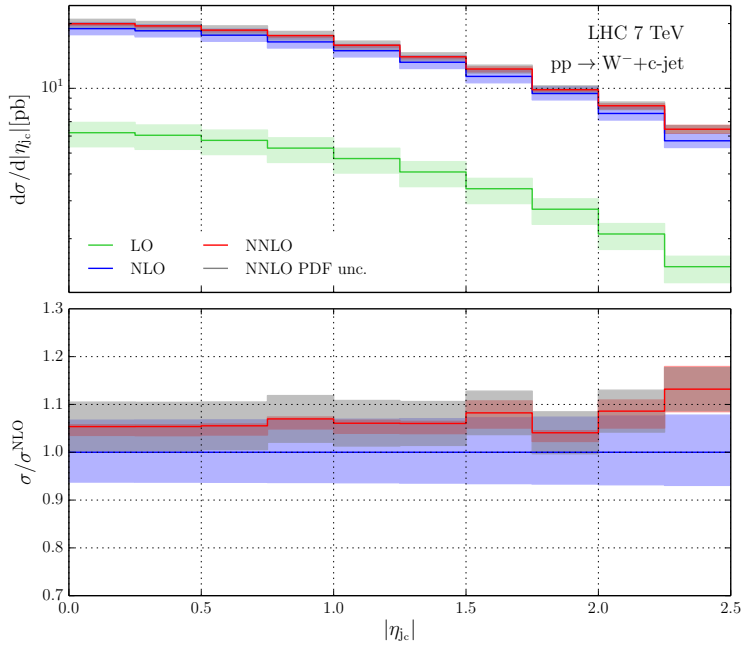


Thank you

BACK-UP

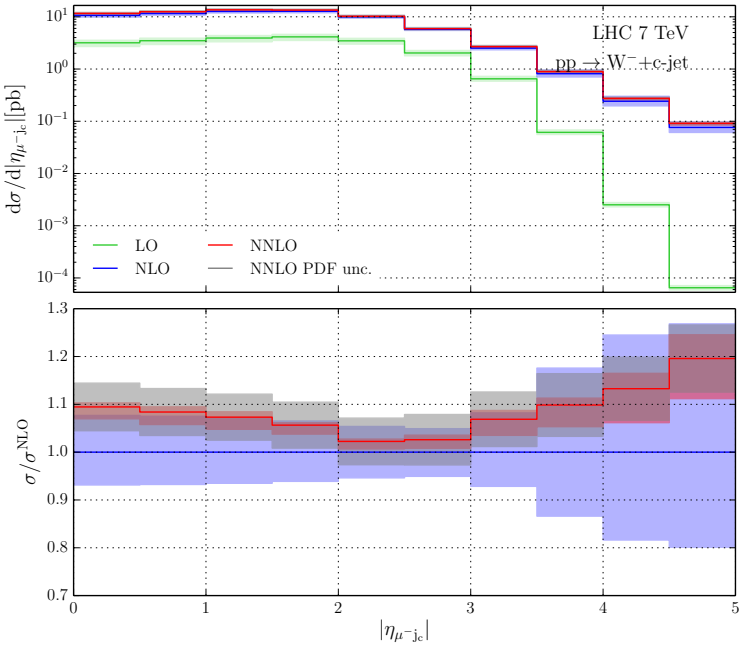
Differential distributions

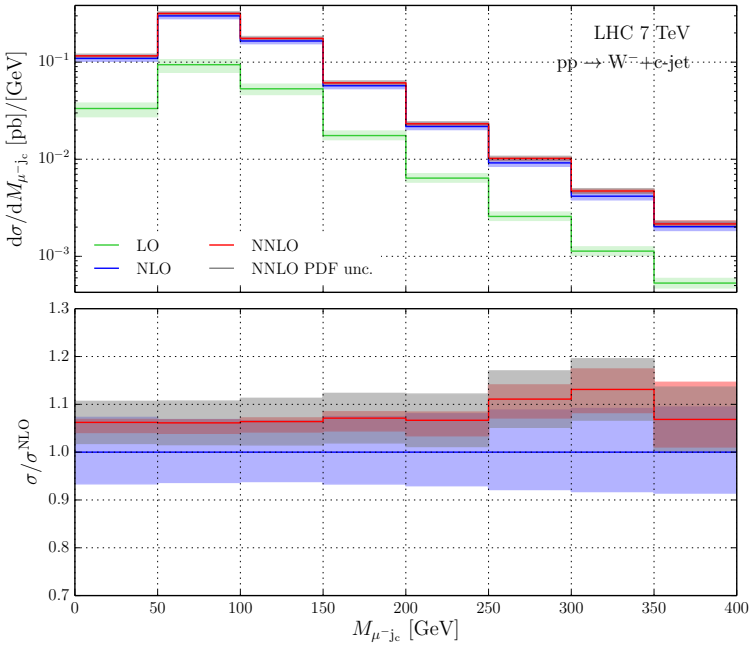




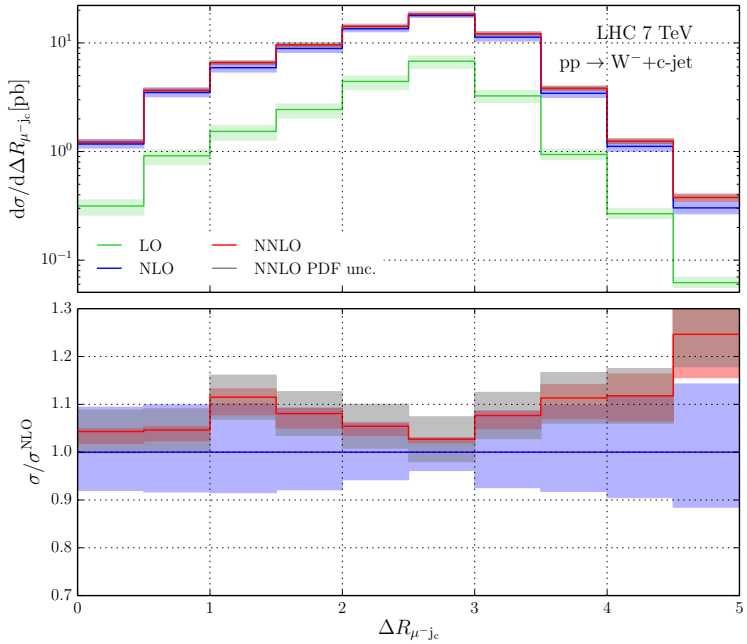
$$m_{\mathrm{T}}^{\mathrm{W}} = \sqrt{2 p_{\mathrm{T},\ell} p_{\mathrm{T,miss}} \left(1 - \cos \Delta\phi\right)}$$

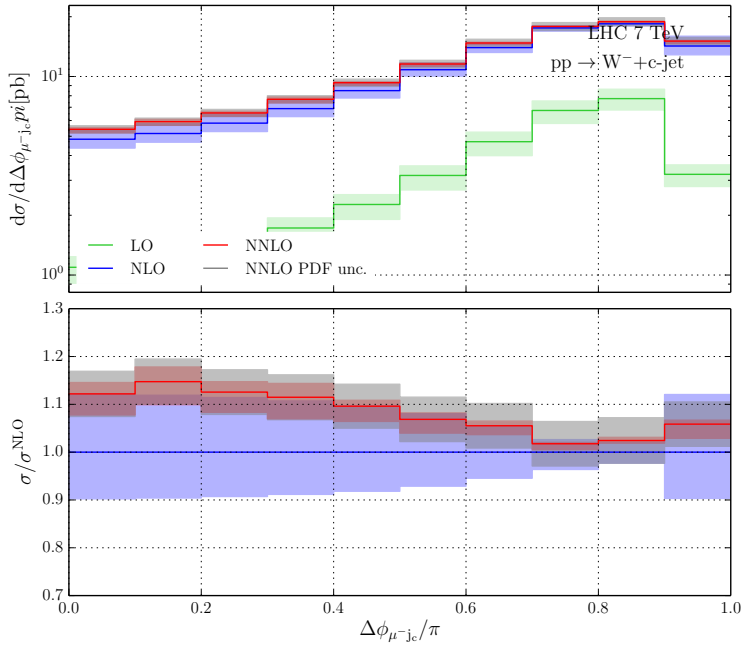
Differential distributions





Differential distributions





Differential distributions