W+charm with massive c quarks in `PowHel`

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in collaboration with

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Based on arXiv:2106.11261 [JHEP]

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Introduction

- x range in HERA data: $10^{-4} < x < 10^{-1}$, light quarks and gluons
- Detailed sea quarks and gluons in high/low x need additional data (pp and fixed target)
- Legacy data from bubble chambers, emulsion, etc. (inconsistency and uncertainty)
- Drell-Yan is sensitive to sea quarks, using DY tension appears with legacy sets
- Strange quark content has large uncertainties

$\Rightarrow$ Have to constrain the strange quark content

- We need new DIS capabilities:
  - Large Hadron-Electron Collider (LHeC) [arXiv:1907.01014]
  - Forward Physics Facility at High-Lumi LHC

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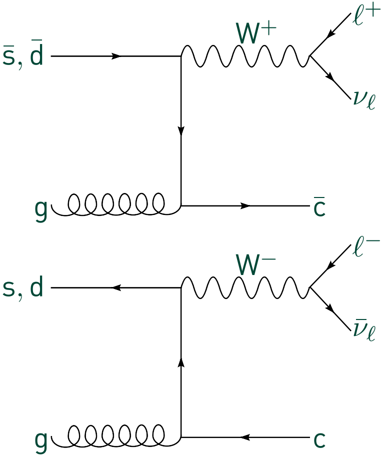
Introduction

Need to measure strange content with higher precision!

- Need strange quark in initial state

$\Rightarrow$ Heavy flavor in $\mathrm{W}+\mathrm{c}$ production

- $\mathrm{W}^{+}+\bar{\mathrm{c}}$ and $\mathrm{W}^{-}+\mathrm{c}$ can be used
- Situation is not ideal:
  - Non-diagonal CKM
  - In higher orders other channels start to contribute (g g at NLO, α_{S} suppression compensated by gluon PDF)



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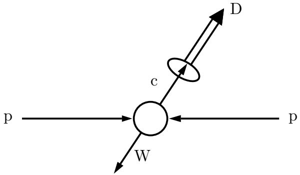
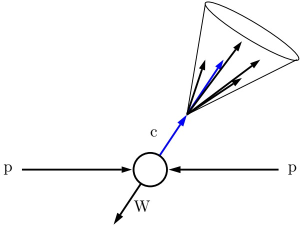
Introduction

- W + c production can be analyzed two ways:
  - fragmentation: c quark into D meson (needs fragmentation function)
  - c-jet production (c-quark tagging) (sensitive to c tagging efficiency)





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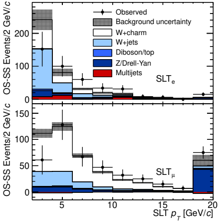
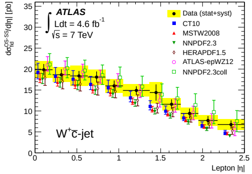
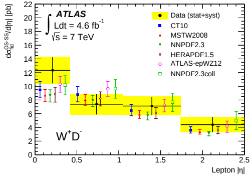
Introduction / Experimental data

- $W+c$ production was studied at Tevatron by CDF and D0
  - Limited data for $W+j_c$
  - c tagging thru soft-lepton tagging (SLT) in jets
  - Contamination ($Zb\bar{b}$ and $Wc\bar{c}$) minimized using $\sigma^{OS}-\sigma^{SS}$
  - OS : $\mathrm{sign}(\ell\,\mathrm{from}\,W)\neq\mathrm{sign}(\mathrm{STL}_\ell)$
  - SS : $\mathrm{sign}(\ell\,\mathrm{from}\,W)=\mathrm{sign}(\mathrm{STL}_\ell)$
- Also studied at LHC during Run I:
  - ATLAS at 7 TeV
  - CMS at 7, 8 and 13 TeV
  - $W+$ D-meson final states
  - $W+j_c$ final states
  - $W+c$ results in the forward region by LHCb







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Introduction / Theory

$W + c$ theory predictions:

- NLO QCD calculation (massive c) by Giele et al. [hep-ph/9511449]
- Available at NLO QCD in MCFM (massive c)
- Also in `MadGraph5_aMC@NLO` at NLO QCD with massive c
- First NNLO QCD results ($m_c = 0$) by Czakon et al. [arXiv:2011.01011]
  - Due to massless charm different jet algo. was used (flavored $k_\perp$)
  - Good agreement with data
  - moderate NNLO corrections found ($\sim 10\%$ central region)

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Our calculation

- POWHEG matching scheme is used through POWHEG-BOX
- Massive charm throughout
- Due to 3 active flavors conversion to the decoupling scheme (if needed)
- Parton shower and hadronization by PYTHIA8
- Two tunes were employed:
  - Monash
  - ATLAS A14
- Different PDFs were used:
  - ABMP16_3_NLO
  - CT18NLO
  - CT18ZNLO

  (CT18NLO, CT18ZNLO) } 5 FNS PDFs $\Rightarrow$ conversion to decoupling scheme
- Including $\mathrm{W}^{\pm} + \mathrm{c} + \bar{\mathrm{c}}$ (same α_{S} order as real emission)

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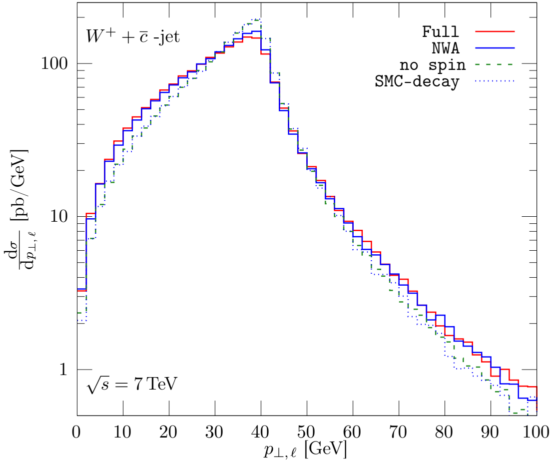
Effect of Spin Correlations

- W is decayed leptonically
  - Full calculation: off-shell W with spin correlation in decay (red)
  - W in NWA (blue)
  - No spin correlations in W decay (dashed green)
- Effect of off-shellness is marginal
- Spin correlation in decay is crucial



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Pheno Results at 13 TeV

- CMS analyzed $\mathrm{W}^{\pm} + \mathrm{D}^{*}(2010)^{\mp}$ events at 13 TeV (see: arXiv:1811.10021)
- $|\eta_\ell|$ is measured in W decay
- W tagging through μ detection with missing energy ($p_{T,\mu} > 26\mathrm{GeV}$, $|\eta_\mu| < 2.4$)
- μ^+, μ^- pseudorapidities were registered with their sums as well
- Event classification according to signs of $\mathrm{D}^{*}(2010)$ meson and central μ:
  - $\mathrm{D}^{*}(2010)^{\pm}$ with a $\mu^{\pm}$ (Same Signed, SS) $\Rightarrow$ background
  - $\mathrm{D}^{*}(2010)^{\pm}$ with a $\mu^{\mp}$ (Opposite Signed, OS) $\Rightarrow$ signal
- CMS compared to theory:
  - `Madgraph5_aMC@NLO`: W production with light jets at hadron level
  - `MCFM`: Unfolded to the parton level, using W production with massive c

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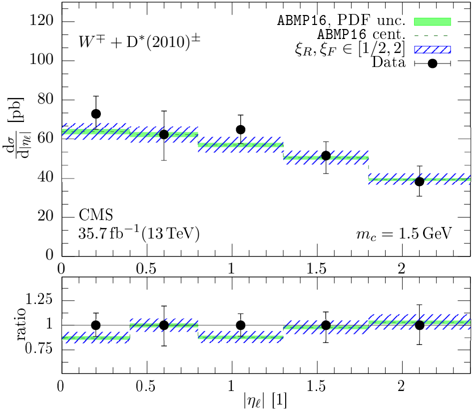
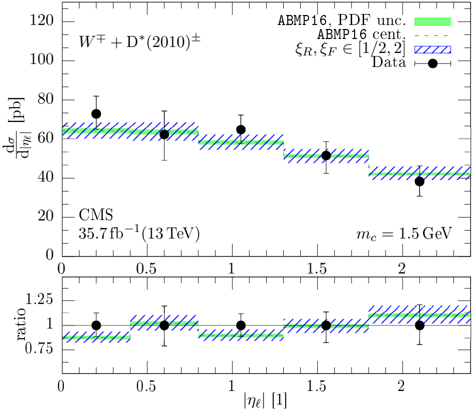
Pheno Results at 13 TeV



Monash tune



ATLAS A14 tune

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Pheno Results at 7 TeV

- Data taken by ATLAS for $\mathrm{W} + \mathrm{D}{-}\mathrm{meson}$ and $\mathrm{W} + j_c$ (see: arXiv:1402.6263)
- Isolated lepton can be produced with same sign as D-meson or charm in j_c jet (SS)
- Isolated lepton can be produced with opposite sign as D-meson or charm in j_c jet (OS)
- Interested in opposite sign (OS) events, if multiple charms present incluse cross section is obtained, going through all charms and registering cross section contribution as OS - SS
- If a charm-pair is produced cross section contribution will be zero
- c-tagging:
  - c semileptonic decay into muon
  - Presence of charmed meson

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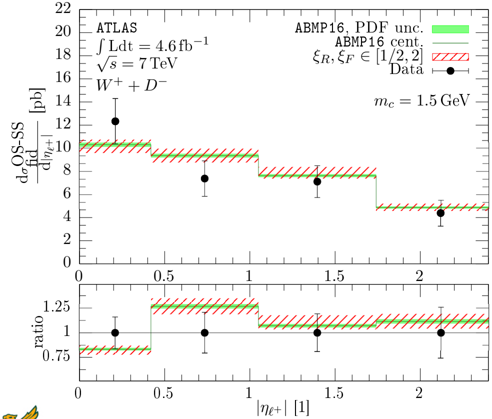
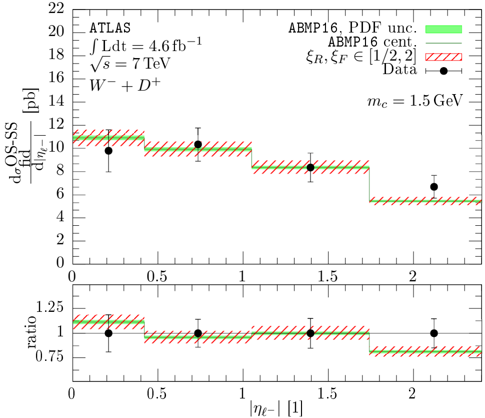
Pheno Results at 7 TeV

Using the ATLAS A14 tune:





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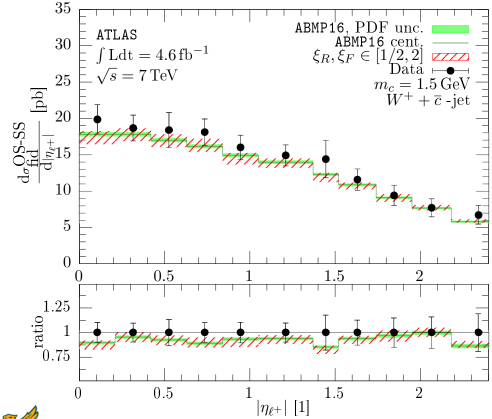
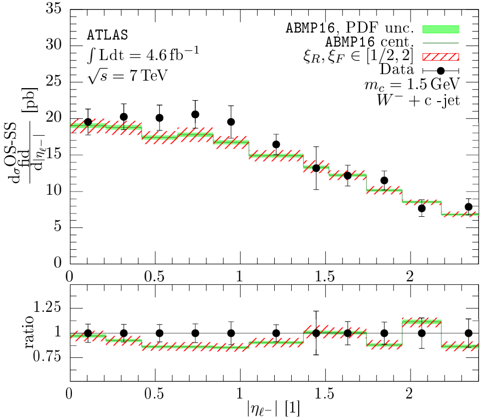
Pheno Results at 7 TeV

Associated charmed jet production with ATLAS A14 tune:





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Conclusions

- First comparison with data at hadron level with NLO QCD accuracy and $m_c \neq 0$
- First implementation of NLO+PS matching with the POWHEG method
- Spin correlation and CKM effects are important
- Good agreement with data
- Useful in low p_T region where charm mass effects are important
- Can be used in PDF fits

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Thank you for your attention!

Back-up slides

Fixed order related

Considered subprocesses (in all-outgoing kinematics):

$$\emptyset \to \ell^+ \nu_\ell \, \bar{c} s \, g \qquad \emptyset \to \ell^- \bar{\nu}_\ell \, c \bar{s} \, g$$
$$\emptyset \to \ell^+ \nu_\ell \, \bar{c} d \, g \qquad \emptyset \to \ell^- \bar{\nu}_\ell \, c \bar{d} \, g$$

$$\emptyset \to \ell^+ \nu_\ell \, \bar{c} s \, gg \qquad \emptyset \to \ell^- \bar{\nu}_\ell \, c \bar{s} \, gg$$
$$\emptyset \to \ell^+ \nu_\ell \, \bar{c} d \, gg \qquad \emptyset \to \ell^- \bar{\nu}_\ell \, c \bar{d} \, gg$$
$$\emptyset \to \ell^+ \nu_\ell \, \bar{c} s \, q\bar{q} \qquad \emptyset \to \ell^- \bar{\nu}_\ell \, c \bar{s} \, q\bar{q}$$
$$\emptyset \to \ell^+ \nu_\ell \, \bar{c} d \, q\bar{q} \qquad \emptyset \to \ell^- \bar{\nu}_\ell \, c \bar{d} \, q\bar{q}$$
$$\emptyset \to \ell^+ \nu_\ell \, c\bar{c} \, \bar{u} d \qquad \emptyset \to \ell^- \bar{\nu}_\ell \, c\bar{c} \, u\bar{d}$$
$$\emptyset \to \ell^+ \nu_\ell \, c\bar{c} \, \bar{u} s \qquad \emptyset \to \ell^- \bar{\nu}_\ell \, c\bar{c} \, u\bar{s}$$

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Fixed order related

Non-physical scales used:

$$\mu_R = \mu_F = H_T/2$$

For $W + c + X$:

$$H_T = \sqrt{p_{T,W}^2 + m_W^2} + \sqrt{p_{T,c}^2 + m_c^2}$$

For $W + c + \bar{c}$:

$$H_T = \sqrt{p_{T,W}^2 + m_W^2} + \sqrt{p_{T,c}^2 + m_c^2} + \sqrt{p_{T,\bar{c}}^2 + m_c^2}$$

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Cross sections

Energy	Process	PDF	m_c[GeV]	$\sigma_{\rm NLO}$ [pb]
13 TeV	$W^+\bar{c}+X$	ABMP16	1.5	4994(7)
		CT18Z	1.4	5298(6)
		CT18	1.4	4838(6)
	W^-c+X	ABMP16	1.5	5190(6)
		CT18Z	1.4	5521(7)
		CT18	1.4	5053(6)
	$W^+c\,\bar{c}$	ABMP16	1.5	156.30(6)
		CT18Z	1.4	213.36(6)
		CT18	1.4	209.72(6)
	$W^-c\,\bar{c}$	ABMP16	1.5	101.82(3)
		CT18Z	1.4	138.97(6)
		CT18	1.4	136.64(6)
7 TeV	$W^+\bar{c}+X$	ABMP16	1.5	2009(2)
	W^-c+X	ABMP16	1.5	2113(2)
	$W^+c\,\bar{c}$	ABMP16	1.5	86.70(3)
	$W^-c\,\bar{c}$	ABMP16	1.5	51.89(2)

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Cross sections

OS, SS contributions (inclusive) at $13\,\mathrm{TeV}$ for $D^*(2010)$ meson:

LHE Partonic Process	$\sigma_{\mathrm{MC}}^{\mathrm{OS-SS}}$ [pb]	$\sigma_{\mathrm{MC}}^{\mathrm{OS}}$ [pb]	$\sigma_{\mathrm{MC}}^{\mathrm{SS}}$ [pb]
$W^+ c + X$	62(1)	70(1)	7.8(4)
$W^- c + X$	66(1)	73(1)	7.3(4)
$W^\pm c + X$	128(2)	143(2)	15.1(6)
$W^+ c \bar{c}$	-0.1(1)	1.4(1)	1.5(1)
$W^- c \bar{c}$	0.0(1)	0.9(1)	0.9(1)
$W^\pm c \bar{c}$	-0.1(2)	2.3(2)	2.4(2)

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Cross sections

OS, SS contributions (inclusive) at $7\,\mathrm{TeV}$ for D meson (A14 tune):

Process	$\sigma_{\mathrm{MC}}^{\mathrm{OS-SS}}$ [pb]	$\sigma_{\mathrm{MC}}^{\mathrm{OS}}$ [pb]	$\sigma_{\mathrm{MC}}^{\mathrm{SS}}$ [pb]
$W^+ c + X$	19.2(3)	20.4(3)	1.19(6)
$W^- c + X$	20.7(3)	21.7(3)	0.93(6)
$W^+ c \bar{c}$	0.05(6)	0.68(4)	0.63(4)
$W^- c \bar{c}$	-0.03(4)	0.36(3)	0.39(3)

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Cross sections

OS, SS contributions (inclusive) at $7\,\mathrm{TeV}$ for c-jet (A14 tune):

Process	$\sigma_{\mathrm{MC}}^{\mathrm{OS-SS}}$ [pb]	$\sigma_{\mathrm{MC}}^{\mathrm{OS}}$ [pb]	$\sigma_{\mathrm{MC}}^{\mathrm{SS}}$ [pb]
W^+ c $+$ X	31.8(4)	32.9(4)	1.06(6)
W^- c $+$ X	34.6(4)	35.3(4)	0.67(4)
W^+ c $\bar{c}$	0.03(6)	0.78(4)	0.75(4)
W^- c $\bar{c}$	0.03(4)	0.41(3)	0.38(3)

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Cross sections

D-meson production cross sections (CMS):

Process	PDF	$\sigma_{\mathrm{MC}}^{\mathsf{M}}$ [pb]	$\sigma_{\mathrm{MC}}^{\mathsf{A}}$ [pb]	δ_{scale}	δ_{PDF}	$\delta_{\mathrm{PDF}}^{68\%}$	σ^{CMS} [pb]
$\mathsf{W}^+ + \mathsf{D}^{*-}$	ABMP16	62	64	$^{+6.9\%}_{-6.4\%}$	$\pm 2\%$	$\pm 2\%$	$65 \pm 5\,(\mathrm{stat})^{+10}_{-10}\,(\mathrm{sys})$
	CT18Z	63	64	–	$^{+14.8\%}_{-10.5\%}$	$\pm 7.2\%$	
	CT18	58	59	–	$^{+11.1\%}_{-11.3\%}$	$\pm 8.4\%$	
$\mathsf{W}^- + \mathsf{D}^{*+}$	ABMP16	66	67	$^{+6.8\%}_{-6.5\%}$	$\pm 2\%$	$\pm 2\%$	$71 \pm 6\,(\mathrm{stat})^{+9}_{-10}\,(\mathrm{sys})$
	CT18Z	67	68	–	$^{+10.1\%}_{-12.9\%}$	$\pm 6.8\%$	
	CT18	61	63	–	$^{+10.8\%}_{-11.7\%}$	$\pm 8.1\%$	

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Cross sections

D-meson and c-jet production cross sections (ATLAS):

Process	PDF	$\sigma^{\mathsf{M}}_{\mathrm{MC}}$ [pb]	$\sigma^{\mathsf{A}}_{\mathrm{MC}}$ [pb]	δ_{scale}	δ_{PDF}	σ^{ATLAS} [pb]
$W^+ + D^-$	ABMP16	18.8	19.2	$^{+5.8\%}_{-5.3\%}$	$\pm 1.5\%$	$17.8 \pm 1.9\,(\mathrm{stat}) \pm 0.8\,(\mathrm{sys})$
$W^- + D^+$		19.8	20.7	$^{+5.8\%}_{-5.5\%}$	$\pm 1.5\%$	$22.4 \pm 1.8\,(\mathrm{stat}) \pm 1.0\,(\mathrm{sys})$
$W^+ + j_{\bar{c}}$		31.1	31.8	$^{+6.2\%}_{-9.1\%}$	$\pm 2.5\%$	$33.6 \pm 0.9\,(\mathrm{stat}) \pm 1.8\,(\mathrm{sys})$
$W^- + j_c$		33.9	34.6	$^{+7.5\%}_{-7.7\%}$	$\pm 2.4\%$	$37.3 \pm 0.8\,(\mathrm{stat}) \pm 1.9\,(\mathrm{sys})$

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