W+charm with massive c quarks in PowHel

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in collaboration with

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Based on arXiv:2106.11261

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Contents

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Introduction

- Heavy flavors are important probes for proton structure
- Gluon and sea quark PDF fit input from heavy-meson production
- $W + c$ ($W^+ + \bar{c}$ and $W^- + c$) is useful for strange quark PDF and sea quark composition
- $W + c$ can be used in two different ways:
  - fragmentation: c quark into D meson
  - c-jet production (c-quark tagging)
- Drell-Yan is also sensitive to strange content
- Status of current fits is not satisfactory for strange content

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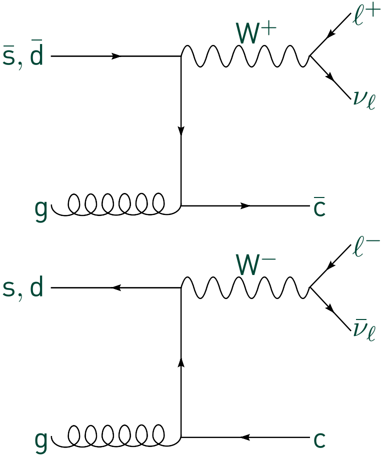
Introduction

- We need new DIS capabilities:
  - Large Hadron-Electron Collider (LHeC) [arXiv:1907.01014]
  - Forward Physics Facility at High-Lumi LHC
- For the time being $W + c$ data can be used
- With $W + c$ care must be taken:
  - Non-diagonal CKM
  - In higher orders other channels start to contribute



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Introduction

- At NLO we can have, like
  - $g\,g \rightarrow W^{+} + \overline{c} + s$
  - $u\,\overline{d} \rightarrow W^{+} + c + \overline{c}$

$\Rightarrow$ Gluon PDF dominates, NLO corrections are important

- $u\,\overline{d} \rightarrow W^{+} + c + \overline{c}$ does not contribute due to analysis cuts
- Non-diagonal CKM decrease sensitivity to s quarks but important to get agreement with data

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Introduction

- s and $\bar{s}$ distributions are fitted separately
- Due to their sea-quark nature we predict:

$$s(x, Q^2) = \bar{s}(x, Q^2)$$

- This assumption can be tested with the ratio:

$$\mathcal{R} = \frac{\sigma(W^+ + \bar{c})}{\sigma(W^- + c)}$$

- $W + c$ production is also interesting for BSM physics being background

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Introduction

- $W + c$ production was studied at Tevatron by CDF and D0
  - Limited data for $W + j_c$
- 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

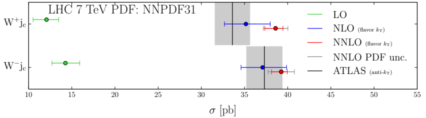
$W + c$ production was also studied from the theory side:

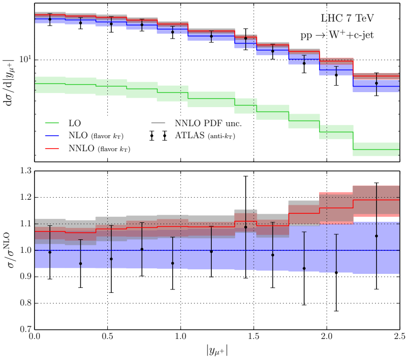
- First NLO QCD calculation (massive c) by Giele et al. [hep-ph/9511449]
- Available at NLO QCD in MCFM (massive c)
- Can be obtained with `MadGraph5_aMC@NLO` at NLO QCD with massive c
- More recently first NNLO QCD results ($m_c = 0$) appeared by Czakon et al. [arXiv:2011.01011]

Introduction

The NNLO calculation of Czakon et al.:

- — Five-flavor scheme was used
- ⇒ Flavored jet algorithm was needed
- — NNLO QCD correction is $\sim 10\%$
- — Good agreement with ATLAS data
- — Direct comparison on hadron level would be great





Introduction

- In the five-flavor scheme c is also massless

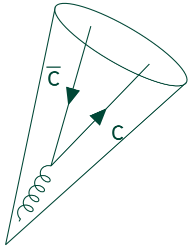
$\Rightarrow$ When produced in pairs the pair can become unresolved

- The process is $W + c + X$

$\Rightarrow$ No subtraction is defined for these regions

$\Rightarrow$ Have to avoid unregularized singularity

$\Rightarrow$ In a jet only a single c is allowed



Introduction

This work:

- NLO QCD accuracy
  - ⇒ Important g g channels of real radiation are considered
- Matched to parton shower and hadronization
  - ⇒ Comparison at hadron (particle) level
- Massive charm
  - ⇒ No need for flavored jet algorithm
  - ⇒ Same jet algorithm can be used as in data taking
  - ⇒ PDFs with 3 active flavors
- Same analysis is implemented as used by experiments
  - ⇒ No unfolding
- PDF and scale uncertainty studies

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Technicalities

- POWHEG matching scheme is used through POWHEG-BOX
- SMEs provided by HELAC (tree and one-loop)
- In-house phase-space generator
- 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 and CT18ZNLO: 5 FNS PDFs $\Rightarrow$ conversion to decoupling scheme

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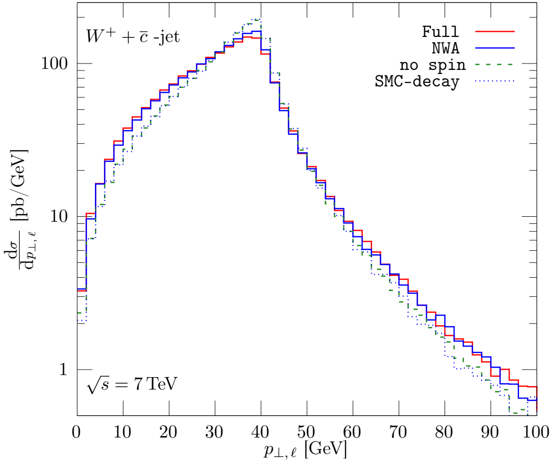
Effect of Spin Correlations

- Decaying W allowed for investigating several aspects:
  - Full calculation: off-shell W with spin correlation in decay
  - W in NWA
  - No spin correlations in W decay
- Effect of off-shellness is marginal
- Spin correlation in decay is crucial

⇒ Effect is carried to rapidity distributions as well



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Pheno Results at 13 TeV

- CMS analyzed $W^{\pm} + D^{*}(2010)^{\mp}$ 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 $D^{*}(2010)$ meson and central μ:
  - $D^{*}(2010)^{\pm}$ with a $\mu^{\pm}$ (Same Signed, SS) $\Rightarrow$ background
  - $D^{*}(2010)^{\pm}$ 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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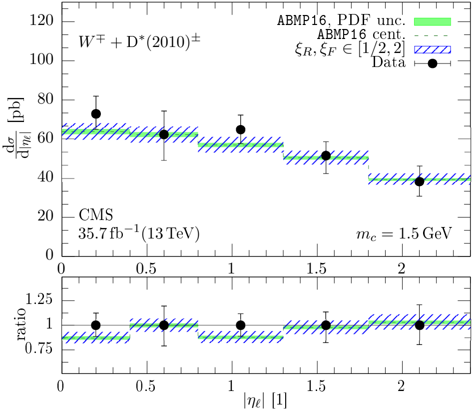
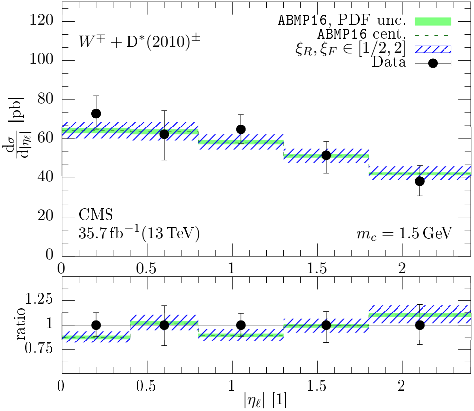
Pheno Results at 13 TeV



Monash tune



ATLAS A14 tune

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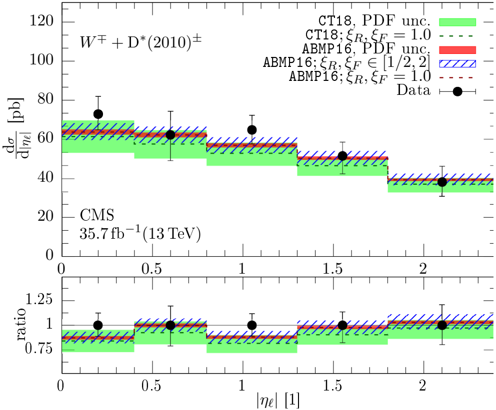
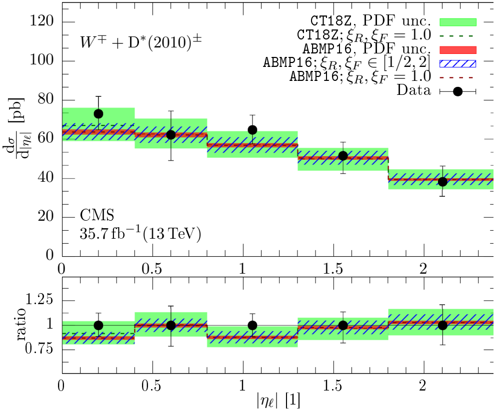
Pheno Results at 13 TeV



Monash tune, CT18NLO at 90% C.L.



Monash tune, CT18ZNLO at 90% C.L.

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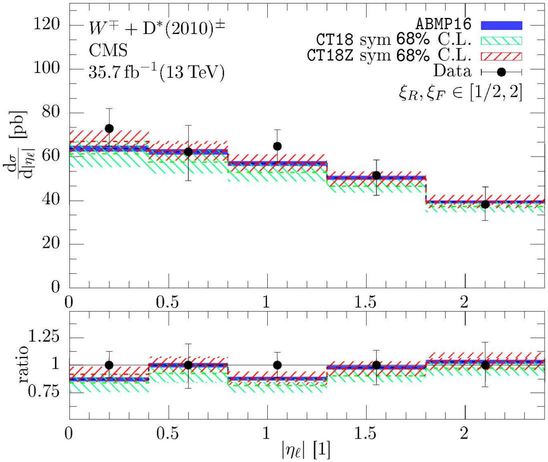
Pheno Results at 13 TeV

- To compare against ABMP16 confidence levels were converted to 68%
- c quark is massive, charm mass from PDF



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Pheno Results at 7 TeV

- Data taken by ATLAS for $W + D\mathrm{-meson}$ and $W + j_c$ (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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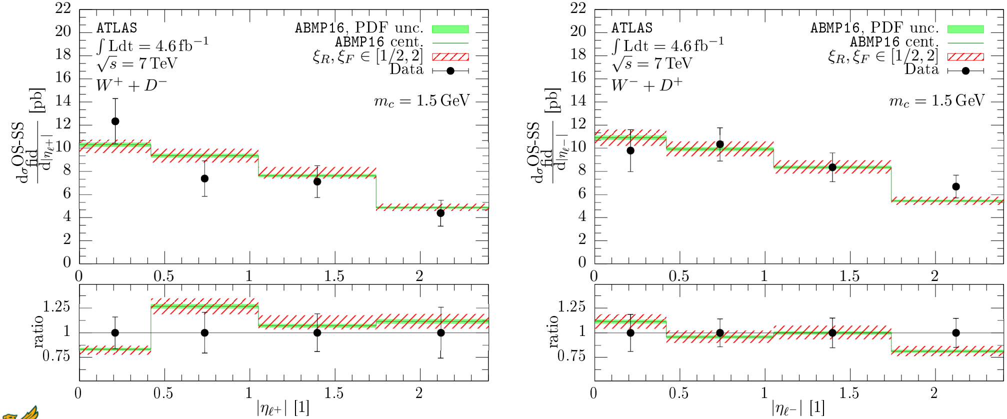
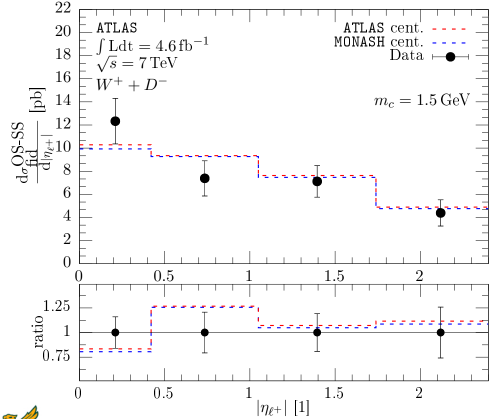
Pheno Results at 7 TeV

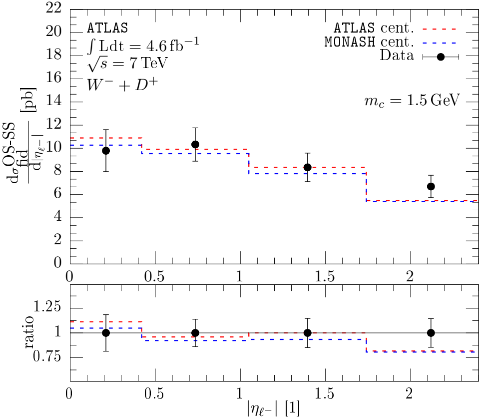
Using the ATLAS A14 tune:



Pheno Results at 7 TeV

Comparison of tunes:





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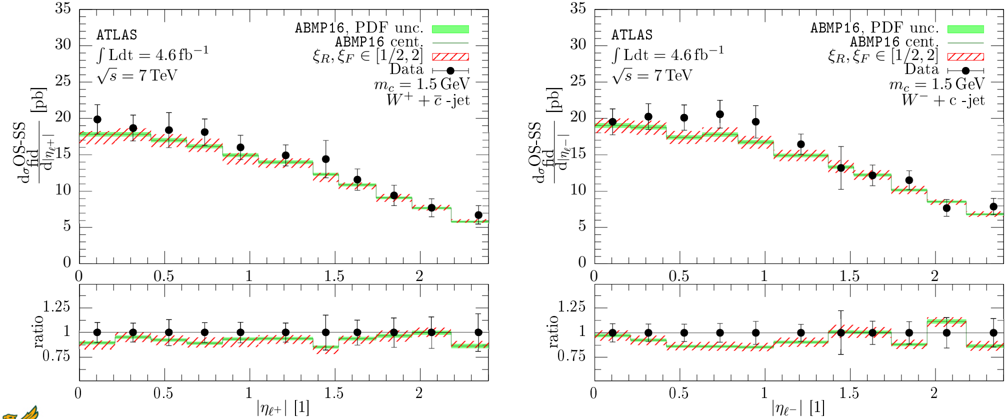
Pheno Results at 7 TeV

Associated charmed jet production with ATLAS A14 tune:



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!