Associated W + charm production: indications for PDF analysis

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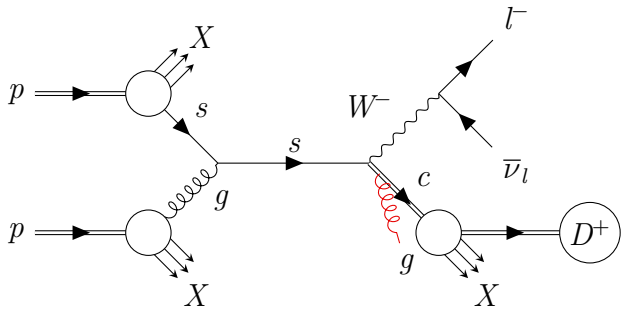
Production of $W^{\mp} D^{(*)\pm}$: framework

- $pp \to W^{\mp}(\to l^{\mp} + \bar{\nu}_l/\nu_l) + c/\bar{c}$ from MCFM [1]
- Subtraction term to get rid of double counting of collinear radiation from the final state charm quark
- OS-SS subtraction to cancel background processes



$$\frac{d\sigma(W^- D^+)}{dp_T(D)\,d\eta_D\,d\eta_{\text{lept}}} = \sum_{i,j=s,d,g} f_i(\mu_{\text{fact}}) \otimes \frac{d\hat{\sigma}_{\text{NLO}}(ij \to W^- c, \mu_{\text{ren}})}{dp_T(c)\,d\eta_c\,d\eta_{\text{lept}}} \otimes f_j(\mu_{\text{fact}}) \otimes D_{c\to D^+}(\mu_{\text{frag}})$$

$$- \frac{d\sigma_{\text{LO}}(W^- c, \mu_{\text{ren}})}{dp_T(c)\,d\eta_c\,d\eta_{\text{lept}}} \otimes \frac{\alpha_s(\mu_{\text{ren}})}{2\pi} C_F \left[\frac{1+l^2}{1-l}\left(\log\frac{\mu^2_{\text{frag}}}{m_c^2} - 1 - 2\log(1-l)\right)\right]_+ \otimes D_{c\to D^+}(\mu_{\text{frag}})$$

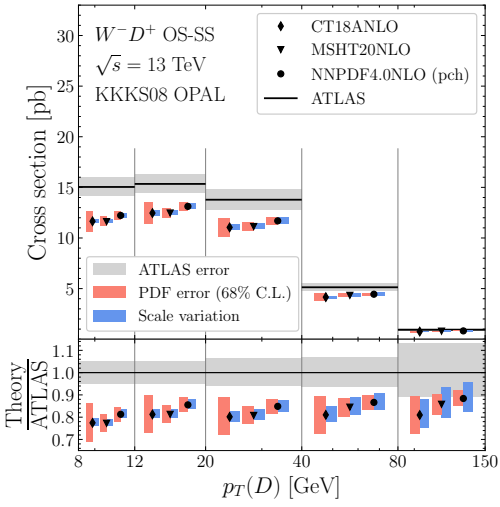
[1] J. Campbell and T. Neumann. DOI: 10.1007/JHEP12(2019)034

Predictions for absolute cross sections have many sources of error

Theory values for cross sections have large uncertainties from the following sources:

- the scales μ_{ren}, μ_{fact} and μ_{frag}
- fitting of PDFs
- fitting of fragmentation functions
- higher-order corrections

NNLO corrections add a near-constant shift of $\sim 15\%$ upwards across the $p_T(D)$ range. [1]



[1] T. Generet, R. Poncelet and M. Muškinja.
DOI: 10.1007/JHEP02(2026)023

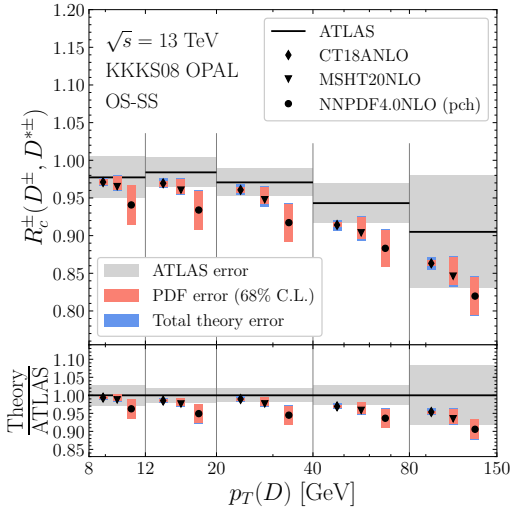
Data: ATLAS Collaboration.
DOI: 10.1103/PhysRevD.108.032012

Production ratio $R_c^{\pm}$ is sensitive only to PDFs — $p_T(D)$ distribution

The scale and fragmentation uncertainties, as well as the constant NNLO correction cancel almost completely in the production ratio

$$R_c^{\pm} \equiv \frac{\sigma(W^+ + D^-) + \sigma(W^+ + D^{*-})}{\sigma(W^- + D^+) + \sigma(W^- + D^{*+})}.$$

- CT18ANLO ($s = \bar{s}$) has the best agreement with the data
- MSHT20NLO and NNPDF4.0NLO ($s \neq \bar{s}$) show more tension



Production ratio $R_c^{\pm}$ is sensitive only to PDFs — $|\eta_{\text{lepton}}|$ distribution

The scale and fragmentation uncertainties, as well as the constant NNLO correction cancel almost completely in the production ratio

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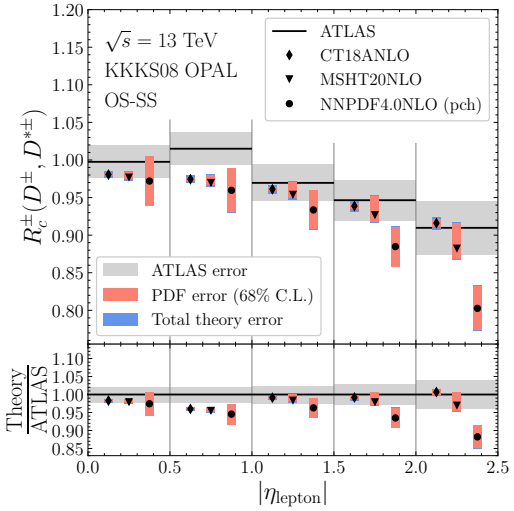


Approximation for $R_c^{\pm}$ in terms of quark PDFs

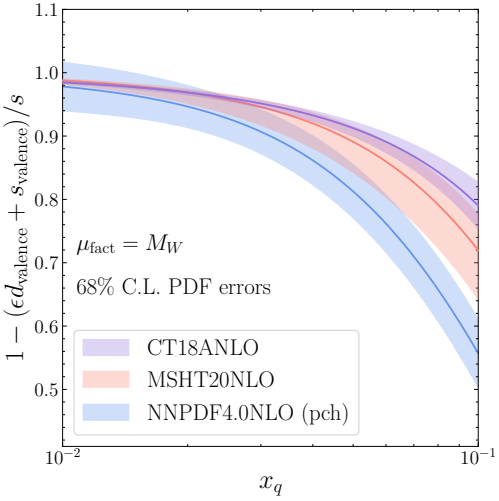
Make the following two simplifications:

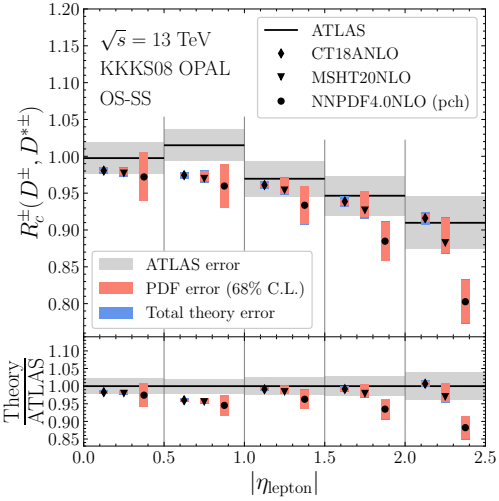
- consider only qg initial states (the gg channel has only a small contribution)
- approximate all momentum fractions of the gluon by a single value $\bar{x}_g$

$$R_c^{\pm}(x_q) \approx \frac{[\bar{d}(x_q)|V_{cd}|^2 + \bar{s}(x_q)|V_{cs}|^2]\cancel{f_g(\bar{x}_g)}}{[d(x_q)|V_{cd}|^2 + s(x_q)|V_{cs}|^2]\cancel{f_g(\bar{x}_g)}}$$

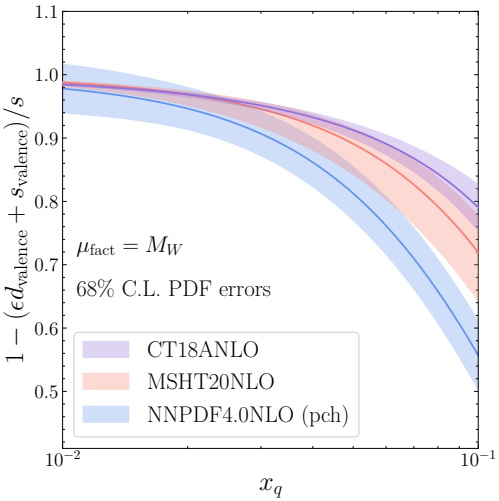
$$\approx 1 - \frac{\epsilon(d-\bar{d})(x_q) + (s-\bar{s})(x_q)}{s(x_q)}, \quad \epsilon \equiv \frac{|V_{cd}|^2}{|V_{cs}|^2}$$

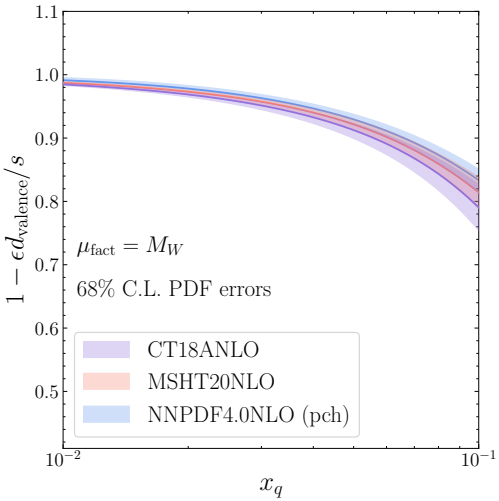
The approximation and our NLO calculation look similar





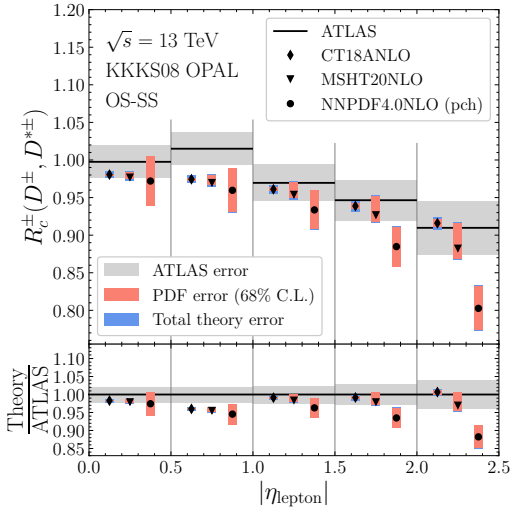
Strangeness asymmetry is the main reason for differences in $R_c^{\pm}$



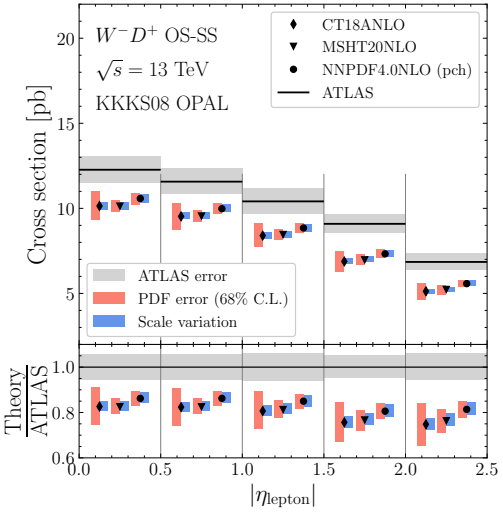


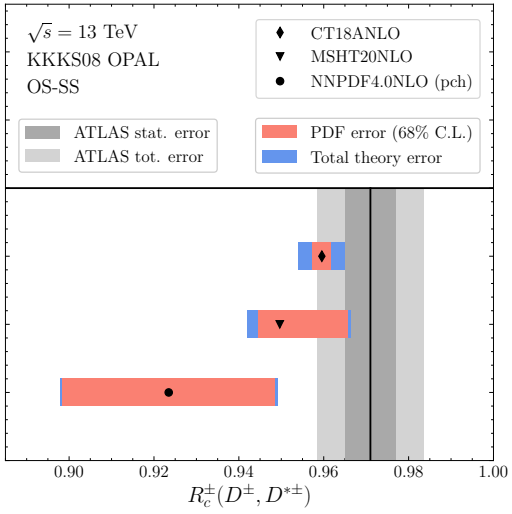
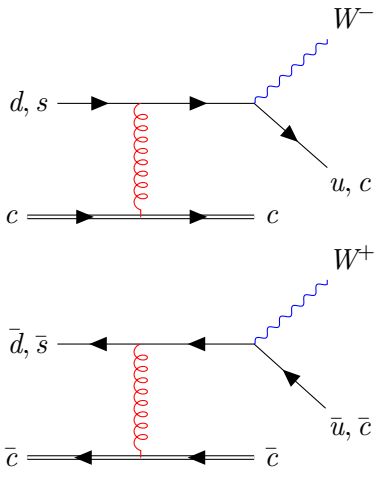
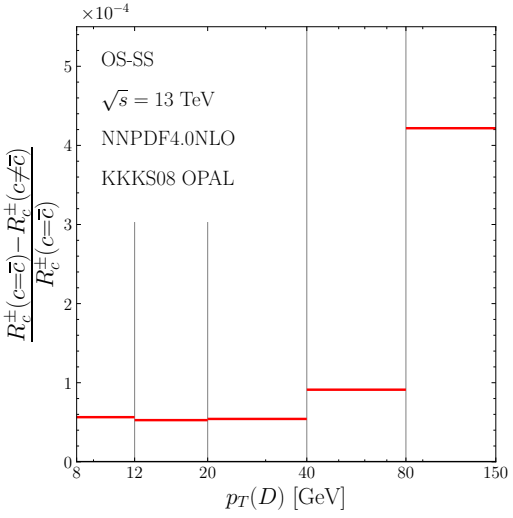
Conclusions

- Simultaneous production of $W^{\mp} D^{(*)\pm}$ was studied at NLO in the collinear factorization framework
- The production ratio $R_c^{\pm}$ isolates the PDF uncertainty
- Comparison between our results for $R_c^{\pm}$ and the data indicates some combination of
  - larger s,
  - smaller s_{valence} and/or
  - smaller d_{valence}



More plots


W^-D^+ OS-SS
$\sqrt{s} = 13$ TeV
KKKS08 OPAL
CT18ANLO
MSHT20NLO
NNPDF4.0NLO (pch)
ATLAS
ATLAS error
PDF error (68% C.L.)
Scale variation
Cross section [pb]
Theory / ATLAS
$|\eta_{\text{lepton}}|$


$\sqrt{s} = 13$ TeV
KKKS08 OPAL
OS-SS
CT18ANLO
MSHT20NLO
NNPDF4.0NLO (pch)
ATLAS stat. error
ATLAS tot. error
PDF error (68% C.L.)
Total theory error
$R_c^{\pm}(D^{\pm}, D^{*\pm})$

Low sensitivity to intrinsic charm