The Associated Production of Vector Bosons and a c-quark in proton-proton Collisions

Cesar Gonzalez Renteria, Francesco Giuli, Gregory Ottino, Heather Gray, Josh McFayden, Marjorie Shapiro, **Miha Muškinja**, Rohith Karur, Sasha Glazov, Simone Amoroso, and many others from the ATLAS Collaboration

Les Houches Open Discussion

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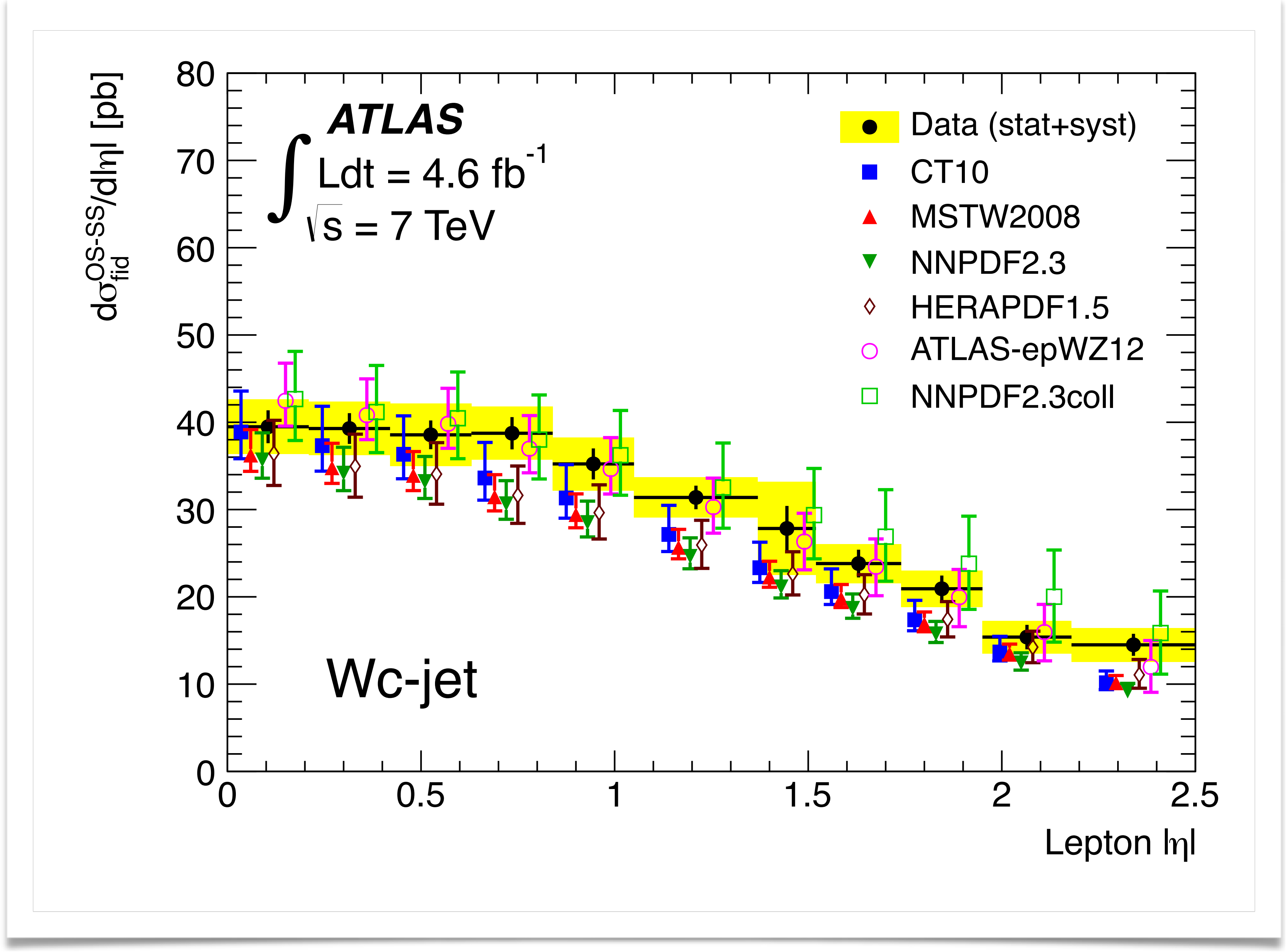
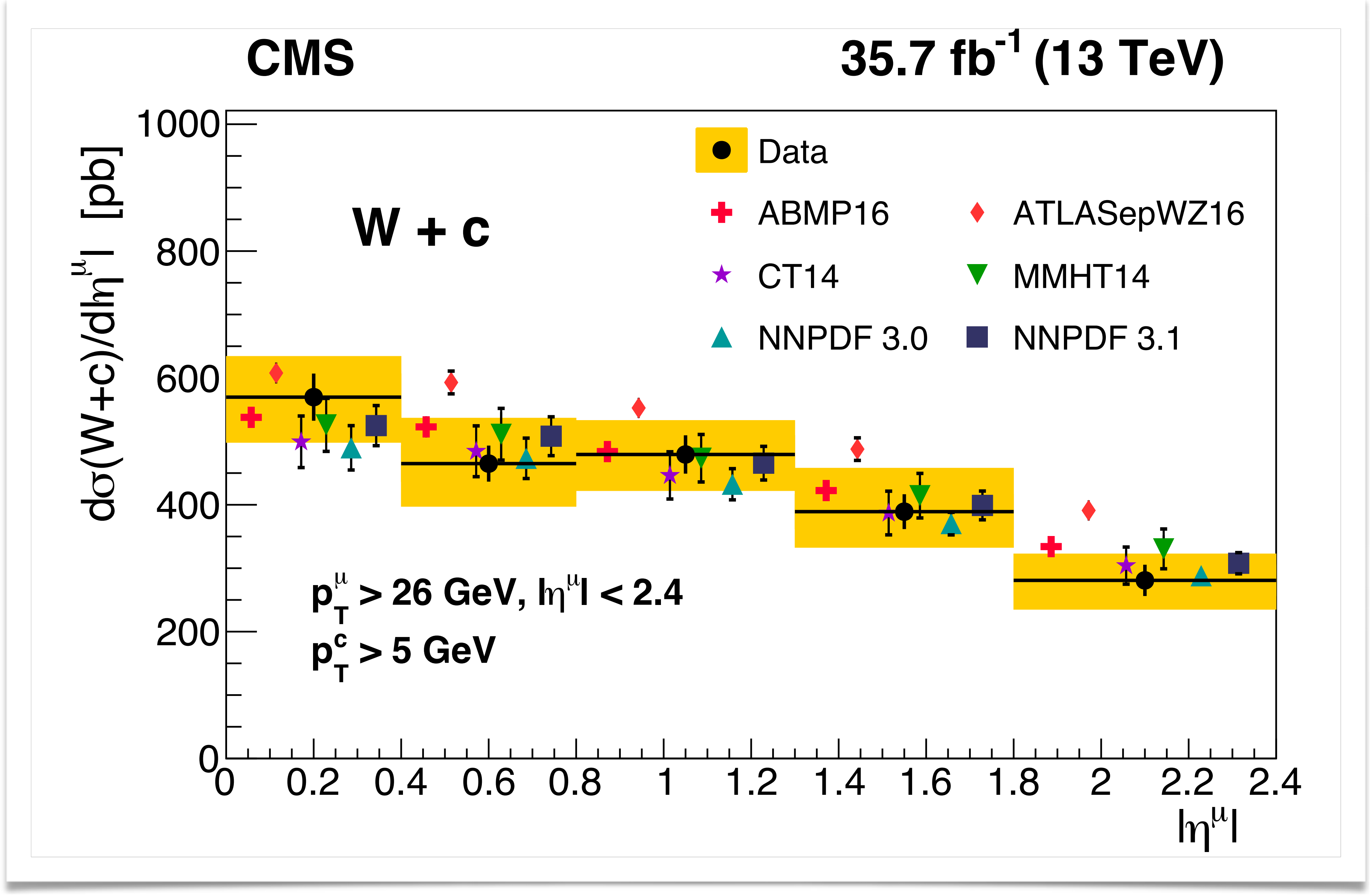
BERKELEY LAB

ATLAS EXPERIMENT

- W+c experimental results at LHC:
  - ATLAS W+c at 7 TeV,
  - CMS W+c at 7 TeV and 13 TeV with 36 fb^{-1},
- A 5% or better accuracy in differential variables (e.g. p_T(charm), η(lepton)) feasible with full Run 2 data,
- The unfolded data is beneficial for MC tuning and PDF fits (W+c gives access to s-quark PDF),
  - Comparisons of the unfolded data to MC generators interfaced to a parton shower are possible,
  - However, not possible to directly use the W+c data in **PDF fits** — important to solve!





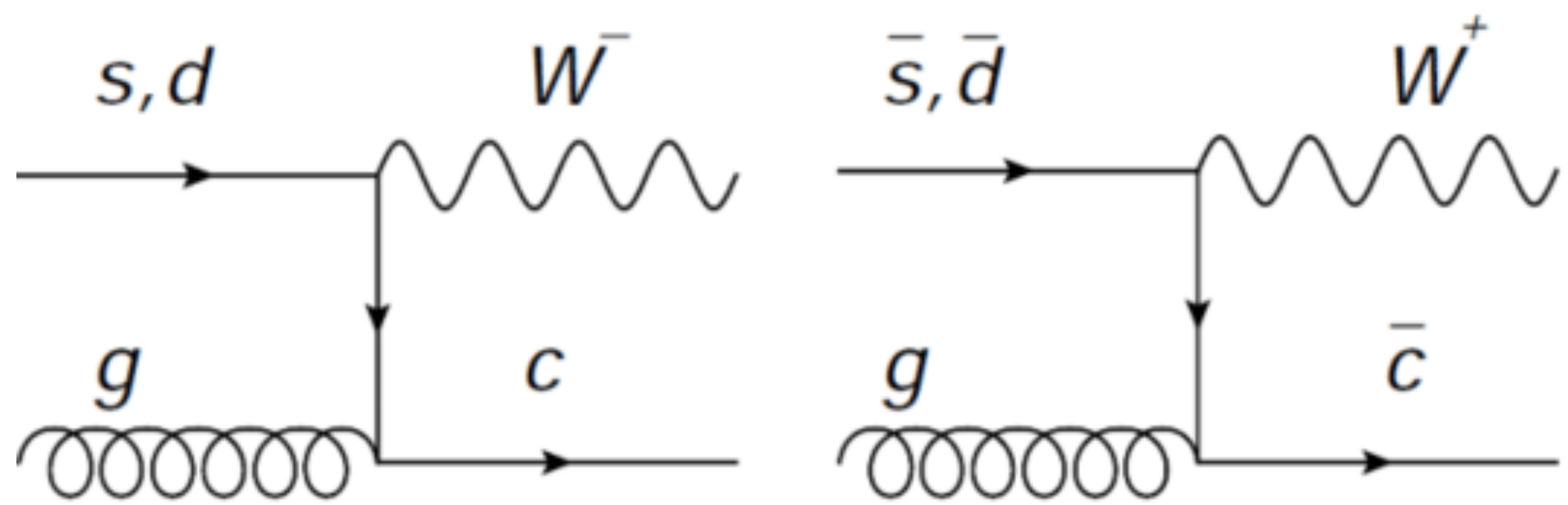
Issues with the W+c interpretations

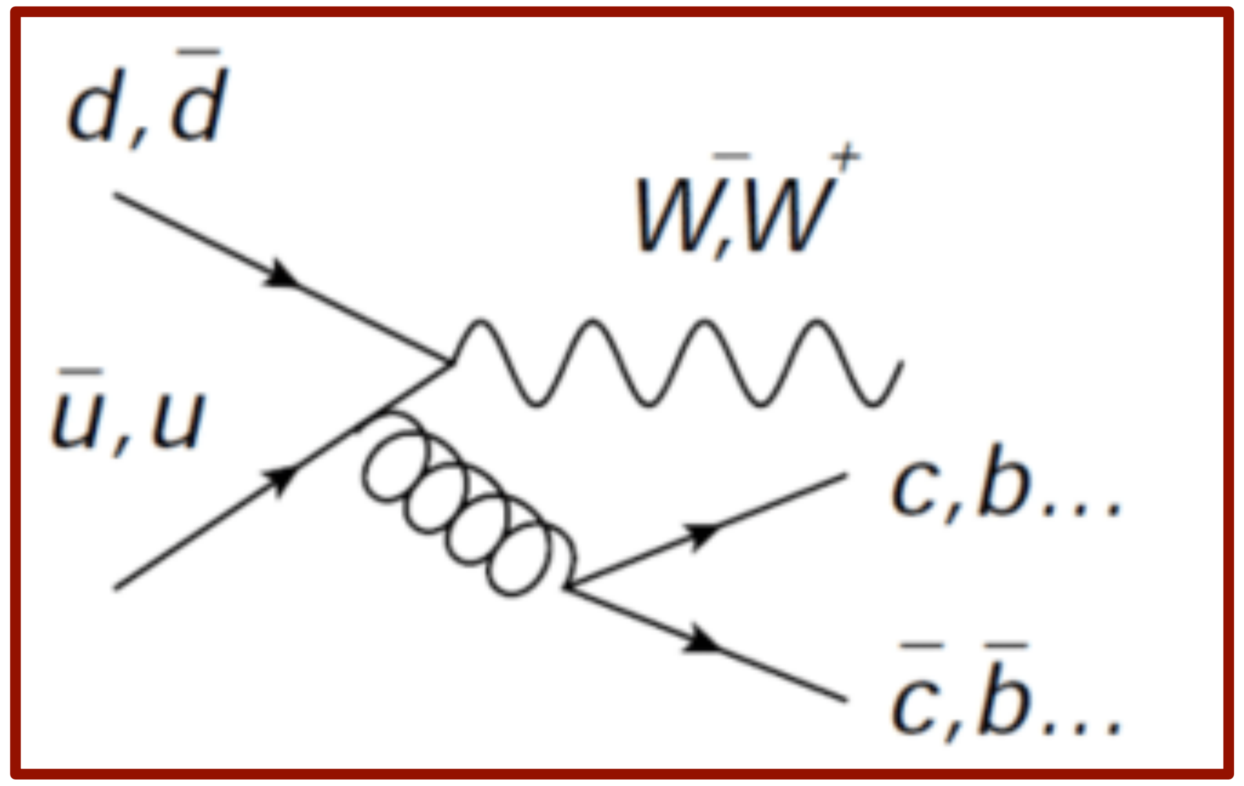
- Thanks to A. Mitov, M. Czakon, M. Pellen, R. Poncelet, T. Generet, and the ATLAS colleagues for already discussing this with us!

- The main issue is the lack of a NLO (or better) W+c calculation that would **include charm fragmentation**,
- A NNLO W+c-jet calculation recently available (2011.01011), overview by Mathieu on June 1 at JSS,
  - It uses a **parton-level** IR safe jet definition (**flavored-kT jets**), but fragmentation not included,
- Experimental measurements are *usually* unfolded to **particle-level**,
  - Either directly to the **c-hadron (D+, D*+)** or an **anti-kT particle jet**, depending on the analysis,
  - Not directly comparable to the calculations without the use of a showering MC generator.

- Ideally, we would have a NNLO W+c-jet calculation including the fragmentation / hadronization,
- Alternatively, 'unfold' the experimental data to partons and accept the large associated uncertainties,
  - Is it possible at an **event-by-event level** or does it require **correction factors** to transform particle-level kinematics to parton-level?
  - How can this be technically performed / calculated (e.g. with `MCFM`, `AMC@NLO`, …)?

- W+c measurements can exploit the charge correlation between the W and c-quark to suppress the charge-symmetric background from gluon splitting,

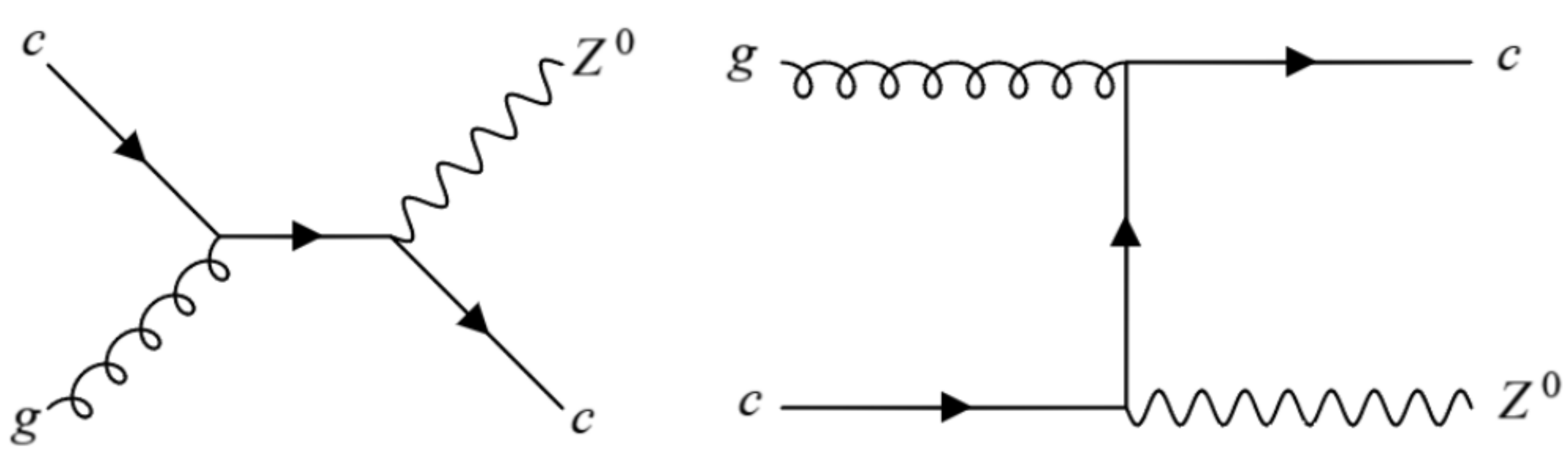


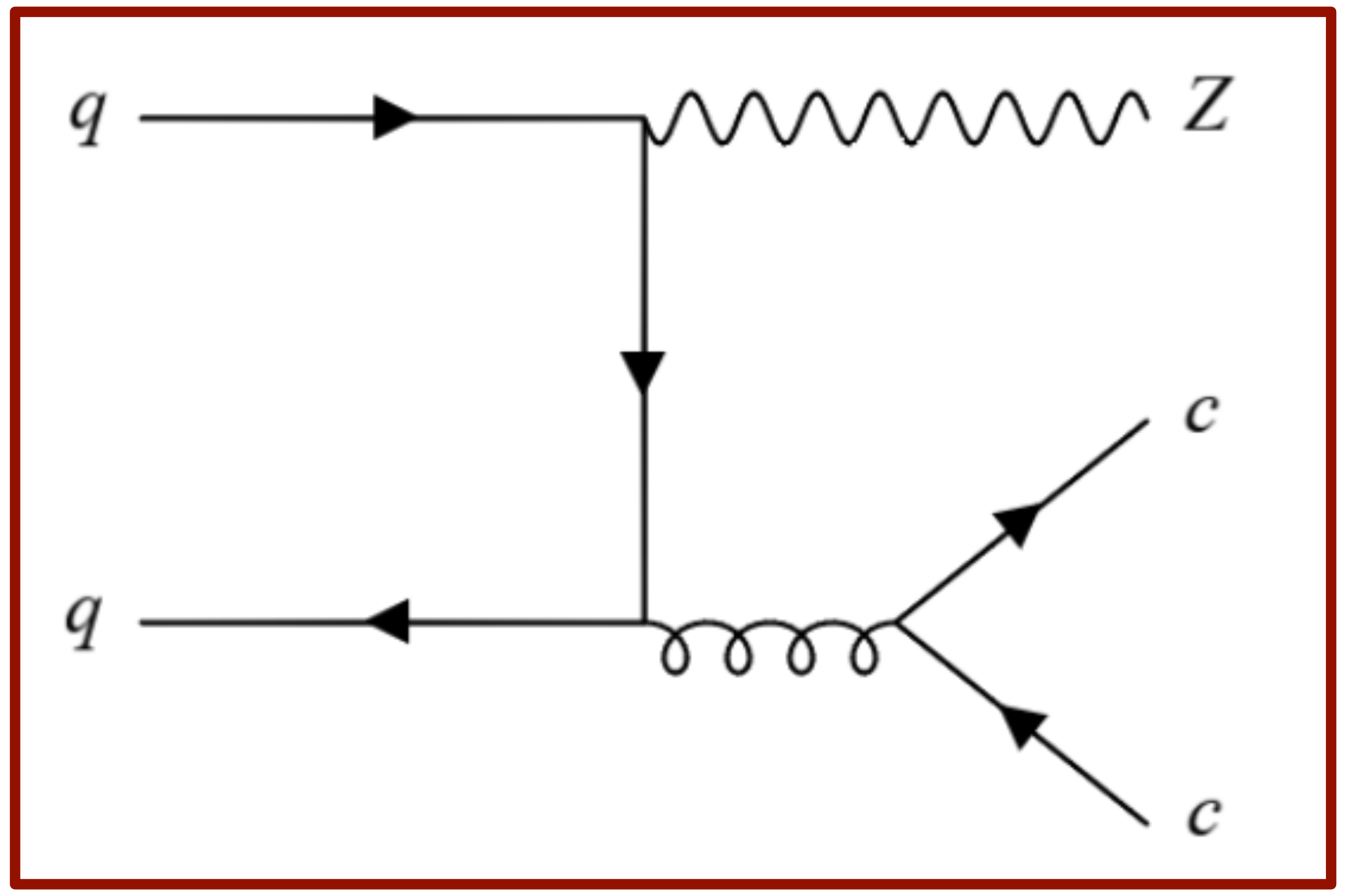


Can be greatly reduced using the ‘OS-SS’ subtraction.

Question: How well does this hold at NNLO?

- Z+c measurements do not have the same luxury, so coherent definitions of gluon splitting and an appropriate treatment of the c-quark PDF are needed and must be consistently applied in theory and in experimental measurements.



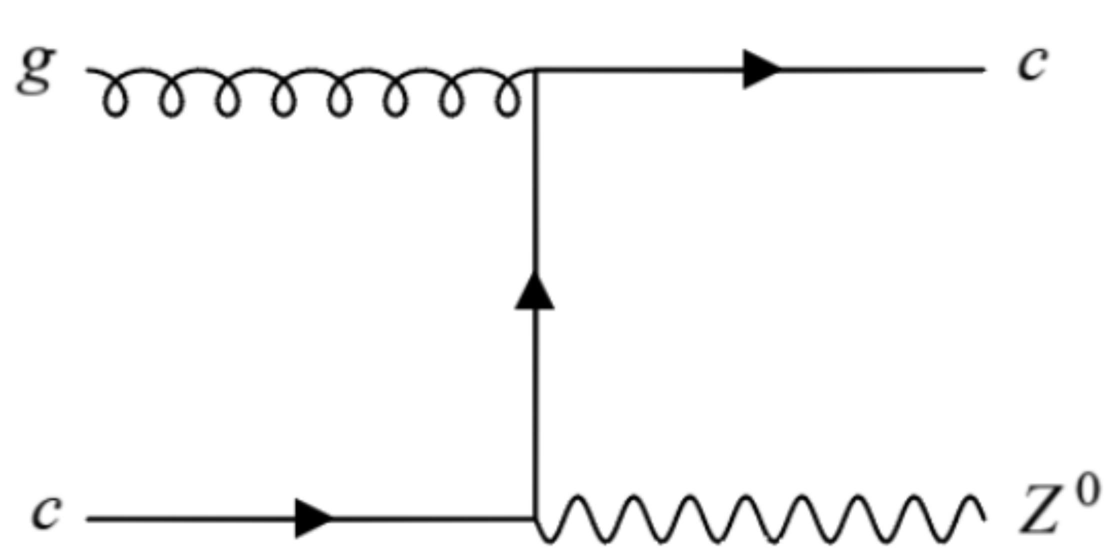


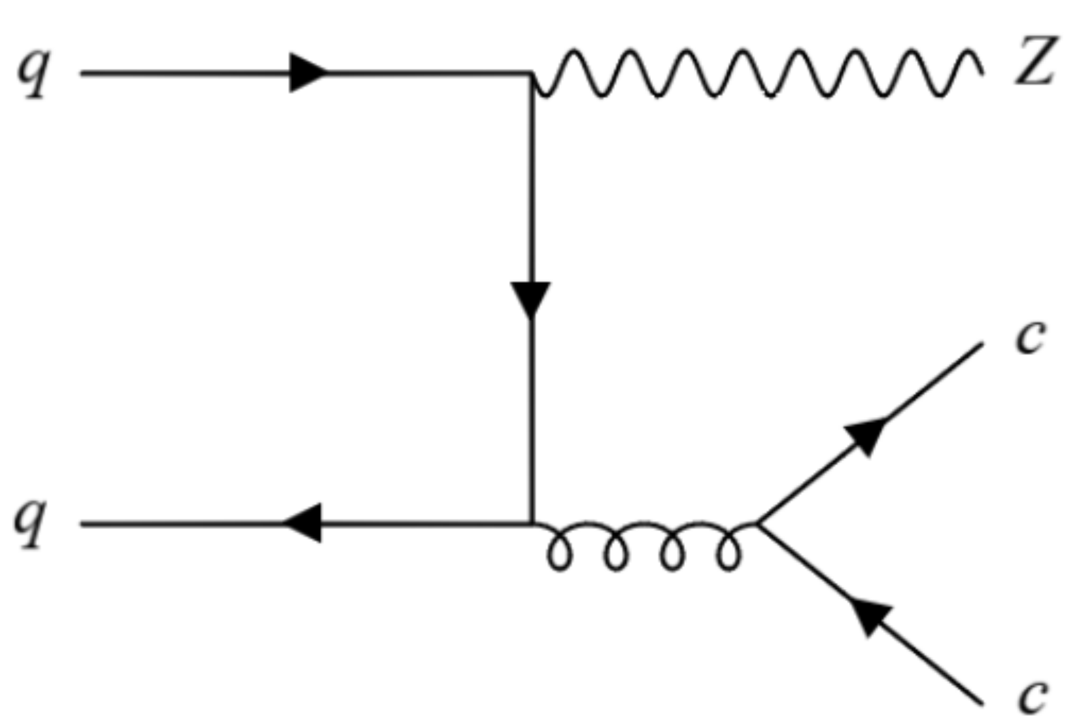
Can not be easily suppressed. A ‘good’ definition of the signal process is needed.

Summary and discussion points

- V+c measurements with Run 2 and Run 3 data will reach a ‘percent level’ precision,
- The data can already be used for MC tuning, i.e. compare unfolded particle-level data to MC predictions,
- Invaluable for **PDF fits**, but a NLO calculation that includes charm fragmentation is needed,
  - Currently one would need to unfold to **parton-level** and add large systematic uncertainties.

- Would benefit from theory / experiment collaboration to work out the details of V+c,
  - Once a calculation with charm fragmentation is available, is anything extra needed from the experiments?
  - If unfolding to parton-level is necessary, how would one do it?
  - Corrections for anti-kT vs flavored-kT and / or particle-level vs parton-level?
  - Unambiguous definition of the V+c signal and gluon splitting background at the event-by-event level?
    - i.e. with 4/5 FNS c-quark present in the initial state, otherwise only in the HS via gluon splitting,
    - Is the ‘OS-SS’ subtraction in W+c sufficient to ignore the gluon splitting component?





Backup

CMS W+c unfolding to parton-level

The number of W+c events corresponds to the number of $D^*(2010)^{\pm}$ mesons after the subtraction of light-flavor and gluon splitting backgrounds. The invariant mass of $K^{\mp}\pi^{\pm}$ candidates, which are selected in a $\Delta m(D^*, D^0)$ window of ± 1 MeV, is shown in Fig. 2, along with the observed reconstructed mass difference $\Delta m(D^*, D^0)$. A clear D^0 peak at the expected mass and a clear $\Delta m(D^*, D^0)$ peak around the expected value of 145.4257 ± 0.0017 MeV [39] are observed. The remaining background is negligible, and the number of $D^*(2010)^{\pm}$ mesons is determined by counting the number of candidates in a window of $144 < \Delta m(D^*, D^0) < 147$ MeV. Alternately, two different functions are fit to the distributions, and their integral over the same mass window is used to estimate the systematic uncertainties associated with the method chosen.

5 Measurement of the fiducial W+c cross section

The fiducial cross section is measured in a kinematic region defined by requirements on the transverse momentum and the pseudorapidity of the muon and the transverse momentum of the charm quark. The simulated signal is used to extrapolate from the fiducial region of the $D^*(2010)^{\pm}$ meson to the fiducial region of the charm quark. Since the $D^*(2010)^{\pm}$ kinematics is integrated over at the generator level, the only kinematic constraint on the corresponding charm quark arises from the requirement on the transverse momentum of $D^*(2010)^{\pm}$ meson. The correlation of the kinematics of charm quarks and $D^*(2010)^{\pm}$ mesons is investigated using simulation, and the requirement of $p_T^{D^*} > 5$ GeV translates into $p_T^c > 5$ GeV. The distributions of $|\eta^{\mu}|$ and p_T^c in the simulation are shown to reproduce very well the fixed order prediction at NLO obtained, using MCFM 6.8 [17–19] calculation. The kinematic range of the measured fiducial cross section corresponds to $p_T^{\mu} > 26$ GeV, $|\eta^{\mu}| < 2.4$, and $p_T^c > 5$ GeV.

The fiducial W+c cross section is determined as:

$$\sigma(W+c) = \frac{N_{sel}\,\mathcal{S}}{\mathcal{L}_{int}\,\mathcal{B}\,\mathcal{C}}, \qquad (2)$$

where N_{sel} is the number of selected OS − SS events in the $\Delta m(D^*, D^0)$ distribution and $\mathcal{S}$ is the signal fraction. The latter is defined as the ratio of the number of reconstructed $W+D^*(2010)^{\pm}$ candidates originating from W+c to the number of all reconstructed $D^*(2010)^{\pm}$. It is determined from the MC simulation, includes the background contributions, and varies between 0.95 and 0.99. The integrated luminosity is denoted by $\mathcal{L}_{int}$. The combined branching fraction $\mathcal{B}$ for the channels under study is a product of $\mathcal{B}(c \to D^*(2010)^{\pm}) = 0.2429 \pm 0.0049$ [43] and $\mathcal{B}(D^*(2010)^{\pm} \to K^{\mp} + \pi^{\pm} + \pi^{\pm}_{slow}) = 0.0266 \pm 0.0003$ [39]. The correction factor $\mathcal{C}$ accounts for the acceptance and efficiency of the detector. The latter is determined using the MC simulation and is defined as the ratio of the number of reconstructed $W+D^*(2010)^{\pm}$ candidates to the number of generated $W+D^*(2010)^{\pm}$ originating from W+c events that fulfill the fiducial requirements. In the measurement of the $W^+ + \bar{c}$ ($W^+ + D^*(2010)^-$) and $W^- + c$ ($W^- + D^*(2010)^+$) cross sections, the factor $\mathcal{C}$ is determined separately for different charge combinations.

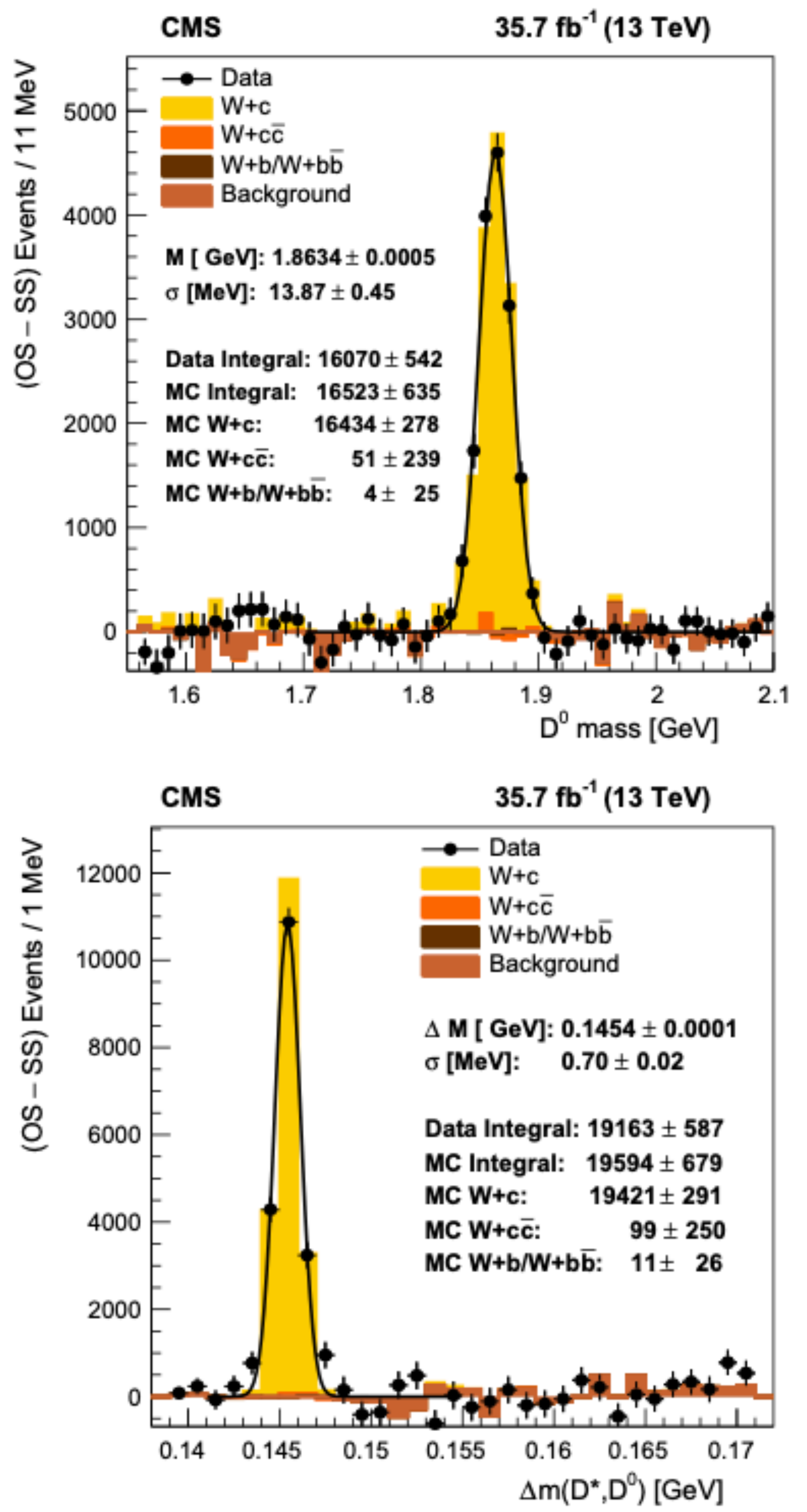


Fig. 2 Distributions of the reconstructed invariant mass of $K^{\mp}\pi^{\pm}$ candidates (upper) in the range $|\Delta m(D^*, D^0) - 0.1454| < 0.001$ GeV, and the reconstructed mass difference $\Delta m(D^*, D^0)$ (lower). The SS combinations are subtracted. The data (filled circles) are compared to MC simulation with contributions from different processes shown as histograms of different shades

Table 1 Systematic uncertainties [%] in the inclusive and differential W+c cross section measurement in the fiducial region of the analysis. The total uncertainty corresponds to the sum of the individual contributions in quadrature. The contributions listed in the top part of the table cancel in the ratio $\sigma(W^+ + \bar{c})/\sigma(W^- + c)$

Pseudorapidity [$\lvert\eta^{\mu}\rvert$]	[0, 2.4]	[0, 0.4]	[0.4, 0.8]	[0.8, 1.3]	[1.3, 1.8]	[1.8, 2.4]
Luminosity	±2.5	±2.5	±2.5	±2.5	±2.5	±2.5
Tracking	±2.3	±2.3	±2.3	±2.3	±2.3	±2.3
Branching	±2.4	±2.4	±2.4	±2.4	±2.4	±2.4
Muons	±1.2	±1.2	±1.2	±1.2	±1.2	±1.2
N_{sel} determination	±1.5	±1.5	±1.5	±1.5	±1.5	±1.5
$D^*(2010)^{\pm}$ kinematics	±0.5	±0.5	±0.5	±0.5	±0.5	±0.5
Background normalization	± 0.5	+0.9/−0.8	+1.9/−0.8	+1.4/−0.5	+0.8/−1.0	0.0/−0.6
$\vec{p}_T^{miss}$	+0.7/−0.9	+0.4/−1.2	+1.3/−0.3	+1.1/−1.0	0.0/−2.6	0.0/+1.5
Pileup	+2.0/−1.9	+0.4/−0.5	+2.9/−3.0	+2.0/−1.9	+4.6/−5.1	+2.7/−2.6
Secondary vertex	−1.1	+1.3	−1.2	−1.5	−2.7	−2.5
PDF	±1.2	±1.3	±0.9	±1.4	±1.5	±1.7
Fragmentation	+3.9/−3.2	+3.4/−1.8	+7.4/−5.2	+3.3/−3.0	+2.2/−1.2	+7.4/−5.7
MC statistics	+3.6/−3.3	+8.8/−7.5	+9.0/−11.9	+7.9/−6.8	+9.8/−14.1	+10.1/−8.5
Total	+7.5/−7.0	+10.7/−9.3	+13.2/−14.2	+10.1/−9.3	+12.7/−16.2	+13.8/−12.1

$\alpha_S(m_Z)$ in the PDF, resulting in an uncertainty of 1.2% in the inclusive cross section.

– The uncertainty associated with the fragmentation of the c quark into a $D^*(2010)^{\pm}$ meson is determined through variations of the function describing the fragmentation parameter $z = p_T^{D^*}/p_T^c$. The investigation of this uncertainty is inspired by a dedicated measurement of the $c \to D^*(2010)^{\pm}$ fragmentation function in electron-proton collisions [48], in which the fragmentation parameters in various phenomenological models were determined with an uncertainty of 10%. In the PYTHIA MC event generator, the fragmentation is described by the phenomenological Bowler–Lund function [49,50], in the form

$$f(z) = \frac{1}{z^{r_c\, b m_q^2}}(1-z)^a \exp(-b\, m_\perp^2/z)\, c,$$

with $m_\perp = \sqrt{m_{D^*}^2 + p_{TD^*}{}^2}$, controlled by the two parameters a and b. In the case of charm quarks, $r_c = 1$ and $m_q = 1.5$ GeV are the PYTHIA standard settings in the CUETP8M1 tune, whereas the value of $m_\perp$ is related to the average transverse momentum of generated $D^*(2010)^{\pm}$ in the MC sample. The parameters a, b and c are determined in a fit to the simulated distribution of $f(z)$, where c is needed for the normalization. Since the presence of a jet is not required in the analysis, the charm quark transverse momentum is approximated by summing up the transverse momenta of tracks in a cone of $\Delta R \leq 0.4$ around the axis of the $D^*(2010)^{\pm}$ candidate. The free parameters are determined as $a = 1.827 \pm 0.016$ and $b = 0.00837 \pm 0.00005\ \mathrm{GeV}^{-2}$. To estimate the uncertainty, the parameters a and b are varied within $\pm 10\%$ around their central values, following the precision achieved for the fragmentation parameters in [48]. An additional constraint on the upper boundary on the a parameter in PYTHIA is consistent with this 10% variation. The resulting uncertainty in the cross section is 3.9%.

5.2 Cross section results

The numbers of signal events and the inclusive fiducial cross sections with their uncertainties are listed in Table 2 together with the ratio of $\sigma(W^+ + \bar{c})/\sigma(W^- + c)$. For the differential measurement of the W+c cross section, the numbers of signal events are summarized in Table 3 together with the corrections $\mathcal{C}$ derived using MC simulations in each $|\eta^{\mu}|$ bin. The results are presented for $d\sigma(W+c)/d|\eta^{\mu}|$, as well as for $d\sigma(W^+ + \bar{c})/d|\eta^{\mu}|$ and for $d\sigma(W^- + c)/d|\eta^{\mu}|$.

The measured inclusive and differential fiducial cross sections of W+c are compared to predictions at NLO ($\mathcal{O}(\alpha_s^2)$) that are obtained using MCFM 6.8. Similarly to the earlier analysis [11], the mass of the charm quark is chosen to be $m_c = 1.5$ GeV, and the factorization and the renormalization scales are set to the value of the W boson mass. The calculation is performed for $p_T^{\mu} > 26$ GeV, $|\eta^{\mu}| < 2.4$, and $p_T^c > 5$ GeV. In Fig. 4, the measurements of the inclusive W+c cross section and the