

# Measurements of the production cross section of a W in association with a charm quark in pp collisions at LHC at $\sqrt{s} = 13$ TeV

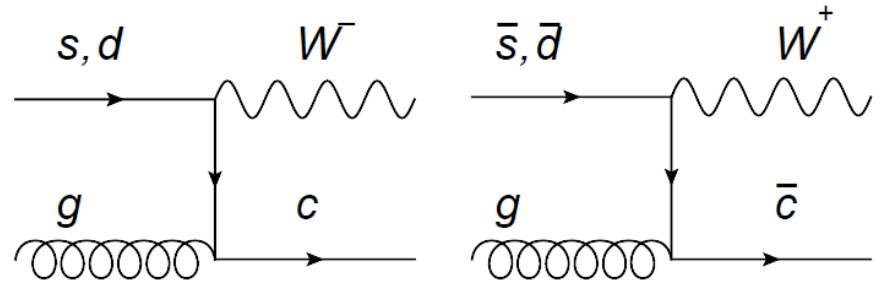
## CMS Collaboration

7<sup>th</sup> Red LHC workshop  
10<sup>th</sup> of May, 2023

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# Introduction



- **Motivation**

$W+c$  probes the strange quark content of the proton

Cross section measurements provide information for extraction of the strange PDF

- **Measurements performed**

Fiducial production cross section

Differential cross sections vs  $p_T$  and  $\eta$  of lepton from  $W$  decay

Cross section ratio  $R_c^\pm \equiv \sigma(W^+ + \bar{c})/\sigma(W^- + c)$  (sensitive to  $s/\bar{s}$  PDF asymmetry)

- **Comparison with predictions** from calculations at **NLO in QCD** (MCFM)

- using several PDF sets at NLO (with and without  $s/\bar{s}$  PDF asymmetry)

- NEW: will include in paper the comparison with recent **NNLO in QCD & NLO in EW predictions**

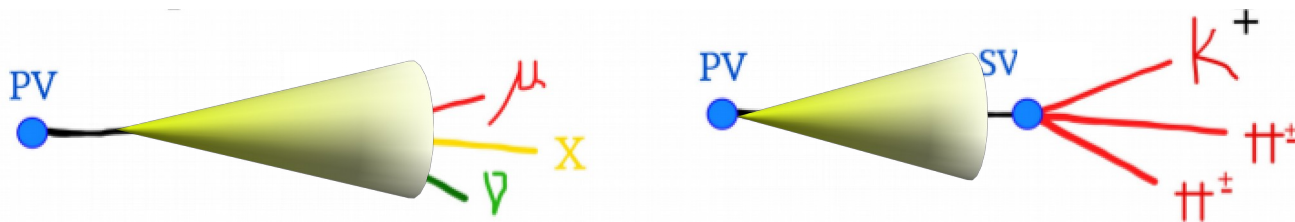
# Analysis strategy:

$W^+ \rightarrow l^+ \nu$  (+c.c.) with  $p_T(l) > 35$  GeV &  $|\eta(l)| < 2.4$  ( $l = e, \mu$ ) [\*]

Transverse mass ( $M_T$ )  $> 55$  GeV

Identify heavy flavour hadrons in final states by taking advantage of long life of heavy hadrons:

- Displaced muon in jet (SL channel)
- Tracks forming a SV (SV channel)

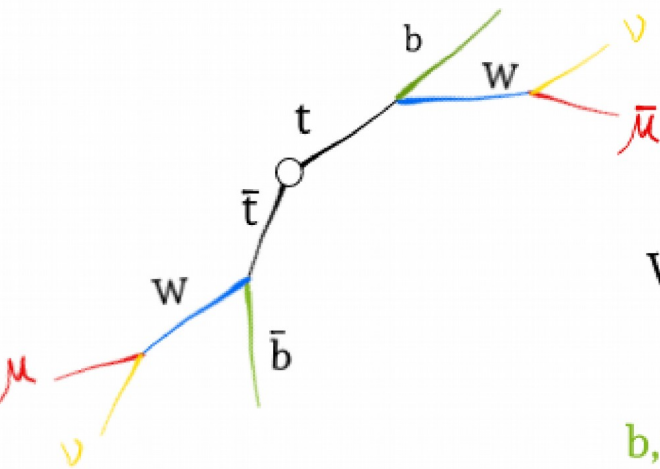
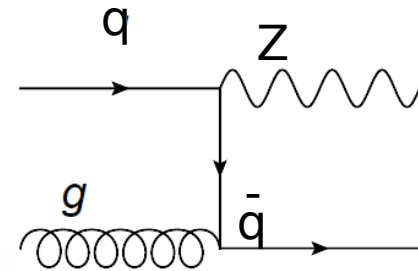
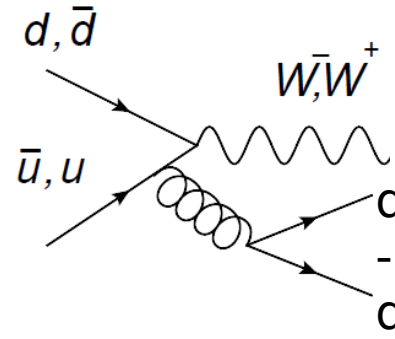
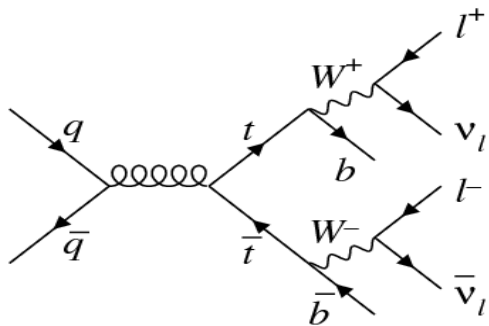


Fiducial kinematic region:  $p_T(l) > 35$  GeV,  $|\eta(l)| < 2.4$  &  $p_T^{c\text{-jet}} > 30$  GeV,  $|\eta^{c\text{-jet}}| < 2.4$ ,  $\Delta R(l, c\text{-jet}) > 0.4$  ( c-jets formed with anti- $k_t$   $R=0.4$  parton jets)

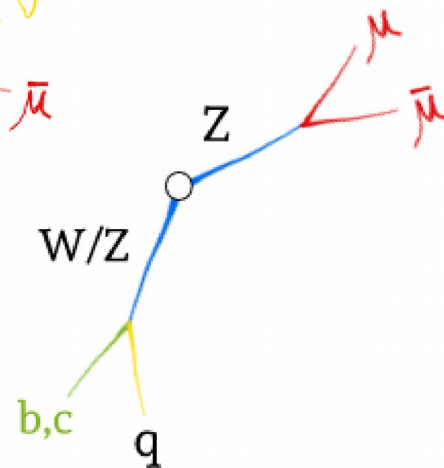
DATA: 2016-2018 13 TeV ( 138 fb $^{-1}$  )

# Background (bkg.) processes:

4



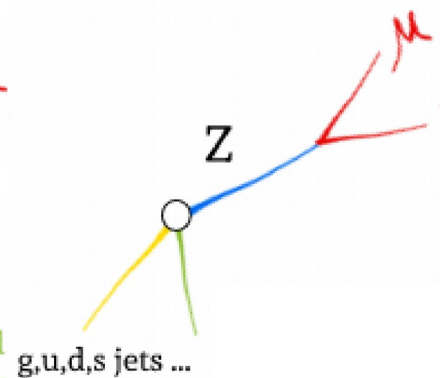
Top pair  
production  
&  
Single top



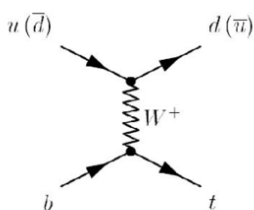
Dibosons



W+light jets

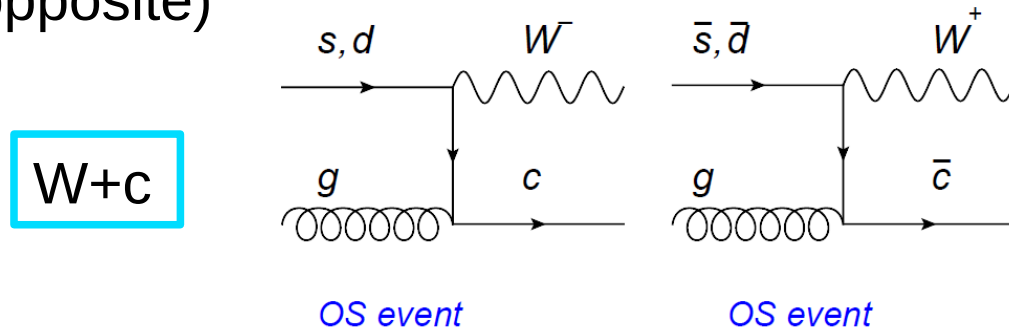


Z+light jets

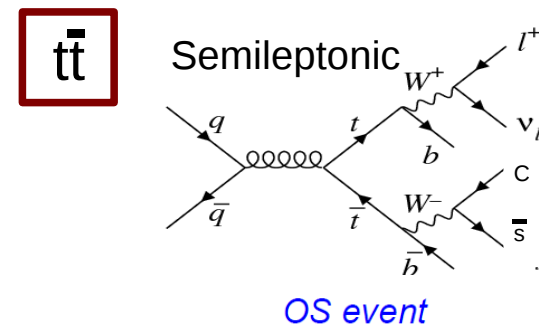
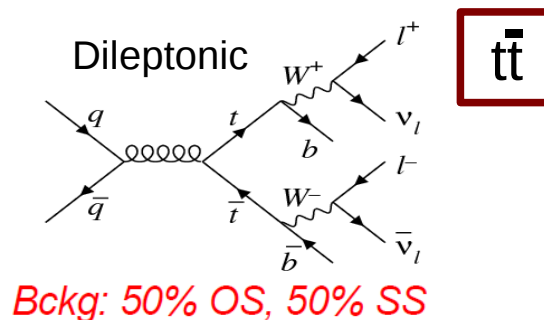
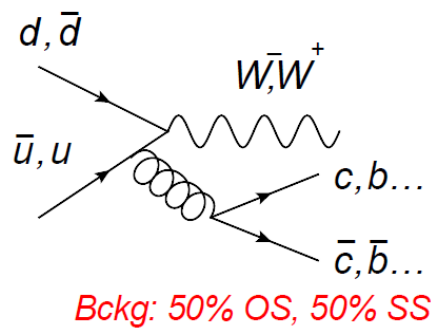


# Opposite sign (OS) – same sign (SS) bkg. subtraction

- Signal is OS (sign of electric charges of W and c are opposite)



- For most backgrounds  $\#events(OS) = \#events(SS)$  with same kinematics



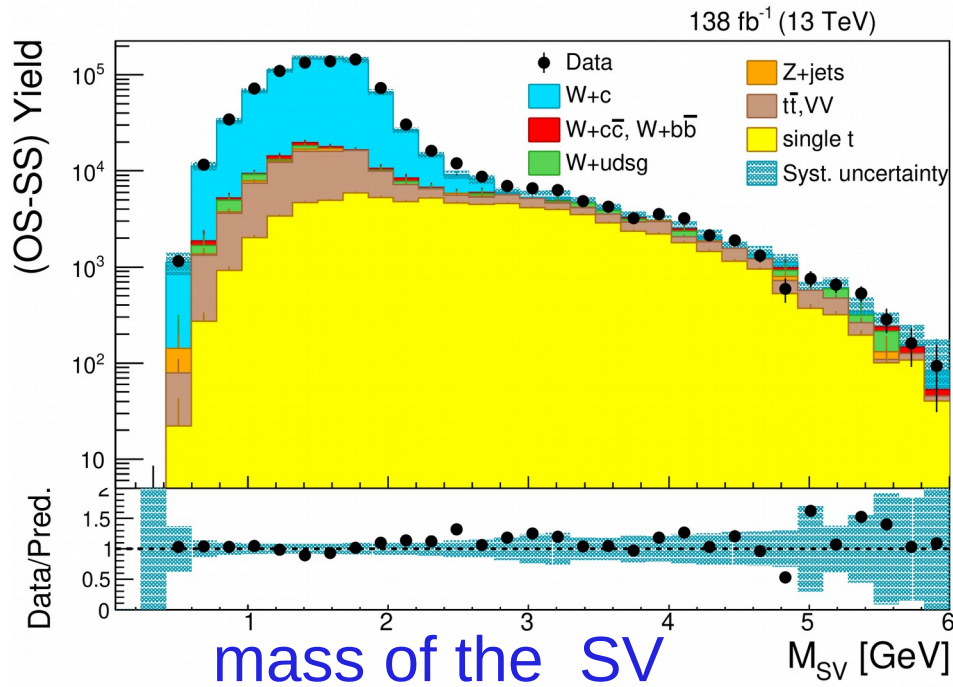
- OS – SS to get rid of symmetric background

(80% purity in W+c, main remaining bck. t-t-bar semil and t)

# Both SL and SV provide sign of electric charge of the charm quark

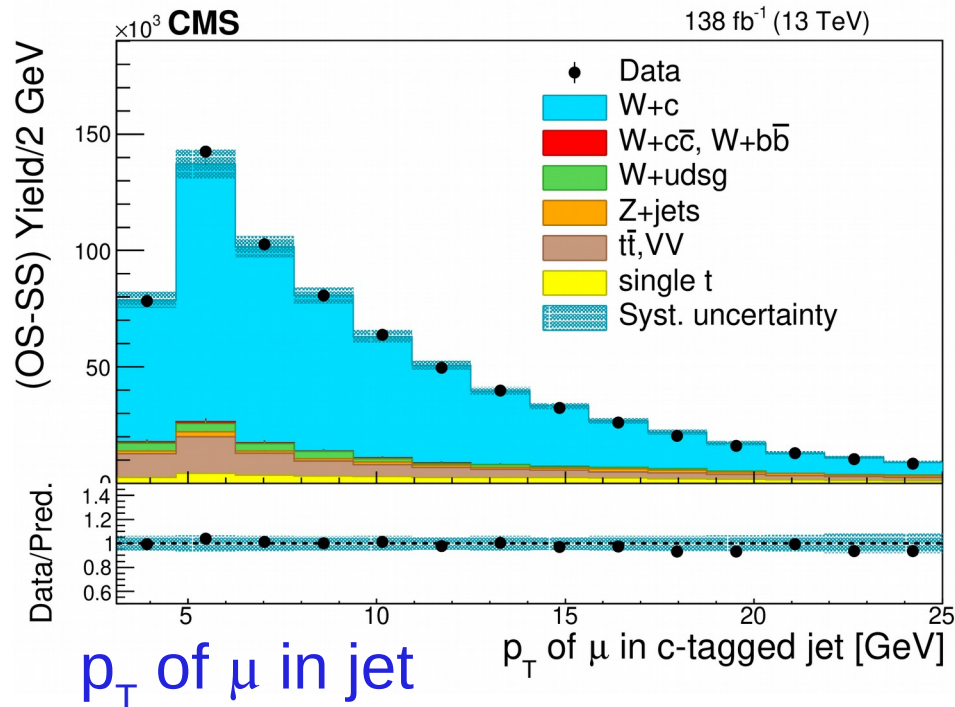
- **SL Charge identification** of the c quark through the charge of the  $\mu$ -in-jet
- **Charge definition:** SS if the  $\mu$ -in-jet has the same charge than the lepton from the W decay      OS  $\rightarrow Q_{W \rightarrow e, \mu} \neq Q_{\mu\text{-in-jet}}$       SS  $\rightarrow Q_{W \rightarrow e, \mu} = Q_{\mu\text{-in-jet}}$
- **SV Charge identification** of the charm quark through the  $\sum_{i(\text{tracks of SV})} Q_i$
- **Charge definition:** SS if the SV has the same charge than the lepton from the W decay      OS :  $Q_{W \rightarrow e(\mu)} \neq Q_{SV}$       SS :  $Q_{W \rightarrow e(\mu)} = Q_{SV}$

All channels (e, $\mu$  for W and SL and SV for charm) are combined



SV channel

~80% signal  
 ~10 %  $t\bar{t}$  bar  
 ~10% single top



SL channel

~80% signal  
 ~10 %  $t\bar{t}$  bar  
 ~5% single top  
 ~ 3% W+uds g

# Systematics: Summary of main sources

## Fiducial cross section:

Uncertainty [%]	SL	SL	SV	SV
	$W \rightarrow e\nu$	$W \rightarrow \mu\nu$	$W \rightarrow e\nu$	$W \rightarrow \mu\nu$
Isolated lepton identification	2	1	2	1
Jet energy scale and resolution	2	2	2	2
Muon in jet identification	3	3	-	-
SV reconstruction	-	-	3	3
Charm fragmentation and decay	2	2	2	2
Limited size of MC samples	1	1	1	1
Integrated Luminosity	1.6	1.6	1.6	1.6
Total	5	5	5	5

Systematics down to 3.8% in the combination of the four channels

## Fiducial cross section ratio:

Most of the systematic effects cancel out in the cross section ratio.

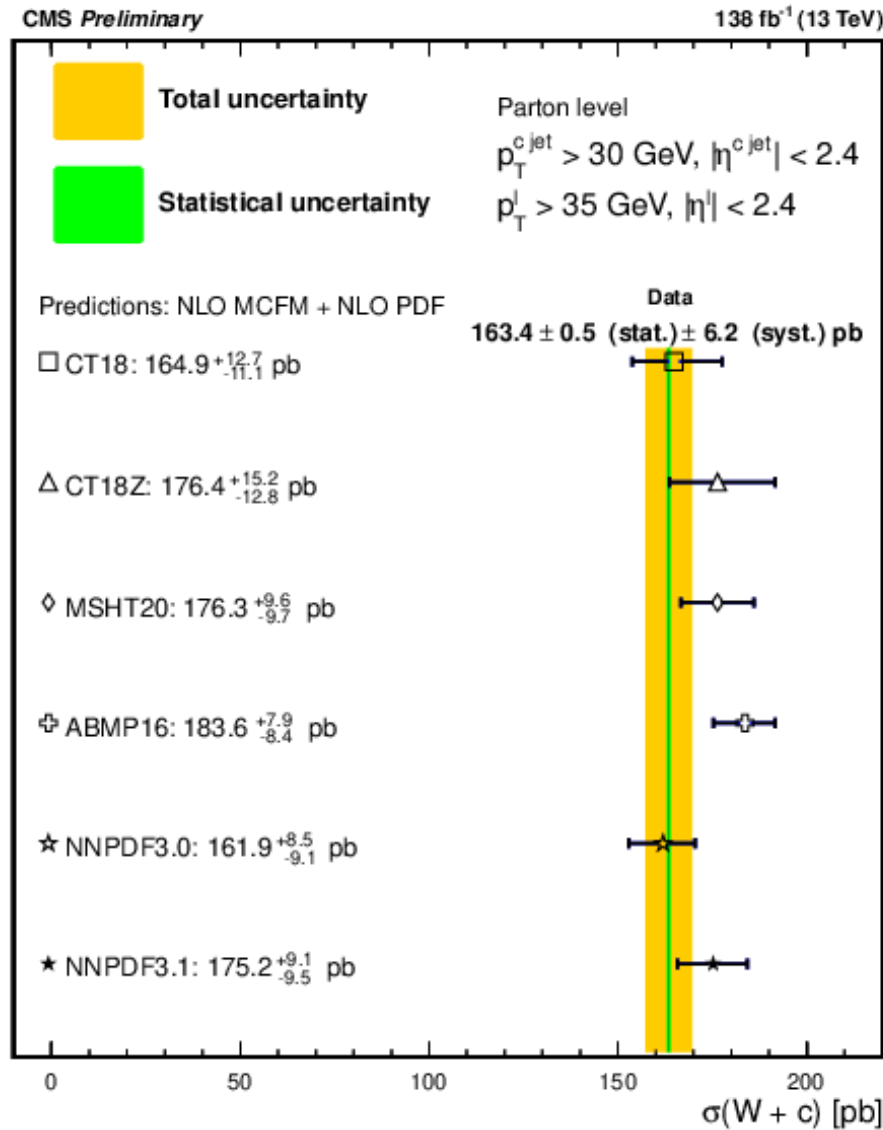
- Potential reconstruction efficiency differences for positive or negative leptons and SVs (1.2-1.4%, statistically limited by simulation)

Systematics down to 1% in the combination of the four channels

# Results and comparison with predictions

# Integrated fiducial cross section

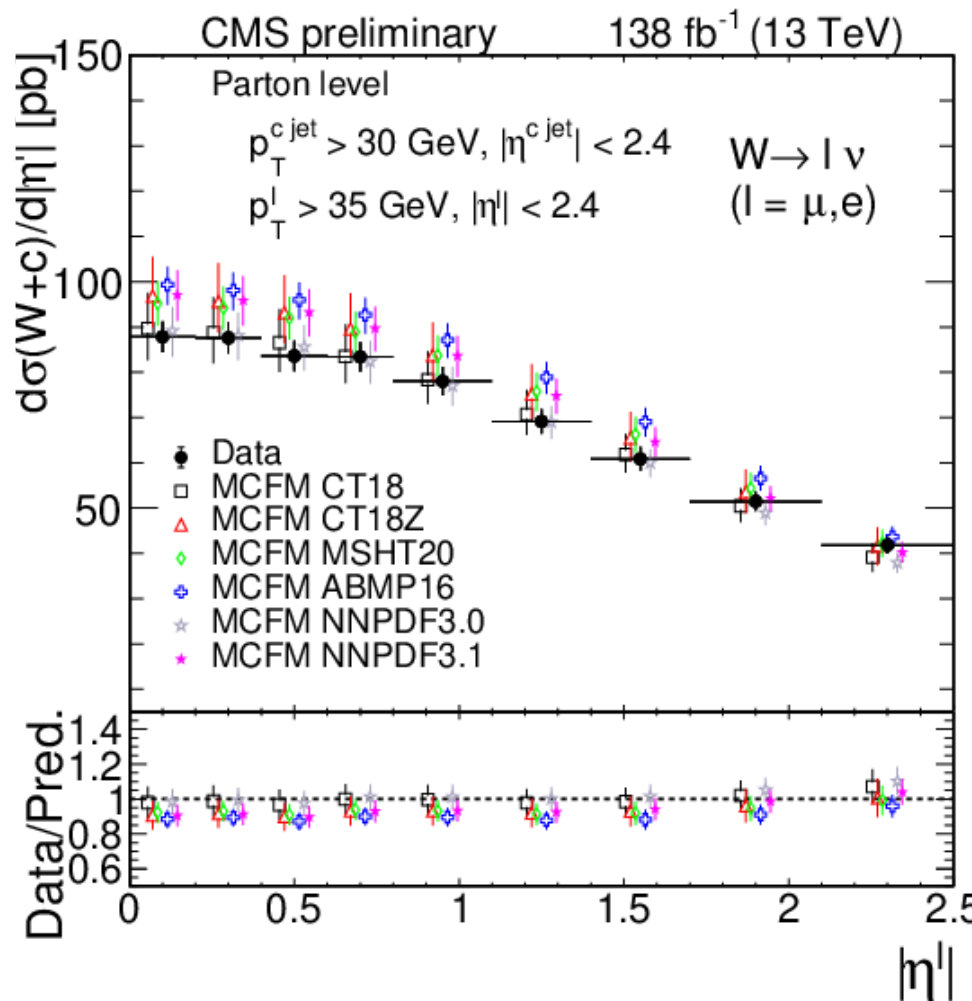
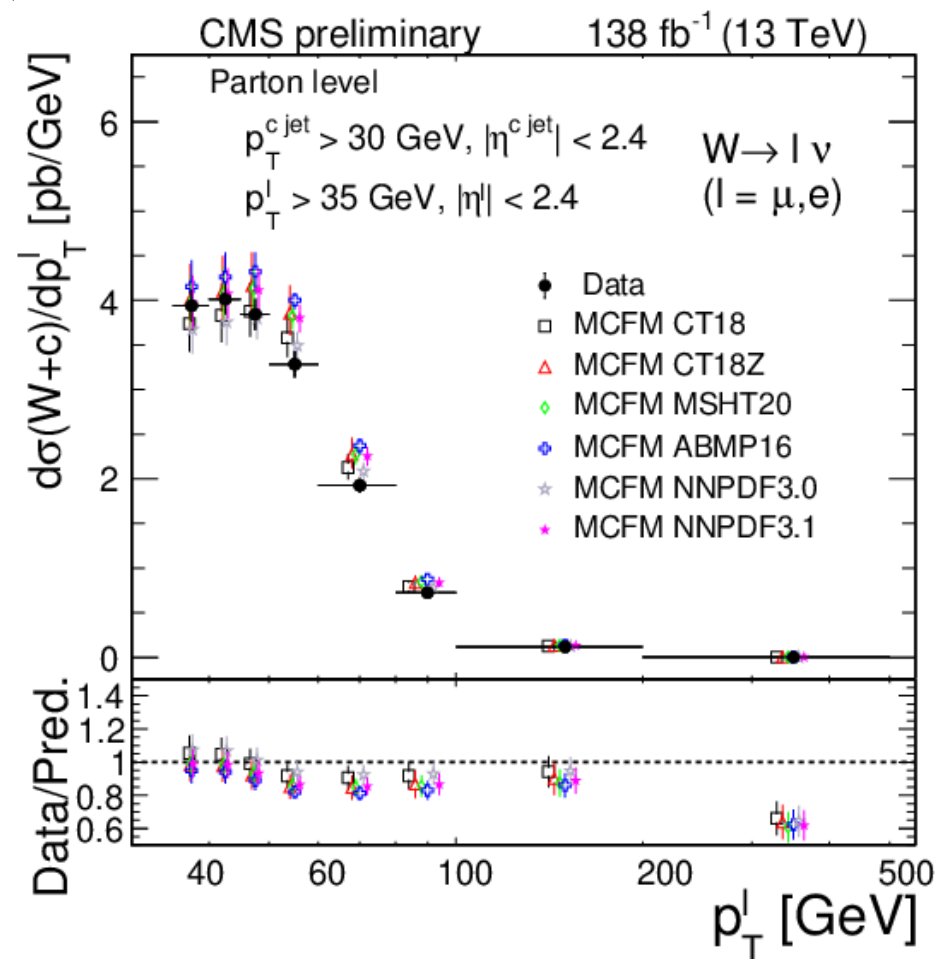
MCFM predictions at NLO for W+c cross section for different PDF sets



Theoretical  
uncertainty dominated  
by PDF uncertainty.

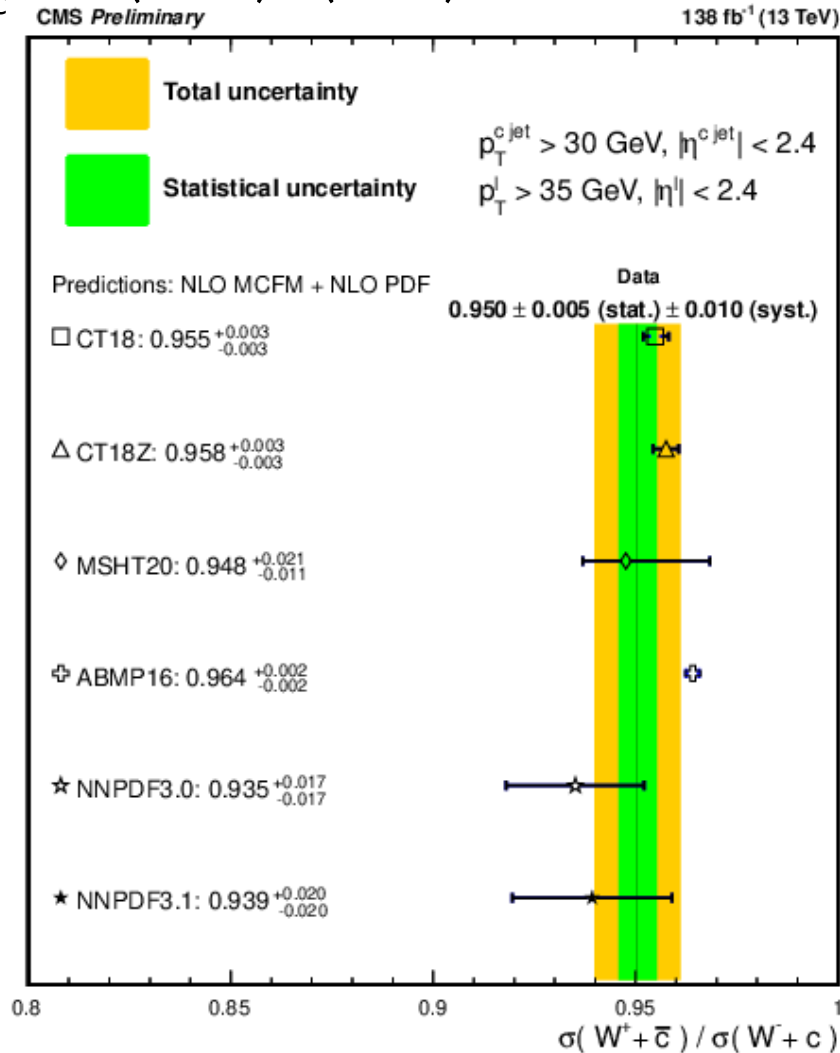
These new  
measurements provide  
input to reduce it.

# Differential cross sections



# Integrated cross section ratio

$$R_c^\pm \equiv \sigma(W^+ + \bar{c}) / \sigma(W^- + c)$$

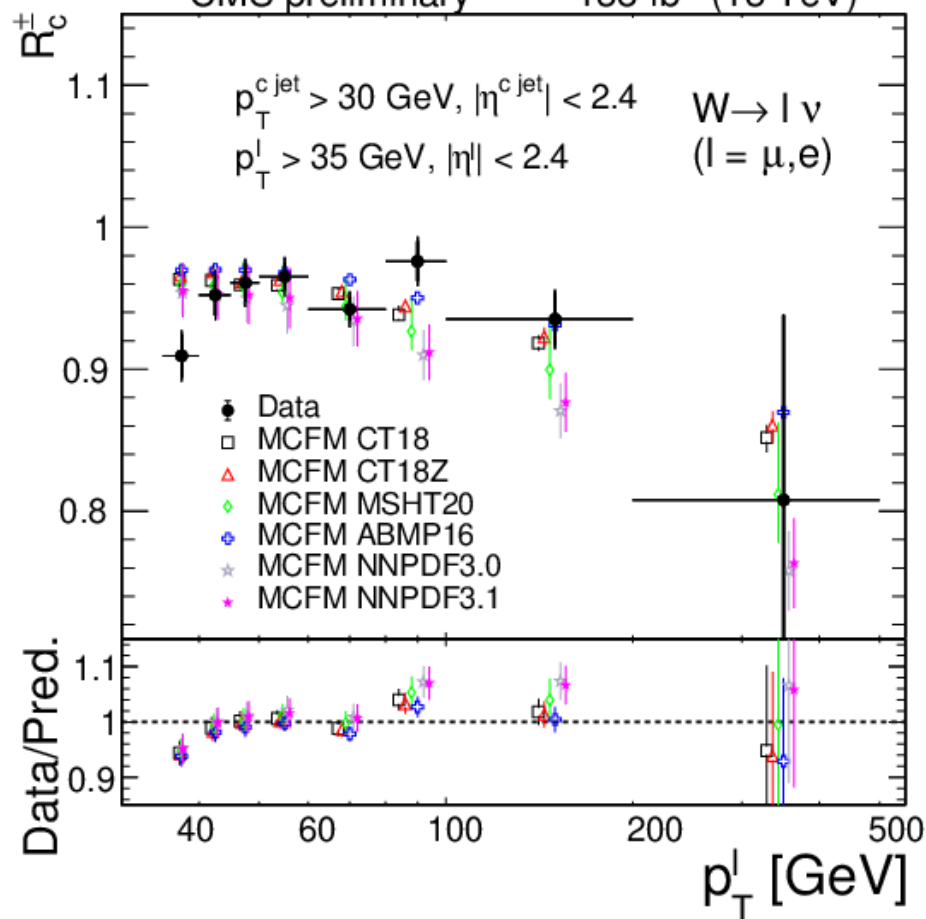


Within experimental and theoretical uncertainties the measurement is compatible both with predictions that assume  $s=\bar{s}$  and  $s \neq \bar{s}$

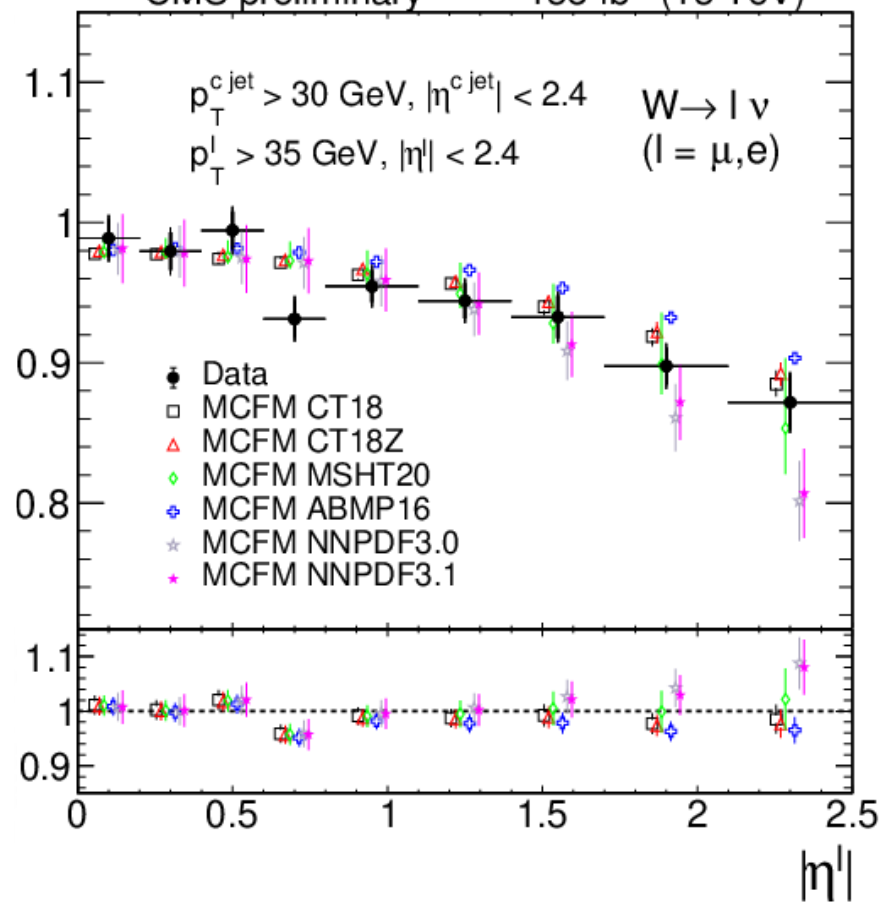
The experimental precision of these measurements is comparable to the PDF uncertainties (when  $s \neq \bar{s}$ ) and smaller than the total theory uncertainty.

# Differential cross section ratio

CMS preliminary 138 fb<sup>-1</sup> (13 TeV)



CMS preliminary 138 fb<sup>-1</sup> (13 TeV)



# NNLO QCD predictions

NNLO QCD and NLO EW calculations recently available  
( JHEP 2021 (2021) 100, JHEP 2023 (2023) 241 ). Predictions computed specifically for our phase space

- Flavor anti-kt jet clustering algorithm, NNLO NNPDF 3.1

## Conclusions:

- The OS-SS cross section reduces the NNLO corrections, but does not remove them completely.
- The inclusion of the NNLO corrections brings the prediction closer (2%) to the experimental measurement.
- The EW NLO corrections further improves (2% closer) the agreement between the theoretical prediction and experimental data.
- The  $R_c^\pm$  observable is rather stable under perturbative QCD corrections, (< 1% from LO to NNLO).
- The NLO EW correction does not affect  $R_c^\pm$ .
- The theoretical prediction and the experimental measurement agree within uncertainties

# Conclusions

- Measured  $W+c$  production fiducial cross section, inclusively and differentially at  $\sqrt{s}=13$  TeV
- Comparison with NLO QCD predictions (MCFM) with different PDF's with and without  $s,\bar{s}$  asymmetry
- With the current experimental and theoretical precision, the measurements are compatible with all predictions.
- Our measurements provide valuable input to reduce the uncertainty in  $s$  PDF for the next iteration of the different PDF groups.

There has been a lot of improvement in the last decades and there is more to come from both , theoretical and experimental results

Back up

Previous measurements at hadron colliders:

- 1) CMS @ 7 TeV ( $D^{*\pm}, D^\pm$  & SL) JHEP 02 (2014) 013,
- 2) CMS @ 8 TeV (SV & SL) Eur. Phys. J. C 82 (2022) 1094,
- 3) CMS @ 13 TeV (2016 ,  $D^{*\pm}$ ) Eur. Phys. J. C 79 (2019) 269,
- 4) ATLAS @ 7 TeV ( $D^{*\pm}$  &  $D^\pm$ ) JHEP 05 (2014) 068
- 5) ATLAS @ 13 TeV (full Run II,  $D^{*\pm}$  &  $D^\pm$ ) doi:10.48550/arXiv.2302.00336.

# NNLO QCD predictions

JHEP 2021 (2021) 100, doi:10.1007/JHEP06(2021)100

JHEP 2023 (2023) 241, doi:10.1007/JHEP02(2023)241

- Calculations at LO, NLO and NNLO for the processes  $pp \rightarrow \mu^+ \nu_\mu j_c + X$  (+c.c.)
- At NLO, QCD corrections include all real and virtual contributions  $O(\alpha_s^2 \alpha^2)$
- At NNLO, corrections include all double virtual, double real, virtual-real  $O(\alpha_s^3 \alpha^2)$
- NLO electroweak corrections of order  $O(\alpha_s \alpha^3)$
- 5-flavour scheme with massless bottom and charm quarks
- Full dependence on the CKM matrix (off-diagonal elements)
- Flavour anti-kt jet algorithm
- Predictions with factorization & normalization scale and PDF uncertainties for the NNPDF3.1 PDF set at NNLO
- Central renormalization and factorization scale:  $0.5(E_{T,W} + p_{T,jc})$ ,  $E_{T,W}^2 = M_W^2 + (p_{T,l} + p_{T,\nu})^2$
- OS-SS cross section
- SS contributions enter at NLO ( $g \rightarrow cc$ , SS=OS correction) and NNLO
- NNLO corrections contain SS double real effects with  $\bar{c}c\bar{c}$  and  $cc\bar{c}$  final states

# HF and charge identification

## Semileptonic $c, b \rightarrow \mu$ decay (**SL channel**):

- Tight  $\mu$  that satisfies:
    - Is one of the PF constituents of a jet with  $p_T(\text{jet}) \geq 25 \text{ GeV}$ ,  $|\eta(\text{jet})| \leq 2.4$ .
    - Non-isolated  $\mu$  (isolation  $\geq 0.2$ ) with  $p_T(\mu) \leq 25 \text{ GeV}$ ,  $|\eta(\mu)| \leq 2.1$ .
  - If several non-isolated  $\mu$  candidates take the one with **highest  $p_T$** 
    - **Charge identification** of the charm quark through the charge of the  $\mu$ -in-jet
    - **Charge definition**: SS if the  $\mu$ -in-jet has the same charge than the lepton from the W decay
- OS  $\rightarrow Q_{W \rightarrow e, \mu} \neq Q_{\mu\text{-in-jet}}$       SS  $\rightarrow Q_{W \rightarrow e, \mu} = Q_{\mu\text{-in-jet}}$

## HF identificacion

### Inclusive HF hadron decays (**SV channel**):

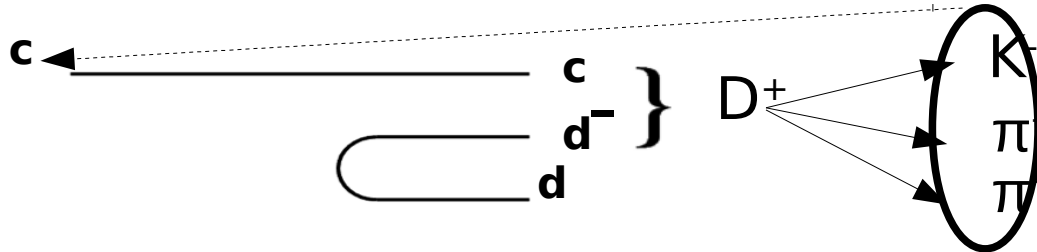
- Reconstructed secondary vertex (SSV or IVF) in jet
- In case of several jets with SV in the event, take the **highest  $p_T$  jet**

# Charge identification

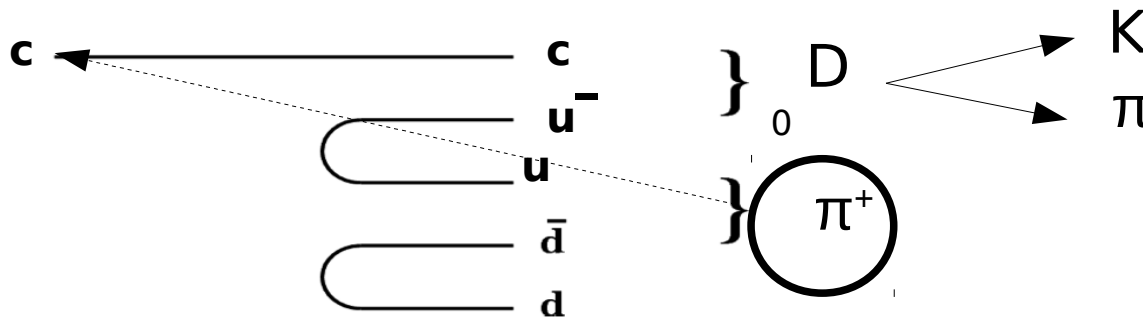
**SV**  
**channel**

Vertex-tracks

- Charge of the SV vertex :  $\sum q_{\text{tracks}}$



- If vertex-charge == 0 use charge of closest PV-track. The sign of that track, the closest track to the  $\text{Charm}_{\text{hadron}}$  in the process of fragmentation, tells you whether we have a  $c$  or a  $\bar{c}$  :



## Charge definition:

- OS if charges of the SV and the lepton from the W decay are opposite

• OS :  $Q_{W \rightarrow e(\mu)} \neq Q_{SV}$

SS :  $Q_{W \rightarrow e(\mu)} = Q_{SV}$