Charm production in association with an electroweak gauge boson at the LHC

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Outline

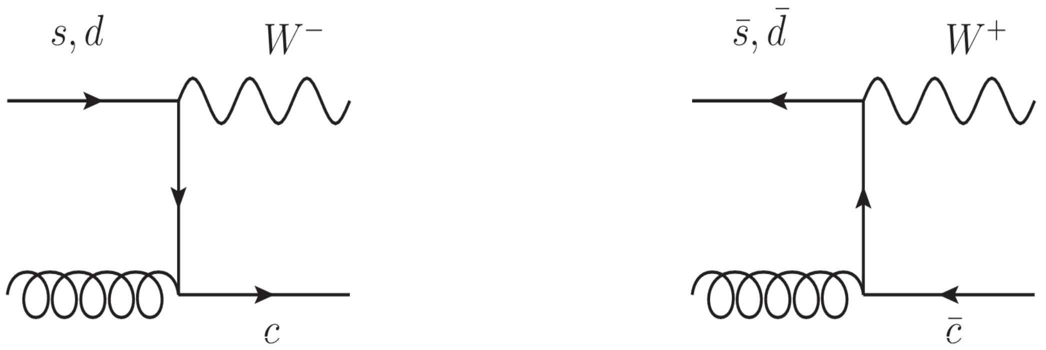
- Motivation
- Definition of cross-section ratios for W+charm
- Results for different PDFs
- CMS measurement of W+charm
- Z plus charm
- Outlook

Motivation

- Production of W/Z+charm provides information on strange and charm PDFs
- Strange quark PDF the least constrained by data, constraints from NuTeV dimuon data
- Tevatron measurements of W+c cross sections (~30% accuracy)
- Advances in charm tagging techniques and high luminosity allow more precise measurements at the LHC, at scales not explored before
- LHC experiments undertaking such measurements
- CMS results on W+charm (CMS PAS SMP-12-002)
- Information complementary to s,c from the total W and Z cross sections (ATLAS, Phys.Rev.Lett. 109 (2012) 012001)

W plus charm production

- At LO the main contribution to W+c comes from quark-gluon scattering.
  Feynman diagrams:



- d-quark contribution Cabbibo-suppressed
- Direct probe of the s-quark PDF
- Scales probed: Q~100 GeV >> Q in the DIS determination of s-quark PDF
- The two measurements combined offer a test of DGLAP evolution

Cross-section ratios

- Use of cross-section ratios as they suffer less from both theoretical and experimental uncertainties.
- Other examples: W^+/W^- (Kom and Stirling (2010))

  photon/Z (Ask et al. (2011))
- Relevant ratios for W plus charm:

$$R_c^{\pm} = \frac{\sigma(W^+ + \bar{c})}{\sigma(W^- + c)}$$

$$R_c = \frac{\sigma(W + c)}{\sigma(W + \text{jet})}$$

- Ratios have a strong dependence on the strange quark PDFs
- $R_c^{\pm} = 1$ at the Tevatron but $R_c^{\pm} < 1$ at the LHC

Results

- Cuts based on CMS-PAS-EWK-11-013, 7 TeV
- $p_T^j > 20$ GeV, $|\eta^j| < 2.1$, $p_T^l > 25$ GeV

  $|\eta^l| < 2.1$, $R = 0.5$, $R^{lj} = 0.3$
- 5 global analysis PDF sets used to calculate the cross sections
- Factorisation and renormalisation scales set to M_W
- NLO cross sections used as implemented in MCFM with NLO PDF sets for *consistency*
- 68%cl (asymmetric, where available) PDF errors calculated
- $R^{\pm} = \frac{\sigma(W^+ + \text{jet})}{\sigma(W^- + \text{jet})}$ also calculated

Results

Ratio	$R_c^\pm$	R_c	$R^\pm$
CT10	$0.953^{+0.009}_{-0.007}$	$0.124^{+0.021}_{-0.012}$	$1.39^{+0.03}_{+0.03}$
MSTW2008NLO	$0.921^{+0.022}_{-0.033}$	$0.116^{+0.002}_{-0.002}$	$1.34^{+0.01}_{-0.01}$
NNPDF2.1NLO	0.944 ± 0.008	0.104 ± 0.005	1.39 ± 0.02
GJR08	0.933 ± 0.003	0.099 ± 0.002	1.37 ± 0.02
ABKM09	0.933 ± 0.002	0.116 ± 0.003	1.39 ± 0.01

Asymmetric errors for CT10 and MSTW2008

Errors obtained using LHAPDF setup within MCFM

NOTE: Expect some changes for NNPDF2.3 as both the total strangeness and the asymmetry differ between the two sets (see arXiv:1207.1303)

- Ratios: LO and NLO difference small (percent level)
- CMS-PAS-EWK-11-013: 36 pb^{-1} results (same cuts):

$$R_c^\pm = 0.92 \pm 0.19\,(\text{stat.}) \pm 0.04\,(\text{syst.})$$

$$R_c = 0.143 \pm 0.015\,(\text{stat.}) \pm 0.024\,(\text{syst.})$$

Are the results what we expect?

- Does $R_c^{\pm} \neq 1$ correspond to an $s - \overline{s}$ asymmetry?
- Even for $s = \overline{s}$, $R_c^{\pm} < 1$ due to the $d - \overline{d}$ difference
- Schematically at LO we expect:

$$R_c^{\pm} \sim \frac{\bar{s} + |V_{dc}|^2 \bar{d}}{s + |V_{dc}|^2 d}$$

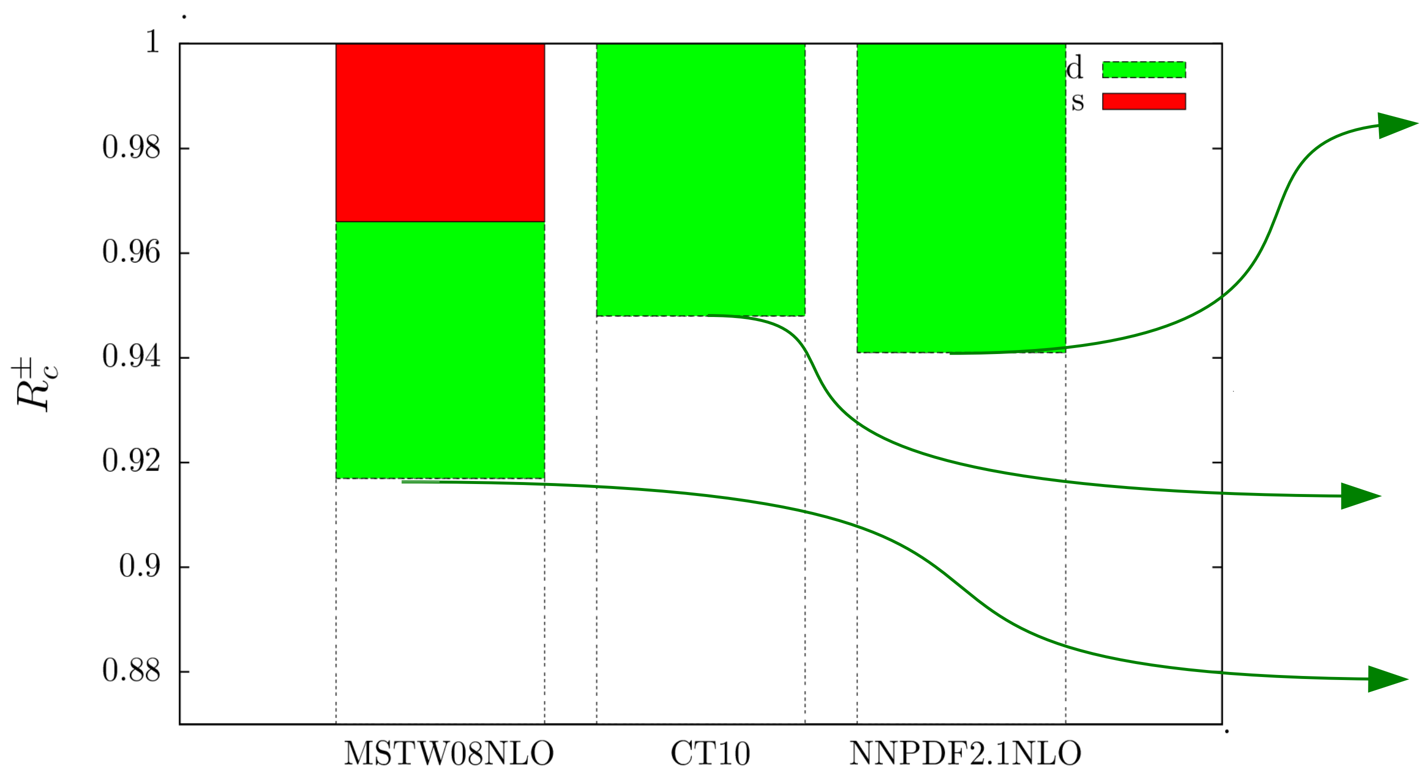
d-contribution suppressed by factor of 20

- CT10 does not have an asymmetric strange sea but $R_c^{\pm} < 1$, entirely due to the $d - \overline{d}$ difference
- For MSTW and NNPDF: the result is a *combination* of the two effects

d-quark contribution to $R_c^{\pm}$

How much does the Cabbibo suppressed d-quark contribution affect $R_c^{\pm}$ *?*

Simplified pictorial representation using LO process:

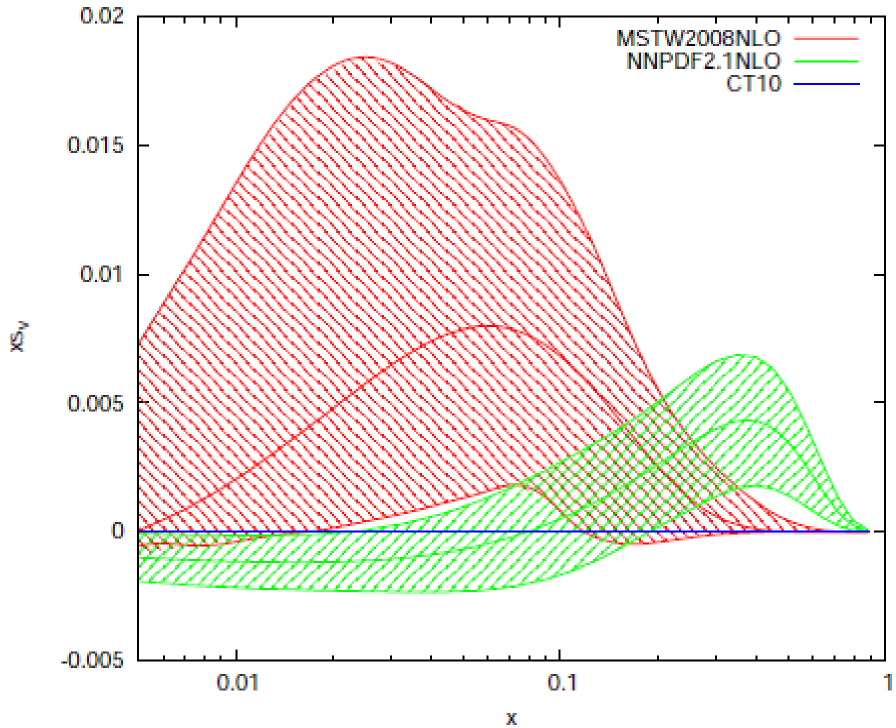


NNPDF does have $s - \bar{s} \neq 0$ but this is small

CT10 has no asymmetry

MSTW has a bigger asymmetry

Strange asymmetry in PDFs



Asymmetry constrained by CCFR and NuTeV dimuon νN and $\bar{\nu} N$ data

Asymmetric sea favoured (MSTW, NNPDF) but symmetric sea (CT10) also consistent with the data

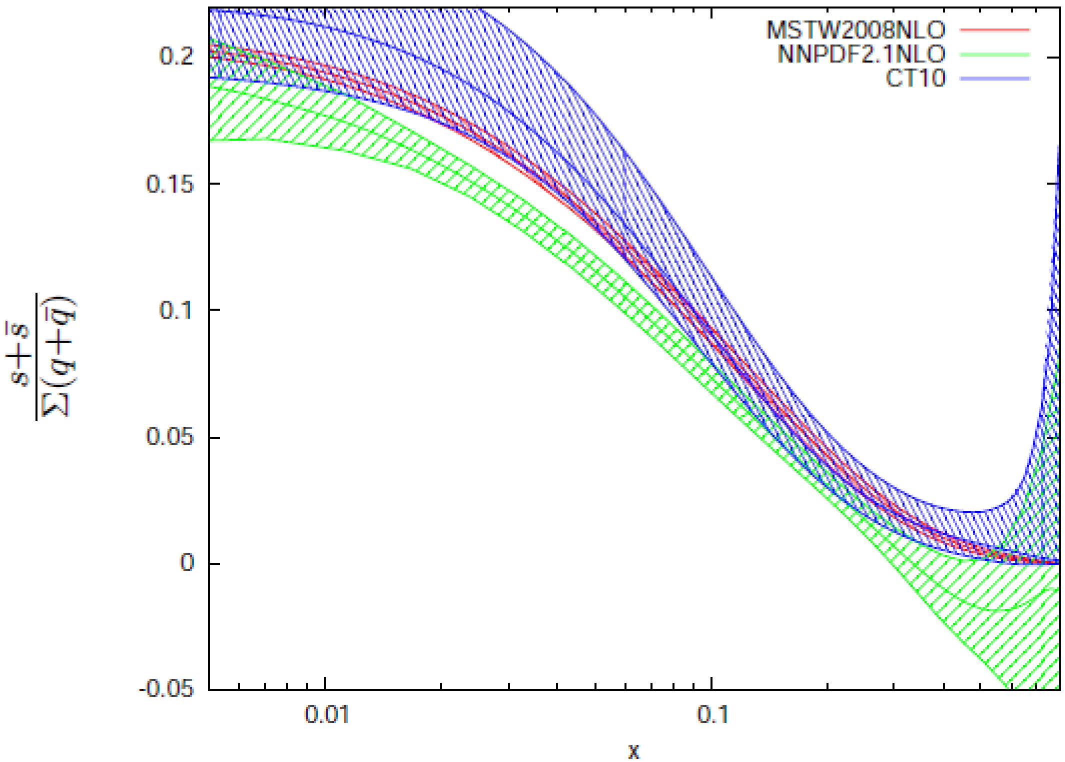
Leads to a large positive s_v in x~0.01-0.1

MSTW2008NLO parametrisation:

$$s_V(x, Q_0^2) \equiv s(x, Q_0^2) - \bar{s}(x, Q_0^2) = A_- x^{\delta_- - 1}(1-x)^{\eta_-}(1 - x/x_0)$$

R_c as a measure of total strangeness

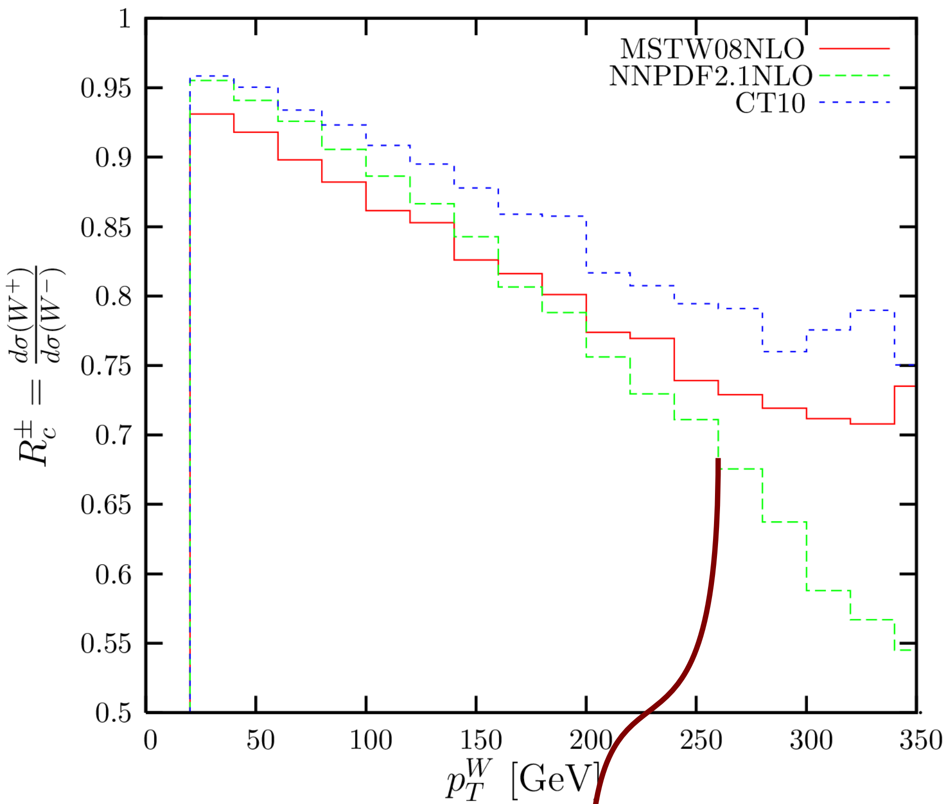
W+jet dominated by qg scattering → $R_c \sim \frac{s+\bar{s}}{\Sigma(q+\bar{q})}$



R_c values and errors for the 3 PDF sets in agreement with total strangeness at x~0.06 (average x-value)

Small MSTW error band due to the assumption that $q(x,Q^2) \sim x^{\delta}$ as $x \rightarrow 0$

Differential distributions



More information from the W p_T distribution

Shapes of distribution closely related to PDFs

Decreasing distribution: Driven by the dominance of d-quark PDF over all others at high p_T

Rapid decrease for NNPDF: d-quark plus s_v increase at high x

Note: Compare to $R^{\pm}$ which is dominated by u/d and is an increasing function of p_T

CMS analysis

- $5fb^{-1}$, muon and electron W decay channels
- W+c cross section and charged ratio measured
- Charm jet identification from the decay of charm hadrons and semileptonic charm quark decays
- Differential distributions of the lepton rapidity
- Results for two different lepton p_T cuts
- Comparison to PDF predictions

$$\sigma(\mathrm{pp} \to \mathrm{W} + \mathrm{c} + \mathrm{X}) \times \mathcal{B}(\mathrm{W} \to \ell\nu, p_{\mathrm{T}}^{\ell} > 35\ \mathrm{GeV}) = 84.1 \pm 2.0\ (\mathrm{stat.}) \pm 4.9\ (\mathrm{syst.})\ \mathrm{pb}$$

$$\frac{\sigma(\mathrm{pp} \to \mathrm{W}^{+} + \bar{\mathrm{c}} + \mathrm{X})}{\sigma(\mathrm{pp} \to \mathrm{W}^{-} + \mathrm{c} + \mathrm{X})}(p_{\mathrm{T}}^{\ell} > 35\ \mathrm{GeV}) = 0.939 \pm 0.019\ (\mathrm{stat.}) \pm 0.005\ (\mathrm{syst.}).$$

CMS PAS SMP-12-002

CMS results

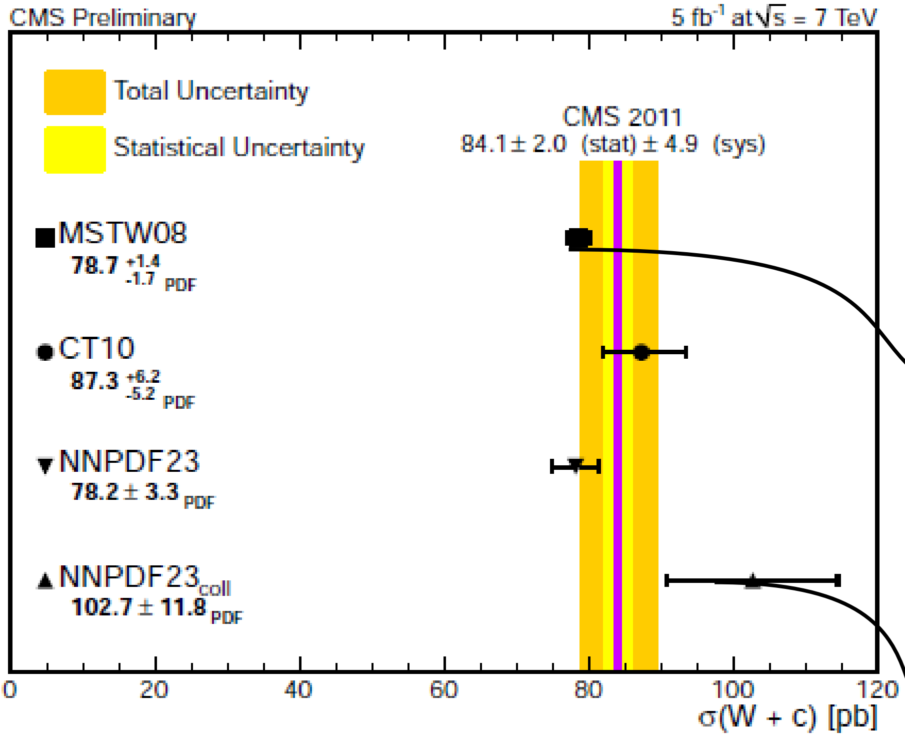
Comparison with different PDF sets predictions:
NNLO sets (with NLO MCFM predictions?), $\mu_R = \mu_f = M_W$

CT10, MSTW2008, NNPDF2.3, NNPDF2.3$_{coll}$

$E_T^{jet} > 25$ GeV and $|\eta^{jet}| < 2.5$
$|\eta^{\ell}| < 2.1 \quad p_T^{\ell} > 35$ GeV

(Slightly different from cuts in our analysis)

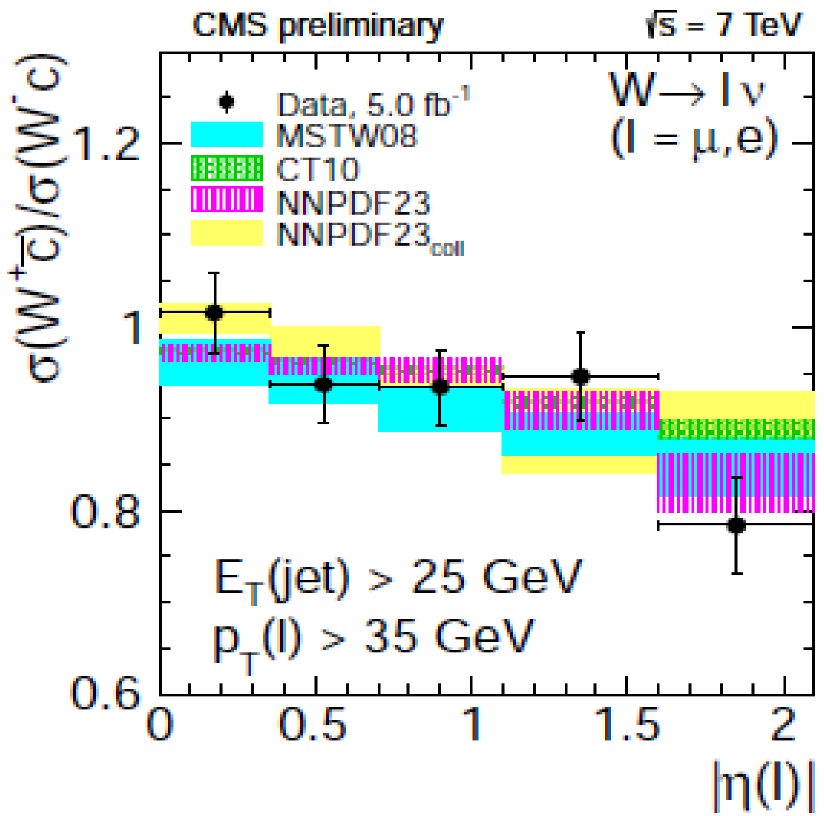
Total cross section

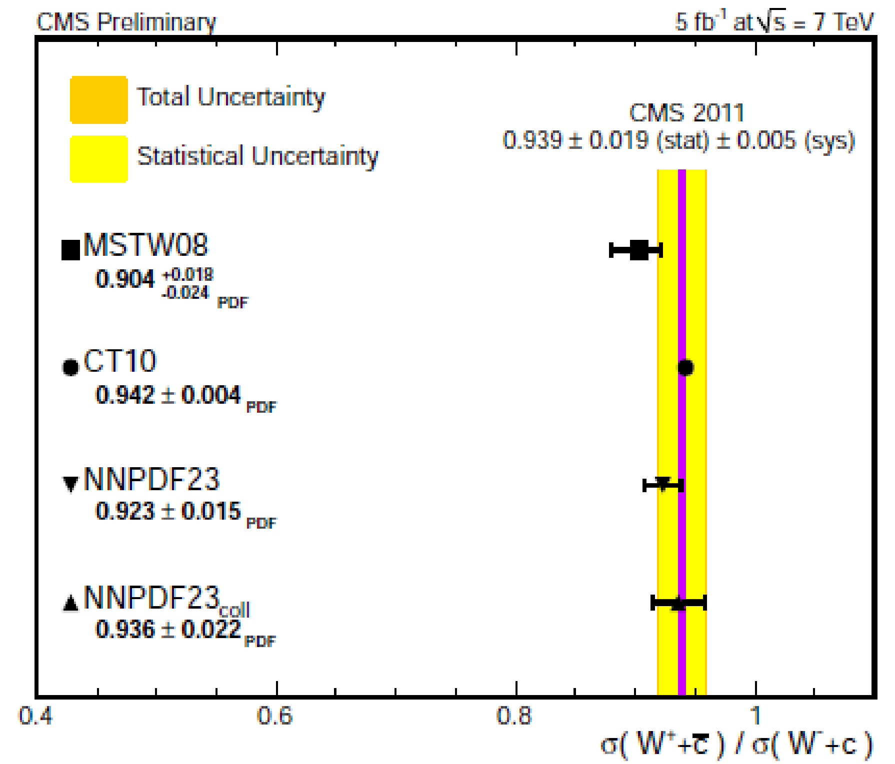


Smaller uncertainty in total strangeness in MSTW2008

Collider data only, including LHC results, larger strangeness and larger uncertainties

CMS charged ratio results





Differential distribution in lepton rapidity: PDF errors increase with $\eta_l \rightarrow$ high x (weaker constraints from data)

Good agreement with the theoretical predictions CT10 small uncertainty due to symmetric strange sea

Z plus charm production

Ratio to be studied:

$$R_c^Z = \frac{\sigma(Z+c)}{\sigma(Z+\text{jet})}$$

Cross section smaller than W (especially when the leptonic decay mode is selected)

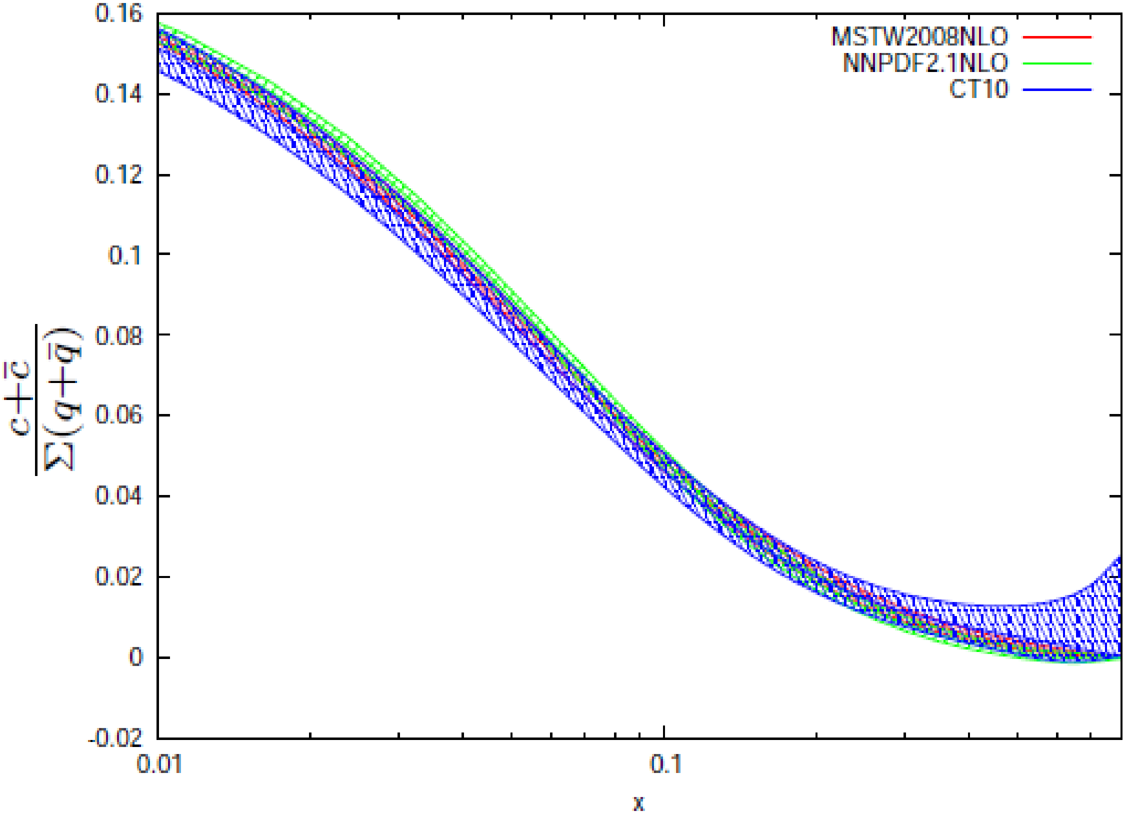
PDF set	R_c^Z
CT10	$0.0619^{+0.0032}_{-0.0032}$
MSTW2008NLO	$0.0640^{+0.0014}_{-0.0016}$
NNPDF2.1NLO	0.0660 ± 0.0013
GJR08	0.0611 ± 0.0011
ABKM09	0.0605 ± 0.0019

$p_T^{\text{jet}} > 20$ GeV, $|\eta^{\text{jet}}| < 2.1$, $p_T^{\text{lepton}} > 25$ GeV, $|\eta^{\text{lepton}}| < 2.1$, $R^{jj} = 0.5$, $R^{lj} = 0.3$ and $60 < m_{ll} < 120$ GeV

Information on the charm content of the proton: *Differences between sets smaller as charm distributions arise perturbatively from* $g \to c\,\bar{c}$

Z plus charm

$$R_c^Z = \frac{\sigma(Z+c)}{\sigma(Z+\text{jet})} \sim \frac{c+\bar{c}}{\Sigma(q+\bar{q})}$$



PDF errors and differences between sets much smaller than for total strangeness ➡
A very precise measurement needed to distinguish between sets

Other related ratios

Intrinsic charm?

$$R_c^{\pm}(Z) = \frac{\sigma(Z+\bar{c})}{\sigma(Z+c)}$$

Automatically equal to 1 if $c = \bar{c}$
True for all public PDF sets, as charm is generated by $g \rightarrow c\,\bar{c}$

- Intrinsic charm component proposed in S. J. Brodsky et al (1980)
- PDF studies in Pumplin et al.(2007) and by MSTW show the effect is small compared to $g \rightarrow c\,\bar{c}$
- In qg → Zq, q is more likely to be positive so we can expect a “natural” charge asymmetry in the misidentified charm-jet background

W/Z ratios?

$$R_c^{WZ} = \frac{\sigma(Z+c)}{\sigma(W+c)} \quad \text{and} \quad R^{WZ} = \frac{\sigma(Z+\text{jet})}{\sigma(W+\text{jet})}$$

Can extract more information about strange and charm

Conclusions-Outlook

- W and Z bosons produced in association with a charm quark jet will provide useful information on the strange and charm quark PDFs
- Ratios can provide information on the strange content of the proton and the strange asymmetry
- Complementary to information from total W and Z cross sections
- Ongoing analysis of LHC data, precise measurements can discriminate between different sets and constrain PDFs
- Incorporation into PDF analyses and ATLAS results