Associated Production of W + charm in pp-Collisions with CMS and Determination of the Strange Quark Content of the Proton

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DESY

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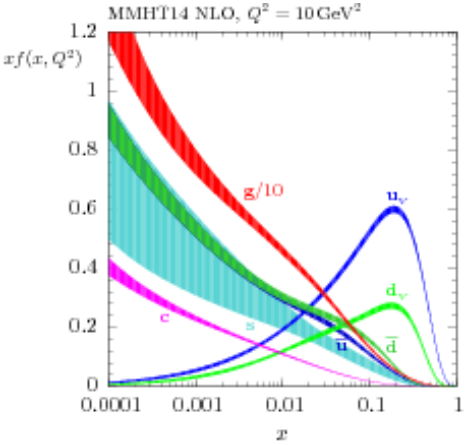
Outline

Strangeness in PDFs

- Strangeness is the least constrained light quark PDF
- Mostly constrained by ν-scattering experiments
  - $\rightarrow$ Need to take nuclear corrections into account
  - $\rightarrow$ Additional uncertainty in the PDF

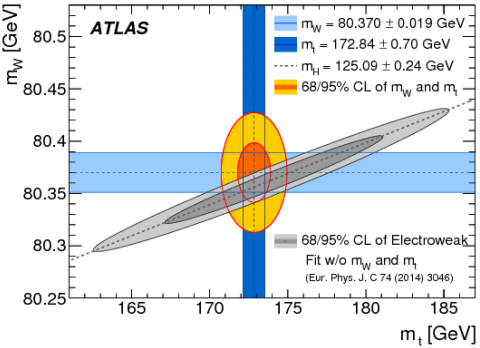


[Eur. Phys. J. C, 75:204, 2015]

Why do we need to improve strangeness?

- Limitations on theoretical calculations
  - → Standard Model parameters (W boson mass)
  - → BSM Searches (SUSY)

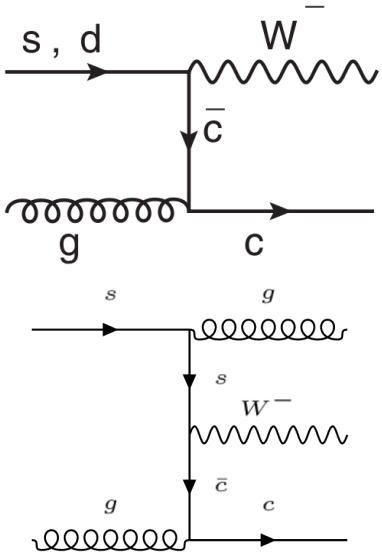
Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T, W^+, e-μ	80370.0	12.3	8.3	6.7	14.5	9.7	9.4	3.4	16.9	30.9	2/6
m_T, W^-, e-μ	80381.1	13.9	8.8	6.6	11.8	10.2	9.7	3.4	16.2	30.5	7/6
m_T, $W^\pm$, e-μ	80375.7	9.6	7.8	5.5	13.0	8.3	9.6	3.4	10.2	25.1	11/13
p_T^ℓ, W^+, e-μ	80352.0	9.6	6.5	8.4	2.5	5.2	8.3	5.7	14.5	23.5	5/6
p_T^ℓ, W^-, e-μ	80383.4	10.8	7.0	8.1	2.5	6.1	8.1	5.7	13.5	23.6	10/6
p_T^ℓ, $W^\pm$, e-μ	80369.4	7.2	6.3	6.7	2.5	4.6	8.3	5.7	9.0	18.7	19/13
p_T^ℓ, $W^\pm$, e	80347.2	9.9	0.0	14.8	2.6	5.7	8.2	5.3	8.9	23.1	4/5
m_T, $W^\pm$, e	80364.6	13.5	0.0	14.4	13.2	12.8	9.5	3.4	10.2	30.8	8/5
m_T-p_T^ℓ, W^+, e	80345.4	11.7	0.0	16.0	3.8	7.4	8.3	5.0	13.7	27.4	1/5
m_T-p_T^ℓ, W^-, e	80359.4	12.9	0.0	15.1	3.9	8.5	8.4	4.9	13.4	27.6	8/5
m_T-p_T^ℓ, $W^\pm$, e	80349.8	9.0	0.0	14.7	3.3	6.1	8.3	5.1	9.0	22.9	12/11
p_T^ℓ, $W^\pm$, μ	80382.3	10.1	10.7	0.0	2.5	3.9	8.4	6.0	10.7	21.4	7/7
m_T, $W^\pm$, μ	80381.5	13.0	11.6	0.0	13.0	6.0	9.6	3.4	11.2	27.2	3/7
m_T-p_T^ℓ, W^+, μ	80364.1	11.4	12.4	0.0	4.0	4.7	8.8	5.4	17.6	27.2	5/7
m_T-p_T^ℓ, W^-, μ	80398.6	12.0	13.0	0.0	4.1	5.7	8.4	5.3	16.8	27.4	3/7
m_T-p_T^ℓ, $W^\pm$, μ	80382.0	8.6	10.7	0.0	3.7	4.3	8.6	5.4	10.9	21.0	10/15
m_T-p_T^ℓ, W^+, e-μ	80352.7	8.9	6.6	6.6	3.1	5.5	8.4	5.4	14.6	23.4	7/13
m_T-p_T^ℓ, W^-, e-μ	80383.6	9.7	7.2	7.8	3.3	6.6	8.3	5.3	13.6	23.4	15/13
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27



[Eur. Phys. J. C (2018) 78]

Strangeness at the LHC: W + charm

- Produced by hard scattering of a strange quark and a gluon at LO
- NLO contributions dominated by radiative corrections to LO processes
- Contributions from d quarks are Cabibbo suppressed
- Probes strangeness at $10^{-3} \leq x \leq 10^{-1}$

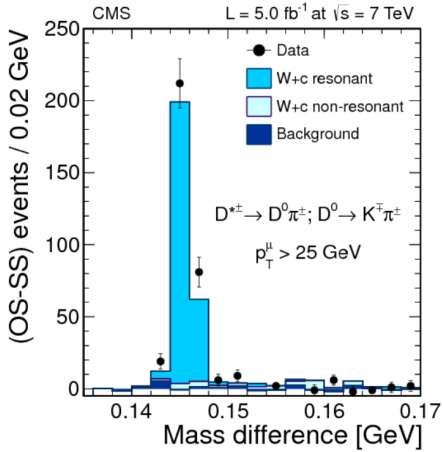


Fist measurement of W+charm at the LHC (5 fb^{-1})

CMS 7 TeV [JHEP 02 (2014) 013]

- $W \to l + \nu \quad (l = \mu, e)$
  - Single, isolated high-p_T lepton
  - + Missing transverse energy

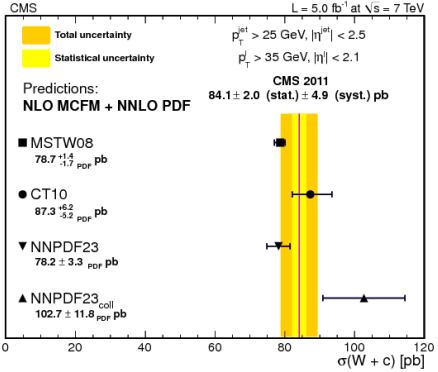
- Selecting charmed-jet signatures, $p_{\mathrm{T}}^{jet} > 25$ GeV:
  - $c \to D^*(2010)^{\pm}$
  - $c \to D^{\pm}$
  - $c \to \mu$ Dominant systematic: $Br(c \to \mu)$

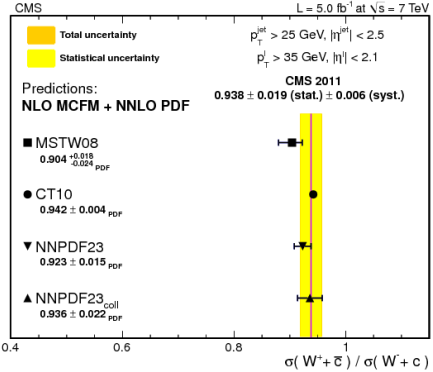


Comparison with Theoretical Predictions

- Calculations done with MCFM at NLO
- Scale: $\mu_r = \mu_f = M_W$
- $\frac{1}{2}\mu < \mu_r = \mu_f < 2\mu$

- $p_{\mathrm{T}}^{l} > 35\,\mathrm{GeV}$
- $|\eta^{\mu}| < 2.1$
- $p_{\mathrm{T}}^{\mathrm{c}} > 25\,\mathrm{GeV}$





QCD Analysis: Parametrization at the Starting Scale

Phys. Rev. D 90, 032004

$$
\begin{aligned}
x u_{\mathrm{v}}(x) &= A_{u_{\mathrm{v}}}\, x^{B_{u_{\mathrm{v}}}}\, (1-x)^{C_{u_{\mathrm{v}}}}\, (1 + E_{u_{\mathrm{v}}} x^2), \\
x d_{\mathrm{v}}(x) &= A_{d_{\mathrm{v}}}\, x^{B_{d_{\mathrm{v}}}}\, (1-x)^{C_{d_{\mathrm{v}}}}, \\
x \overline{\mathrm{U}}(x) &= A_{\overline{\mathrm{U}}}\, x^{B_{\overline{\mathrm{U}}}}\, (1-x)^{C_{\overline{\mathrm{U}}}}, \\
x \overline{\mathrm{d}}(x) &= A_{\overline{\mathrm{d}}}\, x^{B_{\overline{\mathrm{d}}}}\, (1-x)^{C_{\overline{\mathrm{d}}}}, \\
x \overline{\mathrm{s}}(x) &= A_{\overline{\mathrm{s}}}\, x^{B_{\overline{\mathrm{s}}}}\, (1-x)^{C_{\overline{\mathrm{s}}}}, \\
x g(x) &= A_g\, x^{B_g}\, (1-x)^{C_g} + A'_g\, x^{B'_g}\, (1-x)^{C'_g}.
\end{aligned}
$$

15 Parameter Free-s fit:

$f_s = \bar{s}/(\bar{d} + \bar{s})$ released

$B_{\overline{u}} = B_{\overline{d}} = B_{\overline{s}}$

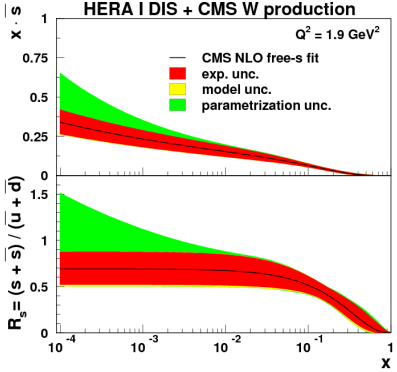
$xs = x\bar{s}$

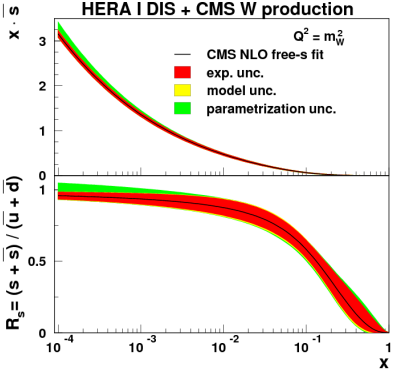
$A_{\overline{u}} = A_{\overline{d}}(1 - f_s)$

$B_{\overline{d}} \neq B_{\overline{s}}$ (Parametrization uncertainty)

Results

- Strangeness suppression factor: $r_s = (\mathrm{s} + \bar{\mathrm{s}})/(\bar{\mathrm{u}} + \bar{\mathrm{d}})$
- Large parametrization uncertainty from $B_{\bar{d}} \neq B_{\bar{s}}$



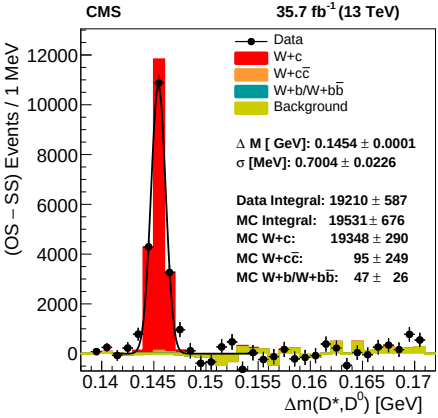


W + charm Analysis at 13 TeV (35.7 fb^{-1})

[arXiv:1811.10021]

- $W \rightarrow \mu + \nu$
  - Single, isolated high-p_T muon
  - + Missing transverse energy

- $c \xrightarrow{0.24} D^{*\pm} \xrightarrow{0.68} D^0 + \pi^{\pm}_{slow}$
  $D^0 \xrightarrow{0.04} K^{\mp} + \pi^{\pm}$
  - No jet required
    $\rightarrow$ low-p_T D^* accessible
  - Low tracking uncertainty
  - Small branching ratios



Event Selection

$W \to \mu\,\nu$

$$M_{\mathrm{T}} \;=\; \sqrt{2 \cdot p_{\mathrm{T}}^{\mu} \cdot p_{\mathrm{T}}^{miss} \cdot (1 - \cos(\phi_{\mu} - \phi_{\vec{p}_{\mathrm{T}}^{\mathrm{miss}}}))} \;>\; 50\,\mathrm{GeV}$$

$D^0 \to K^{\pm} + \pi^{\mp}$

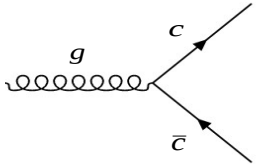
- $p_{\mathrm{T}}^{\mathrm{K},\pi} > 1\,\mathrm{GeV}$
- Fitted secondary vertex
- $|D^0_{rec} - D^0_{pdg}| < 35\,\mathrm{MeV}$

$D^*(2010)^{\pm} \to D^0 + \pi^{\pm}_{slow}$

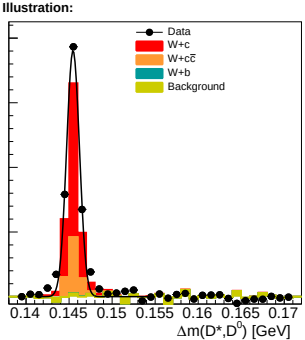
- $p_{\mathrm{T}}^{\pi_{\mathrm{slow}}} > 0.35\,\mathrm{GeV}$
- π_{slow} in a cone around D^0 $\Delta R(D^0, \pi_{\mathrm{slow}}) < 0.15$
- Transverse momentum fraction $p_{\mathrm{T}}^{D^*} / \sum p_{\mathrm{T}} > 0.2$

Extracting W+charm

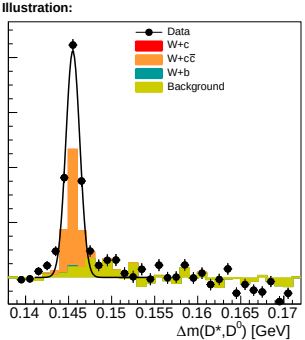
- Large background from gluon splitting
- Opposite Sign (OS): $W^{\pm} + D^{*\mp}$
- Same Sign (SS): $W^{\pm} + D^{*\pm}$



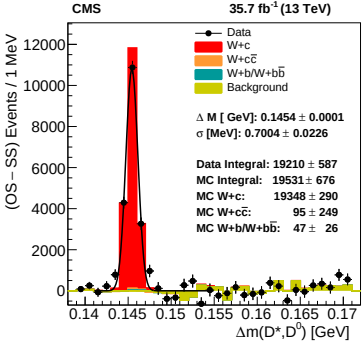
OS



SS



OS - SS



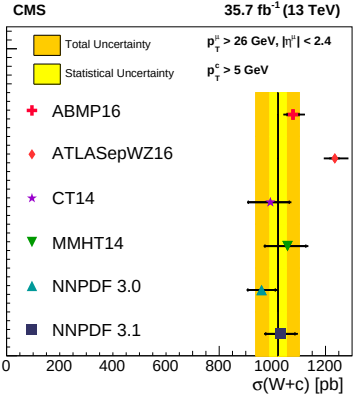
Systematic Uncertainties

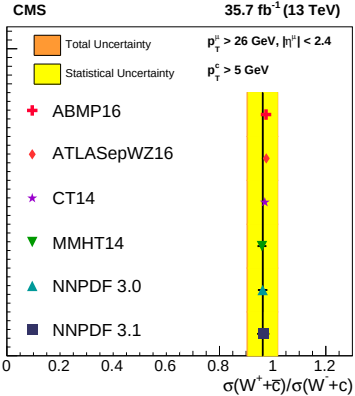
Tracking Efficiency	$\pm$ 2.3%
Branching Ratios ($c \to K, \pi, \pi_{slow}$)	$\pm$ 2.4%
Lumi	$\pm$ 2.5%
Fragmentation	+3.9/-3.3%
MC-Statistics	+3.6/-3.3%
Total	**+7.5/-7.0**

- Other Sources: $\pm$ 3.4%
  - Muons
  - $E_{\mathrm{T}}^{\mathrm{miss}}$
  - Pile-Up
  - $D^*(2010)^{\pm}$ Kinematics
  - Sec. Vtx Fit
  - Signal Extraction
  - PDF

Comparison with Theoretical Predictions

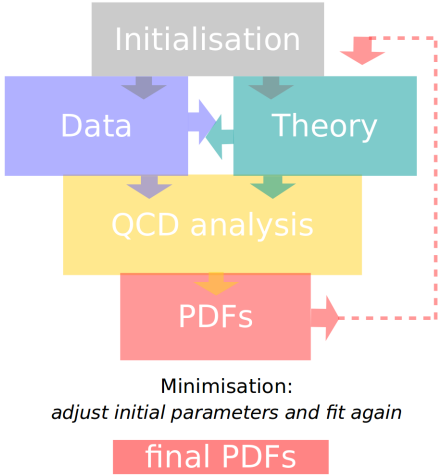
- Calculations done with MCFM
- Scale: $\mu_r = \mu_f = M_W$
- $\frac{1}{2}\mu < \mu_r = \mu_f < 2\mu$ uncertainty of $\approx 3\%$
- $p_{\mathrm{T}}^{\mu} > 26\,\mathrm{GeV}$
- $|\eta^{\mu}| < 2.4$
- $p_{\mathrm{T}}^{\mathrm{c}} > 5\,\mathrm{GeV}$





QCD Analysis: Setup

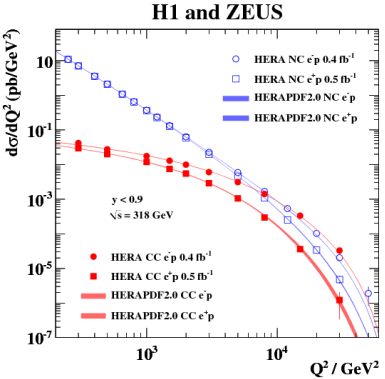
- xFitter 2.0.0 (www.xfitter.org)
- Fit performed at NLO
- Starting scale: $Q_0^2 = 1.9\,\text{GeV}^2$
- Parton evolution in $Q^2 > Q_0^2$
  $\rightarrow$ DGLAP equations



Data Input

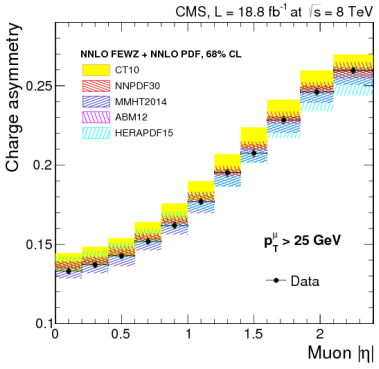
- HERA I+II combined inclusive DIS data [Eur.Phys.J. C75 (2015) 12]
  - Charged Current
  - Neutral Current

→ Quarks and gluons at small and medium x



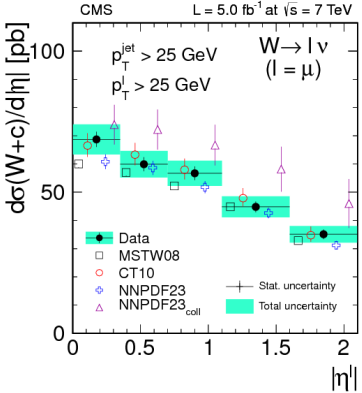
- CMS lepton charge asymmetry
  - 7 TeV [Phys. Rev. D 90, 032004]
  - 8 TeV [Eur.Phys.J. C76 (2016) 469]

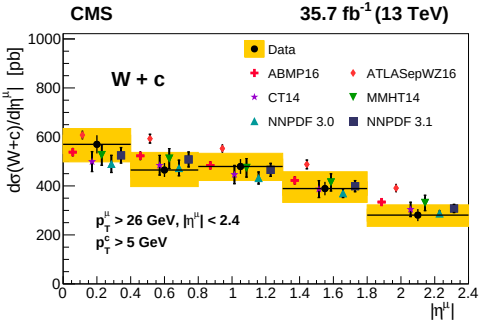
→ further improve u and d valence quarks



Data Input: CMS W+charm

- 7 TeV [JHEP 02 (2014) 013]
- 13 TeV [arXiv:1811.10021]
- systematic errors as nuisance parameters (100% bin-to-bin correlation)





Model Input

Heavy quark treatment:

Thorne-Roberts general mass variable flavour number scheme at NLO

m_c = 1.5 GeV $\quad$ $1.37 < m_c < 1.55$ GeV

m_b = 4.5 GeV $\quad$ $4.3 < m_b < 5.0$ GeV

Strong coupling constant:

α_s = 0.118

Scales:

Q_0^2 = 1.9 GeV^2 $\quad$ $1.6 < Q_0^2 < 2.2$ GeV^2

Q_{min}^2 = 3.5 GeV^2 for HERA data $\quad$ $2.5 < Q_{min}^2 < 5.0$ GeV^2

$\mu_r^2 = \mu_f^2 = m_W^2$ for W-processes $\quad$ $\mu_r^2 = \mu_f^2 = Q^2$ for DIS-processes

Parametrization at the starting scale

15 Parameter Fit

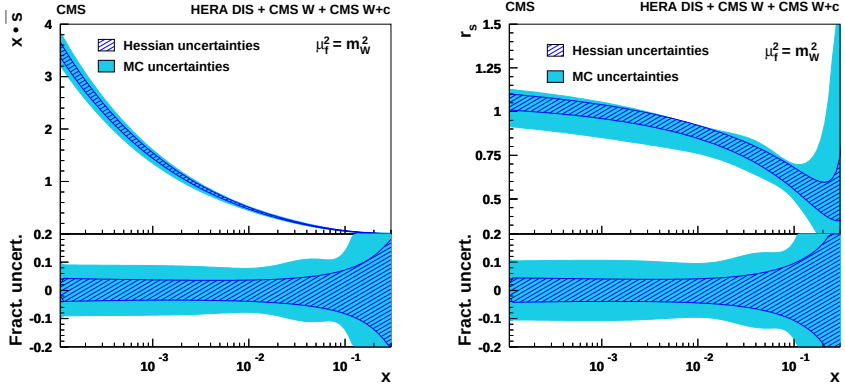
$$
\begin{aligned}
x u_{\mathrm{v}}(x) &= A_{u_{\mathrm{v}}}\, x^{B_{u_{\mathrm{v}}}}\, (1-x)^{C_{u_{\mathrm{v}}}}\, (1 + E_{u_{\mathrm{v}}} x^2), \\
x d_{\mathrm{v}}(x) &= A_{d_{\mathrm{v}}}\, x^{B_{d_{\mathrm{v}}}}\, (1-x)^{C_{d_{\mathrm{v}}}}, \\
x \overline{\mathrm{u}}(x) &= A_{\overline{\mathrm{u}}}\, x^{B_{\overline{\mathrm{u}}}}\, (1-x)^{C_{\overline{\mathrm{u}}}}\, (1 + E_{\overline{\mathrm{u}}} x^2) \\
x \overline{d}(x) &= A_{\overline{d}}\, x^{B_{\overline{d}}}\, (1-x)^{C_{\overline{d}}} \\
x \overline{s}(x) &= A_{\overline{s}}\, x^{B_{\overline{s}}}\, (1-x)^{C_{\overline{s}}} \\
x g(x) &= A_g\, x^{B_g}\, (1-x)^{C_g}\, (1 + D_g x)
\end{aligned}
$$

Constraints:

$B_{\overline{u}} \neq B_{\overline{d}} \neq B_{\overline{s}}$ [Phys.Lett. B777 (2018)] $\qquad xs = x\overline{s}$

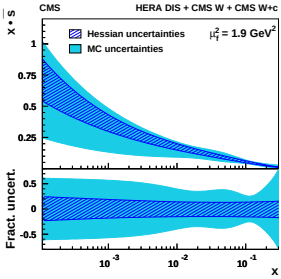
Estimation of PDF Uncertainties

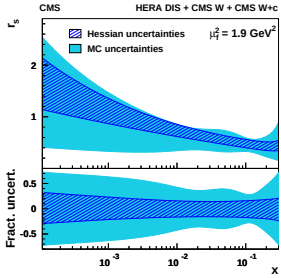
- Hessian Error Treatment: $\Delta\chi^2 = 1$
- MC replicas: Random sampling of datapoints, varied within uncertainties
  - Uncertainties from RMS around mean value



QCD Analysis: Results

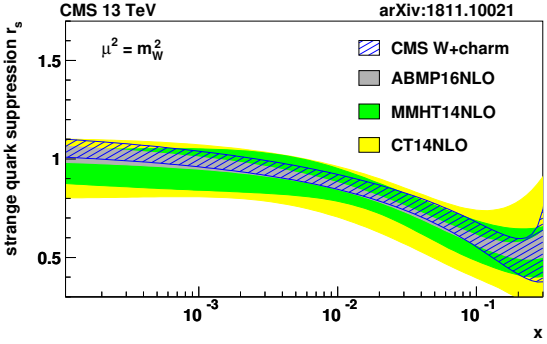
Dataset	χ^2/n_{dp}
HERA1+2 CCep	43 / 39
HERA1+2 CCem	57 / 42
HERA1+2 NCem	218 / 159
HERA1+2 NCep 820	69 / 70
HERA1+2 NCep 920	448 / 377
HERA1+2 NCep 460	216 / 204
HERA1+2 NCep 575	220 / 254
CMS W muon charge asym. 7 TeV	13 / 11
CMS W muon charge asym. 8 TeV	4.2 / 11
W+c 7 TeV	2.2 / 5
W+c 13 TeV	2.1 / 5
Correlated χ^2	87
Total χ^2 / dof	1385 / 1160

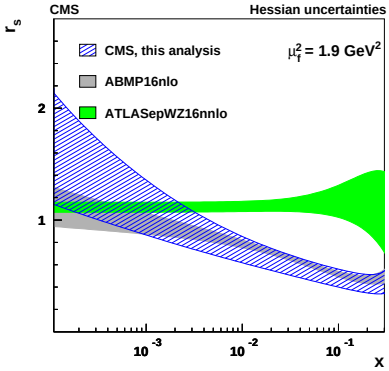




Comparison with other PDFs

- Results for r_s compatible with global PDFs
- No observation of enhanced strangeness





Summary

- W + charm at 7 and 13 TeV
  - Inclusive and differential cross sections as a function of $|\eta^{\mu}|$
  - Good agreement between measurement and MCFM predictions
- QCD analysis
  - Determination of $x\mathrm{s}$ and r_s
  - 7 TeV: 15 parameter free-s fit using xfitter
  - 13 TeV: Release of B parameter constraints possible

Backup

Comparison with 7 TeV results

- In agreement with 7 TeV PDF fits (same parametrization)
- Reduced PDF uncertainties