Experimental Constraints on Collinear PDFs 7, 8, 13 TeV (W, jet production) by CMS

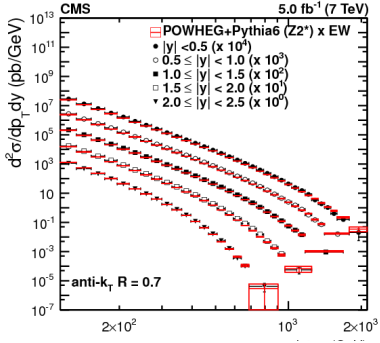
Svenja Pflitsch on Behalf of the CMS Collaboration

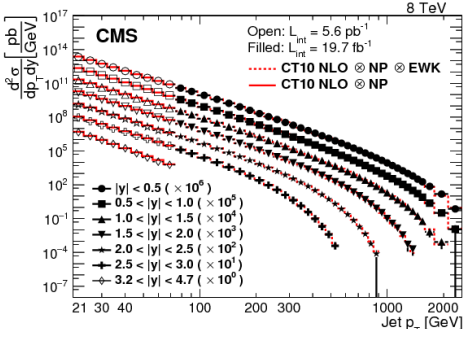
QCD@LHC, 15 - 19 July 2019, Buffalo

Inclusive Jets at 7 and 8 TeV

[Eur. Phys. J. C 75 (2015) 288],[JHEP 1703 (2017) 156]

- Precise test of factorization: 10 GeV - 2.5 TeV
- Jets reconstructed using Anti-k_T with $\Delta R = 0.7$
- Main systematic uncertainty: Jet Energy Scale





Inclusive Jets at 8 TeV: Parametrization

[JHEP 1703 (2017) 156]

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

18 Parameter Fit:

$x\overline{D}(x) = x\overline{d}(x) + dx\overline{s}(x)$

$f_s = \bar{s}/(\bar{d} + \bar{s}) = 0.31 \pm 0.08$

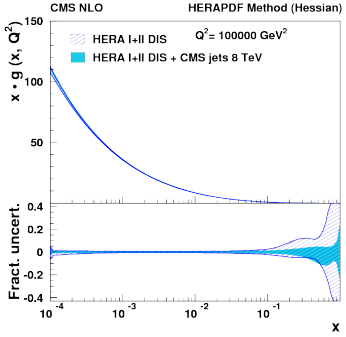
$B_{\overline{U}} = B_{\overline{D}}$

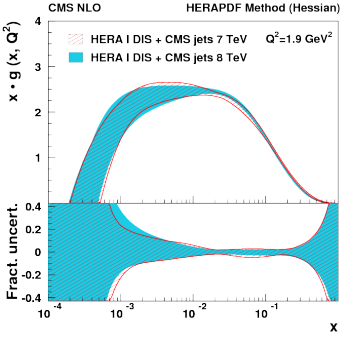
$A_{\overline{U}} = A_{\overline{D}}(1 - f_s)$

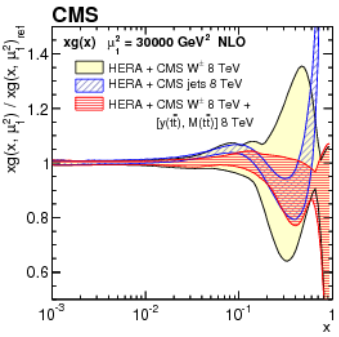
QCD Analysis: PDF Fits

[JHEP 1703 (2017) 156], [Eur. Phys. J. C 77 (2017) 459]

- Fixed α_S , PDFs determined in NLO fit
- Improve constraints on high-x gluons
- Effect comparable to including double differential $t\bar{t}$





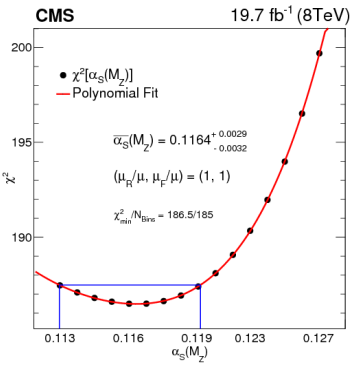


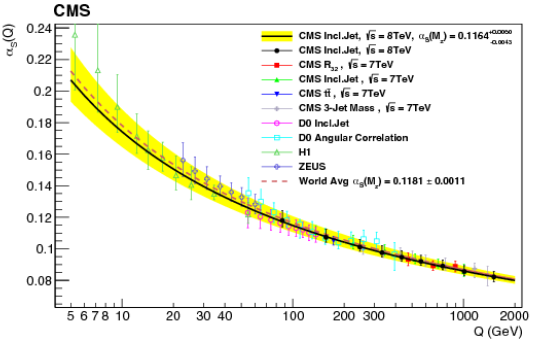
QCD Analysis: Extraction of α_S

[JHEP 1703 (2017) 156]

- PDFs fixed, α_S determined in fit: $\alpha_S(M_Z) = 0.1164\,^{+0.0029}_{-0.0032}\,(\text{fit})\quad ^{+0.0053}_{-0.0028}\,(\text{scale})$
- Simultaneous extraction: $\alpha_S(M_Z) = 0.1188\,^{+0.0019}_{-0.0026}\,(\text{PDF})\,^{+0.0022}_{-0.0018}\,(\text{scale})$

→ Results consistent with world average



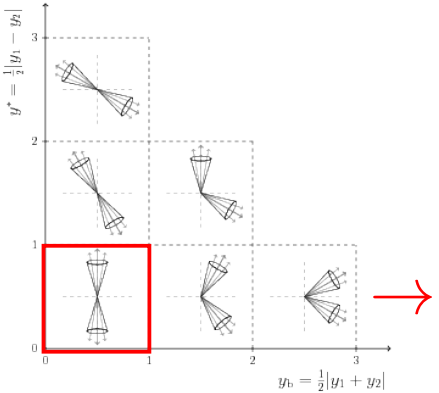


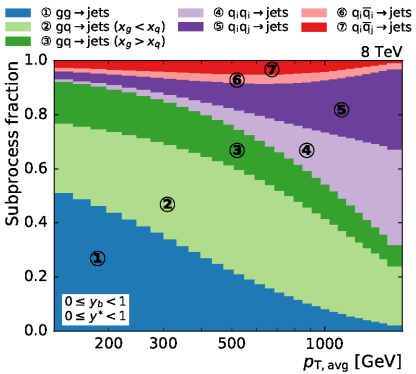
Triple Differential Di-Jets at 8 TeV

Eur.Phys.J. C77 (2017) 746

- Differential in: $\langle p_T^{\text{jet}} \rangle$, Rapidity separation $y^* = \frac{1}{2}|y_1 - y_2|$, Boost $y_b = \frac{1}{2}|y_1 + y_2|$
- Probing x_1 and x_2 via different event topologies

$\rightarrow$ Central region: dominant process gg fusion



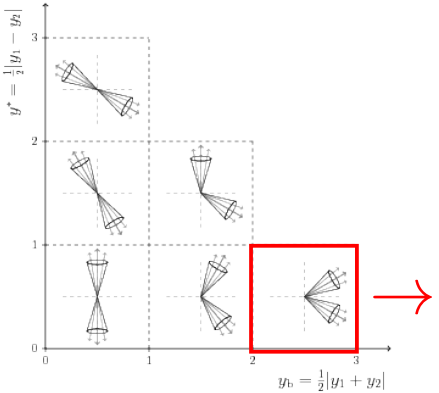


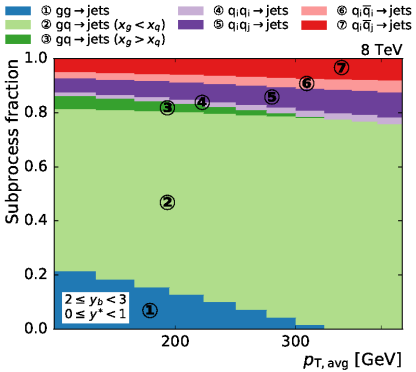
Triple Differential Di-Jets at 8 TeV

Eur.Phys.J. C77 (2017) 746

- Differential in: $\langle p_T^{\text{jet}} \rangle$, Rapidity separation $y^* = \frac{1}{2}|y_1 - y_2|$, Boost $y_b = \frac{1}{2}|y_1 + y_2|$
- Probing x_1 and x_2 via different event topologies

→ Large boosts: sensitive to higher values of x for one of the partons





Triple Differential Dijets: Parametrization

Eur.Phys.J. C77 (2017) 746

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

16 Parameter Fit:

$x\overline{D}(x) = x\bar{d}(x) + dx\bar{s}(x)$ $\qquad$ $B_{\overline{U}} = B_{\overline{D}}$

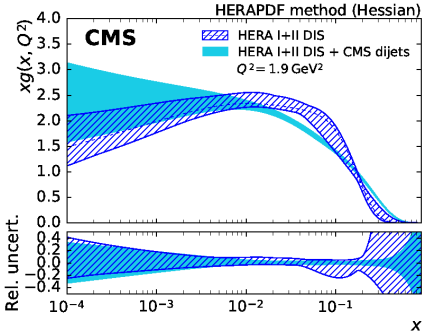
$f_s = \bar{s}/(\bar{d} + \bar{s}) = 0.31 \pm 0.08$ $\qquad$ $A_{\overline{U}} = A_{\overline{D}}(1 - f_s)$

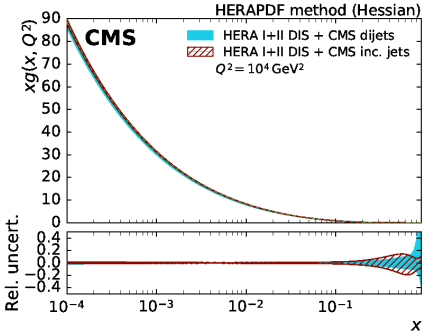
QCD Analysis

Eur.Phys.J. C77 (2017) 746

- Fit performed at NLO with simultaneous extraction of α_S :
- Improved precision of high-x gluons

$$\alpha_S(M_Z) = 0.1199\,^{+0.0015}_{-0.0016}\,(\text{PDF})\,^{+0.0026}_{-0.0016}\,(\text{scale})$$





χ^2 of the Individual Datasets

Eur.Phys.J. C77 (2017) 746

		HERA data		HERA & CMS data	
Data set	n_{data}	χ^2_{p}	$\chi^2_{\text{p}}/n_{\text{data}}$	χ^2_{p}	$\chi^2_{\text{p}}/n_{\text{data}}$
NC HERA-I+II e^+p $E_p = 920\,\text{GeV}$	332	382.44	1.15	406.45	1.22
NC HERA-I+II e^+p $E_p = 820\,\text{GeV}$	63	60.62	0.96	61.01	0.97
NC HERA-I+II e^+p $E_p = 575\,\text{GeV}$	234	196.40	0.84	197.56	0.84
NC HERA-I+II e^+p $E_p = 460\,\text{GeV}$	187	204.42	1.09	205.50	1.10
NC HERA-I+II e^-p	159	217.27	1.37	219.17	1.38
CC HERA-I+II e^+p	39	43.26	1.11	42.29	1.08
CC HERA-I+II e^-p	42	49.11	1.17	55.35	1.32
CMS triple-differential dijet	122	—	—	111.13	0.91

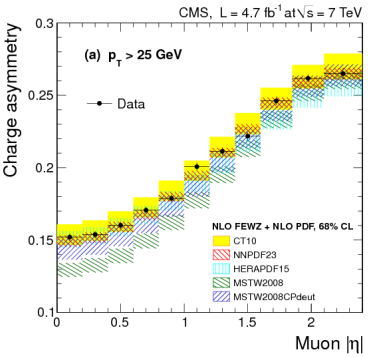
Data set(s)	n_{dof}	χ^2	χ^2/n_{dof}	χ^2	χ^2/n_{dof}
HERA data	1040	1211.00	1.16	—	—
HERA & CMS data	1162	—	—	1372.52	1.18

Lepton Charge Asymmetry at 7 and 8 TeV

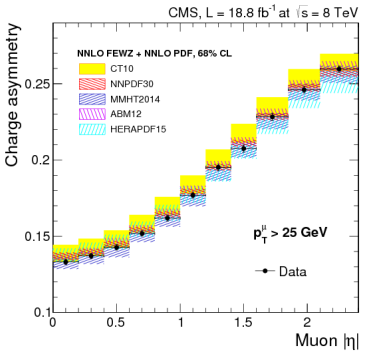
[Phys. Rev. D 90 (2014) 032004], [Eur. Phys. J. C 76 (2016) 469]

- $pp \to W^{\pm}$ dominantly produced by:
  - $u_v + \bar{d} \to W^+$
  - $d_v + \bar{u} \to W^-$
- Indirect s-quark sensitivity:
  - $u + \bar{s} \to W^+$
  - $\bar{u} + s \to W^-$

7 TeV



8 TeV



Lepton Charge Asymmetry at 8 TeV: Parametrization

[Eur. Phys. J. C 76 (2016) 469]

- Fit performed at NNLO (NLO at 7 TeV)

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

13 Parameter Fit:

$x\overline{D}(x) = x\bar{d}(x) + dx\bar{s}(x)$

$f_s = \bar{s}/(\bar{d}+\bar{s}) = 0.31 \pm 0.08$

$xs = x\bar{s}$

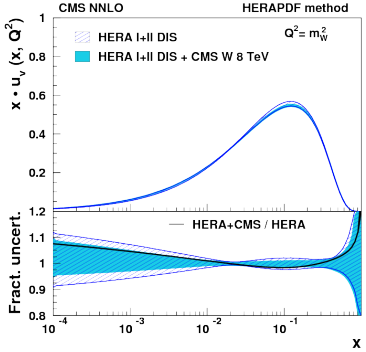
$B_{\overline{U}} = B_{\overline{D}}$

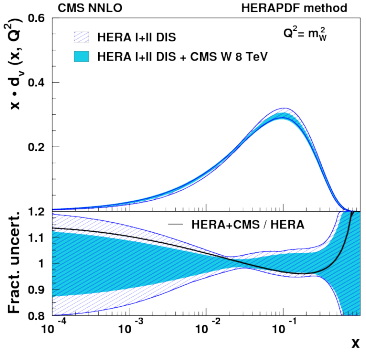
$A_{\overline{U}} = A_{\overline{D}}(1-f_s)$

QCD Analysis

[Phys. Rev. D 90 (2014) 032004], [Eur. Phys. J. C 76 (2016) 469]

- Fit performed at NNLO (NLO at 7 TeV)
- Good agreement between 7 and 8 TeV measurements
- Significant reduction of valence quark PDF uncertainty

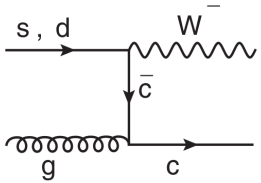


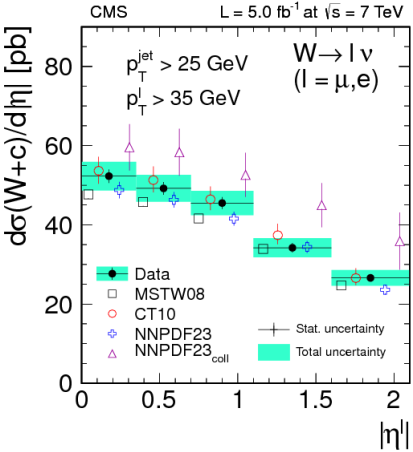


W+charm at 7 TeV

[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, $p_{\mathrm{T}}^{jet} > 25\,\mathrm{GeV}$:
  - $c \to D^*(2010)^{\pm}$
  - $c \to D^{\pm}$
  - $c \to \mu$





W+charm at 7 TeV: Parametrization at the Starting Scale

[Phys. Rev. D 90 (2014) 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

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

$xs = x\bar{s}$

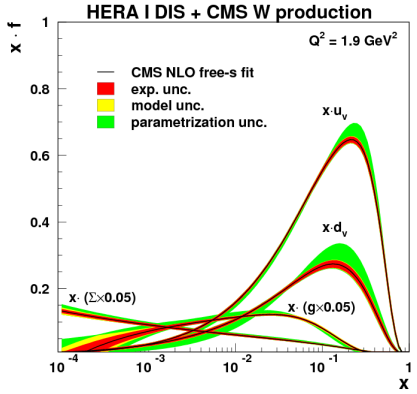
$A_{\overline{u}} = A_{\overline{d}}(1-f_s)$

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

χ^2 of the Individual Datasets

[Phys. Rev. D 90 (2014) 032004]

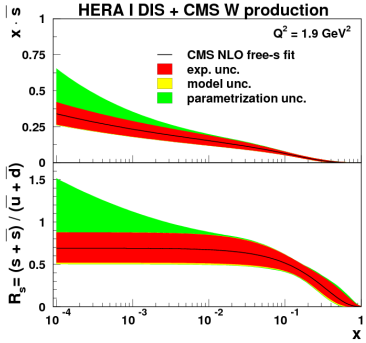
Dataset	χ^2/n_{dp}
NC cross section HERA I H1+ZEUS e^-p	107/145
NC cross section HERA I H1+ZEUS e^+p	417/379
CC cross section HERA I H1+ZEUS e^-p	20/34
CC cross section HERA I H1+ZEUS e^+p	36/34
CMS $W^{\pm}$ muon charge asymmetry $\mathcal{A}(\eta_\mu)$	14/11
CMS W+c cross section $\frac{\mathrm{d}\sigma_{\mathrm{W+c}}}{\mathrm{d}\eta^l}$	5/5
Total χ^2 / dof	598/593

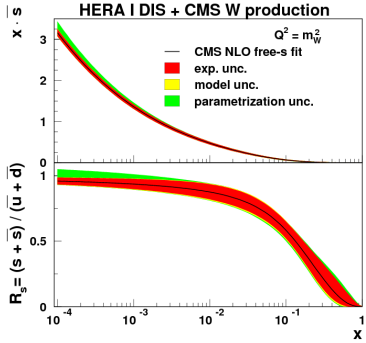


QCD Analysis:

[Phys. Rev. D 90 (2014) 032004]

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



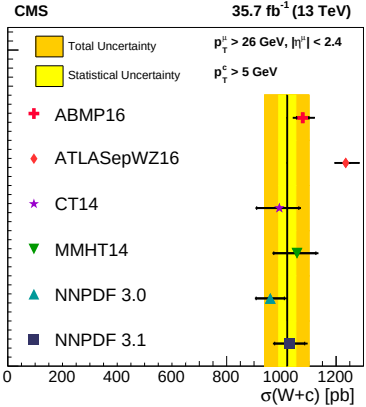


W+charm at 13 TeV

[Eur. Phys. J. C 79 (2019) 269]

- $W \to \mu + \nu$
  - 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
    $\to$ low-p_T D^* accessible
  - Low tracking uncertainty
  - Small branching ratios



W+charm at 13 TeV: Parametrization at the Starting Scale

[Eur. Phys. J. C 79 (2019) 269]

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

15 Parameter Fit:

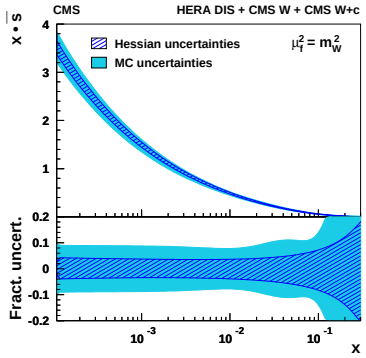
$B_{\overline{u}} \neq B_{\overline{d}} \neq B_{\overline{s}}$ [Phys.Lett. B777 (2018)]

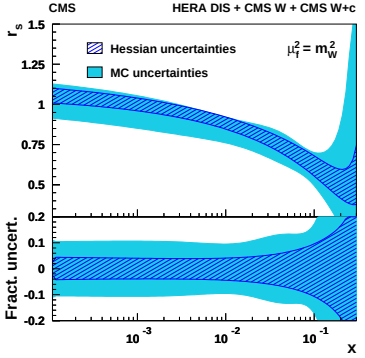
$xs = x\bar{s}$

Estimation of PDF Uncertainties

[Eur. Phys. J. C 79 (2019) 269]

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

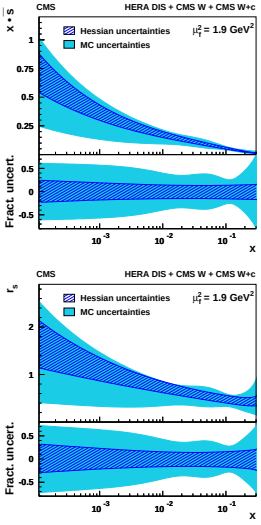




W+charm at 13 TeV: χ^2 Individual Datasets

[Eur. Phys. J. C 79 (2019) 269]

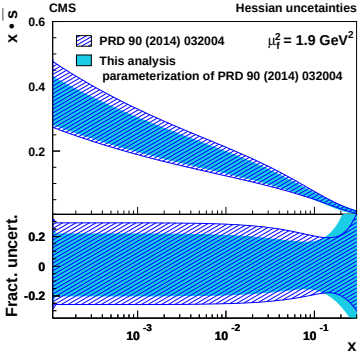
Dataset	χ^2/n_{dp}
HERA1+2 CCep	43 / 39
HERA1+2 CCem	57 / 42
HERA1+2 NCem	218 / 159
HERA1+2 NCep 820	69 / 70
HERA1+2 NCep 920	448 / 377
HERA1+2 NCep 460	216 / 204
HERA1+2 NCep 575	220 / 254
CMS W muon charge asym. 7 TeV	13 / 11
CMS W muon charge asym. 8 TeV	4.2 / 11
W+c 7 TeV	2.2 / 5
W+c 13 TeV	2.1 /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

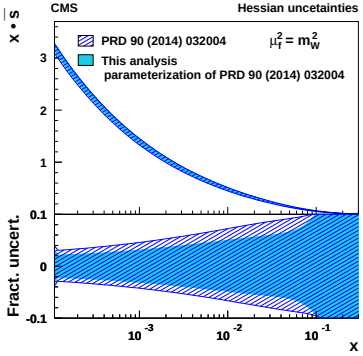


W+charm: Comparison with 7 TeV

[Eur. Phys. J. C 79 (2019) 269]

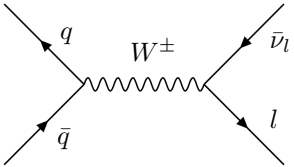
- In agreement with 7 TeV PDF fits with same parametrization
- Reduced PDF uncertainties

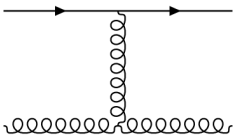


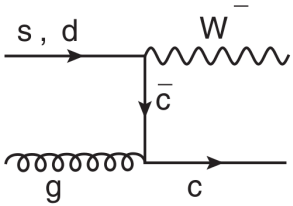


Summary

- CMS data is used in constraining PDFs
  - $W^{\pm}$ asymmetry: valence quarks
  - Inclusive Jets + Dijets: gluons
  - W+charm: strange quarks







Backup

Inclusive Jets at 8 TeV: χ^2 of the Individual Datasets

[JHEP 1703 (2017) 156]

Dataset	χ^2/n_{dp}	
HERA1+2	CCep	41 / 39
HERA1+2	CCem	50 / 42
HERA1+2	NCem	219 / 159
HERA1+2	NCep 820	61 / 63
HERA1+2	NCep 920	376 / 332
HERA1+2	NCep 460	204 / 187
HERA1+2	NCep 575	197 / 234
CMS inclusive jets 8 TeV	$0 < y < 0.5$	53 / 56
	$0.5 < y < 1.0$	34 / 36
	$1.0 < y < 1.5$	35 / 35
	$1.5 < y < 2.0$	52 / 29
	$2.0 < y < 2.5$	49 / 24
	$2.5 < y < 3.0$	4.9 / 18
Correlated χ^2		94
Total χ^2 / dof		1471 / 1216

Lepton Charge Asymmetry at 7 TeV: Parametrization

[Phys. Rev. D 90 (2014) 032004]

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

13 Parameter:

$x\overline{D}(x) = x\bar{d}(x) + dx\bar{s}(x)$

$f_s = \bar{s}/(\bar{d} + \bar{s}) = 0.31 \pm 0.08$

$xs = x\bar{s}$

$B_{\overline{U}} = B_{\overline{D}}$

$A_{\overline{U}} = A_{\overline{D}}(1 - f_s)$

L. Charge Asymm. at 8 TeV: χ^2 of the Individual Datasets

[Eur. Phys. J. C 76 (2016) 469]

Dataset	χ^2/n_{dp}
HERA1+2 CCep	46 / 39
HERA1+2 CCem	50 / 42
HERA1+2 NCem	218 / 159
HERA1+2 NCep 820	69 / 70
HERA1+2 NCep 920	440 / 377
HERA1+2 NCep 460	210 / 204
HERA1+2 NCep 575	214 / 254
CMS W muon charge asym. 8 TeV	3 / 11
Correlated χ^2	141
Total χ^2 / dof	1391 / 1143