New results on parton densities of nucleons and nuclei

XXVI International Workshop on Deep Inelastic Scattering and Related Subjects

16-20 April 2018 Kobe, Japan

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DESY

Outline

- Introduction
- Low-x gluon
- Fitted and perturbative charm
- High-x gluon and valence
- Flavour separation, strangeness
- Nuclear PDFs

Disclaimer:

This talk is covering only unpolarized, collinear PDFs.

Spin: next plenary talk by Hayan Gao

Many results had to be left out.

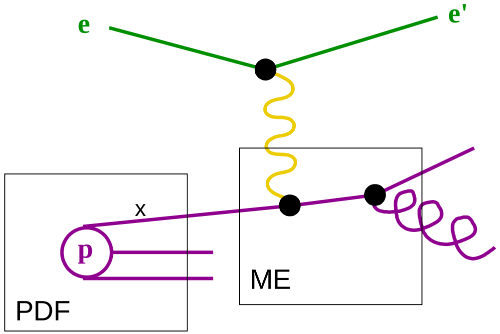
Parallel session on Proton structure and PDF: WG1 [Valerio Bertone, Mario Campanelli, Paolo Gunnellini]

The emphasis is on new experimental results and their PDF interpretation.

I made choices based on personal biases. The selection is not complete and I would like to ask your apologies for missing out many important results.

PDFs and QCD factorisation

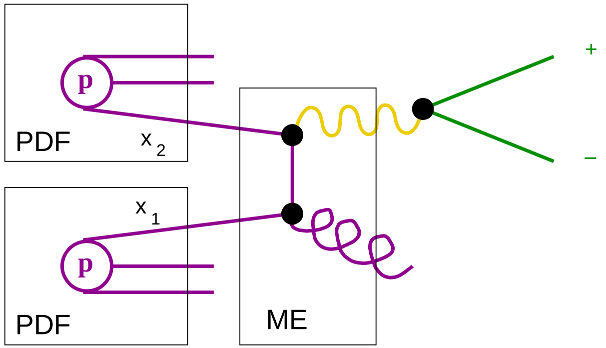
Deep-inelastic scattering



$$\sigma_{DIS} \sim PDF \otimes |ME|^2$$

Integration variable: x

Proton-Proton collisions



$$\sigma_{pp} \sim PDF(x_1) \otimes |ME|^2 \otimes PDF(x_2)$$

Two integration variable: x_1, x_2

Factorisation is proven in pp only for a subset of processes, such as Drell-Yan, jet or heavy quark production

- PDF $f_q(x,\mu)$: probability to find parton of flavour q in the proton
- Factorisation theorem: hard partonic matrix elements factorize from PDFs
- Higher twist terms are suppressed by powers of the factorisation scale μ

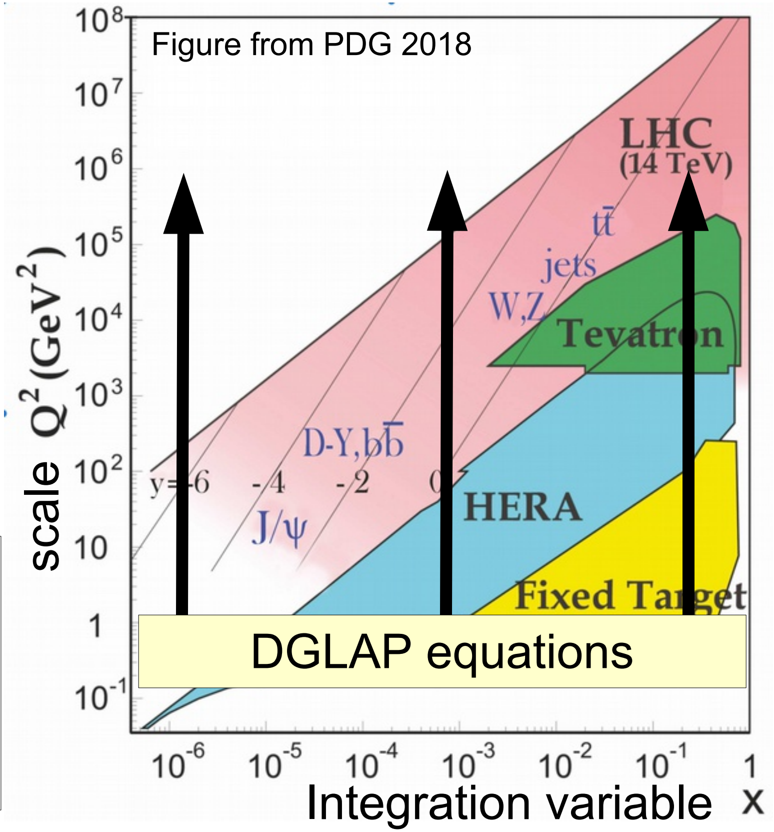
PDF evolution

- PDFs evolve with the scale: DGLAP equations

  → given the x-dependence at a fixed scale μ_0, DGLAP predicts the x-dependence at another scale

- Ingredients: splitting functions and running strong coupling

PDF set
parametrisation of PDFs [u(x),d(x),s(x),g(x),...] at a starting scale μ_0 and a choice of $\alpha_s(m_Z)$.
Using DGLAP, this predicts the PDF for any flavour at any scale and any x



DIS:
$Q^2 = -(e-e')^2$
$x \sim x_{Bj} = 2pq/Q^2$

Drell-Yan:
$Q^2 = m_Z^2$
$x_1 x_2 \sim M_Z^2 / s$
$\frac{x_1}{x_2} \sim \exp[2y_Z]$

PDF fit

- PDF fit: determine a PDF set from data using NLO or (where possible) NNLO theory
- Requirements:
  - Data
  - Predictions for the reactions of interest
  - PDF Parametrisation at starting scale μ_0
  - Fitting framework
- Result: “central” PDF set +uncertainties
- PDF uncertainties are often expressed by publishing several PDF sets

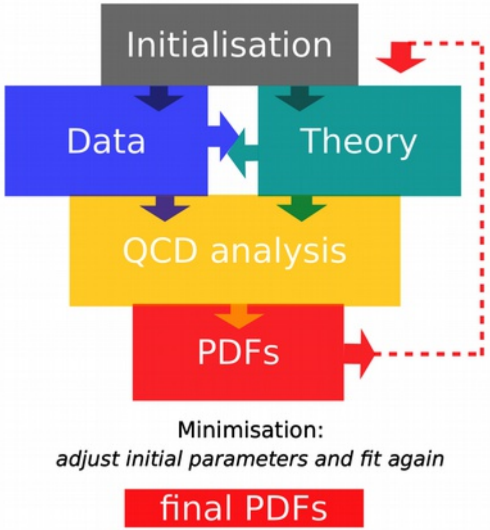


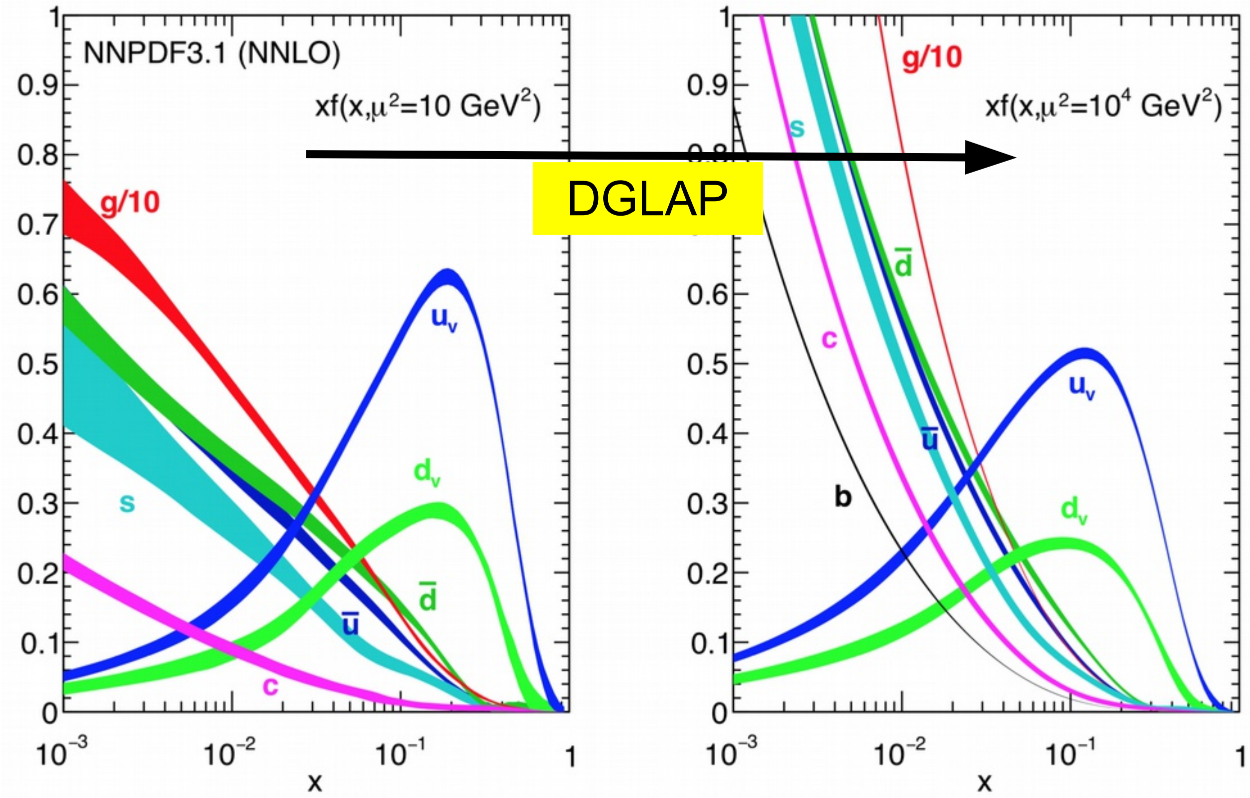
Figure from talk by R. Placacyte, CTEQ/MCnet school 2016

http://xfitter.org

- xFitter: open-source tool to do PDF fits
- Global fitting groups: NNPDF, ABM, CTEQ, MMHT, ...

See parallel session talks:
MMHT,CTEQ-TEA,NNPDF: WG1 17.4. 14:20-15:20
xFitter: WG1(212) 18.4. 16:30

Example PDF set



NNPDF3.1: EPJ C77 (2017) 663 [arXiv:1706.00428]; **WG1(252) 17.4. 15:00**

- Shown here: result of NNPDF3.1 analysis
- Valence quarks, gluon, sea-quarks
- Uncertainties are encoded in the widths of the bands
- DGLAP evolution to high scales causes steep rise of gluon and sea at low-x
- Charm and beauty quark PDFs are non-zero at scales $\mu > M_Q$ (variable-flavour-number)
- Alternative: fixed-flavour number schemes, $N_f=\{3,4,5\}$

Relevance of PDF uncertainties

- The PDFs seem to be rather well known, so why care about precision?
- Example: recent high-precision W-mass determination by ATLAS

  → PDF is the dominating uncertainty
- The same is true for many other LHC results

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	8.2	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

ATLAS W-mass: EPJ C78 (2018) 110 [arXiv:1701.07240]

PDF fits: many possible input datasets

low-x → high-x

flavour separation

HERA inclusive NC and CC data
Backbone of all PDF fits
Low-x resummation

HERA c,b data
New data for DIS2018
Low-x gluon, flavour schemes, c, b quark masses

HERA jets
H1 jets NNLO analysis
Low/medium-x gluon, α_s

LHC c+Z,c+γ
New ATLAS+CMS results
Fits with “intrinsic” charm

pp jets
ATLAS jets 8&13 TeV
CMS jets 8 TeV
RHIC 0.5 TeV
High-x valence and gluon

LHC ttbar
ATLAS, CMS, LHCb at various √s
High-x gluon

LHC W+charm
New CMS data: strangeness

Collider W,Z,DY
New W,Z LHC
u,d,s flavour separation

Fixed target DY
SeaQuest 2017 run
u(bar)-d(bar)

Fixed target DIS
Quark flavours at high-x
JLAB prospects

Nuclear PDFs

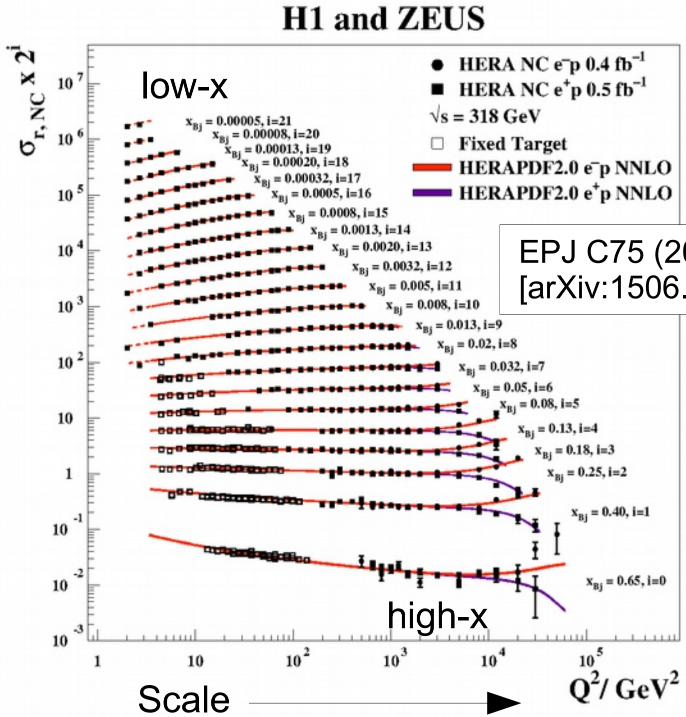
pA and AA data
Z,W in pA,AA
Jets, charm in pA, AA

Highlighted: results covered in this talk
(there are many more [mostly older] results included in PDF fits but not discussed in this talk)

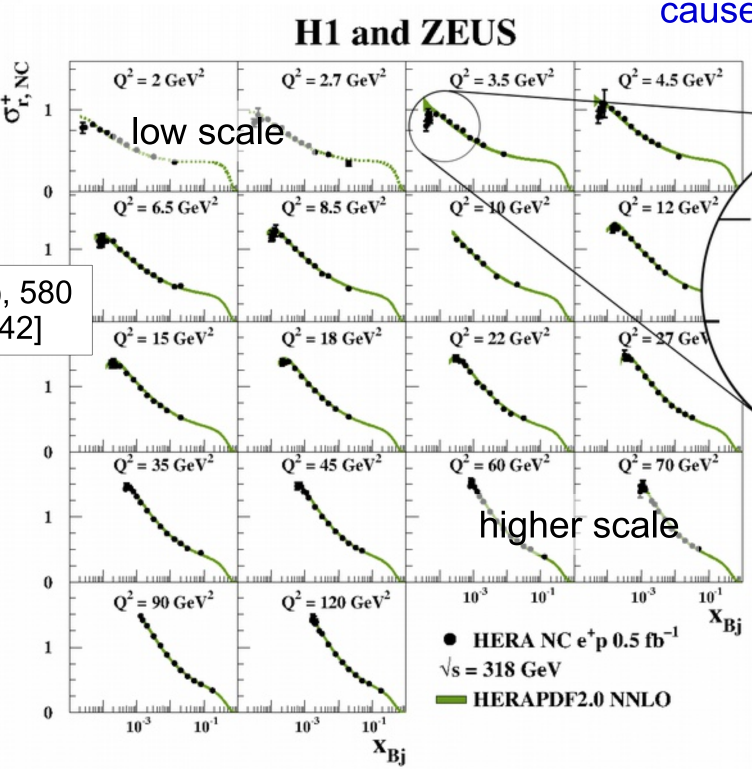
Low-x gluon

HERA data and low-x

- HERA combined inclusive data: the backbone of all PDF fits

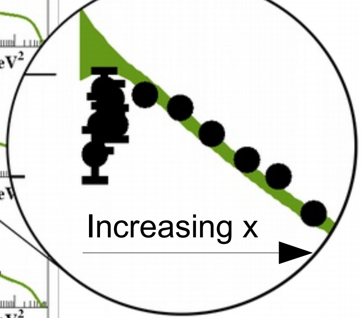


EPJ C75 (2015), 580
[arXiv:1506.06042]



Cross-section turn-over at low x is caused by the structure function F_L

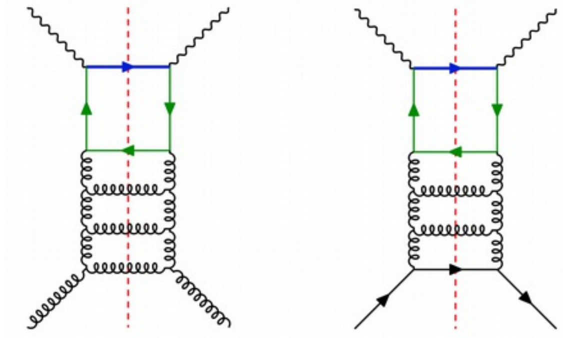
$$\sigma_r \simeq F_2 - \frac{Q^4}{2s^2 x^2} F_L$$



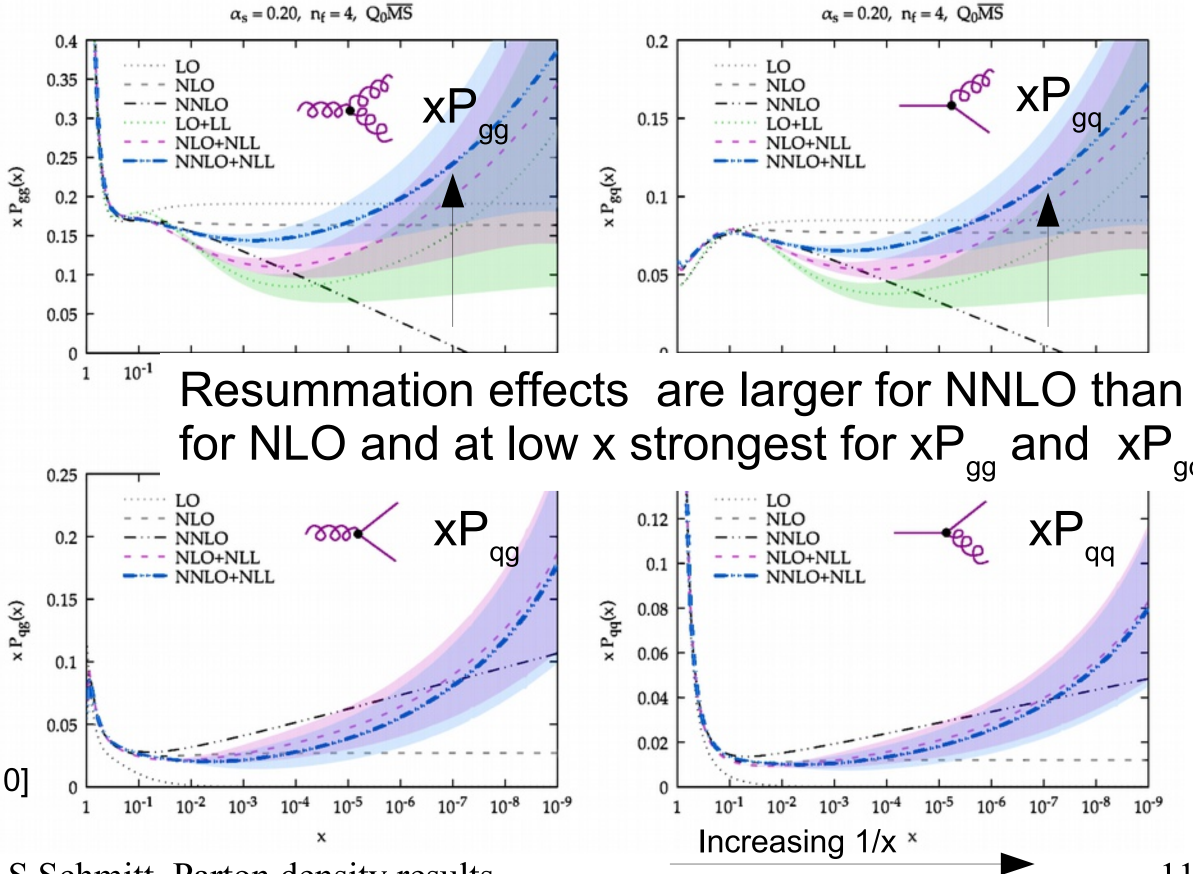
- Low-x, low-Q²
- Turn-over is not well described by NNLO QCD fit
- Low-x resummation?

Low-x resummation

- Resum leading logs in 1/x: BFKL-type gluon ladders
- Code for resummed splitting kernels and resummed DIS coefficient functions available in the package “HELL2.0”



HELL2.0: JHEP 1712 (2017) 117 [arXiv:1708.07510]



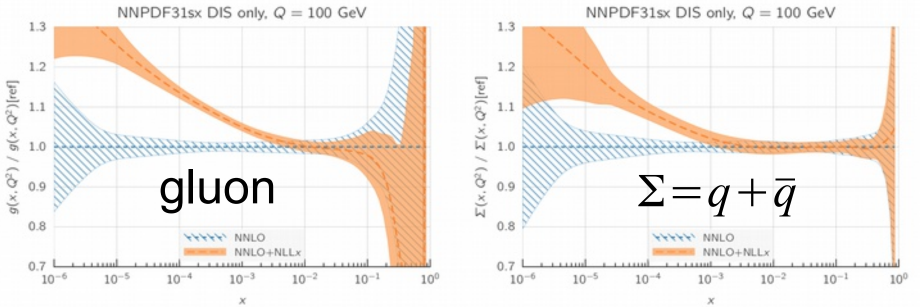
Resummation effects are larger for NNLO than for NLO and at low x strongest for xP_{gg} and xP_{gq}

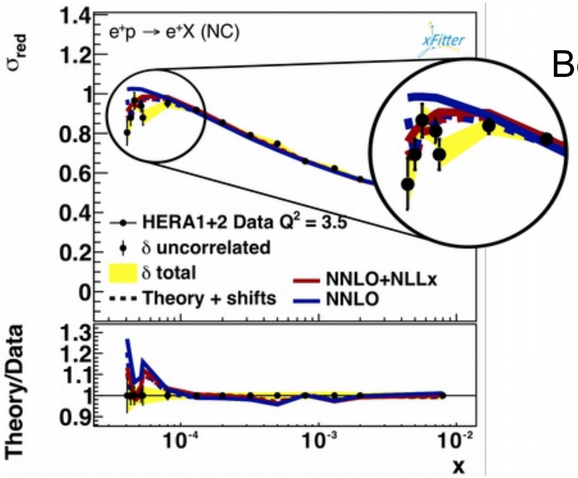
Low-x resummation and HERA data

- Recent PDF fits with low-x resummation
  - NNPDF group
  - xFitter group
- Fits include HERA inclusive data and HERA charm (2012) data
- NNPDF3.1sx also includes non-ep datasets, with restricted x-range (resummed coefficient functions available only for DIS)
- Result: better description of HERA low-x data and of HERA charm data

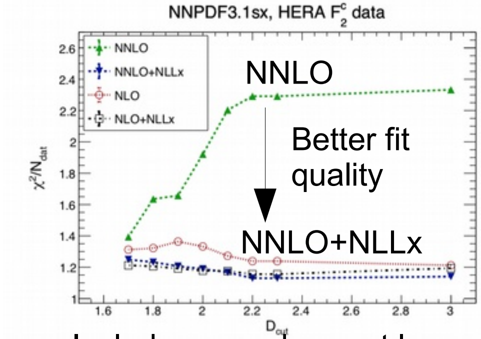
NNPDF+resummation: arXiv:1710.05935
xFitter+resummation: arXiv:1802.00064; **WG1(213) 19.4. 10:00**

Resummed NNLO PDFs: enhanced gluon and sea at low-x





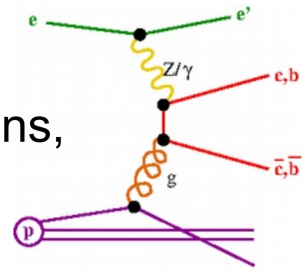
Better description of HERA charm



Include more charm at low-x

New HERA c and b combination

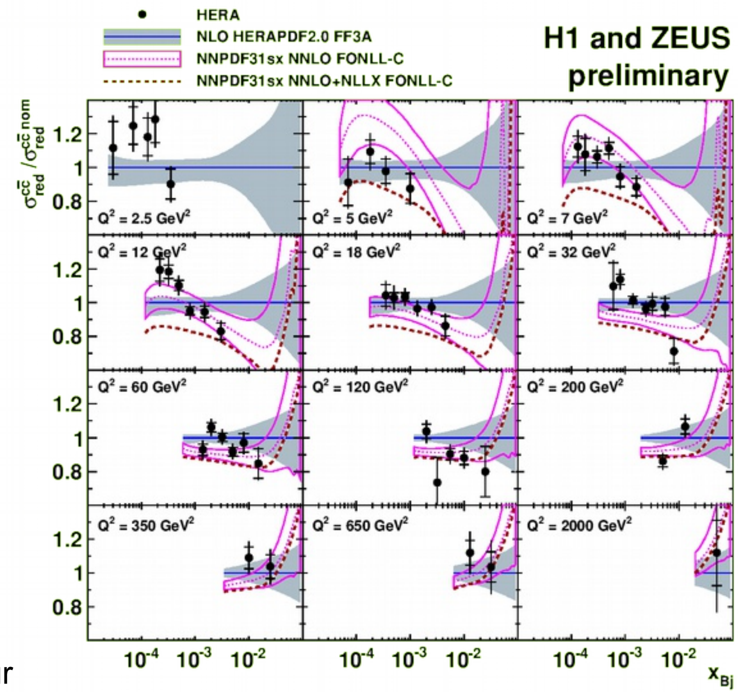
- New H1+ZEUS data combination of charm and beauty cross sections, supersedes 2012 charm combination



- Main result of the paper: extract charm and beauty quark masses

$$m_c(m_c)=1.290^{+0.077}_{-0.053} \text{ and } m_b(m_b)=4.049^{+0.138}_{-0.118}$$

- Here: focus on comparisons of charm data to QCD predictions
  - NLO+HERAPDF2.0 FF3A — Fixed-flavour
  - NNPDF31sx (NNLO+NLLX) — Variable-flavour +low-x resummation



Shown here: ratios to HERAPDF2.0 FF3A

Data have x-slope different from fixed-flavour NLO HERAPDF2.0 FF3A

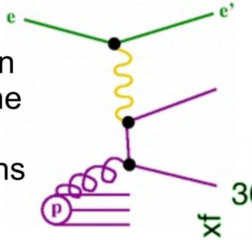
x-slope described better for variable-flavour+NLLX NNPDF3.1 but Q^2 dependence is not correct

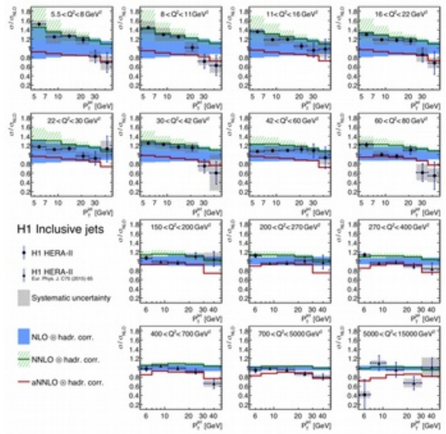
New HERA charm: submitted to EPJC, arXiv:1804.01019; **WG1+5(54) 18.4. 14:00**
HERAPDF2.0: EPJ C75 (2015), 580 [arXiv:1506.06042]
NNPDF3.1: EPJ C77 (2017) 663 [arXiv:1706.00428]; **WG1(252) 17.4. 15:00**

Valuable input for future PDF fits and QCD studies: low-x resummation, flavour thresholds, ...

HERA jets and PDF+α_s fit

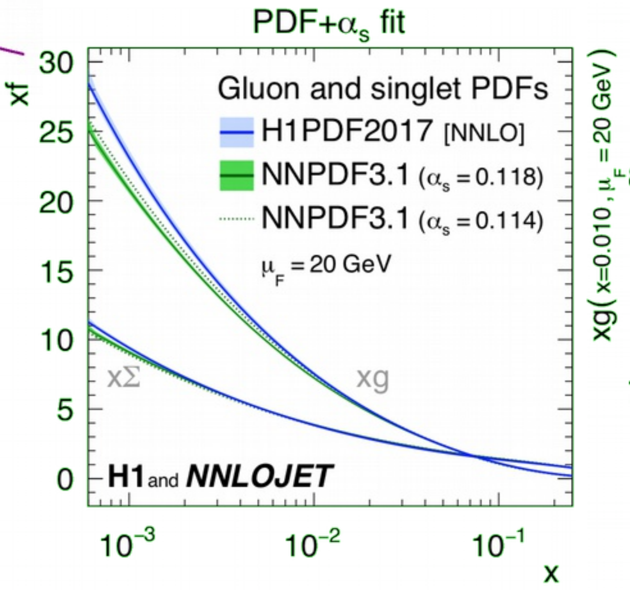
DIS jet production in Breit frame: one of the leading-order contributions

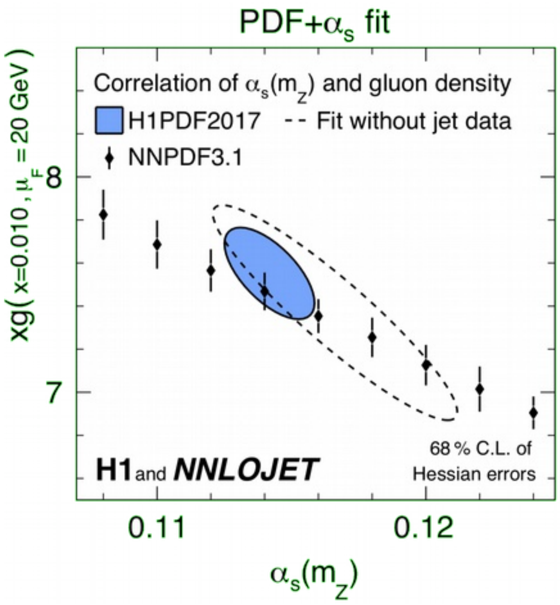




Recent inclusive H1 jet data:
EPJ C77 (2017), 215 [1611.03421]

H1 data analysis at **NNLO**: fit of α_s and PDFs using inclusive jets + dijets in Breit frame, main result: α_s=0.1157(20)$_{exp}$(29)$_{theo}$





H1+NNLOJET PDF+α_s fit: EPJC 77 (2017) 791 [arXiv:1709.07251];
WG1(6) 17.4. 9:00

H1 jet+inclusive data prefer somewhat steeper gluon than global fit

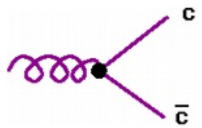
Similar precision to global fit → DIS jet data have a large potential for PDF fits

Decorrelates gluon and α_s

Data and NNLO calculations are available: ready for use in global fits

Fitted and perturbative charm

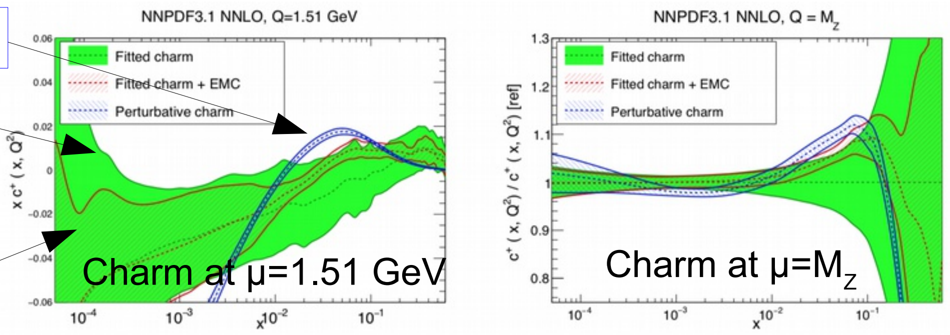
- Variable flavour number scheme: “perturbative charm” from gluon splitting



Perturbative charm

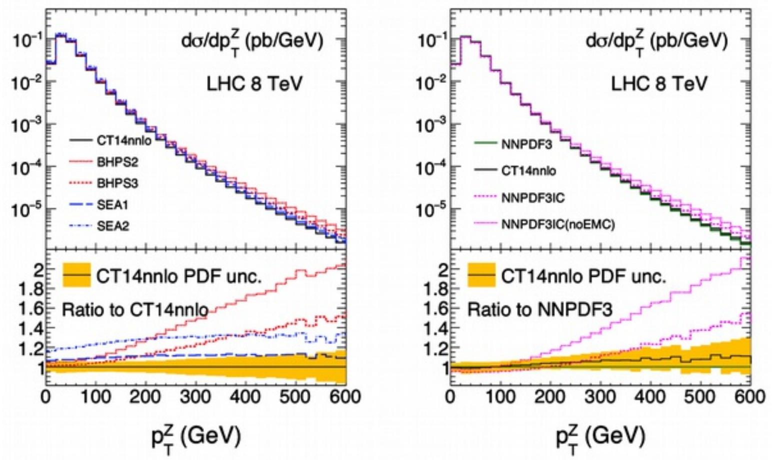
Fitted charm

Fitted charm +EMC data (Charm in DIS, high-x)



- NNPDF3.1 and CTEQ-TEA: additional “fitted” charm contribution, onset at $\mu_0 > M_c$

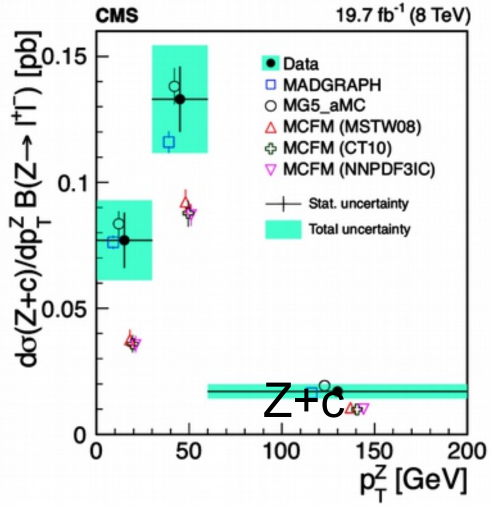
LHC Z+c is sensitive to fitted charm at large transverse momentum
BHPS: valence-like charm
SEA: sea-like charm

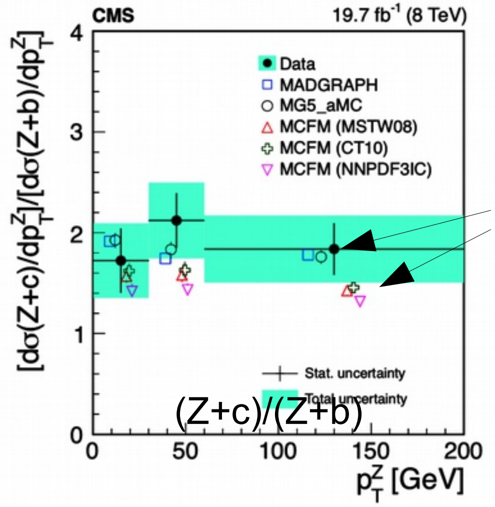


NNPDF3.1: EPJ C77 (2017) 663 [arXiv:1706.00428]; **WG1(252) 17.4. 15:00**
CTEQ-TEA: JHEP 1802 (2018) 059 [arVix:1707.00657]; **WG1(236) 17.4. 14:40**

Fitted charm: new LHC data

- γ+c and γ+b by ATLAS
- Z+c and Z+b by CMS

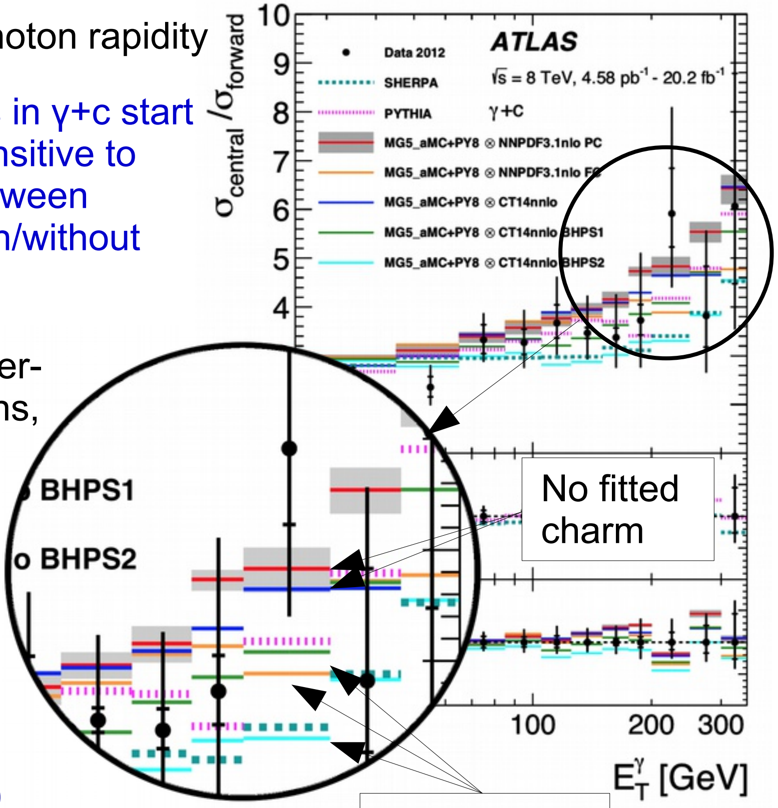




significant higher-order corrections, parton shower

ATLAS: ratio central/forward photon rapidity

Measurements in γ+c start to become sensitive to differences between predictions with/without fitted charm



Models with fitted charm

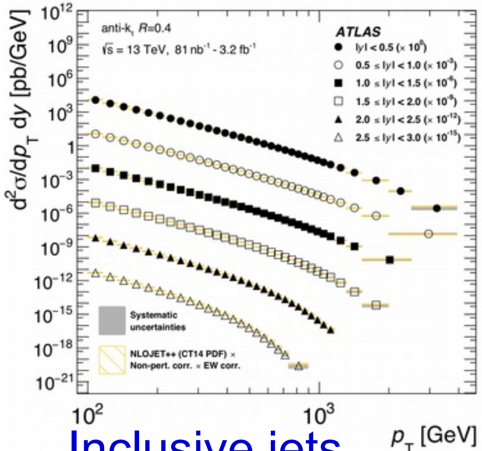
Uncertainties in Z+c too large to differentiate between predictions with/without fitted charm

ATLAS γ+c,b: Phys.Lett. B776 (2018) 295 [arXiv:1710.09560]; **WG1(57) 17.4. 12:30**
CMS Z+c: arXiv:1711.02143, Z+b: EPJ C77 (2017) 751 [arXiv:1611.06507]; **WG1(19) 18.4. 14:55**

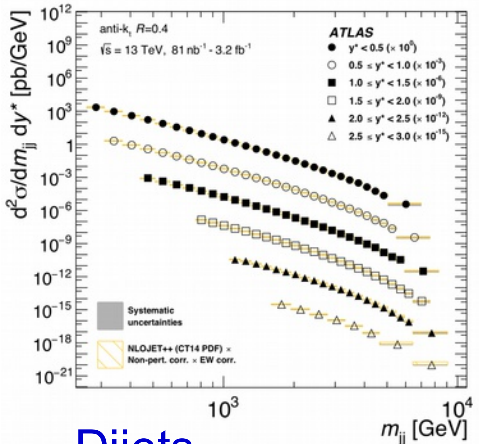
High-x gluon and valence

Double-differential jet data at the LHC

- ATLAS double-differential cross sections
- Inclusive jets √s=8 and 13 TeV $\frac{d^2\sigma}{dp_T dy}$
- Dijets √s=13 TeV $\frac{d^2\sigma}{dm_{jj} dy^*}$, where $y^* = |(y_1 - y_2)/2|$

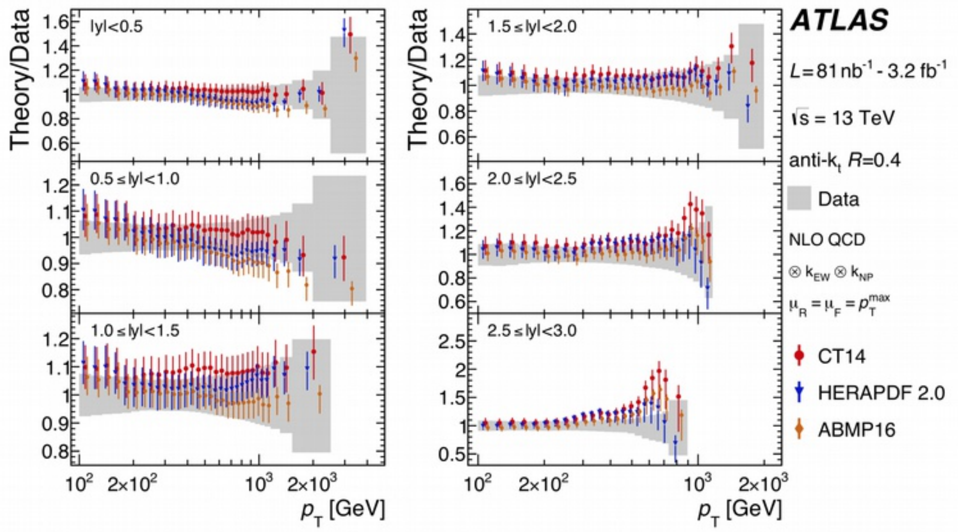


Inclusive jets



Dijets

(only the newer (√s=13 TeV) data are shown here)



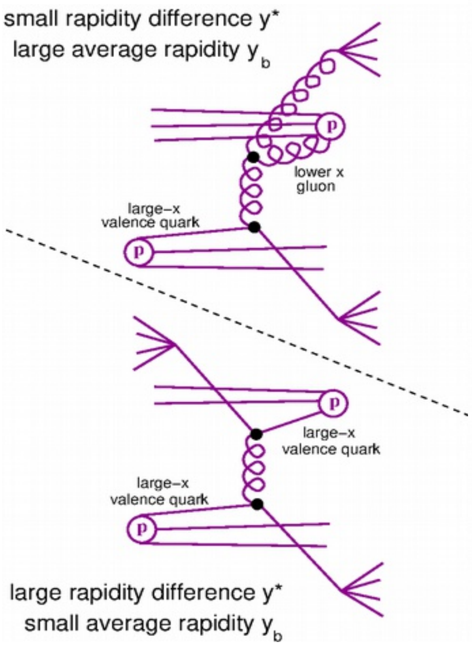
- Data uncertainties similar in size to predictions from global PDF fits
- Shape differences NLO ↔ data
- Data to be used in future PDF fits

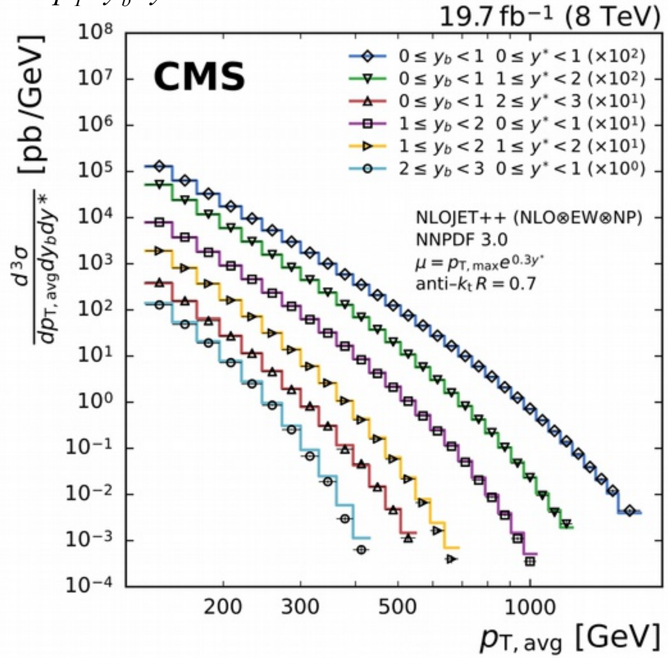
ATLAS: 8 TeV inclusive jets: JHEP 1709 (2017) 020 [arXiv:1706.03192]
ATLAS: 13 TeV inclusive jets and dijets: arXiv:1711.02692; **WG1(59) 18.4. 10:25**

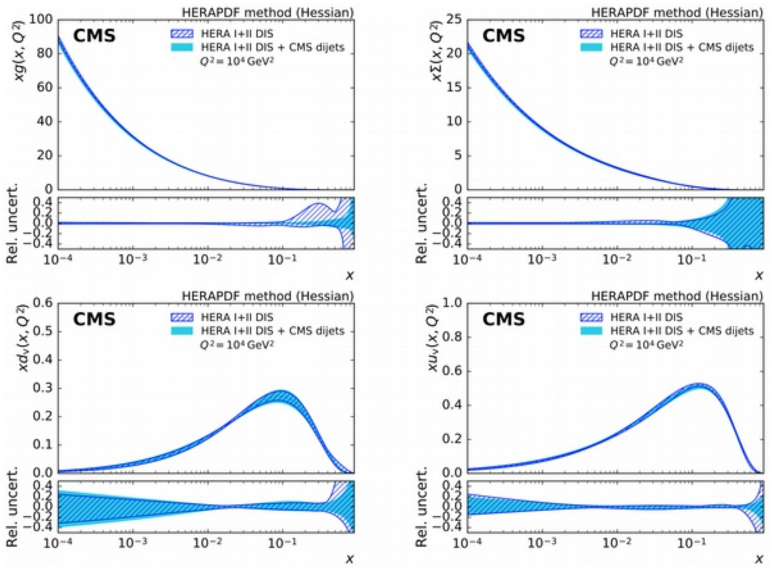
Quantitative comparisons: backup

Triple-differential jet data at the LHC

- CMS dijet cross sect. at $\sqrt{s}$=8 TeV
- Triple-differential $\frac{d^3\sigma}{dp_T dy_b dy^*}$, where $y_b = |(y_1+y_2)/2|$





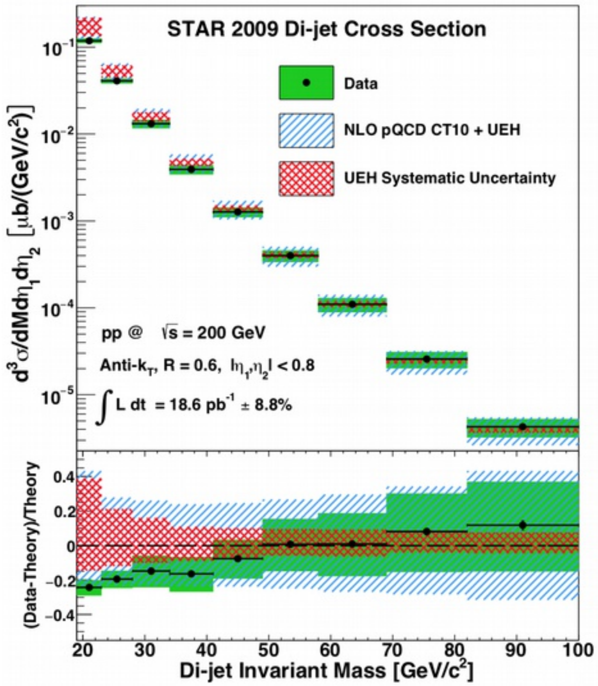


- PDF fit together with HERA data
- CMS jet data constrain valence quarks and gluon at high-x

EPJ C77 (2017) 746 [arXiv:1705.02628]; **WG1(30) 17.4. 15:40**

Jet production at RHIC

- Data from polarized pp collisions at $\sqrt{s}$=200 GeV
- Main measurement: polarisation asymmetry A_{LL}
- Add-on: unpolarized cross sections
- Explores regions of very large x, at lower scales than LHC
- Data uncertainties are much smaller than predictions → possible constraints on PDFs



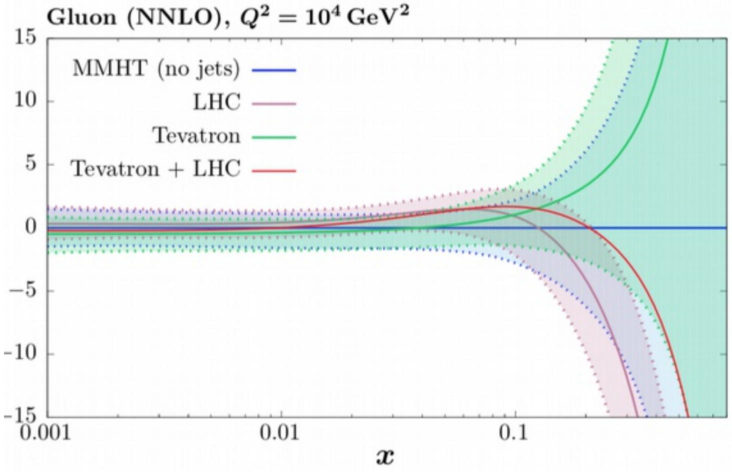
STAR jets: Phys.Rev. D95 (2017) 071103 [arXiv:1610.06616]; **WG6(126) 18.4. 11:30**

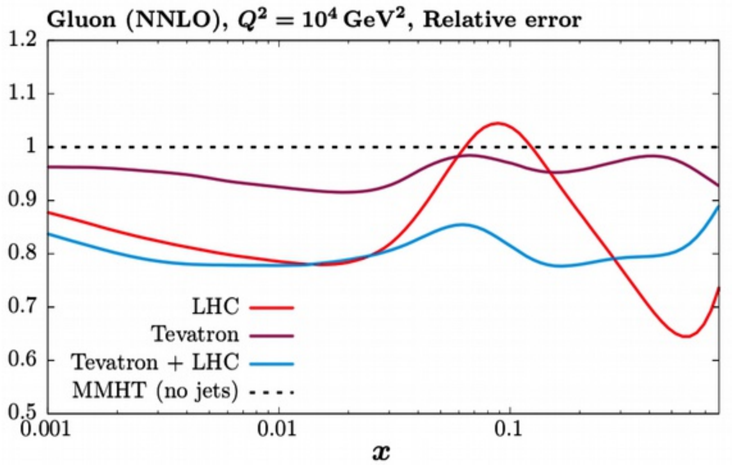
Global fits with LHC jet data

- NNLO calc. available
- MMHT study, including only √s=7 TeV jet data at NNLO
- Difficulties to fit the ATLAS data → change syst. correlations

X^2 for NLO and NNLO fits

	NLO theory	NNLO	NNLO (no errors)
ATLAS, R_{low}	215.3	172.3	179.1
ATLAS, R_{high}	159.2	149.8	153.5
CMS, R_{low}	194.2	177.8	182.8
CMS, R_{high}	198.5	182.3	188.8



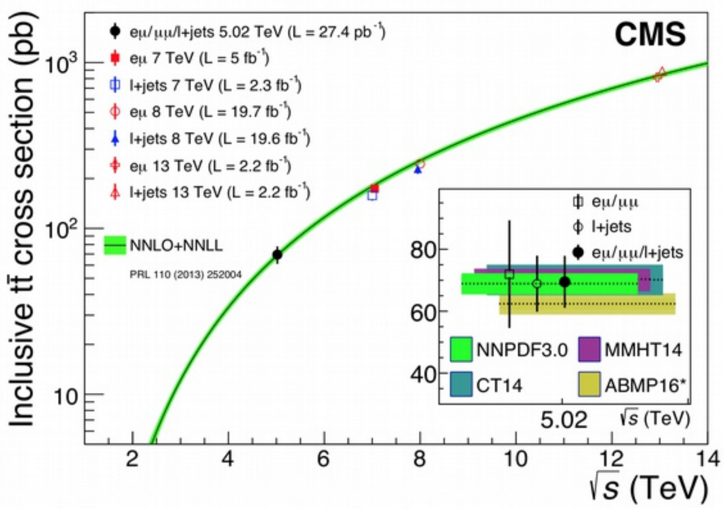


- NNLO describes the data better than NLO
- LHC data do improve gluon in global fits, in particular at large-x

NNLO jets,V+jets calculations: **WG4(165) 18.4. 9:00**
MMHT+jets: EPJ C78 (2018) 248 [arXiv:1711.05757]; **WG1(250) 17.4. 14:20**
CMS 7 TeV: Phys.Rev. D90 (2014) 072006 [arXiv:1406.0324]
ATLAS 7 TeV: JHEP 1502 (2015) 153 [arXiv:1410.8857], Erratum JHEP 1509 (2015) 141

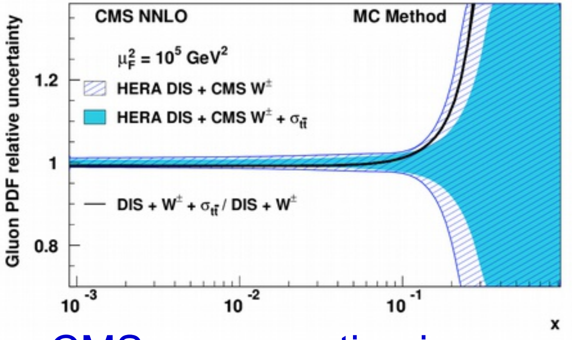
Gluon density and tt(bar) cross sections

- New CMS measurements at 5 and 13 TeV



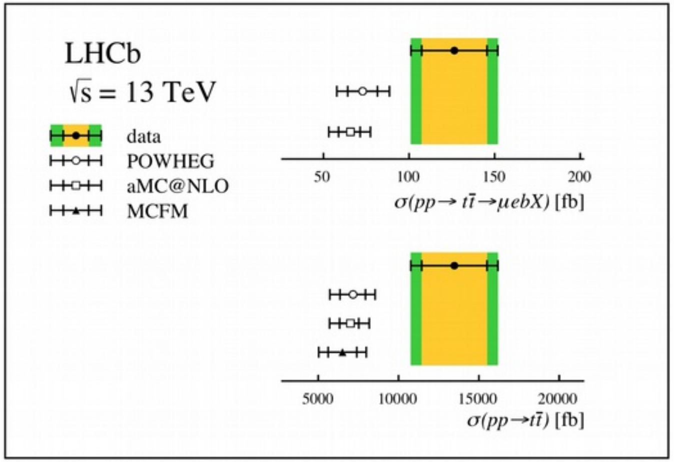
2016 ATLAS measurement of tt(bar)/Z: backup slides

CMS PDF fit with HERA data



CMS cross-section is constraining high-x gluon

- New LHCb measurement at 13 TeV in the forward direction ($2<y_{top}<5$, $p_T>10$ GeV)



LHCb: forward ttbar prediction is ~2σ below data

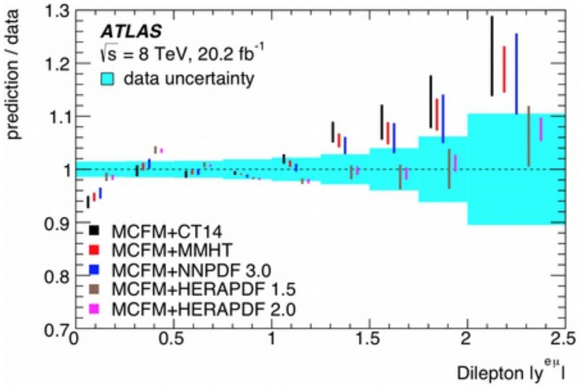
$$\sigma_{LHCb} \sim g(x_1)\, g(x_2)$$

$$\text{where } x_1 > 10^{-1},\ x_2 < 10^{-2}$$

LHCb 13 TeV: arXiv:1803.05188; **WG1(220) 17.4. 11:50**
CMS 5 TeV: JHEP 1803 (2018) 115 [arXiv:1711.03143]; **WG1(30) 17.4. 15:40**
CMS 13 TeV: JHEP 1709 (2017) 051 [arXiv:1701.06228]

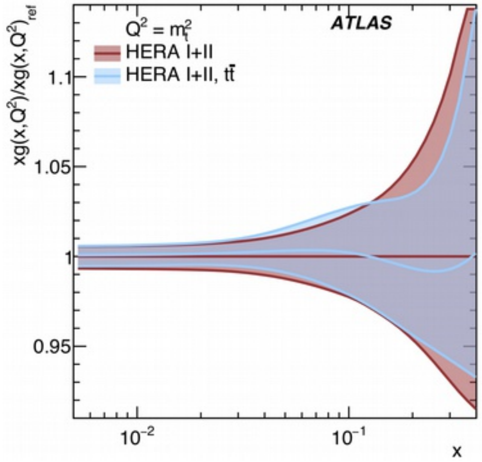
Single-differential tt(bar) cross sections

- New ATLAS data: normalized single-differential dilepton cross sections at 8 TeV
- Many variables are measured and are compared to various PDF sets



Example: difference in rapidity of the two leptons compared to predictions

	Generator	p_T^ℓ	$\|\eta^\ell\|$	$p_T^{e\mu}$	$m^{e\mu}$	$\|y^{e\mu}\|$	$\Delta\phi^{e\mu}$	$p_T^e + p_T^\mu$	$E^e + E^\mu$
	N_{dof}	9	8	8	11	8	9	7	9
χ^2	MCFM + CT14	11.5	14.1	7.2	11.2	13.0	7.2	11.4	11.2
	MCFM + MMHT	11.3	12.8	7.2	11.2	12.6	7.1	11.2	9.6
	MCFM + NNPDF 3.0	11.7	11.3	7.2	11.4	9.4	7.3	11.5	8.5
	MCFM + HERAPDF 1.5	9.1	10.9	6.4	12.1	8.0	6.9	8.5	2.6
	MCFM + HERAPDF 2.0	8.4	12.0	6.2	12.4	8.0	6.8	8.0	2.7
p-value	MCFM + CT14	0.24	0.080	0.51	0.43	0.11	0.62	0.12	0.27
	MMHT	0.26	0.12	0.51	0.42	0.13	0.62	0.13	0.38
	NNPDF 3.0	0.23	0.18	0.52	0.41	0.31	0.61	0.12	0.49
	MCFM + HERAPDF 1.5	0.43	0.21	0.61	0.36	0.44	0.65	0.29	0.98
	MCFM + HERAPDF 2.0	0.49	0.15	0.63	0.33	0.44	0.66	0.34	0.97



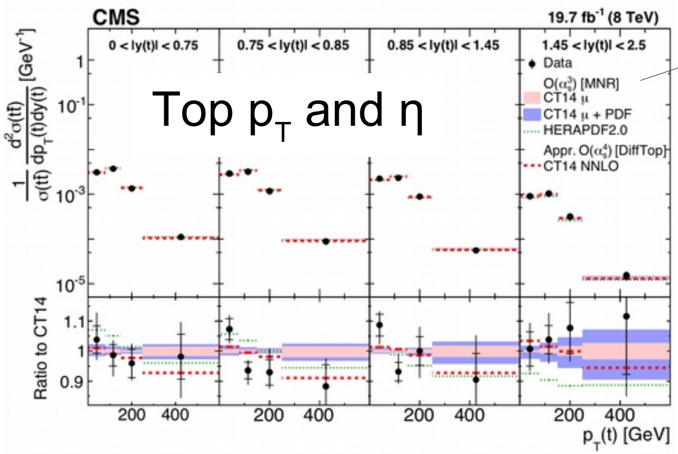
- ATLAS PDF fit with HERA data
- Data gives extra sensitivity to the high-x gluon

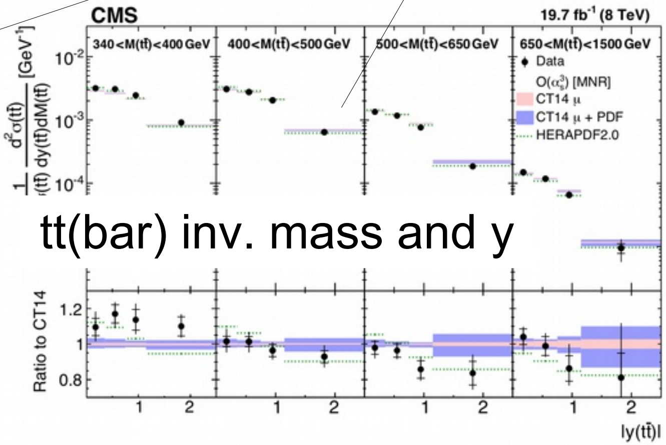
EPJ C77 (2017) 804 [arXiv1709.09407]; **WG1+5(160) 18.4. 14:35**

Double-differential tt(bar) cross sections

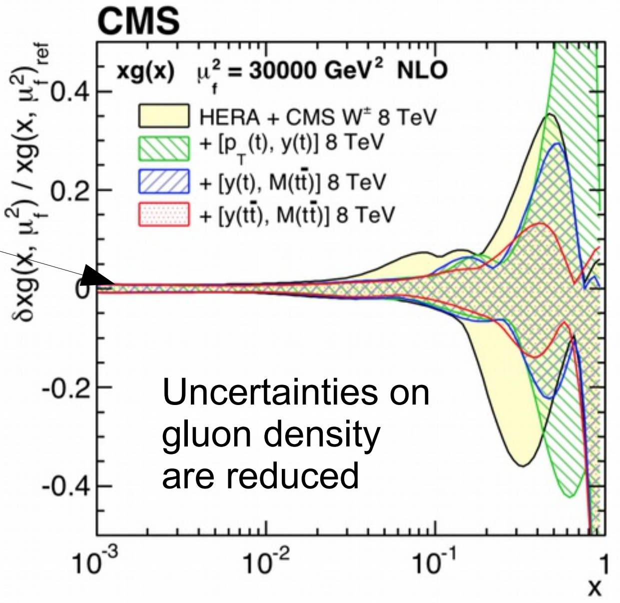
- New CMS tt(bar) 8TeV normalized double-differential cross sections in combinations of several variables

$y(t),\ p_T(t),\ M(t\bar{t}),\ y(t\bar{t}),\ \Delta\eta(t,\bar{t}),\ p_T(t\bar{t}),\ \Delta\phi(t,\bar{t})$





PDF fit with HERA data



- Double-differential data put significant constraints on the high-x gluon

EPJ C77 (2017) 459 [arXiv1703.01630]; **WG1(30) 17.4. 15:40**

Flavour separation, strangeness

Strangeness in PDF fits

- Indirect constraints on strangeness by combining structure functions, W-prod and Drell-Yan + sum rules (each probing different flavour combination)
- Direct measurements:
  - High-x semi-inclusive DIS, K^{+}&K^{-}
  - Charm in charged current, νN

    NLO calc: WG1(146) 18.4. 15:30
  - LHC W+c
- Look at suppression factor

$$r_s = \frac{\bar{s}}{\bar{d}} \sim R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$$

HERA NC: $\sigma_r \sim 4(u+\bar{u}+c+\bar{c})+d+\bar{d}+s+\bar{s}+b+\bar{b}$

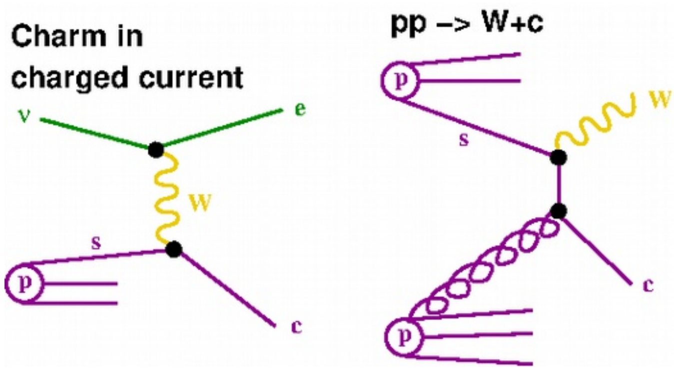
HERA CC $e^{+}p$: $\sigma_{CC}^{-} \sim d+s+b+\bar{u}+\bar{c}$

HERA CC $e^{-}p$: $\sigma_{CC}^{-} \sim u+c+\bar{d}+\bar{s}+\bar{b}$

LHC Z: $\sigma_{DY} \sim u\bar{u}+c\bar{c}+1.3(d\bar{d}++s\bar{s}+b\bar{b})$

LHC W+: $\sigma_{W^{+}} \sim u\bar{d}+c\bar{s}+$Cabbibo suppr.prod.

LHC W+: $\sigma_{W^{-}} \sim \bar{u}d+\bar{c}s+$Cabbibo suppr.prod.

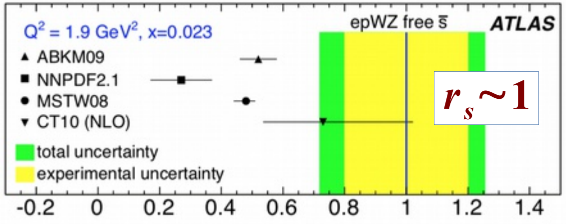


Recap: LHC data and the strange sea

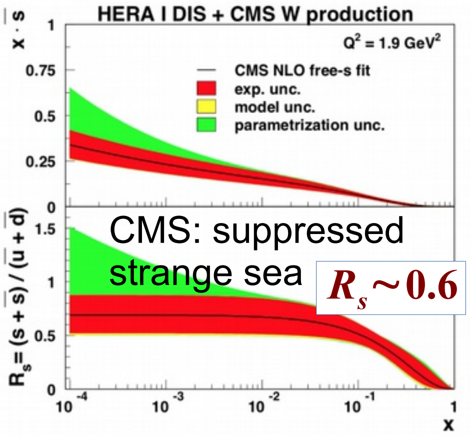
- Global fits+NuTeV/CCFR, NOMAD, CHORUS: “suppressed” strange sea, $r_s<1$
- HERMES 2014: r_s is x-dependent (leading-order analysis)
- ATLAS 2012 fit of W and Drell-Yan +HERA: “unsuppressed” strange sea $r_s=1$
- CMS 2013 data on W asymmetry plus PDF fit: “suppressed” strange sea
- CMS 2013 data on c+W compatible with “suppressed” strange sea
- ATLAS 2014 data on c+W compatible with with “unsuppressed” ATLAS fit

HERMES: Phys.Rev. D89 (2014) 097101 [arXiv:1312.7028]
ATLAS fit: Phys.Rev.Lett. 109 (2012) 012001 [arXiv:1203.4051]
CMS c+W: JHEP 1402 (2014) 013 [arXiv:1310.1138]
CMS W asym: Phys.Rev. D90 (2014) 032004 [arXiv:1312.6283]
ATLAS c+W: JHEP 1405 (2014) 068 [arXiv:1402.6263]

ATLAS: unsuppressed strange sea

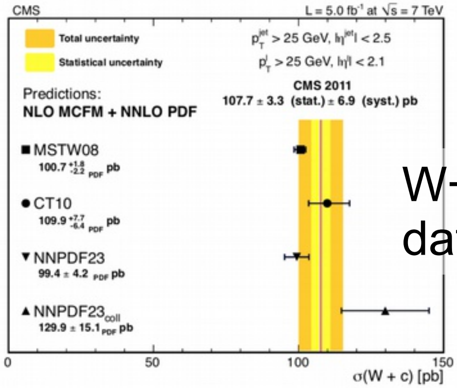


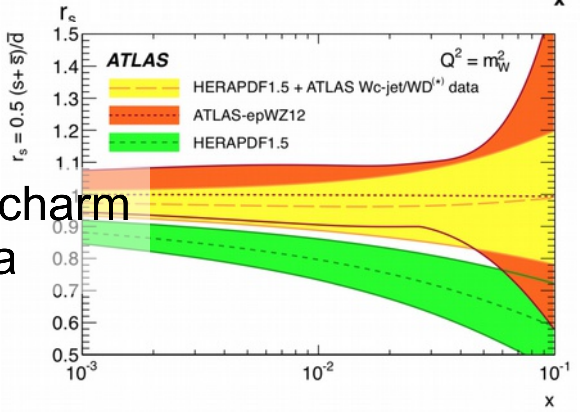
$r_s \sim 1$



CMS: suppressed strange sea

$R_s \sim 0.6$

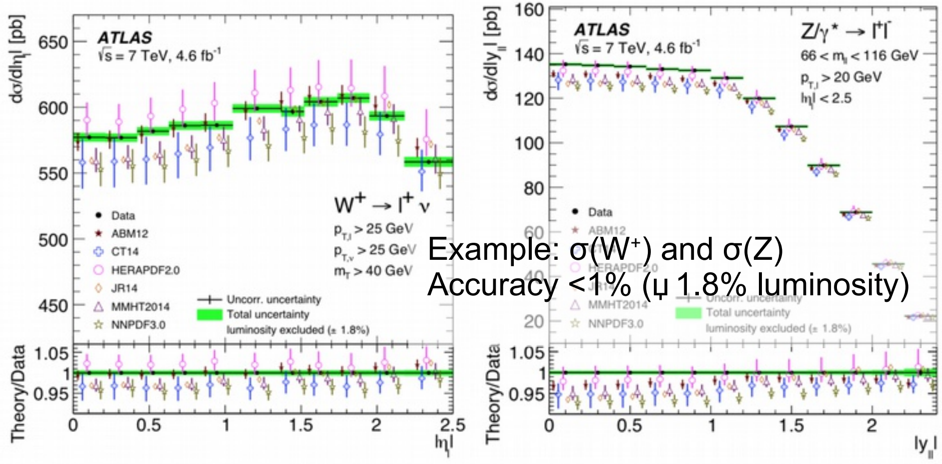




W+charm data

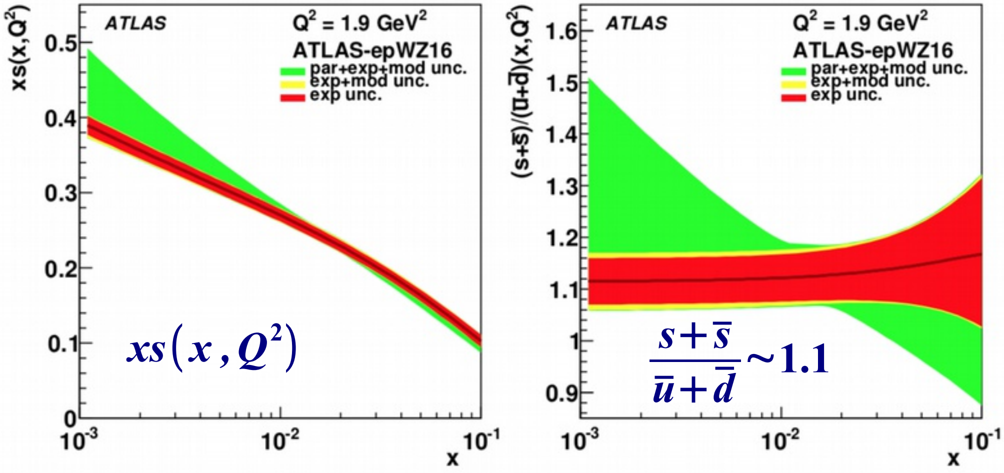
New LHC W and Drell-Yan data

- Recent data: ATLAS √s=7 TeV
- W: single-differential in lepton η
- DY: differential in y_{ll} for three mass regions, forward and central rapidity



Example: σ(W⁺) and σ(Z)
Accuracy <1% (µ 1.8% luminosity)

EPJ C77 (2017) 367 [arXiv:1612.03016]; **WG1(58) 17.4. 12:10**

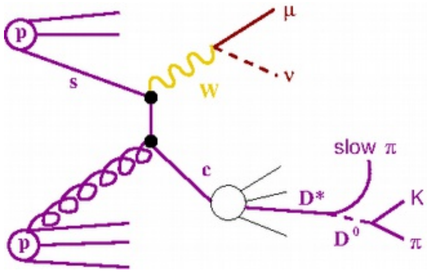


- ATLAS+HERA data PDF fit: confirms unsuppressed strange sea at low/medium x
- PDF parametrisation uncertainties at low-x and high-x are large

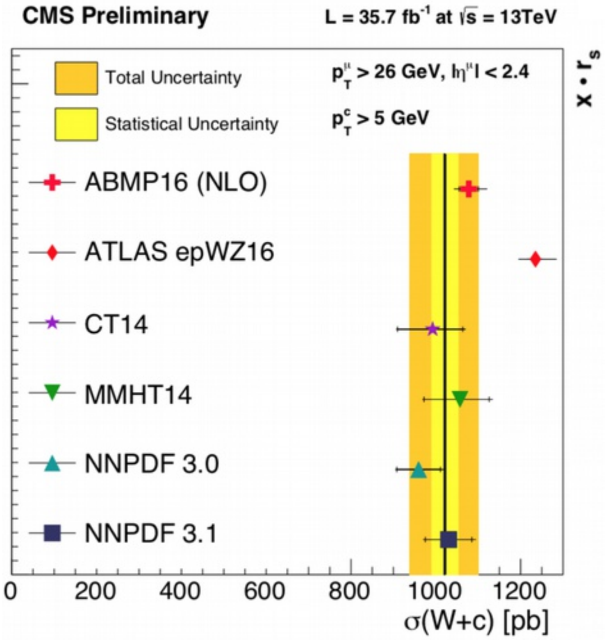
Triple-differential ALTAS DY data are also available:
JHEP 12 (2017) 059 [arXiv:1710.05167]

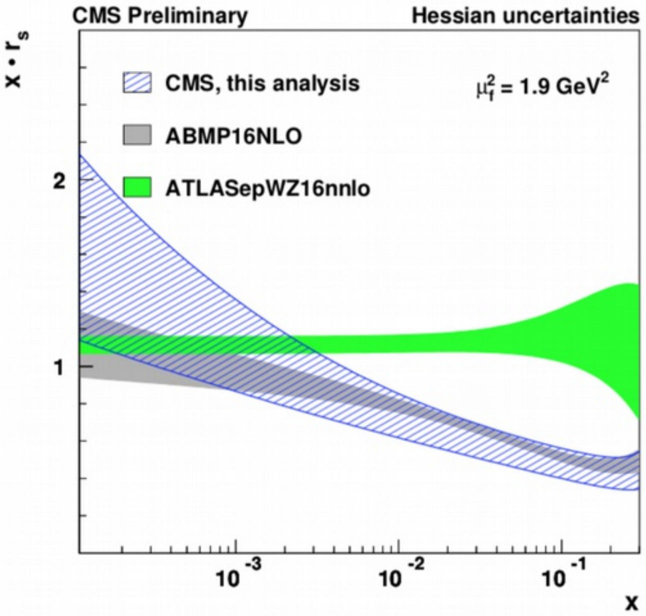
New data on c+W

- New CMS analysis for DIS2018 W+c at √s=13 TeV



- Fully-reconstructed D* mesons
- Direct probe of strangeness in the proton
- Integrated and single-differential $|\eta_\mu|$ cross sections
- PDF fit with HERA, CMS W asymmetry and previous CMS W+c



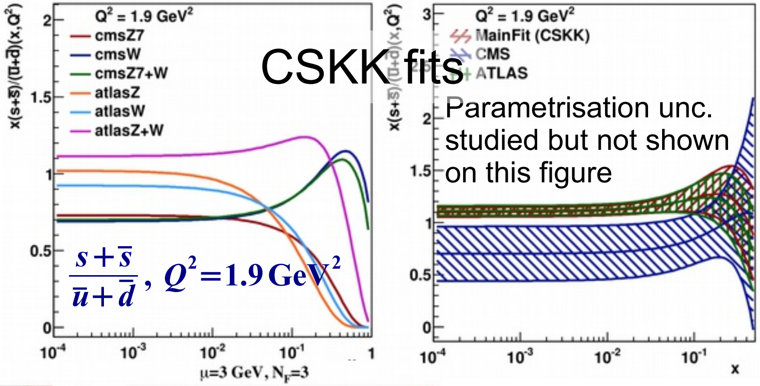


CMS-PAS-SMP-17-014; parallel session talk: **WG1(30) 17.4. 15:40**

New CMS data: not compatible with ATLASepWZ16nnlo central fit. Overlap within parametrisation unc. under study

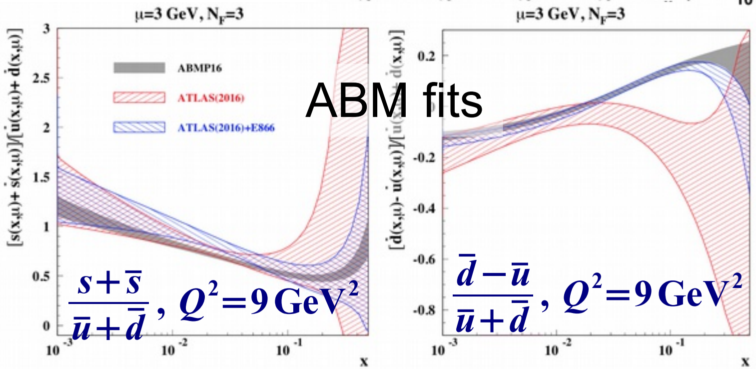
Fits using ATLAS and CMS W+DY data

- Cooper-Sarkar & Wichmann (CSKK fit): compatibility of ATLAS and CMS data
- ABM group: revisit PDF parametrisation and compatibility with other data

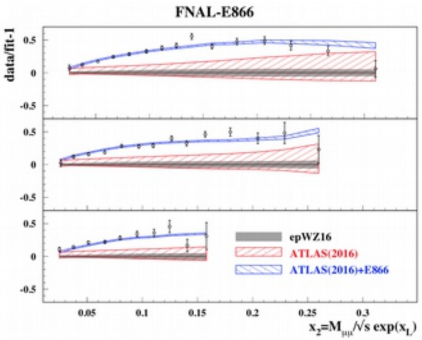


CSKK (using "ATLAS" parametrisation): ATLAS and CMS data are compatible. Fit results in unsuppressed strange sea. Parametrisation and d(bar)-u(bar) are also studied.

- Not shown: NNPDF3.1 also investigates strangeness



Comparison to E866



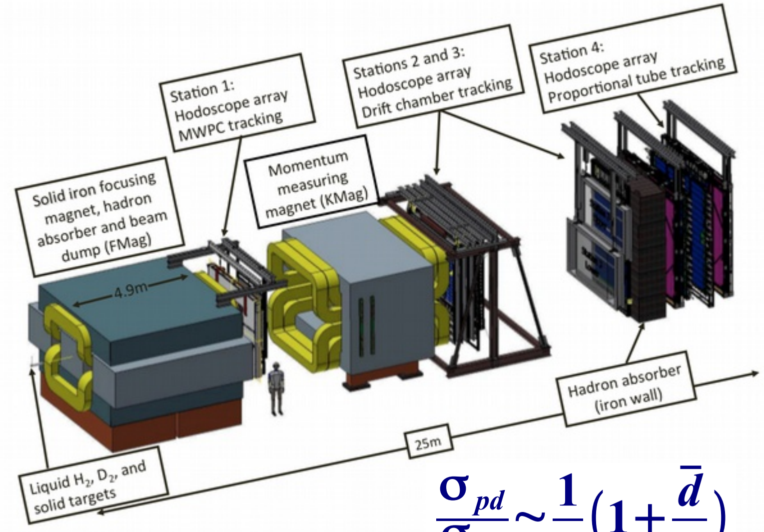
ABM: "ATLAS" central parametrisation is not flexible enough to accommodate E866 [NuSea] data.
have to use different parametrisation and study d(bar)-u(bar) and strangeness together.

→ can improved d(bar)/u(bar) data help?

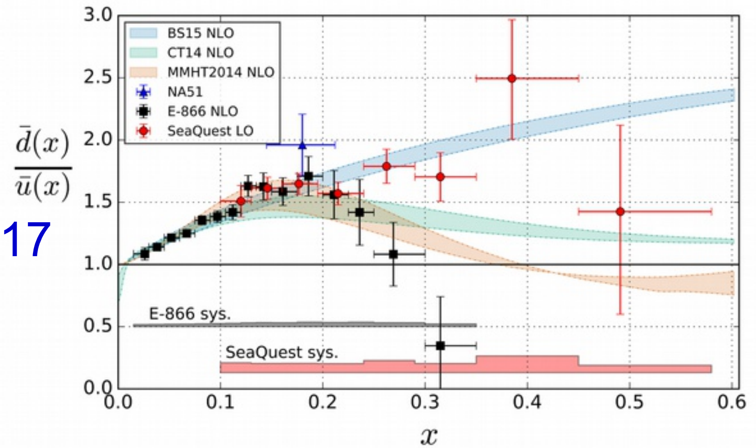
CSKK: arXiv:1803.00968; **WG1(227) 17.4. 15:20**
ABM: Phys.Lett. B777(2018) 134 [arXiv:1708.01067]; **WG1(153) 17.4. 14:00**
NNPDF3.1: EPJ C77 (2017) 663 [arXiv:1706.00428]; **WG1(252) 17.4. 15:00**

SeaQuest preliminary data

- Sea Quest: fixed-target Drell-Yan experiment with hydrogen and deuterium targets
- Recent run finished in summer 2017



$$\frac{\sigma_{pd}}{\sigma_{pp}} \sim \frac{1}{2}\left(1+\frac{\bar{d}}{\bar{u}}\right)$$



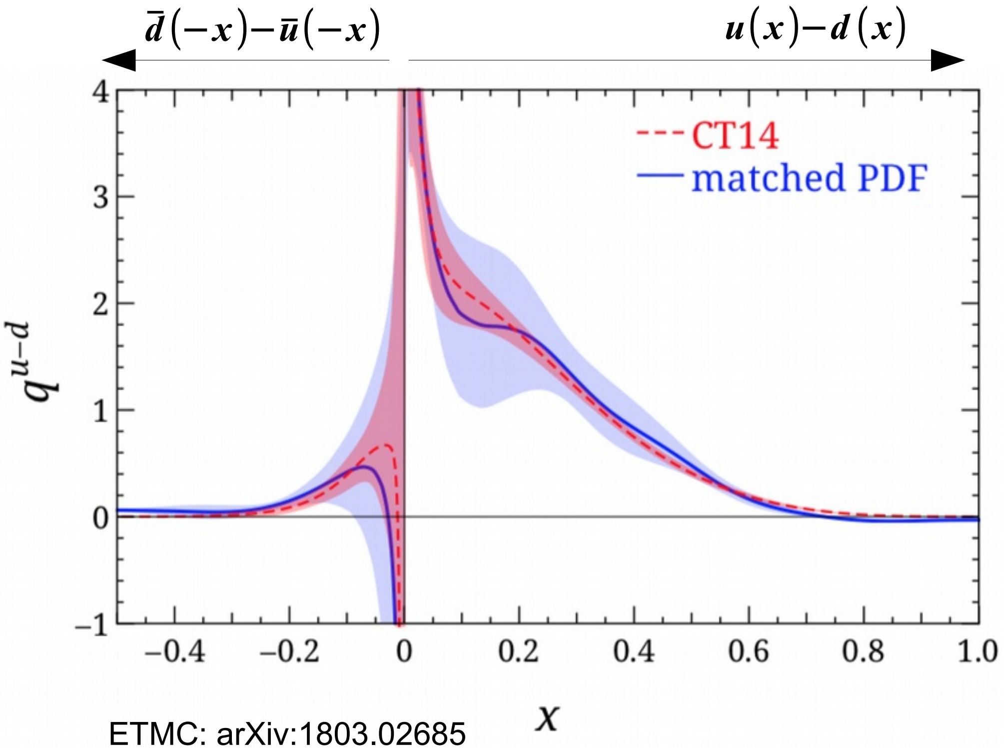
- E866/NuSea: restricted to x<0.35
- SeaQuest/E906: reduced beam energy, higher x
- Only 15% of the full dataset – analysis ongoing

- No evidence for dbar/ubar<1 at high x
- Also recorded: data from heavier targets → better systematics, option to measure EMC effect in DY
- Late 2018: operation with polarized target

NuSeaE866: Phys.Rev. D64 (2001) 052002 [hep-ex:0103030]
SeaQuest detector: arXiv:1706.09990
Preliminary result e.g.: JPS Conf.Proc. 13 (2017) 020051;
Parallel session talk: **WG1(266) 18.4. 12:30**

Lattice QCD

- Recent Lattice calculations reach scales μ~2 GeV
  → compare with fitted PDFs
- Two new results predicting difference u-d and dbar-ubar at large x:
  1) European Twisted Mass Collaboration
  2) LP^3 collaboration
- Shown here: LP^3 results on u-d and dbar-ubar at μ=3 GeV
- Lattice results on unpolarized PDFs may become increasingly interesting for PDF fits in the future

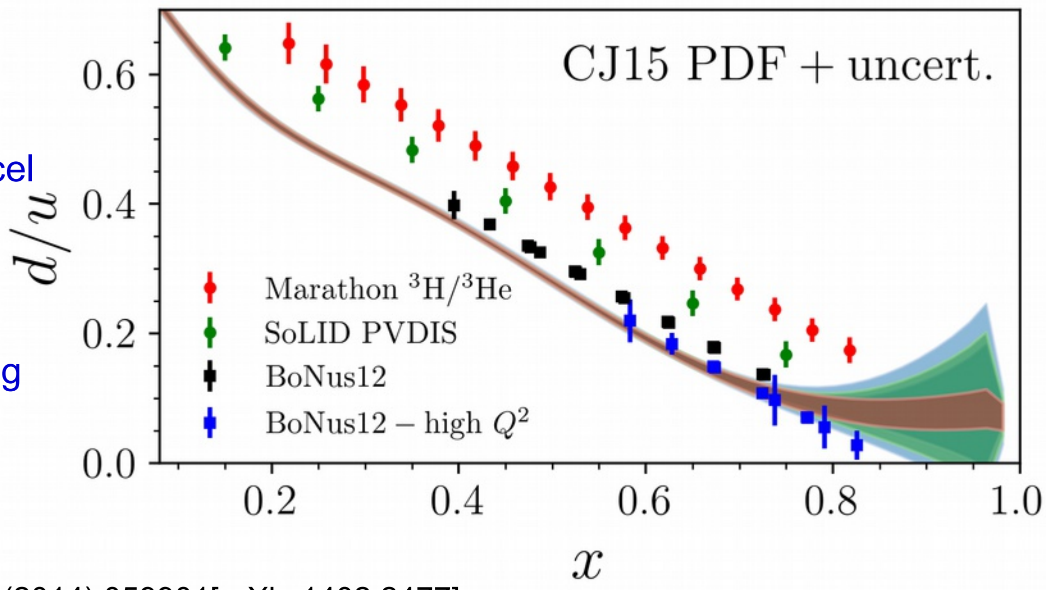


ETMC: arXiv:1803.02685
LP3 collab: arXiv:1803.04393

Ratio d/u from fixed-targed DIS

- JLAB 12 GeV program includes dedicated experiments to improve structure functions and d/u ratio at high x
  - Hall C: precision F_2 for ep and ed scattering
  - MARATHON: ^3H and ^3He, nuclear corrections cancel in ratio
  - BONuS12: effective free neutron target in ed scattering with proton tag
  - SoLID PVDIS: u/d from parity-violating ep scattering
- Fitting group CJ at JLAB, focussing on the use of high-x data in PDFs

Projected precision on u/d from future 12 GeV JLAB experiments



CJ15 PDFs: Phys.Rev. D93 (2016) 114017 [arXiv:1602.03154]
BONuS 5 GeV: Phys.Rev. C89 (2014) 045206, add: Phys.Rev. C90 (2014) 059901[arXiv:1402.2477]
MARATHON: https://www.jlab.org/exp_prog/proposals/10/PR12-10-103.pdf
SoLID PVDIS: https://www.jlab.org/exp_prog/proposals/10/PR12-10-007.pdf
Hall C precision F2: https://www.jlab.org/exp_prog/proposals/10/PR12-10-002.pdf

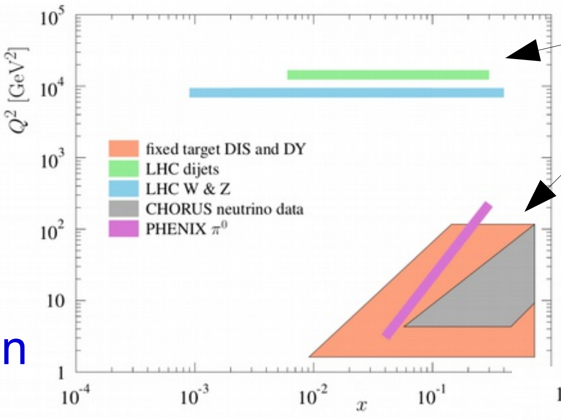
Parallel session talks:
BONuS12: WG7(261) 18.4. 10:24
JLAB 12GeV: WG7(255) 18.4. 16:54

Nuclear PDFs

Nuclear PDF fits

- Parton content of a heavy target with charge Z and atomic number A?
- Heavy target is composed of bound protons and neutrons.
- Given isospin asymmetry, bound neutron is inferred from bound proton PDFs
- Bound proton is taken from free proton PDFs with A-dependent modifications
- Recent nuclear PDF fits: EPPS16, nCTEQ

nCTEQ: Phys.Rev. D93 (2016) 085037 [arXiv:1509.00792]
EPPS16: EPJ C77 (2017) 163 [arXiv:1612.05741]

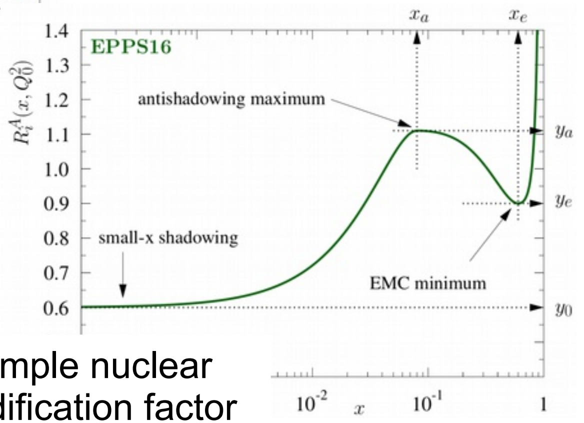


LHC data (recent fits)

Fixed-target DIS and DY experiments: backbone of nuclear PDF fits

EPPS16: free proton from CT14NLO

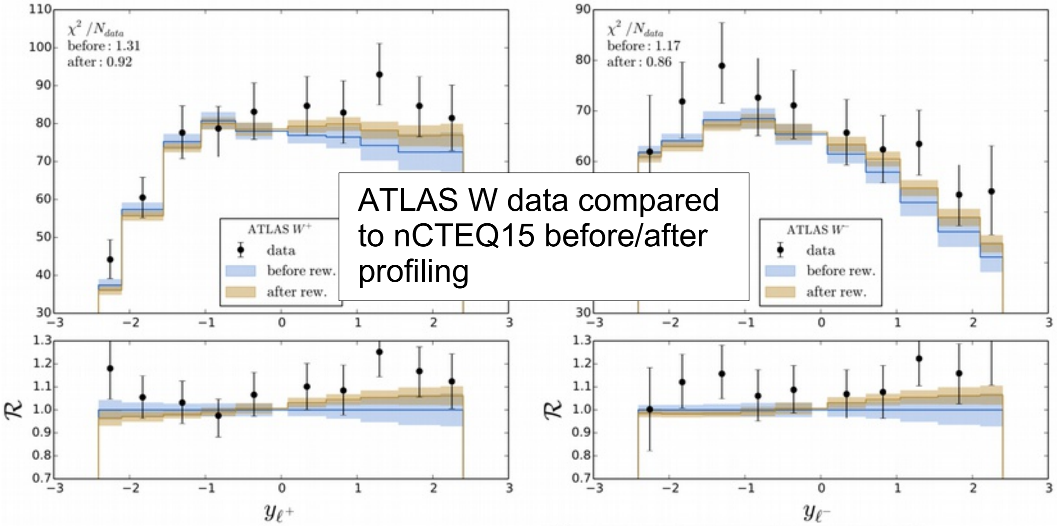
nCTEQ: free proton from CTEQ6.1



Example nuclear modification factor

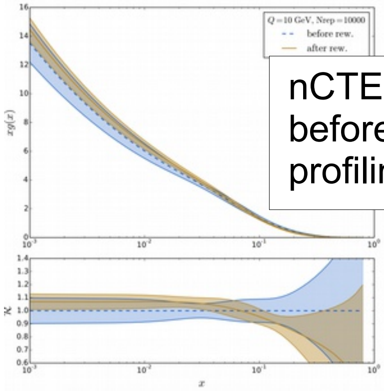
LHC data in nuclear PDF fits

- Collider data in nuclear PDF fits: production of W and Z is theoretically cleanest
- Jet data add constraints on gluon
- EPPS: LHC jet, W and Z data from pPb [5.02] ATLAS & CMS
- nCTEQ+LHC: W,Z data pPb [5.02] and PbPb [2.76] ATLAS,ALICE,CMS,LHCb



ATLAS W data compared to nCTEQ15 before/after profiling

LHC data add important constraints to the nuclear PDFs



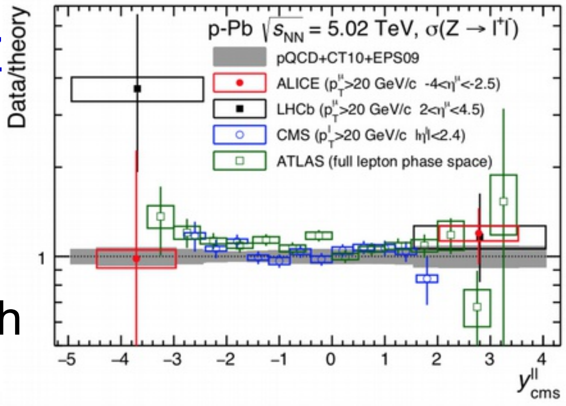
nCTEQ gluon before/after profiling

nCTEQ15+LHC W,Z: EPJ C77 (2017) 488 [arXiv:1610.02925]; **WG1(155) 18.4. 11:50**
EPPS16: EPJ C77 (2017) 163 [arXiv:1612.05741]

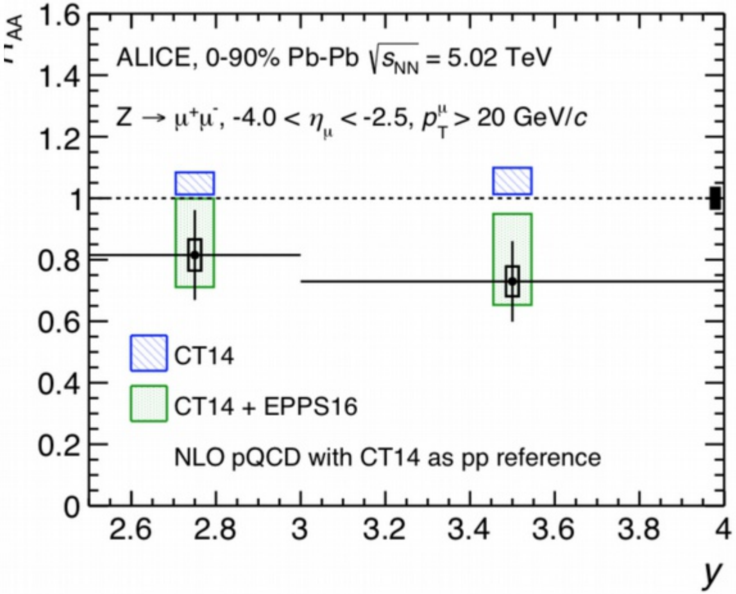
New LHC W and Z data in pPb and PbPb

Alice: fwd production of W and Z

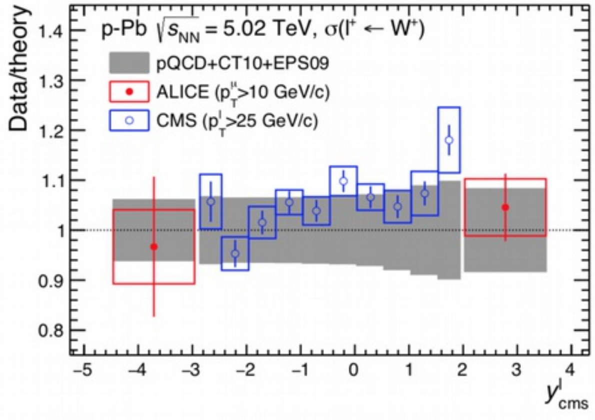
- Forward W,Z in pPb
- Forward Z in PbPb

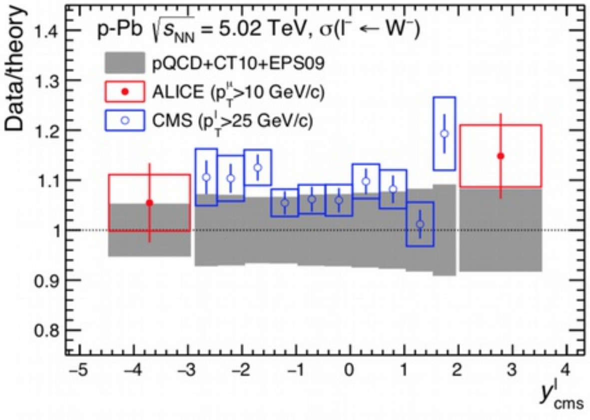


Z in PbPb 5.02TeV: confirms prediction with nuclear modification<1



W,Z in pPb: kinematic reach beyond other experiments





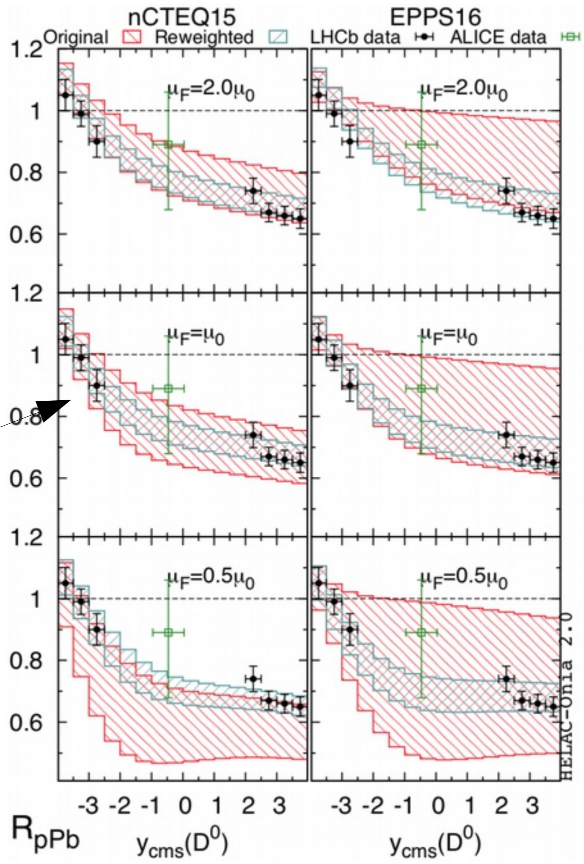
pPb W,Z: JHEP 1702 (2017) 077 [arXiv:1611.03002]
PbPb Z: Phys.Lett. B780 (2018) 372 [arXiv:1711.10753]

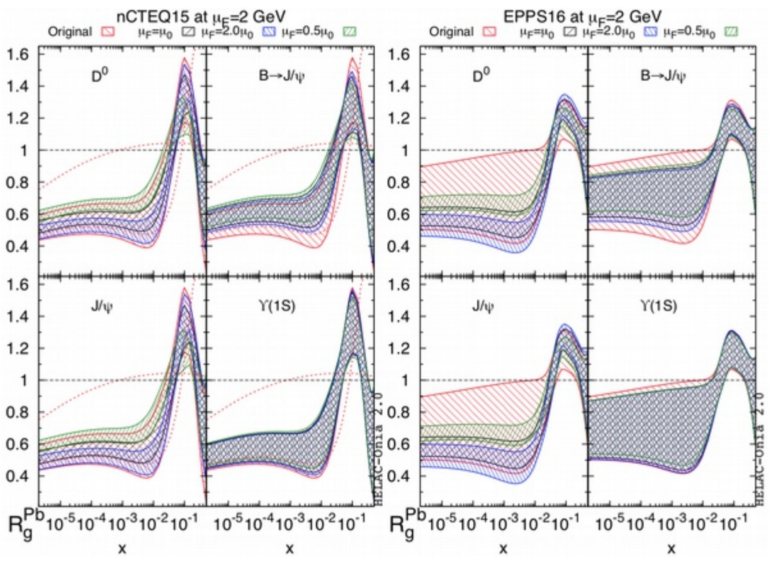
Collider data beyond W,Z in nuclear PDFs

- Recent study by Kusina et al, on the use of heavy-flavour probes to constrain low-x gluon
- Includes many datasets from LHC and RHIC

Data add sizable constraints (shown here: prompt D^0, LHCb and ALICE data)

Kusina et al.: arXiv:1712.07024
WG1(116) 18.4. 11:30





Extracted gluon modification factors are similar for all probes

Gluon nuclear modification factors are constrained in both shadowing and antishadowing regime

Summary

- Many measurements rely on a precise knowledge of the proton PDFs
- The field is driven both by new data and by theory advances
- LHC data are becoming increasingly important for constraining PDFs: Drell-Yan and W, top, jets, charm, etc
- "Old" experiments such as HERA continue to improve their results: charm and beauty combination, DIS jets with NNLO calculations
- Several fixed-target experiments at lower energies are coming soon. pp and pA: SeaQuest/E906, ep and eA: JLAB (BONuS, SoLID, …)
- Global analyses are preferentially done in NNLO – not yet available for all measurements of interest
- Nuclear PDF analyses start to use LHC data – not covered in detail here

Backup

ATLAS jet data: comparison to theory

- Quantitative comparisons of ATLAS 14TeV jet data to theory (various PDFs)
- Dijet theory in good agreement with most PDFs
- Inclusive jets are poorly described by all PDFs (in some bins of η)

Inclusive jets, all bins together

χ^2/dof all $\|y\|$ bins	CT14	MMHT 2014	NNPDF 3.0	HERAPDF 2.0	ABMP16
p_T^{max}	419/177	431/177	404/177	432/177	475/177
p_T^{jet}	399/177	405/177	384/177	428/177	455/177

Inclusive jets differential in η

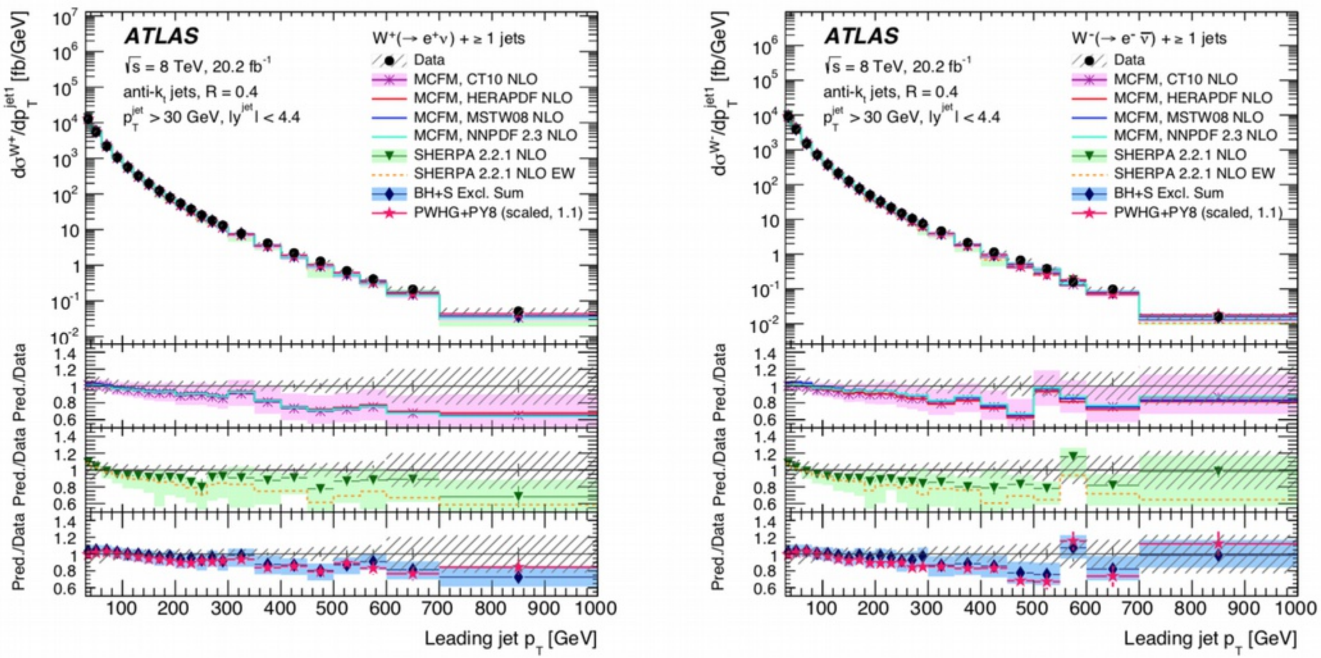
Rapidity ranges	P_{obs} CT14	MMHT 2014	NNPDF 3.0	HERAPDF 2.0	ABMP16
p_T^{max}					
$\|y\| < 0.5$	67%	65%	62%	31%	50%
$0.5 \leq \|y\| < 1.0$	5.8%	6.3%	6.0%	3.0%	2.0%
$1.0 \leq \|y\| < 1.5$	65%	61%	67%	50%	55%
$1.5 \leq \|y\| < 2.0$	0.7%	0.8%	0.8%	0.1%	0.4%
$2.0 \leq \|y\| < 2.5$	2.3%	2.3%	2.8%	0.7%	1.5%
$2.5 \leq \|y\| < 3.0$	62%	71%	69%	25%	55%
p_T^{jet}					
$\|y\| < 0.5$	69%	67%	66%	30%	46%
$0.5 \leq \|y\| < 1.0$	7.4%	8.9%	8.6%	3.4%	2.0%
$1.0 \leq \|y\| < 1.5$	69%	62%	68%	45%	54%
$1.5 \leq \|y\| < 2.0$	1.3%	1.6%	1.4%	0.1%	0.5%
$2.0 \leq \|y\| < 2.5$	8.7%	6.6%	7.4%	1.0%	3.6%
$2.5 \leq \|y\| < 3.0$	65%	72%	72%	28%	59%

Dijets

y^* ranges	P_{obs} CT14	MMHT 2014	NNPDF 3.0	HERAPDF 2.0	ABMP16
$y^* < 0.5$	79%	59%	50%	71%	71%
$0.5 \leq y^* < 1.0$	27%	23%	19%	32%	31%
$1.0 \leq y^* < 1.5$	66%	55%	48%	66%	69%
$1.5 \leq y^* < 2.0$	26%	26%	28%	9.9%	25%
$2.0 \leq y^* < 2.5$	43%	35%	31%	4.2%	21%
$2.5 \leq y^* < 3.0$	45%	46%	40%	25%	38%
all y^* bins	8.1%	5.5%	9.8%	0.1%	4.4%

ATLAS W+jet

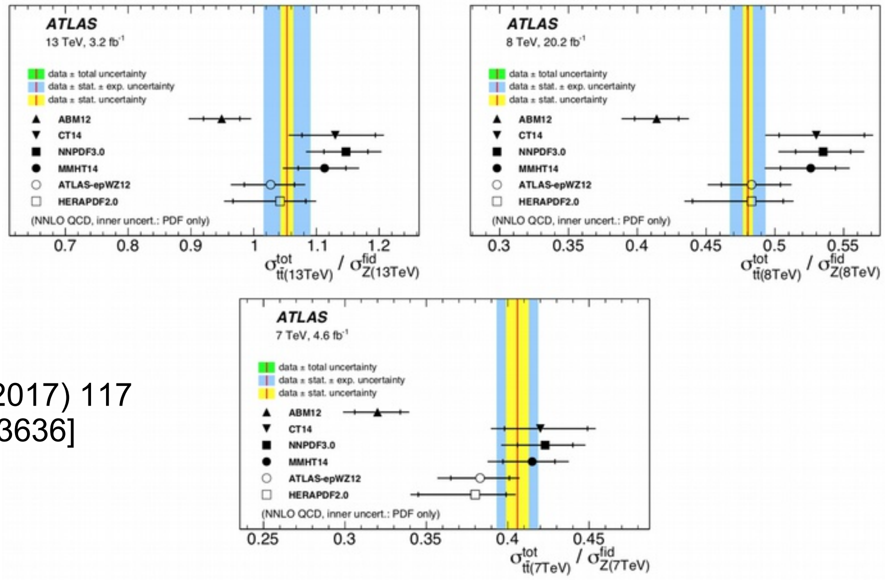
- W+jets and W-asymmetry+jets, √s=8 TeV
- Sensitive to QCD models, less so to PDFs
- Example: PDF prediction wrt jet p_T

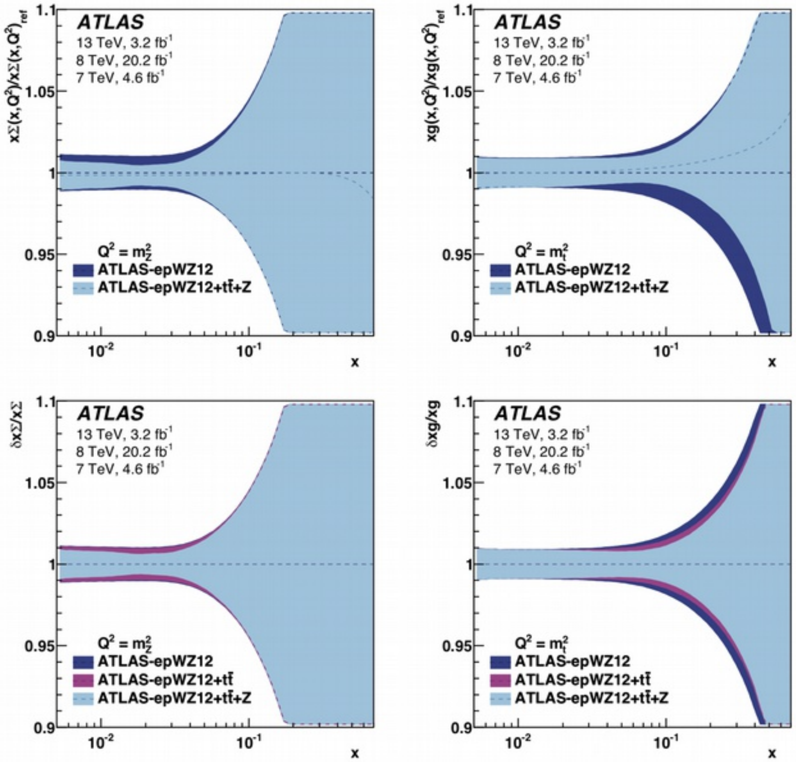


arXiv:1711.03296

ATLAS top pair to Z cross section ratio

- Ratio of tt(bar) to Z cross sections at three centre-of-mass energies
- Already shown at DIS2017
- Adds PDF sensitivity over ATLAS-epWZ12 fit



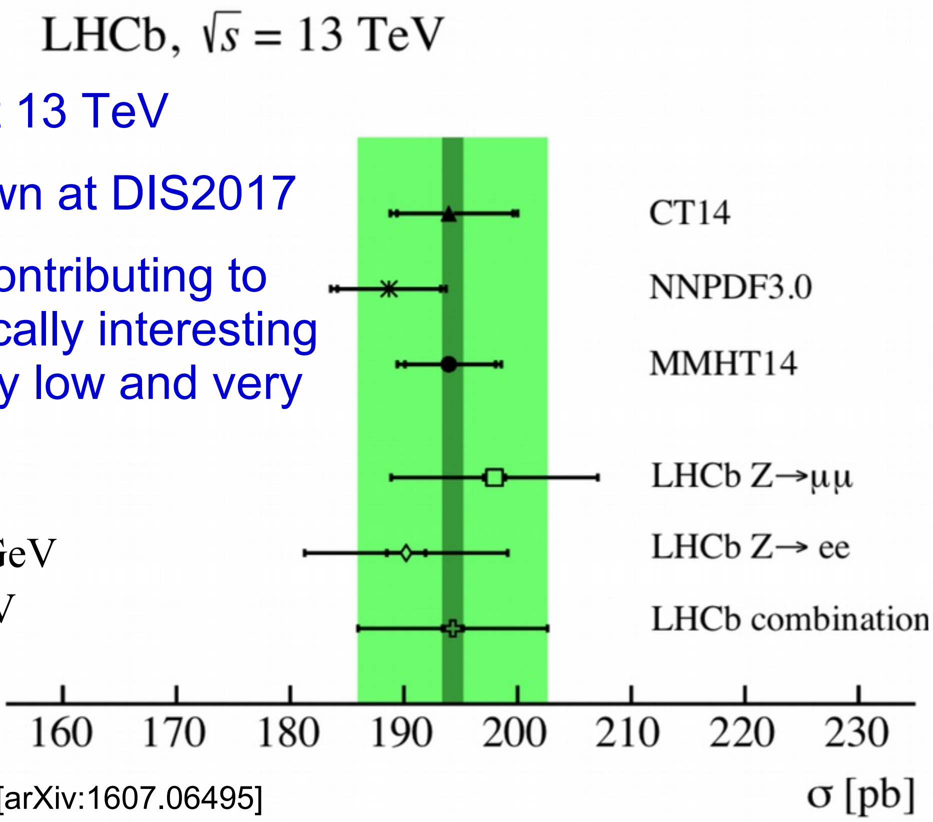


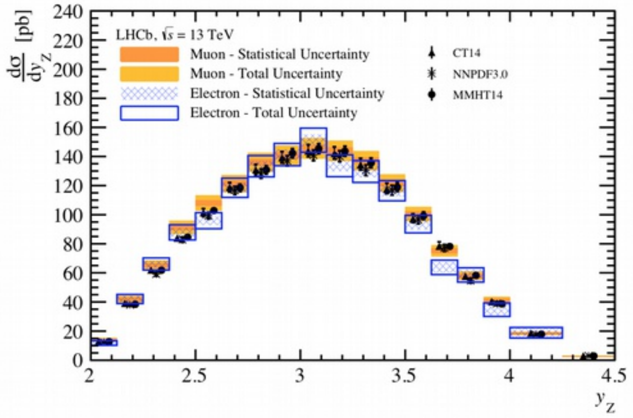
JHEP 1702 (2017) 117
[arXiv:1612.03636]

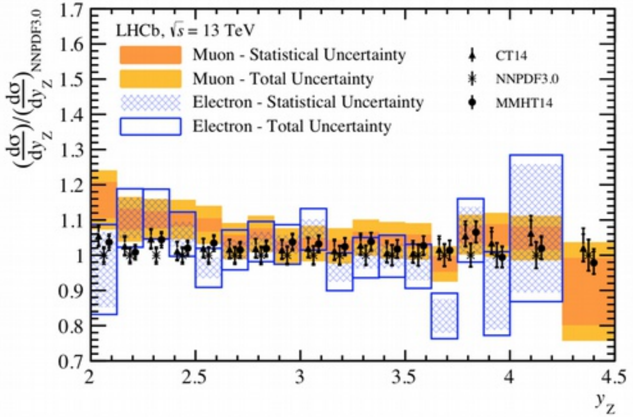
LHCb forward Z

- Forward Z at 13 TeV
- Already shown at DIS2017
- In PDF fits contributing to the kinematically interesting region of very low and very high x

$$60 < m_{\ell\ell} < 120 \text{ GeV}$$
$$p_{T,\ell} > 20 \text{ GeV}$$
$$2 < \eta_\ell < 4.5$$



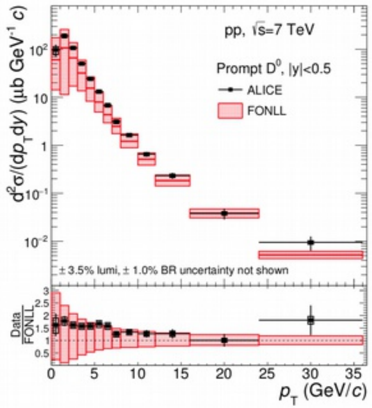


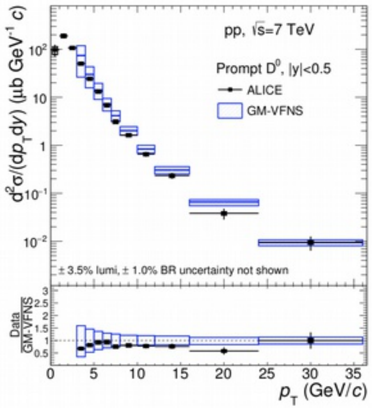


JHEP 1609 (2016) 136 [arXiv:1607.06495]

ALICE D mesons in pp

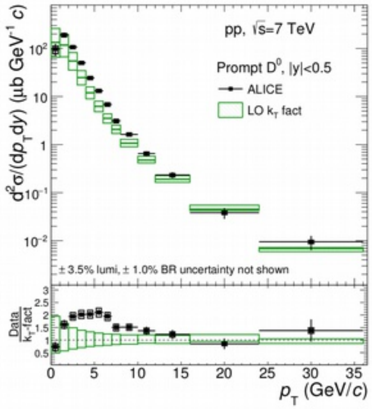
- Measure D0,D+,D*+,Ds+ at √s=7 TeV
- Reach to very low p_T
- Theory has large scale uncertainties
- Possibility to constrain PDFs in ratios to future data at different √s





D⁰ is measured down to p_T=0

Theory uncertainties from scale variation dominate

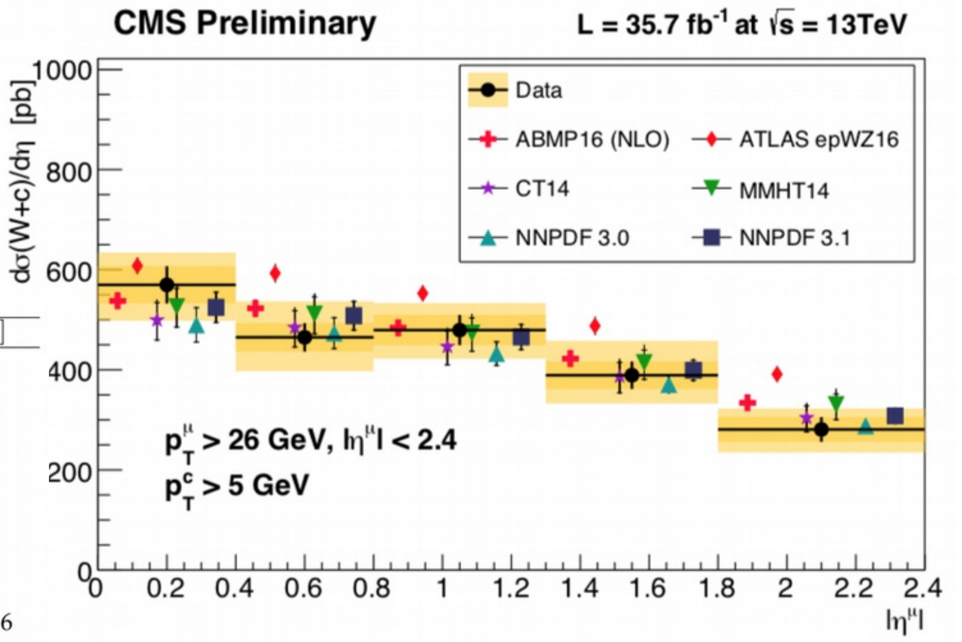


EPJ C77 (2017) 550 [arXiv:1702.00766]

CMS new result on W+c

- Using high-statistics 13 TeV data
- Uncertainty dominated by charm fragmentation and signal MC statistics
- Differential in $|\eta_\mu|$ → enhances PDF sensitivity

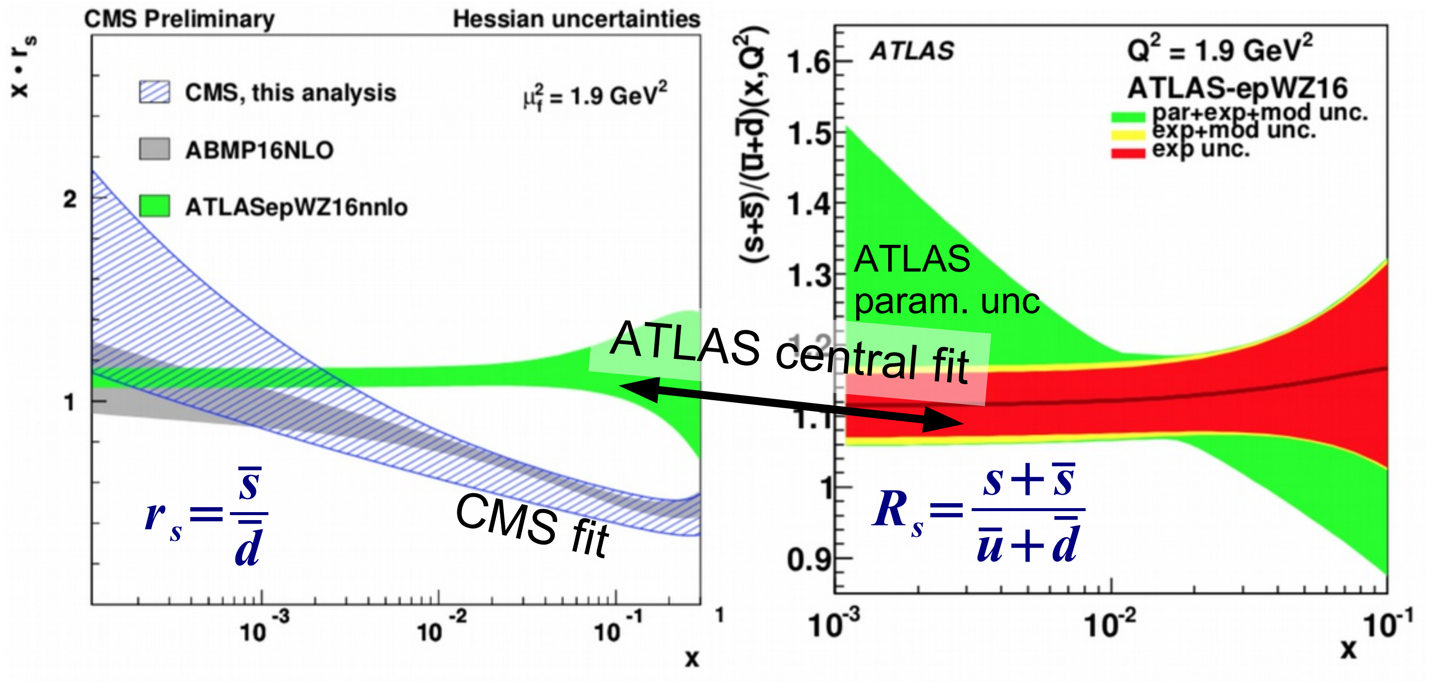
	[0, 2.4]	[0, 0.4]	[0.4, 0.8]	[0.8, 1.3]	[1.3, 1.8]	[1.8, 2.4]
Lumi	±2.5	±2.5	±2.5	±2.5	±2.5	±2.5
Tracking	±2.3	±2.3	±2.3	±2.3	±2.3	±2.3
Branching	±2.4	±2.4	±2.4	±2.4	±2.4	±2.4
Muons	±1.2	±1.2	±1.2	±1.2	±1.2	±1.2
N_{sel} determination	±1.5	±1.5	±1.5	±1.5	±1.5	±1.5
$D^*(2010)^\pm$ kinematics	±0.5	±0.5	±0.5	±0.5	±0.5	±0.5
Bg normalization	± 0.5	+0.9/-0.8	+1.9/-0.8	+1.4/-0.5	+0.8/-1.0	-0.6
p_T^{miss}	+0.7/-0.9	+0.4/-1.2	+1.3/-0.3	+1.1/-1.0	-2.6	+1.5
Pile Up	+2.0/-1.9	+0.4/-0.5	+2.9/-3.0	+2.0/-1.9	+4.6/-5.1	+2.7/-2.6
PDF	±1.2	±1.3	±0.9	±1.4	±1.5	±1.7
Sec. Vtx.	-1.1	+1.3	-1.2	-1.5	-2.7	-2.5
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



CMS-PAS-SMP-17-014;
parallel session talk:
WG1(30) 17.4. 15:40

Comparison: CMS W+c and ATLAS DY

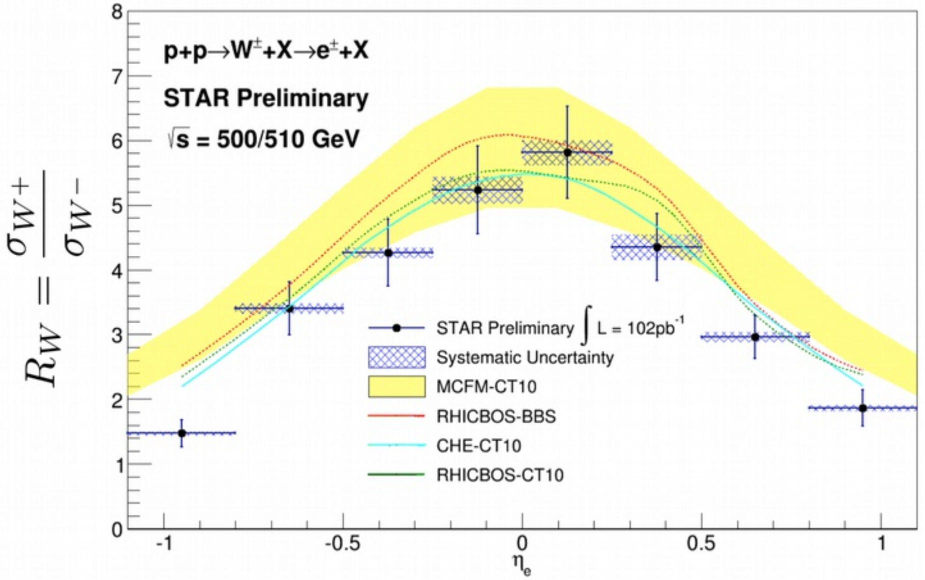
- PDF fit by ATLAS, using 2016 W+DY data
- PDF fit by CMS, using W+c data
- Differences covered by parametrisation uncertainties?



ATLAS: EPJ C77 (2017) 367 [arXiv:1612.03016]; **WG1(58) 17.4. 12:10**
CMS: CMS-PAS-SMP-17-014; **WG1(30) 17.4. 15:40**

RHIC preliminary data on W

- RHIC measurements of W production: polarisation and charge asymmetries
- Accessible region of large x complements LHC and fixed-target measurements
- Only 15% of the available data have been analyzed so far

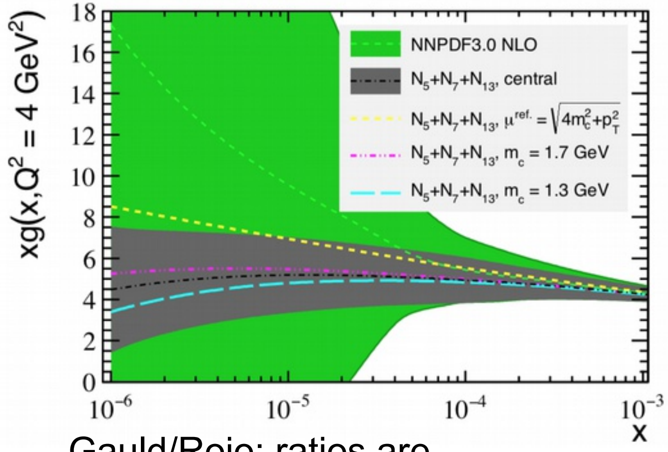


Shown at INT Workshop, The Flavor Structure of Nucleon Sea. Bernd Surrow, October 2017

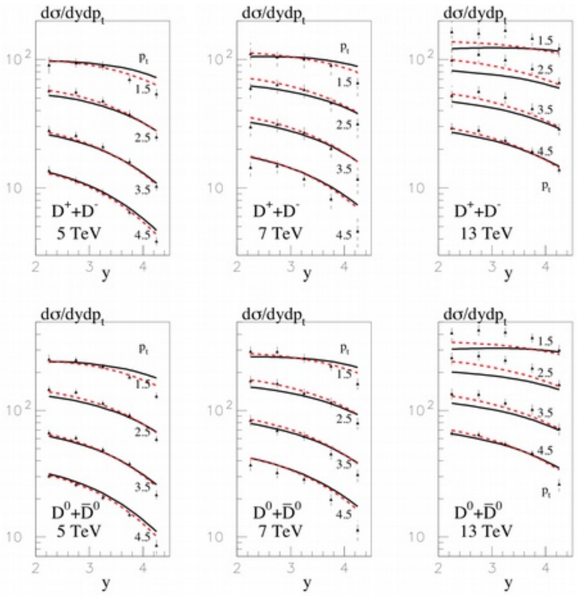
Parallel session: **WG6(128) 18.4. 9:25**

Gluon at very low-x: LHCb charm data

- LHCb spectrometer: large rapidities → low-x
- Constrain gluon at x down to 10^{-6} with LHCb open charm data
- Recent works by Gauld/Rojo (cross section ratios), Oliveira/Martin/Ryskin (absolute cross sections)



Gauld/Rojo: ratios are compatible with global PDF fits and add substantial constraints



Oliveira et al: fit with two-parameters (red) describes LHCb data but does not easily match global PDF fit

Gauld/Rojo: Phys.Rev.Lett. 118 (2017) 072001 [arXiv:1610.09373]
Oliveira/Martin/Ryskin: arXiv:1712.06834
LHCb 5 TeV D mesons: JHEP 1706 (2017) 147 [arXiv:1610.02230]; **WG1+5(49) 18.4. 15:10**
LHCb 13 TeV D mesons: JHEP 1603 (2016) 159, Erratum: JHEP 1609 (2016) 013, Erratum: JHEP 1705 (2017) 074 [arXiv:1510.01707]
LHCb 7 TeV D mesons: Nucl.Phys. B871 (2013) 1 [arXiv:1302.2864]