Status of Parton Density Function measurements.
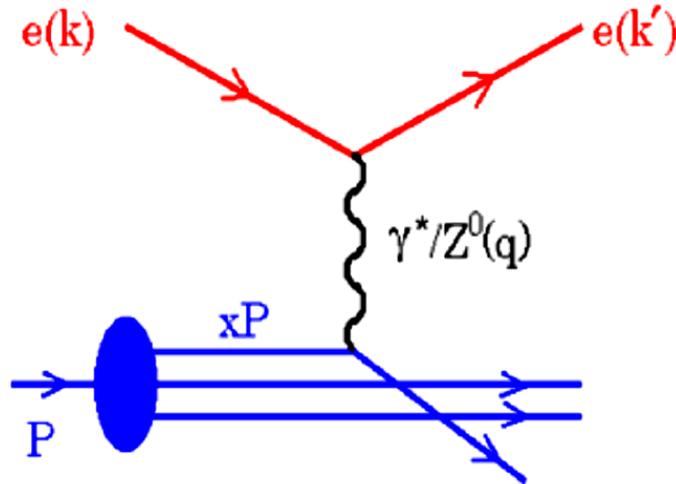
S. Glazov

DESY

ICHEP 2012, Melbourne.

Proton structure probe

Neutral current Deep Inelastic Scattering (DIS) cross section:

$$\frac{\mathrm{d}^2\sigma^{\pm}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{2\pi\alpha^2 Y_+}{Q^4 x}\sigma_r^{\pm} =$$

$$= \frac{2\pi\alpha^2 Y_+}{Q^4 x}\left[F_2(x, Q^2) - \frac{y^2}{Y_+}F_L(x, Q^2) \mp \frac{Y_-}{Y_+}xF_3\right]$$

where factors $Y_{\pm} = 1 \pm (1 - y)^2$ and y^2 define polarisation of the exchanged boson and $y = Q^2/(S\, x)$.

Kinematics is determined by Q^2 and Bjorken x.

At leading order:
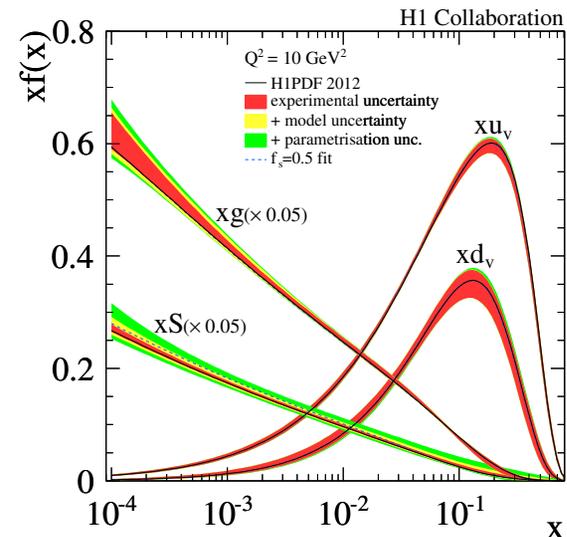
$$F_2 = x\sum e_q^2(q(x) + \bar{q}(x))$$
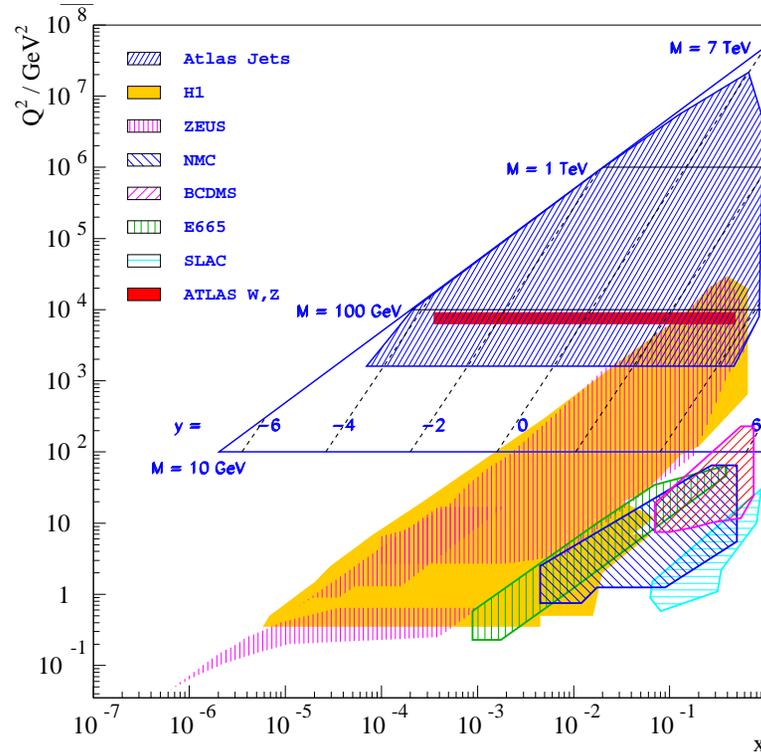
$$xF_3 = x\sum 2e_q a_q(q(x) - \bar{q}(x))$$

$$\sigma_{CC}^+ \sim x(\bar{u} + \bar{c}) + x(1 - y)^2(d + s)$$

$$\sigma_{CC}^- \sim x(u + c) + x(1 - y)^2(\bar{d} + \bar{s})$$

$xg(x)$ — from F_2 scaling violation, jets and F_L

2

Cross sections at the LHC

The cross sections are given by a convolution of the parton densities and coefficient functions, $\sim x_1 f_1(x_1, \mu)\, x_2 f_2(x_2, \mu)\, \hat{\sigma}(x_1, x_2, \mu)$. Leading order relation between rapidity y and x_1, x_2: $x_{1,2} = \frac{M_{\ell\ell}}{\sqrt{S}} e^{\pm y_{\ell\ell}}$.

Kinematic range of the LHC is covered by the HERA measurements. LHC measurements check validity of pQCD, provide information for PDF decomposition.

$\rightarrow$ PDFs have on average > 1.3 citation per LHC paper (estimated based on study of G. Salam, La Thuile 2012)

3

PDF Sets

Several groups determine PDFs in fits to various data samples:

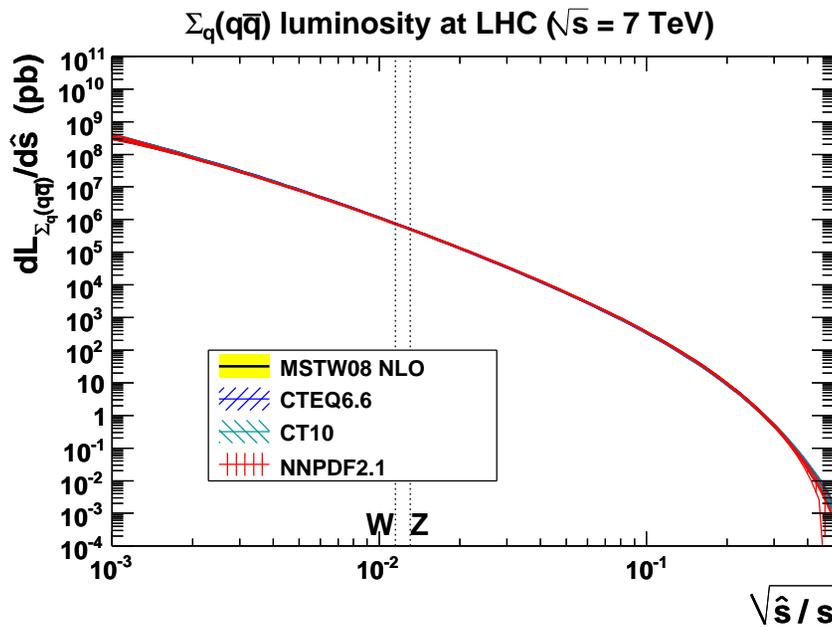|	MSTW08	CTEQ6.6/CT10	NNPDF2.1/2.3	HERAPDF1.0/1.5	ABKM09/ABM11	GJR08/JR09
Evolution	LO	LO	LO	—	—	—
Order	NLO	NLO	NLO	NLO	NLO	NLO
	NNLO	NNLO	NNLO	NNLO	NNLO	NNLO
HF Scheme	RT-GMVF	ACOT-GMVF	FONLL-GMVF	RT-GMVF (*)	BMSN-FFNS	FFNS
α_S NLO	0.120	0.118(f)	0.1191(b)	0.1176(f)	0.118	0.1135
α_S NNLO	0.1171	0.118(f)	0.1174(b)	0.1176(f)	0.1135	0.1124
HERA DIS	not up-to-date	+	+	+/prelim.	partial	+
Fixed target DIS	+	+	+	-	+	+
DY	+	+	+	-	+	+
Tevatron W,Z	some	some	some	-	some	some
Tevatron jets	some	+	+	-	some	some
LHC	-	-	*W,Z*+jets (NNPDF2.3)	-	-	-

The analyses differ in many areas:

- Higher orders counting (e.g. F_L), heavy flavour corrections, α_S treatment, EW corrections, extra theory assumptions.

- Inclusion of datasets, accounting for data-data-theory tensions.

- PDF parameterisation.

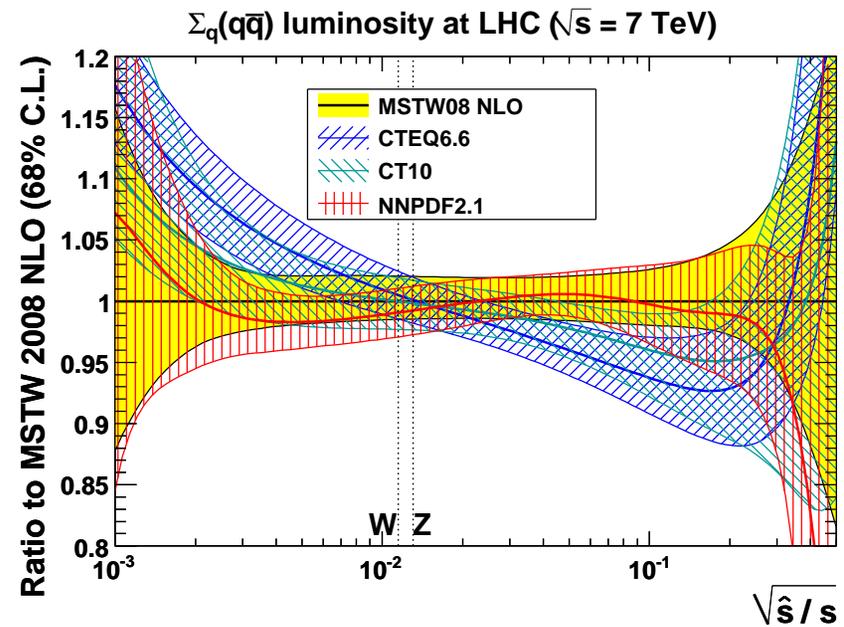PDF4LHC meetings is a forum to discuss/understand these differences.
HERAFitter, open source PDF fit project, to study them in details.

arXiv:1101.0536, arXiv:1101.0538

4

Cross-section predictions for the LHC

$\Sigma_q(q\bar{q})$ luminosity at LHC ($\sqrt{s}$ = 7 TeV)

$\Sigma_q(q\bar{q})$ luminosity at LHC ($\sqrt{s}$ = 7 TeV)

- MSTW08 NLO
- CTEQ6.6
- CT10
- NNPDF2.1

G. Watt (March 2011)

(http://mstwpdf.hepforge.org/pdf4lhc/partonlumi7TeVnlo.html), by G. Watt.

- $q\bar{q}$ luminosity, mostly relevant for DY (W, Z production) total cross section, S-channel processes.

- Overall good agreement between predictions over many orders of magnitude. However differences up to 10% level for the ratios.

For $M_h = 126$ GeV, $\sqrt{\hat{s}/s} \approx 0.02$ which corresponds to Bjorken-x of the central Higgs production.

5

Cross-section predictions at the LHC: Higgs

- Uncertainties for the dominant $gg \to H$ process are mostly from gluon density and α_S. VBF process given at LO by $qq \to Hqq$ has smaller uncertainties.

- Overall $\sim 10\%$ agreement for the same α_S. Somewhat larger uncertainty for HERAPDF since no jet data are included.
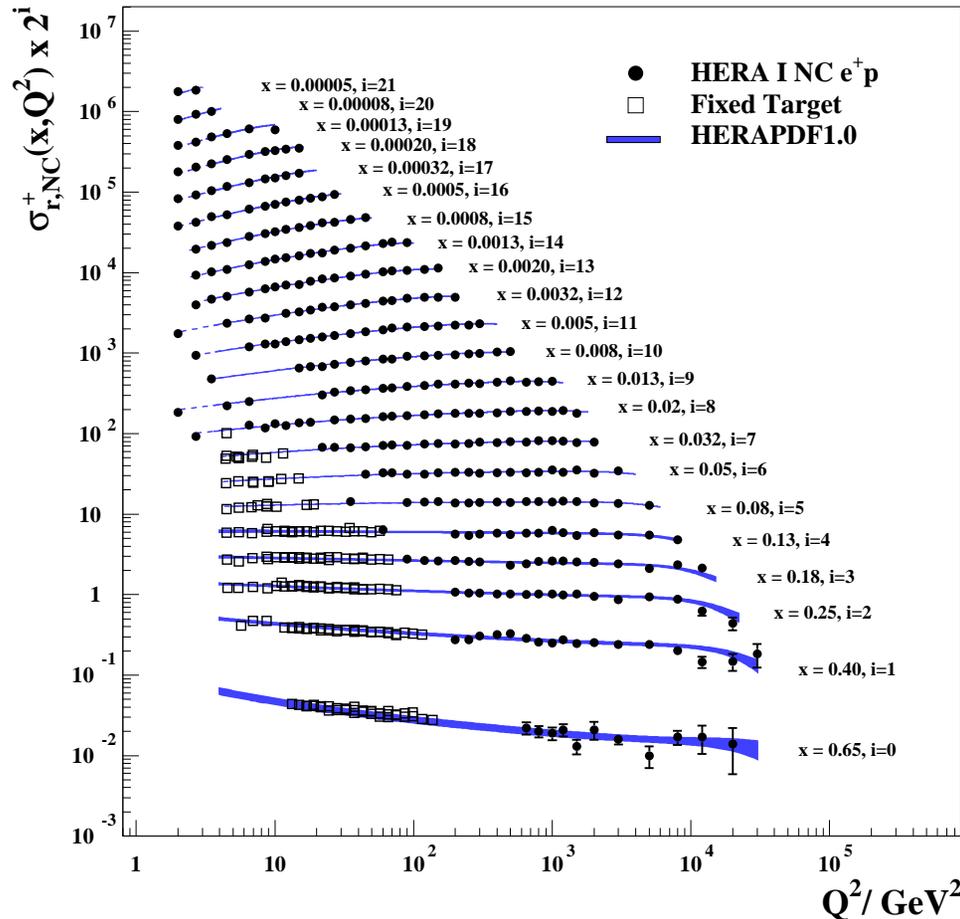

G. Watt, http://mstwpdf.hepforge.org/pdf4lhc/ringberg
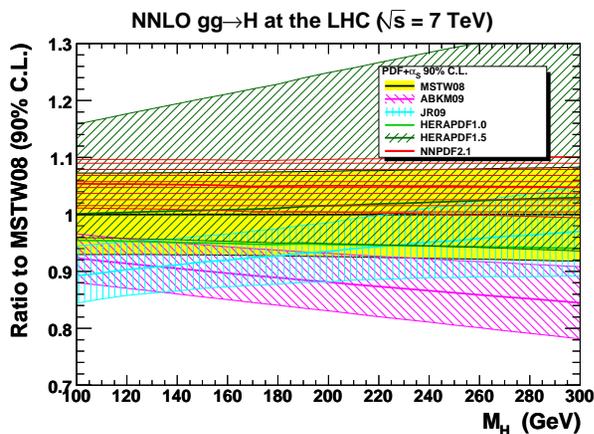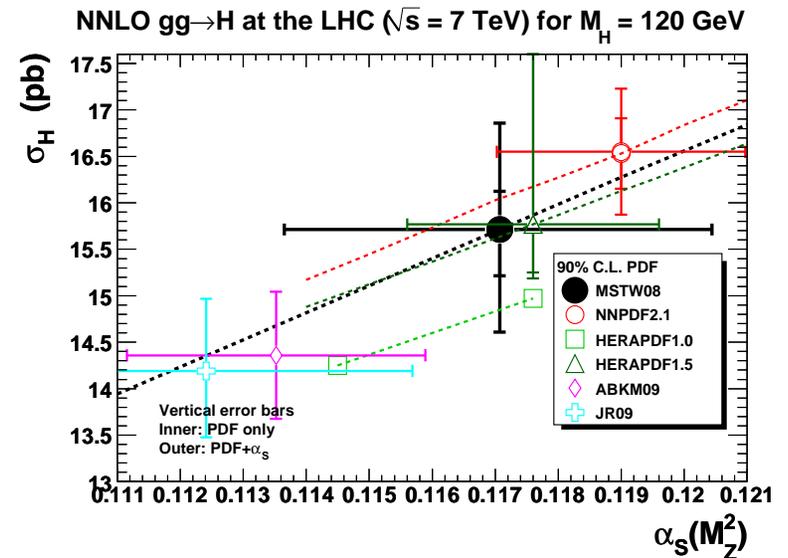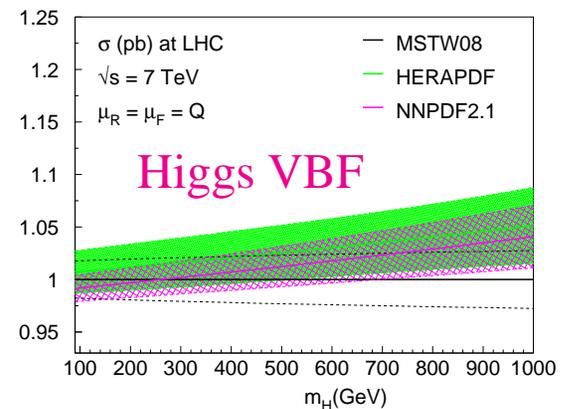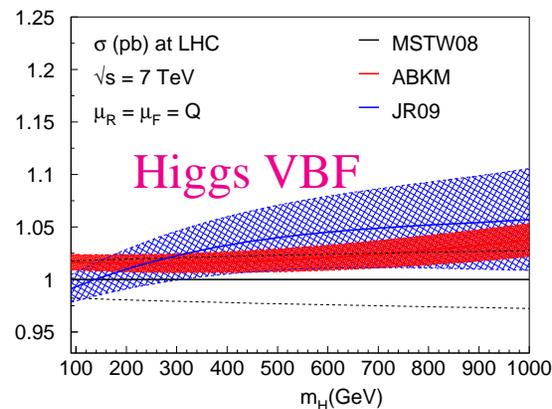
P. Bolzoni, *et. al.* Phys. Rev. D 85, 035002 (2012), Anastasiou, *et. al.* arXiv:1202.3638.

6

HERAPDF1.0 fit

H1 and ZEUS

Combination of the published H1/ZEUS data collected at HERA-I for CC,NC, $e^{\pm}p$ mode. 14 publications, 1402 input and 741 output σ_r measurements, 110 correlated experimental error sources. For NC e^+p, $6 \cdot 10^{-7} < x < 0.65$ and $0.045 < Q^2\ 30000\,\mathrm{GeV}^2$.
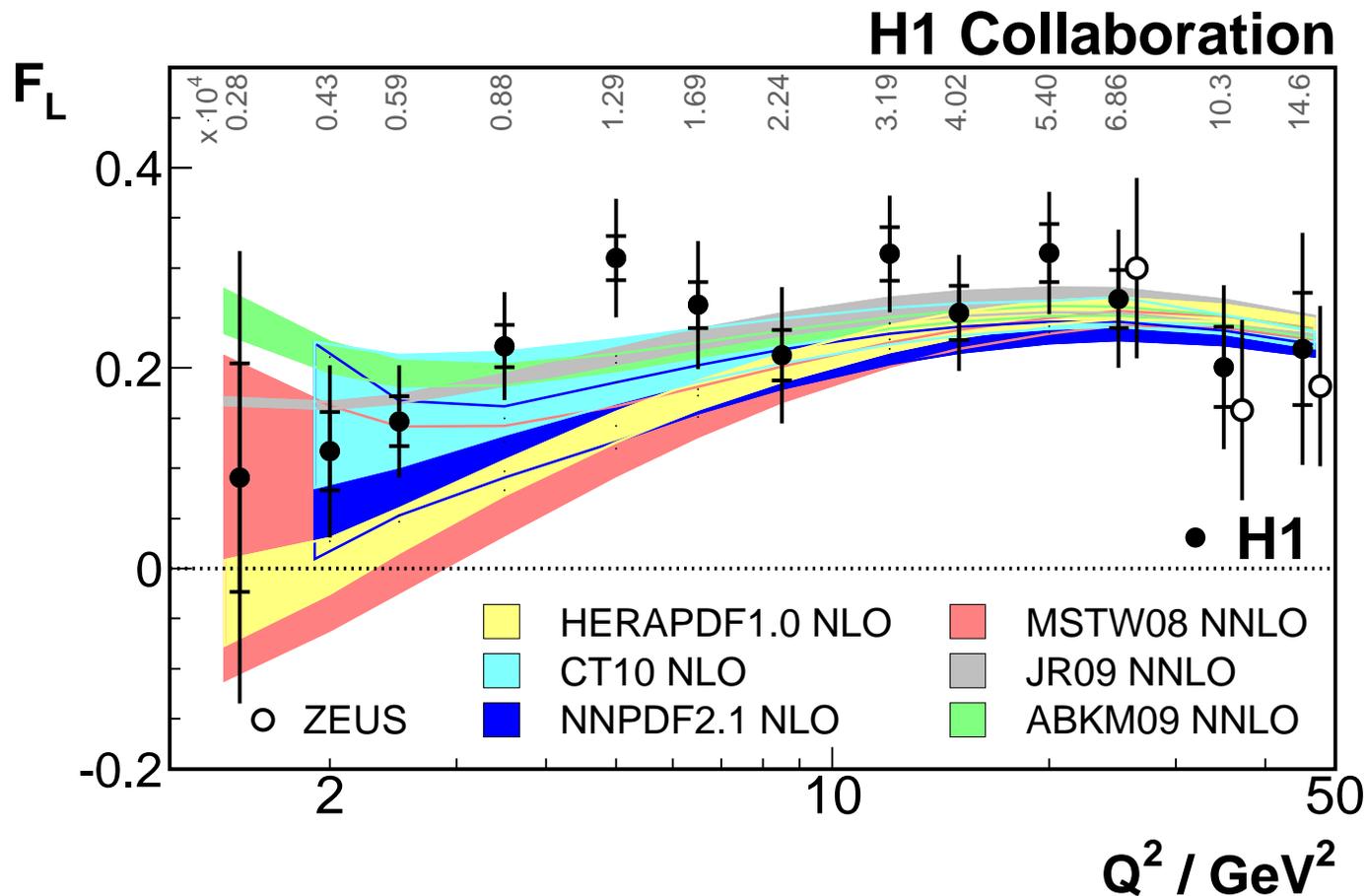
Combination:

$$\chi^2/dof = 637/656$$

QCD Fit (to the combined HERA data with $Q^2 \geq 3.5\,\mathrm{GeV}^2$):

$$\chi^2/dof = 574/582$$

JHEP 1001 (2010) 109.

Good consistency between H1 and ZEUS. Stringent test of DGLAP evolution.

7

Measurement of the Structure Function F_L

Measurement of the structure function F_L extended to $Q^2 \geq 1.5 \text{ GeV}^2$ and compared to predictions from PDF groups. Good agreement, within the uncertainties. Critical test for gluon density.

H1 Collaboration, Eur.Phys.J **C71** (2011) 1579
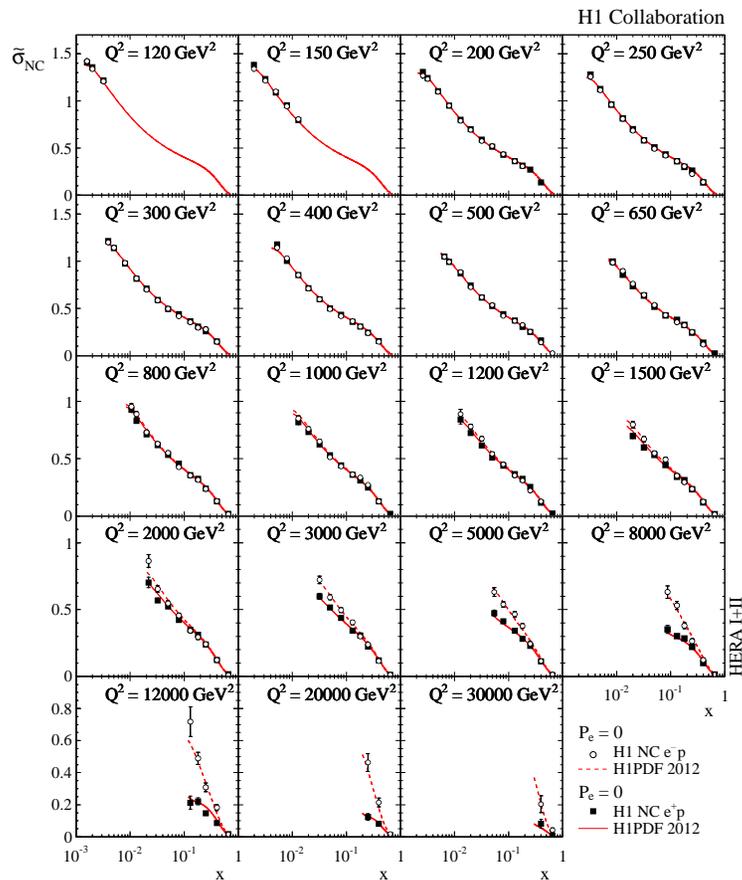
8

HERAPDF1.0 and HERAPDF1.5 fits
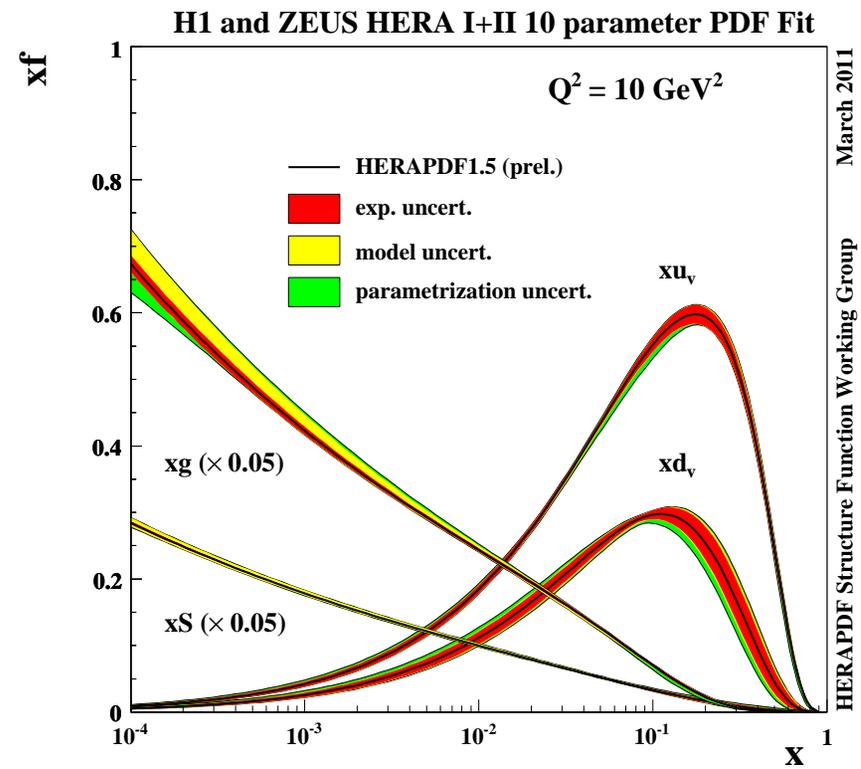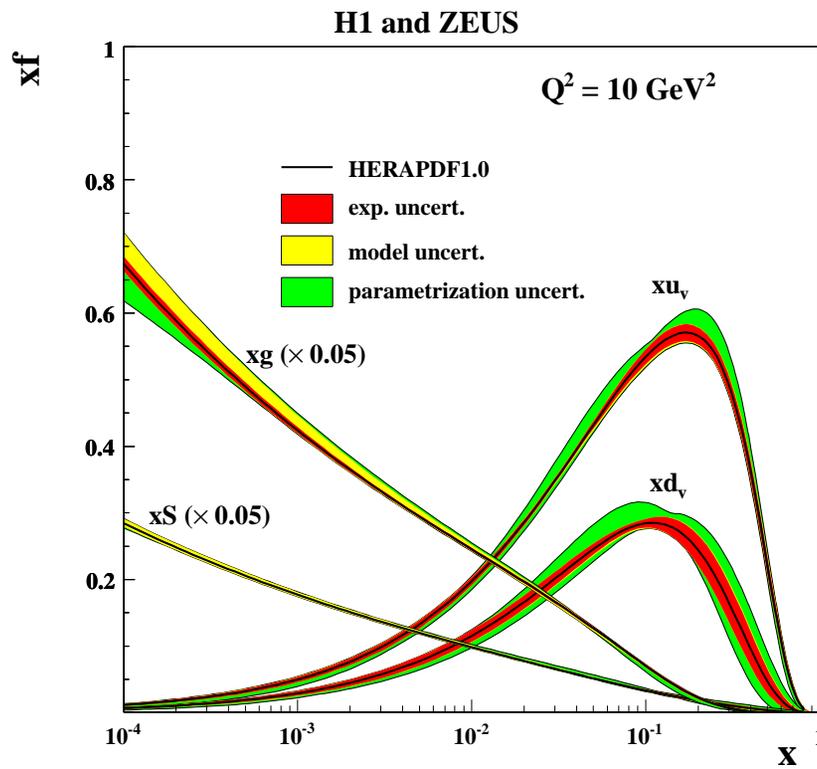
H1prelim-10-142, ZEUS-prel-10-018

- Preliminary combination of H1 and ZEUS complete data samples.

- Experimental, model and parameterisation uncertainties are estimated.

- HERAPDF1.5 fit provides determination of the valence quark densities at high x with reduced uncertainties compared to HERAPDF1.0.

H1 Collaboration, arXiv:1206.7007
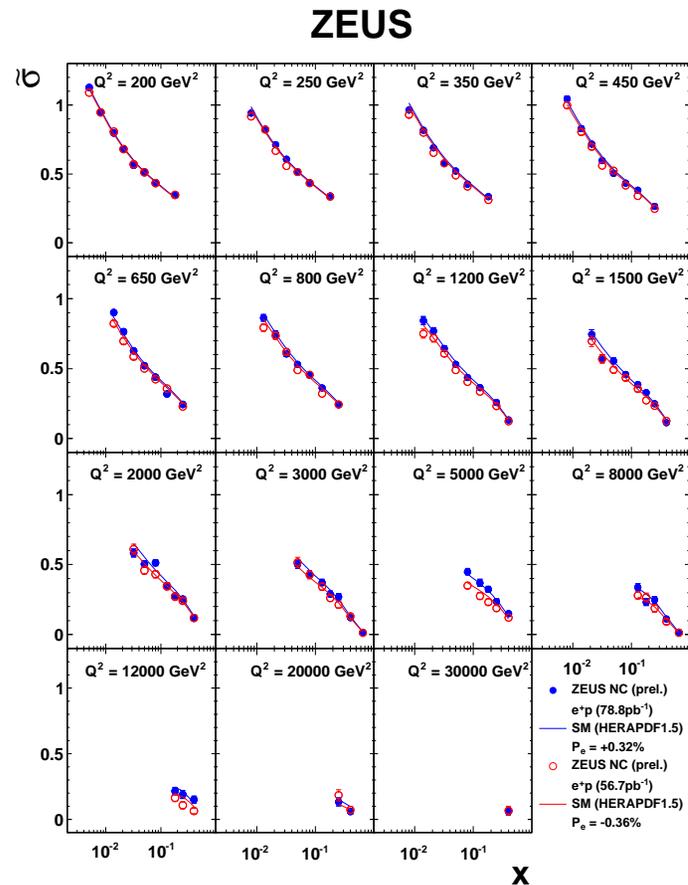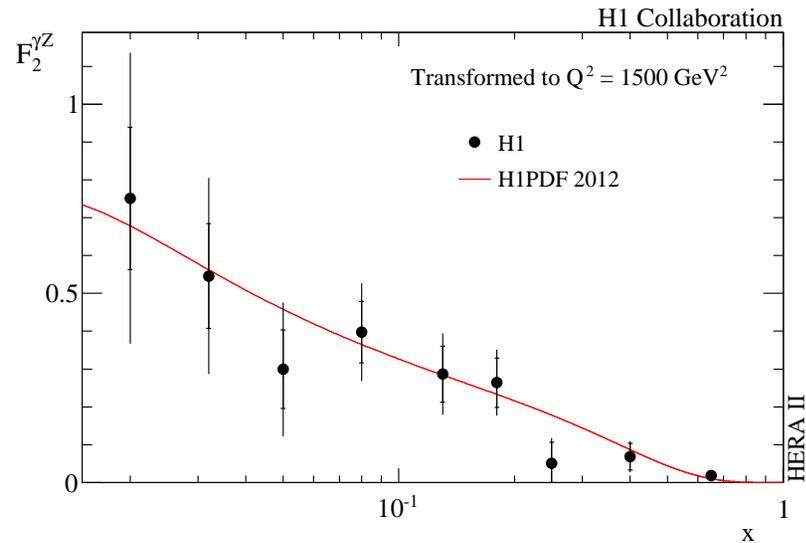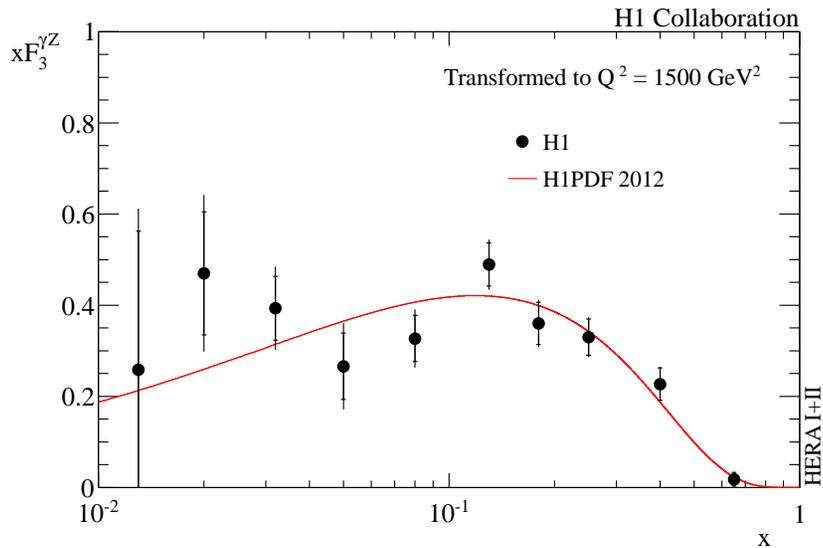
ZEUS-prel-11-003

H1 measurement of CC and NC $e^{\pm}p$ cross sections based on complete HERA sample. ZEUS preliminary result for e^+p NC cross section, last unpublished result for inclusive measurements at HERA.

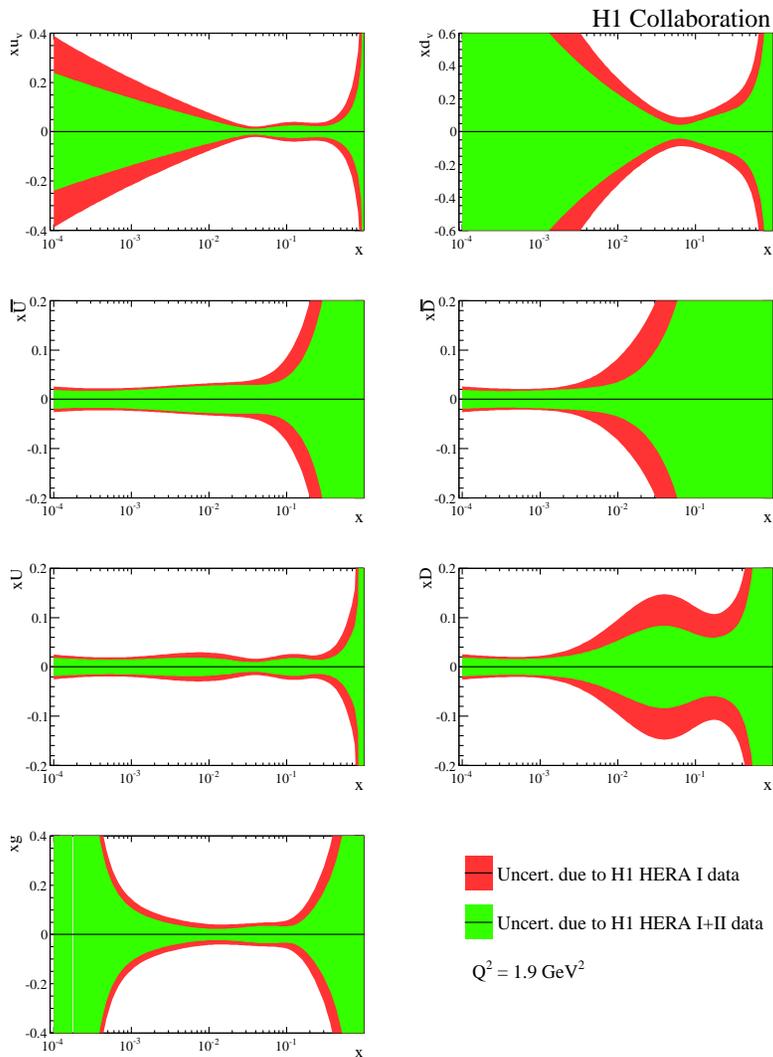# H1 measurement of $xF_3^{\gamma Z}$ and $F_2^{\gamma Z}$

$$\sigma_r^{\pm} = \tilde{F}_2^{\pm} \mp \frac{1-(1-y)^2}{1+(1+y)^2} x\tilde{F}_3 - \frac{y^2}{1+(1-y)^2}\tilde{F}_L \qquad \tilde{F}_2^{\pm} \approx F_2 - (v_e \pm P_e a_e)\kappa \frac{Q^2}{Q^2+M_Z^2}F_2^{\gamma Z}$$

Explore charge asymmetry to extract $xF_3^{\gamma Z}$ and polarisation P_e asymmetry to extract $F_2^{\gamma Z}$.

First measurement of the structure function $F_2^{\gamma Z}$.

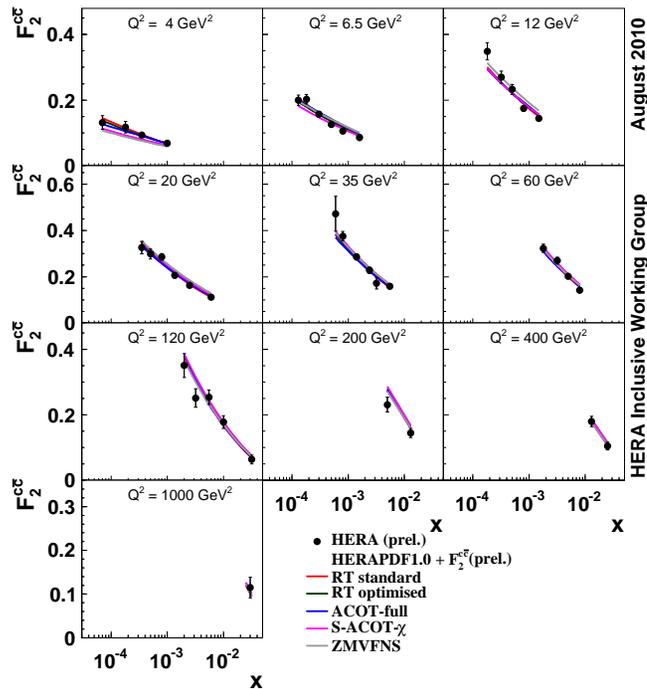H1 Collaboration, arXiv:1206.7007

11

Impact of the HERA-II measurement

H1 measurement allows to significantly reduce PDF uncertainties at high x, in particular for $D = d + s$-type quarks.

$\rightarrow$ important step towards combination of complete H1 and ZEUS data samples.

H1 Collaboration, arXiv:1206.7007
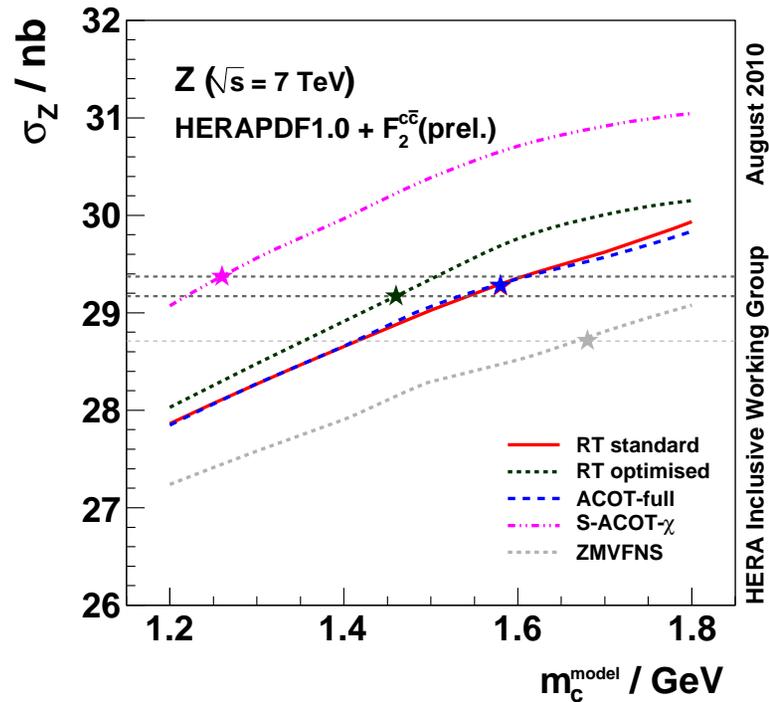
12

W, Z cross sections and charm-sea density.

Large ~ 7% spread of the *Z* total cross section prediction at the LHC for m_c^{model} scan between $1.2 - 1.8$ GeV and also for a fixed m_c^{model} when considering different models. However, the spread is reduced significantly when predictions are evaluated at the $m_c^{model}(opt)$ values, determined from the fit to HERA F_2^{cc} data.

H1prelim-10-143, ZEUS-prel-10-019

13

Charm and Bottom densities theory improvements
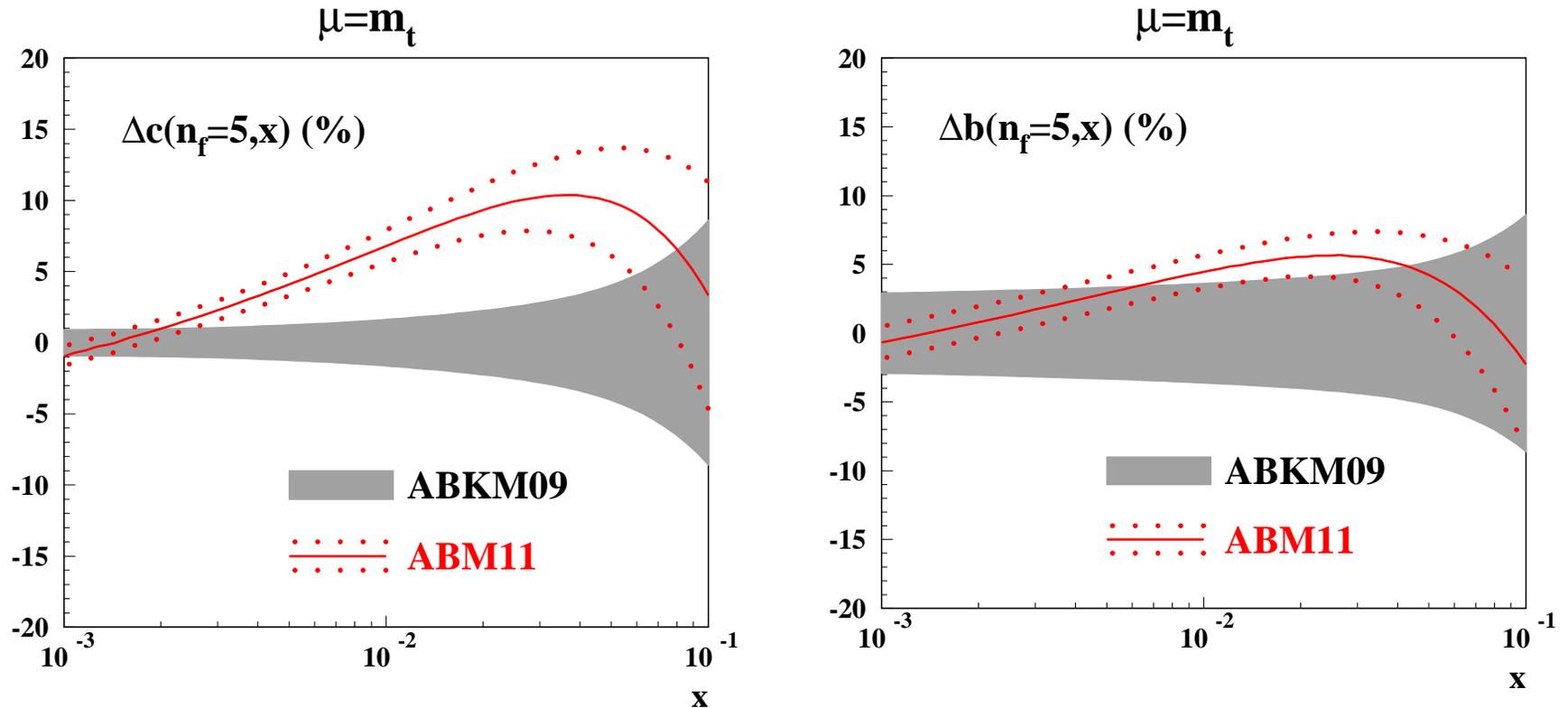
Theoretical uncertainty in charm and bottom quark densities can be reduced by using $\overline{\text{MS}}$-scheme for the masses. The scheme is implemented in the recently released ABM11 set. The improvement in b-quark density is important for single top production at the LHC.

S. Alekhin, J. Blümlein, S. Moch, arXiv:1202.2281
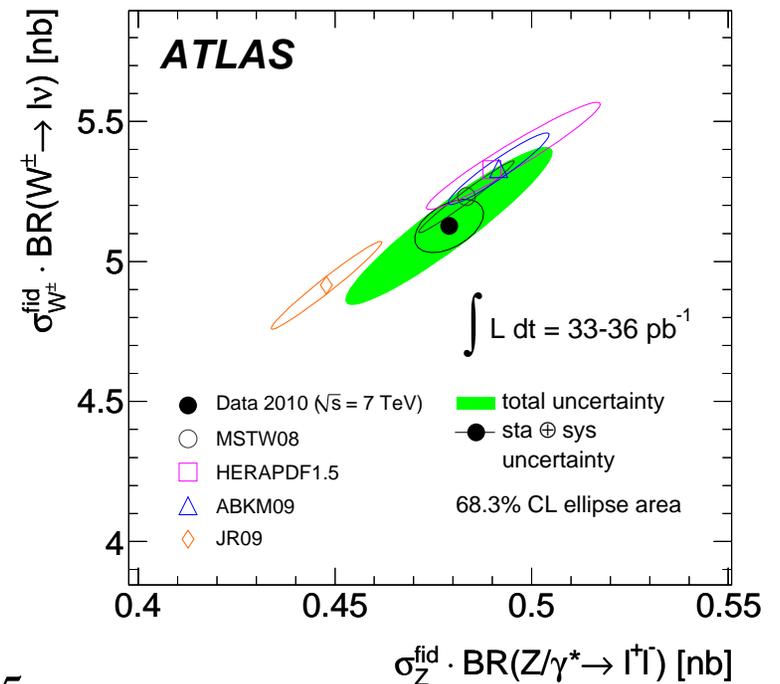
14

W, Z Total cross section results
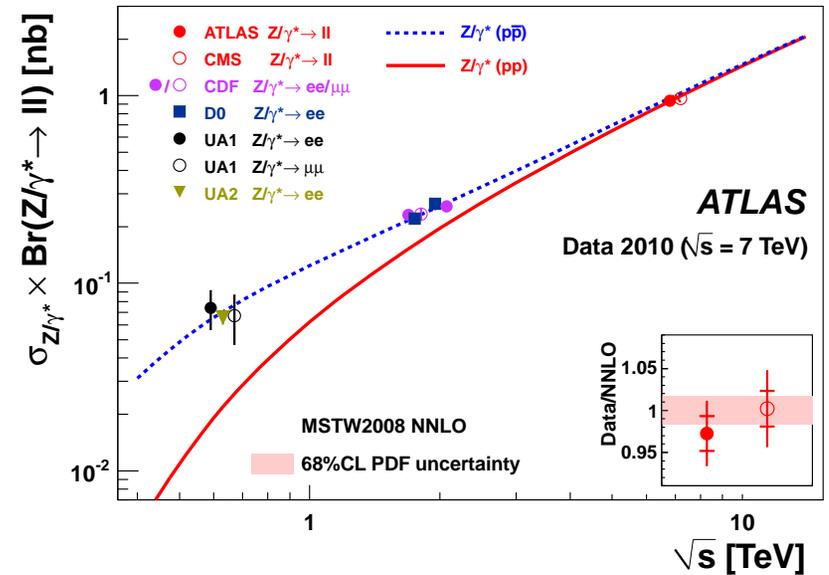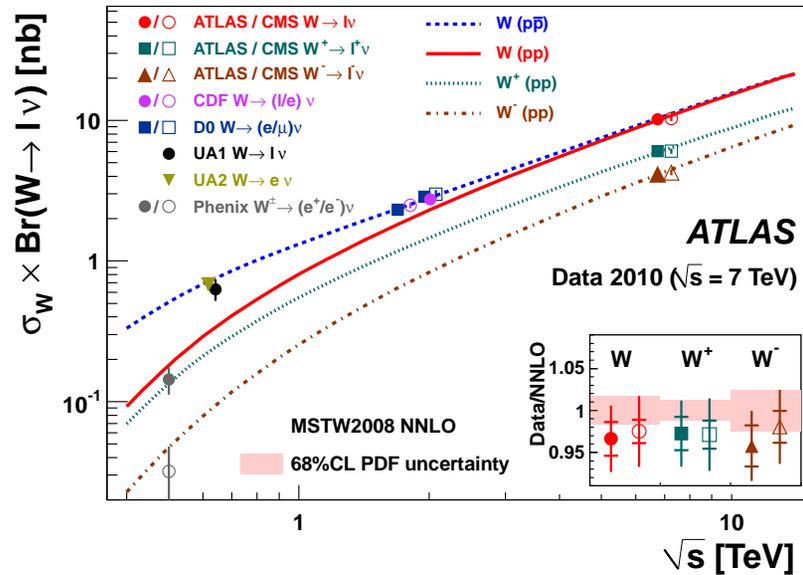
Total cross section measurements for *W, Z* production at the LHC agree between ATLAS and CMS and also with theoretical predictions.
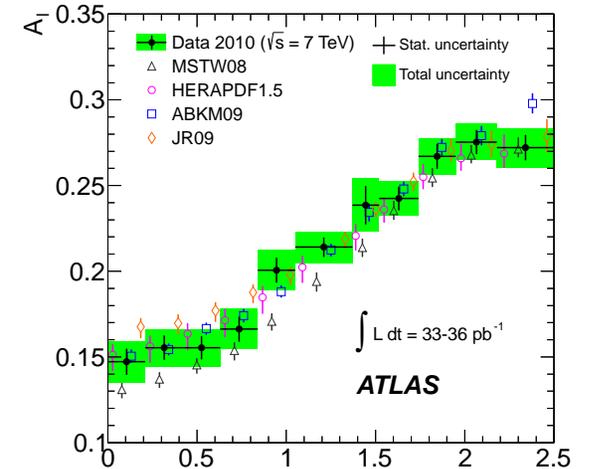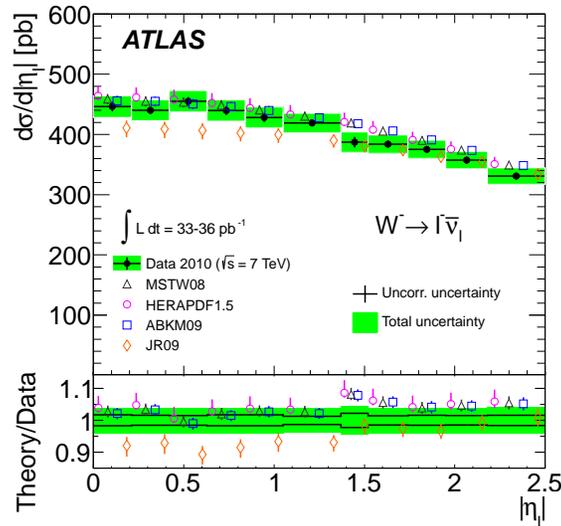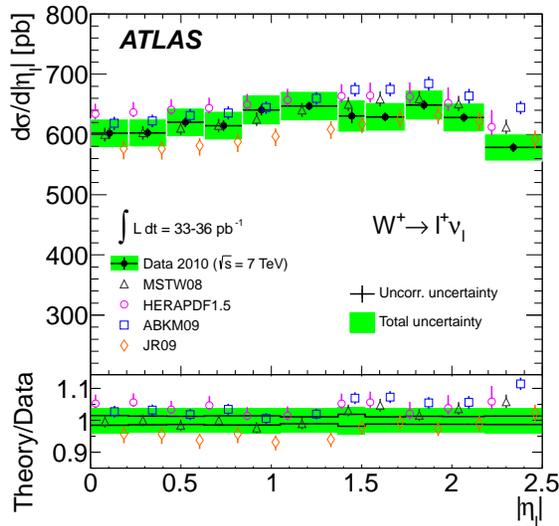
Largest uncertainty is due to luminosity measurement in 2010, 3.4% which improves to 1.8% in 2011.

ATLAS, Phys. Rev. D85 (2012) 072004.
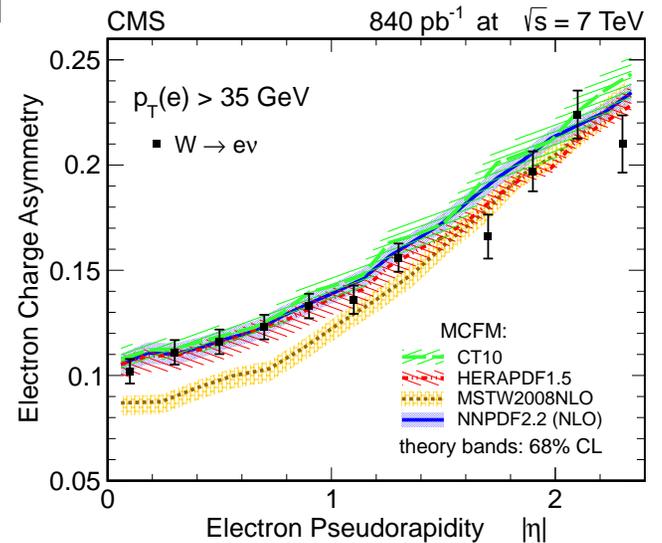CMS, JHEP 10 (2011) 132.

15

Differential Cross Sections: W

Measurement of W^+ and W^- production cross sections differentially in lepton rapidity η_ℓ give access to u_v and d_v PDFs. ATLAS measurements based on 2010 data can be translated to charge asymmetry A_l, given for $p_t^\ell > 20$ GeV, $p_t^\nu > 25$ GeV while CMS result based on 2011 data is for $p_t^\ell > 35$ GeV.

ATLAS, Phys. Rev. D85 (2012) 072004,   CMS, arXiv:1206.2598

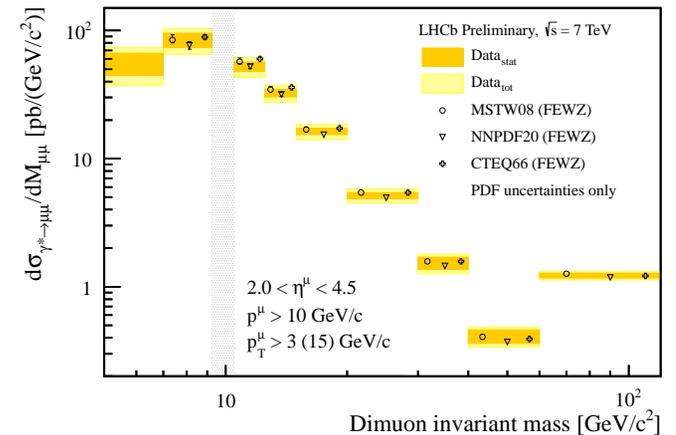# Differential Cross Sections: Z
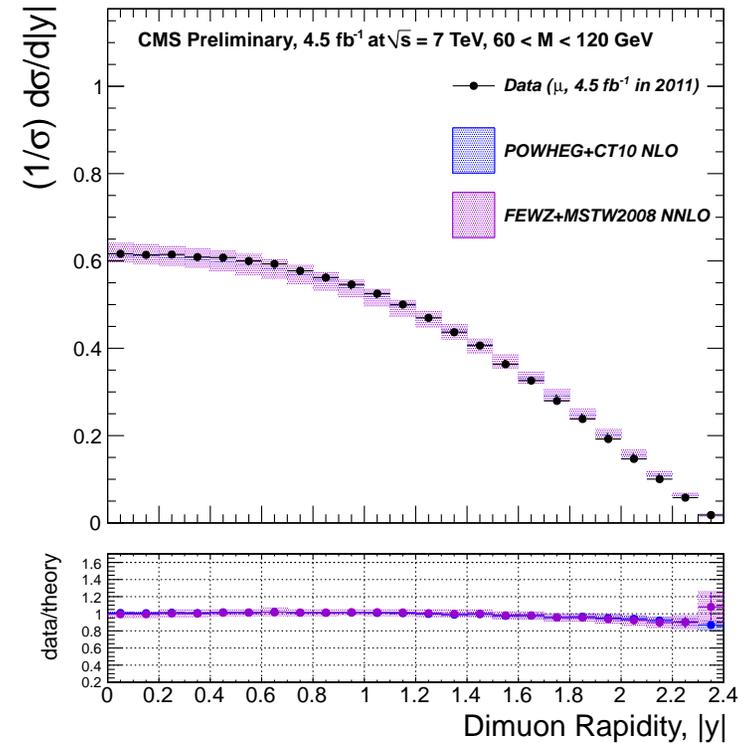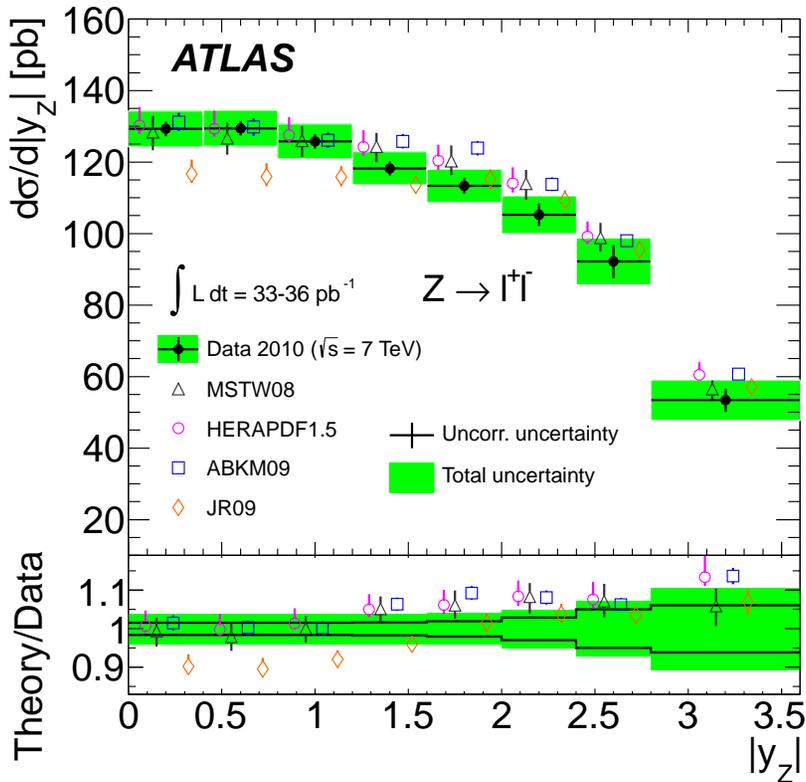
Compared to measurements of the F_2 structure function at HERA, which is dominated by γ exchange, Z production at the LHC is more sensitive to d-type quarks, provides information on $\bar{d}$, $\bar{u}$ and s decomposition at $x \sim 0.01$. ATLAS reports absolute cross sections, based on 2010 data. CMS measures normalised cross sections, based on complete 2011 data sample.

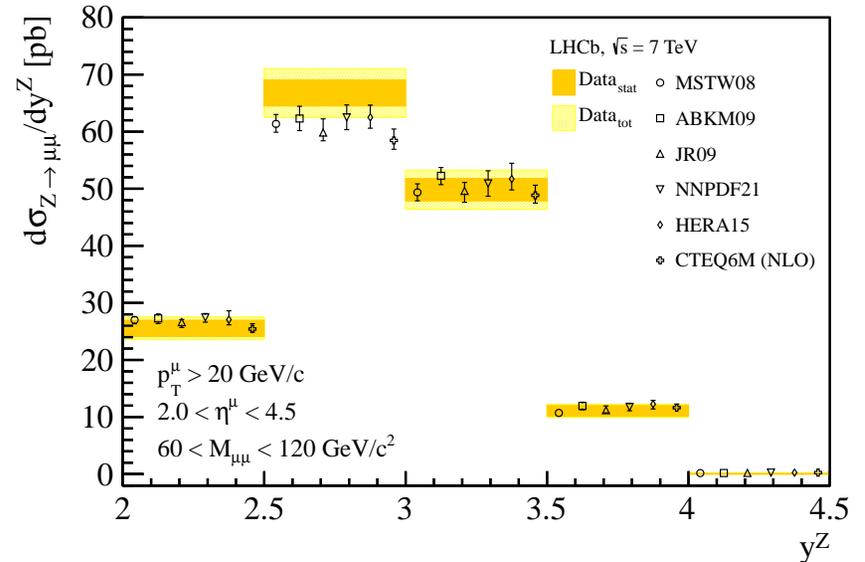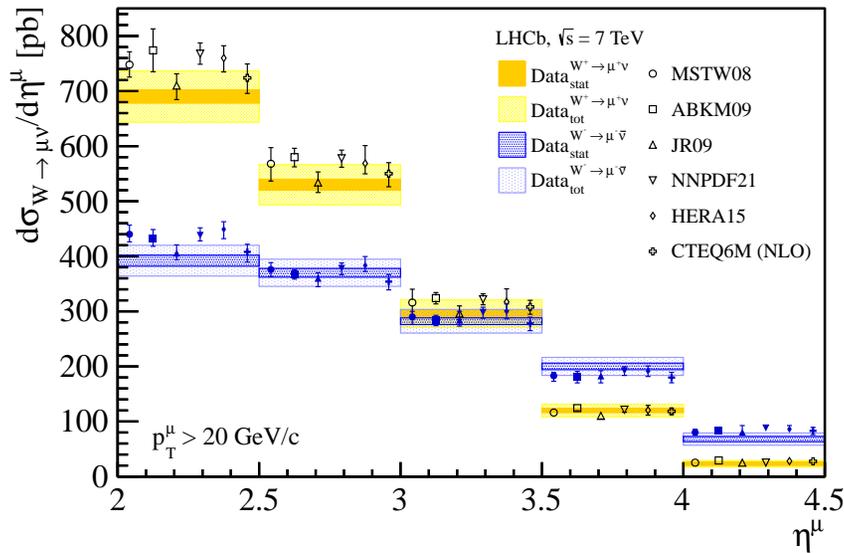ATLAS, Phys. Rev. D85 (2012) 072004,   CMS PAS EWK-11-007

Differential Cross Sections: γ^*
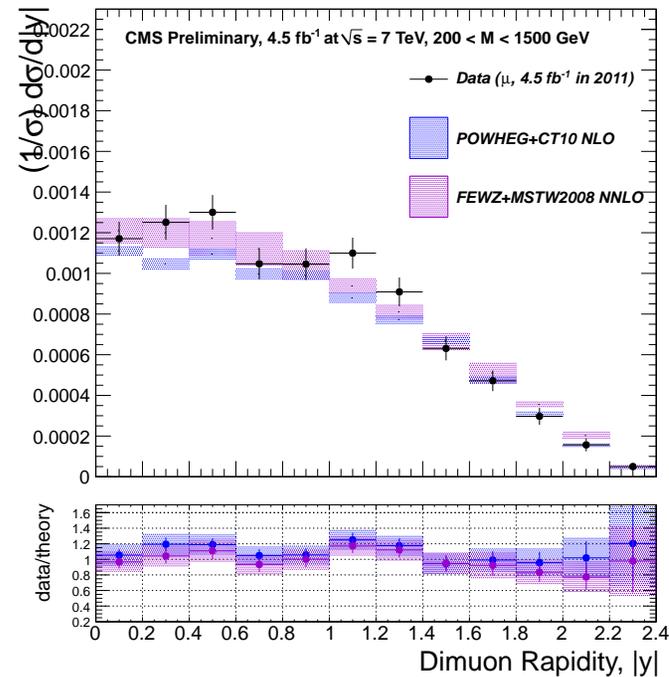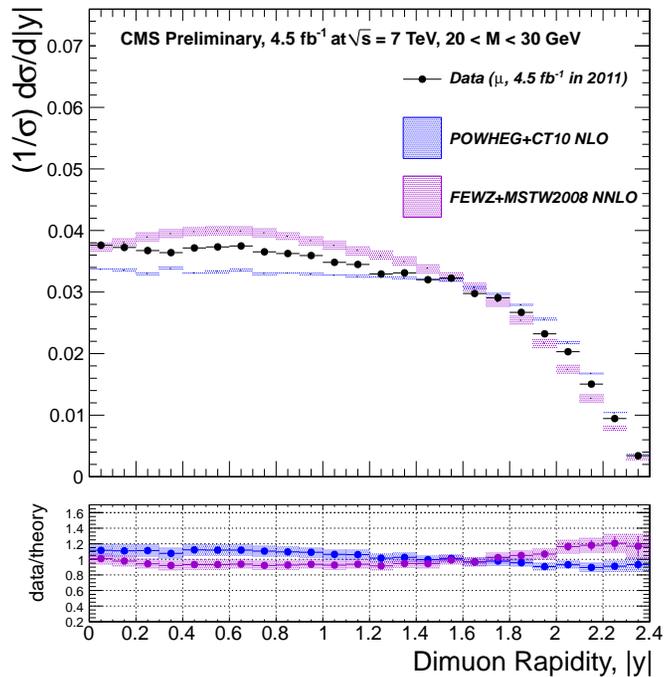
Low mass DY process has similar PDF sensitivity to HERA data. CMS measures normalised $(1/\sigma)d\sigma/d|Y|$ for $20 < M_{\mu\mu} < 1500$ GeV range. The measurements are complemented by LHCb, which measures down to 5 GeV.

CMS PAS EWK-11-007,   LHCb-CONF-2012-013

18

LHCb extends *W* differential cross-section measurement to $2 < \eta_\mu < 4.5$ range. For $\eta_\mu > 3.5$, W^- cross section exceeds W^+ due to V-A structure of *W* production.

ATLAS and CMS measure up to $y_Z = 3.6$ using central-forward topology of the scattered electrons; LHCb measures in the same range for symmetric configurations of the scattered muons: complimentary information for PDFs and electroweak fits.

LHCb, arXiv:1204.1620

19

Strange density from different PDFs
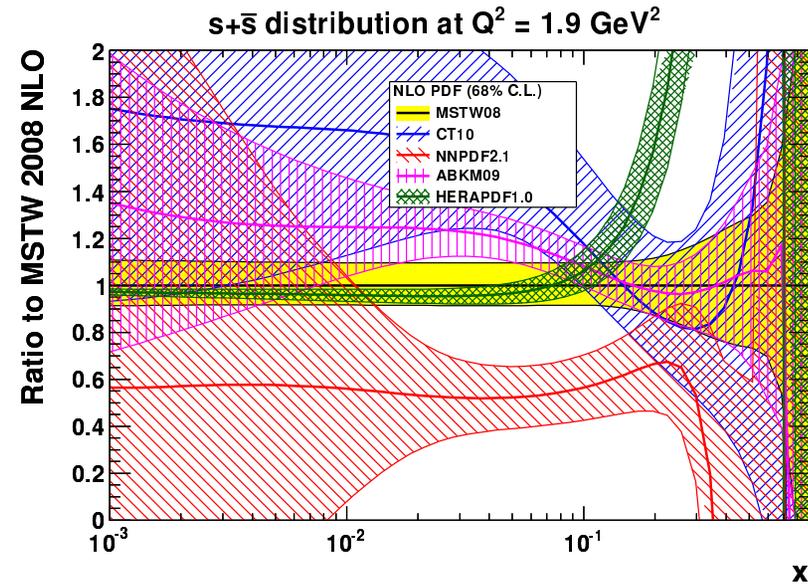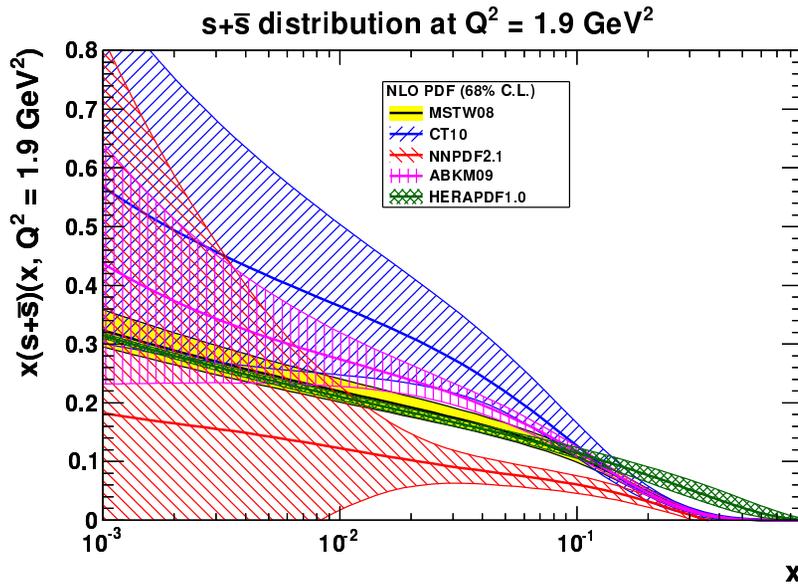
Plots prepared by G. Watt

- Strange-sea density is determined from neutrino scattering, $\nu N \to X\mu^+\mu^-$ with dimuon final state, with the second muon produced from the charm decay.

- These data are included in PDF fits leading, however, to results which are hardly consistent with each other,

20

Determination of the strange-sea density
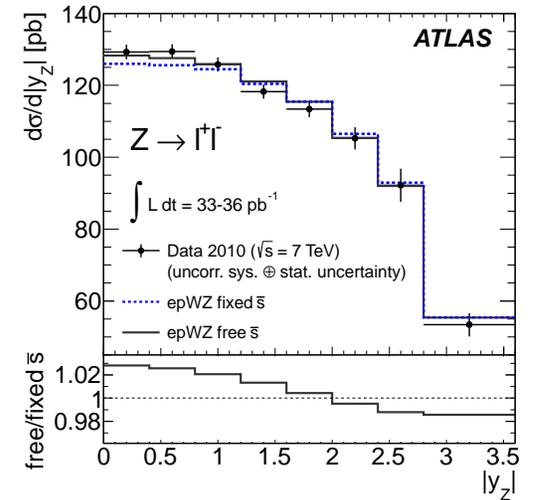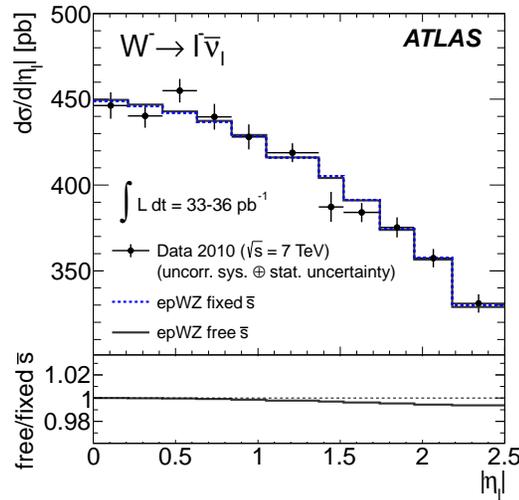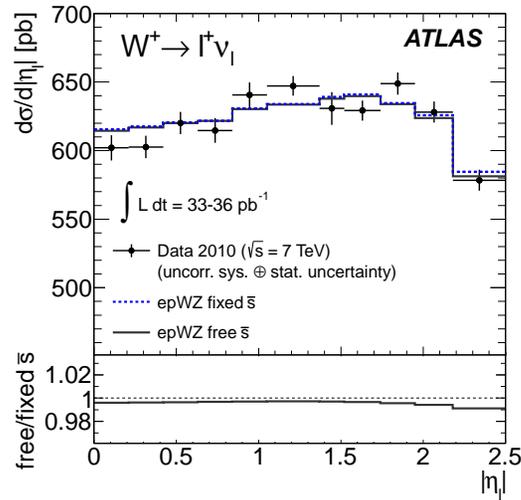
Perform two NNLO fits: with fixed strangeness fraction $r_s = 0.5(s + \bar{s})/\bar{d}$, $r_s = 0.5$ and free strange density parametrized as

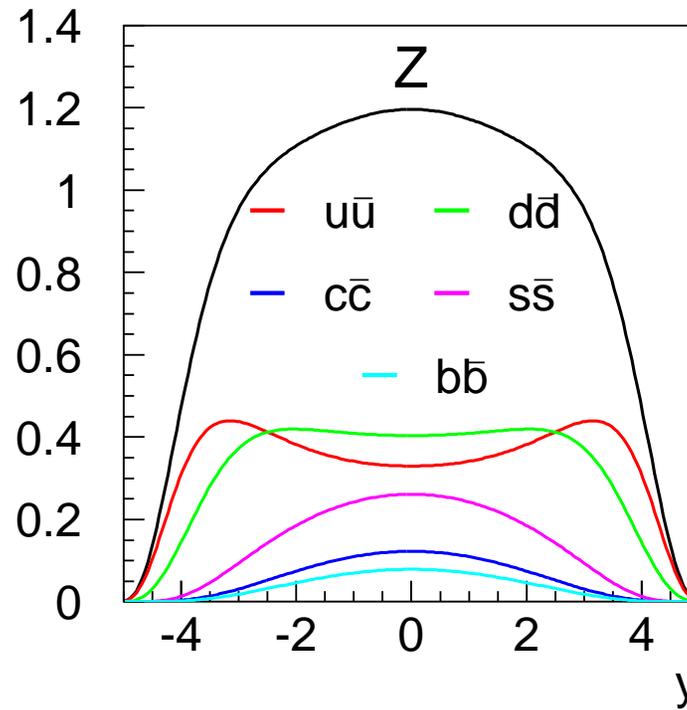$$x\bar{s}(x) = A_s x^{B_{\bar{d}}}(1 - x)^{C_s}$$

For $x = 0.023$ and $Q^2 = 1.9$ GeV^2, corresponding to the maximum of ATLAS data sensitivity extrapolated to low Q^2

$$r_s = 1.00 \pm 0.20_{\text{exp}} \pm 0.07_{\text{mod}}{}^{+0.10}_{-0.15}{}_{\text{par}}{}^{+0.06}_{-0.07}\alpha_S \pm 0.08_{\text{th}}.$$
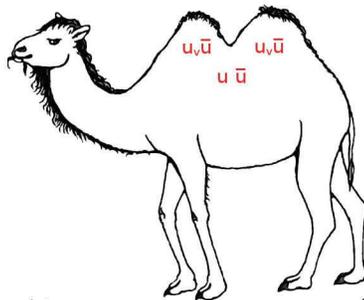
consistent with sea quark flavour democracy at low x.

ATLAS, arXiv:1203.4051
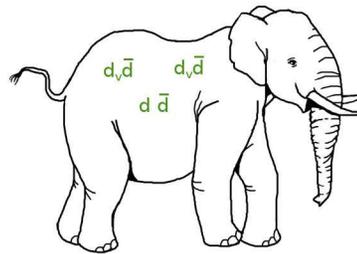
21

Flavor decomposition of the *Z* production at the LHC
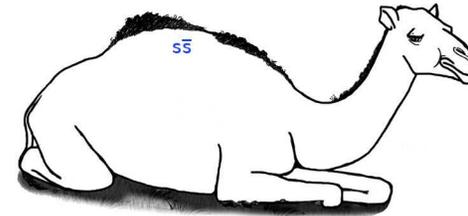
Strange-sea determination at the LHC
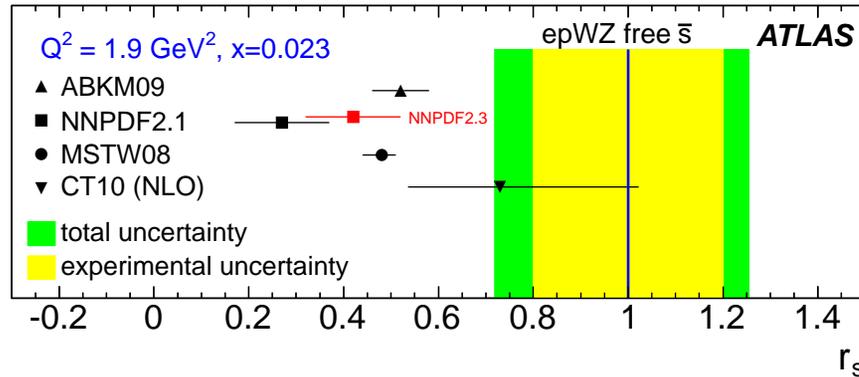
$$r_s = 0.5 \frac{s + \bar{s}}{\bar{d}}$$

ATLAS uses PDF fit to inclusive W, Z measurements. CMS result is based on $W + c$ production.

NNPDF2.3 result uses improved m_c threshold correction, affecting dimuon data (dominant effect) and includes ATLAS result (smaller effect).

ATLAS fit provides the best description of the measured W/Z cross sections ratio.

ATLAS, arXiv:1203.4051   CMS PAS EWK-11-013

23
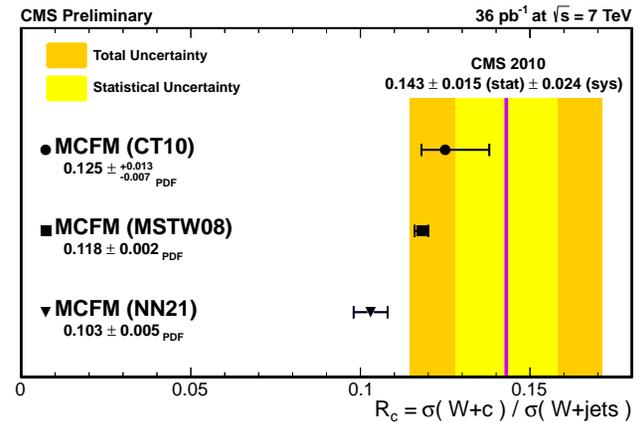
NNPDF2.3 Strangeness Study

$r_s(x, Q^2 = M_Z^2)$
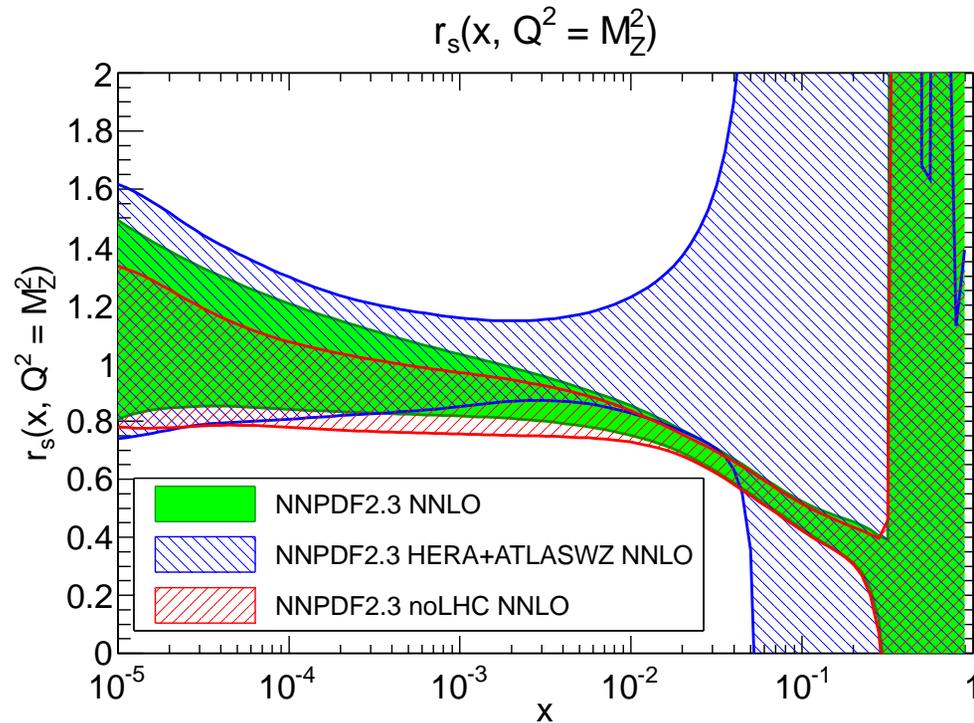
NNPDF analysis also studies strangeness fraction, fitting HERA+ATLAS only and in a global fit. For $Q^2 = M_Z^2$ and $x = 0.013$ NNPDF finds for ATLAS+HERA fit $r_s = 1.04 \pm 0.23$ which has larger uncertainty compare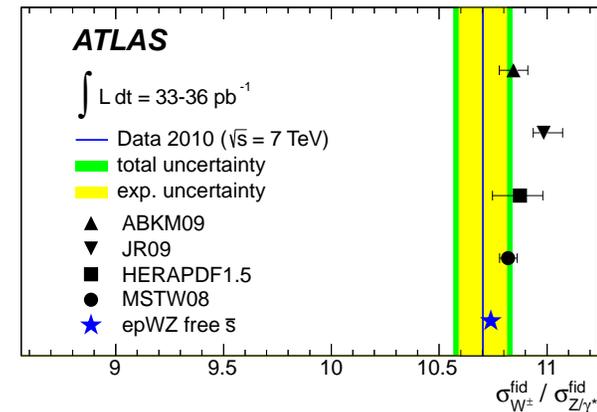d to the ATLAS result $r_s = 1.00^{+0.08}_{-0.09}$. The maximum sensitivity on strangeness fraction for NNPDF analysis is at $x \sim 0.005$, the ATLAS data pulls strangeness of the combined fit at low x.

NNPDF Collaboration, arXiv:1207.1303

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LHeC: high energy frontier for *ep* physics
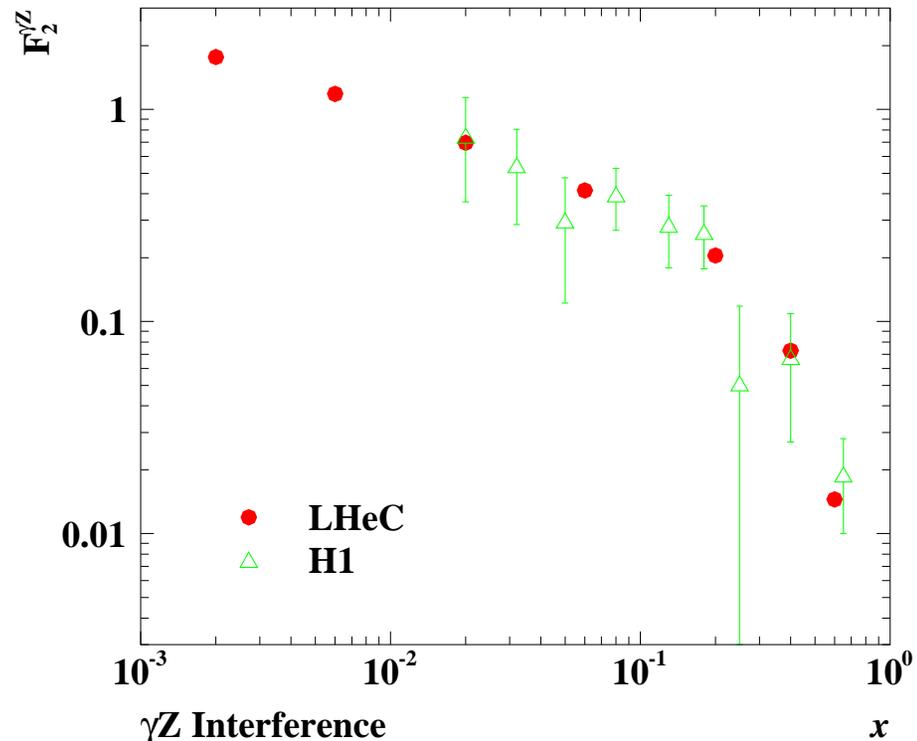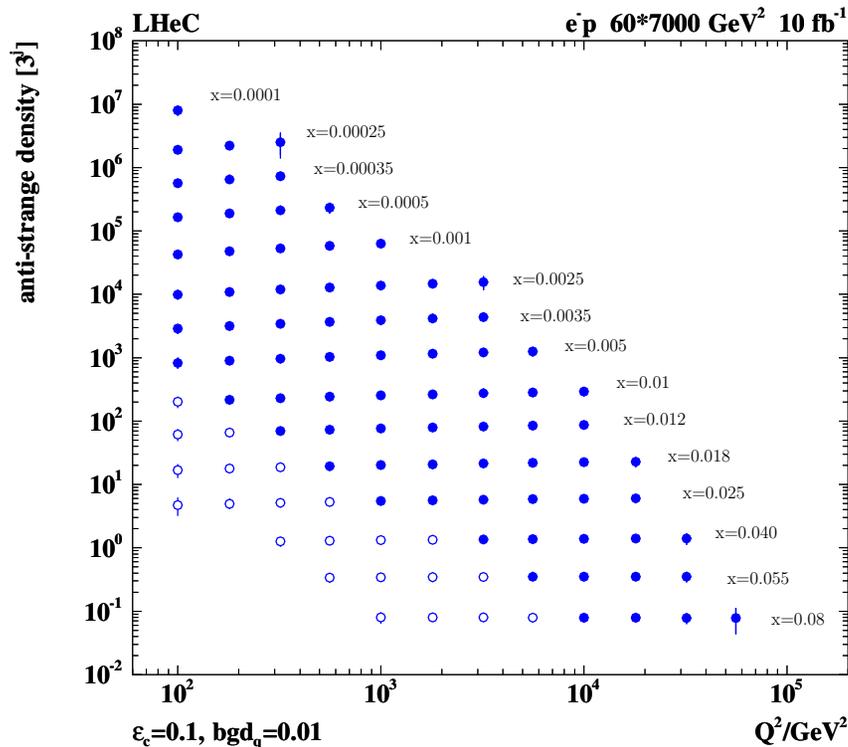
Future of DIS depends on proposed collider projects: EIC and LHeC.

LHeC is the high energy frontier which would use 7 TeV protons from LHC and 60 GeV polarised electrons from a dedicated racetrack linac.

The large center-of-mass energy of the LHeC together with high luminosity allows to measure strange density, using CC process with tagged charm. Polarisation of the electron beam provides a way to measure $F_2^{\gamma Z}$ accurately.

LHeC — expected measurement of heavy flavours.
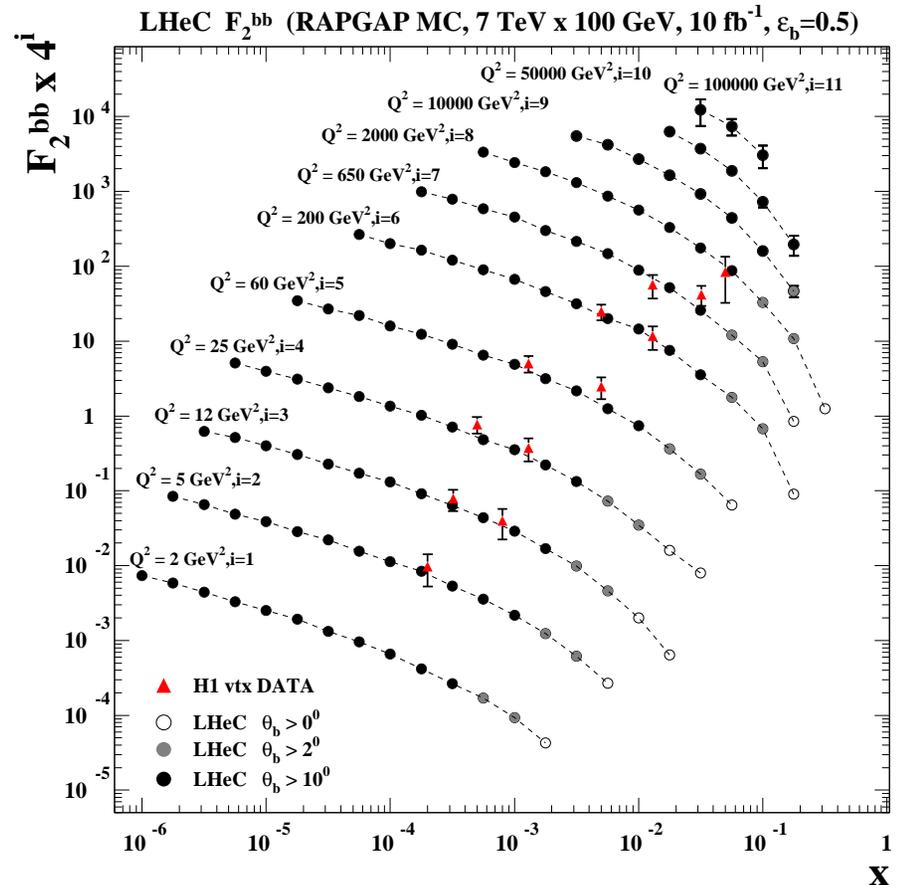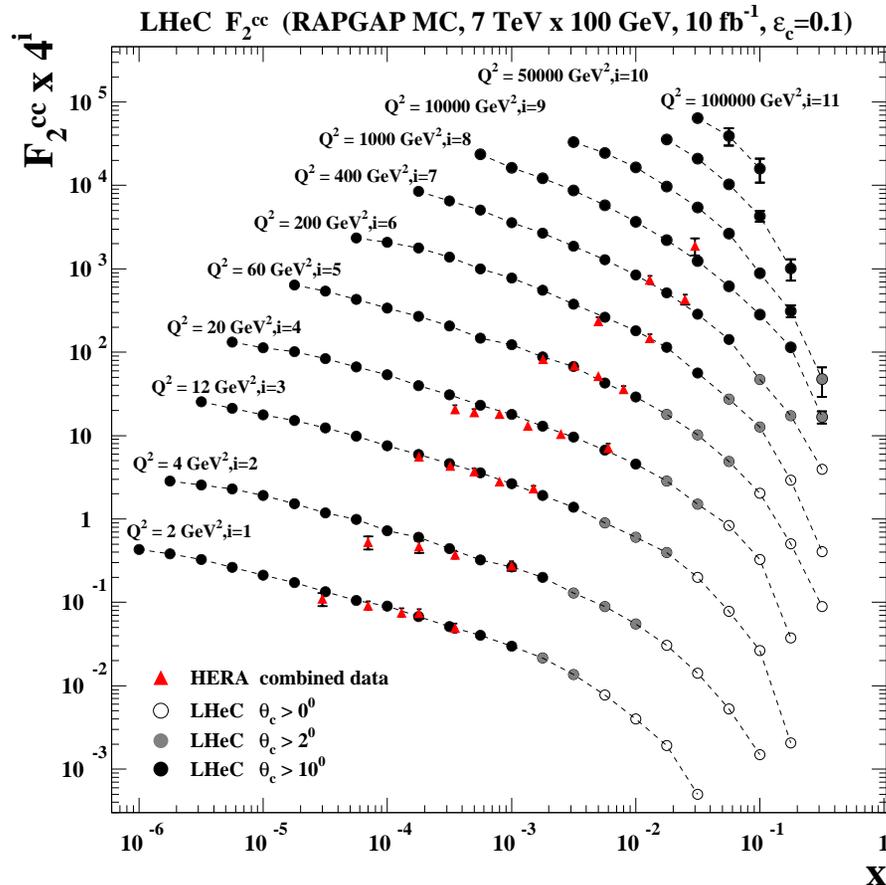
Large center-of-mass energy means that LHeC would access very low x at low Q^2. Combined with heavy flavour tagging, this would provide unique opportunity to measure heavy flavours from the threshold region and Bjorken-x down to 10^{-6} up to EW scales.

LHeC study group arXiv:1206.2913

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Summary

- HERA data provide essential information on the proton structure for the LHC. The analysis of the HERA inclusive data enters final stages.

- Predictions for the LHC are overall in good agreement with the data. LHC results start to have constraining power e.g on strange-sea density, valence PDFs.

- Future ep colliders promise large improvements in the understanding of the proton structure.

Extras

HERAFitter Open Source Code

- **HERAFitter** code is available for download from `hepforge`

- Beta-2 version of the code is based on `QCDNUM17` for parton evolution, contains codes from MSTW, CTEQ, ABKM for structure function calculation. LHC processes can be included using APPLGRID, FastNLO (for jets and DY) and Hathor (for $t\bar{t}$) interfaces.

$\rightarrow$ a tool for benchmarking and QCD analysis of LHC data.

HERA jet measurements

H1Prelim-12-031

- Main information on the gluon density comes from scaling violation at HERA.

- Jet cross section can be also used to control gluon density, measure α_S.

- Correlated measurement of inclusive, di- and trijets by H1.

Combined Jet+DIS inclusive fit and $\alpha_S(m_Z)$

H1 and ZEUS HERA I+II 14 parameter PDF Fit

$Q^2 = 10\ GeV^2$ — March 2011

- HERAPDF1.5f (prel.)
- exp. uncert.
- model uncert.
- parametrization uncert.
- HERAPDF1.5 (prel.)

xu_v, $xg\ (\times 0.05)$, xd_v, $xS\ (\times 0.05)$
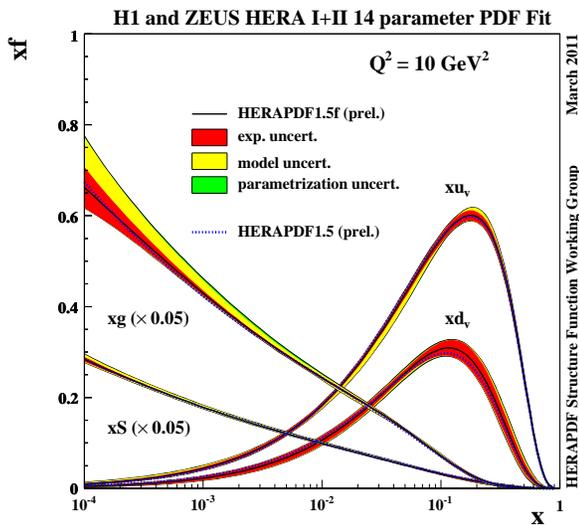
H1 and ZEUS HERA I+II PDF Fit

$Q^2 = 10\ GeV^2$ — March 2011

- HERAPDF1.5f (prel.) free $\alpha_s(M_Z)$
- exp. uncert.
- model uncert.
- parametrization uncert.

xu_v, $xg\ (\times 0.05)$, xd_v, $xS\ (\times 0.05)$

H1 and ZEUS HERA I+II PDF Fit with Jets

$Q^2 = 10\ GeV^2$ — March 2011

- HERAPDF1.6 (prel.) free $\alpha_s(M_Z)$
- exp. uncert.
- model uncert.
- parametrization uncert.

xu_v, $xg\ (\times 0.05)$, xd_v, $xS\ (\times 0.05)$

Fix α_S, no jets   Free α_S, no jets   Free α_S, + jets

H1prelim-11-034, ZEUS-prel-11-001

- Freeing α_S in fits increases $xg(x)$ uncertainty at low x due to large $xg(x)$-α_S correlation.

- Inclusion jets allows to reduce this correlation and improve uncertainty.

- $\alpha_S(M_Z) = 0.1202 \pm 0.0013(\text{exp}) \pm 0.0007(\text{mod}) \pm 0.0012(\text{had})^{+0.0045}_{-0.0036}(\text{th})$.

H1 and ZEUS (prel.)

- - - HERAPDF1.5f
— HERAPDF1.6

$\chi^2 - \chi^2_{min}$ vs $\alpha_S(M_Z)$

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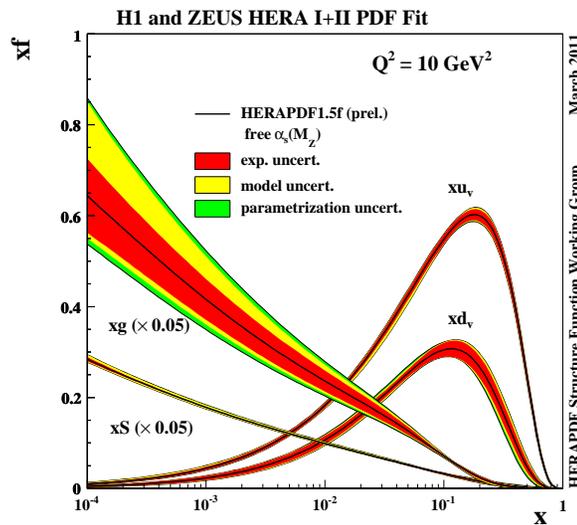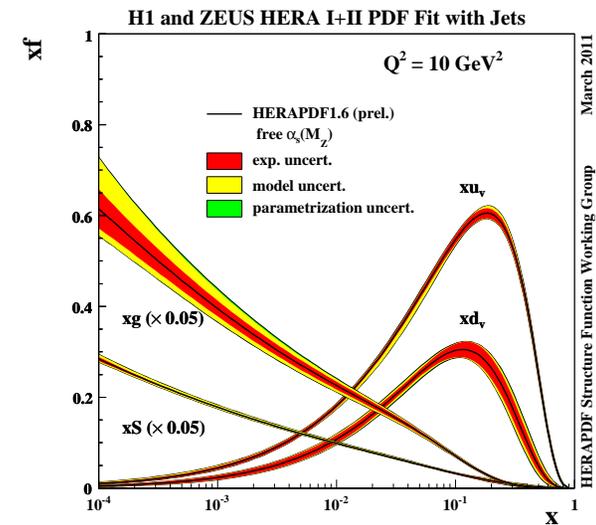
Probing proton strangeness at the LHC

W⁻

gluon

s **c̄** **c**

Direct probe, using $W + c$-jet production. CMS measures

$$R_c = 0.143 \pm 0.015_{stat} \pm 0.024_{syst}$$

vs expectation, based on CT10,

$$R_c = 0.13 \pm 0.02 \,.$$
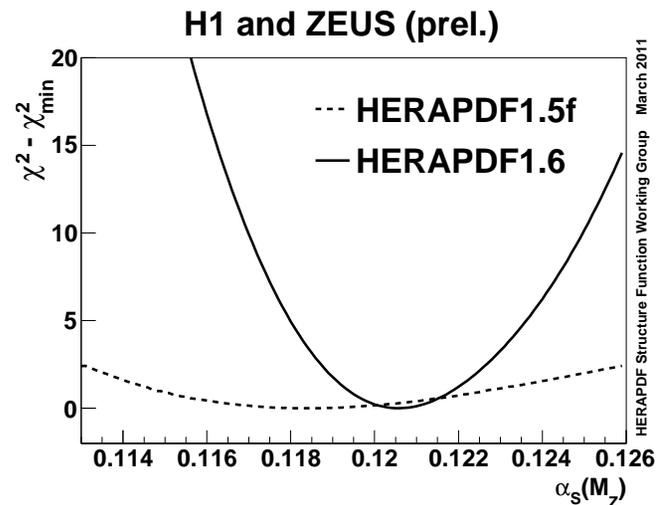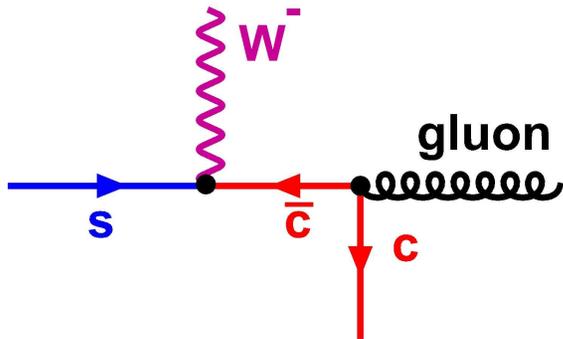
CMS PAS EWK-11-013

Indirect probe, using different W and Z cross-section dependence, from their correlated measurement. For W/Z ratio, smaller values are expected for larger strangeness fraction since Z production is more affected than W.

CMS   36 pb⁻¹ at √s = 7 TeV

NNLO, FEWZ+MSTW08 prediction
[with MSTW08NNLO 68% CL uncertainty]

10.74 ± 0.04

W → eν, Z → ee
10.56 ± 0.12 stat. ± 0.19 syst.

W → μν, Z → μμ
10.52 ± 0.09 stat. ± 0.20 syst.

W → lν, Z → ll (combined)
10.54 ± 0.07 stat. ± 0.18 syst.

$R_{W/Z} = [\,\sigma \times B\,](W) / [\,\sigma \times B\,](Z)$
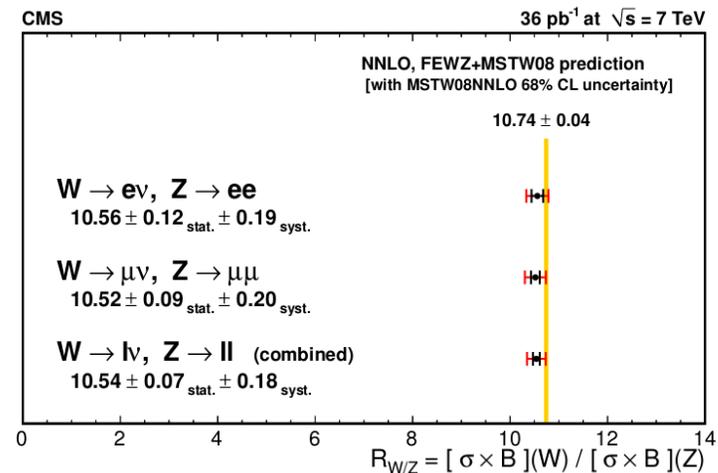
CMS, JHEP 10 (2011) 007

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Decomposing u and c densities at low x

Inclusive structure function F_2 is sensitive to

$$F_2 \sim 4\left(U + \bar{U}\right) + \left(D + \bar{D}\right),$$

where $U = u + c$ and $D = d + s + b$. At low x, contribution of charm to F_2 reaches 30%.

The charm density can be calculated given the gluon density, however description of the charm threshold is complicated leading to a number of matching schemes (RT, ACOT, FNOLL...).
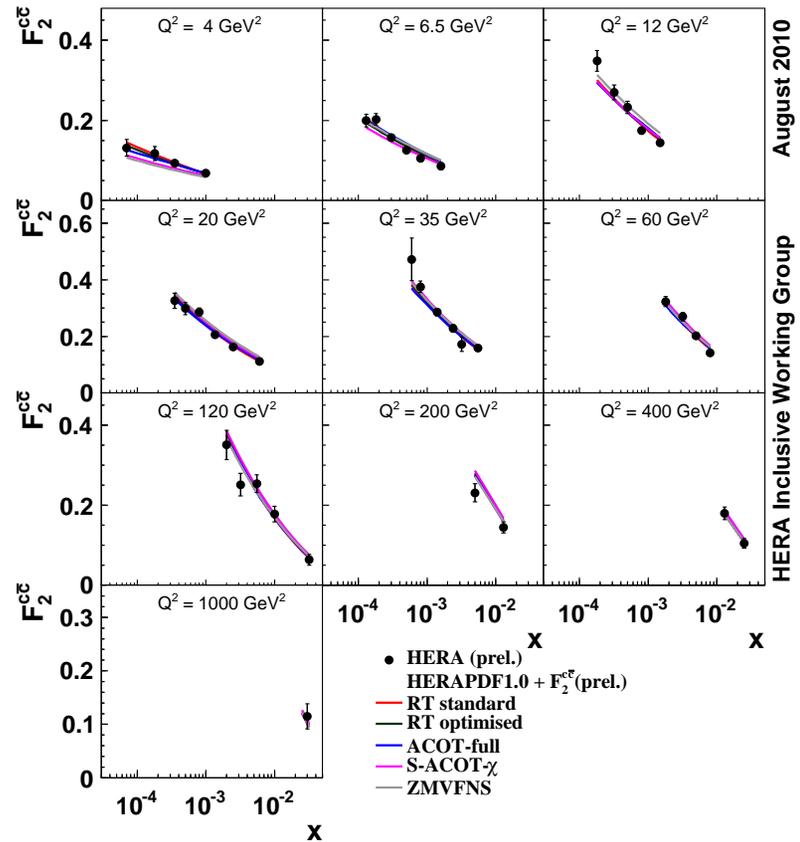
Combined HERA F_2^{cc} data reaches $5 - 10\%$ precision per point, can be used to study different HF models.

# *W, Z* cross sections and charm-sea density.
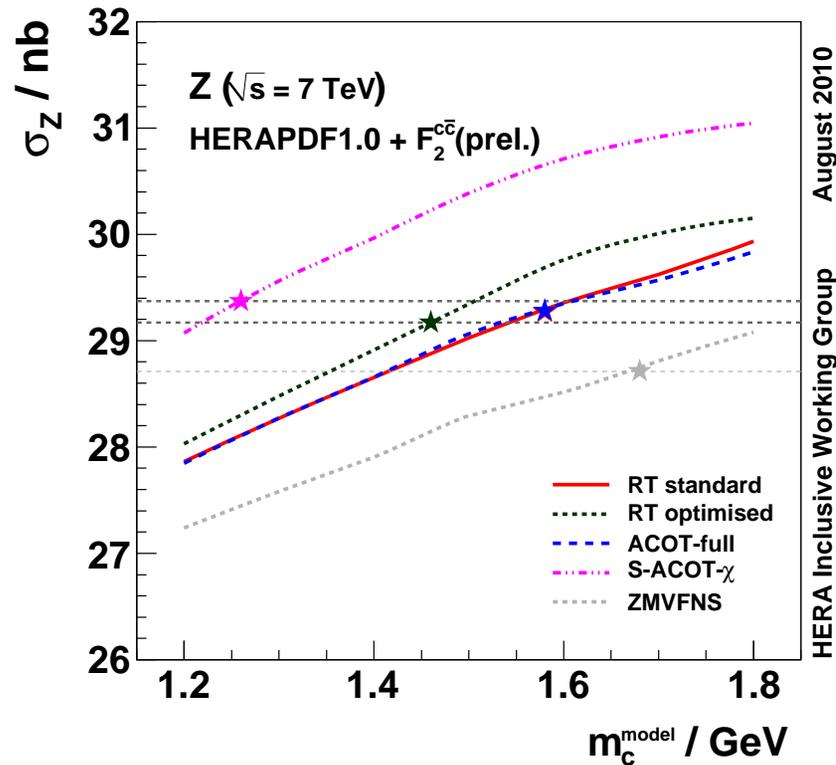
Fit the m_c^{model} parameter for various models such that they describe HERA data.

Large $\sim 7\%$ spread of the *Z* total cross section prediction at the LHC for m_c^{model} scan between $1.2 - 1.8$ GeV and also for a fixed m_c^{model} when considering different models.

However, the spread is reduced significantly when predictions are evaluated at the $m_c^{\text{model}}(opt)$ values.

H1prelim-10-143, ZEUS-prel-10-019

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ATLAS r_s result at $Q^2 = 1.9$ GeV^2 and $Q^2 = M_Z^2$
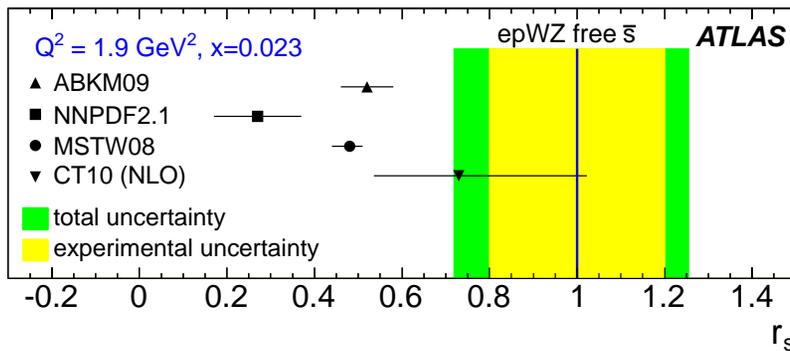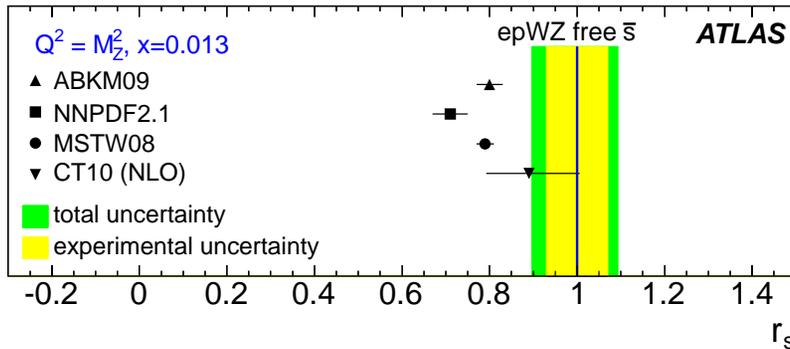
ATLAS data have largest sensitivity to the strangeness fraction r_s for $Q^2 = M_Z^2$ and for $y_Z = 0$ corresponding to $x = 0.013$.

Due to the QCD evolution, this corresponds to $x = 0.023$ at $Q^2 = 1.9$ GeV^2

Flavour-blind gluon splitting process reduces and initial strangeness suppression as PDFs evolve to higher scales. Consequently, the uncertainties are also reduced, by about factor 2, for $Q^2 = M_Z^2$ compared to $Q^2 = 1.9$ GeV^2, for all PDF sets.

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Measurement of the neutron structure — tagged proton

- d/u limit for $x \to 1$ probes different theory predictions, important for high energy predictions (e.g. jet rates, W-mass).

- Measured using F_2^n/F_2^p assuming isospin symmetry:

$$\frac{F_2^n}{F_2^p} = \frac{u + \bar{u} + 4(d + \bar{d}) + s + \bar{s}}{4(u + \bar{u}) + d + \bar{d} + s + \bar{s}}$$

However, large uncertainties due to nuclear corrections (EMC effect).

(from CTEQ-JLAB collaboration)

nuclear uncertainty
PDF uncertainty
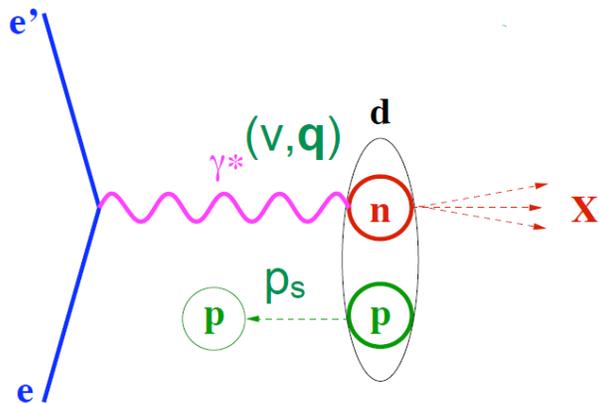
Detect the spectator proton from deuterium following *en* scattering. Use spectator proton momentum to correct kinematics. This can be done at colliders, EIC and LHeC, too.
BoNuS experiment using CLAS.

BoNuS and MARATHON


BoNuS preliminary (N. Baillie)
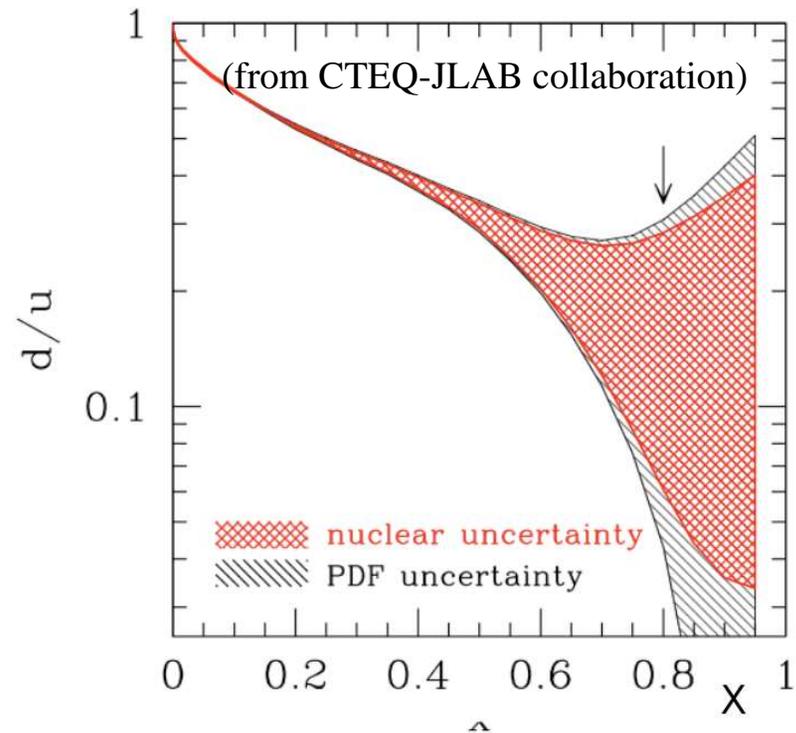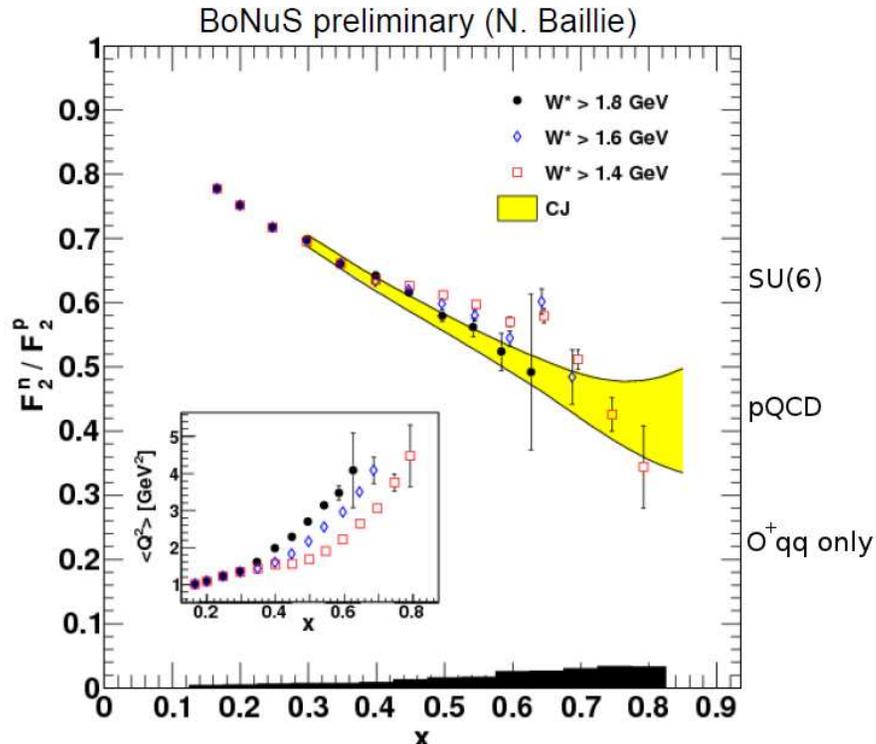
- First results from the BoNuS collaboration, using CLAS at hall B.

- Results approximately agree with CTEQ-JLAB analysis

- Higher beam energy is needed to measure at higher x and $W > 2$ GeV.

Another approach: use SuperRation R^*:

$$\frac{\sigma^{He^3}}{\sigma^{H^3}} \approx \frac{F_2^{He^3}}{F_2^{H^3}} = R^* \frac{2F_2^P + F_2^n}{F_2^p + 2F_2^n}$$

which is expected to be close to 1 to $< 1.5\%$. Proposed to be measured by MARATHON with $E_e = 12$ GeV.

Future *ep* colliders
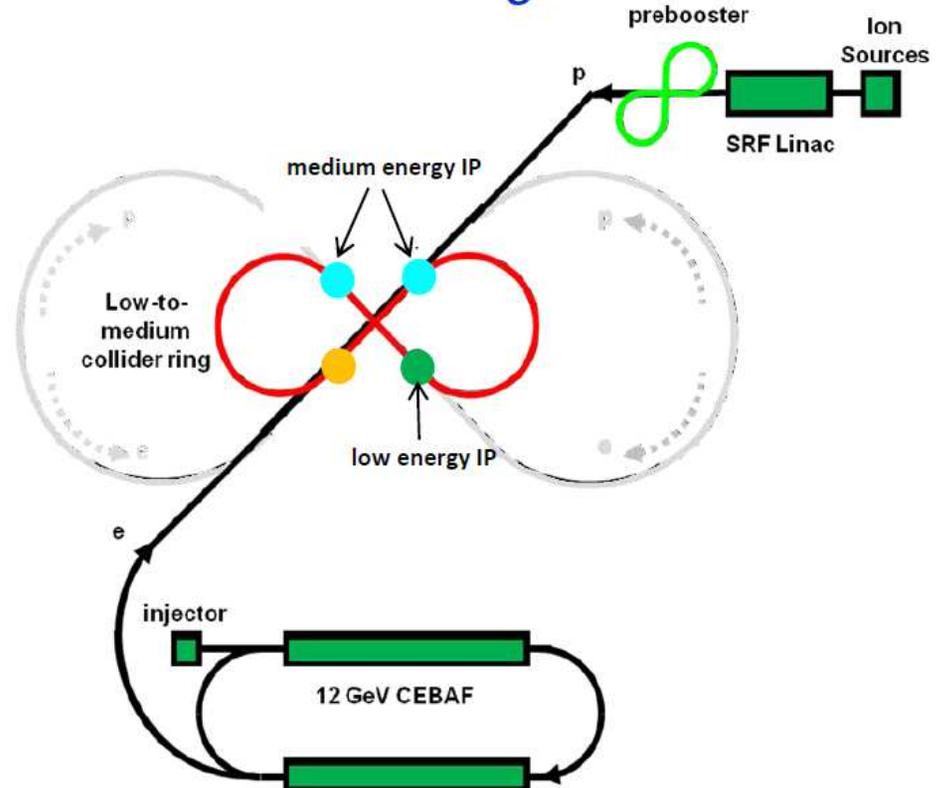
Lepton-Proton Scattering Facilities
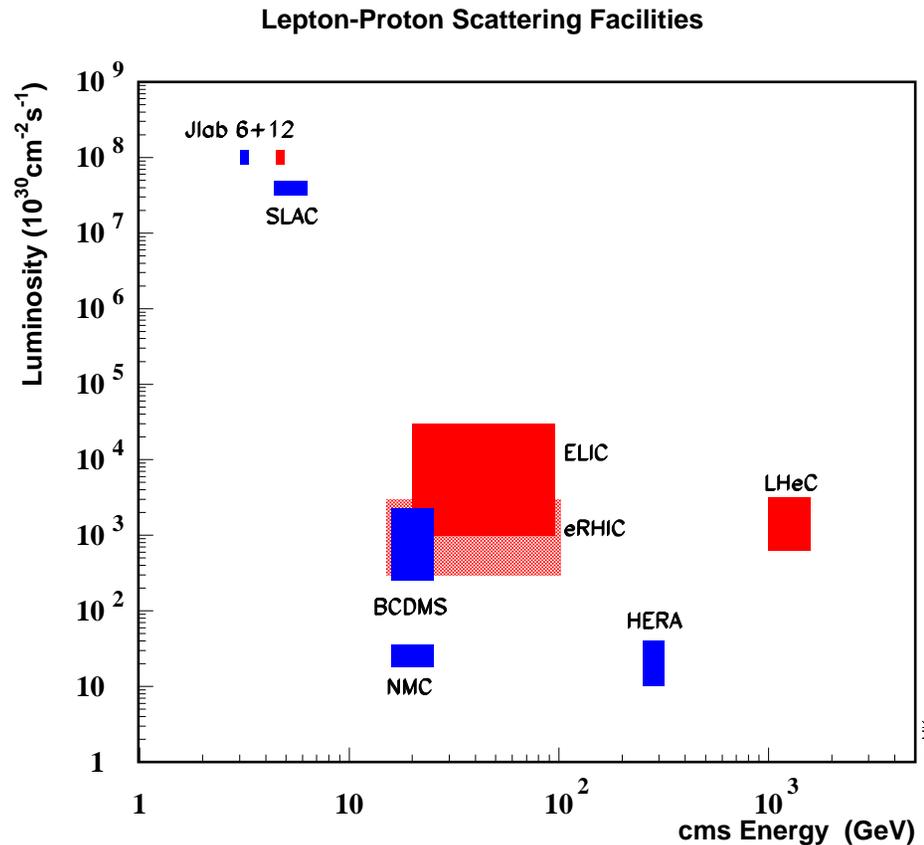
- Much increased luminosity for EIC and LHeC colliders compared to HERA.

- Increased center of mass energy for the LHeC allows for accurate measurements in electroweak regime.

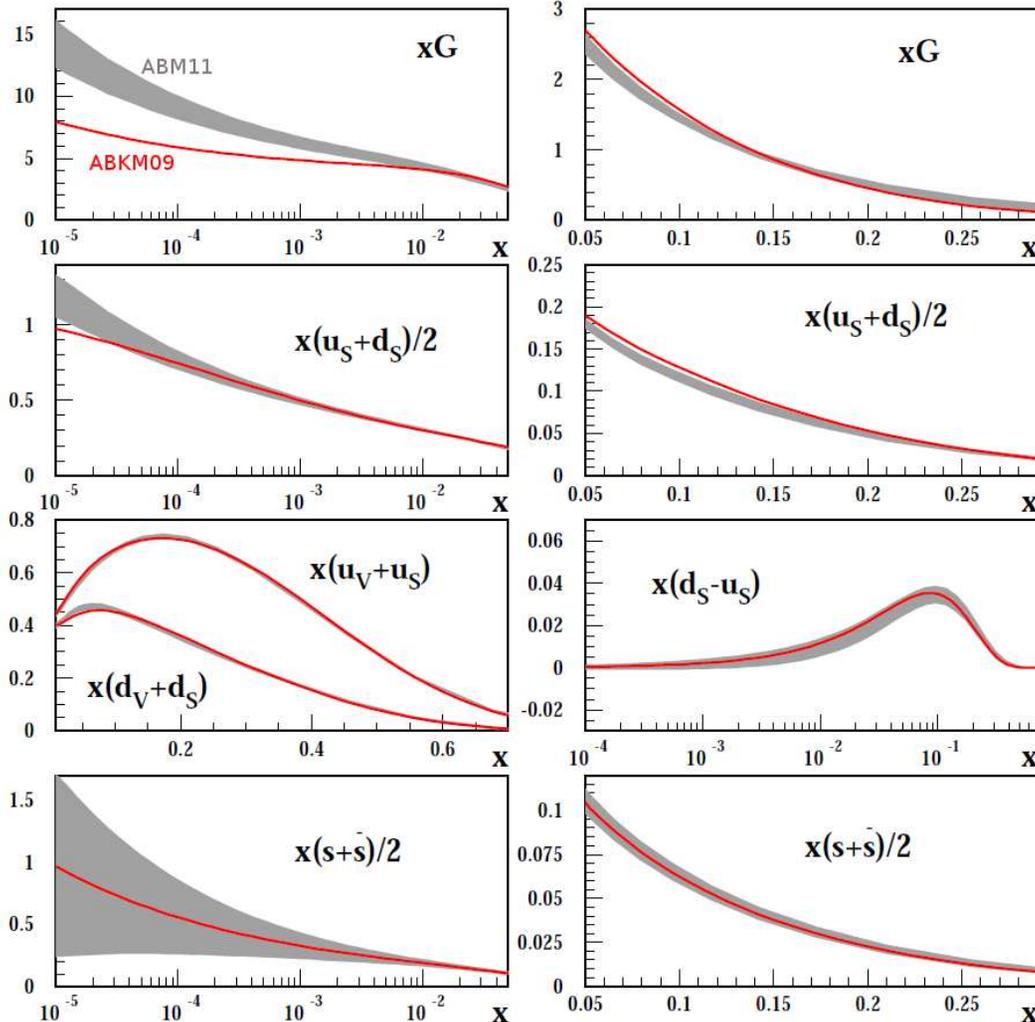eRHIC @ BNL: add electron Energy Recovery Linac in RHIC tunnel
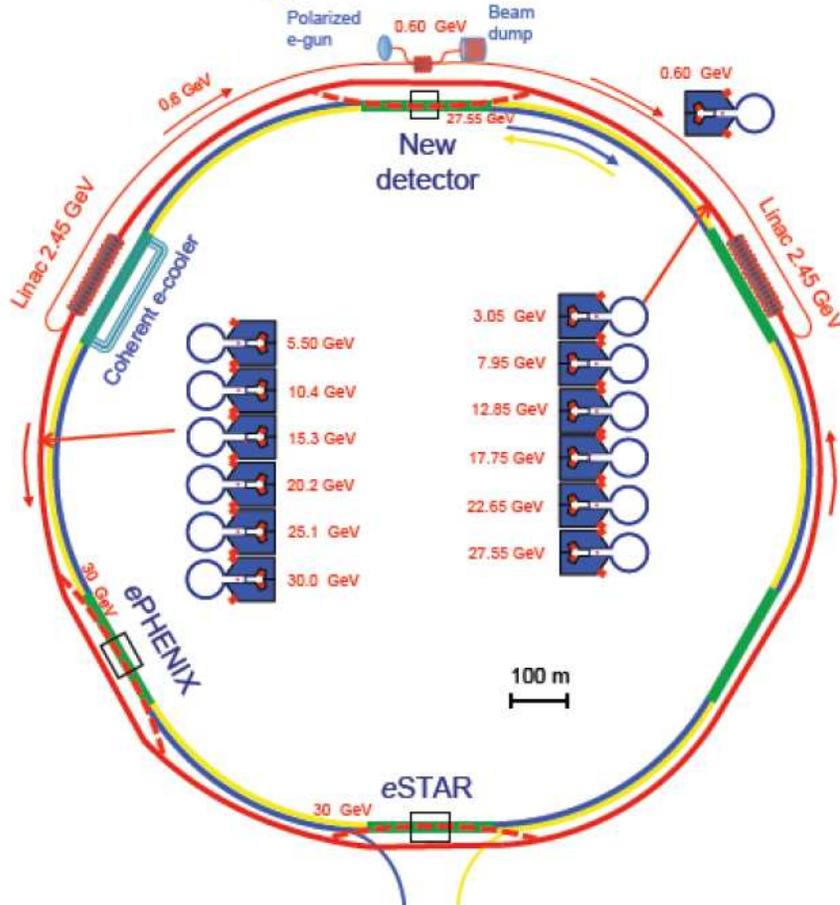
ELIC @ JLab: add figure-8 hadron & electron rings to CEBAF

Two designs for EIC collider. Both designs consider flexible setting for E_p, to measure F_L accurately.

ABM11 set

μ=2 GeV, n_f=4

ABM11 is a recent update of the analysis based on non-LHC data. Comprehensive analysis with a detailed study of experimental uncertainties.
Some changes vs previous ABKM09 set (shown as a red line) are due to usage of combined HERA data and improved treatment of heavy flavours.

S. Alekhin, J. Blümlein, S. Moch, arXiv:1202.2281

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