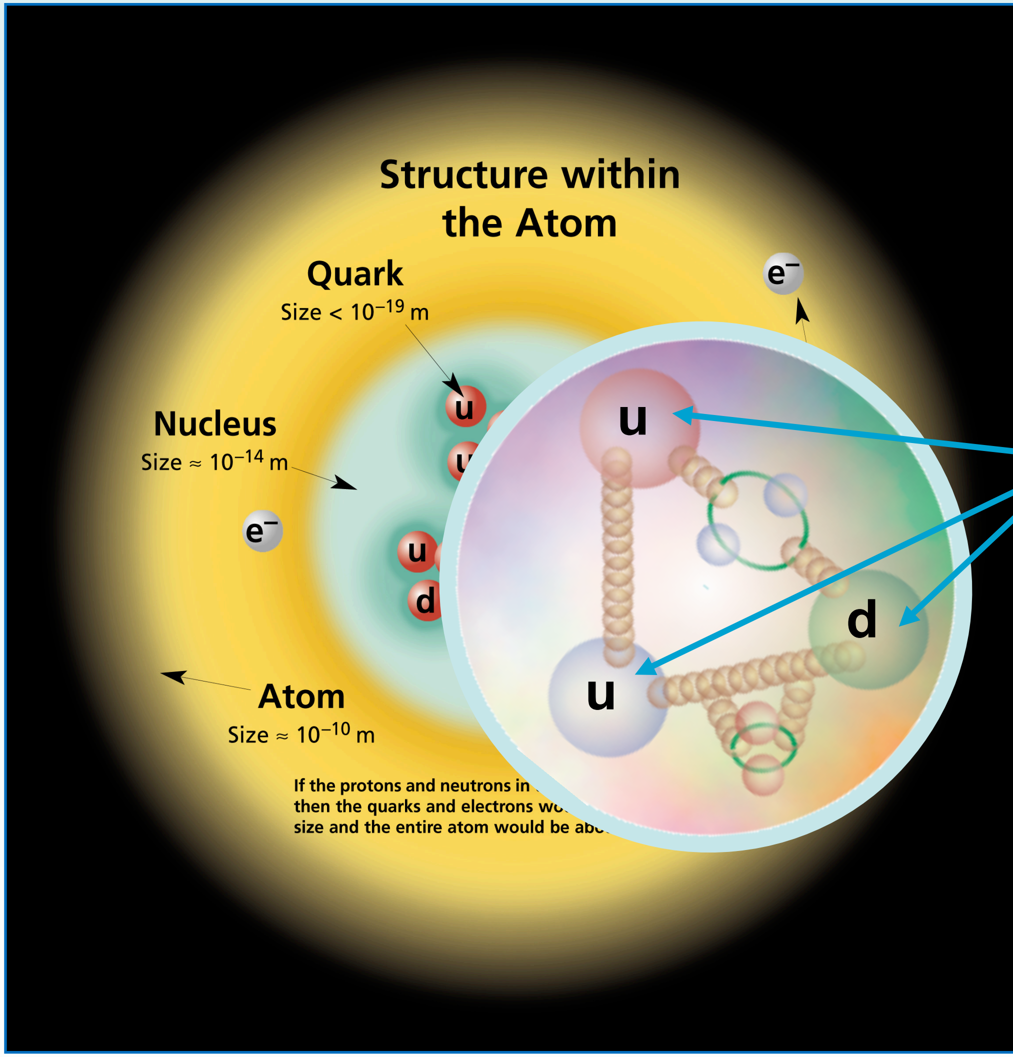
Proton Structure from HERA and the impact for the LHC

Katerina Lipka, DESY

for the H1 and ZEUS Collaborations

Lomonosov Conference on High Energy Physics 2013

Proton structure: fundamental subject in matter studies



baryonic matter

nucleons (protons, neutrons)

mass M_N ~ 1 GeV

partons (quarks & qluons)

valence quarks (u, d)

→ most quantum properties

BUT:

M_u~0.003 M_N , M_d~0.006 M_N

Origin of the proton mass:

QCD energy

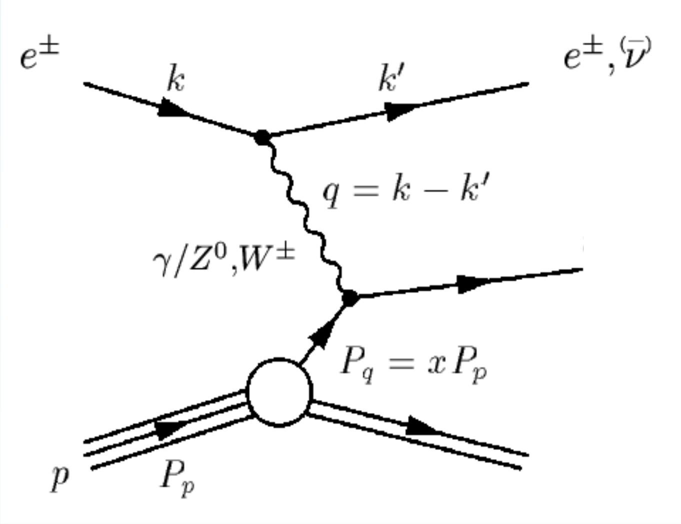
parton composition,
coupling, masses and
momentum distributions

Proton structure in quark-parton model

- Point-like constituents (partons) behave **incoherently**
- Probability $f(x)$ for a parton f to carry the fraction x of the nucleon momentum is an intrinsic property of the nucleon, i.e. **process independent**

Learn about the nucleon structure via lepton-nucleon scattering

Electron-proton scattering in parton picture



Electron scatters off a charged constituent (parton) of the proton

Identify the charged partons with quarks

γ, Z^0 exchange: Neutral Current (NC)

$W^{\pm}$ exchange: Charged Current (CC)

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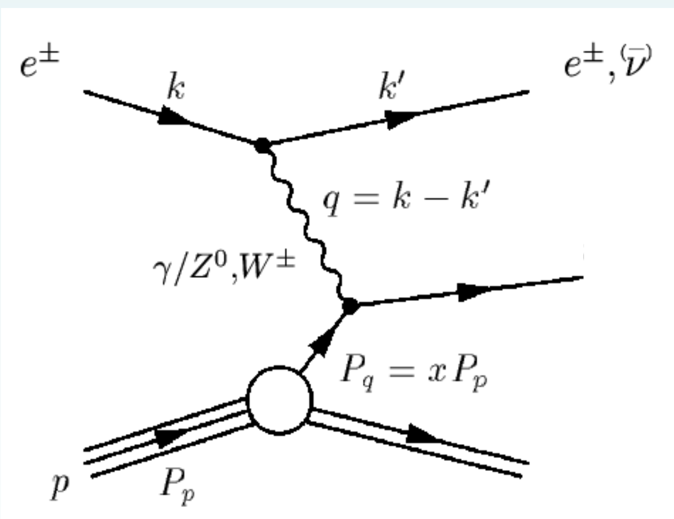
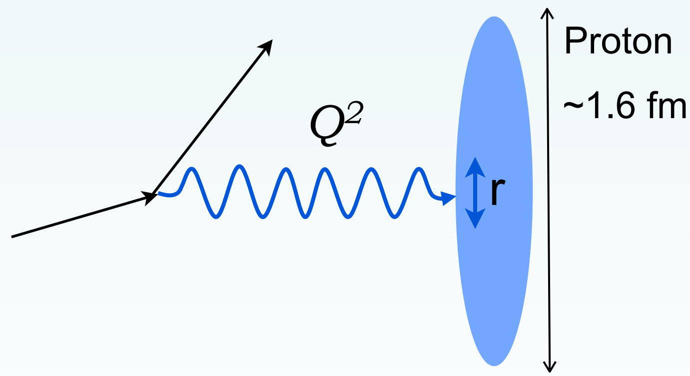


$Q^2 = -q^2$ *photon virtuality*

Kinematics

4-momentum transfer Q^2 defines distance scale r at which proton is probed



$r \approx \hbar c / Q = 0.2[fm] / Q[GeV]$

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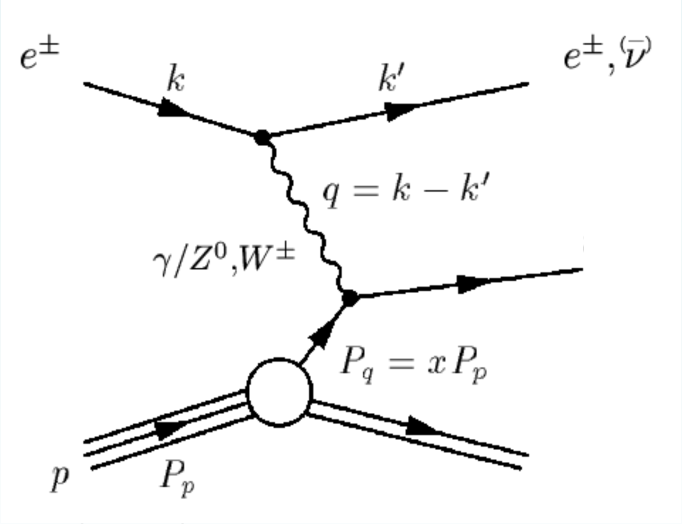
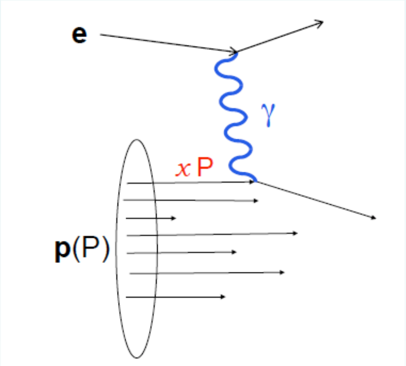


$Q^2 = -q^2$ *photon virtuality*

$x = -q^2 / 2p \cdot q$ *Bjorken scaling*

Kinematics

Infinite proton momentum frame:



partons do not interact, move parallel to the proton, massless, no transverse momentum

parton i carries fraction x_i of P_p

$0 < x_i < 1, \sum x_i = 1$

Proton structure in quark-parton model

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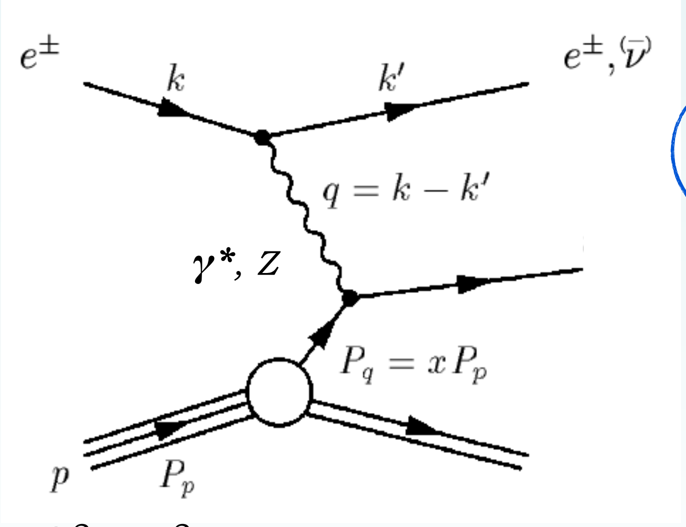
Lepton-proton scattering cross section and proton structure functions

Neutral Current



$Q^2 = -q^2$	*photon virtuality*
$x = -q^2/2p \cdot q$	*Bjorken scaling*
y	*inelasticity*

measured cross-section

$$\frac{d^2\sigma^{e^{\pm}p}}{dx dQ^2} \propto \frac{2\pi\alpha^2}{xQ^4}\left[(1+(1-y)^2)F_2 - y^2 F_L \mp x F_3\right]$$

structure functions

$$F_2 \propto x \sum_f q_f + \bar{q}_f$$

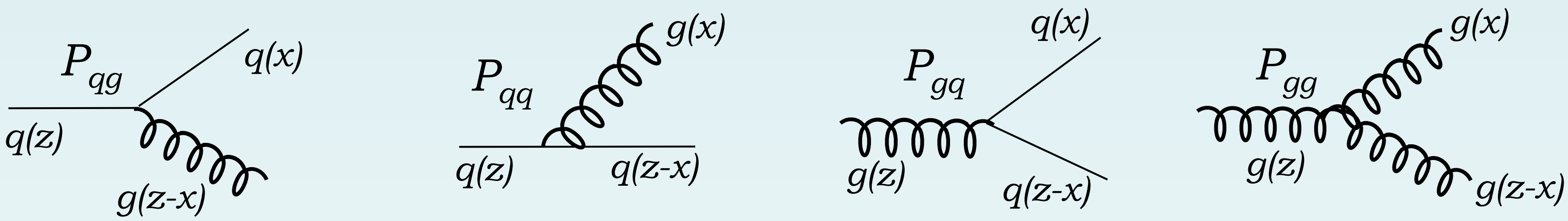
parton distributions

Bjorken scaling:

if partons do not interact, $q=q(x)$; $F_2=F_2(x)$

Proton structure in Quantum ChromoDynamics

Quarks do interact via gluon exchange. Probability via splitting functions:



Parton Distribution Functions: number of partons in the proton, carrying momentum between xP and $(x+dx)P$, as resolved at Q^2.

Scaling violation: $F_2(x) \rightarrow F_2(x,Q^2)$, $q(x) \rightarrow q(x,Q^2)$

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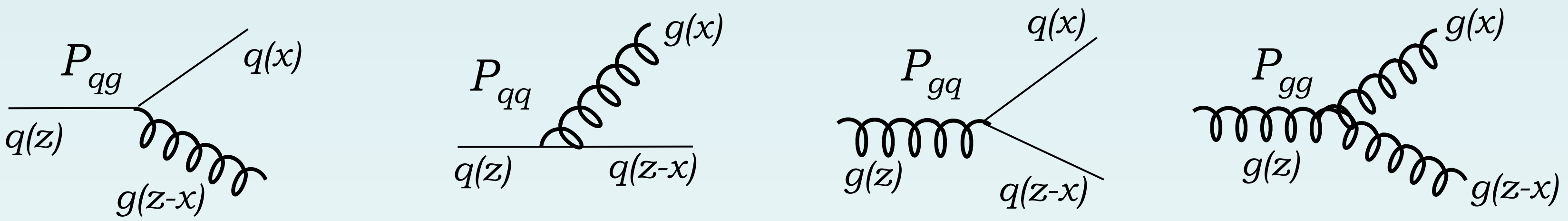

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Additional dependence on Q^2 quantitatively described in perturbative QCD via Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) Evolution Equations

$$\frac{\partial q(x,Q^2)}{\partial lnQ^2} \propto \int_x^1 \frac{dz}{z}\left[q(z,Q^2)P_{qq}\left(\frac{x}{z}\right) + g(z,Q^2)P_{qg}\left(\frac{x}{z}\right)\right]$$

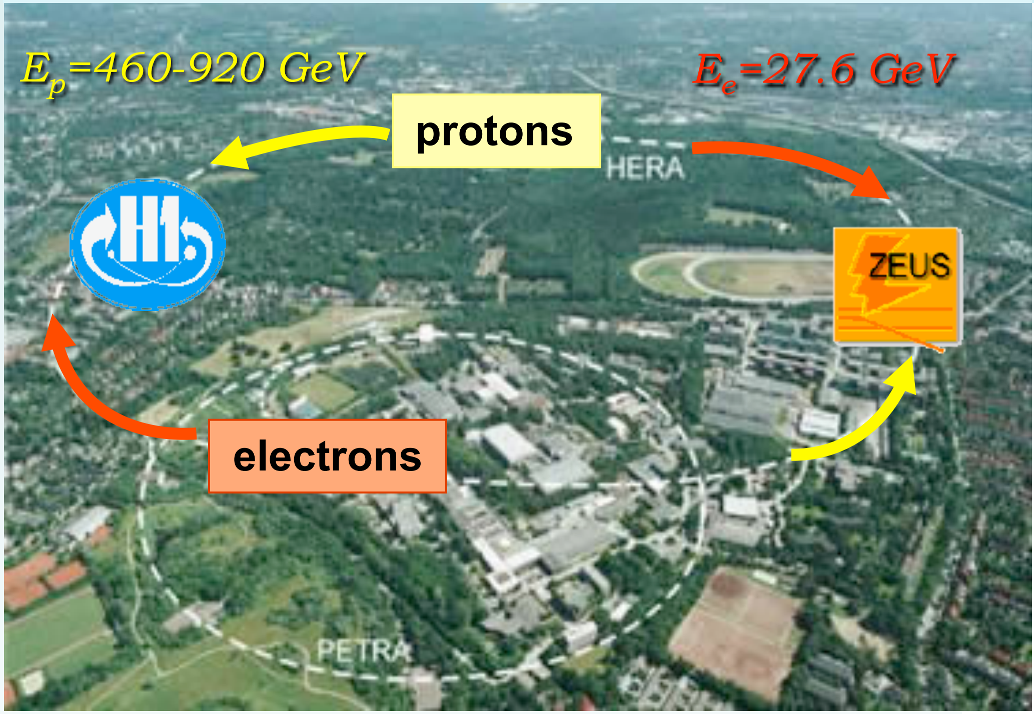
$$\frac{\partial g(x,Q^2)}{\partial lnQ^2} \propto \int_x^1 \frac{dz}{z}\left[q(z,Q^2)P_{gq}\left(\frac{x}{z}\right) + g(z,Q^2)P_{gg}\left(\frac{x}{z}\right)\right]$$

Quark and gluon PDF coupled in DGLAP

PDFs determined experimentally, mostly using data on Deep Inelastic Scattering

DIS at Hadron-Electron-Ring-Accelerator at DESY

World-only *ep* collider

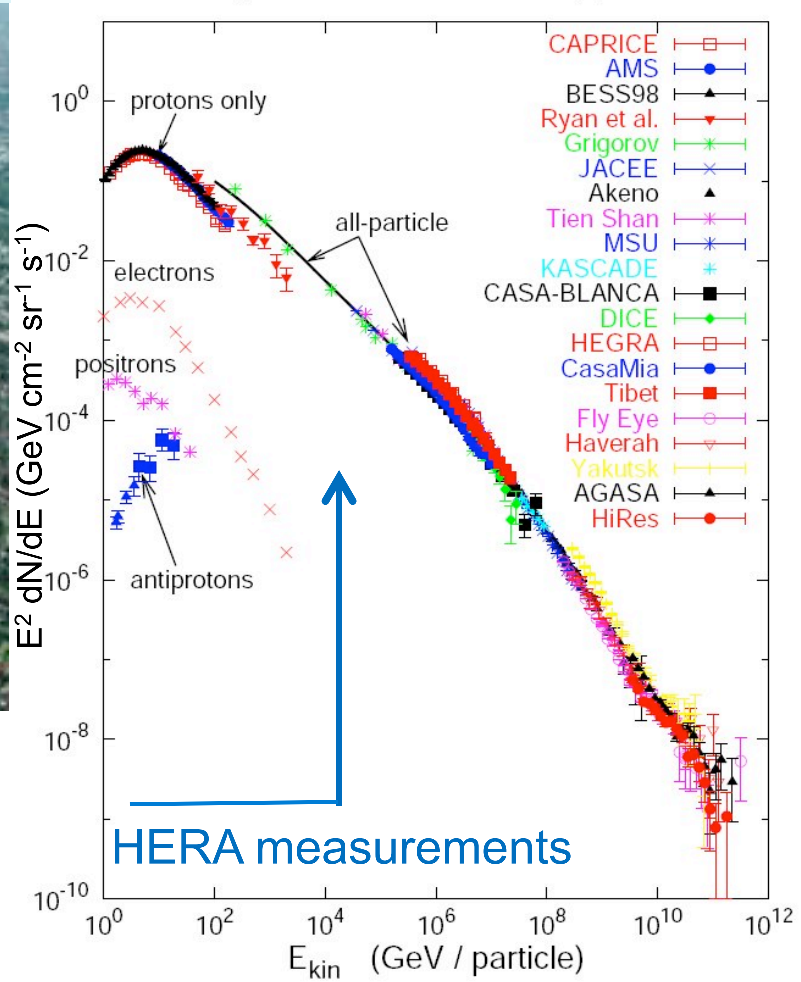


Unique machine to study the proton structure

e → ← p compatible with

50 TeV γ beam on a fixed *p* target

Energies and rates of cosmic ray particles



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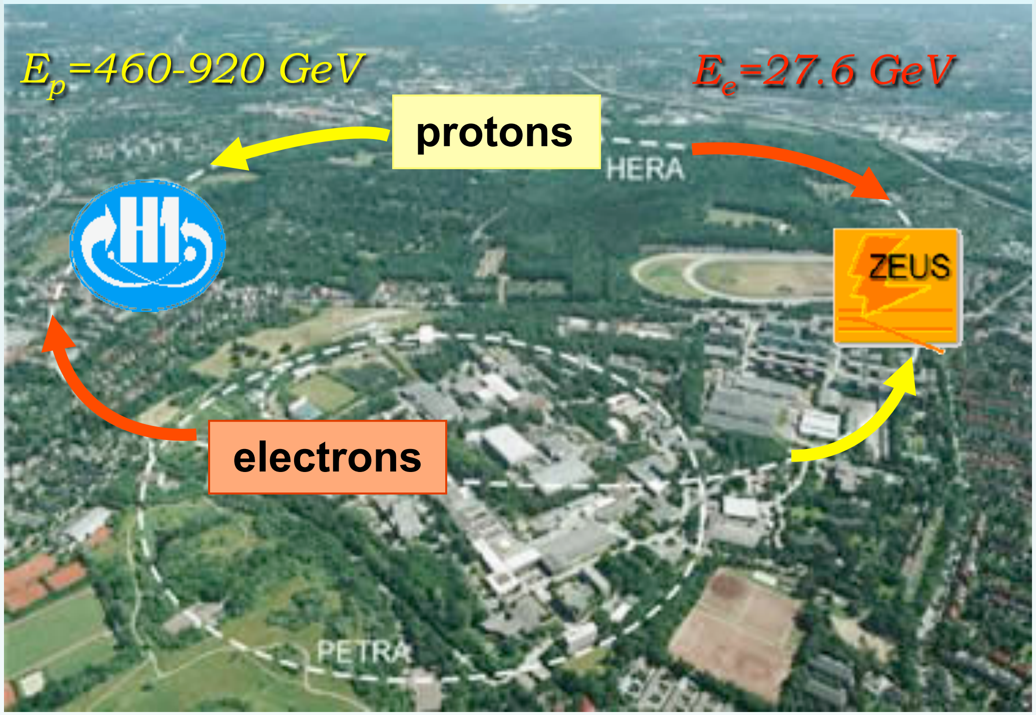


- HERA I : 1992-2000
- HERA II: 2003-2007
- collider experiments

H1 & ZEUS, $\sqrt{s}_{max} = 318\ GeV$

- integrated Luminosity

$\sim 0.5\ fb^{-1}$/ experiment

HERA switched off June 2007, analyses ongoing on the way to final precision

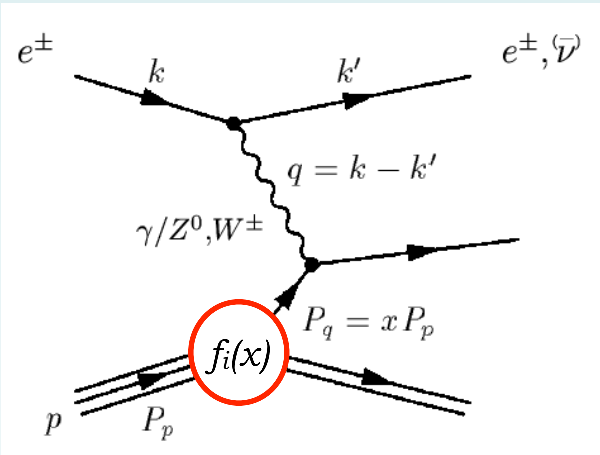
H1 and ZEUS combine experimental data accounting for systematic correlations

HERA performs the QCD analysis of (semi) inclusive DIS data (HERAPDF)

H1 and ZEUS collaborations provide/support the PDF Fitting Tool (HERAFitter)

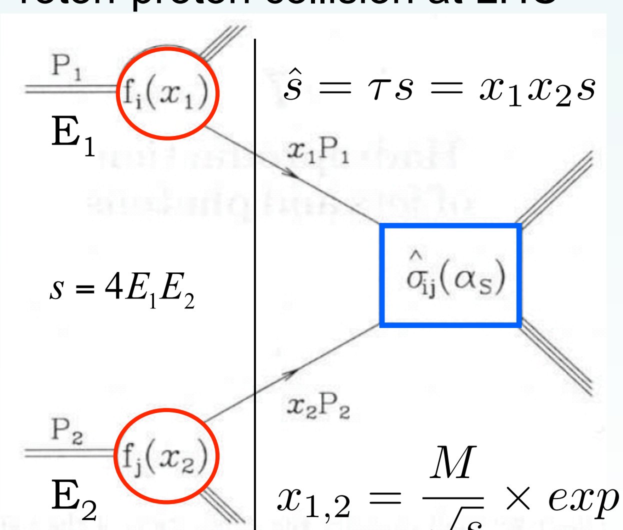
Kinematics at HERA as compared to the LHC

DIS at HERA: clean lepton probe



Kinematics reconstructed from
the scattered lepton (or hadronic final state)

Proton-proton collision at LHC



$$\hat{s} = \tau s = x_1 x_2 s$$

$$s = 4E_1E_2$$

$$x_{1,2} = \frac{M}{\sqrt{s}} \times exp(\pm y)$$

Reconstruction of x_1 and x_2 not straightforward

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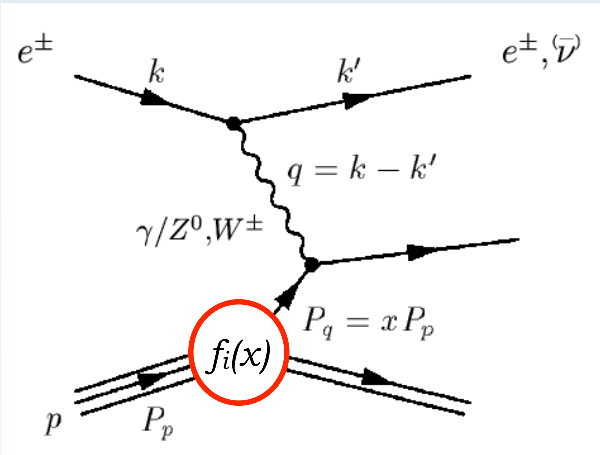

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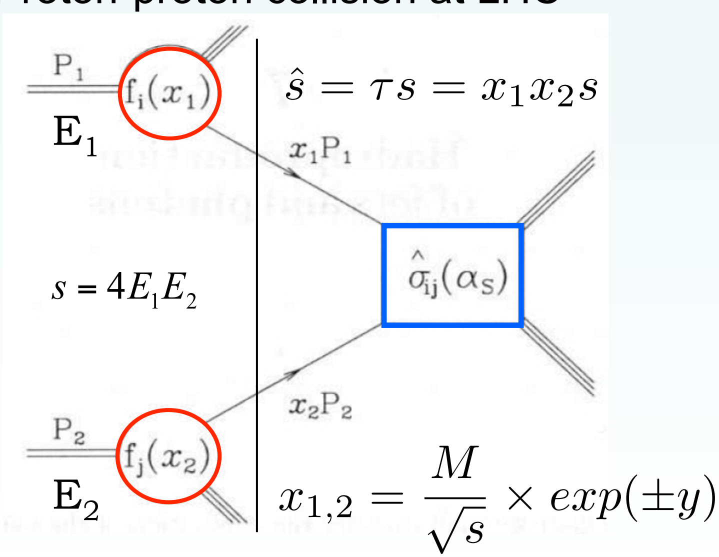
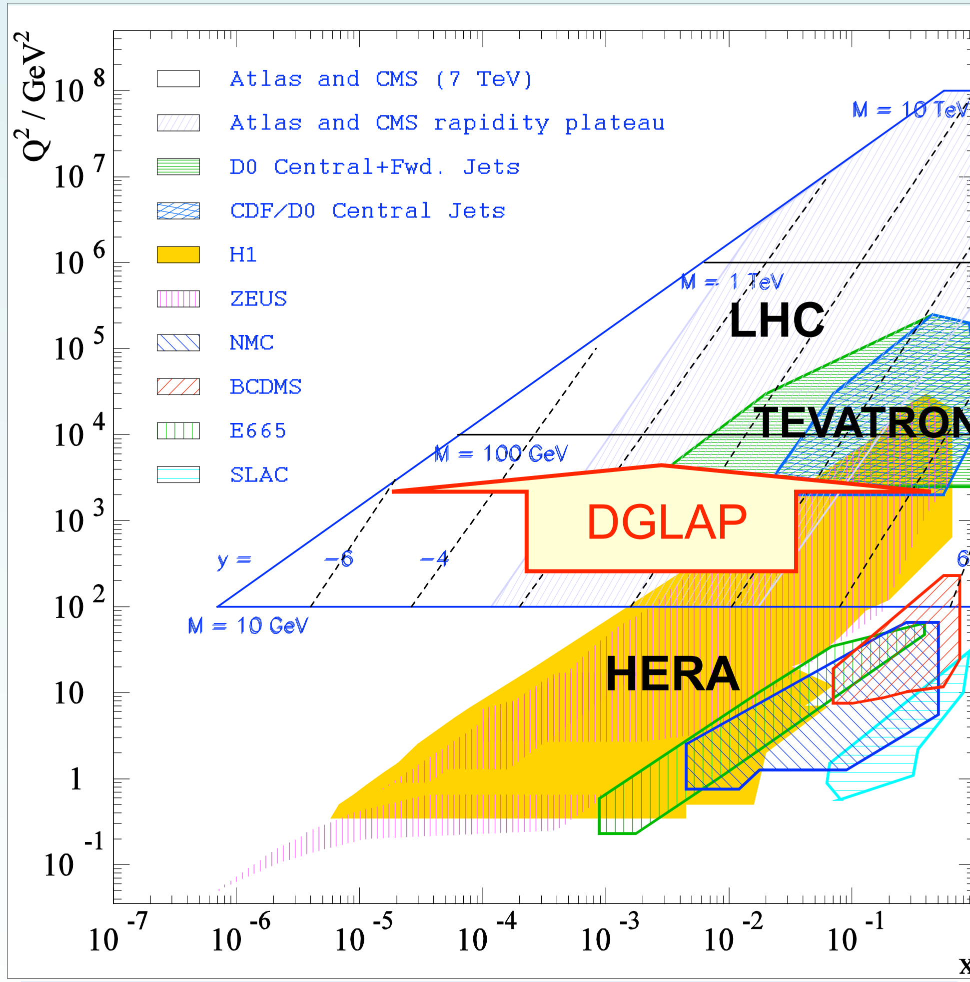


HERA covers low, medium x range of the LHC

Q^2 evolution via QCD

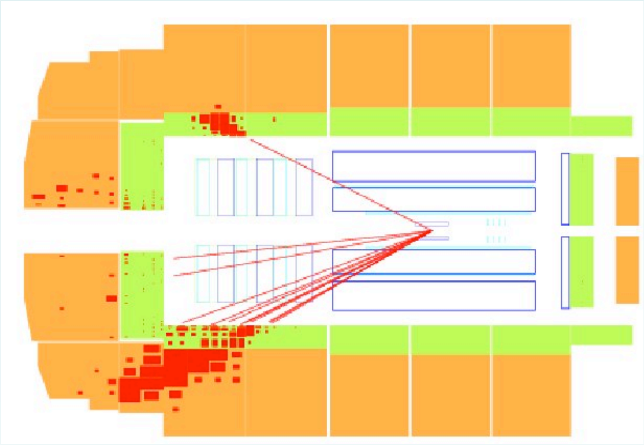


HERA data: backbone for PDF determination

Structure functions in DIS and proton PDFs

DIS cross sections provide an access to parton distribution functions in proton

γ, Z Exchange: Neutral Current $ep \rightarrow e\,X$



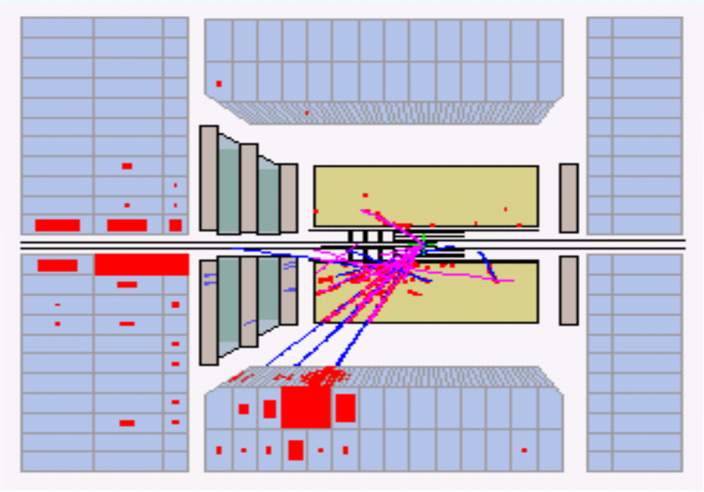
$$\frac{d^2\sigma^{e^\pm P}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}[Y_+ F_2 \mp Y_- x F_3 - y^2 F_L]$$

$LO:\ F_2 \propto \sum_i (q_i(x) + \bar{q}_i(x))$ dominant contribution

$LO:\ F_3 \propto \sum_i (q_i(x) - \bar{q}_i(x))$ γ/Z interference

$NLO:\ F_L \propto x \cdot \alpha_S \cdot g(x, Q^2)$ contribution from gluon

$W^\pm$ Exchange: Charged Current $ep \rightarrow \nu\,X$



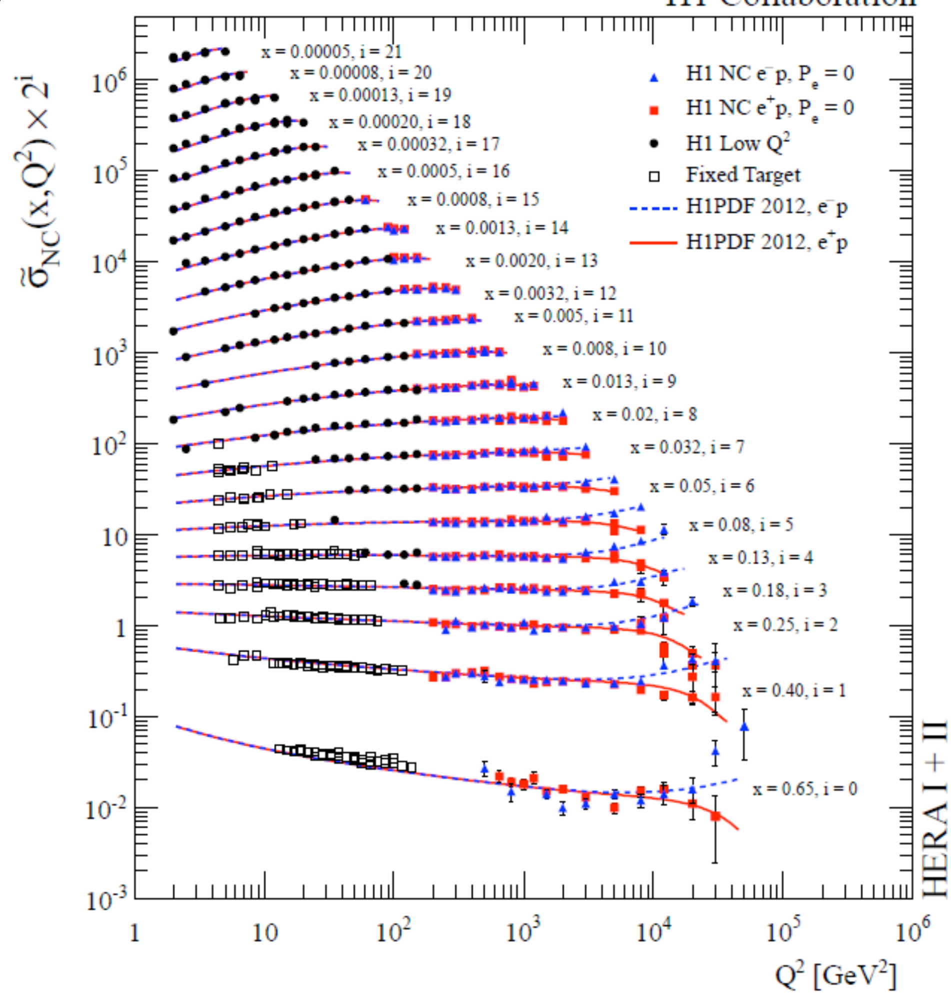
$$\sigma_{CC}^{e^+p} \propto x\{(\bar{u} + \bar{c}) + (1-y)^2(d+s)\}$$
$$\sigma_{CC}^{e^-p} \propto x\{(u + c) + (1-y)^2(\bar{d}+\bar{s})\}$$

sensitive to individual quark flavours

Recent results on Neutral Current Cross Sections

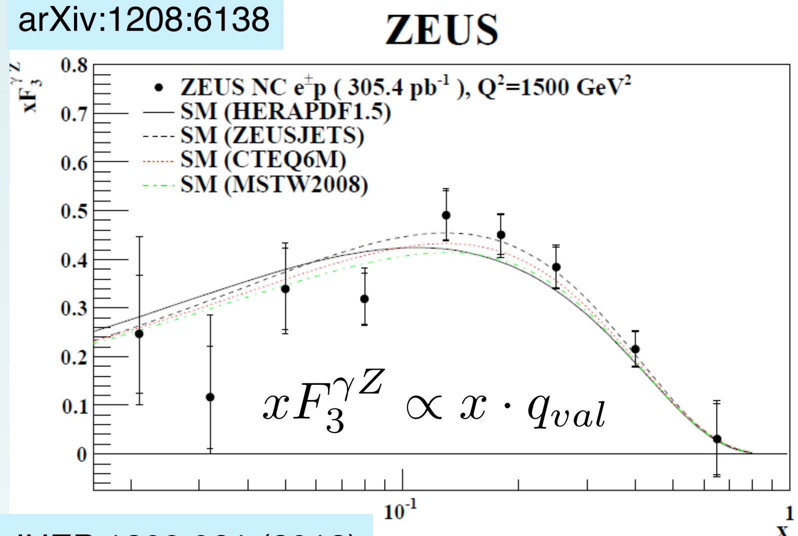
JHEP 1209:061 (2012)

precision 1.5% for $Q^2 < 500$ GeV^2



gluon distribution via scaling violations

arXiv:1208:6138



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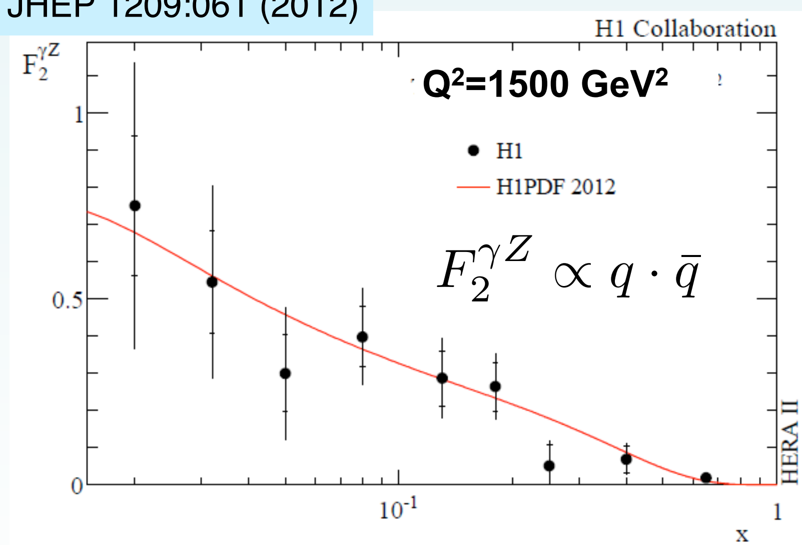
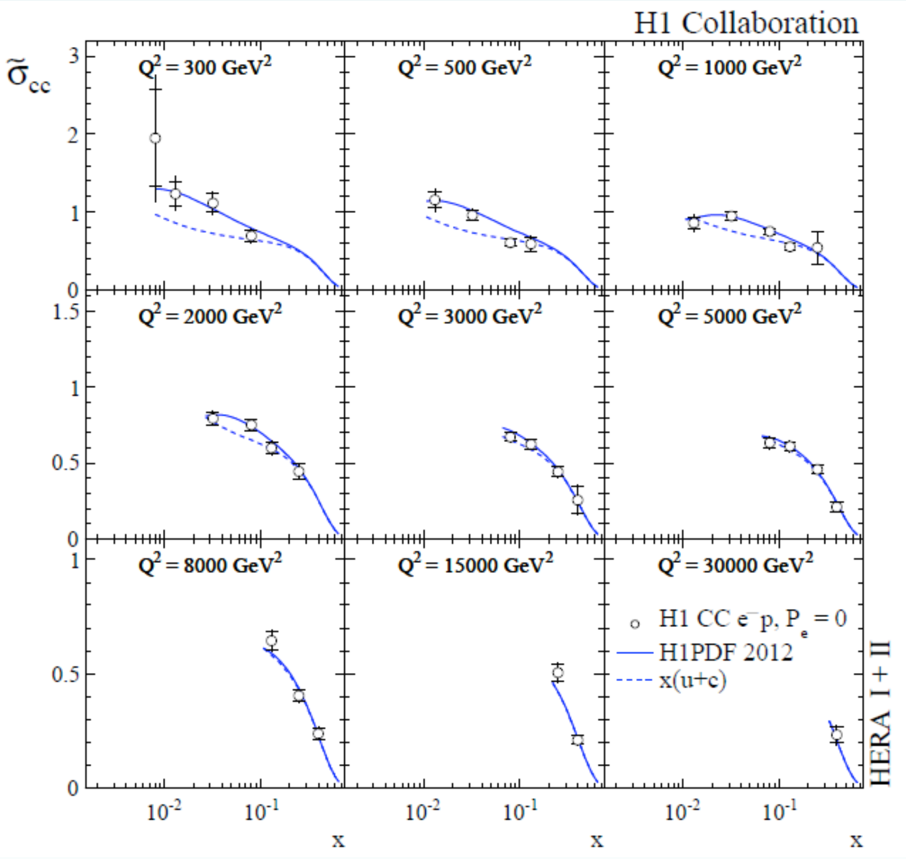


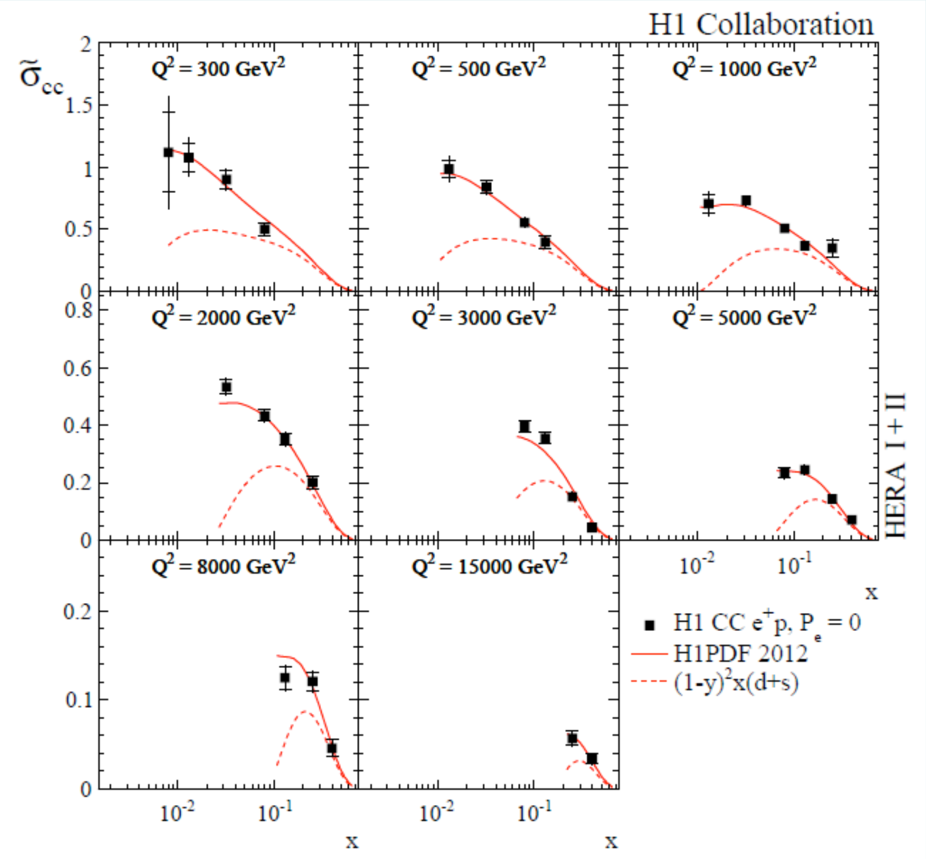
sensitivity to valence composition

Recent results on Charged Current Cross Sections

HERA II: improvement in precision: $e+$ ($e-$) p by a factor of 3 (10) luminosity wrt. HERA I

JHEP 1209:061 (2012)



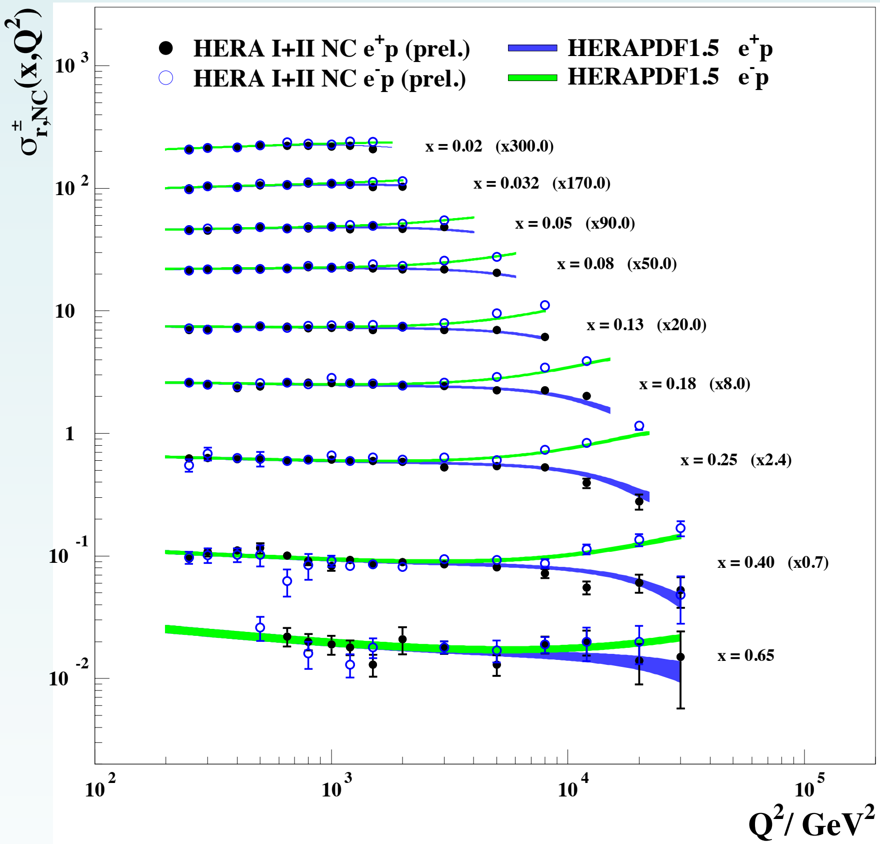


improved sensitivity to quark flavour composition

Combined HERA DIS Cross Sections

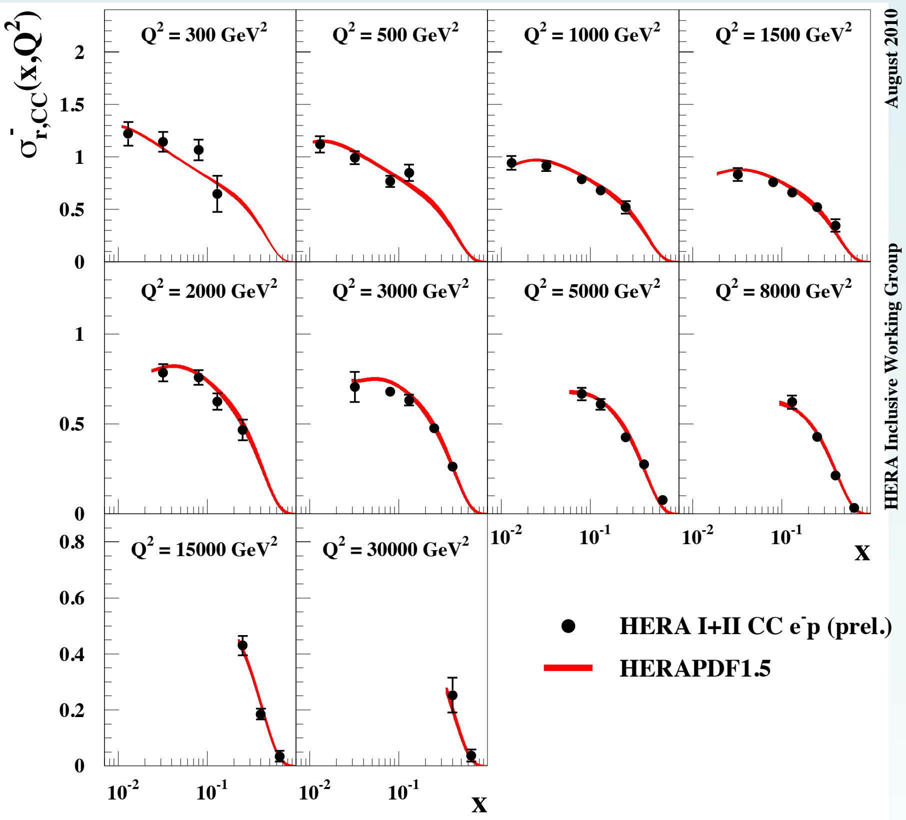
Neutral Current

H1 and ZEUS



Charged Current

H1 and ZEUS



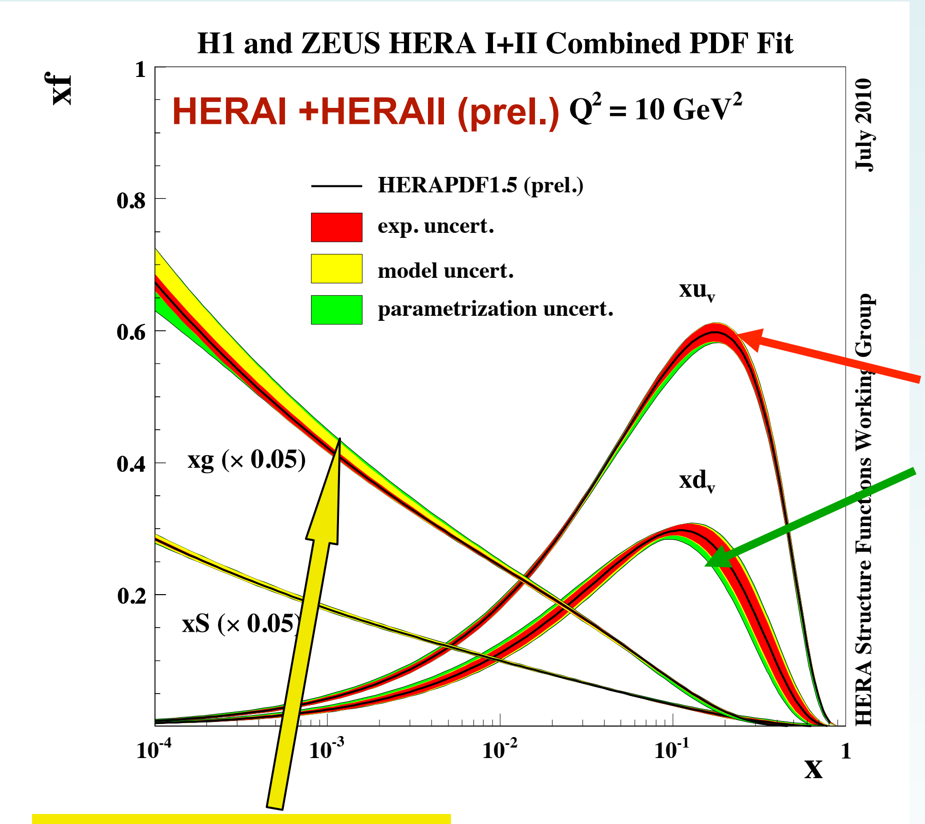
Preliminary H1 and ZEUS measurements are combined accounting for correlations

Impressive precision up to high Q^2 and high x

QCD analysis of combined HERA NC and CC data: HERAPDF

HERA parton density functions

HERAPDF1.5: most precise DIS data, **recommended HERA PDF** set



Model assumptions:

Q_{min}^2=3.5 GeV², $\alpha_s(M_Z)$=0.1176

m_c=1.4 GeV; m_b=4.75 GeV; $f_s(Q_0^2)$=0.31

DGLAP evolution (QCDNUM, arXiv:1005.1481)

Heavy quarks: massive

Variable Flavour Number Scheme

Scales: $\mu_r = \mu_f = Q^2$, starting scale 1.9 GeV²

Experimentally uncertainty ($\Delta\chi^2$ =1)

Parameterization at starting scale:

$$xg(x) = A_g x^{B_g}(1-x)^{C_g}$$

$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+E_{u_v}x^2)$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}$$

$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}$$

$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}$$

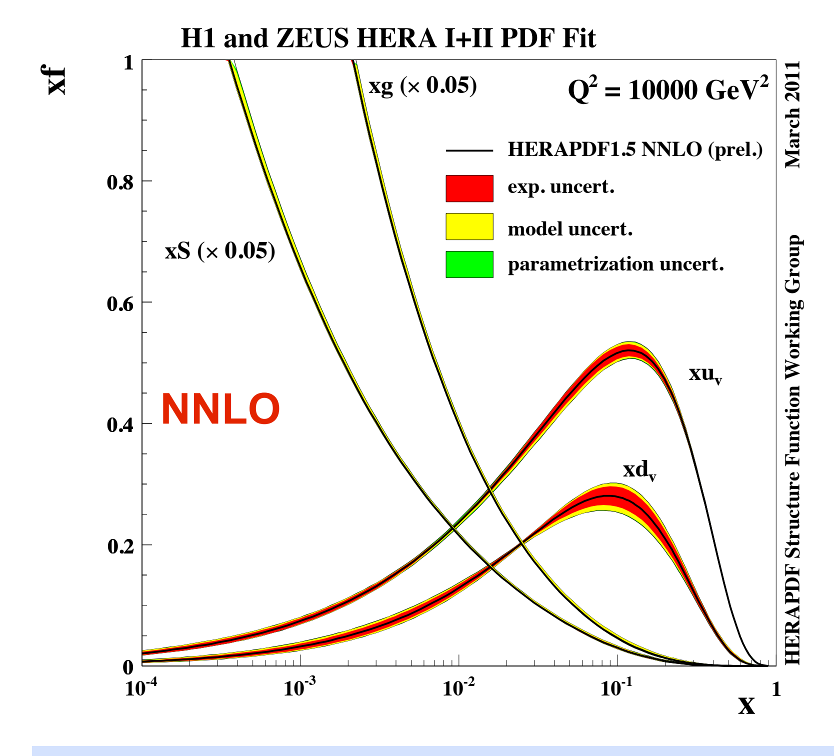
HERA parton density functions

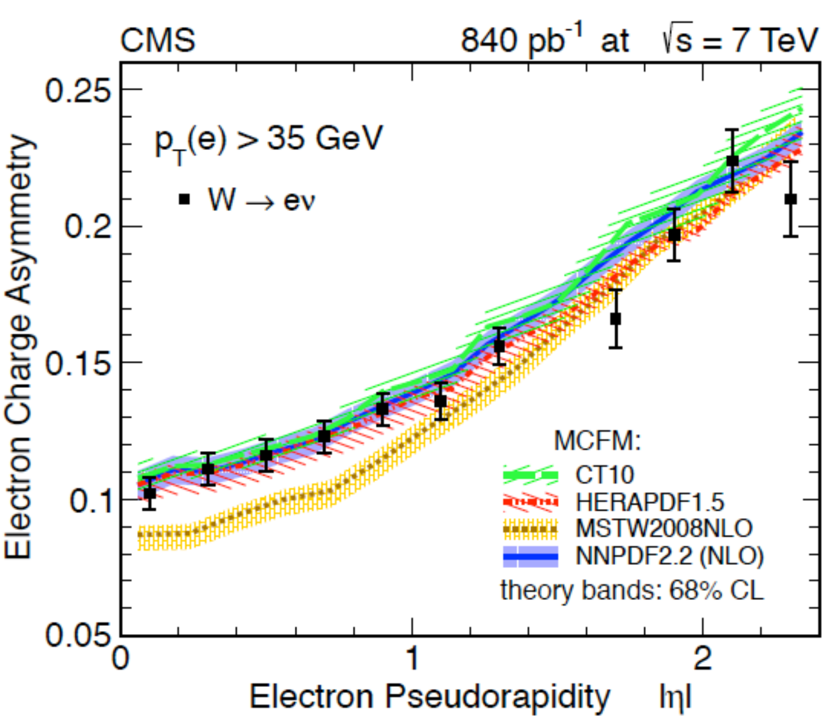
HERAPDF1.5 NLO and NNLO

most precise DIS data, proper treatment of correlation of errors, allows for model studies

Available in LHAPDF with eigenvectors for uncertainties and α_s variation

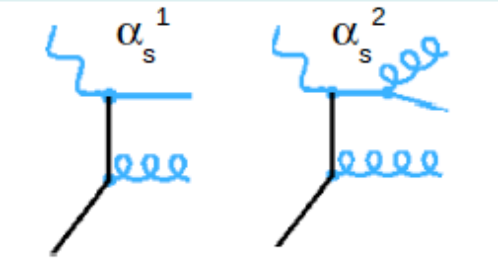
Describes LHC data very well, used in ATLAS, CMS and LHCb analyses





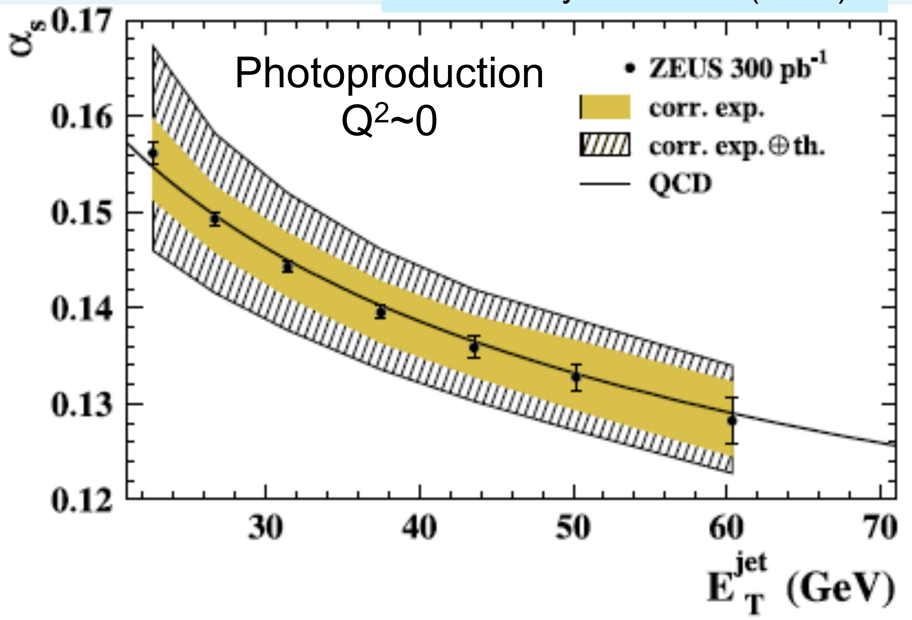
Final combination of HERA inclusive data and QCD analysis on the way (HERAPDF2.0)

Precision QCD: jet production at HERA



(Multi)-jet production directly sensitive to the strong coupling constant

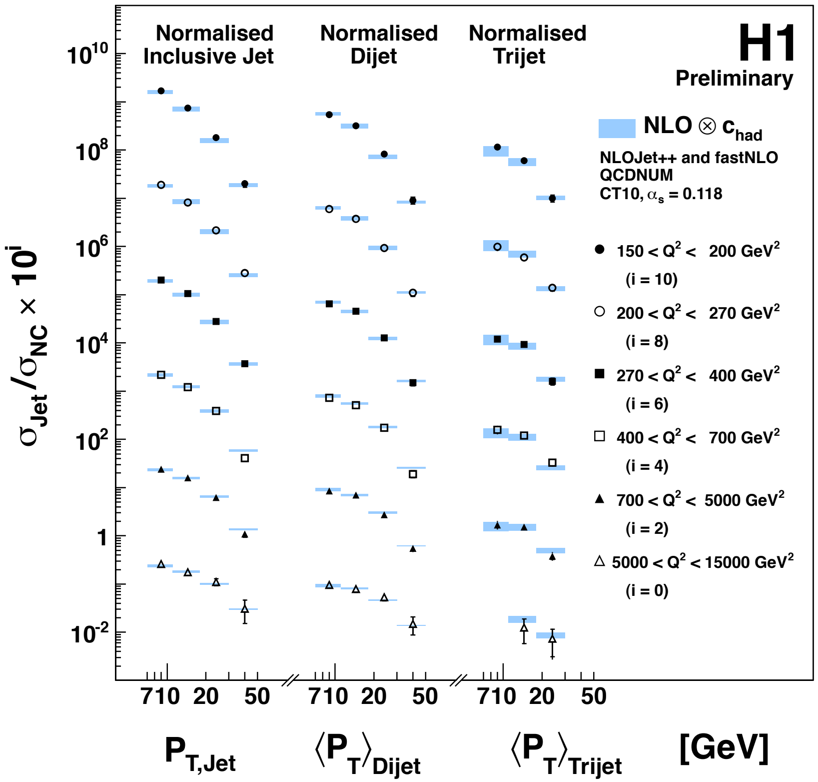
Nuclear Physics B 864 (2012) 1



$\alpha_s(M_Z)=0.1206^{+0.0023}_{-0.0022}$ (exp) $^{+0.0042}_{-0.0035}$ (theory)

Measure α_s running in a single experiment
different measurement methods agree

DIS, 150 GeV² < Q² < 15000 GeV²



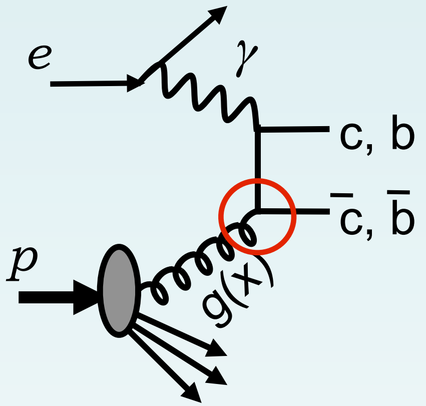
$\alpha_s(M_Z)=0.1163^{+0.0011}_{-0.0011}$ (exp) $^{+0.0042}_{-0.0042}$ (theory)

< 1% experimental error

Additional Constraints on PDFs: Charm at HERA

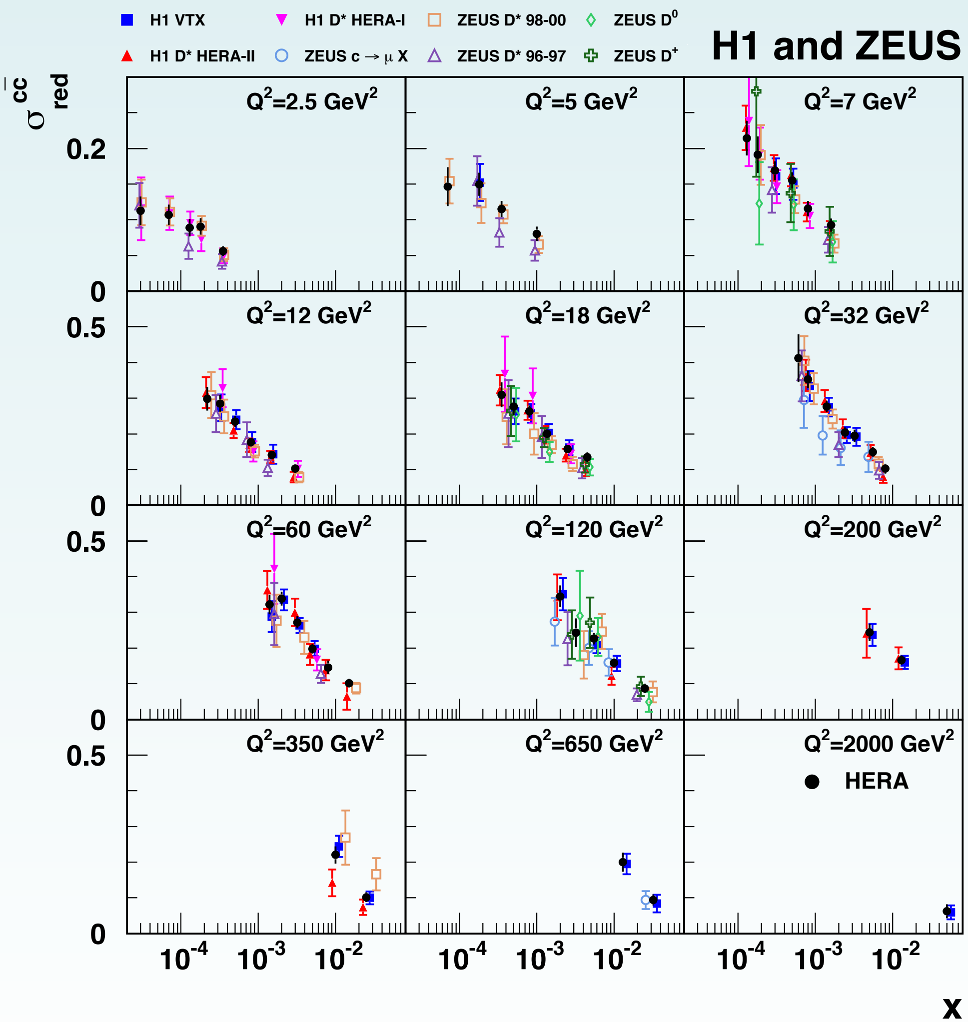
stringent test of QCD, direct probe of the gluon

Eur. Phys. J. C 73:2311 (2013), [arXiv:1211.1182]



use different tagging methods:
- meson reconstruction,
- large mass and long lifetime

combination:
- orthogonal uncertainties
- take into account correlations



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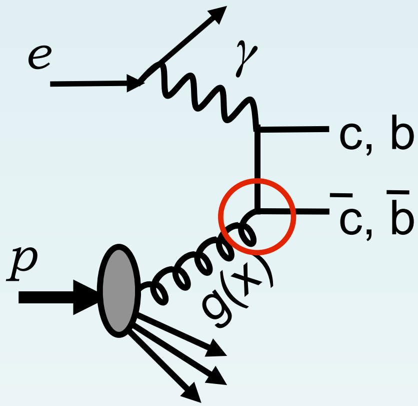

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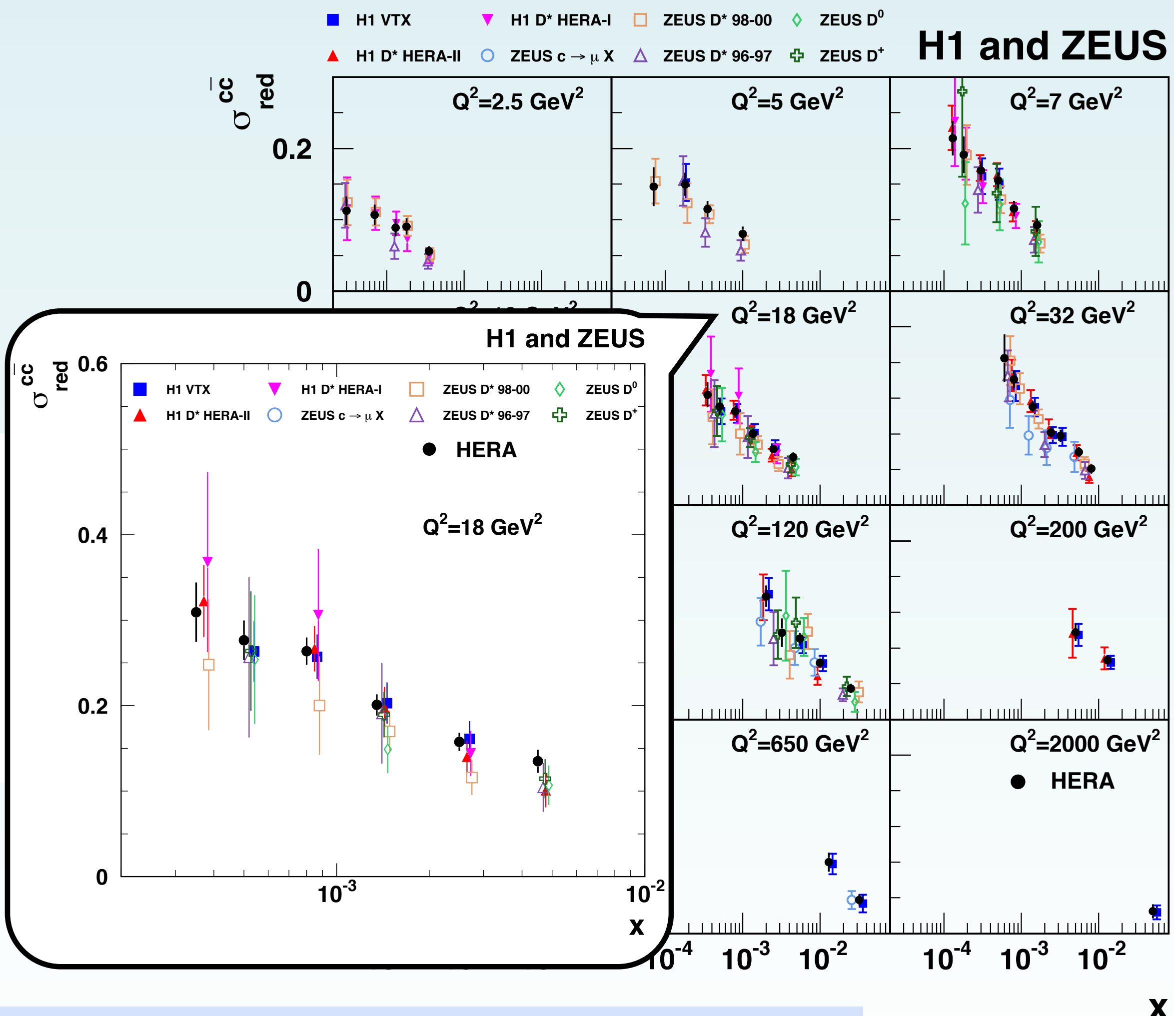
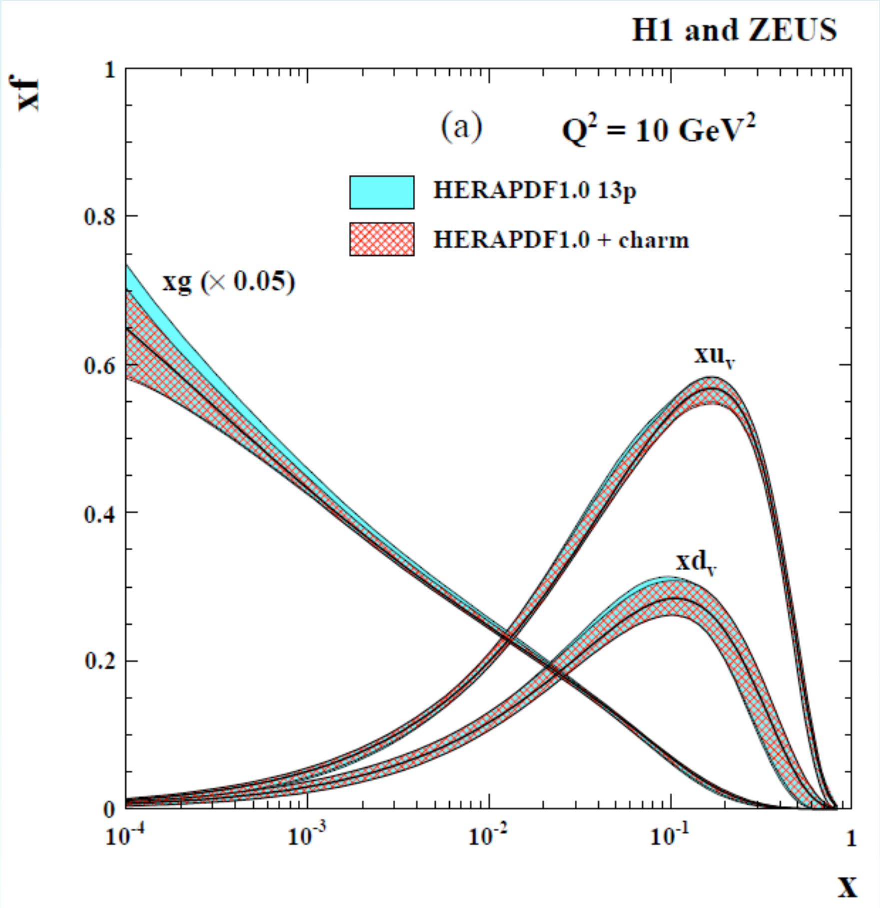
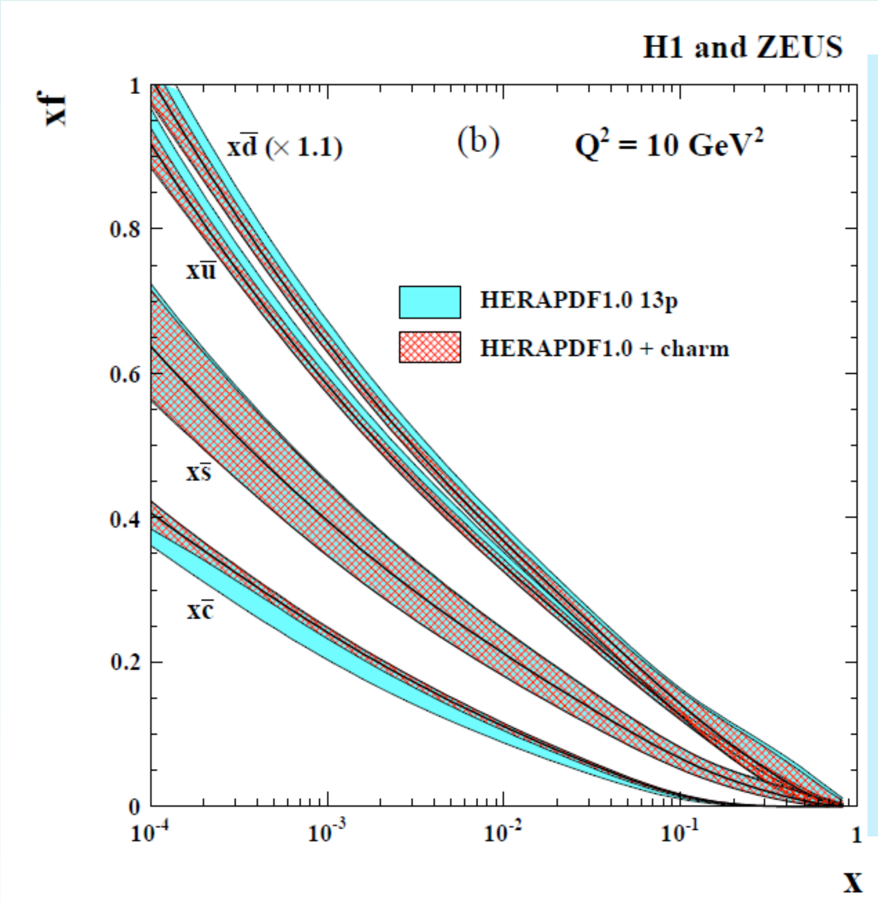


Precision ~ 5% at medium Q^2 reached

Additional Constraints on PDFs: Charm at HERA





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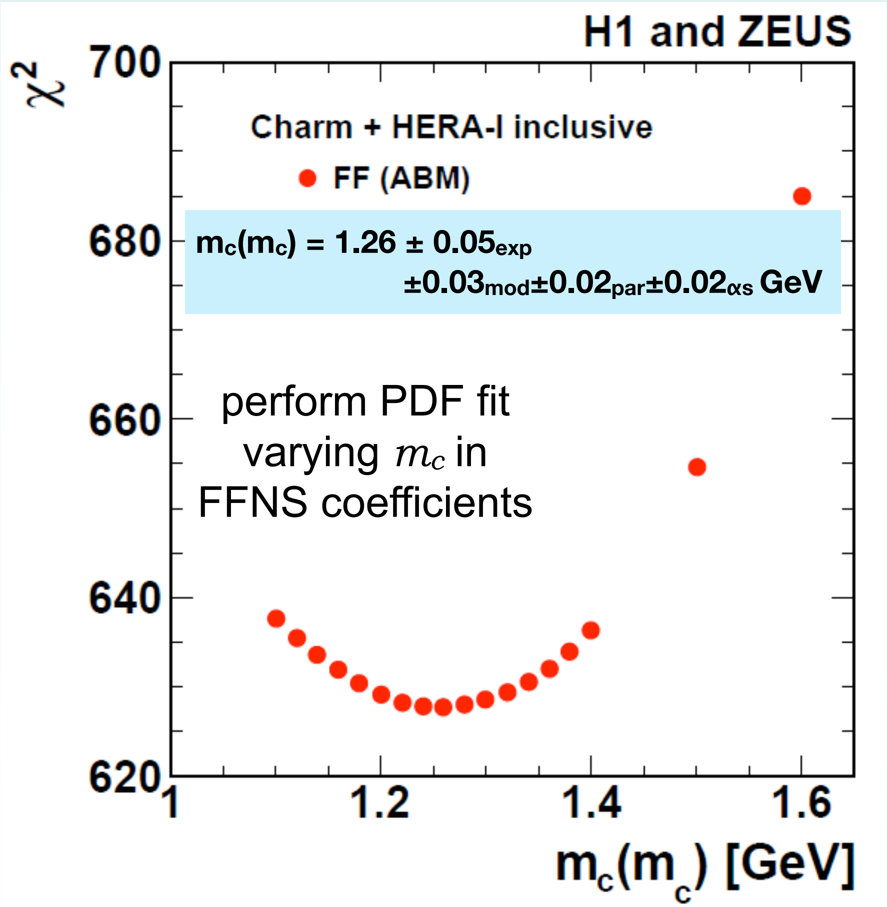
Inclusion of charm: reduced uncertainty on gluon, charm and light sea

...mostly due to better constrained charm-quark mass

Additional Constraints on PDFs: Charm at HERA

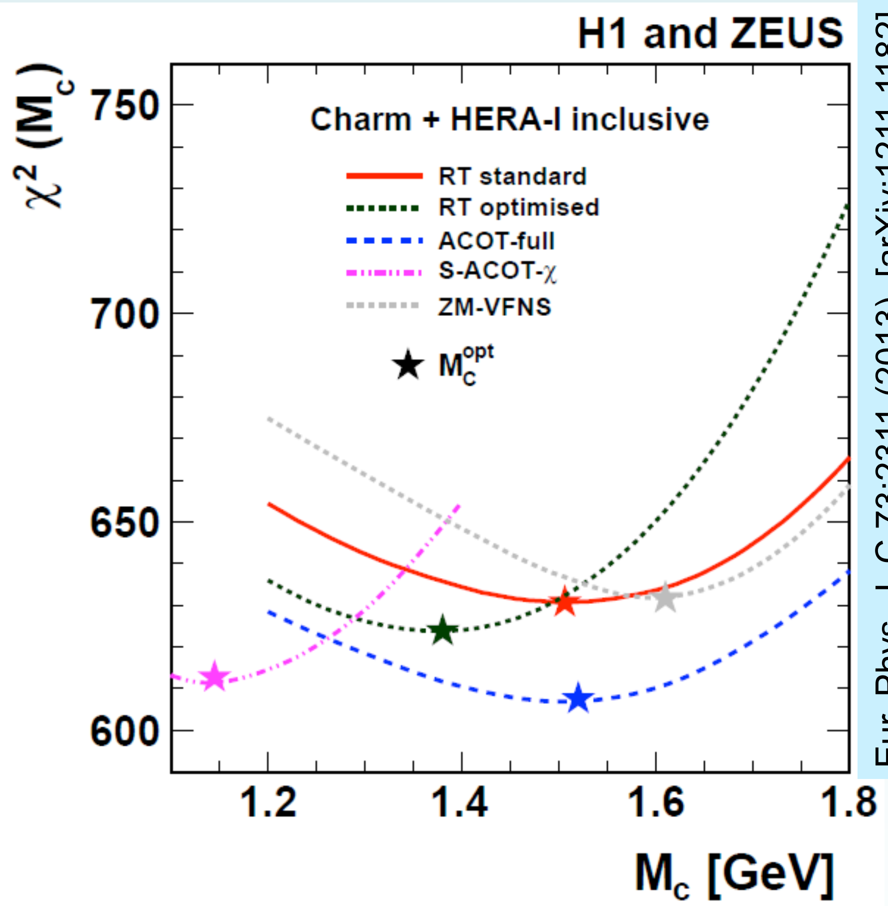
Determination of $m_c(m_c)$ $\overline{\text{MS}}$ at NLO



Consistent with the world average

$m_c(m_c)_{wa}$ = 1.275 ±0.025 GeV

Study m_c -choice in
variable flavor number schemes



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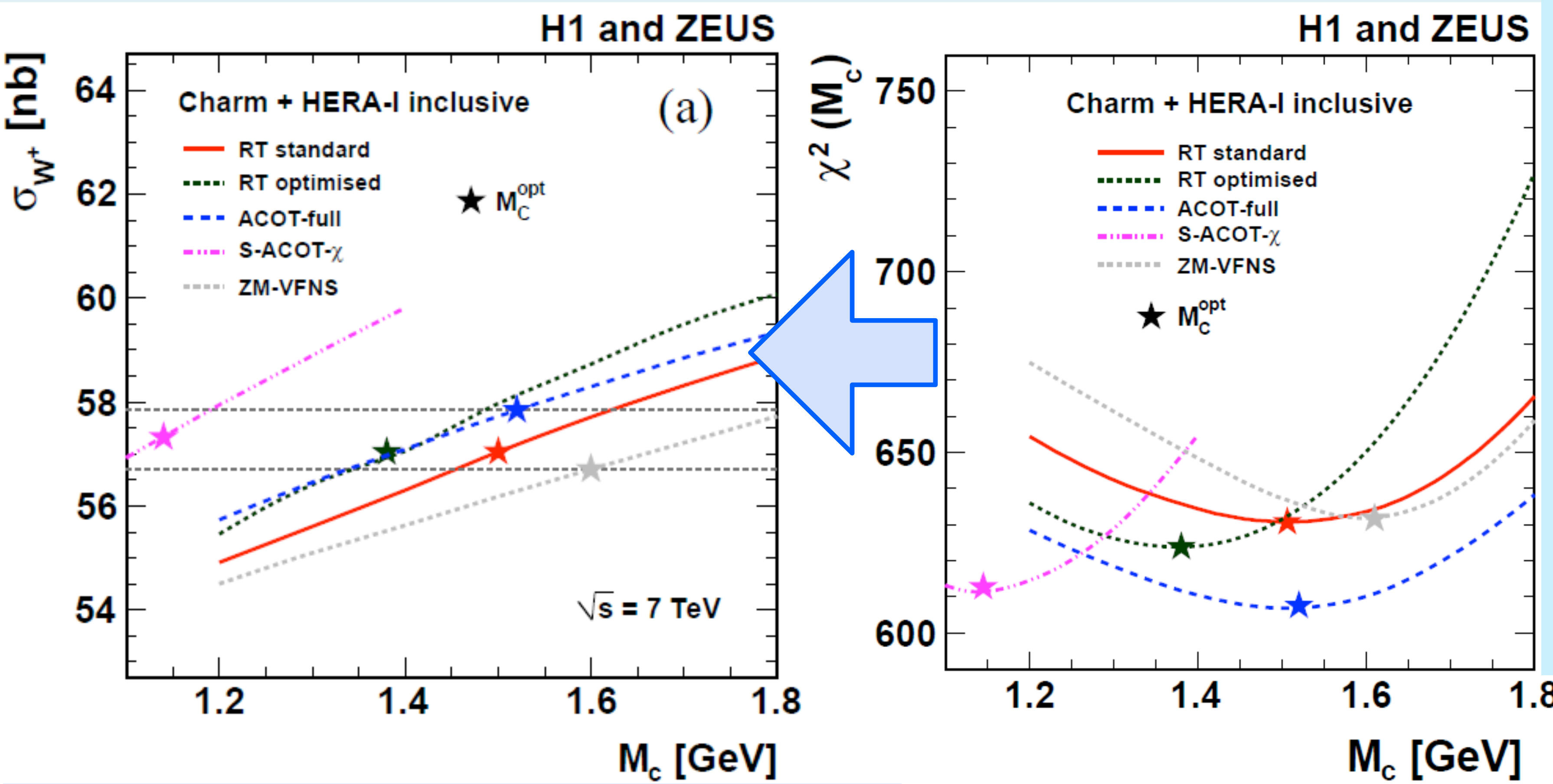
Different schemes prefer different M_c

Additional Constraints on PDFs: Charm at HERA

Prediction for $W+$ ($W-$, Z) production at the LHC

Study m_c -choice in variable flavor number schemes



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Uncertainty due to differences in charm treatment in PDFs significantly reduced by using optimal M_c

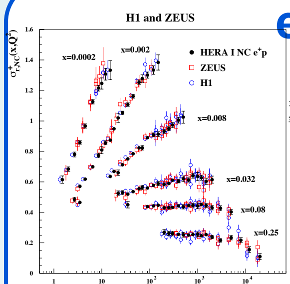
Different schemes prefer different M_c

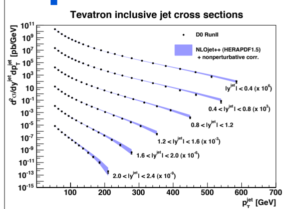
HERAFitter: Open-Source Modular Tool for QCD Analysis

Developed at HERA, extended to LHC and theory groups, https://www.herafitter.org/HERAFitter

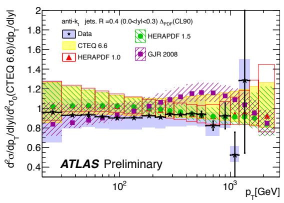
Study the impact of different data on PDFs and test different theory approaches

experimental input





experiments:
HERA, Tevatron,
LHC, fixed target



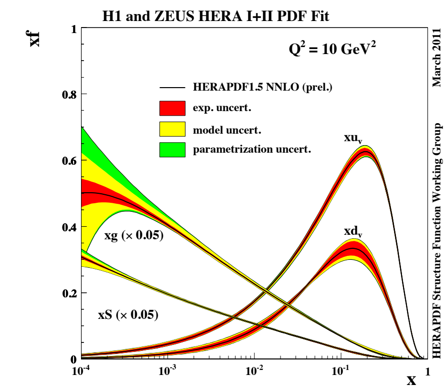
processes:
NC, CC DIS, jets, diffraction,
heavy quarks (c,b,t)
Drell-Yan, W production

theoretical calculations/tools

Heavy quark schemes:	MSTW, CTEQ, ABM
Jets, W, Z production:	fastNLO, Applgrid
Top production	NNLO (Hathor)
QCD Evolution	DGLAP (QCDNUM)
	k_T factorisation
Alternative tools	NNPDF reweighting
Other models	Dipole model

+ Different error treatment models
+ Tools for data combination (HERAaverager)

HERAFitter



PDF or DPDF,...

$\alpha_S(M_Z), m_c, m_b, m_t, f_s$,..

Theory predictions

Benchmarking

Comparison of schemes

Summary

HERA data are unique and of particular importance for PDF determination

- **HERA II inclusive DIS cross section measurements are published**
- **H1+ZEUS combination and analysis towards HERAPDF2.0 ongoing**
- **HERA jet and charm data provide additional constrains on α_S and charm-quark mass**

HERA Expertise in QCD analysis preserved in HERAFitter development

- **developed and supported by several experiments and theory groups**
- **allows experimentalists to perform QCD analysis and test theory approaches**
- **open source program, successfully used by the LHC experiments**

Back up

Determination of parton density functions

Structure function factorization: for the exchange of Boson V $(\gamma, Z, W^{\pm})$

$$F_2^V(x, Q^2) = \sum_{i=q,\bar{q},g} \int_x^1 dz \times C_2^{V,i}(\frac{x}{z}, Q^2, \mu_F, \mu_R, \alpha_S) \times f_i(z, \mu_F, \mu_R)$$

from measured cross sections

calculable in pQCD

PDF

x-dependence of PDFs is not calculable in perturbative QCD:

- parameterize at a starting scale Q^2_0 : $f(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$
- evolve these PDFs using DGLAP equations to $Q^2 > Q^2_0$
- construct structure functions from PDFs and coefficient functions: predictions for every data point in (x, Q^2) – plane
- χ^2- fit to the experimental data

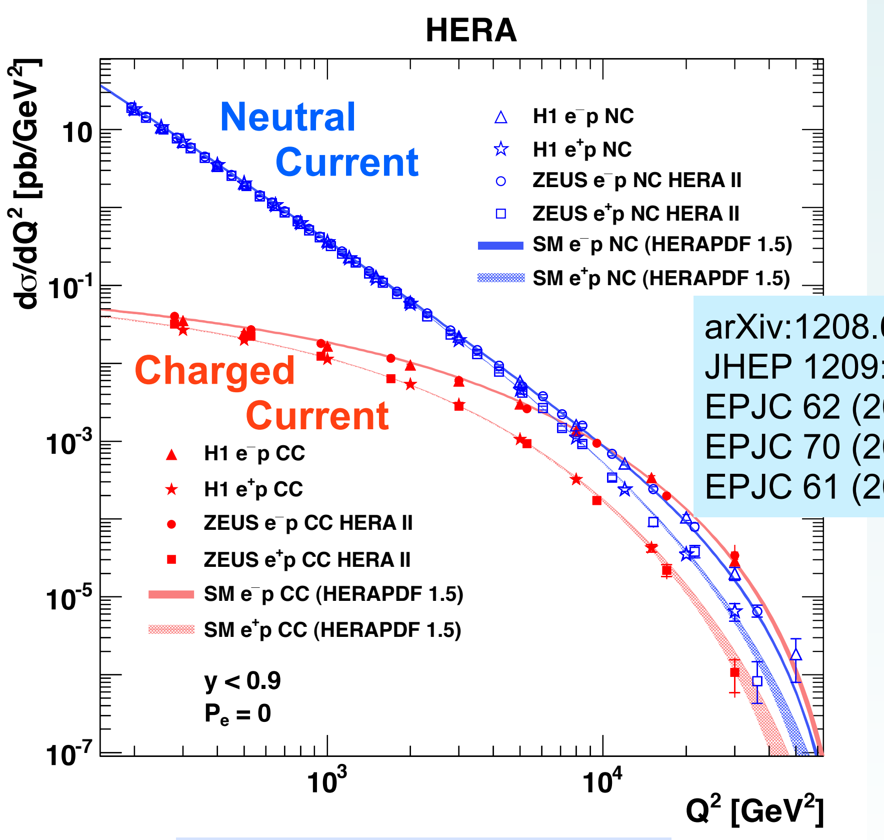
HERA Inclusive DIS Measurements at highest Q^2

HERA textbook measurements in electroweak physics

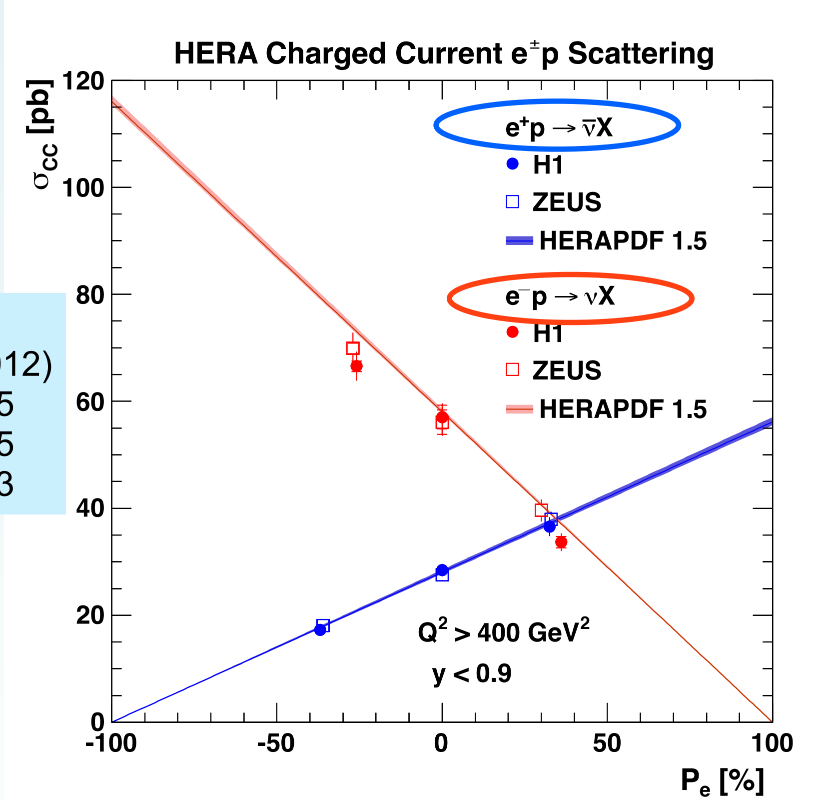
NC and CC cross sections at large scales:

Inclusive HERA I and II data
precision NC: ~1.5%, CC: ~4%

SM: zero cross section for a RH e- or LH e+



arXiv:1208.6138
JHEP 1209:061 (2012)
EPJC 62 (2009) 625
EPJC 70 (2010) 945
EPJC 61 (2009) 223



Electroweak unification

Good agreement with the SM

Combination Procedure

Minimized value:

$$\chi^2(\vec{m},\vec{b}) = \sum_i \frac{\left(m^i - \sum_j \gamma^i_j m^i b_j - \mu^i\right)^2}{(\delta_{i,stat}\mu^i)^2 + (\delta_{i,unc} m^i)^2} + \sum_j b_j^2$$

μ^i measured value at point i

δ_i statistical, uncorrelated systematic error

γ^j_j – correlated systematic error

b_j – shift of correlated systematic error sources

m^i – true value (corresponds to min χ^2)

Measurements performed sometimes in slightly different range of (x,Q^2)

swimming to the common (x,Q^2) grid via NLO QCD in massive scheme

HERAPDF1.7: DIS+ low energy+jets+charm

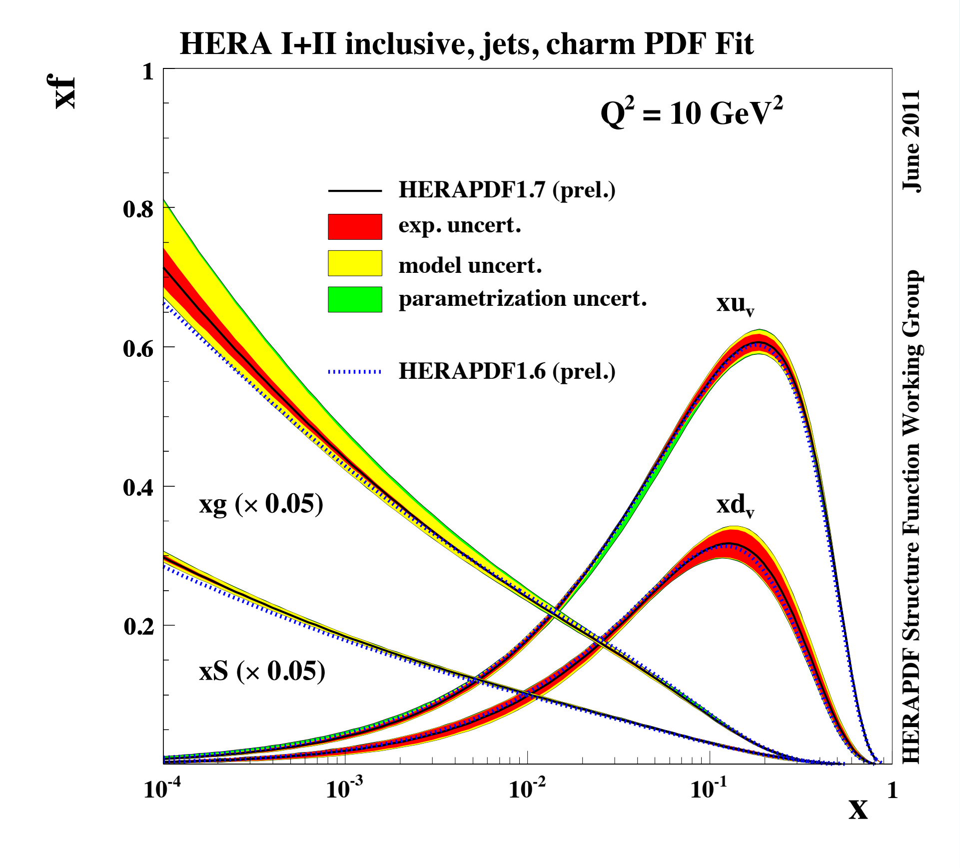
Flexible parametrization

heavy flavours:

m_c=1.5±0.15 GeV

α_S (M_Z)=0.119

steeper gluon as HERAPDF1.6



Including the jet and the charm data: decouple the gluon from α_S and m_c

Heavy Quarks and PDF Fits

Factorization: $$F_2^V(x,Q^2) = \sum_{i=q,\bar{q},g} \int_x^1 dz \times C_2^{V,i}(\frac{x}{z}, Q^2, \mu_F, \mu_R, \alpha_S) \times f_i(z, \mu_F, \mu_R)$$

i - number of active flavours in the proton: defines the factorization (HQ) scheme

- i fixed : Fixed Flavour Number Scheme (FFNS)

  only light flavours in the proton: $i = 3$ (4)

  c- (*b*-) quarks massive, produced in boson-gluon fusion

  $Q^2 \gg m_{HQ}^2$: can be less precise, NLO coefficients contain terms ~ $ln(\frac{Q}{m_{HQ}})$

- i variable: Variable Flavour Number Scheme (VFNS)

- Zero Mass VFNS: all flavours massless. Breaks down at $Q^2 \sim m_{HQ}^2$

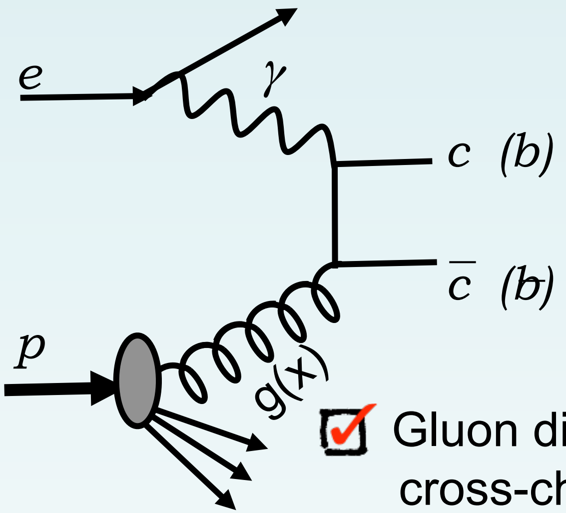
- Generalized Mass VFNS: different implementations provided by PDF groups

  smooth matching with FFNS for $Q^2 \rightarrow m_{HQ}^2$ must be assured

QCD analysis of the proton structure: treatment of heavy quarks essential

Heavy Quark Production at HERA

Heavy quarks in *ep* scattering produced in boson-gluon fusion



Contribution to total DIS cross section:

charm: ~ 30% at large Q^2

beauty: at most few %

☑ Gluon directly involved:
cross-check of *g(x)* from NC and CC DIS cross sections

☑ HQ contributions to the proton structure function F_2 : (e.g. charm)

$$\sigma^{cc} \propto F_2^{cc}(x,Q^2) - \frac{y^2}{1+(1-y)^2} F_L^{cc}(x,Q^2)$$

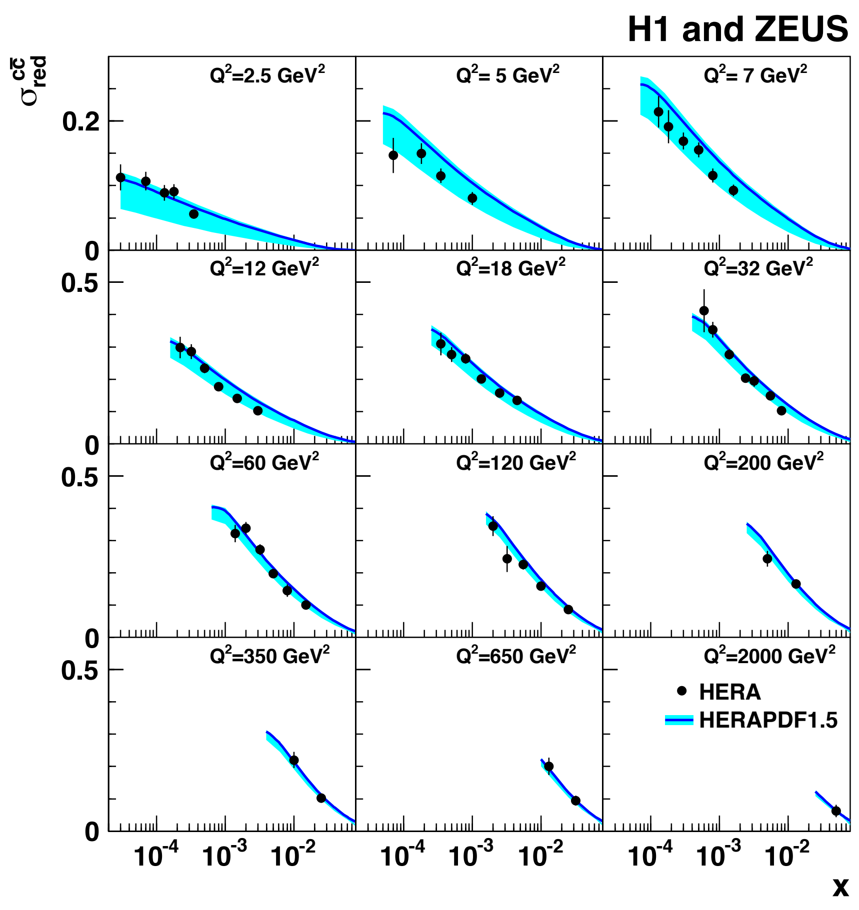
→ Direct test of HQ schemes in PDF fits

HERA Charm Data test PDFs obtained with inclusive DIS

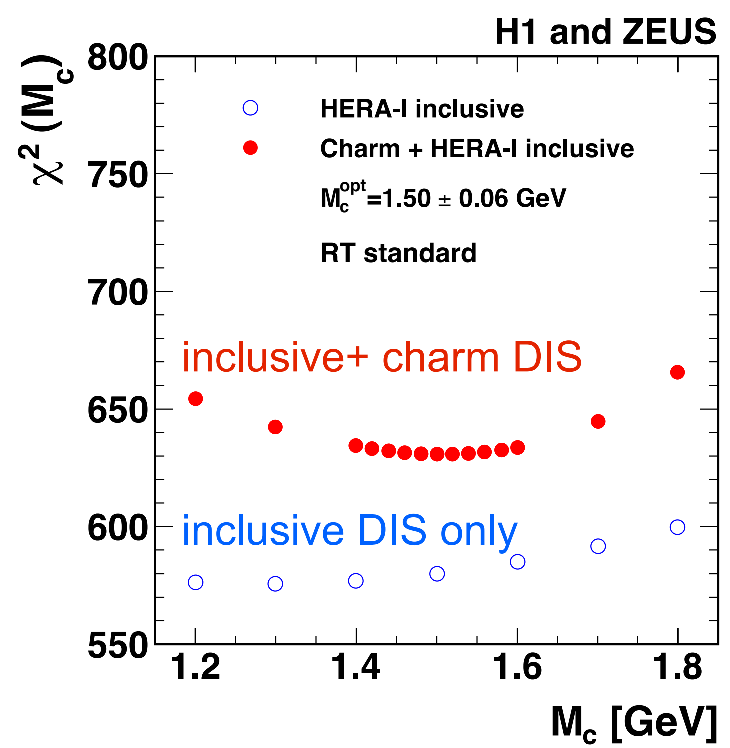
HERAPDF is obtained using only **inclusive** HERA DIS NC and CC data, use VFNS

Describes charm cross-sections very good

Uncertainty band mostly due to variation of charm quark mass in PDF: 1.35<m_c<1.65 GeV

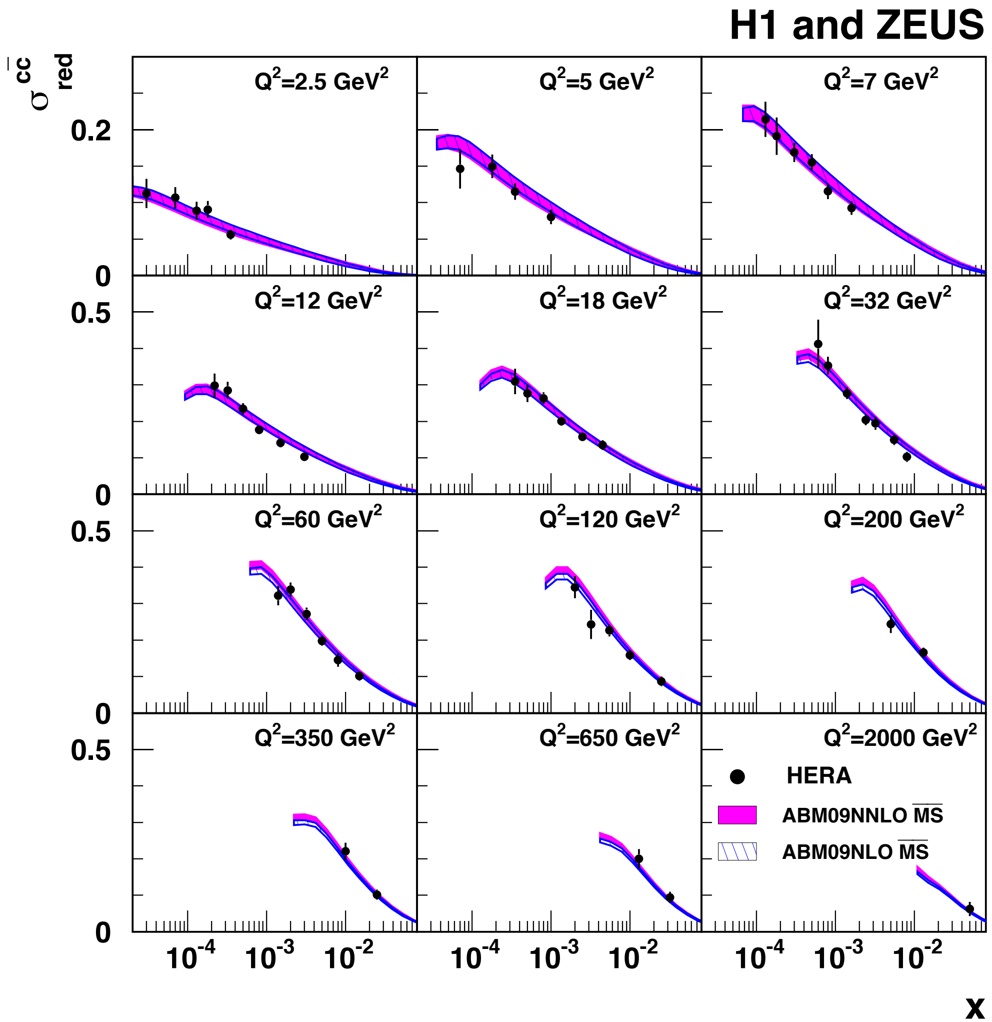


Sensitivity to charm mass in PDF fit increased once HERA charm data used together with inclusive DIS data

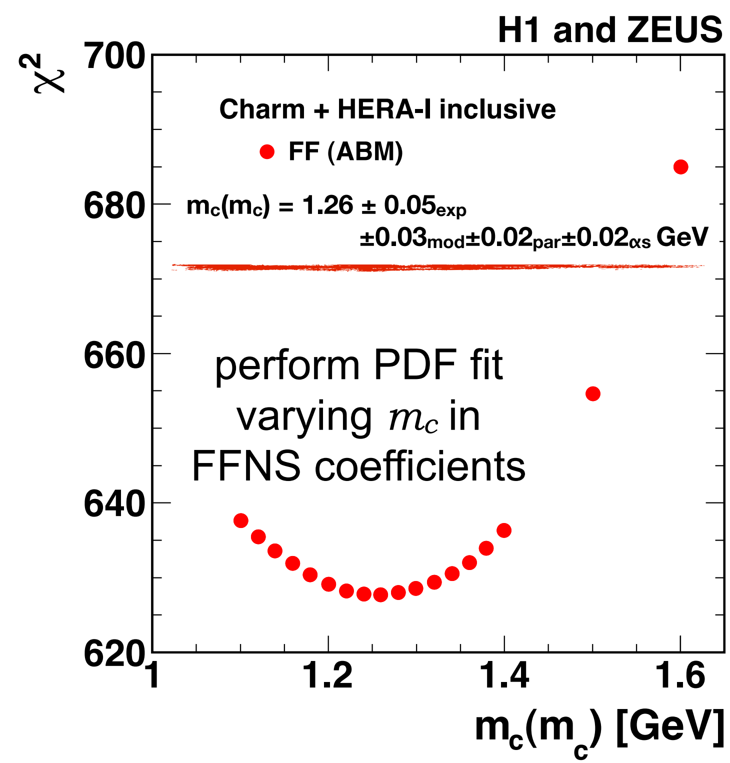


HERA Charm Data vs QCD Analysis in FFNS

QCD Predictions at NLO (~α_s^2) and NNLO (~α_s^3) describe data very well
Running mass of charm quark is used in coefficient functions in QCD analysis



Determine $m_c(m_c)$ in $\overline{MS}$ at NLO

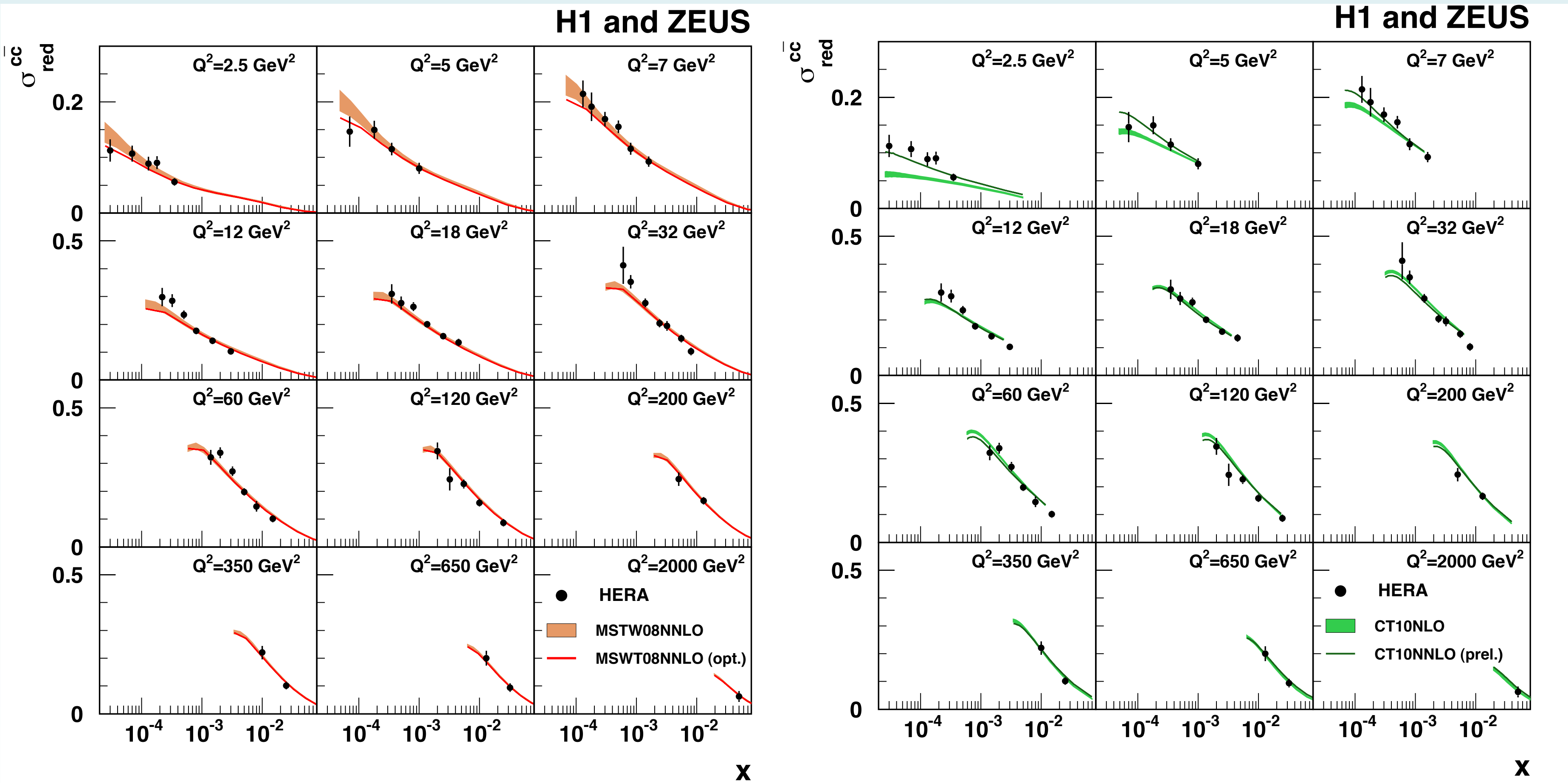


Consistent with the world average

$m_c(m_c)_{wa}$ = 1.275 ±0.025 GeV

HERA Charm Data vs QCD Analysis in VFNS

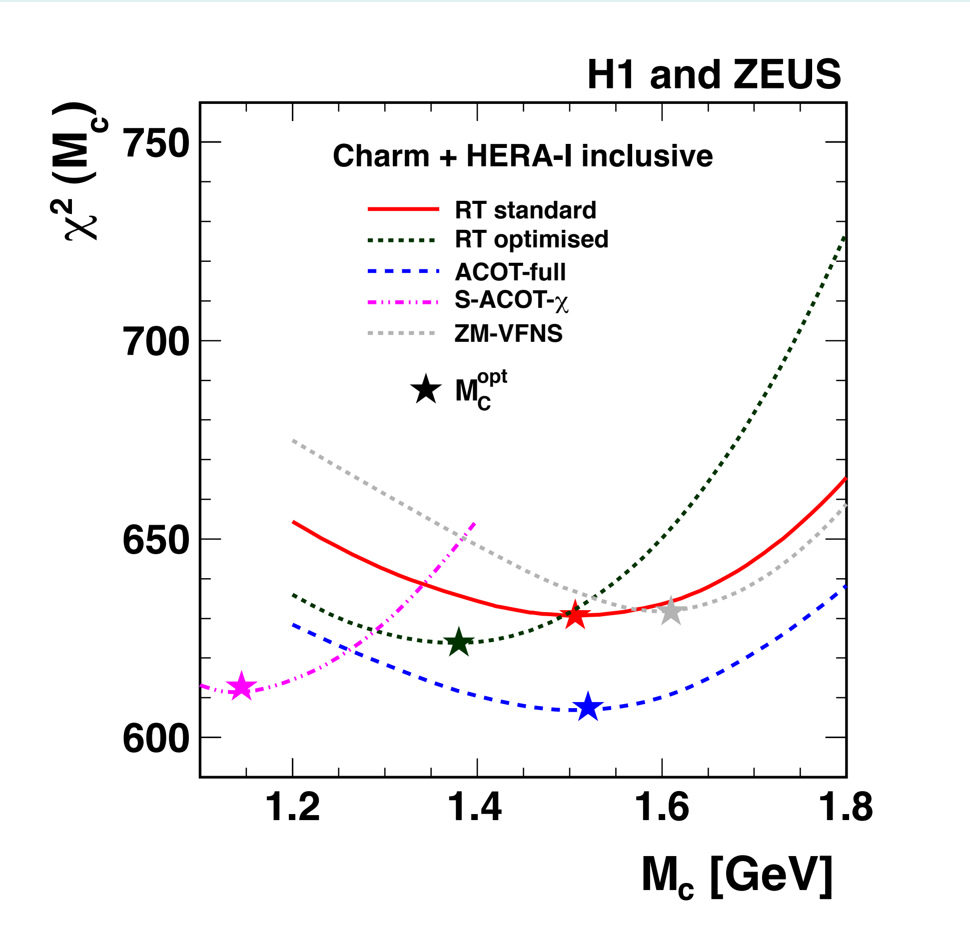
Data are confronted to predictions using Variable-Flavour Number Scheme at NLO (α_s) and NNLO (α_s^2)



Predictions using heavy quark coefficients at higher order describe data better at lower Q^2

Charm mass in Variable Flavor Number Scheme

Study charm mass choice in PDF using different VFNS implementations using HERAFitter



different implementation of VFNS
use m_c^{pole} in the HQ coefficients

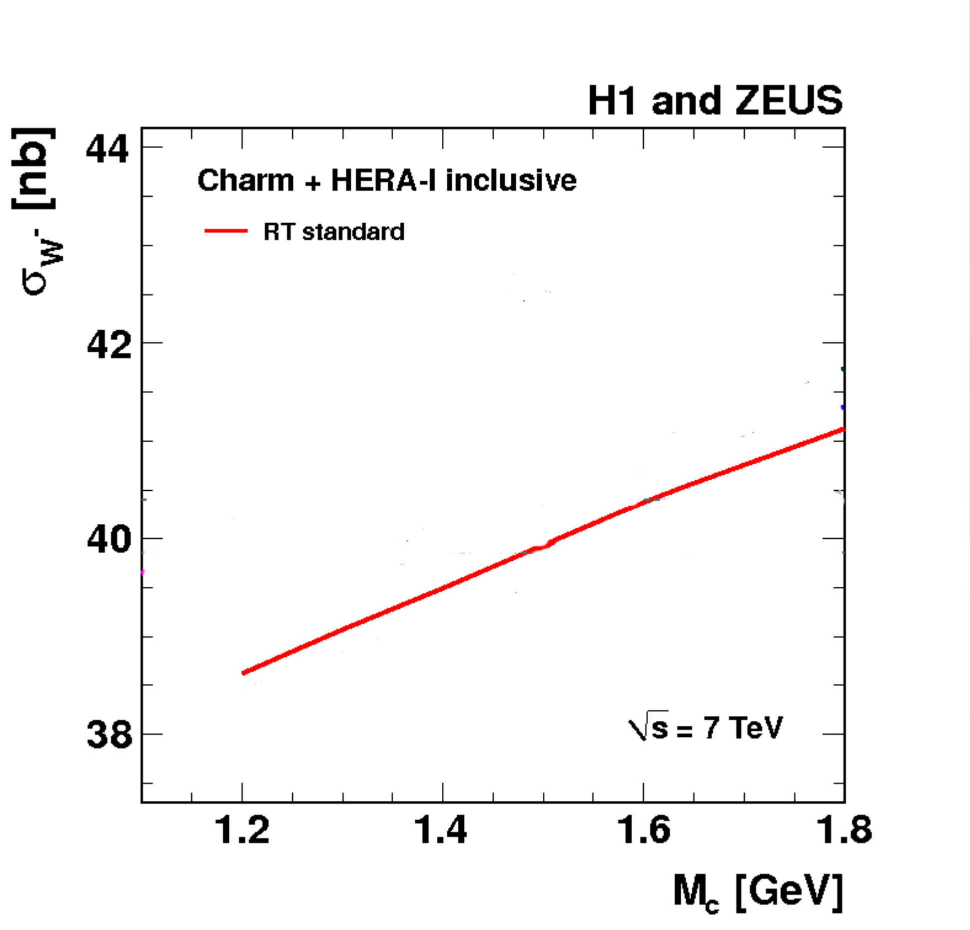
matching between N_{flavor} to $N_{flavor+1}$,
(*choosing an interpolation approach and different methods for truncation of the perturbative series*)
→ definition of m_c(pole) gets as uncertain as matching conditions: $m_c^{pole} \rightarrow M_c$

parameter M_c is implicitly used in predictions for the LHC processes using VFNS PDFs (CTEQ, MSTW, NNPDF, HERAPDF)

Different schemes prefer different M_c

Effect of charm mass in VFNS PDF on σ(W, Z) at NLO

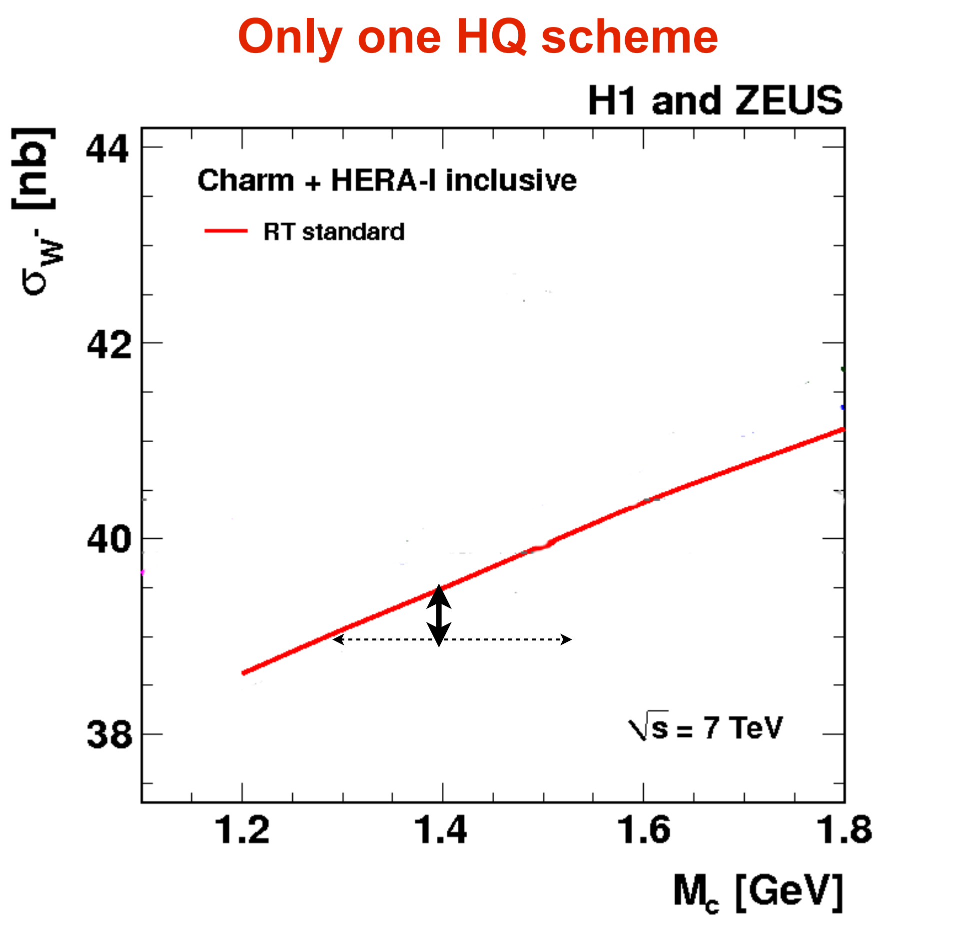
NLO prediction for $W+$ ($W-$, Z) production at the LHC: dependence on charm mass in PDF



Larger M_c → more gluons, less charm → more light quarks → larger σ_W

Effect of charm mass in VFNS PDF on σ(W, Z) at NLO

NLO prediction for $W+$ ($W-$, Z) production at the LHC: dependence on charm mass in PDF



M_c variation in PDF

1.3 < M_c < 1.5 GeV

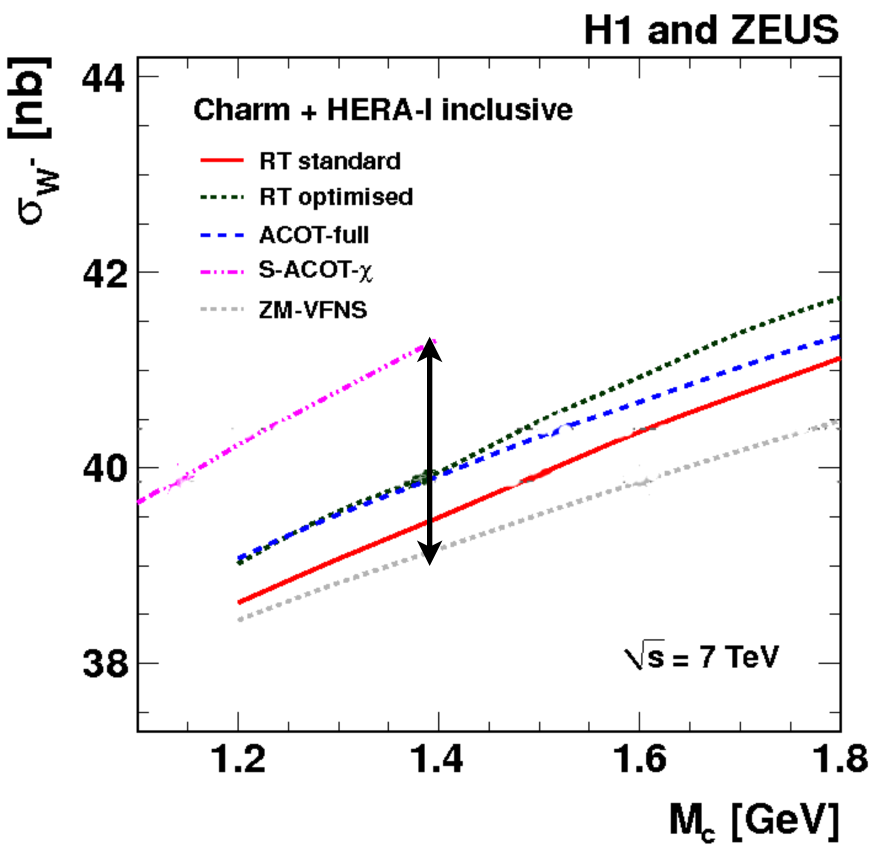
3% uncertainty on W prediction

Larger M_c → more gluons, less charm → more light quarks → larger σ_W

Effect of charm mass in VFNS PDF on σ(W, Z) at NLO

NLO prediction for $W+$ ($W-$, Z) production at the LHC: dependence on charm mass in PDF

Several HQ schemes



M_c variation in PDF

$1.3 < M_c < 1.5$ GeV

3% uncertainty on W prediction

Using different HQ schemes:

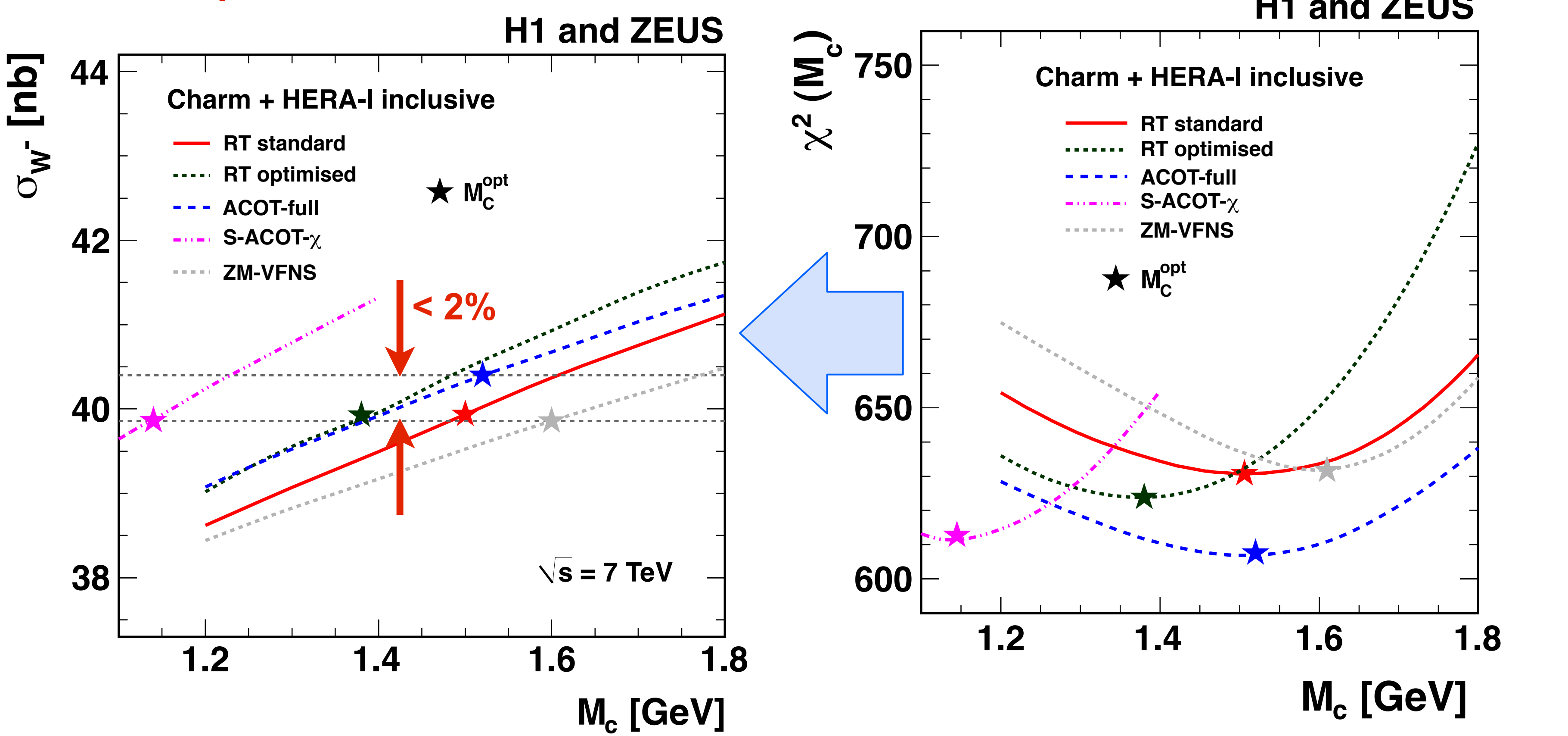
+ 7% uncertainty

Larger M_c → more gluons, less charm → more light quarks → larger σ_W

Data sensitivity to different heavy quark treatments in PDFs

NLO prediction for W+ (W-, Z) production at the LHC: dependence on charm mass in PDF

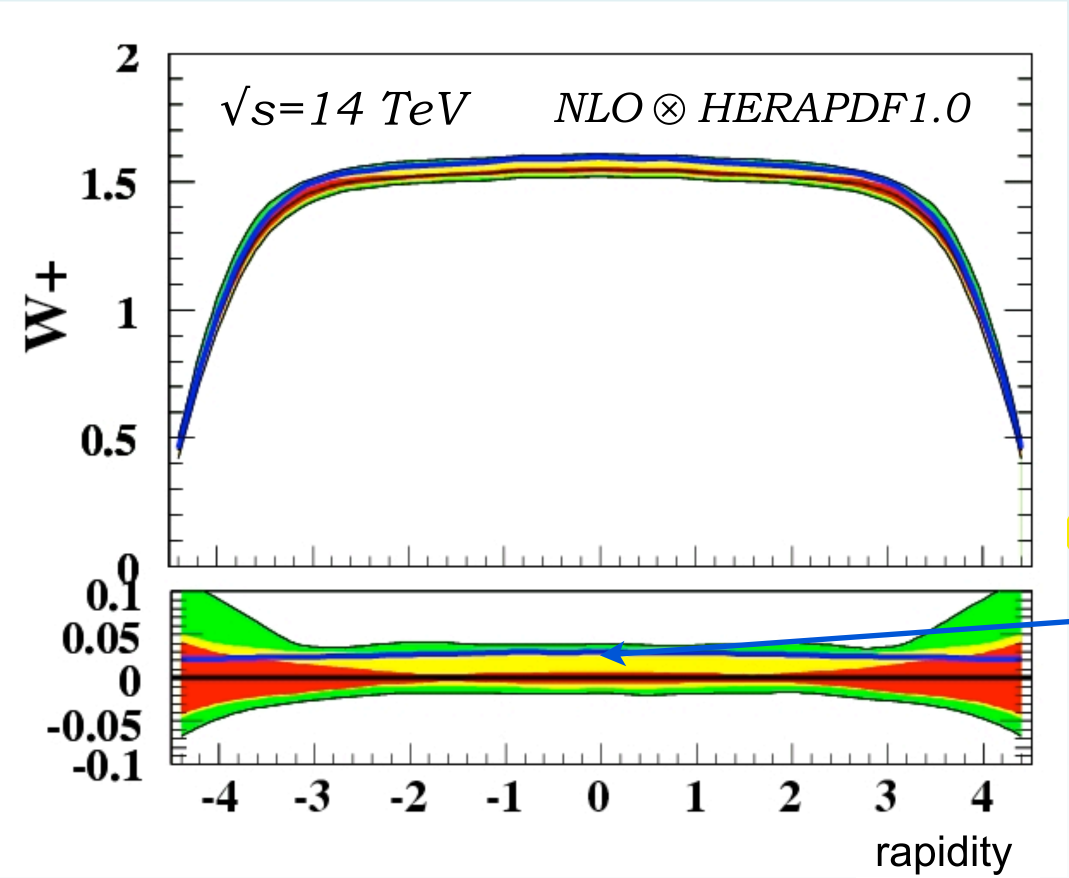
Use optimal M_c in each scheme



Uncertainty due to differences in charm treatment in PDFs significantly reduced by using optimal M_c in each HQ scheme in PDF

Heavy Quarks in PDFs and W/Z at LHC

Prediction of W± cross section @ LHC: dominant uncertainty due to PDF



Prediction using m_c=1.4 GeV

Error band: PDF uncertainty

Experimental error

Parametrization variation

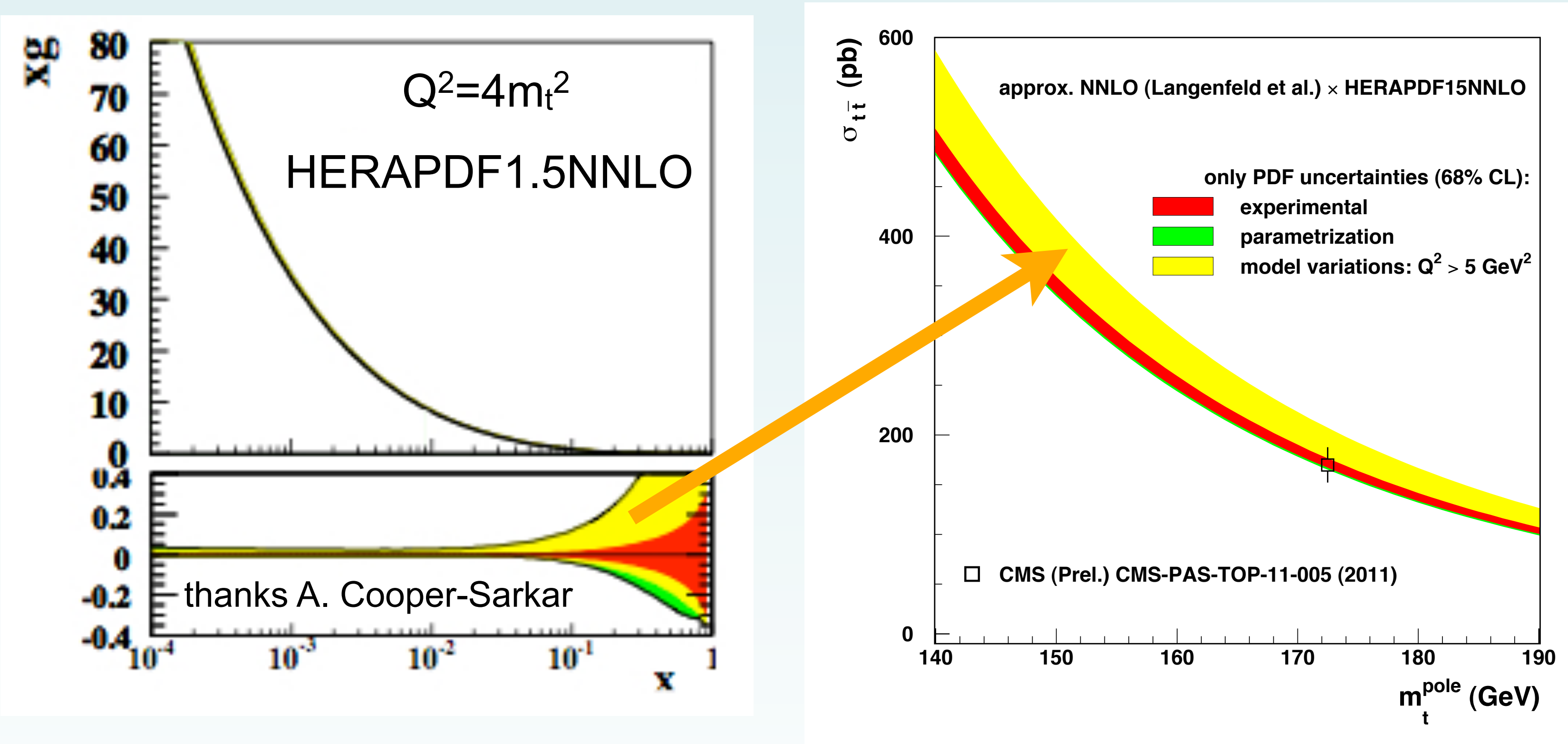
Model assumptions

including m_c variation

m_c variation in PDF: significant uncertainty on W@LHC in central region

(HERA)PDF and top quark at the LHC

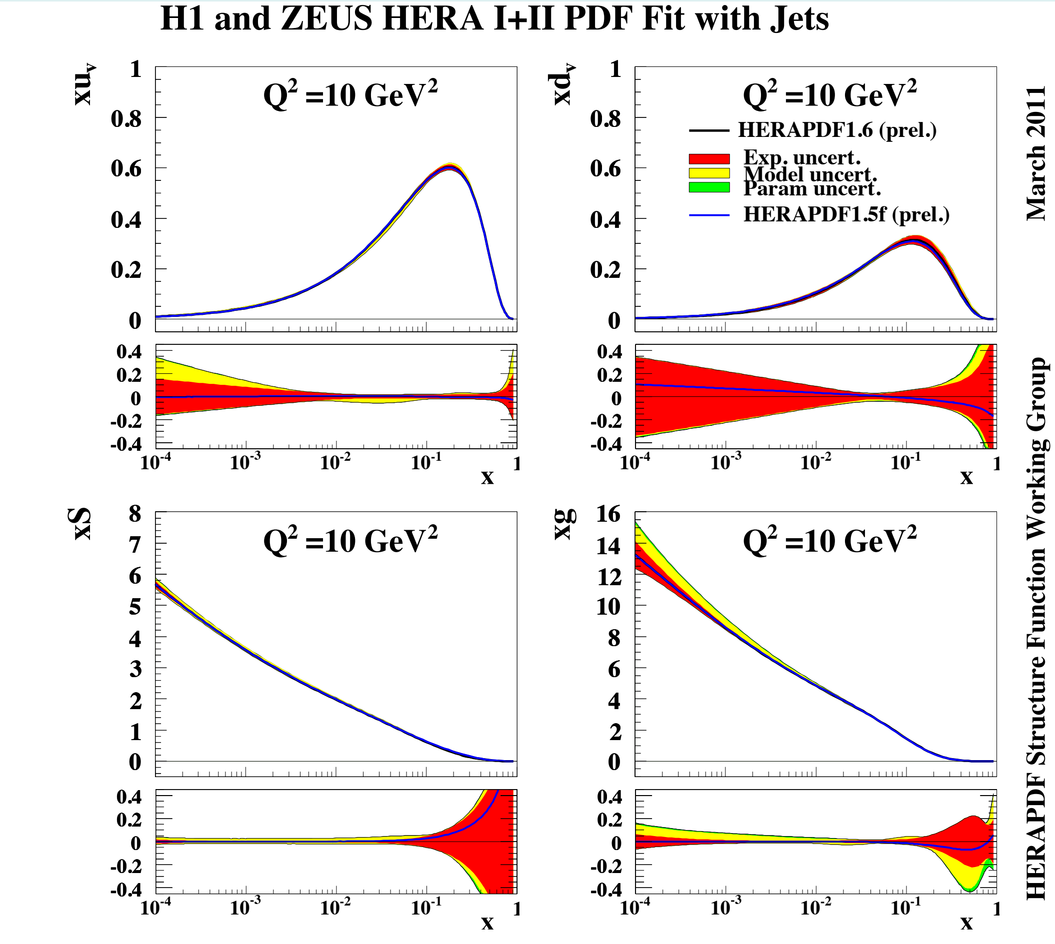
Top quark at CMS: cross section @ approx. NNLO



Dominant uncertainty: variation of Q^2_{min} imposed on data used in the fit

top quark production at the LHC has potential to constrain the high-x gluon

PDF fits using HERA jet data: fixed α_s



Inclusive DIS data:
combined HERAI+HERAII

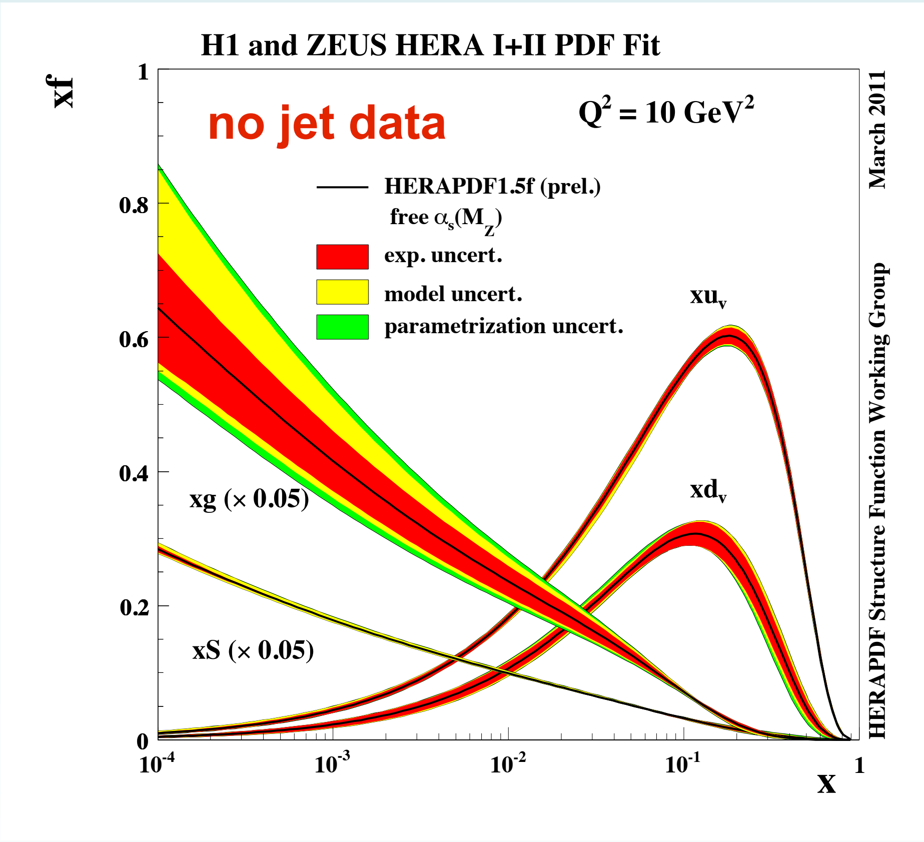
Jet data:
H1 high Q^2 , *EPJ C**65** (2010)*
low Q^2, *EPJ C**67** (2010)*

ZEUS incl. jets *PLB**547** (2002)*
incl.+2jets *NP B**765** (2007)*

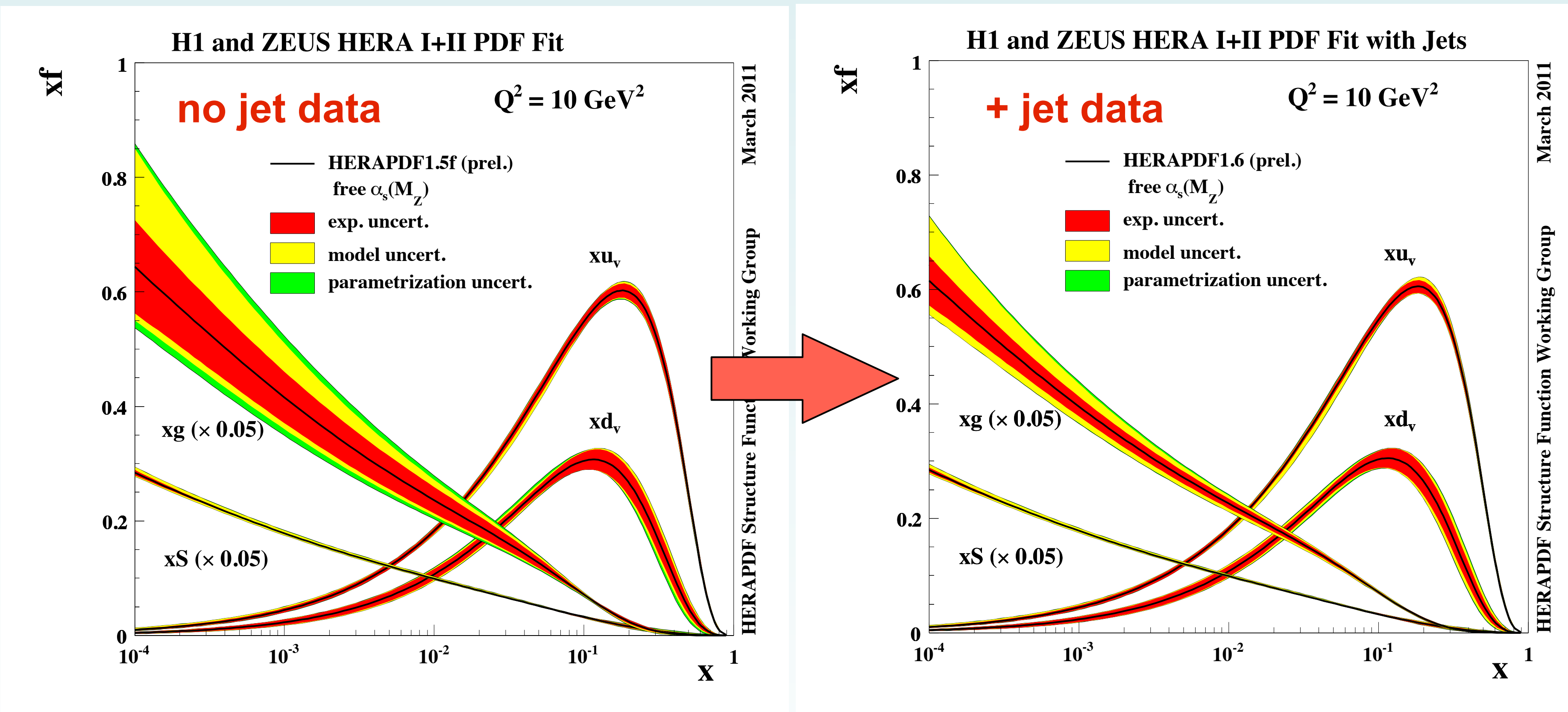
PDF Fit:
- flexible parametrisation
- $\alpha_s(M_Z)$ fixed

Inclusion of jet data into the PDF fit **using fixed α_s** does not have large impact

PDF fits with free α_s (Mz)



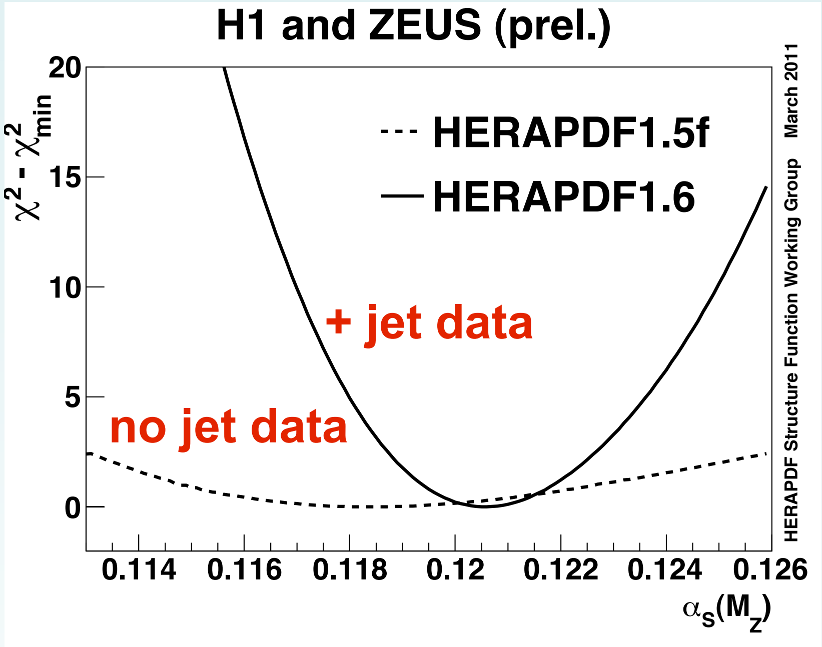
PDF fits with free α_s (Mz)

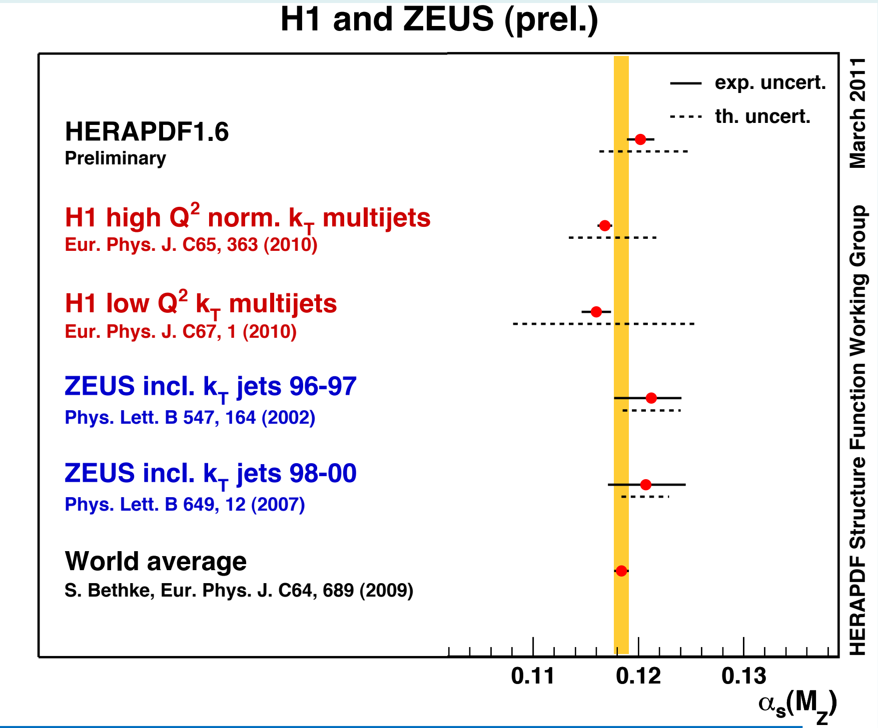


Inclusion of jet data into the PDF fit **decouples** the gluon and α_s (Mz)

α_s (Mz) from PDF fits including HERA jet data

Scan of the α_s (Mz) in the PDF fit





PDF and α_s (Mz) determined in the common fit:

$\alpha_s (M_Z) = 0.1202 \pm 0.0013_{exp} \pm 0.0007_{model/param} \pm 0.0012_{had} + 0.0045_{scale}$

From including the Jet data in the PDF fit: determine gluon and α_s (M_Z)

HERAFitter: Open-Source Modular Tool for QCD Analysis

Open source code, available at https://www.herafitter.org/HERAFitter
Version 0.3.0 released in March 2013.

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HERAFitter

Welcome to HERAFitter

The proton parton distribution functions (PDFs) are essential for precision physics at the LHC and other hadron colliders. The determination of the PDFs is a complex endeavor involving several physics process. The main process is the lepton proton deep-inelastic scattering (DIS), with data collected by the HERA ep collider covering a large kinematic phase space needed to extract PDFs. Further processes (fixed target DIS, ppbar collisions etc.) provide additional constraining powers for flavour separation. In particular, the precise measurements obtained or to come from LHC will continue to improve the knowledge of the PDF. HERAFitter project is an open source QCD fit framework ready to extract PDFs and assess the impact of new data which we would like to present here. The framework includes modules allowing for a various theoretical and methodological options, capable to fit a large number of relevant data sets from HERA, Tevatron and LHC. This framework is already used in many analyses at the LHC.

Downloads of HERAFitter software package

New HERAFitter release is publicly available. The HERAFitter releases can be accessed HERE .

HERAFitter Meetings

- User's Meetings: monthly meetings to enhance communication between users and developers (open access)
- Developer's Meeting: technical weekly meetings to ensure communication among developers (restricted access)
- Steering Group's Meeting (restricted access)

Developers Info (restricted to developers)

Internal Developments

Organisation

- **Conveners:** Voica Radescu, Ringaile Placakyte, Amanda Cooper-Sarkar
- **Release coordinator:** Sasha Glazov
- **Contact Persons:** Klaus Rabbertz (CMS), Bogdan Malaescu (ATLAS), Olaf Behnke (ZEUS), Cristi Diaconu (H1), Ronan McNulty (LHCb)
- **Steering Group:** Voica Radescu, Ringaile Placakyte, Sasha Glazov, Amanda Cooper-Sarkar, , Gavin Salam (theory), Klaus Rabbertz (CMS), Bogdan Malaescu (ATLAS), Ronan McNulty (LHCb), Olaf Behnke (ZEUS), Cristi Diaconu (H1, chair)
- **Librarians:** authors/developers of individual modules
- **Getting help**: Send email to herafitter-help@desy.de

Joined effort of experimentalists, theorists and tool-developers
Successfully used by the LHC experiments