

QCD Results from HERA and JLAB

- Introduction: HERA and JLAB
- Inclusive ep and eN Scattering
- Jet Production in ep collisions
- Heavy Quark Production in ep collisions

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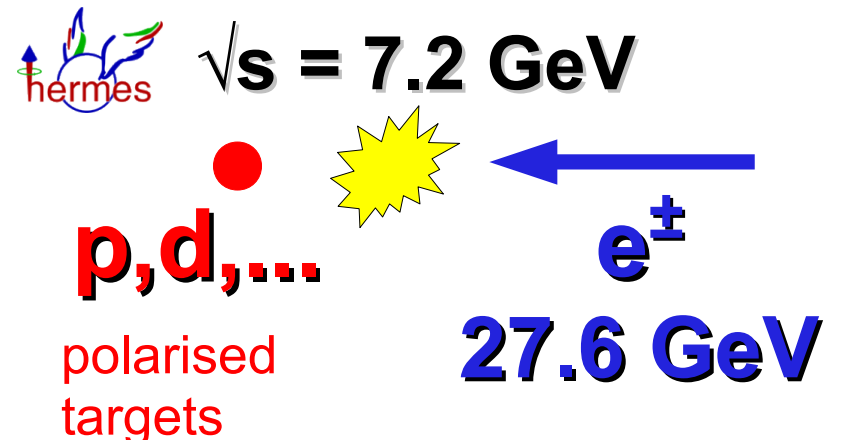
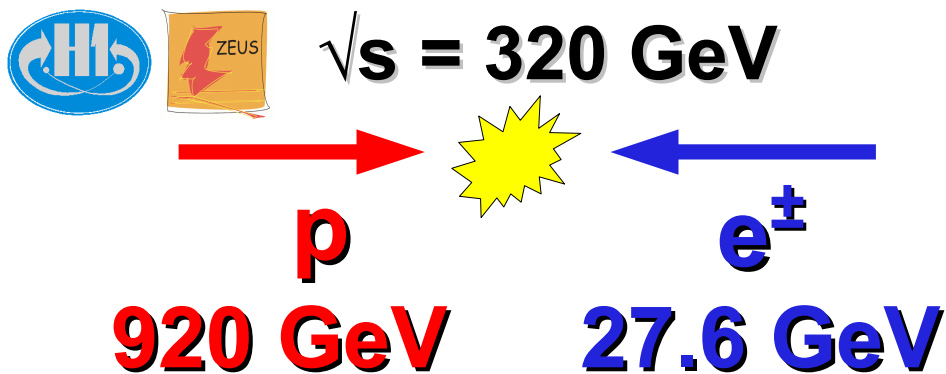


Lepton Photon 2011
22 - 27 August 2011

HERA

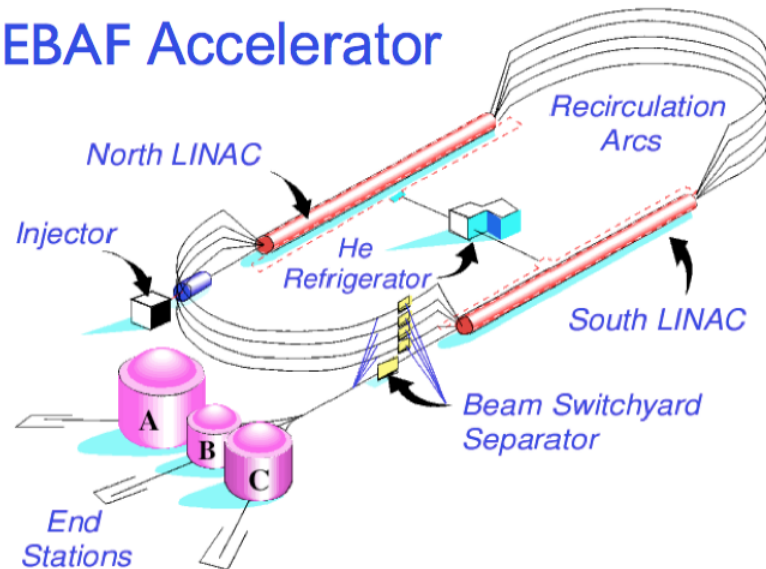


- in operation 1992–2007
- e^- and e^+ running
- longitudinal e beam polarisation



JLAB

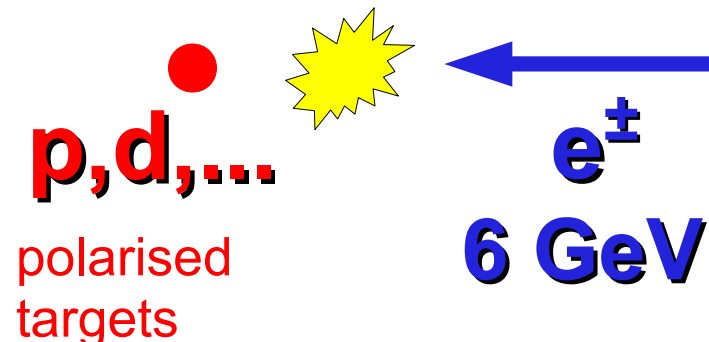
The CEBAF Accelerator



- e beam energy: 6 GeV
- longitudinal e beam polarisation



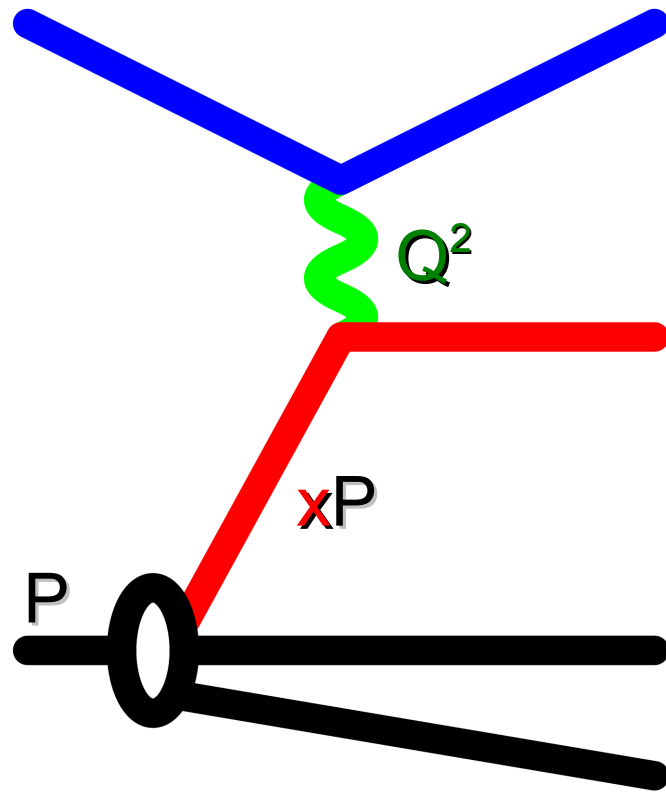
$$\sqrt{s} = 3.4 \text{ GeV}$$



experiments:

- Hall A and C: small angle spectrometers
- Hall B: CLAS (Cebaf Large Acceptance Spectrometer)

Electron Proton Scattering



Q^2 : virtuality of the exchanged boson

x : Bjorken scaling variable,
in QPM: fraction of proton
momentum carried by struck quark

y : inelasticity: relative energy
transfer from electron to boson

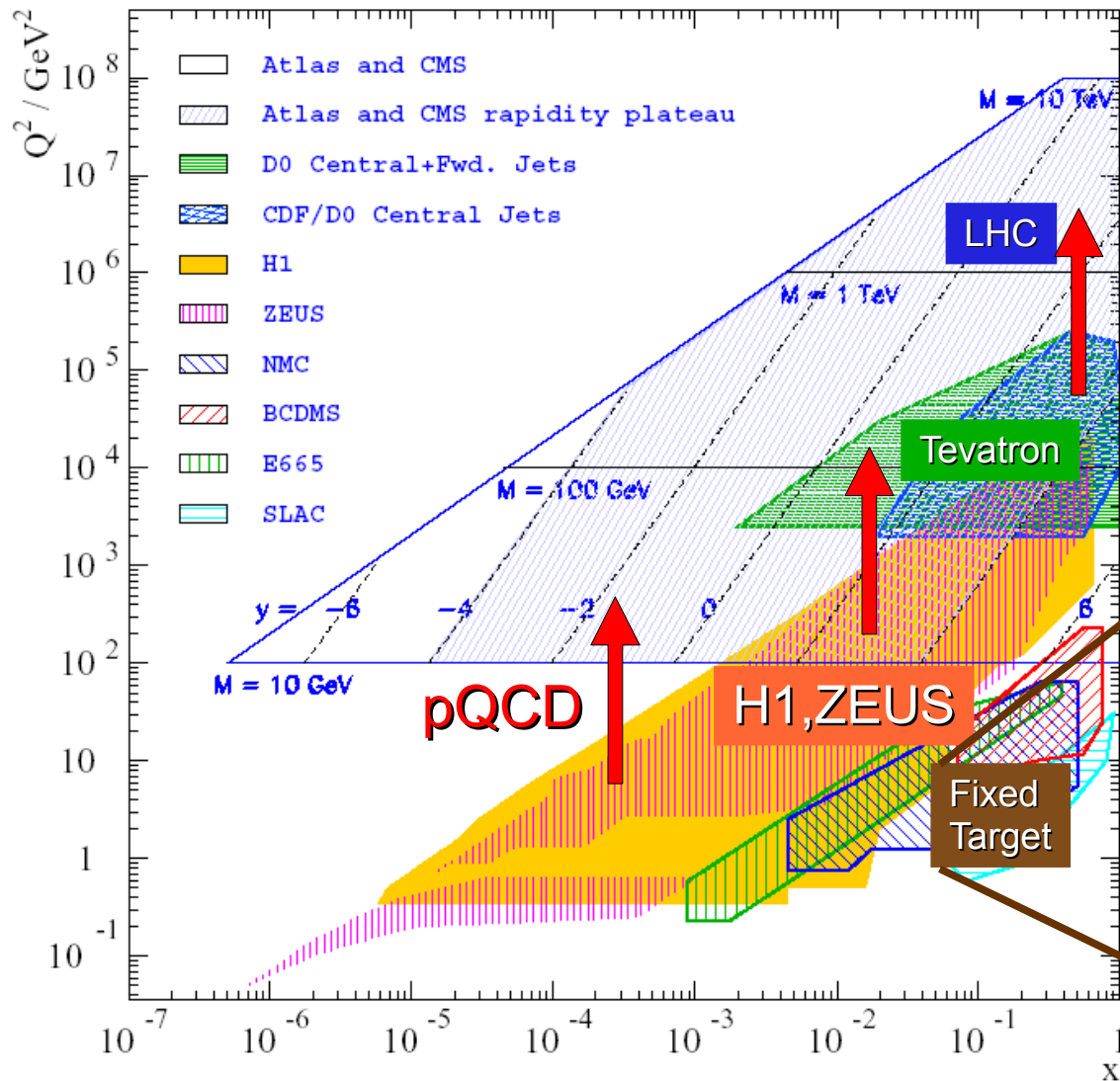
→ ideal process to study
proton structure

$$Q^2 = x y s$$

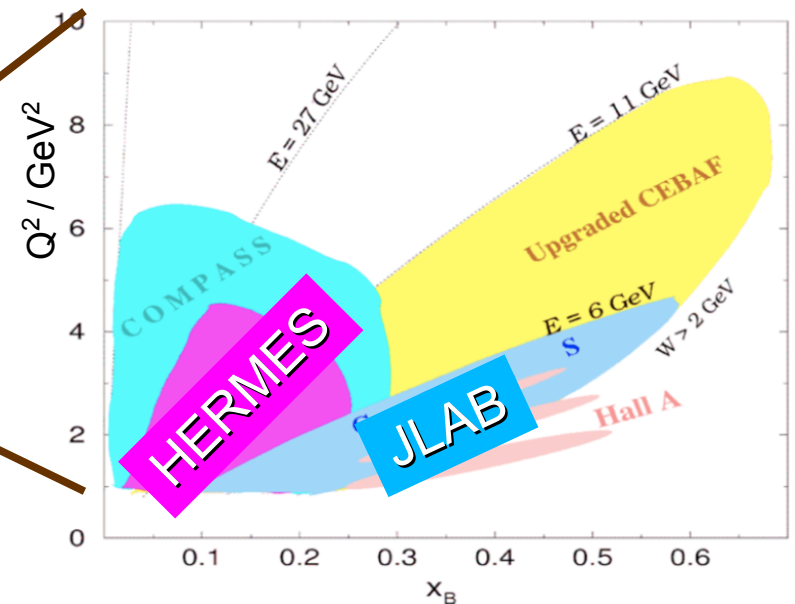
$Q^2 > 1 \text{ GeV}^2$: Deep Inelastic Scattering (DIS)

$Q^2 \approx 0 \text{ GeV}^2$: Photoproduction (γP)

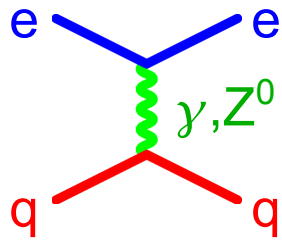
Kinematics



- H1, ZEUS: large coverage in x and Q^2
- HERMES, JLAB: access to large x and low Q^2
- pQCD (DGLAP) predicts Q^2 dependence



Structure Functions



reduced cross section:

$$\sigma_r^{NC}(e^\pm p) = \frac{d^2 \sigma^{NC}}{dx dQ^2} \frac{x Q^4}{2\pi \alpha^2 Y_+} \quad \text{with } Y_\pm = 1 \pm (1-y)^2$$

$$= \tilde{F}_2 \mp \frac{Y_-}{Y_+} x \tilde{F}_3 - \frac{y^2}{Y_+} \tilde{F}_L$$

valence and
sea quarks

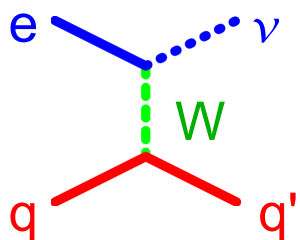
$$\tilde{F}_2 \sim x(q + \bar{q})$$

valence
quarks

$$x \tilde{F}_3 \sim x(q - \bar{q})$$

gluons

$$\tilde{F}_L \sim \alpha_s x g$$



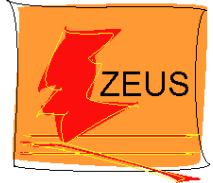
$$\sigma_r^{CC}(e^+ p) \sim x(1-y^2)(d+s)$$

$$\sigma_r^{CC}(e^- p) \sim x(u+c)$$

flavour
decomposition

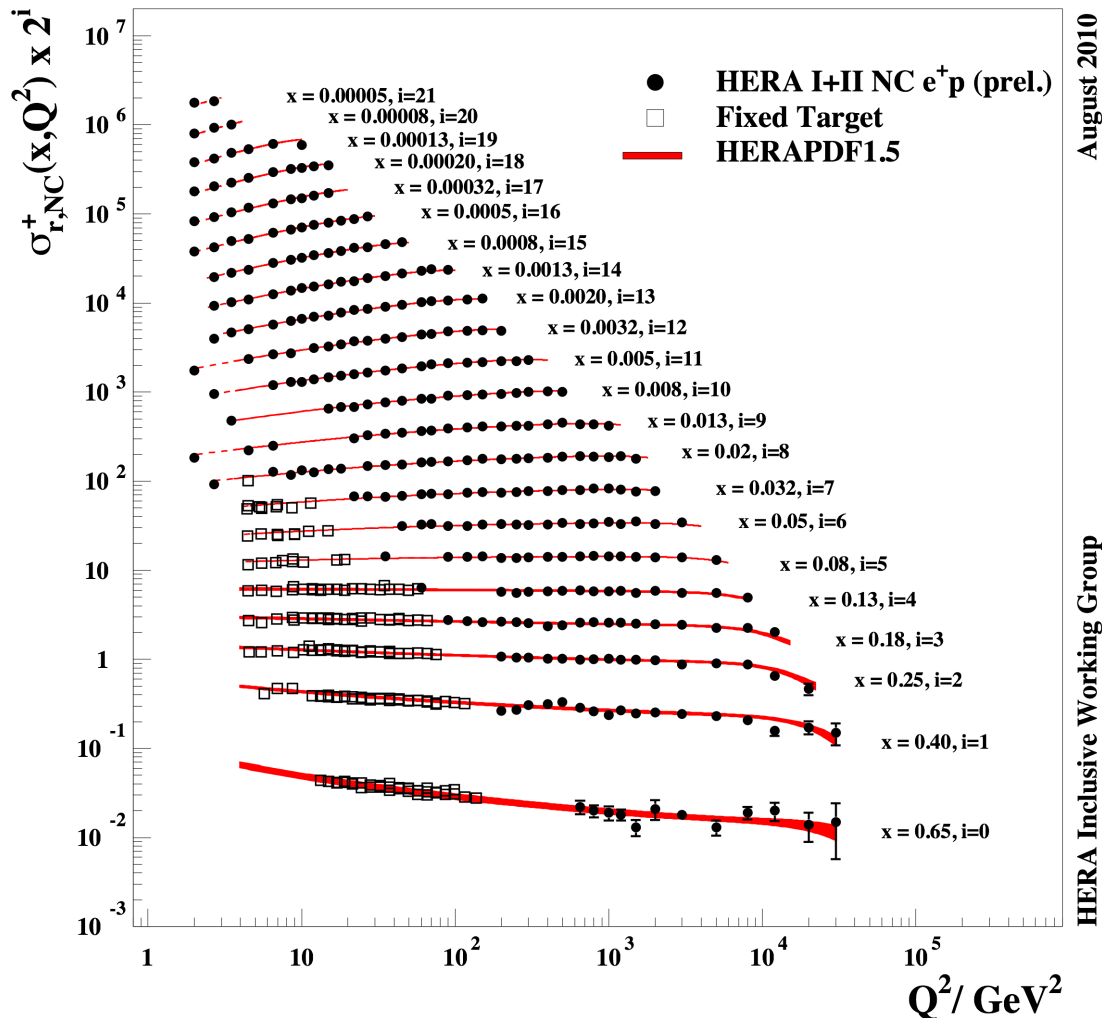


Inclusive HERA NC data



H1prelim-10-141 /
ZEUS-prel-10-017

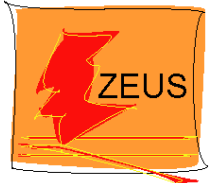
H1 and ZEUS



- inclusive NC DIS cross sections with full HERA statistics combined from H1 and Zeus data, cover very large x - Q^2 region
- O(1%) precision in the range $10 < Q^2 < 100 \text{ GeV}^2$
- scaling violations at low x : provide information on gluon density

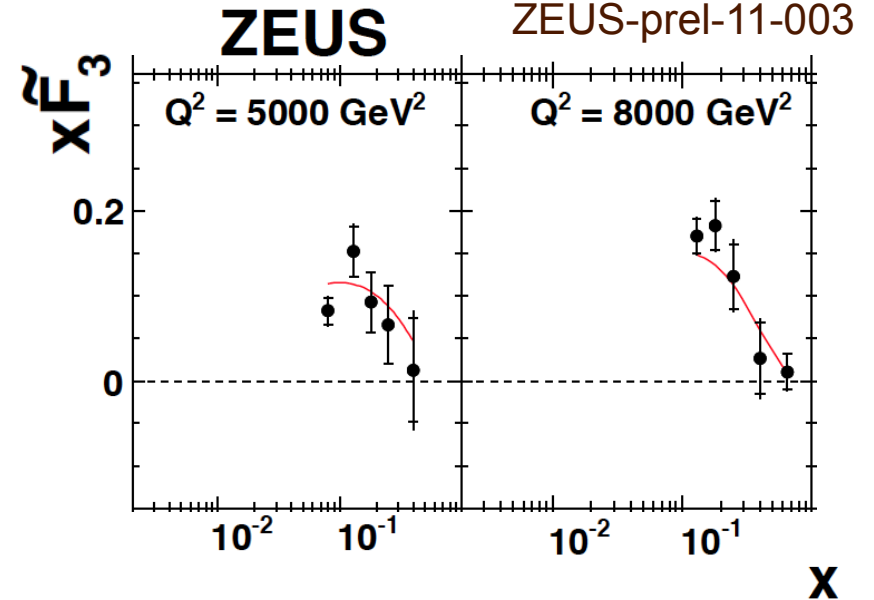
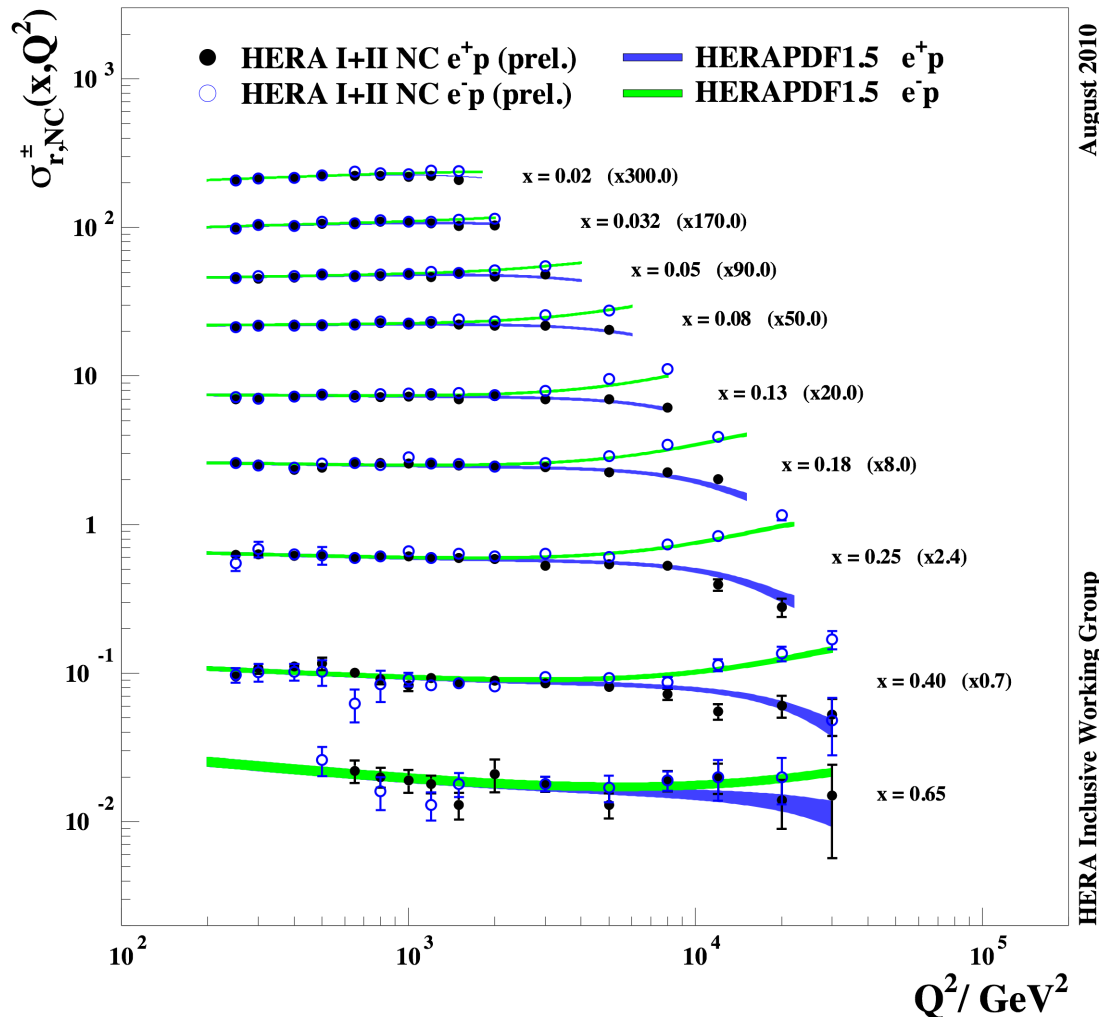


Inclusive HERA NC data



H1prelim-10-141 /
ZEUS-prel-10-017

H1 and ZEUS



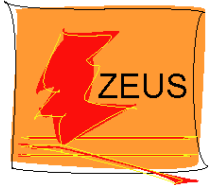
$$x \tilde{F}_3 \sim x(q - \bar{q})$$

- ZEUS NC (prel.) $e^\pm p$ (305.4 pb $^{-1}$)
- SM (HERAPDF1.5)

→ difference of e^+ and e^- scattering at high Q^2 from γZ interference (xF_3)



Inclusive HERA CC data

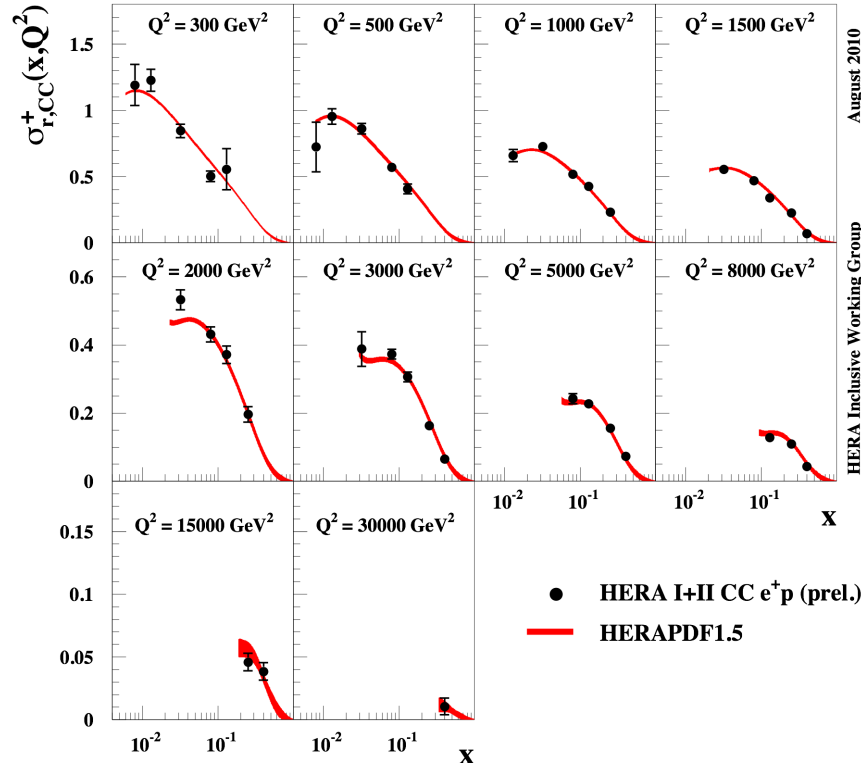


- inclusive CC DIS cross sections with full HERA statistics combined from H1 and Zeus data

H1prelim-10-141 / ZEUS-prel-10-017

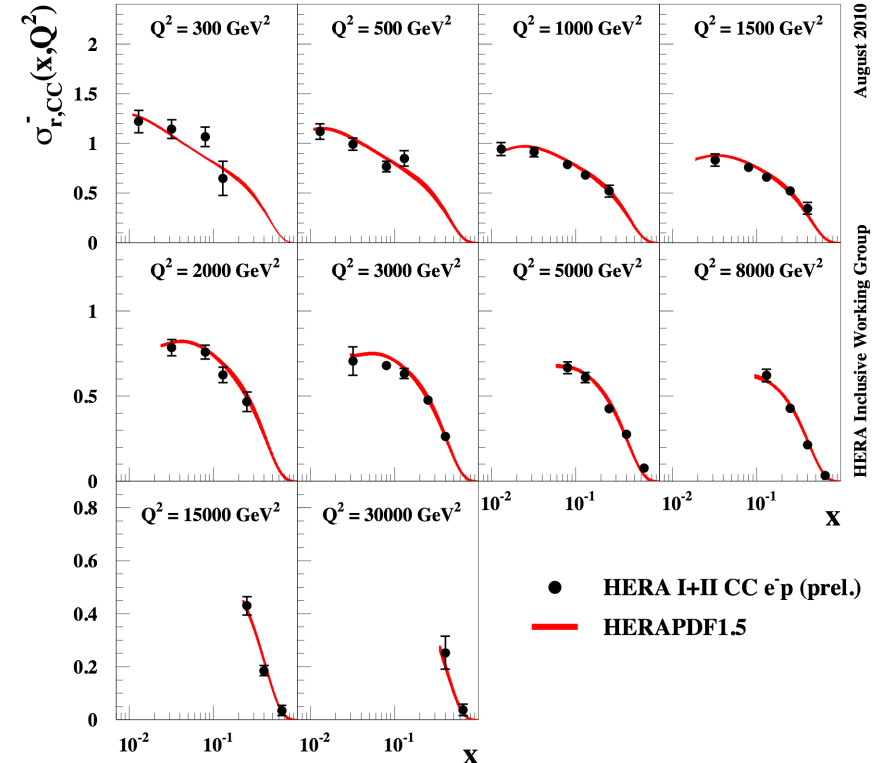
→ CC data provide sensitivity to quark flavour

H1 and ZEUS



$$\sigma_r^{CC}(e^+ p) \sim x(1-y^2)(d+s)$$

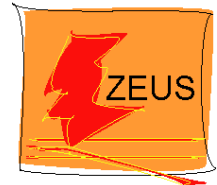
H1 and ZEUS



$$\sigma_r^{CC}(e^- p) \sim x(u+c)$$

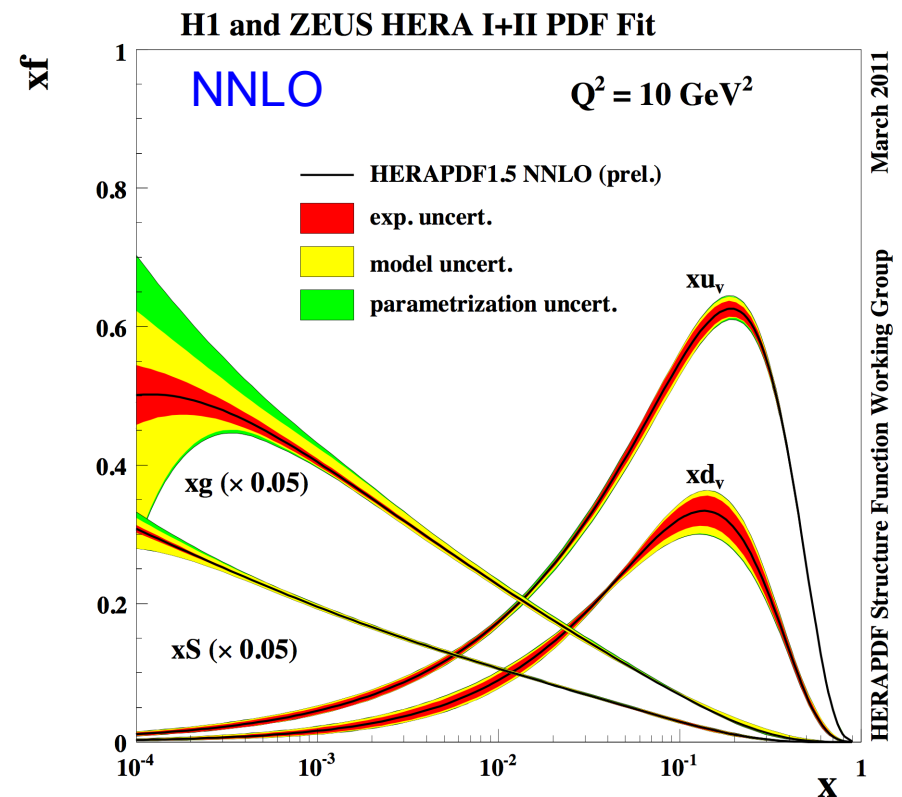
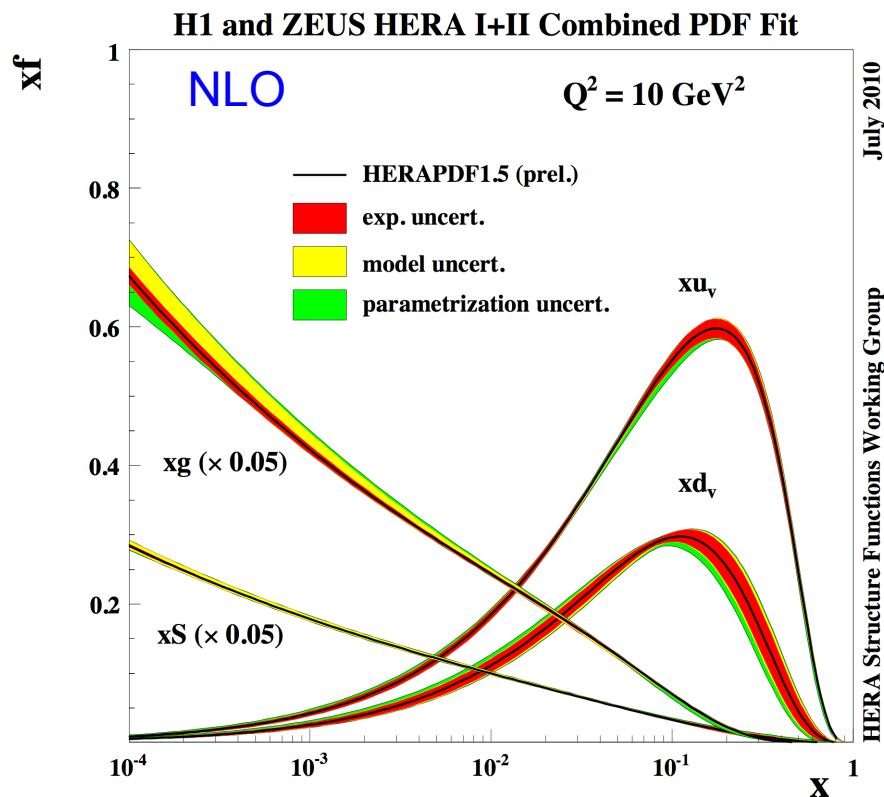


PDF Fit to Inclusive HERA data



- HERAPDF1.5 at NLO and NNLO
- available in LHAPDF

uses only HERA NC and CC data
experimentally and theoretically
well controlled



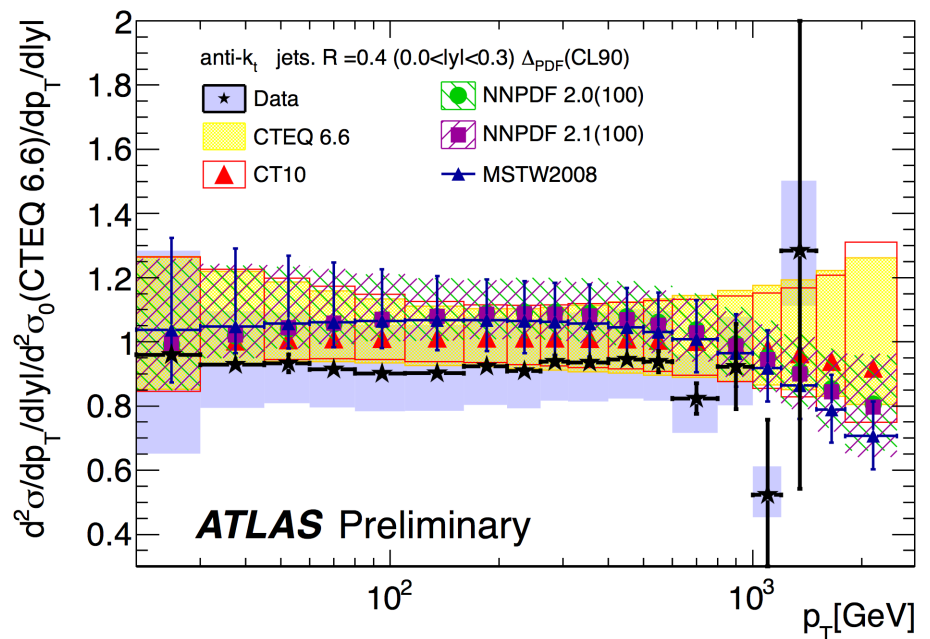
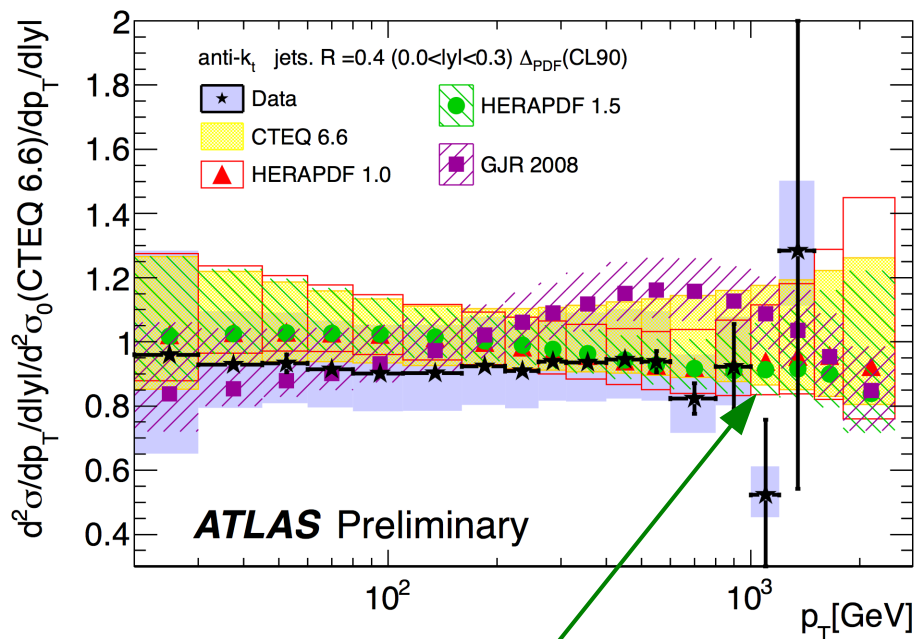
H1prelim-10-142 / ZEUS-prel-10-018

H1prelim-11-042 / ZEUS-prel-11-002

Predictions for LHC: Jets

ATL-PHYS-PUB-2011-005

- HERAPDF1.5 uses no jet data as input



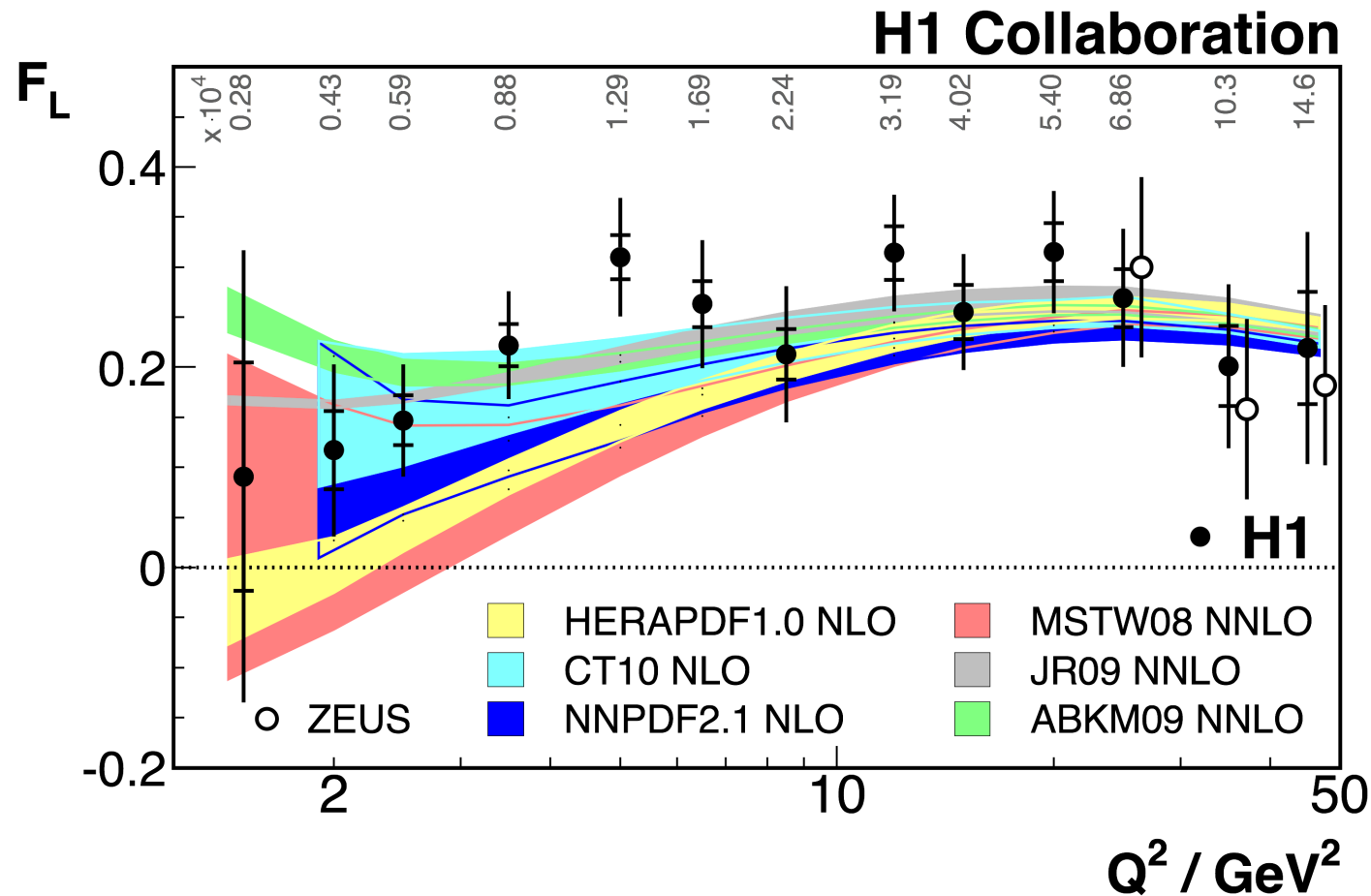
→ HERAPDF1.5 predictions describe jets at LHC well



Logitudinal Structure Function F_L

- model-independent determination of F_L

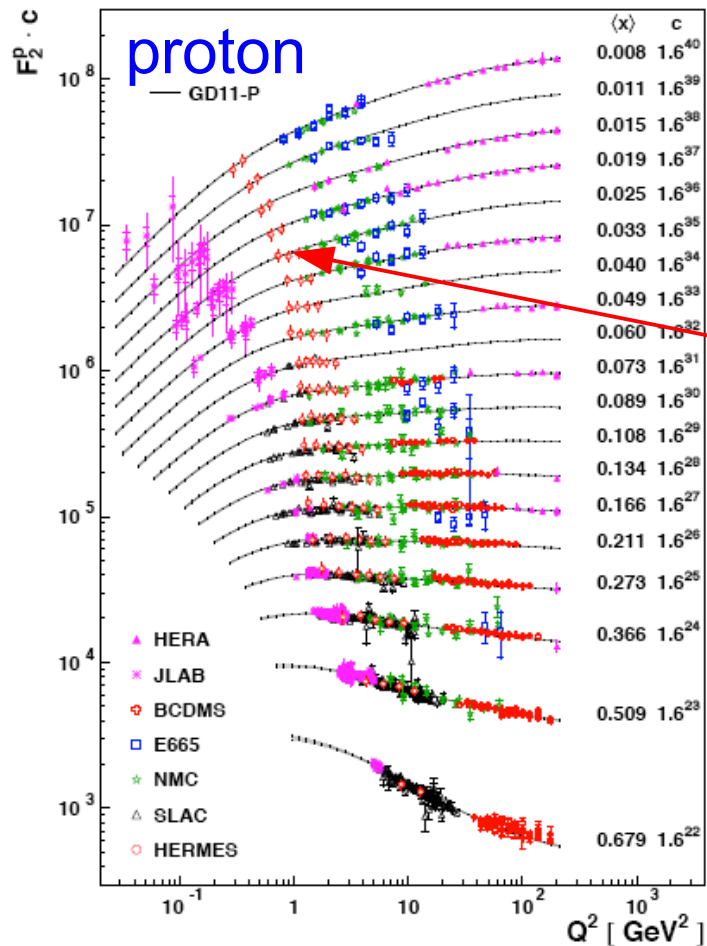
Eur.Phys.J.C71 (2011) 1579



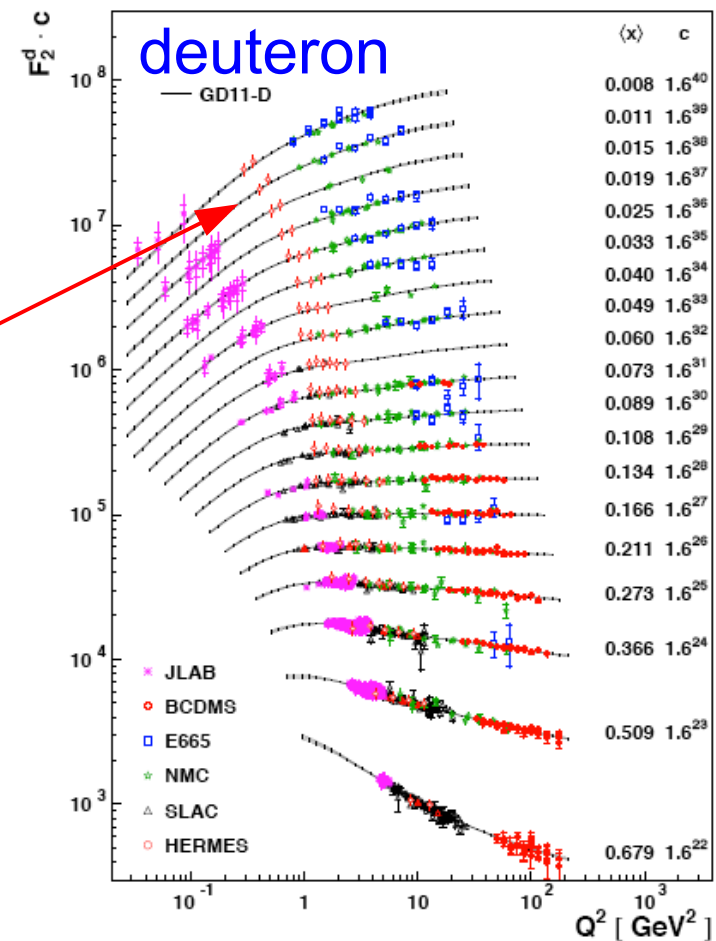
→ F_L allows independent cross check of gluon density $\tilde{F}_L \sim \alpha_s x g$

F_2 at low Q^2 and high x

- HERMES accesses transition region between perturbative and non-perturbative regime: $0.006 < x < 0.9$ and $0.1 < Q^2 < 20 \text{ GeV}^2$



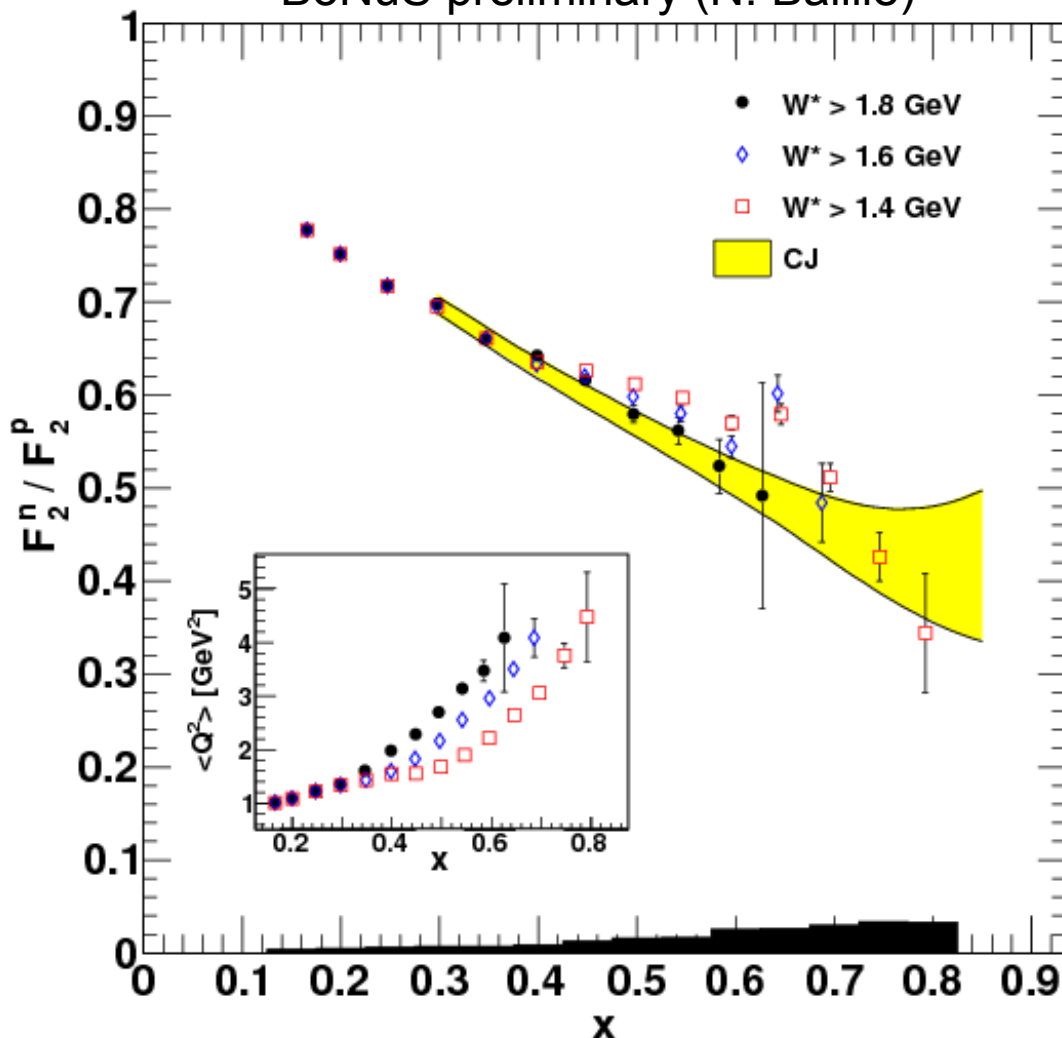
HERMES
data



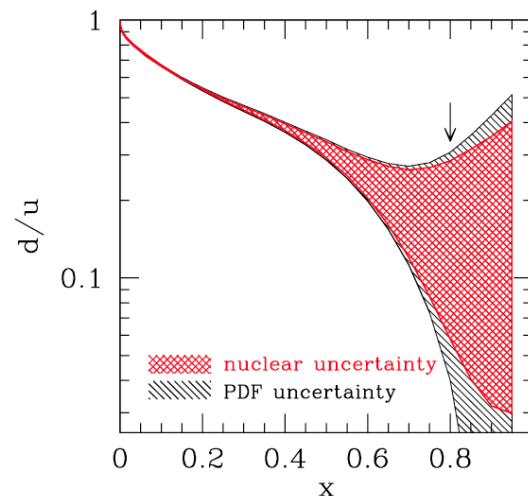
→ data described by Regge-inspired phenomenological fit

Neutron F_2

BoNuS preliminary (N. Baillie)



- BoNuS experiment (Hall B) detects spectator proton from deuterium following *en* scattering
- model-independent access to neutron structure function
- can be used to constrain d/u from F_2^n / F_2^p



CTEQ-JLAB
collaboration

The Spin of the Proton

$$\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g$$

- $\Delta \Sigma$: contribution from quark spins Δq
 $\Delta \Sigma = 0.330 \pm 0.025(\text{exp}) \pm 0.011(\text{theo}) \pm 0.028(\text{evol})$

- ΔG : contribution from gluon spin

$$\Delta G = \int_0^1 \Delta g(x) dx$$

$$\Delta g/g = 0.049 \pm 0.034(\text{stat}) \\ +0.126 -0.099(\text{syst})$$

HERMES, JHEP 08 (2010) 130

- L_q, L_g : orbital angular momenta:
 accessible via Generalised Parton Distributions

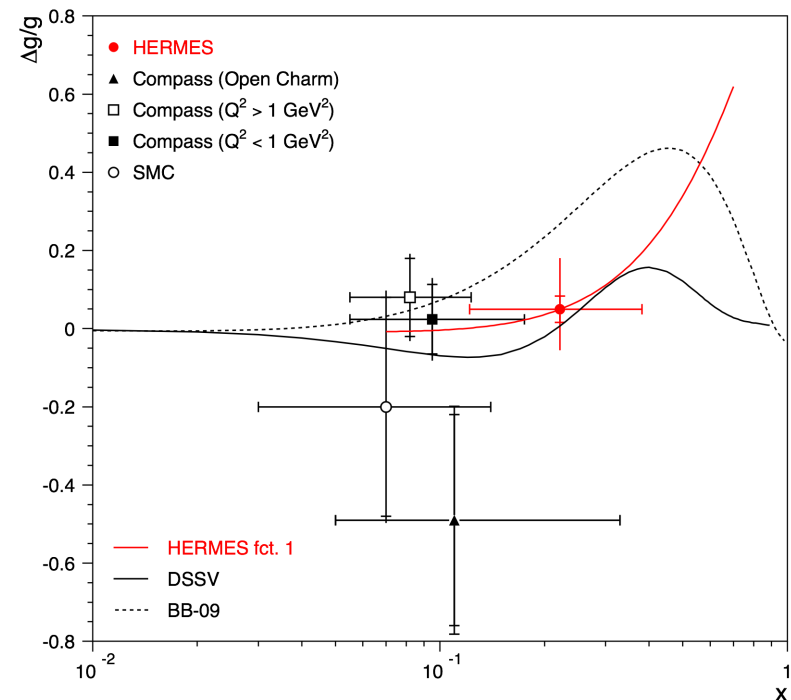


Image from: A.V. Belitsky, A.V. Radyushkin,
Phys.Rept.418:1-387,2005



- Image from: A.V. Belitsky, A.V. Radyushkin,
Phys.Rept.418:1-387,2005

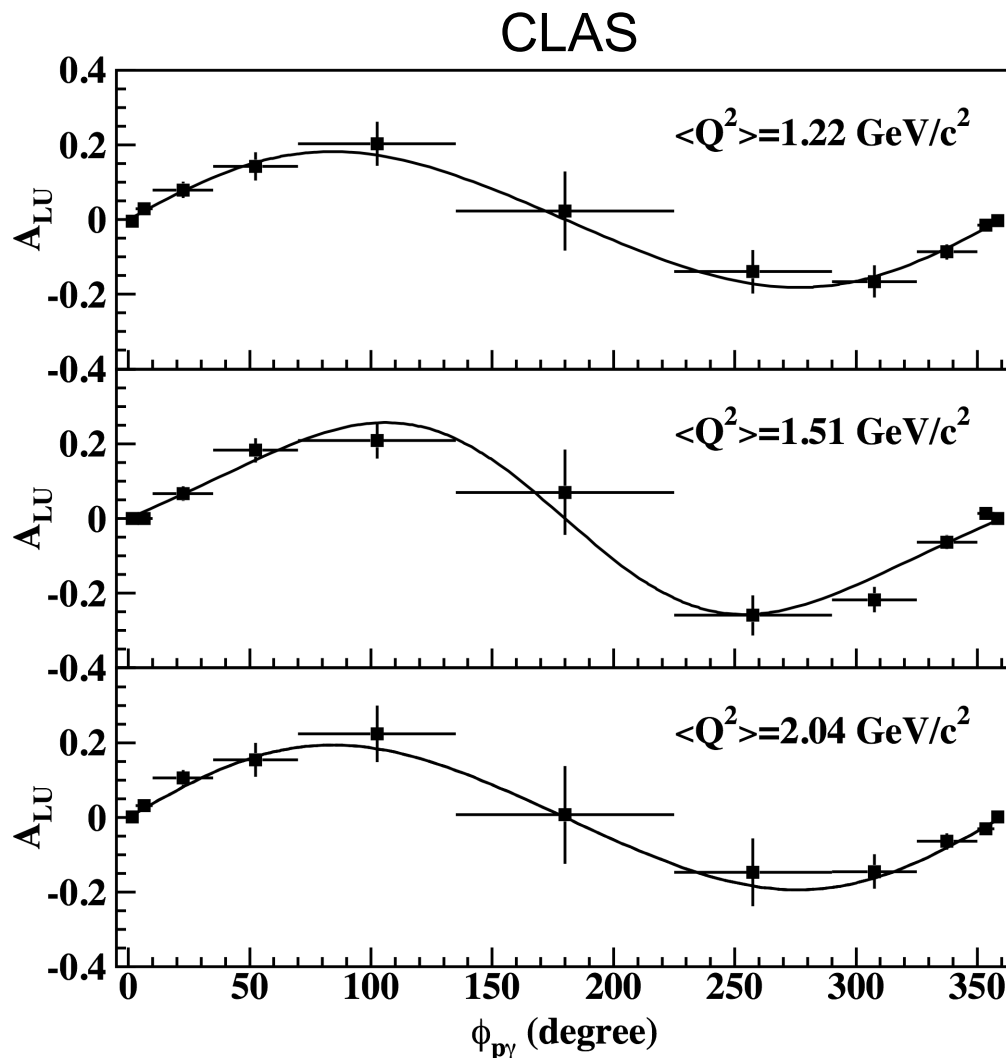
Image from: A.V. Belitsky, A.V. Radyushkin,
Phys.Rept.418:1-387,2005

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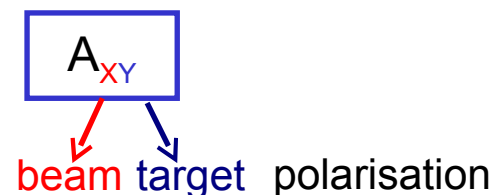


DVCS Beam Spin Asymmetry

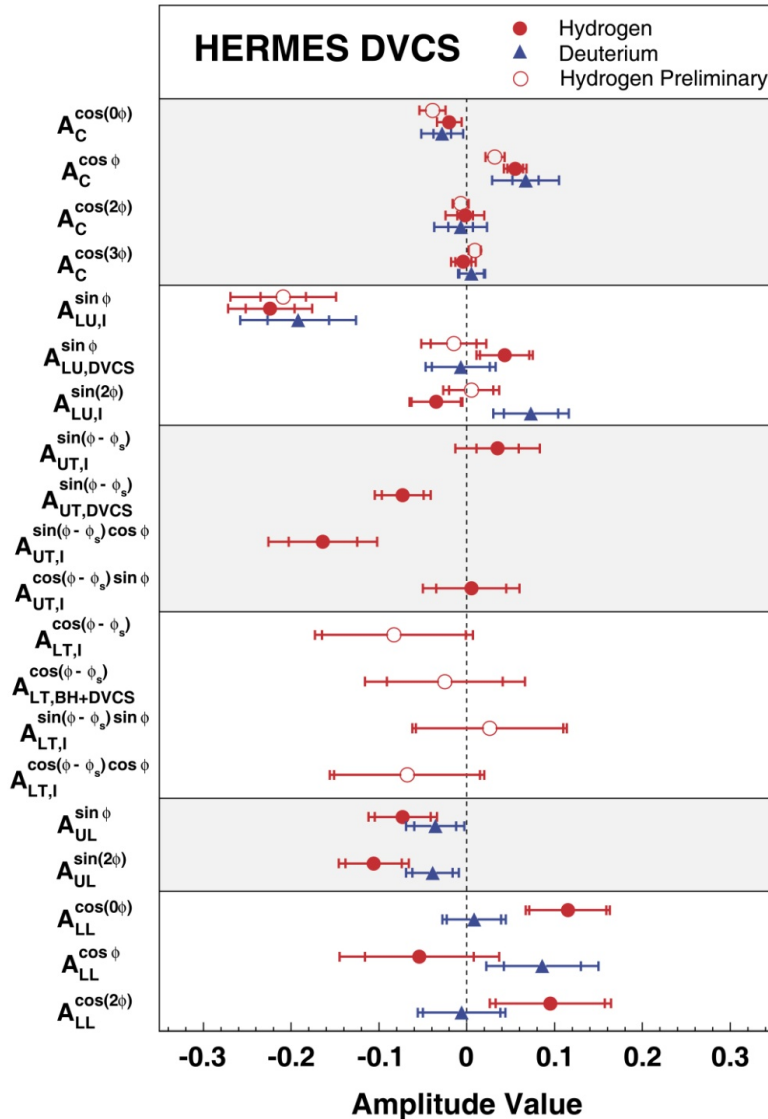
Phys. Rev. C 80 (2009) 035206



- angular dependence of asymmetry between positive and negative beam helicity measured by CLAS
- provides information on the GPDs



DVCS Asymmetries



Beam charge asymmetry

GPD H

H: PRL 87 (2001) 182001

PR D 75 (2007) 011103

JHEP 11 (2009) 083

D: Nucl. Phys. B 829 (2010) 1

Beam helicity asymmetry

GPD H

Transverse target-spin asymmetry

GPD E

H: JHEP 06 (2008) 066

Transverse double-spin asymmetry

GPD E

H: arXiv:1106.2990

Longitudinal target spin asymmetry

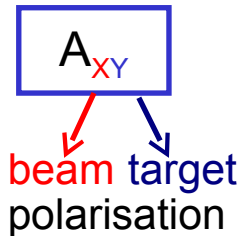
GPD \tilde{H}

H: JHEP 06 (2010) 019

D: Nucl. Phys. B 842 (2011) 265

Longitudinal double spin asymmetry

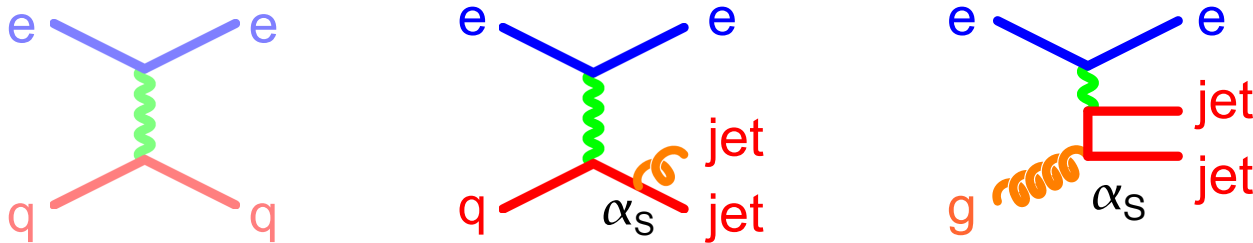
GPD \tilde{H}



→ filling in the picture of GPDs

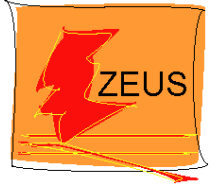
Jet Production at HERA

- dominating processes in ep scattering:



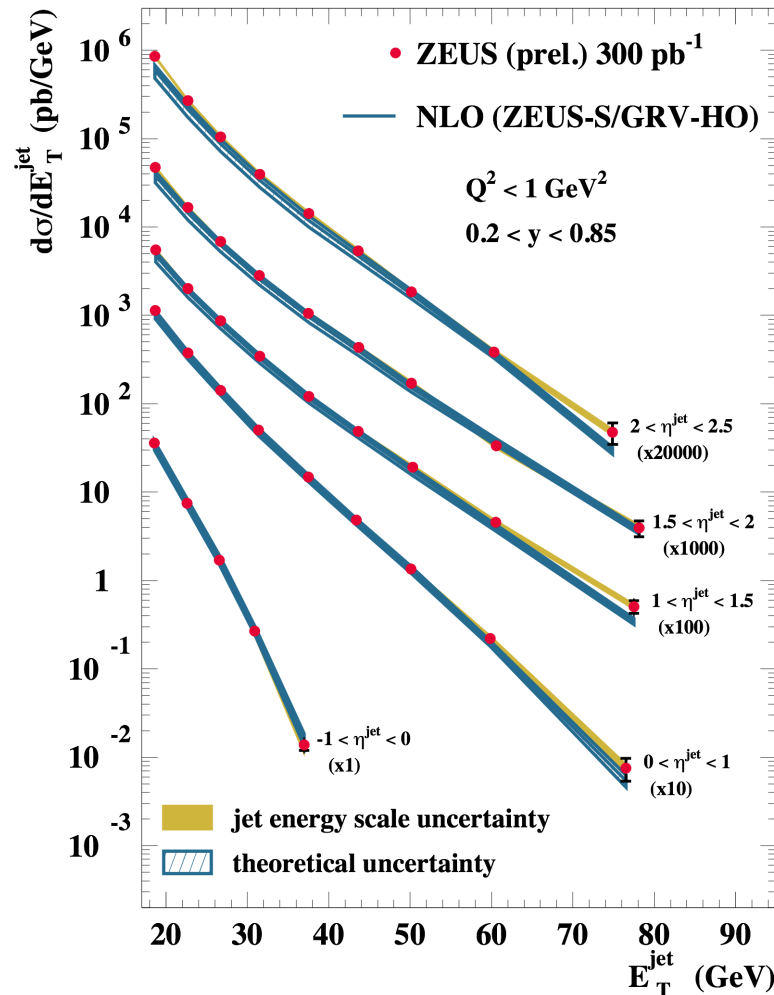
- Jets are measured in a frame where the photon and the proton collide head-on (Breit frame)
- LO process produces no transverse momentum in the final state
- Jet cross sections are directly sensitive to the strong coupling α_S and the gluon density in the proton

Jets in γp : α_s

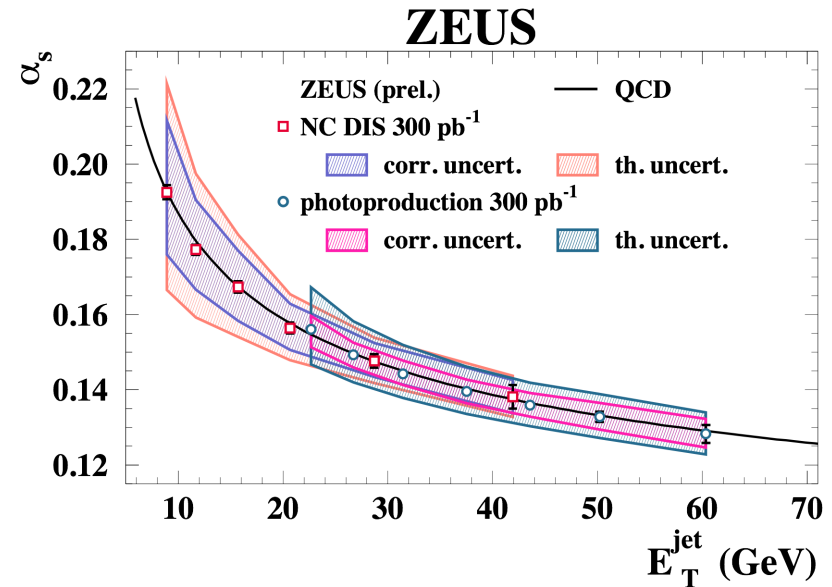


ZEUS

ZEUS-prel-11-005



- 1% jet energy scale uncert.
- very large p_T accessible
- running of α_s measured in a single experiment



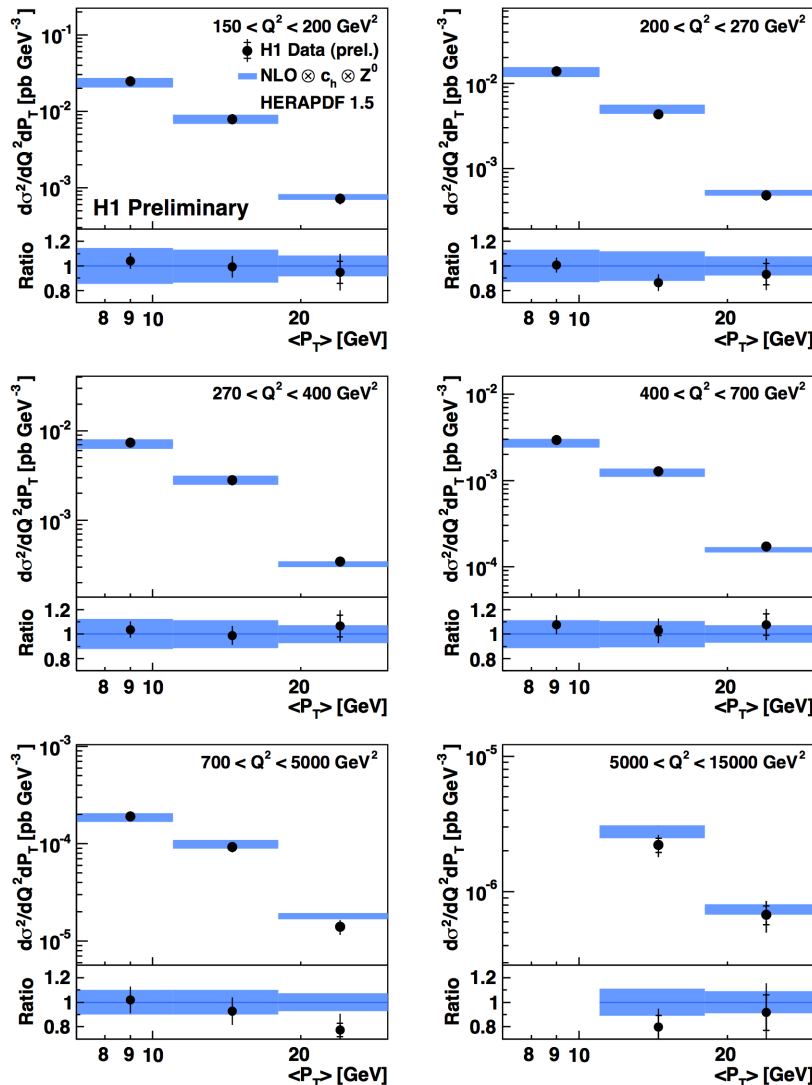
$$\alpha_s(M_Z) = 0.1206 + 0.0023 - 0.0022(\text{exp}) + 0.0042 - 0.033(\text{th})$$



Jets in DIS

H1prelim-11-032

Trijet Cross Section



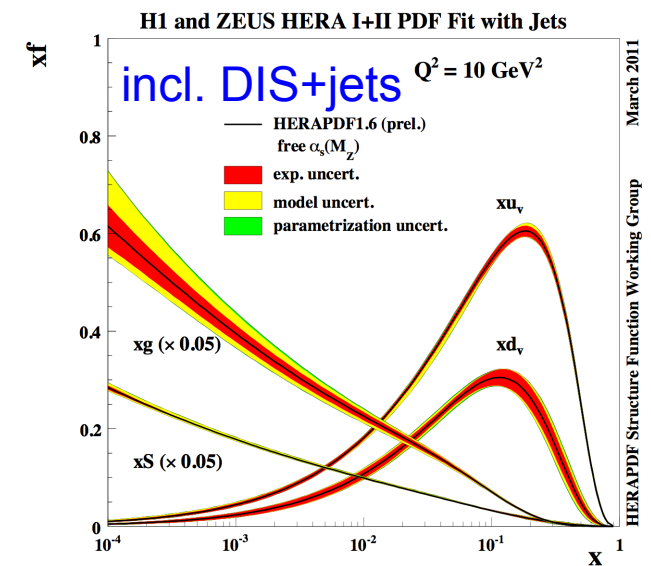
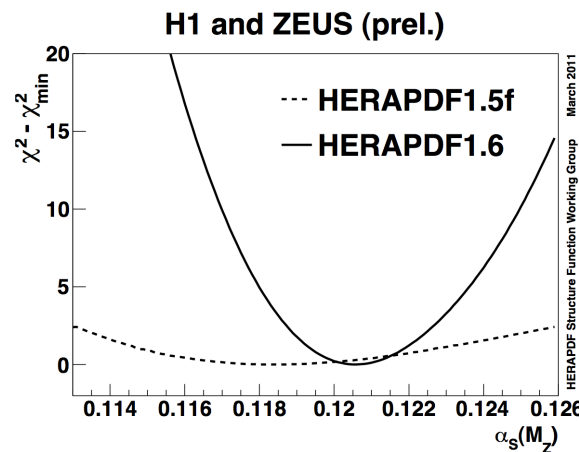
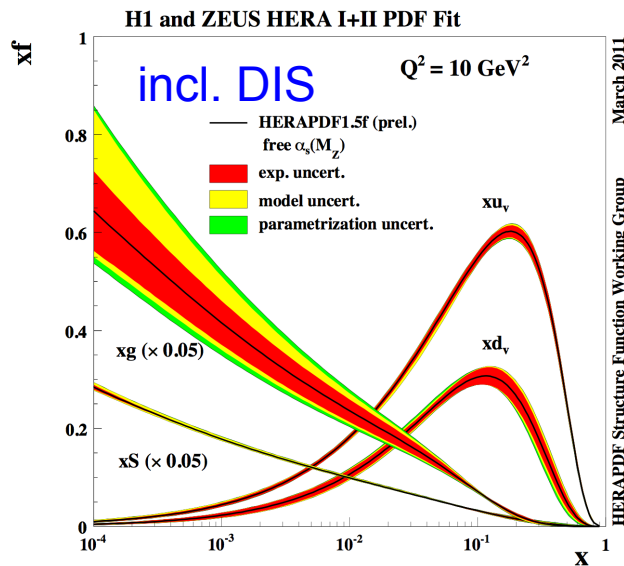
- inclusive jet, 2jet and 3jet production
- 1% jet energy scale uncertainty
- first double-differential 3jet measurement

→ data reasonably well described by NLO calculation with $\alpha_s(M_Z) = 0.118$

$$3\text{jet: } \alpha_s(M_Z) = 0.1196 \pm 0.0016(\text{exp}) \pm 0.0010(\text{pdf}) + 0.0055 - 0.0039(\text{th})$$

- PDF fit of inclusive DIS data: freeing α_s leads to very large uncertainty on gluon density

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

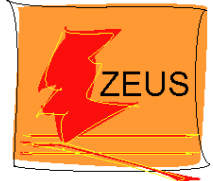


→ including jet data allows to disentangle α_s and gluon

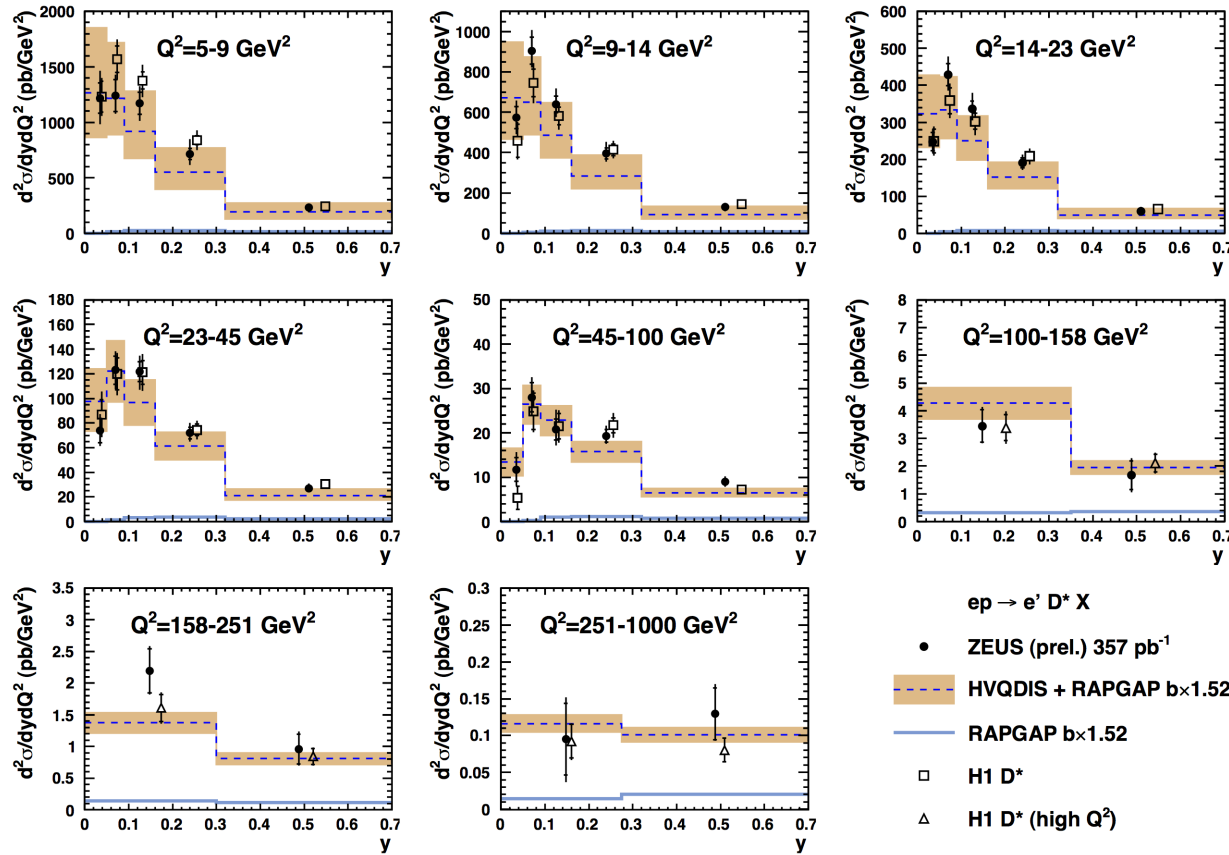
$$\alpha_s(M_Z) = 0.1202 \pm 0.0013(\text{exp}) \pm 0.0007(\text{param}) \pm 0.0012(\text{had}) \pm 0.0045(\text{scale})$$



Charm Production in DIS



ZEUS



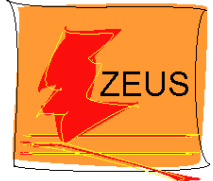
ZEUS:
ZEUS-prel-11-012

H1:
DESY-11-066 (subm. to EPJC)
Phys. Lett. B 686 (2010) 91

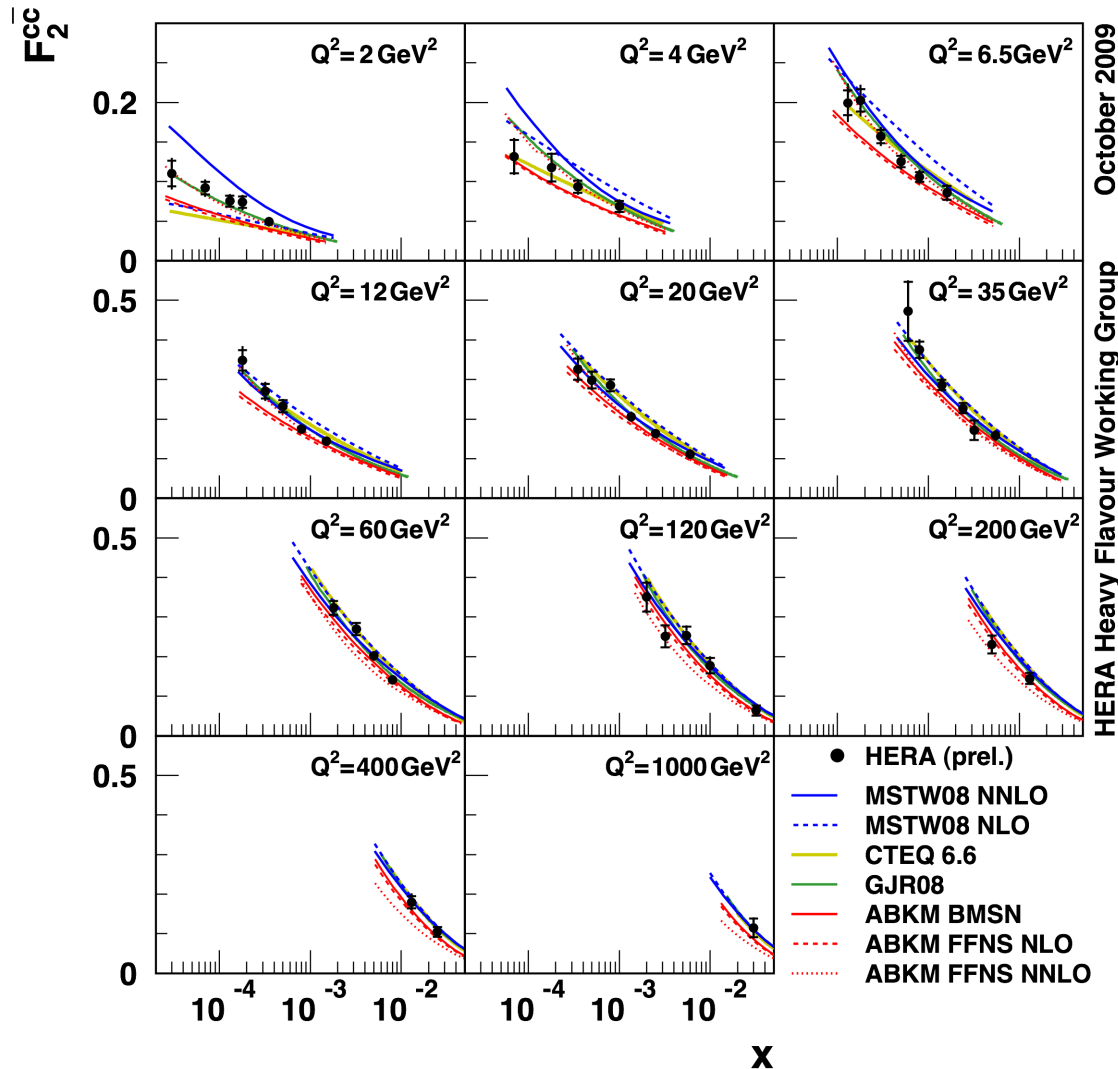
- *charm* contributes up to 30% of inclusive cross section
- new precise H1 and Zeus results from D* meson production
- charm production well described by NLO QCD calculation



$F_2^{c\bar{c}}$: Charm Contribution to F_2



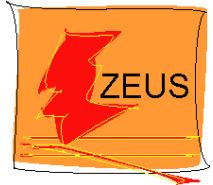
H1prelim-09-171 / ZEUS-prel-09-015



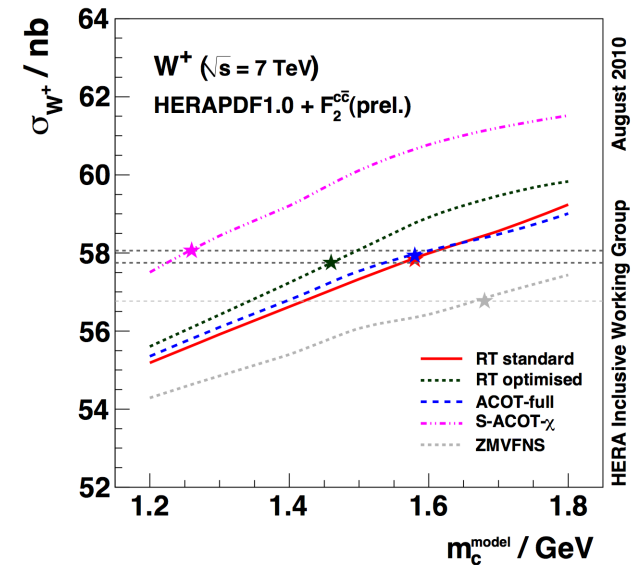
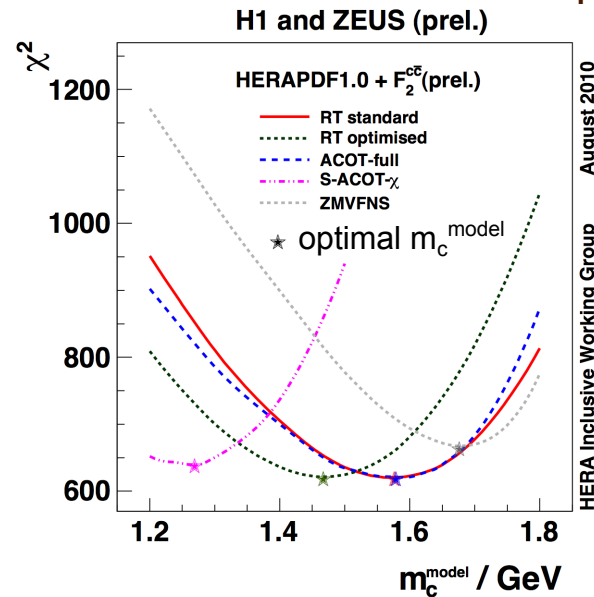
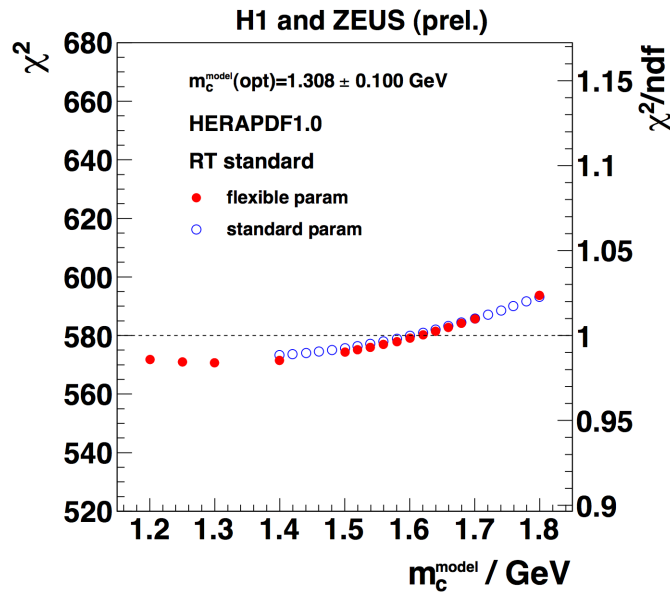
- combination of H1 and Zeus measurement with different techniques
- combination leads to 5-10% precision
- NLO QCD predictions with different charm mass treatments describe the data



PDF Fit including F_2^{cc} data



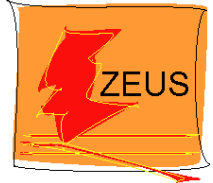
H1prelim-10-143 / ZEUS-prel-10-019



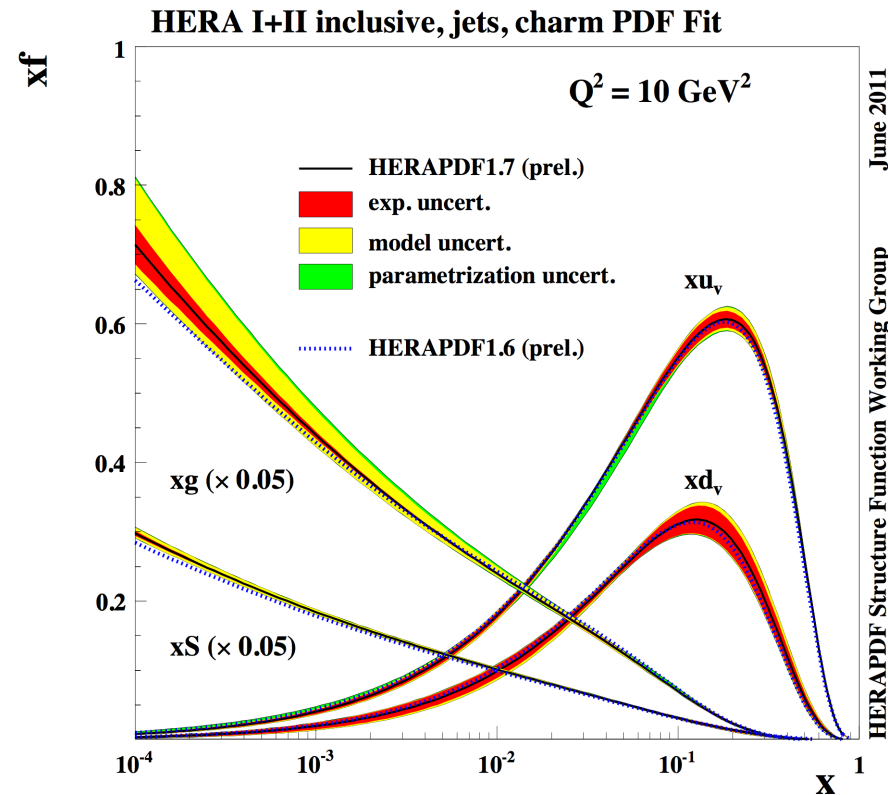
- inclusive data have little sensitivity to m_c
- optimal m_c depends on heavy flavour treatment (“model”)
- m_c has influence on flavour decomposition of sea quarks and thus on W production cross section at LHC
- use of optimal m_c^{model} reduces difference between predictions to $<2\%$



PDF Fit to NC, CC, jets & $F_2^{c\bar{c}}$



H1prelim-11-143 / ZEUS-prel-11-010



- fitting inclusive NC and CC cross sections, F_L , jets and charm data gives a consistent picture of the proton

Summary

HERA inclusive ep DIS cross sections provide essential information on the proton structure

→ HERAPDF1.5 at NLO and NNLO

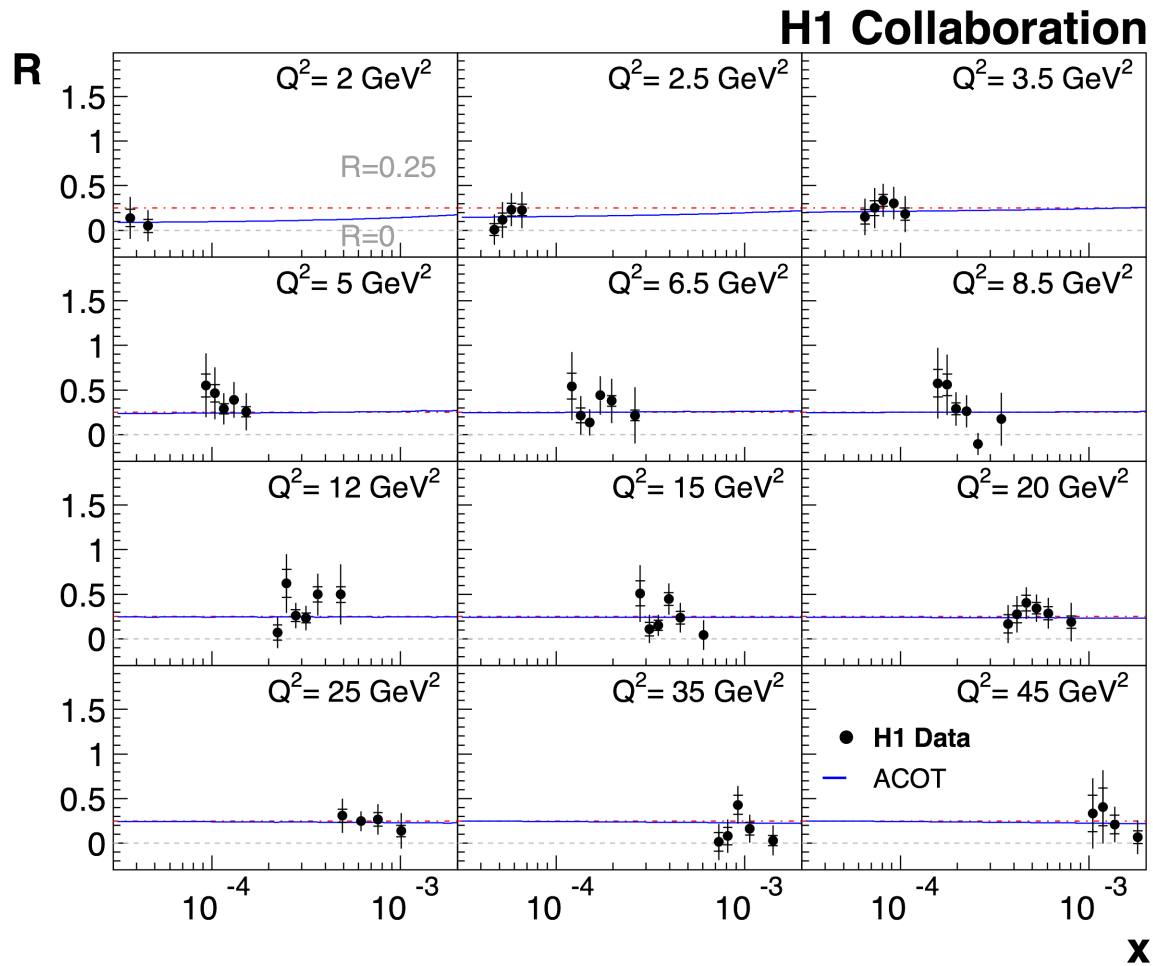
spin structure of the proton studied in polarised ep and eN scattering at HERA and JLAB

DVCS provides information on GPDs

measurements of the hadronic final state (jets, heavy quarks) are well described by NLO QCD calculations and provide additional information:

- disentangle gluon density and α_s
- sensitivity to charm mass

Backup



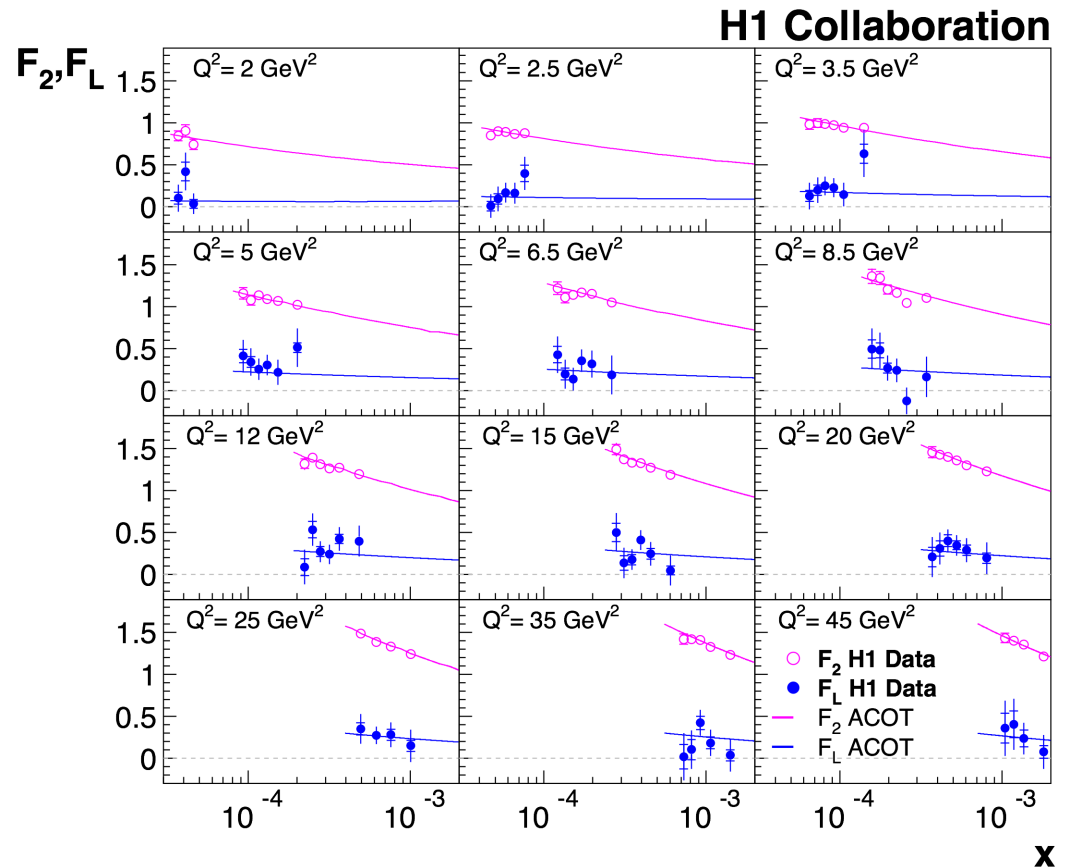
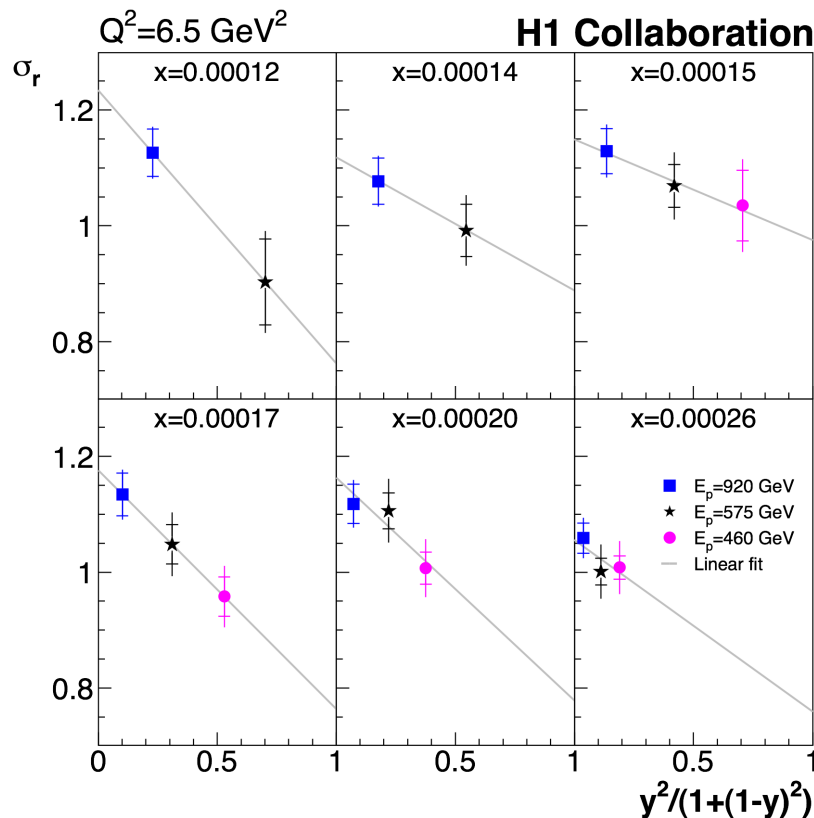


F_L

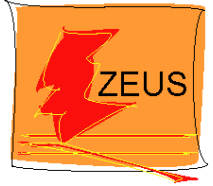
- data taking with different proton beam energies allows model-independent determination of F_2 and F_L

Eur.Phys.J.C71 (2011) 1579

$$\sigma_r^{NC}(e^\pm p) = \tilde{F}_2(x, Q^2) - \frac{y^2}{1+(1-y)^2} \tilde{F}_L(x, Q^2) \quad Q^2 = x y s$$

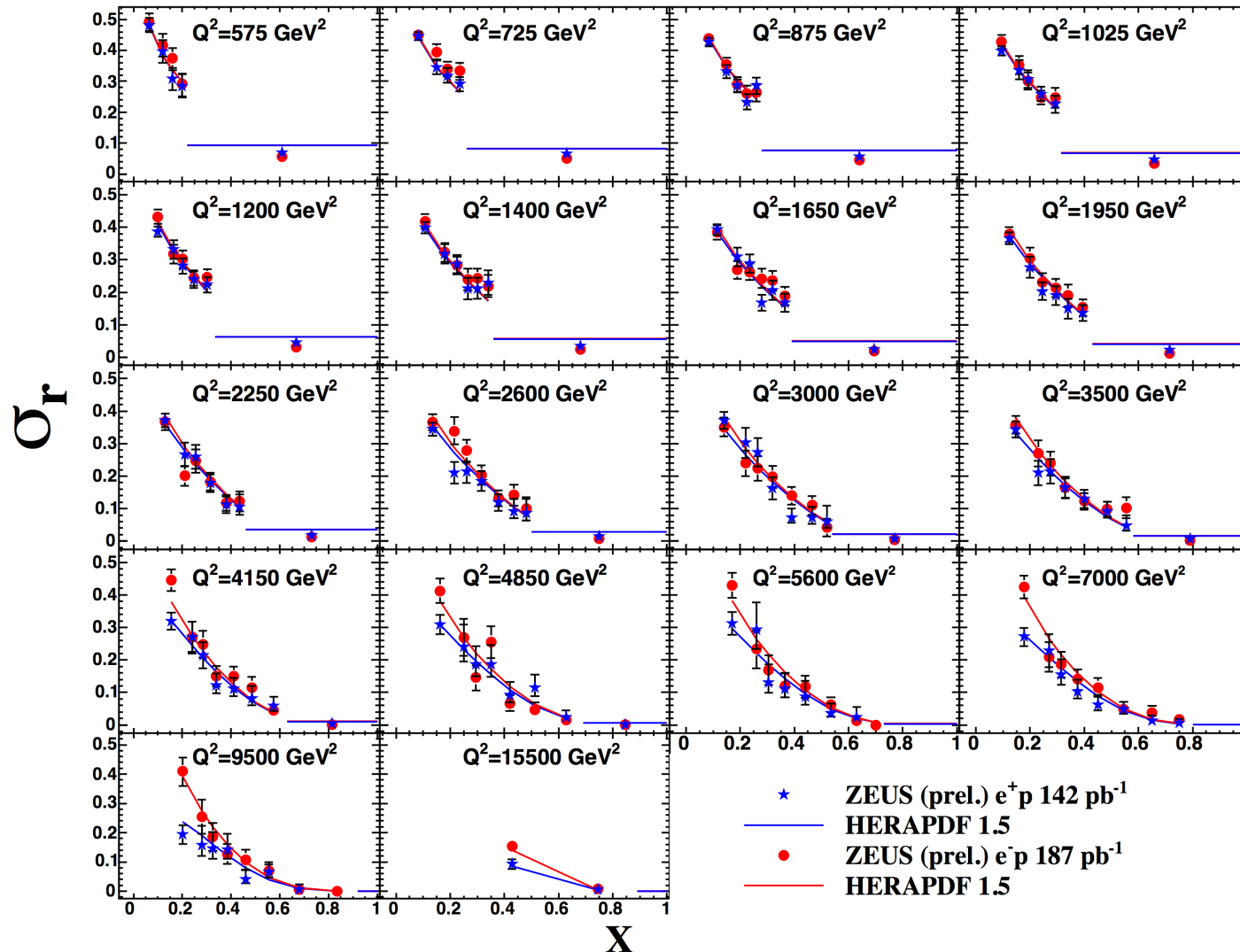


NC at high x



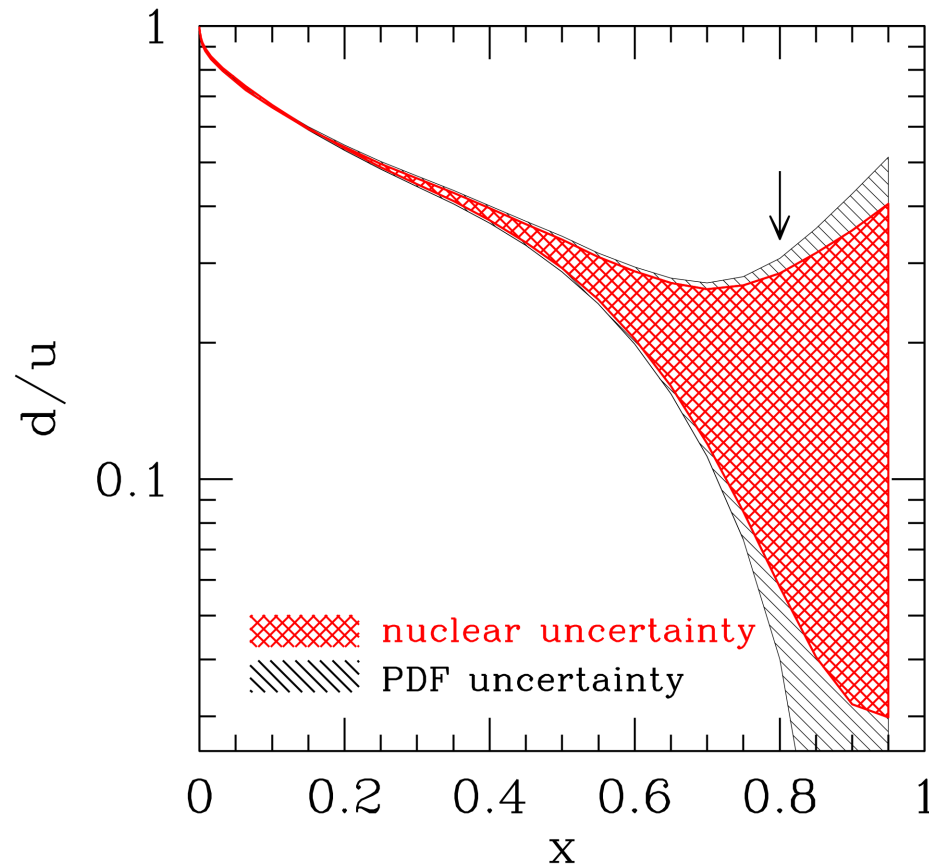
ZEUS

ZEUS-prel-11-004



- inclusive NC DIS cross sections for full HERA II
- x resolution deteriorates at high x : measure integrated cross section
- extend measurement to x region most sensitive to valence quarks

down quark density





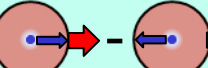
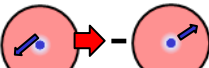
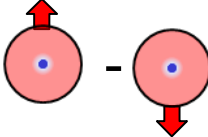
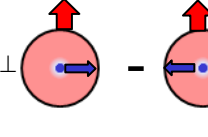

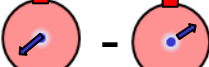
- d pdf not well constrained at large x by proton data
- usually deuteron to proton ratio F_2^d/F_2^p is used to constrain d/u , depends on nuclear corrections
- ▶ new neutron data can significantly reduce uncertainty

Polarised Parton Densities

Accessible in **inclusive DIS**

Quark polarisation

Lepton polarisation

N/q	U	L	T
U	f_1  Number Density		h_1^\perp  Boer-Mulders
L		g_1  Helicity	h_{1L}^\perp  Mulders-Kotzinian
T	 Sivers	g_{1T}^\perp  Worm-gear	h_1  Transversity h_{1T}^\perp  Pretzelosity

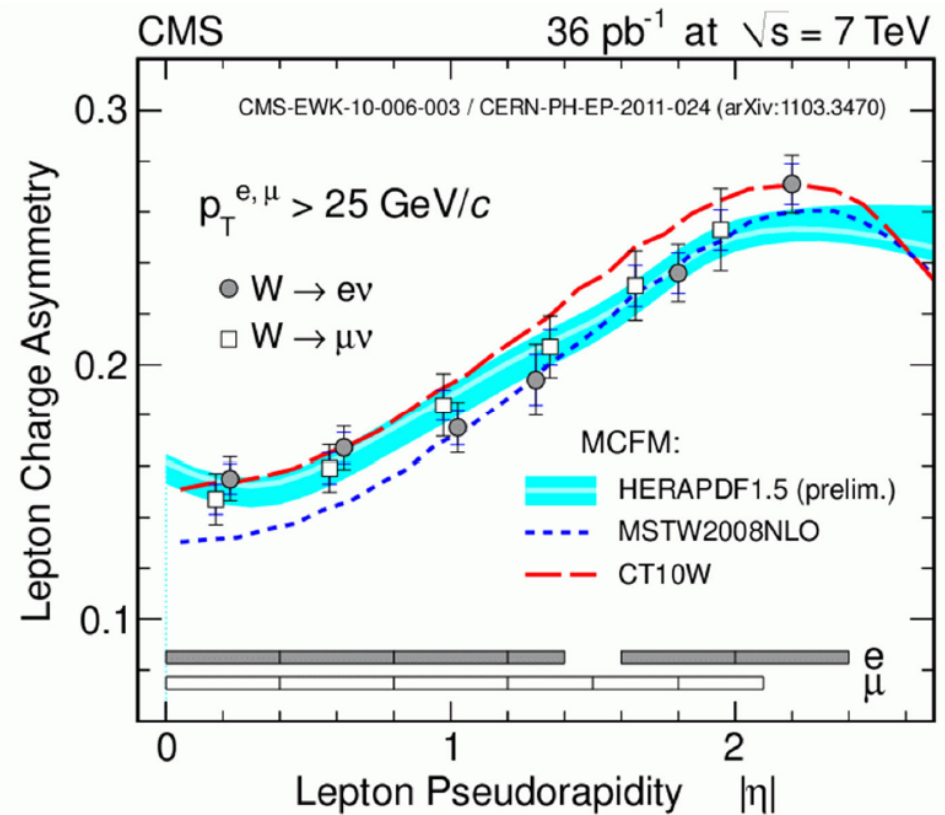
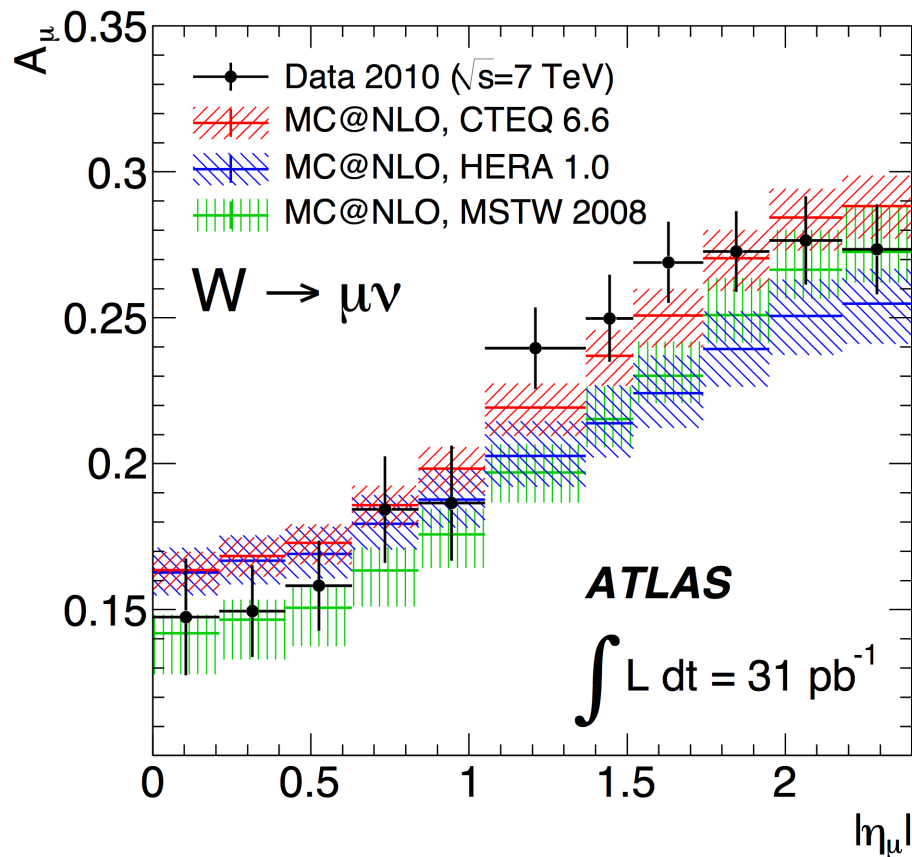
Nucleon structure is described by 8 leading-twist (+ many subleading) quark distributions containing information about quark orbital motion and spin-orbit effects

2 distributions are accessible in incl. DIS

all others need measurement of the angle of the hadronic final state

Predictions for LHC: W

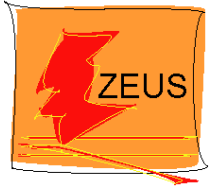
- predictions based on HERAPDF give reasonable description of W lepton asymmetry at LHC



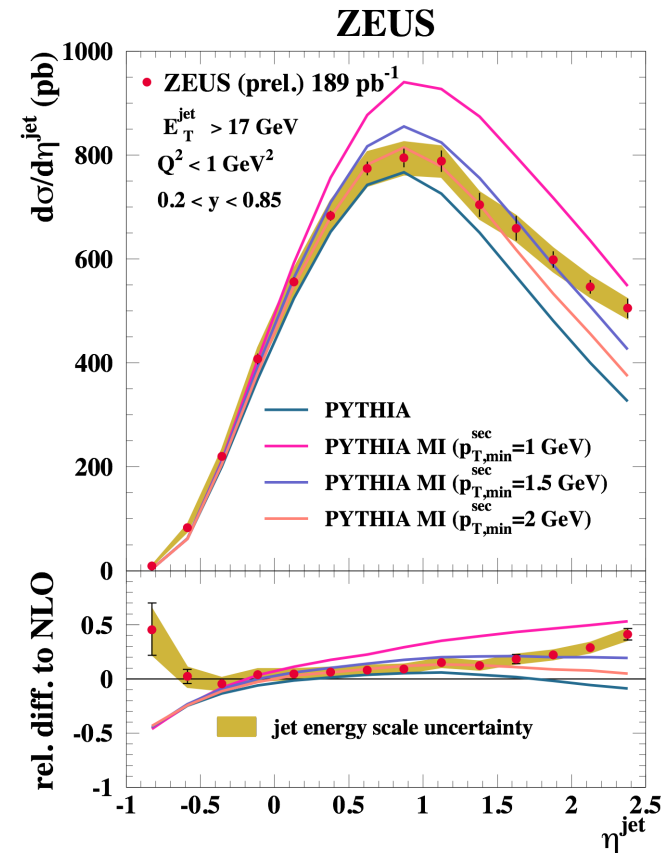
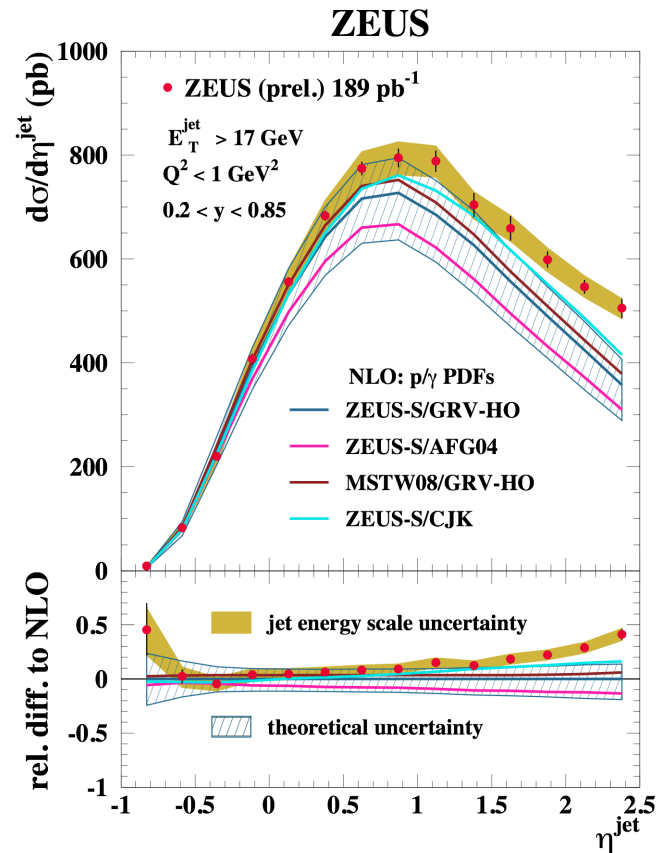
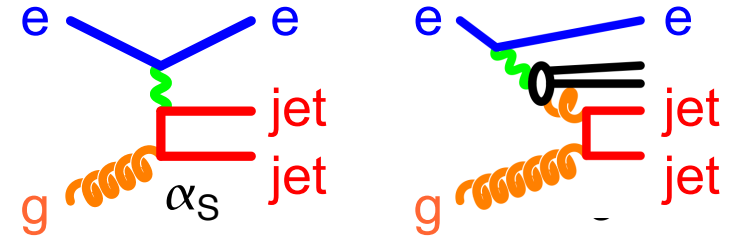
Jet Production at HERA

- pQCD predictions of jet cross sections depend on several scales: Q^2 , p_T^2
- sources of uncertainty for pQCD predictions:
 - renormalisation scale dependence
 - proton PDFs
 - strong coupling α_s
 - photoproduction: photon PDFs, MPI

Jets in Photoproduction



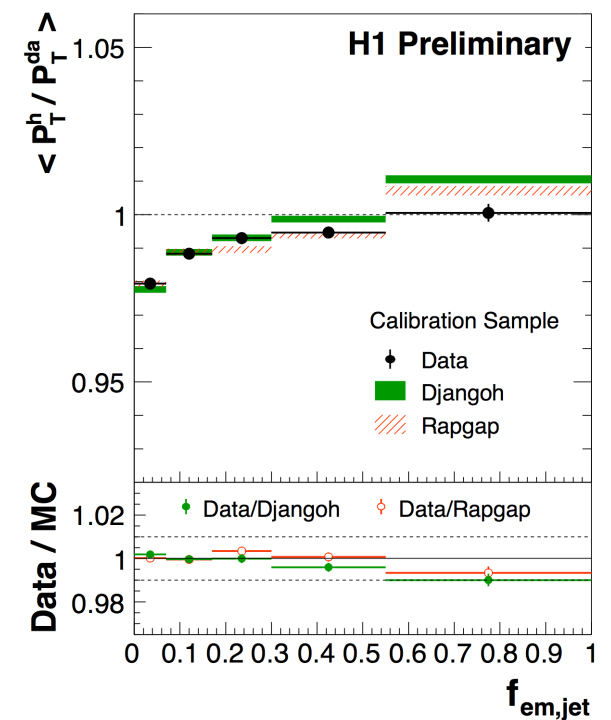
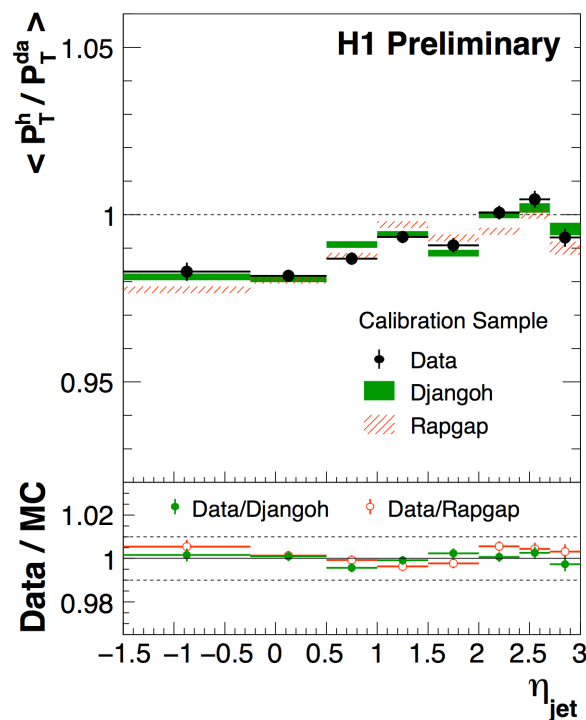
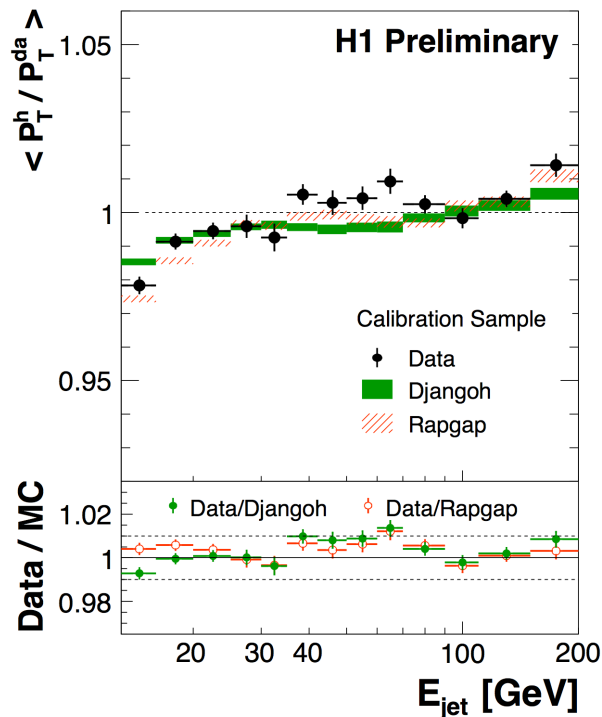
- contribution from resolved photons:
- sensitivity to photon PDF
- sensitivity to multi-parton interactions





Jets in DIS: Calibration

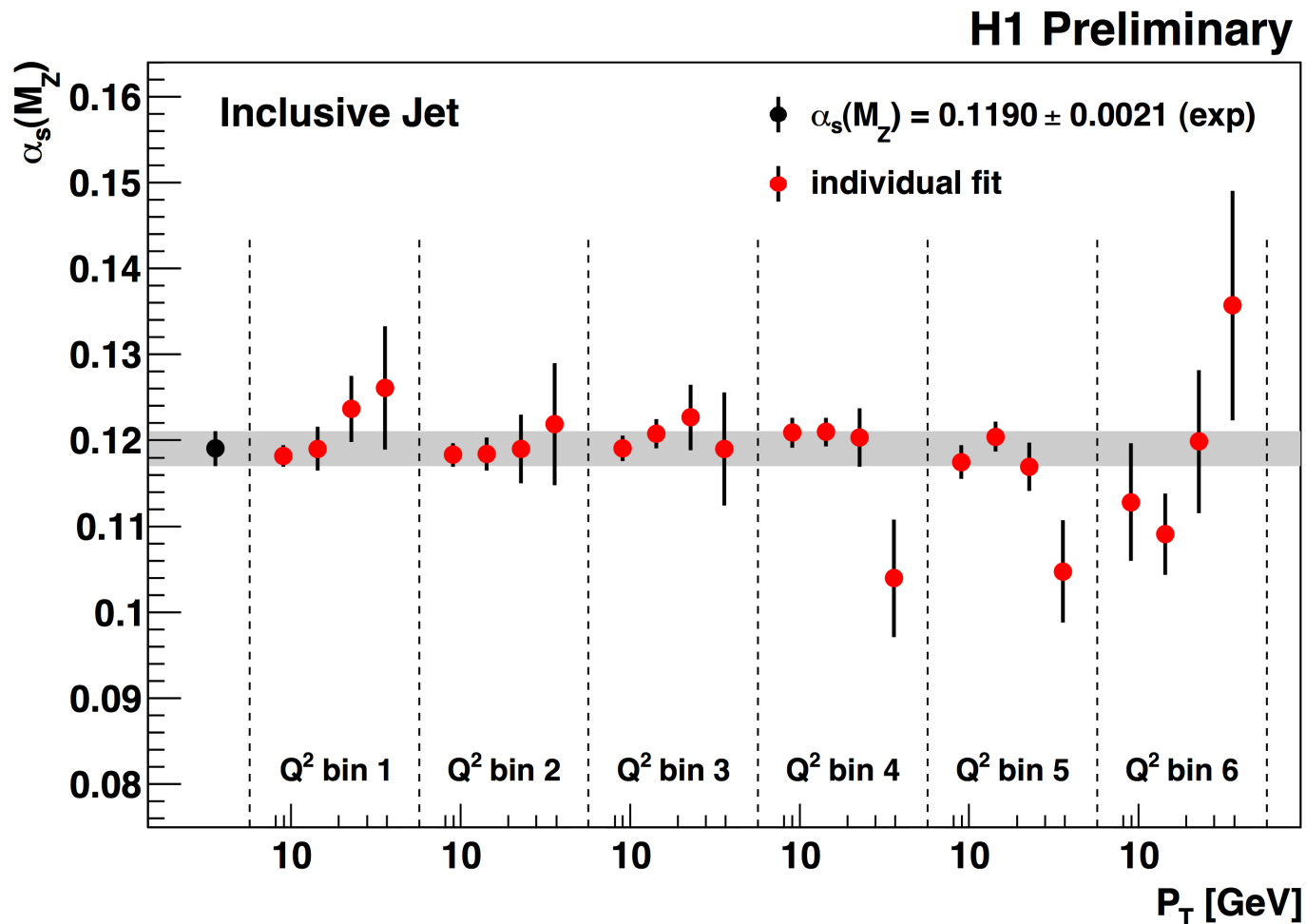
- new dedicated calibration taking into account electromagnetic sub-showers in hadronic energy depositions
- 1% jet energy scale uncertainty in large η and p_T range

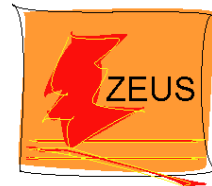




Jets in DIS

double diff. measurement in Q^2 and P_T is used to determine $\alpha_s(M_Z)$

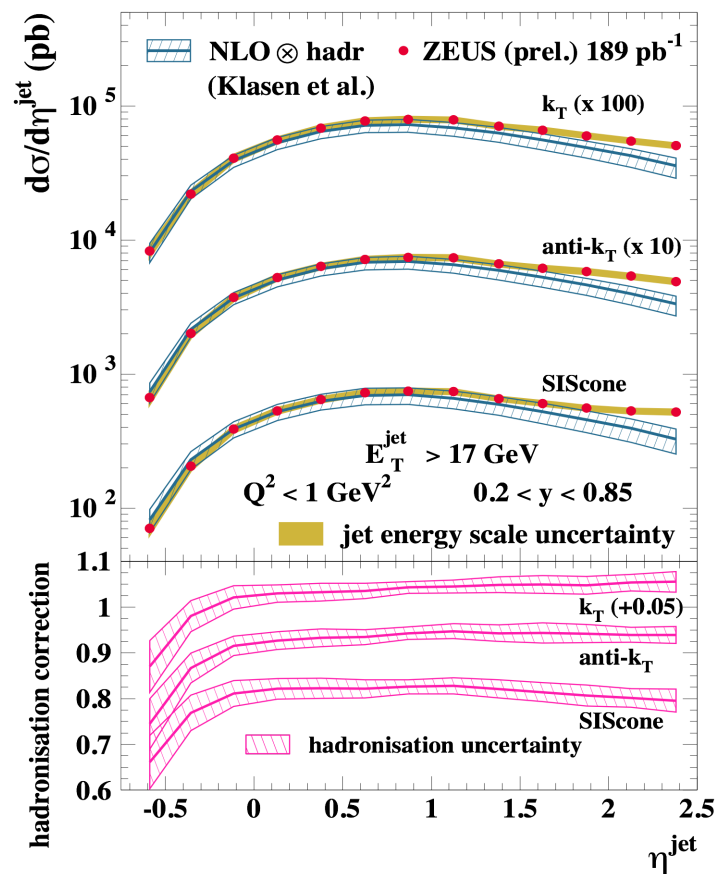




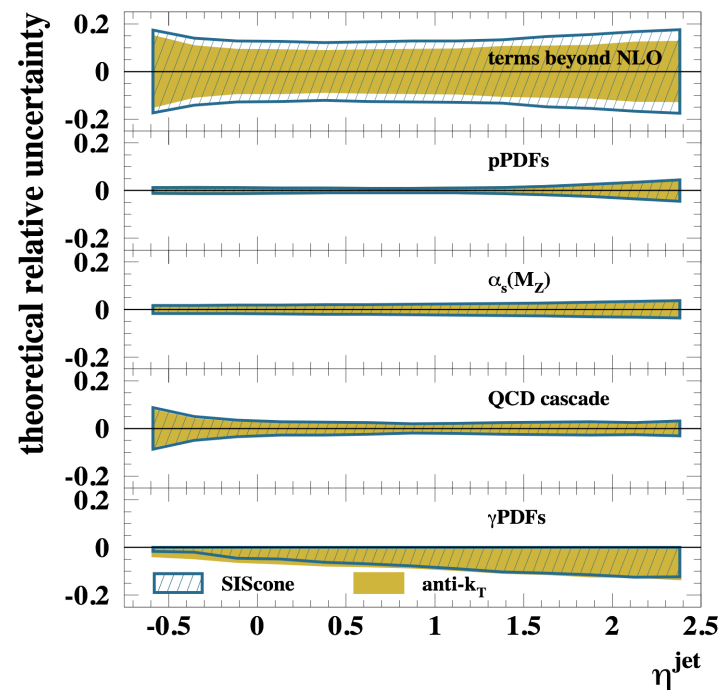
Jets in γp : Jet Algorithms

- HERA provides clean environment to study jet algorithms
- data well described by NLO QCD for all algorithms

ZEUS



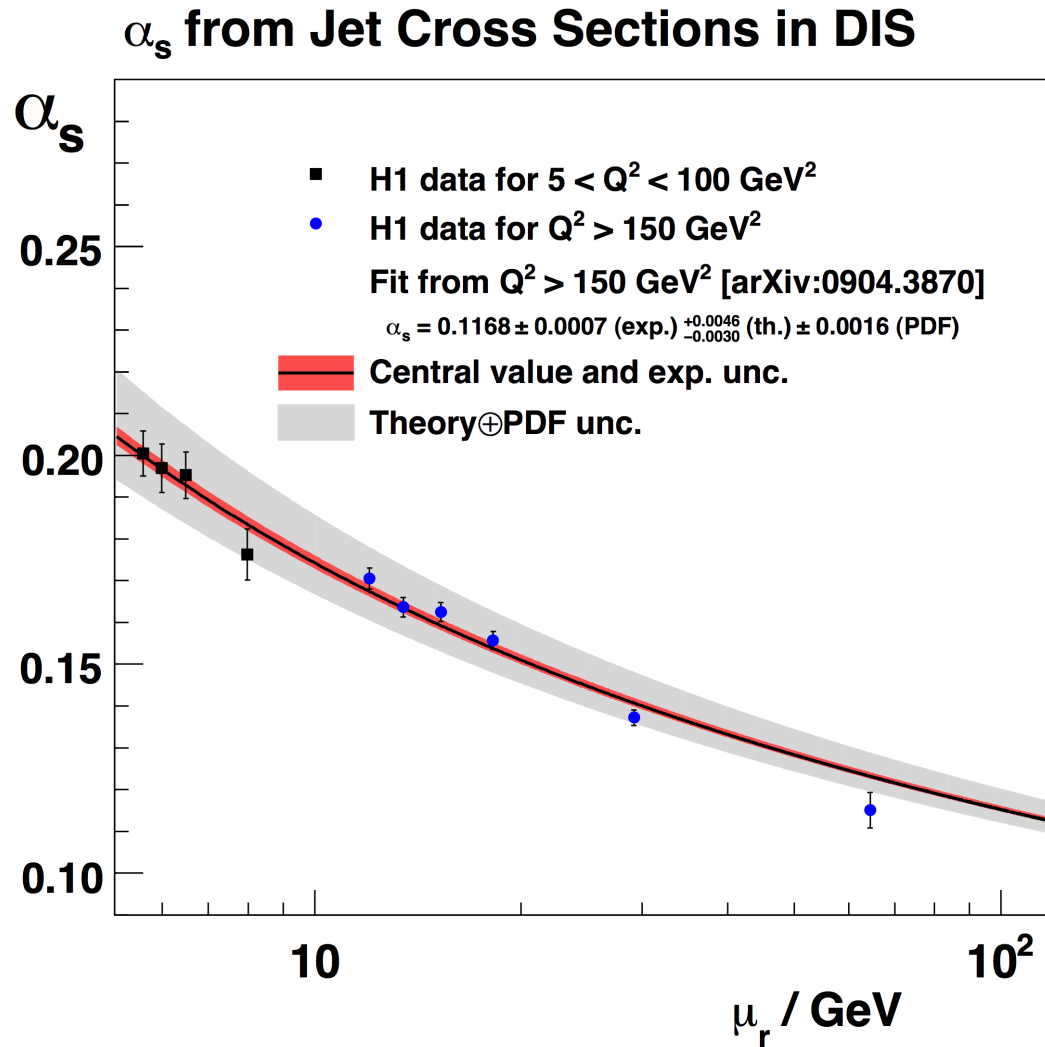
ZEUS



- k_T and anti- k_T similar performance, SIScone a bit larger hadronisation corrections and uncertainties

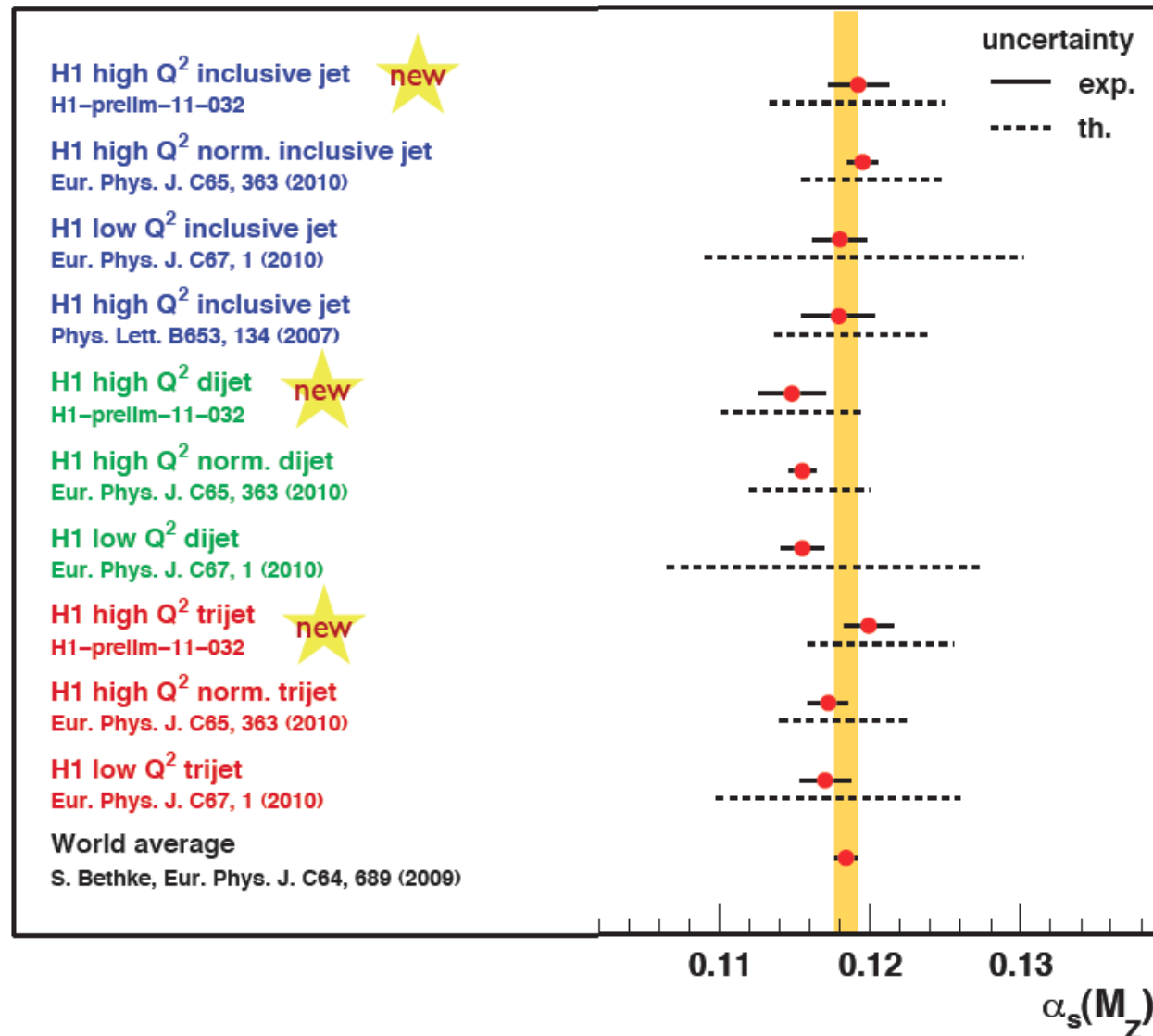


DIS Jets: Running of α_s



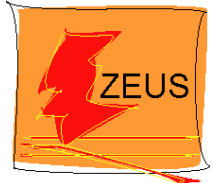
- double differential inclusive jet, 2jet and 3jet cross sections in Q^2 and P_T used to determine α_s
- measurement in two regions:
 $5 < Q^2 < 100 \text{ GeV}^2$
and $Q^2 > 150 \text{ GeV}^2$
- agreement of $\alpha_s(M_Z)$ in whole Q^2 range
- running of α_s from one experiment

Jets in DIS



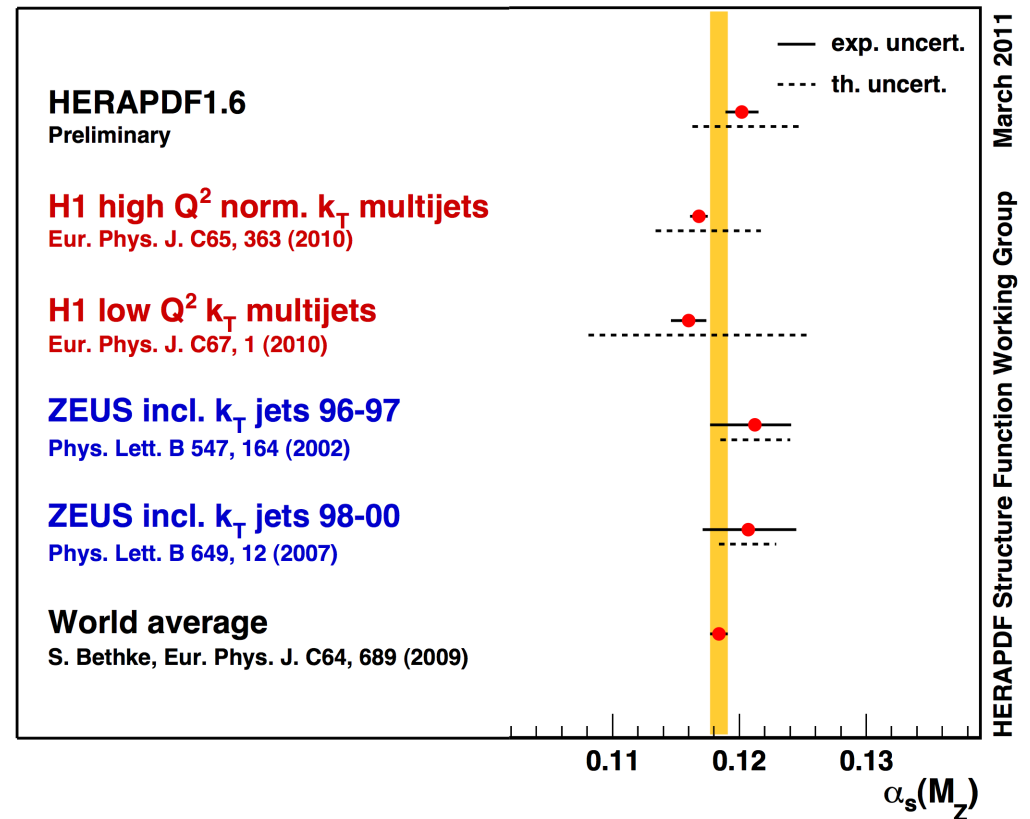
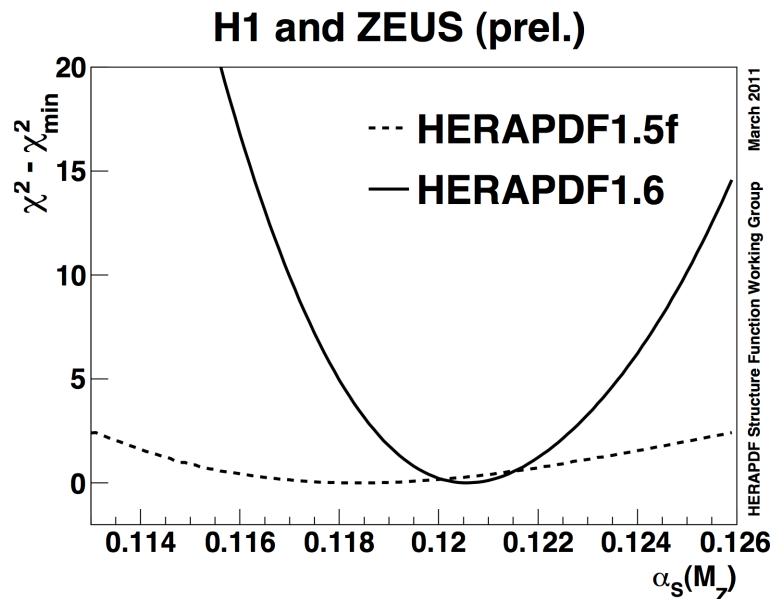


Combined PDF and α_s fit



→ including jet data
constrains α_s

H1 and ZEUS (prel.)



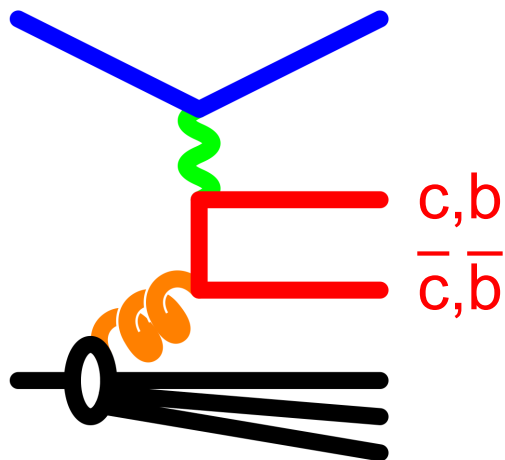
$$\alpha_s(M_Z) = 0.1202 \pm 0.0013(\text{exp})$$

$$\pm 0.0007(\text{param}) \pm 0.0012(\text{hadr})$$

$$\pm 0.0045(\text{scale})$$

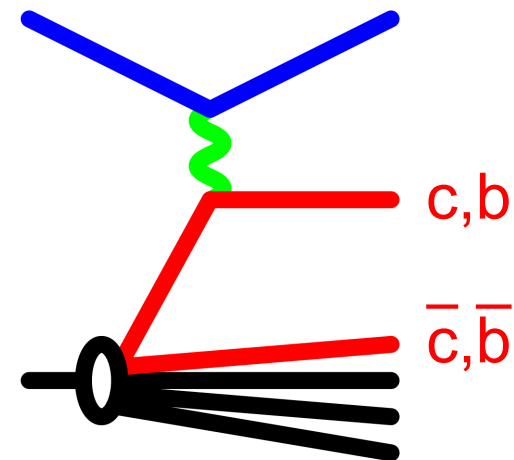
Heavy Quark Production

- *charm* contributes up to 30% to the inclusive cross section, *beauty* up to a few %
- mass of heavy quark (c or b) introduces additional hard scale
- several schemes for the treatment of the mass



FFNS

GM-VFNS



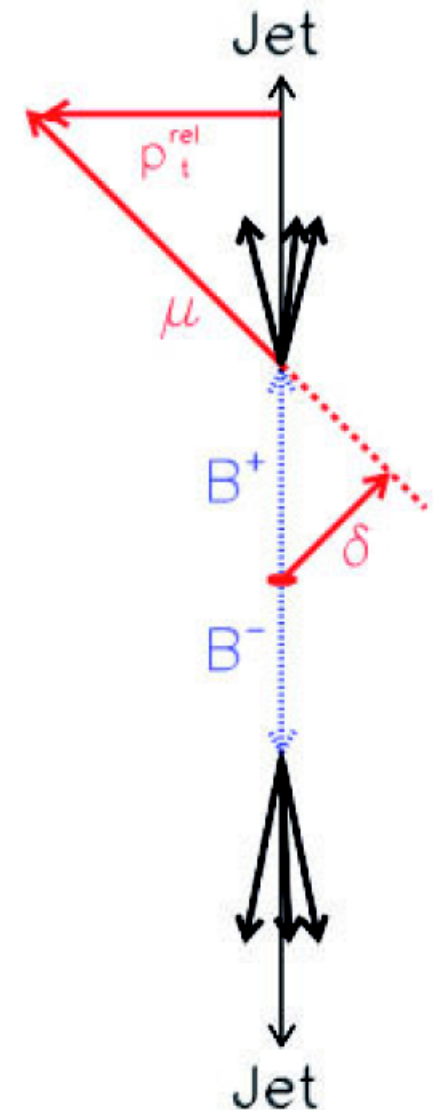
ZM-VFNS

Heavy Quarks Production

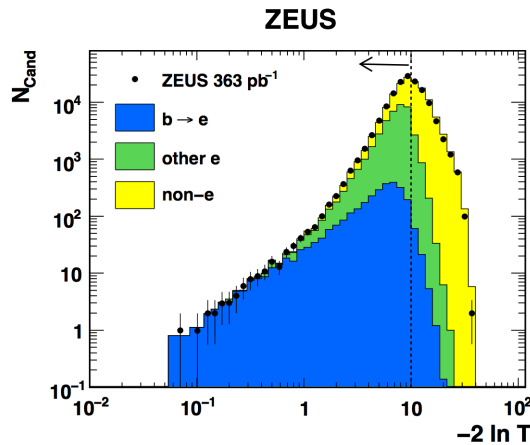
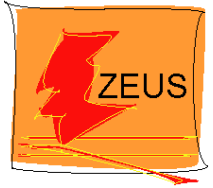
- *charm* contributes up to 30% to the inclusive cross section, *beauty* up to a few %
- mass of heavy quark (*c* or *b*) introduces additional hard scale
- several schemes for the treatment of the mass

several quantities allow a distinction of heavy from light quarks

- mass
 - full reconstruction of heavy hadron
 - transverse momentum p_T^{rel} relative to jet axis
- lifetime
 - reconstruction of a secondary vertex
 - impact parameter δ
- semileptonic decays (μ, e)

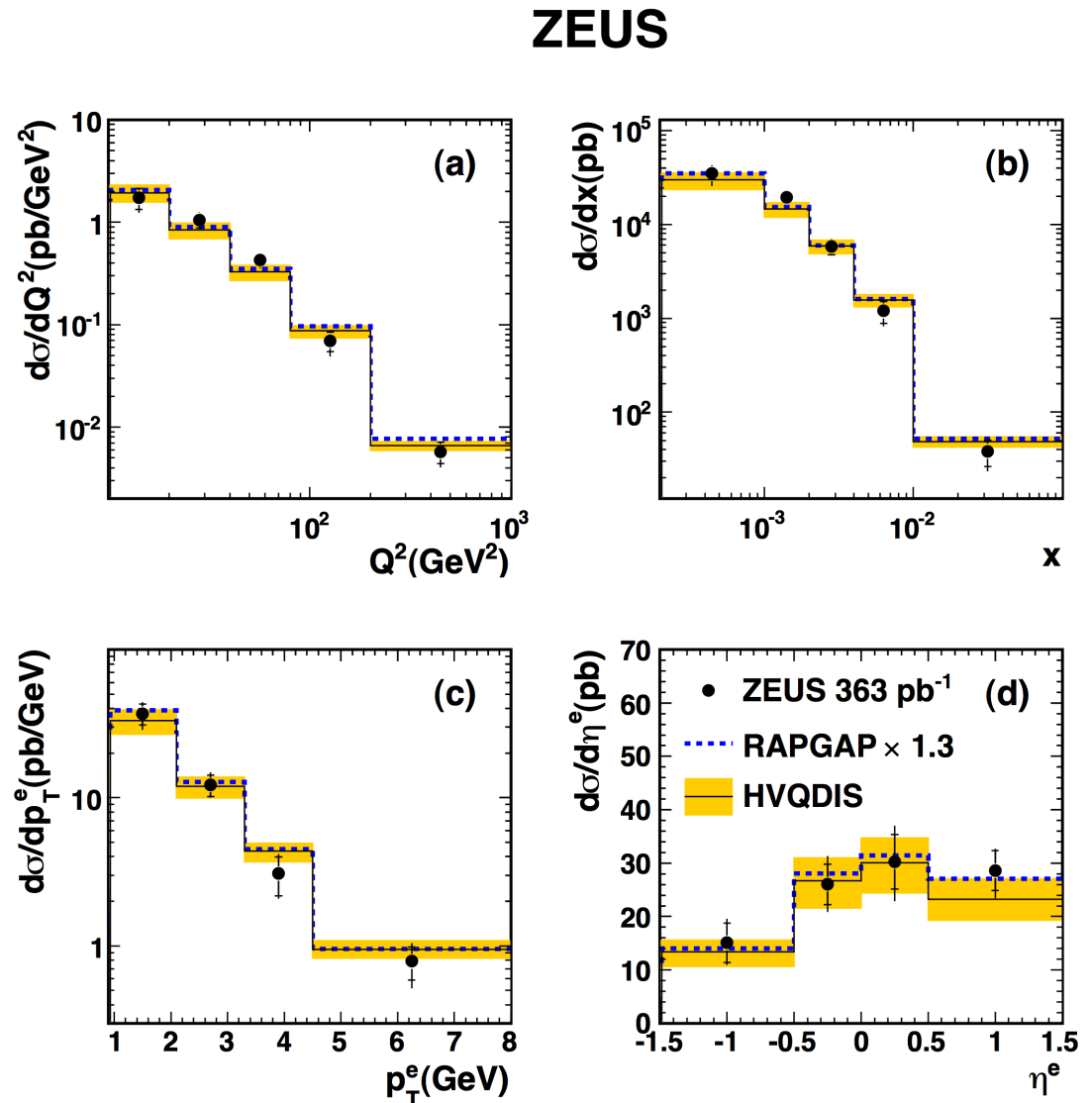


$b \rightarrow e$ in DIS



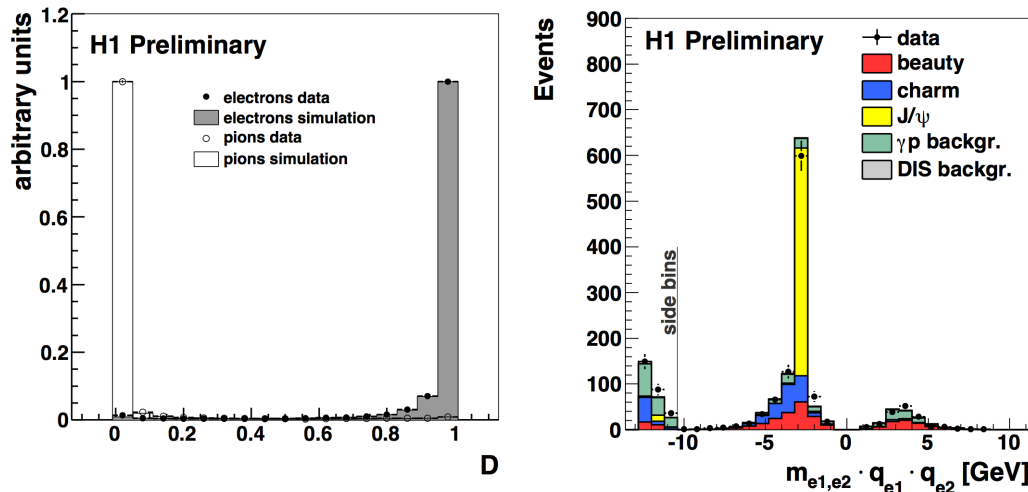
- use multivariate analysis to distinguish $b \rightarrow e$ from other e and fake

→ data well described by FFNS NLO calculation



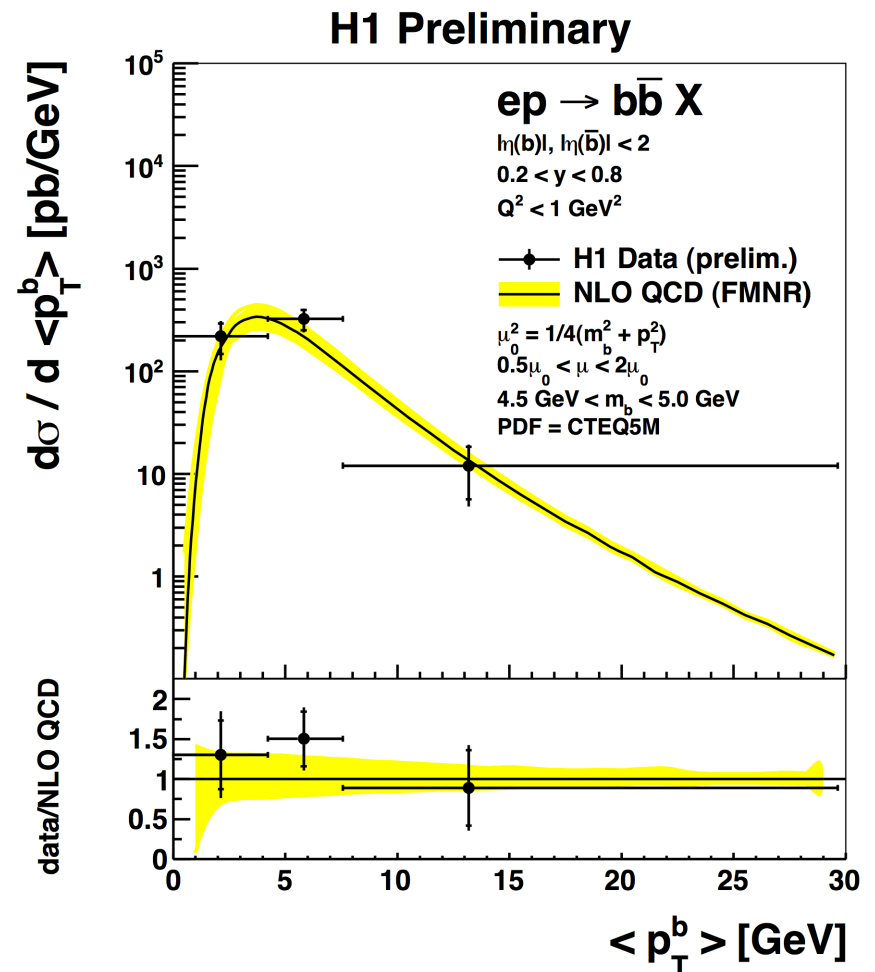


$bb \rightarrow ee$ in Photoproduction

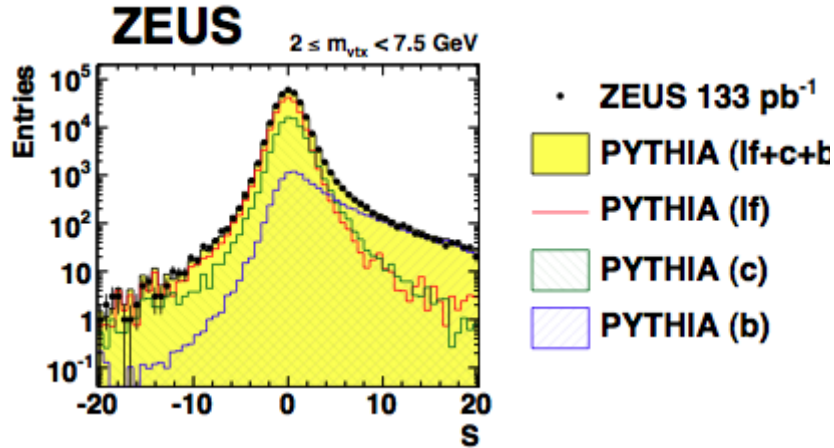
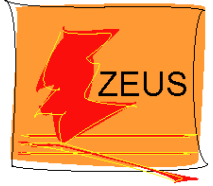


- very good e/π separation
- triggering on low p_T electrons
- quark flavour separation by invariant mass and charge correlations
- measurement of b production at very low p_T

→ good description by FFNS
NLO calculation



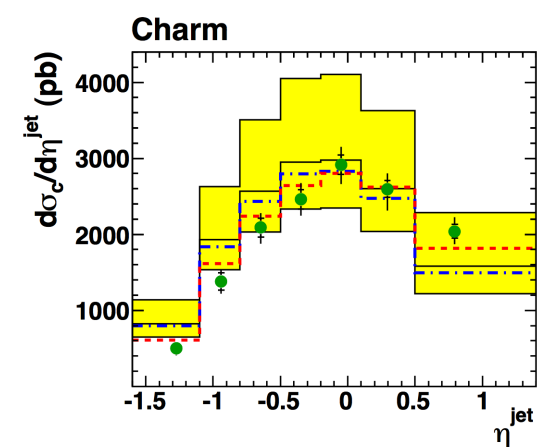
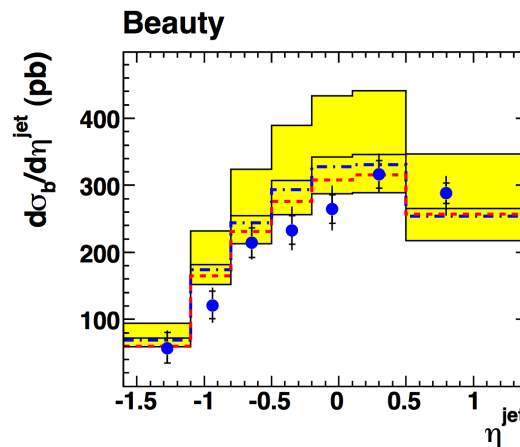
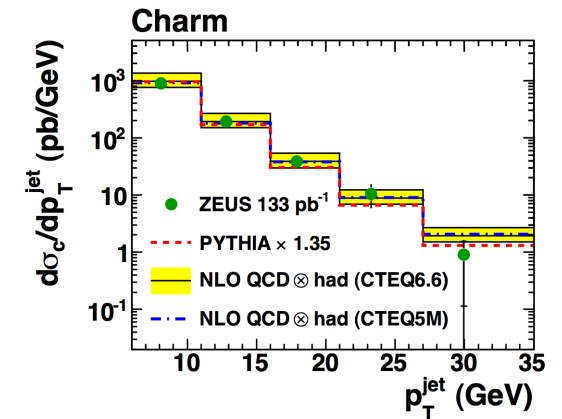
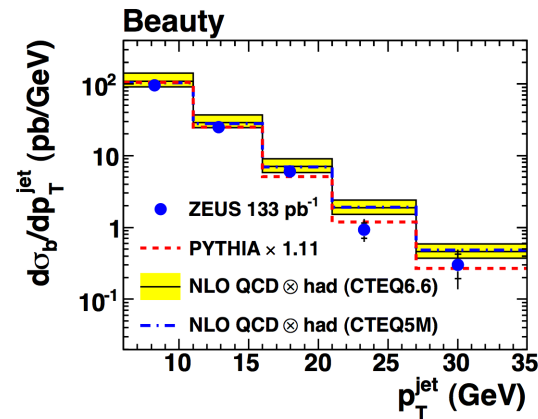
HQ Jets in Photoproduction



→ good description by FFNS NLO calculation

- quark flavour separation by lifetime (decay length) and mass (secondary vertex mass)
- simultaneous measurement of c and b production at large p_T

ZEUS

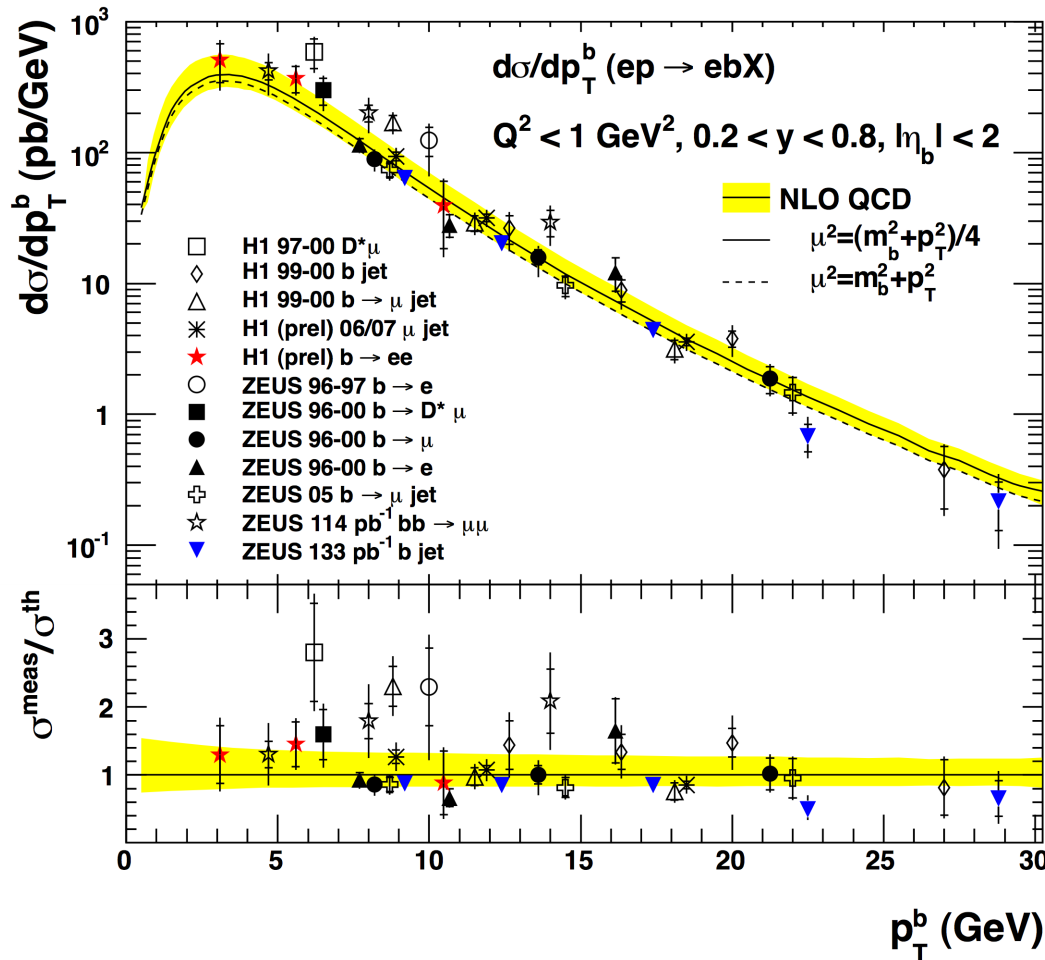


b in Photoproduction

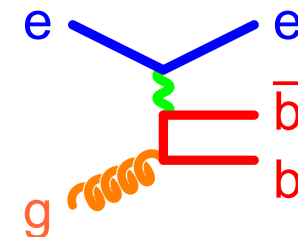
H1: H1prelim-11-071

ZEUS: Eur.Phys.J.C71 (2011) 1659

HERA

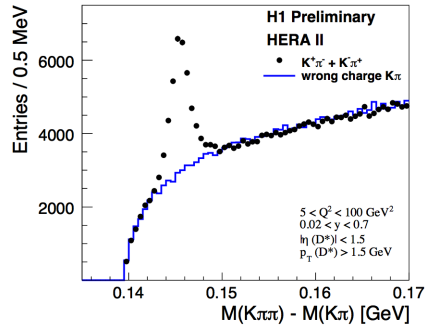


- new measurements at small and large p_T
- good agreement between measurements
- data described by FFNS NLO calculation

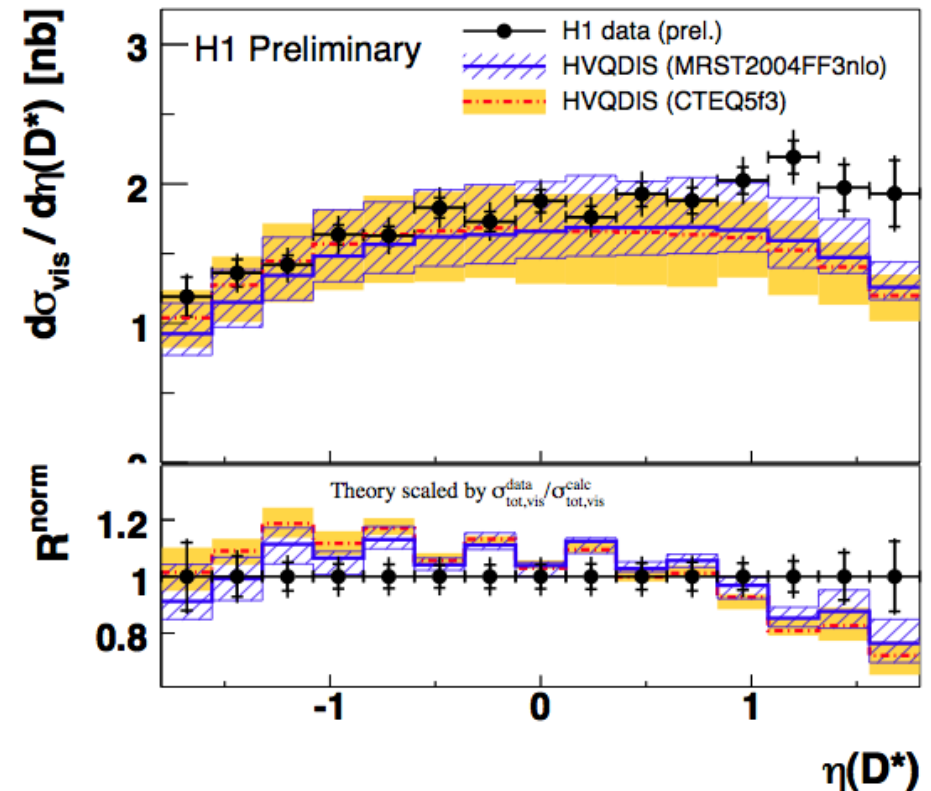
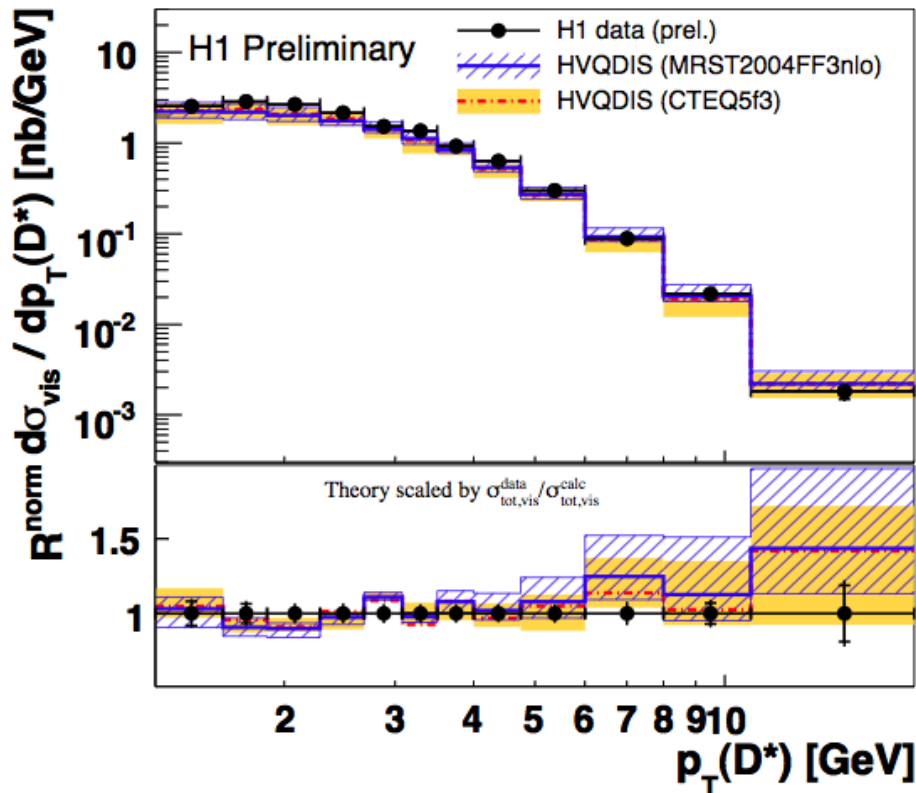




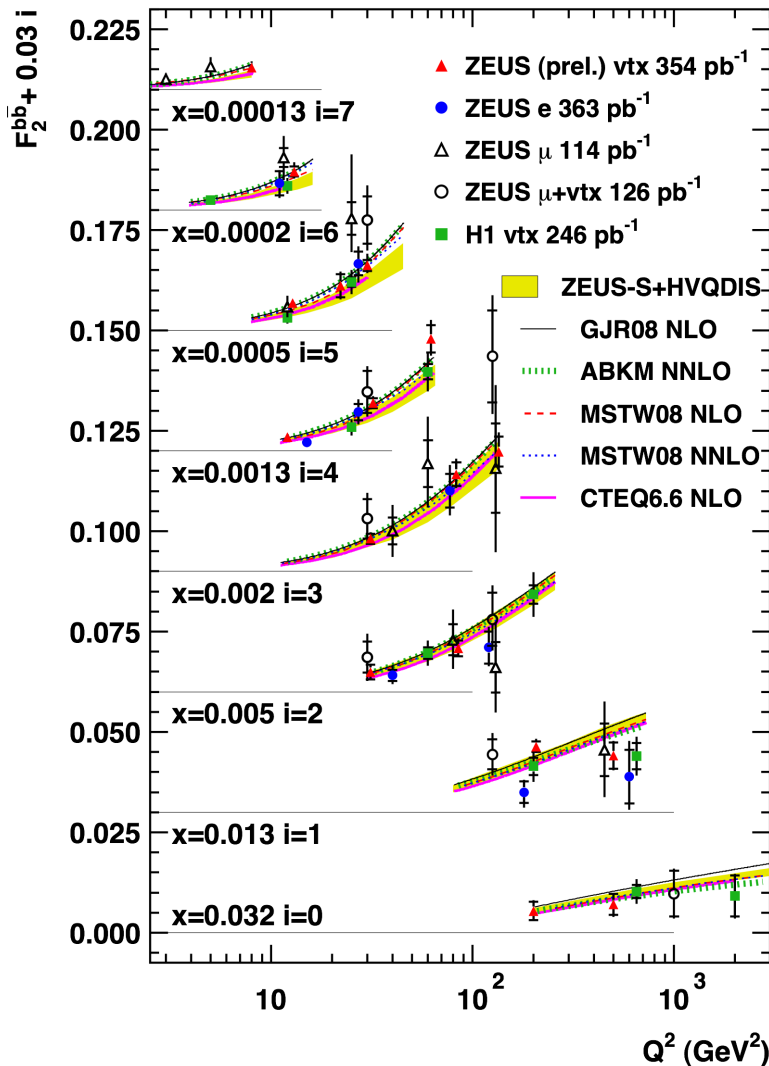
D* in DIS



- $D^* \rightarrow K\pi\pi$ reconstruction in large p_T and η range
- reasonable description by FFNS NLO calculation



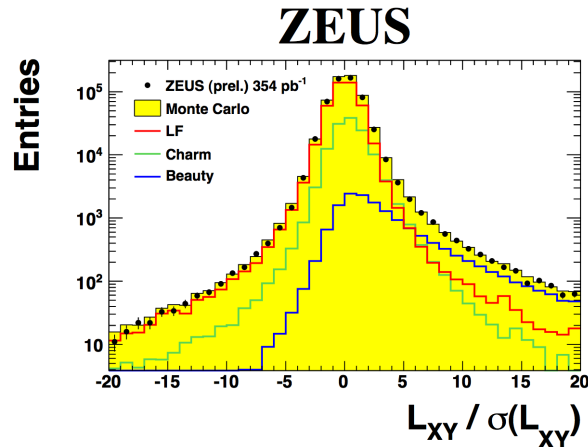
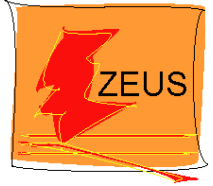
HERA



$$\frac{d^2 \sigma^{b\bar{b}}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} [(1+(1-y)^2) \cdot F_2^{b\bar{b}} - y^2 \cdot F_L^{b\bar{b}}]$$

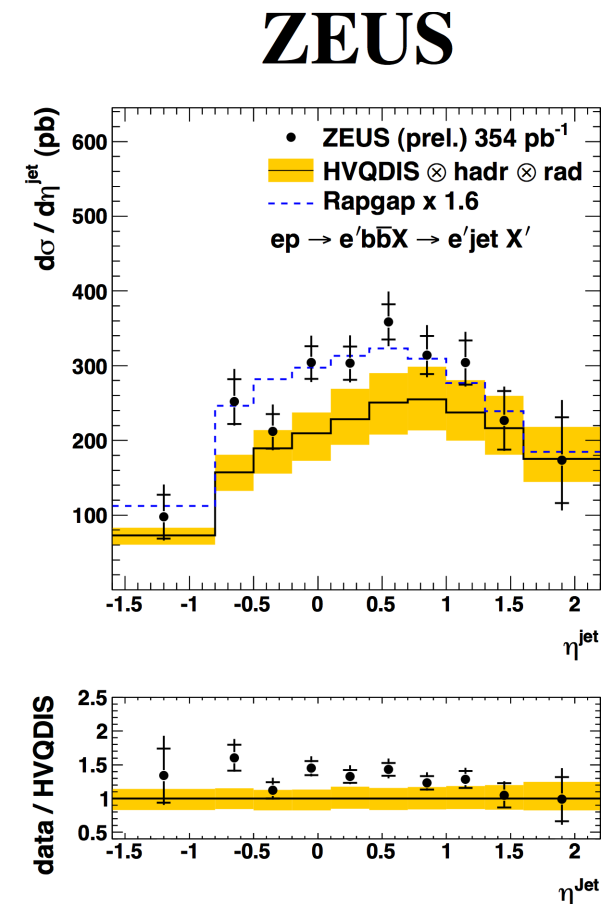
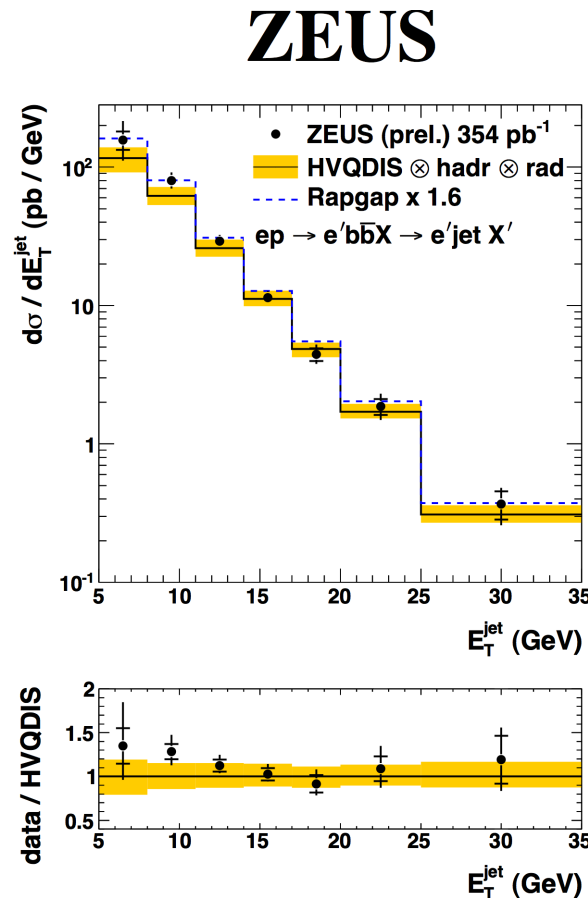
- several new measurements:
ZEUS: ZEUS-prel-10-004,
Eur.Phys.J.C71 (2011) 1573
H1: Eur.Phys.J. C65 (2010) 89
- good agreement between the different measurements
- good description of the data by NLO predictions based on different heavy flavour schemes

Lifetime



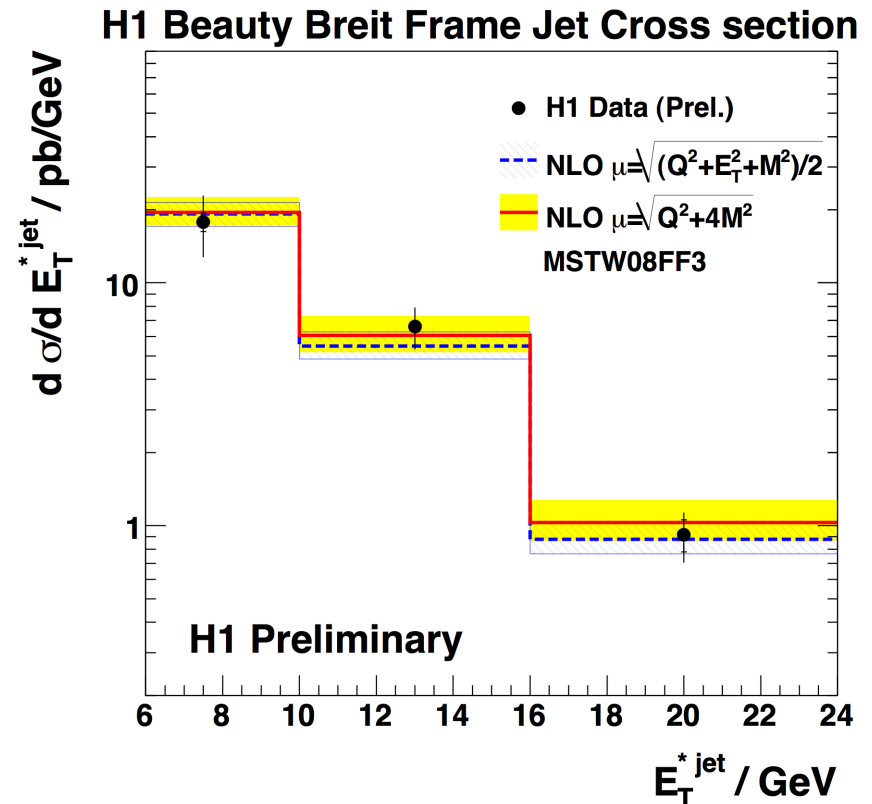
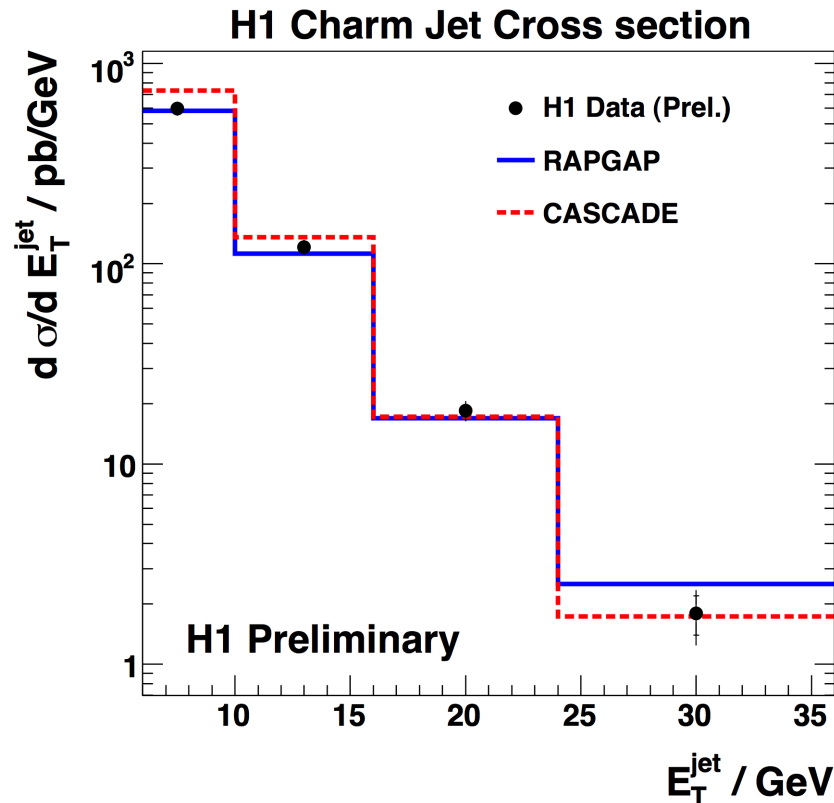
- *beauty* distinction by lifetime (decay length) and mass (secondary vertex mass)

→ reasonable description by FFNS NLO calculation

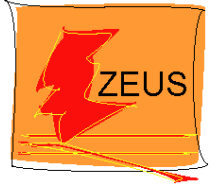


Charm and Beauty Jets

- complete HERA II data
- use lifetime technique to tag events with c and b jets
- cross sections in lab and Breit frame
- comparison to LO ME+PS MC and NLO predictions

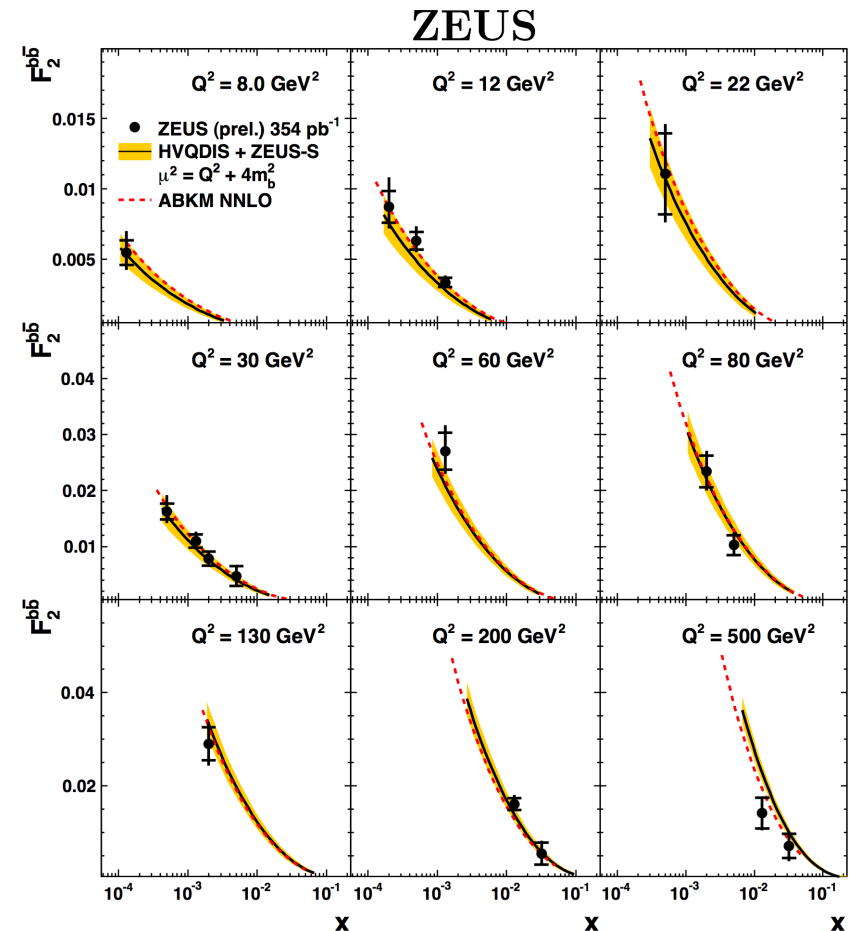


Lifetime



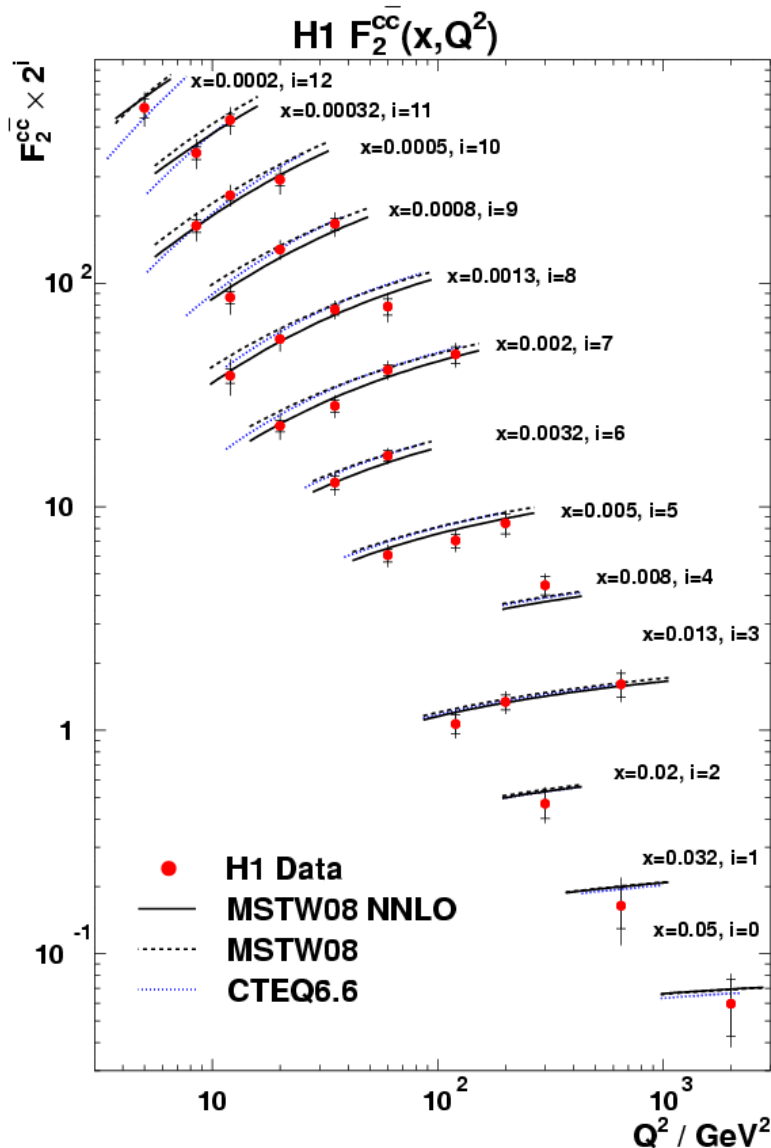
$$\frac{d^2 \sigma^{b\bar{b}}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} [(1 + (1-y)^2) \cdot F_2^{b\bar{b}} - y^2 \cdot F_L^{b\bar{b}}]$$

- double differential b cross section can be converted to $F_2^{b\bar{b}}$ measurement
- $F_L^{b\bar{b}}$ contribution is small
- extrapolation from measured phase space to total b cross section needed
- good agreement with NLO QCD prediction

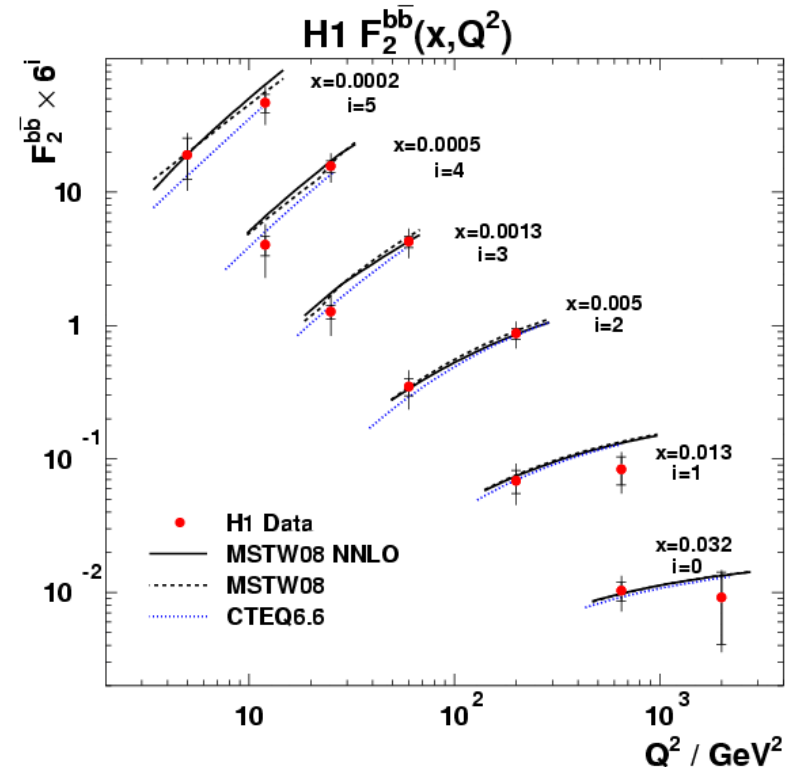




$F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ from Lifetime

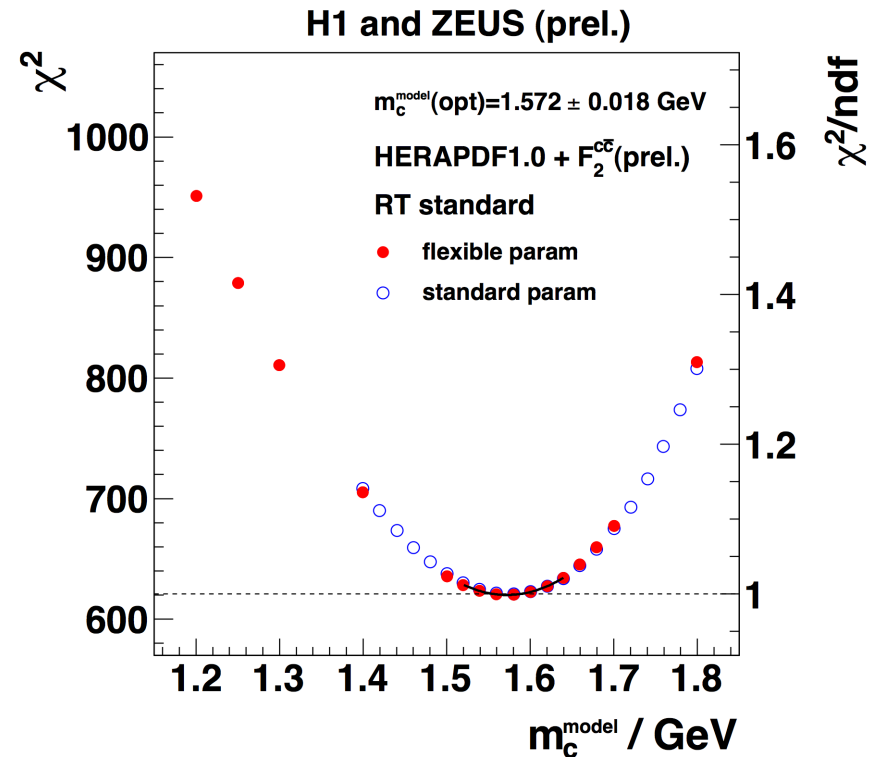
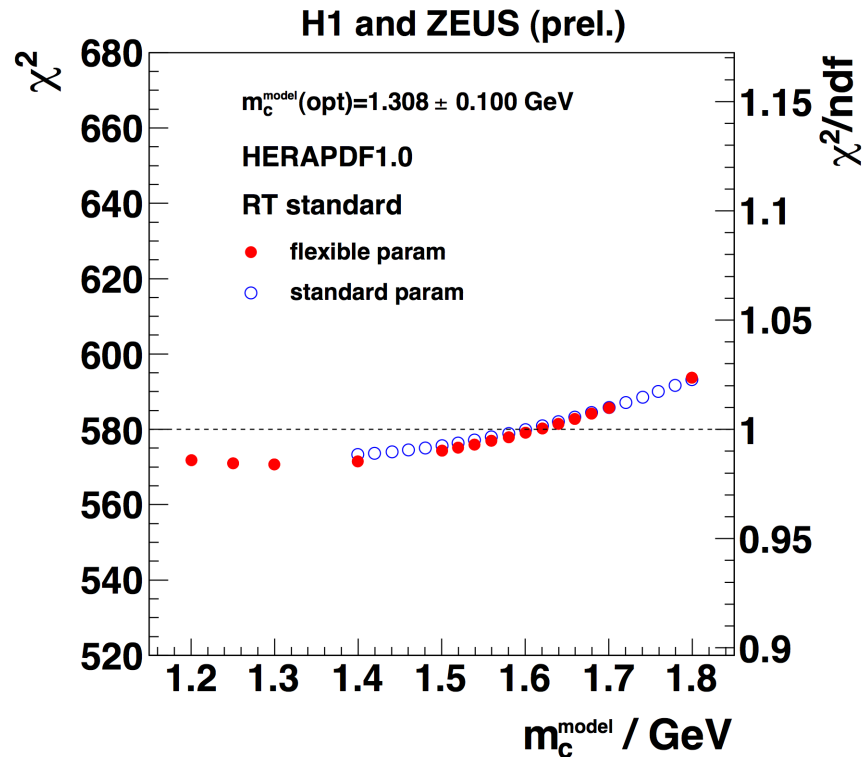
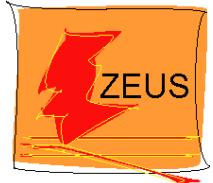


- simultaneous measurement of b and c fraction of inclusive cross section
- good agreement with GMVFNS NLO & NNLO predictions



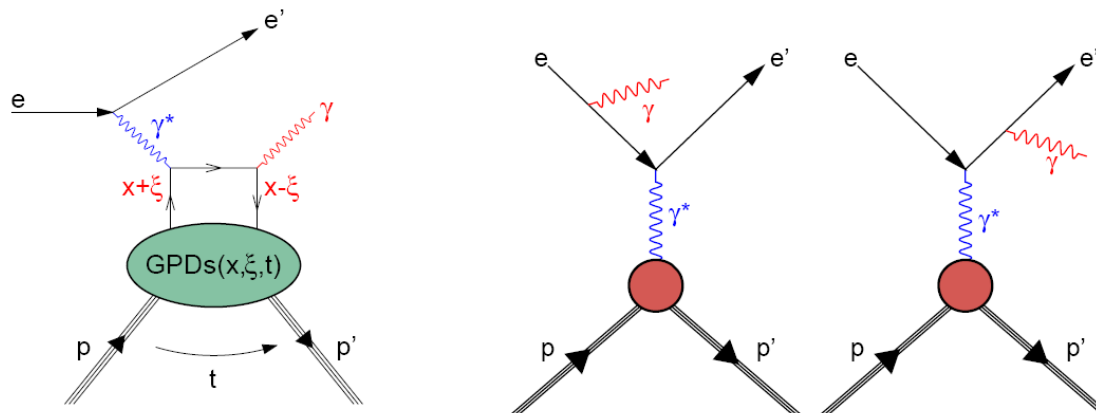


PDF Fit including $F_2^{c\bar{c}}$ data

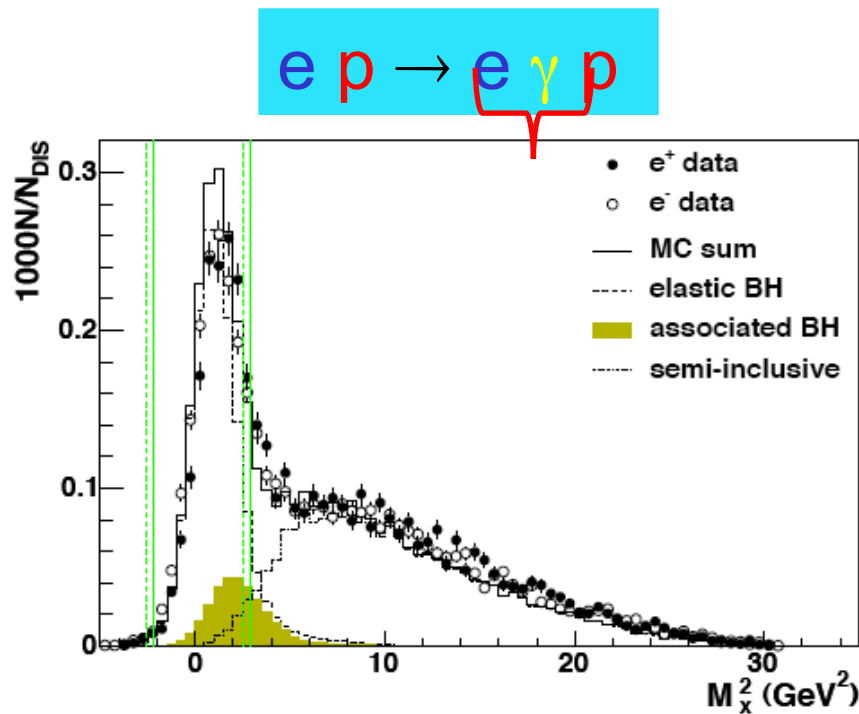
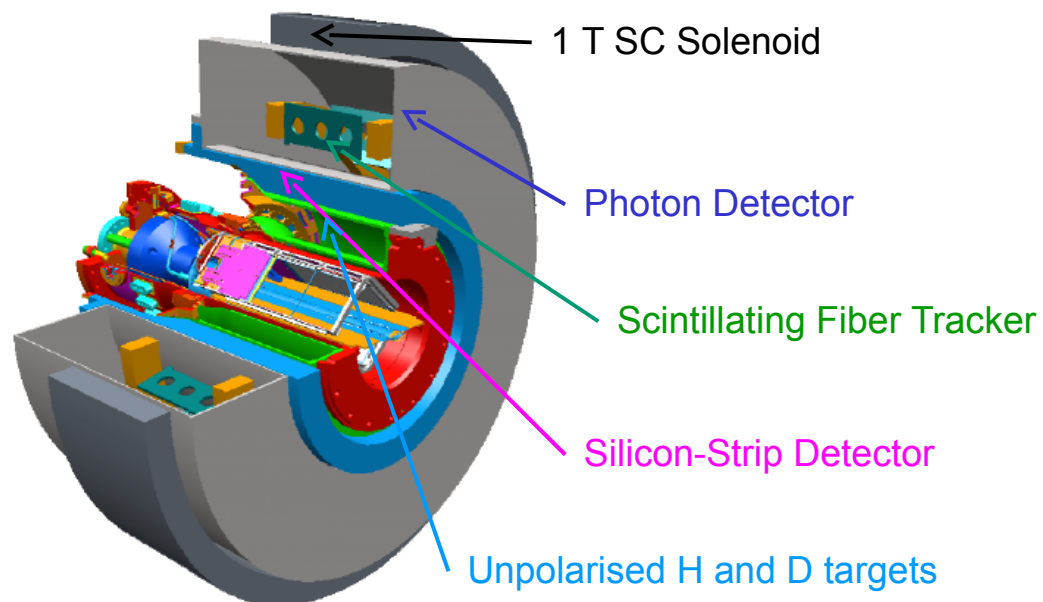


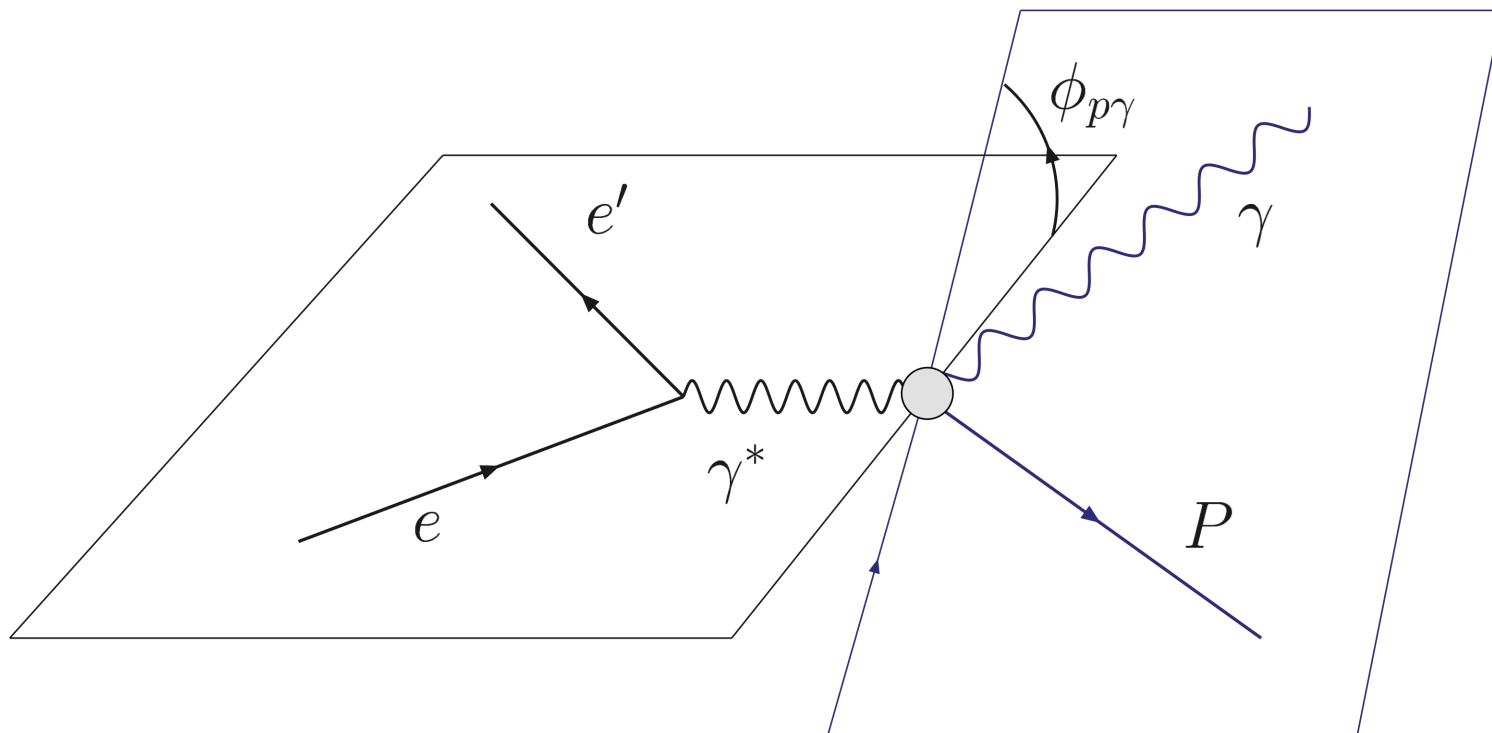
- inclusive data have little sensitivity to m_c
- description of $F_2^{c\bar{c}}$ data depends on m_c

DVCS with Recoil Detector

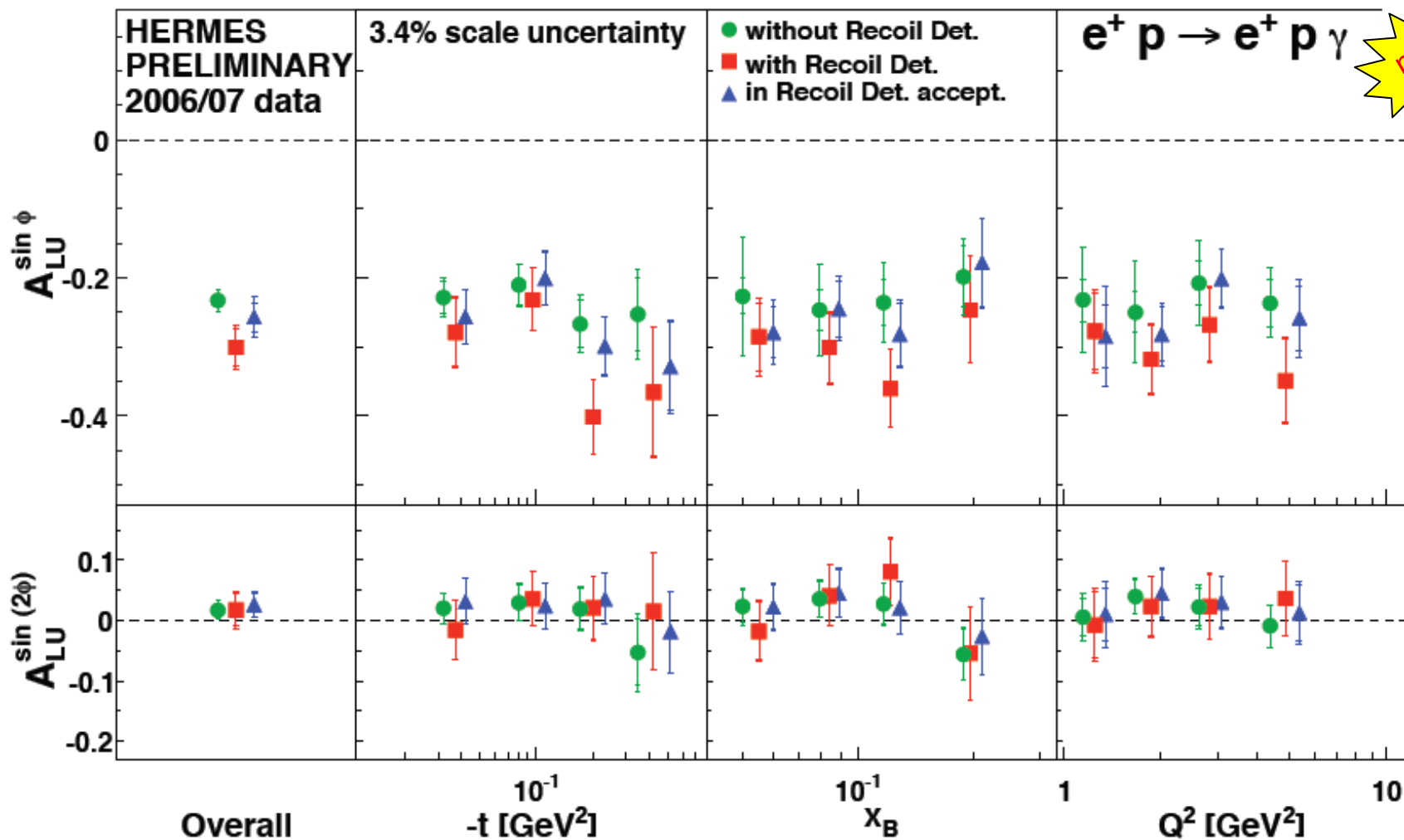


Recoil Detector to tag exclusivity





Pure elastic DVCS



Indication that leading amplitude for pure elastic process is slightly larger than for unresolved signal (elastic + associated)