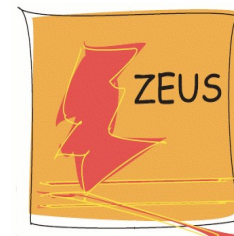




Martin Brinkmann, DESY
for the H1 and ZEUS Collaborations



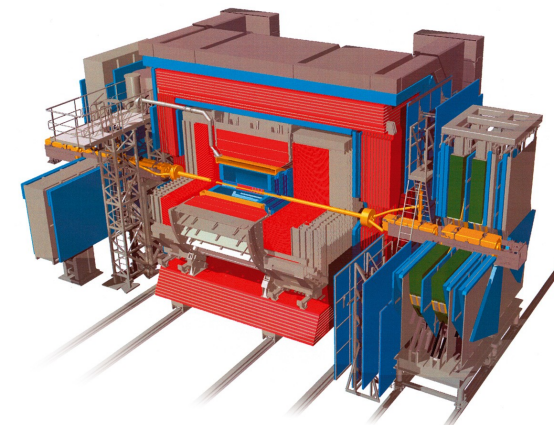
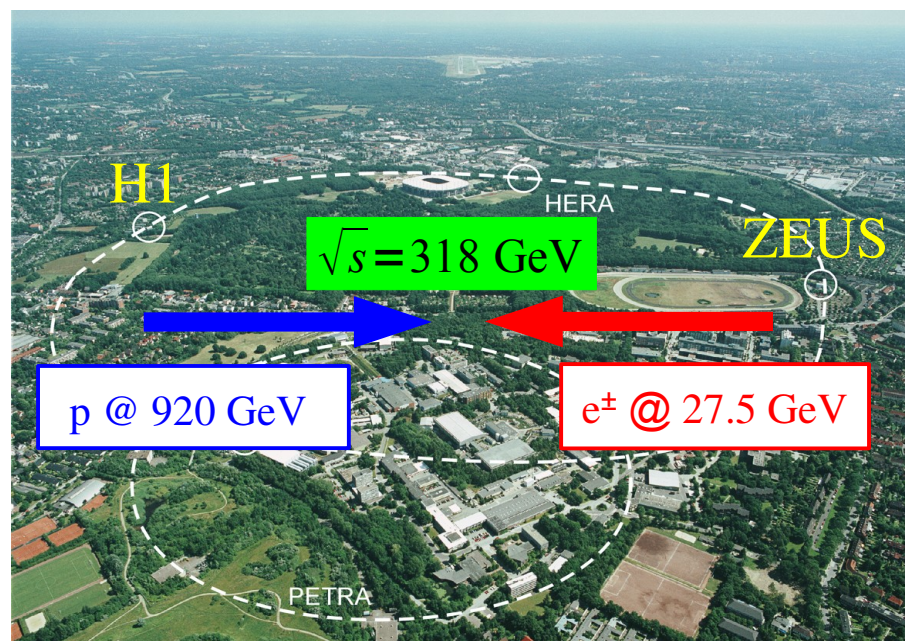
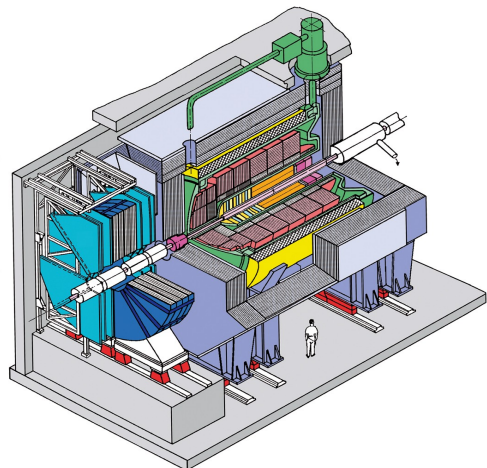
Precision Tests of QCD at HERA

- Introduction
- Inclusive DIS
- HERAPDF
- Jets
- Summary

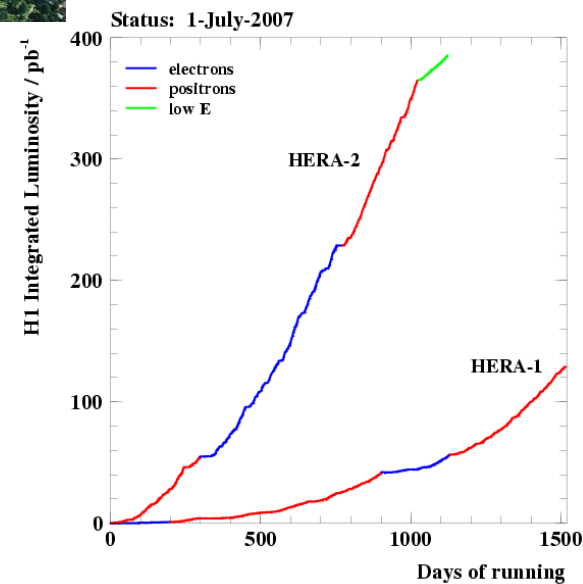




HERA



- HERAI: 1992-2000 and HERAII: 2003-2007
- $\sim 0.5 \text{ fb}^{-1}$ per experiment



Kinematic quantities:

- Photon virtuality: Q^2
- Inelasticity: y
- Bjorken Variable: x

Kinematic regimes:

- $Q^2 \approx 0 \text{ GeV}^2$: Photoproduction (PHP)
- $Q^2 \geq 1 \text{ GeV}^2$: Deep inelastic scattering (DIS)

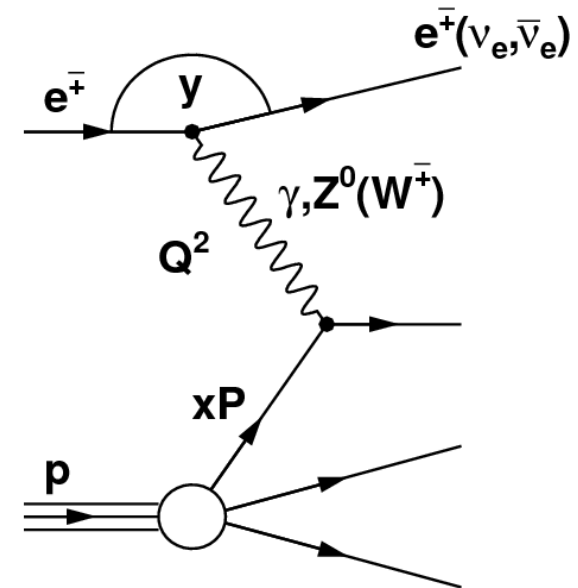
QCD factorisation:

 σ
 \propto
 $f_{p/\gamma}$

Parton distribution
functions (PDFs)

 \otimes
 $\hat{\sigma}$

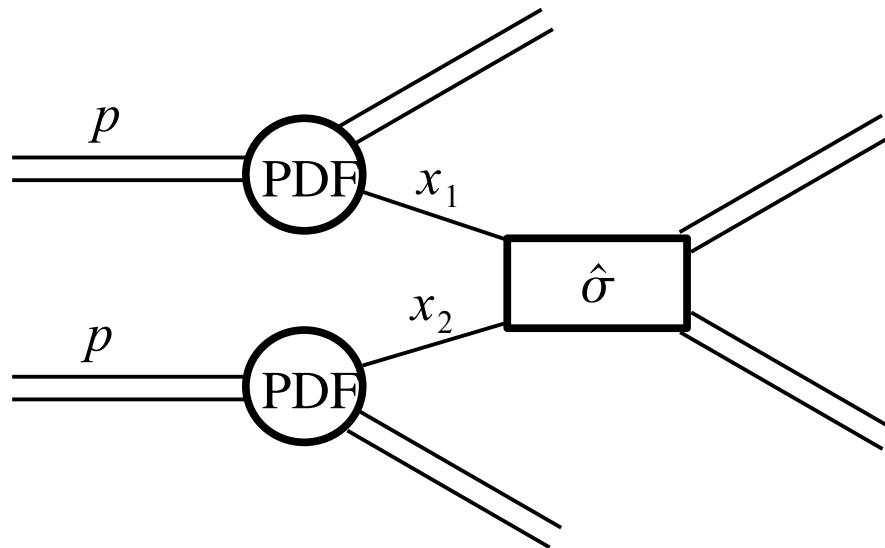
Hard scattering
matrix element



Measurements of inclusive DIS and jet production provide:

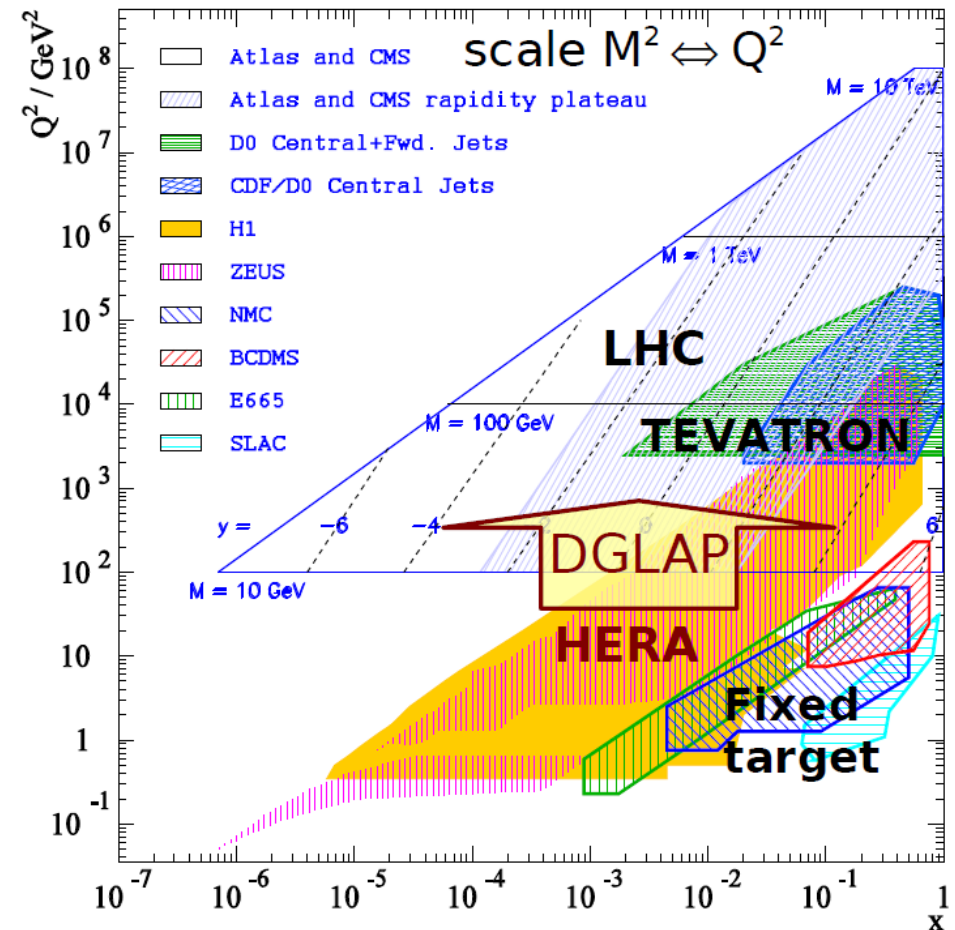
- Good testing ground of perturbative QCD
- Constraints on PDFs

- PDFs measured at HERA can be used to predict pp collisions



- QCD factorisation:

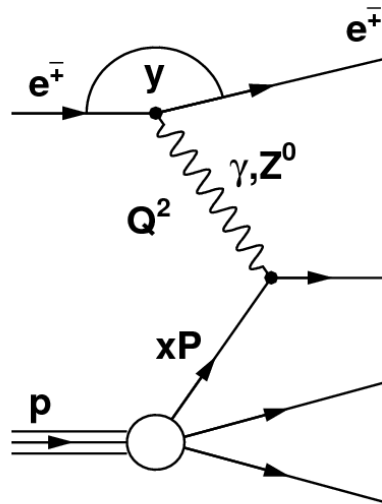
$$\sigma \propto \text{PDF} \otimes \hat{\sigma}$$



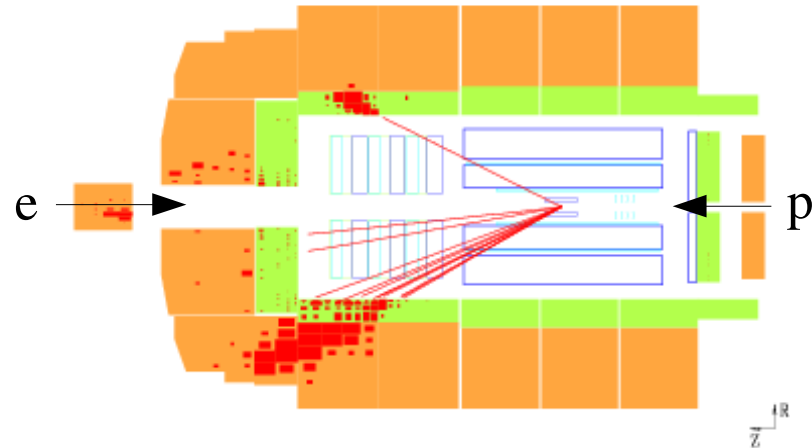
- HERA covers x range of the LHC
- Evolution of PDFs in Q^2 via DGLAP

High Q^2 NC DIS

LO process:



Example event (H1):



Reduced cross section:

$$\sigma_{\text{NC}}(e^\pm p) \sim \tilde{F}_2 \mp \frac{Y_-}{Y_+} x \tilde{F}_3 - \frac{y^2}{Y_+} \tilde{F}_L$$

- Contributions from valence and sea quark distributions

- Sensitivity to valence quarks at high Q^2

- Non zero due to gluon radiation
- Sensitive at high y

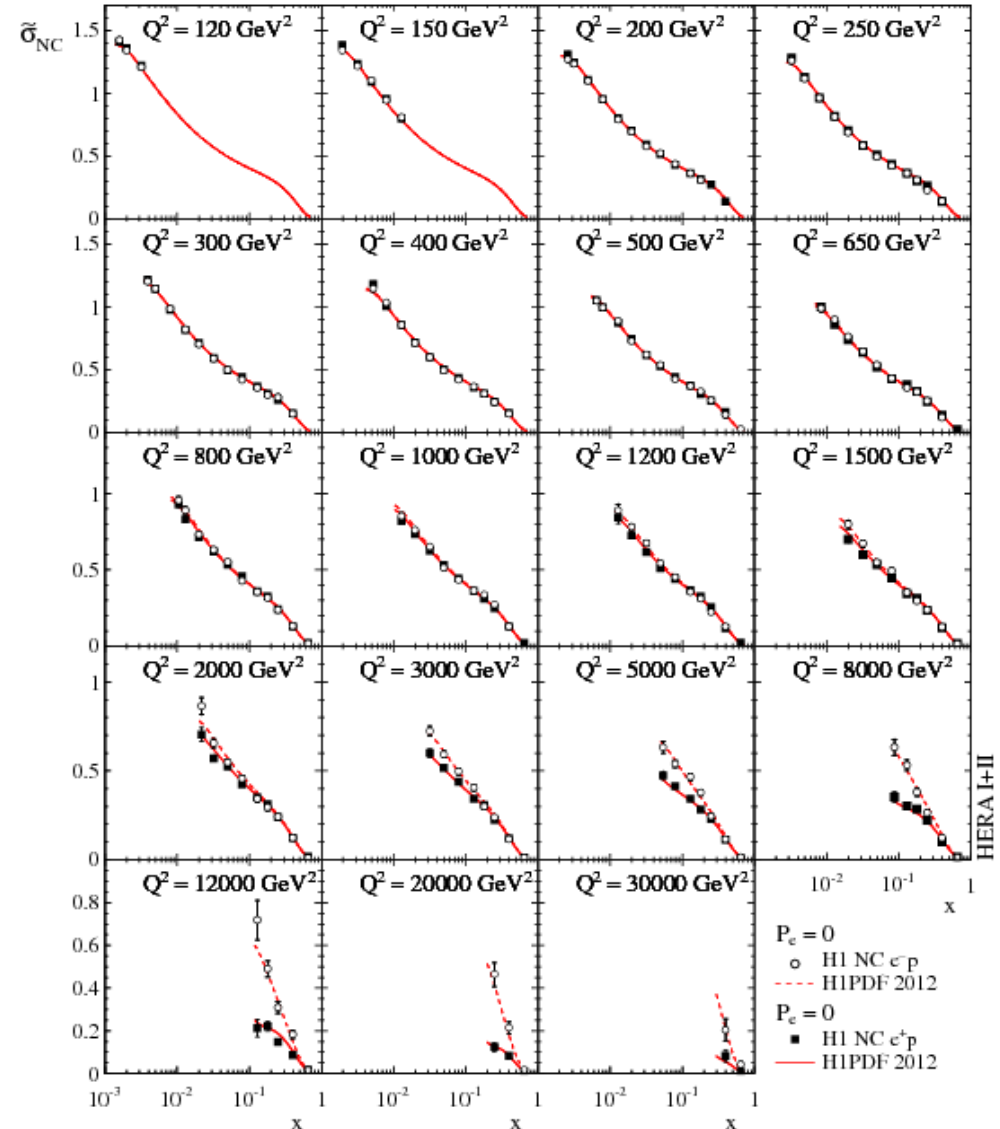


High Q^2 NC DIS

arXiv:1206.7007[hep-ex]

H1 Collaboration

- Reduced cross section results from brand-new H1 high Q^2 measurement covering full HERA data set
- Results compared to H1 NLO QCD fit (H1PDF2012)
- Very high precision: for $Q^2 < 1000 \text{ GeV}^2$ 1.5% systematic uncertainty and 1 – 3 % statistical accuracy
- Data well described by NLO QCD in a wide range of x, Q^2



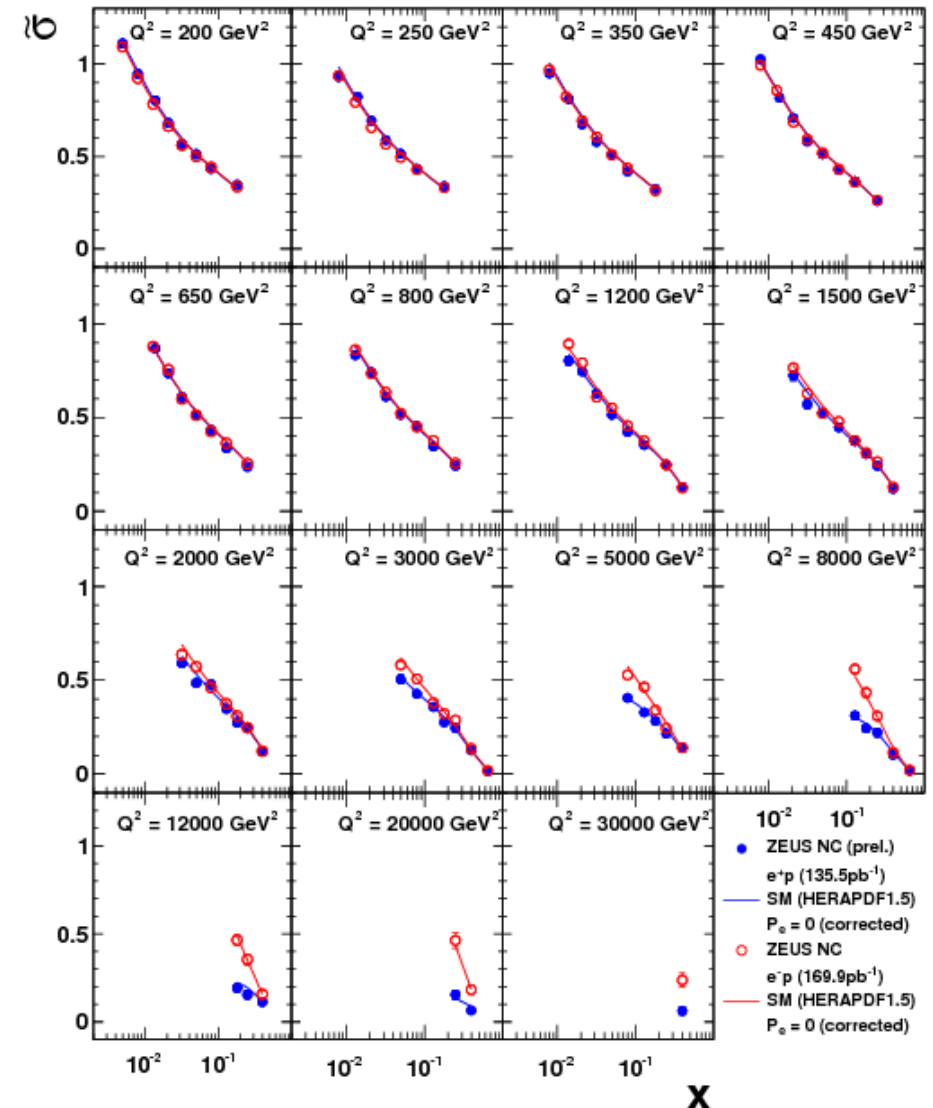
High Q^2 NC DIS



ZEUS-prel-11-003

- Reduced cross section results from recent ZEUS high Q^2 measurement covering HERAII 2006/2007 e^+ ($\mathcal{L}=136 \text{ pb}^{-1}$)
- Also shown former results covering HERAII e^- run period
- Results compared to predictions from HERA NLO QCD fit

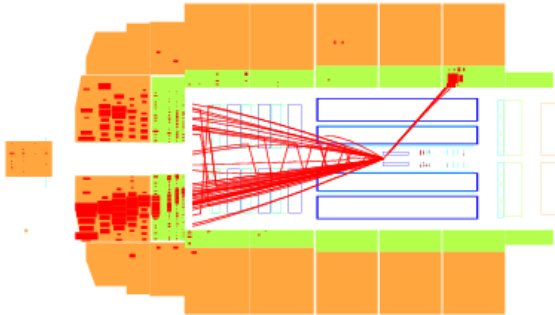
→ Data well described by NLO QCD



High x extension of NC DIS measurement

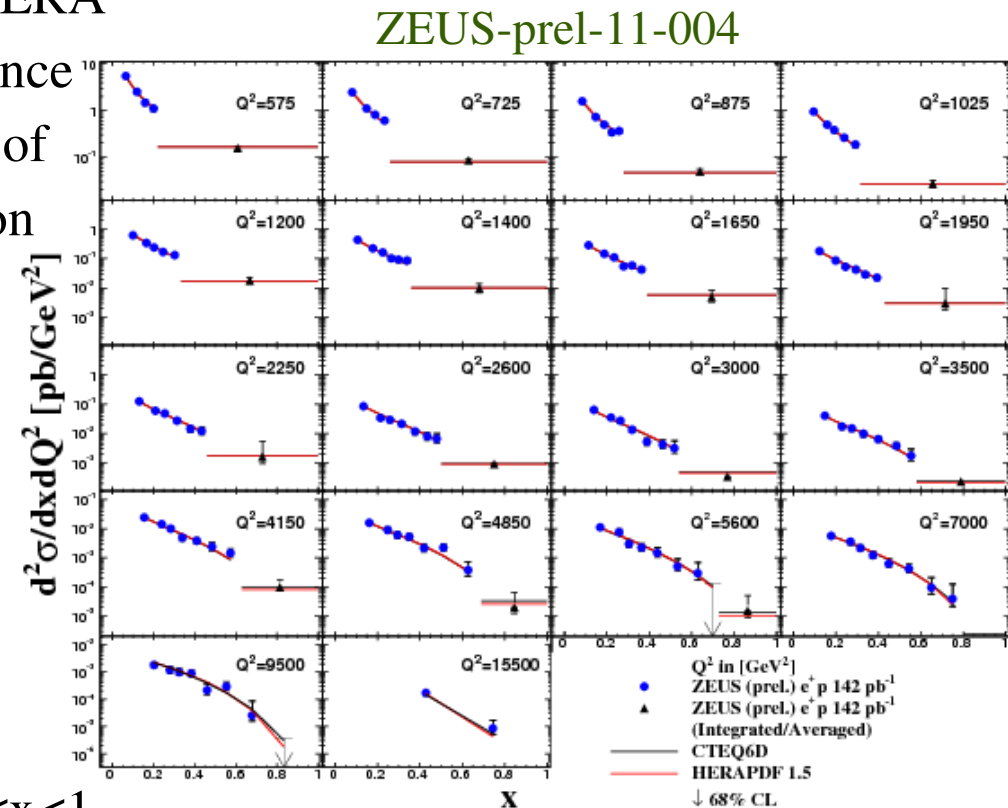


- Not so many accurate constraints on PDF at largest x
- Resolution of kinematic reconstruction at HERA degrades for $y < 0.01$ due to detector acceptance
- Use modified jet method for reconstruction of kinematic variables with improved resolution at high x



- If jets outside detector acceptance : count event for cross section integrated over $x_{\text{edge}} < x < 1$

- Good agreement with Standard Model predictions – including last integrated x bins
- Important constraint on PDF especially at largest x expected

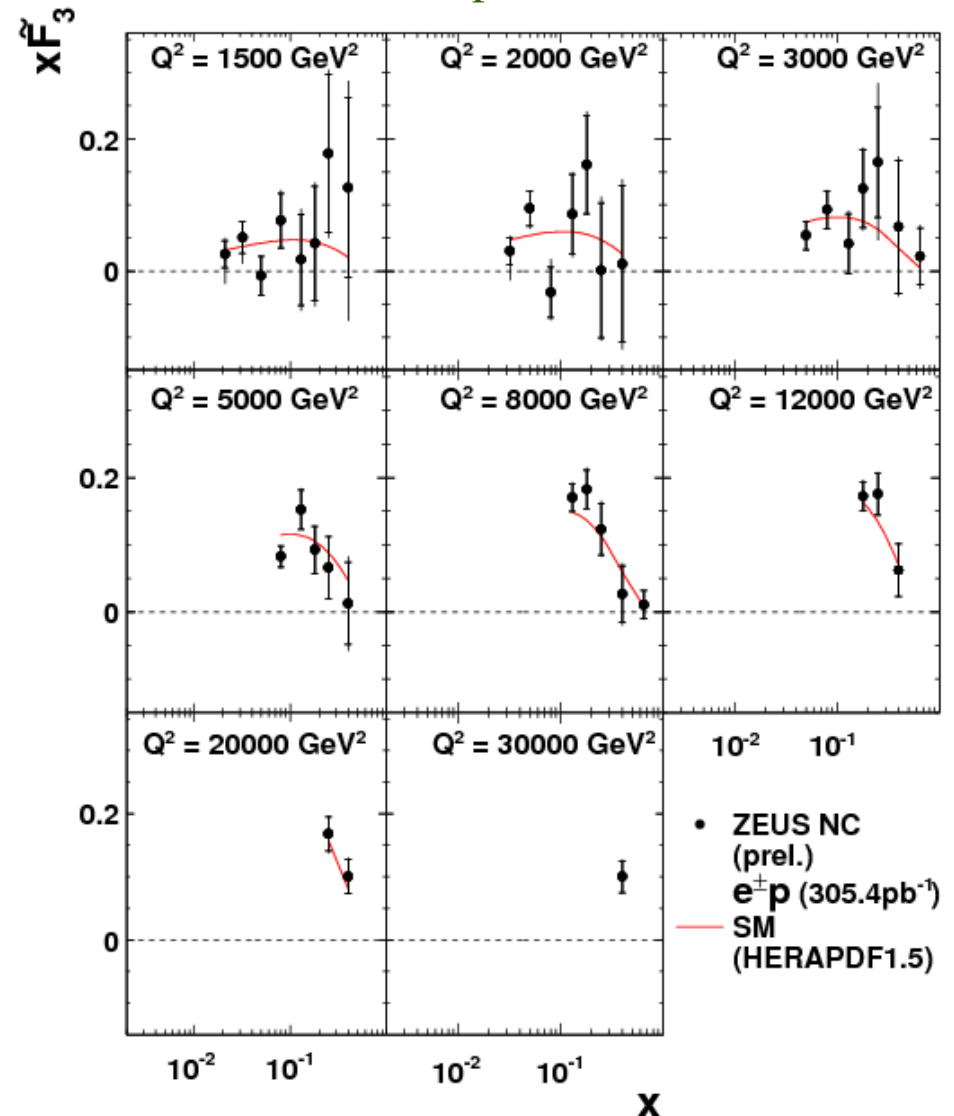


High Q^2 NC DIS



ZEUS-prel-11-003

- Results of $x\tilde{F}_3$ from the same high Q^2 ZEUS measurement combined with the e^- data
 - Extracted from difference of the cross sections for e^+ and e^- data
 - Results shown for $Q^2 > 1500 \text{ GeV}^2$
 - Results compared to HERAPDF1.5
- Data agree well with expectations
- Understood t-channel weak interaction contribution and γZ interference term
- The results can be used for PDF fits to constrain valence quark distributions



Direct measurement of F_L

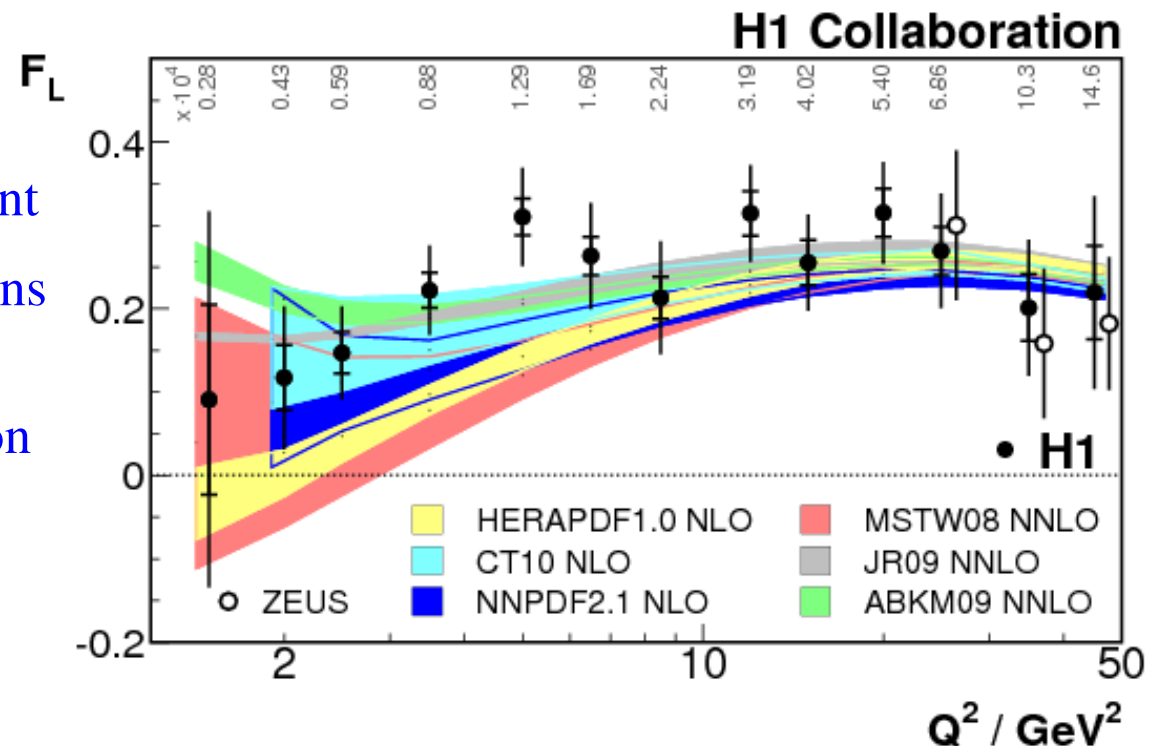
- Relation between F_L and measured cross section:

Eur. Phys. J. C71 (2011) 1579

$$\sigma_{\text{NC}}^{\text{red}}(x, Q^2) = \tilde{F}_2(x, Q^2) - \frac{y^2}{Y_+} \tilde{F}_L(x, Q^2) \quad , \quad Q^2 \sim x y s$$

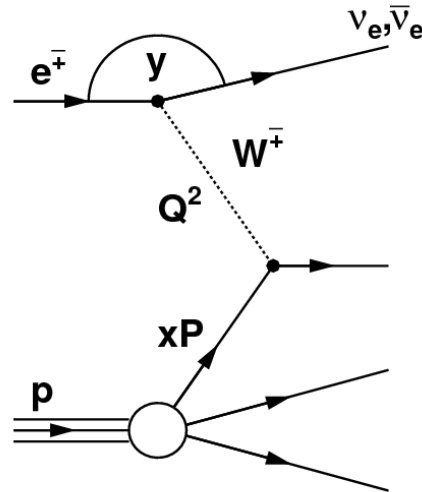
- Extraction of F_L is based on HERAII data with different proton beam energies: $E_p = 460, 575$ and 920 GeV

- Direct F_L measurement in agreement with NLO (NNLO) QCD predictions using different PDF sets
- Provides a direct constraint of gluon density in the proton

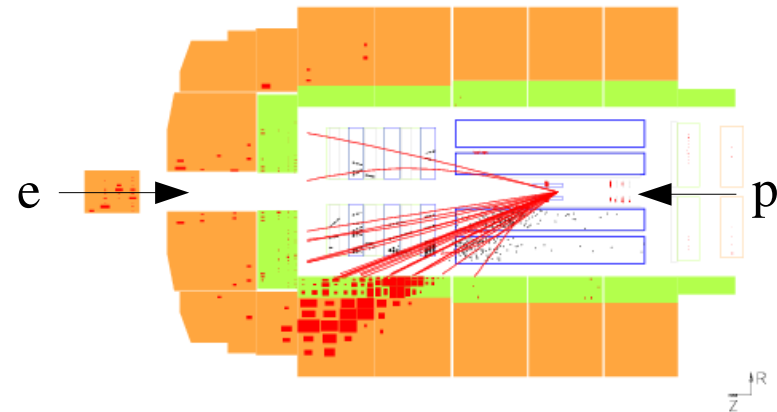


High Q^2 CC DIS

LO process:



Example event (H1):



Reduced cross section:

- In LO e^+/e^- charged current cross sections are sensitive to different quark densities:

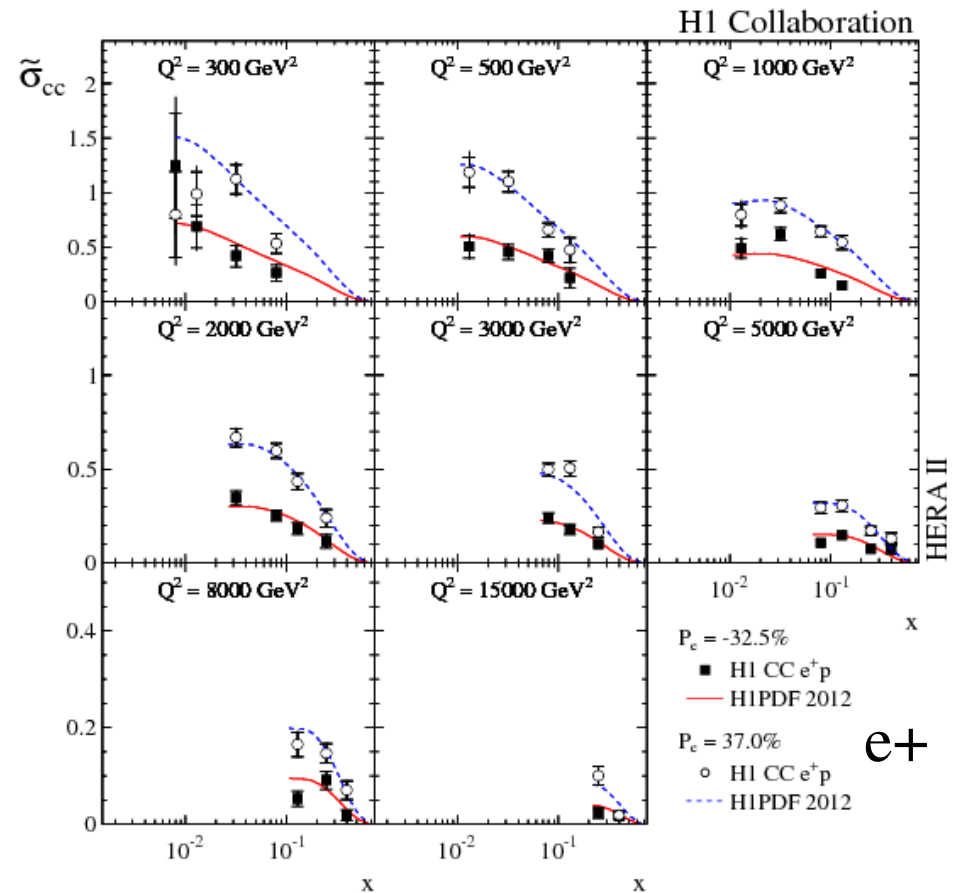
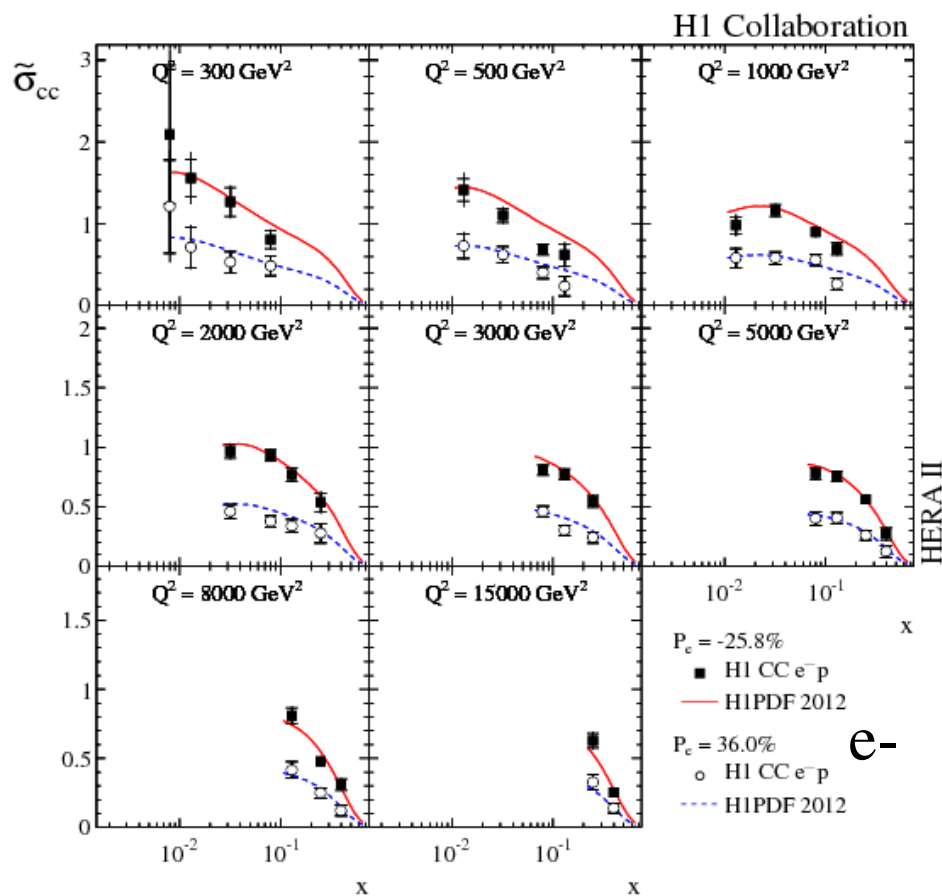
$$\sigma_{CC}^{e^+p} \sim x[\bar{u} + \bar{c}] + (1-y)^2 x[d + s]$$

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



High Q^2 CC DIS

- CC cross sections from new H1 high Q^2 inclusive analysis arXiv:1206.7007[hep-ex]
- Separated into charge and polarisation of the incoming lepton
- Compare measurements with NLO QCD fit H1PDF2012



- CC data well described by NLO QCD prediction
- Important input for PDF fits concerning valence quarks

- Use only HERA data – consistent data with well understood correlations, no need for nuclear corrections
- For fit use NLO, NNLO pQCD predictions with DGLAP evolution
- PDFs parametrized by

H1-prel-10-142

ZEUS-prel-10-018

$$xf(x, Q_0^2) = Ax^B(1-x)^c(1+Dx+Ex^2)$$

A : overall normalisation

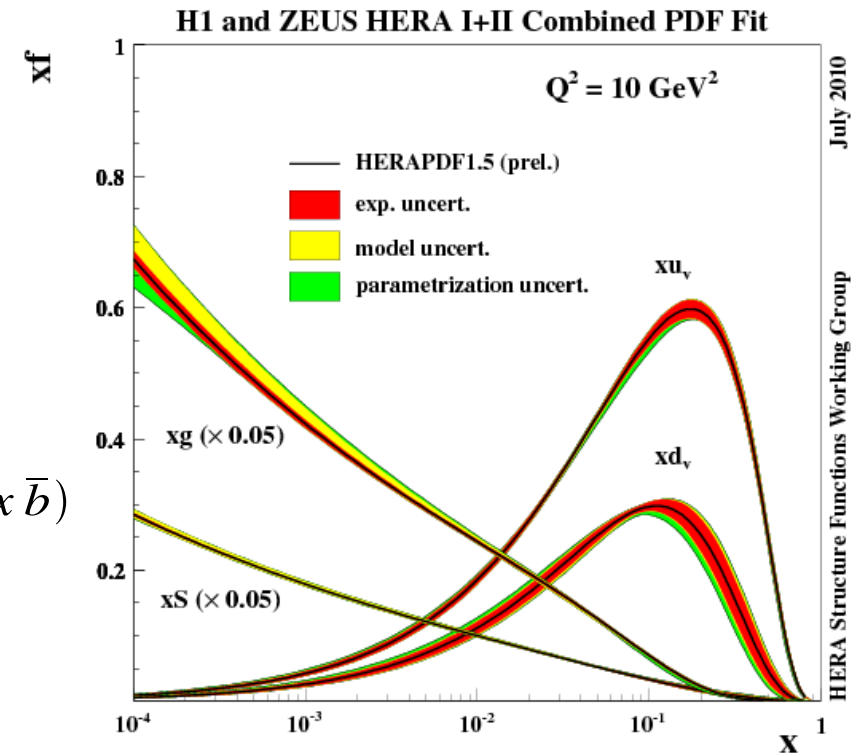
B : small x behavior

C : $x \rightarrow 1$ shape

- Fitted PDFs:

$$xg, xu_v, xd_v, x\bar{U} = x\bar{u} (+x\bar{c}), x\bar{D} = x\bar{d} + x\bar{s} (+x\bar{b})$$

- Fixed strong coupling constant: $\alpha_s = 0.1176$
- Use HERA NC, CC inclusive DIS data

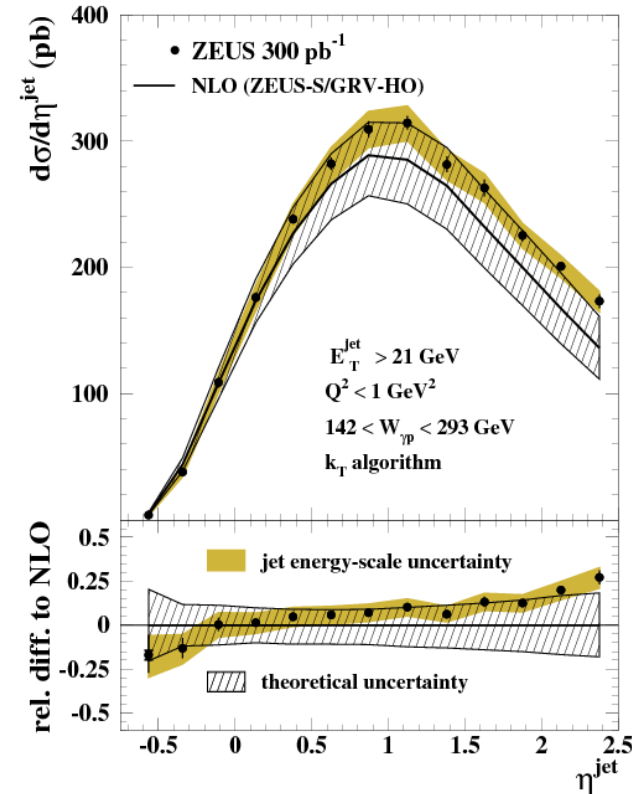
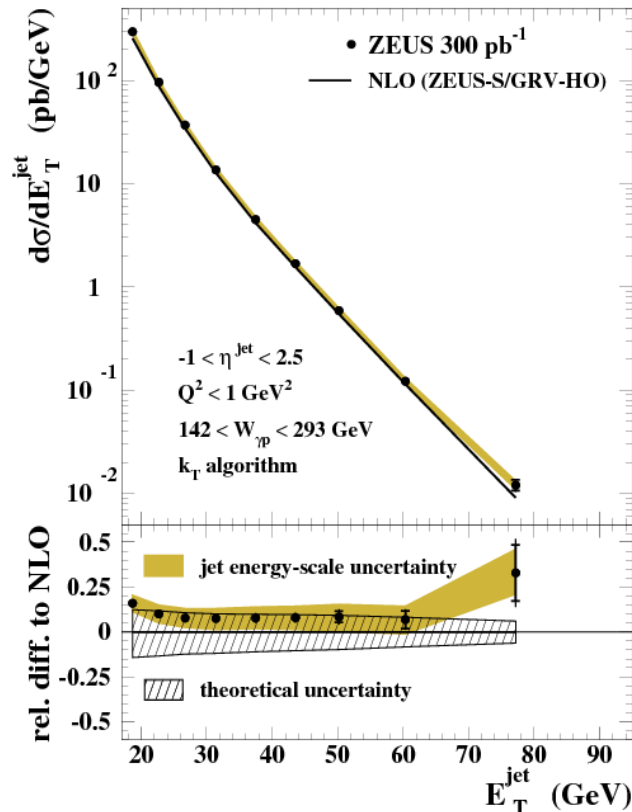


Inclusive jets in photoproduction



Nucl. Phys. B864 (2012), pp. 1-37

- Kinematic region: $Q^2 < 1 \text{ GeV}^2$, $0.2 < y < 0.85$
- ≥ 1 jet (k_T algorithm) with $E_T^{\text{jet}} > 21 \text{ GeV}$, $-1 < \eta^{\text{jet}} < 2.5$



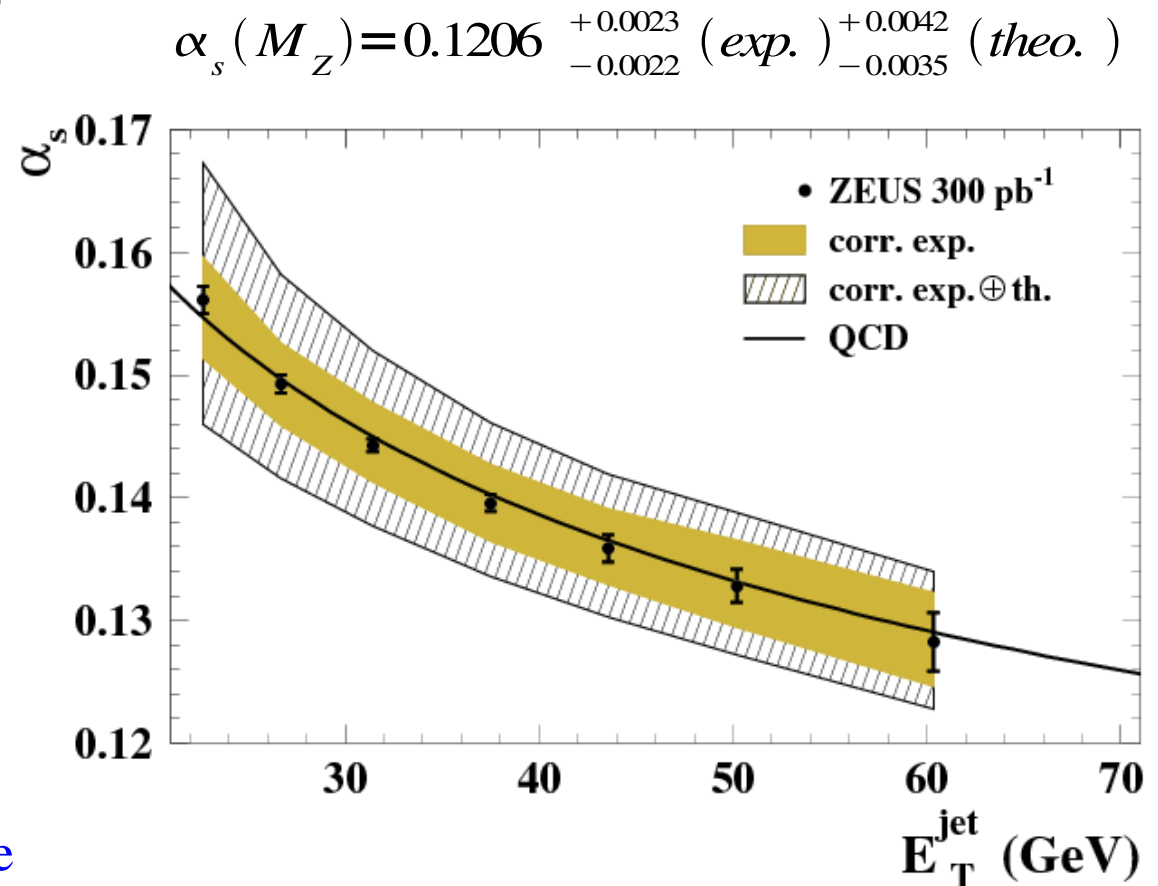
→ NLO pQCD calculation describes data reasonably well

Inclusive jets in photoproduction



Nucl. Phys. B864 (2012), pp. 1-37

- Extract strong coupling α_s via NLO QCD fit to measured cross sections $d\sigma/dE_T^{\text{jet}}$
- Data are compared with QCD prediction of α_s at two loops



- Running of α_s clearly visible
- Theory uncertainties are dominating due to missing NNLO calculations

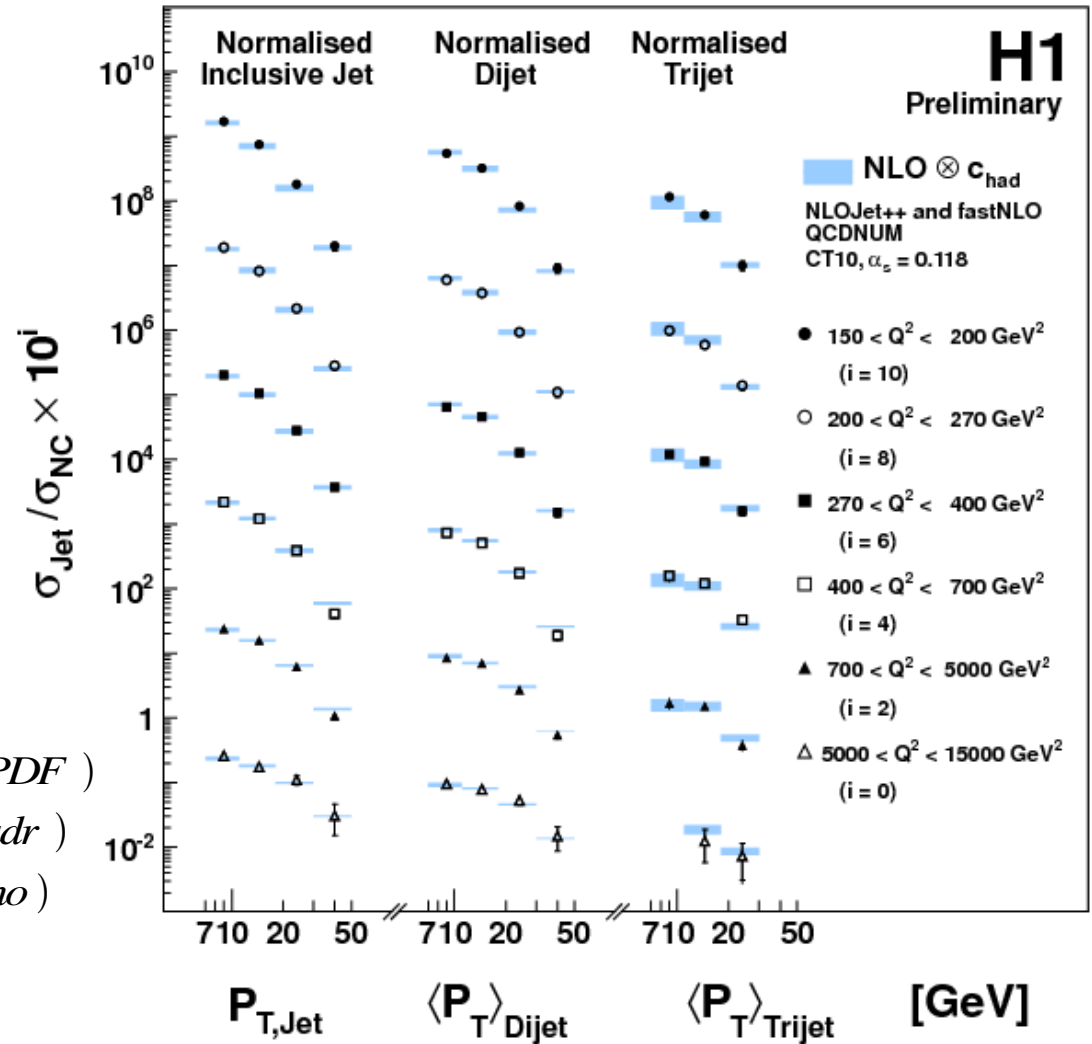


Normalized jet cross sections in DIS

H1prelim-12-031

- Inclusive jet, dijet and trijet cross sections normalized to inclusive NC DIS cross section in each Q^2 region
- Combined NLO fit to normalized inclusive, dijet and trijet cross sections to extract α_s :

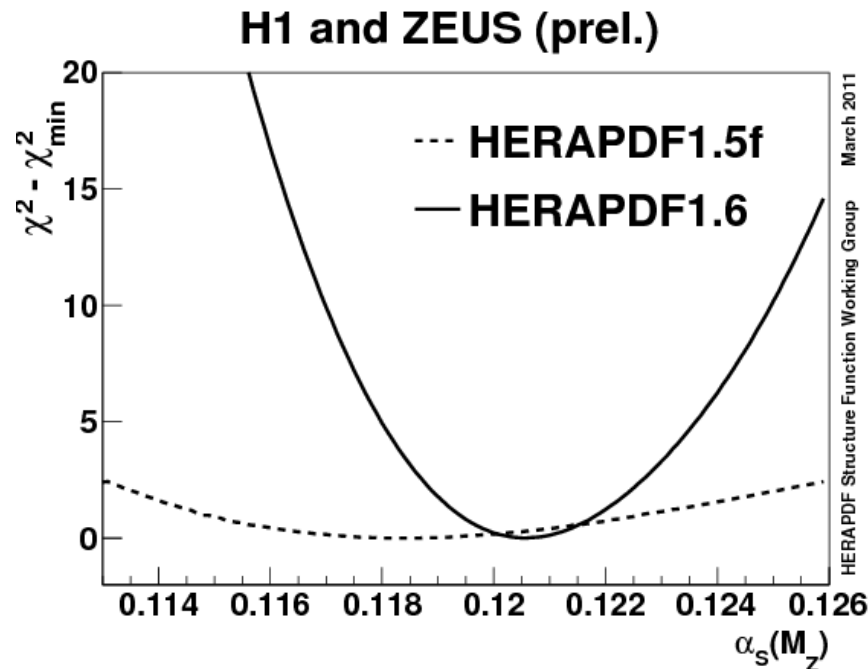
$$\alpha_s(M_Z) = 0.1163 \pm 0.0011 \text{ (exp.)} \pm 0.0014 \text{ (PDF)} \pm 0.0008 \text{ (hadr)} \pm 0.0039 \text{ (ho)}$$



- NLO QCD predictions describe measured cross sections well
- Dominant error on α_s due to missing higher orders in pQCD

HERAPDF1.6

- Jet production processes provide direct sensitivity to gluon and α_s H1-prel-11-034
- QCD fits with jet data allow to constrain simultaneously α_s and gluon ZEUS-prel-11-001
- Use HERA NC, CC inclusive data + inclusive jet measurements from H1 and ZEUS



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

$$+0.0045 \text{ (th)} -0.0036$$

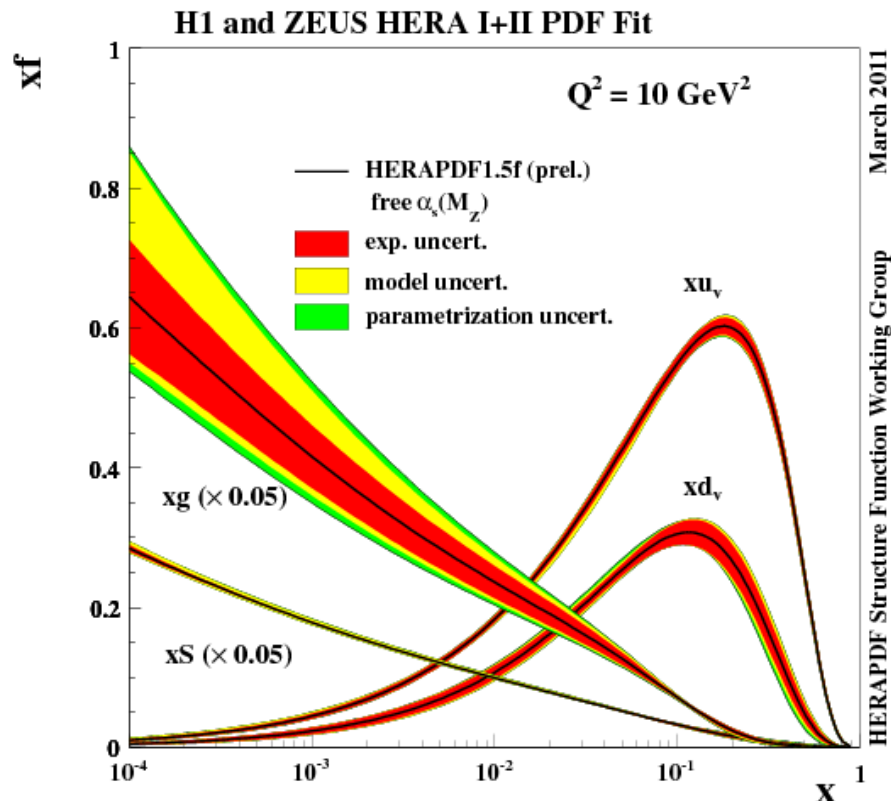
- Local minimum in $\Delta\chi^2(\alpha_s(M_Z))$ much more distinct after including jet data
- Free α_s fit stabilized

- Dominant error on α_s due to missing higher orders in pQCD

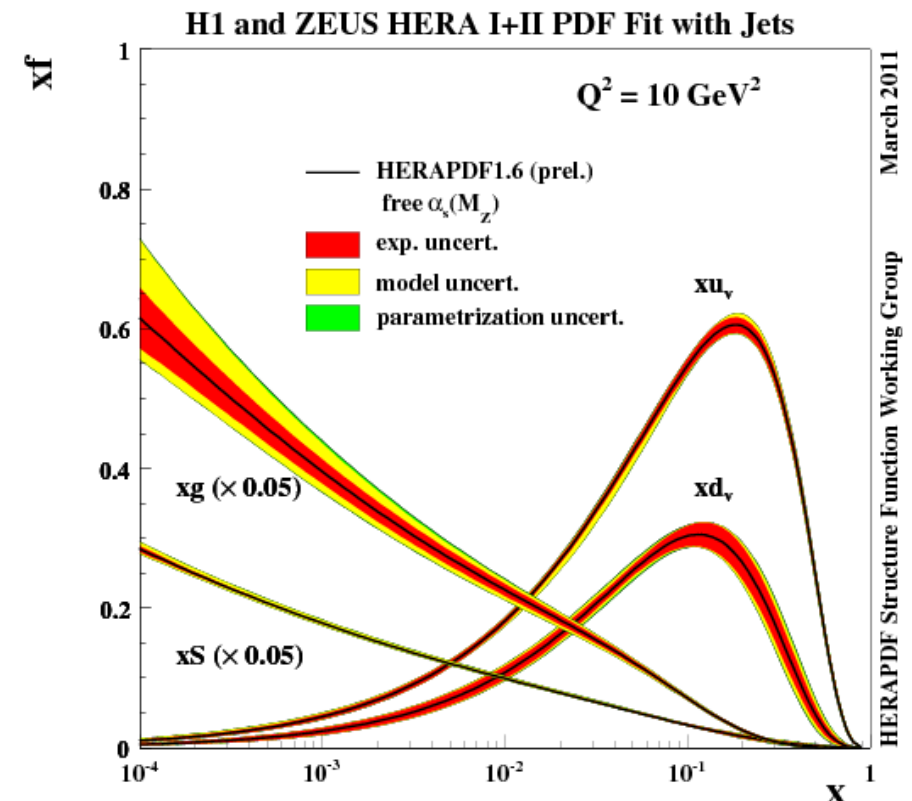
H1-prel-11-034

ZEUS-prel-11-001

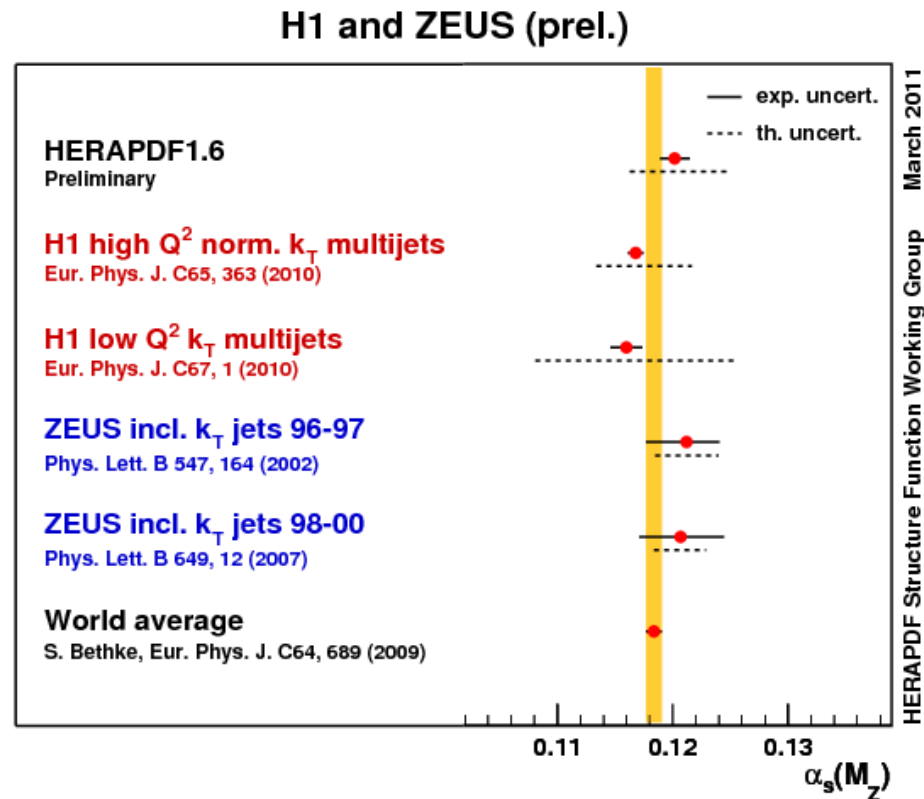
Free α_s no jets:



Free α_s with jets:



→ Uncertainty on gluon for free α_s fit drastically reduced when including jets



- α_s determinations at HERA with sizable uncertainties – missing NNLO
- α_s from HERAPDF1.6 consistent with world average



Summary



- New inclusive and jet measurements presented with high experimental precision in an extended range of x, Q^2
- Inclusive HERA data provide backbone for all modern PDF
- Measured $\alpha_s(M_Z)$ is consistent with world average with comparable error

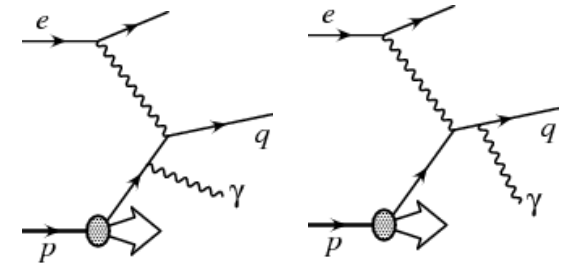
Backup

Isolated photon plus jet in NC DIS

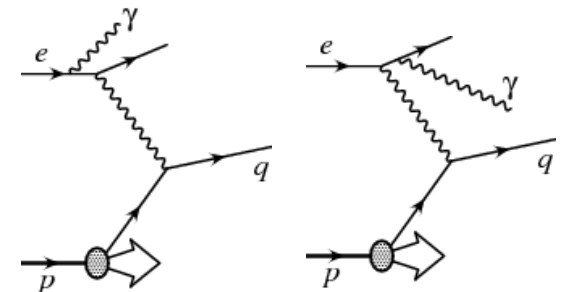


- Direct probe of underlying partonic process less affected by hadronisation than pure jet production
- QQ contribution provides stringent test of pQCD in kinematic region with two hard scales: Q and E_t^{jet}
- Theoretical predictions for comparison with data:
 - ♦ GKS (A Gehrmann-De Ridder, G. Kramer and H Spiesberger): $\text{LO}(\alpha^3)$ and $\text{NLO}(\alpha^3\alpha_s)$ calculations with QQ, LL and interference terms, uses HERAPDF1.0
 - ♦ BLZ (SP Baranov, AV Lipatov and NP Zotov): k_t factorisation method with LL and QQ terms, uses unintegrated PDFs

Photon radiated from quark line (QQ):



Photon radiated from lepton line (LL):

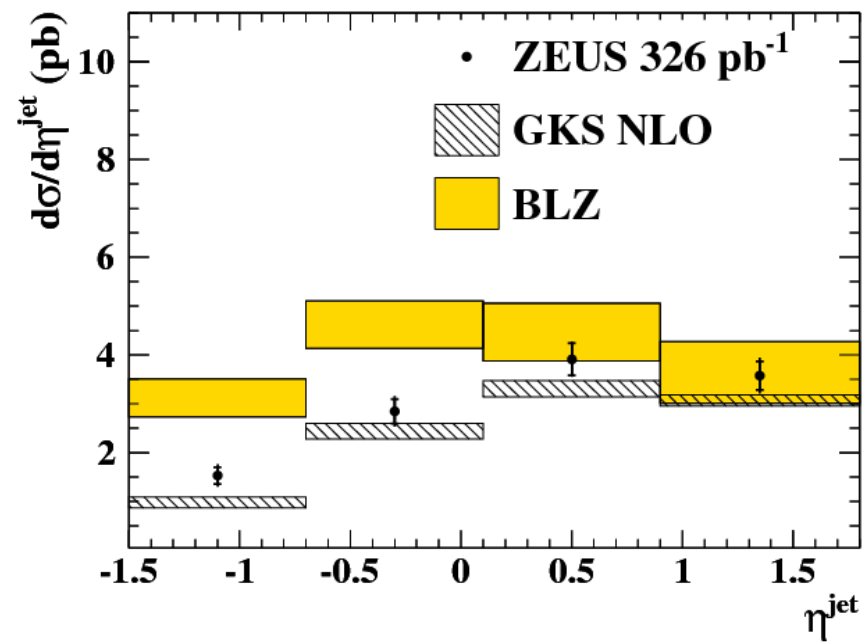
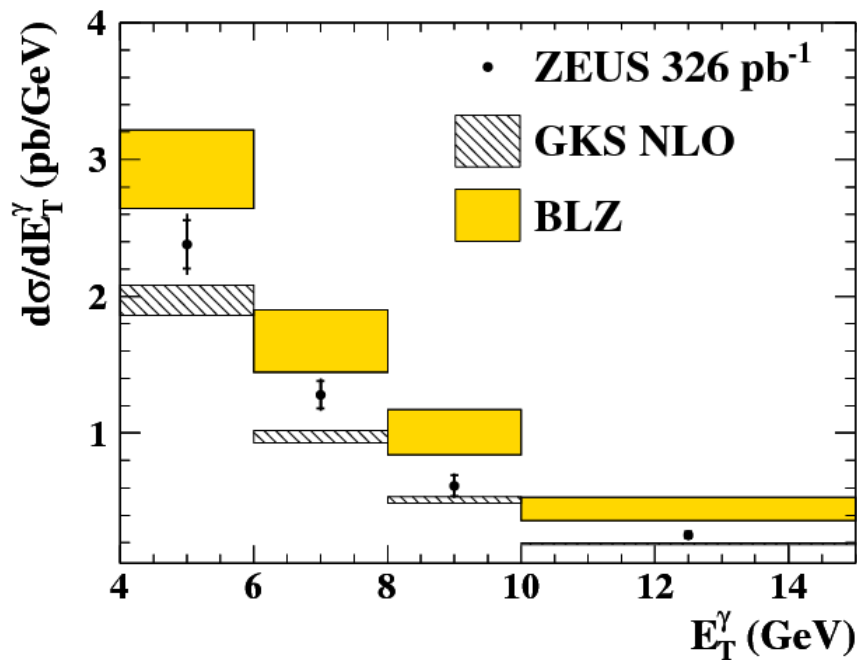


Isolated photon plus jet in NC DIS



arXiv:1206.2270 [hep-ex]

- Measured cross sections differential in E_T of the photon and η of the jet



- Reasonable description of shape by NLO calculations
- Deficits of both calculations in description of the normalisation
- Need improved theoretical description of γ + jet production