Precise proton structure and QCD measurements at HERA

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LAL, Orsay, July 10, 2012

Outline

- **e-p collider HERA;**
- **Proton under the HERA microscope: physics highlights;**
- **Between past and future of *e-p* physics: new results from ZEUS;**
- **HERAPDF;**

1992-2012: 20 years of DIS at HERA

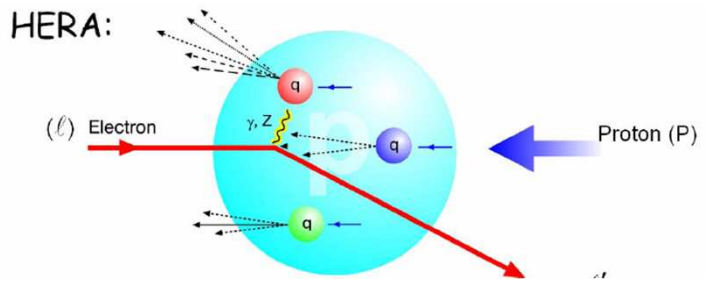
Data taking at HERA ended in the summer of 2007: end of an **era of research at the world's only e-p storage ring** facility in which particles with different masses are brought to collision;

Future (> 2020):

EIC@JLAB

eRHIC@BNL

LHeC@CERN



One of possible physics objectives could be the *e-p* physics book.

Today: at least an **occasion to take a backward look at this era and look ahead at what HERA still has to offer**.

1980s: ambitious plan

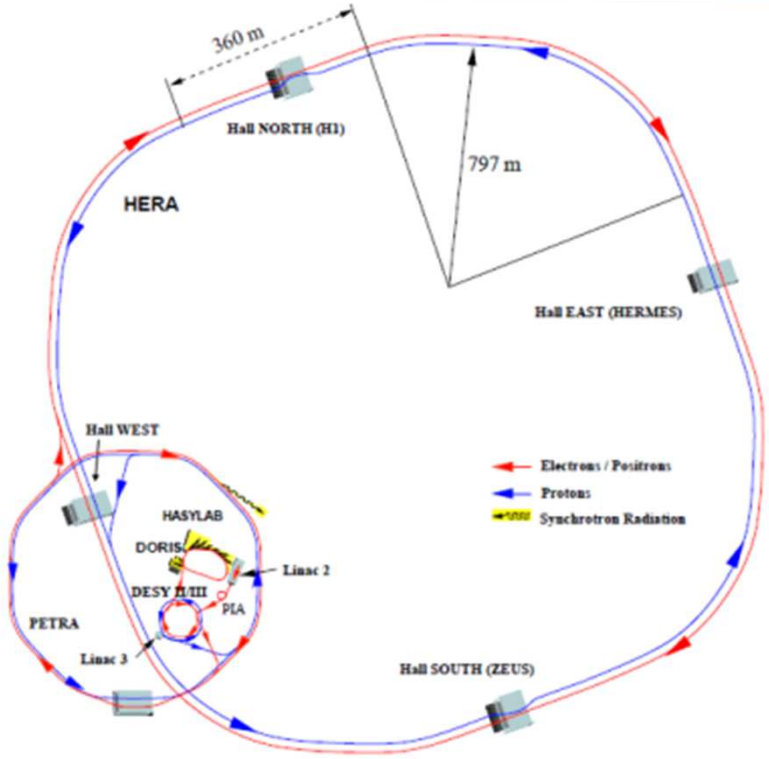
1971: Bjorn Wiik's ground-breaking

idea - construct a huge electron microscope for viewing protons.

But this idea slipped into the background:
in 1970s physicists were obtaining a wealth of
exciting results from e+e- experiments.

However, once it became clear in the late 1970s
that CERN plans LEP,
DESY decided to adopt the idea
of the super electron microscope instead.

1980: first project study and proposal;
1984: groundbreaking ceremony;
1985: boring machine begins digging the tunnel;
1990: completion of HERA;
1991: first electron-proton collisions;
1992: research begins at HERA - experiments H1 and ZEUS;



HERA was the first facility of its kind, the most complicated accelerator project: accelerate electrons and protons separately and have then collide ;

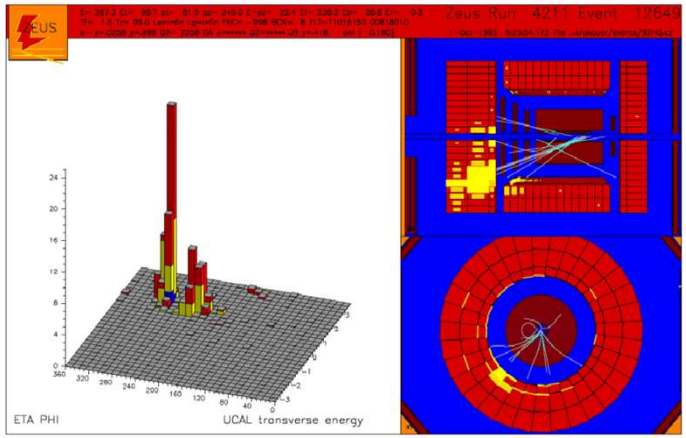
In 1992, the first two HERA experiments went into operation:

ZEUS in the South Hall and **H1** in the North Hall.

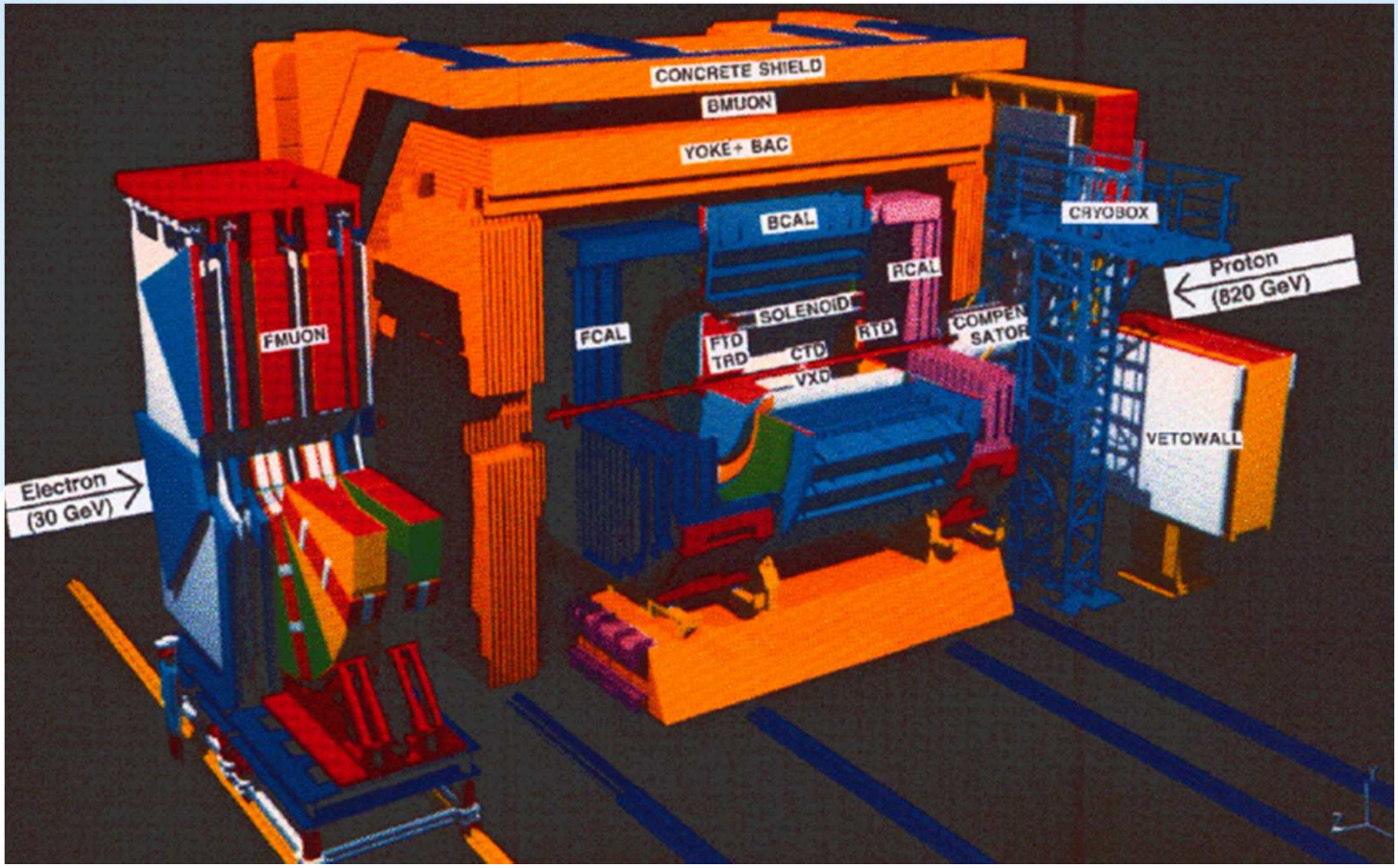
These detectors were optimized for:

- Neutral and Charged Currents at high Q2;
- Exotics (leptons, missing Et, multi-jets…);
- Photoproduction studies;

One of the very first ZEUS CC events




H1
HERA
ZEUS
PETRA



ZEUS : Main optimistion for CC at high Q^2

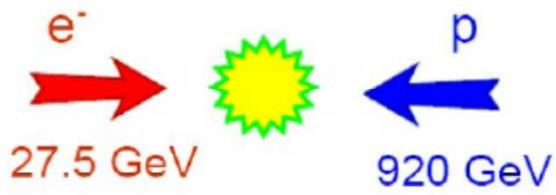
0.35 / √Eh excellent resolution for hadron energy :

0.18 /√Ee resolution for electron energy

Uranium calorimeter outside the solenoid coil

The HERA Collider

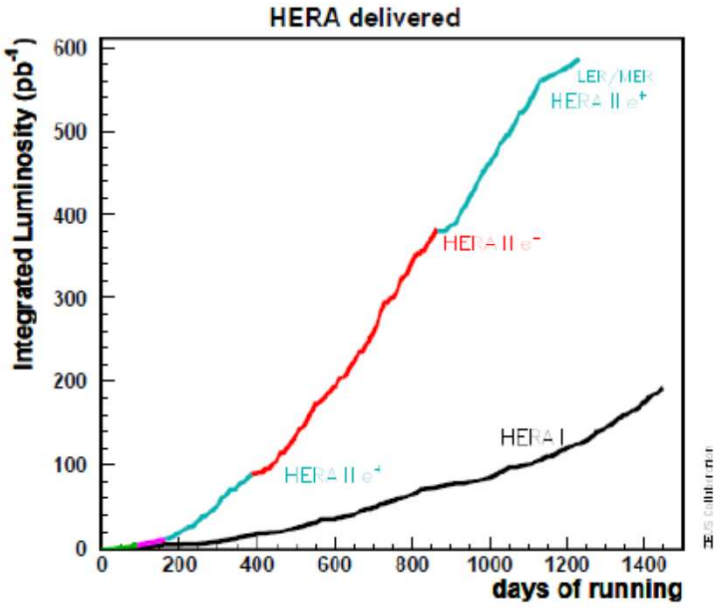
- World's only *ep* collider, located at DESY in Hamburg
- In operation from 1992-2007



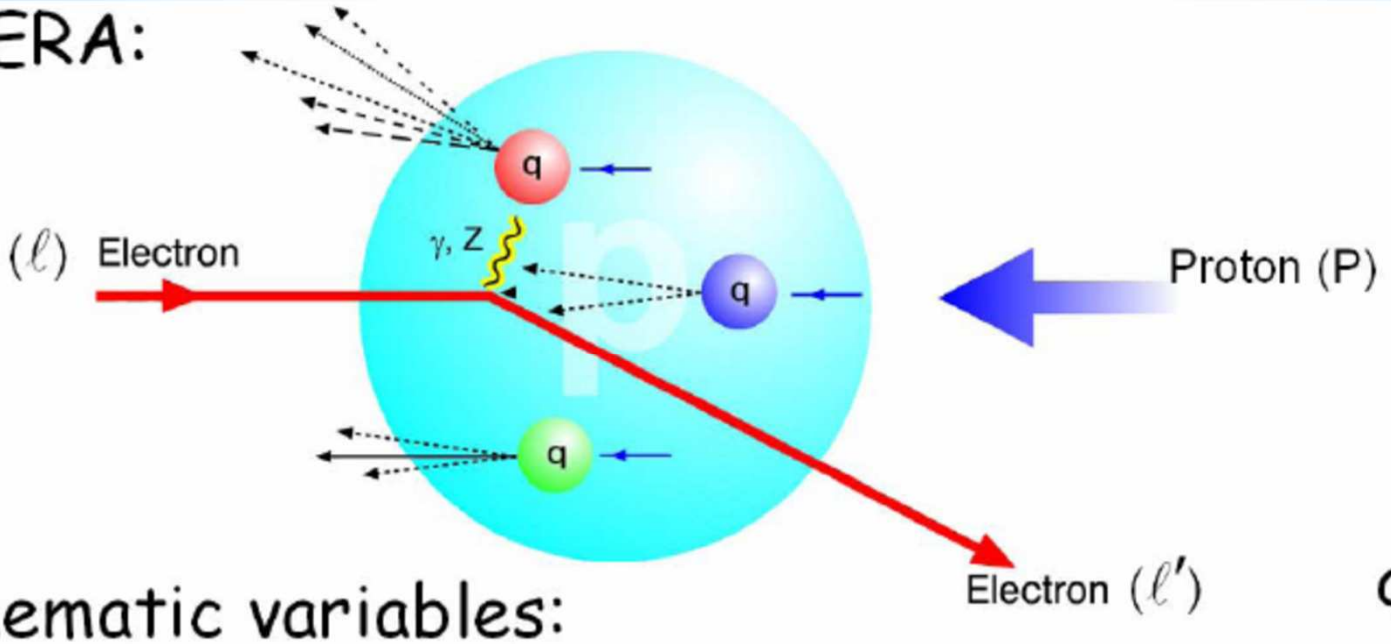
Center of mass energy:

$$\sqrt{s} = 318 \text{ GeV}$$

- Lepton beam longitudinally polarized in HERA-II running period (since 2002, P ≈ 30-40%)
- Two colliding experiments: H1 and ZEUS
- 0.5 fb^{-1} of data collected by each experiment



HERA:



$q = \ell - \ell'$

kinematic variables:

$Q^2 = -q^2$ photon (or Z) virtuality, squared momentum transfer

$x = \frac{Q^2}{2Pq}$ Bjorken scaling variable, for $Q^2 \gg (2m_q)^2$: momentum fraction of p constituent

$y = \frac{qP}{\ell P}$ inelasticity, γ momentum fraction (of e)

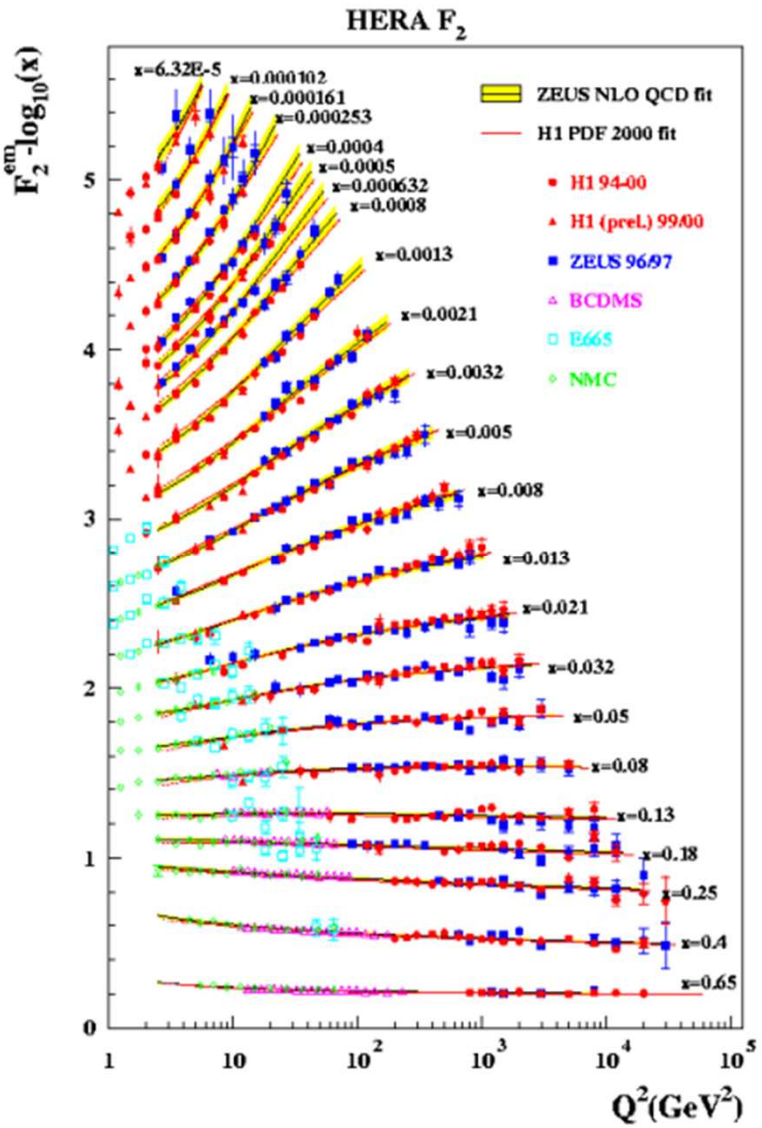
$Q^2 \lesssim 1$ GeV^2: photoproduction

$Q^2 \gtrsim 1$ GeV^2: DIS

Today many of the insights gained with HERA belong to our fundamental knowledge of how the world is put together.

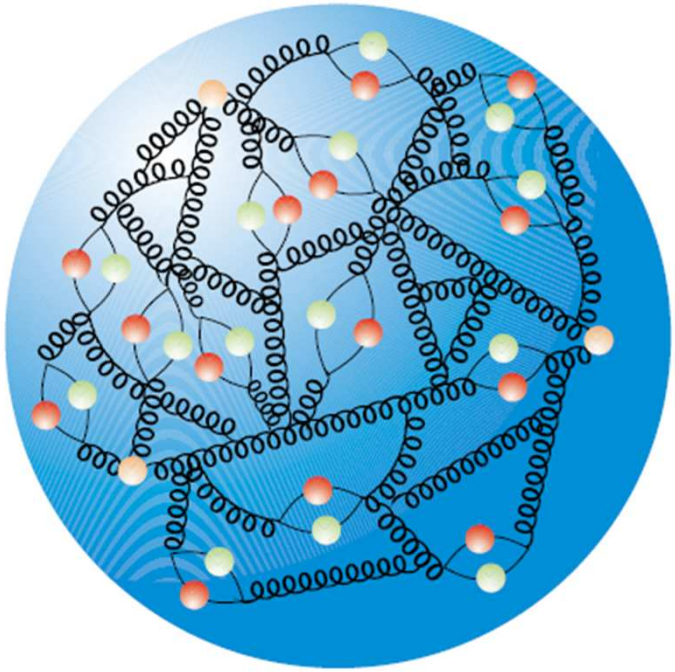
HERA physics highlights

HERA physics highlights: Structure function F2(x, Q2)



Measured the structure function F2 over a range that spans four orders of magnitude of the kinematic parameters x and Q2 – two to three orders of magnitude more than were accessible to earlier experiments.

HERA physics highlights

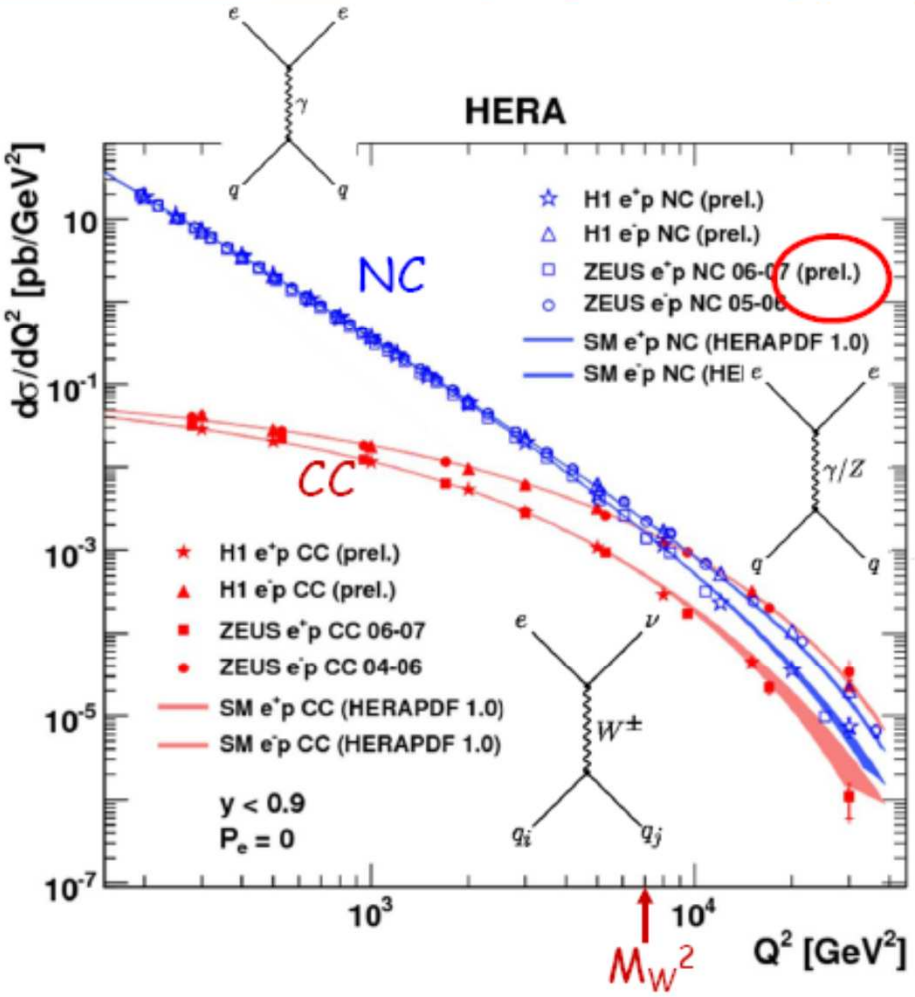


HERA provided totally new insights into the workings of the proton

Super electron microscope HERA makes the proton's detailed structure visible: three valence quarks and whole "sea" of gluons and short-lived quark-antiquark pairs.

The smaller the momentum fractions x are to which the HERA microscope is set, the more quark-antiquark pairs and gluons are seen in the proton.

HERA physics highlights: electroweak force



Strength of weak and electromagnetic forces become similar at scale $Q^2 \sim M_W^2$

$$\frac{d^2\sigma_{NC}}{dQ^2\,dx} \sim \alpha^2 \frac{1}{Q^4} \frac{1}{x}\Phi_{NC}(x,Q^2)$$

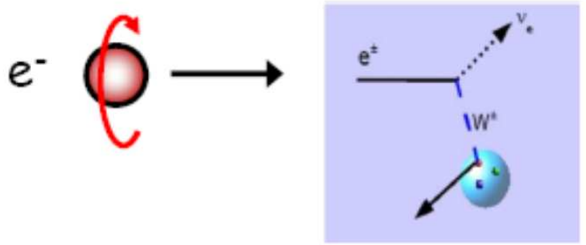
$$\frac{d^2\sigma_{CC}}{dQ^2\,dx} \sim G_F^2 \left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \frac{1}{x}\Phi_{CC}(x,Q^2)$$

ZEUS final soon !

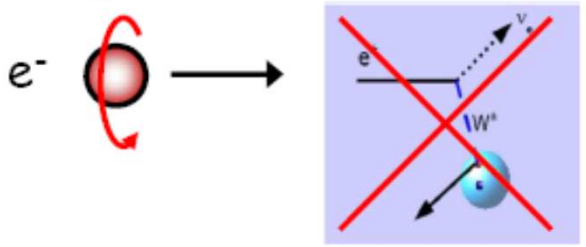
H1 and ZEUS directly observe the effects of (theoretically predicted) electroweak unification: first step toward the grand unification of the fundamental forces of nature.

HERA physics highlights: weak interactions are "left-handed"

- lefthanded electrons interact (CC)

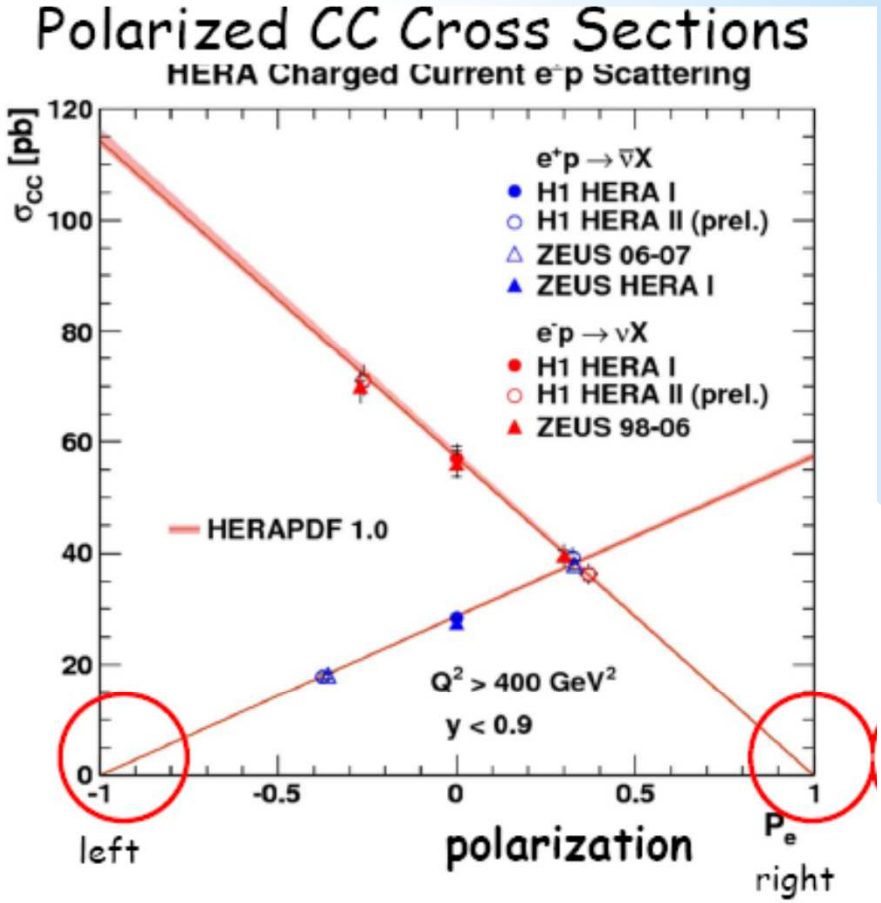


- righthanded electrons do not!



- cross section linearly proportional to polarization

$$\sigma^{e^{\pm}p}_{polCC} = (1 \pm P_e) \cdot \sigma^{e^{\pm}p}_{unpolCC}$$



ZEUS final !

Event rates disappear when extrapolating to completely right-handed electrons, Pe = +1.
Opposite for positrons, with the cross section approaching zero for lefthanded polarization.

HERA:

collaborations continue to finalize and publish their data analyses at high rate: 5 years after the end of HERA data taking - still a unique place to perform precision QCD studies**;** the relevance of these experimental results on the proton structure is appreciated as input for LHC analyses.

ZEUS today:

- **attractive and lively** collaboration, many young people:

  15 PhD, 13 MSc and 7 BSc (+9 BSc starting);

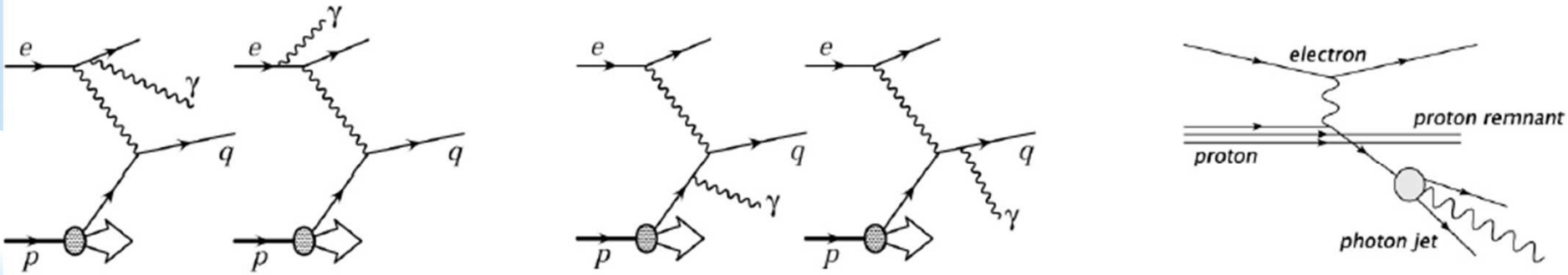
- **producing important physics results**: ~50 ongoing analyses;

New results from ZEUS

Isolated Photons + Jets in DIS

Predictions from GKS:

- Theoretical prediction of A. Gehrmann-De Ridder, G. Kramer and H. Spiesberger (Nucl. Phys. B. 578 (2000) 326)
- LO(α^3) with three components:



- (LEFT) photon radiated from incoming or outgoing lepton (LL radiation)
- (MIDDLE) photon radiated from a quark (QQ radiation)
- (RIGHT) photon from jet fragmentation (photon carries fraction z of quark momentum) ($D_{q\to\gamma}(z)$)
- Prediction: Total = LL + QQ + $D_{q\to\gamma}(z)$
- LO(α^3) and NLO($\alpha^3\alpha_s$) predictions are calculated

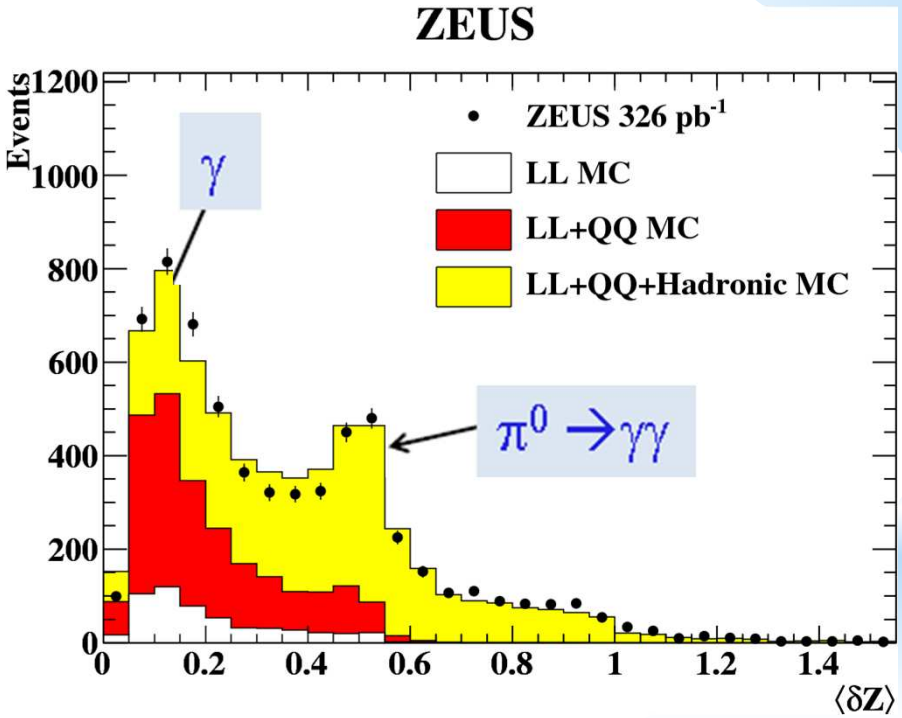
Isolated Photons + Jets in DIS

Phase Space

- $10 < Q^2 < 350\ \mathrm{GeV}^2$
- $4 < E_T^{\gamma} < 15\ \mathrm{GeV}$
- $-0.7 < \eta^{\gamma} < 0.9$
- $E_T^{jet} > 2.5\ \mathrm{GeV}$
- $-1.5 < \eta^{jet} < 1.8$

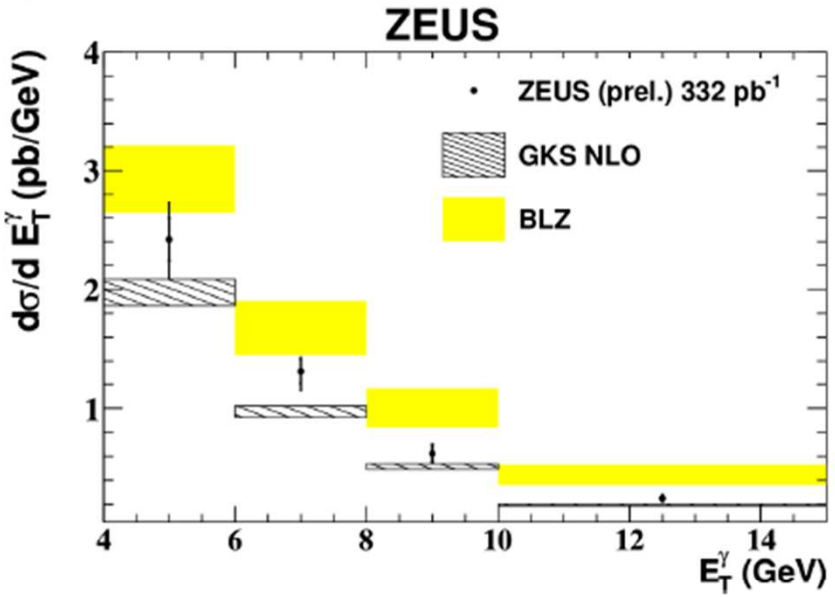
Photon Tagging:

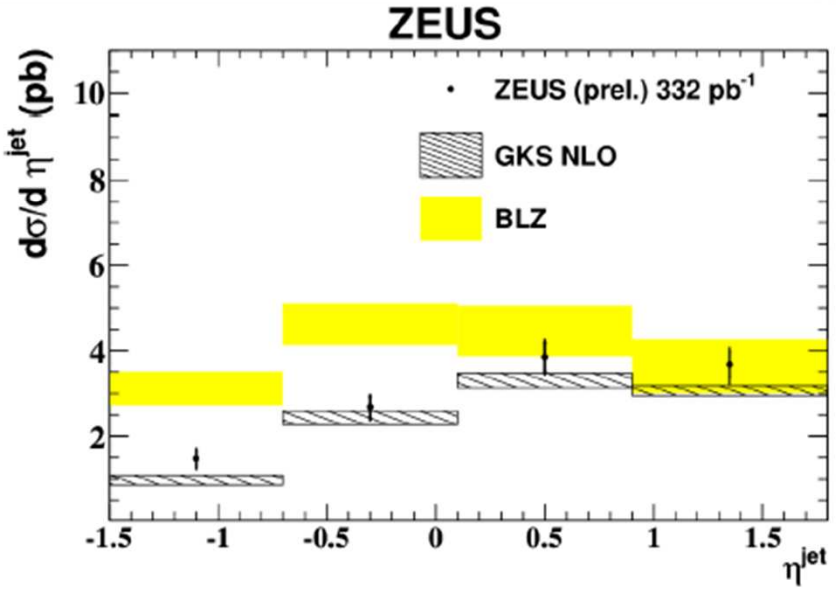
- Use lateral w i d t h $\langle \delta z \rangle$ of cluster
- Apply template fit to determine signal and bgr.



Prompt Photons + Jets in NC DIS

- Measurement of prompt photons provide direct probe of the underlying parton dynamics, because the γ emission is not affected by hadronisation.



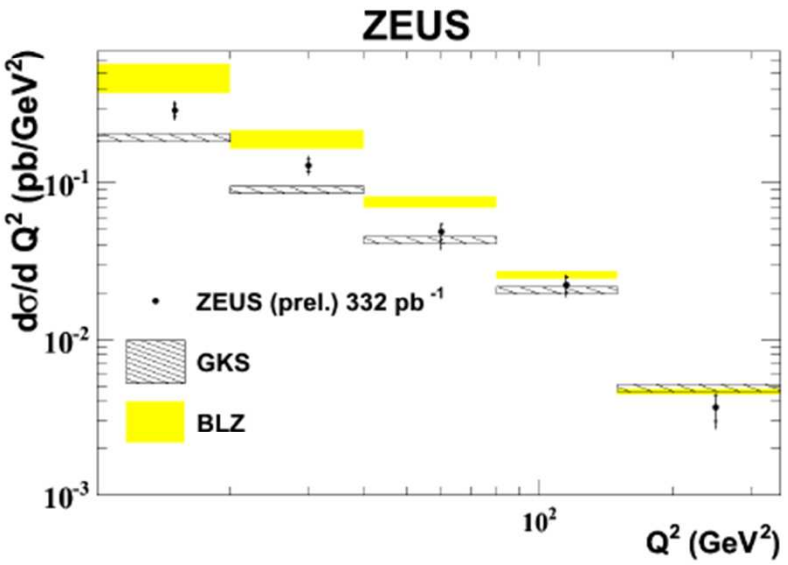


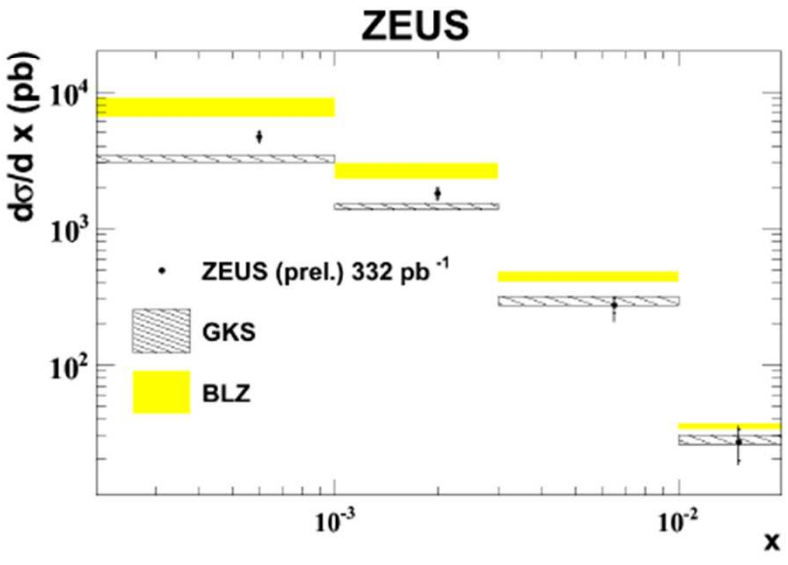
- Data were previously stamped preliminary for DIS2011.
- New theory predictions prepared for the measurement: Fixed order calculations, k_T-factorisation approach

→ GKS describes the data reasonably well.

Isolated Photons + Jets in DIS

Cross Sections as functions of Q^2 and x



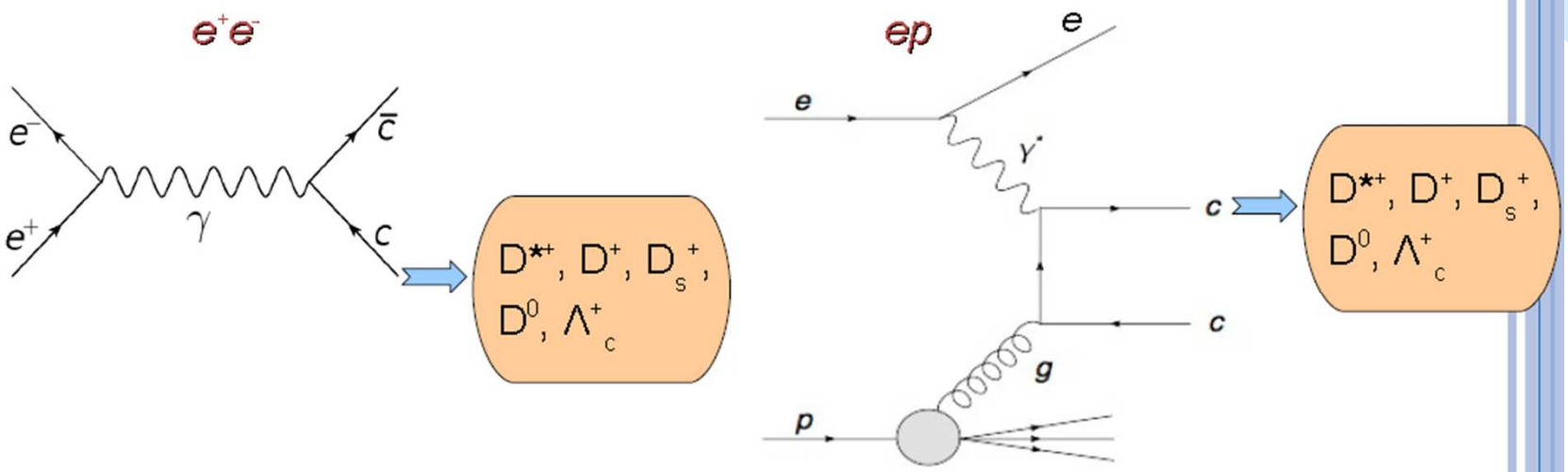


- in general GKS predictions underestimate data, and BLZ overestimate
- at high Q^2 both predictions agree

Charm Fragmentation Fractions: motivation

Charm Fragmentation fraction – the probability of c-quark to hadronize into particular charm meson

Charm production



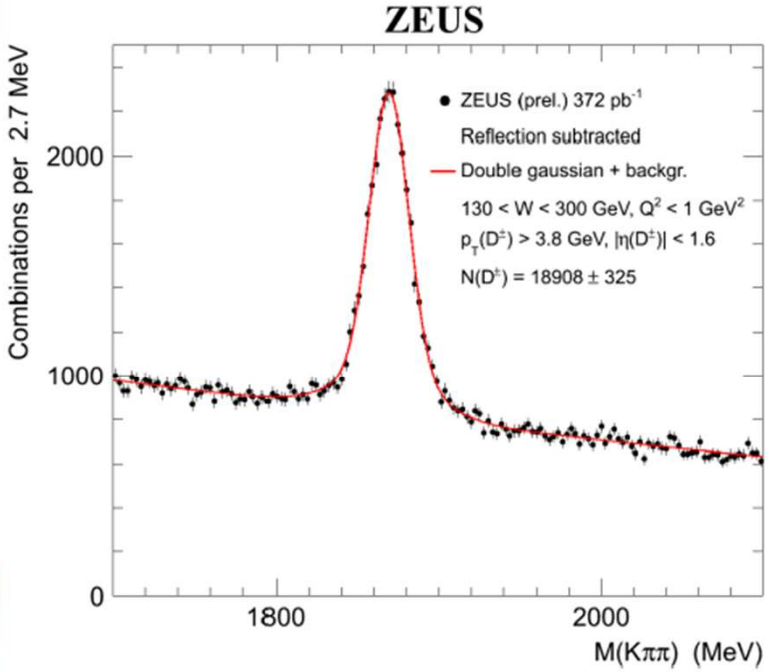
Is fragmentation universal?

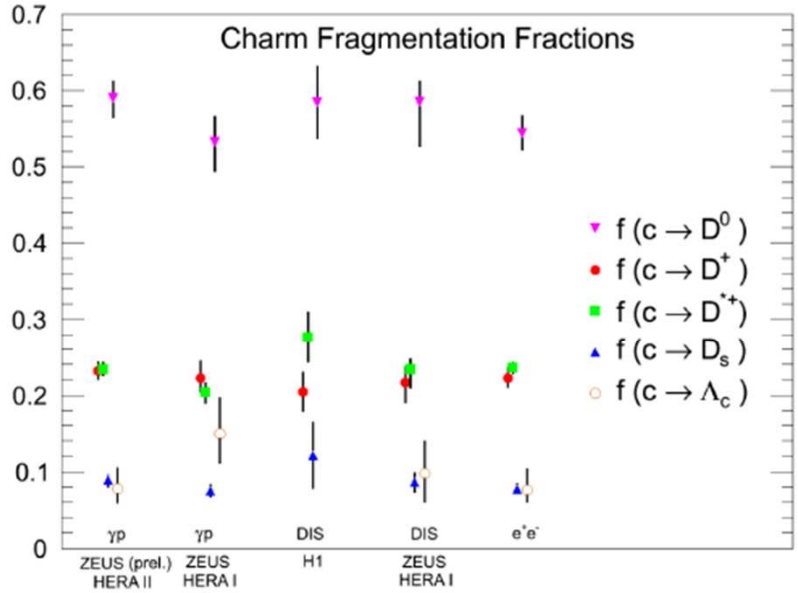
Charm Fragmentation Fractions in PHP

- Measure the probability of the c quark to hadronise into a particular charmed meson.
  - → Test universality of parton fragmentation!

Studied Channels:

- $D^+ \to K^-\pi^+\pi^+$
- $D^0 \to K^-\pi^+$
- $D_s^+ \to \phi^0\pi^+ \to K^+K^-\pi^+$
- $\Lambda_c^+ \to pK^-\pi^+$
- $D^{*+} \to D^0\pi_s^+ \to K^-\pi^+\pi^-$





→ **Most precise result.**

→ **Universality is confirmed!**

Charm in DIS: New inclusive sec. vertex results

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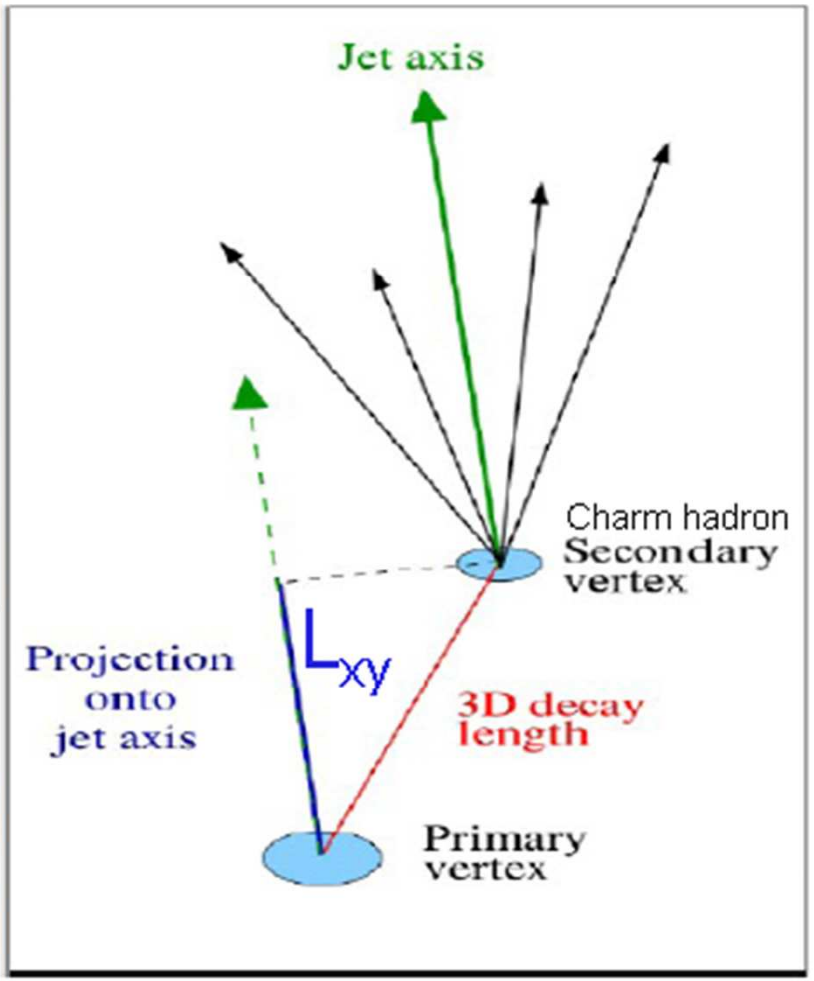
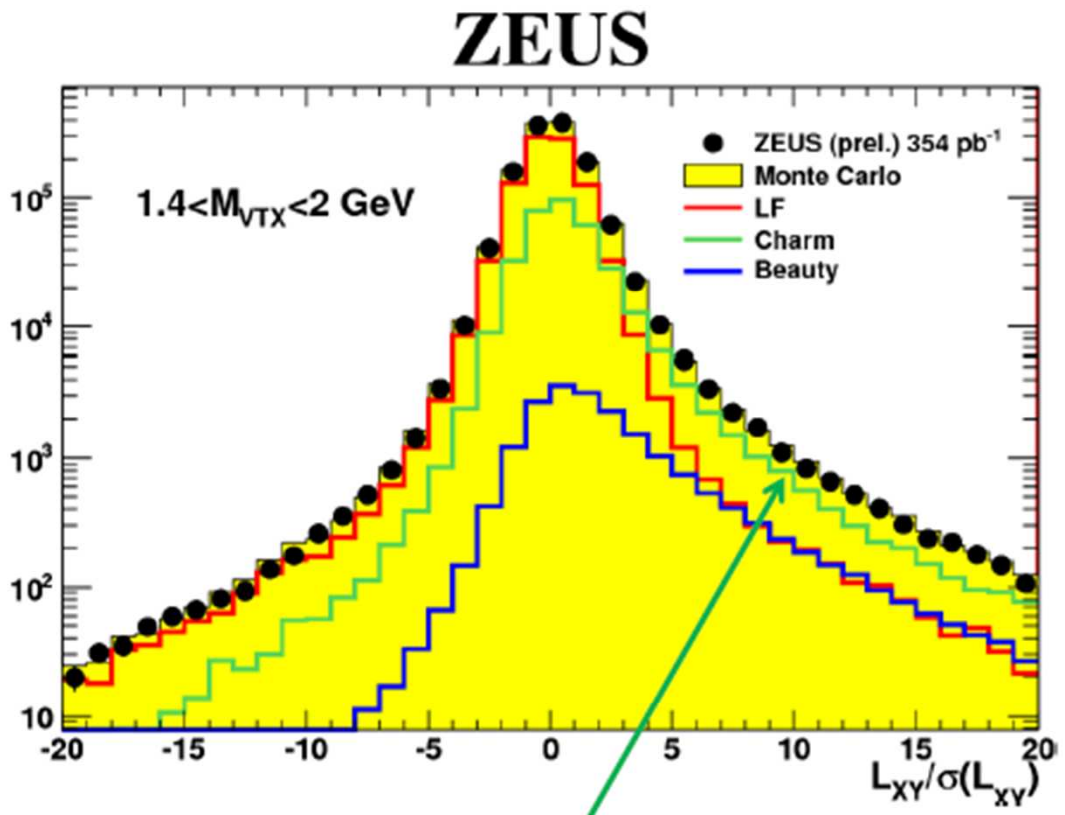
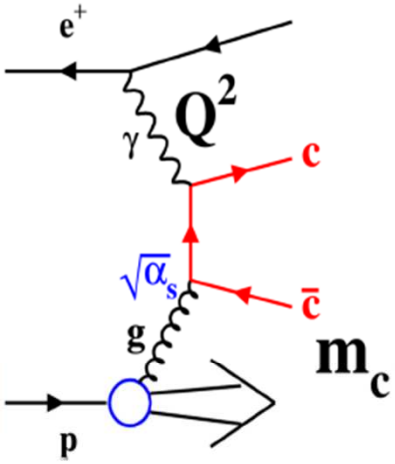




➔ Nice charm enhancement at positive significances Lxy/σ(Lxy) (reflecting lifetime of D mesons)

Charm Production using Secondary Vertices



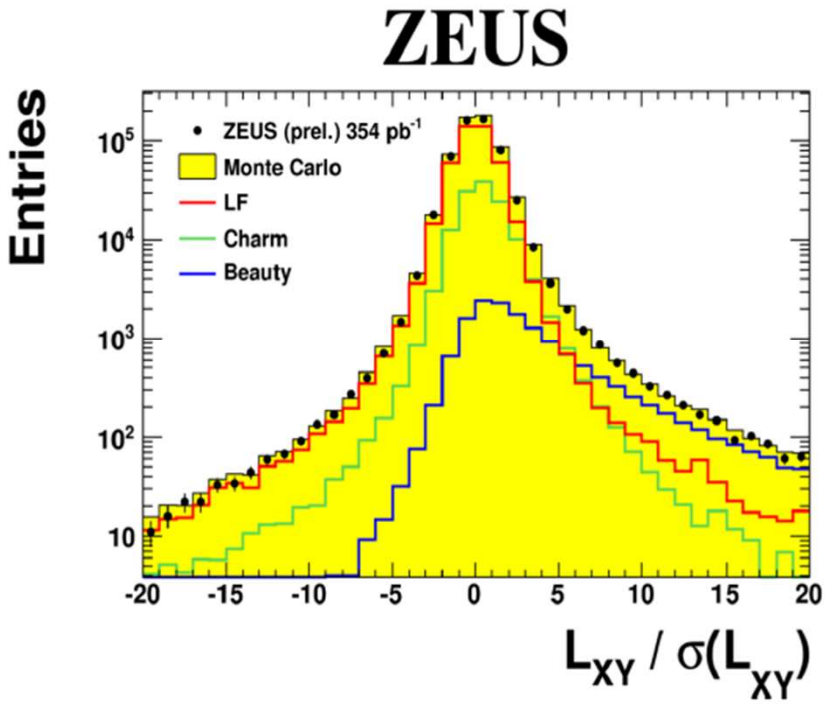
Charm production in DIS

→ Well established tool to study pQCD predictions.

→ Probe the gluon density in the proton.

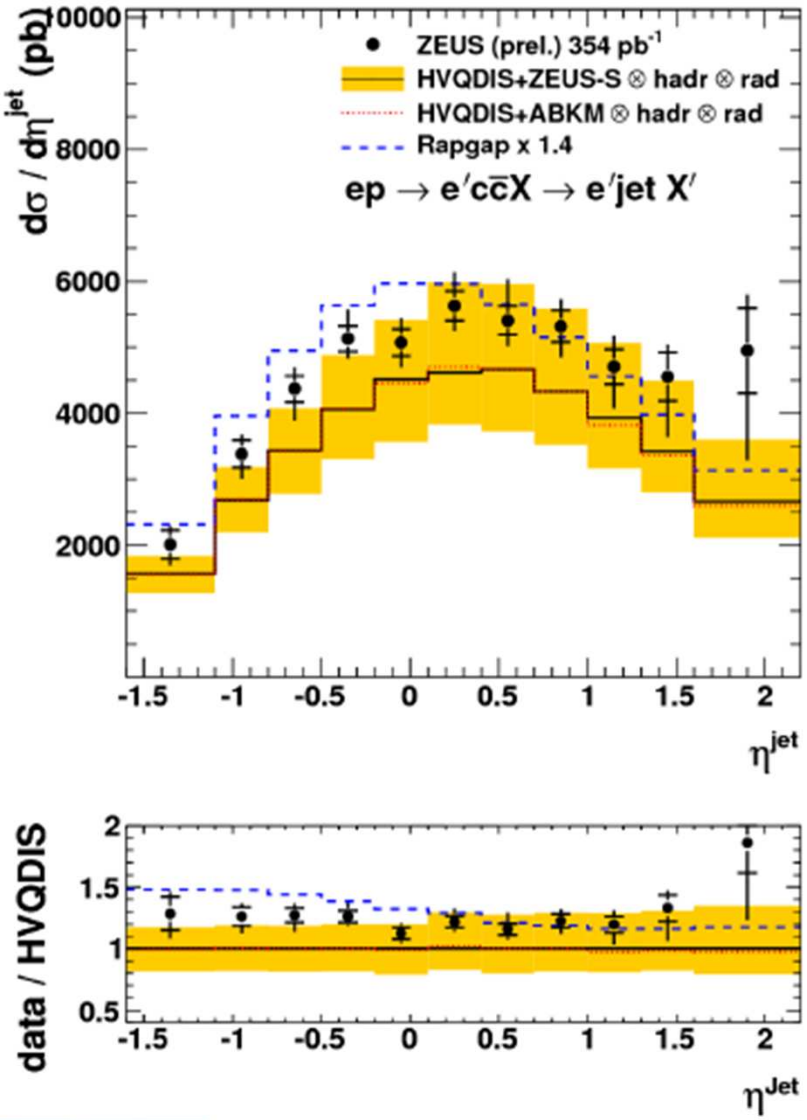
→ Sensitive to the charm mass. ← Important e.g. for theory predictions of W production at LHC.

- Measurement employs long lifetime of heavy quarks.
- Reconstruction of displaced secondary vertices to determine decay length significance, $L_{xy}/\sigma\,(L_{xy})$.
- Suppress light flavour contribution by "mirroring".



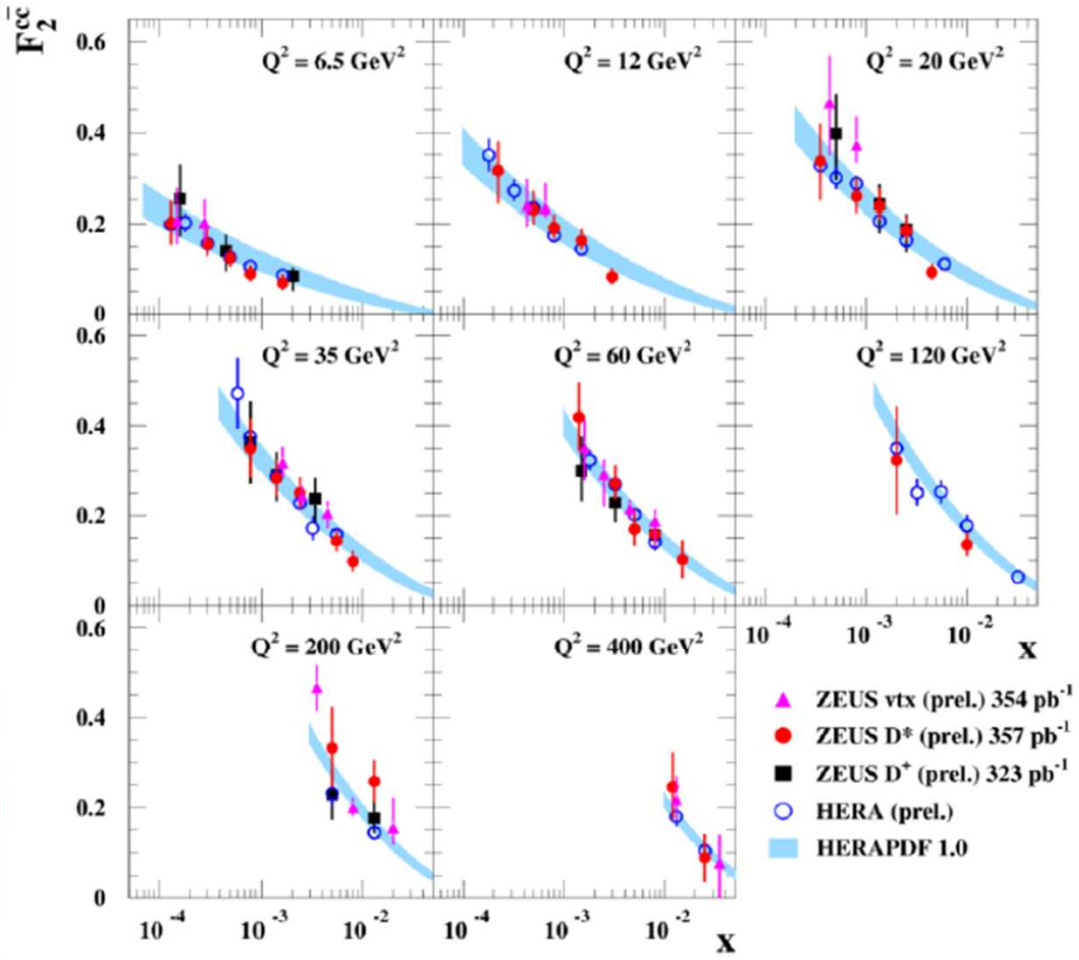
Charm in DIS: New inclusive sec. vertex results

ZEUS-prel-12-



→ Reasonable description by **massive** NLO QCD (HVQDIS)

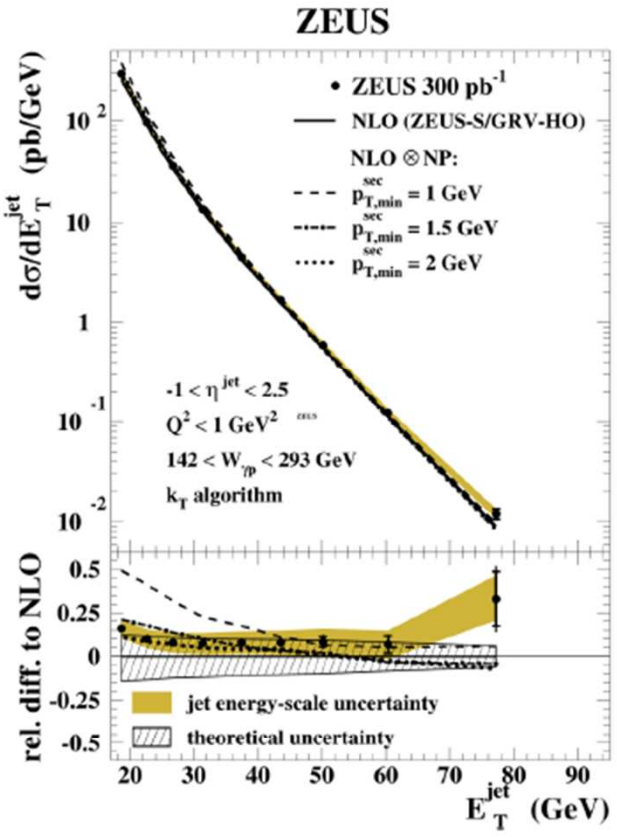
Charm Production using Secondary Vertices - charm contribution to DIS: F2cc

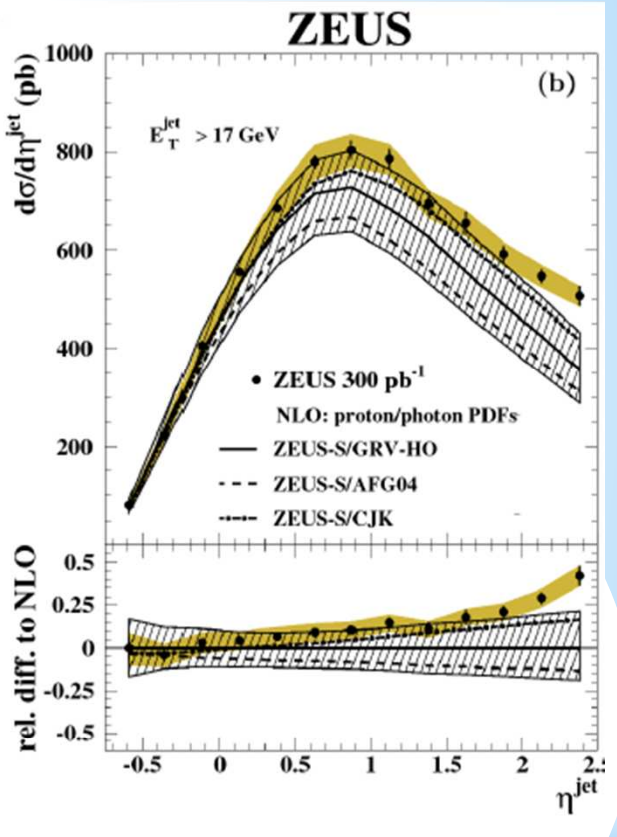


- NLO QCD calculations were used to extrapolate from the visible to the full phase space to extract $F_2^{c\bar{c}}$.
- **Consistent with previous measurements.**
- **High precision**, significant improvement of combination expected.

Inclusive Jet Production in PHP

- Measurement of jet cross sections in γp using k_T, anti-k_T and SIScone jet algorithm.
- Stringent test of new algorithms in an environment closer to that encountered in pp collisions.





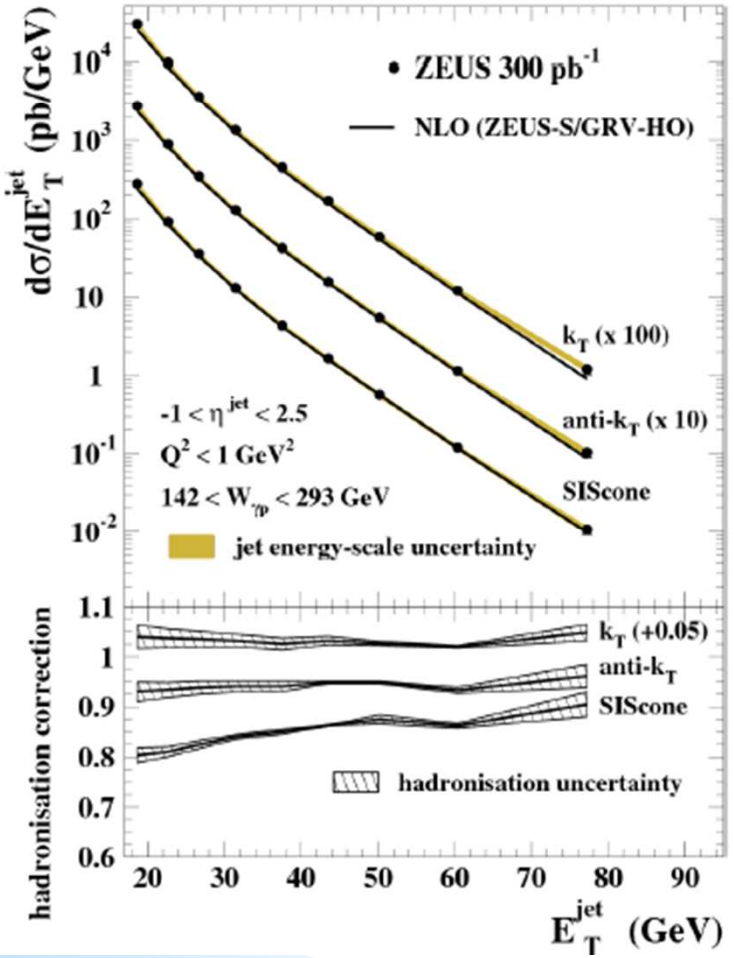
- NLO QCD calculations provide a good data description except at high η^{jet}
- non-perturbative effects or the γ PDFs could explain observed difference between data and the theory.

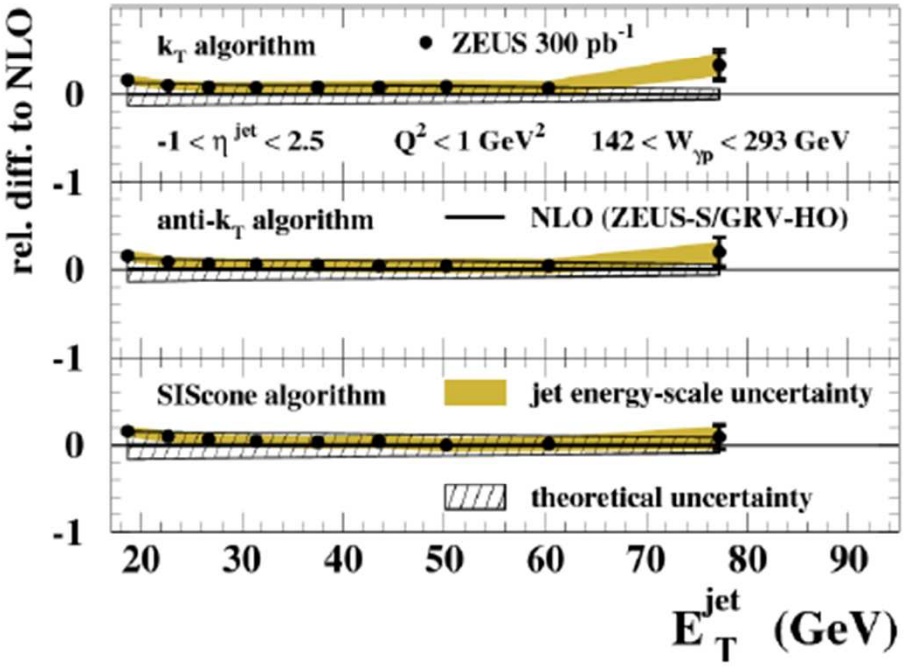
Inclusive jets in photoproduction: jet algorithms DESY-12-045

Anti-k_T and SIScone: recent new jet algorithms

- produce more circular shaped jets than inclusive k_T
- could be favourable to use them at LHC to calibrate jet energy & underlying event

⇒ **HERA jet measurements can provide nice benchmark tests for these algorithms**





→ Data similarly well described by all the algorithms

Inclusive Jet Production in PHP

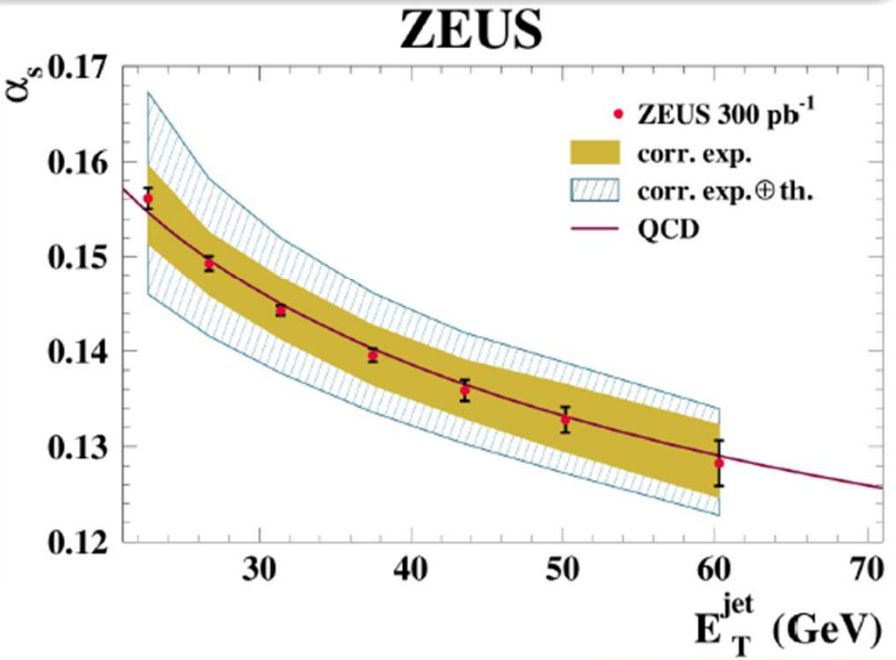
- Extraction of α_s for all three jet algorithms in the region $21 < E_T^{\text{jet}} < 71$ GeV.

- k_T algorithm: $\alpha_s(M_Z) = 0.1206^{+0.0023}_{-0.0022}(\text{exp.})^{+0.0022}_{-0.0035}(\text{th.})$
- anti-k_T algorithm: $\alpha_s(M_Z) = 0.1198^{+0.0023}_{-0.0023}(\text{exp.})^{+0.0041}_{-0.0034}(\text{th.})$
- SIScone algorithm: $\alpha_s(M_Z) = 0.1196^{+0.0022}_{-0.0021}(\text{exp.})^{+0.0046}_{-0.0043}(\text{th.})$

→ Precision extraction of $\alpha_s(M_Z)$ with total uncertainty of $\approx 3.9\%$.

→ **Predicted running of α_s agrees very well with the data.**

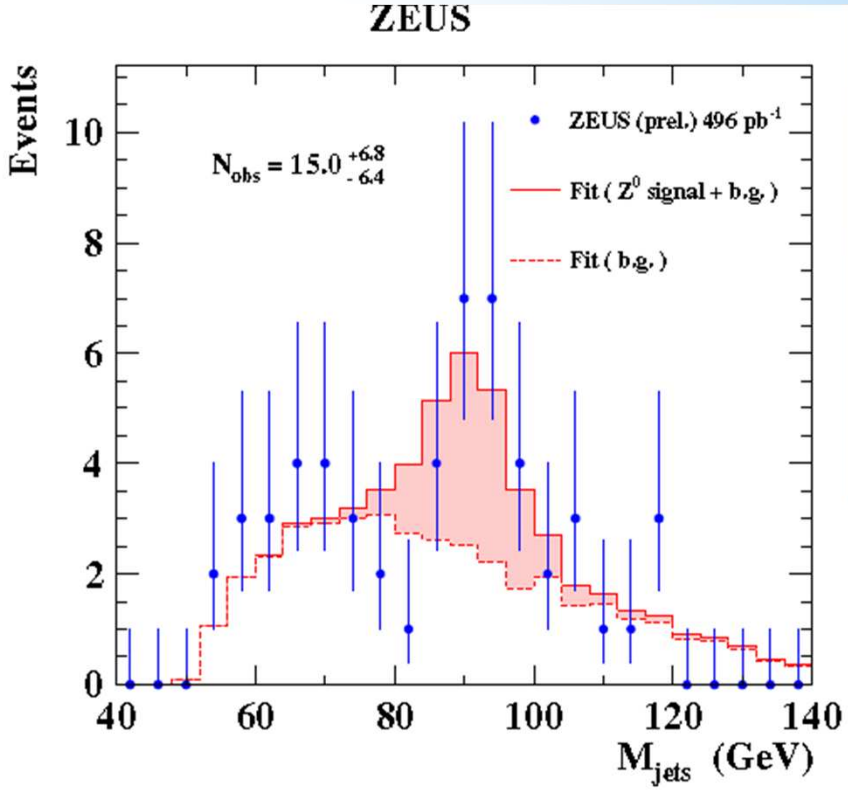
→ **Running is measured in a single experiment.**



Search for Elastic Z0 Production

- Search for Z^0 production.
- Due to small cross section difficult to use the leptonic decay mode.
- On the other hand, in the hadronic decay mode (BR ~ 0.7), the QCD dijet background is large.

$\rightarrow$ Perform analysis in the elastic regime defined by $\eta_{\max} < 3$.



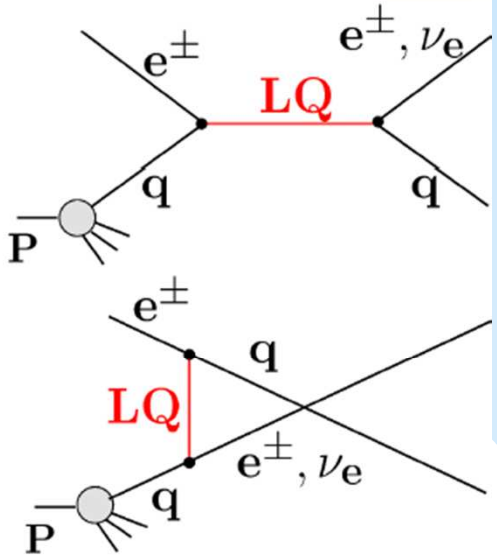
$$\sigma\left(ep \rightarrow eZ^0 p^*\right) = 0.133^{+0.060}_{-0.057}\,(\text{stat.})^{+0.049}_{-0.038}\,(\text{sys.})$$

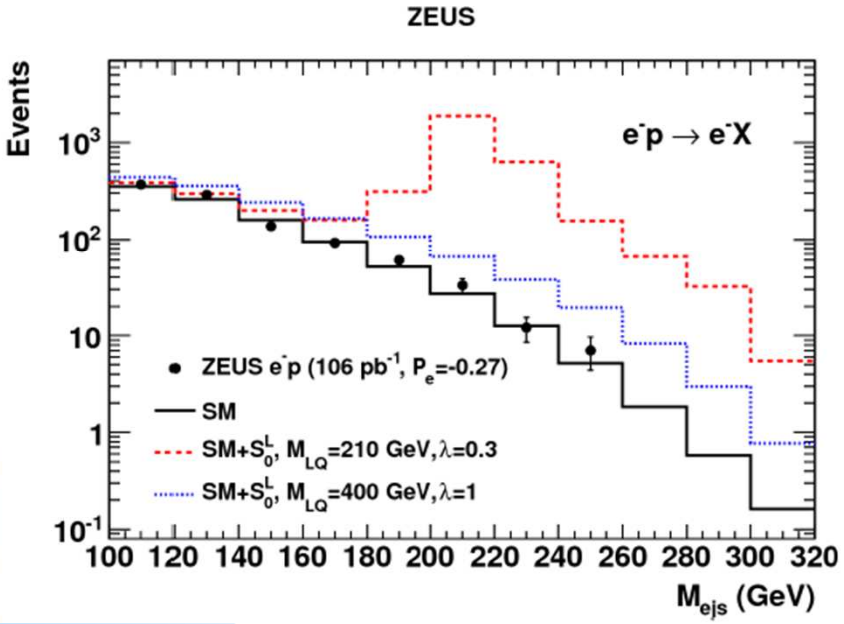
$\rightarrow$ **Result consistent with SM expectation of 0.16 pb.**

$\rightarrow$ **Demonstrates excellent resolution of the ZEUS calorimeter.**

First Generation Leptoquarks

- Leptoquarks are an extension of the Standard Model.
  - → Carry both baryon and lepton number.
- Can be produced as resonances if $M_{LQ} < \sqrt{s}$.
  - → Would decay into e or ν_e plus quark.
- For $M_{LQ} > \sqrt{s}$ existence would cause deviations in the NC/CC DIS cross sections.

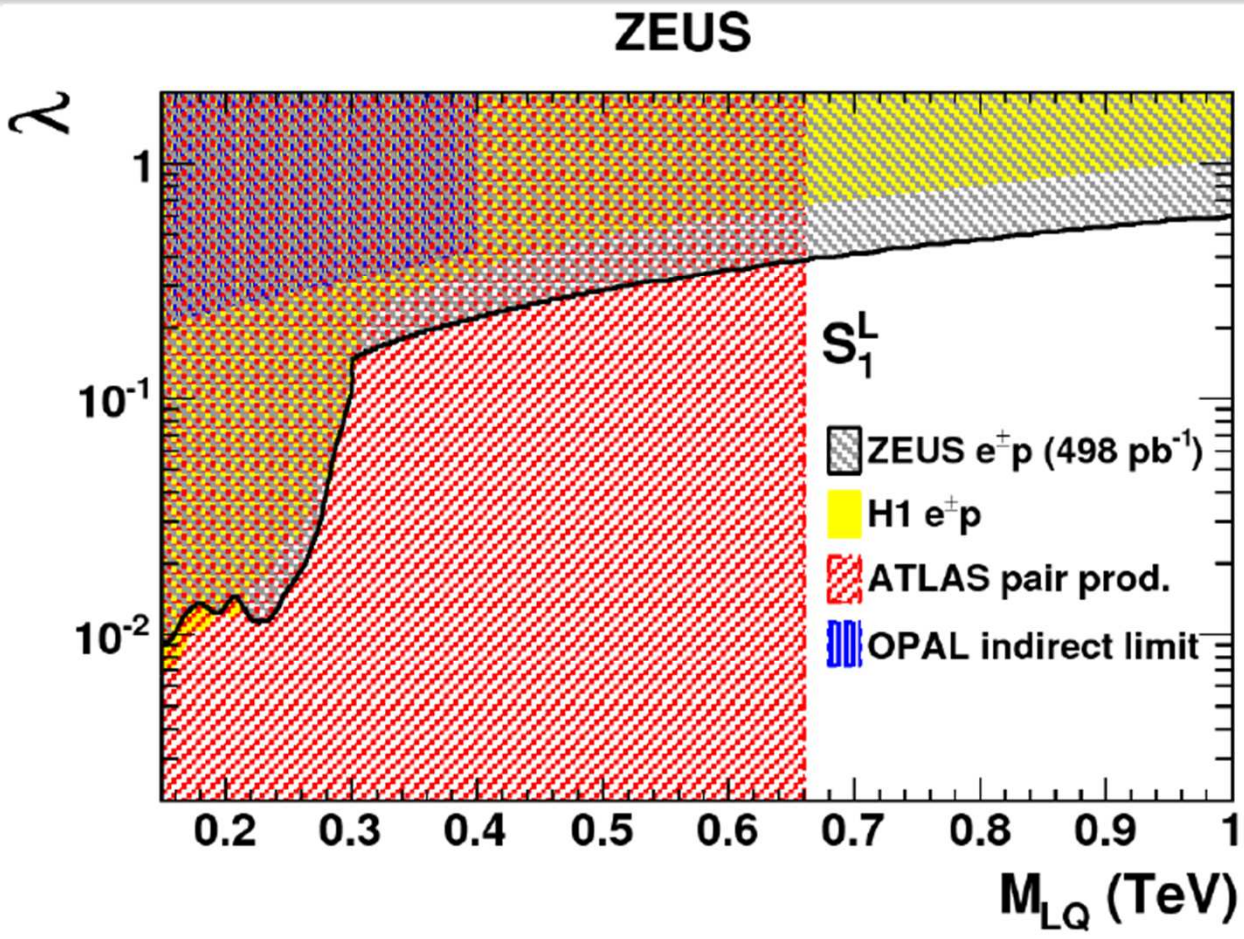




→ **No deviations from the Standard Model were observed.**

First Generation Leptoquarks

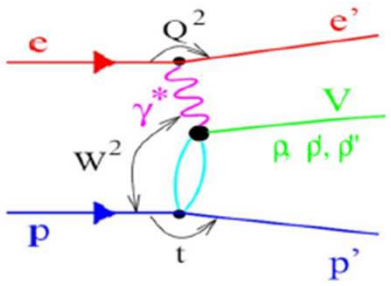
- Limits were extracted for the Yukawa coupling λ and M_{LQ}.

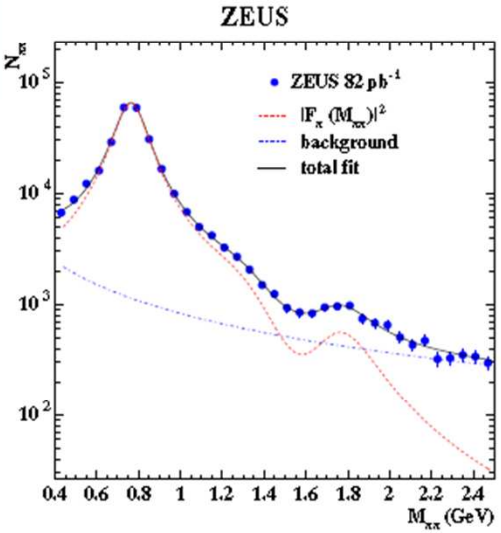


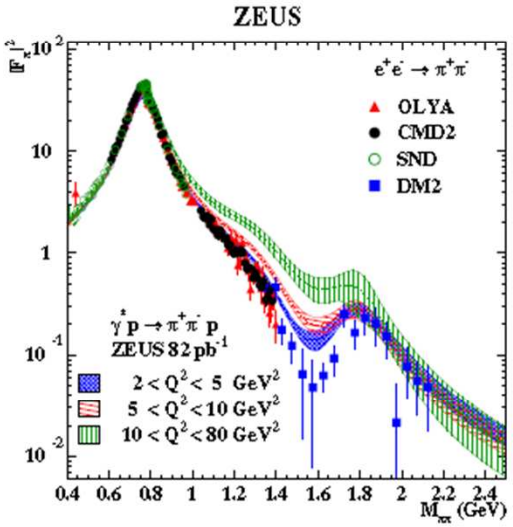
→ ZEUS limit is the best at high M_{LQ}.

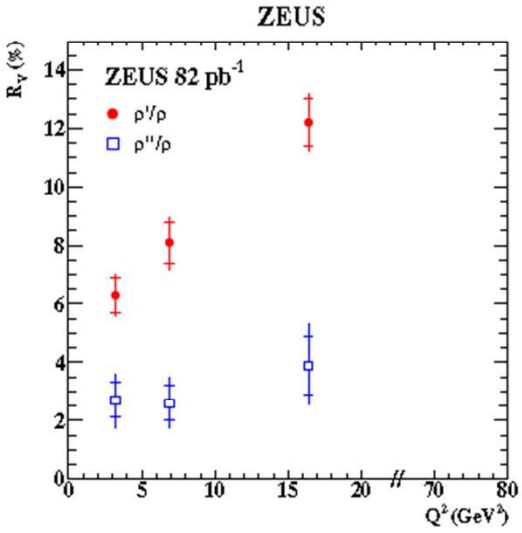
Exclusive Electroproduction of Two Pions

- Exclusive electroproduction of two pions $\gamma^* p \to \pi^+\pi^- p$ was measured.
  - Allow to study the radially excited 2S (ρ') and orbitally excited 2D (ρ'') states of the ρ vector-meson.





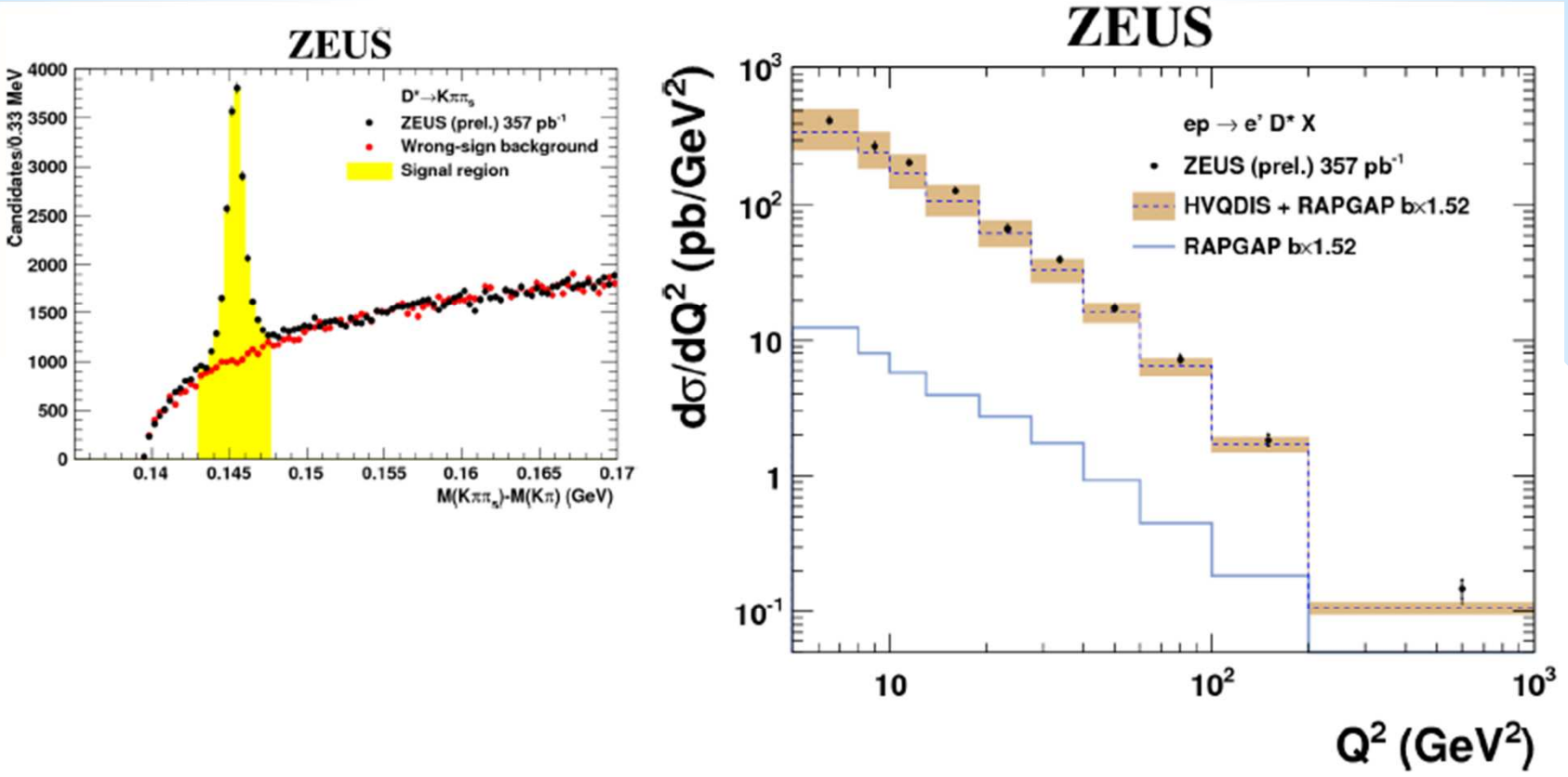




→ Features of pion form factor are also observed in e^+e^-.

→ Cross section ratio, $R_{\rho'/\rho}$, increases with Q^2. → Suppression of ρ' at low Q^2 is connected to a node effect.

D* Production in DIS and F2cc Measurements

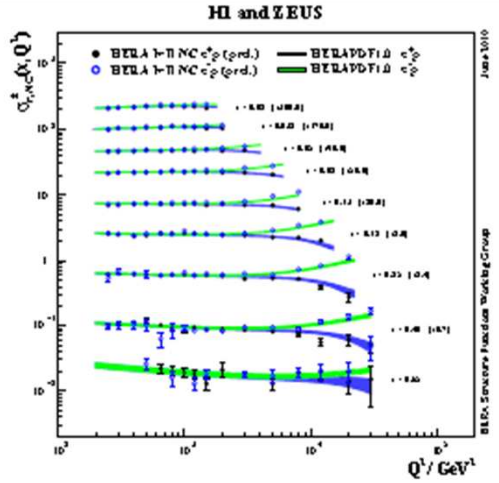


➔ Good description for all Q^2 by **massive** NLO QCD (HVQDIS)

HERAPDF:
precise measurement of parton distribution functions (quarks and gluons)

Proton structure measurements at HERA

PDF determination



$$\frac{d^2\sigma^{e^\pm p}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ \tilde{\sigma}^{e^\pm p}_{NC} \equiv \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L\right]$$

$F_2 = x\sum e_q^2\left(q(x)+\bar{q}(x)\right)$

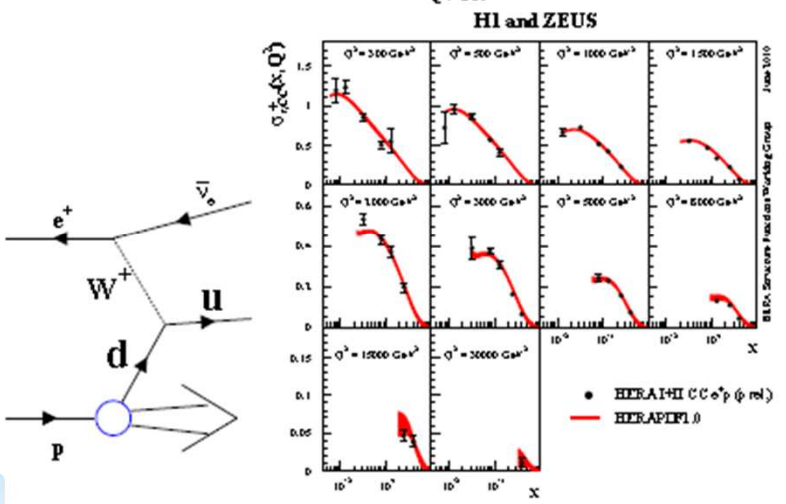
↪ sensitive to all quarks

$F_3 = \sum 2e_q a_q\left(q(x)-\bar{q}(x)\right)$

↪ sensitive to valence quarks

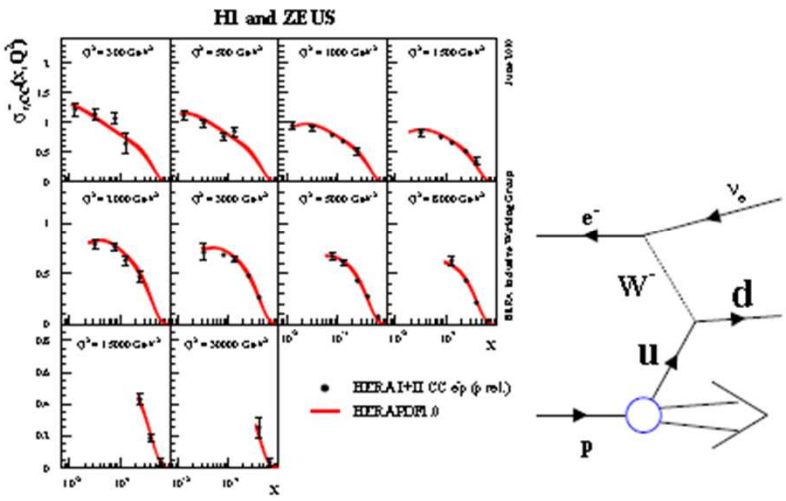
F_L

↪ sensitive to gluons



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

↪ sensitive to d_V at large x

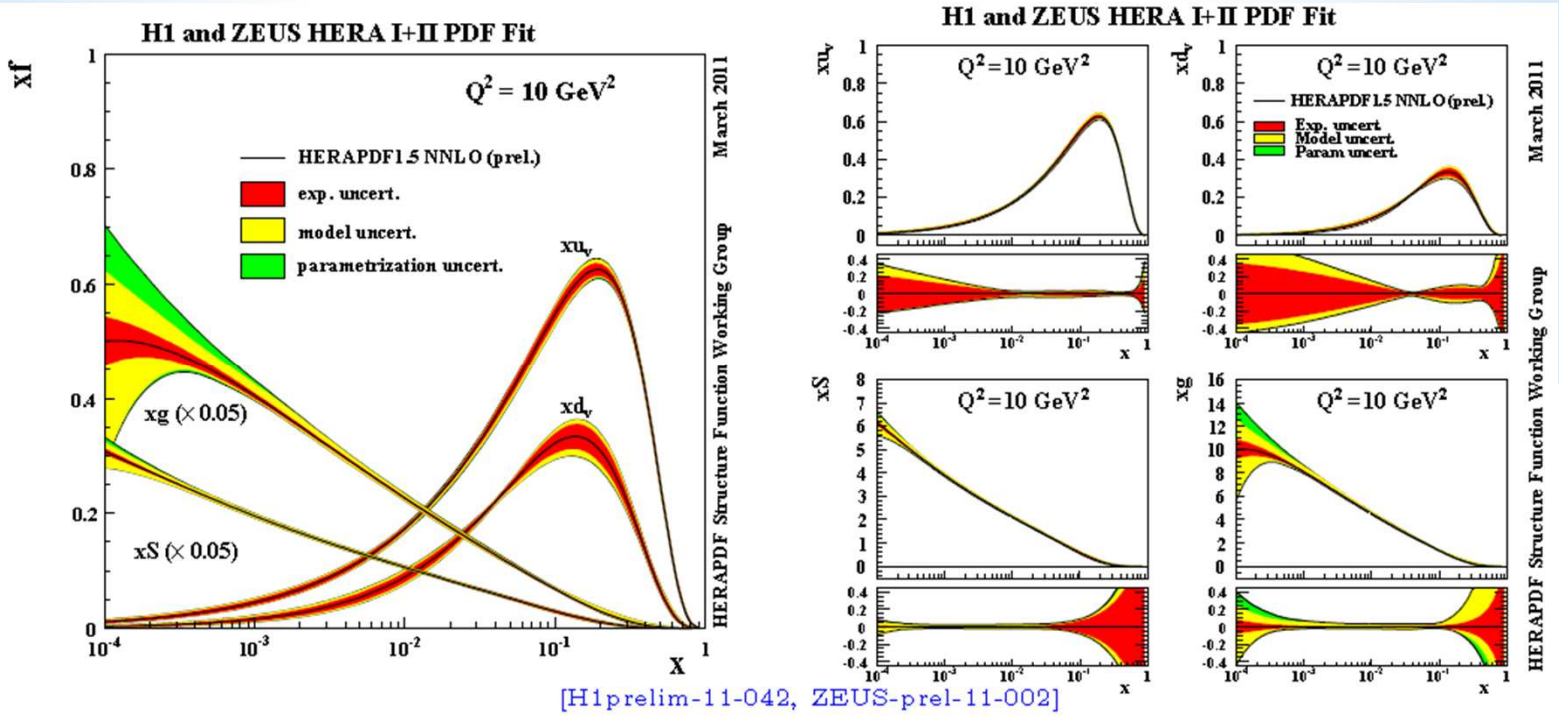


$\sigma^{e^-p}_{CC} \sim x\left[(u+c) + (1-y^2)(\bar{d}+\bar{s})\right]$

↪ sensitive to u_V at large x

- NLO and NNLO DGLAP evolution QCDNUM
- RT-VFNS (as for MSTW08)
- PDF parametrisation at Q_0^2: $xg, xu_V, xd_V, x\bar{U} = x\left(\bar{u} + \{\bar{c}\}\right), x\bar{D} = x\left(\bar{d} + \bar{s} + \{\bar{b}\}\right)$
  - 10 free parameters fit (HERAPDF1.0, HERAPDF1.5 NLO)
    $xf\left(x, Q_0^2\right) = Ax^B\left(1-x\right)^C\left(1 + Dx + Ex^2\right)$
  - 14 free parameters fit (HERAPDF1.5 NNLO, HERAPDF1.6, HERAPDF1.7)
    $xf\left(x, Q_0^2\right) = Ax^B\left(1-x\right)^C\left(1 + Dx + Ex^2\right) - A'x^{B'}\left(1-x\right)^{25}$

HERAPDF 1.5 NNLO



[H1prelim-11-042, ZEUS-prel-11-002]

Data:

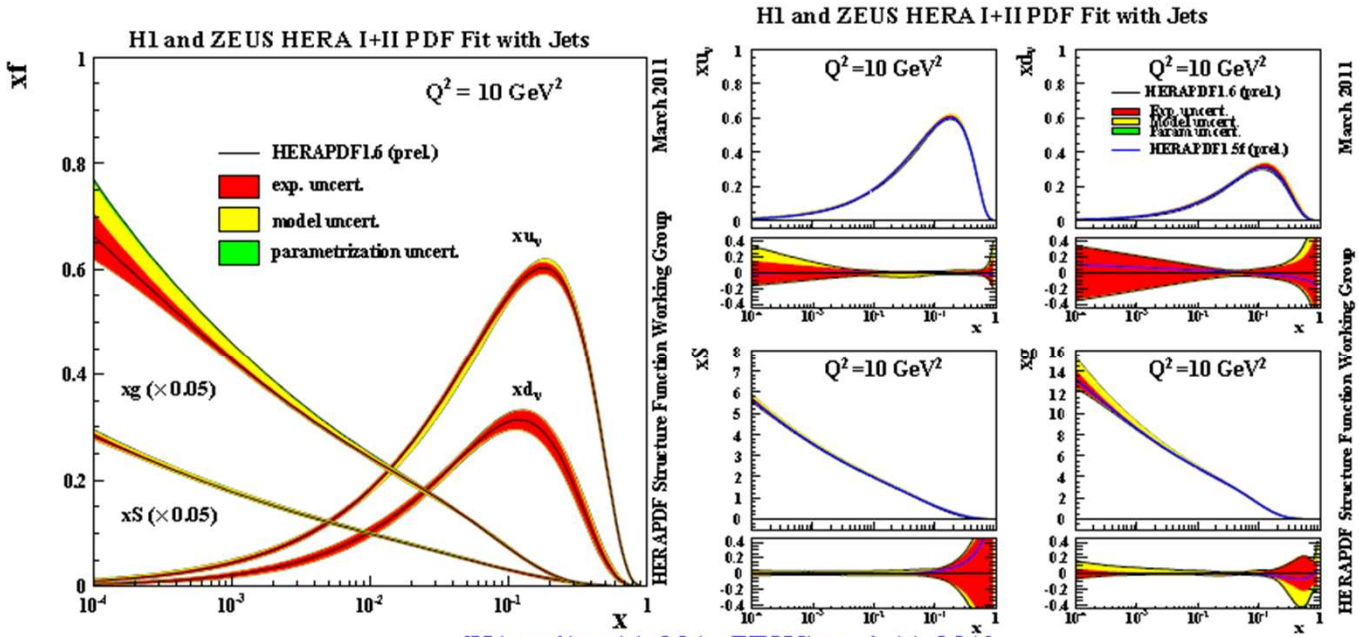
- Combined HERAI NC and CC data.
- Combined HERAII NC and CC data.

Fit settings:

- NNLO
- extended gluon parametrisation
- $\alpha_s(M_Z) = 0.1176$ fixed

- Combined HERAI+HERAII data have higher precision at high Q^2 and high x.
- The precision of the PDFs at high x, particularly in the valence sector, is significantly improved.

HERAPDF 1.6



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

Data:

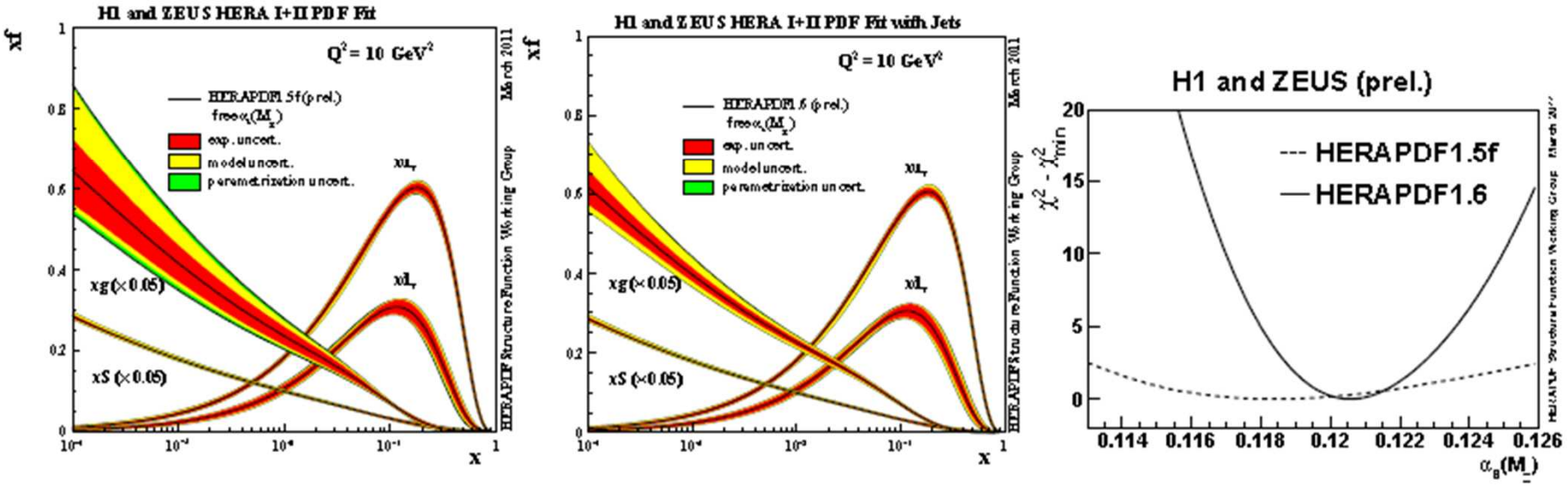
- Combined HERAI NC and CC data.
- Combined HERAII NC and CC data.
- H1 jet data.
- ZEUS jet data.

Fit settings:

- NLO
- extended gluon parametrisation
- $\alpha_s\,(M_Z)$ free

- Inclusion of the jet data into HERAPDF1.6 fit results in similar parton densities when compared to HERAPDF1.5f.

HERAPDF 1.6 and determination of $\alpha_s(M_Z)$



$$\alpha_s\,(M_Z) = 0.1202 \pm 0.0013\,(\text{exp.}) \pm 0.0007\,(\text{model/param}) \pm 0.0012\,(\text{hadr.})^{+0.0045}_{-0.0036}\,(\text{scale})$$

- Inclusion of jet data significantly reduces the correlation between the gluon PDF and α_s.
- Jet data provides an additional constrain on the gluon density.
- This analysis provides accurate and unbiased extraction of $\alpha_s\,(M_Z)$.

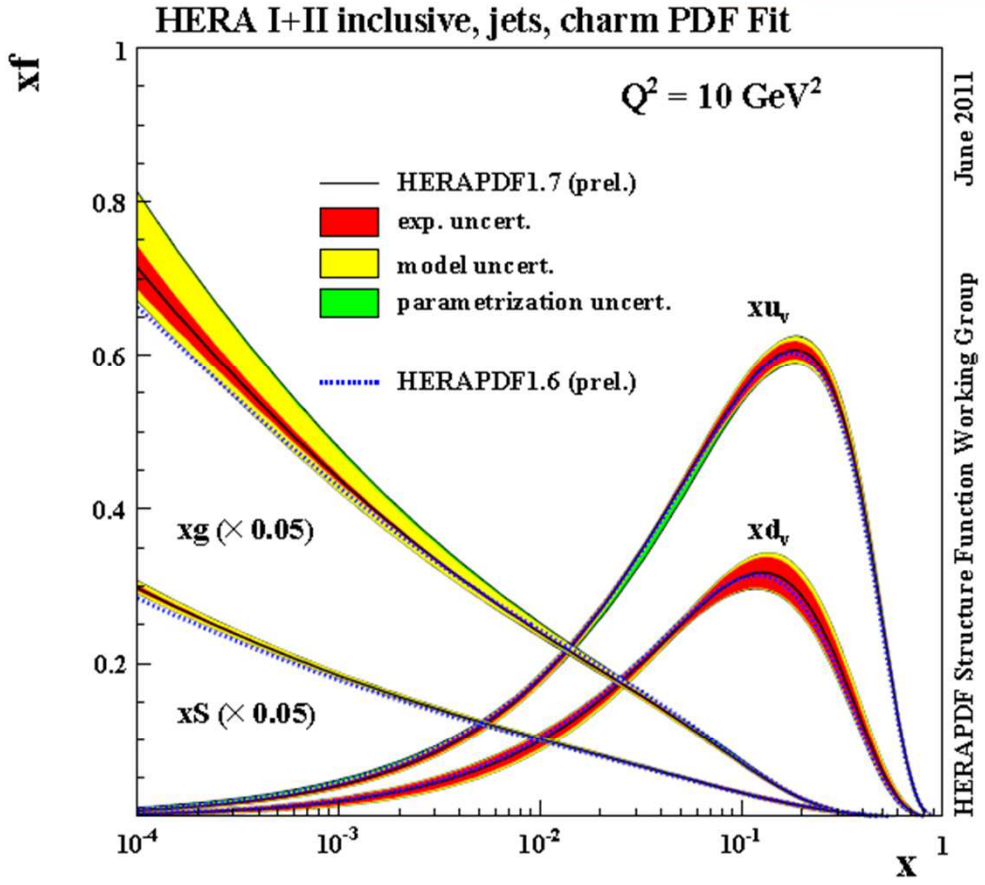
HERAPDF 1.7

Data:

- Combined HERAI NC and CC data.
- Combined HERAII NC and CC data.
- H1 jet data.
- ZEUS jet data.
- Combined $F_2^{c\bar{c}}$ data.
- Combined reduced energy NC data.

Fit settings:

- NLO
- extended gluon parametrisation
- $\alpha_s(M_Z)$ free
- RT optimal scheme



[H1prelim-11-148, ZEUS-prel-11-010]

- Inclusion of additional measurements is most sensitive to the charm and gluon PDFs.
- Combined $F_2^{c\bar{c}}$ data have sensitivity to m_c parameter.

HERAFitter project

HERAFitter is a QCD Fit Package used to determine HERAPDFs.
`herafitter.hepforge.org`

- Data:
  - DIS ep
    - Inclusive
    - Jets
  - DY pp and $p\bar{p}$
    - W, Z cross sections
    - Z rapidity
    - W asymmetries
    - Jets
  - Error treatment:
    - Correlated, ucorrelated
    - Hessian method
    - MC method
- Parametrisation studies:
  - Standard functional form of PDFs
  - CTEQ
  - Chebyshev
- Theory (DIS):
  - ZM-VFNS accessed from QCDNUM
  - RT optimal as in MSTW
  - ACOT as in CTEQ
  - FONLL as in NNPDF
  - FFNS and BMSN as in ABM
- Treatment for jets:
  - FastNLO:
    - A wrapper around NLOjet++
  - Applgrid
    - A wrapper around MCFM, NLOjet++
- DY cross sections at LO x K-factors
- Output:
  - PDFs predefined scales
  - LHAPDF grids
  - Theory predictions per data points
  - Pulls per data points

- HERAFitter code is a mixture of C++ and Fortran with reduced dependence on external packages.
- Inclusion of new data tables should be possible without recompilation
- Inclusion of new theory in a standardised, modular way.

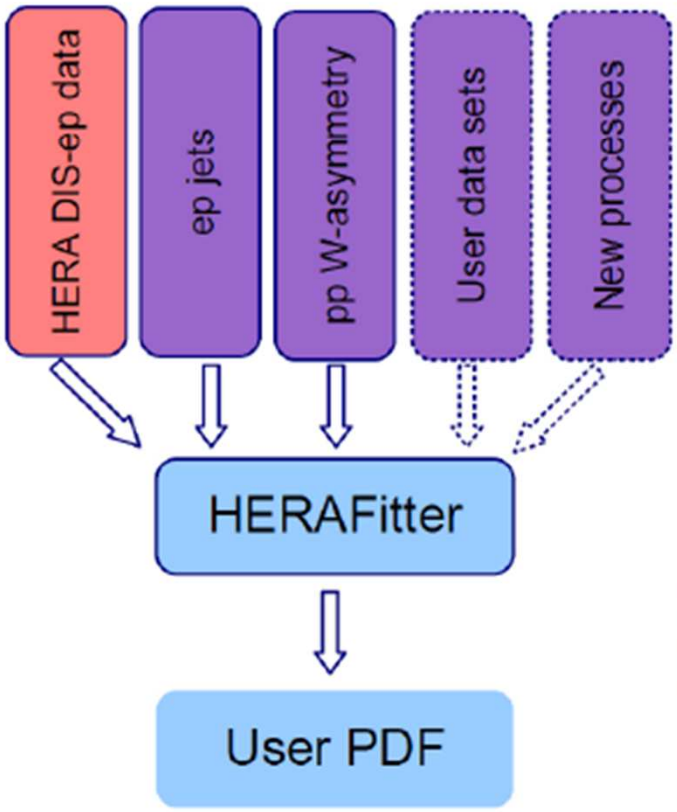
HERAFitter Platform

Legacy of HERA preserved in a long-term project HERAFitter
HERAFitter is a ready QCD platform to analyse new data in context of PDFs
It is now publicly available under GNU General Public License

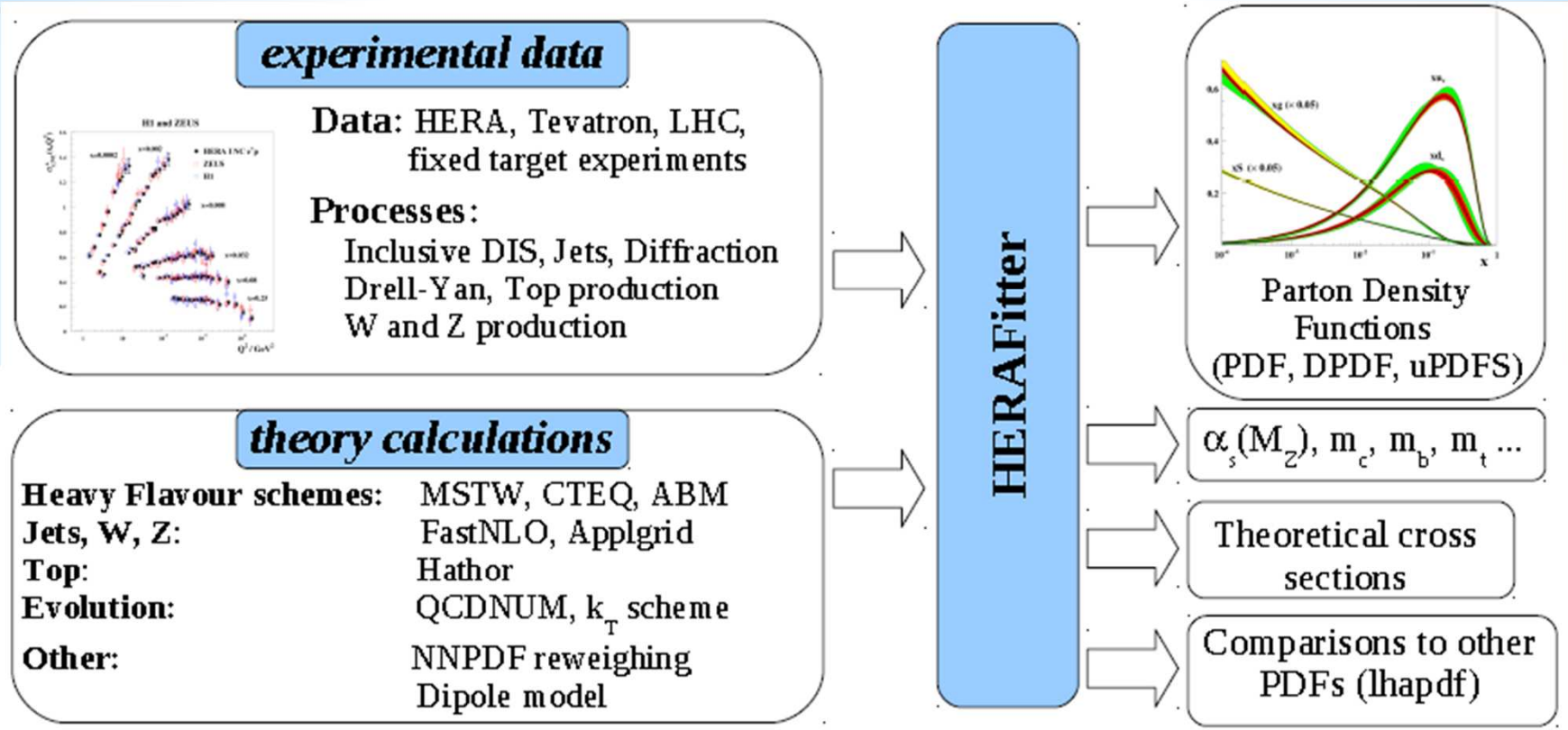
The code was originally used to determine HERAPDF

Package developers:
- H1 and ZEUS members
- LHC experiments
- Theory groups

Modular strategy adopted
- independent development of separate modules
- new modules can be added fairly easy

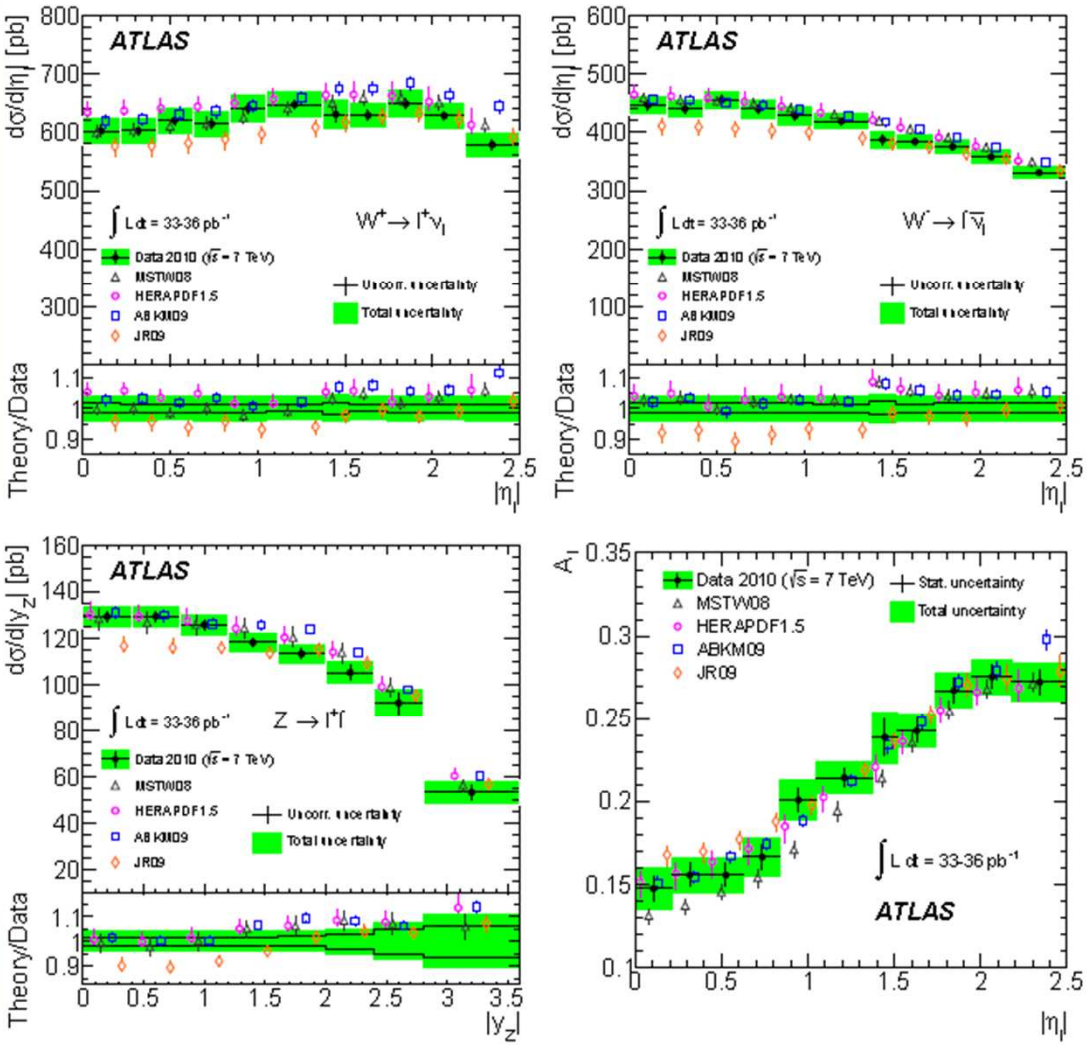


HERAFitter Platform



Active and committed contributions from all the involved theory groups, regular participation in meetings, etc.

HERAPDF predictions for W and lepton asymmetries at LHC



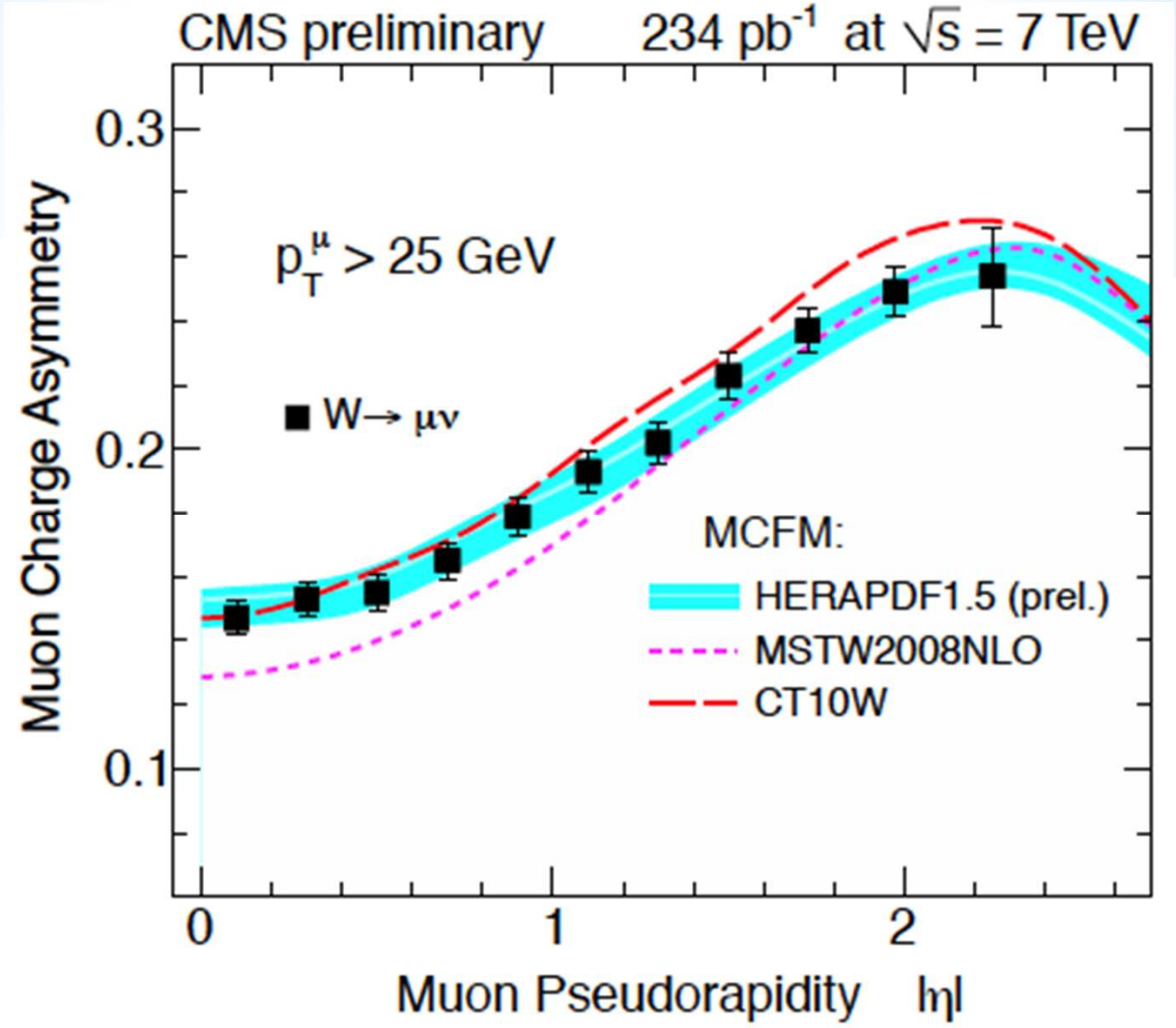
Parton distribution functions HERAPDF verified by successful predictions for ATLAS

W assymetry is sensitive to differences between u- and d-type quarks

$$A_{\pm} = \frac{d\sigma/dy_W(W^+) - d\sigma/dy_W(W^-)}{d\sigma/dy_W(W^+) + d\sigma/dy_W(W^-)}$$

- HERAPDF1.5 NNLO provides reasonable predictions to pp processes at high energy.

Successful HERAPDF1.5 Predictions for CMS



Conclusions

- ✓ New precision results still coming in: jets, isolated photons, vector mesons, diffraction, charm and beauty etc.;
- ✓ HERA provides an ideal QCD laboratory to probe the underlying theory as well as the structure of the proton;
- ✓ A legacy from HERA: precise measurement of parton distribution functions (quarks and gluons) in kinematic range of interest for LHC;