# HERA proton structure measurements


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# Outline

- Discussion of the HERA collider and detectors
- Measurements of inclusive DIS
- A few other selected HERA measurements

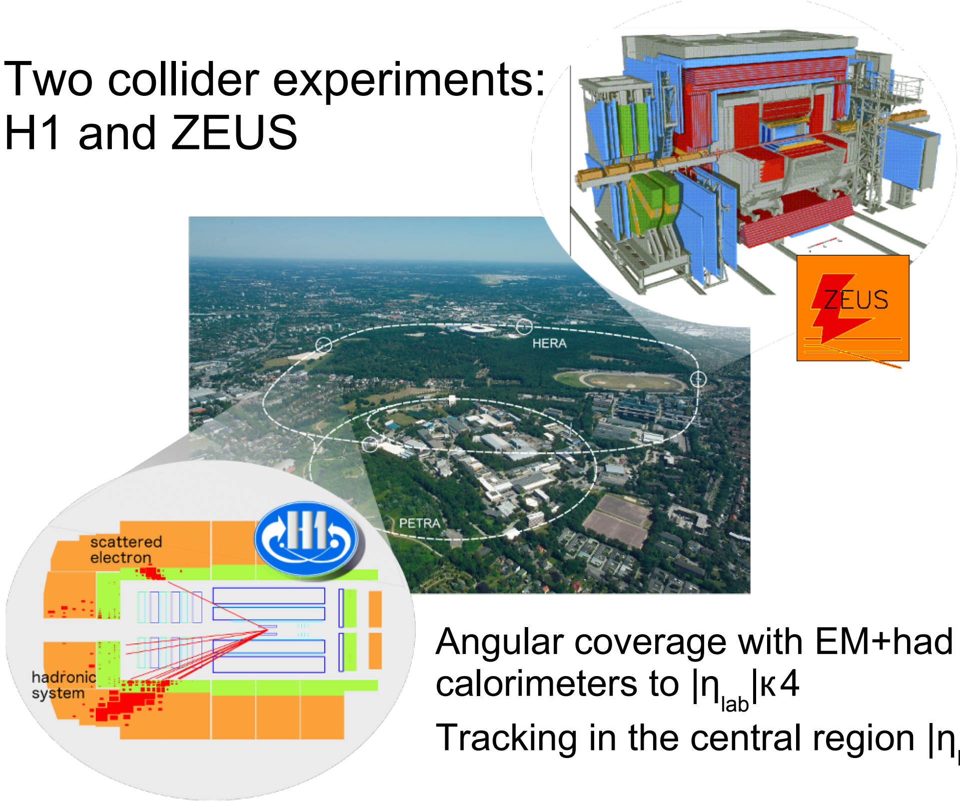
(Attempts are made to connect with JLEIC on some slides)

# The HERA collider

- So far the only ep collider, operated 1992-2007
- 920 x 27.5 GeV ($\sqrt{s}$=318 GeV)
- Two collider experiments, H1 and ZEUS
- Integrated Luminosity:

  ~2×0.5 $fb^{-1}$
- $e^+p$ and $e^-p$ data

Two collider experiments:
H1 and ZEUS

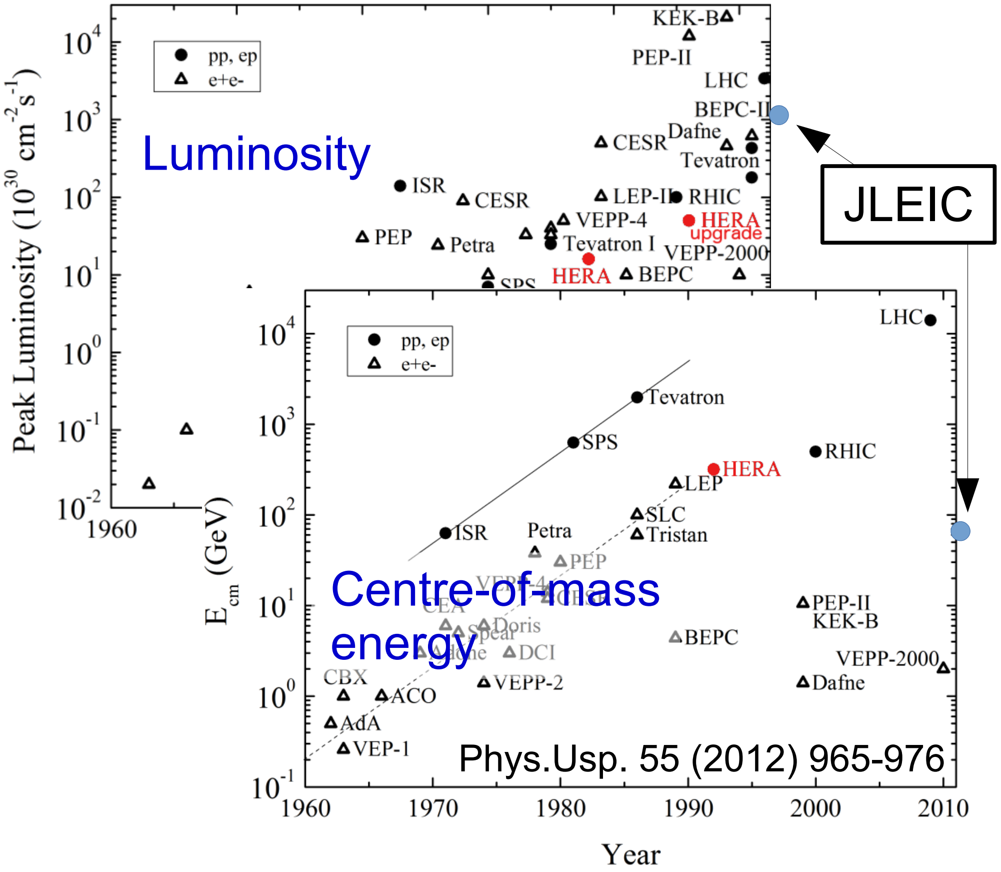



Angular coverage with EM+had calorimeters to $|\eta_{lab}|$κ4

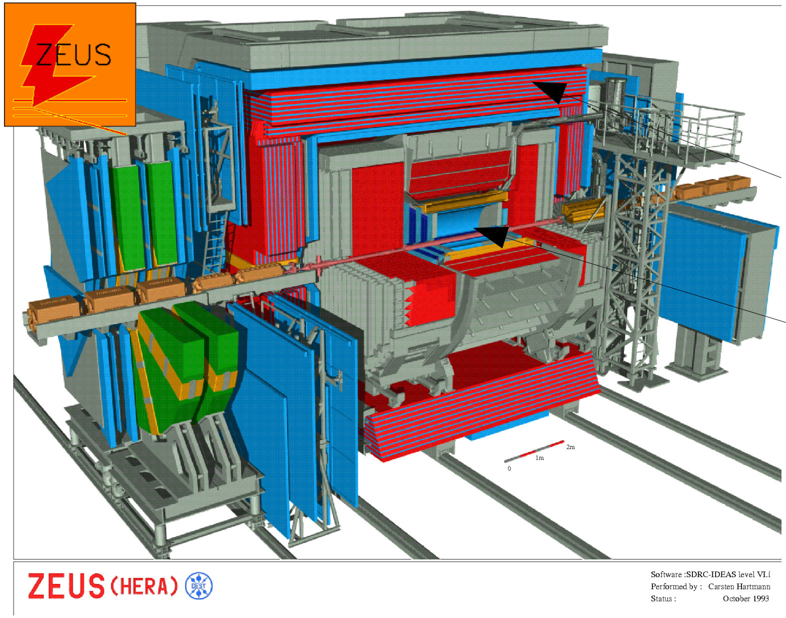
Tracking in the central region $|\eta_{lab}|$κ2

# HERA compared to other machines

- At construction time: a machine at the energy frontier ($E_p$~Tevatron, $E_e$~ ½ LEP)
- Detectors designed for discoveries (e.g. leptoquarks or excited e), less so for low $P_T$ physics
- Luminosity $1.5{\times}10^{31}cm^{-2}s^{-1}$ (Upgrade in 2001-2002: factor 5 improvement)
- Lepton beam polarisation by Sokolov-Ternov effect



# The HERA detectors H1 and ZEUS




Muon chambers

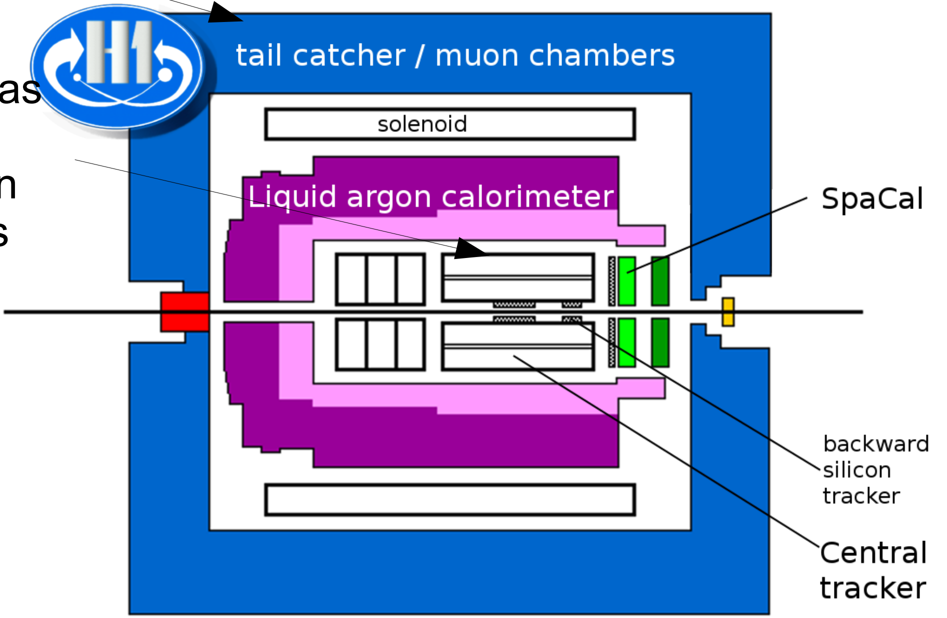
Drift-chambers as main tracking devices + silicon vertex detectors

Liquid Argon calorimeter

$\sigma_{had}$=0.5/√E, $\sigma_{EM}$=0.11/√E, -1.5<η<3.4

Lead+fiber in backward (electron) direction

[SpaCal] $\sigma_{EM}$=0.07/√E, -4<η<1.4



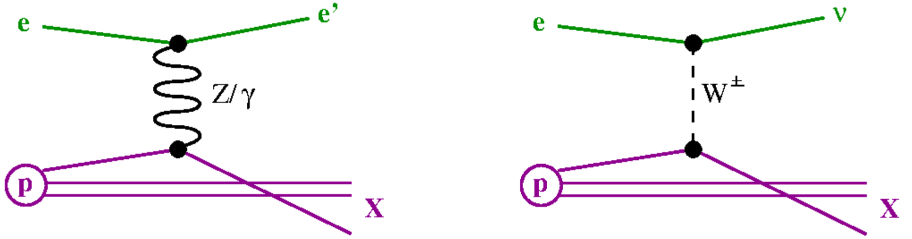

Uranium-scintillator calorimeter

$\sigma_{had}$=0.35/√E, $\sigma_{EM}$=0.18/√E, -3.5<η<4

# HERA inclusive measurements

- Select events with electron (neutral current) or with missing transverse momentum (charged current)
- Kinematic variables Q² and x-Bjorken
- Double-differential measurement of the reduced cross section $\sigma_r$
- Corrected for QED radiative effects
- Reduced cross sections: related to structure functions
- Case of lepton polarisation → not discussed in this talk

Neutral Current (NC) Charged Current (CC)




Neutral current reduced cross section:

$$\frac{d^2\sigma^{\pm}_{NC}}{dx\,dQ^2}\frac{Q^4 x}{2\pi\alpha^2 Y_+}=\sigma^{\pm}_{r,NC}=\tilde{F}_2\mp\frac{Y_-}{Y_+}x\tilde{F}_3-\frac{y^2}{Y_+}\tilde{F}_L$$

Charged Current reduced cross section:

$$\frac{d^2\sigma^{\pm}_{CC}}{dx\,dQ^2}\frac{2\pi x}{G_F^2}\left[\frac{M_W^2+Q^2}{M_W^2}\right]^2=\sigma^{\pm}_{r,WC}=Y_+W_2^{\pm}\mp Y_-xW_3^{\pm}-y^2W_L^{\pm}$$

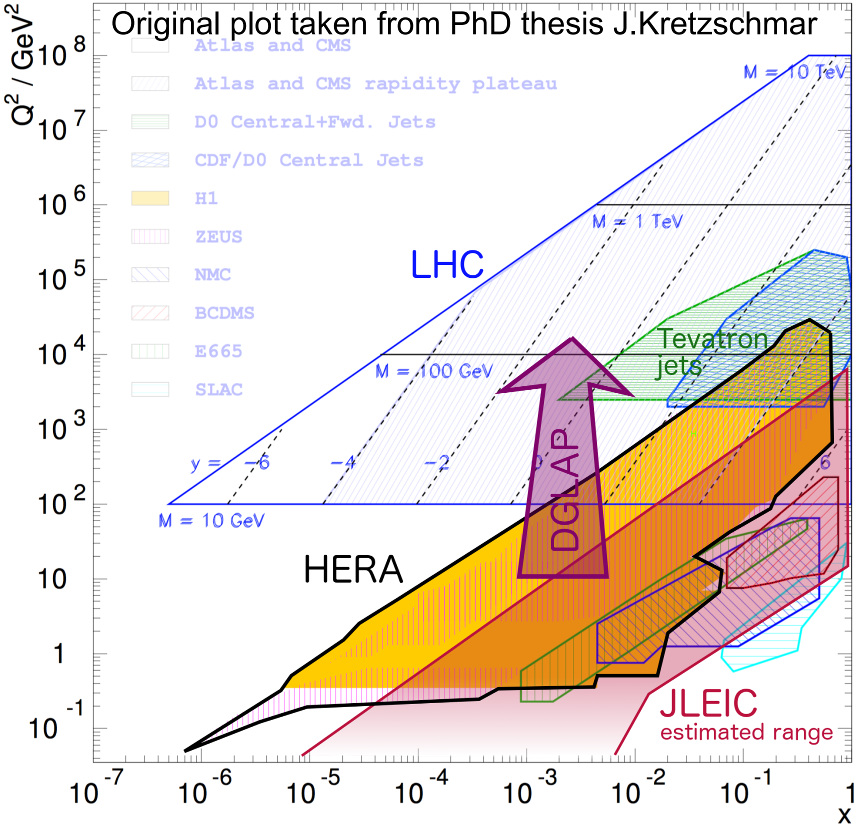
helicity factors: $Y_{\pm}=1\pm(1-y)^2$

# HERA and Proton PDFs

- Inclusive cross sections probe proton parton density functions (PDFs) $f_i(x,\mu=Q)$
- HERA: $0.05<Q^2<10^5$ GeV² and $10^{-6}<x<0.6$
- Inclusive cross sections from HERA are the backbone of all modern PDF determinations, using DGLAP for NLO or NNLO QCD fits

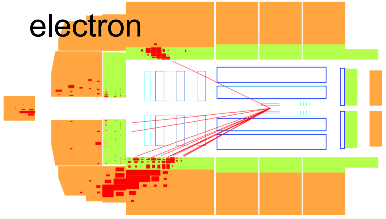
  → large impact on LHC physics
- JLEIC: overlap with HERA, expect substantial improvements at high x

  → inclusive measurements are an important part of the JLEIC physics program



# HERA kinematics for neutral current

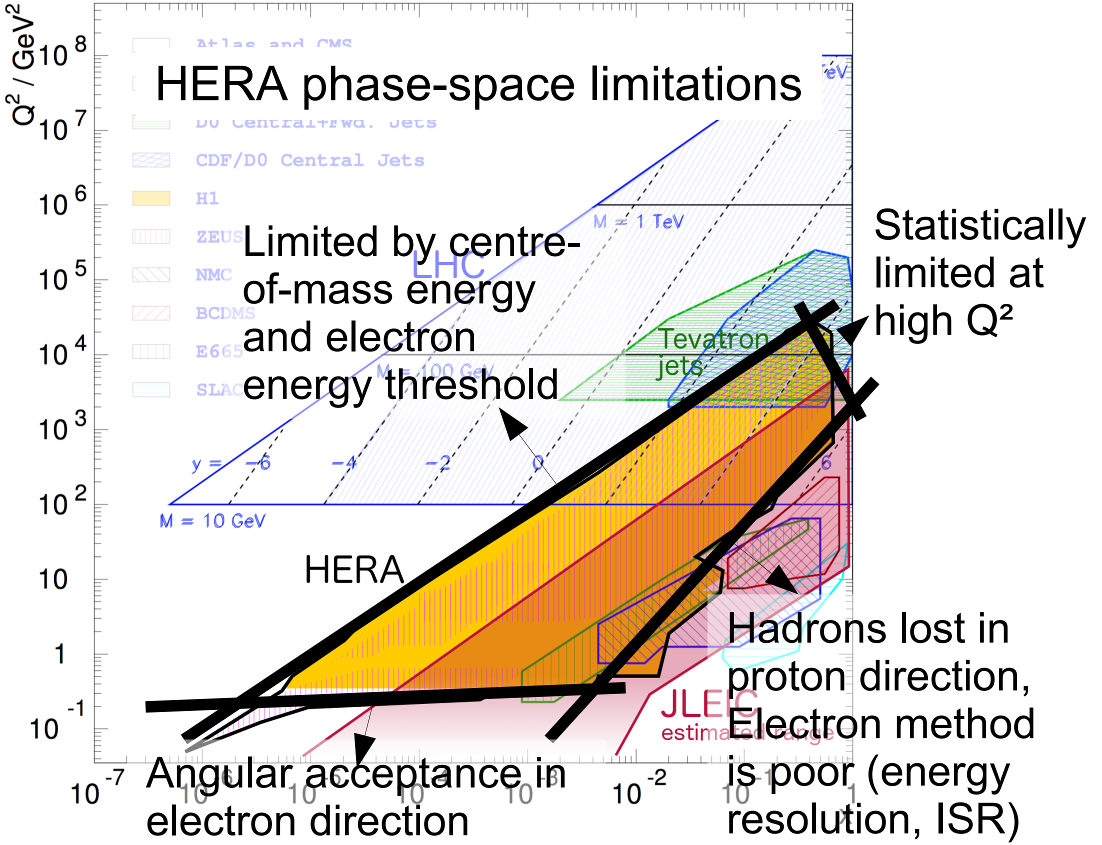
- Kinematic variables: $Q^2$, x, y, $Q^2=sxy$
- Determined using scattered electron and hadronic final state




$$y_e = 1 - \frac{(e'p)}{(ep)}, \; y_h = \frac{(Xp)}{(ep)}$$

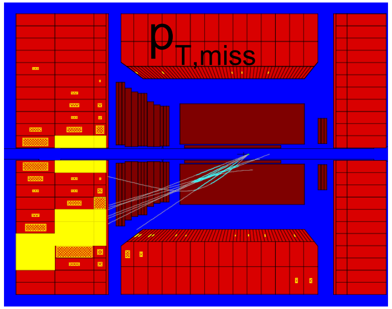
$$Q^2 = \frac{p_T^2}{1-y}, \; x = \frac{Q^2}{sy}$$

- "Electron" method: $y=y_e$ and $p_T=p_{T,e}$
- Al low y, use $y=y_h$ (sigma method)
- Other methods: double-angle, etc



# Charged current kinematics

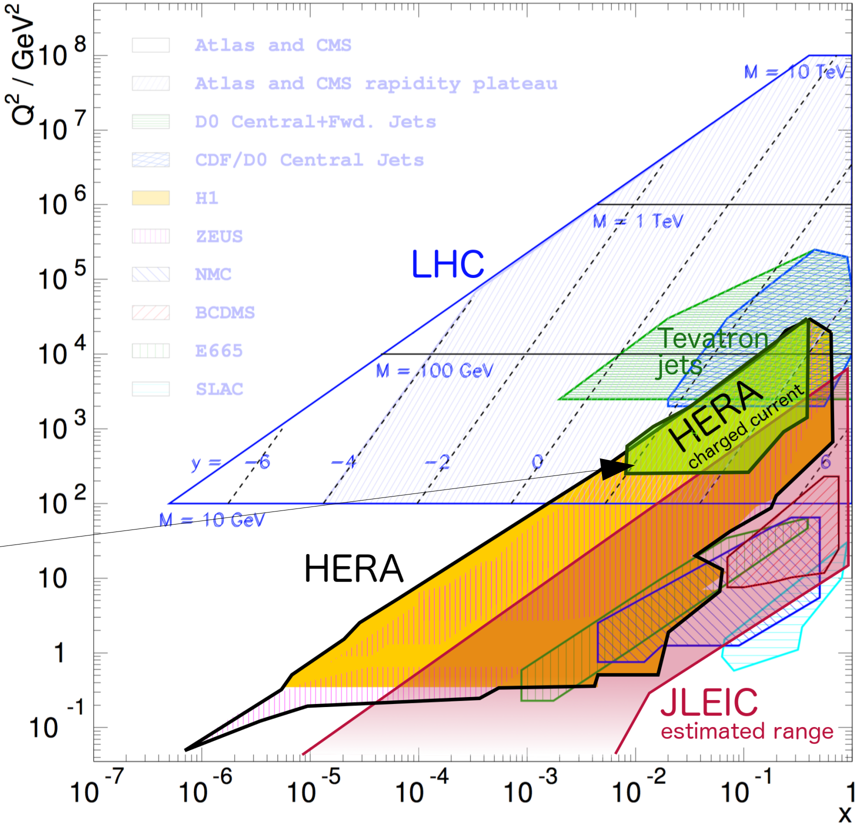
- CC kinematics is reconstructed from hadrons alone: moderate resolution




$$y_h = \frac{(Xp)}{(ep)}$$

$$Q_h^2 = \frac{p_{T,miss}^2}{1 - y_h},\ x = \frac{Q^2}{sy}$$

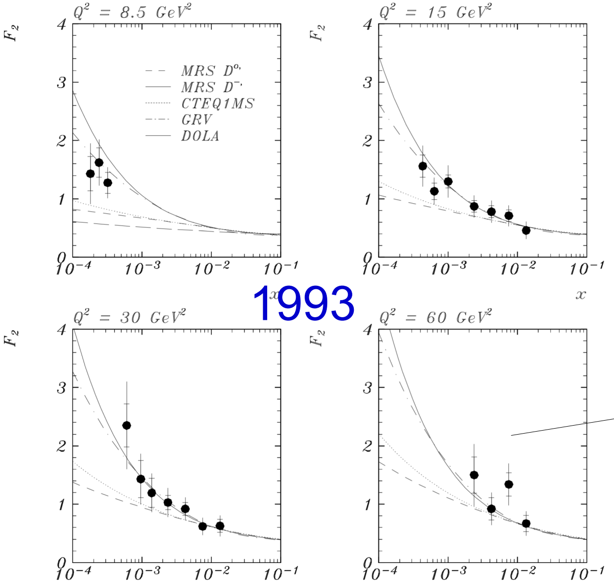
- HERA CC analysis is limited to large $p_{T,miss} \geq 15$ GeV, or $Q^2 \geq 200$ GeV²
- Data-driven analysis of systematic effects: use neutral current events and remove the electron (at H1 called "pseudo-CC events")



# Reminder: the HERA discovery

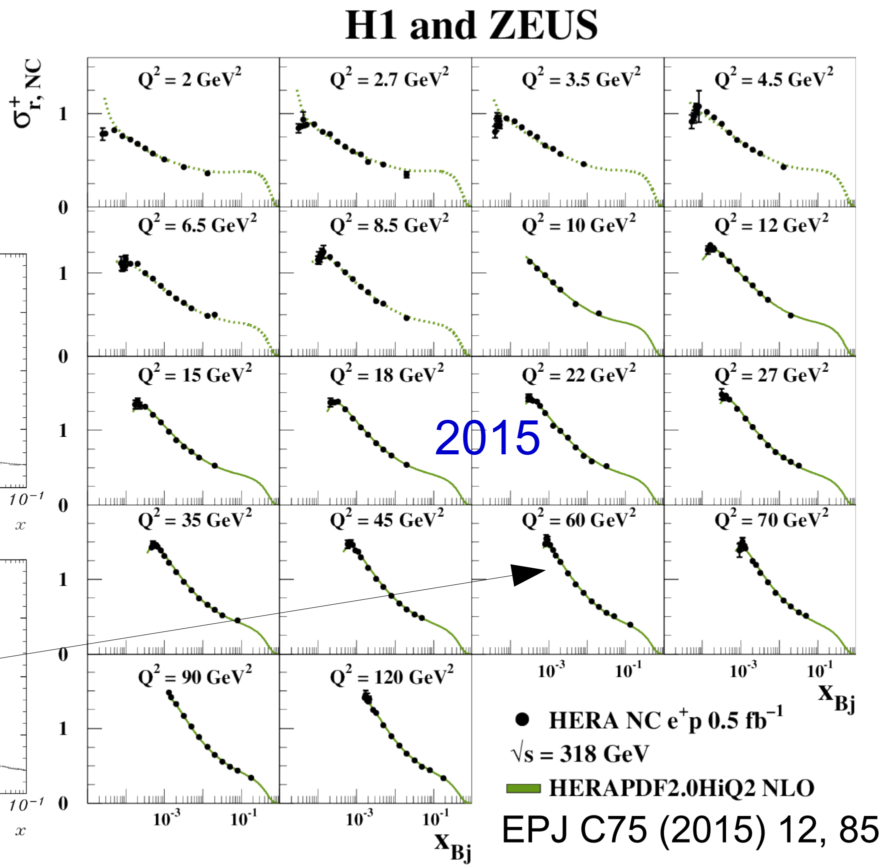
- Discovery in the early HERA data: structure function $F_2$ rises strongly at low x
- At the time: a surprise
- Impressive improvement in precision – it took >20 years to achieve this

Shown here: $F_2$ (1993), reduced cross section (2015), as a function of x, in bins of Q²




1993

Nucl.Phys. B407 (1993) 515




EPJ C75 (2015) 12, 85

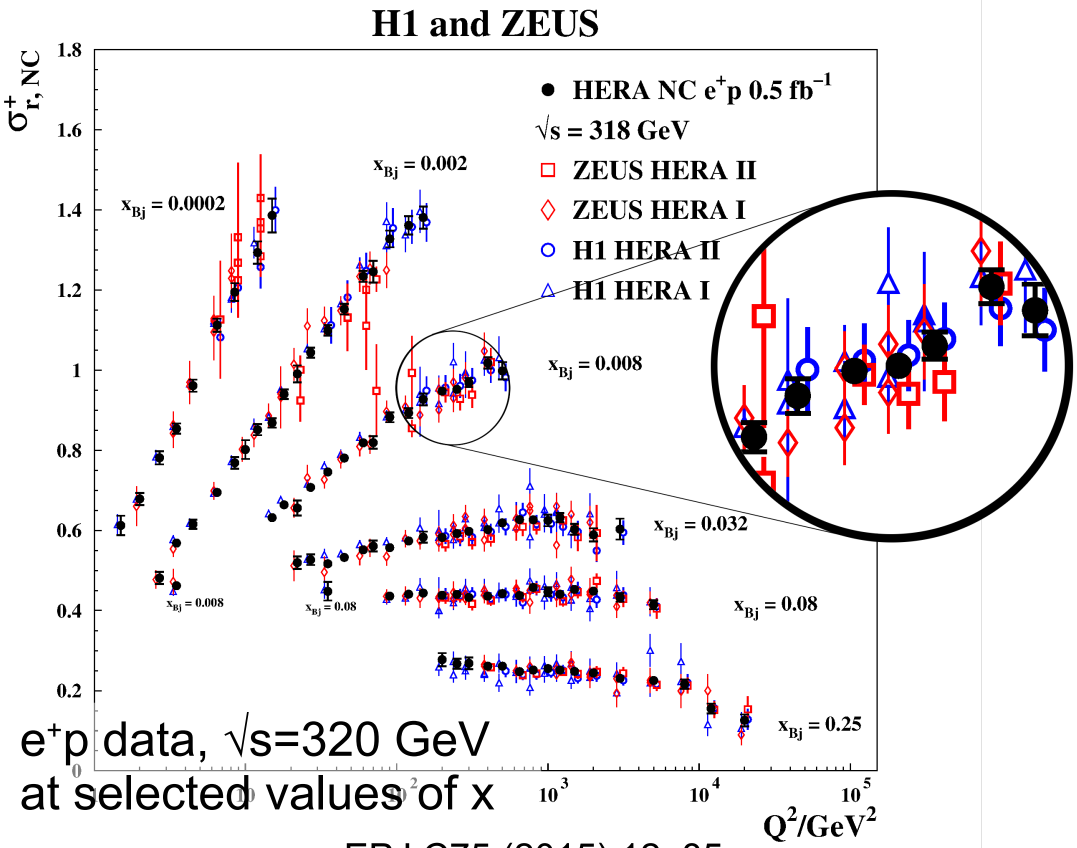
# HERA data analysed over two decades

- Measurements of inclusive NC and CC processes are published in a total of 41 H1 and ZEUS papers
- Data are combined to a uniform HERA dataset: **EPJ C75 (2015) 12, 85**
- Seven combined datasets:
  - Measurements of NC and CC for both $e^+p$ and $e^-p$ scattering at $\sqrt{s}$=318 GeV
  - Measurements of NC $e^+p$ scattering at reduced $\sqrt{s}$={225,252,300} GeV

| Data Set | | $x_{Bj}$ Grid | | $Q^2$[GeV$^2$] Grid | | $\mathcal{L}$ | $e^+/e^-$ | $\sqrt{s}$ | $x_{Bj}$,$Q^2$ from | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| | | from | to | from | to | pb$^{-1}$ | | GeV | equations | |
| HERA I $E_p$ = 820 GeV and $E_p$ = 920 GeV data sets | | | | | | | | | | |
| H1 svx-mb [2] | 95-00 | 0.000005 | 0.02 | 0.2 | 12 | 2.1 | $e^+p$ | 301, 319 | 13,17,18 | [3] |
| H1 low $Q^2$ [2] | 96-00 | 0.0002 | 0.1 | 12 | 150 | 22 | $e^+p$ | 301, 319 | 13,17,18 | [4] |
| H1 NC | 94-97 | 0.0032 | 0.65 | 150 | 30000 | 35.6 | $e^+p$ | 301 | 19 | [5] |
| H1 CC | 94-97 | 0.013 | 0.40 | 300 | 15000 | 35.6 | $e^+p$ | 301 | 14 | [5] |
| H1 NC | 98-99 | 0.0032 | 0.65 | 150 | 30000 | 16.4 | $e^-p$ | 319 | 19 | [6] |
| H1 CC | 98-99 | 0.013 | 0.40 | 300 | 15000 | 16.4 | $e^-p$ | 319 | 14 | [6] |
| H1 NC HY | 98-99 | 0.0013 | 0.01 | 100 | 800 | 16.4 | $e^-p$ | 319 | 13 | [7] |
| H1 NC | 99-00 | 0.0013 | 0.65 | 100 | 30000 | 65.2 | $e^+p$ | 319 | 19 | [7] |
| H1 CC | 99-00 | 0.013 | 0.40 | 300 | 15000 | 65.2 | $e^+p$ | 319 | 14 | [7] |
| ZEUS BPC | 95 | 0.000002 | 0.00006 | 0.11 | 0.65 | 1.65 | $e^+p$ | 300 | 13 | [11] |
| ZEUS BPT | 97 | 0.0000006 | 0.001 | 0.045 | 0.65 | 3.9 | $e^+p$ | 300 | 13, 19 | [12] |
| ZEUS SVX | 95 | 0.000012 | 0.0019 | 0.6 | 17 | 0.2 | $e^+p$ | 300 | 13 | [13] |
| ZEUS NC [2] high/low $Q^2$ | 96-97 | 0.00006 | 0.65 | 2.7 | 30000 | 30.0 | $e^+p$ | 300 | 21 | [14] |
| ZEUS CC | 94-97 | 0.015 | 0.42 | 280 | 17000 | 47.7 | $e^+p$ | 300 | 14 | [15] |
| ZEUS NC | 98-99 | 0.005 | 0.65 | 200 | 30000 | 15.9 | $e^-p$ | 318 | 20 | [16] |
| ZEUS CC | 98-99 | 0.015 | 0.42 | 280 | 30000 | 16.4 | $e^-p$ | 318 | 14 | [17] |
| ZEUS NC | 99-00 | 0.005 | 0.65 | 200 | 30000 | 63.2 | $e^+p$ | 318 | 20 | [18] |
| ZEUS CC | 99-00 | 0.008 | 0.42 | 280 | 17000 | 60.9 | $e^+p$ | 318 | 14 | [19] |
| HERA II $E_p$ = 920 GeV data sets | | | | | | | | | | |
| H1 NC $^{1.5p}$ | 03-07 | 0.0008 | 0.65 | 60 | 30000 | 182 | $e^+p$ | 319 | 13, 19 | [8]$^1$ |
| H1 CC $^{1.5p}$ | 03-07 | 0.008 | 0.40 | 300 | 15000 | 182 | $e^+p$ | 319 | 14 | [8]$^1$ |
| H1 NC $^{1.5p}$ | 03-07 | 0.0008 | 0.65 | 60 | 50000 | 151.7 | $e^-p$ | 319 | 13, 19 | [8]$^1$ |
| H1 CC $^{1.5p}$ | 03-07 | 0.008 | 0.40 | 300 | 30000 | 151.7 | $e^-p$ | 319 | 14 | [8]$^1$ |
| H1 NC med $Q^2$ $^{*y.5}$ | 03-07 | 0.0000986 | 0.005 | 8.5 | 90 | 97.6 | $e^+p$ | 319 | 13 | [10] |
| H1 NC low $Q^2$ $^{*y.5}$ | 03-07 | 0.000029 | 0.00032 | 2.5 | 12 | 5.9 | $e^+p$ | 319 | 13 | [10] |
| ZEUS NC | 06-07 | 0.005 | 0.65 | 200 | 30000 | 135.5 | $e^+p$ | 318 | 13,14,20 | [22] |
| ZEUS CC $^{1.5p}$ | 06-07 | 0.0078 | 0.42 | 280 | 30000 | 132 | $e^+p$ | 318 | 14 | [23] |
| ZEUS NC $^{1.5}$ | 05-06 | 0.005 | 0.65 | 200 | 30000 | 169.9 | $e^-p$ | 318 | 20 | [20] |
| ZEUS CC $^{1.5}$ | 04-06 | 0.015 | 0.65 | 280 | 30000 | 175 | $e^-p$ | 318 | 14 | [21] |
| ZEUS NC nominal $^{*y}$ | 06-07 | 0.000092 | 0.008343 | 7 | 110 | 44.5 | $e^+p$ | 318 | 13 | [24] |
| ZEUS NC satellite $^{*y}$ | 06-07 | 0.000071 | 0.008343 | 5 | 110 | 44.5 | $e^+p$ | 318 | 13 | [24] |
| HERA II $E_p$ = 575 GeV data sets | | | | | | | | | | |
| H1 NC high $Q^2$ | 07 | 0.00065 | 0.65 | 35 | 800 | 5.4 | $e^+p$ | 252 | 13, 19 | [9] |
| H1 NC low $Q^2$ | 07 | 0.0000279 | 0.0148 | 1.5 | 90 | 5.9 | $e^+p$ | 252 | 13 | [10] |
| ZEUS NC nominal | 07 | 0.000147 | 0.013349 | 7 | 110 | 7.1 | $e^+p$ | 251 | 13 | [24] |
| ZEUS NC satellite | 07 | 0.000125 | 0.013349 | 5 | 110 | 7.1 | $e^+p$ | 251 | 13 | [24] |
| HERA II $E_p$ = 460 GeV data sets | | | | | | | | | | |
| H1 NC high $Q^2$ | 07 | 0.00081 | 0.65 | 35 | 800 | 11.8 | $e^+p$ | 225 | 13, 19 | [9] |
| H1 NC low $Q^2$ | 07 | 0.0000348 | 0.0148 | 1.5 | 90 | 12.2 | $e^+p$ | 225 | 13 | [10] |
| ZEUS NC nominal | 07 | 0.000184 | 0.016686 | 7 | 110 | 13.9 | $e^+p$ | 225 | 13 | [24] |
| ZEUS NC satellite | 07 | 0.000143 | 0.016686 | 5 | 110 | 13.9 | $e^+p$ | 225 | 13 | [24] |

# The power of combining data

- A total of 2927 H1 and ZEUS measurements are averaged to about 1307 combined reduced cross sections
- Up to six measurements contribute to a single point
- Systematic uncertainties and their cross-correlations are handled consistently
- Better than 1.5% precision is reached over a wide kinematic range
- Excellent data consistency: $\chi^2/N_{D.F.}$=1687/1620

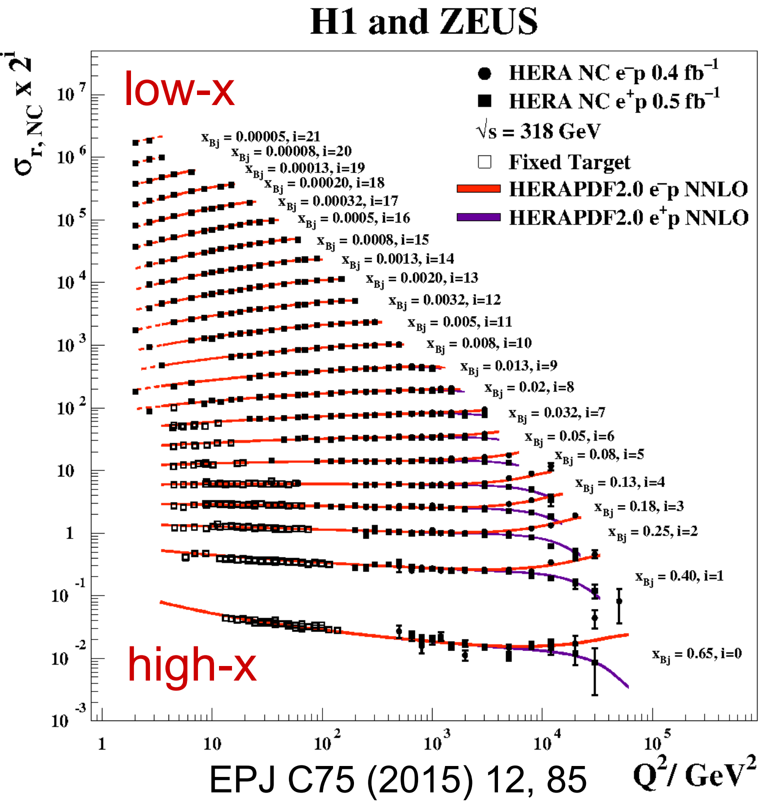



e+p data, √s=320 GeV at selected values of x

EPJ C75 (2015) 12, 85

# The HERA combined NC data

- Shown here: reduced cross section at √s=318 GeV for $e^+p$ and $e^-p$ as a function of $Q^2$. Dominating contribution is from structure function $F_2$
- Scaling violations of are clearly visible: cross section rises with $Q^2$ at low-x but drops with $Q^2$ at high-x
- Gaps between fixed-target data and HERA measurements → **JLEIC**
- High $Q^2$ data precision is statistically limited
- Difference between $e^+p$ and $e^-p$ at high $Q^2$: extract $xF_3$

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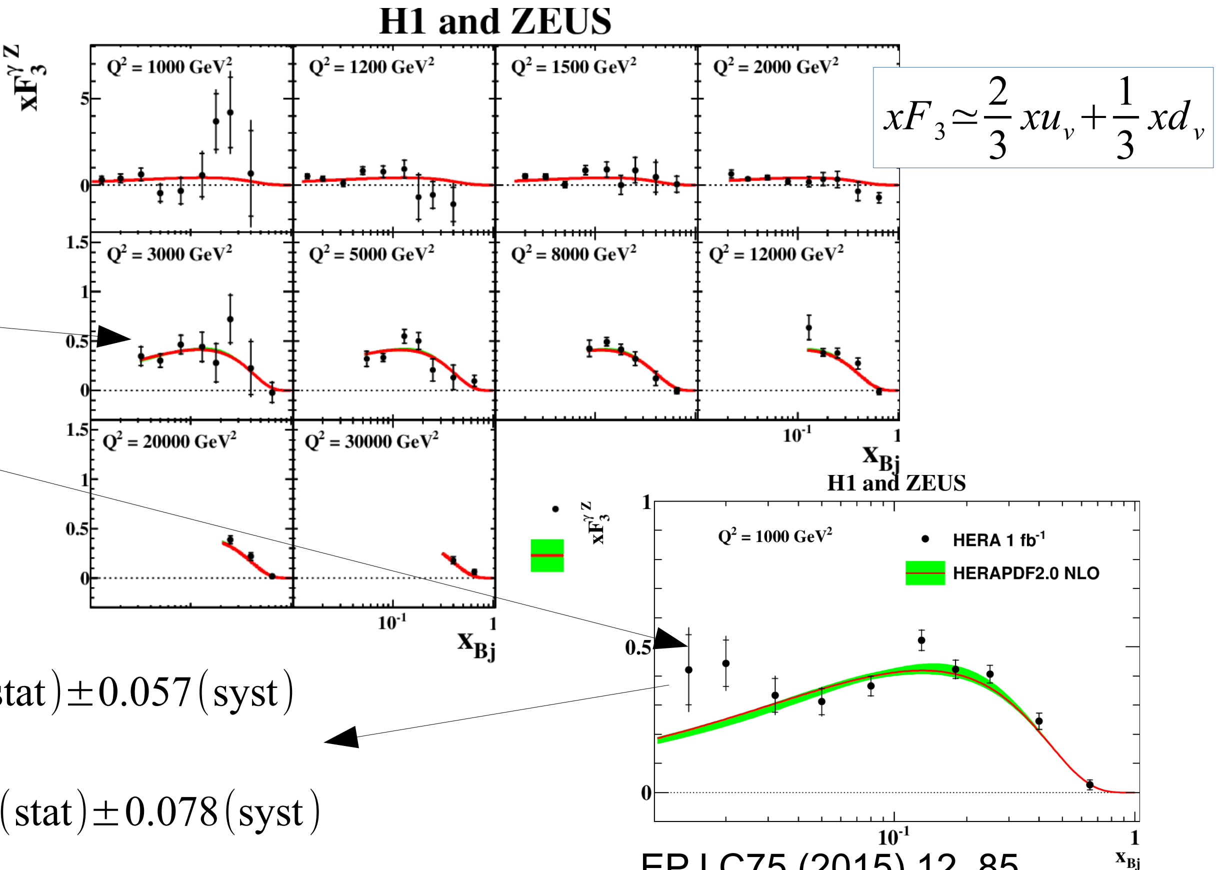
# Measurement of $xF_3^{\gamma Z}$

- Measurement of $xF_3$ at high $Q^2$
- Structure function is nonzero due to the γ/Z interference
- Data are extracted point-by-point by subtracting $e^+p$ from $e^-p$ cross sections
- Extrapolate to $Q^2$=1000 GeV² and average for each x
- Integrate over x: expect 5/3 from naive quark counting

$$xF_3 \simeq \frac{2}{3} xu_v + \frac{1}{3} xd_v$$




$$[\int_{0.016}^{0.725} \frac{xF_3^{\gamma Z}(x)}{x} dx]_{\text{data}} = 1.314 \pm 0.057(\text{stat}) \pm 0.057(\text{syst})$$

$$[\int_{0}^{1} \frac{xF_3^{\gamma Z}(x)}{x} dx]_{\text{data+extrapol}} = 1.790 \pm 0.078(\text{stat}) \pm 0.078(\text{syst})$$

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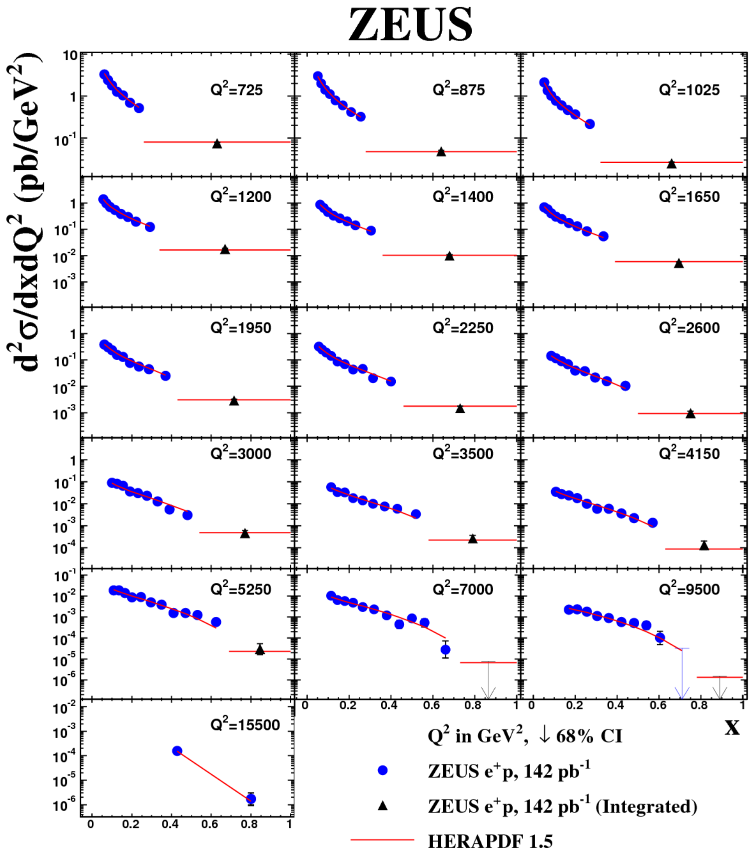
# HERA measurements at high x

- Detector limitations: events at high x are difficult to reconstruct
- High x can be measured only at high $Q^2$ → statistically limited
- H1: largest x=0.65 is measured only for $Q^2 \geq 1500$ GeV$^2$ (x=0.4 for $Q^2 \geq 650$ GeV$^2$)
- ZEUS: dedicated analysis to measure high x up to x=1 (bin-integrated cross section is quoted for last bin)
- Possibility to use these data in future PDF fits



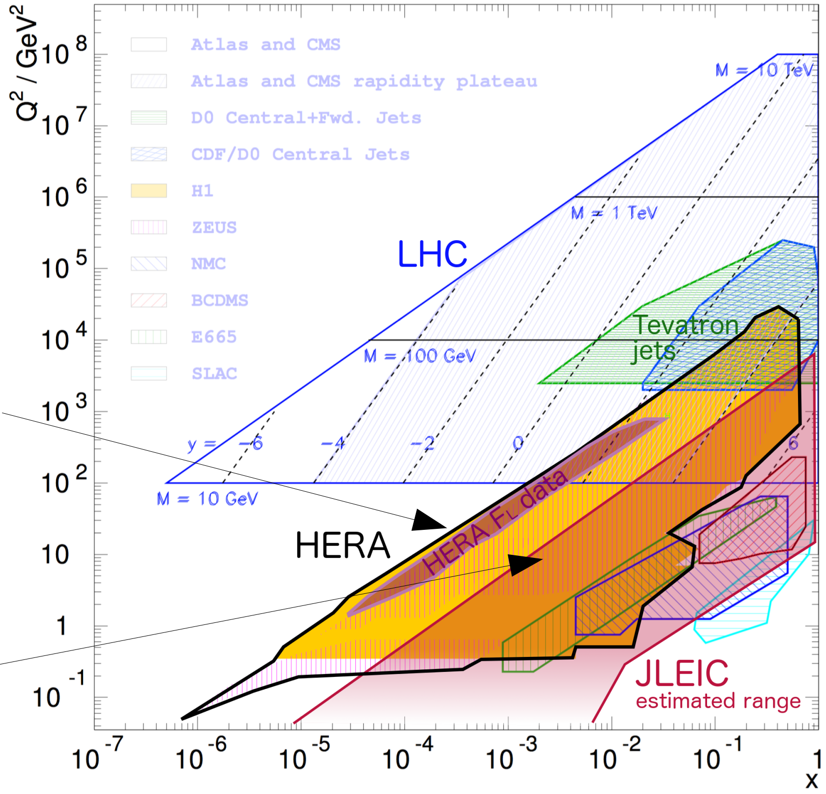

Phys.Rev. D89 (2014) no.7, 072007

# High-y: Measurement of $F_L$

- Structure function $F_L$ can be measured by combining datasets taken at different √s (Rosenbluth)

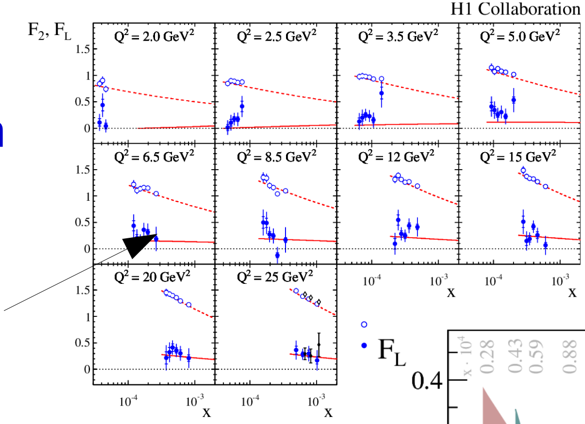
$$\sigma_{r,NC}=F_2-\frac{y^2}{Y_+}F_L,\; y=\frac{Q^2}{sx} \qquad F_L\sim xg(x)\ \text{[gluon density]}$$

- Use HERA runs with reduced proton beam energy $E_p$=460 or 575 GeV, √s=225 or 252 GeV
- $F_L$ is extracted from high y data: only a small area of the kinematic plane is accessible
- Using HERA+JLEIC data, $F_L$ could be turned into a truly double-differential measurement covering a much wider x-range → **gluon at high x& high Q²**



# Measurement of $F_L$ at HERA

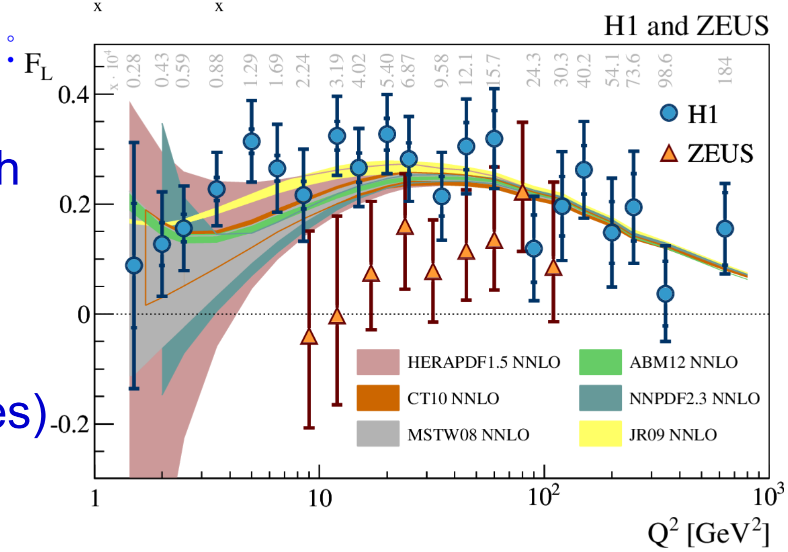
- Most precise HERA $F_L$ data: H1
- Main ingredients: backward silicon tracker and dedicated trigger for low-energy electrons
- Double-differential extraction of $F_L$




$$\sigma_{r,NC} \simeq F_2 - \frac{y^2}{Y_+} F_L, \; y = \frac{Q^2}{sx}$$

H1: Eur.Phys.J.C 74 (2014) 2814
ZEUS: Phys.Rev. D89 (2014), 072007

- Average over the [small] accessible x-range in each Q² bin → one-dimensional projection with Q² and x varying simultaneously
- H1 and ZEUS data are consistent within 2 sigma (errors are dominated by normalisation uncertainties)

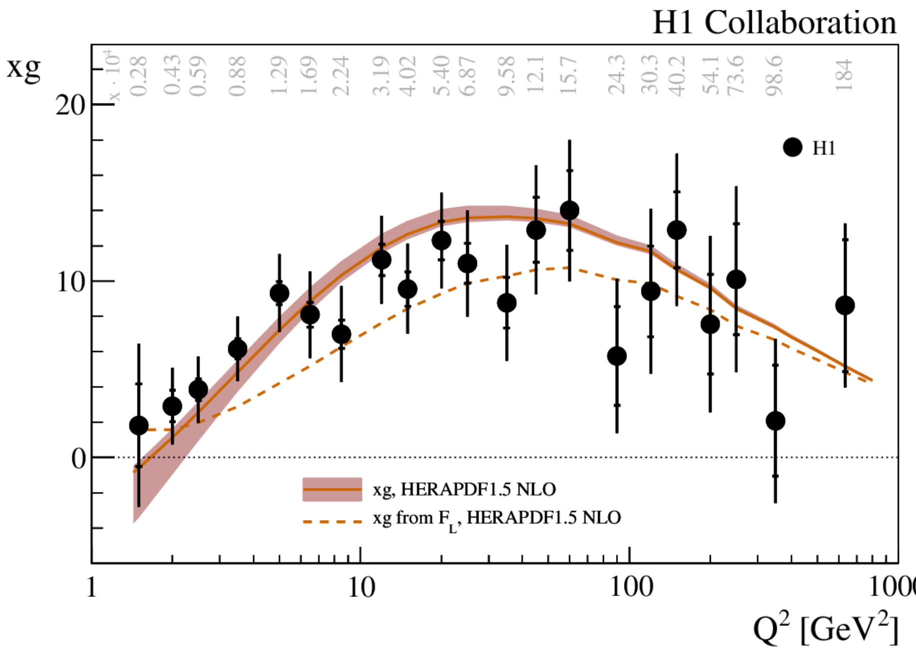


# Gluon density from $F_L$

- Gluon density determined from H1 $F_L$ measurement

$$xg(x, Q^2) \approx 1.77 \frac{3\pi}{2\alpha_S(Q^2)} F_L(ax, Q^2)$$

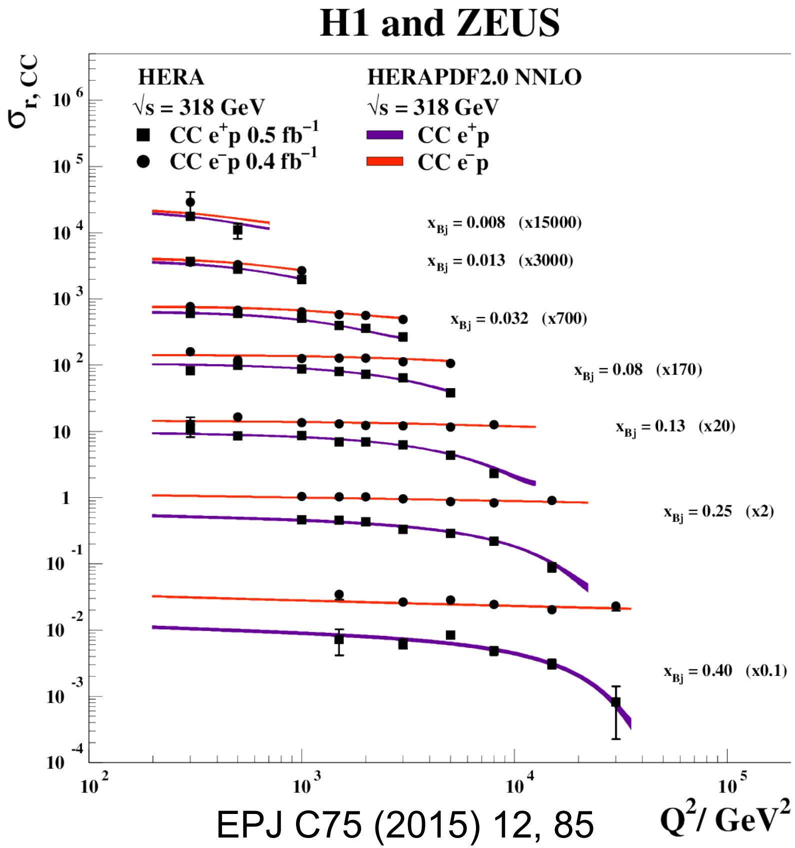
- Consistent with determination from scaling violations (HERAPDF fit)
- Available data at high x is limited → could be changed by JLEIC [+HERA]




Eur.Phys.J.C 74 (2014) 2814

# The combined Charged Current data

- As compared to NC: reduced number of points and limited to high $Q^2 \geq 300$ GeV²
- Cross section for $e^+p$ is lower than $e^-p$
  - u-valence quark available for $e^-p$ and d-valence for $e^+p$ [~factor 1/2]
  - Helicity factor: extra suppression of valence quark in $e^+p$ [at low y]
- Although statistically limited, the CC data are essential in the HERAPDF fit to separate u-type and d-type quarks and to constrain the valence quarks at high x

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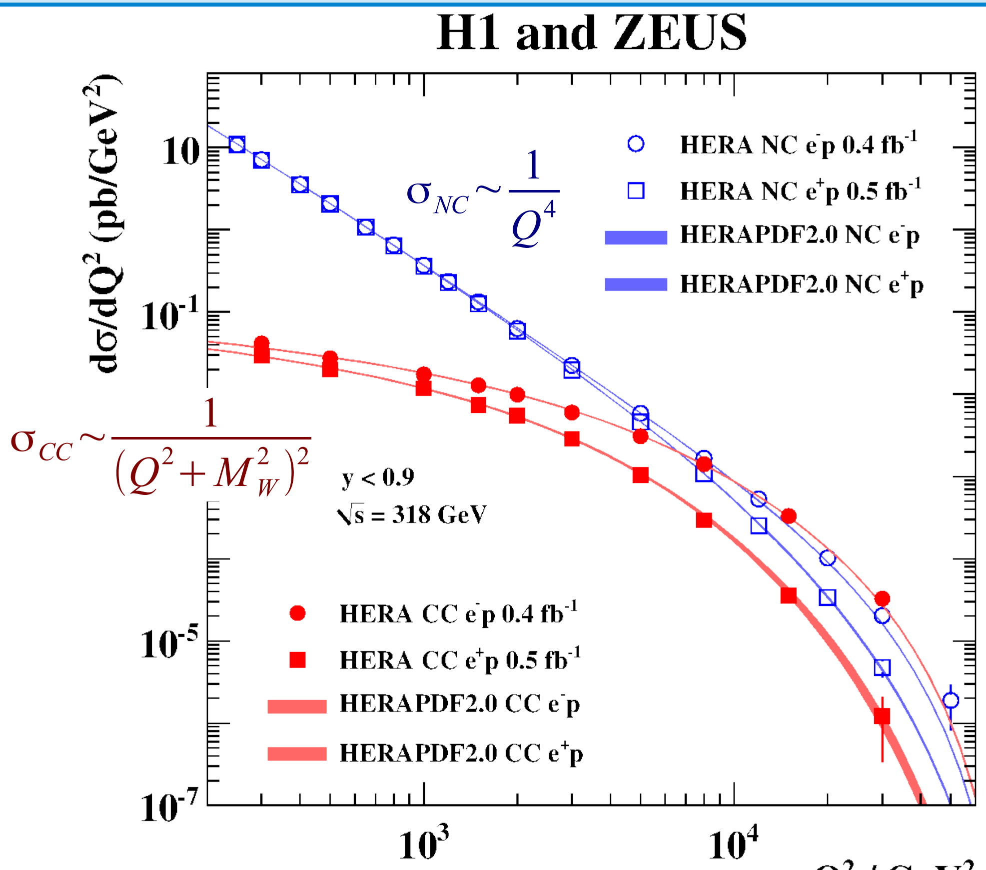
# Single differential high Q² cross sections

- Single-differential cross sections $d\sigma/dQ^2$
- Neutral Current (NC) and Charged Current (CC) measurements, each for $e^+p$ and $e^-p$
- At low $Q^2 \leq 3000\ \mathrm{GeV}^2$ NC is much larger than CC [photon compared to W propagator]
- At high $Q^2$ all cross sections are similar, “electroweak unification”
- A text-book plot from HERA

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# QCD fit of HERA data

- PDFs traditionally are extracted from simultaneous fits of many datasets
- The **HERAPDF** is extracted from HERA data alone: proton PDFs are determined at NLO and NNLO
- Fit ansatz: at a low scale $\mu_{f0}<m_c$ parameterize the (u,d,s,g) PDFs
- Evolve PDFs to higher scales and fit cross section predictions to DIS data

Parametrisation at the starting scale:

gluon
$$xg(x) = A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g},$$

valence
$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right),$$
$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}},$$

sea
$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}(1+D_{\bar{U}}x),$$
$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.$$

Strange quark is described by a fraction $f_s$

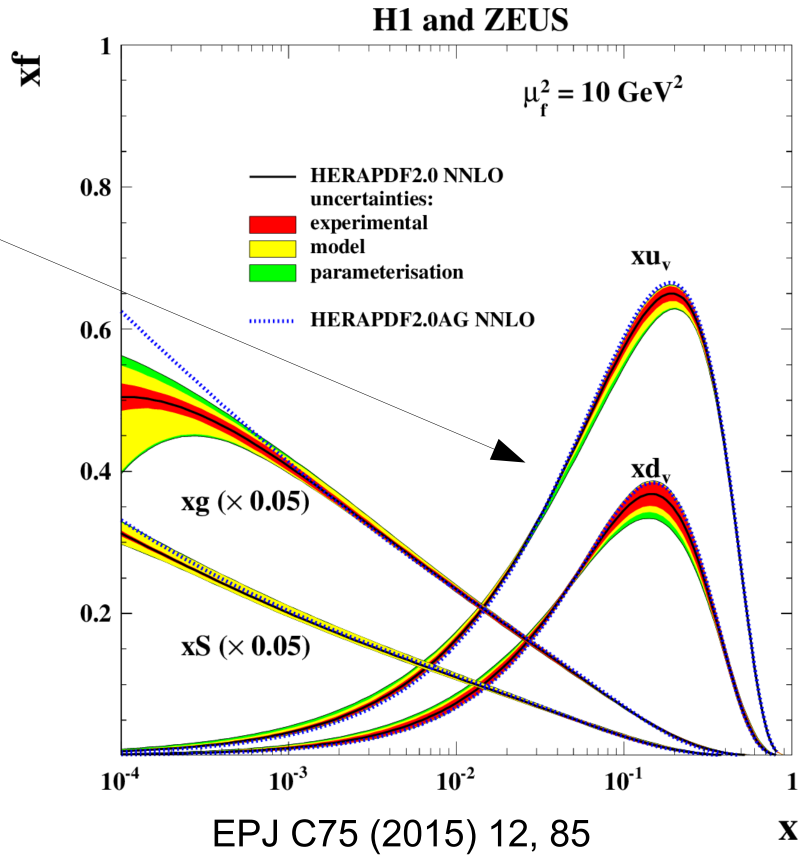
$$x\bar{D} = (1-f_s)x\bar{d} + f_s x\bar{s}$$

[$f_s$ is not constrained by HERA data]

- Charm and beauty is created above thresholds in the PDF evolution (Variable Flavor-Number Scheme, VFNS) or is present only in the hard matrix elements (Fixed Flavor Number Scheme, FFNS)

# The HERAPDF2.0 QCD fit

- Proton PDFs at a scale μ²=10 GeV², determined in an NNLO QCD fit of HERA data
- The experimental uncertainties are small
- For low $x<10^{-3}$, model and parameterisation uncertainties are dominant
- The high-x region is not measured well but is constrained mainly by the choice of parameterisation
- With additional data (JLEIC), the assumptions on the parameterisation at high x possibly could be relaxed

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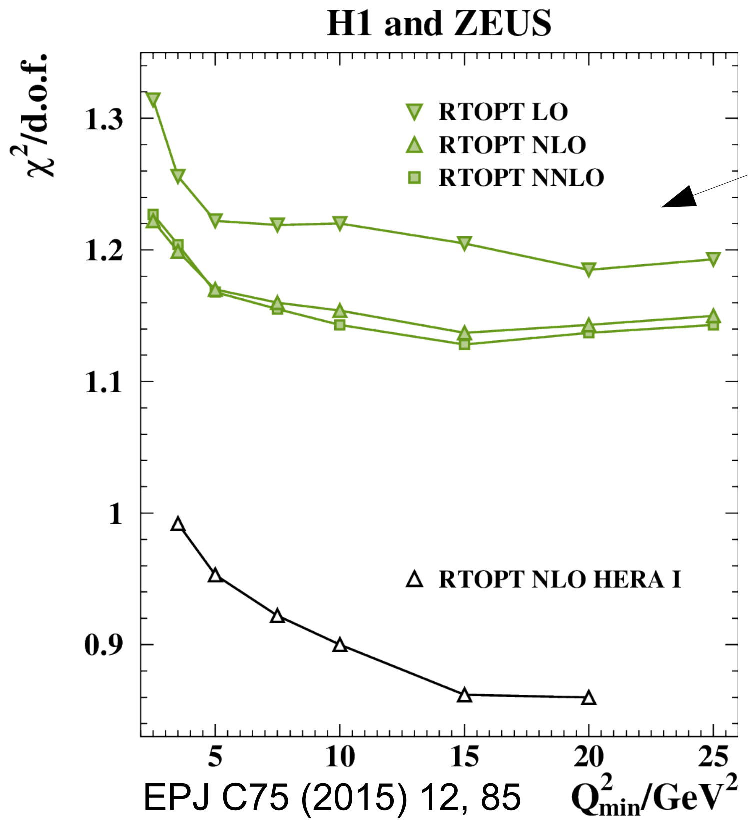
# Comparisons of data and QCD fit

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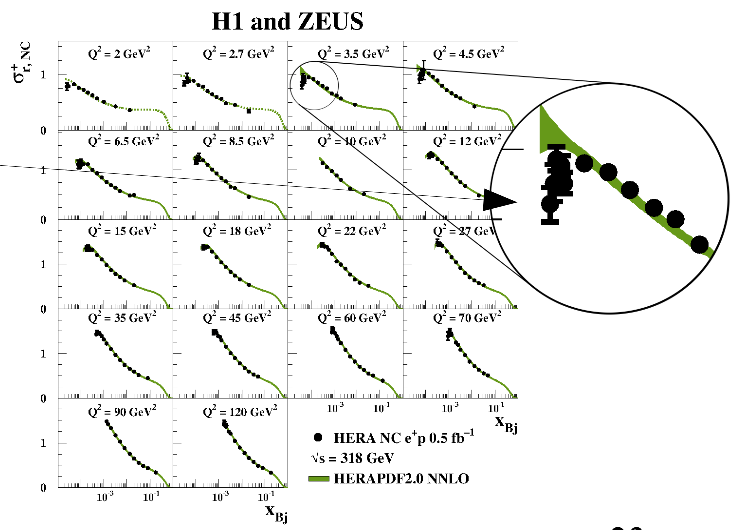
- The consistency between data and QCD fit is investigated by excluding data below a certain $Q^2$ from the fit and looking at $\chi^2/N_{DF}$
- Data at lowest $Q^2$ are least compatible with the QCD fit, the $\chi^2/N_{DF}$ curve flattens out for $Q^2 \geq 10$ GeV$^2$
- At low $Q^2$/low-x there are discrepancies in the turn-over region, where the $F_L$ contribution is relevant

$$\sigma_{r,NC} \simeq F_2 - \frac{y^2}{Y_+} F_L$$

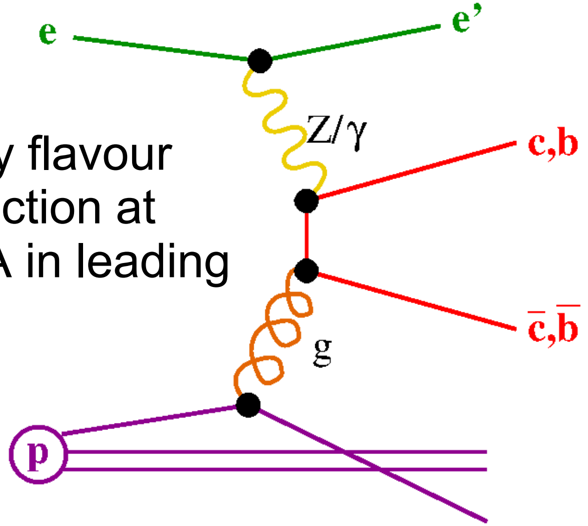


# Examples of other HERA measurements

- Charm and beauty production and determination of the respective quark masses
- Jet production and the determination of $\alpha_s$

# Charm and beauty production at HERA

Heavy flavour production at HERA in leading order

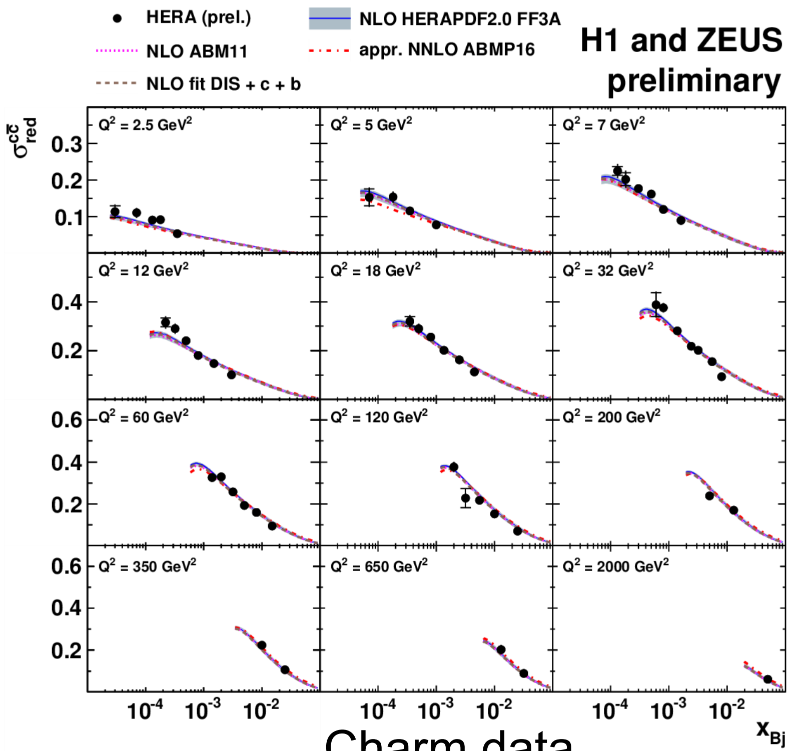



Measured quantity: reduced cross section $\sigma_{red}$ with charm or beauty in final state as a function of $Q^2$ and x

NLO calculations: fixed-flavour number scheme (FFNS) where PDF only contains light flavours u,d,s and the gluon. Massive heavy quarks are in the matrix elements

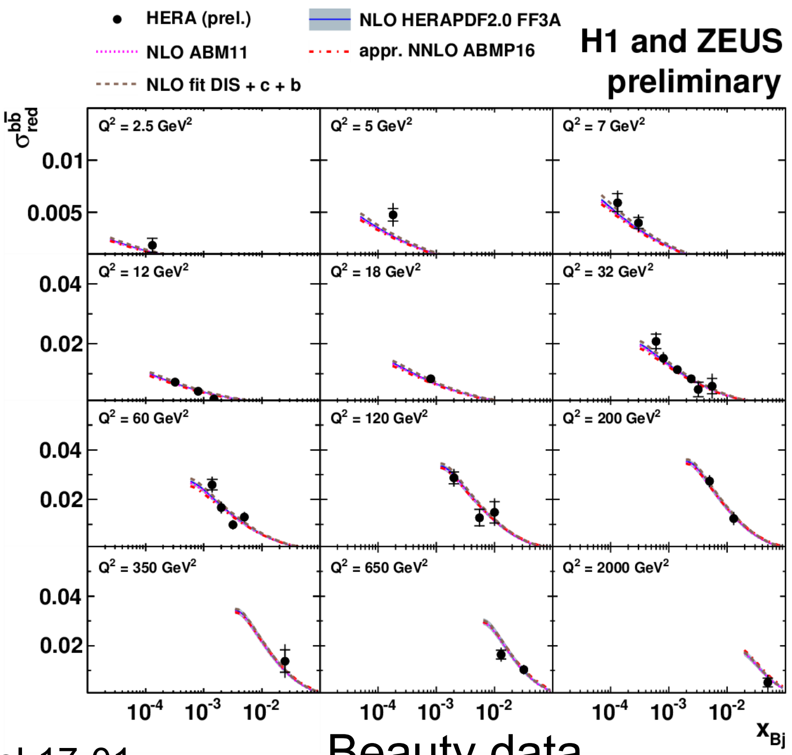
Experimental methods:
- High pt lepton
- Reconstructed D,D* mesons
- Impact parameter, secondary vertex

# HERA charm and beauty data




Charm data

- New combined data (preliminary 2017)
- Rise to low x: typical for sea and gluon
- Cross section evolves with Q²
- NLO predictions describe data reasonably well
- Rather limited data at high x

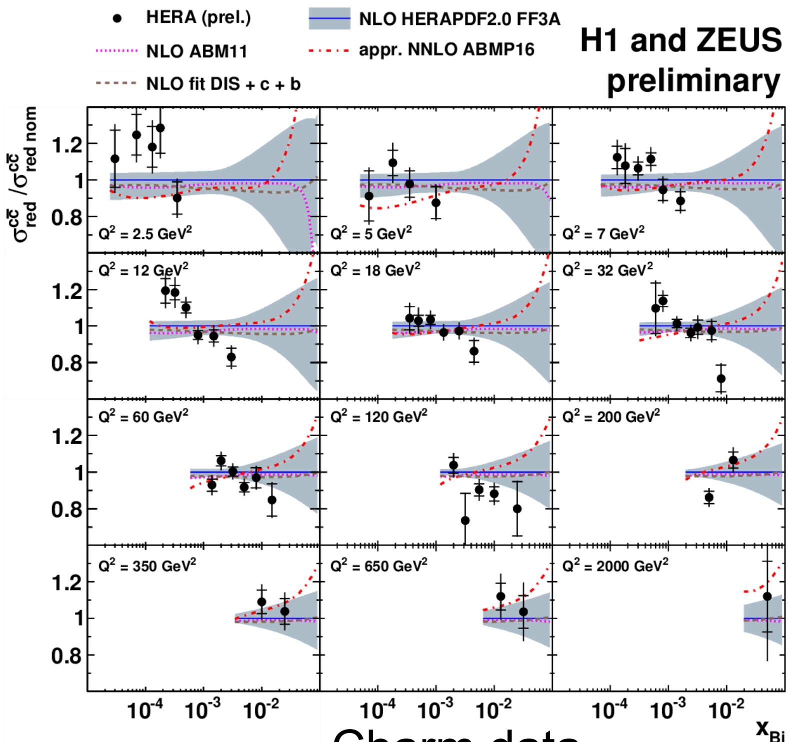



Beauty data

H1prelim-17-071, ZEUS-prel-17-01

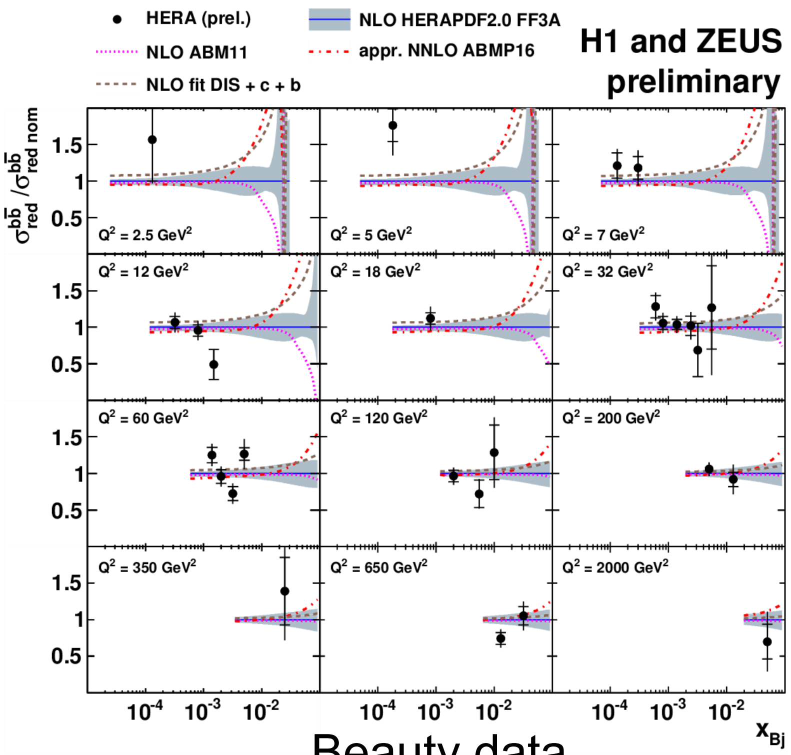
https://www.desy.de/h1zeus/combined_results/index.php?do=heavy_flavours

# Charm and beauty: ratio to NLO QCD




Charm data

- Overall satisfactory description of the HERA c and b data by NLO QCD, not much dependent on PDF choice
- Slope difference data/theory as a function of x is visible for charm data at $Q^2 \sim 12$ GeV²
- Data at higher x will be very interesting to test theories

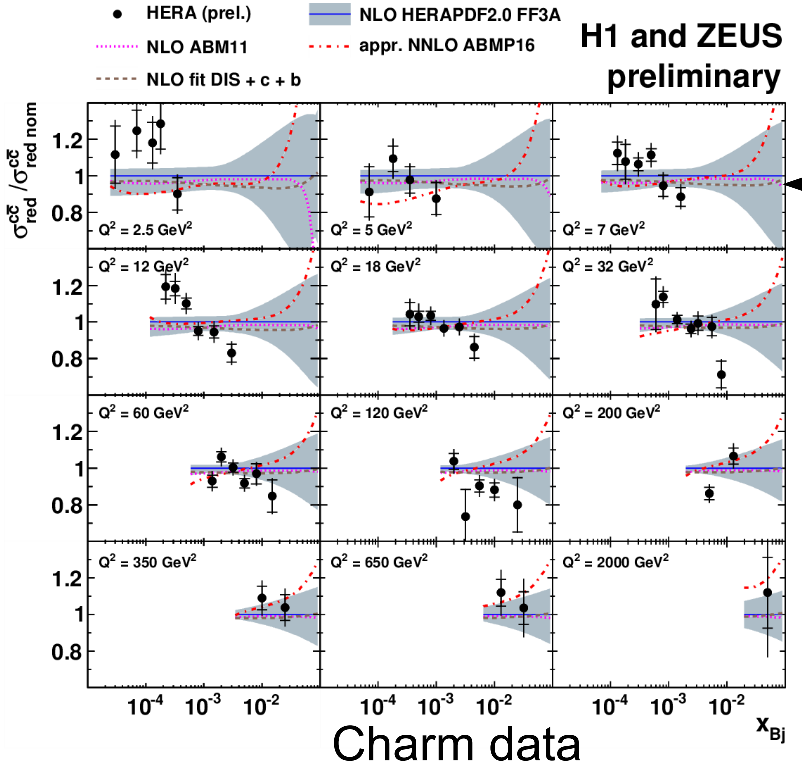



Beauty data

H1prelim-17-071, ZEUS-prel-17-01

https://www.desy.de/h1zeus/combined_results/index.php?do=heavy_flavours

# Charm and beauty quark masses




- Charm and beauty data together with HERA inclusive DIS data are taken as input to a NLO QCD fit (dashed line)
- Simultaneously extract PDFs and c,b masses

$$m_c(m_c) = 1209^{+46}_{-41}(\text{fit})^{+62}_{-14}(\text{model})^{+7}_{-31}(\text{param})\ \text{MeV}$$
$$m_b(m_b) = 4049^{+104}_{-109}(\text{fit})^{+90}_{-32}(\text{model})^{+1}_{-31}(\text{param})\ \text{MeV}$$

- Compatible with previous HERA analyses and with world data

PDG: $m_c(m_c) = 1270 \pm 30$ MeV and $m_b(m_b) = 4180 \pm 30$ MeV

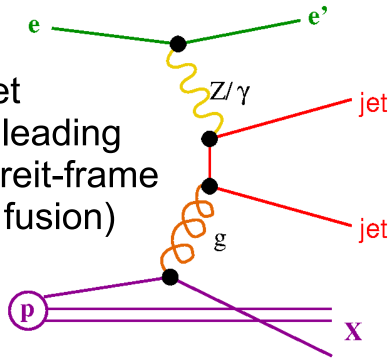
H1prelim-17-071, ZEUS-prel-17-01 https://www.desy.de/h1zeus/combined_results/index.php?do=heavy_flavours

# Jet production in the Breit frame

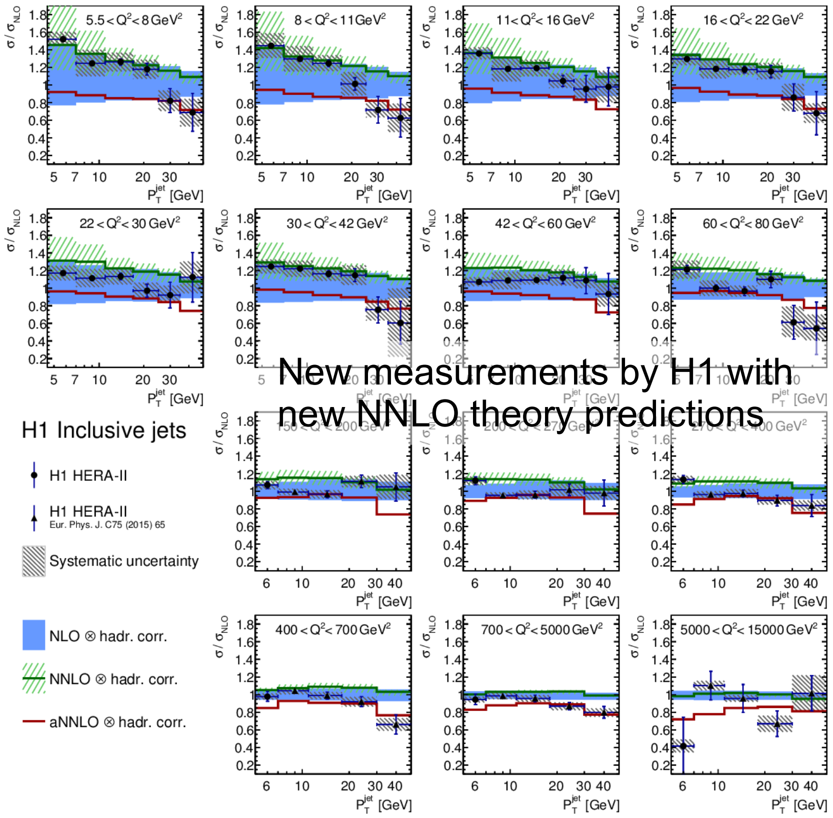
- New data on jet production in the Breit frame published recently by H1
- NNLO theory calculation became available recently

  → unique change to improve both on the experimental and the theoretical precision

Diagram for jet production at leading order in the Breit-frame (boson-gluon fusion)



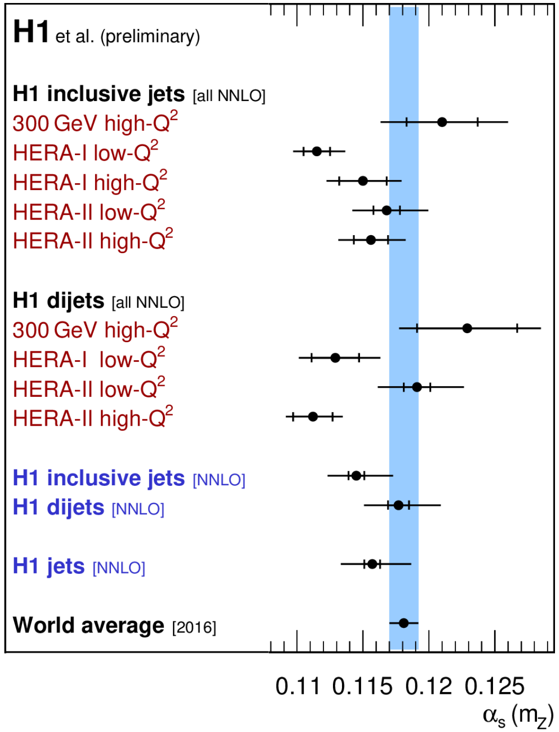

Data at high jet $p_T$ and high Q² are statistically limited but theoretically most precise
→ JLEIC



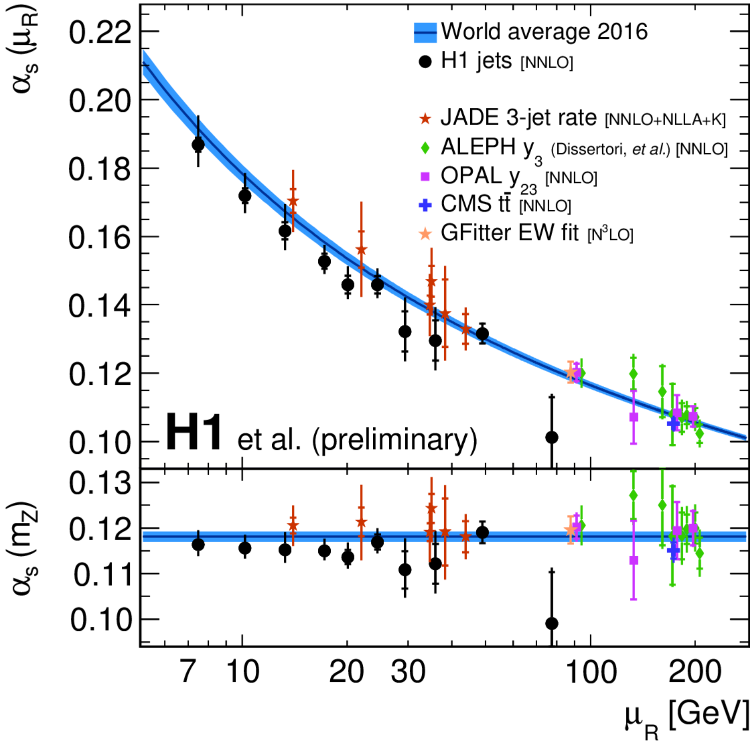

New measurements by H1 with new NNLO theory predictions

Eur.Phys.J.C77 (2017) 4, 215

# $\alpha_s$ determination at NNLO from jet data




- First determination of $\alpha_s$ from jets in DIS at NNLO accuracy
- Close cooperation with theorists
- DIS jets can compete with LEP results
- Paper in editorial process



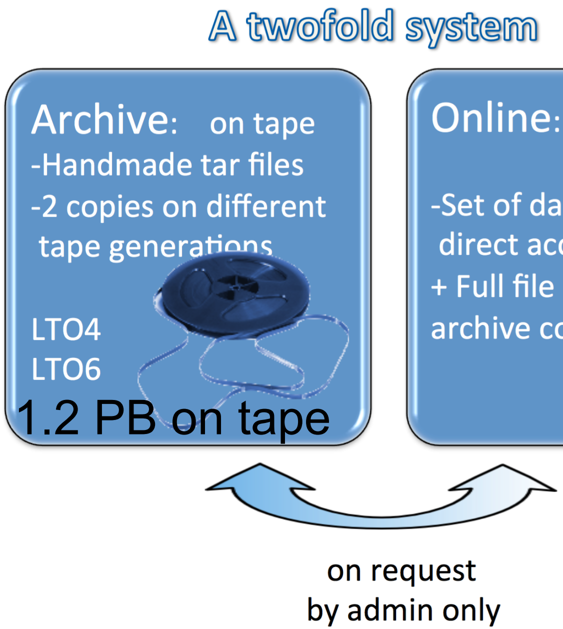

H1prelim-17-031, close to publication

# HERA analysis and data preservation

- HERA data are preserved at DESY and MPI Munich
- The HERA collaborations are still active in producing papers
- A chance for JLEIC students or post-docs to do analysis on real data
- Both H1 and ZEUS welcome new members
- No financial commitment involved

Contact M.Wing or S.Schmitt to join ZEUS or H1
m.wing@ucl.ac.uk , Stefan.Schmitt@desy.de

DPHEP storage system at DESY




700 TB on disk (data and MC) analysis on DESY batch farm

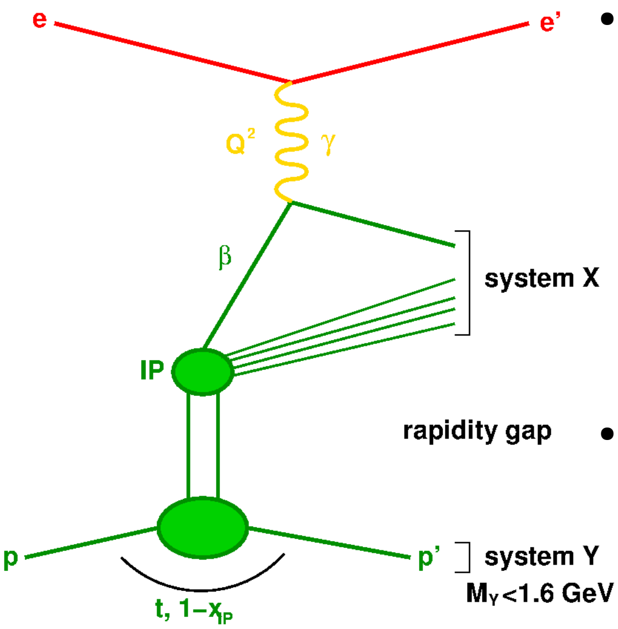
# Summary

- World's only ep collider HERA was operated 1992-2007
- Hera kinematic domain: low-x [awaiting high-x from JLEIC]
- Results shown in this talk: inclusive cross sections and PDFs, charm and beauty production, jets and $\alpha_s$
- Another big area of analyses at HERA: diffractive and exclusive processes (not shown in this talk → backup)
- HERA collaborations are still doing analysis, data is preserved for long-term usage

  → join us now to analyze HERA data in view of JLEIC

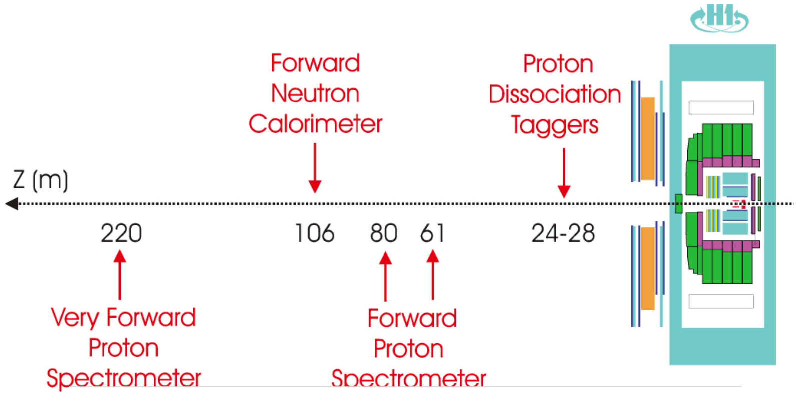
# Backup slides

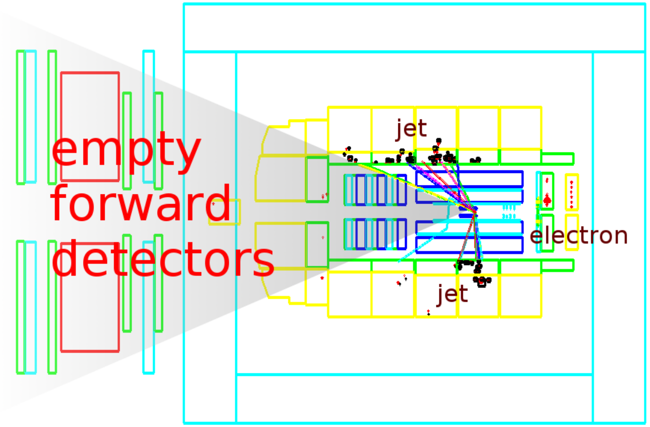
# Diffraction at HERA




- Proton taggers
  - no proton dissociation
  - Direct reconstruction of system Y
  - Low acceptance and/or low statistics
- Large rapidity gap event selection
  - Include dissociation
  - Poor reconstruction of system Y
  - High statistics

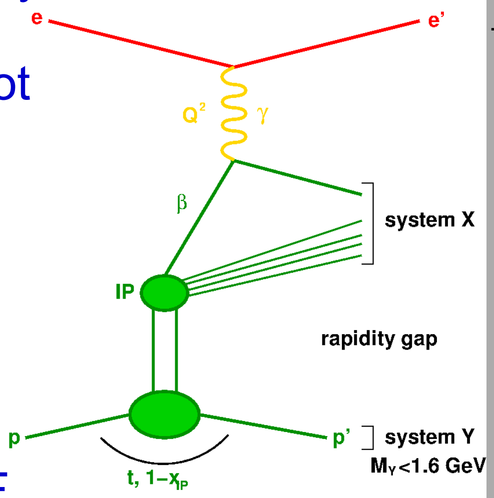
Hard diffraction: DPDF
Soft diffraction: IP trajectory, ...

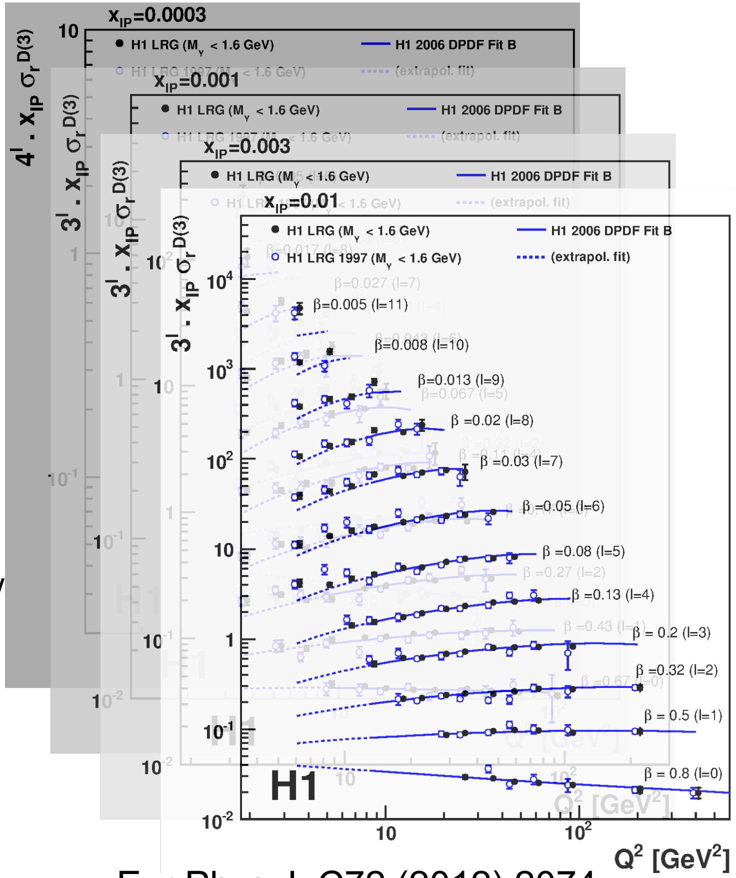


# Inclusive diffraction $F_2^{D3}$

- Select events with large rapidity gap method → momentum transfer t at proton vertex is not measured
- Measure diffractive cross section $\sigma_r^{D3}(Q^2, \beta, x_{IP})$
- Extract diffractive PDFs
- Status: full (H1) dataset analyzed, but no recent DPDF fit (shown H12006 DPDF Fit-B uses only part of the data)

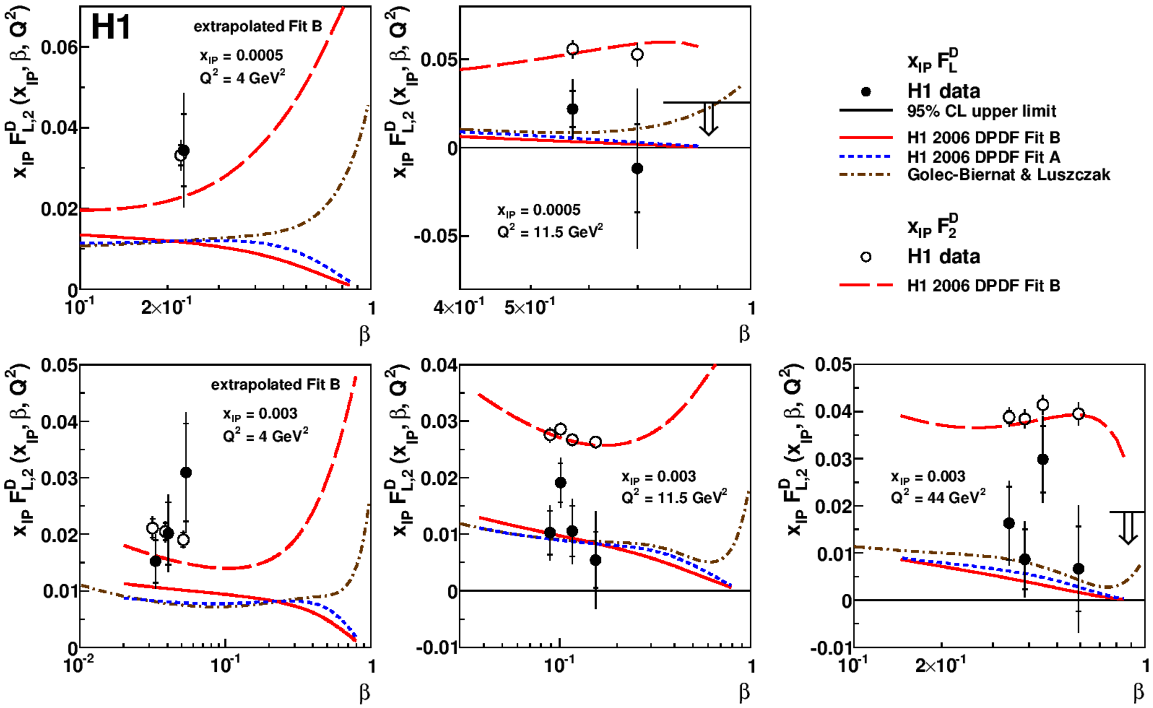



Eur.Phys.J. C72 (2012) 2074

# Measurement of $F_L^D$

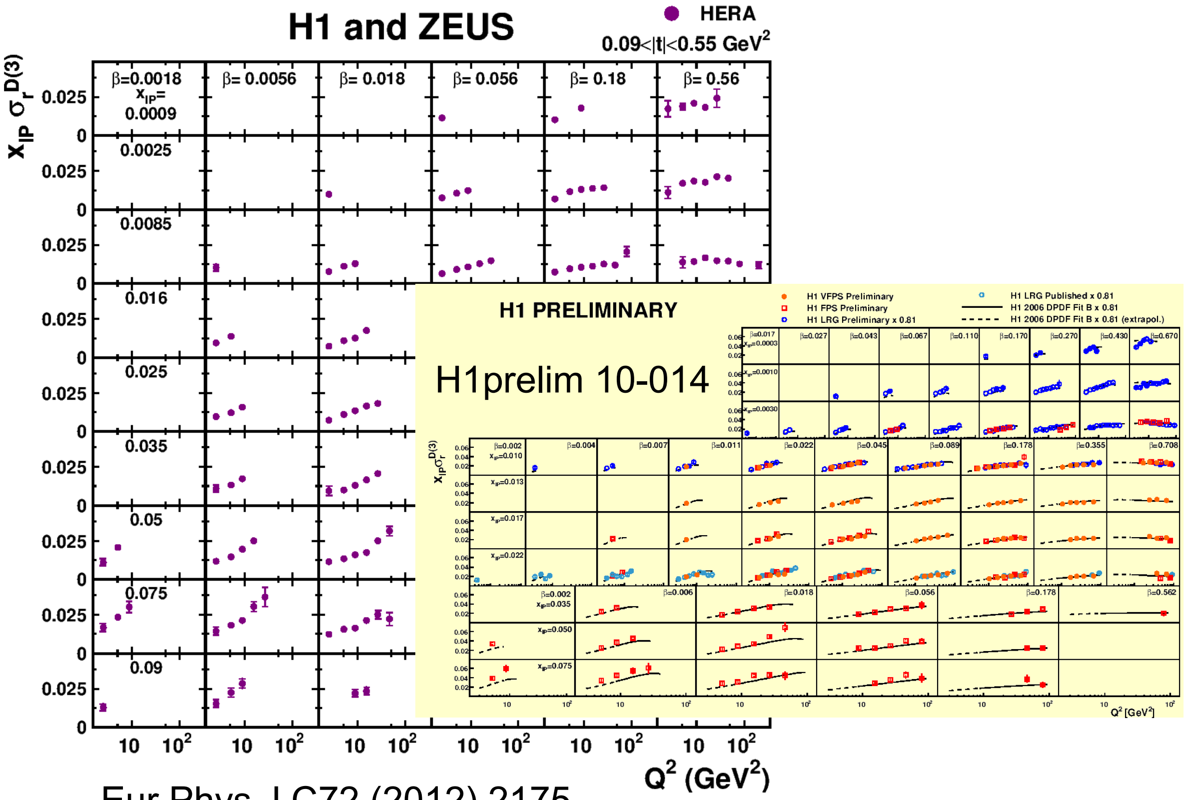
- Rosenbluth separation in diffraction: measure longitudinal structure function
- HERA measurements are statistically limited and do not reach to the regions where the model predictions are divergent of each other
- Interesting for JLEIC or JLEIC+HERA?




Eur. Phys. J. C (2011) 71:1836

# Forward proton data

- Forward proton was detected at HERA using “Roman pot” detectors
- Measurement of $F_2^{D4}(Q^2, \beta, x_{IP}, t)$
- H1: FPS (HERA-I), FPS and VFPS (HERA-II)
- ZEUS: LPS (HERA-I)
- Data of ZEUS LPS and H1 FPS are combined in a limited t-range
- H1 VFPS data not yet published, preliminary $F_2^{D3}$ measurement

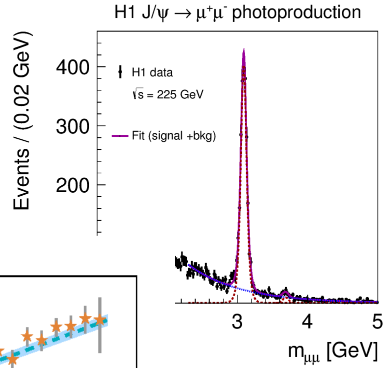


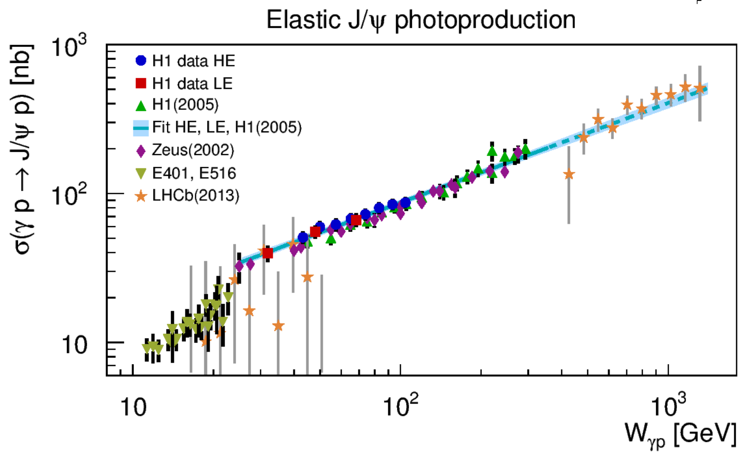
Eur.Phys.J.C72 (2012) 2175

# Exclusive measurements

- Many measurements were performed with HERA-I data but not yet with HERA-II data
- Typical measurements: diffractive vector meson production ρ,φ,J/ψ,ψ',Y and DVCS
- HERA-II data sample is interesting because of large available luminosity and dedicated (track) triggers for low-multiplicity states – but not all channels have been analyzed yet

Example: J/ψ photoproduction: 83 citations in only 4 years




Eur.Phys.J.C73 (2013) 2466