HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

HERA Collider physics - introduction

Center for Frontiers in Nuclear Science
Workshop series

Workshop on

EW and BSM physics at the EIC

May 2020

Stefan Schmitt

Results from H1 and ZEUS

Outline

- Introduction
  - The HERA collider and collider experiments
  - HERA kinematics
- Selected physics results in perturbative QCD
  - Inclusive cross sections, structure functions, PDFs
  - Heavy flavor production

Next talk: E. Gallo about searches and electroweak physics at HERA

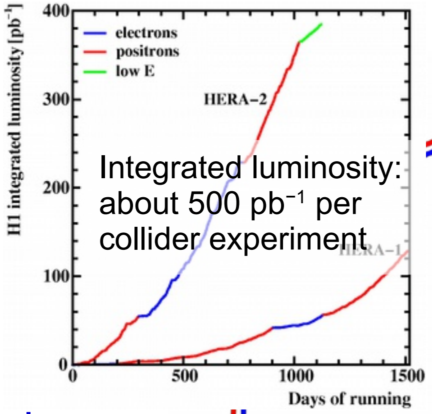
Disclaimer:

this talk is on HERA result, but reflects my personal opinions only.

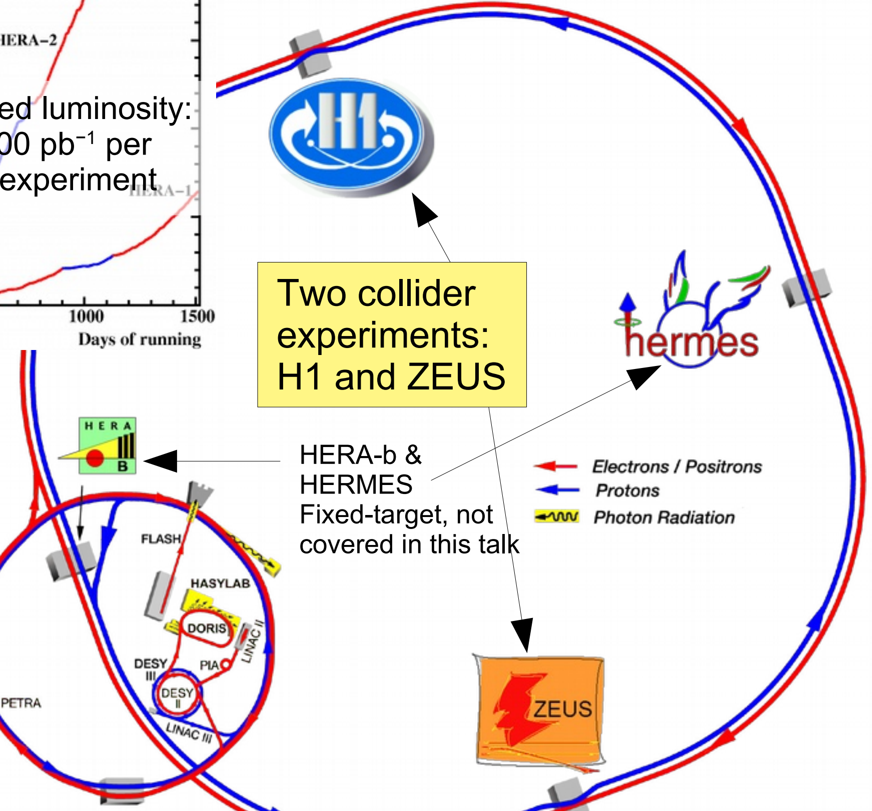
There is a slight preference in showing results from H1 rather than ZEUS, simply because I know the H1 results better. Please apologize for that.

The HERA collider

- Operated from 1992 to 2007
- Circumference 6.3 km
- Electrons or positrons colliding with protons
- Proton: 460-920 GeV, Leptons 27.6 GeV
- Peak luminosity ~7×10^{31} cm^{-2}s^{-1}
- Lepton beam polarisation up to 40-60% (Sokolov-Ternov effect, rise-time ~30 minutes)



Integrated luminosity: about 500 pb^{-1} per collider experiment



Two collider experiments: H1 and ZEUS

HERA-b & HERMES Fixed-target, not covered in this talk


Straight section

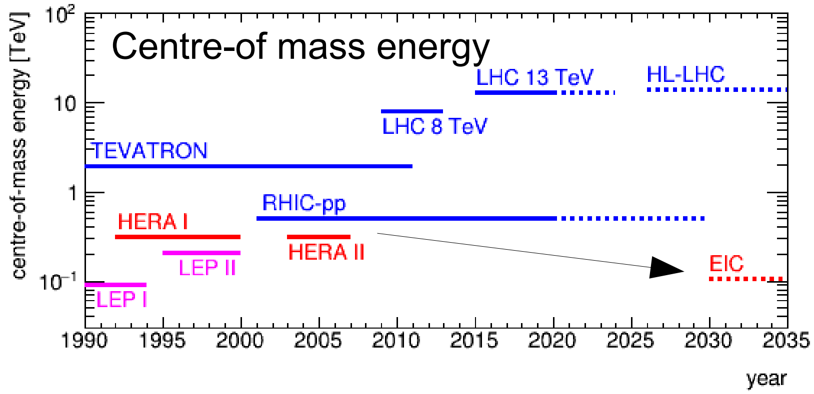

Curved section

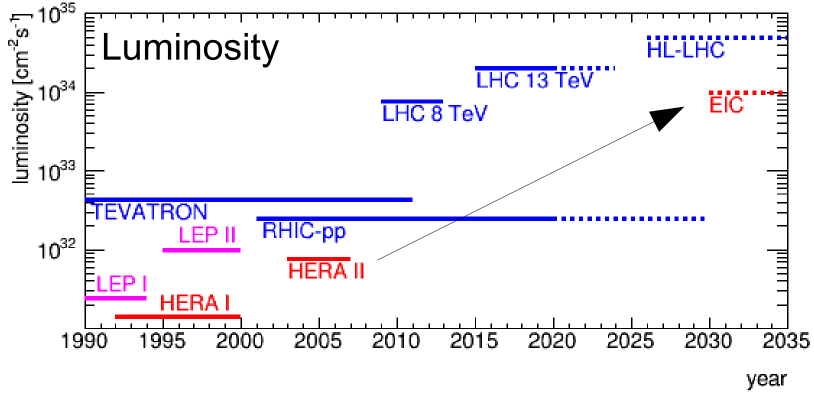
HERA compared to other colliders

- HERA at construction time: energy frontier (E_p~Tevatron, E_e~ ½ LEP)

  Detectors were designed for discoveries, not so much for precision

- EIC compared to HERA:
  - Reduced center-of-mass energy ×0.3
  - Much higher luminosity ×100
  - Better lepton polarisation
  - Target polarisation
  - Heavy targets
  - Much improved detectors: tracking, acceptance, particle identification, forward detectors, ...





The HERA publication harvest

Status: Feb 2020

H1+ZEUS combined	8 publication
H1	223 publications
ZEUS	250 publications

- Both collaborations are still active and open for new members
- Data are available for analysis at DESY, including computing infrastructure (batch system)

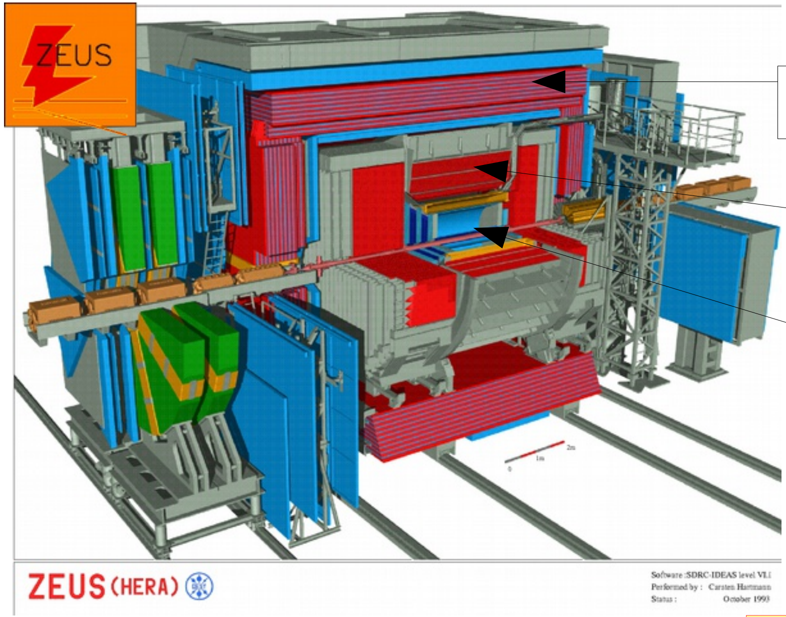
- Top-ten cited (excluding detector papers)

JHEP 1001 (2010) 109	H1+ZEUS	1000+ Data combination, PDF
Eur.Phys.J. C21 (2001) 33	H1	700+ Low-x, PDF, alpha_s
Nucl.Phys. B470 (1996) 3	H1	500+ Low-x, PDF
Eur.Phys.J. C21 (2001) 443	ZEUS	500+ Low-x, PDF
Phys.Lett. B315 (1993) 481	ZEUS	500+ Observation of diffraction
Nucl.Phys. B407 (1993) 515	H1	400+ Rise of F2 at low-x
Eur.Phys.J. C75 (2015) 580	H1+ZEUS	400+ Data combination, Low-x, PDF
Phys.Lett. B316 (1993) 412	ZEUS	400+ Rise of F2 at low-x
Z.Phys. C76 (1997) 613	H1	400+ Difffractive PDF
Z.Phys. C74 (1997) 207	ZEUS	400+ High Q^2 DIS

- 500+ citations: proton at low-x and PDFs
- 250+ citations: total cross-section, diffractive PDF, diffractive vector mesons, pentaquark
- 200+ citations: charm, jets, DVCS

HERA data are used mainly to study:
PDFs and perturbative QCD, low-x and diffraction, transition from soft to hard QCD

The HERA detectors H1 and ZEUS



Muon chambers

4π em+had. calorimeters

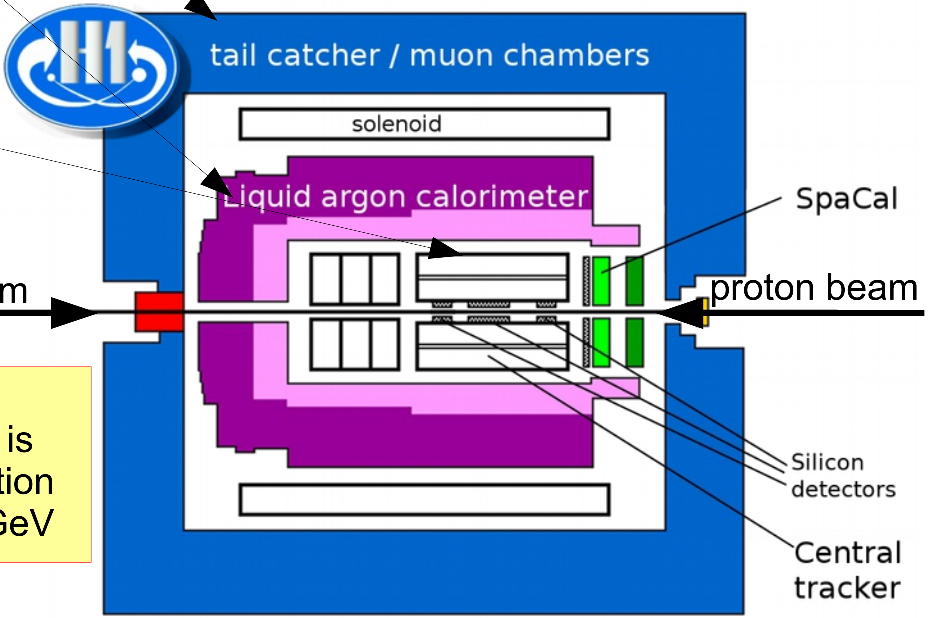
Drift-chambers as main tracking devices + silicon vertex detectors

Uranium-scintillator calorimeter
$\sigma_{had}=0.35/\sqrt{E}$, $\sigma_{EM}=0.18/\sqrt{E}$, $-3.5<\eta<4$

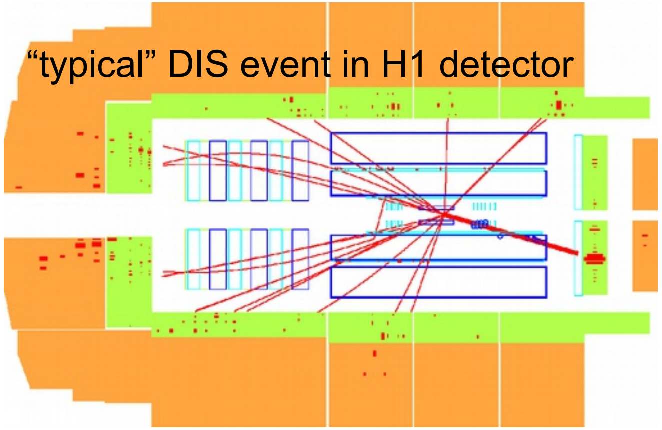
Asymmetric detectors
Centre-of-mass system is boosted to proton-direction
$E_e=27.6$ GeV, $E_p=920$ GeV

Liquid Argon calorimeter
$\sigma_{had}=0.5/\sqrt{E}$, $\sigma_{EM}=0.11/\sqrt{E}$, $-1.5<\eta<3.4$
Lead+fiber in backward (electron) direction
[SpaCal] $\sigma_{EM}=0.07/\sqrt{E}$, $-4<\eta<1.4$

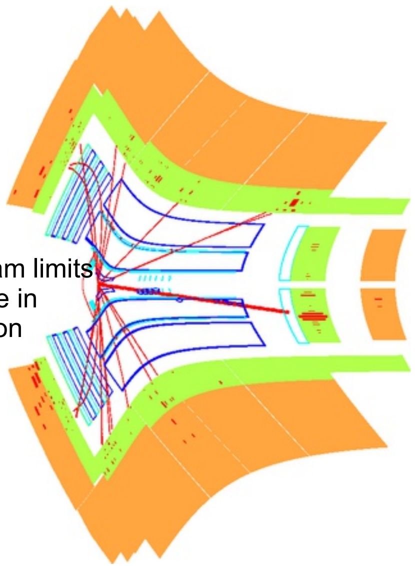
electron beam

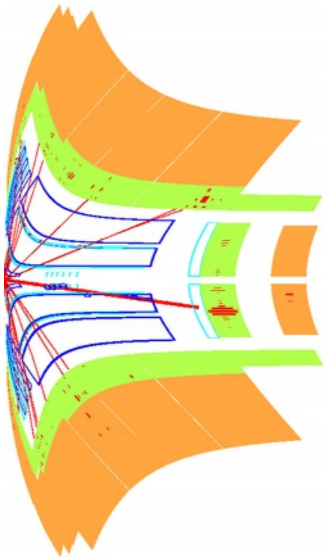


HERA boost visualized



Proton beam limits acceptance in target region





E_e=27.6 GeV E_p=920 GeV

Laboratory system

E_e=160 GeV E_p=160 GeV

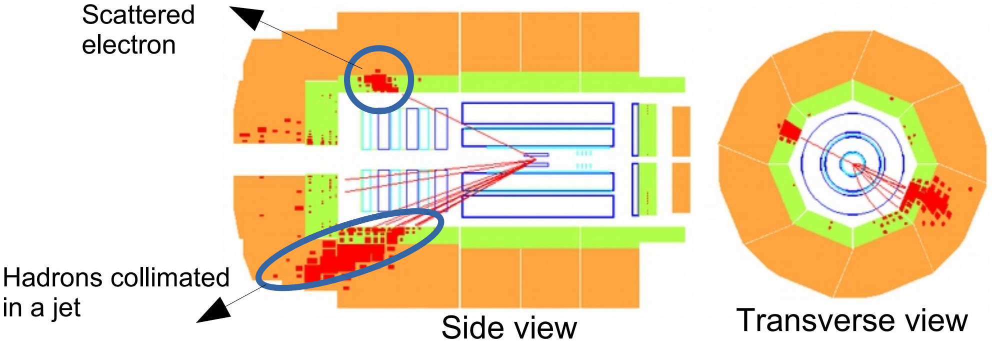
ep center-of-mass system

E_e=54000 GeV

Proton rest-frame
c.f. fixed-target experiment

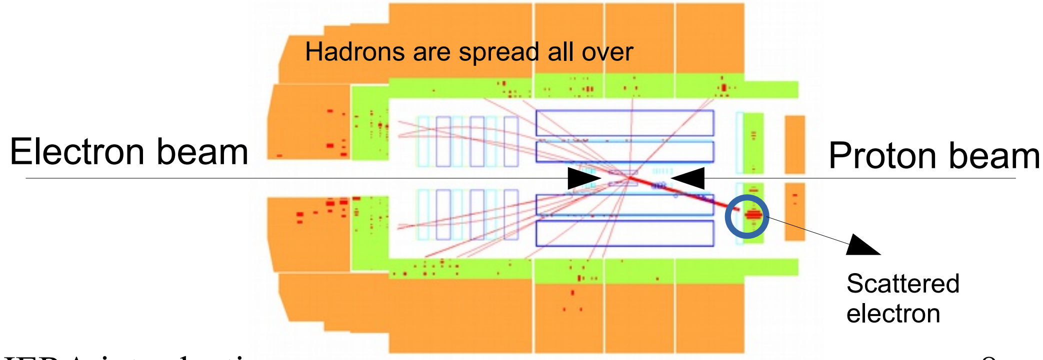
Processes studied at the HERA collider

- Neutral Current DIS (Deep Inelastic Scattering)
  - electron in main detector
- Charged current DIS
  - neutrino with high transverse momentum (escapes detection)
- Photoproduction
  - Electron scattered at very low angle (dedicated low-angle detector or not detected)



Large electron scattering angle (rare event)

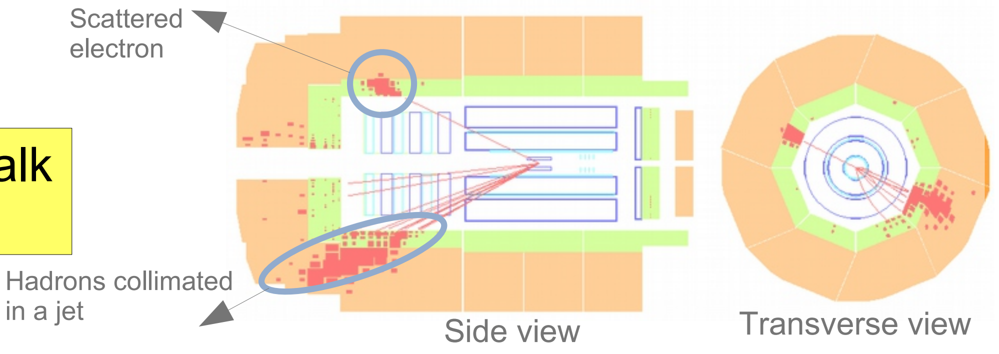
Small electron scattering angle (frequent event)



Processes studied at the HERA collider

- Neutral Current DIS
  - electron in main detector
- Charged current DIS
  - neutrino with high transverse momentum (escapes detection)
- Photoproduction
  - Electron scattered at very low angle (dedicated low-angle detector or not detected)

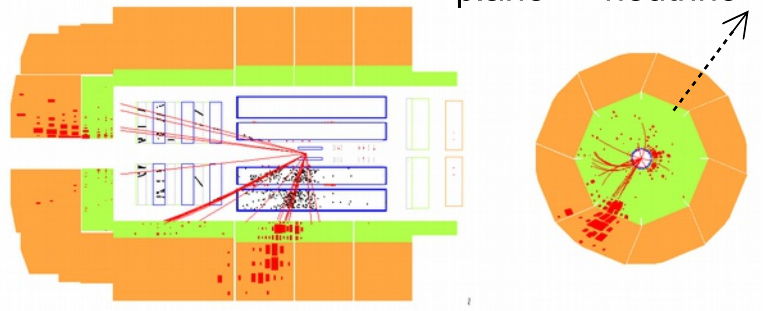
See next talk
E. Gallo



Neutral current (NC) event

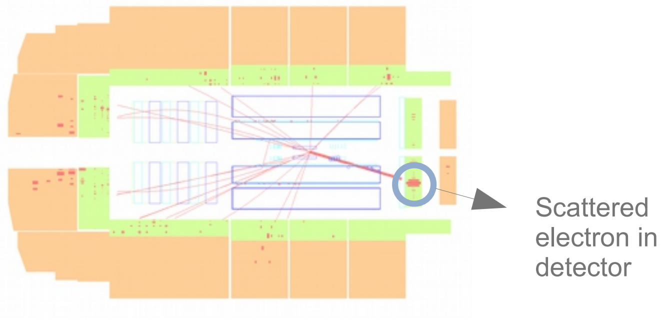
Charged current (CC) event

Imbalance in transverse plane → neutrino



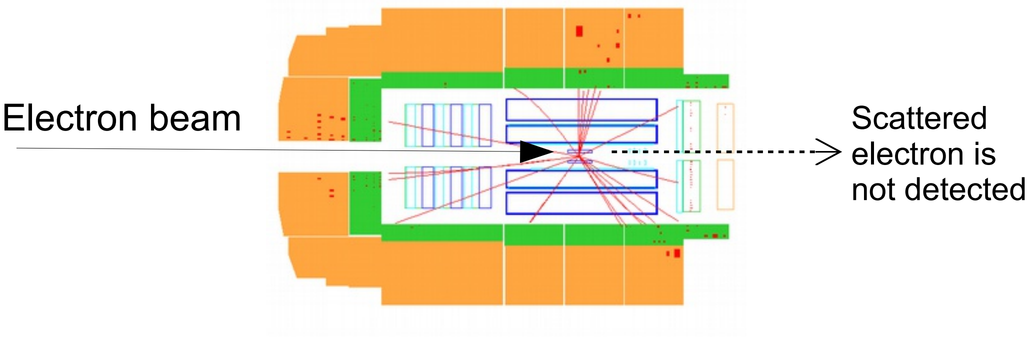
Processes studied at the HERA collider

- Neutral Current DIS
  - electron in main detector
- Charged current DIS
  - neutrino with high transverse momentum (escapes detection)
- Photoproduction
  - Electron scattered at very low angle (not detected or scattered into dedicated low-angle tagger)



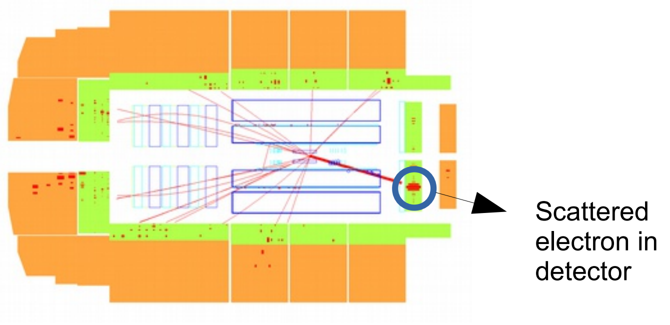
Neutral current (NC) event

Photoproduction (most frequent type of event)



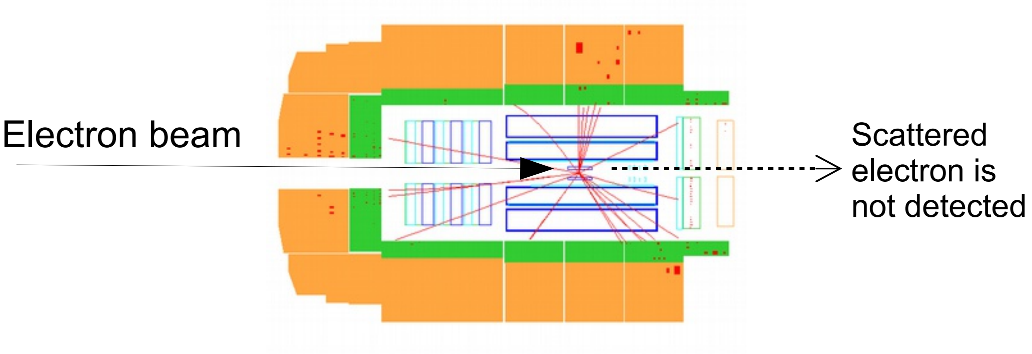
Photoproduction and DIS

- **Main kinematic variable: negative four-momentum squared $Q^2 = -(e-e')^2$**
- Q^2 provides a natural hard scale for perturbative calculations
- Deep-inelastic scattering (**DIS**): $Q^2 \gg 0$
  - Perturbative QCD applicable
- **Photoproduction**: $Q^2 \sim 0$
  - Perturbative QCD works only if there is another hard scale (jet, heavy quark, etc)



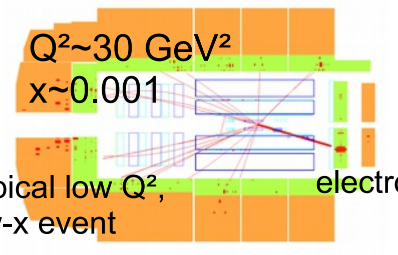
Neutral current (NC) event

Photoproduction (most frequent type of event)



Neutral current DIS kinematics at HERA

- Kinematic variables: Q^2, x, y, Q^2=sxy
- Determine from 4-vectors of beam particles e, p, scattered electron e' and hadronic final state X

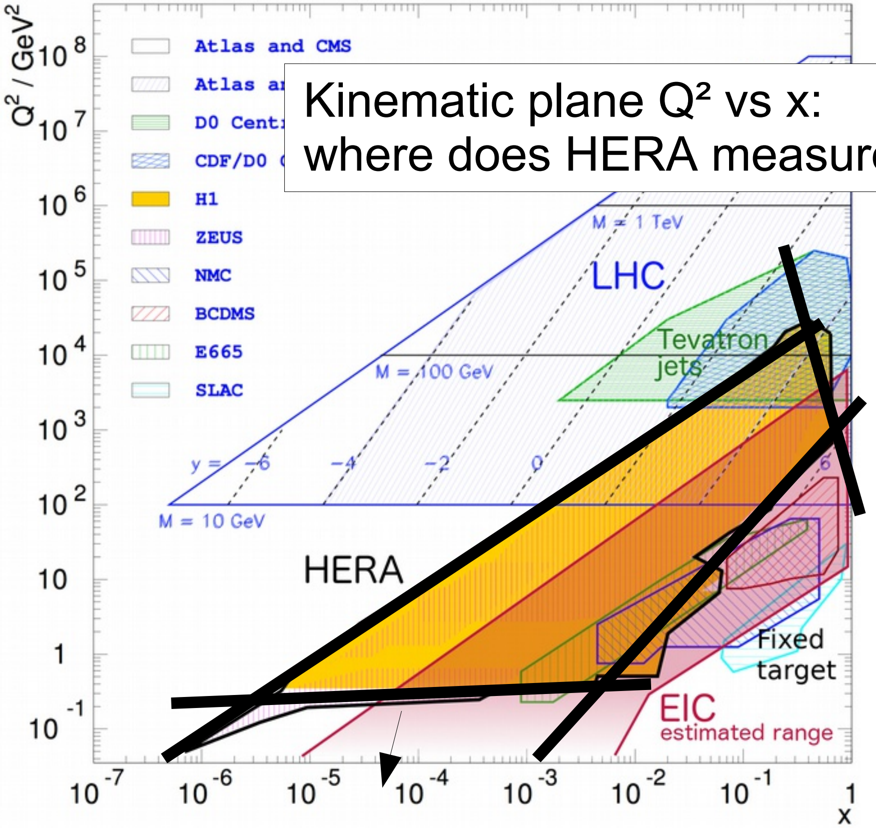


Typical low Q², low-x event

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

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

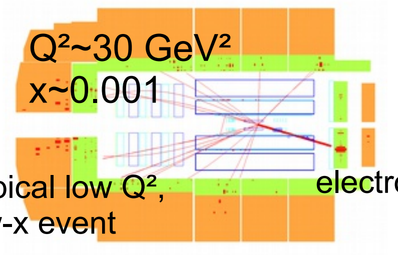
- "Electron" method: $y=y_e$ and $p_T=p_{T,e}$
- At low y, the electron method is limited by energy resolution, initial and final state radiation
  → use $y=y_h$ (sigma method)
- Other methods also in use: double-angle, etc



Kinematic plane Q² vs x: where does HERA measure?

Neutral current DIS kinematics at HERA

- Kinematic variables: Q^2, x, y, $Q^2=sxy$
- Determine from 4-vectors of beam particles e, p, scattered electron e' and hadronic final state X

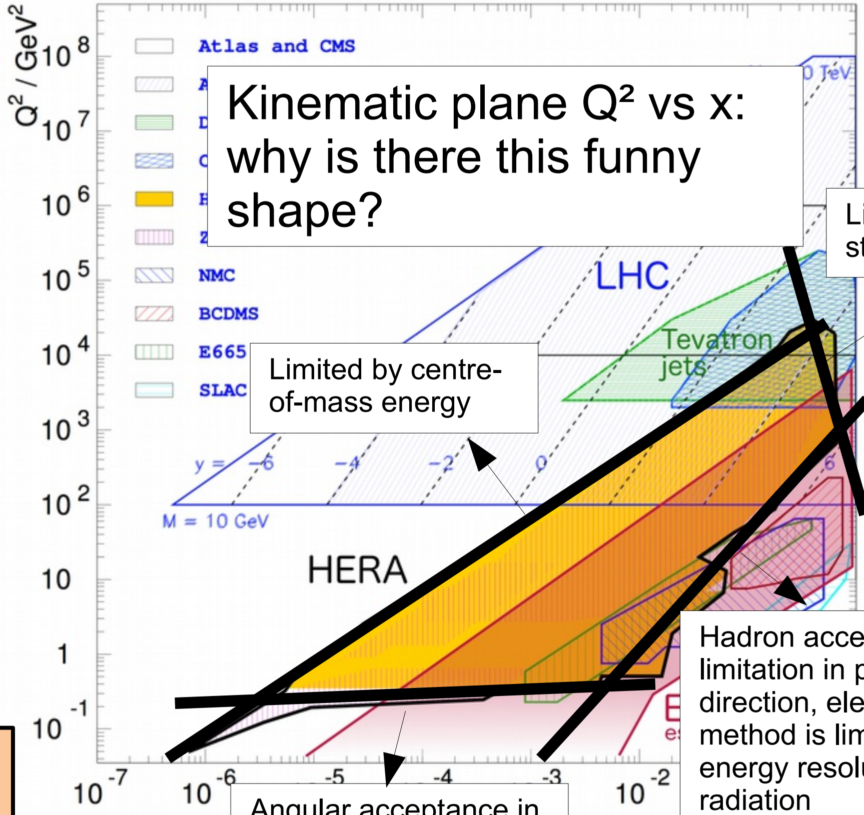


$$y_e = 1 - \frac{(e'p)}{(ep)}, \; y_h = \frac{(Xp)}{(ep)}$$

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

- "Electron" method: $y=y_e$ and $p_T=p_{T,e}$
- At low y, use $y=y_h$ (sigma method) → hadrons contributing to y_h have to be within detector acceptance → low y / high x is not accessible

HERA is "low-x" because of acceptance limitations in the forward (proton) direction



Kinematic plane Q² vs x: why is there this funny shape?

Limited statistics

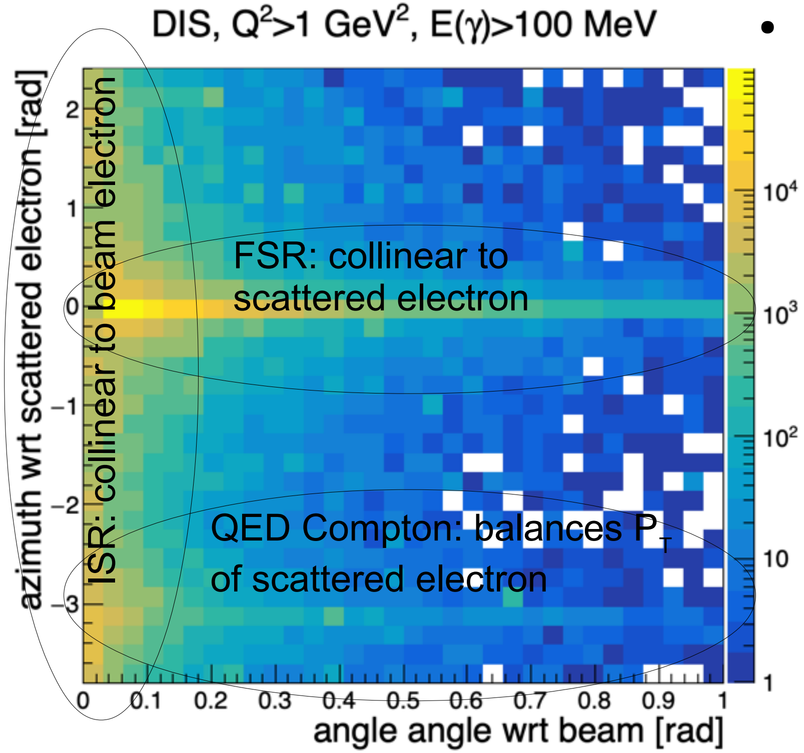
Limited by centre-of-mass energy

Angular acceptance in electron direction

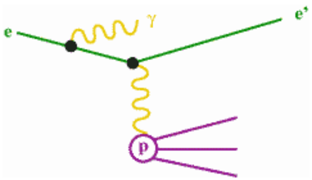
Hadron acceptance limitation in proton direction, electron method is limited by energy resolution & radiation
HERA = low-x

Radiative effects

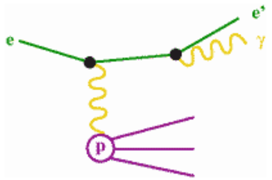
Kinematics of radiative photons



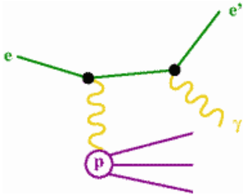
- Radiation from electron line
  - Initial state (ISR)
    effectively reduces beam energy



  - Final state (FSR)
    reduces measured electron momentum → use calorimeter

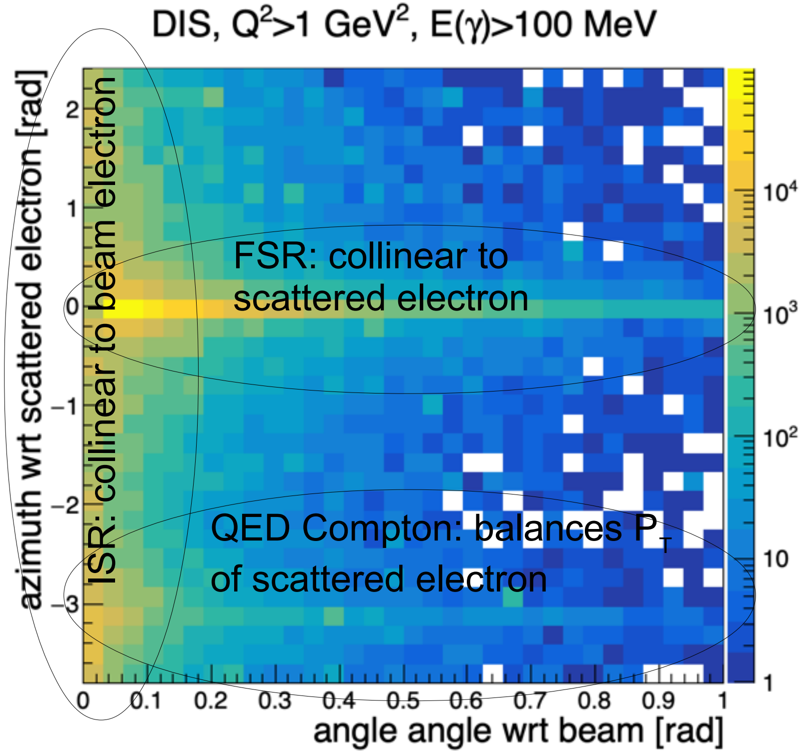


  - QED Compton
    corresponds to very low "true" Q^2 at proton vertex



Radiative effects: HERA methods

Kinematics of radiative photons



Radiation from electron line has three poles: ISR, FSR, QED Compton

Radiation has two effects

- **For a given event, the kinematic reconstruction is distorted**

  → apply cuts, use “robust” kinematic reconstruction (Sigma method or similar)

- **For a given class of events, the predicted cross section changes wrt. the Born level**

  → radiative corrections, ratio of prediction with and without radiation, model-dependent

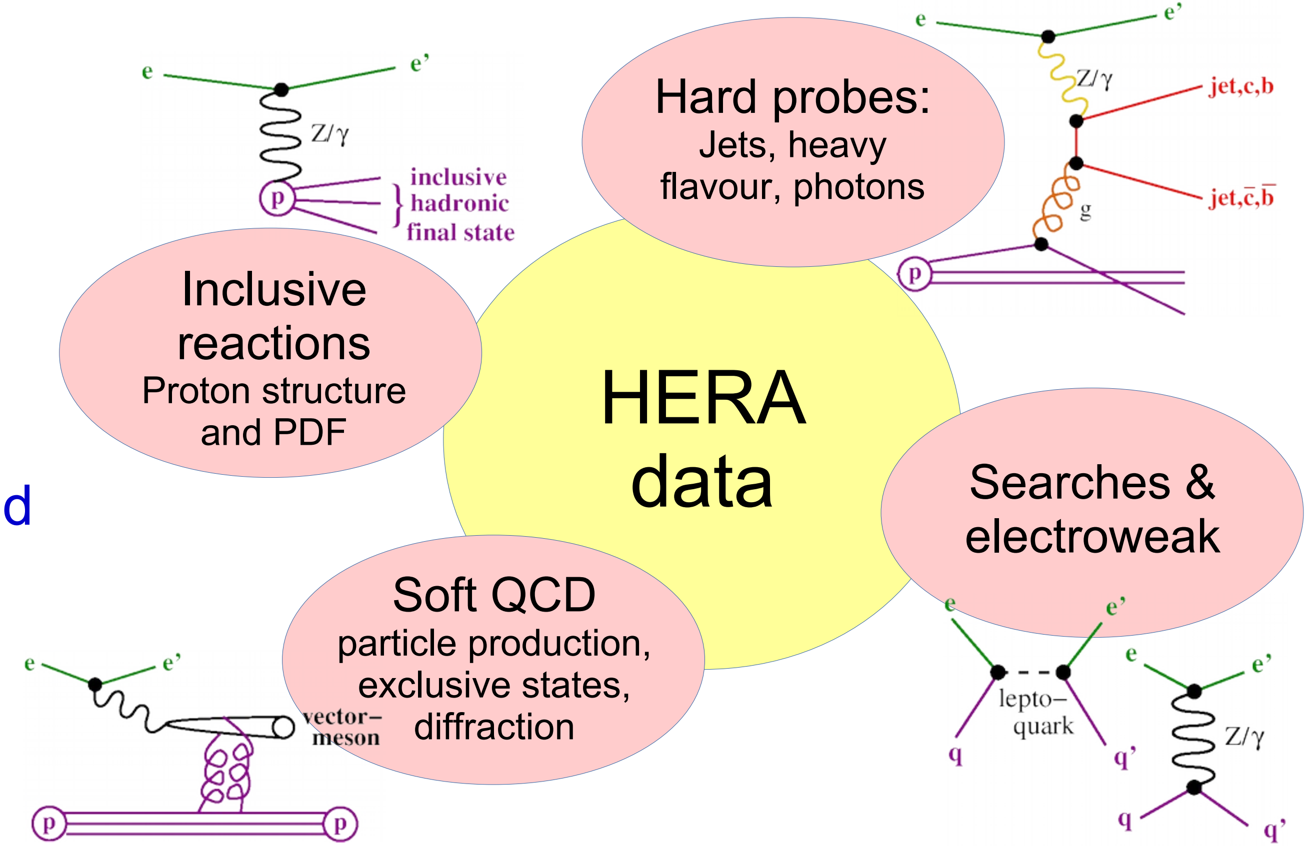
HERA physics topics

Electron

- Color-neutral probe, source of virtual or quasi-real photons

Proton

- Source of quarks and gluons



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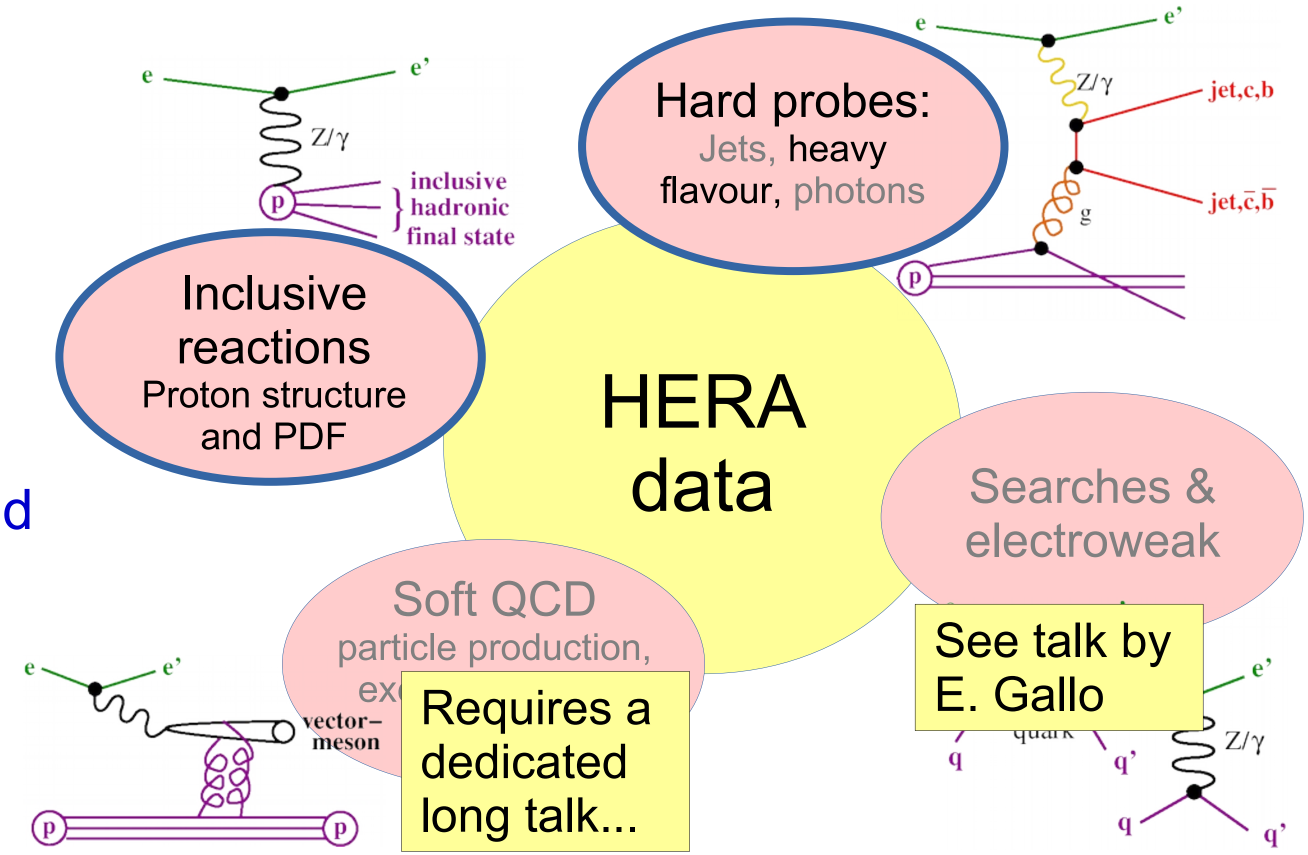


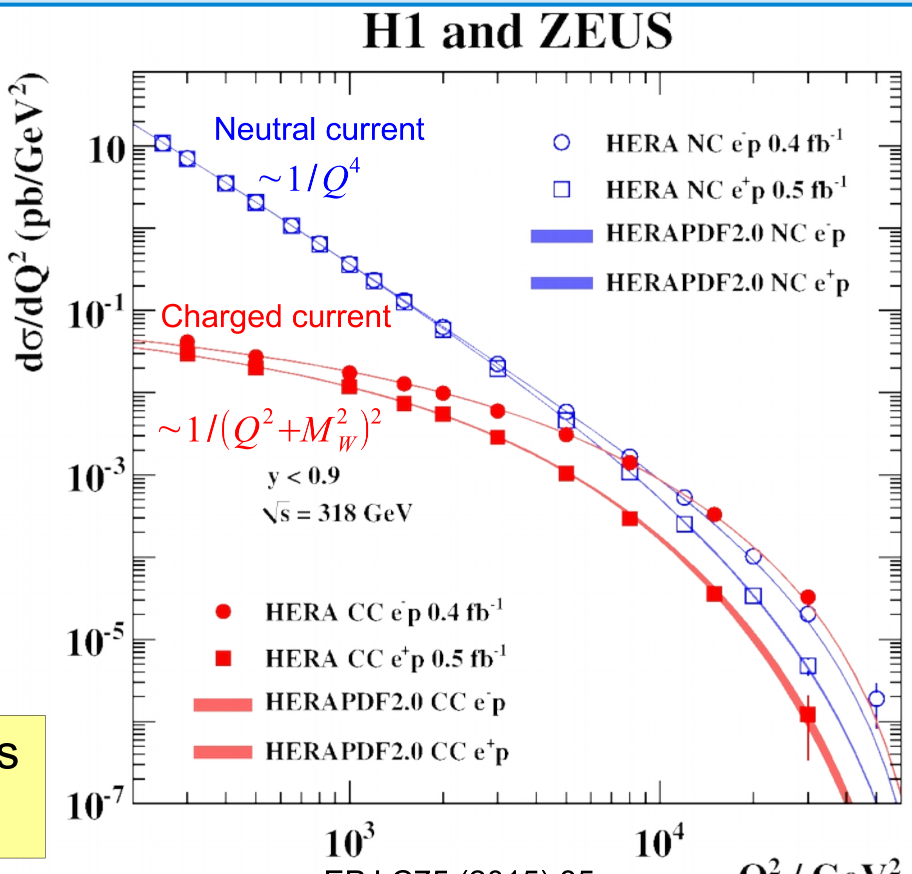
Inclusive cross sections, PDFs

H1+ZEUS Data combination
Inclusive cross sections, PDF fit
Longitudinal structure function

Deep-inelastic scattering at HERA

- Measure Cross section as a function of Q^2
- High $Q^2 \sim 10^4$ GeV² probes smallest distances
- **Combination of H1 and ZEUS data (41 datasets)**
- Neutral Current (NC):
  - photon, Z-boson exchange
  - Cross section shape similar to $1/Q^4$
- Charged Current (CC):
  - W-boson exchange M_W=80.4 GeV
  - Cross section shape $\sim 1/(Q^2+M_W^2)^2$

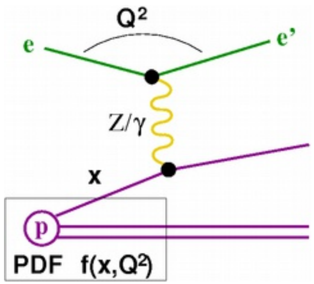
High Q^2: rare events
→ Talk by E. Gallo



EPJ C75 (2015) 85

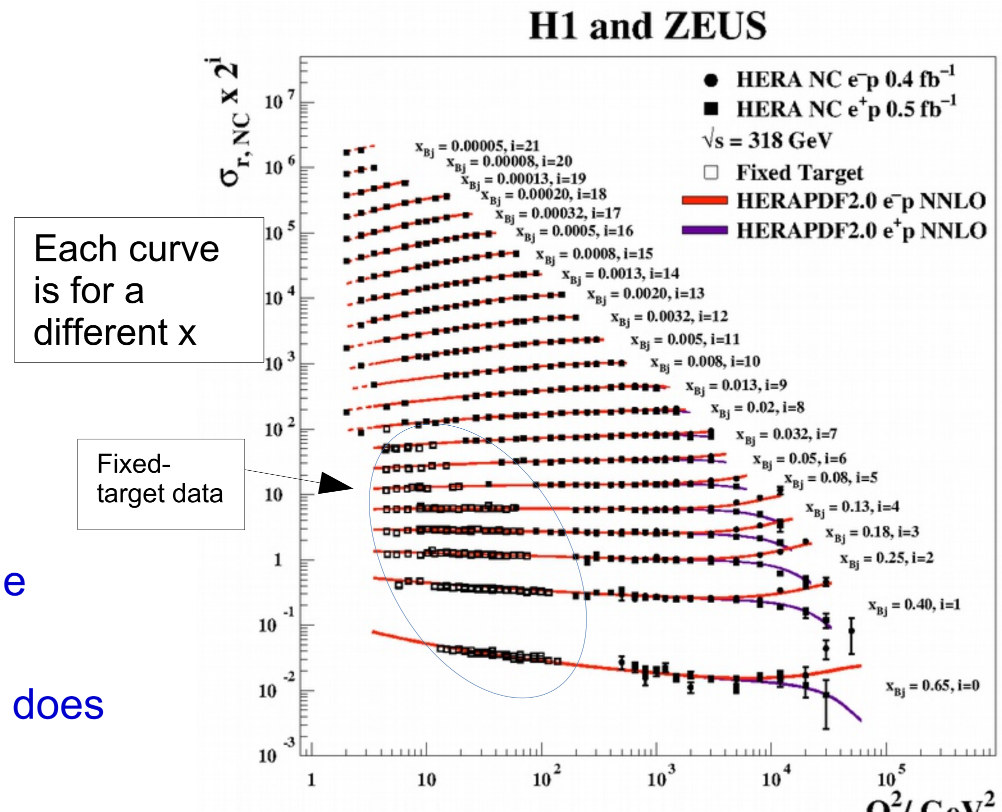
Proton structure measurement at HERA

- Momentum transfer Q²
- Second variable: Bjorken-x
- Cross sections depend on Q² and Bjorken-x



$$Q^2 = -(e-e')^2 \text{ and } x = \frac{Q^2}{2p(e-e')}$$

e : beam electron 4-momentum
p : beam proton 4-momentum
e' : scattered electron 4-momentum



EPJ C75 (2015) 85

- Interpretation in the quark-parton model: x is the momentum fraction of the struck quark
- Scaling violations: for fixed x, the cross section does change with Q²

Structure functions and parton densities

- Cross section differential in Q^2,x is related to structure functions

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

inelasticity $y=Q^2/(sx)$

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

Suppressed by y^2в 1

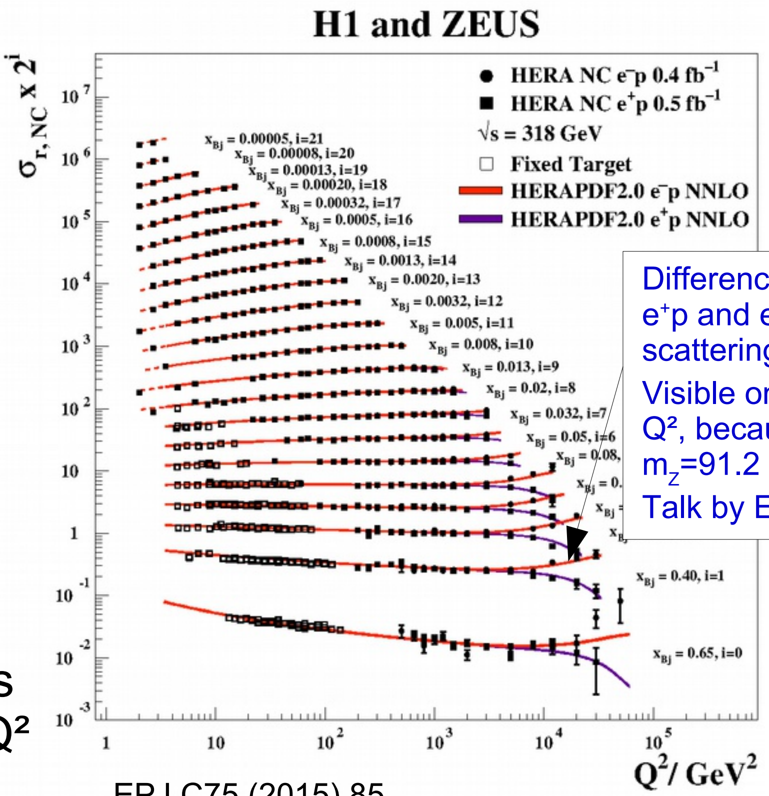
- Structure functions are related to quark and gluon count in the proton

$\tilde{F}_2\sim\sum(xq+x\bar{q})$ valence plus sea quarks → dominant

$x\tilde{F}_3\sim\frac{Q^2}{Q^2+m_Z^2}\sum(xq-x\bar{q})$ valence quarks → contributes only at high Q^2

talk by E. Gallo

$\tilde{F}_L\sim xg$ gluons



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Difference between e^+p and e^-p scattering: xF_3

Visible only at high Q^2, because m_Z=91.2 GeV

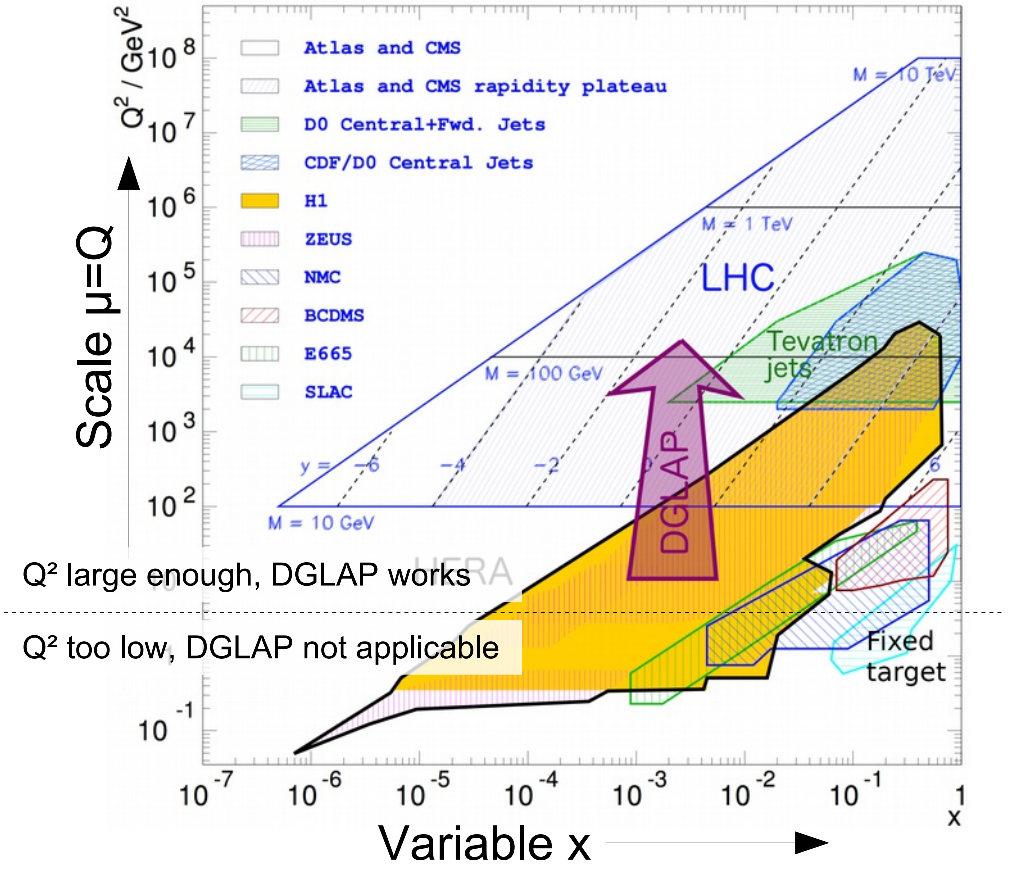
Talk by E. Gallo

DGLAP and PDF fit: from HERA to LHC

- QCD fit: extract PDF (i.e. quark and gluon densities) from structure functions
- Based on DGLAP equations Dokshitzer, Gribow, Lipatow, Altarelli, Parisi
- Given the PDF as a function of x at one scale μ_0, DGLAP predicts the PDF at another scale μ_1
- Factorisation: PDFs are universal: ep, pp, ...

$$\sigma_{ep} = \mathrm{PDF}(\mu, x) \otimes |M|^2 + \text{higher twist}$$
$$\sigma_{pp} = \mathrm{PDF}(\mu, x_1) \otimes \mathrm{PDF}(\mu, x_2) \otimes |M|^2 + \text{higher twist}$$

- Measure at HERA → predict LHC cross section
- Within HERA: measurements at different $\mu^2=Q^2$ are fitted to the same PDF using DGLAP

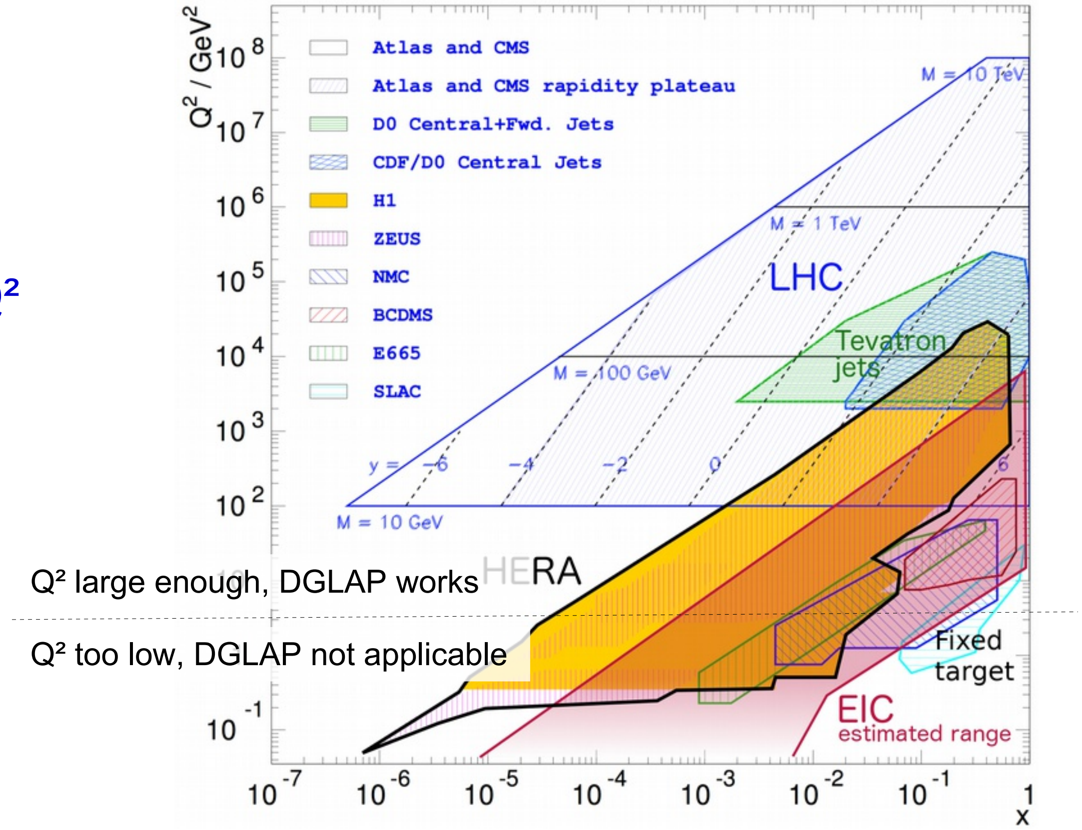


HERA and EIC kinematic reach

- HERA kinematic reach
  - For low $Q^2<100\ \text{GeV}^2$:

    low-x: $3\times10^{-5}<x<3\times10^{-2}$
  - High-x is probed only for or high Q^2 (but is statistically limited)
- Nevertheless, HERA data is the fundament of all modern PDF determinations

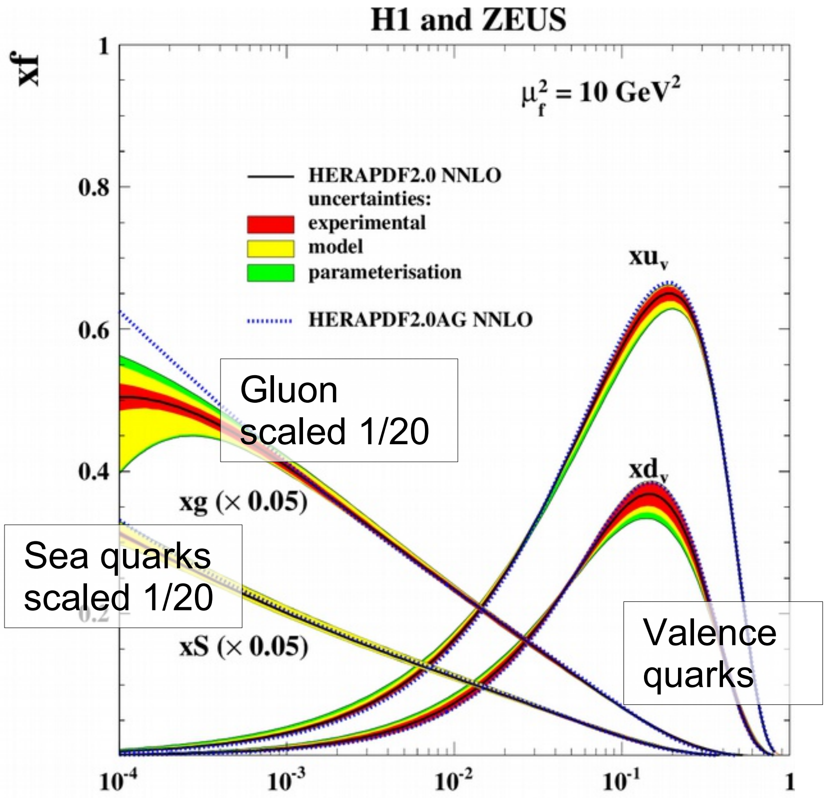
- **The EIC is going to improve substantially the precision at high x**



HERAPDF NNLO QCD fit

- Proton PDFs at a scale $\mu^2=10\ GeV^2$, from NNLO QCD fit of HERA data (14 parameter fit)
- The experimental uncertainties are small
- At low $x<10^{-3}$, model and parametrization uncertainties dominate
- The high-x region is not measured well, only constrained by sum-rules and choice of parametrization

→ EIC data are needed to improve on this



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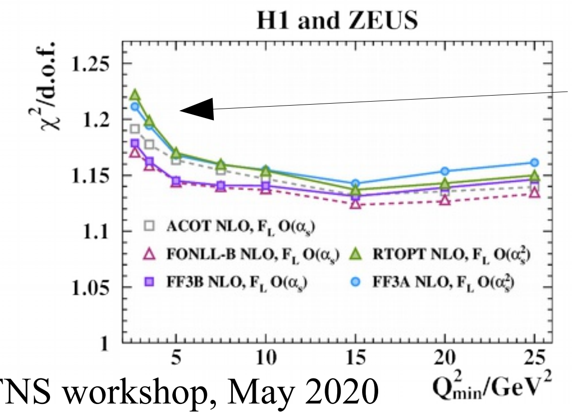
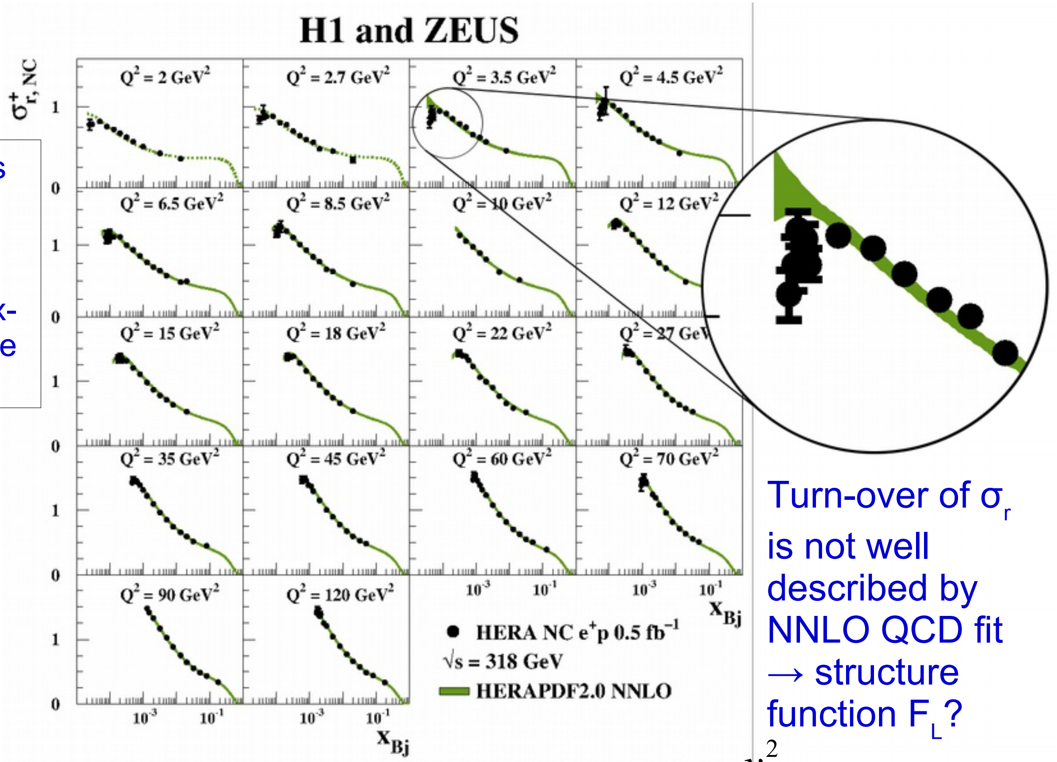
Data at low-x and DGLAP fit

- Zoom in at low-x, low Q²
- Theoretically and experimentally challenging
- Experiment: low-y → low electron energy, background
- Theory: higher orders, resummation, …



Fit quality deteriorates as more data at lower Q² are included

Q² changes between subpanels. For a given panel, the x-dependence is shown



Turn-over of σ_r is not well described by NNLO QCD fit → structure function F_L?

EPJ C75 (2015) 12, 85

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

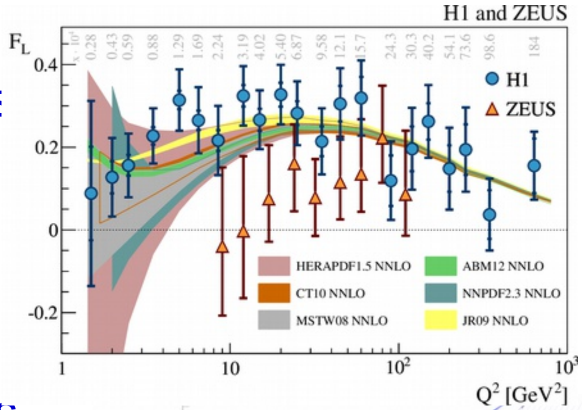
Measurement of F_L

- DGLAP fit probes gluon by scaling violations
  F_L probes the gluon more directly

$$\sigma_{r,NC} \simeq F_2 - \frac{y^2}{Y_+} F_L \qquad y = Q^2/(s\,x)$$

$F_L \sim \alpha_s\, xg(x)$ direct probe of gluon density

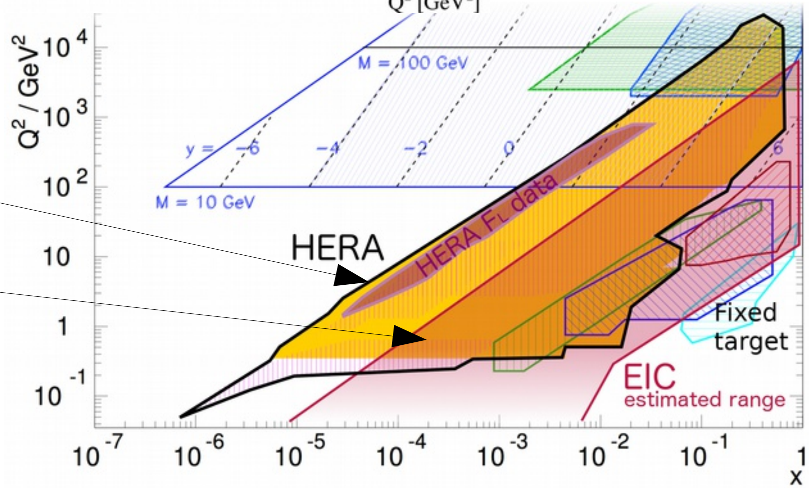
- Reasonable agreement of F_L and predictions
- HERA: small energy range √s=225-320 GeV, so only limited range of F_L is accessible
- **HERA+EIC: possible measurement of F_L over a much large range → powerful test of QCD**



H1/ZEUS compatible at 1-2σ

HERA measurements of F_L: large range in Q² but Q²/x is fixed.

EPJC 74 (2014) 2814
PRD 90 (2014) 072002

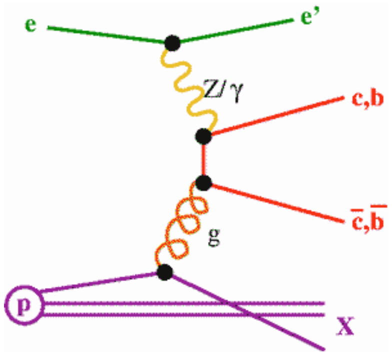


Hard probes: heavy flavour

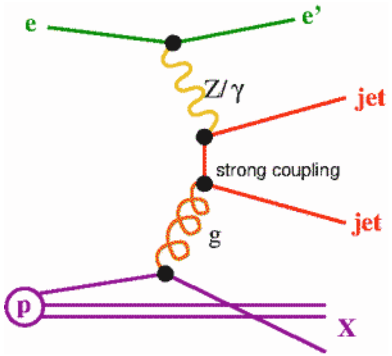
H1+ZEUS charm and beauty data combination
Charm and beauty masses

Heavy flavor and jet production

- Charm and beauty quarks or extra partons are emitted in higher order QCD processes
- Sensitive to fundamental QCD parameters: couplings and quark masses
- Measurement presented here
  - Charm and beauty structure functions



Example contribution to charm and beauty production

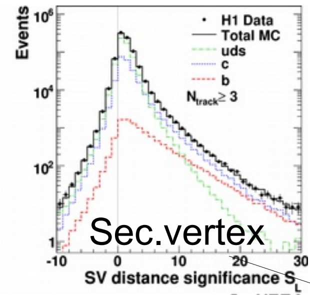


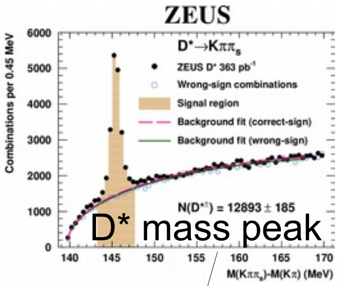
Example contribution to jet production

Charm and beauty data combination

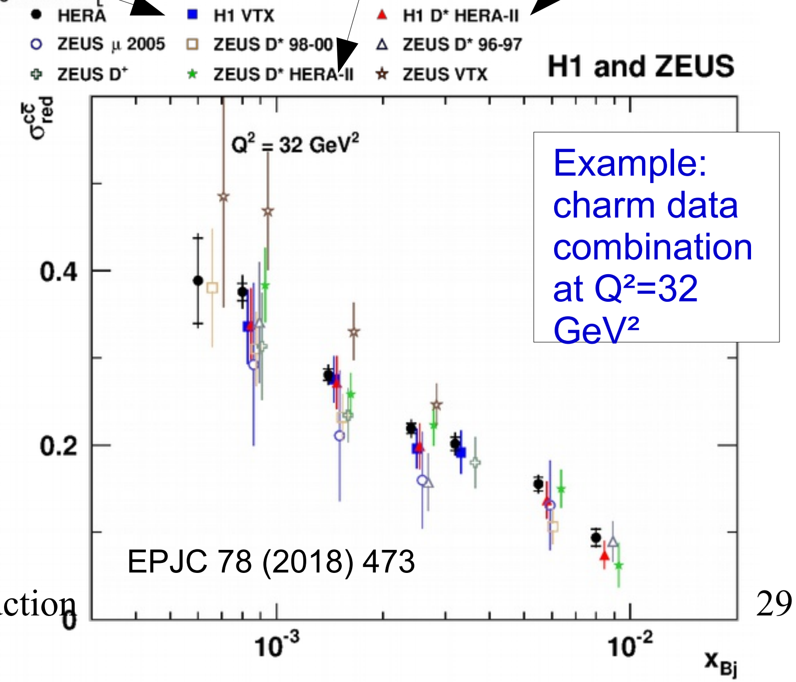
- Combination of 13 datasets on charm and beauty in DIS from H1 and ZEUS
- Experimental methods
  - Fully reconstructed D or D* decays
  - High P_T leptons from heavy flavor decays
  - Secondary decay vertices
- Accuracy of the combined data:

  ~5-9% for charm, ~15-25% for beauty





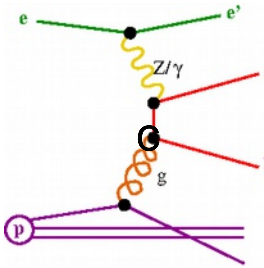
+11 more HERA (H1 or ZEUS) analyses

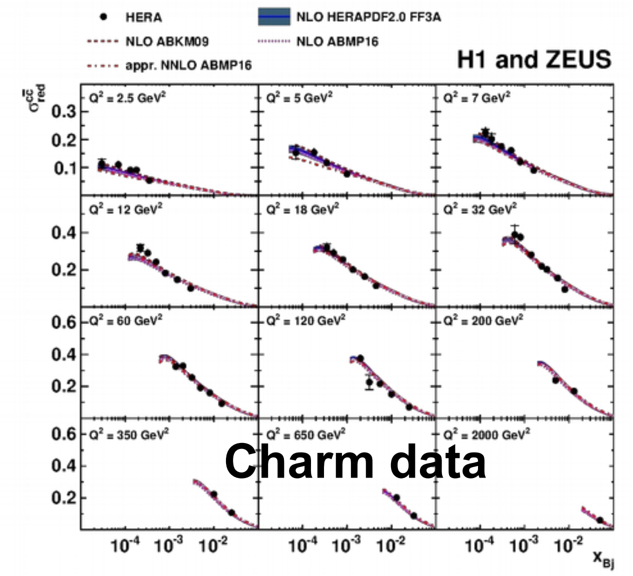


Example: charm data combination at Q²=32 GeV²

Structure functions with charm, beauty

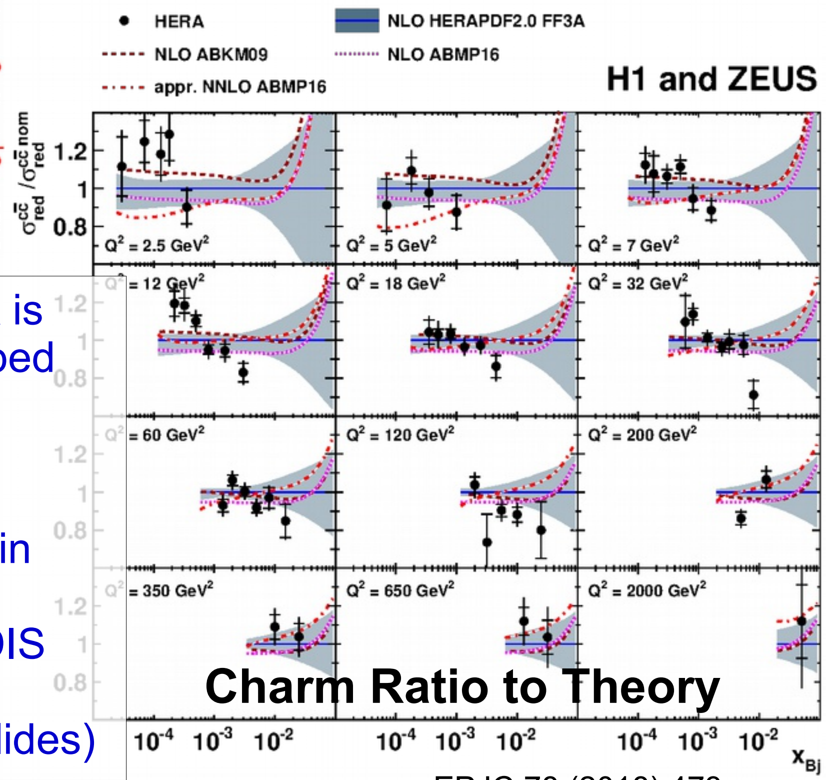
- Heavy quarks are produced mainly in boson-gluon fusion
- Theory is challenging: multiple hard scales, massive particles, etc





Q² is changing between subpanels
Each subpanel showns the x dependence

Shape in x is not described perfectly. Could be related to difficulties in describing inclusive DIS data (see previous slides)



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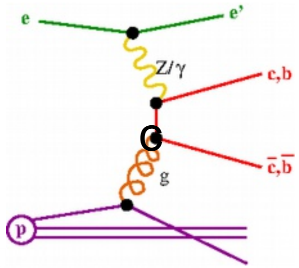
Structure functions with charm, beauty

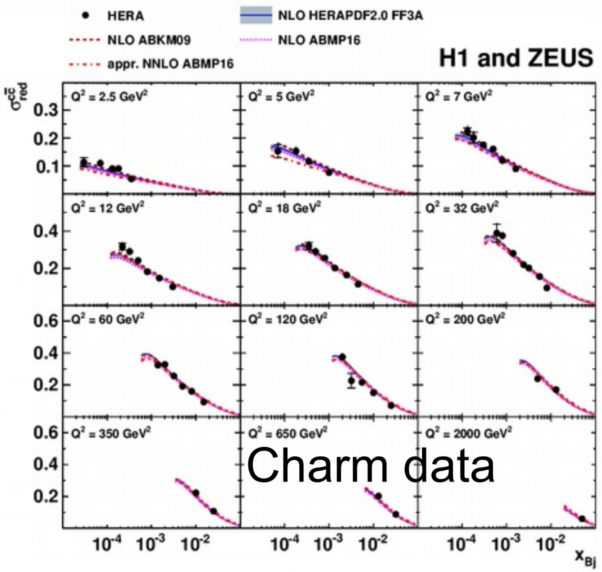
- Probability to produce heavy quark depends on its mass

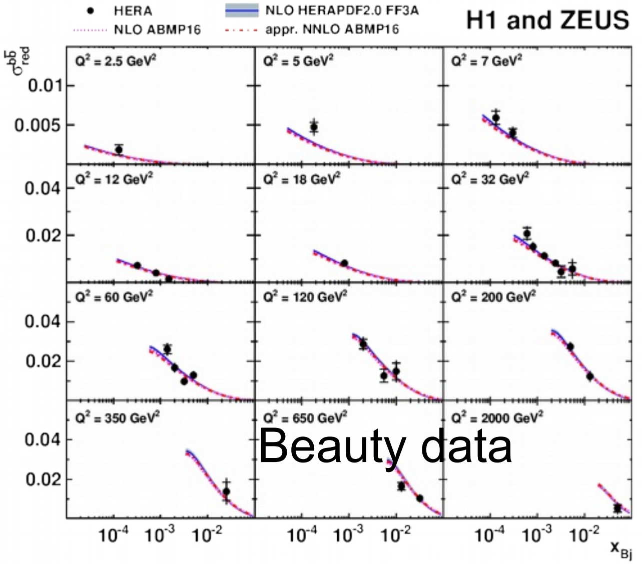
  → can extract quark masses m_c and m_b from HERA data alone:

$$m_c(m_c) = 1.290^{+0.077}_{-0.053}$$
$$m_b(m_b) = 4.049^{+0.138}_{-0.118}$$

Particle data group:
m_c =1.28±0.025 GeV
m_b = 4.18±0.03 GeV







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Data are statistically limited → **looking forward to have precision data from EIC**.

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Summary

- HERA: operated 1993-2007, still with active analyses
- New members are welcome in H1 or ZEUS, to contribute some of the studies we missed in the past
- Kinematic reconstruction: forward (proton) acceptance and photon radiation from electron line together limit the accessible range in (Q^2,x)

  $\rightarrow$ improvement at EIC expected from 3× lower centre-of-mass energy (at same Q^2 access ~10× higher x) and from better detector acceptance
- Some highlights from HERA combined data: inclusive cross sections, PDF fits, charm and beauty production in DIS

Backup slides

Accelerators for particle physics at DESY

- DESY was founded in 1959
- German national laboratory for particle physics, accelerators, synchrotron sources
- Accelerators for particle physics
  - DESY 1964-1978 [6 GeV]
    Since 1978: used as pre-accelerator only
  - DORIS 1974-1992 [e^+e^- $\sqrt{s}$=12 GeV]
    1992-2012: used as synchrotron source
  - PETRA 1978-1986 [e^+e^- $\sqrt{s}$=45 GeV]
    1990-2007: pre-accelerator, since 2009 synchrotron source
  - **HERA 1992-2007 [$e^\pm p$ $\sqrt{s}$=320 GeV]**
- DESY accelerators in 2020

  → photon science

~5 miles to city center

The Sigma method

- Kinematic reconstruction using four-vectors (neglecting p and e masses):

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

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

- HERA frame: electron beam along -z axis → ratios of 4-vector products result in expressions involving $(E\text{-}p_z)$

  For electron: $(E\text{-}p_z)_e = E_e(1\text{-}\cos\theta_e)$

  Low Q²: $(E\text{-}p_z)_e$ is close to $2E_e$

- Electron method:

$$y_e = \frac{2E_0 - E_e(1-\cos\theta_e)}{2E_0}$$

$$Q_e^2 = 2E_0E_e(1+\cos\theta_e)$$

- ISR effectively changes beam energy E_0 → very poor reconstruction of low y
- Sigma method: estimate effective E_0 from data and get y from hadrons

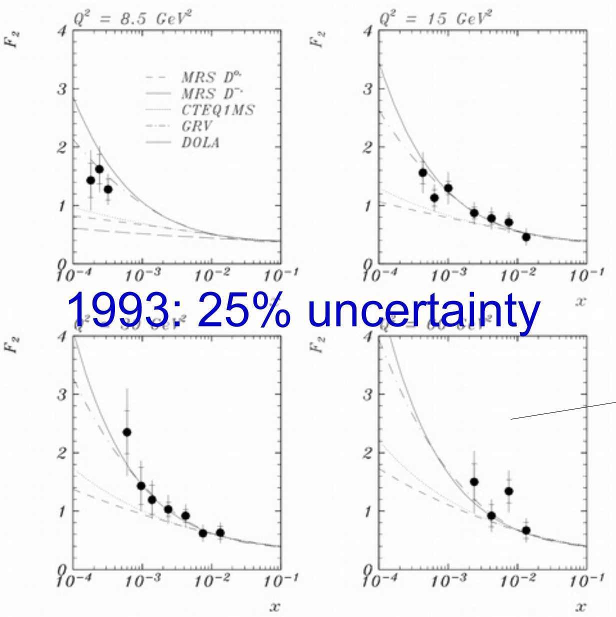
$$\Sigma = (E-p_z)_e + (E-p_z)_X$$

$$y_h \rightarrow y_\Sigma = \frac{(E-p_z)_X}{\Sigma}$$

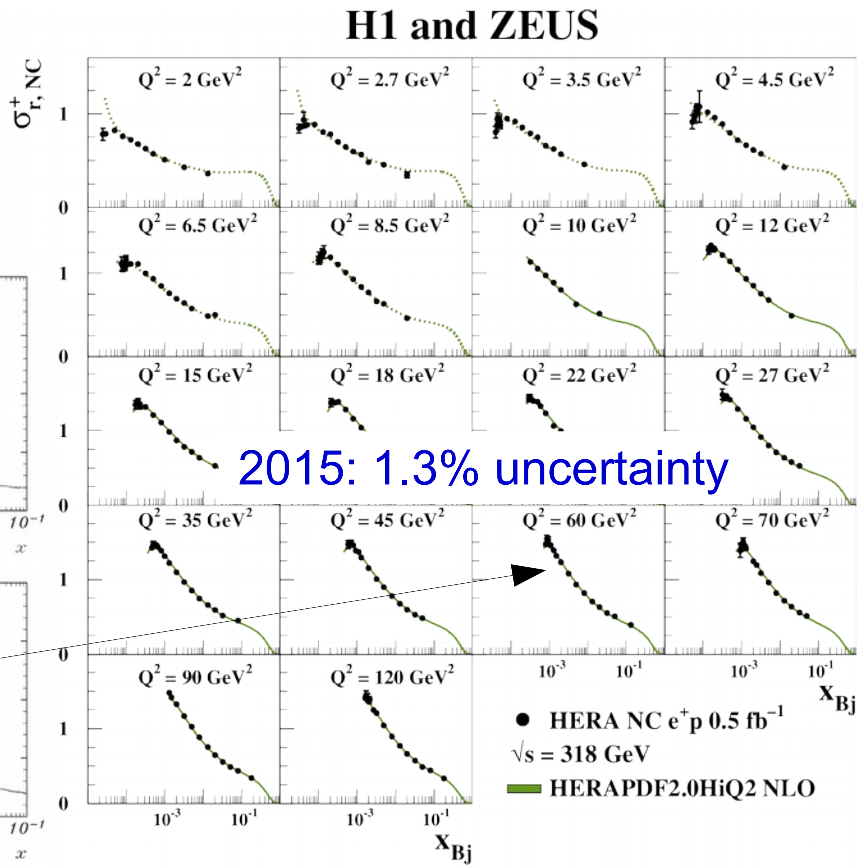
Take Q² from electron method (eΣ) or use Σ also in the Q² calculation

The HERA "discovery": rise of F_2 at low x

- **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



1993: 25% uncertainty



2015: 1.3% uncertainty

Towards the best precision: data combination

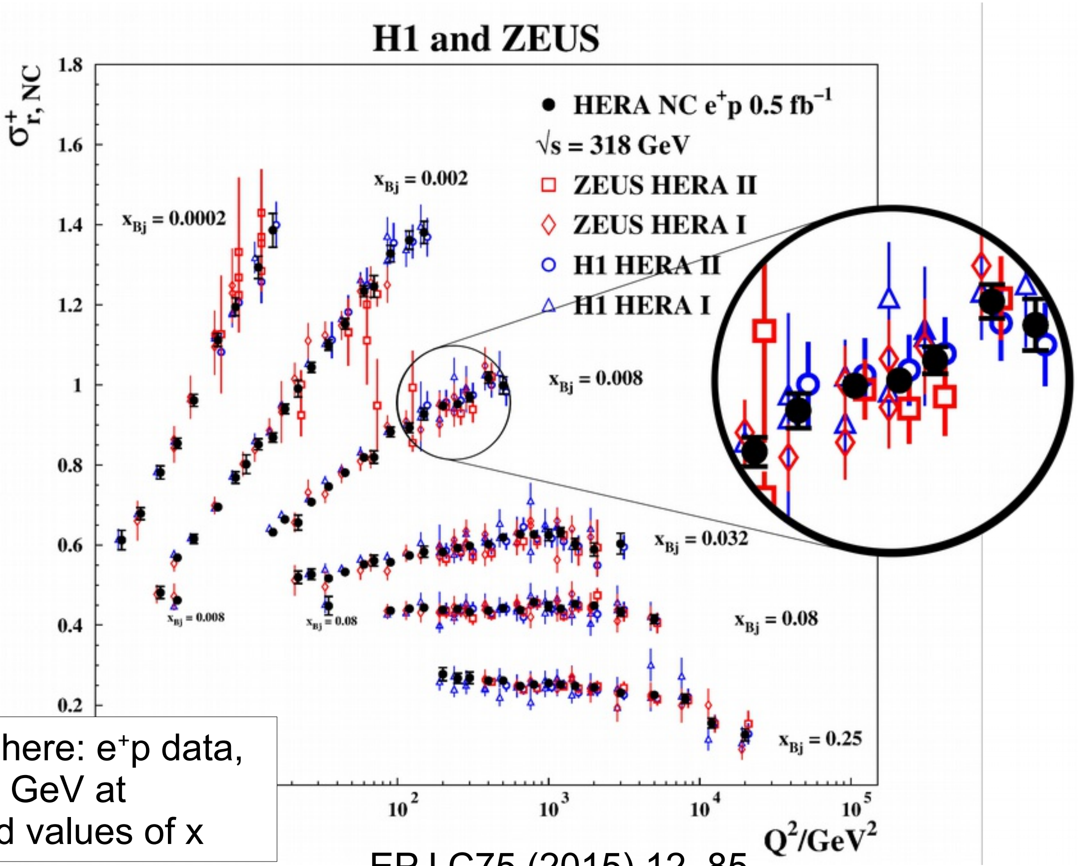
- Measurements of inclusive processes have been published in a total of

  41 H1 and ZEUS papers
- Data have been combined to a uniform HERA dataset: **EPJ C75 (2015) 12, 85**
  - 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 $\sqrt{s}$={225,252,300,318} GeV
- Precision better than 1.5% is reached for large parts of the data

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

- 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



Shown here: e^+p data, √s=320 GeV at selected values of x

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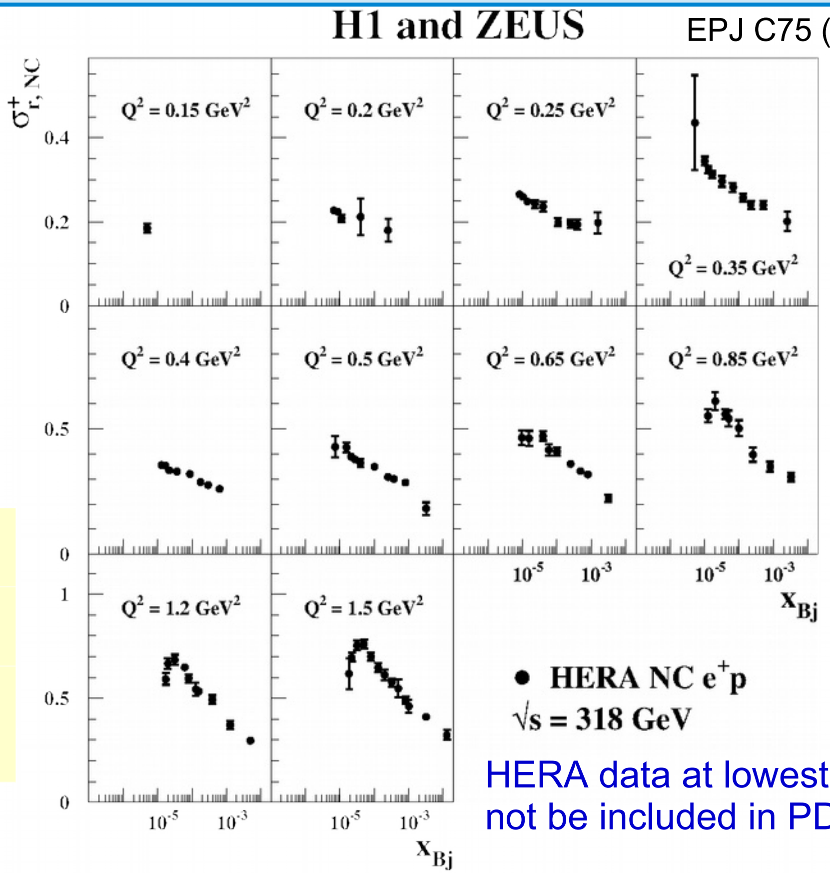
Transition to photoproduction

- At HERA, both deep-inelastic scattering ($Q^2>0$) and photoproduction ($Q^2=0$) can be measured
- Can map the transition region, where Q^2 is very small
- challenge for perturbative calculations

Perturbative QCD	Regge theory
High $Q^2 \gg 1$ GeV²	High energy $W \gg Q$
Q^2 evolution: DGLAP equations	W-dependence: Regge trajectories

$W=\sqrt{(q+p)^2}=Q^2(1/x-1)$ photon-proton energy

EPJ C75 (2015) 12, 85



HERA data at lowest Q² can not be included in PDF fit

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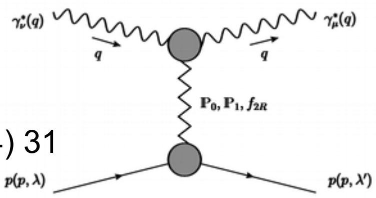
Fit of photoproduction and HERA DIS data

- Tensor-pomeron model (Ewerz, Maniatis, Nachtmann) Ann.Phys 342 (2014) 31
- Coherent description of photoproduction and low-x DIS data

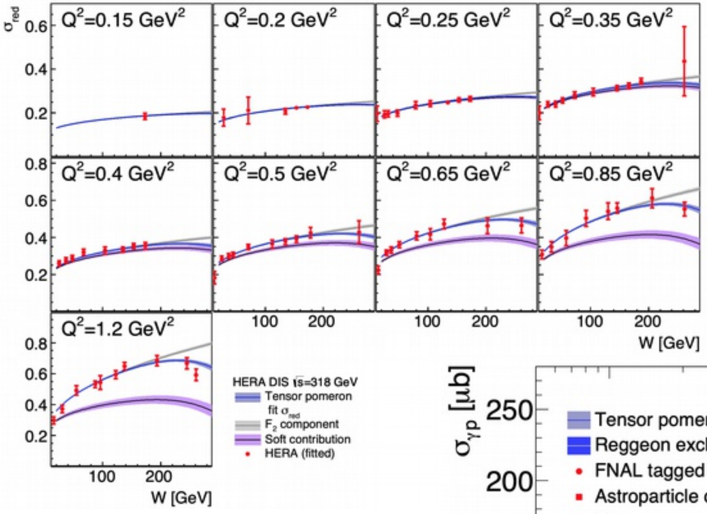


DIS cross section: forward virtual Compton scattering amplitude

- Fit three trajectories and Q² dependencies
  - Reggeon $\sim W^{2\epsilon_2}$ where $\epsilon_2 = 0.0485^{+0.0088}_{-0.0090}$
  - Hard Pomeron $\sim W^{2\epsilon_0}$ where $\epsilon_0 = 0.3008^{+0.0073}_{-0.0084}$
  - Soft pomeron $\sim W^{2\epsilon_1}$ where $\epsilon_1 = 0.0935^{+0.0076}_{-0.0064}$

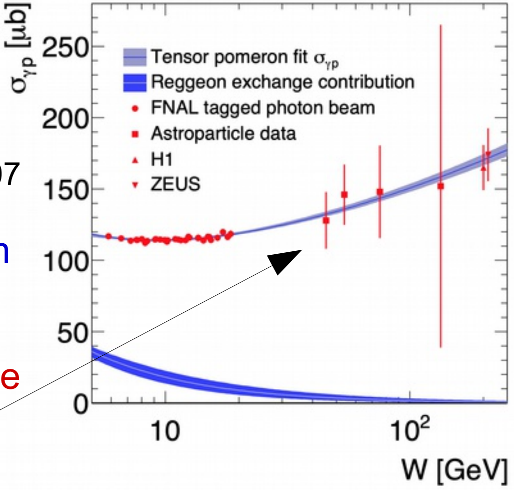
Compatible with canonical DL intercept $\alpha_0=1+\varepsilon=1.0808$

Good fit quality: $\chi^2/N_{D.F.}=587.9 / 536$ (probability 6%)



Subset of HERA DIS data at low Q² wrt. W

PRD 100 (2019) 114007



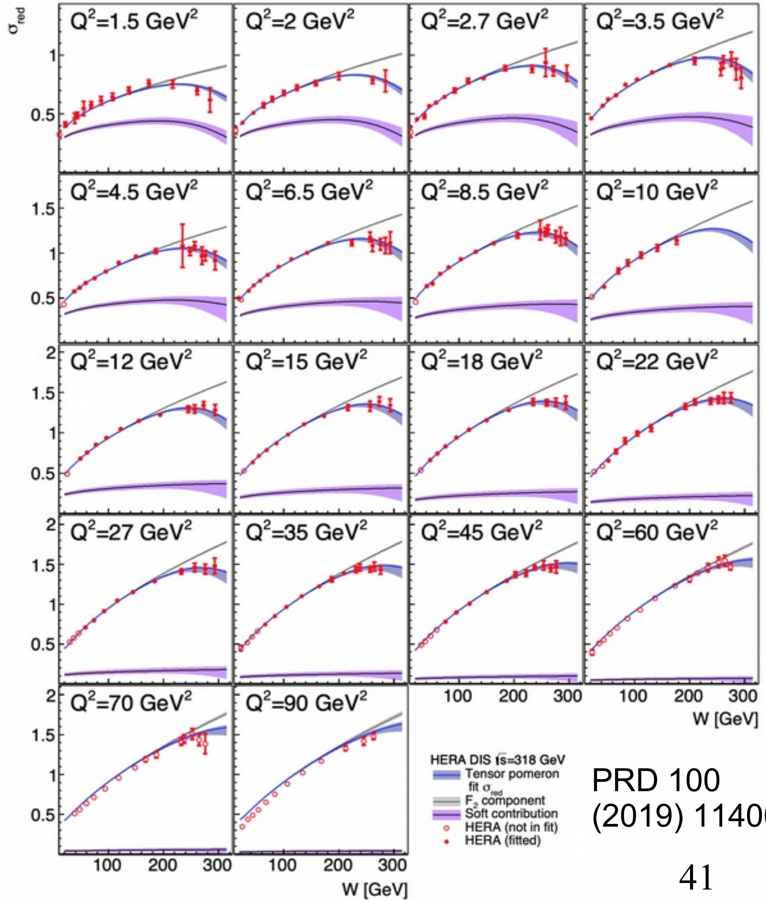
HERA photoproduction data: W~200 GeV

EIC data can bridge the gap to fixed target in photoproduction

Tensor pomeron fit at larger Q²

- HERA data at √s=318 GeV, Q²≥1.5 GeV²
- Described well by the Tensor pomeron fit
- **Soft pomeron contribution is significant even at Q²=10 GeV²**
- Could be an indication of sizable non-perturbative contributions to the DIS data relevant for PDF fits

  (e.g. HERAPDF fit includes data at Q²≥3.5 GeV²)



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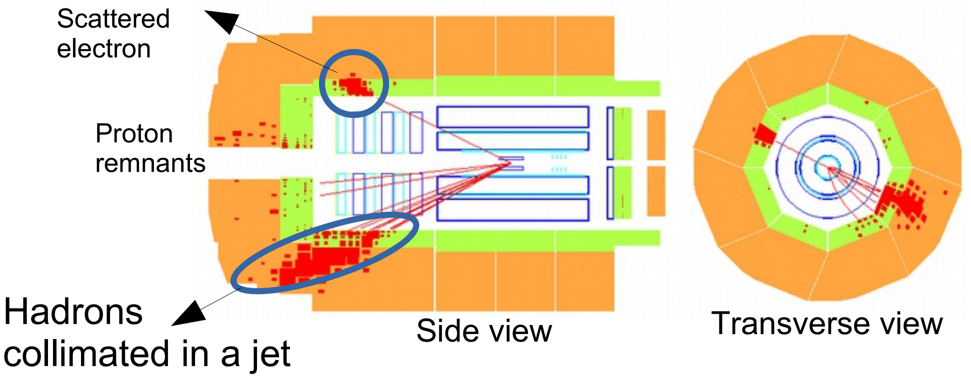
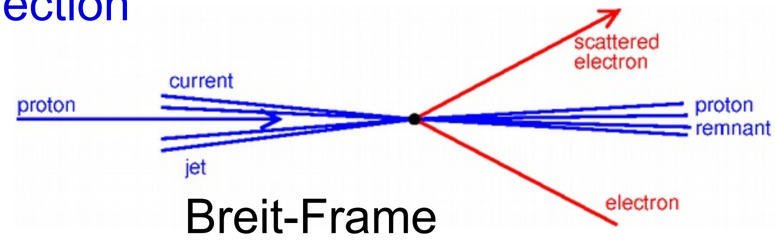
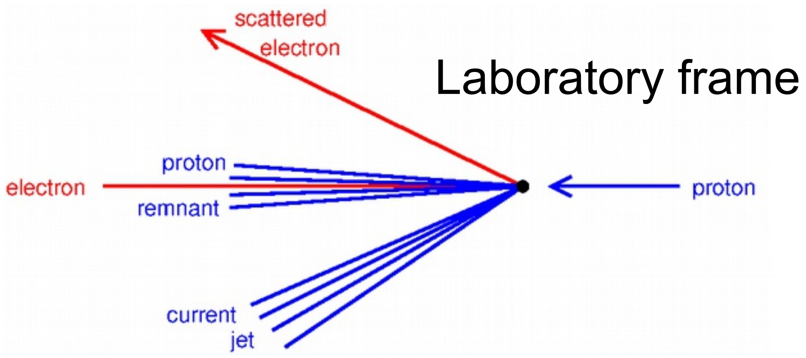
Jet production in the Breit frame

- Hadrons are emitted in jets
- Interpretation: a parton is scattered off the proton and fragments
- Breit-frame: Lorentz-transformation to have proton remnant and current-jet well separated
- Measure the emission of further jets which have P_T>0 wrt expected current jet direction

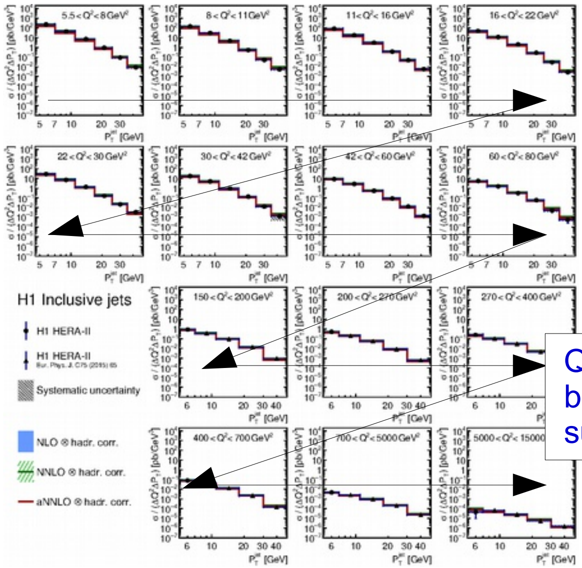




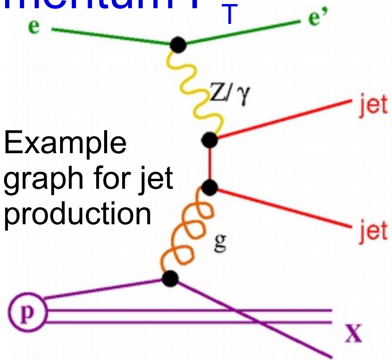


Jet cross section measurements

- Jet production measured as a function of Q^2 and the jet transverse momentum P_T



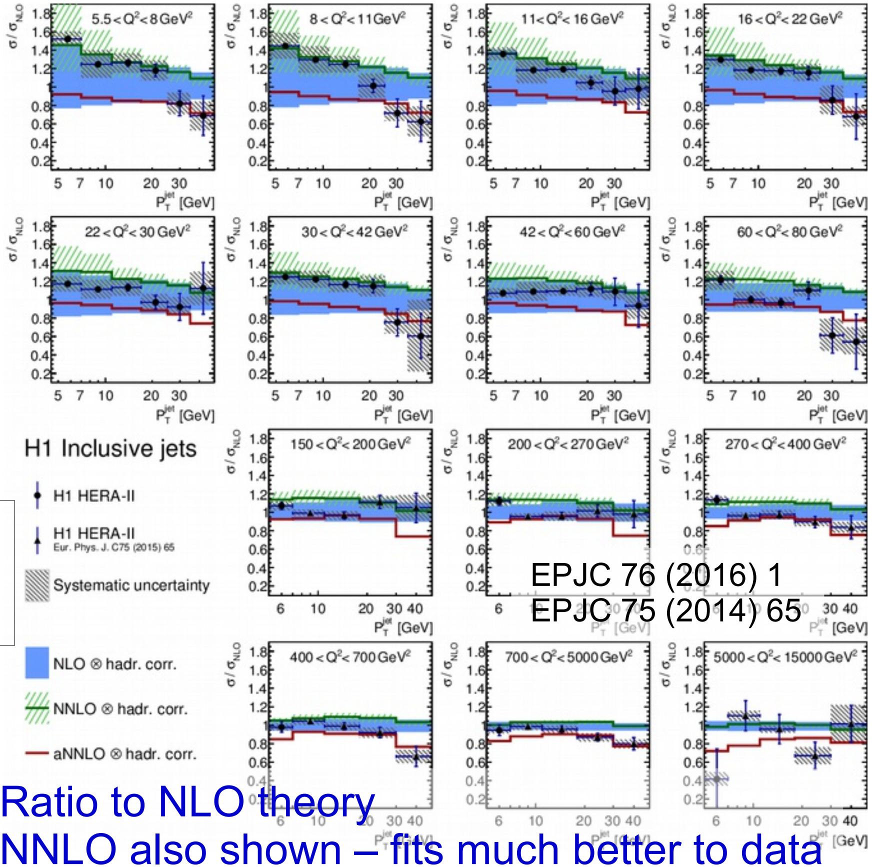
Q² increases between subfigures



Example graph for jet production

Accuracy: 1-2% plus 2.5% normalisation

Achieved with sophisticated unfolding technique



EPJC 76 (2016) 1
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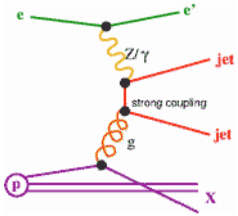
Each subfigures shows the P_T dependence
Steeply falling cross section → look at ratio to theory

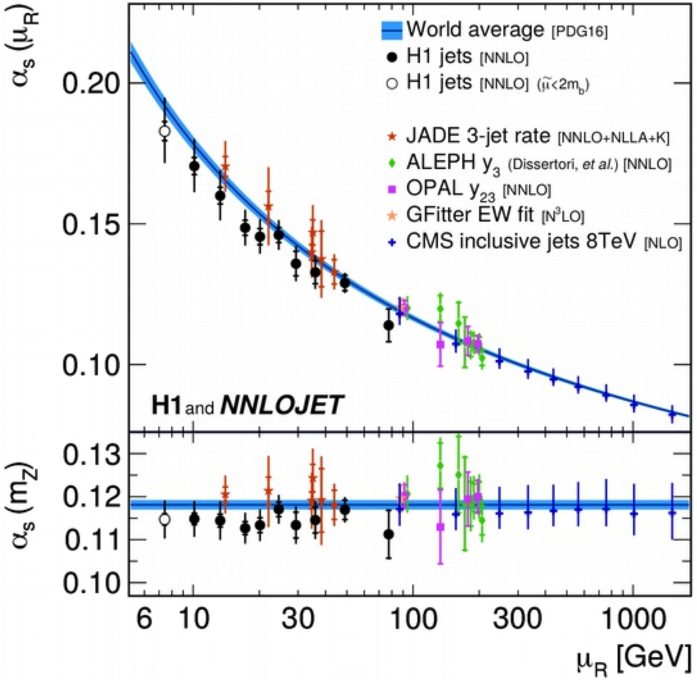
Ratio to NLO theory
NNLO also shown – fits much better to data

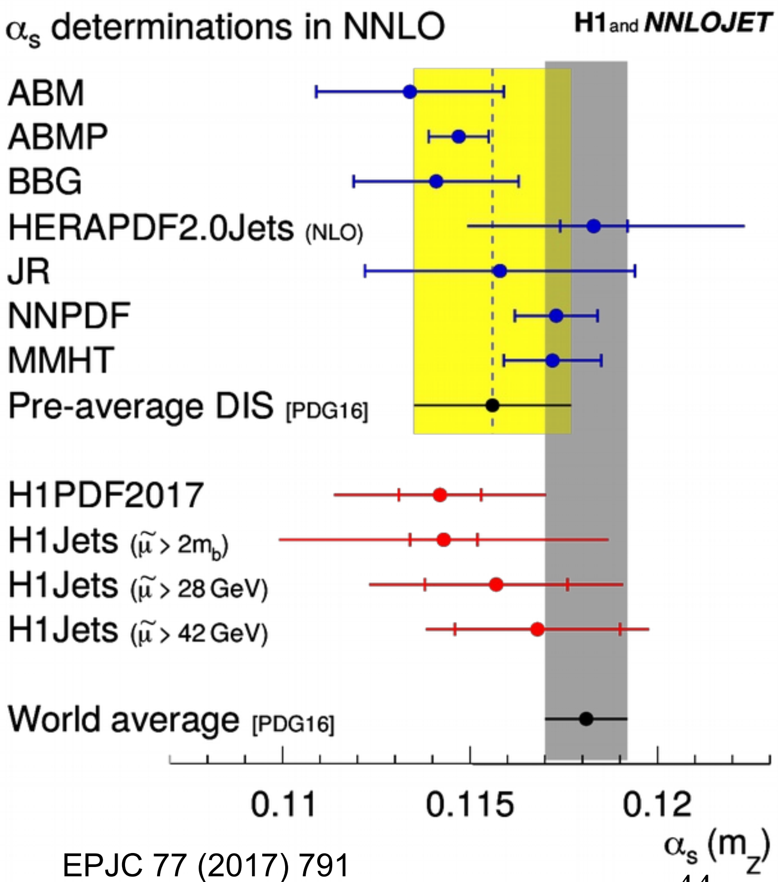
Measurement of α_s

- Fundamental parameter in QCD: coupling α_s
- Coupling is running with the scale $\mu^2=Q^2+P_T^2$



- Probe this running in a single experiment
- Extract the coupling at the conventional scale $\mu=m_Z$





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