Proton Structure and PDFs at HERA

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On Behalf of the ZEUS and H1 Collaborations

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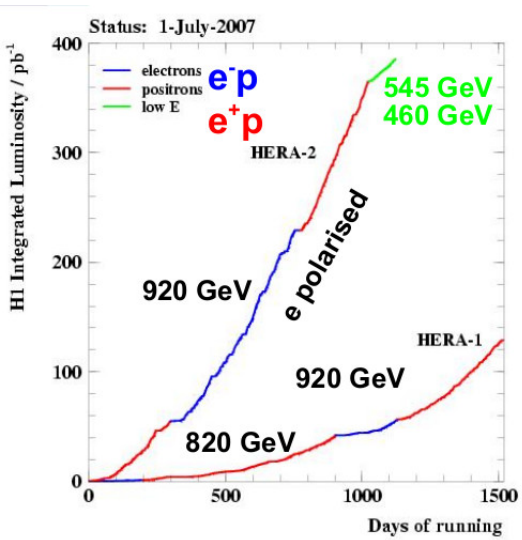
DESY Hamburg, Germany

1. Inclusive NC and CC Cross Sections
2. (HERA) PDFs
   - charm contribution
3. (HERA)PDFs @ LHC

The HERA Collider



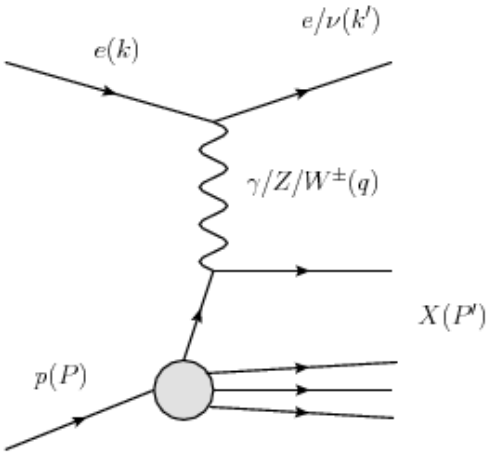
Integrated luminosity:
$1\ \mathrm{fb}^{-1}$ (H1 and ZEUS)

- HERA: electron-proton collider with $\sqrt{s} = 318\ \mathrm{GeV}$

27.5 GeV 920 GeV

- Two *ep* colliding experiments: H1 and ZEUS
- Two data-taking periods: HERA I (92-00) and HERA II (03-07)
- HERA-II: longitudinally polarised lepton beam

DIS @ HERA

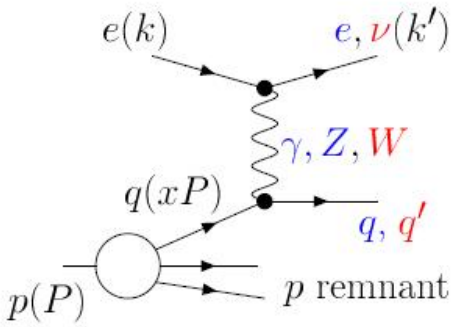


- Neutral Current (NC), γ or Z exchange.
  $e^{\pm}p \rightarrow e^{\pm}X$
- Charged Current (CC), $W^{\pm}$ exchange.
  $e^{\pm}p \rightarrow \nu X$

Variables describing DIS @ HERA:

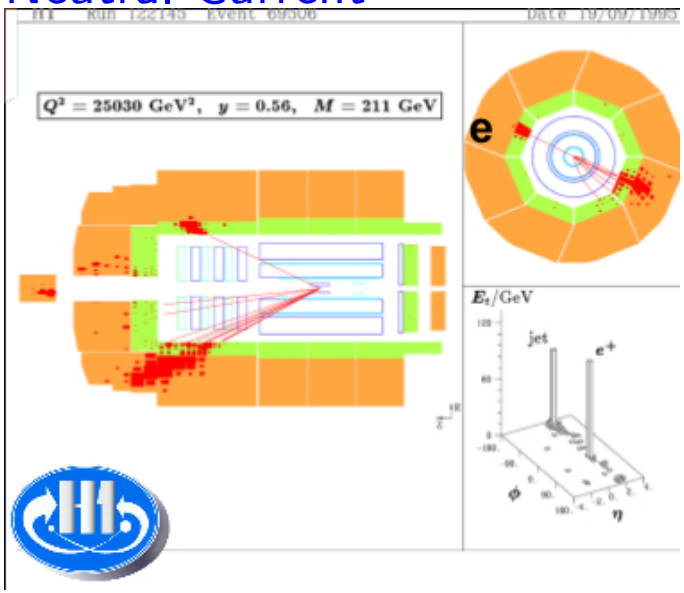
- Q^2 probing power, negative 4-momentum squared:
  $Q^2 = -q^2 = -(k - k')$
- Bjorken x, momentum fraction of proton carried by struck quark:
  $x = Q^2/2P \cdot q$
- Inelasticity y:
  $y = P \cdot q/P \cdot k$
- s is the centre-of-mass energy squared:
  $s = (P + k)^2$
- These are related by:
  $Q^2 = sxy$

NC and CC Events

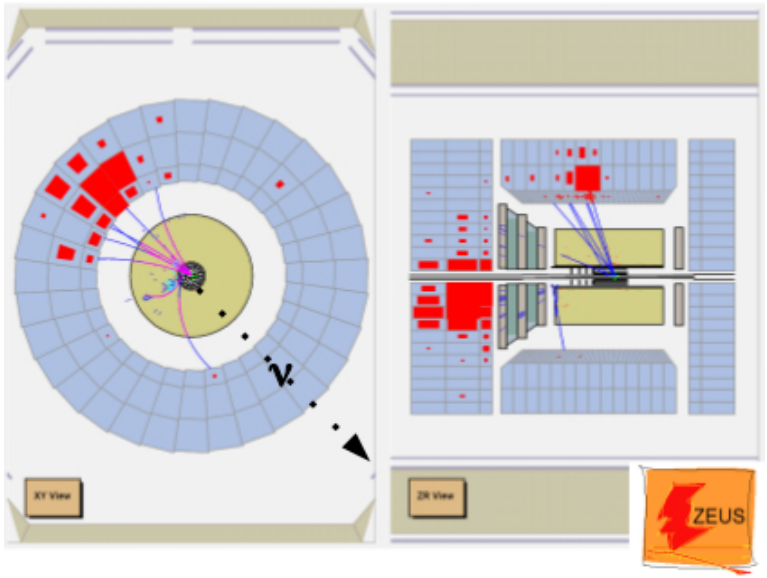


Factorisation: $\sigma \approx \hat{\sigma} \otimes PDF$

Neutral Current

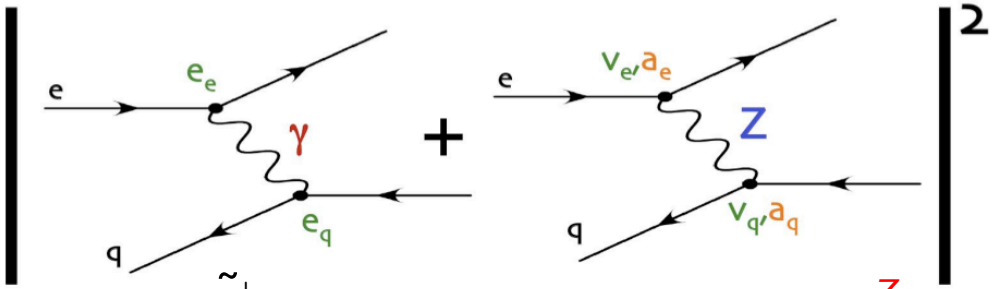


Charged Current



Proton Structure Functions: NCDIS

$$\frac{d^2\sigma_{NC}^{e^\pm p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[\underbrace{Y_+\tilde{F}_2(x,Q^2)}_{\text{dominant}} \mp \underbrace{Y_- x\tilde{F}_3(x,Q^2)}_{\text{relevant at high } Q^2} - \underbrace{y^2\tilde{F}_L(x,Q^2)}_{\text{relevant at high } y}\right]$$



where

$$Y_\pm = 1 \pm (1-y)^2$$

$$\tilde{F_2^\pm} = F_2^\gamma - (v_e \mp P_e a_e)\chi_Z F_2^{\gamma Z} + (v_e^2 + a_e^2 \mp 2P_e v_e a_e)\chi_Z^2 F_2^Z$$

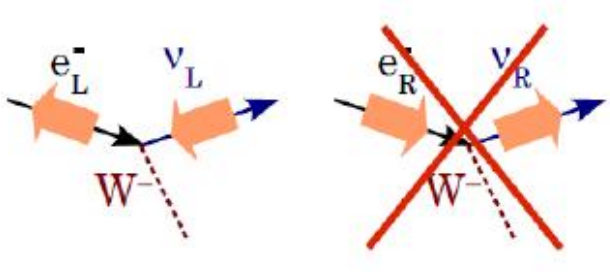
$$x\tilde{F_3^\pm} = -(a_e \mp P_e v_e)\chi_Z x F_3^{\gamma Z} + (\mp P_e(v_e^2 + a_e^2) + 2v_e a_e)\chi_Z^2 x F_3^Z$$

- $[F_2^\gamma, F_2^{\gamma Z}, F_2^Z] = \sum_q [e_q^2, 2e_q v_q, v_q^2 + a_q^2] x(q + \bar{q})$
- $[xF_3^{\gamma Z}, xF_3^Z] = \sum_q [e_q a_q, v_q a_q] x(q - \bar{q})$
- $\tilde{F_L} \approx \frac{\alpha_s}{8.3} xg$

HERA providing access to $e^- p$ and $e^+ p$ with RH, LH, 0 polarisation.

Proton Structure Functions: CCDIS

$$\frac{d^2\sigma^{\pm}_{\mathrm{CC}}}{dxdQ^2} = (1 \pm P_e)\frac{G_F^2}{4\pi x}\kappa^2 \cdot \left[Y_+ W_2^{\pm} \mp Y_- x W_3^{\pm} - y^2 W_L^{\pm}\right] \cdot (1+\delta^{\mathrm{CC}})$$



$$\kappa = \frac{M_W^2}{M_W^2 + Q^2}$$

$$W_2^+ = x[d + s + \bar{u} + \bar{c}] \qquad W_2^- = x[\bar{d} + \bar{s} + u + c]$$

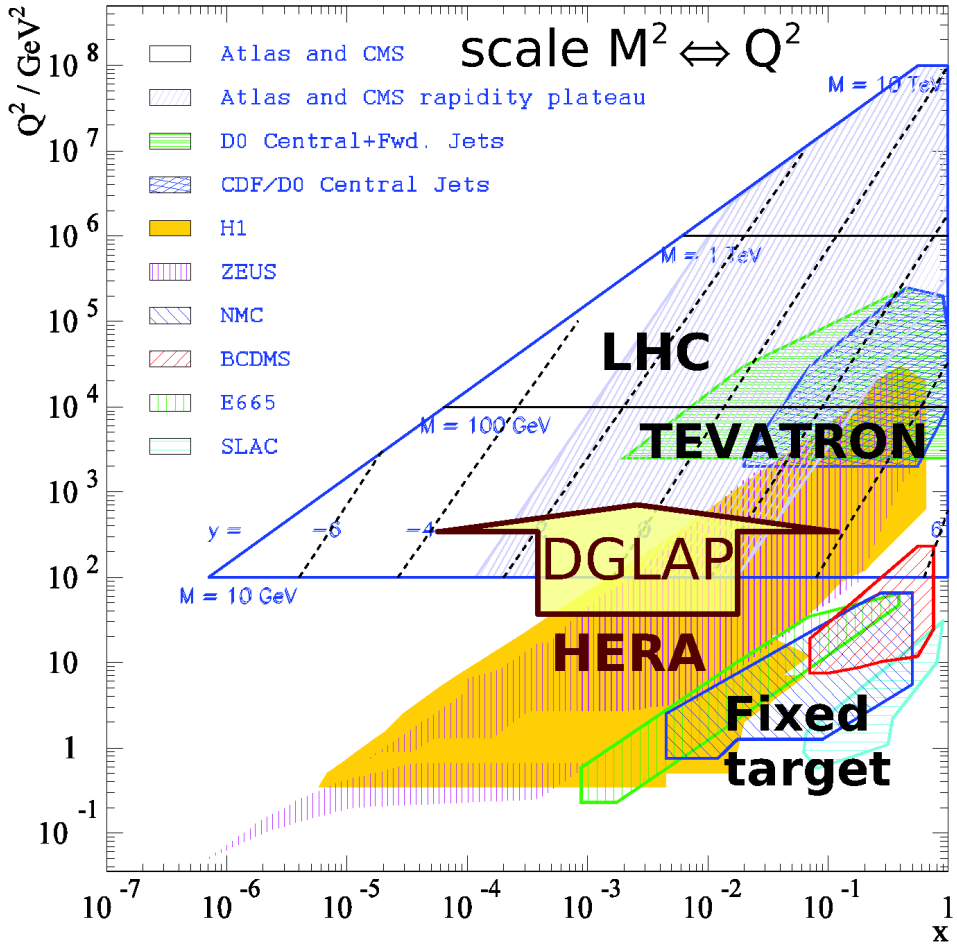
$$xW_3^+ = x[d + s - \bar{u} - \bar{c}] \qquad xW_3^- = x[\bar{d} + \bar{s} - u - c]$$

- e^- and e^+ sensitive to different quark densities
- linear dependence on polarisation

HERA and the LHC

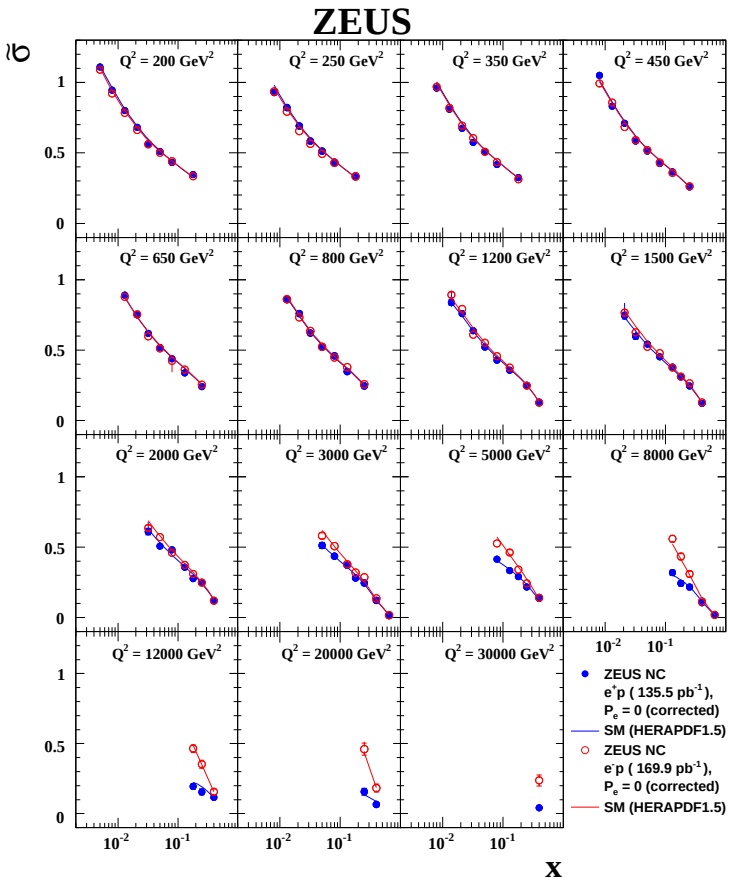
HERA data is indispensable for PDFs.

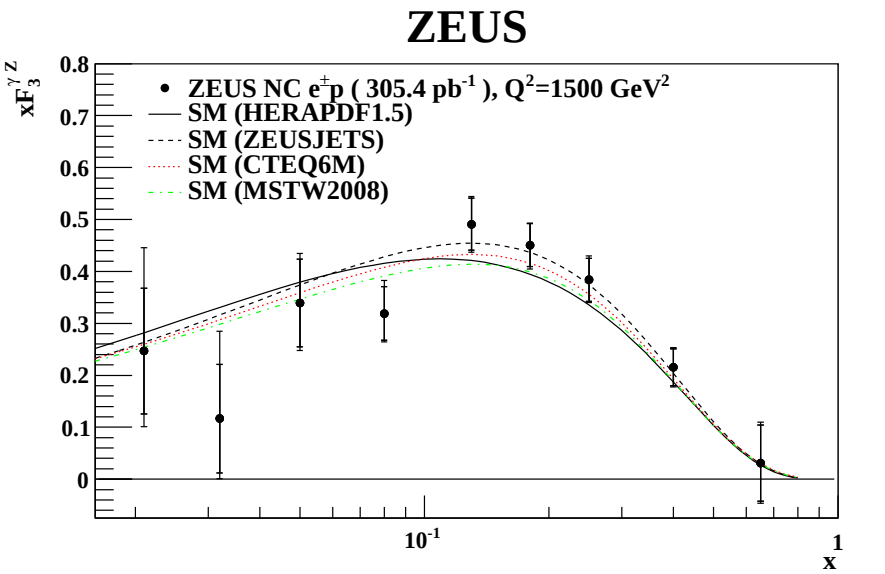
- HERA has a large kinematic reach covering nearly the whole x region relevant for the LHC.
- HERA PDFs can be extrapolated into the LHC region (DGLAP evolution).
- HERA data crucial for calculations of measurements and new physics at the LHC.



Final Pieces of NC - F_2, F_3

H1 JHEP 09 (2012) 061 and ZEUS Phys Rev D Vol 87: 052014 published the final pieces of HERA-II NC inclusive data.





$$x\tilde{F}_3(x,Q^2) = \frac{Y_+}{2Y_-}\left(\tilde{\sigma}^{e^-p} - \tilde{\sigma}^{e^+p}\right)$$

$\rightarrow$Precision measurement of e^-p and e^+p NC DIS enables precise xF_3 extraction.

Final Pieces of NC - Asymmetry, $F_2^{\gamma Z}$

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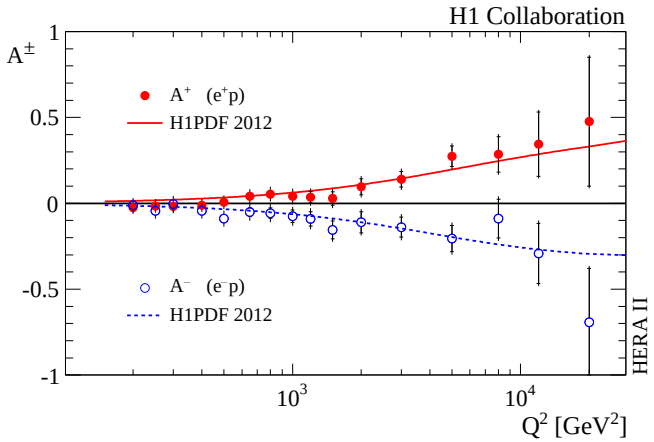
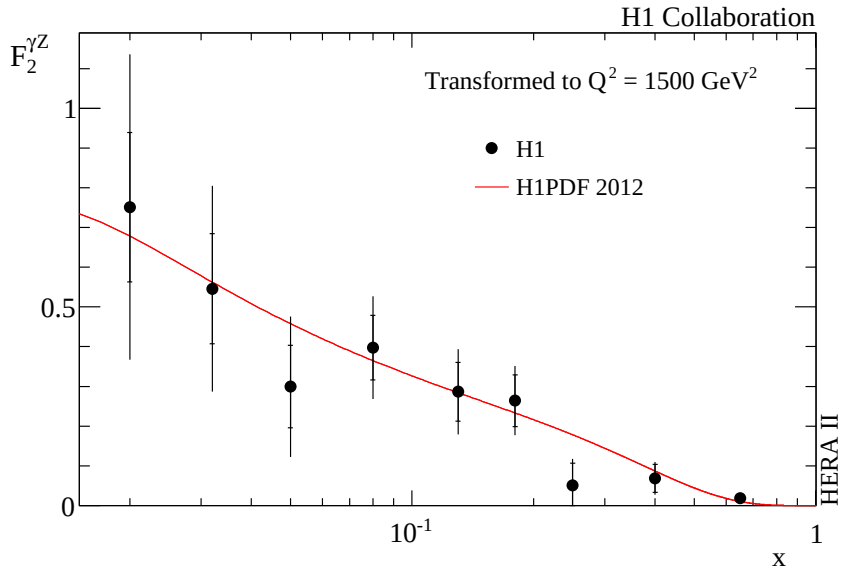


$$A^{\pm} = \frac{2}{P_{e,R} - P_{e,L}} \cdot \frac{\sigma(P_{e,R}) - \sigma(P_{e,L})}{\sigma(P_{e,R}) + \sigma(P_{e,L})}$$

$$\approx \pm a_e \chi_Z \frac{F_2^{\gamma Z}}{F_2^{\gamma}} = a_e \chi_Z \frac{2 e_q v_q}{e_q^2} \propto a_e v_q$$

- Direct measure of parity violation.
- A sensitive to v_q.
- $|A|$ increases with Q^2, $A^- = -A^+$.

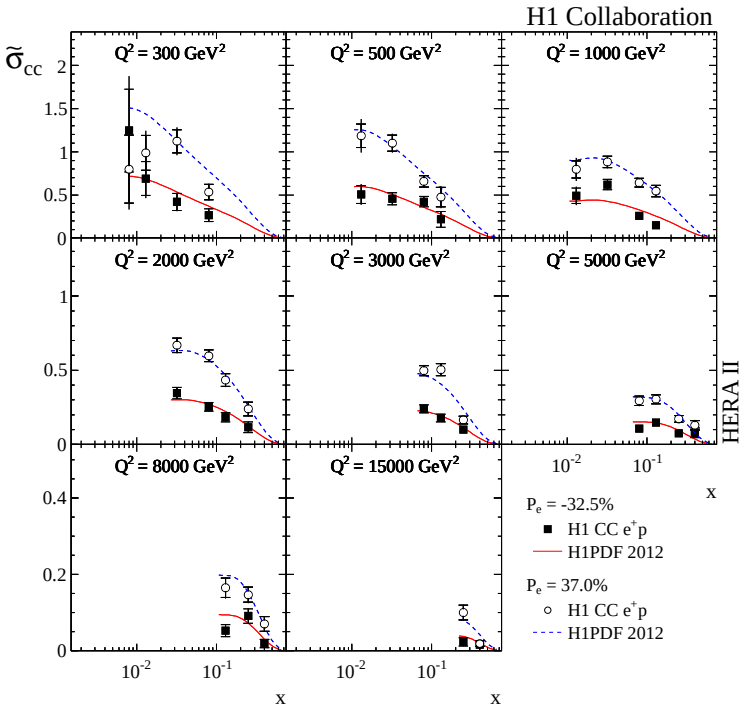


$$\tilde{F_2^{\pm}} = F_2^{\gamma} - (v_e \mp P_e a_e)\chi_Z F_2^{\gamma Z} + (v_e^2 + a_e^2 \mp 2 P_e v_e a_e)\chi_Z^2 F_2^Z$$

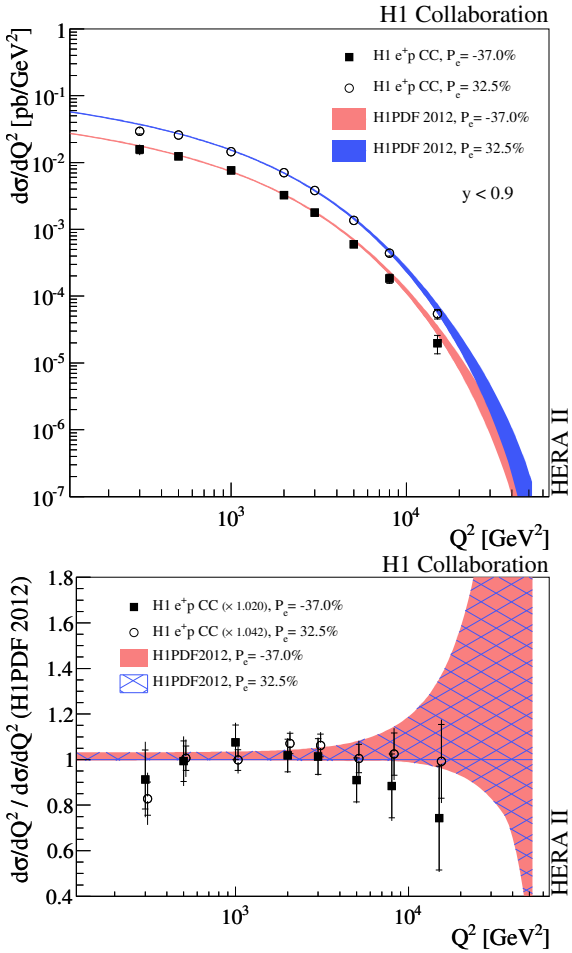
First measurement of $F_2^{\gamma Z}$, sensitive to v_q.

Final Pieces of CC

H1 JHEP 09 (2012) 061 and ZEUS EPJ C 70, Issue 4 (2010) 945-963 published the final pieces of HERA-II CC inclusive data.

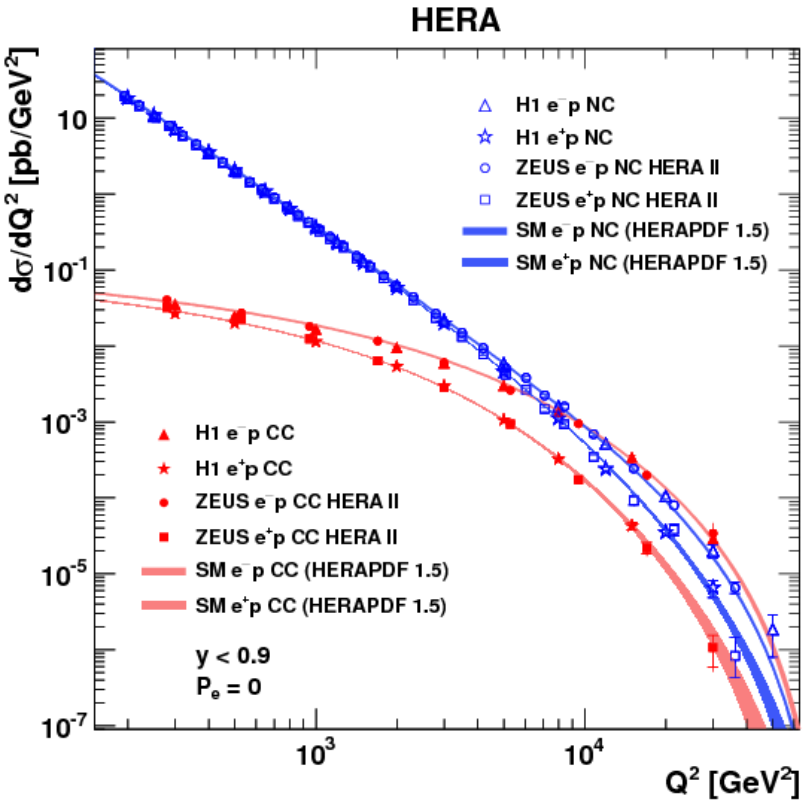


Expected dependence on polarisation shown.
Precise CC measurements probe quark flavours.

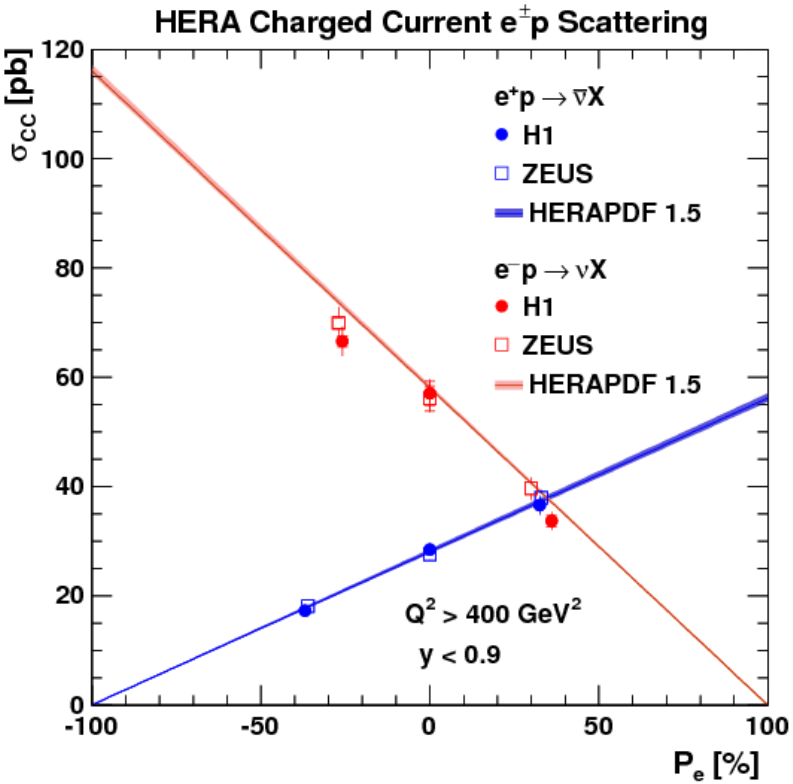


Inclusive NC and CC: HERA Textbook Plots

Electroweak Unification

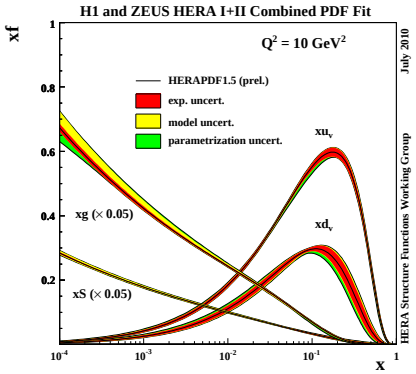


Linear Polarisation Dependence



Good agreement with SM (HERAPDF 1.5) prediction.

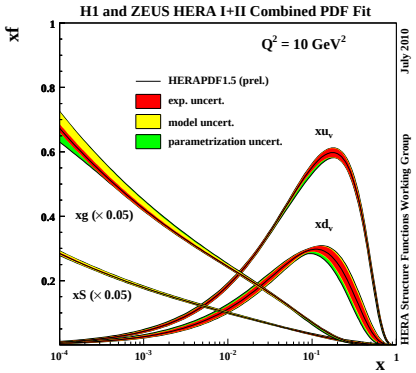
HERAPDFs



HERA data allows providing PDFs **exclusively** from HERA data
$\longrightarrow$ well understood correlations, no need for nuclear corrections.

HERAPDF Version	Included data	Order
HERAPDF 1.0	HERA-I NC,CC data	NLO, NNLO
HERAPDF 1.5	HERA-I NC,CC data partial HERA-II data	LO, NLO, NNLO recommended
HERAPDF 1.6	HERA-I NC,CC data partial HERA-II data, jets	NLO
HERAPDF 1.0 +charm	HERA-I NC,CC data charm	NLO
HERAPDF 1.7	HERA-I NC,CC data partial HERA-II data, jets, charm	NLO

HERAPDFs



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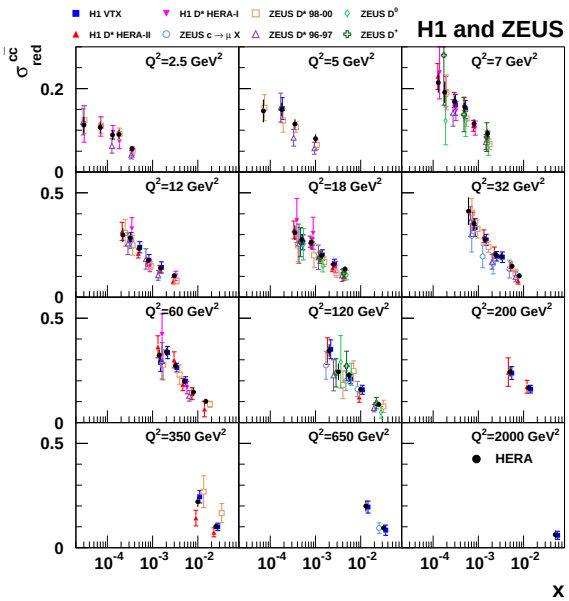
HERAPDF 1.7	HERA-I NC,CC data partial HERA-II data, jets, charm	NLO
HERAPDF 2.0	HERA-I NC,CC data HERA-II data	LO, NLO, NNLO planned

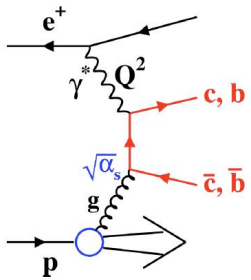
Charm Combination

H1 and ZEUS combined their charm data and included it in PDF fits

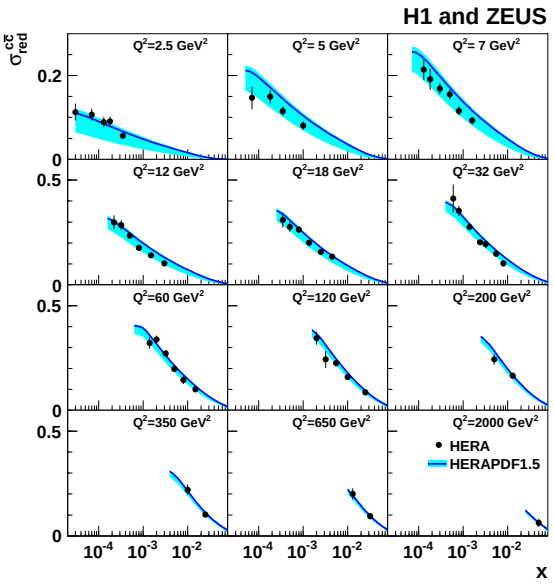
Eur. Phys. J. C73 (2013) 2311.



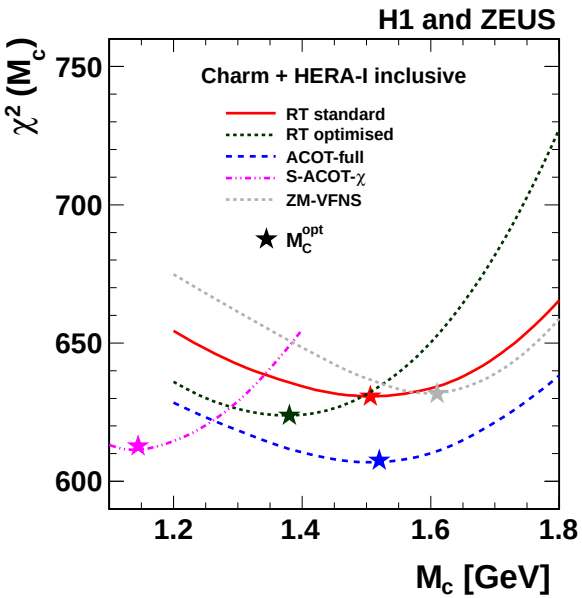
Boson-gluon-fusion⟶direct access to gluon.



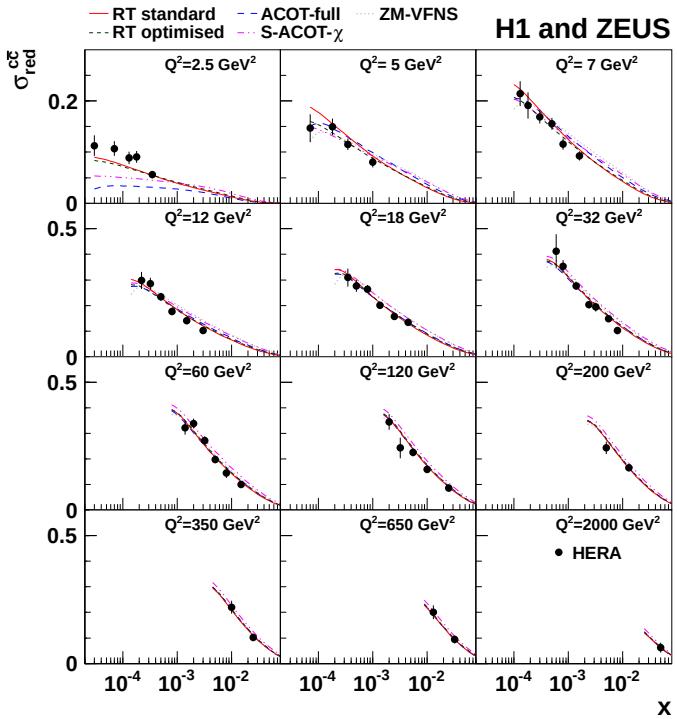
Large gain on precision by combination.



Charm mass scan

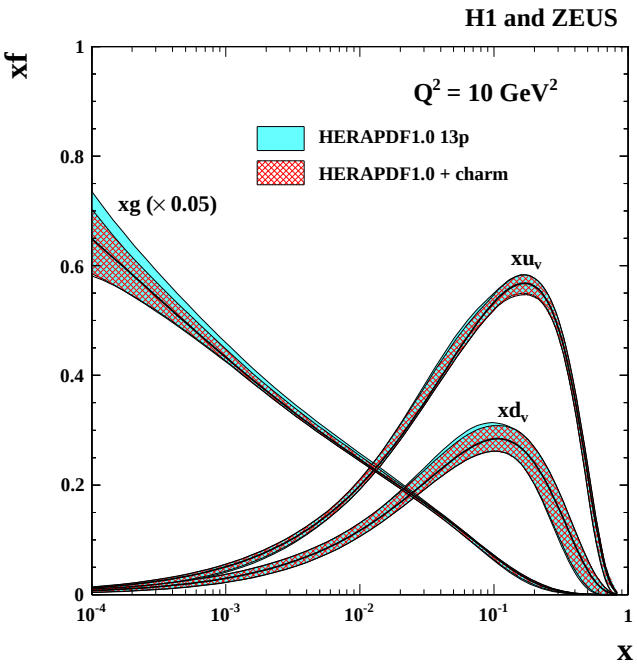


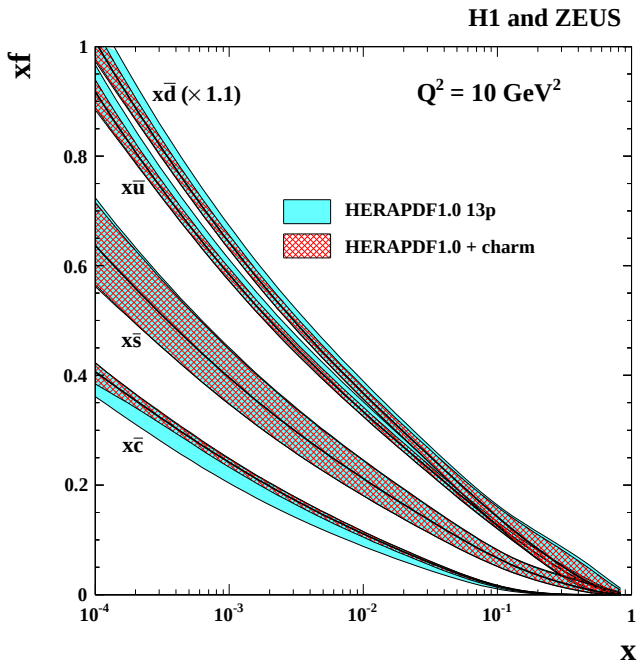
χ^2 scans of the QCD fits determining the best charm mass parameter for different implementations of the VFNS.



Different schemes prefer different charm mass parameters.

Impact of Charm on PDFs

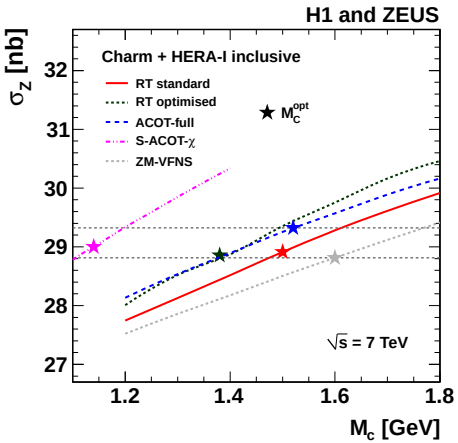




- Reduction of charm distribution function uncertainty.
- Influence on gluon and light sea.

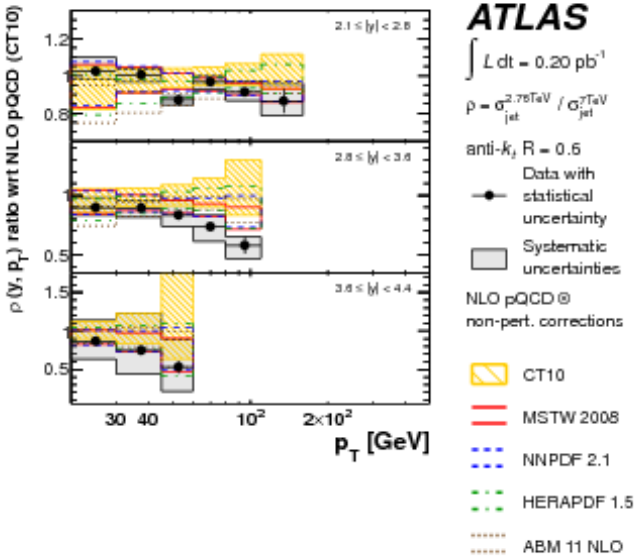
PDFs for LHC

Eur. Phys. J. C73 (2013) 2311



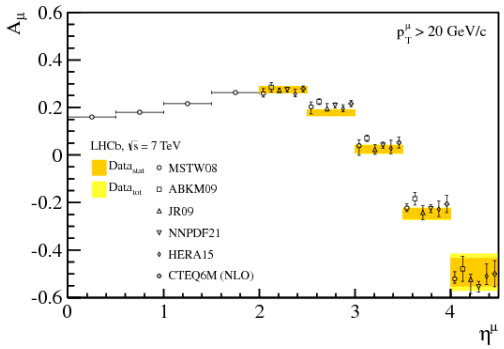
Charm data reduces uncertainty from 6% to 2% for Z and W production predictions.

Eur.Phys.J. C73 (2013) 2509



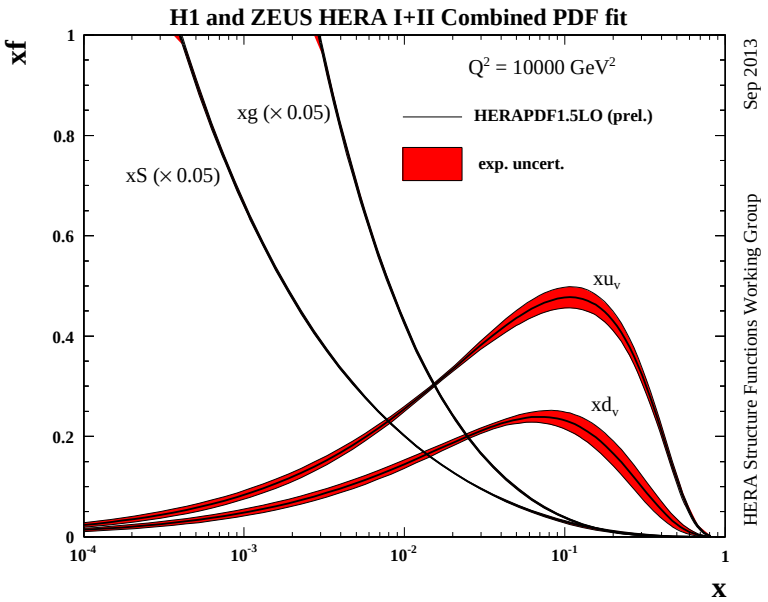
Jets are sensitive to gluon and α_s.

JHEP 1206 (2012) 058



W lepton asymmetry is sensitive to difference $u_v - d_v$.

New: HERAPDF 1.5 LO



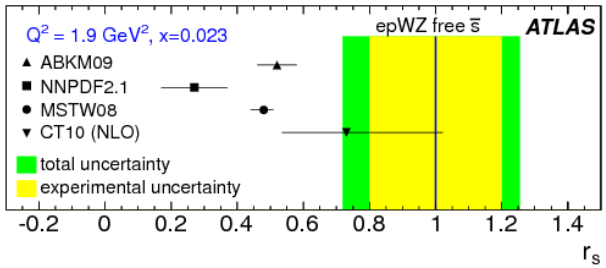
PDFs at LO are essential for the proper simulation of parton showers and underlying event properties.

Now: HERAPDF 1.5 LO available.

HERAFitter

- Finding the maximum out about proton structure
  using the high precision HERA data
- Need easy access to the data and PDF fitting → **HERAFitter**
- Open source project for QCD fits, available at herafitter.org
- Easy to use, everybody can download, include data and fit
- Heritage of HERA transferred to the world
- About 30 developers from HERA and LHC experiments as well as theory
- → more details in Renat Sadykov's talk

Phys.Rev.Lett. 109 (2012) 012001



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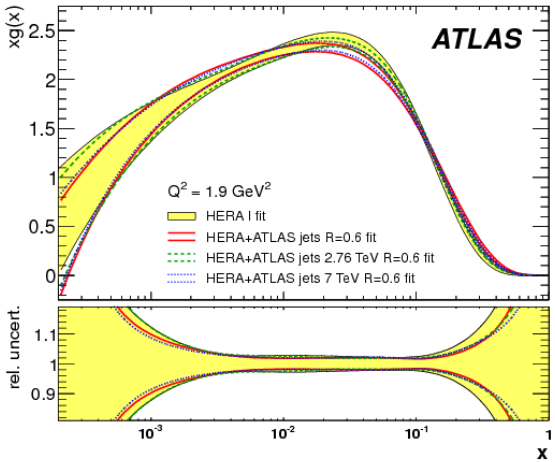
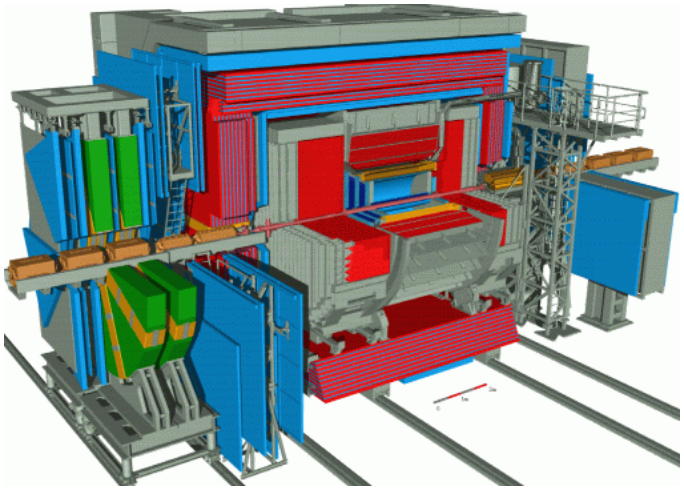


Conclusion

- HERA remains the main source of information on proton structure
- NC and CC HERA-II final cross sections published
- Impressive precision of the data used to extract the PDFs reached
- Jet and charm data included in PDF fits
- Understanding of the PDFs very important for LHC
- Final HERA PDF fits are on the way.
- With HERAFitter a powerful open source QCD fit framework is available.

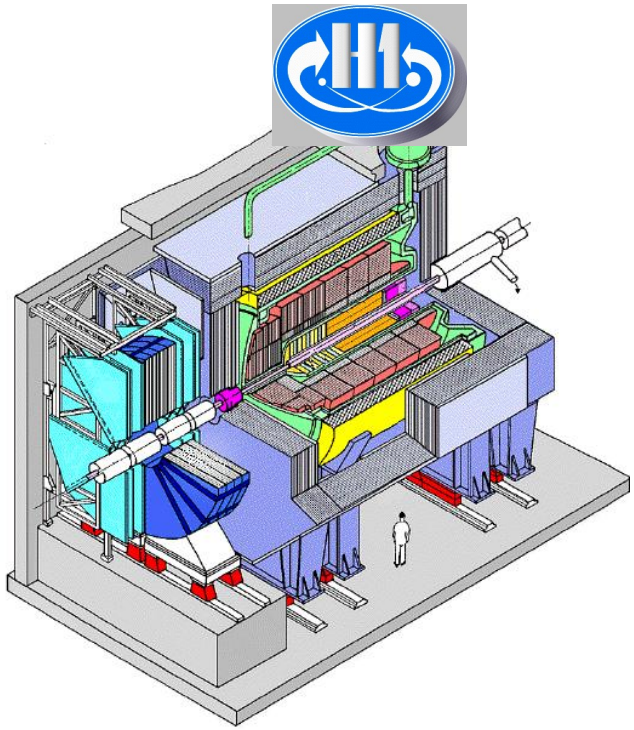
BACKUP

H1 and ZEUS Detectors



Uranium-scintillator Calorimeter

Optimised for precision measurement of the hadronic final state



Liquid Argon Calorimeter

Optimised for precision measurement of the scattered lepton