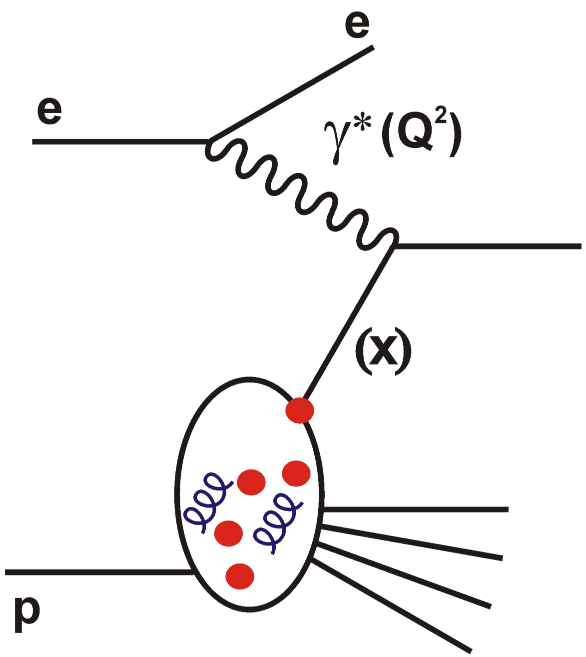
Inclusive Deep Inelastic Scattering at HERA

Paul Newman
(Birmingham)

… for the H1 & ZEUS collaborations

Supported in part by
IPPP, Durham

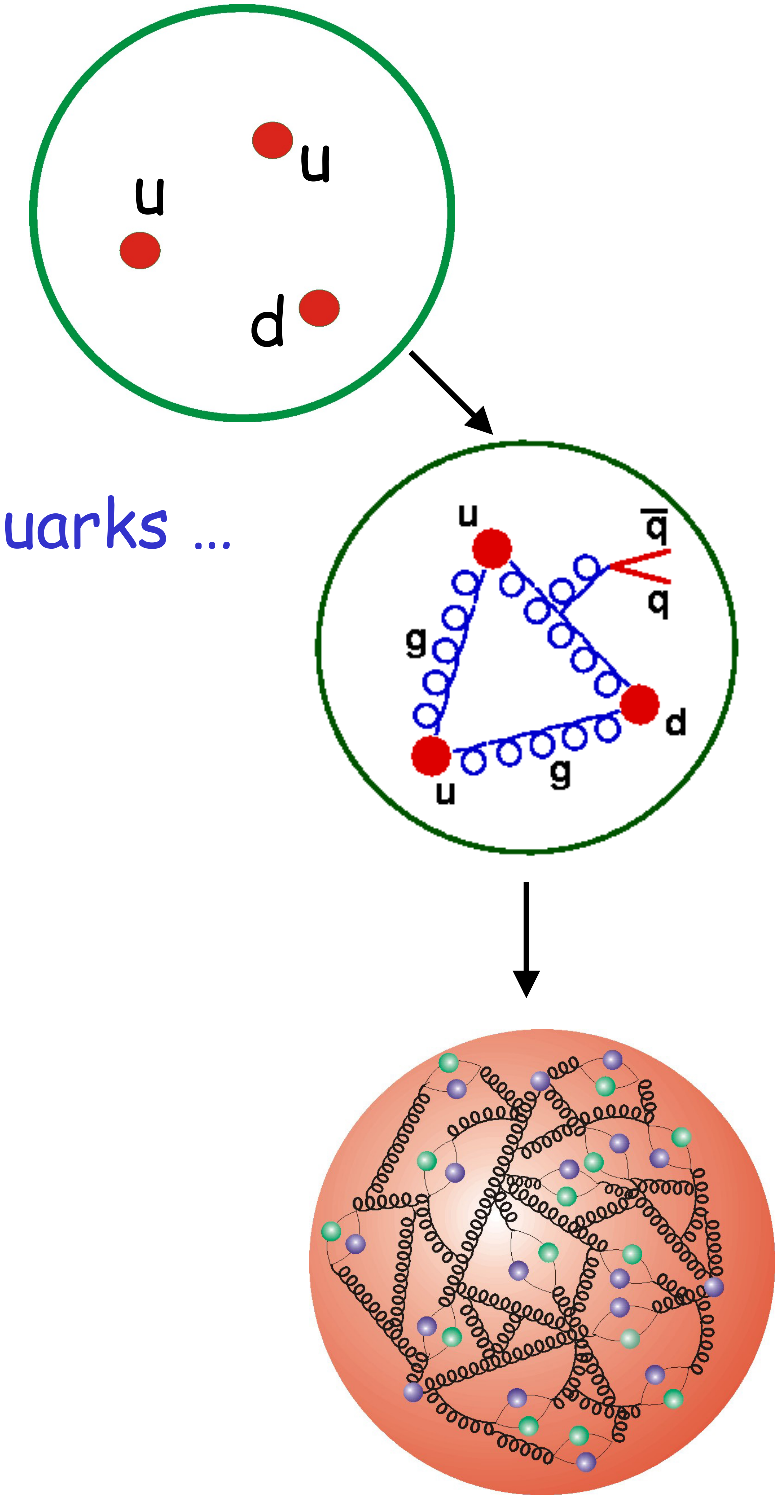


Diffraction'10
Otranto
11 September 2010

Proton “Structure”?

Proton constituents …

- 2 up and 1 down **valence quarks**
- … and some **gluons**
- … and some **sea quarks**
- … and lots more gluons and sea quarks …



Proton "Structure"?

Proton constituents …

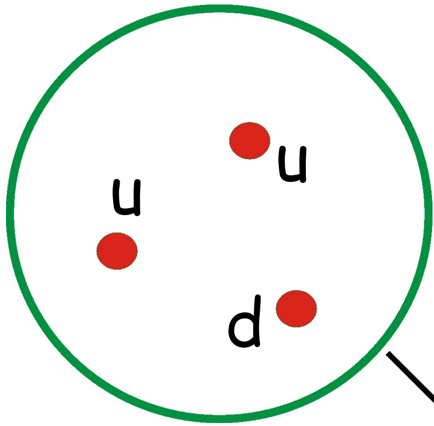
2 up and 1 down **valence quarks**

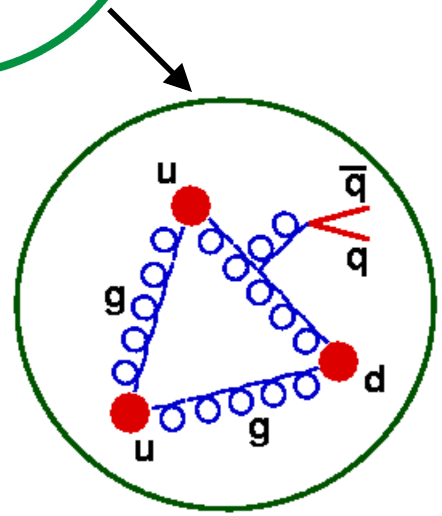
… and some **gluons**

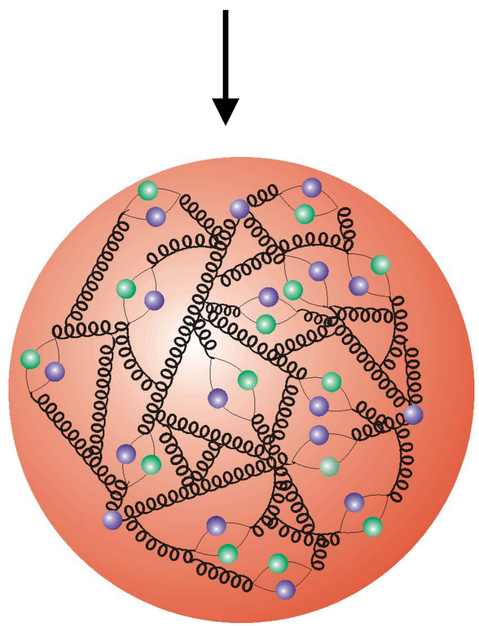
… and some **sea quarks**

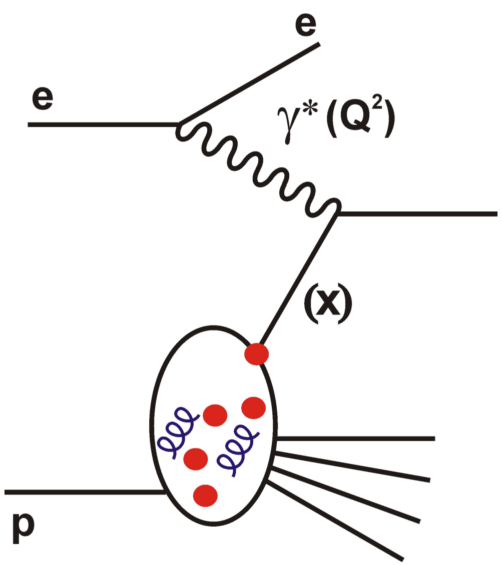
… and lots more gluons and sea quarks …

→ strong interactions induce rich and complex `structure' of high energy proton interactions!









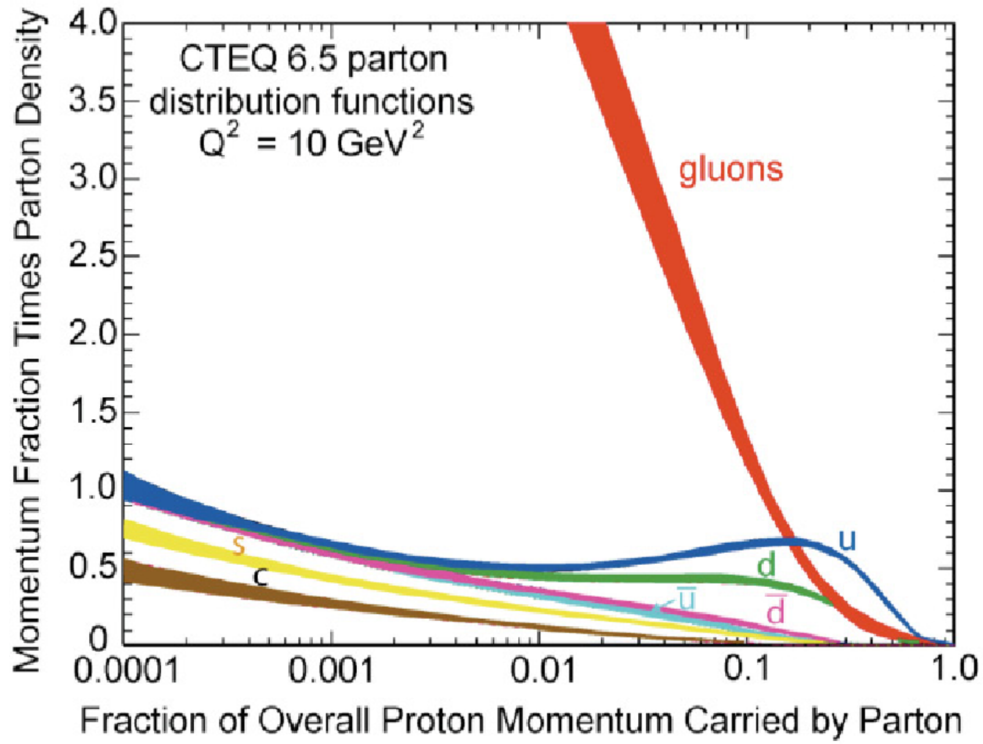
Scattering electrons from protons at $\sqrt{s}$ > 300GeV at HERA has established low x proton structure & provided a testing ground for QCD over a huge kinematic range

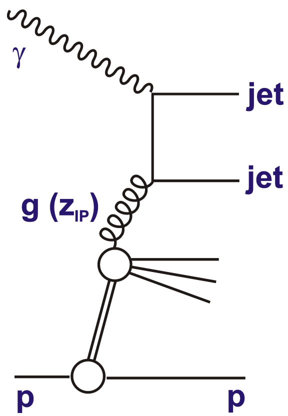
… **parton density functions**

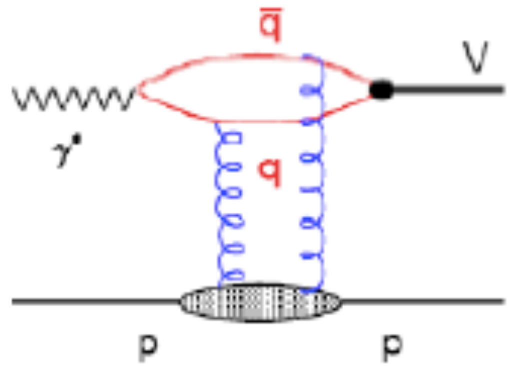
Main Relation to Diffraction …
the Low x Gluon

- Low x physics, as revealed by HERA, is the physics of huge gluon densities…

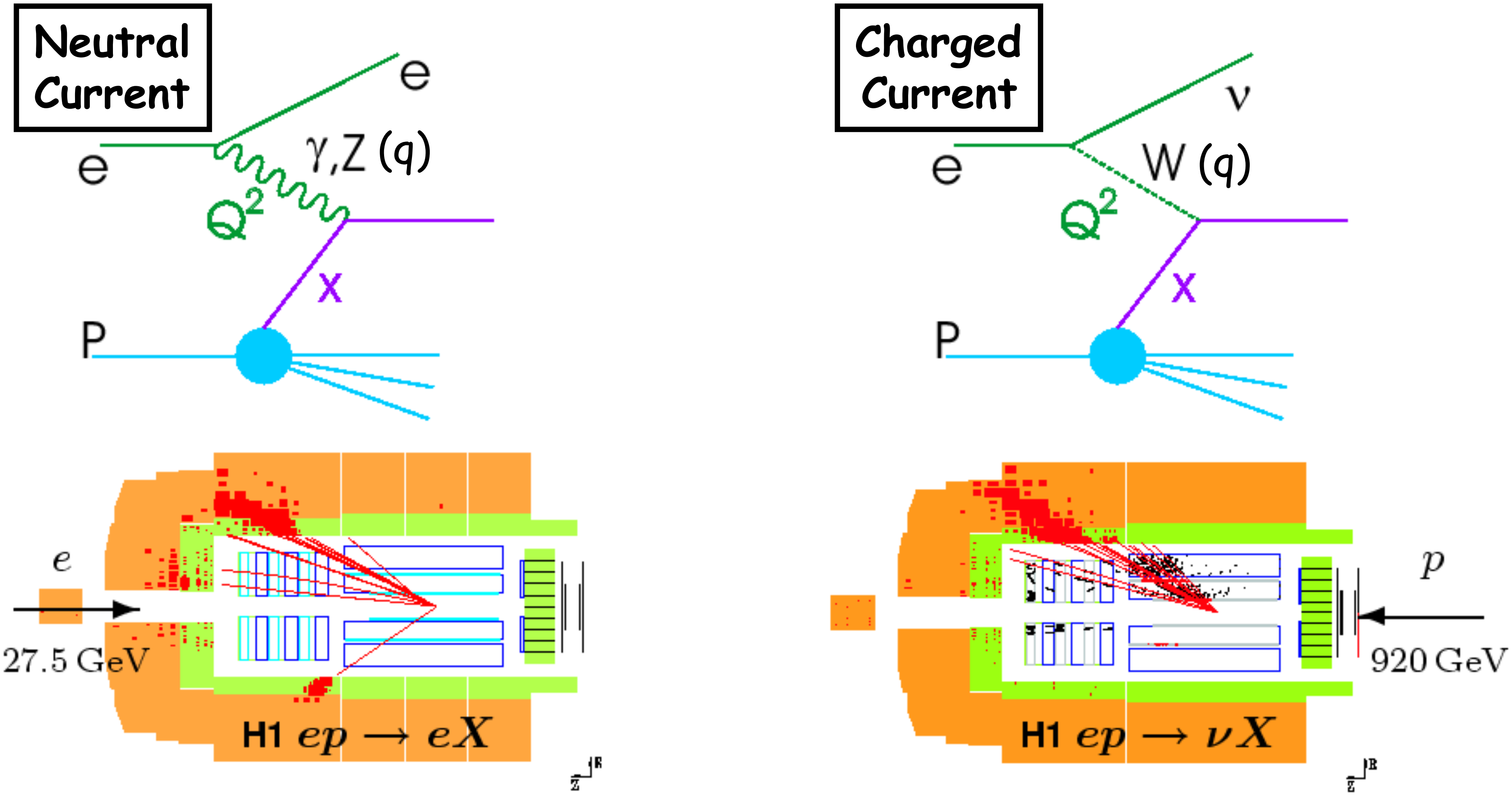
- Associated with a large (> 10%) contribution from diffractive processes







Basic Deep Inelastic Scattering Processes



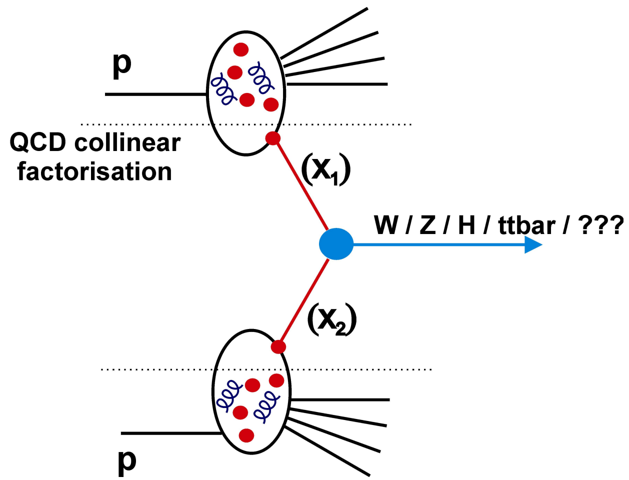
$Q^2 = -q^2$:resolving power of interaction

$x = Q^2 / 2q.p$: fraction of struck quark / proton momentum

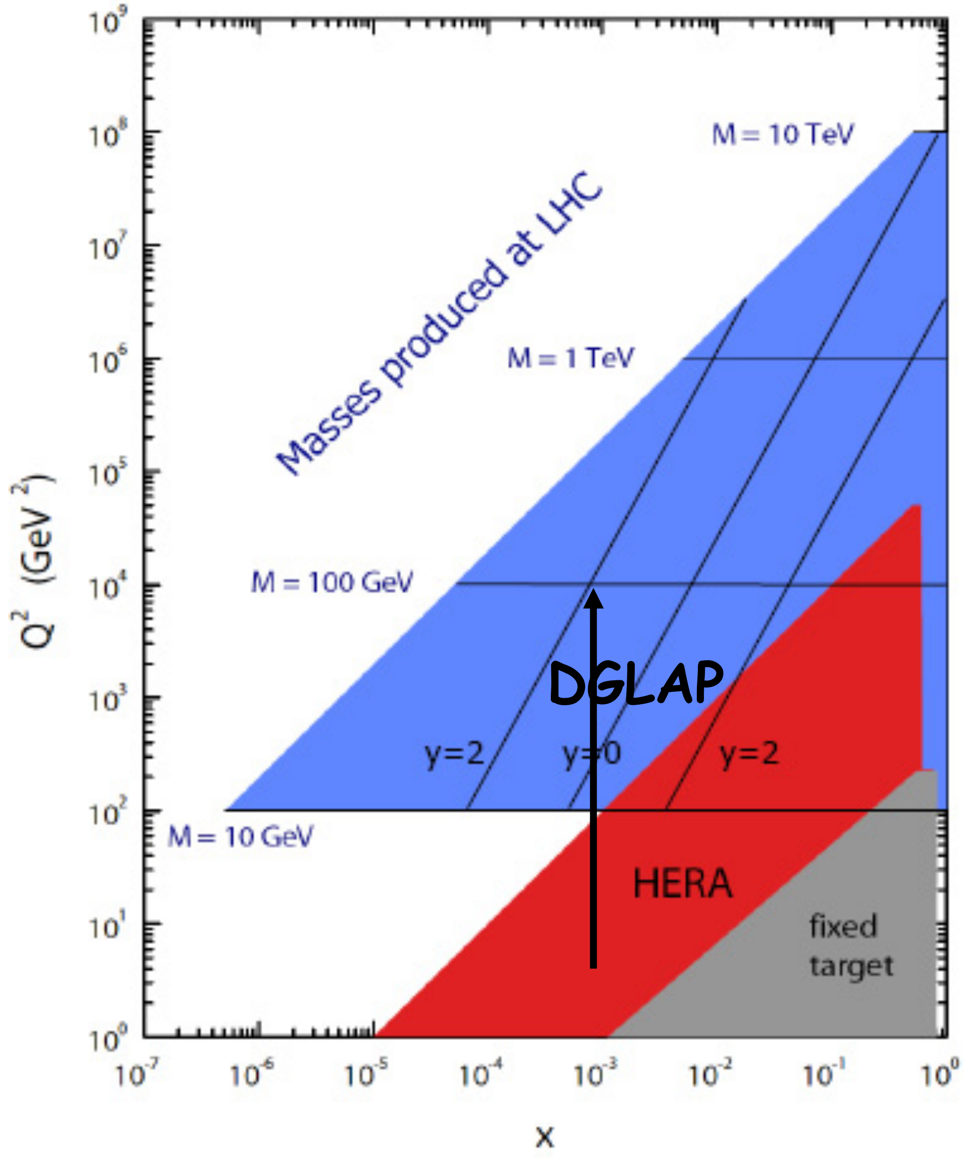
HERA kinematic range

- Unprecedented low x and high Q^2 coverage in DIS!

- HERA + **QCD factorisation** → parton densities in full x range of LHC rapidity plateau

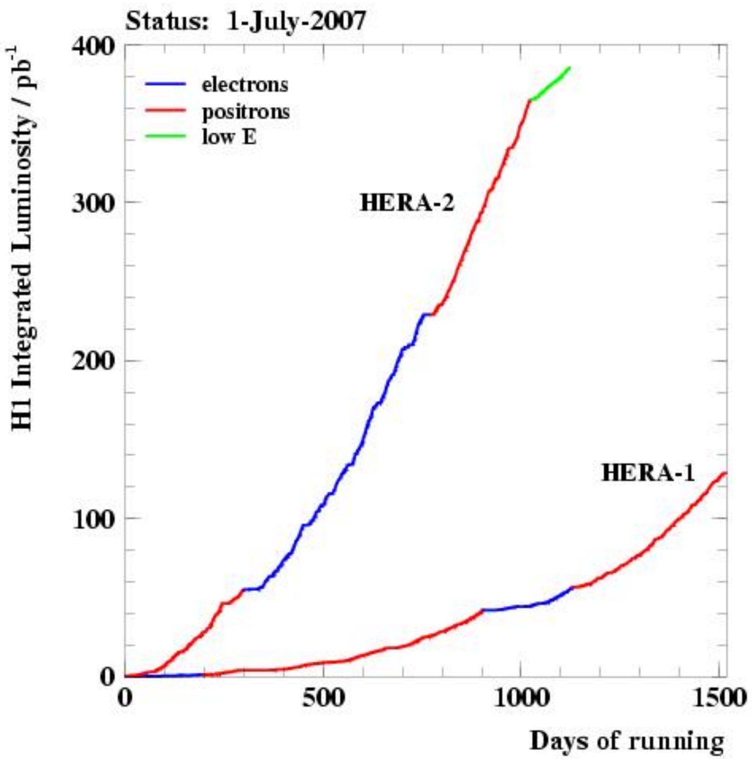


- Well established `**DGLAP**' **evolution** equations generalise to any scale (for not too small x)

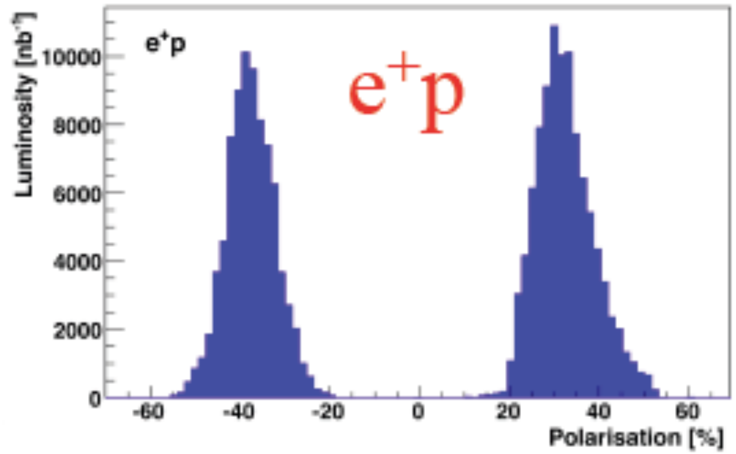


e.g. pp dijets at central rapidity: $x_1 = x_2 = 2p_t / \sqrt{s}$

Final HERA Data Samples



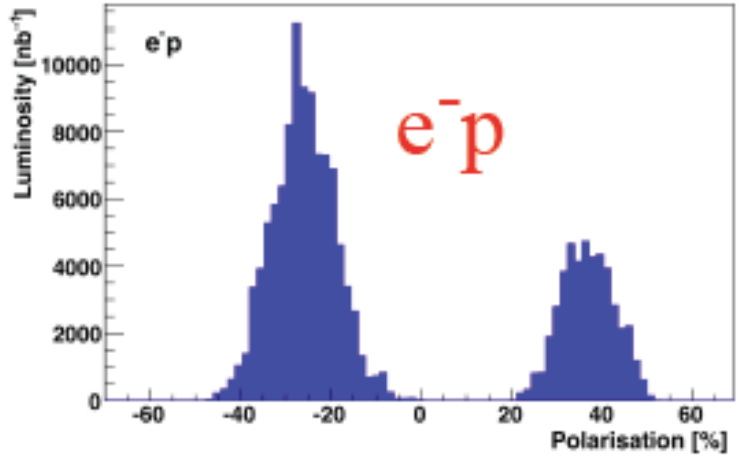
- Total of ~200 pb^{-1} e^-p, 300 pb^{-1} e^+p per experiment.
- Both lepton polarisation states
- ~25 pb^{-1} @ lower E_p = 575, 460 GeV



- HERA-I publications ~ complete

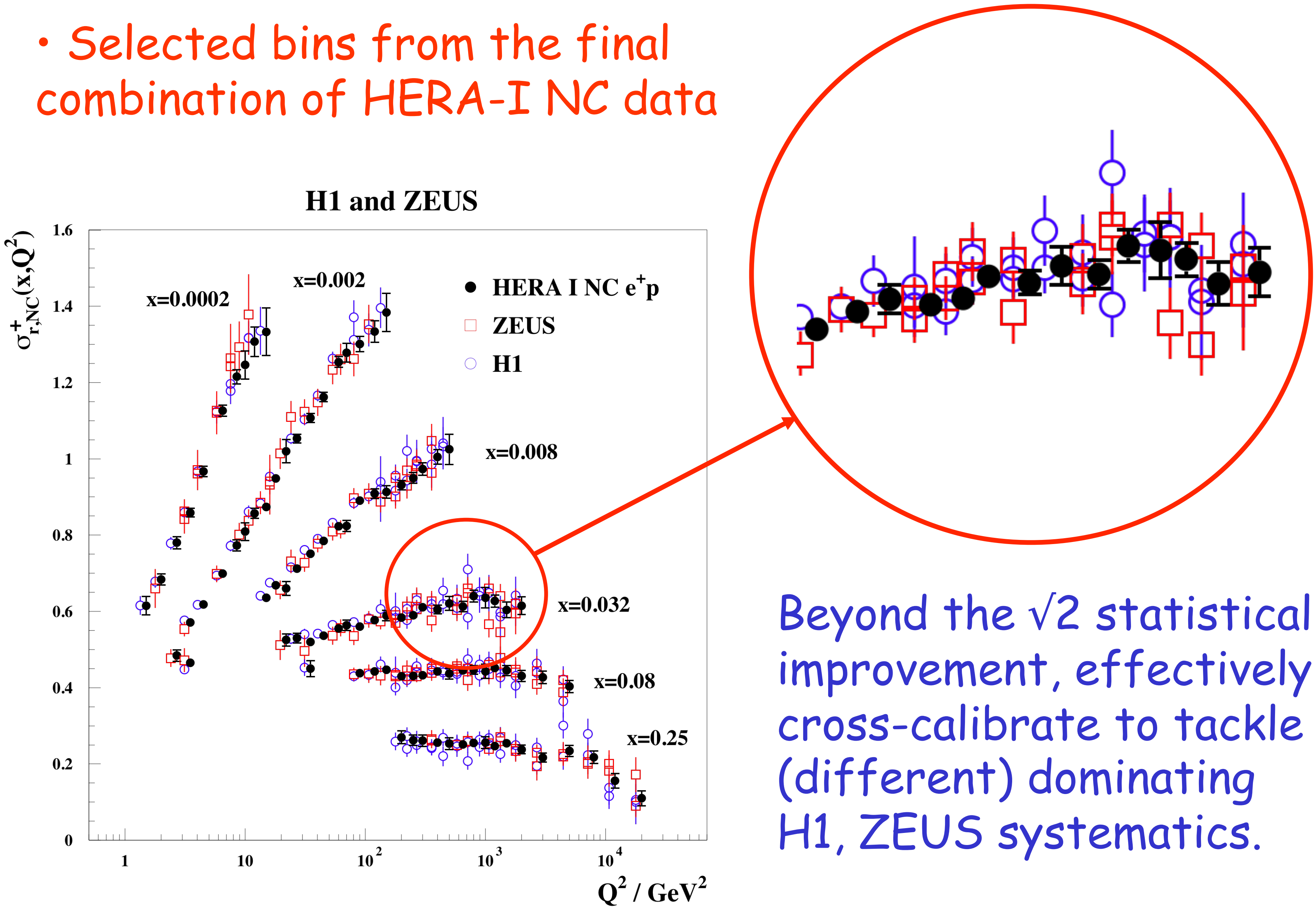
- Many HERA-II analyses still in progress (e.g. complicated final states such as diffraction)

- Work to combine H1, ZEUS results well underway



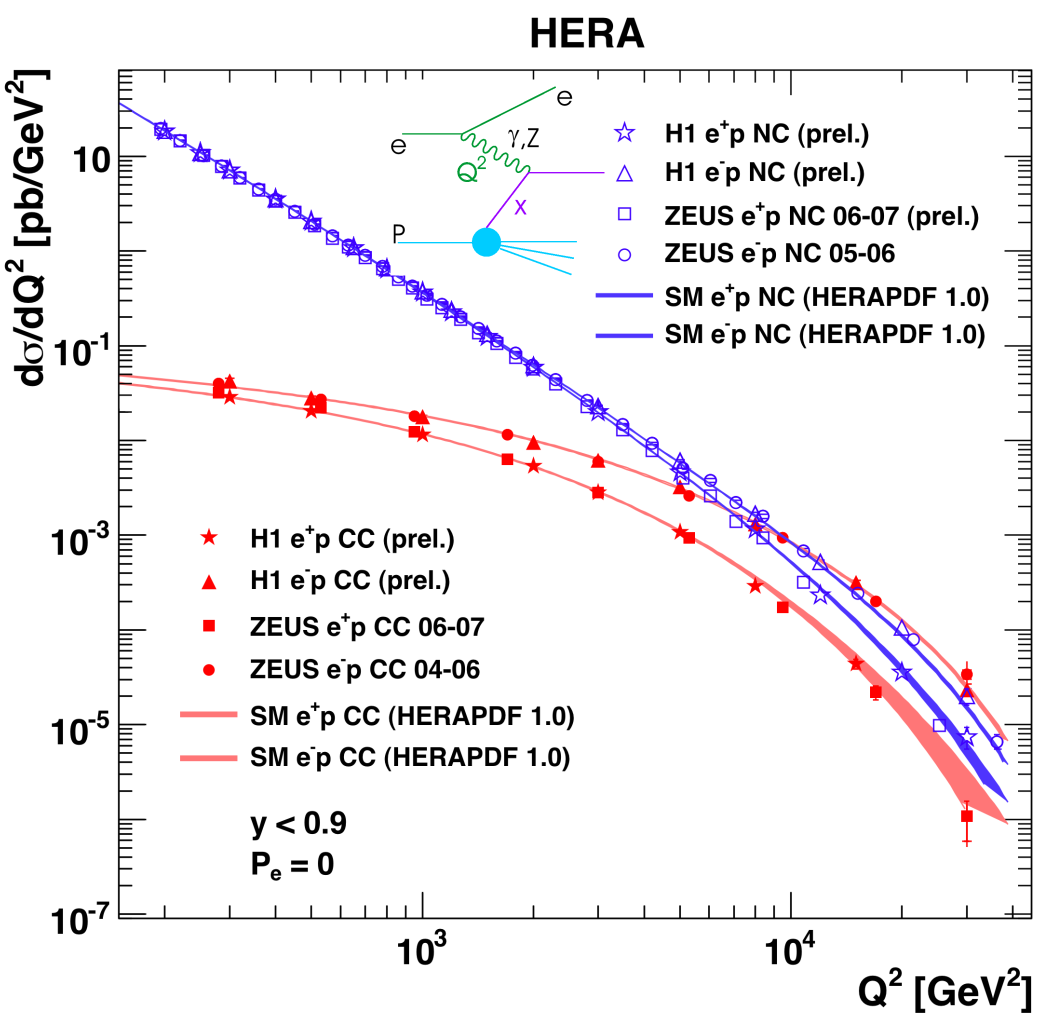
The Power of Combinations [JHEP 1001:109 (2010)]

- Selected bins from the final combination of HERA-I NC data



Beyond the √2 statistical improvement, effectively cross-calibrate to tackle (different) dominating H1, ZEUS systematics.

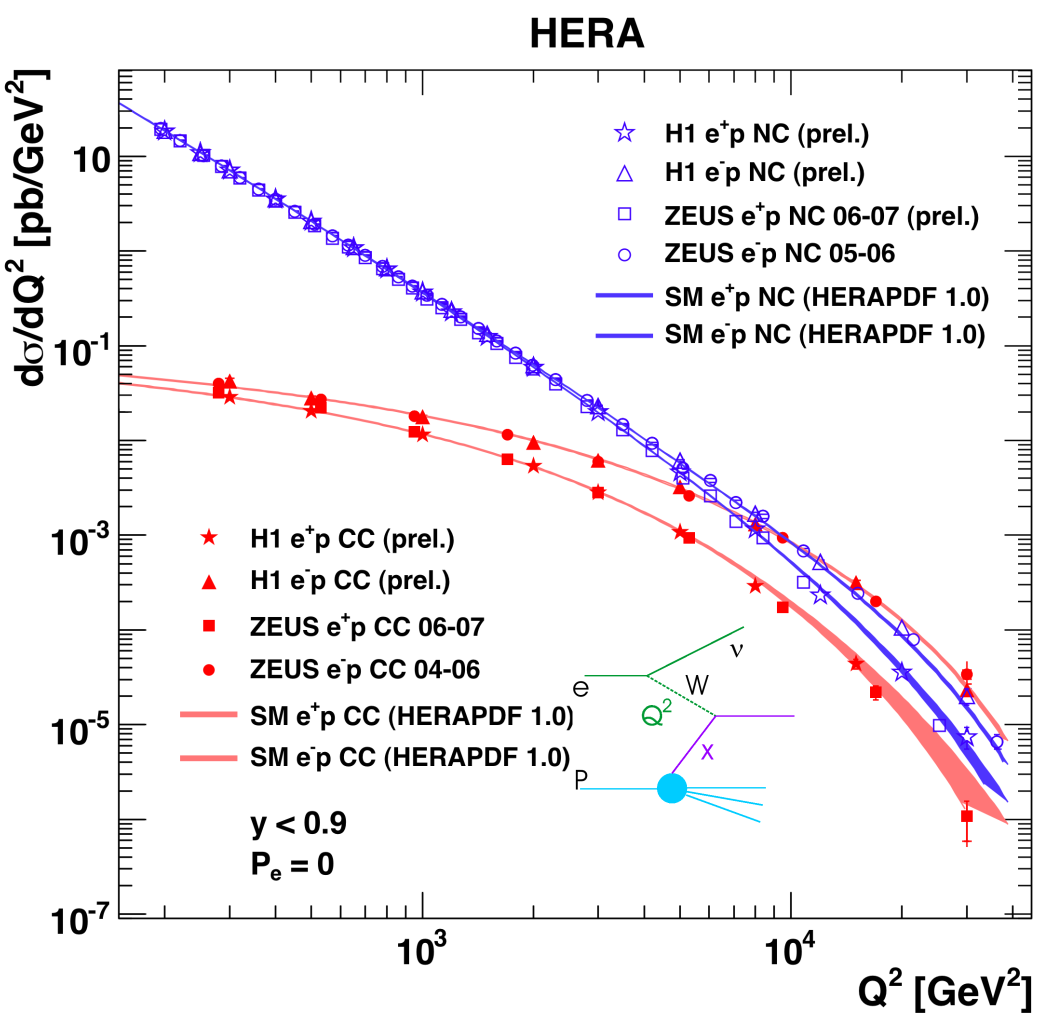
Electroweak Unification for Space-like Bosons



Neutral Current x-sec

$$\frac{d\sigma^{NC}}{dx\, dQ^2} \sim \alpha_{em}^2 \quad \bullet \quad \left(\frac{1}{Q^2}\right)^2 \quad \bullet \quad \tilde{\sigma}_{NC}$$

Electroweak Unification for Space-like Bosons



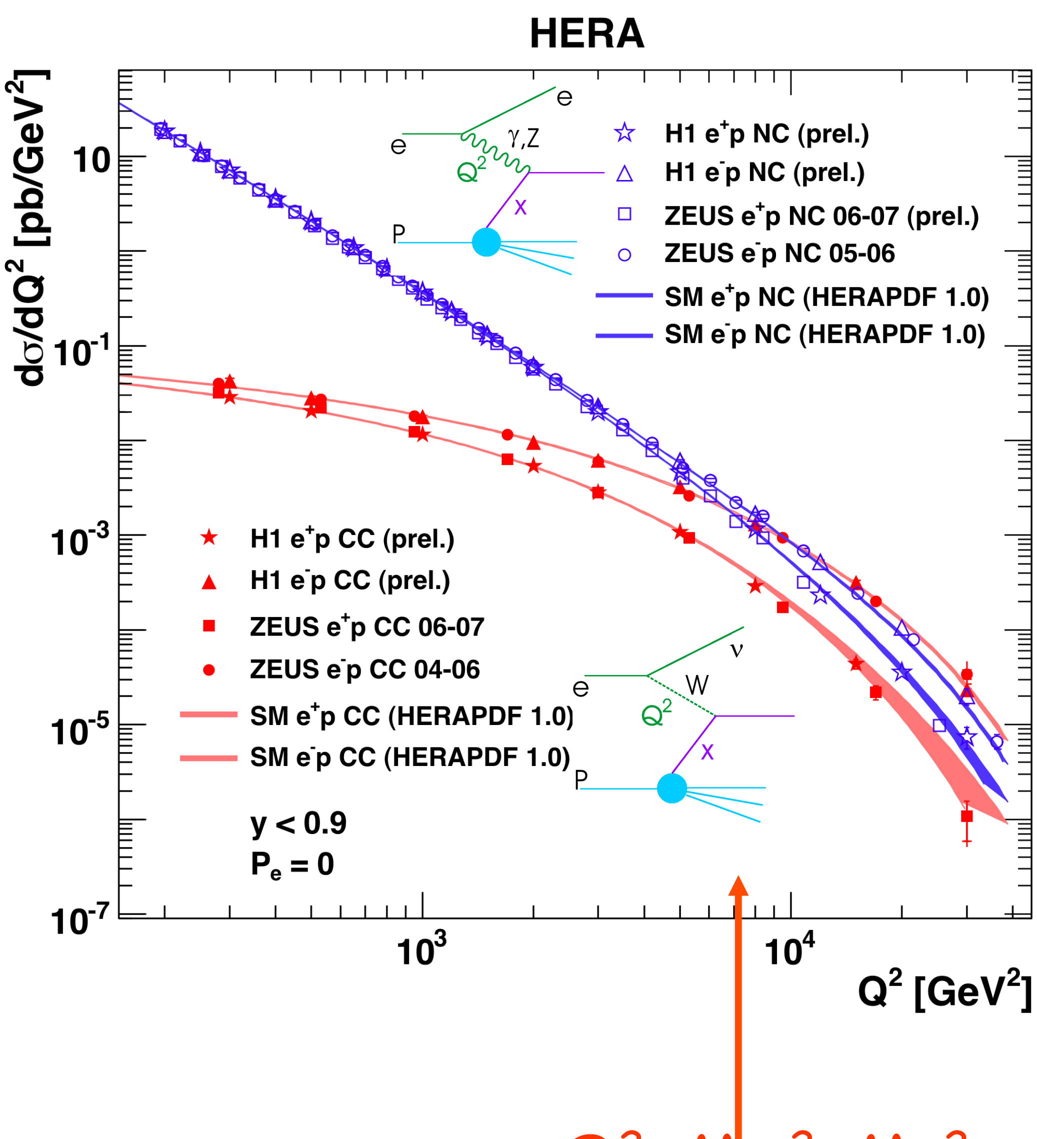
Neutral Current x-sec

$$\frac{d\sigma^{NC}}{dx\, dQ^2} \sim \alpha_{em}^2 \bullet \left(\frac{1}{Q^2}\right)^2 \bullet \tilde{\sigma}_{NC}$$

Charged Current x-sec

$$\frac{d\sigma^{CC}}{dx\, dQ^2} \sim G_F^2 M_W^2 \bullet \left(\frac{1}{Q^2 + M_W^2}\right)^2 \bullet \tilde{\sigma}_{CC}$$

Electroweak Unification for Space-like Bosons



$Q^2 \sim M_W^2, M_Z^2$

Neutral Current x-sec

$$\frac{d\sigma^{NC}}{dx\, dQ^2} \sim \alpha_{em}^2 \quad \bullet \quad \left(\frac{1}{Q^2}\right)^2 \quad \bullet \; \tilde{\sigma}_{NC}$$

Charged Current x-sec

$$\frac{d\sigma^{CC}}{dx\, dQ^2} \sim G_F^2 M_W^2 \bullet \left(\frac{1}{Q^2 + M_W^2}\right)^2 \bullet \tilde{\sigma}_{CC}$$

- NC and CC cross sections become comparable at EW unification scale (couplings unified)

- Parton density info encoded in $\tilde{\sigma}_{NC}$ and $\tilde{\sigma}_{CC}$

Neutral Current Sensitivity to the Quarks

Unpolatised NC cross section depends on 3 structure fns …

$$\tilde{\sigma}^{NC}(e^{\pm}p) = \boxed{F_2} \mp \frac{Y_-}{Y_+}\boxed{xF_3} - \frac{y^2}{Y_+}\boxed{F_L}$$

… where $Y_{\pm} = 1 \pm (1-y)^2$

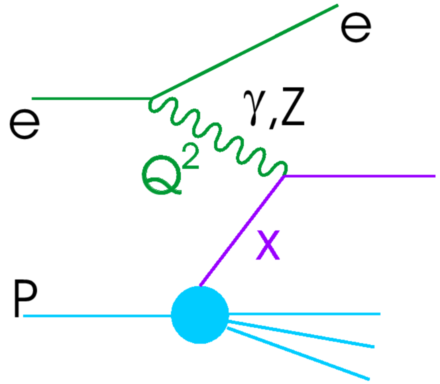
… and y measures the process inelasticity

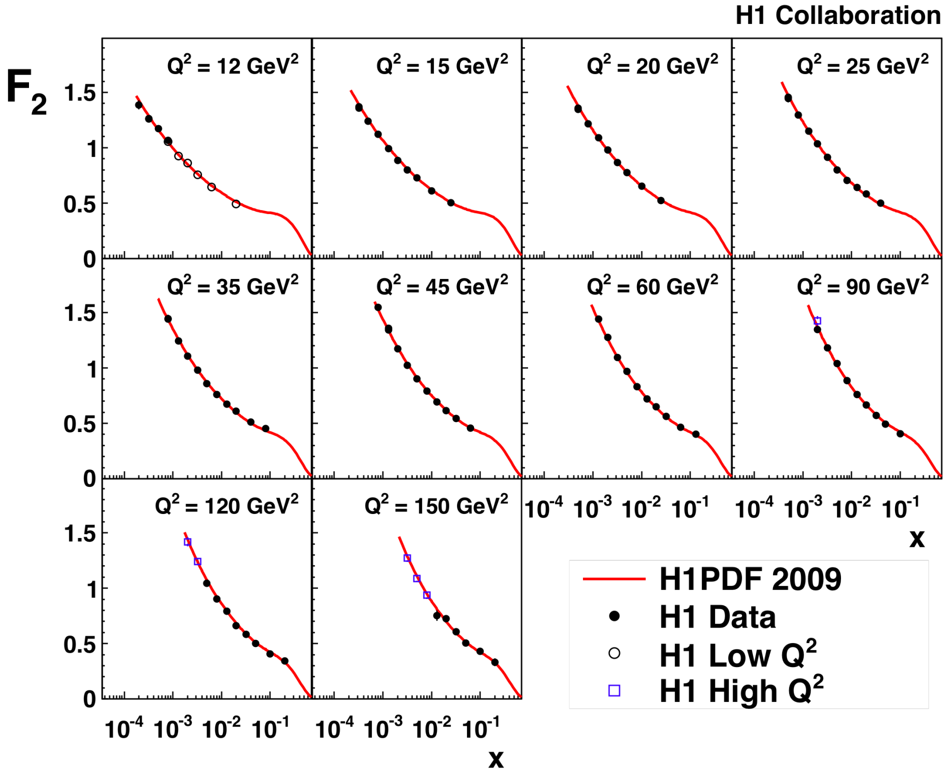
- F_2 dominates throughout most of the phase space
- xF_3 contributes at high Q^2 (Z exchange) can be obtained from difference between e^+p and e^-p cross sections
- F_L contributes at high y (longitudinally polarised photons)

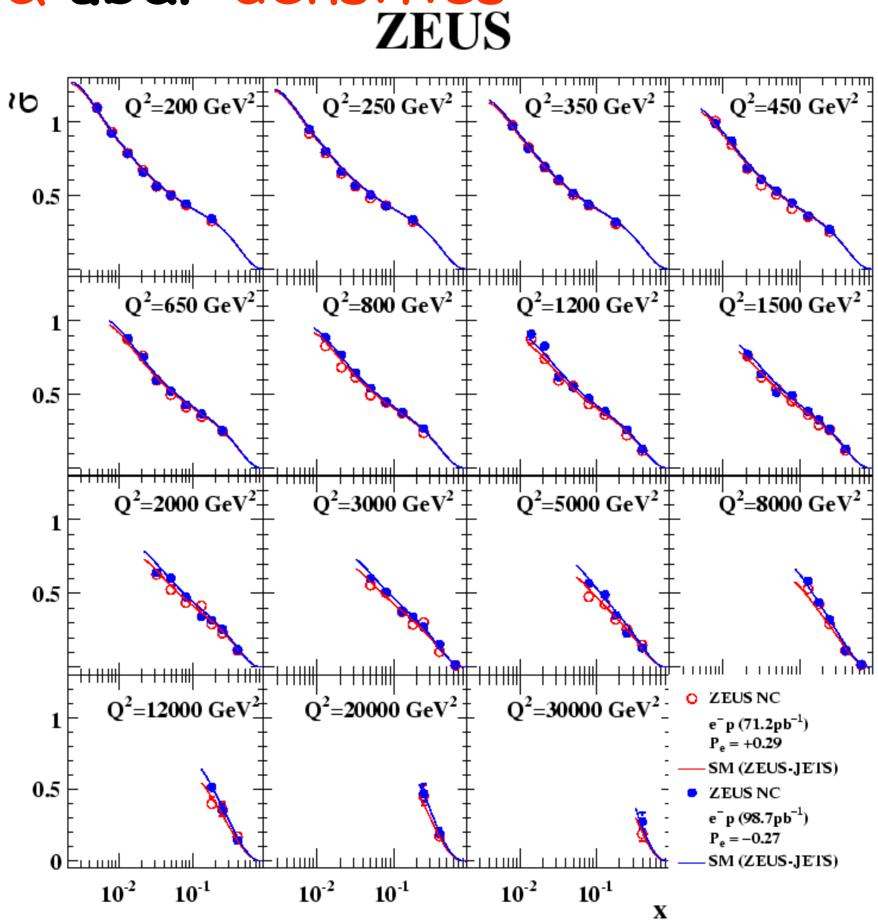
Recent Neutral Current Data

- NC data primarily measure $F_2 = \sum_q e_q^2\, x\,(q + \bar{q})$
- Due to e_q^2 photon coupling, NC

Provides best constraints on **u** & **ubar** densities



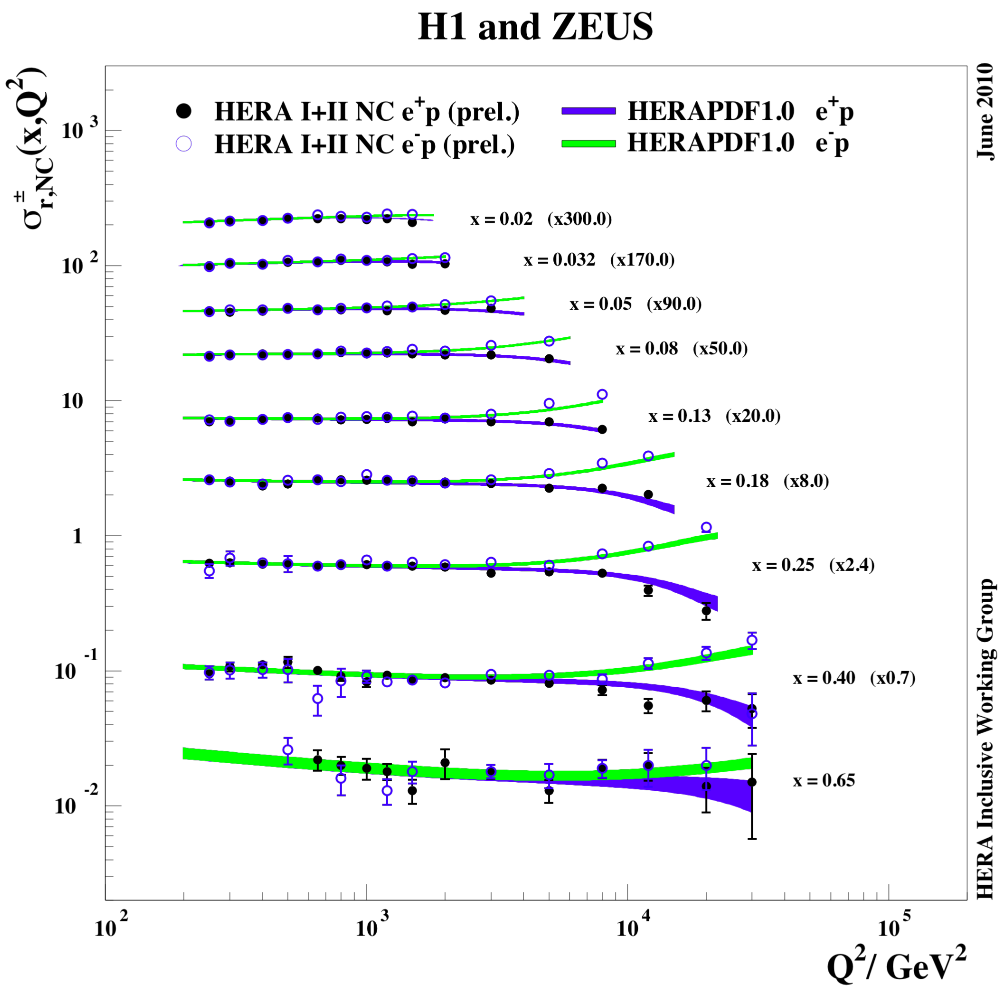




- 1.5-2% precision in final H1 intermediate Q^2 data

- 169pb^{-1} (final ZEUS high Q^2 e^-p data) … 2-3% syst precision

NC Lepton Charge Dependence & xF_3

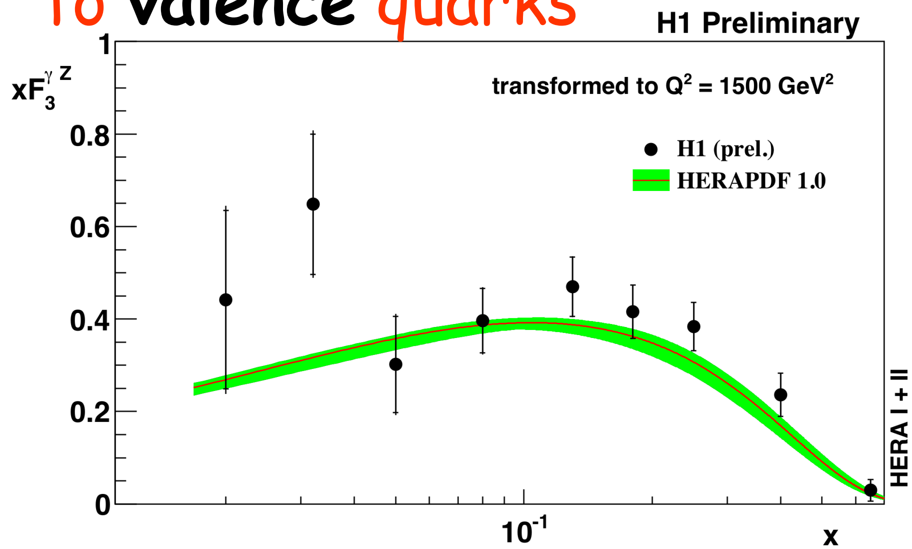


- Difference between e^-p and e^+p NC cross sections at large Q^2 measures **xF_3** structure fn…
- Dominated by interference Between γ and Z exchange

… unique sensitivity to **valence** quarks

$$xF_3 = \frac{Y_+}{2Y_-}\left(\tilde{\sigma}_{NC}^{-} - \tilde{\sigma}_{NC}^{+}\right)$$

$$\approx \frac{x}{3}\left(2u_v + d_v\right)$$

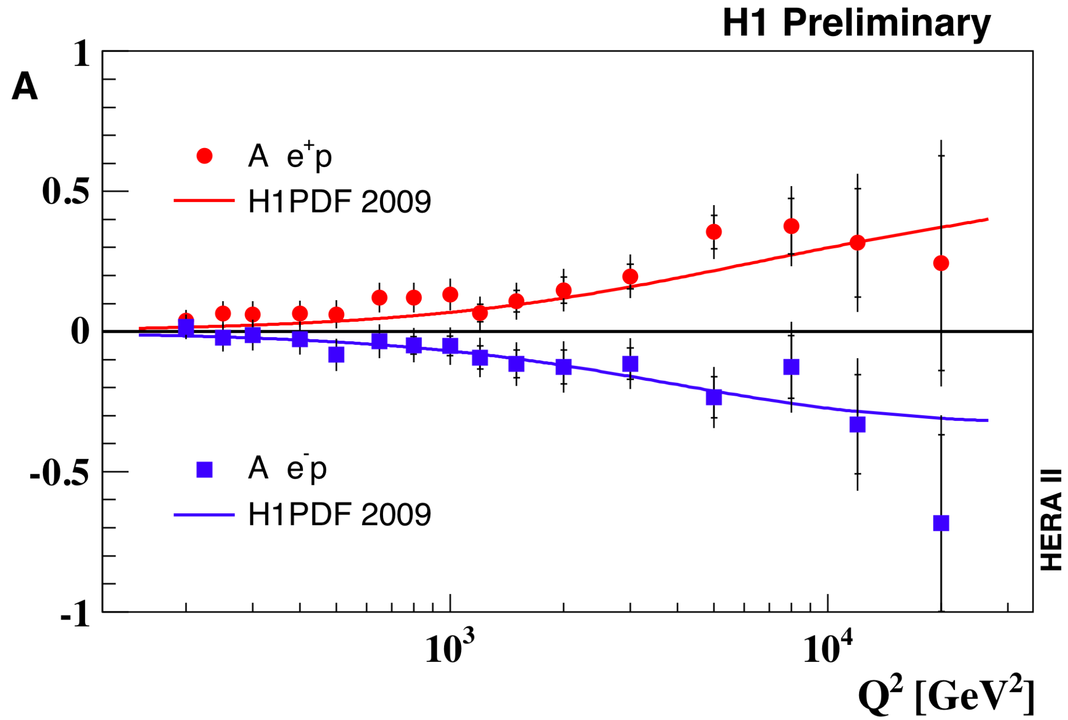


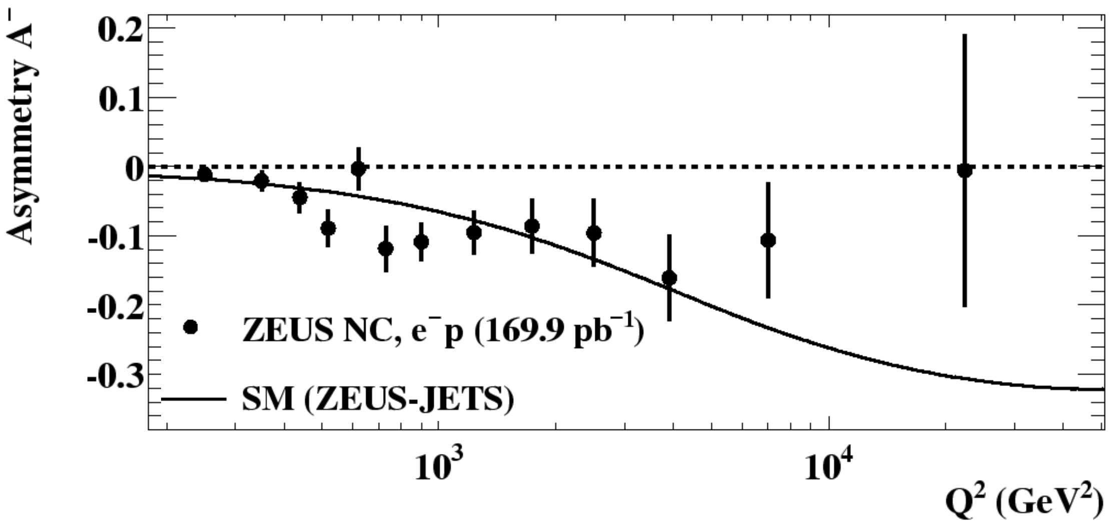
Left v Right Hand Polarised Leptons

Significant NC lepton polarisation asymmetry observed … tests vector and axial EW **lepton couplings** and **d/u** ratio as x→1

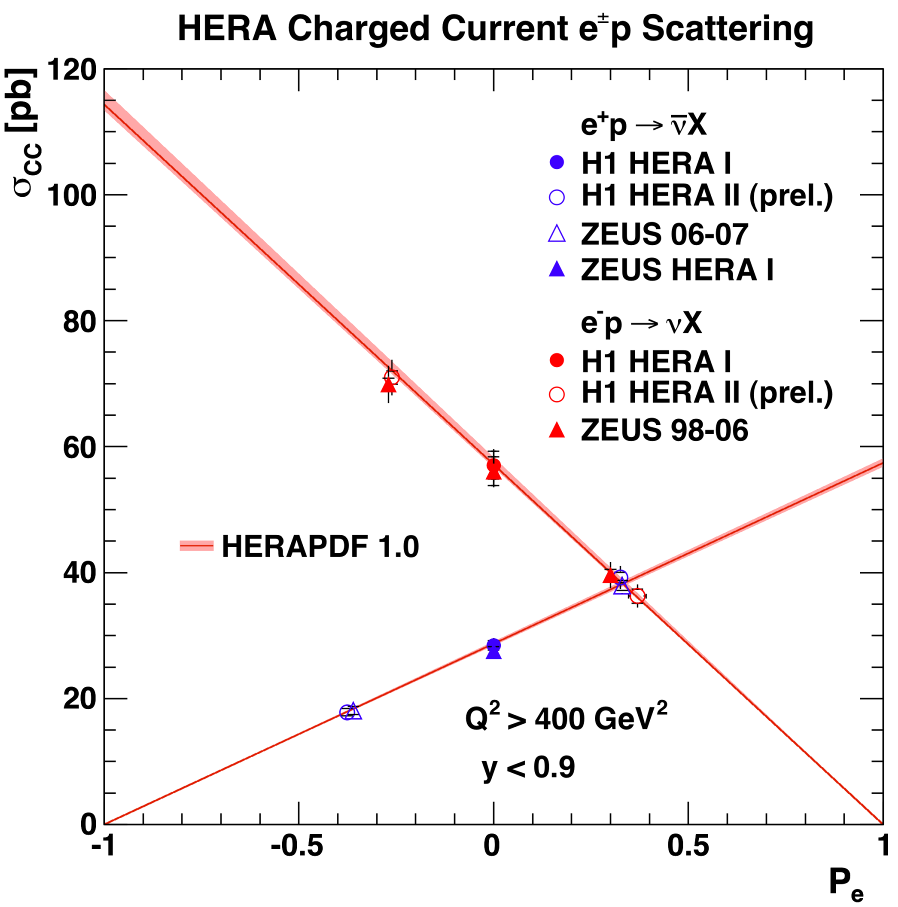
$$A = \frac{\tilde{\sigma}_{NC}(R) - \tilde{\sigma}_{NC}(L)}{\tilde{\sigma}_{NC}(R) + \tilde{\sigma}_{NC}(L)}$$

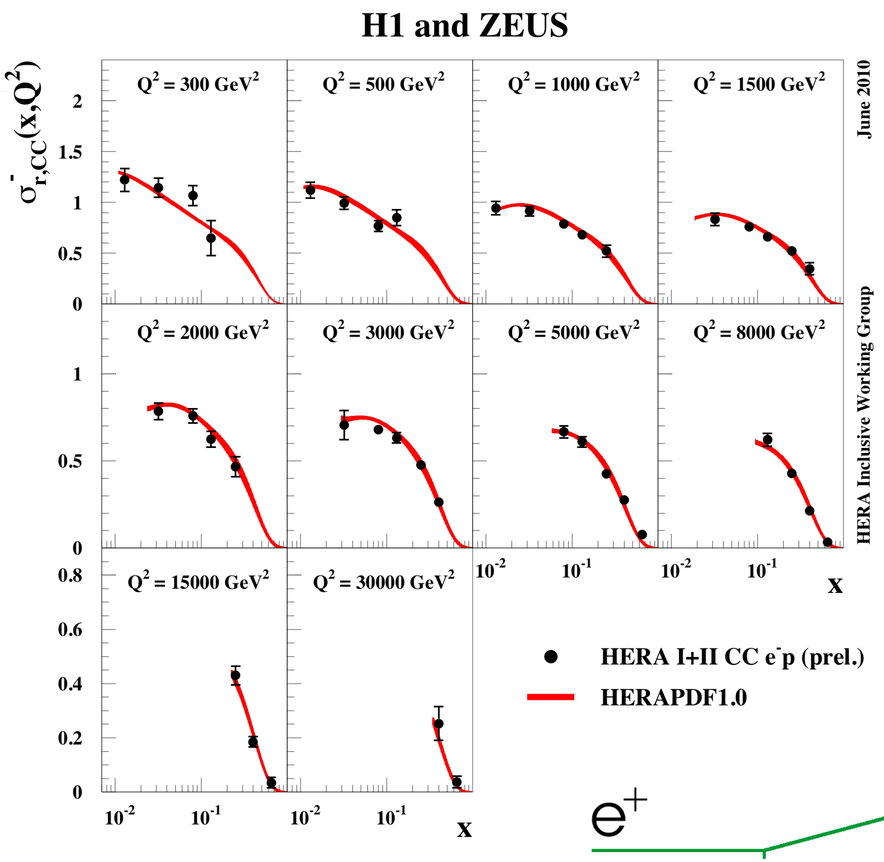
$$\approx \kappa\left(M_W, M_Z\right) \frac{(1 + d_v / u_v)}{(4 + d_v / u_v)}$$

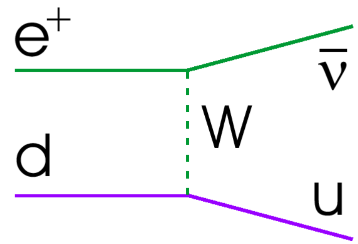




Recent Charged Current Data



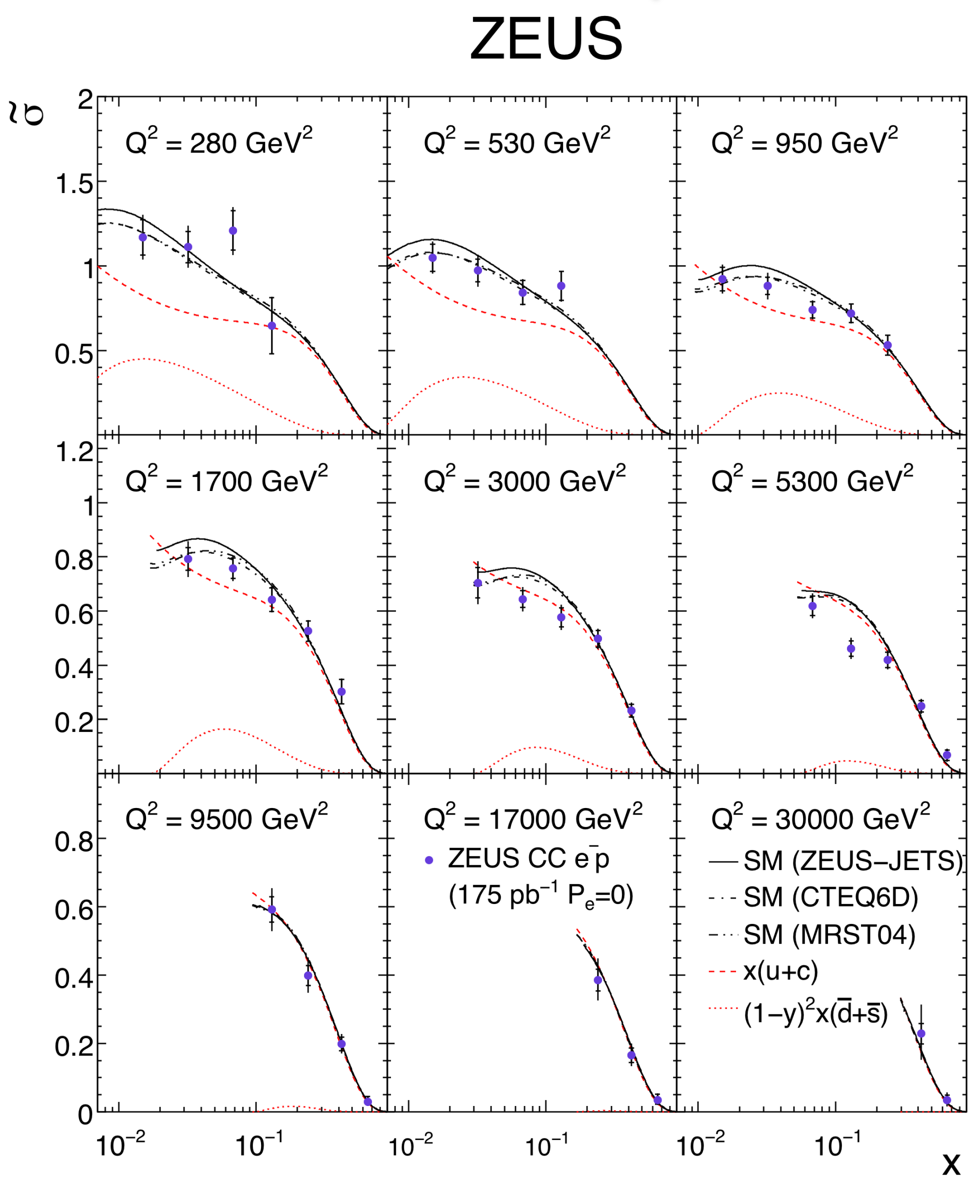




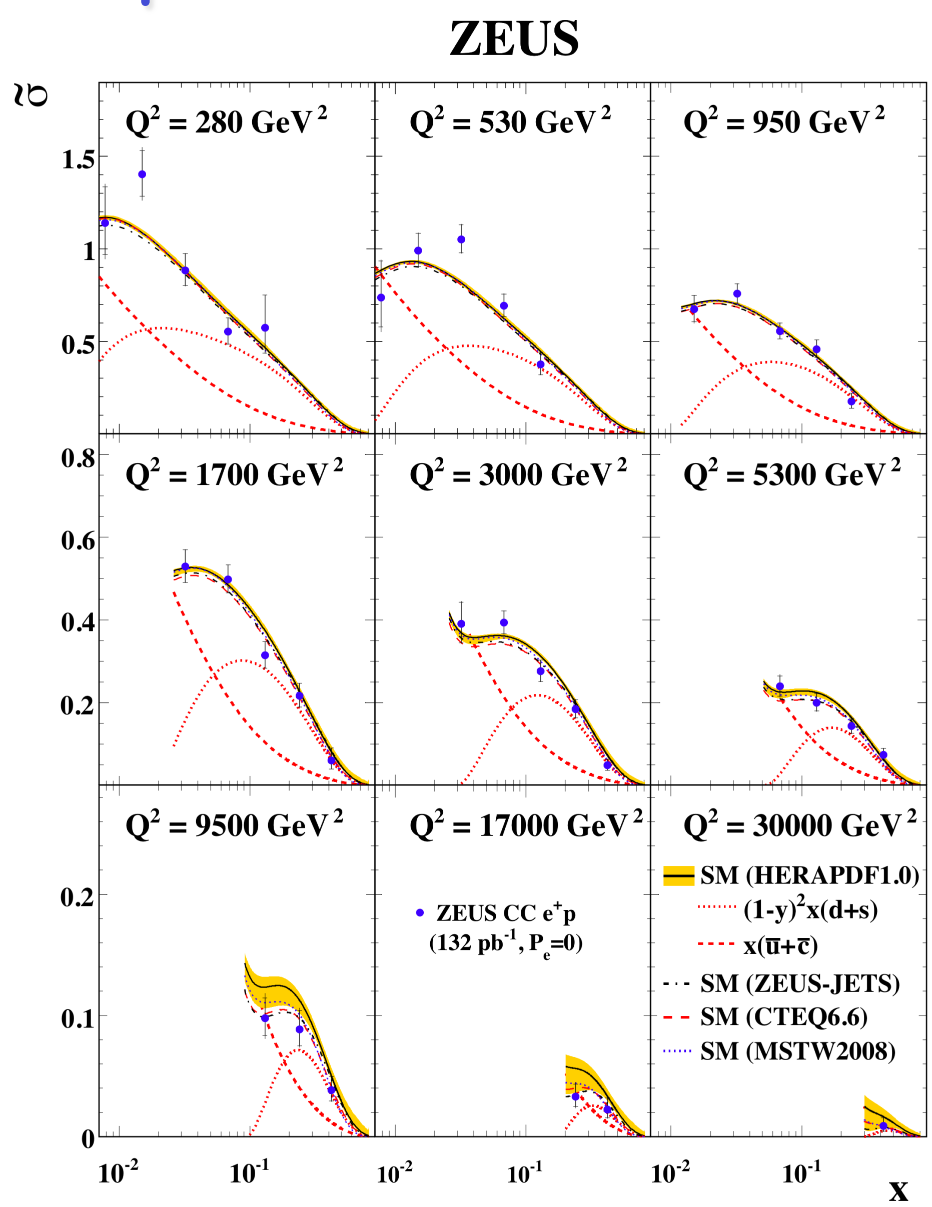
- Linear dependence on polarisation well tested … **chiral structure** of SM

- Charged current sensitive to flavour decomposition … e.g. e^+p constrains **d** density

CC Quark Decomposition

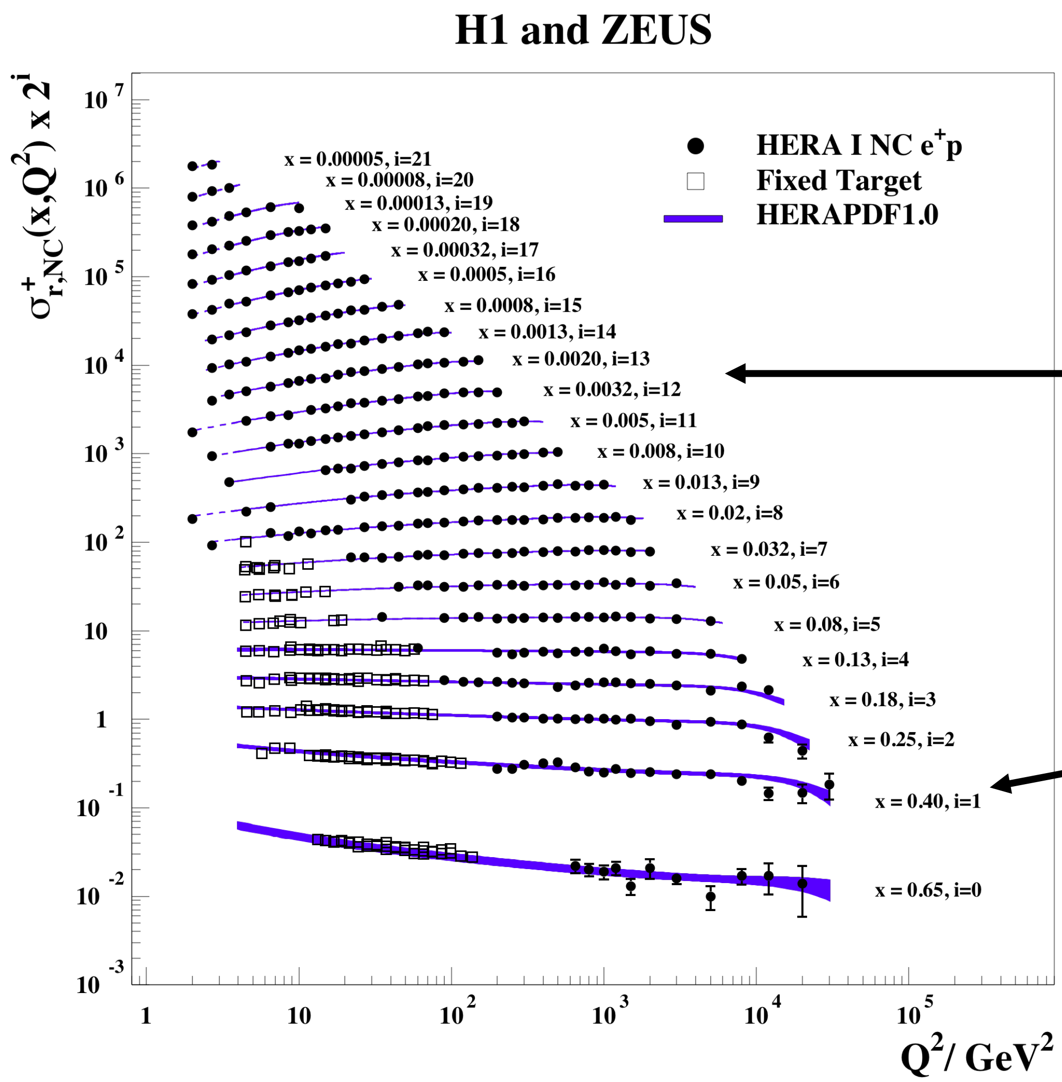


e⁻ p

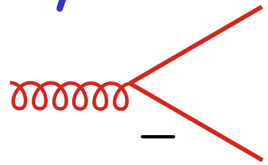


e⁺ p

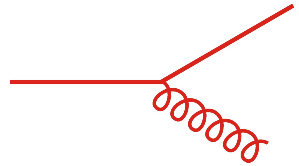
QCD Evolution and the Gluon Density



- NC Q^2 dependence driven by …



$g \to q\bar{q}$



$q \to qg$

- Excellent QCD fit description over vast range.

- Q^2 evolution of F_2 yields **low x gluon**, assuming DGLAP
- Other observables needed @ high x, where g sensitivity lost

Extracting Parton Densities: HERAPDF1.0

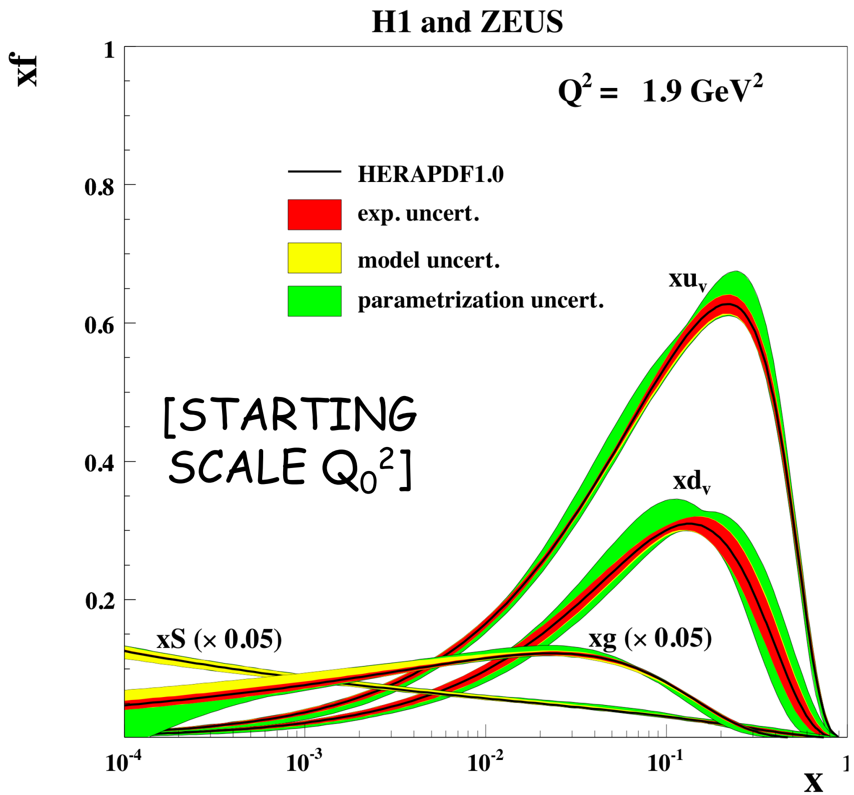
- NLO DGLAP fits [to $O(\alpha_s^2)$] performed to combined H1 and ZEUS NC and CC data **using HERA-I data alone**

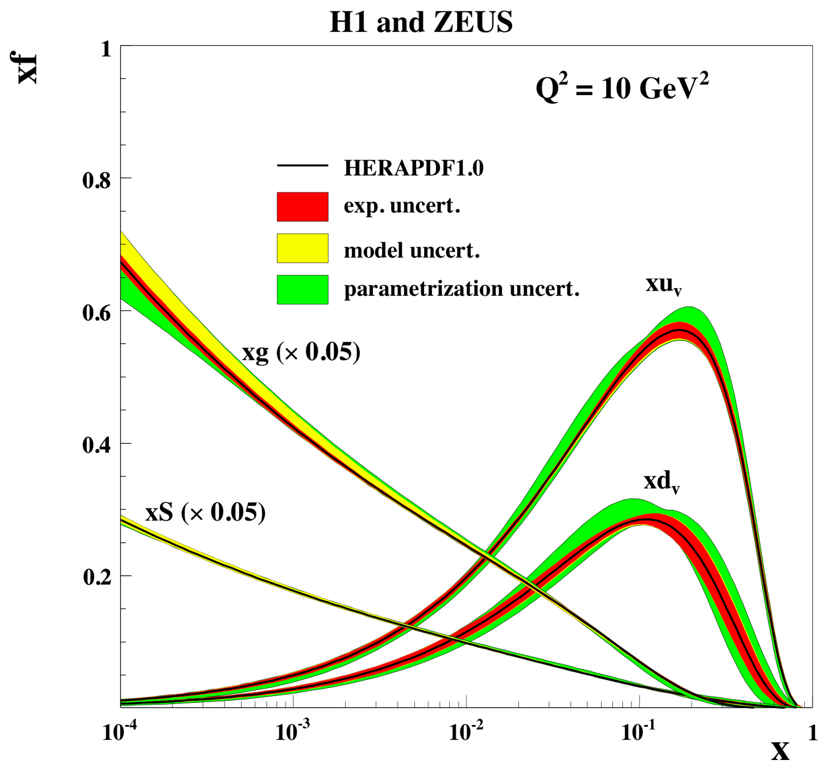
- Parameterise valence and sea quarks and gluon at starting scale $Q^2 \sim 2$ GeV^2 $$xf(x) = Ax^B(1-x)^C(1+\varepsilon\sqrt{x}+Dx+Ex^2)$$
  … evolve with DGLAP and fit data
  [Thorne-Roberts GM VFNS heavy flavour scheme]

- Good quality fit: χ^2 / ndf = 574 / 582

- Now with full assessment of **uncertainties:**
  - **Experimental**, using $\Delta\chi^2 = 1$
  - **Model**, by varying m_c, m_b, data Q^2_{min}, strangeness frac
  - **Parameterisation**, by forming envelope of results with acceptable variations

So What *is* a Proton?



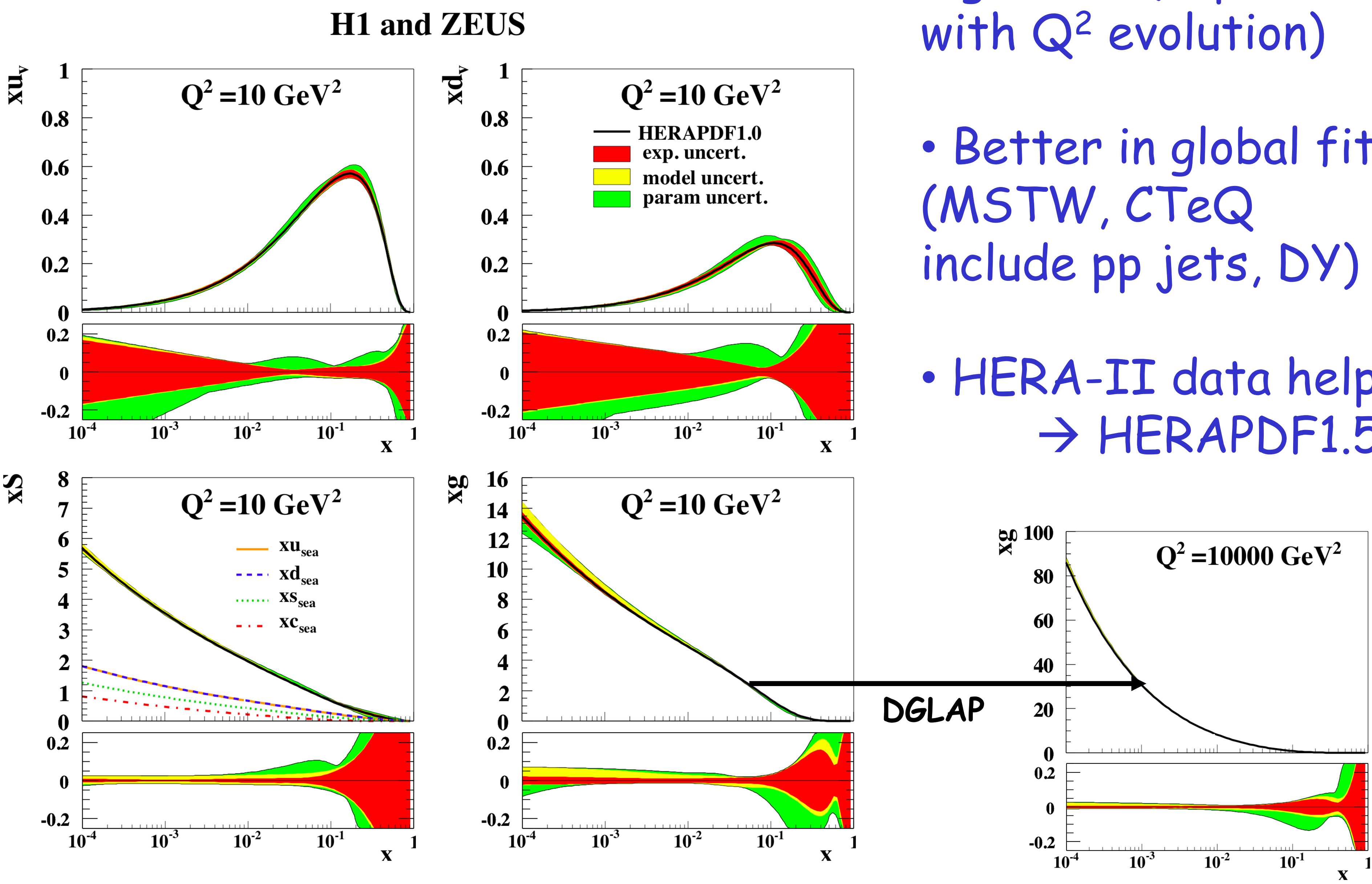


Parameterisation uncertainty dominates

Gluon 'valence-like' at starting scale, evolves to be very large at low x already by $Q^2 = 10\ GeV^2$

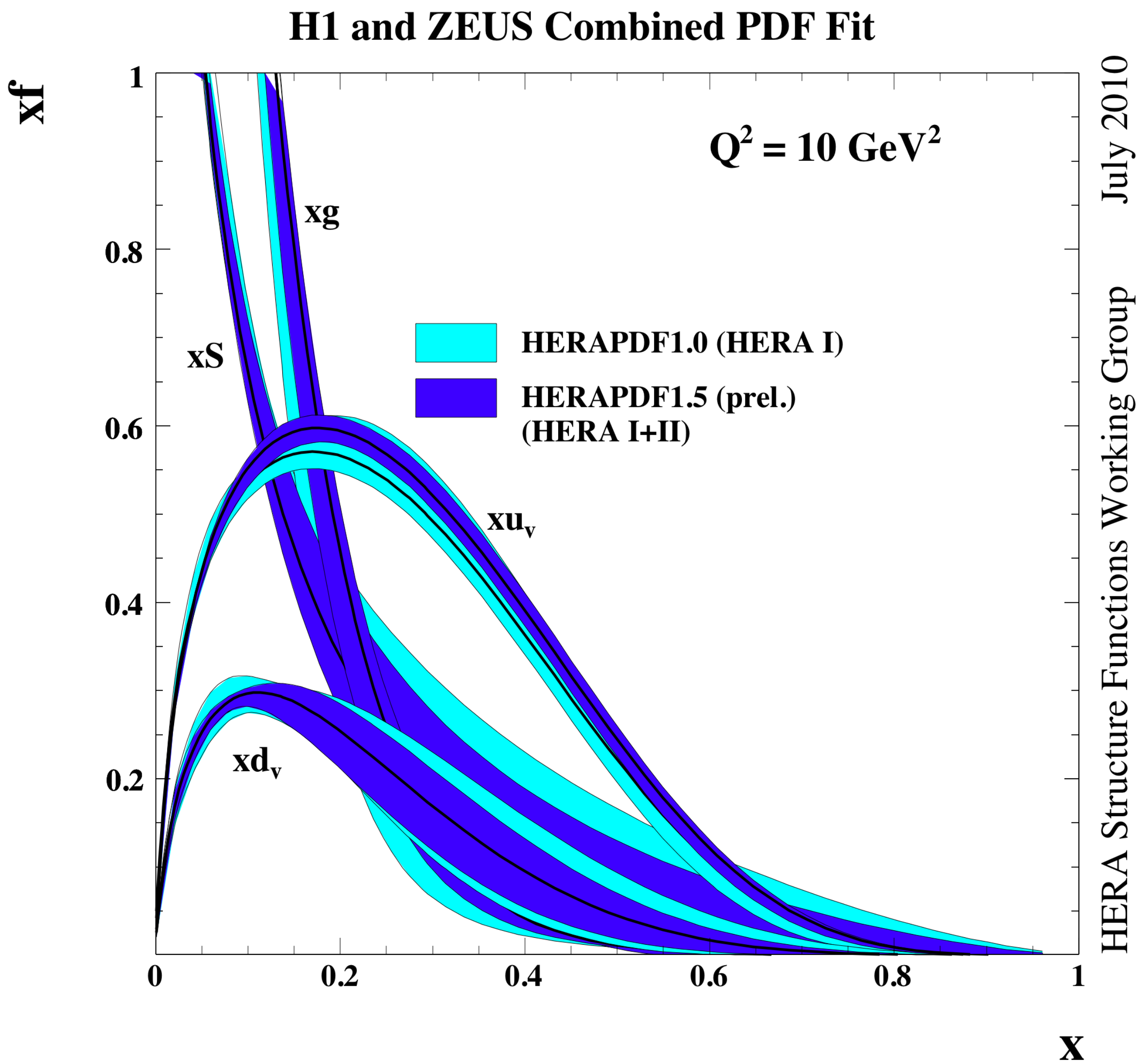
Broadly consistent with global fits (MSTW, CTeQ, NNPDF)

A Closer Look at High x



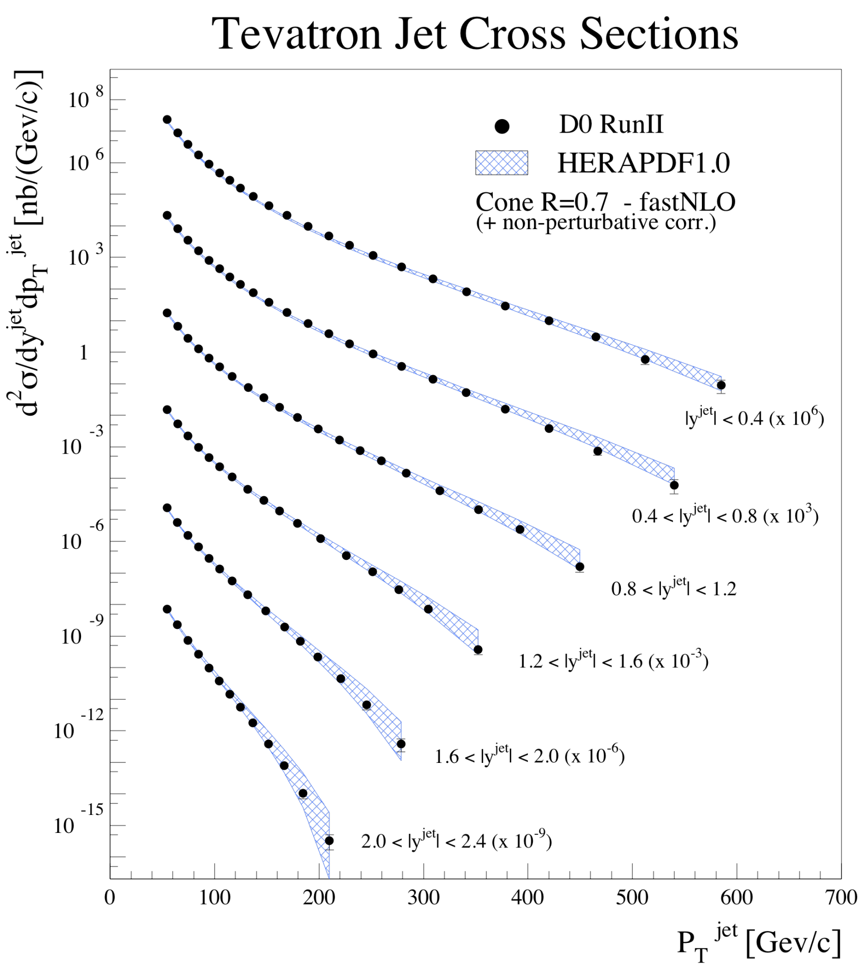
- Errors explode at highest x (improves with Q^2 evolution)
- Better in global fits (MSTW, CTeQ include pp jets, DY)
- HERA-II data help → HERAPDF1.5

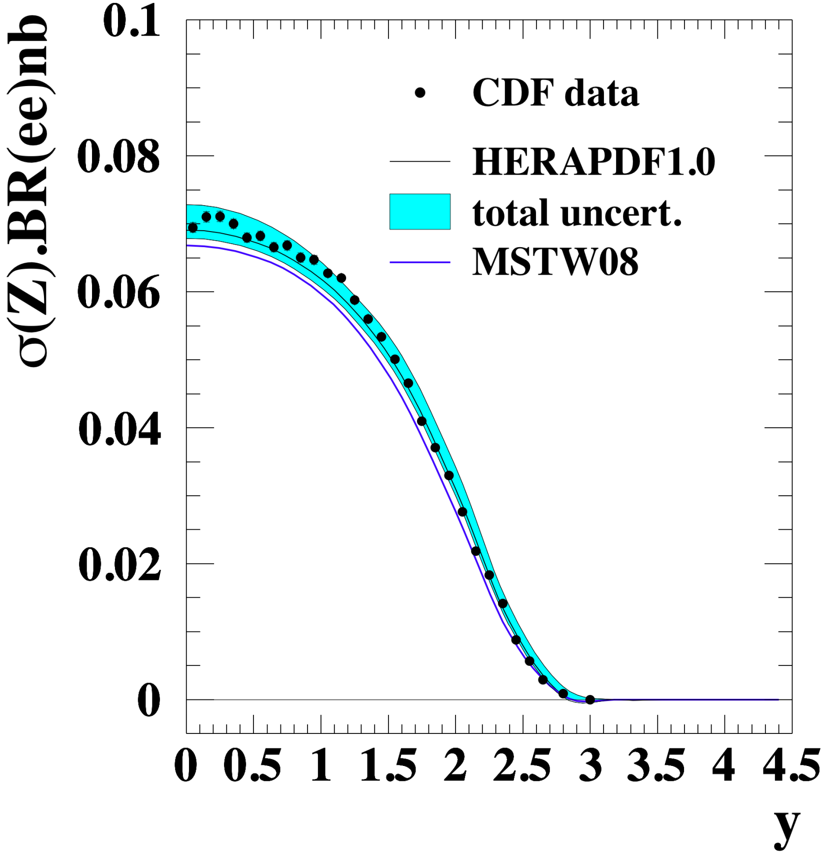
Including HERA-II Data: HERAPDF 1.5



- Identical procedure to HERA-I case, but with enhanced statistics in high x, high Q^2 region.
- Experimental and parameterisation uncertainties reduced at high x
- Including low Ep data also helps (high x, medium Q^2)

Comparisons with Tevatron Data





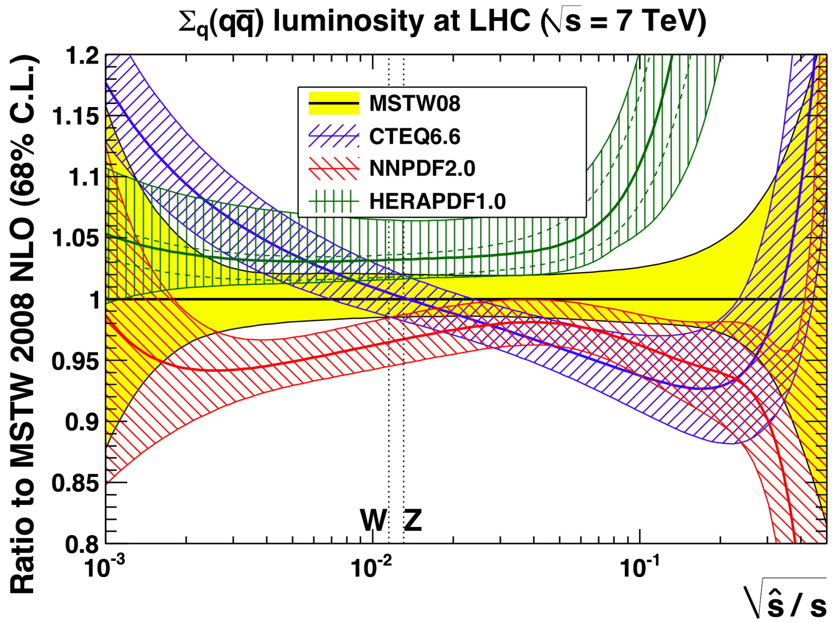
Tevatron observables well described by HERAPDF1.0

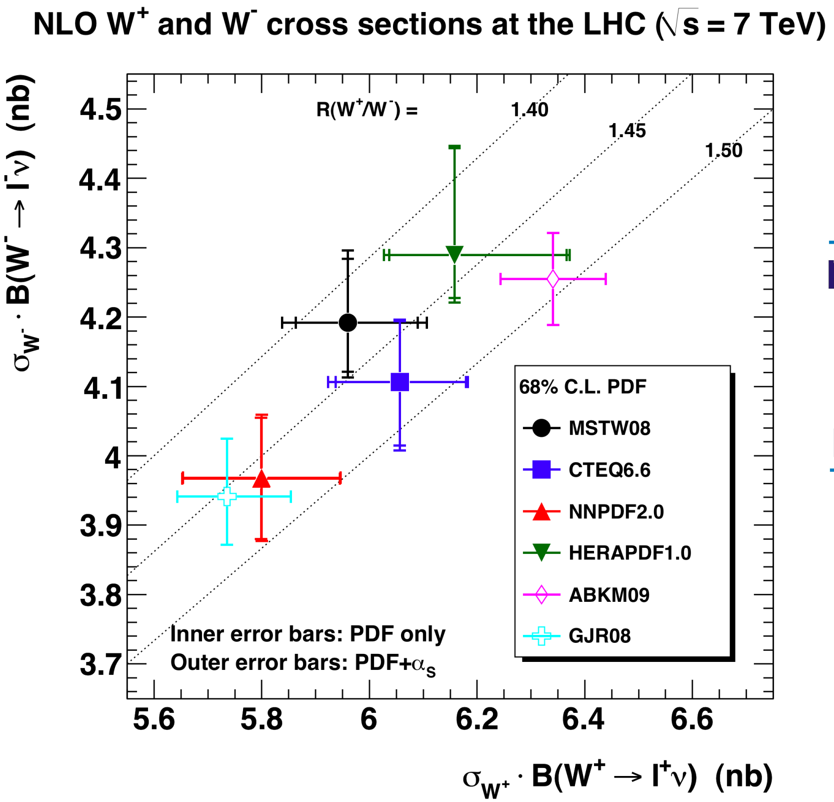
… universal parton densities describe ep and pp

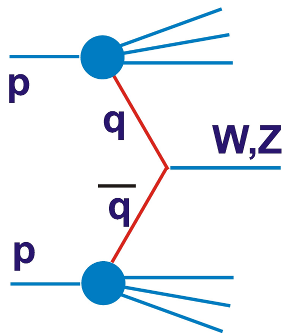
… **the cleanest test of QCD collinear factorisation**

Predictions for LHC: Quark Initiated Processes

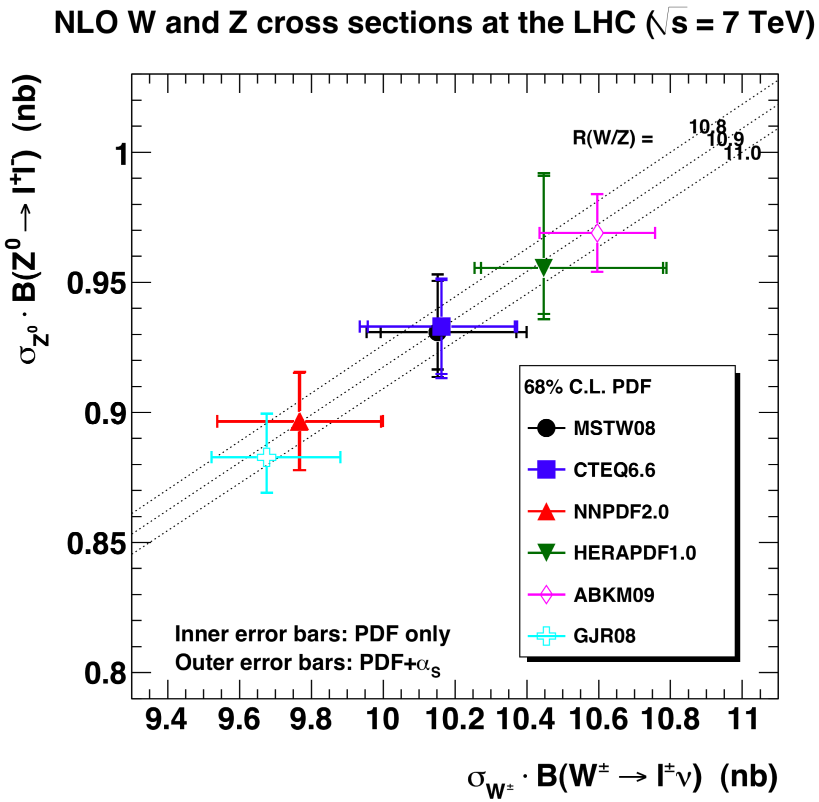
~5% uncertainty on $\sigma(W)$, $\sigma(Z)$
... is MSTW/CTeQ/NNPDF sufficient to define uncertainty?





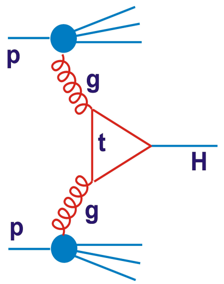


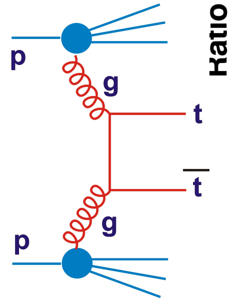
[Plots by G. Watt]

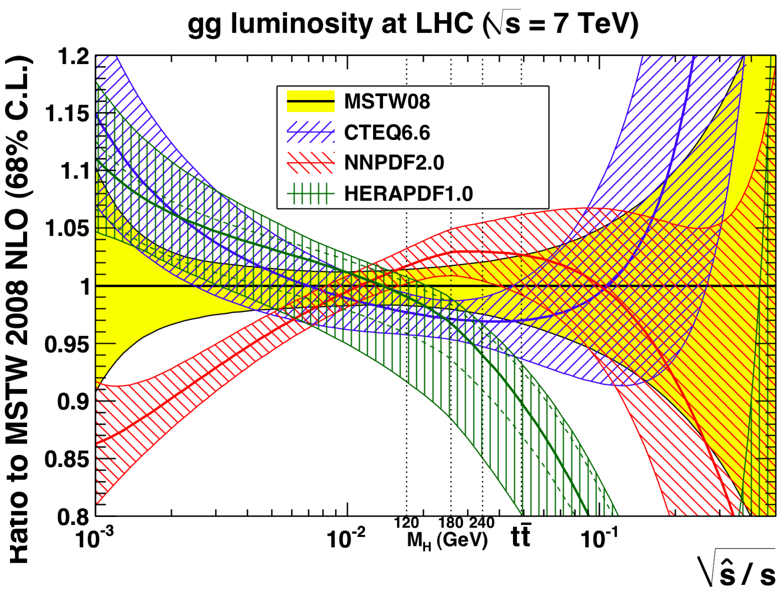


Predictions for LHC: Gluon Initiated Processes

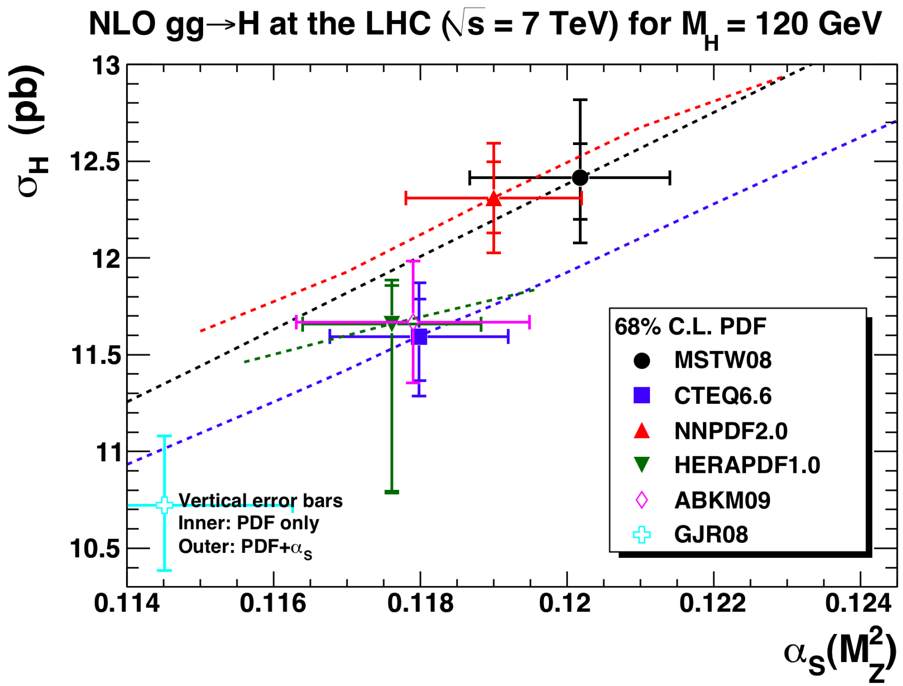
Top, Higgs cross section uncertainites up to 10-15%

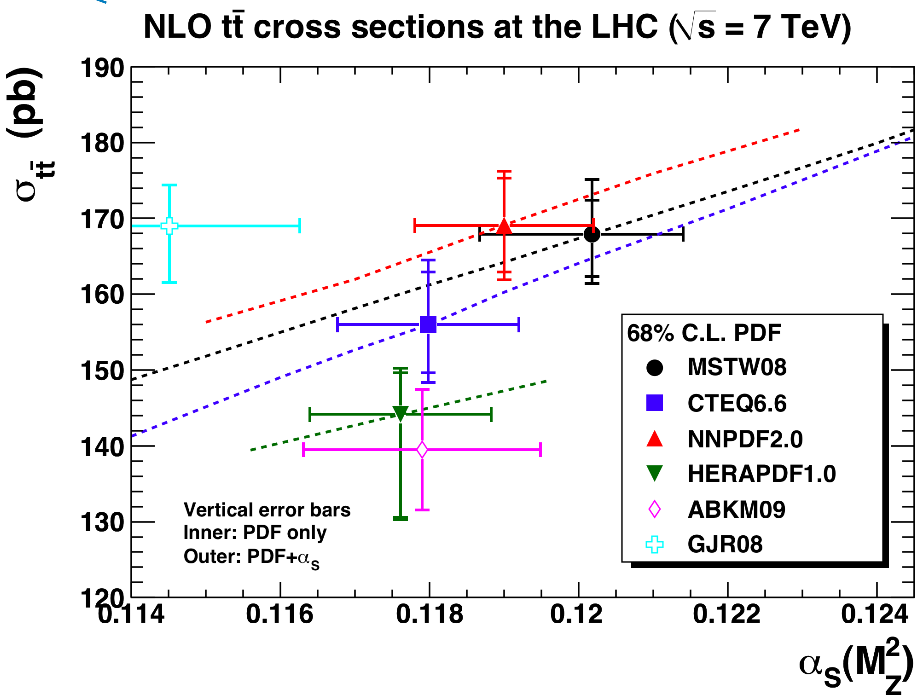




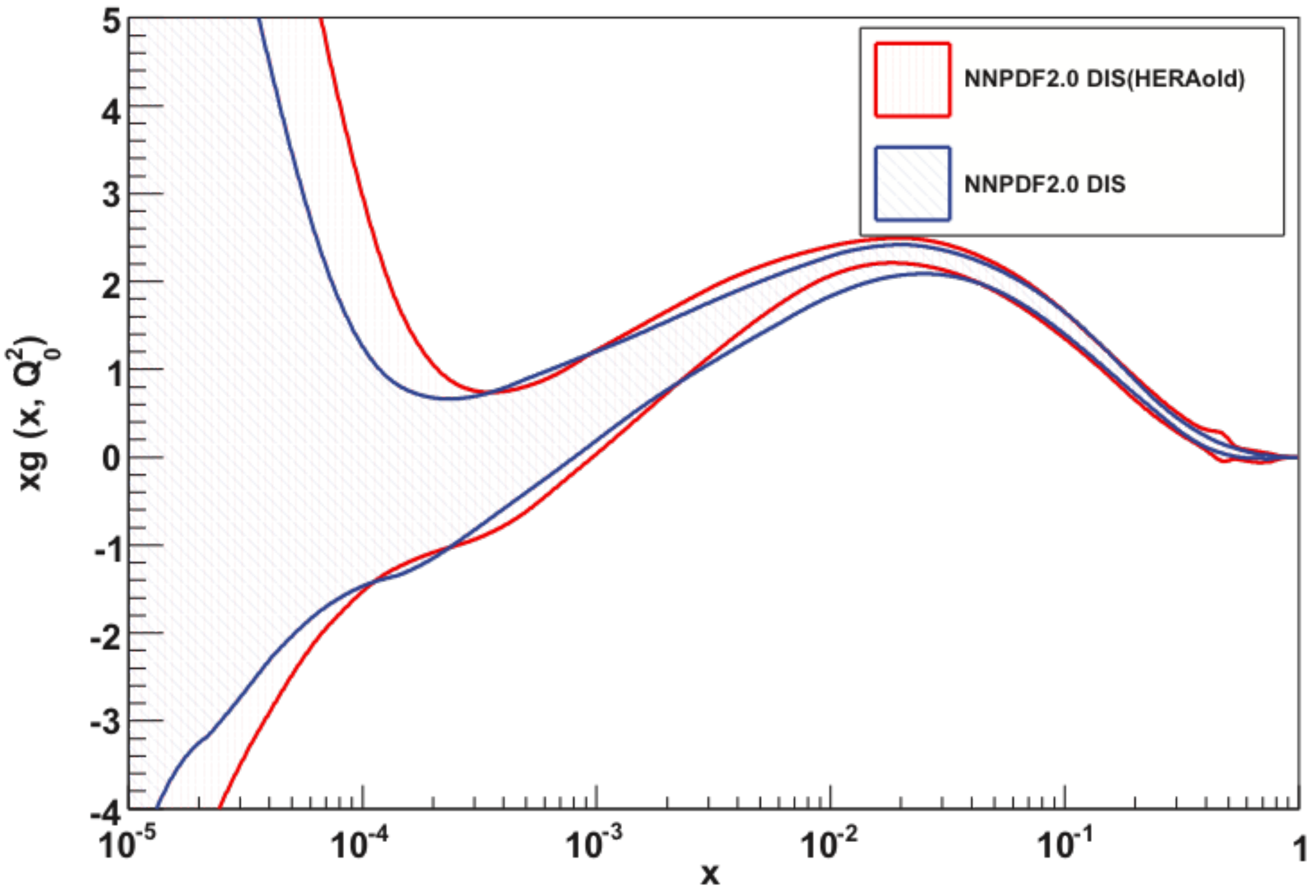


[Plots by G. Watt]



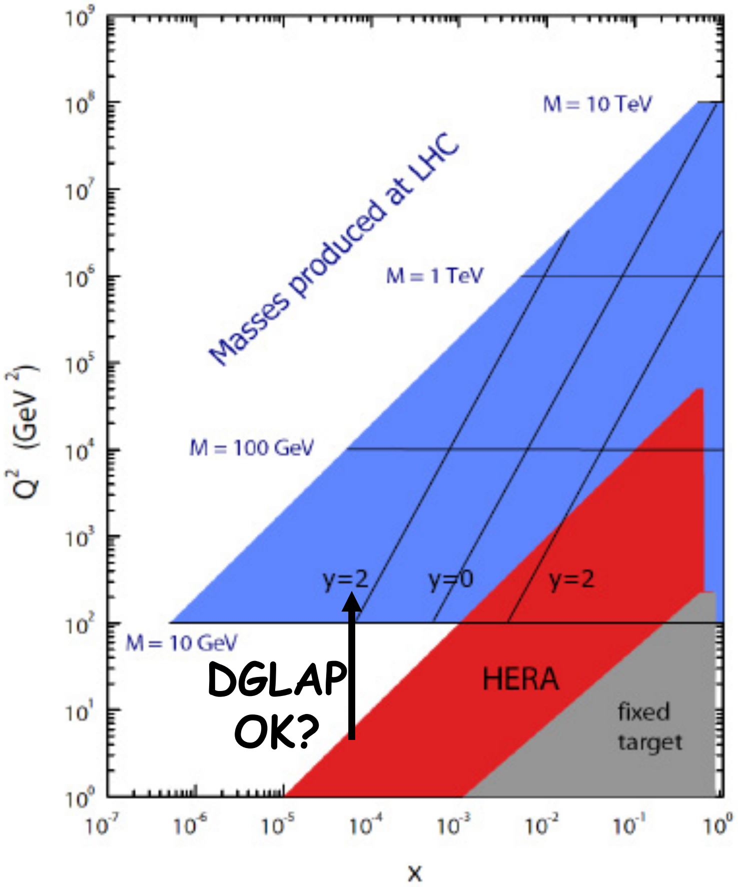


How Well do we Know the Low x Gluon?

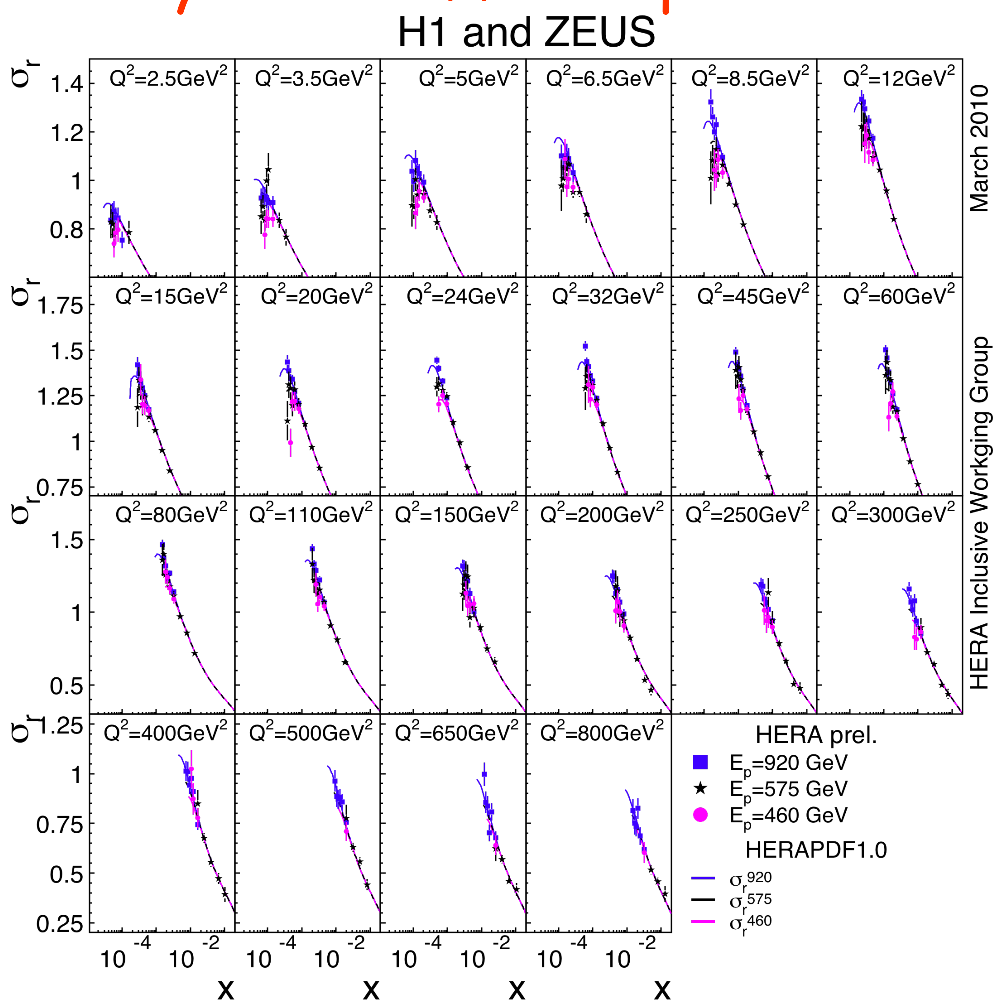


- According to NNPDF, gluon very poorly known for x <~ 10^{-4}
- Would we notice if there were problems in assumed theory?

Are DGLAP Dynamics Sufficient at Low x?



- At low x, LHC predictions rely on assumption of DGLAP evolution … yet many novel effects predicted …

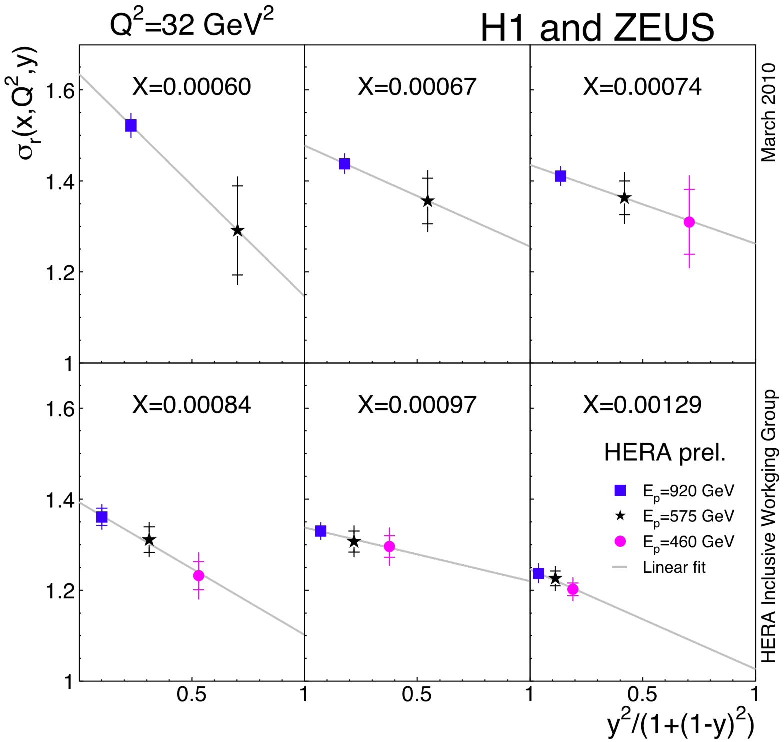


Test overall picture with F_L **extracted using reduced proton beam energy data**.

Where gluon dominates,

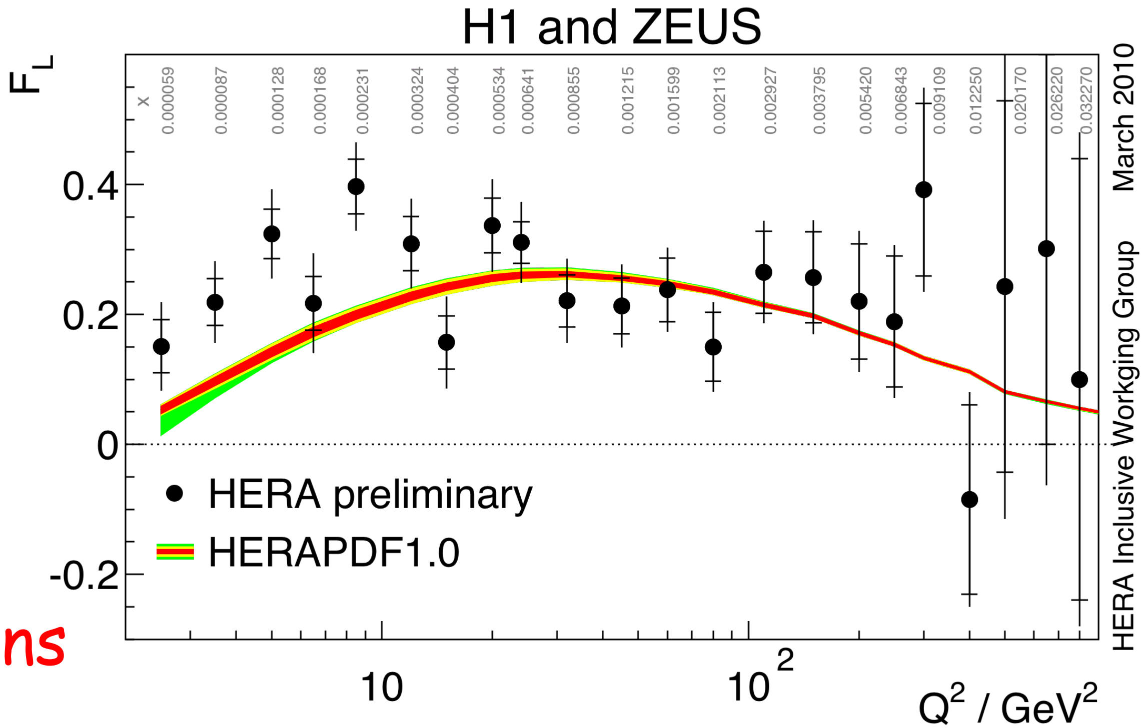
$F_L \sim \alpha_s \, xg(x)$.

Combined H1 + ZEUS F_L Measurement



Extracted double differentially

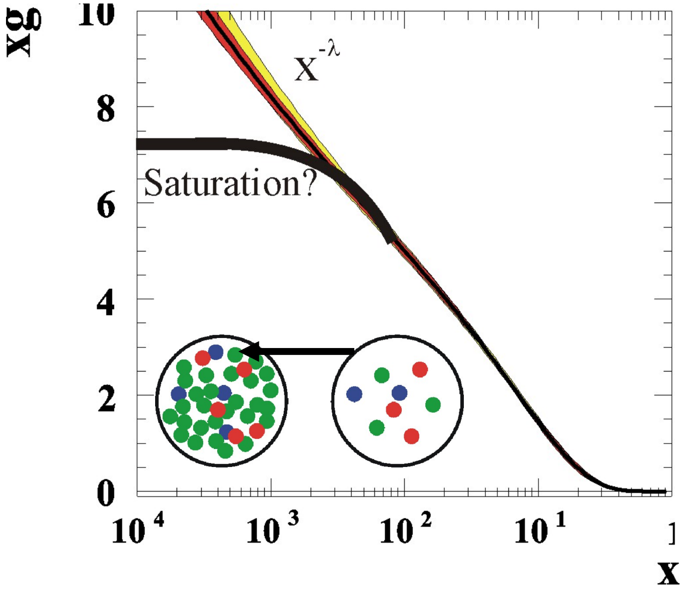
... Summary of Q^2 dependence here



$$\sigma_r = F_2 - \frac{y^2}{Y_+} F_L$$

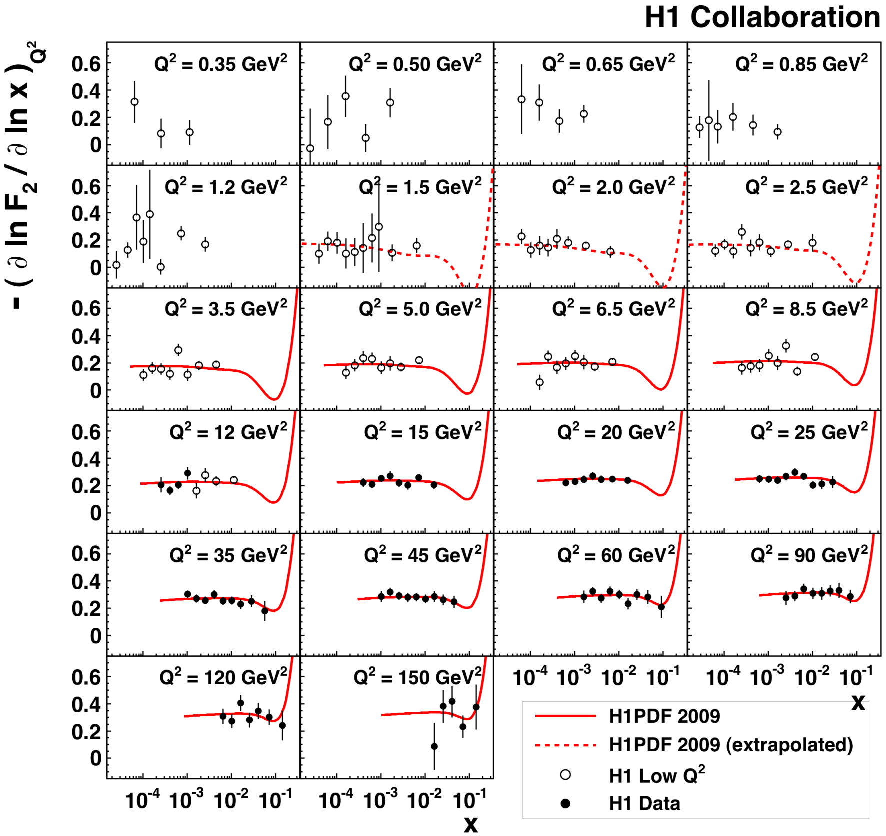
Basically good agreement
With HERAPDF predictions

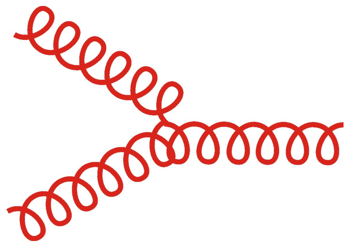
Hints of deviations at low x, Q^2 may be resolved with modified heavy flavour treatment or inclusion of NNLO terms?



Search for Gluon Saturation

- Gluon density cannot rise indefinitely as x decreases (unitarity)
- DGLAP approximation to QCD may be insufficient e.g. due to neglect of $gg \to g$ recombination





from local derivatives with respect to x …

… no evidence for any deviation from a single power law $F_2 = A(Q^2).x^{-\lambda(Q2)}$ for Q^2 >~ 1 GeV^2

Summary

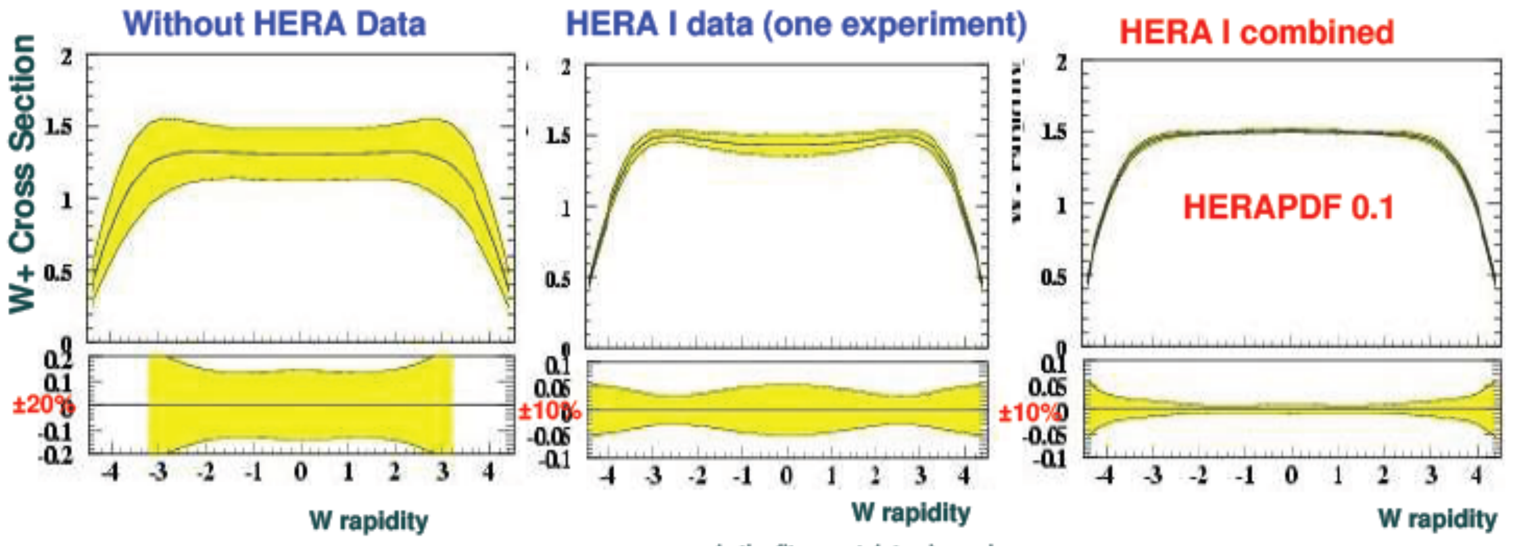
- After 15 years of running, HERA provided a unique data-set

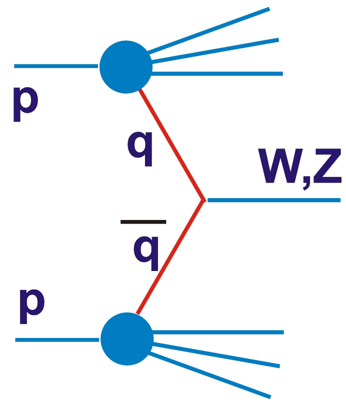
- ~450 publications to date:
  - The main source of our knowledge of the LHC initial state
  - Big advances in understanding QCD
  - Dedicated low x dynamics studies

- Combinations of H1 and ZEUS data and fits proves powerful in reducing errors
  - HERAPDF1.0 gives competitive precision for many LHC observables without tension between datasets
  - Final HERA-II data to be included

Back-Ups Follow

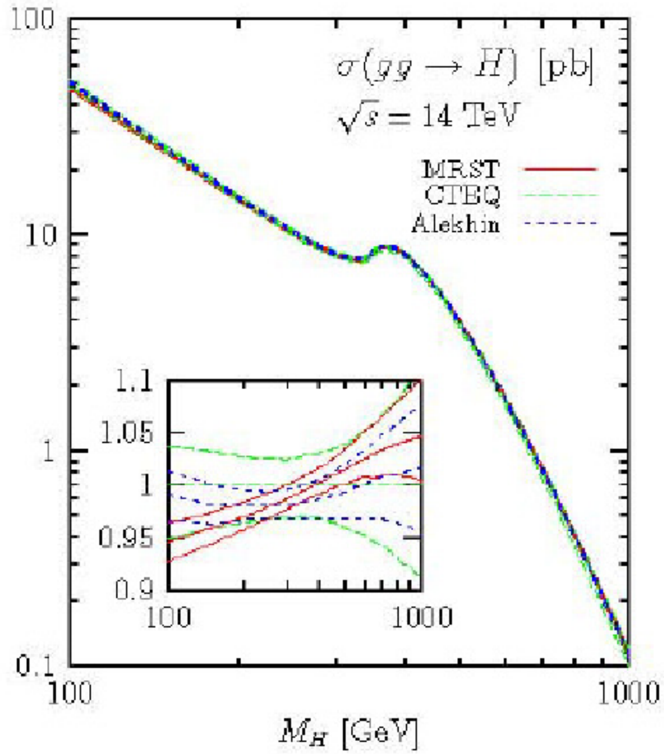
Examples of Precision on LHC Cross Sections





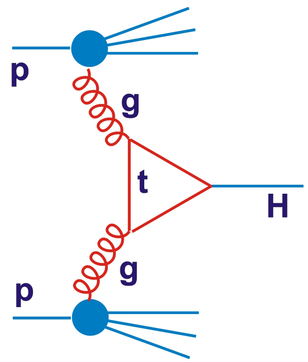
W Rapidity Spectra:

- 1.5% experimental error in central region (… from HERA-I only!)
- … a further 3-4% theory uncertainty
- Z/W ratio <2% total uncertainty …



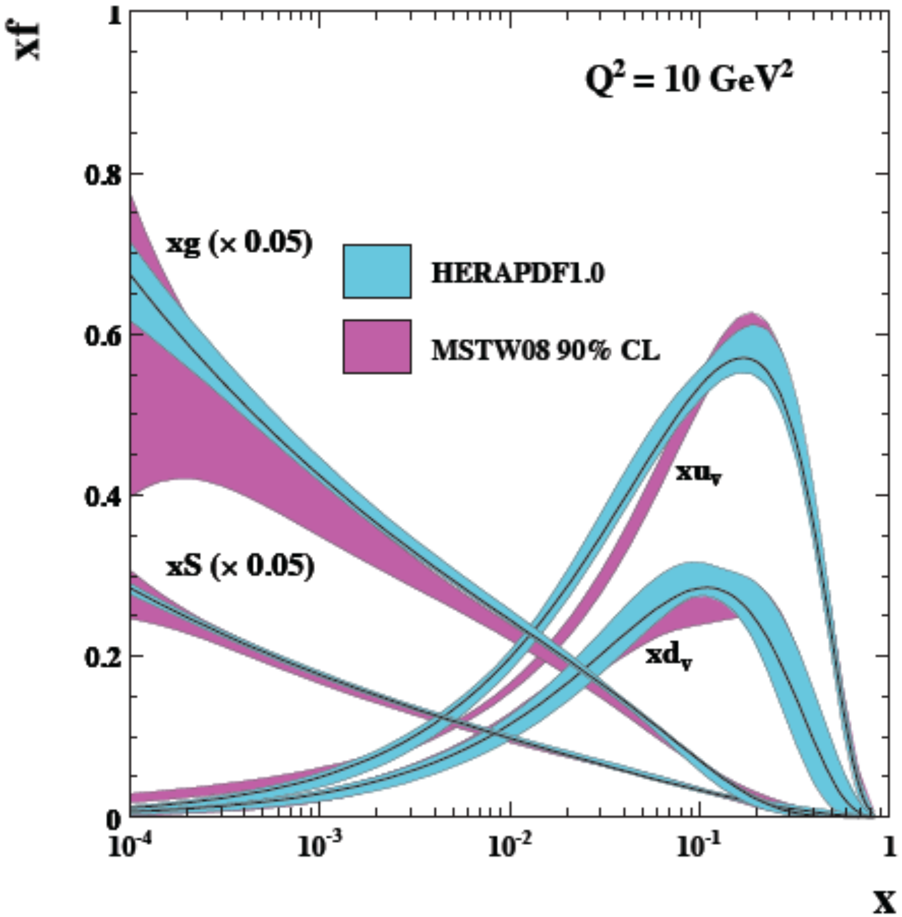
Higgs cross section:

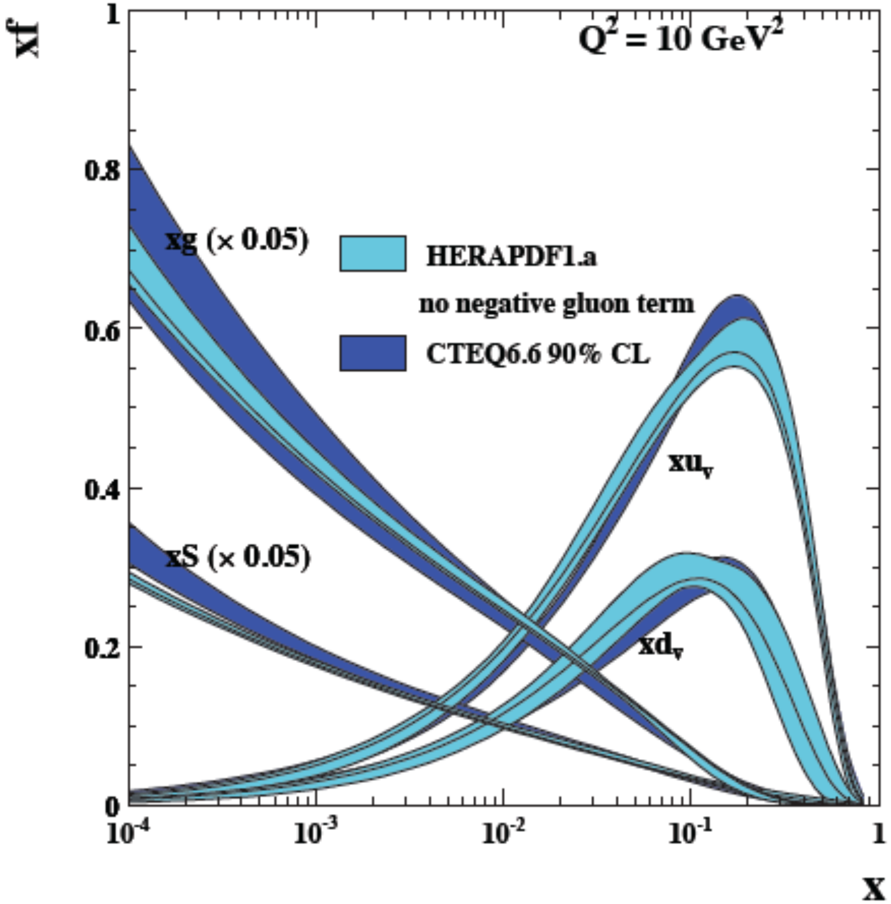
- PDF uncertainty ~ 3%
- Scale uncertainty ~ 10%



Comparisons with Global PDF Sets

Comparison with other PDFs



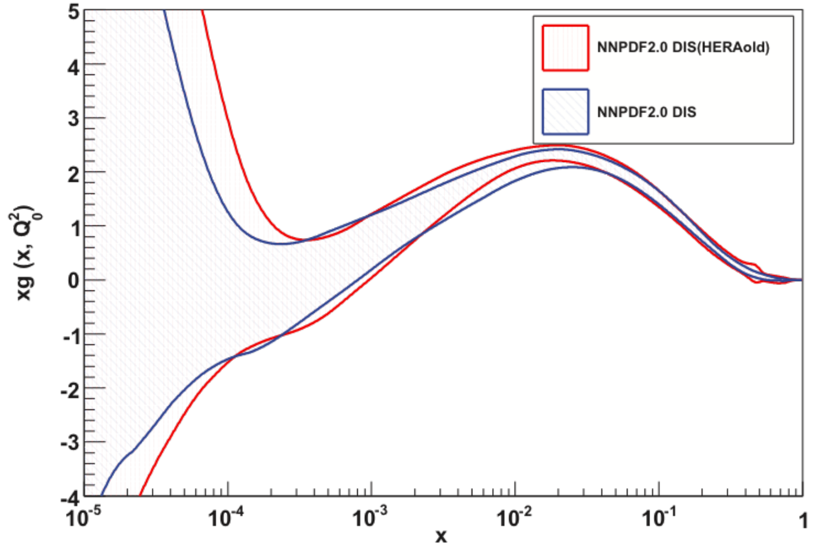


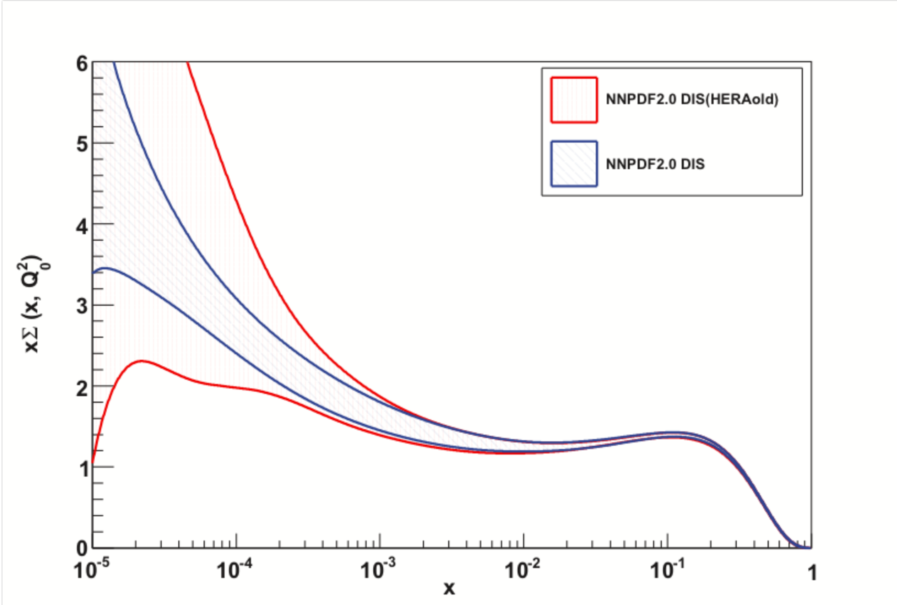
Comparison with other PDFs not trivial :

- HERAPDF uses combined data and MSTW (CTEQ) did not
- Different error treatment, model assumptions
- Consider all when making a measurement

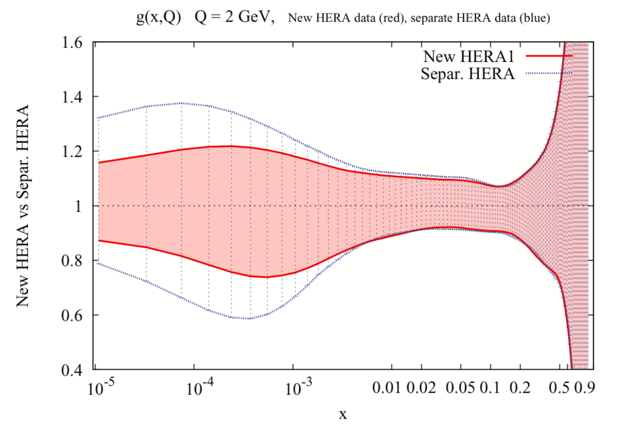
See also Voica – NNLO Version!!!!

Precision on the Low x Sea and Gluon





Relative uncertainties from paramete
Free NNPDF fit.



Gluon essentially unknown for x < 10-4

Looks completely different from CTEQ