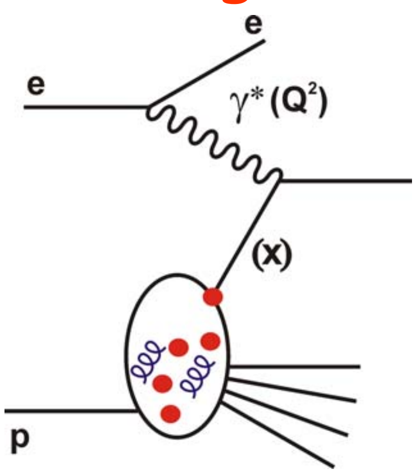
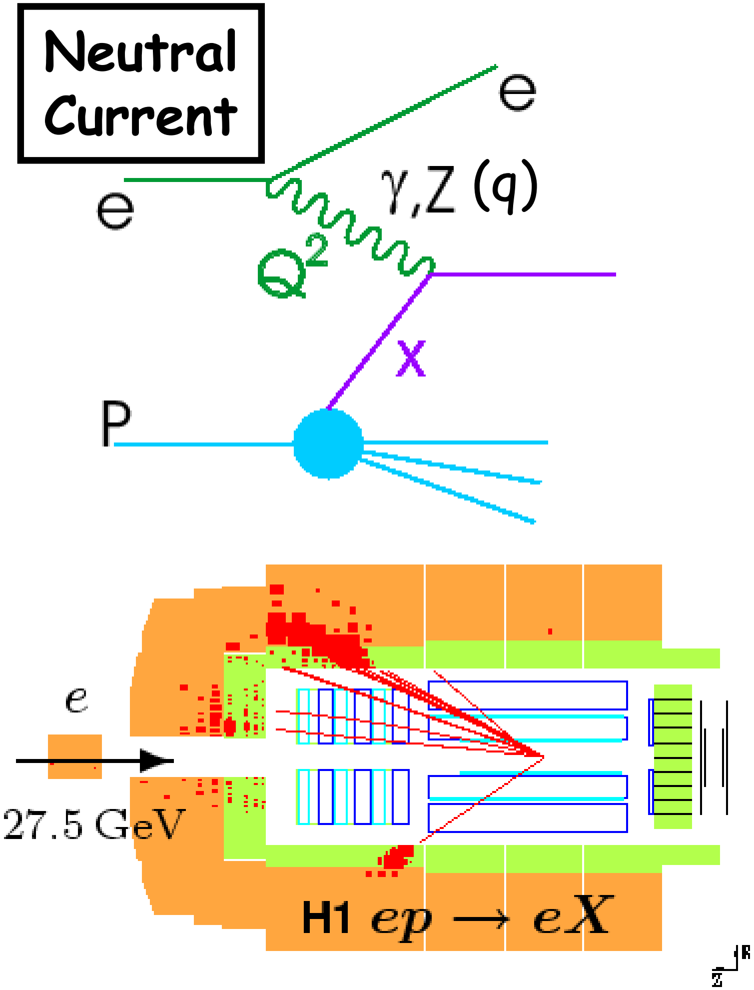
Highlights of HERA and Deep Inelastic Scattering

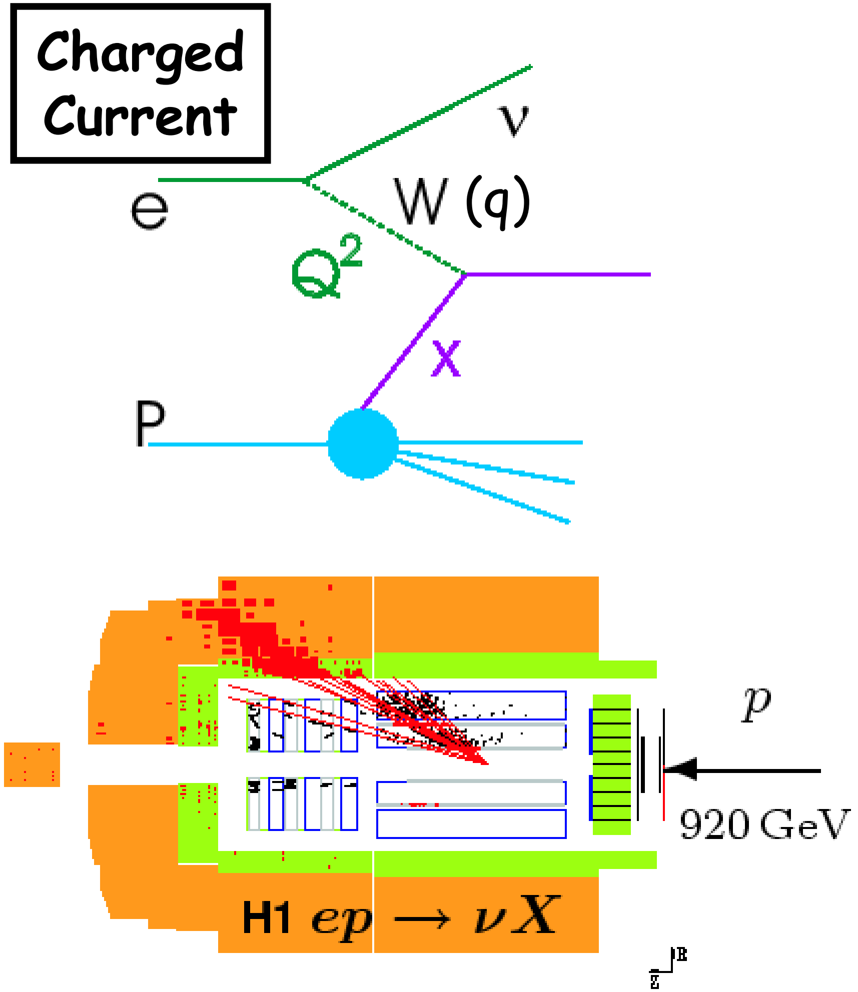
Paul Newman
(Birmingham)



IOP HEPP Meeting, Oxford
6 April 2009

Basic Deep Inelastic Scattering Processes





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

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

Proton "Structure"?

Physics at the Tevatron and the LHC is about interactions between proton constituents …

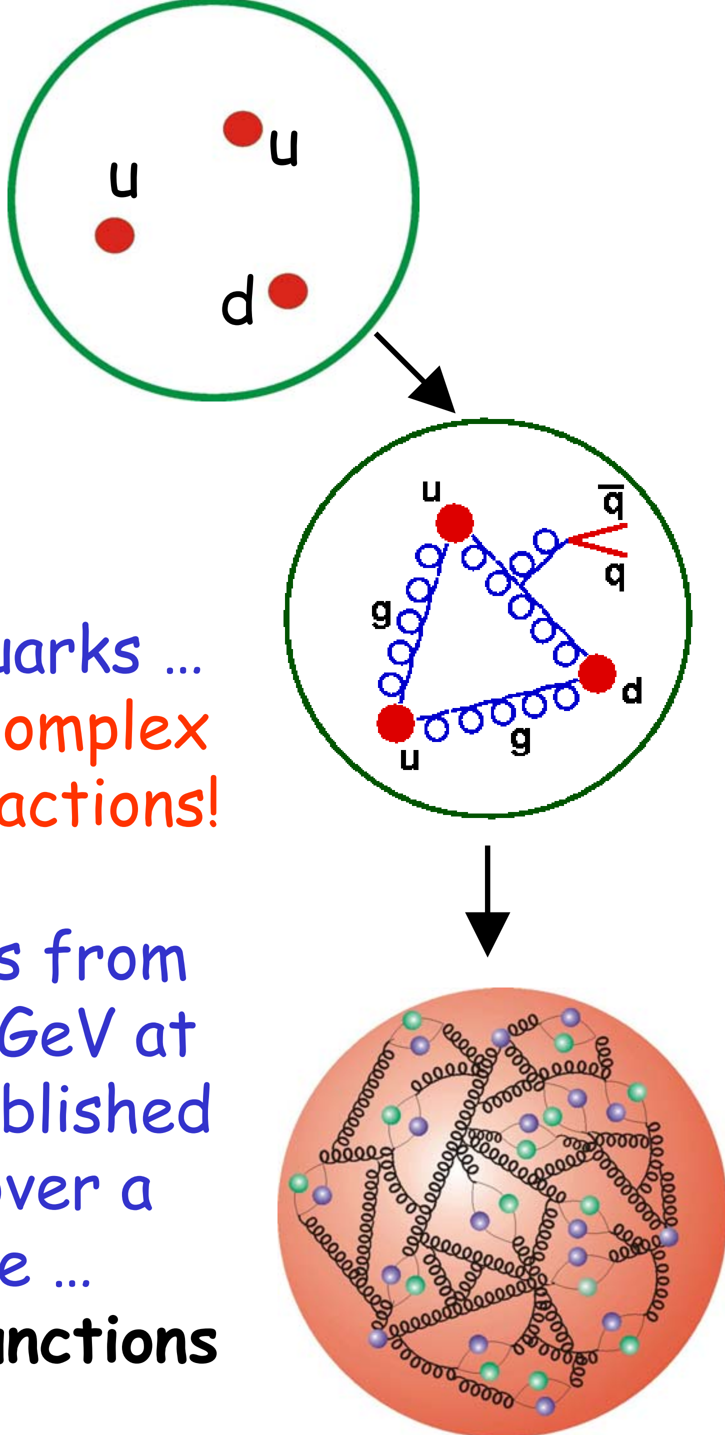
2 up and 1 down **valence quarks**

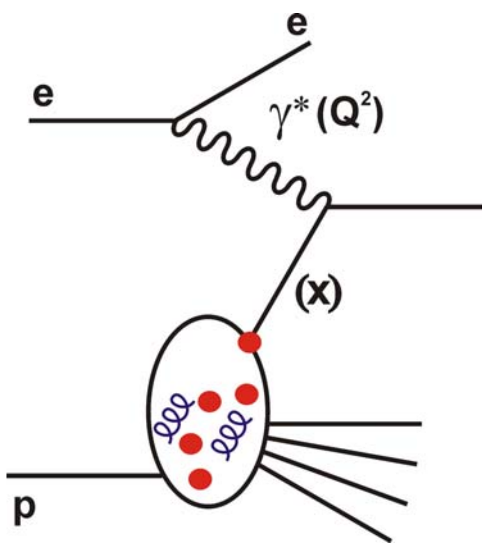
… and some **gluons**

… and some **sea quarks**

… and lots more gluons and sea quarks …

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





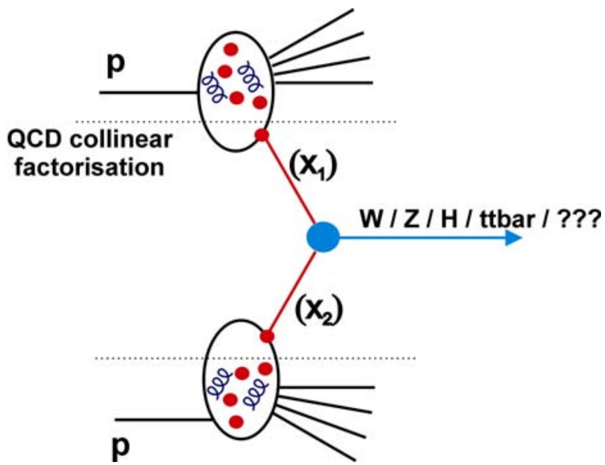
Scattering electrons from protons at √s > 300GeV at HERA data has established proton `structure' over a huge kinematic range …

… **parton density functions**

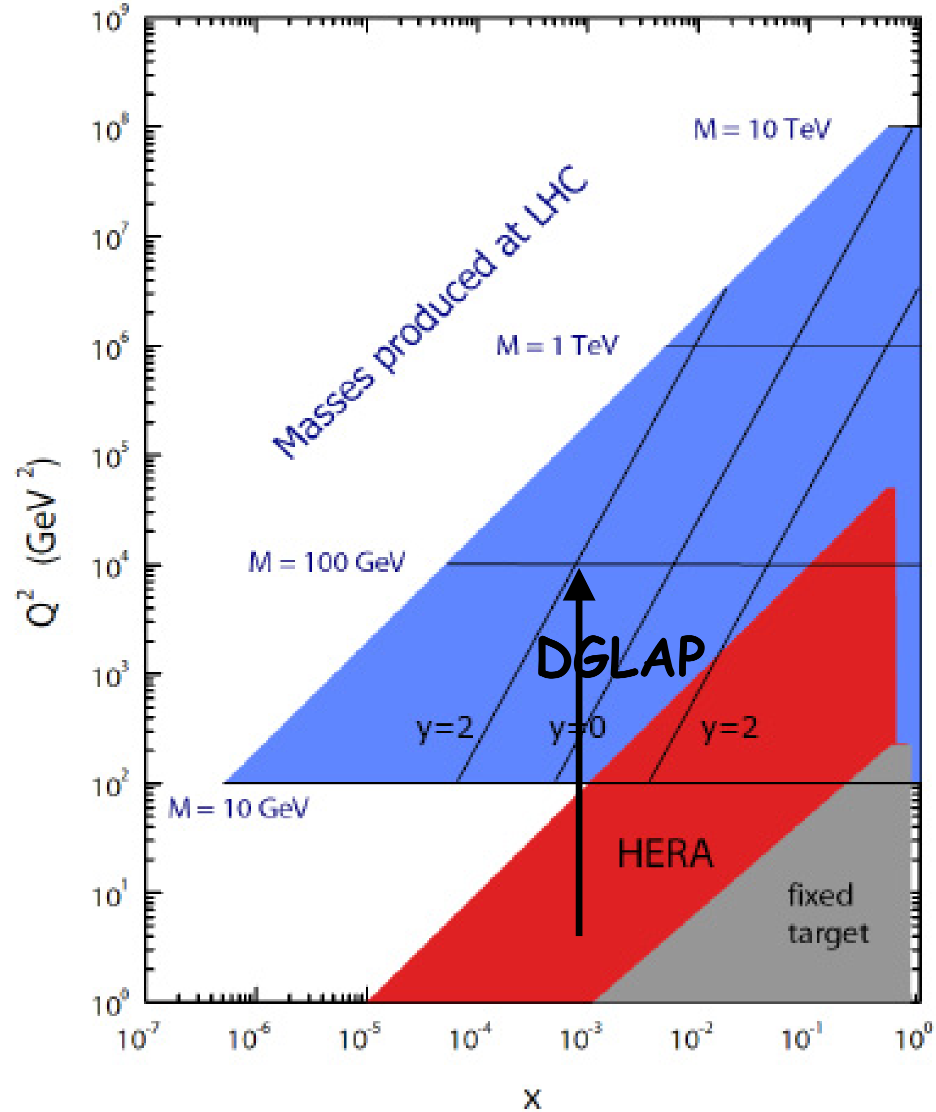
HERA kinematic range

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

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

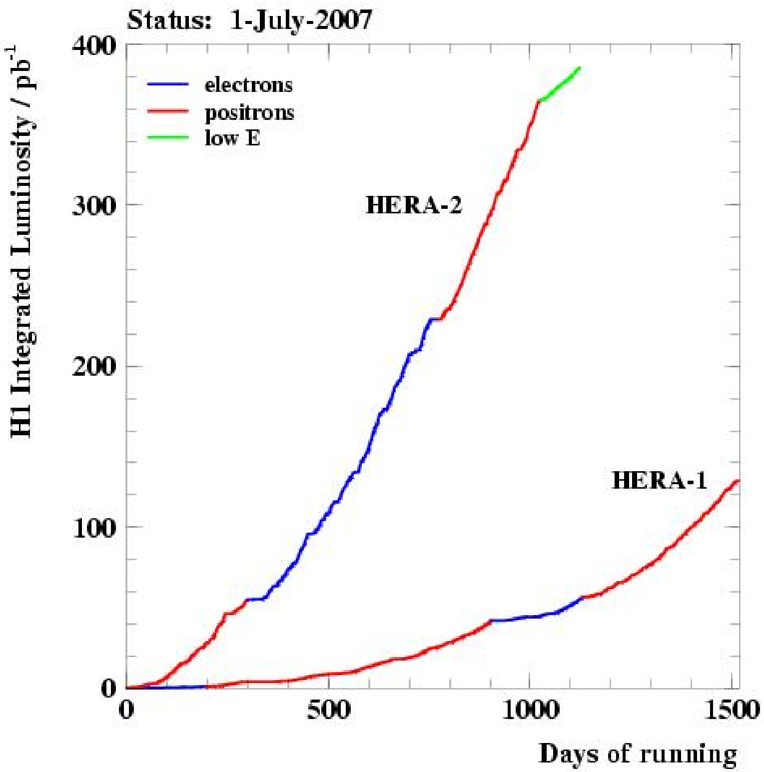


- Well established `**DGLAP' evolution** equations generalise to any scale (for not too small x)



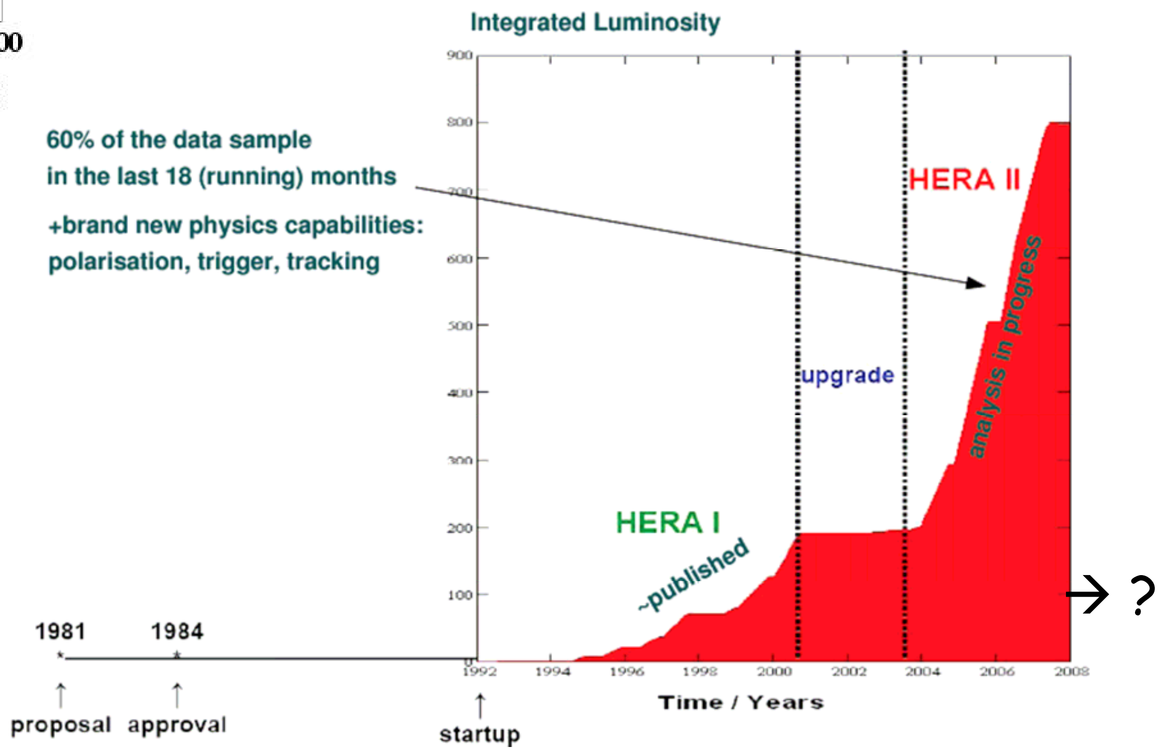
e.g. pp dijets at central rapidity: $x_1=x_2=2p_t / \sqrt{s}$

Luminosity and Status



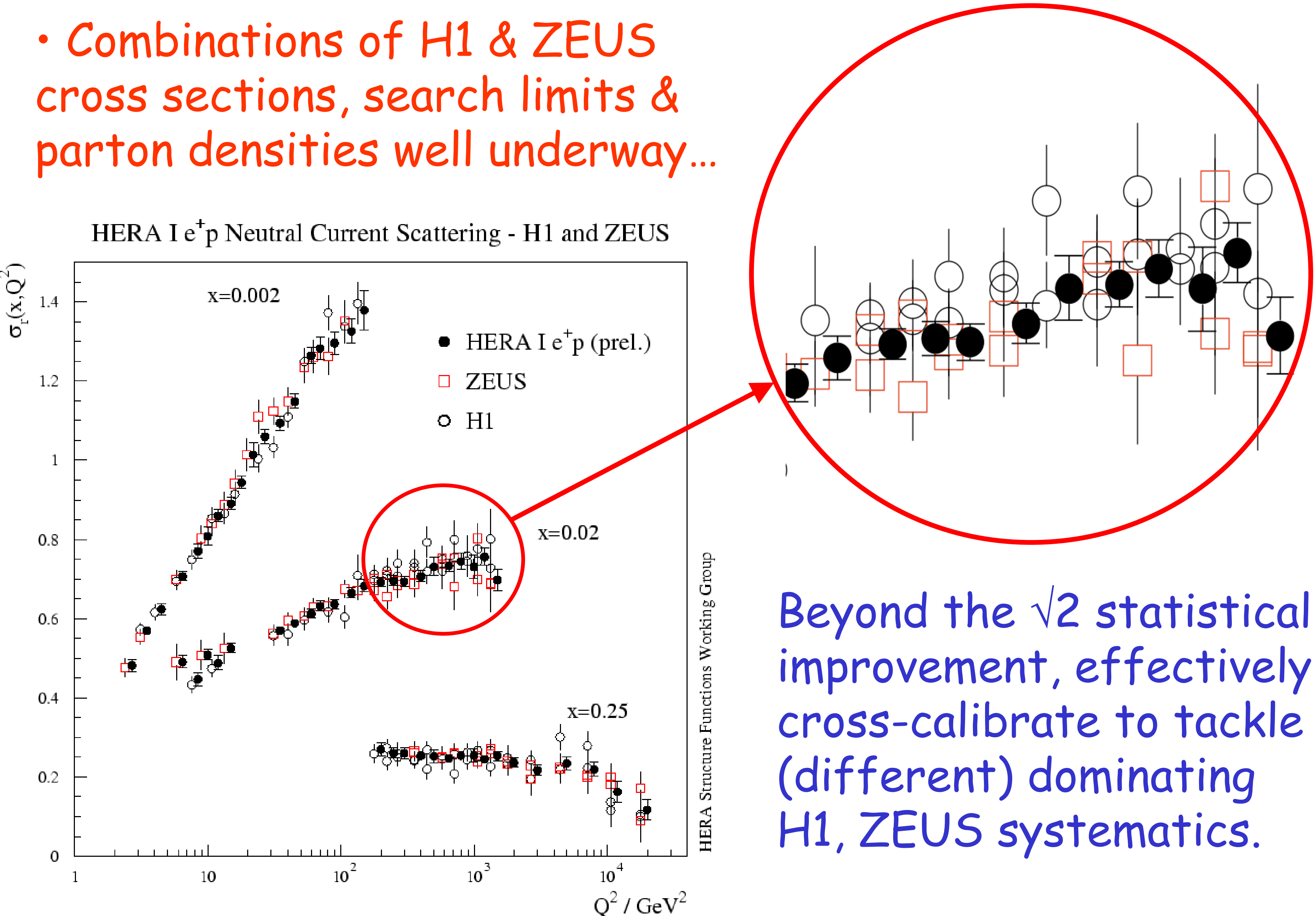
- Total of ~200 pb^{-1} e^-p, 300 pb^{-1} e^+p per experiment.
- Both lepton polarisation states
- ~25 pb^{-1} @ lower E_p = 575, 460 GeV

- HERA-I publications coming to an end.
- HERA-II searches largely complete
- Complicated final states take time (& UK experts) to analyse



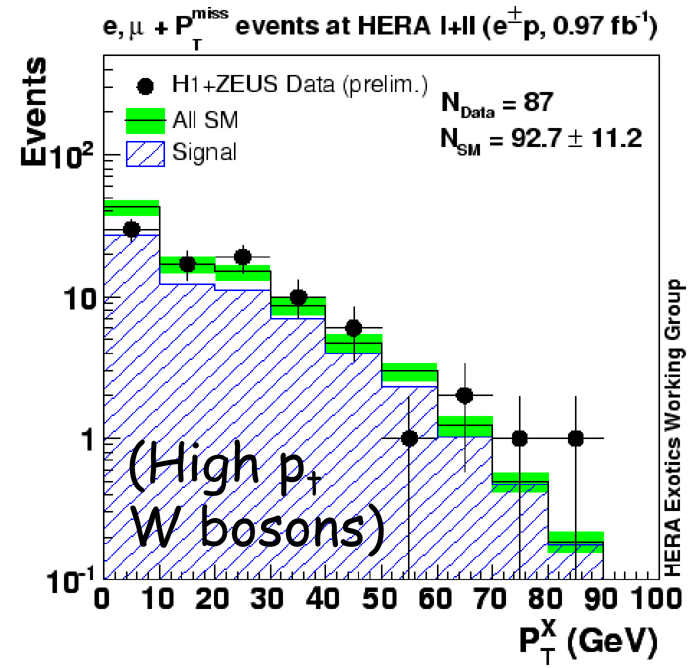
The Power of Combinations

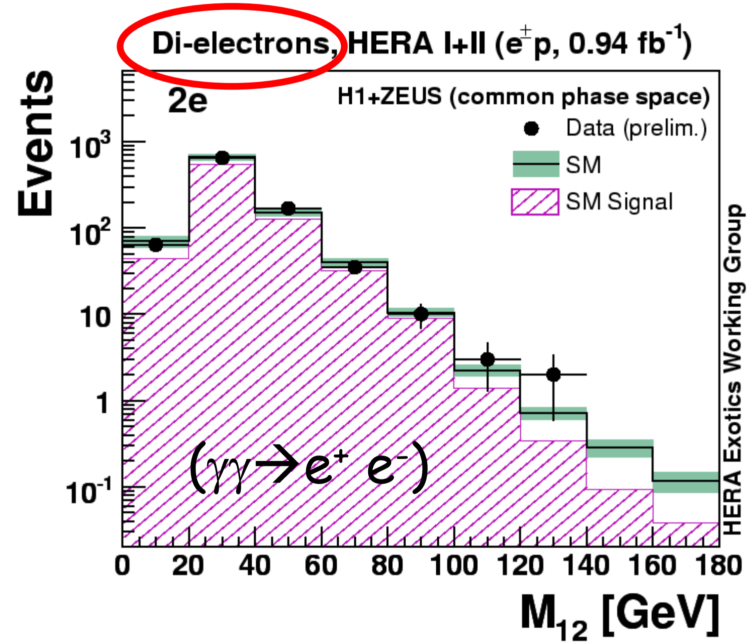
- Combinations of H1 & ZEUS cross sections, search limits & parton densities well underway…

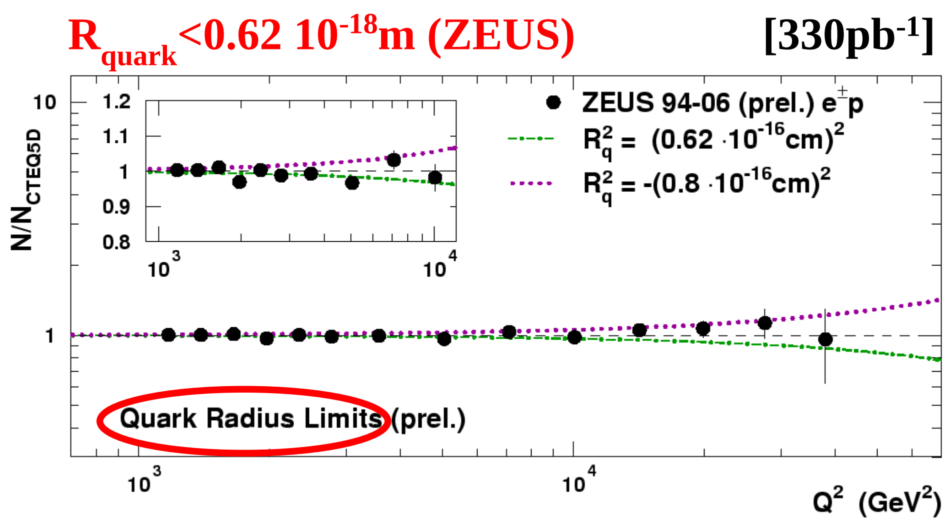


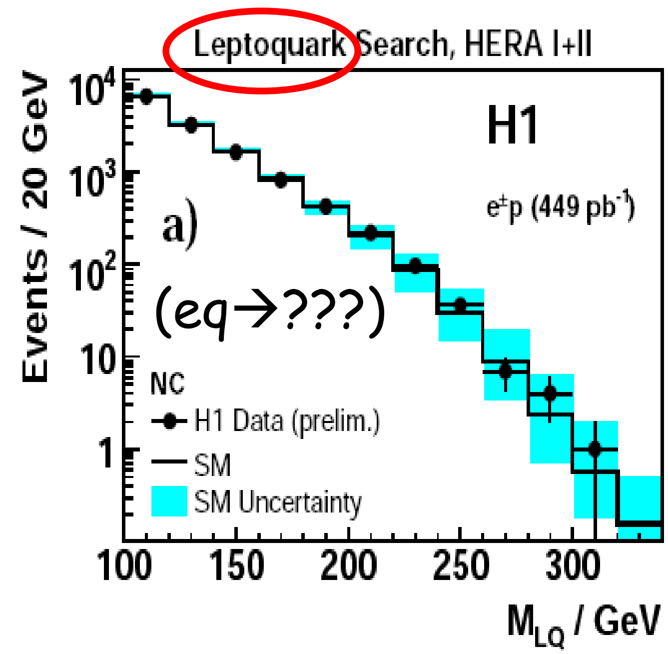
Beyond the √2 statistical improvement, effectively cross-calibrate to tackle (different) dominating H1, ZEUS systematics.

Probing 300 GeV eq Interactions with 1 fb^{-1}

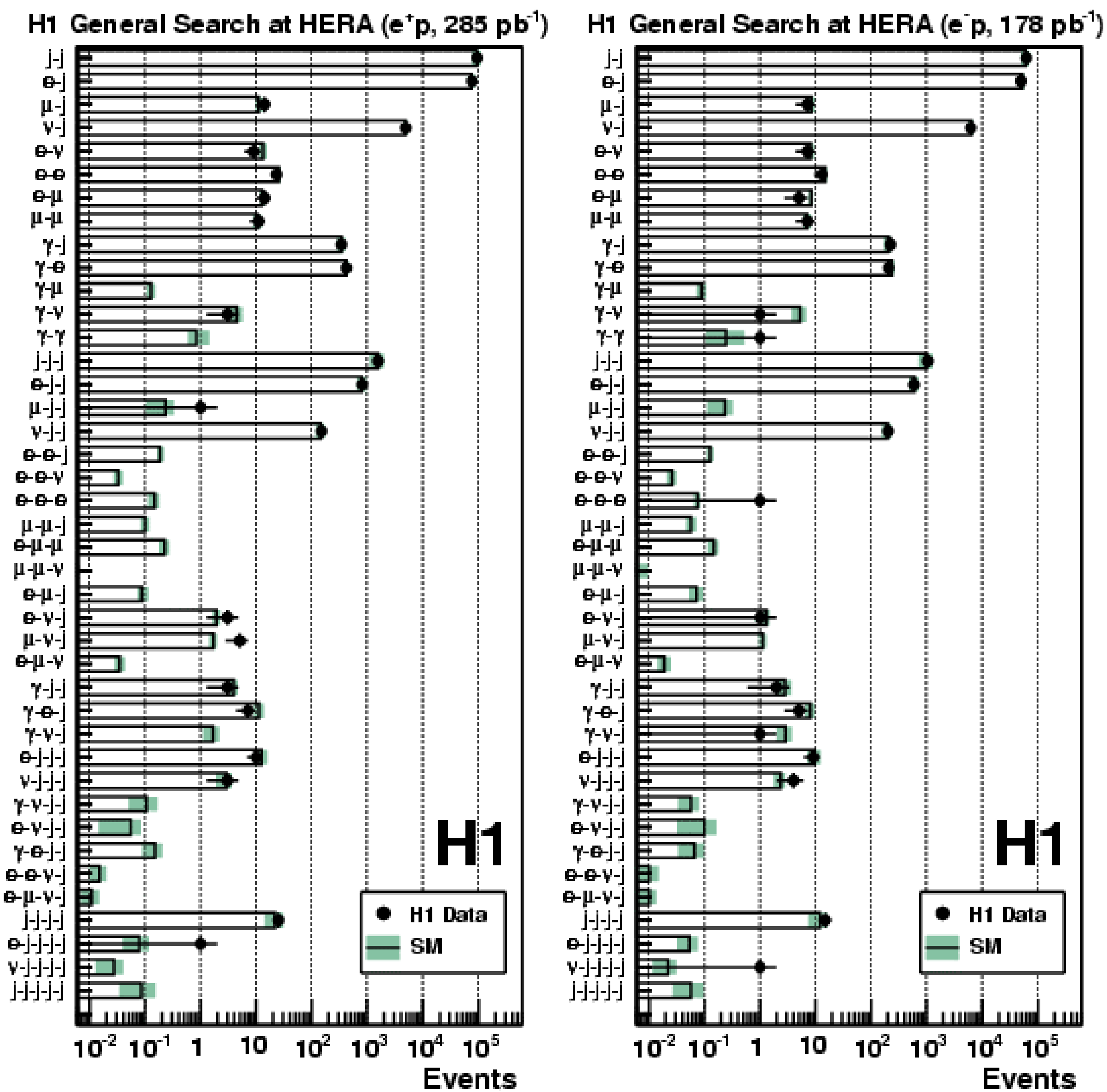








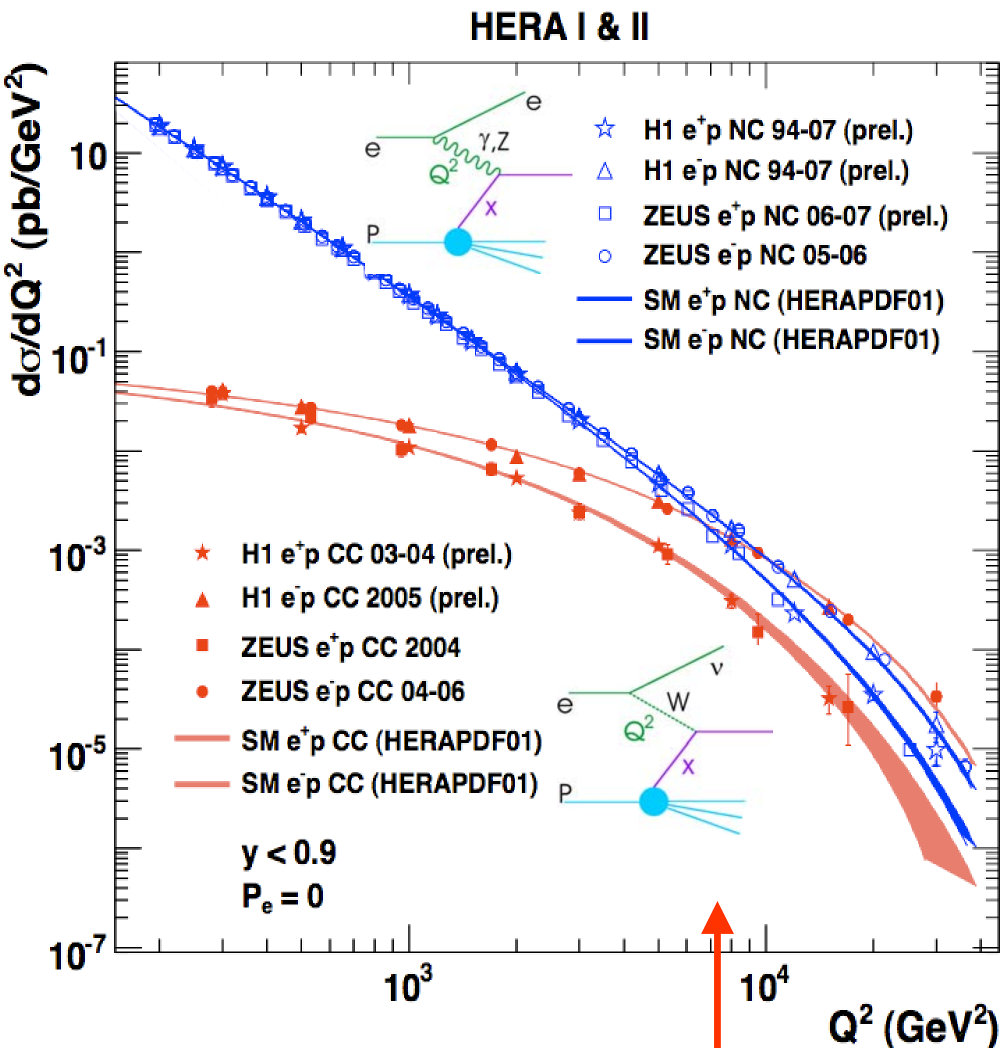
A `General' high pt Summary



- No significant BSM signals
- Also studied in all possible ΣM intervals …
- Detectors and physics processes well understood!

The Standard Model & HERA part as good friends!

Electroweak Unification for Space-like Bosons



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

Neutral Current x-sec

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

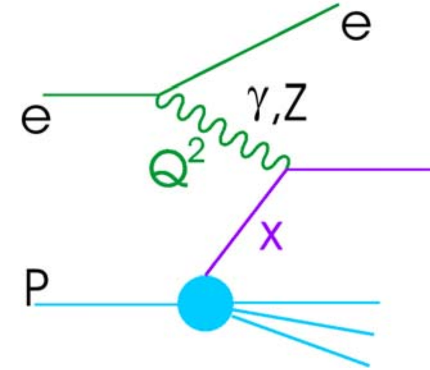
Charged Current x-sec

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

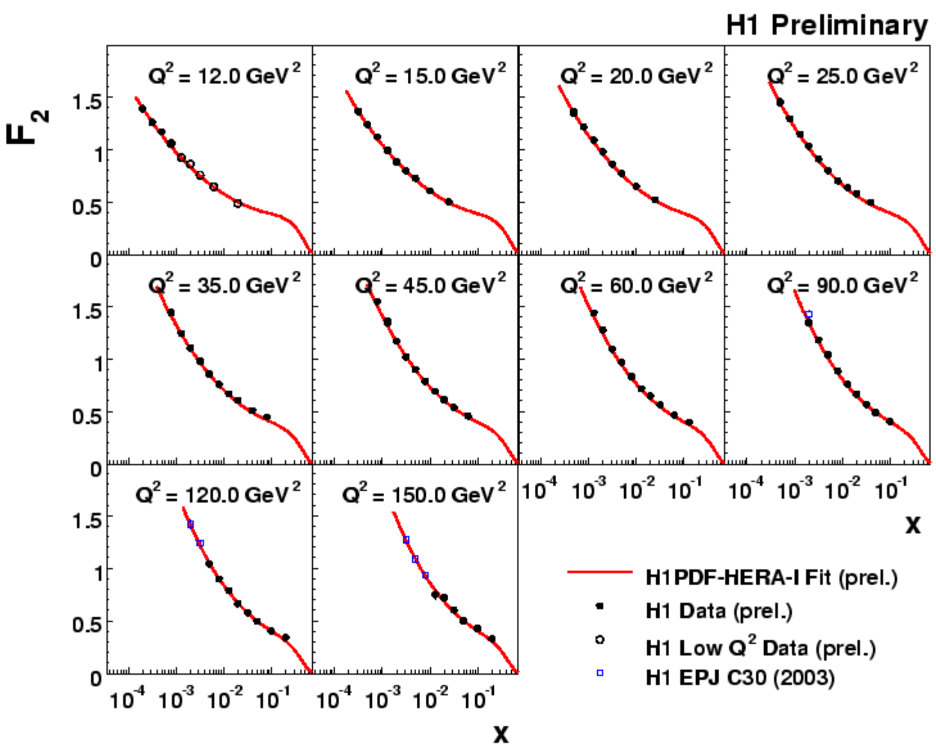
- NC and CC cross sections become comparable at EW unification scale (couplings unified)

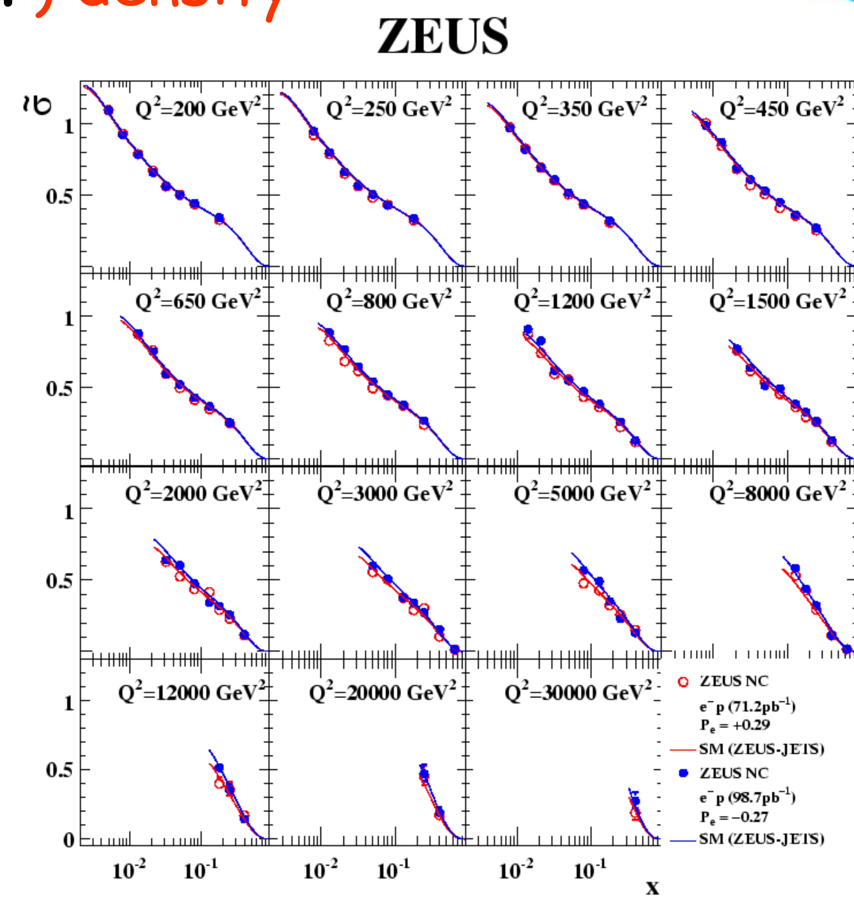
- Parton density info encoded in $\tilde{\sigma}_{NC}$ and $\tilde{\sigma}_{CC}$

Recent Neutral Current Data



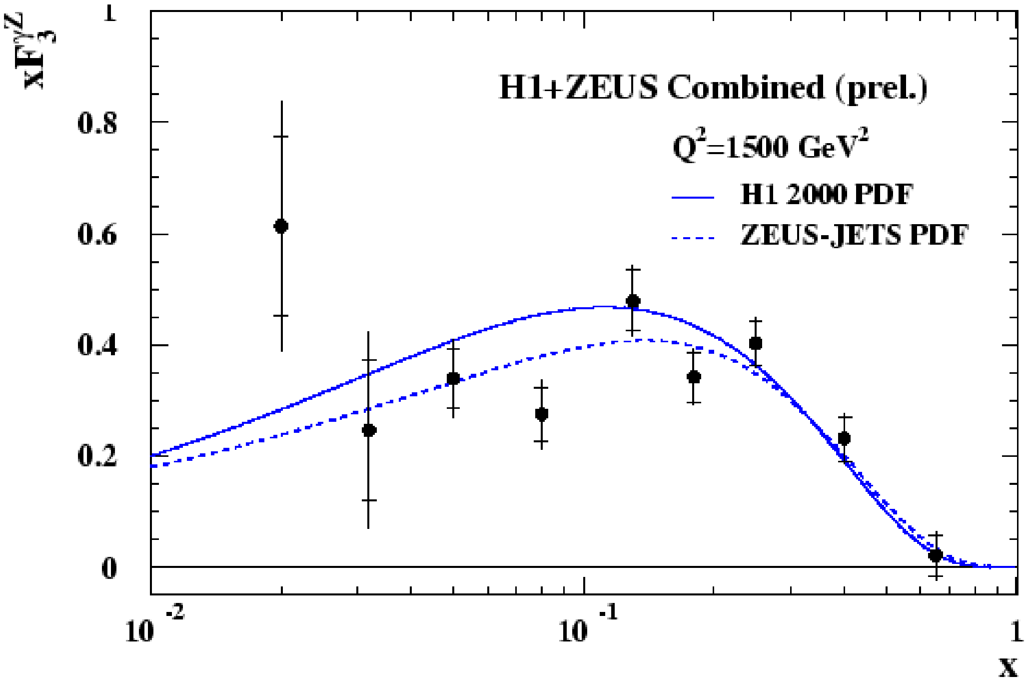
- NC data primarily measure F_2 structure fn …
- Due to e_q^2 photon coupling, NC provides best constraints on **u** (and **ubar**) density





- 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

Varying the Lepton Charge and Polarisation

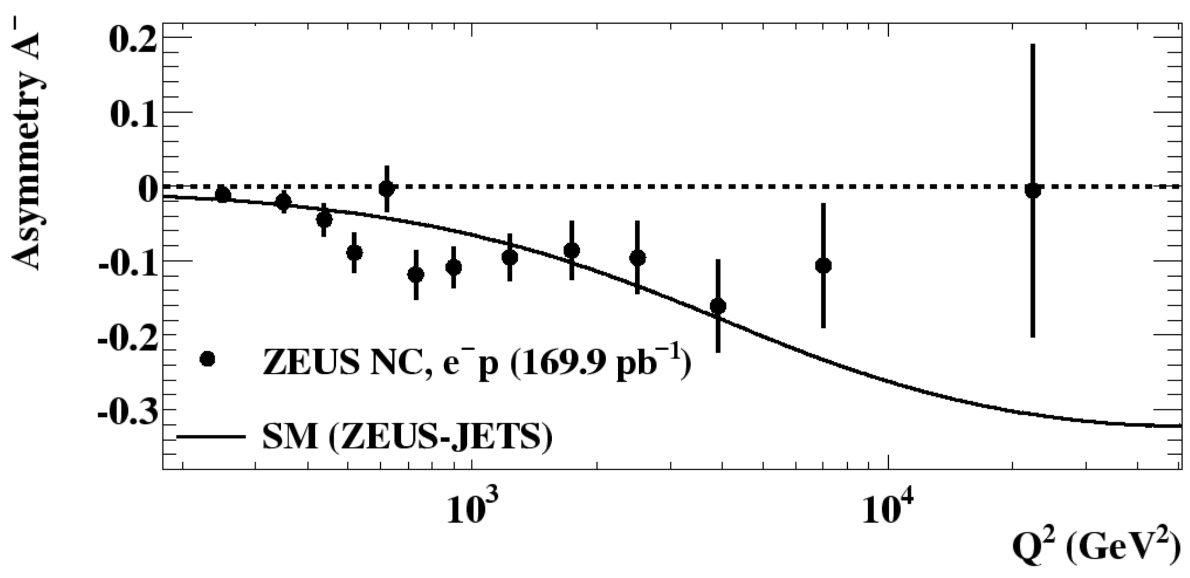


- Difference between e^-p and e^+p NC cross sections measures **xF_3** structure fn…

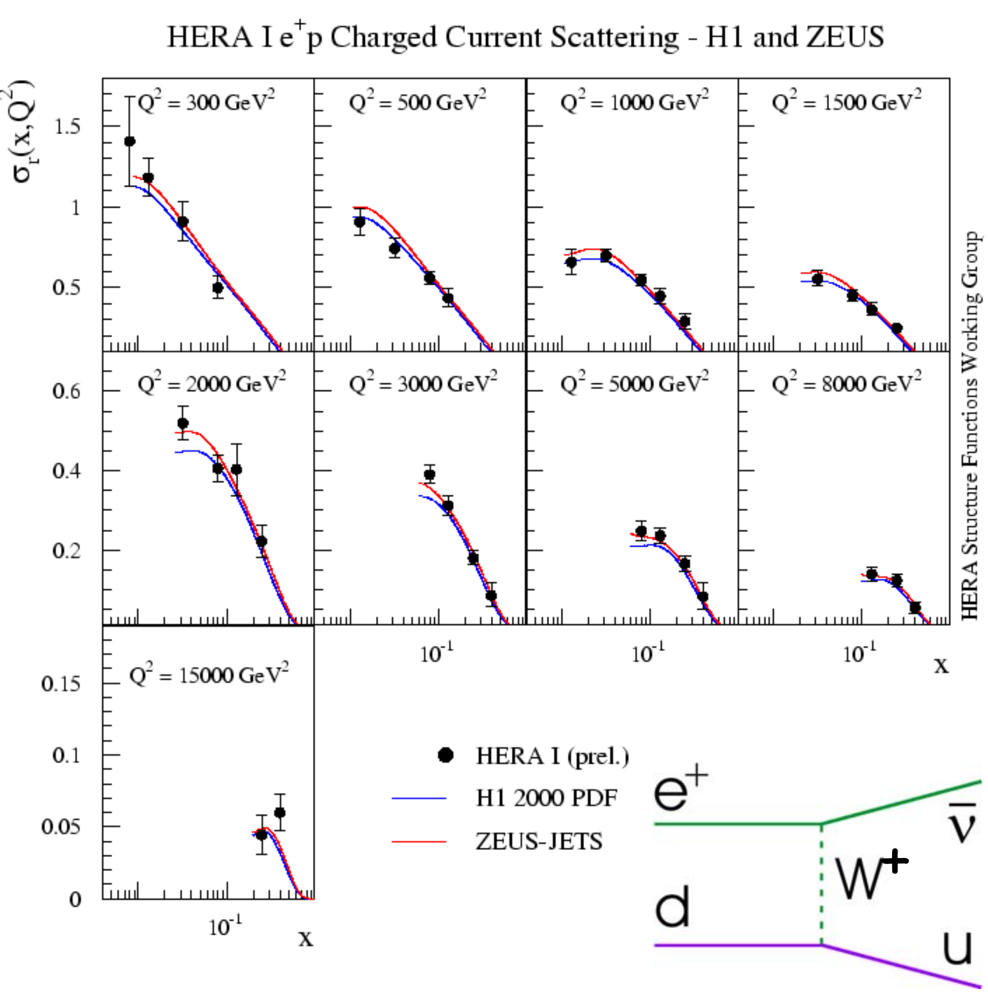
$$xF_3 \sim 2x \sum_q e_q a_q (q - \overline{q}) \sim q_v$$

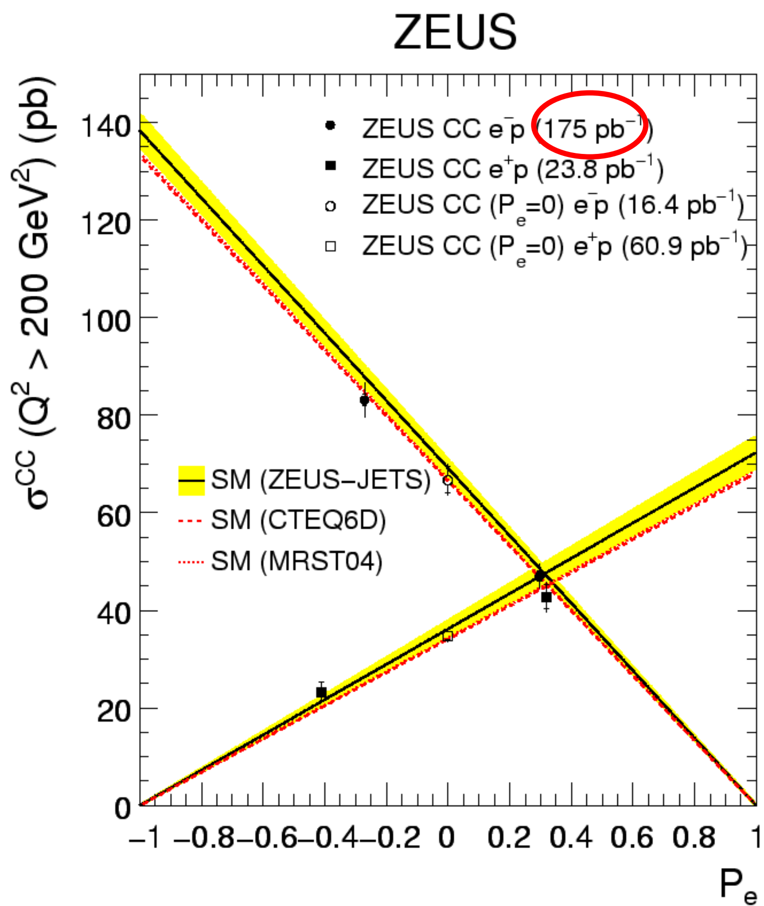
… unique sensitivity to **valence** quarks

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



Recent Charged Current Data

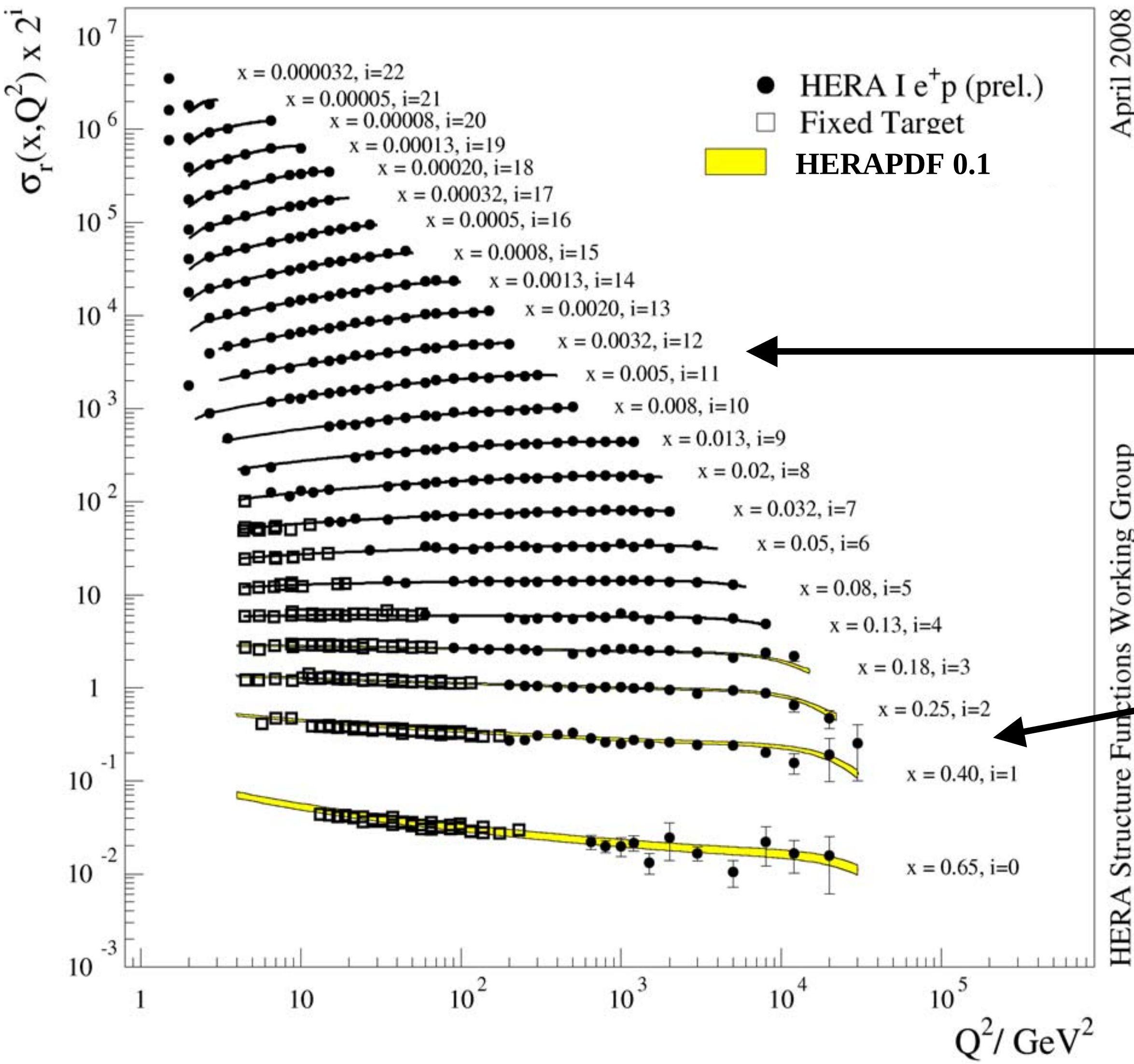




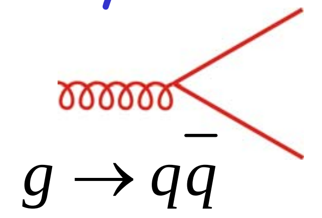
- Charged current sensitive to flavour decomposition … e.g. e^+p constrains **d** density

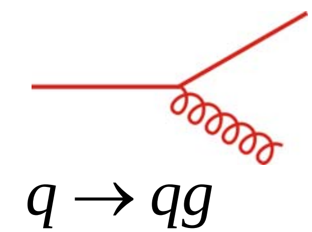
- Linear dependence on polarisation well tested … **chiral structure** of SM

Q^2 Evolution and the Gluon Density



- NC Q^2 dependence driven by …

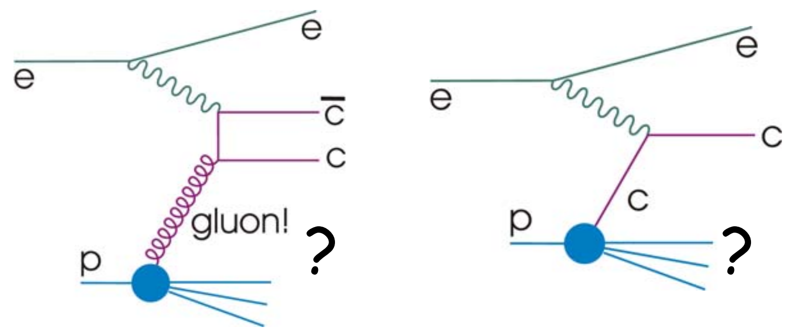




- Excellent QCD fit description over vast range.

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

Measuring Heavy Quarks



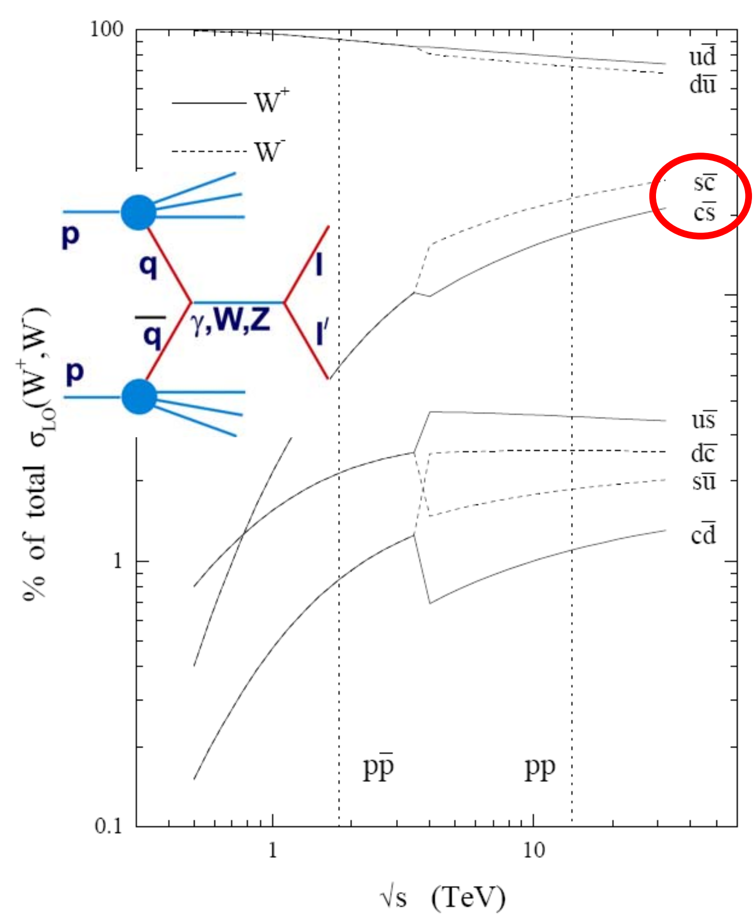
- Ambiguities in treating heavy flavours in parton densities …
  - Generate dynamically from gluon?
  - Treat as an active flavour?

- HF evolution HERA→LHC important for σ(W), σ(Z) in SM

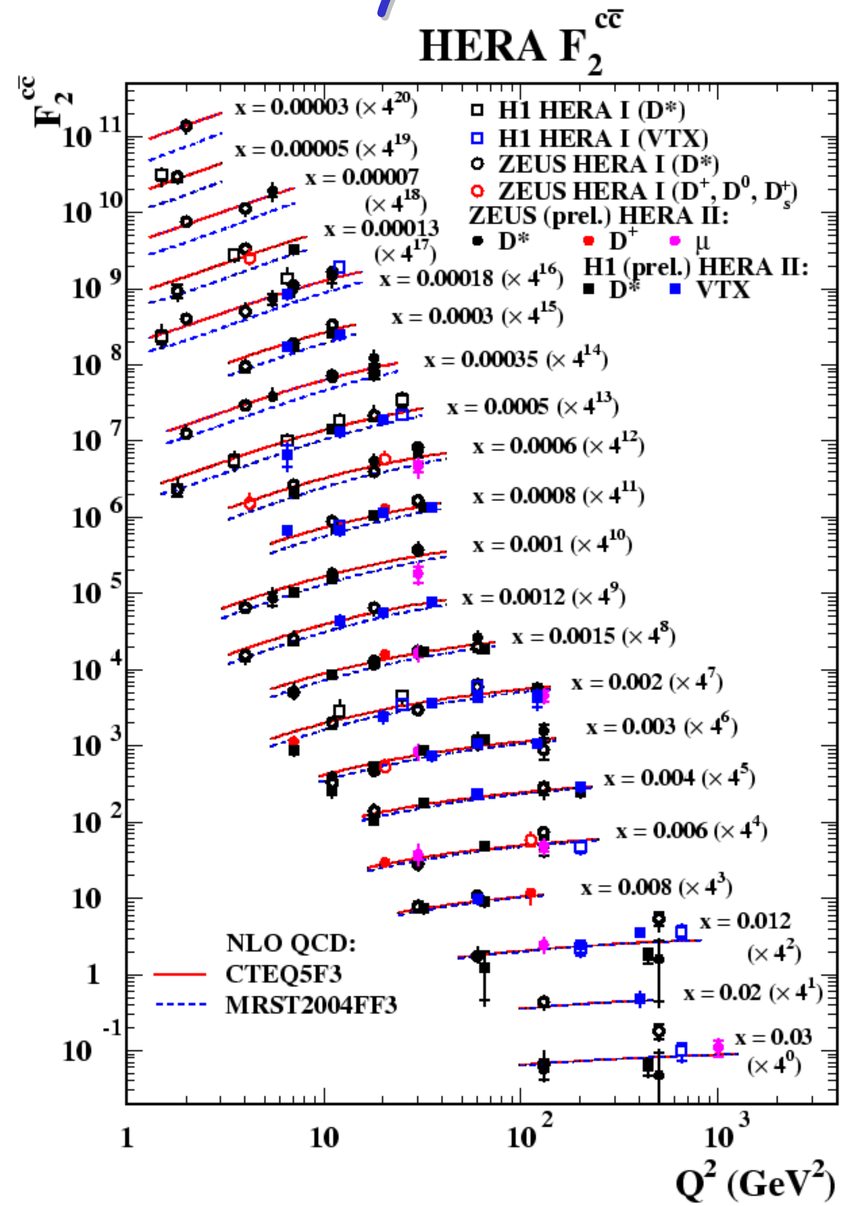
- bbbar → H … e.g. big differences between predictions in SM & high tan β MSSM

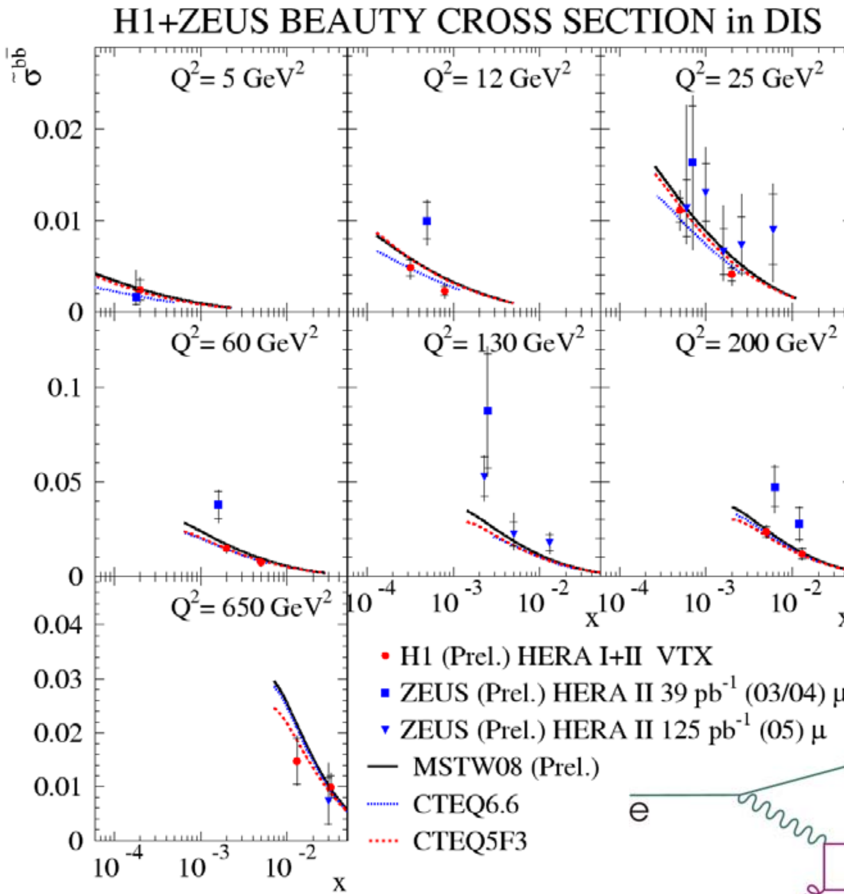
- Extensive HERA data (D* tagging, secondary vertices) are used to constrain models → **increasingly sophisticated HF schemes** in fits

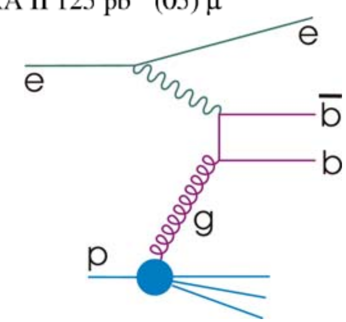
flavour decomposition of W cross sections



Understanding Charm and Beauty Production

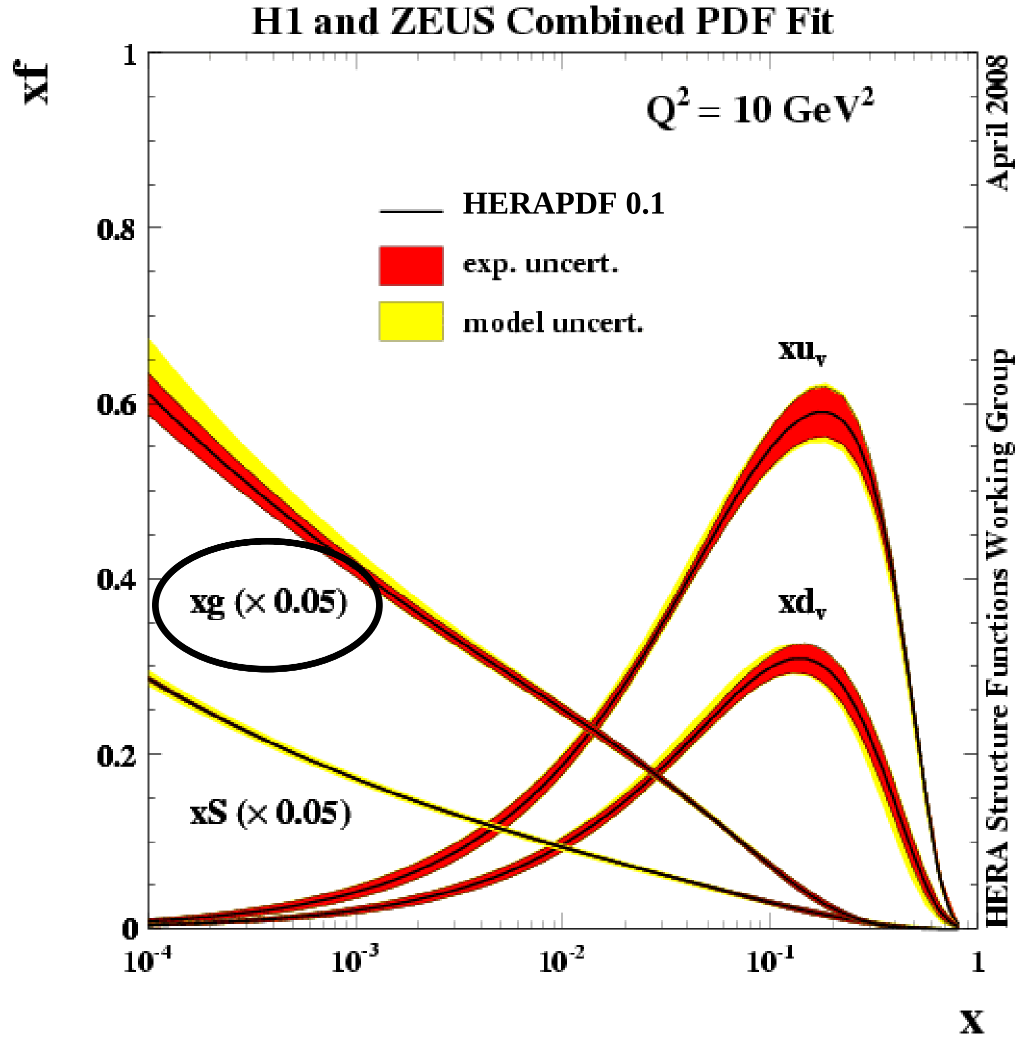






- Charm contributes up to ~30% of NC cross section, beauty ~ 1%
- Extensive data including Q^2 <~ m_q^2 where different NLO treatments diverge …

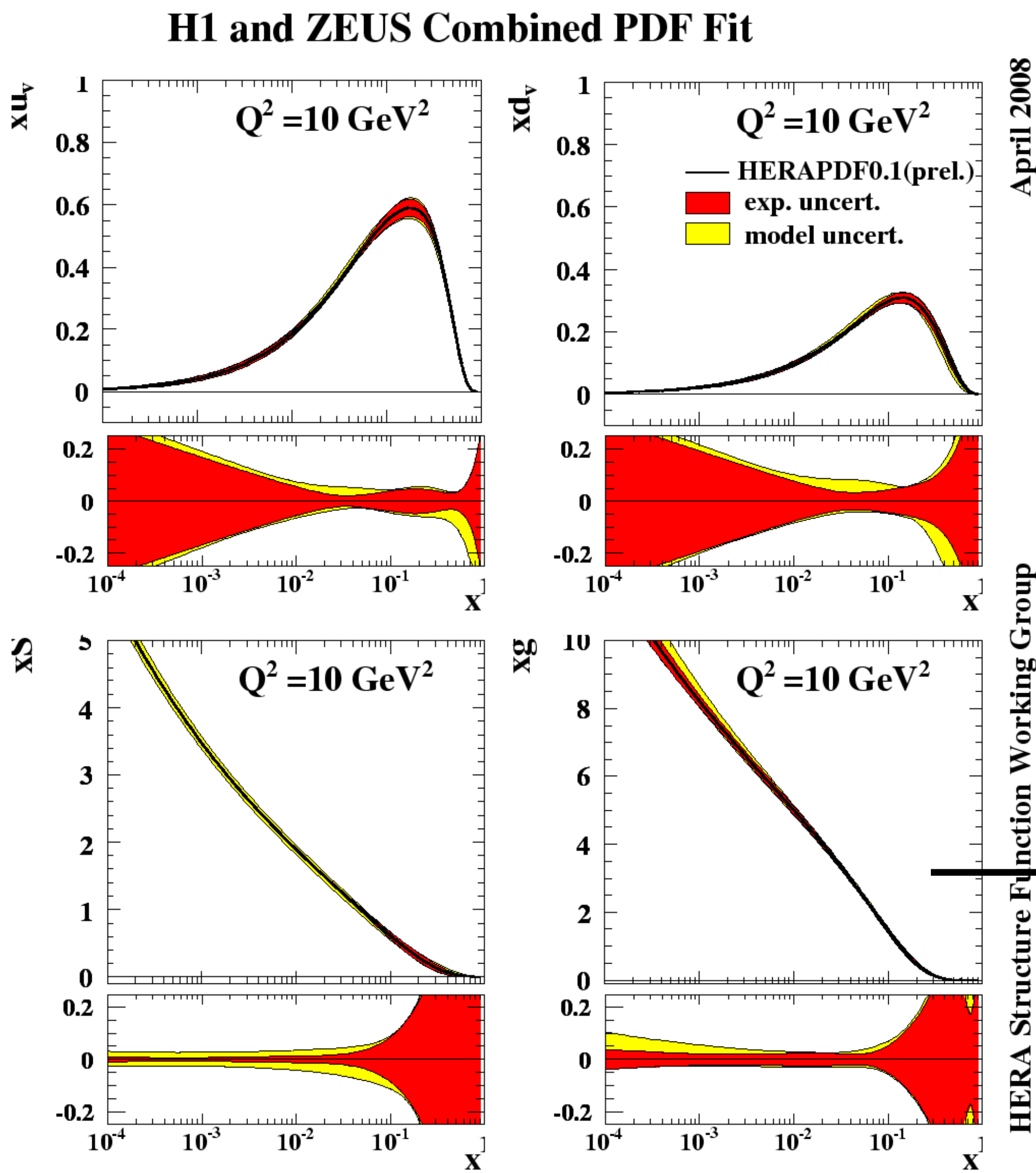
What *is* a Proton?



- NLO DGLAP fits to NC and CC data [to $O(\alpha_s^2)$] used to obtain valence, sea quarks and gluon **using HERA-I data alone** (zero mass VFNS)
- Improved low x uncertrainties due to inclusion of combined H1-ZEUS data
- **Gluon density becomes enormous at low x**
- Broadly consistent with global fits (MSTW, CTEQ)

Caveats:
- No param^n uncertainites
- High x region …

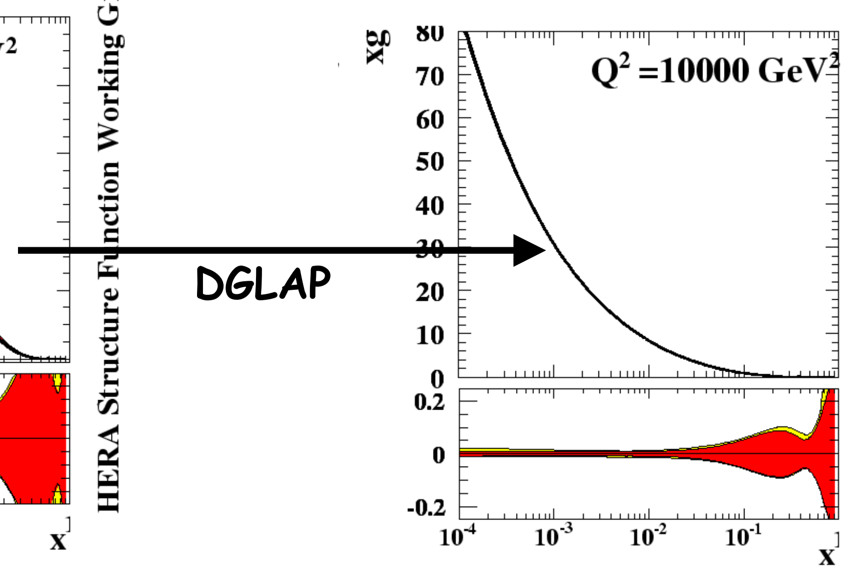
A Closer Look at High x



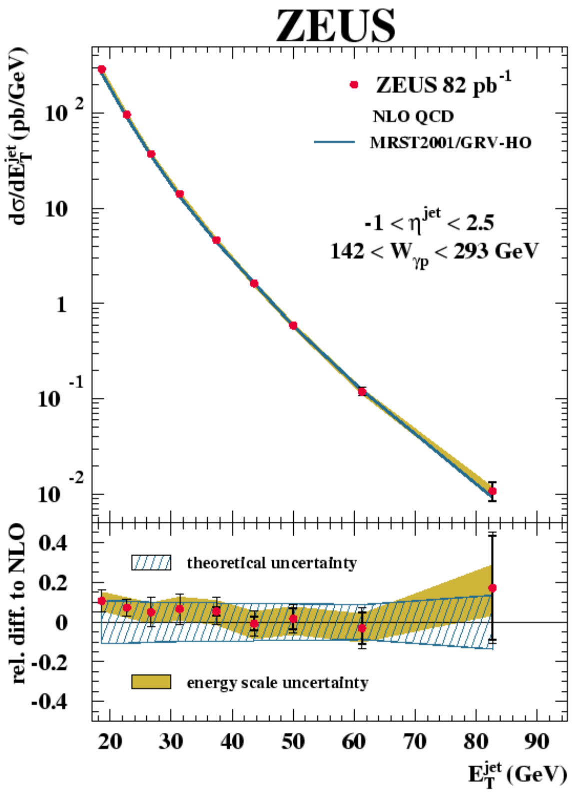
- Errors explode at highest x (improves with Q^2 evolution)

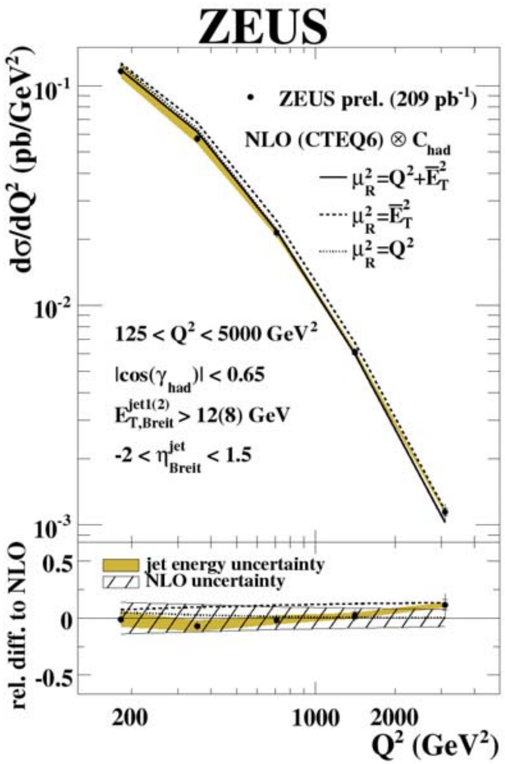
Better precision (MSTW, CTEQ) with TeVatron jets

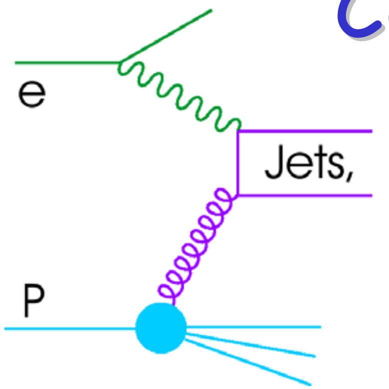
- Will be better with HERA-II data …



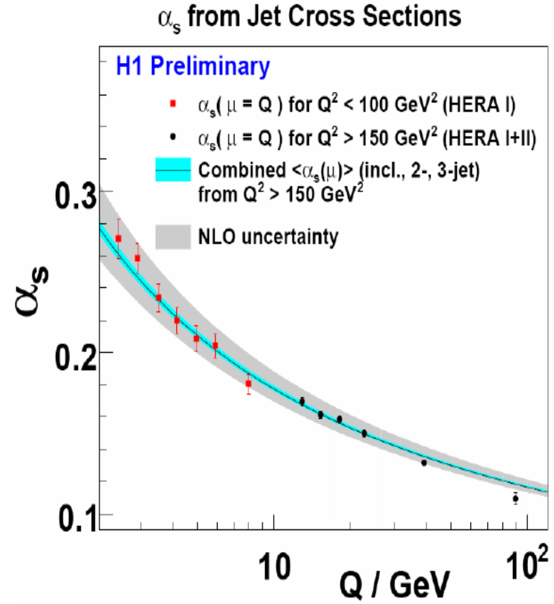
Jets, Gluons & the Strong Coupling

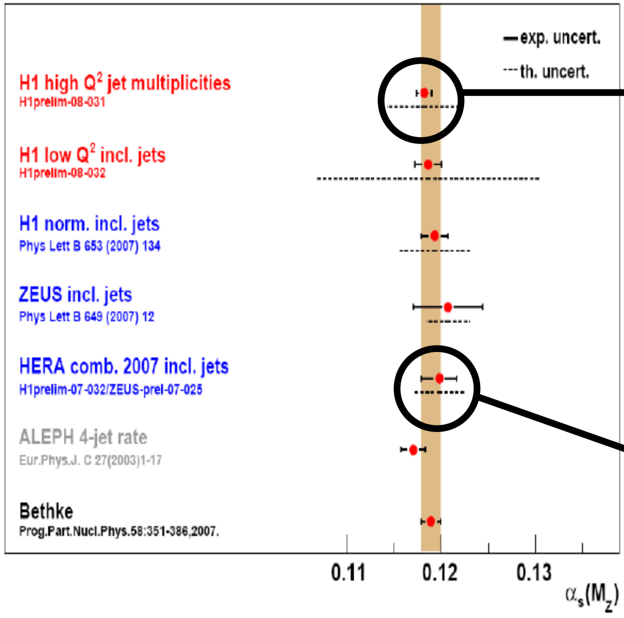






… QCD fac'n tests …



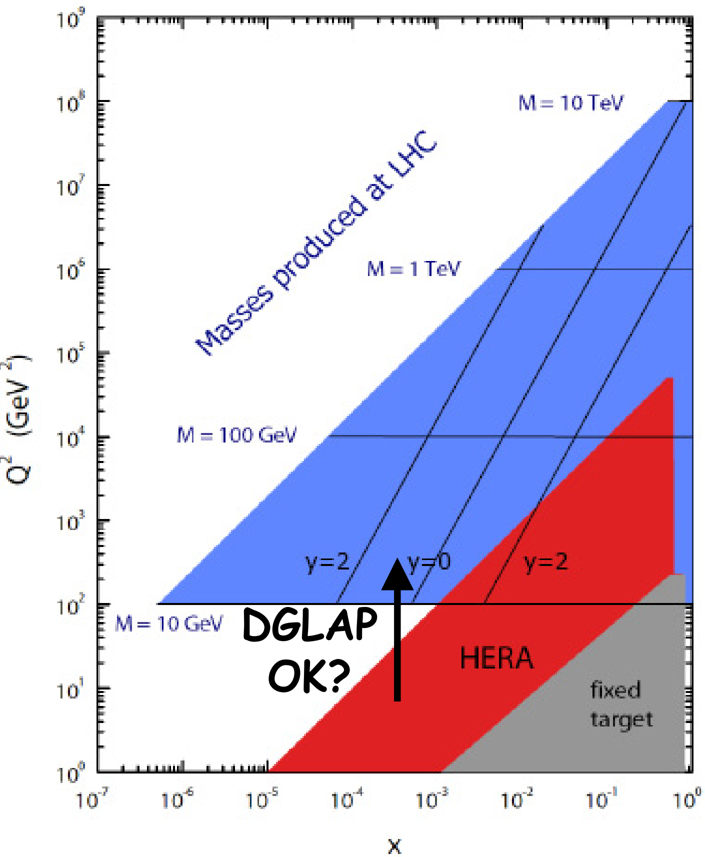


α_s running … theory error dominates

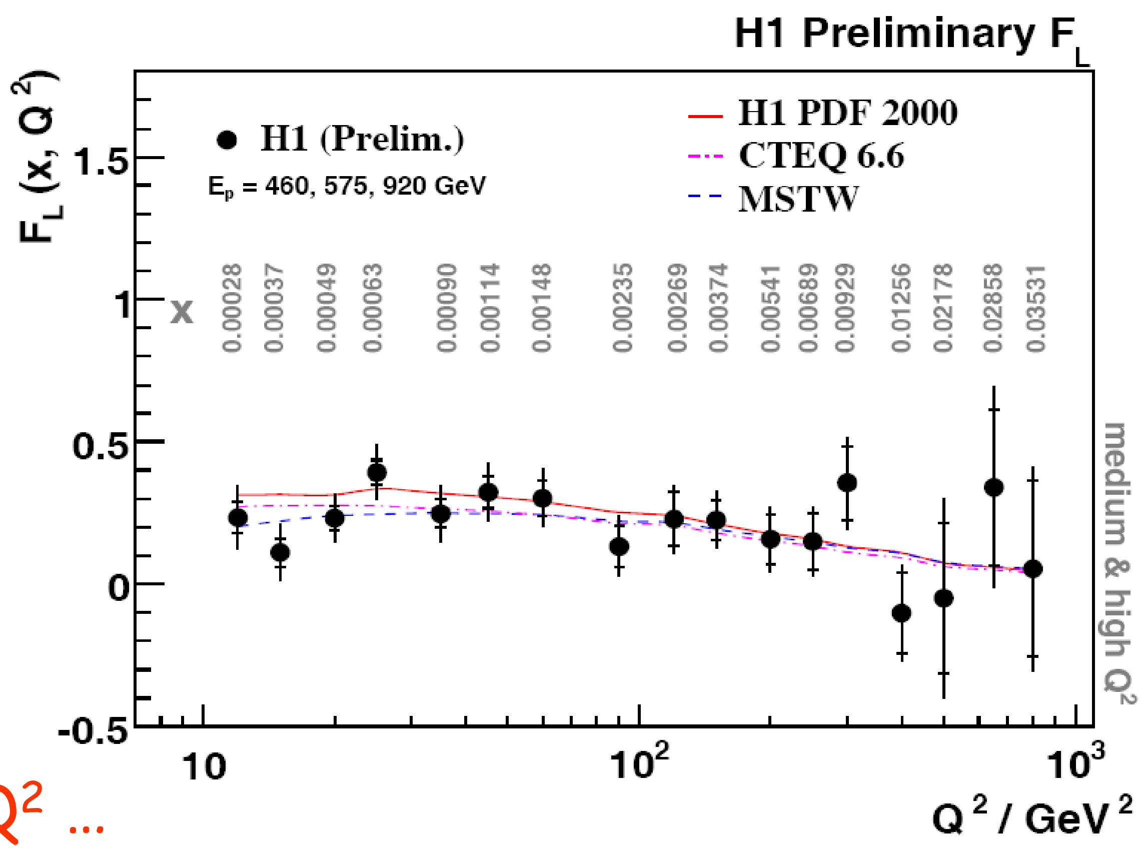
$$\alpha_S = 0.1198 \pm 0.0019 \text{ (exp.) } \pm 0.0026 \text{ (th)}$$

(overall 2.7% uncertainty @ HERA)

A Test of the Validity of DGLAP



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

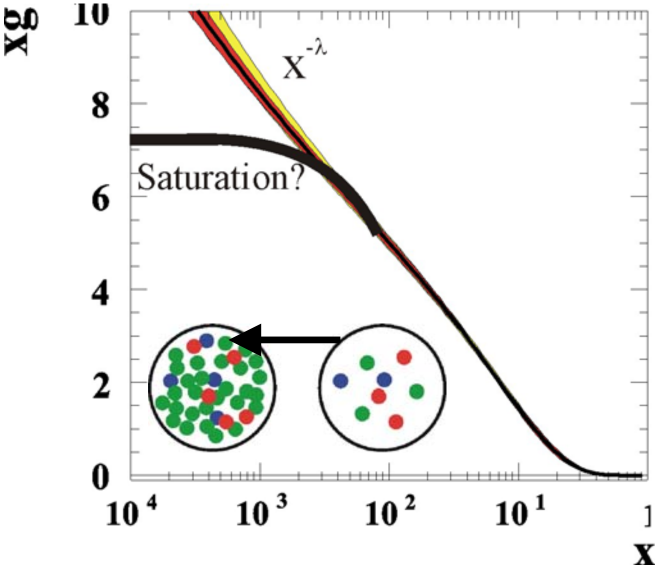


Test overall picture with F_L **extracted by varying beam energy**.

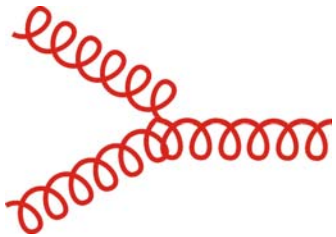
If gluon dominates, $F_L \sim \alpha_s\, xg(x)$.

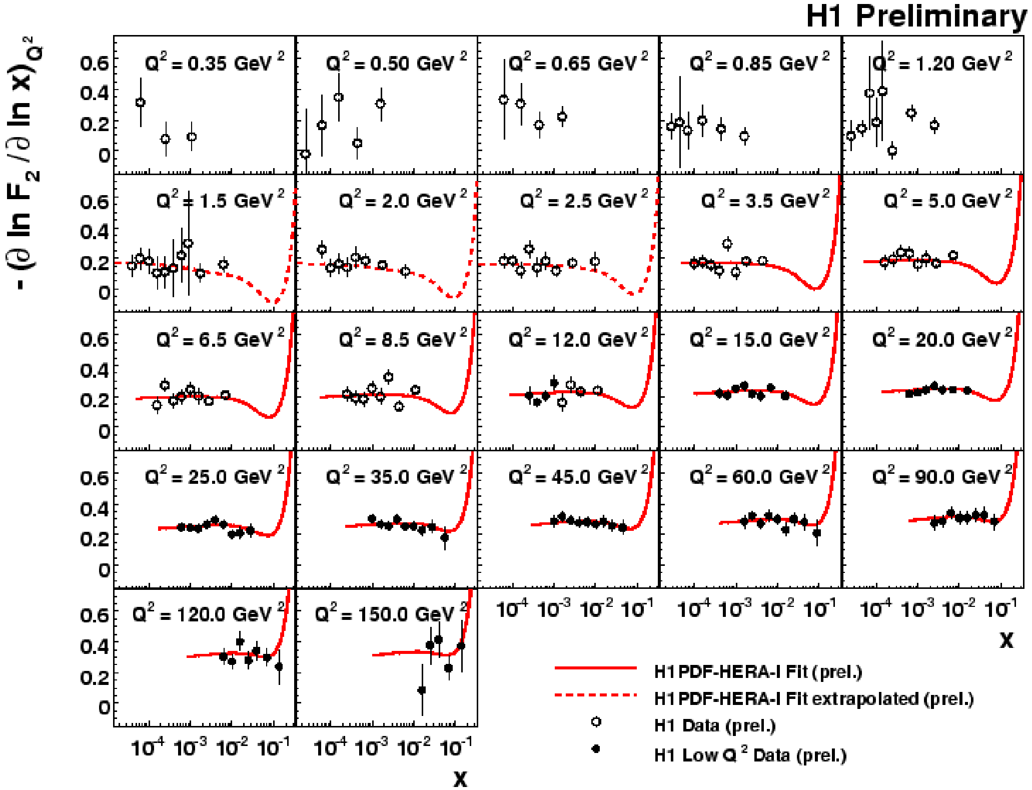
… More to come at low Q^2 …

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→g recombination





e.g. from local derivatives with respect to x …

… no evidence for any deviation from a single power law for $Q^2 >\sim 1\ \mathrm{GeV}^2$

HERA-LHC Workshop … (see also PDF4LHC)

Workshop on the implications of HERA for the LHC

(partons, jets, heavy flavours, diffraction, MC tools …)

807 pages!
(March 2009) →

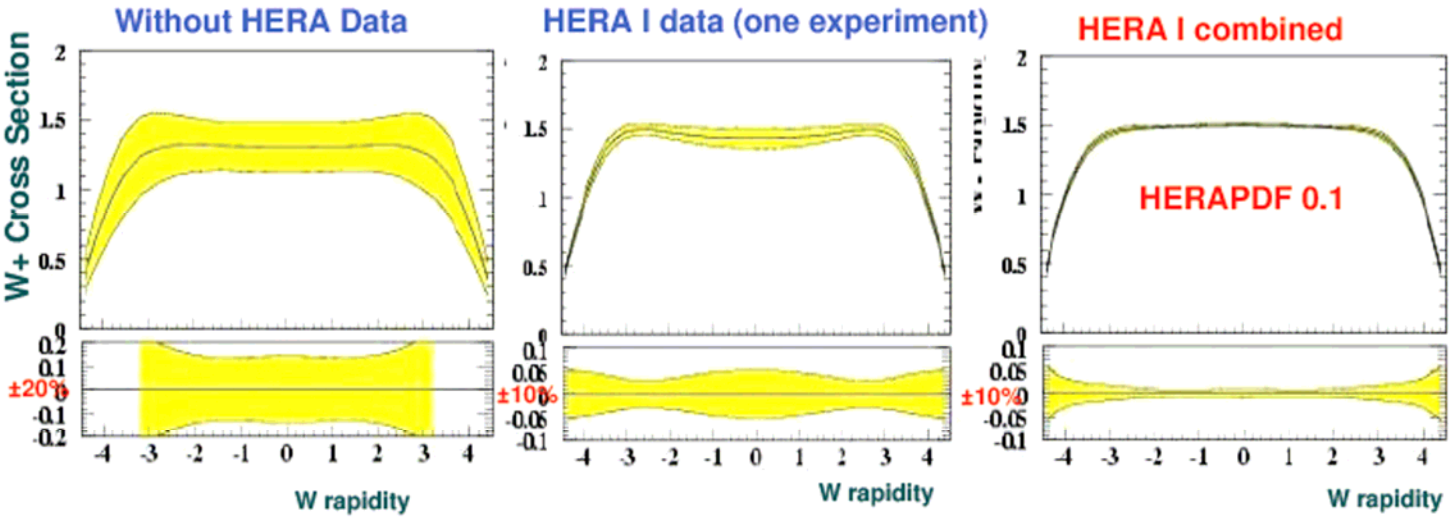
Impressum

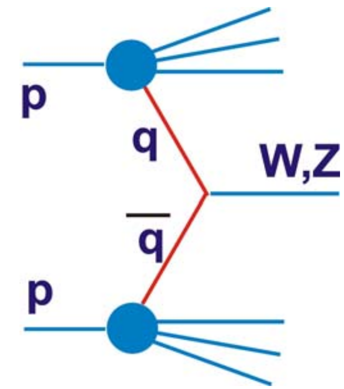
Proceedings of the workshop
HERA and the LHC
2nd workshop on the implications of HERA for LHC physics
2006 - 2008, Hamburg - Geneva

Conference homepage
http://www.desy.de/~heralhc

Online proceedings at
http://www.desy.de/~heralhc/proceedings-2008/proceedings.html

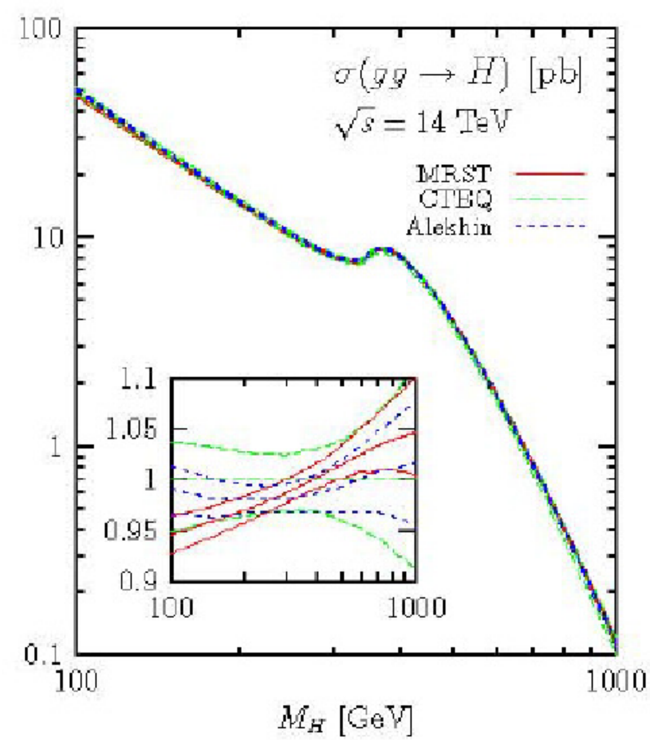
Examples of Precision on LHC Cross Sections





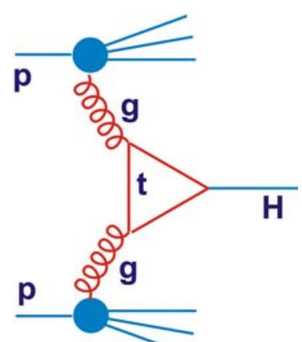
W Rapidity Spectra:

- 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%

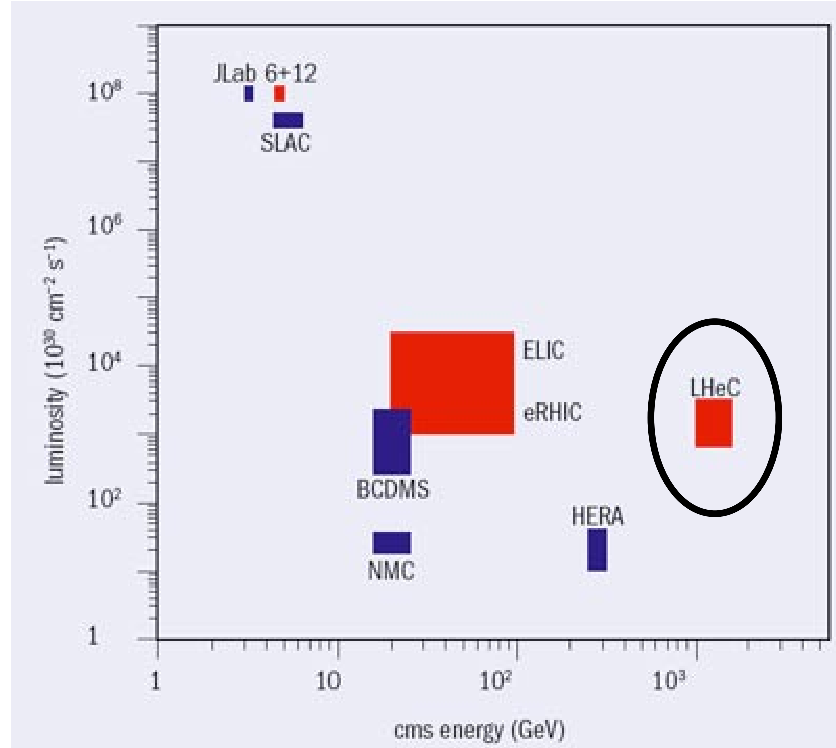


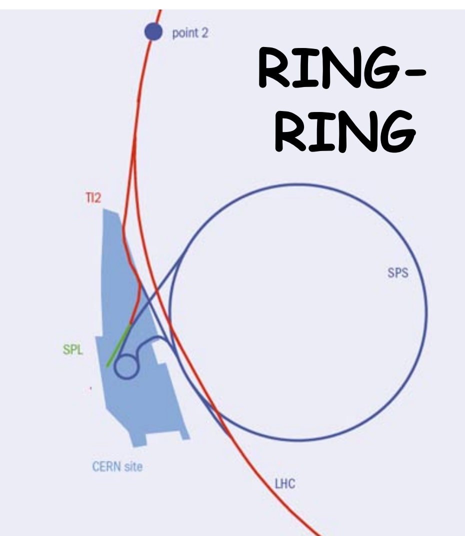
A possible DIS future?

No high energy ep physics approved beyond 2007!..

LHeC: Latest of several proposals to take ep physics into the TeV energy range …
… but with unprecedented lumi!

… achievable at LHC simultaneously with normal pp operation… [JINST 1 (2006) P10001]

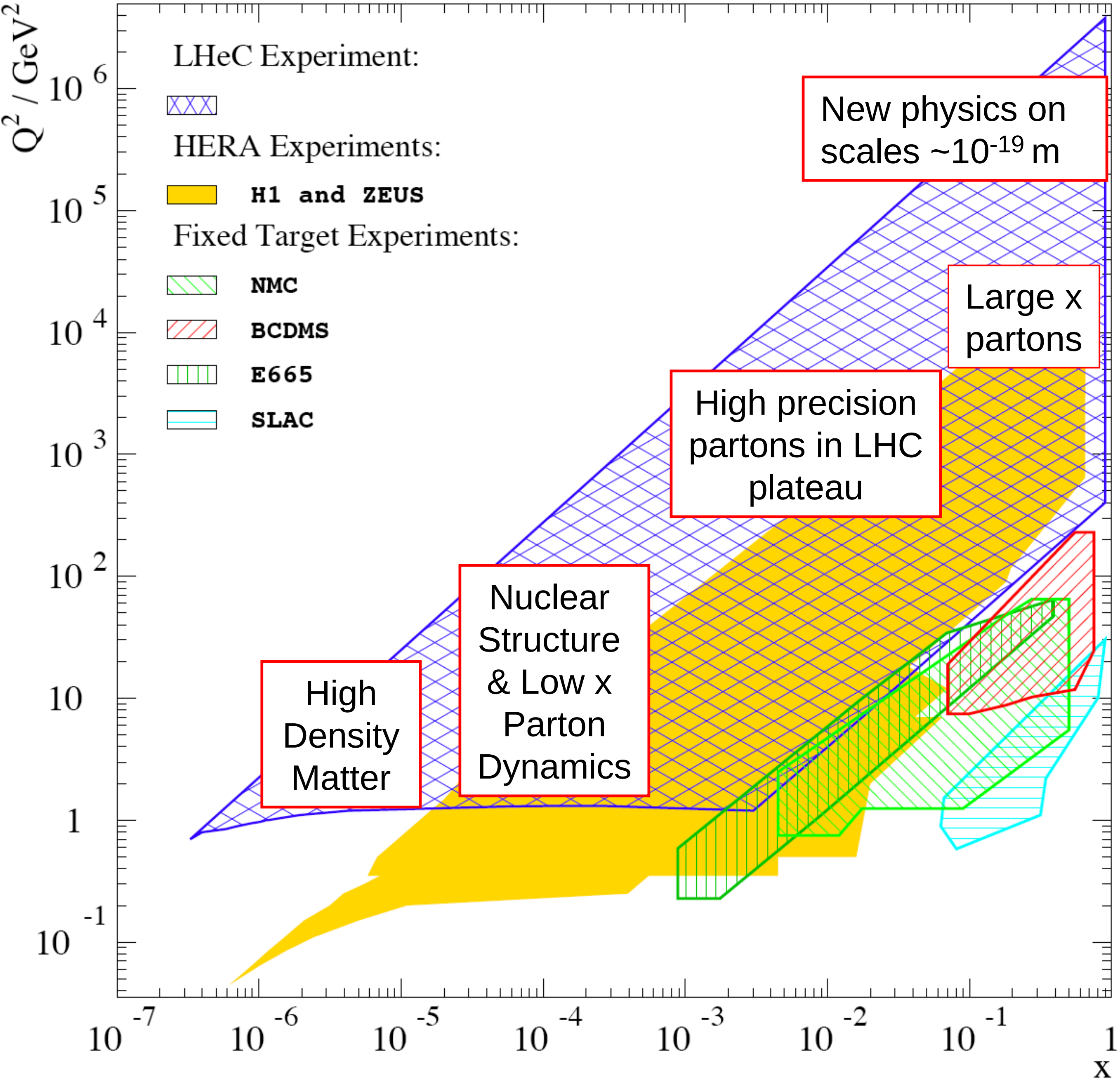




Ongoing ECFA-CERN Commissioned workshop
www.lhec.org.uk

Contributions welcome!

Kinematics & Motivation for 100 GeV x 7 TeV



$\sqrt{s} = 2$ TeV

- High mass (M_{eq}, Q^2) frontier
- EW & Higgs
- Q^2 lever-arm at moderate & high x → PDFs
- Low x frontier → novel QCD …

$x \geq 5.10^{-7}$ at $Q^2 \leq 1$ GeV^2

Summary

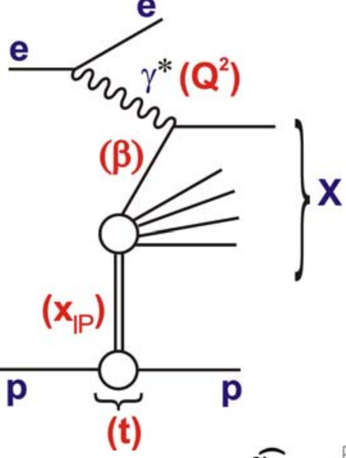
- After 15 years of running, HERA provided a unique data-set.

- ~400 publications, mostly on HERA-I:
  - The basis of our knowledge of the LHC initial state
  - Big advances in understanding QCD
  - Searches, EW, spectroscopy …

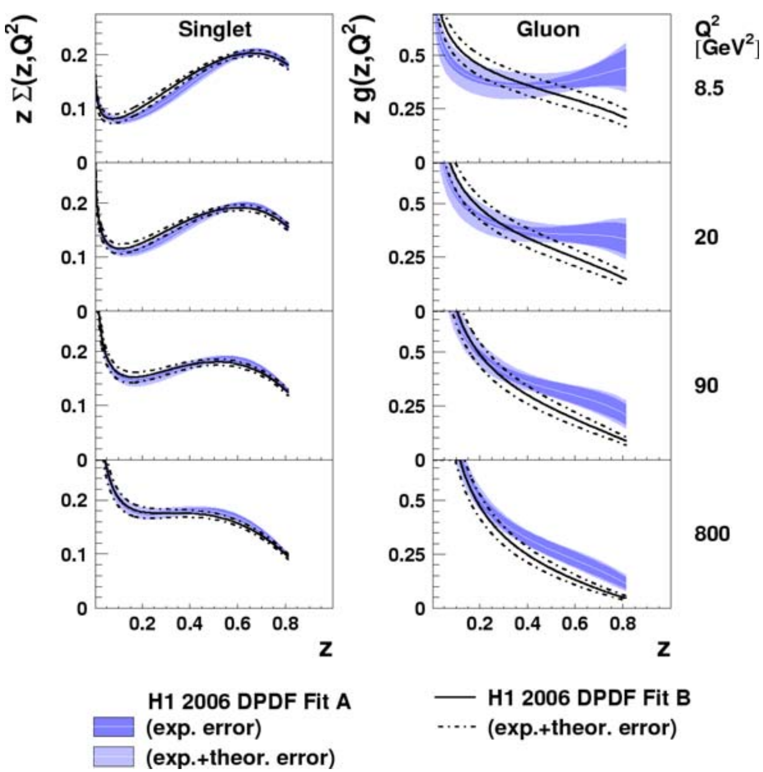
- ~100 publications with final precision expected '09-'12 if HERA-II exploited:
  - Factor ~4 in statistics
  - Best detector understanding and performance
  - H1 + ZEUS combinations
  - …

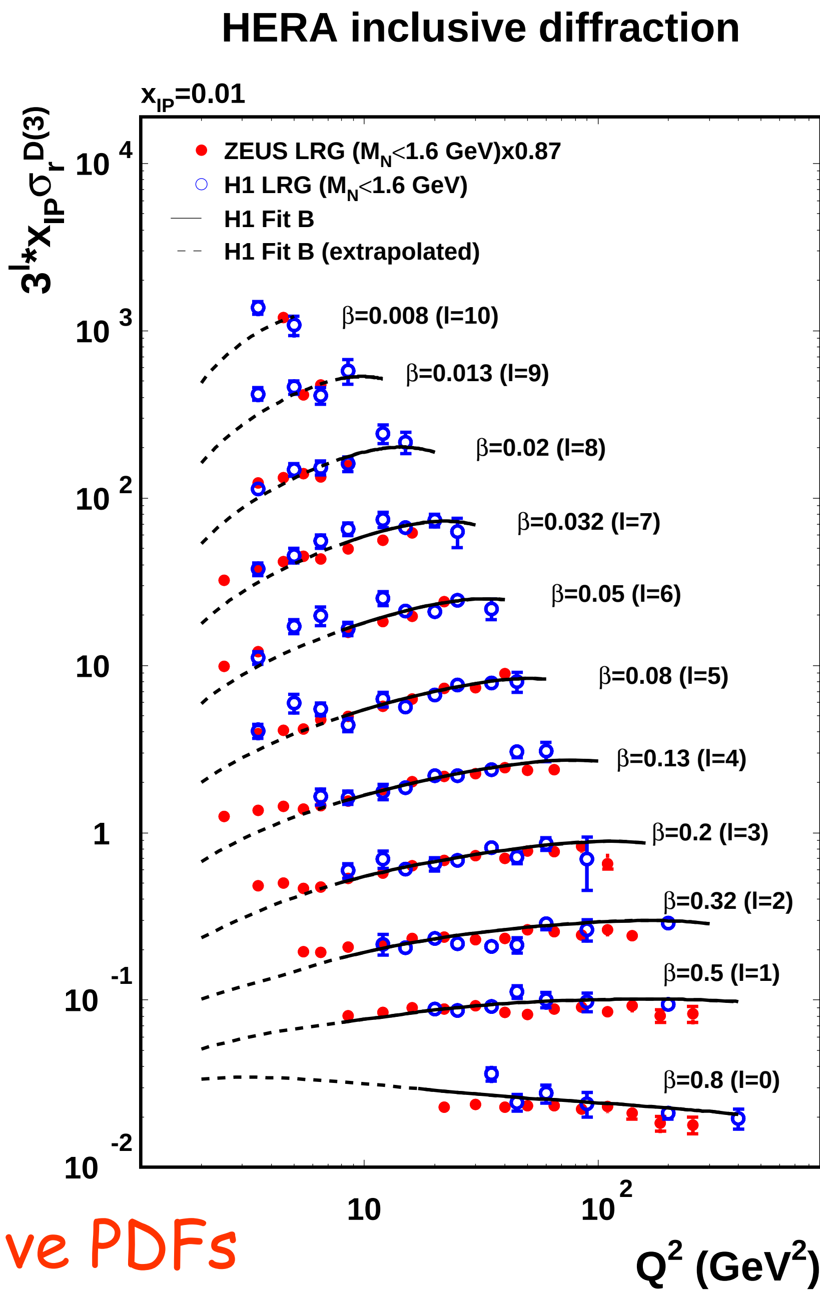
Back-Ups Follow

Exploring QCD at Low x … Diffraction



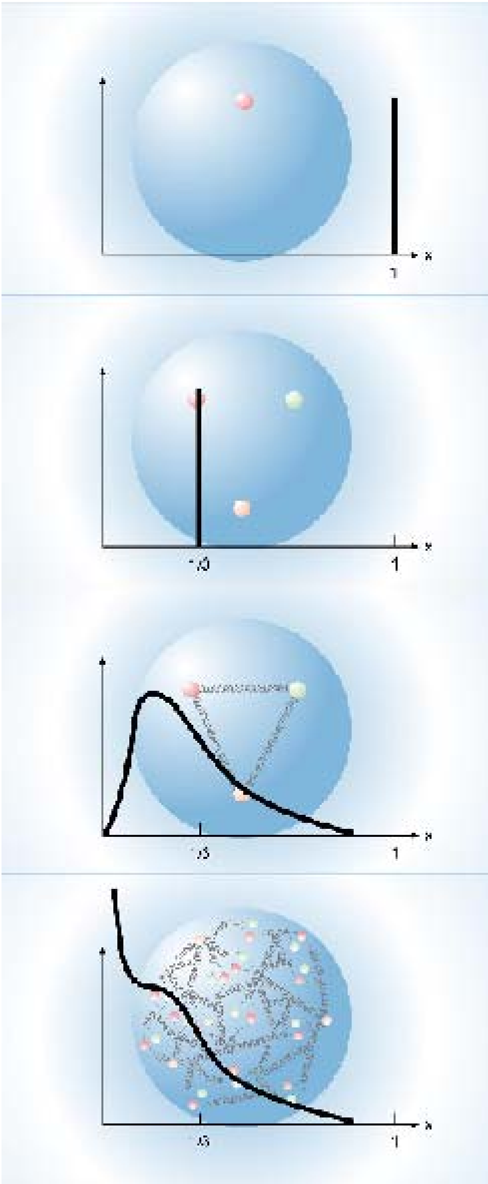
- ~10% of low x intⁿs in which proton survives





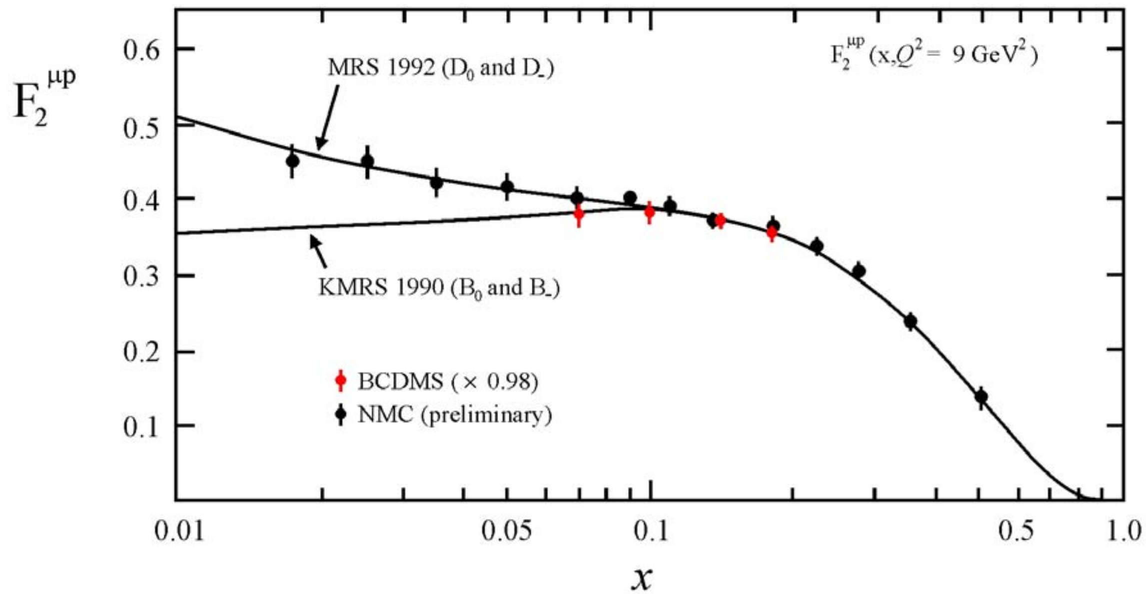
- Data reached 4% precision
- Understood in terms of Diffractive PDFs

Structure Function $F_2(x, Q^2)$



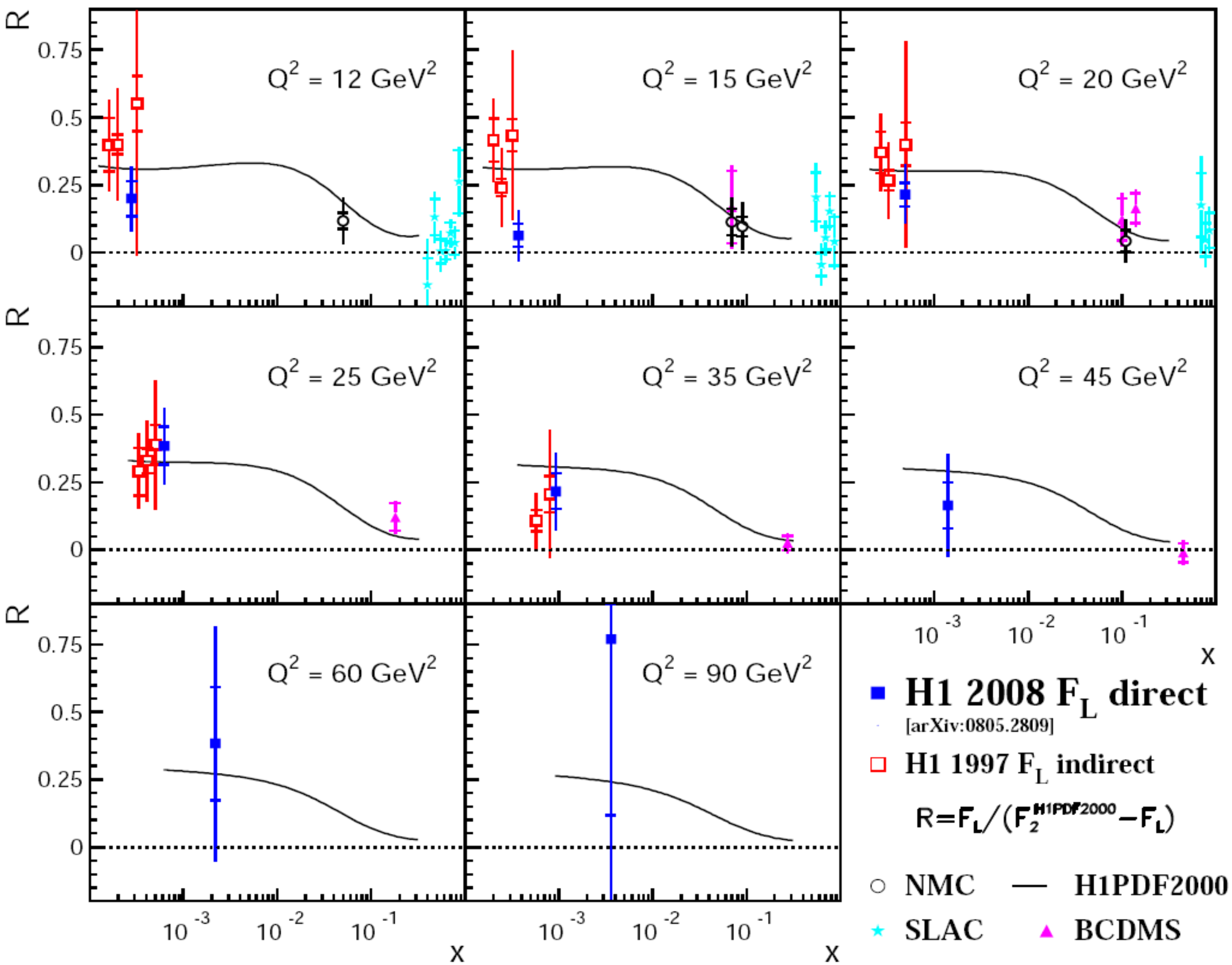
$$F_2(x,Q^2) \sim x\sum_q e_q^2(q+\bar{q})$$

The data before HERA …



In 1992, low x physics was an obscure field, known only to Russians!

$F_L(x, Q^2)$ v Fixed Target and Indirect Data



Neutral Current Sensitivity to the Quarks

NC cross section depends on 3 structure functions …

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

… where $Y_{\pm} = 1 \pm (1-y)^2$

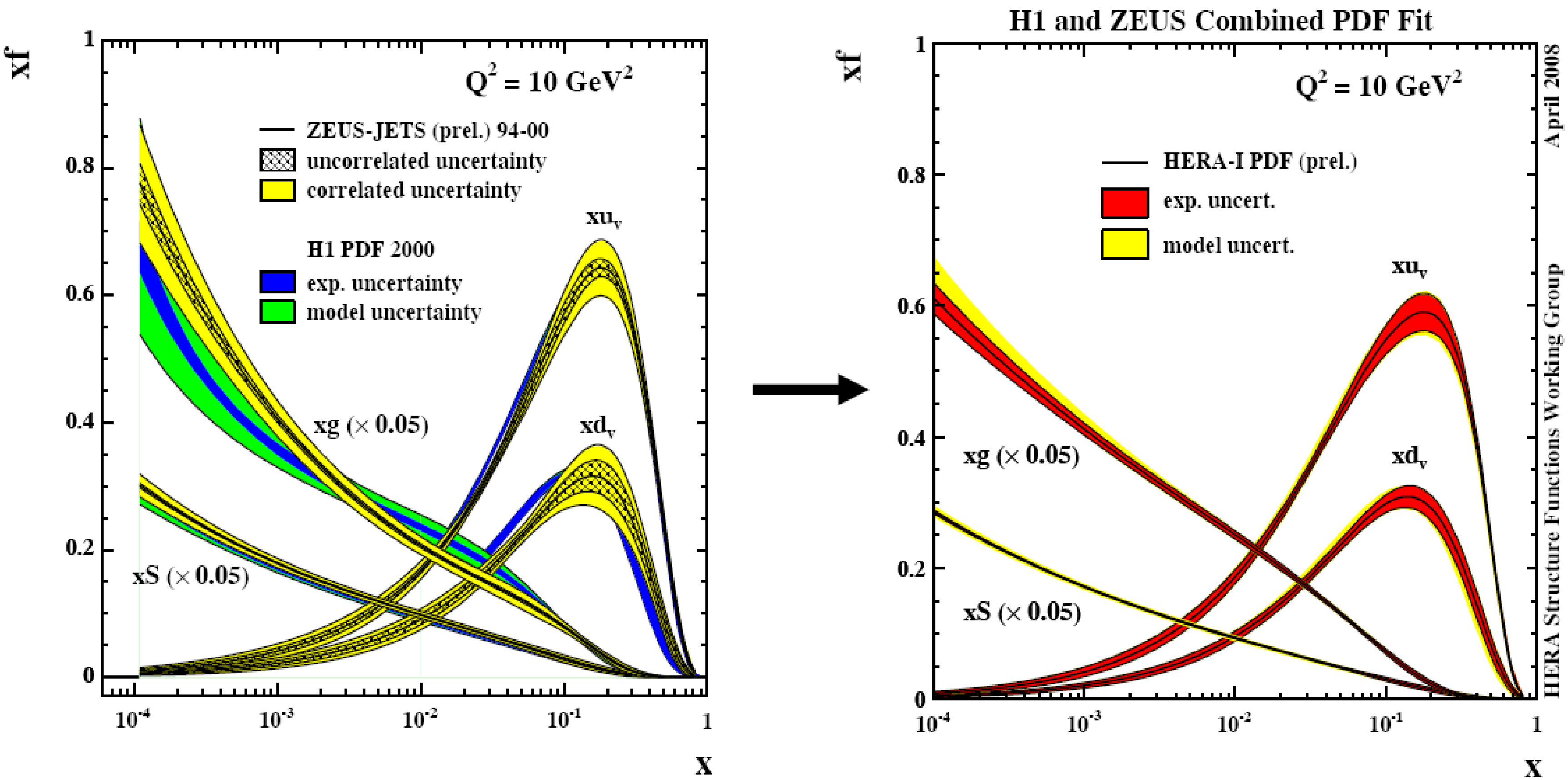
… and y measures the process inelasticity

- F_2 dominates throughout most of the phase space

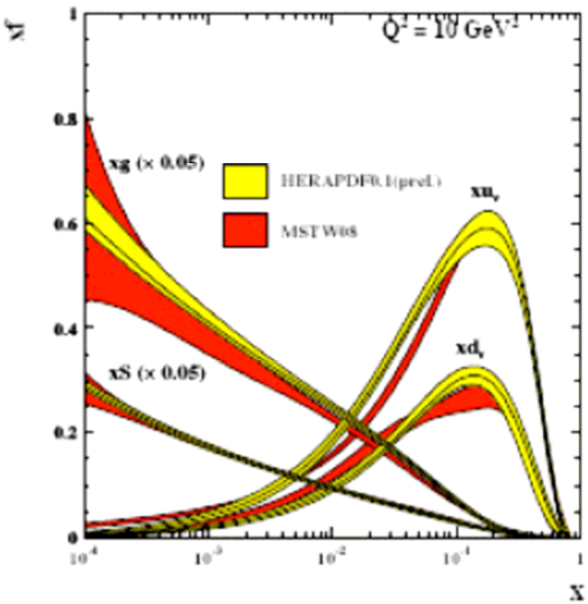
- xF_3 contributes at high Q^2 (Z exchange) can be obtained from difference between e^+p and e^-p cross sections

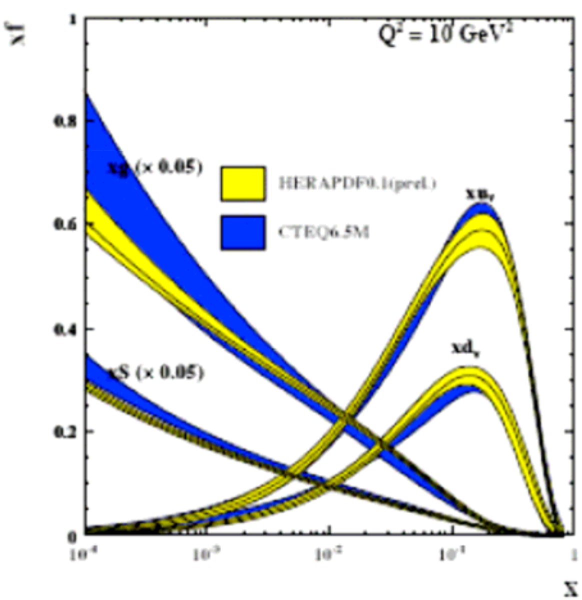
- F_L contributes at high y (longitudinally polarised photons)

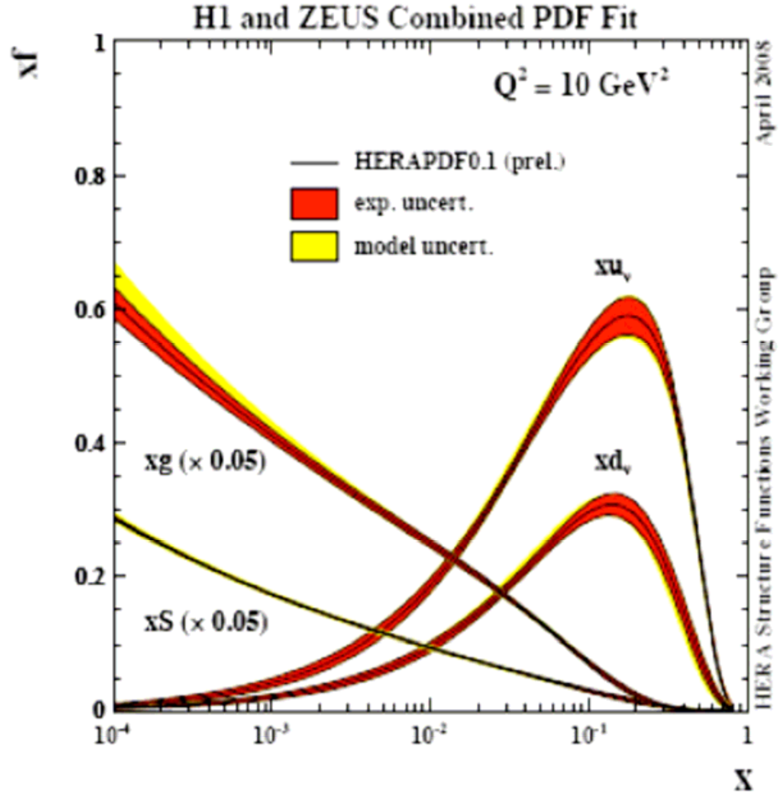
HERA-only Partons: Combination Power



HERA-only Partons v Global Fits



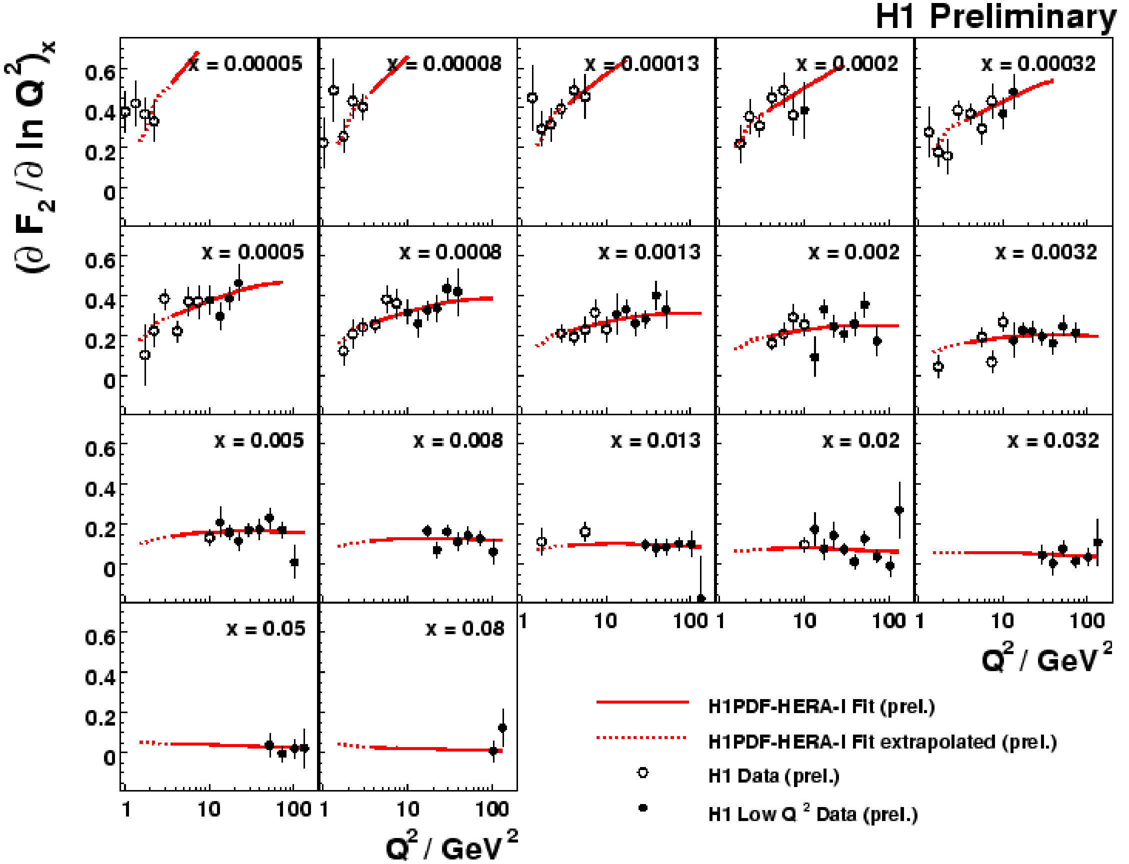




Good comparison to global fits, improved precision, however the error treatment also differs.

Q^2 Evolution via Local Derivatives

$$\frac{dF_2}{d\ln Q^2} \sim \alpha_s \left(P_{qg} \otimes g \;+\; P_{qq} \otimes q \right)$$



DGLAP-based fit provides a good description at level of derivatives from differences between neighbouring points