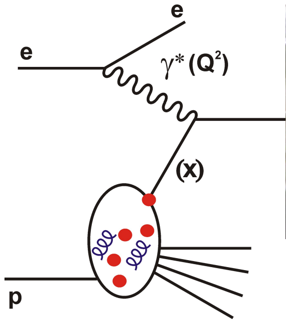
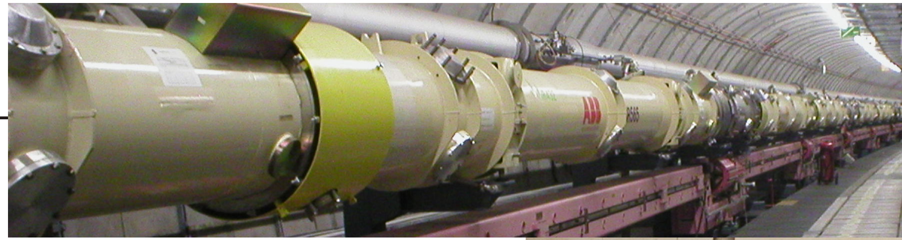
DIS16
DESY, HAMBURG 11-15 APRIL 2016





The HERA Legacy

Paul Newman
(University of Birmingham)

11 April 2016
DESY, Hamburg

24th International Workshop on Deep-Inelastic Scattering and Related Subjects

- The only ever collider of electron beams with proton beams:

$\sqrt{s_{ep}} \sim 300$ GeV

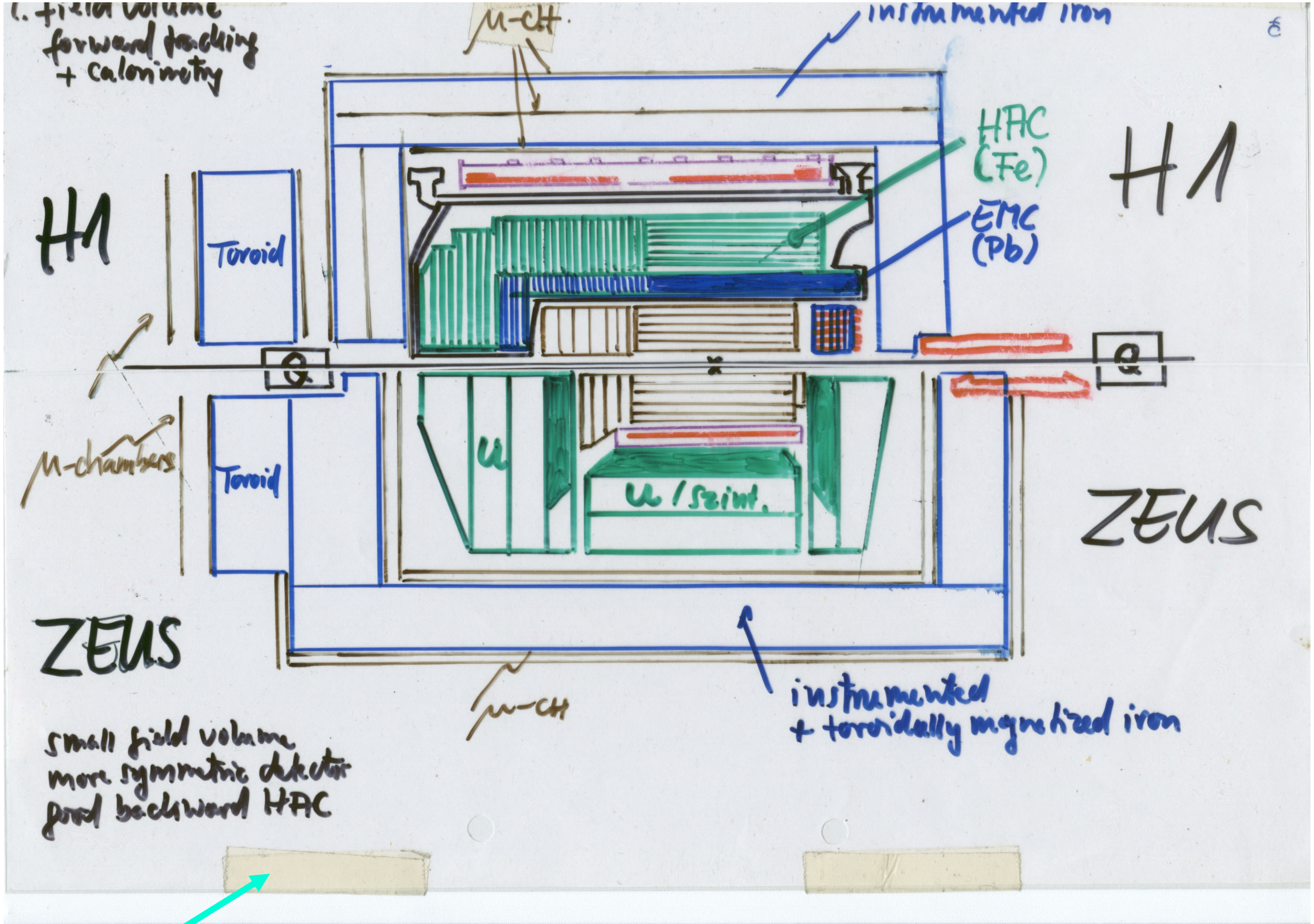
- ~0.5 fb^{-1} per exp't
- Both lepton charges and polarisations
- Additional ~25 pb^{-1} @ E_p = 575, 460 GeV

- DESY / accelerator group did amazing job!

"We expect your talk to cover a summary of the general HERA legacy, recent highlights such as the final H1ZEUS data combination (HERAPDF2.0) as well as an outlook to future experiments (LHeC and others) ... You have 30+10 minutes"

Sincere apologies for the many obvious omissions

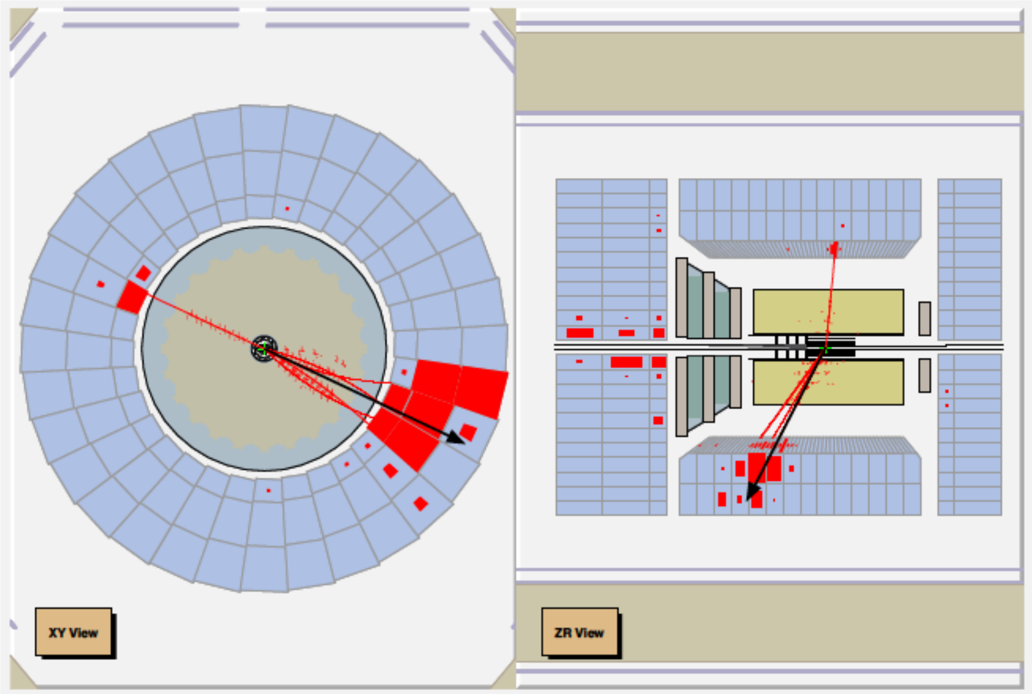
A period that included the digital revolution

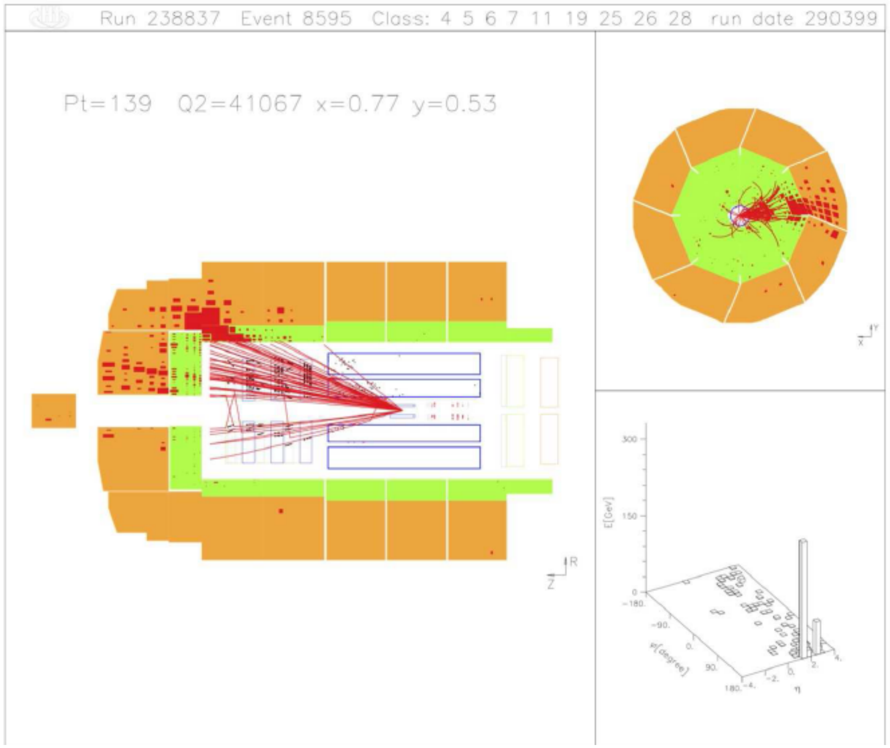


User defined animation

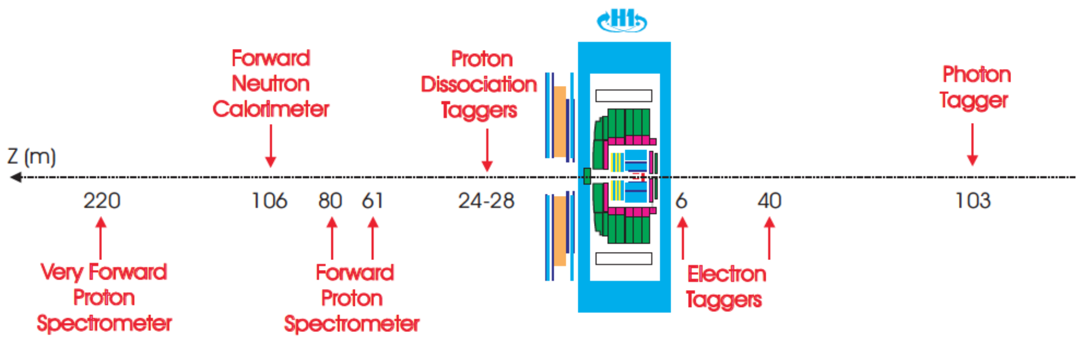
[F Eisele, ~ 1986]

Post Digital Revolution: Detector Legacy





- Vital contributions to developments of detectors, accelerator technologies, polarimetry, triggers …
- Impressive calibration (e.g. ~0.5% electron energy scale, 1% jet energy scale)
- Extensive Beamline instrumentation



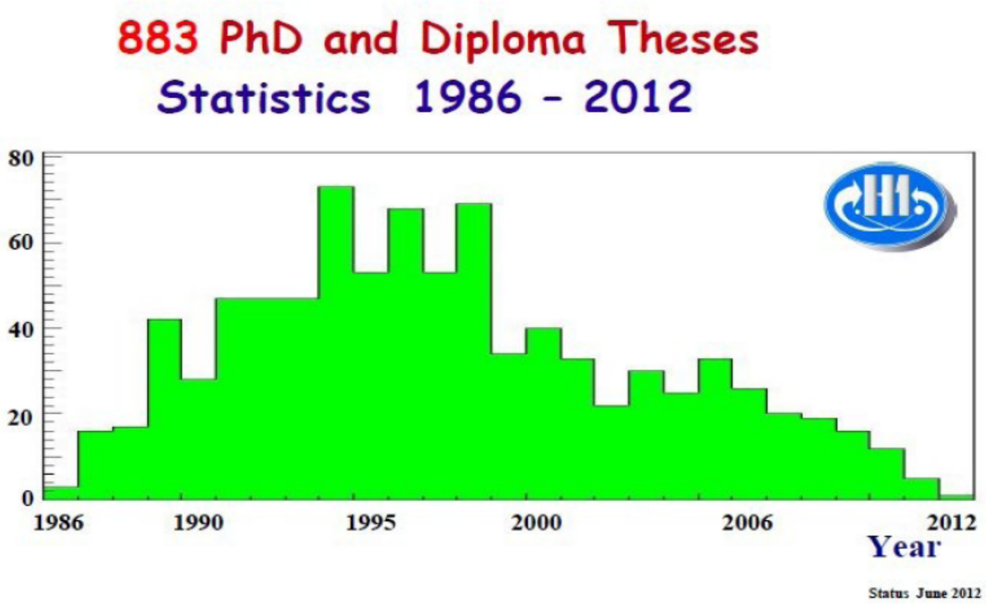
Early Collaboration Mugshots (~1993)

Early Collaboration Mugshots (~1993)

23 Years Later: emerging HERA legacy

The Paper Legacy

~100m of library shelf space per experiment



The People Legacy

HERA-educated people highly visible in particle physics experiments world-wide, running university physics departments, directing labs, making major and diverse contributions to life well beyond our field.

The Physics Legacy

Eur. Phys. J. C (2015) 75:580
DOI 10.1140/epjc/s10052-015-3710-4

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Regular Article - Experimental Physics

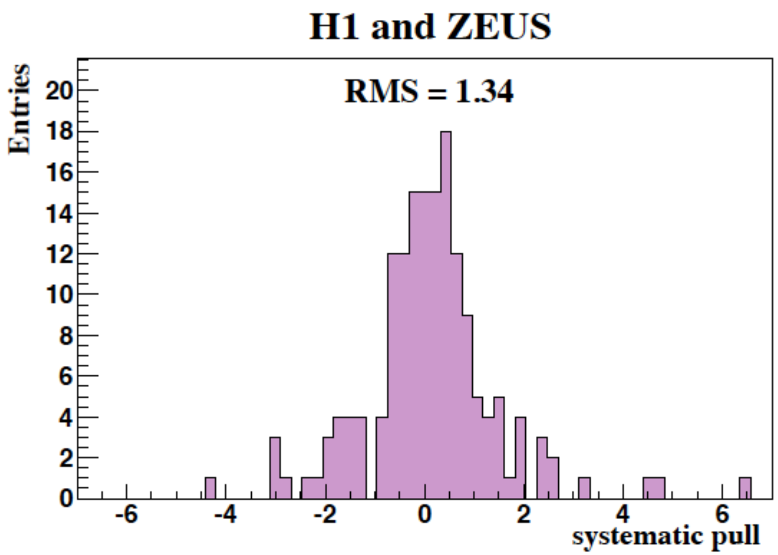
Combination of measurements of inclusive deep inelastic $e^{\pm}p$ scattering cross sections and QCD analysis of HERA data

Since DIS'15 … Flagship HERA-II paper belonging to all who dedicated their time to HERA

4 x e+p HERA-I lumi
15 x e-p HERA-I lumi

Combining Final ZEUS and H1 Inclusive NC/CC Data

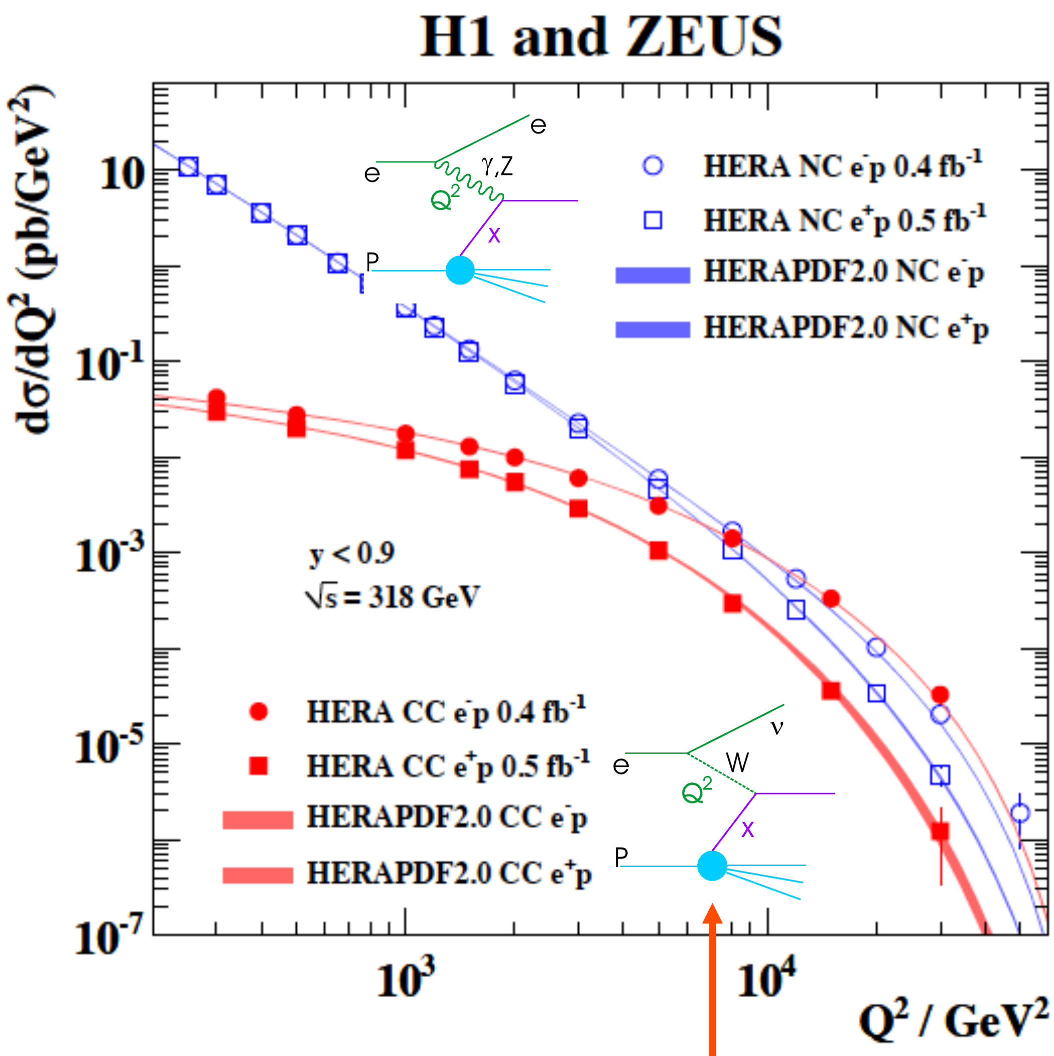
- Data span 6 orders of mag in x / Q^2 [$0.045 < Q^2 < 50000$ GeV^2]
- 41 data sets with 2927 input data points
- Combined into 1307 final points ($\chi^2 = 1687 / 1620$)
- 162 sources of correlated systematic error allowed to float



- Beyond $\sqrt{2}$ statistical improvement … cross-calibrating to tackle (different) dominating H1, ZEUS systematics.

Final NC precision:
< 1.5% for $3 < Q^2 < 500$ GeV^2
< 3% up to $Q^2 = 3000$ GeV^2

SM Textbook Legacy:
EW Unification for Space-like Bosons



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

Neutral Current x-sec

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

Charged Current x-sec

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

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

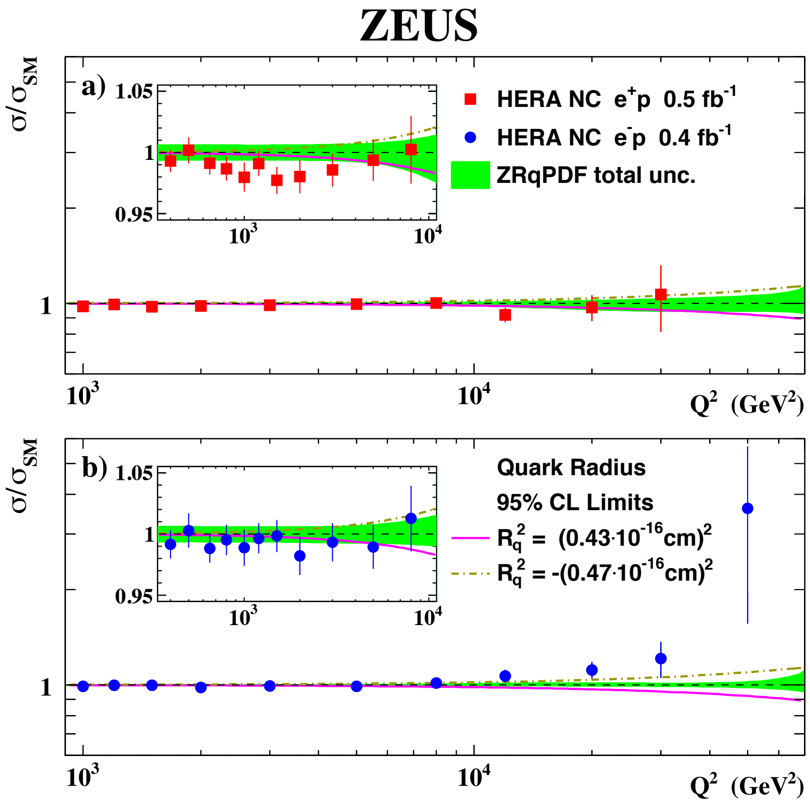
- Parton density info encoded in σ_{NC} and σ_{CC}

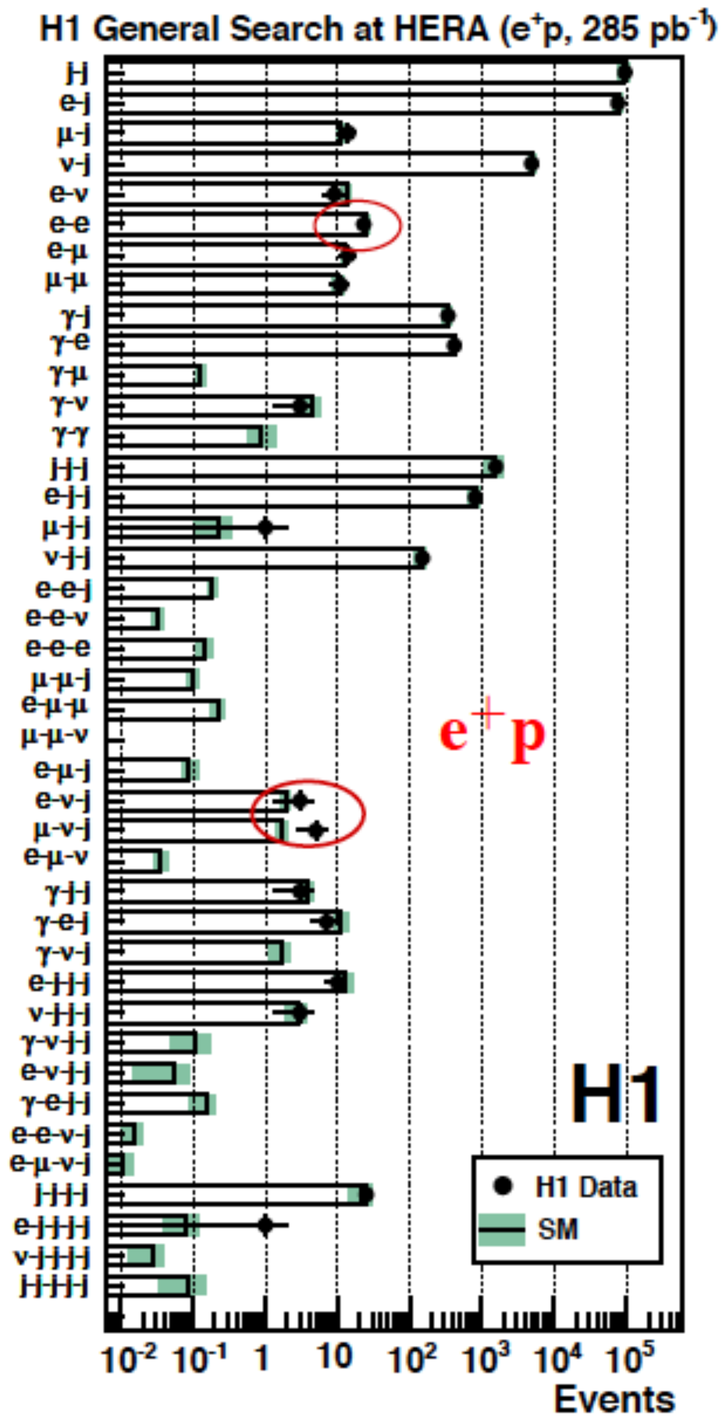
Legacy of Testing the SM

Despite huge number of searches and some world-leading sensitivity, HERA found the Standard Model …

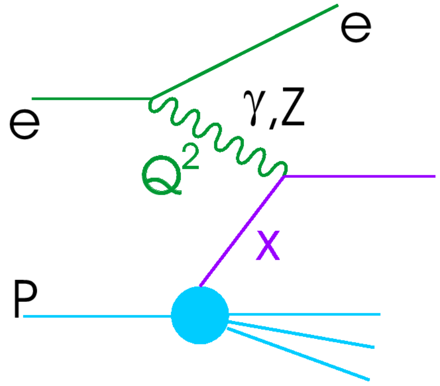
- Fantastic agreement across wide range of final states … no deviations >2.5σ.
- Compositeness $R_q < 0.43 \times 10^{-18}$ m

[ZEUS analysis using combined HERA Data]



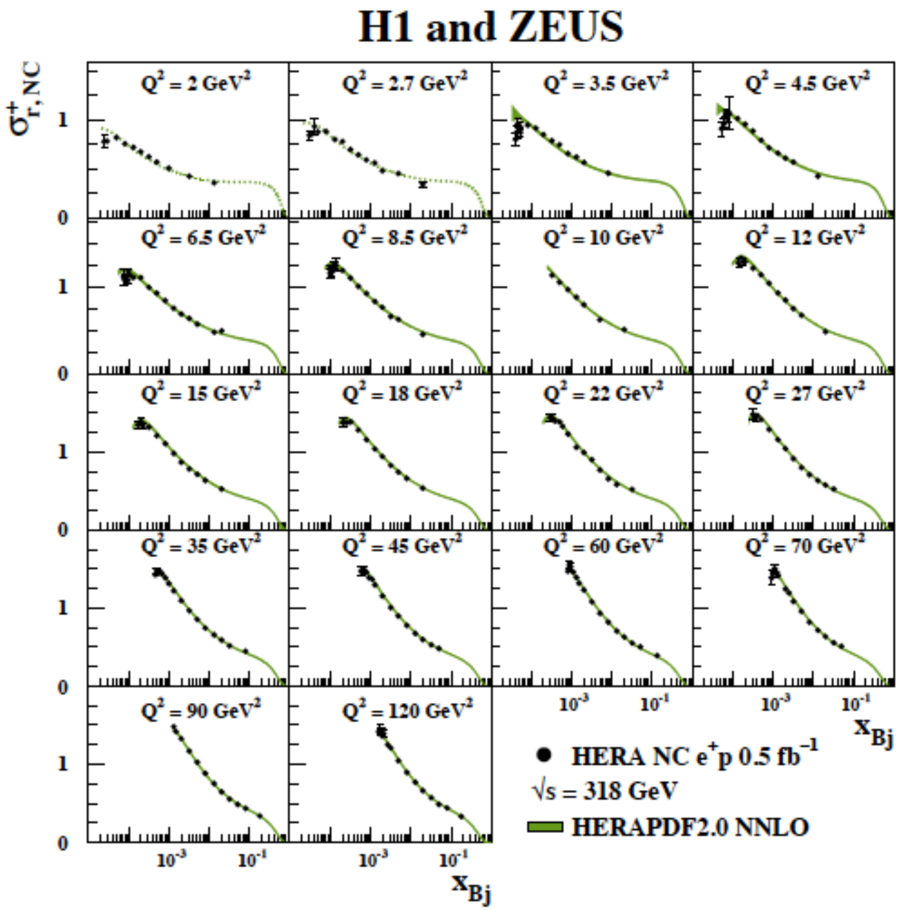


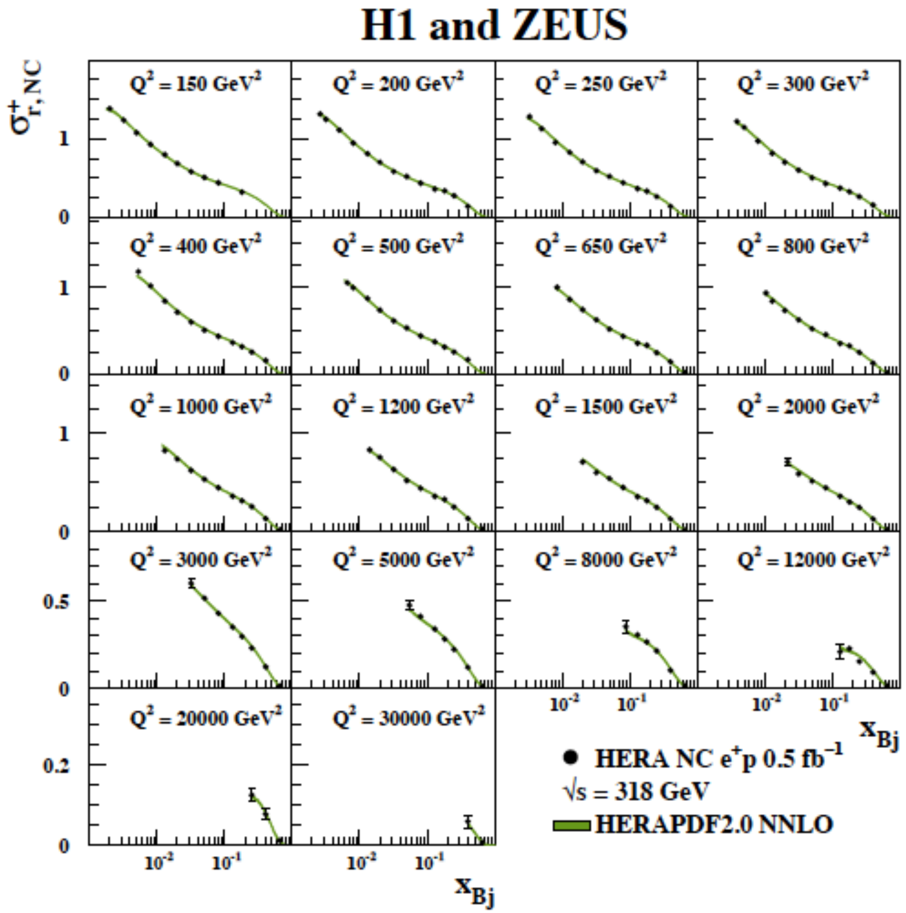
Neutral Current Data (e^+p only)



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

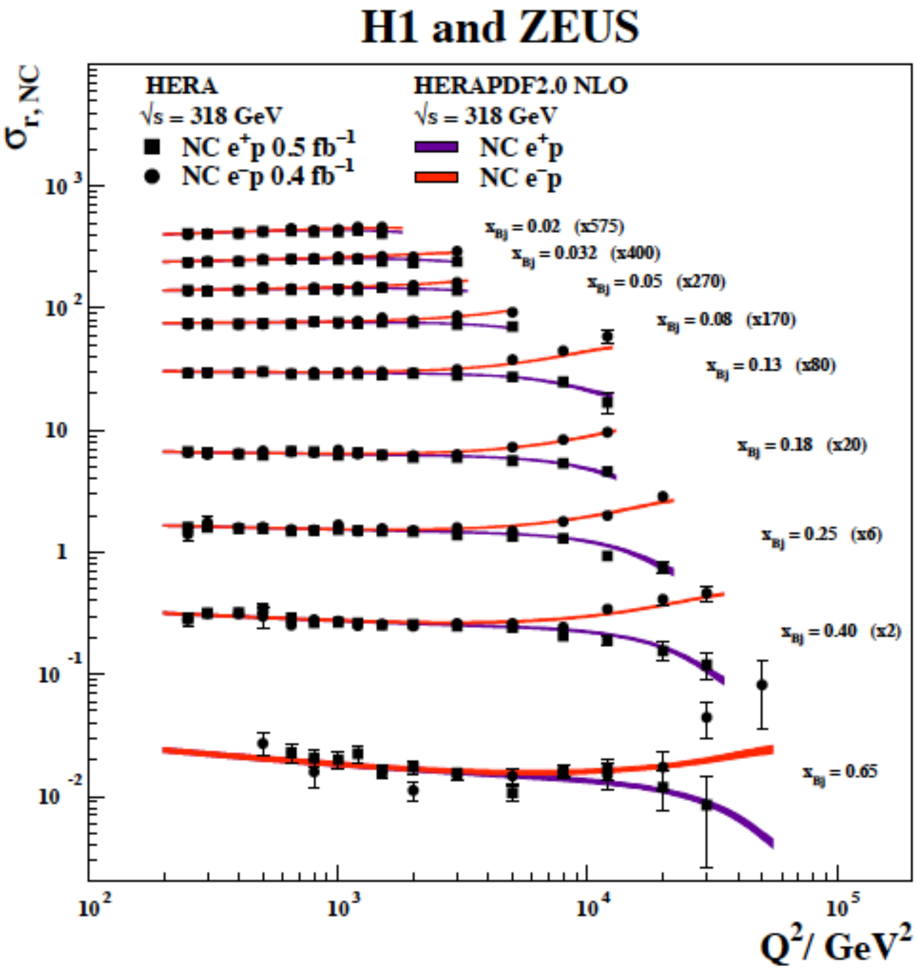
provides best constraints on **u** & **ubar** densities



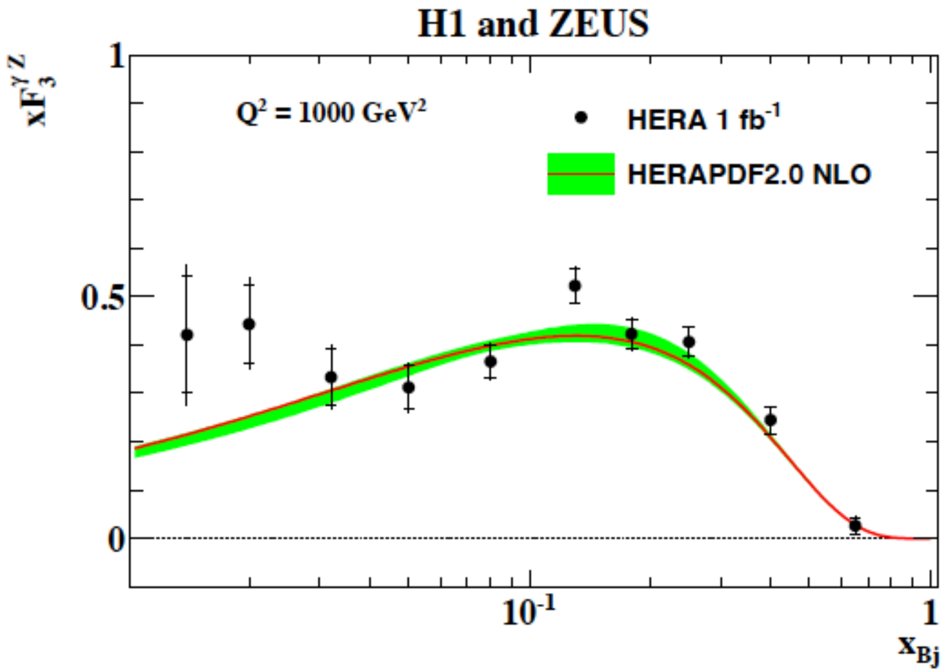


- plus dedicated low Q^2 datasets ($0.045 < Q^2 < 1.5$ GeV^2)
- plus reduced proton beam energy data → F_L …

NC $e^{+/-}$ Charge Dependence & Valence Quarks

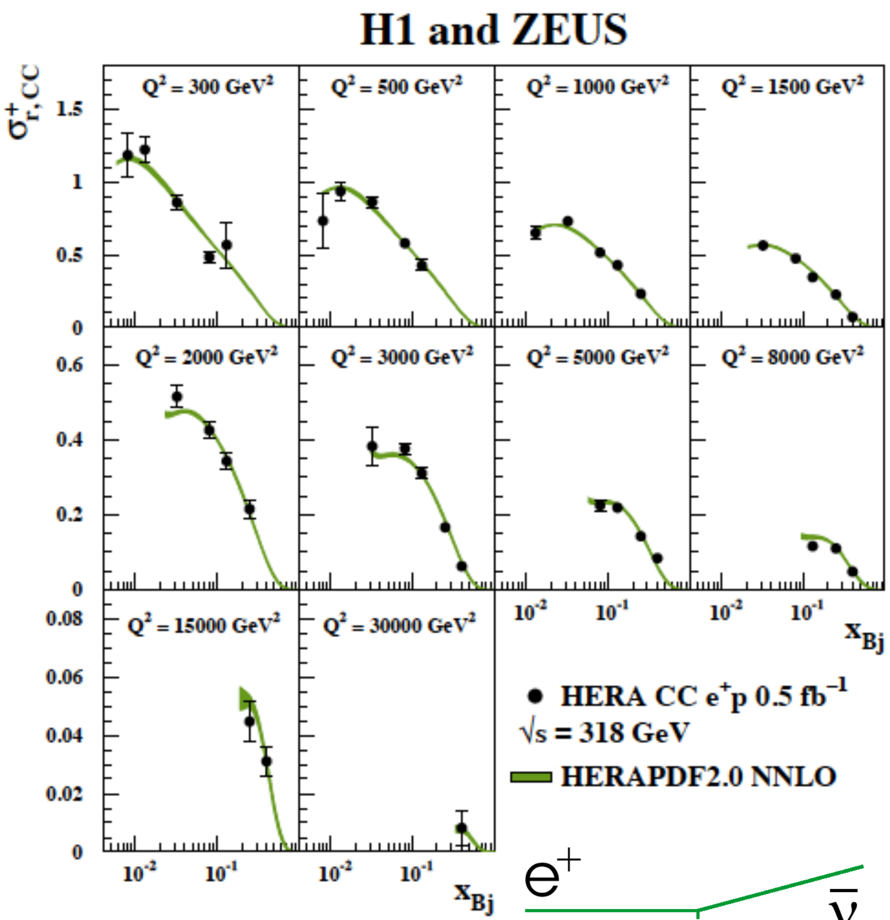


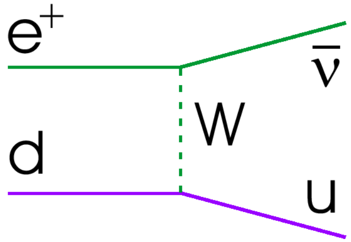
- Difference between e^-p and e^+p NC cross sections at large Q^2 measures **$xF_3^{\gamma Z}$** structure function …
- Interference between γ and Z exchange
- Minimal scale dependence → interpolate to $Q^2 = 1000$ GeV^2



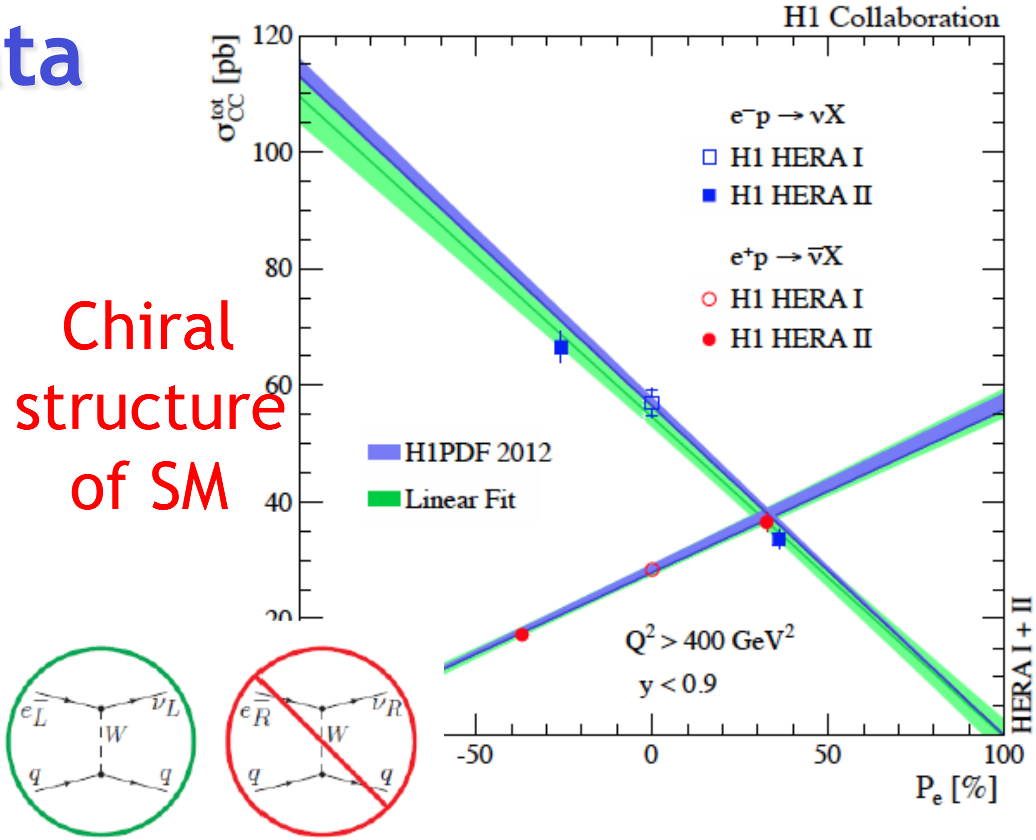
… Direct sensitivity to **valence** quarks (incl low x)

Charged Current Data





Chiral structure of SM



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

Electroweak Parameters

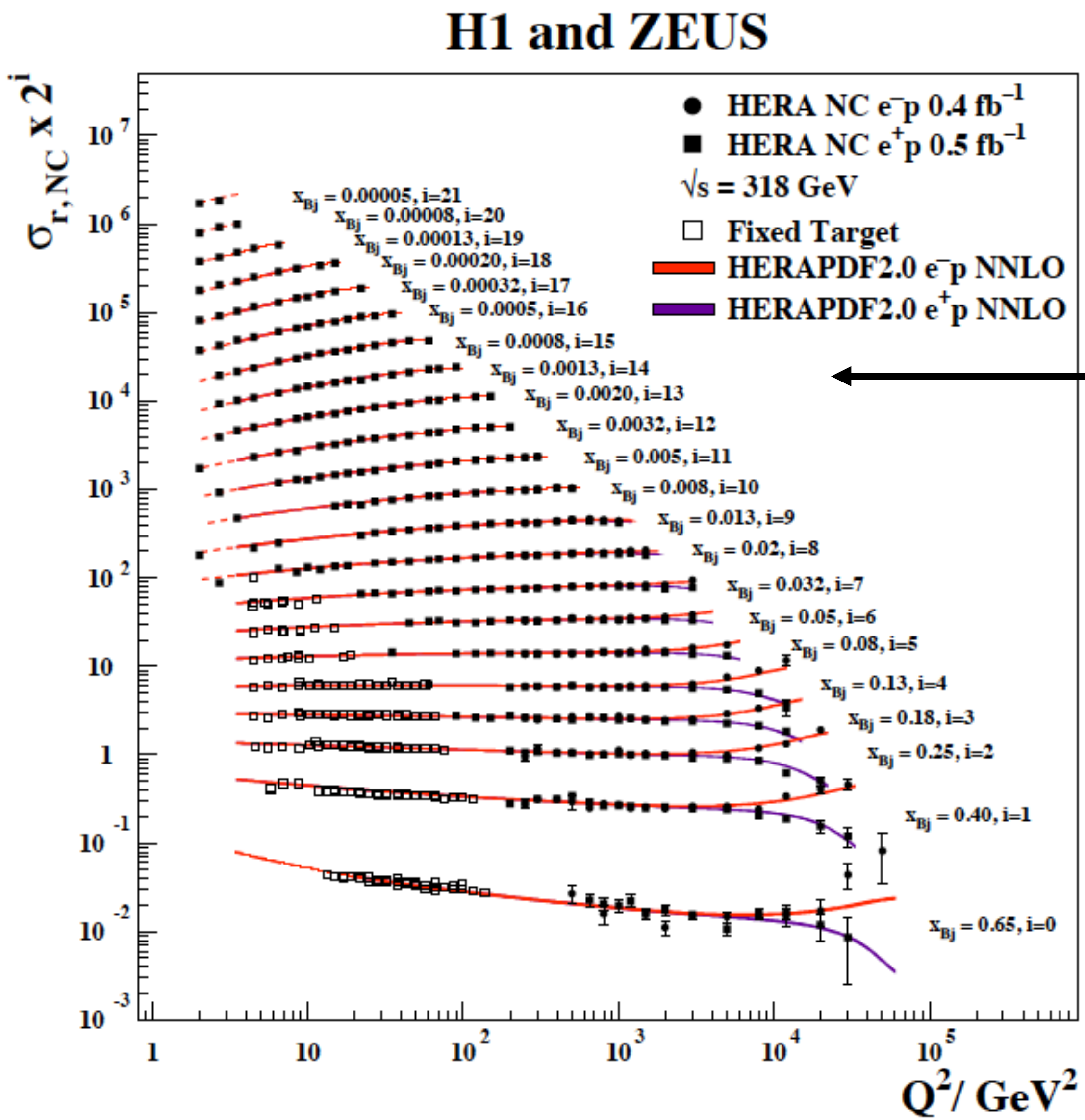
e.g. with M_W fixed to PDG:

$$\sin^2\theta_W = 0.2252 \ \pm 0.0011 \ \text{(experimental/fit)}$$

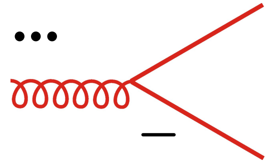
$$^{+0.0003}_{-0.0001} \ \text{(model)} \ ^{+0.0007}_{-0.0001} \ \text{(parameterisation)}$$

[ZEUS electroweak fit using ZEUS pol + ZEUS & H1 unpol data]

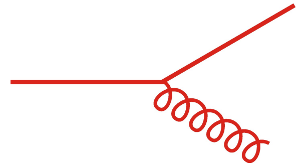
QCD Evolution and the Gluon Density



NC Q^2 dependence driven by …



$g \to q\bar{q}$



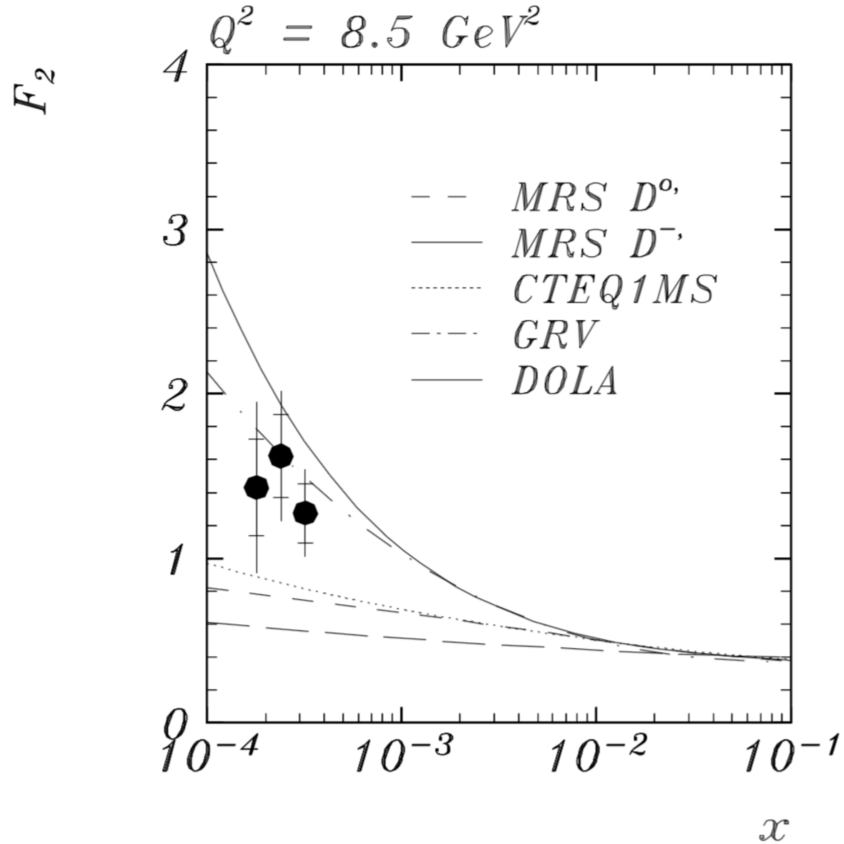
$q \to qg$

… QCD fit description over vast range

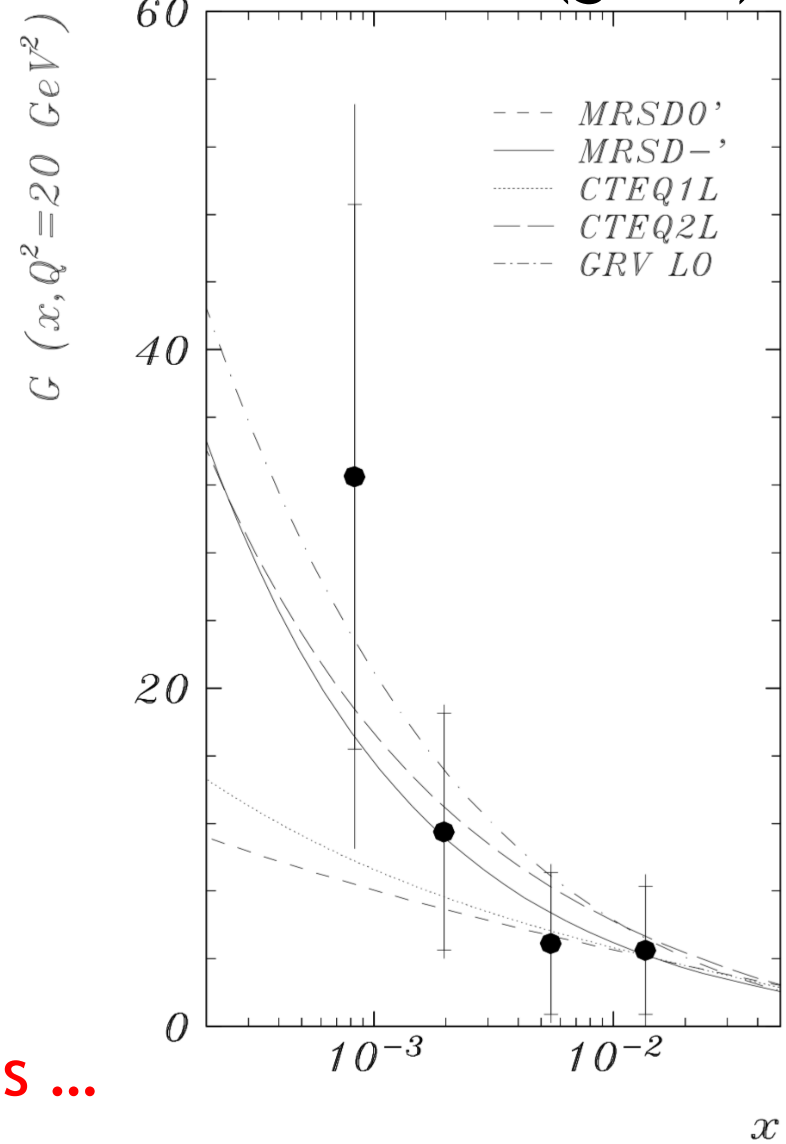
- NC Q^2 evolution yields **low-medium x gluon**, assuming DGLAP
- **High x gluon is tough!** - Other observables / more data needed

An Early Picture of the Proton through the HERA Microscope

F_2 (quarks)

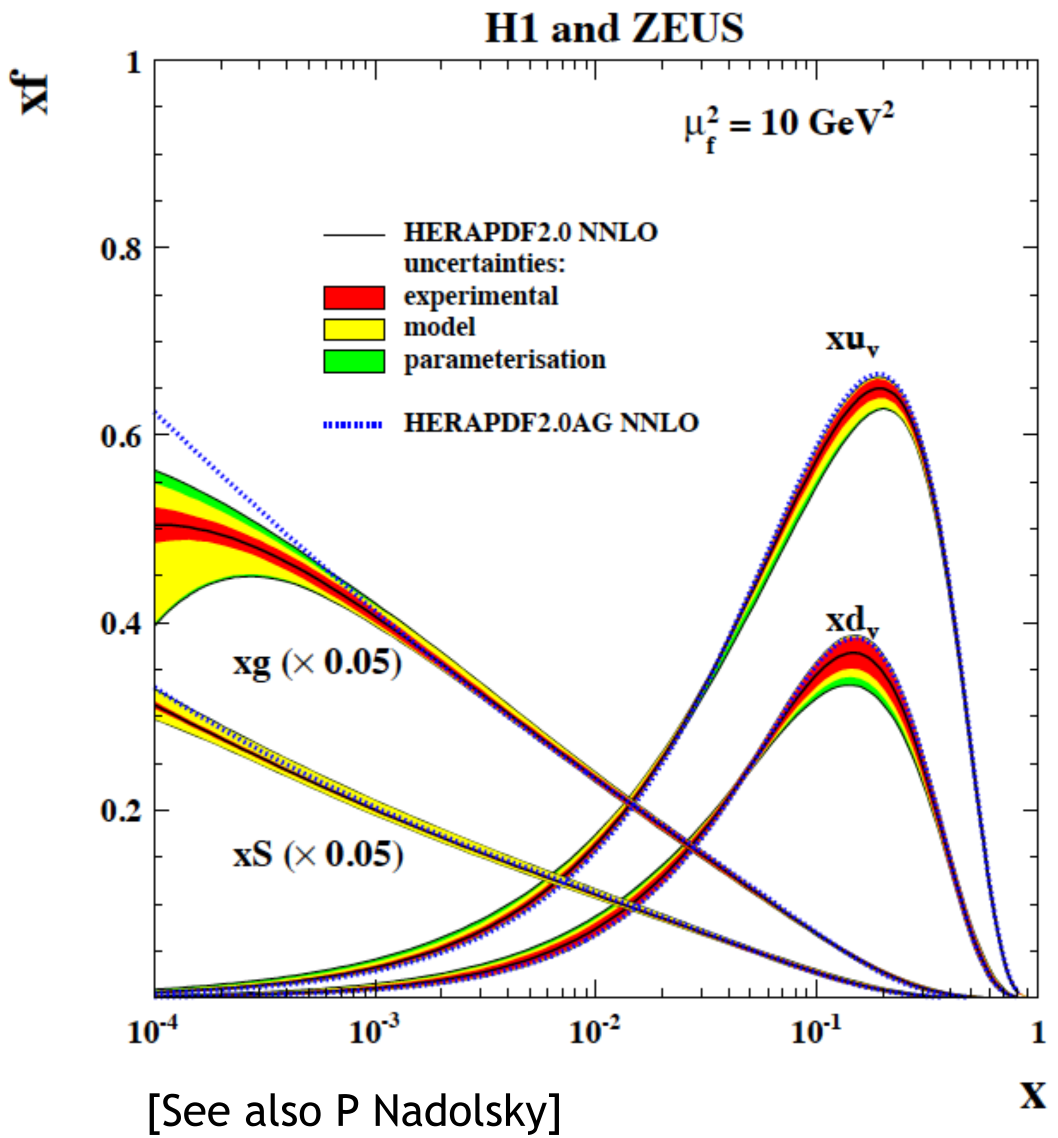


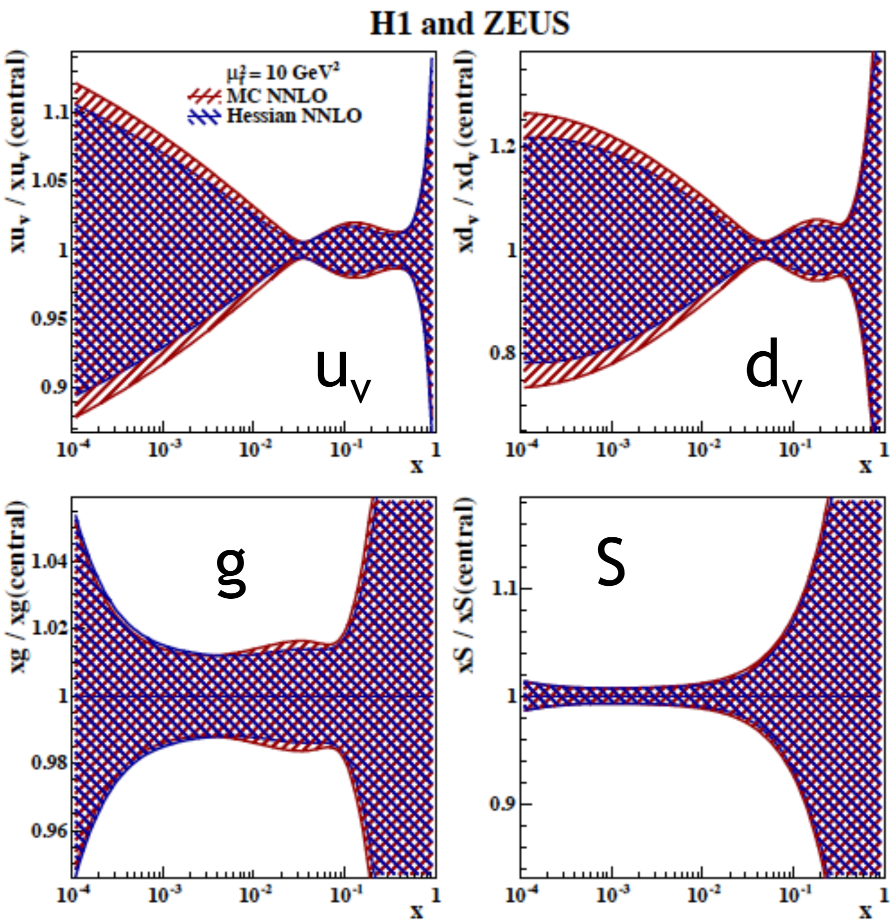
(gluon)



H1 – 1992 data (22.5 nb^{-1})
compared with early variants
of some popular parameterisations …

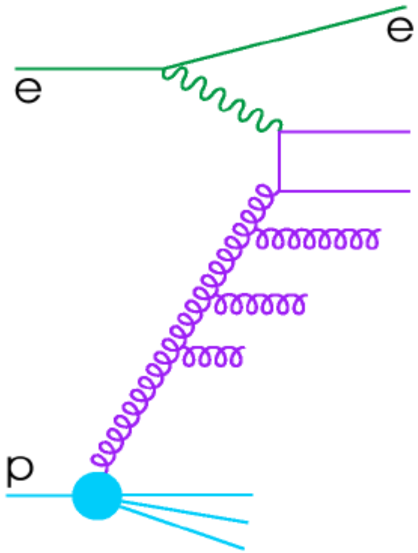
Final Picture of the Proton through the HERA ~~Micro~~Attoscope

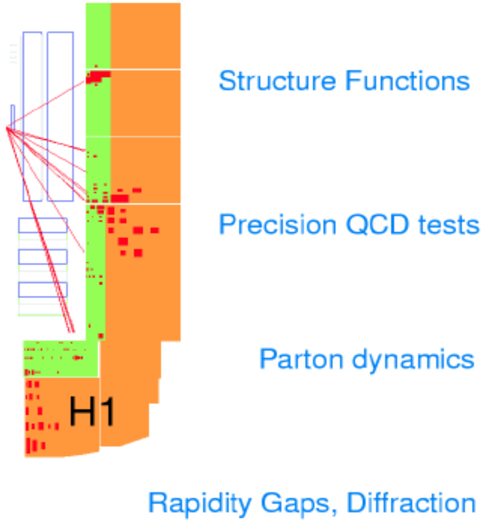




[See also P Nadolsky]

The Hadronic Final State Legacy





Unique laboratory for precision testing of QCD and searching for novel dynamics at low x

- Impossible to do justice to the huge number of results
- A very limited personal selection follows
- More complete documentation at e.g…

The Hadronic Final State at HERA

Paul R. Newman*

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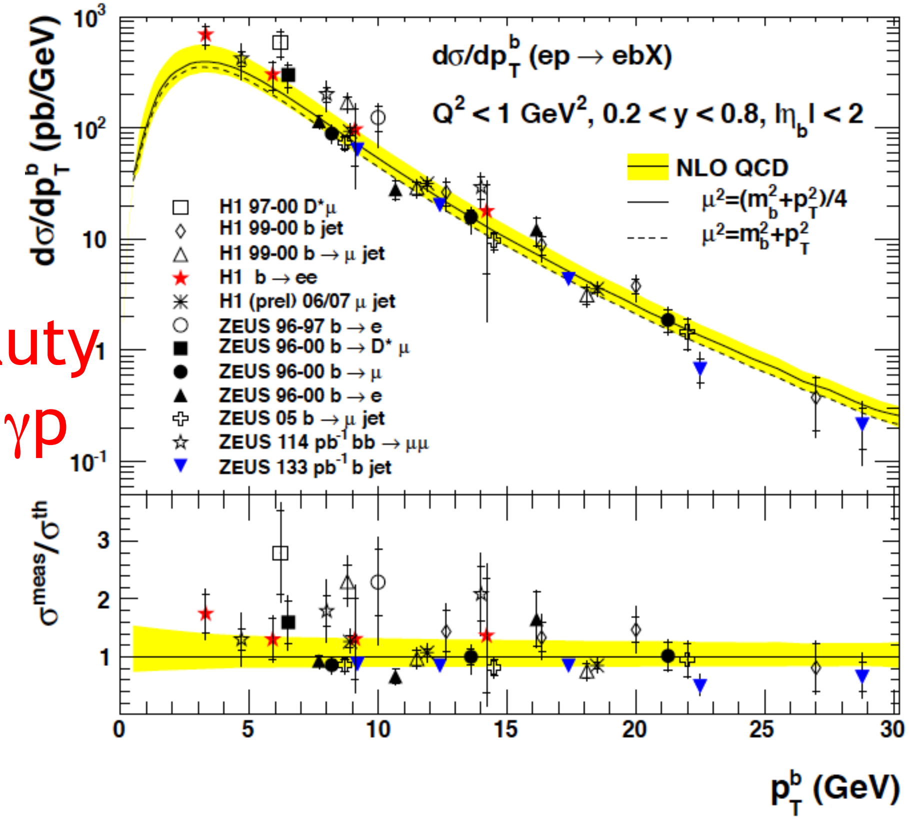
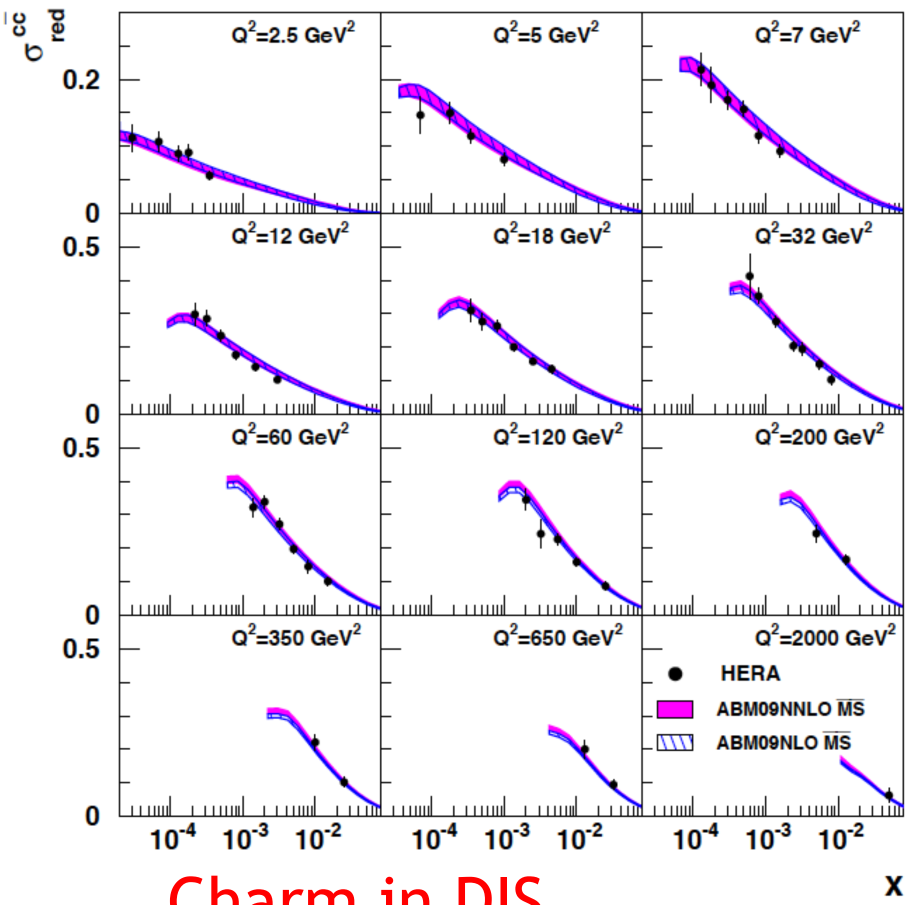
(Dated: January 15, 2014)

[Rev.Mod.Phys. 86 (2014), 1037]

High Precision Heavy Flavour Data



Beauty in γp



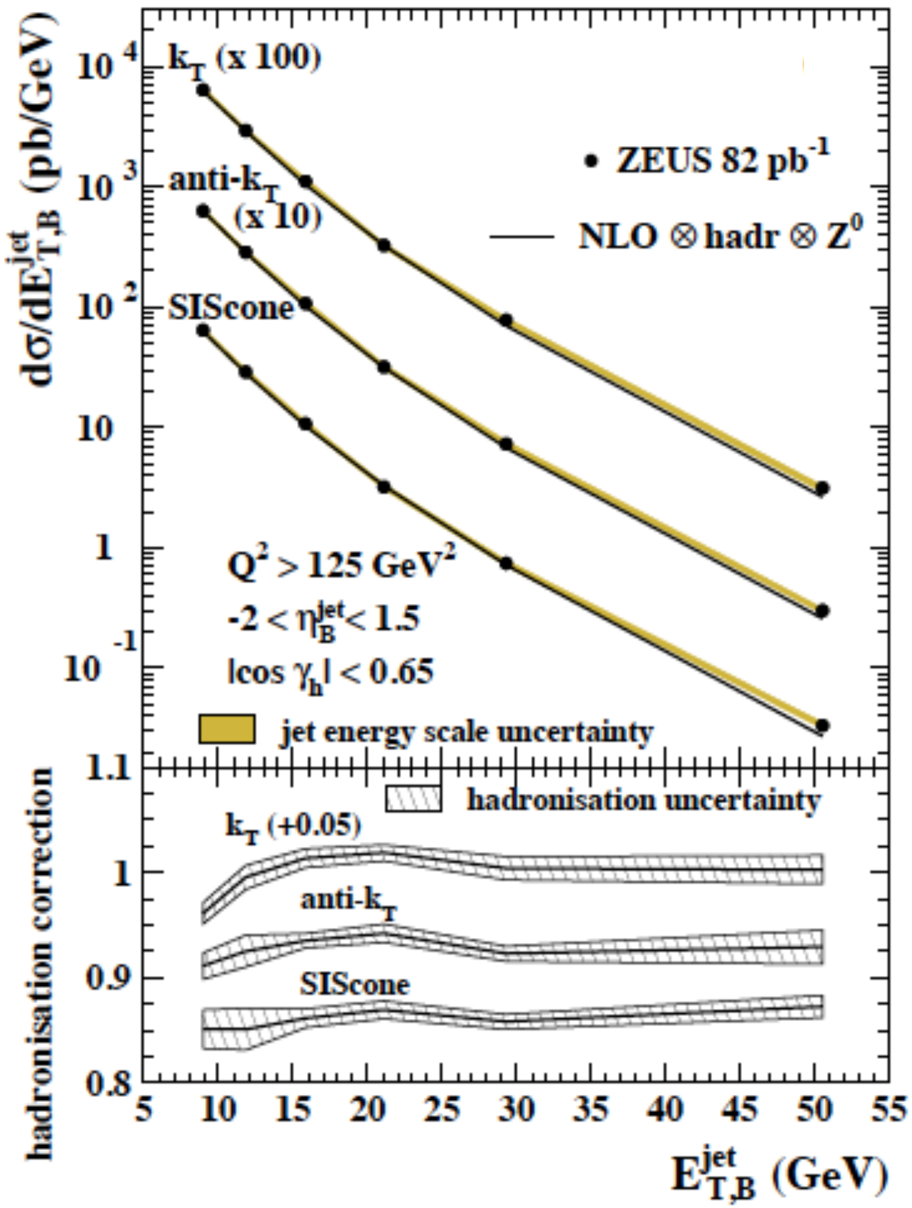
Charm in DIS

- Stunning consistency with incl data via PDFs and (N)NLO QCD

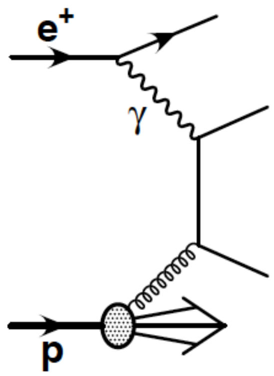
- Clear presentation of charm and beauty contribution to σ(NC)

-Testing ground for development of heavy flavour schemes in QCD

High Precision Jet Data in DIS



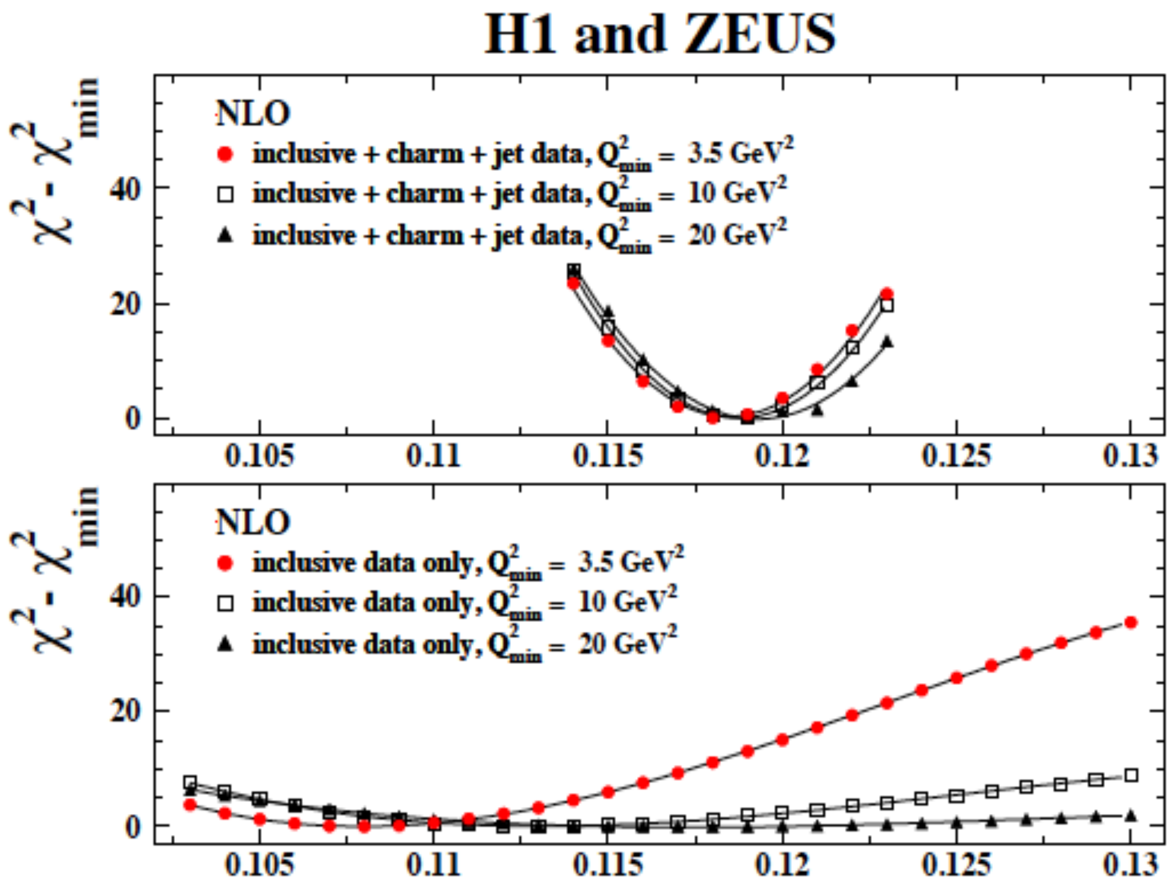
- Excellent agreement with QCD over wide kinematic range.
- Sensitive to gluon density in lowest order
- Role in benchmarking jet algorithms



Other inventive uses for HERA jet data …

- Hard scattering in γp → constraining photon structure
- Searches for BFKL-topologies
- Jet substructure
- Underlying event treatment
- Searches for Multi-Parton Interactions
- …

Jet and Charm Data in Fits → α_s

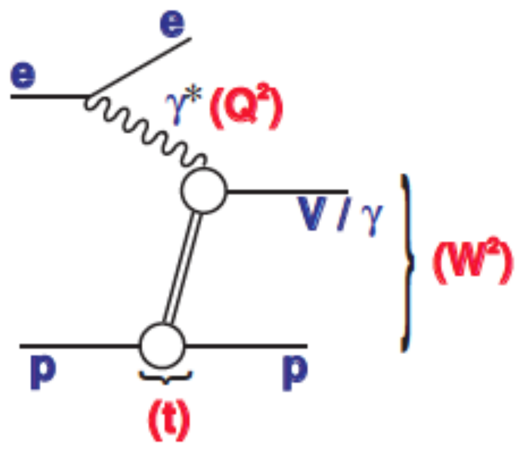


Including jet and charm data in HERA-II fits allows simultaneous α_s (and m_c) without significant impact on PDFs

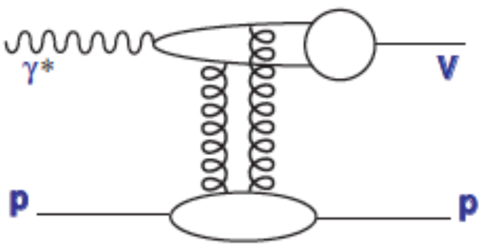
$$\alpha_s(M_Z^2) = 0.1183 \pm 0.0009(\text{exp}) \pm 0.0005(\text{model/parameterisation}) \pm 0.0012(\text{hadronisation}) \ {}^{+0.0037}_{-0.0030}(\text{scale}) \ .$$

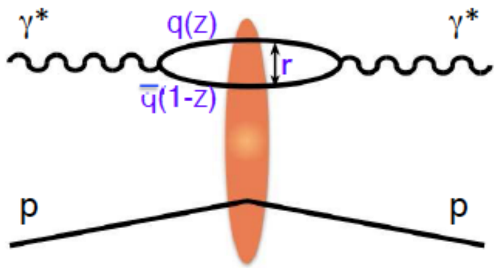
- Experimental errors << theory scale variation
- Competitive result and good agreement with world average

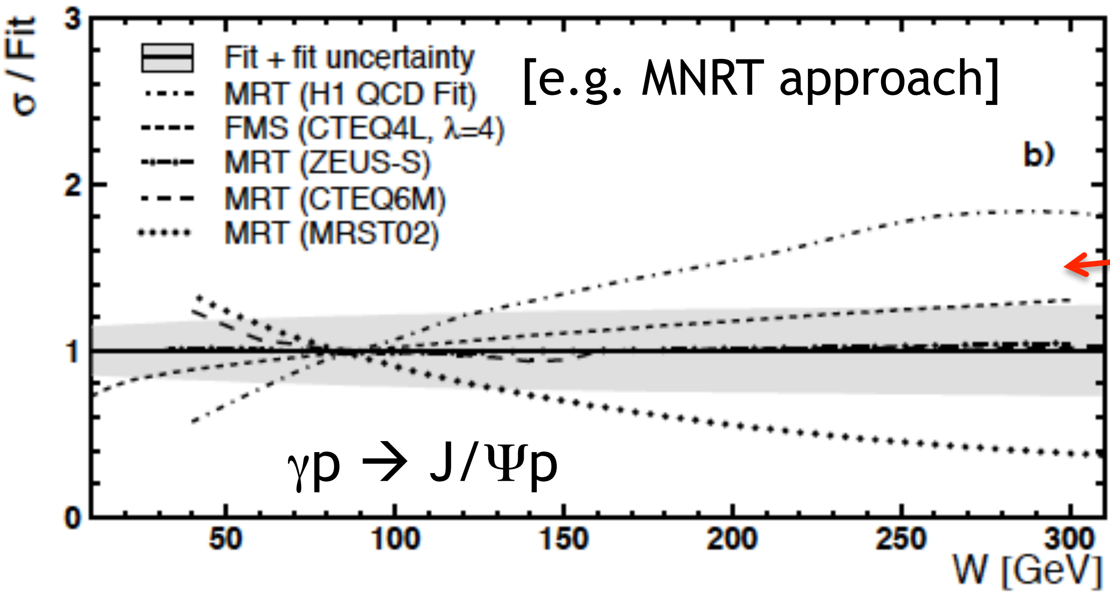
Perturbatively Calculable Exclusive Vector Mesons!

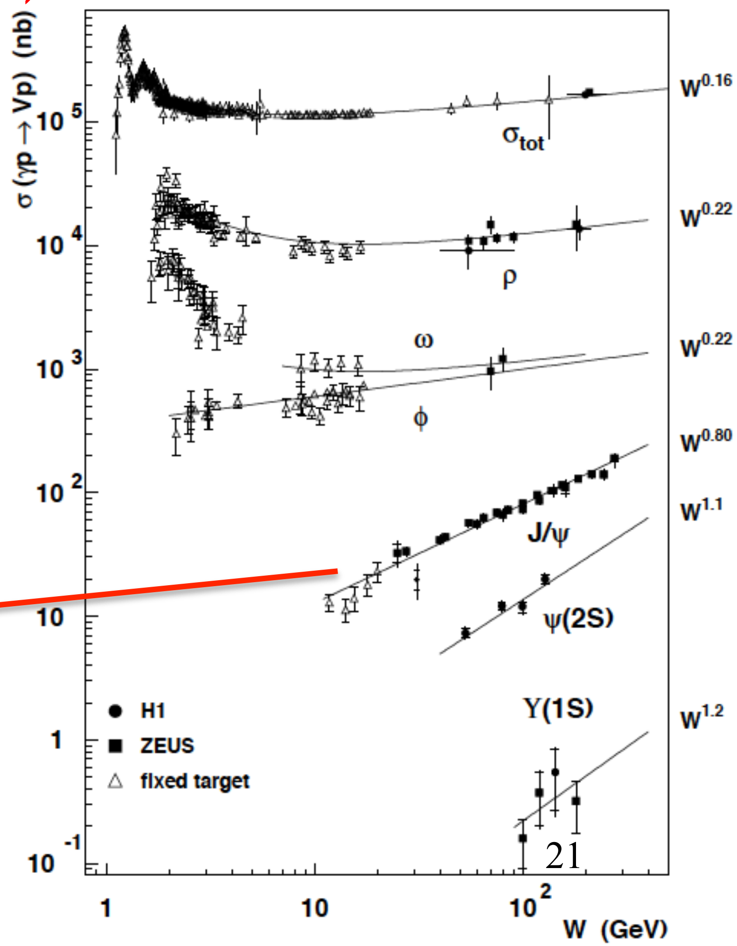


- Capability to switch pQCD on or off by varying hard scale (Q^2 or $M_V{}^2$)
- Hard processes calculable starting from proton PDFs (or colour dipole + proton x- section)

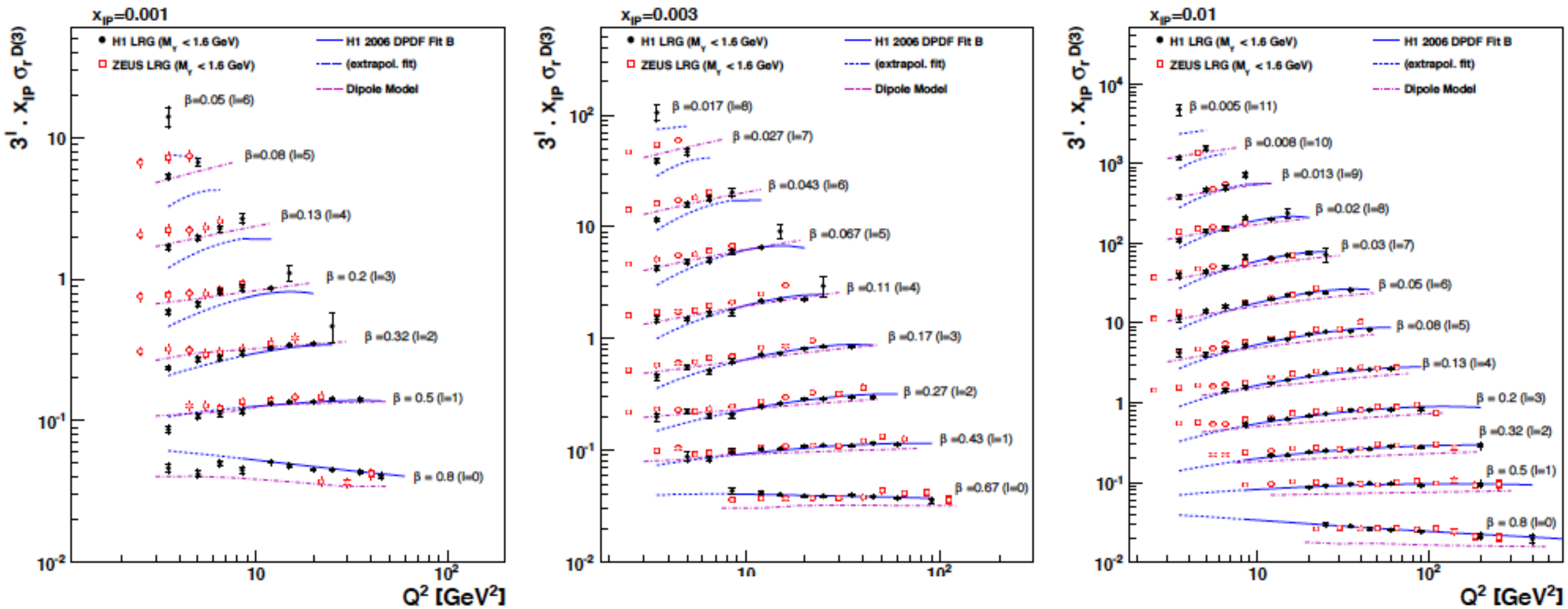




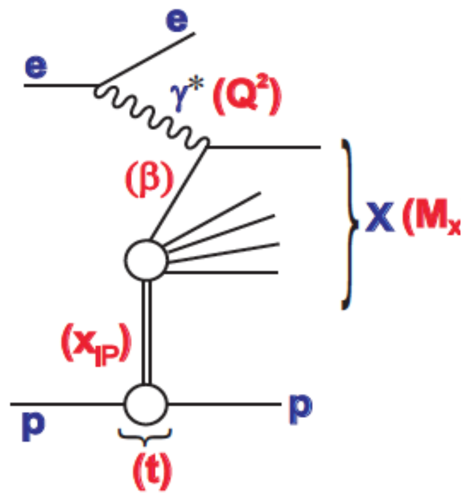


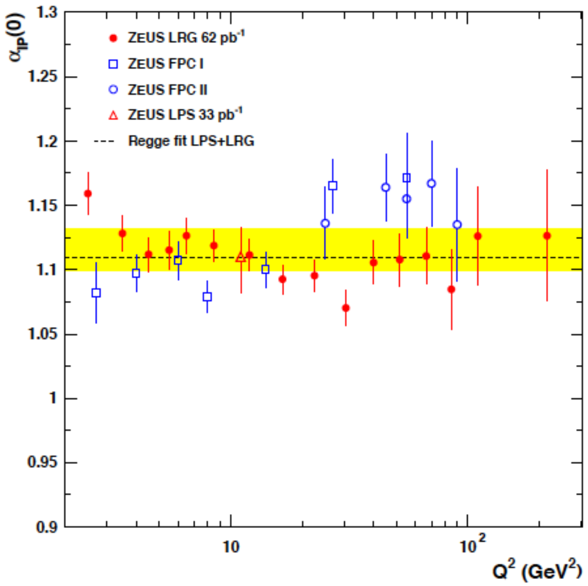


Three (even four) -fold Differential Diffractive X-Sections / Structure Functions



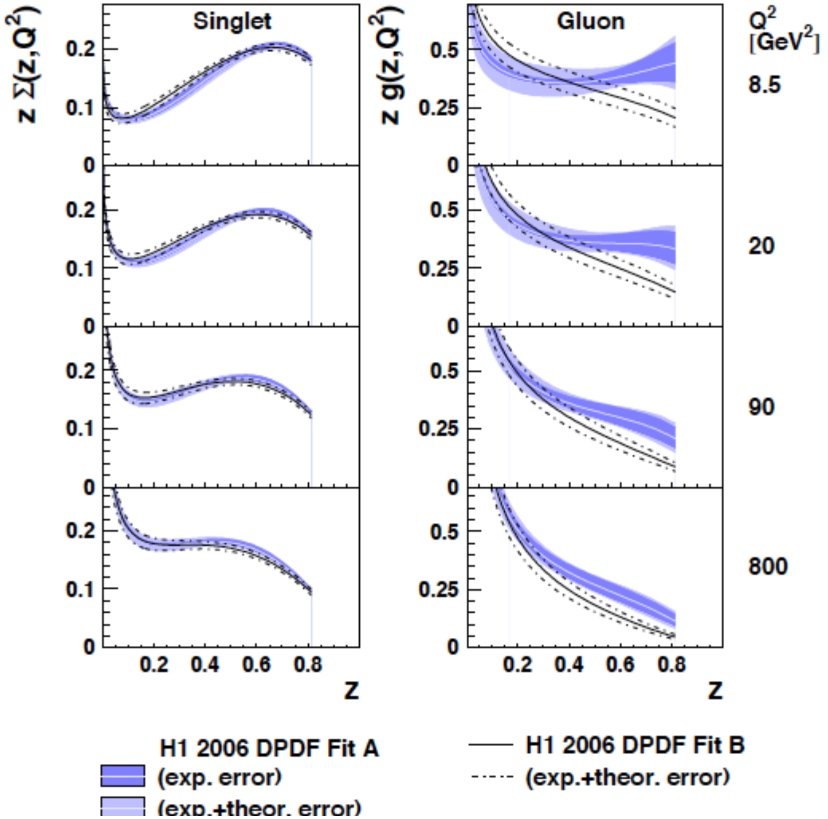
Diffractive process with excitation to continuum of masses contributes ~10% of low x cross section

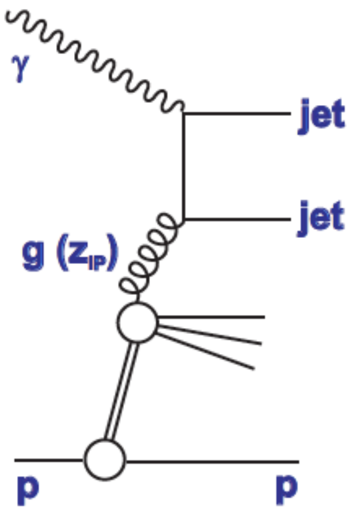


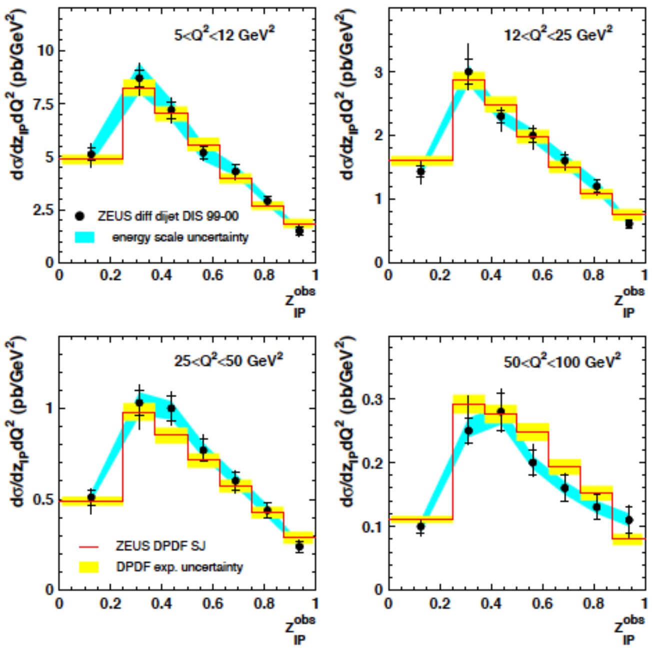


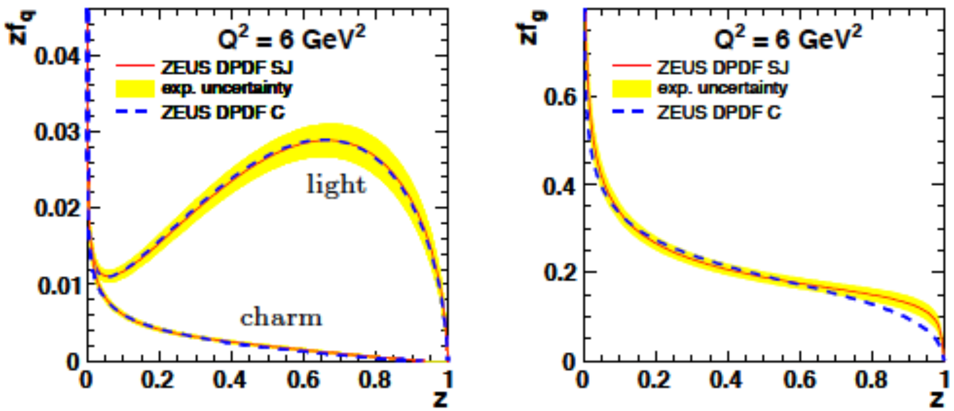
- The soft stuff factorises!
- Looks remarkably like a soft pomeron!

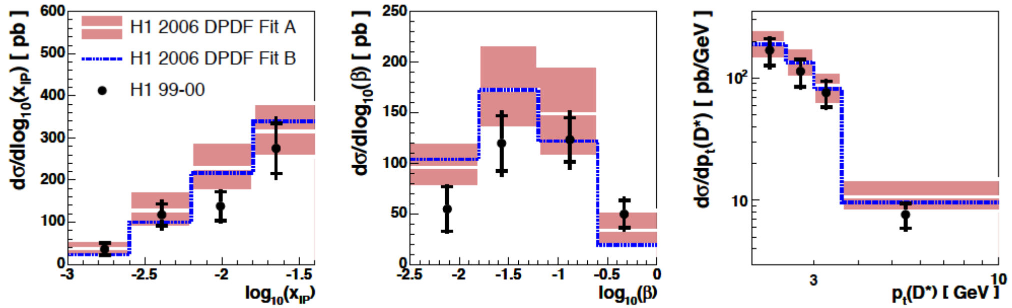
Diffractive Parton Densities Describing Everything in Final State Diffractive DIS





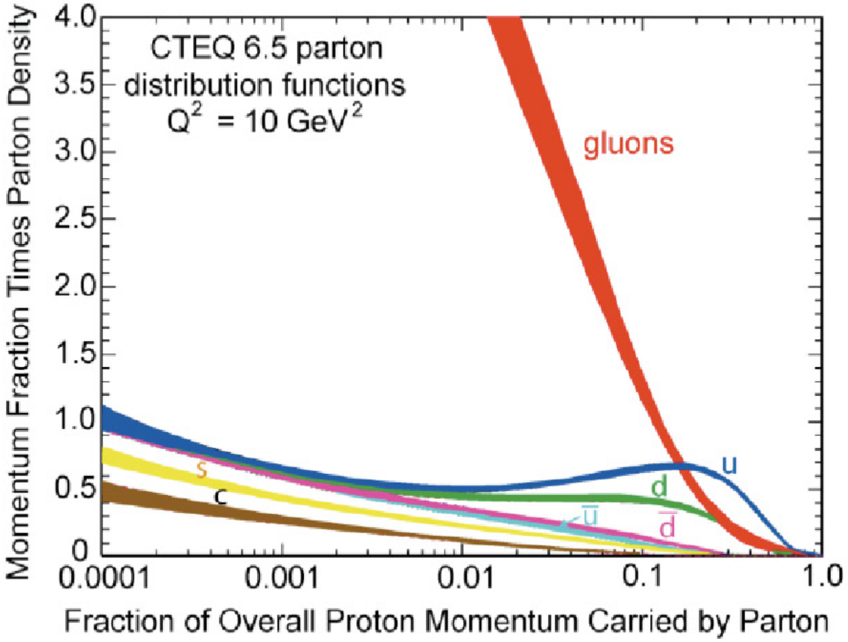






Used extensively in MC models of diffraction at the LHC

Low x Physics: the "Pathological" Gluon



Does the low x gluon saturate?

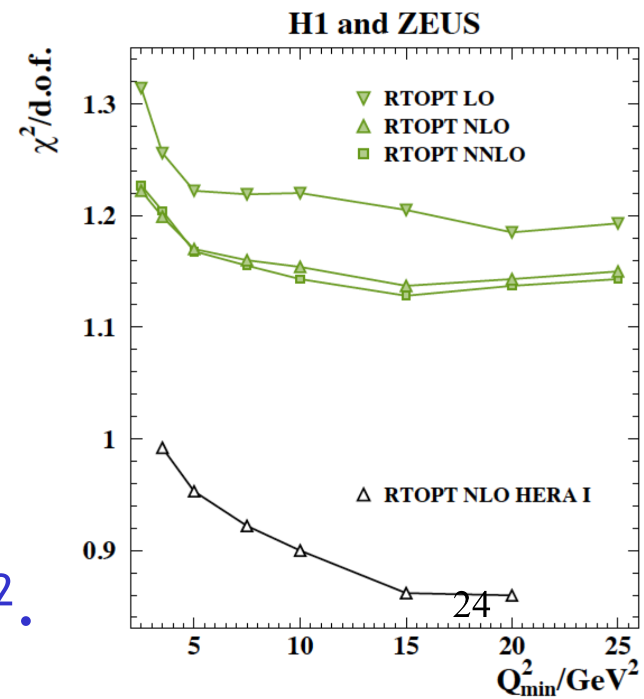
- Recombination (gg→g) ?
- Resummation?
- Just N(N)LO DGLAP + HT?

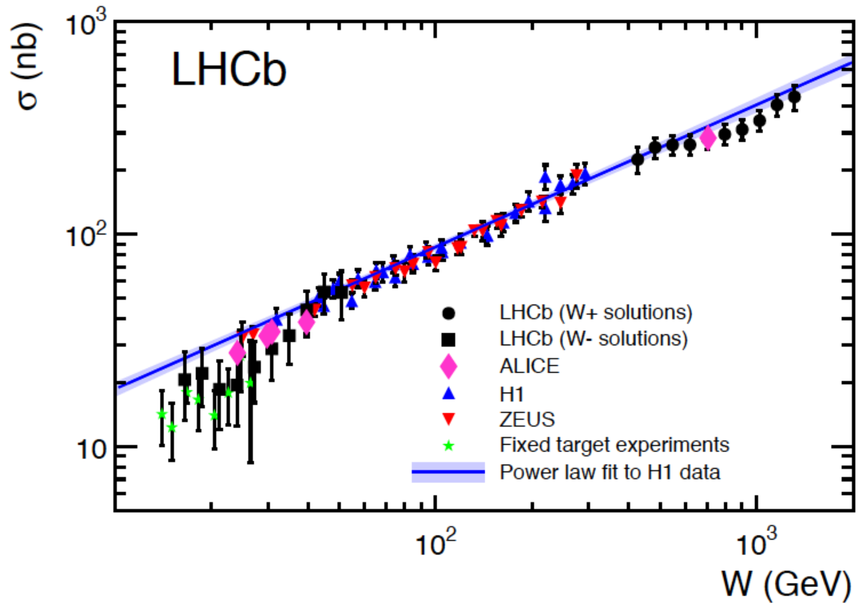
→towards new high density, small coupling, parton regime with non-linear parton evolution (e.g. CGC)?

→ cf confinement, hadronic mass …

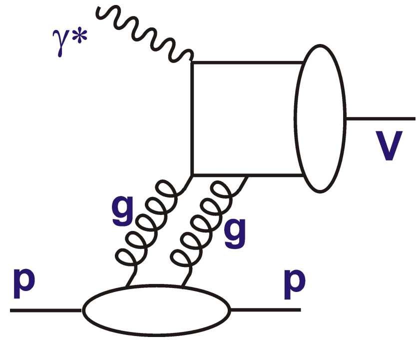
HERA-II Paper: "some tension in fit between low & medium Q^2 data… not attributable to particular x region" (though kinematic correlation)

Others (e.g. NNPDF) showed NLO DGLAP description deteriorates when adding data in lines parallel to 'saturation' curve in x/Q^2.



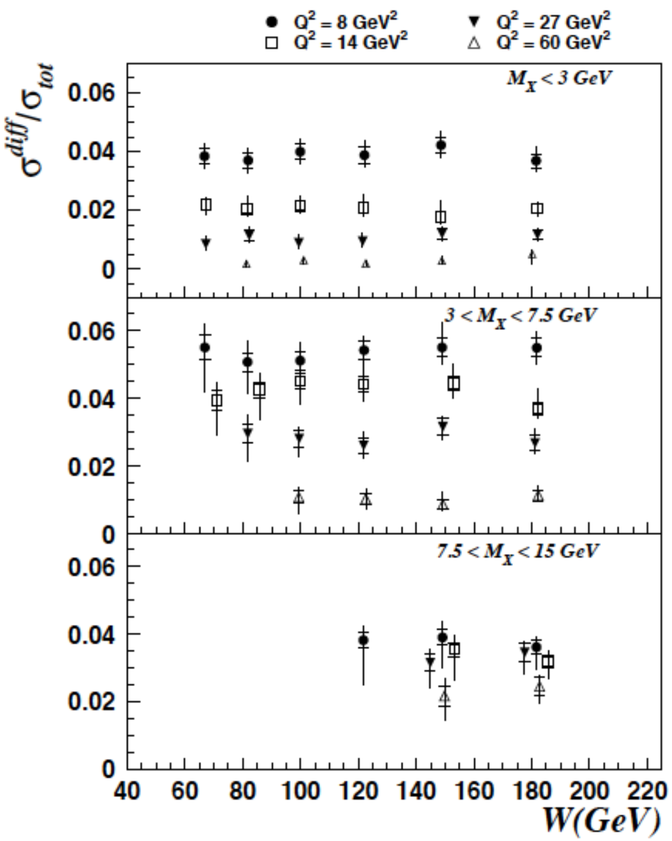


Low x Saturation in Diffractive Data?



- Elastic J/Ψ in γp …

- No evidence for change in shape at high W (i.e. low x), even at LHC (t dependence yet to be exploited)



- Rather flat diffractive/inclusive ratio

and failure of Diffractive PDF fits to data below Q^2 ~ 5 GeV^2 best described by dipole models incorporating saturation …

BOTTOM LINE … HERA not conclusive and LHC has not given greater clarity

Establishing the Legacy

… but HERA is not quite ready to be consigned to history yet!...

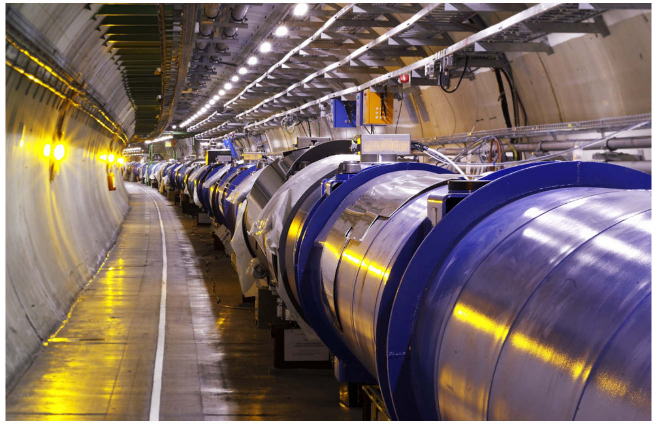
DESY–15–253
IPPP/15/76
DCPT/15/152
MAN/HEP/2015/21
December 2015

… and Data Preservation Project ensures new analyses possible over timescale of >= 10 years.

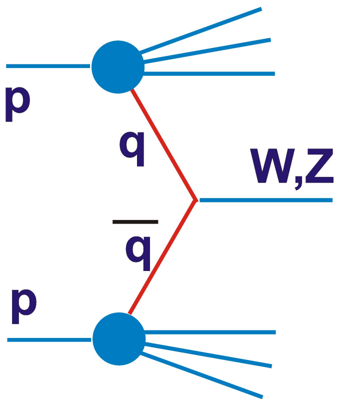
Summary of workshop on Future Physics with HERA Data

A. Bacchetta[1], J. Blümlein[2], O. Behnke[3], J. Dainton[4], M. Diehl[3], F. Hautmann[5,6], A. Geiser[3], H. Jung[3,7], U. Karshon[8], D. Kang[9], P. Kroll[10], C. Lee[9], S. Levonian[3], A. Levy[11], E. Lohrmann[3,12], S. Moch[12], L. Motyka[13], R. McNulty[14], V. Myronenko[3], E.R. Nocera[6,15], S. Plätzer[16,17], A. Rostomyan[3], M. Ruspa[18], M. Sauter[19], G. Schnell[20,21], S. Schmitt[3], H. Spiesberger[22,23], I. Stewart[24], O. Turkot[3], A. Valkárová[25], K. Wichmann[3], M. Wing[26,3,12], A.F. Żarnecki[27]

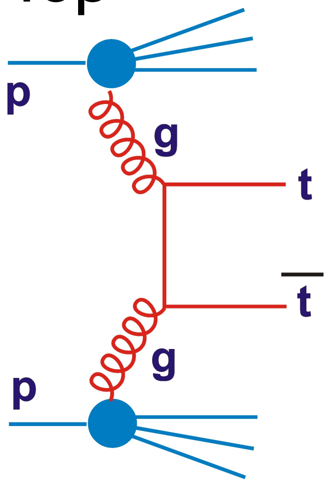
PDFs and the LHC



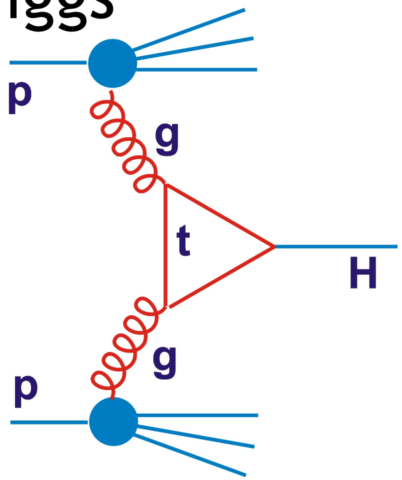
EW SM



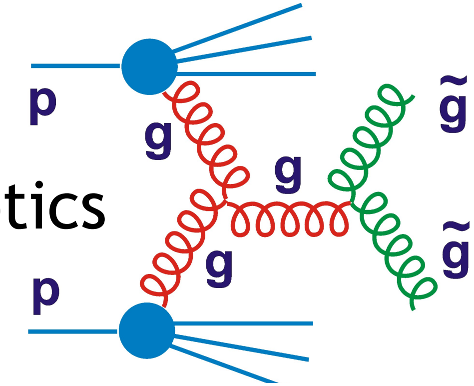
Top

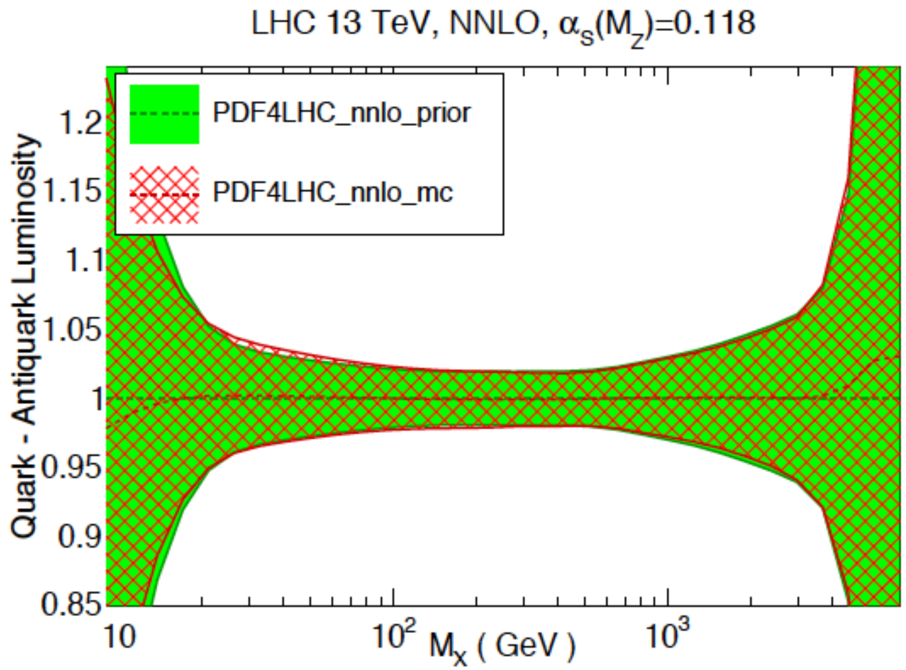


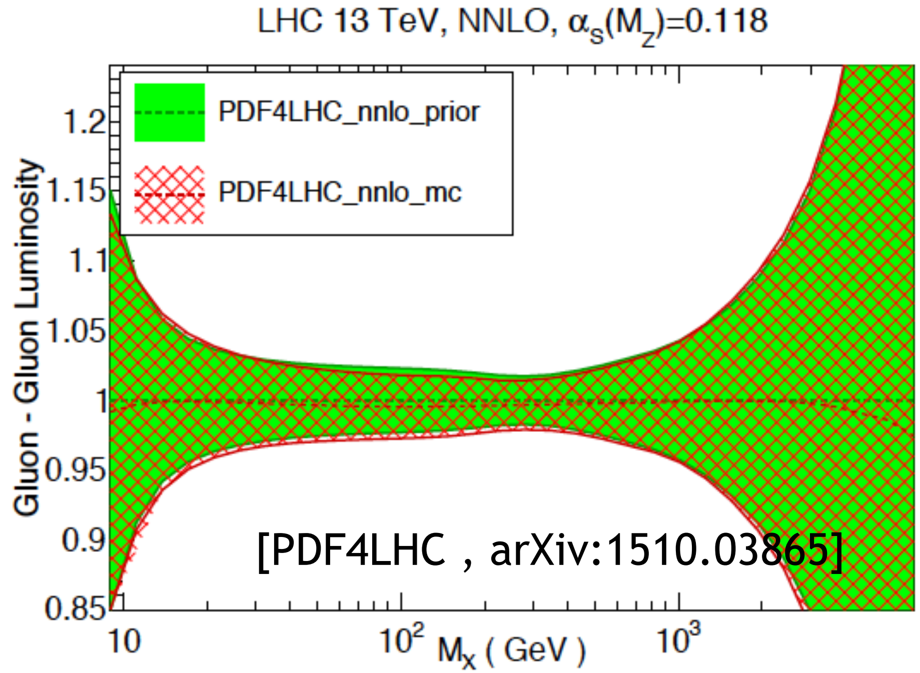
Higgs



Exotics

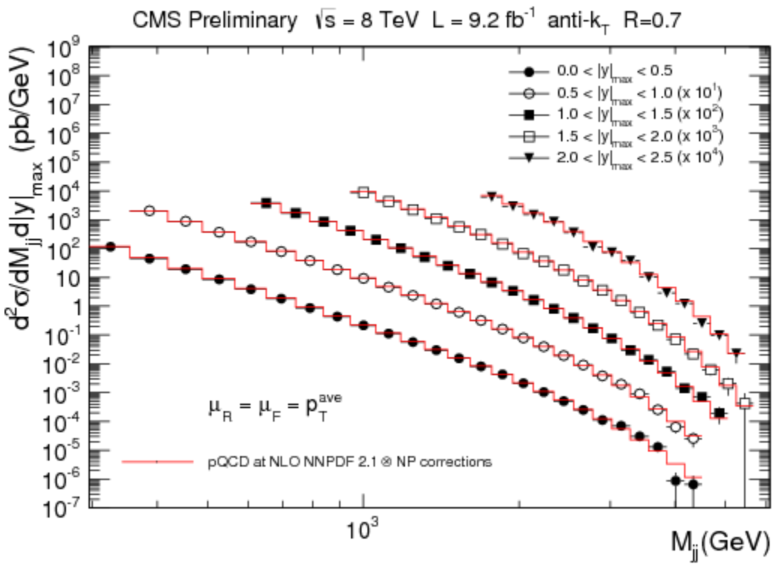






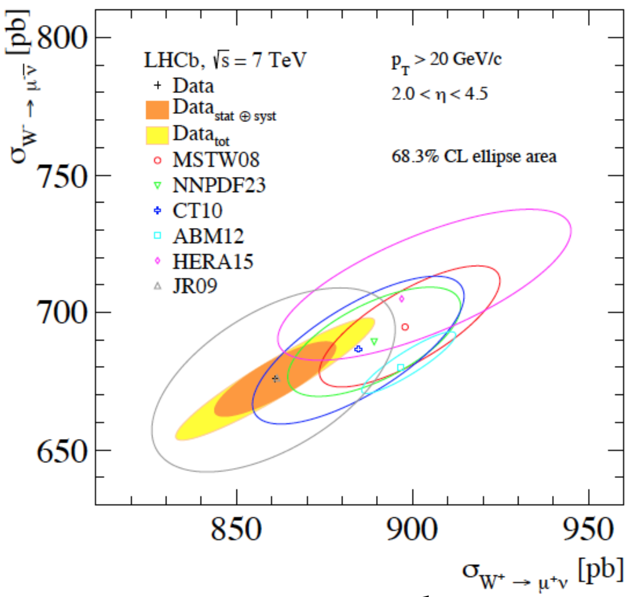
[PDF4LHC , arXiv:1510.03865]

PDFs working in extreme cases at the LHC …

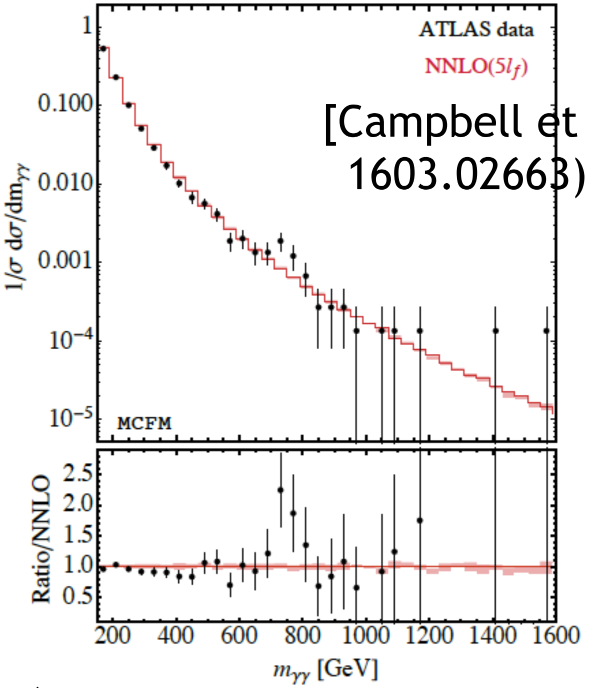


- Jets with cross sections varying over many orders of magnitude, extending to eg M_{jj} ~ 5 TeV

- LHCb Electroweak gauge bosons, extending well into forward region



- (NNLO) shape comparison of γγ background v "X(750)", for perfect rec'n and no backgrd



[Campbell et al, 1603.02663)]

… but LHC has a VERY long programme
what are the limiting factors in 15 years time?...

Higgs X-Section / Coupling PDF Uncertainties

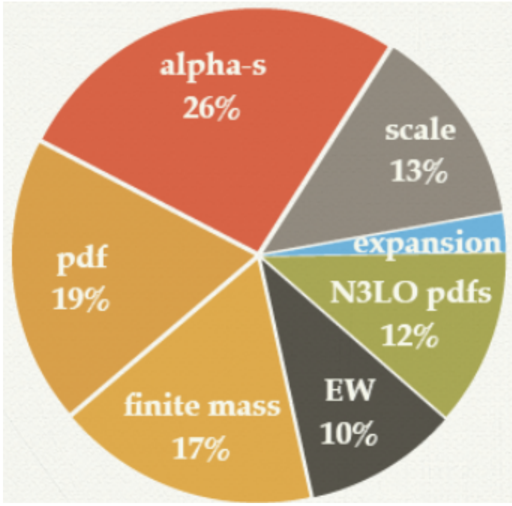
Theoretical Uncertainties

After N^{3}LO calculation of gluon-fusion Higgs cross section at 13 TeV → much reduced scale uncertainty

… largest sources of unertainty:

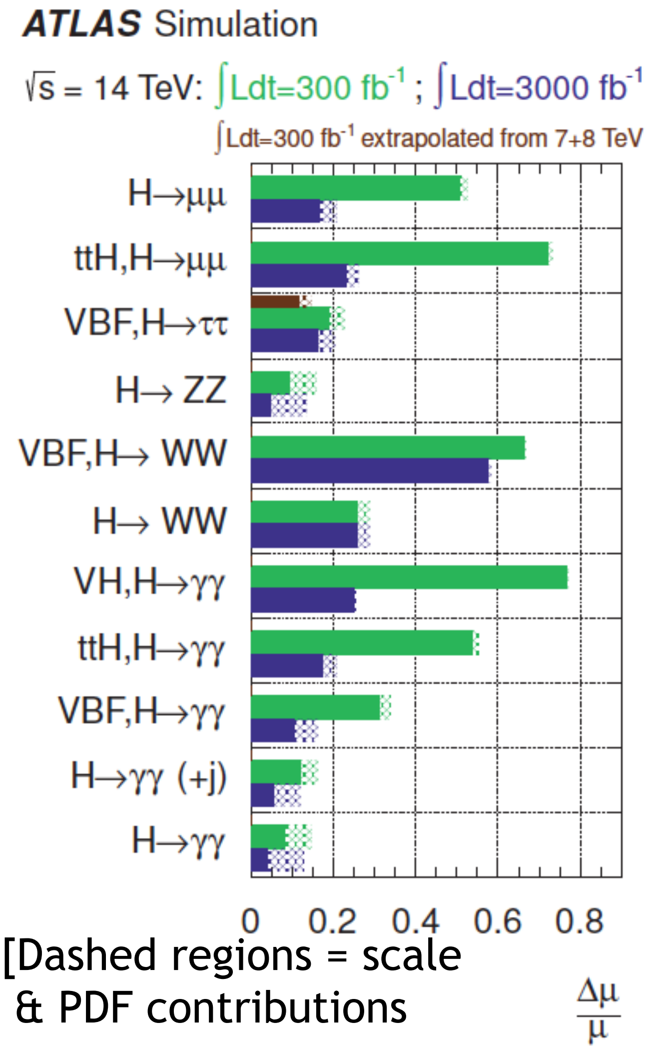
- PDFs [1.9%]
- α_s [2.6%]

with additional 1.2% uncertainty on non-availability of N^{3}LO PDFs



[Anastasiou et al [1503.06056], Dulat, CERN Dec ’15]

Projected Experimental Uncertainties



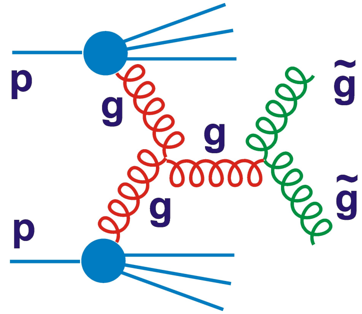
[Dashed regions = scale & PDF contributions]

… reaching this precision is a major legacy of HERA

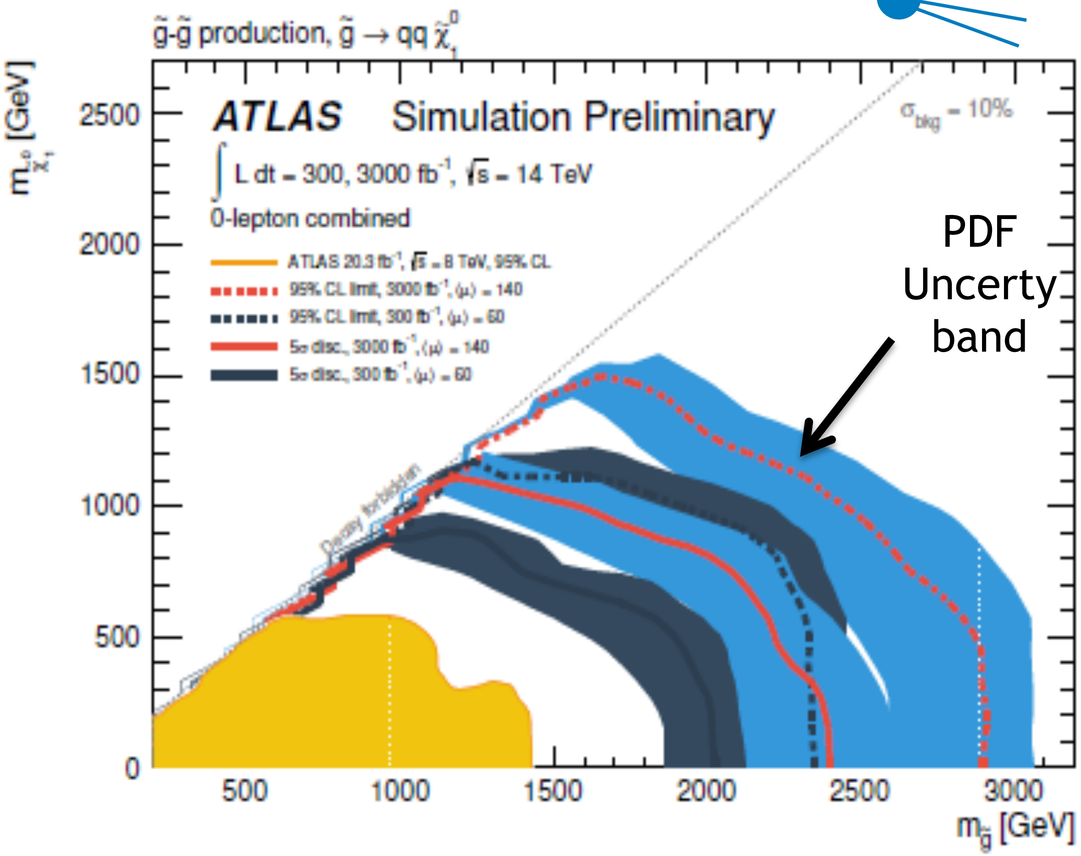
… much of Higgs sector becomes PDF limited in HL-LHC era …

PDFs → New High Mass LHC Particles

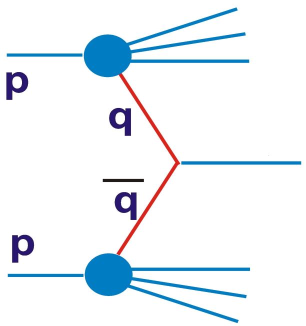
- Gluino pair signatures appear as deviations from theory, not resonances



- Both signal & background driven by high x gluon …
  → x-sec poorly known beyond 1 TeV



- For gluino pair at 1.5TeV, σ(13TeV)/σ(8TeV) > 40 …
  Already an issue in 2016



Similarly, BSM sensitivity through excess in high mass Drell-Yan limited by high x antiquark

HERA's Non-Legacy

Some of HERA's Limitations …

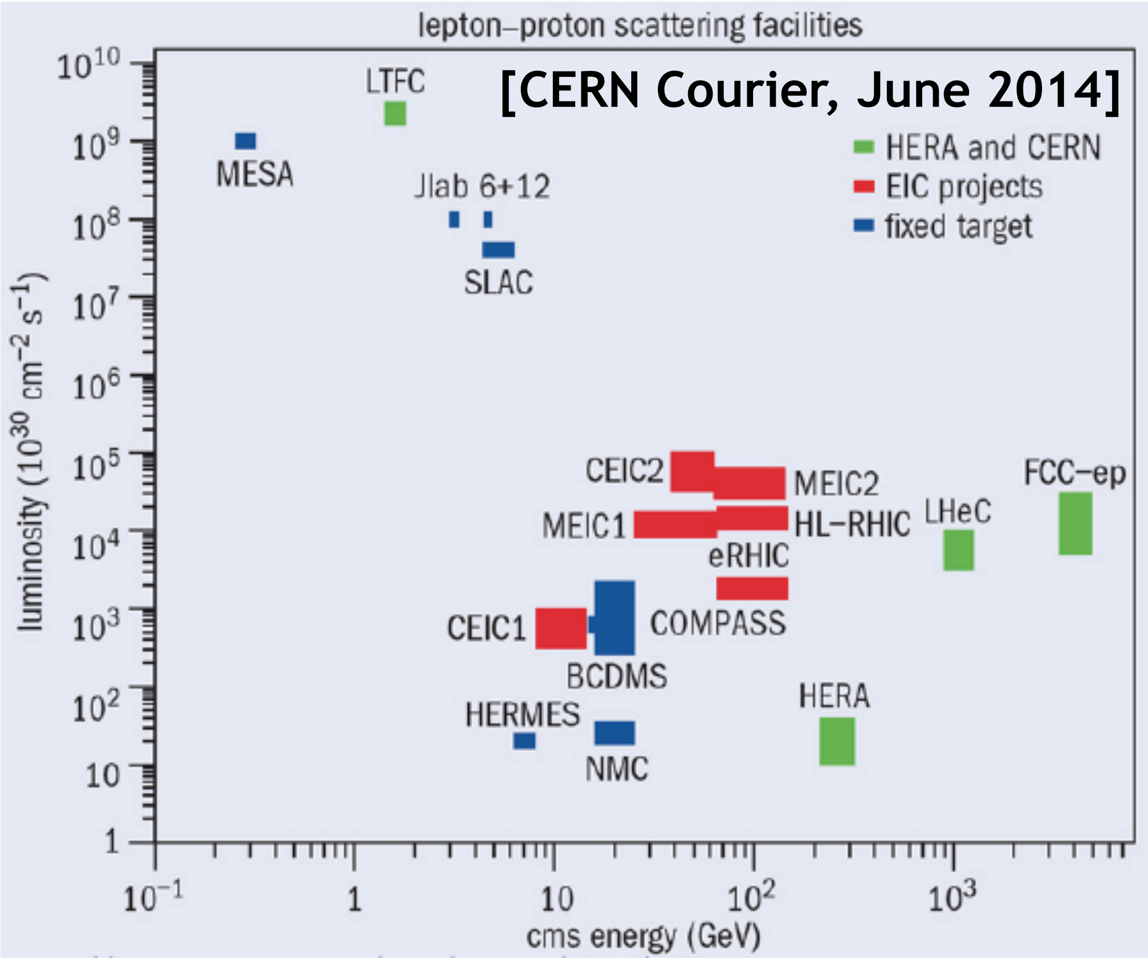
- Insufficient lumi for high x precision or searches
- Lack of Q^2 lever-arm restricts precision on low x for gluon
- Limited quark flavour info (no deuterons to separate u and d)
- Protons not polarised except HERMES
  (no access to spin, transverse structure at low x)
- No nuclear targets

ALL of these limitations are addressed by currently proposed future DIS projects in the USA and at CERN.

Needs strong support from the DIS community to have a chance of success (HERA was ~1000 at its peak).

Short summary follows - see parallel sessions for more …

Future DIS Facilities



EIC (eRHIC / MEIC): <~ 10 GeV electrons <~ 250 GeV polarised protons and ions

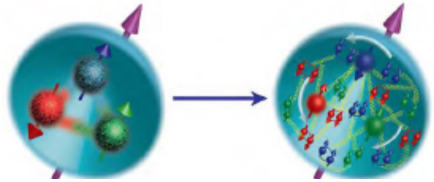
LHeC: 60 GeV electrons x LHC protons & ions

FCC-ep: 60 GeV electrons x 50 TeV protons from FCC (now @ Roma)

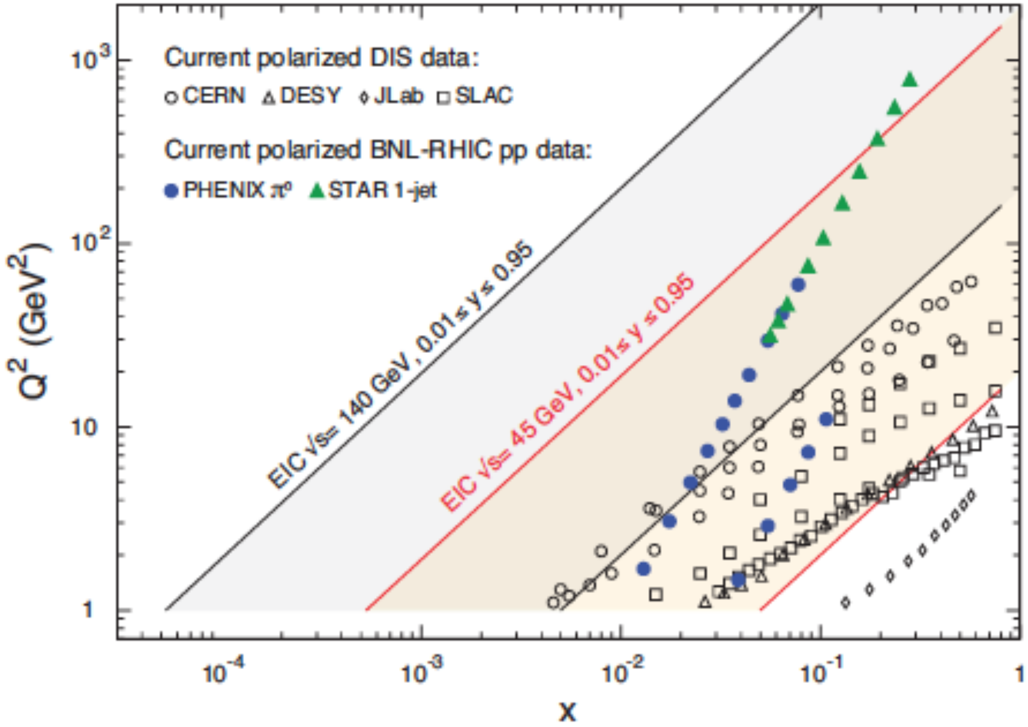
All @ lumi ~10^{34} cm^{-2}s^{-1} … very significant increase over HERA

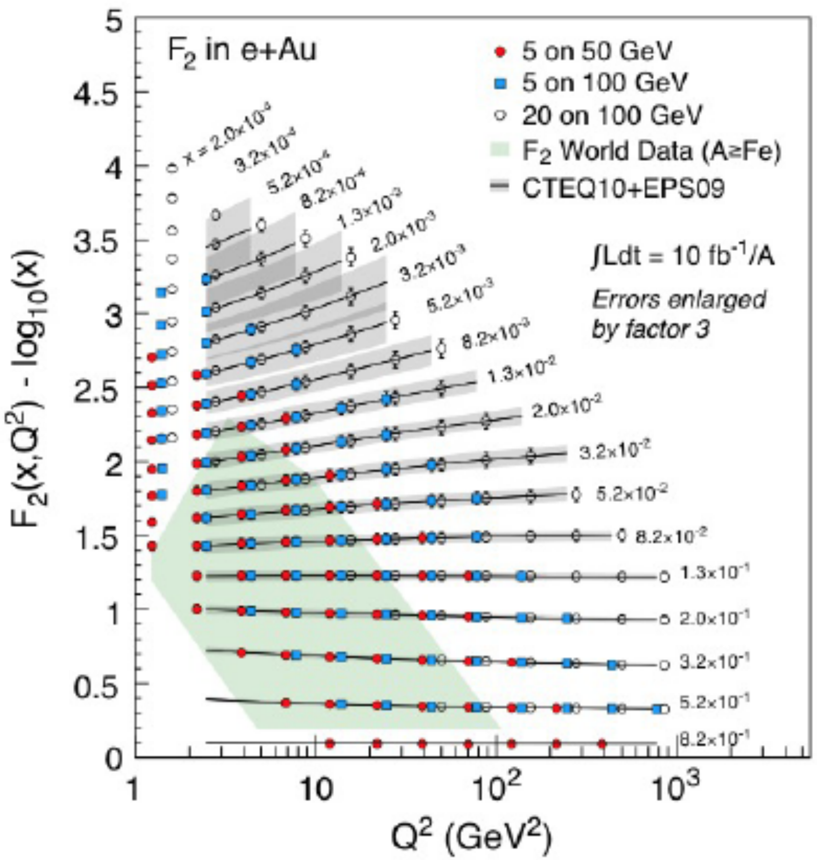
EIC: White paper 2012, Construction Recommendation NSAC Long Range Plan 2015, User Group 2016, DIS'16 pre-meet
LHeC: CDR 2012, ongoing CERN-sponsored working group, Presented to ECFA 2015 + on NuPECC (long-term) roadmap

EIC Physics



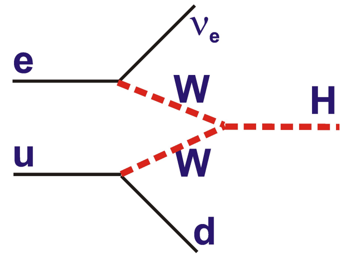
Polarised hadrons → DIS spin puzzle and 2+1D proton structure tackled in unprecedented low x regime

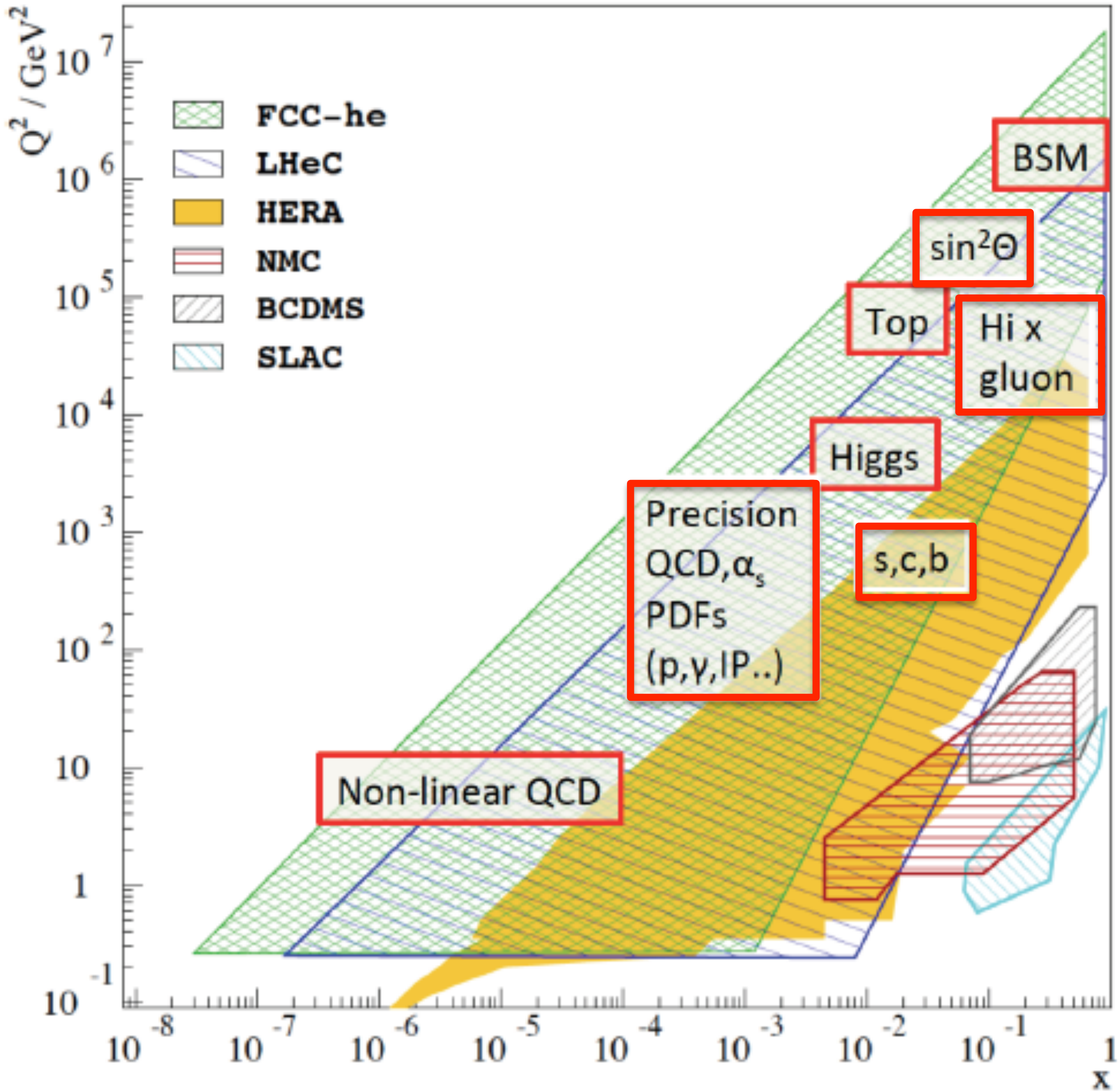




Wide range of ions and large step in eA kinematic range
→ Nuclear parton densities
→ Potential access to low x sat'n
→ Struck partons in cold nuclear matter

LHeC Physics





- Substantial Higgs programme

- Revolutionary p PDF (& α_s) precision improves LHC sensitivity to Higgs and new physics

- Elucidates low x dynamics in ep & eA

- 4 orders of mag. in kinematic range of nuclear structure

A HERA Legacy Summary

"Alright, but apart from:
- precisely measuring parton densities for LHC rapidity plateau
- providing a precision testing ground for QCD calculations
- showing how to handle diffractive processes in QCD
- opening the way to a new field of low x physics
- pointing the way on photon structure, hadronisation corrections, underlying event, jet substructure, BFKL searches …
- publishing over 500 papers
- training 1000s of young people
- leaving behind data, preserved in case we need it in the future …

Another Summary

"To achieve great things, two things are needed: a plan and not quite enough time"
[Leonard Bernstein]

Thanks to many H1 and ZEUS colleagues for inspiring, educational and fun times over >20 years.

Thanks to A Cooper-Sarkar, M Klein, T Ullrich, M Wing and many others from whom I borrowed talk material