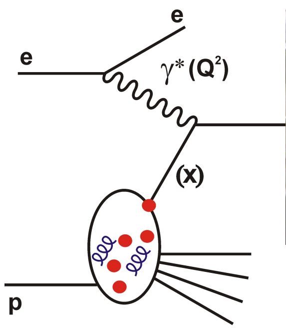
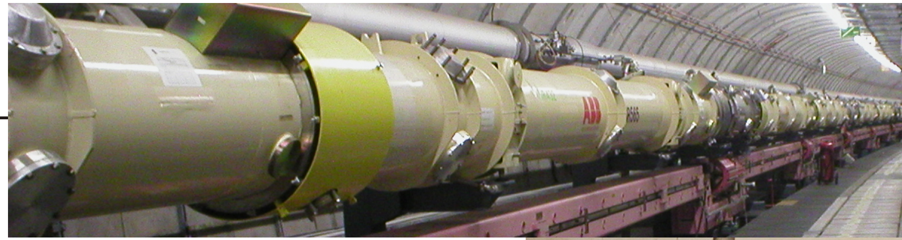
DIS16
DESY, HAMBURG 11-15 APRIL 2016





The HERA Legacy

Paul Newman
(University of Birmingham)

PER ARDUA AD ALTA

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:

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

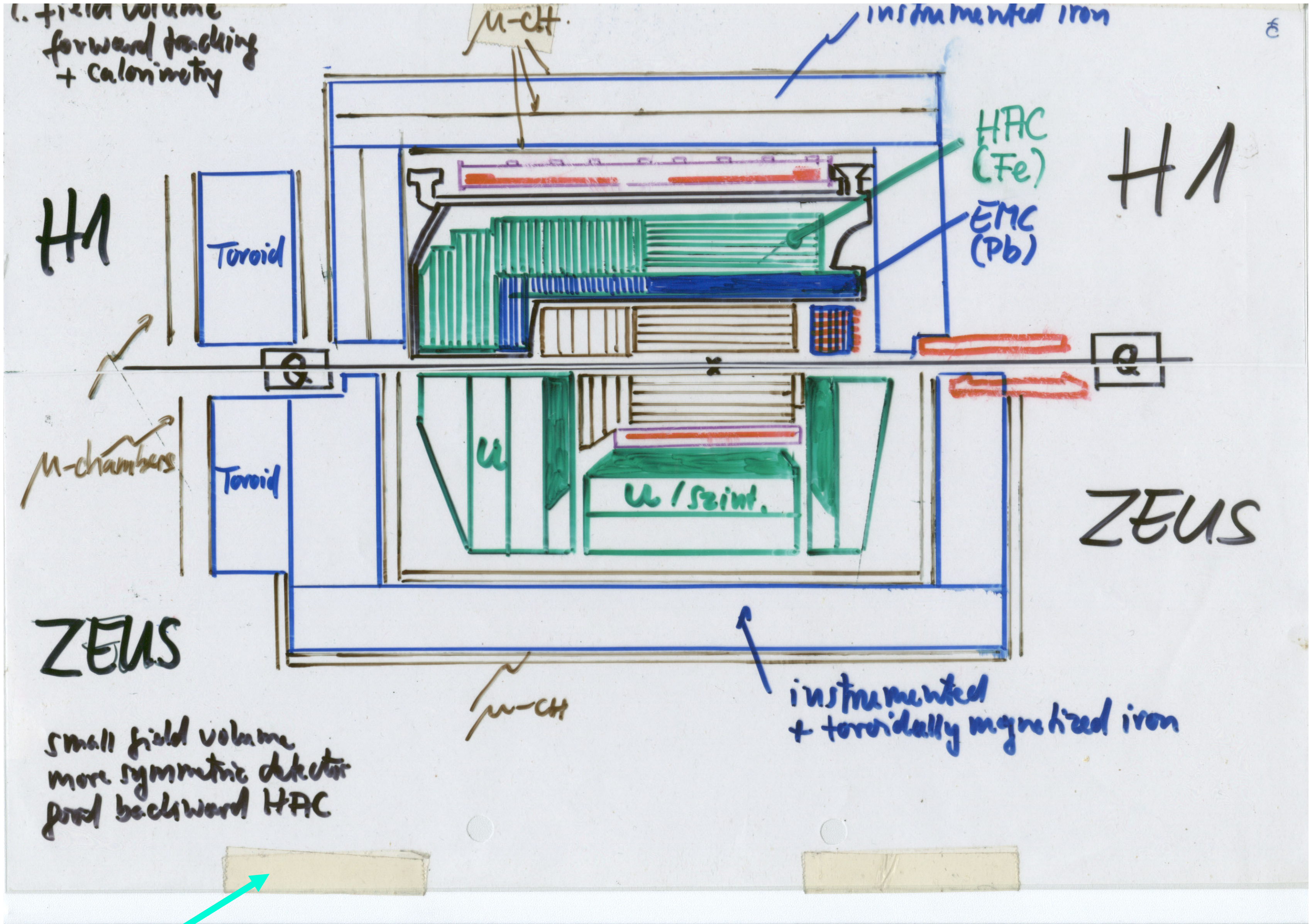
- ~0.5 fb^{-1} per exp't
- Both lepton charges and polarisations
- Additional ~25 pb^{-1} @ E_p = 575, 460 GeV

- 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

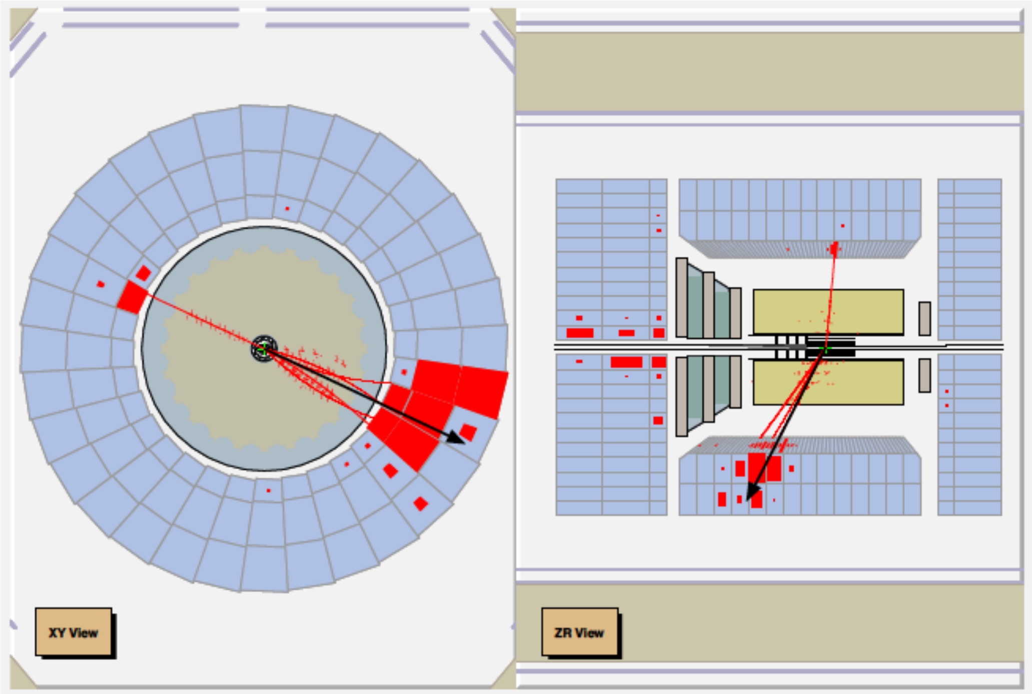
A period that included the digital revolution

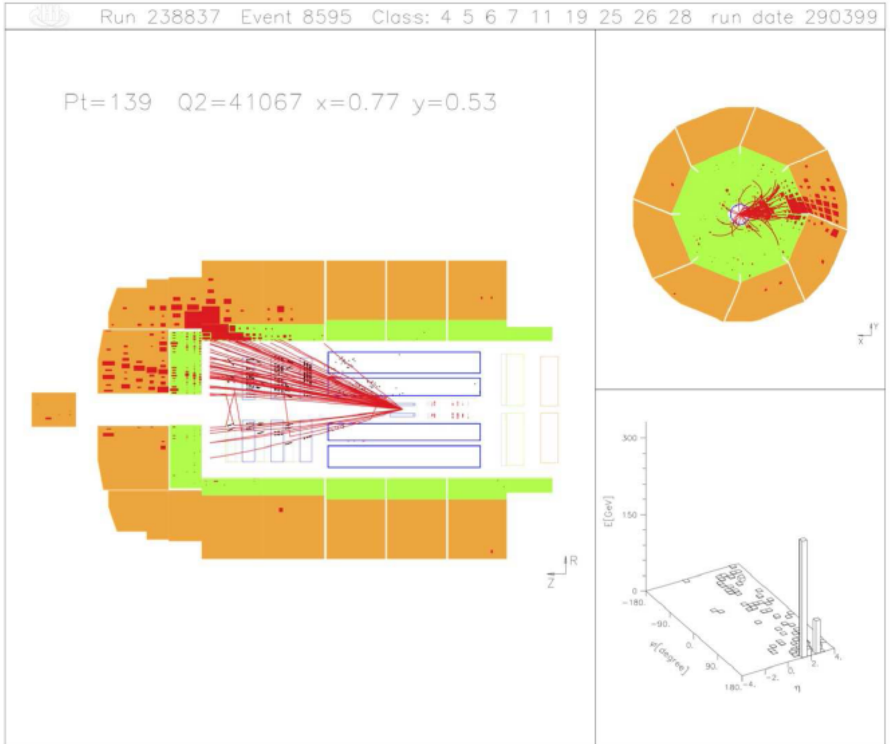


User defined animation

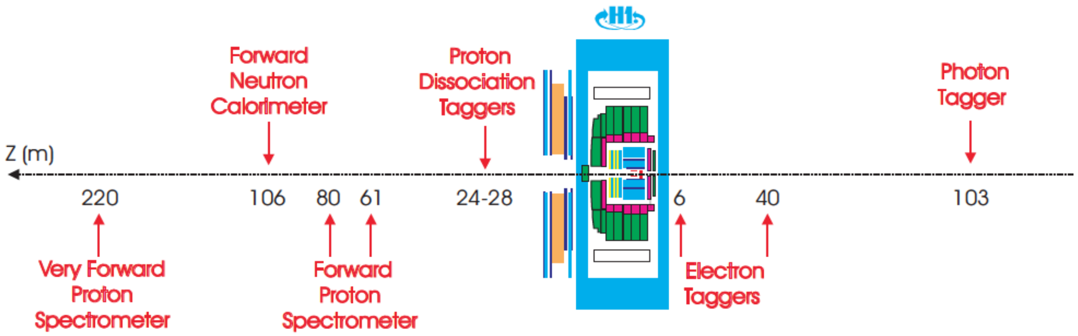
[F Eisele, ~ 1986]

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

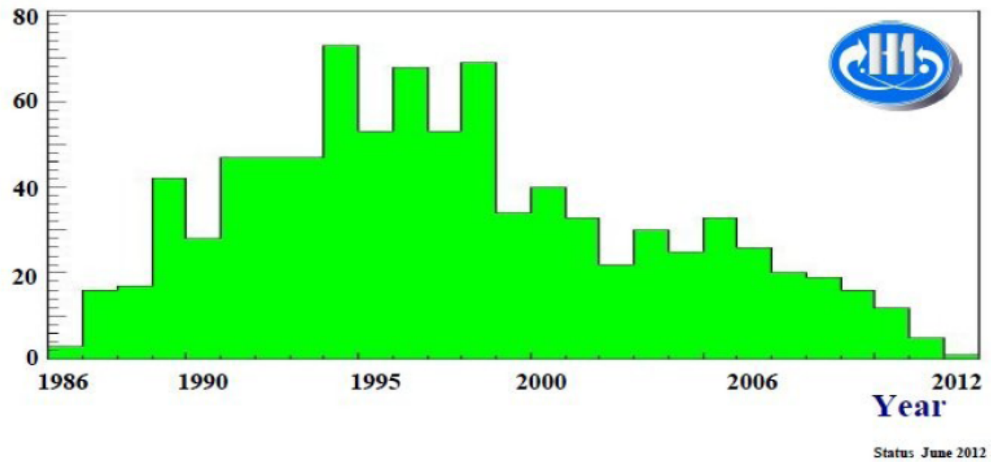
The Paper Legacy

~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.

883 PhD and Diploma Theses
Statistics 1986 - 2012



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

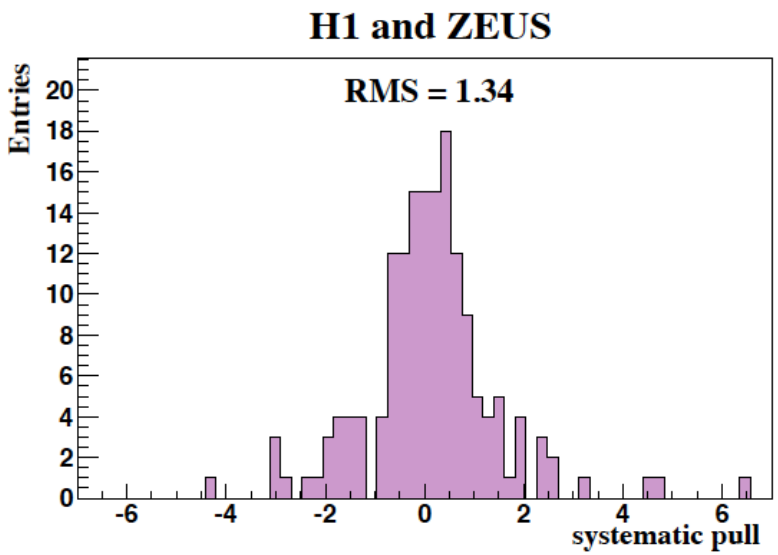
Combination of measurements of inclusive deep inelastic $e^{\pm}p$ scattering cross sections and QCD analysis of HERA data

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

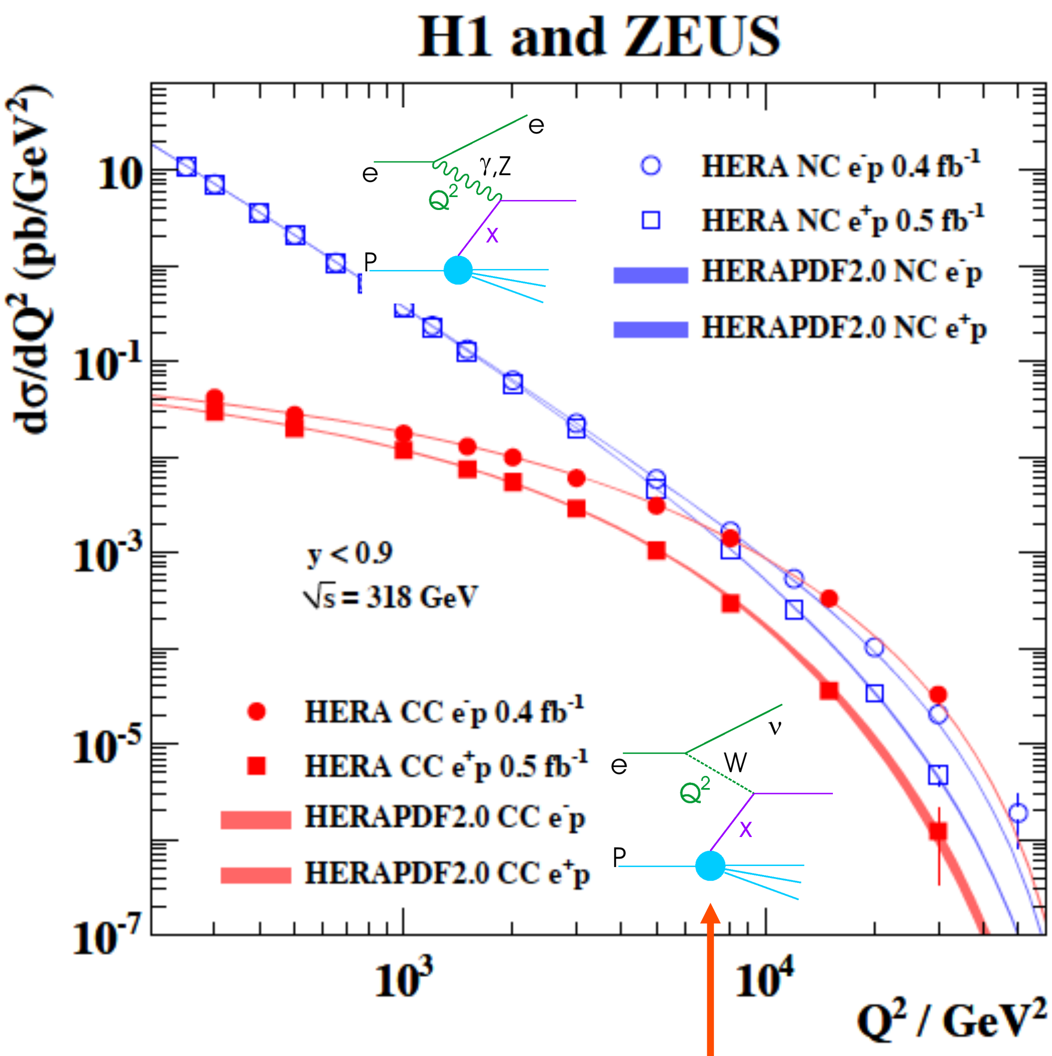
- Data span 6 orders of mag in x / Q^2 [$0.045 < Q^2 < 50000$ GeV^2]
- 41 data sets with 2927 input data points
- Combined into 1307 final points ($\chi^2 = 1687 / 1620$)
- 162 sources of correlated systematic error allowed to float



- Beyond √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)

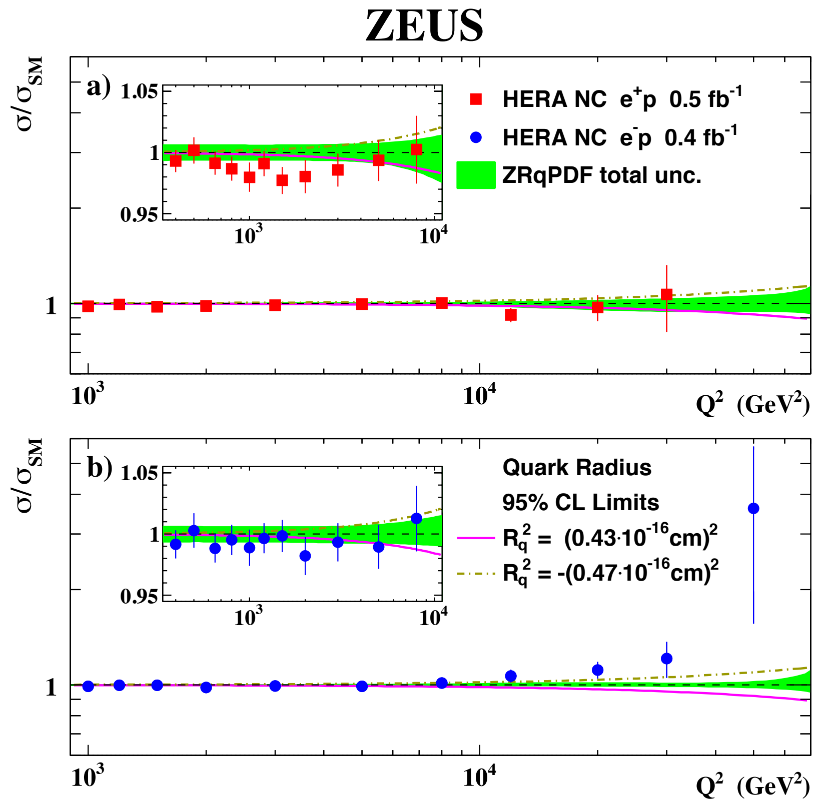
- Parton density info encoded in σ_{NC} and σ_{CC}

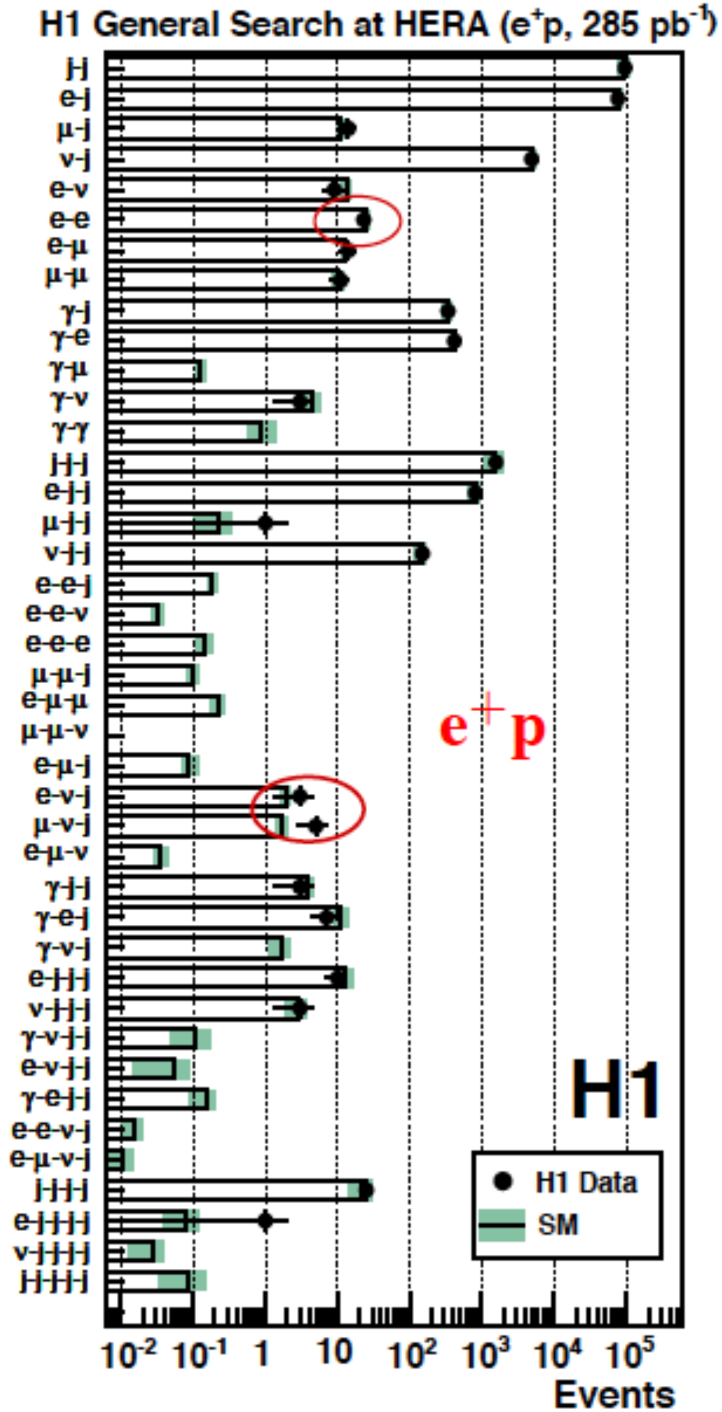
Legacy of Testing the SM

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 x 10^{-18} m

[ZEUS analysis using combined HERA Data]

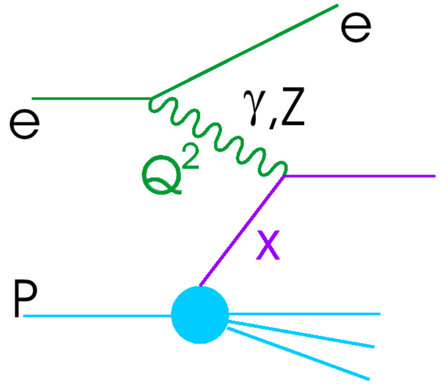


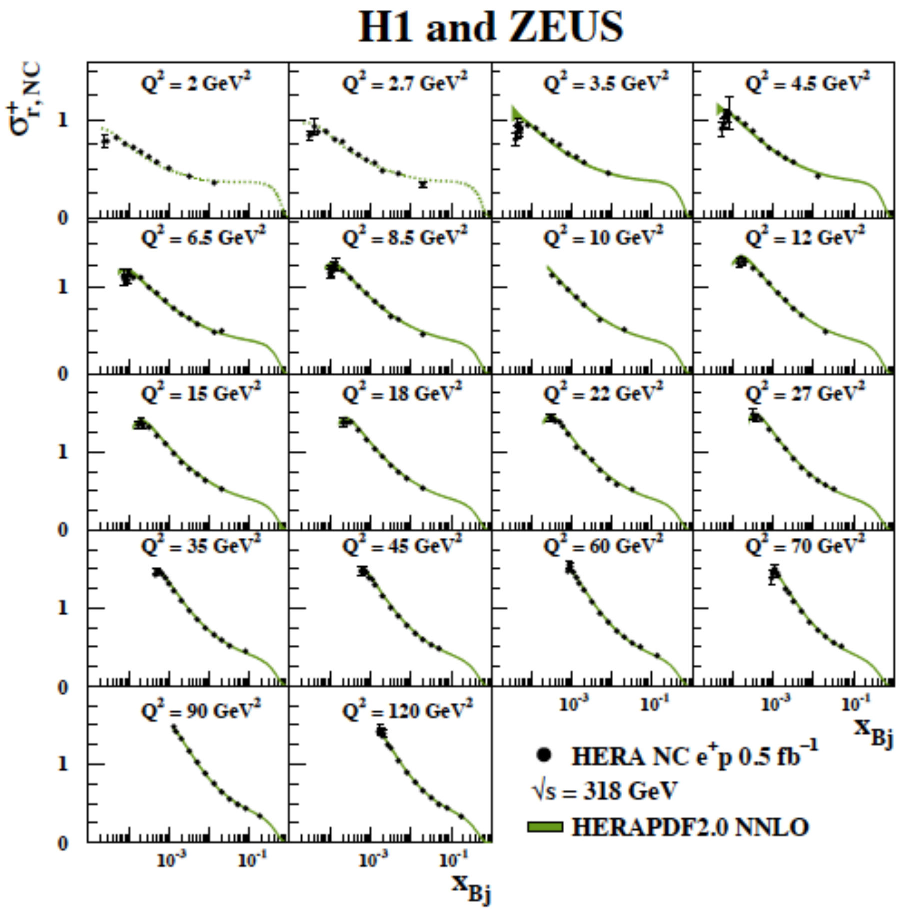


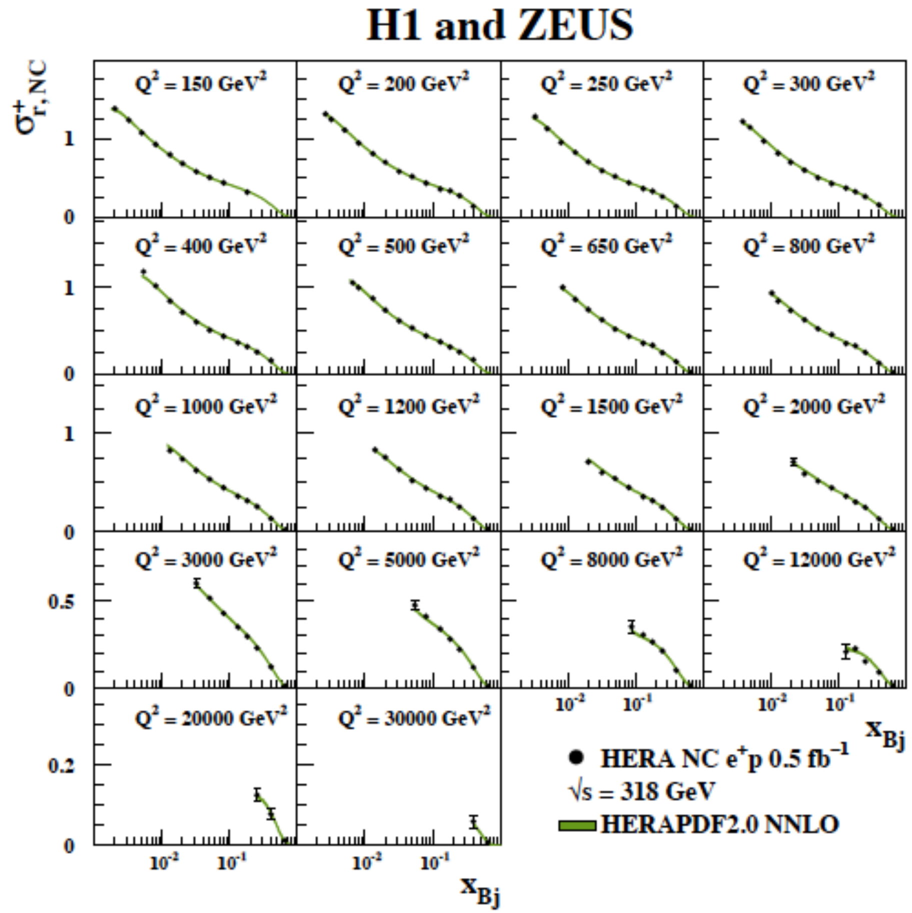
Neutral Current Data (e^+p only)

- 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

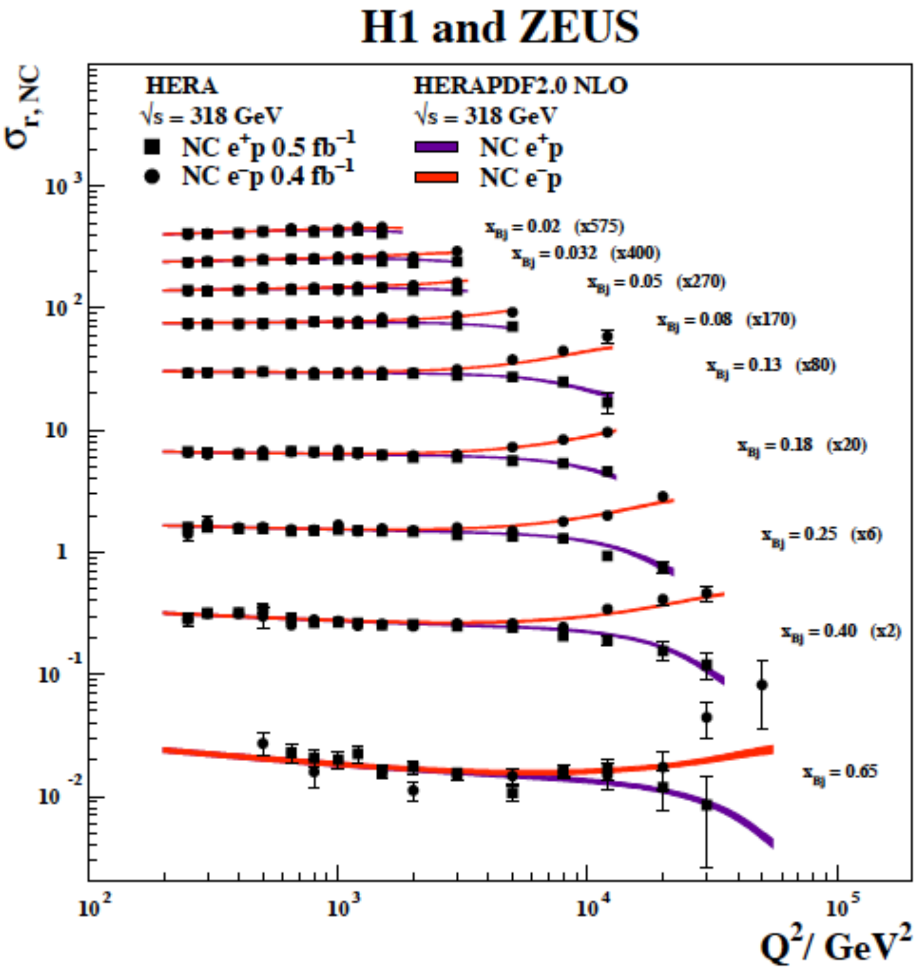




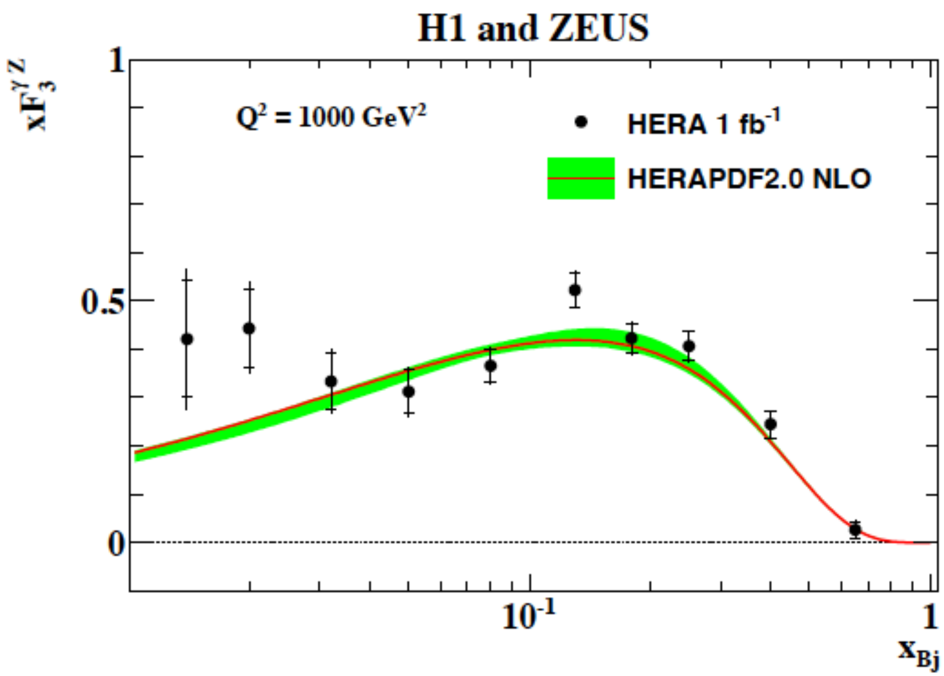


- plus dedicated low Q^2 datasets ($0.045 < Q^2 < 1.5$ GeV^2)
- plus reduced proton beam energy data → F_L …

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

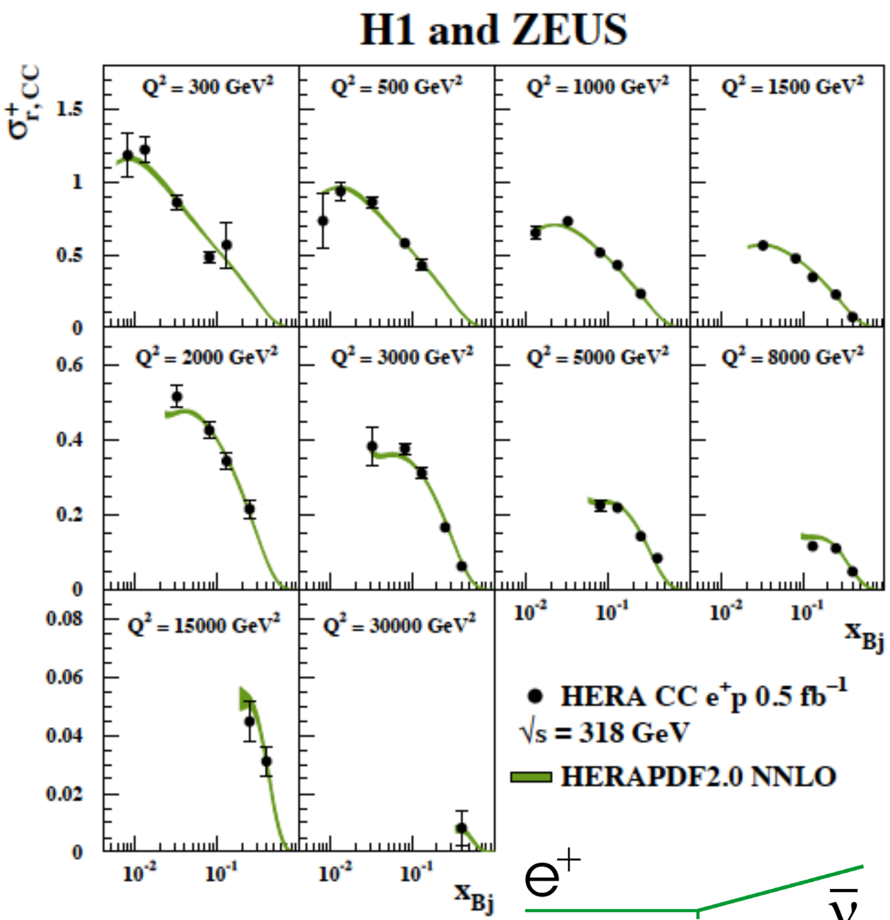


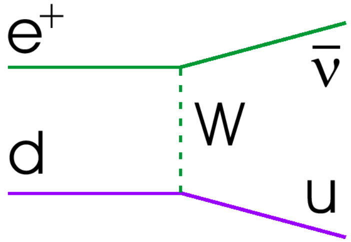
- Difference between e^-p and e^+p NC cross sections at large Q^2 measures $xF_3^{\gamma Z}$ structure function …
- Interference between γ and Z exchange
- Minimal scale dependence → interpolate to Q^2 = 1000 GeV^2



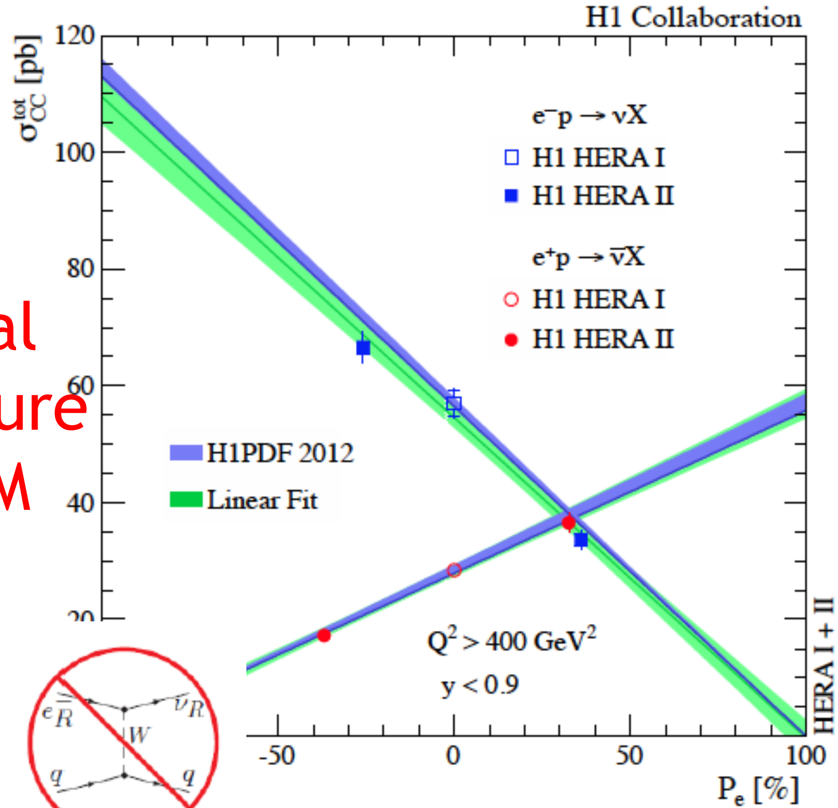
… Direct sensitivity to **valence** quarks (incl low x)

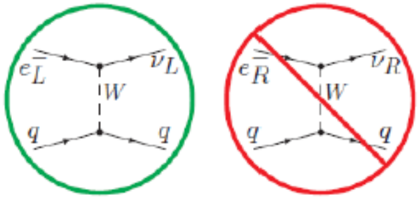
Charged Current Data





Chiral structure of SM





Electroweak Parameters

e.g. with M_W fixed to PDG:

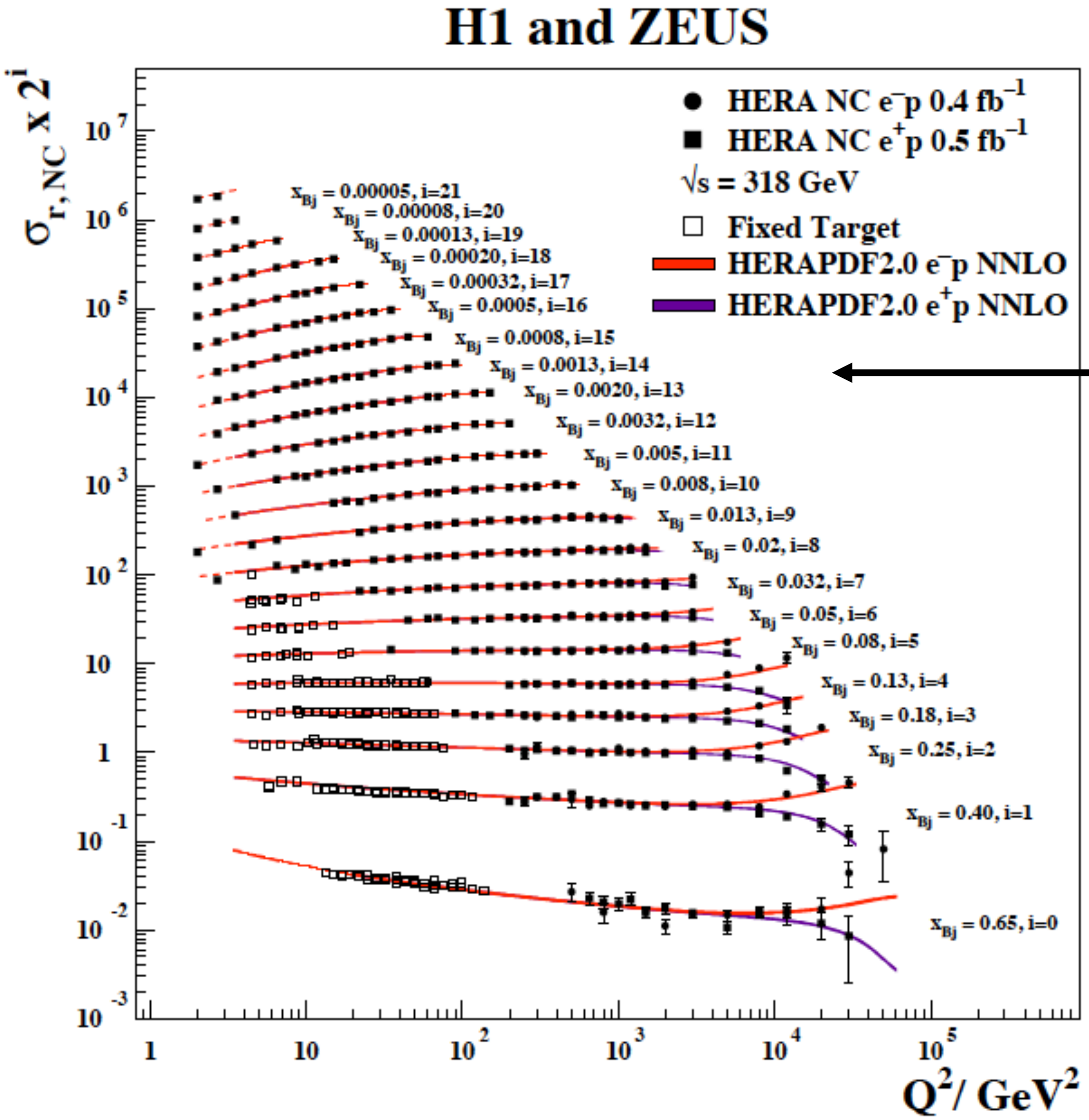
$$\sin^2\theta_W = 0.2252 \ \pm 0.0011 \ \text{(experimental/fit)}$$

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

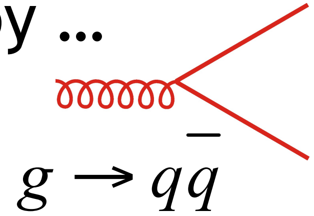
[ZEUS electroweak fit using ZEUS pol + ZEUS & H1 unpol data]

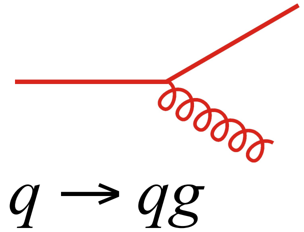
Charged current sensitive to **flavour decomposition …**
e.g. e^+p constrains **d** density

QCD Evolution and the Gluon Density



NC Q^2 dependence driven by …

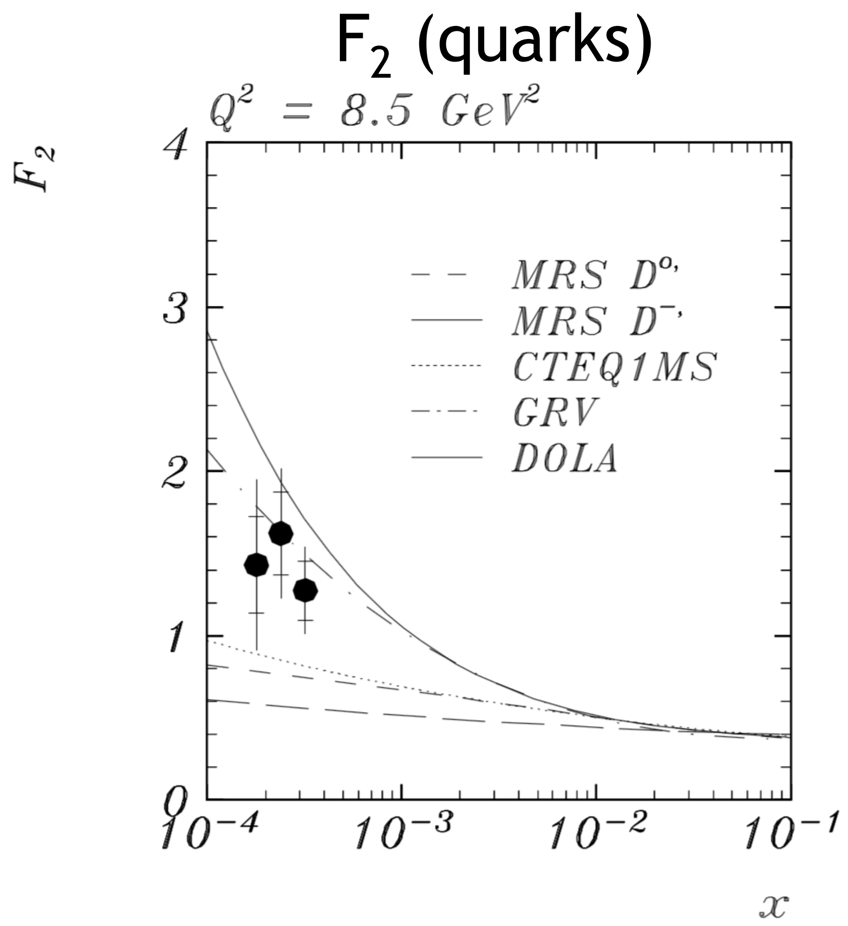


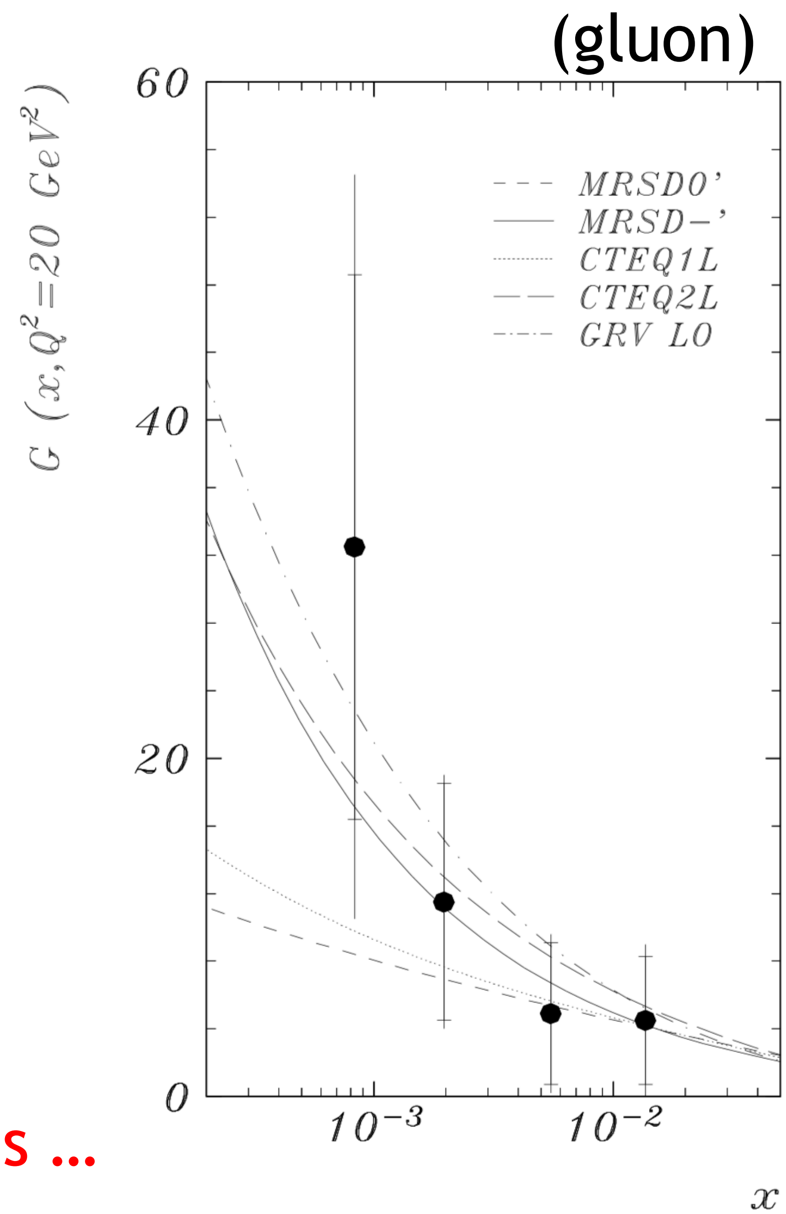


… QCD fit description over vast range

- 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

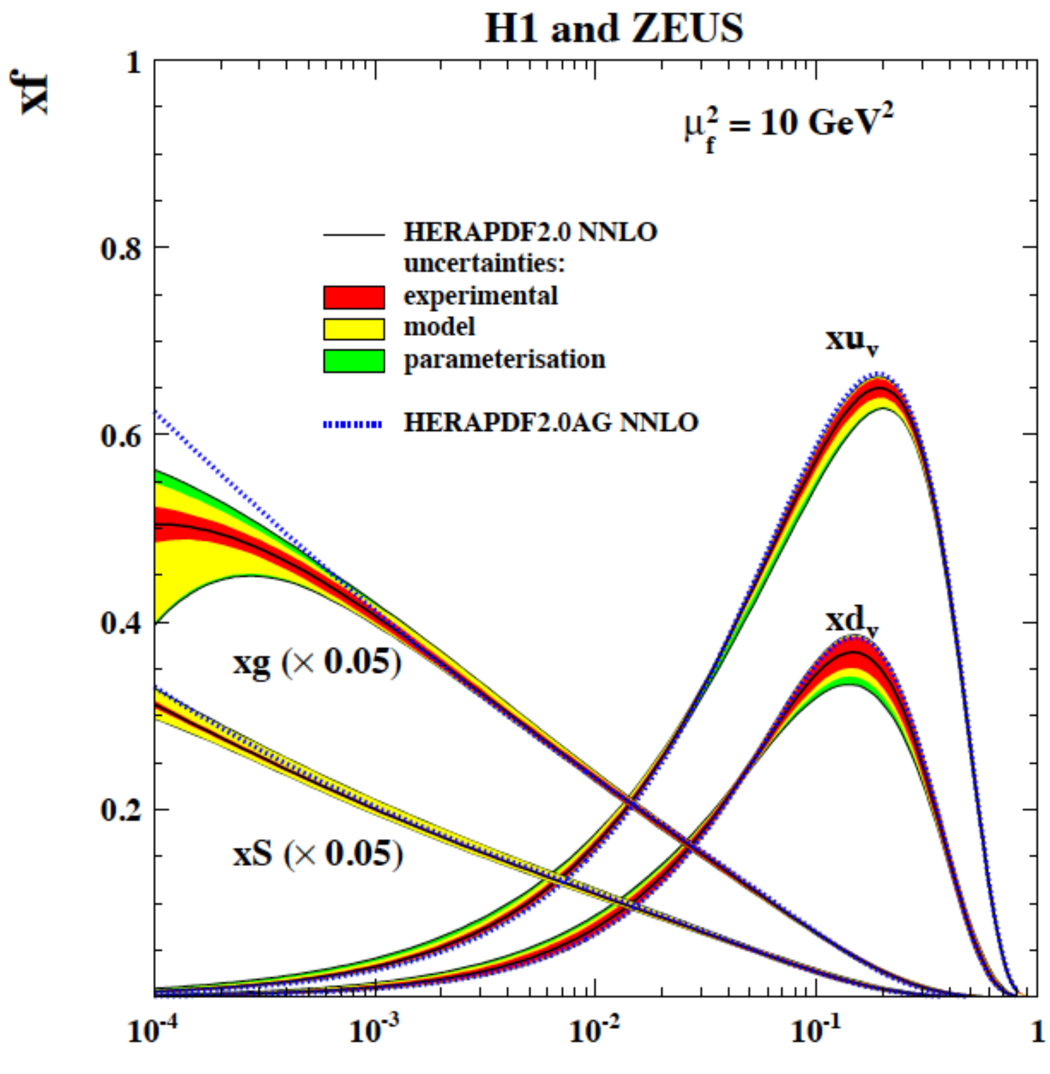




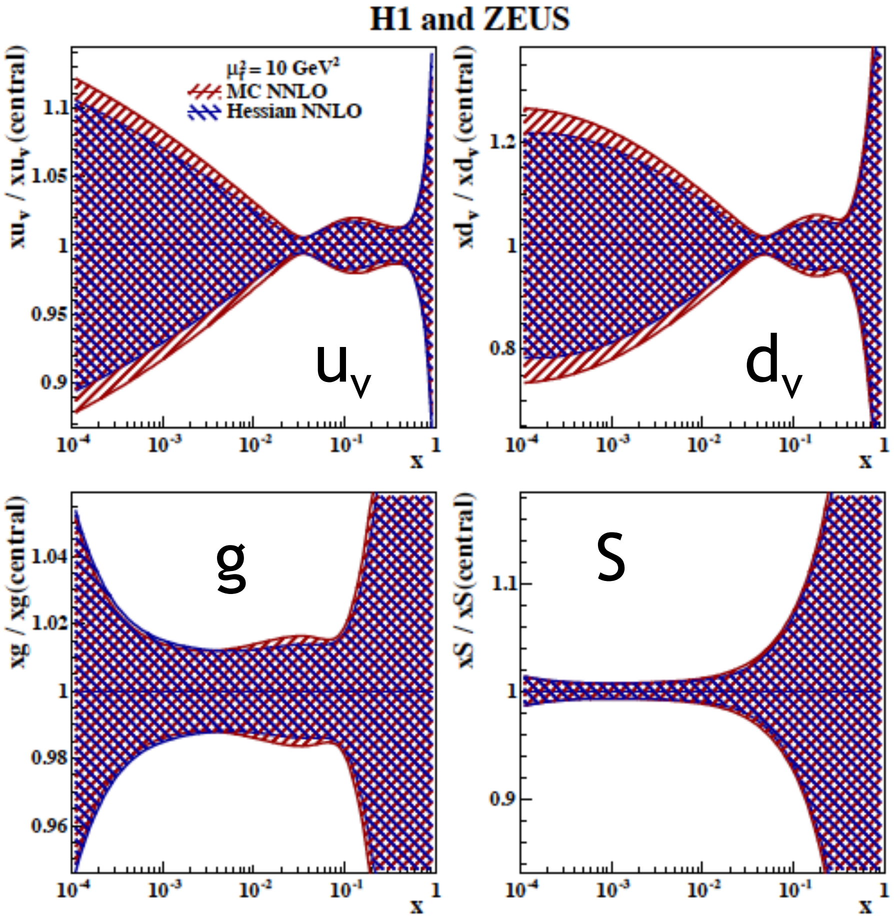
H1 – 1992 data (22.5 nb^{-1})
compared with early variants
of some popular parameterisations …

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

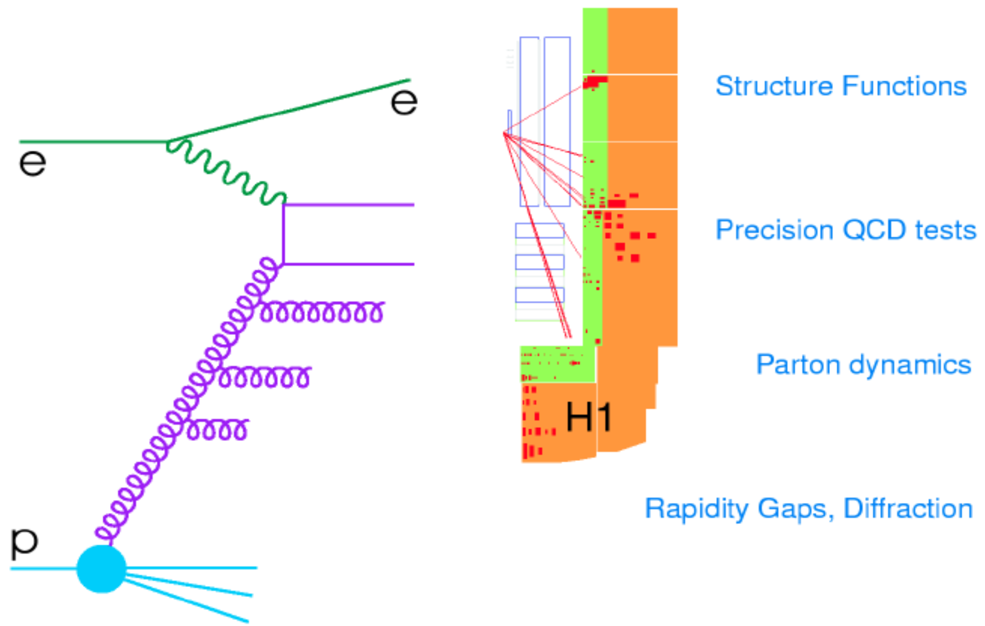
herøism
a



[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

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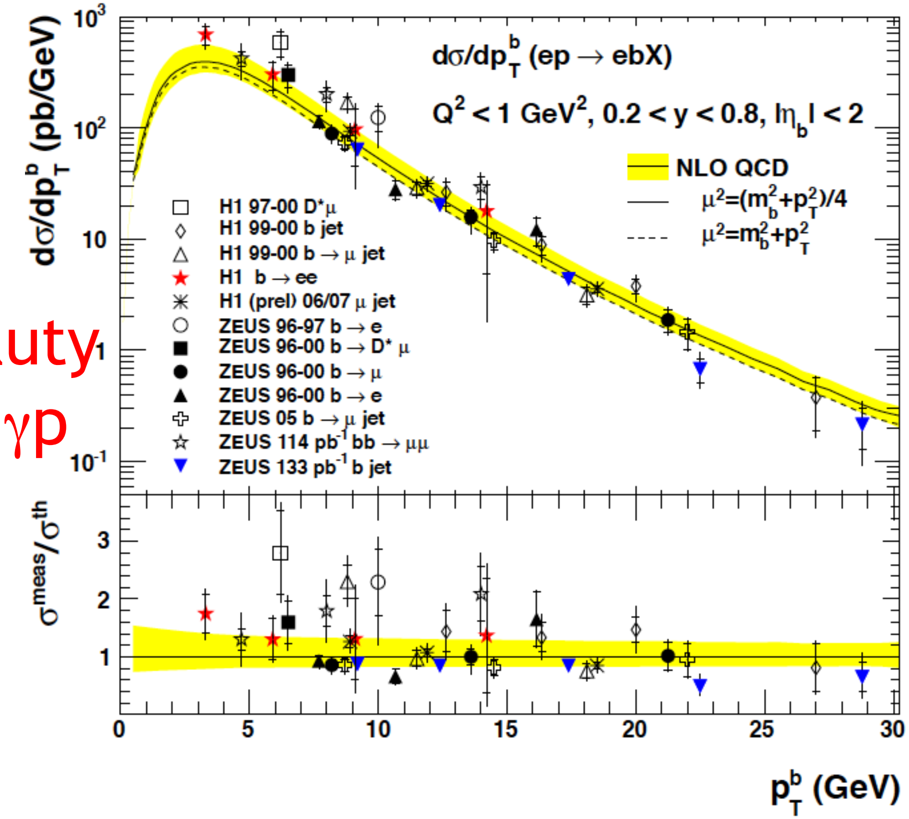
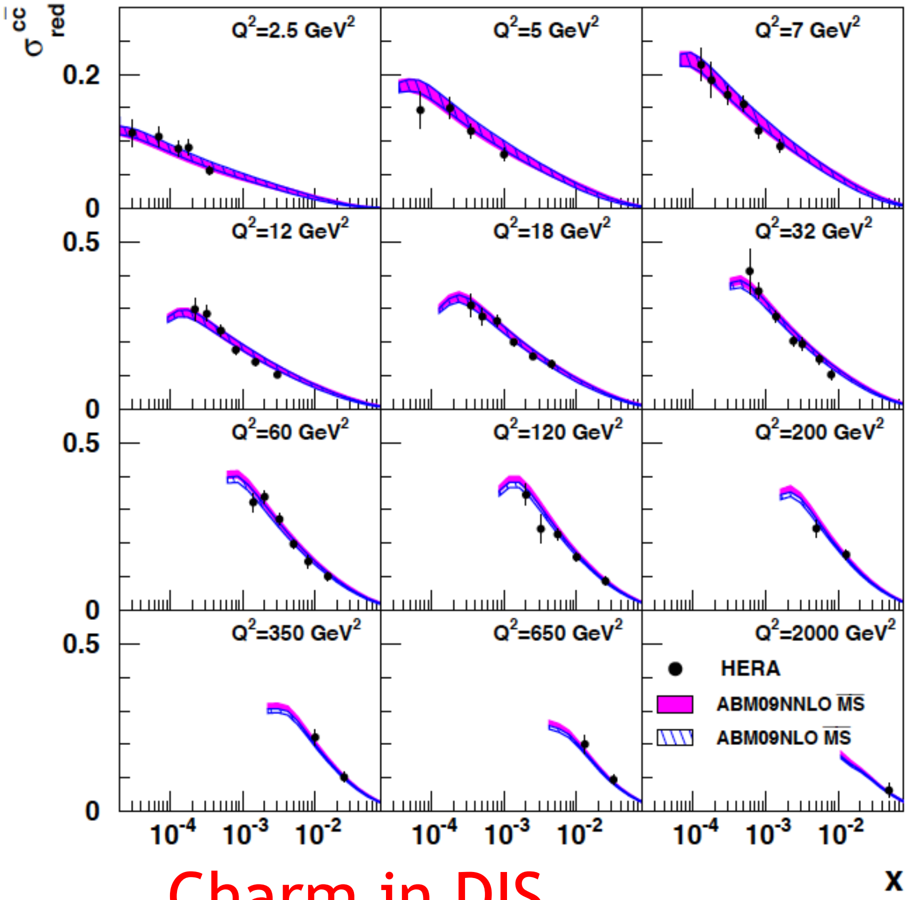
(Dated: January 15, 2014)

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

High Precision Heavy Flavour Data

Beauty in γp





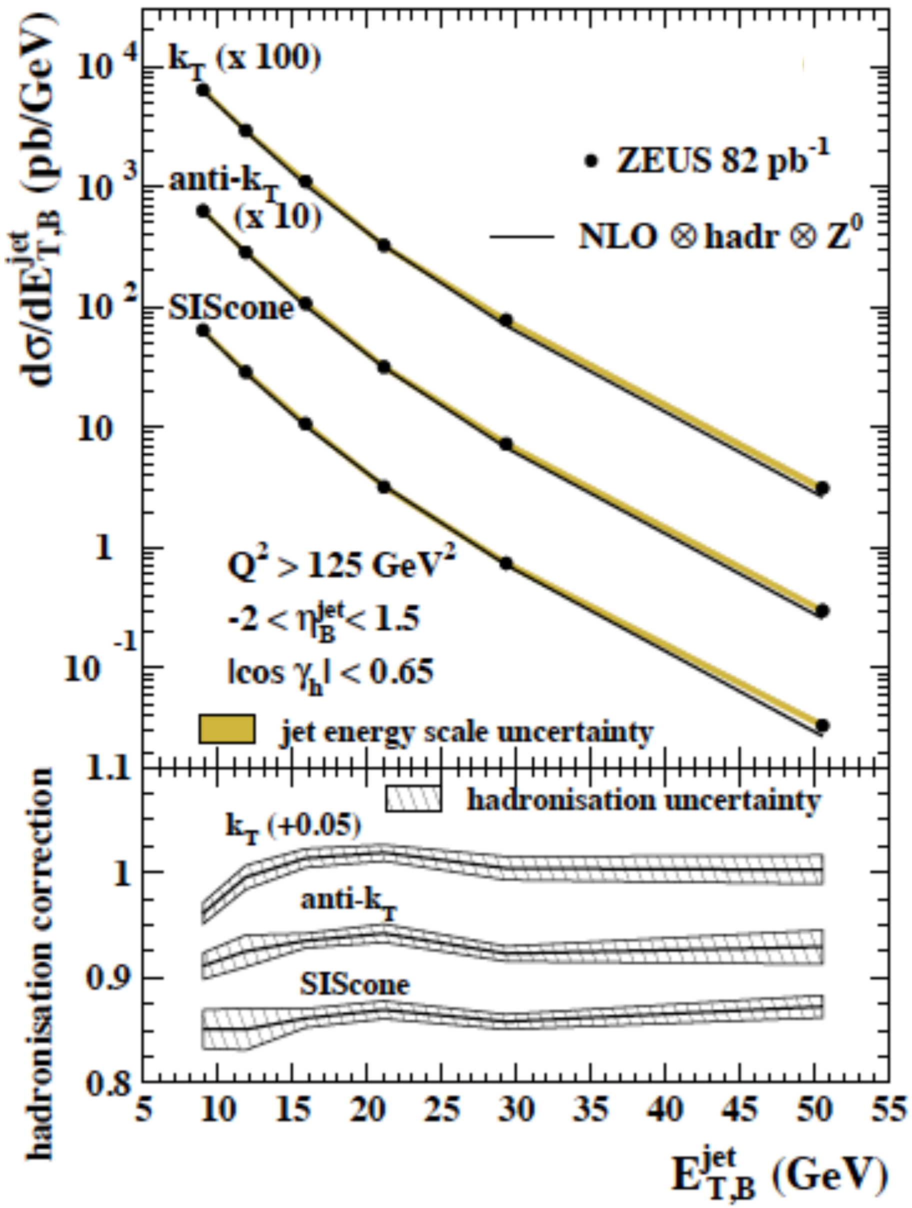
Charm in DIS

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

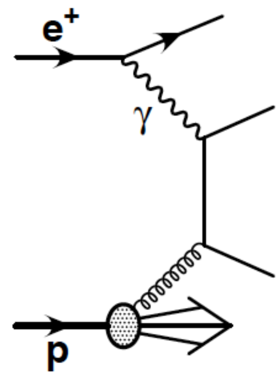
- Clear presentation of charm and beauty contribution to σ(NC)

-Testing ground for development of heavy flavour schemes in QCD

High Precision Jet Data in DIS



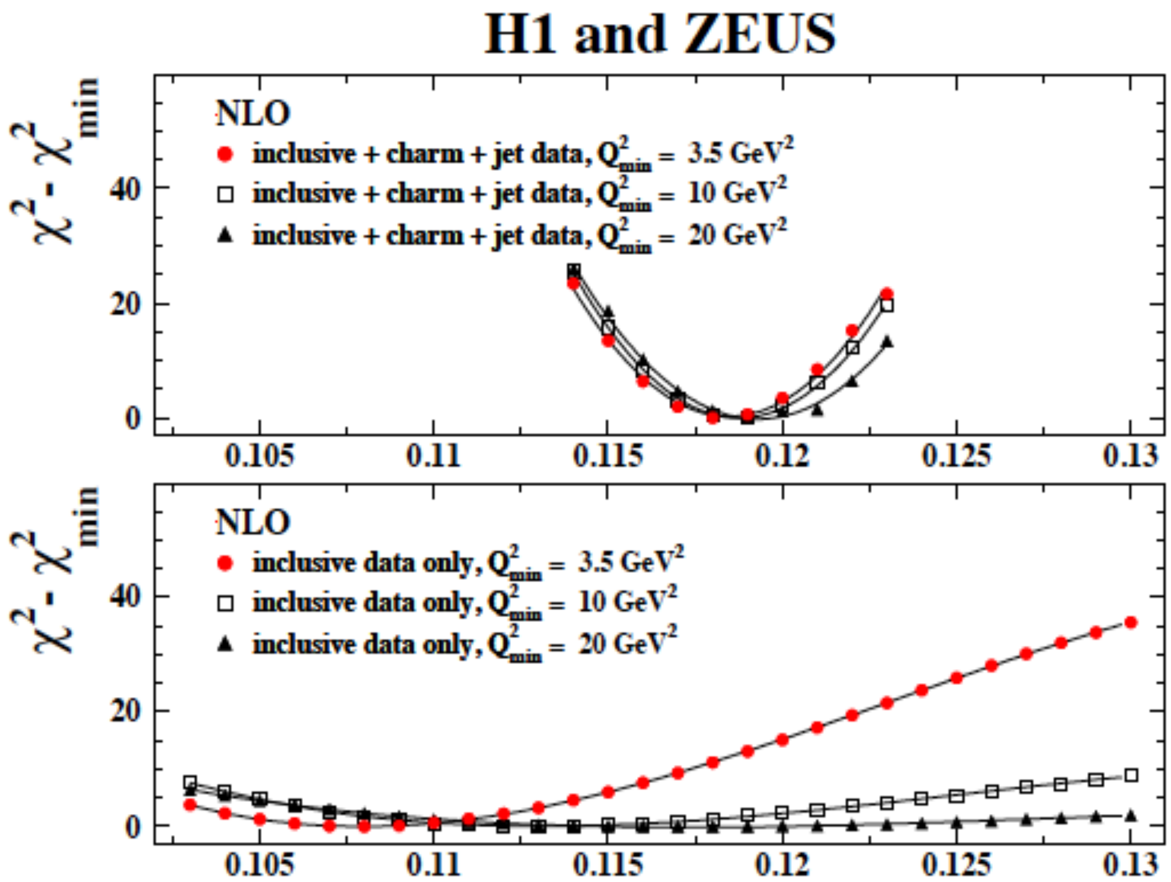
- Excellent agreement with QCD over wide kinematic range.
- Sensitive to gluon density in lowest order
- Role in benchmarking jet algorithms



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

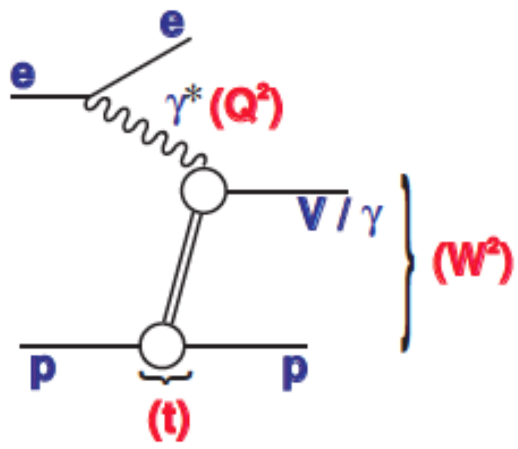


Including jet and charm data in HERA-II fits allows simultaneous α_s (and m_c) without significant impact on PDFs

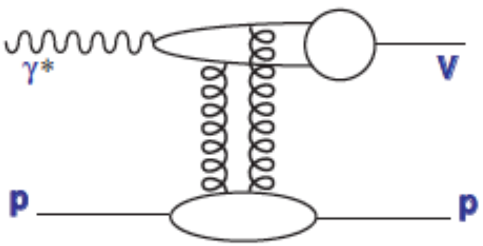
$$\alpha_s(M_Z^2) = 0.1183 \pm 0.0009(\text{exp}) \pm 0.0005(\text{model/parameterisation}) \pm 0.0012(\text{hadronisation}) \ ^{+0.0037}_{-0.0030}(\text{scale}) \ .$$

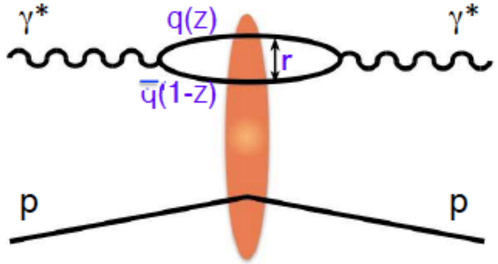
- Experimental errors << theory scale variation
- Competitive result and good agreement with world average

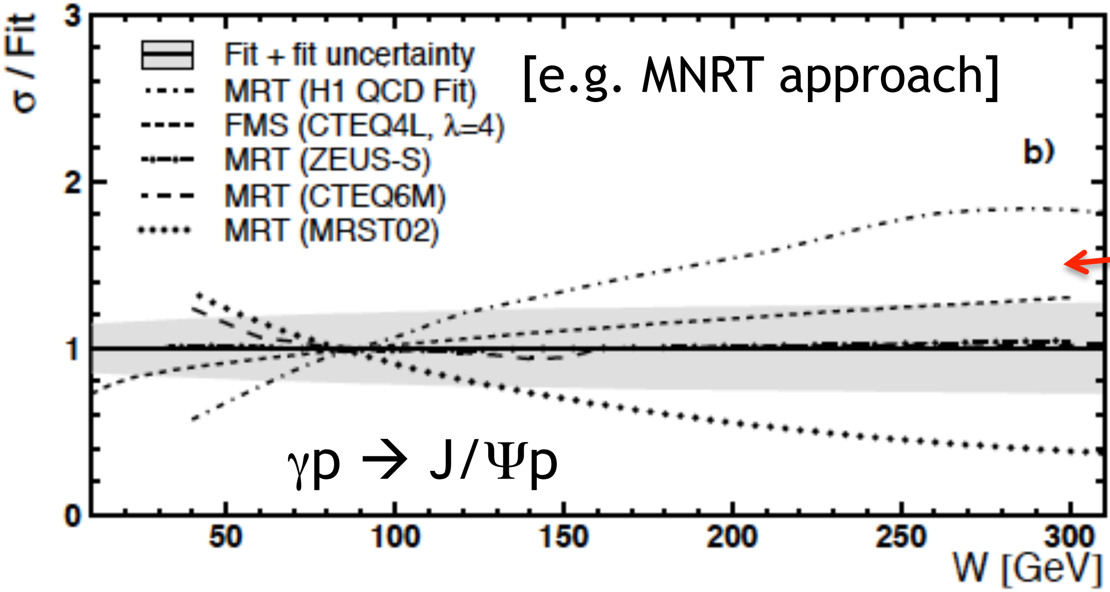
Perturbatively Calculable Exclusive Vector Mesons!

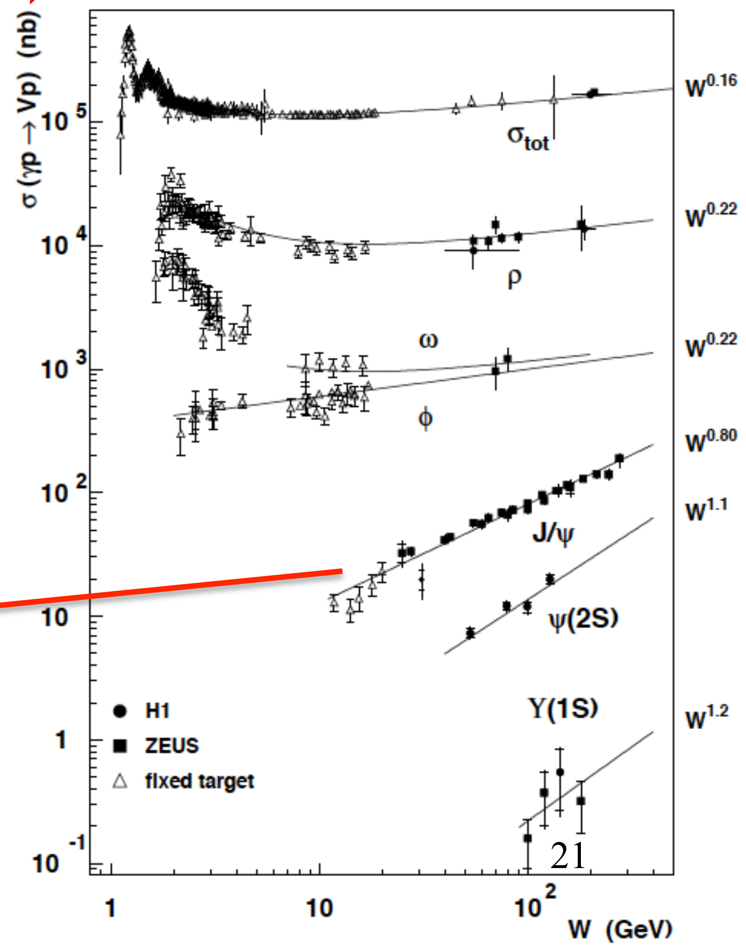


- Capability to switch pQCD on or off by varying hard scale (Q^2 or $M_V{}^2$)
- Hard processes calculable starting from proton PDFs (or colour dipole + proton x- section)

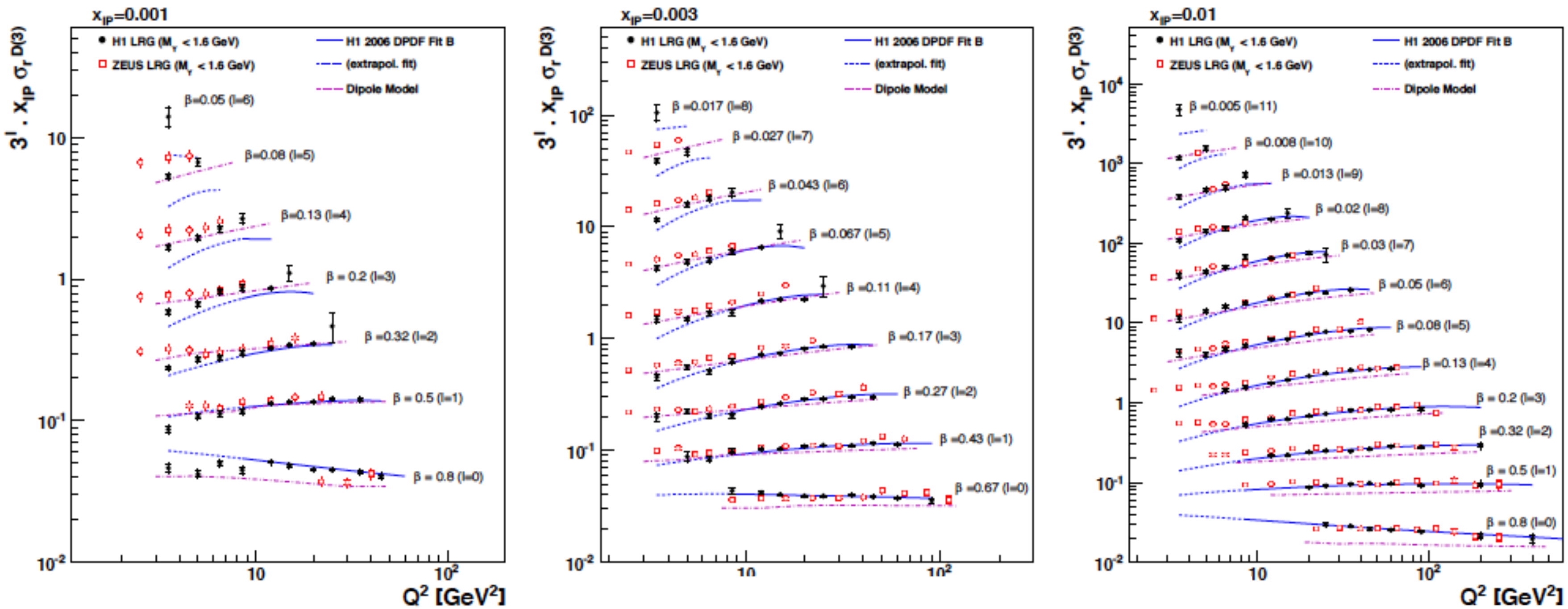




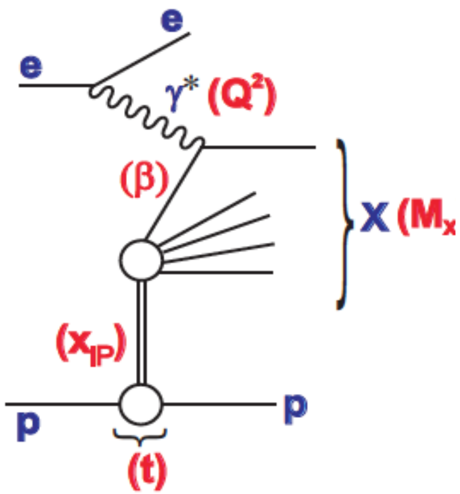


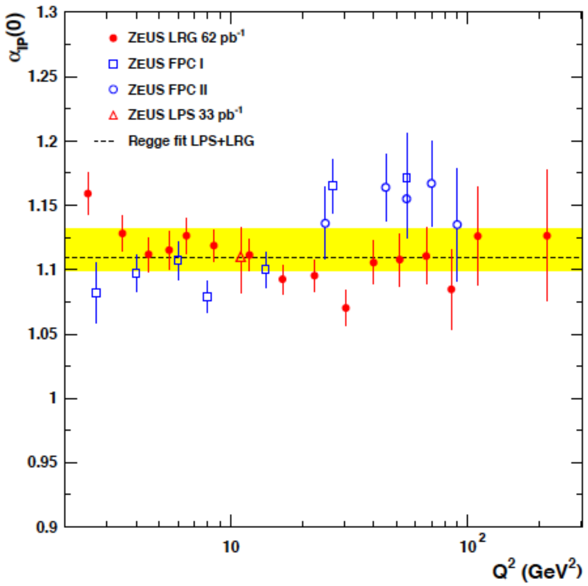


Three (even four) -fold Differential Diffractive X-Sections / Structure Functions



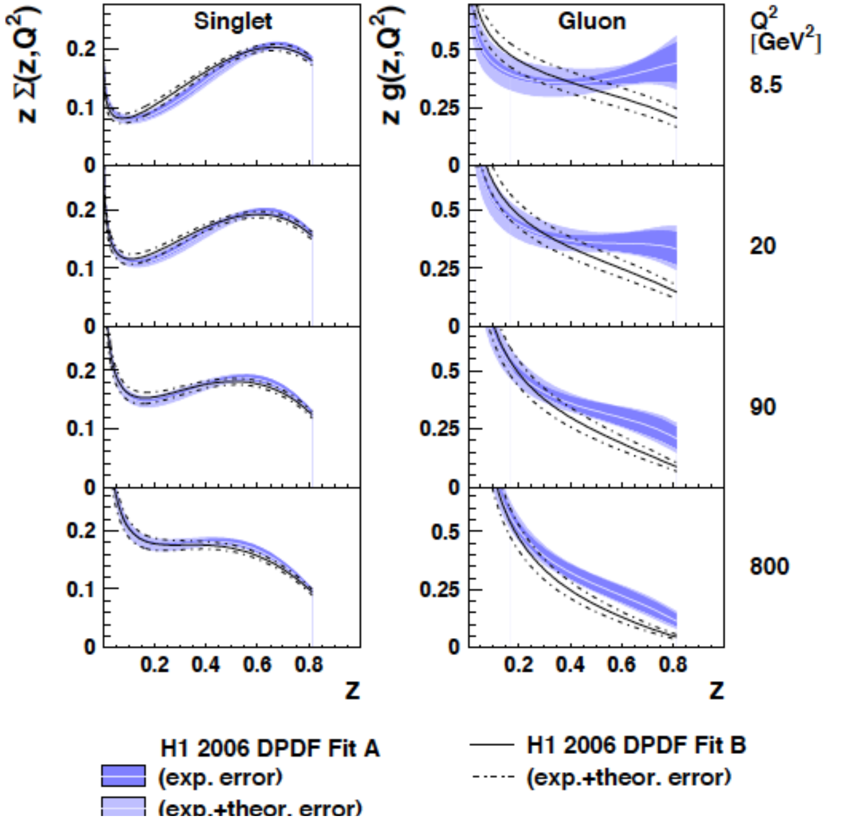
Diffractive process with excitation to continuum of masses contributes ~10% of low x cross section

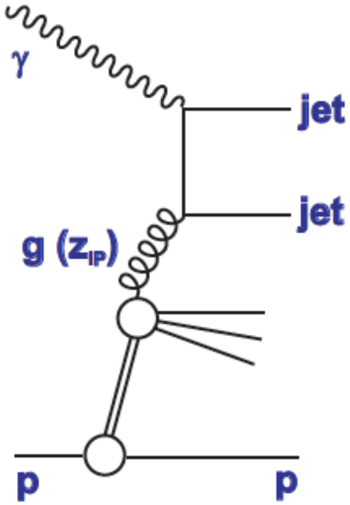


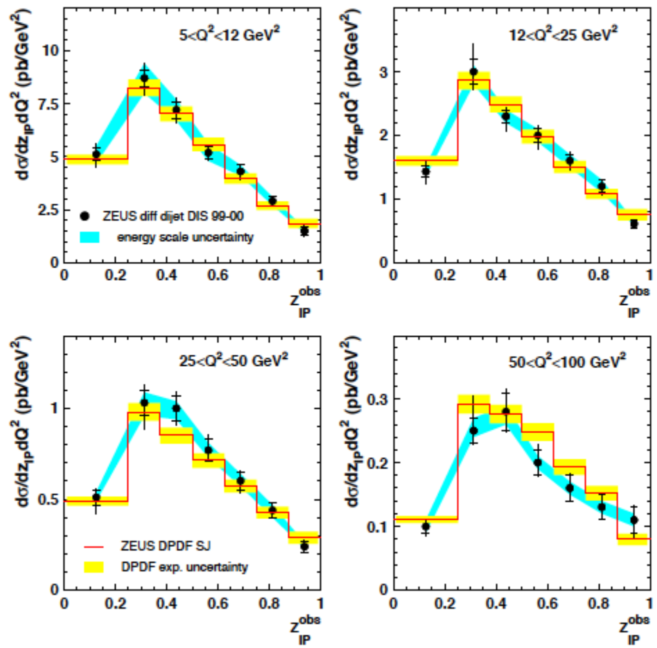


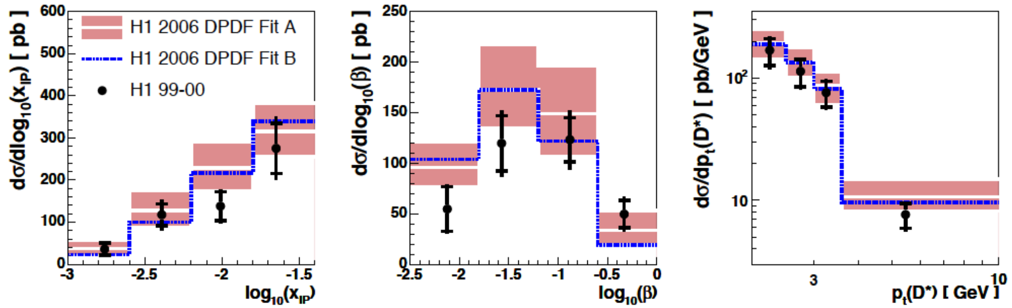
- The soft stuff factorises!
- Looks remarkably like a soft pomeron!

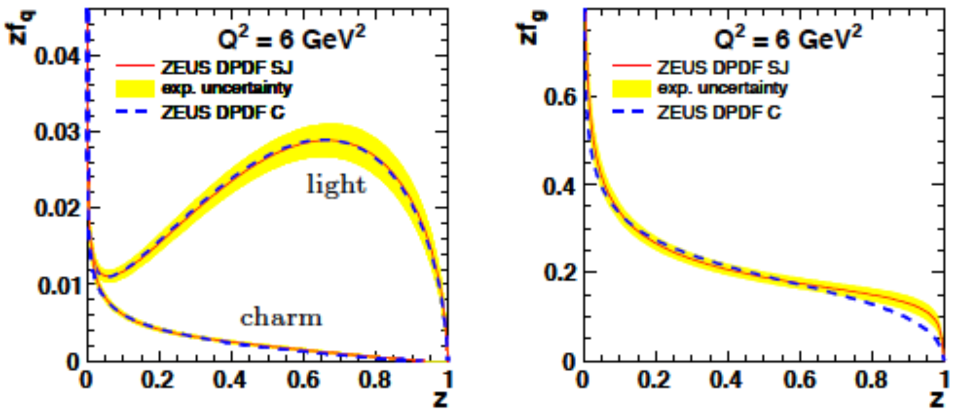
Diffractive Parton Densities Describing Everything in Final State Diffractive DIS





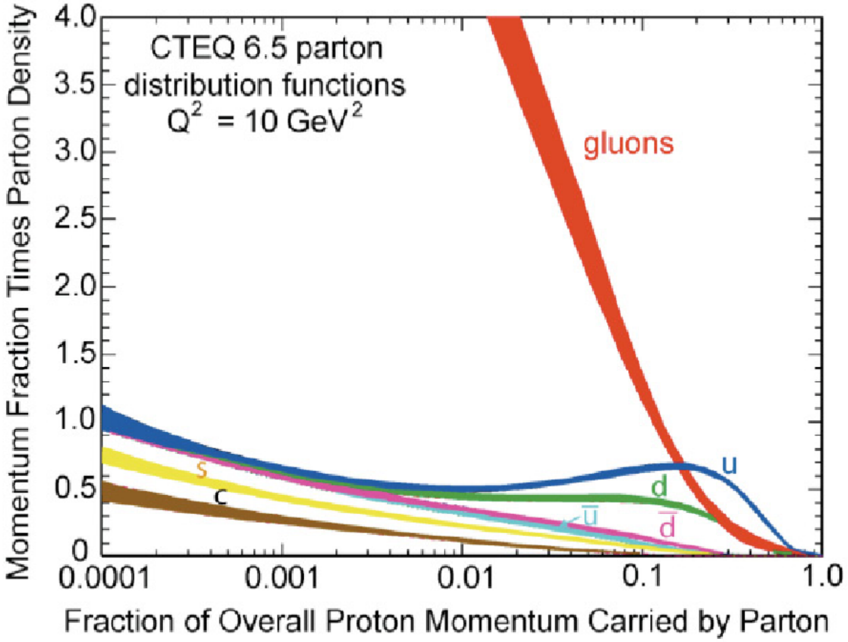






Used extensively in MC models of diffraction at the LHC

Low x Physics: the "Pathological" Gluon



Does the low x gluon saturate?

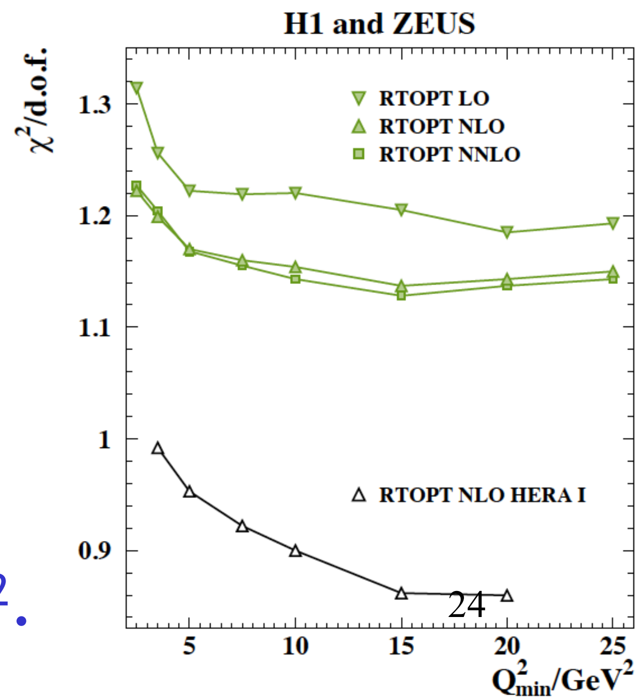
- Recombination (gg→g) ?
- Resummation?
- Just N(N)LO DGLAP + HT?

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

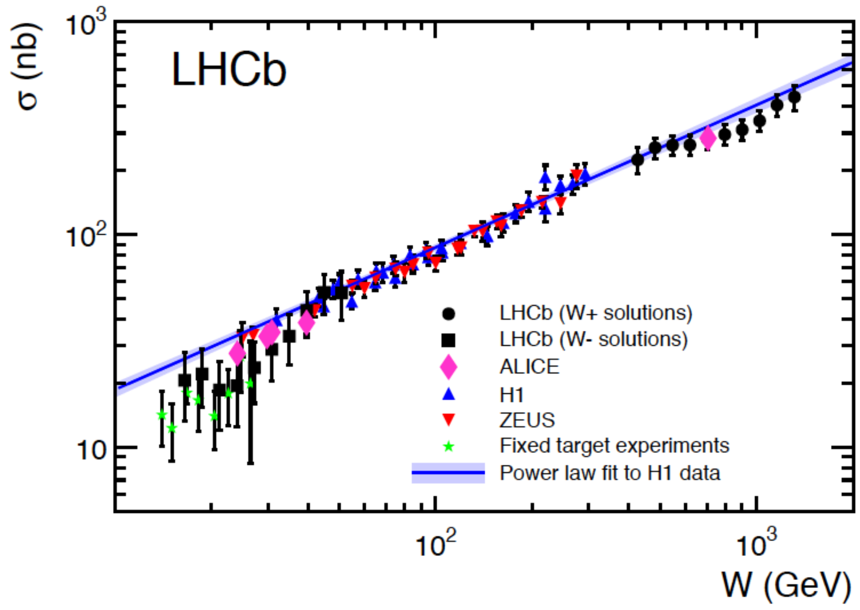
→ cf confinement, hadronic mass …

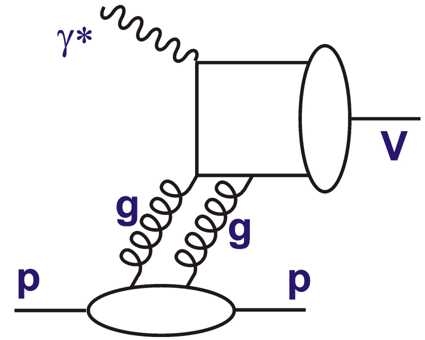
HERA-II Paper: "some tension in fit between low & medium Q^2 data… not attributable to particular x region" (though kinematic correlation)

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



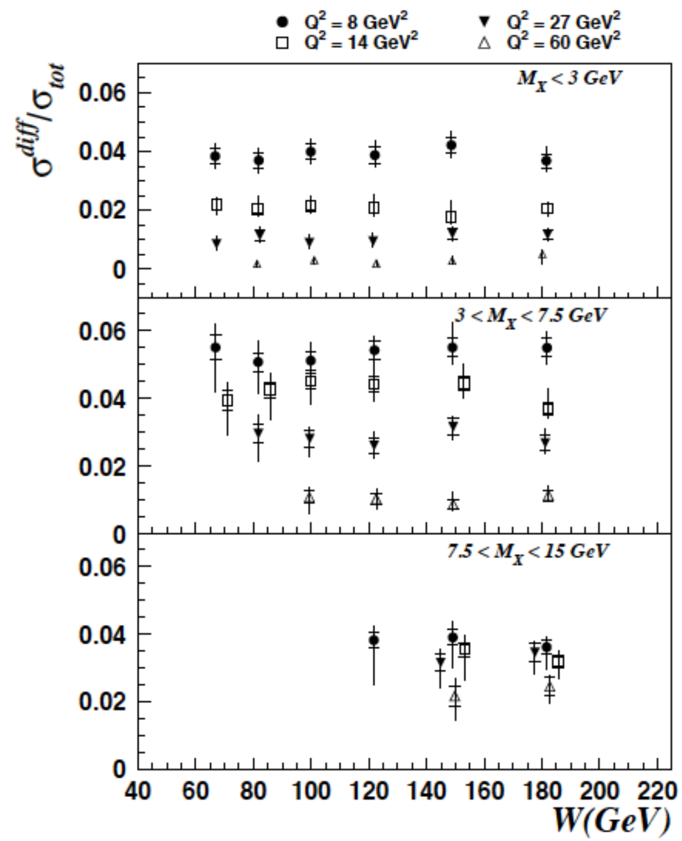
Low x Saturation in Diffractive Data?





- 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!...

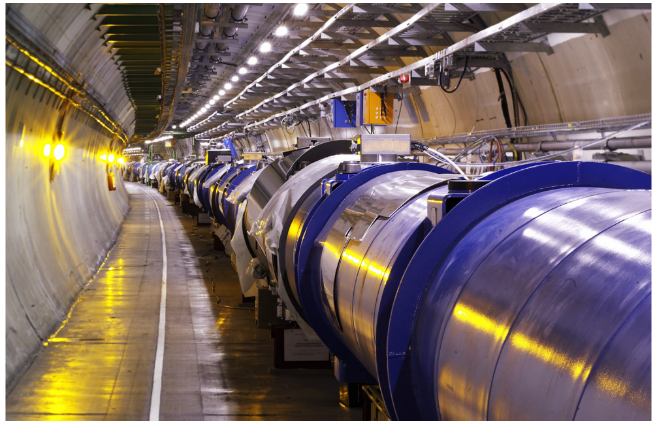
DESY–15–253
IPPP/15/76
DCPT/15/152
MAN/HEP/2015/21
December 2015

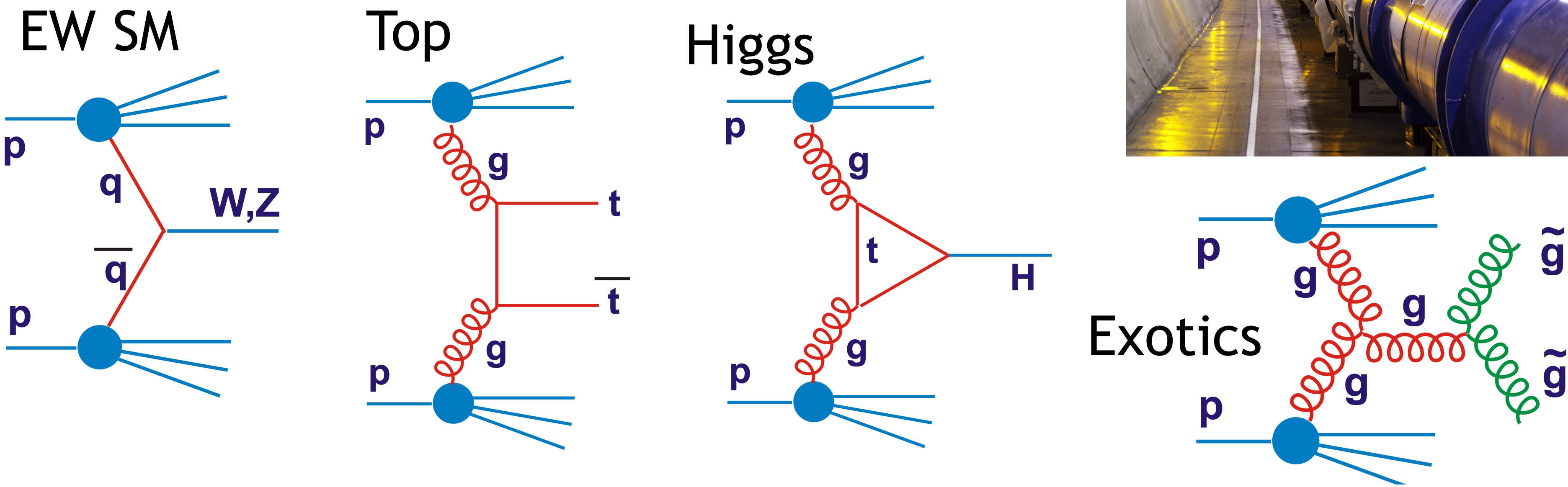
… and Data Preservation Project ensures new analyses possible over timescale of >= 10 years.

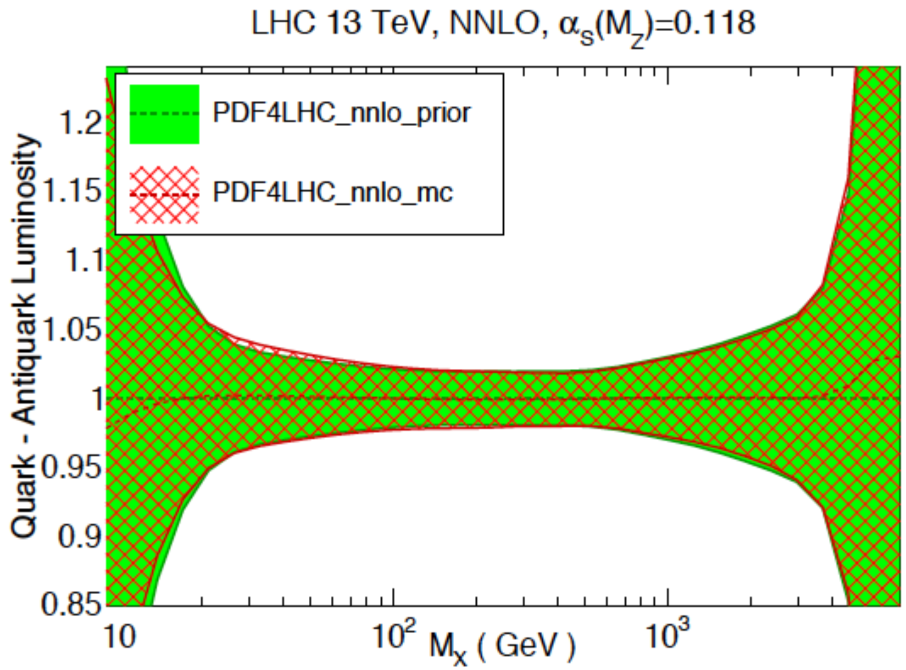
Summary of workshop on Future Physics with HERA Data

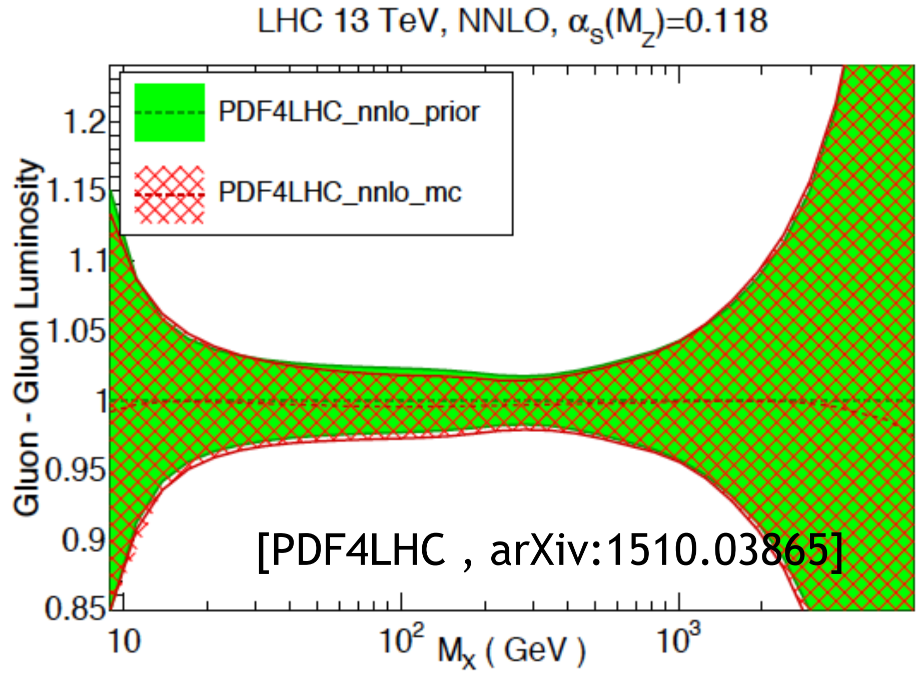
A. Bacchetta[1], J. Blümlein[2], O. Behnke[3], J. Dainton[4], M. Diehl[3], F. Hautmann[5,6], A. Geiser[3], H. Jung[3,7], U. Karshon[8], D. Kang[9], P. Kroll[10], C. Lee[9], S. Levonian[3], A. Levy[11], E. Lohrmann[3,12], S. Moch[12], L. Motyka[13], R. McNulty[14], V. Myronenko[3], E.R. Nocera[6,15], 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



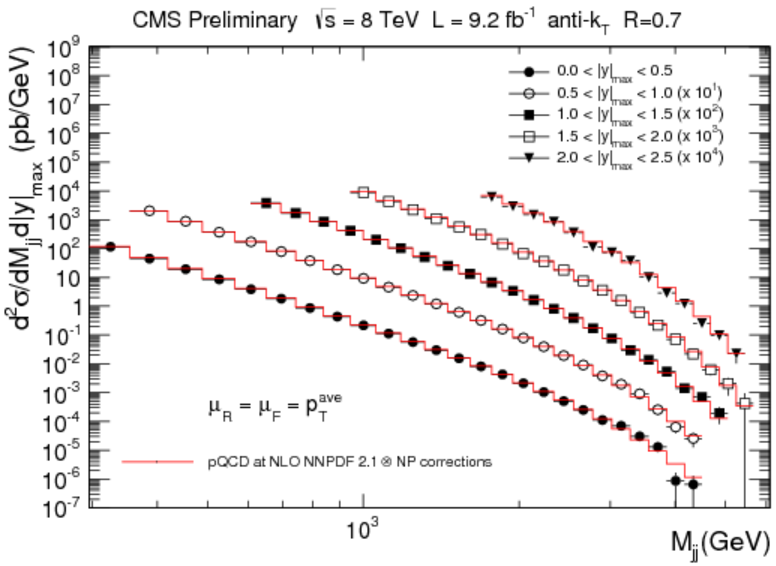






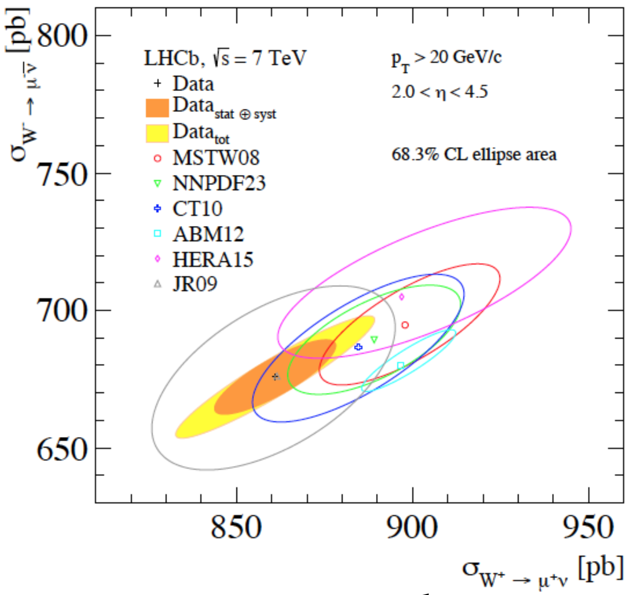
[PDF4LHC , arXiv:1510.03865]

PDFs working in extreme cases at the LHC …

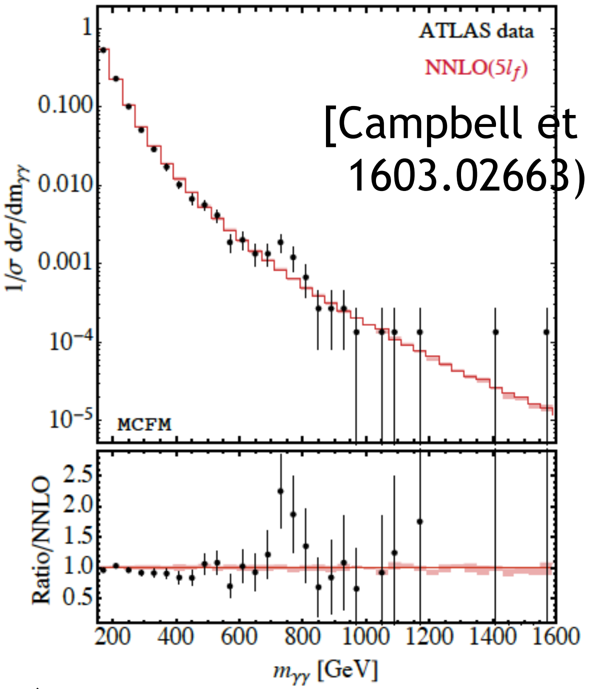


- Jets with cross sections varying over many orders of magnitude, extending to eg M_{jj} ~ 5 TeV

- 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?...

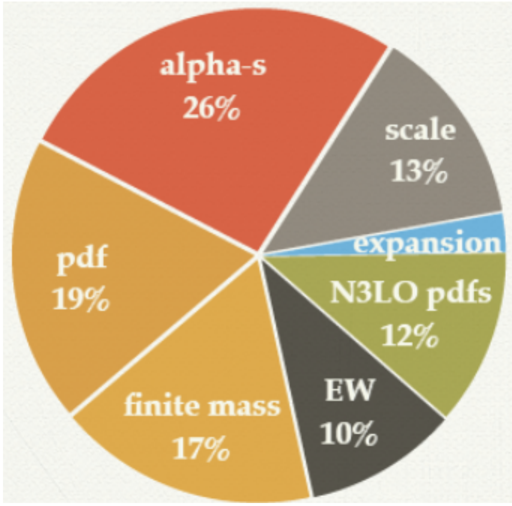
Higgs X-Section / Coupling PDF Uncertainties

Theoretical Uncertainties

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

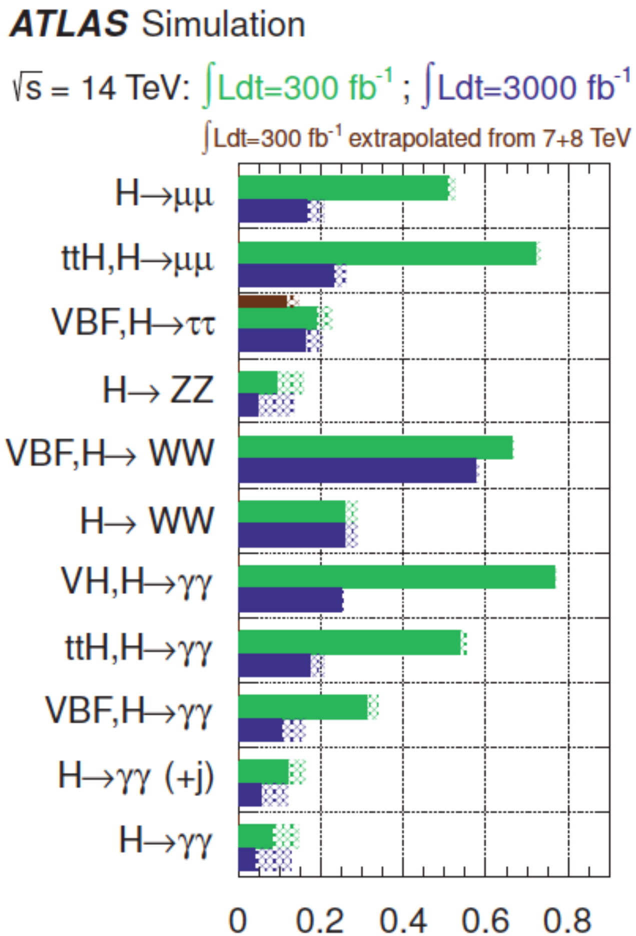
… largest sources of unertainty:
- PDFs [1.9%]
- α_s [2.6%]

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



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

Projected Experimental Uncertainties



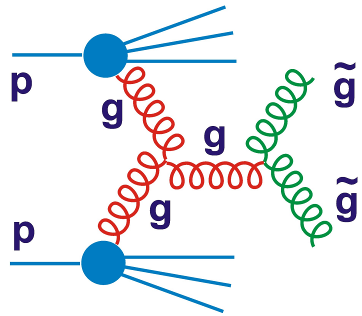
[Dashed regions = scale & PDF contributions]

… reaching this precision is a major legacy of HERA

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

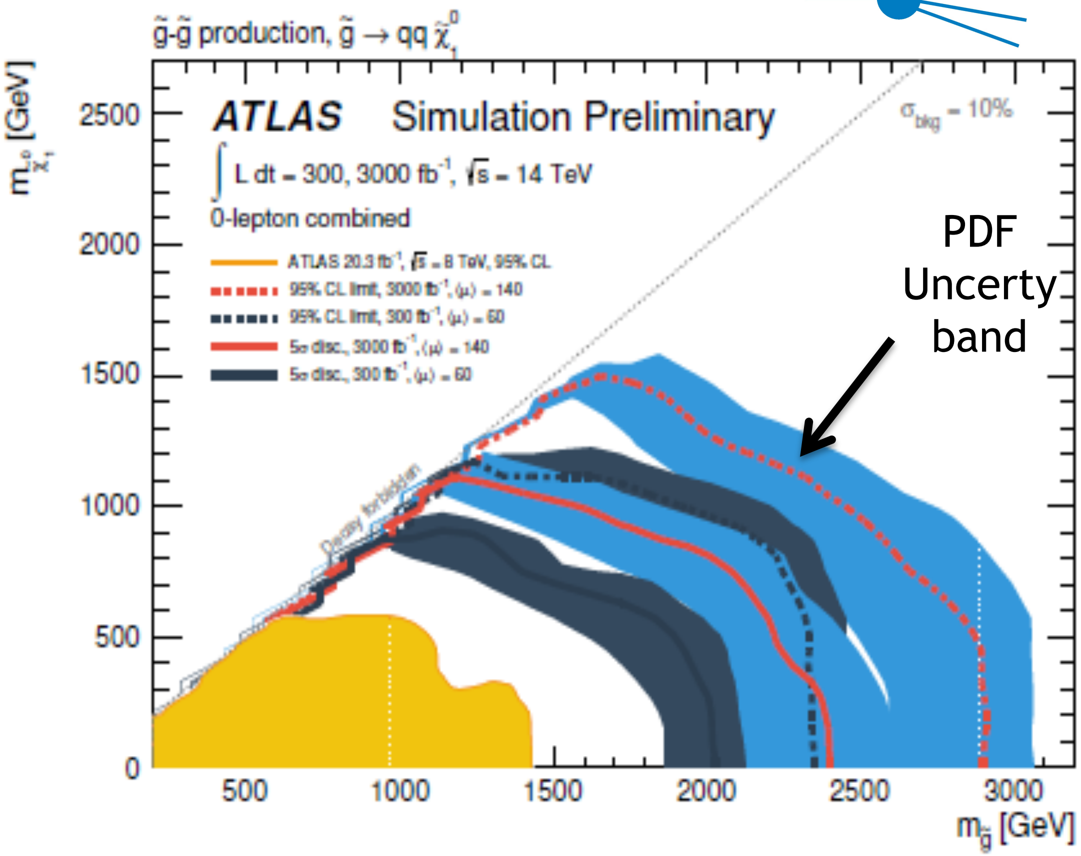
PDFs → New High Mass LHC Particles

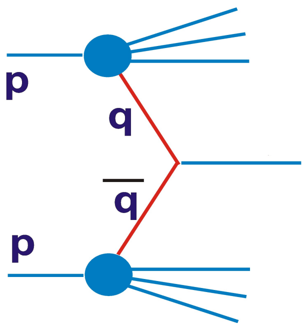
- Gluino pair signatures appear as deviations from theory, not resonances



- 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 …

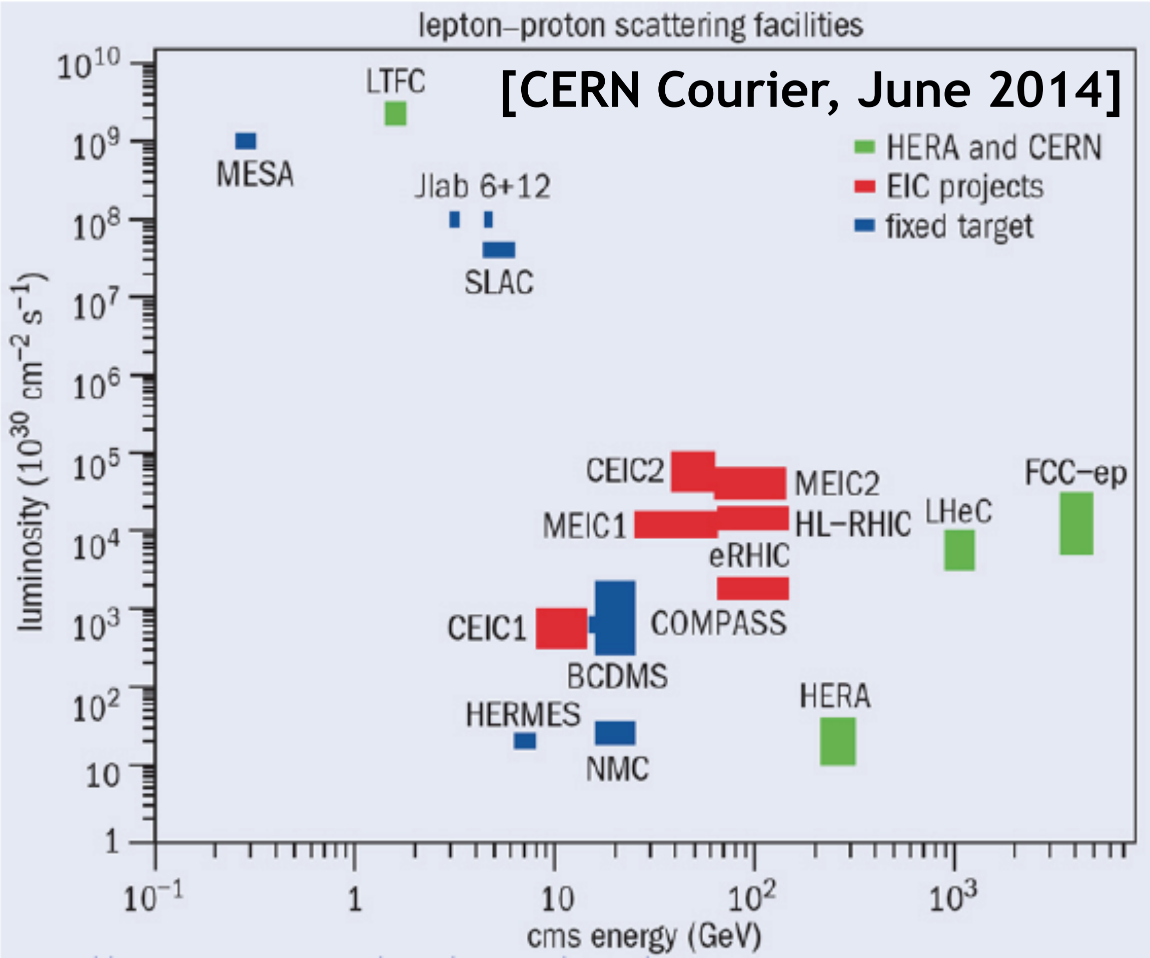
- Insufficient lumi for high x precision or searches
- Lack of Q^2 lever-arm restricts precision on low x for gluon
- Limited quark flavour info (no deuterons to separate u and d)
- Protons not polarised except HERMES
  (no access to spin, transverse structure at low x)
- No nuclear targets

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

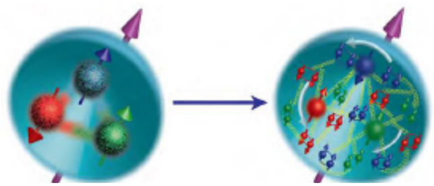
LHeC: 60 GeV electrons x LHC protons & ions

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

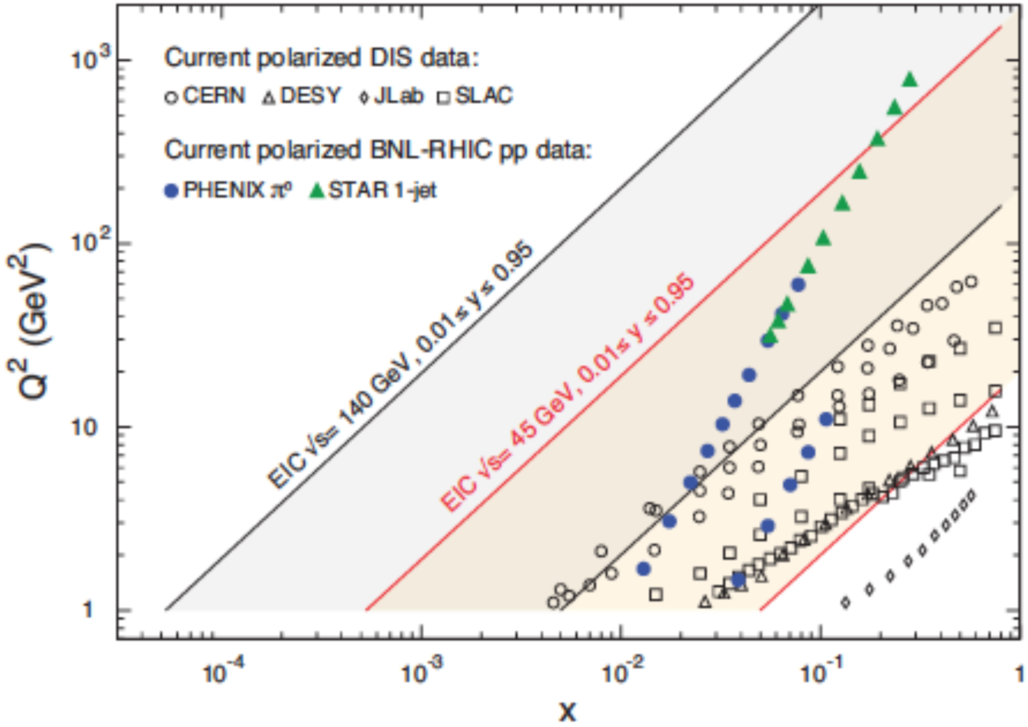
All @ lumi ~10^{34} cm^{-2}s^{-1} … very significant increase over HERA

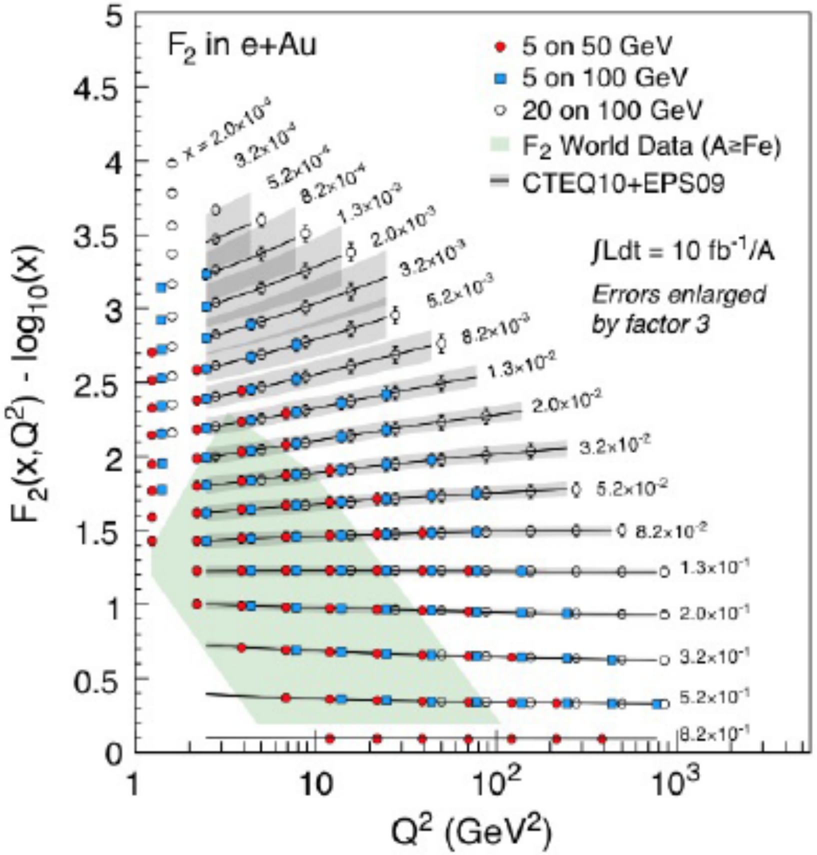
EIC: White paper 2012, Construction Recommendation NSAC Long Range Plan 2015, User Group 2016, DIS'16 pre-meet
LHeC: CDR 2012, ongoing CERN-sponsored working group, Presented to ECFA 2015 + on NuPECC (long-term) roadmap

EIC Physics



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





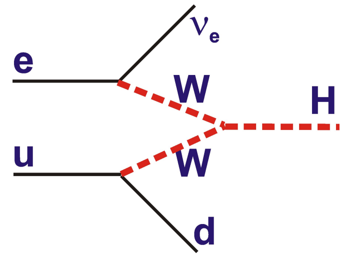
Wide range of ions and large step in eA kinematic range

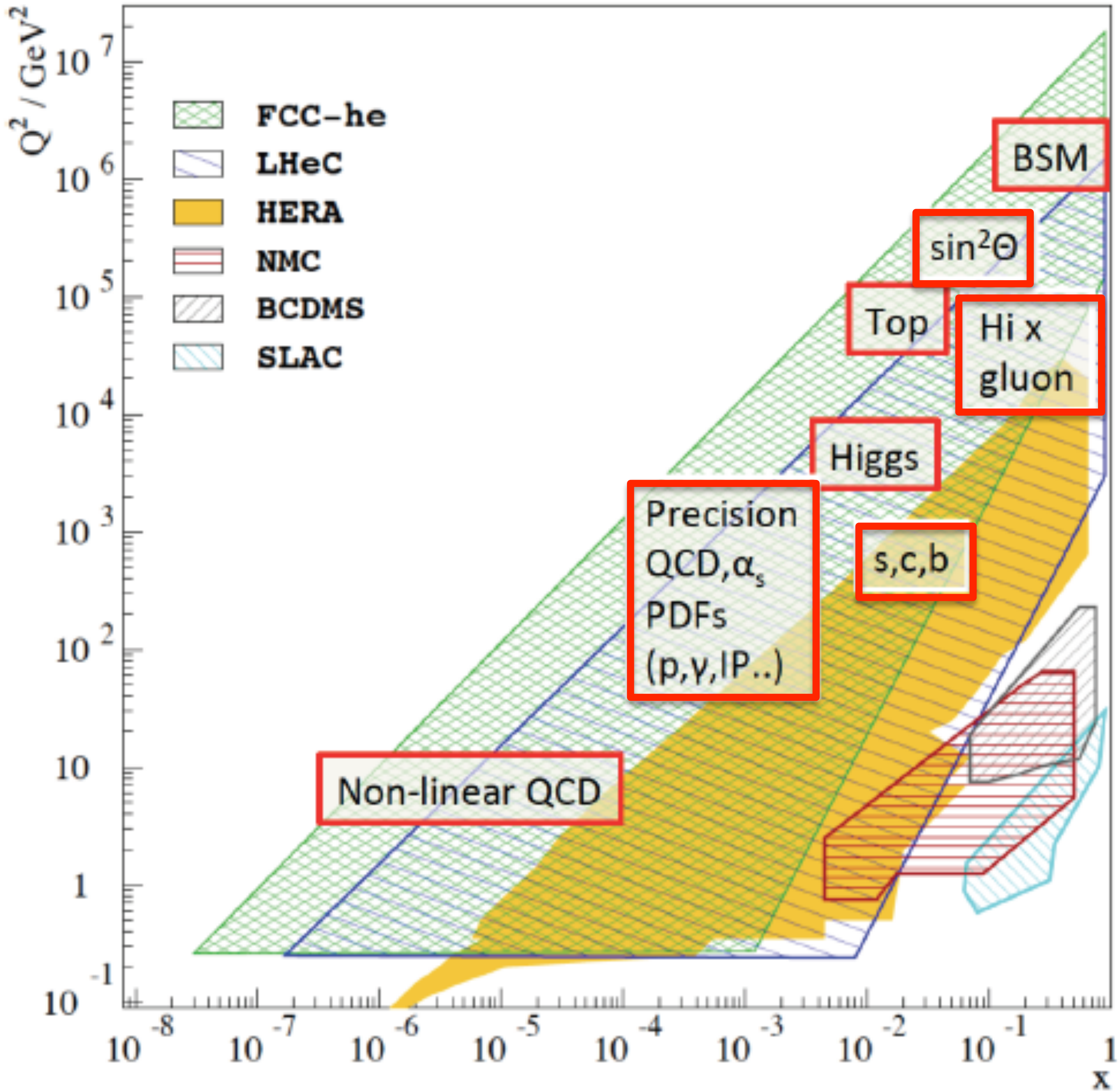
→ Nuclear parton densities

→ 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]

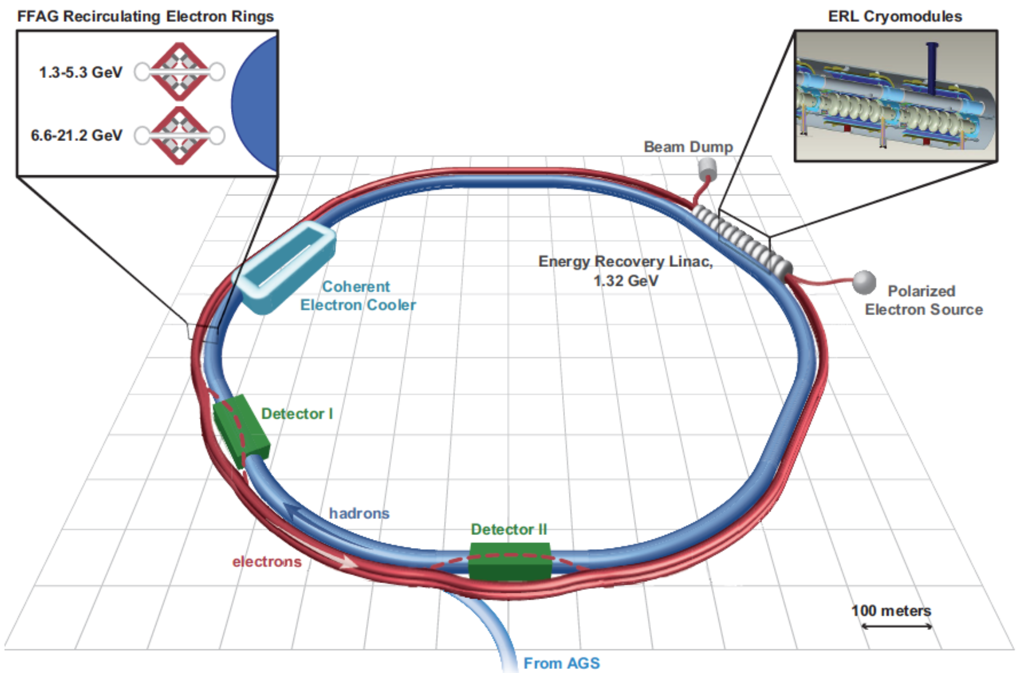
Thanks to many H1 and ZEUS colleagues for inspiring, educational and fun times over >20 years.

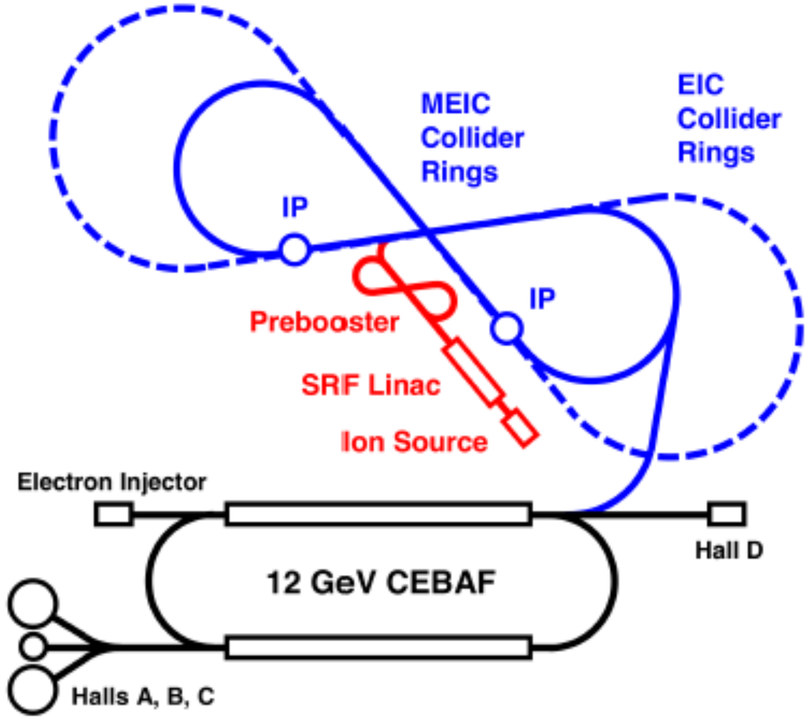
Thanks to A Cooper-Sarkar, M Klein, T Ullrich, M Wing and many others from whom I borrowed talk material

Back-ups / Rejects Follow

US Electron Ion Collider (EIC)

- eRHIC @ BNL: Add energy recovery LINAC in RHIC tunnel
- MEIC @ Jlab: Add figure of 8 hadron rings to CEBAF

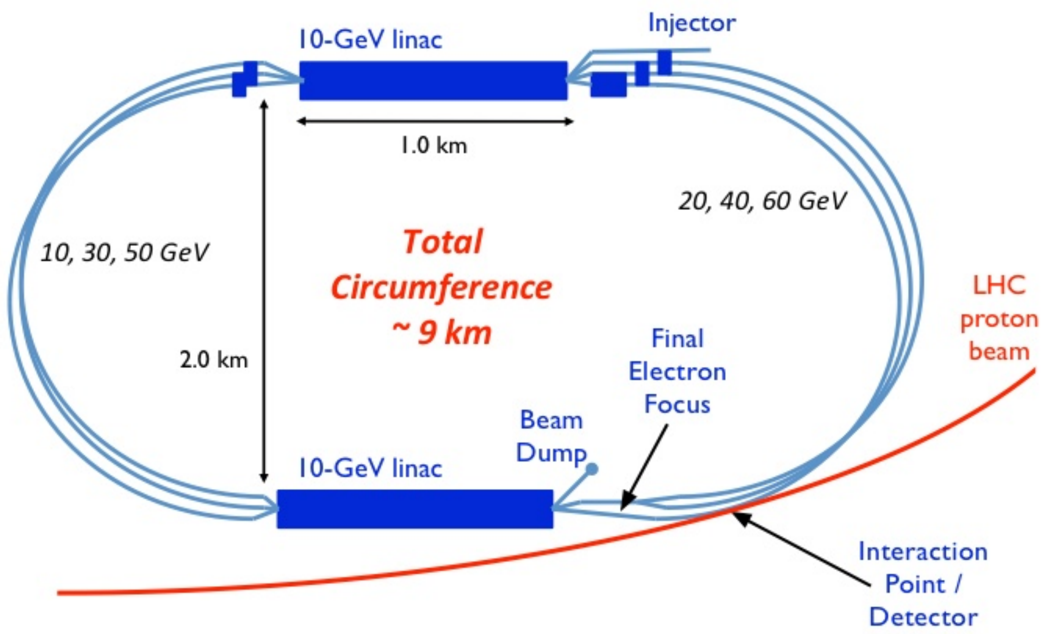




- White paper 2012
- Construction Recommendation in NSAC Long Range Plan 2015
- User Group 2016
- DIS'16 pre-meet

Baseline LHeC Design (Electron "Linac")

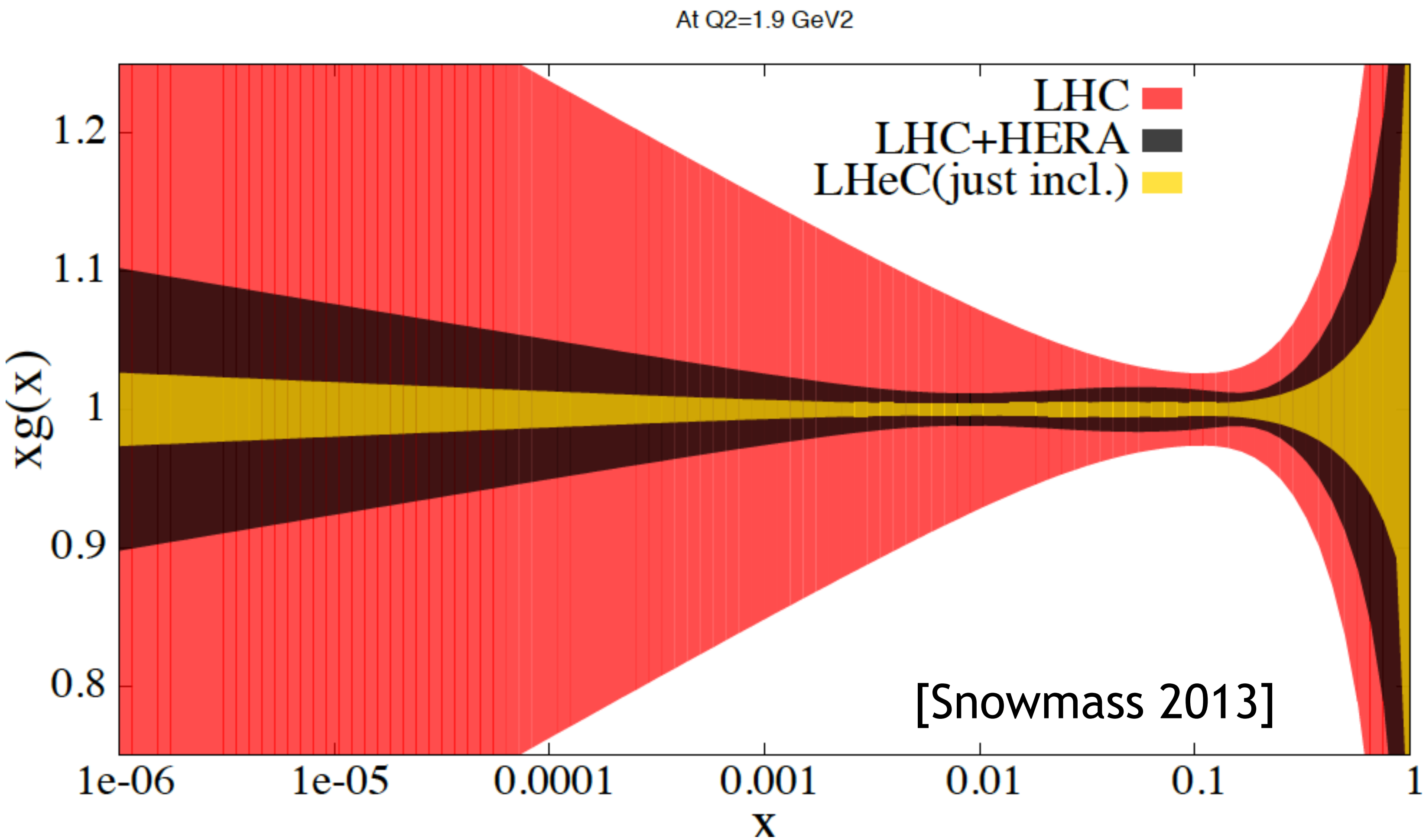
- Two 10 GeV linacs inside LHC
- 3 returns, 20 MV/m
- Energy recovery in same structures



- CDR 2012, ongoing CERN-sponsored working group, presented to ECFA 2015 + on NuPECC (long-term) roadmap

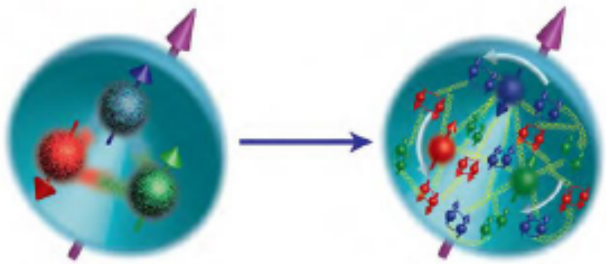
- Renewed interest following
  1) Possibility of 10^{34} cm^{-2} s^{-1} luminosity
  2) Higgs discovery, searches and new measurements at LHC→ PDFs / QCD limit HL-LHC.
  3) Technical interest (high gradient cavities, ER linacs)
  4) Longer term perspective of FCC

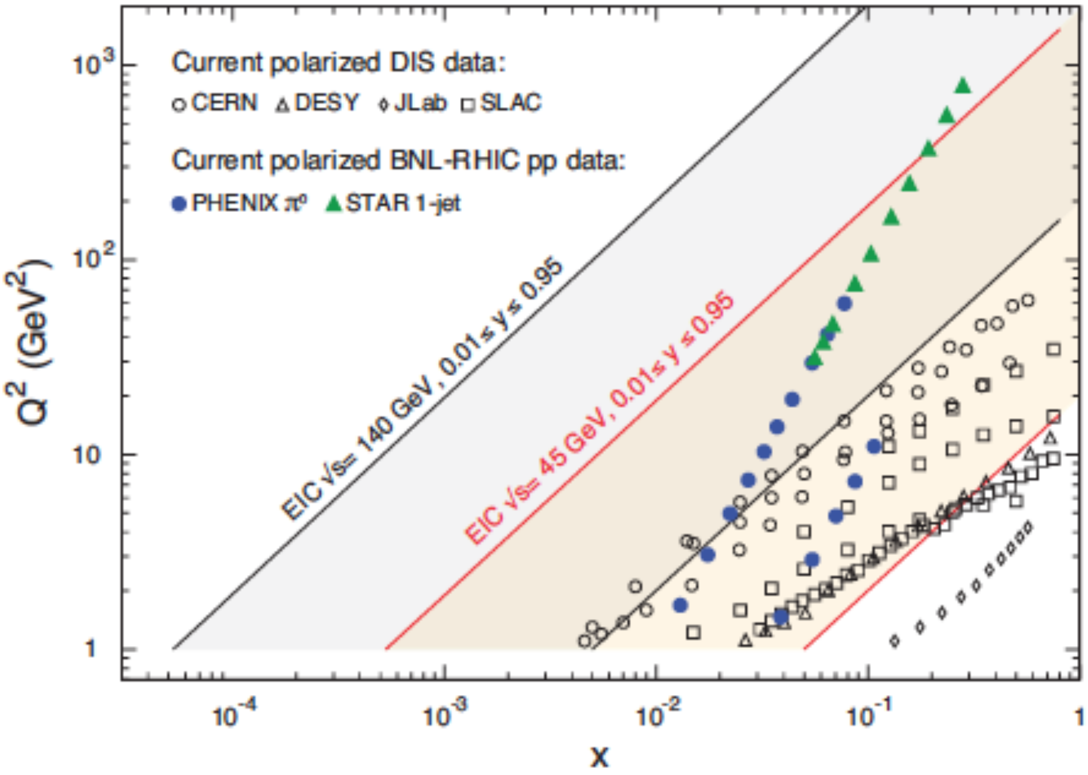
What can be done with LHC alone?

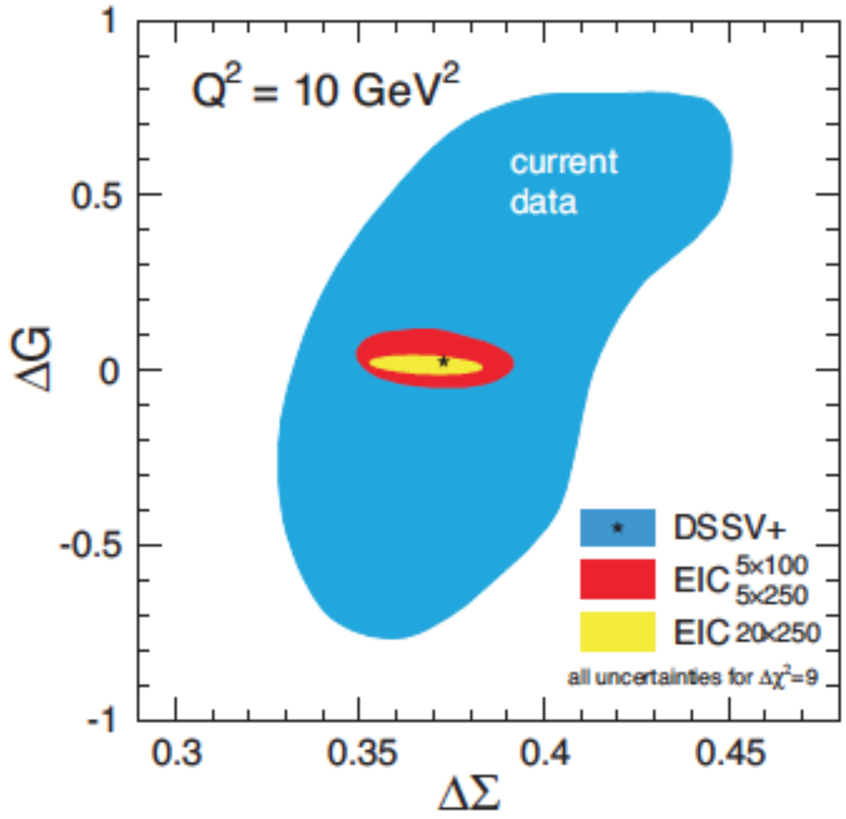


- LHC = current LHC W, Z and jet data
- Remarkable what can be achieved with LHC data alone
- Can we improve substantially? – Often already systs limited

Proton Spin at EIC



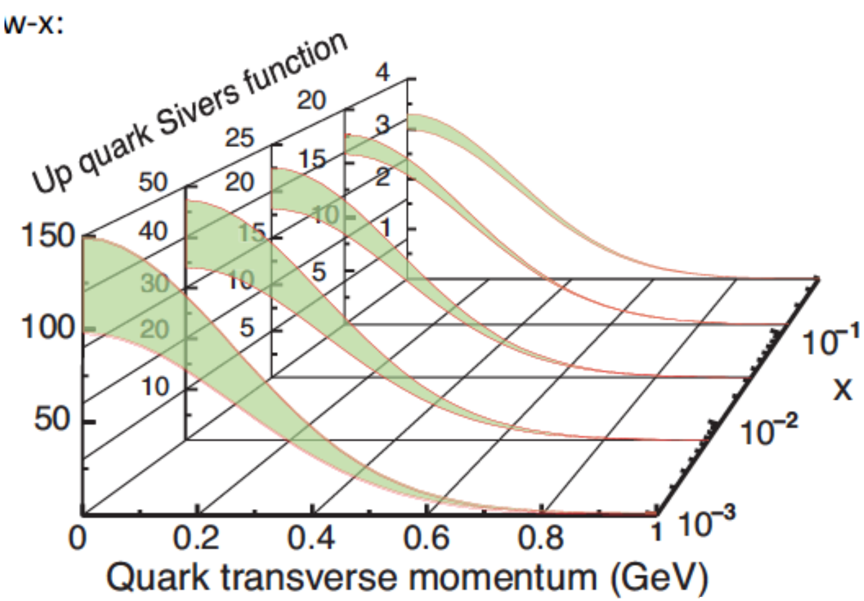


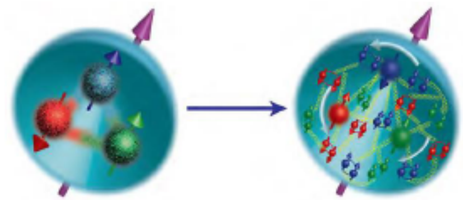


[integrated x = 10^{-5} → 1]

Unprecendented low x reach for a spin DIS experiment, allowing quark and gluon contributions to nucleon spin to be pinpointed

Proton Tomography at EIC



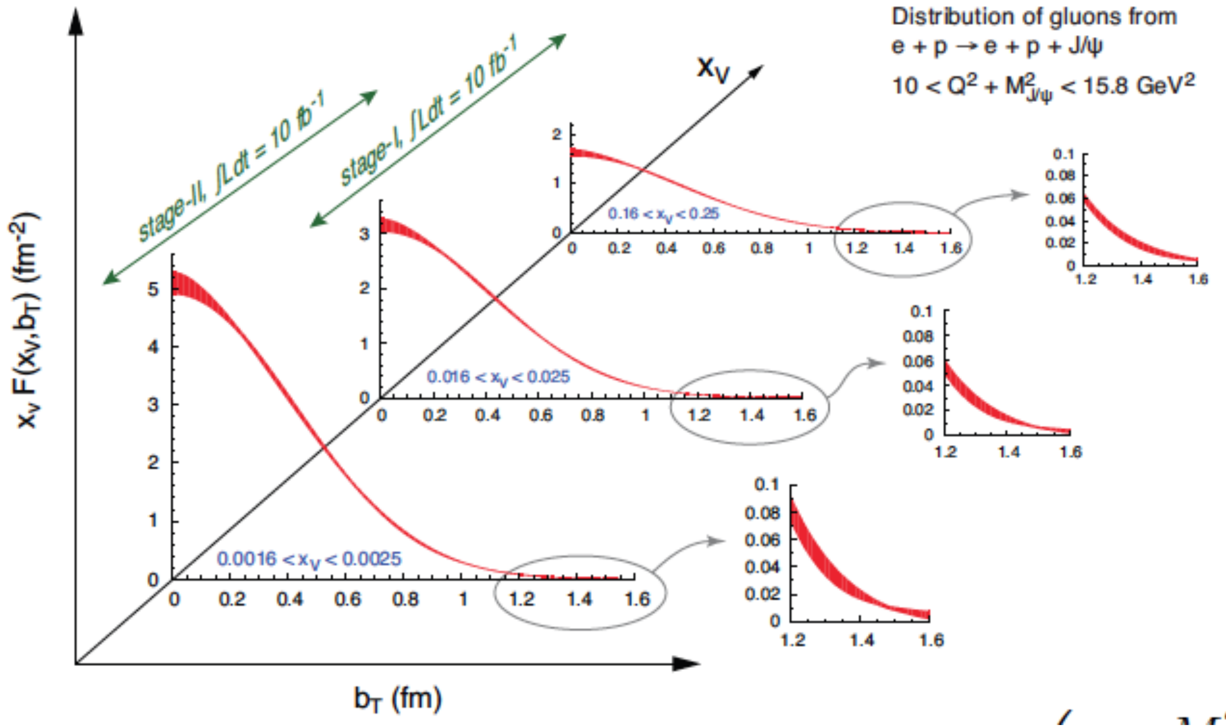


<u>Correlations between parton momenta:</u>

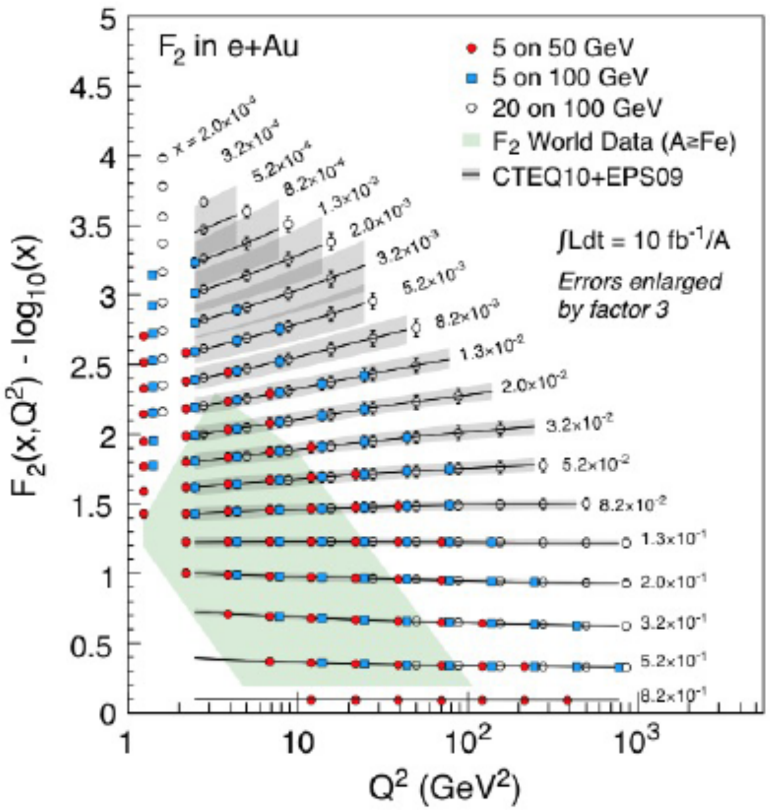
Sivers TMD distribution is single transverse spin Asymmetry → low x

<u>Correlations between parton longitudinal momenta and transverse positions:</u>

GPDs… from DVCS & Vector Mesons



eA Collisions at EIC



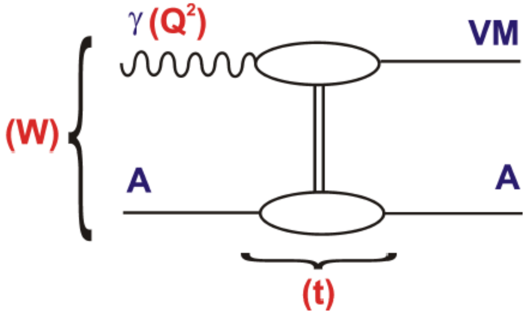
Very large advance in eA kinematic range over previous (fixed target) facilities

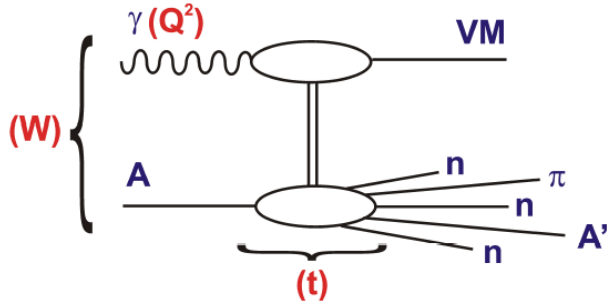
→ Nuclear Parton densities

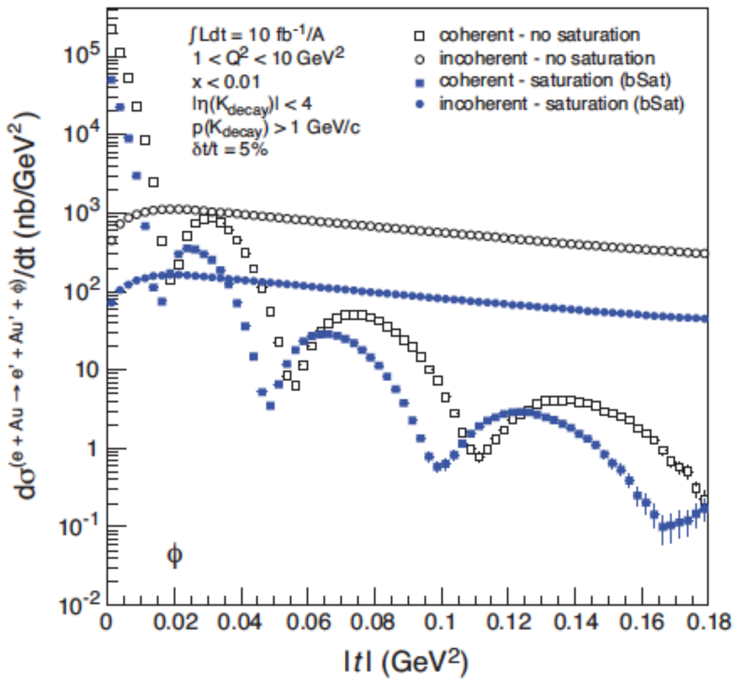
→ Potential access to low x saturation region

→ Passage of 'struck' partons through cold nuclear matter

e.g. Possible saturation signatures in (coherent) vector meson production: $\gamma p \rightarrow \phi p$







Recent Developments

Post-CDR: LHeC Baseline Parameter

→ **for first time a realistic option of an 1 ab^{-1} electron-proton collider** also due to **excellent performance of LHC;** ERL : 960 superconducting cavities (20 MV/m) and 9 km tunnel [arXiv:1211.5102, arXiv:1305.2090; EPS2013 talk by D. Schulte]

10^{34} cm^{-2} s^{-1} Luminosity reach	PROTONS	ELECTRONS	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60	7000	60
Luminosity [$10^{33}cm^{-2}s^{-1}$]	16	16	1	1
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	2.5	20	3.75	50
Beta Funtion $\beta^*_{x,y}$ [m]	0.05	0.10	0.1	0.12
rms Beam size $\sigma^*_{x,y}$ [μm]	4	4	7	7
rms Beam divergence $\sigma'^*_{x,y}$ [μrad]	80	40	70	58
Beam Current [mA]	1112	25	430 (860)	6.6
Bunch Spacing [ns]	25	25	25 (50)	25 (50)
Bunch Population	$2.2*10^{11}$	$4*10^{9}$	$1.7*10^{11}$	$(1*10^{9})$ $2*10^{9}$
Bunch charge [nC]	35	0.64	27	(0.16) 0.32

Operations simultaneous with HL-LHC *pp* physics

Recent Developments

LHC programme runs to >2035. Longer term at CERN? → FCC?

... CERN-sponsored ongoing work to evaluate how LHeC fits in.

→ Further develop physics aims, accelerator & detector, both LHeC & FCC

→ Continue building collaboration

→ Design ERL test facility @ CERN

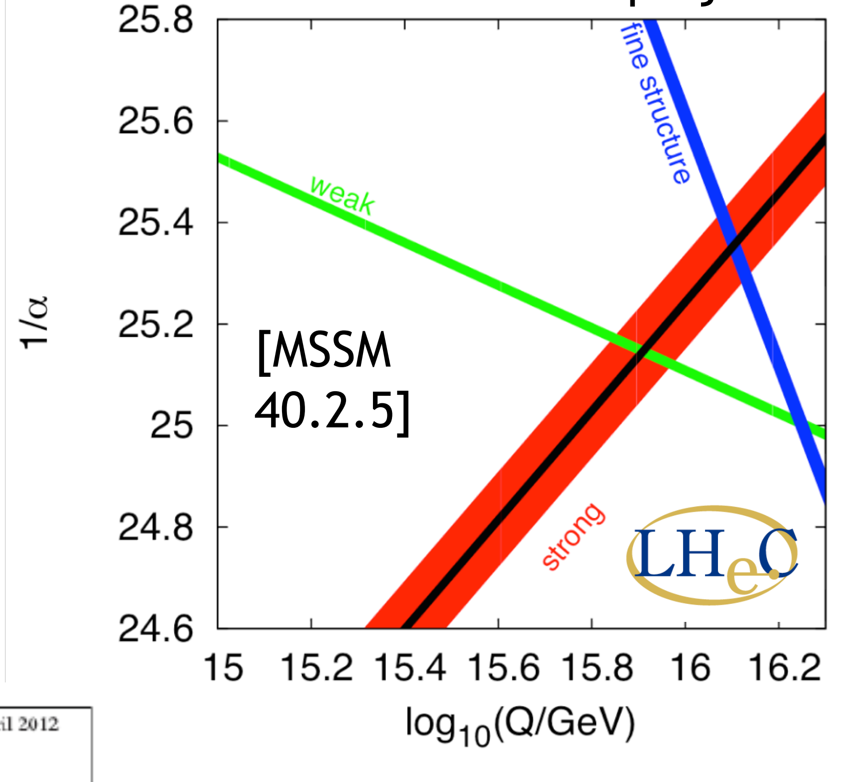
ERL Test Facility:

- Test centre for accelerator development, LHeC prototype
- Most ambitious design (2 x 150 MeV linacs, 3 passes → 900 GeV) has significant physics potential of its own (10^{40} cm^{-2} s^{-1} fixed target) … EW parameters, proton radius, photonuclear physics, dark photons …
- Conceptual Design Report by end 2015

Measuring α_s

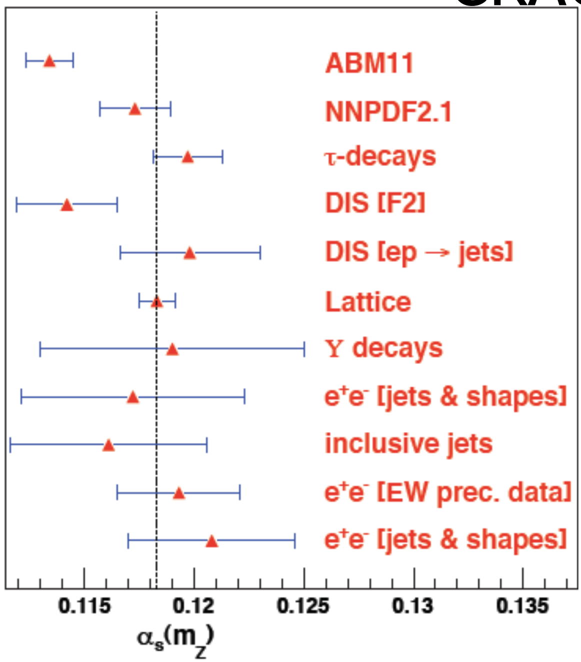
Cracow

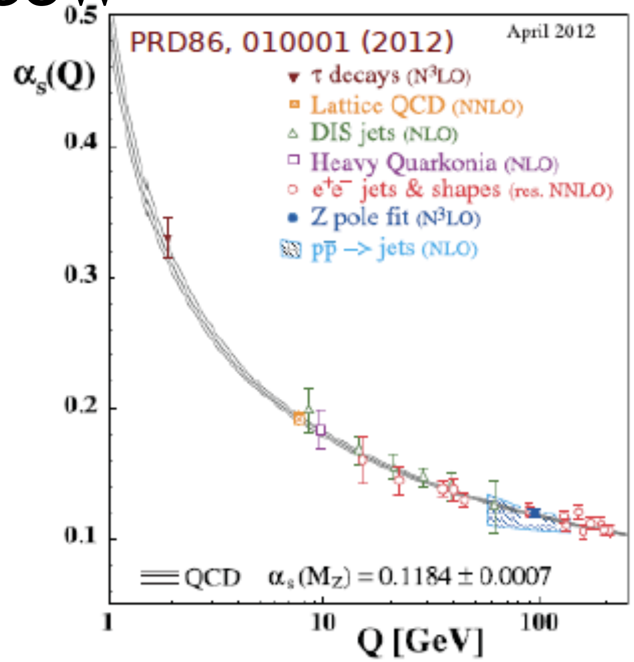
Red = current world average
Black = LHeC projected



- Least constrained fundamental coupling by far (known to ~1%)
- Do coupling constants unify (with a little help rom SUSY?)
- Future measurement precision
→ per-mille (experimental) with LHeC, high energy lepton colliders

CRACOW





- Important to check compatibility between different experiments (and lattice)
- Scale dependence (running) also sensitive to new effects

Context of Precision α_s

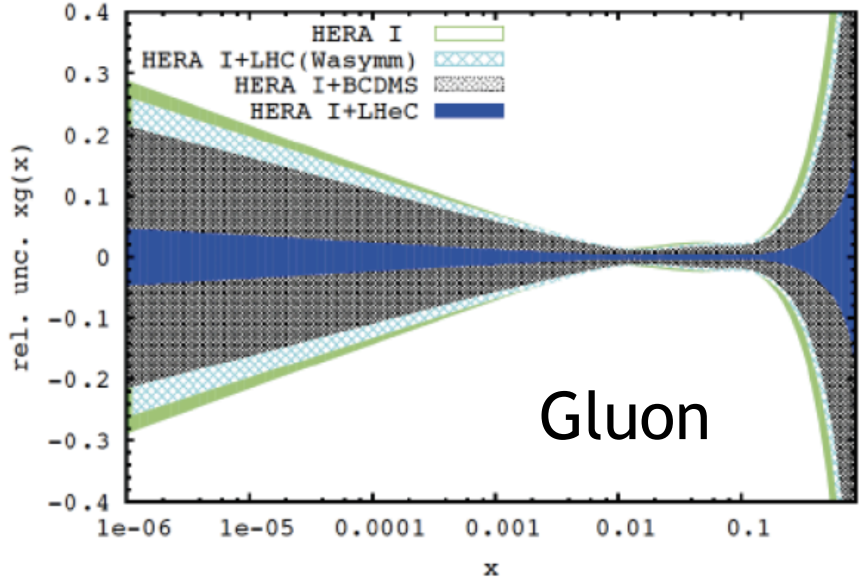
Snowmass13 report – arXiv:1310.5189

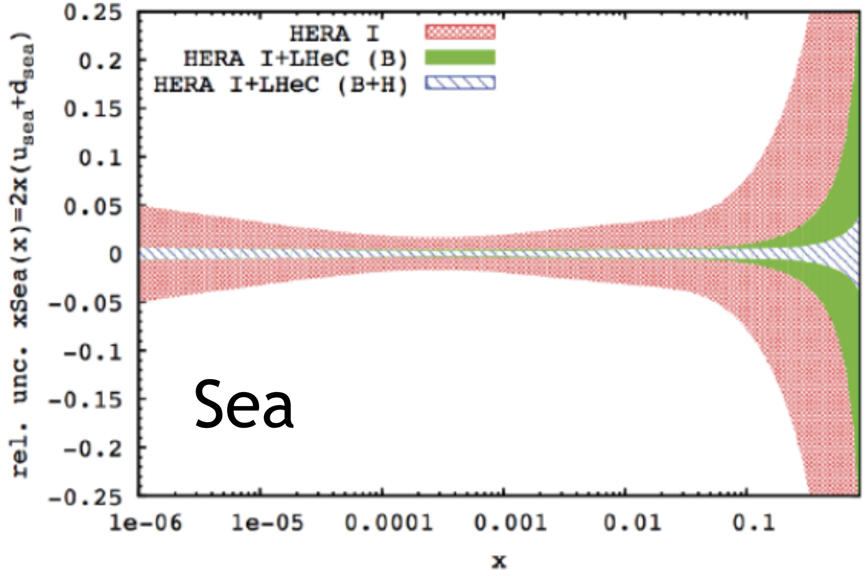
Method	Current relative precision	Future relative precision	
e^+e^- evt shapes	expt $\sim 1\%$ (LEP) thry ~ 1–3% (NNLO+up to N^{3}LL, n.p. signif.) [27]	$< 1\%$ possible (ILC/TLEP) $\sim 1\%$ (control n.p. via Q^2-dep.)	
e^+e^- jet rates	expt $\sim 2\%$ (LEP) thry $\sim 1\%$ (NNLO, n.p. moderate) [28]	$< 1\%$ possible (ILC/TLEP) $\sim 0.5\%$ (NLL missing)	
precision EW	expt $\sim 3\%$ (R_Z, LEP) thry $\sim 0.5\%$ (N^{3}LO, n.p. small) [9,29]	0.1% (TLEP [10]), 0.5% (ILC [11]) $\sim 0.3\%$ (N^{4}LO feasible, ~ 10 yrs)	**per mille**
τ decays	expt $\sim 0.5\%$ (LEP, B-factories) thry $\sim 2\%$ (N^{3}LO, n.p. small) [8]	$< 0.2\%$ possible (ILC/TLEP) $\sim 1\%$ (N^{4}LO feasible, ~ 10 yrs)	
ep colliders	~ 1–2% (pdf fit dependent) [30,31], (mostly theory, NNLO) [32,33]	0.1% (LHeC + HERA [23]) $\sim 0.5\%$ (at least N^{3}LO required)	**per mille**
hadron colliders	$\sim 4\%$ (Tev. jets), $\sim 3\%$ (LHC $t\bar{t}$) (NLO jets, NNLO $t\bar{t}$, gluon uncert.) [17,21,34]	$< 1\%$ challenging (NNLO jets imminent [22])	
lattice	$\sim 0.5\%$ (Wilson loops, correlators, ...) (limited by accuracy of pert. th.) [35–37]	$\sim 0.3\%$ (~ 5 yrs [38])	

… tensions between lattice and DIS α_s results as a sensitive probe of new physics?...

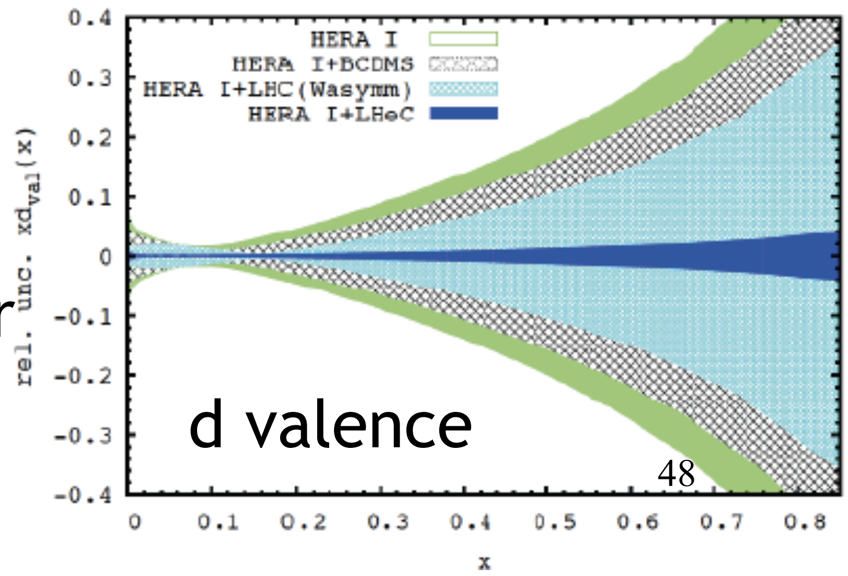
PDF Constraints at LHeC

Full simulation of inclusive NC and CC DIS data, including systematics → NLO DGLAP fit using HERA technology…

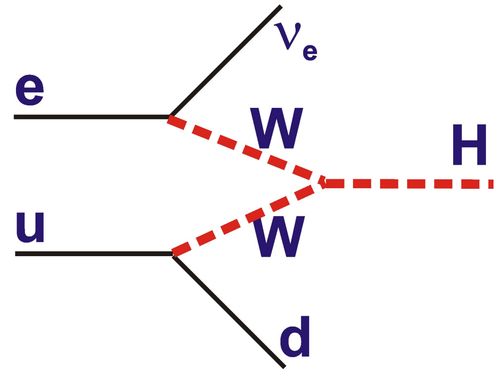




- Low x → novel QCD / unitarity
- Medium x → precision Higgs and EW (essentially removes Higgs PDF error)
- High x → new particle mass frontier
- Per-mille experimental α_s precision
- Full Flavour decomposition

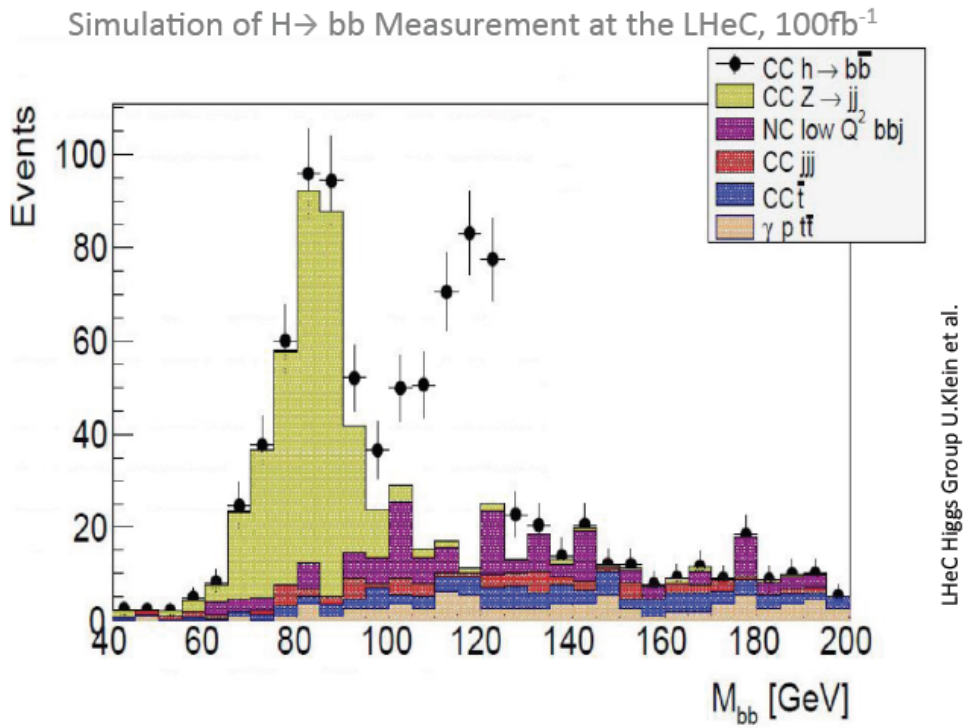


Higgs Production at LHeC



Study of H → bbbar in generic simulated LHC detector

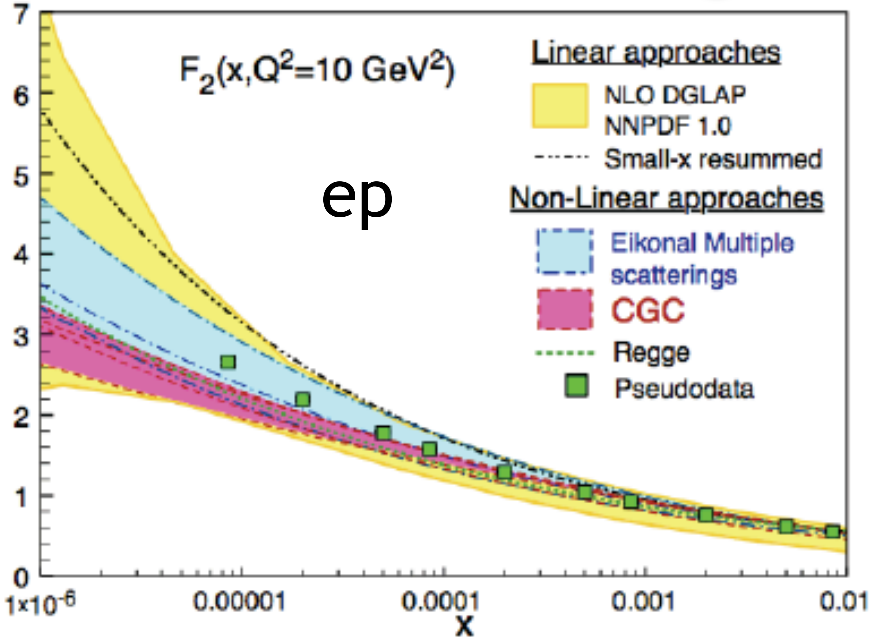
- → Signal/Background ~ 1-2
- → ~1% H→bbbar coupling
- → Ongoing studies of ccbar
- → Lots of other possibilities to be evaluated



Higgs in e^-p		CC - LHeC	NC - LHeC	CC - FHeC
Polarisation		-0.8	-0.8	-0.8
Luminosity [ab^{-1}]		1	1	5
Cross Section [fb]		196	25	850
Decay	BrFraction	N^H_{CC}	N^H_{NC}	N^H_{CC}
$H \to b\bar{b}$	0.577	113 100	13 900	2 450 000
$H \to c\bar{c}$	0.029	5 700	700	123 000
$H \to \tau^+\tau^-$	0.063	12 350	1 600	270 000
$H \to \mu\mu$	0.00022	50	5	1 000
$H \to 4l$	0.00013	30	3	550
$H \to 2l2\nu$	0.0106	2 080	250	45 000
$H \to gg$	0.086	16 850	2 050	365 000
$H \to WW$	0.215	42 100	5 150	915 000
$H \to ZZ$	0.0264	5 200	600	110 000
$H \to \gamma\gamma$	0.00228	450	60	10 000
$H \to Z\gamma$	0.00154	300	40	6 500

Estimated integrated Yields for 10 year programme.

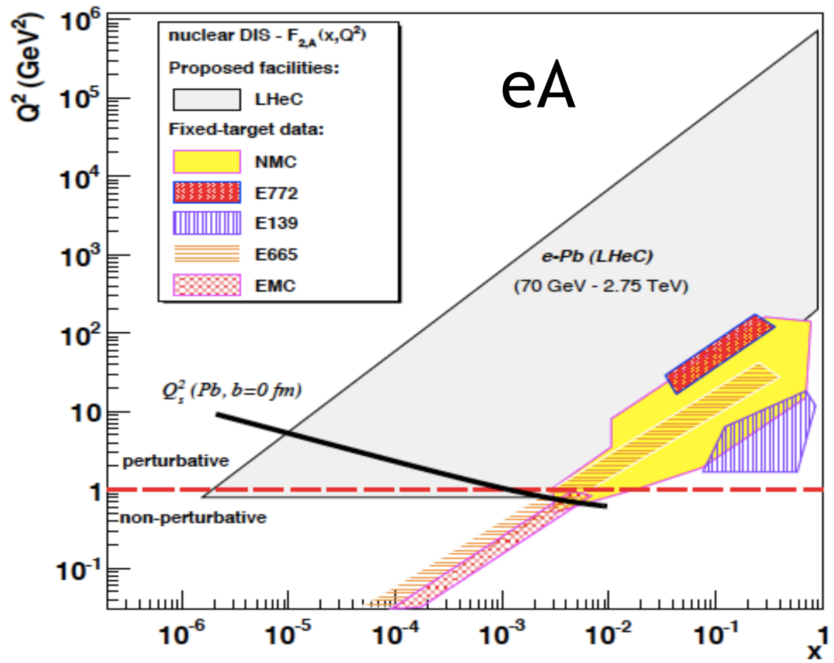
Resolving Low x Physics at LHeC



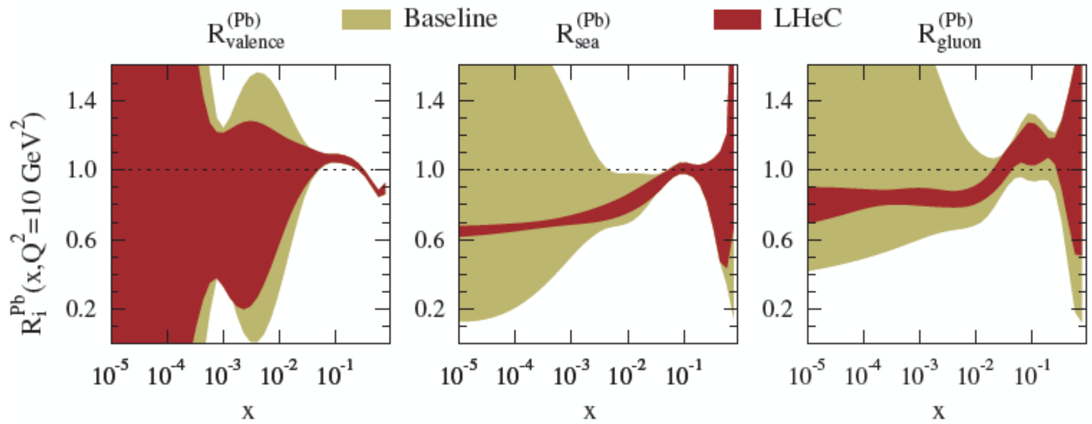
LHeC can distinguish between different QCD-based models for the onset of non-linear dynamics

→ Unambiguous observation of saturation will be based on tension between different observables

e.g. F_2 v F_L in ep or F_2 in ep v eA



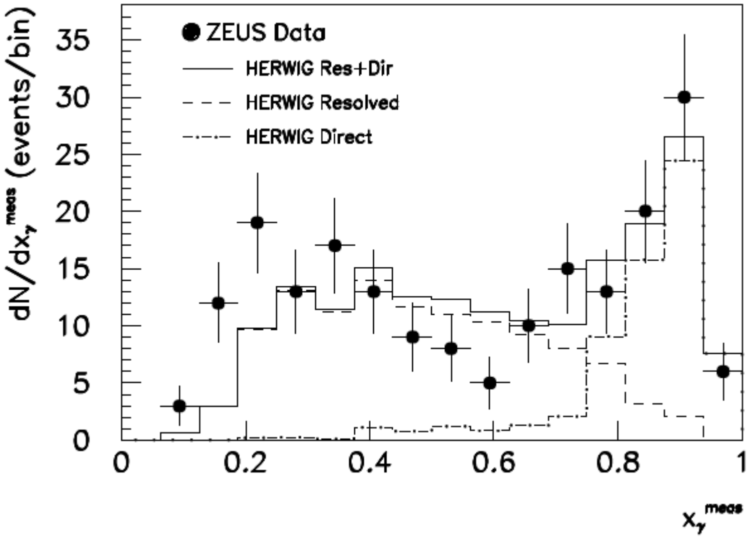
Four orders of magnitude increase in eA kinematic range

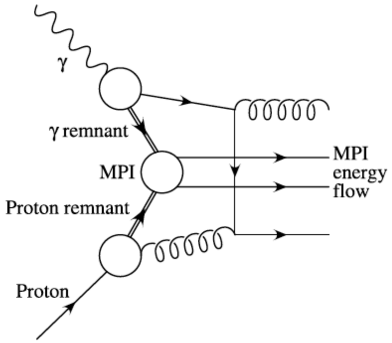


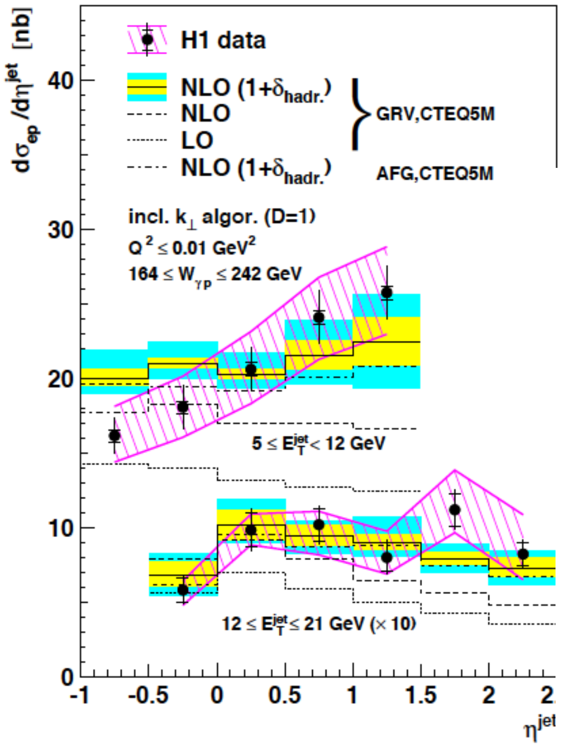
nPDF sensitivity in EPS09 framework

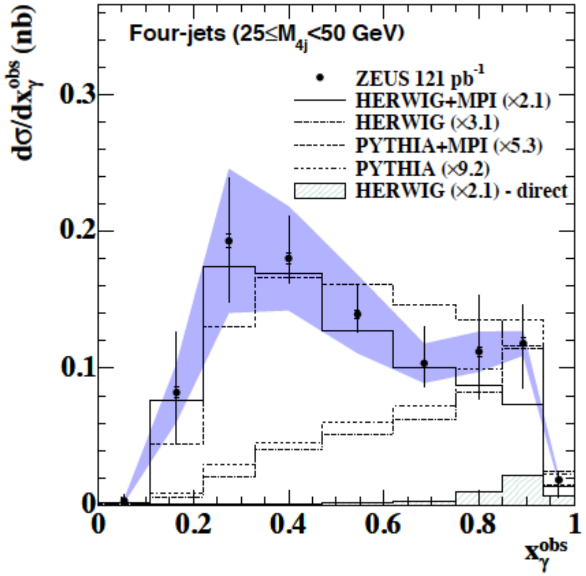
More Final State Jet Legacy

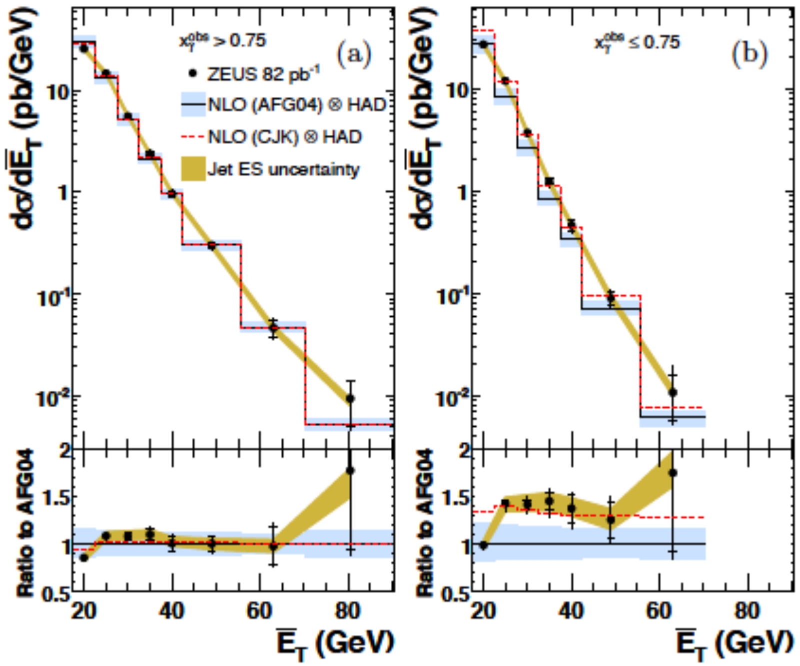
- Discovered hard scattering in γp and used it to constrain the photon pdfs
- Led on how to treat underlying event and hadronisation effects & how to search explicitly for MPI











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

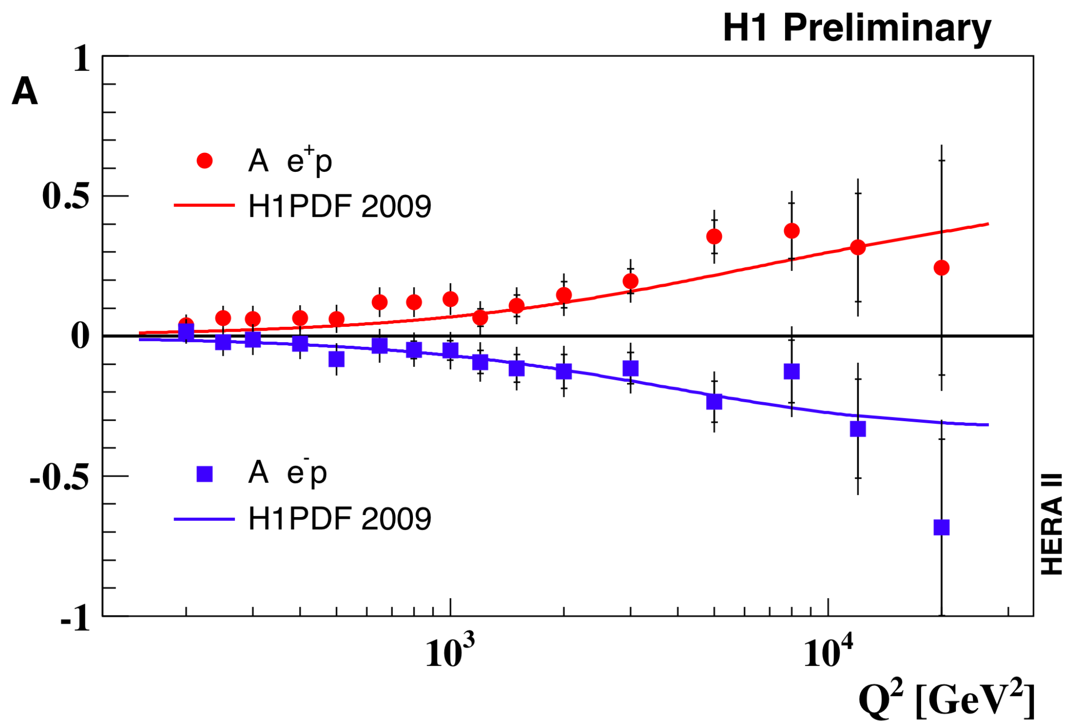
- F_L contributes at high y (longitudinally polarised photons)

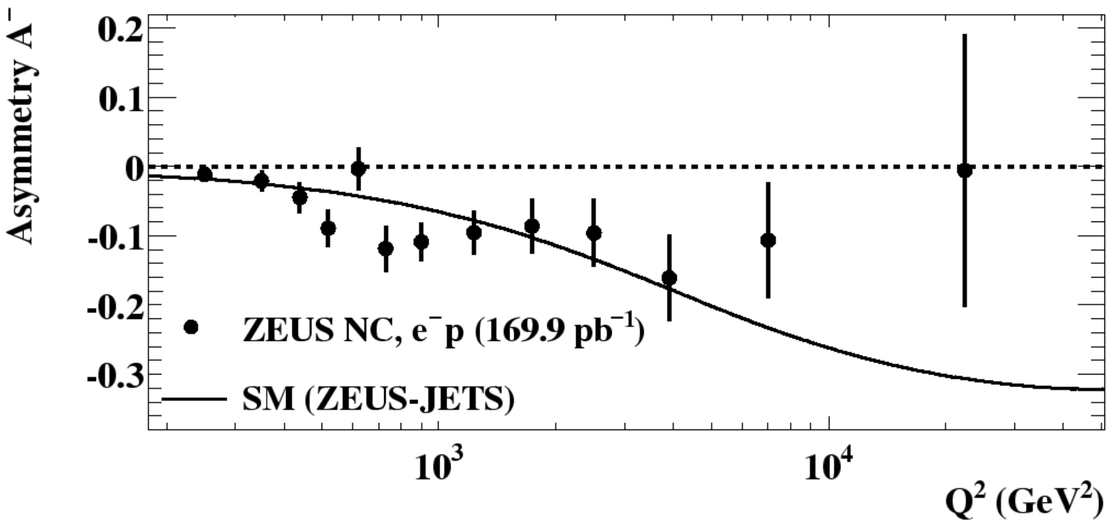
Left v Right Hand Polarised Leptons

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

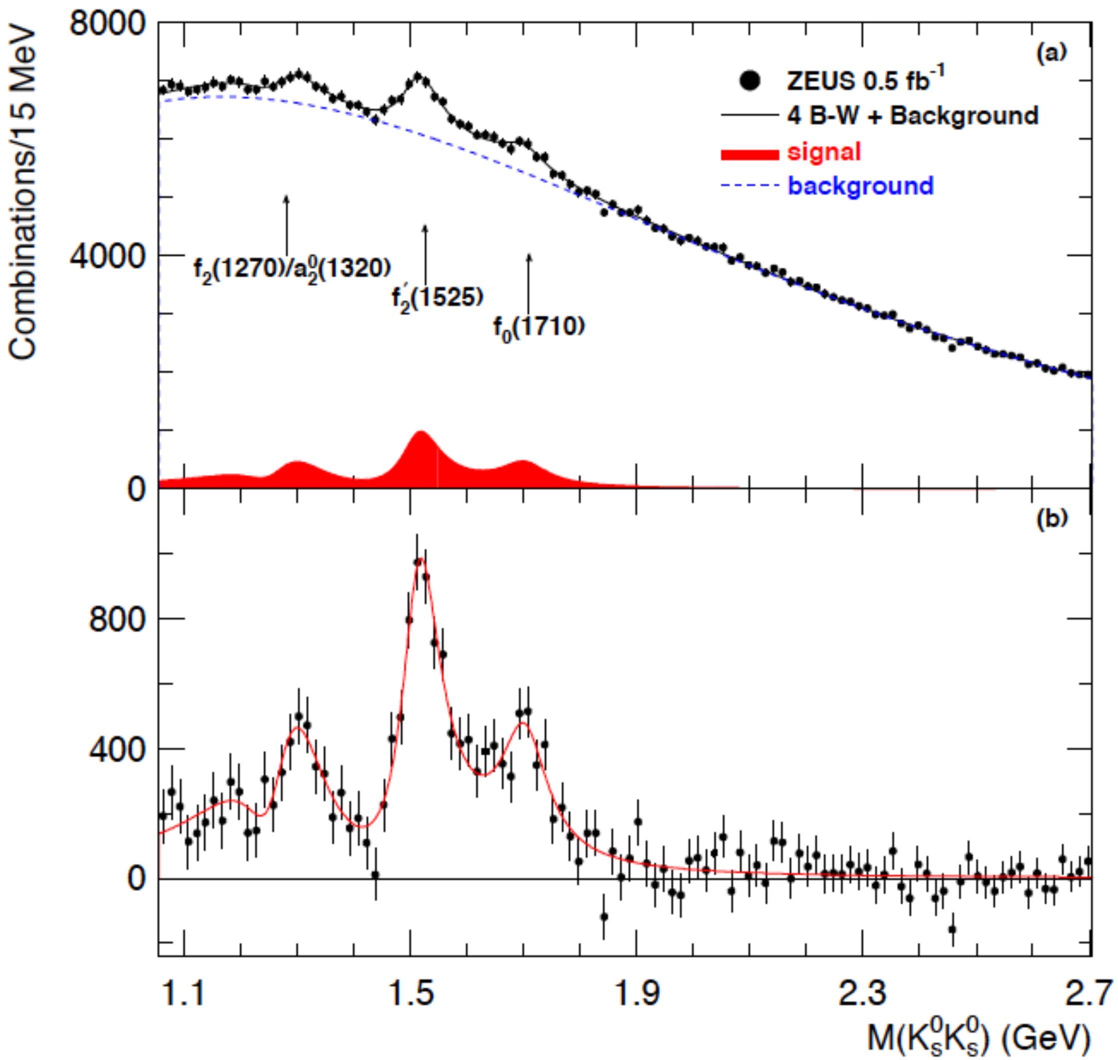
$$A = \frac{\tilde{\sigma}_{NC}(R) - \tilde{\sigma}_{NC}(L)}{\tilde{\sigma}_{NC}(R) + \tilde{\sigma}_{NC}(L)}$$

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





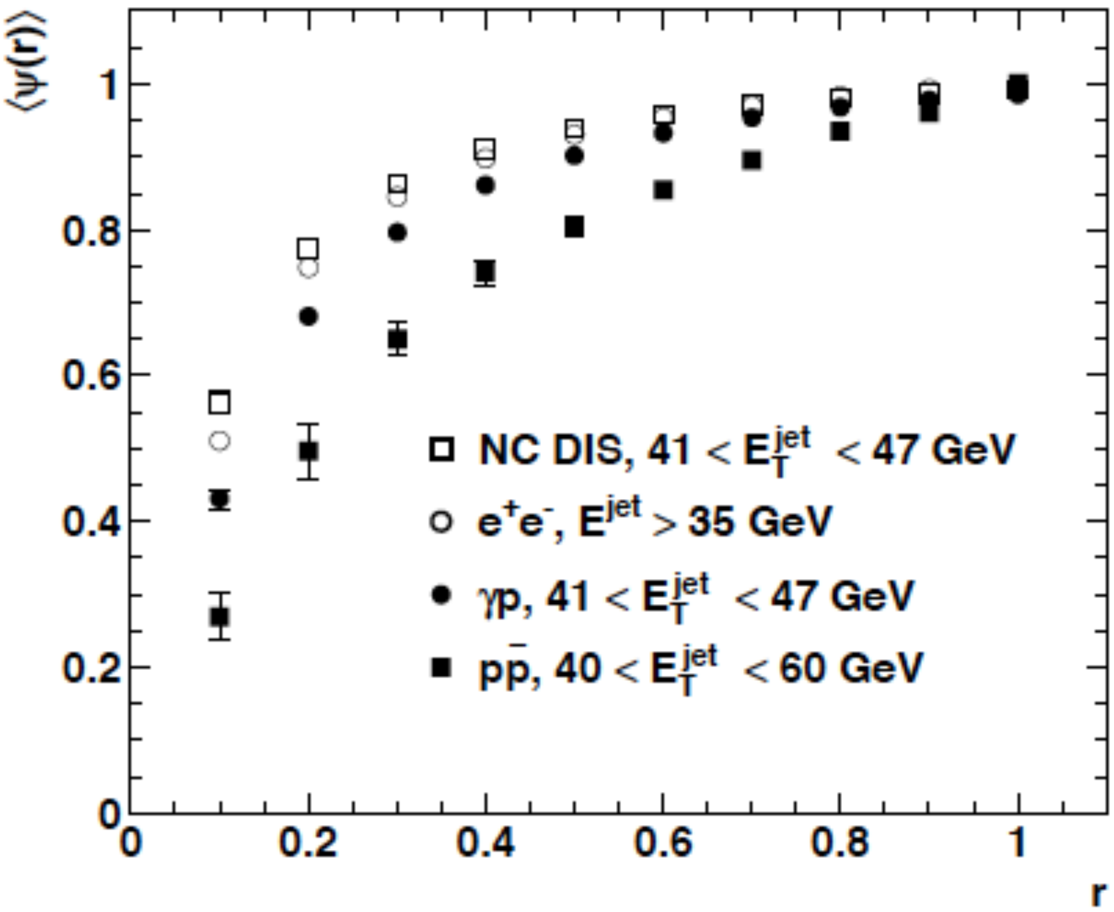
More HERAoism & The Final State:
A selection of personal favourites



4) There were no Pentaquarks,

… but were there
Other strong interaction Exotics …
… Glueballs?
… or instantons
… or odderons?

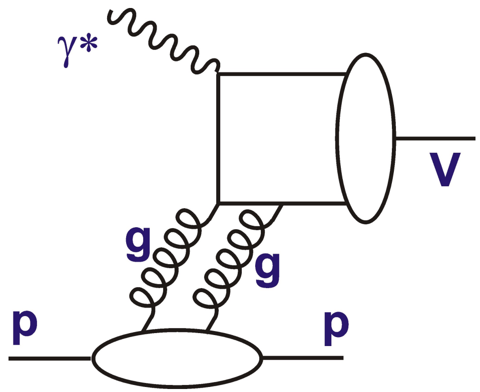
More HERAoism & The Final State: A selection of personal favourites



3) “Pioneered” jet Substructure (cf LHC)
… though there’s Other data here …

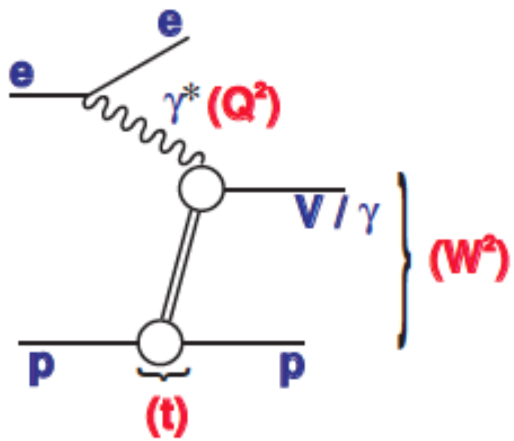
Exclusive/Diffractive Channels & Low x Gluons

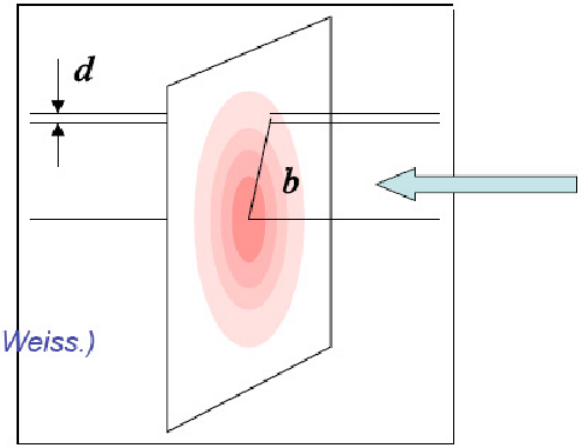
1) [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to low x gluon



2) Additional variable t gives access to impact parameter (b) dependent amplitudes

→ Large t (small b) probes densest packed part of proton?





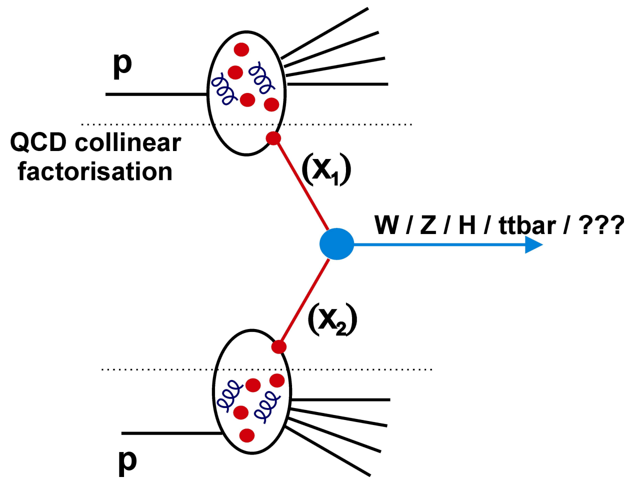
(figure from C. Weiss.)

Central black region growing with decrease of x.

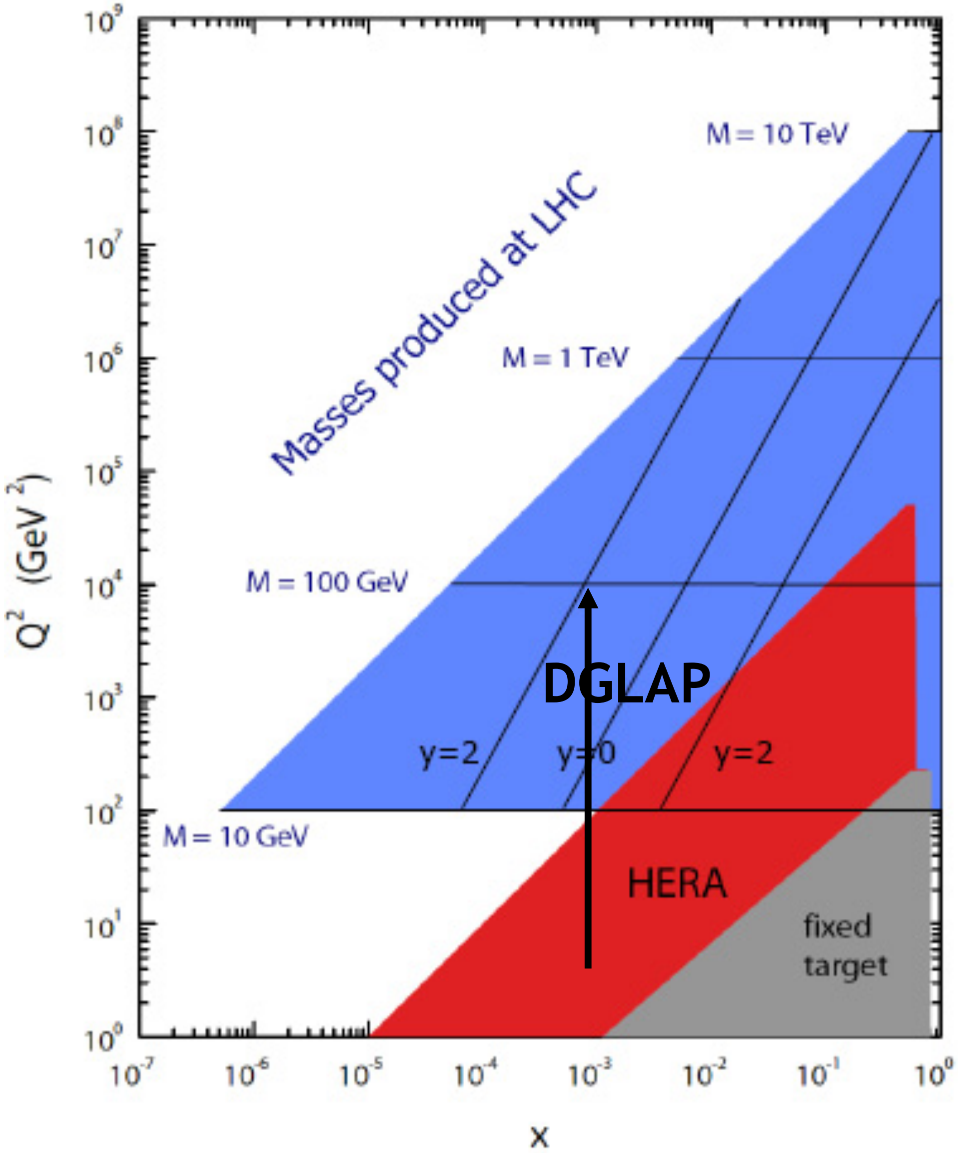
HERA kinematic range

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

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



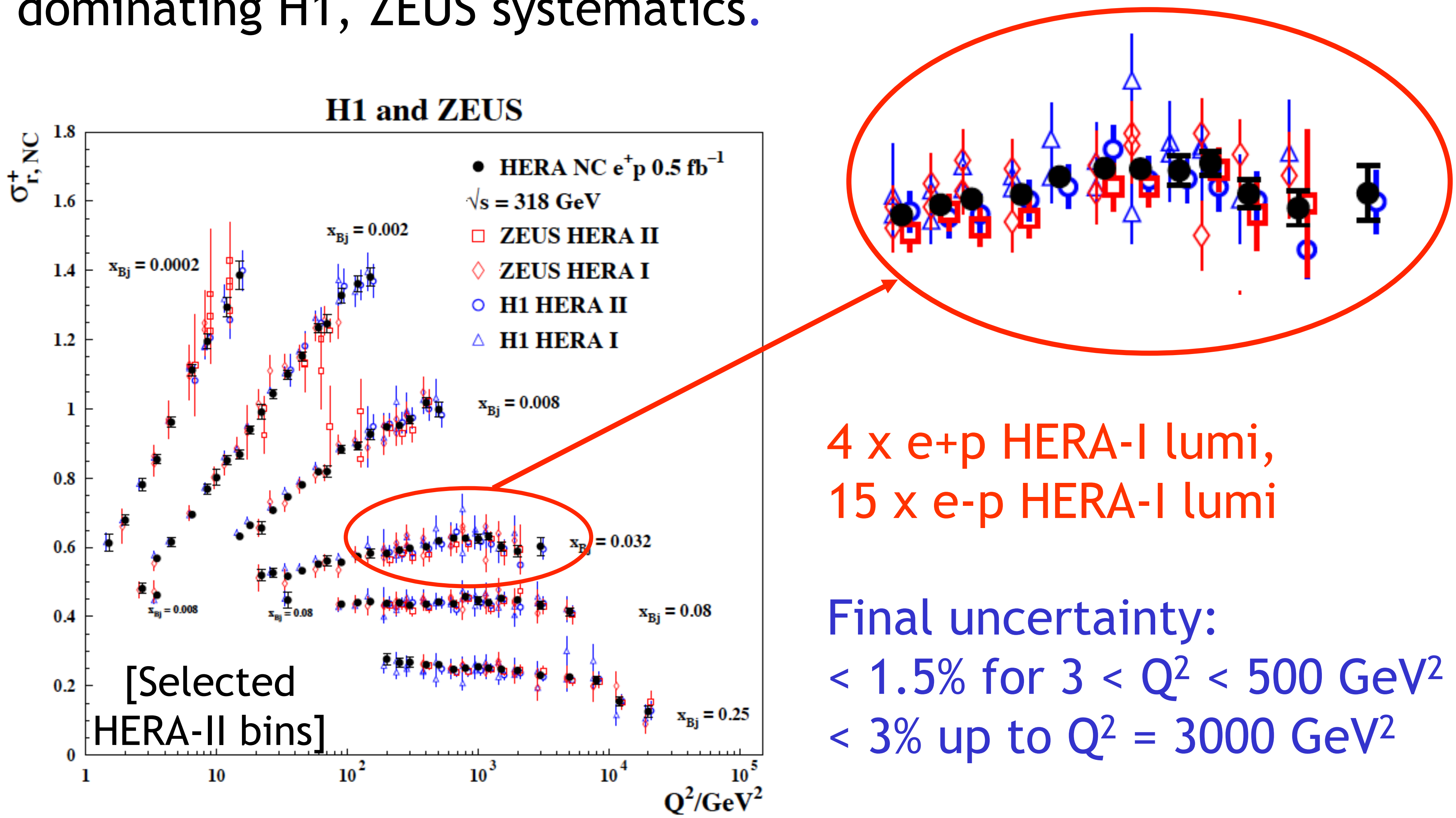
- Well established **`DGLAP' evolution** equations generalise to any scale (for not too small x)



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

The Power of Combinations: Precision Legacy

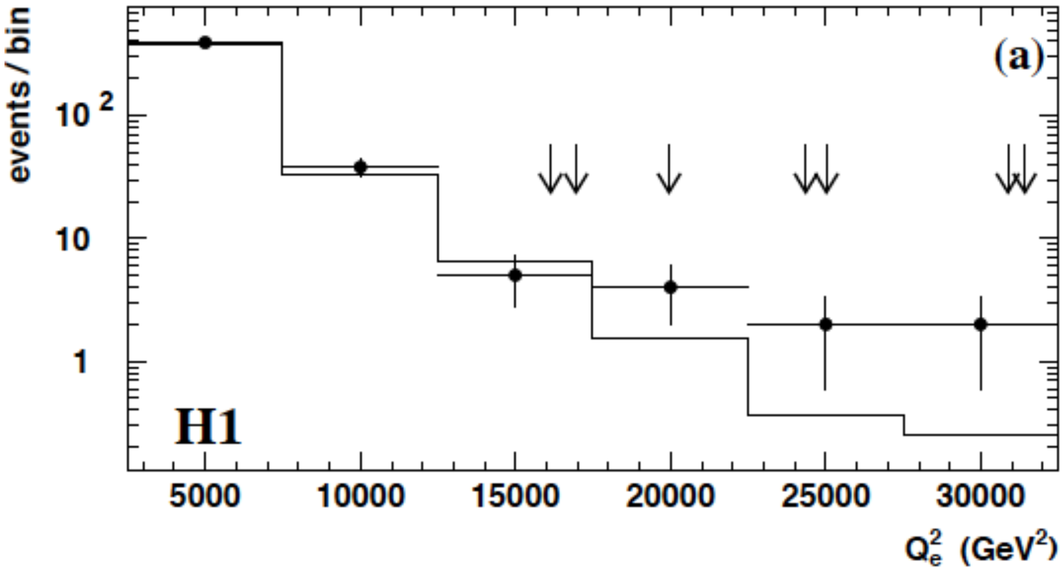
Beyond the √2 statistical improvement, effectively cross-calibrating to tackle (different) dominating H1, ZEUS systematics.

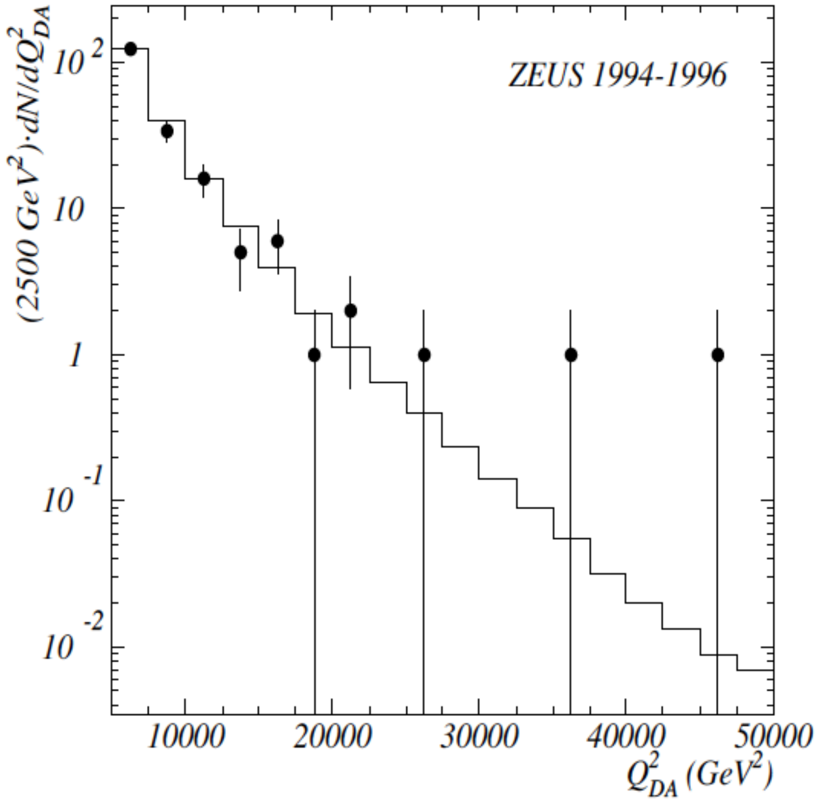


4 x e+p HERA-I lumi,
15 x e-p HERA-I lumi

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

New Physics Legacy?

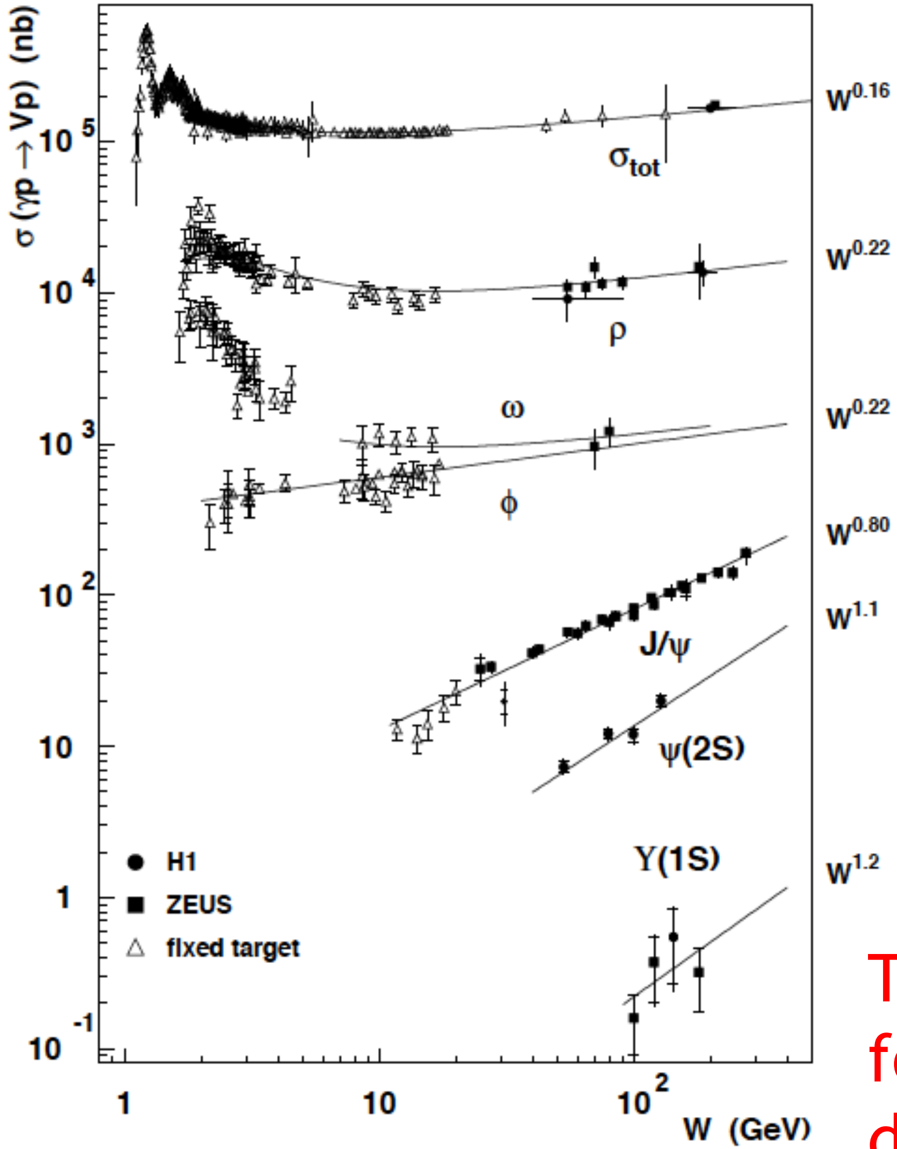


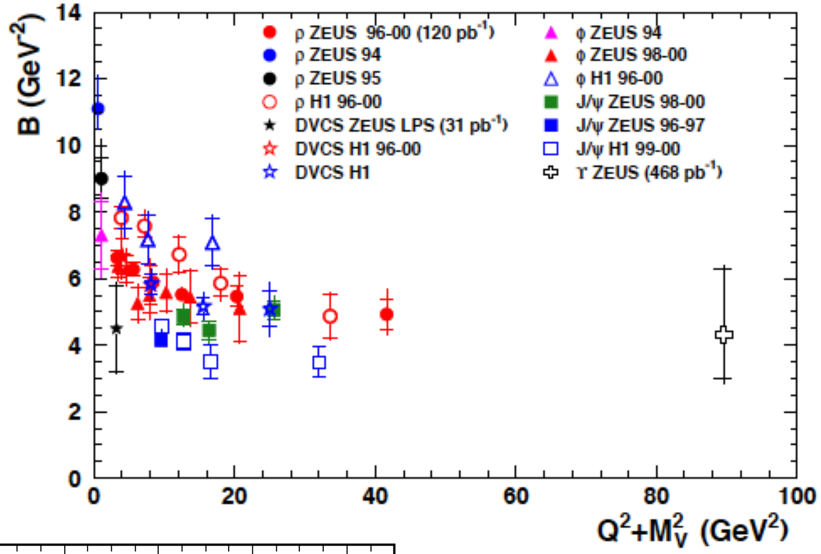


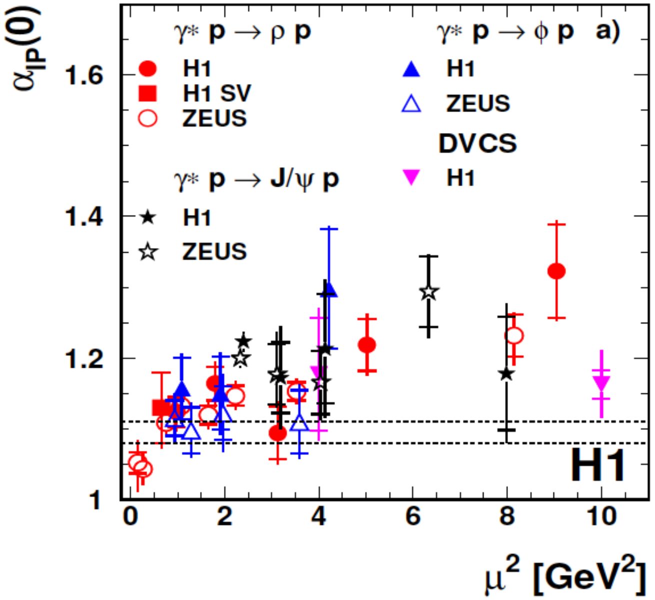
- There were moments of excitement (eg 1997) high Q^2
  … but signal sadly became less significant with further data.

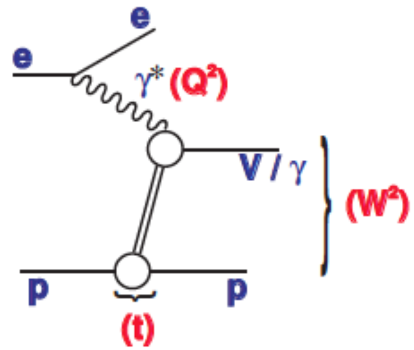
- Despite huge number of searches and some world-leading sensitivity, HERA found the Standard Model …

Switching perturbative QCD on or off







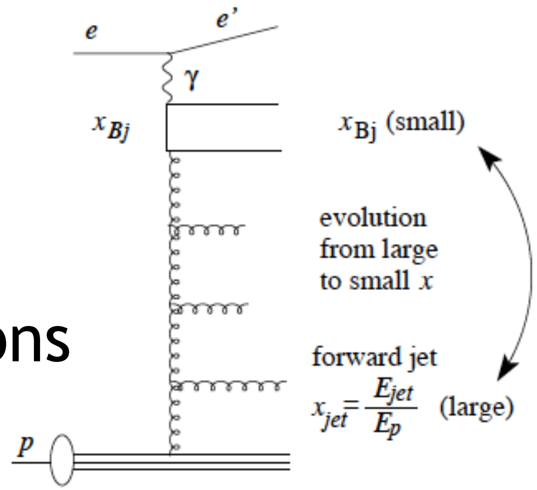


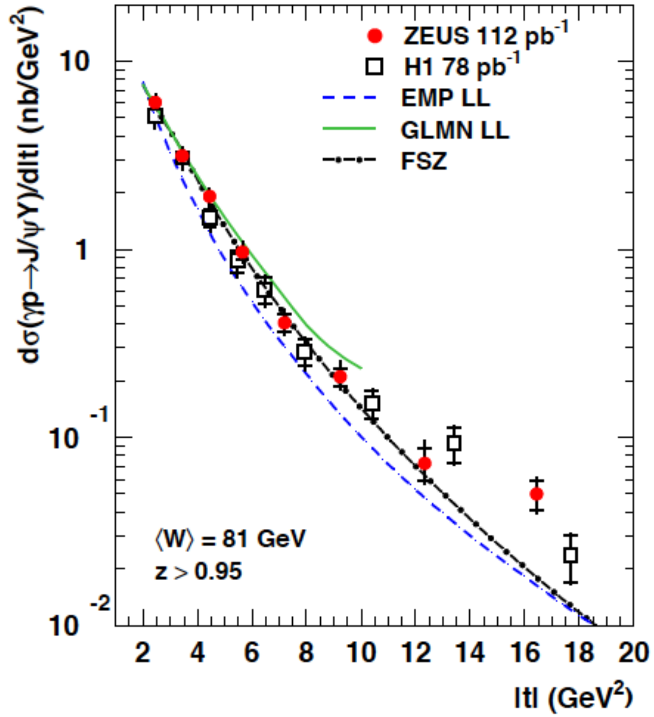
Transition in energy (W) and squared four-momentum transfer (t) dependence as hard scale ($\mu^2 = Q^2$ or M_V^2) turns on

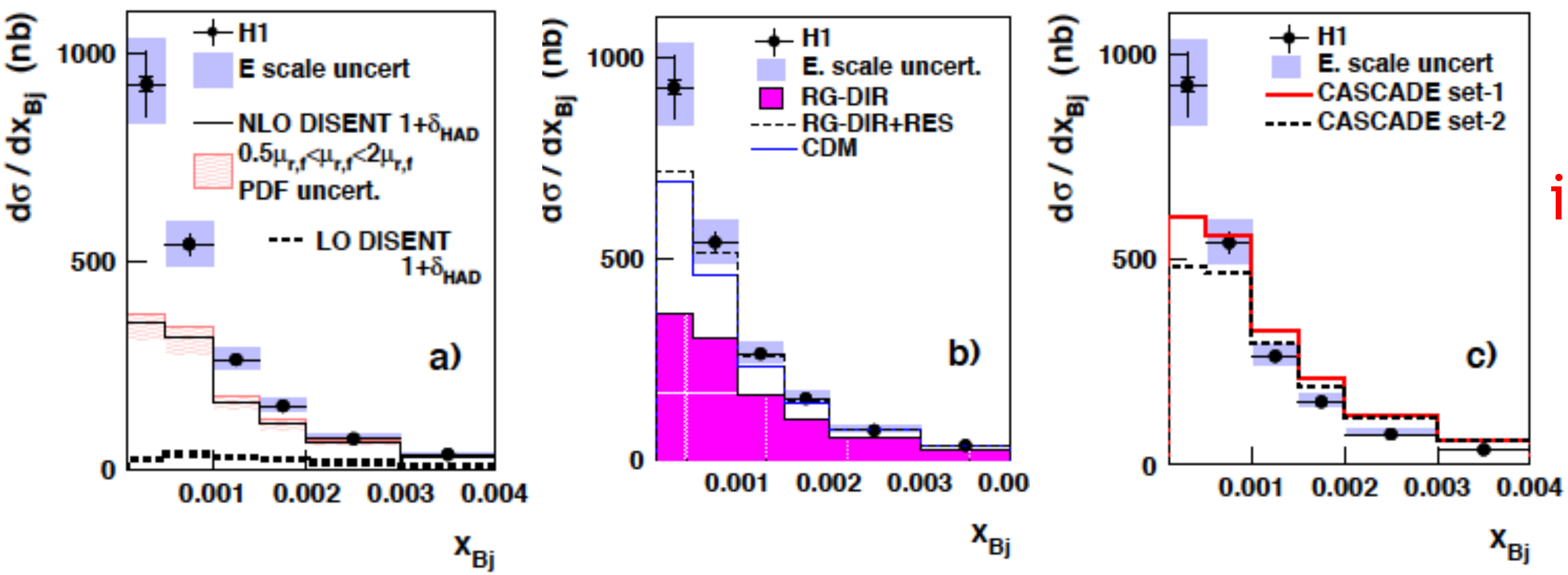
“BFKL” Dynamics in the Low x Hadronic Final State?

Inventive new observables to search for deviations from p_T ordering in the parton cascade …

- Forward jets
- Azimuthal decorrelations
- High |t| p-diss J/Ψ…







Some interesting effects …