Deep Inelastic Scattering at HERA

Outline

- HERA: the end of an era
- Proton Structure: the HERA-I legacy
- Probing the High Q2 Regime
- Final States and the Gluon
- What's Down at Low Q2?

Lepton-Photon 2007, Daegu, Korea

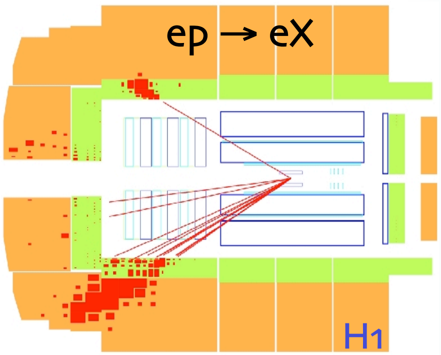
Claire Gwenlan (UCL, STFC Fellow)

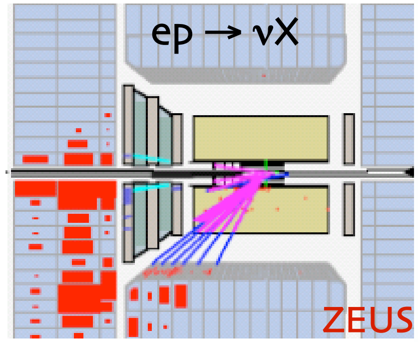
★ = NEW for LP07

HERA Physics:

HERA : wealth of high precision data covering a broad range of subjects

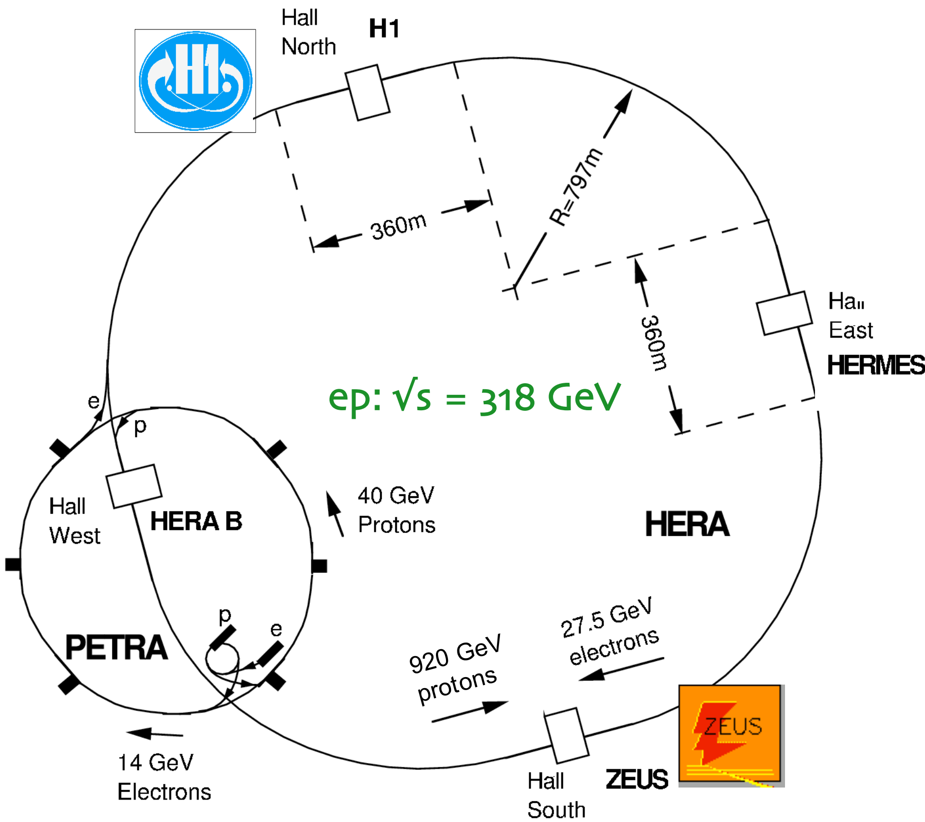
- Proton Structure (and Electroweak) → this talk
  (including some final state measurements)
- QCD at Hadron Colliders → Lance Dixon
- Diffraction → Andrei Rostovtsev
- Searches for Exotic Phenomena → Claude Vallee
- Impact of HERA on LHC → Markus Diehl



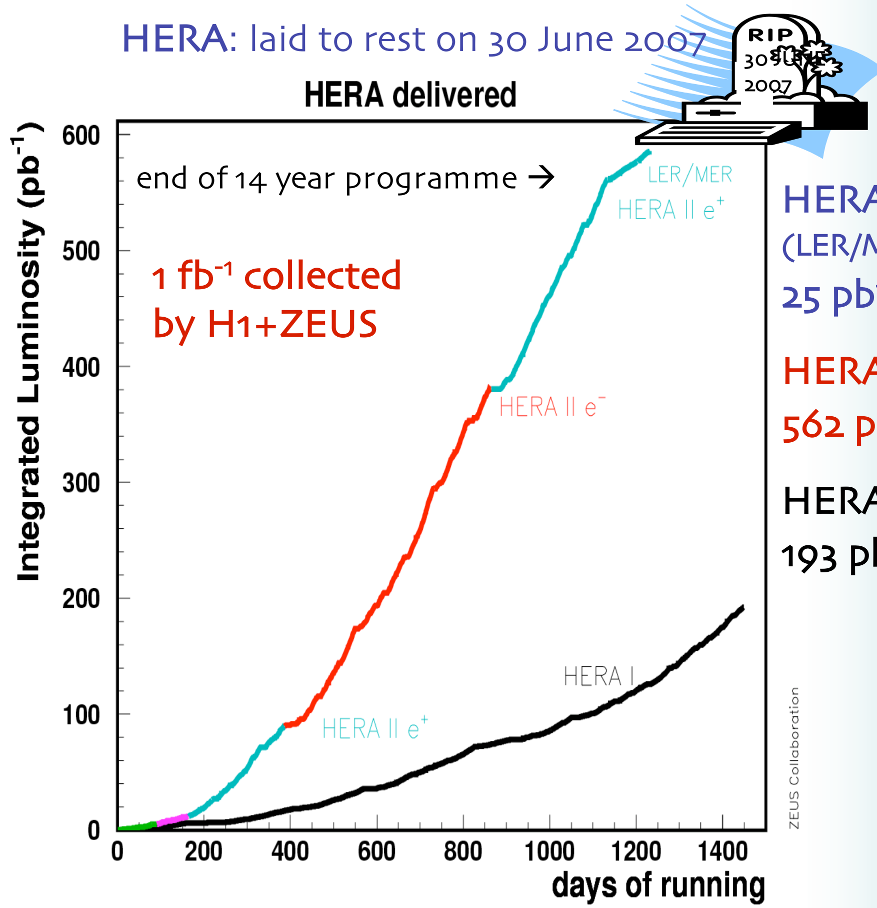


HERA: World's Only ep Collider (in memoriam)

HERA: world's largest "electron-microscope"
(with "resolving power": $Q2 \sim 1/\lambda^2$)



HERA: laid to rest on 30 June 2007



HERA-II (LER/MER): 25 pb^{-1}

HERA-II: 562 pb^{-1}

HERA-I: 193 pb^{-1}

HERA-I: 1993 – 2000

- Precision measurements at low/medium Q2
  … and a glimpse of high Q2 potential

HERA-II: 2002 – 30 June 2007

- High luminosity → larger statistics for high Q2
- Polarised e+/e- beams → direct EW sensitivity
- Detector upgrades → heavy flavour
- LER/MER (last 3 months) → FL

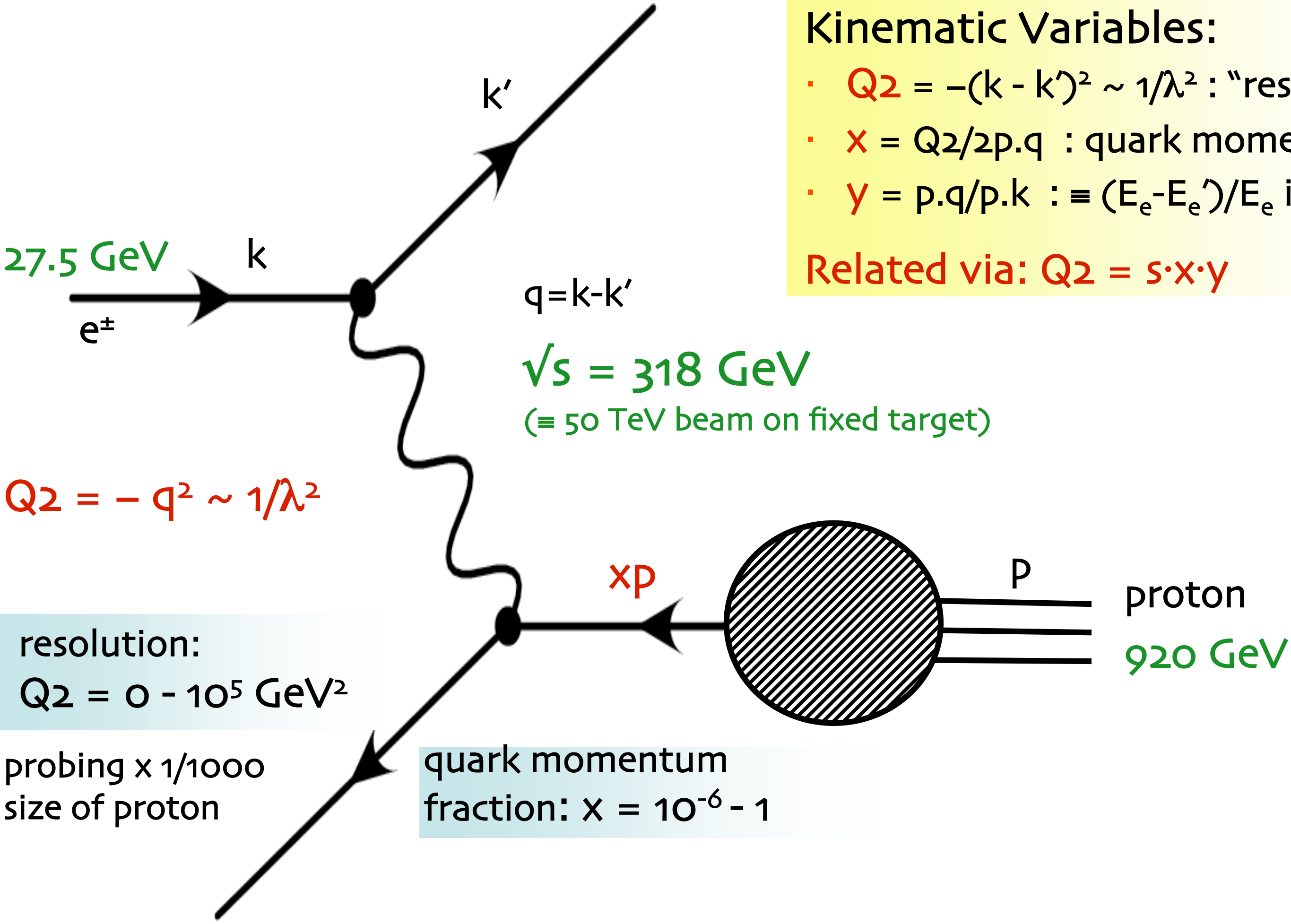
Deep Inelastic Scattering at HERA

Kinematic Variables:

- Q2 = $-(k - k')^2 \sim 1/\lambda^2$: "resolution"
- x = Q2/2p.q : quark momentum fraction
- y = p.q/p.k : ≡ $(E_e - E_e')/E_e$ in p rest frame

Related via: Q2 = s·x·y

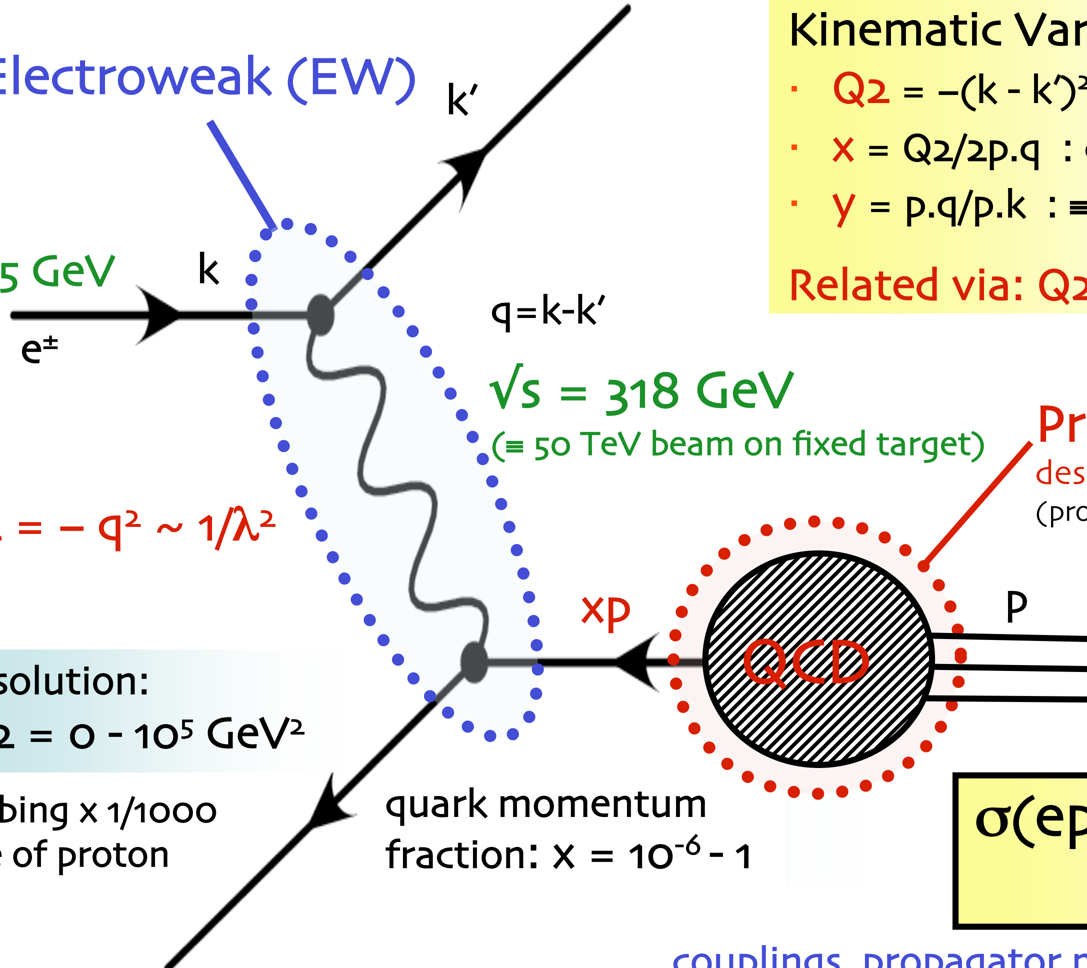
[Reconstructed from scattered e or HFS]



Deep Inelastic Scattering at HERA

Electroweak (EW)

27.5 GeV



$\sqrt{s}$ = 318 GeV
(≡ 50 TeV beam on fixed target)

$Q2 = -q^2 \sim 1/\lambda^2$

resolution:
$Q2 = 0 - 10^5\ GeV^2$

probing x 1/1000
size of proton

quark momentum
fraction: $x = 10^{-6} - 1$

proton
920 GeV

Kinematic Variables:

- $Q2 = -(k - k')^2 \sim 1/\lambda^2$: "resolution"
- $x = Q2/2p.q$: quark momentum fraction
- $y = p.q/p.k$: $\equiv (E_e - E_e')/E_e$ in p rest frame

Related via: $Q2 = s \cdot x \cdot y$

[Reconstructed from scattered e or HFS]

Proton Structure

described by parton density functions (PDFs):
(prob. of finding parton (q,g) with x at resolution Q2)

$$\sigma(ep) \sim \Sigma\, \sigma(eq) \otimes \text{PDF}$$
EW ⊗ QCD

couplings, propagator mass, … ↗ ↗ proton structure

DIS @ HERA: 1) a "super-microscope" to study Proton Structure (PDFs)
2) sensitivity to EW (through t-channel gauge boson exchange)

HERA: a Rough Guide

Neutral Current:

$$\frac{d^2\sigma_{NC}(e^{\pm}p)}{dxdQ^2} \sim \frac{2\pi\alpha^2}{x}\frac{1}{Q^4}\left(Y_+ F_2 \mp Y_- xF_3 - y^2 F_L\right)$$

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

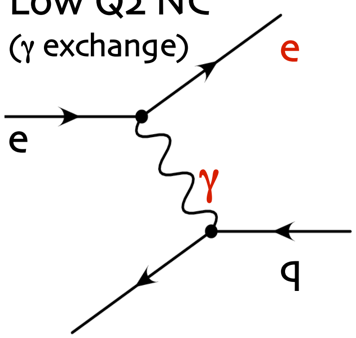
Modified at high Q2 by Z propagator

Charged Current:

$\sigma_{CC}(e^+p) \sim (1-y)^2 (d+s) + (ubar+cbar)$

$\sigma_{CC}(e^-p) \sim (u+c) + (1-y)^2 (dbar+sbar)$

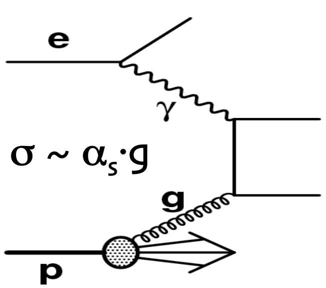
Low Q2 NC
(γ exchange)

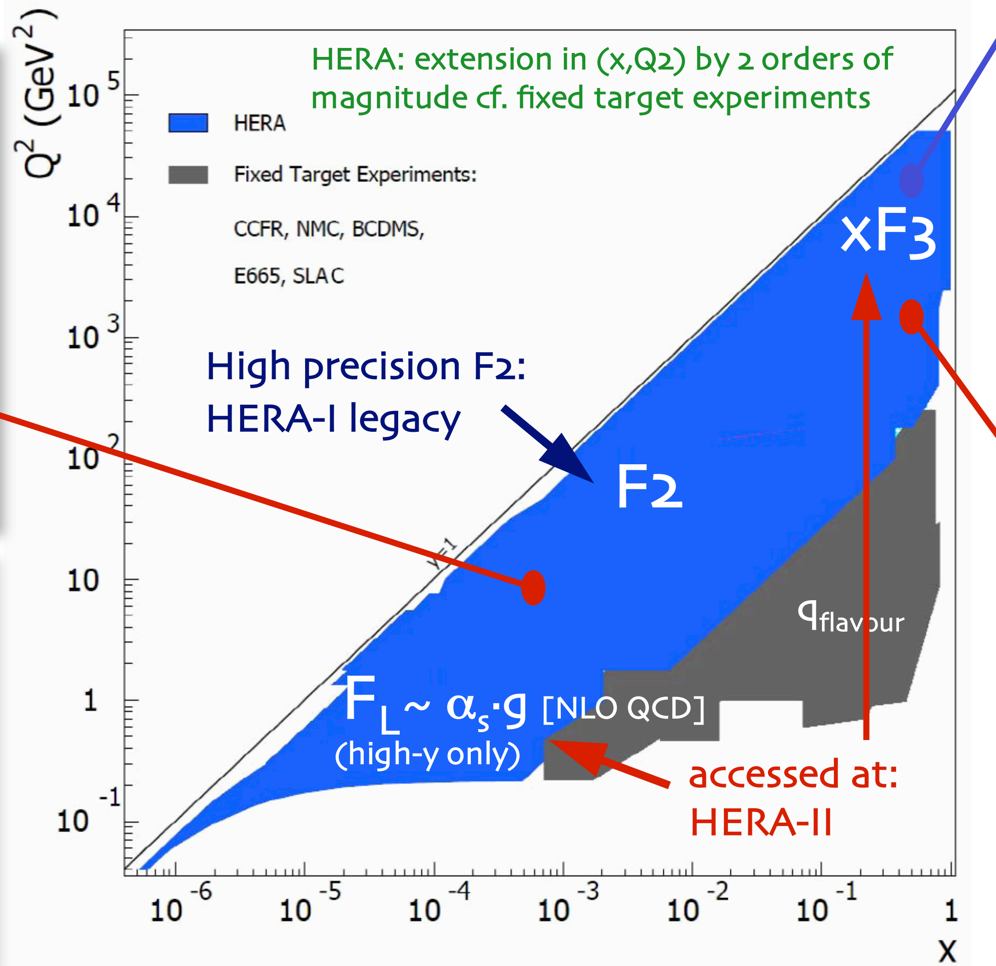


$F_2 \sim \Sigma x\,(q+qbar)$

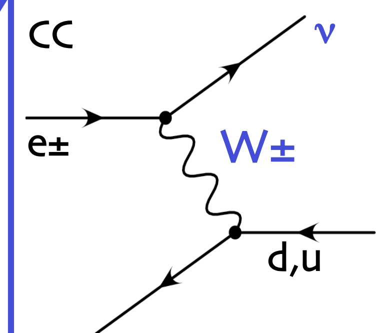
$dF_2/d\ln Q^2 \sim \alpha_s \cdot g$

Final States:
(Jets, Charm, …)



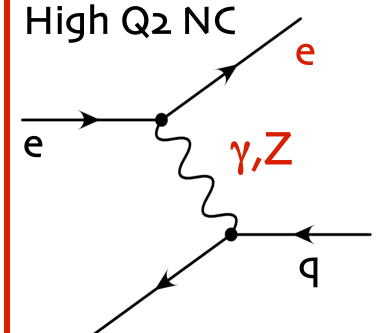


CC



flavour composition
e+: d   e-: u

High Q2 NC



Z → Parity Violation

$xF_3 \sim \Sigma x\,(q-qbar)$ valence

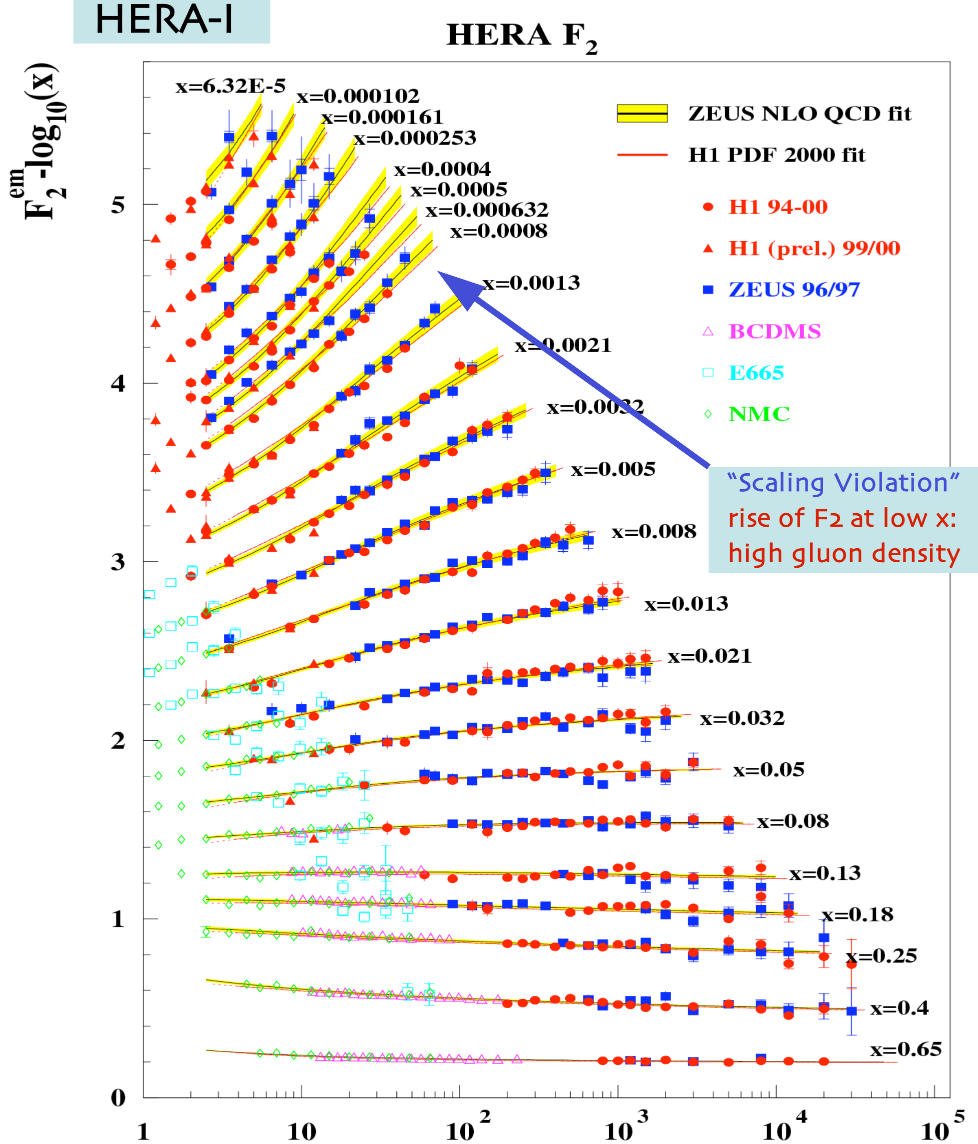
Measure σ → fit data → extract PDFs and EW

I. Proton Structure: the HERA-I Legacy

- F_2 and the Low-x Sea and Gluon
- HERA Proton PDFs

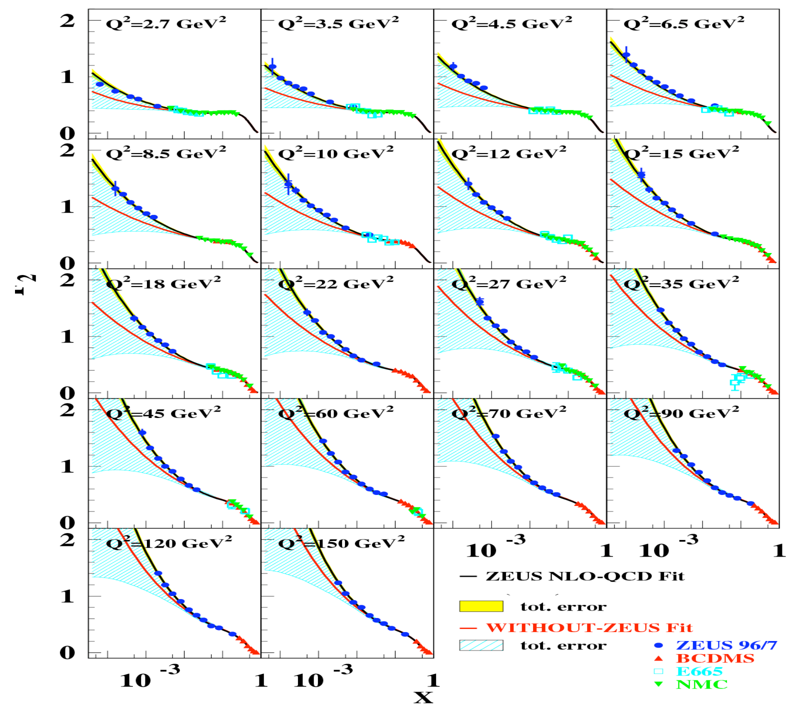
HERA F2

HERA-I



"What HERA is famous for!"

What we would$^{(n't)}$ know without HERA:



$F_2 \sim \Sigma x\,(q+\bar{q})$ | $dF_2/d\ln Q^2 \sim g$

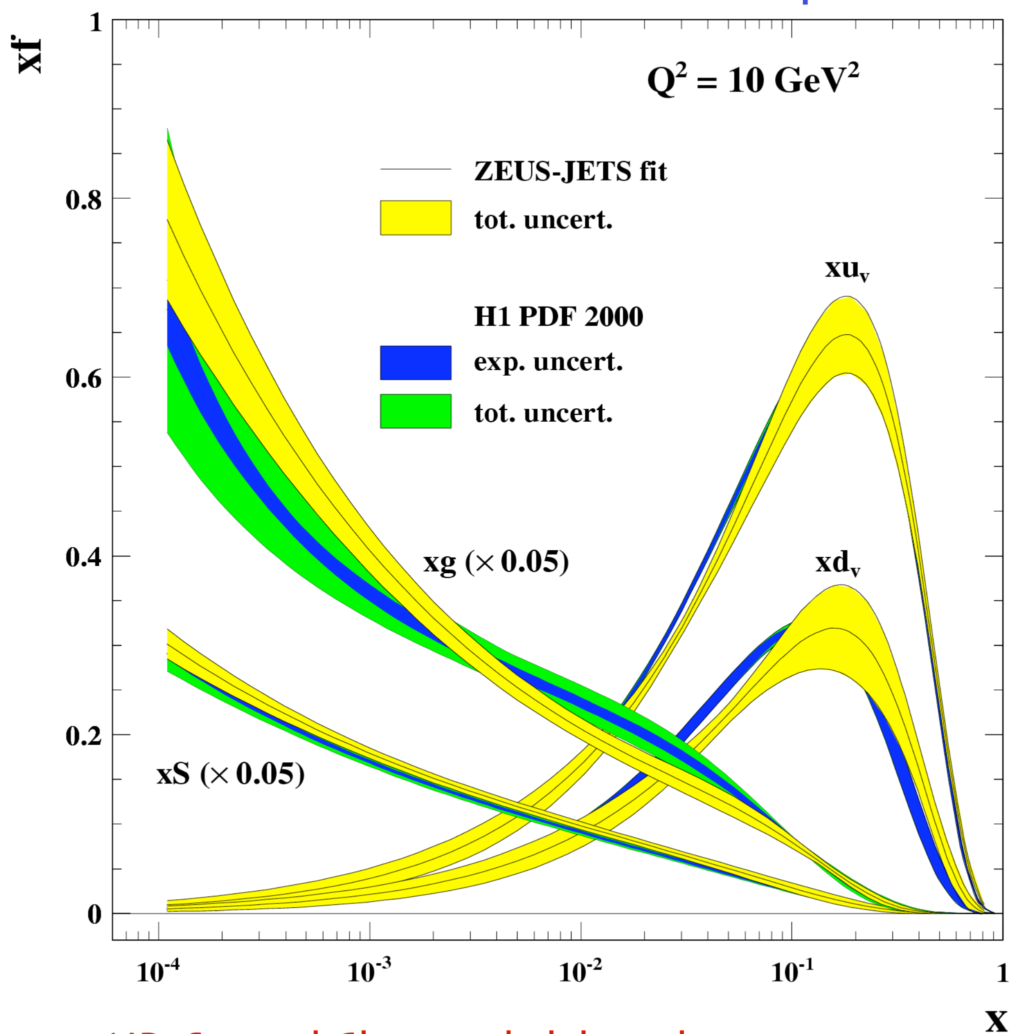
- HERA-I F2 precision: ~ 2-3% (systs. limited)
- NLO QCD describes F2 over 4 orders of mag. in (x,Q2), including scaling violation
- Low-x sea and gluon precisely determined!!!

HERA Proton PDFs

NLO QCD DGLAP fit for PDFs:
(to HERA data only)

- HERA-I (F2) famously constrains the low-x sea quarks and gluon (x: 10^{-1}~10^{-4})
- Additional information on: q_v (high-Q2 NC/CC); high-x g (Jets)

PDFs from HERA-I: ~ 120 pb-1



NB. Sea and Gluon scaled down by x20

PDF Fits (the basics)

- Parameterise PDFs in x at low $Q2_0$
- Evolve in Q2 (NLO DGLAP)
- Fit NLO QCD PDFs to data (constrained by sum rules and assumptions)

→ extract q,g PDF parameters

HERA Proton PDFs

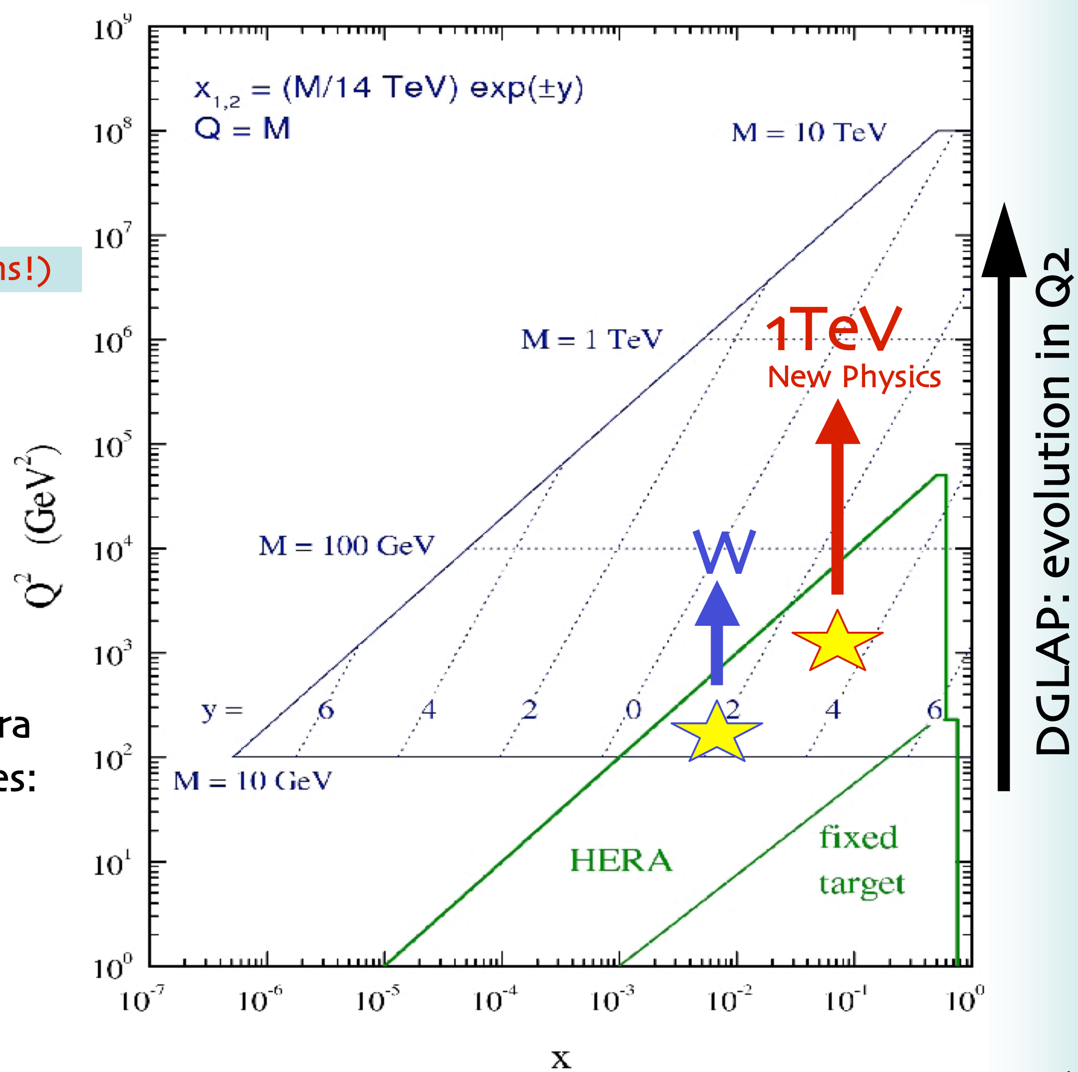
NLO QCD DGLAP fit for PDFs:
(to HERA data only)

- HERA-I (F2) famously constrains the low-x sea quarks and gluon (x: 10^{-1}~10^{-4}) ← Main LHC region (gluons!)
- Additional information on: q_v (high-Q2 NC/CC); high-x g (Jets)

HERA PDFs extrapolate to LHC
Crucial input for SM/BSM @ LHC
→ need precise q,g over all x

NOW @ HERA: higher statistics/extra kinematic reach/new analysis techniques:
→ further PDF constraints
→ exploration at the EW scale

Basis of the rest of this talk!!!



II. Probing the High Q2 Regime

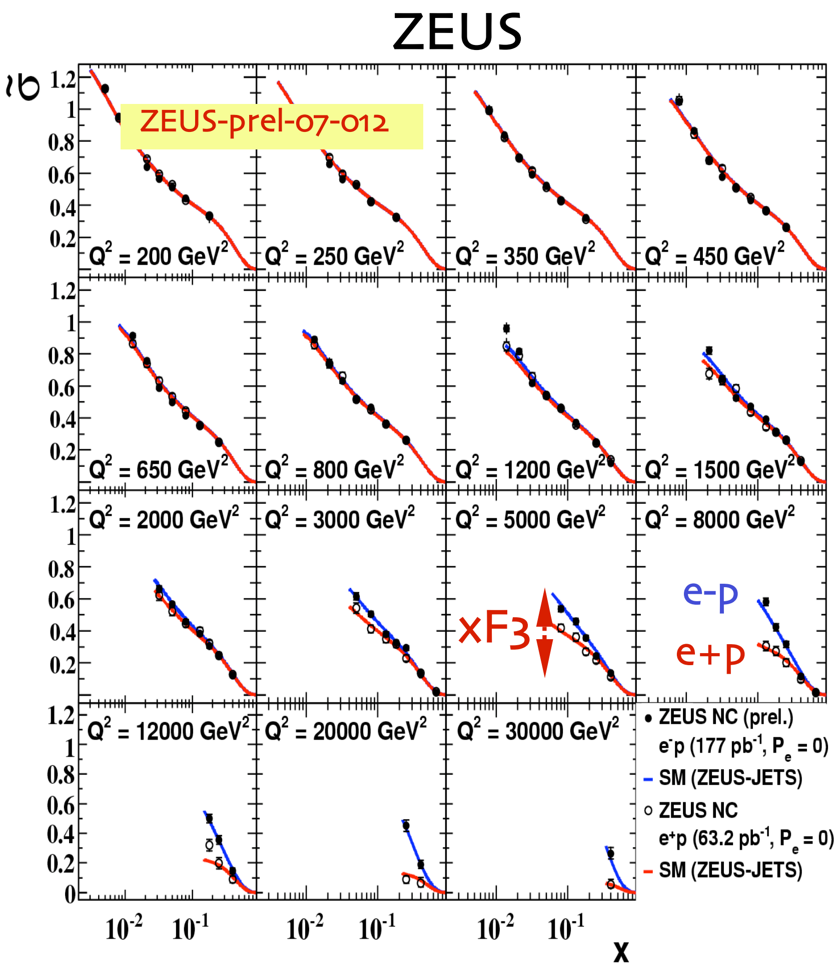
- Proton Structure at High Q2
- EW Physics with Polarisation at HERA
  → RH CC Cross Sections
  → Weak Parity Violation in NC
  → Combined QCD+EW fits

Valence Quarks and xF3

HERA-I+II

$\tilde{\sigma}_{NC}(e^{\pm}p) \sim Y_+ F2 \mp Y_- xF3$ (neglecting F_L)

(γZ interference flips sign ↑)



New HERA-II high precision e-p data at high Q2

(HERA-II delivered > x10 e-p cf. HERA-I)

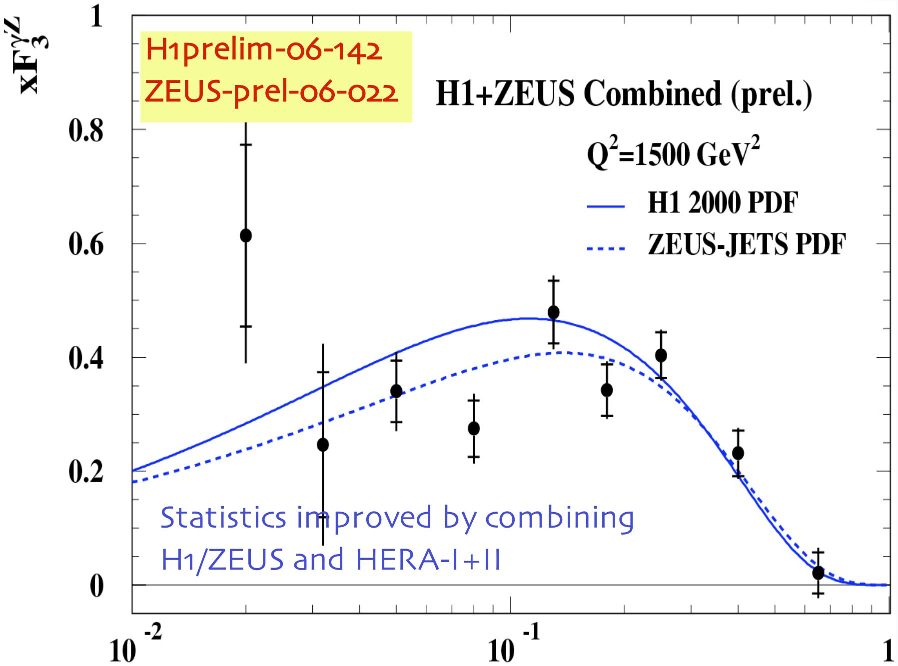
- σ(e-p) > σ(e+p) at high Q2 (sign flip)

  → extract xF3 from difference

$xF3 \sim \sigma(e^-p) - \sigma(e^+p) \sim 2/3u_v + 1/3d_v$

(assuming SM EW couplings ↑)

- Important information on valence quarks in the proton (x < 0.1)



xF3: First combined H1+ZEUS SF result (using ~ 1/2 full HERA dataset)

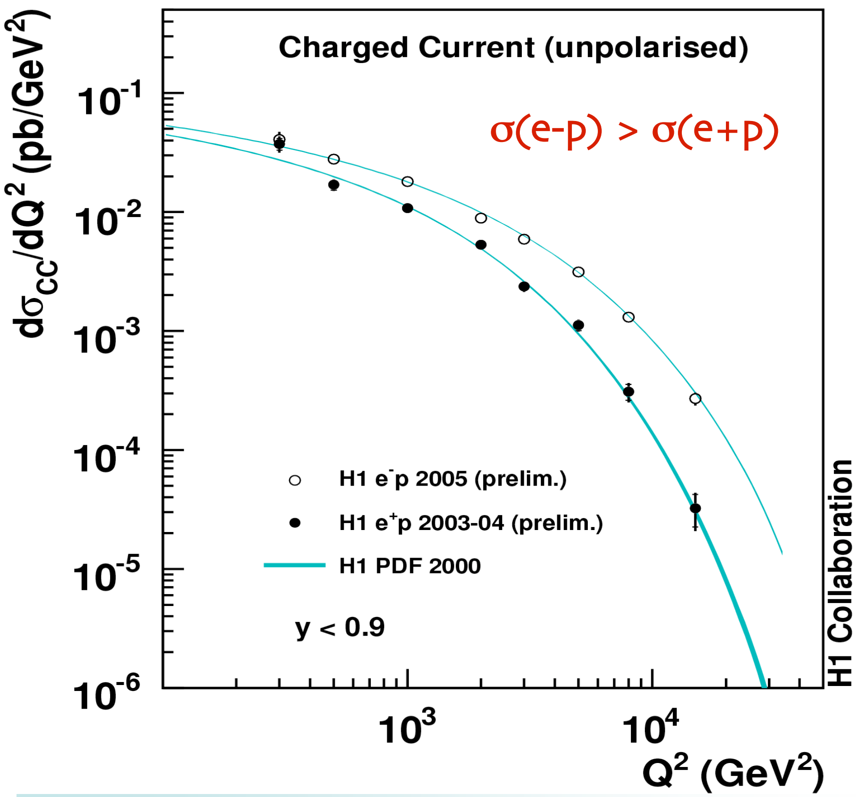
↖ simple weighted average

CC DIS and Quark Flavour

$\tilde{\sigma}_{CC}(e^+p) \sim (\text{ubar}+\text{cbar}) + (1-y)^2 (d+s)$
$\tilde{\sigma}_{CC}(e^-p) \sim (u+c) + (1-y)^2 (\text{dbar}+\text{sbar})$

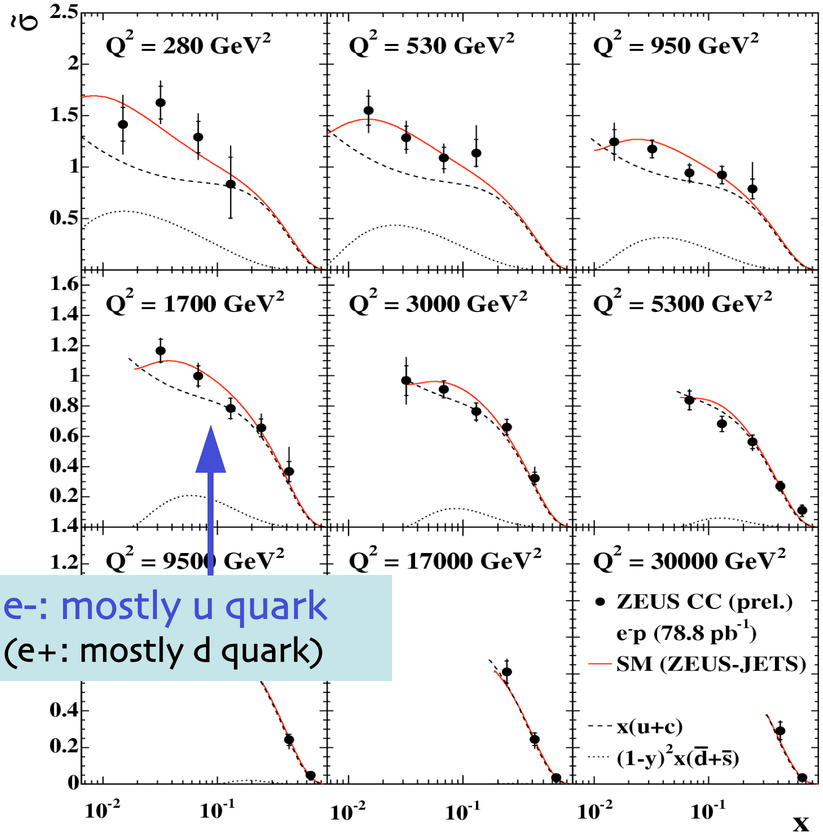
- Clear difference in e+p/e-p CC cross sections (helicity factors and PDFs)

H1prelim-06-041 H1 Preliminary



CC e-p (e+p) unique for constraining u (d)

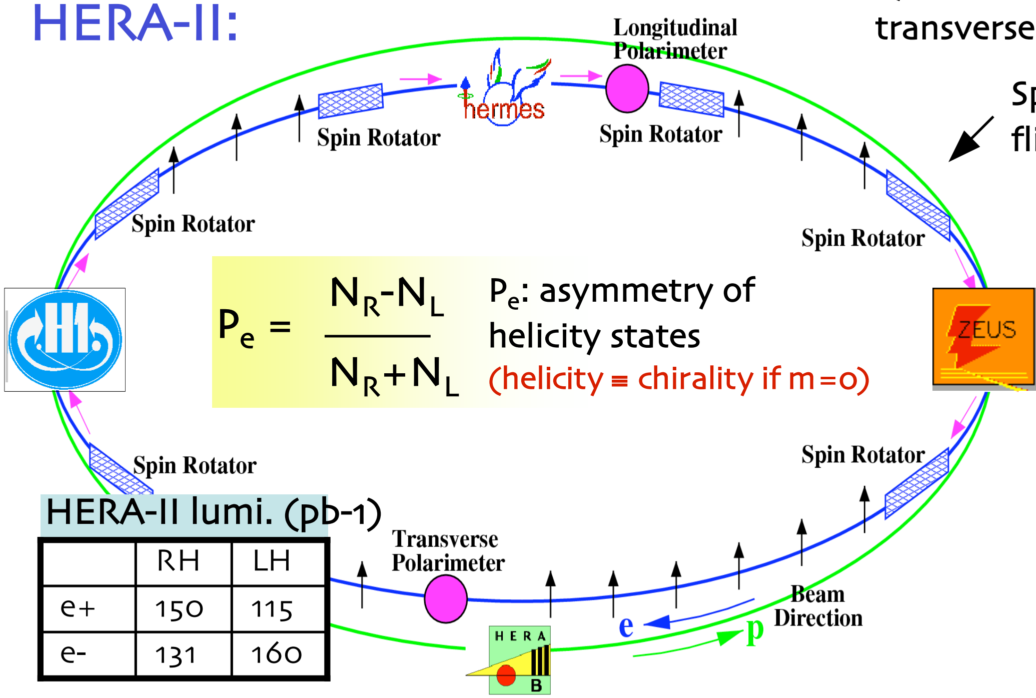
ZEUS-prel-06-002 ZEUS HERA-II



- Large increase in statistics at HERA-II (especially e$^-$) constrains flavour composition of proton at high x using HERA data alone
(avoids nuclear corrections from fixed target data)

EW Physics with Polarised Lepton Beams

HERA-II:



$$P_e = \frac{N_R - N_L}{N_R + N_L}$$

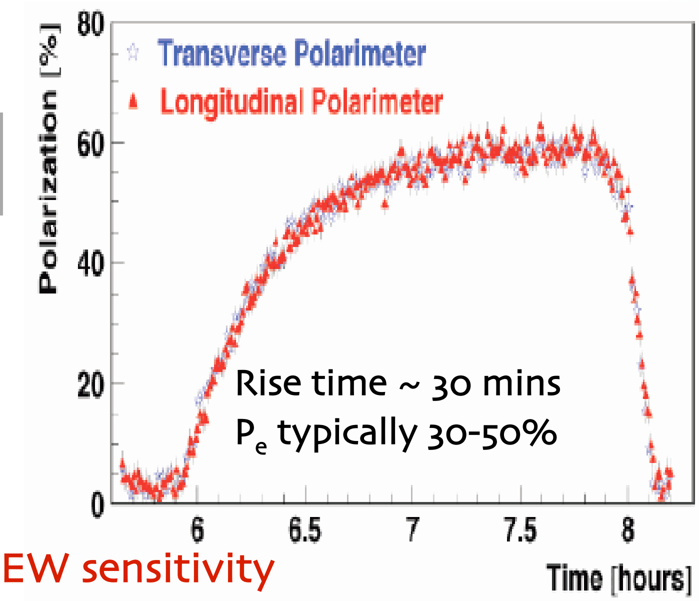
P_e: asymmetry of helicity states (helicity ≡ chirality if m=0)

HERA-II lumi. (pb-1)

	RH	LH
e+	150	115
e-	131	160

Synchrotron radiation off lepton induces transverse polarisation (Sokolov-Ternov effect)

Spin rotators (installed during HERA-II upgrade) flip transverse and longitudinal polarisation



Rise time ~ 30 mins

P_e typically 30-50%

HERA-II: Longitudinally polarised leptons → direct EW sensitivity

(directly test chiral structure of SM: RH ≠ LH ⇔ parity violation)

CC: pure weak = 100% parity violating in SM → only LH particles (RH anti-particles) interact

cross section modified by linear scale factor: $\sigma^{\pm}_{CC}(P_e) = (1 \pm P_e)\, \sigma^{\pm}_{CC}(P_e = 0)$ ← $\sigma_{CC}=0$ for RH particles

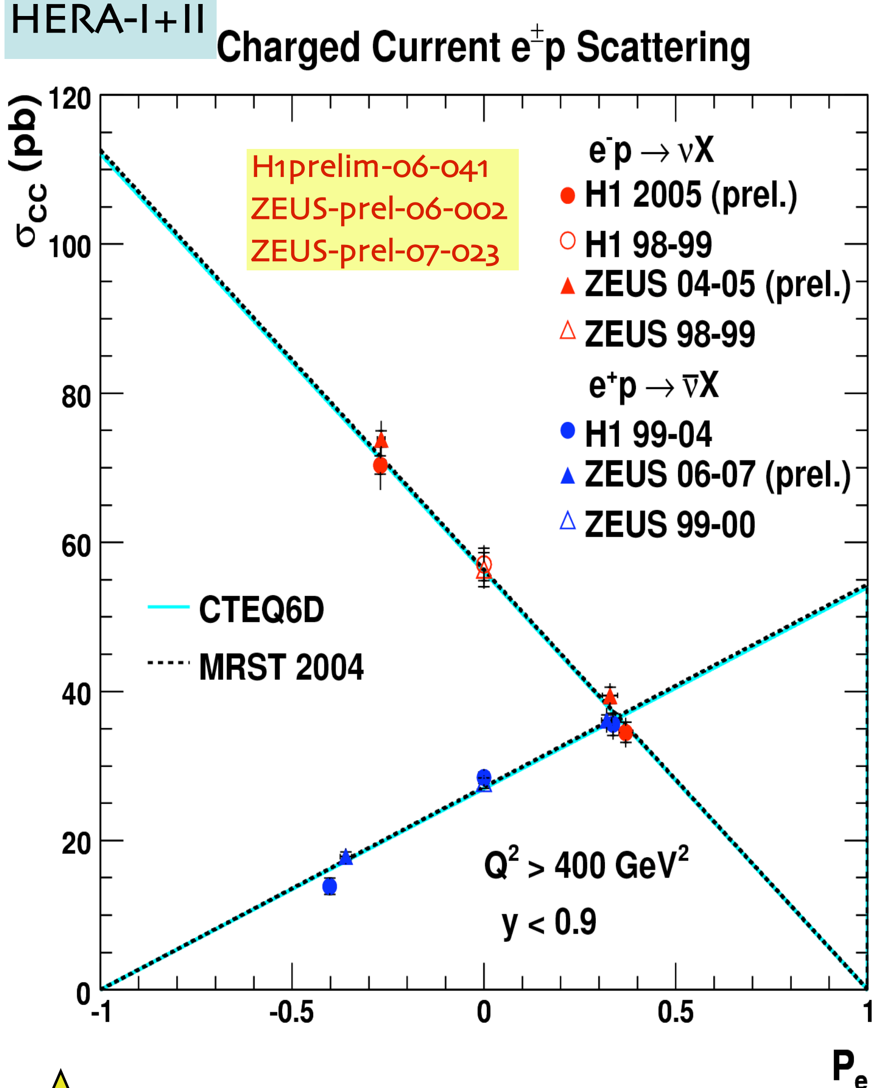
NC: weak parity violation through γZ interference and pure Z → visible only at high Q2

(γZ, Z terms contain EW parameters: quark couplings to Z, $\sin^2\theta_W$, M_Z,...)

Investigate both CC and NC....

CC Polarisation Dependence

HERA-I+II



ZEUS 06-07 (prel.) NEW for EPS07/LP07

$\sigma^{\pm}_{CC}(P_e) = (1 \pm P_e)\, \sigma^{\pm}_{CC}(P_e = 0)$

Linear dependence demonstrated

Extrapolation to $P_e = \pm 1$ → limits on RH σ_{CC}

$\sigma_{CC}(e^-p)$ [pb] extrapolated to P_e = +1	
H1 (prel.)	$-0.9 \pm 2.9_{stat} \pm 1.9_{syst} \pm 2.9_{pol}$
ZEUS (prel.)	$0.8 \pm 3.1_{stat} \pm 5.0_{syst+pol}$

$\sigma_{CC}(e^+p)$ [pb] extrapolated to P_e = -1	
H1 (pub.)	$-3.9 \pm 2.3_{stat} \pm 0.7_{syst} \pm 0.8_{pol}$
ZEUS (pub.)	$7.4 \pm 3.9_{stat} \pm 1.2_{syst+pol}$

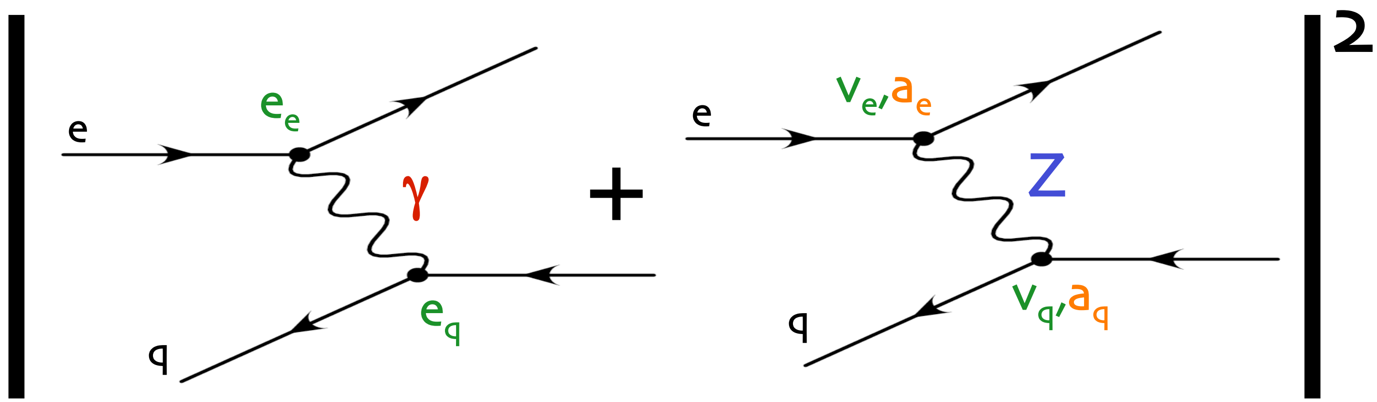
Consistent with NO RH Charged Currents!

Convert to 95% CL on heavy W_R boson
(assuming $g_L = g_R$ and ν_R is light):

- M_{WR} > 208 GeV (H1, e+p)
- M_{WR} > 186 GeV (H1, e-p)
- M_{WR} > 180 GeV (ZEUS, e-p)

Complementary to Tevatron direct searches
cf. W' > 786 GeV by CDF (W' → eν,μν)

Polarisation Effects in NC



Polarisation effects are subtle in NC DIS

Reduced cross section: $\sigma_{NC}(e^{\pm}p) \sim Y_+ F2 \mp Y_- xF3$ κ_Z ~ Z propagator

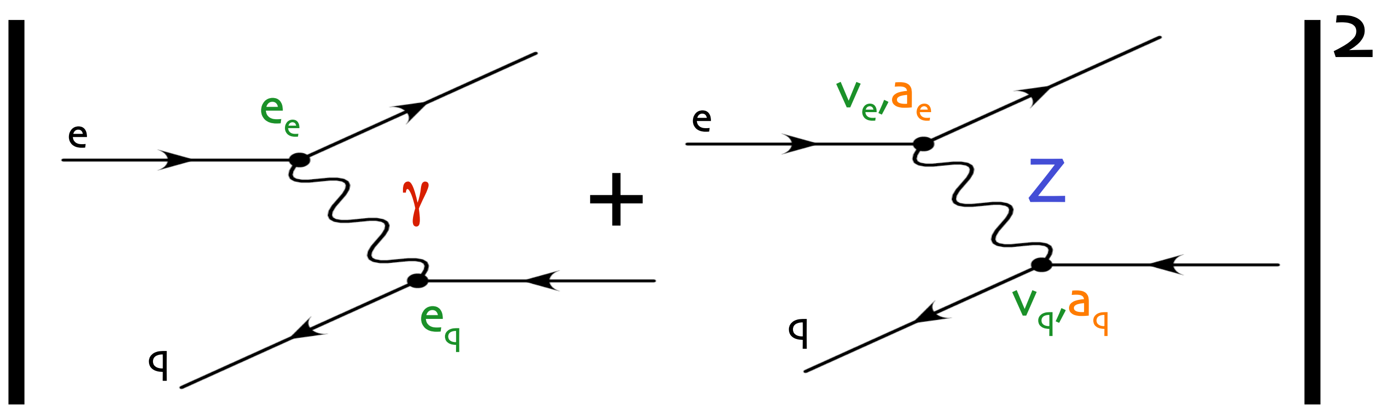
$$F2(\pm Pe) = F2^{\gamma} - (v_e \pm Pe\, a_e)\, \kappa_Z\, F2^{\gamma Z} + ((v_e^2+a_e^2) \pm Pe\, 2v_e a_e)\, \kappa_Z^2\, F2^Z$$

$$xF3(\pm Pe) = - (a_e \pm Pe\, v_e)\, \kappa_Z\, xF3^{\gamma Z} + (2v_e a_e \pm Pe\, (v_e^2+a_e^2))\, \kappa_Z^2\, xF3^Z$$

Weak parity violating effect though γZ interference and pure Z → high Q2 only

γZ dominates (pure Z suppressed by additional propagator i.e. $\kappa_Z >> \kappa_Z^2$ and $v_e \approx 0.04$)

Polarisation Effects in NC



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Weak parity violating effect though γZ interference and pure Z → high Q2 only

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EW structure functions in QPM (γZ):

$F2^{\gamma Z} = 2\, e_q v_q\, \Sigma x(q+qbar)$

$xF3^{\gamma Z} = 2\, e_q a_q\, \Sigma x(q-qbar)$

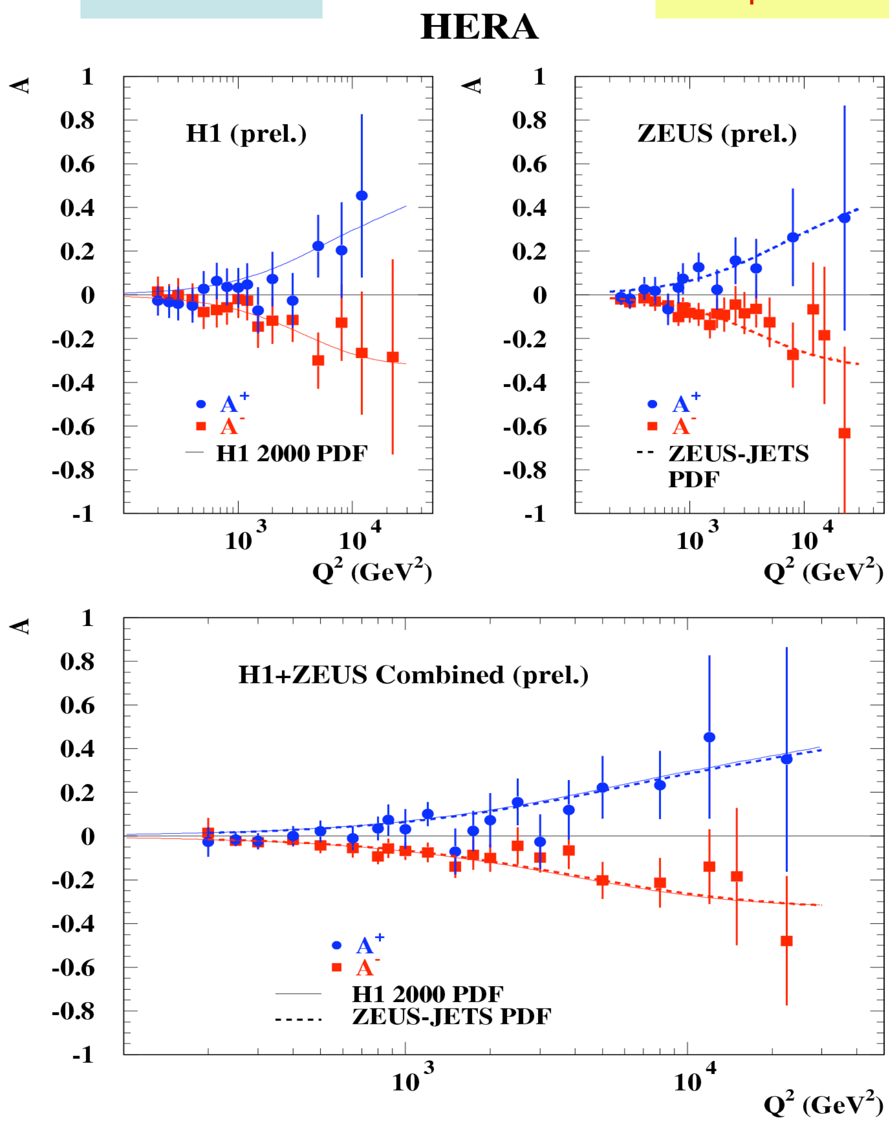
Unpolarised: $\sigma(e^+p) - \sigma(e^-p) \rightarrow xF3^{\gamma Z}$

Polarised: $\sigma(P_R) - \sigma(P_L) \rightarrow F2^{\gamma Z}$

NC Cross Section Asymmetry

HERA-II

H1prelim-06-142
ZEUS-prel-06-022



Asymmetry of RH/LH cross sections:

$$A^{\pm} = \frac{2}{P_R - P_L} \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)}$$

Expect $A^+ \approx -A^-$ in the SM:

$$A^{\pm} \approx \mp \kappa_Z a_e \frac{F_2^{\gamma Z}}{F_2^{\gamma}} \propto a_e v_q$$

Direct measure of
Parity Violation through $a_e v_q$ term

χ^2 of $\delta A = A^+ - A^- = 0$ is 4.0 (3.1×10^{-3} prob.)

Parity violation observed for the first time @ EW scale

At high x, assuming SM couplings:

$$A \sim \frac{u_v + d_v}{4u_v + d_v}$$

Sensitive to d/u ratio of valence quarks

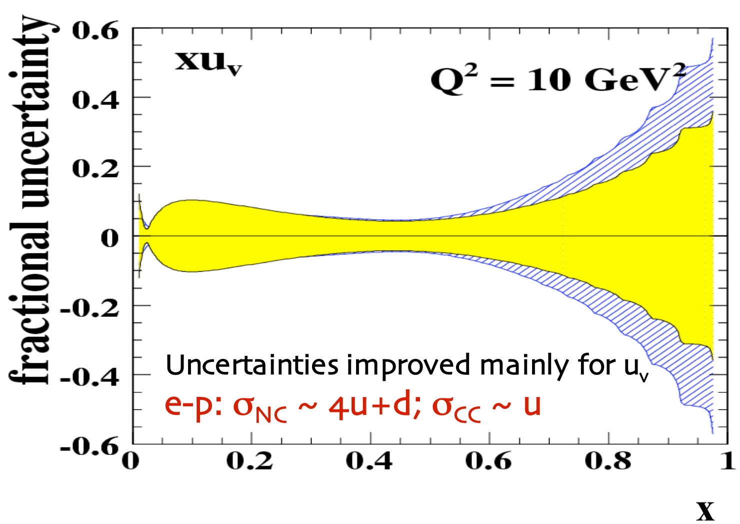
QCD+EW Fits to HERA Data

QCD+EW Fit: to simultaneously determine EW and PDF parameters

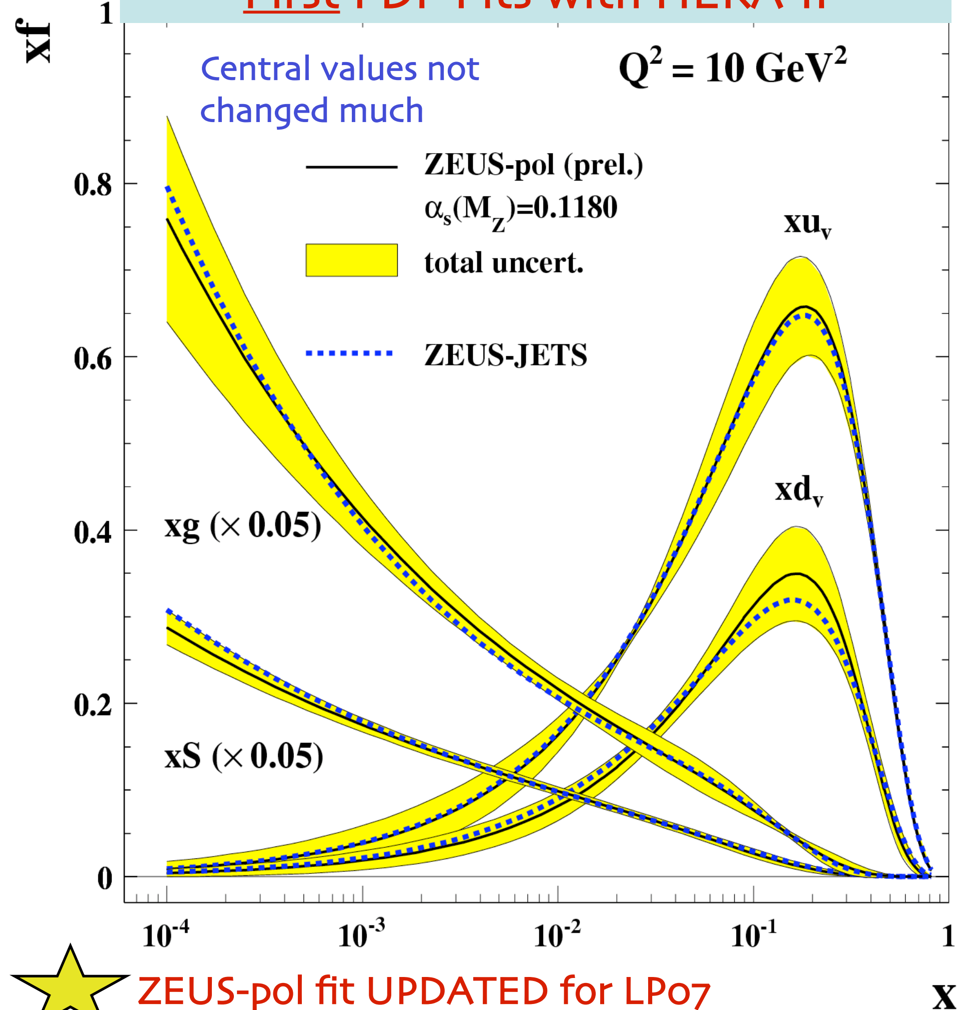
H1 and ZEUS fit to their own data only
(simplifies treatment of systematics)

HERA QCD+EW Fits:

- H1 fits:
  - HERA-I 94-00 (pub.)
  - HERA-I+II 94-05 (prel.)
- ZEUS-pol fit (prel.): ➔
  - HERA-I+II 94-06 (only e-p for HERA-II)



First PDF Fits with HERA-II



ZEUS-pol fit UPDATED for LP07
(now includes 05-06 NC e-p cf. 05 previously)

NC Couplings to Light Quarks

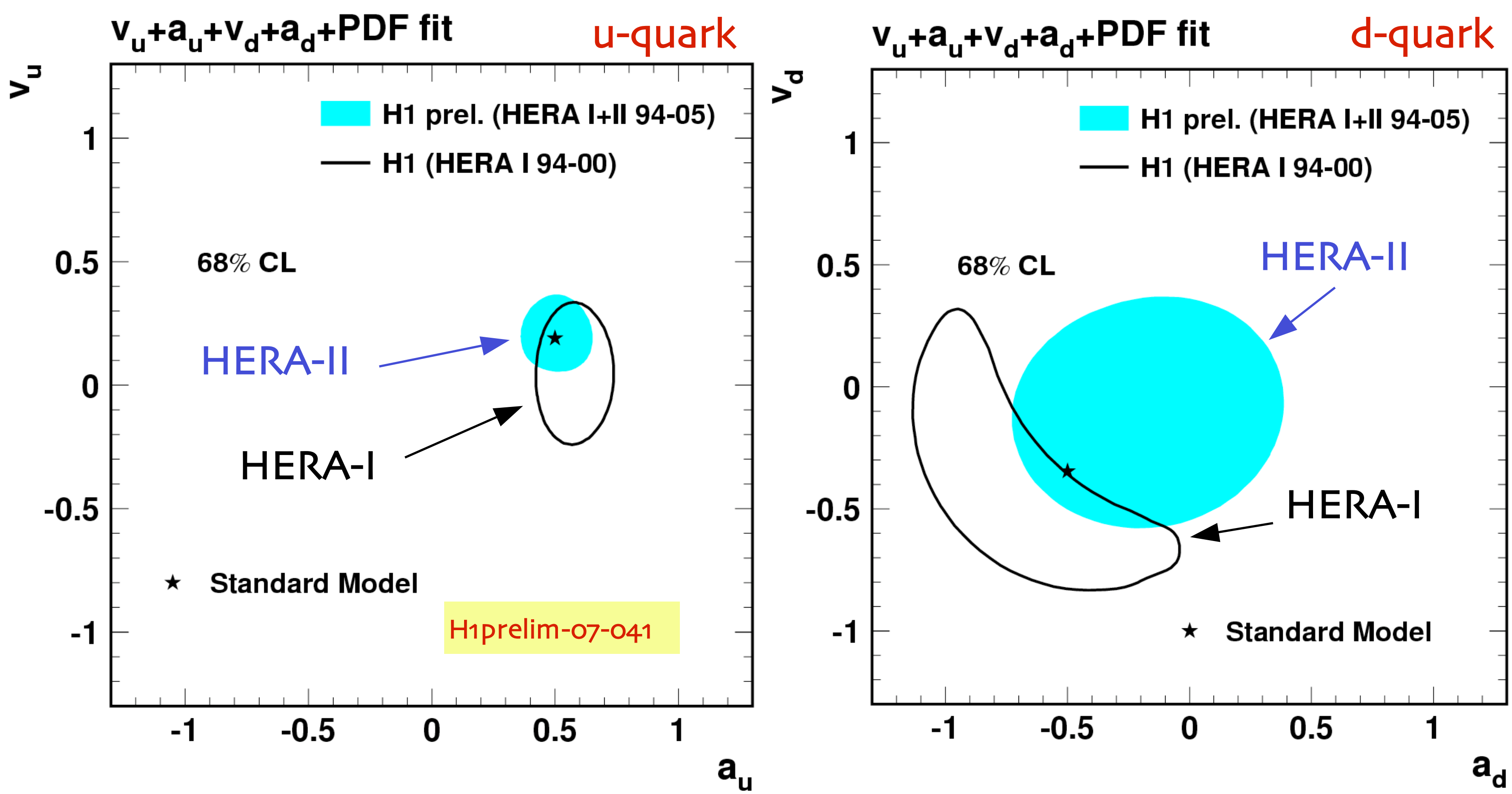
QCD+EW fit: to determine PDFs and u,d quark axial and vector couplings to Z

unpol.: $\sigma(e^+p)-\sigma(e^-p) \rightarrow xF_3^{\gamma Z} \propto e_q a_q$

pol.: $\sigma(P_R)-\sigma(P_L) \rightarrow F_2^{\gamma Z} \propto e_q v_q$

↑ luminosity helps

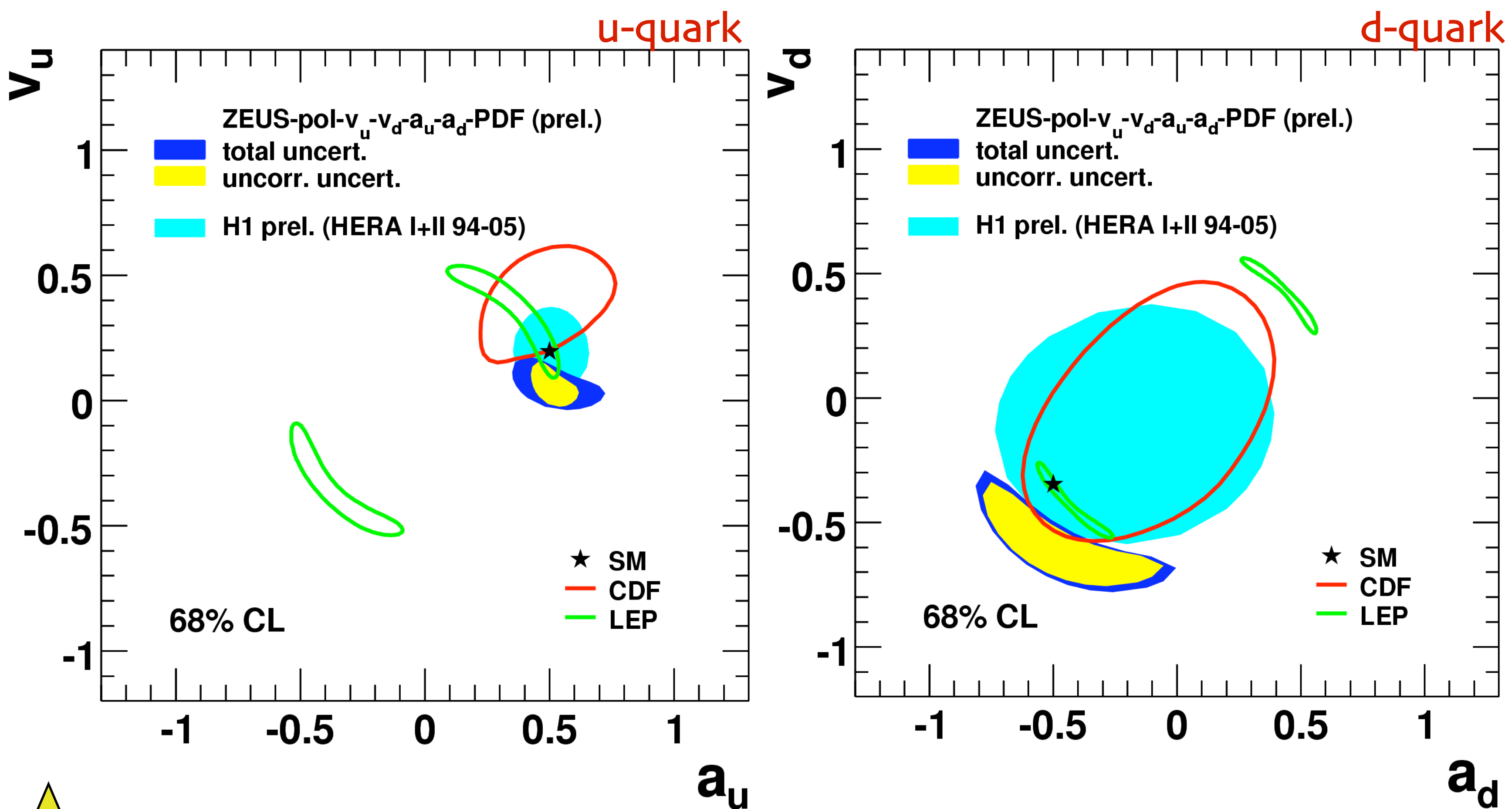
polarisation helps ↑



HERA-I vs HERA-II: HERA-II greatly improves precision (especially for v)

NC Couplings to Light Quarks

Comparison with other exps.: HERA competitive with extractions from LEP/Tevatron



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III. Final States, the Gluon and α_s

- Jets and the High-x Gluon
- Prompt Photons
- Heavy Flavour
  → Charm
  → Beauty
- α_s from HERA

The Gluon PDF and Final States

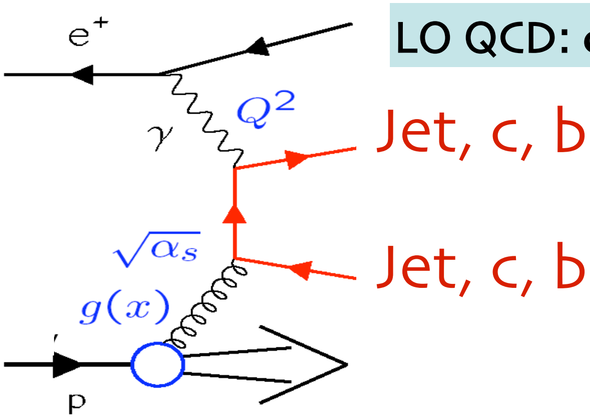
F_2 only <u>indirectly</u> sensitive to gluon via scaling violations: $dF_2/d\ln Q^2 \sim \alpha_s . g(x)$ (constrains low x)

Global QCD fits:

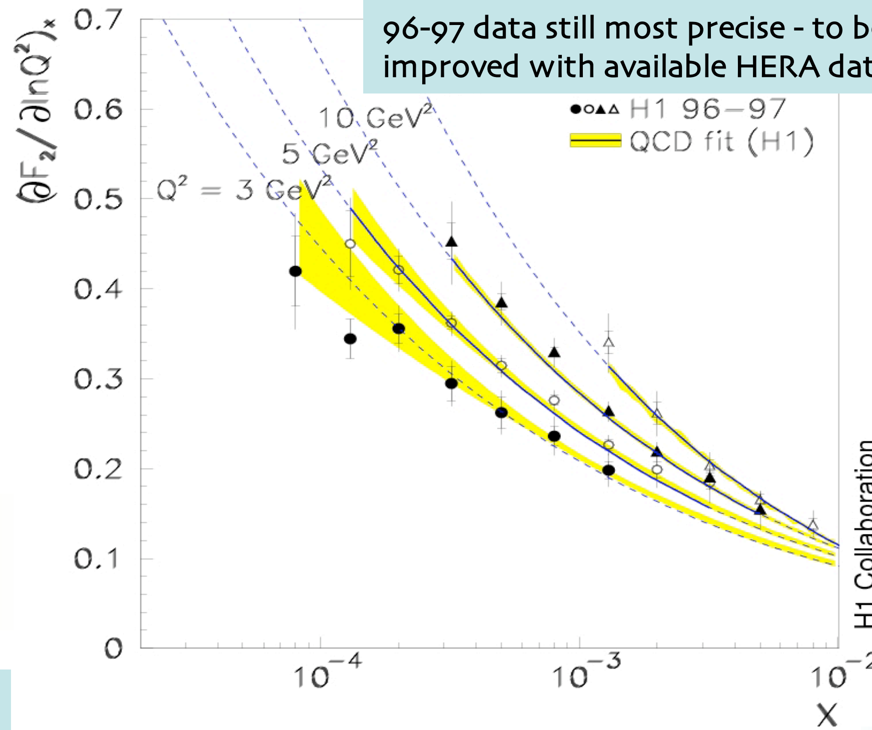
- High x: gluon poorly known (impact on New Physics at LHC)
- Low x: gluon very large … is DGLAP sufficient?

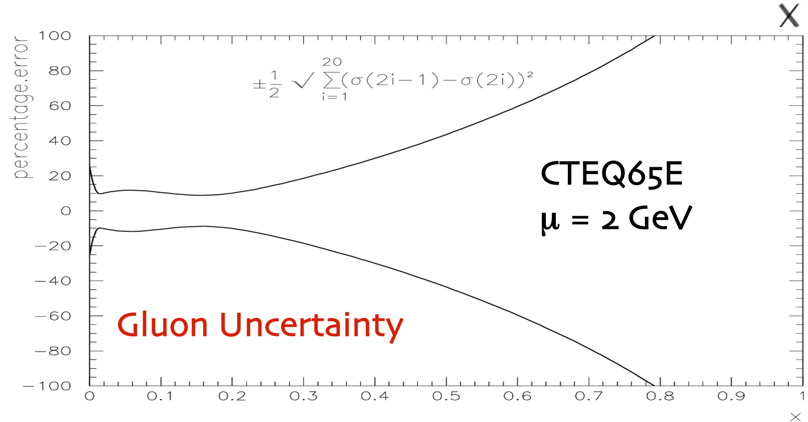
Several final states directly sensitive to gluon:
Jets, prompt photon, charm, beauty

LO QCD: $\sigma \sim \alpha_s . g(x)$



96-97 data still most precise - to be improved with available HERA data





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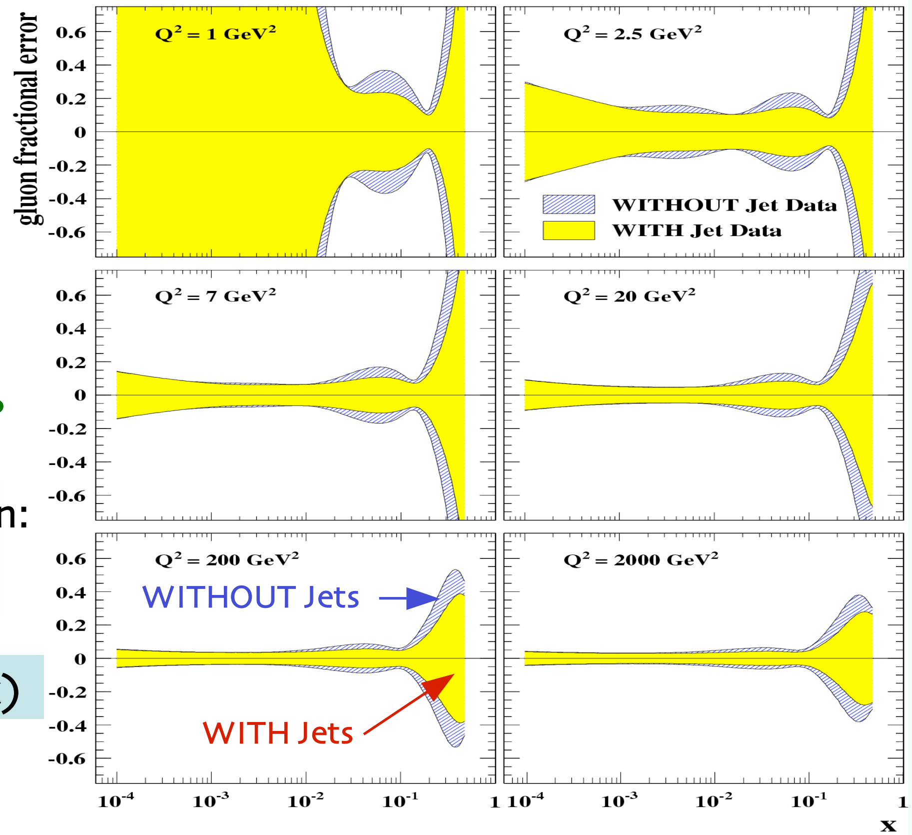
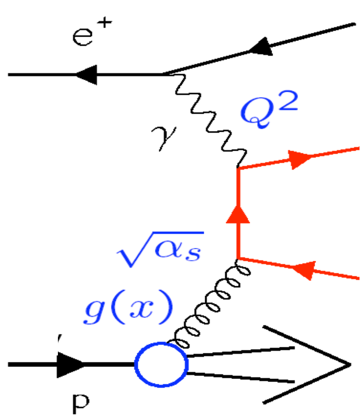
ZEUS-JETS PDF: Eur. Phys. J. C42 (2005), 1



LO QCD: $\sigma \sim \alpha_s.g(x)$



HERA data in inclusive jet DIS and dijet photoproduction (96-97 HERA-I) already successfully used to constrain high x gluon

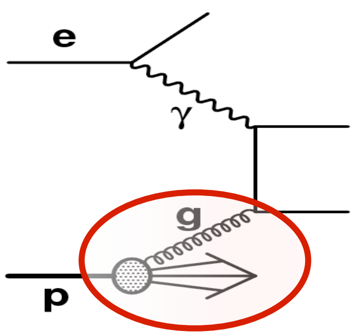
"Proof of Principle": what other measurements are there?

Gluon PDF from Jets at HERA

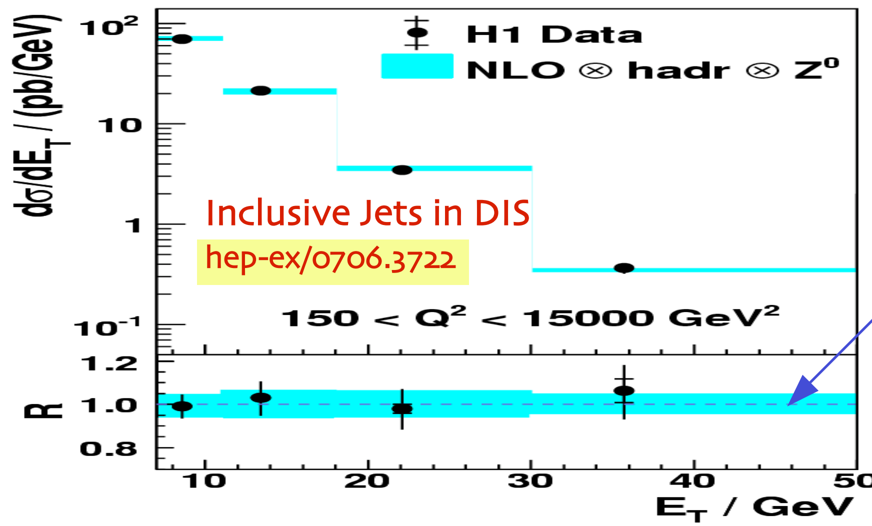
NOW: Wealth of new jet data from HERA available to provide further constraints on gluon PDF at high x

LHC: high-x gluon often dominant theoretical uncertainty for New Physics

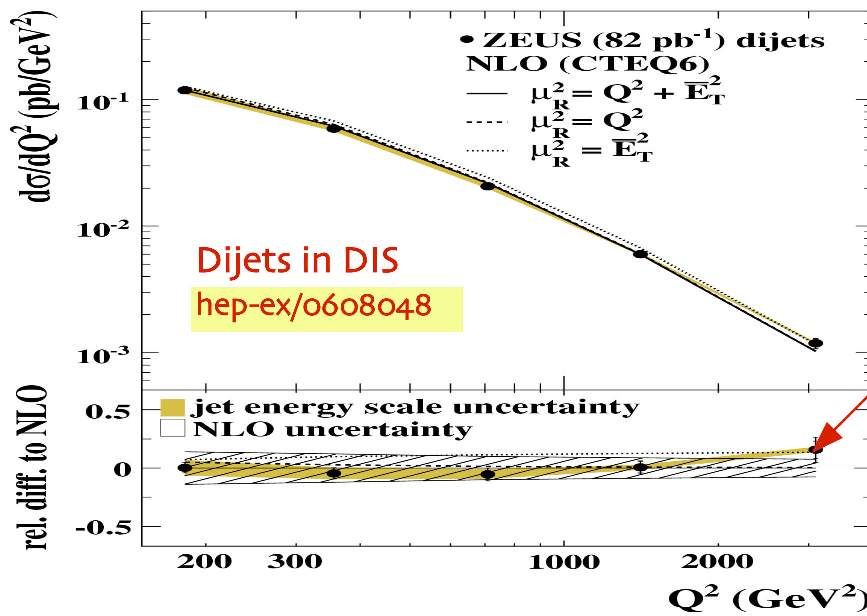
DIS: $Q^2 > 1\ GeV^2$



- Inclusive jet and dijets in NC DIS at high-Q2/ET from HERA-I



Data well described by NLO QCD



JES known to ~ 1% via p_T balance with scattered e

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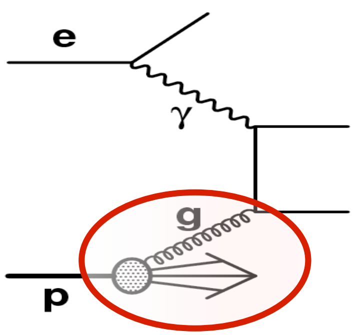
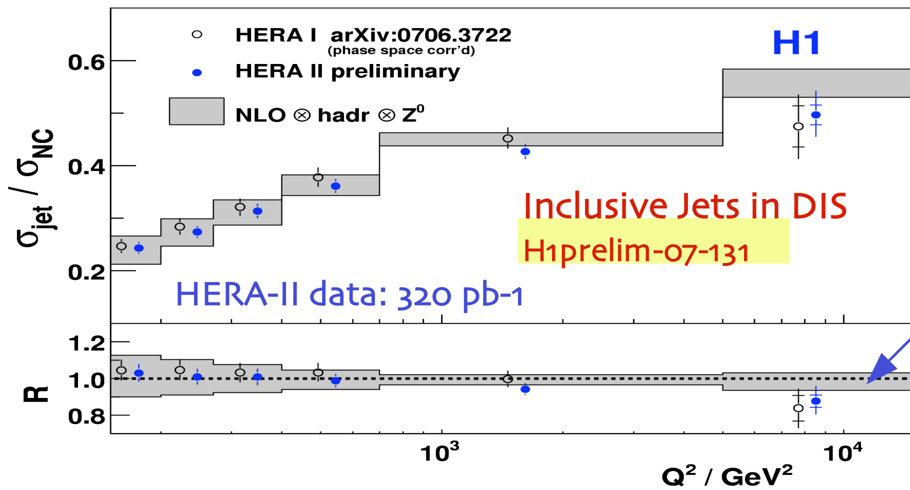


- … and first jet measurements now arriving from HERA-II…

(clear improvement in precision cf. HERA-I)



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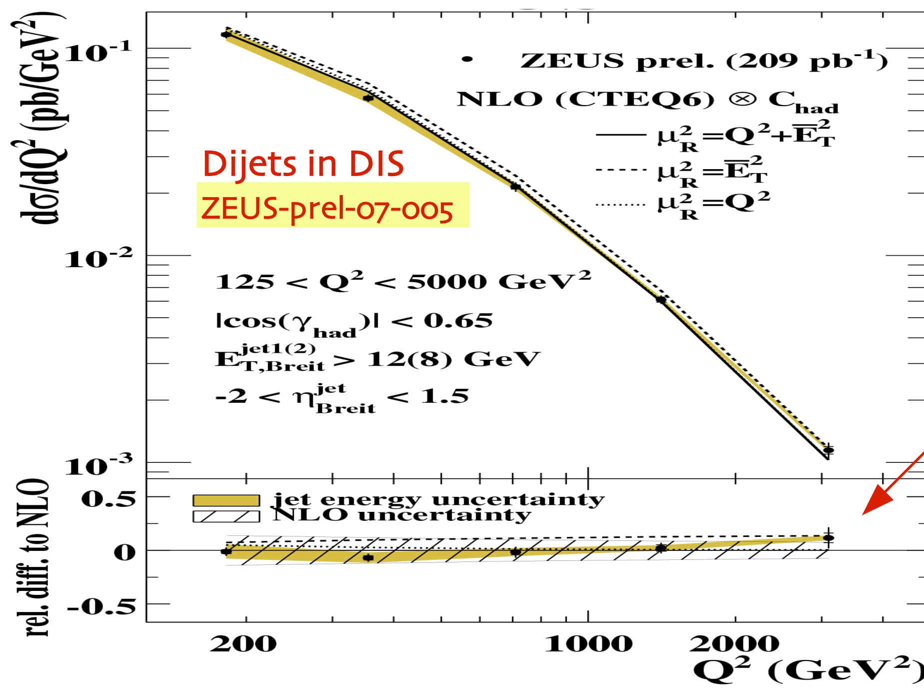

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Gluon PDF from Jets at HERA

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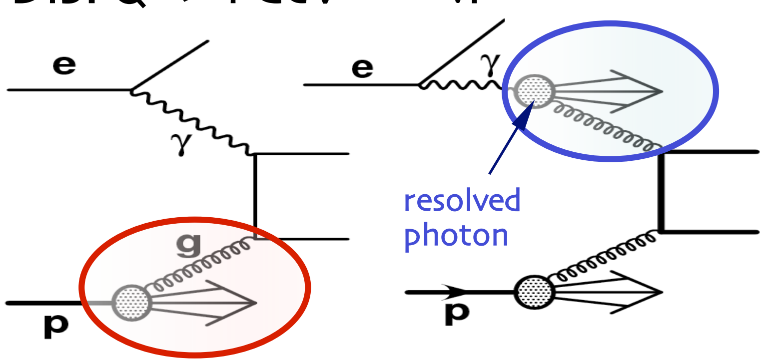
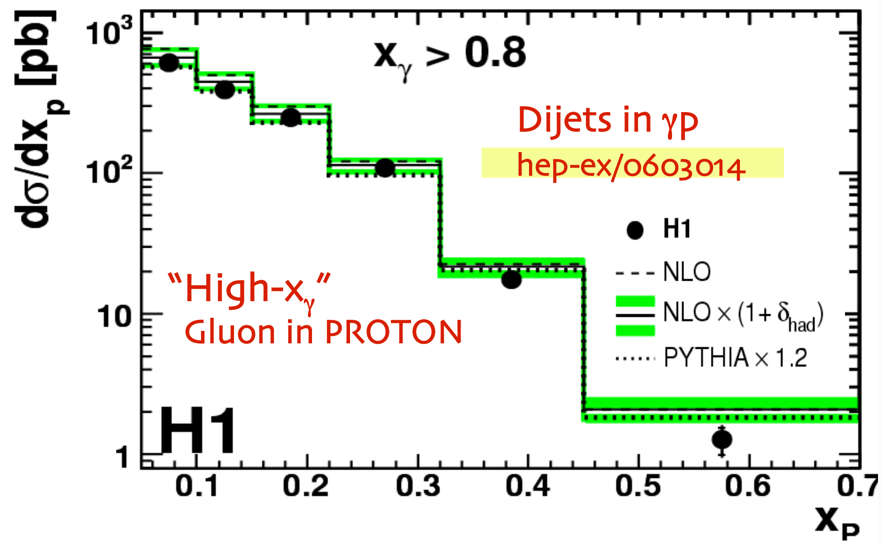
LHC: high-x gluon often dominant theoretical uncertainty for New Physics

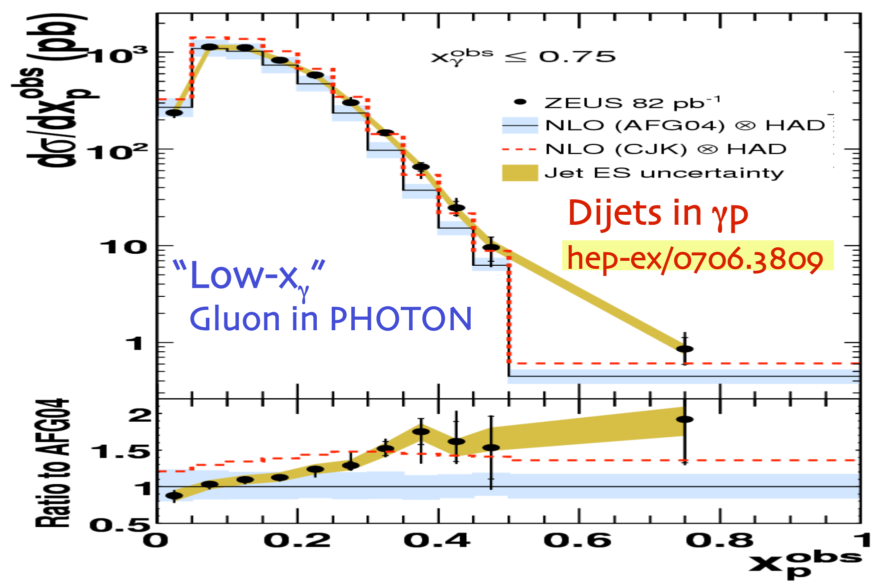
DIS: $Q^2 > 1\ GeV^2$ γp: $Q^2 \sim 0\ GeV^2$



- … and also from high-E_T dijets in γp
  → direct and resolved photons
  ⇒ sensitive to gluon in proton and photon

+ more to come from both experiments in DIS and γp



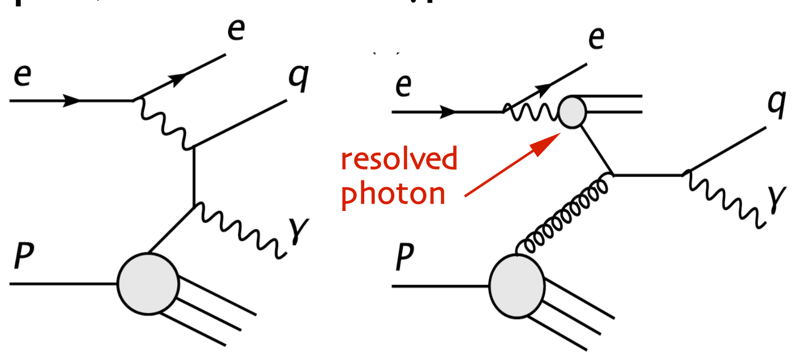


Sensitive data for use in global fits for p and γ PDFs

Prompt Photons at HERA

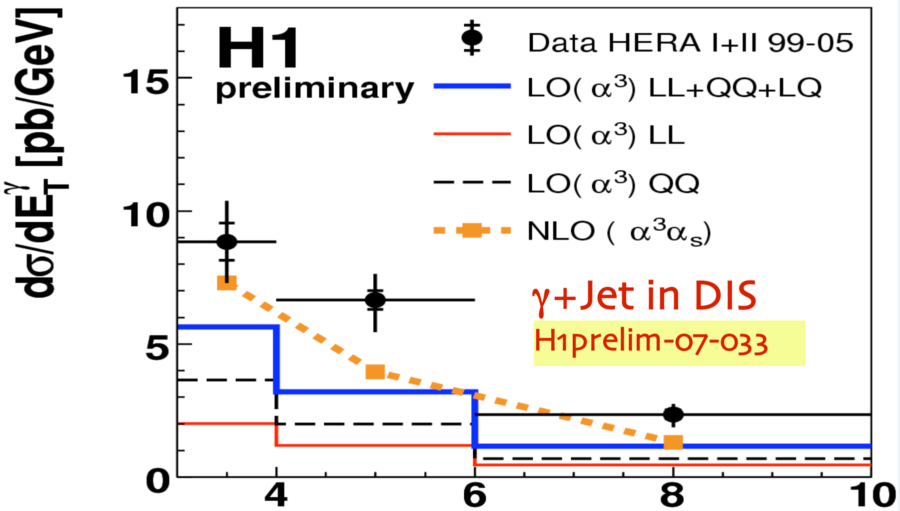
Prompt Photons:
- Sensitive (and clean) probe of QCD
- Constraints on proton and photon PDFs

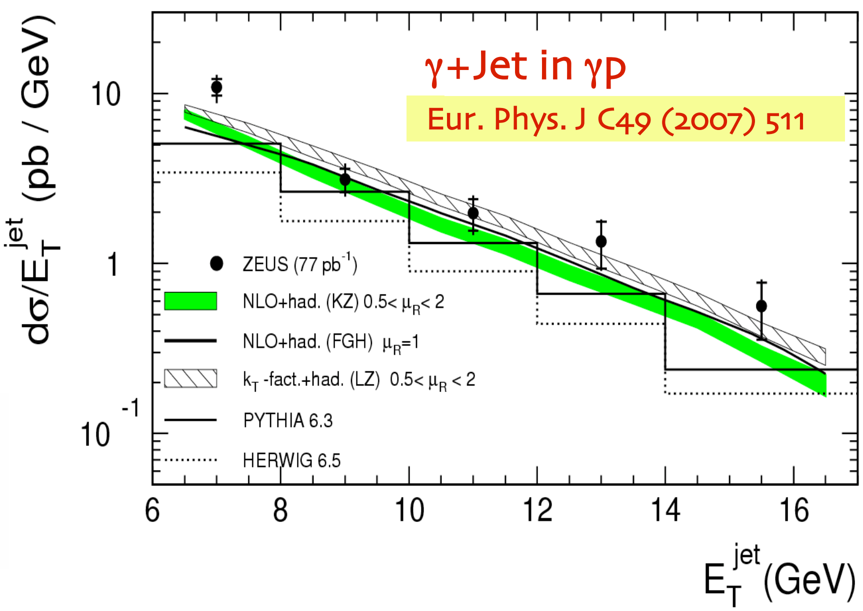
ep: $Q^2 > 1$ GeV^2 γp: $Q^2 \sim 0$ GeV^2



SURPRISE: NLO QCD too low at small E_T^γ

LHC: good understanding of SM production important for searches e.g. prompt photon is dominant background for $H \to \gamma\gamma$





Gluon via Charm at HERA

$\sigma^{cc} \sim Y_+ F_2^{cc}(x,Q^2) - y^2 F_L^{cc}(x,Q^2)$

Charm contribution to F2 ↑

Scaling violations in charm clearly observed (gluons!!!)

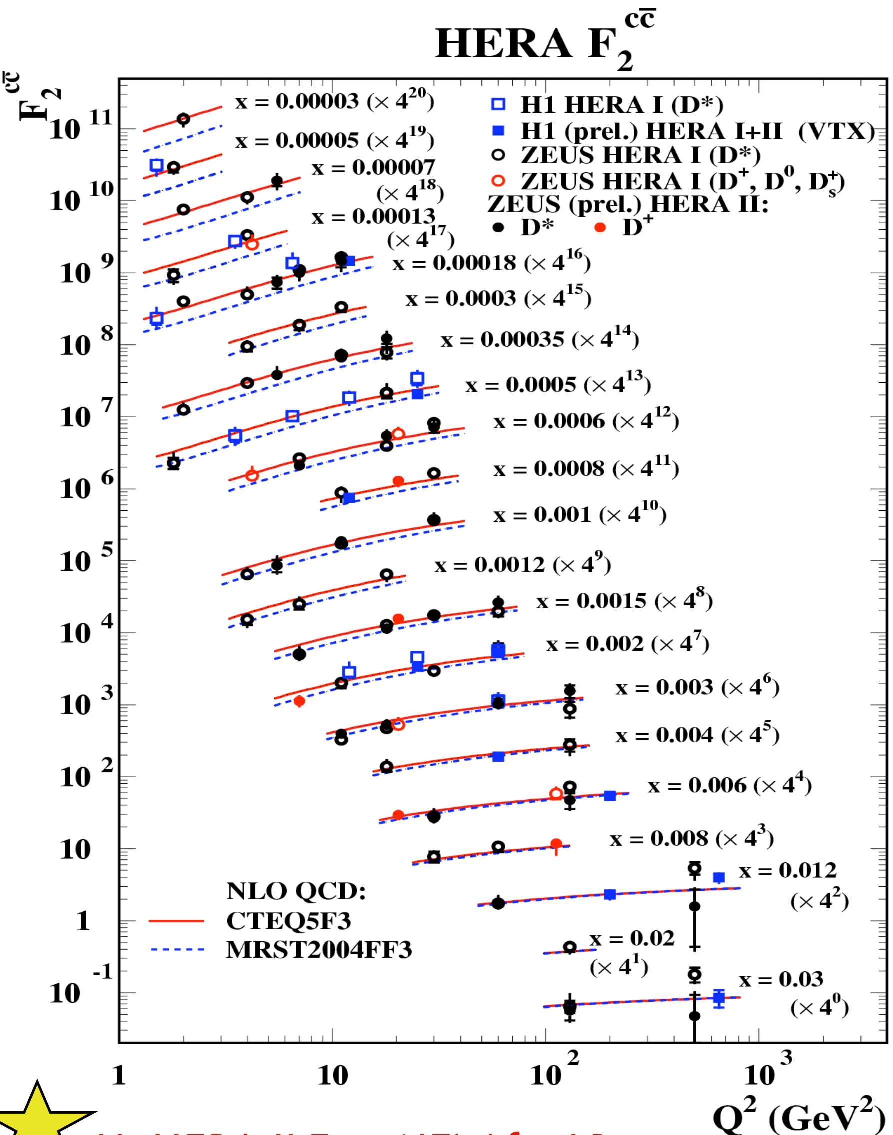
Improved precision wrt HERA-I

For highest precision: await HERA-II combined meson results!

Potentially strong constraints on gluon PDF with full HERA statistics?

METHOD(S):

1. Measure D meson cross sections and extrapolate to full phase space in η(D), pT(D) (NLO HVQDIS) [H1/ZEUS]
2. Use impact parameter, in transverse plane, of tracks to primary vertex [H1]



H1 HERA-II F2cc NEW for LP07

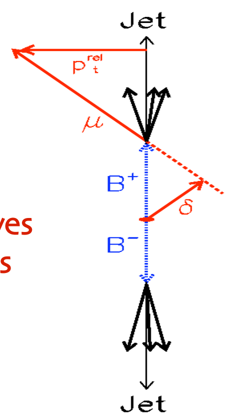
Beauty Production

Beauty Production:

- Understand multi-scale QCD
- Previously reported HERA and Tevatron beauty anomalies…

METHOD(S):

- Measure in variety of channels eg. $b \to c\mu(e)\nu$, $bb \to \mu\mu$ $b \to D^*\mu$
- Unfold beauty from charm using p_T^{rel} or impact parameter δ

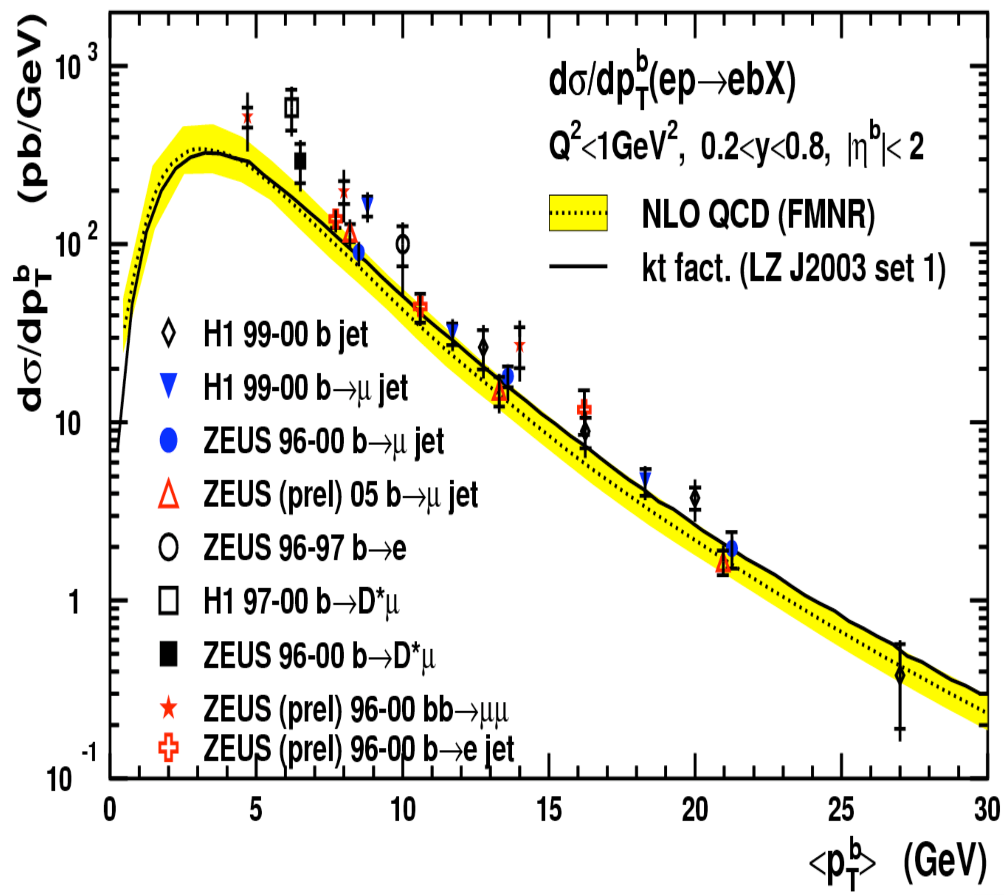


Large B-meson mass gives large p_T^{rel} cf. light quarks

Long B-meson lifetime gives large positive δ cf. light quarks

Fit uds, c, b MC to distributions

HERA-I+II

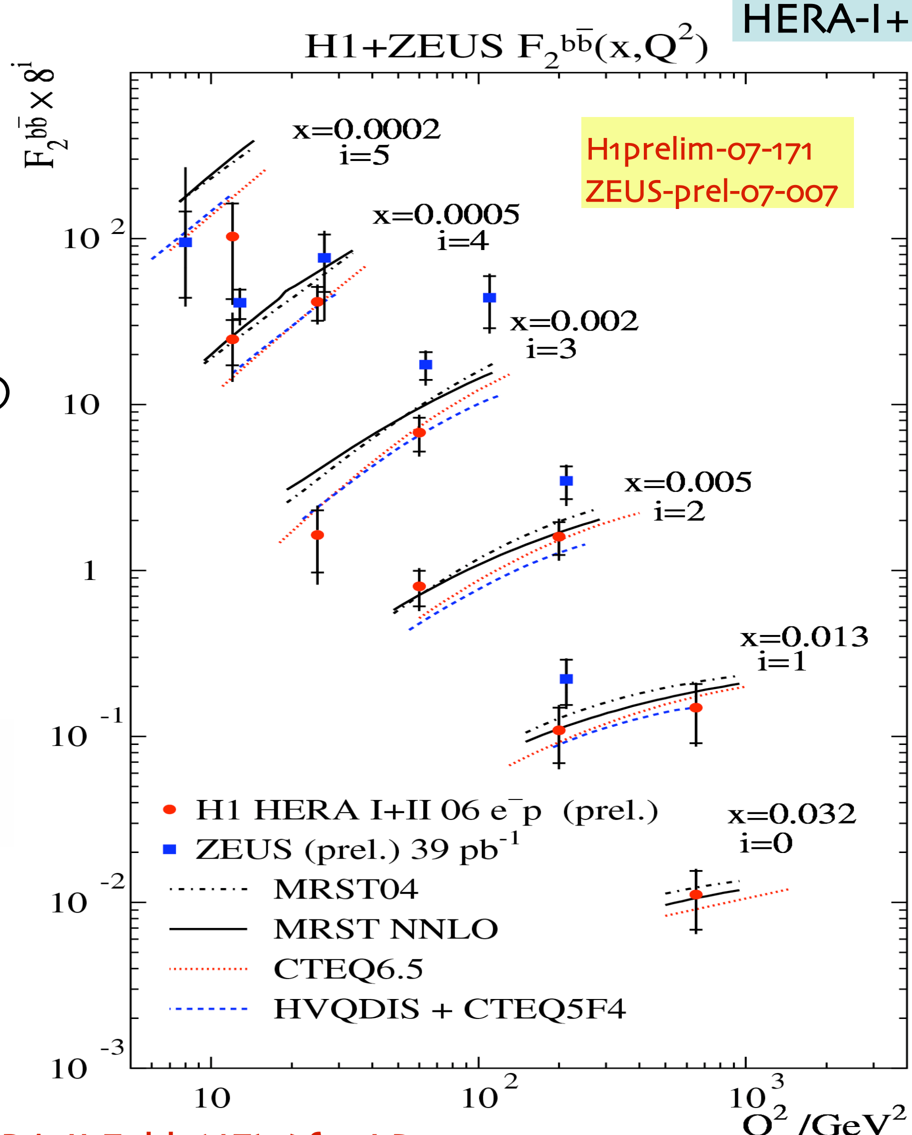


ZEUS (prel.) 05 $b \to \mu$Jet and ZEUS (prel.) 96-00 $b \to e$Jet NEW for EPS07/LP07

Measurements performed using very different methods in agreement and generally well described by NLO QCD

Beauty Production

HERA-I+II



Beauty contribution to proton F2

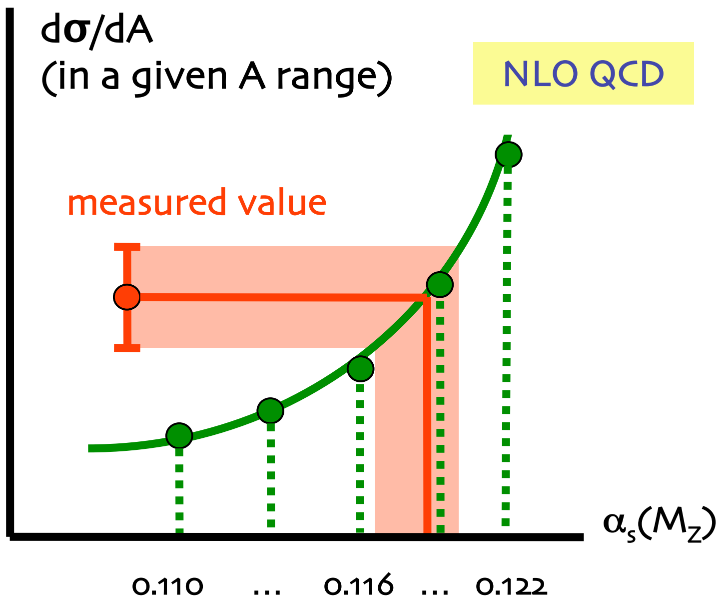
- FIRST measurements of F2bb
- H1 and ZEUS in agreement and comparable precision for very different methods (H1: impact parameter, ZEUS: p_T^{rel})
- Huge spread in theoretical predictions: (choice of scale, treatment at mass threshold,…) Data not yet decisive
- Gluon probed for x < 10^{-3}

Await final results from HERA (x5-10 more data available)

★ H1 HERA-II F2bb NEW for LP07

Extraction of α_s from HERA

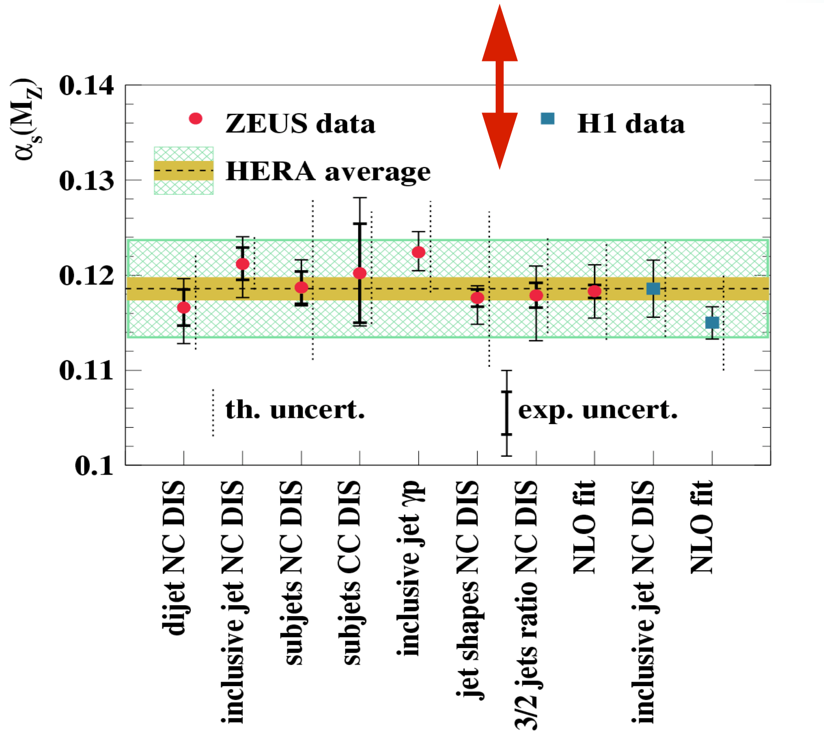
α_s : fundamental parameter of QCD → BUT must be extracted from experiment



METHOD (for Jet Observables)
Parameterise observable using NLO QCD with different α_s (and appropriate PDFs) to extract α_s and its uncertainty from measured observable

Many precise determinations of α_s from H1/ZEUS (from jets, NLO QCD fits, jet substructure)

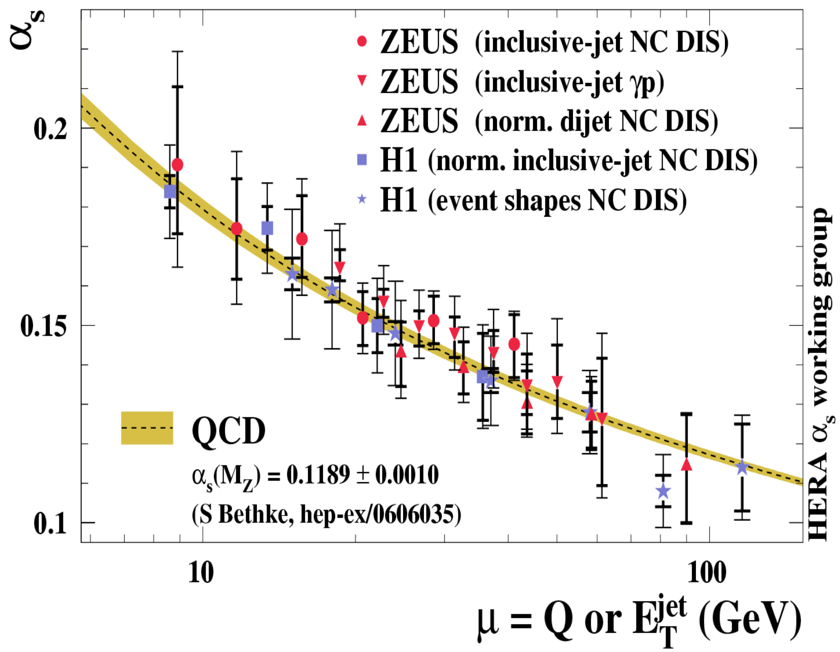
"HERA average" (hep-ex/0506035):
$\alpha_s(M_Z)=0.1186\pm0.0011(\text{exp.})\pm0.0050(\text{theo.})$
(weighted average of individual α_s measurements)



Combined HERA α_s from HERA

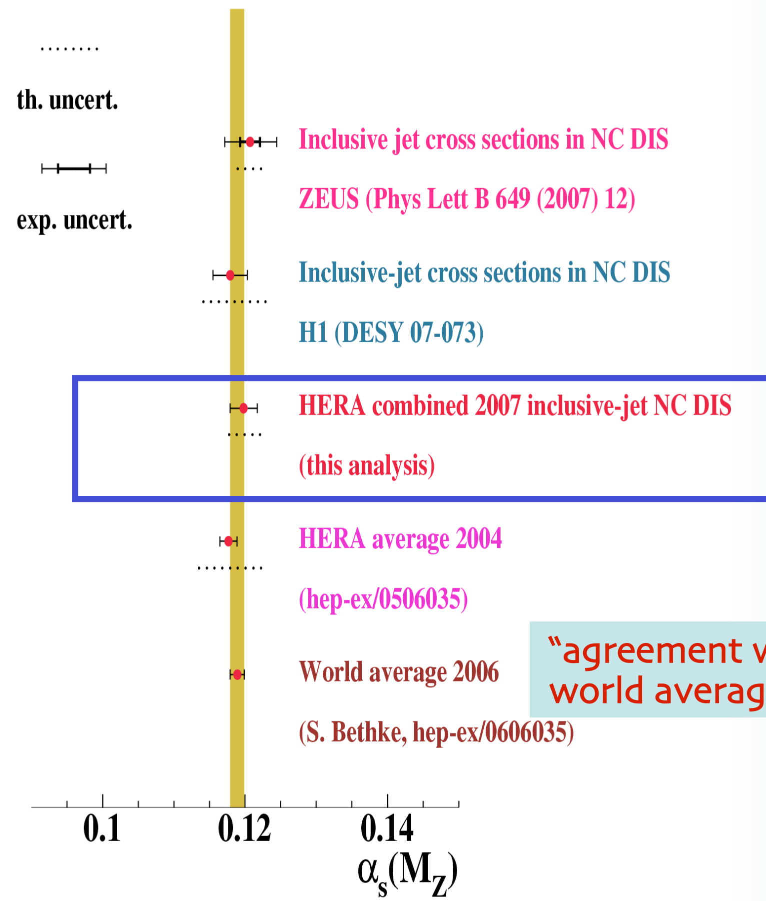
HERA combined α_s NEW for EPS07/LP07

NEW IDEA: extract α_s from simultaneous fit to most precise measurements from H1 and ZEUS (instead of combining α_s values)
"most precise" = inclusive jets at high Q2 ➔



Clear demonstration of running of α_s from HERA alone

HERA combined α_s 2007 (NEW):
$\alpha_s(M_Z)$=0.1198±0.0019(exp.)±0.0026(theory)



"agreement with world average"

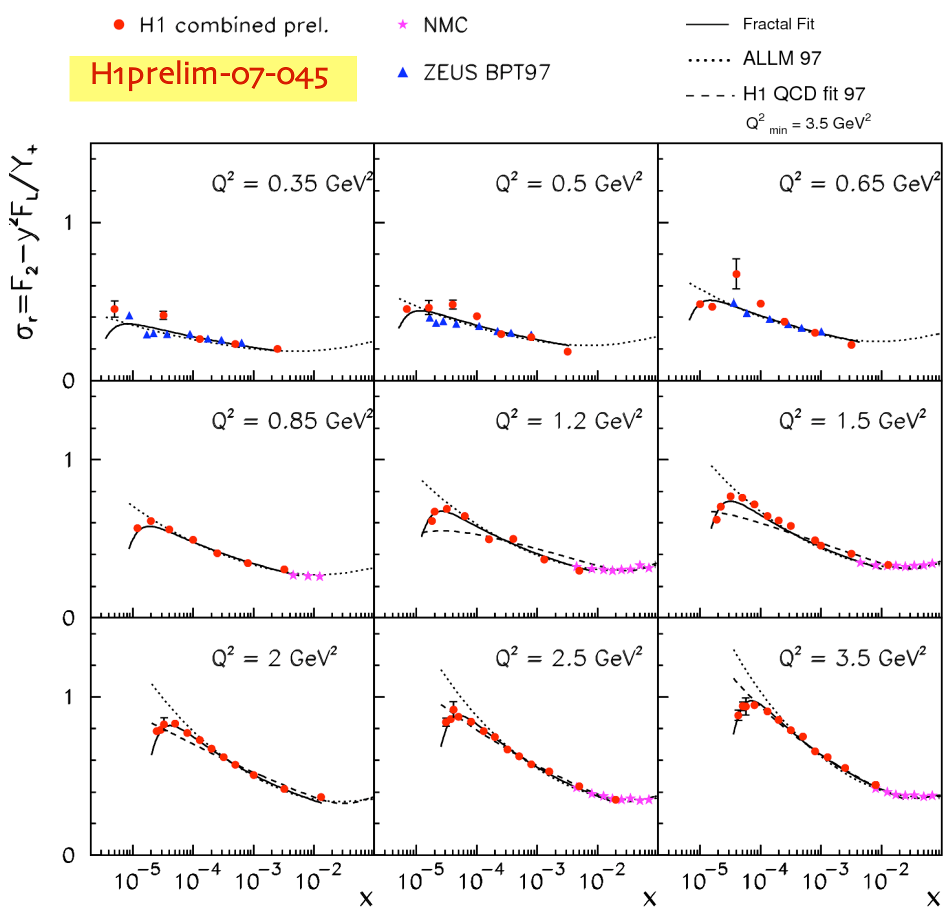
H1prelim-07-132
ZEUS-prel-07-025

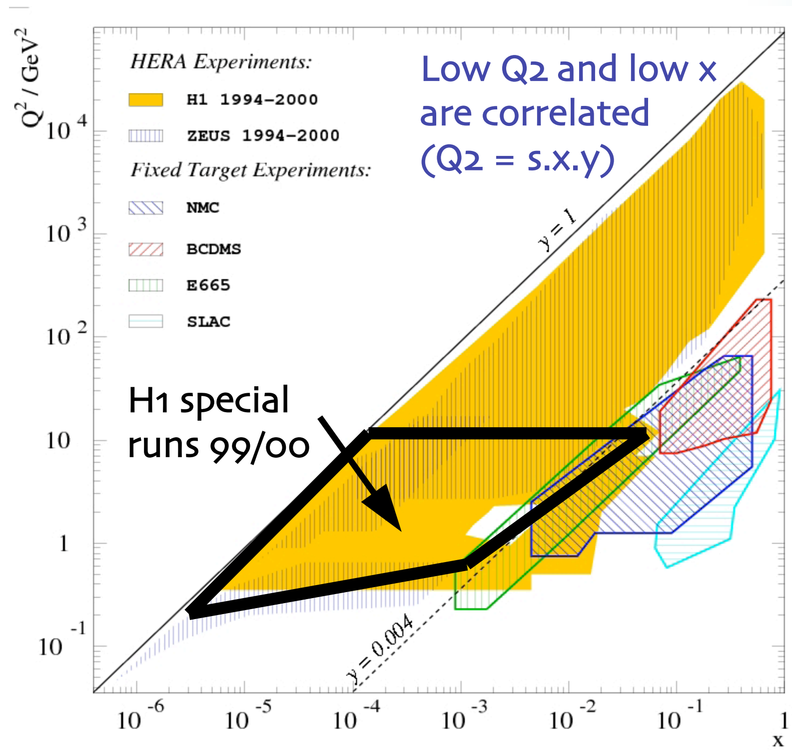
IV. The Low (Q^2,x) Regime

- Low Q^2 Transition Region
- Forward Jets at Low x
- Longitudinal Structure Function F_L
  - → Measurements at High y
  - → Low Energy Running for F_L

Final Word from HERA on Low Q2 (< 5 GeV²)

$\sigma_{NC}(e^{\pm}p) \sim Y_+ F2 - y^2 F_L$ (sensitive to F2 and F_L)





H1: Low Q2 regime probed via special runs

MB: minimum bias (high trigger rate)

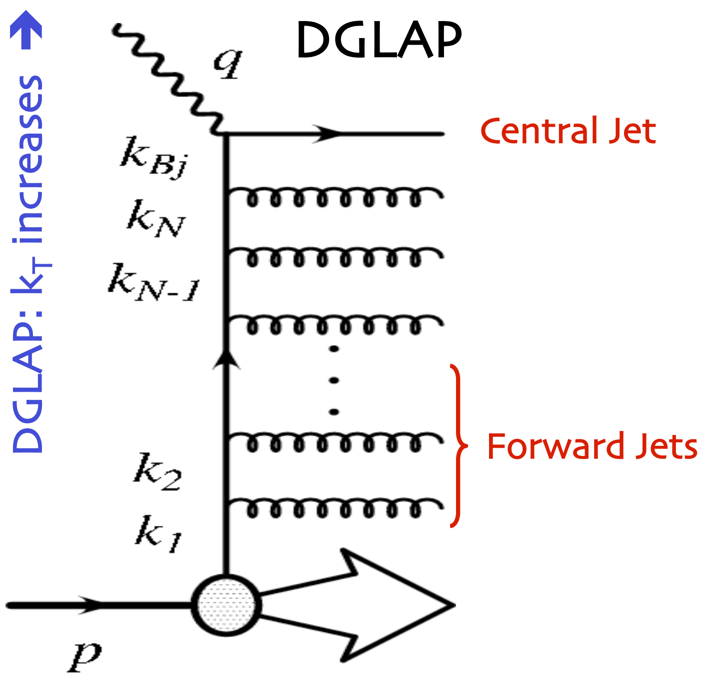
SVX: shifted vertex (increase acceptance at low Q2)

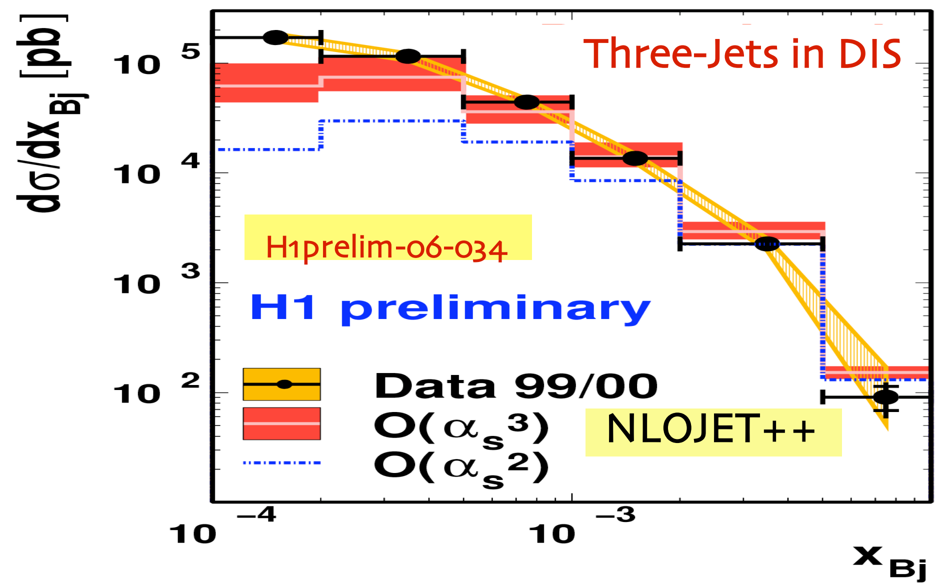
NEW: H1 special runs datasets combined

considered phase space: 0.2 GeV² ≤ Q2 ≤ 12 GeV² ($4\times10^{-6} < x < 0.02$)

- Data fill the transition region (Q2 ~ 1 GeV²) between DIS and γp → unique data for models
- 2-3% precision (H1 combined data cover gap between published ZEUS results and agree in overlap regions)

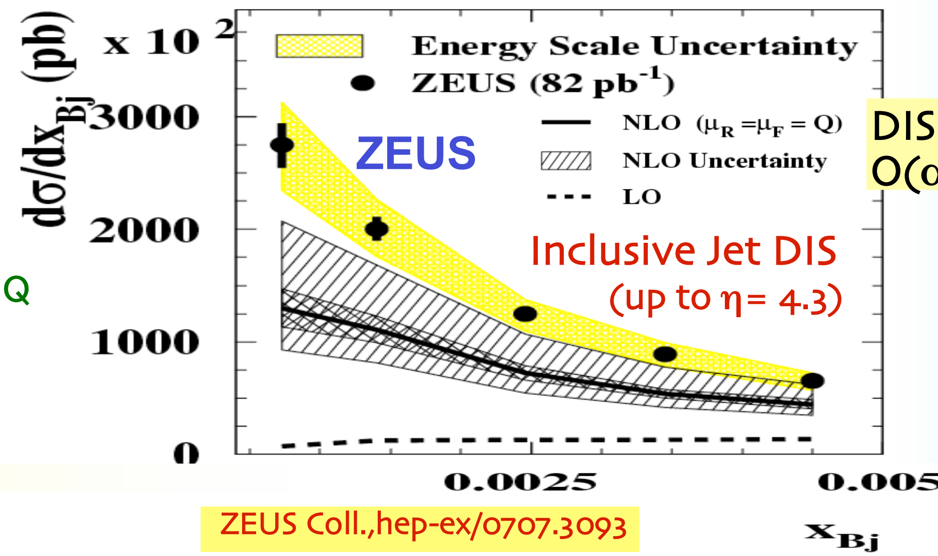
Low x: Breakdown of DGLAP?





NLO calculation based on DGLAP strongly ordered in k_T: $k_{T,1}^2 << k_{T,2}^2 << \ldots << Q^2$

→ LOW probability for forward jets with $E_T \sim Q$



DISENT: $O(\alpha_s^2)$

Hints for k_T unordered gluon emissions

→ need for BFKL? or NNLO enough?

(see also: ZEUS Coll., DESY-07-062)

ZEUS Coll.,hep-ex/0707.3093

Low x Gluon via F_L at HERA

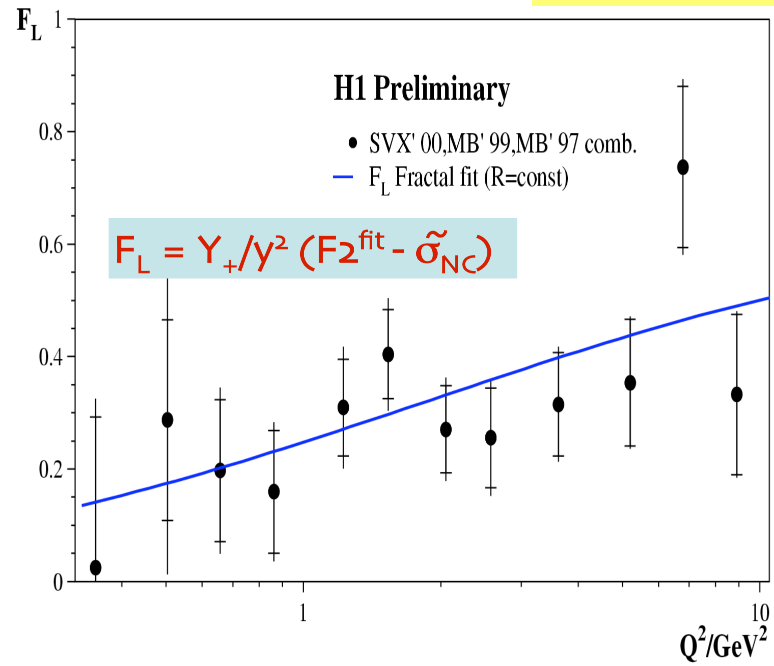
$\tilde{\sigma}_{NC}(e^{\pm}p) \sim Y_+ F2(x,Q2) - y^2 F_L(x,Q2)$

While F_2 only <u>indirectly</u> sensitive to gluon via scaling violations: $dF_2/d\ln Q^2 \sim \alpha_s.g(x)$

F_L is directly sensitive to gluon PDF
(in regions inaccessible to jets, charm,...):
$F_L \sim \alpha_s.g(x,Q2)$ (contributes at $O(\alpha_s)$ and HO)

- Measured at fixed target experiments ($x > 10^{-3}$)
- BUT so far only indirectly at HERA ↗
  model dependent: fit F2 for y < ycut (cutting out lowest x)
  → extrapolate to low x → extract $F_L = Y+/y^2(F2^{fit}-\sigma_{NC})$

H1prelim-07-045



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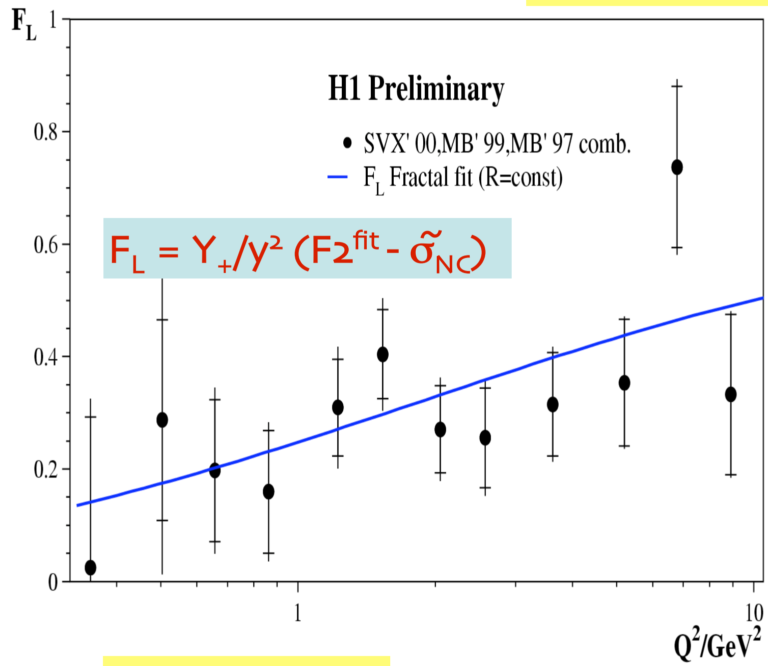
H1prelim-07-045



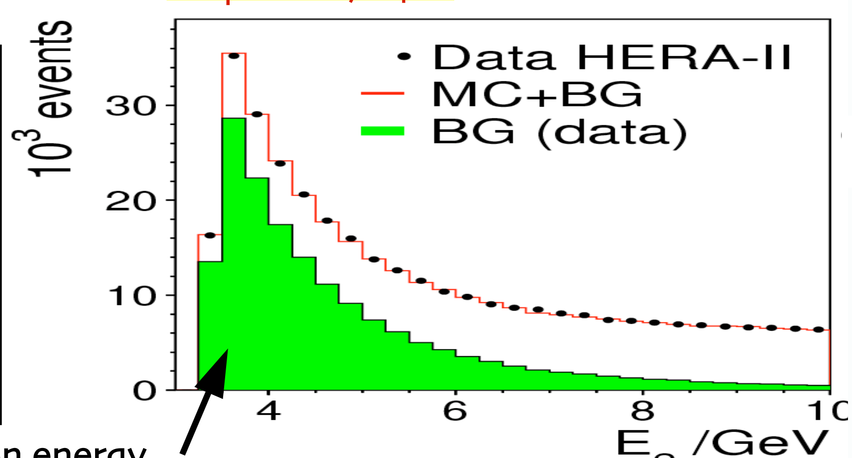
NEW analyses (preparing for direct measurement)

- Measure cross sections at as high y as possible → maximise sensitivity to F_L

$y = 1 - Ee'/2Ee(1-\cos\theta e)$

High-y ⇔ low energy of scattered e (Ee')
Experimental challenge (large γp background)!

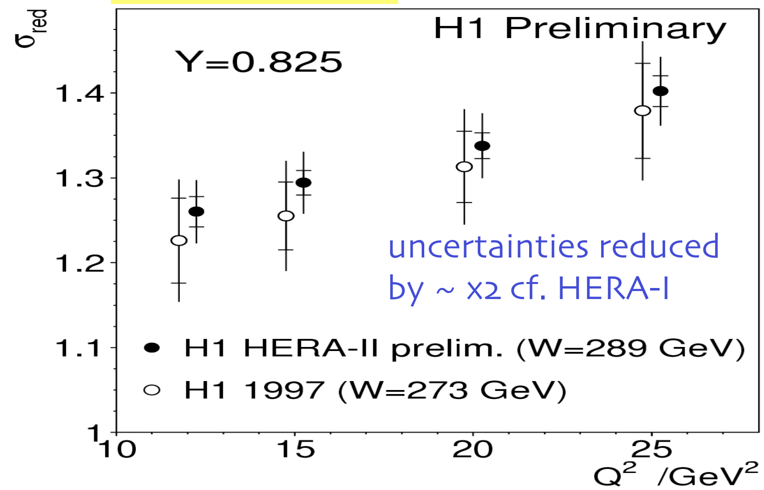
H1prelim-07-042

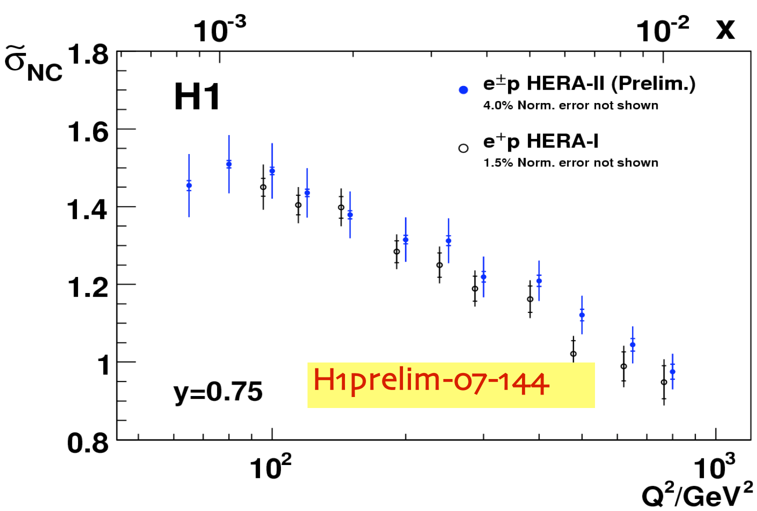


small scattered electron energy

Measurements at High y

H1prelim-07-042





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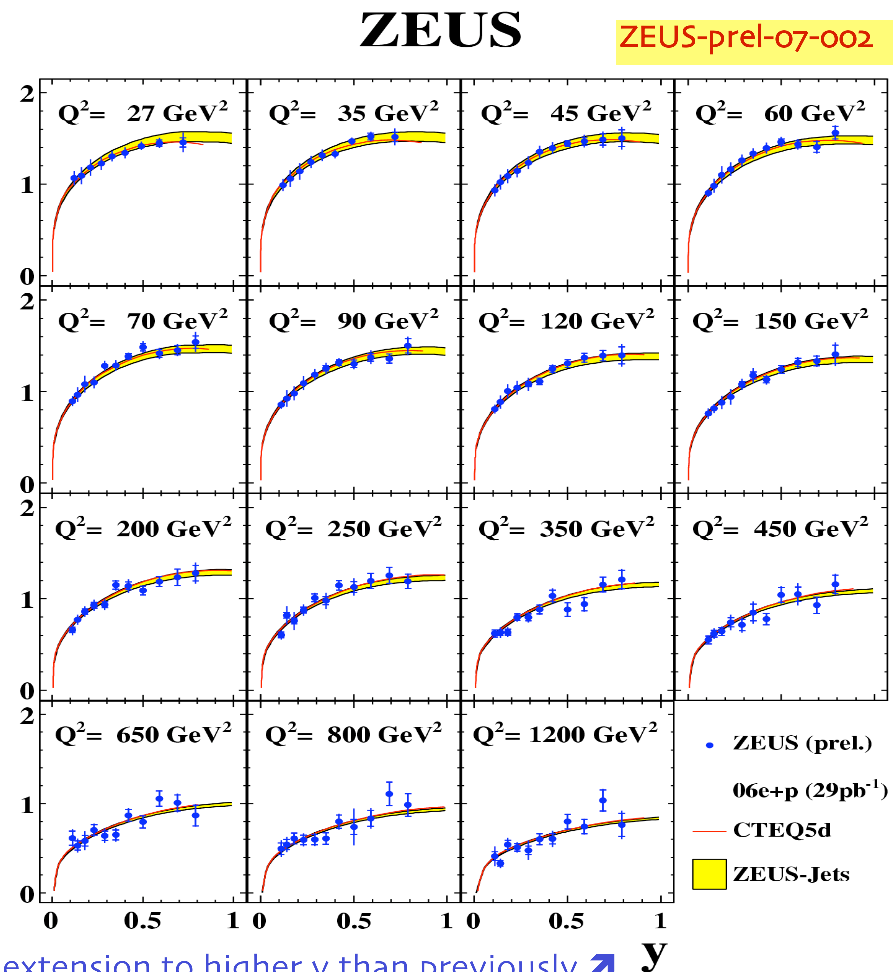
ZEUS-prel-07-002



extension to higher y than previously ↗

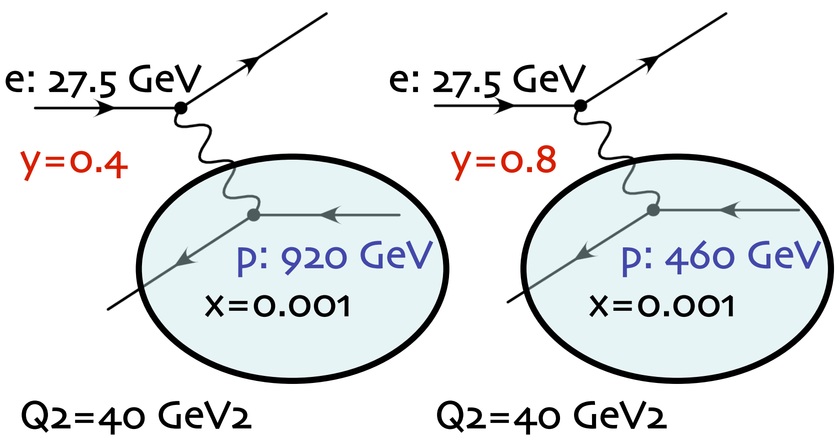
Ideal samples to study experimental conditions for direct F_L measurement

Low x Gluon via F_L at HERA

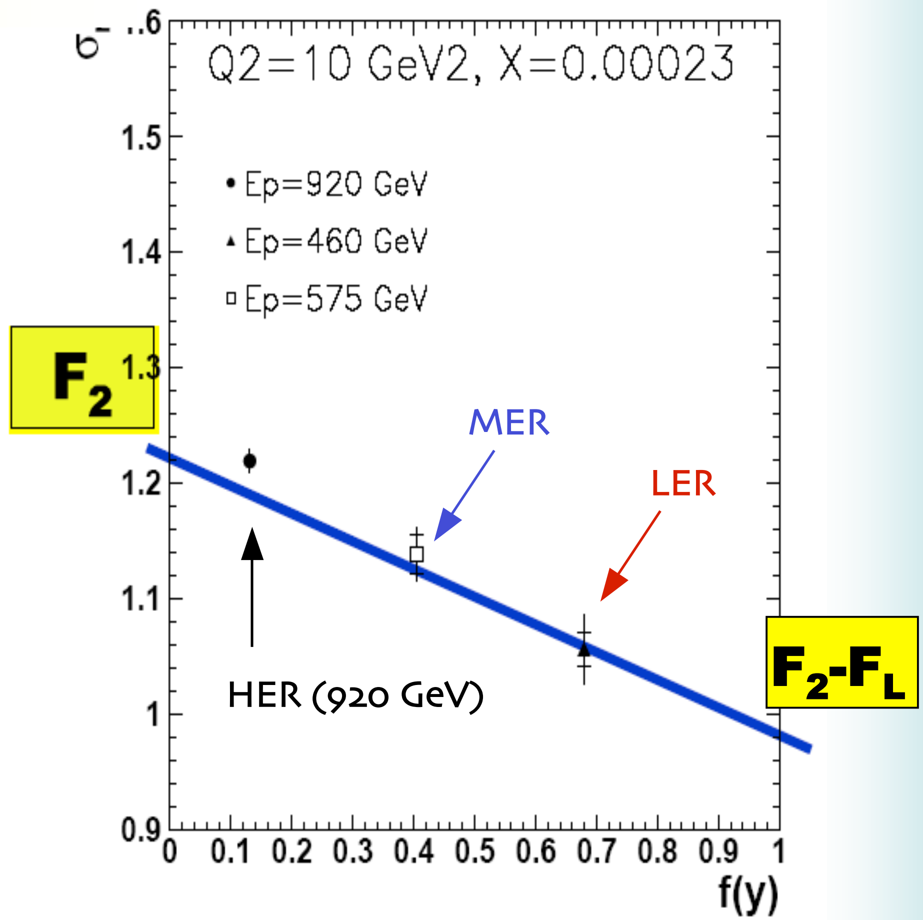
$\sigma_{NC}(e^{\pm}p) \sim Y_{+}F2(x,Q2) - y^2 F_L(x,Q2)$

HERA Structure Function programme will be completed by direct measurement of F_L:

Extract F_L from σ_{NC} at same x,Q2 but different y ⇒ different s (Q2 = s.x.y)
⇒ requires low Ep running (s = 4 EeEp)



Simulation!!!



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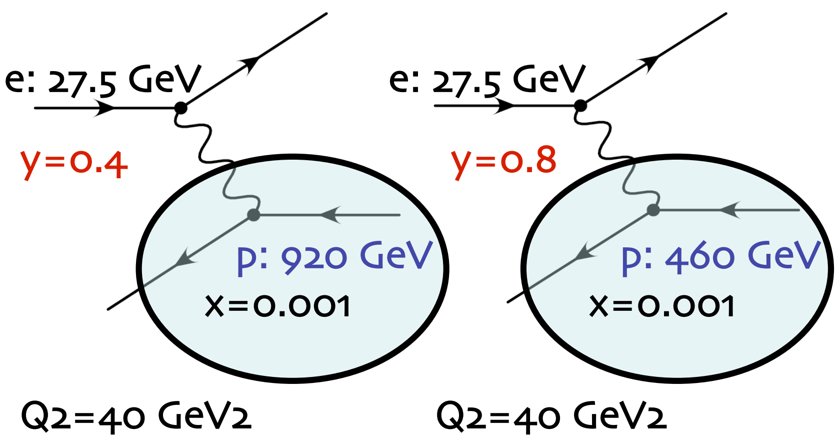
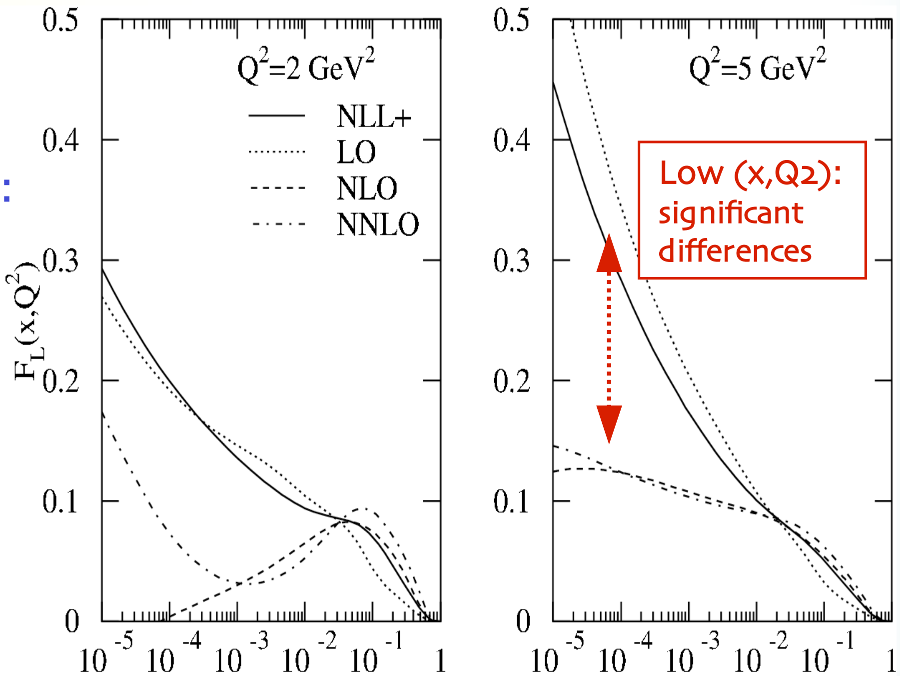


R. Thorne, C. White, PRD 75 (2007) 034005

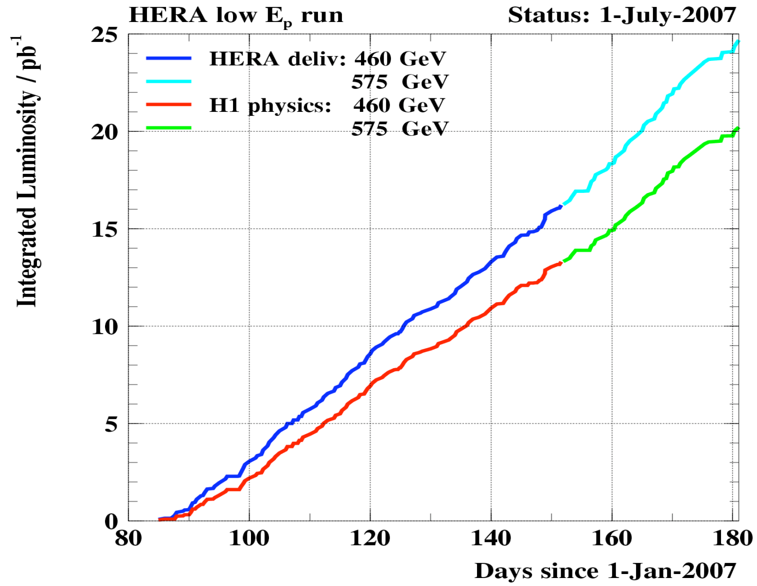


What could F_L from HERA do?

- Pin down F_L (and hence gluon) at low x
- Provide information on correct approach at low x → NNLO enough? Or full resummation of ln(1/x) terms needed?

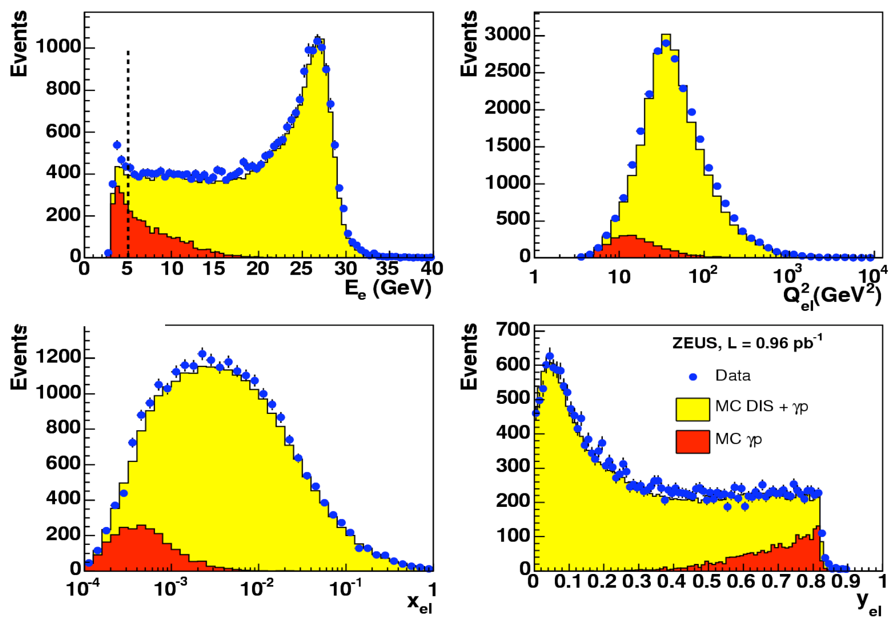
Lower Energy Runs for F_L at HERA

- Last 3 months of HERA running:
  LER/MER dedicated to measurement of F_L
- Very successful!!! HERA delivered:
  ~ 14 pb^{-1} at E_p=460 GeV ($\sqrt{s}$=225 GeV): LER
  ~ 7 pb^{-1} at E_p=575 GeV ($\sqrt{s}$=252 GeV): MER
- H1 and ZEUS dedicated groups for F_L



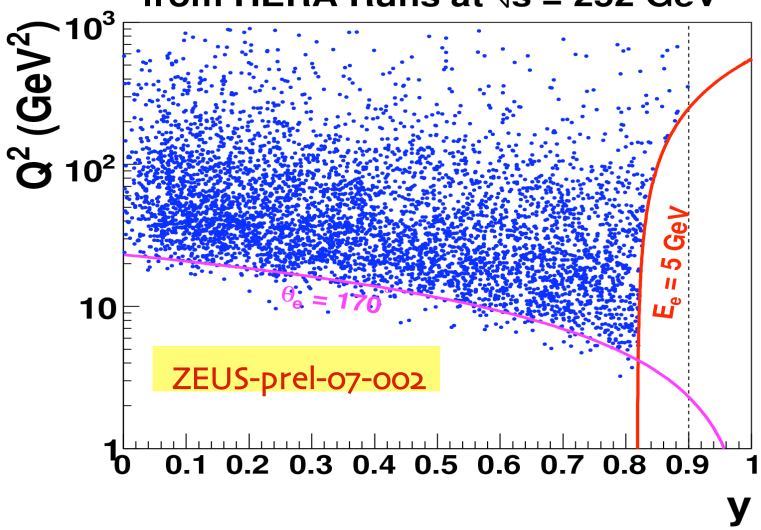
ZEUS Control Plots

First Data from HERA Runs at $\sqrt{s}$= 225 GeV



ZEUS First Events

from HERA Runs at $\sqrt{s}$ = 252 GeV



Eagerly await HERA F_L measurement !!!

… and Finally (HERA Averaged Data)

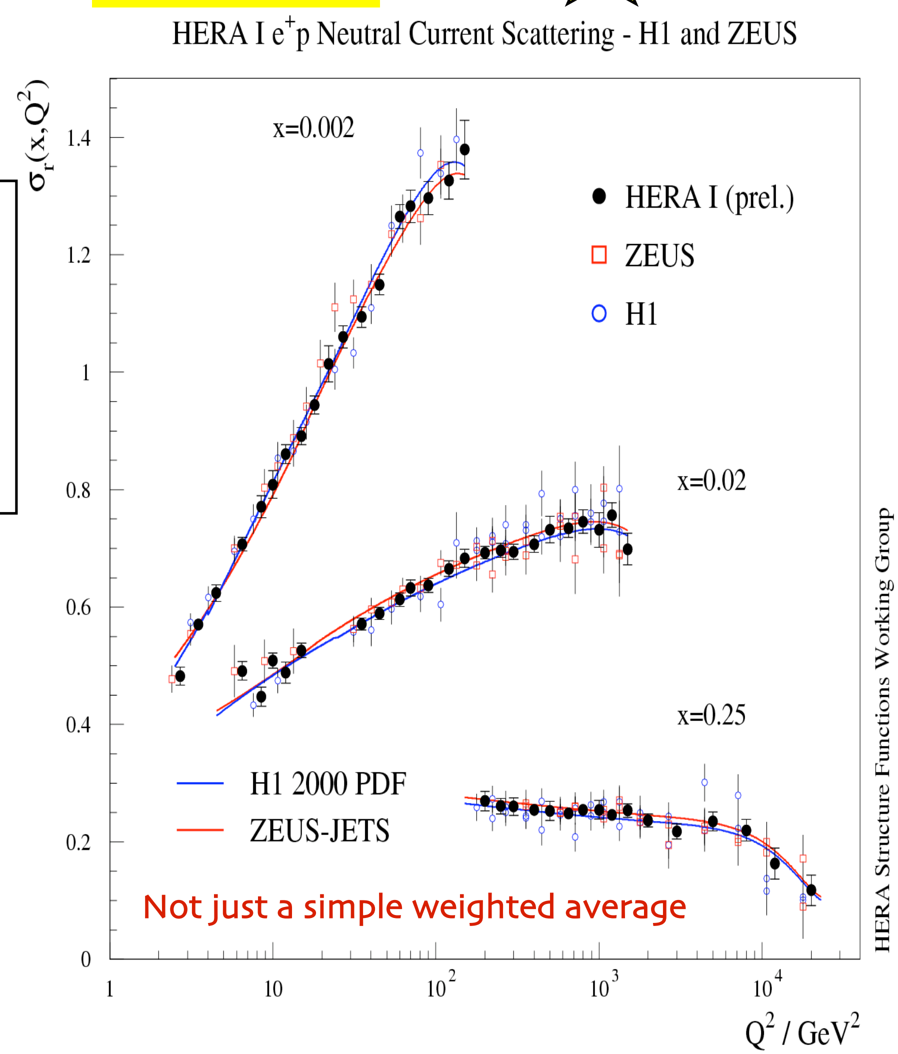
Recent initiative by H1 and ZEUS on averaging HERA DIS cross sections
(So far: published HERA-I NC/CC data only)

IDEA (in a nutshell)
Combined H1/ZEUS data in generalised averaging procedure:

- Fit Chi2 versus cross section
  … taking account of correlated systs. within and between experiments

H1prelim-07-007
ZEUS-prel-07-026

NEW for LP07



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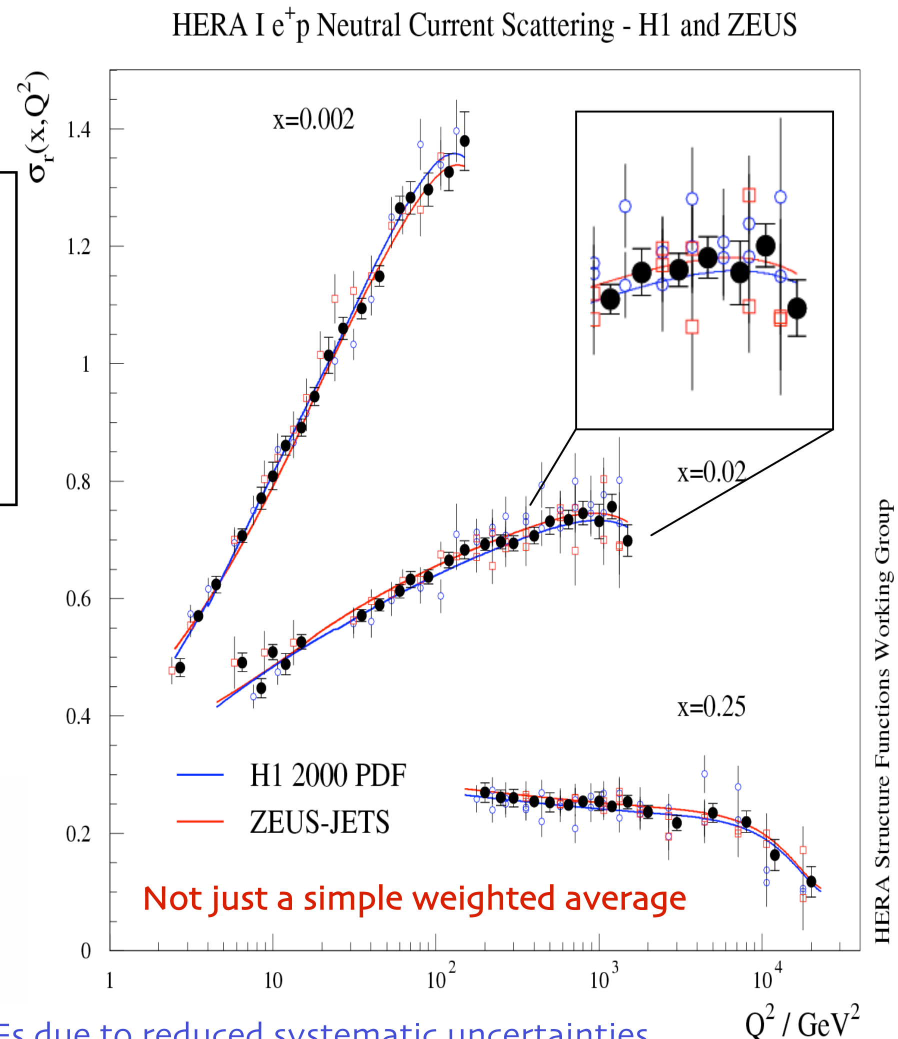
- Fit Chi2 versus cross section
  … taking account of correlated systs. within and between experiments

Experiments "cross-calibrate" each other
→ reduced systs. in combined dataset
⇒ total uncertainties improved by more than √2 in systematics dominated region

Ultimate Goals:
Combine remaining data from HERA-I+II
→ HERA PDF fit using final "HERA datasets"
(+ final legacy for global PDF fitters)

H1prelim-07-007
ZEUS-prel-07-026

NEW for LP07



↖ expect significant further constraints on PDFs due to reduced systematic uncertainties

Summary

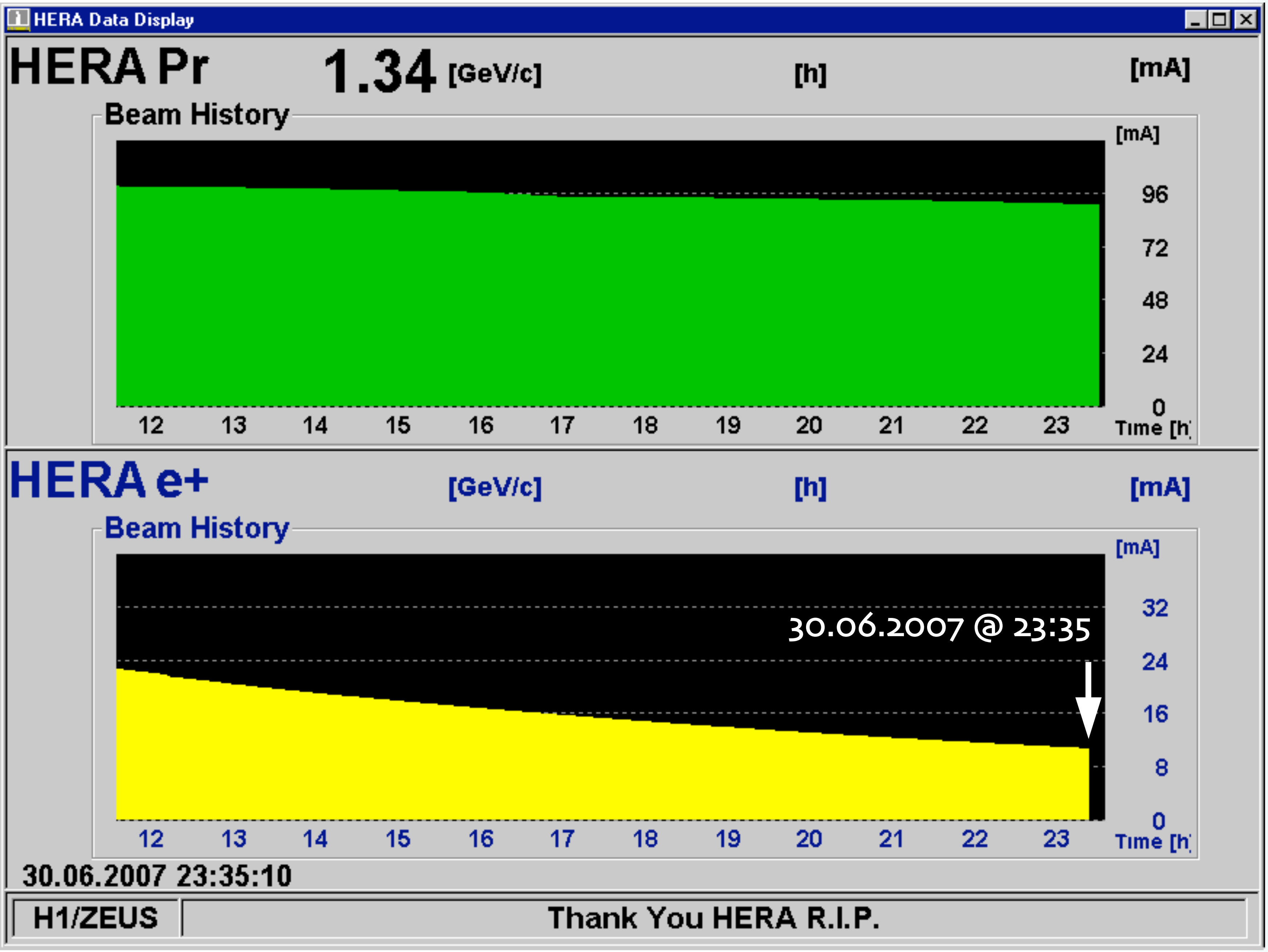
- 30.06.07 : end of a unique machine for DIS at the high energy frontier
- Many new results from HERA-I and II this Summer
- High precision and extended kinematic reach:
  - ✓ new constraints on proton structure: valence, gluon, charm, beauty,….
  - ✓ HERA precision α_s
  - ✓ exploration of EW sector in space-like domain
- New phase of H1 and ZEUS mutual collaboration → combined working groups
  - ✓ combined SFs, α_s, HERA combined data, …
- GOODBYE to the machine – but not to results !!! → eagerly AWAIT …

  Full HERA statistics measurements, F_L, final HERA combined data, …

  (the final legacies!)

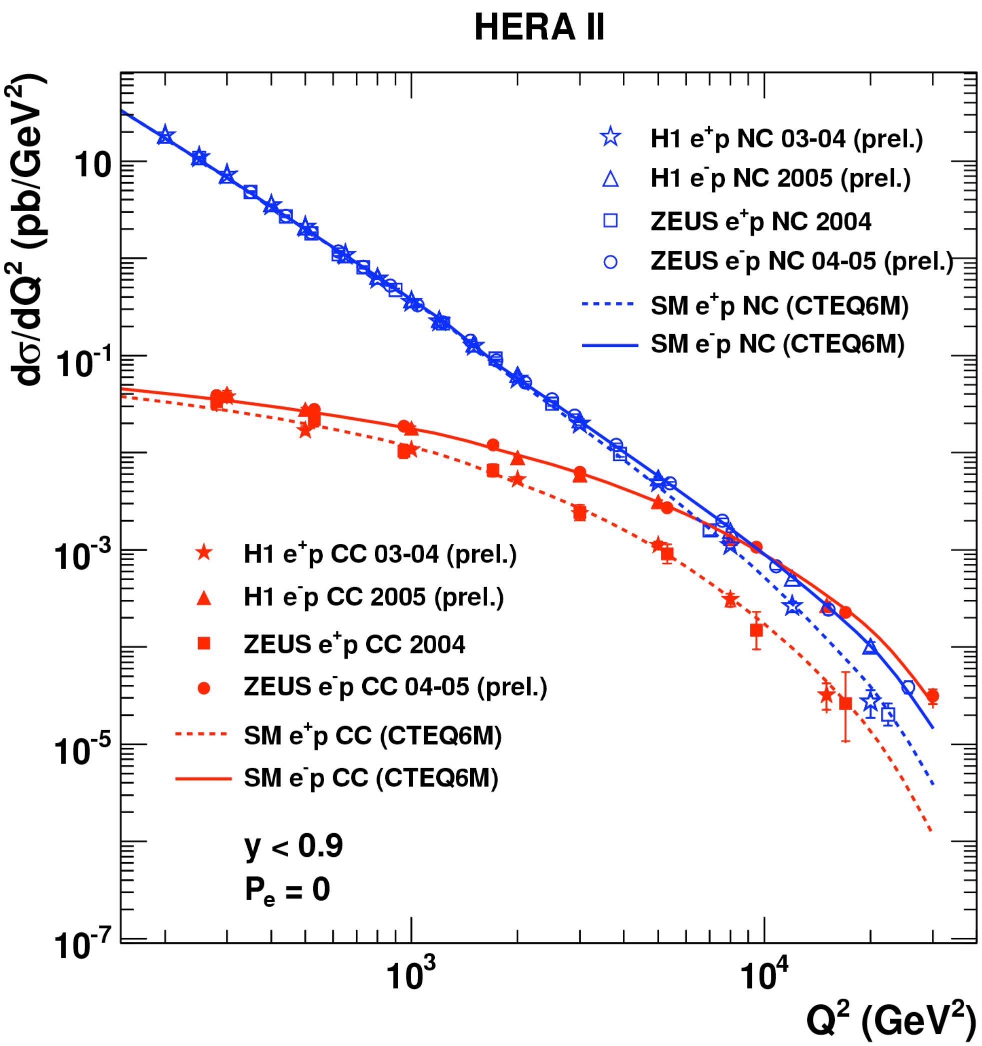
With very many thanks to:
I. Abt, O. Behnke, A. Cooper-Sarkar, M. Diehl, L. Dixon, J. Ferrando, E. Gallo, C. Glasman, M. Klein, U. Klein, J. Loizides, K. Nagano, R. Thorne, M. Wing … and the H1 and ZEUS Collaborations

For further details: http://www-zeus.desy.de/ http://www-h1.desy.de/


HERA Data Display
HERA Pr
1.34 [GeV/c]
[h]
[mA]
Beam History
[mA]
96
72
48
24
0
12 13 14 15 16 17 18 19 20 21 22 23
Time [h]
HERA e+
[GeV/c]
[h]
[mA]
Beam History
[mA]
32
24
16
8
0
30.06.2007 @ 23:35
12 13 14 15 16 17 18 19 20 21 22 23
Time [h]
30.06.2007 23:35:10
H1/ZEUS
Thank You HERA R.I.P.

Backups

NC/CC Cross Sections e-p vs. e+p



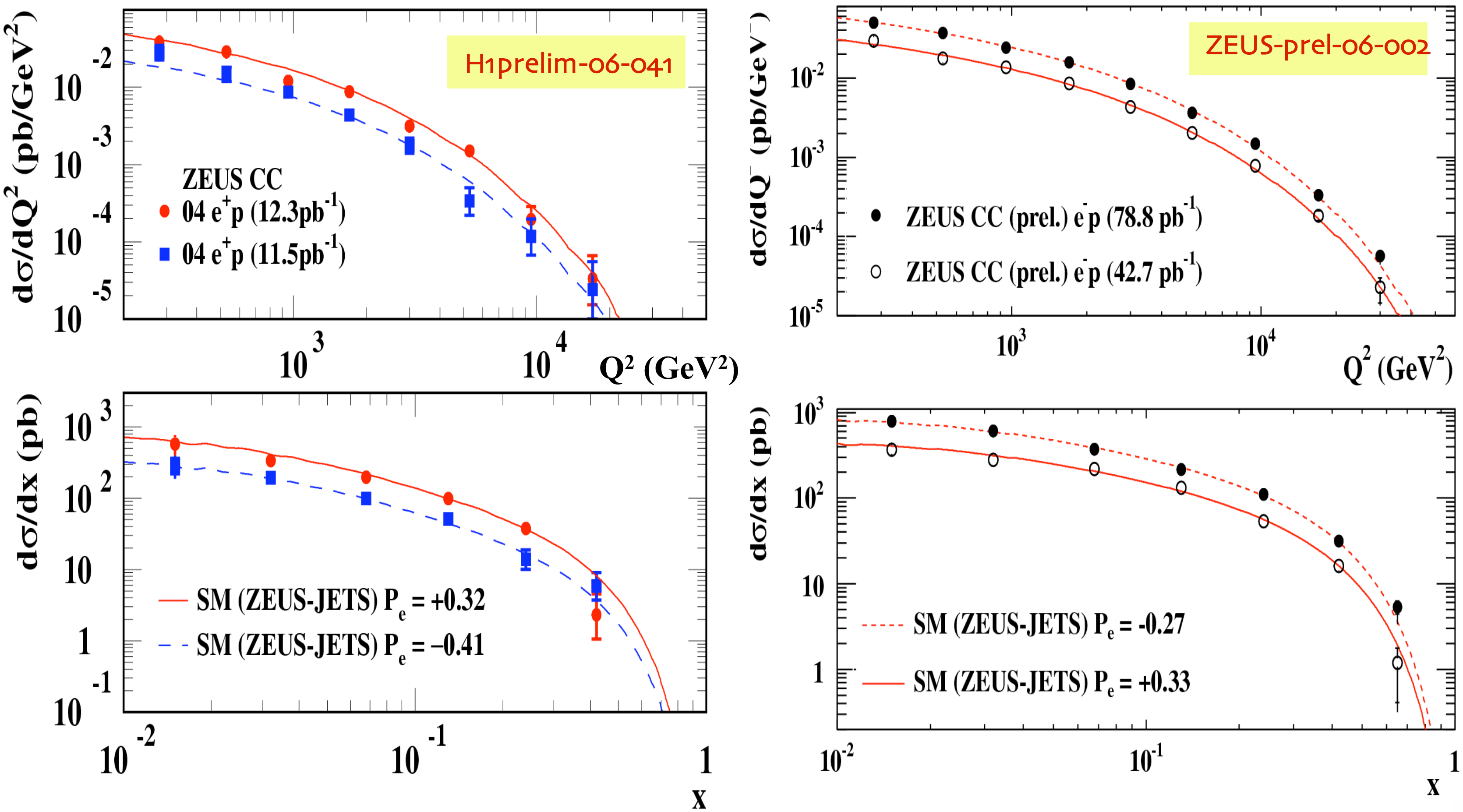
HERA-II

- HERA-II data: better precision (especially for e-p: > x10 cf. HERA-I)
- NC ∝ 1/Q4 - dominated by photon exchange (well measured at HERA-I)
- CC ∝ $M_W^4/(Q2+M_W^2)^2$
- NC and CC cross sections similar at high Q2 → EW unification ("textbook")
- Differences between e+p/e-p:
  NC: Z interference (xF3)
  CC: (d vs. u) PDFs and helicity factors
- Data described by SM over 7 orders of magnitude in the cross section

CC Polarised Cross Sections

HERA-II

Positron | Electron

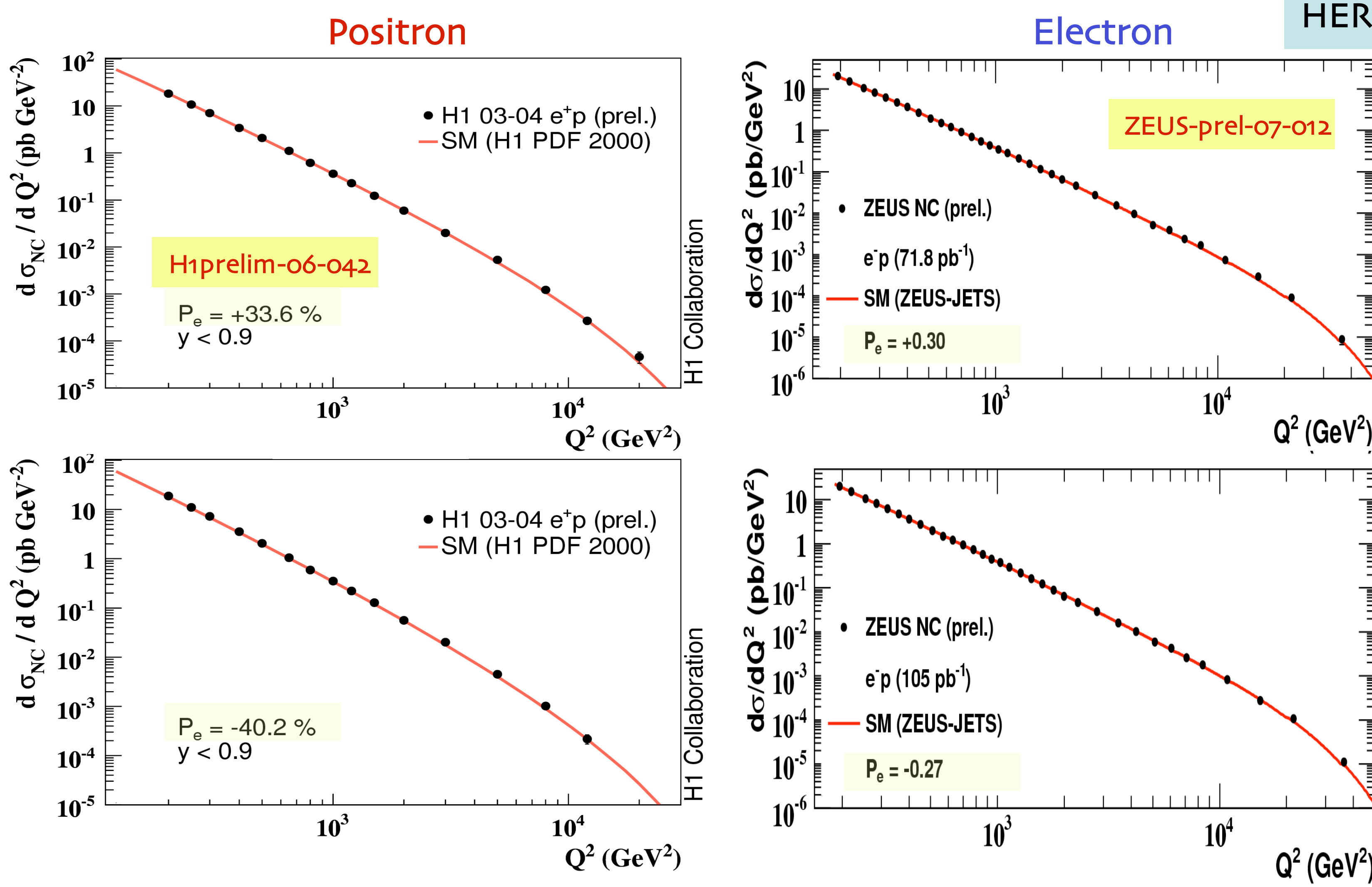


- Single differential cross sections → clear differences in LH/RH polarisation states

Polarisation dependence seen more clearly in total cross section

NC Polarised Cross Sections

HERA-II



- H1 and ZEUS have both measured positron/electron, LH/RH cross sections

NC Cross Section Ratios

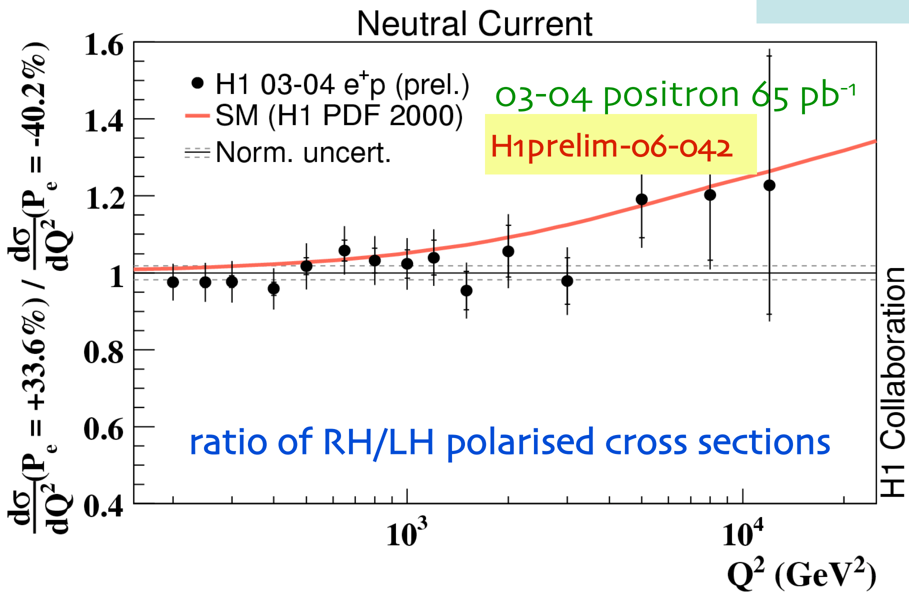
HERA-II

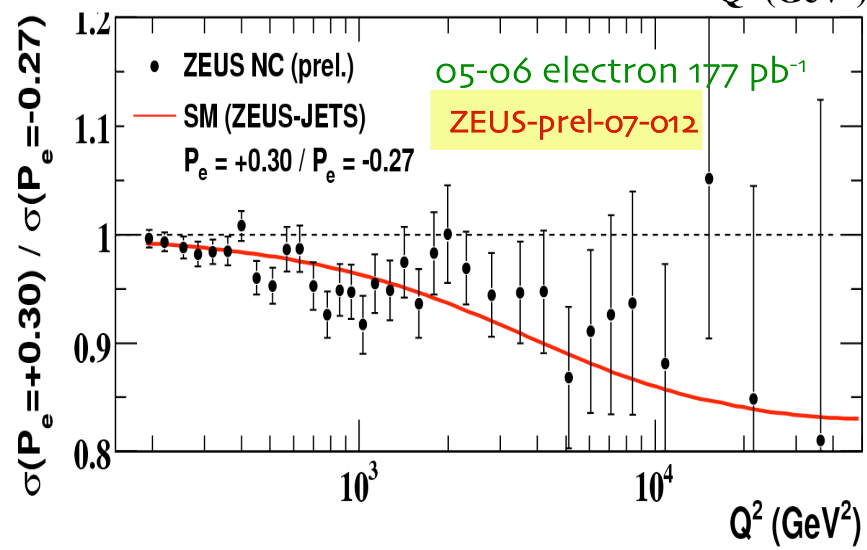
Differences between RH/LH polarisation states more apparent in ratio: σ(RH)/σ(LH)

dσ/dQ2 depends strongly on P_e:
→ effect increases with Q2
→ BUT so do statistical uncertainties…

Data consistent with SM
- enhancement of positron RH
- suppression of electron RH

Parity violation observed for the first time @ EW scale





M_W Determination

H1 Coll., hep-ex/0507080
ZEUS-prel-06-003

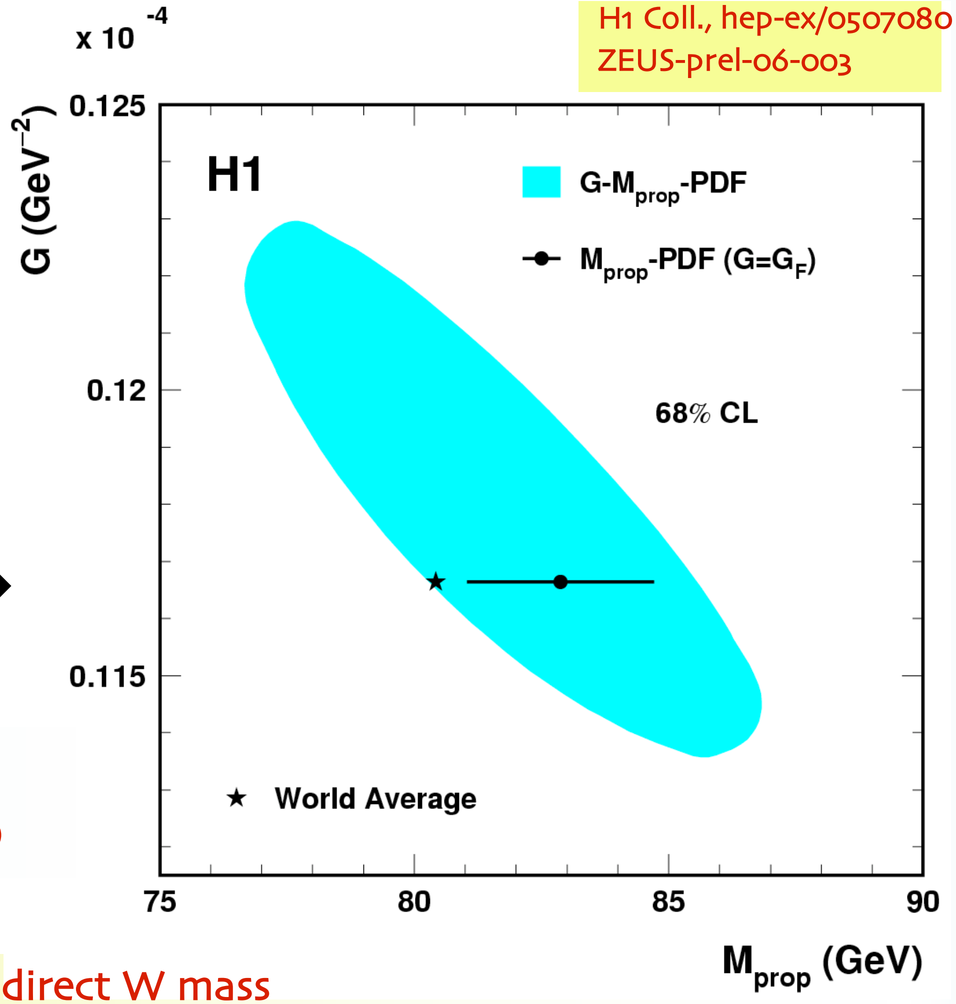
QCD+EW fit: to determine PDFs and M_W, G_F

$$\sigma_{CC@HERA} \propto \frac{G_F^2 M_W^4}{(Q2+M_W^2)^2}$$

Determination of propagator mass in the t-channel (cf. s-channel at LEP/Tevatron):

- Free M_W and G_F:
  G_F consistent with value from μ-decay →
- Fix G_F:

M_W = 82.9 $\pm 1.8_{exp}{}^{+0.3}{}_{-0.2|model}$ GeV (H1)
M_W = 79.1$\pm 0.8_{uncorr} \pm 1.0_{corr}$ GeV (ZEUS)



Complementary to and consistent with direct W mass measurements from LEP/Tevatron → now measured in spacelike domain

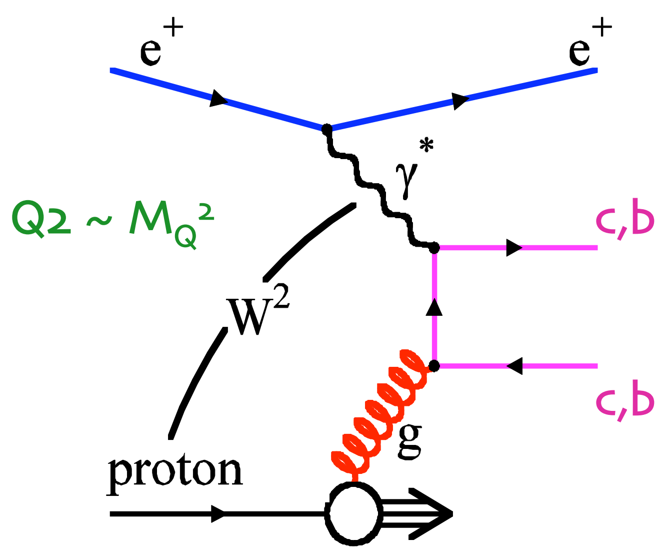
PDG Values:
M_W = 80.4 GeV
G_F=1.16637x10^{-5} GeV^{-2}

Heavy Flavours at HERA

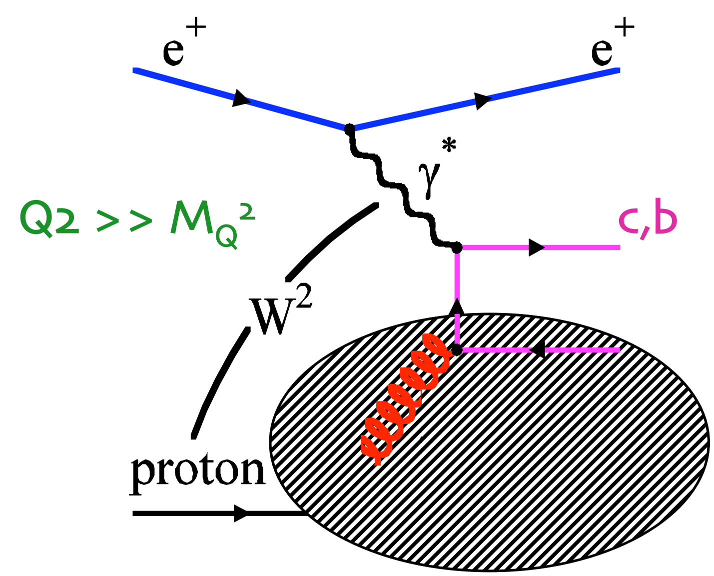
Heavy Flavour Production

- Study of pQCD in regions with additional hard scale i.e. the quark mass (m_c, m_b)
- Provides information on heavy quark production mechanism
- Sensitive to gluon and/or heavy quark content of proton

Heavy Flavour Schemes



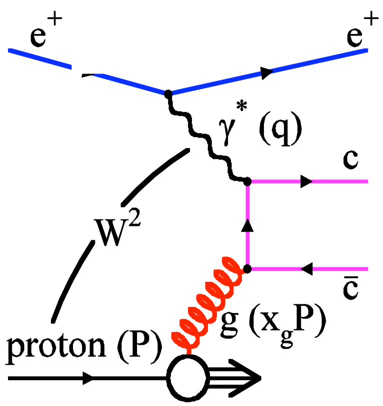
"massive"



"massless"

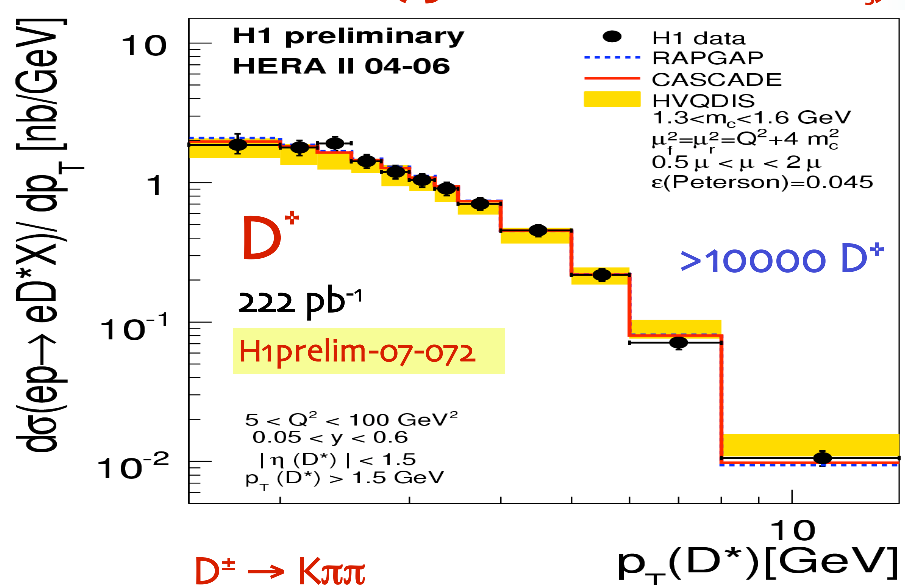
Variable Scheme (VFNS): "massive" (low Q2) → interpolation → "massless" (high Q2)

Charm in DIS (some examples)

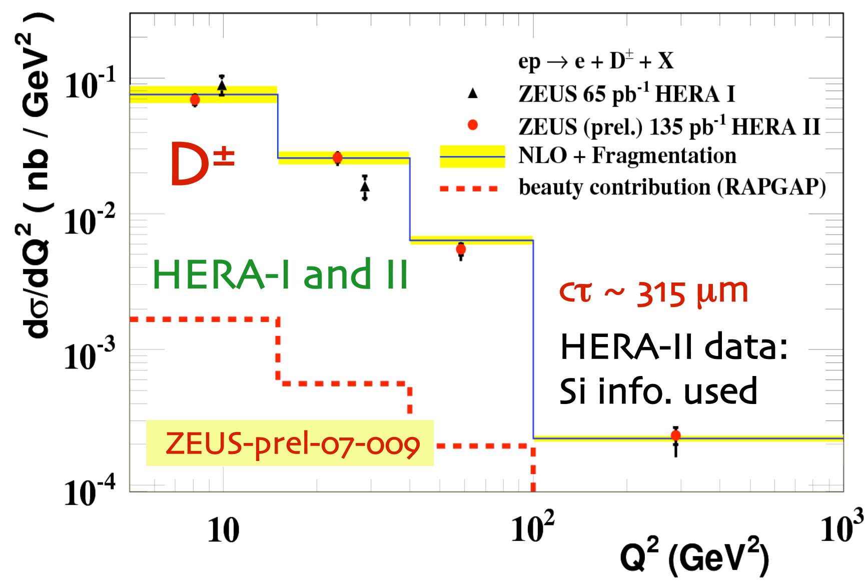


Charm identified by tagging D mesons in the final state

D^* mesons ("golden mode": $D^* \to K\pi\pi_s$)



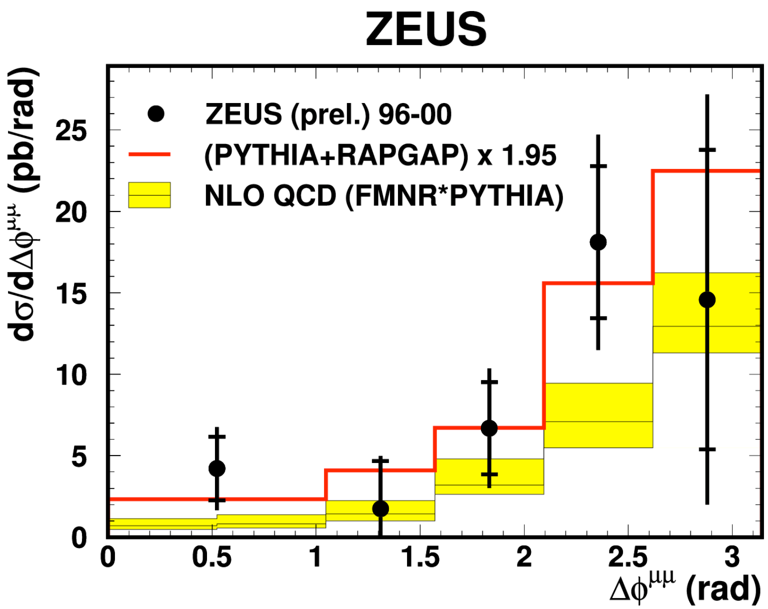
$D^\pm \to K\pi\pi$

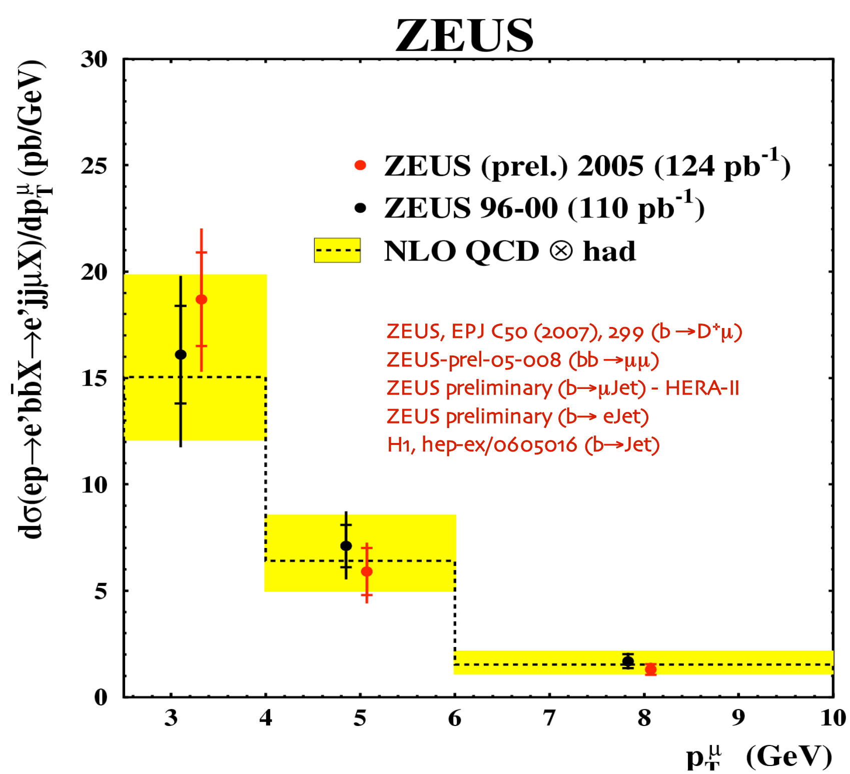


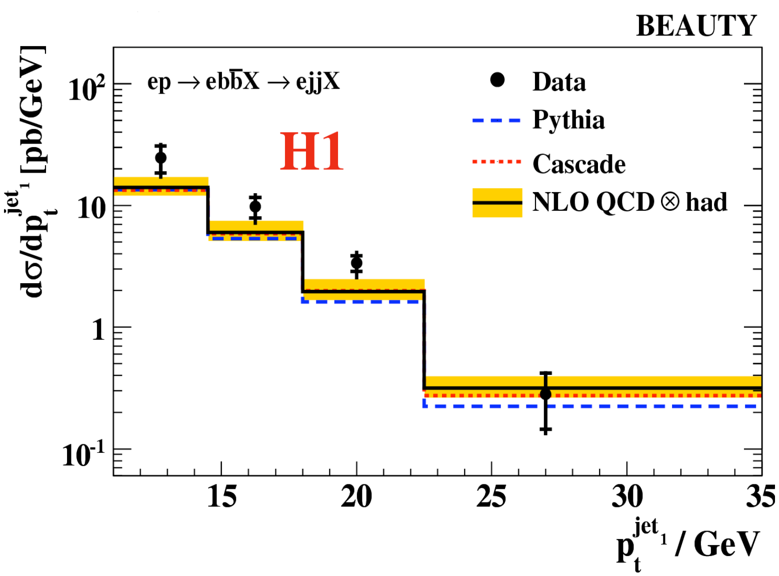
- Wealth of new precision data from HERA-I and II on charm from D mesons (D^*, $D^\pm$, D^0,…)
- Cross sections cf. NLO QCD ⊗ g(x) ("massive scheme") agree to quite high Q2
  theoretical uncerts. dominate (m_c, μ_r, μ_f, ε_c, …)

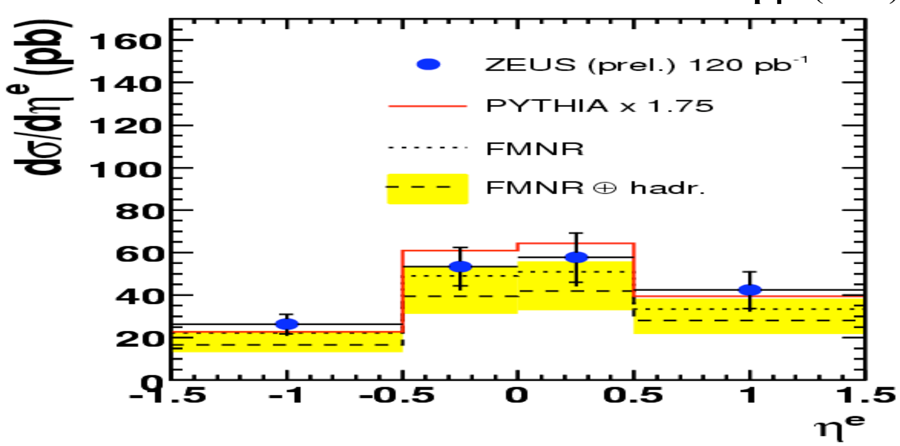
ZEUS detector upgrade (HERA-II):
inner Si tracker → analyses based on tracking techniques (impact parameter, decay length)
→ high purity signals for long-lived D mesons ↗

Beauty Cross Sections (some examples)





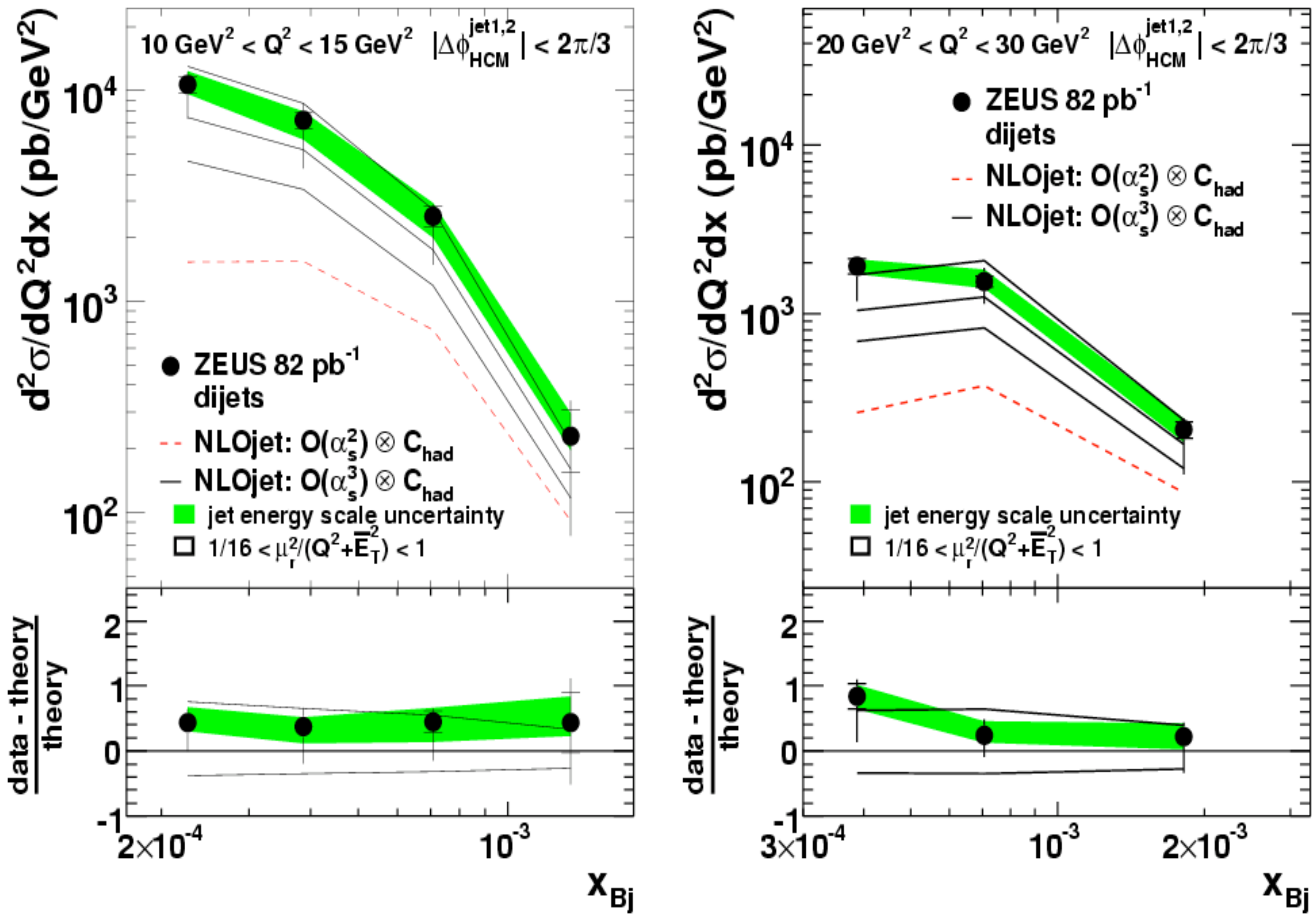




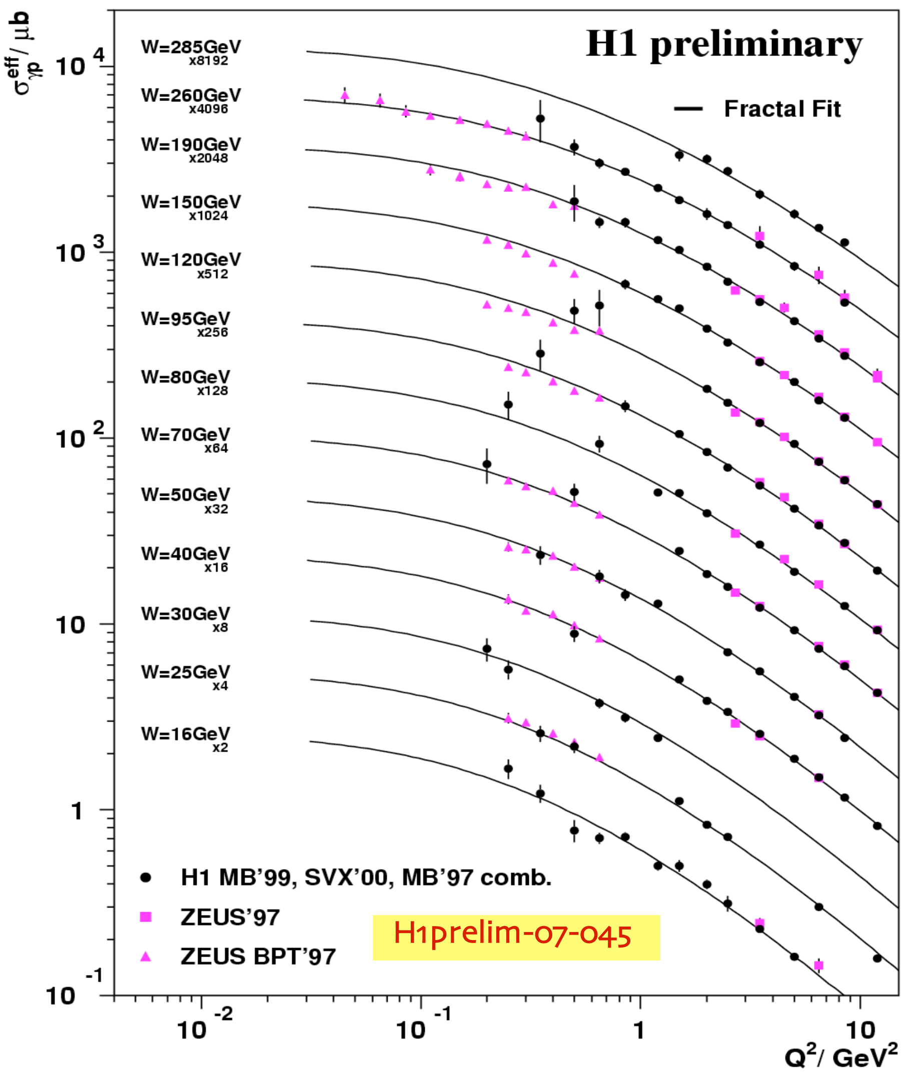
More on Low x Forward Jets

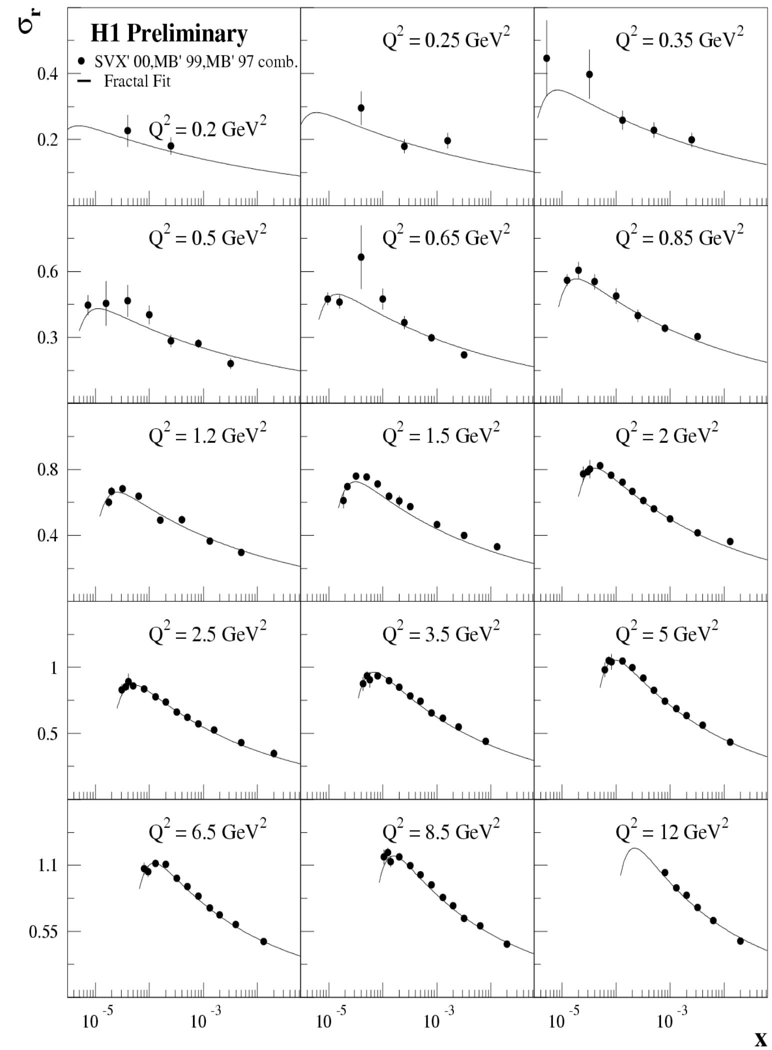
ZEUS Coll., DESY-07-062

$O(\alpha_s^3)$ description of dijets OK (NNLO for this process)

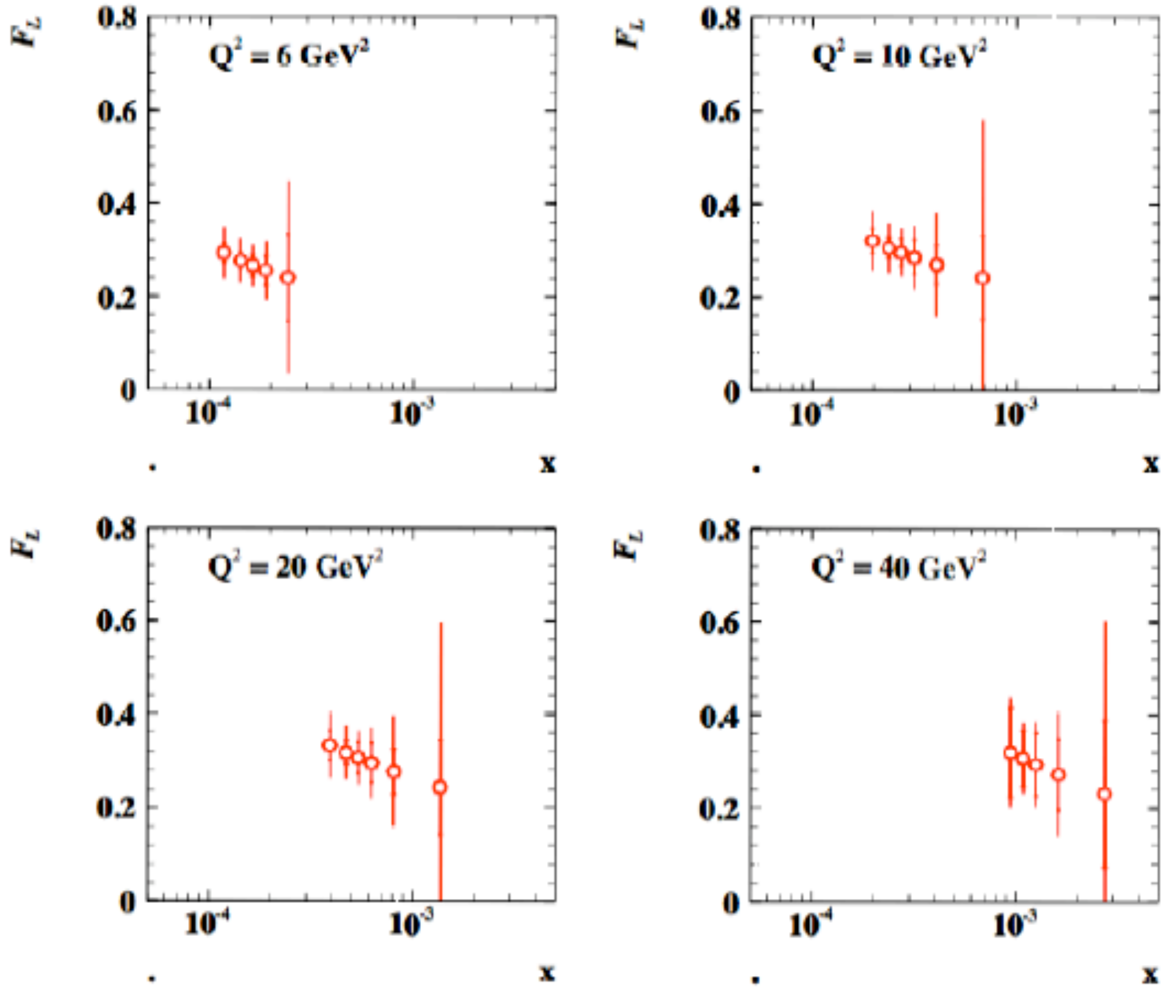


More on the Low Q2 Data





F_L Simulated Data



F_L Simulation

- 30 pb-1 @ 920 GeV
- 7 pb-1 @ 575 GeV
- 10 pb-1 @ 460 GeV