HERA results and their impact for LHC

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on behalf of the H1 and ZEUS Collaborations

Hadron Structure '09

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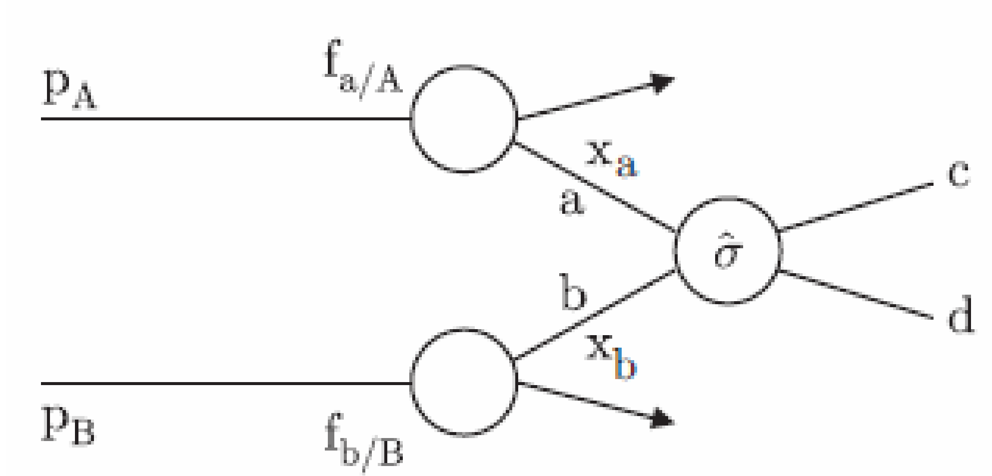
pp collisions at high energy



$$\sigma_{hard}(AB \rightarrow cdX) = \sum_{a,b} \int_0^1 dx_a dx_b f_{a/A}(x_a, \mu^2) f_{b/B}(x_b, \mu^2) \tilde{\sigma}(ab \rightarrow cd, \mu^2)$$

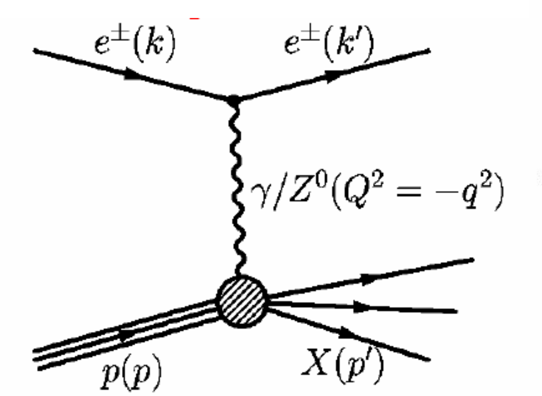
$f_{a/A}$ – momentum density function for parton a in hadron A with fraction x_a of the hadron momentum p_A → functions which have to be measured

μ – the hard scale

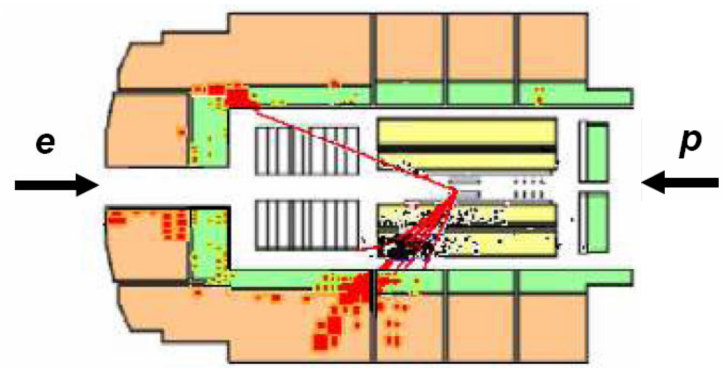
DIS one of the best tools to study proton internal structure and to obtain proton parton momentum distribution functions (PDFs) by probing proton with a exchanged boson, in particular the photon

Inclusive Deep Inelastic Scattering (DIS)

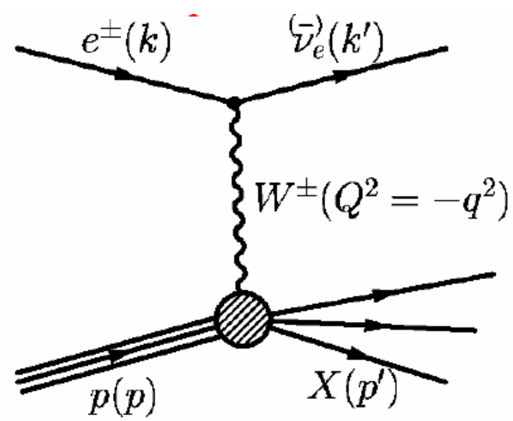
Neutral Current (NC)



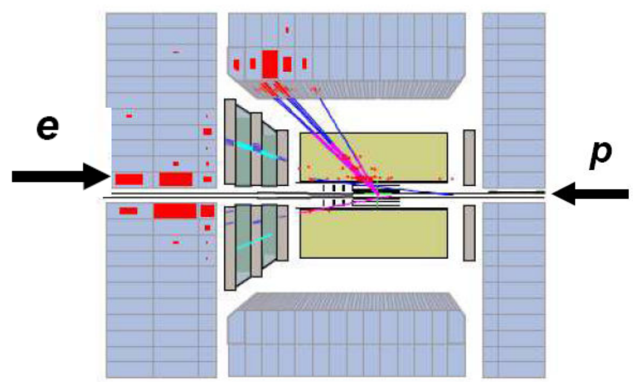
H1 NC event display



Charged Current (CC)



ZEUS CC event display



Virtuality of exchanged boson:

$$Q^2 = -q^2 = -(k - k')^2$$

Fraction of proton momentum carried by struck quark

$$x = \frac{Q^2}{2p \cdot q}$$

Fraction of energy transferred from incoming lepton at proton rest frame

$$y = \frac{p \cdot q}{p \cdot k}$$

Cross Sections and Structure Functions

Neutral current cross section

$\tilde{\sigma}_{NC}(x,Q^2)$ - NC reduced cross-section

$$\frac{d^2\sigma_{NC}(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+\left[\tilde{F}_2 - \frac{y^2}{Y_+}\tilde{F}_L \mp \frac{Y_-}{Y_+}x\tilde{F}_3\right] \qquad Y_{\pm} = 1 \pm (1-y)^2$$

γ-exchange, γZ-interference, Z-exchange

$$\tilde{F}_2 = F_2 - (v_e)K_Z F_2^{\gamma Z} + (v_e^2 + a_e^2)K_Z^2 F_2^Z$$ -dominant contribution

$$x\tilde{F}_3 = -a_e K_Z xF_3^{\gamma Z} + 2v_e a_e K_Z^2\, xF_3^Z$$ - important only at high Q^2

$$F_L = (Q^2/4\pi\alpha)\sigma_L$$ - sizable contribution for high y

(Generalised Structure Functions (SF))

In the Quark Partom Model (QPM): $F_L = 0$

$$[F_2, F_2^{\gamma Z}, F_2^Z] = \sum[e_q^2, 2e_q v_q, v_q^2 + a_q^2](xq + x\bar{q})$$

$$[xF_3^{\gamma Z}, xF_3^Z] = 2\sum[e_q a_q, v_q a_q](xq - x\bar{q})$$

(SFs)

$$K_Z = \frac{Q^2}{(Q^2+M_Z^2)^2}\frac{1}{4\sin^2\theta_W\cos^2\theta_W}$$

In pQCD: $F_L \sim \alpha_s \cdot xg(x,Q^2)$

$xq(x, Q^2), x\bar{q}(x, Q^2), xg(x, Q^2)$ - **P**arton **D**ensity **F**unctions - **PDFs**

Charged current cross section (LO)

$$\frac{d^2\sigma_{CC}^{e^+p}}{dxdQ^2} = \frac{G_F^2 M_W^4}{2\pi x(Q^2+M_W^2)^2}[x(\bar{u}+\bar{c})+(1-y)^2 x(d+s)]$$

$$\frac{d^2\sigma_{CC}^{e^-p}}{dxdQ^2} = \frac{G_F^2 M_W^4}{2\pi x(Q^2+M_W^2)^2}[x(u+c)+(1-y)^2 x(\bar{d}+\bar{s})]$$

d_v at high x

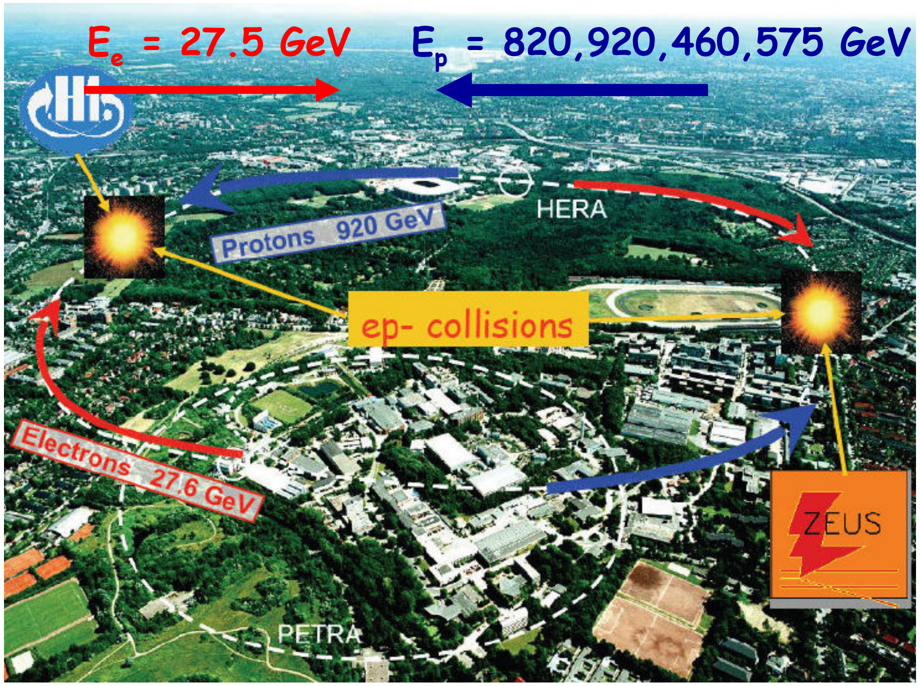
u_v at high x

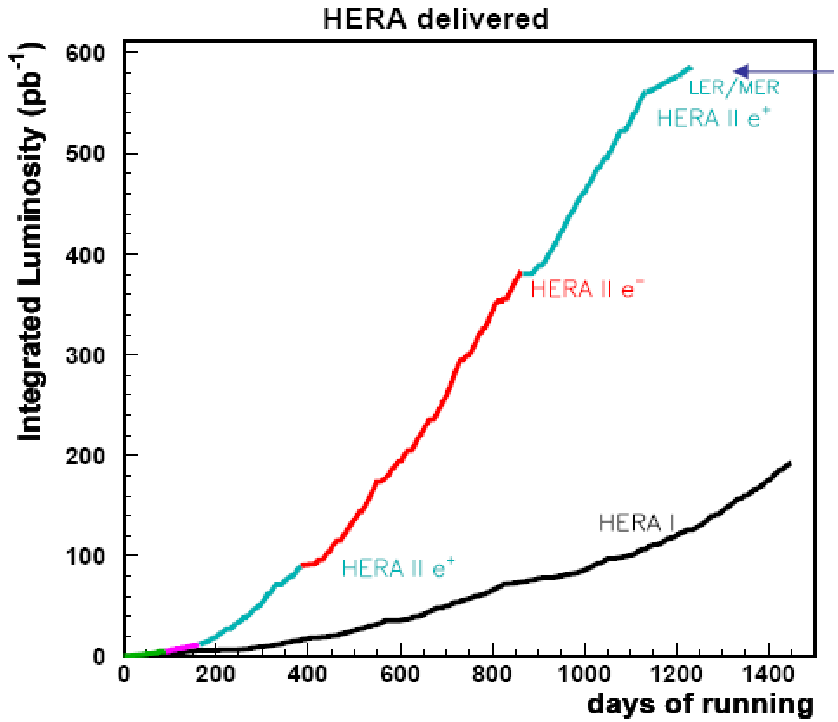
Sensitivity to the flavor of the valence distributions at high x

$\tilde{\sigma}_{CC}(x,Q^2)$ - CC reduced cross-section

- Quark PDFs - from NC (F_2) and CC DIS
- Gluon – indirectly from scaling violation - $dF_2/d\ln Q^2$, directly from F_L

HERA and luminosity





1992 – 2000 HERA-I (E_p = 820, 920 GeV)

2003 – 2007 HERA-II (E_p = 920 GeV) - Increased luminosity

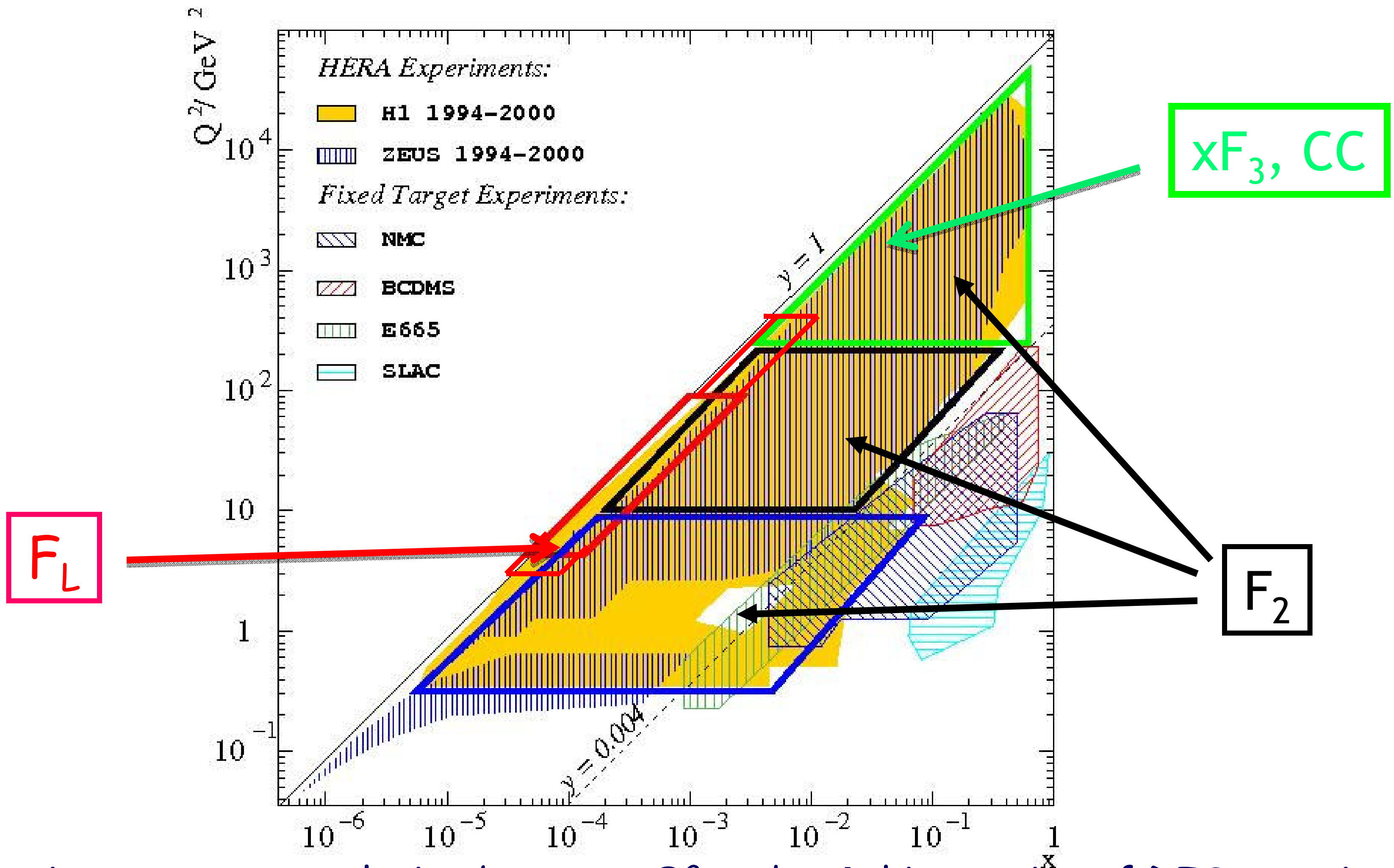
- Polarised lepton in collider mode

Since April 2007 until the end of June

- Low energy run – LER - (E_p = 460 GeV)
- Medium energy run – MER - (E_p = 575 GeV)

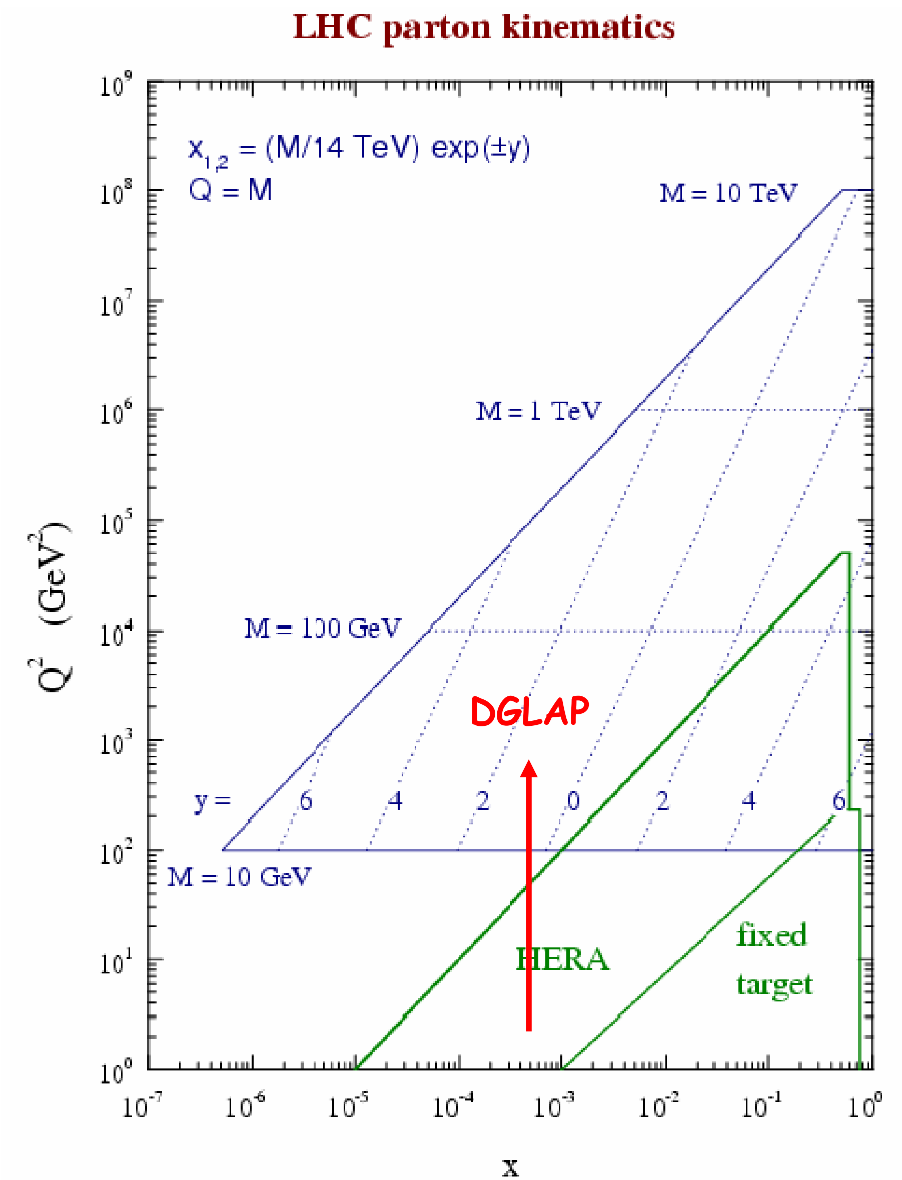
} Measurement of F_L

HERA kinematics – x vs Q^2



- There is a strong correlation between Q^2 and x → kinematics of DIS restricts the physical region

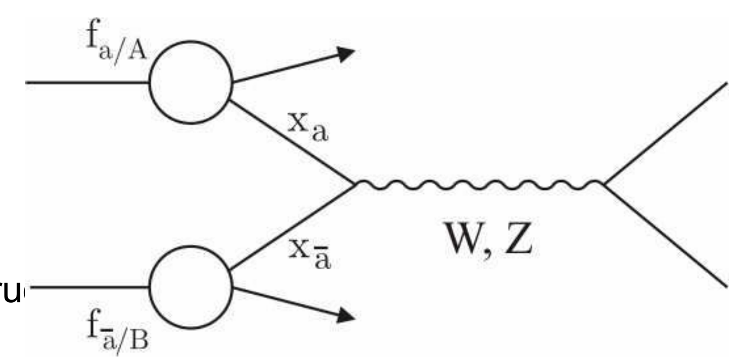
HERA and LHC kinematics – x vs $(Q = M)^2$



- ❑ HERA provides PDFs down to low x
- ❑ DGLAP QCD equations provide Q^2 evolution of the PDFs
- ❑ Low x region from HERA overlaps with central rapidity region from the LHC

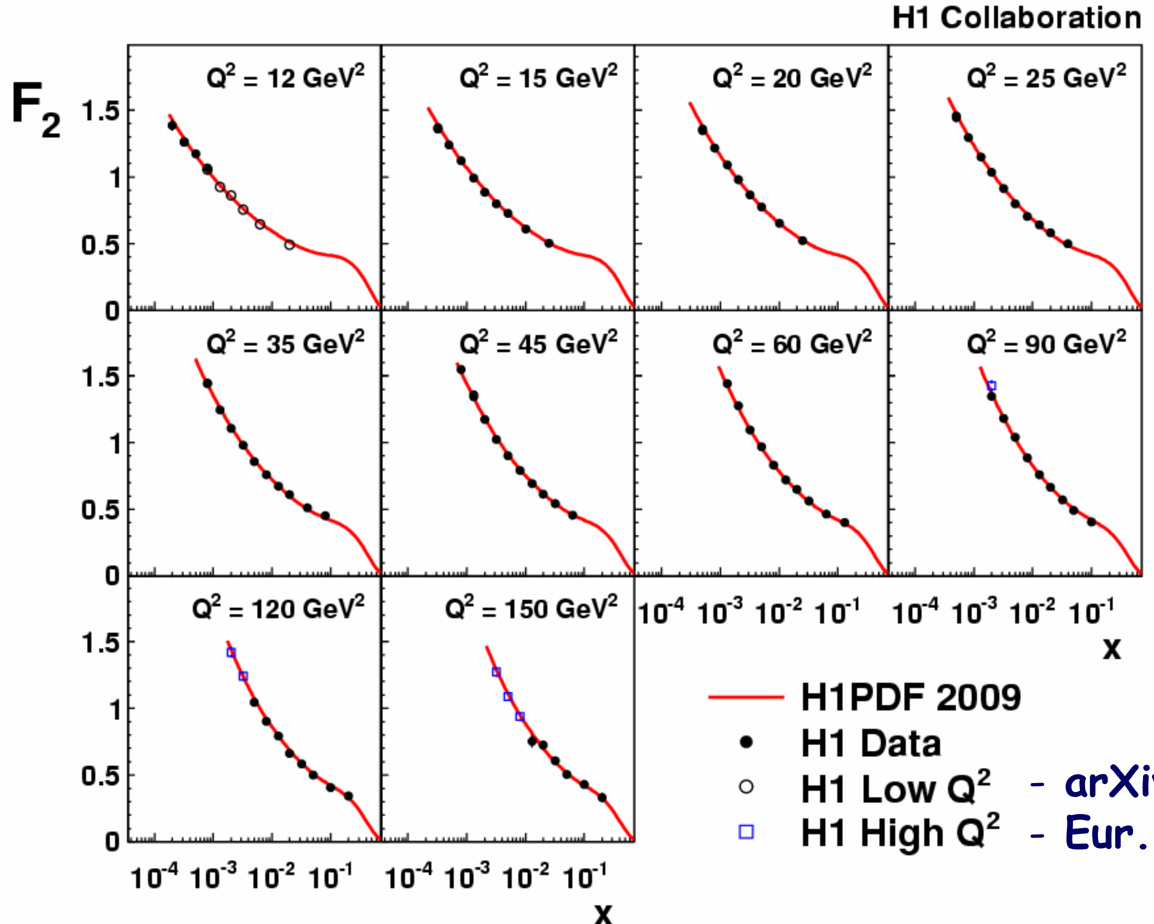
→ HERA provides essential inputs for LHC

- ❑ As a starting point, for early LHC performance focus on Standard Model W and Z production



Structure function F_2 at low x

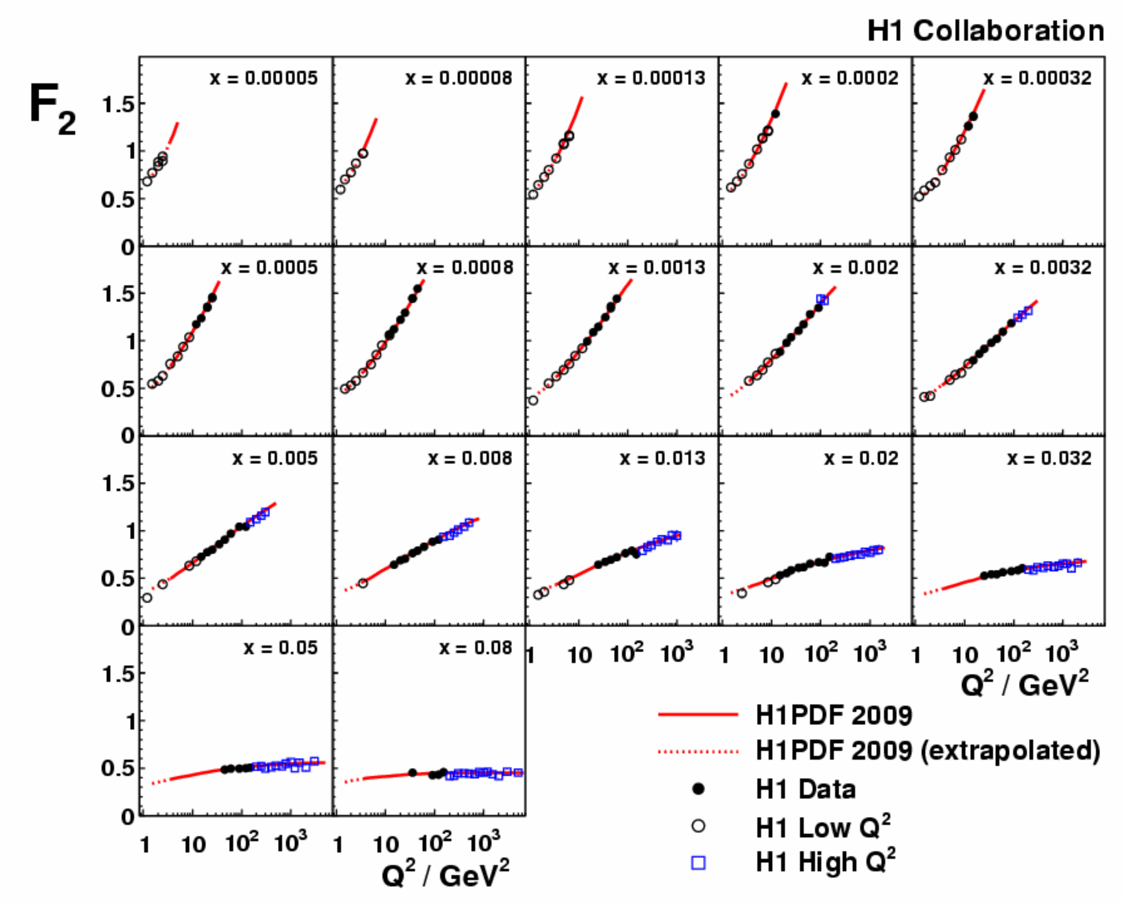
New publication from H1, **arXiv.0904.3513** → EPJ C



- arXiv.0904.0929 → EPJ C
- Eur. Phys. J. C 30, 1 (2003)

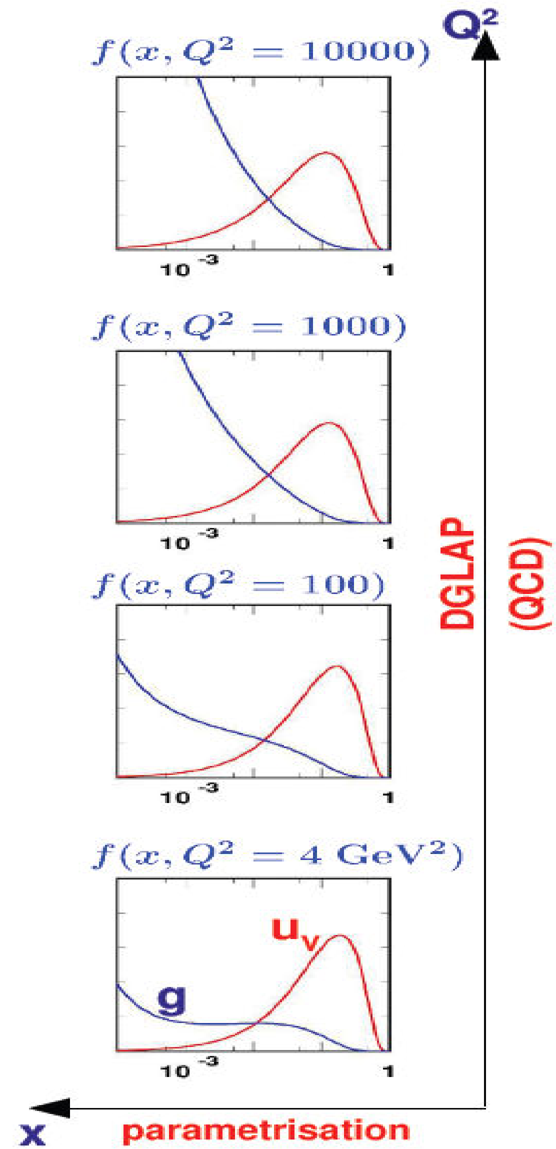
- Final word about F_2 at low x from H1 (1.3%-2% precision)
- F_2 shows strong rise as $x \to 0$, the rise increases with increasing Q^2

Scaling violation of F_2 at low x



- ❑ Large scaling violation at low x → large gluon density
- ❑ Good agreement between the data and theory (also for extrapolation to low Q^2)

QCD analysis



General approach for PDF determination

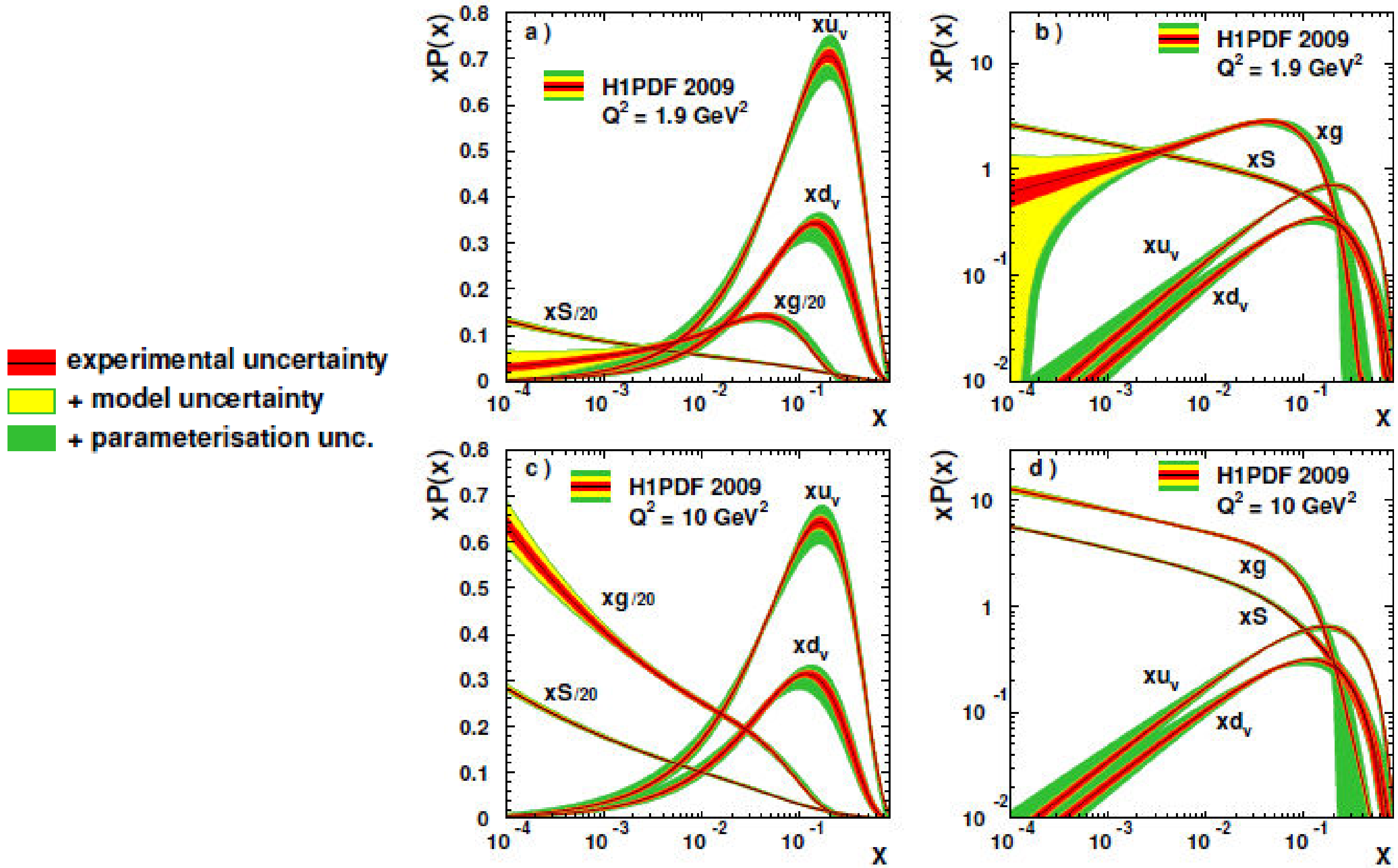
- Parametrise the parton density functions at low starting scale Q_0^2 by smooth analytical functions as $Ax^B(1 - x)^C(1 + Dx + \ldots)$
- Evolve these functions using the DGLAP equations to higher Q^2 and calculate x-sections
- Compare the calculation to experimental data
- Minimisation of χ^2 adjusting the free parameters

Uncertainties

- Experimental – using $\Delta\chi^2 = 1$ criterion
- Model – from variation of theory parameters (Q_0^2, m_c, m_b…)
- Parameterisation – from extra D, E, … terms in parameterisation

Partons at low x – the very new PDF fit from H1

New publication from H1, **arXiv.0904.3513** → EPJ C



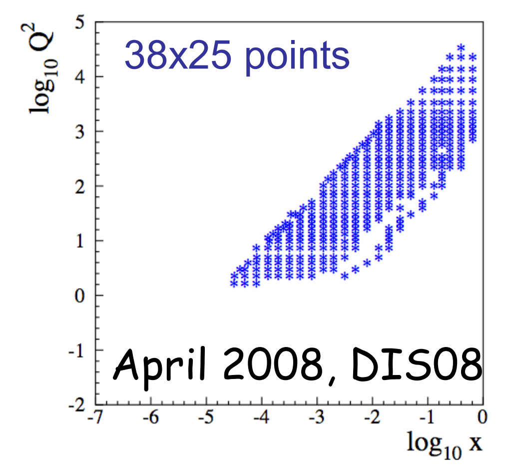
- At low x, $x < 0.01$, sea and gluon contributions dominate
- Rapid increase of sea and gluon contribution with Q^2

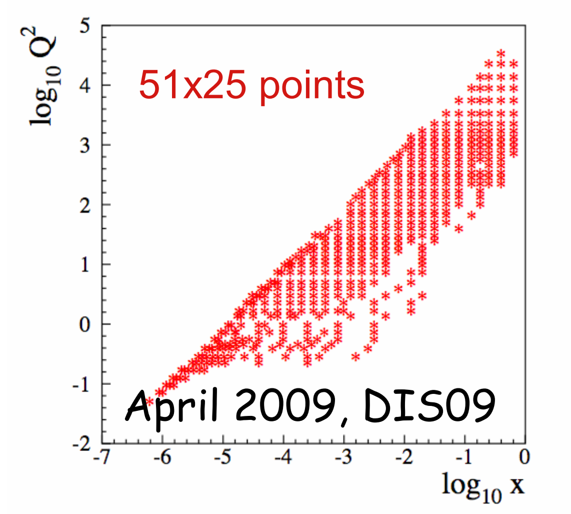
H1 and ZEUS data combination

Motivation: produce a more precise cross section measurement to be used for PDF extraction

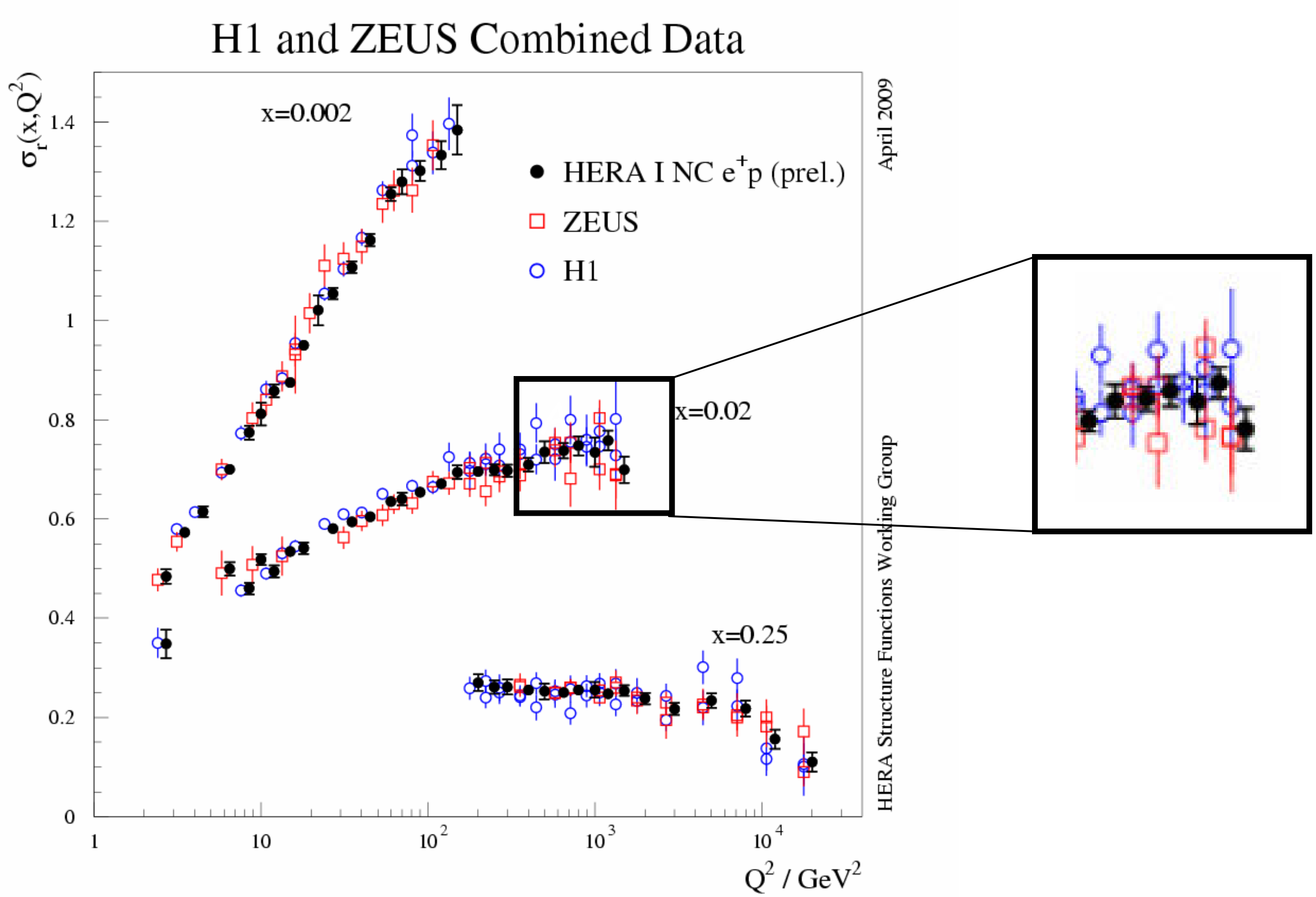
Data sets: published results on inclusive NC and CC cross sections from HERA-I data

Data Set		x range		Q^2 range GeV^2		$\mathcal{L}$ pb^{-1}	$\sqrt{s}$ GeV
H1 svx-mb	95-00	5×10^{-6}	0.02	0.2	12	2.1	301-319
H1 low Q^2	96-00	2×10^{-4}	0.1	12	150	22	301-319
H1 NC	94-97	0.0032	0.65	150	30000	35.6	301
H1 CC	94-97	0.013	0.40	300	15000	35.6	301
H1 NC	98-99	0.0032	0.65	150	30000	16.4	319
H1 CC	98-99	0.013	0.40	300	15000	16.4	319
H1 NC HY	98-99	0.0013	0.01	100	800	16.4	319
H1 NC	99-00	0.00131	0.65	100	30000	65.2	319
H1 CC	99-00	0.013	0.40	300	15000	65.2	319
ZEUS BPT	97	6×10^{-7}	0.001	0.045	0.65	3.9	301
ZEUS BPC	95	2×10^{-6}	6×10^{-5}	0.11	0.65	1.65	301
ZEUS SVX	95	1.2×10^{-5}	0.0019	0.6	17	0.2	301
ZEUS CC	94-97	0.015	0.42	280	17000	47.7	301
ZEUS NC	96-97	6×10^{-5}	0.65	2.7	30000	30.0	301
ZEUS NC	98-99	0.005	0.65	200	30000	15.9	319
ZEUS CC	98-99	0.015	0.42	280	30000	16.4	319
ZEUS NC	99-00	0.005	0.65	200	30000	63.2	319
ZEUS CC	99-00	0.008	0.42	280	17000	60.9	319





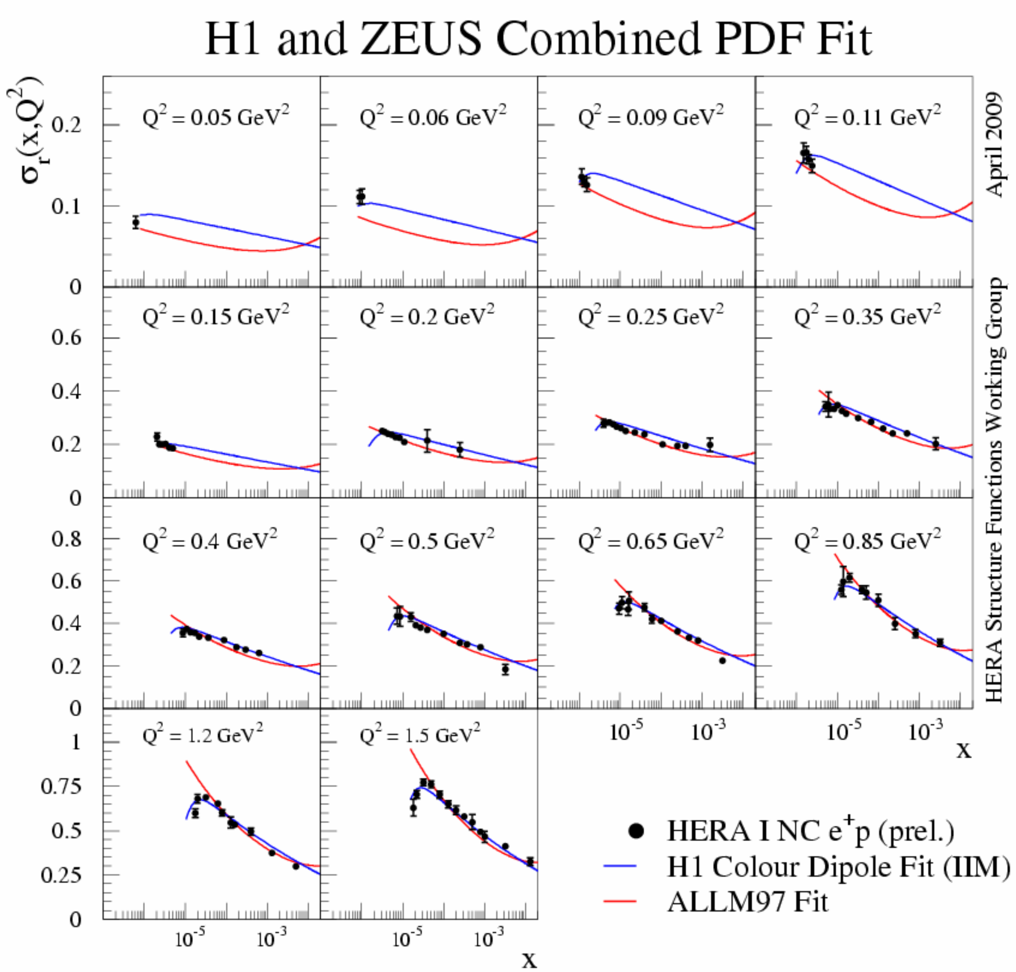
Averaged cross sections



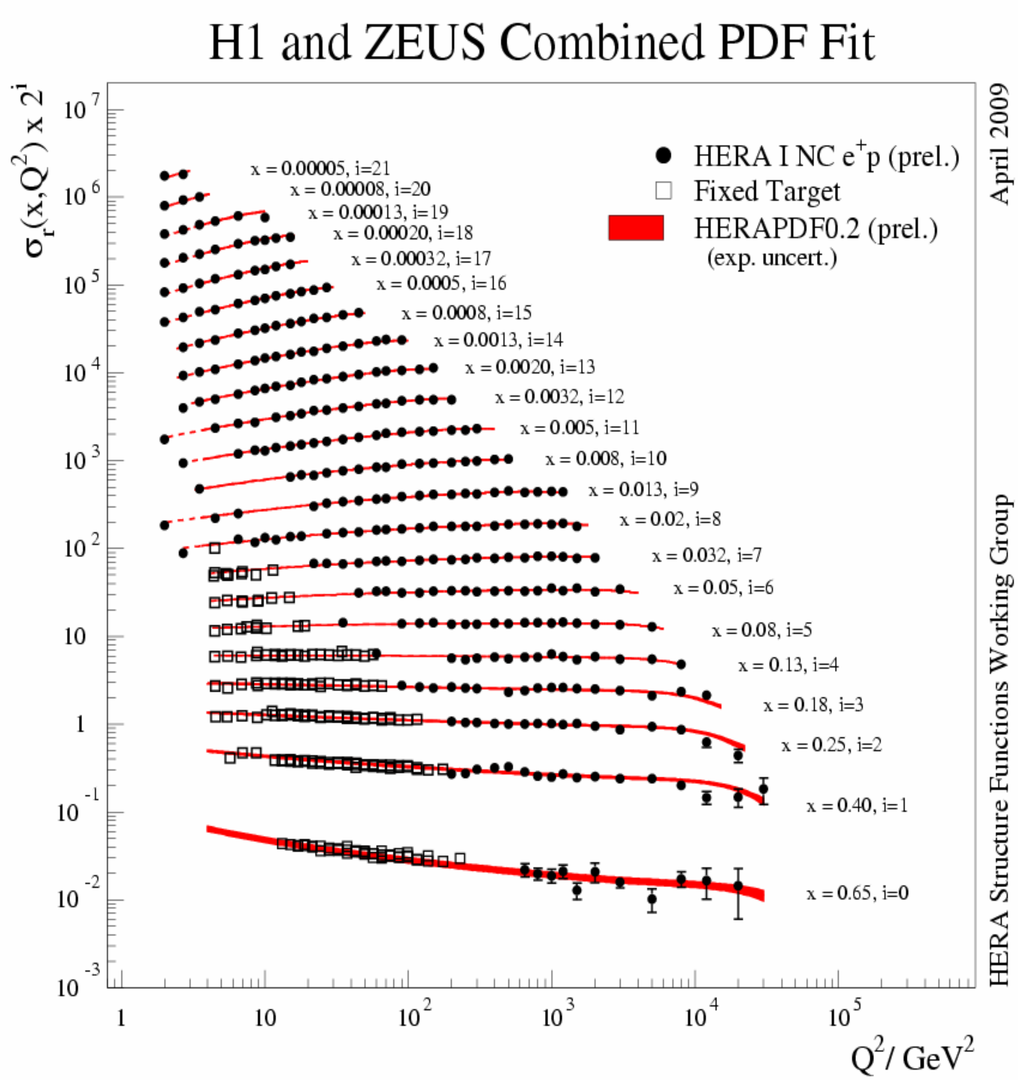
- 1042 points are combined to 741 cross section measurements $\chi^2/ndf=699/716$
- Overall precision: 1% for $20 < Q^2 < 100$ GeV^2, 2% for $3 < Q^2 < 500$ GeV^2

Averaged low Q^2 data from HERA

Lowest $Q^2 \rightarrow 0$ domain - transition to non-perturbative region
- Phenomenological models

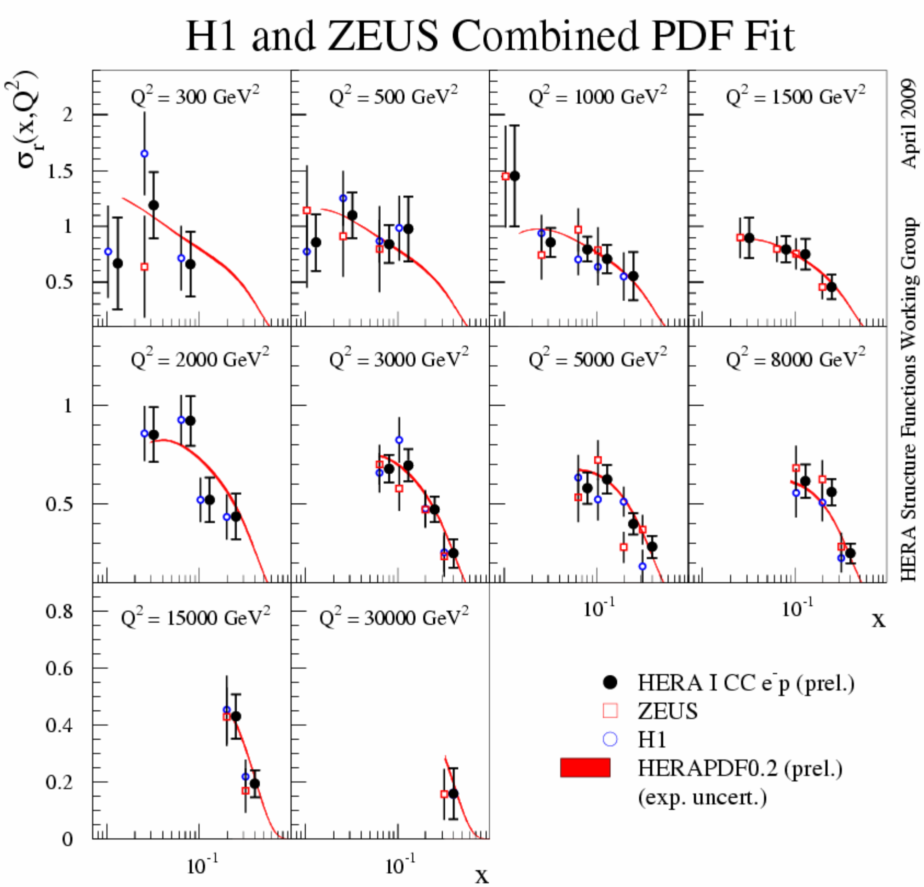


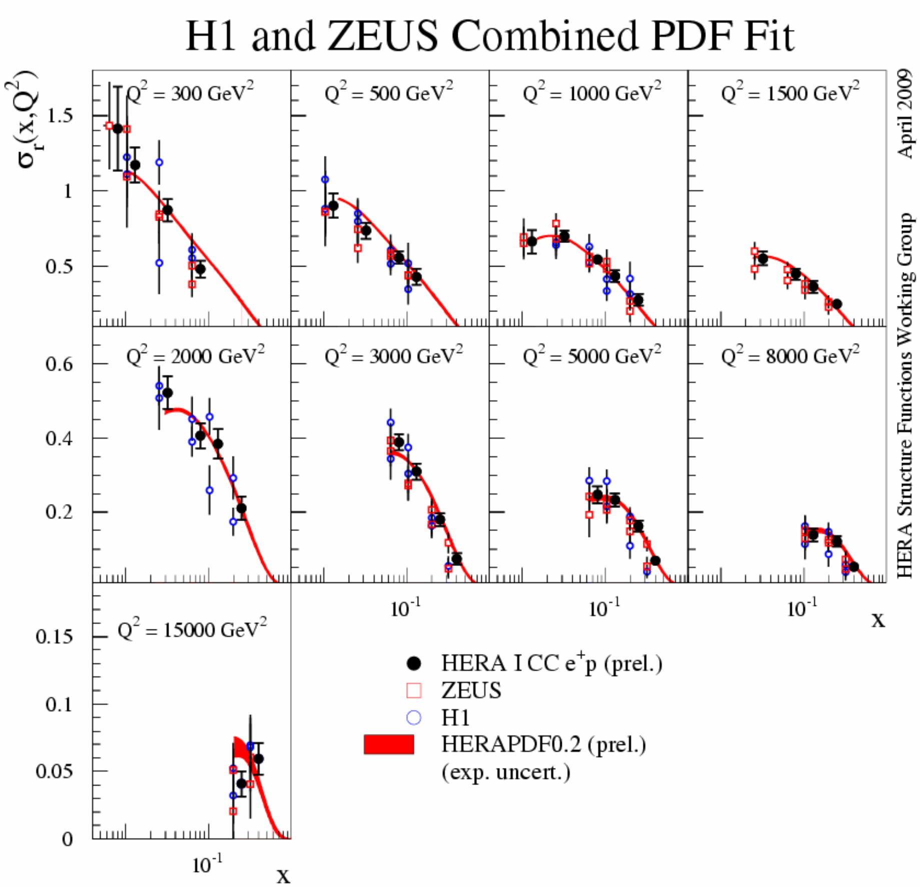
NC cross sections and QCD fit result



- Valence + Sea quarks contribution measured over many orders of magnitude in x and Q^2
- DGLAP works on a very large phase space
- Still a lot of room for improvement in high Q^2 region dominated by statistical uncertainties → HERA II data

CC cross sections and QCD fit result

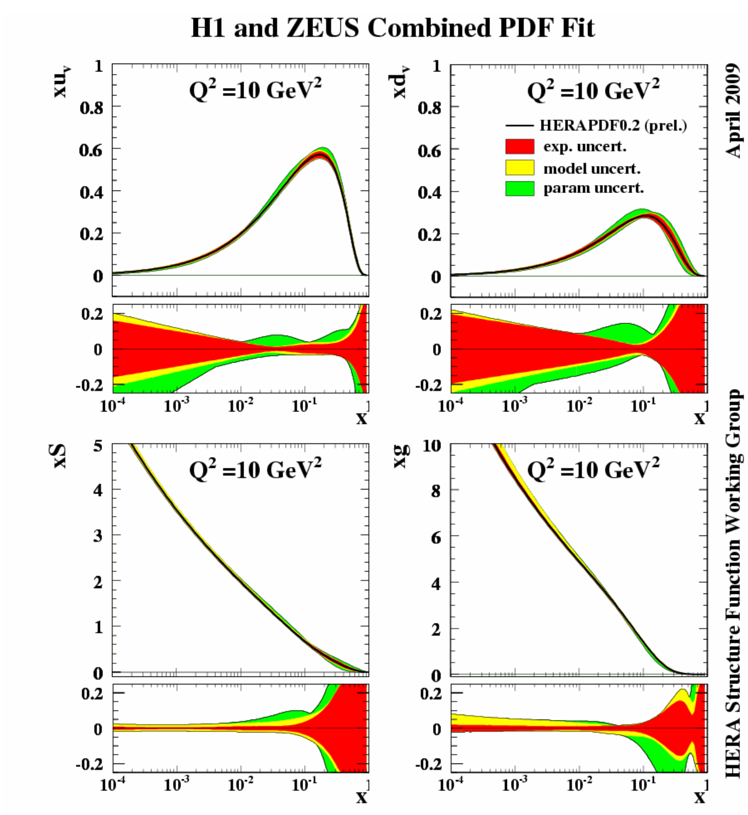


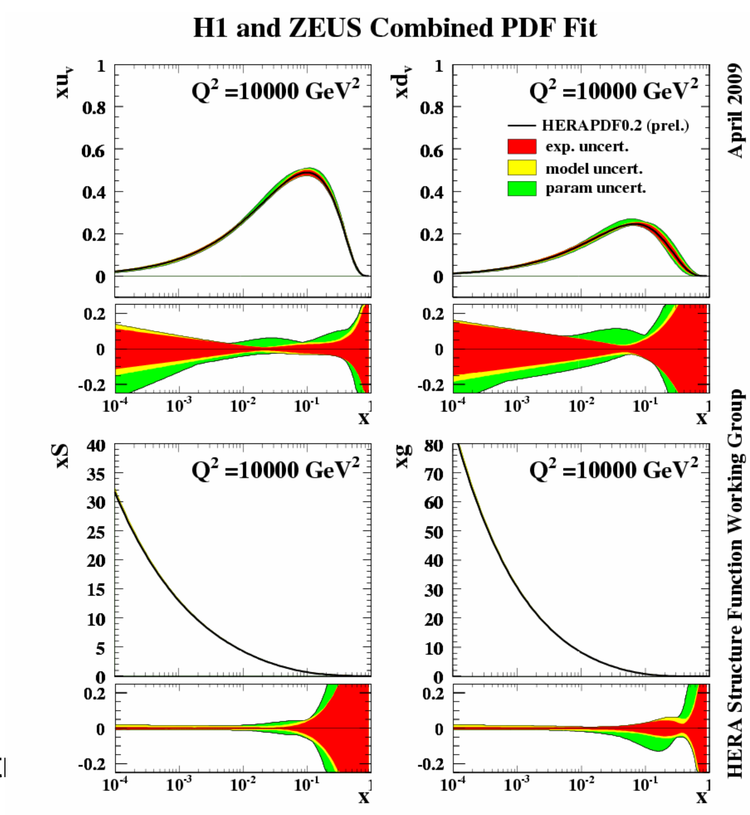


- Impact for LHC: valence quark PDFs at small x can help determination of W^+/W^- asymmetry
- Still a lot of room for improvement → HERA-II data

QCD fit results - HERAPDF0.2

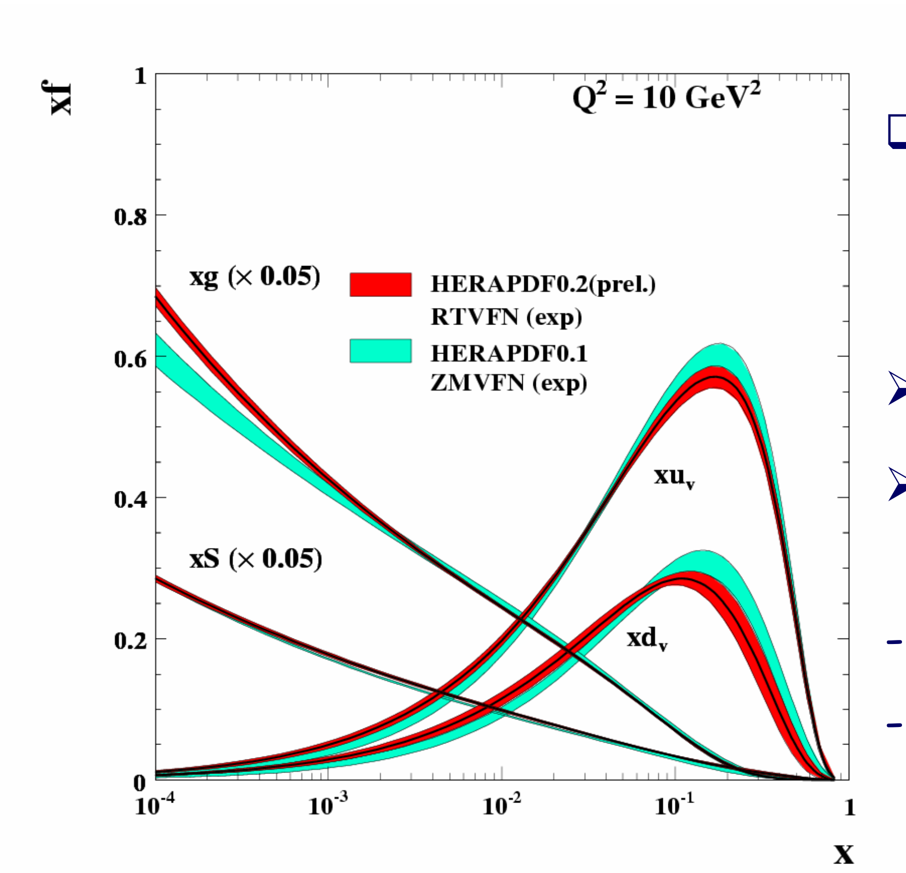
- High-x and valence PDFs are mostly affected by the PDF parameterisation uncertainty
- Accurate sea and gluon at low-x due to precise measurement of F_2
- Q_0^2, Q_{min}^2 dominate the model uncertainty of gluon and valence PDFs
- Impressive precision at the scale relevant for LHC





HERAPDF0.2 vs HERAPDF0.1

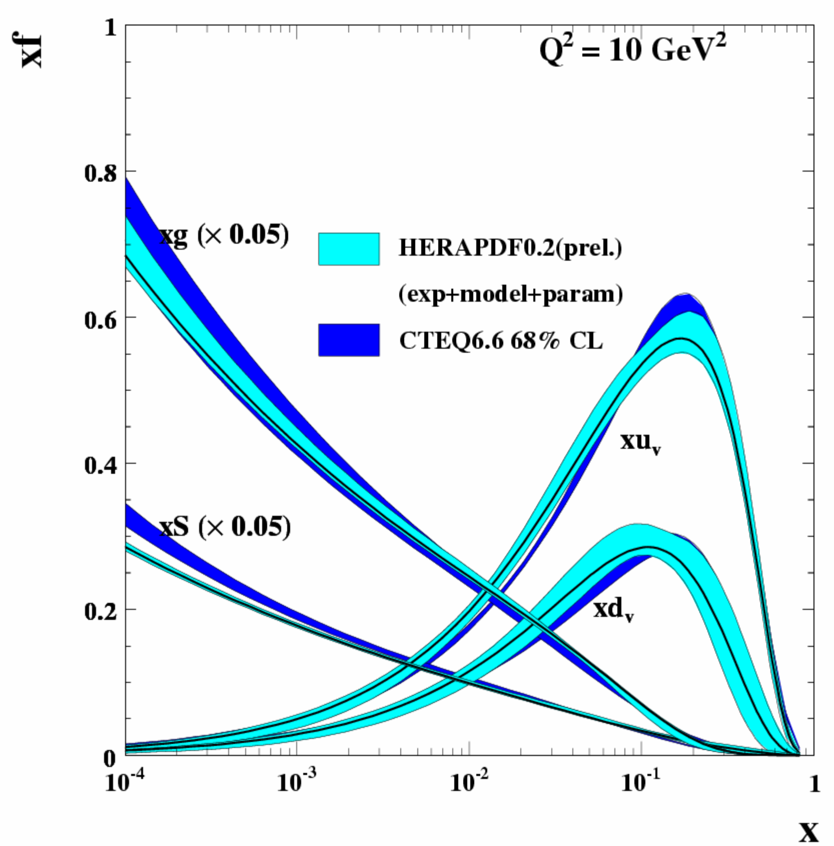
- The new HERAPDF0.2 PDFs are parametrised at Q_0^2 = 1.9 GeV^2 with 10 free parameters → χ^2/ndf=576/592

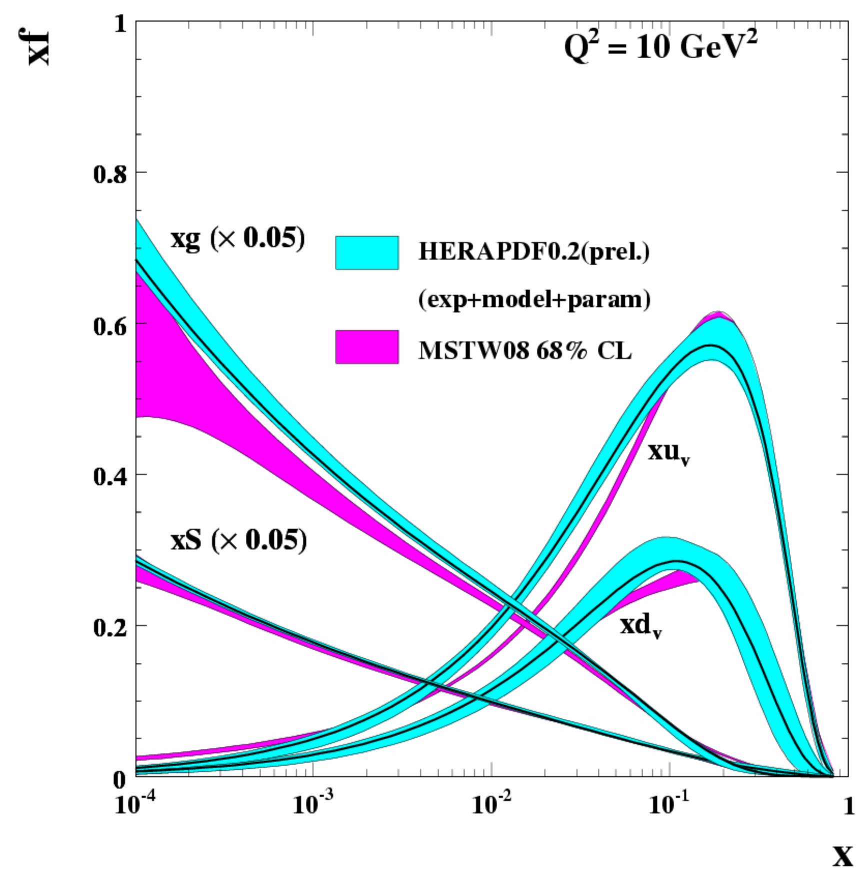


- Only the experimental errors used (the treatment of model uncertainties of the two PDF sets not identical)
  - errors smaller for HERAPDF0.2
  - gluon is steeper (due to the different heavy flavor treatment)

- **HERAPDF0.1** – massless quarks (ZM-VFNS)
- **HERAPDF0.2** – massive quarks (TR-VFNS)

HERAPDF0.2 vs global fits



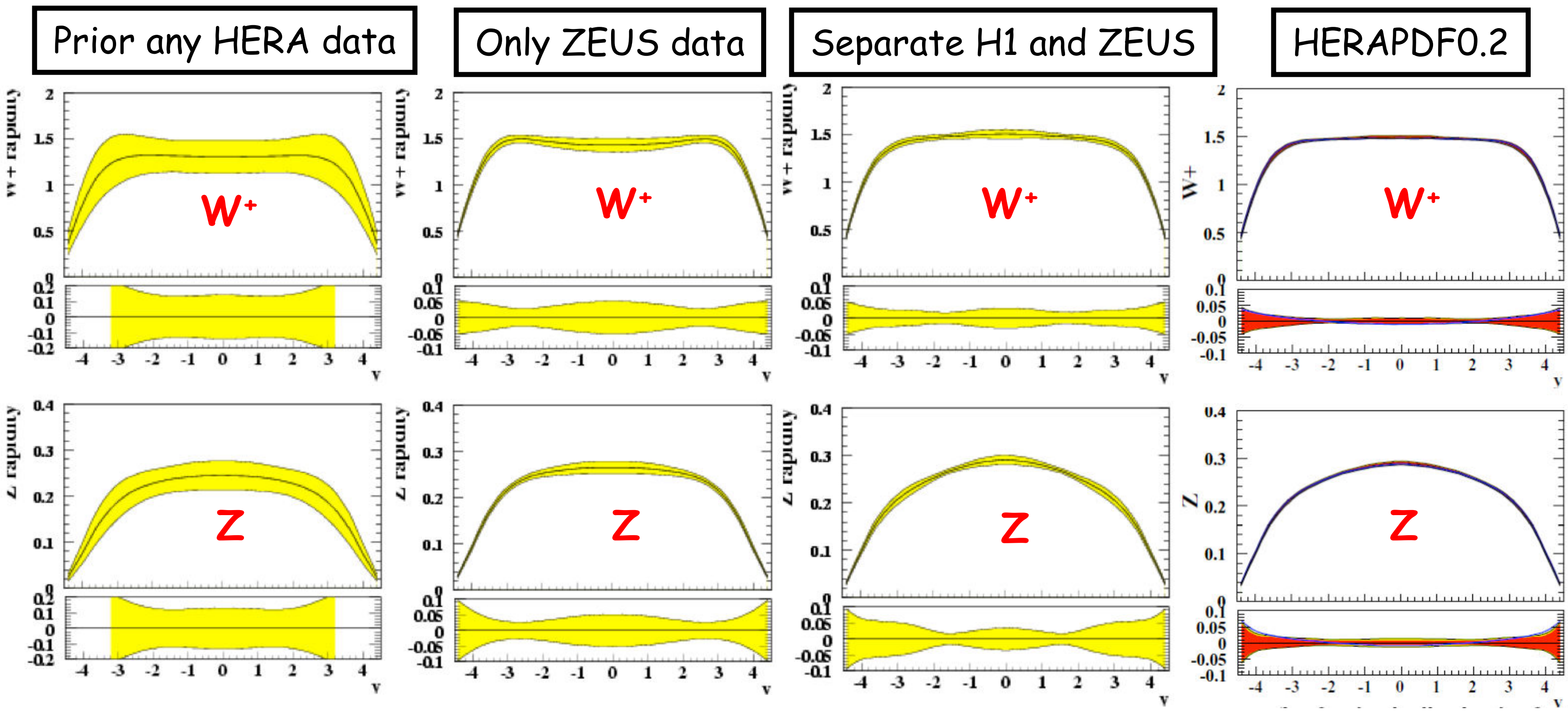


→The new combined HERA-I data provides a strong constraint on PDFs at low x

- Global fits do not include the combined HERA data neither recent H1 results
- Global fits show only experimental uncertainty

Impact of HERA for LHC

W, Z production cross sections at the central rapidity at LHC is much improved by the impressive precision of low-x gluon and sea PDFs from HERA



The errors include only experimental uncertainties.

→ Uncertainty at central rapidities when using combined HERA data ~ 1%

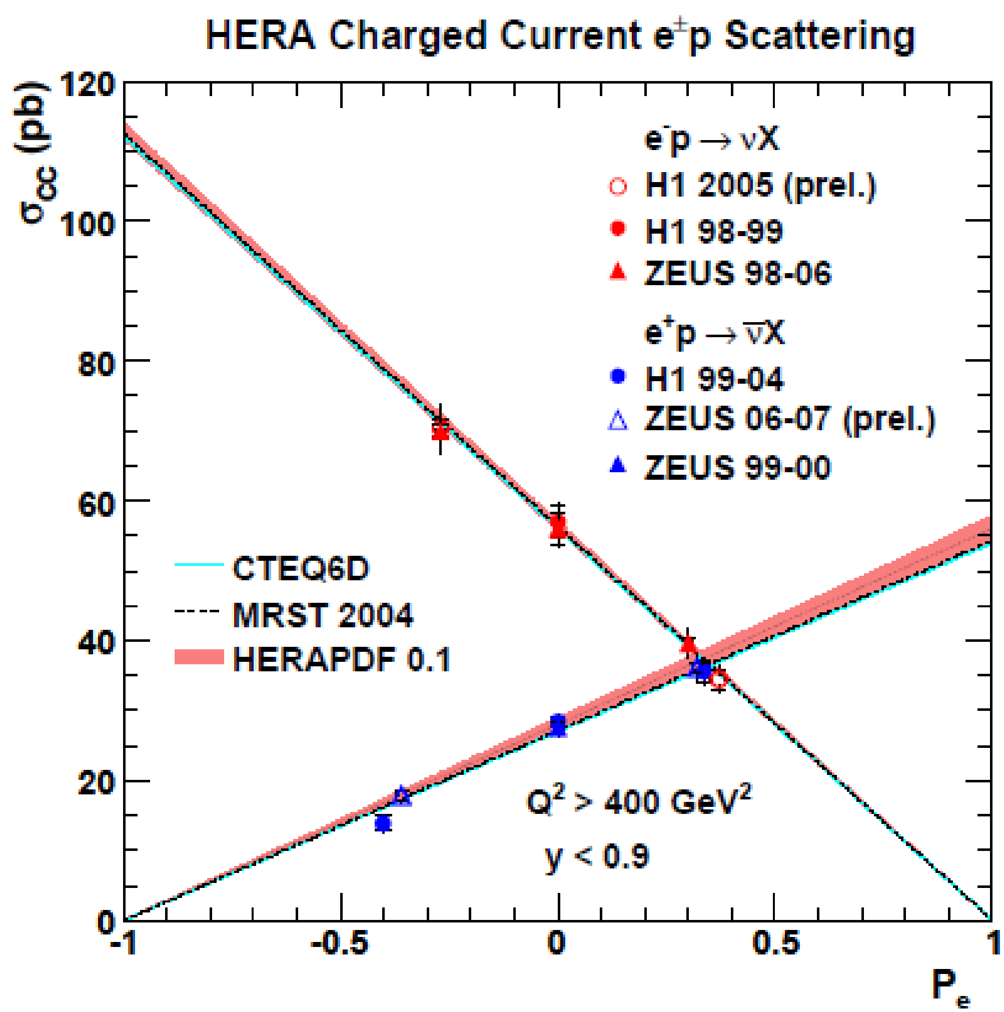
Still many more pieces to include for a final word from HERA

Improvements on PDFs and QCD dynamics expected with HERA-II should come from:

- Higher precision measurements of NC and CC cross section (valence + see quarks at high Q^2, flavor determination at high x)
- Precise measurement of xF_3 (valence quarks at high x)
- Jet data (improve determination of high x gluon and precise and direct measurement of α_s)
- Higher precision of heavy flavor contribution (give information on the gluon distribution since heavy quarks are generated by $g \rightarrow c\bar{c}$ and $g \rightarrow b\bar{b}$)
- Direct measurement of F_L (direct test of gluon contribution at low x)

→ independent investigation of the low-x gluon, where the theoretical formalism of the NLO DGLAP equations (where only leading logs in Q^2 are resummed) may need extending to account for log(1/x) resummation or even non-linear terms (important for $\log Q^2 \ll \log 1/x$)

CC Cross Sections dependence on the degree of Longitudinal Beam polarisation



SM:

Linear dependence of CC cross section on P_e

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

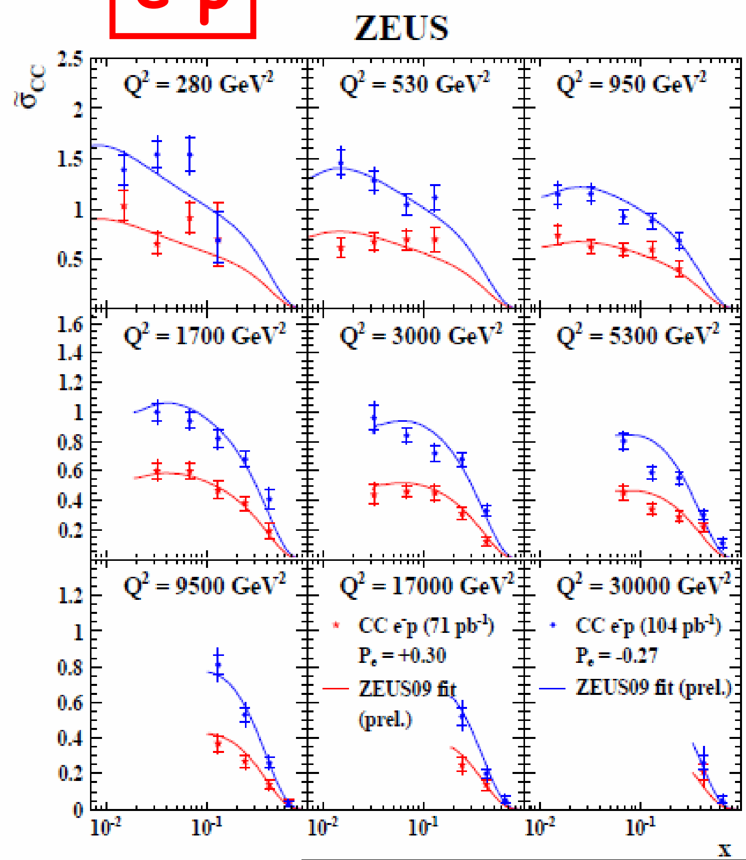
$$P_e = \frac{N_{RH} - N_{LH}}{N_{RH} + N_{LH}}$$

→ **ZEUS and H1 measurements in agreement with SM**

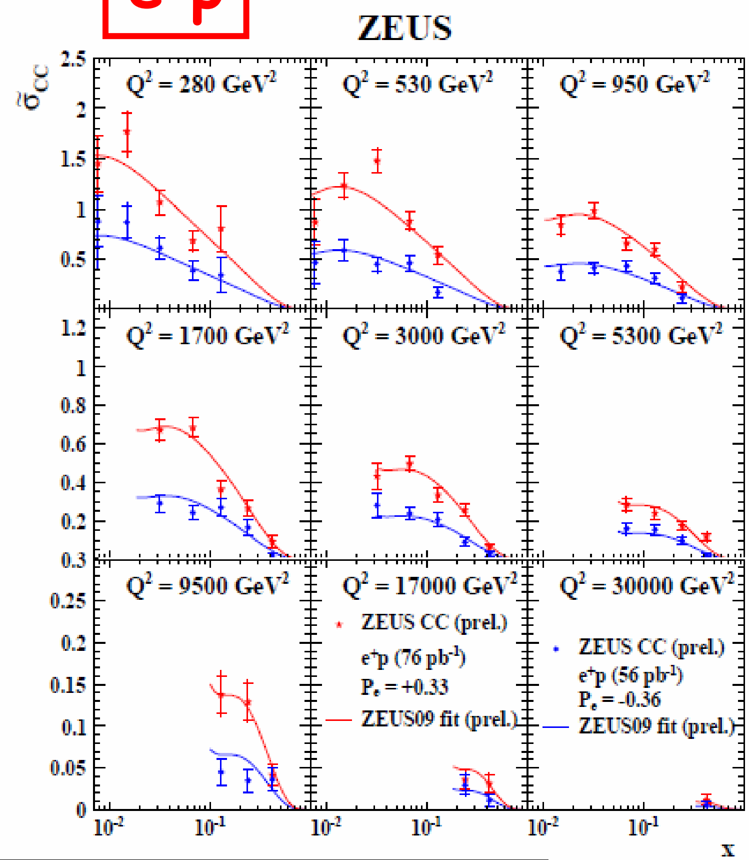
→ no right handed charged currents

Measurements of CC Cross Sections from HERA-II with Longitudinally Polarised Beams

e^-p



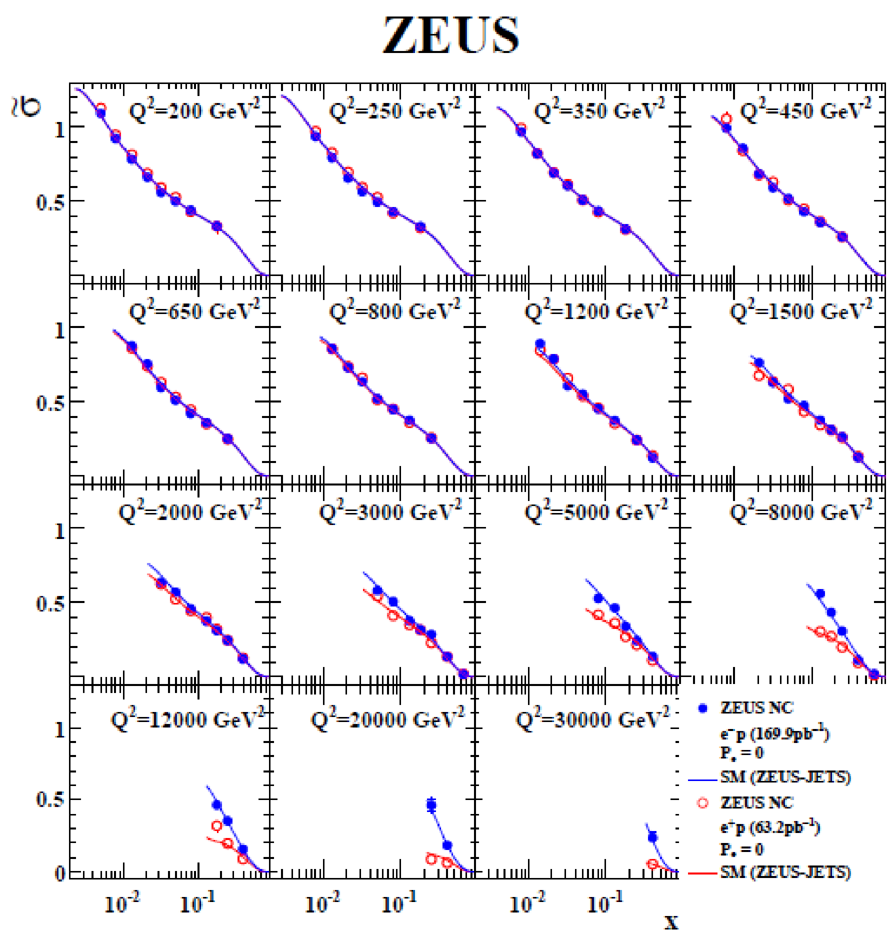
e^+p

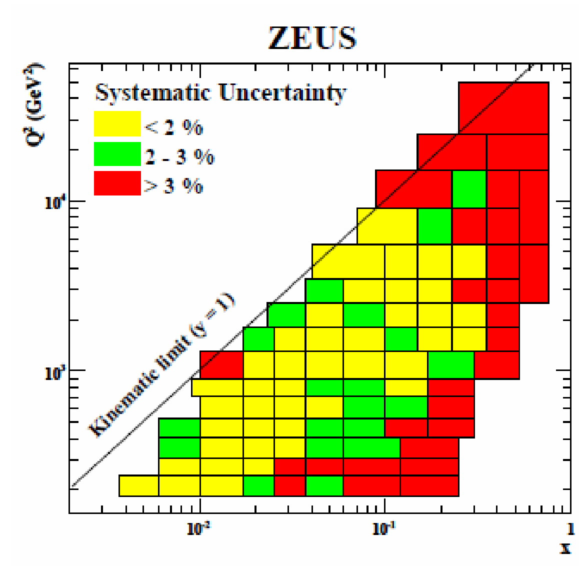


New publication on e^-p *CC* results from ZEUS
Eur.Phys.J.C61:223-235,2009

Neutral current e^-p cross section – new measurement

New publication from ZEUS based on complete e^-p HERA sample
arXiv:0901.2385 → EPJ C

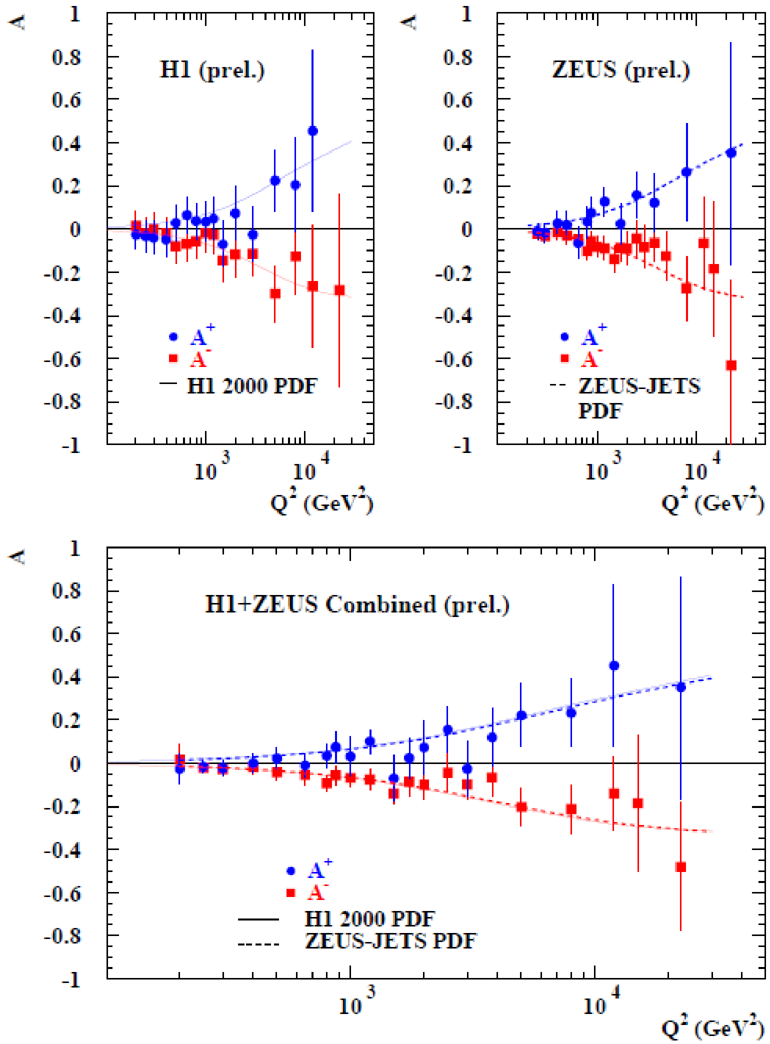




For large region of the phase space precision < 2% achieved

NC Cross section polarisation dependence

HERA



- Polazrisation asymmetry

$$A^{\pm} = \frac{2}{P_R - P_L} \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)} \approx \mp k a_e \frac{F_2^{\gamma Z}}{F_2}$$

directly measures parity violation in NC

- For NC, em. contribution which dominates at low Q^2 does not depend on polarisation
- Polarisation dependence occures via interference between γ and Z boson exchanges

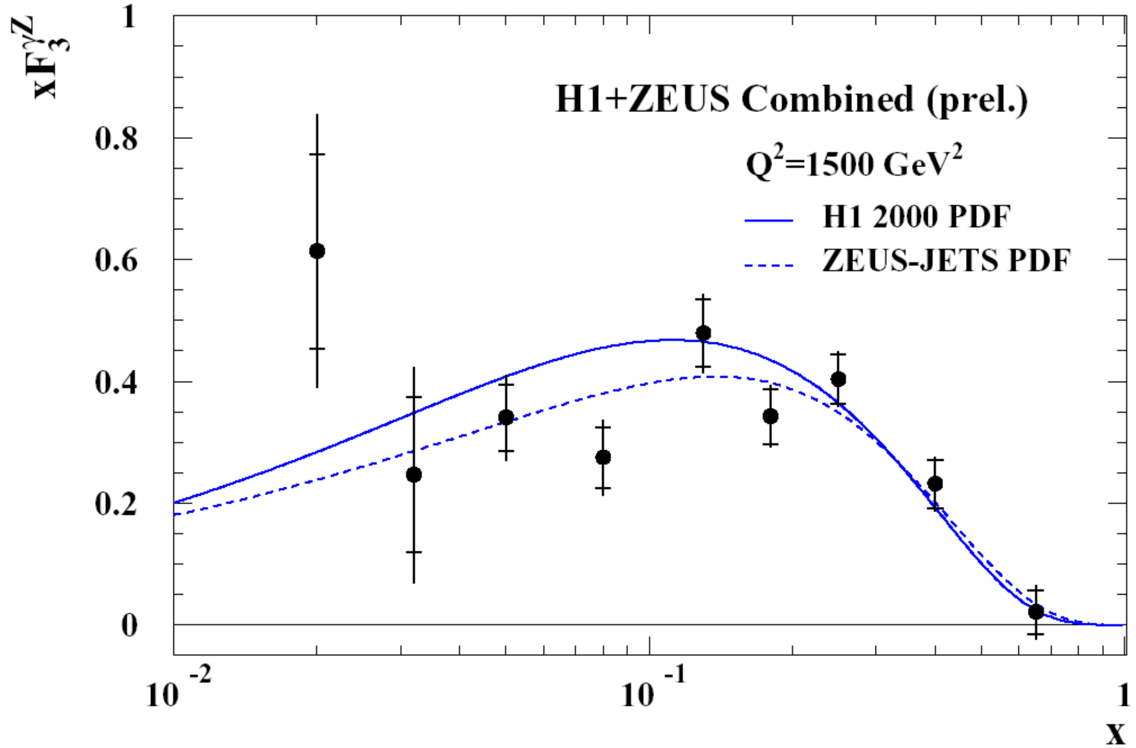
Measurements well described by the SM

Valence quarks at high x: Structure function xF_3

$$x\tilde{F}_3 \sim \sigma^-_{NC} - \sigma^+_{NC}$$

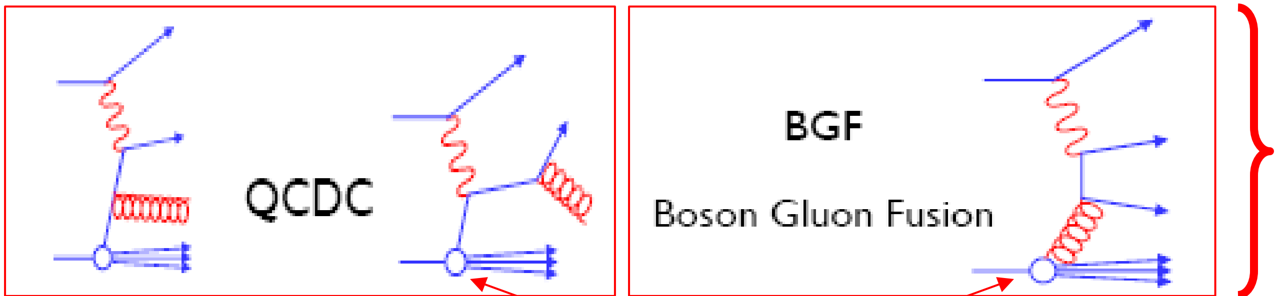
$$x\tilde{F}_3 = -a_e K_Z x F_3^{\gamma Z} + Z\text{-exchange}$$

$$xF_3^{\gamma Z} \sim 2x\, \Sigma_q e_q a_q (q - \bar{q}) \sim q_v$$



- Total lumi ~ 480 pb^{-1} (half of HERA luminosity) → to be measured for all HERA data

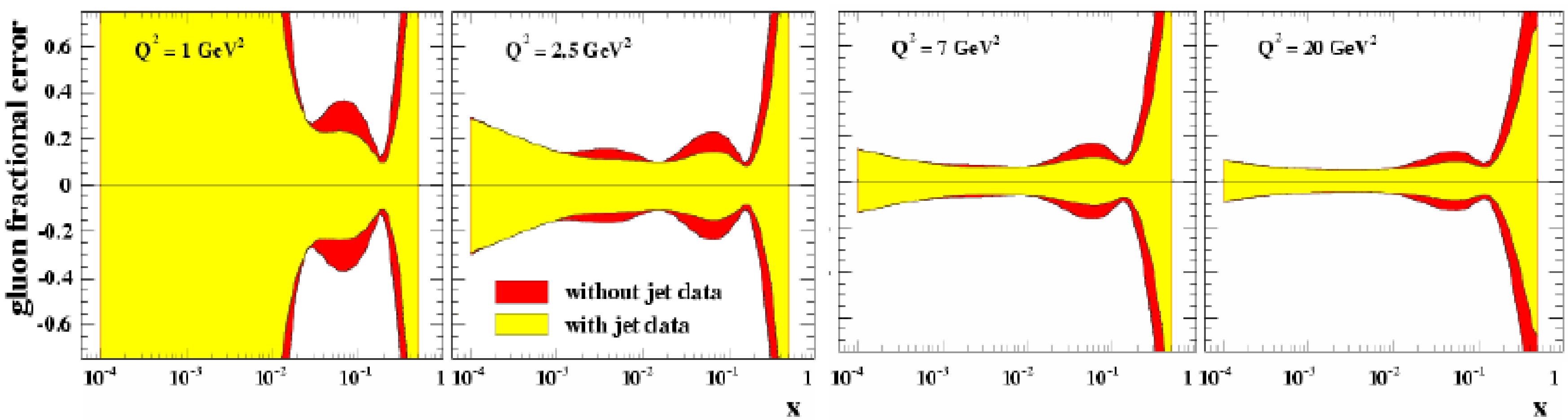
Additional Constrains on Gluon Density from JETS



Events with distinct jets in the final state

Sensitive to α_s and quark/**gluon density**

- ❑ Break the strong correlation between α_s and the gluon PDF from DGLAP
- ❑ α_s can be free parameter simultaneously with all the PDFs (ZEUS-JETS fit)

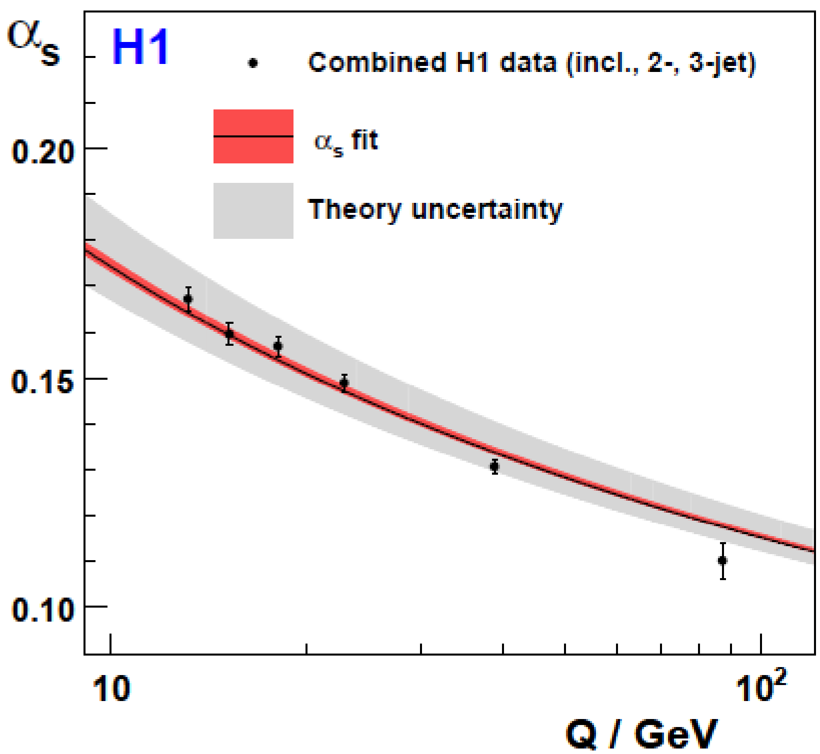


→ Jet data constrain g(x) at medium and high-x (0.01-0.4)

The strong coupling α_s from DIS jet cross section

New publication on jet production in *ep* collisions at high Q^2 at H1 (395 pb-1)
arXiv:0904.3870 → EPJ *C*

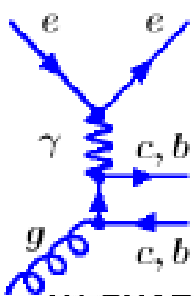
Normalised Jet Cross Sections



- The measurements of inclusive jet, 2-jet and 3-jet cross sections described by perturbative QCD calculations at NLO (not shown here)

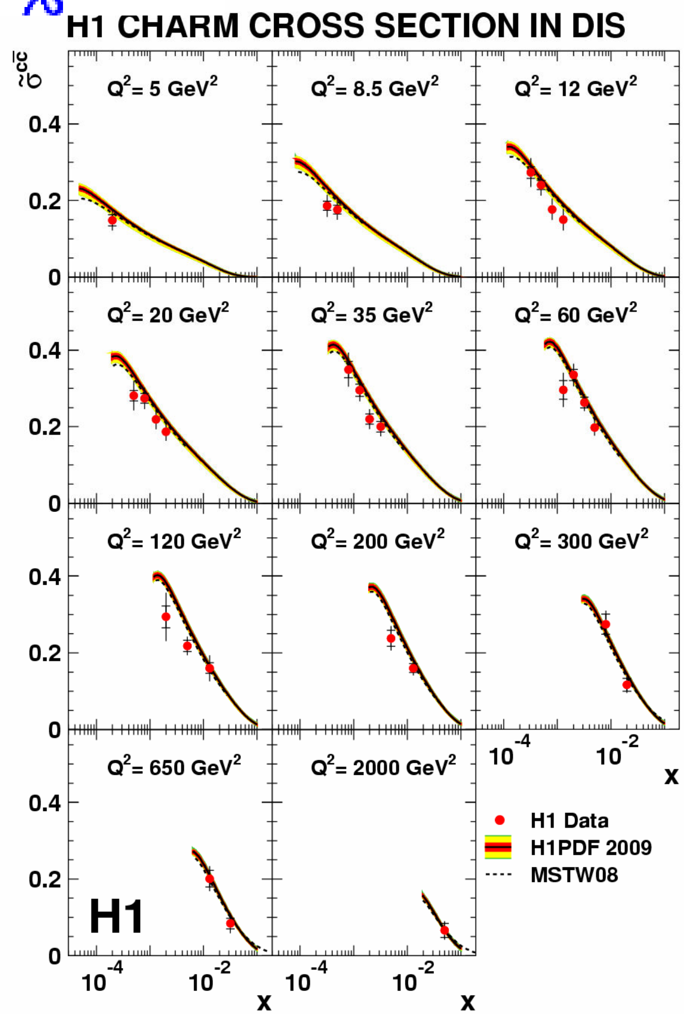
$$\alpha_S(M_Z) = 0.1168 \pm 0.0007\,(\text{exp})\ {}^{+0.0046}_{-0.0030}\,(\text{th.}) \pm 0.0016\,(\text{PDF}).$$

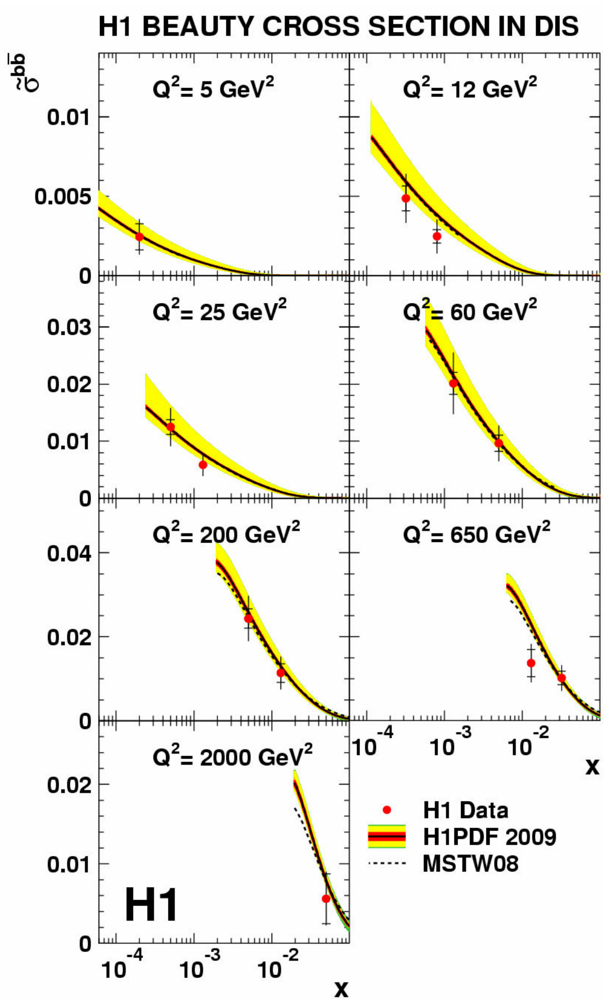
- The total error is strongly dominated by the theoretical uncertainty due to missing higher orders in the perturbative calculation which is about 4%



c and b contributions – displaced vertex method

New publication from H1 based on complete HERA datasets (189 pb^{-1}), **arXiv:0907**.264 → EPJ C





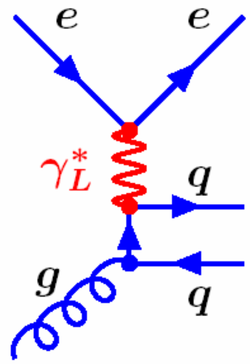
- Data agree with H1PDF 2009 prediction
- Variations of m_c and m_b dominate **model** uncertainty

There is new result from ZEUS also

arXiv:0904.3487 → EPJ C

The predictions of the W and Z bosons, and also Higgs at the LHC are sensitive to the theoretical treatment of heavy quarks

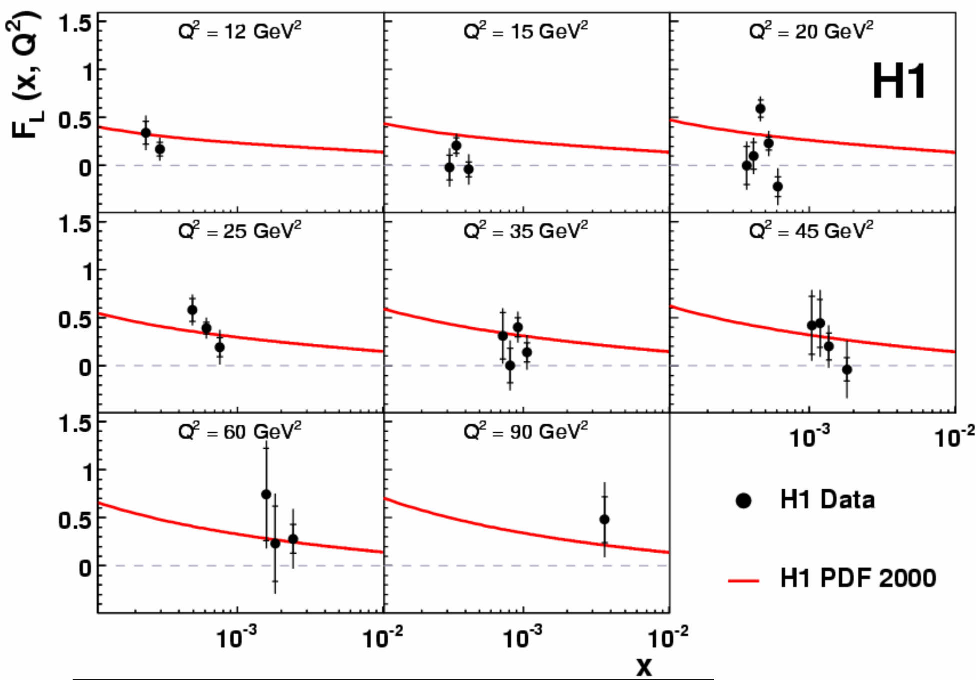
F_L publications from H1 and ZEUS - medium Q^2



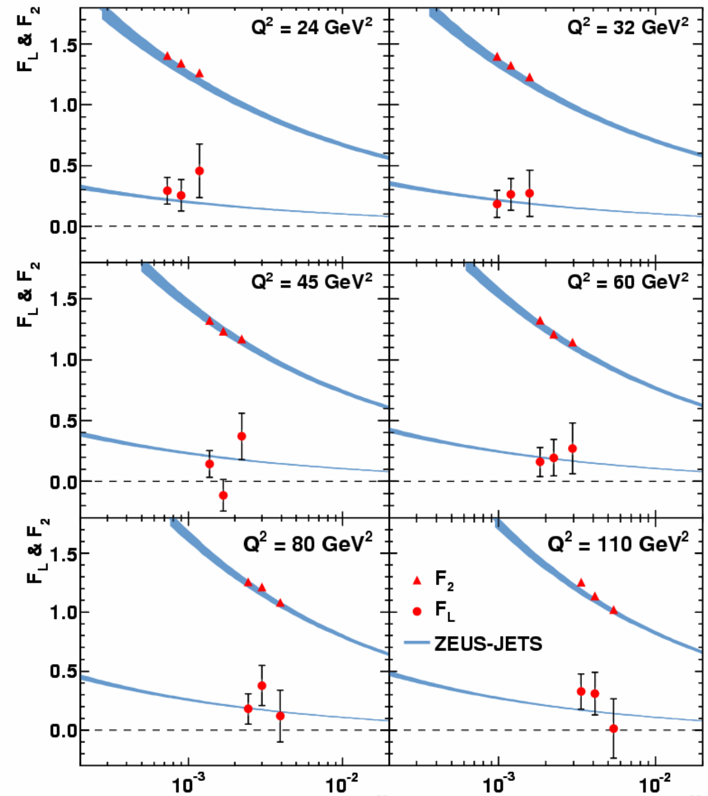
Directly probing the gluon

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

→ F_L is slope of the straight line fit of σ_r vs y^2/Y_+



Phys. Lett. B668 (2008)

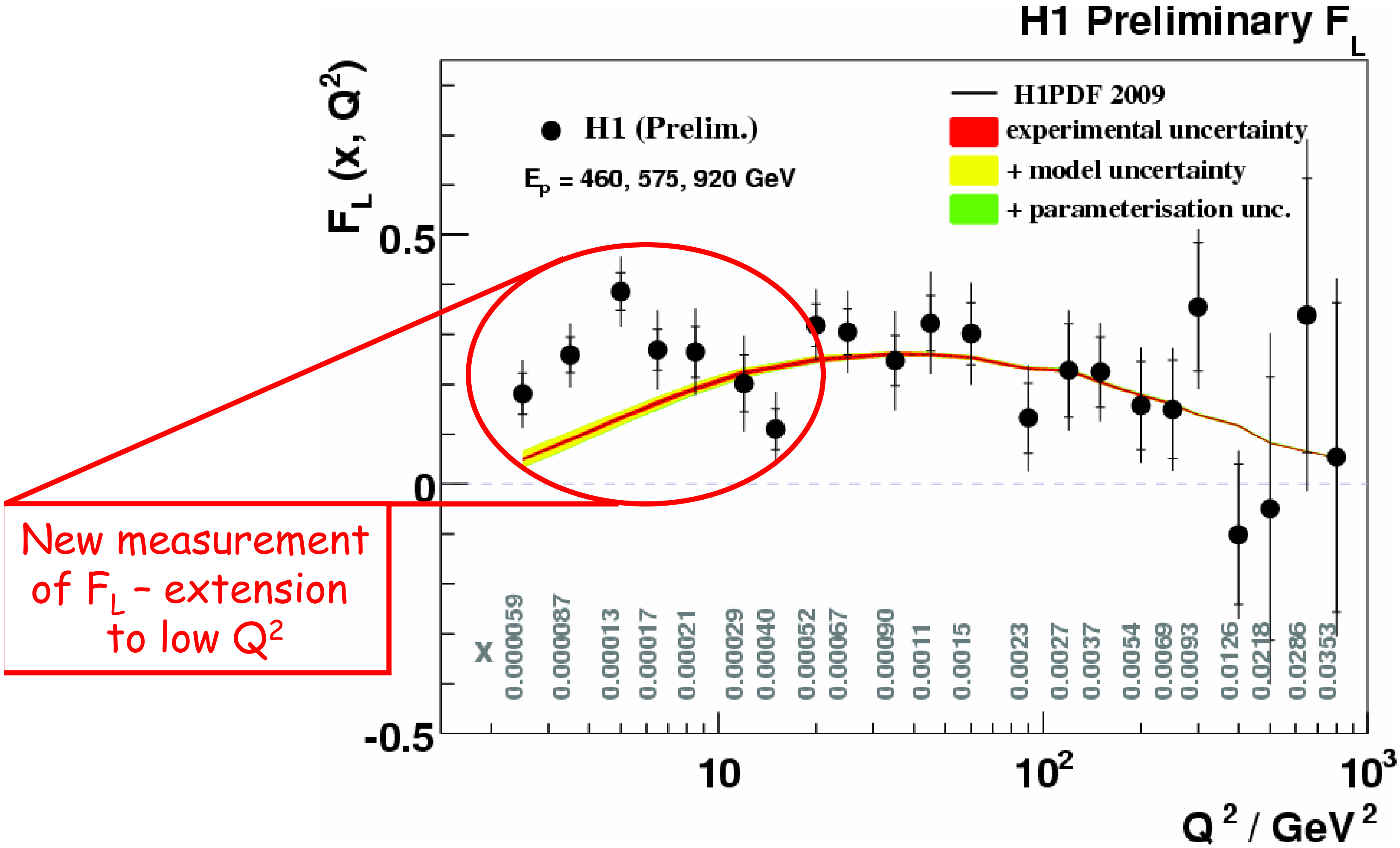


Also easurement of F_2 without assumptions on F_L

arXiv:0904.1092
→ Phys. Lett. B

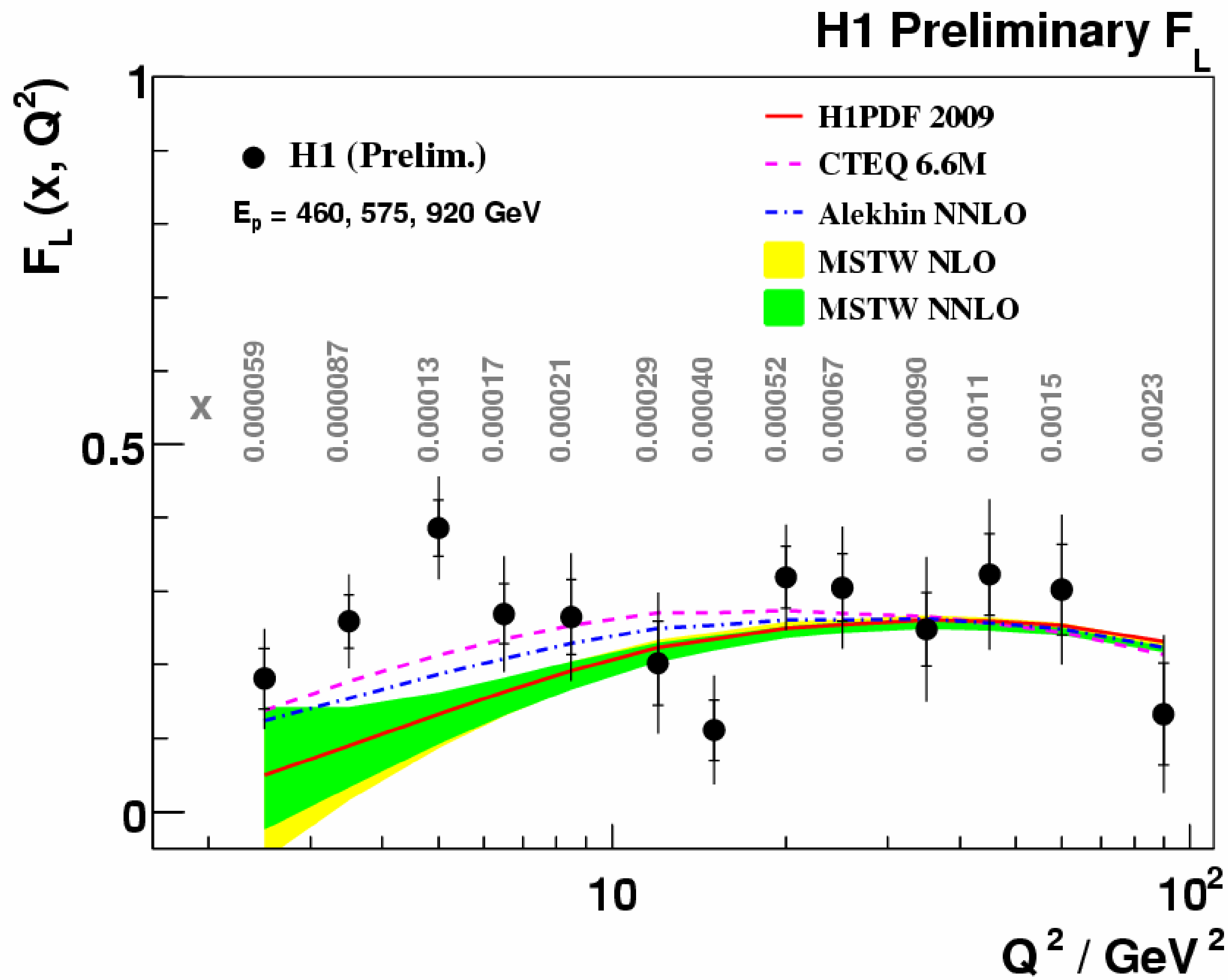
- Good agreement with the QCD predictions

H1 F_L measurement in complete Q^2 range



- For Q^2 > 10 GeV^2 data agree well with H1PDF 2009 prediction

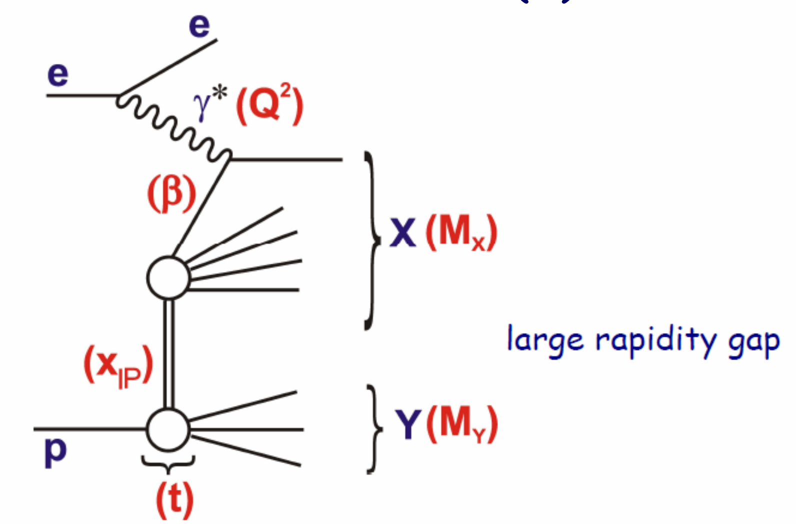
H1 F_L measurement at $Q^2 \leq 100$ GeV^2



- MSTW and H1PDF 2009 predictions use the same scheme to calculate F_L
- Data agree better with calculation of CTEQ and Alekhin NNLO

First measurement of the longitudinal structure function in diffraction - F_L^D

- At HERA about 10 (3)% of events are diffractive at Q^2 = 10 (1000) GeV^2



- momentum fraction of color singlet exchange

$$x_{IP} = \frac{q\cdot(p-p')}{q\cdot p} \approx \frac{Q^2 + M_X{}^2}{Q^2 + W^2}$$

- fraction of exchange momentum, coupling to γ^*

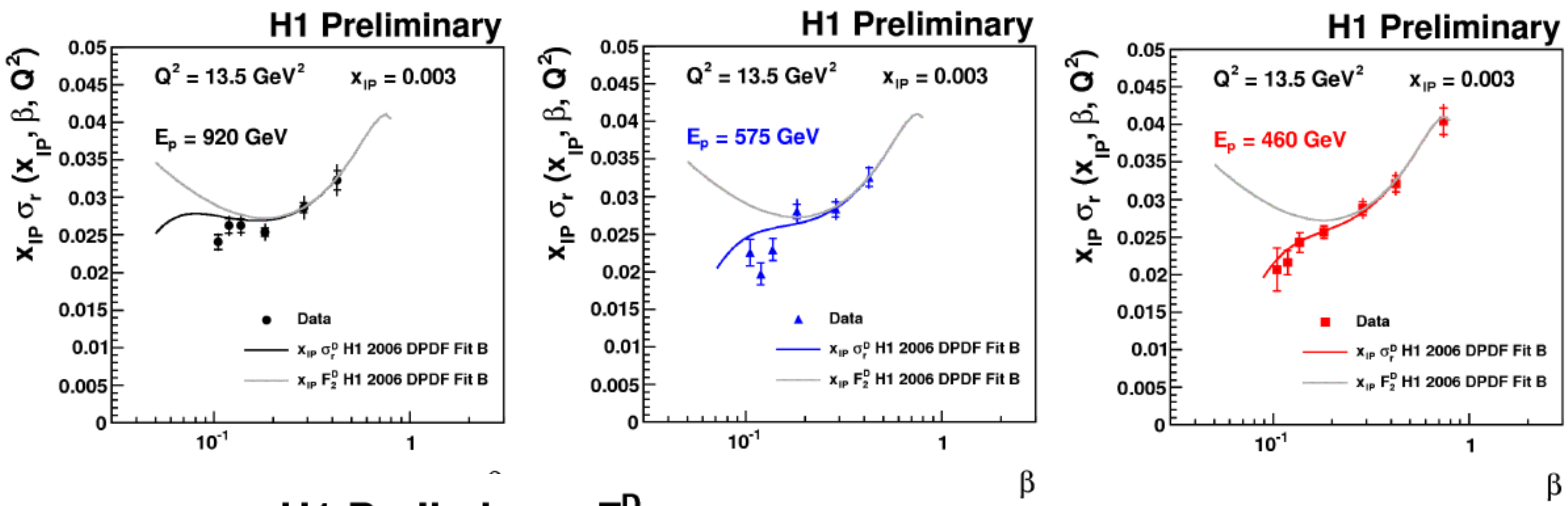
$$\beta = \frac{x}{x_{IP}} \approx \frac{Q^2}{Q^2 + M_X{}^2}$$

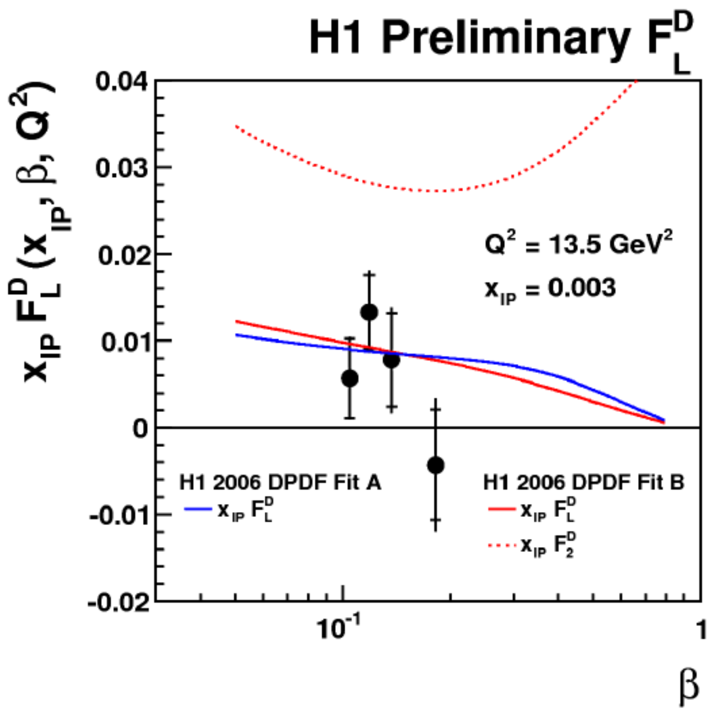
$$\frac{d^3\sigma\ (e^\pm p \to eXY)}{dx_{IP}\, d\beta\, Q^2} = \frac{2\pi\alpha^2}{xQ^4}\, Y_+ \sigma_r^D(x_{IP},\beta,Q^2) \qquad \sigma_r^D = F_2^D - \frac{y^2}{Y_+} F_L^D$$

- F_2^D constrains the quarks, gluons are constrained weakly from the scaling violations
- F_L^D sensitive to the gluons: $F_L^D \sim xg(x)$, contributes at low β (high y, $Q^2 = x_{IP}\beta ys$)

  → Crucial test of the theory and important extra constrains on the gluon

F_L^D result

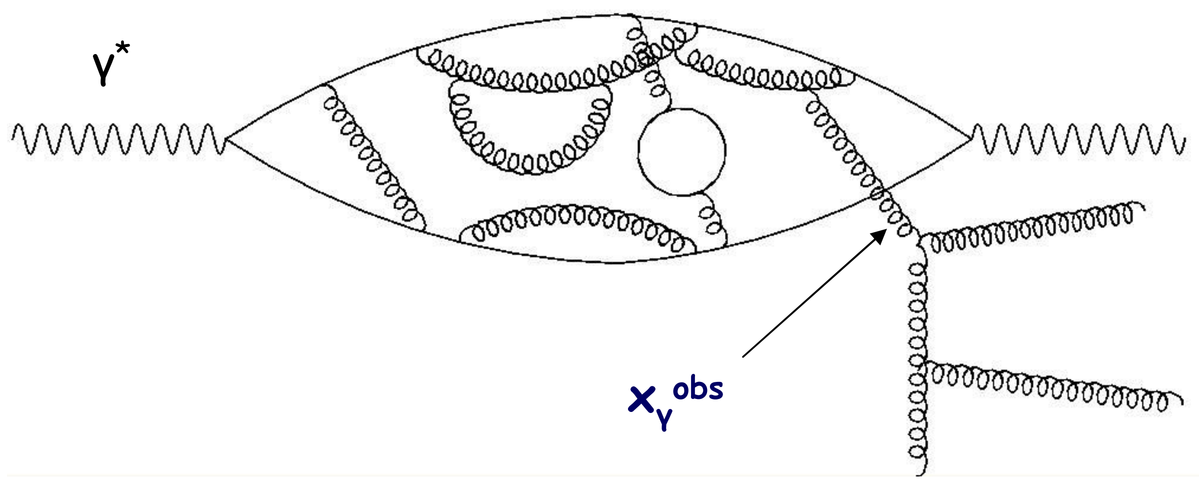




- A significant non-zero value (more than 4 σ)
- Results consistent with the H1 2006 DPDF Fits

Underlying event (UE): jets in photoproduction

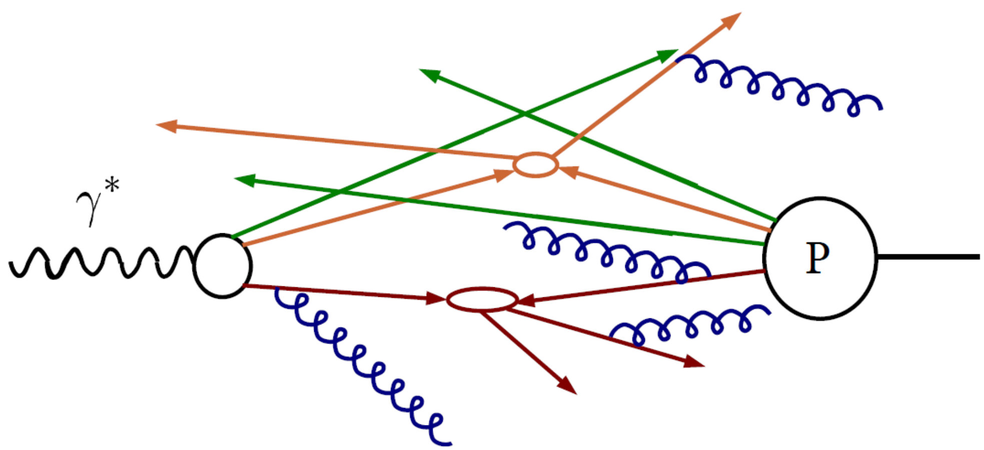
- The underlying event (UE) is everything in addition to the lowest order process
- UE consist of contributions coming from higher order QCD radiation, simulated by parton showers, hadronisation and multiple parton interaction (MPI) which take place when the density of partons in the colliding beams is large enough that more than one interaction happens within one collision
- MPI interactions at HERA studied from multijets in photoproduction (PHP)
- The photon at low virtualities (as in PHP) lives longer and may fluctuate into a quark anti-quark pair developing complicated hadronic structure



x_γ^{obs} - fraction of the photon energy invested in the hard interaction

- $x_\gamma^{obs} < 1$ – resolved proces (photon interacts via its partonic structure, giving the rise to a hadron-like final state)
- $x_\gamma^{obs} \approx 1$ - direct process (photon interacts as a point-like particle with the partons)

- In resolved process, partons from the remnants can interact (MPI) – similar situation to the hadron-hadron collisions

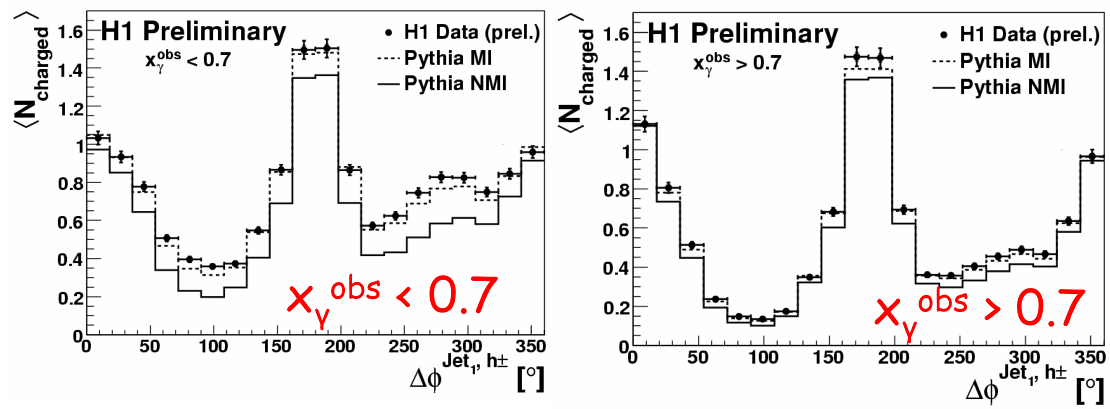


UE contributes with additional energy density on top of hard interaction, but is not related to it, non-perturbative effect not included in the calculations

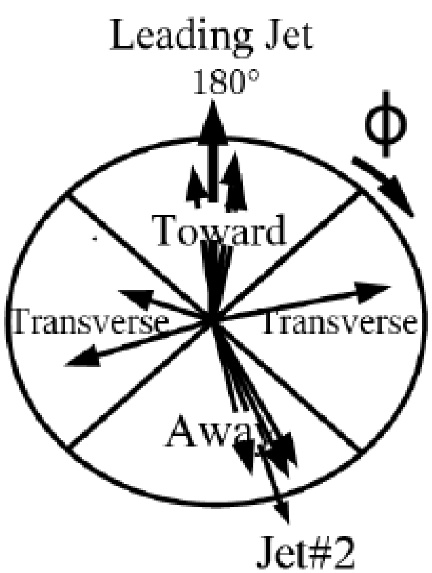
- UE can be simulated with MC simulations and are extremely model dependent → good understanding of the UE at the available energies is crucial to model its effects at LHC energies

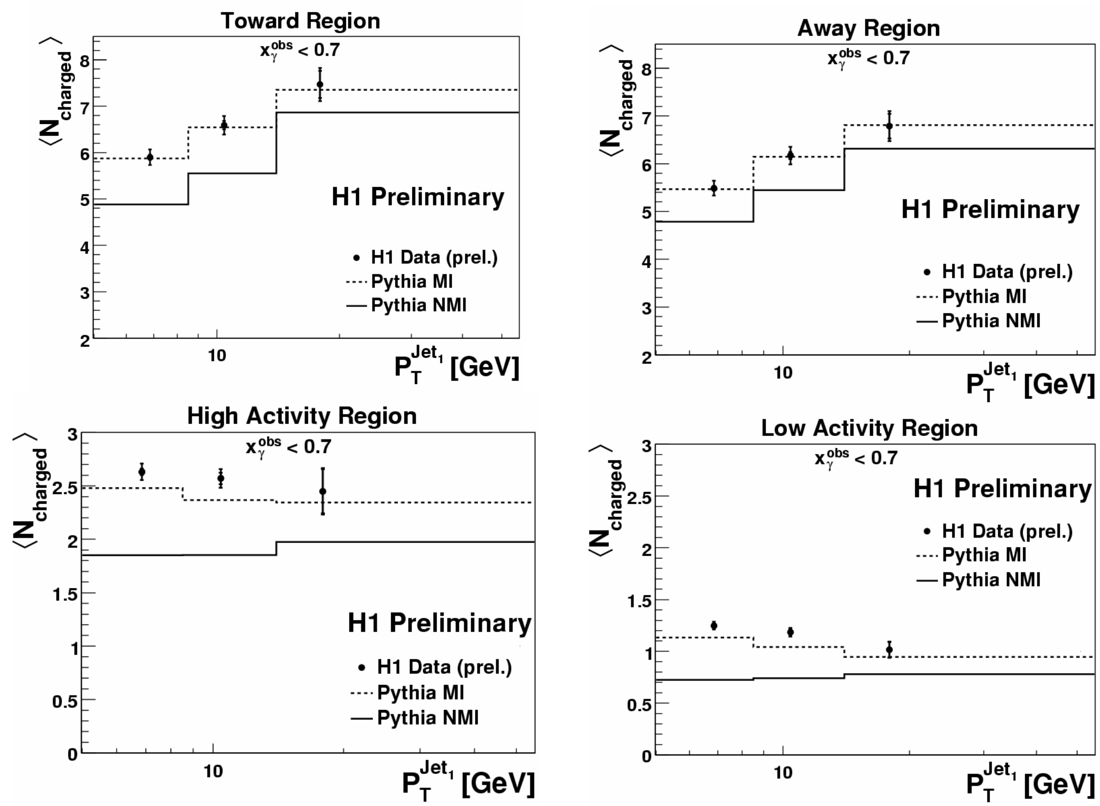
Underlying event (UE): dijets in photoproduction

- Mean charge multiplicty as function of ΔΦ wrt leading jet



- Mean charge multiplicity vs leading jet E_T^{jet} for $x_\gamma^{obs} < 0.7$





Summary and Outlook

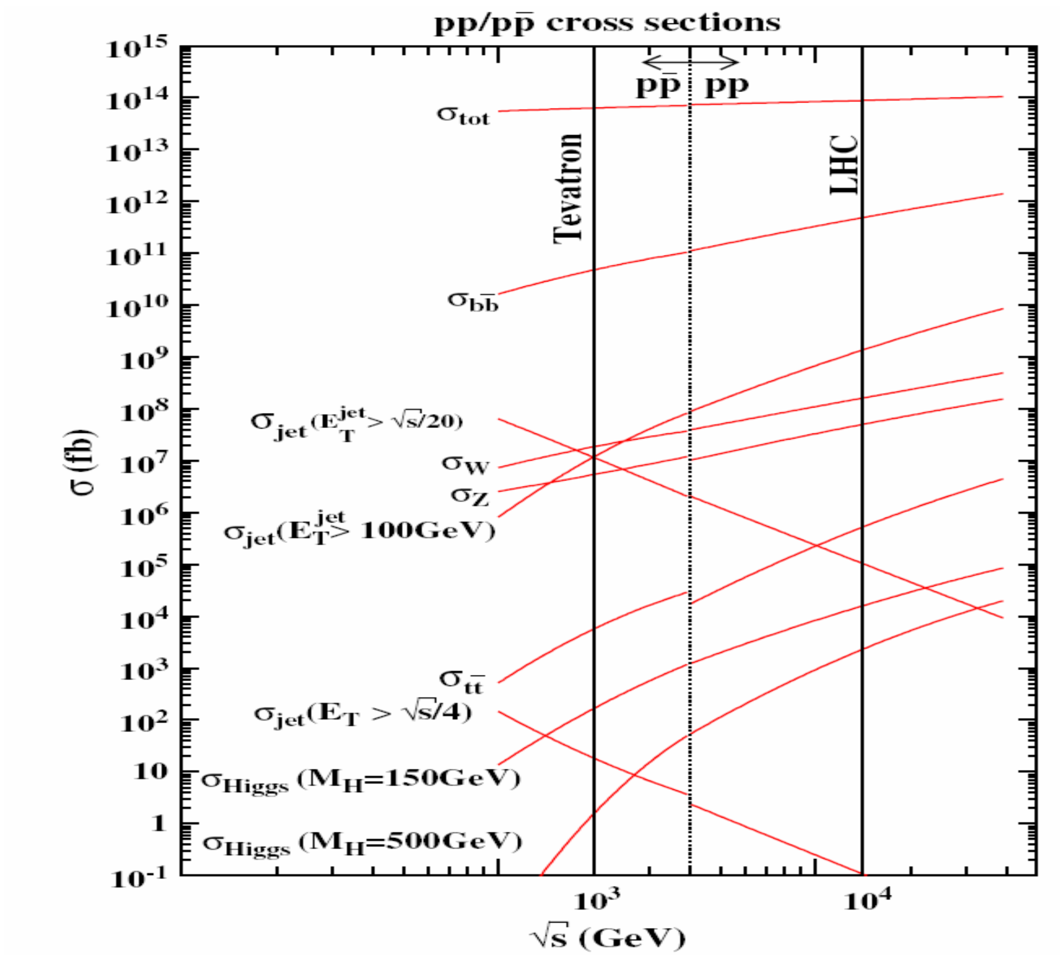
- HERA has provided crucial input for understanding proton structure
- Published results from all HERA-I data combined
  - essential reduction of systematical and statistical errors
- New fit from HERA to the combined data performed
  - experimental uncertainty significantly reduced
  - smaller uncertainty of PDFs than of those from global fits
- Broadly, the observations, F_2 (inclusive, charm, beauty, diffractive) and F_L (inclusive, diffractive) can be understood by NLO QCD
- HERA is the perfect place where the parton radiation pattern from the initial state can be studied – analysis of multiparton interactions

  → **significant impact for LHC physics**

- Final publications with ultimate precision to come in the next years

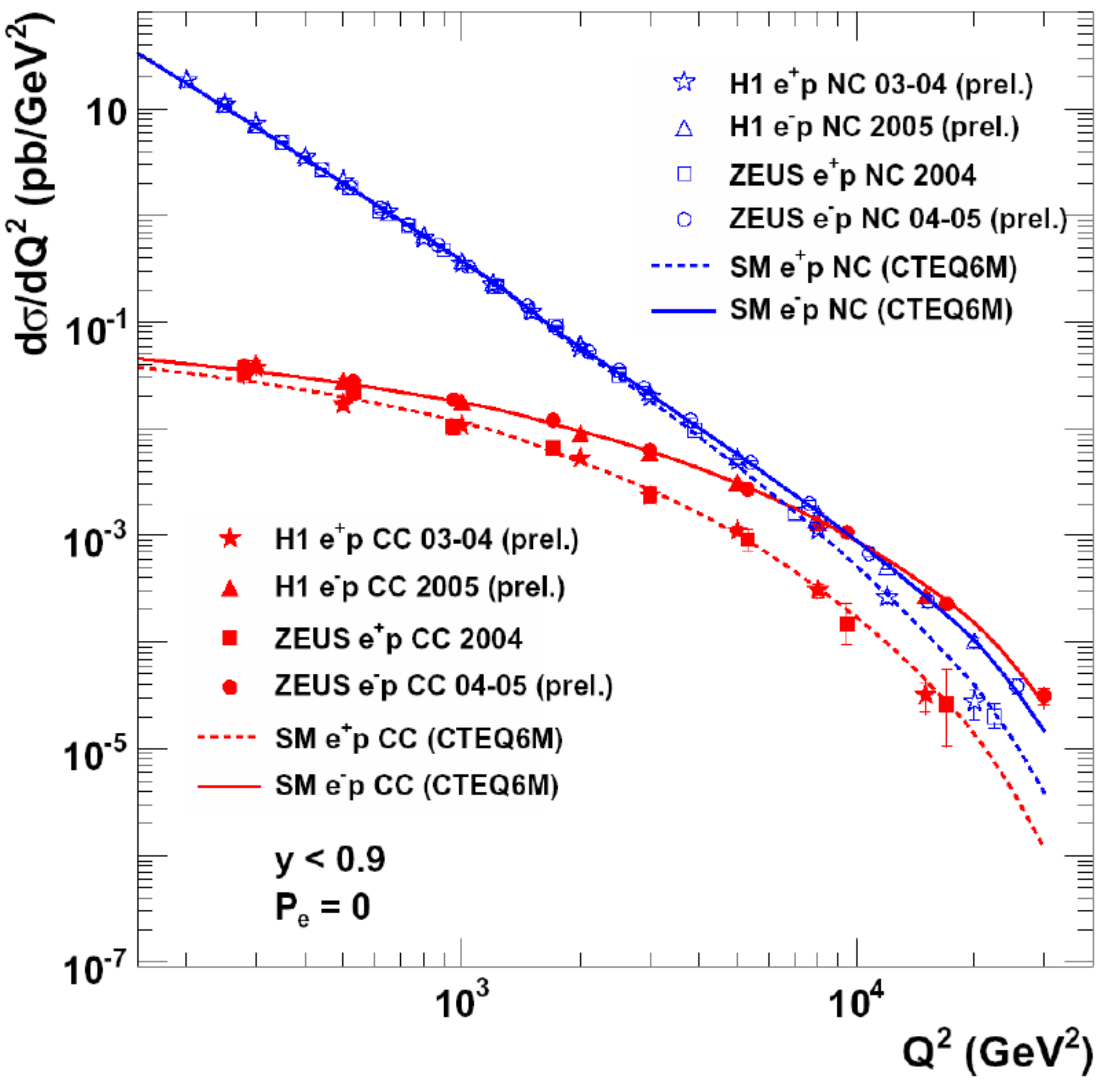
extras

pp and p$\bar{p}$ cross sections



- Cross sections of interest are very small → precision od PDFs very important

Does the lepton probe behaves as expected?



- ❑ EW unification at the $M_{W,Z}$ scale
- ❑ SM provides perfect description of data over many orders of magnitude

→ Lepton probe behaves as expected

Averaging procedure

- Swim all points to a common x-Q^2 grid
- Moved 820 GeV data to 920 GeV p-beam energy
- Calculate average values and uncertainties
  χ^2 minimization in which the parameters are the true values of the cross section and the correlated systematic error parameters (arXiv:0904.0929)
- Evaluate "procedural uncertainties"

1. Aditive vs multiplicative nature of the error sources – typically bellow 0.5%

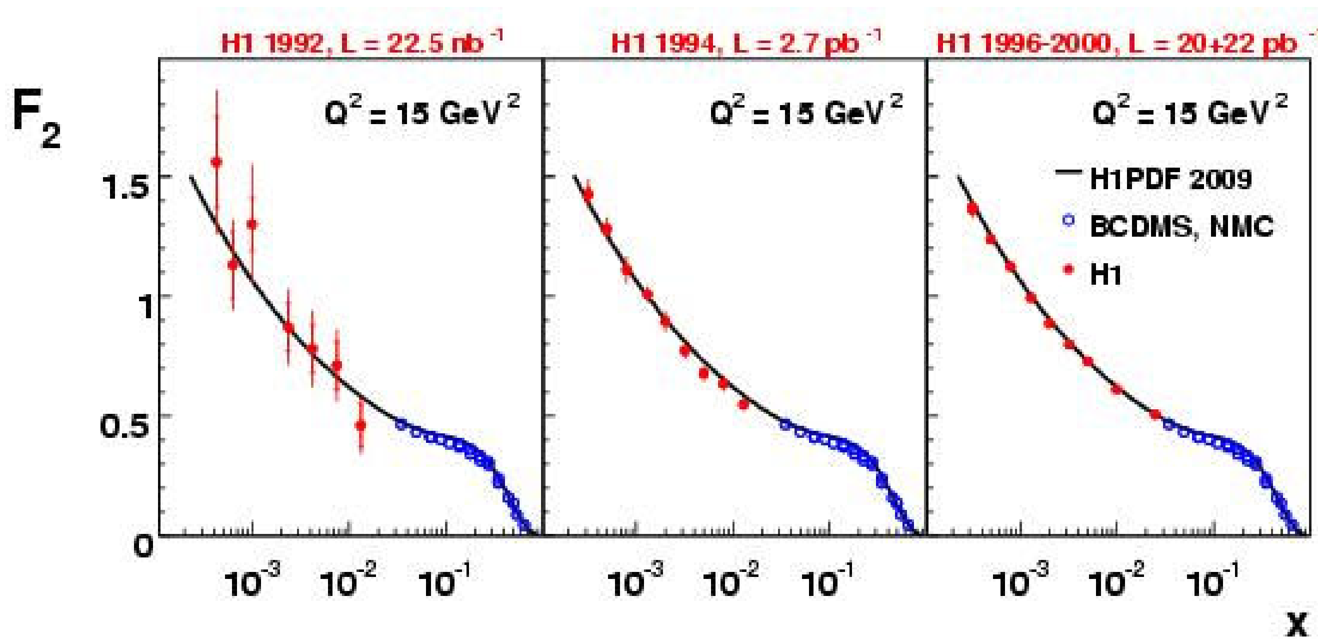
A more general study of the possible correlated systematic uncertainties between H1 and ZEUS has been performed:
- Identified 12 possible uncertainties of common origin
- \- Compare 2^{12} averages taking all pairs as corr./uncorr. in turn.

Mostly negligible except for:

2. Photoproduction background - few % only at high-y and
3. Hadronic energy scale - at the ‰ level

Structure function F_2 at low x – precision improvement

- Most accurately measured structure function since majority of DIS data is sensitive to F_2
- New measurement from H1 of HERA I data gives best precision so far achieved



- Achieved accuracies improved to 1.3%-2% (arXiv.0904.3513, submitted to EPJ C)

H1 and ZEUS Combined QCD and EW fit

- Preliminary results for light quark axial (a_u, a_d) and vector (v_u, v_d) couplings to Z-boson are obtained from H1 and ZEUS experiments using HERA-I and HERA-II data
- Combined fit of a_u, v_u, a_d, v_d and PDFs → QCD-EW fit

Standard Model:

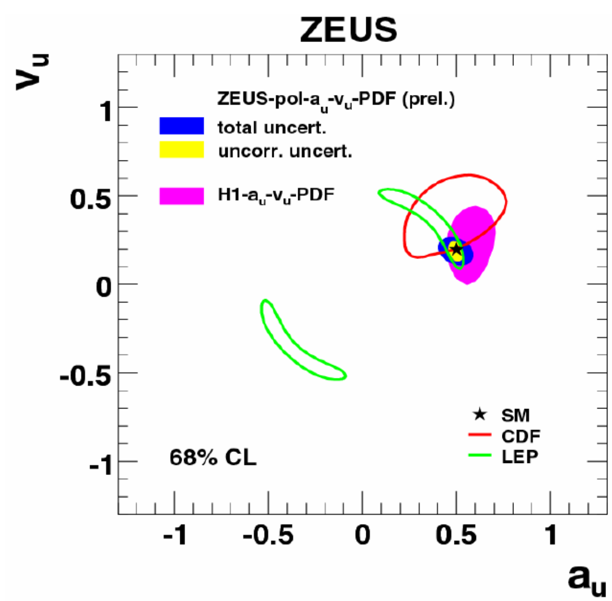
$a_q = I_q^3$

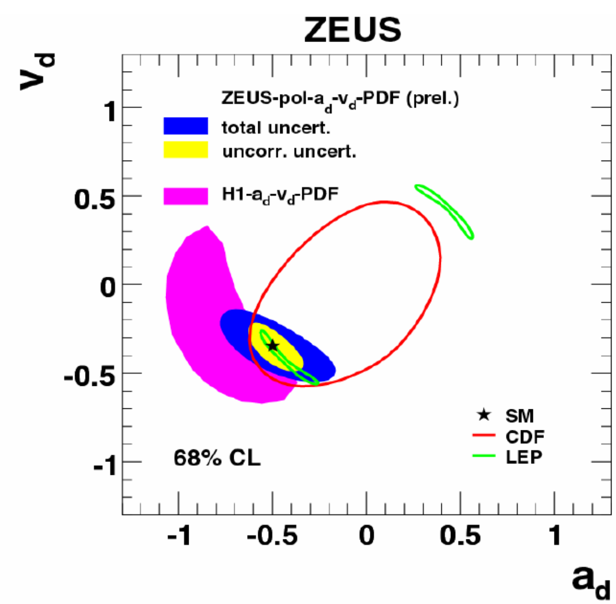
$a_u = +1/2$, $a_d = -1/2$

$v_q = I_q^3 - 2e_q \sin^2\theta_W$

$$xF_3^{\gamma Z} = 2\sum e_q a_q (xq - x\bar{q})$$

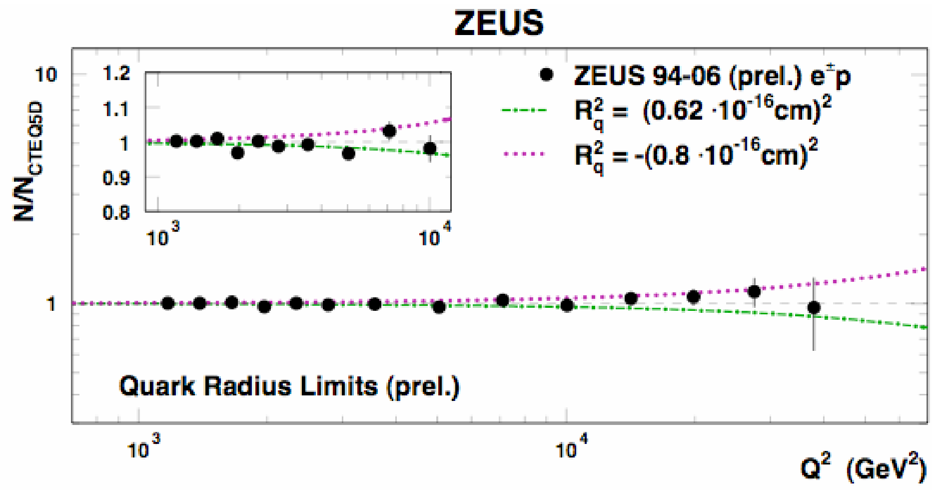
More sensitivity to a_u then to v_u

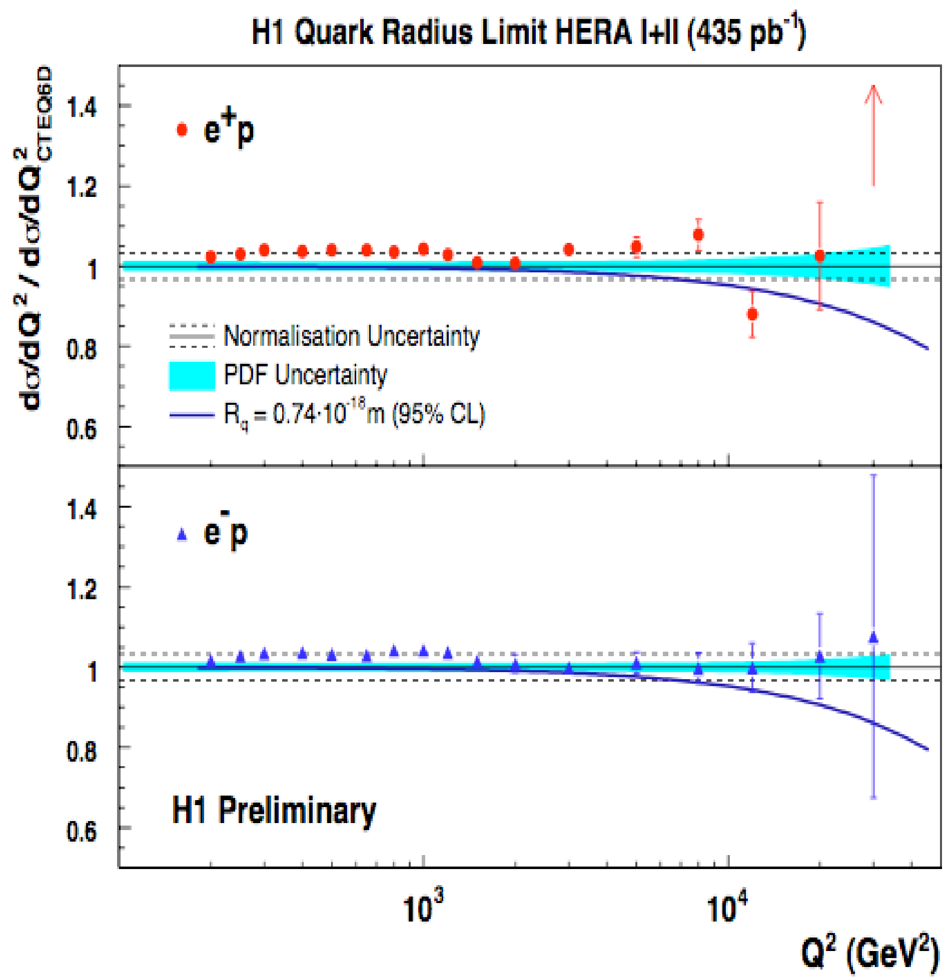




→ HERA-II will brought improvement with statistics and polarisation (which provides better sensitivity to v_q)

Does the quark have substructure?

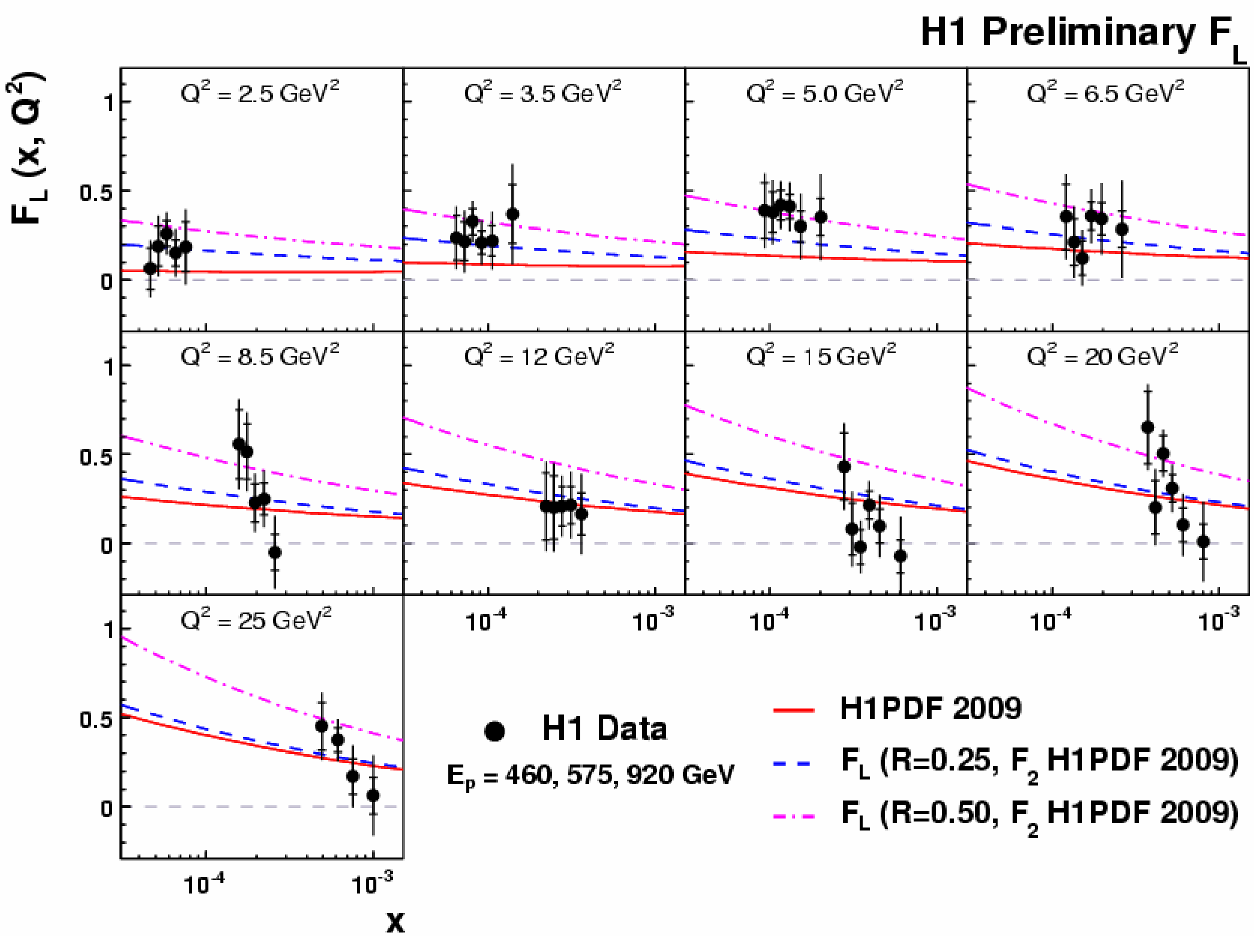




$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} \cdot \left(1 - \frac{R_q^2}{6} Q^2\right)$$

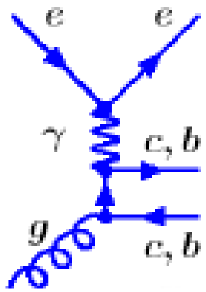
- Limit on quark size:
  - H1: $R_Q < 0.74 \times 10^{-18}$ m
  - ZEUS: $R_Q < 0.62 \times 10^{-18}$ m
- No substructure of quarks

New result on F_L from H1 - extension to low Q^2



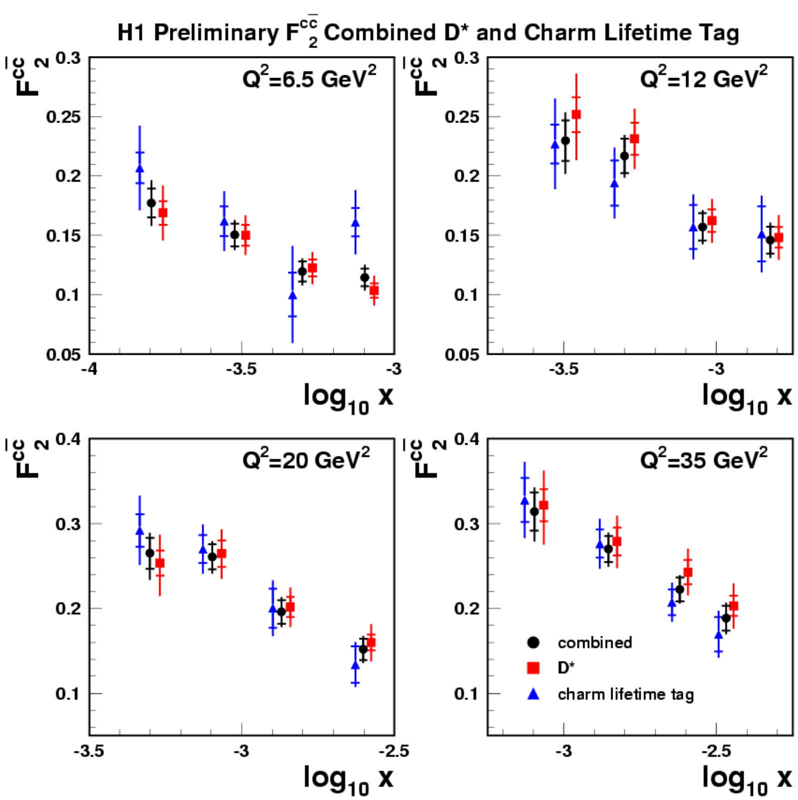
- Data are consistent with $R = \sigma_L/\sigma_T \approx 0.25 \rightarrow F_L = R/(1 + R) \approx 0.2 \cdot F_2$

Heavy quarks - measurement of F_2^{cc}



Another cross check of gluon contribution and QCD dynamics

Important impact to the LHC physics: W, Z, H production via heavy quarks

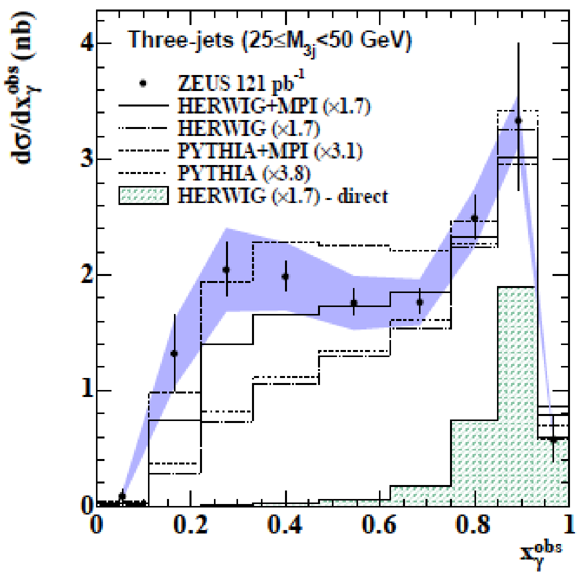


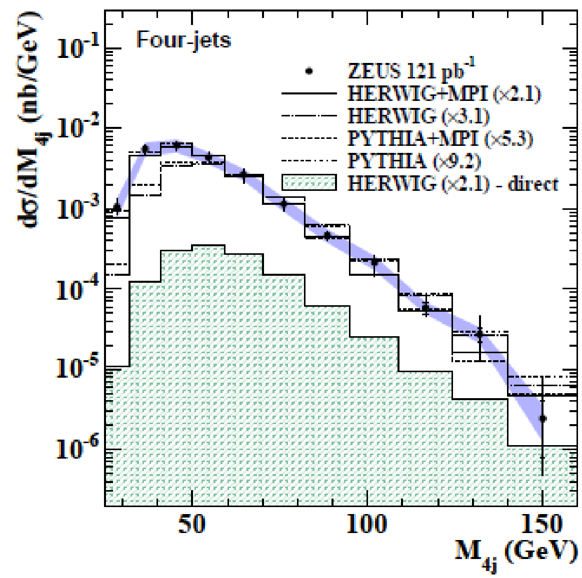
Two methods to measure F_2^{cc}

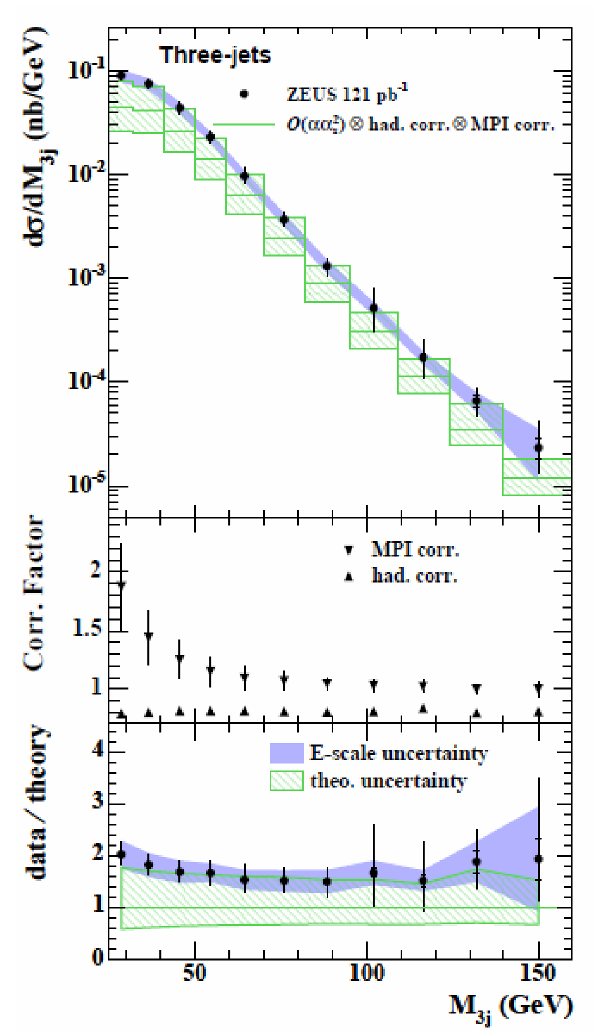
- Displaced secondary vertex (lifetime tag)
- Tagging by measuring D* meson production

The two methods have different exp. and theoretical uncertainties: combine taking into account correlations → significant reduction of the uncertainty

Underlying event (UE): multijets in photoproduction







- MC models without MPI describe data at high M_{nj} for all x_γ^{obs}, but fail at low M_{nj} and low x_γ^{obs} values
- MC models with MPI describe data in full range
- MPI corrections improve description of data by pQCD calculations (LO) → corrections increase as M_{3j} decreases