QCD and EW results from HERA

Daniel Britzger
for the H1 and ZEUS Collaborations

QCD@LHC 2016
Zürich, Switzerland
23.08.2016

Deep-inelastic scattering

Kinematic variables

- virtuality of exchanged boson

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

- Bjorken scaling variable

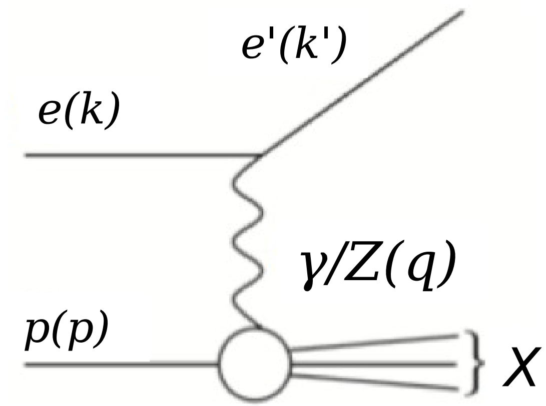
$$x = \frac{Q^2}{2\, p \cdot q}$$

- Inelasticity

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

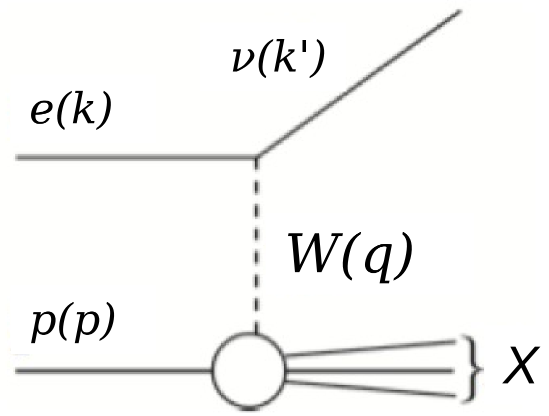
Neutral current scattering

$ep \rightarrow e'X$



Charged current scattering

$ep \rightarrow \nu_e X$



NC and CC scattering at tree level expressed by structure functions

Neutral current

$$\frac{d\sigma^{\pm}_{NC}}{dQ^2\, dx} = \frac{2\pi\alpha^2}{x}\left[\frac{1}{Q^2}\right]^2 \left(Y_+ \boldsymbol{F_2} + Y_- x \boldsymbol{F_3} + y^2 \boldsymbol{F_L}\right)$$

Charged current

$$\frac{d\sigma^{\pm}_{CC}}{dQ^2\, dx} = \frac{1 \pm P}{2}\,\frac{G_F^2}{4\pi x}\left[\frac{m_W^2}{m_W^2 + Q^2}\right]^2 \left(Y_+ \boldsymbol{W_2^{\pm}} \pm Y_- x \boldsymbol{W_3^{\pm}} - y^2 \boldsymbol{W_L^{\pm}}\right)$$

Calculation of structure functions employ factorisation theorem

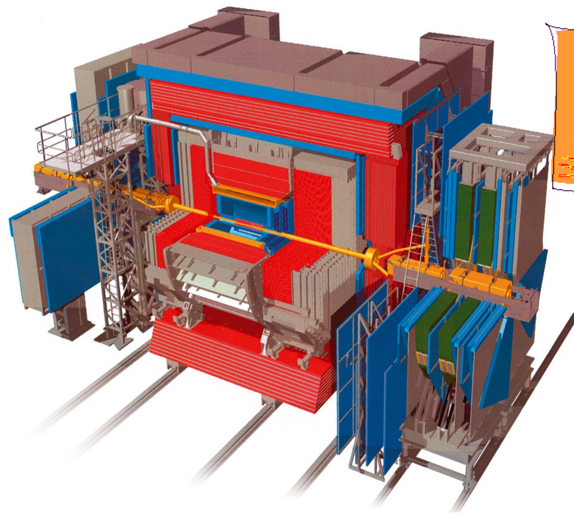
PDFs are largely determined from DIS data

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

H1 and ZEUS

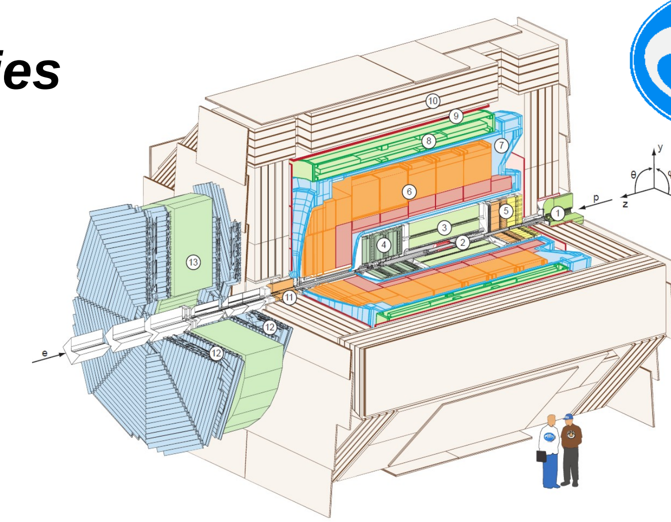
H1 and ZEUS

- Two multi-purpose collider experiments:
    - Asymmetric design
    - Trackers
    - Calorimeters
    - Magnet field from solenoid
    - Muon System
    - Lumi system, taggers, forward stations, etc...
- High statistics
    - Luminosity: approx. 0.5 fb^{-1} per experiment



Excellent control over experimental uncertainties

- Overconstrained system in DIS
- Electron measurement: 0.5 – 1% scale uncertainty
- Jet energy scale: 1%
- Trigger and normalization uncertainties: 1-2 %
- Luminosity: 1.8 – 2.5%



HERA operation

HERA electron-proton collider

- Electrons and positrons: E_e = 27.6 GeV
- Nom. proton energy: E_p = 920 GeV
- Two multi-purpose experiments: H1 and ZEUS

HERA-I operation: 1993 – 2000

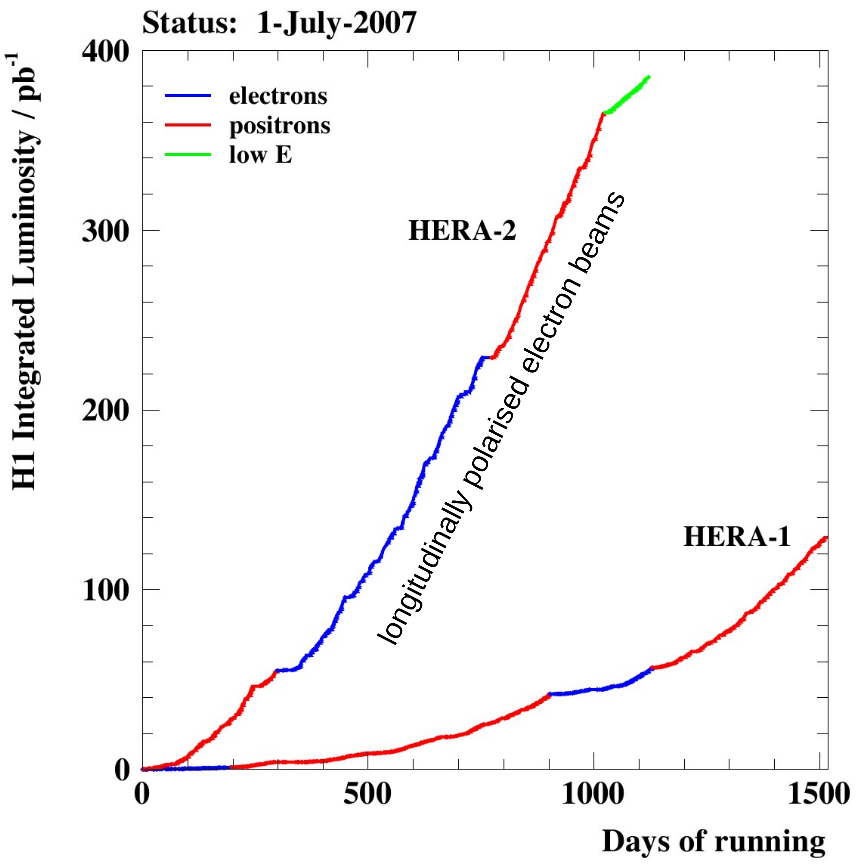
- Proton energies: 820 and 920 GeV
- int. Lumi. ~ 110 pb^{-1} per experiment

HERA-II operation: 2003 – 2007

- Longitudinally polarised leptons
- Proton energy: 920 GeV
- $\sqrt{s}$ = 319 GeV
- int. Lumi. ~ 350 pb^{-1} per experiment

Low-Energy Run 2007

- $\sqrt{s}$ = 225 & 251 GeV
- Dedicated F_L measurement



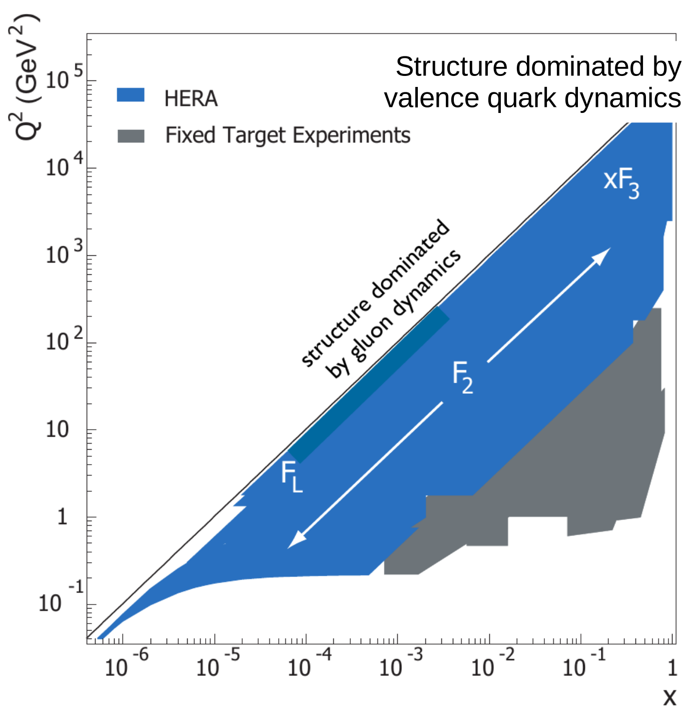
HERA kinematic plane and HERA legacy

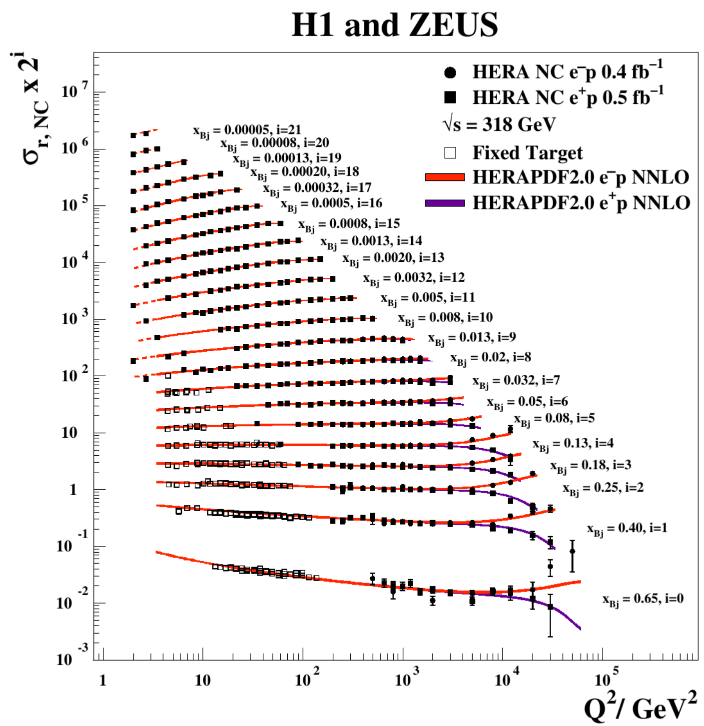
HERA inclusive DIS data

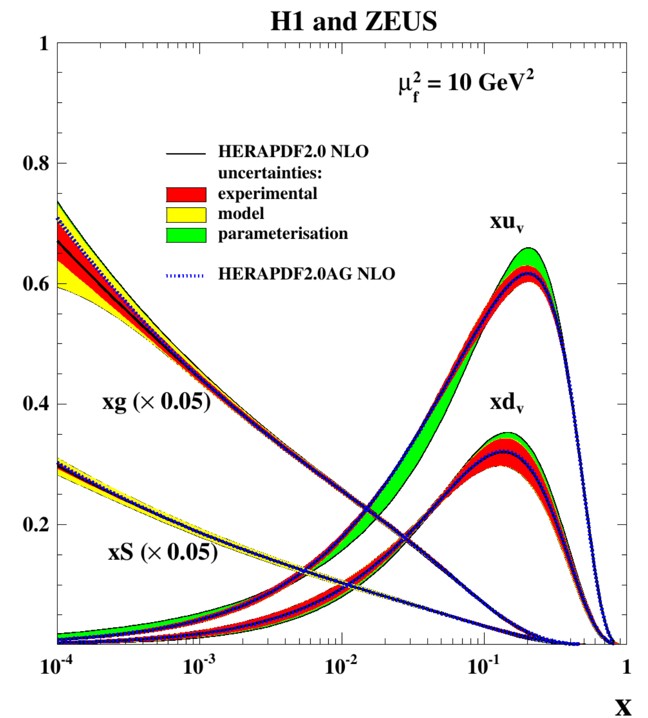
- Large kinematic region in x, Q^2
- NC and CC cross sections
- Inevitable basis for future PDFs

Reminder: Final HERA data published EPJ C75 (2015) 12

- 'HERA' = combined H1+ZEUS data
- 2927 data points combined into 1307 combined points
- Extracted PDF set: HERAPDF2.0







Data is now employed for studies beyond PDF fits ...

Fit of electroweak parameter to HERA data

Both, H1 and ZEUS, have performed fits of EW parameters

- Use polarised DIS data from HERA-II -> Increase sensitivity to EW parameters

Generalised structure functions for polarised NC DIS

$$F_2 = F_2^{\gamma} + \kappa_Z(-v_e \mp P a_e) F_2^{\gamma Z} + \kappa_Z^2 (v_e^2 + a_e^2 \pm P v_e a_e) F_2^Z$$

$$x F_3 = +\kappa_Z (\pm a_e + P v_e) F_3^{\gamma Z} + \kappa_Z^2 \left(\mp 2 v_e a_e - P(v_e^2 + a_e^2)\right) x F_3^Z$$

Structure functions in QPM

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

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

Weak couplings to Z-boson

axial coupling: $a_f = I_{f,L}^{(3)}$ $(f = e, u, d, \ldots)$

vector-axial: $v_f = I_{f,L}^{(3)} - 2 e_f \sin^2\theta_W$

Z^0-exchange

$$\kappa_Z(Q^2) = \frac{Q^2}{Q^2 + m_Z^2} \frac{G_F m_Z^2}{2\sqrt{2}\pi\alpha}$$

Calculations in on-shell scheme

$$G_F = \frac{2\pi\alpha}{2\sqrt{2} m_W^2} \left(1 - \frac{m_W^2}{m_Z^2}\right)^{-1} (1 + \Delta r)$$

Corrections to G_F

$$\Delta r = \Delta r(\alpha, m_W, m_Z, m_t, m_H, \ldots)$$

Parameters to cross section calculation:	α, m_Z, m_W, (m_t, m_H, ...)
More general, also couplings are free:	v_e,a_e , v_u,a_u and v_d,a_d

Input data to EW fits

Input data to ZEUS fit

HERA-I: NC and CC

- All **H1** and ZEUS HERA-I datasets
  - e^+ and e^-
  - NC and CC; low and high-Q^2
  - unpolarised

HERA-II: NC and CC

- ZEUS high-Q^2 polarised data
- H1 high-Q^2 unpolarised data
- ZEUS Reduced-E_p (unpolarised)
- H1 Reduced-E_p (unpolarised)

Correlations as in HERAPDF2.0

- More than 2900 data points

ZEUS-Fitter as fitting framework

Input data to H1 fit

H1 Low-Q^2 data

- NC and CC, e^+ and e^-
- All H1 HERA-I and HERA-II data are combined into one dataset

H1 High-Q^2 data

- NC and CC, e^+ and e^-
- HERA-I
  - H1 unpolarised data
- HERA-II
  - H1 polarised data

Polarisation measurements

- treated as measurement on its own

Alpos used as fitting framework

Fit of electroweak parameters

Determinations of light-quark couplings, mass of W-boson, Weinberg-angle

- Extract parameters through fitting theory to data
- Test of Standard model

PDFs have considerable uncertainties

- Unfortunate correlation!
- PDFs are essentially determined from HERA DIS data
- Consider PDF uncertainty by <u>simultaneous fitting the PDFs and EW parameters</u>

PDF-fit follows closely HERAPDF2.0 methodology

- DGLAP evolution of PDFs
  - H1: NNLO QCD with ZMVFNS
  - ZEUS: NLO QCD with RTop HF scheme
- PDFs are parameterised at starting scale $Q_0^2 = 1.9\,\mathrm{GeV}^2$

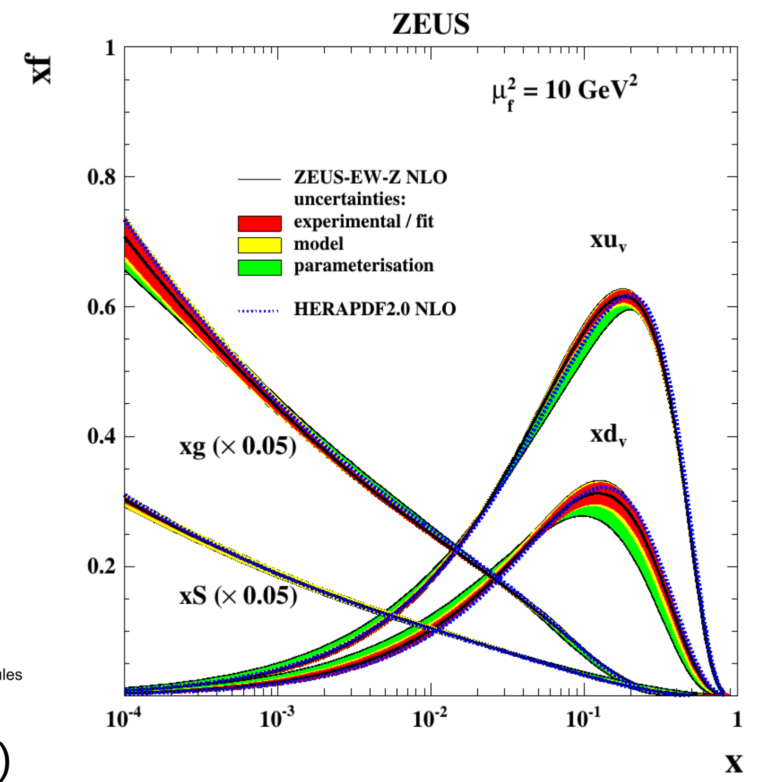
xg	xg	$xg(x) = A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}$,
xu_v	$xU = xu + xc$	$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1 + E_{u_v}x^2\right)$,
xd_v	$xD = xd + xs$	$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}$,
$x\bar{U}$	$x\bar{U} = x\bar{u} + x\bar{c}$	$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}(1 + D_{\bar{U}}x)$,
$x\bar{D}$	$x\bar{D} = x\bar{d} + x\bar{s}$	$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}$.

fixed or constrained by sum-rules

parameters set equal but free

- Use only data with $Q^2 >= 3.5\,\mathrm{GeV}^2$ (ZEUS) or $12\,\mathrm{GeV}^2$ (H1)

Result of *ZEUS-EW-Z NLO* compared to <u>HERAPDF2.0</u>



Couplings of light quarks to Z-boson

Results from H1 and ZEUS collaborations

- χ^2/ndf typically around 1
  - ZEUS: 2946 datapoints
  - H1: 1388 datapoints
- *u*-type coupling better constrained than *d*-type coupling
  -> sensitivity from valence quarks
- *d-type* coupling:
  -> benefit from polarisation

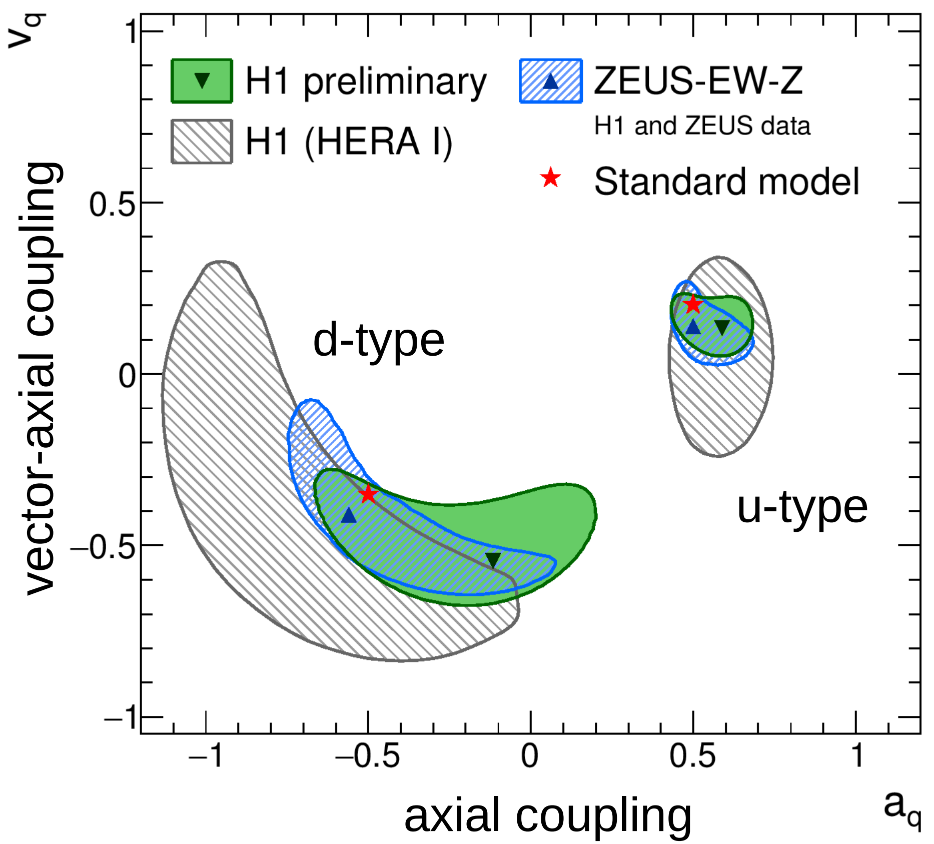
Results from H1 and ZEUS compatible

- Results compatible with SM expectation

Comparison to H1 HERA-I

Phys.Lett.B 632 (2006) 35

- Considerably improved sensitivity using polarised HERA-II data
- Polarisation in HERA-II important for axial-vector couplings



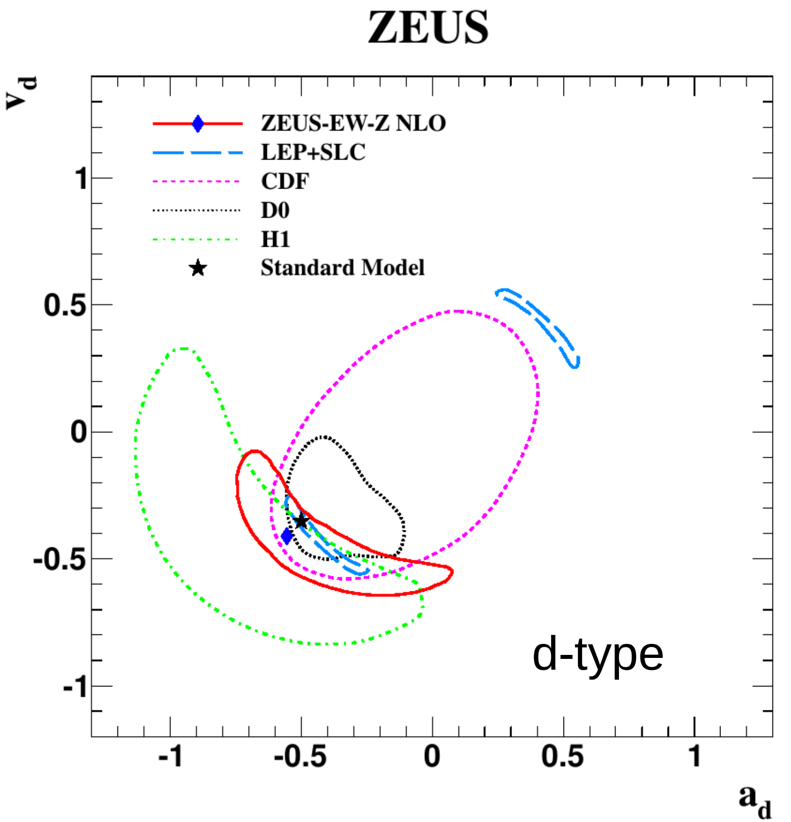
Comparison to other data

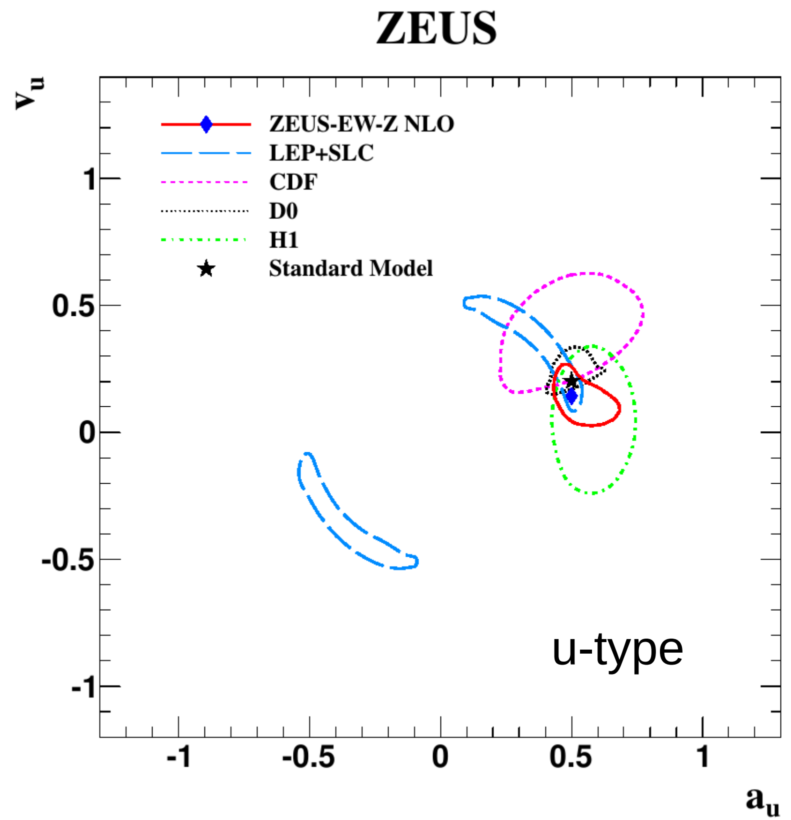
Comparison to other processes

- Results competitive with other processes
- Dissolve LEP sign-ambiguity
- u-type coupling highly competitive

Further studies

- PDF uncertainties are small
- Large correlation between u- and d-type





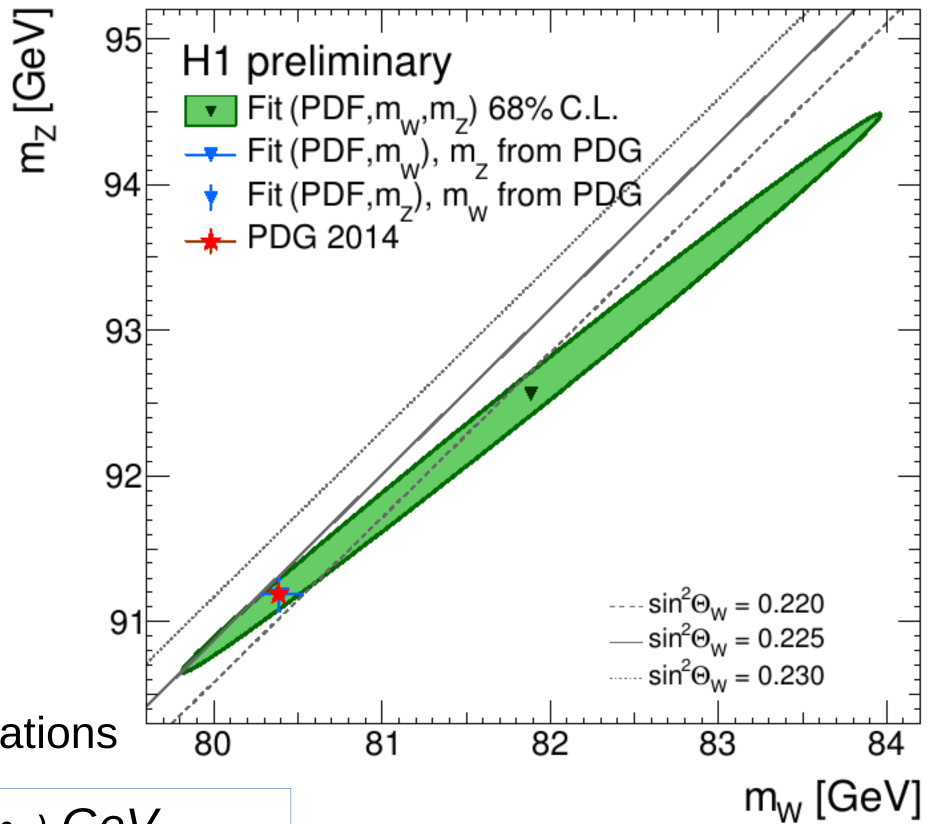
Study of Standard Model parameters

Standard Model is now overconstrained

- Important to study consistency in many complementary processes
- HERA: Space-like momentum transfers
- Only purely virtual exchange of bosons

(m_W – m_Z) + PDF fits

- Assume α is known
- on-shell masses m_W and m_Z are only free EW parameters
- Agreement within PDG14 SM values
- Large correlation between m_W and m_Z



Mass of W-boson

Take other masses (m_Z) as external input to calculations

$m_W = 80.407 \pm 0.118$ (exp,pdf-fit) ± 0.005 (m_Z, m_t, m_H) GeV

Approx. half the exp. uncertainty may be attributed to PDFs

Compare to H1 HERA-I: $m_W = 80.786 \pm 0.205$ (exp) $^{+0.063}_{-0.098}$ (th) GeV

$m_{W,PDG} = 80.385 \pm 0.015$ GeV

Study of Standard Model parameters

Different view on SM parameters

- Fermi coupling constant G_F

$$G_F = \frac{\pi \alpha}{\sqrt{2} m_W^2 \sin^2\theta_W} (1 + \Delta r)$$

- Weak mixing angle

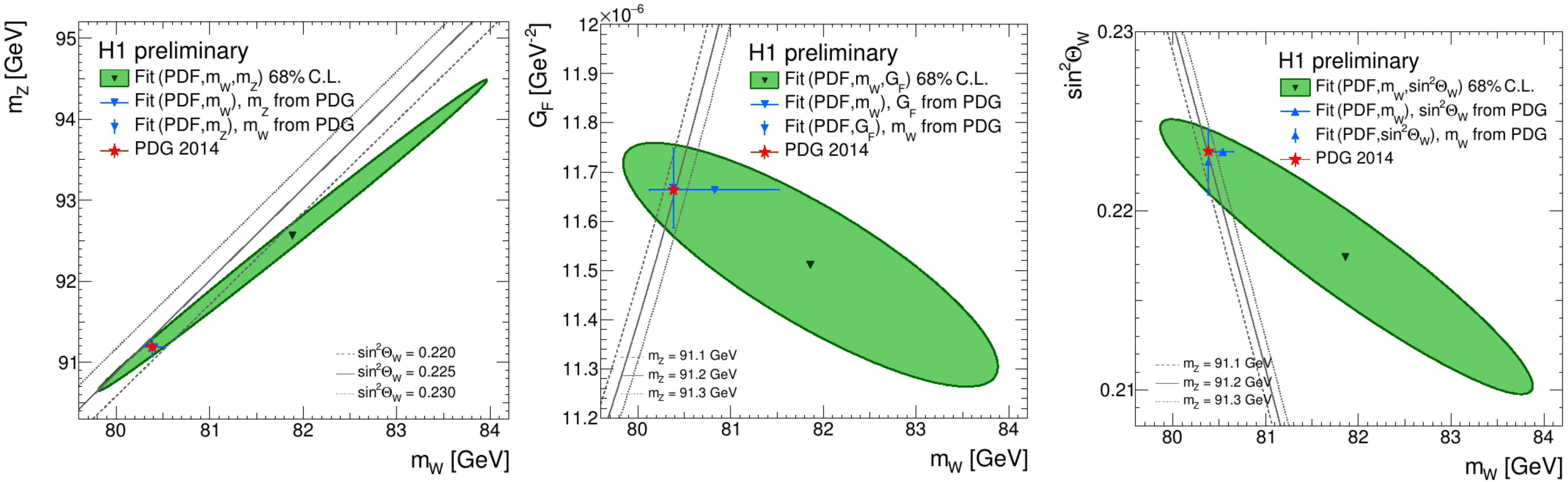
$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

Perform calculations consistently in on-shell scheme (α,m_Z,m_W)

- Calculate m_Z (iteratively) from G_F or $\sin^2\theta_W$

Results from fits together with PDF and m_W

- H1 values consistent with precise values from PDG
- Correlation to m_W are different for m_Z, $\sin^2\theta_W$ and G_F



Study of Standard Model parameters

Simultaneous extraction of $\sin^2\theta_W$ and m_W

- Identify parameters in cross section predictions

$$M_W = 79.30 \pm 0.76_{(exp/fit)}\,{}^{+0.38}_{-0.08}{}_{(mod)}\,{}^{+0.48}_{-0.10}{}_{(par)}\,GeV = 79.30^{+0.98}_{-0.77}{}_{(tot)}\,GeV$$

$$\sin^2\theta_W = 0.2293 \pm 0.0031_{(exp/fit)}\,{}^{+0.0005}_{-0.0001}{}_{(mod)}\,{}^{+0.0003}_{-0.0001}{}_{(par)} = 0.2293^{+0.0032}_{-0.0031}{}_{(tot)}$$

- quantities agree with world average values

Fit of $\sin^2\theta_W$ with m_W as external input

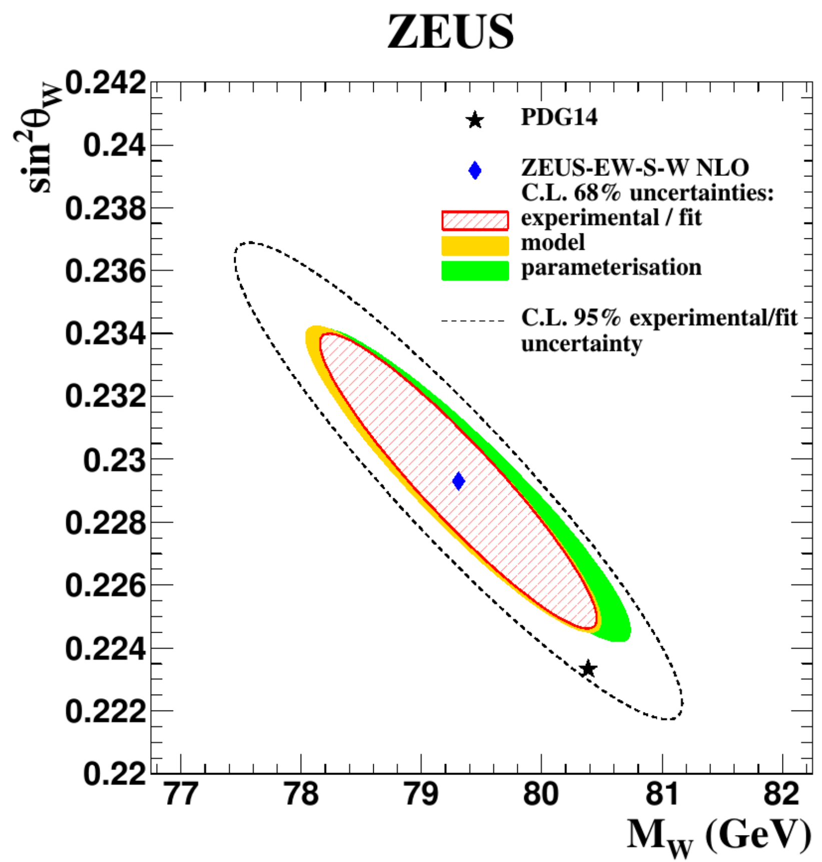
$$\sin^2\theta_W = 0.2252 \pm 0.0011_{(exp/fit)}\,{}^{+0.0003}_{-0.0001}{}_{(mod)}\,{}^{0.0007}_{-0.0001}{}_{(par)} = 0.2252^{+0.0013}_{-0.0011}{}_{(tot)}$$

Extraction of W-boson mass

- Fix all other parameters in the fit

$$M_W = 80.68 \pm 0.28_{(exp/fit)}\,{}^{+0.12}_{-0.01}{}_{(mod)}\,{}^{+0.23}_{-0.01}{}_{(par)}\,GeV = 80.68^{+0.38}_{-0.28}{}_{(tot)}\,GeV$$

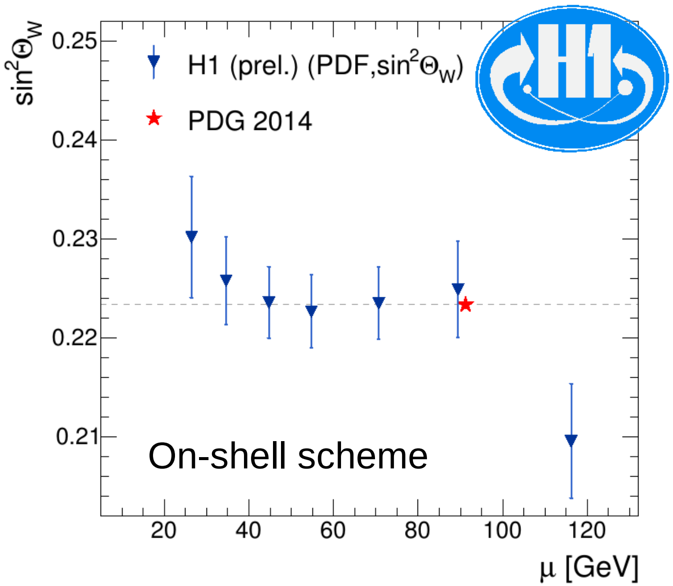
- Value compatible with world average
- Unique test of SM in space-like processes

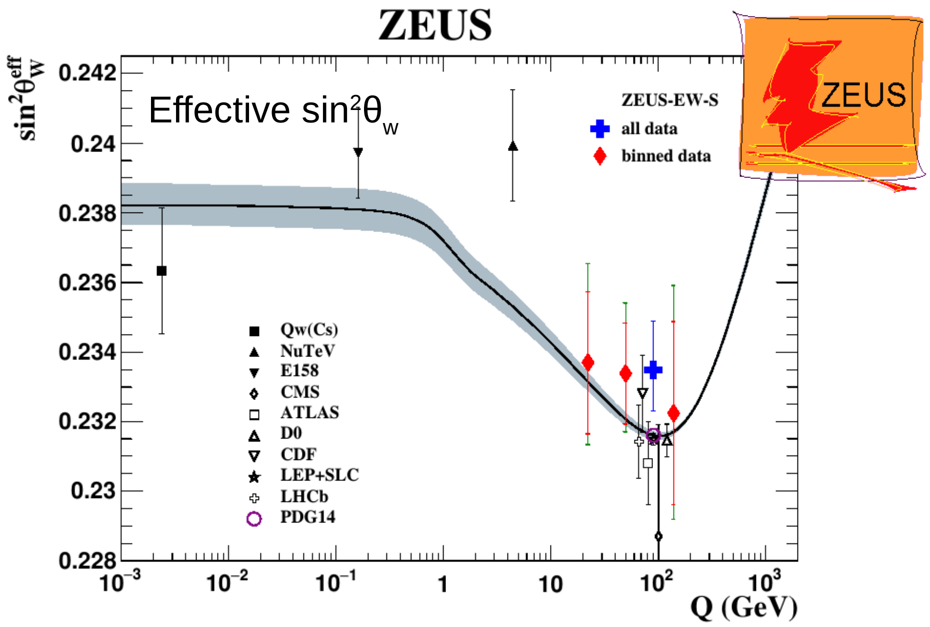


$\sin^2\theta_W$

Probe scale dependence of weak mixing angle

- Unique measurement taking advantage of space-like momentum transfer
- Extract weak mixing angle at different scales $\mu = \sqrt{Q^2}$
- HERA EW-fits studies kinematic region of approx. 20 < μ < 120 GeV^2





Results

- Results are compatible with precise value from Z-pole measurements
- Unique measurement of weak mixing angle at different scales
- Comparison in different EW-schemes straight forward

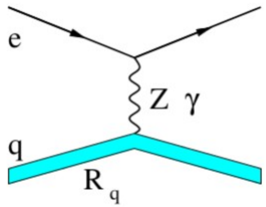
Limit on effective quark radius

One of the possible parameterisations of deviations from SM

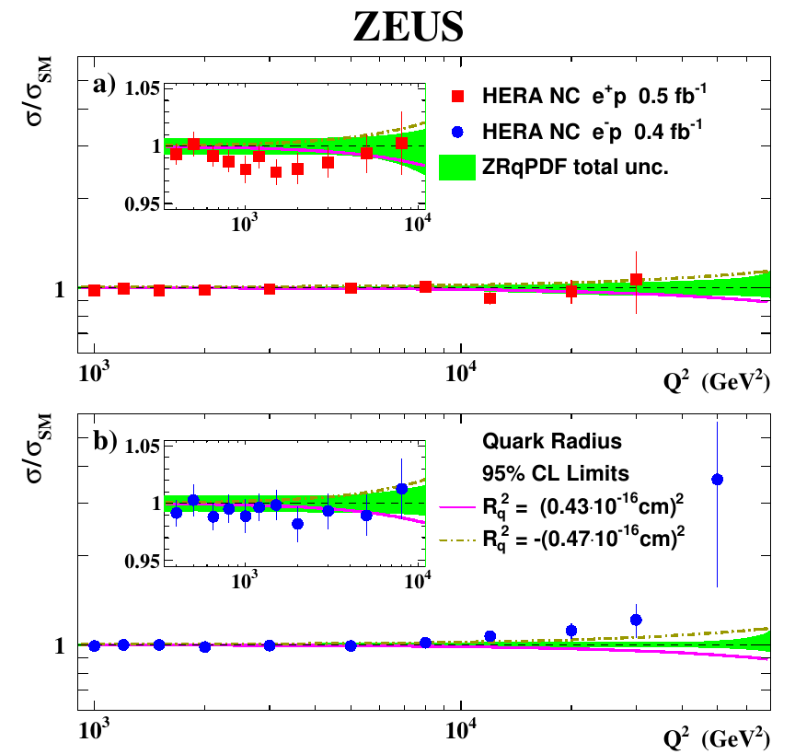
- Spatial distribution or substructure of electrons and/or quarks.

Fit with form-factor approach to final combined HERA-II data

- semi-classical form-factor -> cross sections are expected to decrease at highest Q^2 values



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



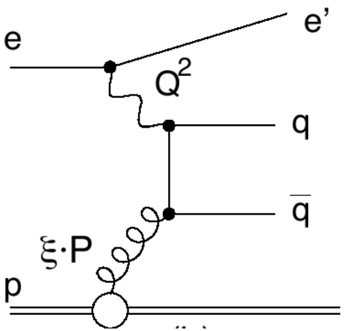
- R_q – RMS-radius of EW-charge distributions of quarks
- QCD+BSM analysis of combined HERA data

Limit on quark radius

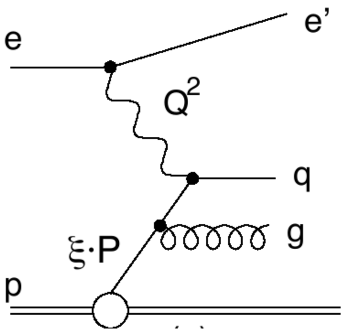
$$-[0.47 \cdot 10^{-16}\ \text{cm}]^2 < R^2_q < [0.43 \cdot 10^{-16}\ \text{cm}]^2$$

- Improved limit compared to earlier H1 result
- Limit compatible with L3 result in complementary process
- Limit on quark radius ~2000 times smaller than proton

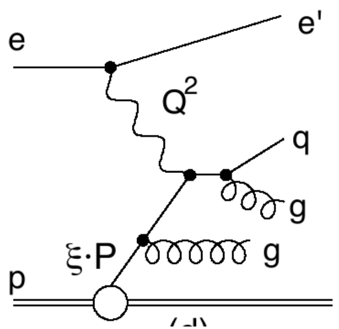
Jet production in DIS



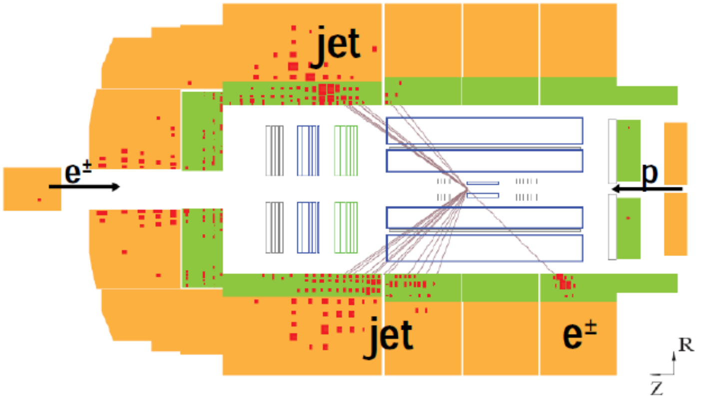
Boson-gluon fusion



QCD Compton



Trijet leading-order



Jet measurements are performed in Breit reference frame

- Exchanged virtual boson collides 'head-on' with parton from proton

Jet measurement sensitive to α_s already at leading-order

- Boson-gluon fusion -> Provides also direct sensitivity to gluon content of PDFs
- QCD compton

Trijet measurement

- More than three jets with significant transverse momenta
- Leading-order already at $O(\alpha_s^2)$

Jet production in DIS at low Q2

Simultaneous measurement/unfolding

- of: inclusive jets, dijet and trijet
- Int. Lumi: 184 pb^{-1}
- Similar strategy as it was done by H1 at high-Q2 in: *EPJ C75(2015)65*

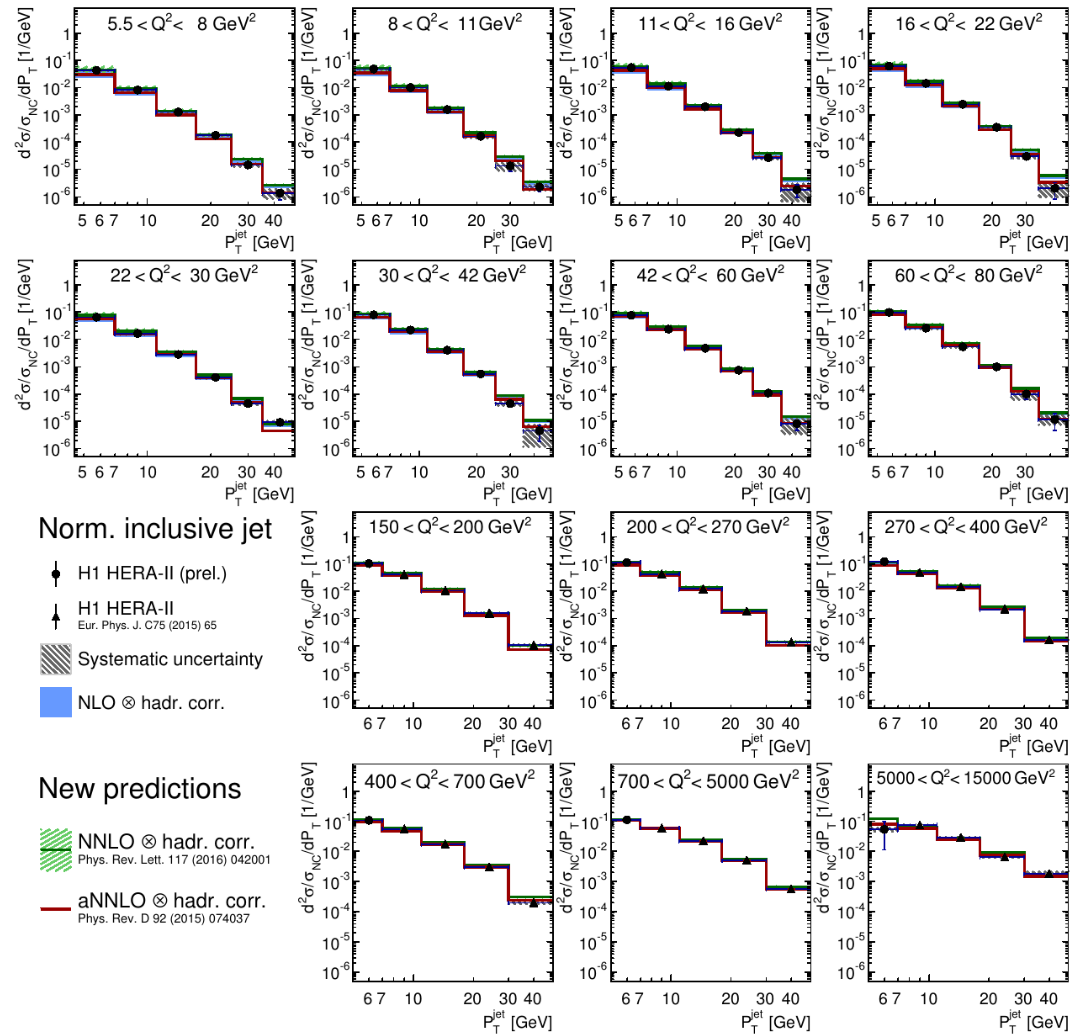
'Normalised' jet cross sections

- Normalise jet cross sections w.r.t. inclusive NC DIS cross section
  - Full/partial cancellation of uncertainties

Phase space of cross sections	
NC DIS	$5.5 < Q^2 < 80$ GeV^2
	$0.2 < y < 0.6$
(inclusive) Jets	$P_T^{jet} > 4.5$ GeV
	$-1.0 < \eta^{lab} < 2.5$
Dijet and Trijet Measure average p_T	$\langle P_T^{jet} \rangle_2 > 5.0$ GeV
	$\langle P_T^{jet} \rangle_3 > 5.5$ GeV

High-Q2

- New cross sections for $5 < p_T < 7$ GeV



Jet production in DIS at low Q2

Detailed ratio to NLO prediction

- Data reasonably described by NLO theory, but NLO scale uncertainty large

New predictions: ***<u>NNLO</u> from NNLOJET***

- NNLO predictions for inclusive jet and dijet production in NC DIS (*PRL 117 (2016) 042001*)
- Normalised with NC DIS predictions from APFEL using FONLL-C

NNLO

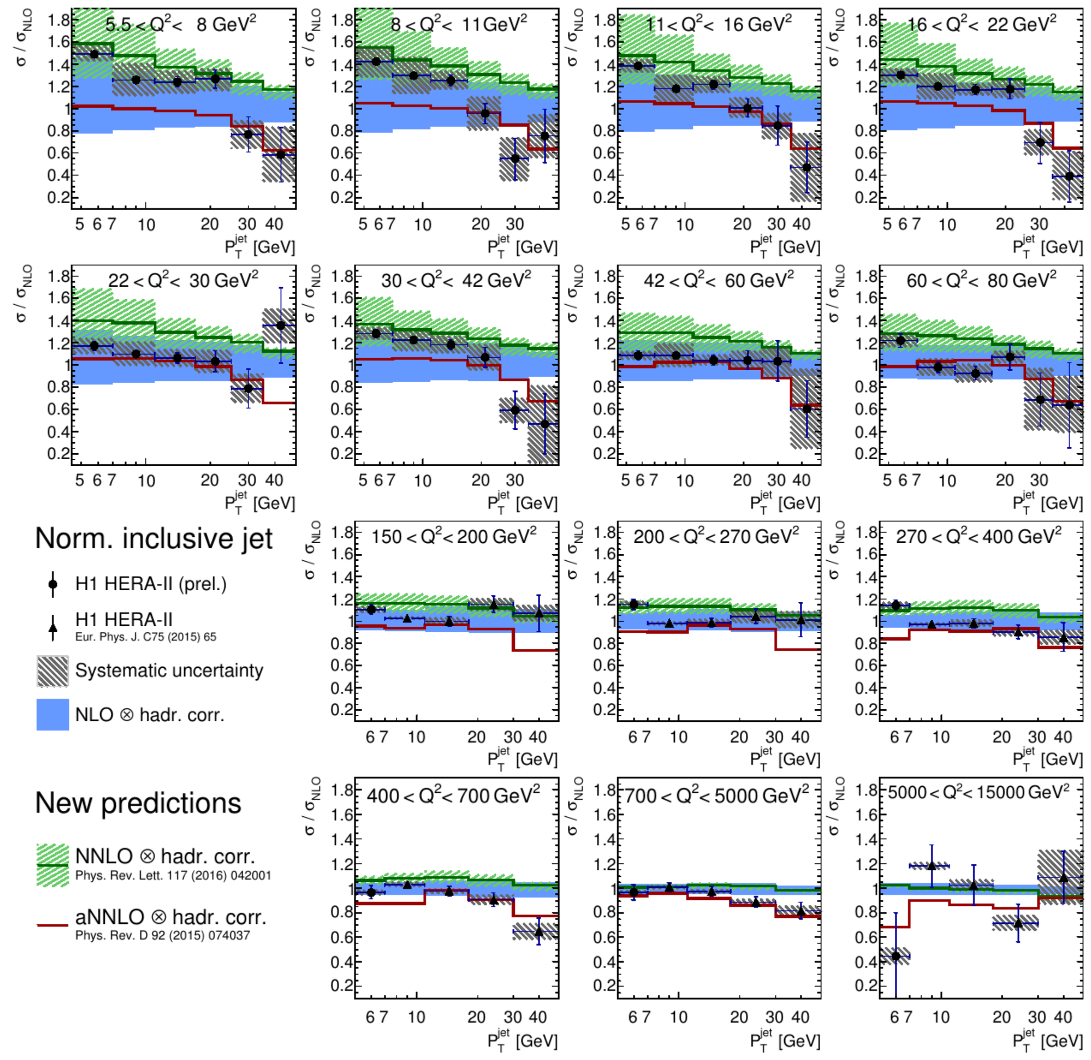
- Improved description of data by NNLO
- Significantly reduced scale uncertainty (particularly for higher scales)

aNNLO from JetViP

- Approximate NNLO using threshold resummation *PR D 92 (2015) 074037*
- Improved data description at high-pT

High-Q2 inclusive jets

- New datapoints for $5<p_T<7$ GeV plus *EPJ C75 (2015) 65*



Dijet production in DIS

Dijet production in NC DIS

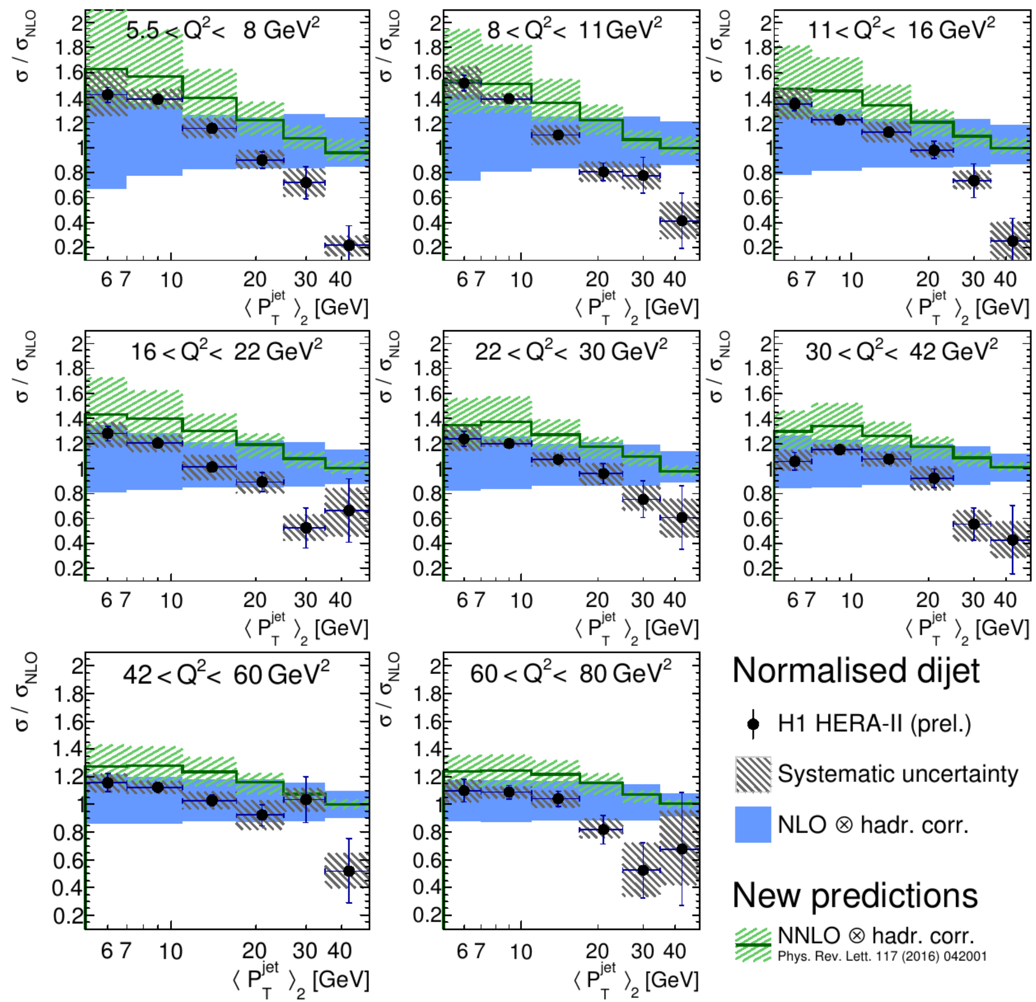
- Low-Q^2: $5.5 < Q^2 < 80$ GeV^2
- $\langle P_T \rangle_2 = (P_T^{jet1} + P_T^{jet2})/2$
  with: $P_T^{jet} > 4$ GeV
- High experimental precision

Comparison to NLO

- Reasonable description within large scale uncertainties

New NNLO predictions

- Significant reduced scale uncertainty for higher values of $\langle P_T \rangle_2$
- Significant improvement of the shape
- Slightly higher in normalisation
  -> Partially due to the normalisation to NC DIS cross sections



Inclusive jet, dijet and trijets in DIS

Normalised trijet production in DIS

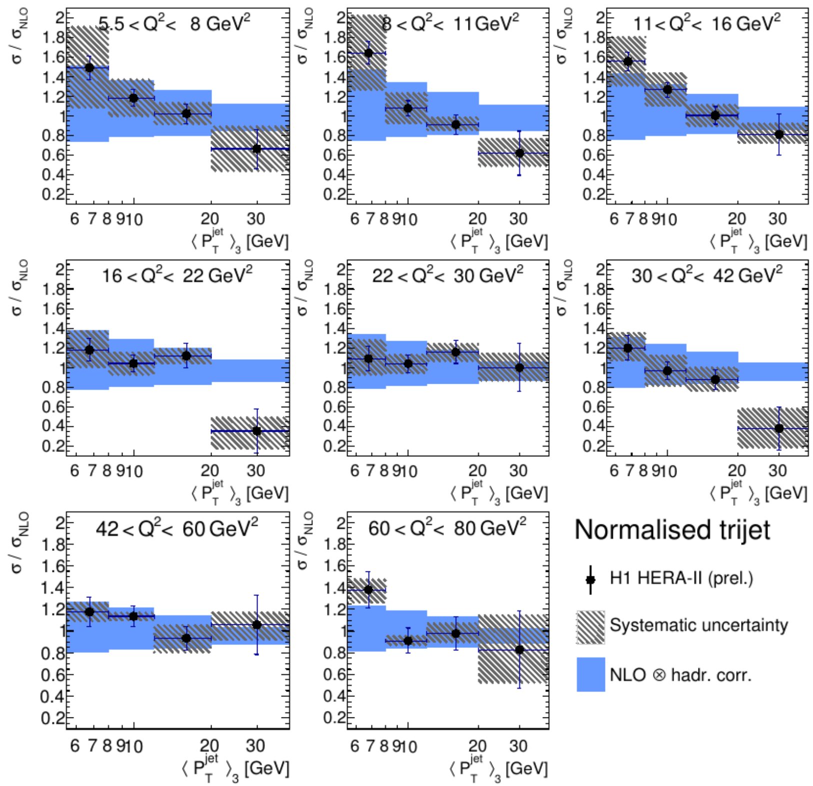
- Data well-described by NLO theory
- No NNLO predictions available yet

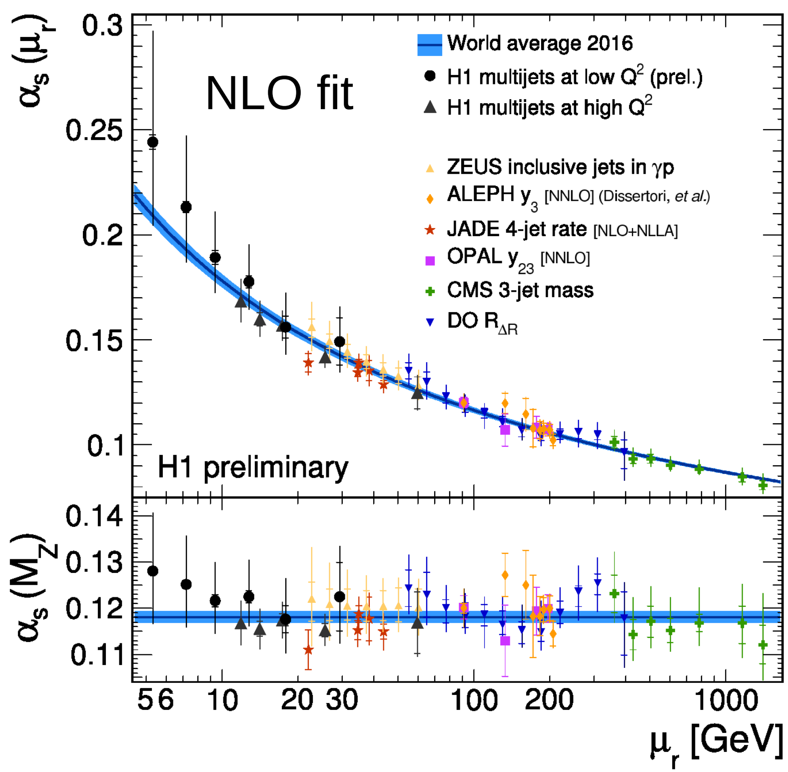
$\alpha_s(m_Z)$ from normalised low-Q2 multijets w/ NLO

- Probe running of $\alpha_s(\mu)$ in range $6 < \mu < 30$ GeV

Use normalised low-Q^2 and high-Q^2 H1-multijets

- Experimental precision about ***0.4%***





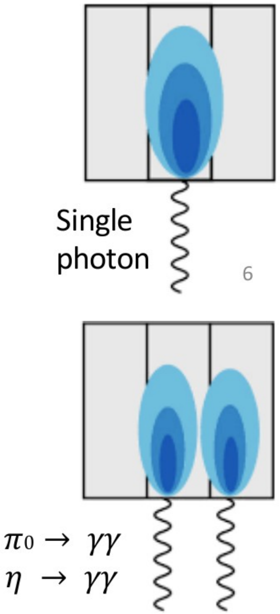
Prompt photons in DIS

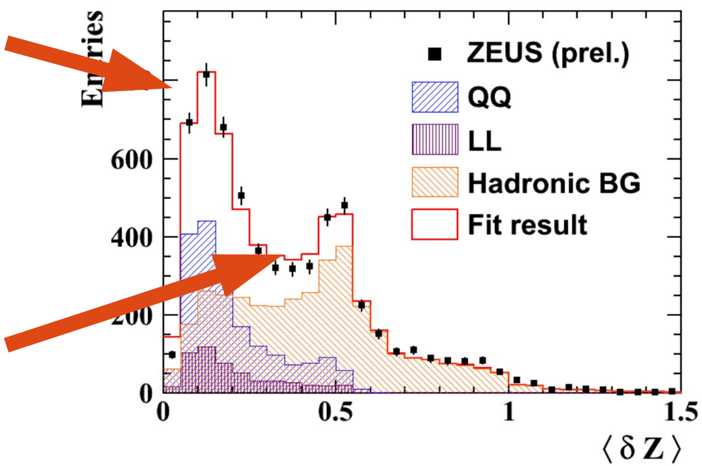
Prompt photons with jets in DIS

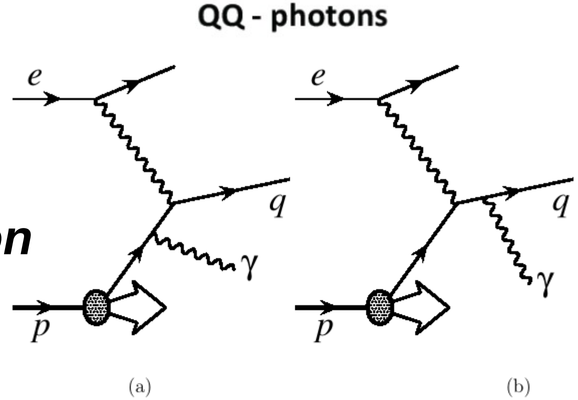
- Photons emitted from quark or lepton
- Photons are radiated before hadronisation
- Direct test of ME
- Complements earlier result *Phys. Lett. B 715 (2012) 88*

Fine segmentation of calorimeter in z-direction

- Suppression of $\pi^0 \to \gamma\gamma$ background

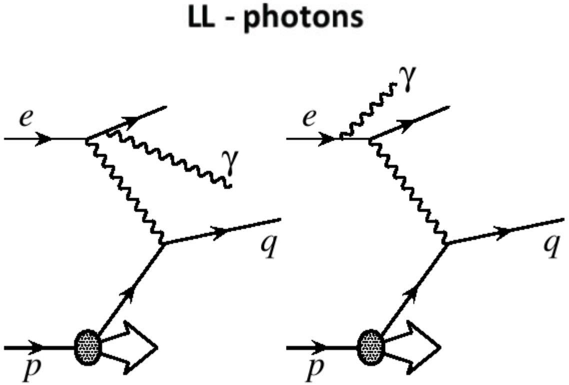






γ is emitted from quark as part of hard process

→ hard process, similar to multi-jets



γ is radiated from incoming or outgoing lepton

→ theoretically well determined

Prompt photons in DIS

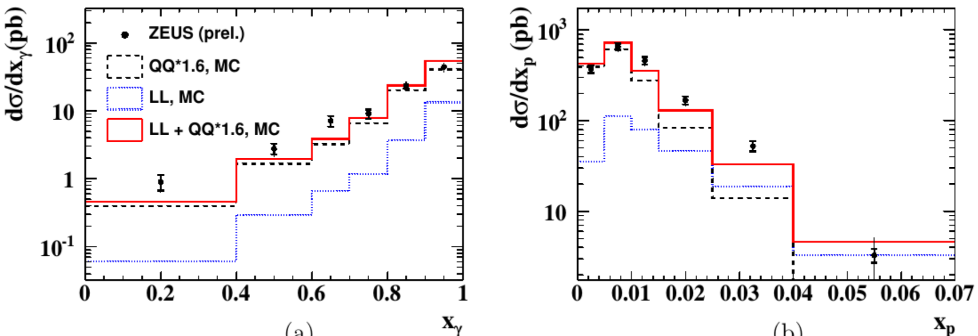
Cross section as function of

- x_γ, x_p – fraction of incoming photon (proton) energy taken by γ+jet (parton)
- Δφ,Δη – separations of photon and e or jet

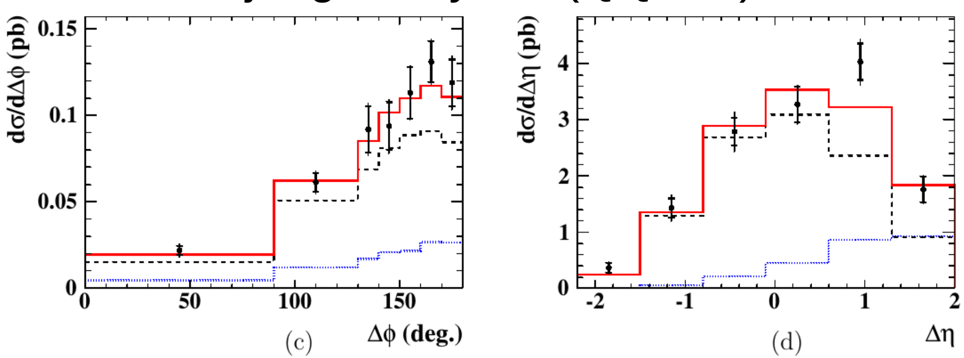
Weighted LO MC – Djangoh/Pythia

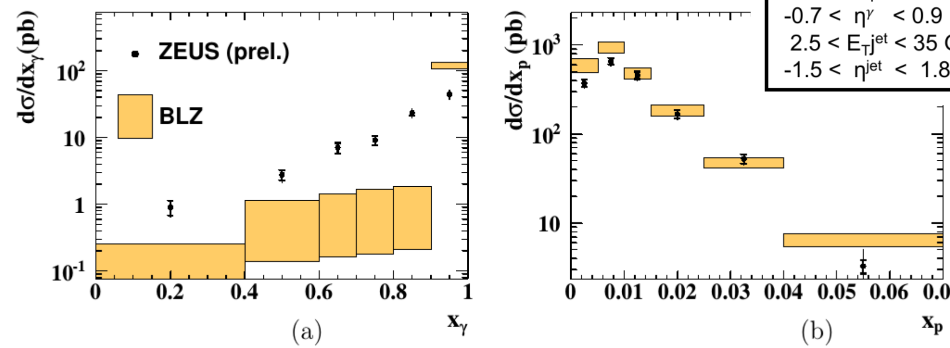
- Weighting of QQ by 1.6 provides good description
- k_T-factorisation fails to describe x_γ
  -> More investiagations needed

$10 < Q^2 < 350$ GeV^2
$4 < E_T^\gamma < 15$ GeV
$-0.7 < \eta^\gamma < 0.9$
$2.5 < E_T^{jet} < 35$ GeV
$-1.5 < \eta^{jet} < 1.8$

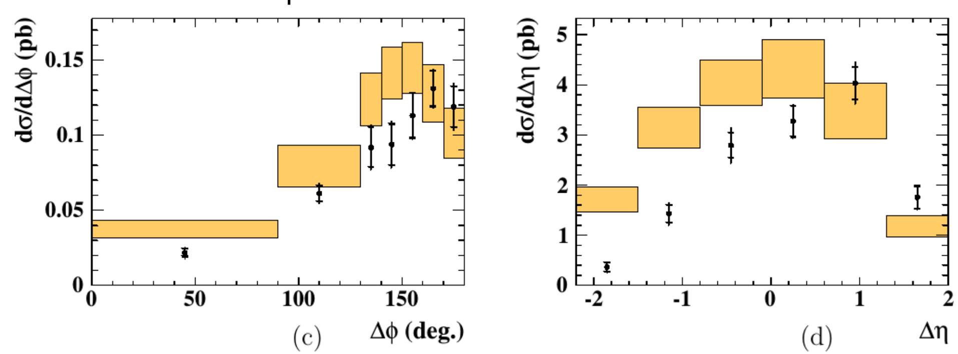


Djangoh+Pythia (QQ*1.6)





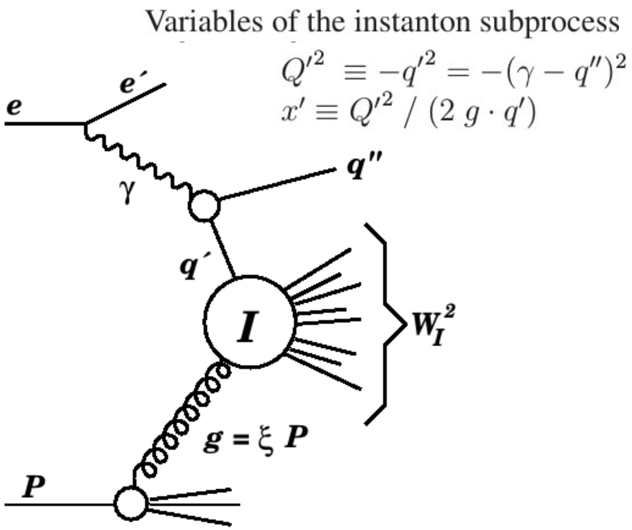
k_T-factorisation (BLZ)



QCD Instantons

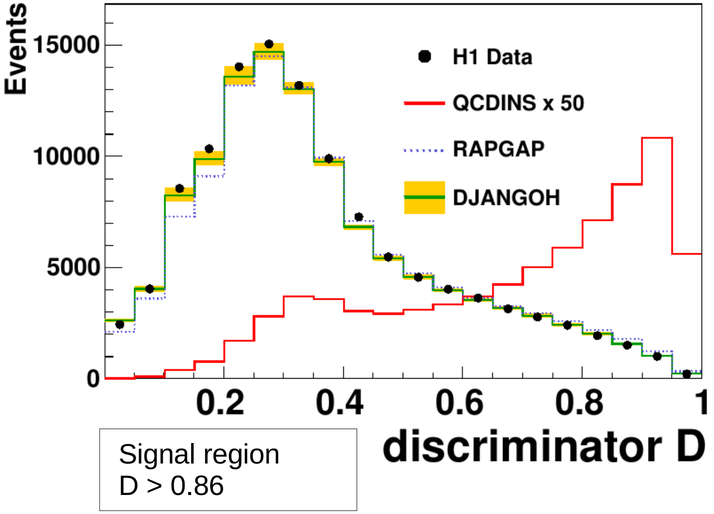
QCD Instantons

- Solution to Yang-Mills equation of motion
  - Non-perturbative fluctations of the gauge field
  - Physical interpretation: Pseudo-particle or tunneling process between topologicaly different vacuum states
- The discovery of instantons would be the first evidence for non-perturbative QCD effect at high energies
- QCDINS MC generator by Ringwald/Schrempp
  - Sizeable cross section using Instanton-perturbation theory
  - Uncertainty coming from Λ_{QCD}(MSbar)



Characteristic signature of Instanton

- One hard jet (not originating from instanton)
- Densily populated narrow band; flat in φ
- Large particle multiplicities



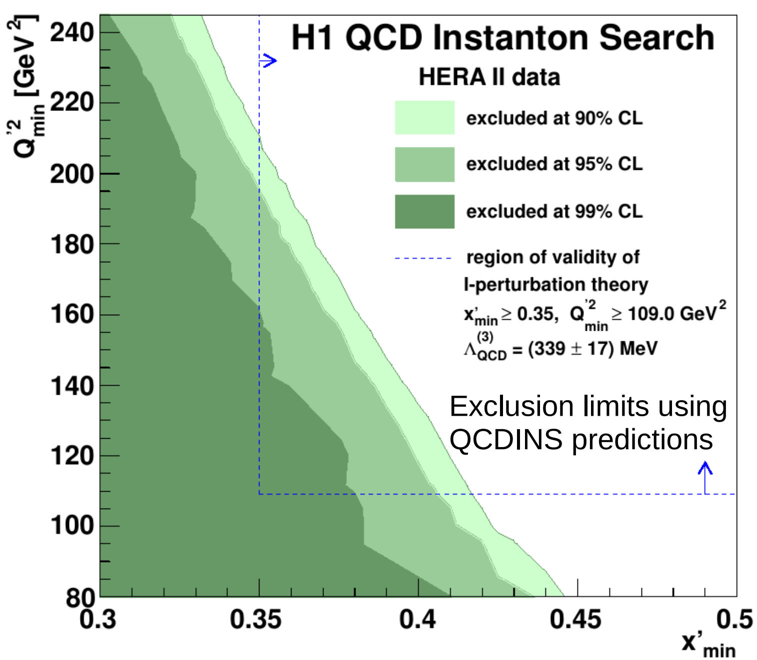
Strategy

- Find jets in hadronic center of mass frame
- Remove hardest jets from HFS
- Define topological input-variables in 'instanton rest-frame' which are input to TMVA
  - Train MVA with QCDINS Monte Carlo

QCD Instantons

Exclusion limits for QCDINS

- In Q'^2_{min} and x'_{min} plane
  - Outside QCDINS predictions are zero
- Validity of I.-perturbation theory indicated
- Significant part excluded:
  Observed limit: 2 pb @ 95% C.L.
  Predicted CS: 10 ± 3 pb



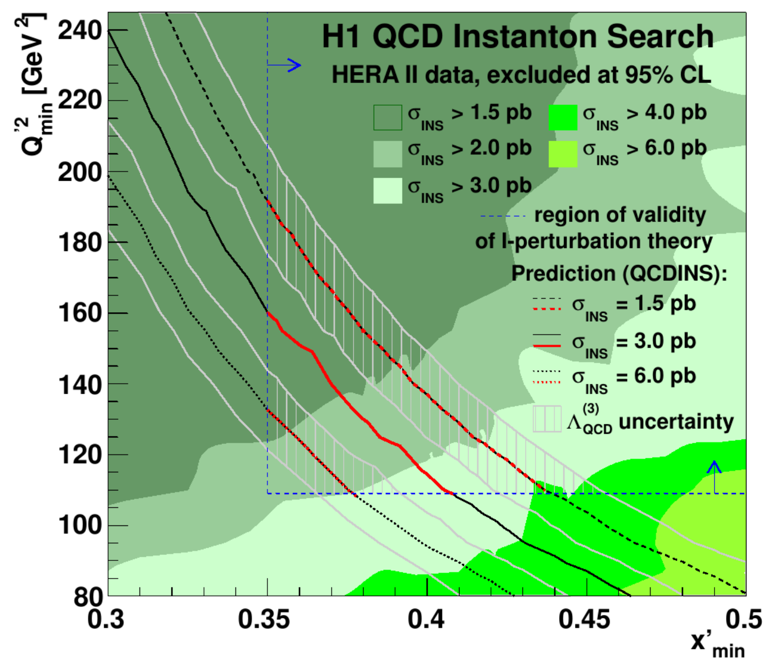
Exclusion limits on I.-production cross section

- Using QCDINS signal shape, but without uncertainty on the normalisation
- Upper limit at 95% C.L.

$$\sigma_{lim} \sim 1.5 - 6 \text{ pb}$$

Depending on kinematic domain

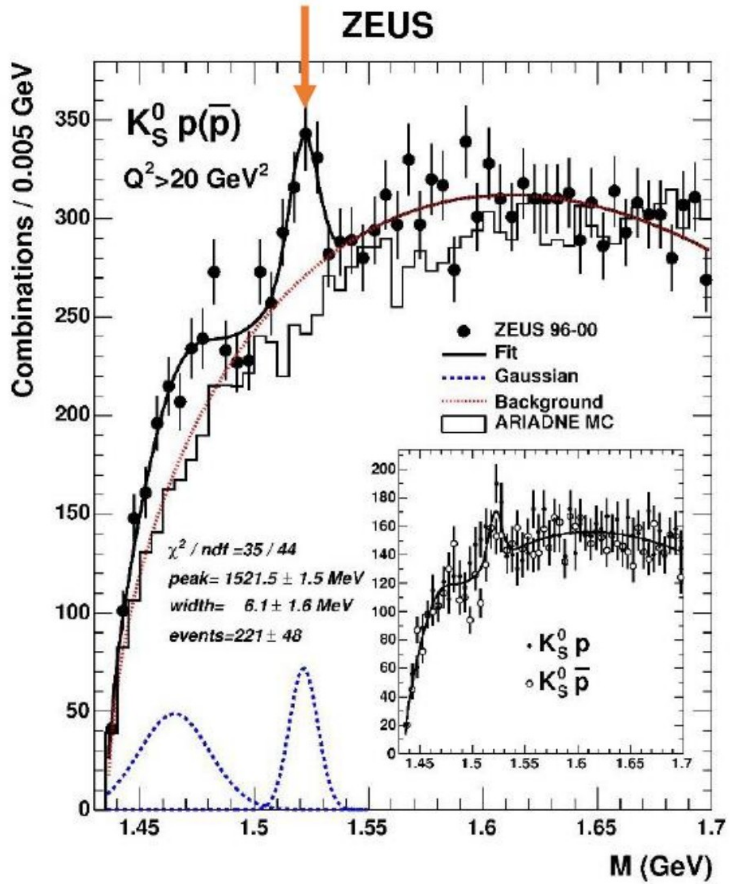
- Most stringent exclusion limits observed for large Q'^2_{min} and small x'_{min}



Pentaquarks

Pentaquarks

- Early 2000‘s: reported exotic objects consisting with 5 quarks.
- ZEUS: evidence for a peak in pK^0_s ($\bar{p}K^0_s$) corresponding to <u>$uudd\bar{s}$ state</u> at 1.52 GeV (HERA I)
- In 2015 LHCb: possible discovery of two pentaquark states at 4.38 and 4.45 GeV corresponding to $uudc\bar{c}$
- Narrow resonance close to 1.52 GeV predicted in chiral soliton model: named Θ



History

- ZEUS Phys.Lett.B 591 (2004) 7:
  Peak at 1.52 GeV consistent with Θ state

- H1 Phys.Lett B 639 (2006) 202:
  No signal seen

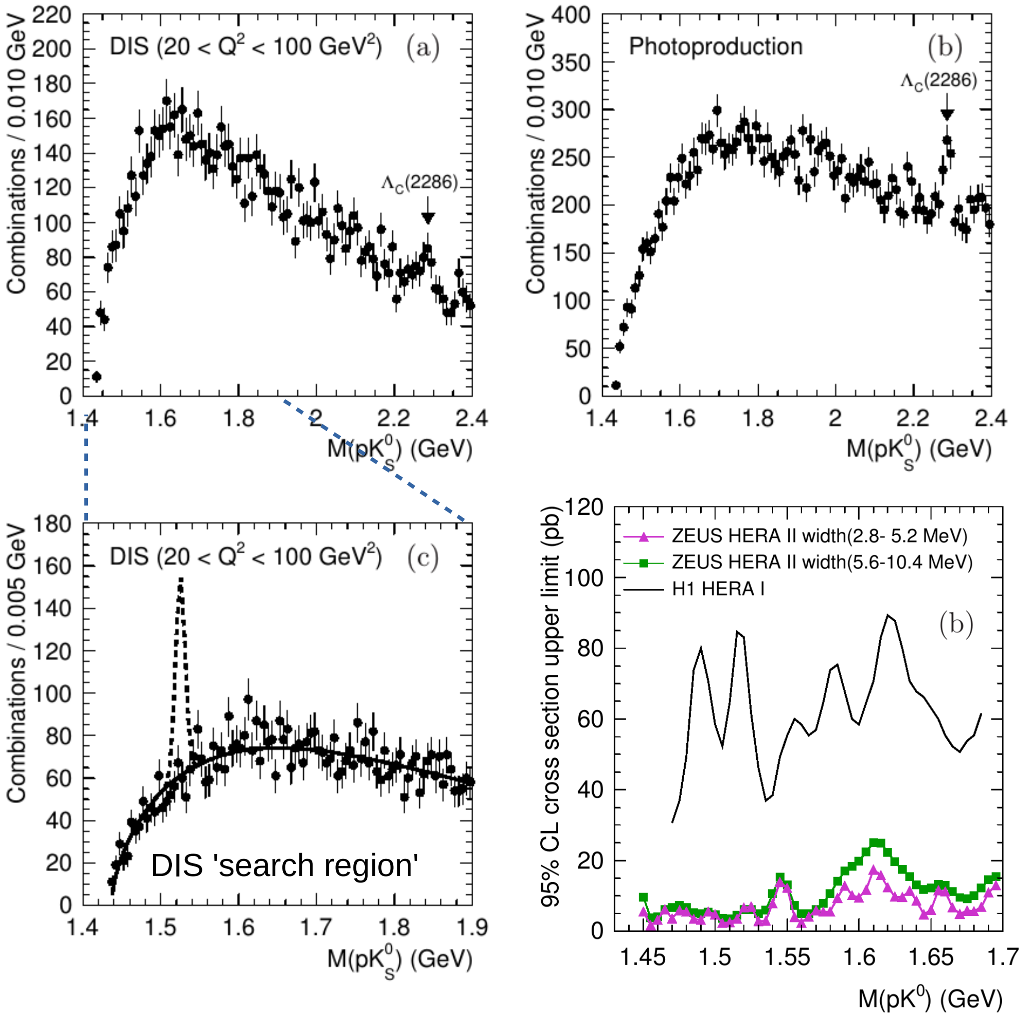
Pentaquarks

The pK^0_S invariant-mass distribution

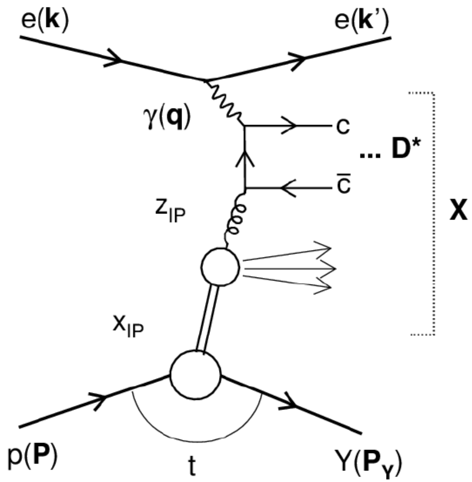
- Benefit from improved dE/dX for proton-identification using MVD
- The dashed line represents the expected signal corresponding to the ZEUS HERA I result:
  - 286 events expected
- Clear Λ_c (2286) peak observed in photoproduction and DIS sample

Results

- Upper limits on production cross section as a function of the *pK^0* mass set
- A peak at 1.52 GeV observed in a previous ZEUS analysis, based on HERA-I data is not confirmed



D* in diffractive DIS

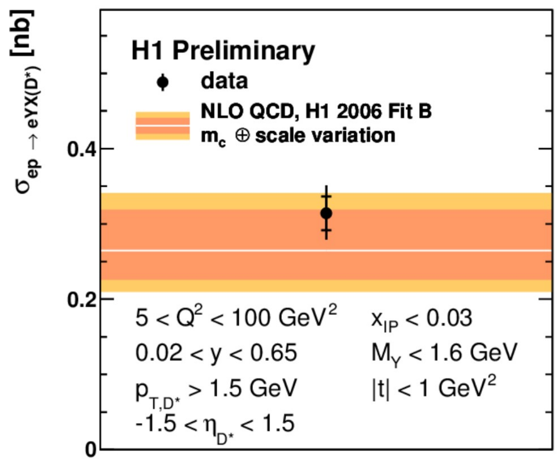


Open charm production cross sections in diffr.-DIS

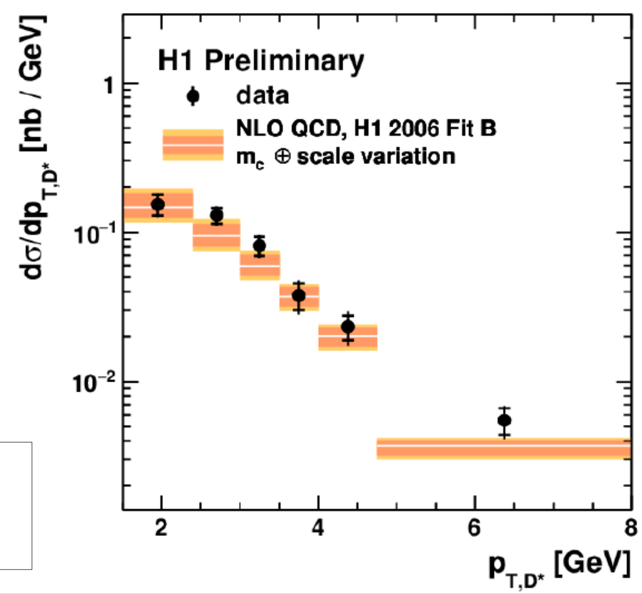
- Larger dataset than previous analysis
- Large rapidity gap selection for diffr. final state

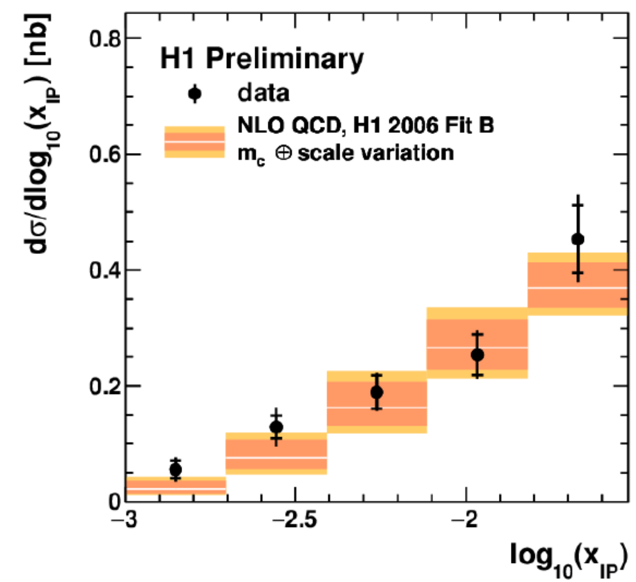
NLO QCD predictions (NLO ⊕ DPDFs ⊕ FF)

- Good description within uncertainties
- Tests assumptions of collinear and proton-vertex factorisation
- Tests assumptions of universality of fragmentation



NLO employs
DPDFs from H1 inclusive diffr.-DIS
fragmentation func. from non-diffr. analysis





Conclusions

After finalisation of HERA inclusive NC and CC DIS cross sections... EPJ C75 (2015) 12

- Determination of electroweak parameters — H1prelim-16-041; Phys. Rev. D 93 (2016) 092002
  - High sensitivity to light-quark couplings
  - Important complementary tests of SM
- Improved limits on effective quark radius — Phys. Lett. B 757 (2016) 468

Hard QCD

- (Normalised) inclusive jet, dijet and trijet cross sections in DIS — H1prelim-16-062
  - New NNLO predictions will allow precision tests of the strong coupling and suggest to use HERA jet data for PDF determinations — H1prelim-16-061
- New observables for prompt photon production in DIS studied -> direct tests of hard process — ZEUS-prel-16-001

Soft QCD

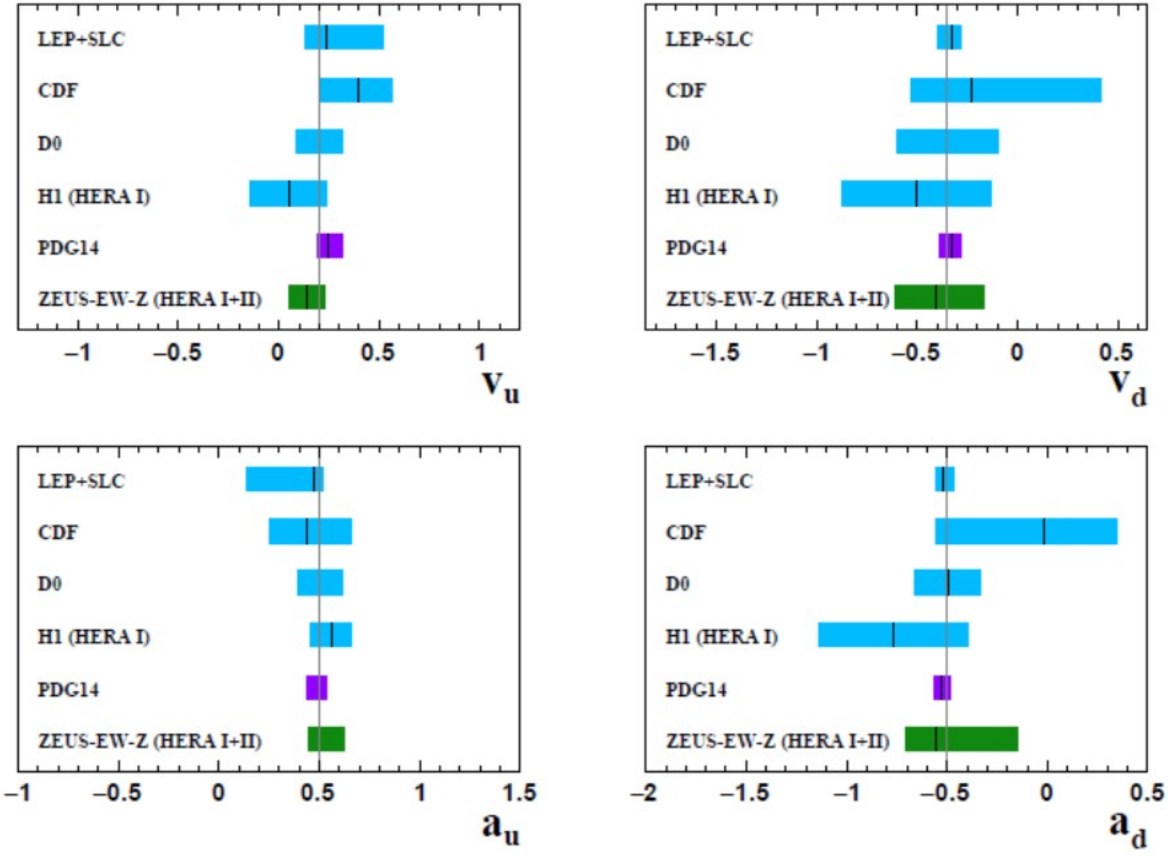
- Search for QCD instantons — Phys. Lett. B 759 (2016) 446
  -> excludes significant part of phase space predicted by Instanton model
- Improved limit on Pentaquark production cross section (pK^0_s) -> Previous hint disappeared — EPJ C76 (2016) 7
- Open charm production (D*) — H1prelim-16-011
  -> probes: DPDFs, NLO theory & factorisation properties in diffr. DIS

Not covered recent HERA results

- ZEUS Exclusive electroproduction of vector meson: Ratio of ψ(2s) over J/ψ(1s) — Nucl. Phys. B 909 (2016) 934
- H1 Exclusive photoproduction of ρ^0 meson with leading neutron — EPJ C76 (2016) 1

Backup

The ZEUS result is the best for a single measurement for a_u, v_u
It is not yet included in the PDG average and will have impact.



Stat. correlations of H1 low-Q^2 multijets