Heavy flavours and QCD studies at HERA

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Outline

(new results 2011)

- **HERA and two colliding experiments: ZEUS and H1;**
- **Jets and α_s;**
- **Heavy flavours;**
- **Precision measurements of the proton structure;**
- **Conclusion;**

- (selection of topics, not complete)

HERA

- German's largest research instrument, the only one in the world electron-proton collider(DESY, Hamburg);
- Although research operation was concluded on June 2007 → continue the evaluation of the recorded data (steady data analysis period until 2014): we consider our activity in the context of the question: **what HERA still has to offer?**
- We will correct our physics analysis programme accounting for the current constraints from the LHC (need to be mindful of the potential from 2012 data taking at the LHC → understand the changing landscape after first data run at the LHC and define the ZEUS discovery, and science reach using *ep* data) ;
- >2014: Given the uniqueness of the HERA data, analyses by present members of ZEUS, are expected to continue. Long term data preservation period and continue ZEUS physics analysis.

HERA between past and future of the *e-p* physics

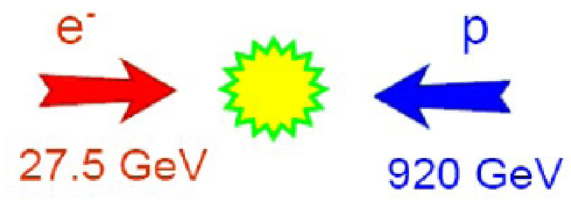
- Recorded a large amount of data; only fraction of statistics has been analyzed so far in many cases.
- Many of the insights gained with HERA belong to our fundamental knowledge of how the world is put together. For many years to come, the evaluation of the HERA data will continue to provide unique insights into the inner structure of the proton and the fundamental forces of nature."

Past (1950th – mid-1990th)	Era of HERA (mid-1990th - …)	Future (> 2020)
Elastic → Deep Inelastic Scattering (DIS)	Photoprod & DIS studies	EIC@JLAB eRHIC@BNL LHeC@CERN

No higher energy e-p collider than HERA! → other than "LHeC"

The HERA Collider

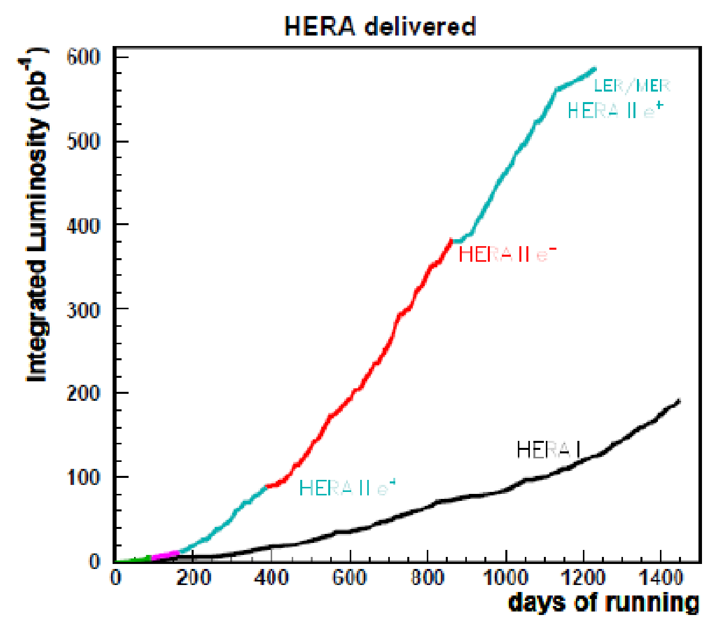
- World's only *ep collider*, located at DESY in Hamburg
- In operation from 1992-2007



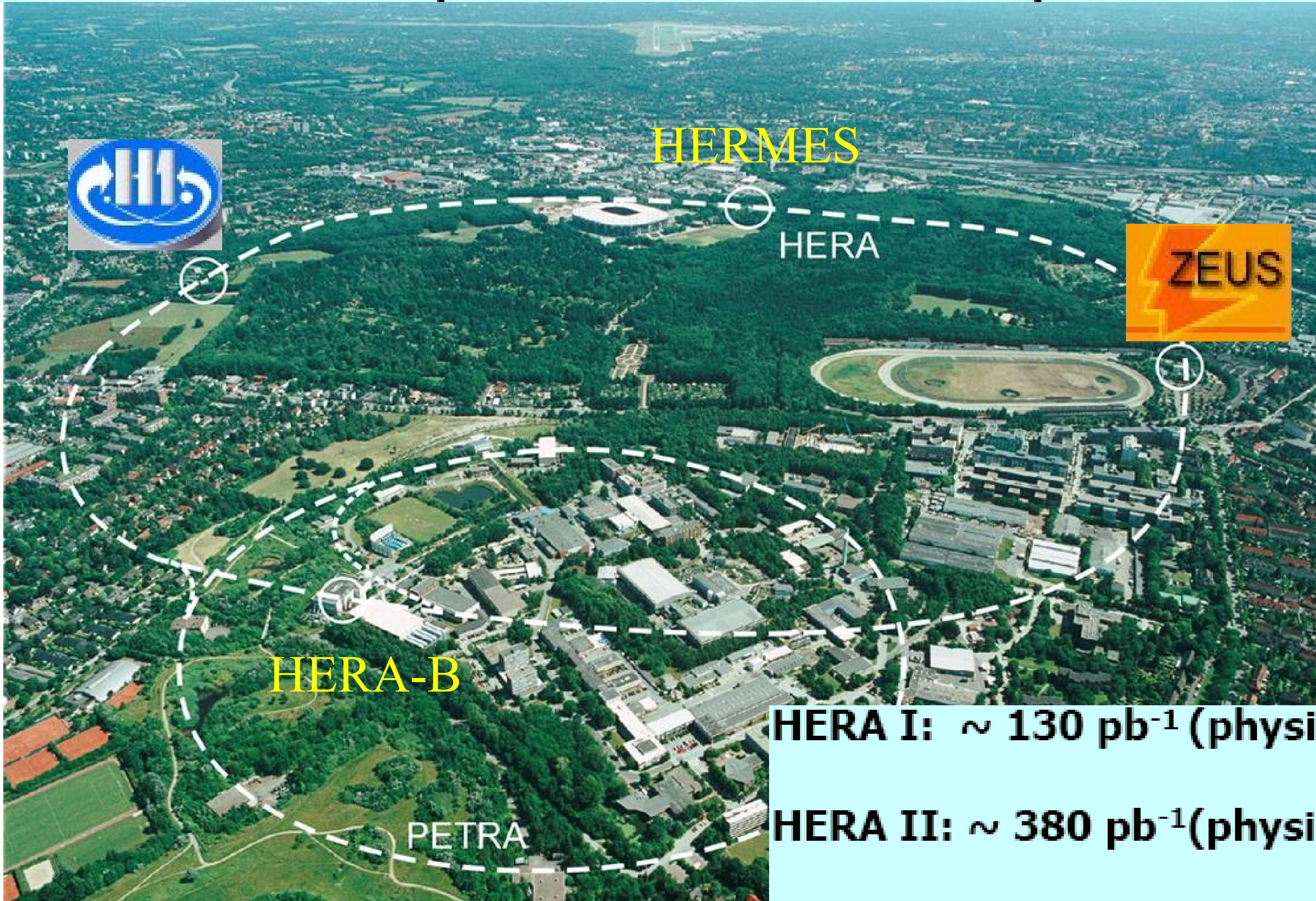
Center of mass energy:

$$\sqrt{s} = 318 \text{ GeV}$$

- Lepton beam longitudinally polarized in HERA-II running period (since 2002, P ≈ 30-40%)
- Two colliding experiments: H1 and ZEUS
- 0.5 fb^{-1} of data collected by each experiment



The HERA ep collider and experiments

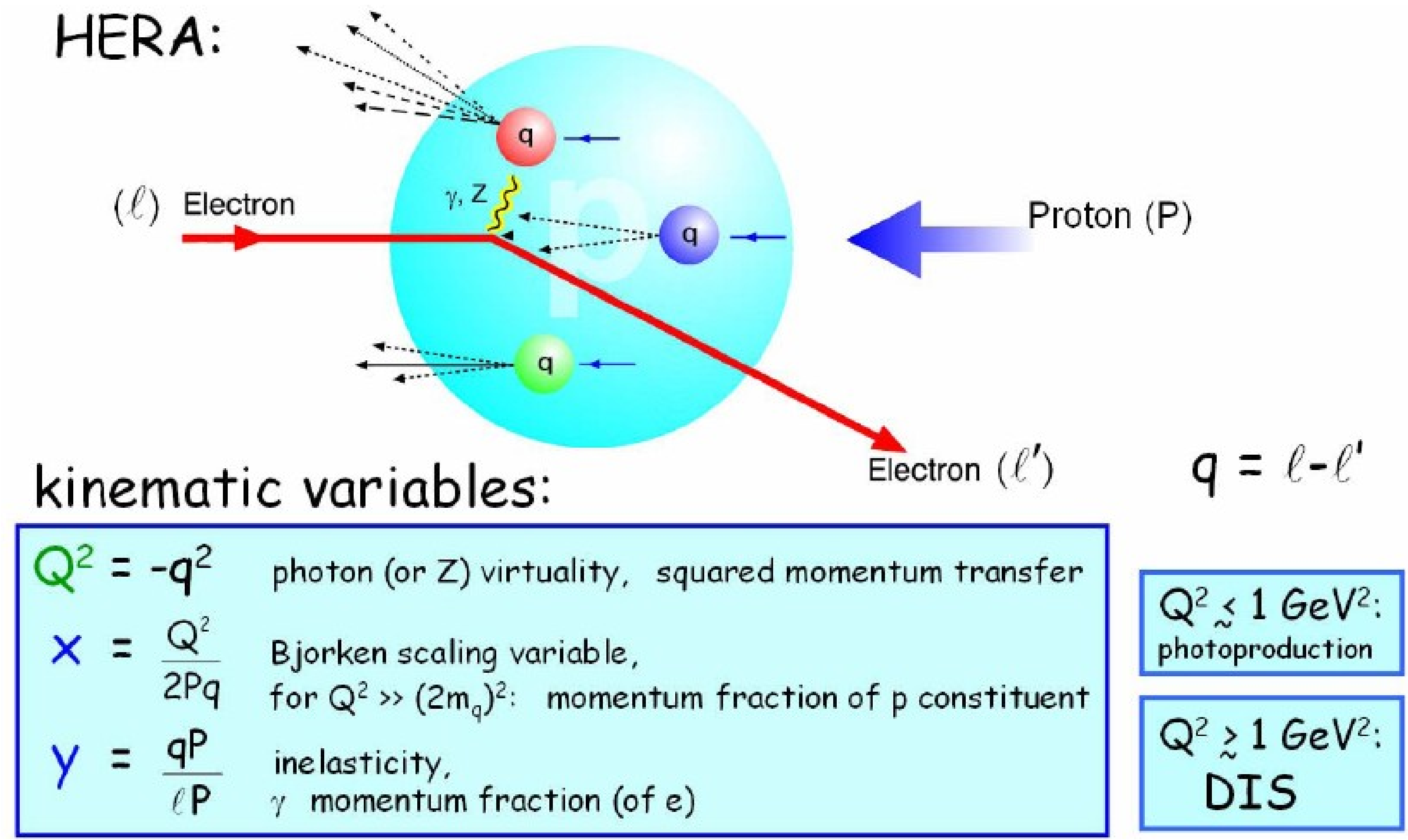


HERA I: ~ 130 pb^{-1} (physics)

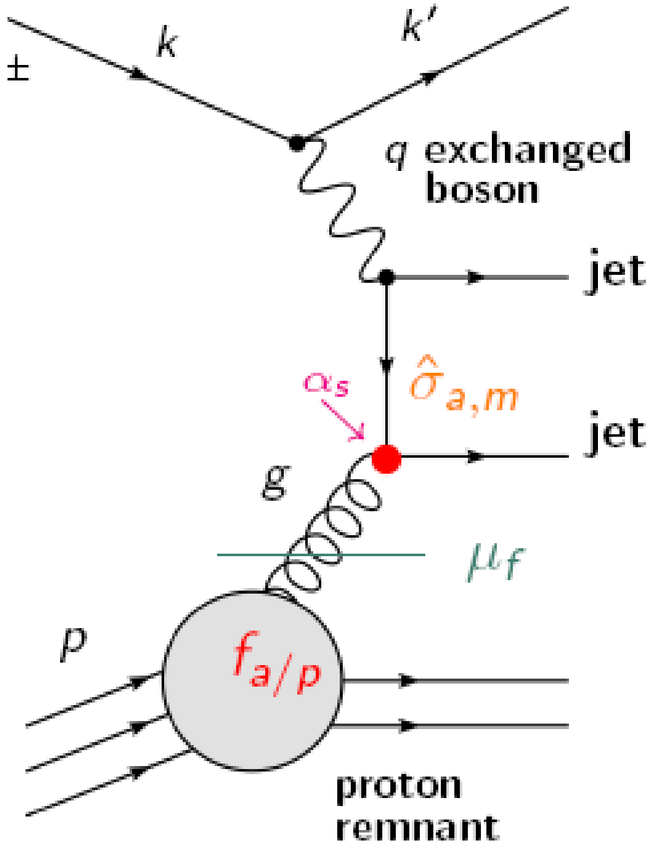
HERA II: ~ 380 pb^{-1}(physics)

combined: ~ 2 x 0.5 fb^{-1}

Deep inelastic scattering at HERA



Jet Production at HERA with ZEUS



Inclusive Jets in Photoproduction (PHP) and Deep-Inelastic Scattering (DIS). Extraction of the Strong Coupling α_s

As you will see:

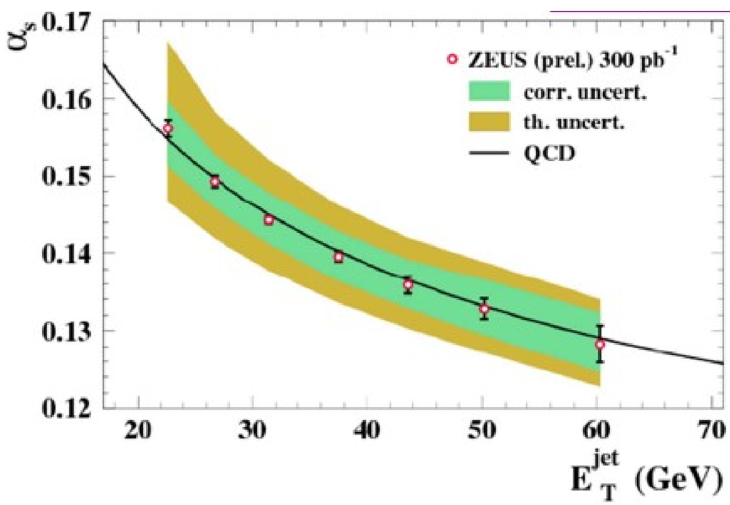
- → pQCD calculations describe the data over a wide range of phase space!
- → theoretical uncertainties are often larger than experimental uncertainties.
- → α_s extractions are competitive!

Inclusive Jet Production in PHP

photoproduction $(\gamma p) \rightarrow Q^2 \approx 0 \text{ GeV}^2$

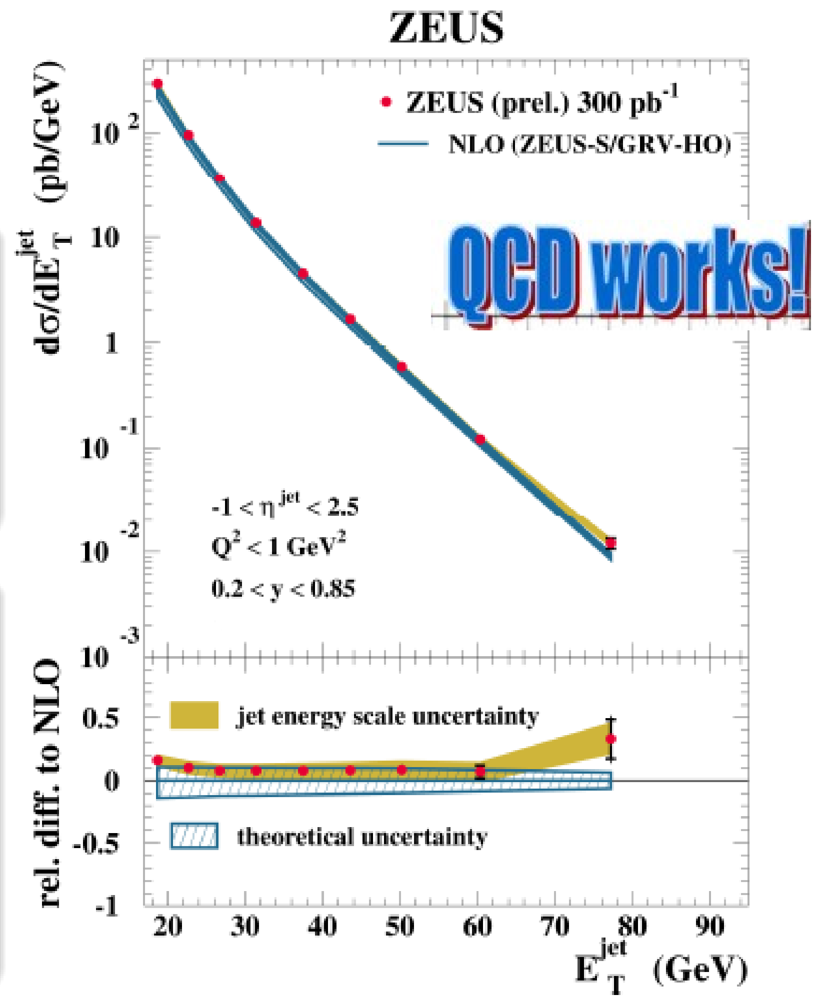
at least one jet with in the range
$-1 < \eta^{\text{jet}} < 2.5$ with $E_T^{\text{jet}} > 17$ GeV

⇒ **Good description of data by NLO calculations**



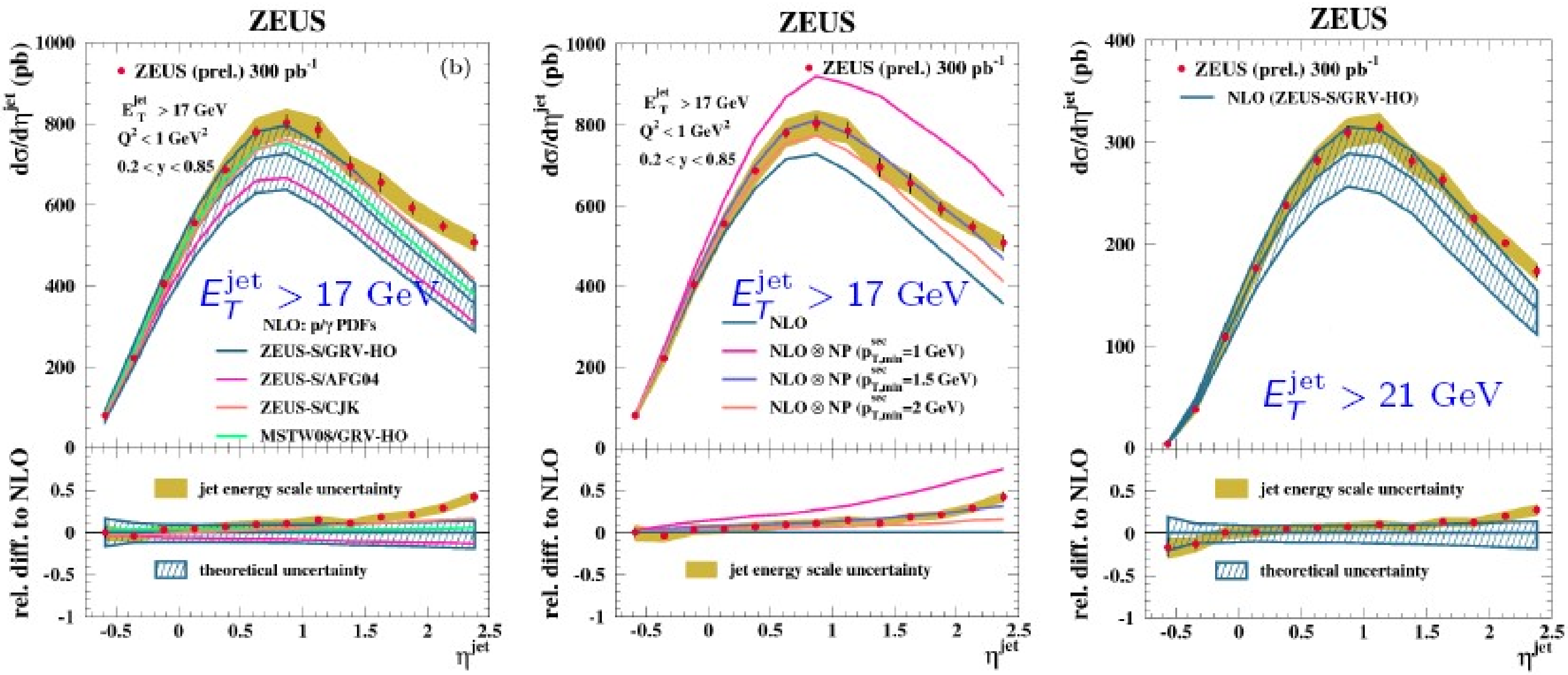
$\alpha_S(M_Z) = 0.1206 \ ^{+0.0023}_{-0.0022}(exp.) \ ^{+0.0042}_{-0.0033}(theo.)$

running of α_s consistent with QCD expectations



Measurement suited for $\alpha_s(M_Z)$ extraction with small uncertainties

Inclusive Jet Production in PHP



→ after increasing the E_T^{jet} cut the theory agrees with the data

non-perturbative effects or the γ PDFs at high η^{jet} could cause observed discrepancy between data and the theory

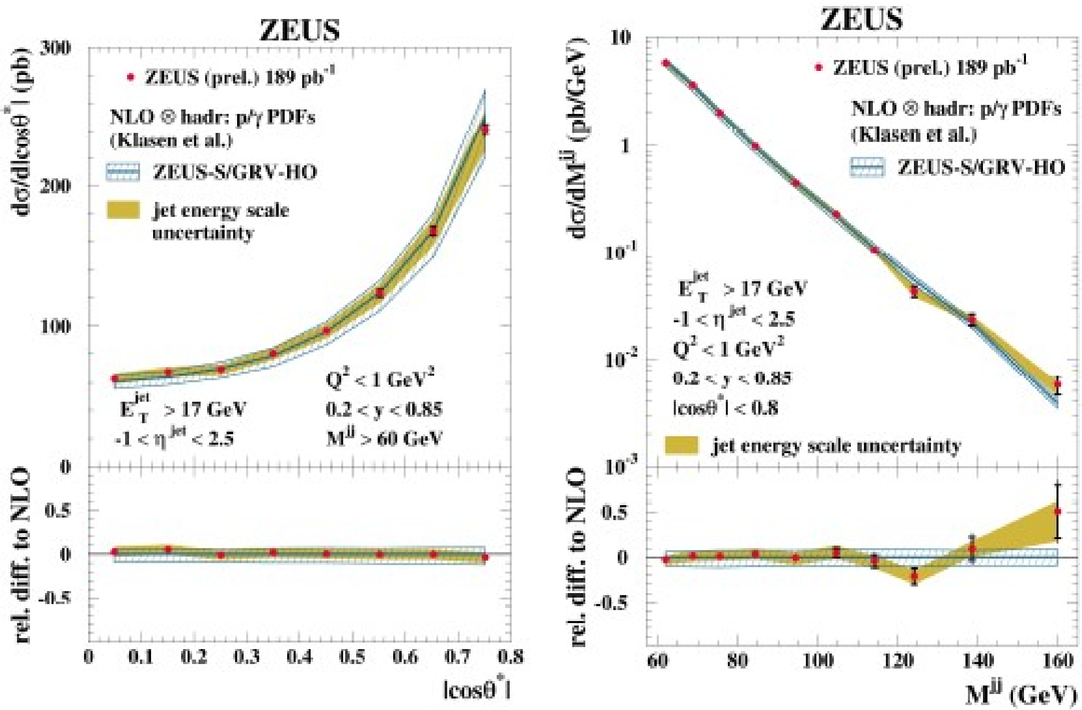
Dijet Production in PHP

CMS Scattering Angle:

- $\theta^* \to \cos\theta^* = \tanh\frac{\eta_1 - \eta_2}{2}$

QCD Dynamics:

- study underlying dynamics by measuring differentially in M^{jj} and θ^*



→ **good description of data by NLO predictions at $O\left(\alpha_s^2\right)$**

→ **concept of resolved photons holds**

Inclusive Jets at High Q^2

- at least one jet with $E^{\text{jet}}_{T,B} > 8$ GeV and $-2 < \eta_B < 1.5$

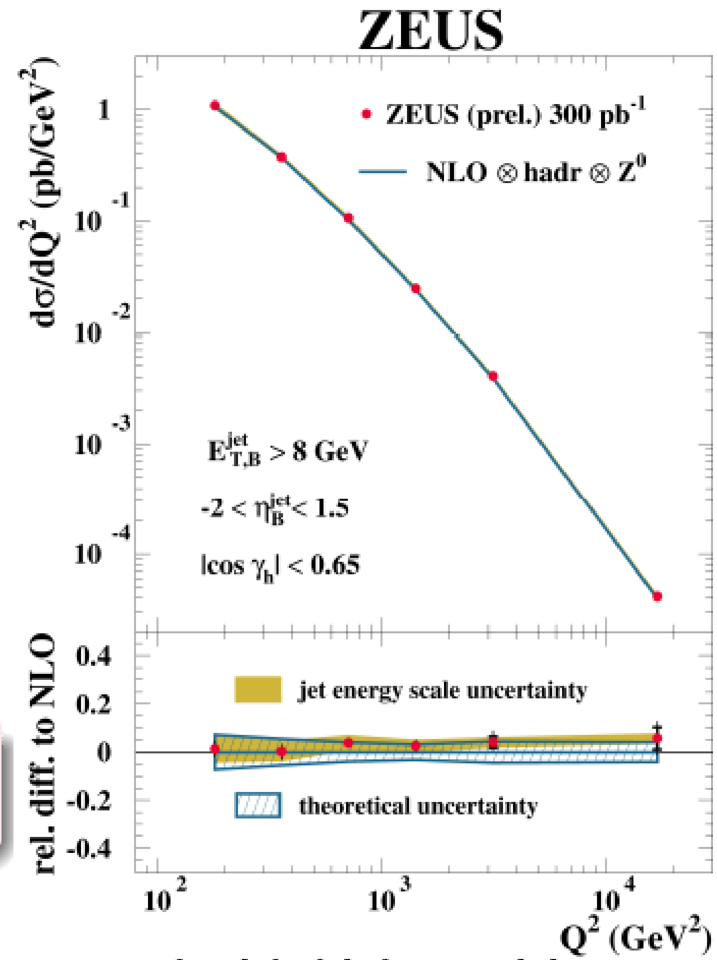
Experimental Uncertainties:

- uncorrelated: $\pm 3\,(7)\,\%$ at low (high) Q^2
- correlated: $\approx 5\,(2)\,\%$ at low (high) Q^2

Theory Uncertainties:

- dominated by choice of μ_R ($\approx \pm 5\%$) and PDF (typically $< 3\%$)

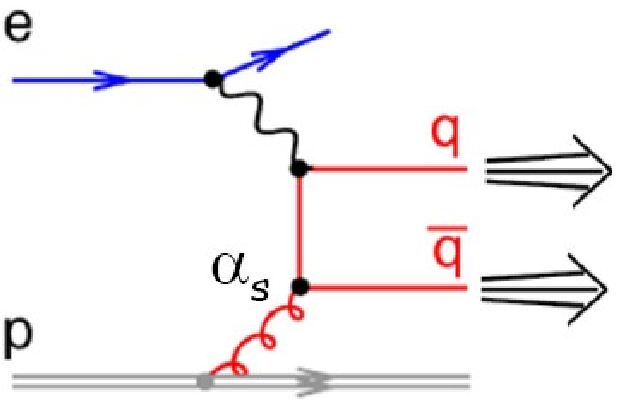
- **NLO pQCD describes the data very well in the whole measured range**

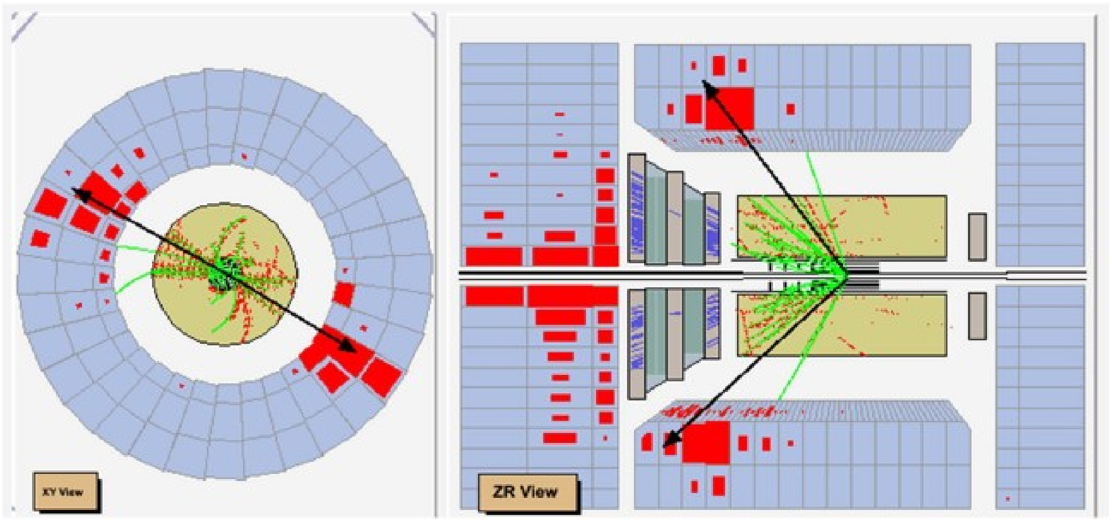


→ **Due to small uncertainties α_s can be extracted with high precision**

Jets and α_s

Quantum Chromodynamics (QCD)





Extraction of $\alpha_s(M_Z)$

Inclusive Jets in ...	**NC DIS**	**PHP**
phase space:	$Q^2 > 500$ GeV yields smaller α_s uncertainty	$21 < E_T^{jet} < 71$ GeV
theoretical uncertainty dominated by terms beyond NLO:	$\pm 1.5\%$	$\pm 2.5\%$
experimental uncertainty ruled by jet energy scale:	$\pm 1.9\%$	$\pm 1.8\%$

NC DIS:

$\alpha_s(M_Z) = 0.1208^{+0.0037}_{-0.0032}(\text{exp.}) \pm 0.0022(\text{th.})$

→ **total uncertainty:** $\pm 3.5\%$

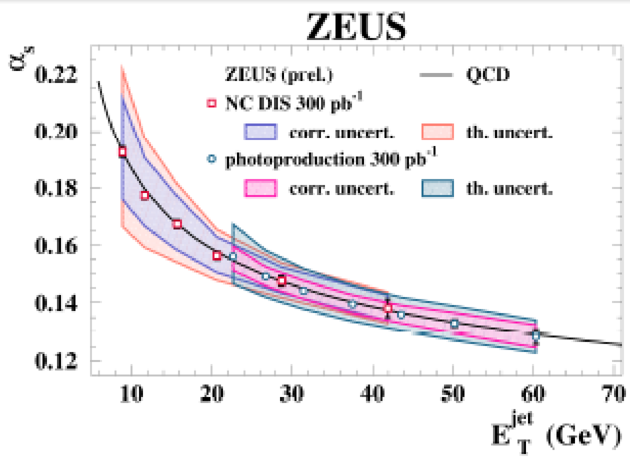
PHP:

$\alpha_s(M_Z) = 0.1206^{+0.0023}_{-0.0022}(\text{exp.})^{+0.0042}_{-0.0033}(\text{th.})$

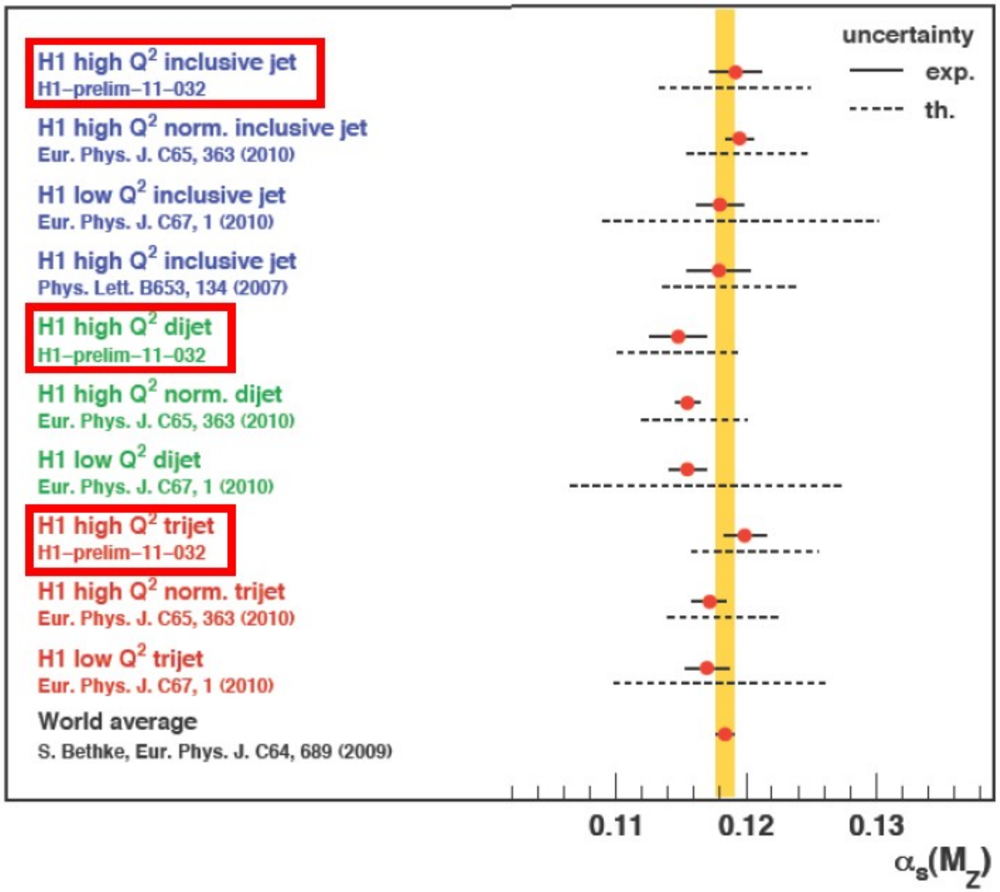
→ **total uncertainty:** $\pm 4.0\%$

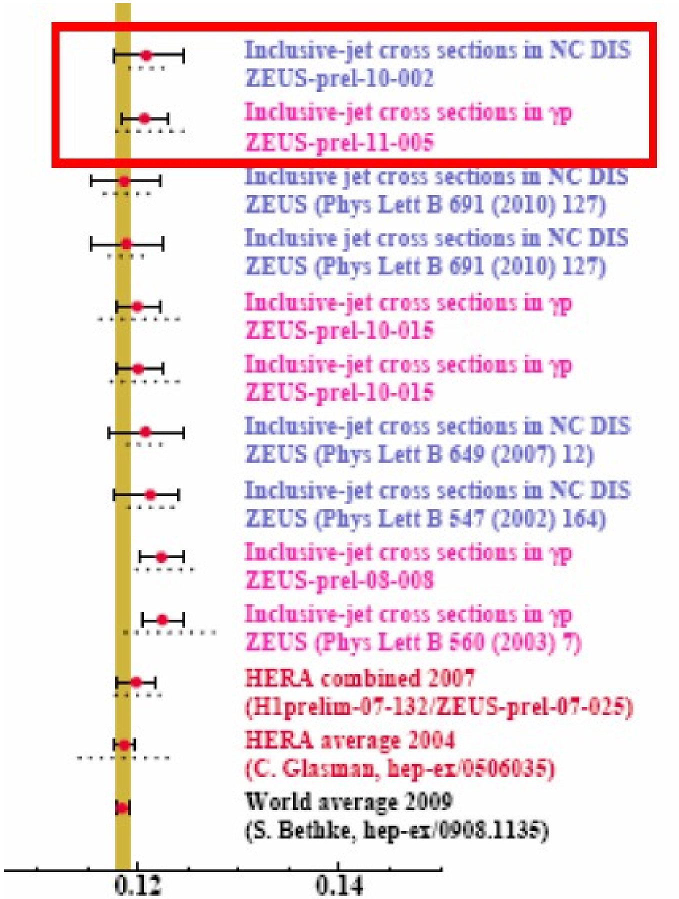
- world average (2009): $\alpha_s(M_Z) = 0.1184 \pm 0.0007$

- **predicted running of α_s agrees very well with the data**

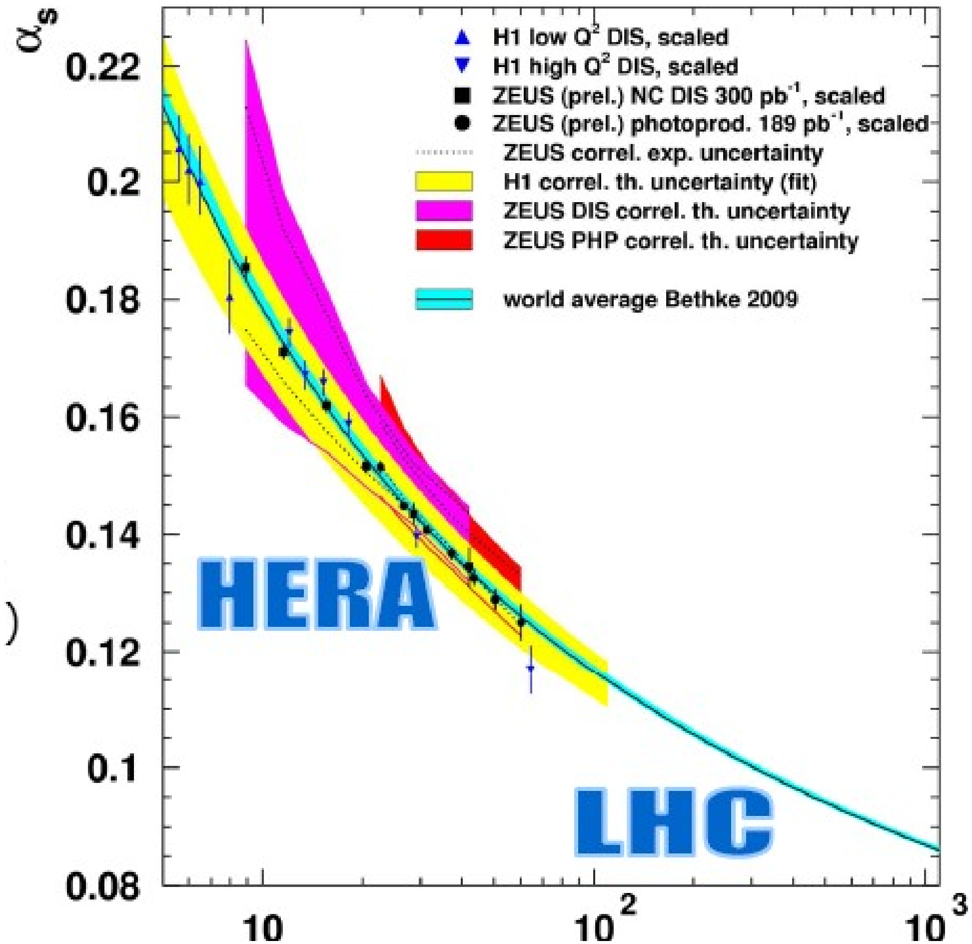


Summary of ZEUS and H1 α_s measurements





α_s from the HERAscale to the Terascale



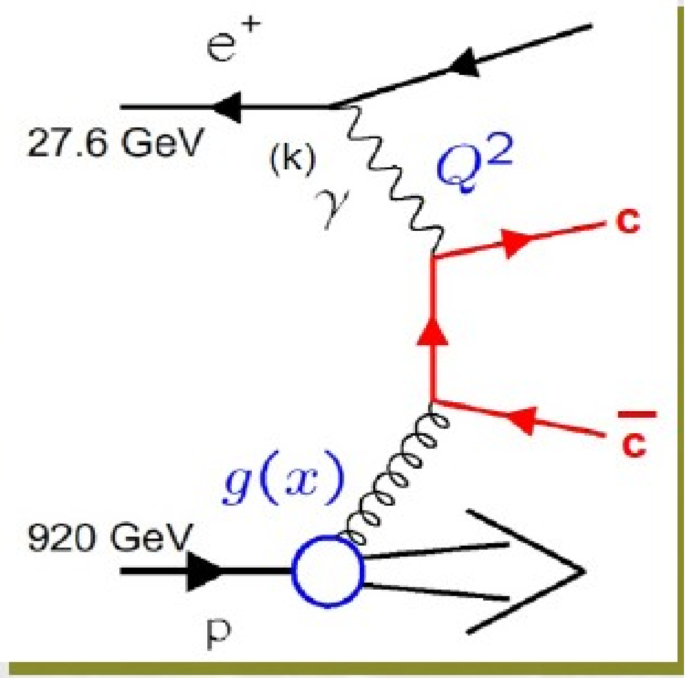
Charm Quark Production in DIS at ZEUS

Boson-gluon fusion is a dominant process for the charm creation in DIS, charm contribution to the inclusive DIS cross section is up to 30% (sizable part of cross section)

Multiple hard scale give us a possibility to test pQCD p_T, Q^2, m_c

Charm production is sensitive to the gluon density of the proton

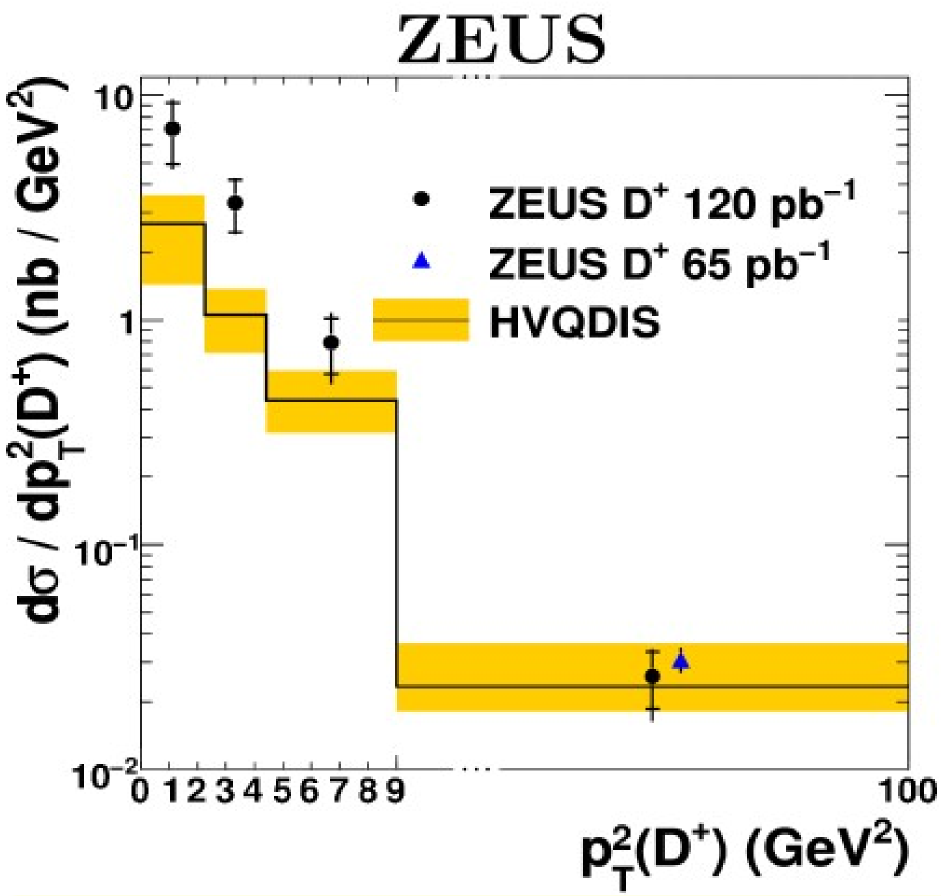
Measurements of the charm structure function are the subject of interest because:



- Better understanding of the charm is one of the key issues for higher energies experiments (e. g. pp collisions)

D+ production at a low p_T threshold

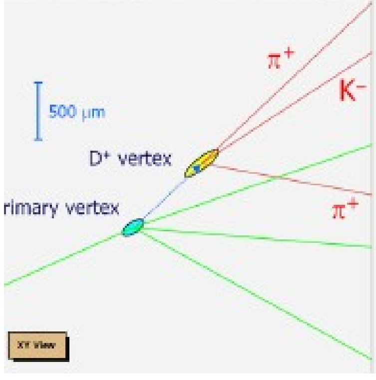
$D^+ \rightarrow K^0_s \pi^+ \rightarrow \pi^- \pi^+ \pi^+$

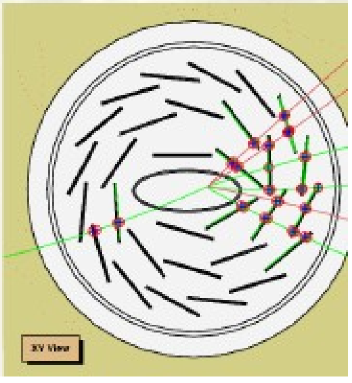


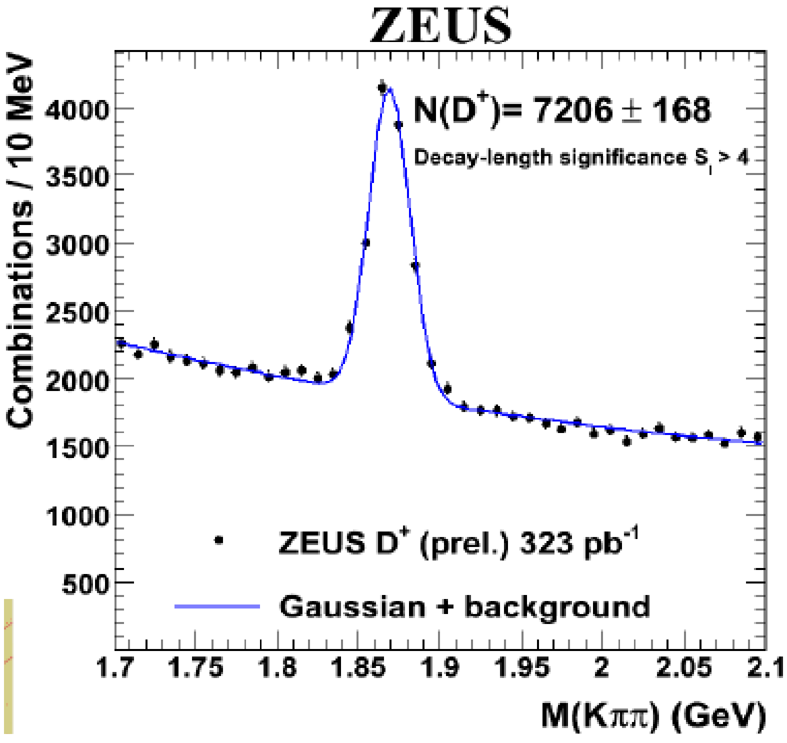
- Measurements are in agreement with previous **high p_T D^+** measurements
- Measurements are in agreement with NLO QCD predictions in a range of 2 sigma
- It is the first measurement at HERA in a **low p_T** kinematic region

$D^+ \to K^- \pi^+ \pi^-$ measurement

- Life time information were used to extract signal with a help of MVD detector HERAII. $S_l = L_{xy} / \sigma_{xy}$
- Significant improvement in signal to background ratio
- Smaller stat. Errors due to the HERAII statics





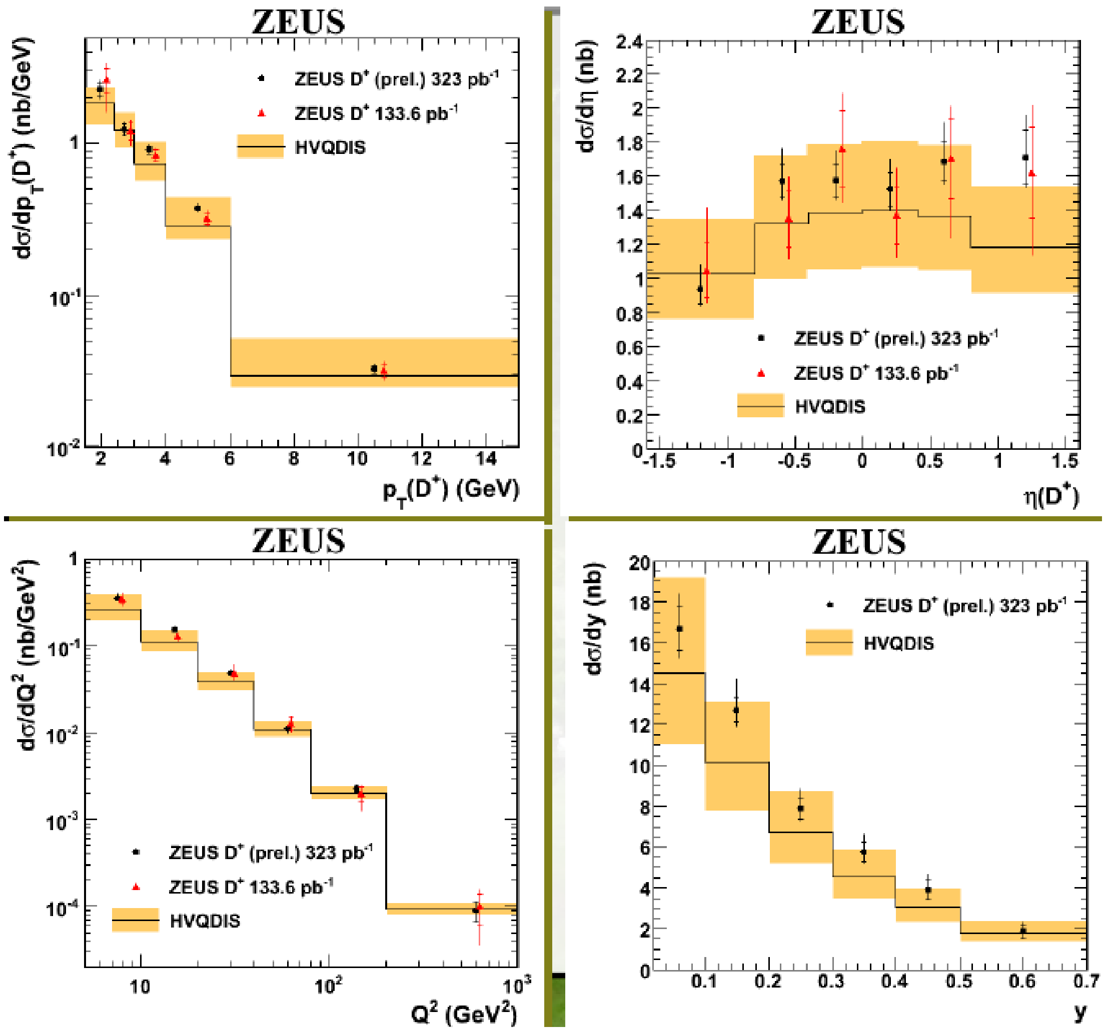


$5 < Q^2 < 1000$ GeV^2

$0.02 < y < 0.07$

$|\eta(D+)| < 1.6$, $1.5 < p_T(D+) < 15$ GeV

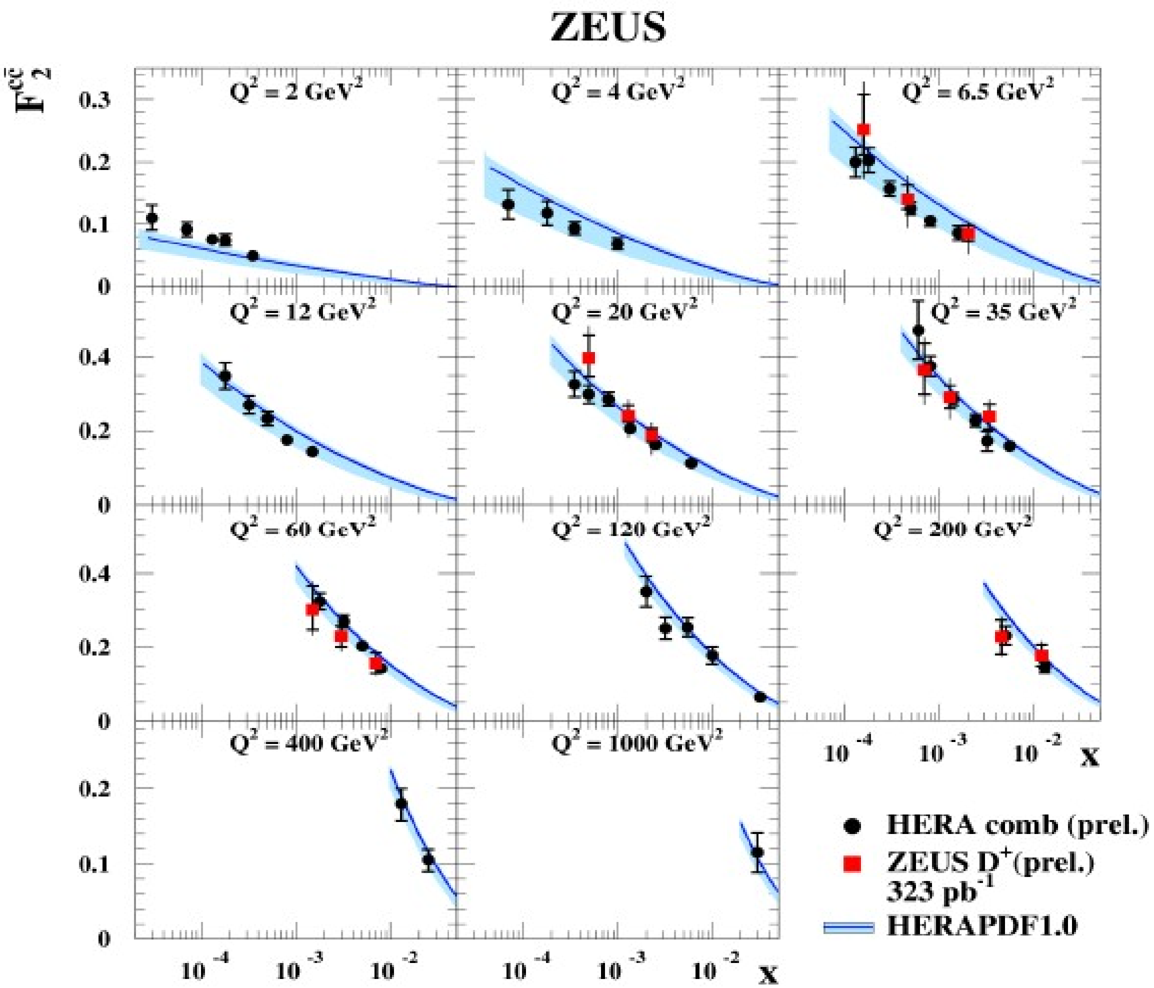
Diff. cross sections



Improved statistical precision w.r.t. published results

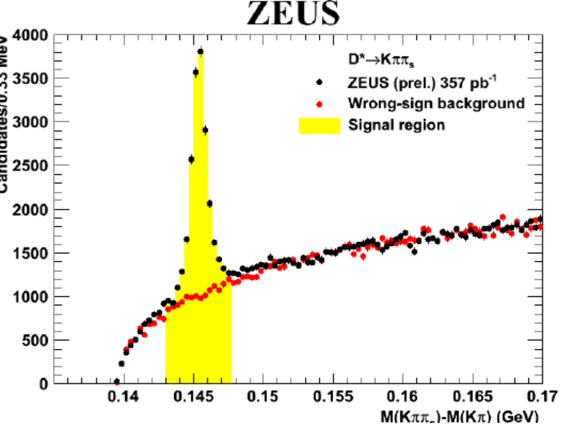
NLO QCD predictions describe the measured cross sections

F_2^{cc} measurement from D+ → K- π+ π-

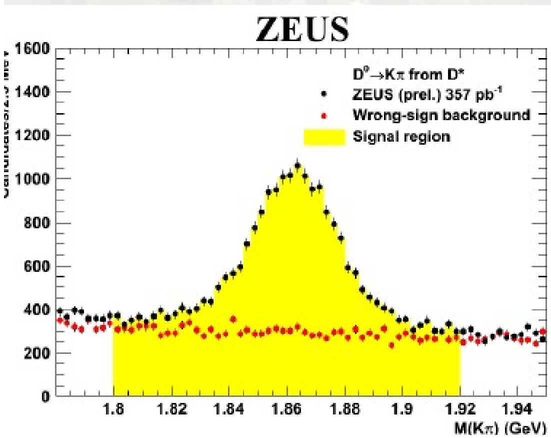


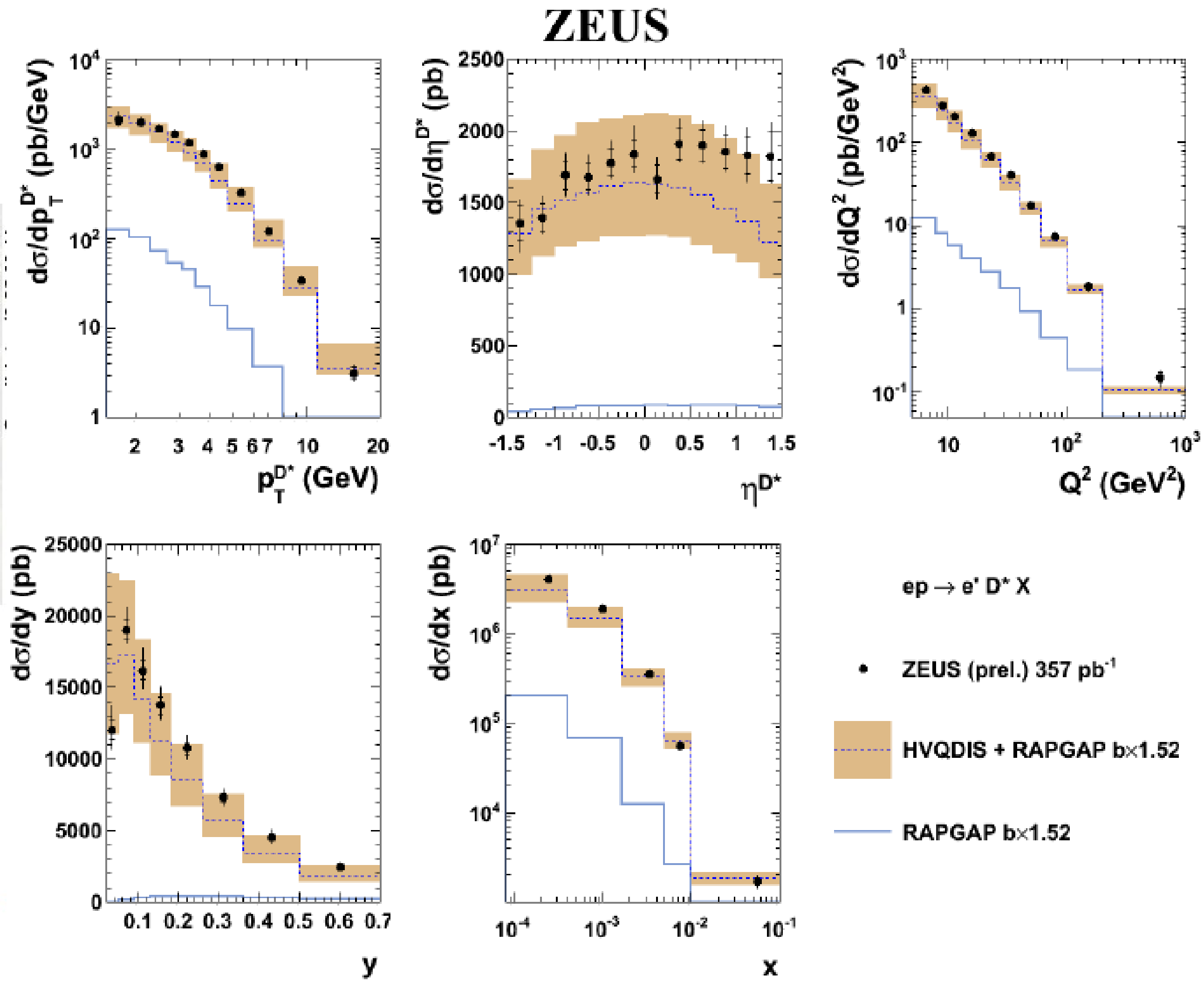
Measurements agree with the combined HERA results

D* → $D^0\pi_s$ measurement

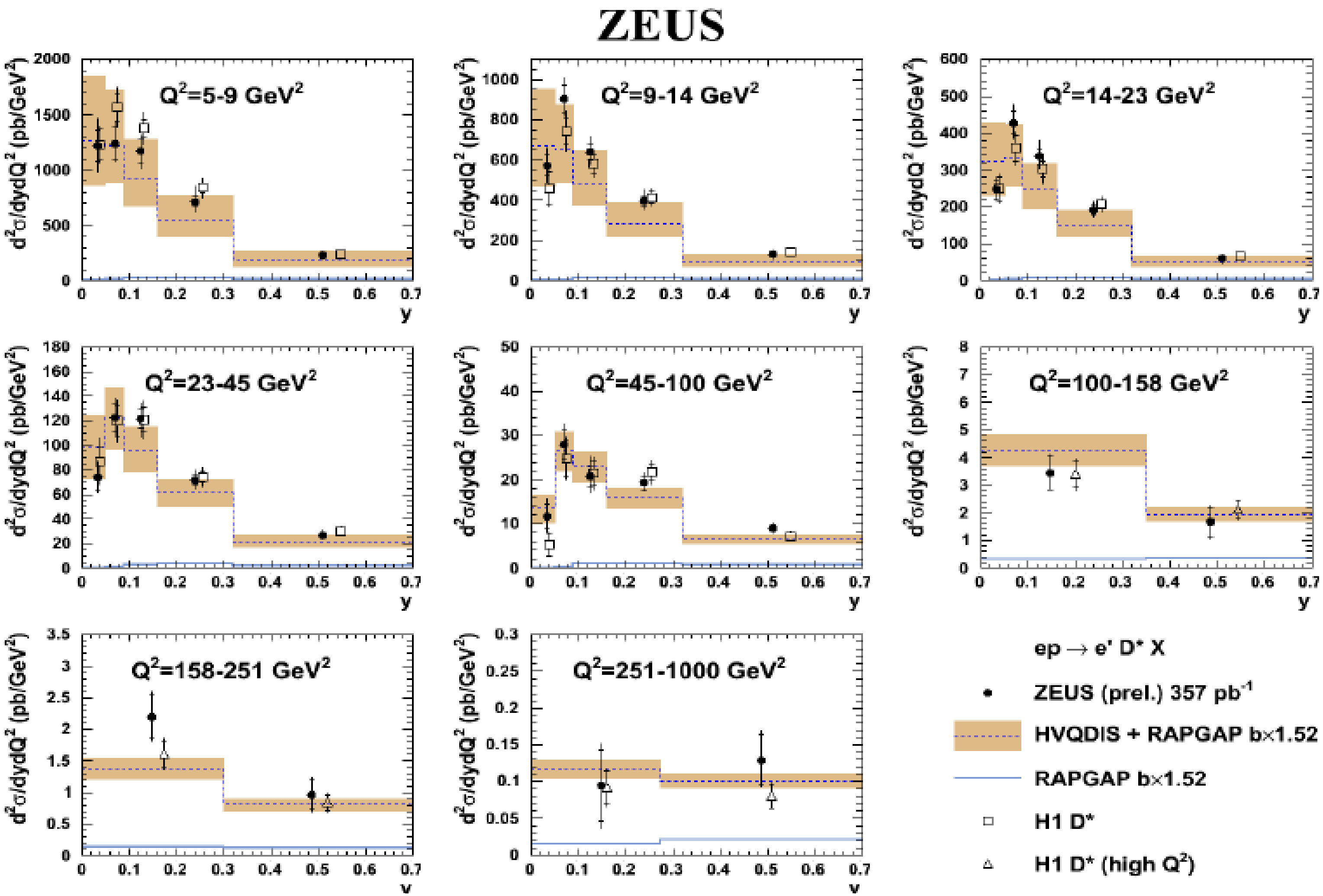


- HERAII 357 pb^{-1}
- p_T>1.5 GeV, |η|<1.5
- 5<Q^2<1000 GeV^2
  0.02<y<0.7
- D* from B meson origin are included in the cross sections





D* double differential cross sections



On a way to extract F_2^{cc} with D*s

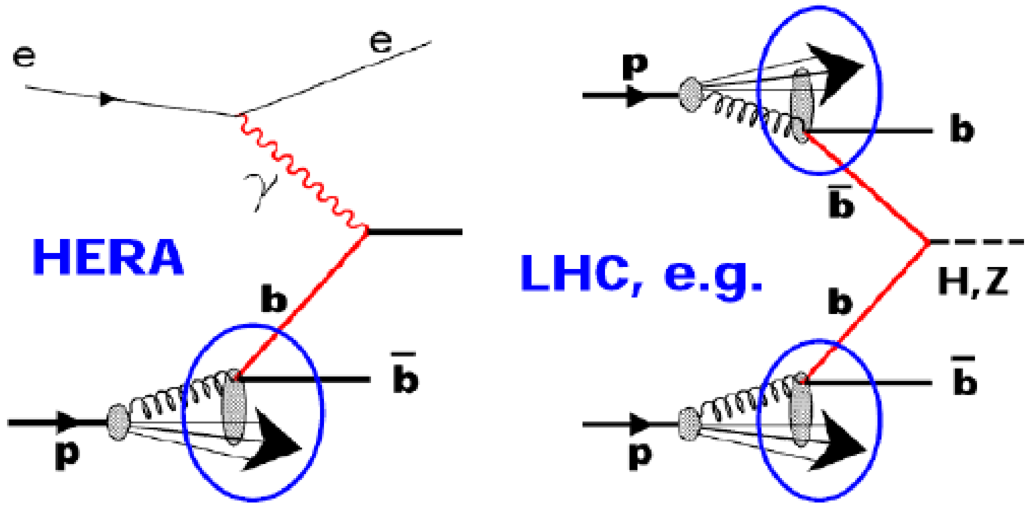
ZEUS measurements are in agreement with H1 results

Beauty jet production in ZEUS

Beauty quark contribution to the structure function F_2 at low Q^2:

$$\frac{d\sigma^{b\bar{b}}(e^{\pm}p)}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}[1+(1-y)^2](F_2^{b\bar{b}}(Q^2,x) - \frac{y^2}{1+(1-y)^2}F_L^{b\bar{b}}(Q^2,x))$$

At high Q^2- check of the b PDF for LHC:

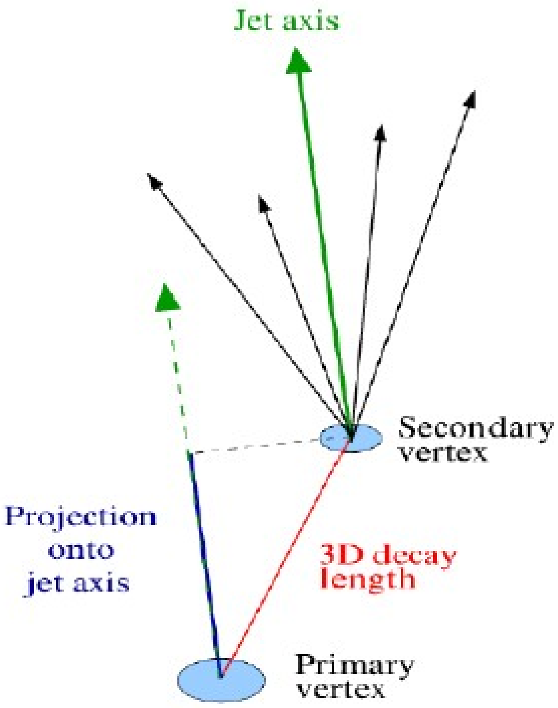


Vertexing in ZEUS

During HERAII ZEUS was equipped with the silicon-strip Micro Vertex detector (MVD):
this enabled reconstruction of secondary vertices from charm and beauty decays.

Analysis strategy:

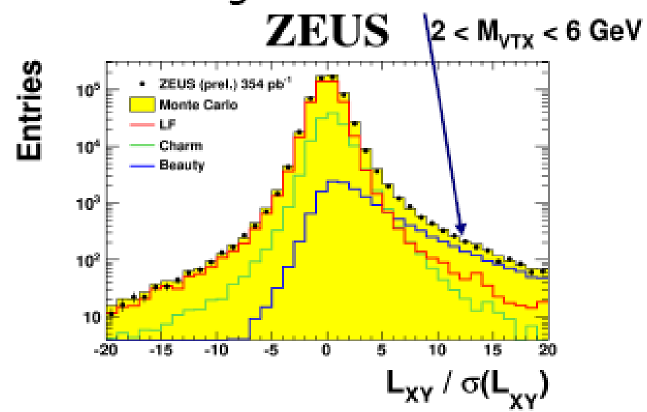
- Associate tracks with $p_T > 500$ MeV to a jet using $\Delta R = 1$.
- Fit these tracks to a secondary vertex in 3D.
- Calculate 2D decay length projected on the jet axis, L_{XY}.
- Use significance of the 2D projected decay length ($S=L_{XY}/\sigma(L_{XY})$) to differentiate between flavour components.

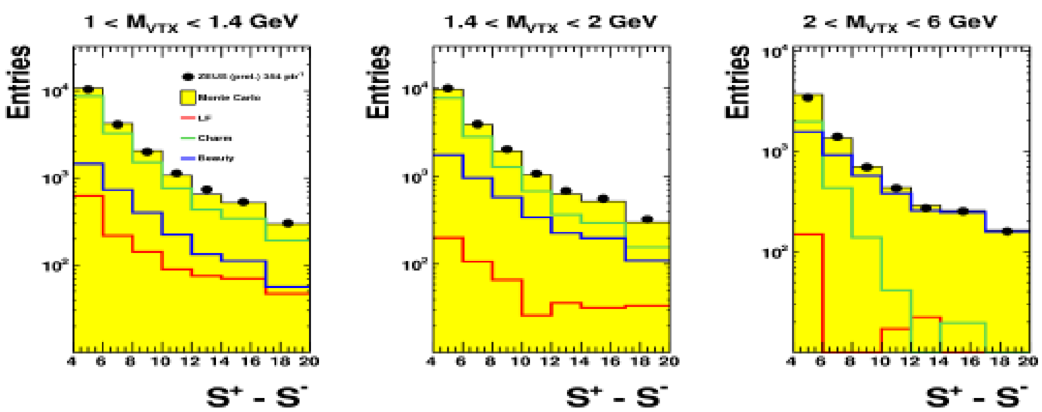


Secondary vertices in DIS: method

- The beauty fraction is extracted from a fit to the mirrored (to get rid of the symmetric part) significance in bins of the secondary vertex mass using templates from MC.
- Total light flavour normalization is constrained by the unmirrored distributions.

Beauty is dominant at high values of significance.

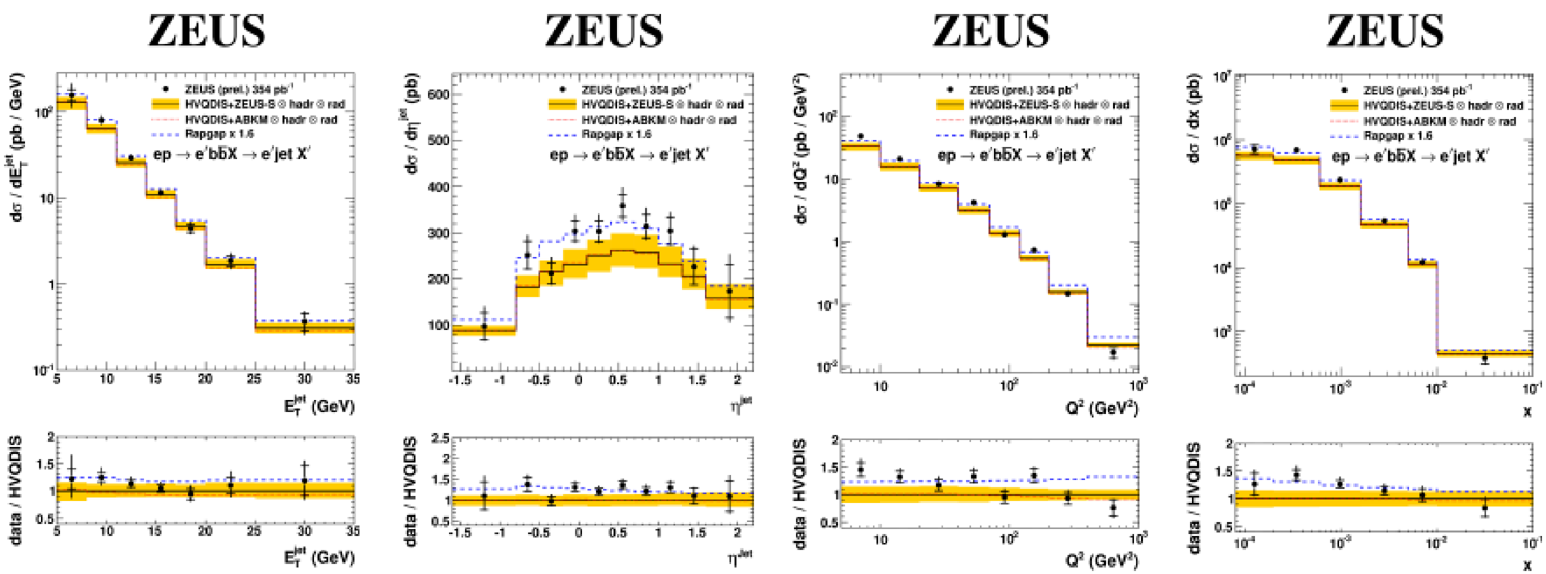




charm enriched

beauty enriched

Secondary vertices in DIS: cross sections



$5 < Q^2 < 1000$ GeV^2

$0.02 < y < 0.7$

$E_T^{jet} > 5$ GeV

$-2.0 < \eta^{jet} < 2.2$

$\mathcal{L}$ = 354 pb^{-1}

(2004-2007)

- The cross section shapes in data are well described by both ZEUS-S and ABKM09 NLO QCD predictions.
- The data are typically 20-30% above the central NLO predictions, but agree within the uncertainties.

Beauty from jet+μ: vs. Q^2

Kinematic region:

$Q^2 > 2\ GeV^2$

$0.05 < y < 0.7$

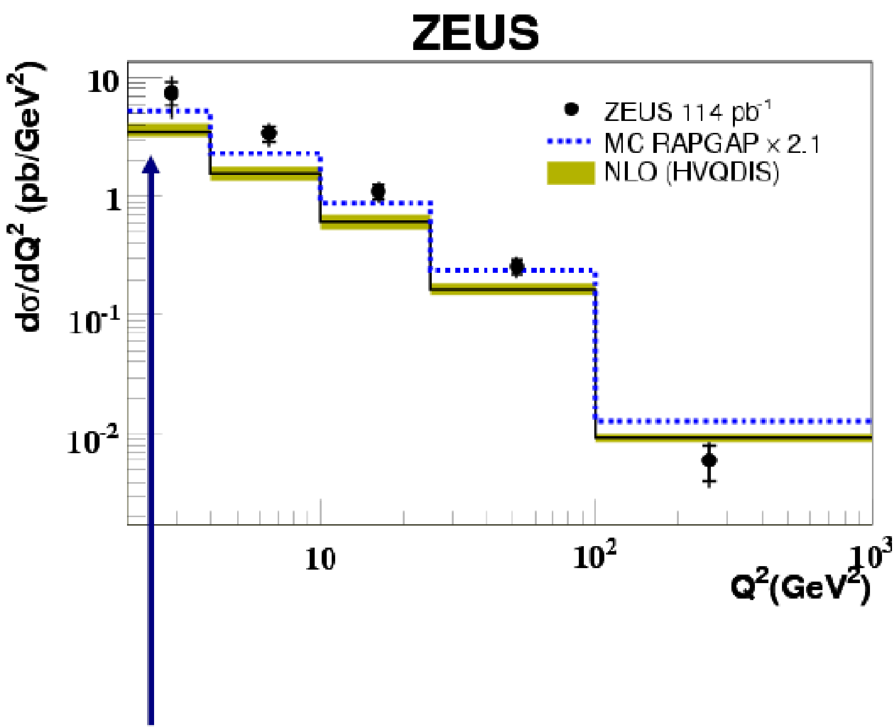
$E_T^{jet} > 5\ GeV$

$-2.0 < \eta^{jet} < 2.5$

$p_T^{\mu} > 1.5\ GeV$

$-1.6 < \eta^{\mu} < 2.5$

$\mathcal{L} = 114\ pb^{-1}$
(1996-2000)



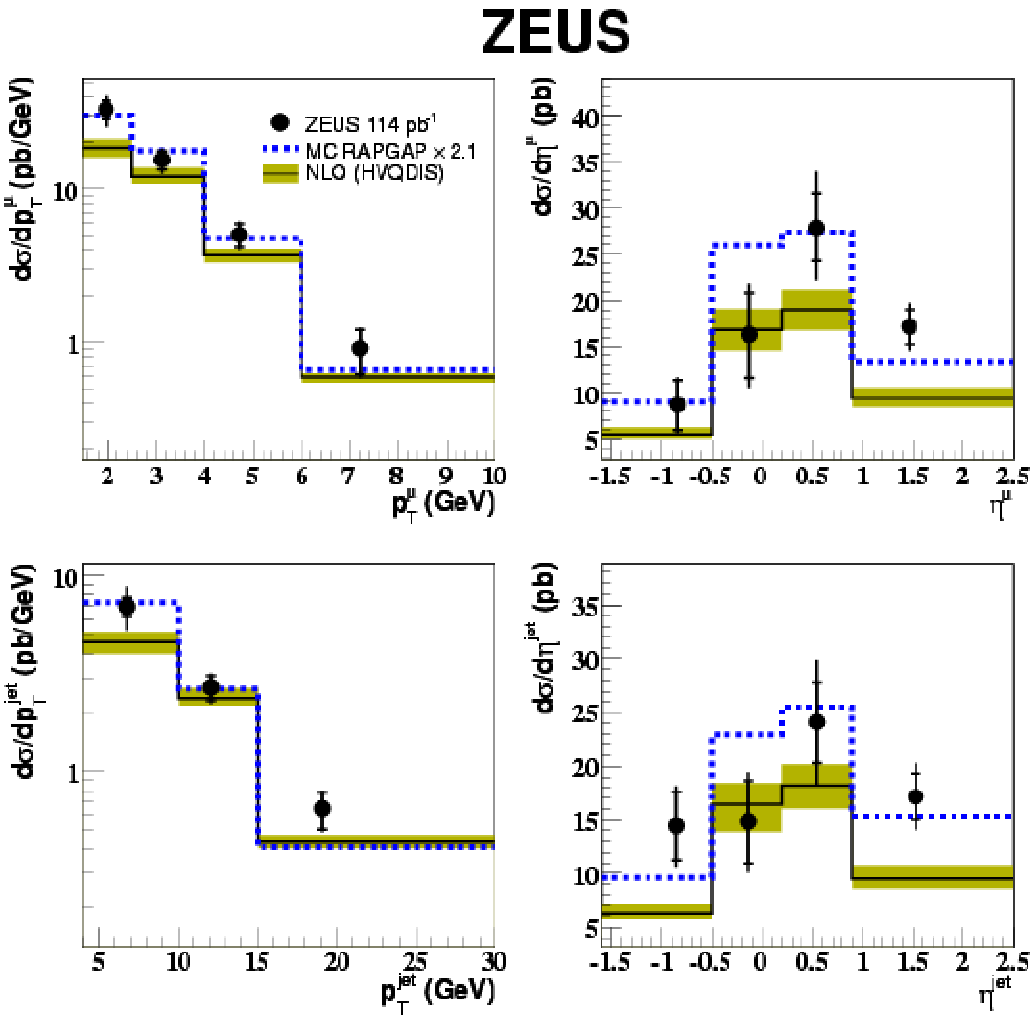
Low-Q^2 region is accessible in HERAI only.

The NLO QCD predictions by HVQDIS (FFNS) tend to lie below data at low Q^2.

Beauty from jet+μ: vs. p_T and η

Both LO+parton shower Monte Carlo and NLO QCD predictions describe the data in shape

Also double-differential cross sections in Q^2 and x were measured and F_2^b was extracted (see later).

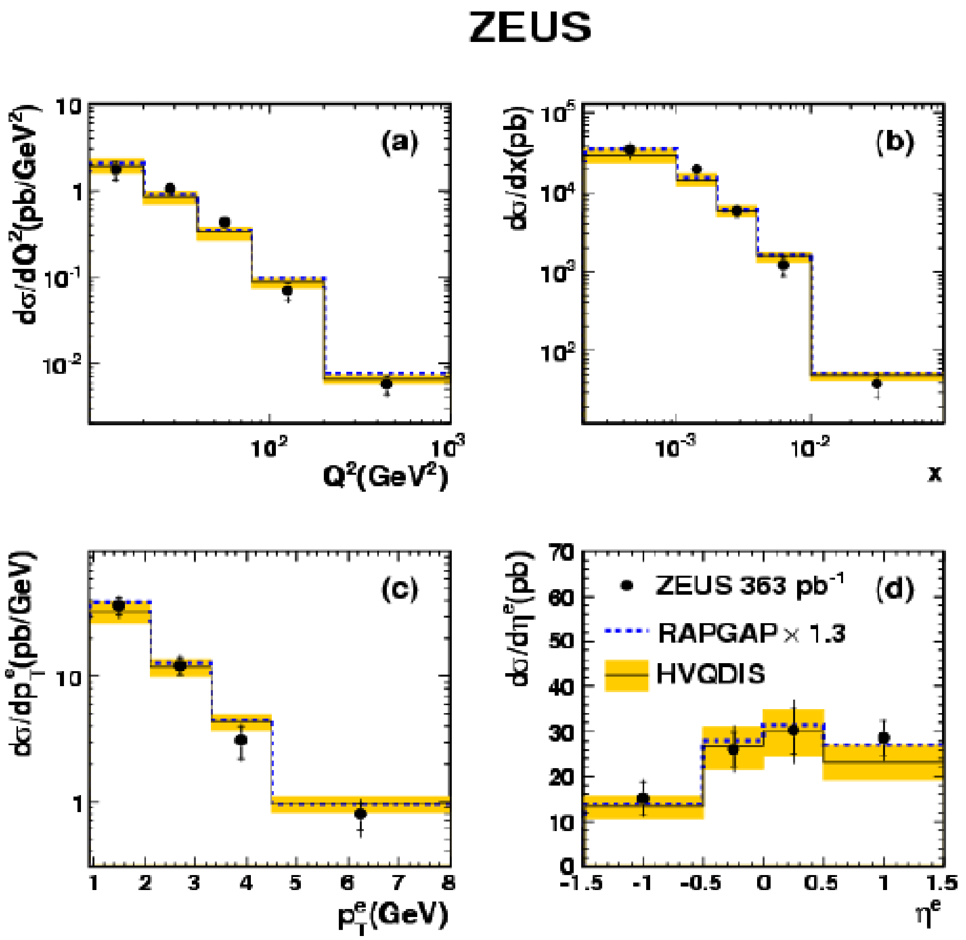


Beauty from dijets+e

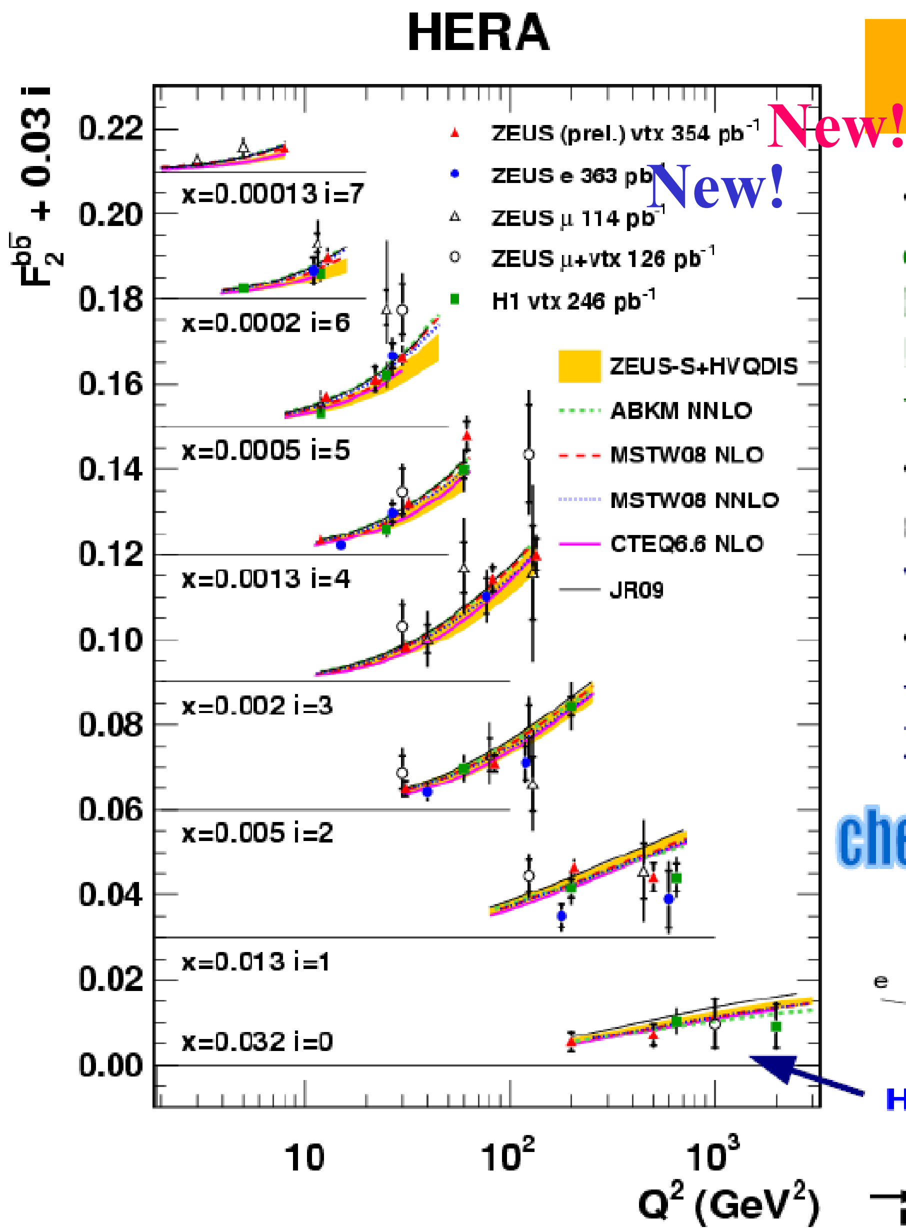
Kinematic region:
$Q^2 > 10$ GeV^2
$0.05 < y < 0.7$
$0.9 < p_T^e < 8$ GeV
$-1.5 < \eta^e < 1.5$

$\mathcal{L} = 363$ pb^{-1}
(1996-2000)

- NLO QCD predictions describe the data.
- Also double-differential cross sections have been measured and F2b has been extracted (see later)

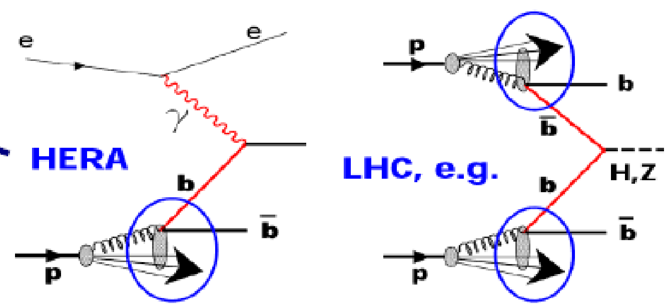


F_2^b



- All measurements are in good agreement with each other. The NLO and NNLO QCD predictions based on various PDFs describe the data well.
- Jet+μ analysis provides measurement at the lowest Q^2 values.
- Secondary vertex analysis is the most precise measurement in ZEUS.

check „b in proton“ for LHC: Z, Higgs

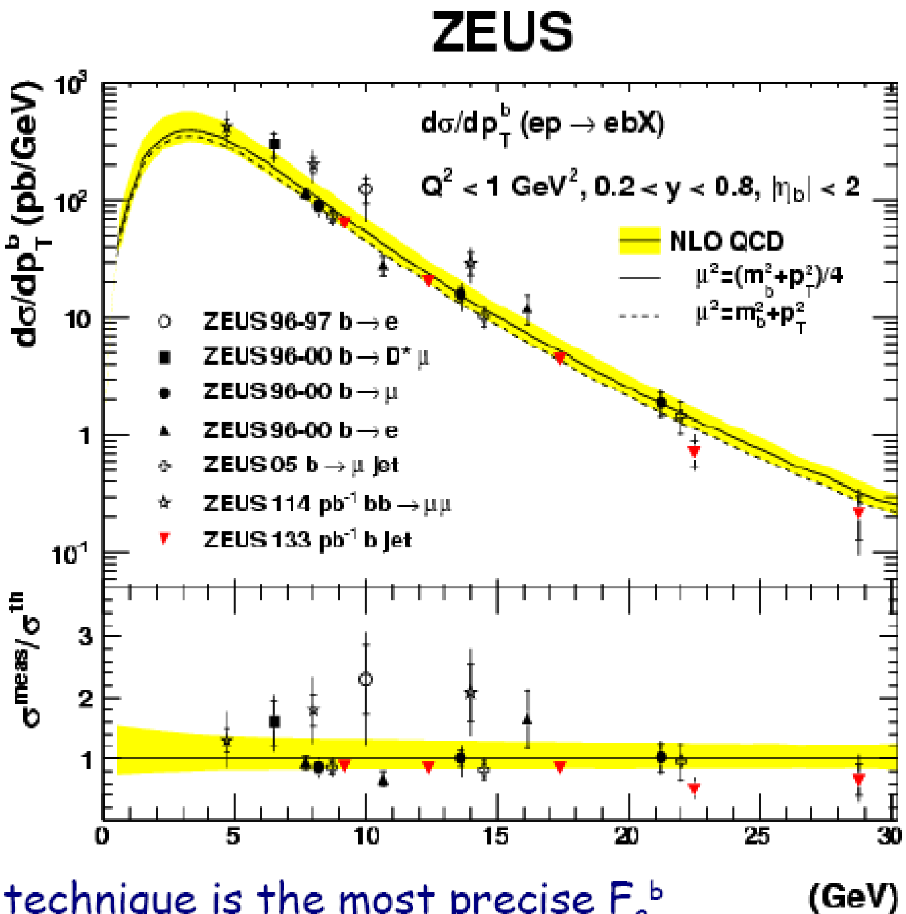


Secondary vertices in PHP

Kinematic region:
$Q^2 < 1$ GeV^2
$0.2 < y < 0.8$
$p_T^{jet\ 1(2)} > 7(6)$ GeV
$-2.5 < \eta^{jet} < 2.5$

$\mathcal{L}$ = 133 pb^{-1}
(2005)

- Both charm and beauty fractions were extracted simultaneously.
- Single differential cross sections as well as p_T^b and p_T^c spectra were measured.

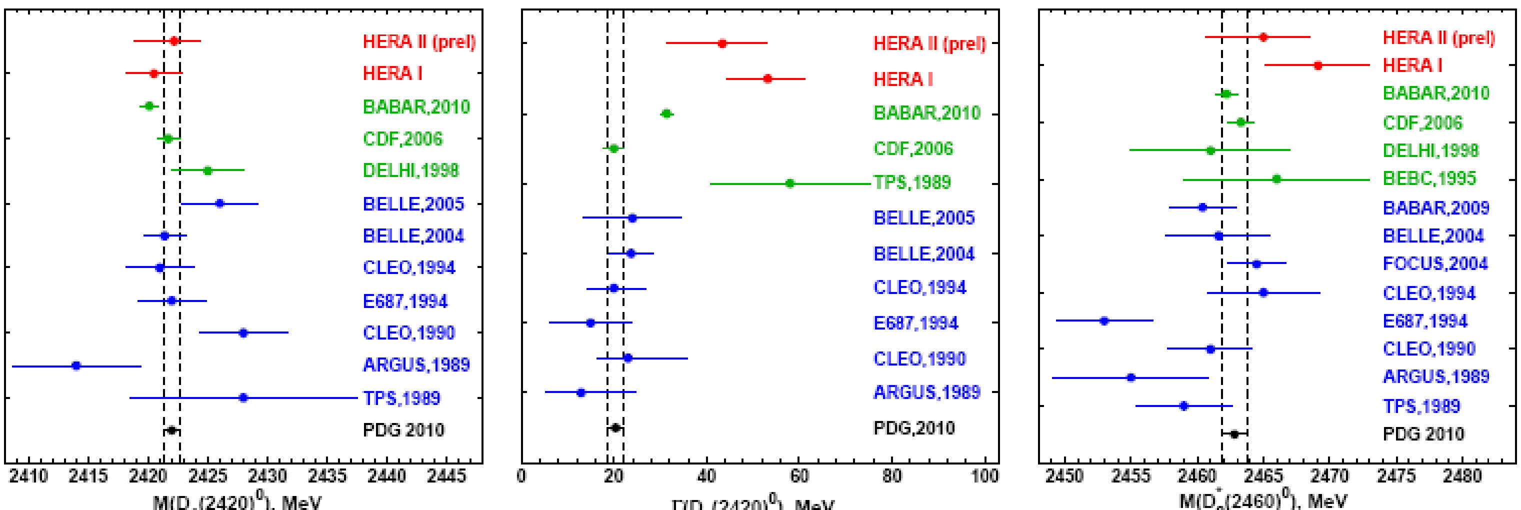


- The secondary vertex technique is the most precise F_2^b measurement from ZEUS
- Combination with other measurements, would further improve precision.

Production of the excited charm mesons D_1^0 and D_2^{*0} at HERA

$D_1(2420)^0$ and $D_2^*(2460)^0$ fit results and comparison

Parameter	HERAI	HERAII (prelim)	BABAR,2010	PDG,2010	PDG,2011
$M(D_1^0)$,MeV	$2420.5 \pm 2.1(stat) \pm 0.9(syst)$	$2422.2 \pm 1.7(stat)^{+1.2}_{-2.8}(syst)$	$2420.1 \pm 0.1(stat) \pm 0.8(syst)$	2422.0 ± 0.6	2421.3 ± 0.6
$\Gamma(D_1^0)$,MeV	$53.2 \pm 7.2(stat)^{+3.3}_{-4.9}(syst)$	$43.4 \pm 6.2(stat)^{+7.3}_{-10.4}(syst)$	$31.4 \pm 0.5(stat) \pm 1.3(syst)$	20.4 ± 1.7	27.1 ± 2.7
$h(D_1^0)$	$5.9^{+3.0}_{-1.7}(stat)^{+2.4}_{-1.0}(syst)$	$3.5^{+1.6}_{-1.0}(stat)^{+2.0}_{-0.8}(syst)$	5.72 ± 0.25	–	5.72 ± 0.25
$M(D_2^{*0})$,MeV	$2469.1 \pm 3.7(stat)^{+1.2}_{-1.3}(syst)$	$2465.0 \pm 3.3(stat)^{+1.2}_{-2.9}(syst)$	$2462.2 \pm 0.1(stat) \pm 0.8(syst)$	2462.8 ± 1.0	2462.6 ± 0.7
$\Gamma(D_2^{*0})$,MeV	43(*fixed*)	43(*fixed*)	$50.5 \pm 0.6(stat) \pm 0.7(syst)$	42.9 ± 3.1	49.0 ± 1.4
$h(D_2^{*0})$	-1(*fixed*)	-1(*fixed*)	-1	–	–



Points: blue – included into PDG2010 averaging, green and red (ZEUS) – not included

Isolated hard photons measured in DIS

High-p_T photons produced in Deep Inelastic Scattering (DIS) using incident e^+/e^- are of several main types:

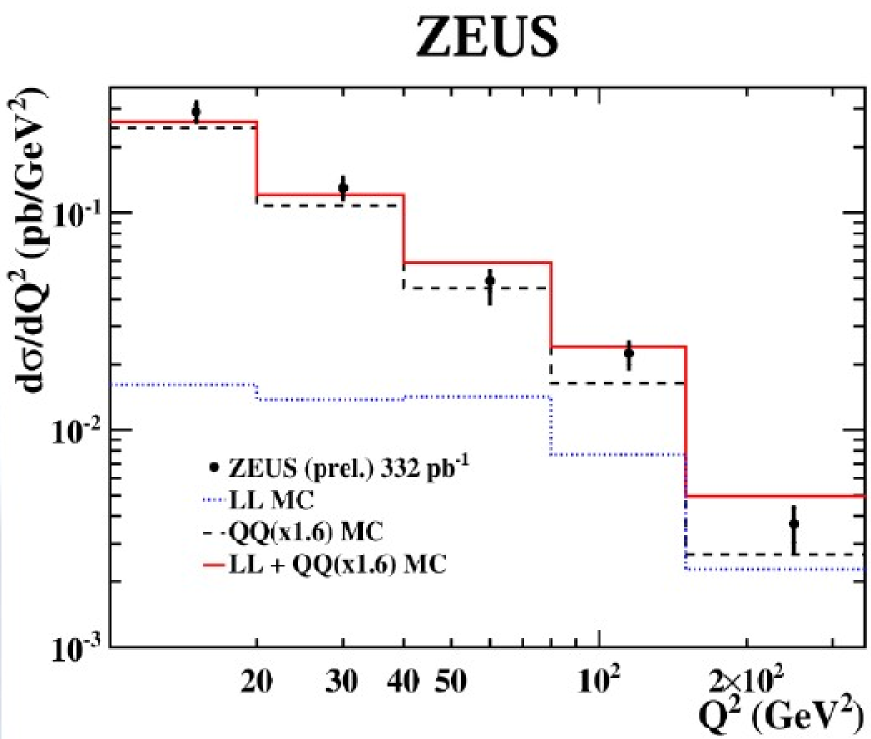
- Produced in a hard partonic interaction ("QQ") ("prompt photons")
- Radiated from the incoming or outgoing lepton ("LL")
- Radiated from a quark within a jet
- A decay product of a hadron within a jet

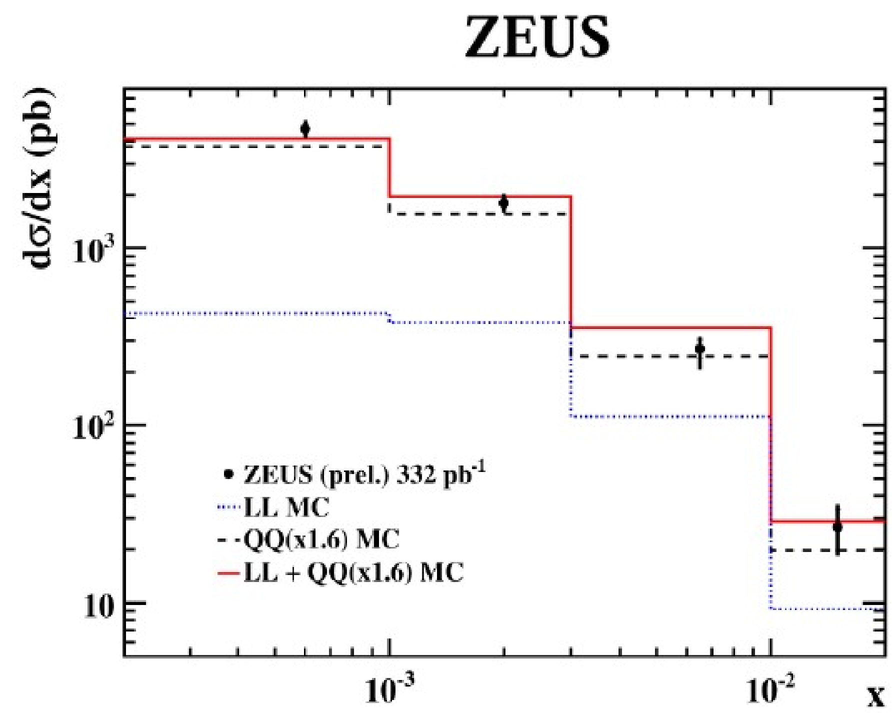
The first two types are photons that are relatively isolated from other outgoing particles, and are the subject of this study.

Some particular motivations for these measurements:

- The prompt photons emerge directly from the hard scattering process and give a particular view of this.
- This allows tests of specific QCD models.
- Prompt photons form a potential background to some interesting "new physics" process (e.g. Higgs → γγ) and this needs to be well understood.

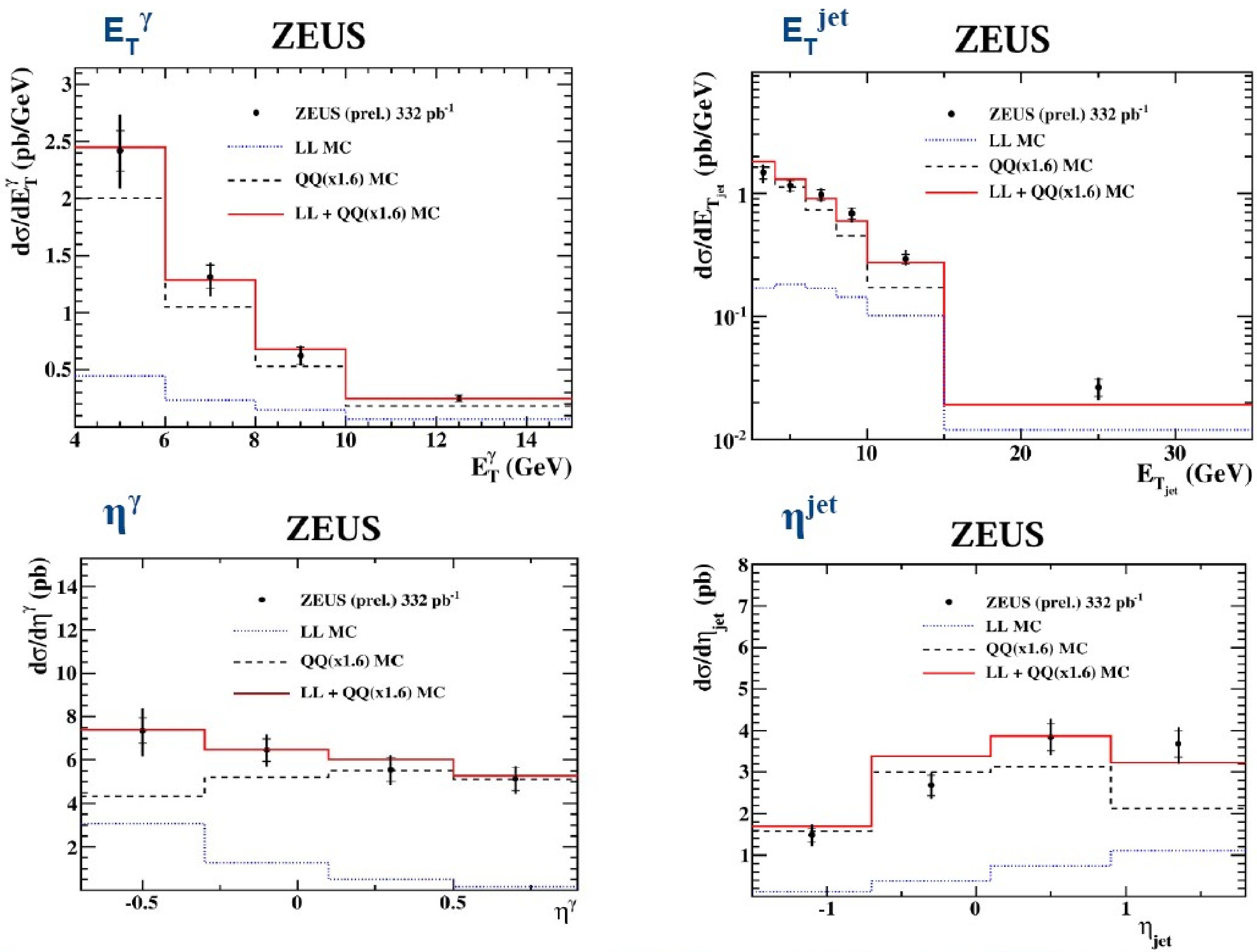
Prompt photon with jets cross. sec. vs. Q^2 and x



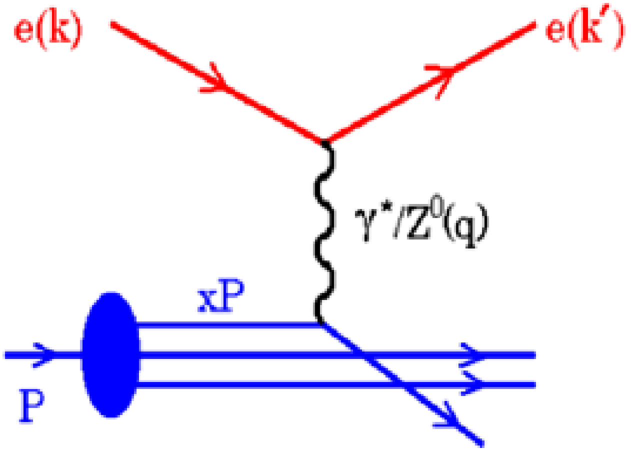


Q^2 = squared momentum transferred from initial to outgoing lepton
x = Bjorken variable

Prompt photon with jets cross. sec. vs. E_T and η



Proton structure probe



Neutral current Deep Inelastic Scattering (DIS) cross section:

$$\frac{d^2\sigma^\pm}{dx dQ^2} = \frac{2\pi\alpha^2 Y_+}{Q^4 x}\sigma_r^\pm =$$

$$= \frac{2\pi\alpha^2 Y_+}{Q^4 x}\left[F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2) \mp \frac{Y_-}{Y_+}xF_3\right]$$

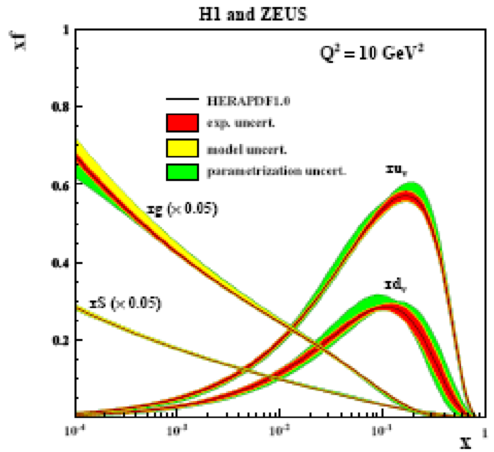
where factors $Y_\pm = 1 \pm (1-y)^2$ and y^2 define polarisation of the exchanged boson and $y = Q^2/(Sx)$.

Kinematics is determined by boson virtuality Q^2 and Bjorken x.

At leading order:

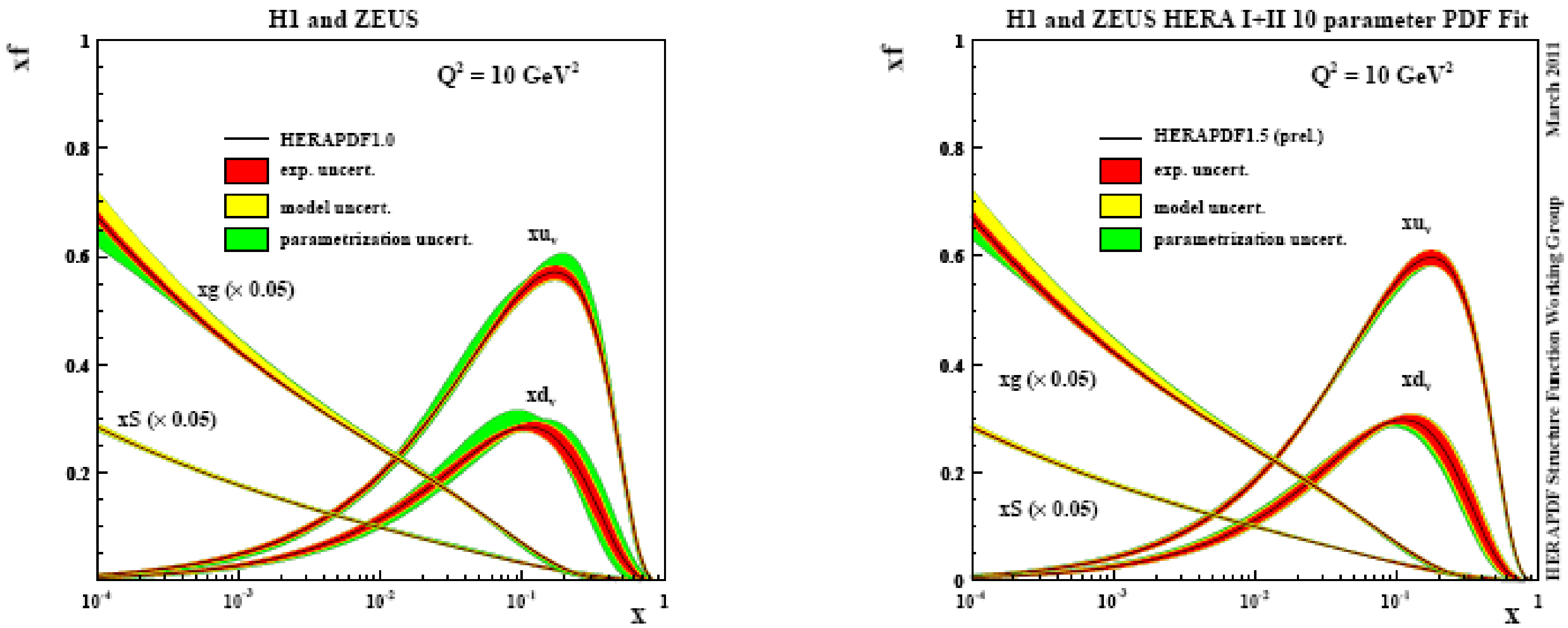
$$F_2 = x\sum e_q^2(q(x) + \bar{q}(x))$$
$$xF_3 = x\sum 2e_q a_q(q(x) - \bar{q}(x))$$
$$\sigma_{CC}^+ \sim x(\bar{u} + \bar{c}) + x(1-y)^2(d+s)$$
$$\sigma_{CC}^- \sim x(u + c) + x(1-y)^2(\bar{d}+\bar{s})$$

$xg(x)$ — from F_2 scaling violation, jets and F_L



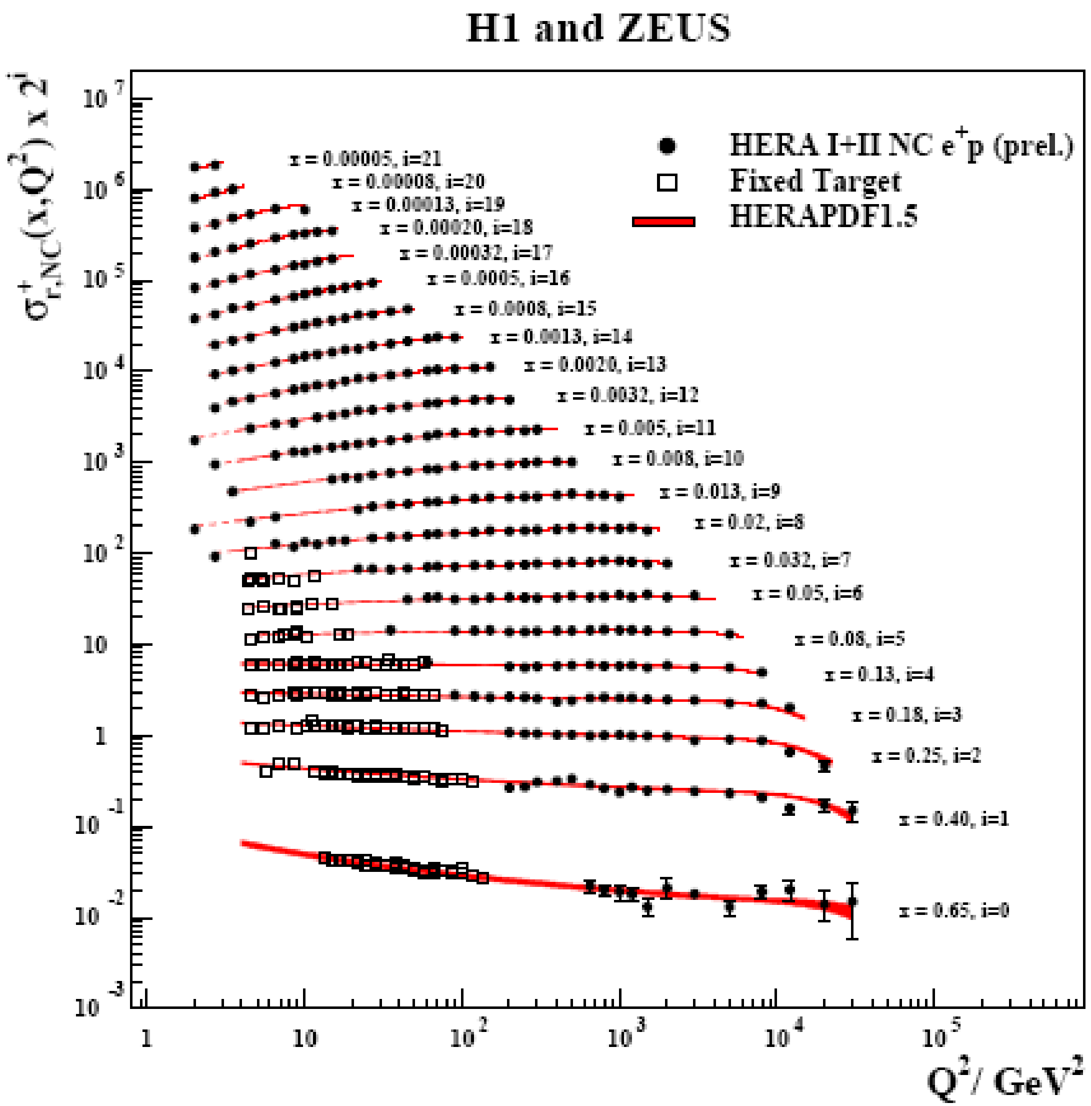
HERAPDF1.0 and HERAPDF1.5 fits

- The combined NC and CC HERA data have been used as the sole input for the extraction of the HERAPDF1.5.



- Fits parameterise $x\bar{U}$, $x\bar{D}$, xu_v, xd_v and g using $xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$ form.
- Experimental, model and parameterisation uncertainties are estimated.
- HERAPDF1.5 fit provides determination of the valence quark densities at high x with reduced uncertainties compared to HERAPDF1.0.

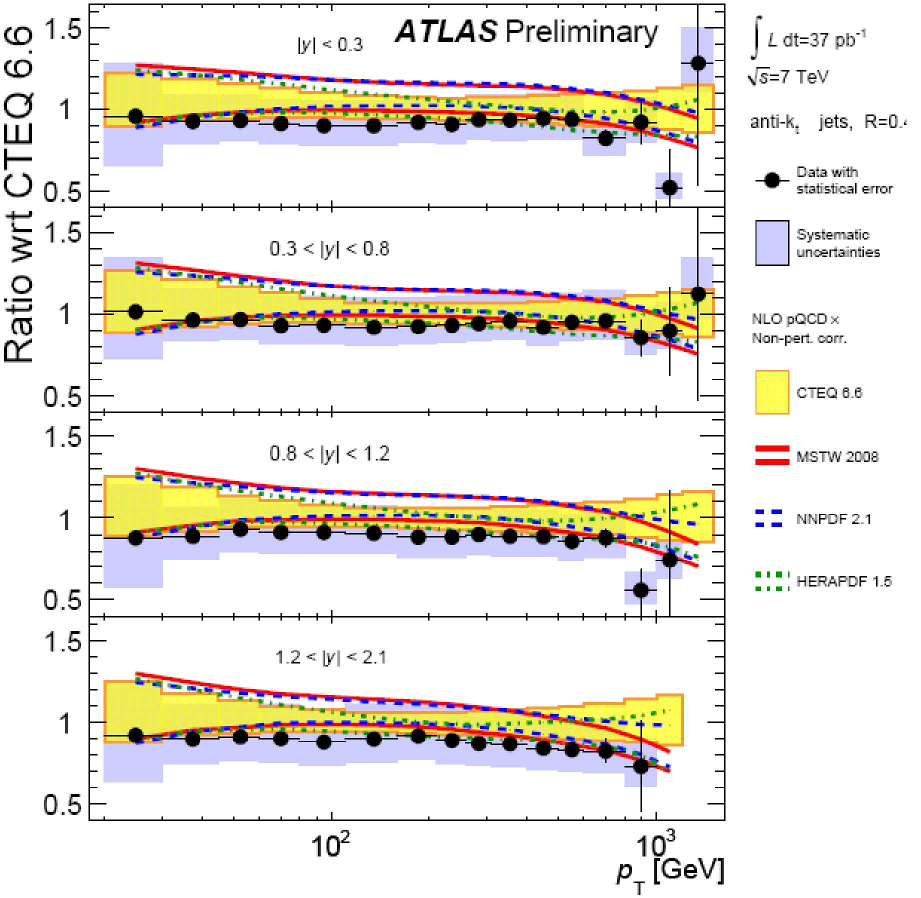
HERAPDF1.5 Fit



Extrapolation to low *Q2* is consistent with fixed target data.

HERA PDF Compared to *pp* Jets

For ATLAS, HERAPDF provides the best description of the data.

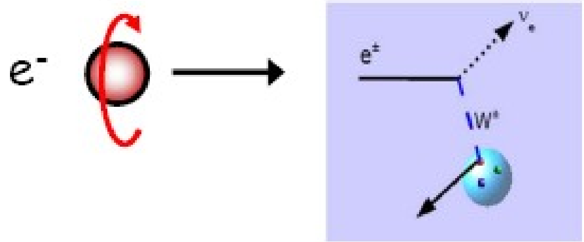


Combination of the H1 and ZEUS data brings ultimate precision for PDFs.
PDF analysis is performed at NLO and NNLO.

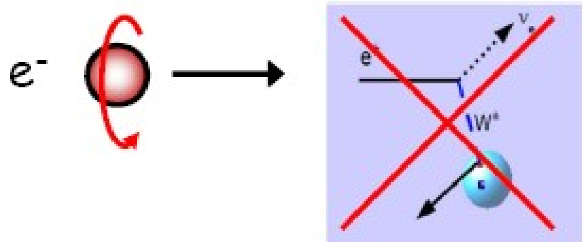
HERA continues to provide data essential for physics at the LHC. The data is the main ingredient for all modern PDF fits. HERAPDF fits provide alternative PDF sets with well understood experimental and theory uncertainties.

Weak interactions are "left-handed"

- lefthanded electrons interact (CC)



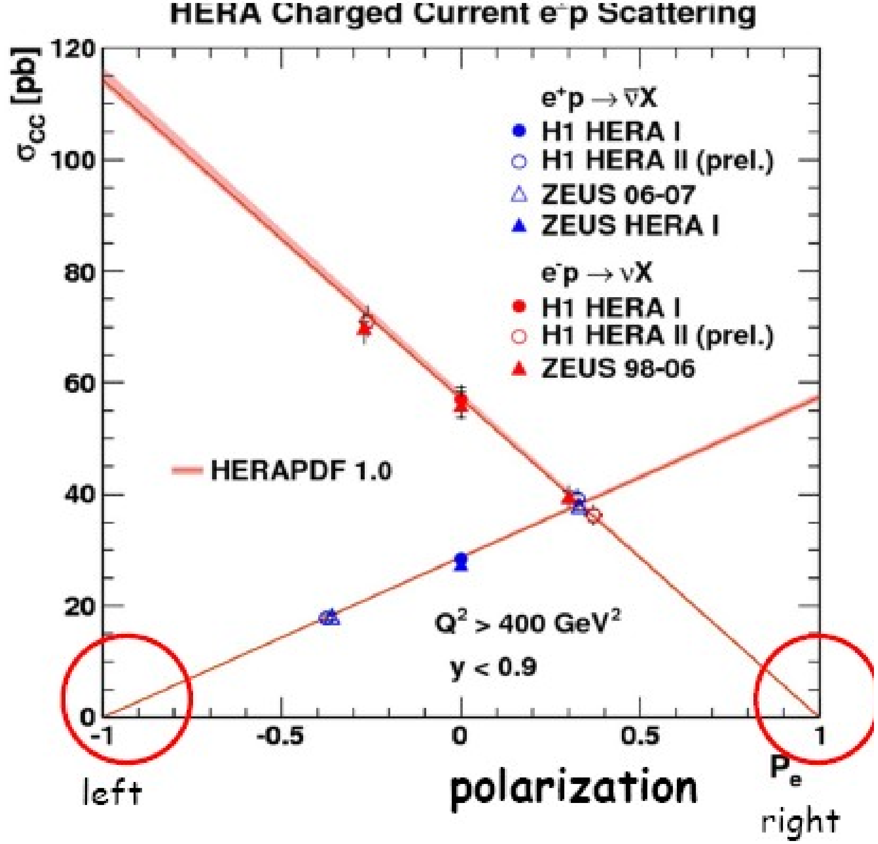
- righthanded electrons do not!



- cross section linearly proportional to polarization

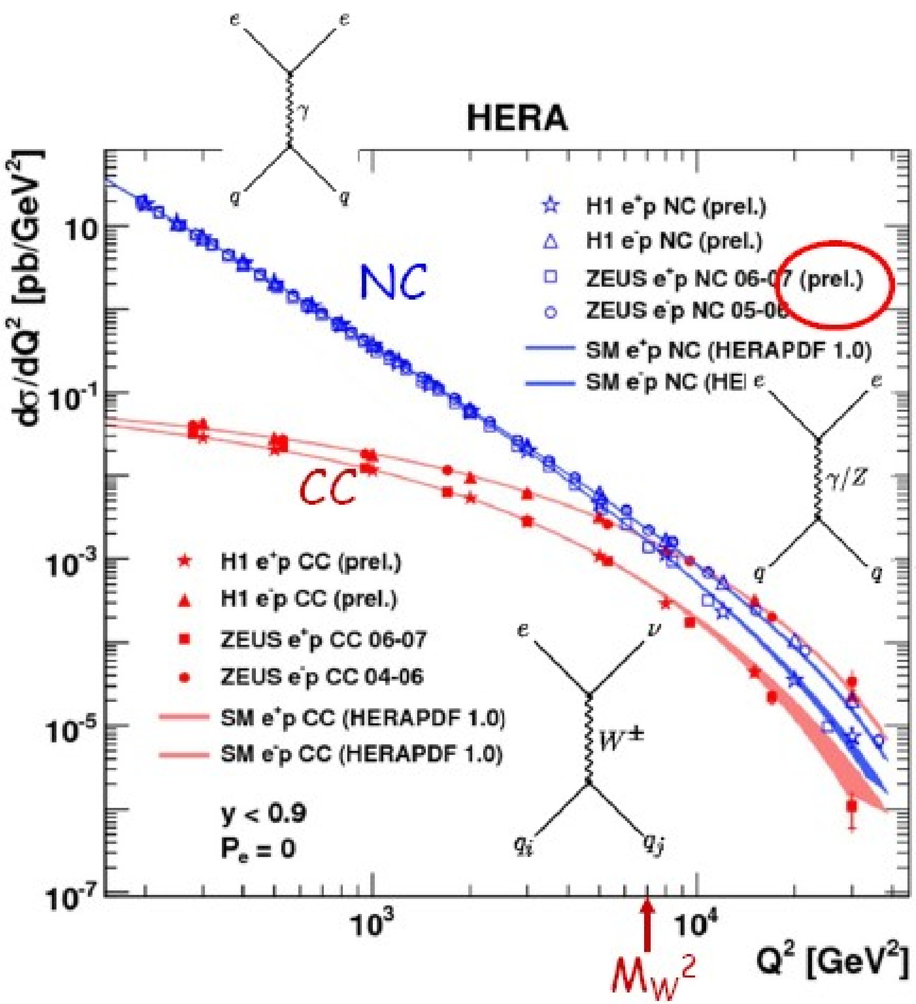
$$\sigma^{e^{\pm}p}_{polCC} = (1 \pm P_e) \cdot \sigma^{e^{\pm}p}_{unpolCC}$$

Polarized CC Cross Sections



ZEUS final !

Electroweak Unification



Strength of weak and electromagnetic forces become similar at scale $Q^2 \sim M_W^2$

$$\frac{d^2\sigma_{NC}}{dQ^2\,dx} \sim \alpha^2 \frac{1}{Q^4} \frac{1}{x}\Phi_{NC}(x,Q^2)$$

$$\frac{d^2\sigma_{CC}}{dQ^2\,dx} \sim G_F^2 \left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \frac{1}{x}\Phi_{CC}(x,Q^2)$$

ZEUS final soon !

Conclusions

- Combination of the H1 and ZEUS data brings ultimate precision for PDFs. HERA continues to provide data essential for physics at the LHC.
- HERA still one of the best QCD laboratories; in general, agreement with NLO QCD, success of the Standard Model !
- HERA jet measurements successfully test and constrain QCD parameters -> potential to yield world best measurements of α_s;
- Heavy Flavour measurements at HERA successfully described by QCD, contribute to improve cross section predictions for LHC;
- combination of H1/ZEUS results ongoing:
- -> towards full 1 fb-1 results (H1+ZEUS, HERA1+2).
- -> expect significant further improvements over next few years
- for QCD only fraction of statistics has been analyzed so far in many cases; physics analysis is in full swing and will continue for a long time.