QCD@Work - International Workshop on QCD – Theory and Experiment
Giovinazzo, 16 - 19 June 2014

Riccardo Brugnera
Padova University and INFN

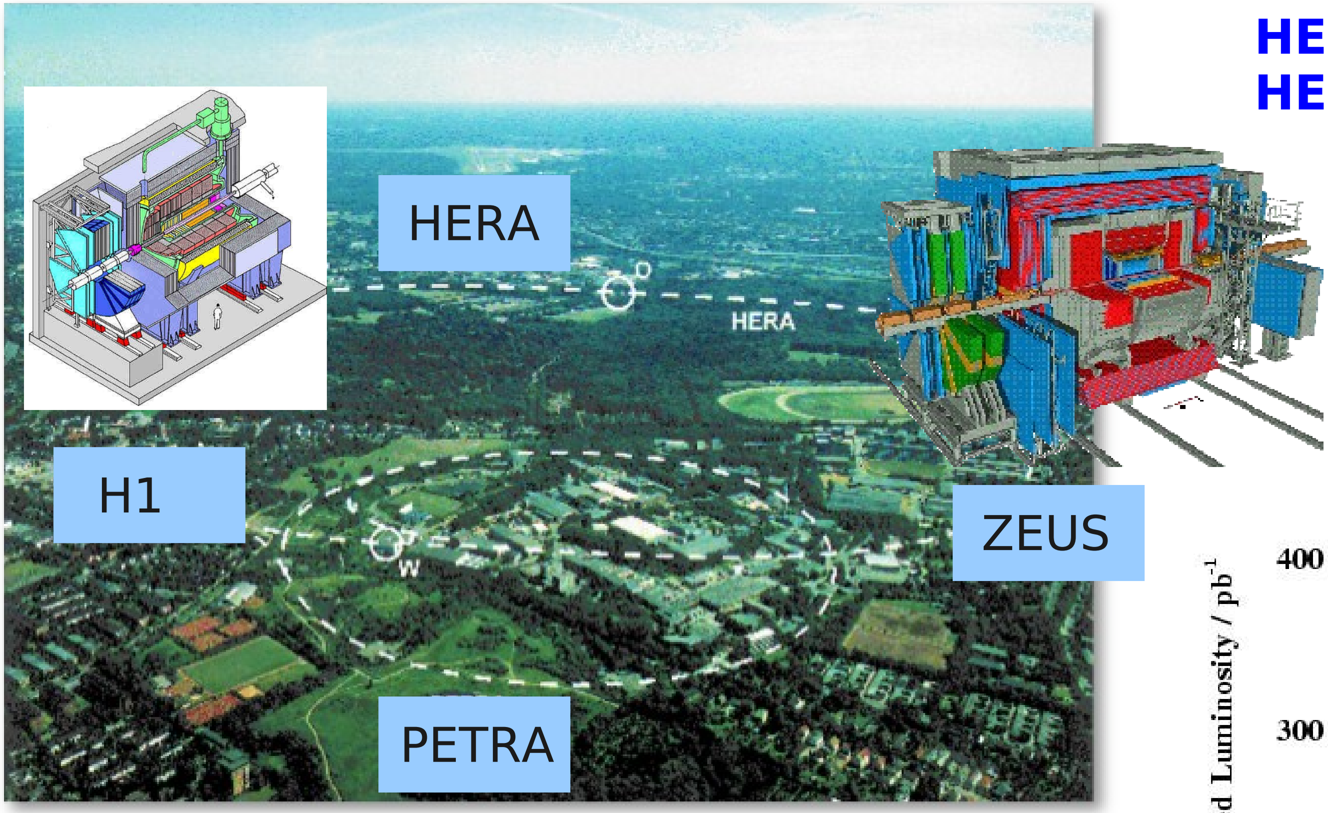
on behalf of the
H1 and ZEUS Collaborations

Heavy flavour production at HERA

Outline:

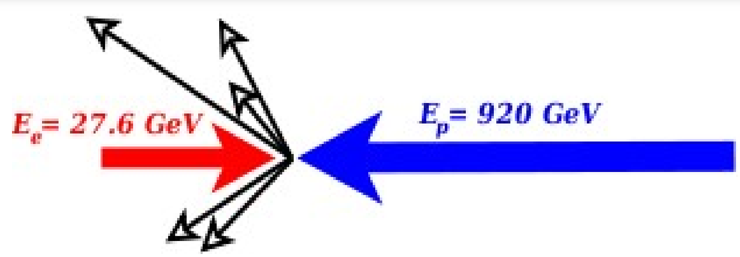
- **Charm fragmentation fractions**
- **Open charm production in DIS**
- **Open bottom production in DIS**
- **elastic and inelastic photoproduction of J/ψ mesons**

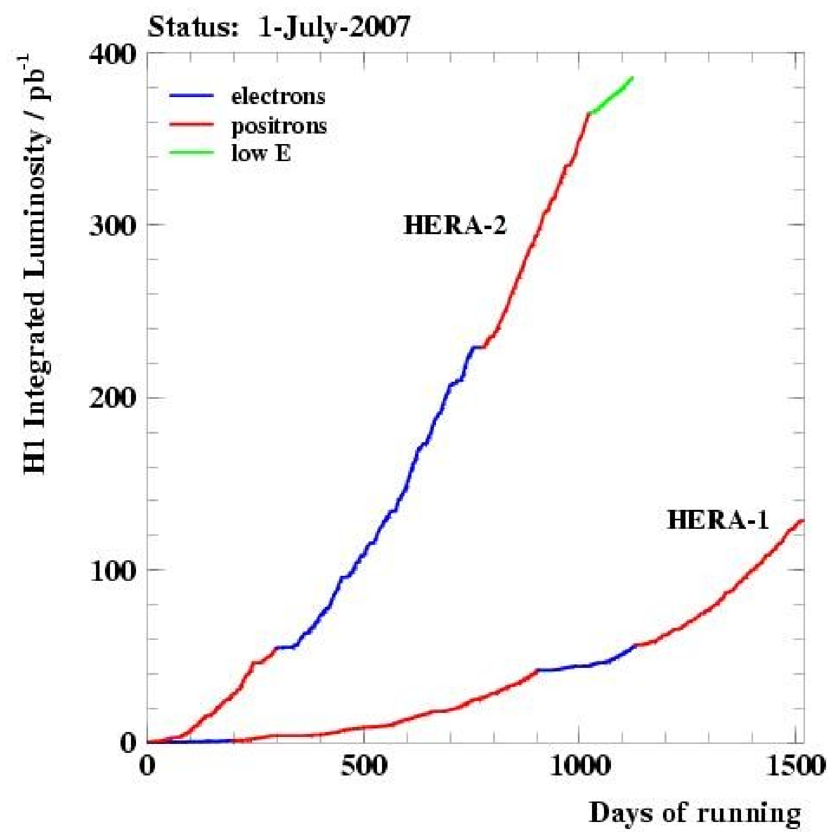
HERA data



HERA-1 (1993-2000) ≃ **120** pb^{-1}
HERA-2 (2003-2007) ≃ **380** pb^{-1}

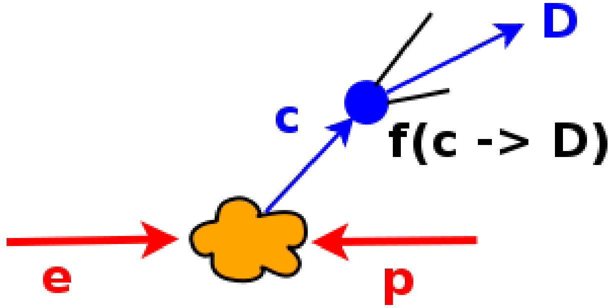
Final data samples
H1+ZEUS = **2×0.5** fb^{-1}

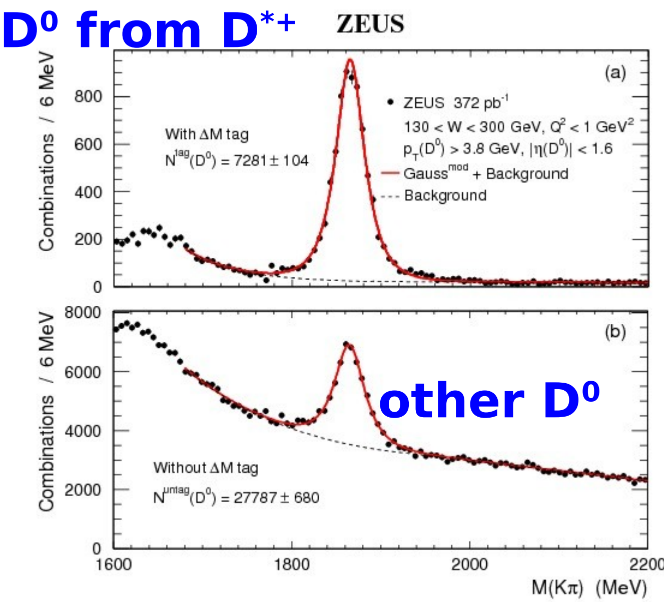


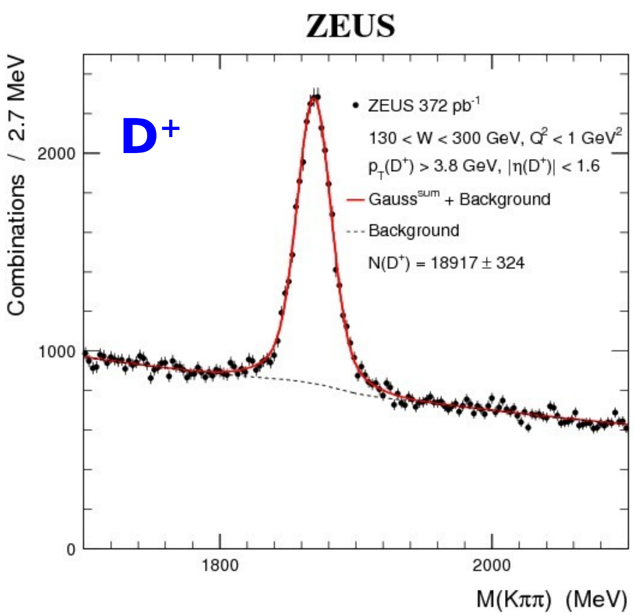


- 1998 E_p upgrade : 820 ⇒ 920 GeV
  (√s : 301 ⇒ 319 GeV)
- 2001 HERA-2 upgrade: 3×$\mathscr{L}$, polarized e^+/e^-
  (<P> = 40%)

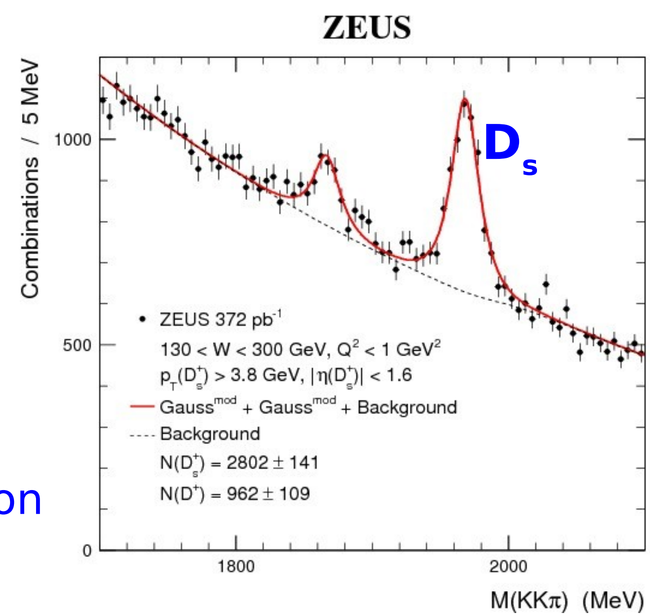
charm fragmentation fractions

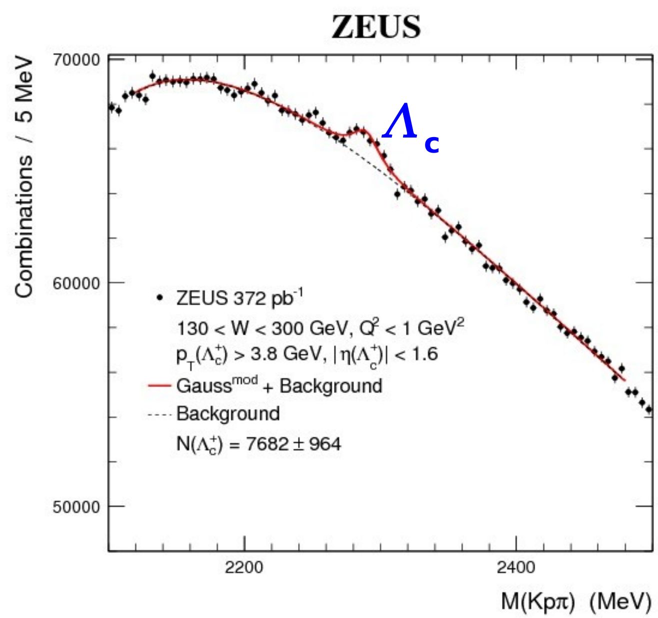






- New ZEUS photoproduction measurement: ***JHEP09 (2013) 058***
- Fragmentation fraction f(c→D): needed to go from partonic QCD calculations to hadron cross sections
- All charm ground state hadrons are measured (except charm-strange baryons)
- Measured for p_T > 3.8 GeV "equivalent phase space" treatment minimizes extrapolation to p_T = 0

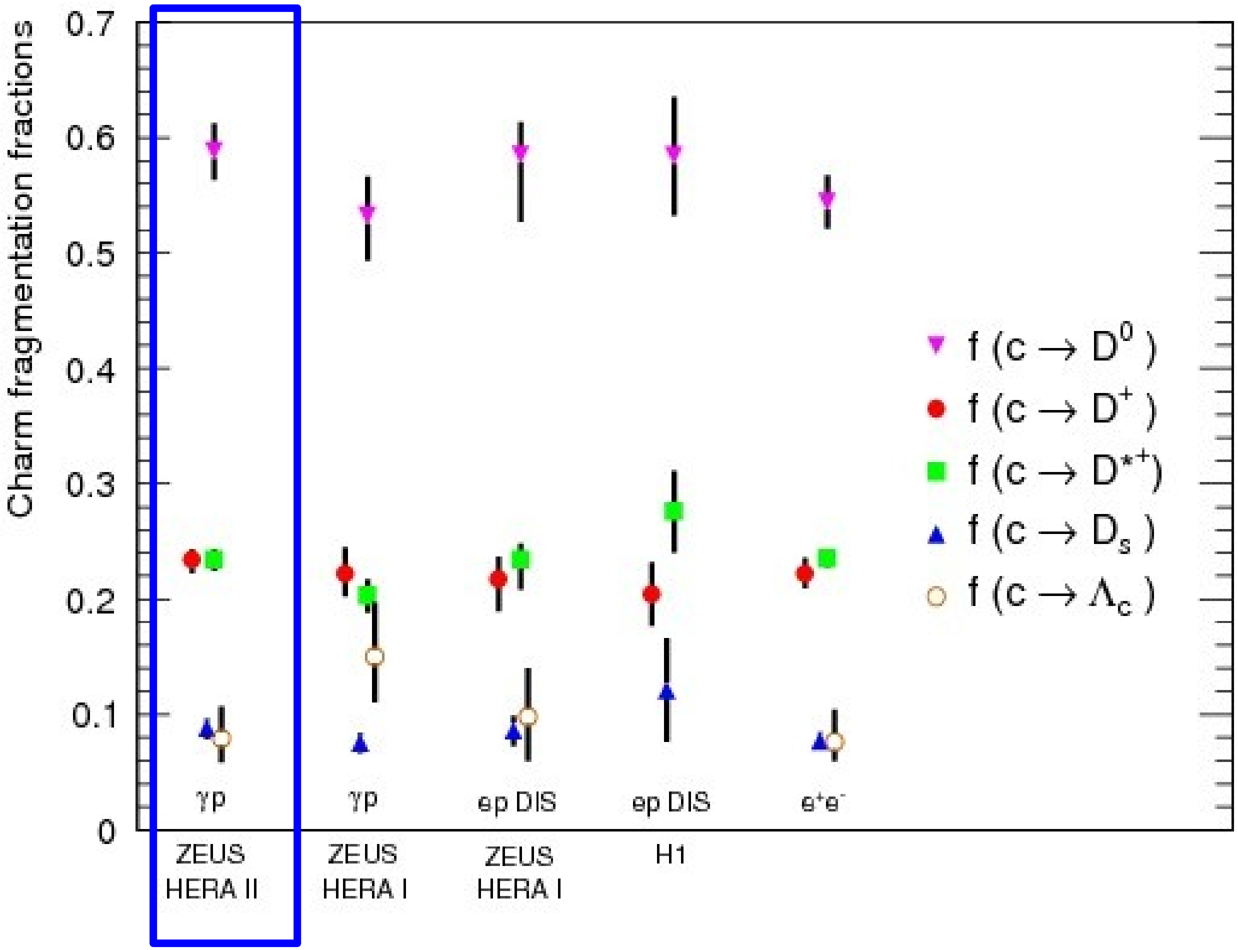




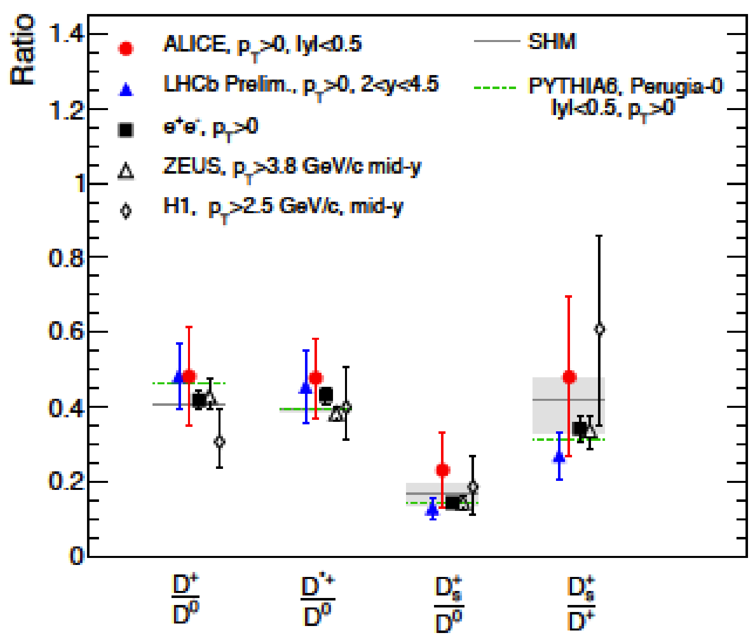
fragmentation fraction results

- New results compared to previous photoproduction (γp), DIS and e+e- **support universality**

NEW

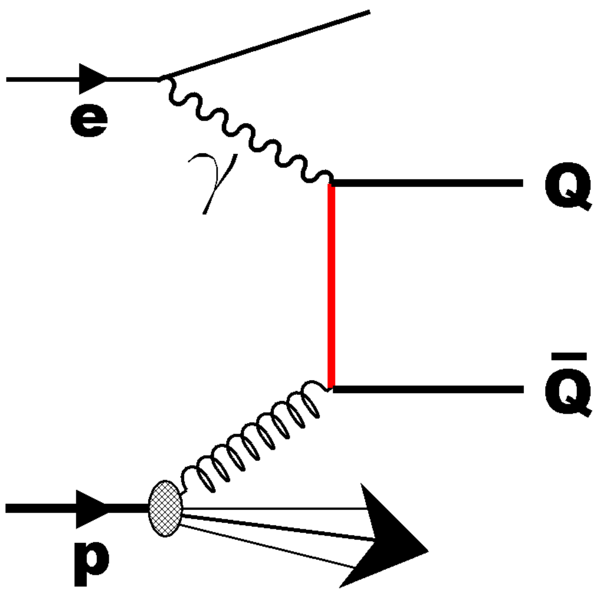


- Universality supported by LHC pp data (ALICE +LHCb)



heavy quark production in DIS

Leading Order:
Boson-gluon fusion (BGF)



- access to g(x)
- sensitivity to m_c and to m_b
- test of GM-VFNS heavy flavour schemes used in global PDF fits

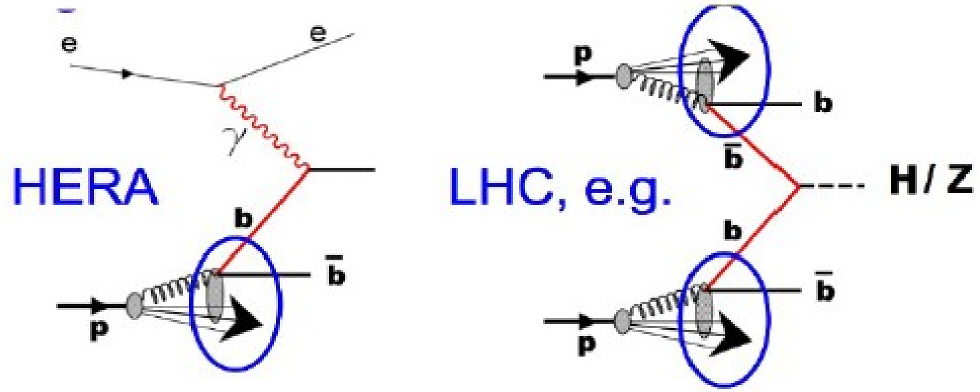
Theory of heavy quark production:

1) Fixed Flavour Number Scheme (FFNS)

- n_f = 3 active flavours in *p*
- c,b produced in hard scattering
- mass effects correctly included
- spoiled by large logs of Q^2/m^2, p_T/m ...

2) General-Mass Variable Flavour Scheme(GM-VFNS)

- equivalent to FFNS for $Q^2 < m_c^2$
- c, b treated as massless parton for $Q^2 \gg m_c^2$
- interpolation in between (various scheme available)
- used by global PDF fits (useful at LHC ...)



charm production in DIS

several methods to tag charm:

- D*,D+,D0, μ, secondary vertices

New results from ZEUS-HERA-II data

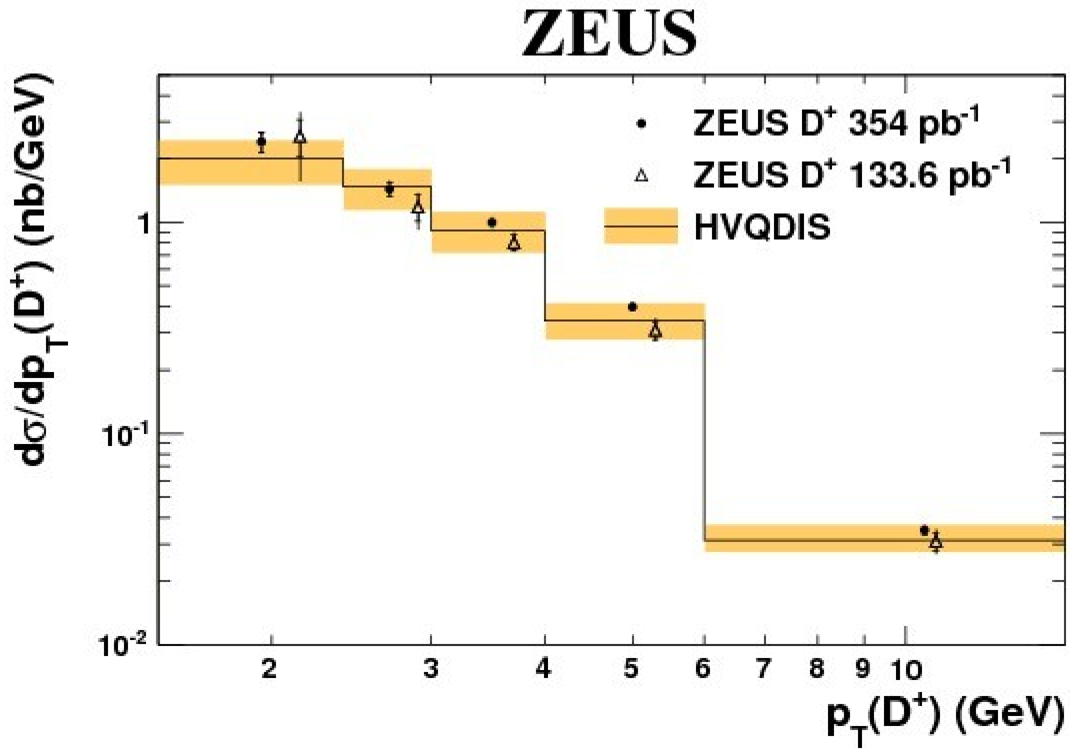
- D* arXiv:1303.6578 JHEP05(2013)097
- D+ arXiv:1302.5058 JHEP05(2013)023

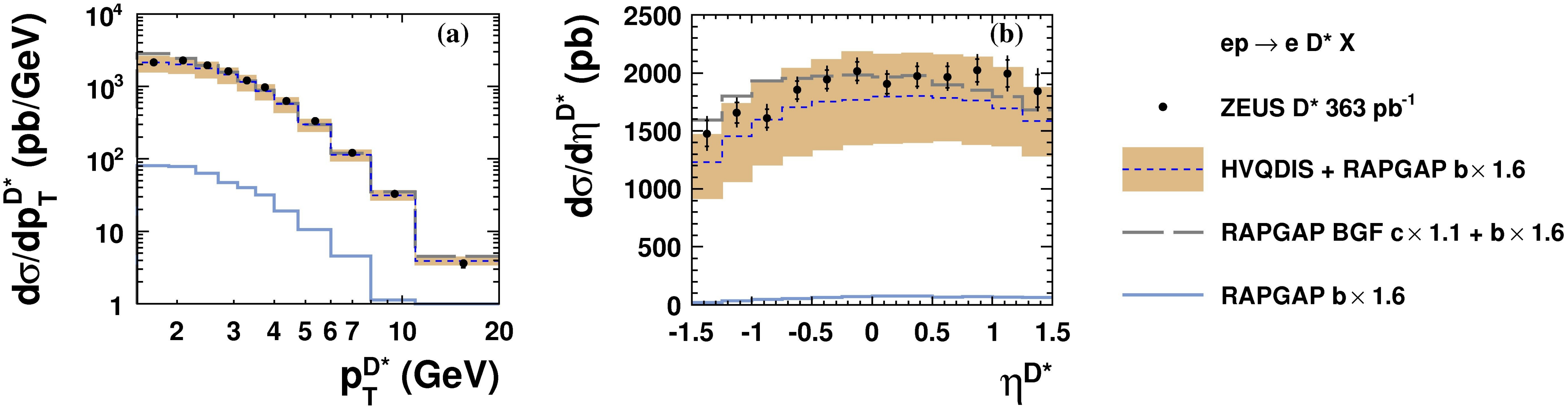
- Cross sections in "visible" phase space (for D*):

  $p_T > 1.5$ GeV, $|\eta| < 1.5$

  $0.02<y<0.7$, $Q^2 > 5$ GeV^2

- Good agreement with NLO FFNS theory (HVQDIS) complemented with fragmentation model based on ep data



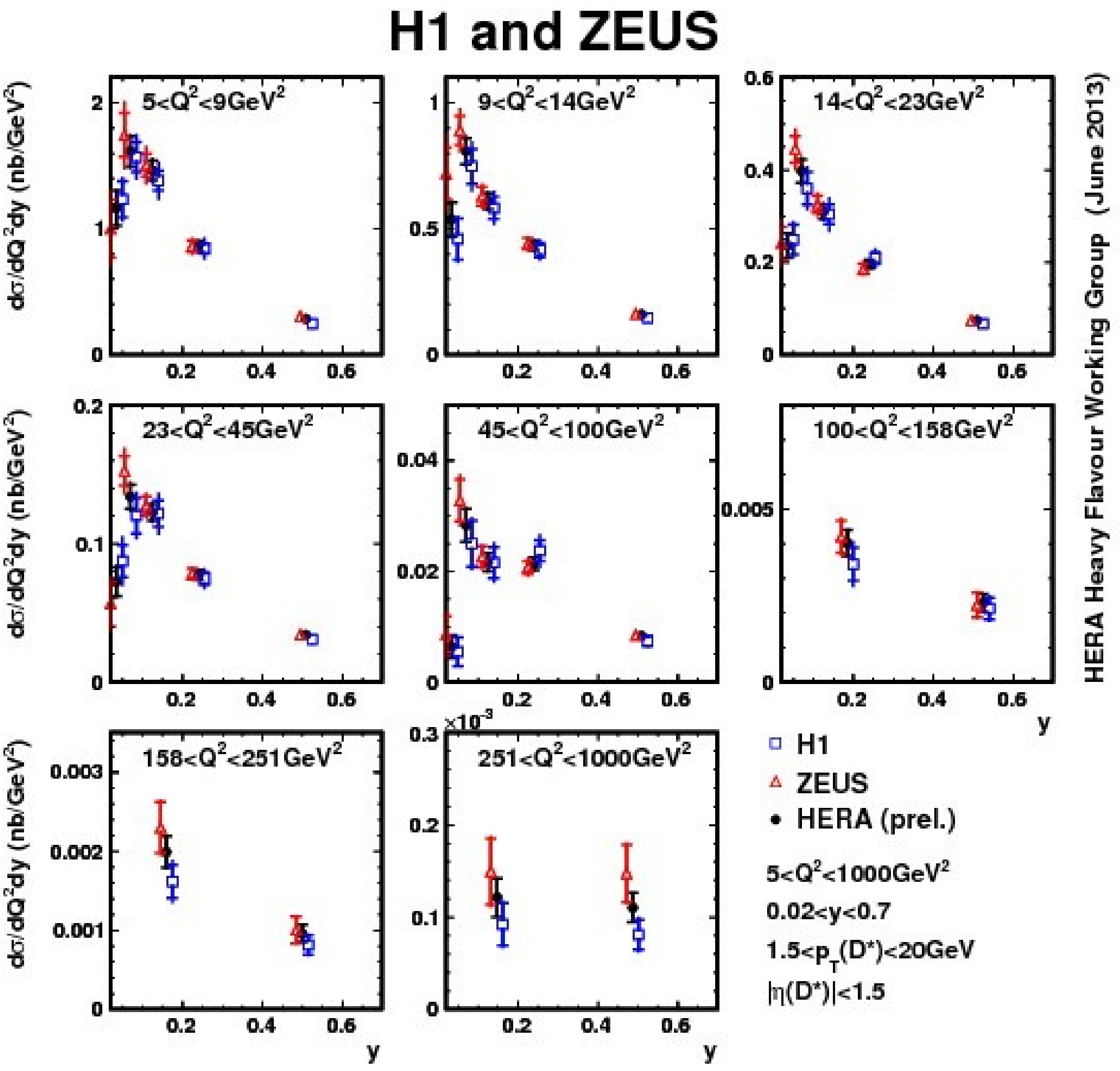


charm production in DIS

Double-differential "visible" D* cross sections in Q^2-y bins

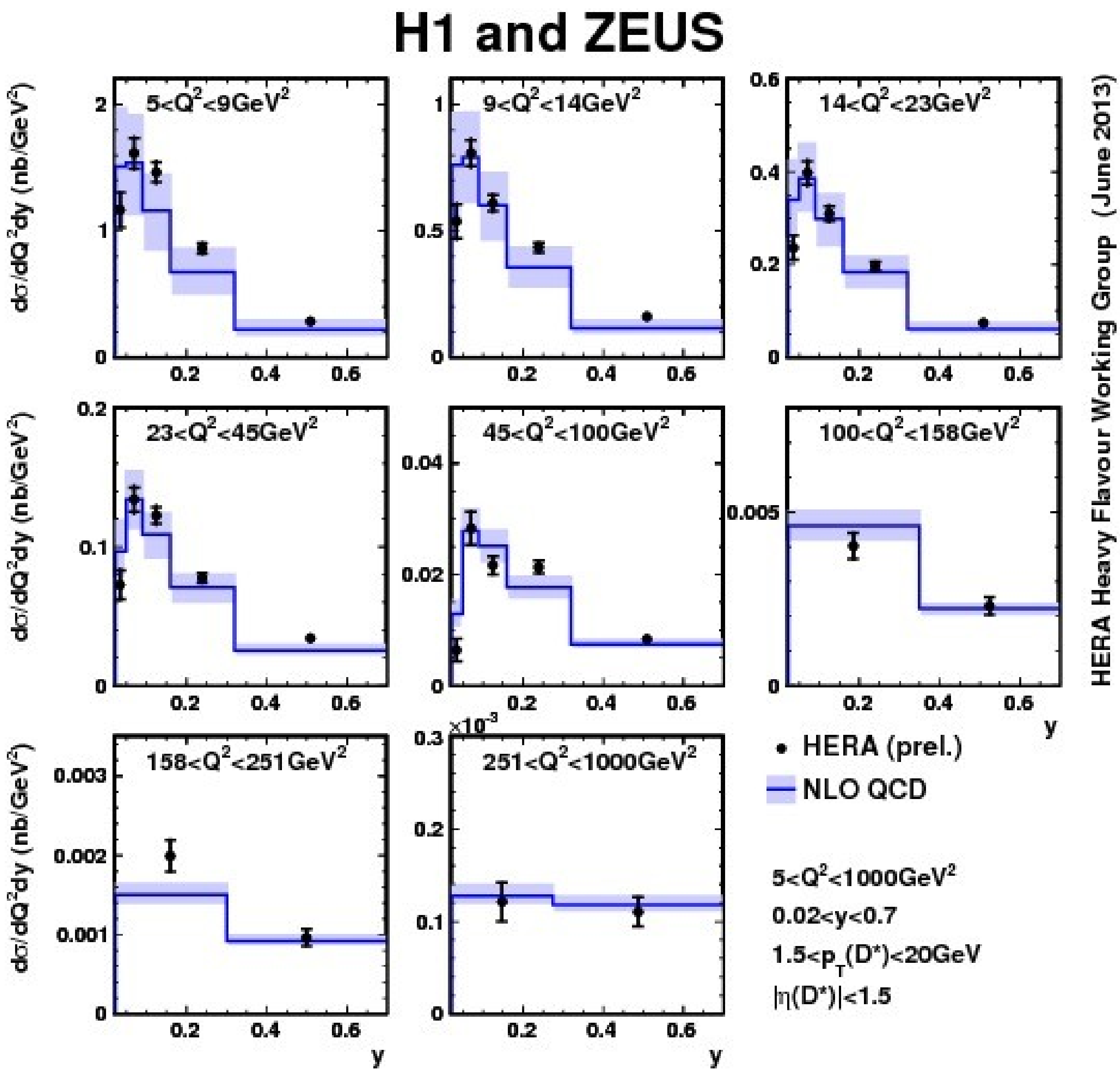
ZEUS data in good agreement with previous results from H1 in the same bins

The two results have been combined in HERA "visible" cross sections



charm production in DIS

Combination in good agreement with NLO FFNS theory (HVQDIS)



$F_2^{c\bar{c}}$ and $\sigma_{red}^{c\bar{c}}$ ... but the same for $F_2^{b\bar{b}}$, $\sigma_{red}^{b\bar{b}}$

reduced charm cross sections defined in analogy to inclusive DIS:

$$\frac{d^2\sigma^{c\bar{c}}}{dx\,dQ^2} = \frac{2\pi\alpha_{em}^2}{xQ^4} Y_+ \sigma_{red}^{c\bar{c}}(x, Q^2, s) \qquad Y_+ = 1 + (1-y)^2$$

$$\sigma_{red}^{c\bar{c}}(x, Q^2, s) = F_2^{c\bar{c}}(x, Q^2) - \frac{y^2}{Y_+} F_L^{c\bar{c}}(x, Q^2)$$

Defined in analogy with inclusive DIS but considering events with charm in the final state.

Obtained from cross sections in visible phase space (σ_{vis}) in [Q^2,y] bins

$$\sigma_{red}^{c\bar{c}}(x, Q^2) = \left(\sigma_{vis} - \sigma_{vis}^{beauty}\right)\left(\frac{\sigma_{red,HVQDIS}^{c\bar{c}}}{\sigma_{vis,HVQDIS}}\right)$$

The method accounts for extrapolation into the full phase space
Visible phase space acceptance for ZEUS D* ~50%, from 17% (low-y) to 64% (high Q^2)

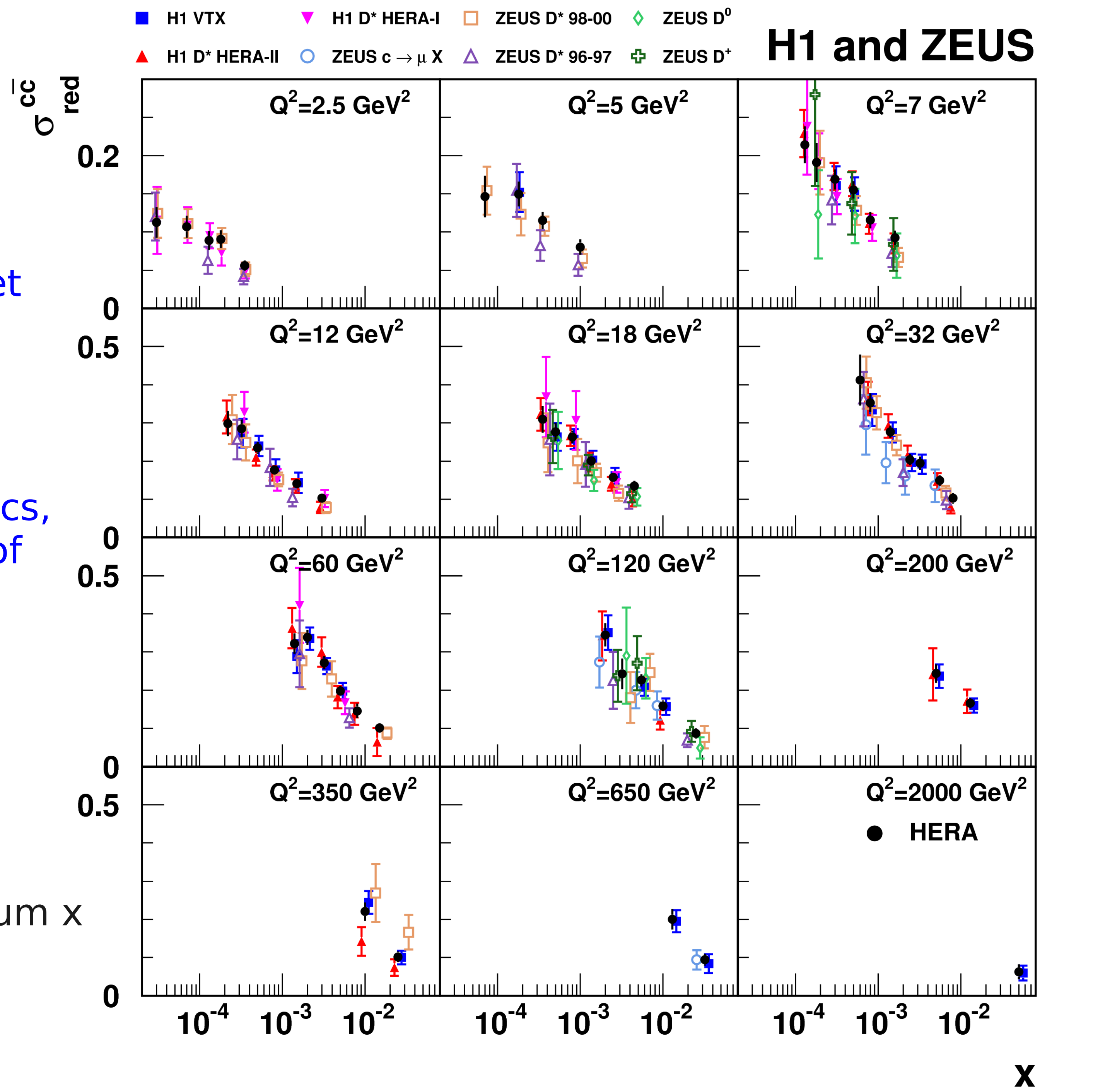
combination of HERA $\sigma_{red}^{c\bar{c}}$ cross sections

H1 and ZEUS:
arXiv:1211.1182
EPJC 73(2013)2311

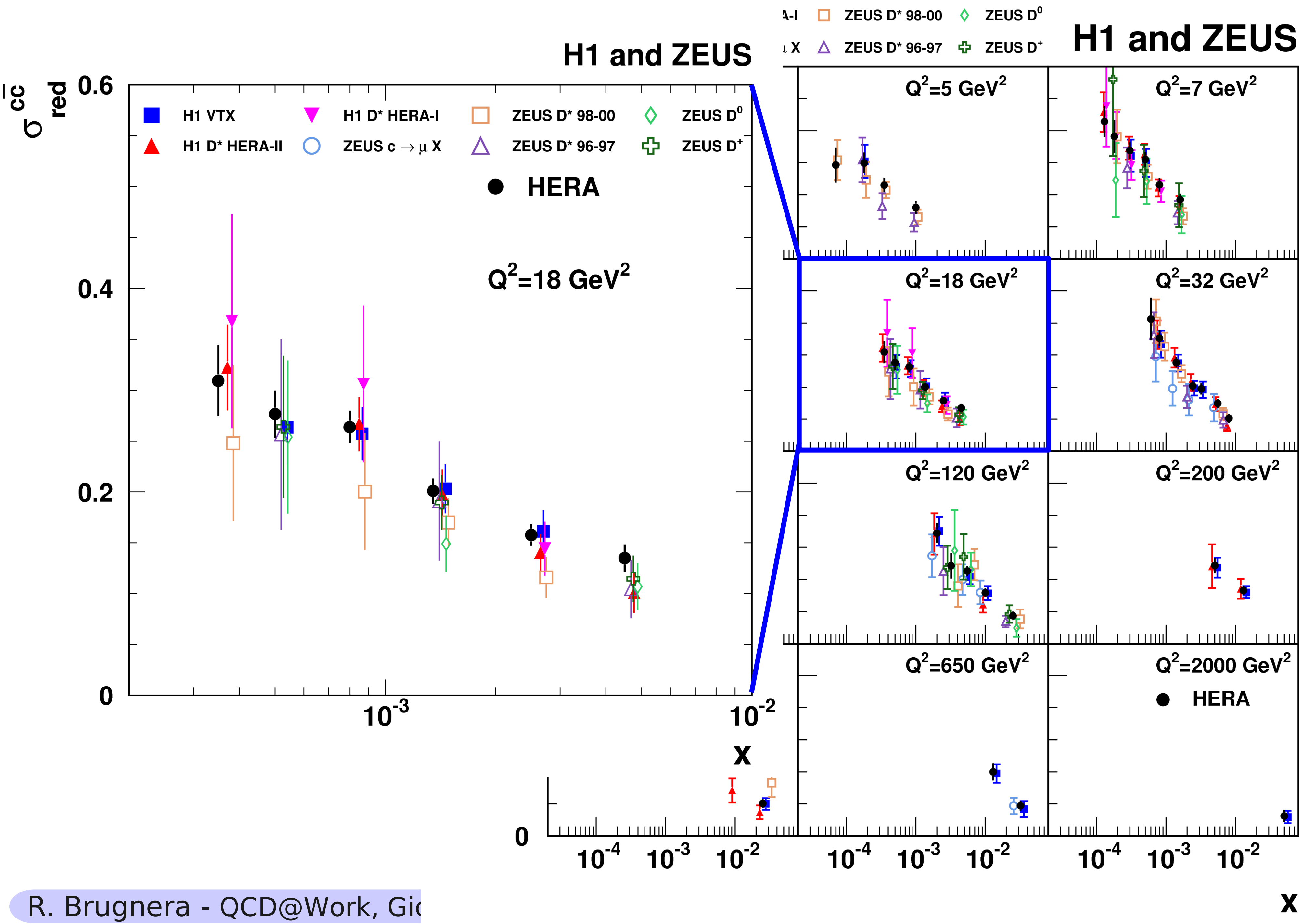
- 9 different data sets, (new ZEUS D*,D⁺ not yet included)
- 155 measurements combined into 55 $\sigma_{red}^{c\bar{c}}$ points
- 48 correlated systematics, 9 related to extraction of $\sigma_{red}^{c\bar{c}}$
- χ^2/n_{dof} = 62/103

Combination significantly more precise than single measurements

Uncertanty ~6% at medium x and 12 < Q^2 < 60 GeV^2



combination of HERA $\sigma_{red}^{c\bar{c}}$ cross sections

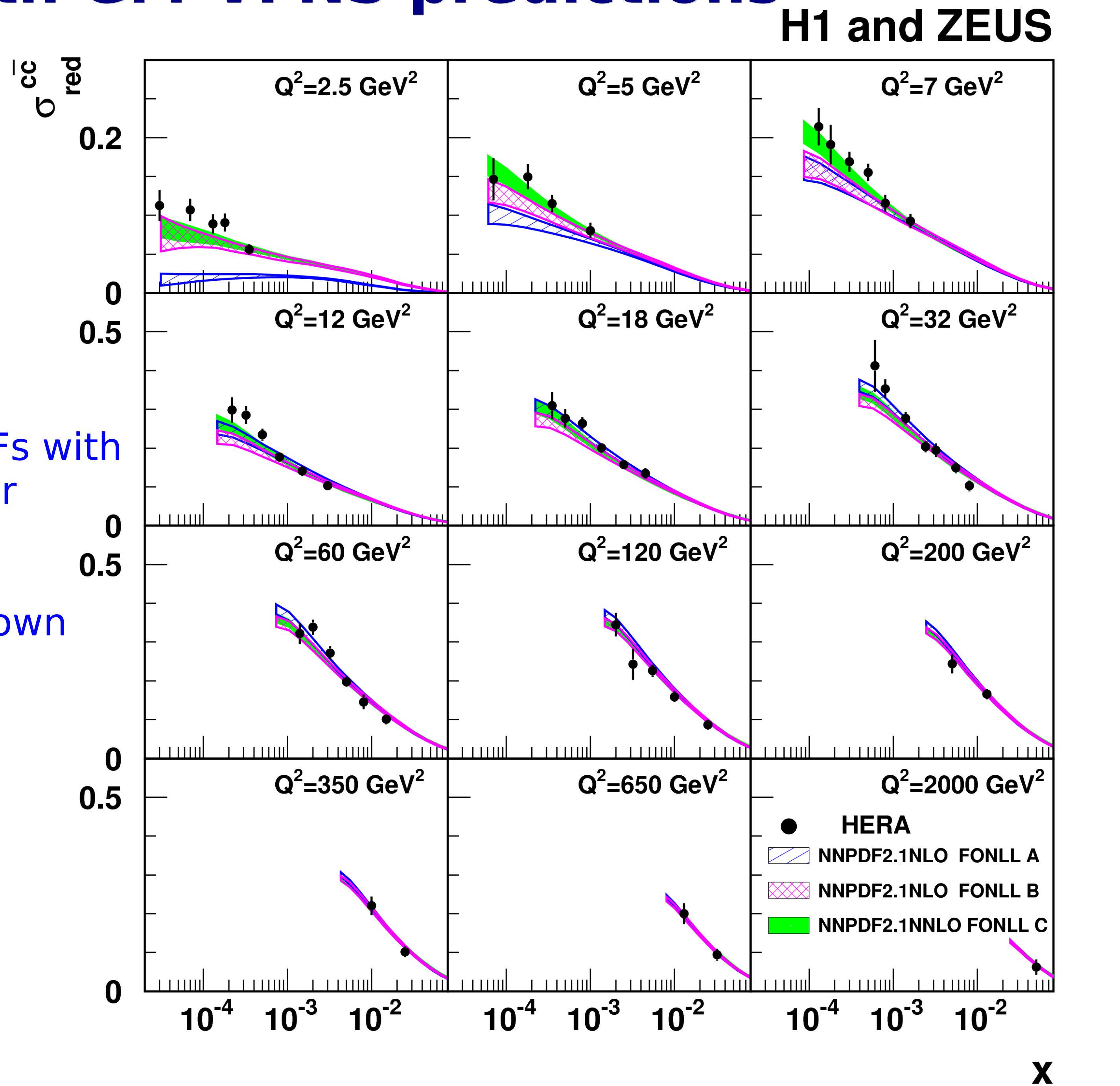


comparison with GM-VFNS predictions

- Combined HERA data are able to discriminate between different GM-VFNS approaches

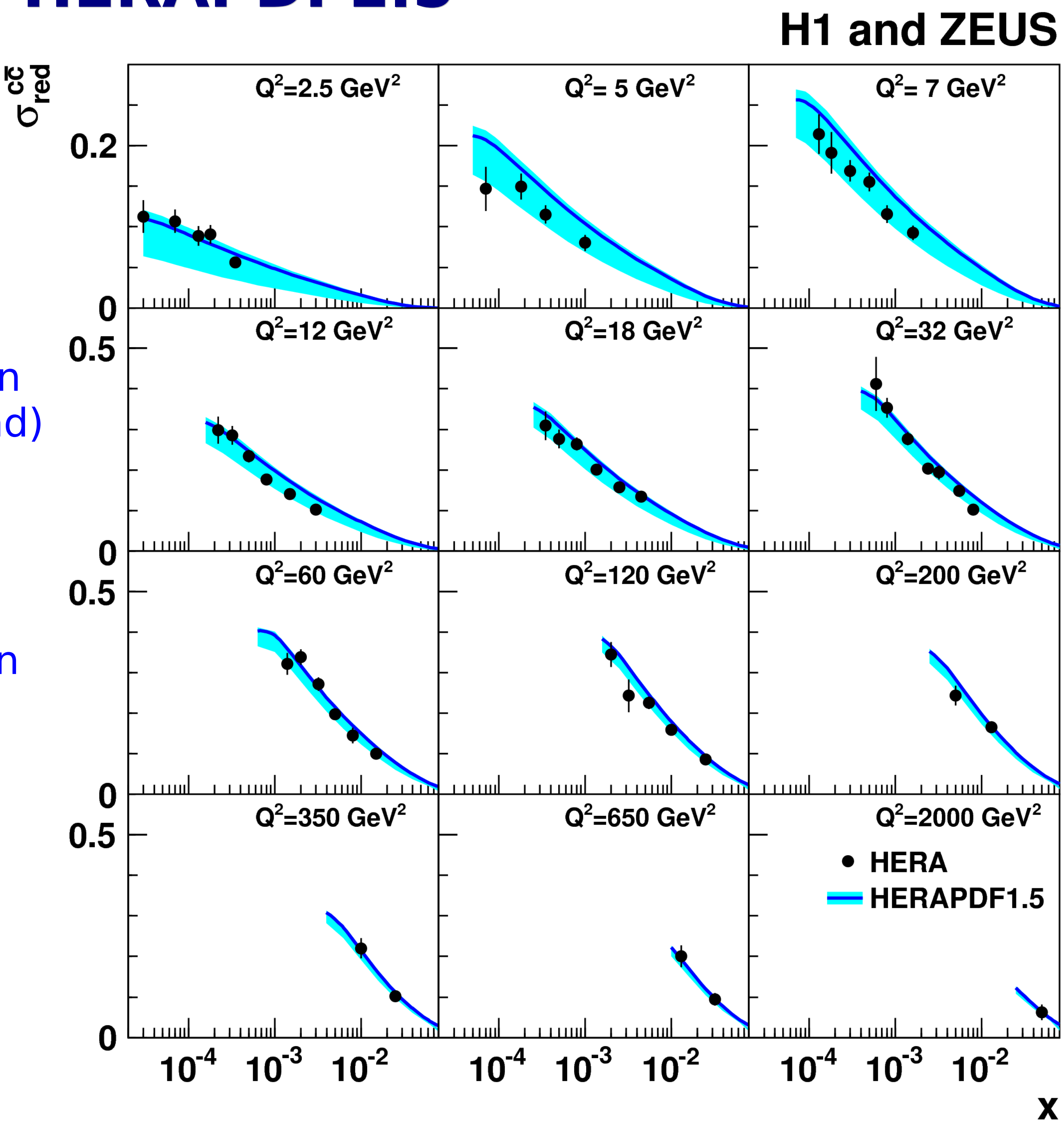
- Example: NNPDF2.1 PDFs with 3 different heavy-flavour matching schemes

- no mass uncertainty shown



comparison with HERAPDF1.5

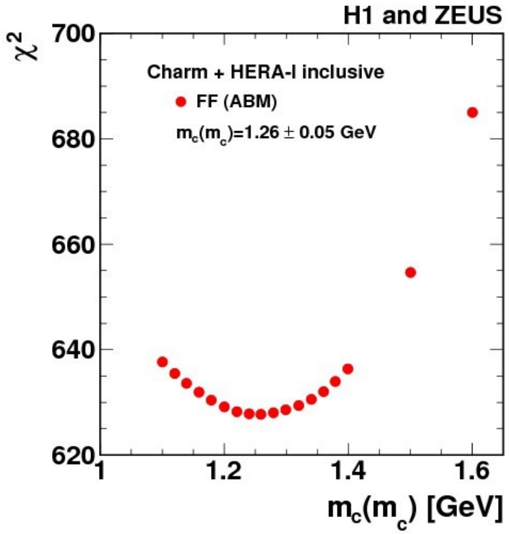
- HERAPDF1.5: GM-VFNS calculation based on a PDF fit to inclusive HERA data
- Main uncertainty from (pole) charm mass variation $1.35 < m_c < 1.65$ GeV (band)
- Consistency of charm data with inclusive fit
- Charm data have been then include into the HERAPDF fit …

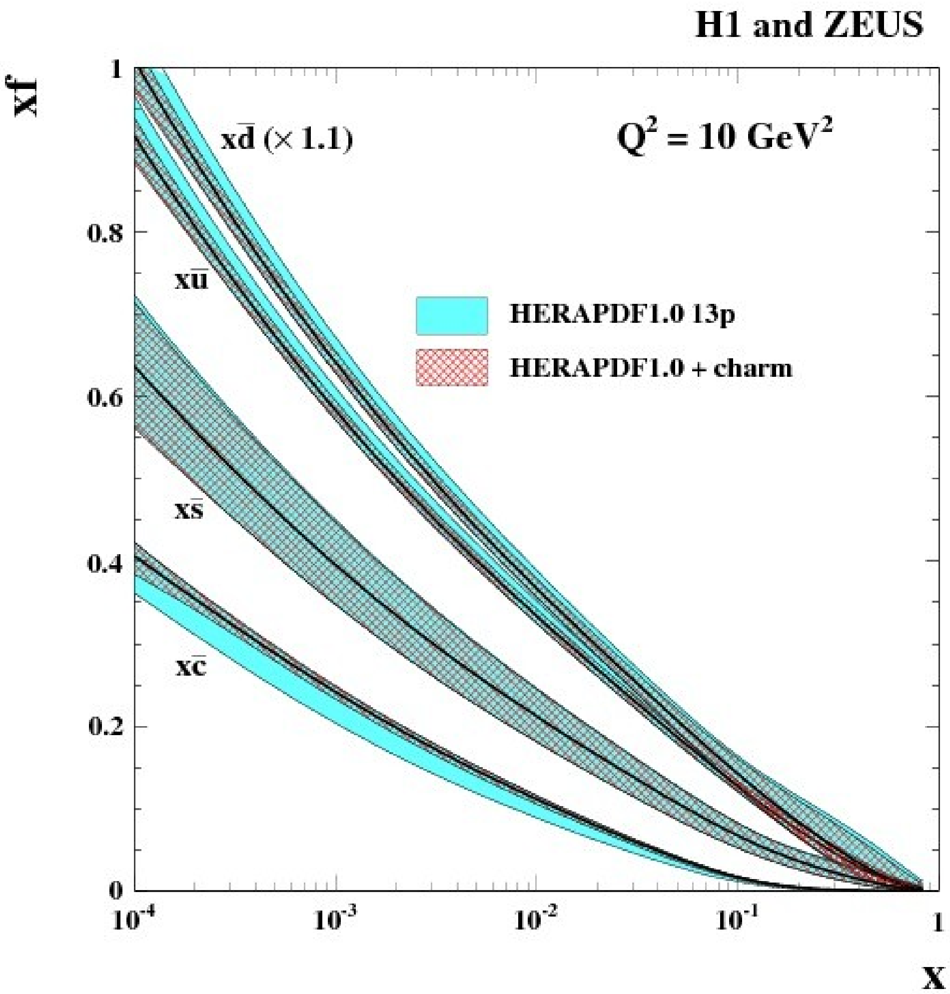


inclusion of charm data into PDF fit

New fit HERAPDF1.0 + charm

- uncertainty on c(x) (and g(x)) reduced mainly due to reduced uncertainty on charm mass.
- uncertainty on sea quarks also reduced due to reduced c(x)
- sensitivity to charm quark mass





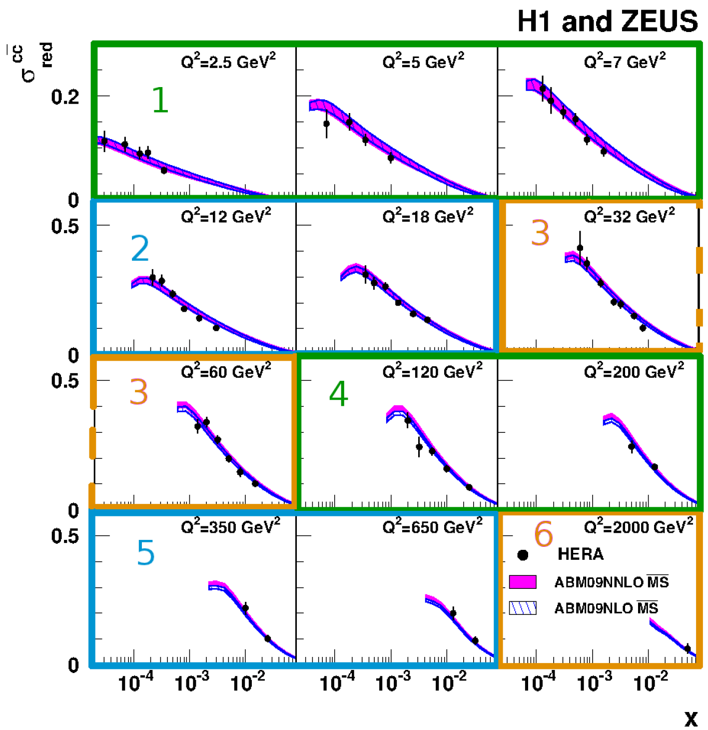
NLO FFNS fit used to extract the charm quark mass ($\overline{MS}$ scheme):

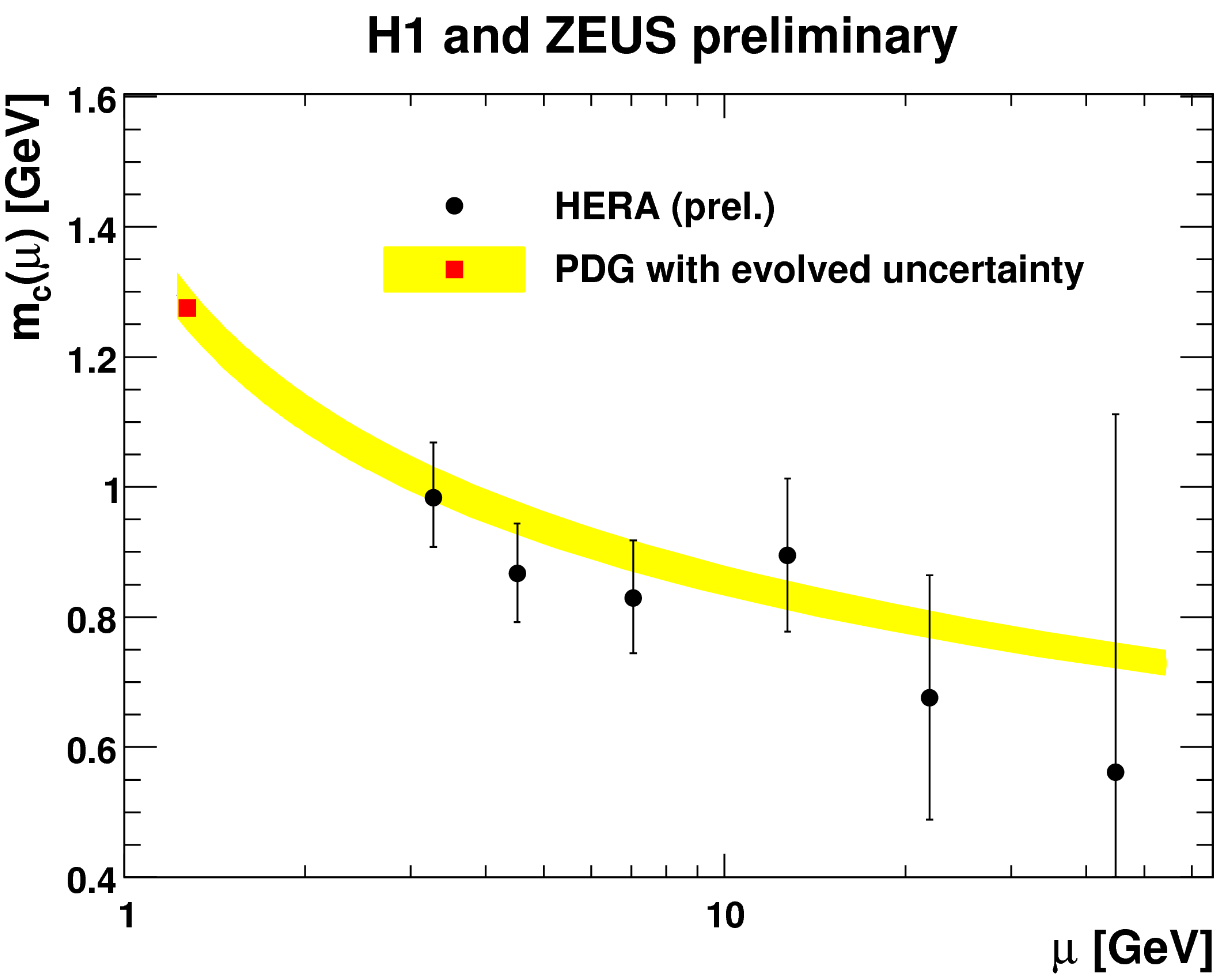
HERA: $m_c(m_c) = 1.26 \pm 0.05_{exp} \pm 0.03_{mod} \pm 0.02_{param} \pm 0.02_{\alpha s}$ GeV

PDG: $m_c(m_c) = 1.275 \pm 0.025$ GeV

charm mass running

H1-prelim-14-071
ZEUS-prel-14-006





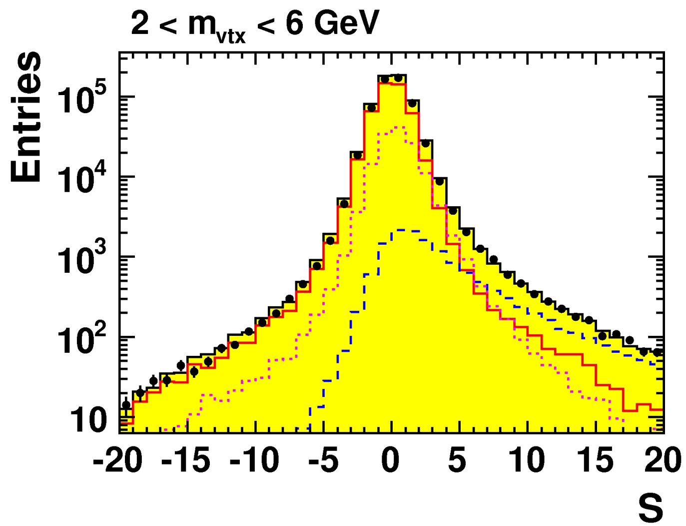
- The running of the charm mass in the $\overline{MS}$ scheme is measured for the first time from the combined HERA charm reduced cross section
- found to be consistent with expectations from QCD
- PDG value of m_c mainly obtained from lattice gauge theory and time-like processes → important consistency check

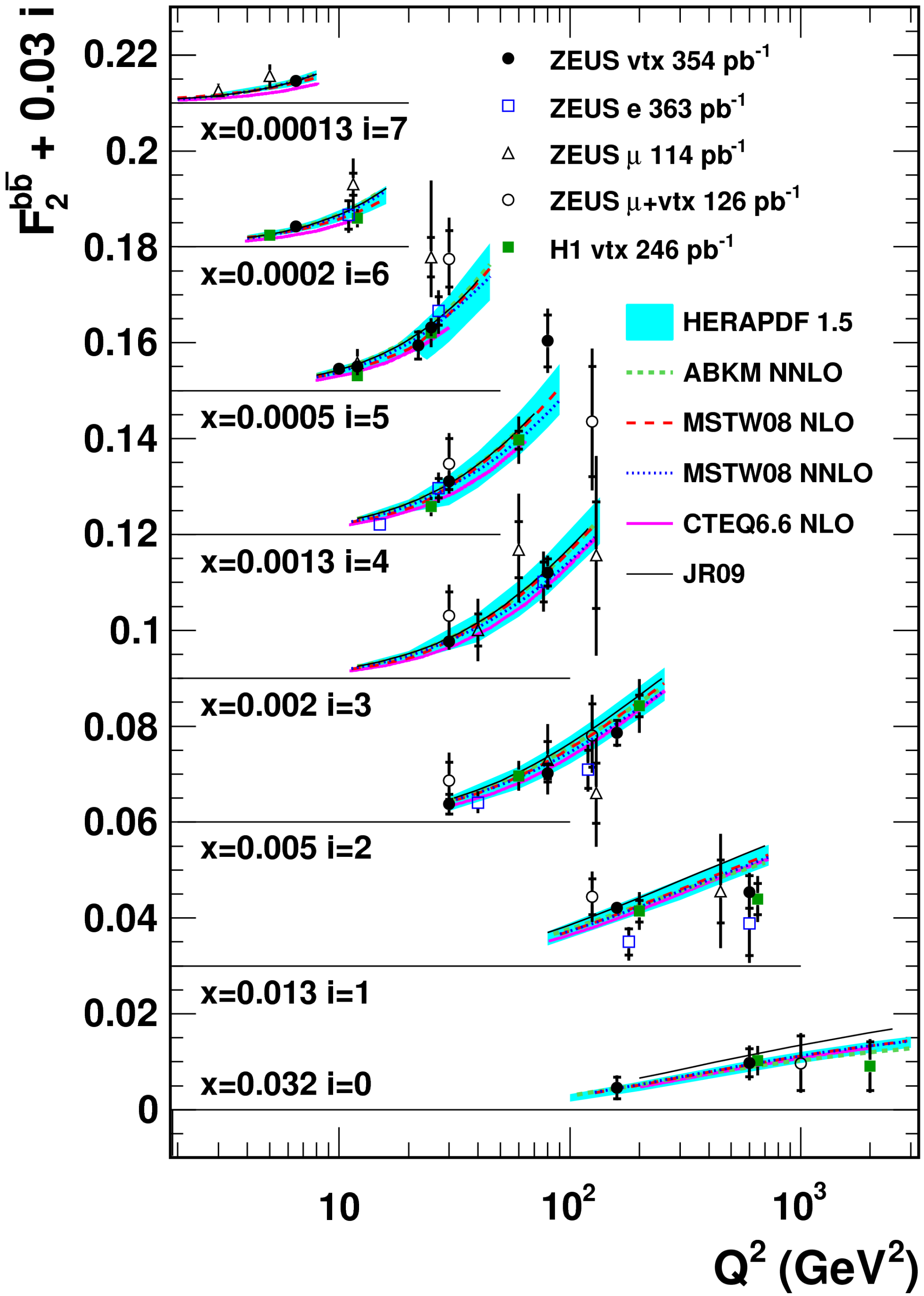
$F_2^{b\bar{b}}$ structure function

ZEUS: arXiv:1405.6915v1

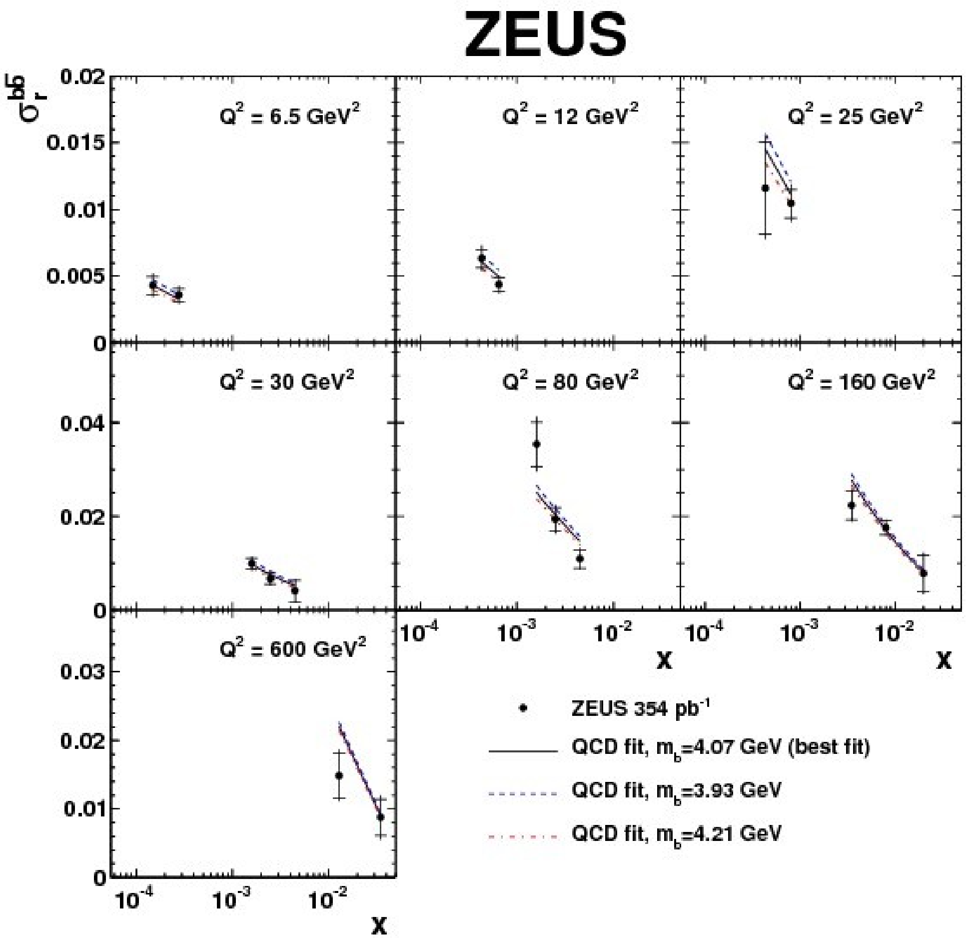
$\mathscr{L}$ = 354 pb^{-1}
Phase space: $5 < Q^2 < 1000$ GeV^2
$1.5 \cdot 10^{-4} < x < 0.035$

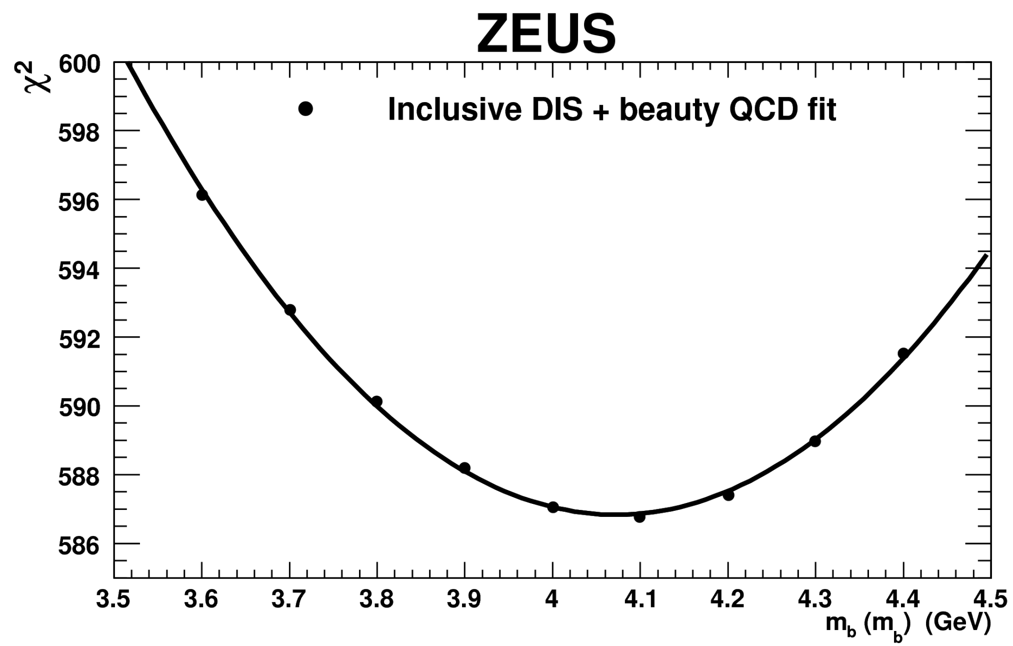
Events with at least 1 jet with invariant mass of charged tracks associated with secondary vertices and decay-length significance of these vertices





running beauty-quark mass





NLO FFNS fit used to extract the bottom quark mass ($\overline{MS}$ scheme):

ZEUS: $m_b(m_b) = 4.07 \pm 0.14\,(\text{fit})\ ^{+0.01}_{-0.07}(\text{mod.})\ ^{+0.05}_{-0.00}(\text{param.})\ ^{+0.08}_{-0.05}(\text{theo.})$ GeV

PDG: $m_b(m_b) = 4.18 \pm 0.03$ GeV

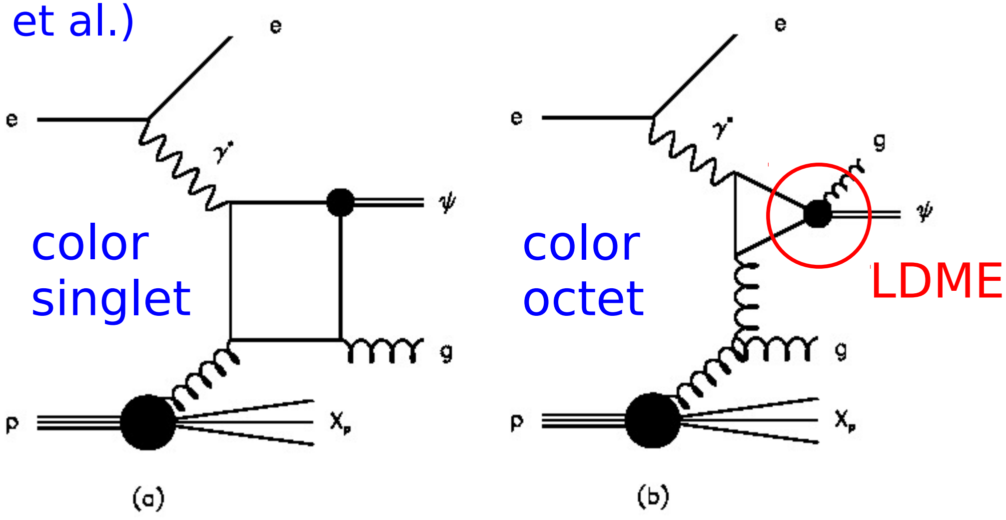
inelastic J/ψ photoproduction

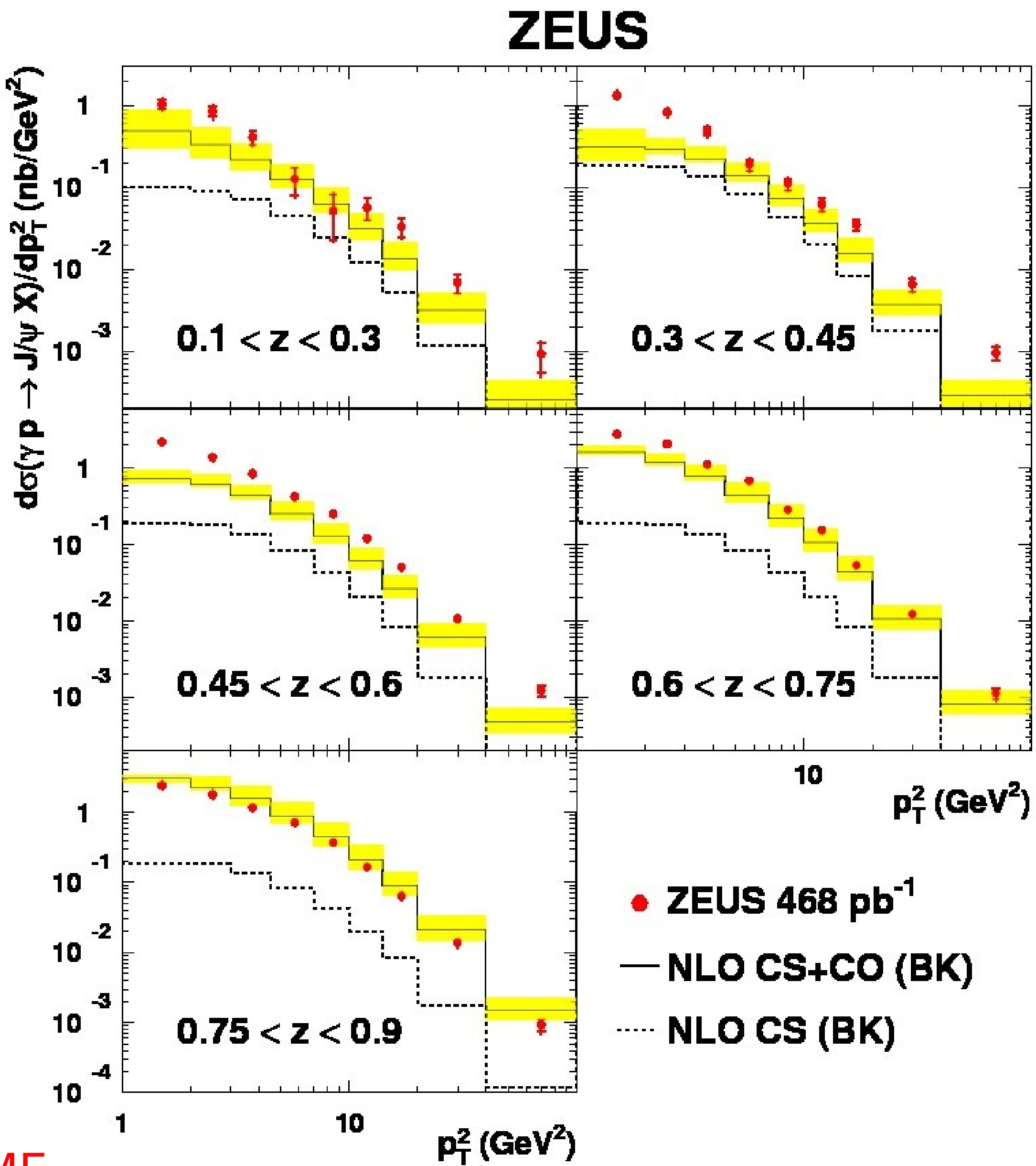
New measurement
ZEUS:arXiv:1211.6946 JHEP02(2013)071

Full HERA data
Photoproduction (Q^2 < 1 GeV^2)
γ-p cms energy 60 < W< 240 GeV

Double -differential in z, p_T^2
(z = E(J/ψ)/E(γ) in p rest frame)

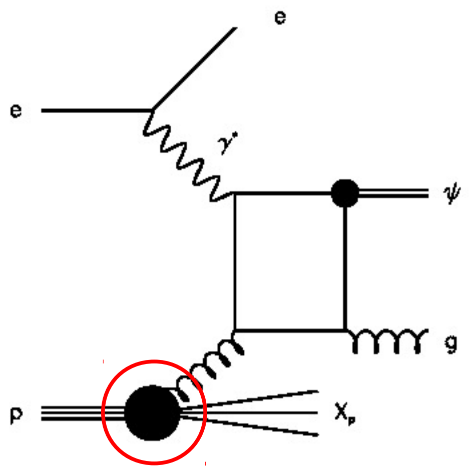
Compared to NLO NRQCD calculation
color octet long-distance matrix elements (LDMEs) from global fit to J/ψ data (Kniehl et al.)



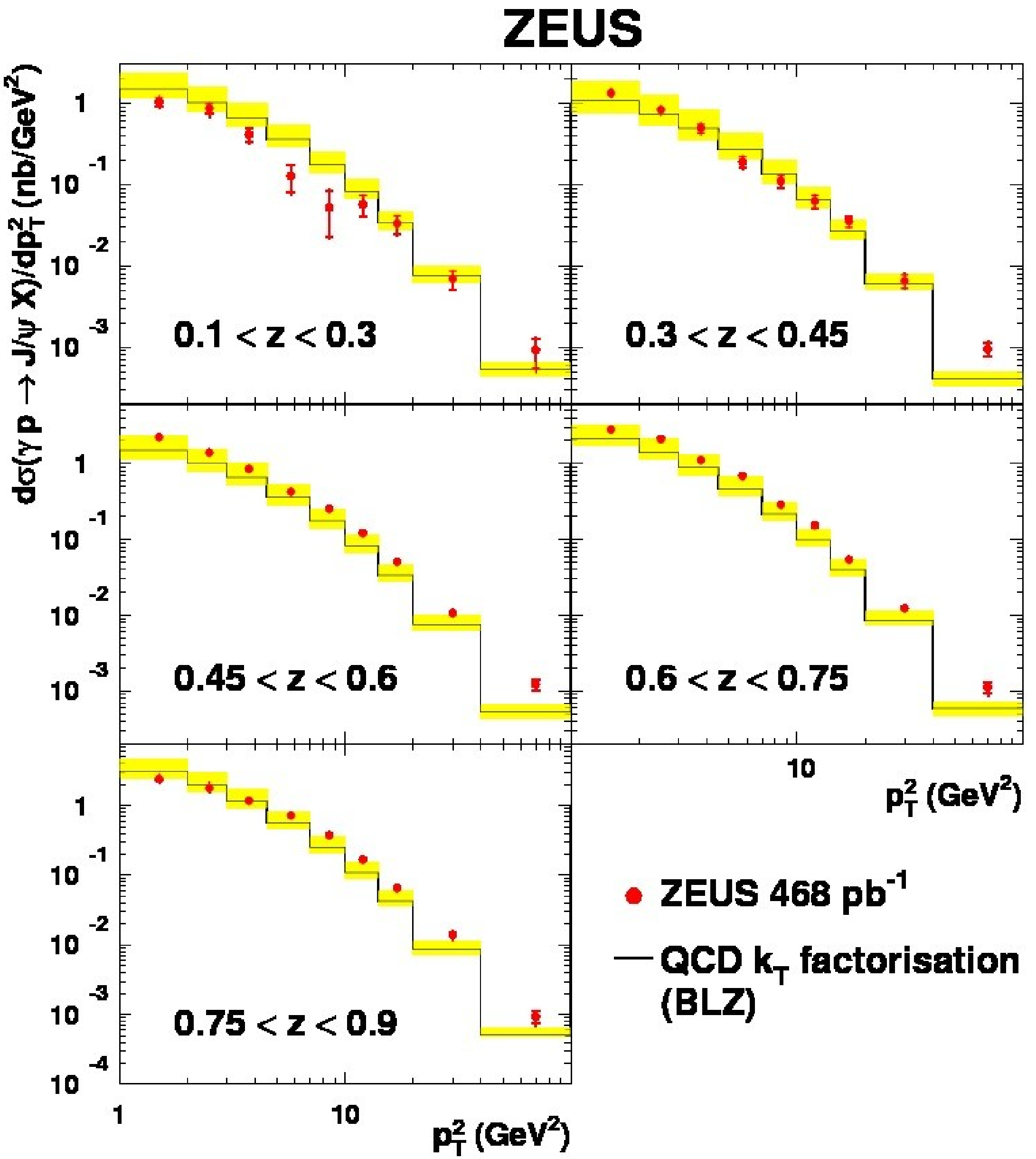


inelastic J/ψ photoproduction

Compared also to color singlet calculation with k_T factorization model (Baranov, Lipatov, Zotov)



unintegrated pdf $g(x,k_T,Q^2)$



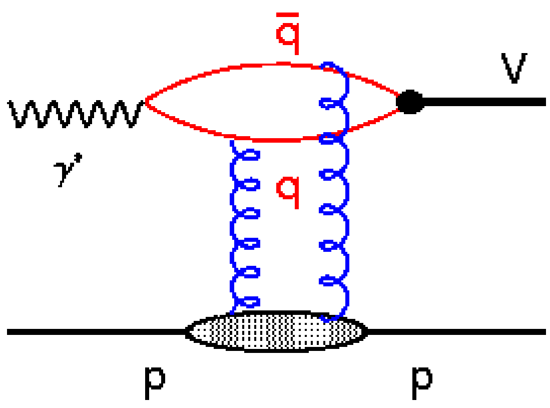
Both NRQCD and k_T factorization models provide reasonable but not perfect description of the data.

elastic J/ψ photoproduction

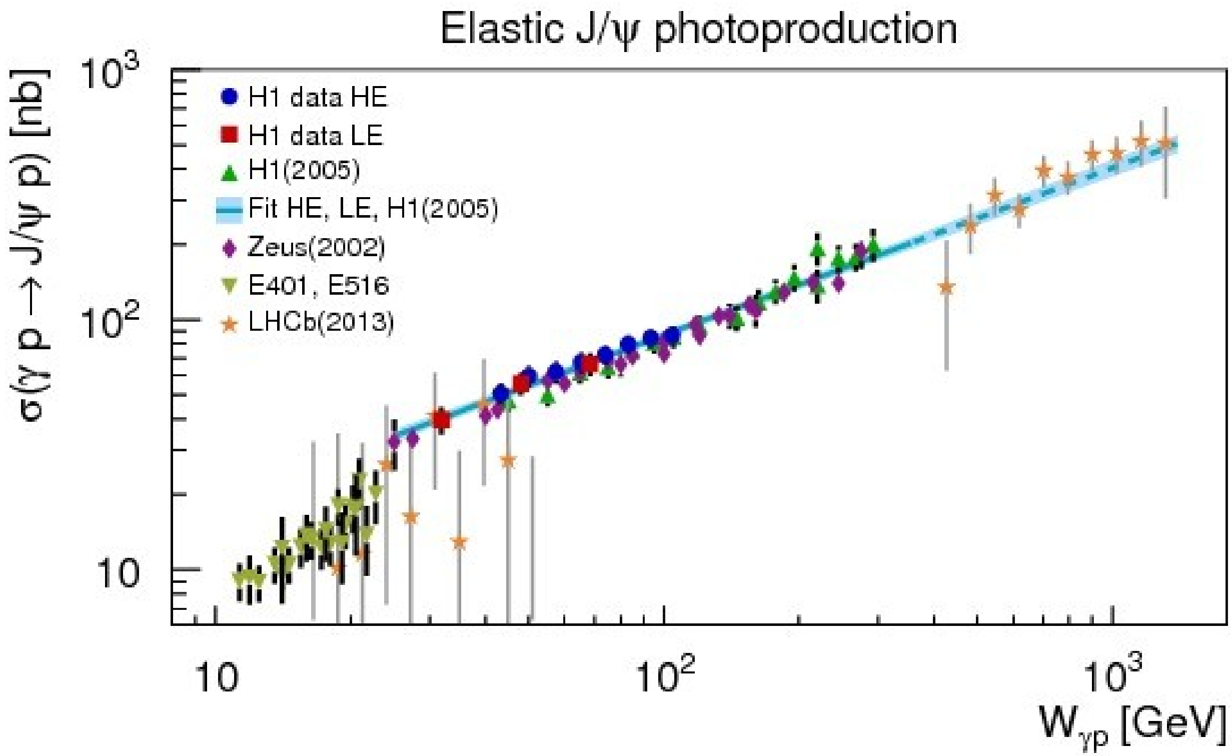
New H1 data: arXiv:1304.5162
EPJC 73(2013)2466

Significant gain in luminosity wrt previous data.

Elastic vector meson (VM) production:
the proton does not break
(no color exchange)



W = γp cms energy
t = $(p'-p)^2$



Power-law fit to W dependence at HERA:
Steeper than light VMs

Qualitative agreement with slope expected from g(x) growth at low x

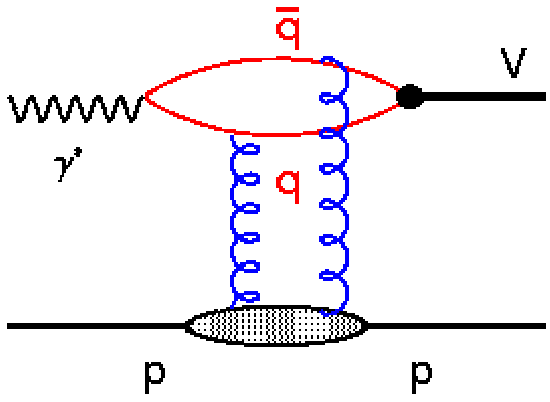
Extrapolation agrees well with LHCb data

elastic J/ψ photoproduction

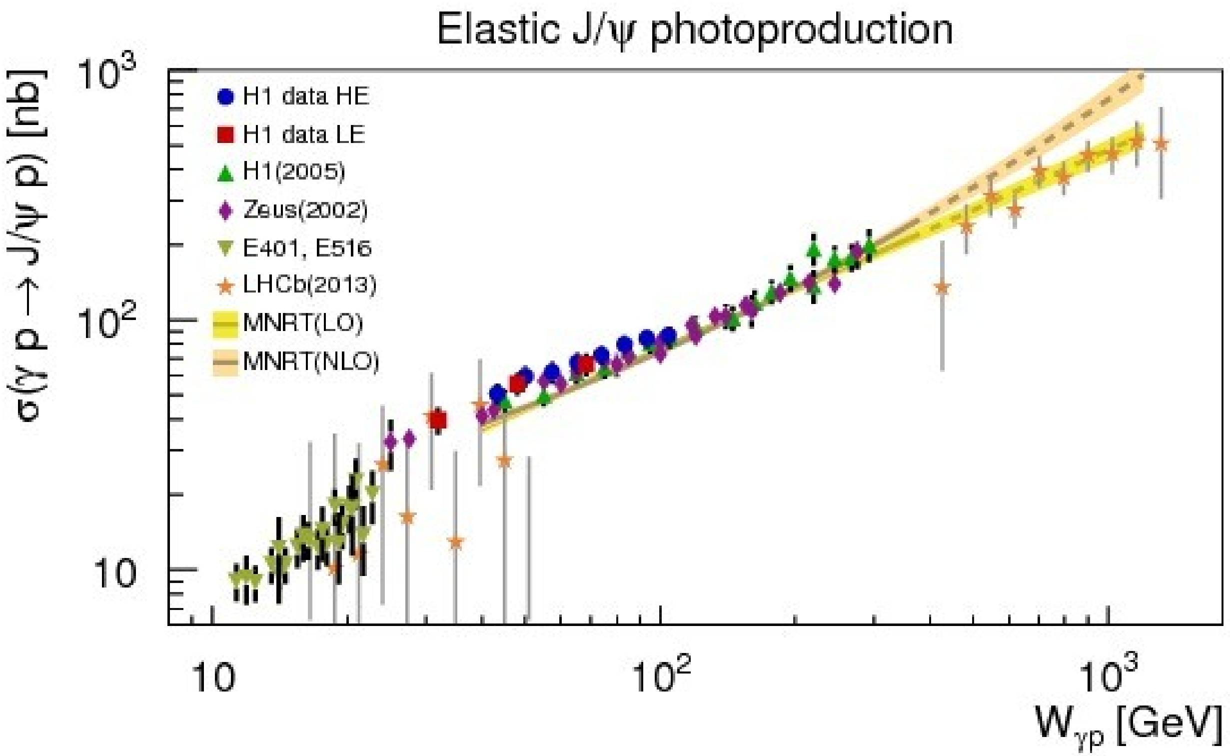
New H1 data: arXiv:1304.5162
EPJC 73(2013)2466

Significant gain in luminosity wrt previous data.

Elastic vector meson (VM) production:
the proton does not break (no color exchange)



W = γp cms energy
t = $(p'-p)^2$



Comparison to QCD analysis with g(x) based on fit to previous HERA data

W dependence too step, especially at NLO

Conclusions

- **H1 and ZEUS still providing new heavy flavour results, exploiting the full HERA statistics to put tighter constraint on QCD**

  - Fragmentation fractions:
    new precise measurements, support universality

  - Charm production in DIS:
    new measurements and HERA combination of previous ones put constraints on PDFs and on treatment of Heavy Quarks in QCD calculations

  - Beauty production in DIS:
    new precise measurements at high statistics (using secondary vertices)

  - Inelastic J/ψ production:
    new results, disfavour pure color-singlet models

  - Elastic J/ψ production:
    new precise measurements: tighter constraints on QCD models

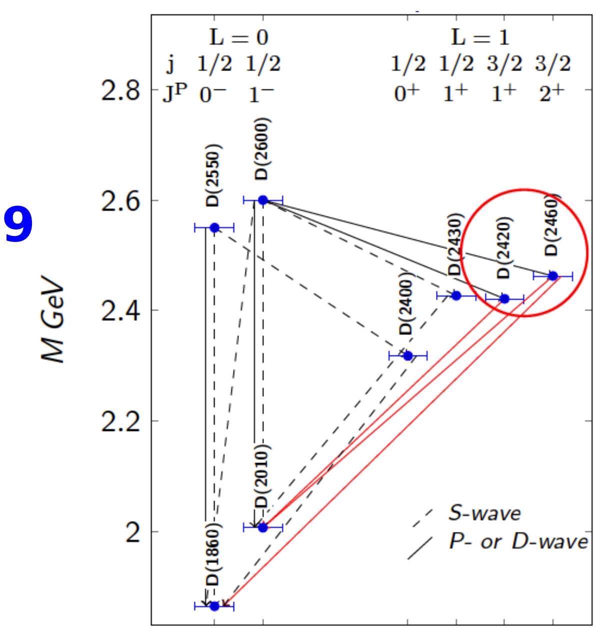
backup slides

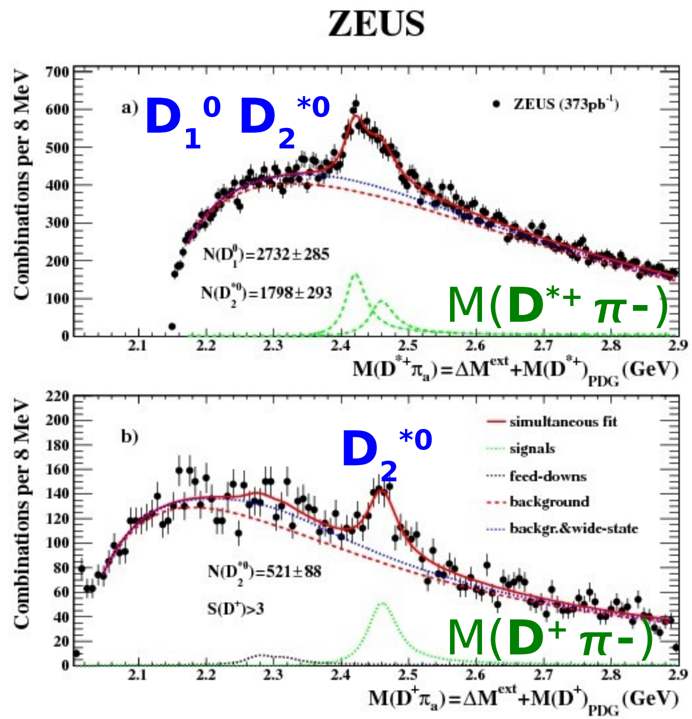
Excited Charm Mesons

$D_1(2420)^0$ and $D_2^*(2460)^{0,+/-}$

ZEUS: **NPB 866 (2013) 229**

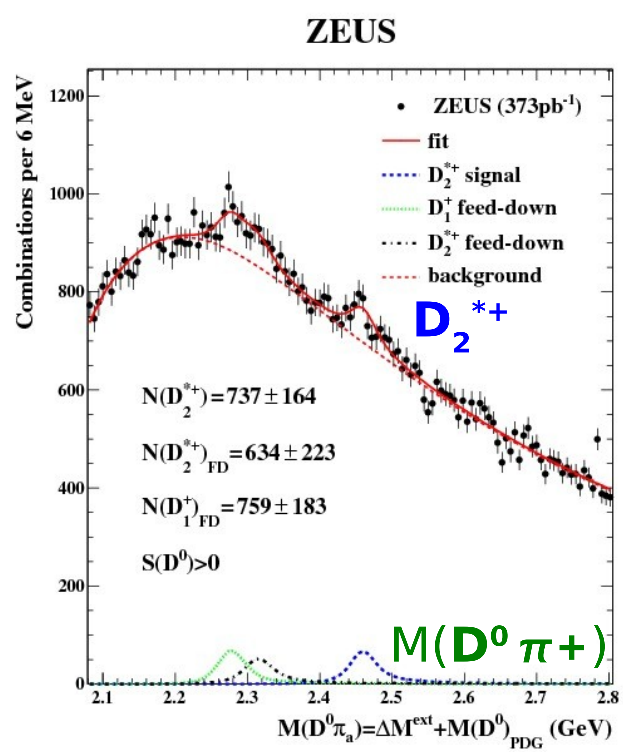
Masses, width of neutral states, D_1^0 helicity and BRs compatible with B-factory results





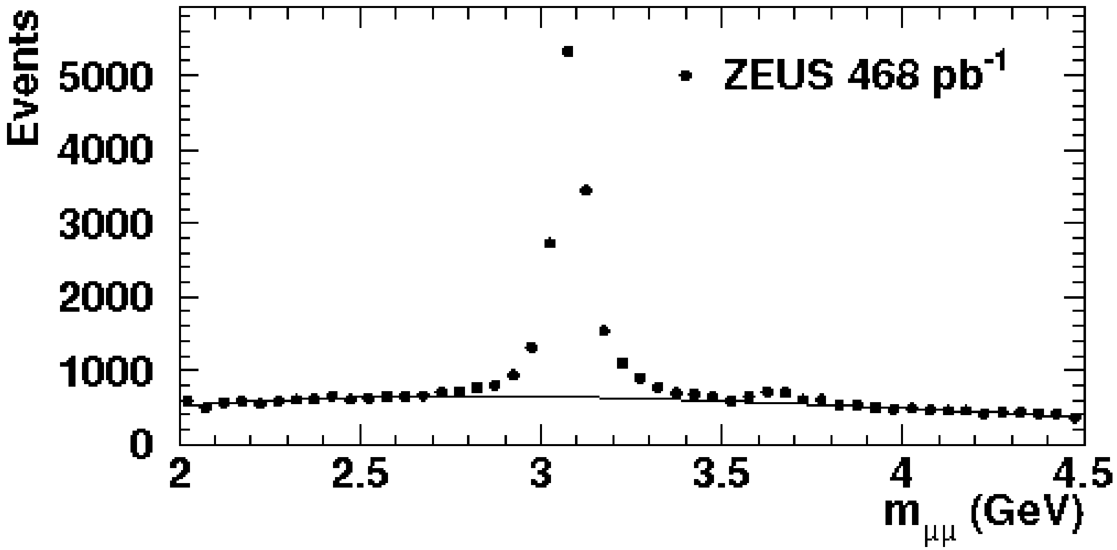
Fragmentation fractions %

	$f(c \to D_1^0)$	$f(c \to D_2^{*0})$	$f(c \to D_1^+)$	$f(c \to D_2^{*+})$
HERA-II	$2.9 \pm 0.5^{+0.5}_{-0.5}$	$3.9 \pm 0.9^{+0.8}_{-0.6}$	$4.6 \pm 1.8^{+2.0}_{-0.3}$	$3.2 \pm 0.8^{+0.5}_{-0.2}$
HERA-I	$3.5 \pm 0.4^{+0.4}_{-0.6}$	$3.8 \pm 0.7^{+0.5}_{-0.6}$		
OPAL	$2.1 \pm 0.7 \pm 0.3$	$5.2 \pm 2.2 \pm 1.3$		



data sample and selection

- $\mathcal{L}$ = 468 pb^{-1} (1996-2007)
- $Q^2 \sim 0$ GeV^2
- $60 < W < 240$ GeV
- $p_{T,\psi} > 1.0$ GeV
- $0.1 < z < 0.9$



backgrounds from other J/ψ production mechanisms

p-diffractive J/ψ

- *cut: Ntracks* ≧ **3**
- overall ~ 6 %
- **contribution** **subtracted**

ψ(2S) feed down (diff. + inel.)

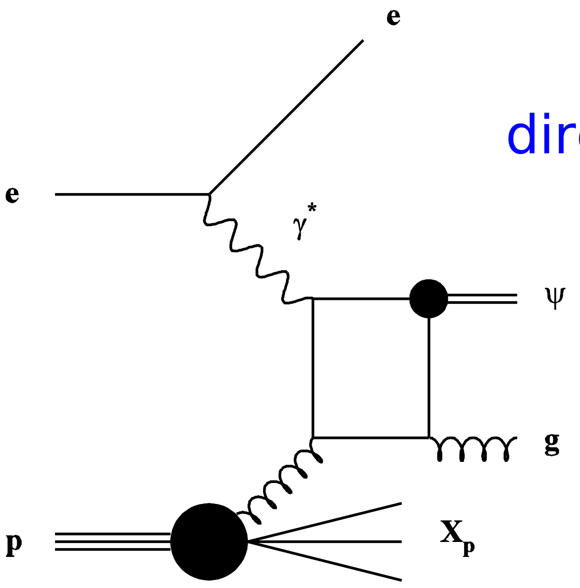
- overall ~ 15 %
- **contribution** **partially subtracted**

B **meson decays**

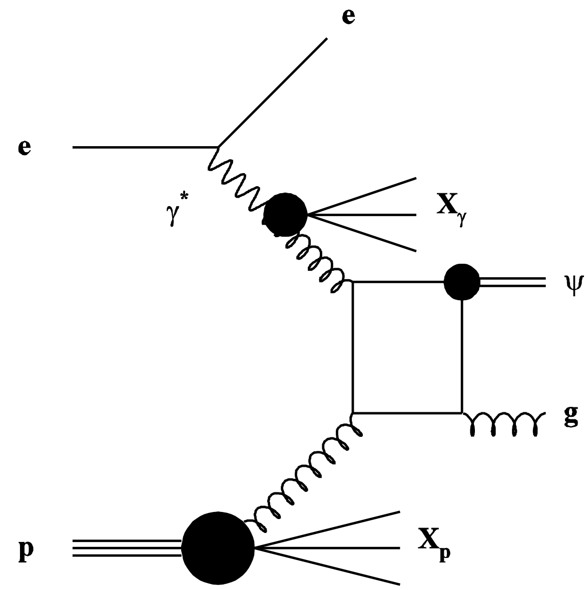
- overall ~ 1.6 %
- **contribution** **not subtracted**

inelastic J/ψ photoproduction

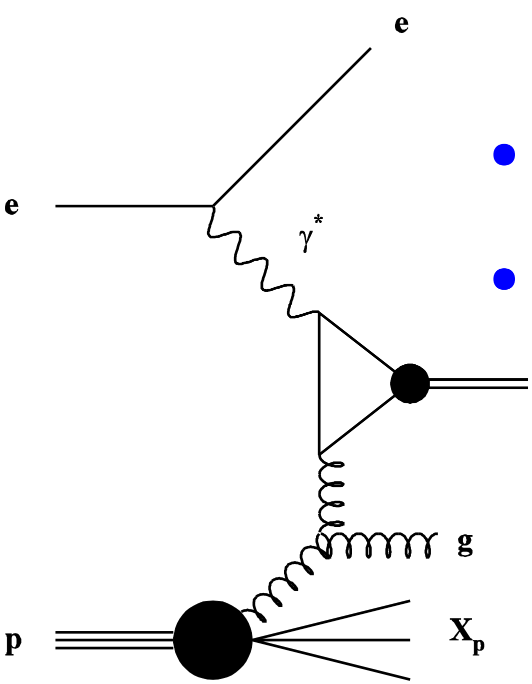
z = E(J/ψ)/E(γ)
p rest frame



direct γ, "CS model"
$0.2 < z < 0.9$



resolved γ, "CS model"
$z < 0.2$



direct γ, "CO model"

- this particular diagram
  $0.2 < z < 0.9$
- more "typical" ones:
  $z > 0.9$

+ other J/ψ production mechanisms:

- J/ψ from diffraction
- J/ψ from ψ' decays
- J/ψ from B mesons decays

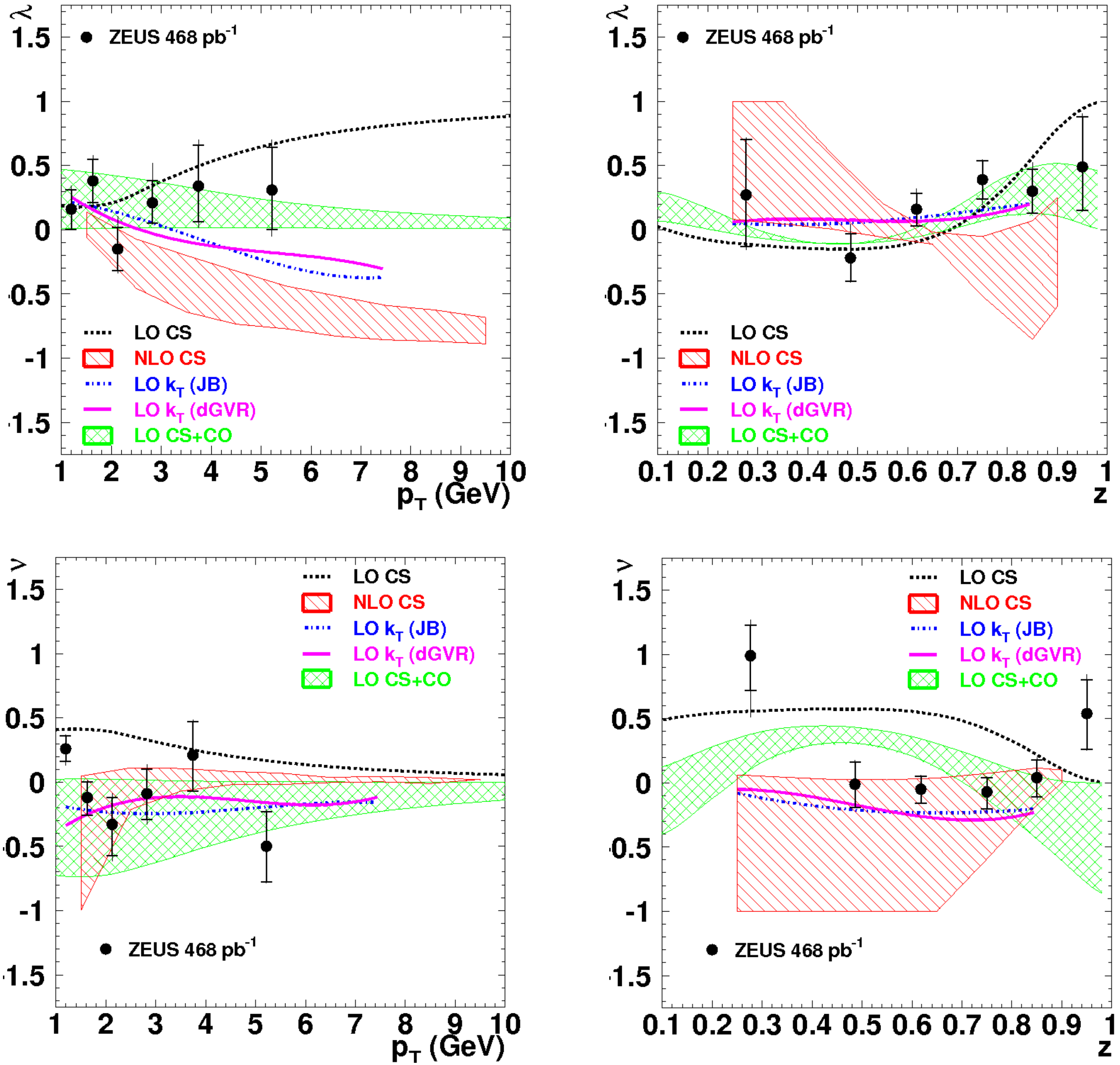
theoretical calculations

The measurements are compared with the following calculations:

- **NLO-CS+CO**: M. Butenschön, B. A. Kniehl, Phys. Rev. Lett. **104**, 072001 (2010).
  M. Butenschön, B. A. Kniehl, DESY 11-046 arXiv:1105.0820v1
  - the calculation contains both direct and resolved photon contributions
  - includes the full relativistic corrections due to $^1S_0^{[8]}$, $^3S_1^{[8]}$, $^3P_J^{[8]}$ CO states
  - CO long-distance matrix elements (universal function) extracted from all available high-quality data of inclusive J/ψ production

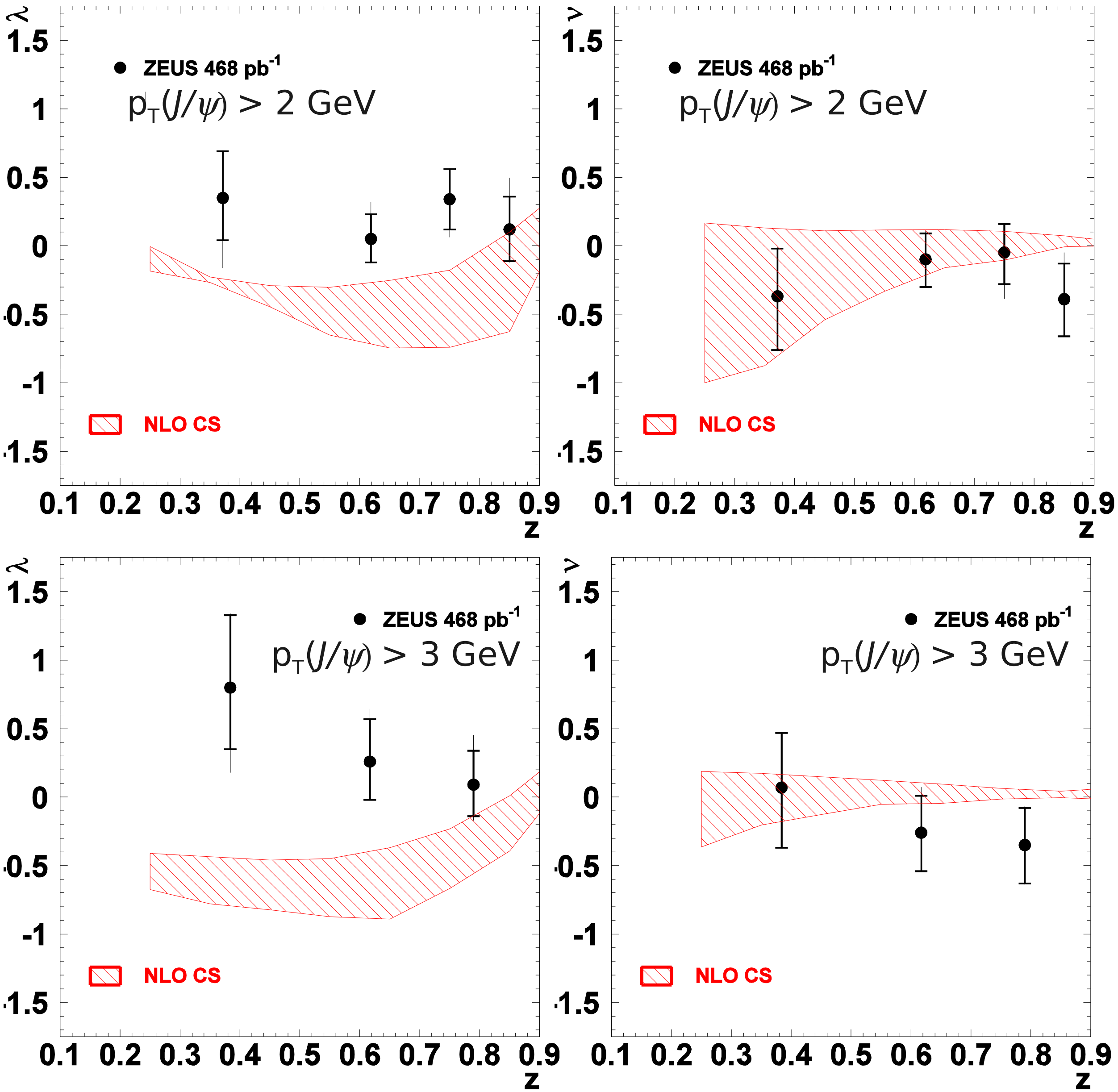
- **LO-k_T** : S.P. Baranov, A.V. Lipatov and N.P. Zotov, Eur. Phys. J. **C 71**, 1631 (2011)
  - only CS contribution taken into account
  - k_T factorization
  - unintegrated gluon distribution

ZEUS data: Helicity frame



JHEP 12 (2009) 007

ZEUS data: Helicity frame



NLO predictions for:

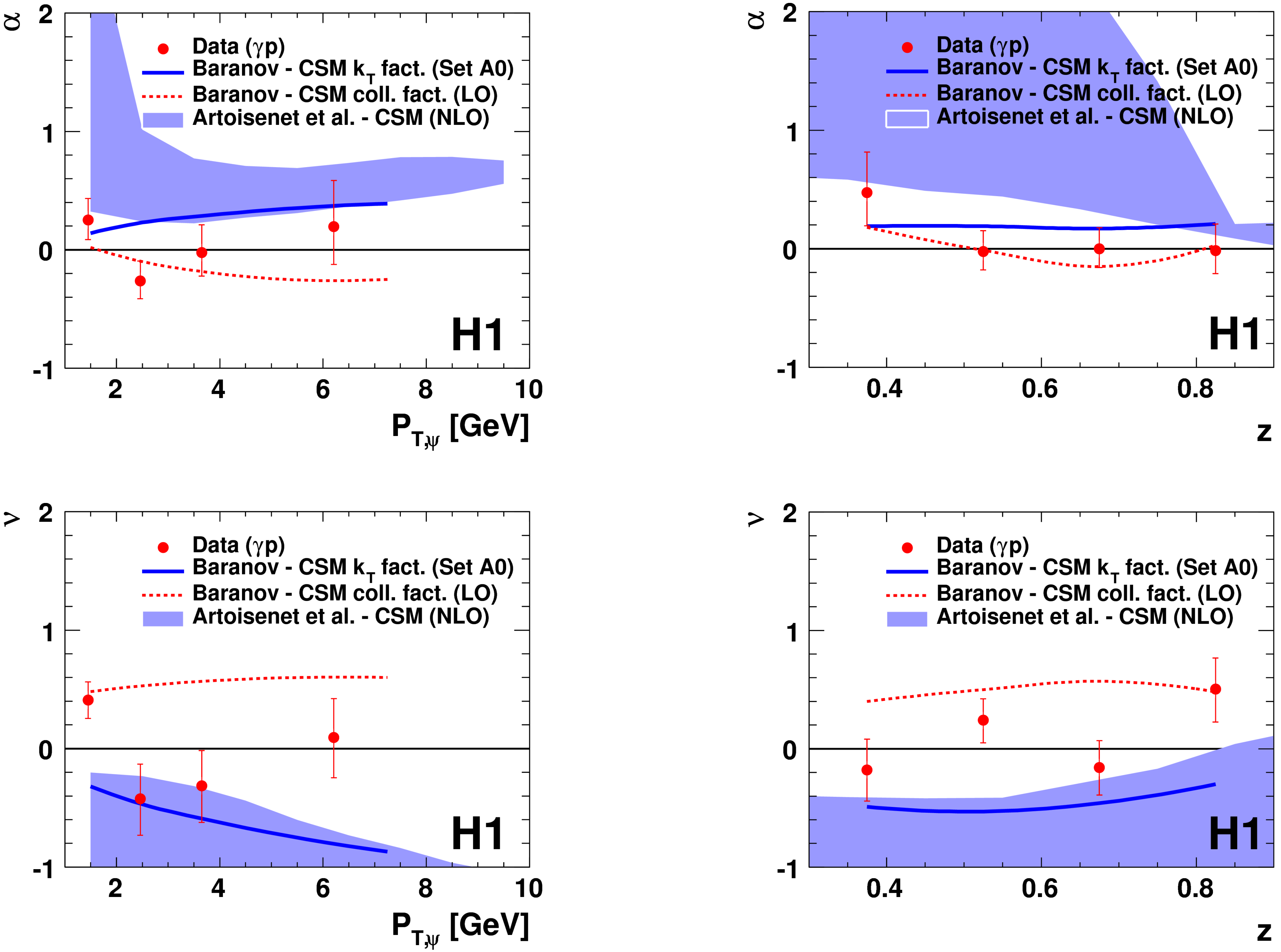
- $p_T(J/\psi) > 2$ GeV
- $p_T(J/\psi) > 3$ GeV

NLO calculation has reduced uncertainties … unlikely experimental errors grow … and the agreement between NLO and data does not really improve …

JHEP 12 (2009) 007

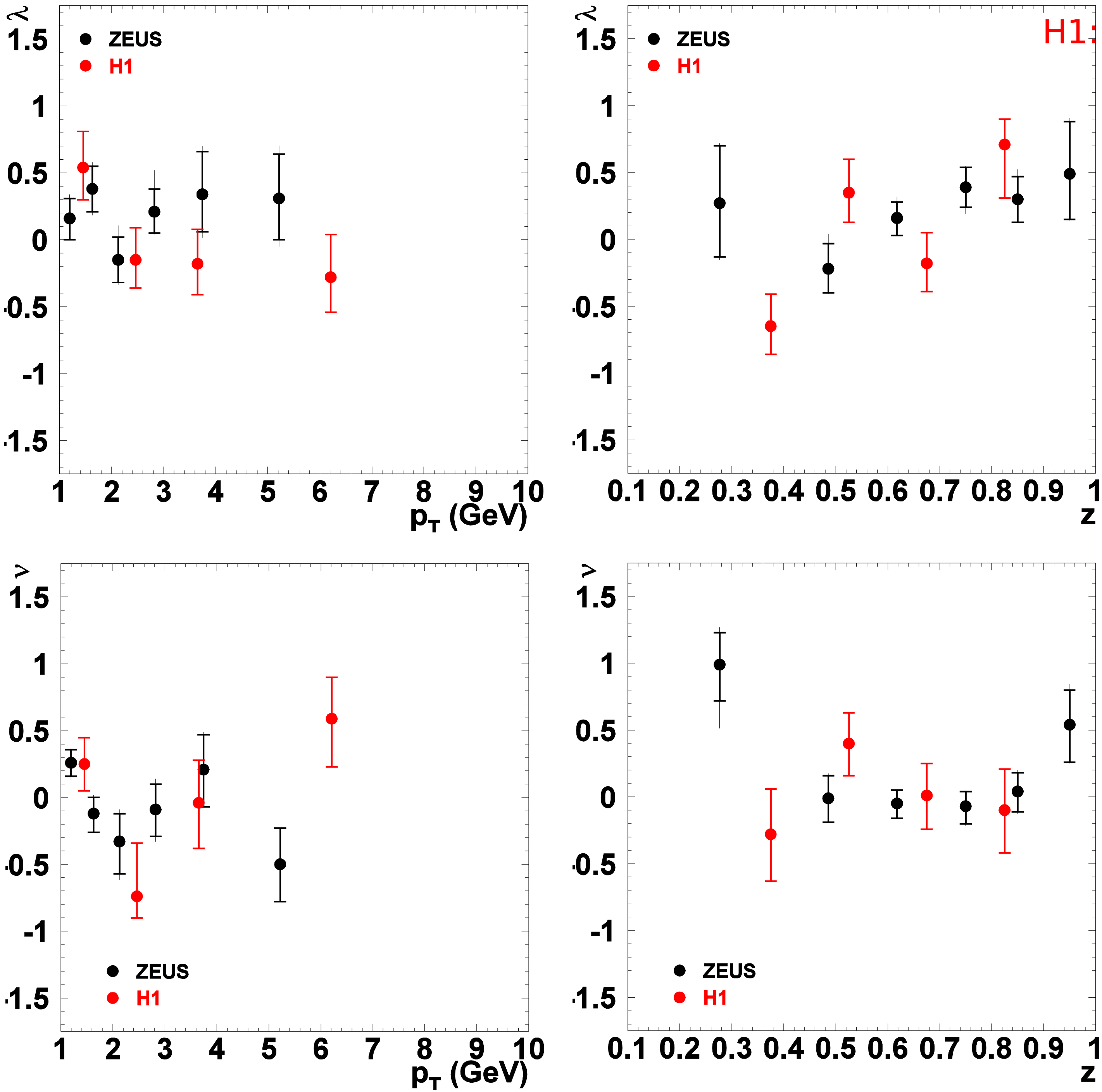
H1 data: Collins-Soper Frame

Eur. Phys. J. C68 (2010) 401



ZEUS: JHEP12 (2009) 007

H1: Eur. Phys. J. C 68 (2010) 401



even if the ZEUS and H1 analysises differ in several details the overall results are compatible