PHI/PSI 13 Workshop,
Roma September 9-13, 2013

# Charm Physics at HERA

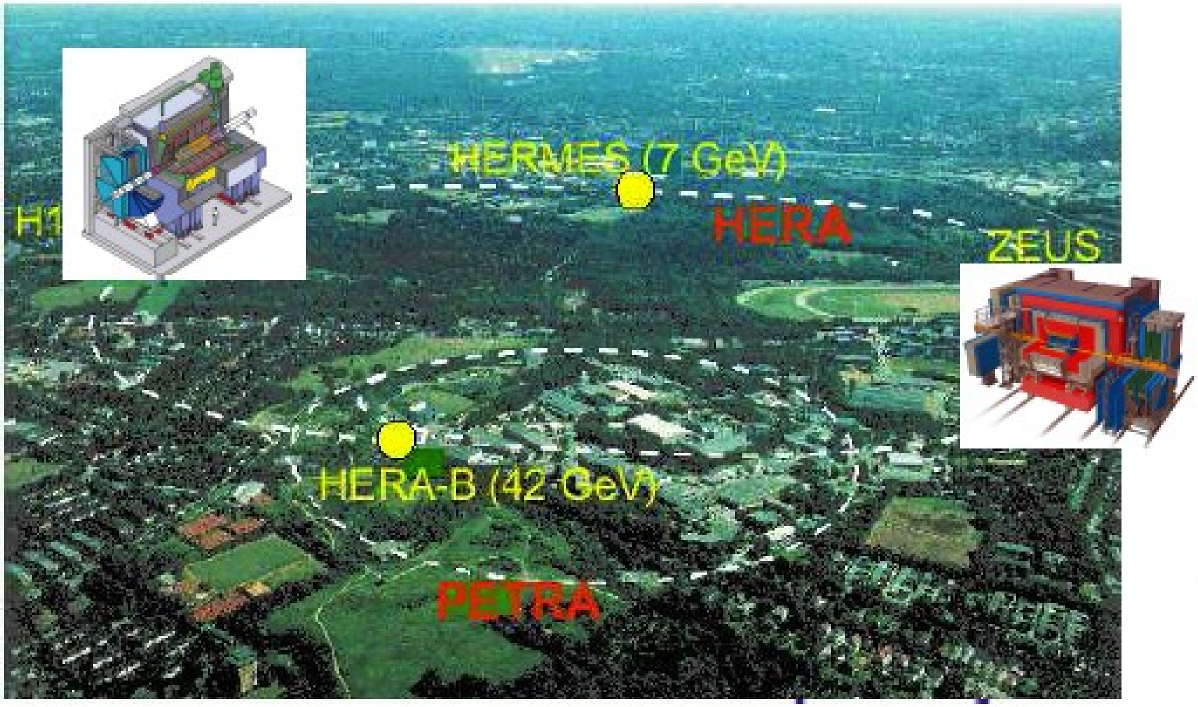
*Massimo Corradi (INFN Bologna)*
*on behalf of*

ZEUS
1992 - 2007

# Overview

- Charm fragmentation fractions
- Open charm production in DIS
- $J/\psi$ photo-production

# HERA data

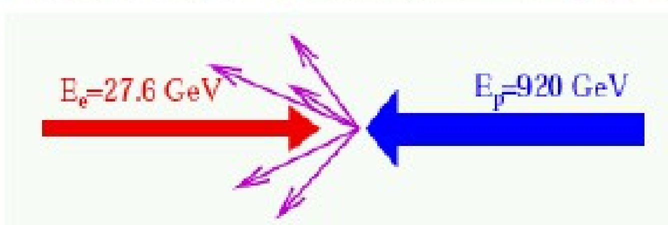


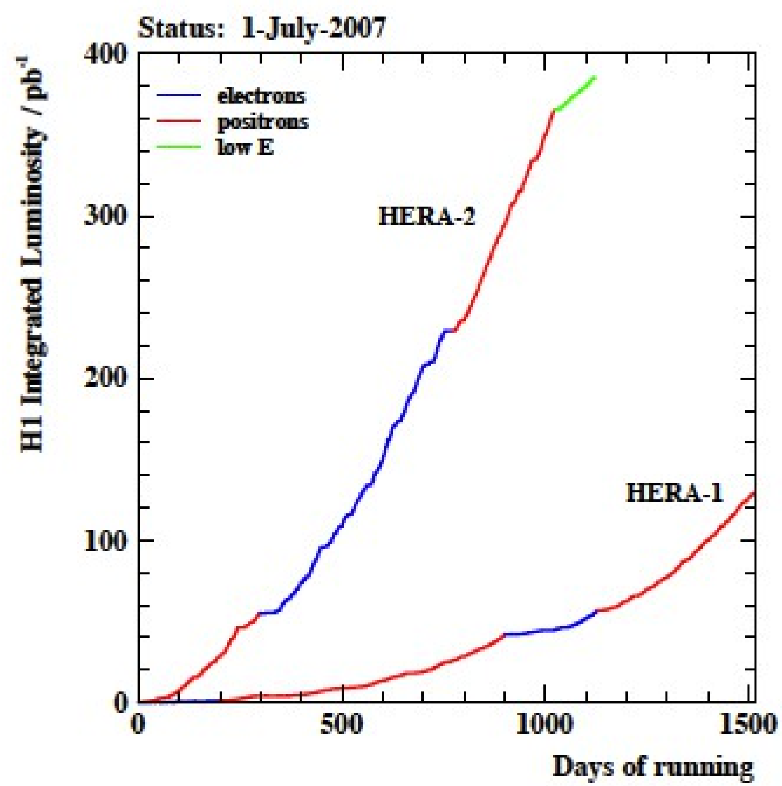

**HERA-1** (1993-2000) $\simeq 120\ \text{pb}^{-1}$

**HERA-2** (2003-2007) $\simeq 380\ \text{pb}^{-1}$

Final Data samples

H1+ZEUS: $2 \times 0.5\ \text{fb}^{-1}$

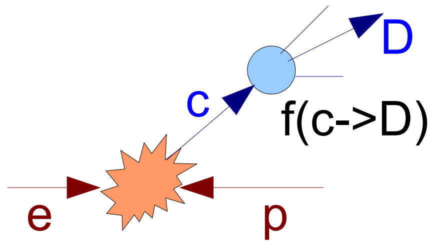



- 1998 $E_p$ upgrade: $820 \Rightarrow 920$ GeV
  ($\sqrt{s}$ : $301 \Rightarrow 319$ GeV)
- 2001 HERA-2 upgrade: $\mathcal{L} \times 3$, Polarised $e^+/e^-$
  ($\langle P \rangle = 40\%$)

# Charm fragmentation fractions

# Charm fragmentation fractions

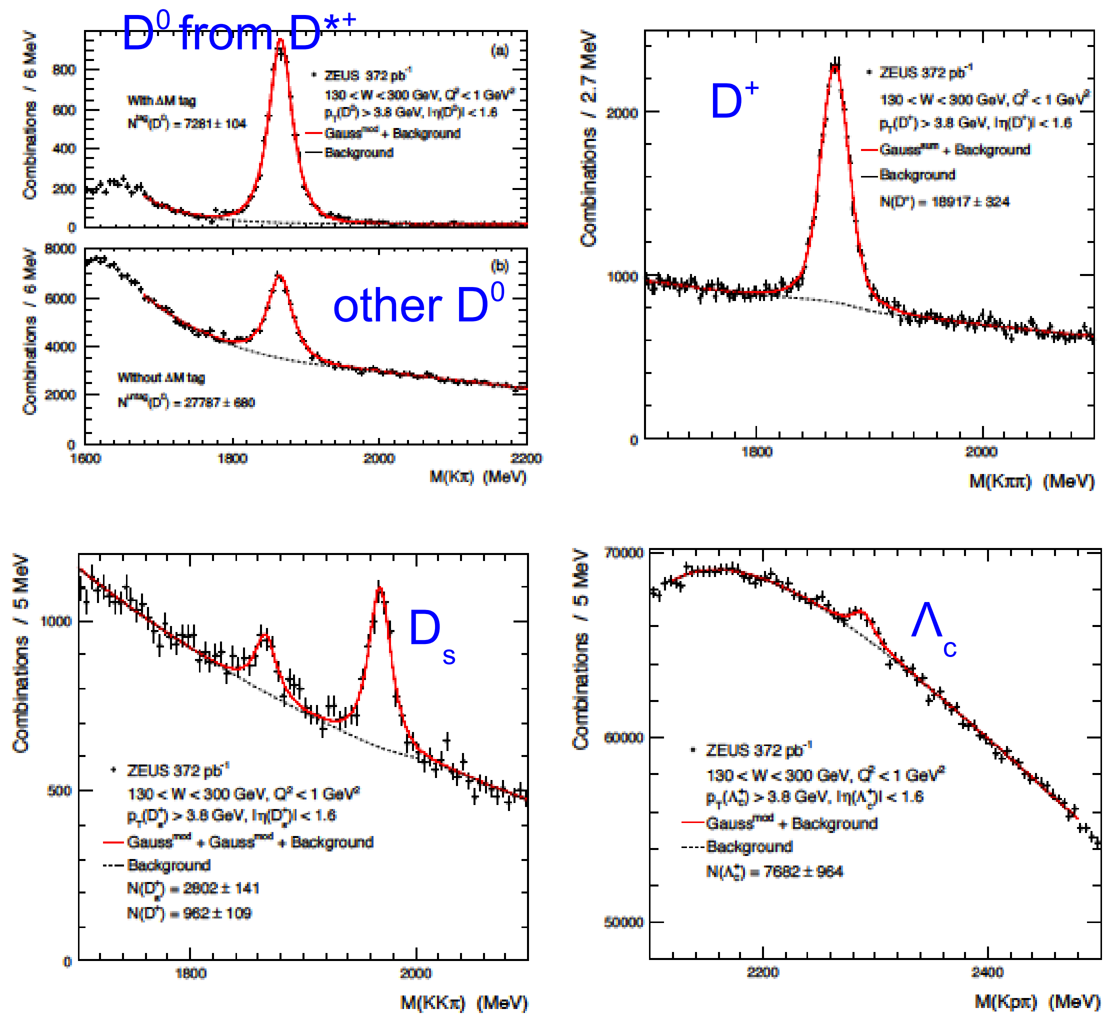



- New ZEUS photoproduction measurement arXiv:1306.4862 (accepted by JHEP)

- Fragmentation fraction f(c->D): needed to go from partonic QCD calculations to hadron cross sections

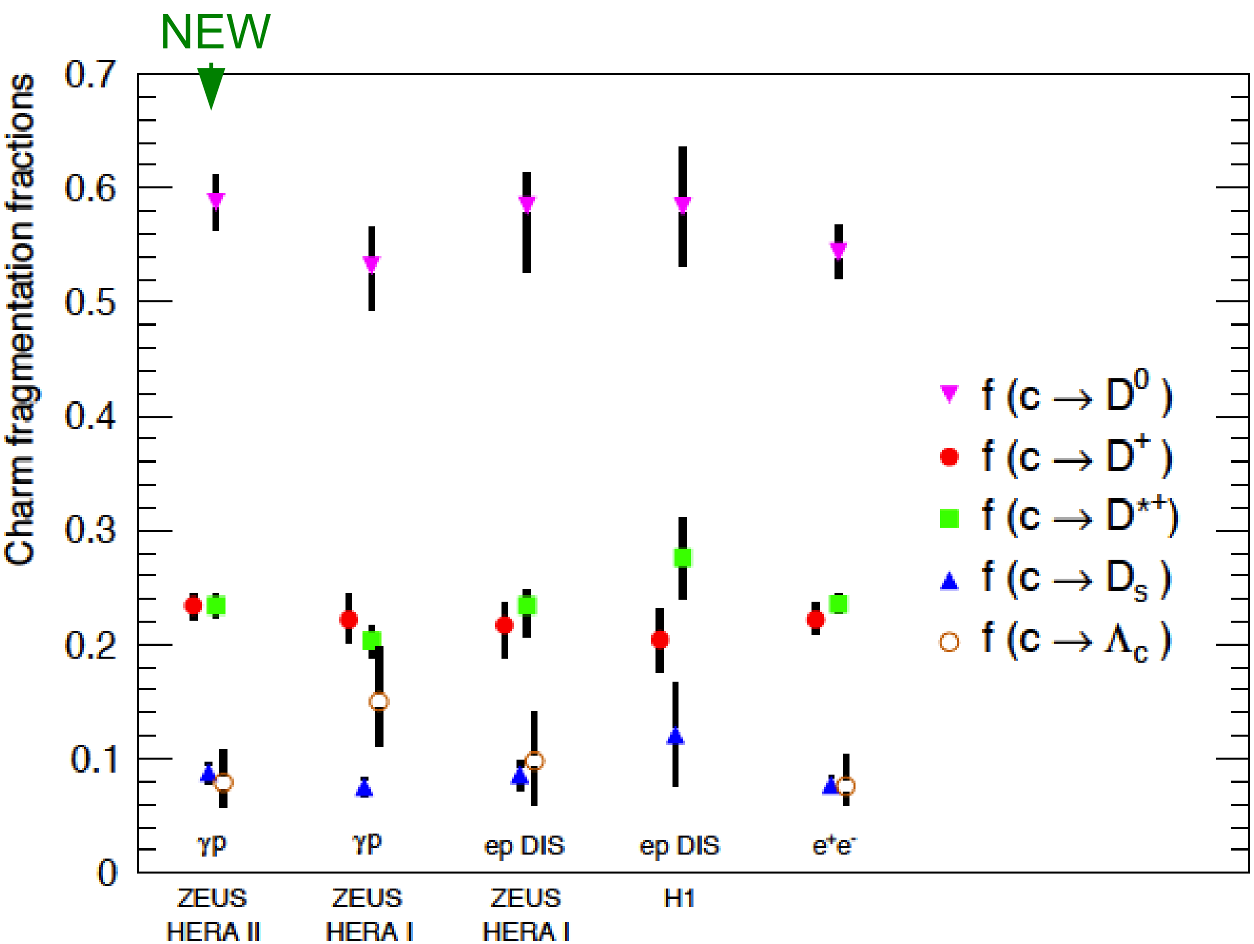
- All charm ground state hadrons are measured (except charm-strange baryons)

- Measured for $p_T$>3.8 GeV
  "equivalent phase space" treatment minimizes extrapolation to $p_T$=0

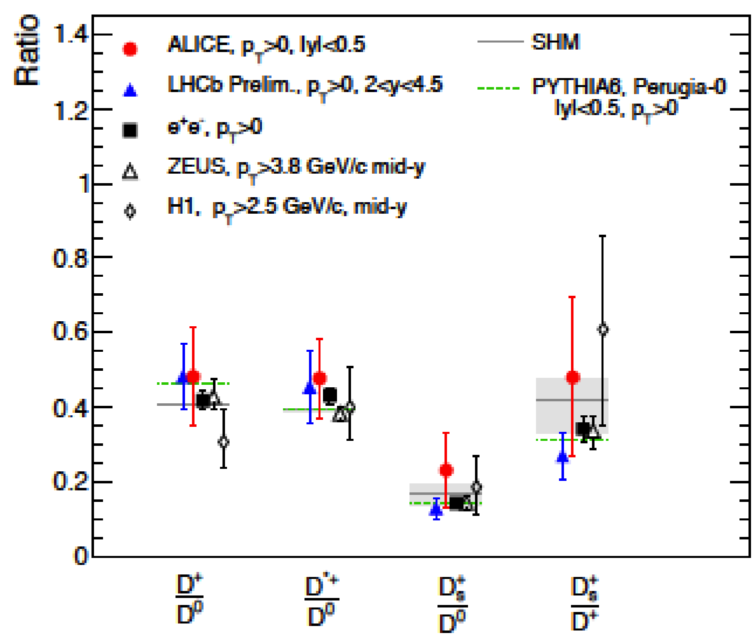


# Fragmentation fraction results

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




Universality supported by LHC pp data (ALICE + LHCb)

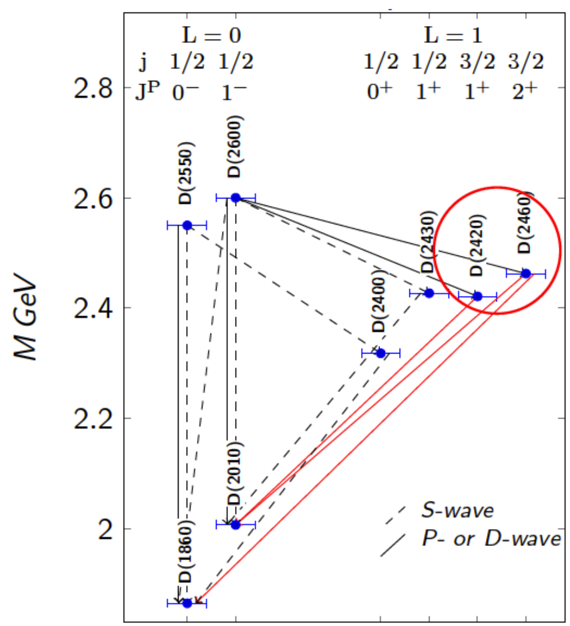


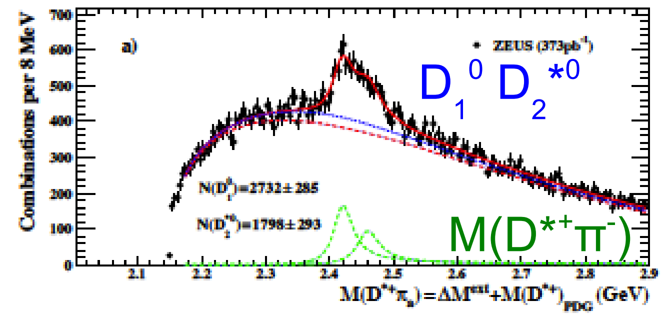
# Excited Charm Mesons

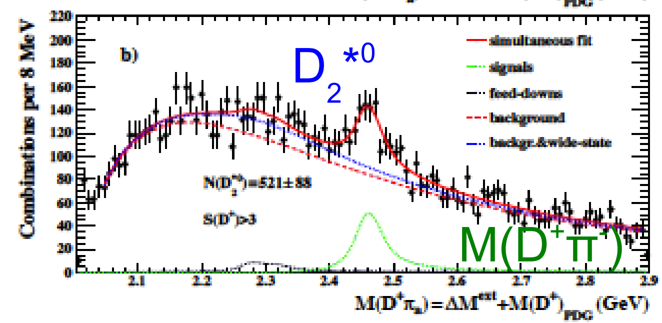
$D_1(2420)^0$ and $D_2^*(2460)^{0,+/-}$

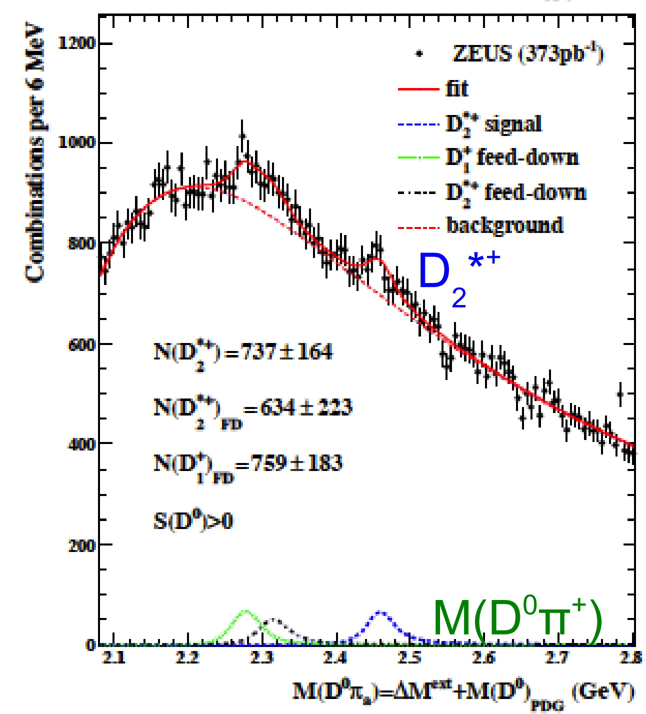
ZEUS arXiv:1208.4468
NPB 866 (2013) 229

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



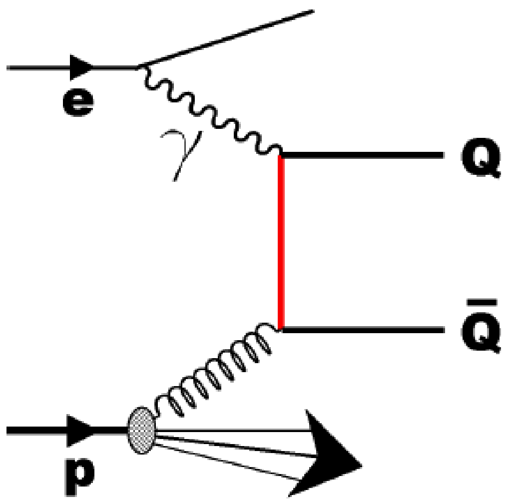

Fragmentation fractions (in %):

| | $f(c \to D_1^0)$ | $f(c \to D_2^{*0})$ | $f(c \to D_1^+)$ | $f(c \to D_2^{*+})$ |
|---|---|---|---|---|
| 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 | $2.1 \pm 0.7 \pm 0.3$ | $5.2 \pm 2.2 \pm 1.3$ | | |

# Charm production in DIS

# Heavy quark production in DIS

Leading Order :
Boson-gluon fusion (BGF)




- access to g(x)

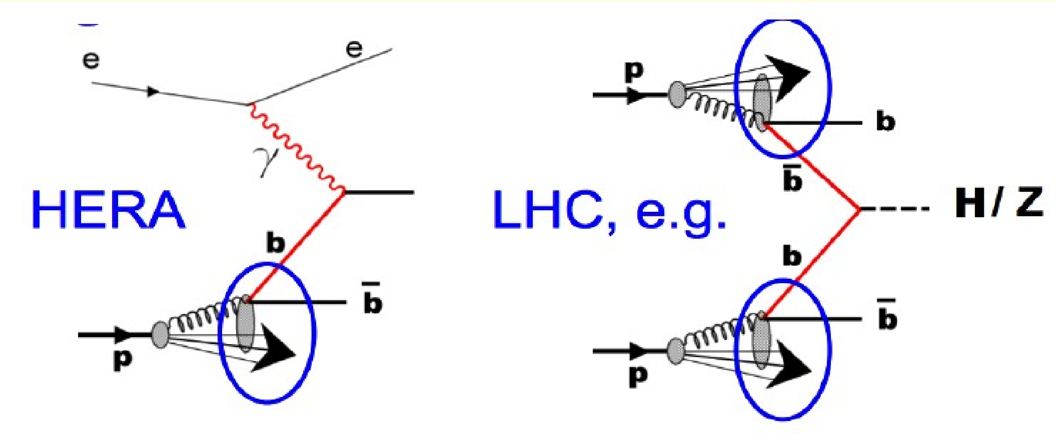
- sensitivity to $m_c$

- test of GM-VFNS heavy flavour schemes used in global PDF fits

Theory of heavy quark production:

1) Fixed Flavour Number Scheme (FFNS)
- nf=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 Numer Scheme (GM-VFNS).
- equivalent to FFNS for $m_c^2 < Q^2$
- c,b treated as massless parton for $Q^2 > m_c^2$
- interpolation in between (various schemes available)
- used by global PDF fits (useful at LHC...)



# Charm production in DIS

Several methods used to tag charm :
- $D^*$, $D^+$, $D^0$, μ, secondary vertices

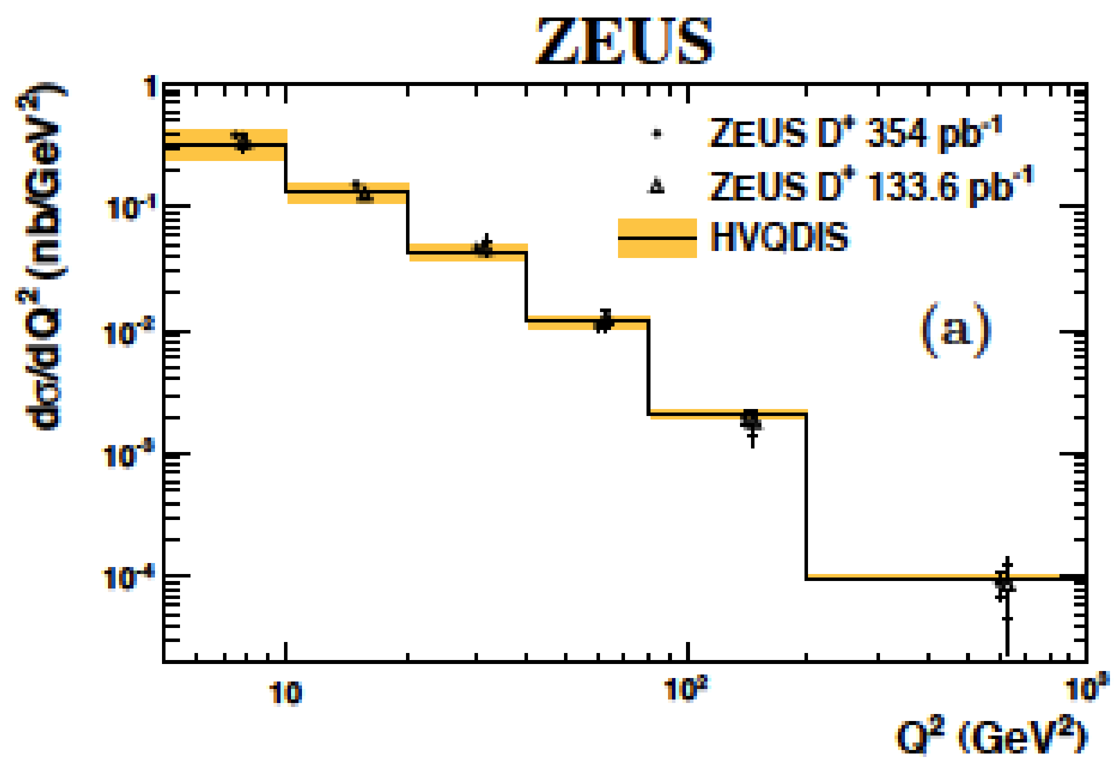
New results from ZEUS HERA-II data:
- $D^*$ arXiv:1303.6578 JHEP05(2013)097
- $D^+$ arXiv:1302.5058 JHEP05(2013)023

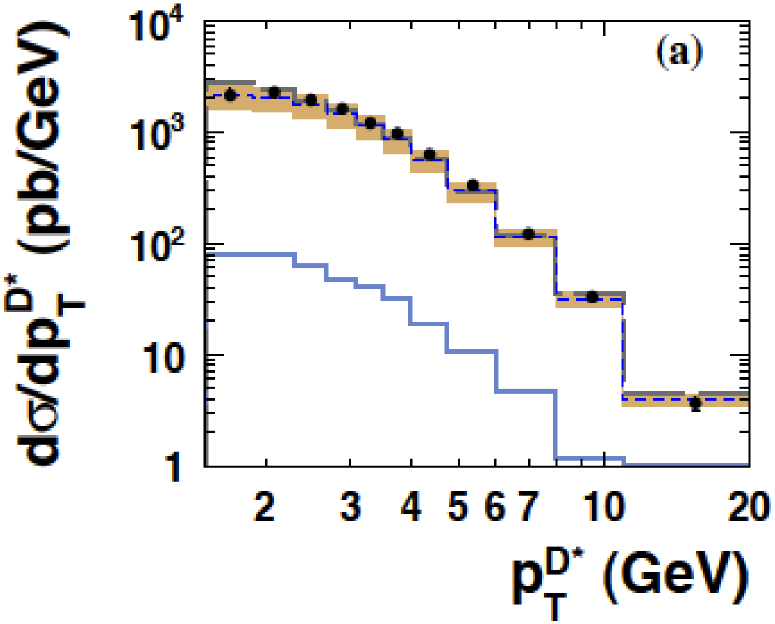
- Cross sections in “visible” phase space (for $D^*$):

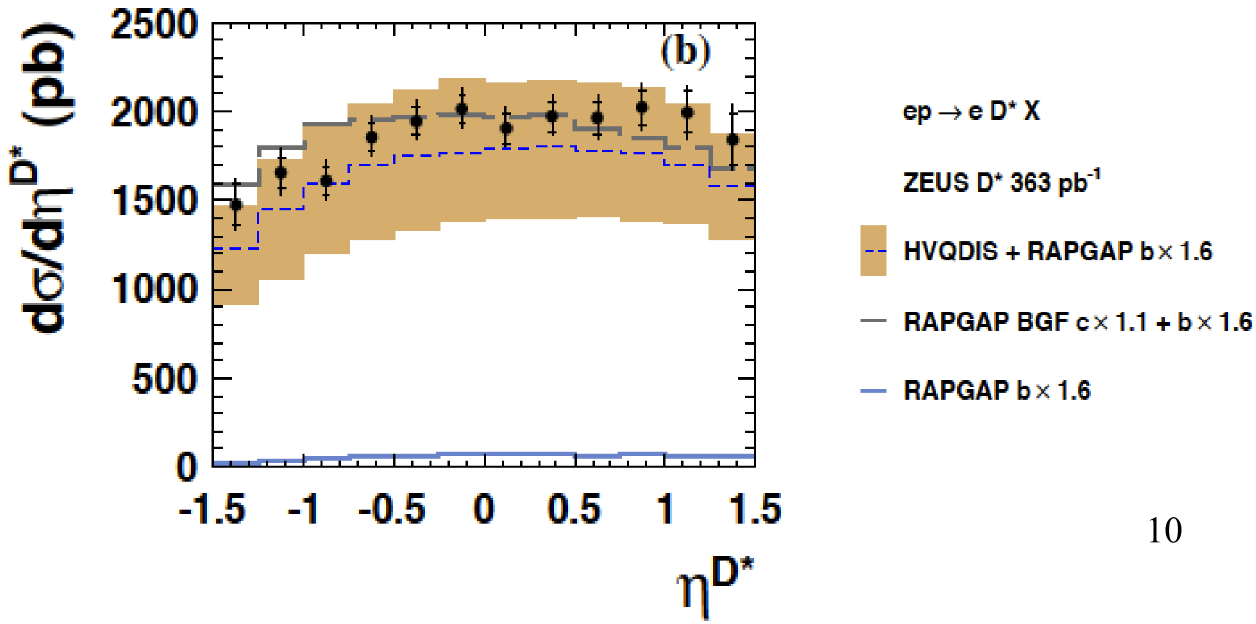
  $p_T > 1.5$ GeV, $|\eta| < 1.5$,

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

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



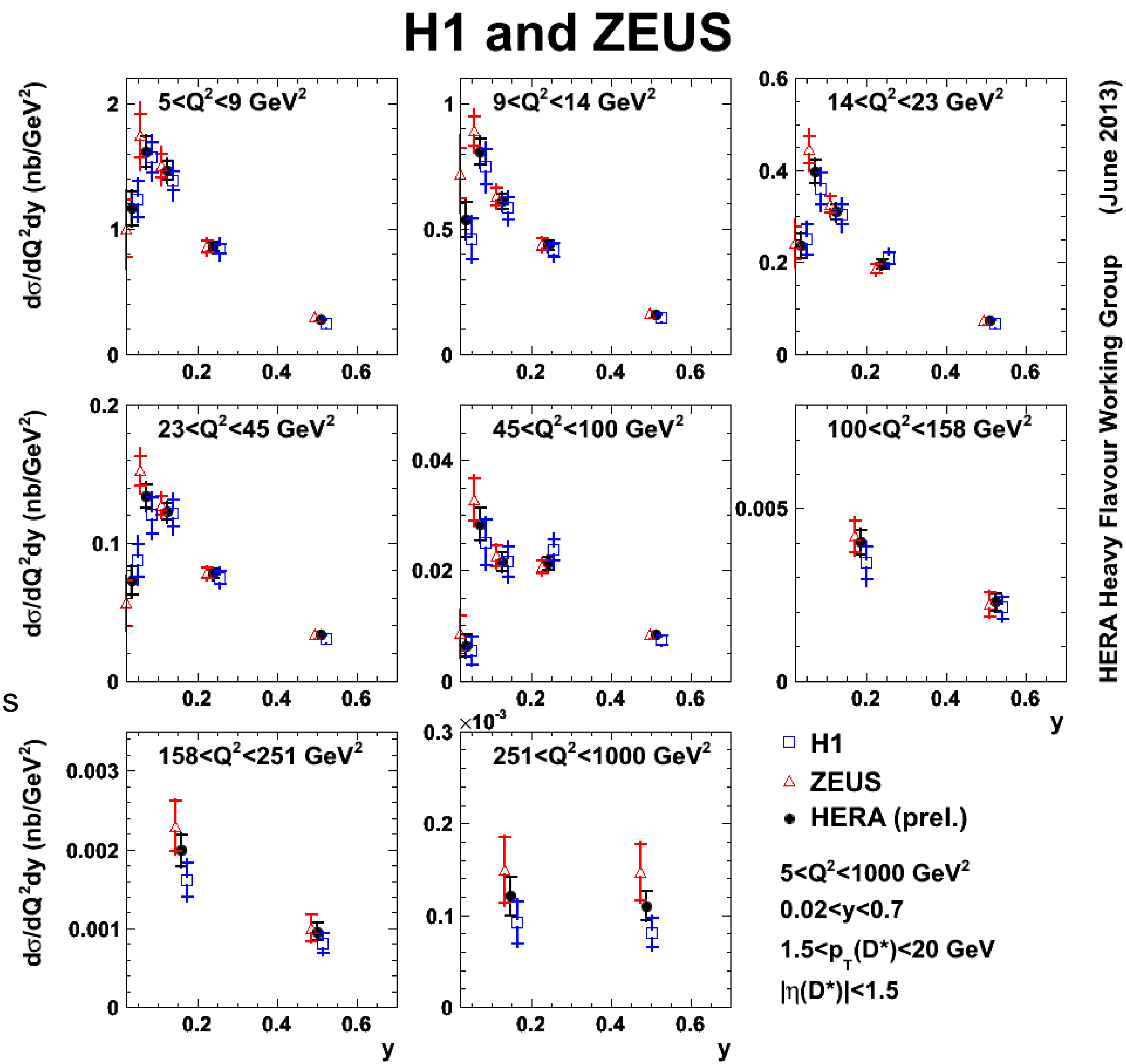



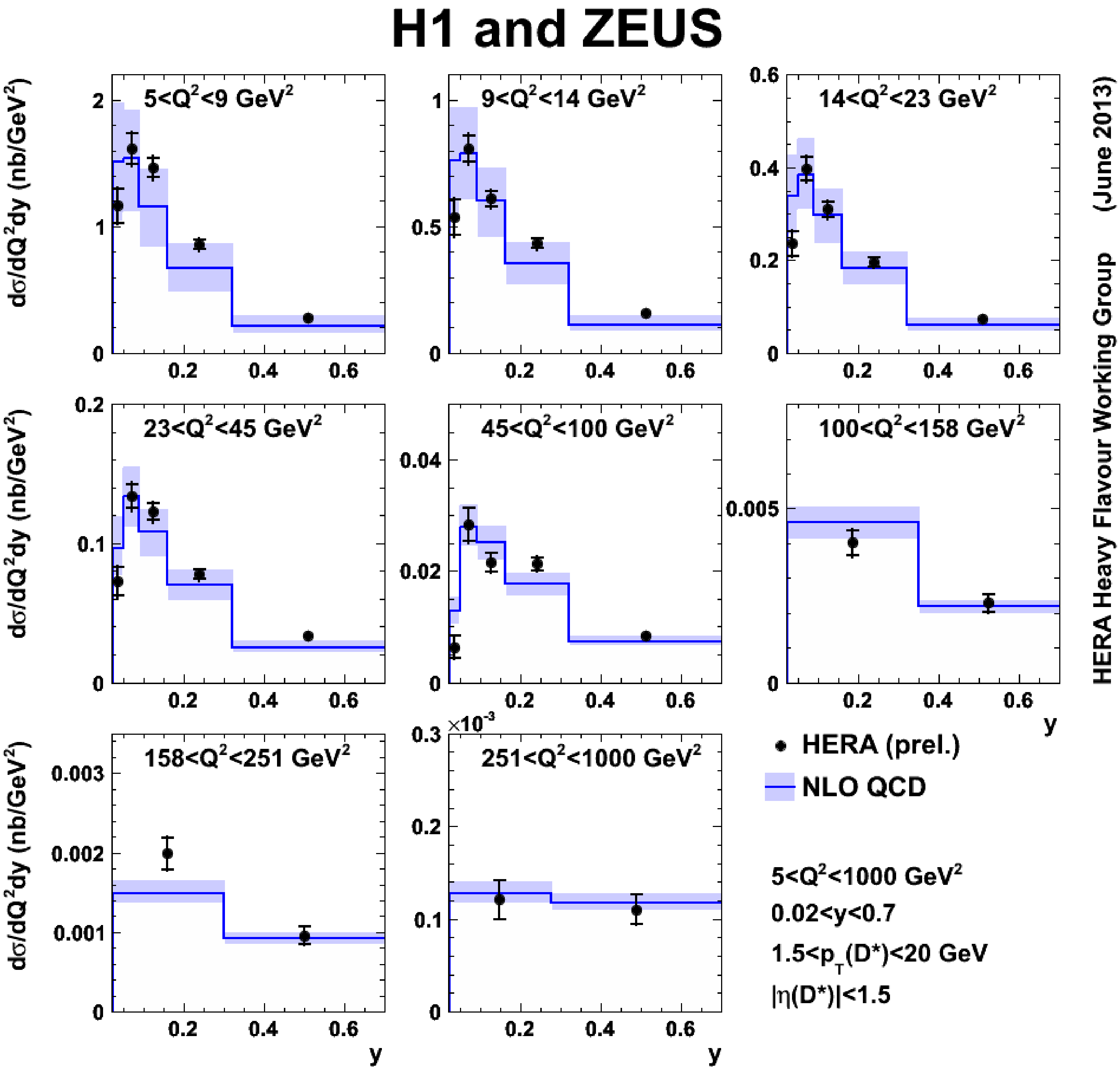
Double-differential "visible" D* cross sections in $Q^2$-y bins

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

The two results have been combined in HERA (prel.) "visible" cross sections



Combination
in good agreement
with NLO FFNS
theory (HVQDIS)



# $F_2^{c\bar{c}}$ and $\sigma_{red}^{c\bar{c}}$

Reduced charm cross section defined in analogy to inclusive DIS:

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

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

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

Obtained from cross sections in visible phase space ($\sigma_{vis}$) in [Q2, y] bins

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

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-$Q^2$)

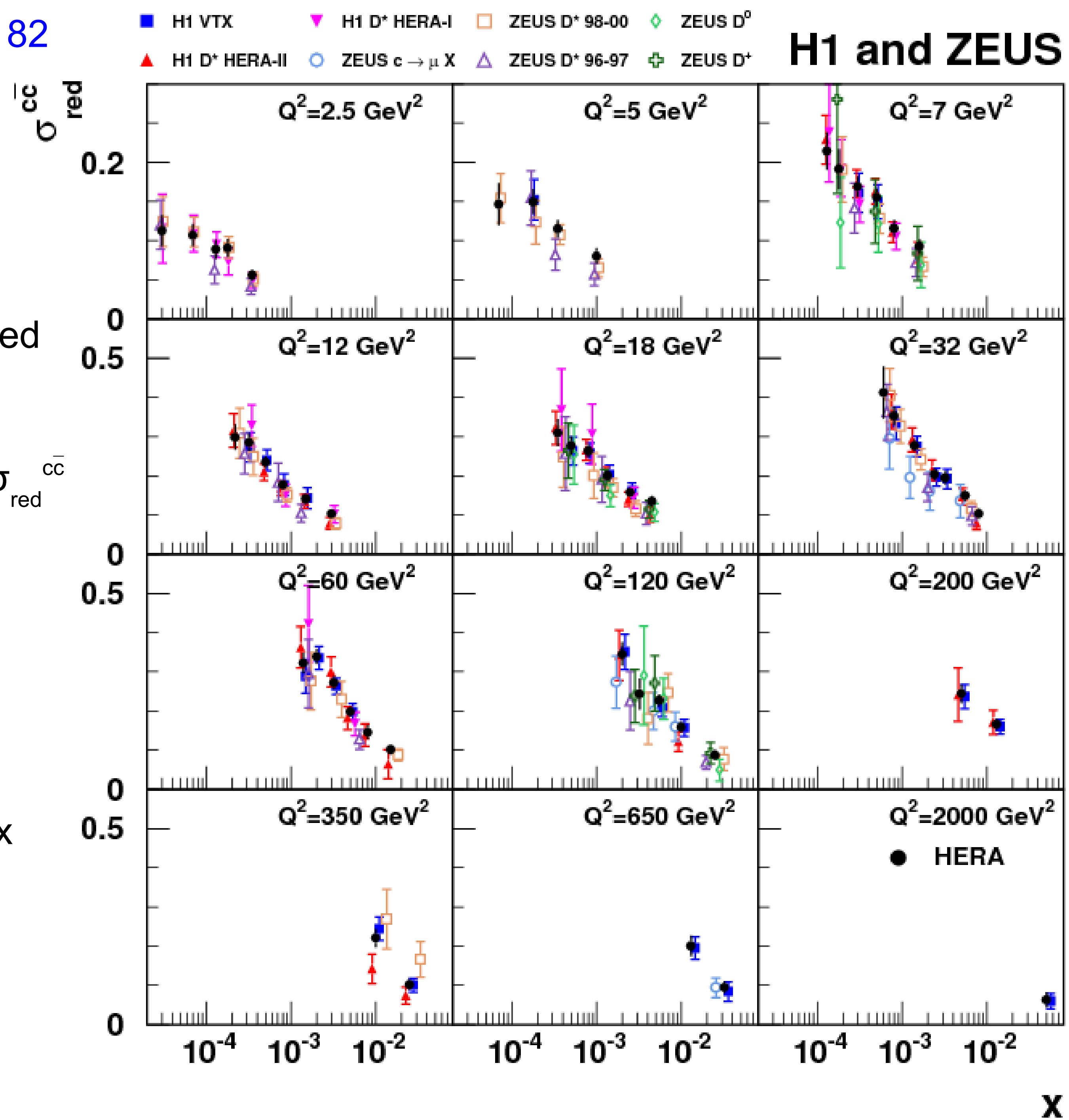
# Combination of HERA $\sigma_{red}^{c\bar{c}}$ cross sections

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

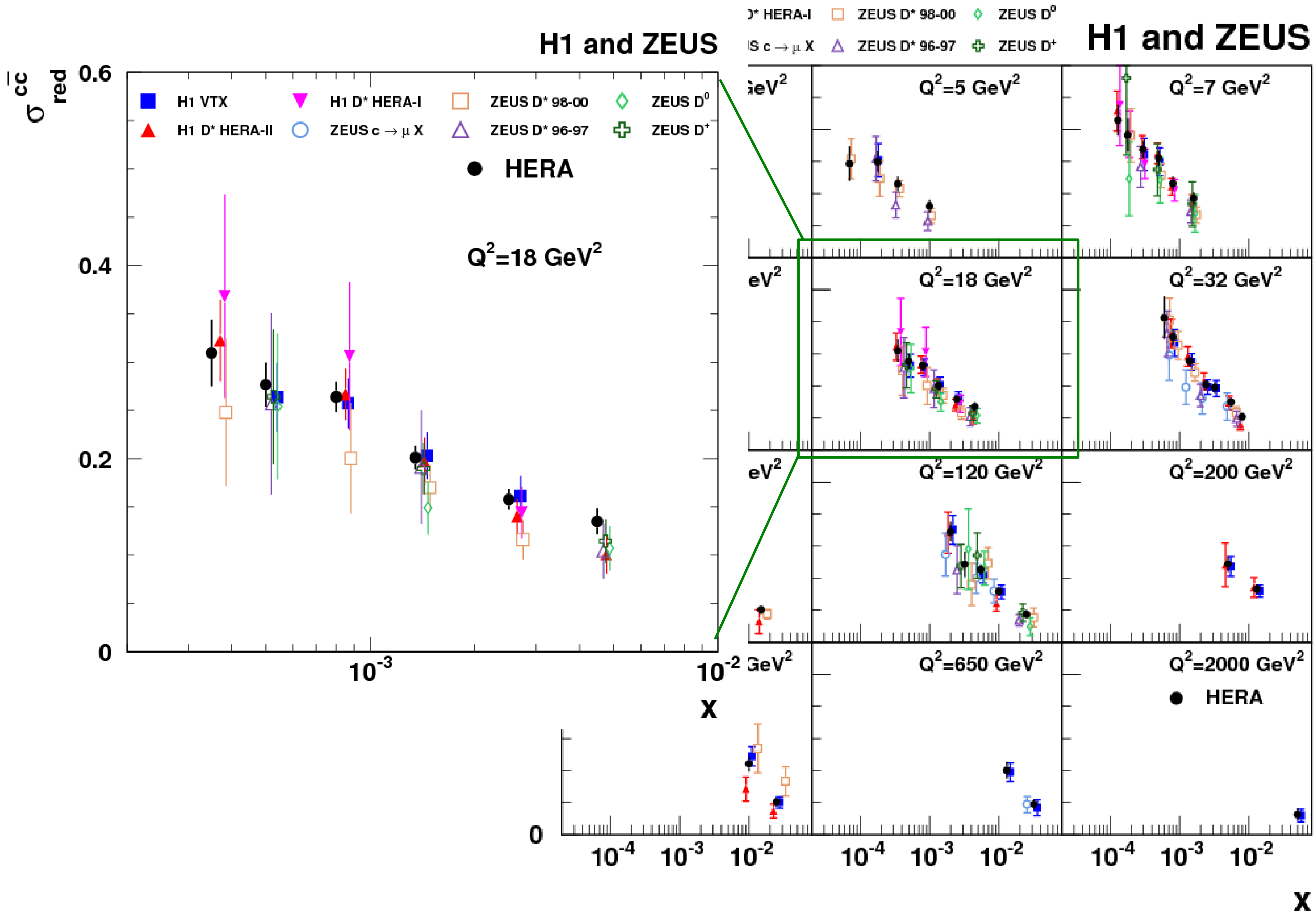
- 9 different data sets, ( new ZEUS D*,D+ not yet included )
- 155 measurements combined into 55 $\sigma_{red}^{c\bar{c}}$ points
- 48 correlated systematics, 9 related to extraction of $\sigma_{red}^{c\bar{c}}$
- $\chi^2/n_{dof} = 62/103$

Combination significantly more precise than single measurements

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



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

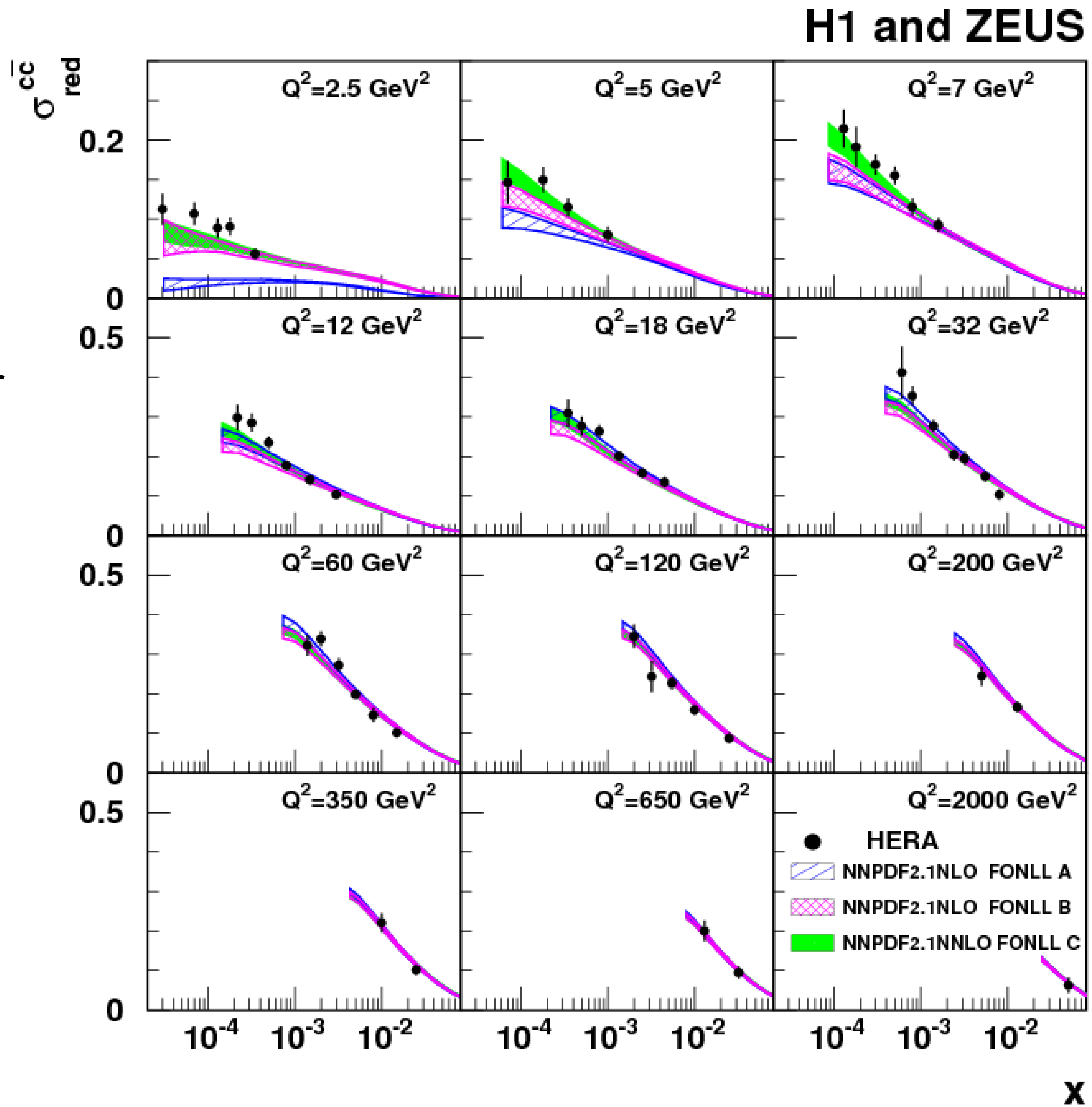


# Comparison with GM-VFNS preditcions

- 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



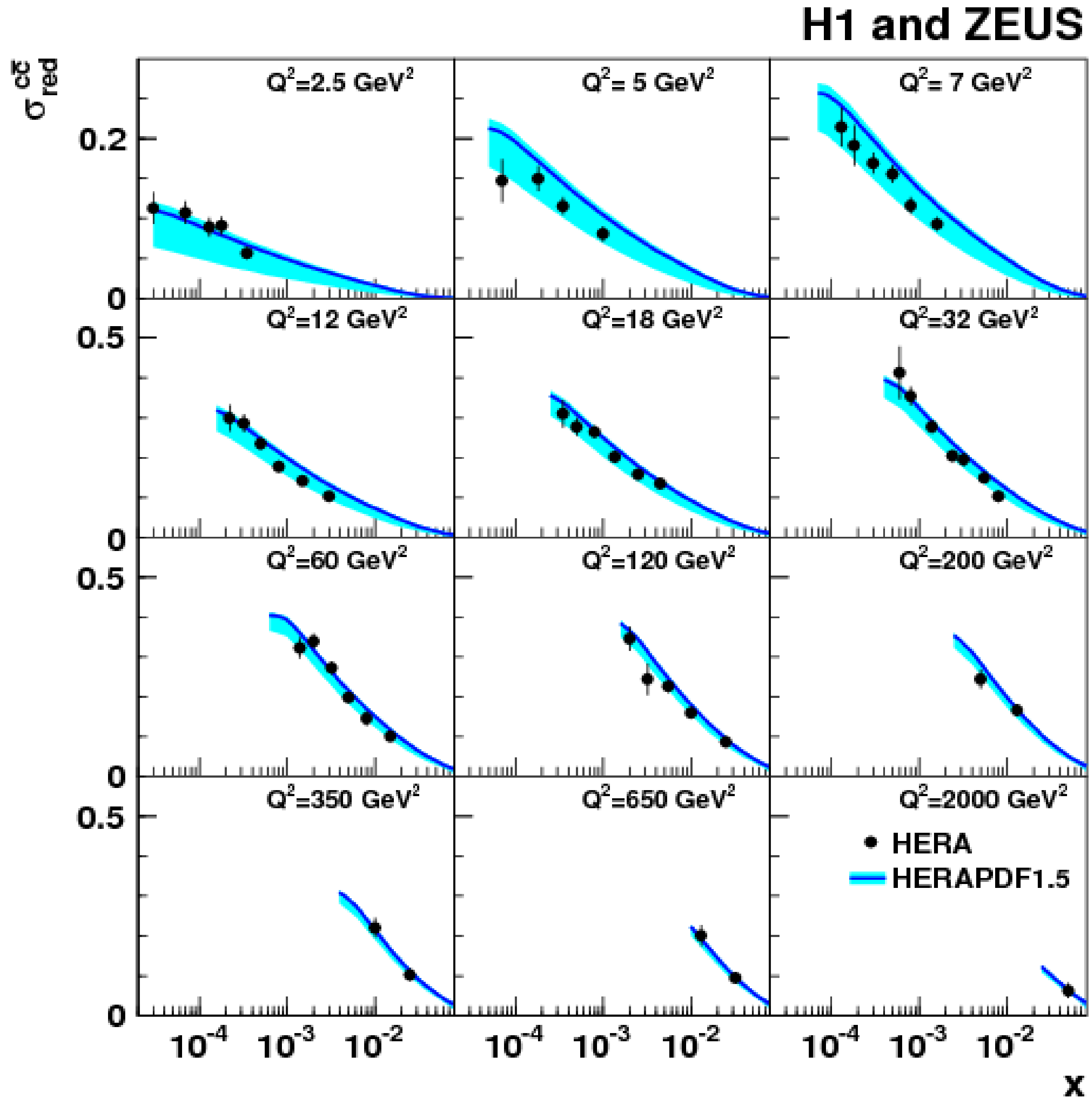
# Comparison with HERAPDF1.5

- 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)

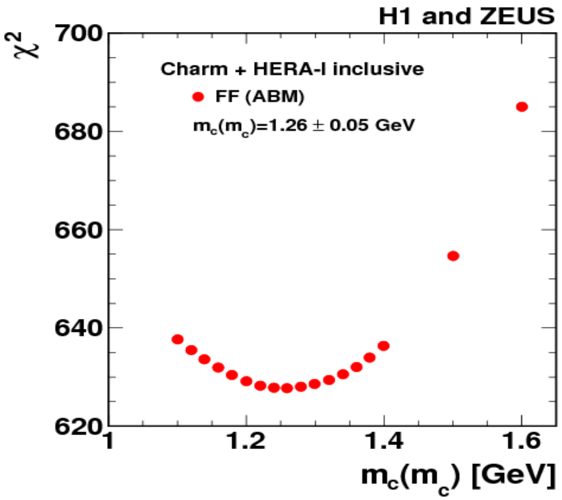
- Consistency of charm data with inclusive fit

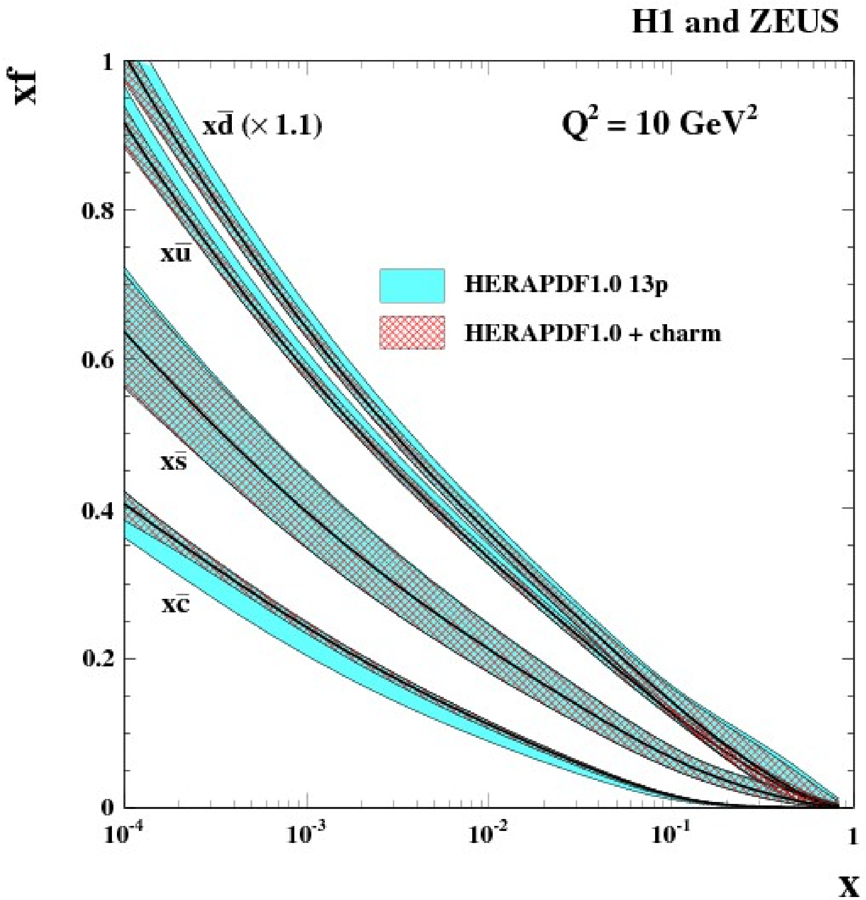
- Charm data have been then included into the HERAPDF fit ....



# Inclusion of charm data in 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 ($\overline{\text{MS}}$ scheme):

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

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

# J/ψ production

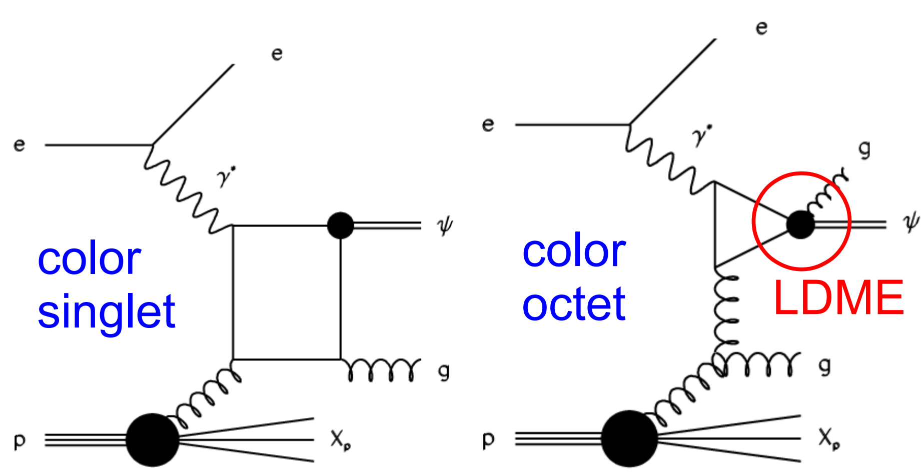
# Inelastic J/ψ production

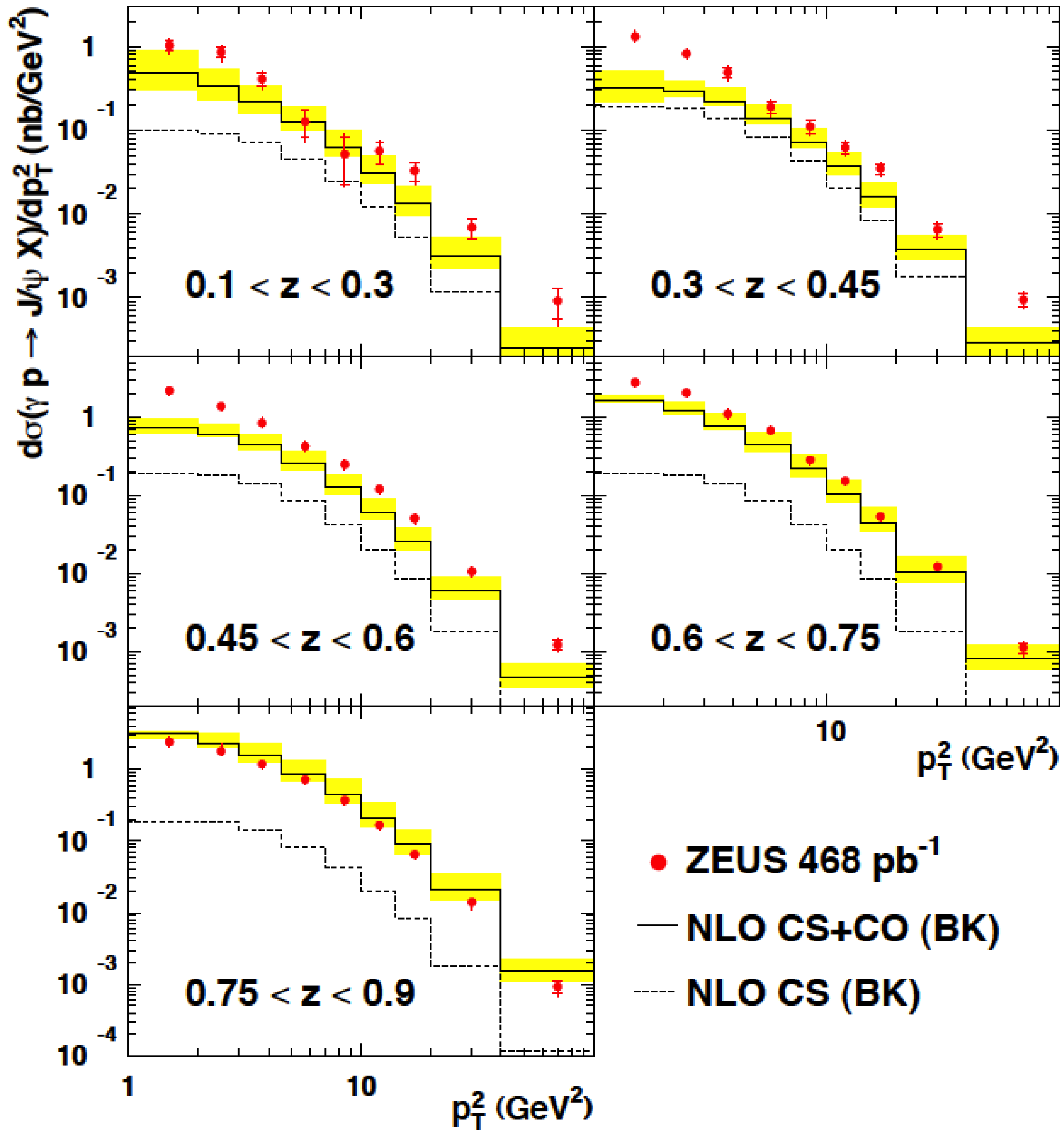
New measurement
ZEUS: arXiv:1211.6946 JHEP02(2013)071

Full HERA data set
Photo-production ($Q^2$<1 GeV$^2$)
γ-p cms energy 60<W<240 GeV

Double-differential in z, $p^2_T$
( z = E(Ψ) / E(γ) in p rest frame )

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

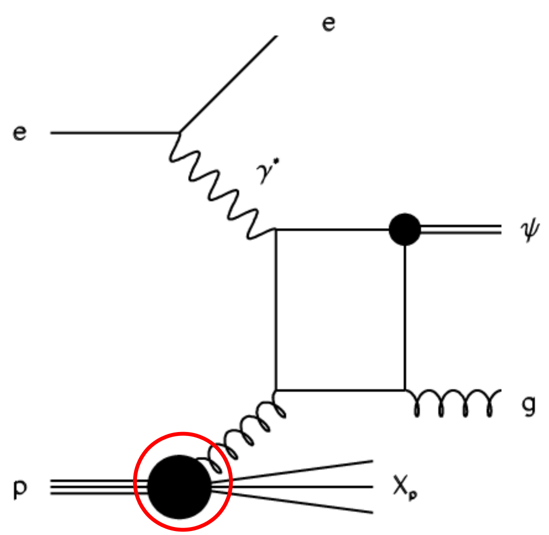


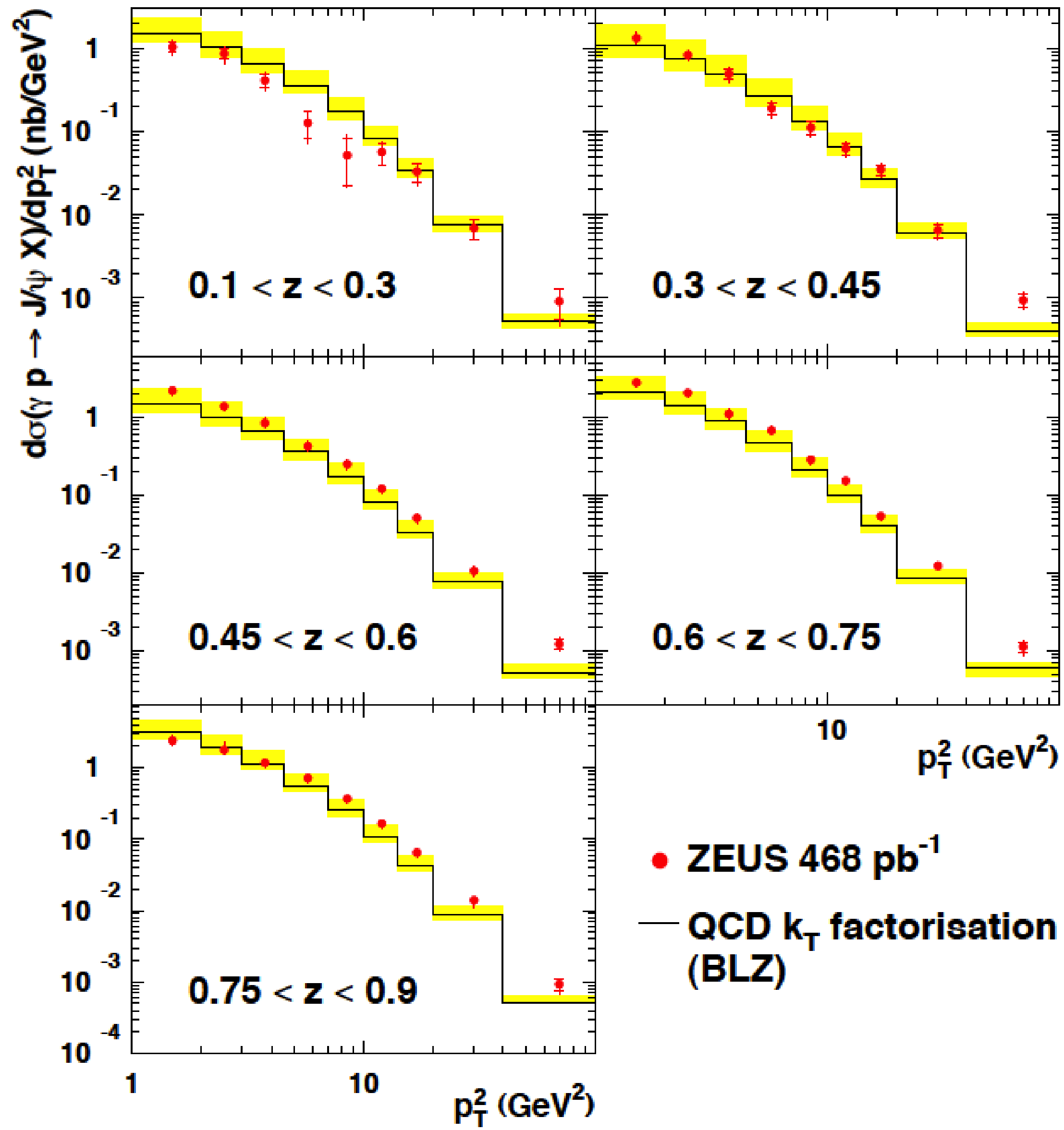

CS NLO calculation too low

# Inelastic J/ψ production, alternative theory

Compared also to color singlet calculations withi $k_T$ factorization model (Baranov, Lipatov, Zotov)




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



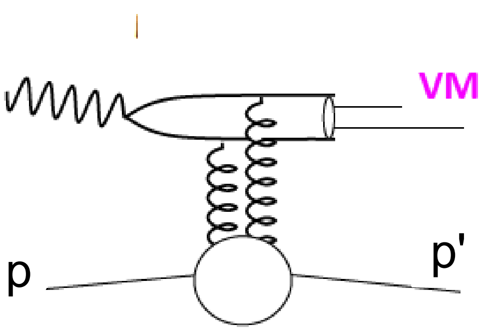

Both NRQCD and $k_T$ factorization models provide a reasonable but not perfect description of the data.

# Elastic J/ψ photo-production

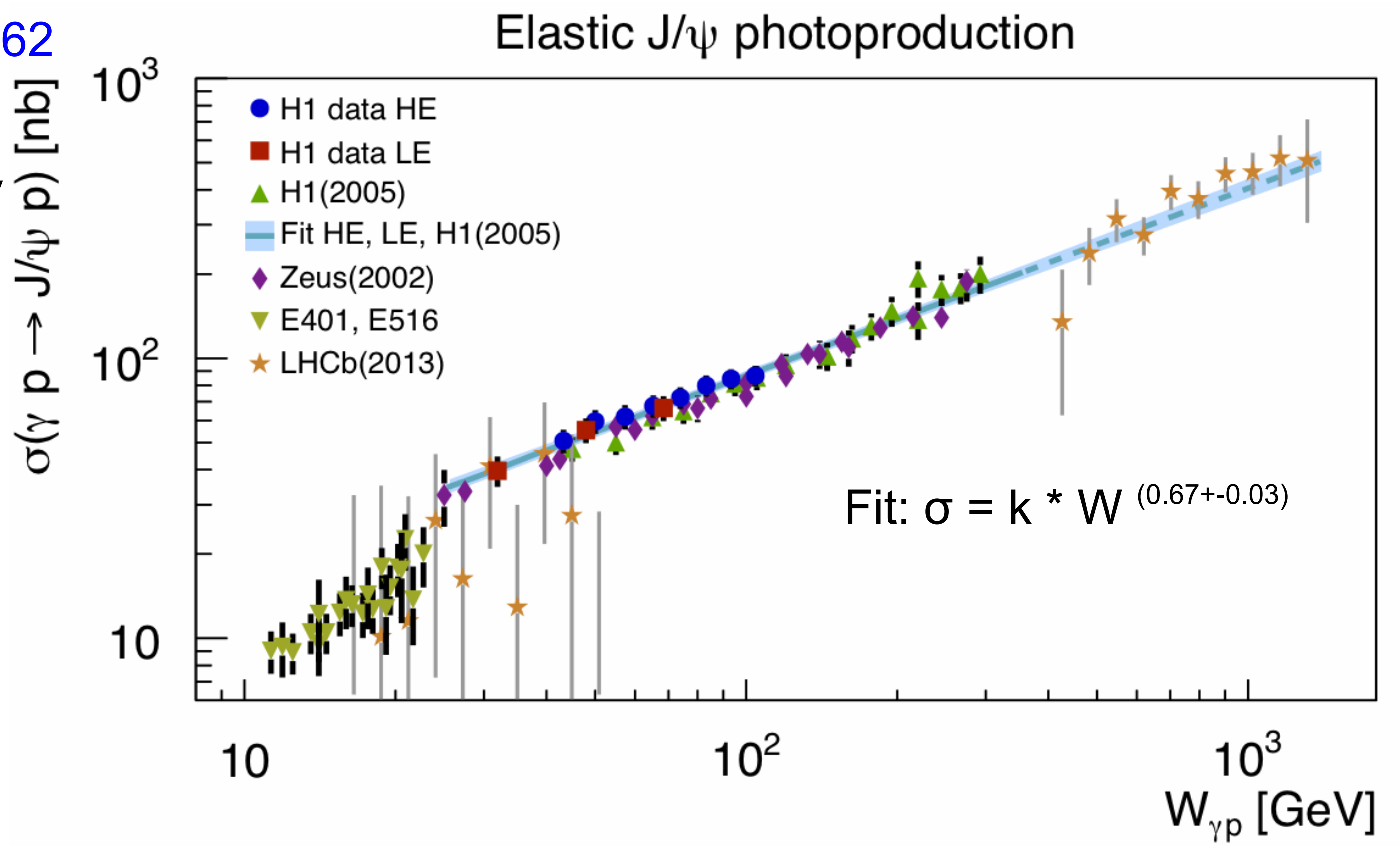
New H1 data: arXiv:1304.5162
EPJC 73(2013)2466

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.

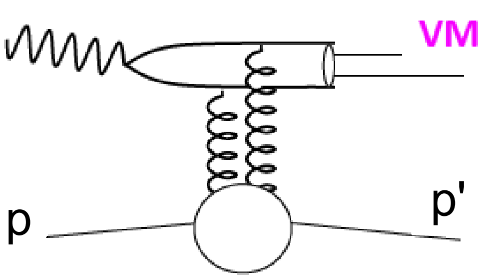
  Extrapolation agrees well with LHCb data

# Elastic J/ψ photo-production

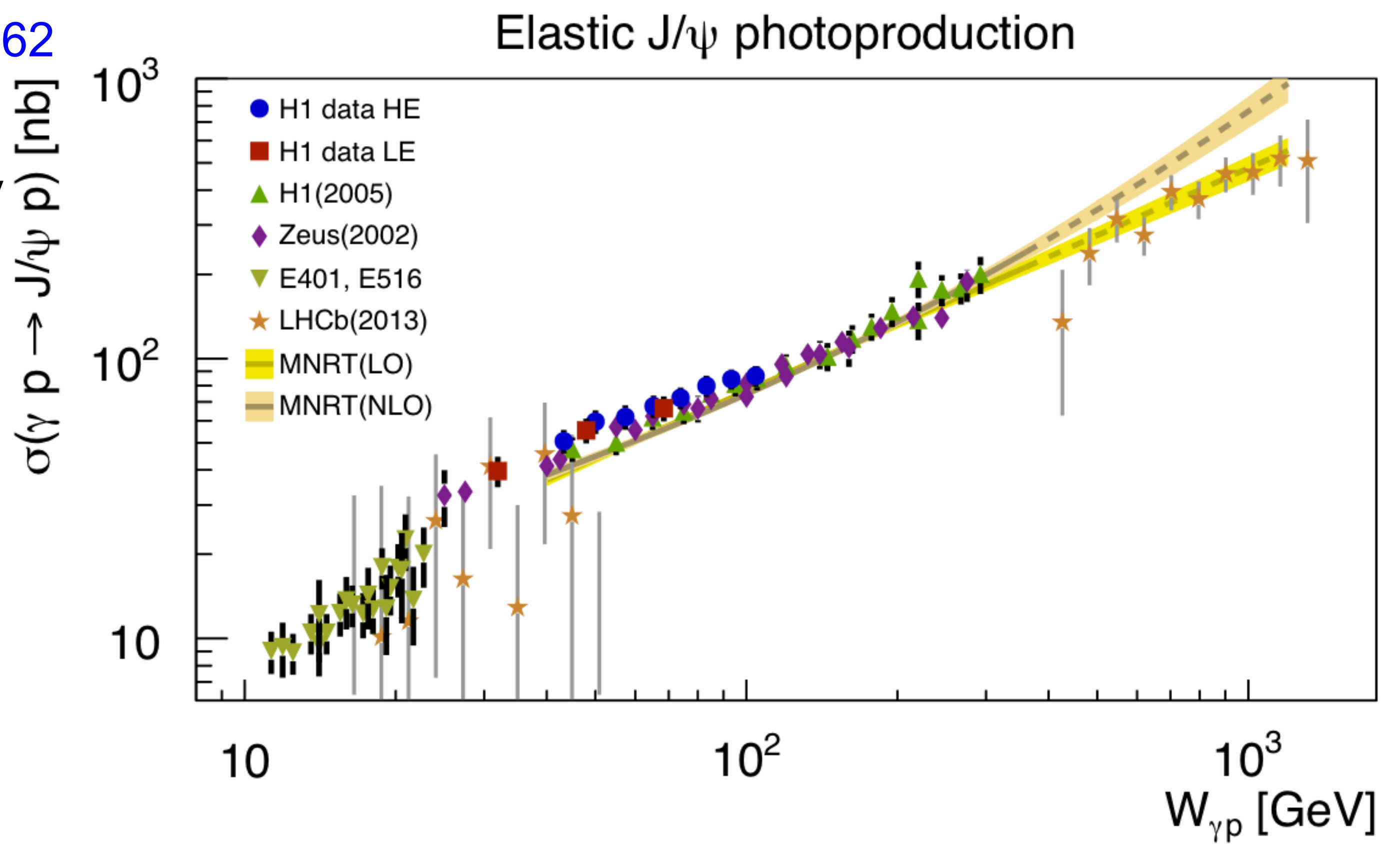
New H1 data: arXiv:1304.5162
EPJC 73(2013)2466

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 steep, especially at NLO

# Conclusions

**H1 and ZEUS still providing new charm results, exploiting the full HERA data 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 Quark in QCD calculations

- Inelastic J/ψ production:

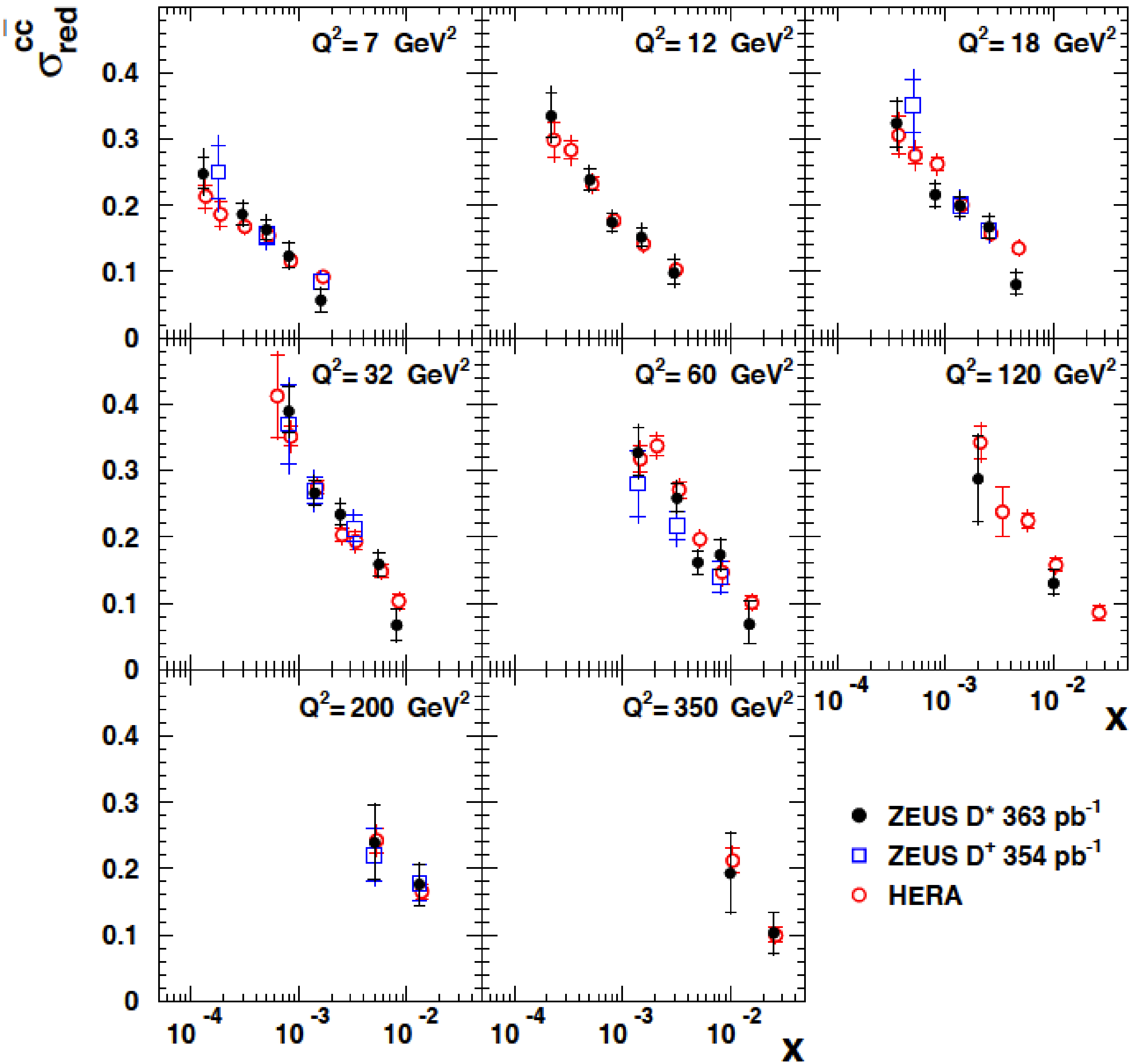
  new results, disfavour pure color-singlet models

- Elastic J/ψ production:

  new precise measurements: tighter constraints on QCD models

# BACKUP SLIDES

# ZEUS D*, D+ and combined HERA $\sigma_{red}^{c\bar{c}}$ data

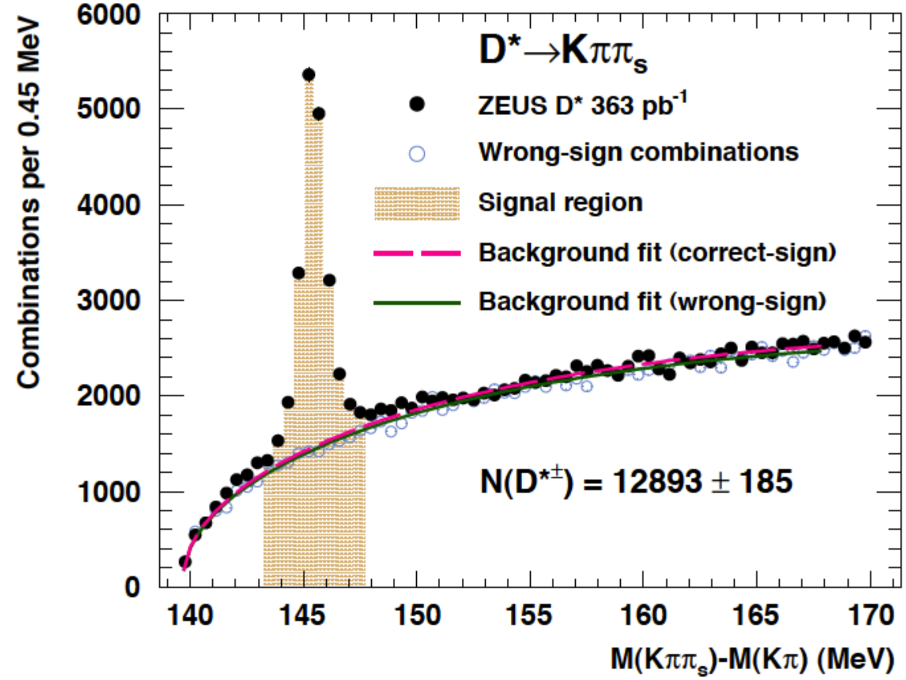


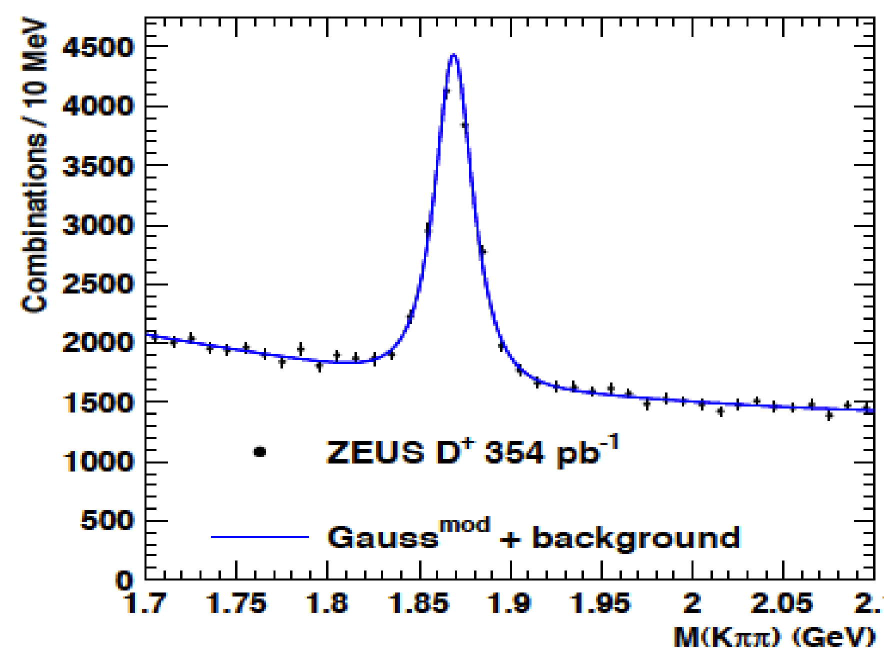
# Charm production in DIS

Several methods used to tag charmat HERA :
- $D^*$, $D^+$, $D^0$, μ, secondary vertices (VTX)

New results from ZEUS:
- ZEUS $D^*$ HERA-II arXiv:1303.6578
- ZEUS $D^+$ HERA-II arXiv:1302.5058

Results compared to FFNS calculation (HVQDIS) complemented with fragmentation model based on ep data



# Comparison with CT10 GM-VFNS

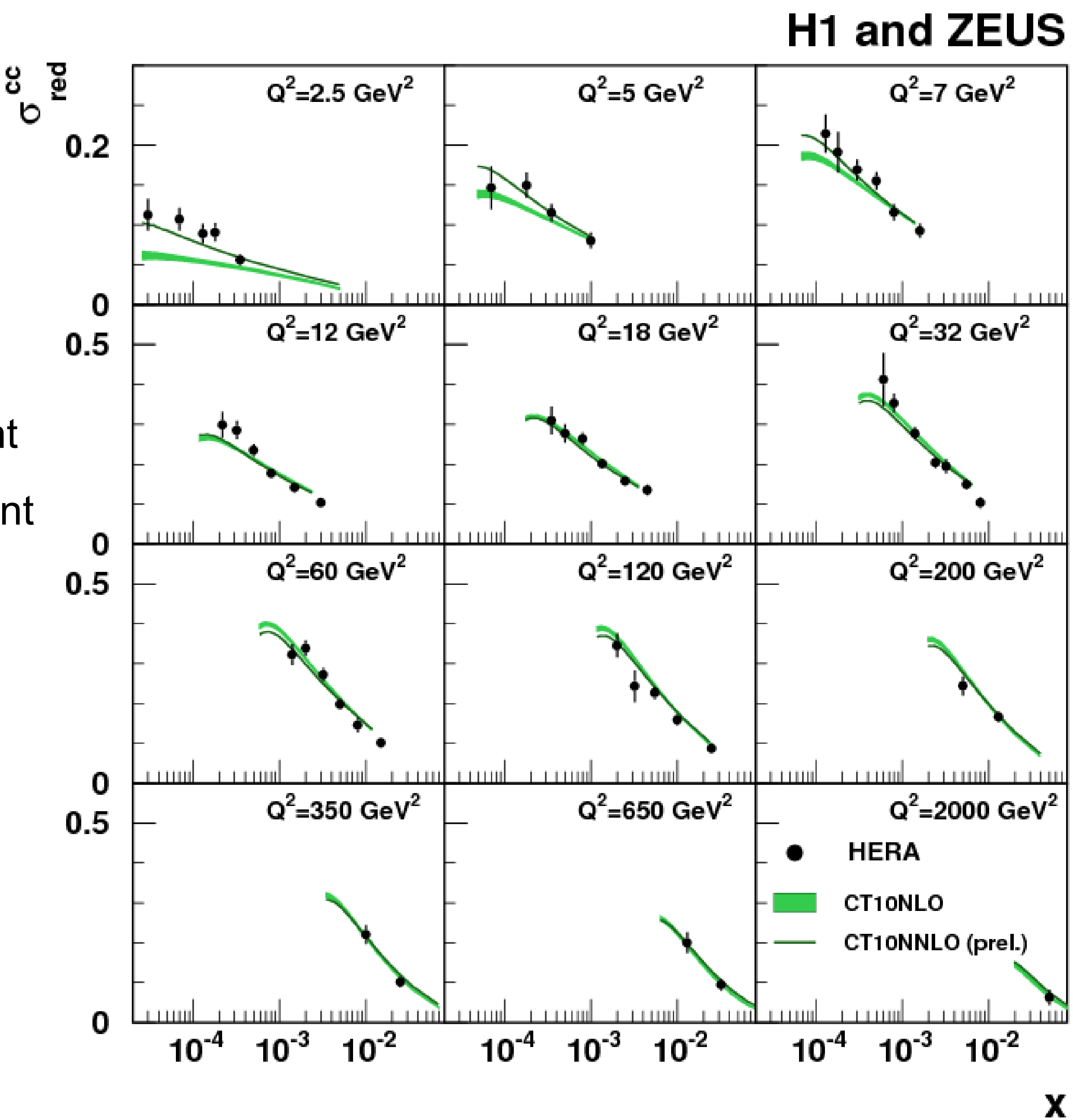
Comparison to CT10

GM-VFNS
S-ACOT-χ scheme:

- NLO : $O(\alpha_s)$ -> poor agreement
- NNLO : $O(\alpha_s^2)$ -> fair agreement

$m_c$ = 1.3 GeV (pole)

Agreement improves going to higher order.



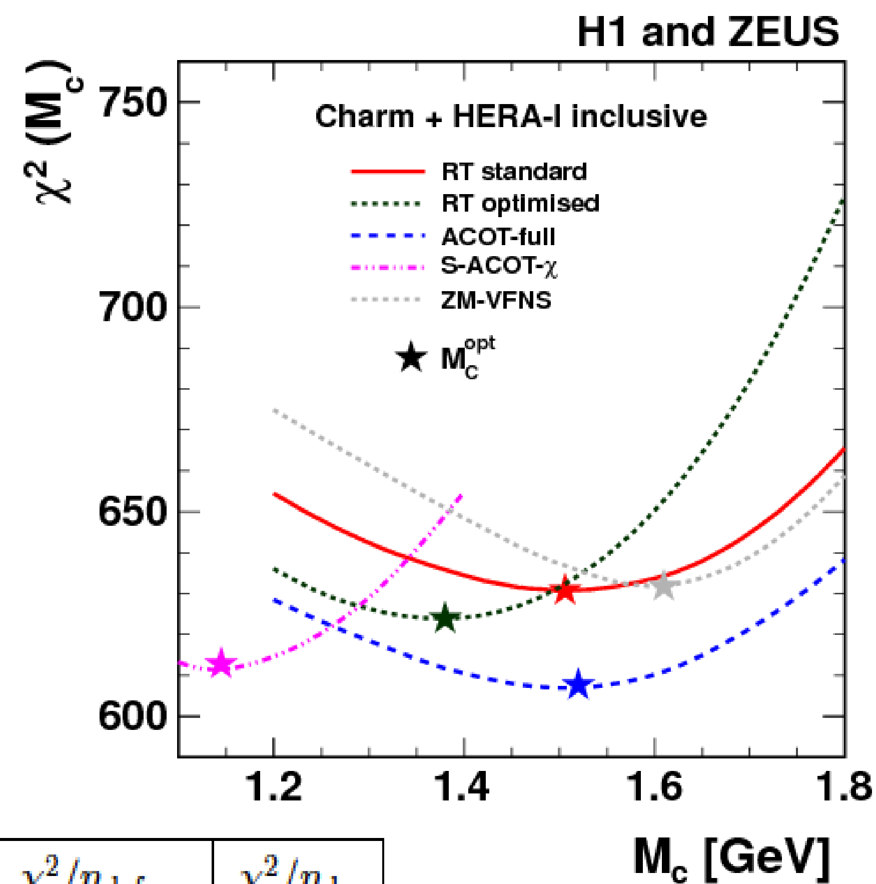
# Optimal Mc for differen schemes

Best fit Mc$^{opt}$ differs for different approaches:

- Best global fit : ACOT-full

- Best fit to charm data : RT standard

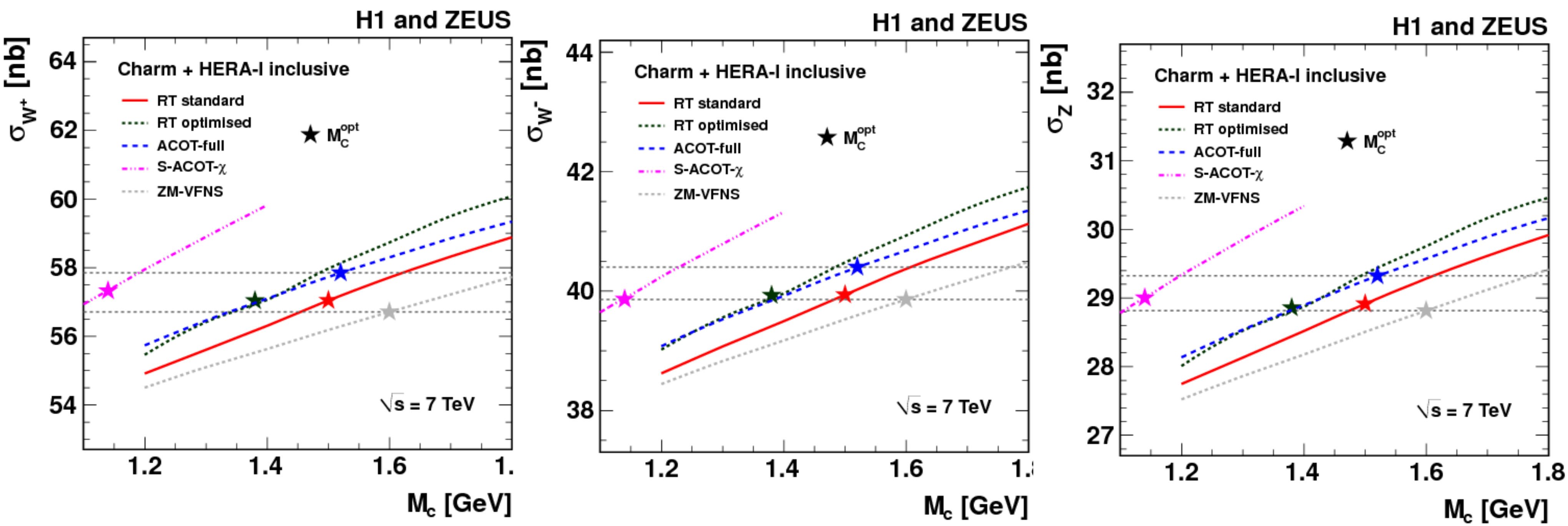
- Systematics calculated similarly to HERAPDF fit




| scheme | $M_c^{opt}$ [GeV] | $\chi^2/n_{dof}$ $\sigma_{red}^{NC,CC}+\sigma_{red}^{c\bar{c}}$ | $\chi^2/n_{dp}$ $\sigma_{red}^{c\bar{c}}$ |
|---|---|---|---|
| RT standard | $1.50 \pm 0.06_{exp} \pm 0.06_{mod} \pm 0.01_{param} \pm 0.003_{\alpha_s}$ | $630.7/626$ | $49.0/47$ |
| RT optimised | $1.38 \pm 0.05_{exp} \pm 0.03_{mod} \pm 0.01_{param} \pm 0.01_{\alpha_s}$ | $623.8/626$ | $45.8/47$ |
| ACOT-full | $1.52 \pm 0.05_{exp} \pm 0.12_{mod} \pm 0.01_{param} \pm 0.06_{\alpha_s}$ | $607.3/626$ | $53.3/47$ |
| S-ACOT-$\chi$ | $1.15 \pm 0.04_{exp} \pm 0.01_{mod} \pm 0.01_{param} \pm 0.02_{\alpha_s}$ | $613.3/626$ | $50.3/47$ |
| ZM-VFNS | $1.60 \pm 0.05_{exp} \pm 0.03_{mod} \pm 0.05_{param} \pm 0.01_{\alpha_s}$ | $631.7/626$ | $55.3/47$ |

# Impact on LHC cross sections

- Cross sections for W+,W-,Z production at LHC as a function of Mc




- For fixed Mc there is a significant spread among different schemes (~ 6%)

- Using optimized Mc the spread is reduced (1.8% for Z at Mc=1.4 GeV)

- The choice of the optimized Mc stabilizes the PDFs

# Elastic J/ψ photo-production: t slope

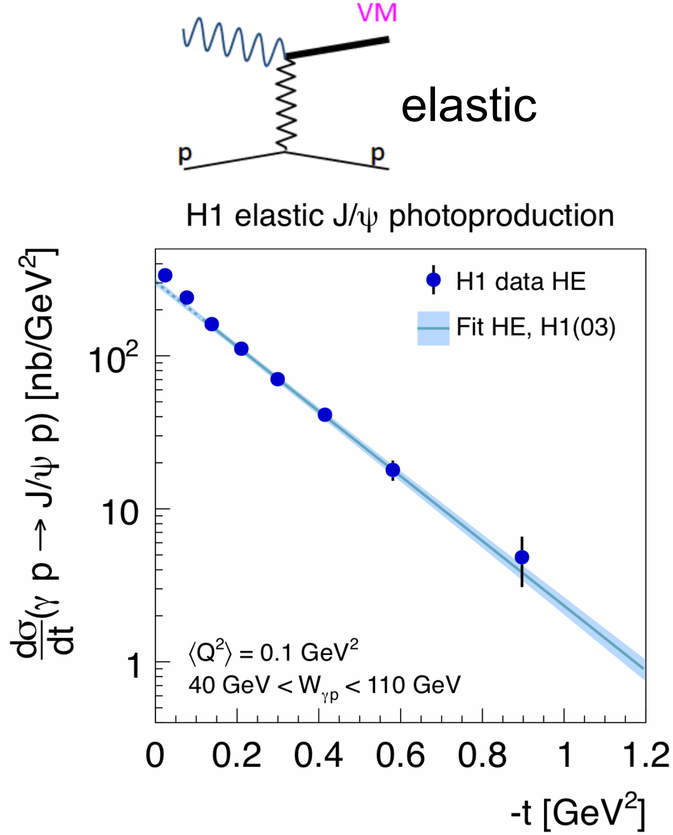
- Fit of t dependence of the form

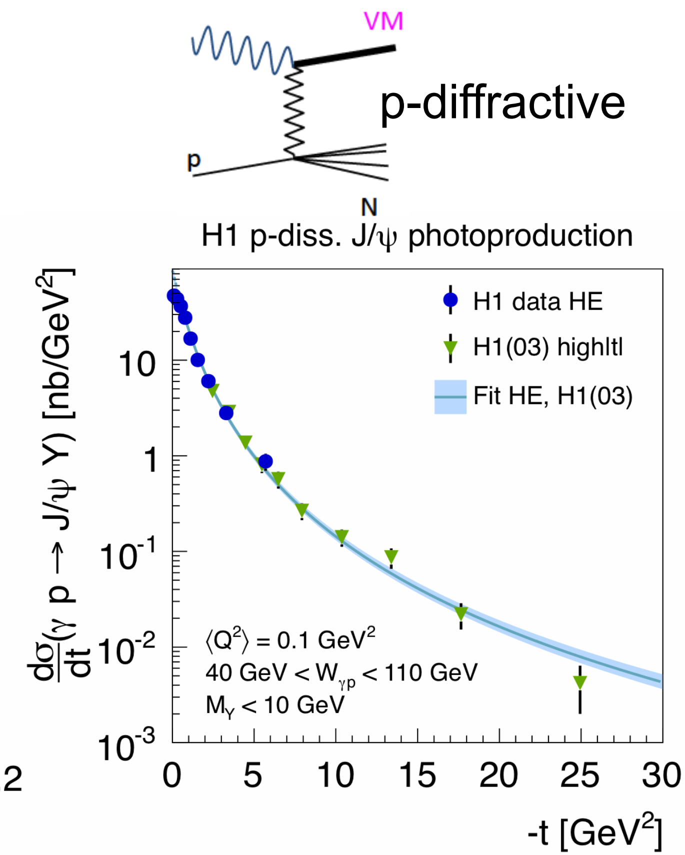
$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$

- $b$ related to the size of the diffractive system: $b \sim b(j/\psi) + b(p)$

- Elastic (el) events : $b$ significantly smaller than low mass VMs

- Proton-diffractive (pd) events : $b$ smaller than in elastic case (proton structure is resolved..) power-law tail at large -t




$b_{el} = 4.88 \pm 0.15\ GeV^{-2}$
$b_{pd} = 1.79 \pm 0.12\ GeV^{-2}$

# Charm measurements at HERA

Many different measurements:

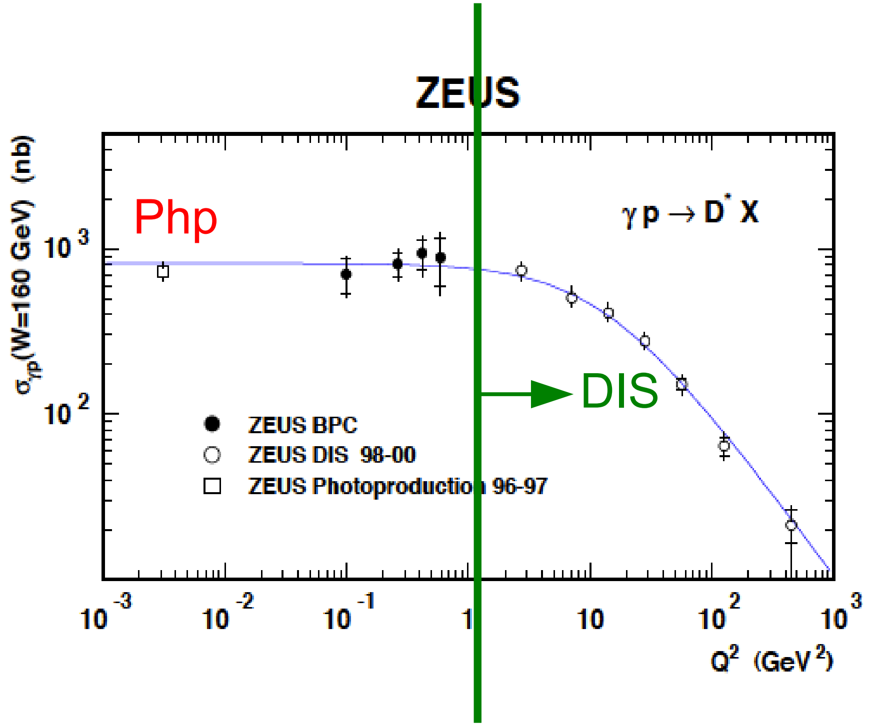
- Wide kinematic range
  0 < Q2 < 10000 GeV2

- Different methods to tag charm:
  - Full reconstruction of D and D* mesons,
  - Semileptonic decays,
  - Inclusive lifetime

  very different systematics and sensitivities

- We present here a combination of
  all DIS data (Q2>1GeV$^2$) published so far

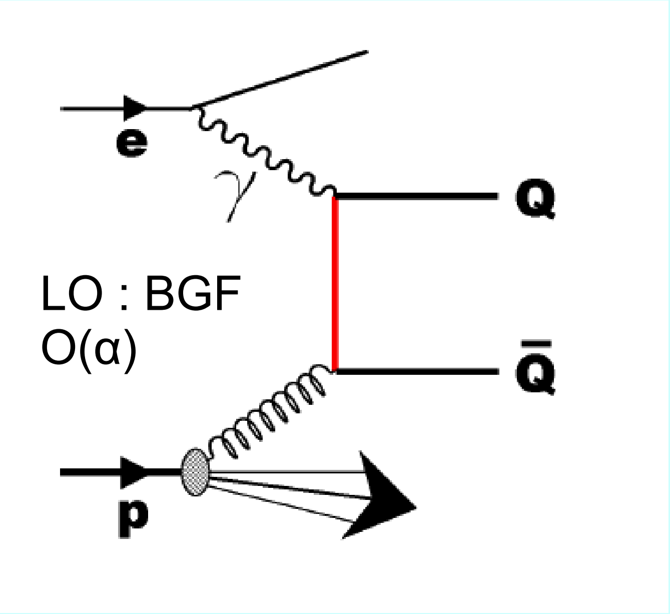
- Improvements wrt preliminary result released in 2008:
  - all data sets used are final
  - consistent approach for kinematical acceptance



# Heavy quark production in DIS

## Fixed Flavour Number Scheme (FFNS)

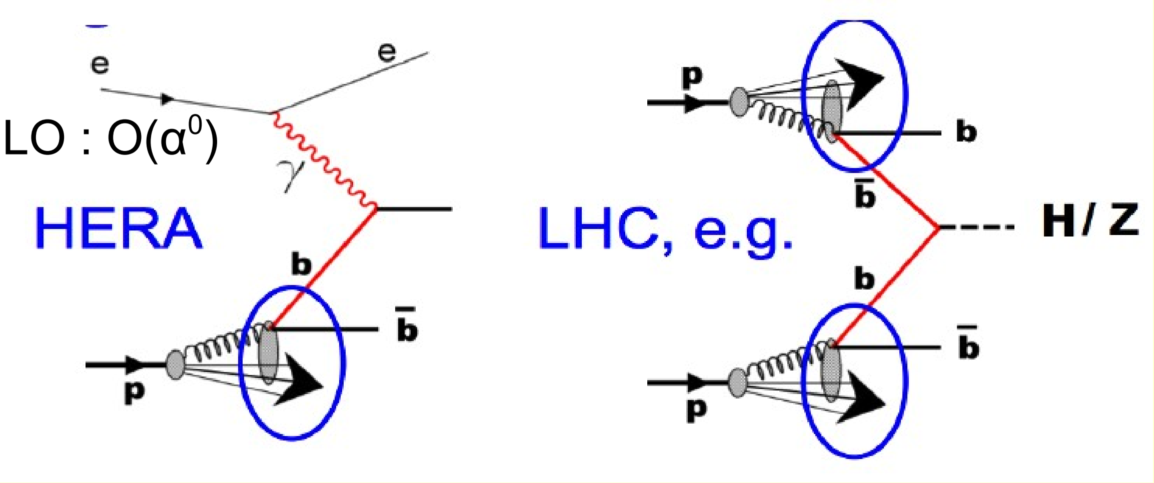
- nf=3 active flavours in p
- heavy-quarks produced in hard scattering
- mass effects correctly included




- spoiled by large logs of $Q^2/m^2$, $p_T/m$ ...

## Variable Flavour Number Scheme(s) (VFNS)

- c, b massless partons for $Q^2 > m_c^2$




- simplifies calculations at colliders (neglecting $m_c$)
- resums large $\log(Q^2/m^2)$

- Zero Mass (ZM) VFNS
  - neglects $m_c$ at all $Q^2$s

- General Mass (GM) VFNS
  - FFNS at $Q^2 < m_c^2$, ZM-FNS at $Q^2 >> m^2$
  - Interpolating in between
  - different prescriptions available