Heavy meson production at HERA

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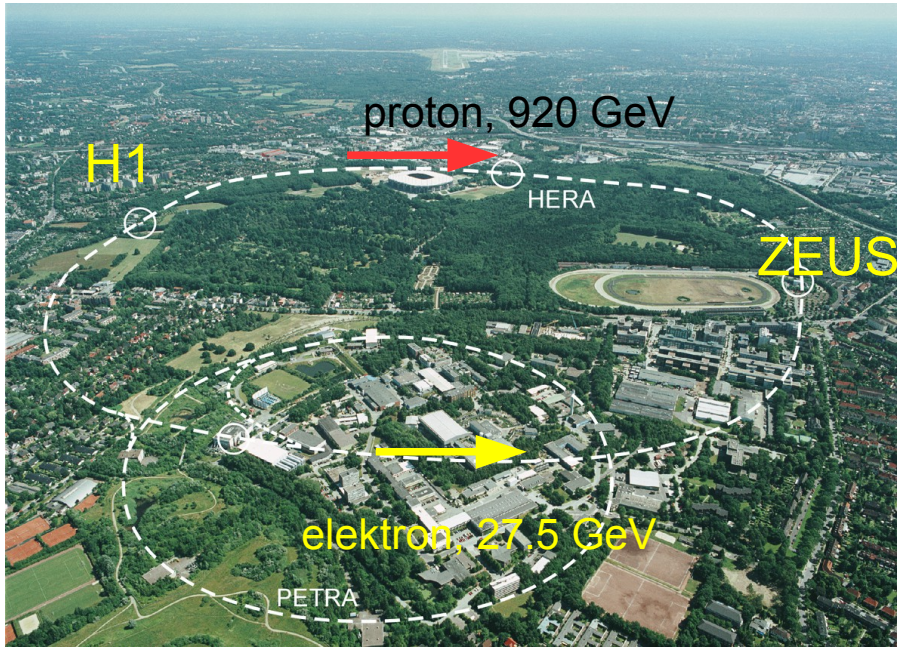
on behalf of the H1 and ZEUS collaborations



... we investigate the **fundamental forces** and **particles** in e p collisions at highest energies – quark and gluon interactions, we verify the Standard Model and seek „new physics" ...

... among the other - studying **heavy meson** production ...

Hadron production in e-p interactions: (1)

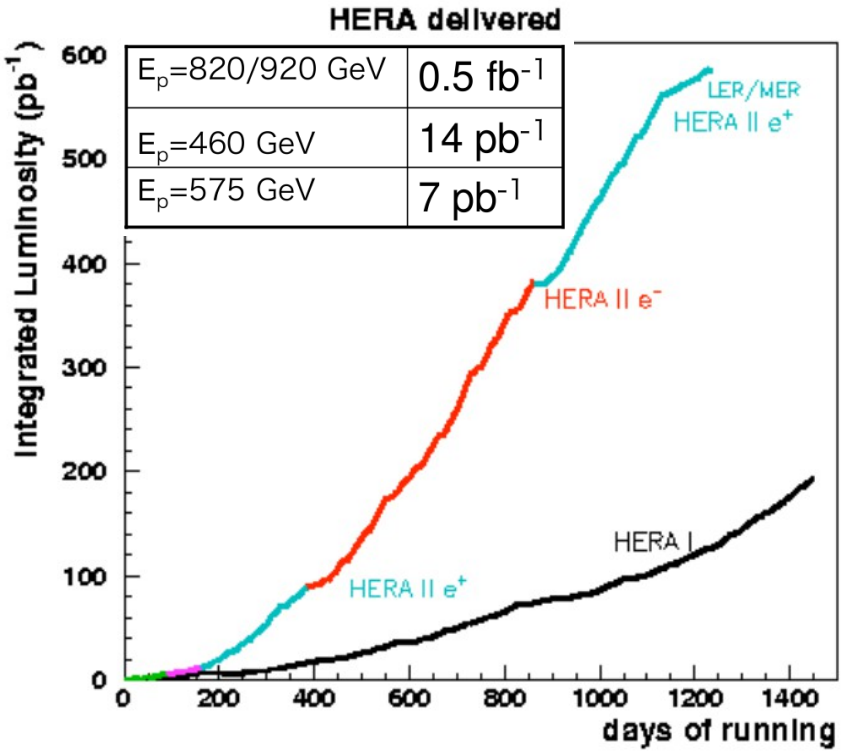
HERA: $e^{\pm}$ (27.5 GeV) – p (820/920/575/460 GeV)

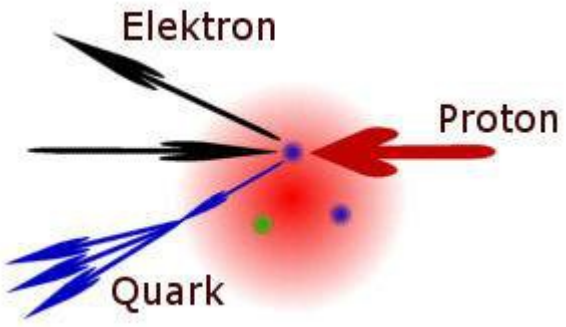
→ $\gamma^* p \rightarrow$ hadrons

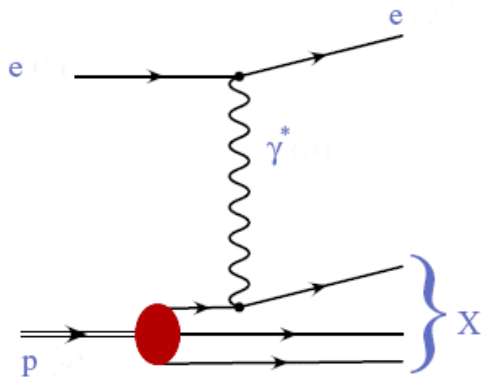
$Q^2 \approx 0$ (quasi-) photoproduction (PHP)
$Q^2 > 0$ deep inelastic scattering (DIS)

DIS (Quark/parton model, QPM):
γ^* proton = sum of inter. γ^* quark/parton
parton fragmentation → hadrons ≈ mesons (!)
= factorisation of the „hard" and „soft" interaction

- Proton structure, quarks, gluons...
- Quantum Chromodynamics (QCD)
  – theory of quarks and gluons interactions



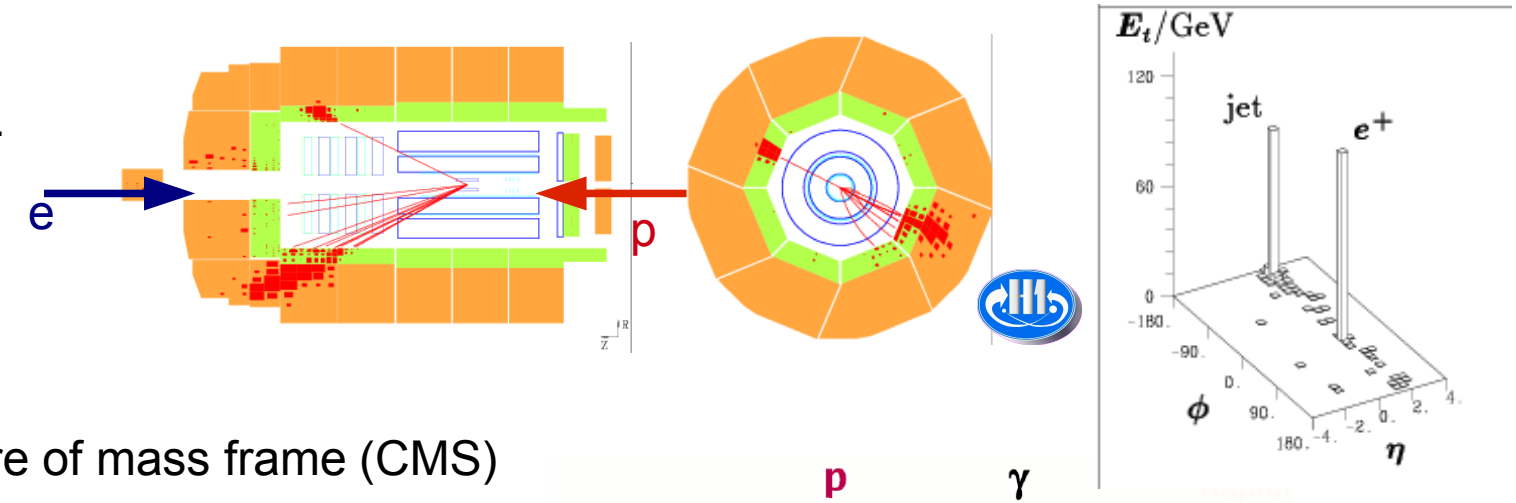




Q^2 – γ^* virtuality $(0 – 10^5\ \text{GeV}^2)$
$s \approx E_e E_p$, $\sqrt{s} \approx 300$ GeV
W – $\gamma^* p$ CMS energy (20 -290 GeV)
$x \approx Q^2/W^2$ – Bjorken x = fractional parton momentum in proton Breit frame
$y \approx Q^2/(sx)$ – fractional energy transfer to p

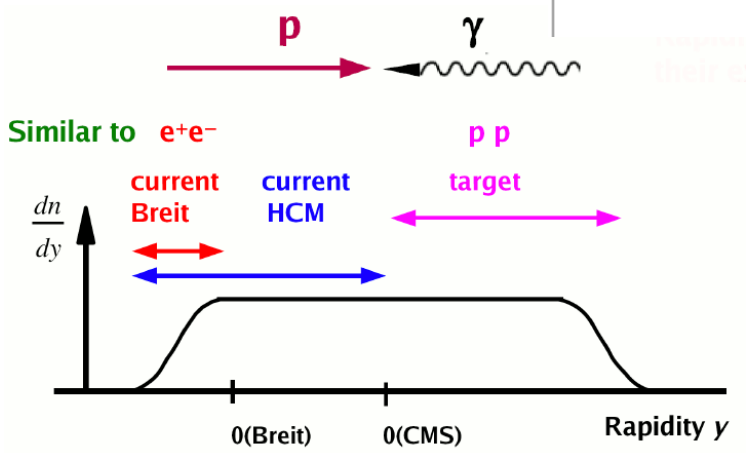
Hadron production in e-p interactions: (2)

- LABoratory frame...



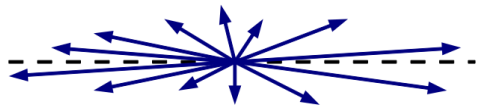
- $\gamma^* p$ (hadronic) centre of mass frame (CMS)
- Breit frame: $q(\gamma^*) = (0,0,0,Q)$

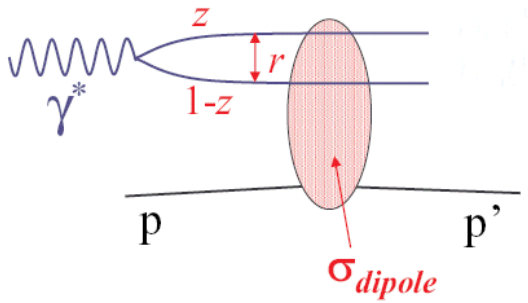
$x_F = p_L/p_{max}$, Feynmann x
$y \approx \eta = -\ln(\tan(\theta/2))$, (pseudo-)rapidity
p_T = transverse momentum



- proton rest frame:

diffraction (coherence) condition:
fluctuation "length" ($\gamma^* \rightarrow$ dipol qq) =
$= 2E_\gamma/(m_{qq}^2 + Q^2) > 1$ fm
$\rightarrow$ x < 0.01





At HERA we observe **diffraction**, (also at $Q^2 >> 0$) and it makes ~10% of the visible cross section !

Heavy meson production at HERA

- Diffractive charmonium production:

  Elastic and proton-dissociative J/Ψ photoproduction

  Ψ'/Ψ ratios

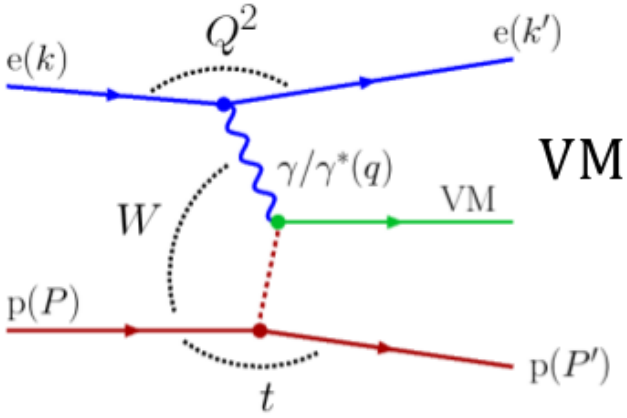
- Inelastic J/Ψ production
- Open charm production:

  Fragmentation of charmed mesons

  Charm in proton structure function

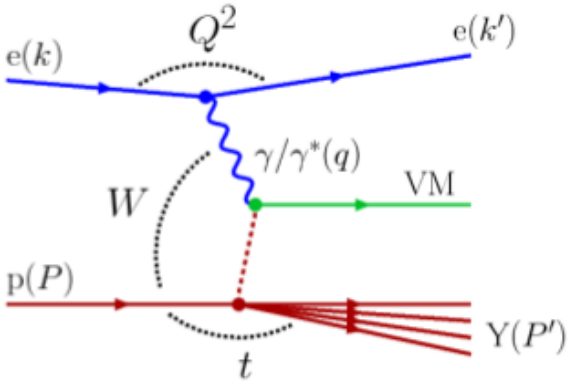
Diffractive meson production at HERA (1)

elastic (exclusive)



$\mathrm{VM} = \rho,\omega,\varphi,J/\psi,\psi',\Upsilon$

proton dissociative



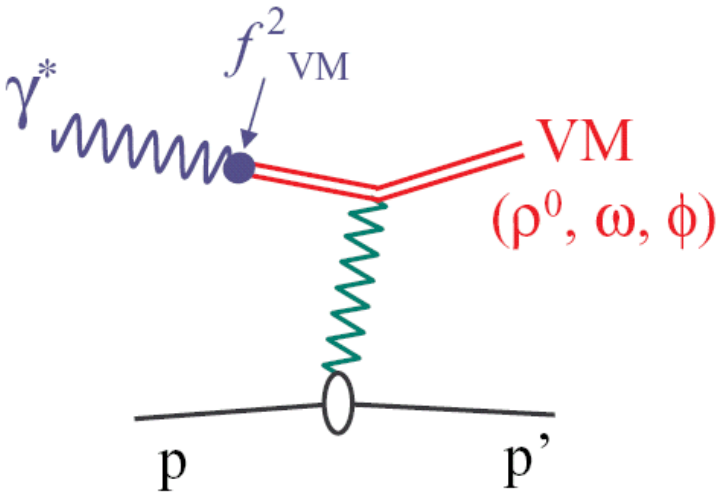
$|t|<1$ GeV^2

dominates at high $|t|$

Q^2	photon virtuality	$Q^2 = -q^2 = -(k - k')^2$
W	CMS energy of γp system	$W^2 = (q + P)^2$
t	(4-mom. transfer)^2 at p-vertex	$t = (P - P')^2$
x	Bjorken x = fractional parton momentum in proton Breit frame	$x \approx \frac{Q_2}{W_2}$

$Q^2 \approx 0$ (PHP)
$Q^2 > 0$ (DIS)

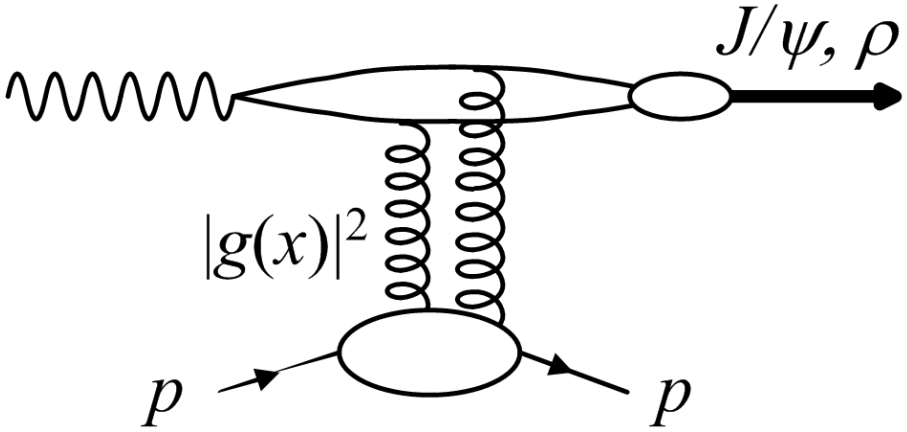
Diffractive meson production at HERA (2)



Vector Dominance Model + Regge

$\gamma^* p \to VM\, p = (\gamma^* \to VM) \otimes (VM\, p \to VM\, p)$

- $VM\, p \to VM\, p \Rightarrow$ DL IPomeron exchange
- $d\sigma/dt \sim \exp(-b(W)t), \quad b \sim R_{int}^{\,2} \approx 10\ \mathrm{GeV}^{-2}$
- $b(W) = (b_{VM} + b_p + \alpha' \ln(W^2))$ ("shrinkage")
- $\sigma_{VMp} \sim W^{4(\alpha 0-1)}/b(W) \sim W^{\delta}, \ \delta \approx 0.22$



Perturbative QCD

Large Q^2, M_{VM} or $|t| \to$ small qq dipol

- QCD Pomeron exchange:

  ≥ 2 gluons (colour singlet)
- $\sigma_{VMp} \sim (xg(x))^2 \sim W^{0.7}$!!!
- $b \ll 10\ \mathrm{GeV}^{-2}$, weak shrinkage

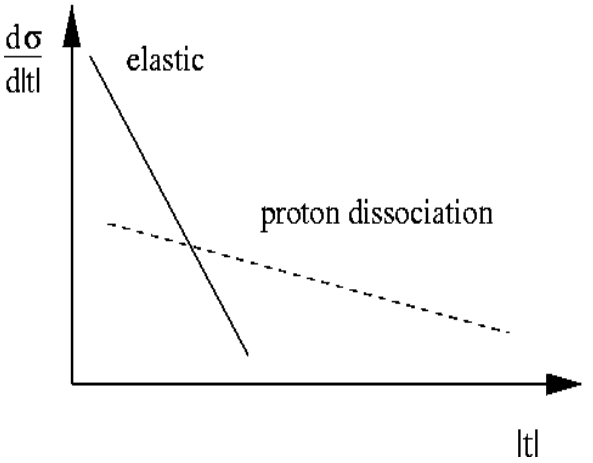
VM at HERA: transition between soft and hard regime; testbed of QCD scales

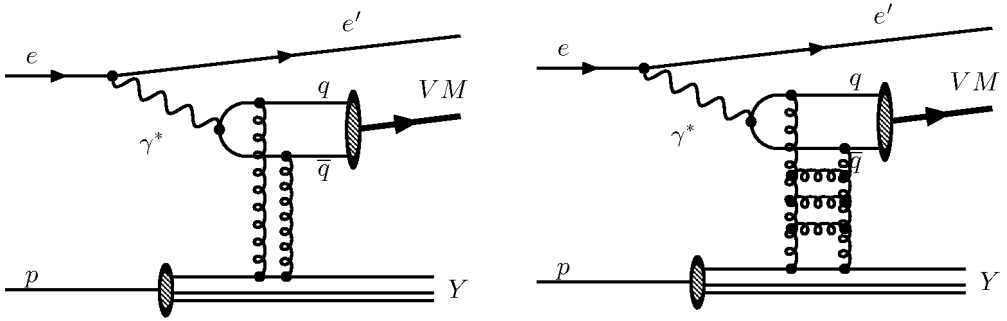
Proton-dissociative VM production...

Colourless exchange (Pomeron) in QCD = ?...

$\gamma\, p \rightarrow J/\psi\, Y \rightarrow \mu^+ \mu^-\, Y$, proton dissociates...

Large $M_{J/\psi}$, $|t| \rightarrow$ **perturbative QCD**





$d\sigma/dt \sim |t|^{-n}$

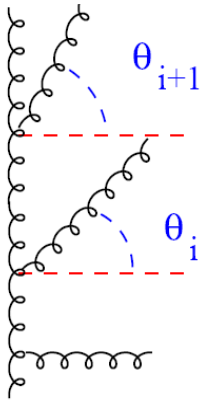
- 2-gluon exchange – $\sigma(W) = \text{const}$!
- gluon "ladder" exchange →

  DGLAP – $\sigma(W) \approx \text{const}(W)$

  BFKL – $\sigma(W) \uparrow$, $W \uparrow$...!

Gluon cascade dynamics:

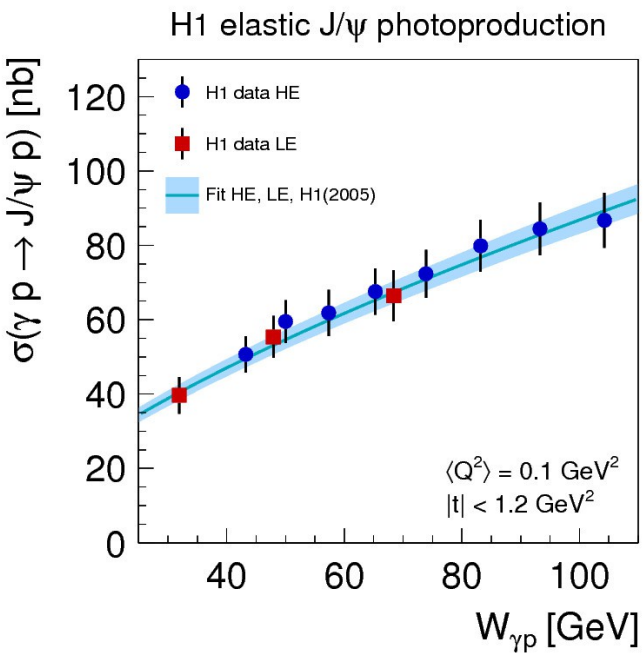
- Dokshitzer, Gribov, Lipatov, Altarelli, Parisi (DGLAP): gluon transverse momenta ordered, ewolution in Q^2
- Balitsky, Fadin, Kuraev, Lipatov (BFKL): no ordering of gluon transverse momenta, ewolution with x (1/W)

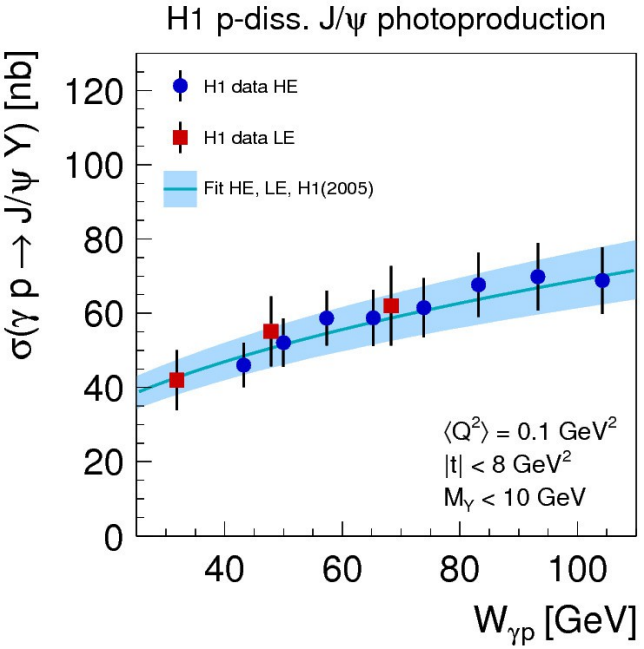


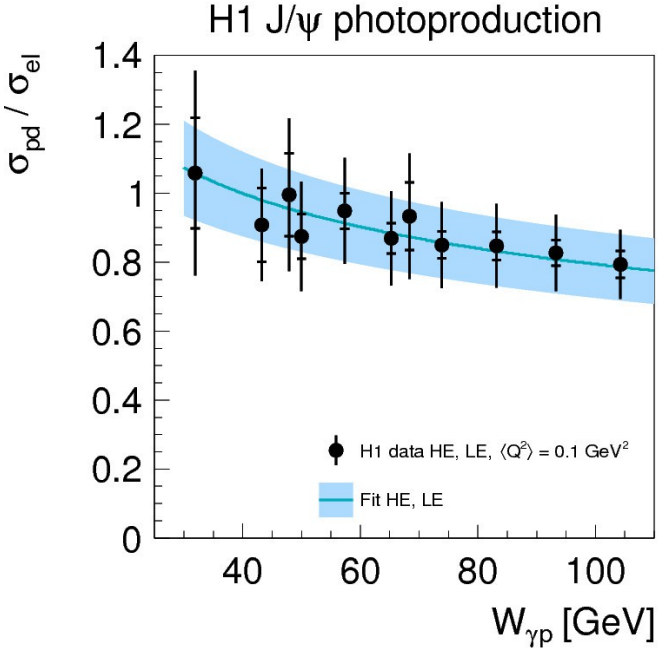
Charmonium production at HERA (1)

H1 (EPJ **C73** (2013) 2466): Elastic and Proton-dissociative Php of J/Ψ Mesons at HERA
HE: $\sqrt{s} \approx 318$ GeV, LE: $\sqrt{s} \approx 225$ GeV

Energy dependence



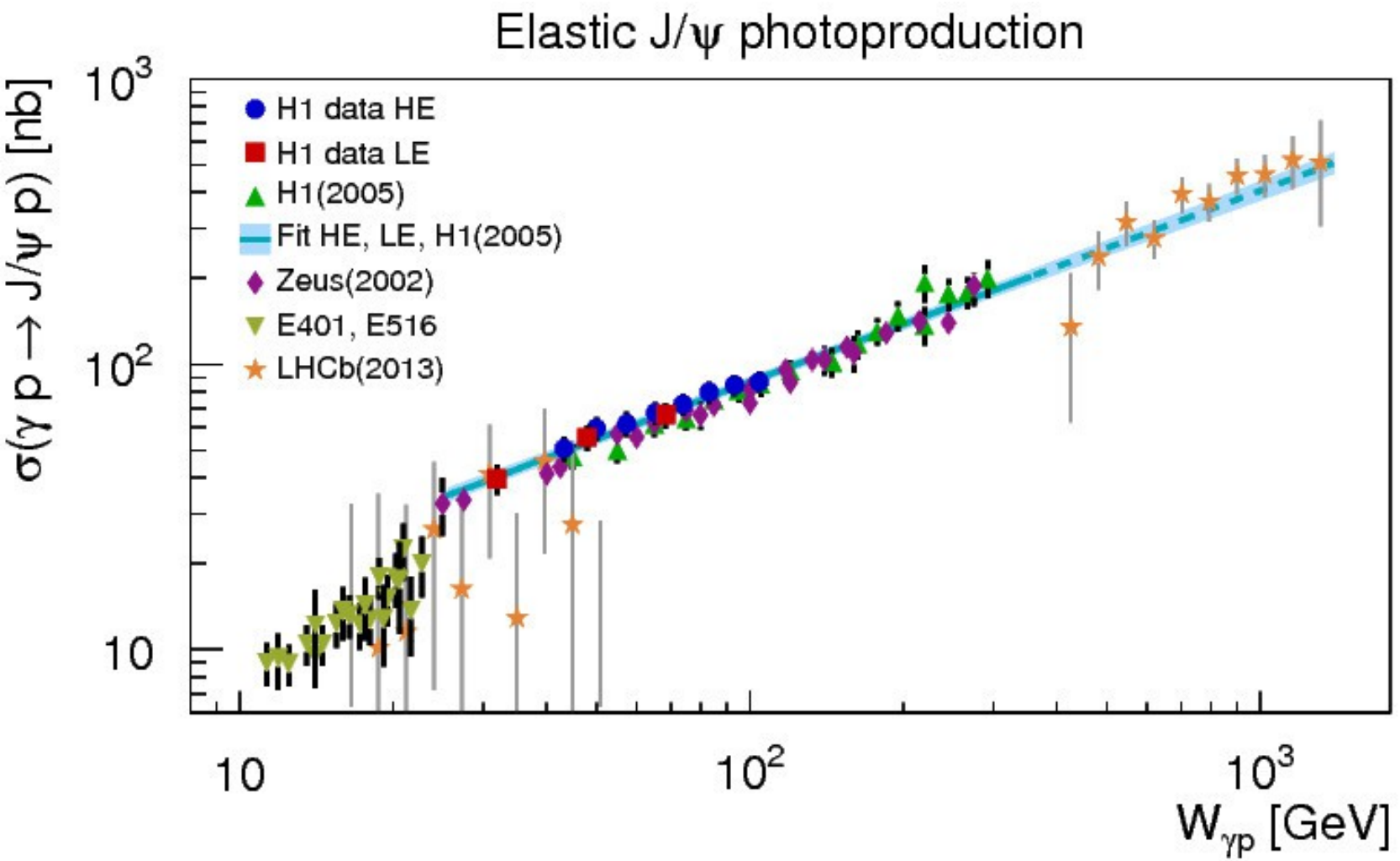




Simultaneous fit of elastic and p-diss. cross section ($\sigma \sim W^{\delta}$):

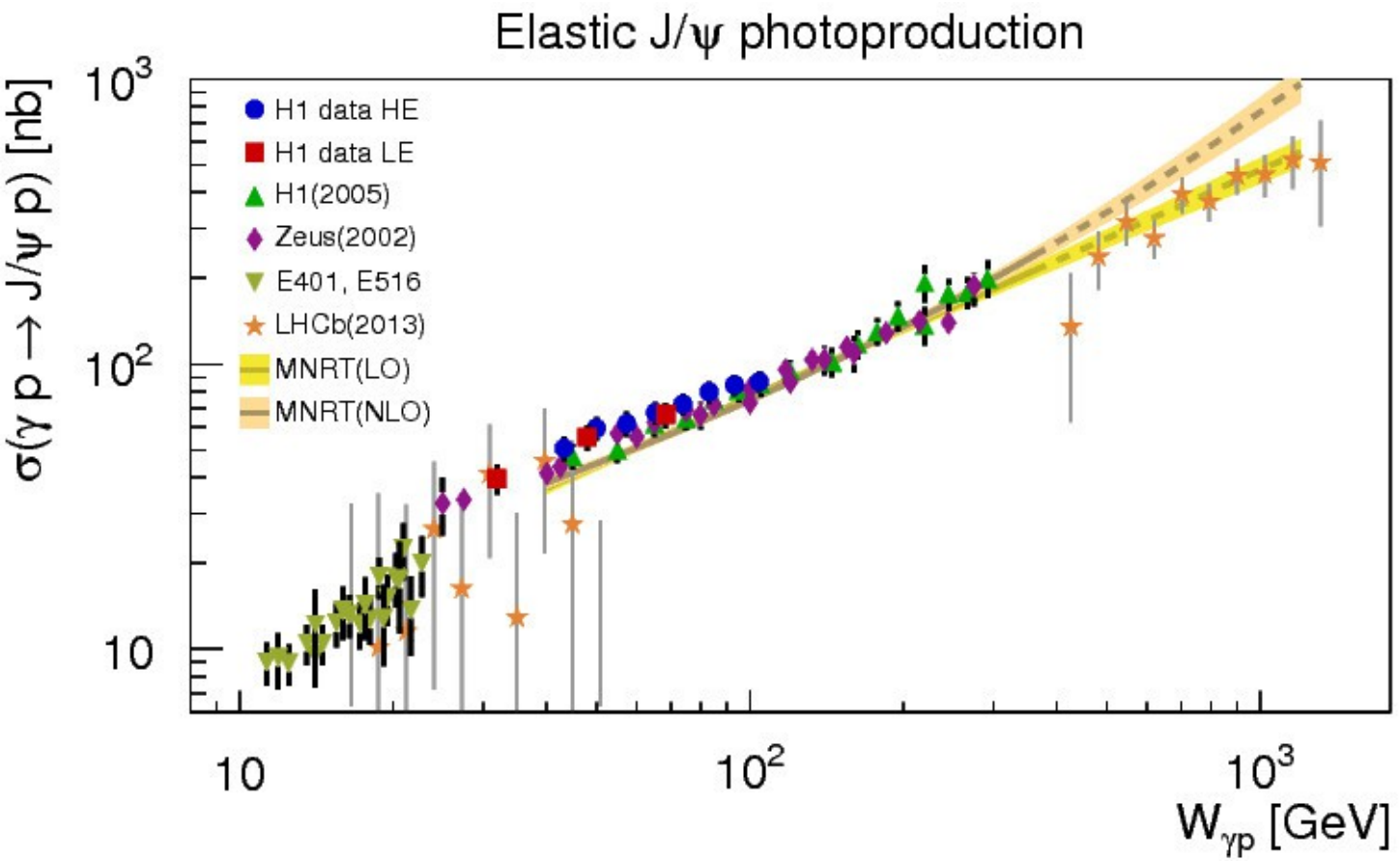
$\delta_{el} = 0.67 \pm 0.03, \qquad \delta_{p\text{-diss}} = 0.42 \pm 0.05$

Energy dependence



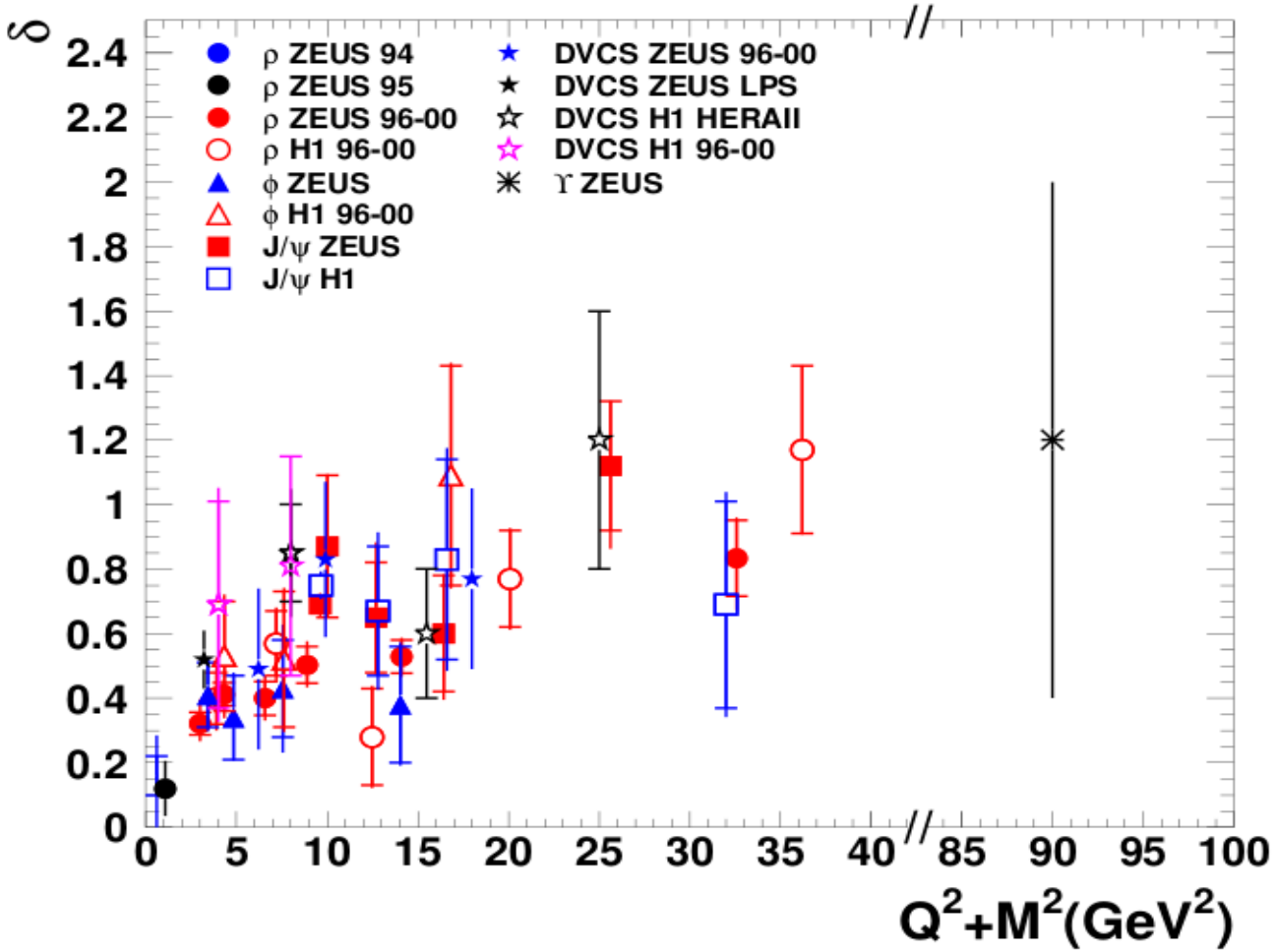
H1 fit extrapolation to higher energy describes LHCb data as well!

Energy dependence



- LO and NLO fits to previous J/Ψ data from HERA (gluon densities!)
- Both fits extrapolated to higher energies...
- LO extrapolation describes LHCb data.

Energy dependence compilation



$$\sigma \sim W^{\delta}$$

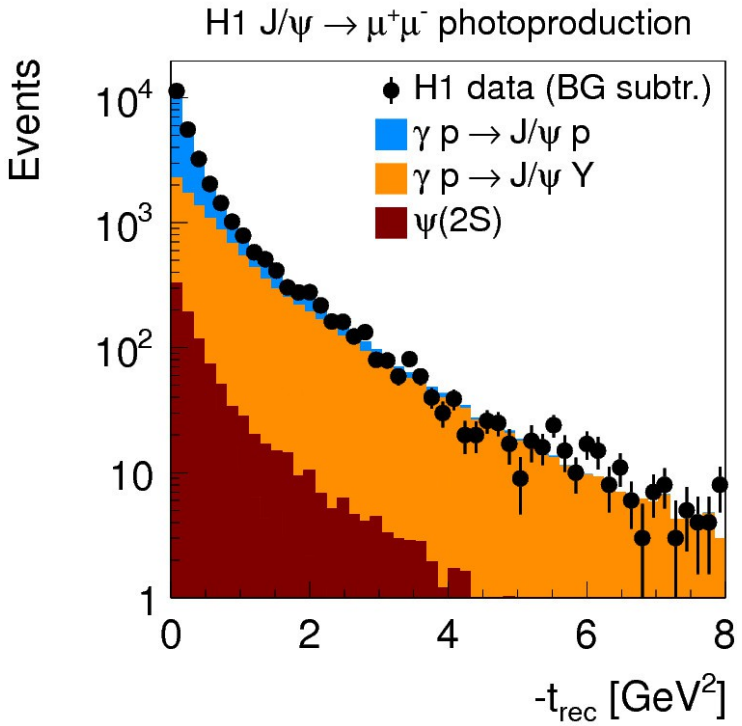
VMs: bigger "hard" scale Q^2+M^2 – steeper rise with W,
Q^2+M^2 scale governs "soft" – "hard" interaction transition

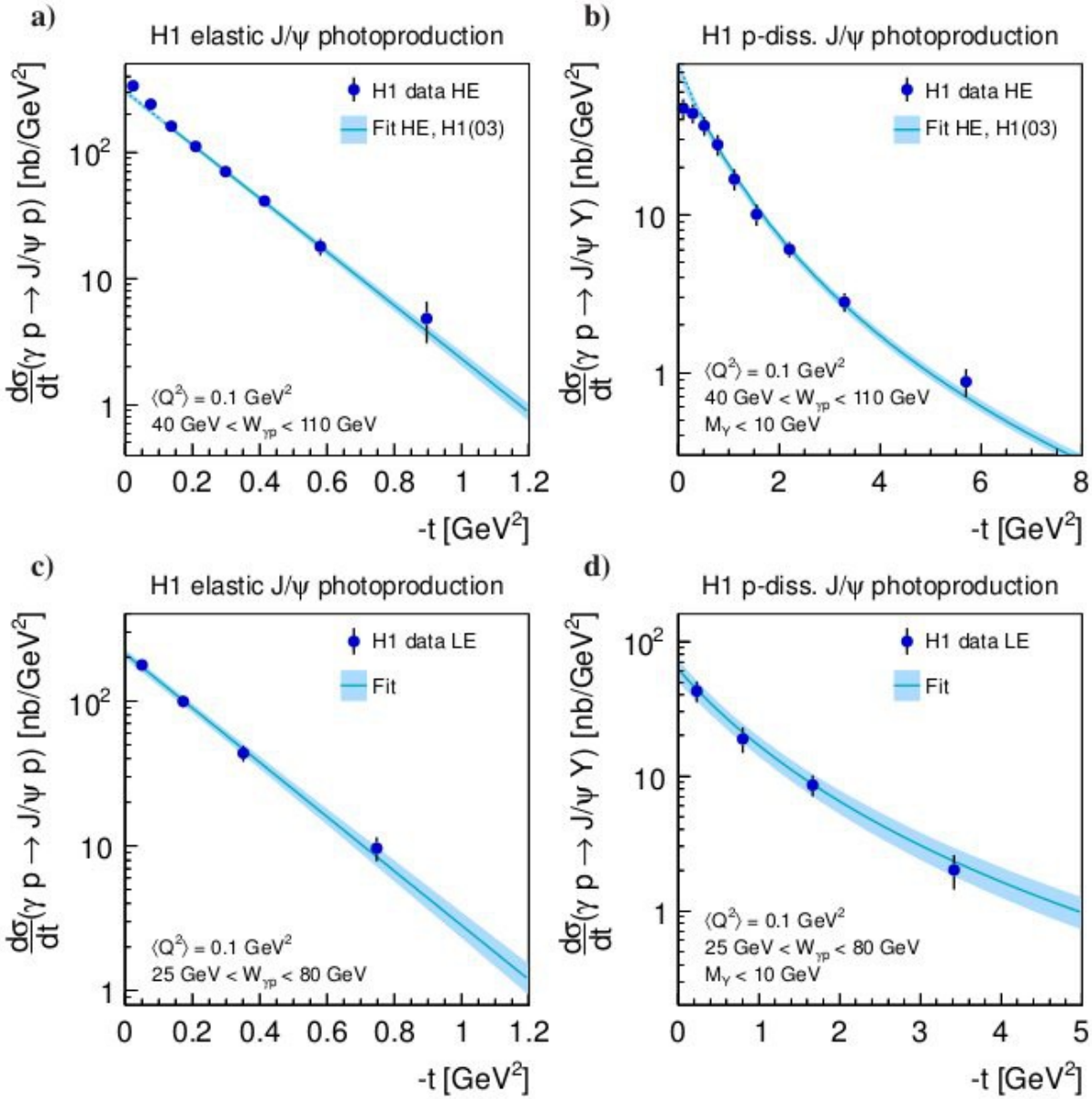
DVCS: always steep rise with W – "hard" interaction...

t-dependence

"elastic": $d\sigma/dt \sim e^{-b|t|}$

"p-diss.": $d\sigma/dt \sim (1+(b_{pd}/n)|t|)^{-n}$



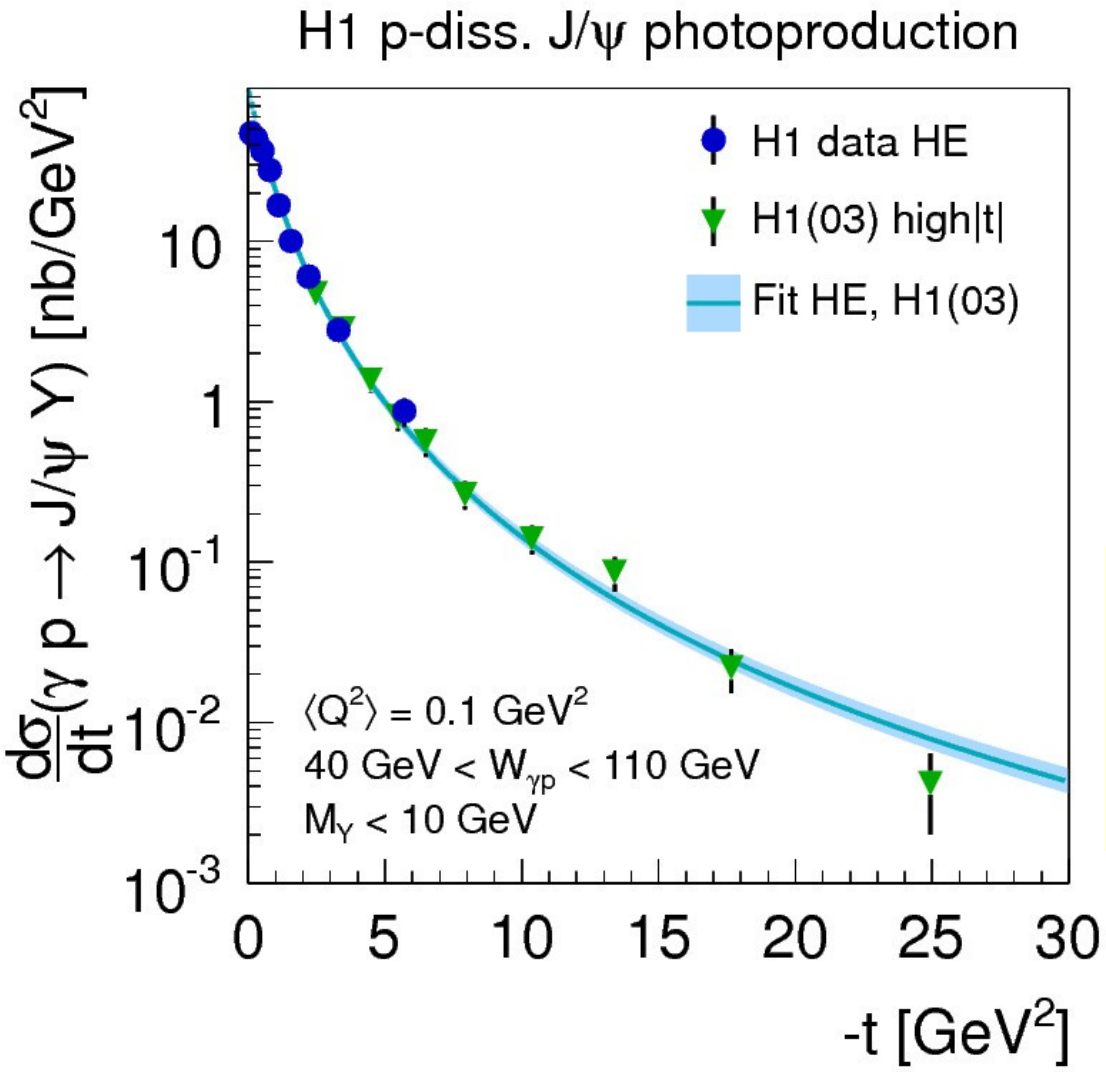


$b = 4.88 - 4.3 \pm 0.2\ GeV^{-2}$

$b_{pd} = 1.79 - 1.6 \pm 0.2\ GeV^{-2}$

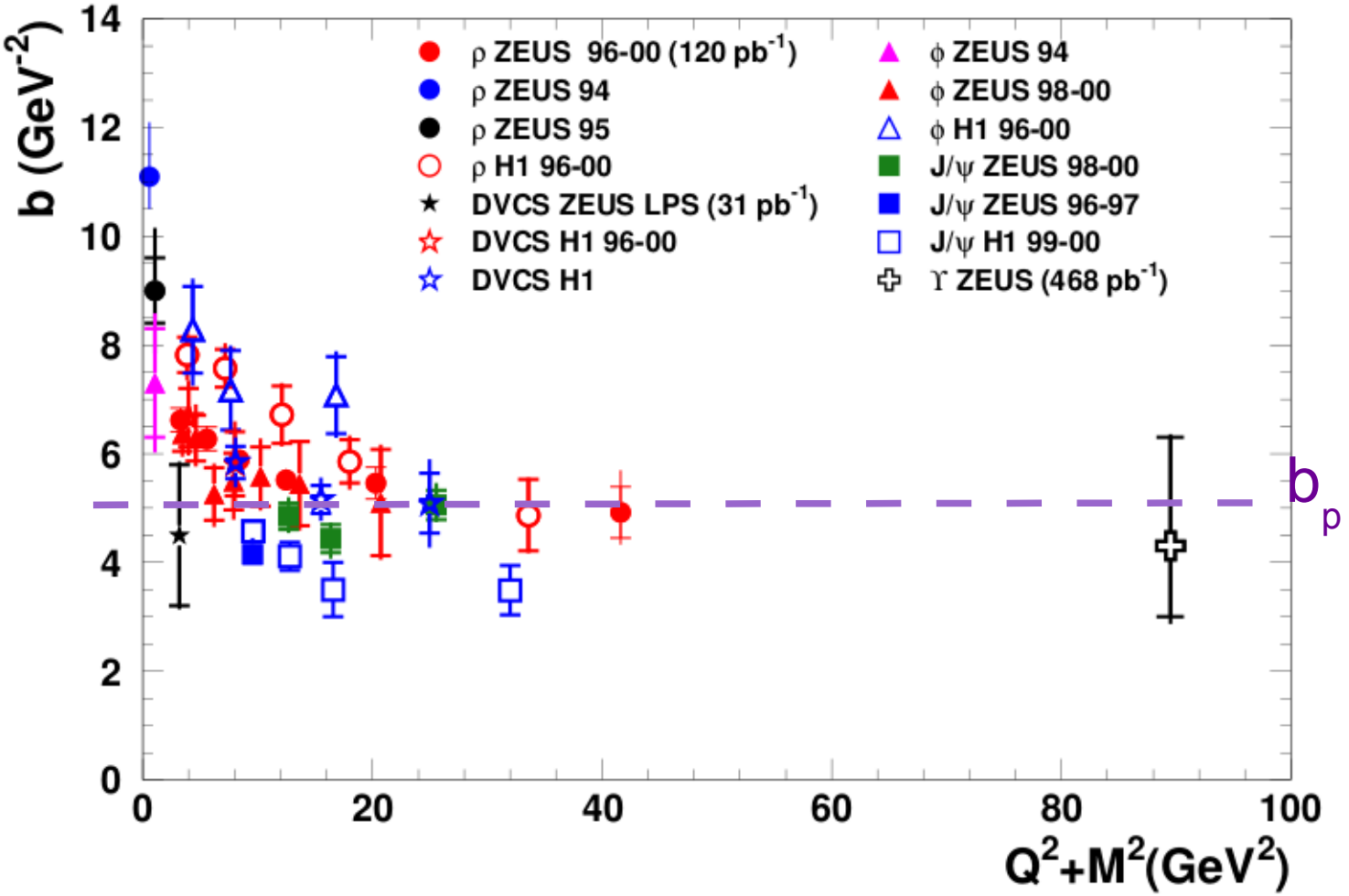
$n = 3.58 \pm 0.15$

t-dependence



- First measurement of p-diss. production at low $|t|$,
- Previous H1(03) high $|t|$ data extrapolated to present W, Q^2, M_Y range,
- Good agreement in the overlap region

t-dependence compilation



$$d\sigma/dt \sim e^{-b|t|}$$

$b = b_{VM} + b_p$

$\langle r^2 \rangle = b \cdot (hc)^2$

Proton target:

$b_p \approx 4.5$ GeV^{-2} =>

=> r_gluon ≈ 0.6 fm

< r_em ≈ 0.8 fm

Decreasing slope (and interaction size) with rising scale Q^2+M^2 -

- transition between “soft” and “hard” interaction

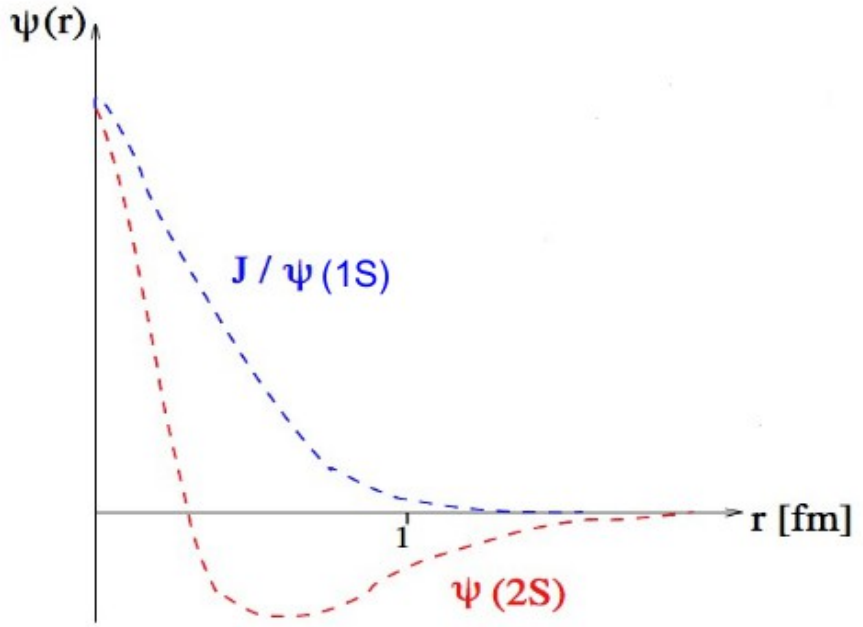
Ψ(2s)/Ψ(1s) ratios (1)

Ratio R = σ(Ψ(2s)/σ(J/Ψ(1s) =>

=> sensitive to radial charmonium wave function...

Ψ(2s) wave function ≠ J/Ψ(1s) w. f.: it has node at r ≈ 0.4 fm,

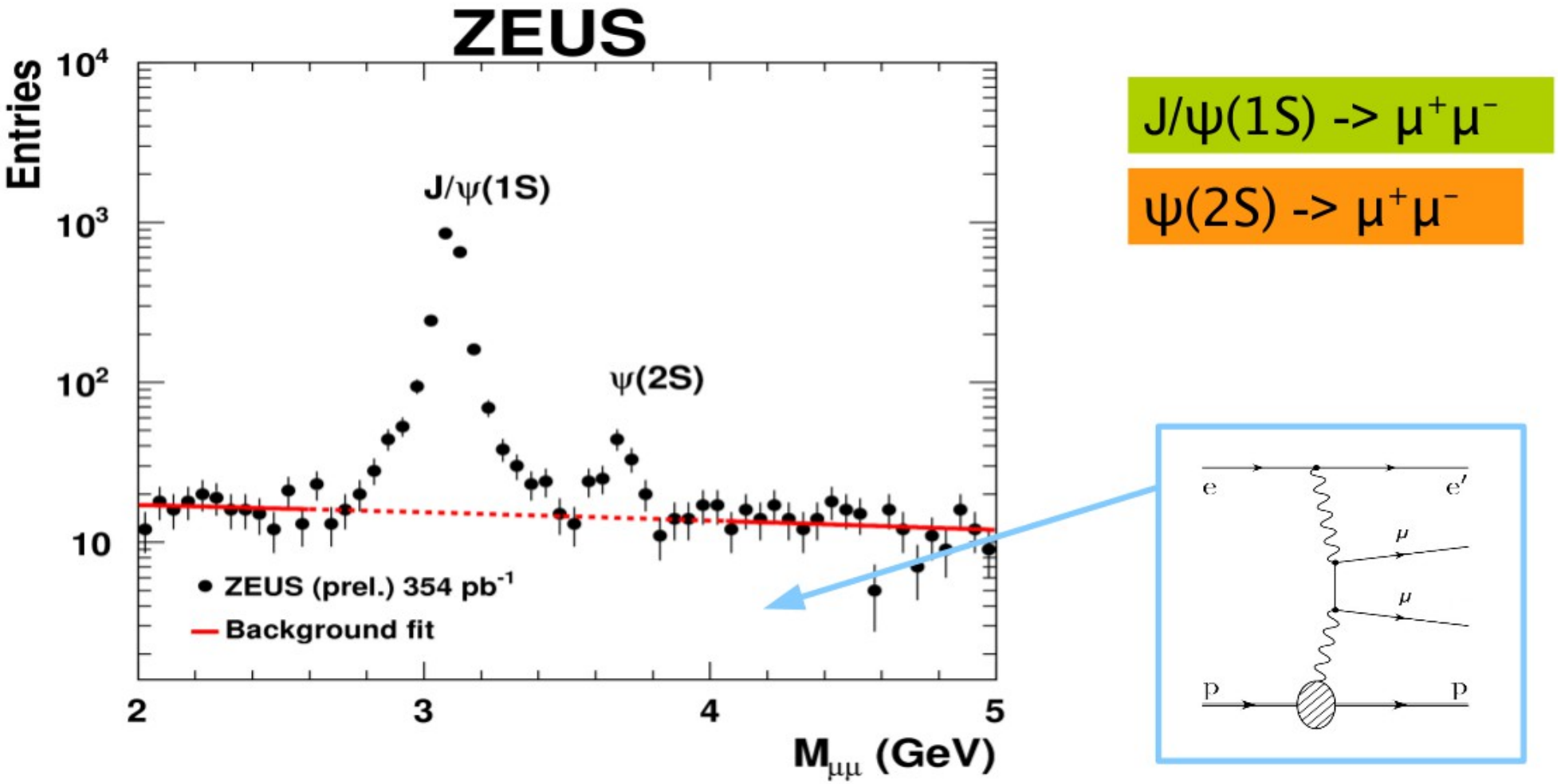
$\langle r^2(\Psi(2s)\rangle = 2\langle r^2(J/\Psi(1s))\rangle$



pQCD prediction: $R \approx 0.17$ $(Q^2 = 0)$ and rises with Q^2
(J. Nemchik et al., 1994, 1998)

Ψ(2s)/Ψ(1s) ratios (2)

ZEUS preliminary, DIS2014: HERA II, int. lumi = 354 pb^{-1}

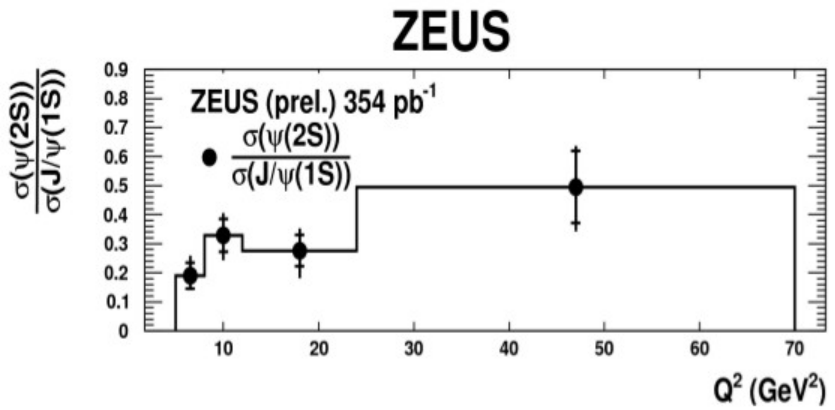


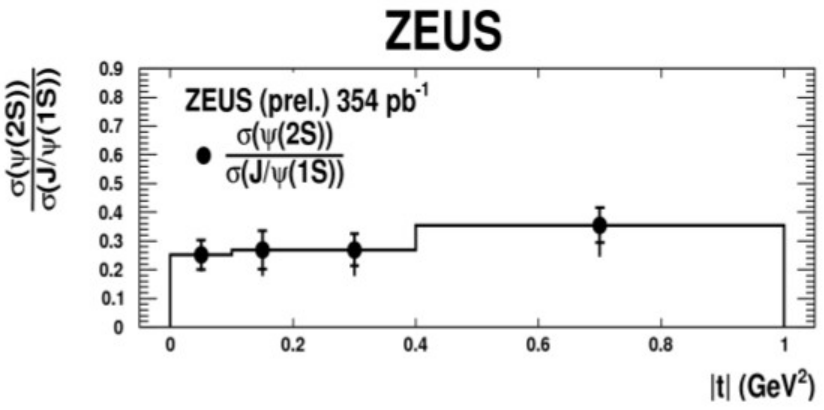
Ψ(2s)/Ψ(1s) ratios (3)

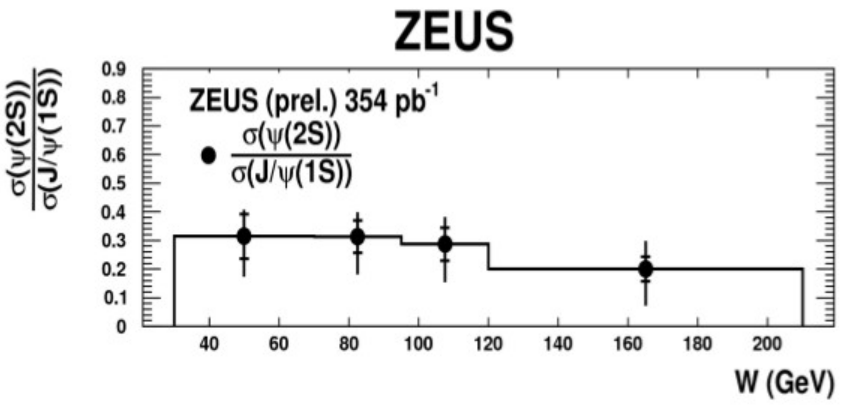
ZEUS preliminary DIS2014: HERA II, int. lumi = 354 pb^{-1}

$\psi(2S)$ decay mode	$\sigma(\psi(2S))/\sigma(J/\psi(1S))$
$\rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$	$0.29 \pm 0.04^{+0.02}_{-0.01}$
$\rightarrow \mu^+\mu^-$	$0.25 \pm 0.05^{+0.04}_{-0.02}$
combined	$0.28 \pm 0.03^{+0.02}_{-0.01}$

$30 \leq W \leq 210$ GeV
$5 \leq Q^2 \leq 70$ GeV^2
$|t| \leq 1$ GeV^2







Ratio R =

$\sigma(\Psi(2s)/\sigma(J/\Psi(1s))$:

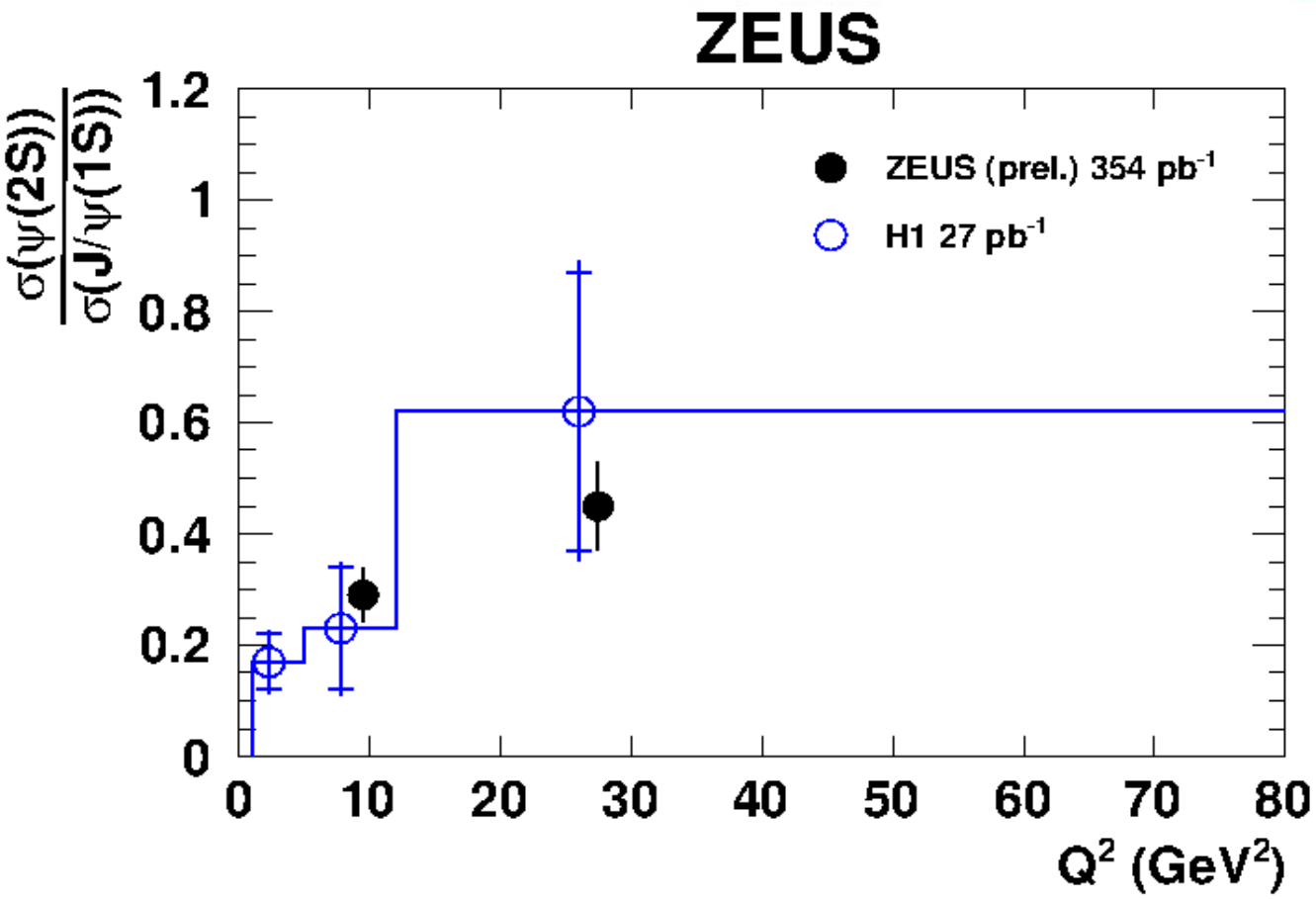
- Increases with Q^2,
- Independent of W and t

Ψ(2s)/Ψ(1s) ratios (4)

ZEUS - **H1** comparison:

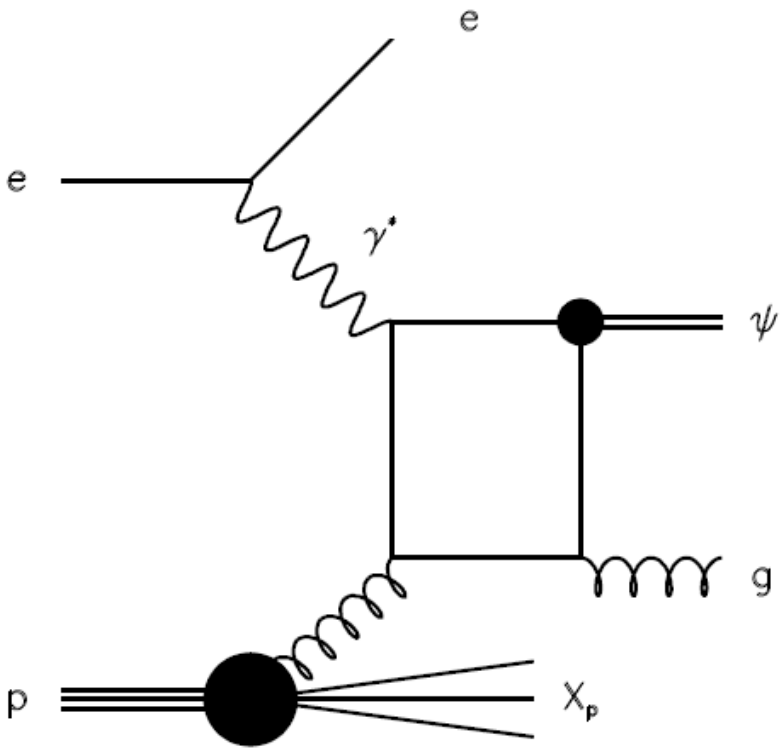
- ZEUS data analysed in Q^2 bins used by H1 (Q^2: 5 — 12 and 12 — 80 GeV^2)

$40 < W < 180$ GeV
$1 < Q^2 < 80$ GeV^2

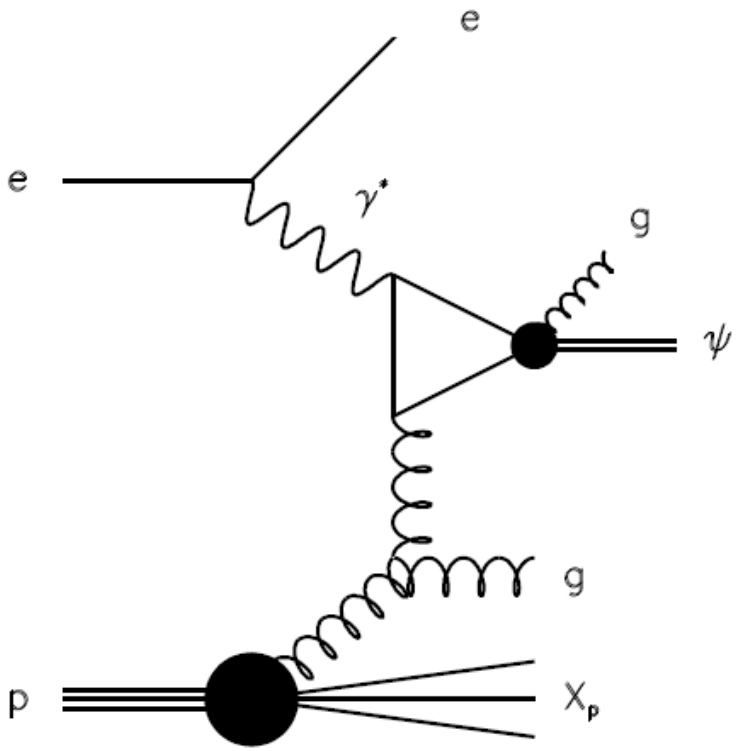


H1 study of ψ' in DIS
Eur.Phys.J.C10:373-393,1999

Inelastic Ψ and Ψ' production (1)



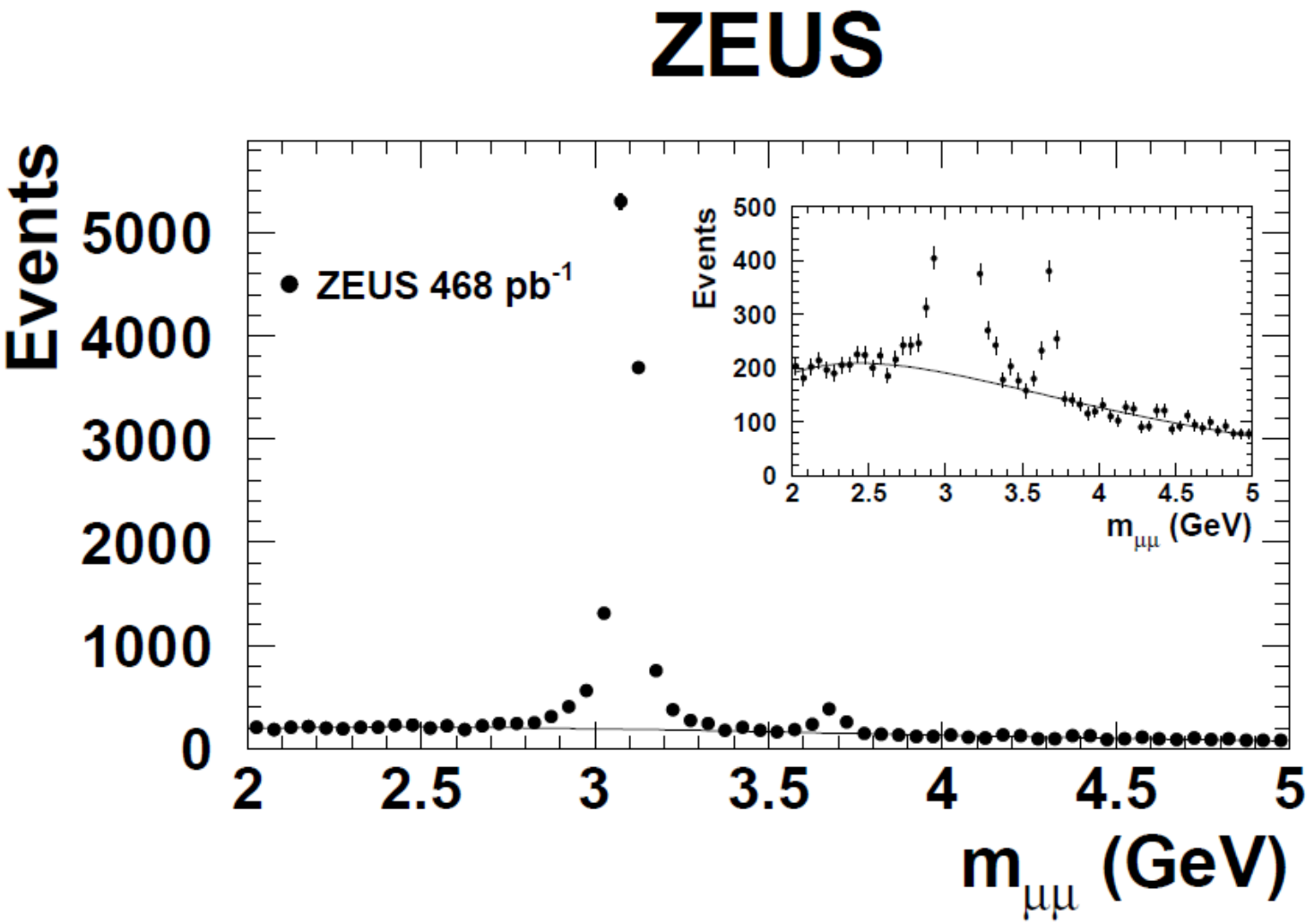
Color **S**inglet model **CS**:
cc q.n. = J/Ψ q.n.



Color **O**ctet model **CO**:
cc q.n. ≠ J/Ψ q.n.

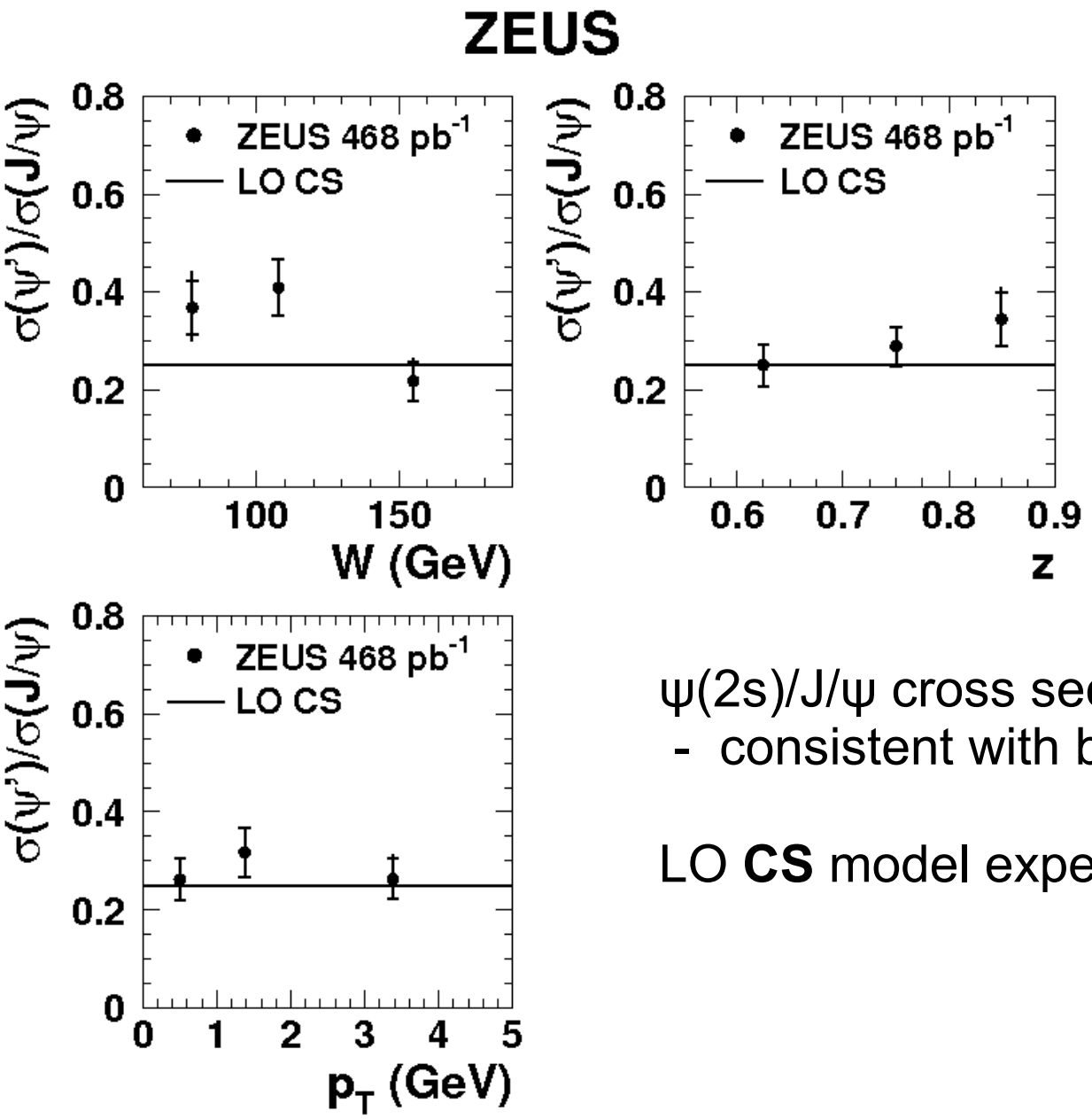
Inelastic Ψ and Ψ' production (2)

ZEUS, JHEP **02** (2013) 071



60 < W < 240 GeV

Inelastic Ψ and Ψ' production (3)

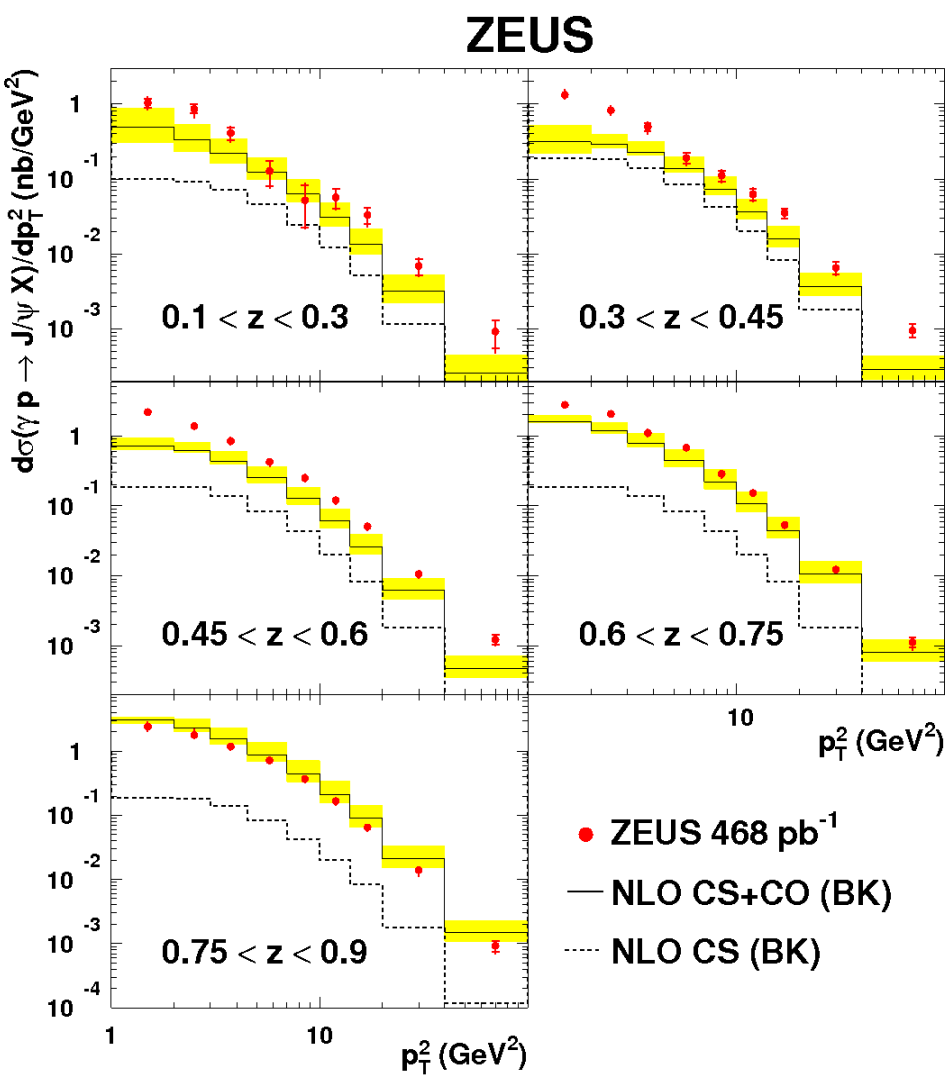


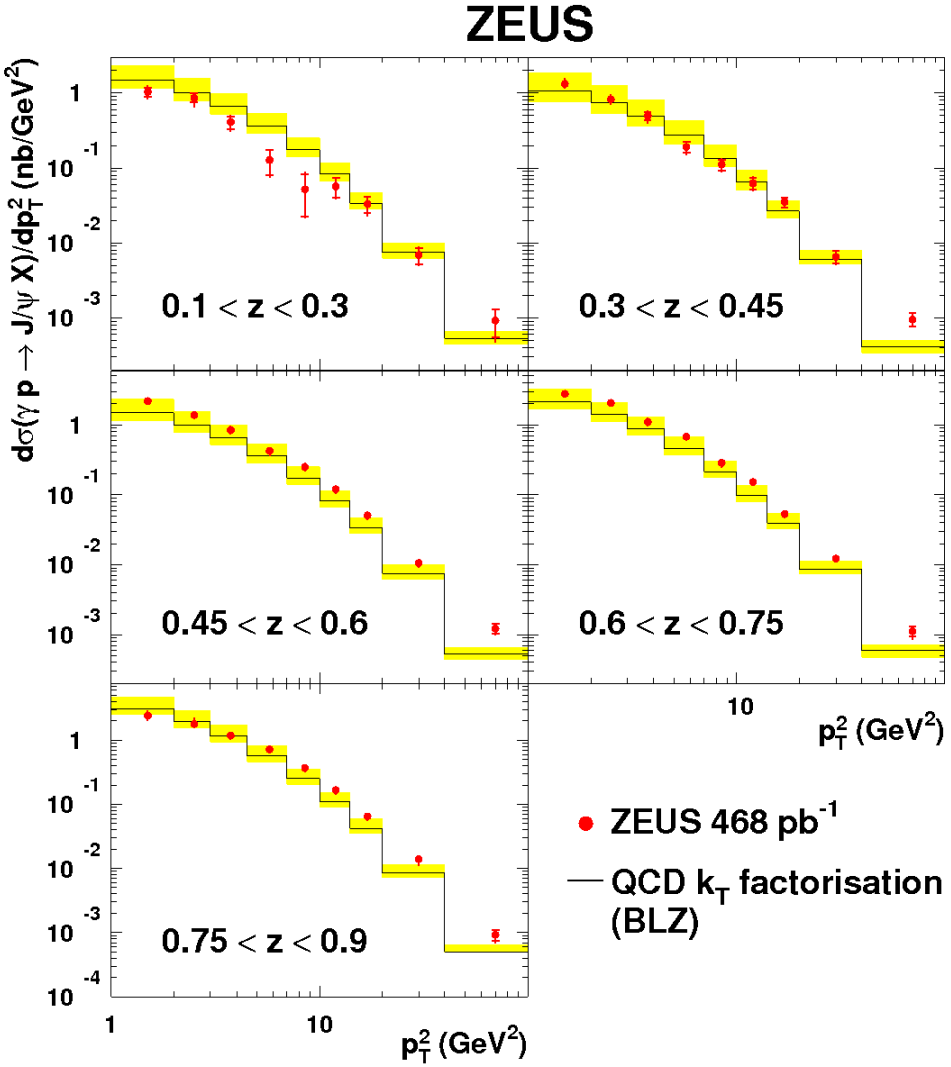
z = E(Ψ)/E(γ*)
(p rest frame)

ψ(2s)/J/ψ cross section ratio vs W, p_T and z
- consistent with being flat,

LO **CS** model expectation = 0.25 (horiz. line)

Inelastic Ψ and Ψ' production (4)





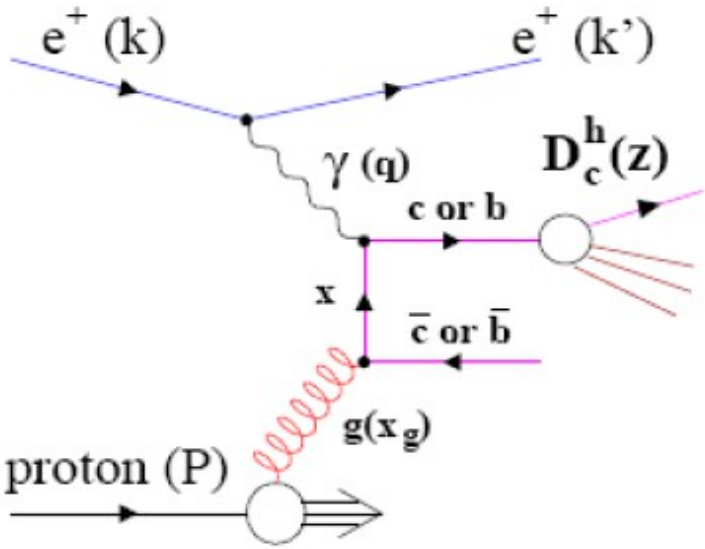
Left **theory**: full **NLO** computation including **CS** and **CO** terms

Right **theory**: **LO CS** model framework amended with non zero initial state gluons k_T

=> better description of the data from k_T factorisation

Open charm production (1)

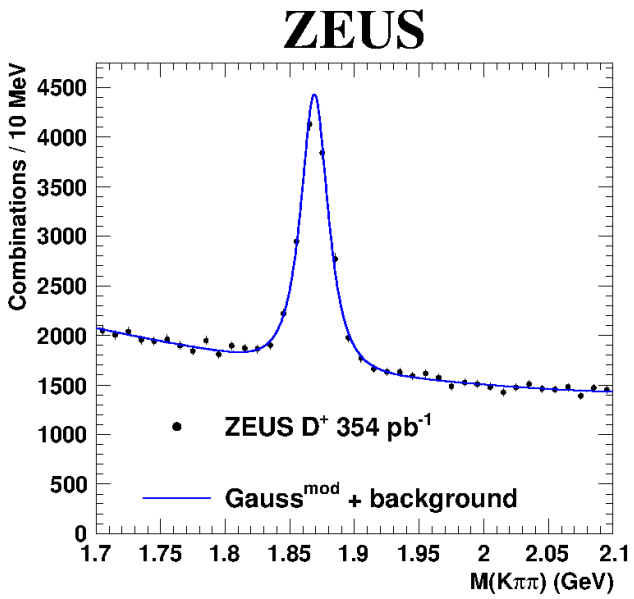
$$D^+ = c\bar{d},\ D^0 = c\bar{u},\ \bar{D}^0 = \bar{c}u,\ D^- = \bar{c}d$$

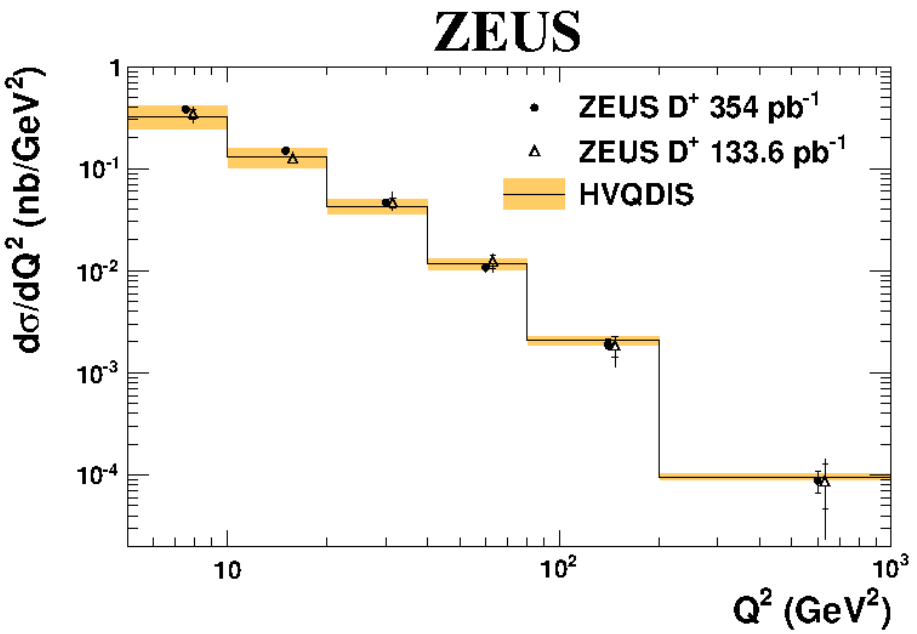


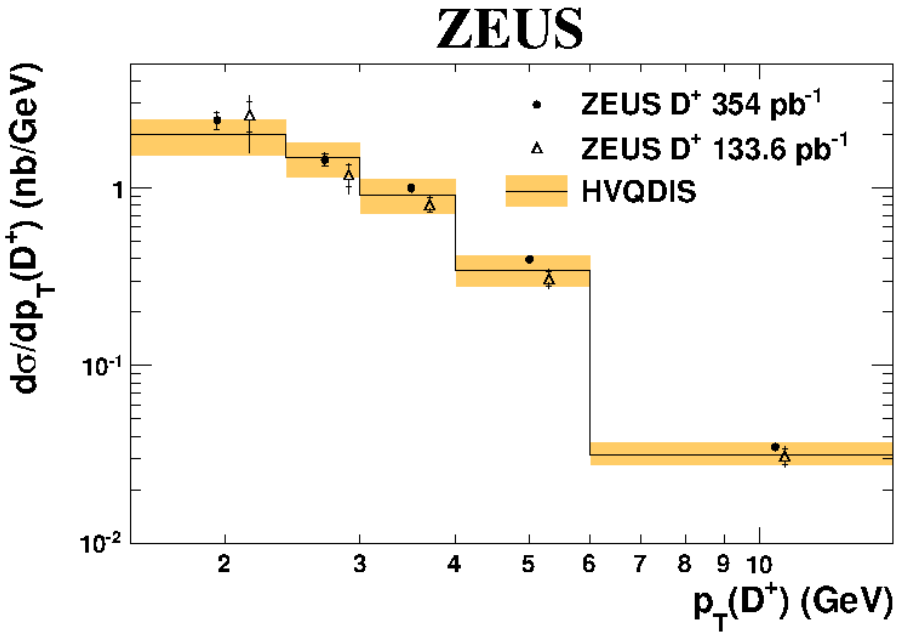
- Predominantly boson-gluon fusion
- Charm contribution to inclusive DIS at HERA up to 30%
- Multi-scale problem: Q^2, M_c^2, p_T^2
- sensitive to c-quark mass...
- sensitive to gluon density in the proton (PDFs)
- Test of pQCD NLO calculations (various mass schemes!)
- Can extract charm contribution to proton structure function
- Charm quark hadronisation to charmed hadrons -
  - test of fragmentation universality

Open charm production (2)

ZEUS, **$D^{\pm}$ production in DIS**, JHEP **05** (2013) 023, HERA II, 354 pb^{-1}





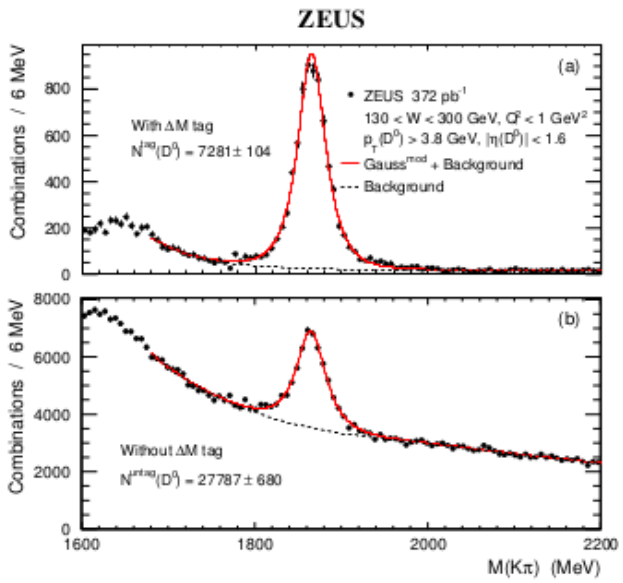


NLO QCD predictions (HVQDIS) based on FFNS mass scheme reproduce the data up to Q^2 = 1000 GeV^2

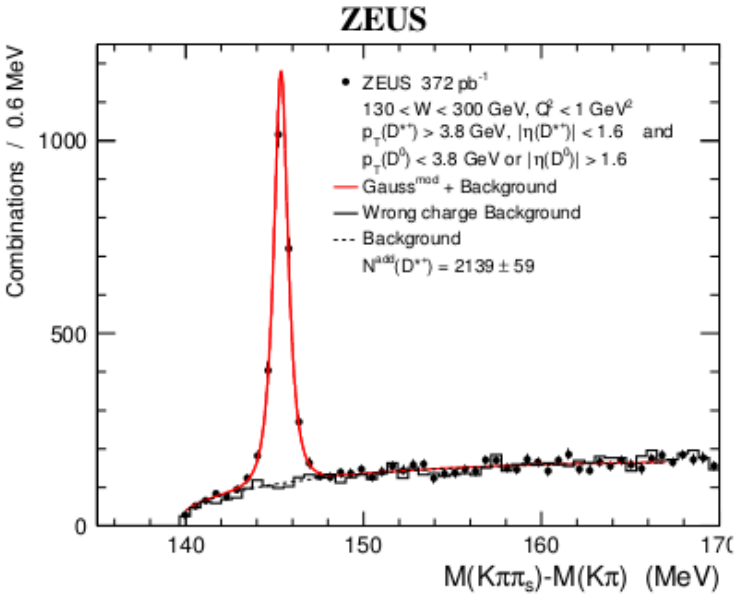
Open charm production (3)

ZEUS, **Charm fragmentation fractions in PHP**,
JHEP **09** (2013) 058, HERA II, 372 pb$^{-1,}$ 130 < W 300 GeV

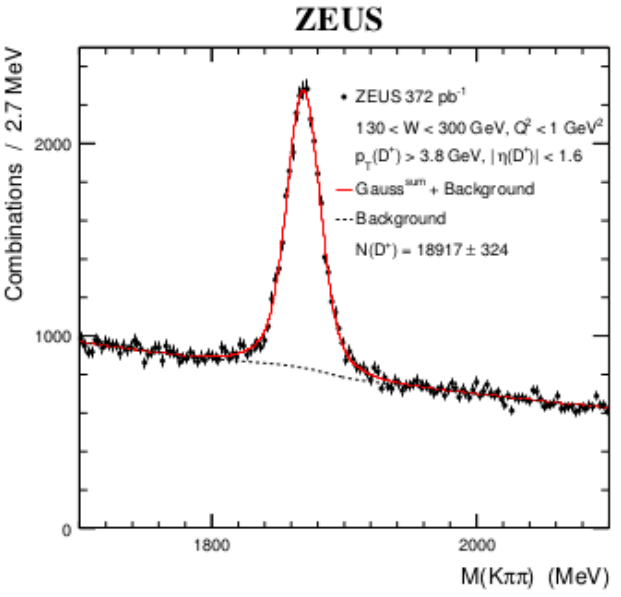
$$D^0 \to K^-\pi^+, \quad D^+ \to K^-\pi^+\pi^+$$
$$D^{*+} \to D^0\pi_s^+ \to K^-\pi^+\pi_s^+$$
$$D_s^+ \to \phi\pi^+, \quad \Lambda_c^+ \to K^-p\pi^+$$



$M(K^-\pi^+)$



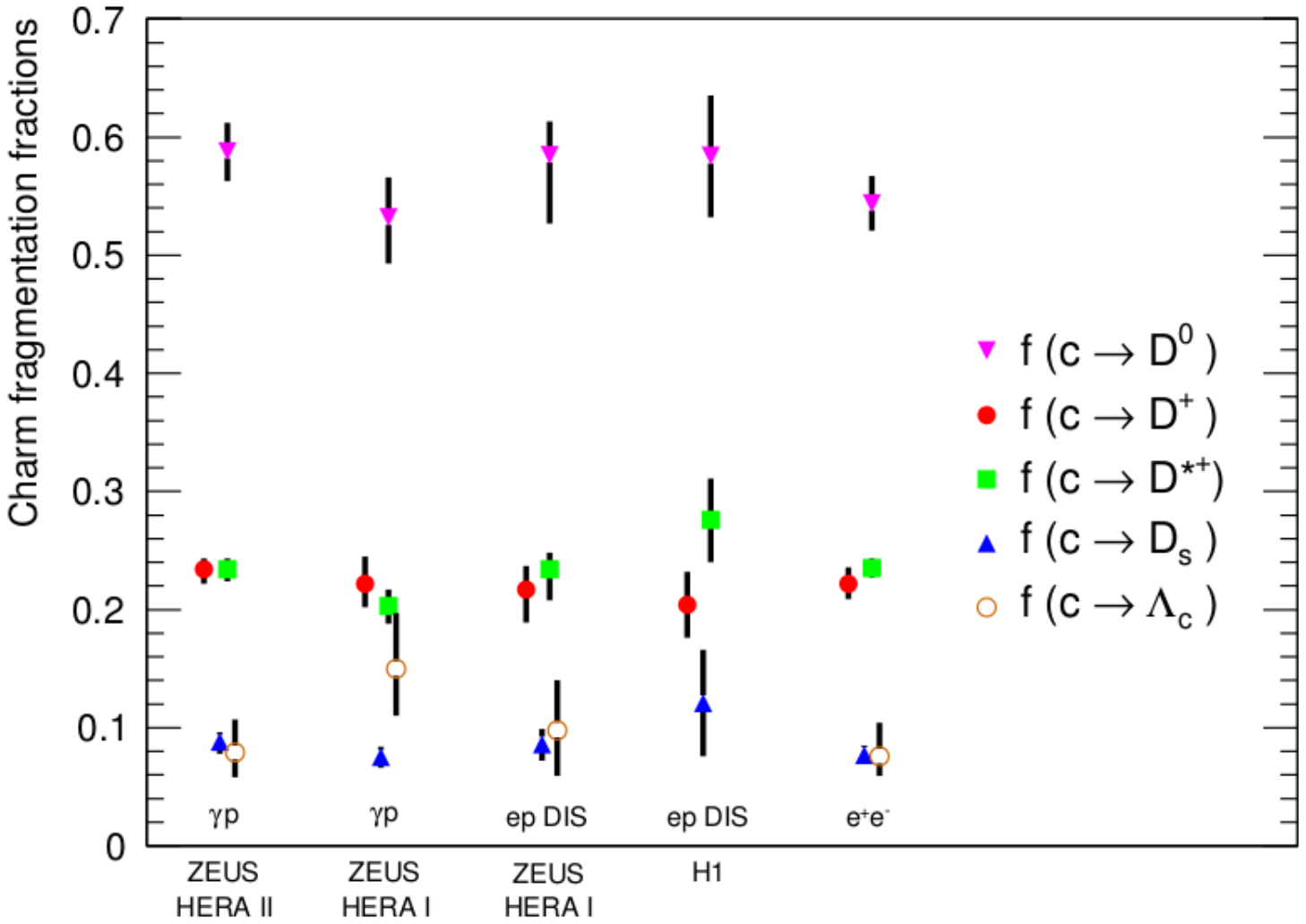
$M(K^-\pi^+\pi_s^+) - M(K^-\pi^+)$



$M(K^-\pi^+\pi^+)$

Open charm production (4)

ZEUS, **Charm fragmentation fractions in PHP**,
JHEP **09** (2013) 058, HERA II, 372 $pb^{-1,}$ 130 < W 300 GeV



ep PHP, ep DIS and e^+e^- agree => universality of heavy quark fragmentation!

H1 + ZEUS: HERA charm data combination in DIS, EPJ **C73** (2013) 2311
Charm structure functions etc.

"Visible" charm cross-section σ^{CC}_{vis} ⟷ "reduced" charm cross-section σ^{CC}_{red} ⟷ Charm structure function F^{CC}_{2}

(NLO pQCD model dependent!)

$$\frac{\mathrm{d}^2\sigma^{c\bar{c}}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{2\pi\alpha^2(Q^2)}{xQ^4}([1+(1-y)^2]F_2^{c\bar{c}}(x,Q^2) - y^2F_L^{c\bar{c}}(x,Q^2)).$$

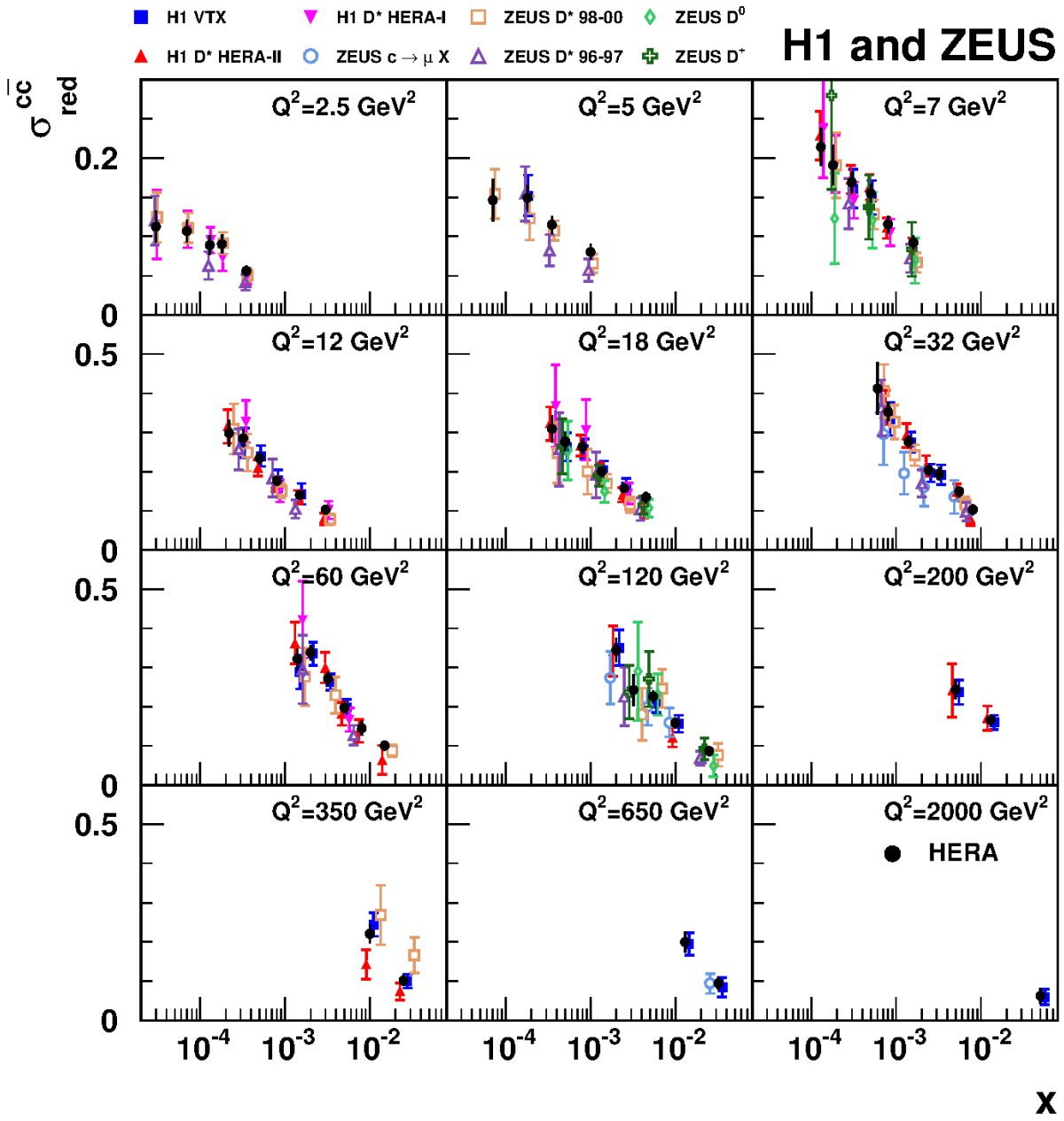
$$\sigma^{c\bar{c}}_{\mathrm{red}} = \frac{\mathrm{d}^2\sigma^{c\bar{c}}}{\mathrm{d}x\mathrm{d}Q^2}\cdot\frac{xQ^4}{2\pi\alpha^2(Q^2)\,(1+(1-y)^2)}$$

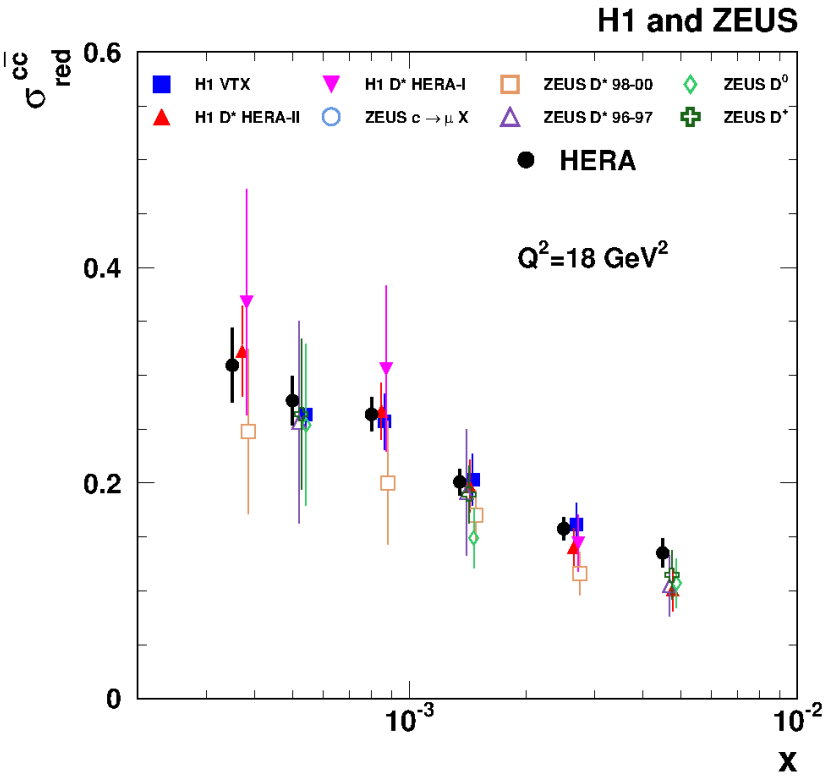
$$= F_2^{c\bar{c}} - \frac{y^2}{1+(1-y)^2}F_L^{c\bar{c}}.$$

$$\sigma^{c\bar{c}}_{\mathrm{red}}(x,Q^2) = \sigma_{\mathrm{vis,bin}}\frac{\sigma^{c\bar{c},\mathrm{th}}_{\mathrm{red}}(x,Q^2)}{\sigma^{\mathrm{th}}_{\mathrm{vis,bin}}}.$$

Open charm production (6)

H1 + ZEUS: HERA charm data combination in DIS, EPJ **C73** (2013) 2311

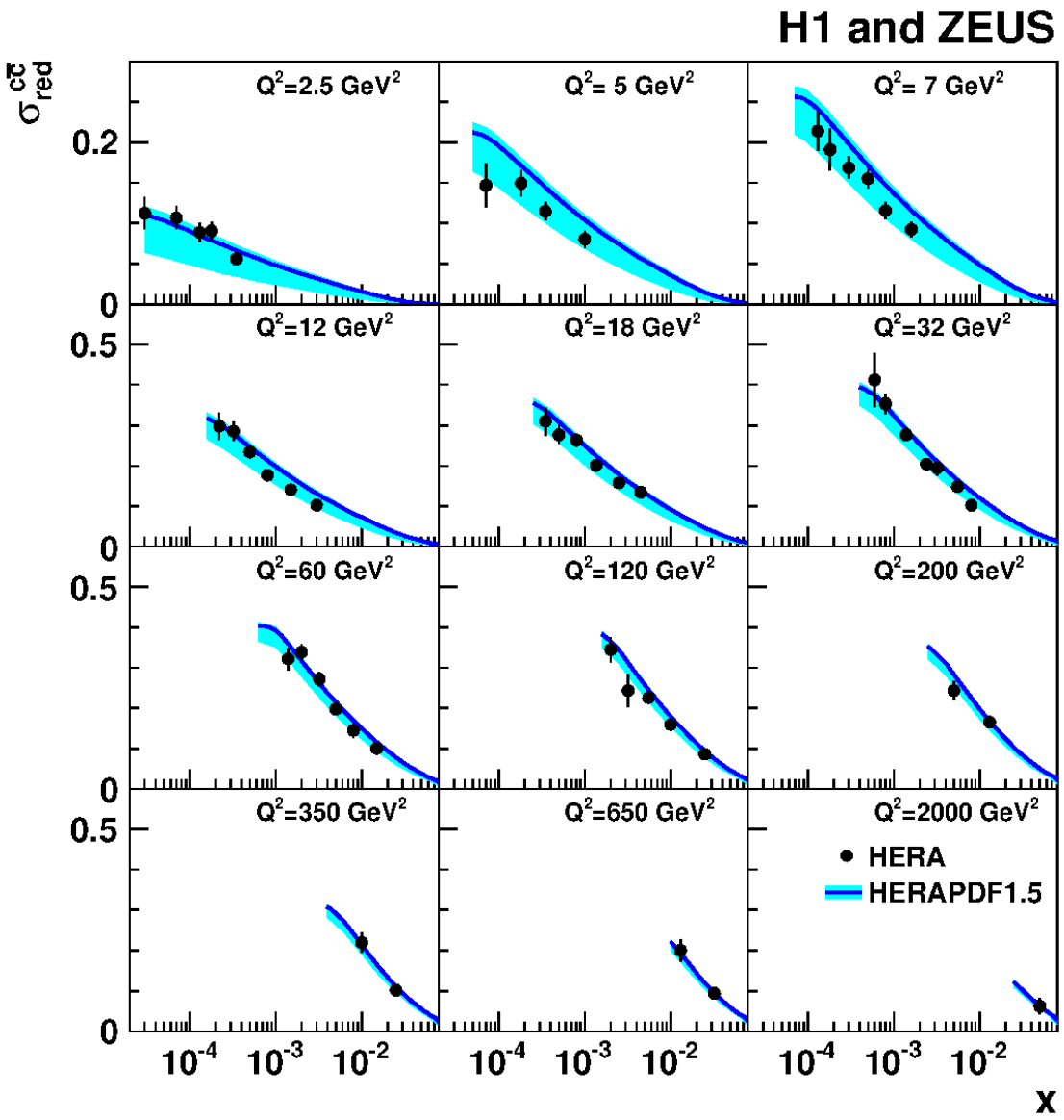




Combined results uncertainty **~2 times lower** than for each most precise data set...

Open charm production (7)

H1 + ZEUS: HERA charm data combination in DIS, EPJ **C73** (2013) 2311



NLO prediction based on inclusive HERAPDF1.5 describes the charm data well...

Summary

- HERA was heavy meson factory: only selected, recent results were presented
- Diffractive and inelastic charmonium production: – semi-quantitative succes of perturbative QCD
- Heavy flavour mesons – perturbative QCD at work
- Charm contribution to proton structure well understood within pQCD framework
- Quality and amount of HERA data – challenge for pQCD calculations