# Measurement of perturbative QCD and hadronic final states at HERA

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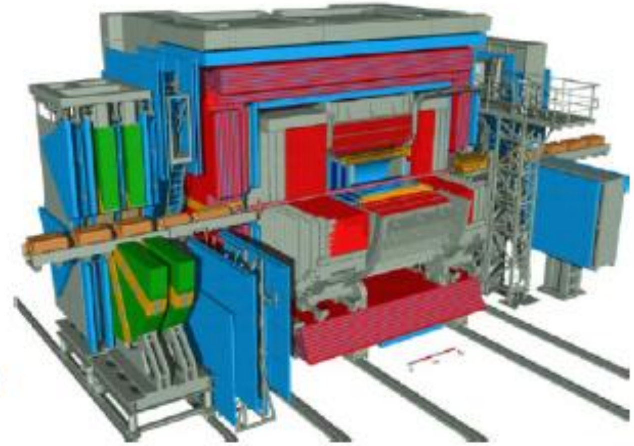
**Outline :** QCD explorer HERA
Jets and $\alpha_s$
Diffractive dijets
Prompt photons in (diffractive) photoproduction
Heavy quark production
Combined HERA $D^{*\pm}$ Cross Sections in DIS
Summary & Prospects

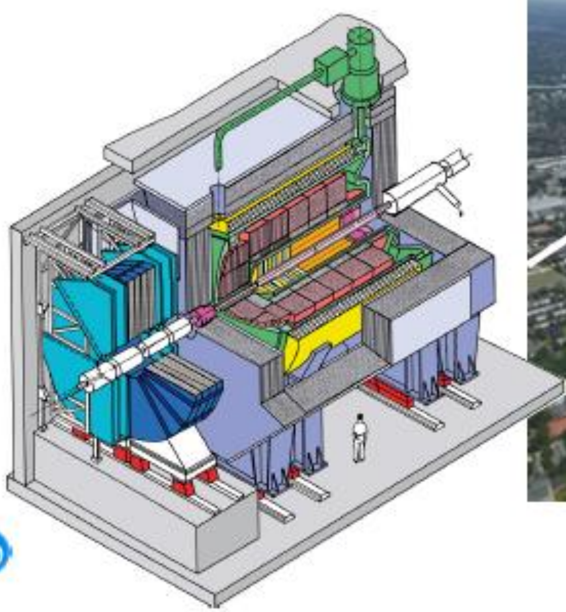
**Back-up :** Extraction of $m_c$ and $m_b$
ratio of $D^{*\pm}$ PhP x-sections at different $\sqrt{s}$
charged particle spectra in DIS

# The HERA ep collider (1992 - 2007)

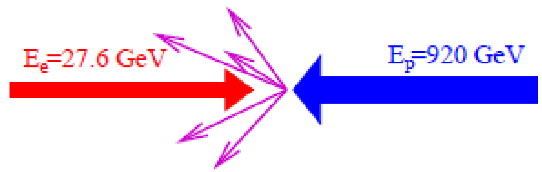
- ep collider:
- $e^{\pm}$ energy: 27.6 GeV
- p energy: 920 GeV
- Center of mass energy: 319 GeV
- 2 collider experiments: H1 and ZEUS
- Integrated luminosity: ~0.5 $fb^{-1}$ (per experiment)



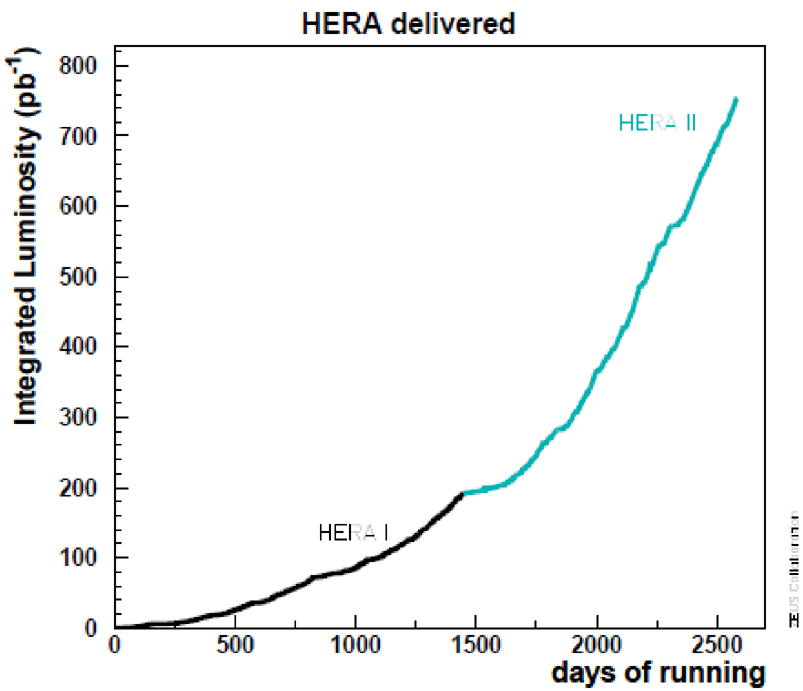
ZEUS



# QCD explorer HERA




| | HERA 1992-2000 | HERA II 2003-2007 |
|---|---|---|
| $\sqrt{s}$ | 320 (300) | 320 GeV |
| $\mathcal{L}$ | $1.5 \cdot 10^{31}$ | $7 \cdot 10^{31}\, cm^{-2}\, s^{-1}$ |
| $\mathcal{L}_{int}$ | 0.13 | $0.37\, fb^{-1}$ |



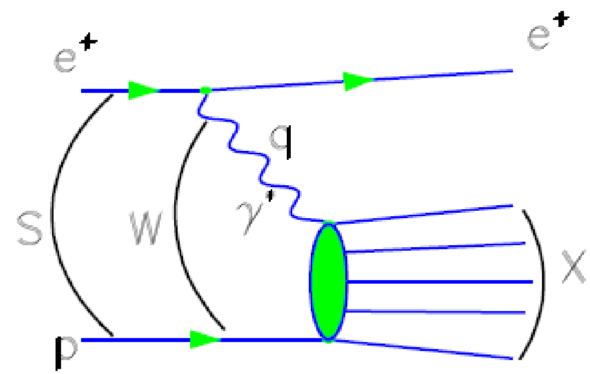

$$e(k) + p(P) \rightarrow e(k') + X \qquad s = (P+k)^2$$

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

| | |
|---|---|
| Photoproduction | $Q^2 \simeq 0\, GeV^2$ |
| DIS | $Q^2 > 1\, GeV^2$ |

$$\sigma_{c\bar{c}} \approx 1\,\mu b \Longrightarrow 10^9 \text{ events } (\mathcal{L}_{int} = 1\, fb^{-1})$$

$$\sigma_{b\bar{b}} \approx 10\,\text{nb} \Longrightarrow 10^7 \text{ events } (\mathcal{L}_{int} = 1\, fb^{-1})$$



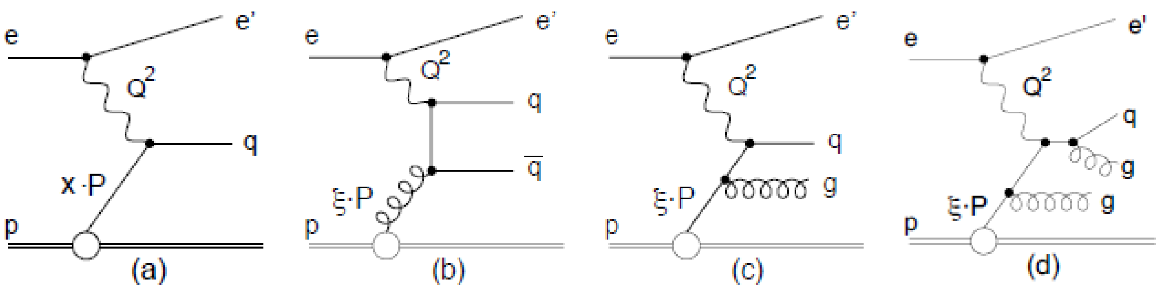

$$W^2 = (P+q)^2$$

$$y = \frac{qP}{kP} \cong \frac{W^2 + Q^2}{s}$$

$$x = \frac{Q^2}{2qP} \cong \frac{Q^2}{sy}$$

# Trijet Production in DIS

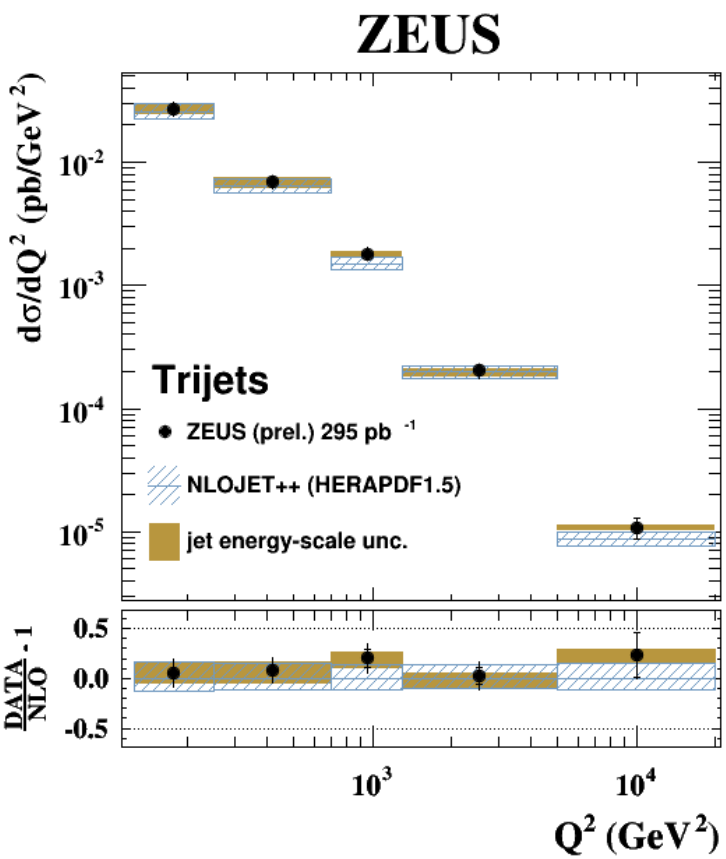
ZEUS-prel-14-008

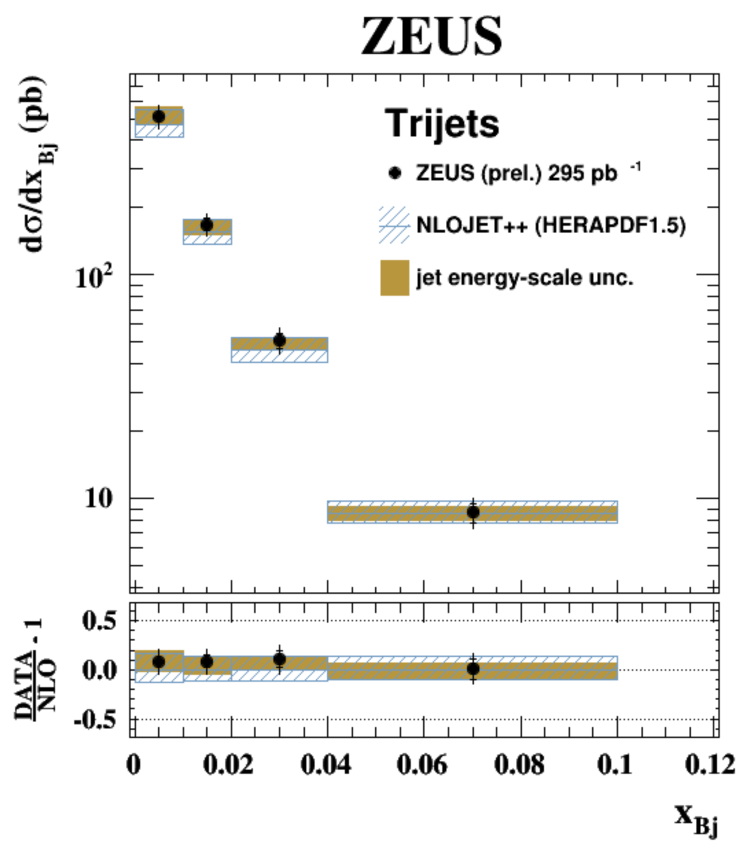



$125 < Q^2 < 20\,000$ GeV$^2$

$0.2 < y < 0.6$

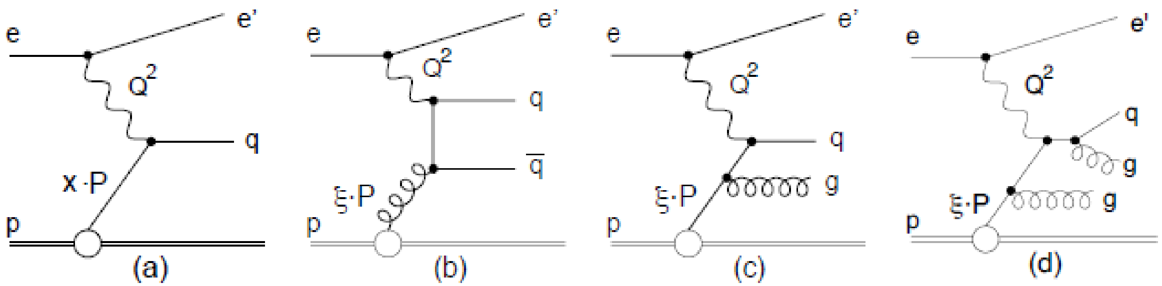
$\mu_r^2 = (Q^2 + P_T^2)/2$ and $\mu_f^2 = Q^2$



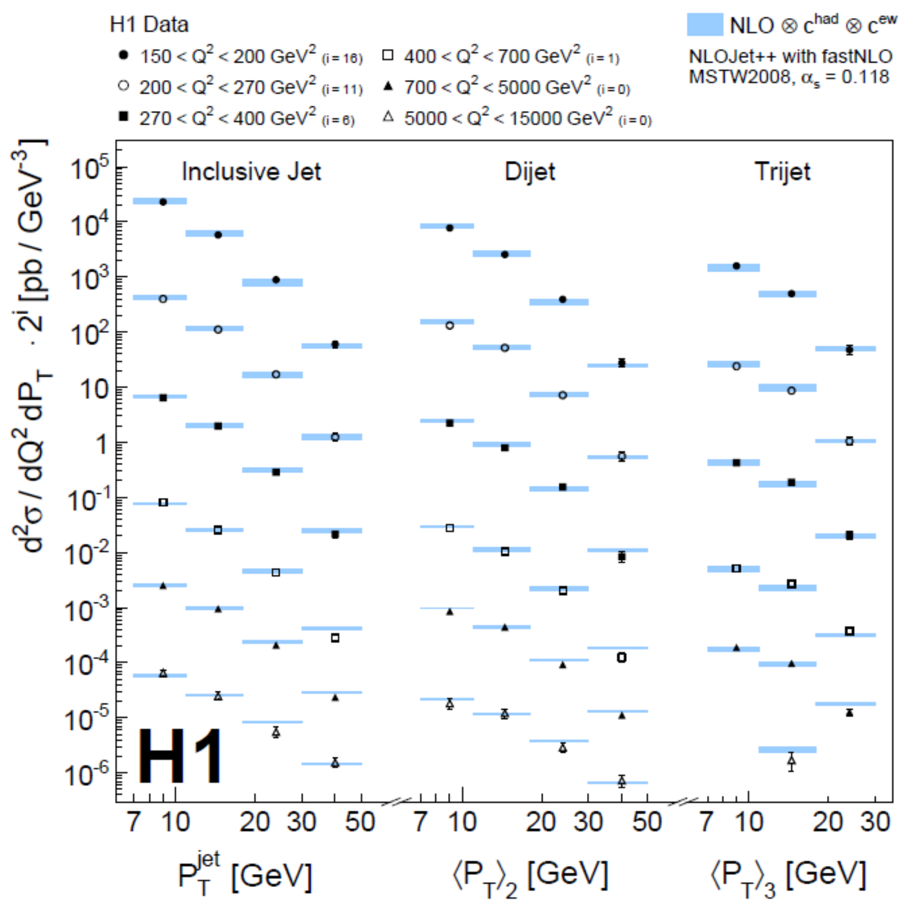
# Multijet Production and $\alpha_s$ extraction

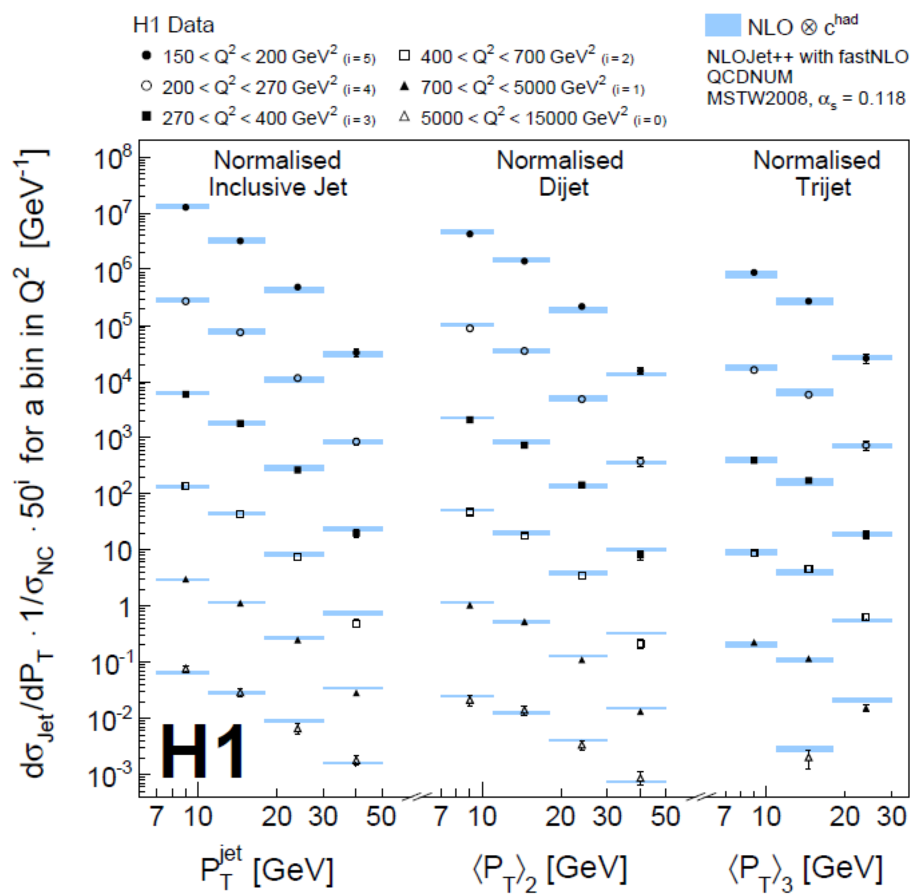
Eur. Phys. J. C75 (2015) 65
arXiv:1406.4709



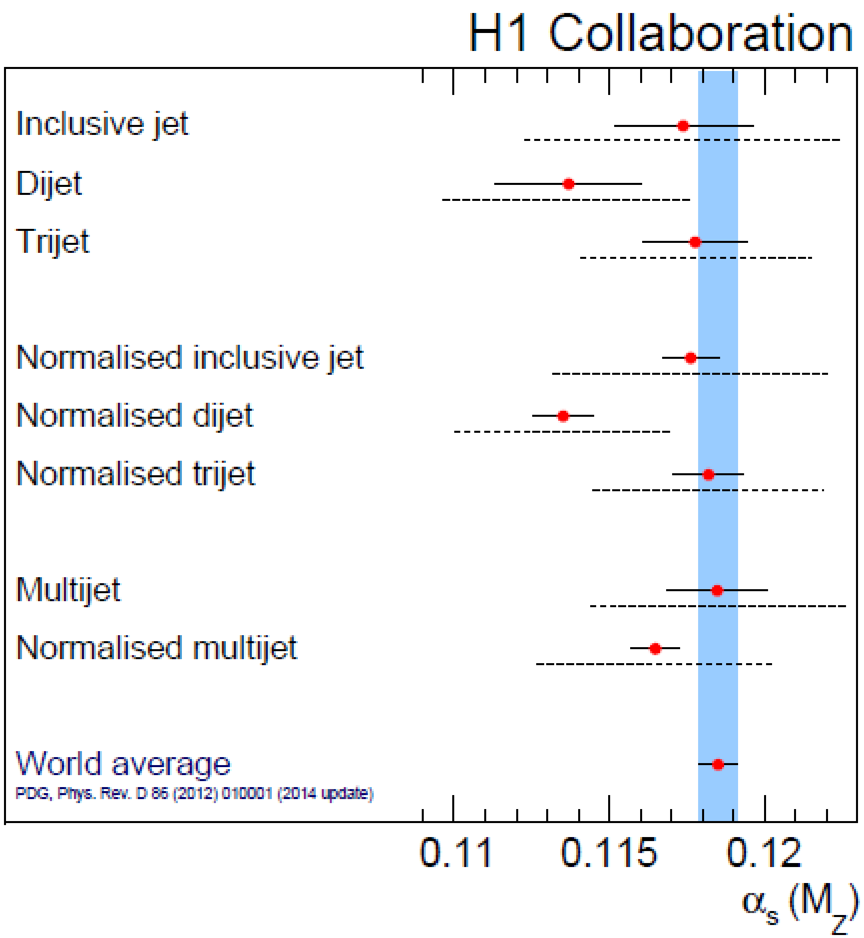

**$150 < Q^2 < 15\,000$ GeV$^2$**
**$0.2 < y < 0.7$**

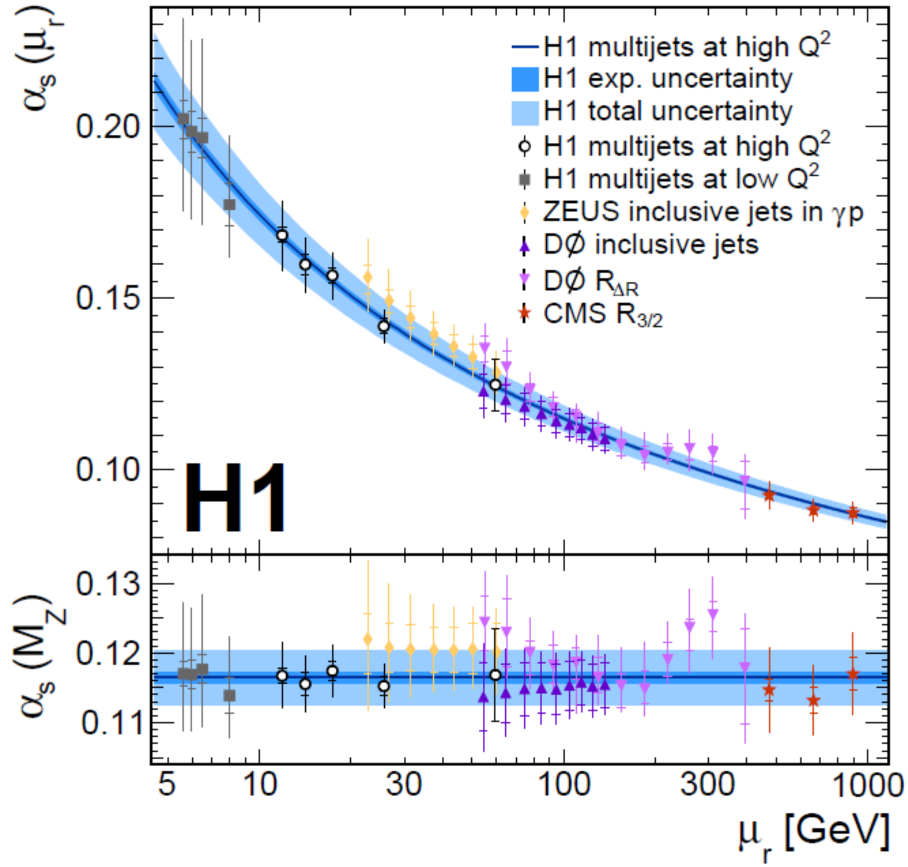
$$\mu_r^2 = (Q^2 + P_T^2)/2 \text{ and } \mu_f^2 = Q^2$$



# Multijet Production and $\alpha_s$ extraction




$\alpha_s = 0.1165 \pm 0.0008_{exp} \pm 0.0038_{theo}$

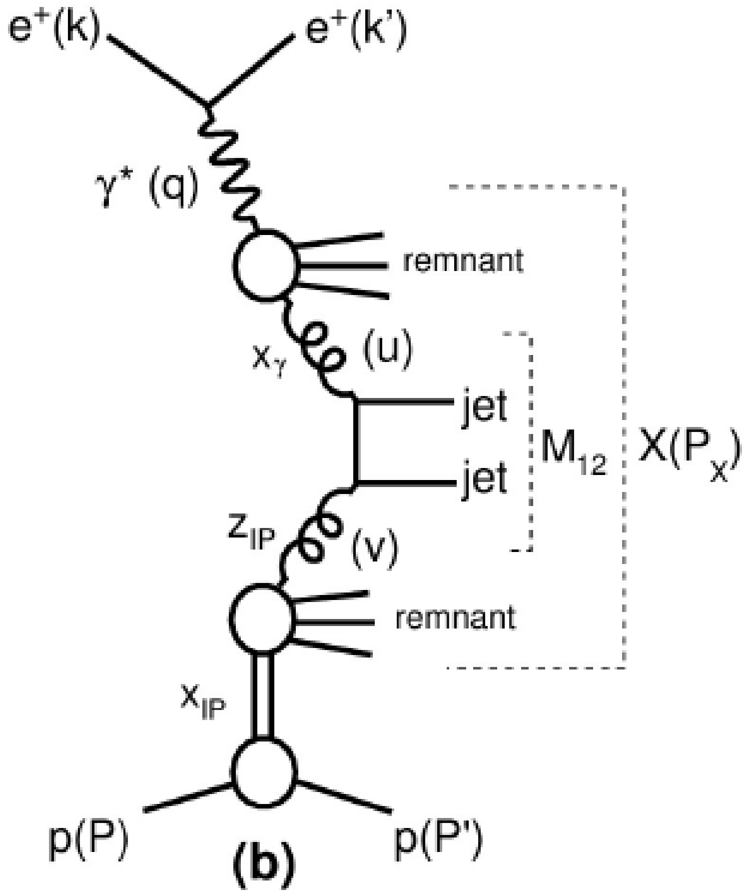
For $Q^2 > 400\ \mathrm{GeV}^2$ :

$$\alpha_s(M_Z)|_{k_T} = 0.1165\ (8)_{\rm exp}\ (5)_{\rm PDF}\ (7)_{\rm PDFset}\ (3)_{\rm PDF(\alpha_s)}\ (8)_{\rm had}\ (36)_{\mu_r}\ (5)_{\mu_f}$$
$$= 0.1165\ (8)_{\rm exp}\ (38)_{\rm pdf,theo}\ .$$

$$\alpha_s(M_Z)|_{k_T} = 0.1160\ (11)_{\rm exp}\ (32)_{\rm pdf,theo}$$

# Diffractive Dijets in DIS and Photoproduction

JHEP 05 (2015) 056
arXiv:1502.01683




Measure scattered proton in VFPS (Very Forward Spectrometer)

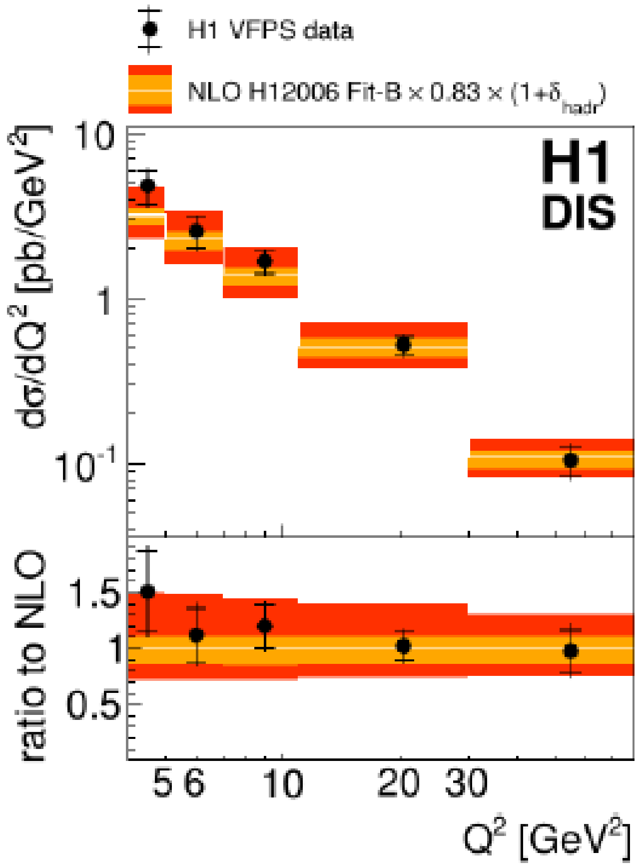
- VFPS is 220m from interatction point
- Complementary method to LRG method

| PHP | DIS |
|---|---|
| $Q^2 < 2\,\mathrm{GeV}^2$ | $4\,\mathrm{GeV}^2 < Q^2 < 80\,\mathrm{GeV}^2$ |
| Common Cuts | |
| $0.2 < y < 0.7$ | |
| $E_T^{*\mathrm{jet1}} > 5.5\,\mathrm{GeV}$ | $E_T^{*\mathrm{jet2}} > 4.0\,\mathrm{GeV}$ |
| $-1 < \eta^{\mathrm{jet1}} < 2.5$ | $-1 < \eta^{\mathrm{jet2}} < 2.5$ |
| $\lvert t\rvert < 0.6\,\mathrm{GeV}^2$ | $0.010 < x_{I\!P} < 0.024$ |
| $z_{I\!P} < 0.8$ | |

# Diffractive Dijets in DIS and Photoproduction

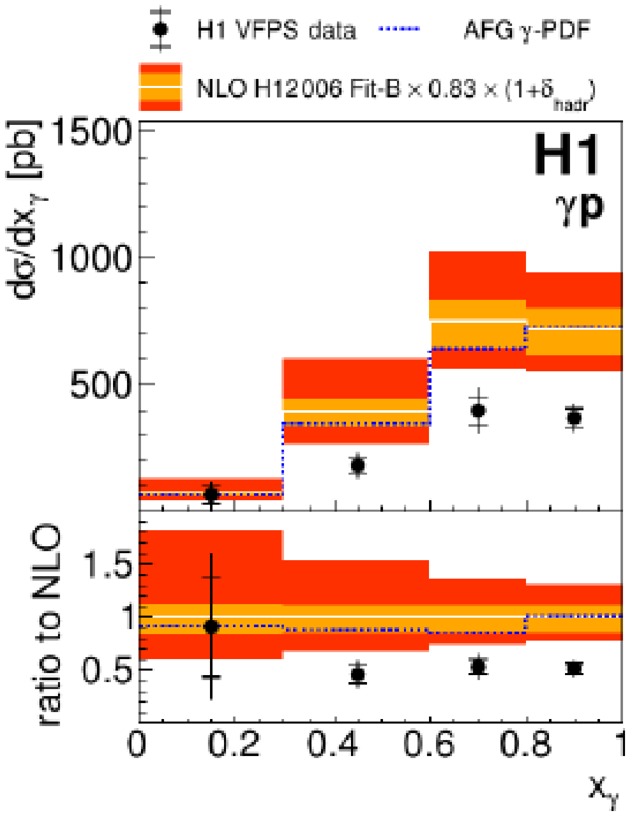
Dijets in **DIS**

- Single diff. cross sections
- NLO by nlojet++
- H12006 Fit-B




Dijets in **γp**

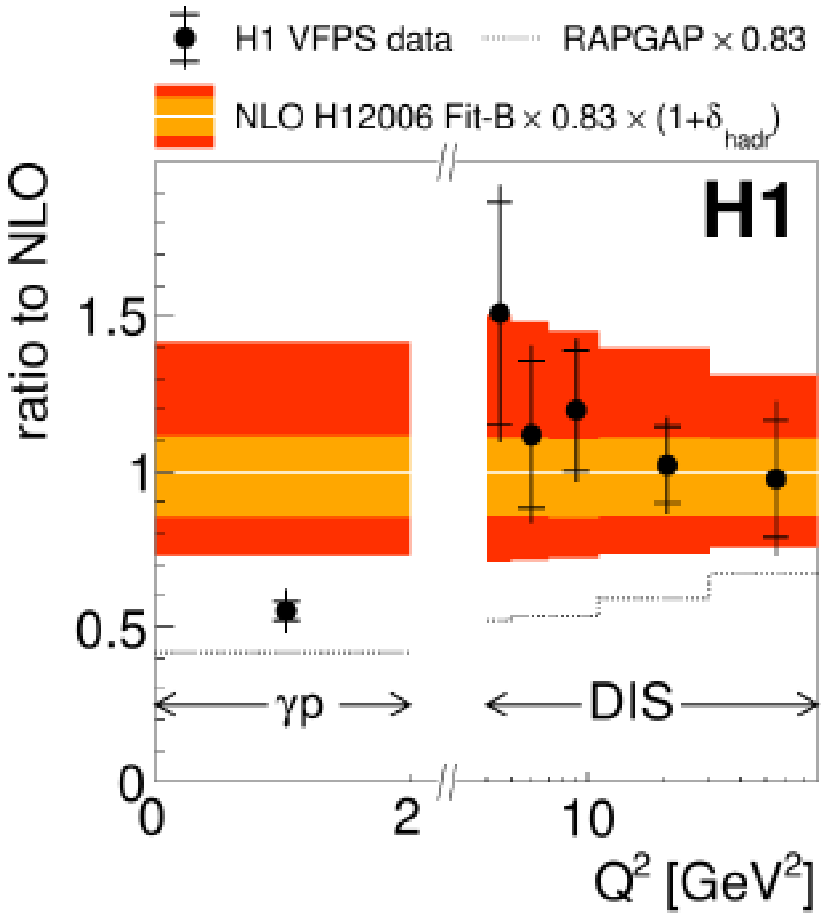
- Single diff. cross sections
- NLO by FKS (Frixione et al.)
- H12006 Fit-B
- GRV and AFG γ-PDF




Shape and normalisation well described by NLO

Shape well described by NLO, but normalisation is overestimated

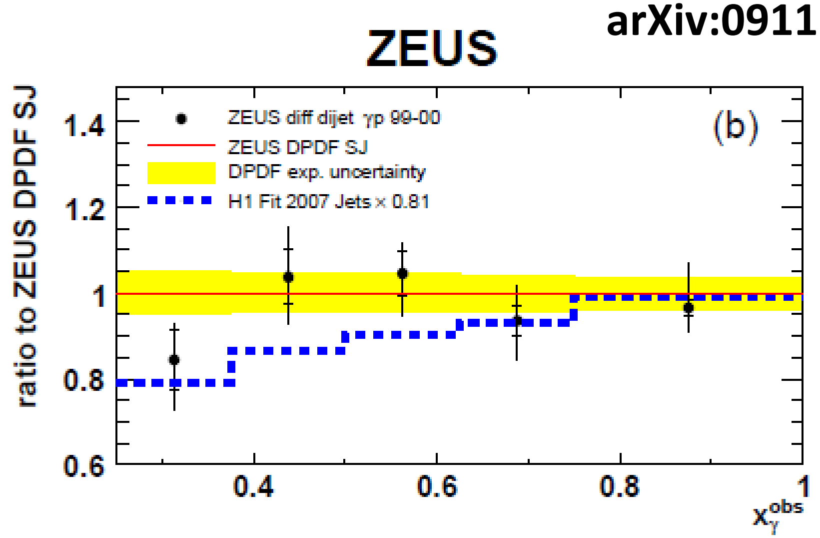
# Diffractive Dijets in DIS and Photoproduction




New analysis confirms previous results from H1 with complementary experimental method

However, there is a disagreement with the ZEUS conclusion:

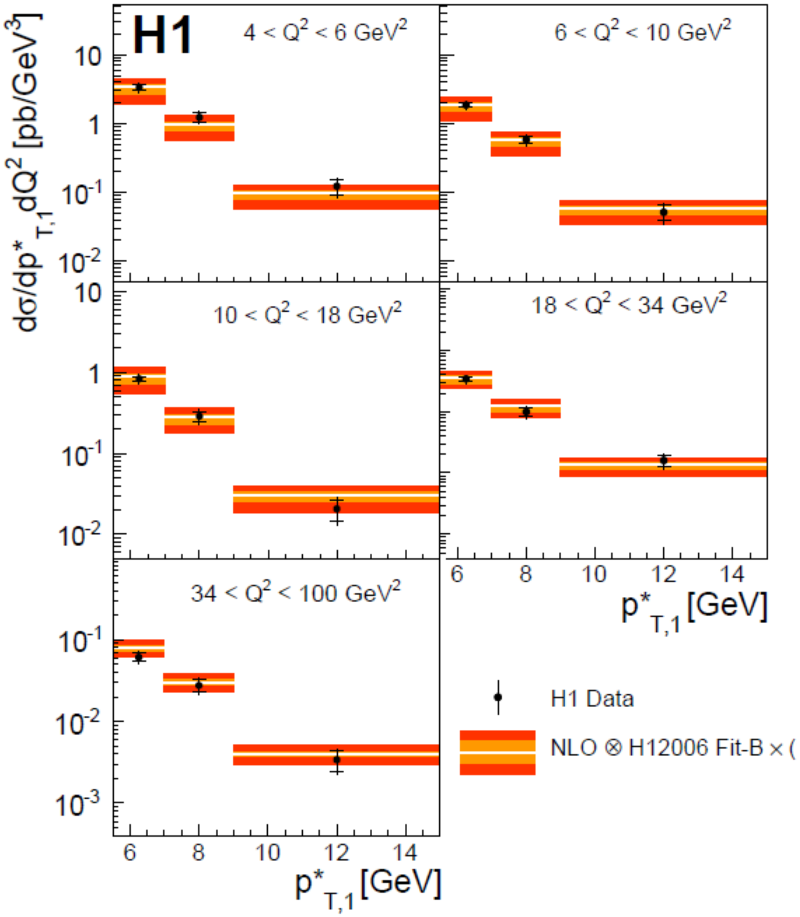
**NPB 831 (2010) 1**
**arXiv:0911.4119**

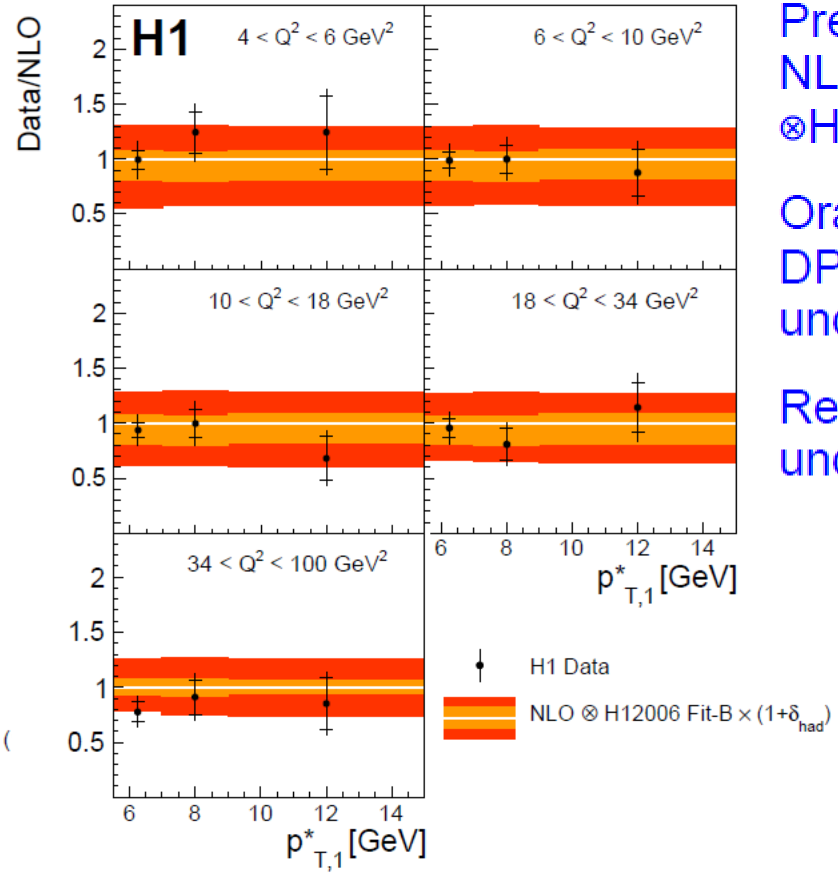



One more round of H1-ZEUS comparison will be needed

# Diffractive Dijets in DIS (LRG)

JHEP 03 (2015) 092
arXiv:1412.0928




Prediction: NLOJET++ ⊗H12006 Fit-B

Orange band: DPDF uncertainty

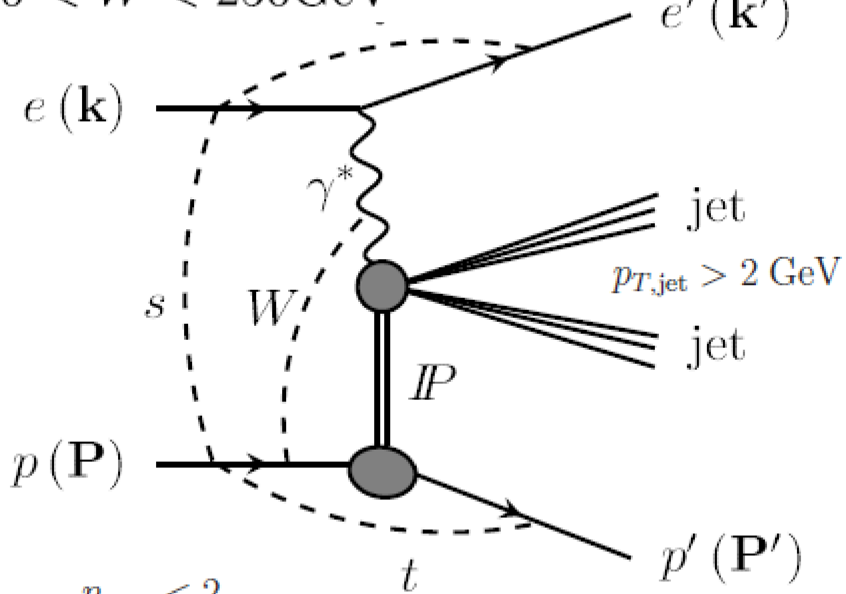
Red band: total uncertainty

Dijets in Diffractive DIS are well descried by NLO with DPDF

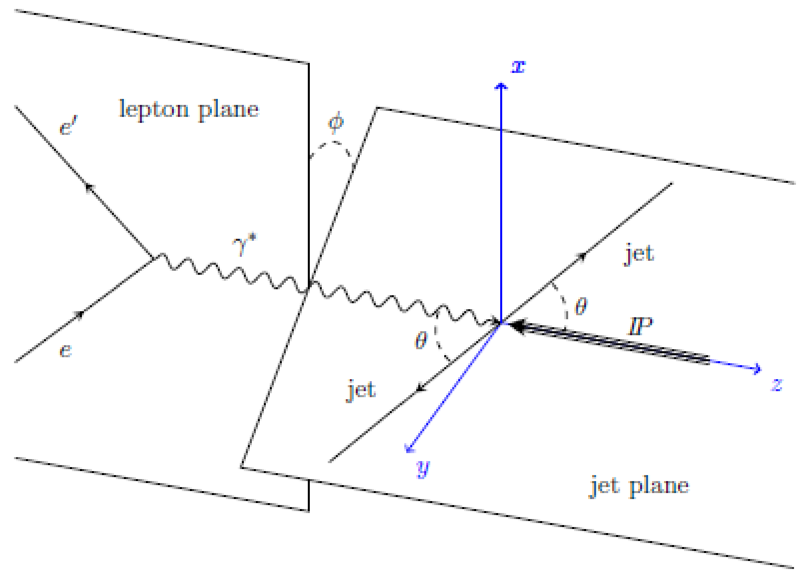
# Exclusive Dijets in Diffractive DIS

arXiv: 1505.05783

$Q^2 > 25\text{GeV}^2$
$90 < W < 250\text{GeV}^2$




$\eta_{\max} < 2$
$x_{I\!P} < 0.01$
$M_X > 5$ GeV




$\phi$ - the angle between lepton plane and jet plane

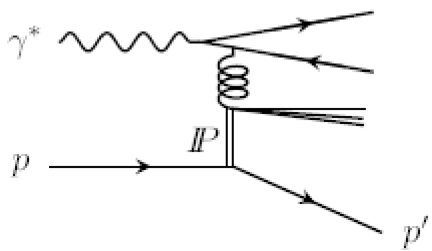
Only dijet, scattered electron and proton in the final state

$\phi$ distribution $\propto 1 + A \cdot \cos 2\phi$

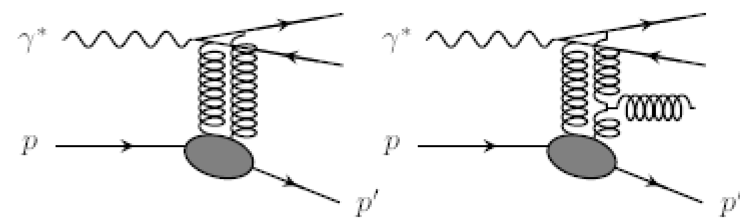
Parameter $A$ sensitive to the nature of the object exchanged between the virtual photon and the proton

# Exclusive Dijets in Diffractive DIS

Resolved-Pomeron model



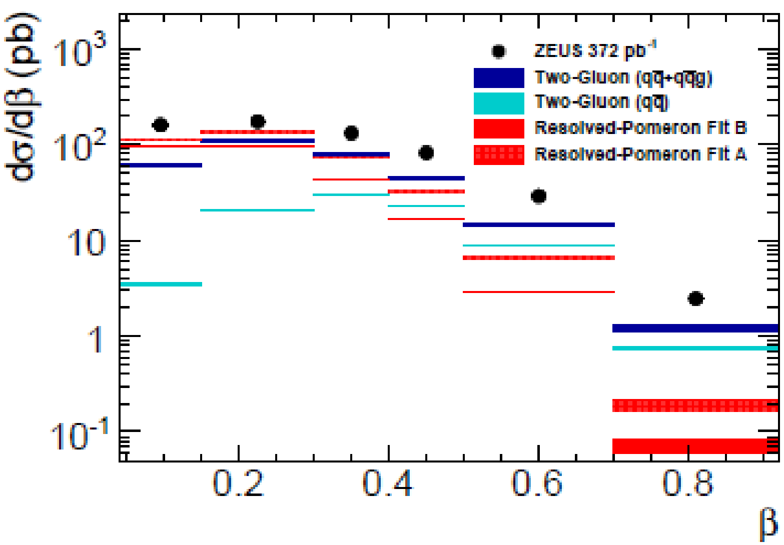

Two-Gluon-Exchange model




Prediction based on diffractive gluon density obtained from fits (H1 2006 fits A and B) to H1 data

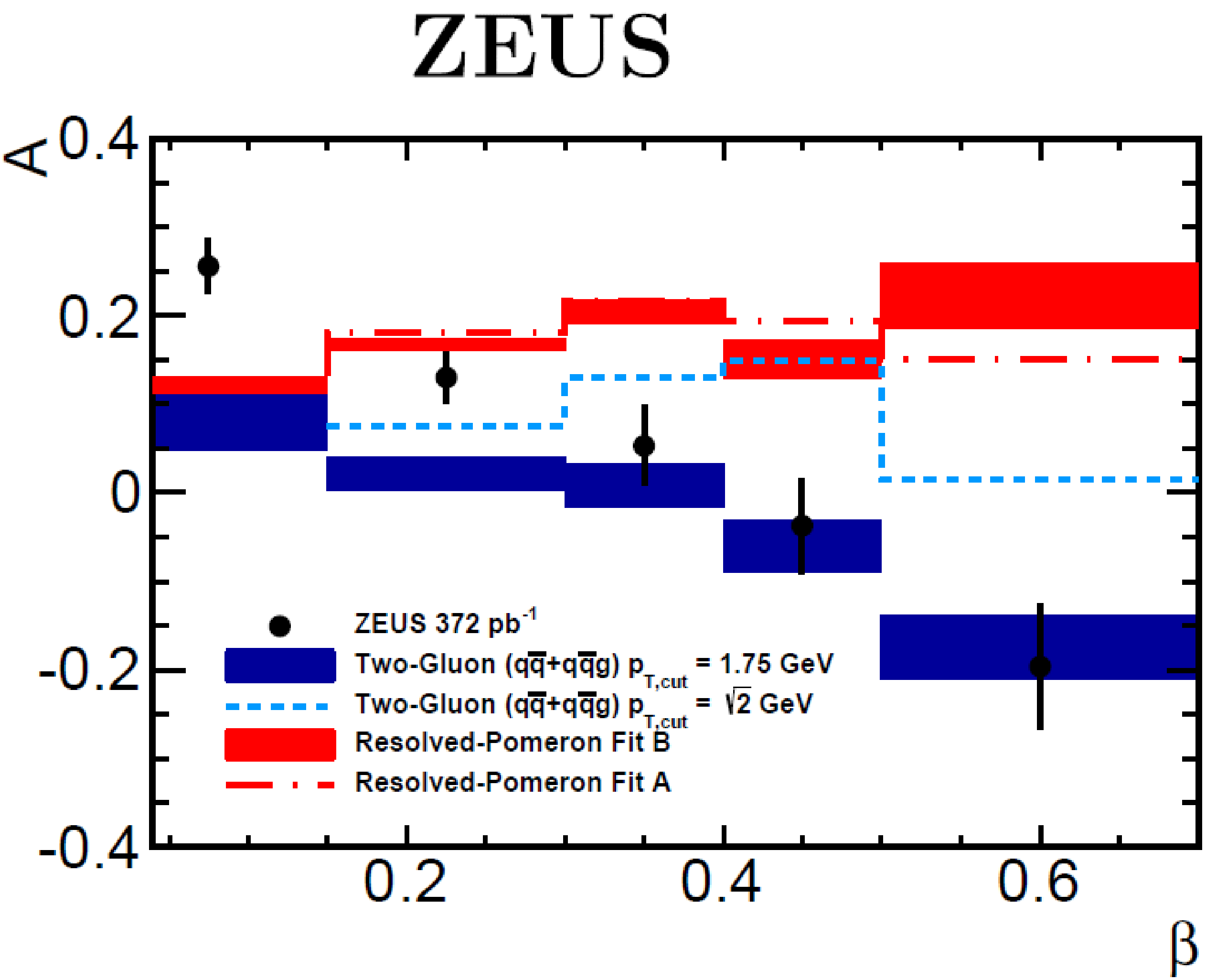
Prediction based on GRV parameterisation of the gluon density

The $q\bar{q}g$ final state is sensitive to the parton-level cut $p_{T,cut}$




$\beta = x/x_{IP}$ - fraction of Pomeron momentum "seen" by the photon

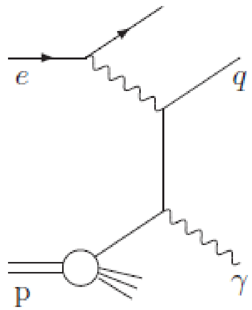
# Exclusive Dijets in Diffractive DIS



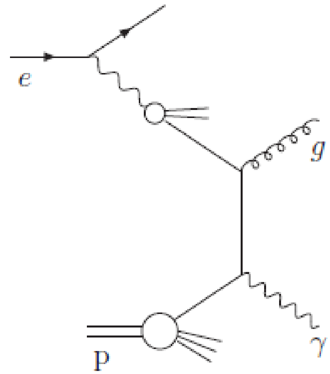

The Two-Gluon-Exchange model predicts reasonably well the measured value of $A$ as a function of $\beta$

# Prompt photons in photoproduction

direct



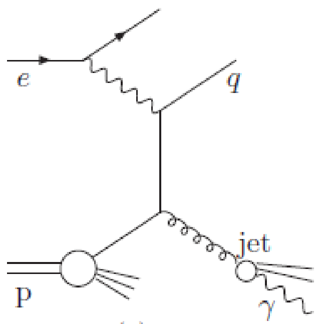
(a)



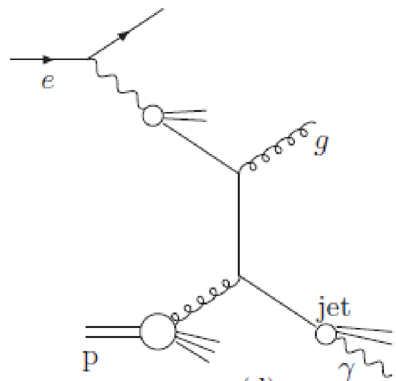
(b)

resolved

direct, fragmentation

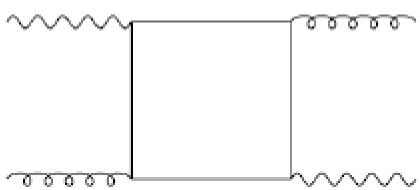


(c)



(d)

resolved, fragmentation

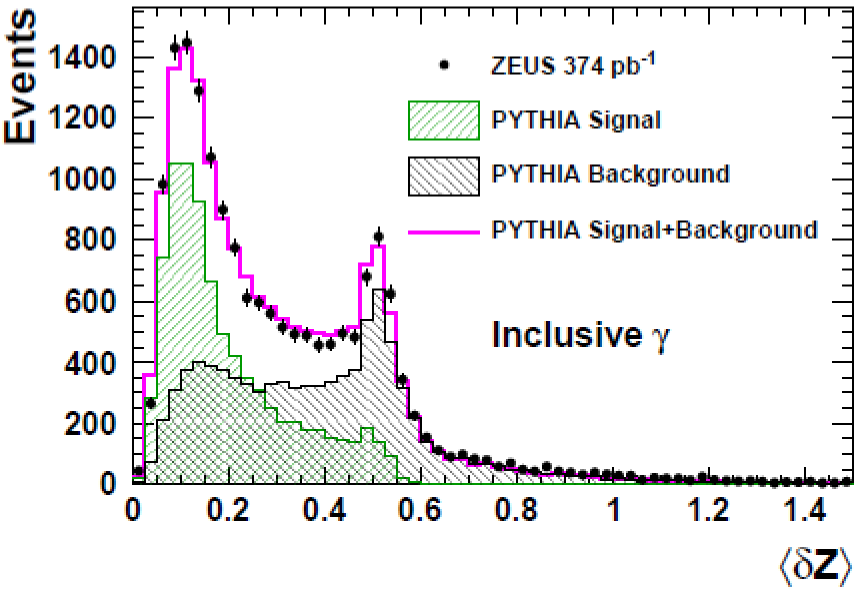


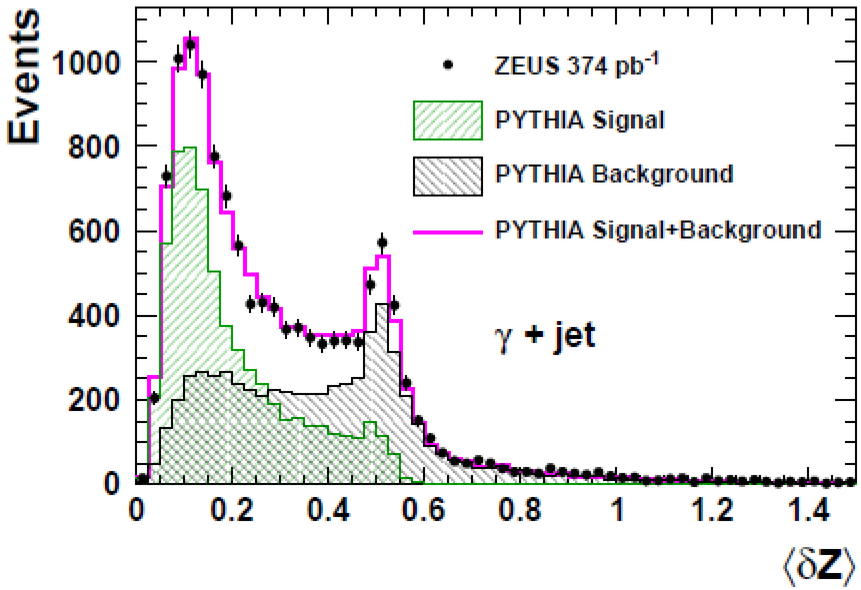
box diagram

# Extraction of Photon Signals

**PLB 730 (2014) 293**
**arXiv:1312.1539**

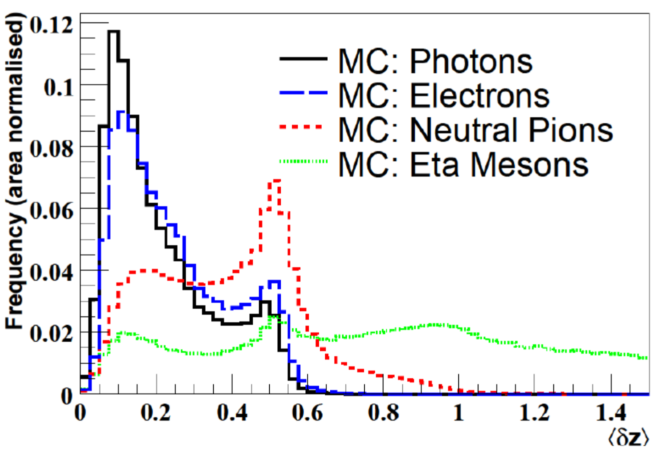
**JHEP 08 (2014) 023**
**arXiv:1405.7127**



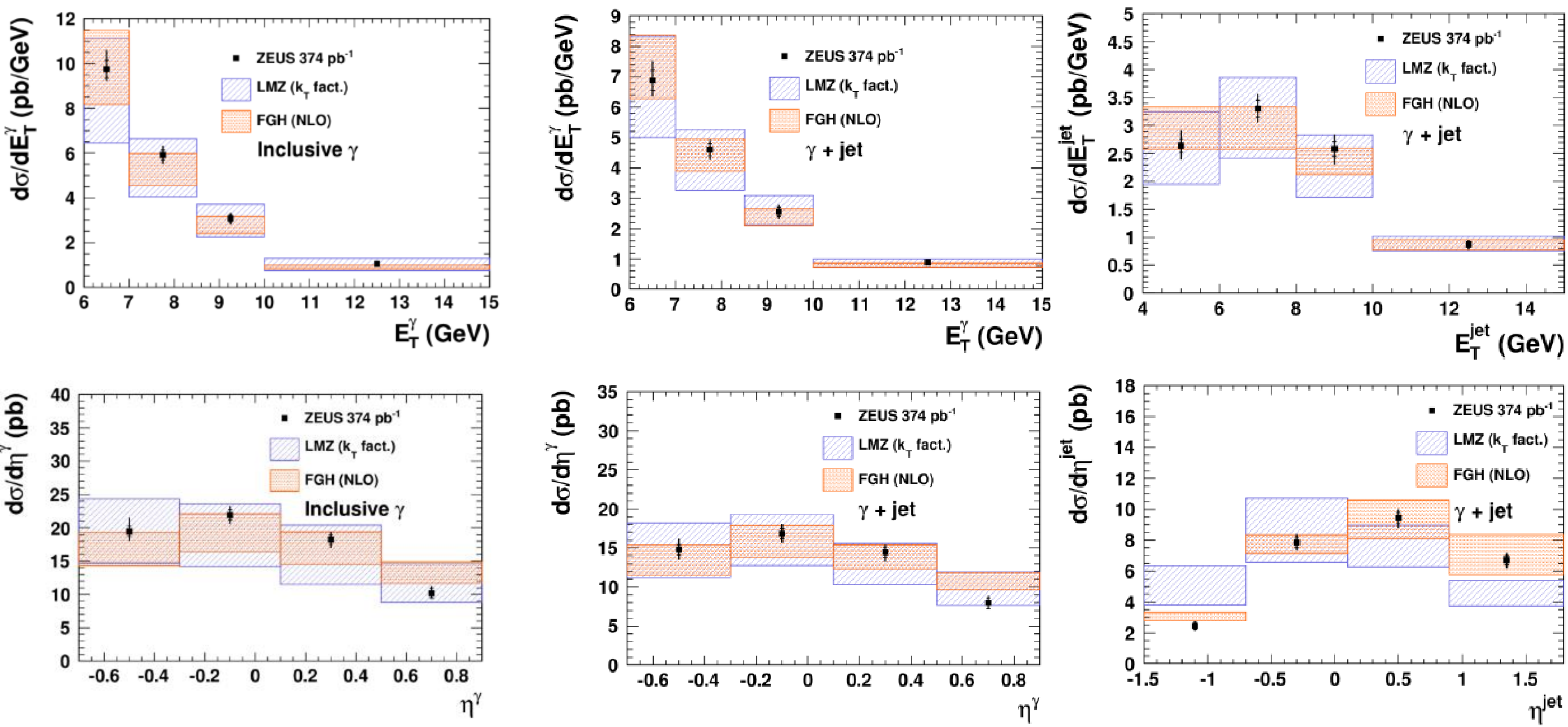

$$< \delta Z > = \frac{\sum_i E_i |Z_i \ - \ Z_{cluster}|}{w_{cell} \sum_i E_i}$$

$E_T$-weighted mean of $|Z_{CELL} - Z_{Mean}|$




$\pi_0 \to \gamma\gamma$ (98.8 %)
$\eta \to \gamma\gamma$ (39.3 %)
$\eta \to \pi_0\pi_0\pi_0$ (32.6 %)

# Prompt photon Cross Sections




## fixed order calculations

- by M. Fontannaz, J.Ph. Guillet and G. Heinrich Eur. Phys. J. C 21 (2001) 303, Eur. Phys. J. C 34 (2004) 191 (FGH)

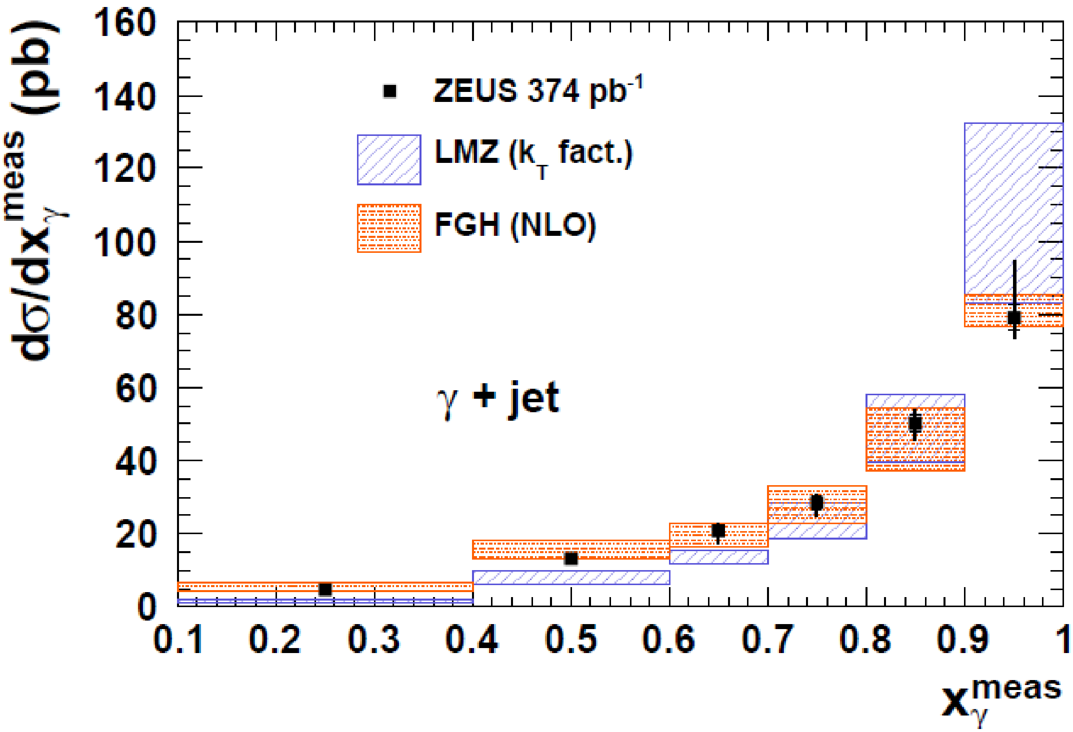
- components:

▷ direct direct, ▷ direct fragmentation
▷ resolved direct, ▷ resolved fragmentation
▷ box diagram (direct direct)

## $k_T$-factorisation approach

- calculated by A.V.Lipatov, M.A. Malyshev, N.P.Zotov, Phys. Rev. D 72 (2005) 054002, Phys. Rev. D 81 (2010) 094027, Phys. Rev. D 88 (2013) 074001 (LMZ):
- investigation of the photoproduction of the isolated photon at HERA in the framework of kt-factorisation QCD approach
- both direct and resolved processes are considered
- the box contribution was included
- fragmentation contribution is neglected

# Direct/Resolved Contributions to γ + jet




**Direct LO process final state:**

- jet
- photon
- scattered electron (escape undetected)
- proton remnant (escape undetected)

$\Rightarrow$ $x_\gamma^{\rm meas} = 1$ (**LO** direct)

**Resolved LO process final state:**

- all mentioned above

**+ resolved photon remnant**

$\Rightarrow$ $x_\gamma^{\rm meas} < 1$

$$x_\gamma^{\rm meas} = \frac{E^\gamma - p_Z^\gamma + E^{\rm jet} - p_Z^{\rm jet}}{E^{\rm all} - p_Z^{\rm all}}$$

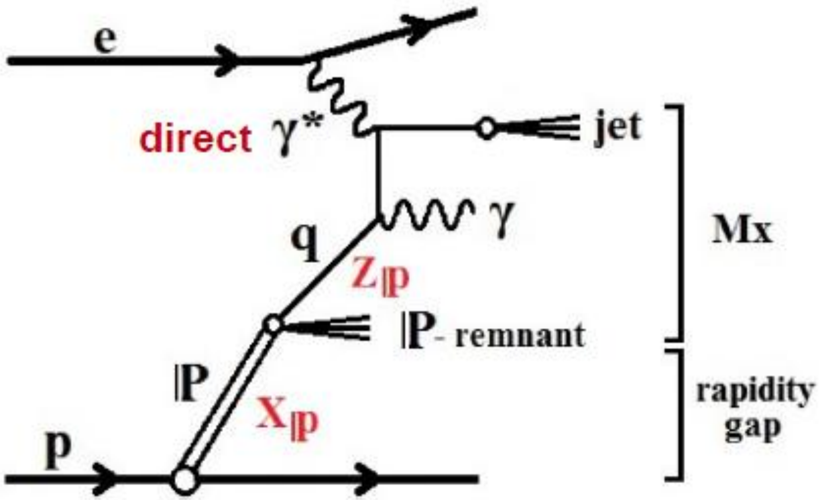
very good description of the $x_\gamma^{\rm meas}$ by FGH

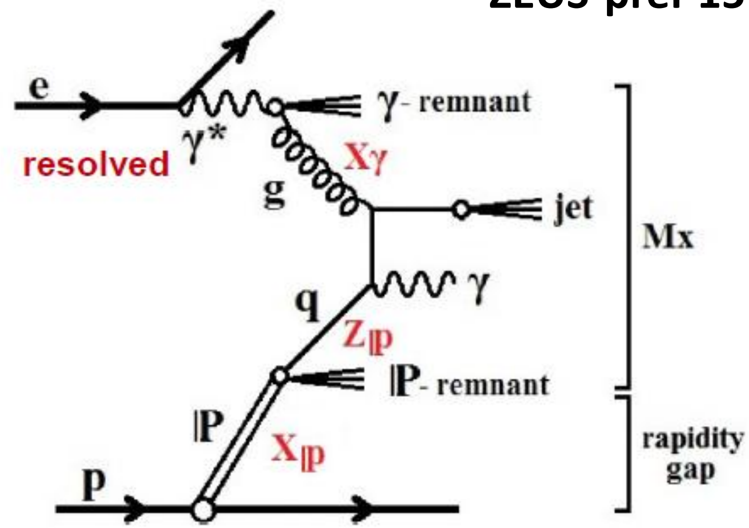
reasonable description by LMZ (typically theory within 1-2 sigma from data)

LMZ is somewhat too "direct"

# Prompt photons in diffractive photoproduction

ZEUS-prel-15-001



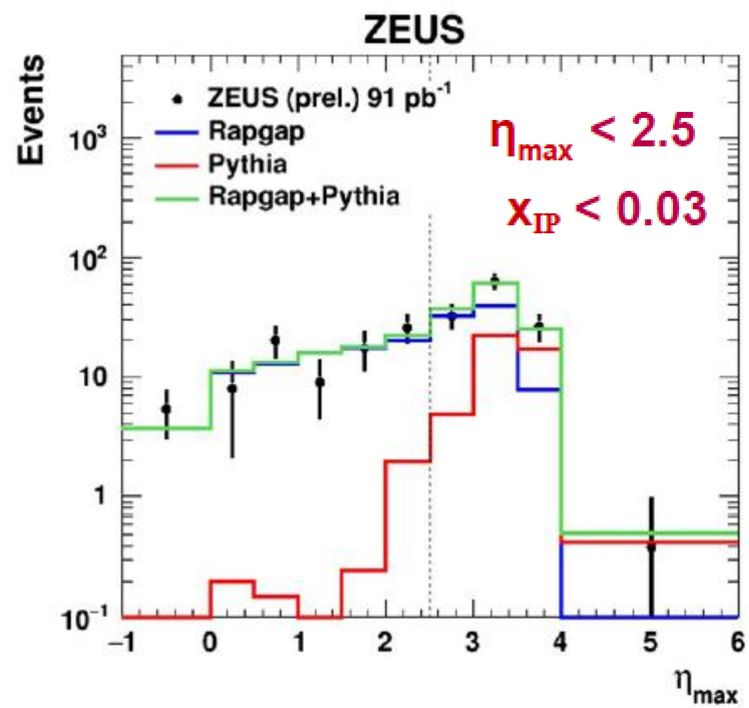




$x_{IP}$ = $\Sigma(E + p_z)_{\text{all EFOs}} / 2 E_p$

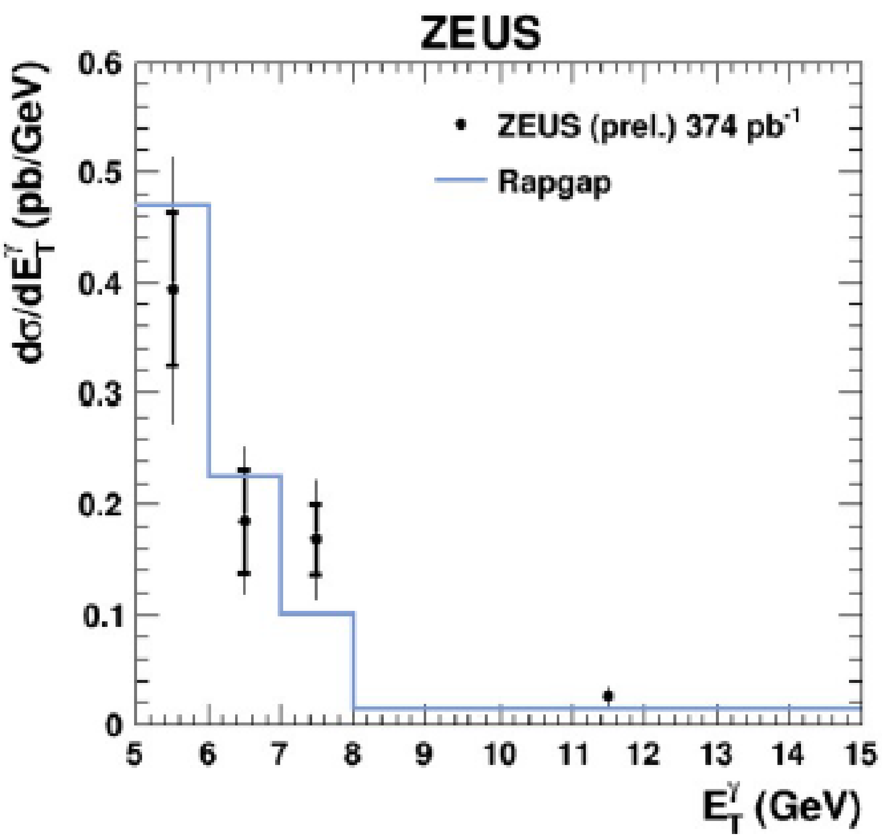
$x_{IP}$ = fraction of proton energy taken by pomeron.

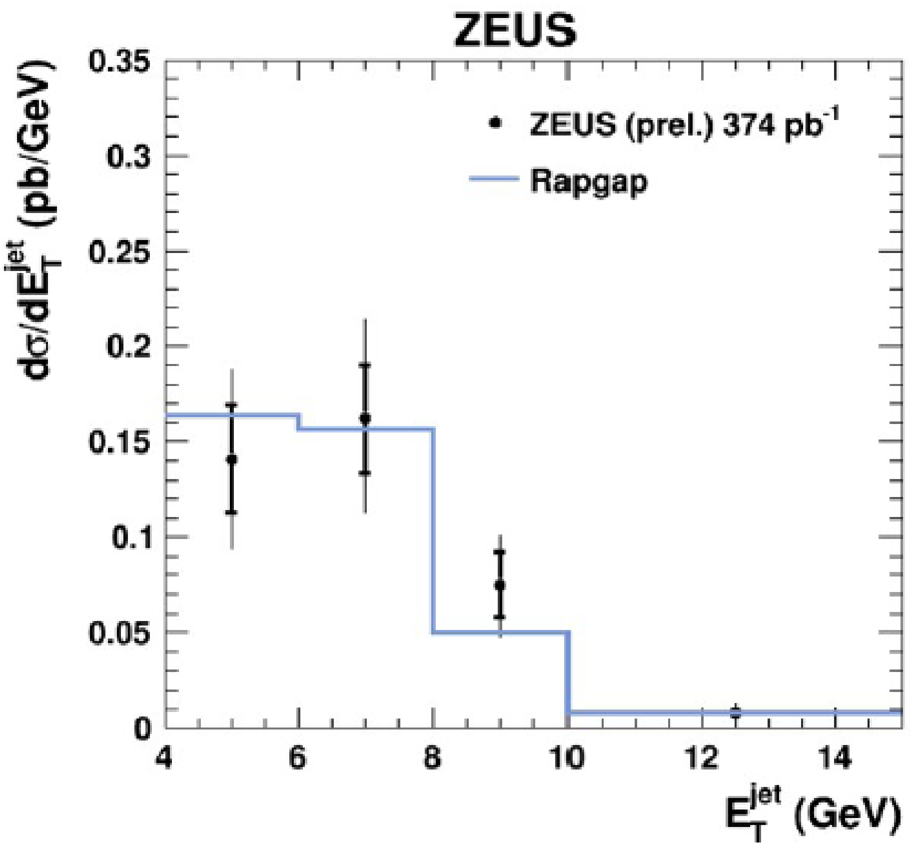
$z_{IP}$ = fraction of pomeron energy taken in scatter.

$\eta_{max}$ = maximum value of pseudorapidity of outgoing particles in scatter (Ignore forward proton.)



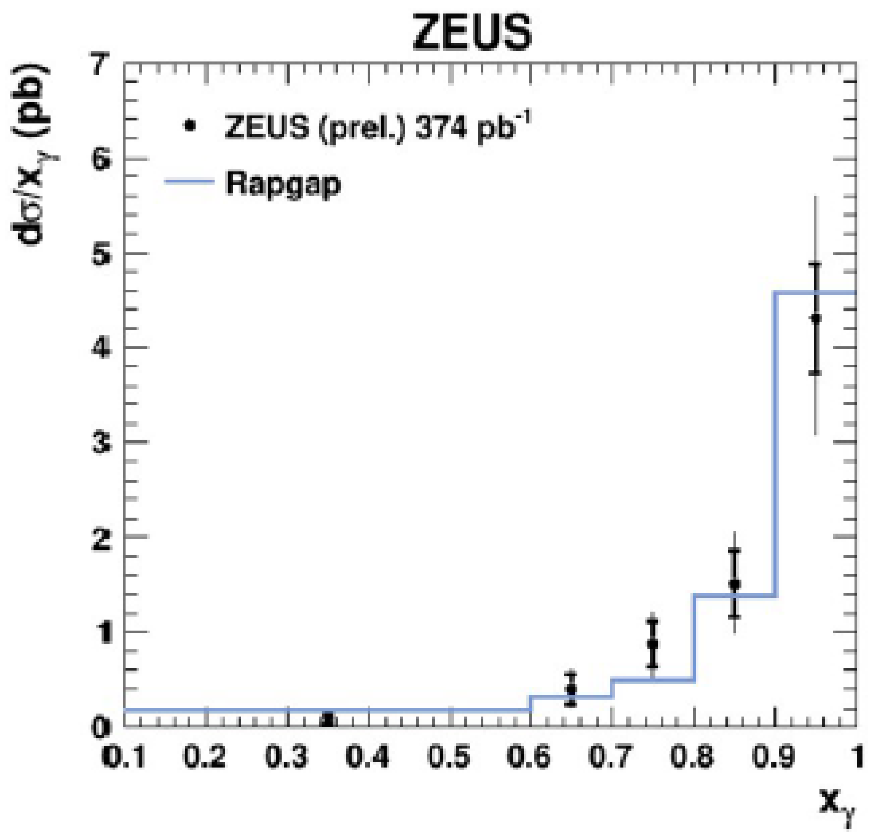
# Prompt photons in diffractive photoproduction

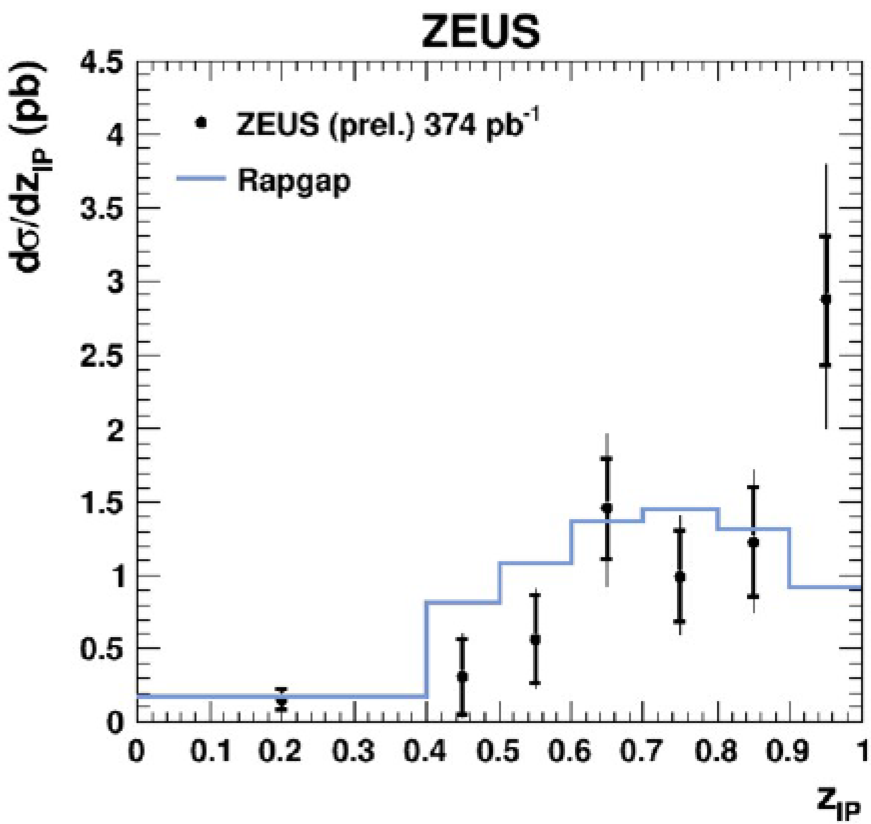



RAPGAP describes the shapes of most of the kinematic variables reasonably well.

# Prompt photons in diffractive photoproduction



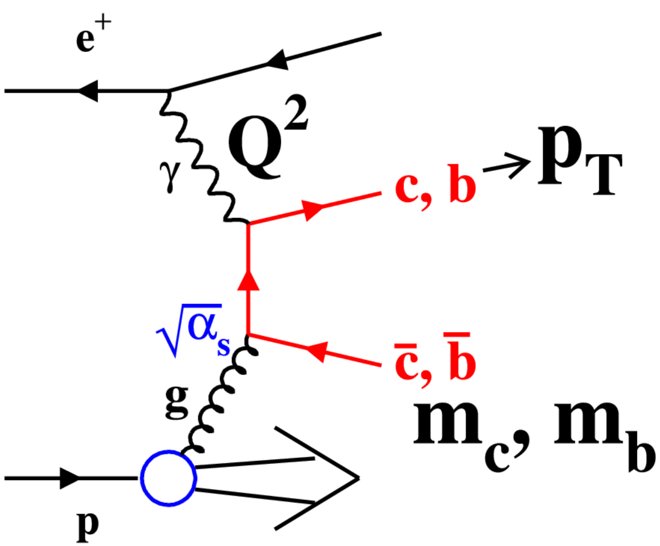

$x_\gamma = \Sigma_{\gamma + jet}(E - p_z) \,/\, \Sigma_{all\ EFOs}(E - p_z)$

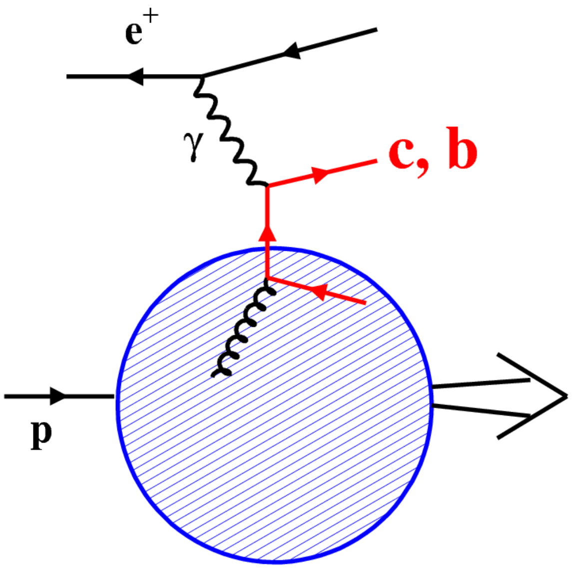
$z_{IP} = \Sigma_{\gamma + jet}(E + p_z) \,/\, \Sigma_{all\ EFOs}(E + p_z)$

dominated by the direct photoproduction

$z_{IP}$ shows a peak at high values

# Heavy Quark Production




## Massive scheme (FFNS)

Expected to be valid at scales ~ $m_{b,c}$

Programs exist to calculate fully differential cross sections (HVQDIS, FMNR)

## Massless scheme (ZM-VFNS)

Allows resummation of terms proportional to $\log(Q^2/m_{b,c}^2)$

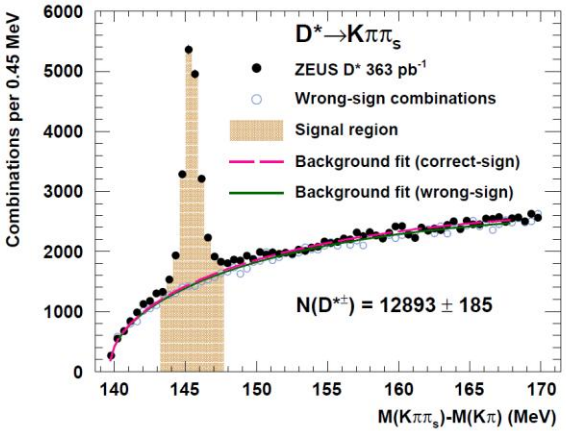
Expected to be valid at scales >>$m_{b,c}$

## Mixed schemes (GM-VFNS)

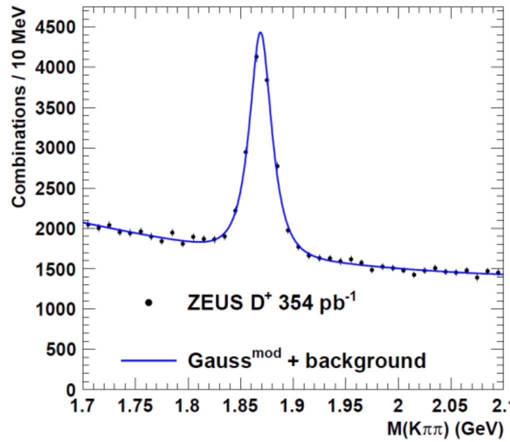
Employ both FFNS and ZM-VFNS

Interpolation is ambiguous → various approaches (RT, ACOT etc.) exist

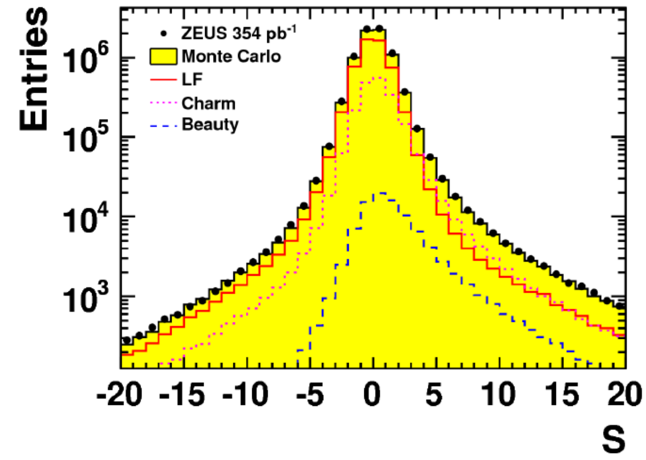
# HQ signals and Cross Sections in DIS



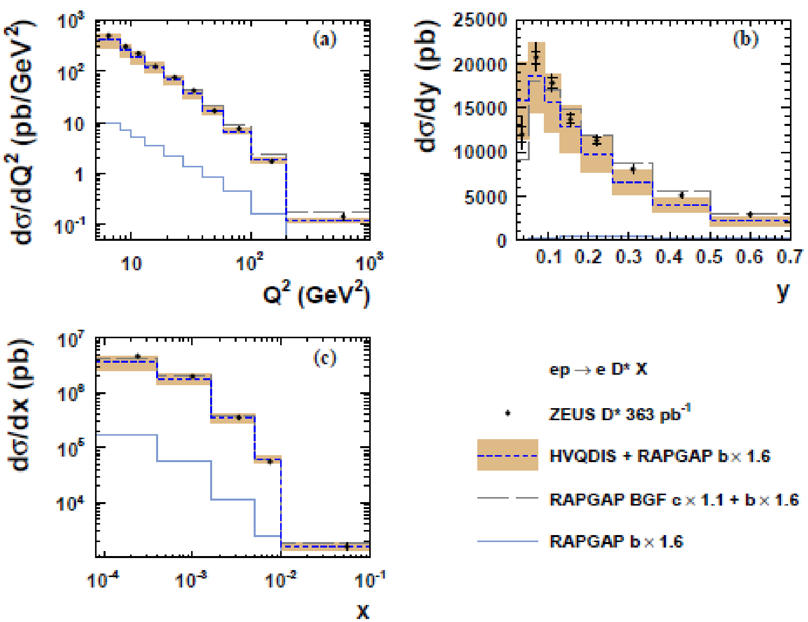

$D^{*\pm} \to D^0(\to K^\mp\pi^\pm)\pi_s^\pm$

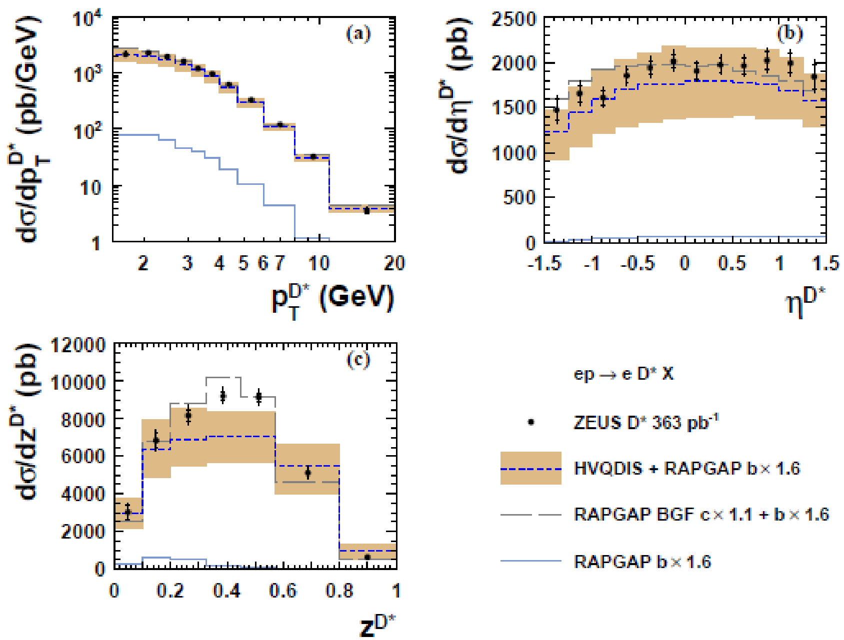



Lifetime tagging of weak decays




Inclusive lifetime tagging



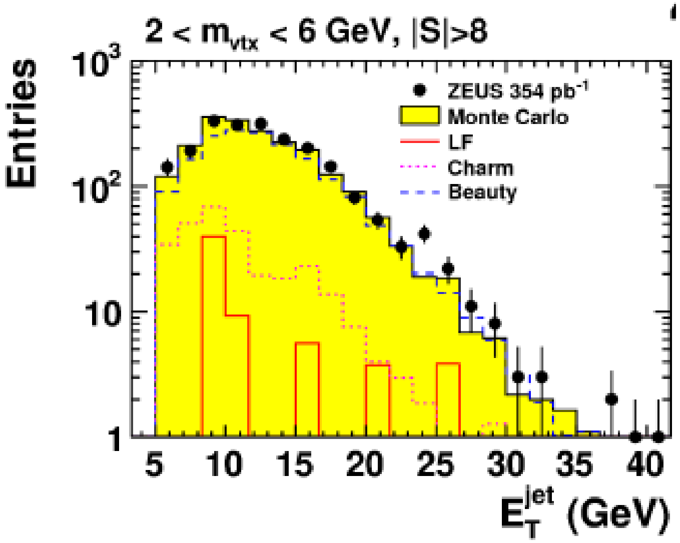



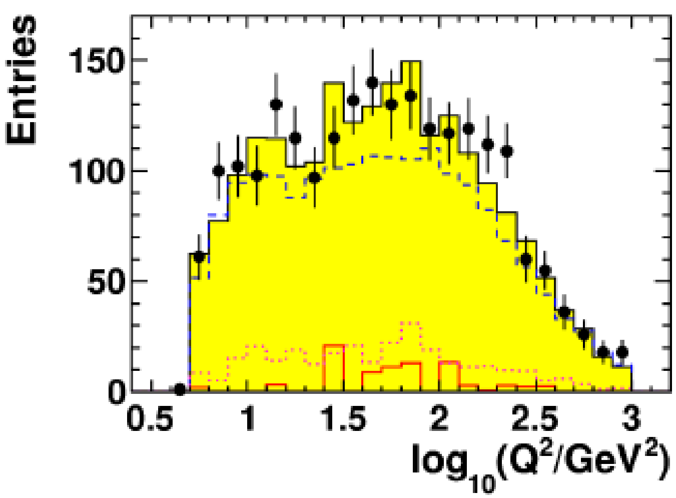

Good agreement with NLO FFNS

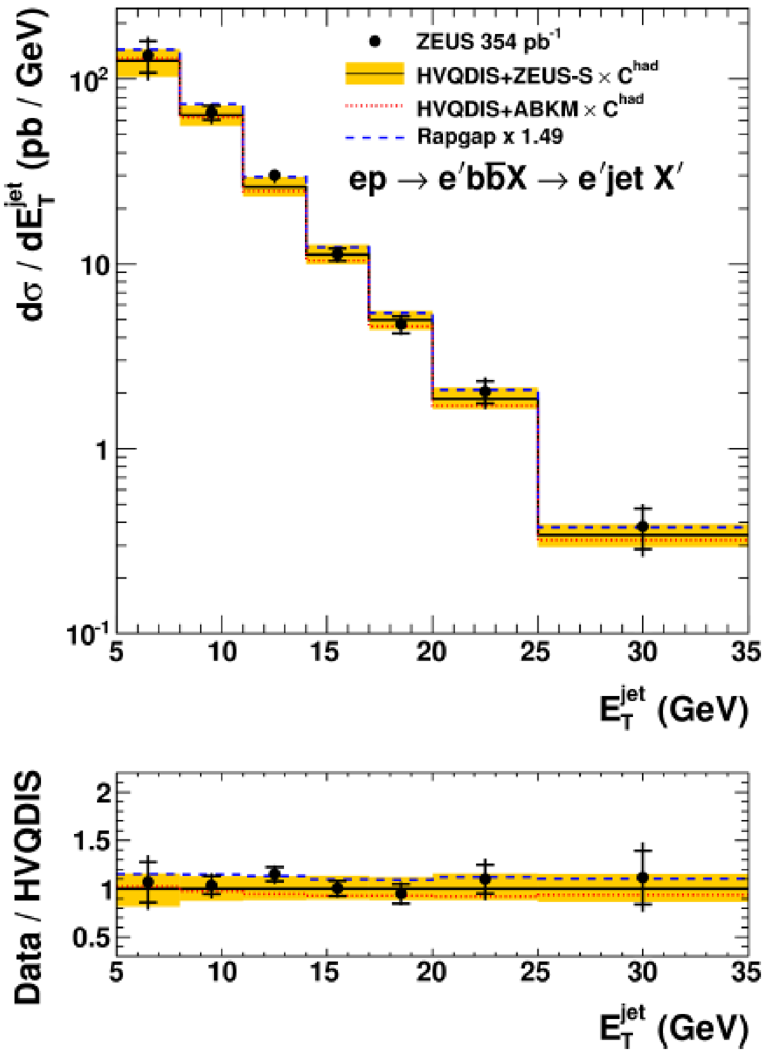
$z^{D^*} = E(D^*)/E(\gamma^*)$
in p rest frame

# Beauty signals and x-sections in DIS

JHEP 09 (2014) 127
arXiv:1405.6915



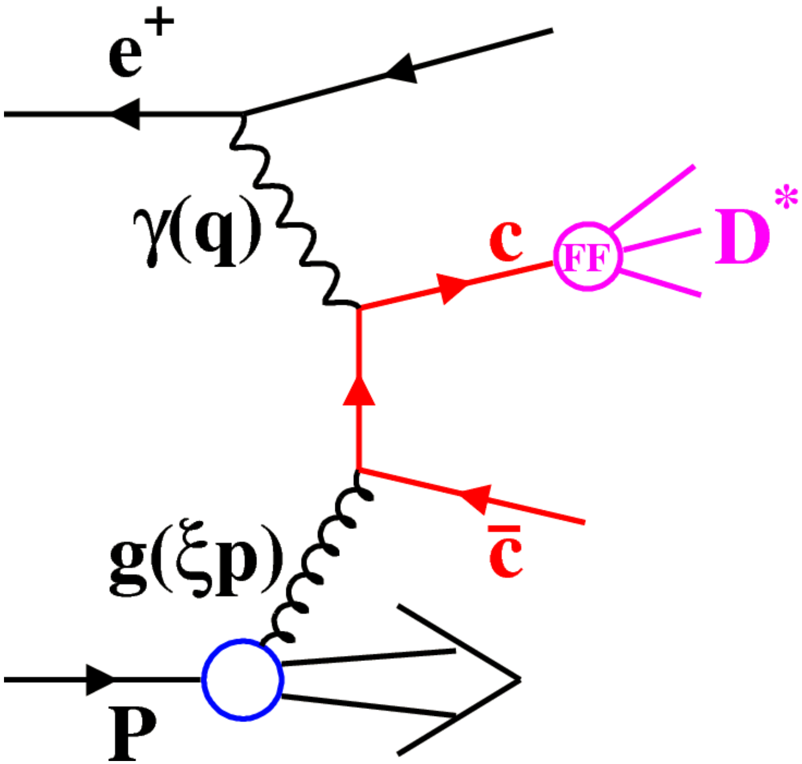




Reasonable description by HVQDIS NLO QCD

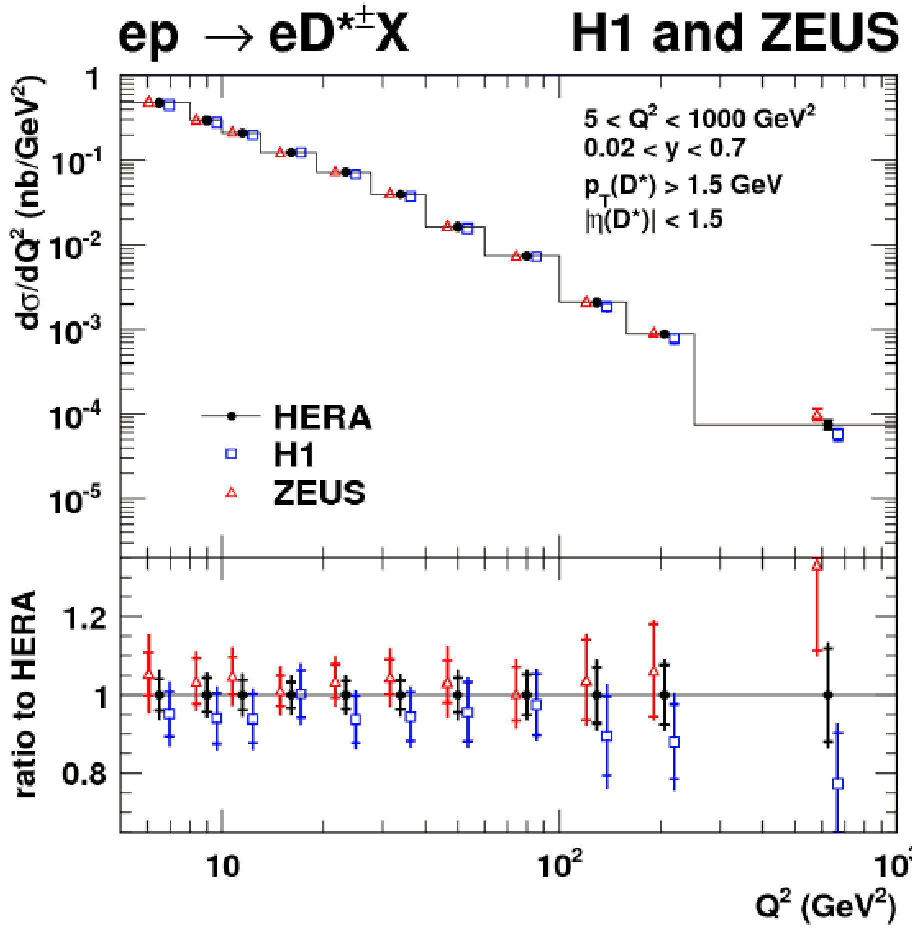
# H1+ZEUS $D^{*\pm}$ Cross Sections in DIS

arXive: 1505.05783




Combine $D^*$ visible cross sections

| | |
|---|---|
| EPJ C71 (2011) 1769 | H1 medium $Q^2$ |
| PL B686 (2010) 91 | H1 high $Q^2$ |
| JHEP 05 (2013) 097 | ZEUS all $Q^2$ |




→ Consistent data

→ Combined data reach precision ~5%

# NLO QCD predictions: HVQDIS

Massive scheme → only light flavours in pdf: u,d,s,g; NLO = $o(\alpha_s^2)$

HVQDIS setup for ep →cc X→D*X (uncertainties):

- $\mu_r = \mu_f = \sqrt{Q^2 + 4m_c^2}$ vary independently by factor 0.5 and 2
- $m_c^{pole} = 1.50 \pm 0.15$ GeV
- $\alpha_s^{nf=3}(m_Z) = 0.105 \pm 0.002$ (corresponds to $\alpha_s^{nf=5}(m_Z) = 0.116 \pm 0.002$)
- HERAPDF1.0 FFNS
- Fragmentation:
  - Longitudinal: Karvelishvili FF with $\alpha_K(D^*)$

| $\hat{s}$ range | $\alpha_K(D^*)$ |
|---|---|
| $\hat{s} \leq \hat{s}_1$ | $6.1 \pm 0.9$ |
| $\hat{s}_1 < \hat{s} \leq \hat{s}_2$ | $3.3 \pm 0.4$ |
| $\hat{s} > \hat{s}_2$ | $2.67 \pm 0.31$ |

$\hat{s}_1 = 70 \pm 40$ GeV$^2$
$\hat{s}_2 = 324$ GeV$^2$

  - Transverse: $f(k_T) = k_T \exp(-\frac{2k_T}{\langle k_T \rangle})$; $\langle k_T \rangle = 0.35 \pm 0.15$ GeV
  - $f(c \to D^*) = 0.2287 \pm 0.0056$

Use HVQDIS also to predict small additional component: ep → bb X → D* X

# Customised NLO QCD predictions: HVQDIS

Try to find parameters such that calculation describes normalisation & shapes of all differential cross sections presented in the following

- $\mu_r = \sqrt{Q^2 + 4m_c^2}$ → $\mathbf{0.5\sqrt{Q^2 + 4m_c^2}}$ → Increase cross section
- $\mathrm{m_c^{pole}} = 1.50\ \mathrm{GeV}$ → **1.40 GeV** → Increase cross section
- Fragmentation:
  - Longitudinal: Karvelishvili FF with $\alpha_K(D^*)$

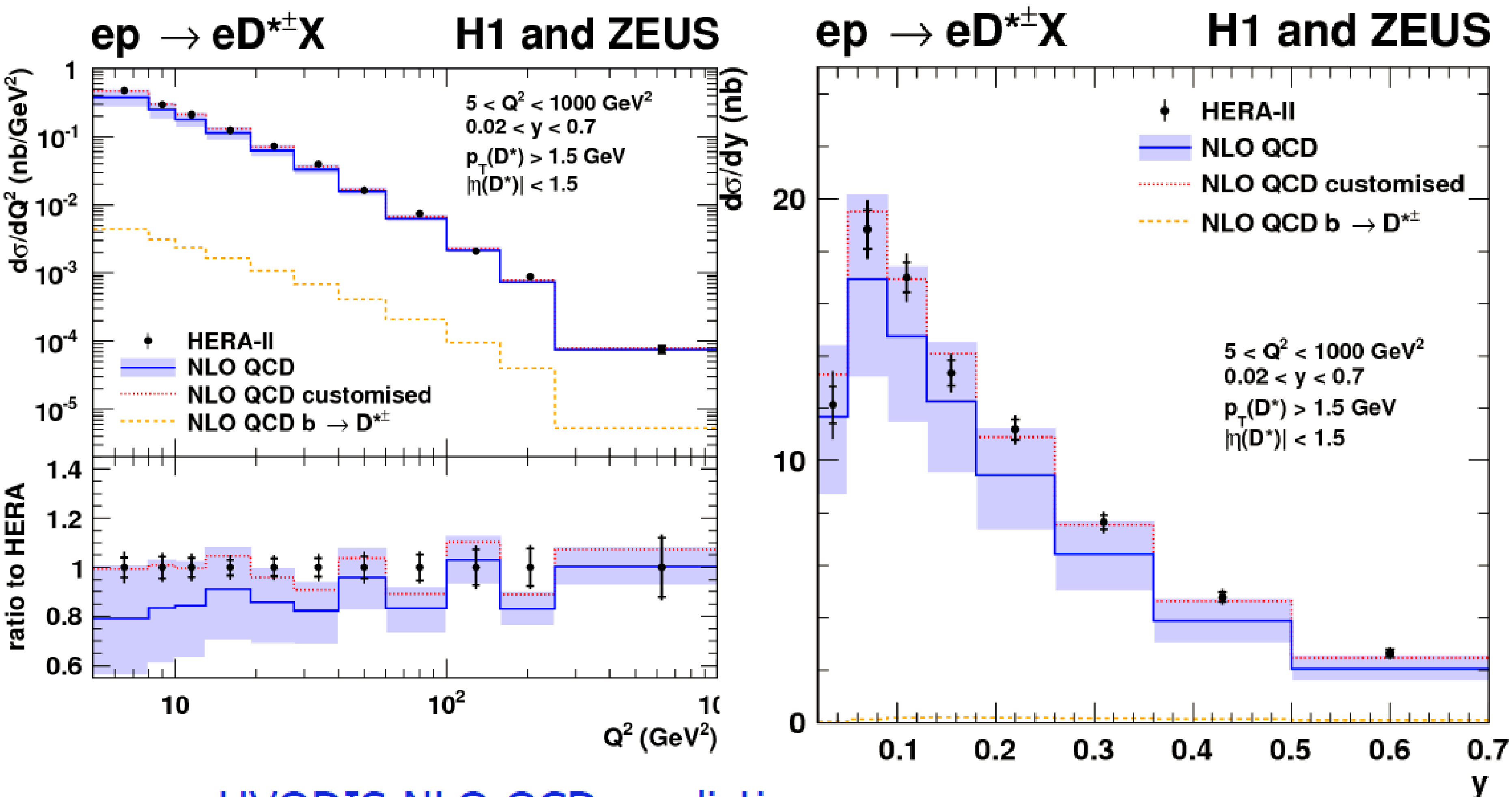
| $\hat{s}$ range | $\alpha_K(D^*)$ |
|---|---|
| $\hat{s} \leq \hat{s}_1$ | $6.1 \pm 0.9$ |
| $\hat{s}_1 < \hat{s} \leq \hat{s}_2$ | $3.3 \pm 0.4$ |
| $\hat{s} > \hat{s}_2$ | $2.67 \pm 0.31$ |

- $\hat{s}_1 = 70\ \mathrm{GeV}^2$ → $\mathbf{30\ GeV^2}$ → Soften fragmentation

Leave all other parameters at their default values

This is no prediction → but may give hints in which direction to develop theory

# H1+ZEUS $D^{*\pm}$ Cross Sections in DIS

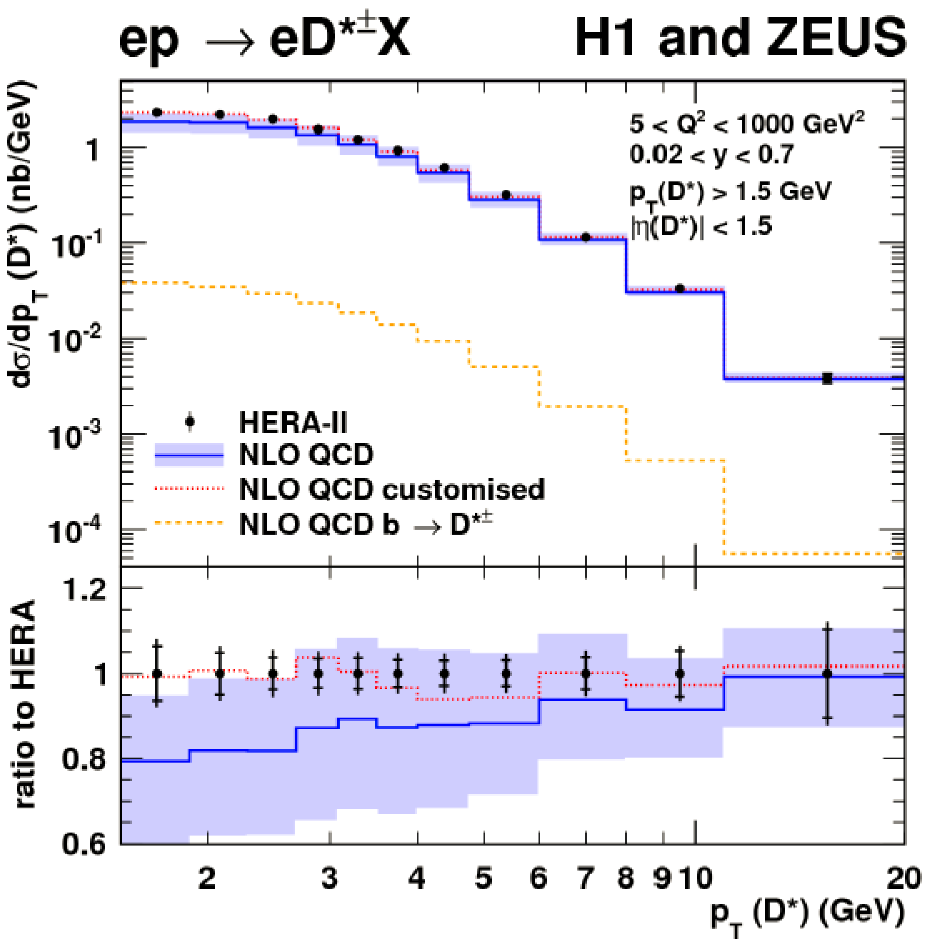


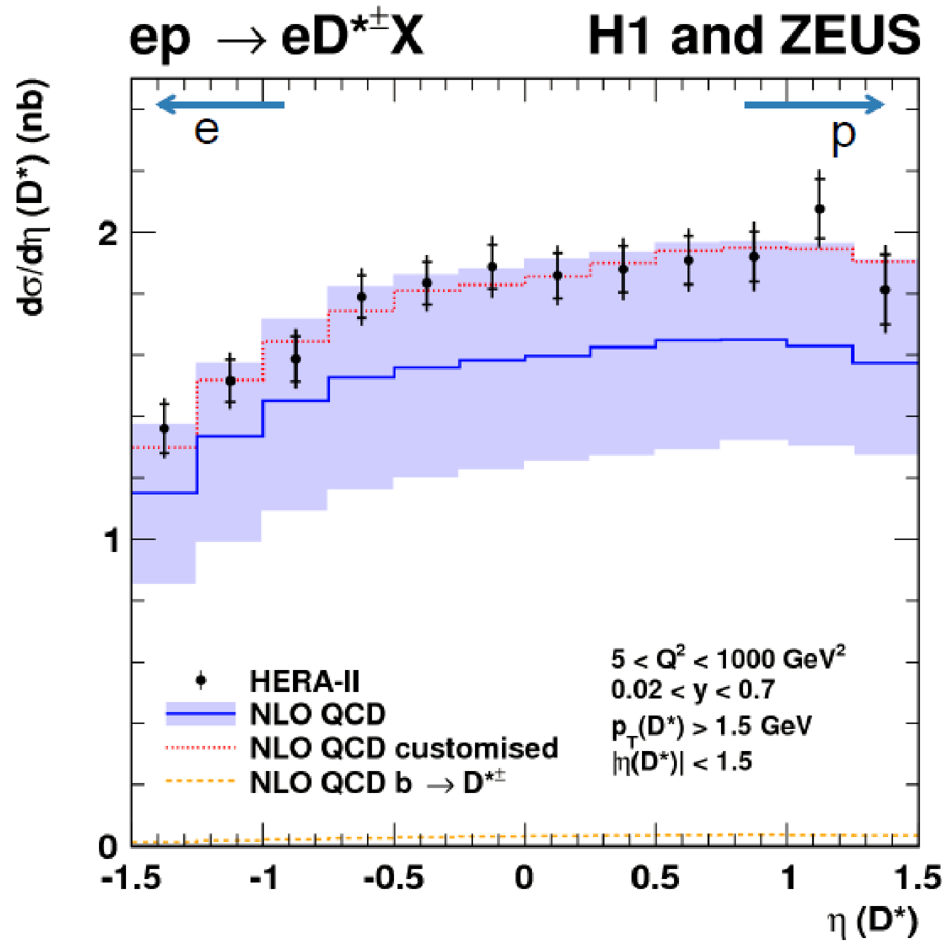

HVQDIS NLO QCD predictions:

- Describe data reasonably
- Large uncertainties 10-30% → **need NNLO and improved fragmentation models**

# H1+ZEUS $D^{*\pm}$ Cross Sections in DIS

DESY 15-037
March 2015

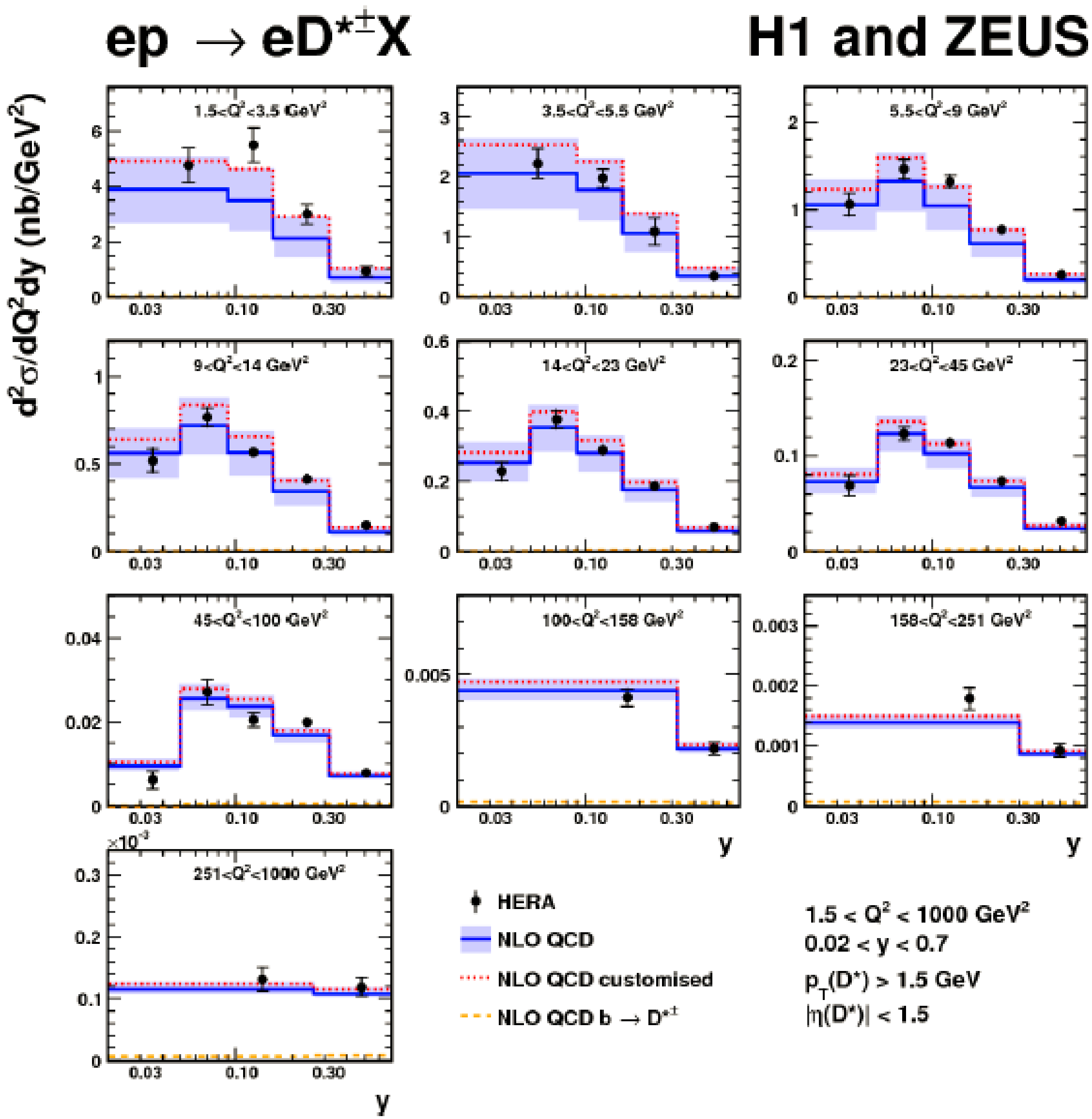



HVQDIS NLO QCD predictions:

- Describe data reasonably
- Large uncertainties 10-30% → **need NNLO and improved fragmentation models**

# H1+ZEUS $D^{*\pm}$ Cross Sections in DIS




Input data: as before

EPJ C71 (2011) 1769 H1
PL B686 (2010) 91 H1
JHEP 05 (2013) 097 ZEUS

plus ZEUS HERA I data

PR D69 (2004) 012004 ZEUS

# Summary & Prospects

## No new data but a lot of new results

- Extensive results on jet production
  Precise $\alpha_s$ measurements

- New results on diffractive dijets in DIS and photoproduction
  Conformation of diffraction suppression in photoproduction

- New precise measurements of prompt photon production
  Verification of collinear and $k_t$ predictions

- Extensive results on charm and beauty production
  Precise combined $D^{*\pm}$ Cross Sections in DIS

- More final and combined H1+ZEUS results

# Back-up Slides

# HERAPDF 1.0, 1.5, 2.0

HERAPDF1.0

HERAPDF1.5

HERAPDF2.0 (prel.)

H1prelim-14-041(2)
ZEUS-prel-14-005(7)

| Data Set | | x Grid from | x Grid to | $Q^2$/GeV$^2$ Grid from | $Q^2$/GeV$^2$ Grid to | $\mathcal{L}$ pb$^{-1}$ | $e^+/e^-$ | $\sqrt{s}$ GeV |
|---|---|---|---|---|---|---|---|---|
| **HERA I $E_p$ = 820 GeV and $E_p$ = 920 GeV data sets** | | | | | | | | |
| H1 svx-mb | 95-00 | 0.000005 | 0.02 | 0.2 | 12 | 2.1 | $e^+p$ | 301, 319 |
| H1 low $Q^2$ | 96-00 | 0.0002 | 0.1 | 12 | 150 | 22 | $e^+p$ | 301, 319 |
| H1 NC | 94-97 | 0.0032 | 0.65 | 150 | 30000 | 35.6 | $e^+p$ | 301 |
| H1 CC | 94-97 | 0.013 | 0.40 | 300 | 15000 | 35.6 | $e^+p$ | 301 |
| H1 NC | 98-99 | 0.0032 | 0.65 | 150 | 30000 | 16.4 | $e^-p$ | 319 |
| H1 CC | 98-99 | 0.013 | 0.40 | 300 | 15000 | 16.4 | $e^-p$ | 319 |
| H1 NC HY | 98-99 | 0.0013 | 0.01 | 100 | 800 | 16.4 | $e^-p$ | 319 |
| H1 NC | 99-00 | 0.0013 | 0.65 | 100 | 30000 | 65.2 | $e^+p$ | 319 |
| H1 CC | 99-00 | 0.013 | 0.40 | 300 | 15000 | 65.2 | $e^+p$ | 319 |
| ZEUS BPC | 95 | 0.000002 | 0.00006 | 0.11 | 0.65 | 1.65 | $e^+p$ | 300 |
| ZEUS BPT | 97 | 0.0000006 | 0.001 | 0.045 | 0.65 | 3.9 | $e^+p$ | 300 |
| ZEUS SVX | 95 | 0.000012 | 0.0019 | 0.6 | 17 | 0.2 | $e^+p$ | 300 |
| ZEUS NC | 96-97 | 0.00006 | 0.65 | 2.7 | 30000 | 30.0 | $e^+p$ | 300 |
| ZEUS CC | 94-97 | 0.015 | 0.42 | 280 | 17000 | 47.7 | $e^+p$ | 300 |
| ZEUS NC | 98-99 | 0.005 | 0.65 | 200 | 30000 | 15.9 | $e^-p$ | 318 |
| ZEUS CC | 98-99 | 0.015 | 0.42 | 280 | 30000 | 16.4 | $e^-p$ | 318 |
| ZEUS NC | 99-00 | 0.005 | 0.65 | 200 | 30000 | 63.2 | $e^+p$ | 318 |
| ZEUS CC | 99-00 | 0.008 | 0.42 | 280 | 17000 | 60.9 | $e^+p$ | 318 |
| **HERA II $E_p$ = 920 GeV data sets** | | | | | | | | |
| H1 NC | 03-07 | 0.0008 | 0.65 | 60 | 30000 | 182 | $e^+p$ | 319 |
| H1 CC | 03-07 | 0.008 | 0.40 | 300 | 15000 | 182 | $e^+p$ | 319 |
| H1 NC | 03-07 | 0.0008 | 0.65 | 60 | 50000 | 151.7 | $e^-p$ | 319 |
| H1 CC | 03-07 | 0.008 | 0.40 | 300 | 30000 | 151.7 | $e^-p$ | 319 |
| H1 NC med $Q^2$ | 03-07 | 0.0000986 | 0.005 | 8.5 | 90 | 97.6 | $e^+p$ | 319 |
| H1 NC low $Q^2$ | 03-07 | 0.000029 | 0.00032 | 2.5 | 12 | 5.9 | $e^+p$ | 319 |
| ZEUS NC | 06-07 | 0.005 | 0.65 | 200 | 30000 | 135.5 | $e^+p$ | 318 |
| ZEUS CC | 06-07 | 0.0078 | 0.42 | 280 | 30000 | 132 | $e^+p$ | 318 |
| ZEUS NC | 05-06 | 0.005 | 0.65 | 200 | 30000 | 169.9 | $e^-p$ | 318 |
| ZEUS CC | 04-06 | 0.015 | 0.65 | 280 | 30000 | 175 | $e^-p$ | 318 |
| ZEUS NC nominal | 06-07 | 0.000092 | 0.008343 | 7 | 110 | 44.5 | $e^+p$ | 318 |
| ZEUS NC satellite | 06-07 | 0.000071 | 0.008343 | 5 | 110 | 44.5 | $e^+p$ | 318 |
| **HERA II $E_p$ = 575 GeV data sets** | | | | | | | | |
| H1 NC high $Q^2$ | 07 | 0.00065 | 0.65 | 35 | 800 | 5.4 | $e^+p$ | 252 |
| H1 NC low $Q^2$ | 07 | 0.0000279 | 0.0148 | 1.5 | 90 | 5.9 | $e^+p$ | 252 |
| ZEUS NC nominal | 07 | 0.000147 | 0.013349 | 7 | 110 | 7.1 | $e^+p$ | 251 |
| ZEUS NC satellite | 07 | 0.000125 | 0.013349 | 5 | 110 | 7.1 | $e^+p$ | 251 |
| **HERA II $E_p$ = 460 GeV data sets** | | | | | | | | |
| H1 NC high $Q^2$ | 07 | 0.00081 | 0.65 | 35 | 800 | 11.8 | $e^+p$ | 225 |
| H1 NC low $Q^2$ | 07 | 0.0000348 | 0.0148 | 1.5 | 90 | 12.2 | $e^+p$ | 225 |
| ZEUS NC nominal | 07 | 0.000184 | 0.016686 | 7 | 110 | 13.9 | $e^+p$ | 225 |
| ZEUS NC satellite | 07 | 0.000143 | 0.016686 | 5 | 110 | 13.9 | $e^+p$ | 225 |

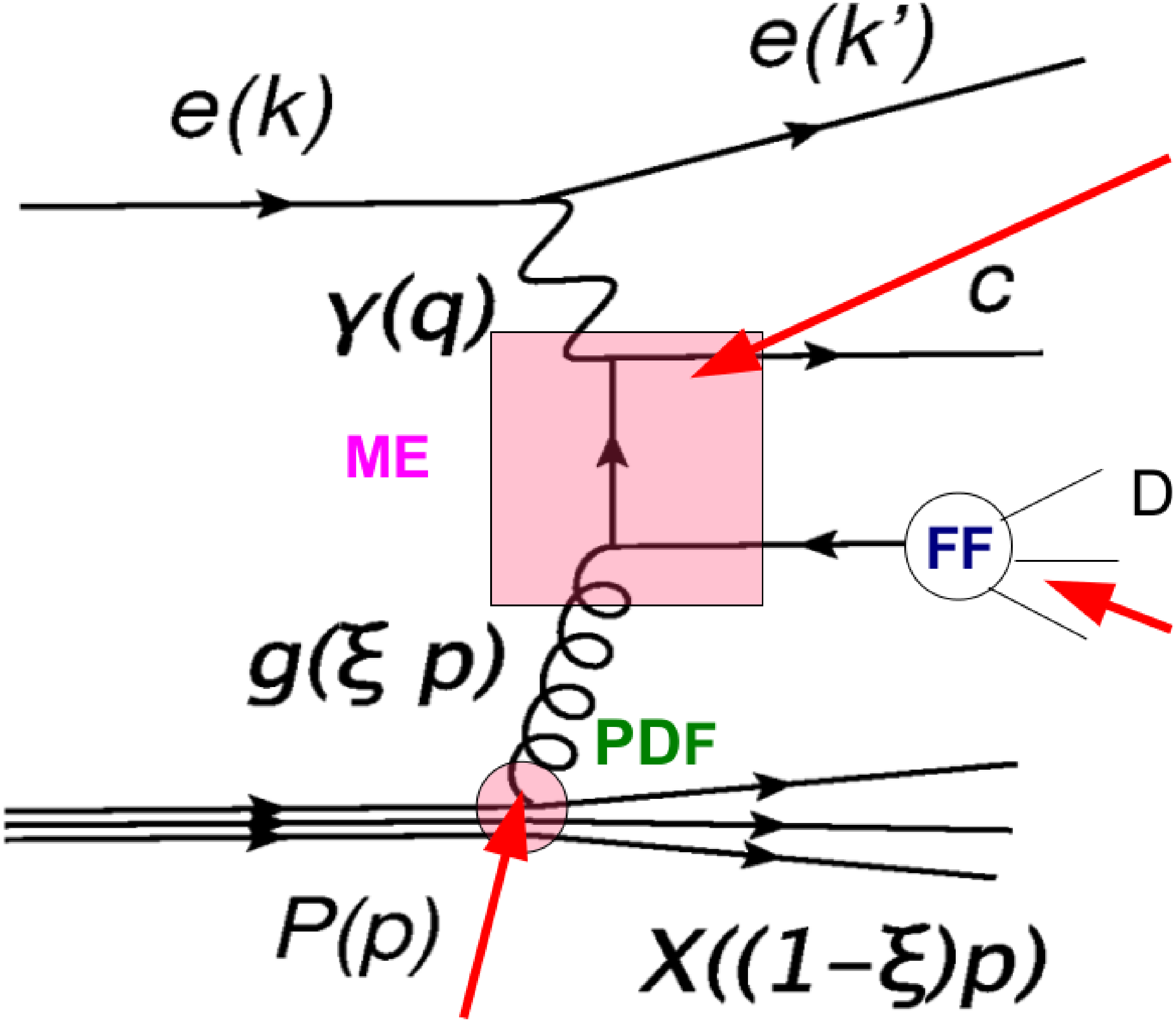
Full HERA I data

HERA II data HER

HERA II data LER

- All results are final and published!

# Heavy Quark Production



# Secondary vertex method

Tag: jet + secondary vertex

Phase space of the measurement:

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

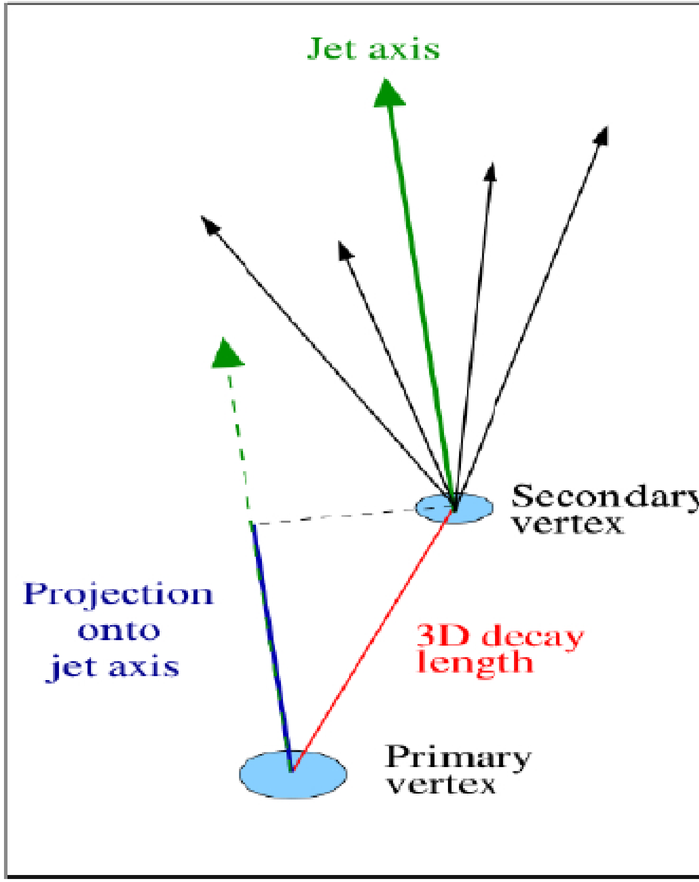
$0.02 < y < 0.7$

$E_T^{jet} > 5(4.2)$ GeV

$-1.6 < \eta^{jet} < 2.2$

- Employs long lifetime of ground state hadrons containing charm or beauty quarks
- No specific decay mode requirement → increase in statistics

- Select tracks belonging to a jet
  - $p_T$(track)>500 MeV
- Fit a secondary vertex
- Project decay length onto a jet axis
- Calculate decay length significance



# Quark mass definitions

Pole quark mass

- Based on (unphysical) concept of quark being a free parton
- Pole mass is ambiguous up to corrections of O($\lambda_{QCD}$)

Running quark mass ($\bar{M}S$)

- $\bar{M}S$ (minimal substraction scheme) mass definition m($\mu_R$) realizes running mass (scale dependence)
- renormalization group equation (mass anomalous dimenstion $\gamma$)

$$\left(\mu_R^2 \frac{\delta}{\delta \mu_R^2} + \beta(\alpha_s) \frac{\delta}{\delta \alpha_s}\right) m(\mu_R) = \gamma(\alpha_s) m(\mu_R)$$

# Charm DIS Data Samples

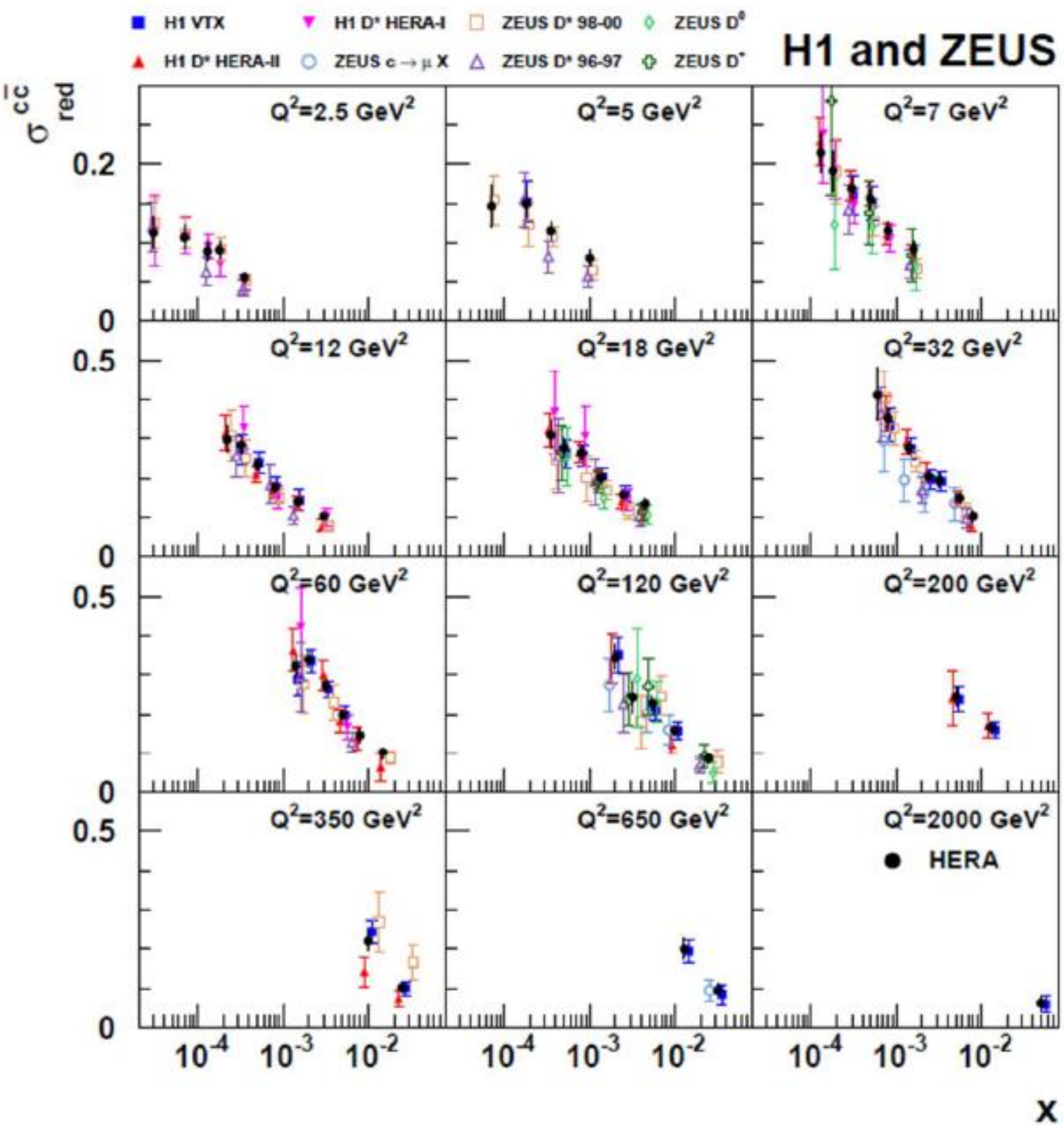
| | Data set | Tagging method | $Q^2$ range [GeV$^2$] | $N$ | $\mathcal{L}$ [pb$^{-1}$] |
|---|---|---|---|---|---|
| 1 | H1 VTX [14] | Inclusive track lifetime | 5 – 2000 | 29 | 245 |
| 2 | H1 $D^*$ HERA-I [10] | $D^{*+}$ | 2 – 100 | 17 | 47 |
| 3 | H1 $D^*$ HERA-II [18] | $D^{*+}$ | 5 – 100 | 25 | 348 |
| 4 | H1 $D^*$ HERA-II [15] | $D^{*+}$ | 100 – 1000 | 6 | 351 |
| 5 | ZEUS $D^*$ (96-97) [4] | $D^{*+}$ | 1 – 200 | 21 | 37 |
| 6 | ZEUS $D^*$ (98-00) [6] | $D^{*+}$ | 1.5 – 1000 | 31 | 82 |
| 7 | ZEUS $D^0$ [12] | $D^{0,\text{no}D^{*+}}$ | 5 – 1000 | 9 | 134 |
| 8 | ZEUS $D^+$ [12] | $D^+$ | 5 – 1000 | 9 | 134 |
| 9 | ZEUS $\mu$ [13] | $\mu$ | 20 – 10000 | 8 | 126 |

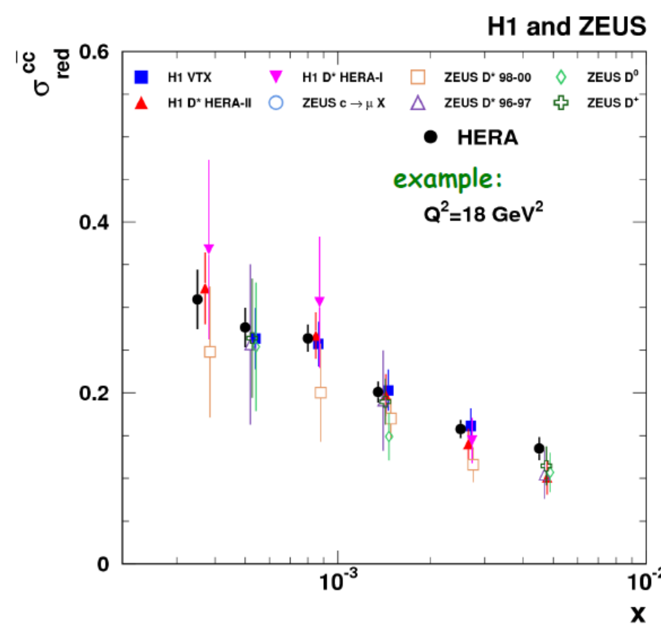
- two independent experiments
- a large variety of tagging techniques: inclusive methods using the large lifetime of charmed hadrons, inclusive track lifetime, complete reconstruction of charmed mesons, $D^{*+}$, charm semileptonic decay, $\mu$
- a large number of measurements, $\sum N = 155$ data points, in a common grid spanning the $x - Q^2$ plane (except for [14] where scaling factors, always smaller than 18 %, have been applied to migrate the original measurements to the closest point of the common grid)
- developped a combination method taking into account properly correlated and uncorrelated uncertainties (155 data points in 52 bins)

key observable:

$$\sigma_{\text{red}}^{c\bar{c}} = \frac{d^2\sigma^{c\bar{c}}}{dx\,dQ^2} \cdot \frac{xQ^4}{2\pi\alpha^2(Q^2)\,(1+(1-y)^2)}$$

# Combined Charm Reduced x-sections



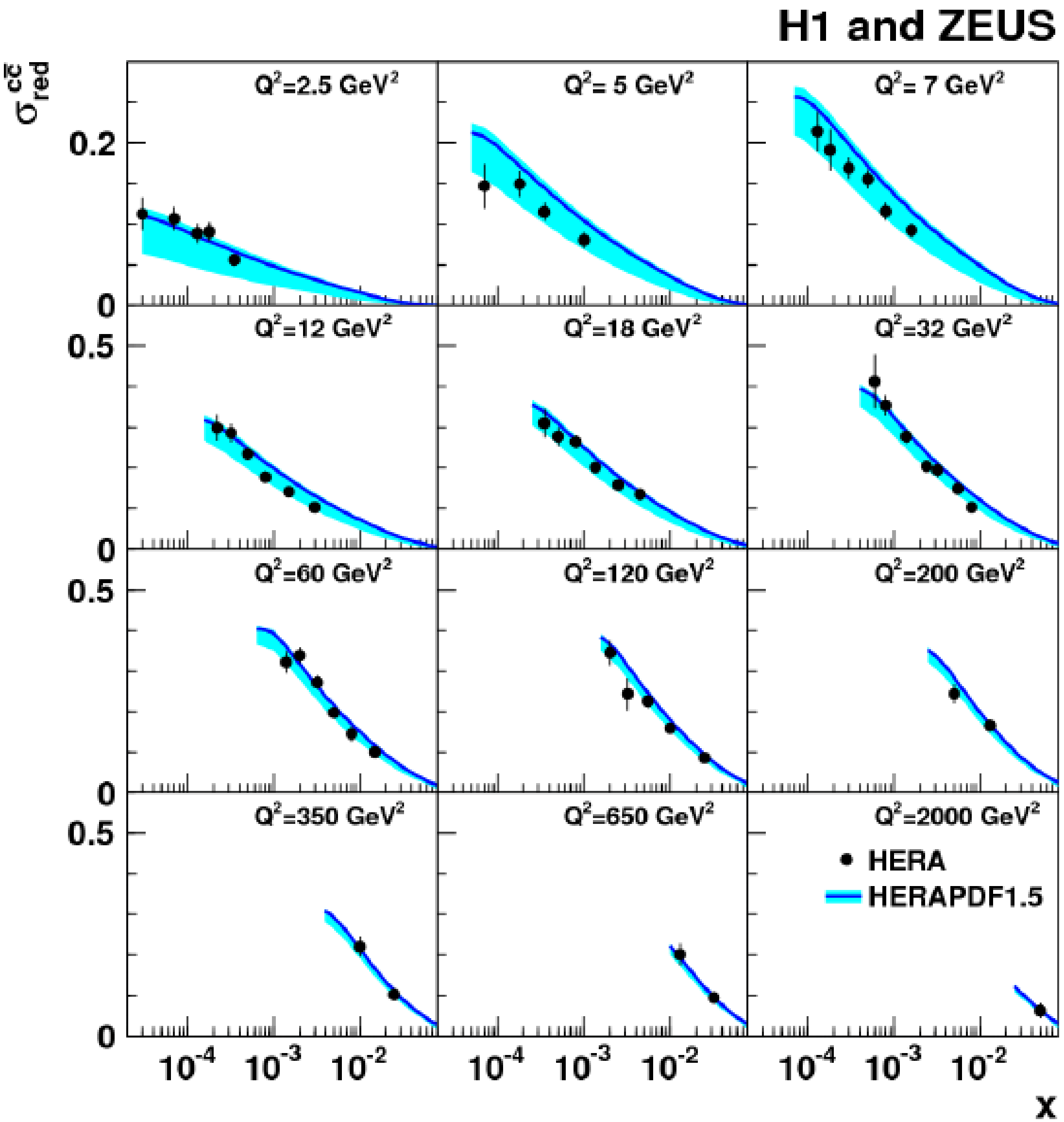




✓ good consistency of data
among the several possible tests
$\chi^2$ / ndf = 62 / 103

✓ good complementarity of data

✓ 10 % uncertainty on average,
6 % at small x and medium $Q^2$

# Sensitivity to $m_c$

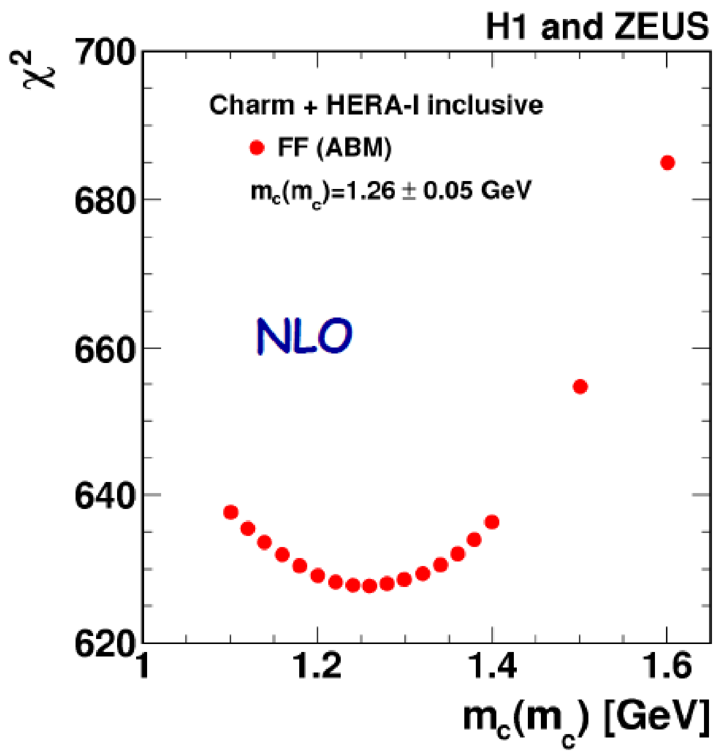


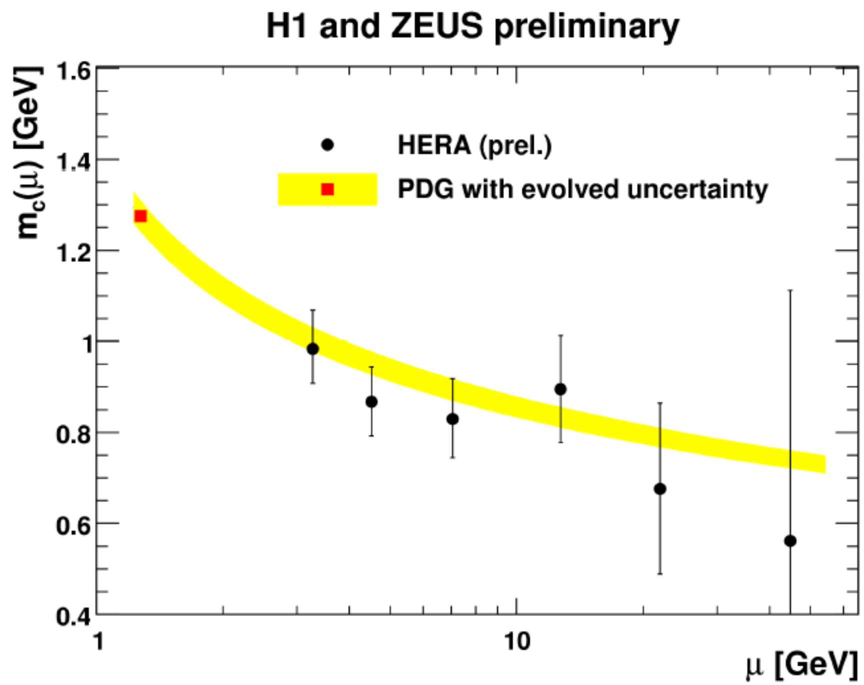

well described using HERAPDF1.5
(fitted from inclusive DIS only)

strong charm mass dependence
(blue band: 1.35->1.6 GeV)

Can be used to constraint $m_c$

# $m_c$ value and running




$$\mu = \sqrt{Q^2 + 4m_c^2}$$

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

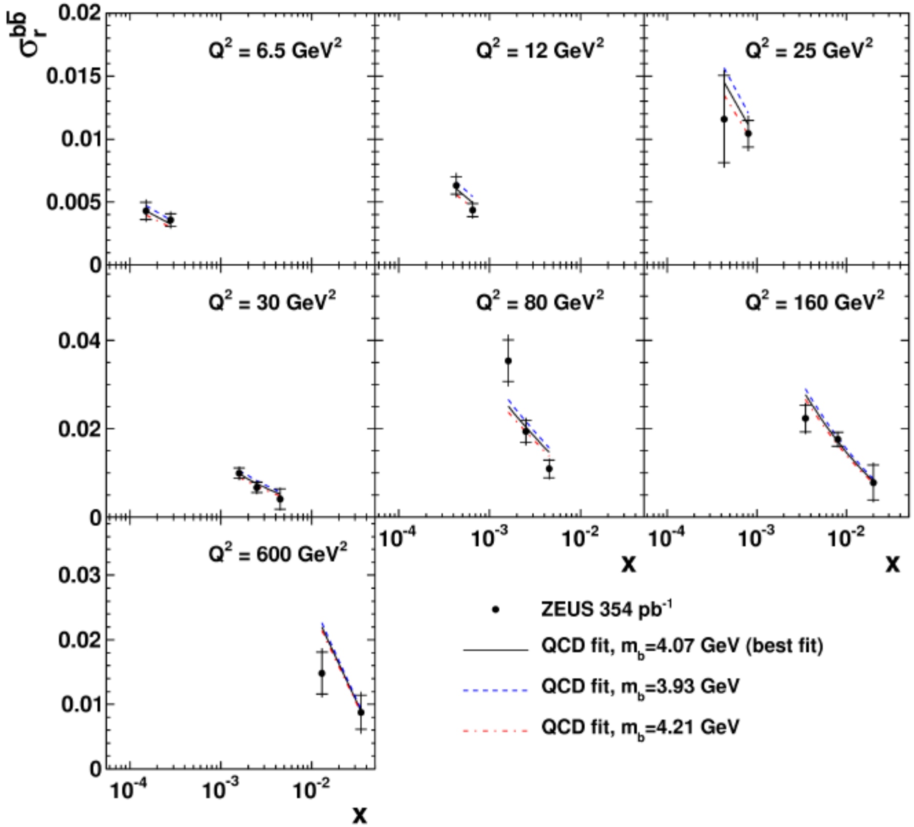
Errors are experimental, model, parametrisation and $\alpha_s$

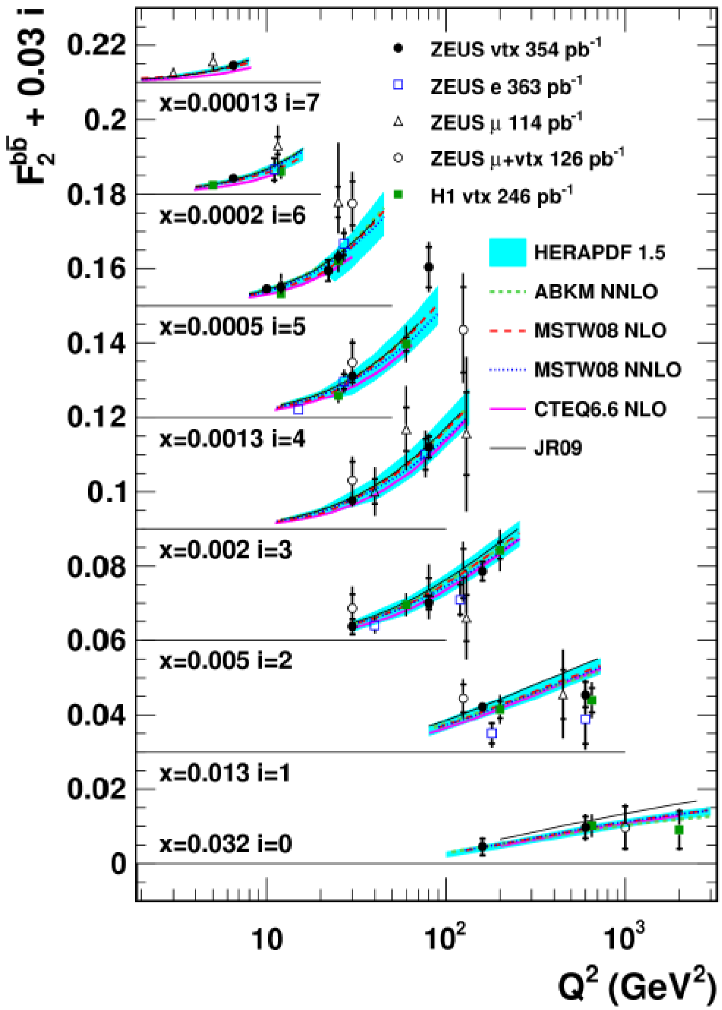
Consistent with PDG: $m_c(m_c) = 1.275 \pm 0.025$ GeV

$$m_c(\mu) = m_c(m_c) \frac{\left(\frac{\alpha_s(\mu)}{\pi}\right)^{\frac{1}{\beta_0}}}{\left(\frac{\alpha_s(m_c)}{\pi}\right)^{\frac{1}{\beta_0}}}$$

$\beta_0$ for $N_f$=3 is $\frac{9}{4}$

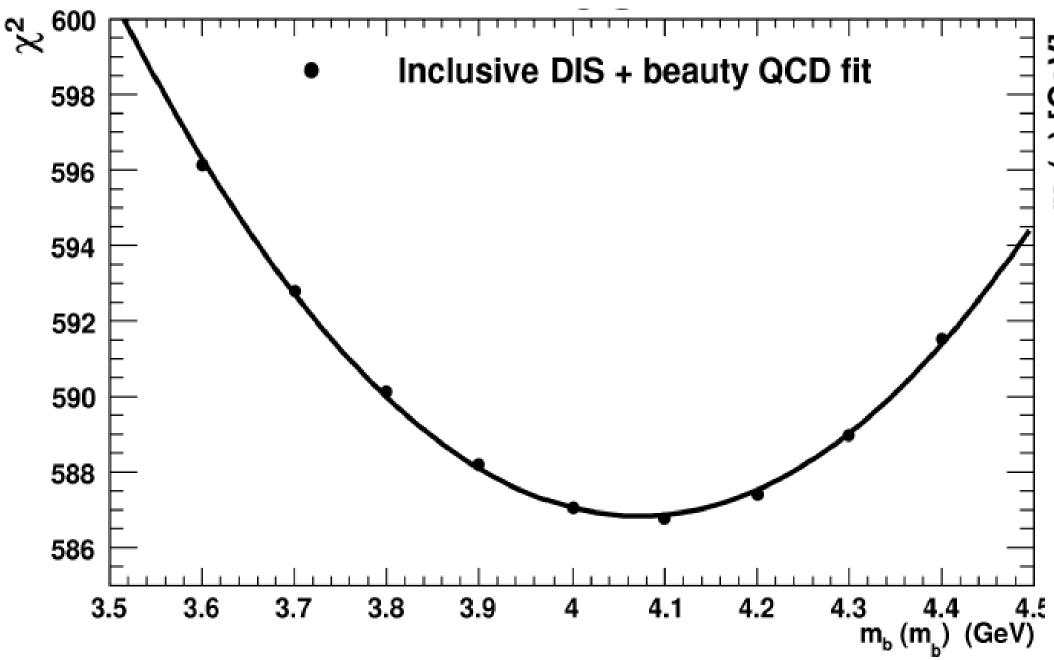
# Beauty Reduced x-sections and $F_2$

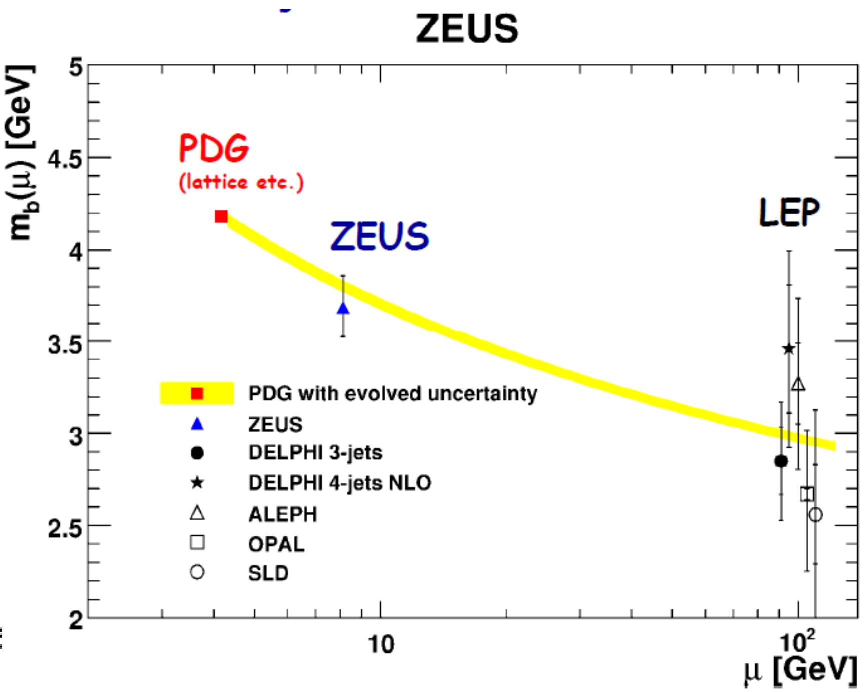



Sensitivity to $m_b$ comes mostly from low $Q^2$

# $m_b$ value and running



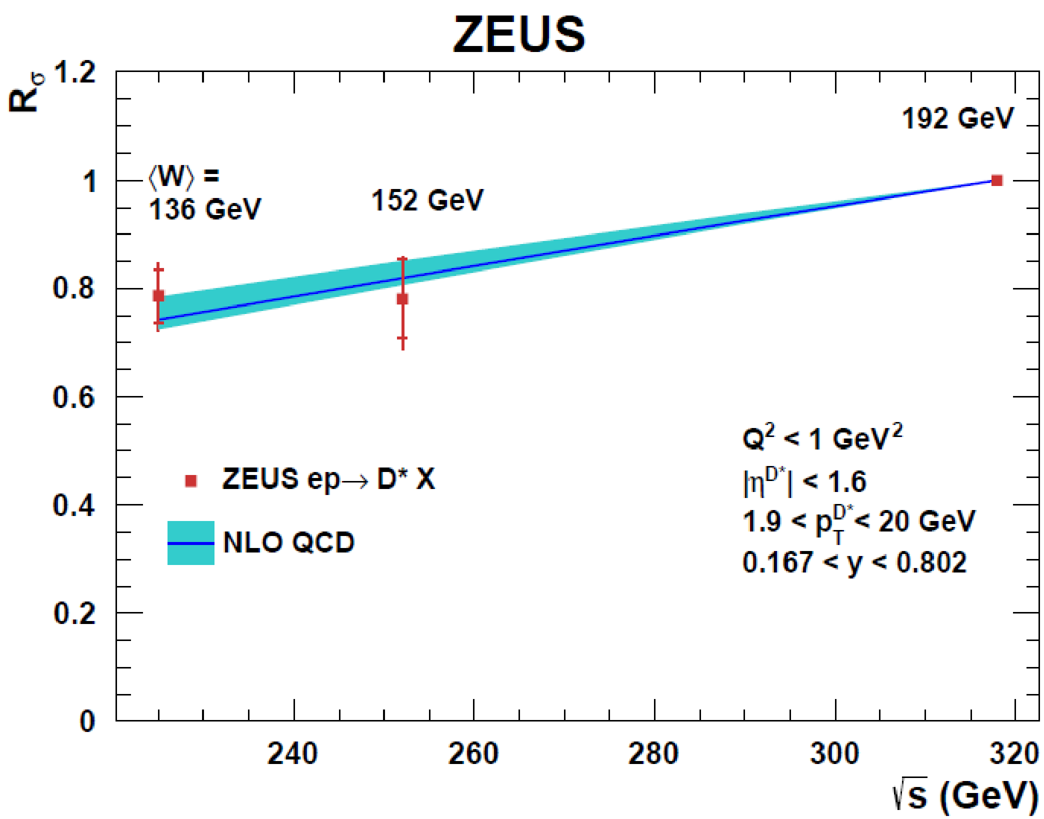

$m_b(m_b)$ = 4.07 $\pm 0.14_{fit}$ ${}^{+0.01}_{-0.07\ mod}$ ${}^{+0.05}_{-0.00\ par}$ ${}^{+0.08}_{-0.05\ th}$ GeV

PDG: 4.18 ± 0.03 GeV (lattice QCD + time-like processes)

translate back to $2m_b$

mass running consistent with QCD

# Ratio of D*± PhP x-sections at different √s




DESY 14 082
May 2014

**Parameters for NLO QCD calculation:**

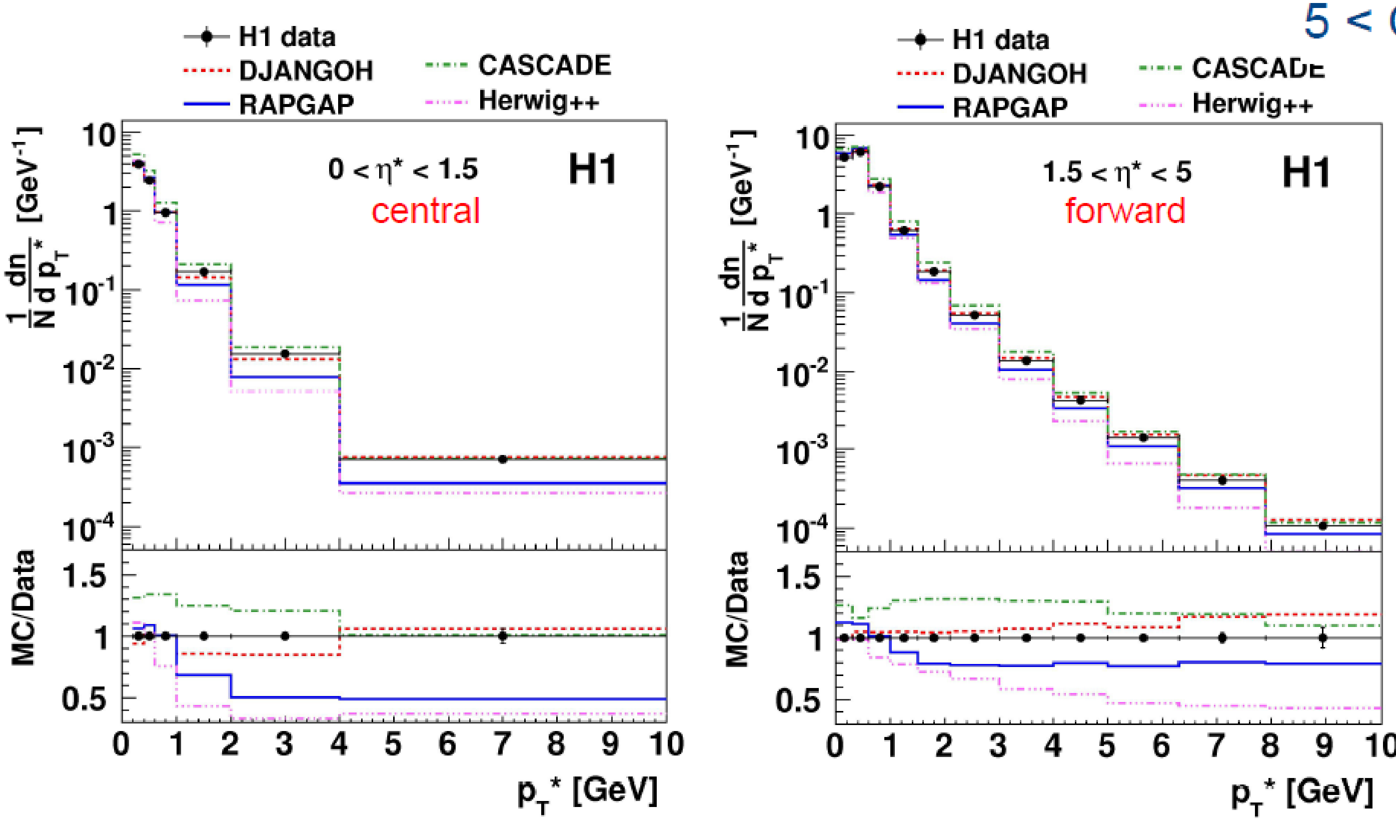
**Fixed-flavor-number scheme (FFNS):**

**Strong coupling constant** : $\alpha_s(M_Z) = 0.118$,
**mass of c quarks:** m =1.50 GeV
**Fragmentation fraction** f(c->D*)=0.237
**PDFs :** proton - ZEUS-S FFNS
photon - GRV-G HO
**Peterson fragmentation function:** = 0.079

**Scales were set to** $\mu = \sqrt{m_c^2 + \hat{p}_T^2}$

# Charged Particle Spectra in DIS

$5 < Q^2 < 100\ GeV^2$




DJANGOH does best, RAPGAP is also satisfactory at low $p_T$ but not at high $p_T$.

CASCADE (based on CCFM) is the least successful model.

Eur. Phys. J C73 (2013) 2406