Heavy Flavour Physics at HERA

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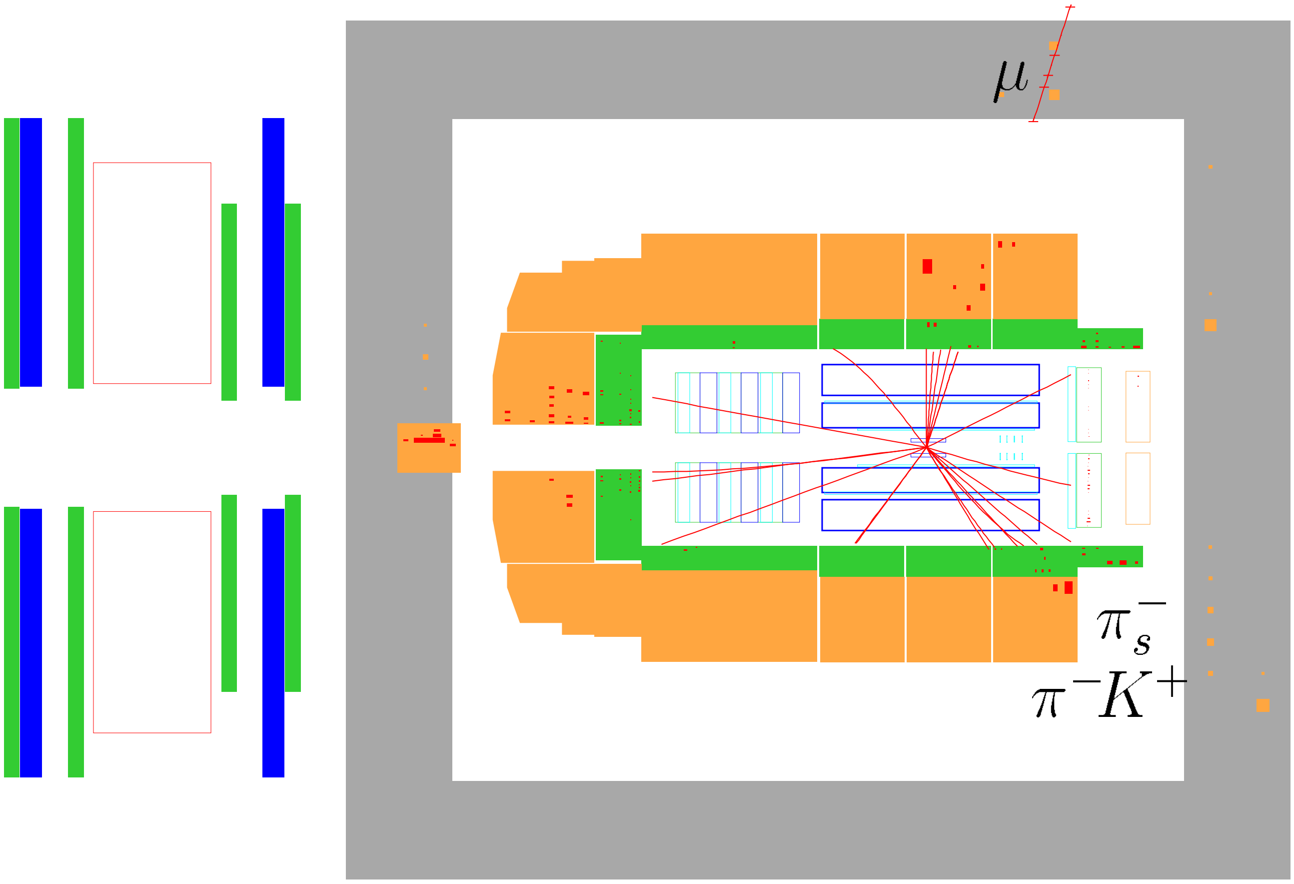
- Introduction
- Open Charm
- Open Beauty
- Quarkonia
- Summary

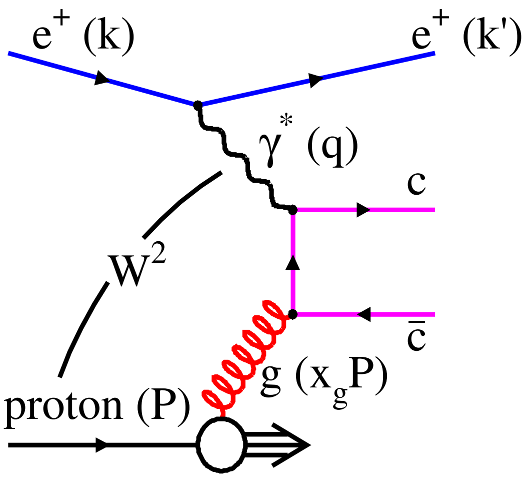
HQ2K, Rio de Janeiro, 10/10/00

$\boldsymbol{ep}$ Interactions at HERA

$$\sqrt{s} = 320 \text{ GeV}$$



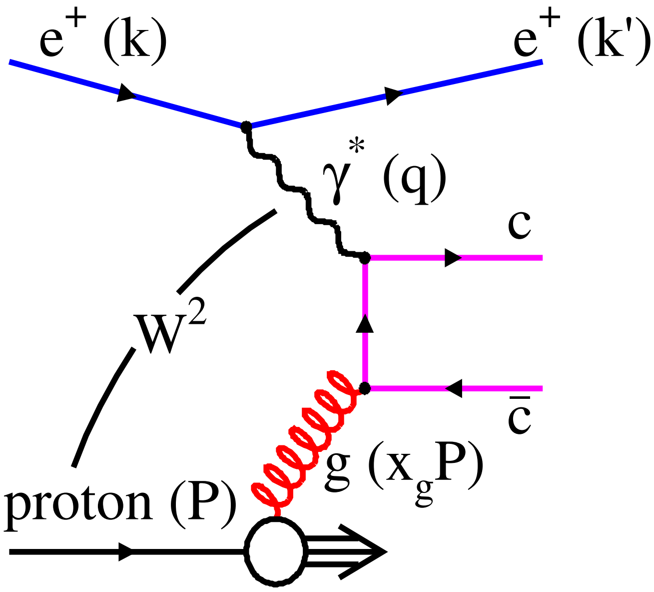
Event Kinematics in ep Scattering:



Q^2	(4-mom. transfer)^2
x	Mom.fraction of q
y	Fract. energy transfer
W^2	(Had. fin. state mass)^2

$Q^2 \sim 0$: quasi-real $\gamma \rightarrow$ 'photoproduction'

Heavy Quark Production Mechanism



$\gamma g \rightarrow c\bar{c}$

Boson-Gluon-Fusion

- direct sensitivity to Gluons in the Proton

Predict differential $c\bar{c}$, $b\bar{b}$ x-sections:

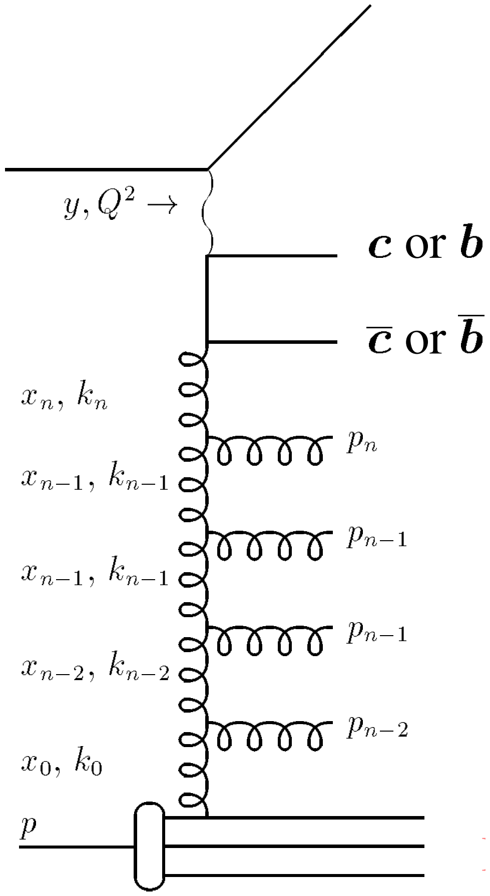
- Fixed Flavor Scheme: 3 active flavors
- Massive Charm/Beauty produced in BGF
- QCD parton dynamics: Evolution Scheme (DGLAP, CCFM)
- Perturbative scales: Q^2, p_t^2, $m_{c,b}^2$
- Low Q^2, p_t^2: $m_{c,b}^2$ serves as pQCD scale

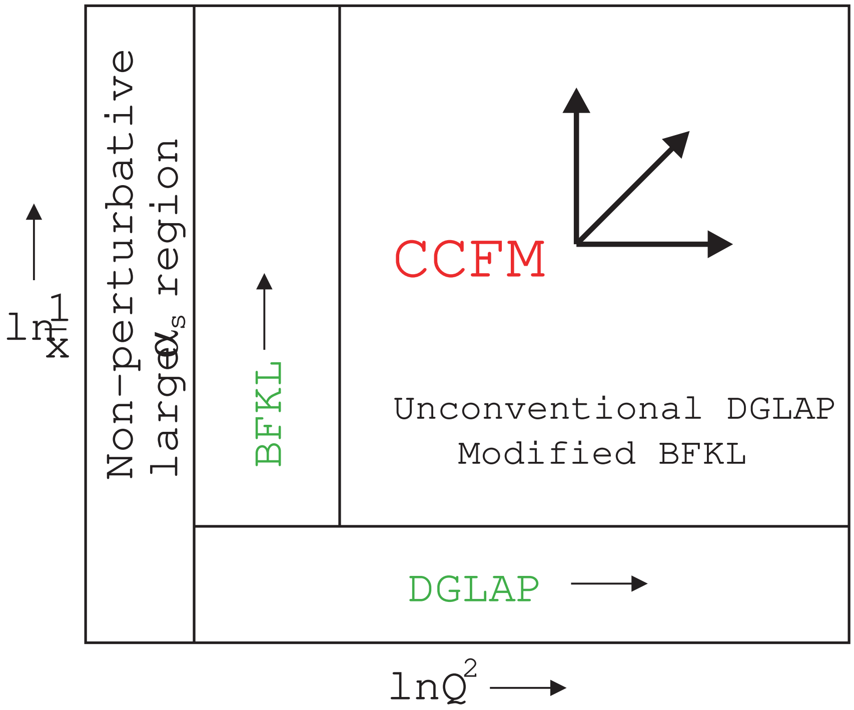
$\rightarrow$ Tests of perturbative QCD:

Factorization & Parton Universality

QCD Evolution Schemes

Perturbative QCD calculations:





	BFKL	$\xleftarrow{x\to 0}$	CCFM	$\xrightarrow{\text{large } x}$	DGLAP
Ordering:	x		η		k_t^2

DGLAP:

– Describes inclusive data over full range

– NLO pQCD of $c\bar{c}$, $b\bar{b}$: FMNR, HVQDIS

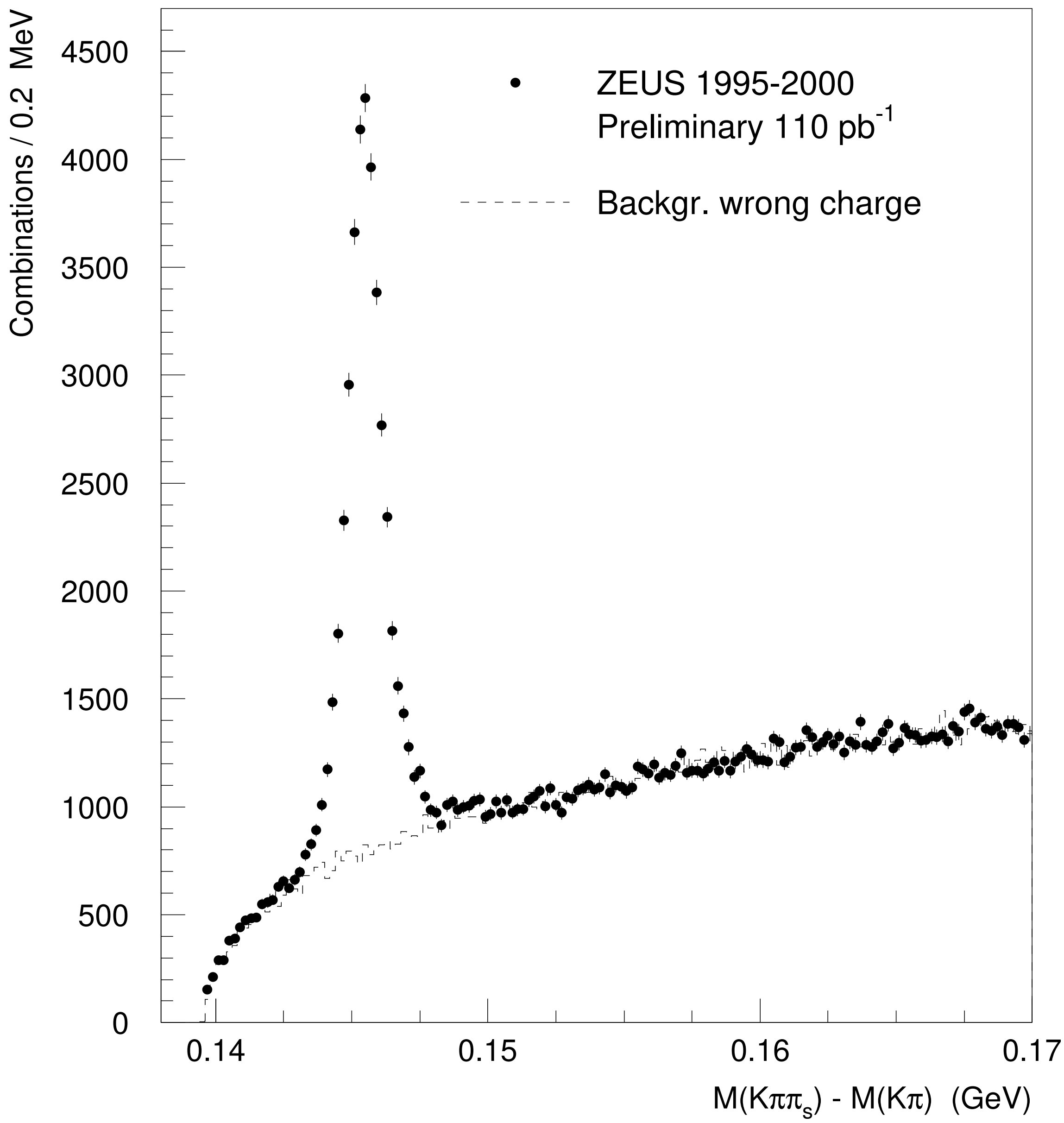
CCFM:

– New MC generator CASCADE available

Heavy Flavour Physics at HERA

H1, ZEUS '95-00: $\int \mathcal{L} dt > 100$ pb^{-1} each

$\rightarrow$ 27,000 $D^* \rightarrow K\pi\pi$ events



Good Access to Physics of Charm and Beauty

$\rightarrow$ Tests of QCD (up to high Q^2, x)

$\rightarrow$ Spectroscopy

HERA-II after $\mathcal{L}$-upgrade: $\sim$ 150 pb^{-1}/a

Outline of this Talk

Probing the Gluon in the Proton

Open Charm:

- Good statistics, $m_c^2 \sim$ pQCD threshold
- Emerging sensitivity to
  - fragmentation effects $f(c \to D)$
  - evolution scheme (DGLAP, CCFM)

1. D^* at high Q^2
2. D^*, D_s at $Q^2 \sim 0$
3. $F_2^{c\bar{c}}(x, Q^2)$ at low Q^2, low x

Open Beauty:

- Low statistics, m_b^2 is hard pQCD scale
- b-tagging:
  - large b-mass
  - long b-lifetime

Heavy Quarkonia:

- Elastic Production of J/ψ, $\Psi(2S)$, Υ

  $\sigma \propto |xg(x)|^2$, enhanced sensitivity

D^* Cross Sections ($Q^2 > 10$ GeV^2)

- Data: 82.6 pb^{-1}, $10 < Q^2 < 1000$ GeV^2

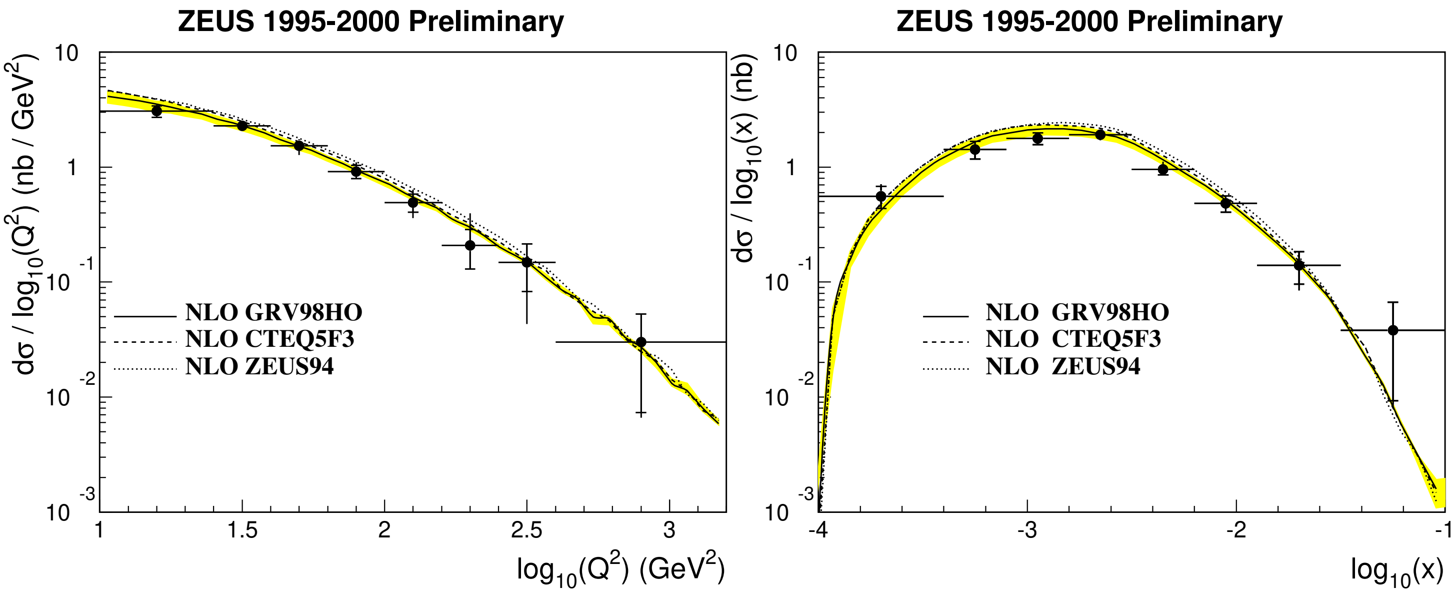
– Visible X-section: $p_t^{D*} > 1.5$ GeV/c, $|\eta| < 1.5$

- Theory: NLO QCD (3 flavor DGLAP $\overline{\text{MS}}$ scheme)
- implemented in HVQDIS-program:

– use $xg(x)$ from scaling violations of inclusive proton structure function $F_2(x, Q^2)$

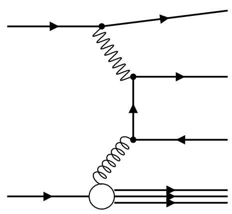
– Peterson Fragm. with $f(c \to D^{*+}) = 0.235$

– Yellow Band: $m_c = 1.3 - 1.6$ GeV



NLO QCD ($Q^2 > 10$ GeV^2):

Charm x-section well reproduced



Other sources of charm?

Need much more statistics

Open Charm in Photoproduction

Visible Cross Sections at $Q^2 \sim 0$:

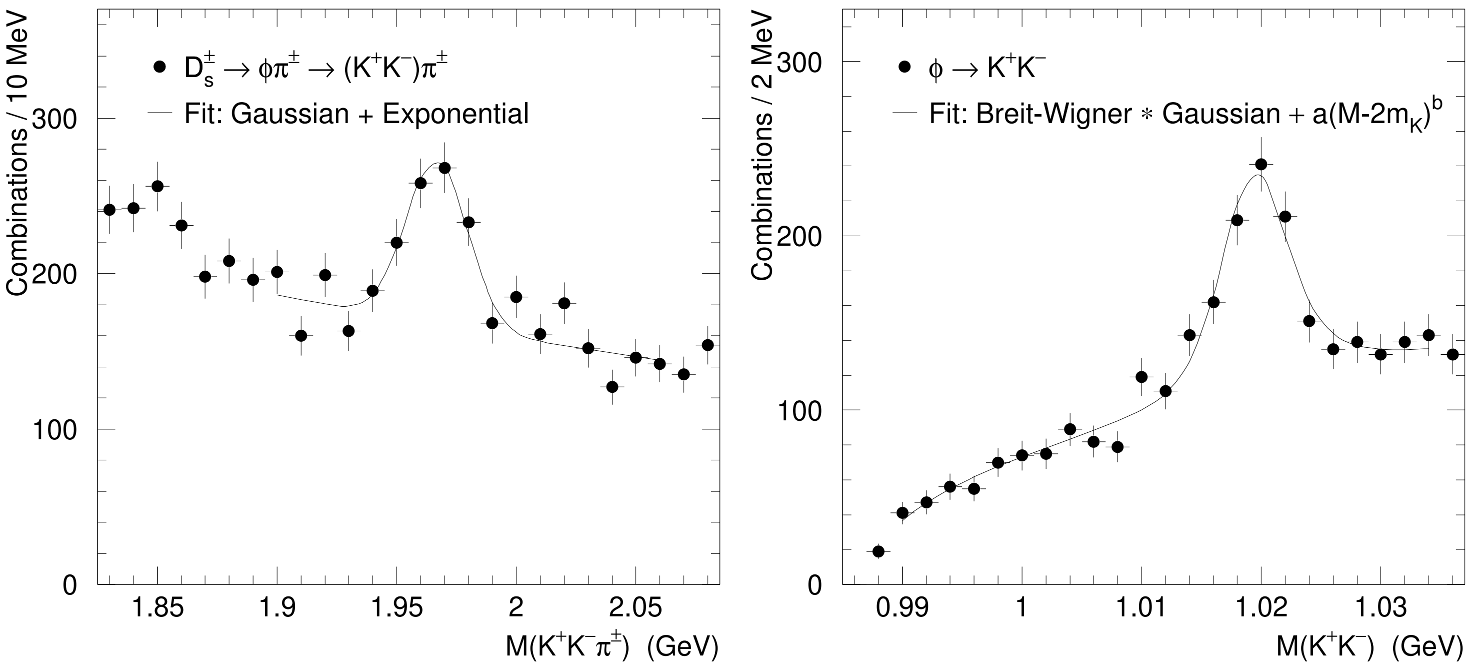
ZEUS:

$D^* \to K\pi\pi$:

$12 > p_t^{D^*} > 2$ GeV, $|\eta^{D^*}| < 1.5$

$$\sigma^{vis}_{ep\to D_* X} = 18.9 \pm 1.2(\text{stat.})^{+1.8}_{-0.8}(\text{syst.})\ \text{nb}$$

$D_s \to \phi\pi$:



$12 > p_t^{D^*} > 3$ GeV, $|\eta^{D^*}| < 1.5$

$$\sigma^{vis}_{ep\to D_s X} = 3.79 \pm 0.59(\text{stat.})^{+0.26}_{-0.46}(\text{syst.}) \pm 0.94(\text{BR})\ \text{nb}$$

Comparison with NLO QCD Calculations

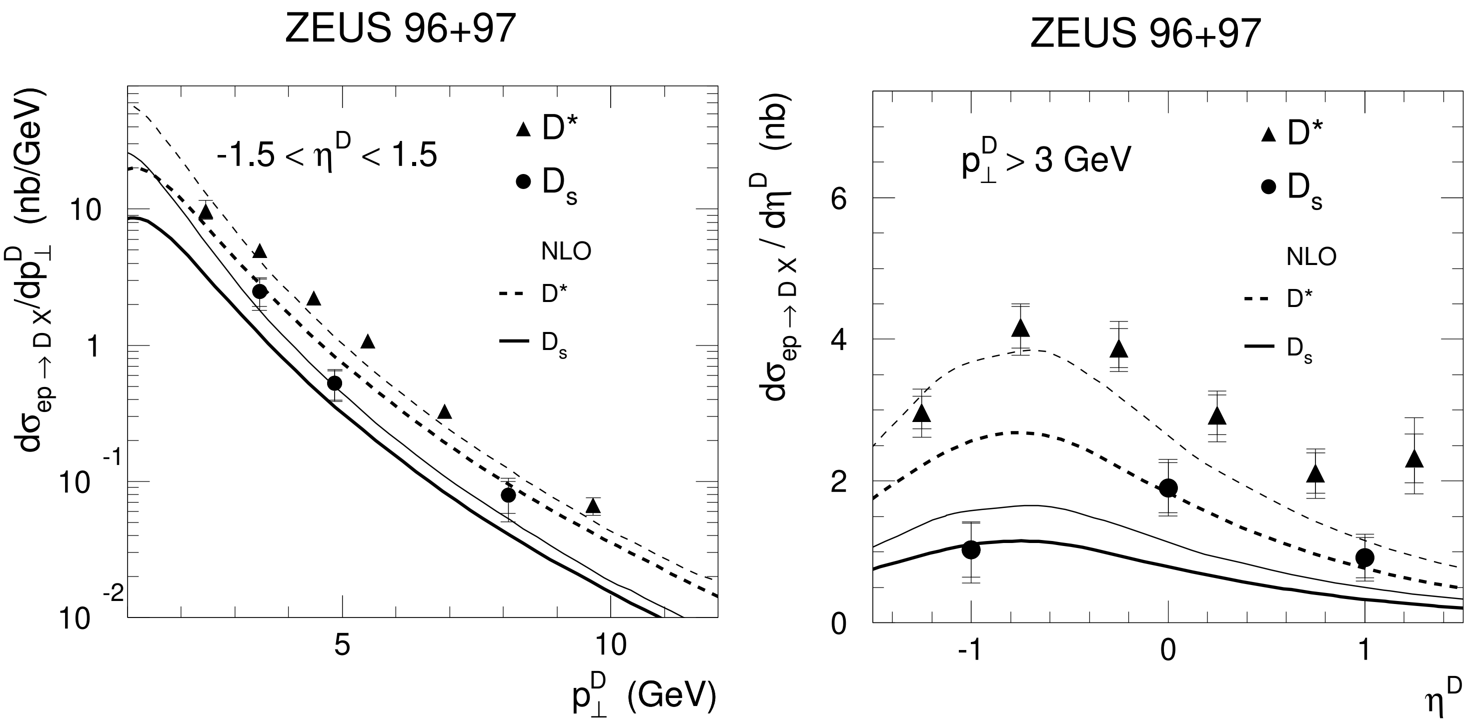
- Theory: NLO FMNR

– 3 flavor DGLAP $\overline{\mathrm{MS}}$ scheme

– Peterson Fragmentation

Bold: $m_c = 1.5$ GeV, $\mu_R = \sqrt{m_c^2 + p_\perp^2}$, $\mu_F = 2m_\perp$

Thin: $m_c = 1.2$ GeV, $\mu_R = 0.5\sqrt{m_c^2 + p_\perp^2}$, $\mu_F = 2m_\perp$
(extreme choice)



NLO QCD at $Q^2 \sim 0$ for both D_s and D^*:

– Normalization far too low

– Inconsistent shape in η^D

'Beam-Drag-Effect' ?

D_s and D^* Cross Section Comparison

Ratio $\sigma(ep \to D_s X)/\sigma(ep \to D^* X)$:

$$\frac{\sigma(ep \to D_s X)}{\sigma(ep \to D^* X)} = 0.41 \pm 0.07^{+0.03}_{-0.05} \pm 0.10(BR)$$

Compare with e^+e^-:

$$\frac{f(c \to D_s)}{f(c \to D^*)} = 0.43 \pm 0.04 \pm 0.11(BR)$$

Strangeness suppression factor (ep):

$$\gamma_s = P_s/P_{u,d} = 0.27 \pm 0.05$$

Compare with e^+e^-:

$$\gamma_s = P_s/P_{u,d} = 0.26 \pm 0.03$$

Consistent picture:

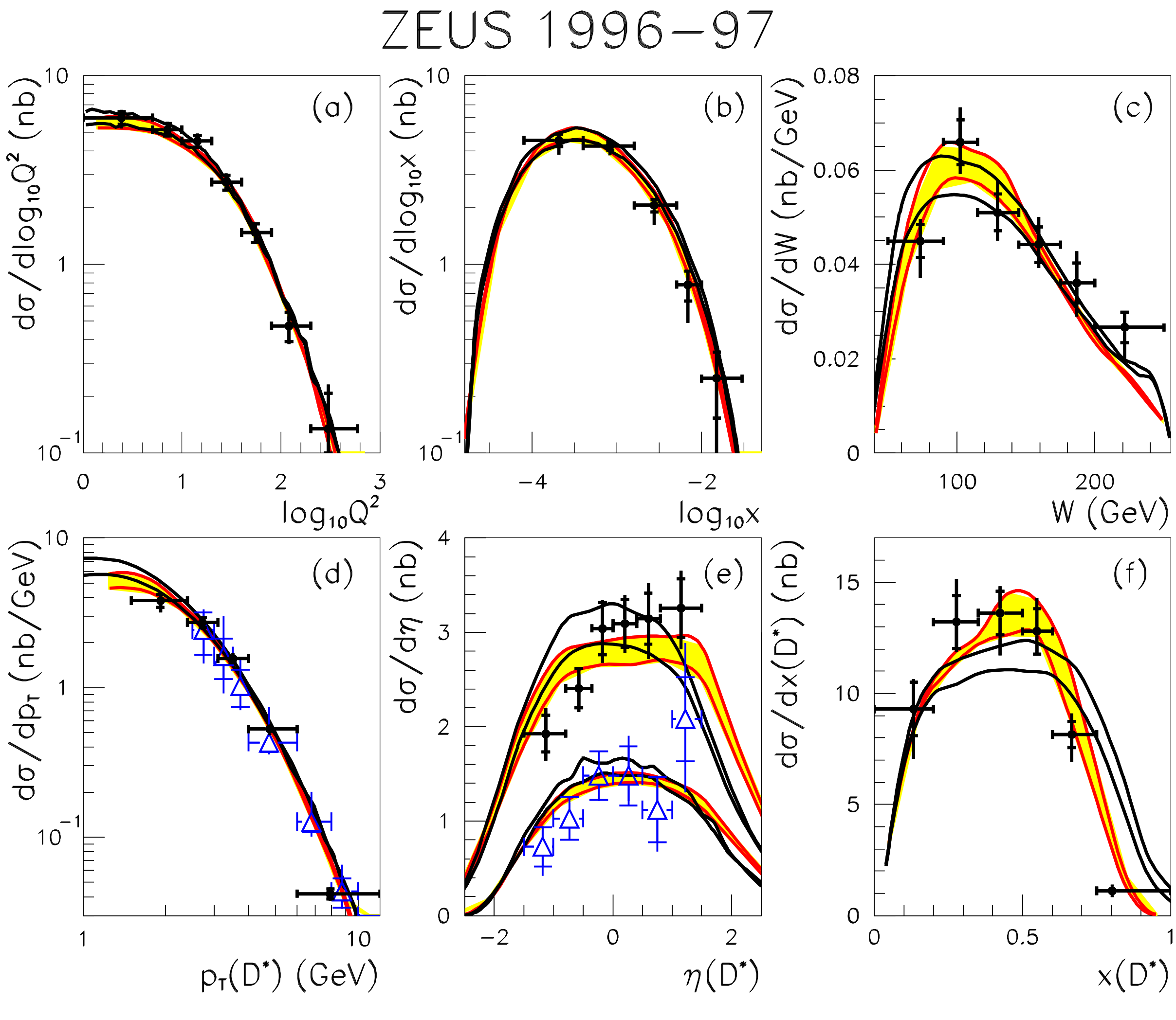
Tends to support

charm fragmentation universality

Direct Measurement of Fragmentation underway

D^* Cross Sections at Small Q^2

- Open Band: HVQDIS ($m_c : 1.3...1.5$ GeV)
  – NLO QCD (3 flavor DGLAP $\overline{\text{MS}}$ scheme)
  – Peterson Fragmentation
- Yellow Band: RAPGAP(JETSET)
  – reweighted to NLO $c\bar{c}$ X-section from HVQDIS



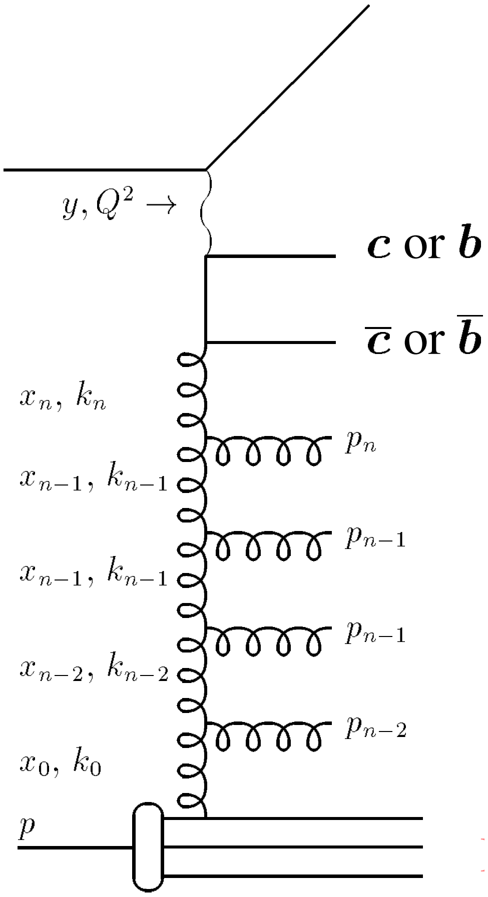
HVQDIS: Too low in fwd. direction, $\eta \gtrsim 0.5$

RAPGAP: Account for Beam-Drag:

Improved description

CCFM Evolution Equation

Catani, Ciafaloni, Fiorani, Marchesini

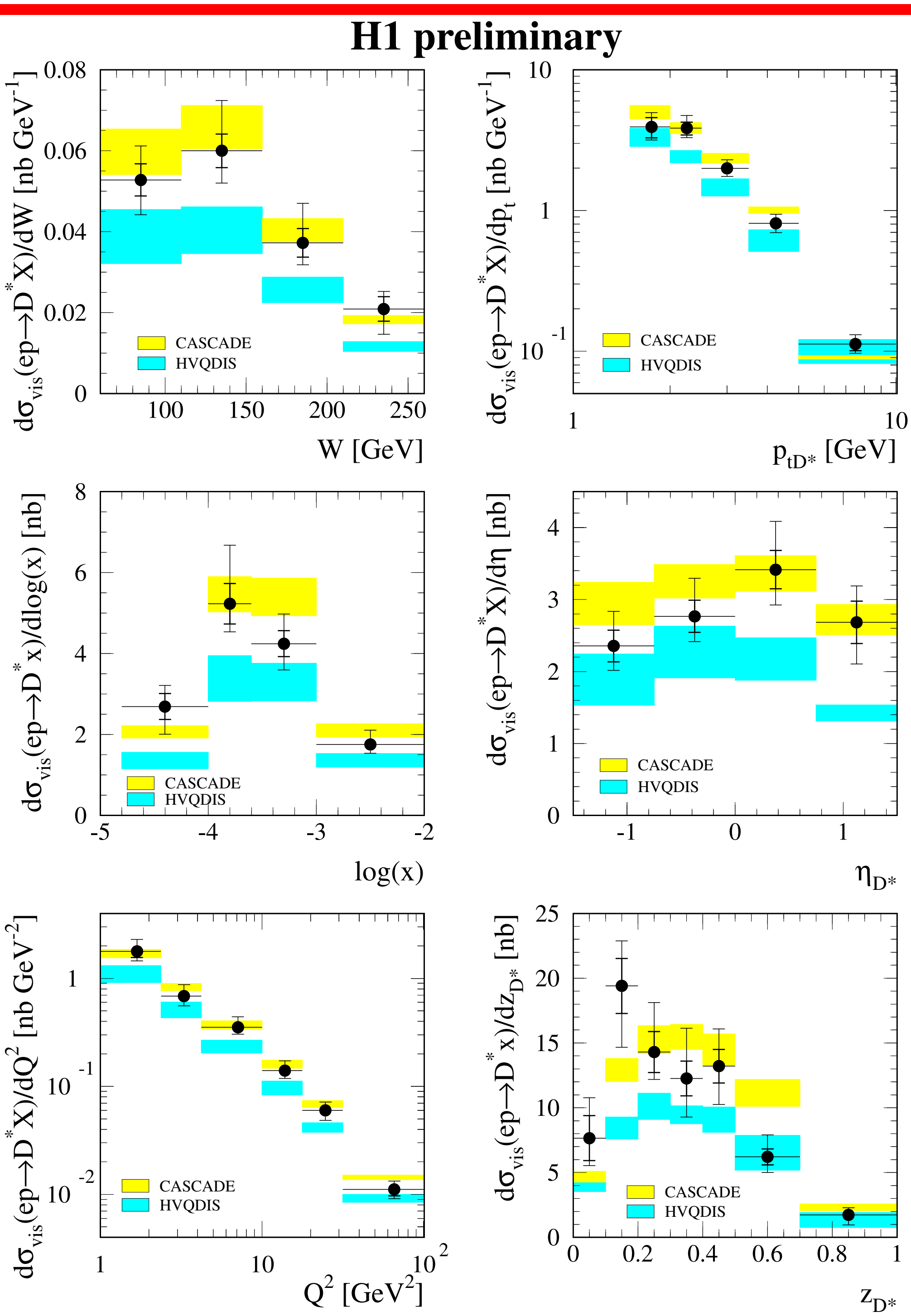


- k_t-unintegrated gluon density:

$$xg(x, Q^2, \mu^2) = \int dk_t^2 \mathcal{G}(x, k_t^2, Q^2, \mu^2)$$

- gluon emission ordered in angle (η)
- incorporates BFKL $x \rightarrow 0$, DGLAP large x

D^* Cross Sections at Small Q^2



HVQDIS (DGLAP): $\sigma_{vis} \sim 5.0 - 6.6$ nb

CASCADE (CCFM): $\sigma_{vis} \sim 8.5 - 10$ nb

CCFM: describes data better

– at small $p_t^{D^*}$ in the forward region, $\eta > 0$

– in overall normalization

Charm Cross Section

Visible D^* cross section at $Q^2 > 1$ GeV^2:

$$1 < Q^2 < 600 \text{ GeV}^2, 0.02 < y < 0.7$$

ZEUS: $1.5 < p_t^{D^*} < 15$ GeV/c, $|\eta_{D^*}| < 1.5$

$$\sigma_{ep \to eD^*X} = 8.31 \pm 0.31(\text{stat.})^{+0.3}_{-0.5}(\text{syst.}) \text{ nb}$$

$$1 < Q^2 < 100 \text{ GeV}^2, 0.05 < y < 0.7$$

H1: $1.5 < p_t^{D^*}$ GeV/c, $|\eta_{D^*}| < 1.5$

$$\sigma_{ep \to eD^*X} = 8.37 \pm 0.41(\text{stat.})^{+1.11}_{-0.82}(\text{syst.})^{+0.64}_{-0.39}(\text{theo.}) \text{ nb}$$

Good agreement between H1 and ZEUS

Extraction of $F_2^{\bar{c}c}(x, Q^2)$:

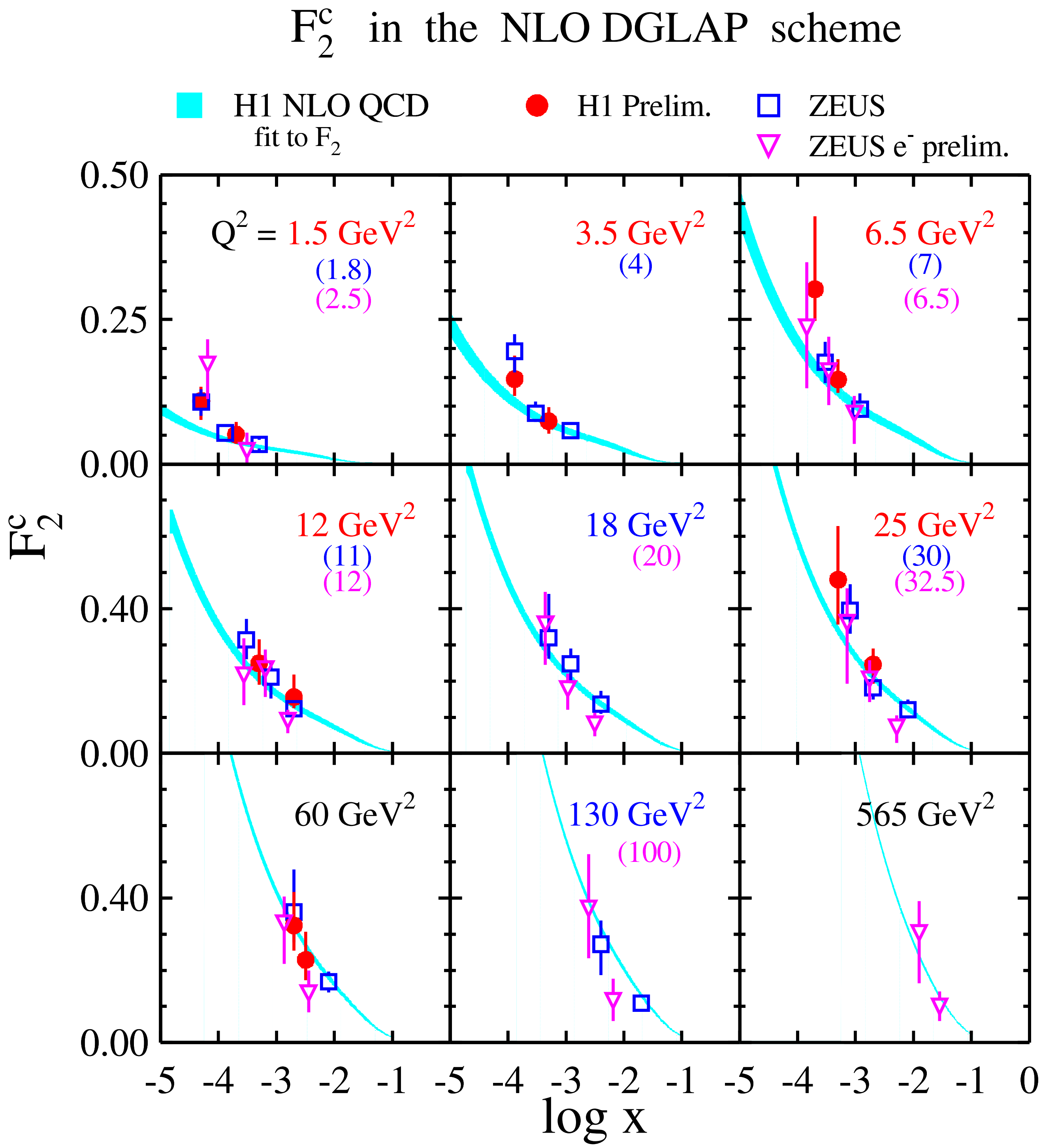
$$\frac{d^2\sigma^{c\bar{c}}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}(1 + (1-y)^2) \cdot F_2^{\bar{c}c}(x, Q^2)$$

Extrapolate $\sigma_{\text{vis}}^{\text{meas.}}$ in p_t and η:

$$F_{2,\text{meas.}}^{\bar{c}c} = \sigma_{\text{vis}}^{\text{meas.}} \frac{F_{2,\text{theory}}^{\bar{c}c}}{\sigma_{\text{vis}}^{\text{theory}}}$$

Input $xg(x)$ from QCD fit to inclusive F_2

$F_2^{\bar{c}c}(x, Q^2)$ H1 and ZEUS

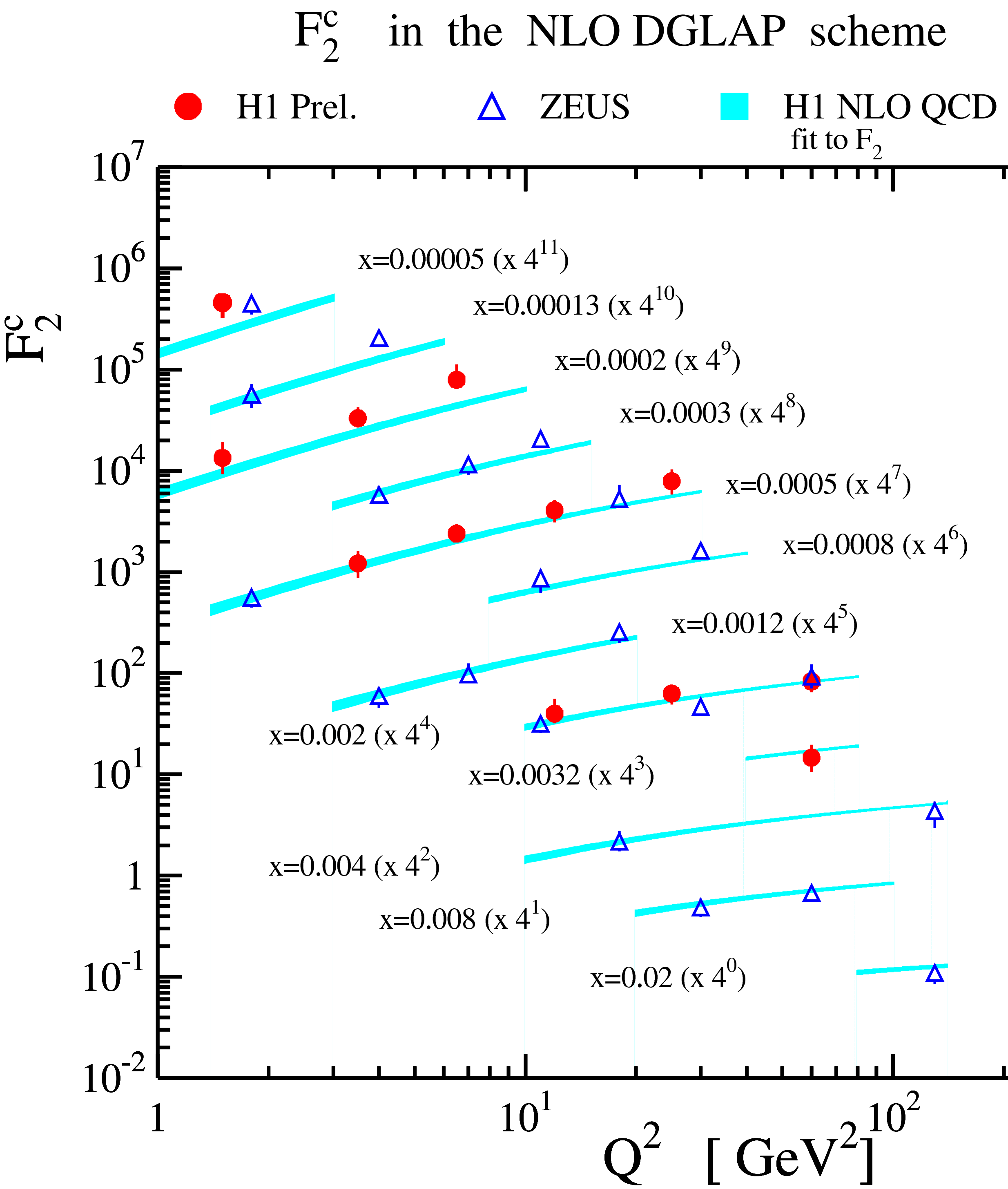


Strong rise towards low x: $F_2^{\bar{c}c} \propto xg(x) \Leftarrow$ BGF

ZEUS and H1 Data: Good Agreement

Lowest x and Q^2: Departure from DGLAP

Scaling Violations

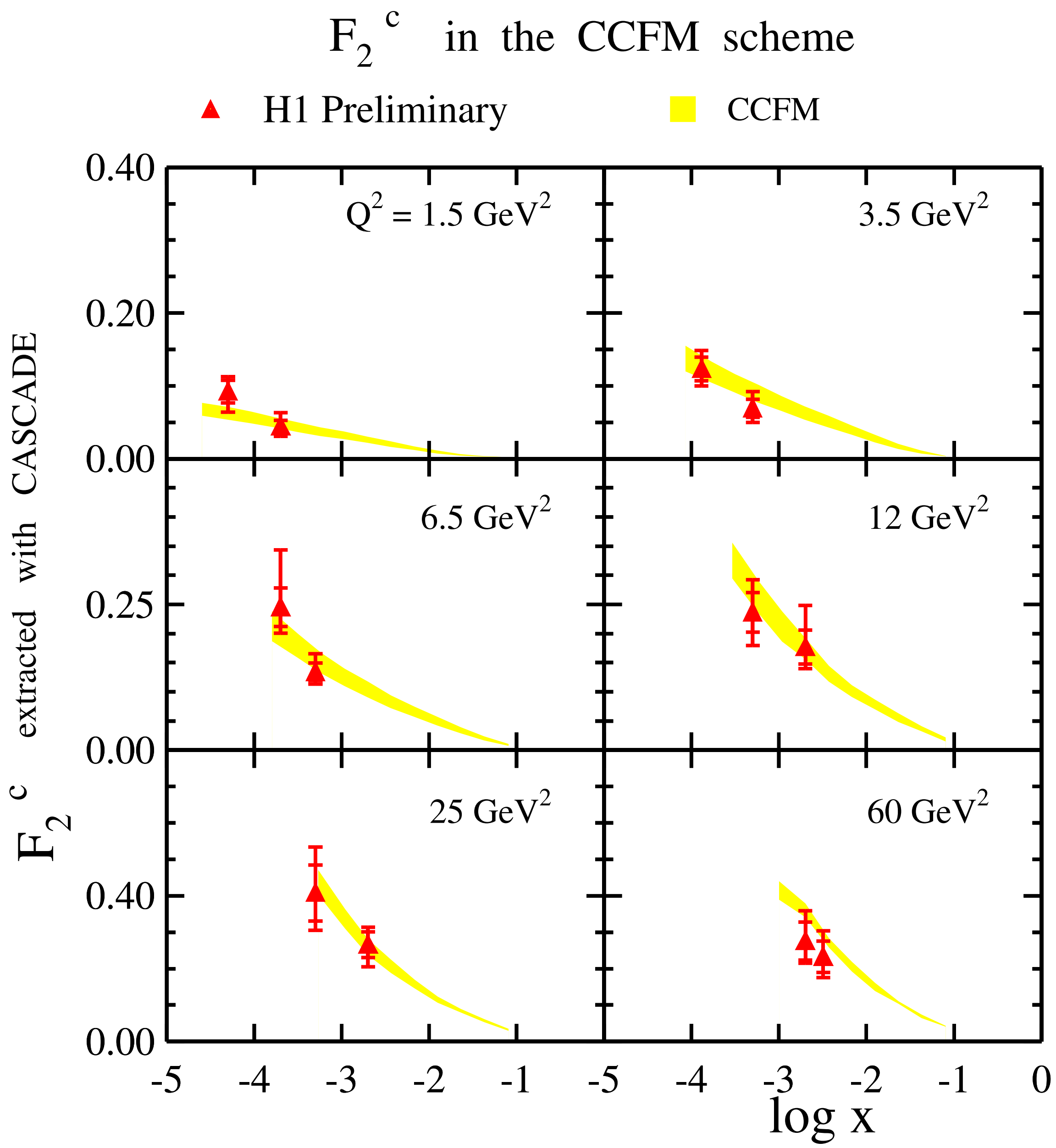


Scaling violations:

Increase of x-dependence of $F_2^{\bar{c}c}$ towards large Q^2

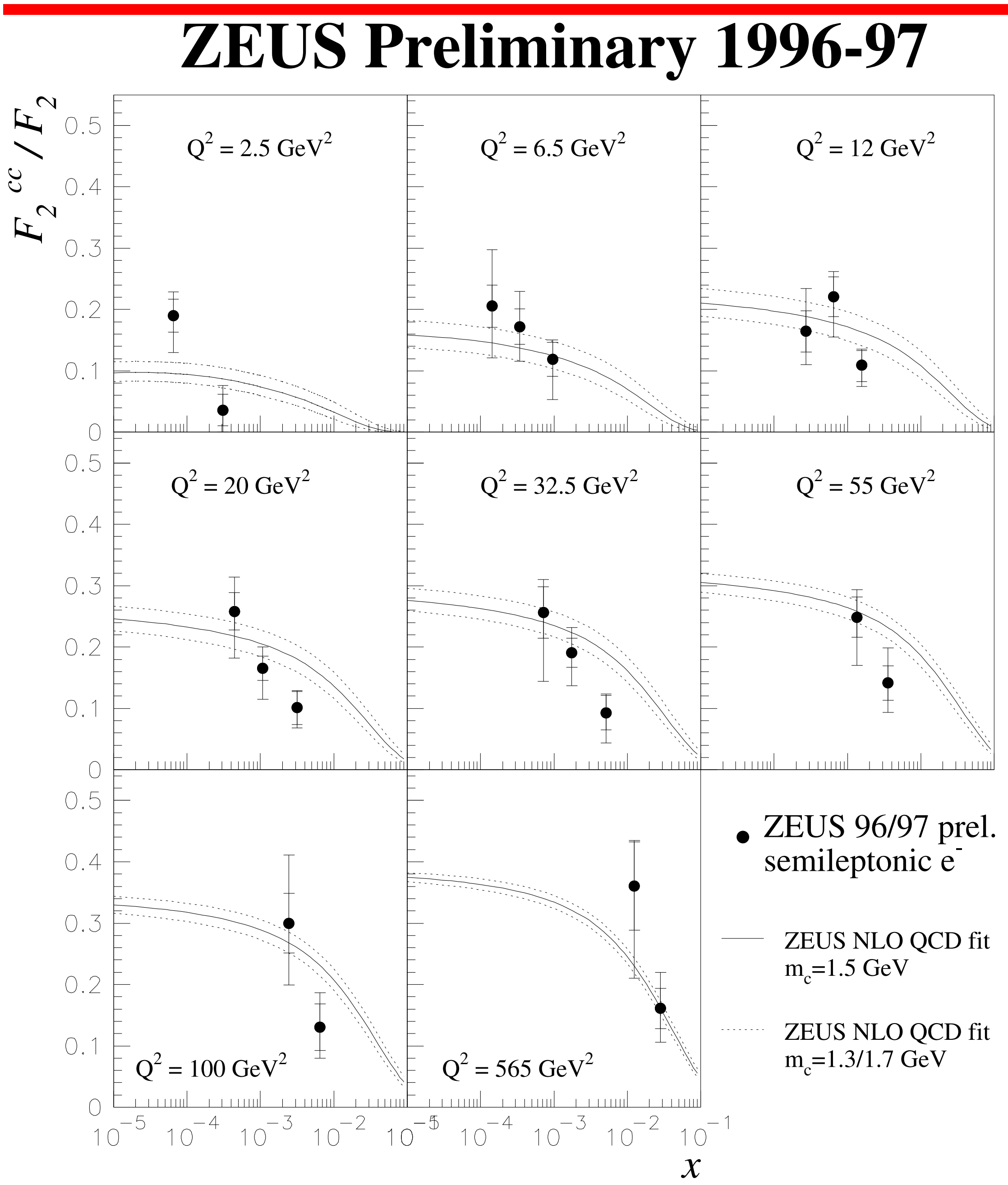
$\rightarrow$ as expected from inclusive $xg(x)$

$F_2^{\bar{c}c}(x, Q^2)$ with CCFM



Good Agreement between Data and CCFM

Charm Contribution to inclusive X-Section



Charm: $\sim 25\%$ of inclusive cross section

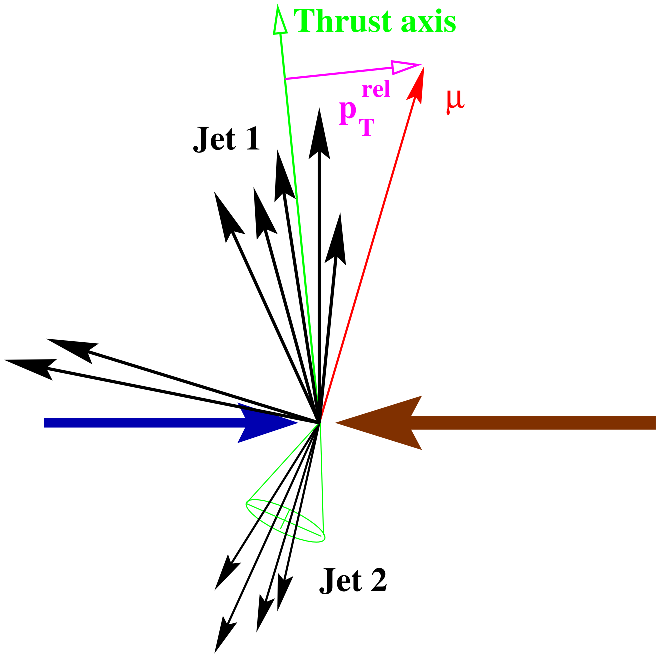
HERA 2000: Consistent quantitative picture of charm in ep arising

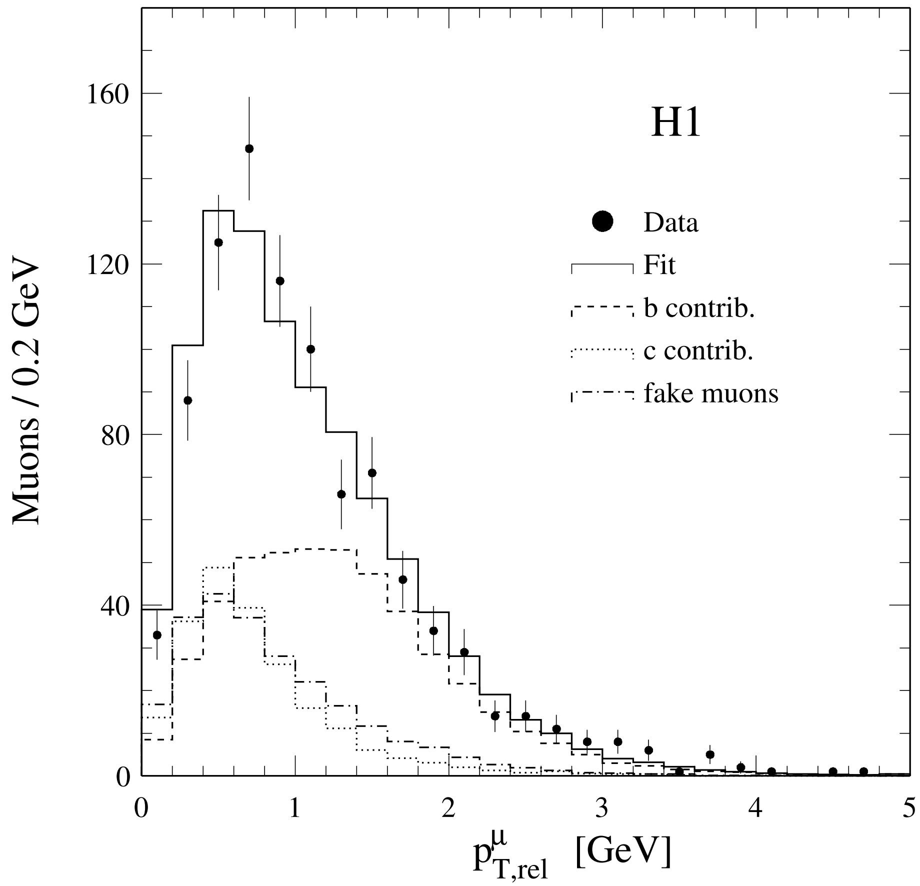
Main Uncertainties: – Experiment: Statistics

– Theory: Value of m_c

OPEN BEAUTY: Exploiting b Mass and Lifetime

b-mass: large relative $p_t^{\mathrm{rel},\mu}$



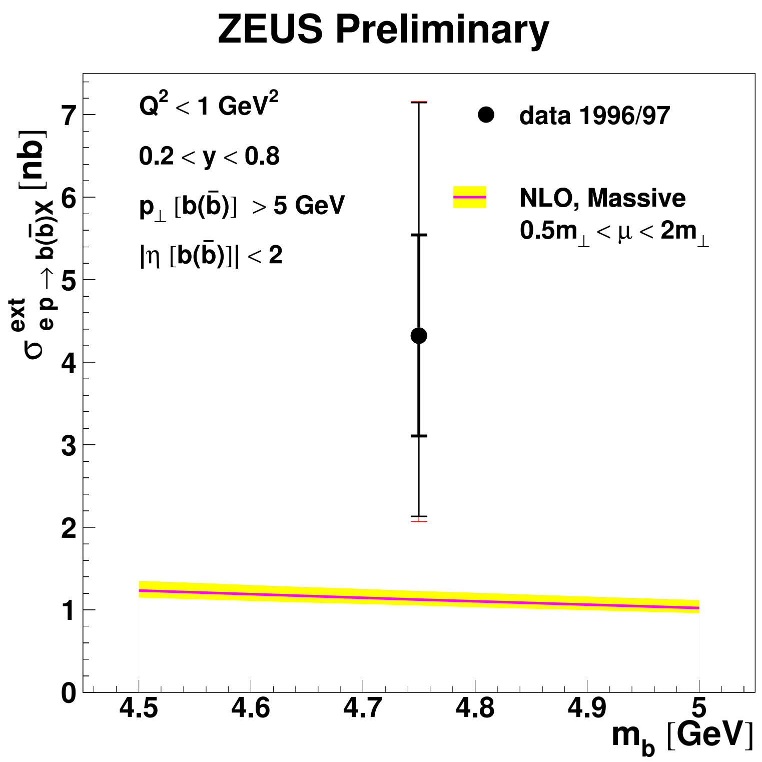


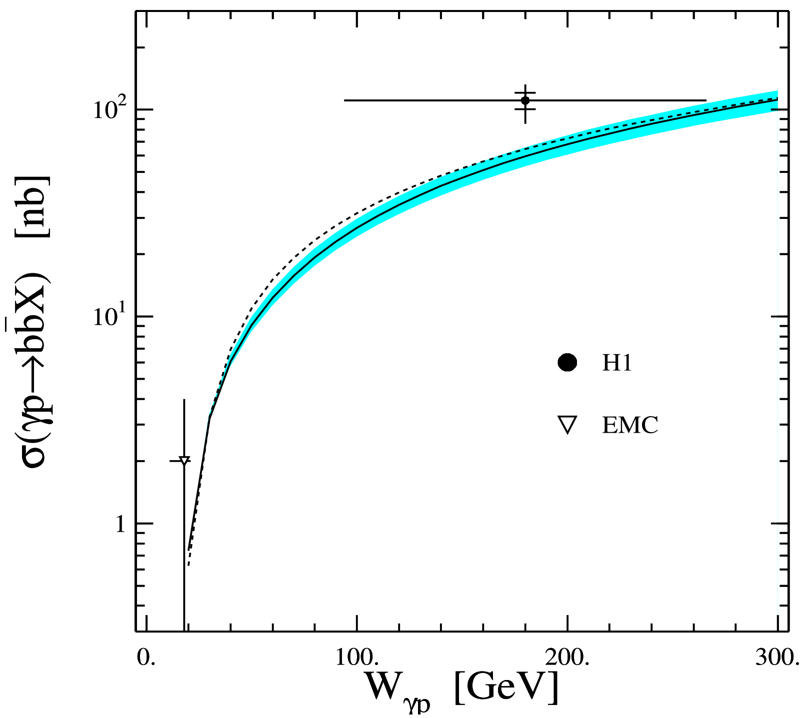
Event Selection:

- $\geq$ 2-Jets: $|\eta^{jet}| < 2.5$, $E_t > 5$ GeV
- $\geq$ 1 Muon: $p_t^{\mu} > 2.0$ GeV, $35^\circ < \theta^{\mu} < 130^\circ$
- Kinematic Range: $Q^2 < 1$ GeV^2, $0.1 < y < 0.8$

b cross sections in comparison with NLO QCD

- ZEUS (e channel)
- H1 (μ channel)





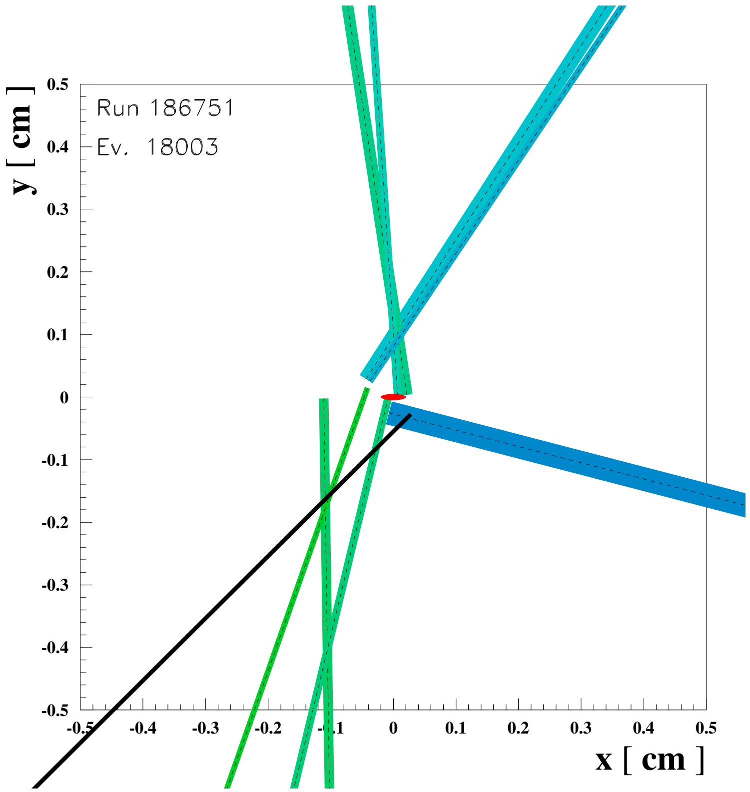
$$\sigma_{ext}(ep \to eb\bar{b}X) =$$
$$[4.3 \pm 1.2(\mathrm{stat.})^{+2.6}_{-1.8}(\mathrm{syst.})^{+0.3}_{-0.5}(\mathrm{ext.})]\ \mathrm{pb}$$

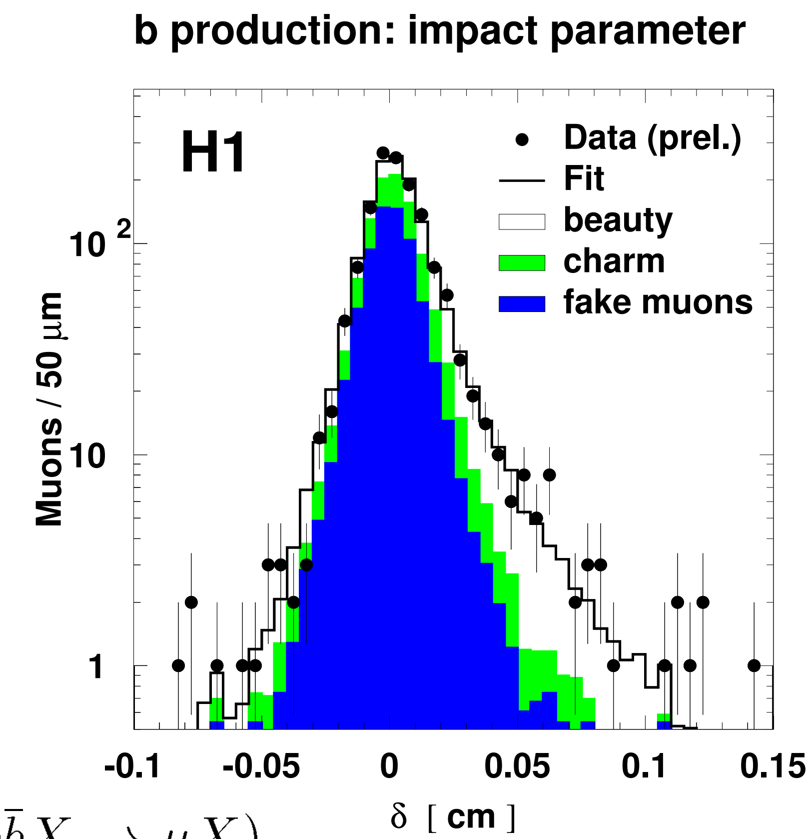
$$\sigma(\gamma p \to b\bar{b}X) =$$
$$[111 \pm 10(\mathrm{stat.})^{+23}_{-20}(\mathrm{syst.})]\ \mathrm{pb}$$

Data consistently higher than NLO QCD expectation

New Measurement Using Lifetime

- H1: 2-layer silicon vertex detector





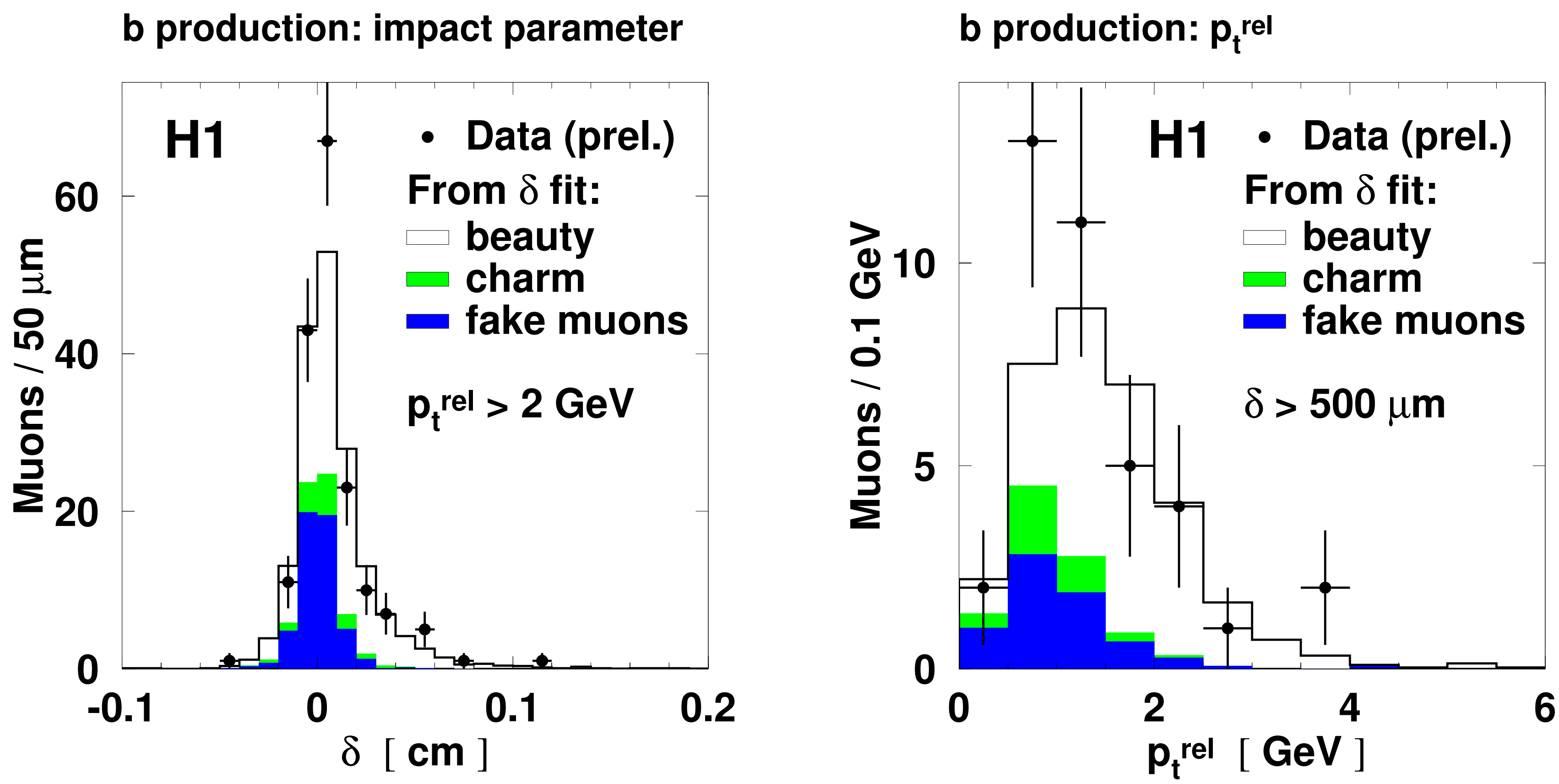
$$\sigma_{vis}(ep \to eb\bar{b}X \to \mu X)$$

Published H1 ($p_t^{\mathrm{rel},\mu}$ only): $[176 \pm 16(\mathrm{stat.})^{+26}_{-17}(\mathrm{syst.})]$ pb

New H1 (impact parameter only): $[159 \pm 30(\mathrm{stat.}) \pm 29(\mathrm{syst.})]$ pb

Independent Systematics: Confirming published Results

High b-purity: Lifetime and $p_t^{\text{rel},\mu}$ combined



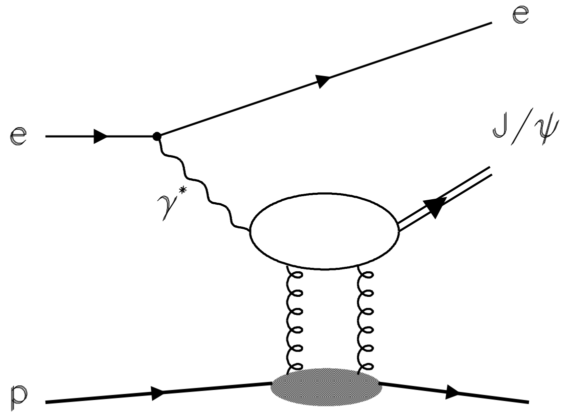
Combined Likelihood Fit in $p_t^{\text{rel},\mu}$ and δ:

$$\sigma_{vis}(ep \to eb\bar{b}X \to \mu X) = [160 \pm 16(\text{stat.}) \pm 29(\text{syst.})] \text{ pb}$$

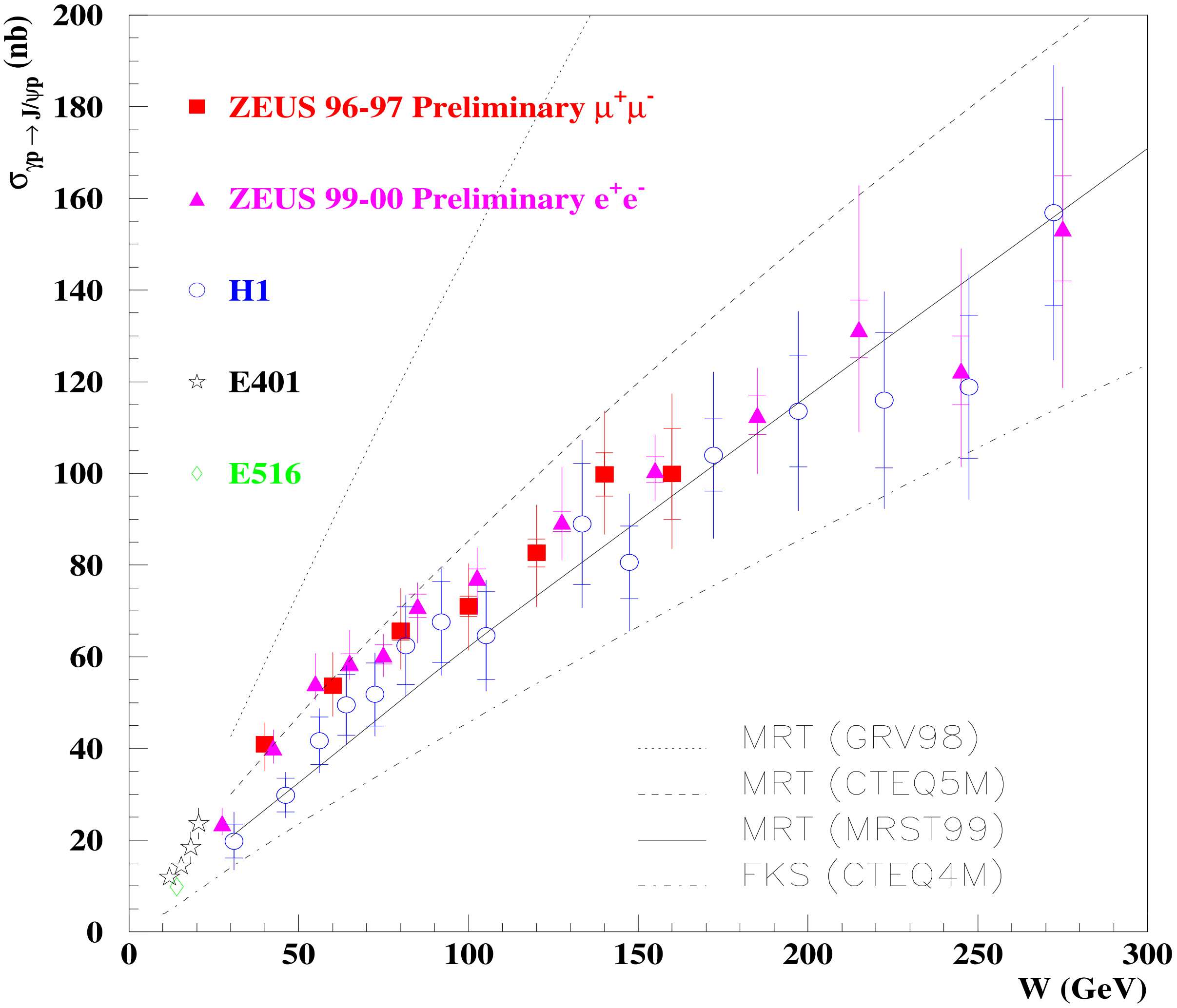
H1 Combined: $[170 \pm 25]$ pb ; NLO pQCD (FMNR): $[104 \pm 17]$ pb

HERA 2000: b-cross sections somewhat larger than expectation

Elastic Quarkonium Production at HERA



LO: $\sigma \propto |xg(x)|^2$



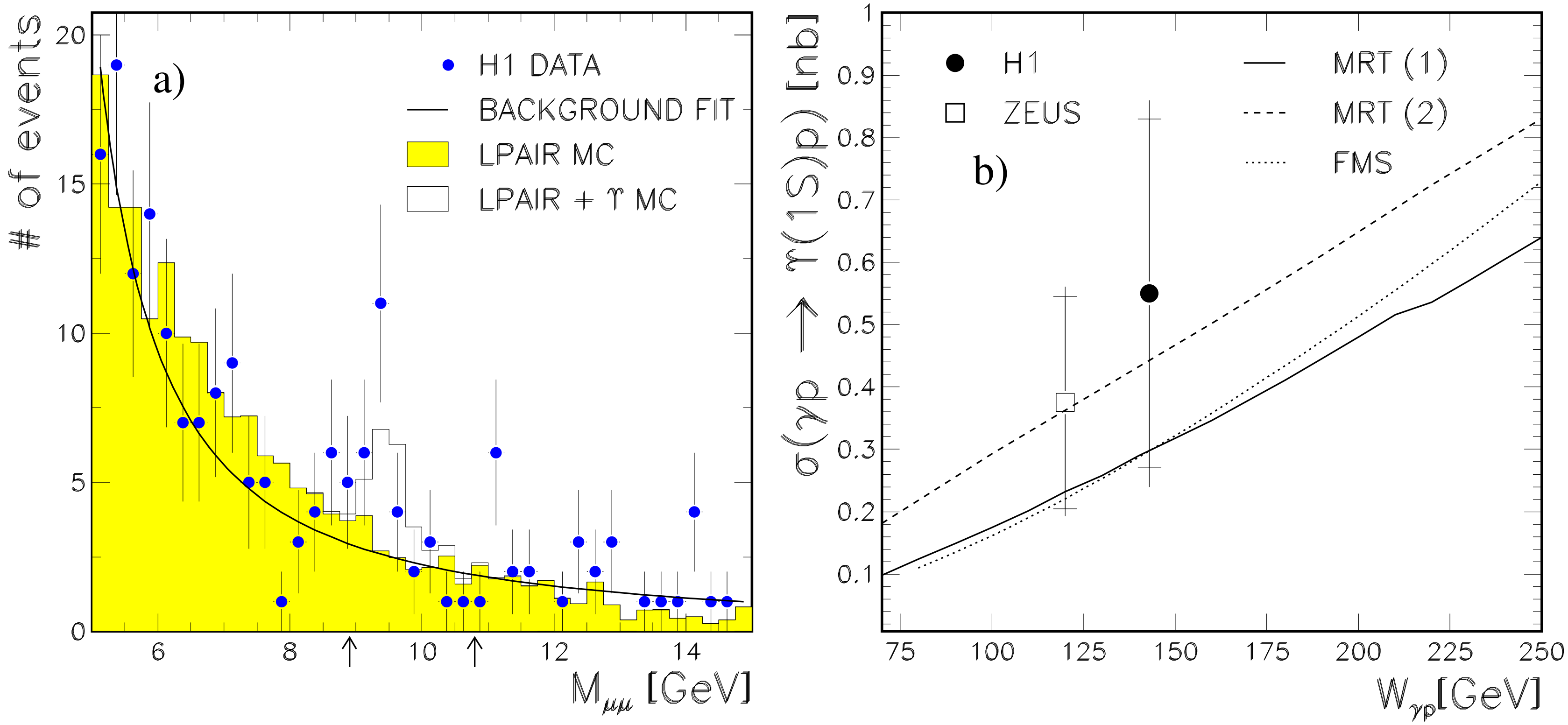
steep rise at $Q^2 \sim 0$: m_c is hard scale

QCD: $\sigma_{\gamma p} \propto W^\delta$, $\delta \sim 0.83$(H1), ~ 0.65(ZEUS)

slope δ: highly sensitive on input $xg(x)$

reproduced by QCD models

Elastic Υ Production



Cross section magnitude: Understood in pQCD

Differential measurements: Need more luminosity

Summary

Heavy Flavour Physics at HERA

– Charm: 25% of total cross section

– Direct probe of gluons in proton

Open Charm: Precision data available

– Tests of QCD: quantitative understanding being established

– CCFM evolution: new insights in low-x parton dynamics ?

Open Beauty: Statistics still low

– Cross section somewhat larger than expectation

– New measurement using lifetime tag confirms previous results

Elastic Charmonium: $\sigma \propto |xg(x)|^2$

– QCD taking control

QCD works well over large region

$\mathcal{L}$-upgraded HERA-II: Much more data

Heavy Flavour Physics will play a major role