Heavy Flavour Results from HERA
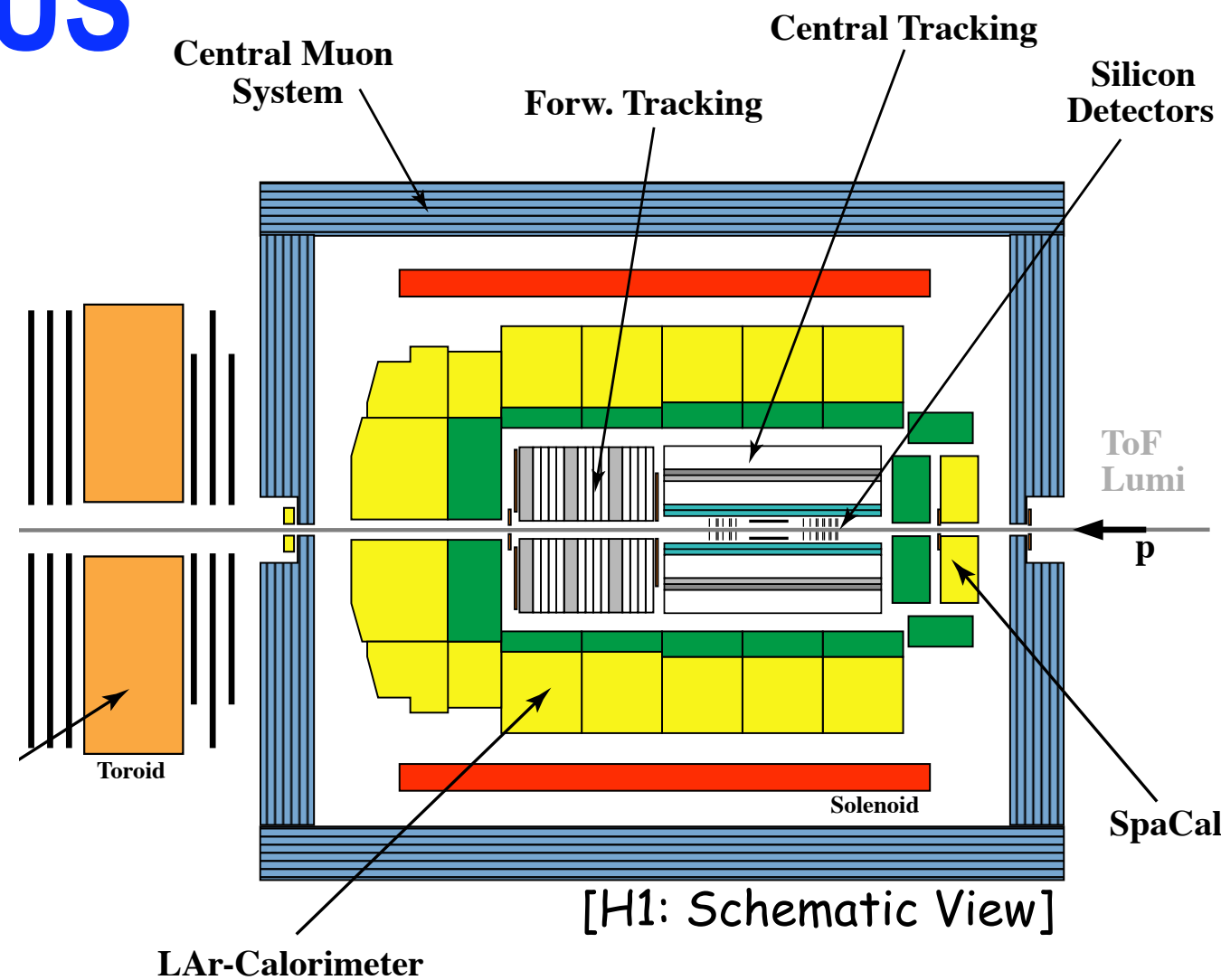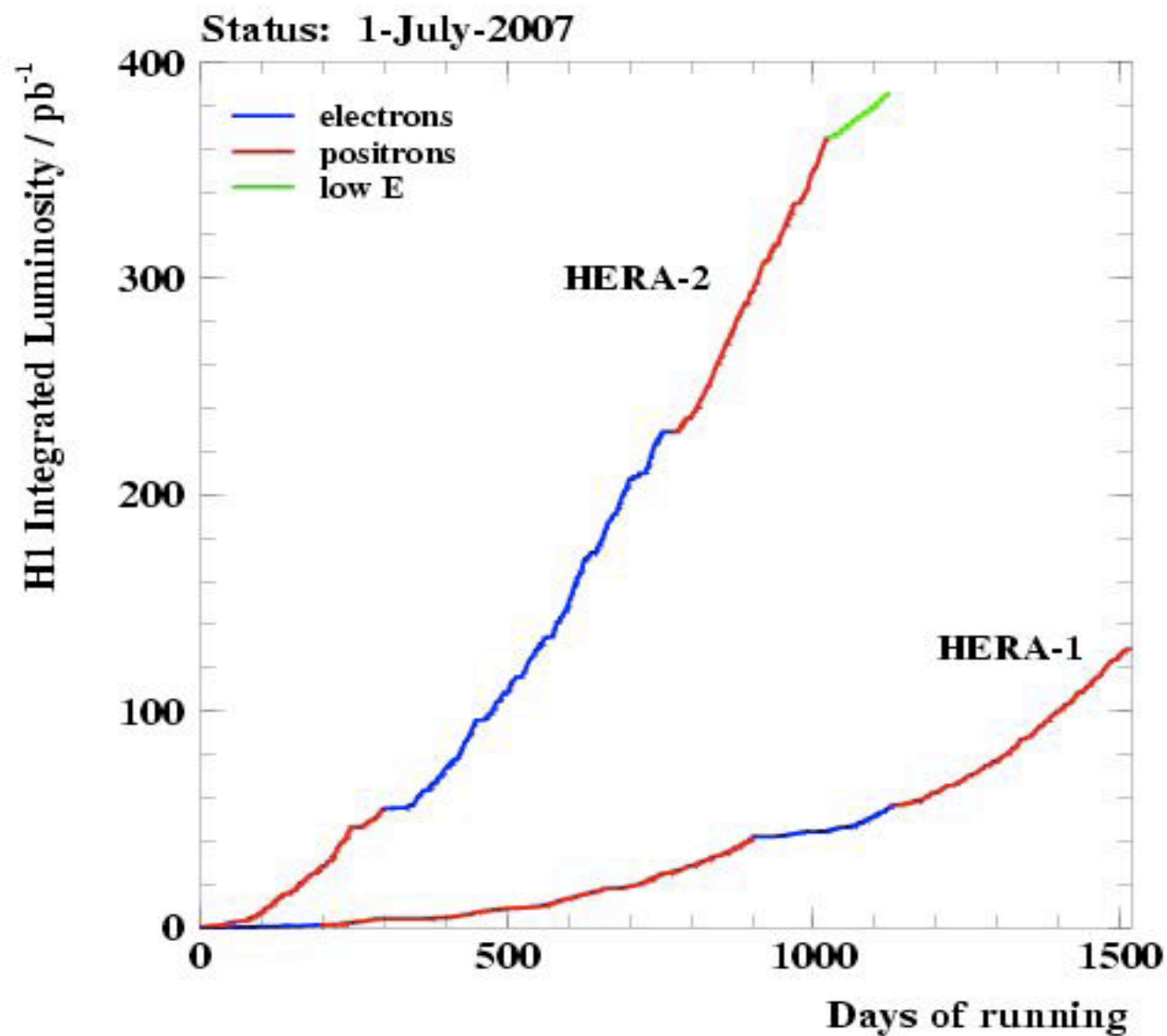

Andreas B. Meyer

The HERA Electron Proton Storage Ring

p: 920 GeV

e: 27.5 GeV

HERA

PETRA

Experiments — H1, ZEUS

Status: 1-July-2007

H1 Integrated Luminosity / pb^{-1}

- electrons
- positrons
- low E

HERA-2

HERA-1

Days of running

Central Muon System

Forw. Tracking

Central Tracking

Silicon Detectors

Toroid

LAr-Calorimeter
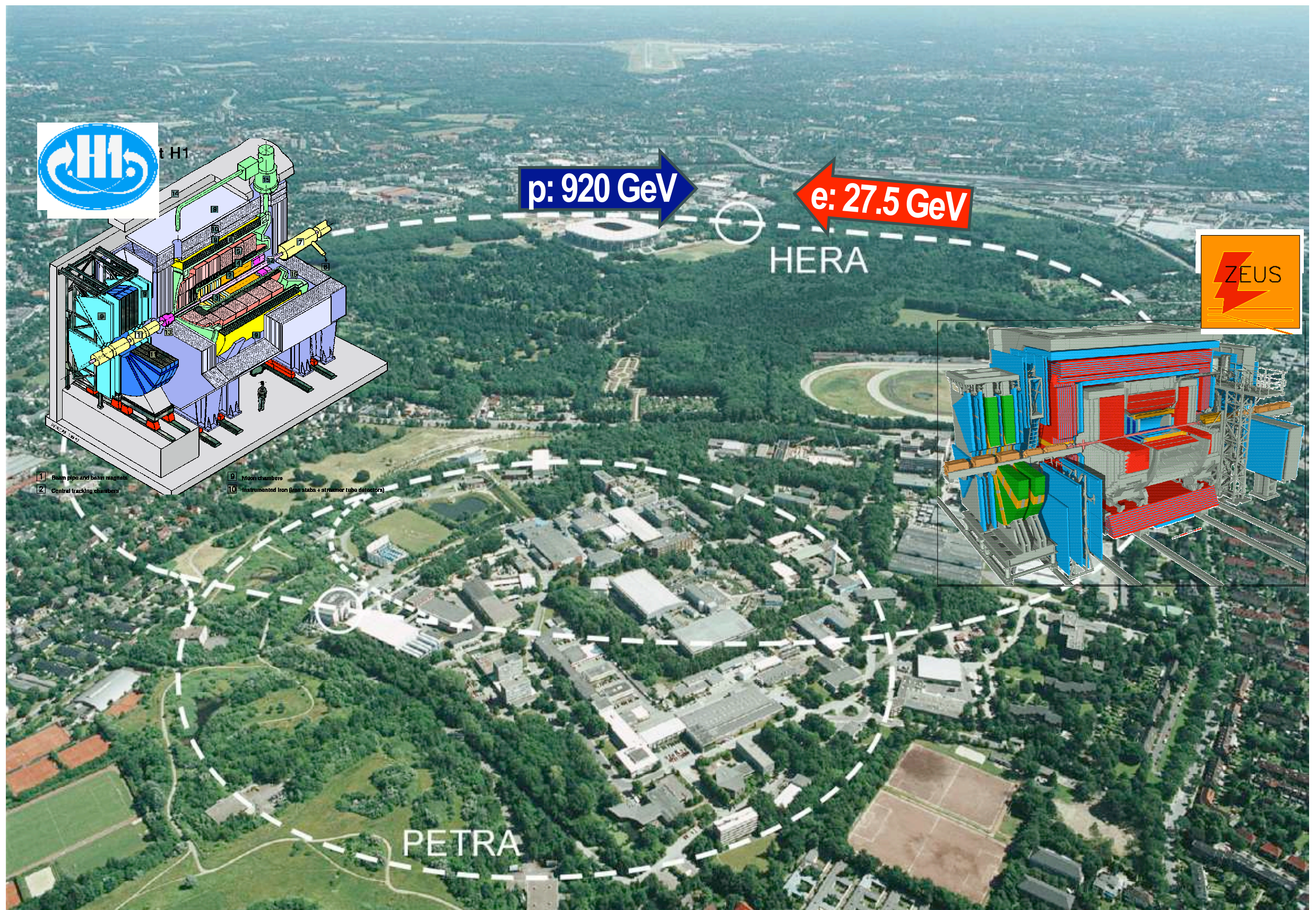
[ZEUS Collaboration]

Integrated Luminosity HERA-I + II: ~500 pb^{-1} per Experiment

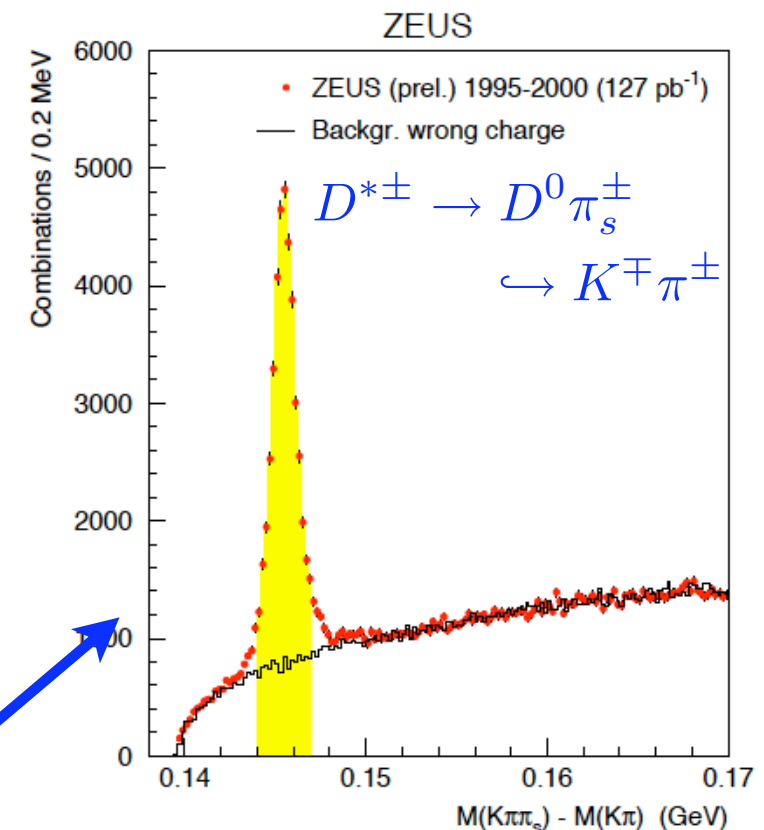**HERA-II: Both Experiments equipped with Silicon Vertex Detectors**

Heavy Quark Production

Multiple Hard Scales: $m_{c,b}$, Q^2, p_t

Q2 ~ 0: Photoproduction
Q2 > 5: DIS

Running coupling α_s

$\alpha_S(\mu)$

$c \rightarrow$
$b \rightarrow$
$0.1 \rightarrow$

m_c m_b

e

e

γ

Q^2

$\sqrt{\alpha_s}$

c, b

BGF Matrix Element

$\bar{c}$, $\bar{b}$

g

μ

p

X
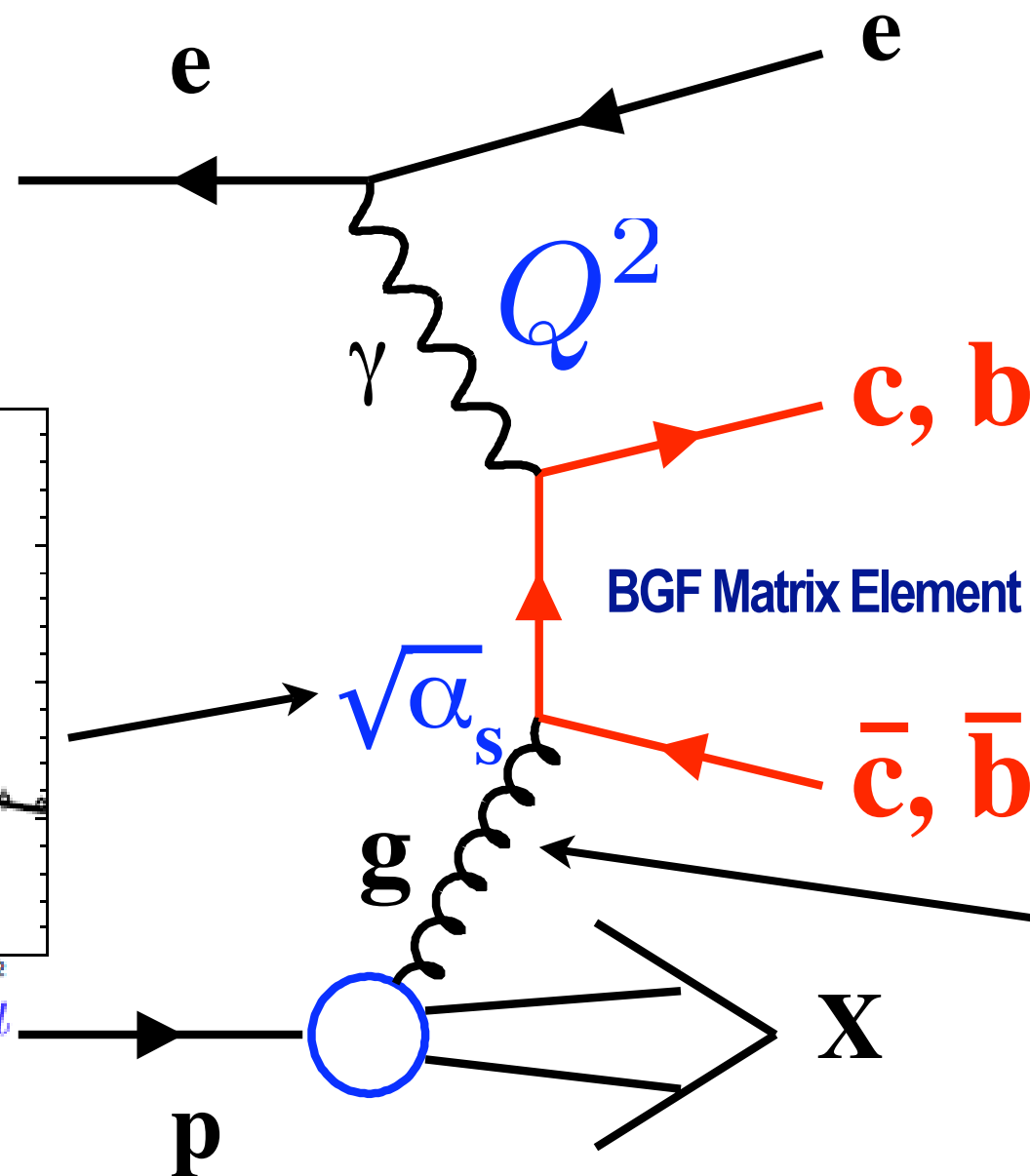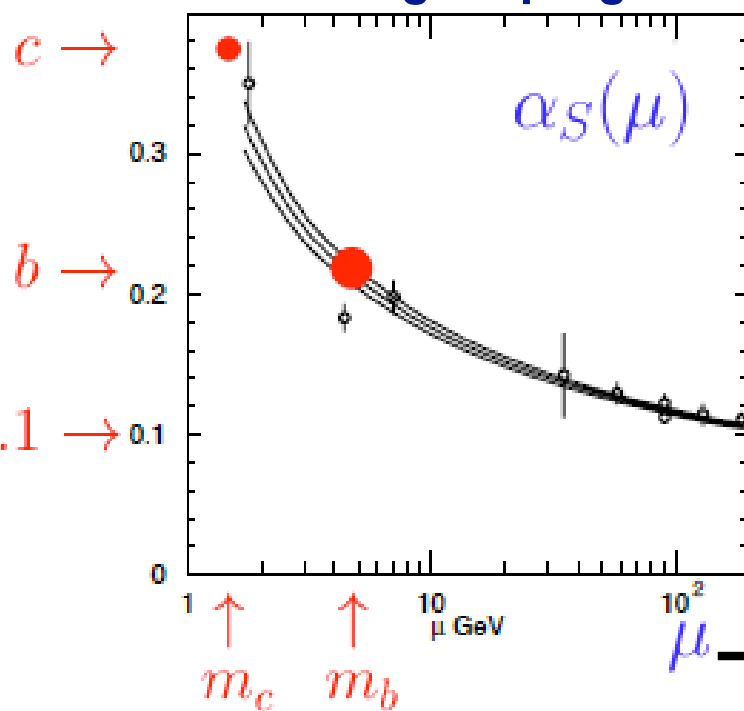
$D^{*\pm} \rightarrow D^0 \pi_s^{\pm}$
$\hookrightarrow K^{\mp} \pi^{\pm}$

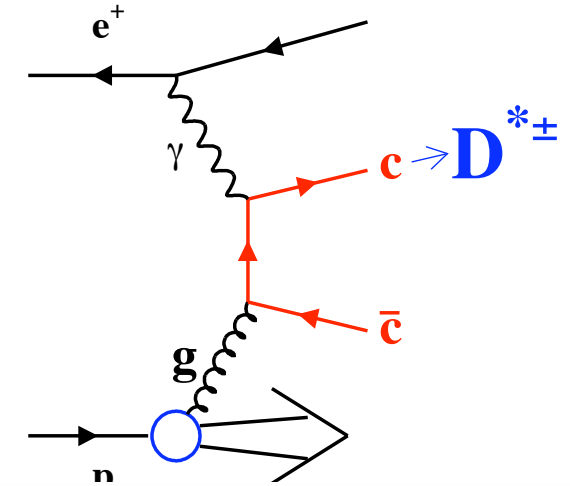**Quark Fragmentation**
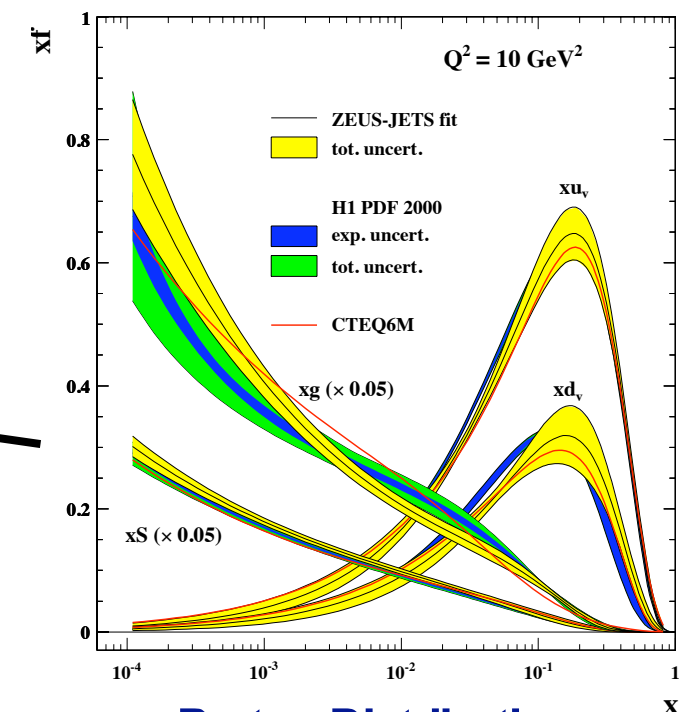
Parton Distributions

Probe of perturbative QCD:
Test factorization / universality of calculable and non-calculable components

D* Production

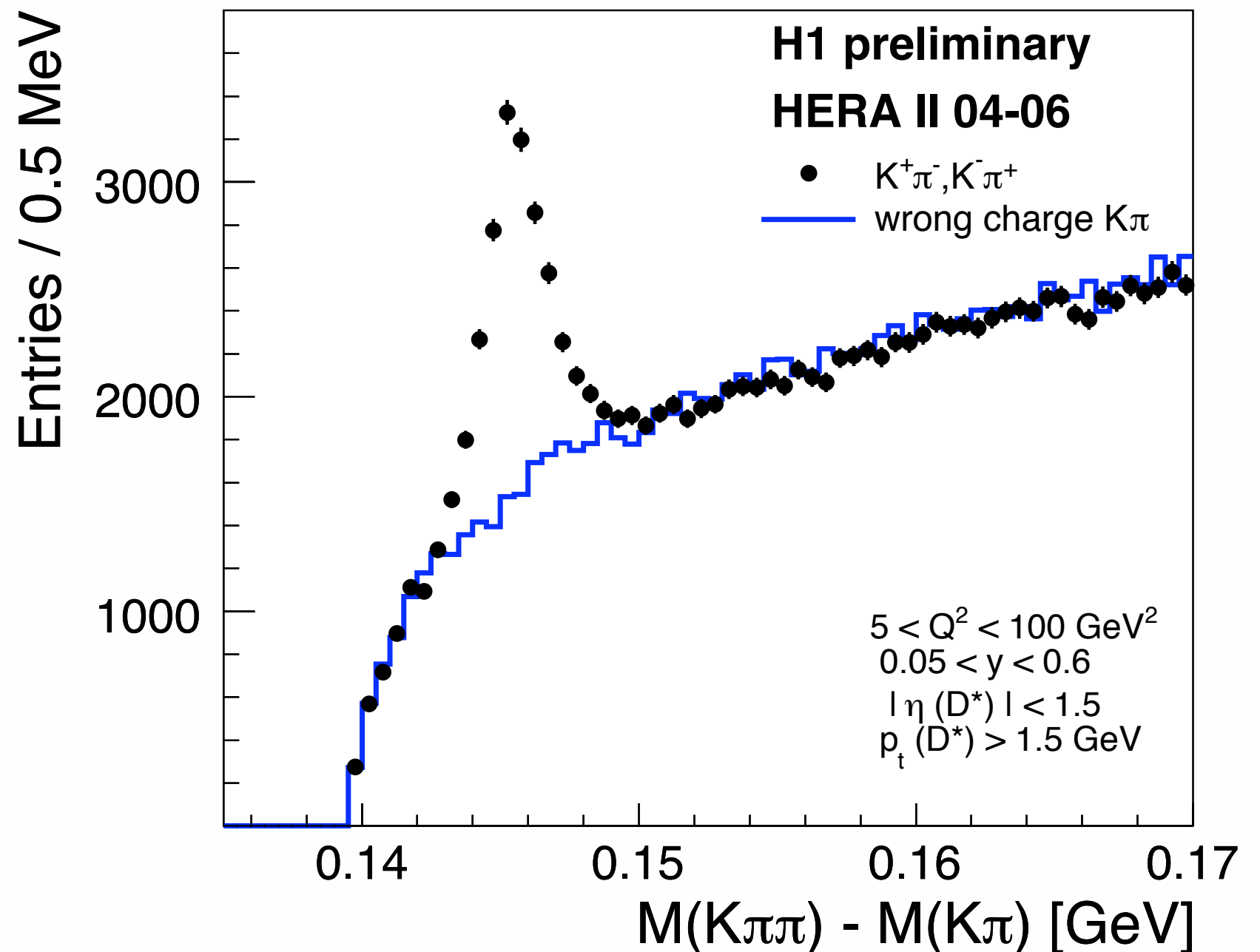$$D^{*\pm} \to D^0 \pi_s^{\pm}$$
$$\hookrightarrow K^{\mp} \pi^{\pm}$$

- **Cross section measured in experimentally visible range:**
  - $Q^2 > 5$ GeV^2
  - $0.05 < y < 0.6$
  - $p_t(D^*) > 1.5$ GeV
  - $|\eta(D^*)| < 1.5$

- **H1 analyzed data set:**
  - $\int L dt \sim 220$ pb^{-1}
  - ~10000 Signal D*

H1 preliminary
HERA II 04-06

- $K^+\pi^-, K^-\pi^+$
— wrong charge $K\pi$

$5 < Q^2 < 100$ GeV^2
$0.05 < y < 0.6$
$|\eta(D^*)| < 1.5$
$p_t(D^*) > 1.5$ GeV

Entries / 0.5 MeV

M($K\pi\pi$) - M($K\pi$) [GeV]

D* Production Cross Sections
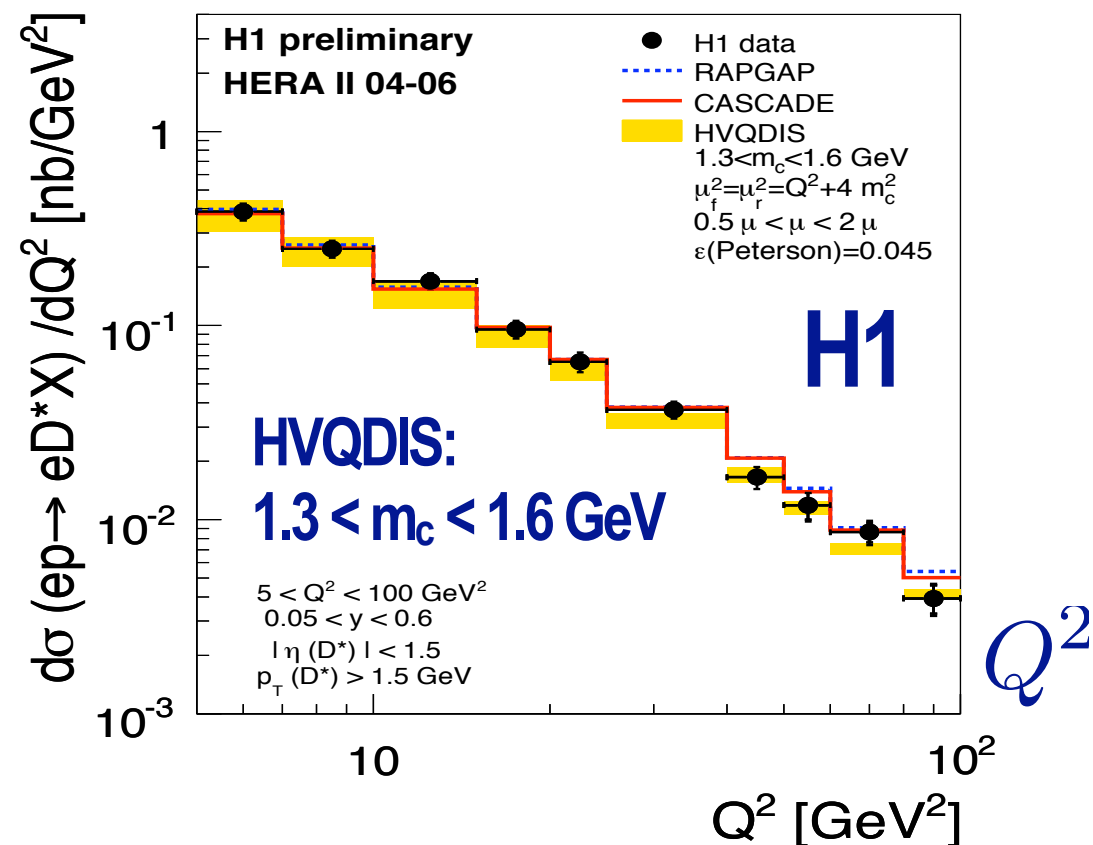
- **Theory calculations all describe data rather well ...**
  - **RAPGAP-MC (DGLAP LO+PS)**
  - **CASCADE-MC (CCFM LO+PS)**
  - **HVQDIS (DGLAP NLO)**
- **... with significant scale uncertainties (order of ±15%)**
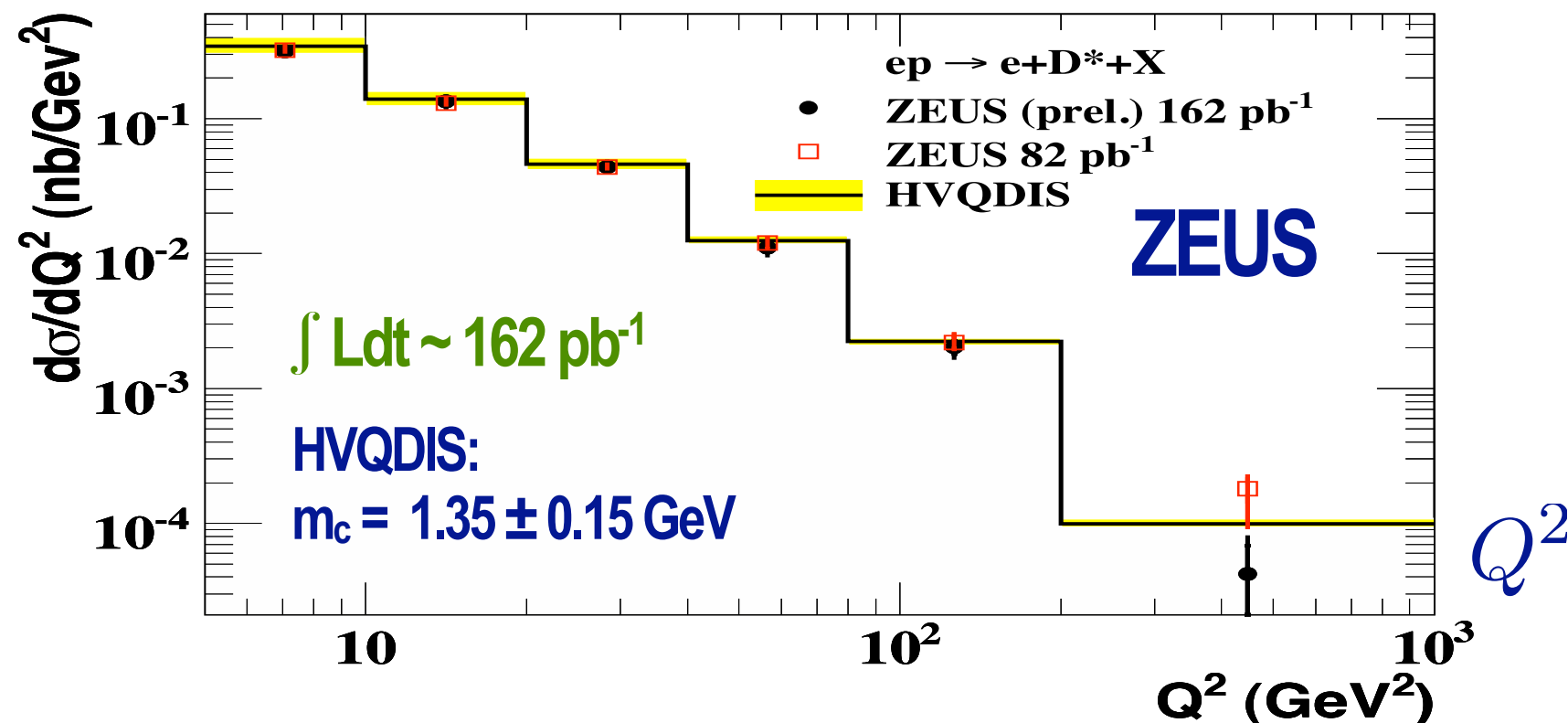
D* Production Cross Sections

Experimental uncertainties generally smaller than scale uncertainties
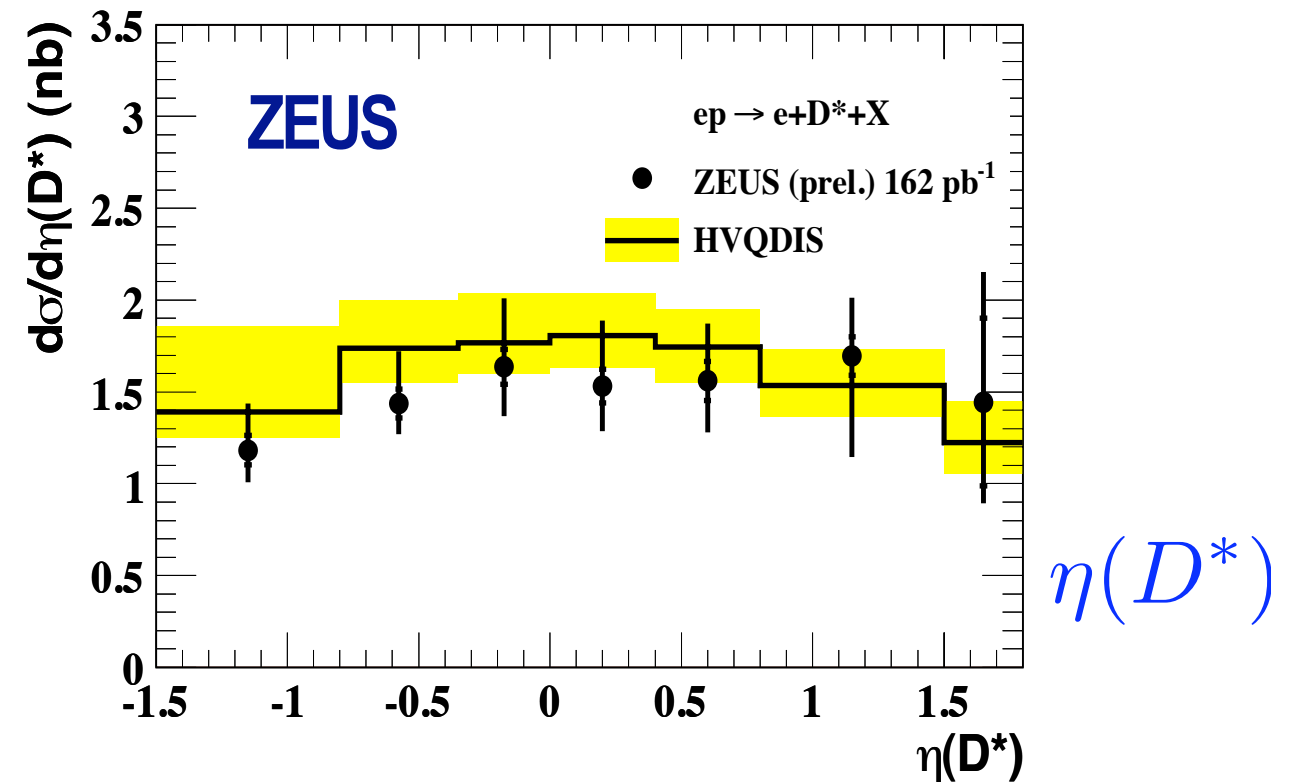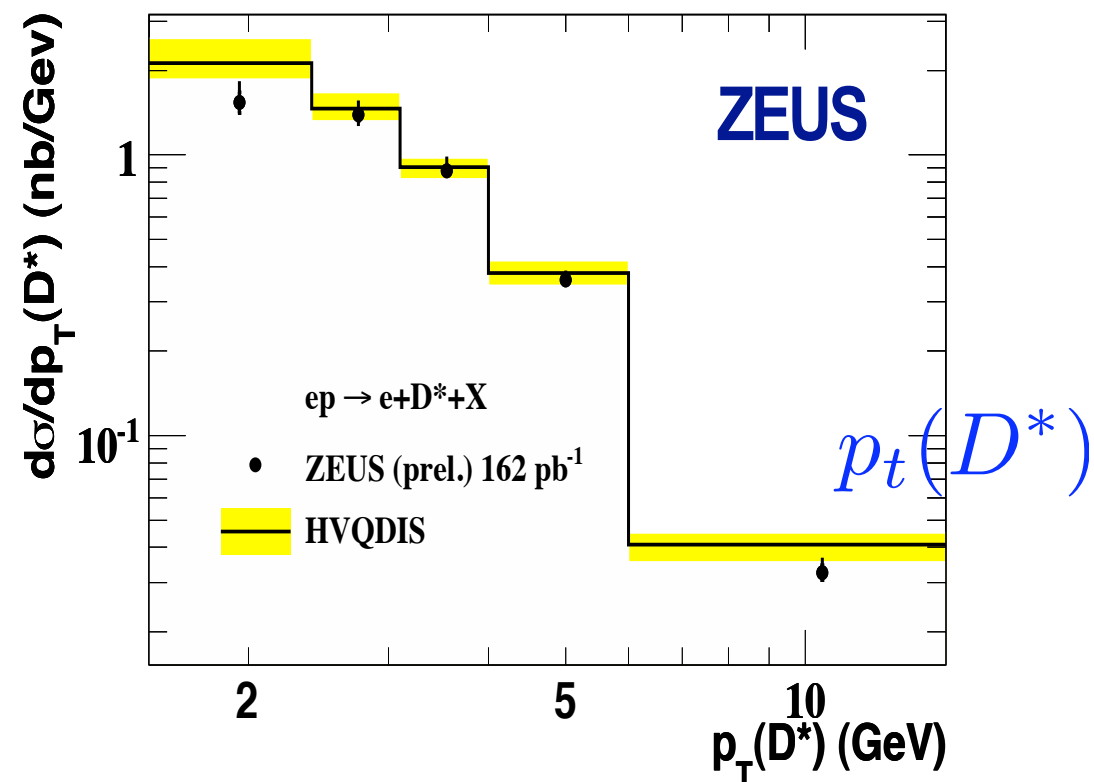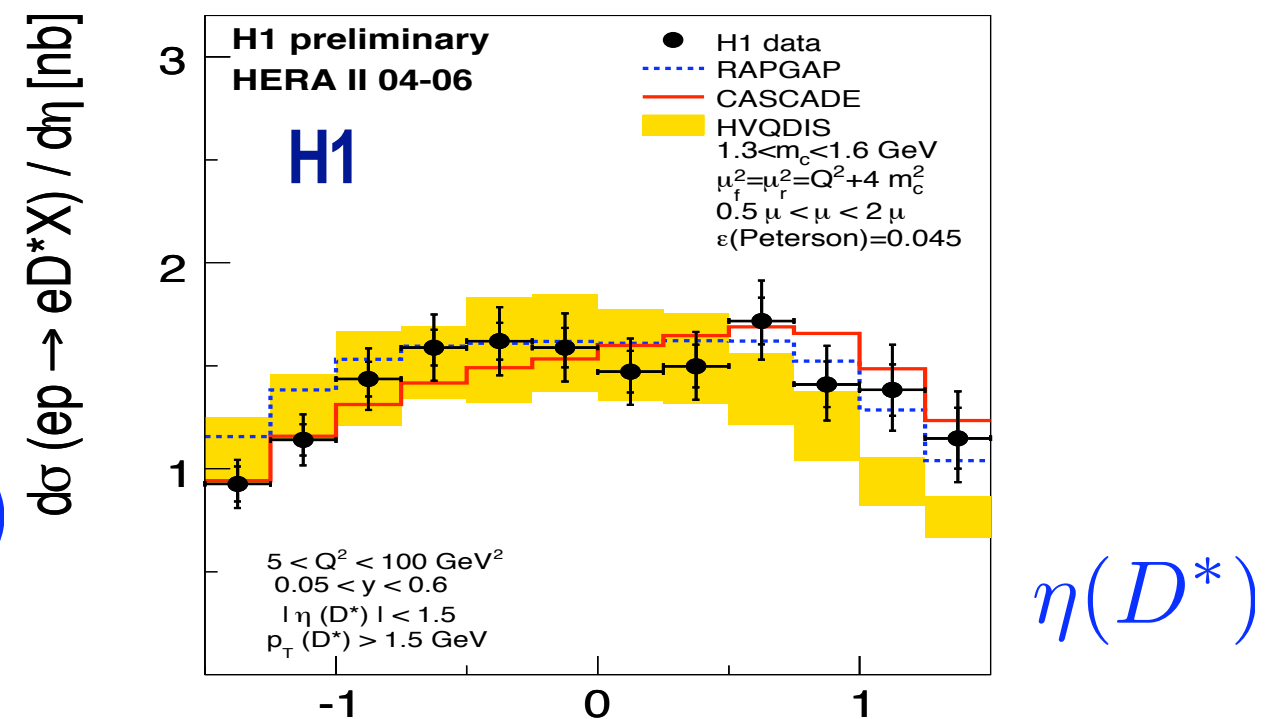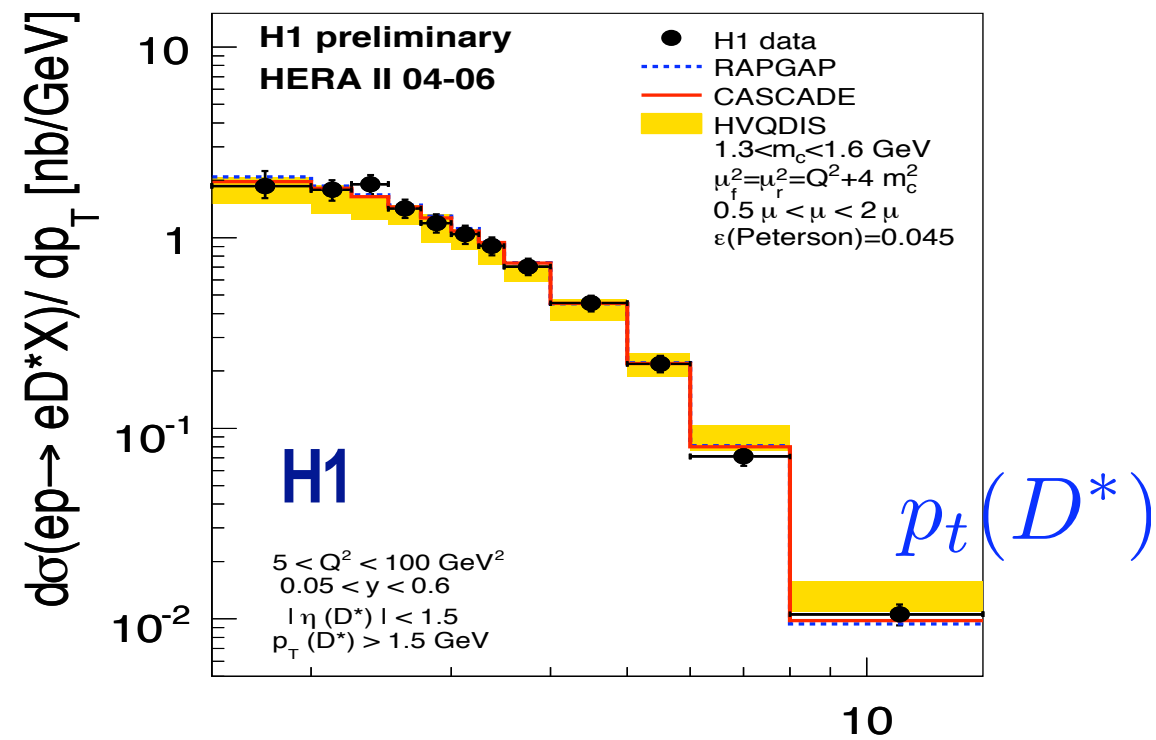
Measurement of D⁺-Mesons

BOTTOM MICRO VERTEX DETECTOR

ZEUS

$ep \rightarrow e + D^{\pm} + X$

Gauss^{mod} + p1

• ZEUS (prel.) 135 pb^{-1} HERA II

$N(D^{\pm})$: 4421 ± 341

$M(K\pi\pi)$ M(Kππ) (GeV)

$D^+ \rightarrow K^- \pi^+ \pi^+$

ZEUS

$ep \rightarrow e + D^{\pm} + X$

$N(D^{\pm})$: 2181 ± 83

2D S$_{DL}$ > 3

Gauss^{mod} + p1

• ZEUS (prel.) 135 pb^{-1}

HERA II

$\ell/\sigma_\ell > 3$

$M(K\pi\pi)$ M(Kππ) (GeV)

ZEUS

$ep \rightarrow e + D^{\pm} + X$

▲ ZEUS 65 pb^{-1} HERA I

● ZEUS (prel.) 135 pb^{-1} HERA II

▬ NLO + Fragmentation

▬ ▬ beauty contribution (RAPGAP)

$\int L dt \sim 65$ pb^{-1}

Q^2

Q^2 (GeV^2)
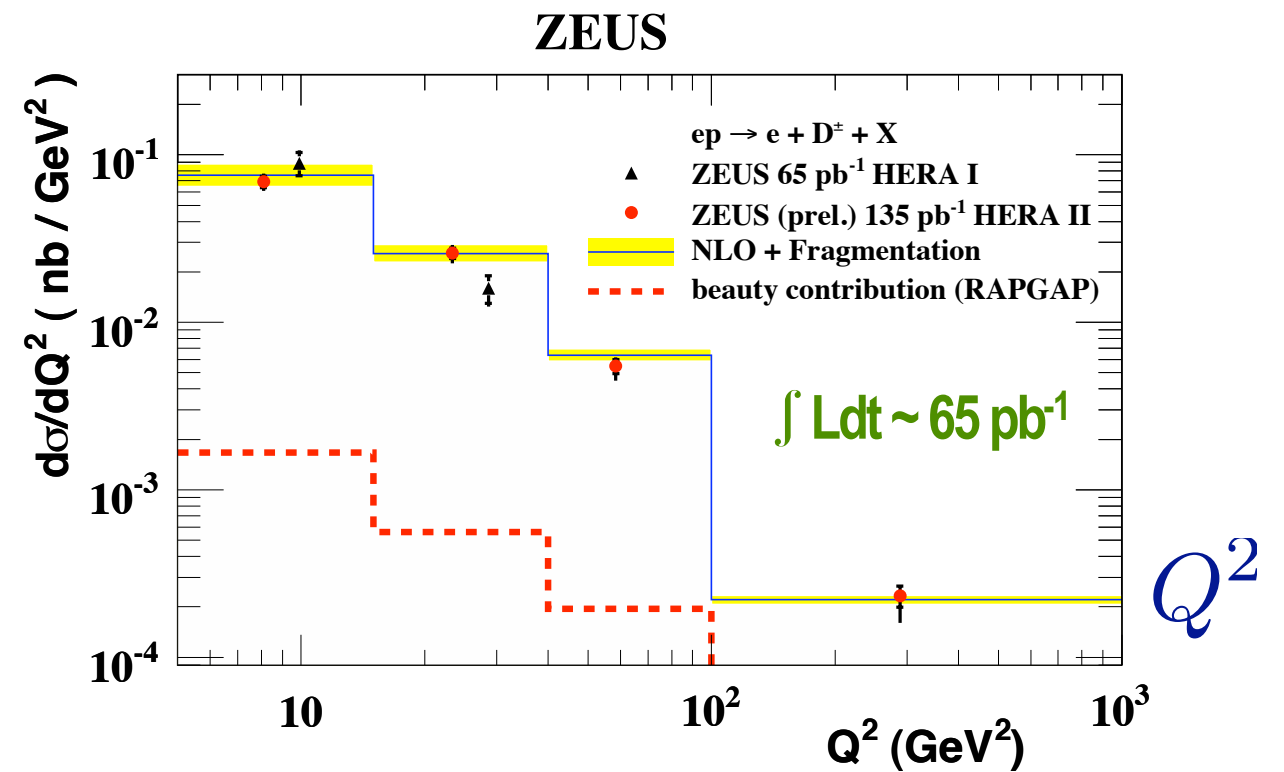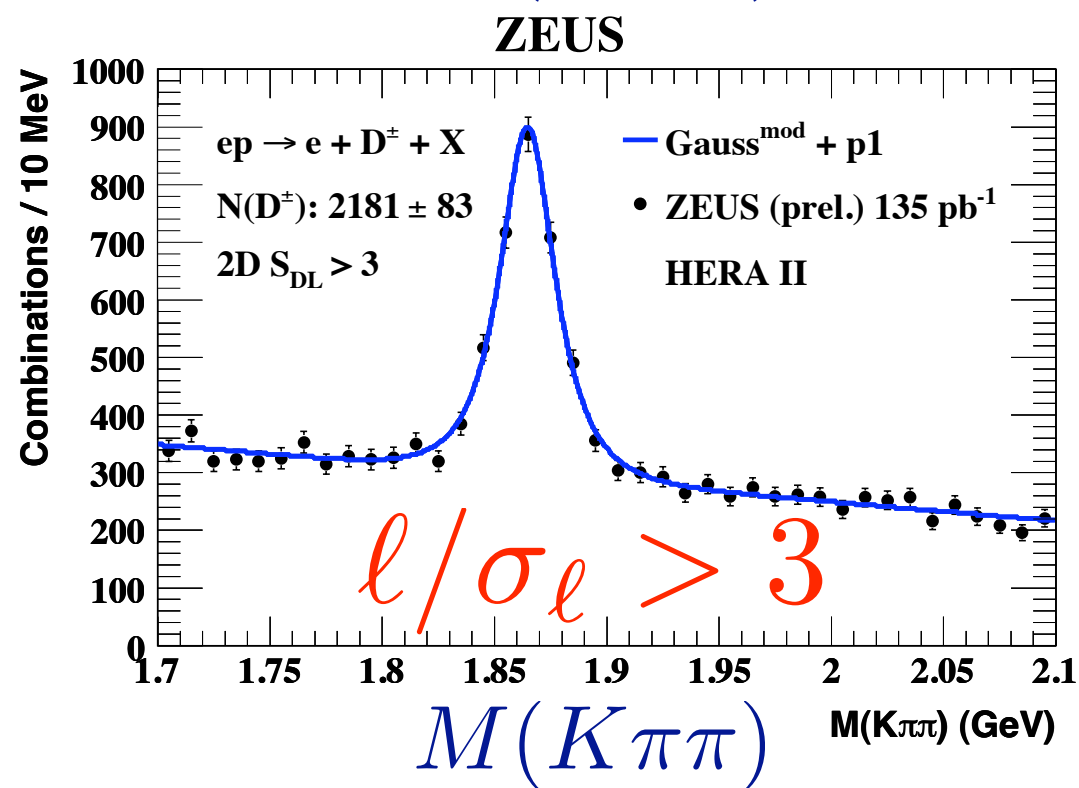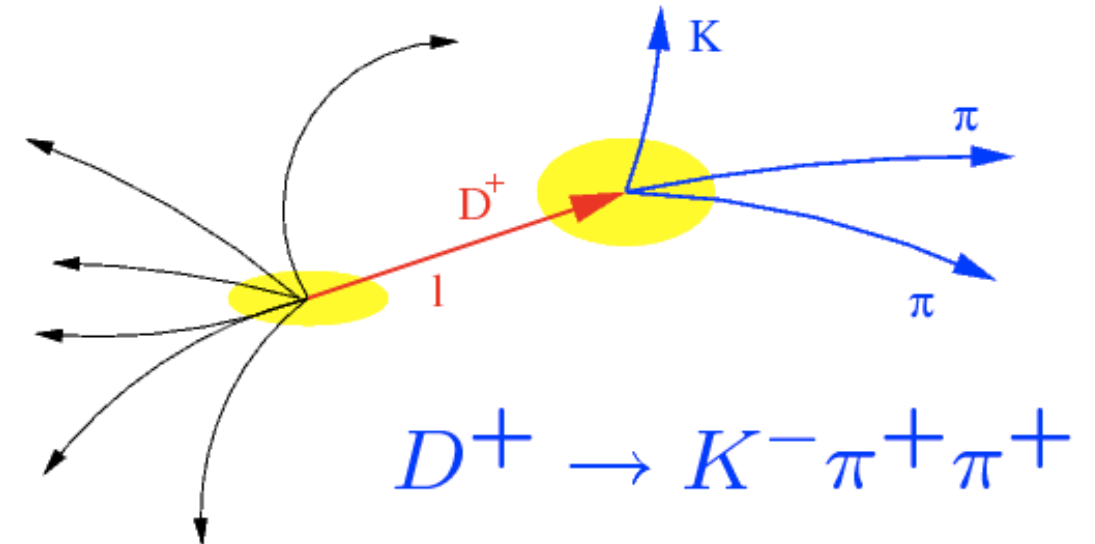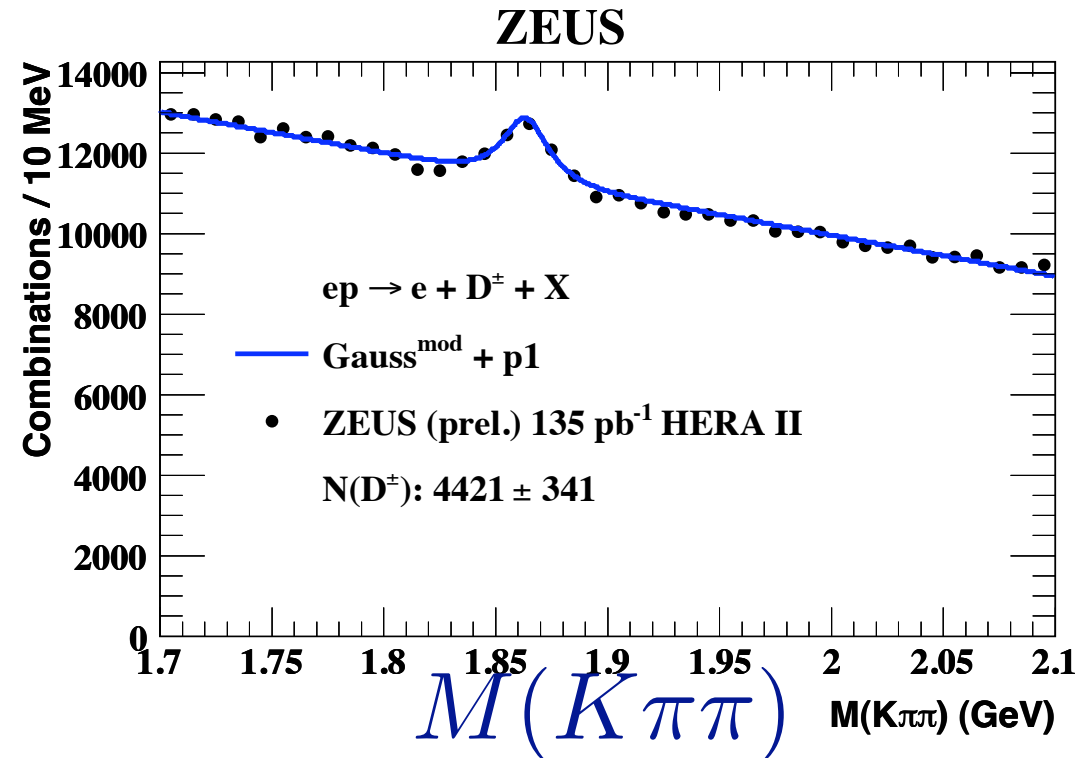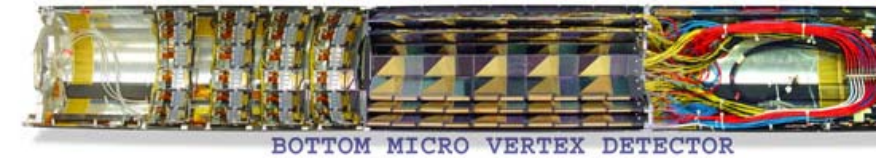
Lifetime tag enhancing charm signal / D⁺ cross sections consistent with expectation

Charm Fragmentation

$c \to D^{*\pm}$

Fractional momentum z(D*)
of D* meson w.r.t. c-quark

$c \to D^*$ or D^+, D_s, D^0, Λ_c

Fractional Rates f(c→D)

- ZEUS(prel.)120 pb^{-1} : $z \equiv (E+P)_{D^*}/2E_{jet}$
- H1(prel.) : $z \equiv (E+P_L)_{D^*}/\Sigma_{hem}(E+P)$
- ARGUS : $\sqrt{s}=10.6$ GeV, $z \equiv P_{D^*}/(E^2_{beam}-m^2_{D^*})^{1/2}$
- OPAL : $\sqrt{s}=91.2$ GeV, $z \equiv 2E_{D^*}/\sqrt{s}$
- CLEO : $\sqrt{s}=10.5$ GeV, $z \equiv P_{D^*}/P_{max}$
- BELLE : $\sqrt{s}=10.6$ GeV, $z \equiv P_{D^*}/P_{max}$

- f (c → D^0)
- f (c → D^+)
- f (c → D^{*+})
- f (c → D_s^+)
- f (c → Λ_c^+)

(b)

ZEUS DIS   ZEUS γp   H1 DIS   e$^+$e$^-$
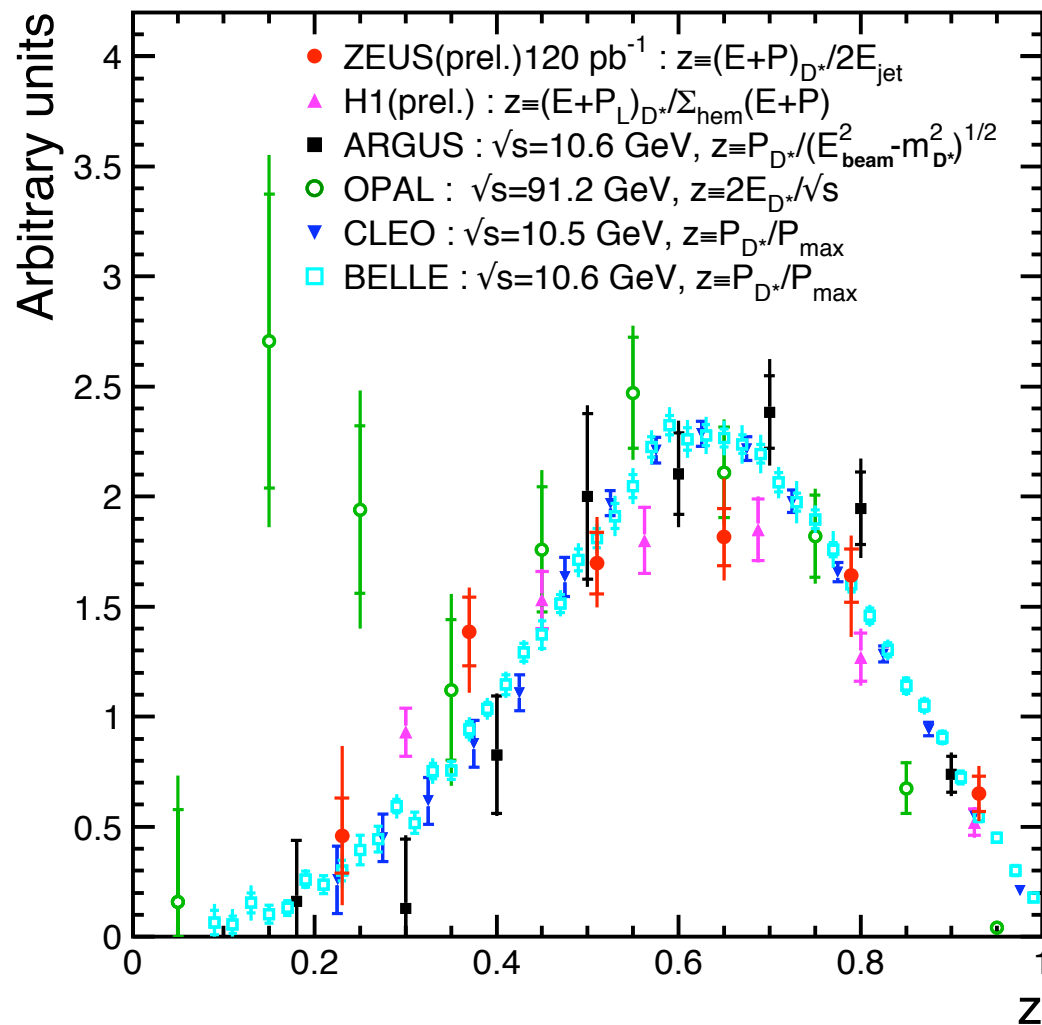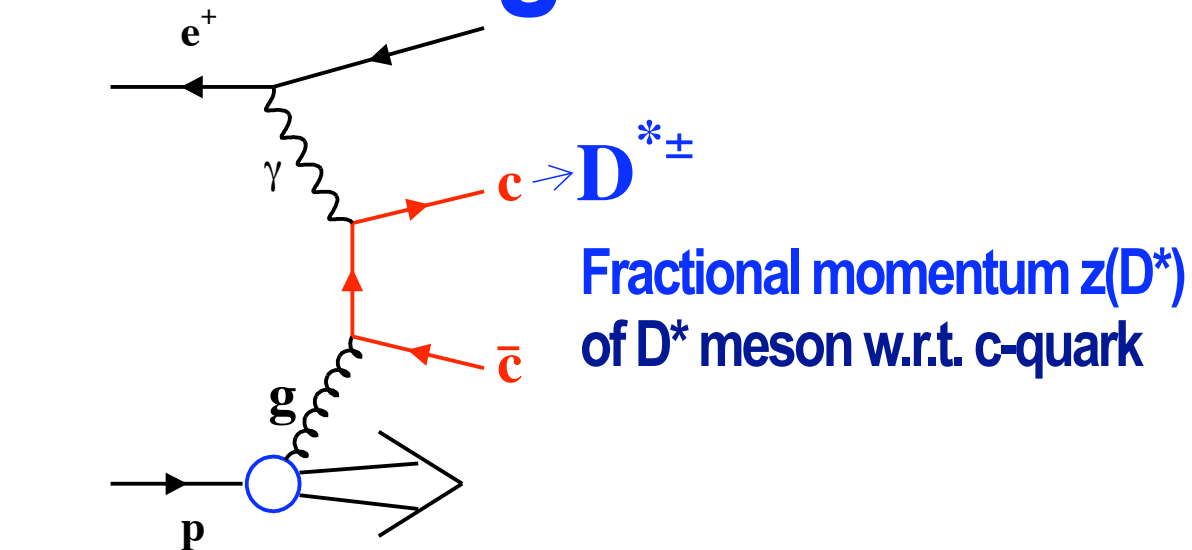
Data from various experiments agree qualitatively: **Universality of Charm Fragmentation**
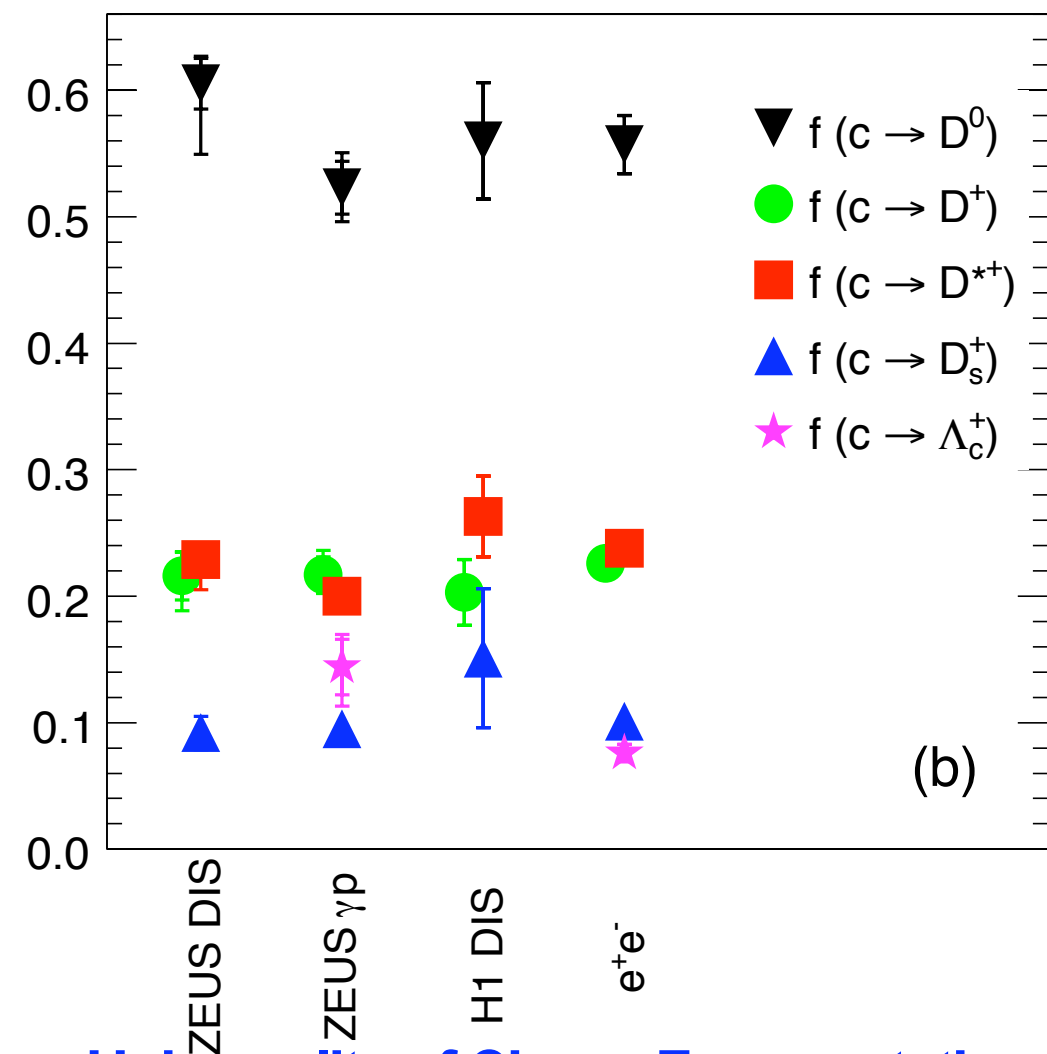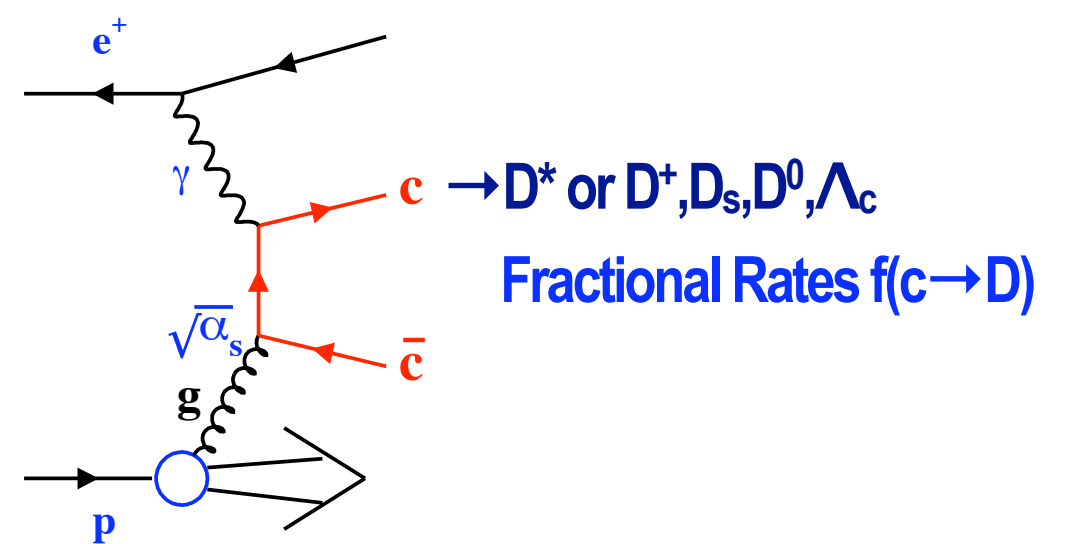
Heavy Quark Contribs. to Inclusive X-Section

Charm and Beauty structure functions $F_2^{c\bar{c}}$ **and** $F_2^{b\bar{b}}$

In analogy to inclusive structure function:

$$\frac{d^2\sigma^{ep}}{dx\,dQ^2} \propto F_2(x,Q^2)$$

define proton structure function for charm contribution

$$\frac{d^2\sigma^{ep \to c\bar{c}X}}{dx\,dQ^2} \propto F_2^{c\bar{c}}(x,Q^2)$$
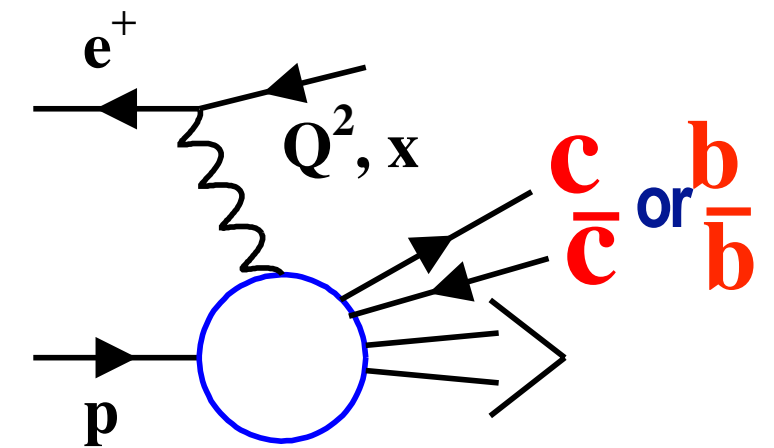
Charm: help constrain gluon density g(x)
Beauty: help predict b-cross section at LHC

H1 Data

x = 0.0002   x = 0.0005

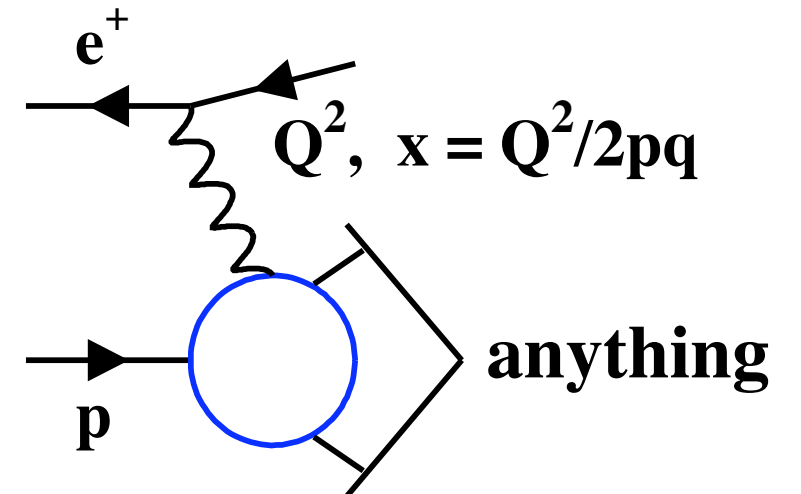MRST04 $f^{c\bar{c}}$
MRST04 $f^{b\bar{b}}$

x = 0.002   x = 0.005

x = 0.013   x = 0.032

H1 Data (High Q^2)
$f^{c\bar{c}}$ $f^{b\bar{b}}$

$f^{b\bar{b}}$

10^{-1}
10^{-2}
10^{-3}

10 10^2 10^3 10 10^2 10^3
Q^2 / GeV^2 Q^2 / GeV^2

$F_2^{c\bar{c}}/F_2$

Q^2, x = Q^2/2pq

Um $F_2^{c\bar{c}}$ zu bestimme
vollem $P_T(D^*)$, $\eta(D^*)$

anything

Q^2, x

$\dfrac{c}{\bar{c}}$ or $\dfrac{b}{\bar{b}}$

$F_2^{b\bar{b}}/F_2$

HERA   LHC

Q=30 GeV   m(h)= 120 GeV

Inclusive Lifetime Tag

Measurement of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$

- H1 Data (Prel.)
- Total MC
- uds
- c
- b

H1

Significance S_2

S_2

$n(S_2) - n(-S_2)$

- H1 Data (Prel.)
- Total MC
- uds
- c
- b

H1   Significance S_2

S_2

e^+

γ

c,b → charged particle

$\bar{c},\bar{b}$

p
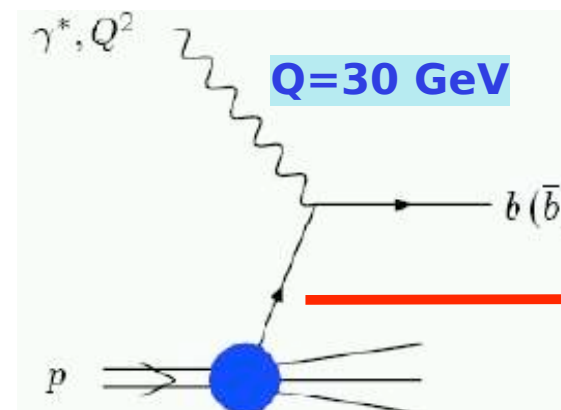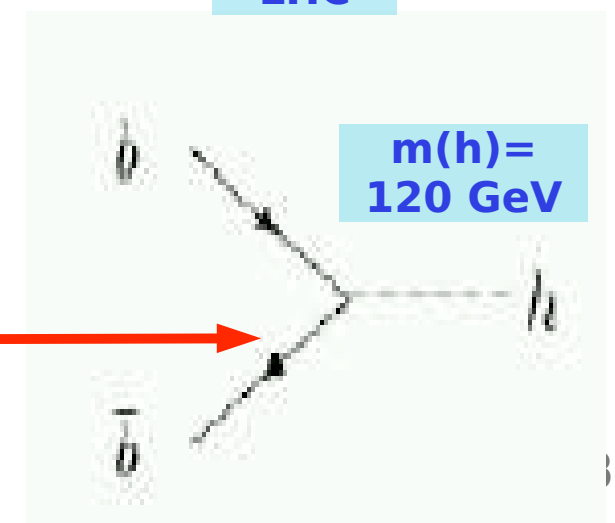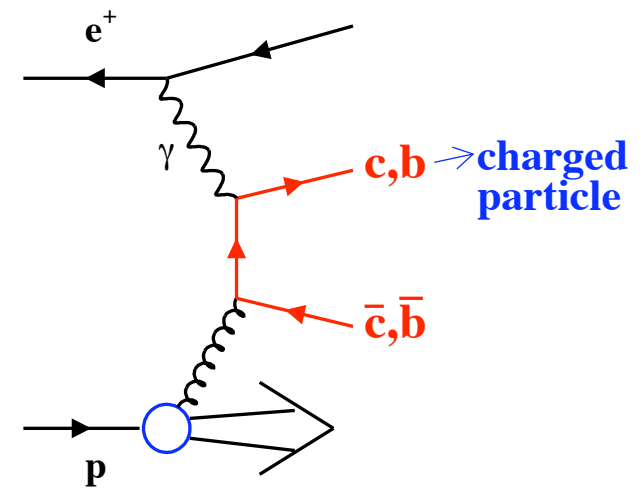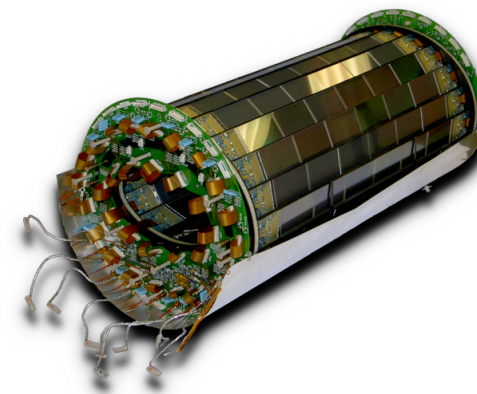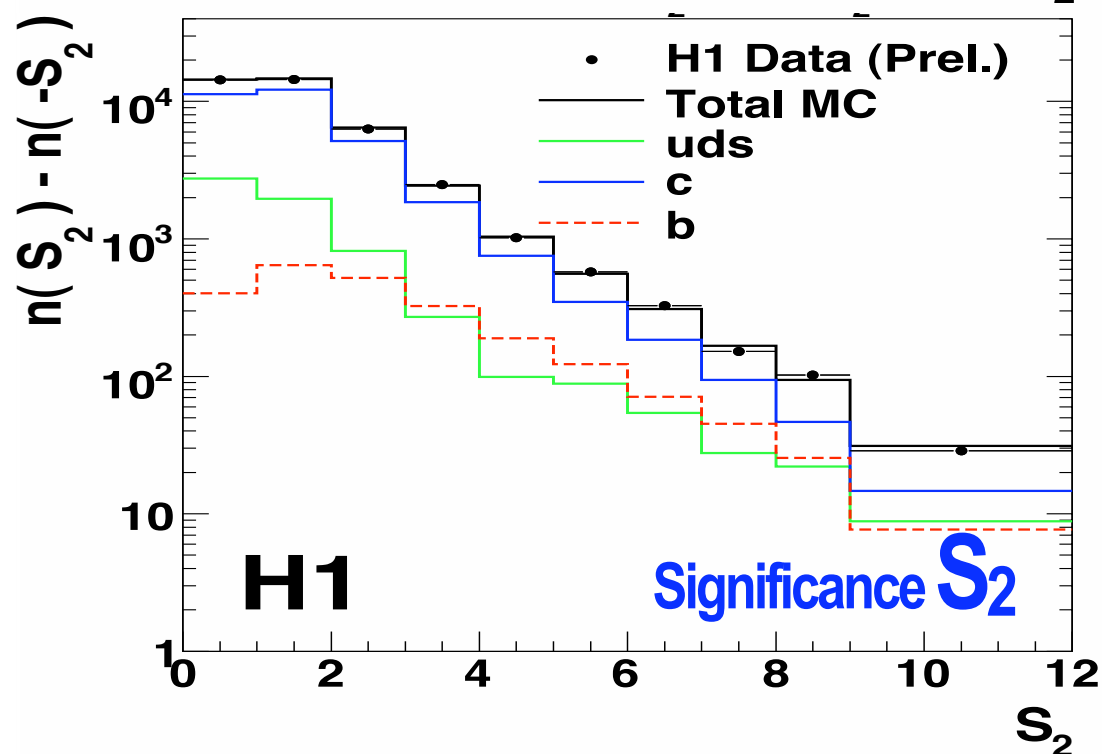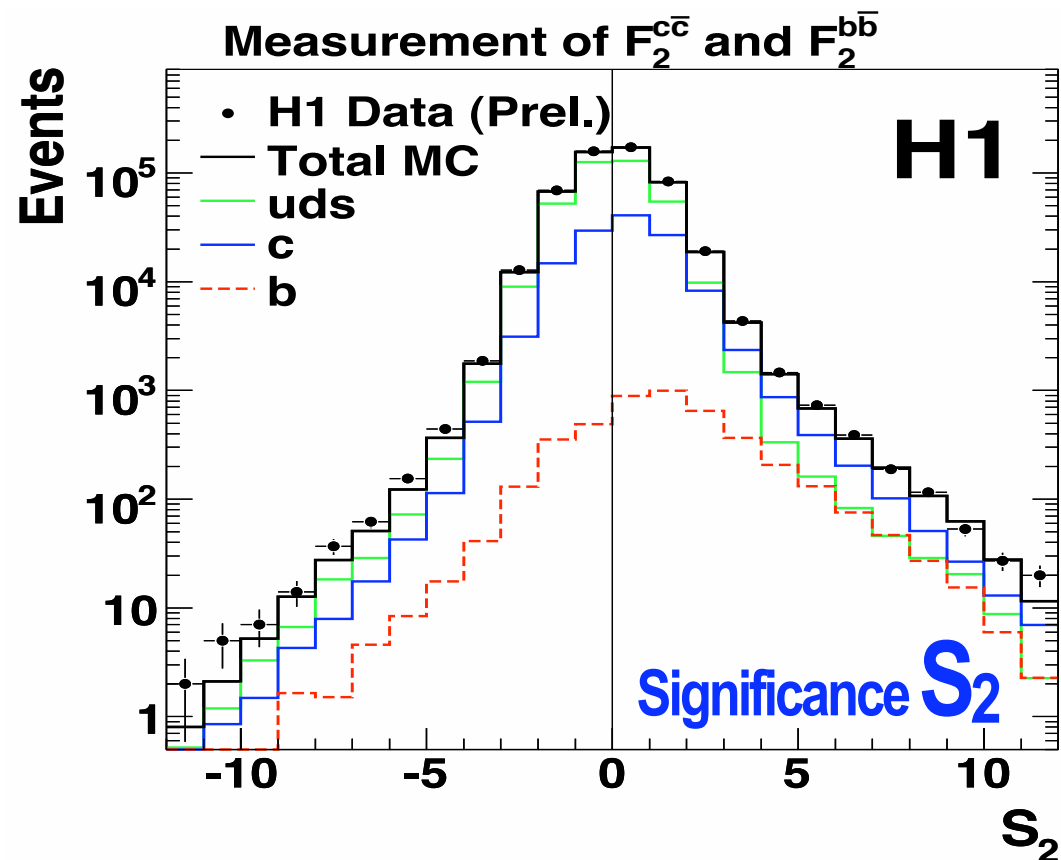
- **Impact parameter:**

Significance:

B^+

δ_1 δ_2

B^-
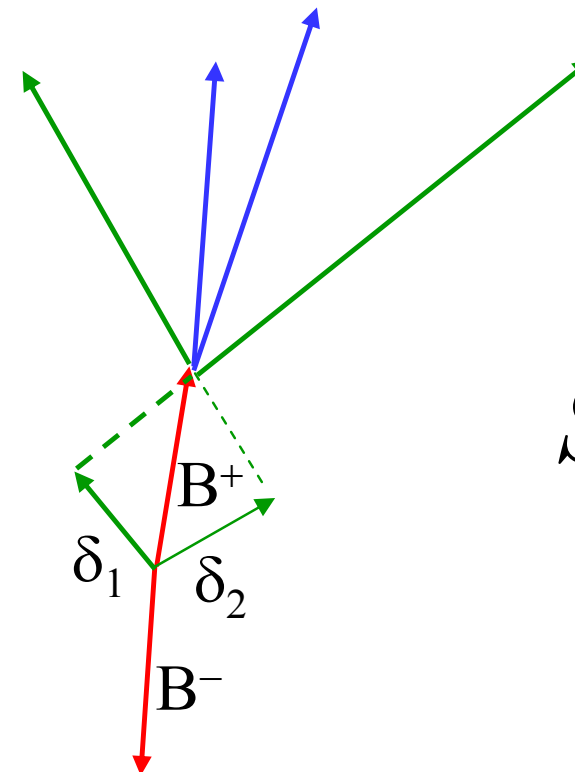
$$ S = \frac{\delta}{\sigma(\delta)} $$

- **Subtract negative side from positive: improved systematics**
- **Tracks with 2nd highest significance S_2: good charm/beauty separation**

Measure Charm, Beauty and Light Quark contributions fully inclusively (events with 1 or more tracks)

Charm & Beauty Structure Functions

e^+

Q^2, x

$\frac{c}{\bar{c}}$ or $\frac{b}{\bar{b}}$

p

HERA $F_2^{c\bar{c}}$

$F_2^{c\bar{c}}$

- $\square$ H1 HERA I (D*)
- $\blacksquare$ H1 (prel.) HERA I+II (VTX)
- $\circ$ ZEUS HERA I (D*)
- $\circ$ ZEUS HERA I (D$^+$, D^0, D$_s^+$)
- ZEUS (prel.) HERA II:
  - $\bullet$ D* $\bullet$ D$^+$

x = 0.00003 ($\times 4^{20}$)
x = 0.00005 ($\times 4^{19}$)
x = 0.00007 ($\times 4^{18}$)
x = 0.00013 ($\times 4^{17}$)
x = 0.00018 ($\times 4^{16}$)
x = 0.0003 ($\times 4^{15}$)
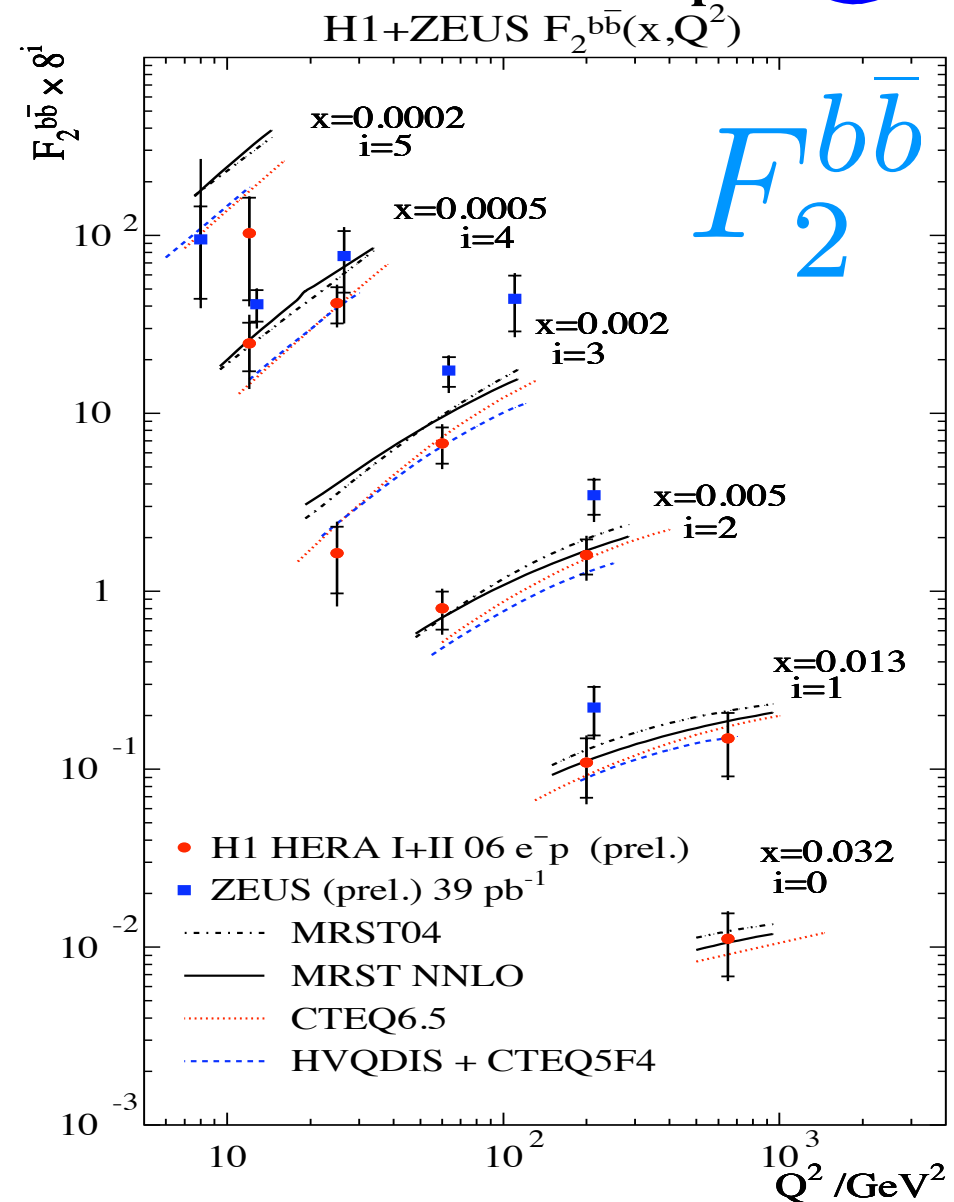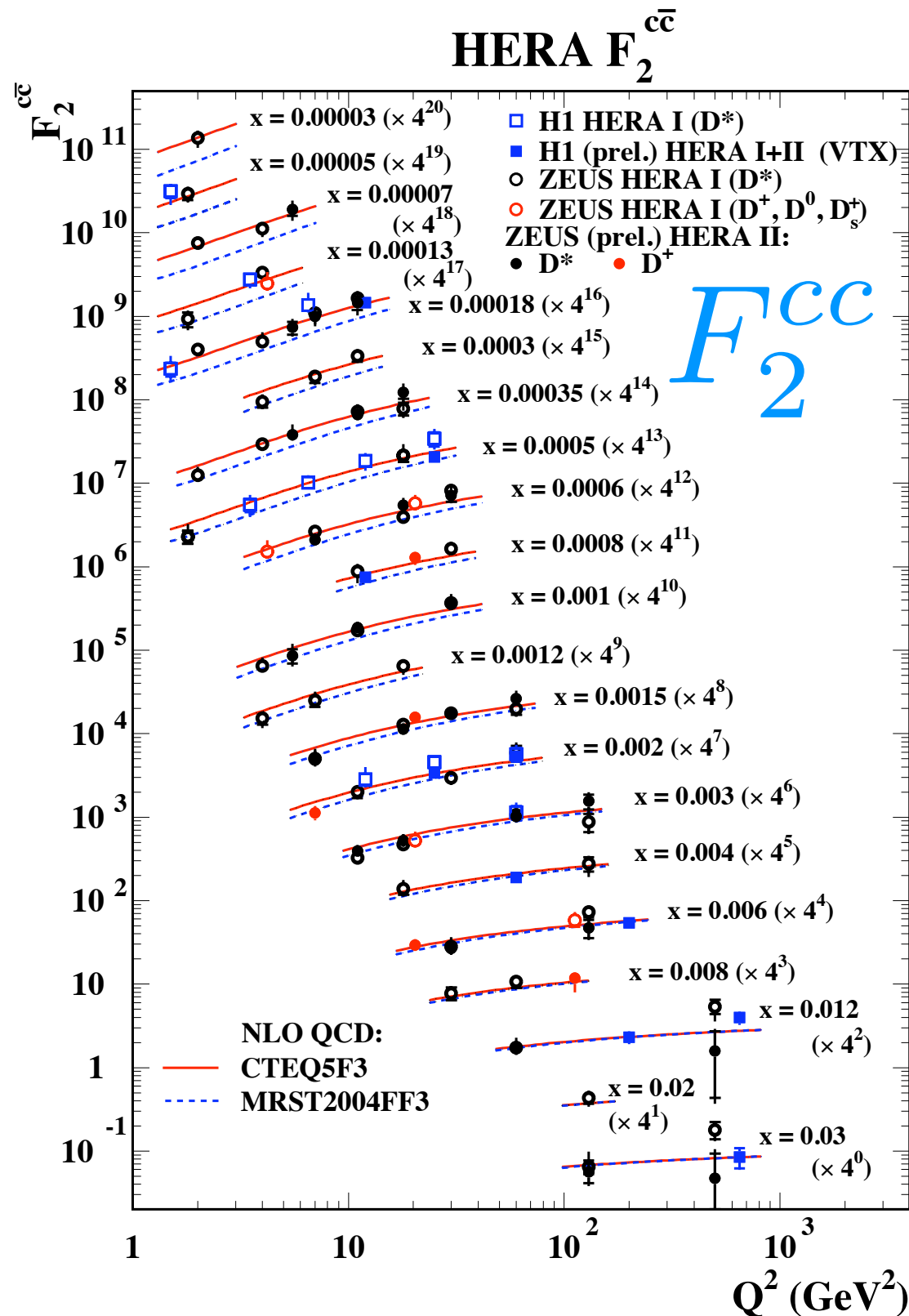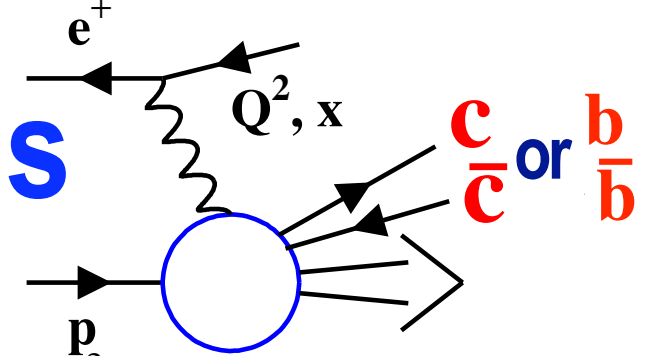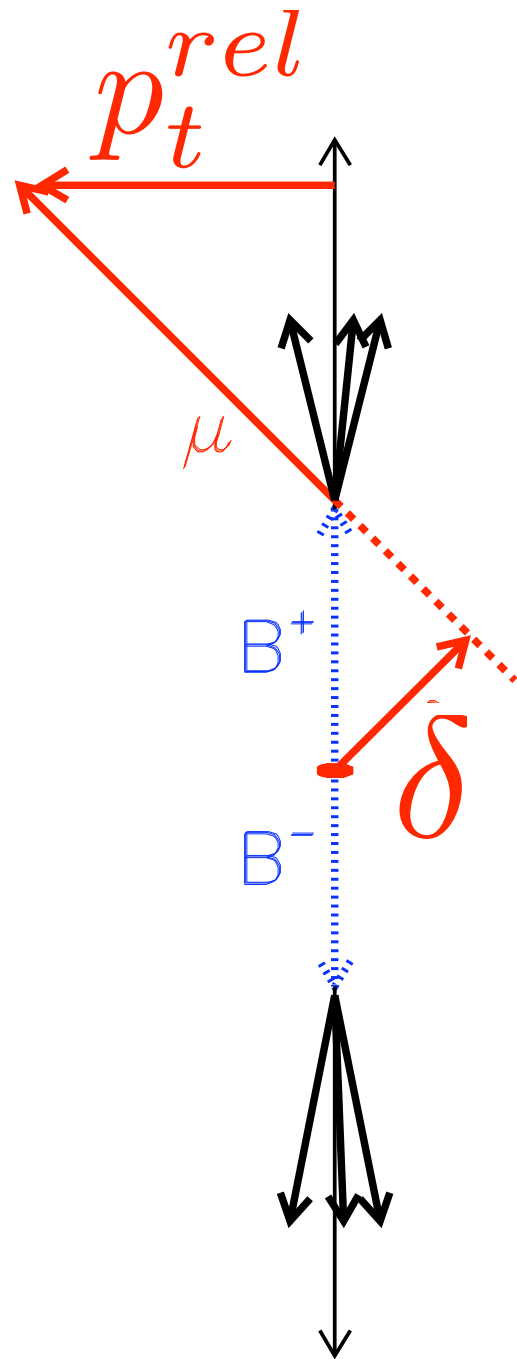x = 0.00035 ($\times 4^{14}$)
x = 0.0005 ($\times 4^{13}$)
x = 0.0006 ($\times 4^{12}$)
x = 0.0008 ($\times 4^{11}$)
x = 0.001 ($\times 4^{10}$)
x = 0.0012 ($\times 4^9$)
x = 0.0015 ($\times 4^8$)
x = 0.002 ($\times 4^7$)
x = 0.003 ($\times 4^6$)
x = 0.004 ($\times 4^5$)
x = 0.006 ($\times 4^4$)
x = 0.008 ($\times 4^3$)
x = 0.012 ($\times 4^2$)
x = 0.02 ($\times 4^1$)
x = 0.03 ($\times 4^0$)

$F_2^{c\bar{c}}$

NLO QCD:
CTEQ5F3
MRST2004FF3

Q^2 (GeV^2)

H1+ZEUS $F_2^{b\bar{b}}(x, Q^2)$

$F_2^{b\bar{b}} \times 8$

x = 0.013
x = 0.032

H1 Data (High Q^2)
f$^{c\bar{c}}$ f$^{b\bar{b}}$

x=0.0002 i=5
x=0.0005 i=4

Q^2 / GeV^2

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

x=0.002 i=3
x=0.005 i=2
x=0.013 i=1
x=0.032 i=0

- $\bullet$ H1 HERA I+II 06 e$^-$p (prel.)
- $\blacksquare$ ZEUS (prel.) 39 pb^{-1}
- MRST04
- MRST NNLO
- CTEQ6.5
- HVQDIS + CTEQ5F4
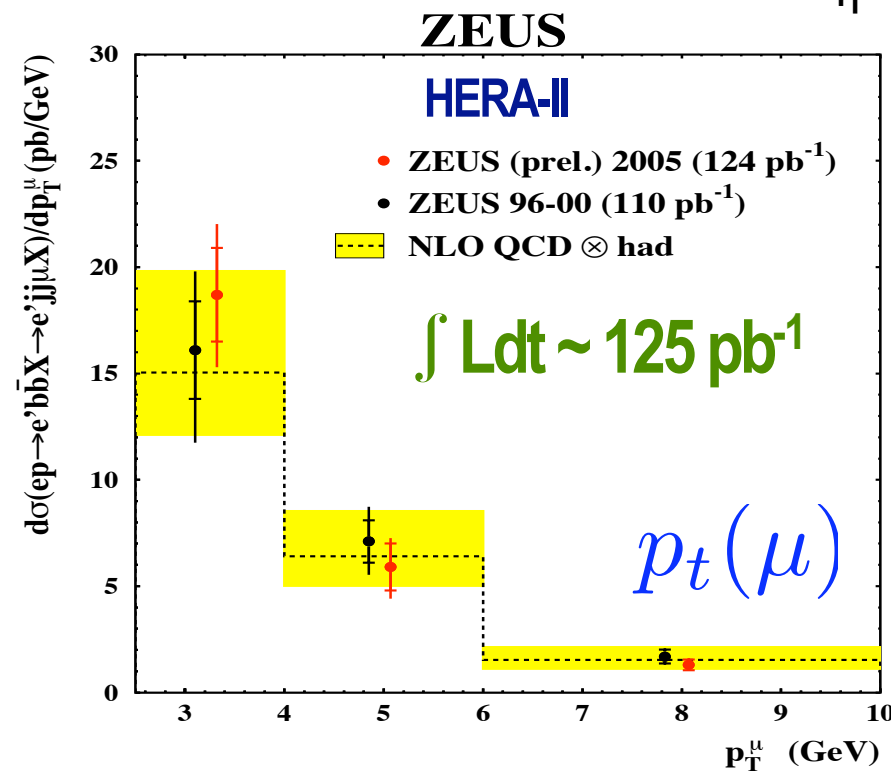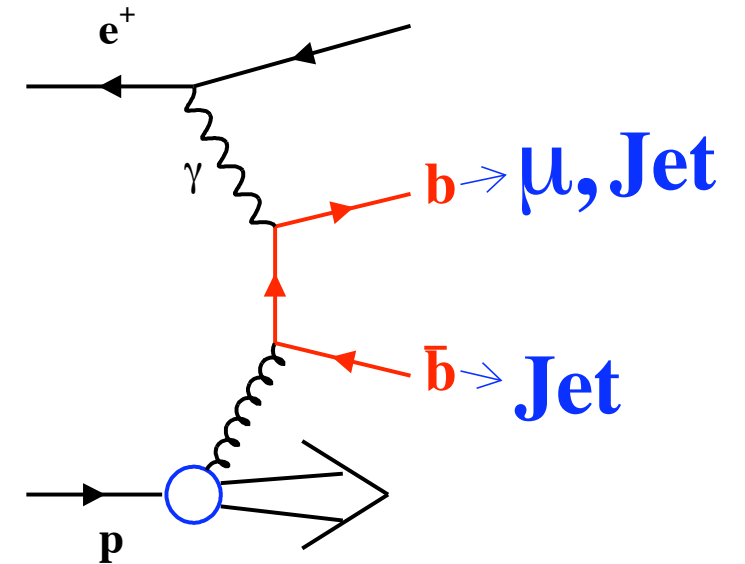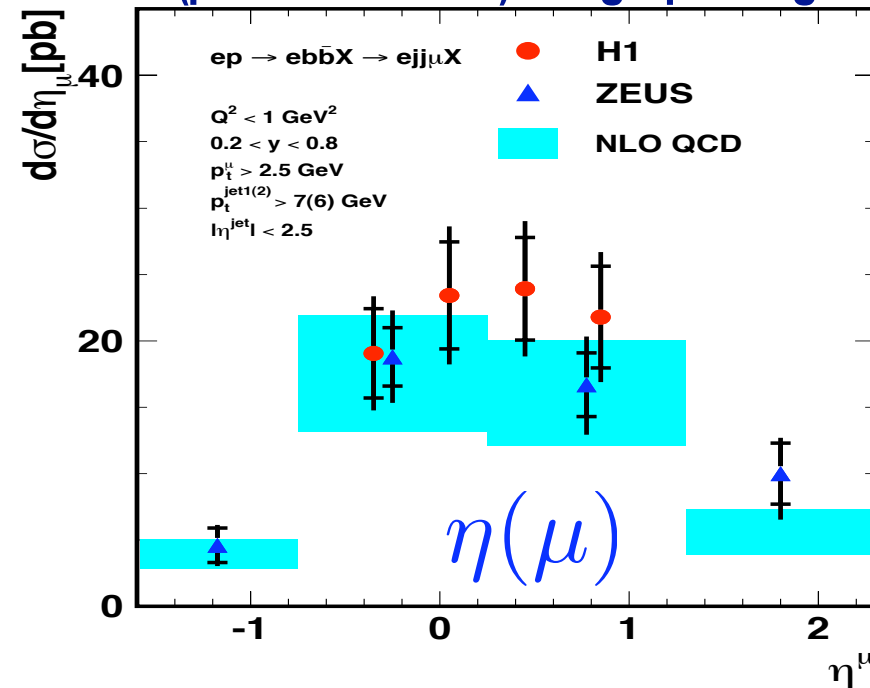
Q^2 /GeV^2

- **Good agreement with predictions using gluon distribution from scaling violations**
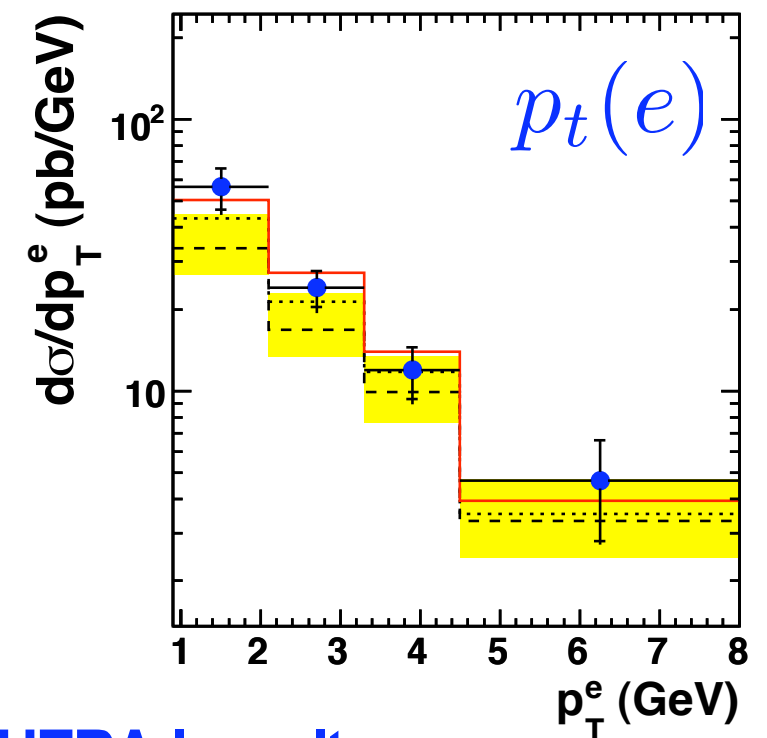- **Charm approaching precision regime constraining gluon density g(x)**

Beauty Photoproduction

$$b\bar{b} \to jj\mu$$

d jets

$$p_t^{rel}$$

μ

p_t^{rel}

B^+

B^-

$\tilde{\delta}$

HERA-I, first measurements (published 2004/5) using lepton tag

$ep \to eb\bar{b}X \to ejj\mu X$

$Q^2 < 1$ GeV^2
$0.2 < y < 0.8$
$p_t^\mu > 2.5$ GeV
$p_t^{jet1(2)} > 7(6)$ GeV
$|\eta^{jet}| < 2.5$

- H1
- ZEUS
- NLO QCD

$d\sigma/d\eta_\mu$ [pb]

$\eta(\mu)$

η^μ

ZEUS

HERA-II

- ZEUS (prel.) 2005 (124 pb^{-1})
- ZEUS 96-00 (110 pb^{-1})
- NLO QCD $\otimes$ had

$\int L dt \sim 125$ pb^{-1}

$p_t(\mu)$

$d\sigma(ep \to e'b\bar{b}X \to e'jj\mu X)/dp_T^\mu$ (pb/GeV)

p_T^μ (GeV)

ZEUS (HERA-I) using electron-tag

$p_t(e)$

$d\sigma/dp_T^e$ (pb/GeV)

p_T^e (GeV)

e^+
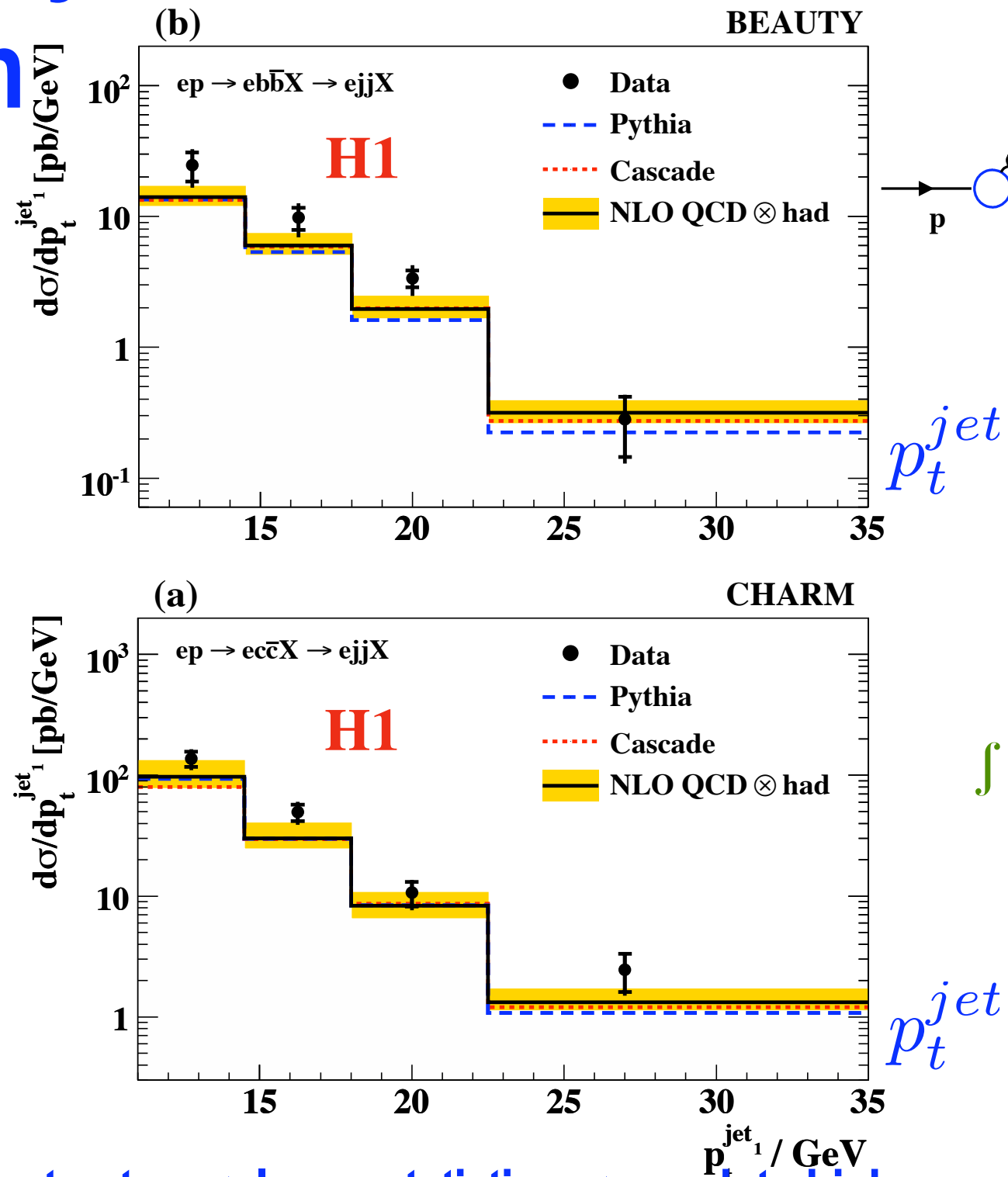
γ

$b \to \mu, Jet$

$\bar{b} \to Jet$

p

Separate B

rge b
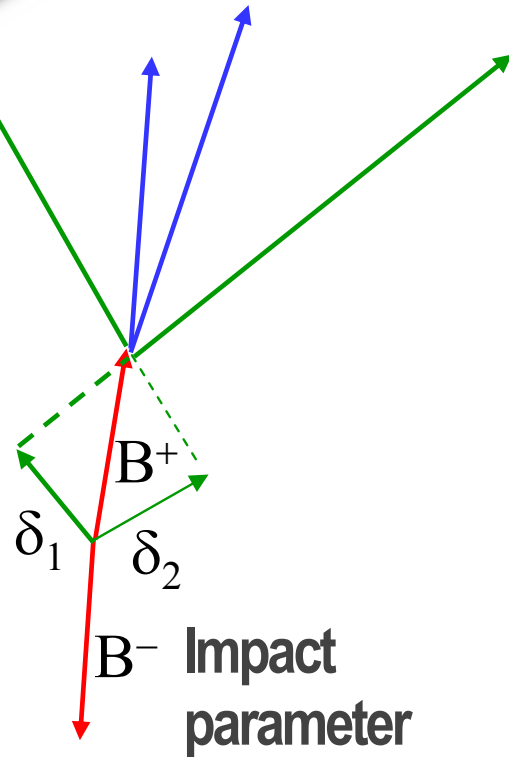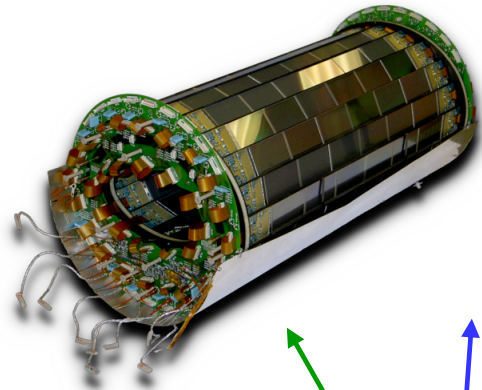
ng b

Preliminary ZEUS data using lifetime tag confirm HERA-I results

Charm and Beauty Photoproduction

Inclusive Lifetime tag

B^+

δ_1 δ_2

B^- **Impact parameter**

(b) BEAUTY

$ep \to eb\bar{b}X \to ejjX$

H1

- Data
- Pythia
- Cascade
- NLO QCD $\otimes$ had

$d\sigma/dp_t^{jet_1}$ [pb/GeV]

p_t^{jet}

(a) CHARM

$ep \to ec\bar{c}X \to ejjX$

H1

- Data
- Pythia
- Cascade
- NLO QCD $\otimes$ had

$d\sigma/dp_t^{jet_1}$ [pb/GeV]

p_t^{jet}

$p_t^{jet_1}$ / GeV

$\int L dt \sim 50\ pb^{-1}$

(HERA-I)

e^+

γ

c,b $\to$ **charged particle**

$\bar{c}, \bar{b}$

p
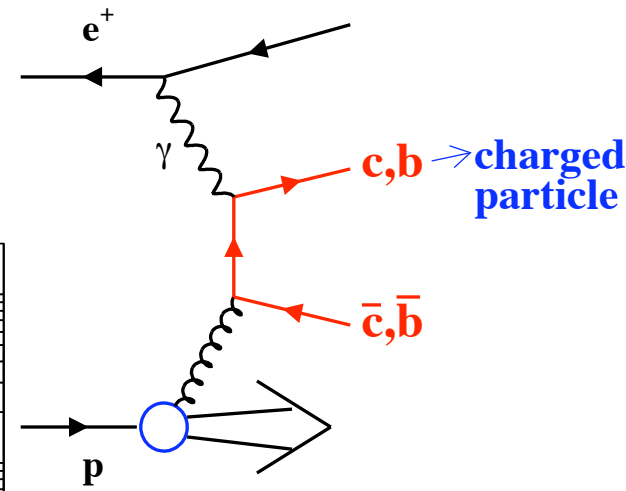
- **No hadron reconstruction or lepton tag $\to$ larger statistics $\to$ reach to higher p$_t$**
- **First combined measurement of charm and beauty in photoproduction**

Photoproduction of Beauty

HERA
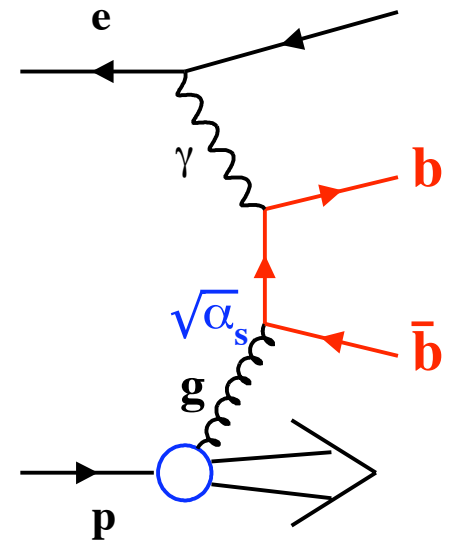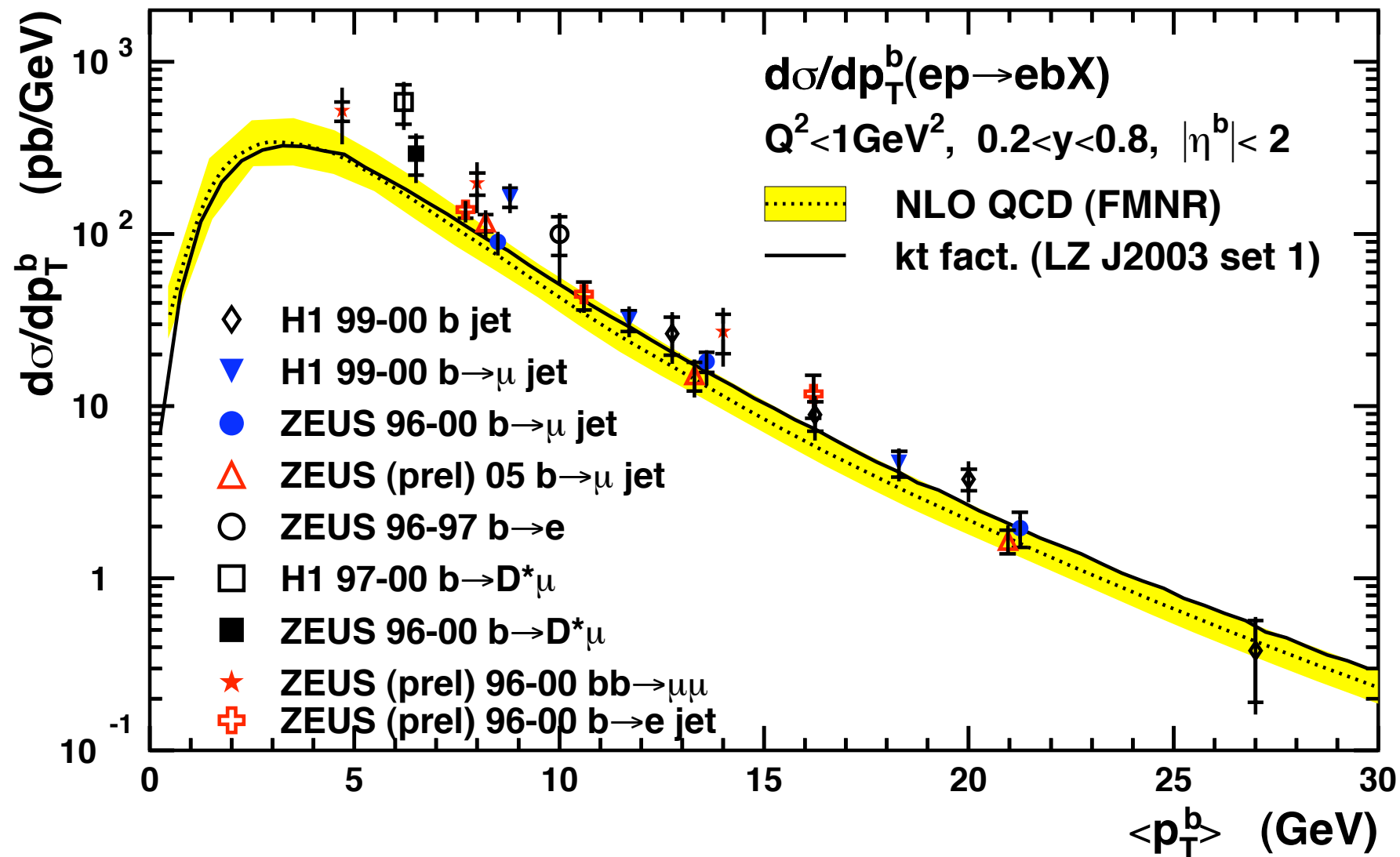
- **Many independent measurements performed in the last years**
- **General trend to be somewhat higher than massive NLO**
- **Statistical and systematic errors still large → HERA-II**

Conclusions

Heavy Quark Production at HERA:
Test of factorization ansatz of perturbative QCD and all of its ingredients

HERA data: 500 pb^{-1} of useful data have been recorded by each H1 and ZEUS

- **HERA-II: Upgraded detectors and increased statistics provide much improved precision**

- **Charm Production:**
    - **Charm data providing tight constraints for proton structure, pQCD parms and fragmentation**
    - **HERA-II: Precision Measurements**
- **Beauty Production:**
    - **Beauty data give input to predictions of LHC signal and background rates**
    - **HERA-II: Differential Measurements**

HERA-II analyses in full swing / first results have been presented / much more to come soon