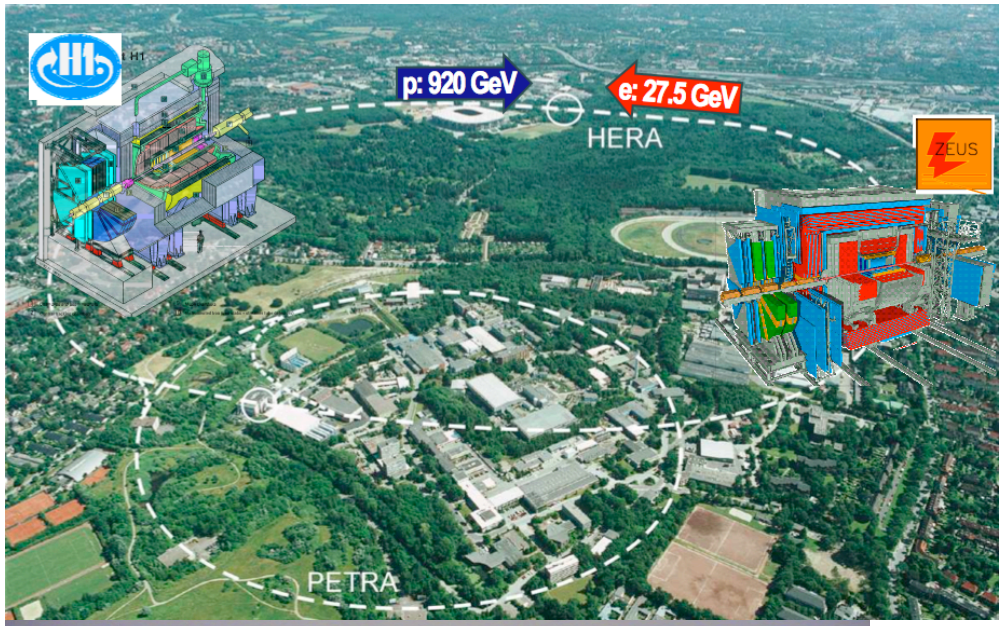
A taste of Heavy Flavour physics at ***HERA***

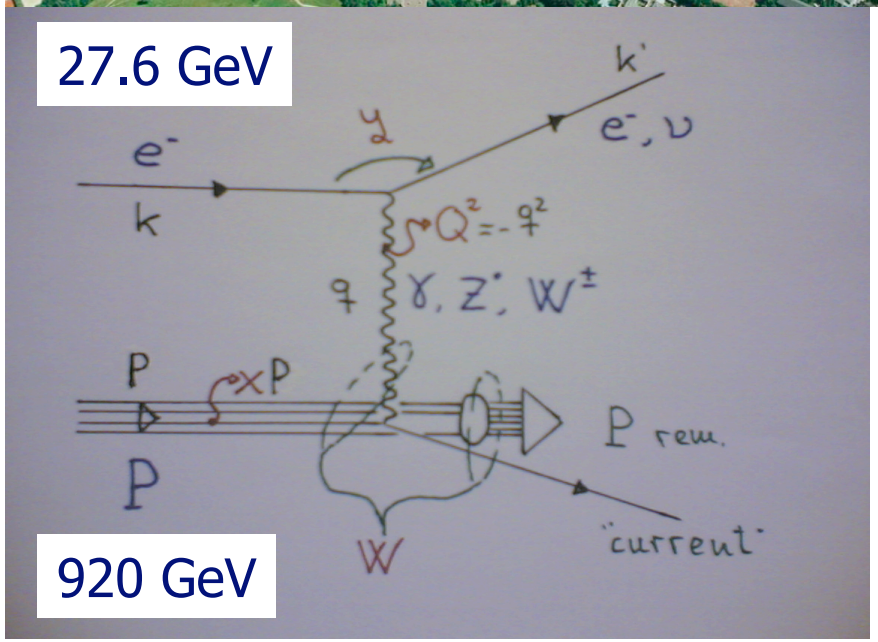
Luis Labarga (University Autonoma Madrid), on behalf of
the **H1** and **ZEUS** Collaborations

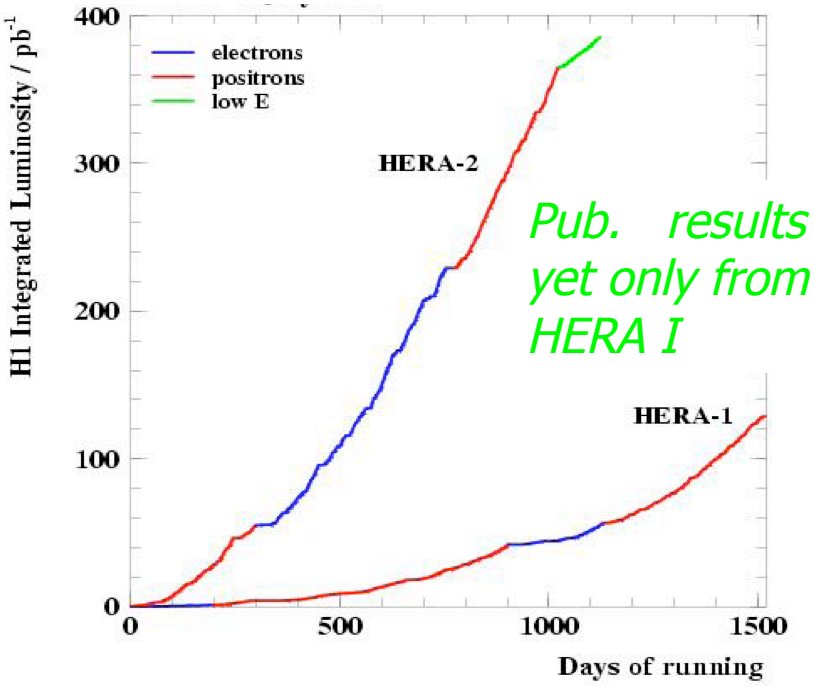
OUTLINE:

- Basics of HERA and HF production at HERA
- Current theoretical description
- Charmed hadron production:
  - charm Fragmentation
  - cross sections; p-QCD description
  - extraction of F_2^{cc} contribution to the proton's F_2
- Beauty (charm) production
  - reconstruction/tagging methods
  - cross-sections; p-QCD description
  - extraction of F_2^{bb} and F_2^{cc} contribution to the proton's F_2

Basics of experimentation at HERA







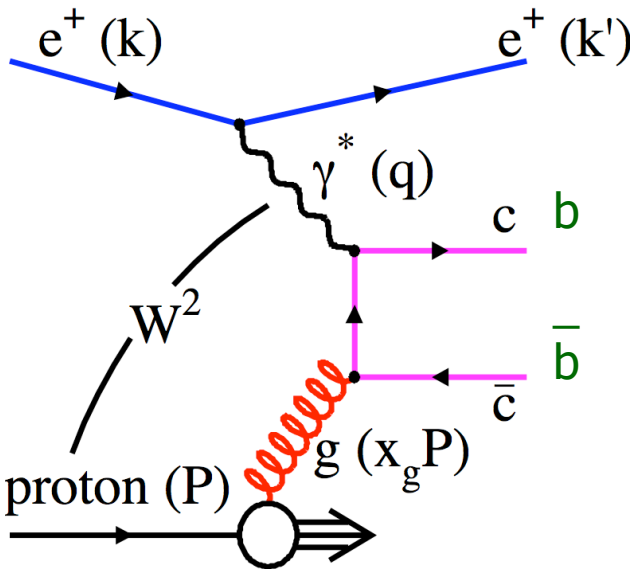
Pub. results yet only from HERA I

Different reactions:

- according to *charge* of ex. boson:
  NC: γ, Z^0 CC: W^{+-}
- according to its *virtuality*:
  DIS: $Q^2 > 2_{(?)}$ GeV^2;
  γ-production: $Q^2 \approx 0$ GeV (γP inter.)

Q^2: squared 4p transferred x (-1); x: in QPM fraction of **p** carried by parton; ...

- Dominant production process in e-p collisions: boson-gluon-fusion



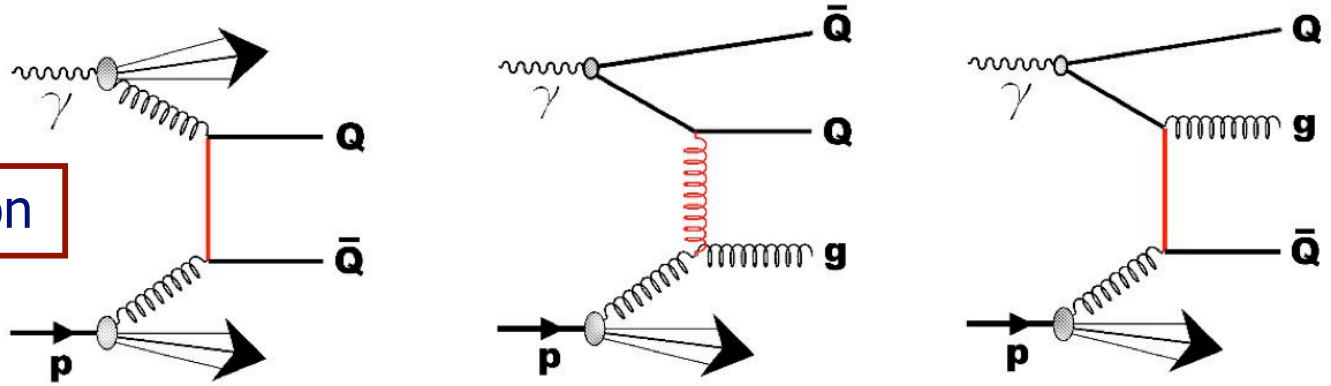
Multiple scales involved:

- $M_b \sim 5$ GeV, $M_c \sim 1.4$ GeV
- $Q^2 \sim 0$ GeV^2 (photoproduction - γp)
- $Q^2 >\sim 1$ GeV^2 (deep inelastic scattering - *DIS*)
- $P_t^{c,b}$ few GeV

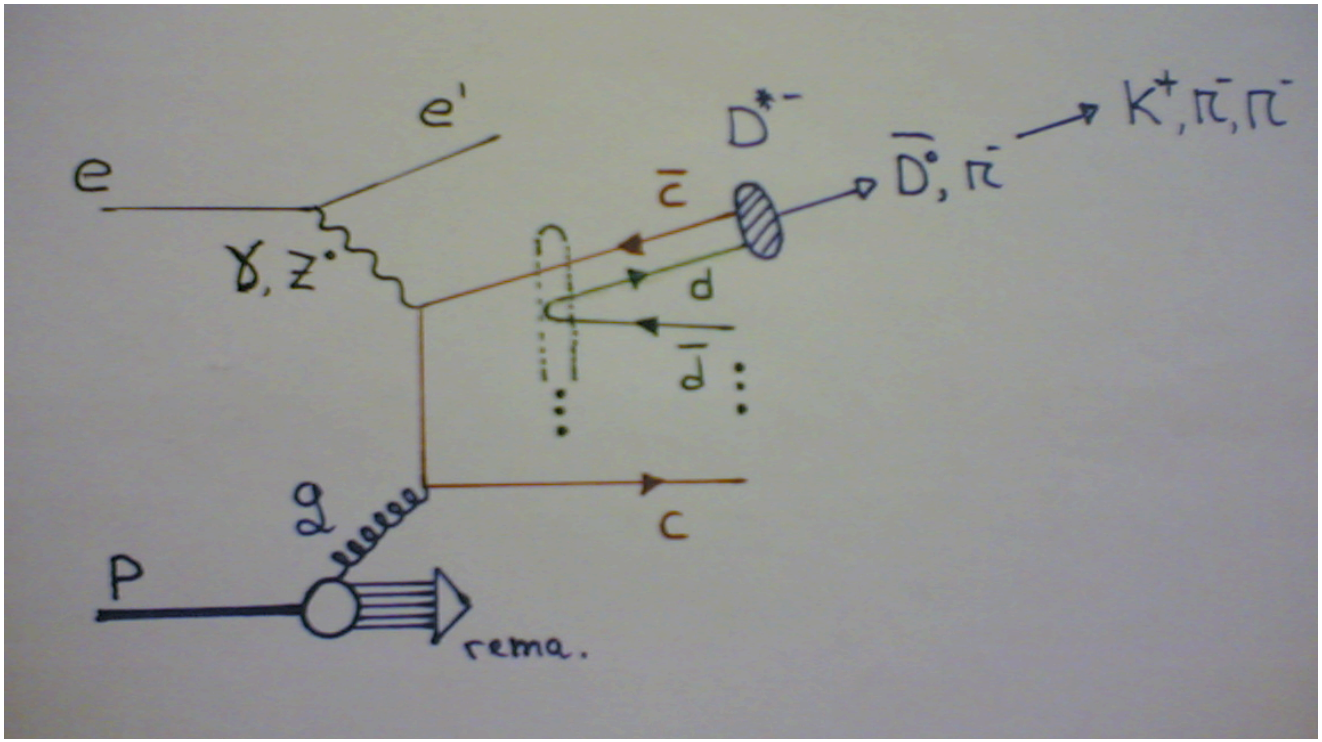
Powerful tool for testing *p* structure and the applicability of *pQCD*

- when the exchanged γ is almost real its hadronic component plays a role:

resolved γ-production



Example of complete reaction involving Heavy Quark production:
D^{*-} production and decay ($K^+\pi^-\pi^-$) in a $\bar{c}c$ BGF reaction



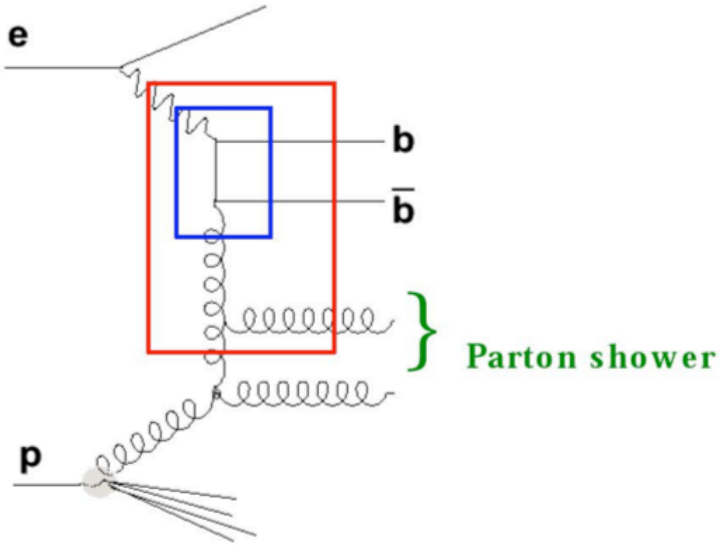
Factorization is assumed:

σ = P(+γ) structure(s) $\otimes$ QCD m.e. $\otimes$ fragmentation & decays

$\Rightarrow$ In this talk we will address (almost) all the ingredients

(and check indirectly the factorization assumption)

Theory calculations and Monte Carlo samples



Prediction:		Describes:
LO+PS: PYTHIA, HERWIG	(DGLAP)	γp
RAPGAP	(DGLAP)	DIS
CASCADE	(CCFM)	γp&DIS
NLO: FMNR		γp
HVQDIS		DIS

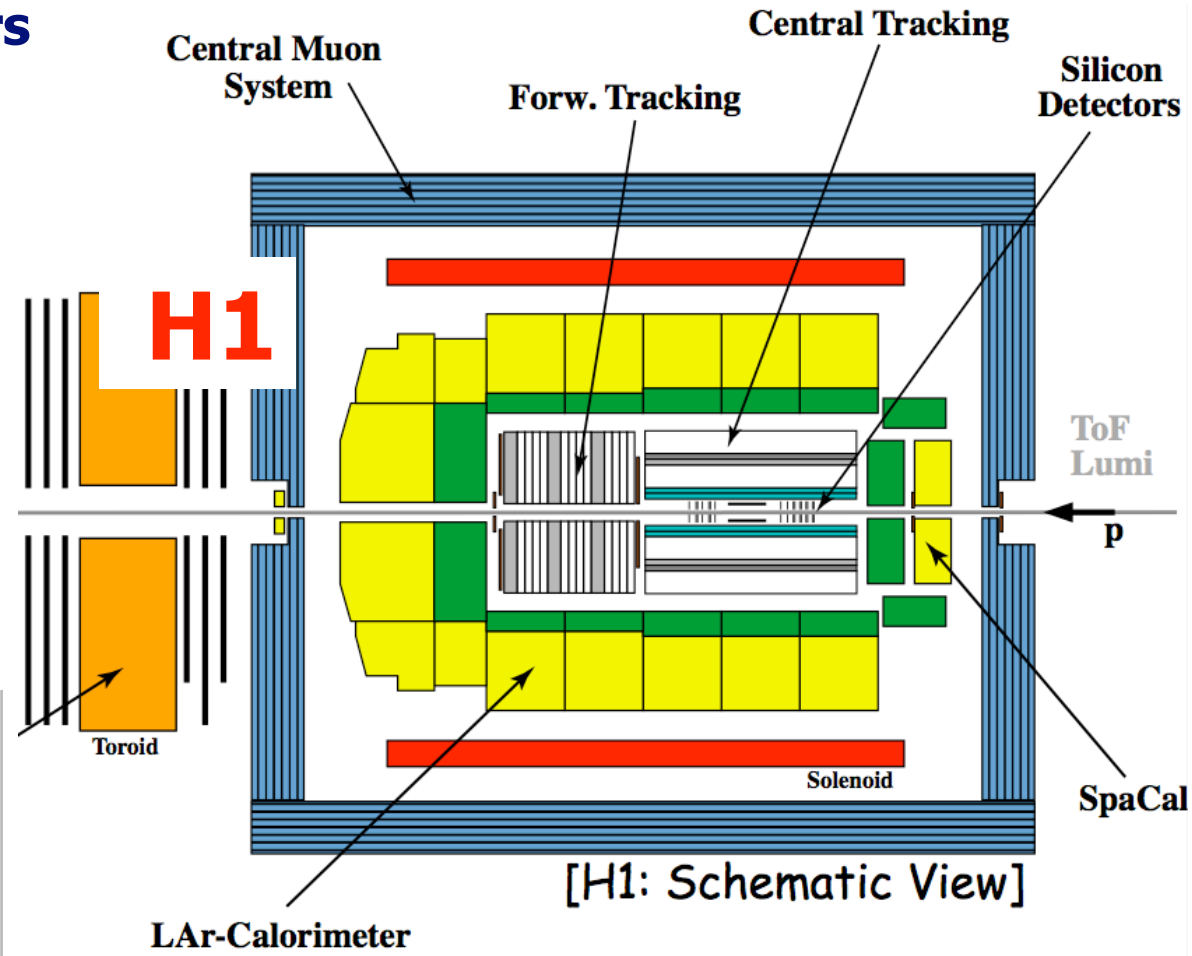
MONTE CARLO

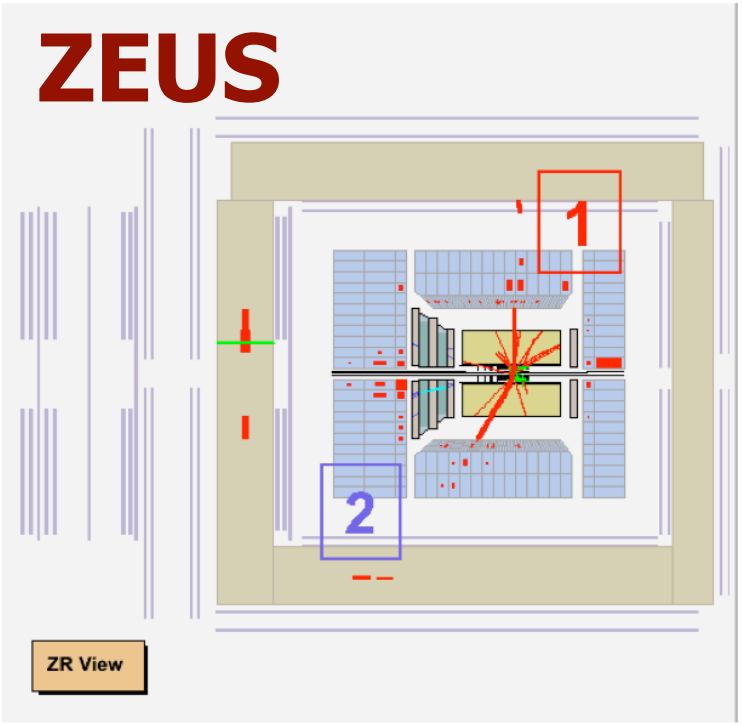
- leading order + parton shower models available, including flavour excitation, DGLAP evolution (PYTHIA, HERWIG)
- CCFM evolution with k_t factorisation (CASCADE)

THEORETICAL CALCULATIONS

- full NLO calculation (FMNR, HVQDIS) available
- massive scheme FFNS (heavy quark dynamically generated in the hard process)

The H1 and ZEUS detectors





Silicon detector in ZEUS only for HERA II

Methods used for the

tagging/measuring of charm

by the HERA experiments

- charmed-hadron full reconstruction (MOST USED TECHNIQUE)
- Displaced Tracks (H1 05, 2 x H1 06)

charmed-hadron full reconstruction

Vector mesons: $D^{*\pm}(2010)$

$$D^{*+} \to D^0\pi_s^+ \to (K^-\pi^+)\pi_s^+,$$

$$D^{*+} \to D^0\pi_s^+ \to (K^-\pi^+\pi^+\pi^-)\pi_s^+$$

golden channel

Pseudo-scalar mesons: D^0 , $D^{\pm}$, $D^{\pm}_s$

$$D^0 \to K^-\pi^+,\ D^+ \to K^-\pi^+\pi^+$$

$$D_s^+ \to \phi\pi^+ \to K^+K^-\pi^+$$

copious production

(therefore suitable to be used further for studies on fragmentation, QCD and others)

Baryons: $\Lambda^{\pm}_c$

$$\Lambda_c^+ \to K^-p\pi^+$$

Excited mesons: $D_1(2420)^0$, $D_2^*(2460)^0$, $D_S(2536)^{\pm}$

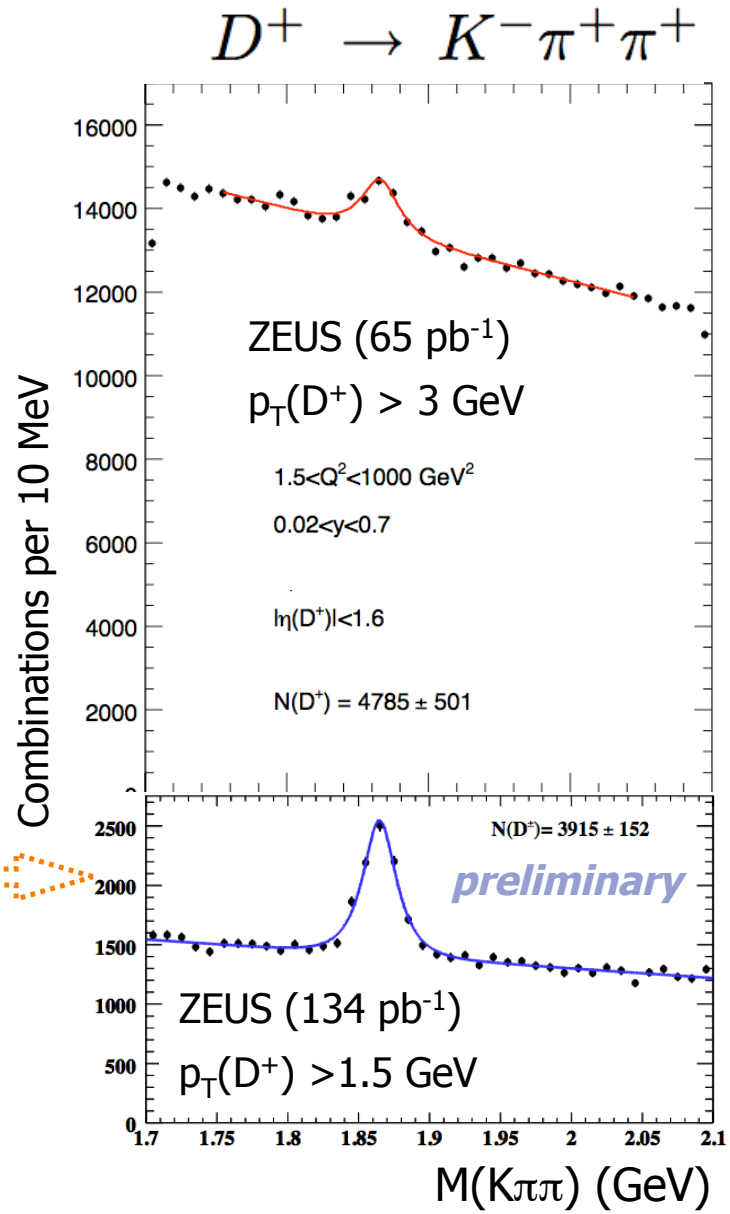
$$D_1(2420)^0 \to D^{*+}\pi^-,$$

$$D_2^*(2460)^0 \to D^{*+}\pi^-, D^+\pi^-,$$

$$D_{s1}(2536)^+ \to D^{*+}K_s^0, D^{*0}K^+$$

not shown

Example signal (no golden)



use of μVTX detector for reconstructing secondary vertices

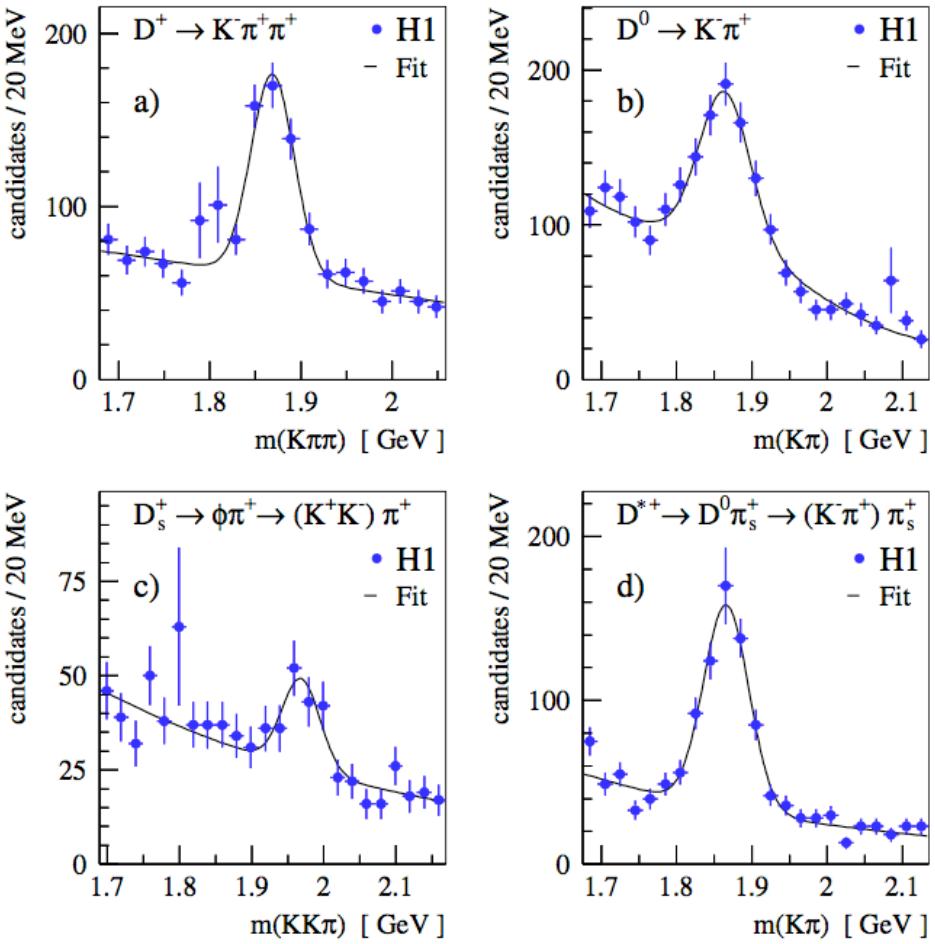
Charm fragmentation

H1 EPJC38(2005)447
ZEUS EPJC44(2005)351
ZEUS JHEP07(2007)074

Other important example signals:

H1 48 pb^{-1}

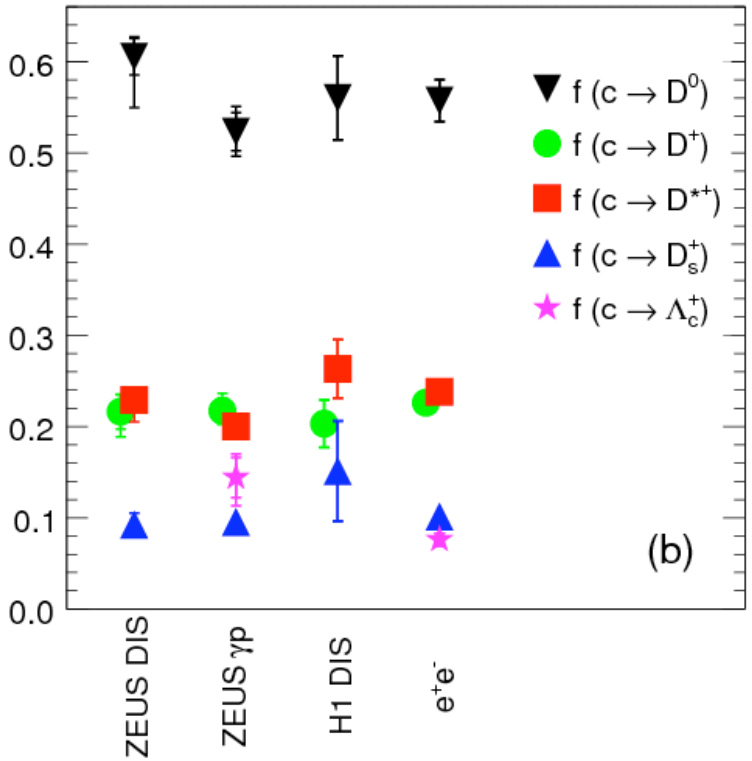
2 <Q^2<100 GeV^2 ; μVTX used



⇨ Very good S/B ratio

Charm fragmentation fractions

$$f(c \to D_j) = \sigma(D_j) \,/\, \Sigma_i \sigma(D_i)$$



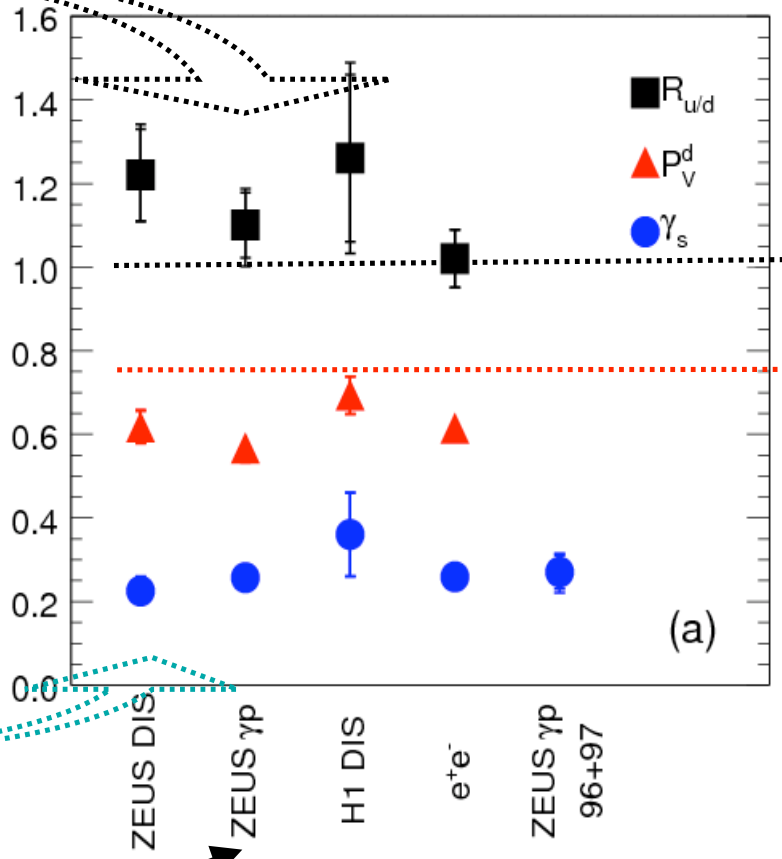
Fragmentation ratios from charm mesons measurements

H1 EPJC38(2005)447
ZEUS EPJC44(2005)351
ZEUS JHEP07(2007)074

$$R_{u/d} = \frac{[charged\ D]}{[neutral\ D]}$$

$$P_V^d = \frac{[ch.\ vector\ D]}{[ch.vec+seud\text{-}scalar\ D]}$$

$$\gamma_s = \frac{2 \times [D\ w/quark\ s]}{[D\ w/quark\ u\ o\ d]}$$



Isospin invariance

Spin counting

competitive errors w.r.t. e^+e^-

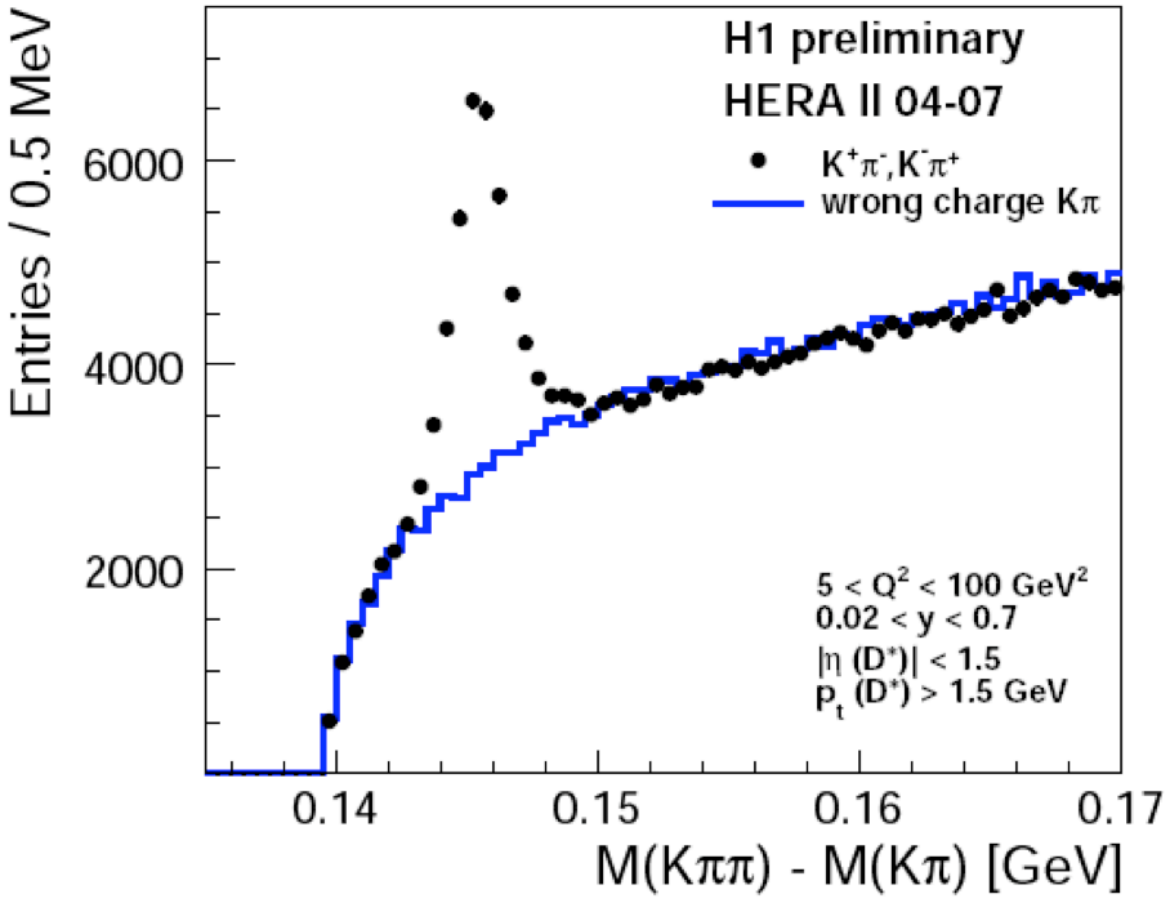
D meson (charm) production cross-sections; p-QCD comparisons

- $D^{*+} \to D^0 \pi_s^+ \to (K^- \pi^+) \pi_s^+,$

Golden channel:

$m_{D^{*+}} - m_{D^0} = 146$ MeV

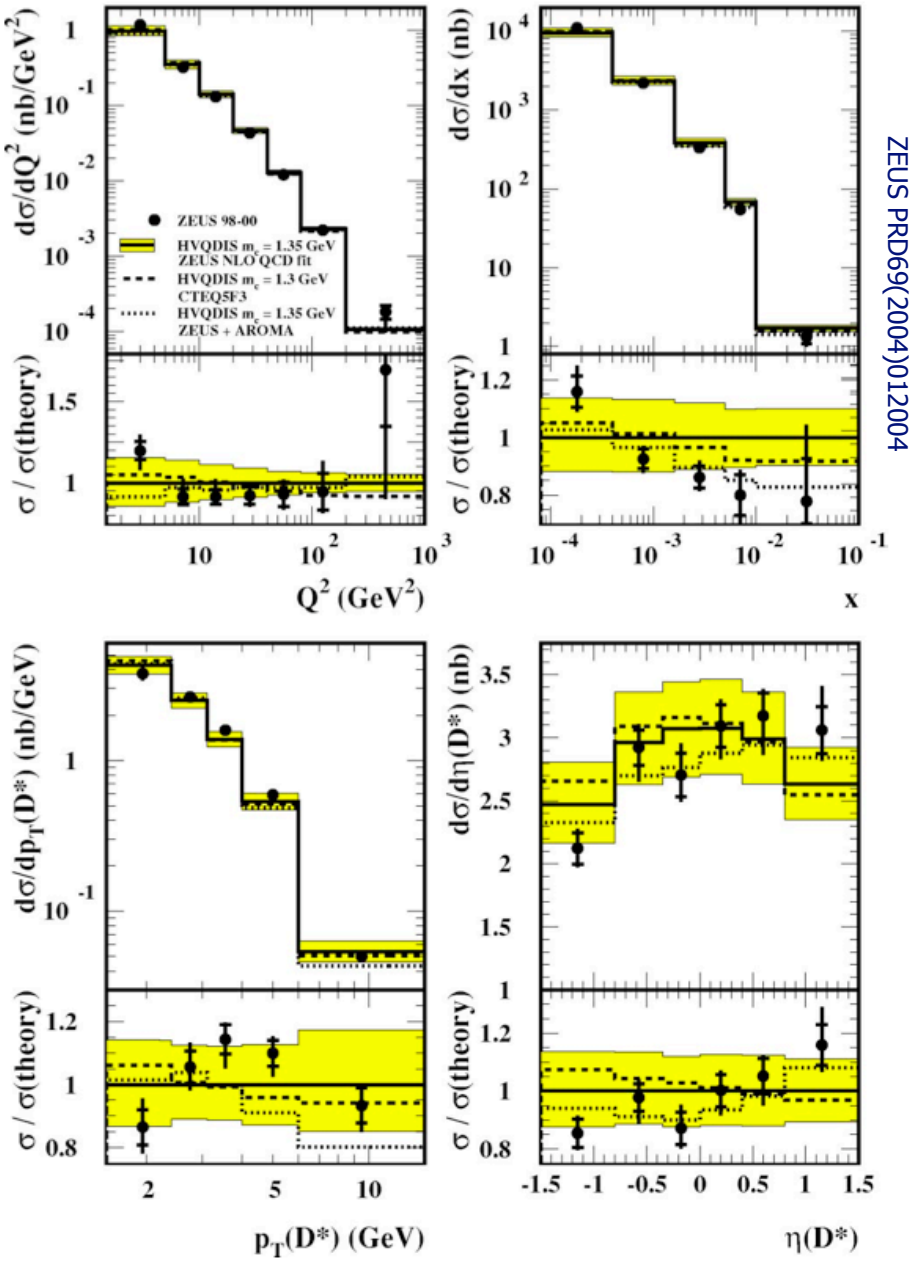
⇨ very restricted kinematics
-> low phase space allowed
⇨ low combinatorial bkg.



- also D^0 , $D^{\pm}$, D_s ...

Differential cross-sections

ZEUS 82 pb^{-1} D*+

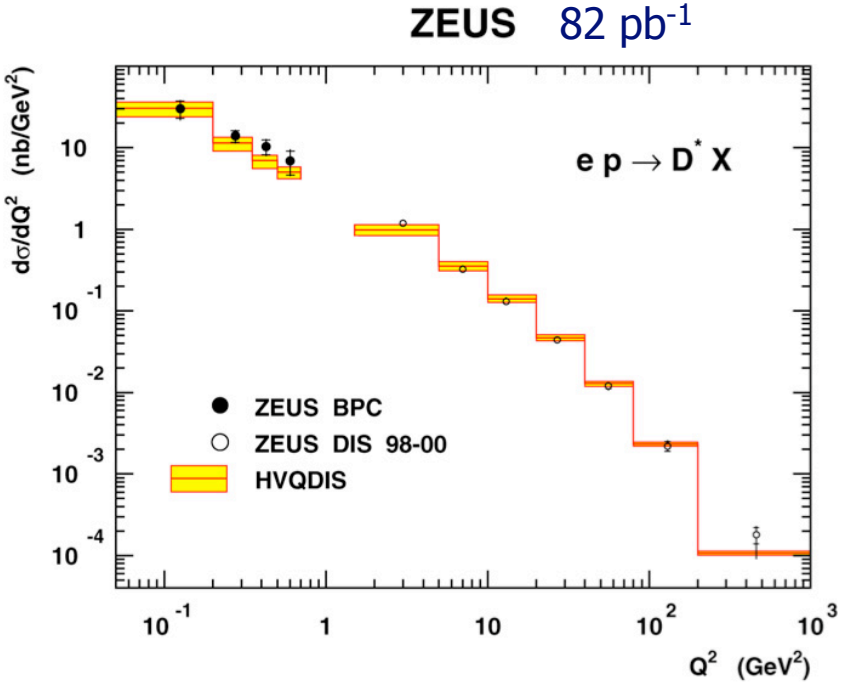


ZEUS PRD69(2004)012004

⇨ behavior as expected
- steep Q^2, p_T
- mild η dependence
- rising towards lower-x

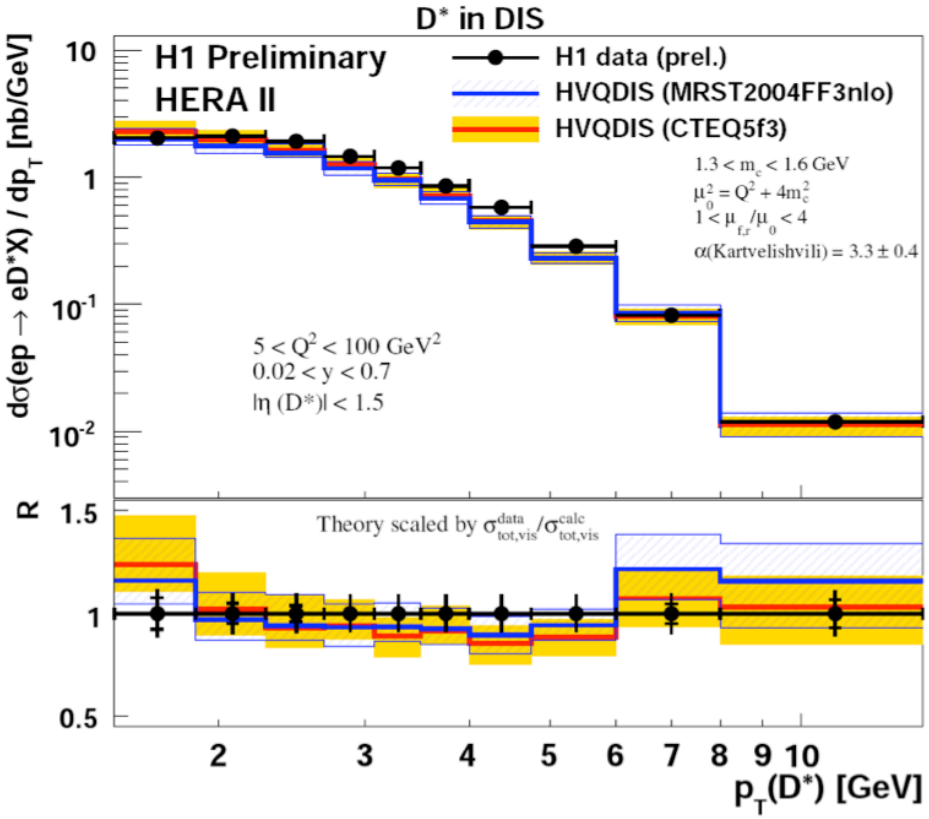
Extending to very low Q^2:

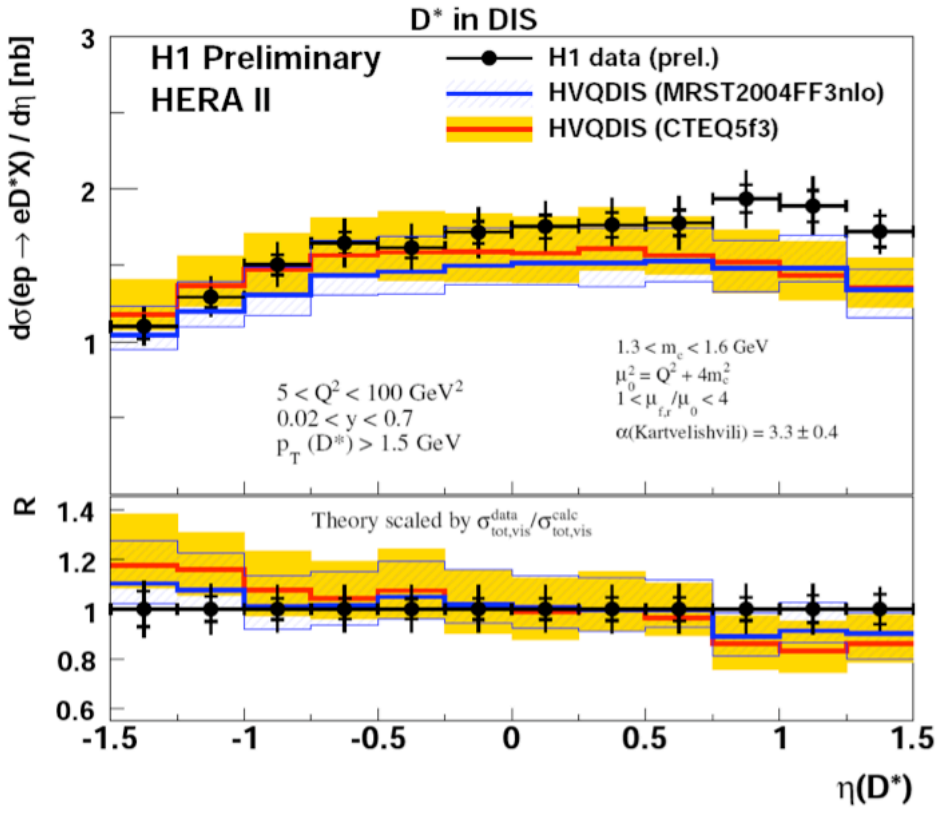
ZEUS PLB649(2007)111



⇨ good description by NLO-QCD

HERA II data analysis at full speed:

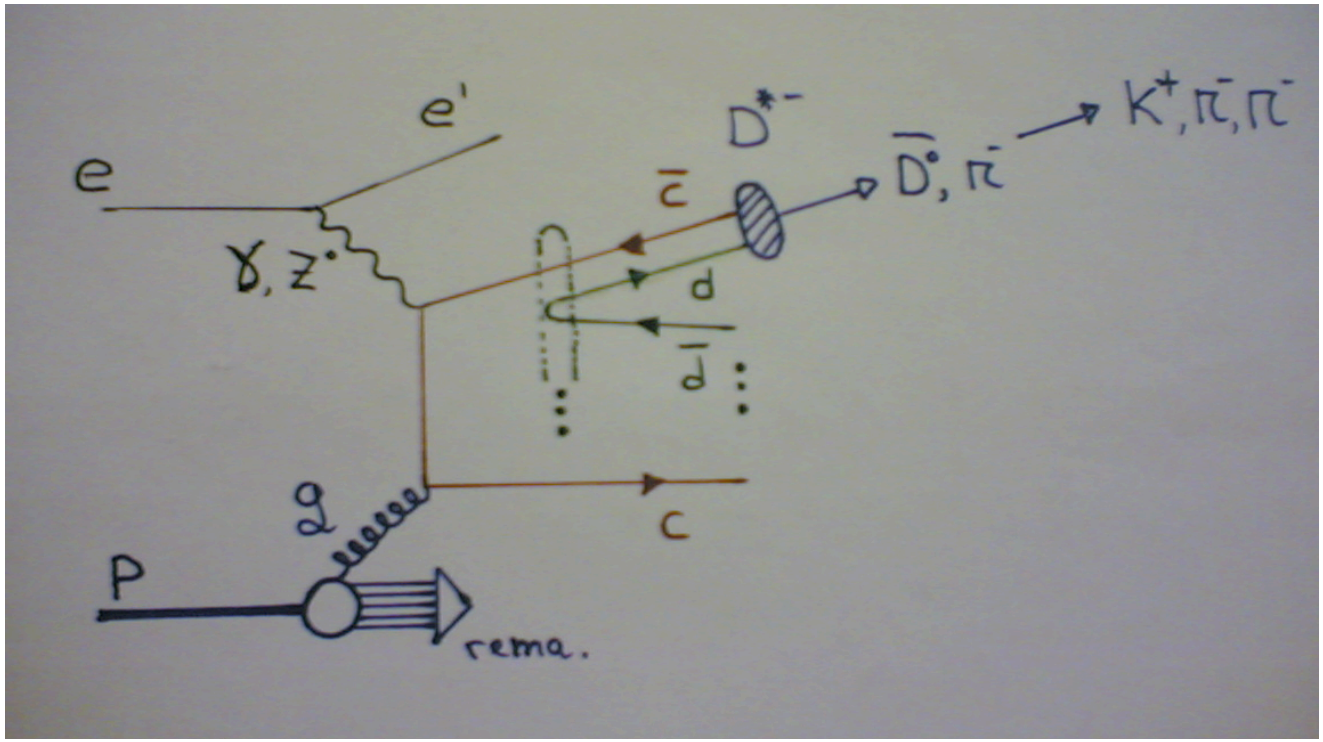




... conclusions qualitative similar but ...

⇨ we are reaching the stage of "high statistics physics"

D meson (charm) production: a comment about p-QCD comparisons



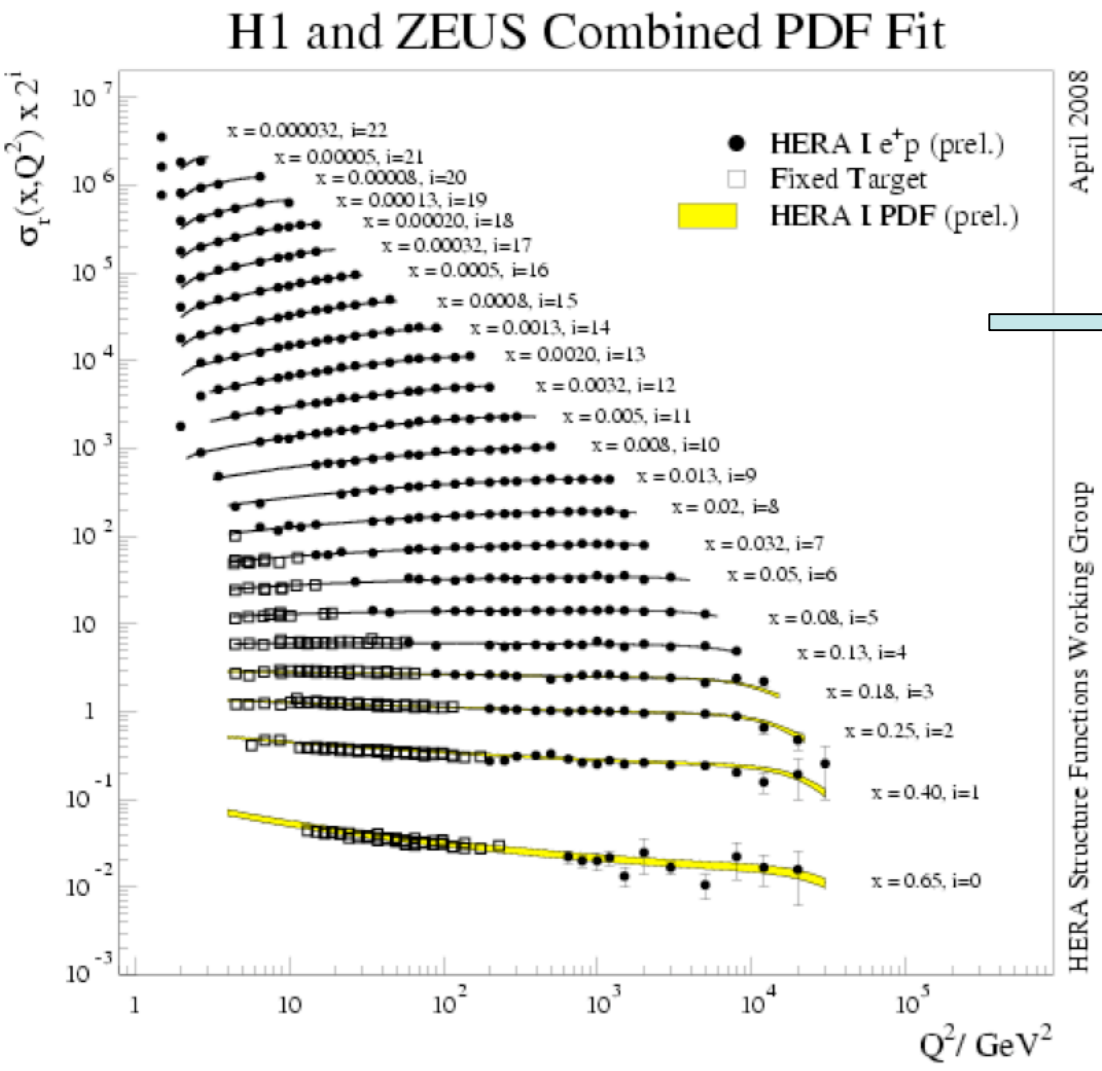
σ = P structure $\otimes$ QCD m.e. $\otimes$ fragmentation & decays

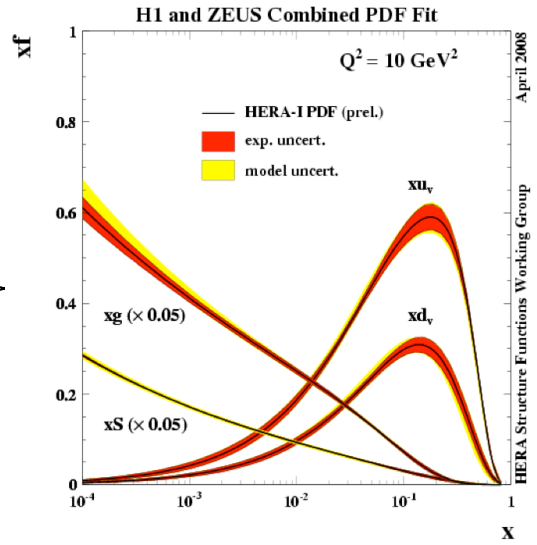
measured at this/other experiments

calculated at NLO

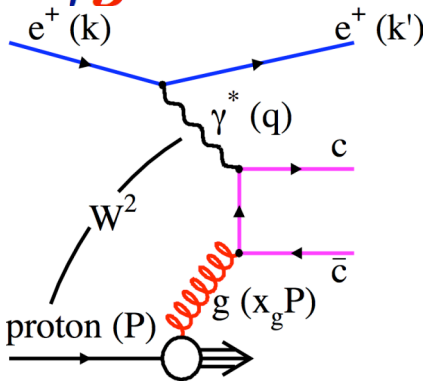
derived from a QCD-NLO analysis of the inclusive F_2 measurement

- distribution of *gluon* in the **p** extracted from a DGLAP NLO analysis of F_2





is the *g* extracted from [ep →eX] consistent with the *g* initial state of the reaction $\gamma g \longrightarrow c\bar{c}$?



⇨ highly non trivial test of the validity of p-QCD

Extrapolation to obtain $F_2^{c\bar{c}}$

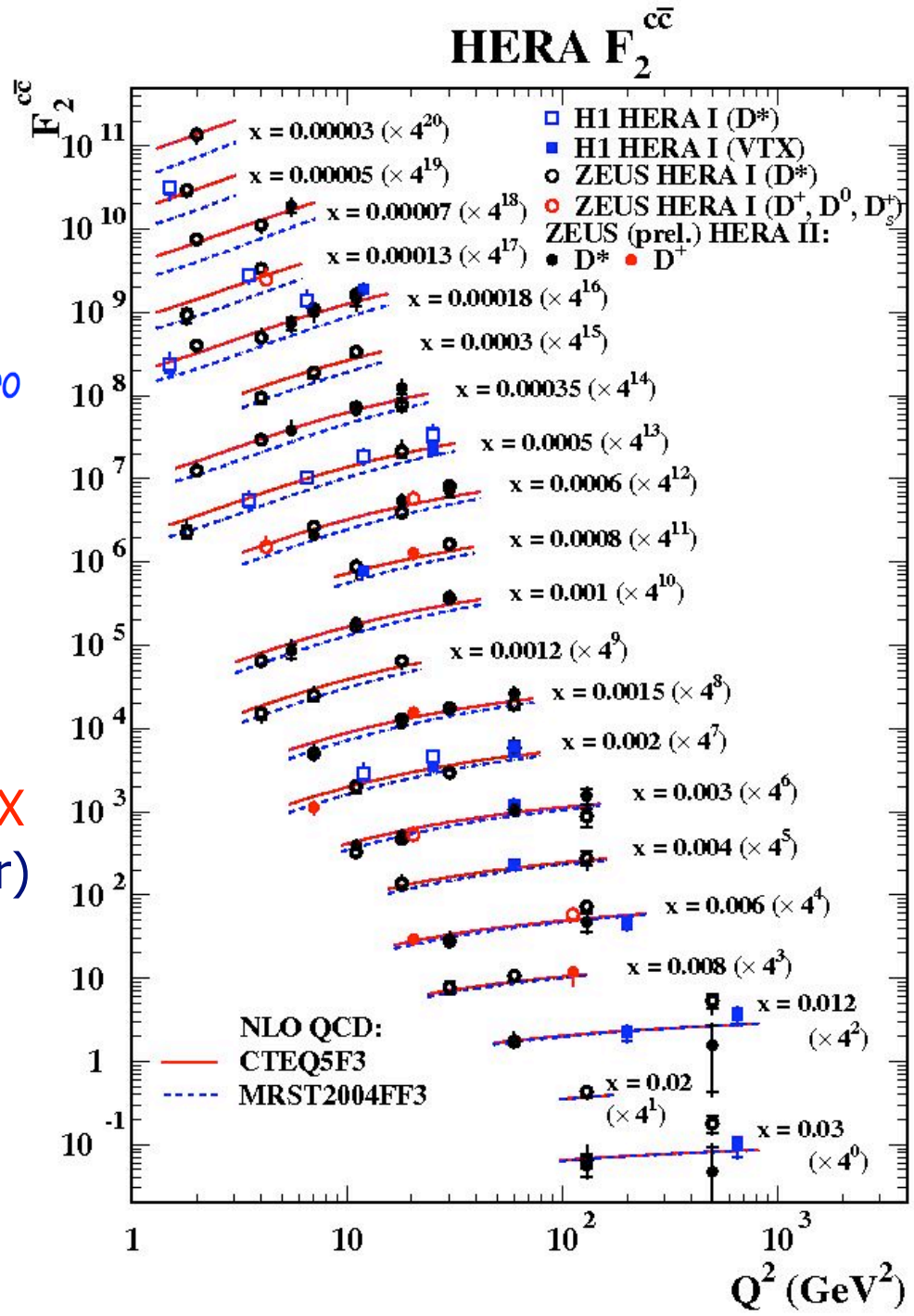
$$F_{2,meas}^{c\bar{c}}(x_i, Q_i^2) = \frac{\sigma_{i,meas}(ep \to D^* X)}{\sigma_{i,theo}(ep \to D^* X)} F_{2,theo}^{c\bar{c}}$$

⇨ Extrapolation factors: 1.4 - 4

⇨ impressive agreement to the μVTX based H1 measurement (see later)

⇨ large scaling violations consistent with a *g* driven process

⇨ good description by NLO-QCD



The methods for the

tagging/measuring of beauty

at the HERA experiments exploit its characteristics of heavy mass and long life-time. There are several:

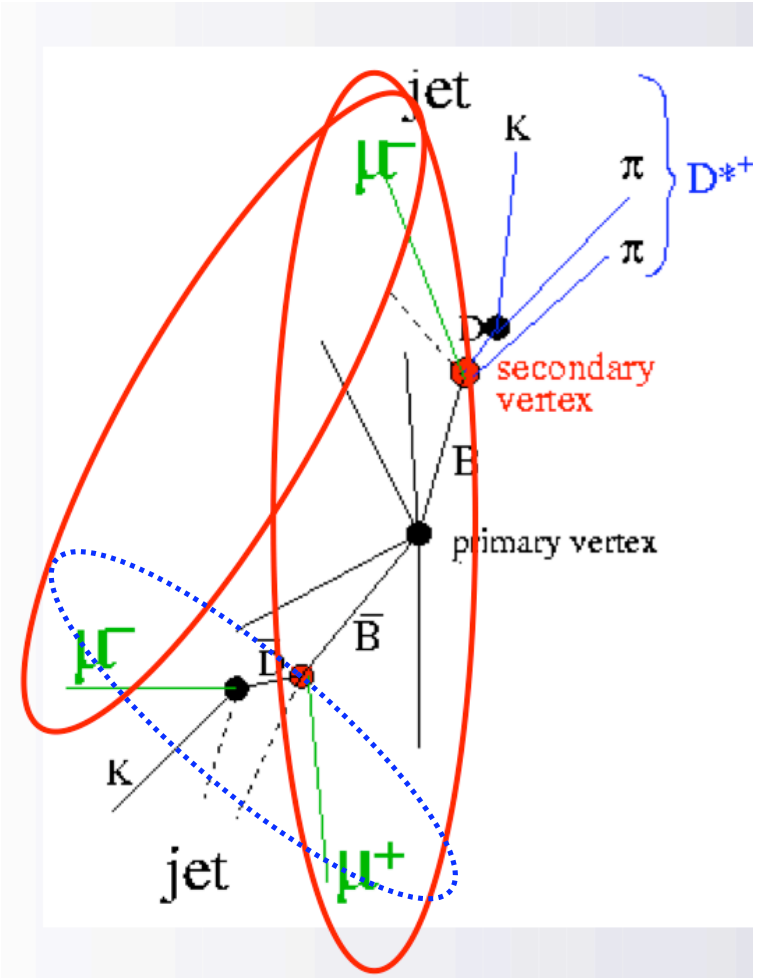
- events with at least 1 μ^+ (H1 99)
- events with 2 *jets* + 1 e^- (ZEUS 01, ZEUS 08)
- events with 1 .or. 2 *jets* + 1 μ^+ (2 x ZEUS 04, H1 05, ZEUS prel-08)
- events with 1 D^{*+} + 1 μ^+ (H1 05, ZEUS 07)
- events with 2 μ,s (ZEUS prel-08)
- Displaced Tracks (H1 05, 2 x H1 06, H1 prel-08)

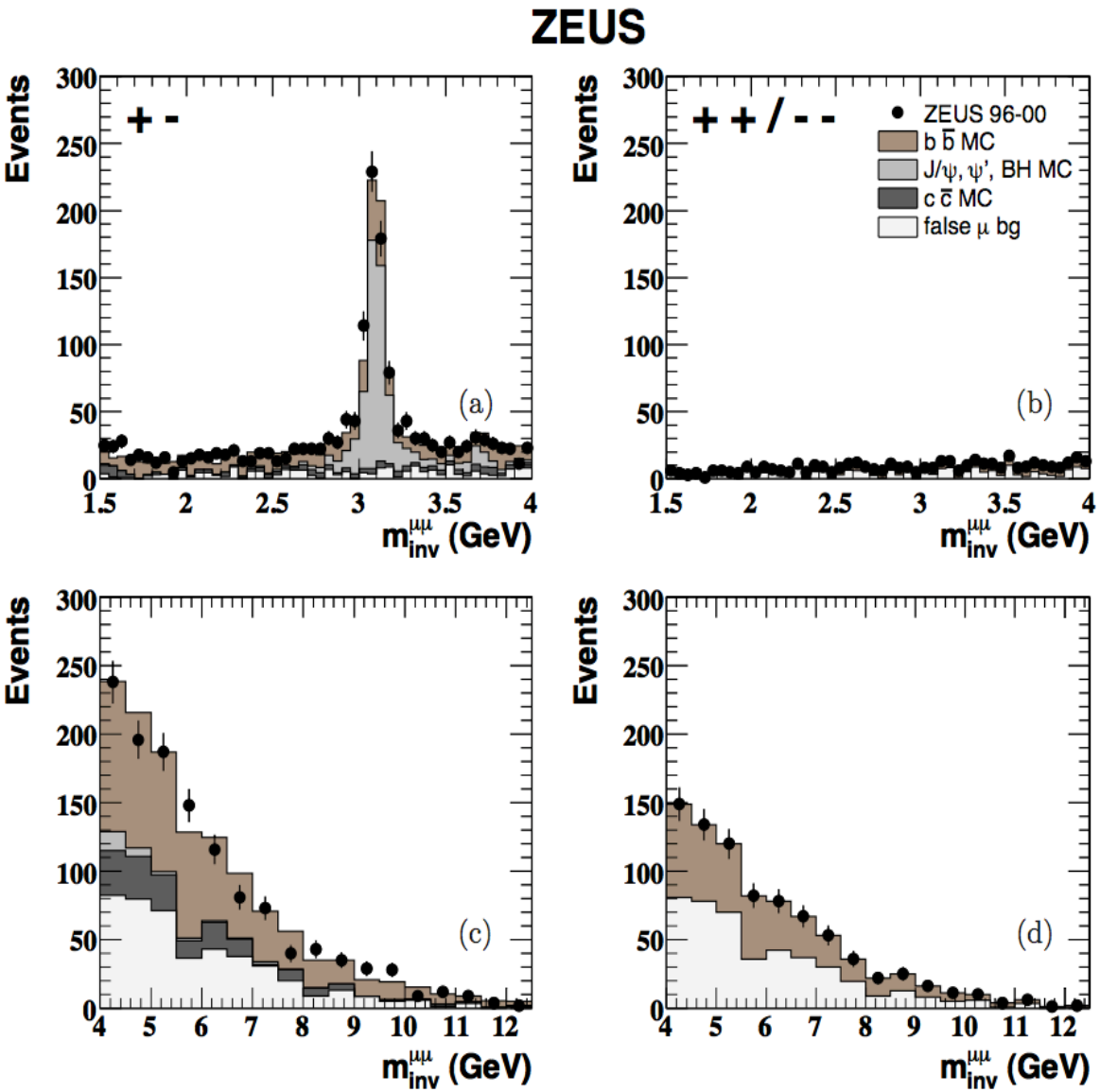
Tagging/measuring beauty: 2-muon events

ZEUS preliminary

⇨ large phase-space: large η(**b**) range, reach of low values of p_t(**b**)

- classify in ***4 samples*** based on the μ,s ***charges*** and $\mu\mu$ ***invariant mass***





Total bb cross sections VISible range:

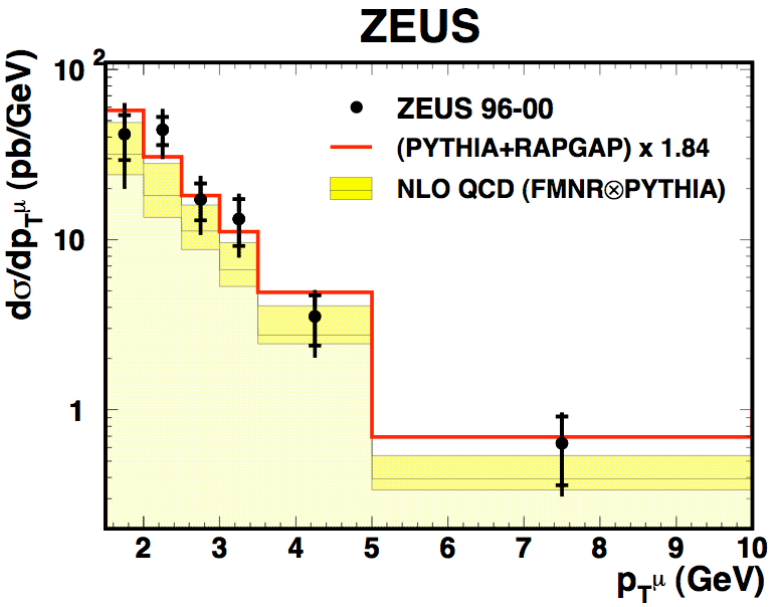
$$\sigma_{\rm vis}(ep \to b\bar{b}X \to \mu\mu X') = 55 \pm 7({\rm stat.})^{+14}_{-15}({\rm syst.})\ {\rm pb}$$
$$\sigma_{vis,NLO}(ep \to eb\bar{b}X \to e\mu\mu X) = 33^{+18}_{-8}({\rm NLO})^{+5}_{-3}({\rm frag.} \oplus {\rm br.})\ {\rm pb}$$

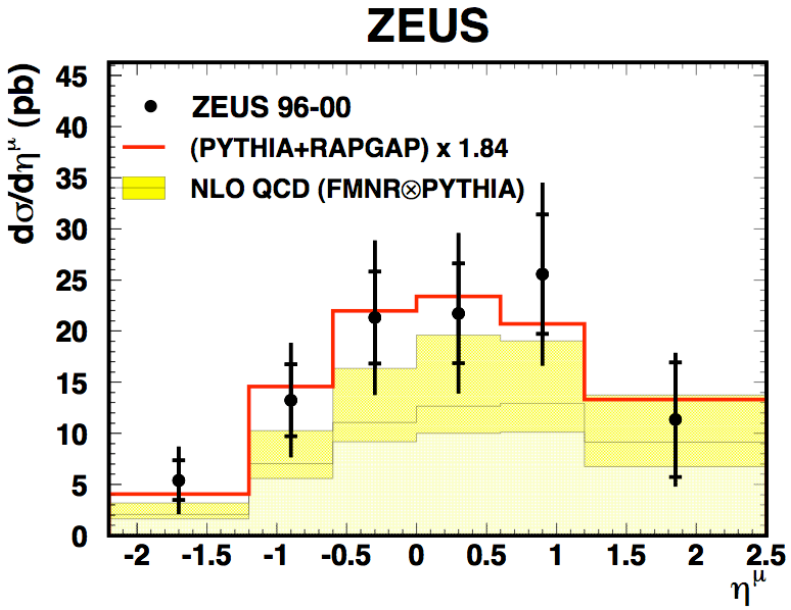
FMNR⊕PYTHIA, PDF(p): CTEQ5M, PDF(γ): GRV-G HO

Corresponding to a total cross section:

$$\sigma_{\rm tot}(ep \to b\bar{b}X) = 13.9 \pm 1.5({\rm stat.})^{+4.0}_{-4.3}({\rm syst.})\ {\rm nb}$$

Differential muon cross-sections (both μ,s: p_T> 1.5 GeV, -2.2< η< 2.5)





⇨ reasonable NLO description of shape and normalization; data slightly above

Tagging/measuring charm and beauty: D*-muon events

Total cc and bb cross-sections

$p_T(D^*) > 1.5$ GeV
$|\eta(D^*)| < 1.5$
$p(\mu) > 2$ GeV
$|\eta(\mu)| < 1.735$
$0.05 < y < 0.75$
$Q^2 < 1$ GeV^2

in VISible region

H1 89 pb^{-1}

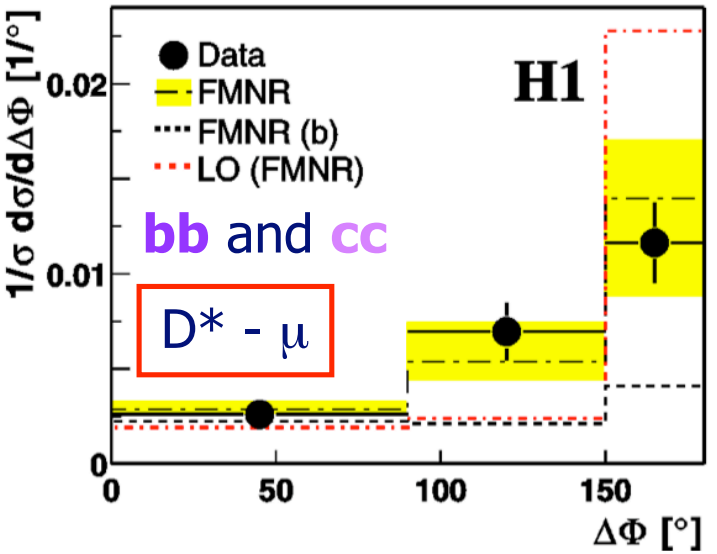
$$ep \to ec\bar{c}X \to eD^*\mu X'$$
$$ep \to eb\bar{b}X \to eD^*\mu X'$$

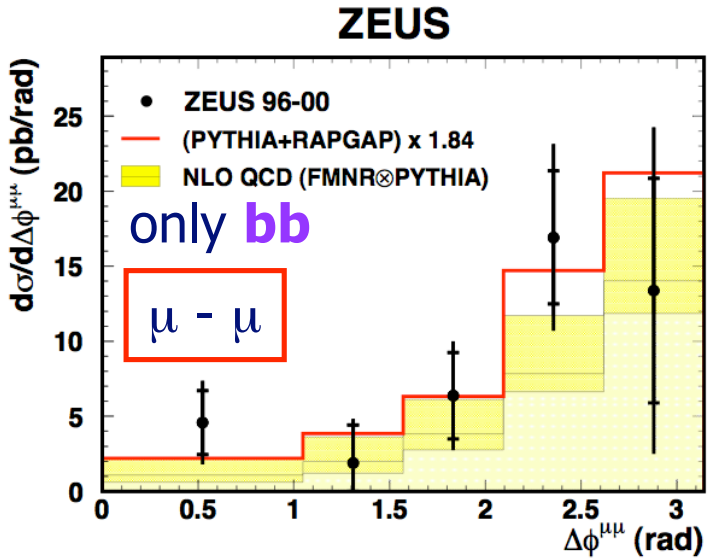
Charm	Cross section [pb]
Data	$250 \pm 57 \pm 40$
PYTHIA (direct)	242 (142)
CASCADE	253
FMNR	286^{+159}_{-59}
Beauty	
Data	$206 \pm 53 \pm 35$
PYTHIA (direct)	57 (44)
CASCADE	56
FMNR	52^{+14}_{-9}

FMNR⊕fragmen, PDF(p): CTEQ5M, PDF(γ): GRV-G HO

⇨ charm OK, beauty data above NLO

Azimuthal Correlations

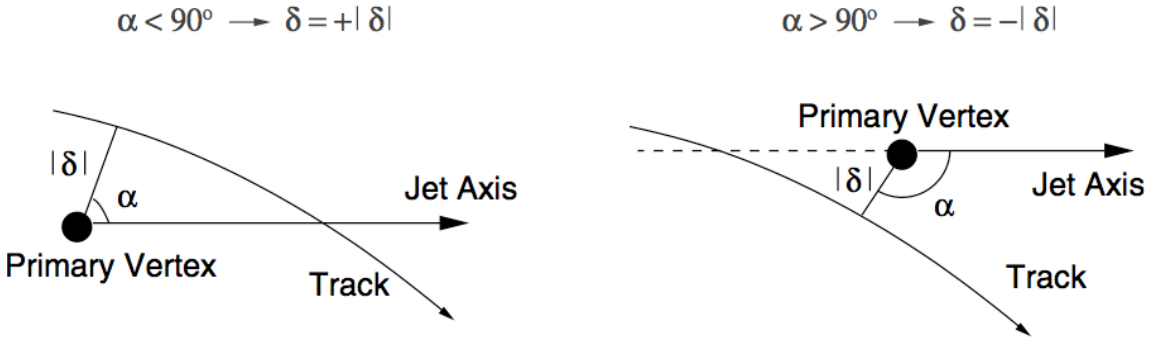


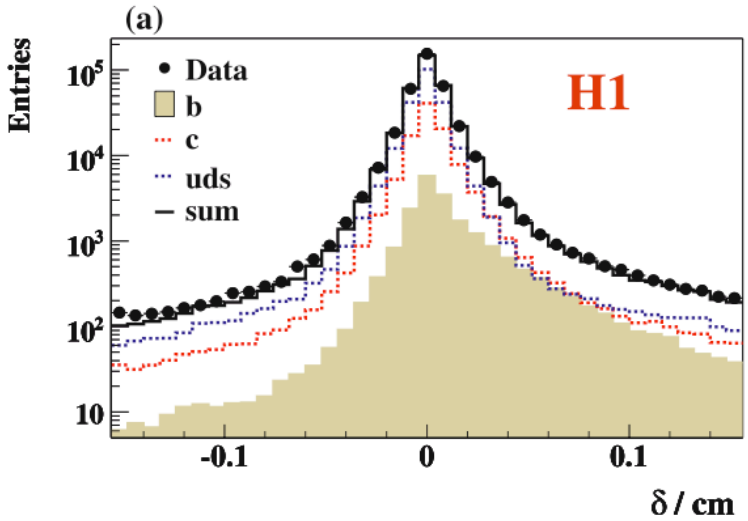


⇨ HO terms needed
good description by NLO

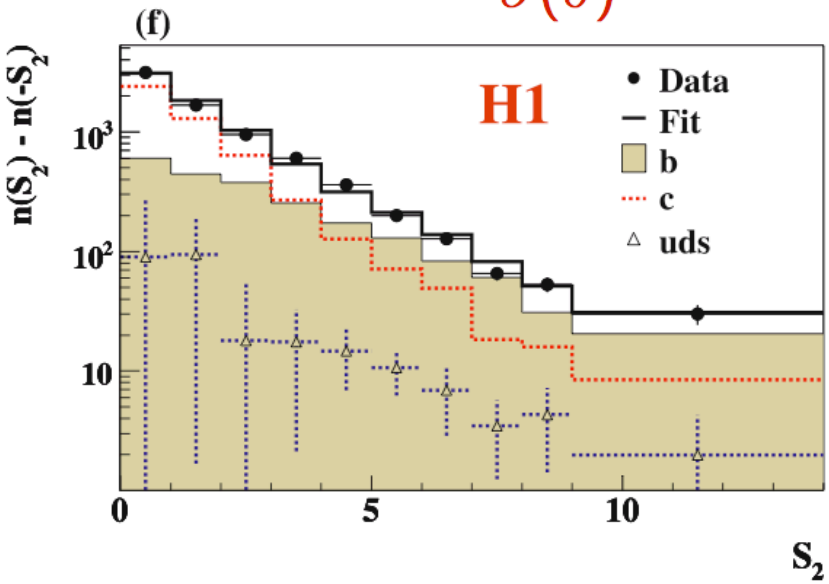
Tagging charm and beauty: Signed Impact Parameter Analysis (SIPA)

- w.r.t. the direction of the jet with highest p_t^{jet} or, if no jet, that of the "hadronic system" γ_h





$$S = \frac{\delta}{\sigma(\delta)}$$



- S_1 (S_2): Significance of highest (2nd high.) Significance tracks of those associated to a jet
- Calculate S_1 and S_2 from PYTHIA for (u,d,s) , c and b events separately

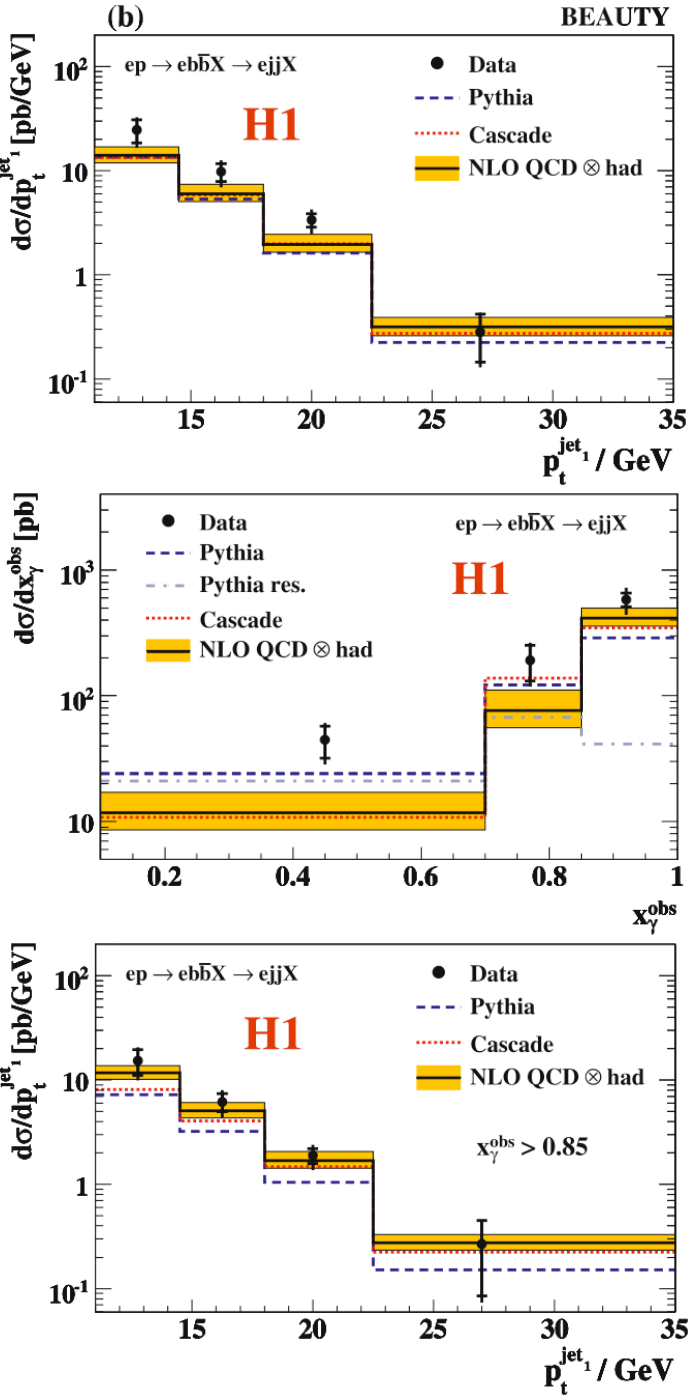
⇨ Extract c and b contributions from fit to subtracted Significance distributions

Measurement of 2-jet cross-sections in beauty photo-production

H1 57 pb^{-1}

H1 EPJC47(2006)597

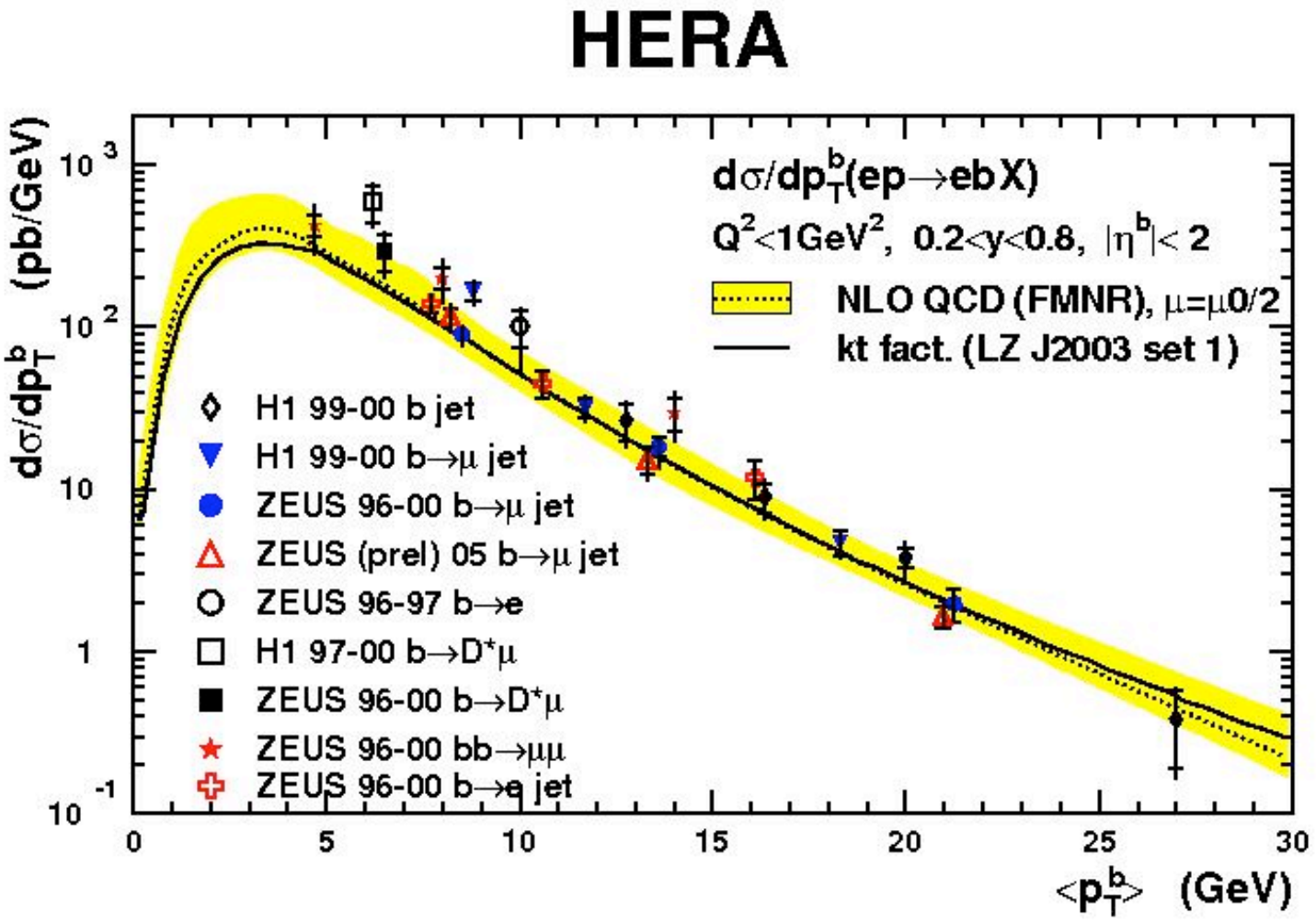
- Q^2 < 1 GeV
- 2 jets: k_t algorithm,
  $-0.9 < \eta < 1.3$,
  $p_t^{jet1(2)} > 11(8)$ GeV
- c and b from SIPA



⇨ **b** cross-sections tend to be above NLO-QCD

⇨ difference mainly from x_γ < 0.85 (resolved do.)

Overall view of beauty photo-production at HERA



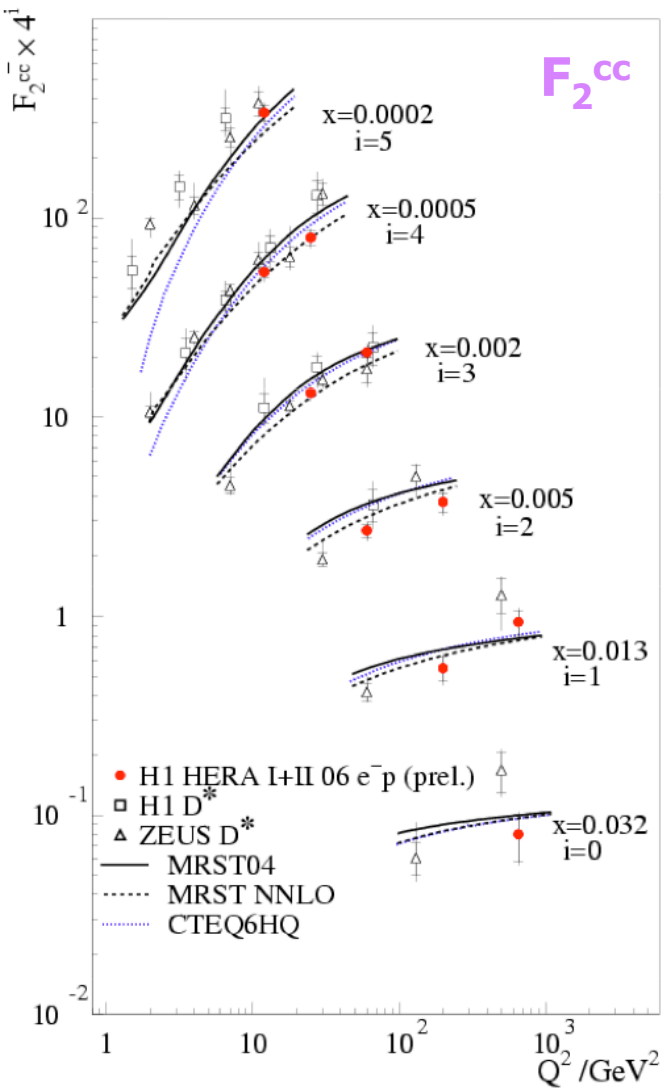
⇨ Many independent measurements performed

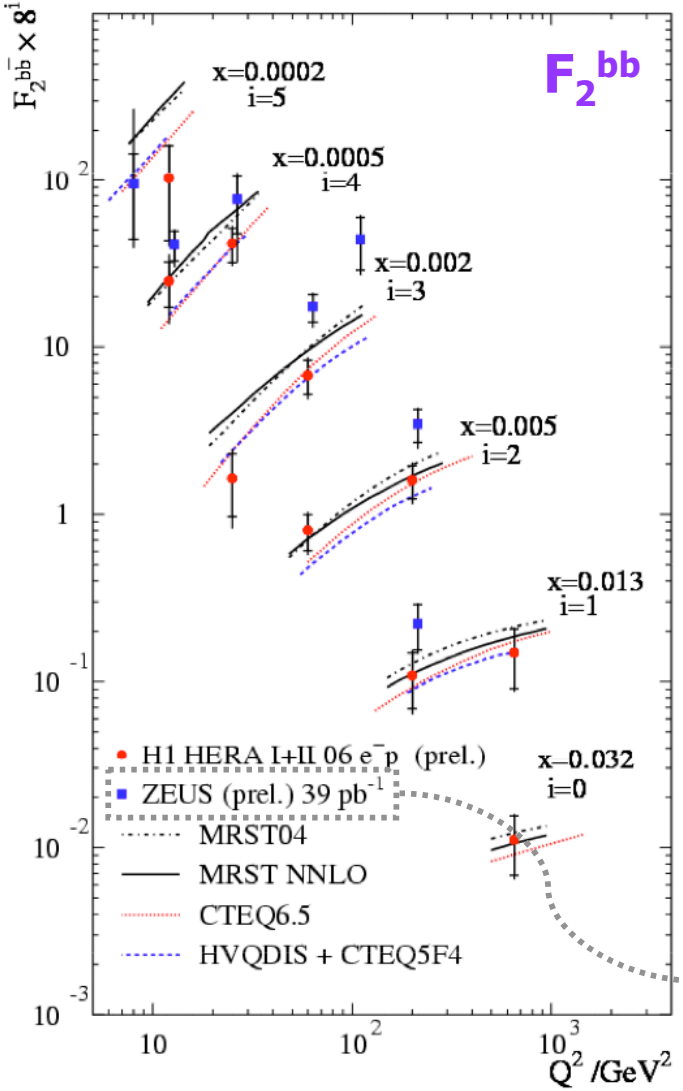
⇨ Trend to be slightly above NLO-QCD (particularly at low PT)

⇨ HERA II data will reduce significantly stat.⊕syst. uncertainties

Measurement of the contributions to the proton´s F_2 from charm (F_2^{cc}) and beauty (F_2^{bb}) using SIPA

- F_2^{cc} and F_2^{bb} are obtained from the corresponding (x,Q^2) differential σ





⇨ First meas. of F_2^{bb}

⇨ Agreement with other techniques

⇨ First NNLO calc. available

⇨ Large spread in theo. predictions

⇨ Measurements consistent with theo. expectations

ZEUS preliminary jet-μ method

SUMMARY and CONCLUSIONS

- ⇨ charm is produced copiously at HERA
- ⇨ measurement of fragmentation variables consistent with universality
- ⇨ highly non trivial tests of p-QCD carried out
- ⇨ HERA II data opens the era of precision charm physics and p-QCD tests

- ⇨ low beauty cross-section at HERA
- ⇨ many different/independent measurements made with consistent results
- ⇨ beauty production slightly above NLO-QCD expectations

- ⇨ F_2^{cc} and F_2^{bb} measured at HERA; reasonably description by NLO-QCD
- ⇨ HERA II data will (further) allow to increase greatly our understanding of p-QCD