

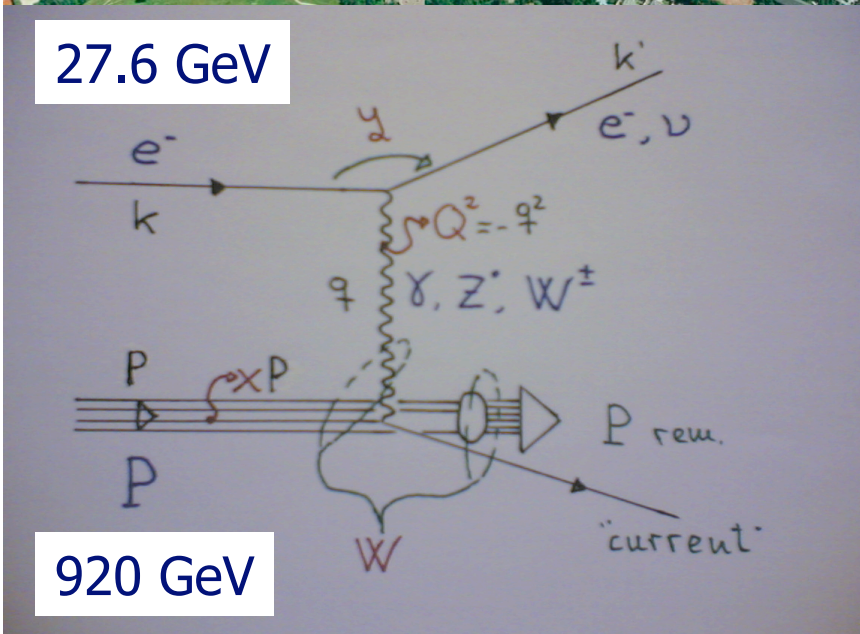
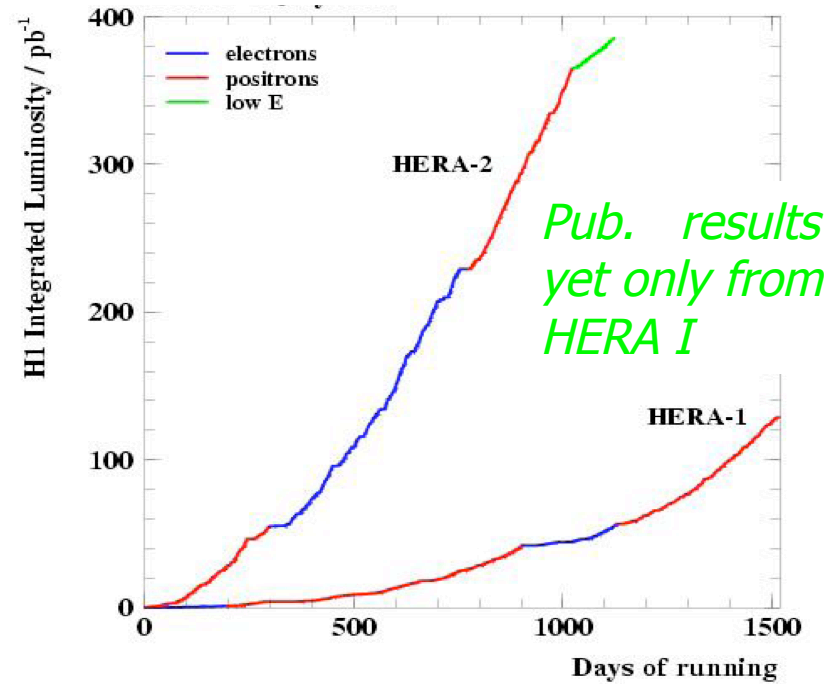
A taste of Heavy Flavour physics at **HERA**

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



27.6 GeV

920 GeV

Different reactions:

- according to *charge* of ex. boson:

NC: γ, Z^0 **CC:** W^{+-}

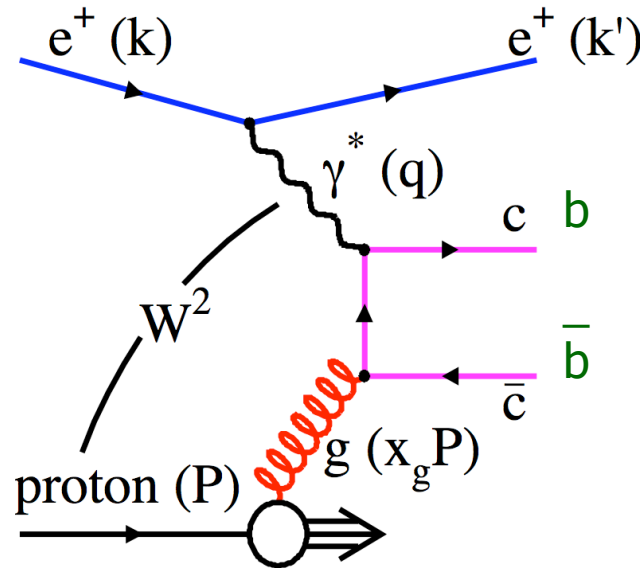
- according to its *virtuality*:

DIS: $Q^2 > 2(?) \text{ GeV}^2$;

γ -production: $Q^2 \approx 0 \text{ GeV}$ (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



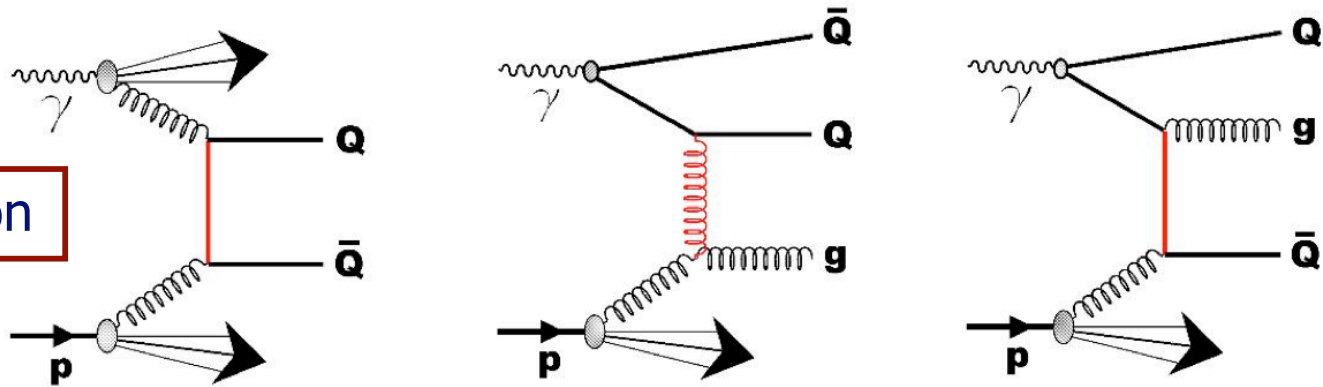
Multiple scales involved:

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

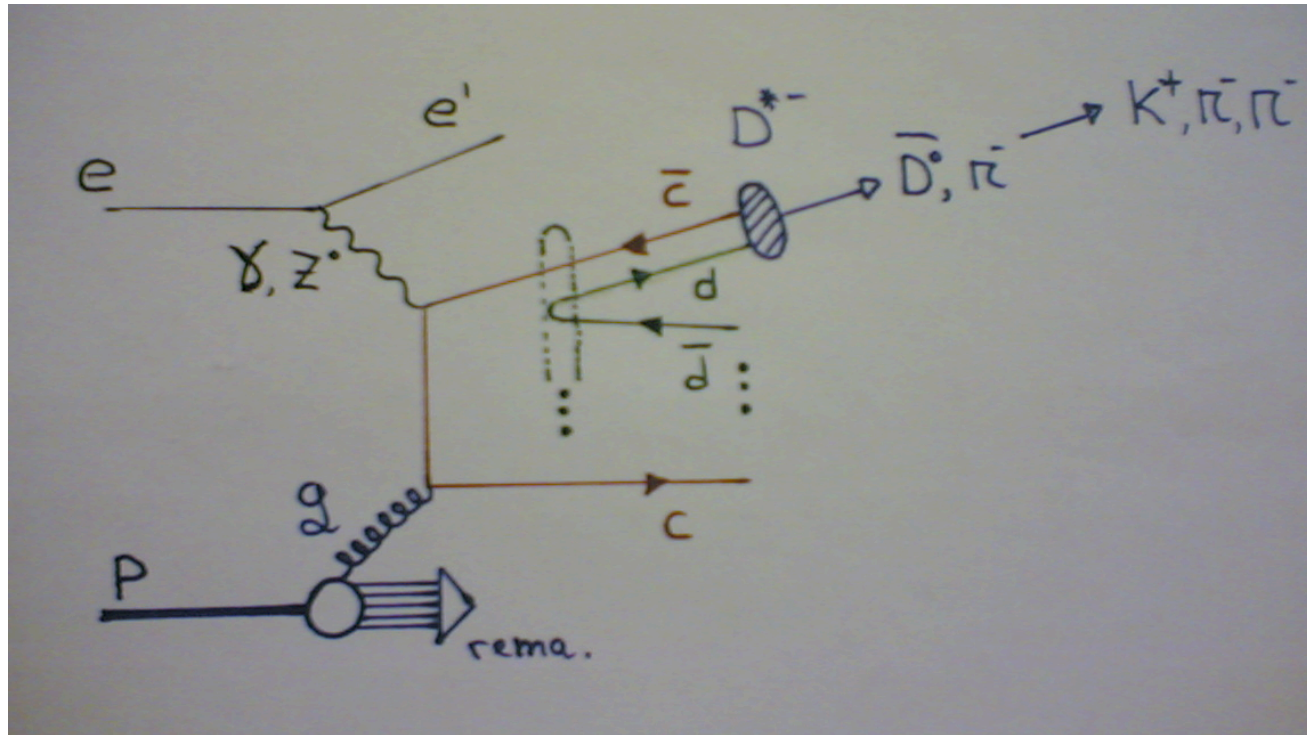
Powerful tool for testing p structure and the applicability of p QCD

- 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 $c\bar{c}$ BGF reaction



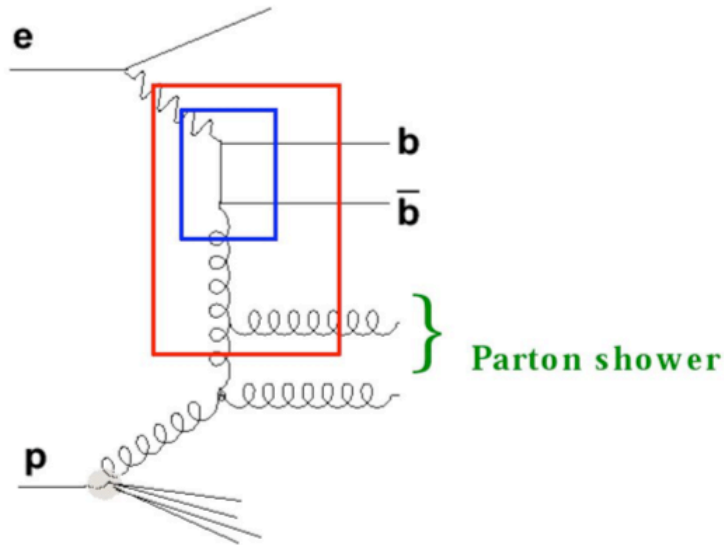
Factorization is assumed:

$$\sigma = P(+\gamma) \text{ structure}(s) \otimes \text{QCD m.e.} \otimes \text{fragmentation \& decays}$$

⇒ 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

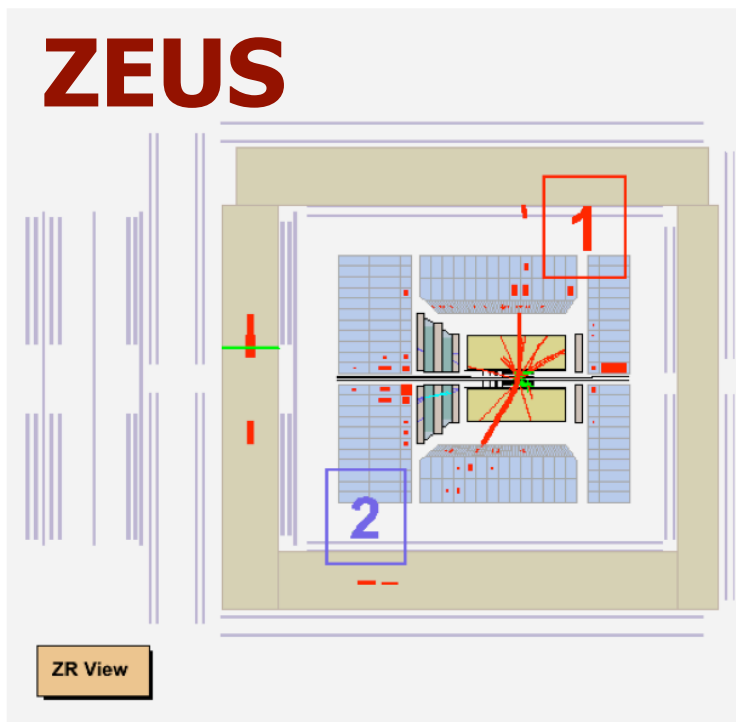
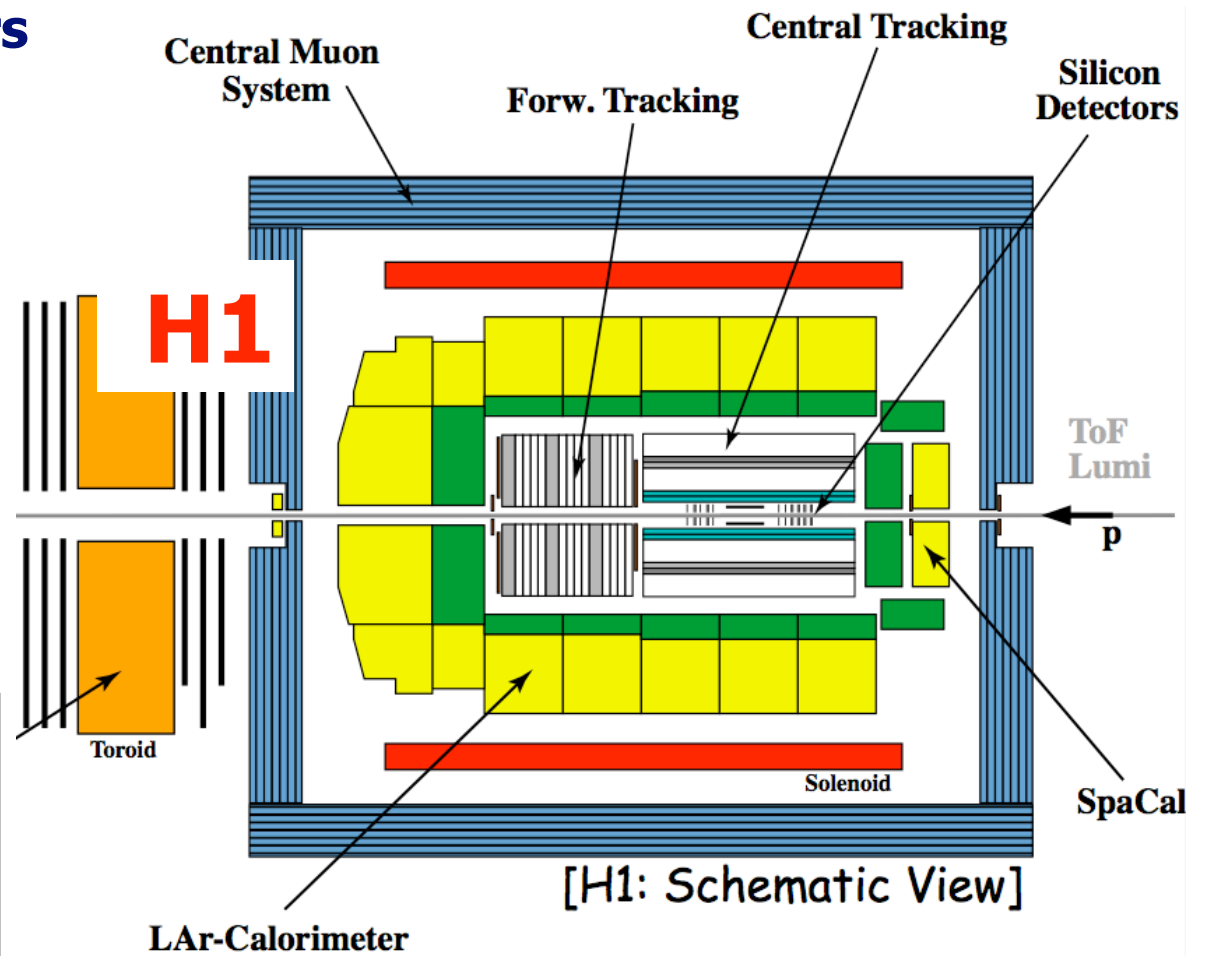
MONTE CARLO

- 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 II₆

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)

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

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

Pseudo-scalar mesons: D^0, D^\pm, D_s^\pm

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

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

golden channel

copious production

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

Baryons: Λ_c^\pm

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

Excited mesons: $D_1(2420)^0, D_2^*(2460)^0, D_{s1}(2536)^\pm$

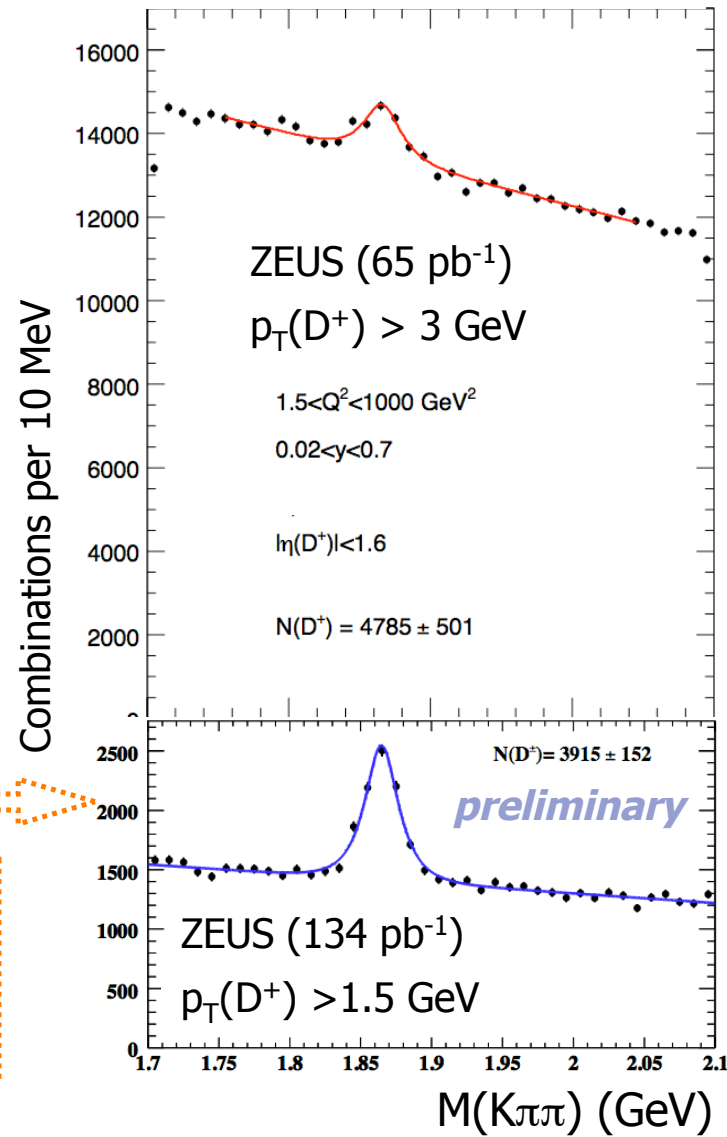
$$D_1(2420)^0 \rightarrow D^{*+} \pi^-,$$

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

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

not shown

Example signal (no golden)



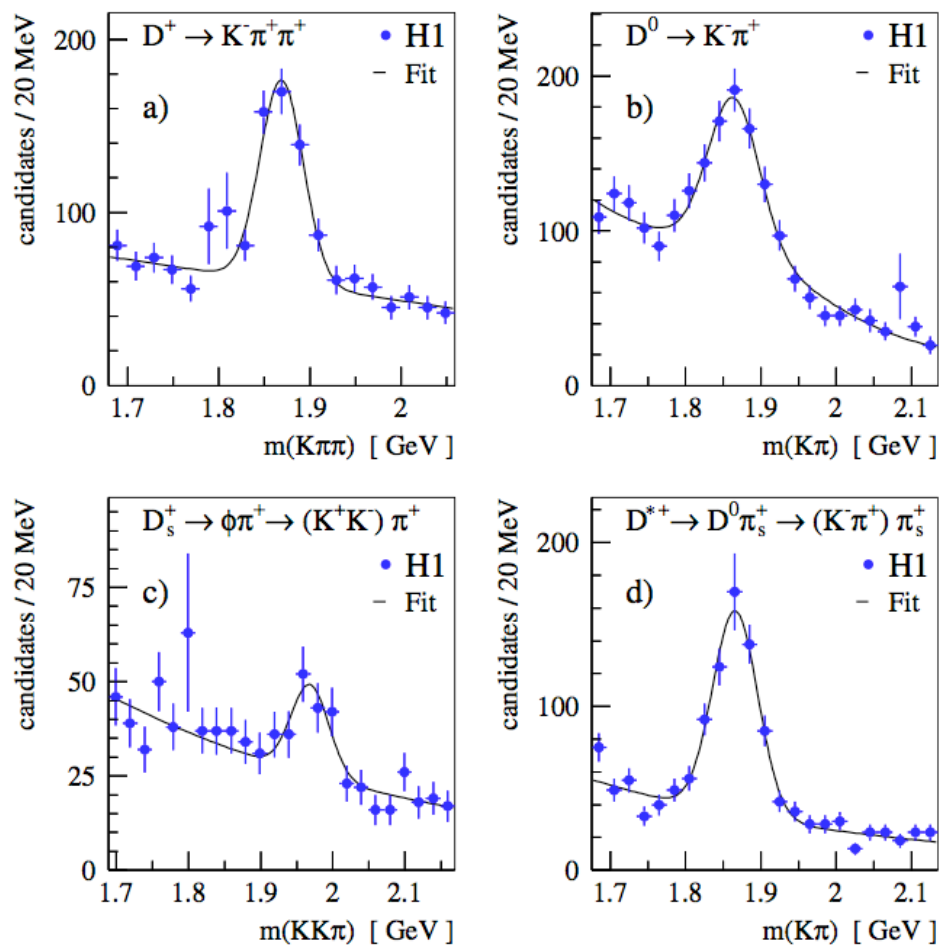
use of μ VTX detector for reconstructing secondary vertices

Charm fragmentation

Other important example signals:

H1 48 pb^{-1}

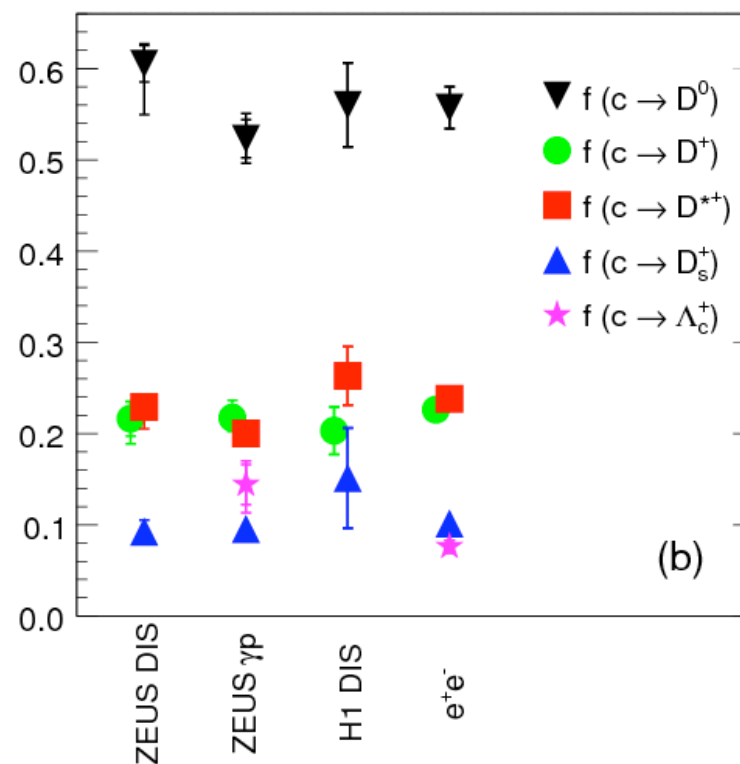
$2 < Q^2 < 100 \text{ GeV}^2$; μVTX used



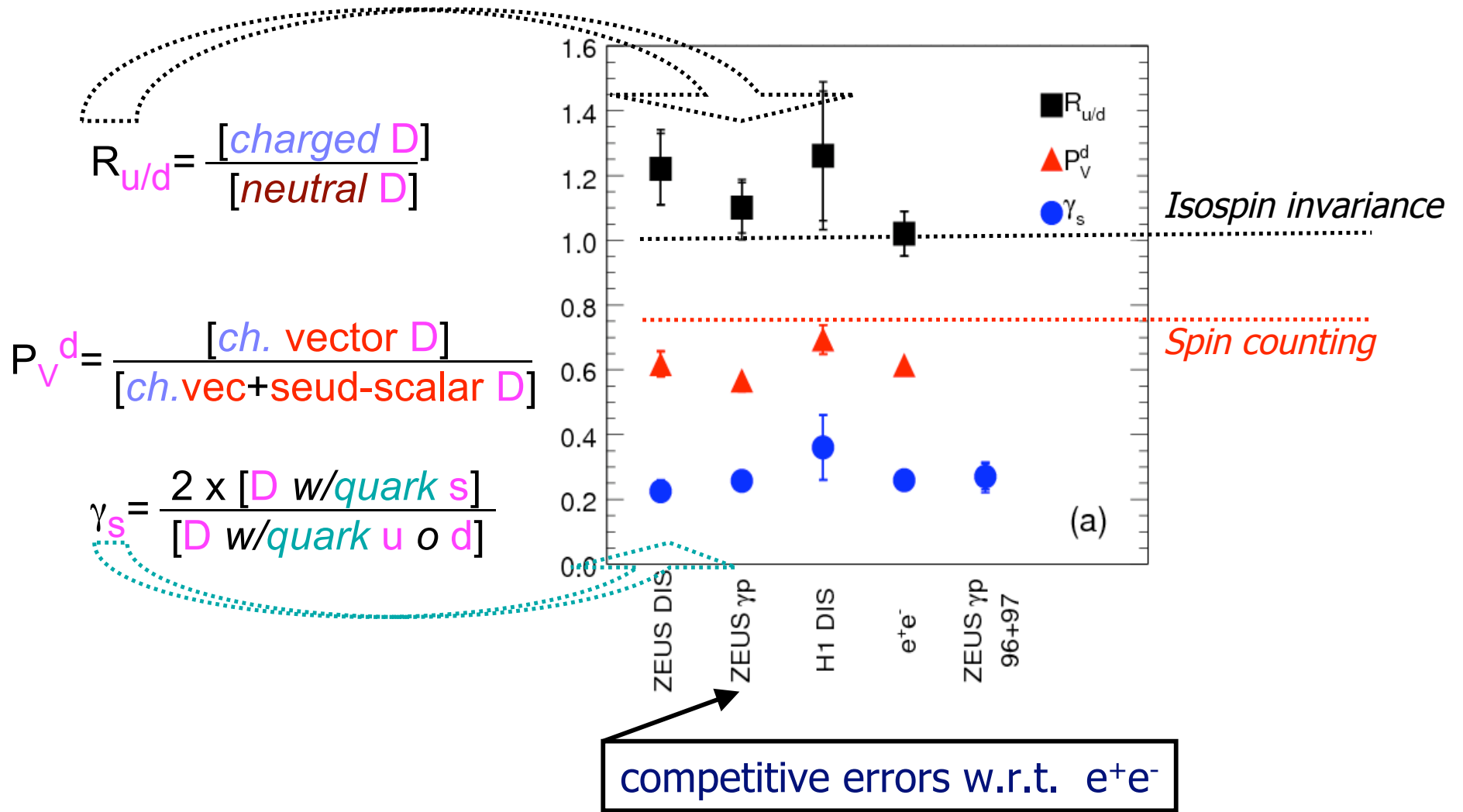
⇒ Very good S/B ratio

Charm fragmentation fractions

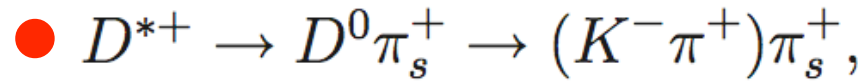
$$f(c \rightarrow D_j) = \sigma(D_j) / \sum_i \sigma(D_i)$$



Fragmentation ratios from charm mesons measurements



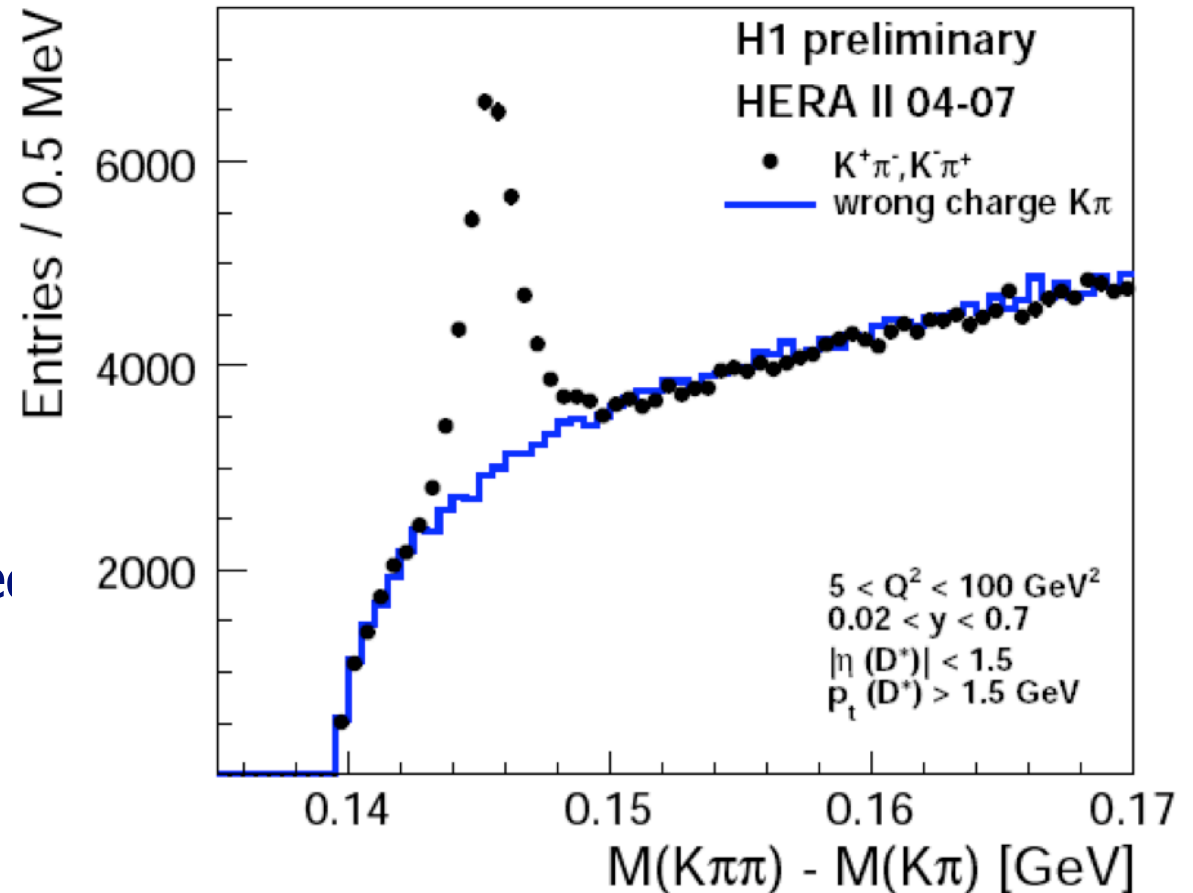
D meson (charm) production cross-sections; p-QCD comparisons



Golden channel:

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

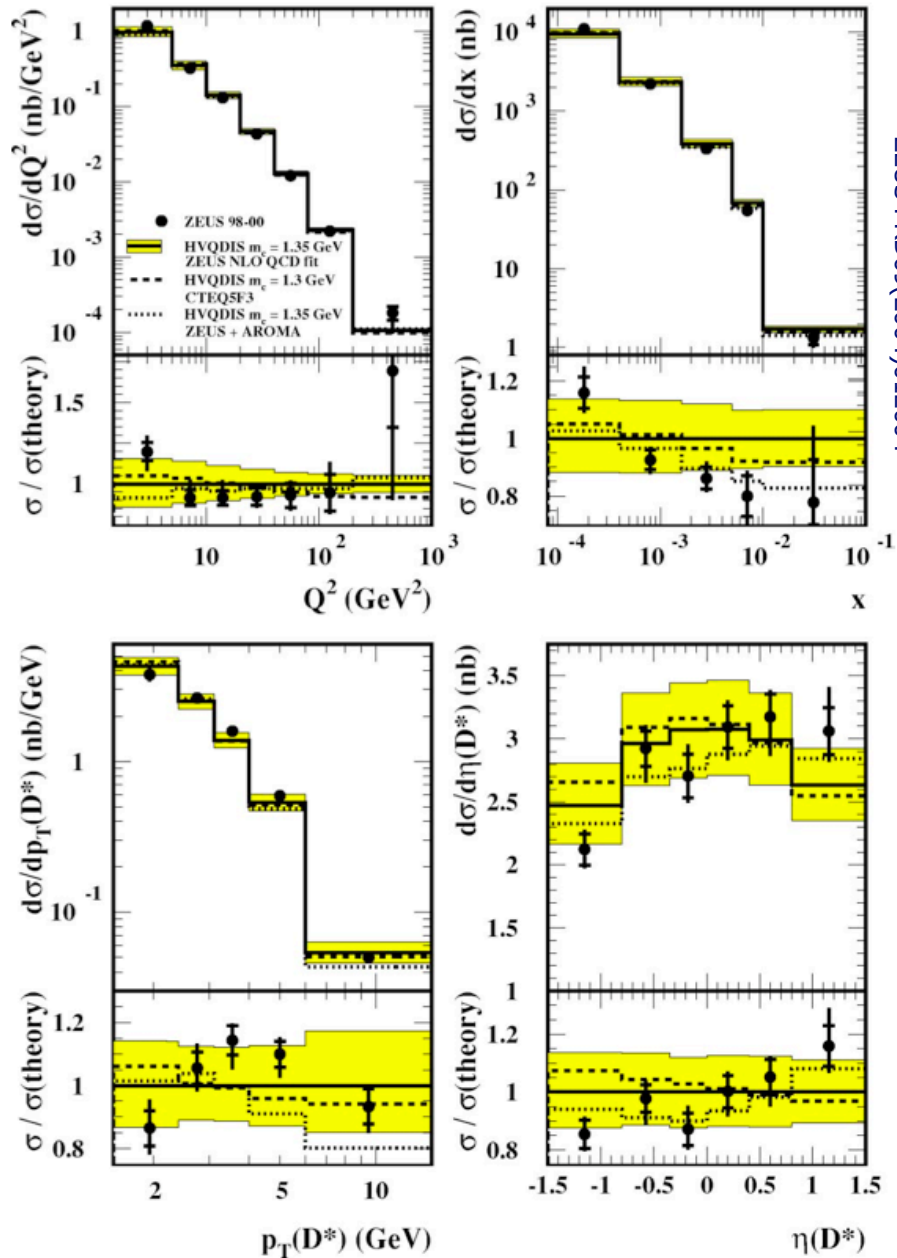
- ⇒ very restricted kinematics
- > low phase space allowed
- ⇒ low combinatorial bkg.



● also D^0 , D^\pm , D_s ...

Differential cross-sections

ZEUS 82 pb⁻¹ D*⁺

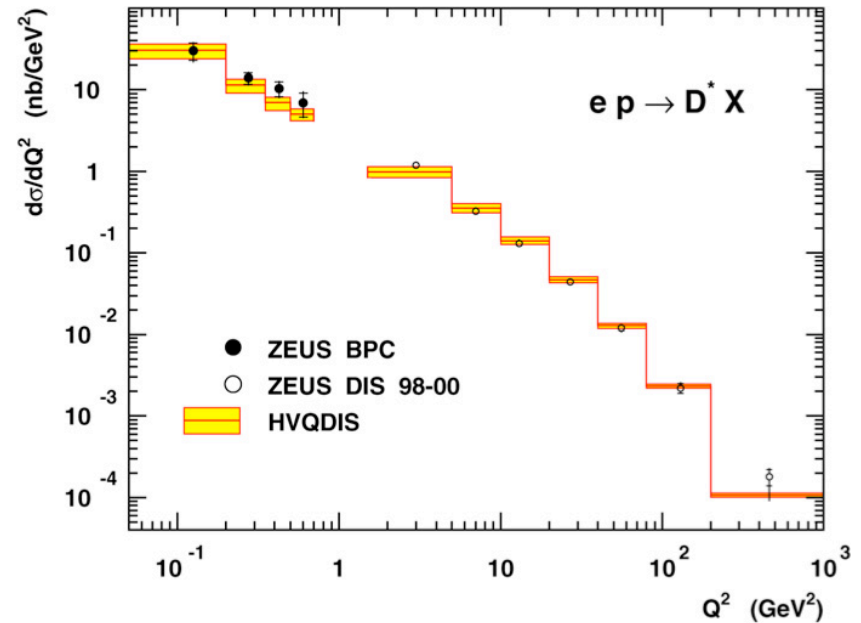


- ⇒ behavior as expected
- steep Q^2 , p_T
 - mild η dependence
 - rising towards lower- x

Extending to very low Q^2 :

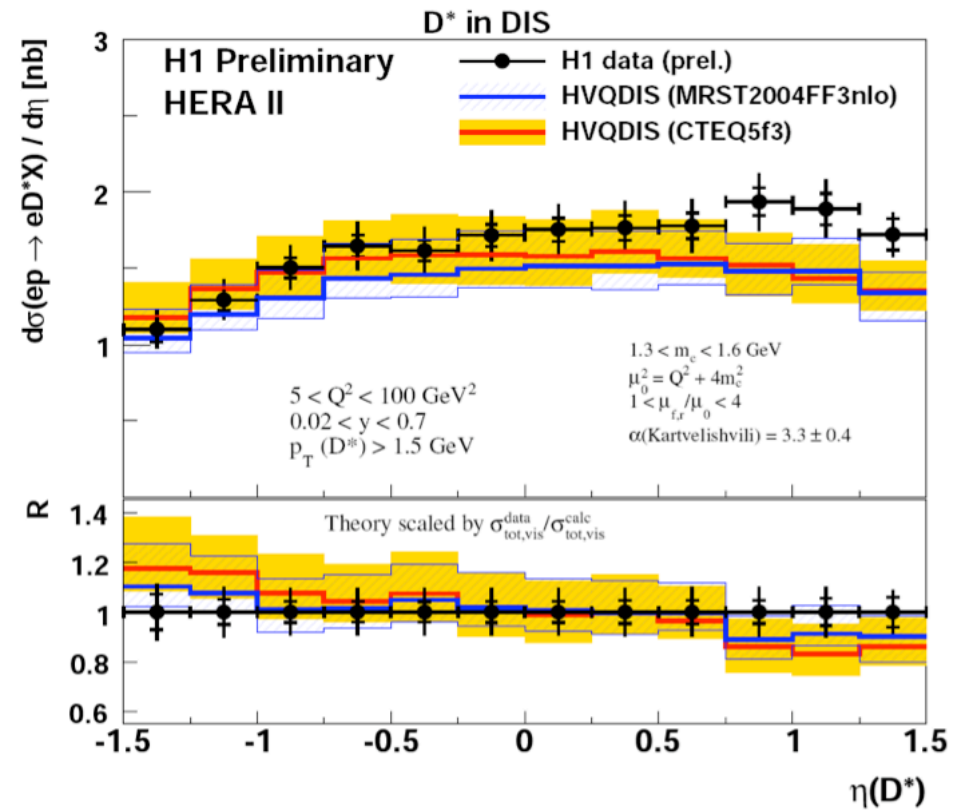
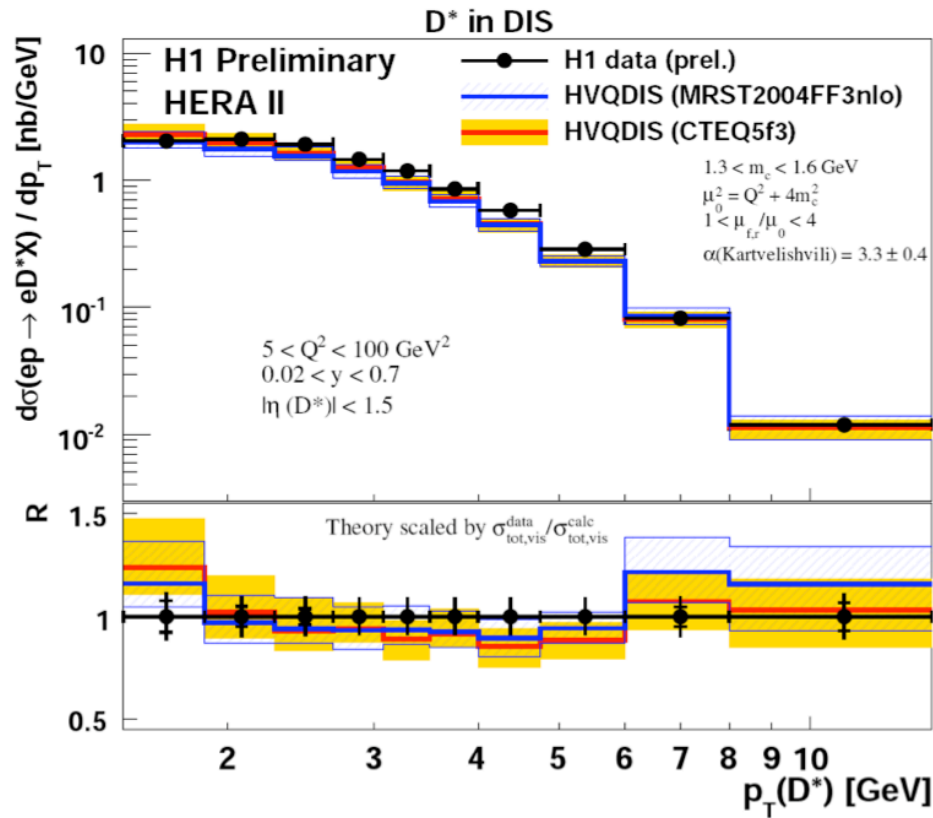
ZEUS PLB649(2007)111

ZEUS 82 pb⁻¹



⇒ good description by NLO-QCD¹³

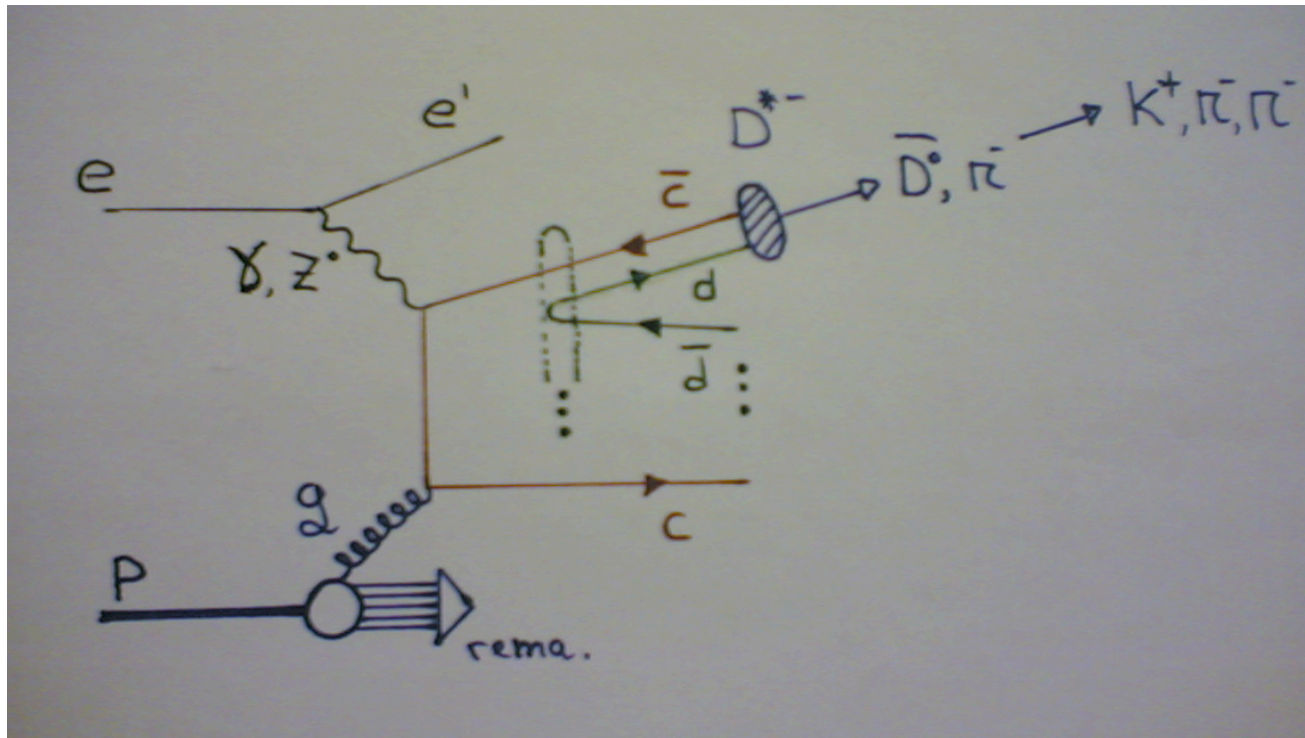
HERA II data analysis at full speed:



... conclusions qualitative similar but ...

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

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



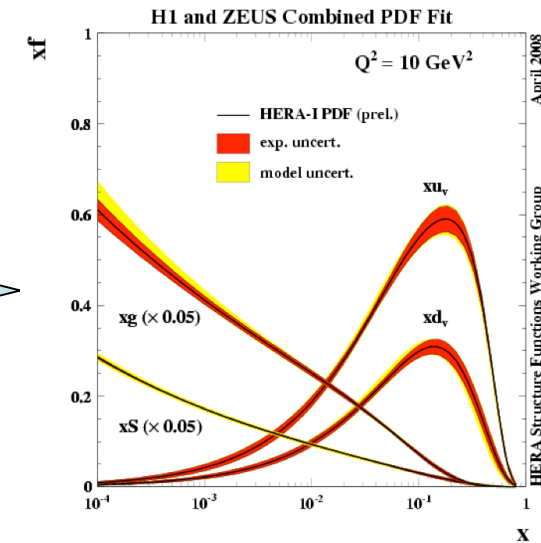
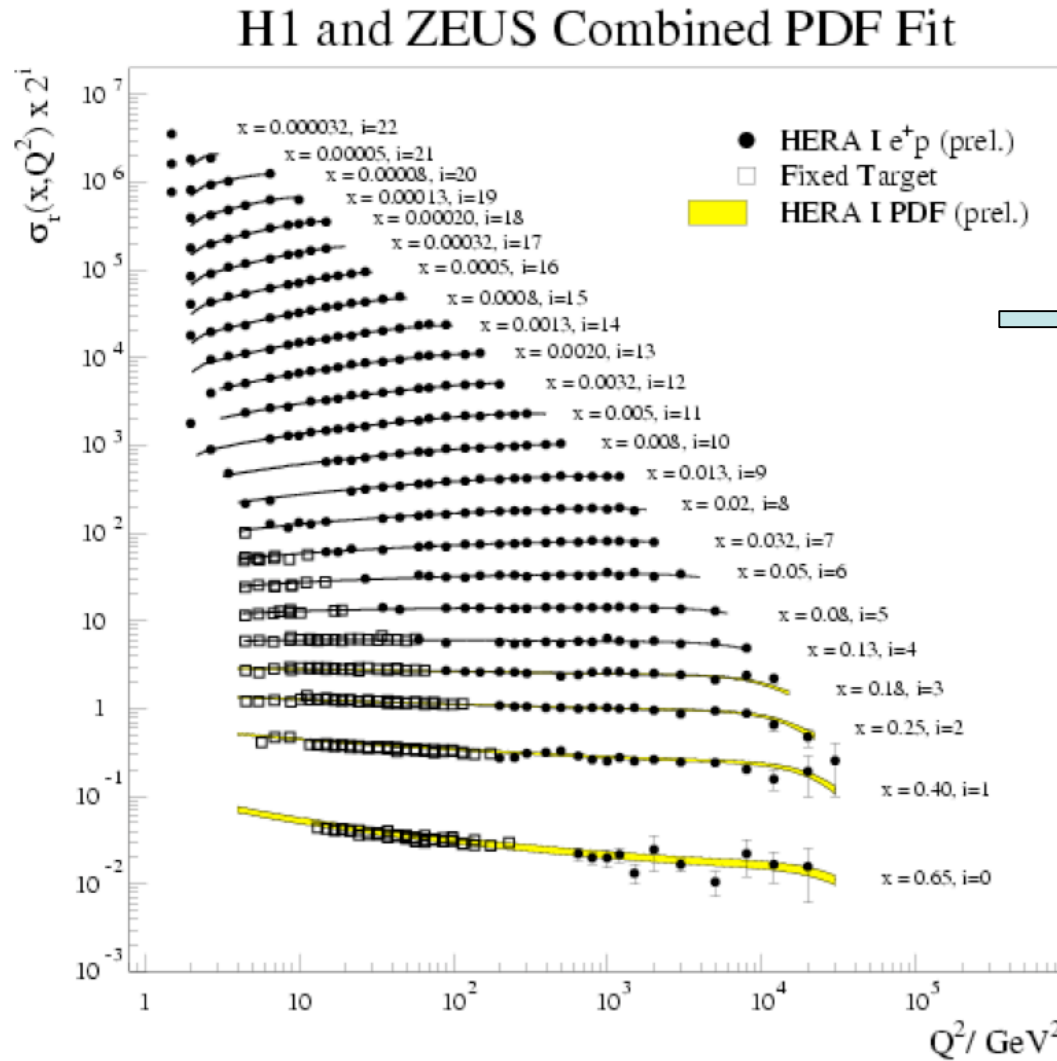
$$\sigma = \text{P structure} \otimes \text{QCD m.e.} \otimes \text{fragmentation \& decays}$$

measured at this/other experiments

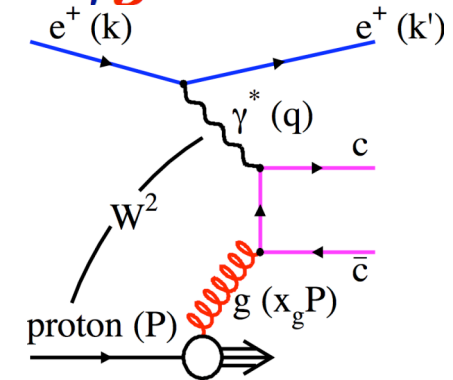
calculated at NLO

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 $[ep \rightarrow eX]$ consistent with the *g* initial state of the reaction $\gamma g \rightarrow c\bar{c}$?



\Rightarrow highly non trivial test of the validity of p-QCD

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

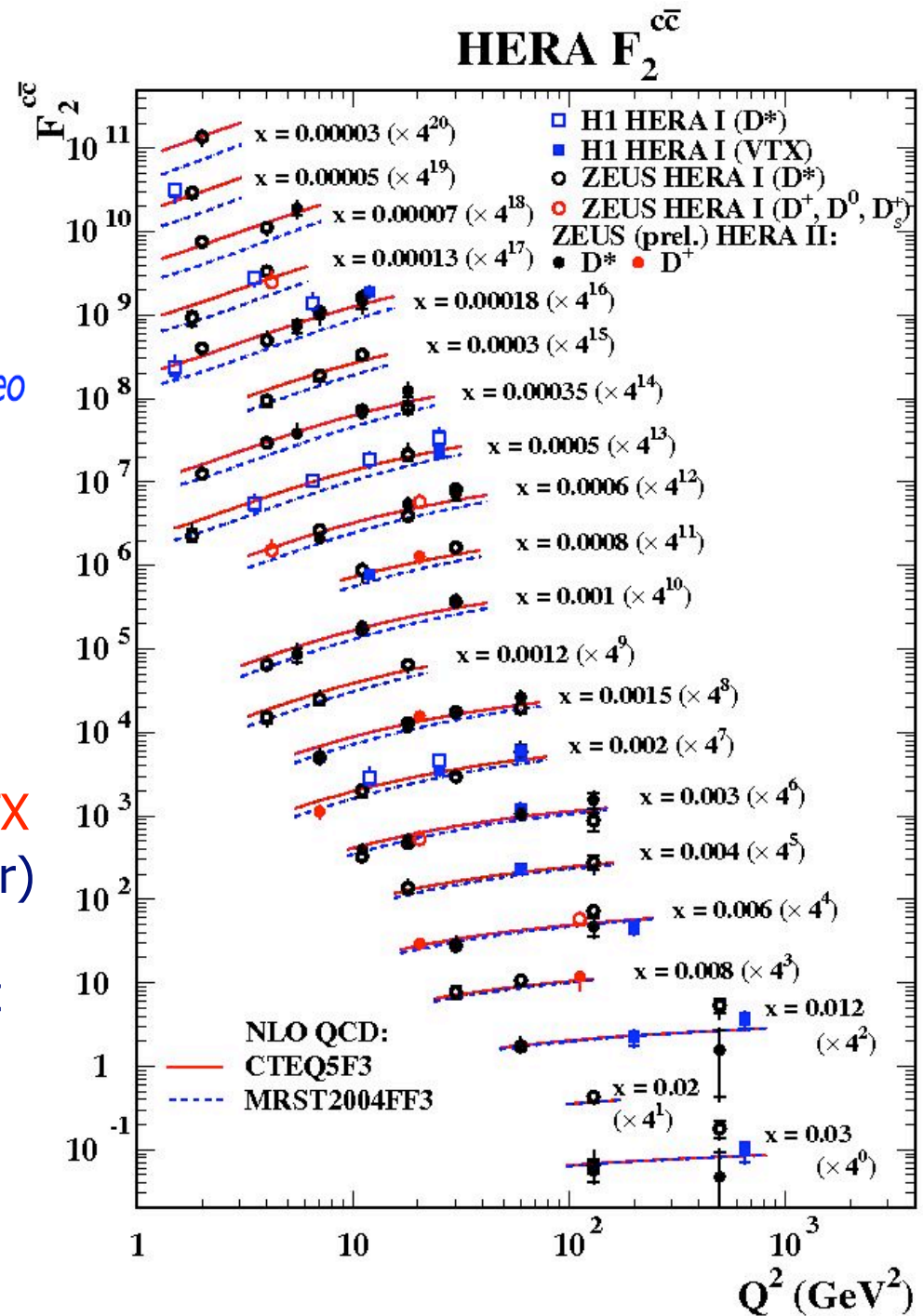
$$F_{2,meas}^{c\bar{c}}(x_i, Q_i^2) = \frac{\sigma_{i,meas}(ep \rightarrow D^* X)}{\sigma_{i,theo}(ep \rightarrow D^* X)} F_{2,theo}^{c\bar{c}}$$

⇒ Extrapolation factors: 1.4 - 4

⇒ impressive agreement to the μ VTX 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:

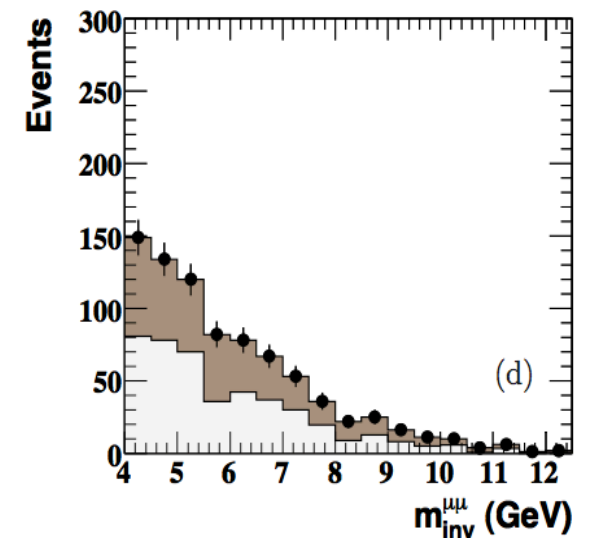
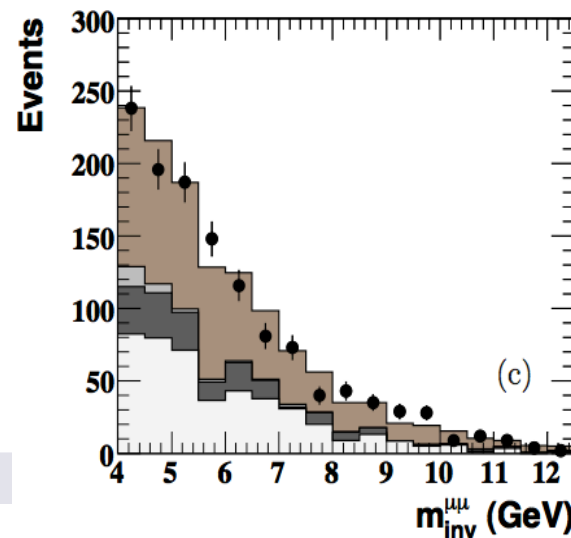
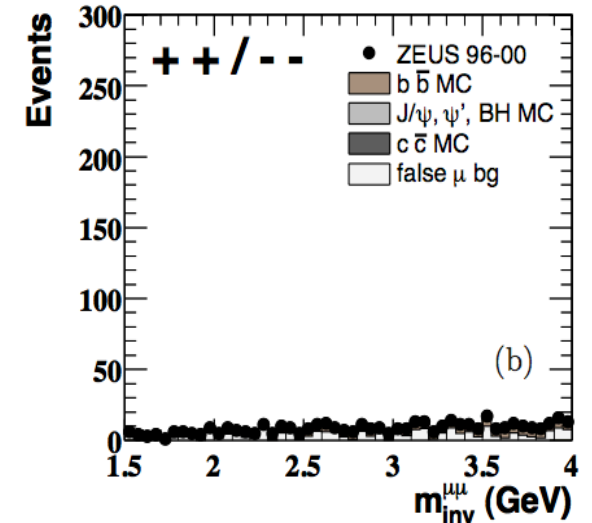
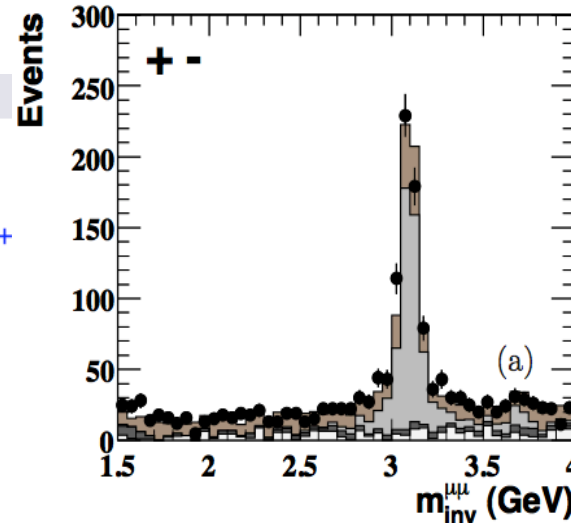
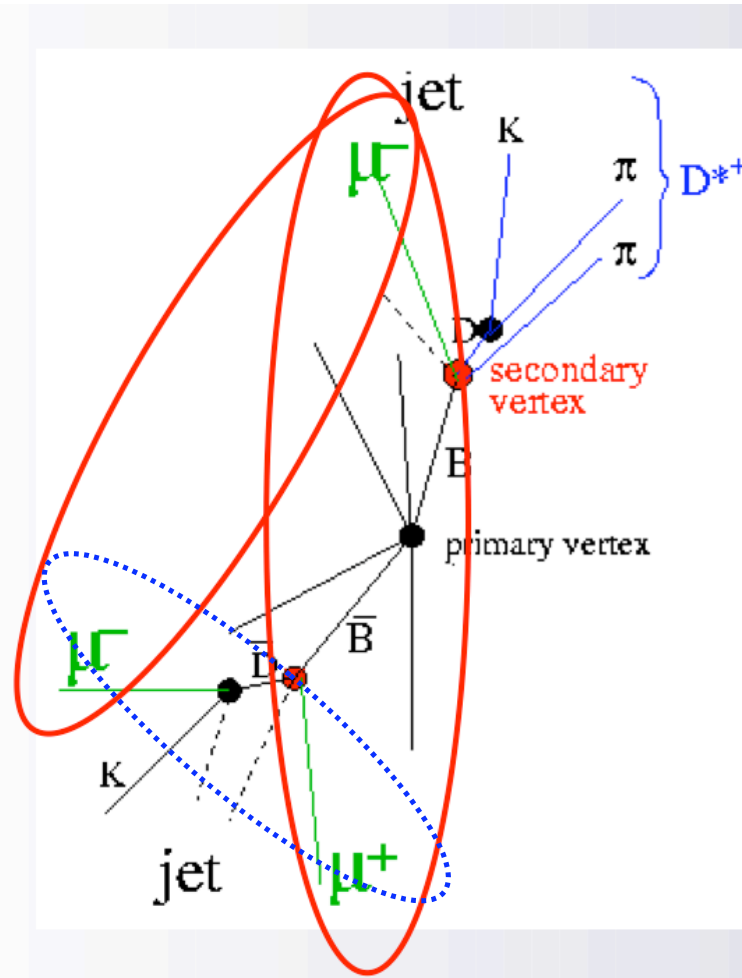
- events with at least 1 μ^+ (H1 99)
- events with 2 *jets* + 1 e^- (ZEUS 01, ZEUS 08)
- events with 1 .or. 2 *jets* + 1 μ^+ (2 x ZEUS 04, H1 05, ZEUS prel-08)
- events with 1 D^{*+} + 1 μ^+ (H1 05, ZEUS 07)
- events with 2 μ, s (ZEUS prel-08)
- Displaced Tracks (H1 05, 2 x H1 06, H1 prel-08)

Tagging/measuring beauty: 2-muon events

⇒ large phase-space: large $\eta(\mathbf{b})$ range, reach of low values of $p_t(\mathbf{b})$

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

ZEUS



Total bb cross sections VISible range:

$$\sigma_{\text{vis}}(ep \rightarrow b\bar{b}X \rightarrow \mu\mu X') = 55 \pm 7(\text{stat.})_{-15}^{+14}(\text{syst.}) \text{ pb}$$

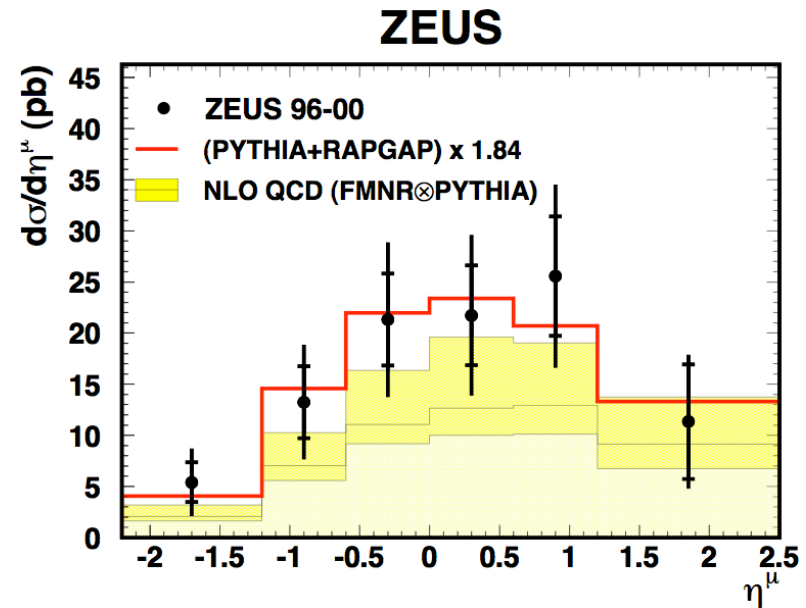
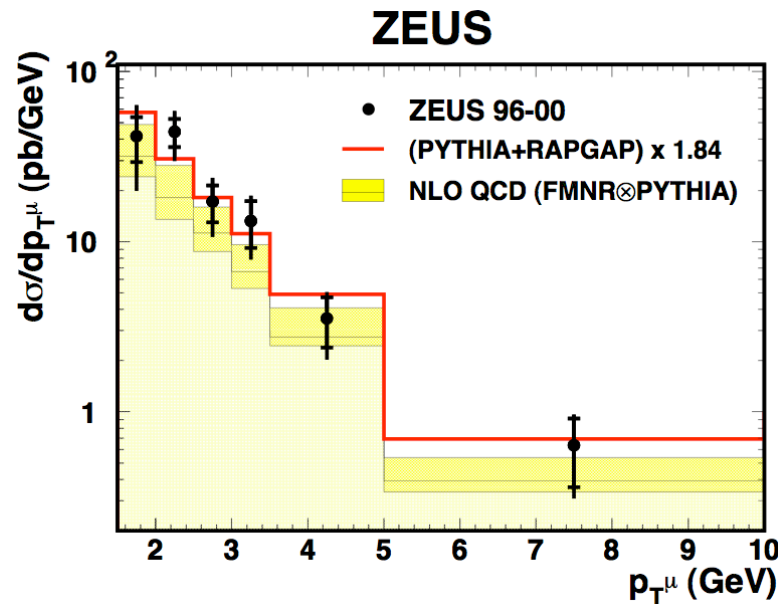
$$\sigma_{\text{vis},NLO}(ep \rightarrow ebb\bar{X} \rightarrow e\mu\mu X) = 33_{-8}^{+18}(\text{NLO})_{-3}^{+5}(\text{frag.} \oplus \text{br.}) \text{ pb}$$

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

Corresponding to a total cross section:

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

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

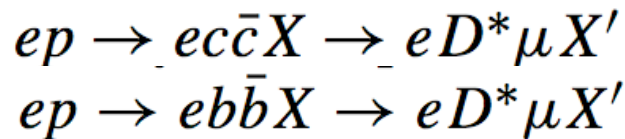
Tagging/measuring charm and beauty: D^* -muon events

Total cc and bb cross-sections

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

in VISible region

H1 89 pb^{-1}

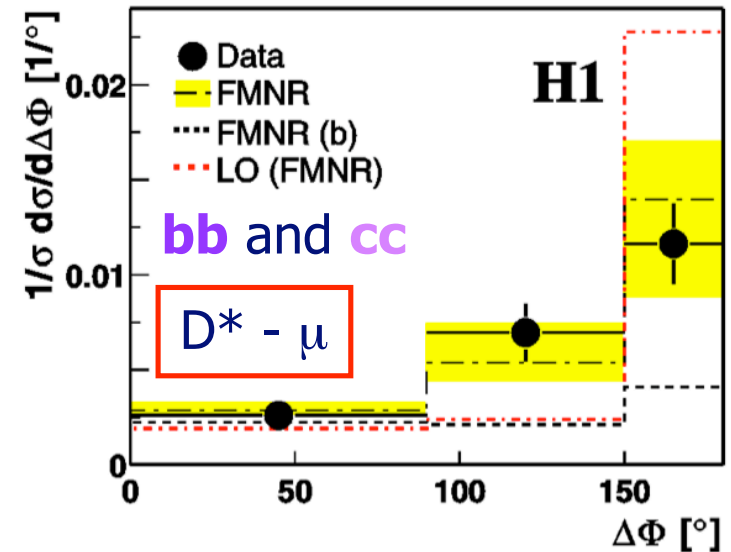


Charm	Cross section [pb]
Data	$250 \pm 57 \pm 40$
PYTHIA (direct)	242 (142)
CASCADE	253
FMNR	286^{+159}_{-59}
Beauty	
Data	$206 \pm 53 \pm 35$
PYTHIA (direct)	57 (44)
CASCADE	56
FMNR	52^{+14}_{-9}

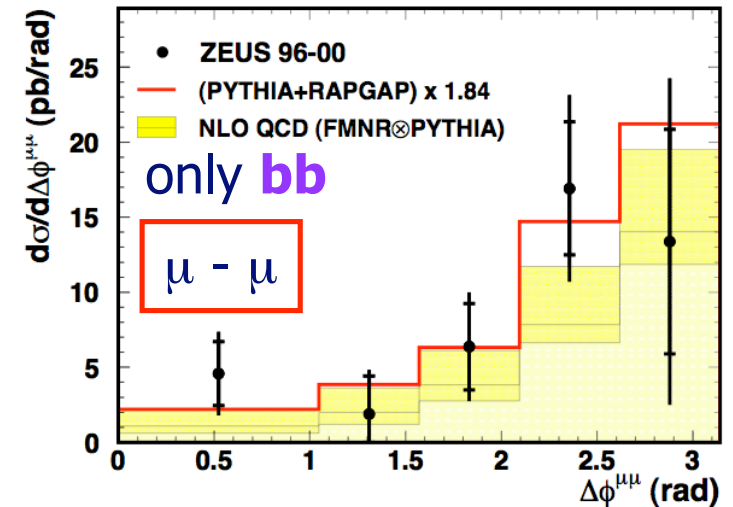
FMNR \oplus fragmen, PDF(p): CTEQ5M, PDF(γ): GRV-G HO

\Rightarrow charm OK, beauty data above NLO

Azimuthal Correlations



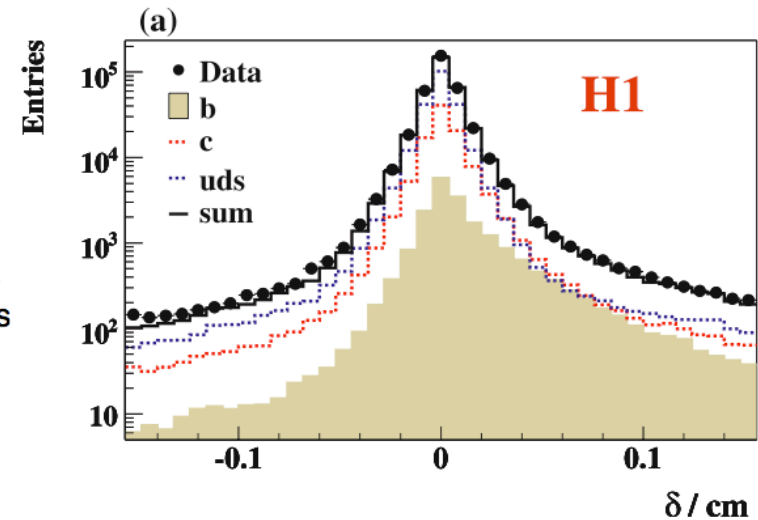
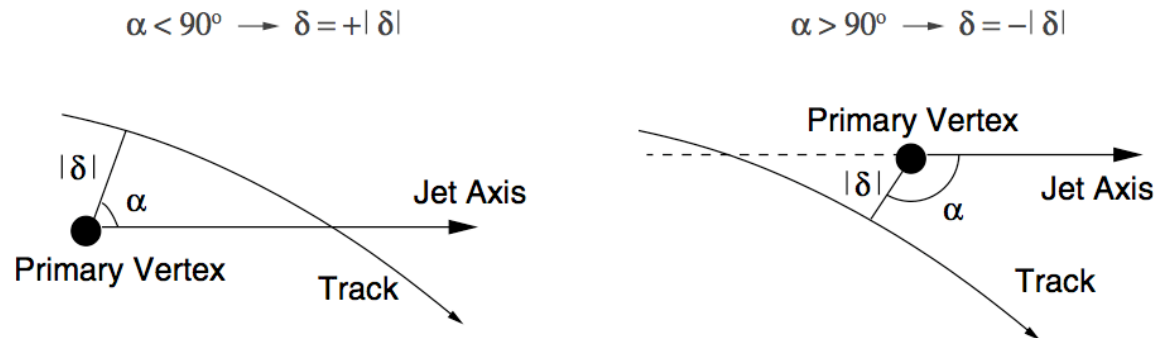
ZEUS



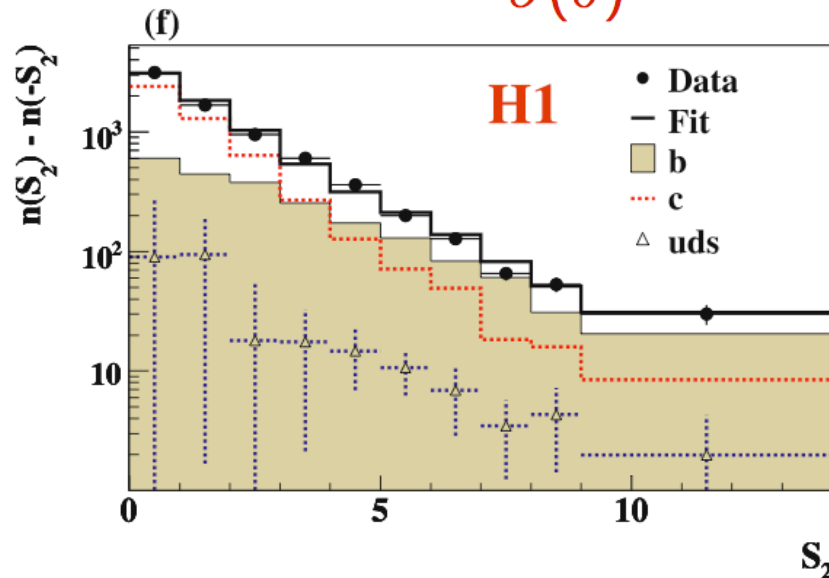
\Rightarrow HO terms needed \Rightarrow good description by NLO

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

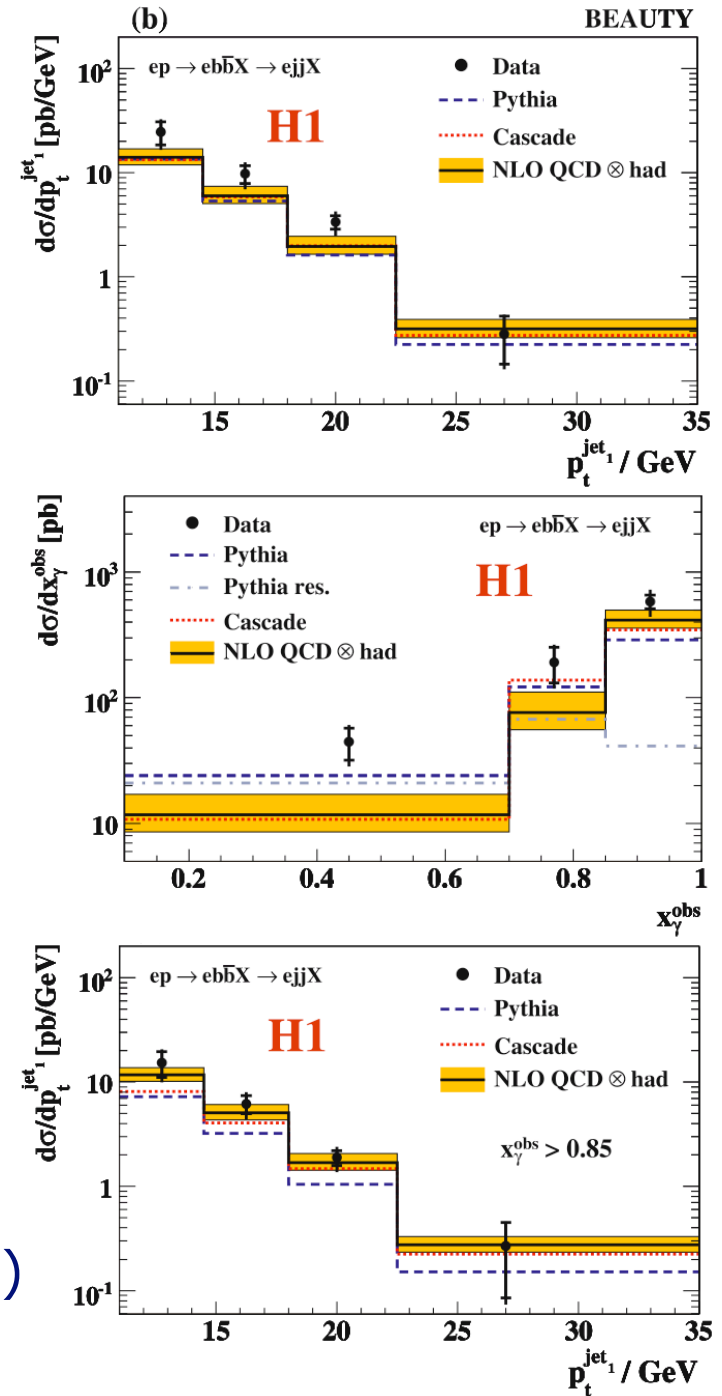
Measurement of 2-jet cross-sections in beauty photo-production

H1 57 pb⁻¹
H1 EPJC47(2006)597

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

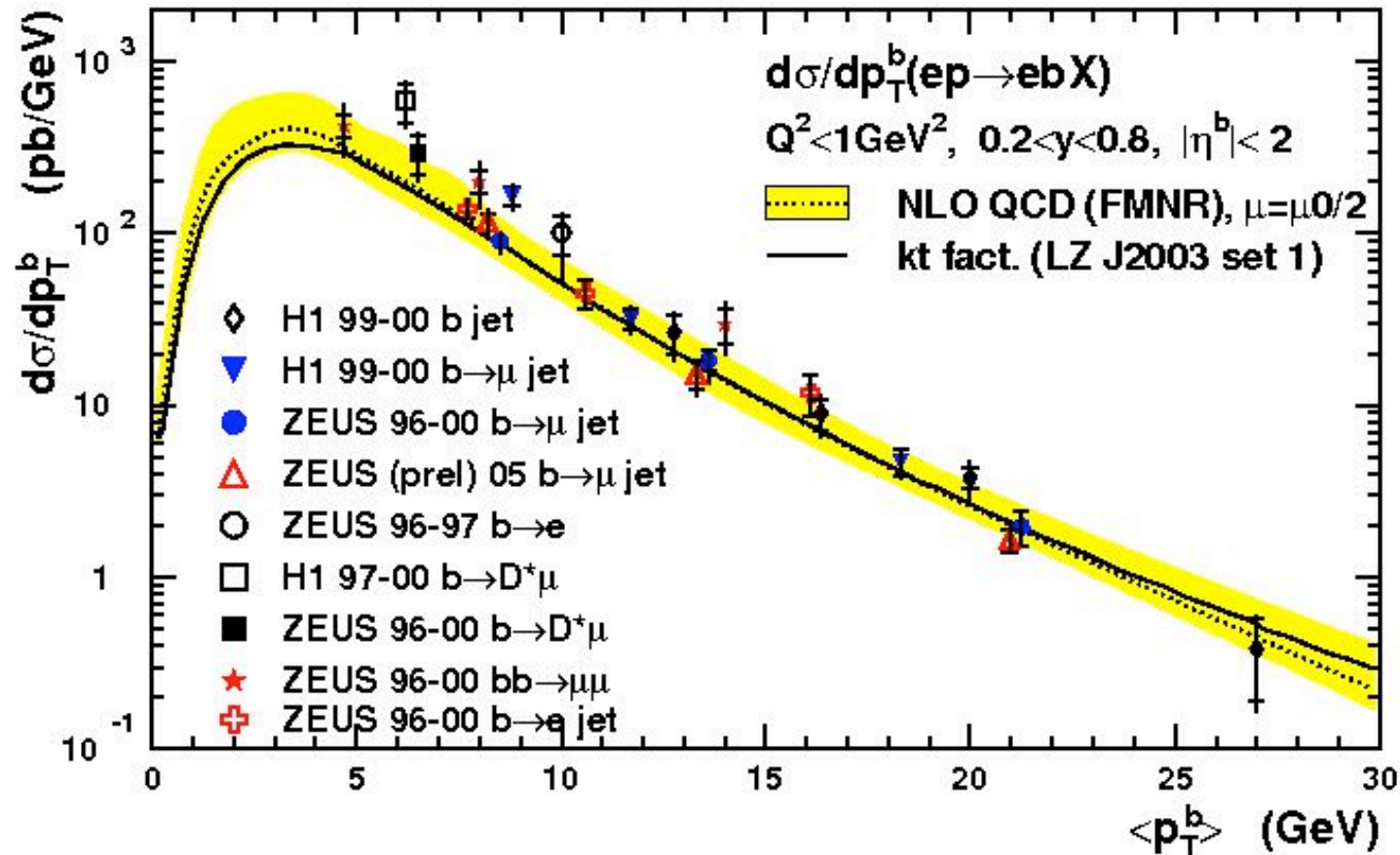
⇒ **b** cross-sections tend to be above NLO-QCD

⇒ difference mainly from $x_\gamma < 0.85$ (resolved do.)



Overall view of beauty photo-production at HERA

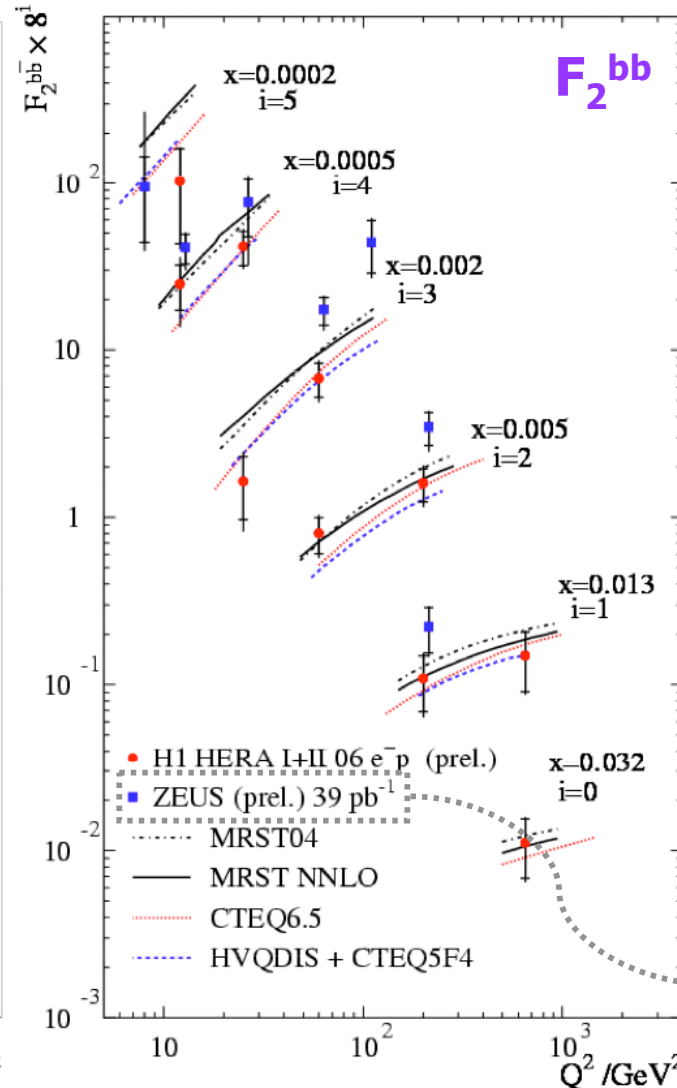
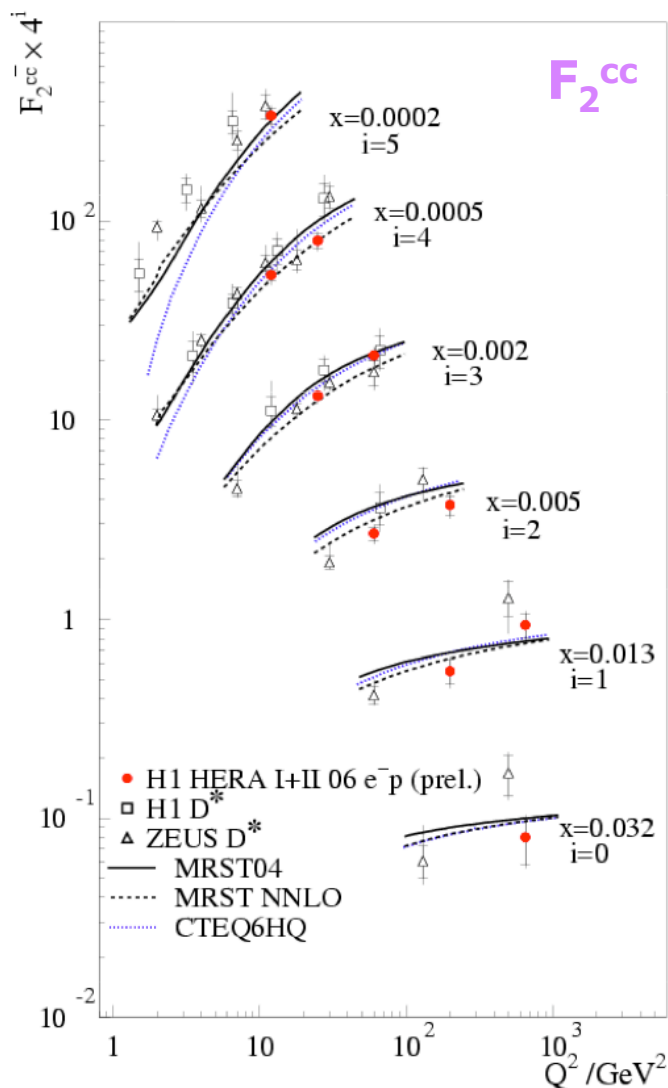
HERA



- ⇒ Many independent measurements performed
- ⇒ Trend to be slightly above NLO-QCD (particularly at low p_T)
- ⇒ 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