Smolenice Castle HS-2004

August 31^{st}, 2004

Heavy Flavours at HERA

Manuel Zambrana (Universidad Autónoma de Madrid, Spain)

On Behalf of the ZEUS and H1 Collaborations

OUTLINE

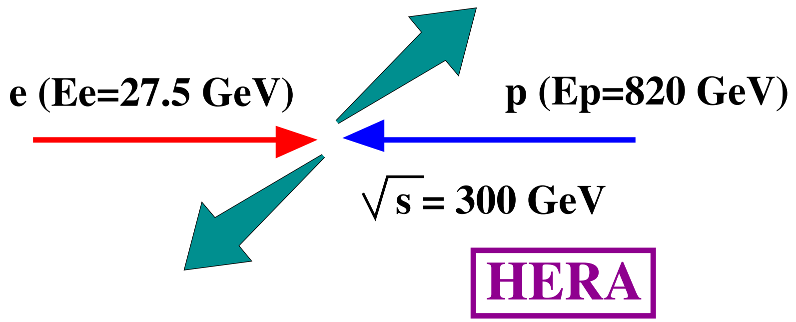
- Introduction
  - → Hera and the experiments
  - → ep kinematics and heavy flavour production
  - → Why study heavy flavour?
  - → Perturbative QCD calculations for heavy flavours
- Charm
  - → Tagging mehods
  - → Experimental results
- Beauty
  - → Tagging mehods
  - → Experimental results
- Summary
- Outlook : HERA II

Introduction : The Experiments

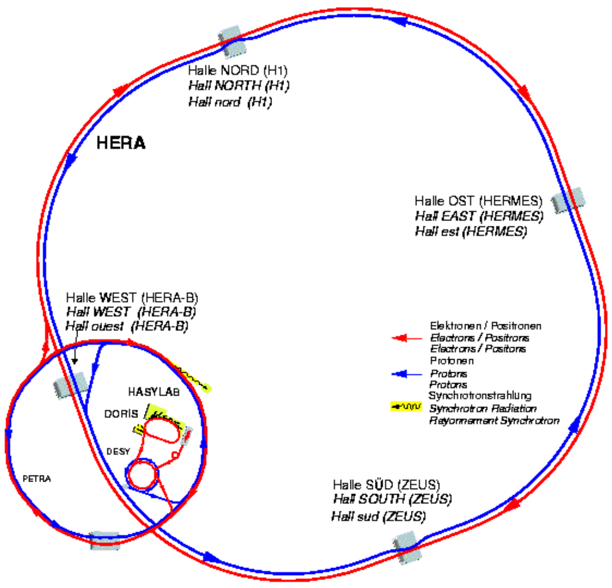
- **HERA** is an accelerator that collides **electrons** and **protons at high energy**

$$E_e = 27.5\ GeV$$

$$E_p = 820(920)\ GeV$$ before(after) 1998



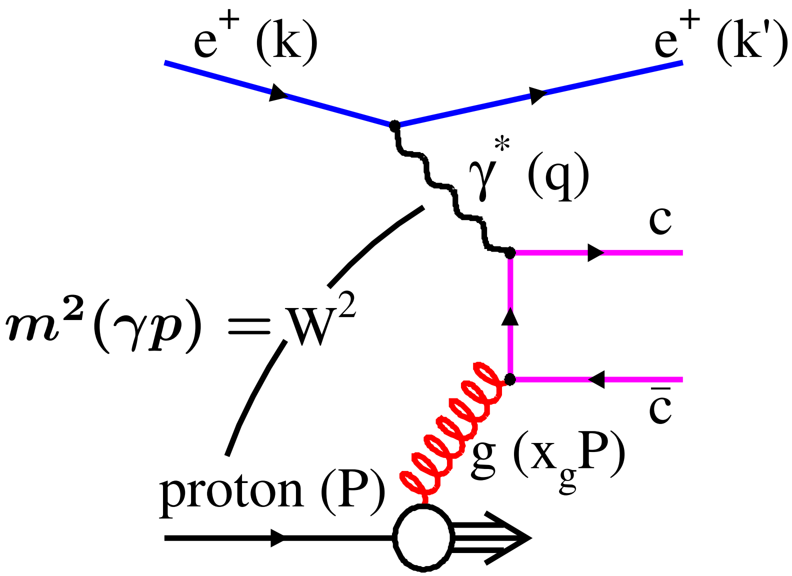
This corresponds to ep CM energy $\sqrt{s} = 300(318)\ GeV$



At the interaction points, two collider experiments, **ZEUS and H1,** are placed to analyse the products after each ep collision

Introduction : ep Kinematics and Heavy Flavour production

- **Heavy flavour production is dominated by Boson Gluon Fusion (BGF) at LO**
  $\Rightarrow$ **pairs $q\bar{q}$ are produced by the interaction of a (virtual) photon emitted by the electron and a gluon in the proton : $\gamma g \rightarrow c\bar{c}$ or $b\bar{b}$**



At a given $\sqrt{s}$, kinematics specified by a number of variables (Lorentz invariant), only two of them independent :

$Q^2 = -q^2 = -(k - k')^2$
(4-momentum transfer squared)

$x = Q^2/(2P \cdot q)$, **for** $Q^2 \gg (2m_q)^2$ **:**
momentum fraction of proton constituent

$y = (P \cdot q)/(P \cdot k)$, **for** $Q^2 \sim 0$ **:**
inelasticity, γ energy fraction of e

Kinematic regimes
$Q^2 < 1\,GeV^2$ **: Photoproduction**
$Q^2 > 1\,GeV^2$ **: DIS**

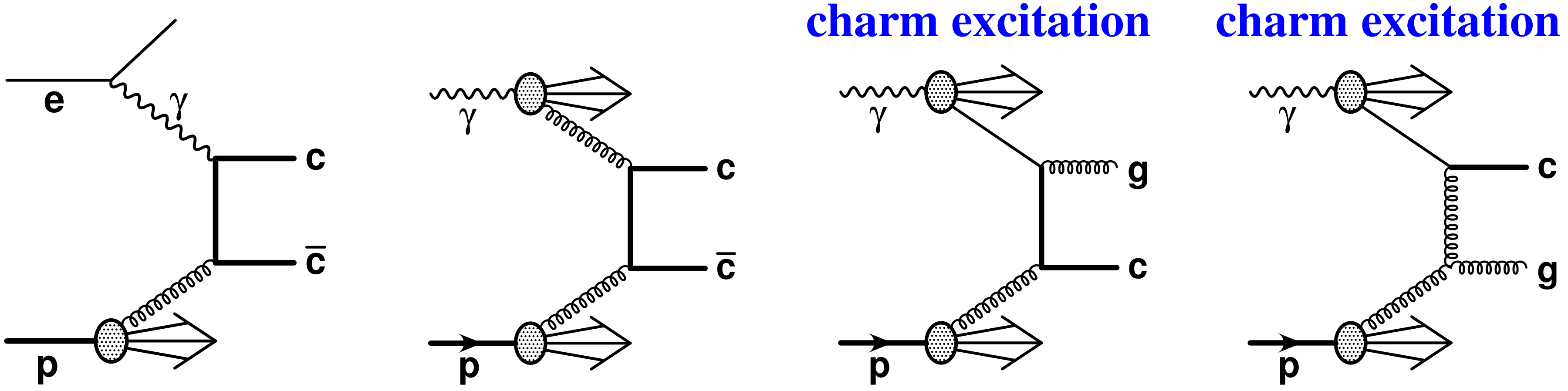
Heavy quark production is dominated by photoproduction : $\sigma(ep \rightarrow eX \sim 1/Q^4)$
and by charm : large m_b and $q_b \Rightarrow \sigma(ep \rightarrow eb\bar{b}X) \sim 10^{-2}\sigma(ep \rightarrow ec\bar{c}X)$

Introduction : Heavy Flavour production

- In pQCD direct processes dominate : the photon couples to the gluon as a point-like particle $\gamma g \longrightarrow q\bar{q}$ (both in DIS and photoproduction)

- But in photoproduction, resolved processes play a significant role: the photon shows a partonic structure $\Rightarrow$ one parton from the photon couples to one parton in the proton (the gluon) to produce the pair $c\bar{c}$ or $b\bar{b}$

direct photon | resolved photon | resolved photon charm excitation | resolved photon charm excitation



$\gamma g \longrightarrow c\bar{c}$ | $g^{\gamma} g^{p} \longrightarrow c\bar{c}$ | $c^{\gamma} g^{p} \longrightarrow gc$ | $c^{\gamma} g^{p} \longrightarrow cg$

- At NLO, the definition of direct/resolved processes is ambiguous

Introduction : Why Study Heavy Flavours ?

- All realistic calculations of measurable cross sections assume that the **Factorisation Theorem** holds :

  The calculation of an observable cross section can be split into a number of independent pieces that are finally convoluted

$$\sigma = \text{proton structure} \otimes \sigma_{\gamma g \to Q\bar{Q}} \otimes \text{photon structure} \otimes \text{fragmentation function}$$

At Hera in HFL production this means

$\longrightarrow$ A parametrisation of the proton structure : PDF's
$\longrightarrow$ A description of the hard scattering $\gamma g \longrightarrow Q\bar{Q}$: pQCD matrix elements
$\longrightarrow$ A parametrisation of the photon structure
$\longrightarrow$ A description of the fragmentation $Q \longrightarrow HADRON$: fragmentation functions

$\Rightarrow$ Heavy Flavour production is sensitive to each one of these pieces :
$*$ m_b, m_c large $\Rightarrow$ useful scale pQCD : reliable predictions (better for b)
$*$ Cross section is directly sensitive to the gluon density in the proton
$*$ Fragmentation is assumed to be universal : can compare HERA results to other experiments

Introduction : Perturbative QCD Calculations for Heavy Flavours

- **NLO calculations are performed in several schemes : massive, massless, combined**
- **All schemes assume a scale sufficiently hard to apply pQCD, and the validity of the factorisation theorem**

"MASSIVE" APPROACH

- **Fixed order calculation in α_s, with $m_Q \neq 0 \Rightarrow$**
  $\longrightarrow$ heavy quark is NOT part of the structure functions
  $\longrightarrow$ Proton : 3 active light flavours
  Quark (+gluon) densities obtained according to DGLAP evolution
- **HQ produced only dynamically; reliable at $p_T \sim m_Q$**
  (when terms that can exploit the perturbative series become small :
  $\log(p_T^2/m_Q^2) \sim 0 \Leftrightarrow p_T \sim m_Q$)
- **Codes : FMNR (Frixione et al.): γp, HVQDIS (Harris+Smith): DIS**

"MASSLESS" APPROACH

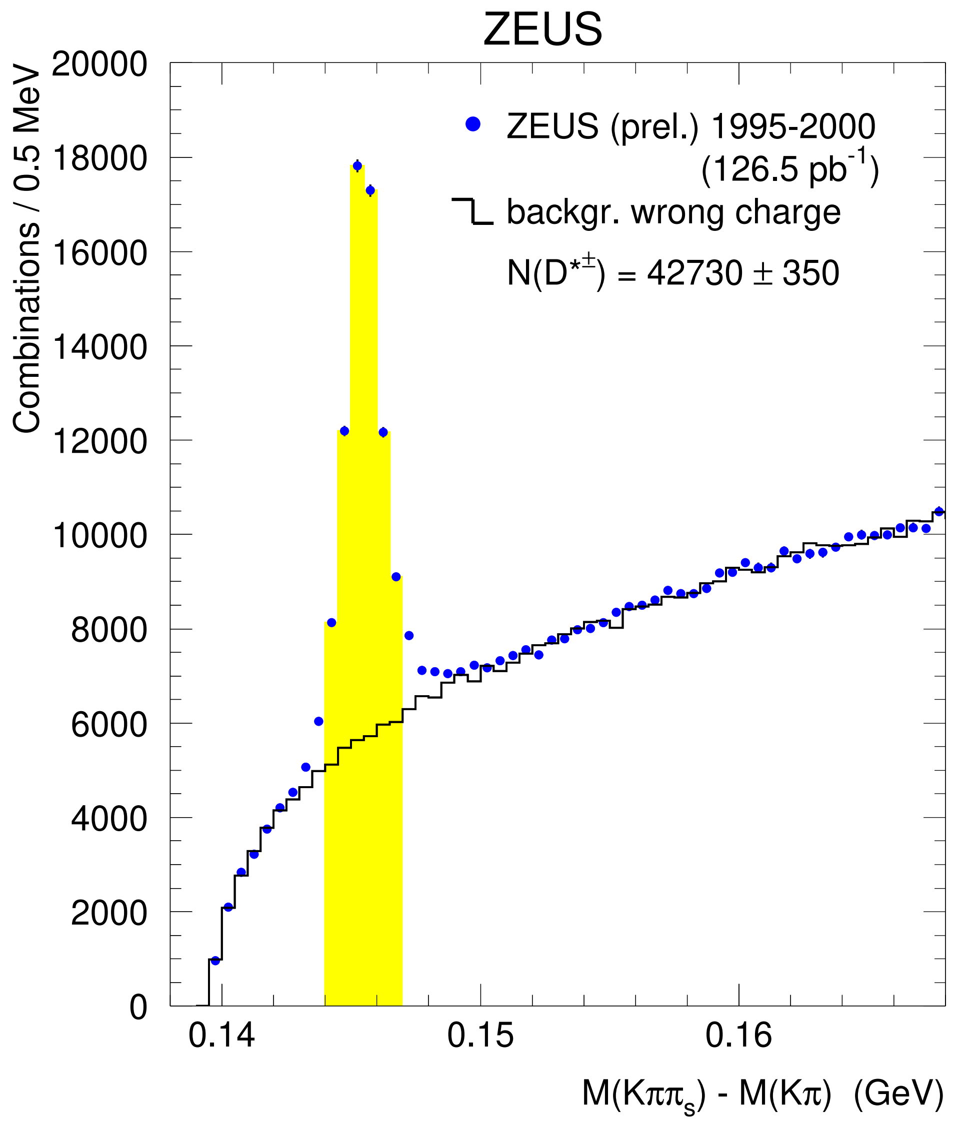
- **All orders in α_s, with $m_Q = 0 \Rightarrow$ heavy quark is an active flavour in the proton (part of the structure functions)**
- **HQ produced also by new processes ("flavour excitation"); reliable $p_T \gg m_Q$**
- **Final state divergencies are absorbed into the fragmentation function**

Charm Tagging

- **Charm is tagged at HERA most efficiently in the "golden" decay channel :**

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

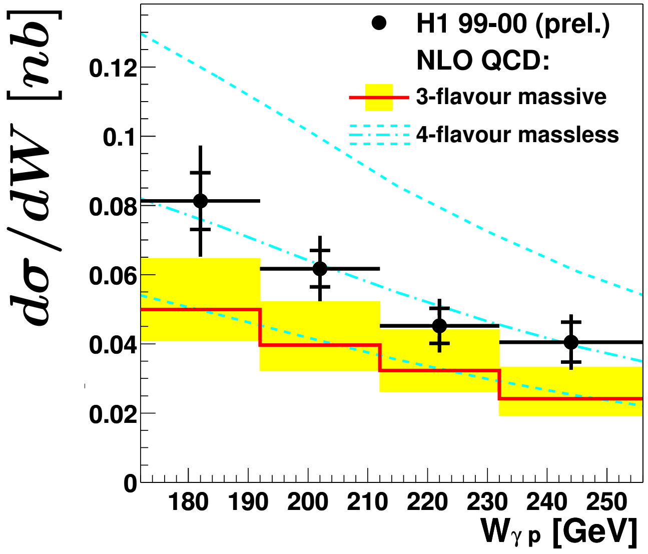
- **Reconstruction : Mass difference method**

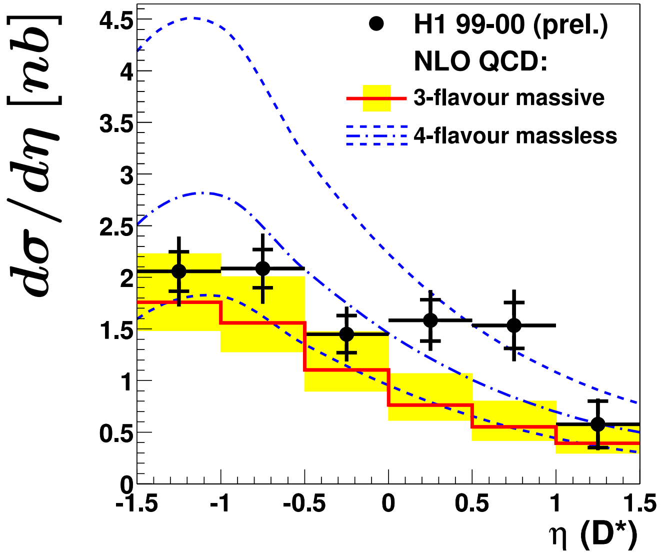


⇒ impressive amount of charm collected by HERA during 1995-2000

Photoproduction of $D^{*\pm}$ mesons at HERA

- D^* selection in γp regime
- **Differential distributions are measured and compared to theoretical predictions in different schemes : "massive" NLO and "massless" NLO**
- **Shape of $d\sigma/dW$ described by all, but both massive and massless NLO fail in describing shape of $d\sigma/d\eta(D^*)$**
- **Theories have large uncertainties**
- **Measurements are able to constrain theories significantly**





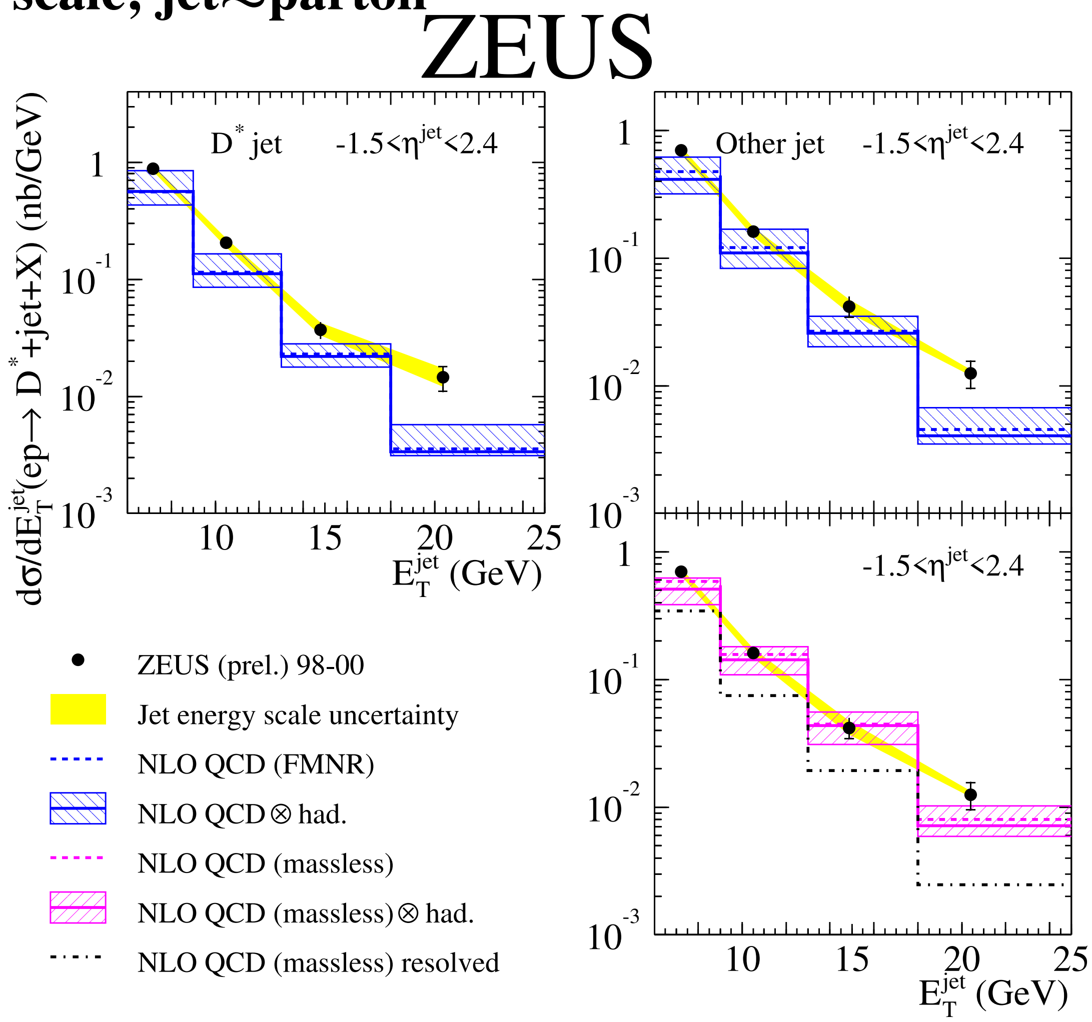
$D^{*\pm}$ photoproduction Inclusive jet cross sections

- D^* + jet; $E_T^{jet} > 6\ GeV$: additional scale; jet≈parton (association in “angular distance”)

- $D^*\ \gamma p$ measurements : discrepancies NLO massive and massless

- Calculations available :
  $\longrightarrow D^*$ + associated jet : massive
  $\longrightarrow D^*$ + other jets : massive/massless

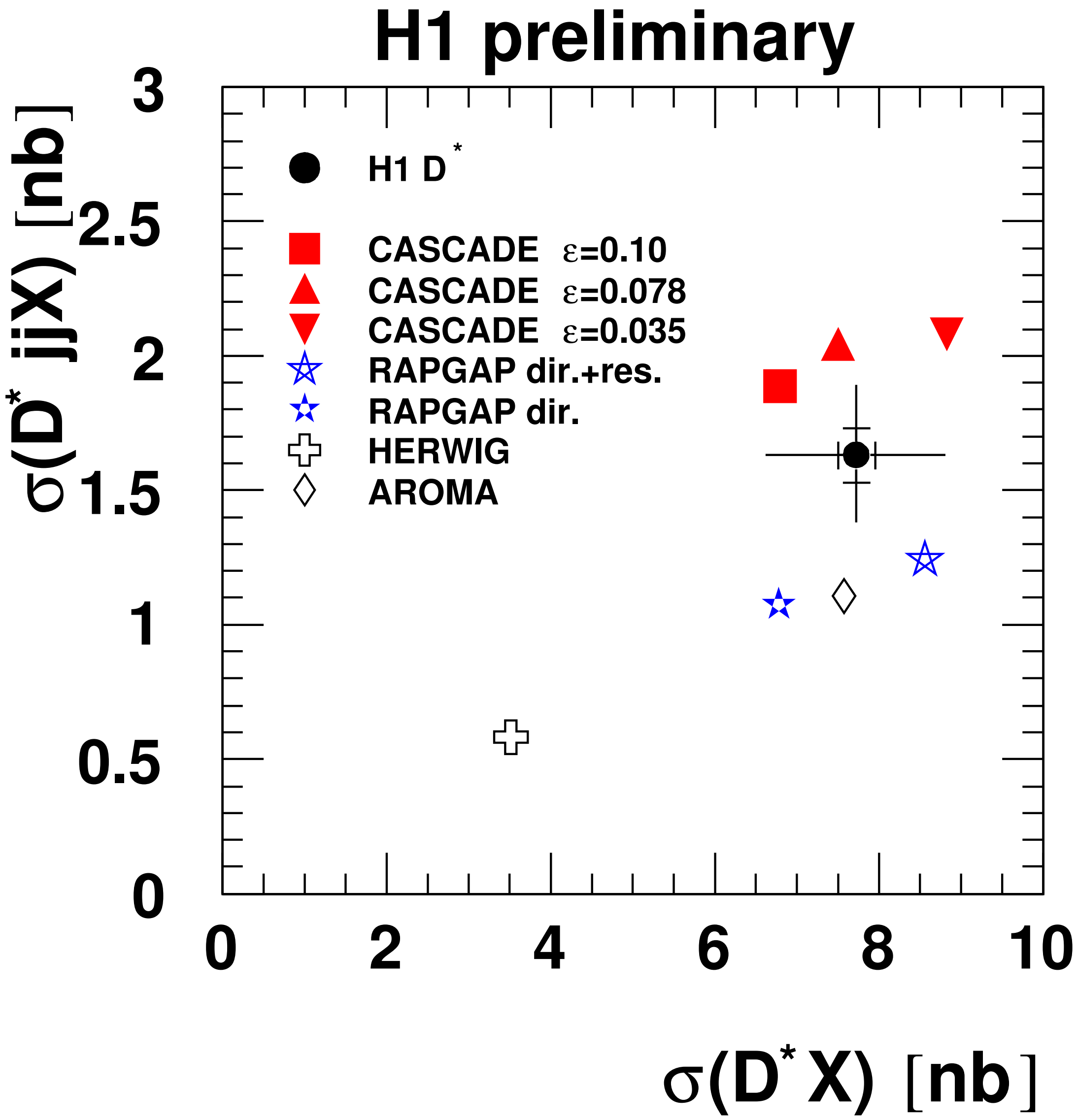
  massless expected to be better at high E_T^{jet} ...



$\Rightarrow$ Massless calculation works better at high E_T^{jet}

Inclusive $D^{*\pm}$ meson and associated dijet production in DIS

- **Use additional scales Q^2 and E_T^{jet}**
- **Inclusive $D^{*\pm}$ meson production well described by Rapgap and CASCADE**
- **Discrepancy between models and with data**

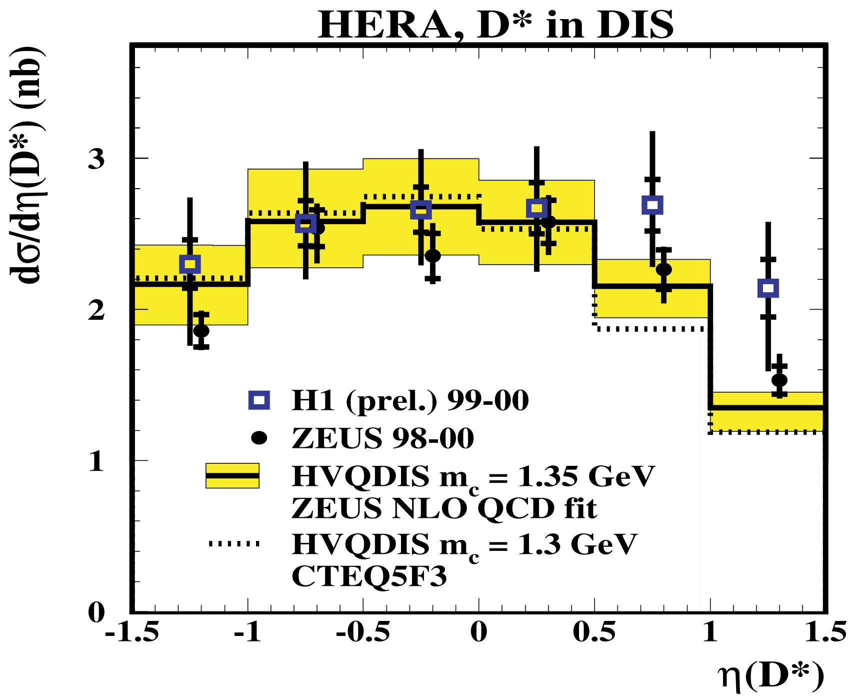


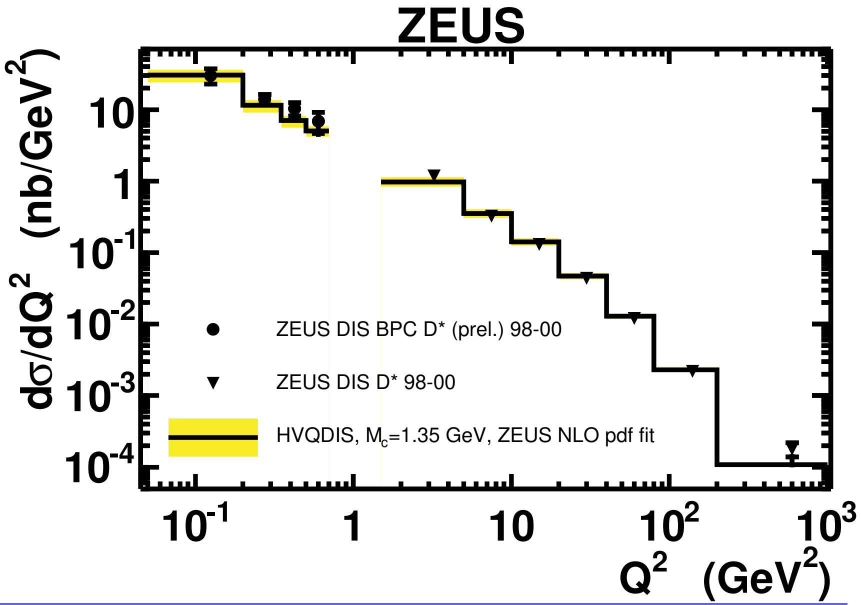
$D^{*\pm}$ cross sections in DIS

- **Data in good agreement with NLO calculations, down to low Q^2**

- **Theoretical uncertainties due to**
  - $\longrightarrow$ **proton PDF**
  - $\longrightarrow$ **charm mass**
  - $\longrightarrow$ **renormalisation/factorisation scales**
  - $\longrightarrow$ **fragmentation**

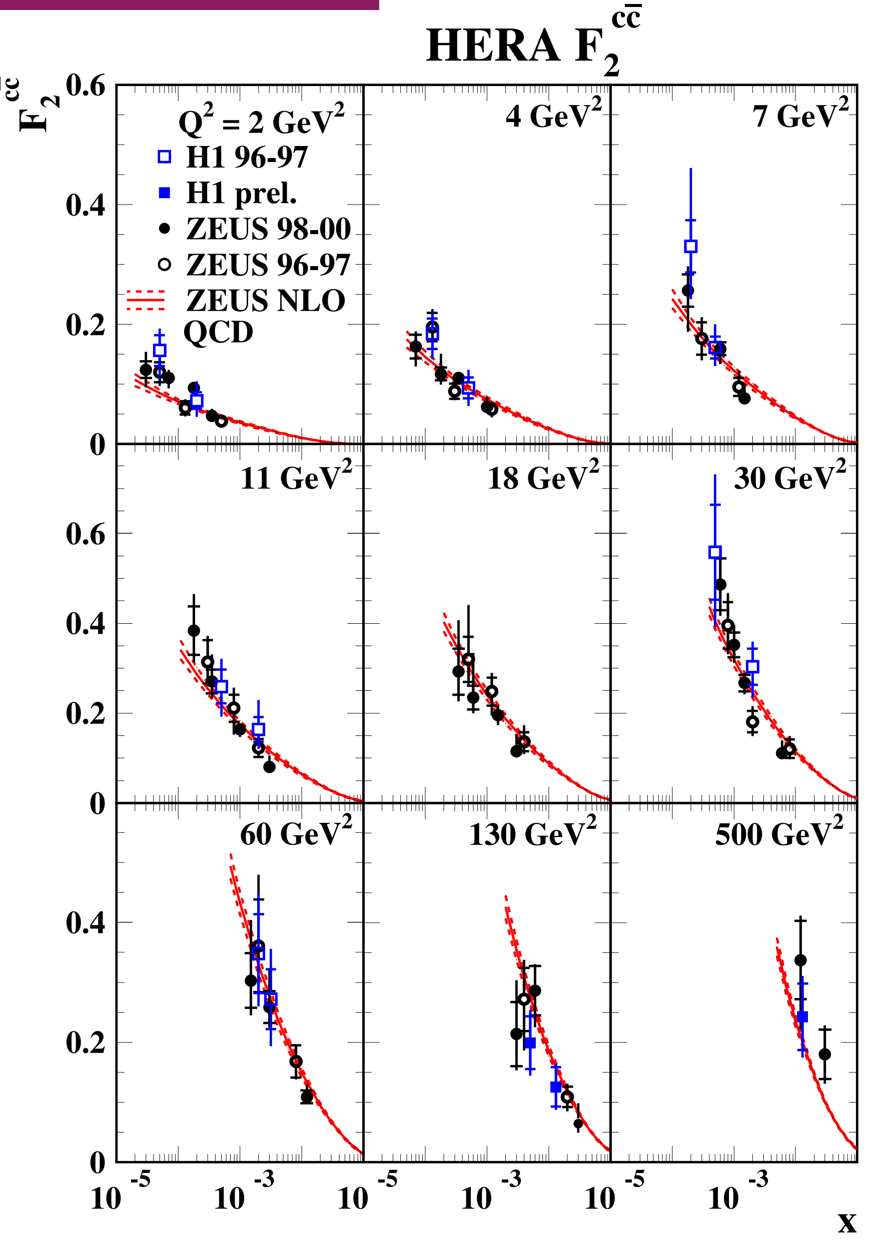
$\Rightarrow$ **Theoretical uncertainties larger than experimental uncertainties**





Charm contribution to proton structure function F_2

- Extraction of (extrapolation to) $F_2^{c\bar{c}}$
- Ratio $F_2^{c\bar{c}}/F_2$ rises from 10% to 30% as Q^2 increases and x decreases
- At low Q^2 errors are comparable to those from PDF fit
- Use cross sections in future fits to constrain the gluon density
- New H1 points at high Q^2 (will see later)



Fragmentation of Charm Quark : Fractions and Ratios

- **Experimentally, heavy quarks are not observed : only charmed/beauty hadrons can be reconstructed in the final state**
- **Fragmentation is a long distance effect : described only by phenomenological models, no pQCD description**
- **All models assume universality : fragmentation process is independent of the production mechanism of the heavy quark**
- **At HERA, fragmentation can be measured in ep collisions, and compared to others experiments to check universality**

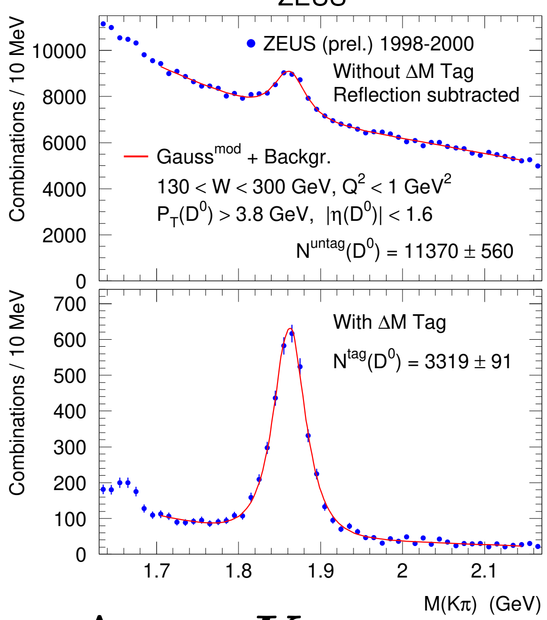
Fragmentation Fractions

- **HERA has measured in γp and DIS inclusive cross sections for all the charm ground states : D^0, $D^{*\pm}$, $D^{\pm}$, $D_s^{\pm}$ and $\Lambda_c^{\pm}$**
  (No measurement of strange-charmed baryons $\Xi_c^{\pm}$, Ξ_c^0 and Ω_c^0 exits at HERA, but contribution is assumed to be small)
- **From cross sections, fragmentation fractions can be calculated**

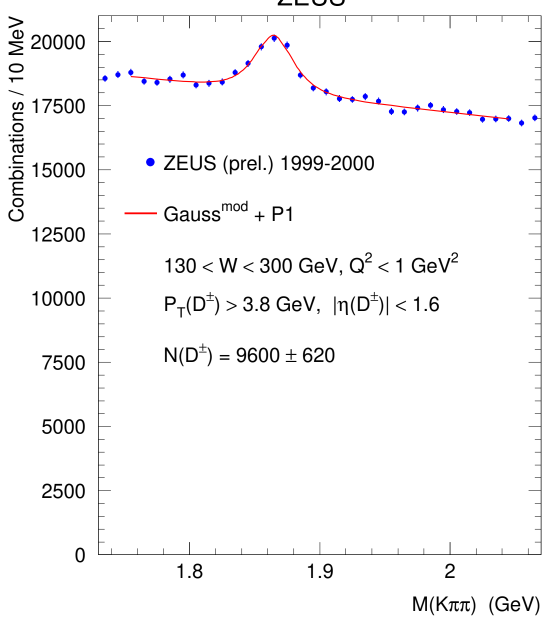
$$f(c \to D, \Lambda_c) = \sigma(D, \Lambda_c) / \sum_{all\ charm\ g.e.} \sigma_i$$

Fragmentation of Charm Quark : Fractions and Ratios

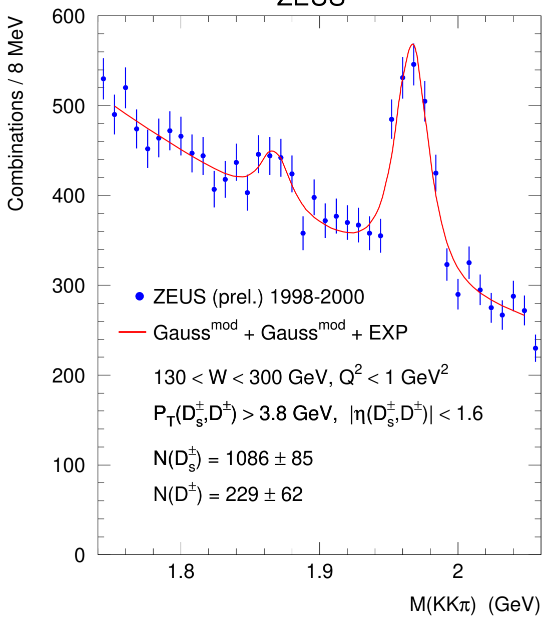
$D^0 \to K\pi$



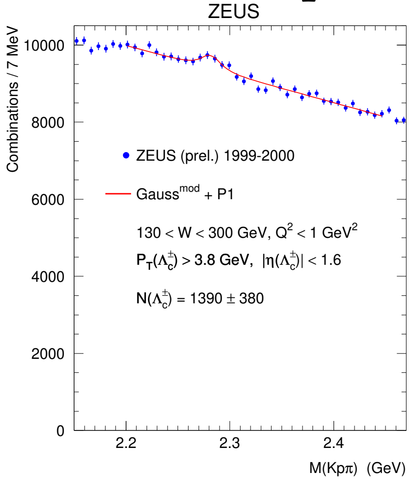
$D^\pm \to K\pi\pi$



$D_s \to \phi(\to KK)\pi$



$\Lambda_c \to Kp\pi$



- **No particle identification**
- **No secondary vertices : many track combinations**
  $\Rightarrow$ large background, reduced when two decays (kinematic constraint)
- **Estimate signal and background with fit**

Fragmentation of Charm Quark : Fractions and Ratios

Charm Fragmentation Fractions/Ratios

- Cross sections $D^{*\pm}, D^0, D^\pm, D_s$

  $\rightarrow$ fragmentation fractions.

	H1	ZEUS(prel.)	e^+e^-
$f(c \rightarrow D^+)$	0.203 ± 0.026	$0.249 \pm 0.014^{+0.004}_{-0.008}$	0.232 ± 0.018
$f(c \rightarrow D^0)$	0.560 ± 0.046	$0.557 \pm 0.019^{+0.005}_{-0.013}$	0.549 ± 0.026
$f(c \rightarrow D_s^+)$	0.151 ± 0.055	$0.107 \pm 0.009^{+0.005}_{-0.005}$	0.101 ± 0.027
$f(c \rightarrow D^{*+})$	0.263 ± 0.032	$0.223 \pm 0.009^{+0.003}_{-0.005}$	0.235 ± 0.010
$f(c \rightarrow \Lambda_c^+)$		$0.076 \pm 0.020^{+0.017}_{-0.001}$	0.076 ± 0.007

Charm fragmentation fractions are universal

$\Rightarrow$ **HERA errors competitive!**

Fragmentation of Charm Quark : Fractions and Ratios

Ratios

There also other important questions concerning charm hadronisation

- **Are u and d quarks produced equally in charm events ? $\longrightarrow R_{u/d} = c\bar{u}/c\bar{d}$ (Measures the rate of neutral to charged D meson production)**

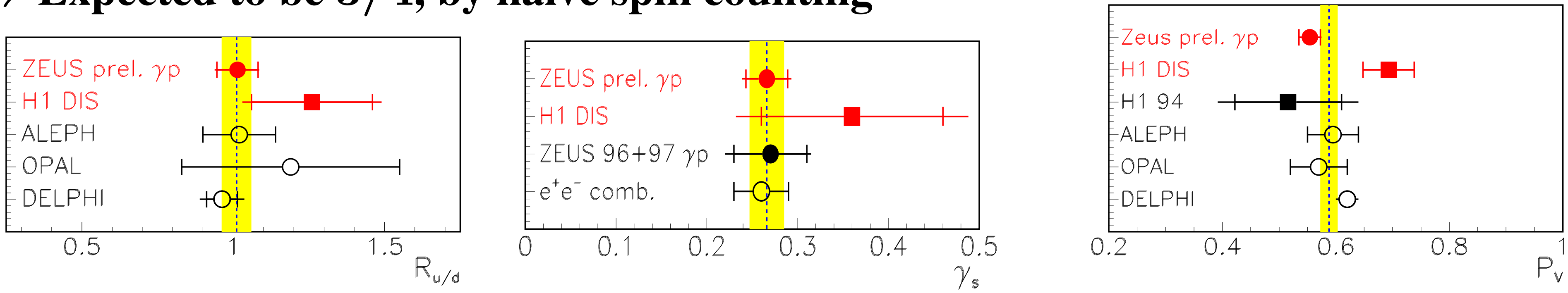
$\Rightarrow$ Expected to be ~ 1, due to smallness of the bare u, d quark masses compared to their dressed masses

- **What is the $s-$quark production suppression ? $\longrightarrow$ strangeness supression factor $\gamma_s = 2c\bar{s}/(c\bar{u} + c\bar{d})$**

$\Rightarrow$ $D_s^{\pm}$ expected to be less frequently produced than D^0 and $D^{\pm}$, due to higher bare s quark mass

- **What is the fraction of D mesons produced in a vector state? $\longrightarrow P_V = V/(V + PS)$**

$\Rightarrow$ Expected to be $3/4$, by naive spin counting

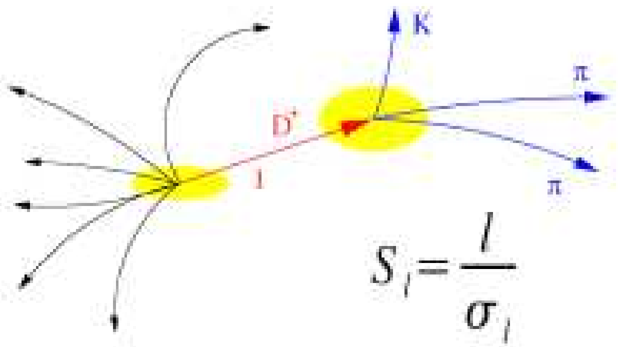


spin counting does not work!

Charm Tagging Methods

- **H1 has improved the tagging of the charm ground states D^0, $D^{\pm}$, D_s and D^* reconstructing secondary vertices : finite lifetime of D-mesons leads to a spacial separation between their production (primary) and decay (secondary) vertices $\Rightarrow$ Hadrons separated from combinatorial background**

Tagging based on (signed) "decay length"



$$L = |\vec{L}| sign(\vec{L} \cdot \vec{p}_D)$$

$\vec{L}$ = **vector from the primary to the secondary vertex**

$\vec{p}_D$ = **Reconstructed momentum for D-meson**

Ideally (perfect reconstruction) :
$\Rightarrow$ **D-meson decaying from a secondary vertex : $L > 0$; background candidate : $L \lessgtr 0$**

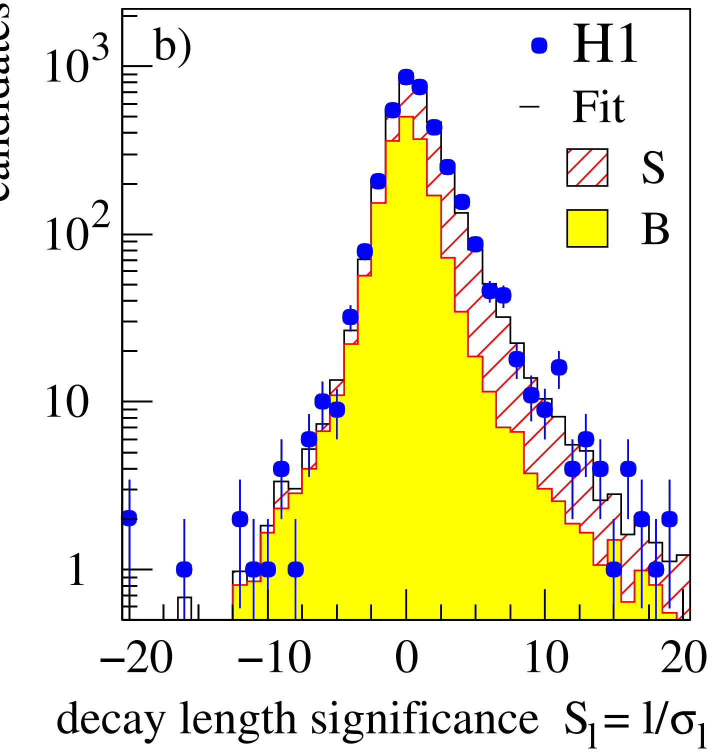
In practice (real reconstruction) this means
$L > 0 \Rightarrow$ Asymmetric ditribution shifted to the positive side : SIGNAL
$L \lessgtr 0 \Rightarrow$ Symmetric ditribution around $L = 0$: BACKGROUND

Charm Tagging Methods

Instead of impact parameter, use "significance"

$S = L/\sigma_L$; σ_L = **error in the impact parameter**

**(Tracks well reconstructed will go more to tha tails of the distribution,
Tracks bad poorly reconstructed will concentrate around the peak of the distribution;
still keep symmetry/asymmetry features of signal and background)**



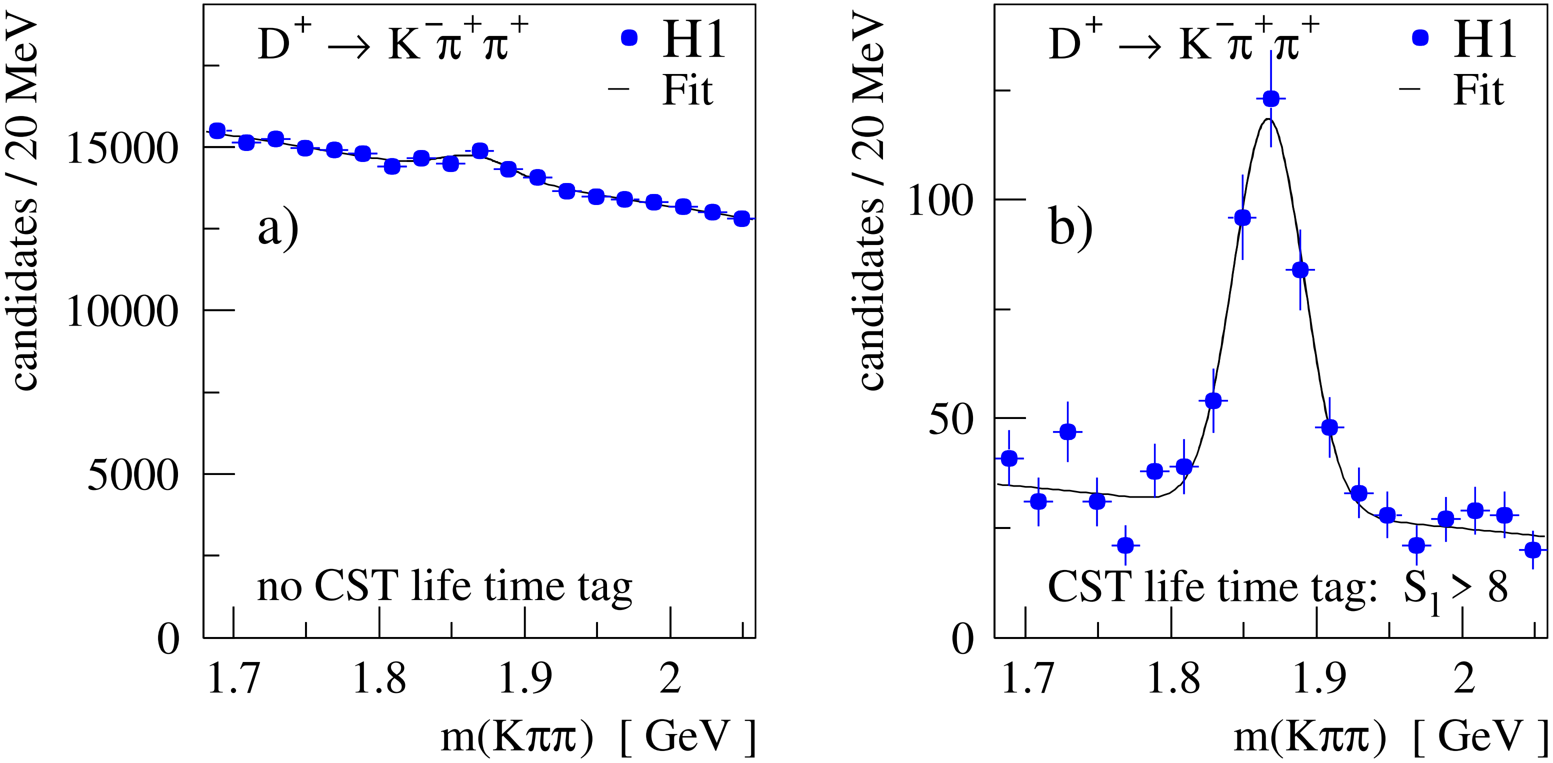
Significance distribution

$\longrightarrow$ **Fit MC to data to get fraction of signal and background**
$\longrightarrow$ **See signal more asymmetric than background**

At high values of S, sample dominated by signal

$\Rightarrow$ **Require candidates to have $S > 8$**

Charm Tagging Methods

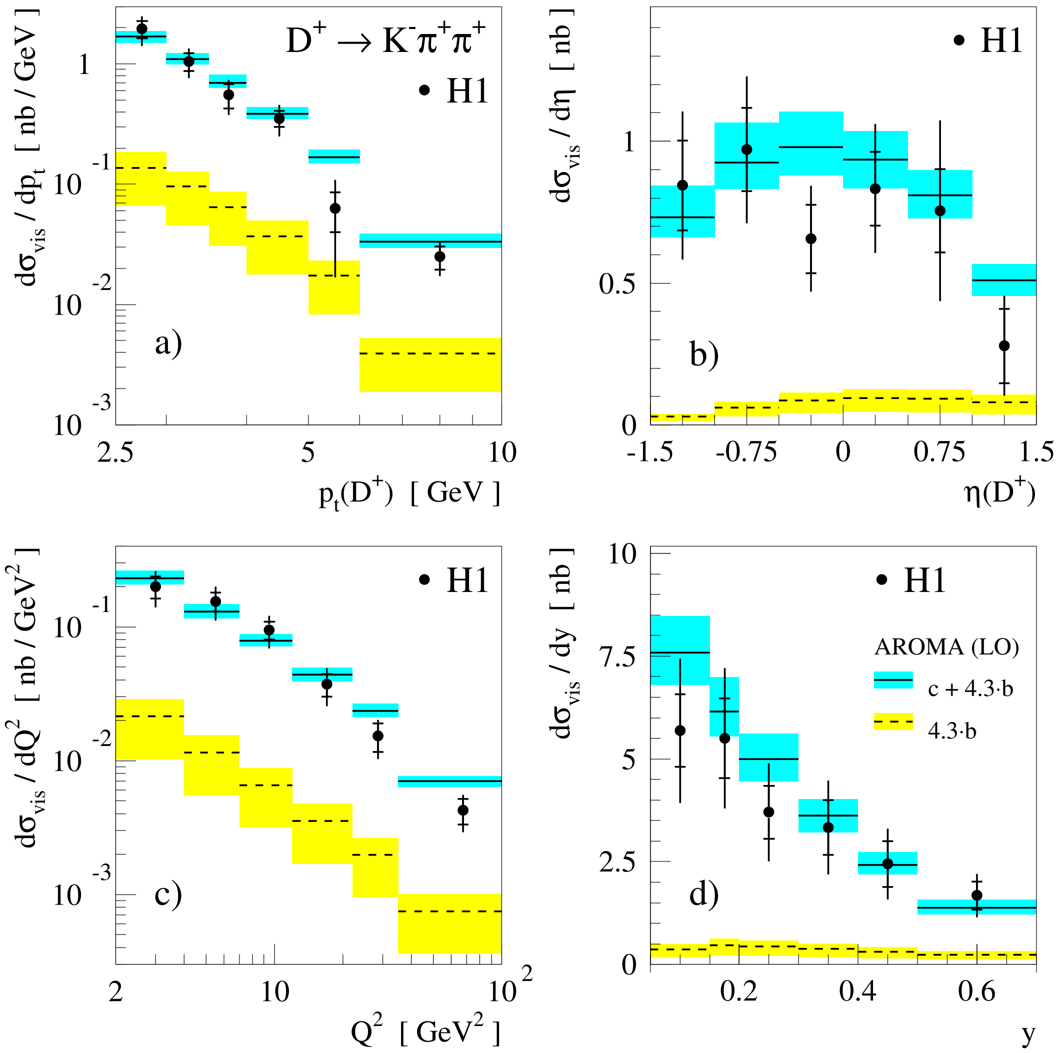


Ratio signal to background improved by a factor 50 !!!

These methods are used (H1) to measure production cross sections (DIS) of the charm hadron spectrum . . .

D meson production in DIS : differential distributions

Differential cross sections for D^+ production $D^+ \rightarrow K^-\pi^+\pi^+$



Both shapes and normalisation

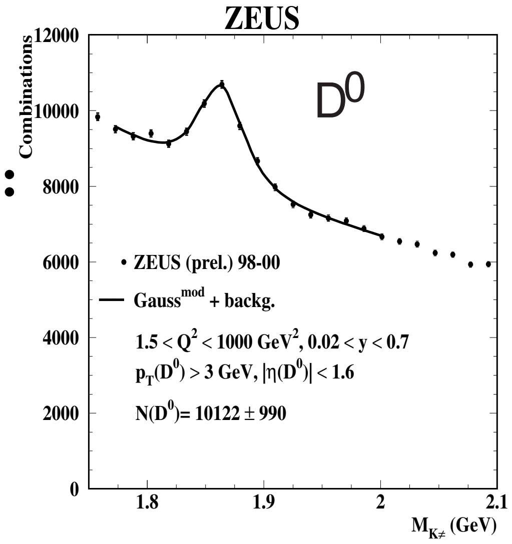
agree well with LO MC (AROMA)

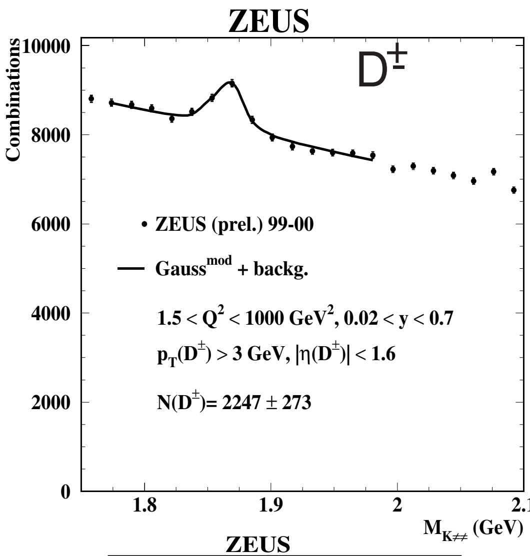
D meson production in DIS : total cross sections

Total production cross section of D^0, $D^{\pm}$, D_s and D^* in DIS (reconstructed in the same decay channels used in the γp analysis)

→ **Test of pQCD/fragmentation**

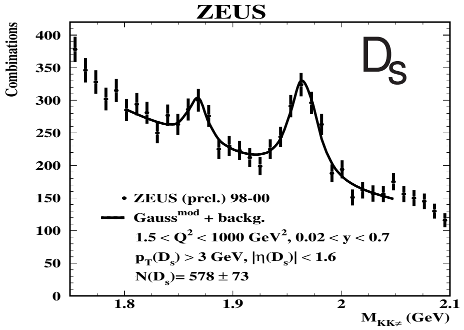
→ **Complement to standard D^* measurement (clean signal, low stat.) :**

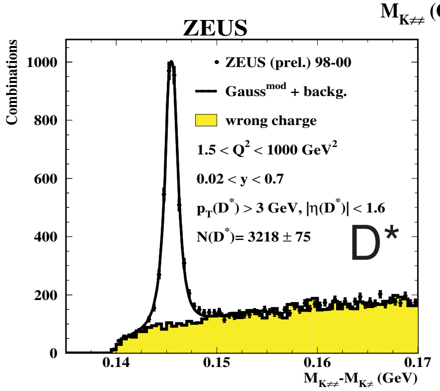




COMPARISON TO QCD (HVQDIS)

	ZEUS	HVQDIS pQCD
$\sigma(e^{\pm}p \to e^{\pm}D^0X)$	$7.44 \pm 0.78^{+0.29}_{-0.49}$nb	7.14nb
$\sigma(e^{\pm}p \to e^{\pm}D^{\pm}X)$	$2.42 \pm 0.30^{+0.21}_{-0.06}$nb	3.02nb
$\sigma(e^{\pm}p \to e^{\pm}D_sX)$	$2.25 \pm 0.30^{+0.09}_{-0.33}$nb	1.32nb
$\sigma(e^{\pm}p \to e^{\pm}D^{*\pm}X)$	$3.22 \pm 0.08^{+0.07}_{-0.05}$nb	3.06nb

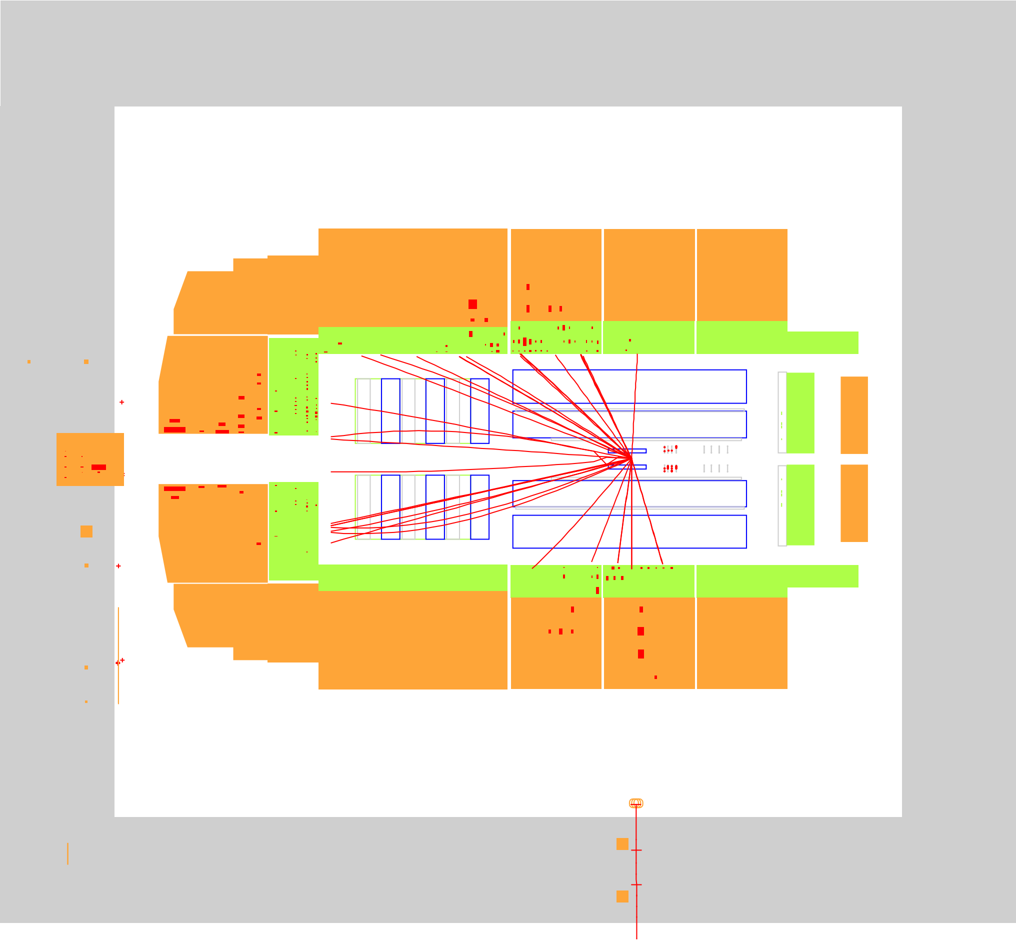


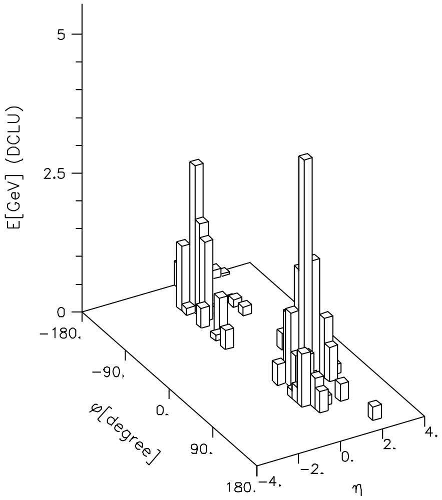


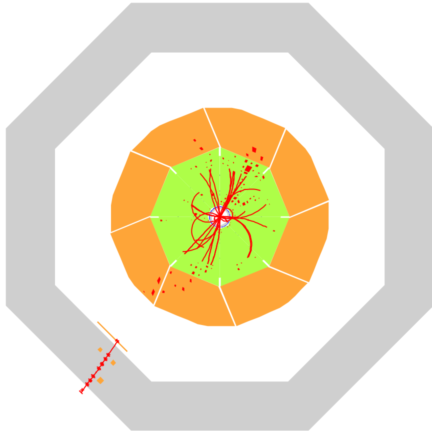
NLO gives reasonable description, but large uncertainties in the fragmentation

Beauty Production : Tagging Methods

Candidate to $b\bar{b}$ event



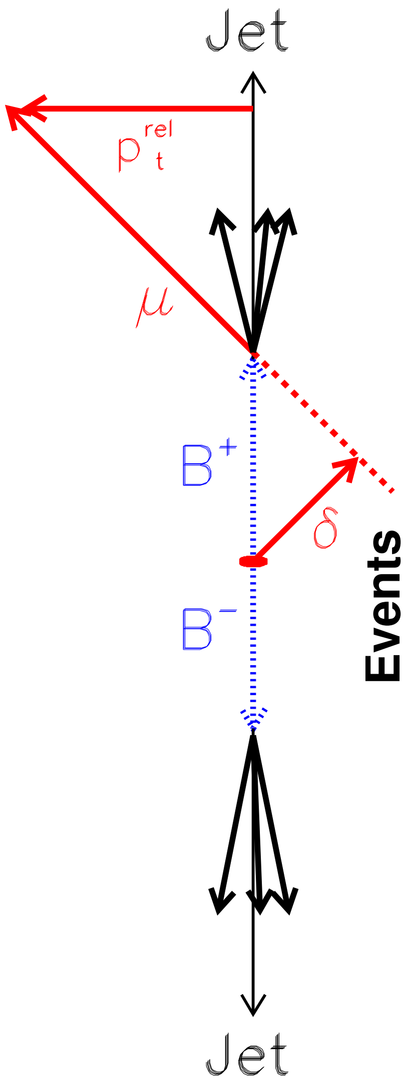




- **Reconstruction of B in particular decay channels does not work : $B.R \sim 10^{-4}$**
- **Use semileptonic decays : jets + μ**
- **Two methods currently used :**
  $\longrightarrow$ Large B-mass : p_T relative
  $\longrightarrow$ Large B-lifetime : impact parameter

Beauty Production : Tagging Methods

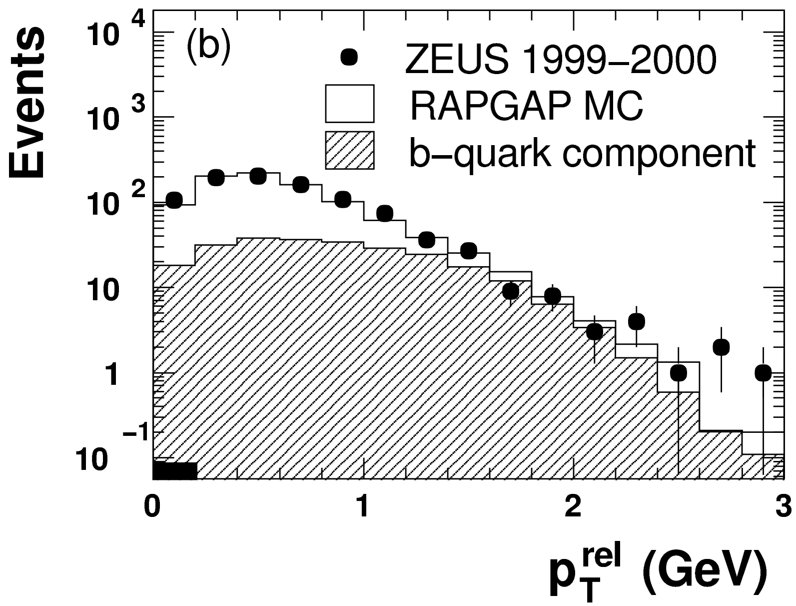
p_T REL. METHOD



- **Large mass of b $\Rightarrow$ decay products from b-hadrons have large opening angles respect to the b-quark direction**

$p_T^{rel} = p_T$ of μ relative to the jet axis (def)

$\Rightarrow$ for b-quark enriched sample, p_T^{rel} is expected to be large



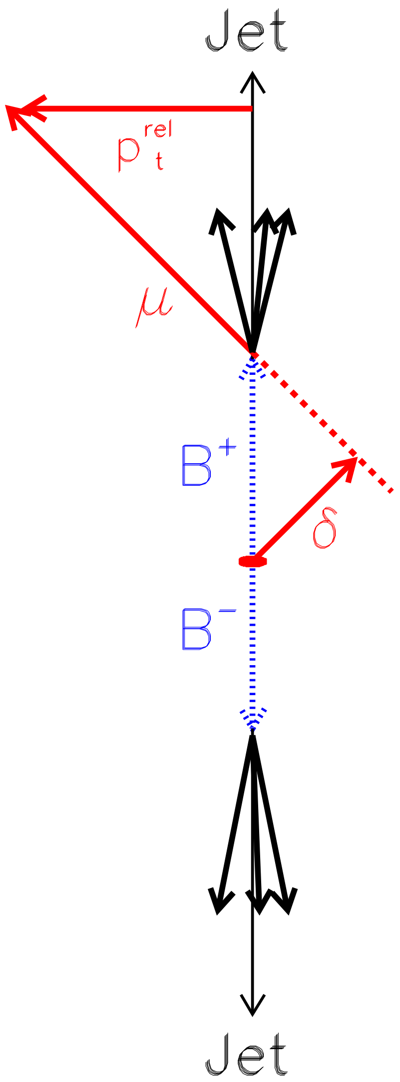
b-contribution dominates at high p_T^{rel}

b-fraction estimated from fit of MC to the data

samples used for fit : b-fraction typically 30%

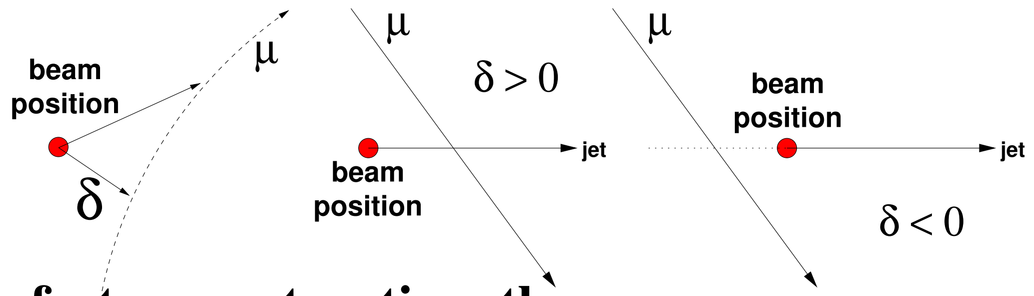
Beauty Production : Tagging Methods

IMPACT PARAMETER METHOD



- Impact parameter (δ) : minimum distance from the muon candidate track to the beam spot ("averaged" primary vertex position)

- Sign of δ can be defined as positive if the muon track intercepts the axis of the jet associated to the muon downstream of the beam spot, negative otherwise



If perfect reconstruction, then

$\longrightarrow$ μ from b-jet : $\delta > 0$ and large (due to large B-lifetime)

$\longrightarrow$ μ from c-jet : $\delta > 0$ and not so large

$\longrightarrow$ light flavours uds : $\delta \sim 0$ (short lifetime of hadron)

In realistic reconstruction, this means

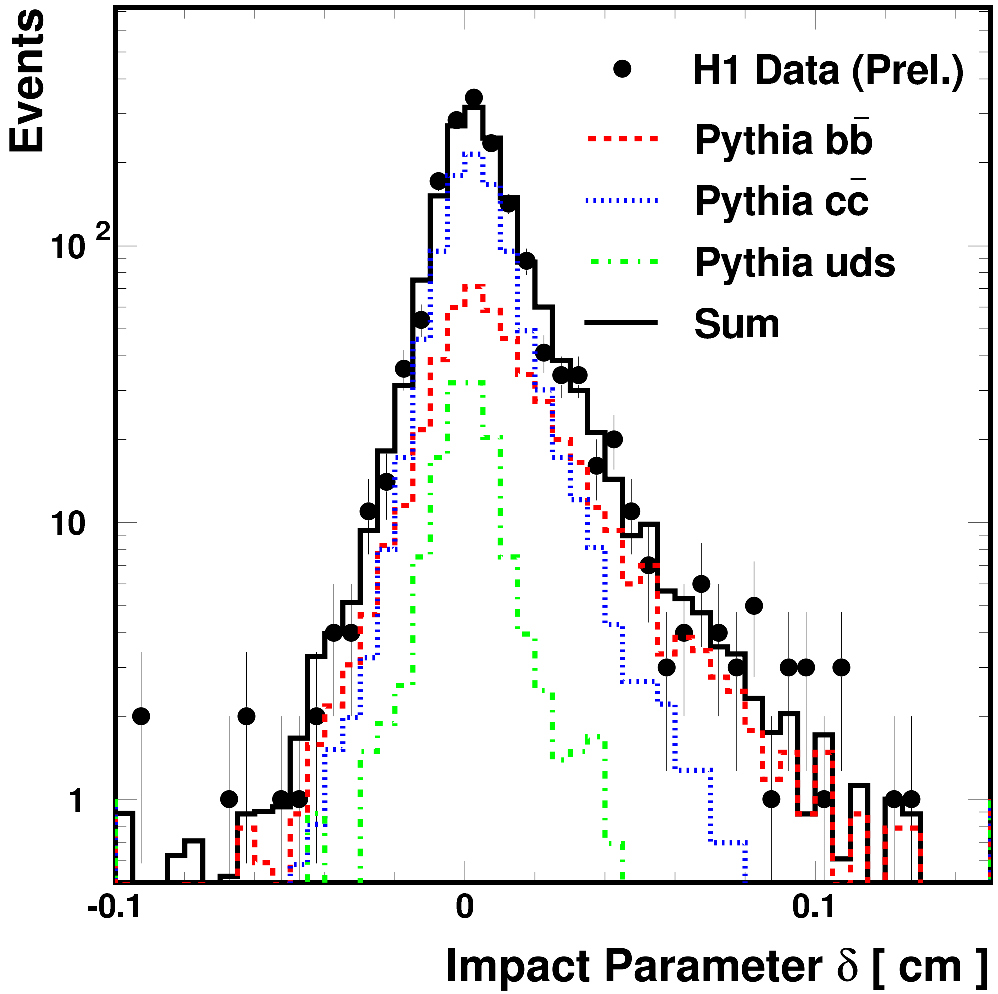
$\delta > 0 \Leftrightarrow$ Asymmetric distribution tilted to the positive side

$\delta \sim 0 \Leftrightarrow$ Symmetric distribution around $\delta = 0$

Beauty Production : Tagging Methods

IMPACT PARAMETER METHOD

Enriched b-sample (μ + dijet)



Shapes of b, c and uds from MC

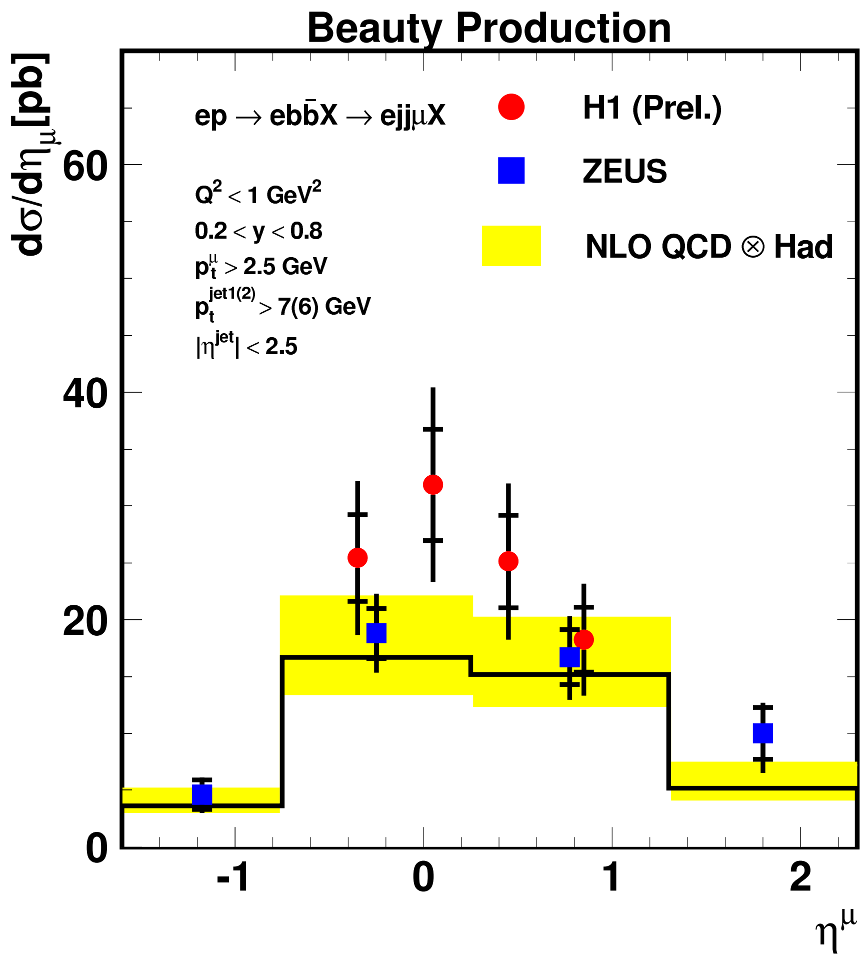
$\longrightarrow$ see asymmetry of $b\bar{c}$ and $c\bar{c}$ components
$\longrightarrow$ see symmetry of light flavour component

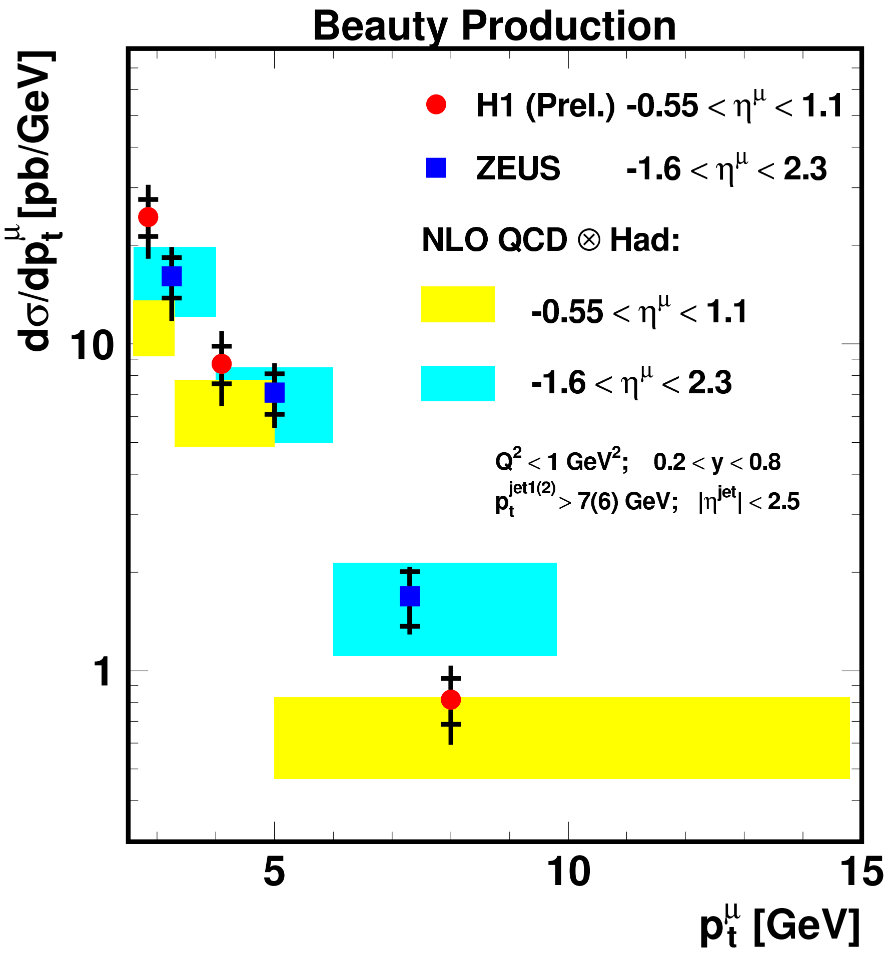
Beauty fraction extracted from fit of MC to data :

$\Rightarrow$ b-fraction typically $\sim 30\%$

Beauty in Photoproduction

$Q^2 \sim 0$ $\quad ep \rightarrow eb\bar{b}X \rightarrow ejj\mu X'$ $\quad 0.2 < y < 0.8, p_T^{jet} > 7(6)$ GeV

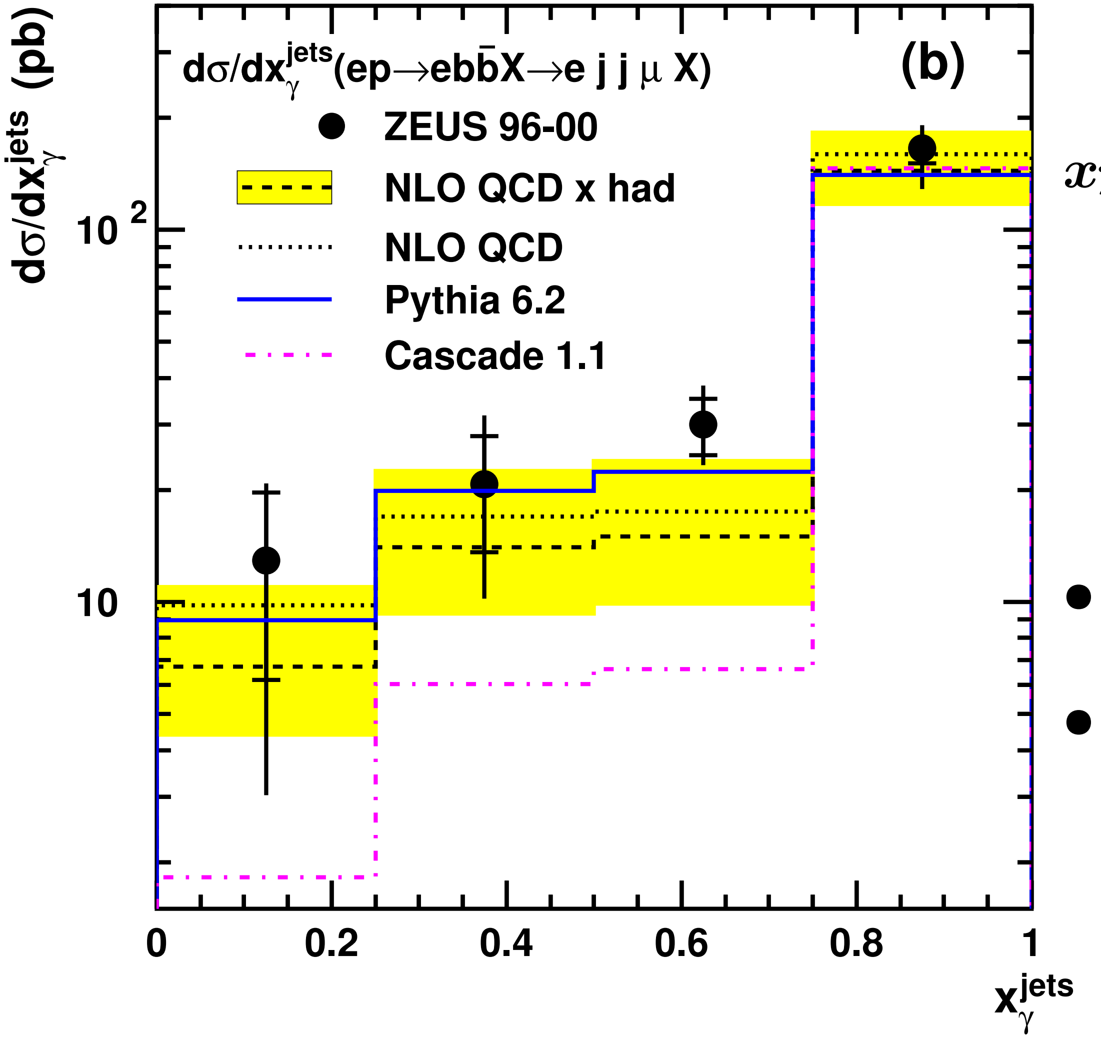




- General agreement between ZEUS and H1
- NLO undershoots data at low p_T^{μ}
- Still agreement within errors with massive NLO QCD (FMNR)

Beauty in Photoproduction : contributions from resolved photons

$Q^2 \sim 0$ $\qquad ep \to eb\bar{b}X \to ejj\mu X'$



- A separation betwen direct/resolved processes can be done according to the variable

$$x_\gamma^{jets} = \frac{\sum_{j_1,j_2}(E_T^j e^{-\eta^j})}{2yE_e}$$

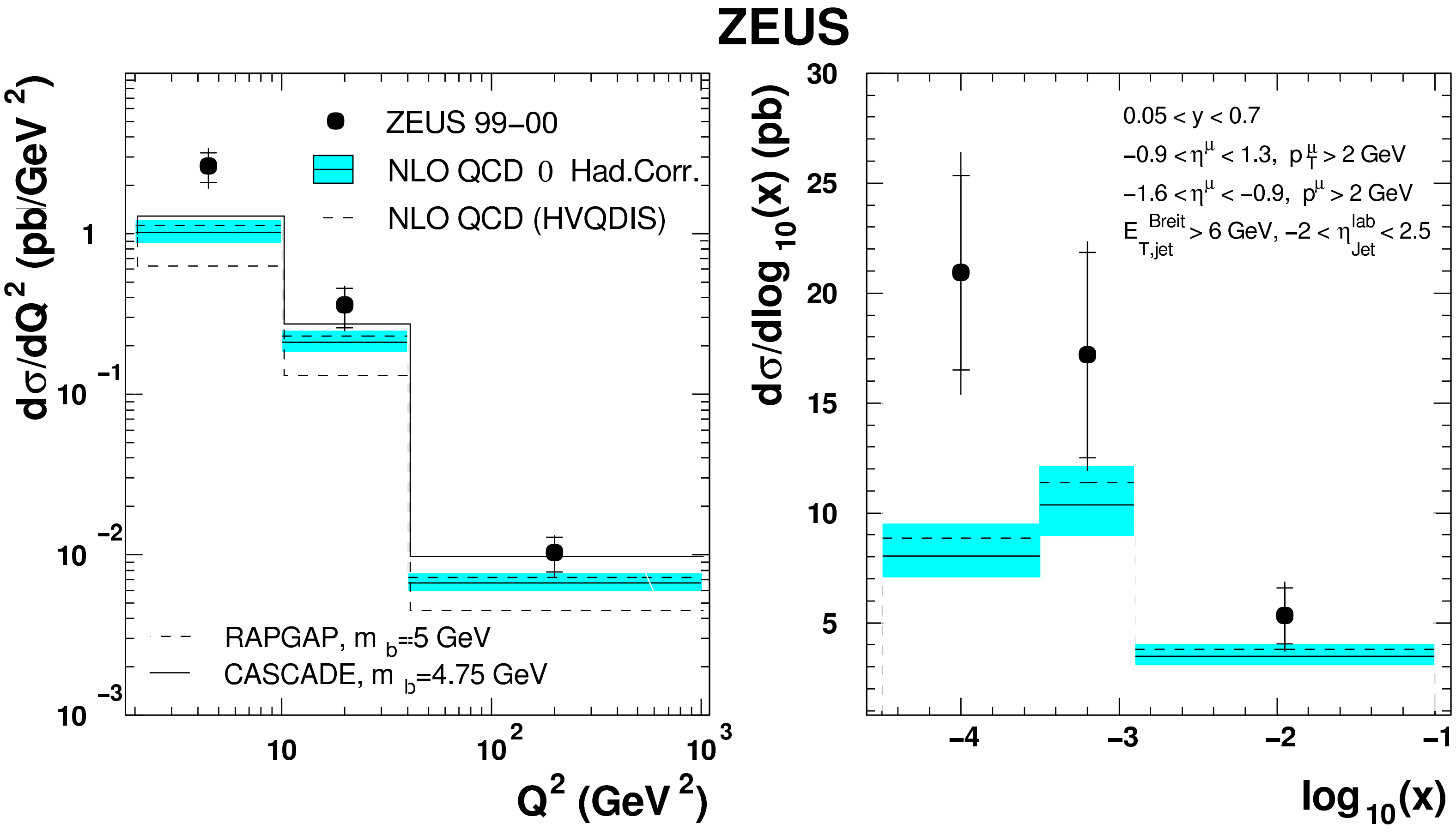
(fraction of the γ energy that contributes to create the two jets; $E_\gamma = yE_e$)

direct enriched sample $\Rightarrow x_\gamma^{jets} \gtrsim 0.75$
resolved enriched sample $\Rightarrow x_\gamma^{jets} \lesssim 0.75$

- At low x_γ^{jets} there is a significant component from resolved processes
- NLO QCD somewhat lower than data in resolved enriched region; OK in direct

Beauty in DIS

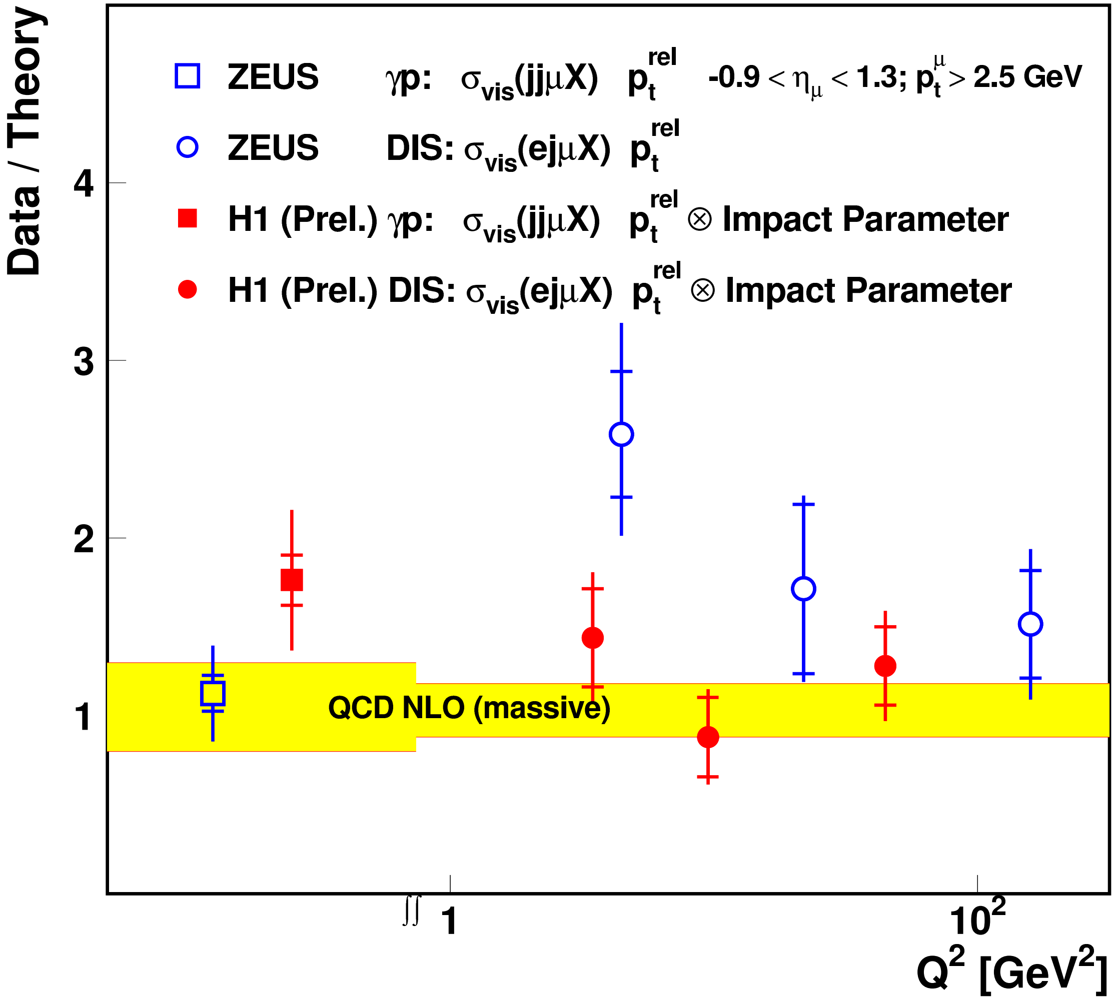
$Q^2 > 2\,GeV^2$ $ep \to eb\bar{b}X \to ej\mu X'$ (only one jet, enough in DIS)



- **Data higher than NLO at low Q^2 and x; theoretical prediction $\sim 2.5\sigma$ below data**
- **Similar results from H1**

Overview $j(j)\mu$ Beauty Cross Sections

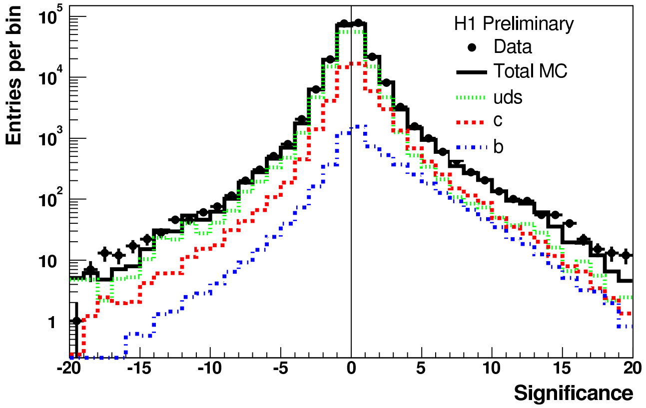
Data/Theory as a function of Q^2, both γp and DIS, both ZEUS and H1 data



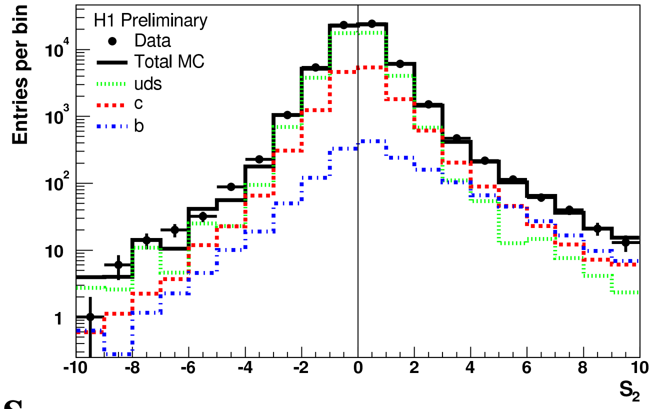
- **As a general tendency, data somewhat higher than (massive) NLO predictions**

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

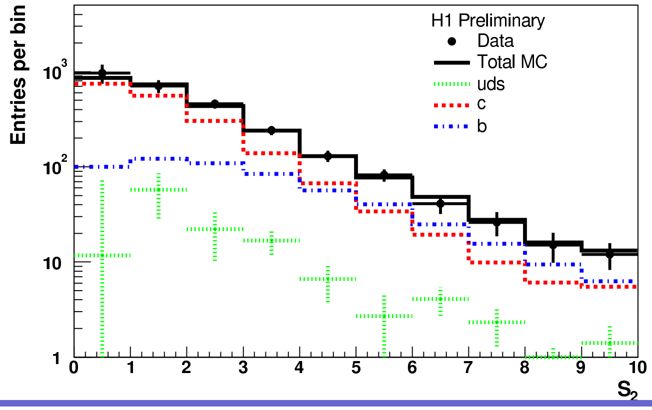
- **All tracks used in significance plot; no μ tagging**
  $\longrightarrow$ different components visible in MC



- **Divide sample in two subsamples :**
  $\longrightarrow$ Events with only one track : S_1
  $\longrightarrow$ Events with at least two tracks :
  plot second highest significance $S_2 \Rightarrow$
  b-component larger



- **After subtraction, only assymmetric part remains**
  $\longrightarrow$ b-component dominant



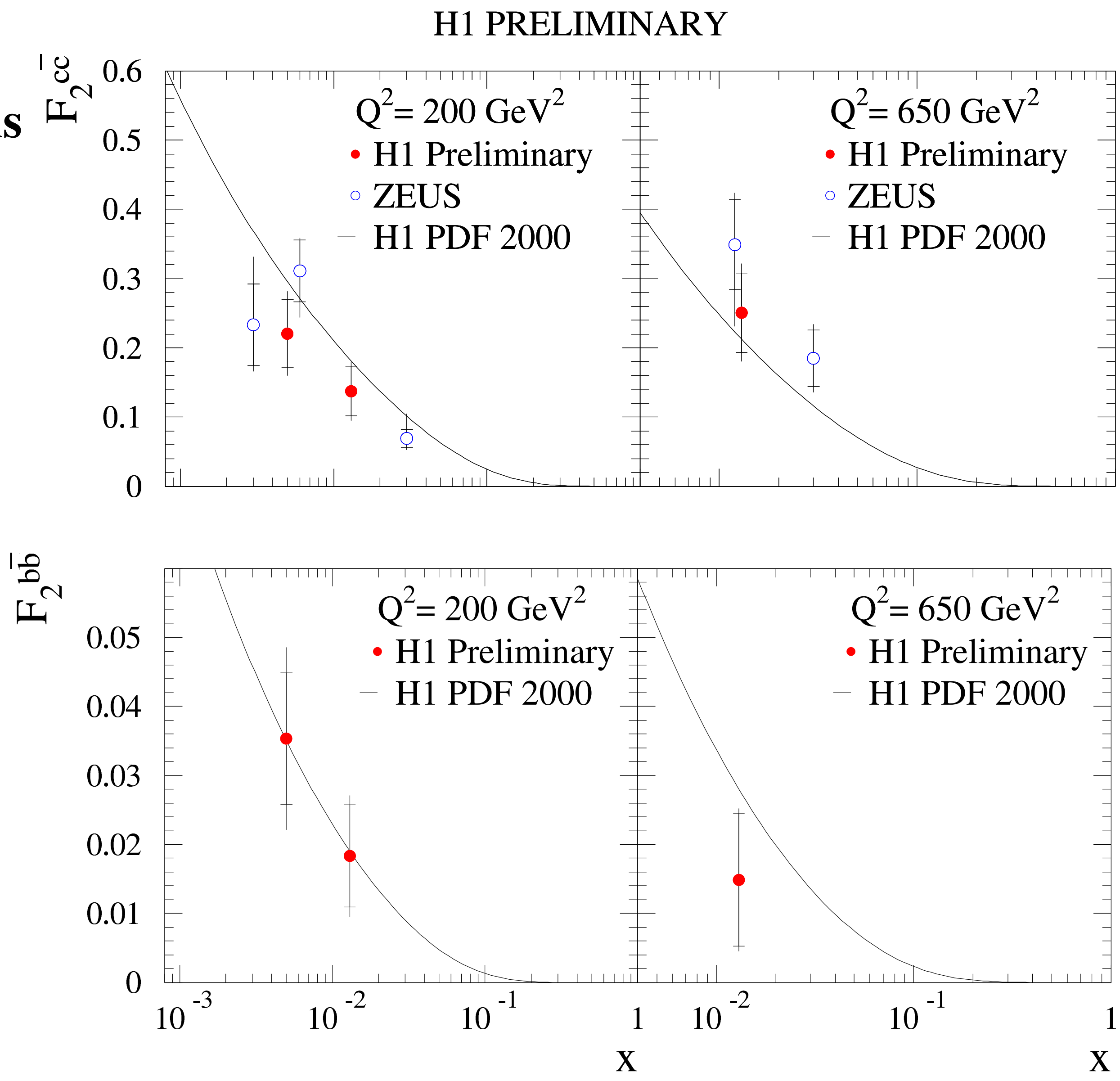
- **Simultaneous fit of S_1 and S_2 to extract**
  b and c fractions (done in γp and DIS)
  $\longrightarrow$ get $F_2^{b\bar{b}}$ and $F_2^{c\bar{c}}$

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

- **First measurement of $F_2^{b\bar{b}}$:**
  $\longrightarrow$ data agree with expectations

- **For $F_2^{c\bar{c}}$ H1 lifetime tagging same results than ZEUS D^* tagging**

- **At high Q^2, extrapolation $\sim 10\%$**
  $\longrightarrow$ model independent



Summary

- **Charm cross sections measured generally well decribed by pQCD**
  $\longrightarrow$ charm cross sections well understood

- **New measurements : low Q^2, p_T, jets ... where theories have large uncertainties**
  $\longrightarrow$ Charm γp and jets showing the need for "massless" calculations : theoretical developments needed

- **Evidence that charm fragmentation is universal in e^+e^- and ep**
  $\longrightarrow$ HERA errors competitive

- **Situation with beauty less clear**
  $\longrightarrow$ generally measurements above calculations

- **New methods and techniques in b-physics**
  $\longrightarrow$ First measurement of $F_2^{b\bar{b}}$

Outlook : HERA II

- Increased luminosity, improved instrumentation will provide more precise measurements
- First look at new data with improved instrumentation shows that lifetime tagging with ZEUS vertex detector works fine

EXPECT MUCH MORE CHARM AND BEAUTY FROM HERA II !!!