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Charm production at HERA

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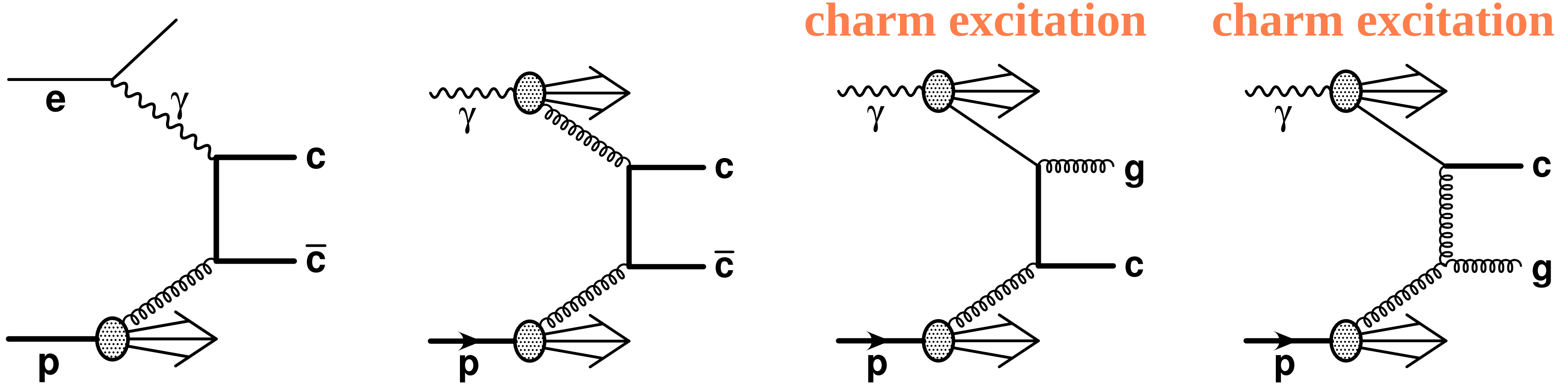
Outline

- **Introduction**
  - → Charm production in ep collisions
  - → Perturbative QCD calculations for heavy flavours
- **Experimental results**
  - → Cross sections and QCD comparison
  - → Fragmentation aspects
- **Summary**

Introduction : charm production in ep collisions

- dominated by **Boson Gluon Fusion (BGF)** at LO : $\gamma g \rightarrow c\bar{c}$ (direct/resolved)

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



$\Rightarrow$ **direct processes dominate, in photoproduction resolved play significant role**

Factorisation

$\sigma =$ **proton PDF** $\otimes$ $\sigma_{\gamma g \rightarrow Q\bar{Q}}$ $\otimes$ **photon PDF** $\otimes$ **fragmentation function**

$\Rightarrow$ **charm production sensitive to these pieces**

* m_c **large** $\Rightarrow$ **useful scale pQCD : reliable predictions**
* **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

"MASSIVE" APPROACH

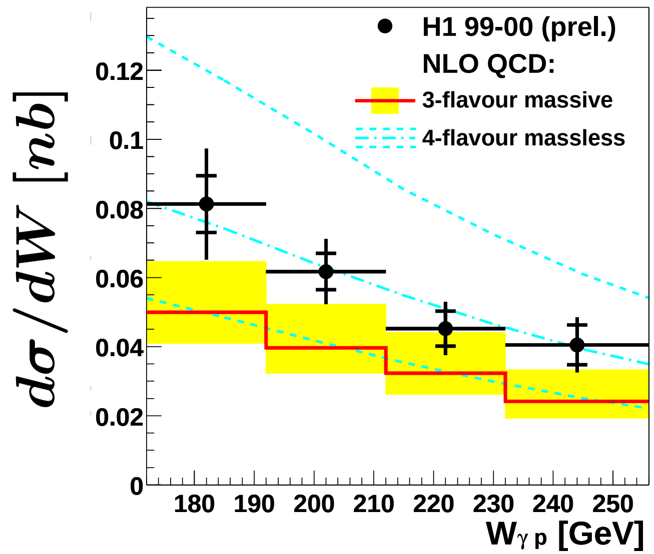
- **Fixed order calculation in α_s, with $m_Q \neq 0 \Rightarrow$**
  $\longrightarrow$ heavy quark is NOT part of the structure functions
  $\longrightarrow$ Proton : 3 active light flavours
  Quark (+gluon) densities obtained according to DGLAP evolution
- **HQ produced only dynamically; reliable at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

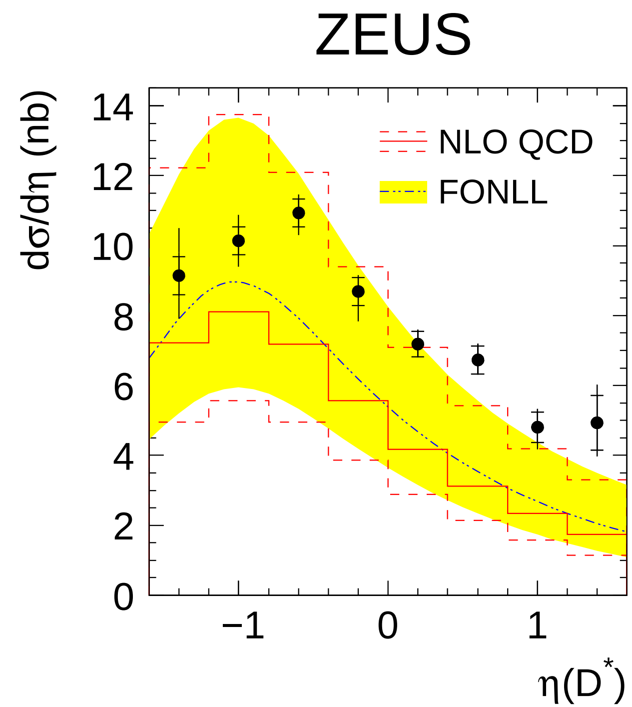
"MASSLESS" APPROACH

- **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 $p_T \gg m_Q$**

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**



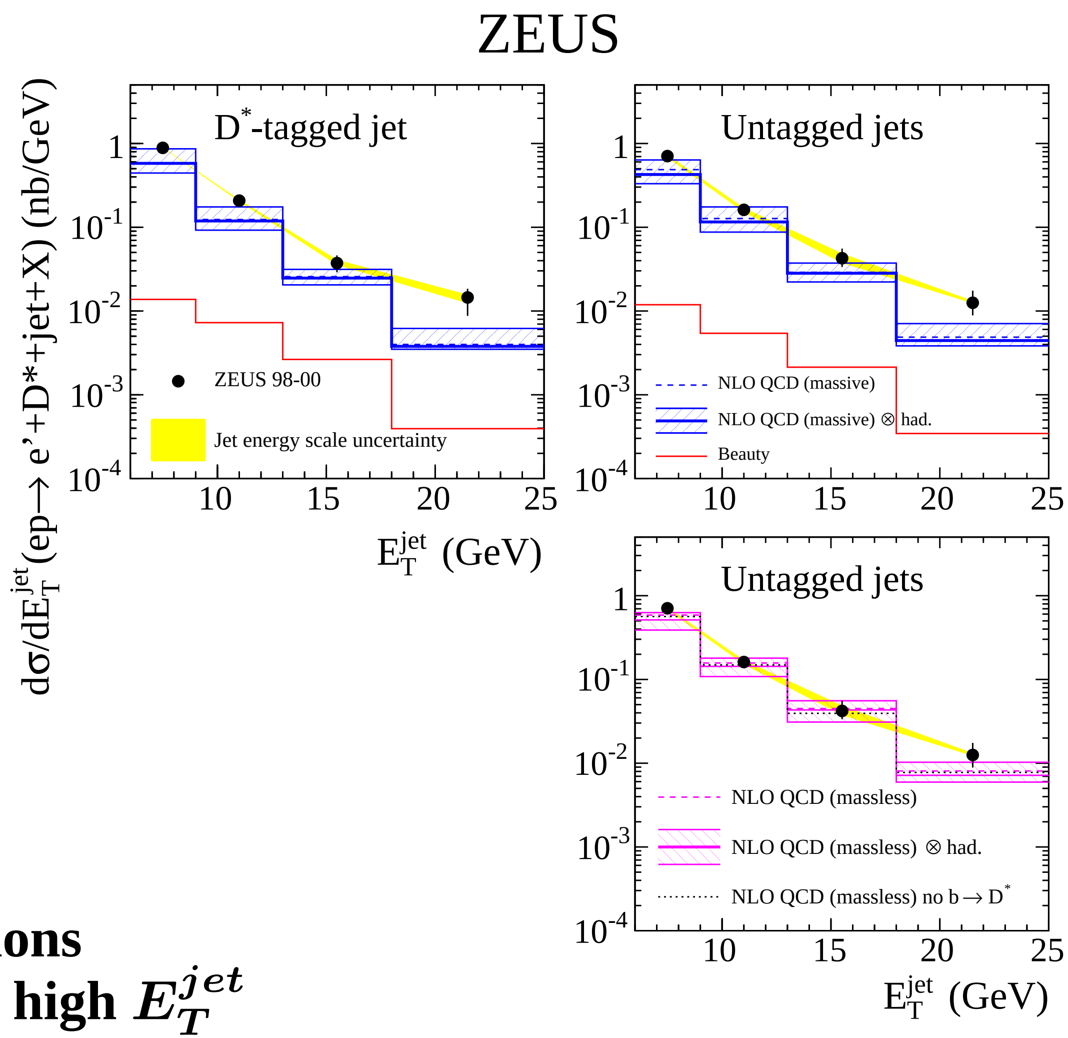


$D^{*\pm}$ photoproduction : inclusive jet cross sections

- 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



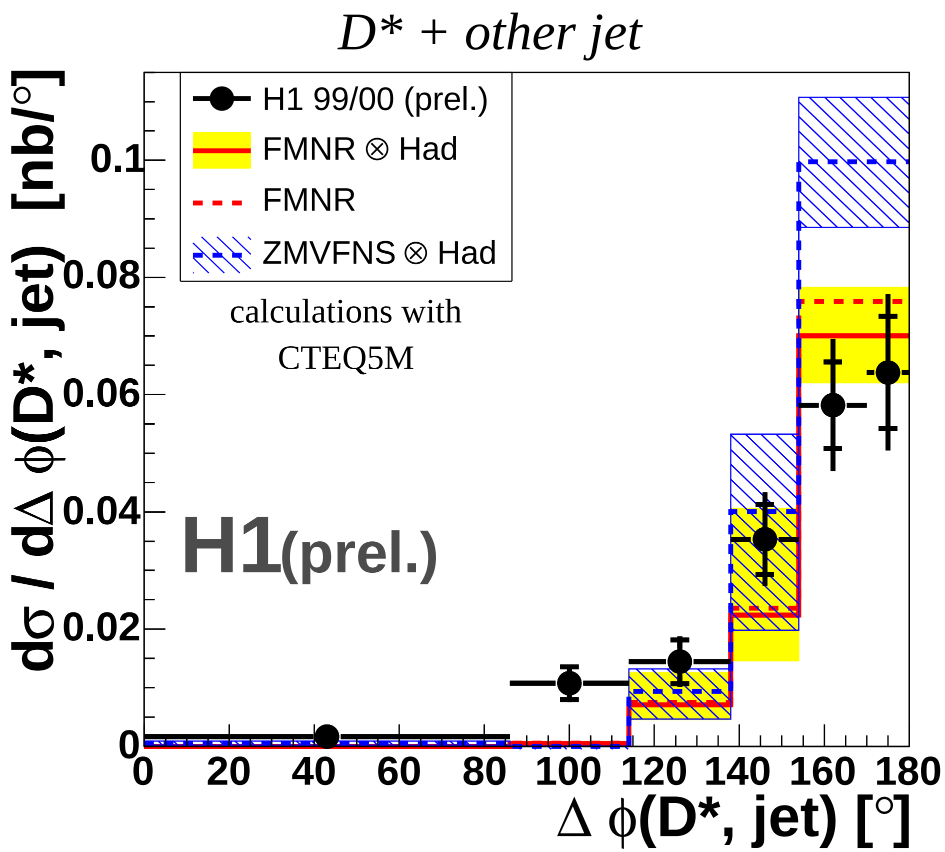
$\Rightarrow$ Good description from both calculations
Massless calculation closer to data at high E_T^{jet}

$D^{*\pm}$ photoproduction : D^* jet correlations

D^*+(untagged)jet ⇒ test higher order QCD contributions, (i.e. gluon radiation)
γp : γ and parton collide head-on
⇒ if no gluon emission, $2 \longrightarrow 2$ process particles in the final state are back to back

are we sensitive to gluon radiation?

- measure cross section in $\Delta\phi(D^*, jet)$
- only 25% from back to back configurations (i.e. $\Delta\phi \sim 180°$)
  ⇒ significant contribution from higher order QCD radiation
- NLO calculation does not describe region $\Delta\phi \sim 100°$
  ⇒ sensitivity to higher order contributions

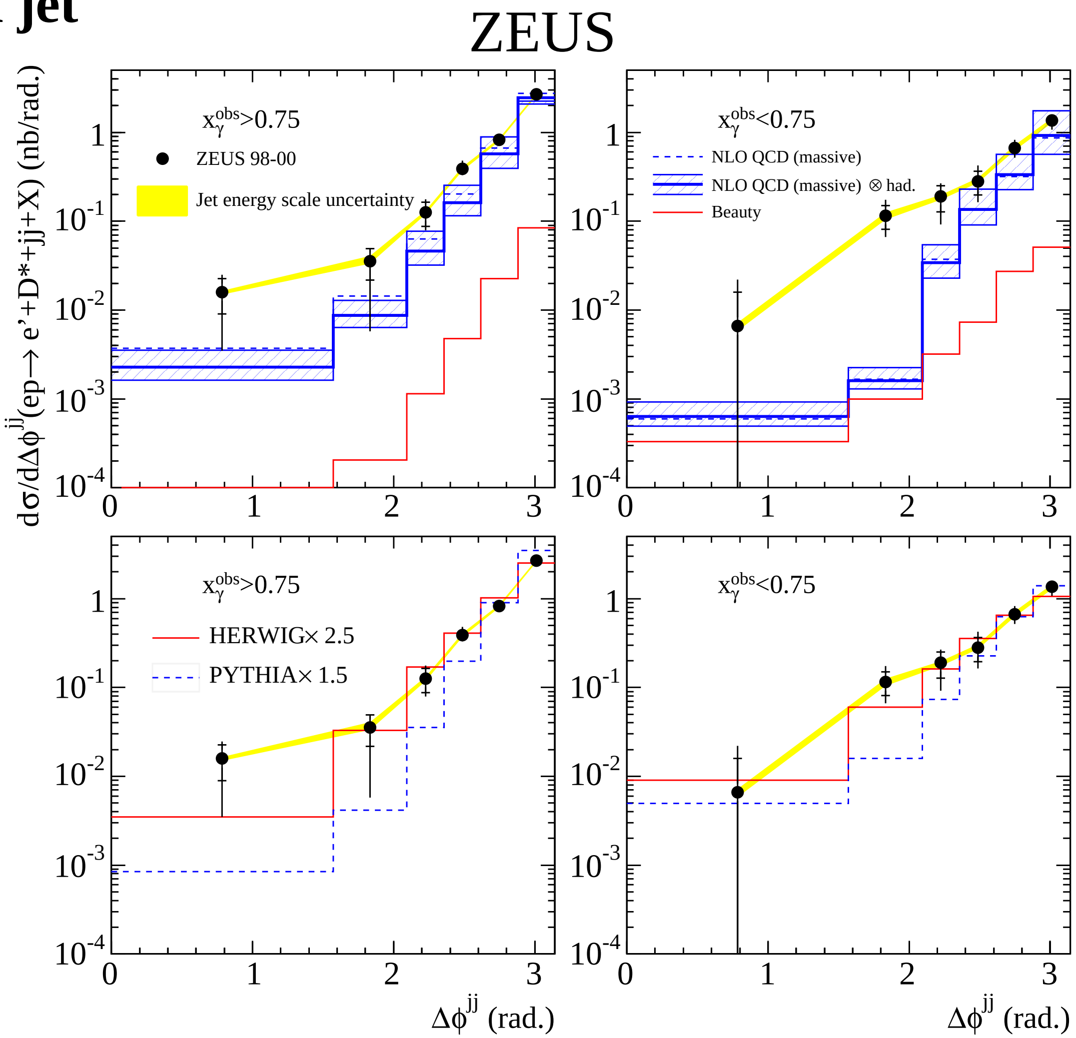


$D^{*\pm}$ photoproduction : dijet correlations

- **Correlations between tagged/untagged jet**
- **Sample divided in**

  direct-enriched : $x_\gamma^{obs} > 0.75$

  resolved-enriched : $x_\gamma^{obs} < 0.75$



- **Comparison to QCD**

  ⟶ LO + parton shower MC describes shape well

  ⟶ NLO QCD + had. corrections deviates from data at low $\Delta\phi^{jj}$

⇒ higher order calculations/ NLO + parton shower needed

Fragmentation of Charm Quark : Fractions and Ratios

- fragmentation $c \longrightarrow D$ is a long distant effect
  (no pQCD description, only phenomenological models)
- is fragmentation universal? (i.e. independent of charm production mechanism)

At HERA we measure

fragmentation fractions
$\longrightarrow$ probabilities for quark charm to hadronize into various hadrons

fragmentation functions
$\longrightarrow$ fraction of the quark's momentum carried by the heavy hadron

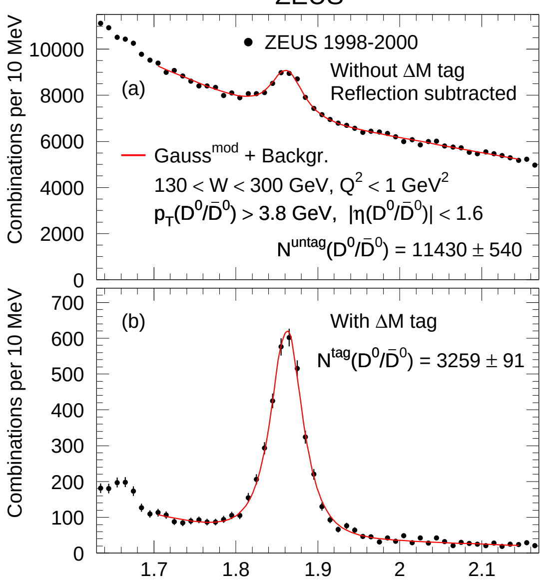
Fragmentation Fractions

- 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 $\Lambda_c^{\pm}$
- From cross sections, fragmentation fractions can be calculated

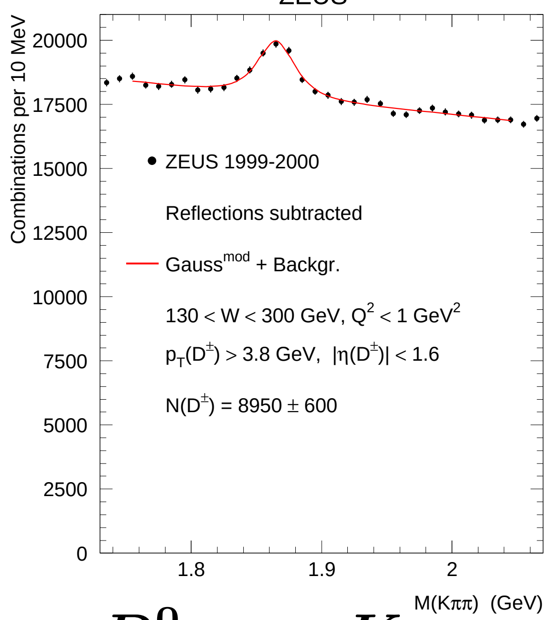
$$f(c \rightarrow D, \Lambda_c) = \sigma(D, \Lambda_c) / \sum_{all\ charm\ ground\ states} \sigma_i$$

Fragmentation of Charm Quark : Fractions and Ratios

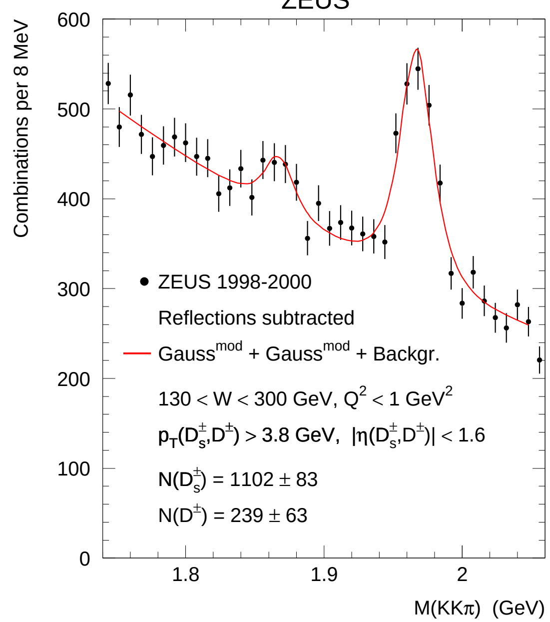
$D^0 \to K\pi$



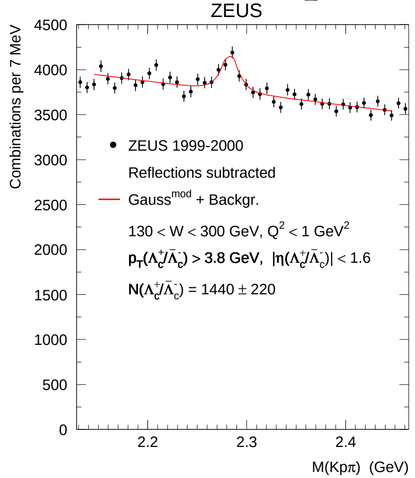
$D^\pm \to K\pi\pi$



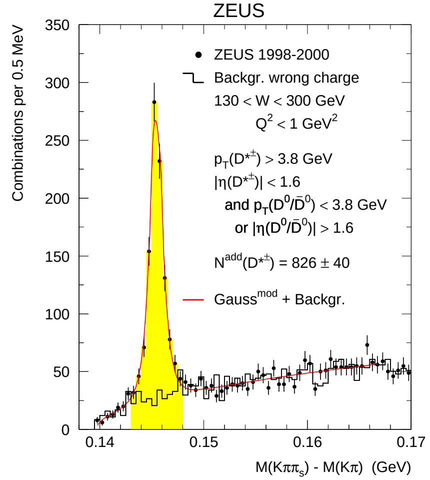
$D_s \to \phi(\to KK)\pi$



$\Lambda_c \to Kp\pi$



$D^* \to D^0\pi_s \to K\pi\pi$



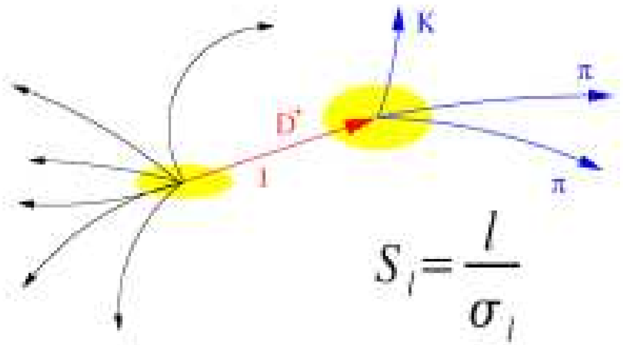
- **No particle identification (except Λ_c)**
- **many track combinations**

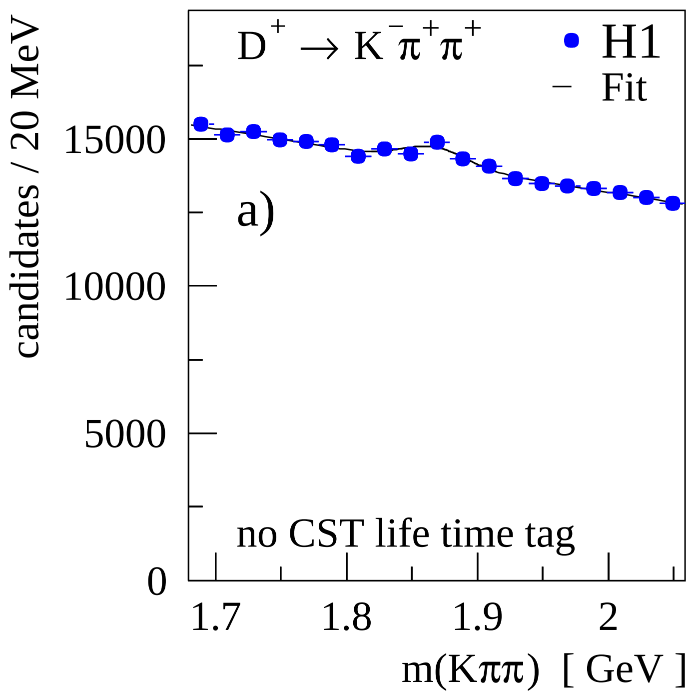
  $\Rightarrow$ large combinatorial background, supressed when two decays (kinematic constraint)

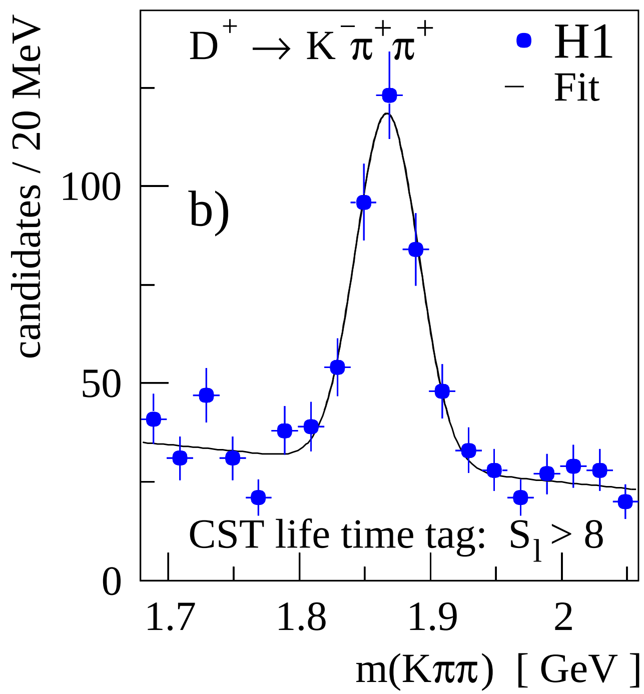
Fragmentation of Charm Quark : fractions and ratios (signals in DIS)

- **charm tagging : reconstruction of secondary vertex**
  lifetime of D-mesons leads to spacial separation between their production (primary) and their decay (secondary) ⇒ hadrons separated from combinatorial background

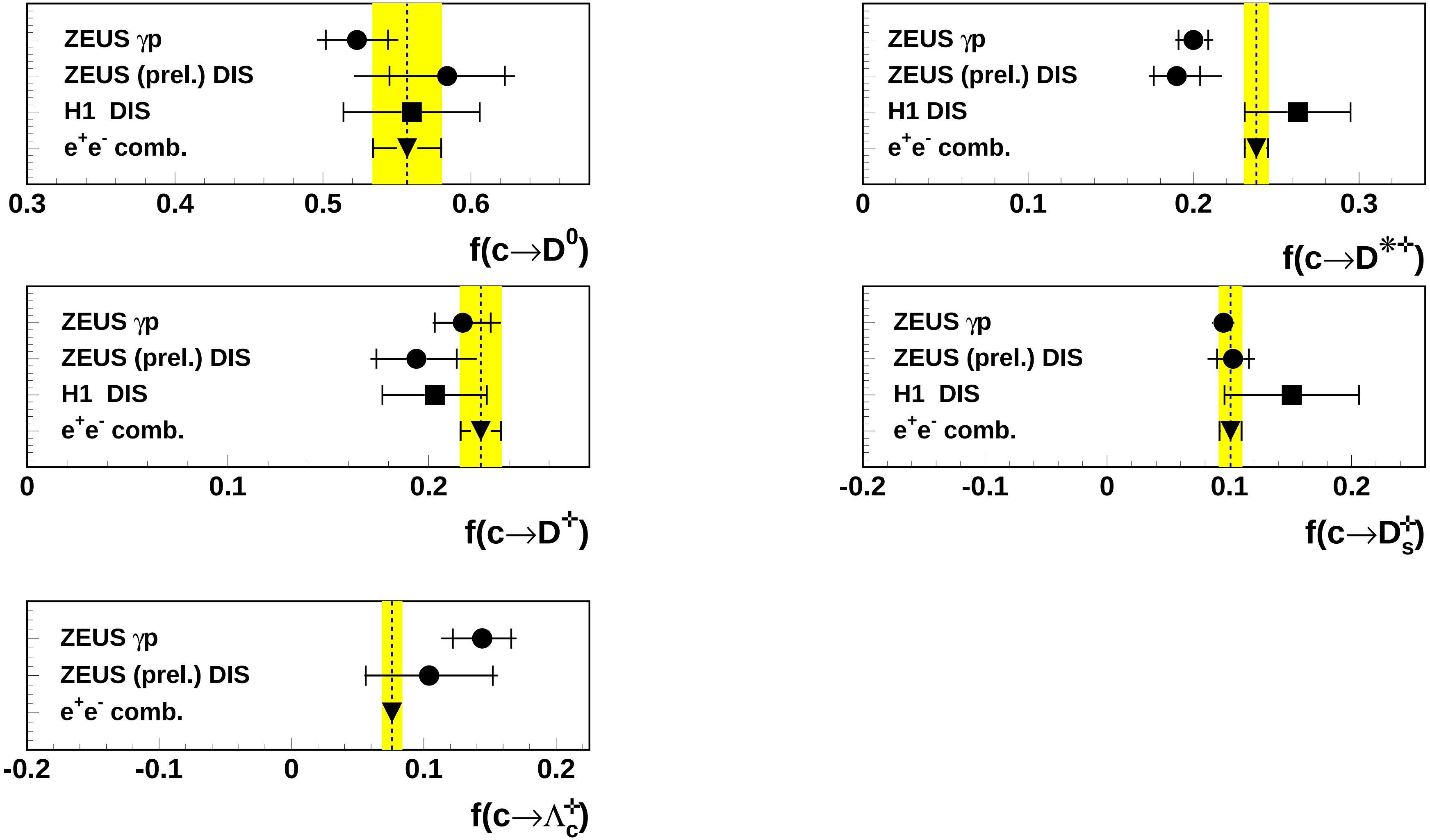
- **signal to background ratio improved significantly**







Fragmentation of Charm Quark : fragmentation fractions (results)



⇒ accurate measurements at HERA : errors competitive!

⇒ all fragmentation fractions in agreement with world average : universality

Fragmentation of Charm Quark : 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

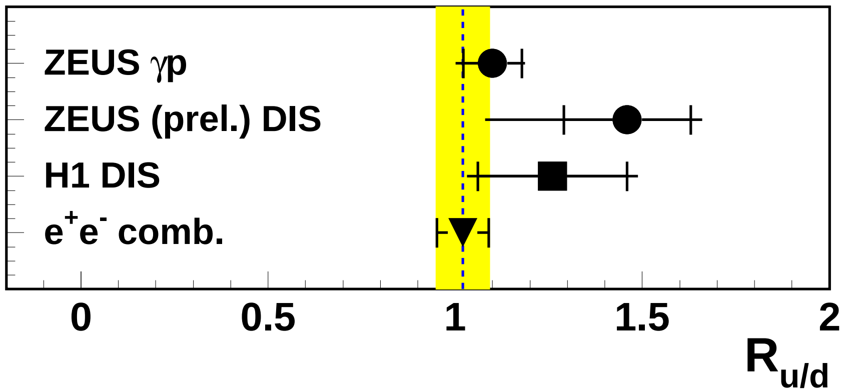
- What is the $s-$quark production suppression ? $\longrightarrow$
  strangeness supression factor $\gamma_s = 2c\bar{s}/(c\bar{u} + c\bar{d})$

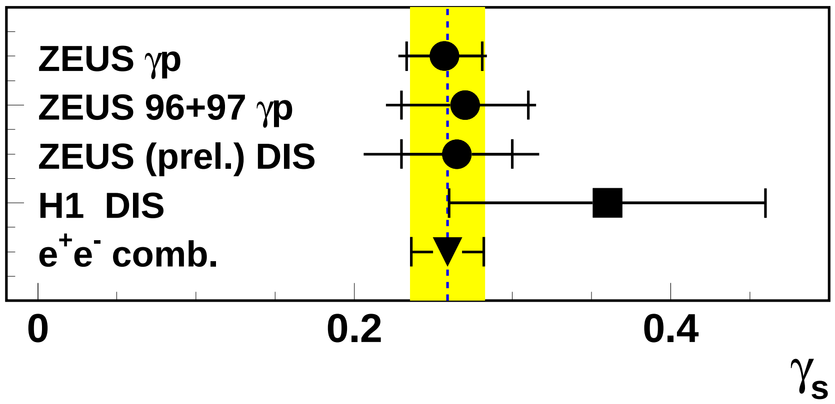
$\Rightarrow$ $D_s^{\pm}$ expected to be less frequently produced than D^0 and $D^{\pm}$, due to higher bare s quark mass

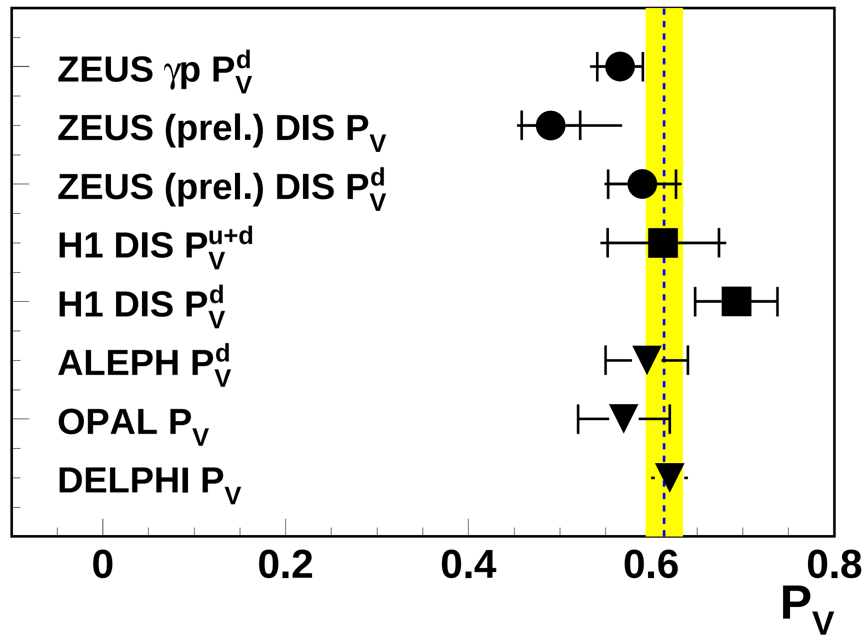
- What is the fraction of D mesons produced in a vector state? $\longrightarrow$ $P_V = V/(V + PS)$

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

Fragmentation of Charm Quark : Fragmentation Ratios (results)







⇒ In agreement with each other, expectation and world average, but naive spin counting not quite correct $(P_V \neq 3/4)$!

Fragmentation of charm quark : fragmentation function

- Fragmentation functions used to parametrise the energy transfer $Q \Rightarrow HADRON$
- Described by phenomenological models $\Rightarrow$ parameters can be fitted to data
- Tunning of parameters needed to reduce theoretical uncertainties

Need to give a definition of "energy transfer"

$\rightarrow$ in $e^+e^- \rightarrow c\bar{c}$: $E(c) = \sqrt{s}/2$, so natural choice $z = \frac{E(D^*)}{E(c)} = \frac{2 \cdot E(D^*)}{\sqrt{s}}$

$\rightarrow$ in ep definition of z not so obvious : depends on experimental method

Jet Method

c quark $\sim$ jet containing D^*

$$z_{jet} = \frac{(E + p_L)_{D^*}}{(E + p)_{jet}}$$

Hemisphere Method

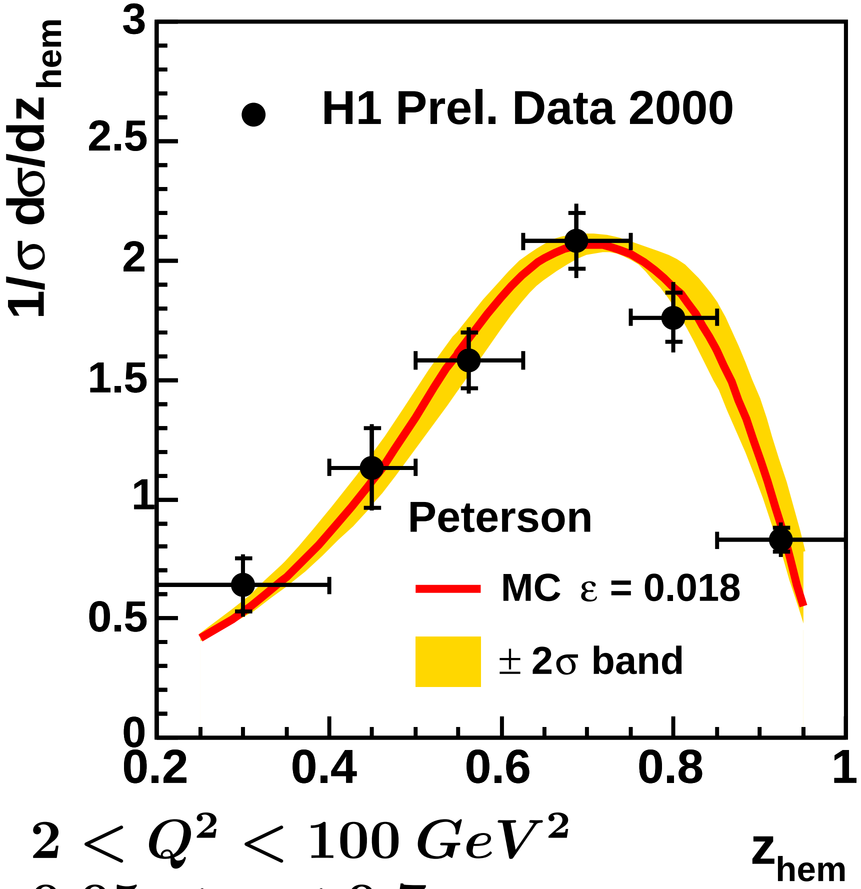
in γp frame the $c\bar{c}$ pair is balanced in p_T
$\Rightarrow$ can divide the event in two hemispheres

c quark $\sim$ all particles in hemisphere containing D^*

$$z_{hem} = \frac{(E + p_L)_{D^*}}{\sum_{hem}(E + p)}$$

The normalized distribution in z is what we call fragmentation function

Fragmentation of charm quark : fragmentation function



$2 < Q^2 < 100\ GeV^2$
$0.05 < y < 0.7$
$p_T(D^*) > 1.5\ GeV$
$|\eta(D^*)| < 1.5$

- Theoretical normalized cross section $\frac{1}{\sigma}\frac{d\sigma}{dz}$

  PYTHIA/RAPGAP + fragmentation model

  Peterson

  $f(z) \sim [z(1 - 1/z - \epsilon/(1-z)^2)]^{-1}$

  Kartvelishvili

  $f(z) \sim z^{\alpha}(1-z)$

- Fit theoretical prediction to data yields best values of ϵ, α parameters (in the used MC model)

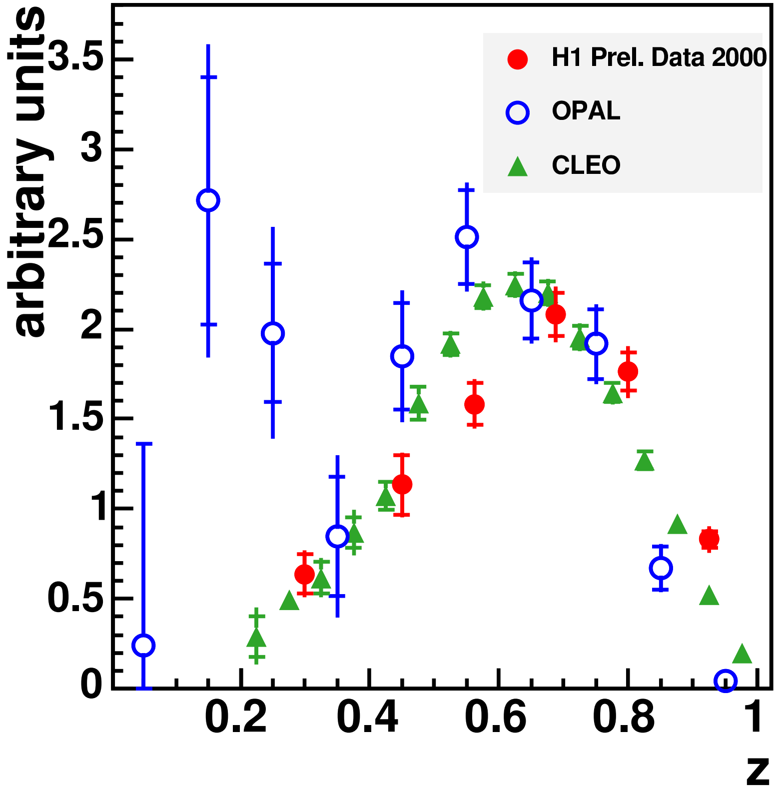
$\epsilon = 0.018^{+0.004}_{-0.004}$ (hem) $\epsilon = 0.030^{+0.006}_{-0.005}$ (jet)

$\alpha = 5.9^{+0.9}_{-0.6}$ (hem) $\alpha = 4.5^{+0.5}_{-0.5}$ (jet)

$\Rightarrow$ difference between the two methods may indicate inadequacies in MC description of hadronic final states in charm events

Fragmentation of charm quark : fragmentation function

Comparison z distribution at HERA with e^+e- experiments



H1 hemisphere method

$<\sqrt{s}> \approx 10$ GeV,

$$z = \frac{(E+p_L)_{D*}}{\sum_{hem}(E+p)}$$

OPAL $\sqrt{s} = 91.2$ GeV,

$$z = 2E_{D*}/\sqrt{s}$$

CLEO $\sqrt{s} \approx 10$ GeV,

$$z = p_{D*}/p_{max}$$

→ **Similar distributions at medium/large z**

⇒ **although different observable definitions, spectra similar shape (universality)**

Summary

- **Description of charm cross sections by QCD good in general, but fails in the details**

- **New measurements : jets . . . give more details of final state/event kinematics**
  → Charm γp and jets showing the need for higher order calculations
  theoretical developments needed (MC@NLO. . .)

- **Charm fragmentation fractions/ratios and fragmentation function measured**
  → accurate measurements : HERA errors competitive
  → Evidence that charm fragmentation is universal in e^+e^- and ep