Heavy flavour production in high energy ep collisions

Igor Katkov

Skobeltsyn Institute of Nuclear Physics

Moscow State University

12th High Energy Physics International Conference on Quantum Chromodynamics

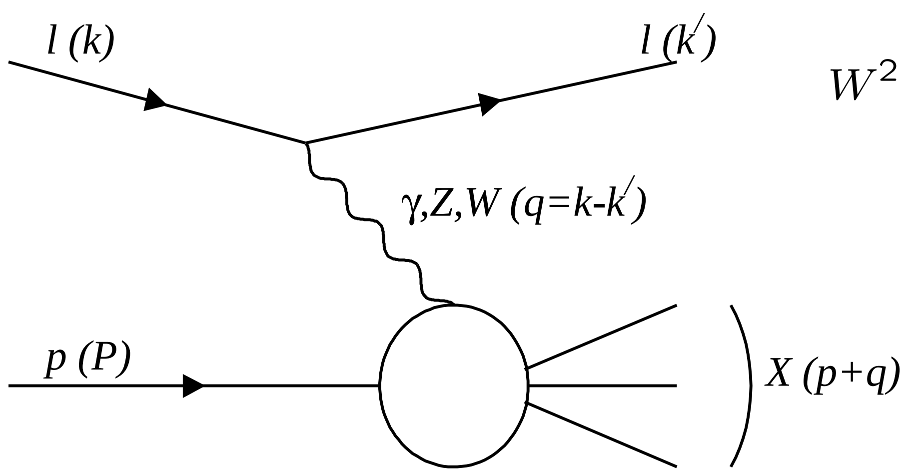
Montpellier - France, 4–9 July 2005

- Introduction
- Inelastic J/ψ production
- Charm fragmentation
- Charm with jets
- $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$
- Beauty dijets and dimuons
- Summary and Outlook

Introduction

- H1 and ZEUS @ HERA collider: 920 (820) GeV p on 27.5 GeV $e^{\pm}$
- Hard scale: $m_Q \gg \Lambda_{QCD} \Rightarrow$ perturbative treatment
- Factorisation in perturbative QCD:

  $\sigma =$ parton distributions $\otimes$ hard scattering $\otimes$ fragmentation/hadronisation
- Test pQCD, provide experimental input for parton distributions, fragmentation functions



$$s = (k+P)^2, \quad \sqrt{s} = 300 \text{ or } 318 \text{ GeV}$$

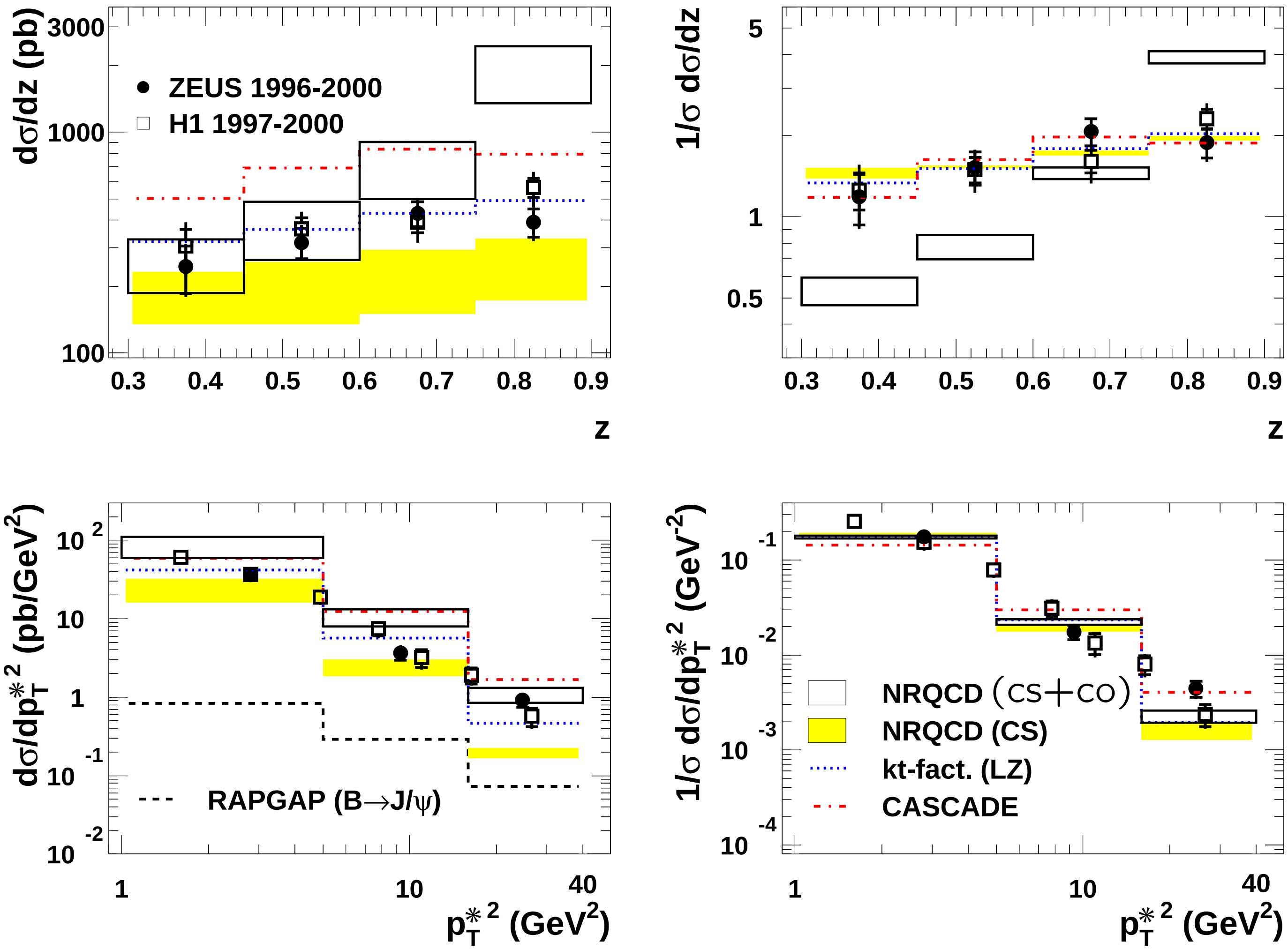
$$W^2 = (q+P)^2,\ Q^2 = -q^2,\ x_{Bj} \equiv x = \frac{Q^2}{2(P\cdot q)}$$

$$y = (q\cdot P)/(k\cdot P)$$

photoproduction: $Q^2 < 1\,\text{GeV}^2$

DIS: $Q^2 \gtrsim 1\,\text{GeV}^2$

Inelastic J/ψ production in DIS



$\mathcal{L} = 109\,\text{pb}^{-1}$

$2 < Q^2 < 100\ \text{GeV}^2$

$50 < W < 225$ GeV

$0.3 < z < 0.9$

$p_T^{*2} > 1\ \text{GeV}^2$

$z = (p_\psi \cdot P)/(q \cdot P)$

LO NRQCD: DGLAP gluon

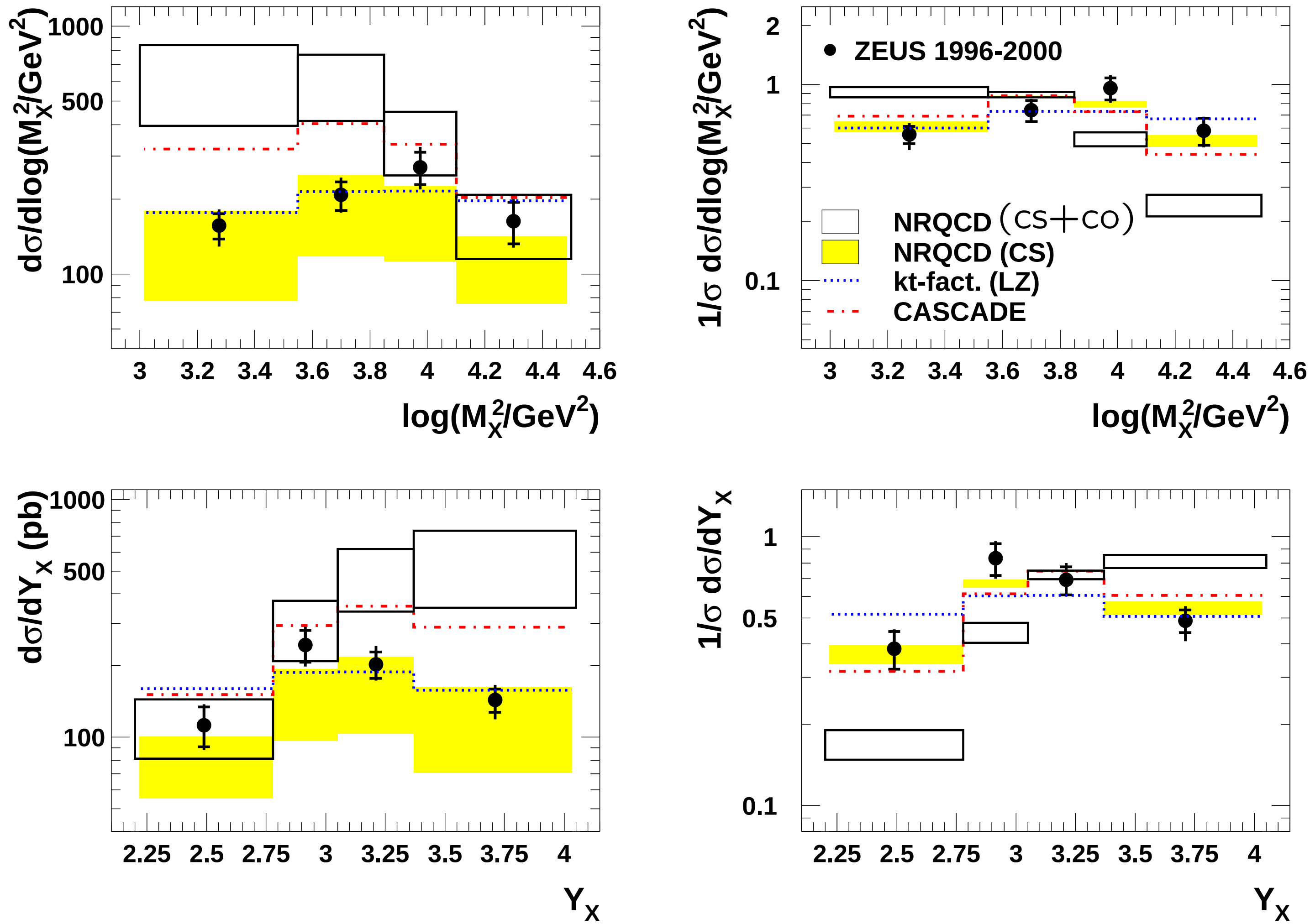
LO NRQCD: CS⊕CO (w/o soft gluon resum.)

kt-fact.: BFKL gluon

CASCADE: CCFM gluon

kt-fact.&CASCADE: CSM

Inelastic J/ψ production in DIS



$2 < Q^2 < 80$ GeV^2

$50 < W < 250$ GeV

$0.2 < z < 0.9$

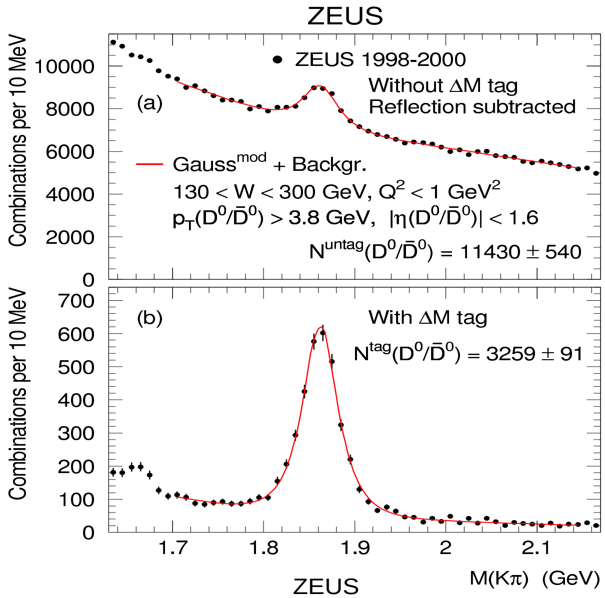
Measurement of hadronic final state

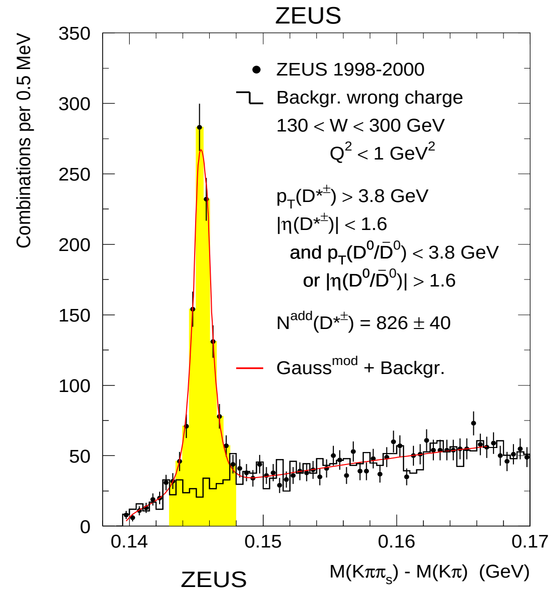
LO CS generally agree with data

LO CO contributions w/o resummation spoil agreement

kt-fact.: best description of data

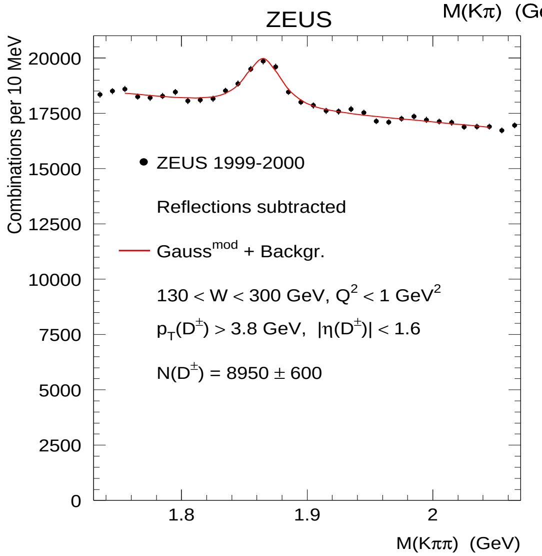
Fragmentation ratios/fractions

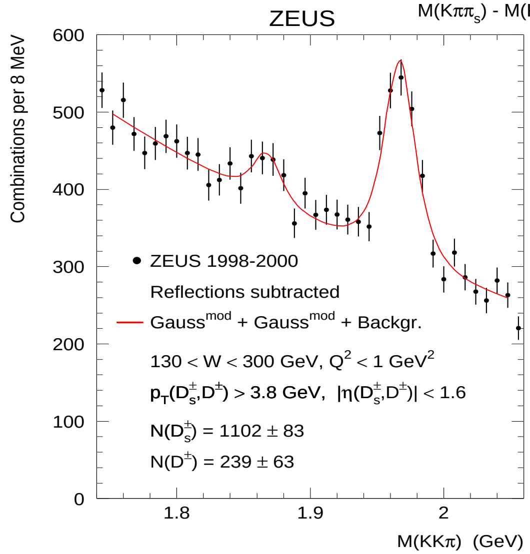


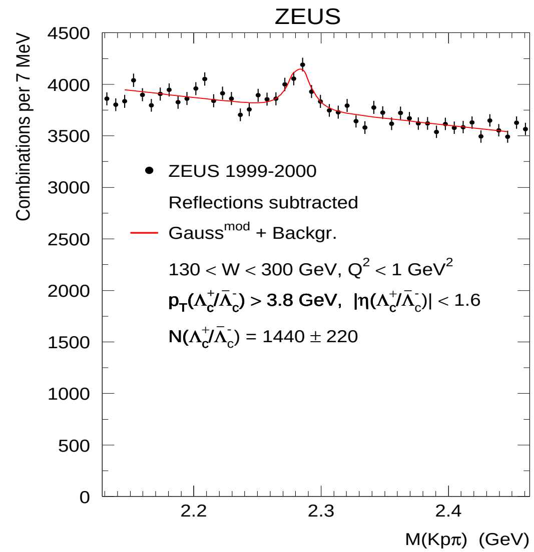


Charm resonances Zoo:

$$\mathcal{L} = 79\,\text{pb}^{-1}$$
$$Q^2 < 1\,\text{GeV}^2$$
$$130 < W < 300\,\text{GeV}$$
$$p_T(D, \Lambda_c) > 3.8\,\text{GeV}$$
$$|\eta(D, \Lambda_c)| < 1.6$$







Fragmentation ratios/fractions

	Neutral to charged D-meson ratio $R_{u/d} = (cu)/(cd)$
ZEUS (γp)	$\boxed{1.100} \pm 0.078(\text{stat.})^{+0.038}_{-0.061}(\text{syst.})^{+0.047}_{-0.049}(\text{br.})$
H1 (DIS)	$1.26 \pm 0.20(\text{stat.}) \pm 0.11(\text{syst.}) \pm 0.04(\text{br.} \oplus \text{theory})$
combined e^+e^- data	$1.020 \pm 0.069(\text{stat.} \oplus \text{syst.})^{+0.045}_{-0.047}(\text{br.})$

$R_{u/d} \sim 1$: u and d quarks produced equally in charm fragmentation (isospin invariance)

	Strangeness-suppression factor $\gamma_s = (2\,cs)/(cd + cu)$
ZEUS (γp)	$\boxed{0.257} \pm 0.024(\text{stat.})^{+0.013}_{-0.016}(\text{syst.})^{+0.078}_{-0.049}(\text{br.})$
ZEUS 96-97	$0.27 \pm 0.04(\text{stat.})^{+0.02}_{-0.03}(\text{syst.}) \pm 0.07(\text{br.})$
H1 (DIS)	$0.36 \pm 0.10(\text{stat.}) \pm 0.01(\text{syst.}) \pm 0.08(\text{br.} \oplus \text{theory})$
combined e^+e^- data	$0.259 \pm 0.023(\text{stat.} \oplus \text{syst.})^{+0.087}_{-0.052}(\text{br.})$

s-quark production suppressed by factor 3–4 in c-fragmentation

	Fraction of charged vector D mesons $P_{\text{v}}^{d} = (V)/(V + PS)$
ZEUS (γp)	$\boxed{0.566} \pm 0.025(\text{stat.})^{+0.007}_{-0.022}(\text{syst.})^{+0.022}_{-0.023}(\text{br.})$
H1 (DIS)	$0.693 \pm 0.045(\text{stat.}) \pm 0.004(\text{syst.}) \pm 0.009(\text{br.} \oplus \text{theory})$
combined e^+e^- data	$0.614 \pm 0.019(\text{stat.} \oplus \text{syst.})^{+0.023}_{-0.025}(\text{br.})$

Value not consistent with naive spin counting (0.75)

Charm fragmentation fractions

Fraction of c quarks hadronising as a hadron:

$$f(c \to D, \Lambda_c) = \frac{N(D, \Lambda_c)}{N(c)} = \frac{\sigma(D, \Lambda_c)}{\sum_{\text{all}} \sigma(D, 1.14 \cdot \Lambda_c)}$$

	ZEUS (γp) $p_T(D, \Lambda_c) > 3.8$ GeV $\lvert\eta(D, \Lambda_c)\rvert < 1.6$	Combined e^+e^- data	H1 (DIS)
	stat. syst. br.	stat.$\oplus$syst. br.	total
$f(c \to D^+)$	$0.217 \pm 0.014 ^{+0.013}_{-0.005} {}^{+0.014}_{-0.016}$	$0.226 \pm 0.010 ^{+0.016}_{-0.014}$	0.203 ± 0.026
$f(c \to D^0)$	$0.523 \pm 0.021 ^{+0.018}_{-0.017} {}^{+0.022}_{-0.032}$	$0.557 \pm 0.023 ^{+0.014}_{-0.013}$	0.560 ± 0.046
$f(c \to D_s^+)$	$0.095 \pm 0.008 ^{+0.005}_{-0.005} {}^{+0.026}_{-0.017}$	$0.101 \pm 0.009 ^{+0.034}_{-0.020}$	0.151 ± 0.055
$f(c \to \Lambda_c^+)$	$0.144 \pm 0.022 ^{+0.013}_{-0.022} {}^{+0.037}_{-0.025}$	$0.076 \pm 0.007 ^{+0.027}_{-0.016}$	
$f(c \to D^{*+})$	$0.200 \pm 0.009 ^{+0.008}_{-0.006} {}^{+0.008}_{-0.012}$	$0.238 \pm 0.007 ^{+0.003}_{-0.003}$	0.263 ± 0.032

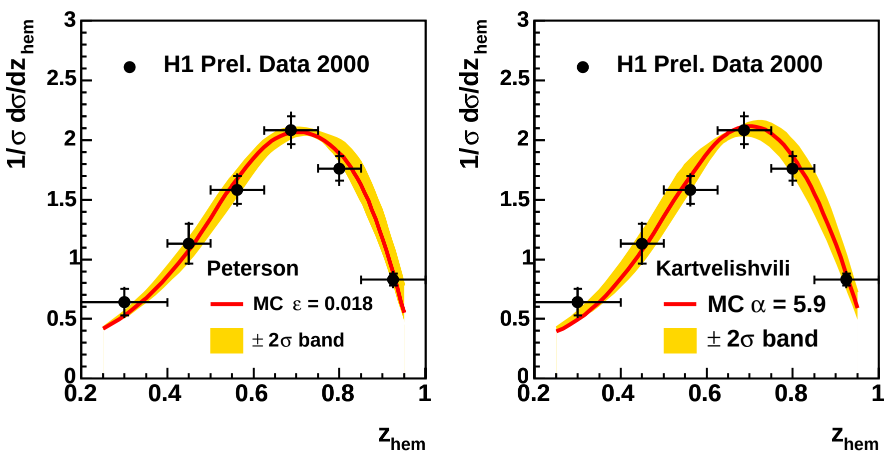
charm fragmentation fractions are universal

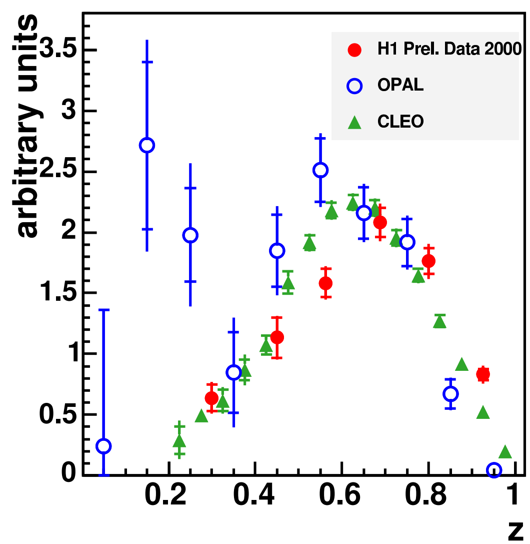
Competitive precision everywhere

Fragmentation function in DIS

- Study parametrisation of the fractional transfer of c quark energy/momentum (z) to a D-meson
- $2 < Q^2 < 100\,\text{GeV}^2, 0.05 < y < 0.7, p_T(D^*) > 1.5\,\text{GeV}, |\eta(D^*)| < 1.5,\ D^* \to K\pi\pi_s$
- Hemisphere method: c-quark energy approximated by energy of a hemisphere of D-meson, $z_{hem} = (E+p_L)_{D^*}/\sum_{hem}(E+p_L)$, γp-frame, analogy to e^+e^-

RAPGAP $\otimes$ Peterson/Kartvelishvili:





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

Peterson: $f(z) \sim z^{-1}\left[1 - \frac{1}{z} - \frac{\varepsilon}{1-z}\right]^{-2}$

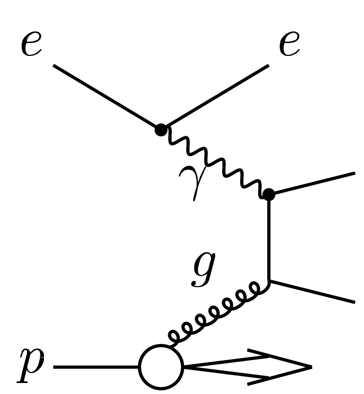
$\varepsilon = \boxed{0.018^{+0.004}_{-0.004}}$

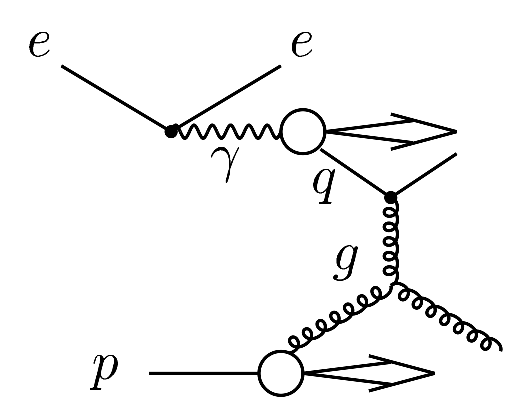
Kartvelishvili: $f(z) \sim z^{\alpha}(1-z)$

$\alpha = \boxed{5.9^{+0.9}_{-0.6}}$

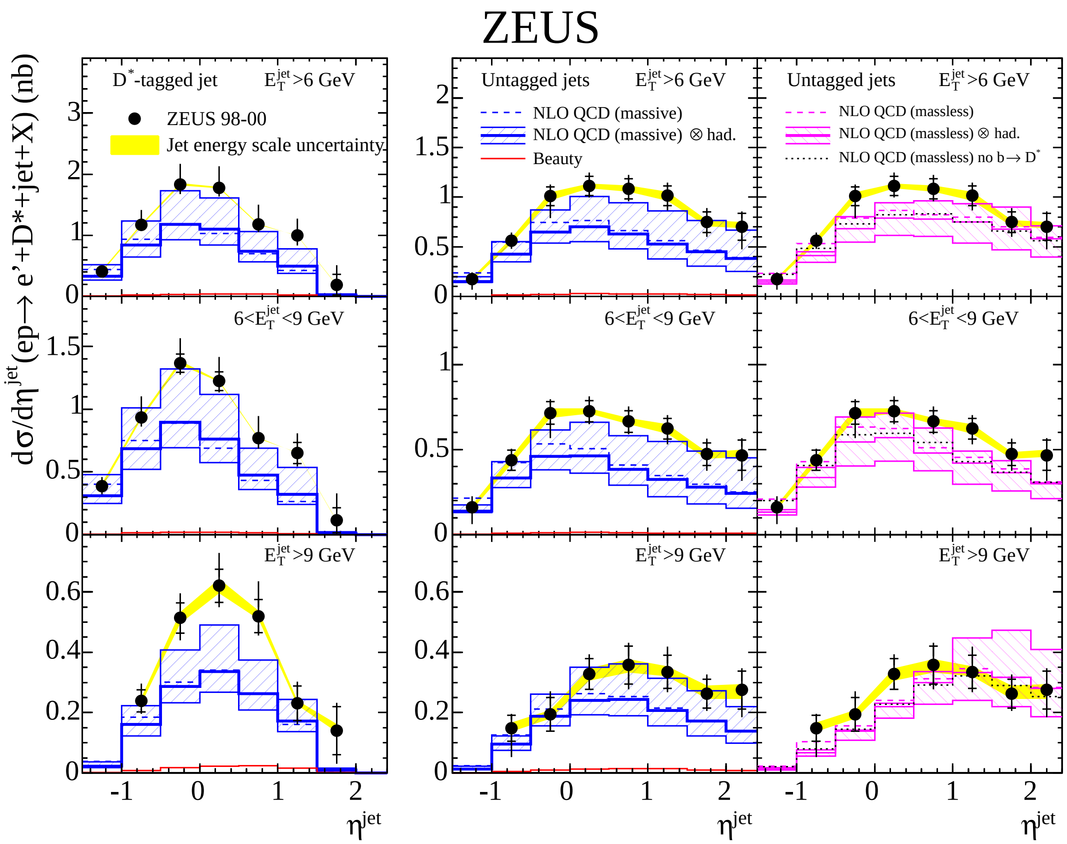
Heavy quarks with jets

- QCD NLO calculations (problem of many scales):
  - Massive scheme: no p_T/m_Q logs resummation, valid for $\boxed{0 \leq p_T \lesssim \text{few} \times m_Q}$, three active partons, no heavy quark excitation
  - Massless scheme: $\alpha_s \ln(p_T^2/m_Q^2)$ terms resummed, valid for $\boxed{p_T \gtrsim \text{few} \times m_Q}$, breaks down for $p_T \lesssim m_Q$, up to five active partons, fragmentation into massive hadrons after hard scatter
  - Combined schemes





Inclusive charm jets (photoproduction)



$\mathcal{L} = 79\,\text{pb}^{-1}$

$Q^2 < 1\,\text{GeV}^2$

$130 < W < 280\,\text{GeV}$

$p_T^{D^*} > 3\,\text{GeV},\ |\eta^{D^*}| < 1.5$

k_T clust. algorithm

$E_T^{\text{jet}} > 6\,\text{GeV}$

$-1.5 < \eta^{\text{jet}} < 2.4$

D^*–tag :

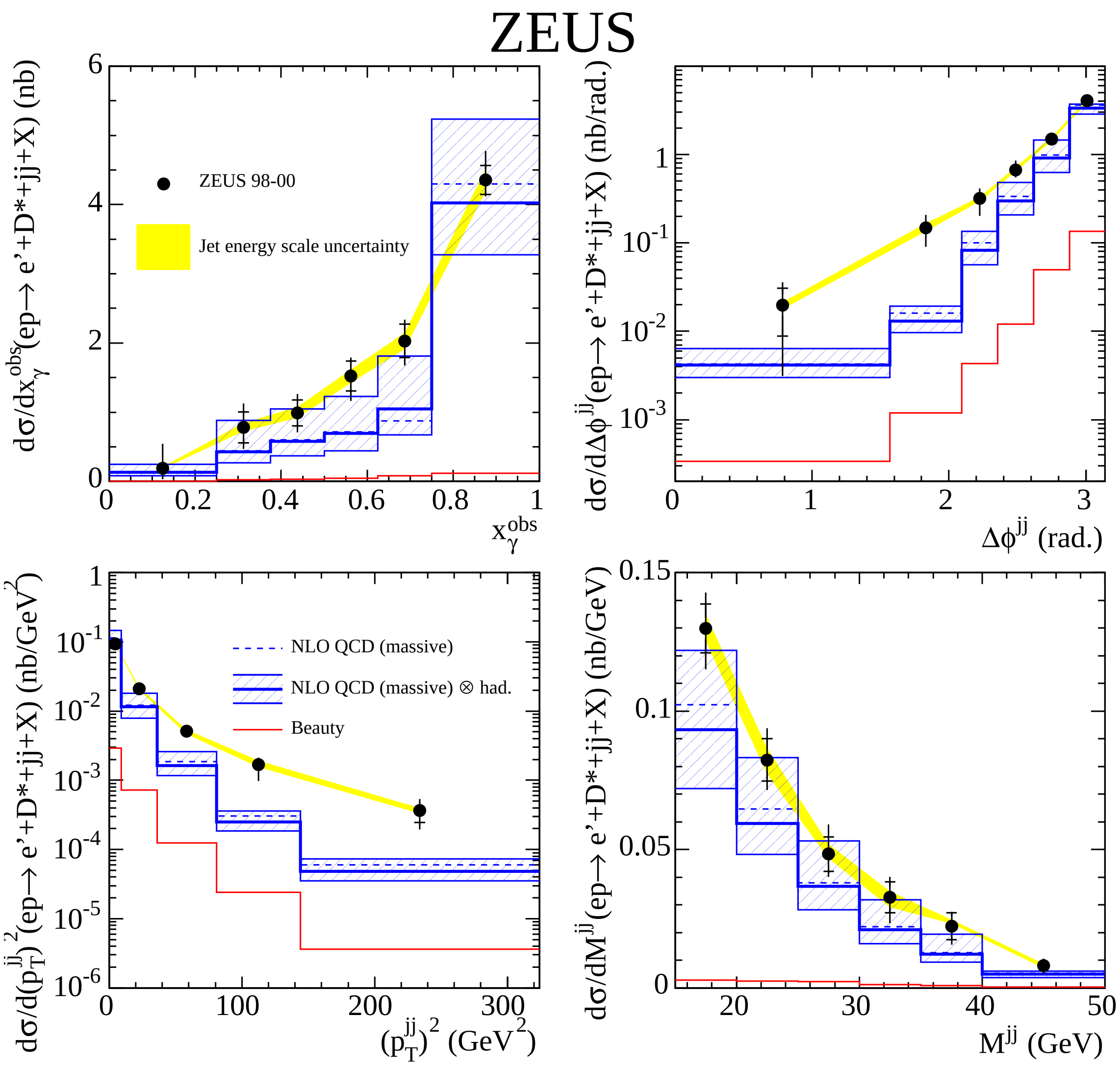
$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.6$

Massive: FMNR

Massless: Heinrich, Kniehl
(only untagged jets)

- For all E_T: shapes described by NLO QCD, normalisation (almost) described by upper bound
- No excess in forward as for inclusive jets

Charm jet correlations (photoproduction)



- Dijet sample: $E_T^{\rm jet} > 6 \rightarrow E_T^{jet1} > 7, E_T^{jet2} > 6$ GeV
- $x_\gamma^{\rm obs} = \sum_{\rm jets} E_T \exp^{-\eta} / (2yE_e)$: fraction of photon energy in hard interaction
- $\Delta\phi^{jj} = \pi$, $(p_T^{jj})^2 = 0$ for lowest order $2 \rightarrow 2$ process in collinear calculations $\Rightarrow$ correlations sensitive to HO corrections
- Large deviations from NLO QCD at low $\Delta\phi^{jj}$ and high $(p_T^{jj})^2$ enhanced for resolved-enriched ($x_\gamma^{\rm obs} < 0.75$) sample; HERWIG describes data
- sensitivity to even higher order corrections

Shape of jets in charm photoproduction

- Insight into hard scatter process using jet structure variables: jet shapes initiated by quarks and gluons are expected to be different

$$\psi(r) = p_T^{\text{jet}}(r)/p_T^{\text{jet}}(r = R(= 1)), r = \sqrt{(\Delta\eta^2 + \Delta\phi^2)}$$

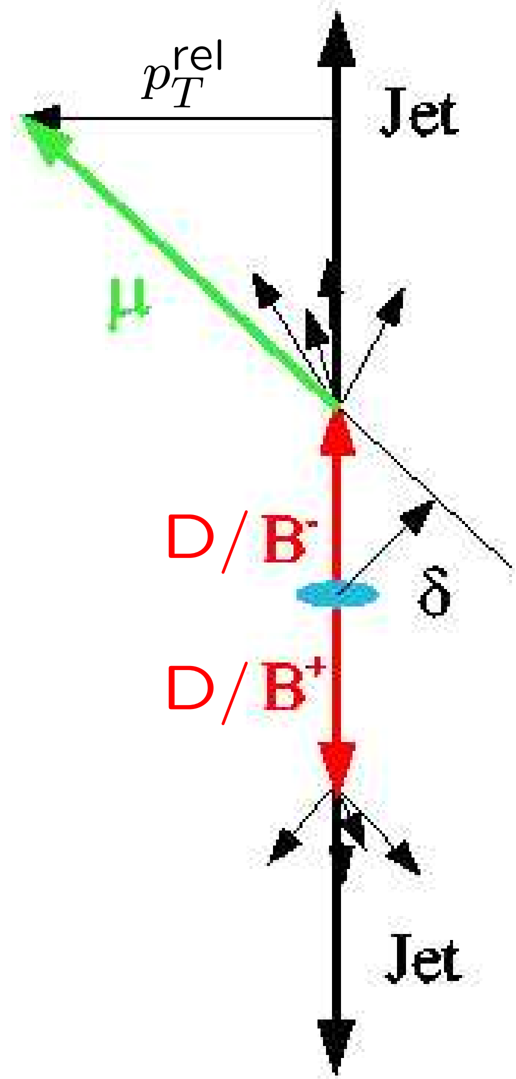
$$\langle\psi(r)\rangle = \frac{1}{N_{\text{jets}}}\sum_{\text{event sample}}\psi(r)$$

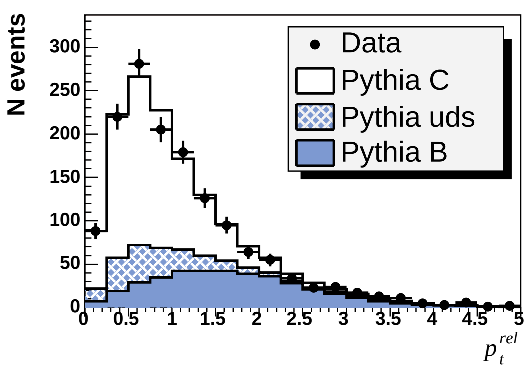
- Two photoproduction dijet samples (with and w/o charm-tag)
- Charm-tag using semi-leptonic decay muon with high p_T

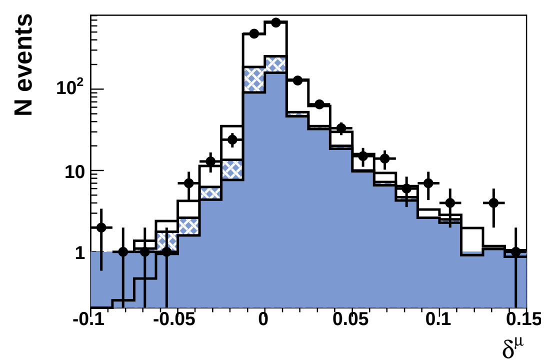
$\mathcal{L} = 48\,\text{pb}^{-1}$		
	Dijet+muon	Dijet
Q^2	< 1 GeV^2	< 0.01 GeV^2
y	$0.2 \ldots 0.8$	$0.3 \ldots 0.65$
inclusive kt cluster algorithm		
p_T^{jet}	> 7 and > 6 GeV	
$\lvert\eta^{\text{jet}}\rvert$	< 1.7	
p_T^{μ}	> 2.5 GeV	

Shape of jets in charm photoproduction

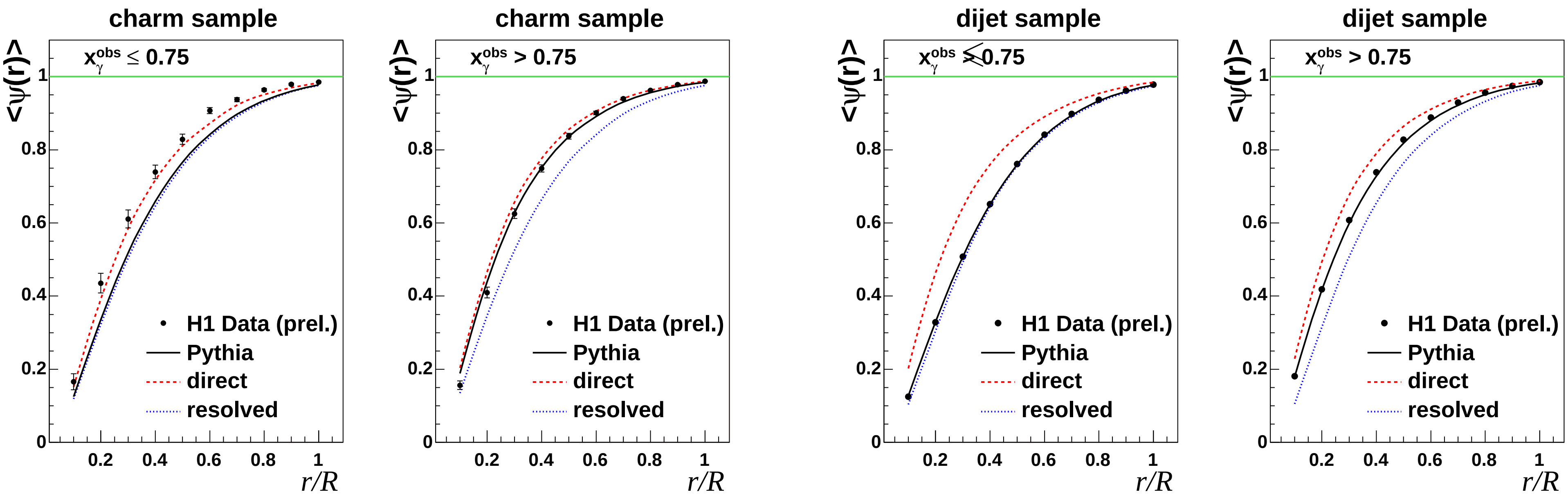
- Tagging technique: 2D fit of p_T^{rel} (p_T w.r.t. closest jet) and δ (track impact parameter) to PYTHIA distributions for uds, c and b as if we wanted beauty but invert p_T^{rel} cut
- $p_T^{\text{rel}} < 1\,\text{GeV} \Rightarrow$ charm enriched sample: $f_c = 73 \pm 3\%$





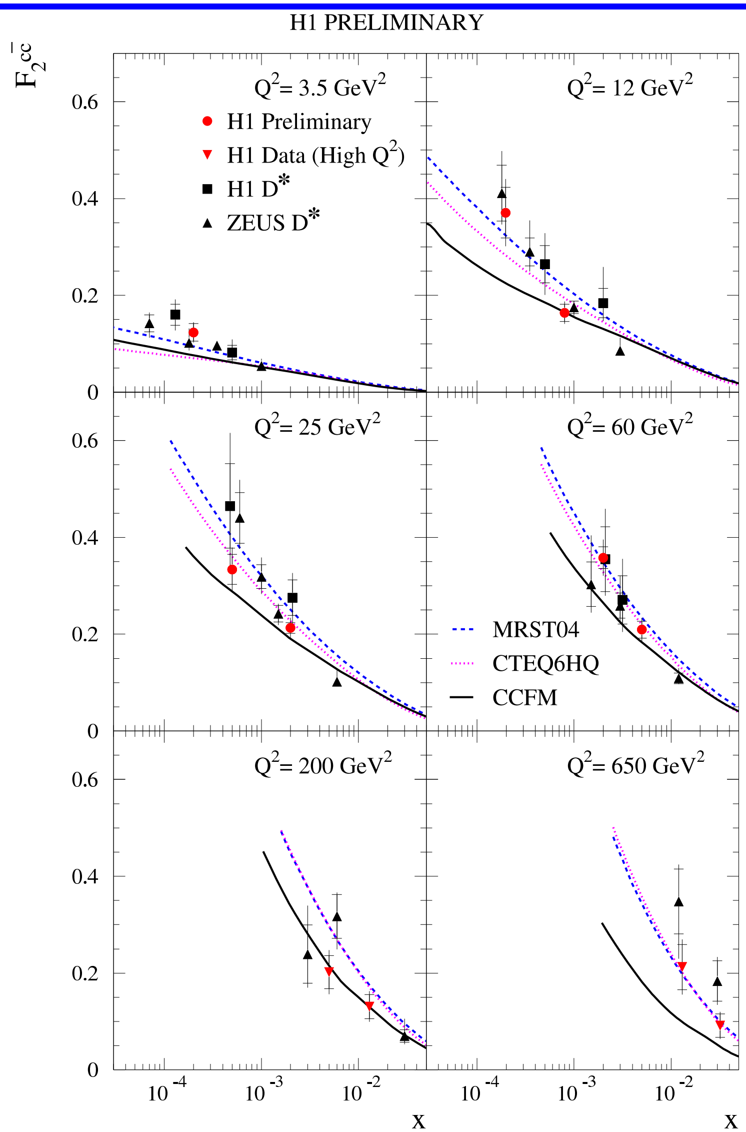


Shape of jets in charm photoproduction

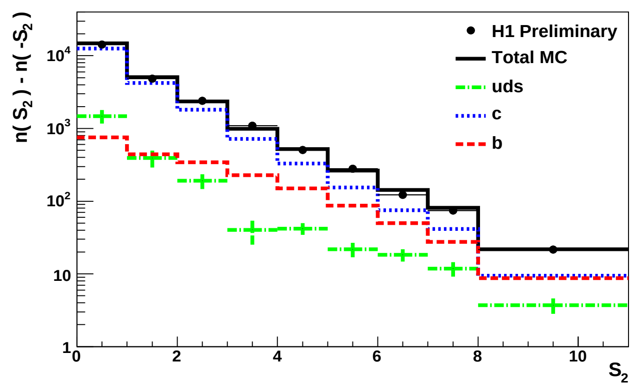


- Charm sample: jet w/o c-tag enters distributions
- PYTHIA direct: mainly quark jets, PYTHIA resolved: mainly gluon jets
- Recall: charm dijet angular dist. in photoproduction at low x_γ^{obs} well described by PYTHIA (charm excitation)
- DATA, dijet sample w/o c-tag: different shapes for low and high x_γ^{obs}, well described by PYTHIA for any x_γ^{obs}
- DATA, dijet sample with c-tag: similar shapes for low and high x_γ^{obs}, not described by PYTHIA at low x_γ^{obs} (lack of gluon jets in DATA)

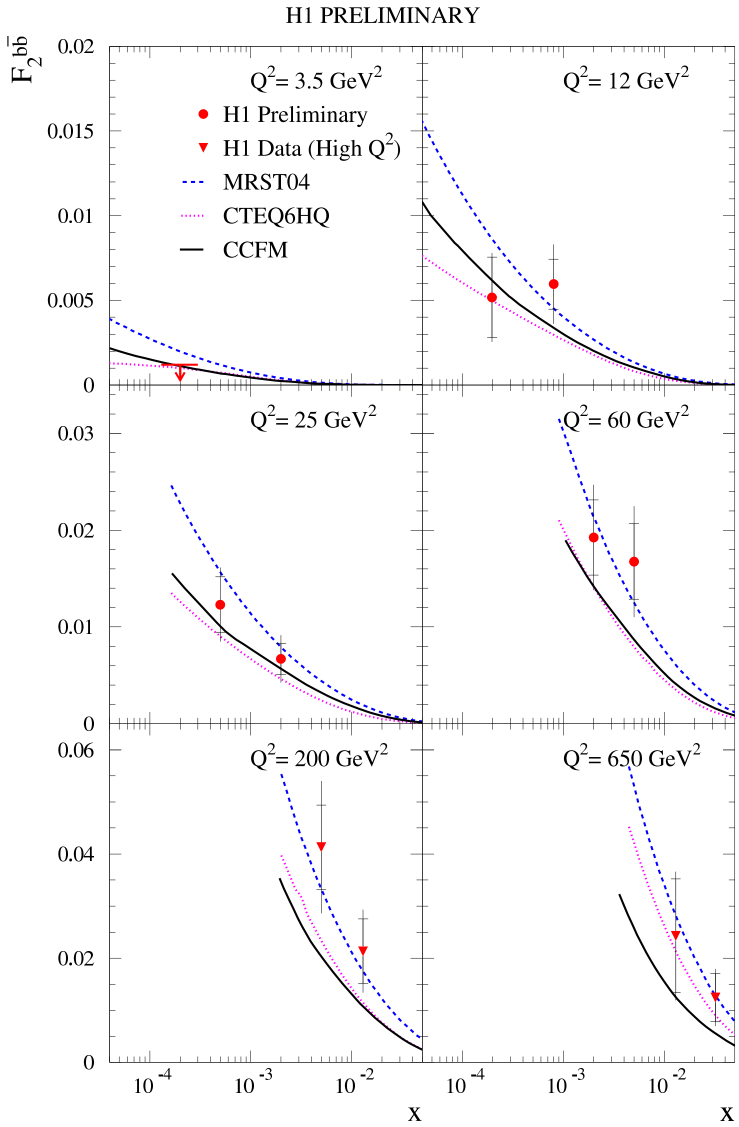
$F_2^{c\bar{c}}$



- Inclusive lifetime tagging: for heavy quarks tracks have high significance $S = \delta/\sigma(\delta)$
- Significance distributions: S_i - significance of track with i th highest abs. significance
- Fractions of c, b and uds from simultaneous fit to at least S_1 and S_2 (and total number of events); very high acceptances
- Extand measurement of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ using S_1, S_2, S_3 to low Q^2
- $3.5 \leq Q^2 \leq 60$ GeV^2, $0.000197 \leq x \leq 0.005$
- New $F_2^{c\bar{c}}$ data in ageement with other measurement techniques (ones with much higher extrapolation)

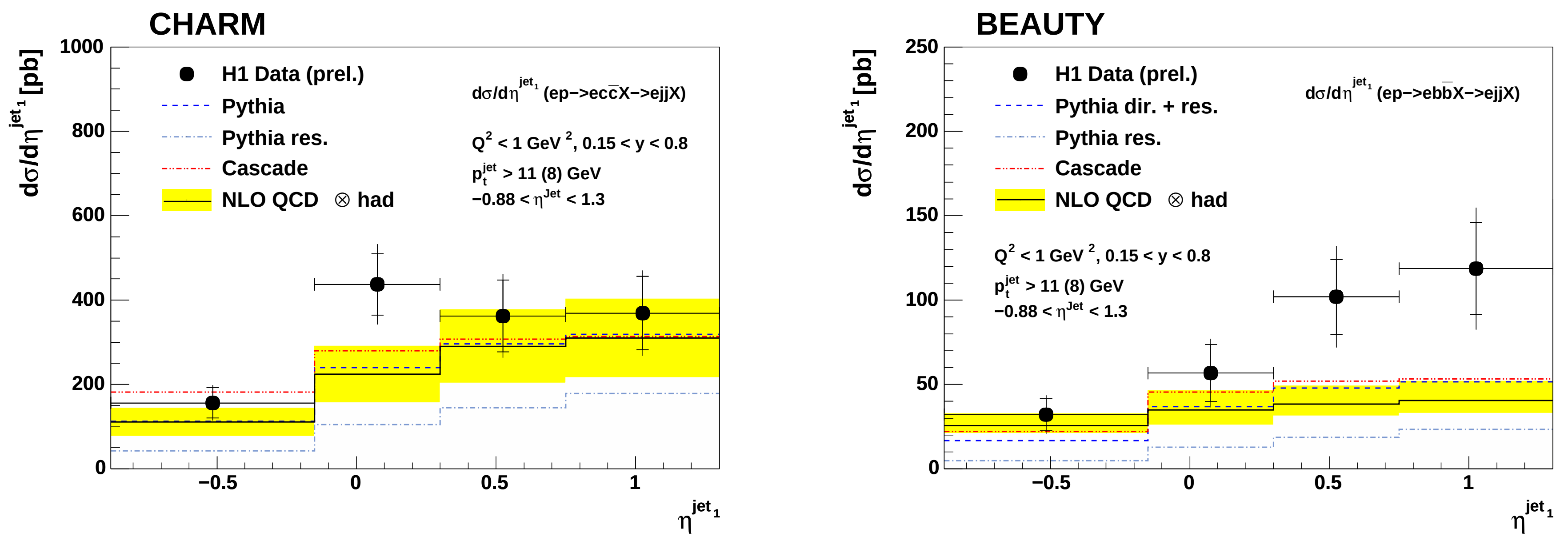


$F_2^{b\bar{b}}$



- Inclusive lifetime tagging: first measurement of $F_2^{b\bar{b}}$
- No evidence for large excess of b compared with NLO "massive $\otimes$ massless" (VFNS) QCD
- In this kinematic range charm and beauty cross sections are on average 22% and 0.8% of total ep cross section

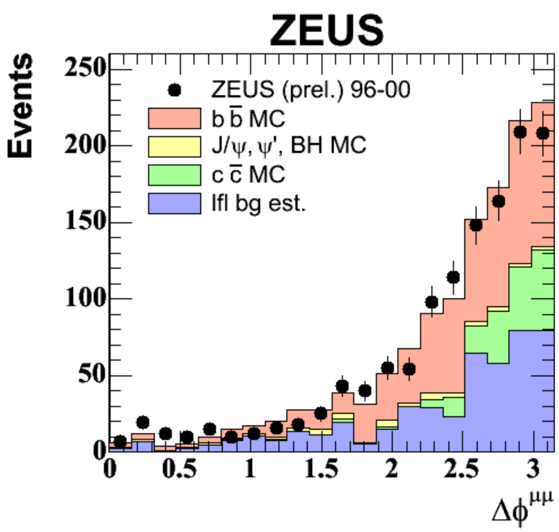
Beauty and charm with dijets (PHP)

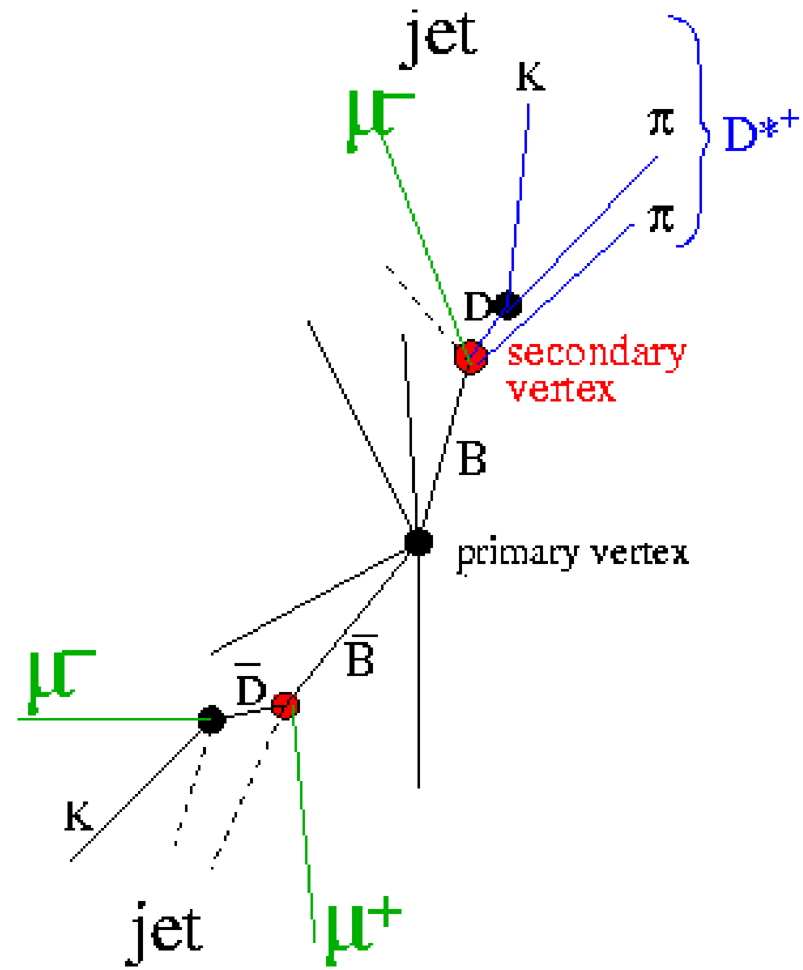


- Inclusive lifetime tagging enables a purely inclusive measurement of charm and beauty dijets (w/o requirement of hight p_T muon $\Rightarrow$ reduced extrapolation)
- H1 99/00 e^+ data: $Q^2 \sim 0\,\mathrm{GeV}^2$, $0.15 < y < 0.8$, $p_T^{\mathrm{jet}} > 11(8)\,\mathrm{GeV}$, $-0.88 < \eta^{\mathrm{jet}} < 1.3$
- Beauty: FMNR (QCD NLO, massive) below data for jets in forward region

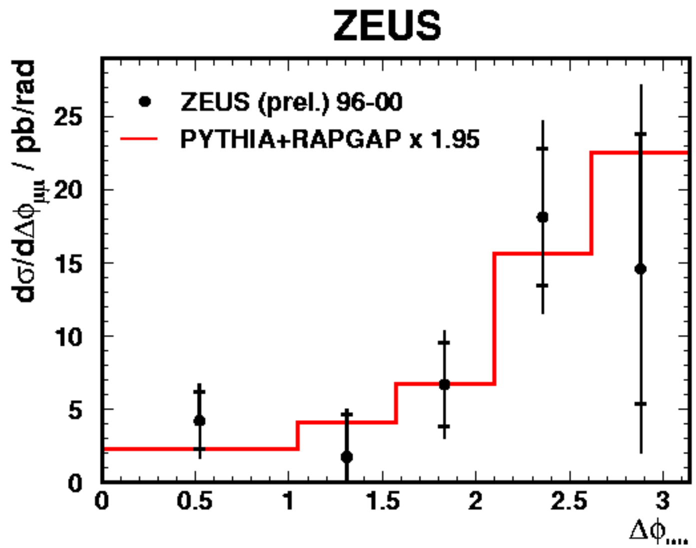
Beauty with di-muons

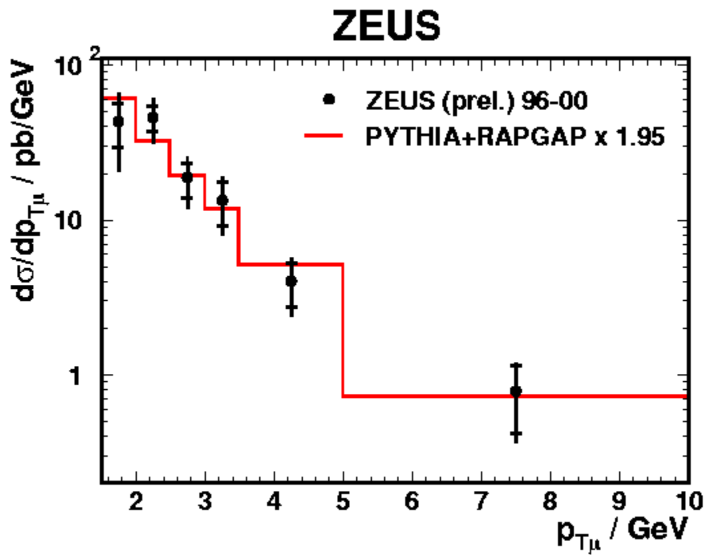
- New results on $b\bar{b}$ production (data 1996-2000): sophisticated analysis of $\mu\mu$ correlations

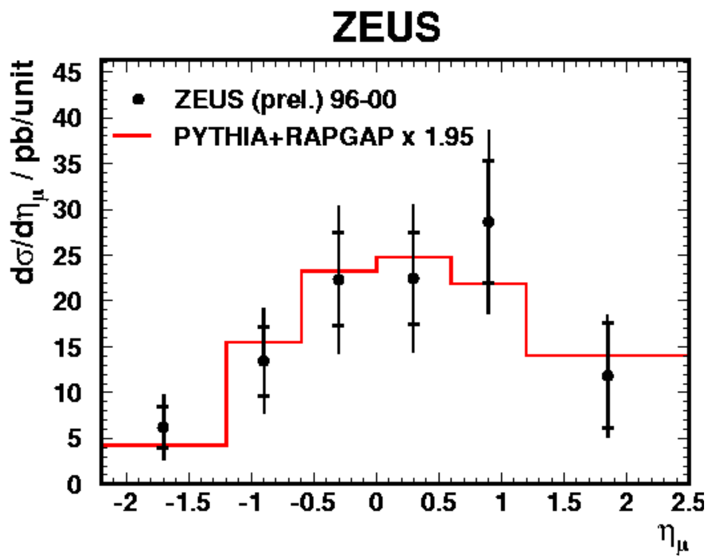




Beauty with di-muons





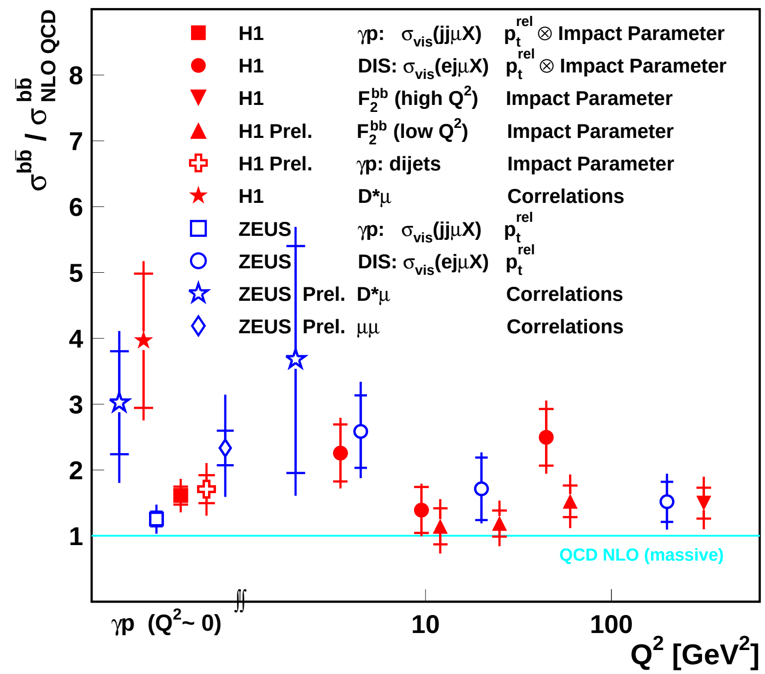


- Acceptance down to very low p_T^μ (B mesons "at rest") ⇒ low extrapolation
- Almost full rapidity coverage by μ-detectors ⇒ large η^μ range $(-2 \cdots +2.5)$
- Direct measurement of $b\bar{b}$ correlation $\Delta\phi^{\mu\mu}$ (NLO predictions coming soon)
- $\sigma_{\mathrm{tot}}(ep \to b\bar{b}X @ \sqrt{s} = 318) = 16.1 \pm 1.8(\mathrm{stat.})^{+5.3}_{-4.8}(\mathrm{syst.})$ nb

  NLO QCD (FMNR(PHP)+HVQDIS(DIS)): $6.8^{+3.0}_{-1.7}$ nb

Summary

- More tests of different aspects of QCD in charm and beauty production processes
- NLO QCD calculations (where available) are in general agreement with data
- Good understanding of “standard” physics is vital for searches of new phyiscs also at future colliders



Outlook

- HERA I (1993–2000): $\mathcal{L} \sim 193\,\text{pb}^{-1}$ delivered; HERA II (from 2002 on): increased rate, polarised beams, upgraded detectors, $\mathcal{L} \sim 187\,\text{pb}^{-1}$ delivered
- New results are expected soon