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Heavy Flavour Production at HERA

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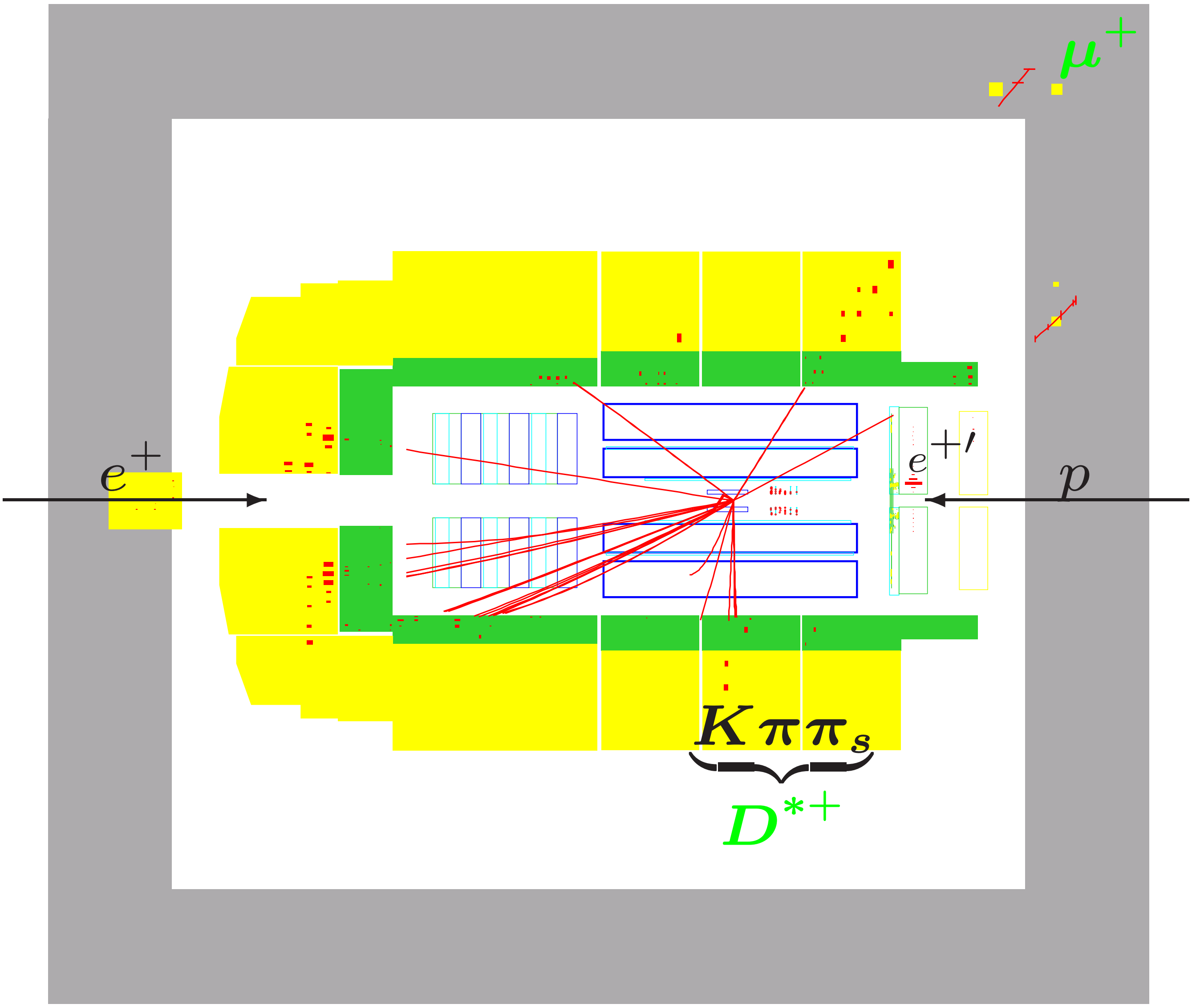
- Heavy Quark Production Mechanisms
- Open Charm Production
- Beauty
- Charmonium
- Conclusions

ep Interactions at HERA

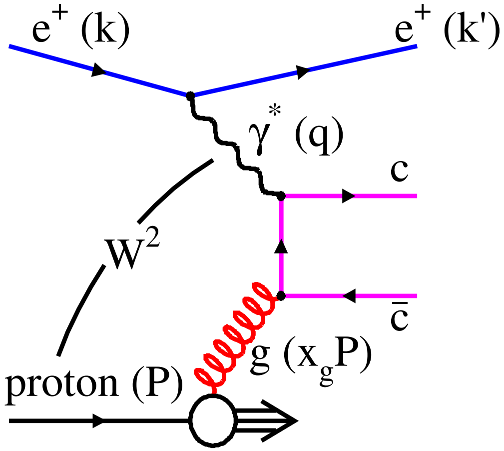
$E_e = 27.5$ GeV, $E_p = 920$ GeV, $\sqrt{s} = 320$ GeV



H1, ZEUS '95-00: $\int \mathcal{L}dt > 100$ pb^{-1} each

Heavy Quark Production Mechanism

$\gamma g \rightarrow c\bar{c}$



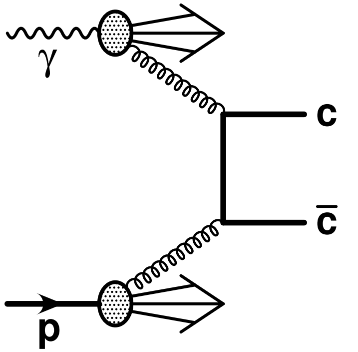
ep Scattering Event Kinematics

Q^2	(4-momentum of virtual photon)^2
x	Momentum fraction of interacting q in proton
y	Fractional energy transfer
W^2	(Hadronic final state mass)^2

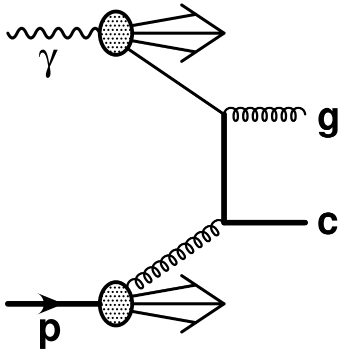
$Q^2 \sim 0$: quasi-real $\gamma \rightarrow$ 'photoproduction'

x_γ	Fract. energy of interacting parton in photon

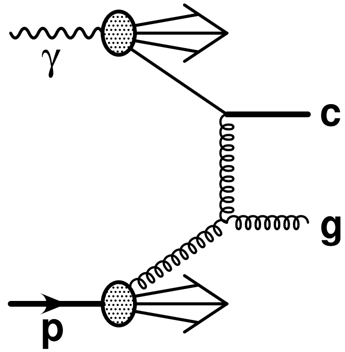
Photoproduction: Resolved hadronic photon structure (LO picture):



q-Propagator



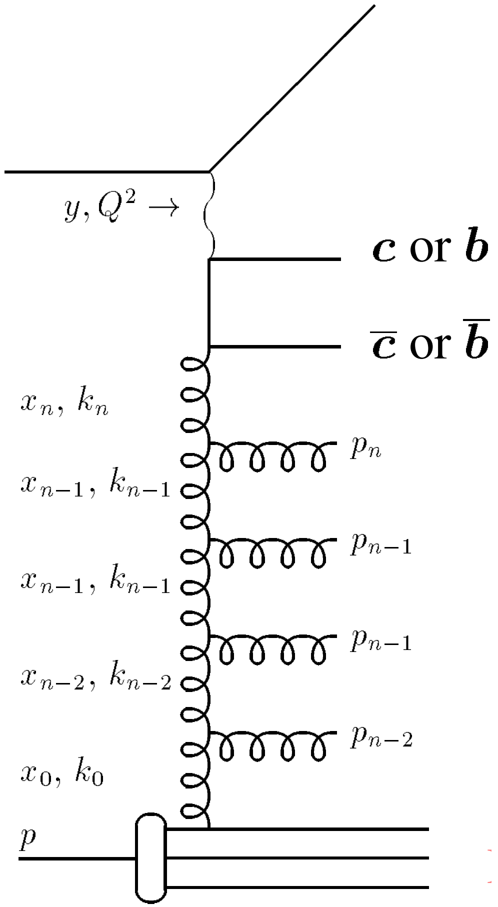
q-Propagator
'c-Excitation'



g-Propagator
'c-Excitation'

Different kinematical distributions $\rightarrow$ info on individual contributions

Calculations



Perturbative Calculations

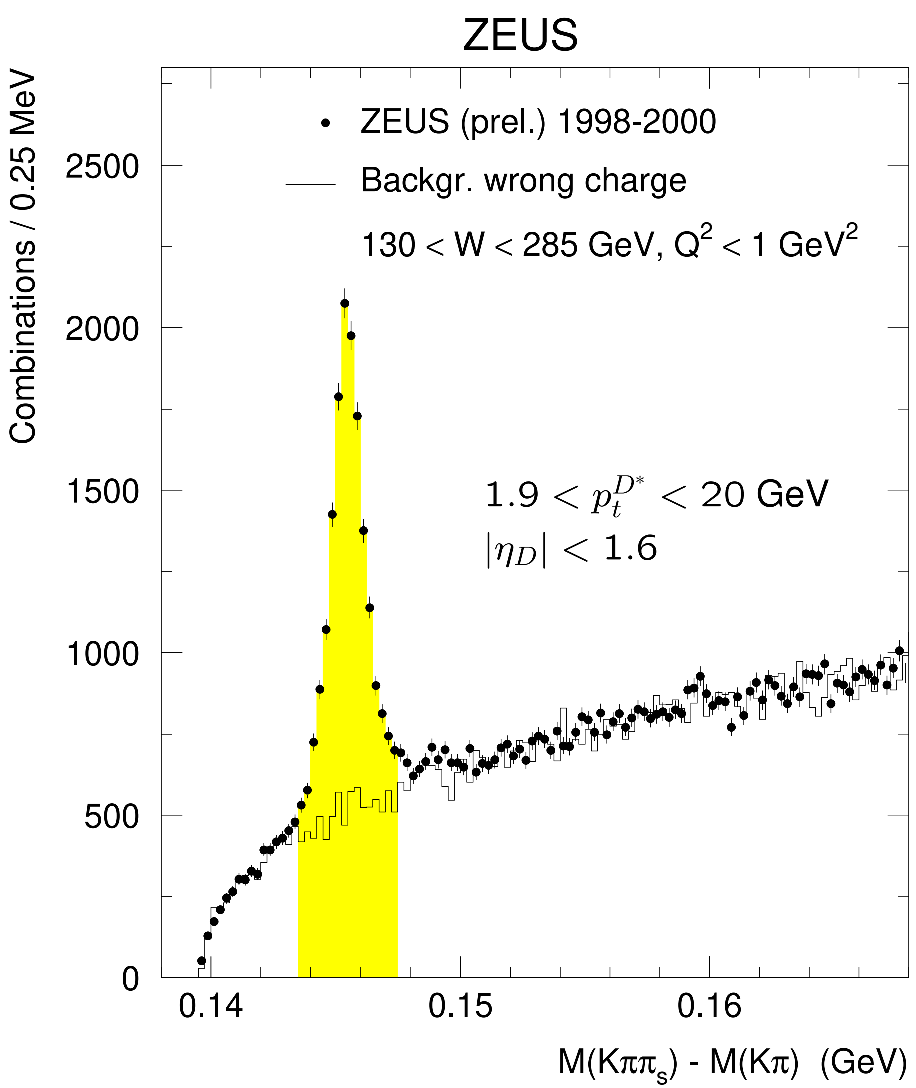
Fixed Order NLO	(FMNR,HVQDIS) HQ are massive
Frixione et al ,Harris et al	ie. perturbatively produced
Resummed (NLL)	HQ are massless,
Cacciari et al ,Kniehl et al	c, b are active flavours in p and γ
	large logarithms $[\alpha_s \log(\frac{p_t}{m_q})]^n$ resummed
FONLL	matched combination of FO and NLL
Frixione, Nason, Cacciari	

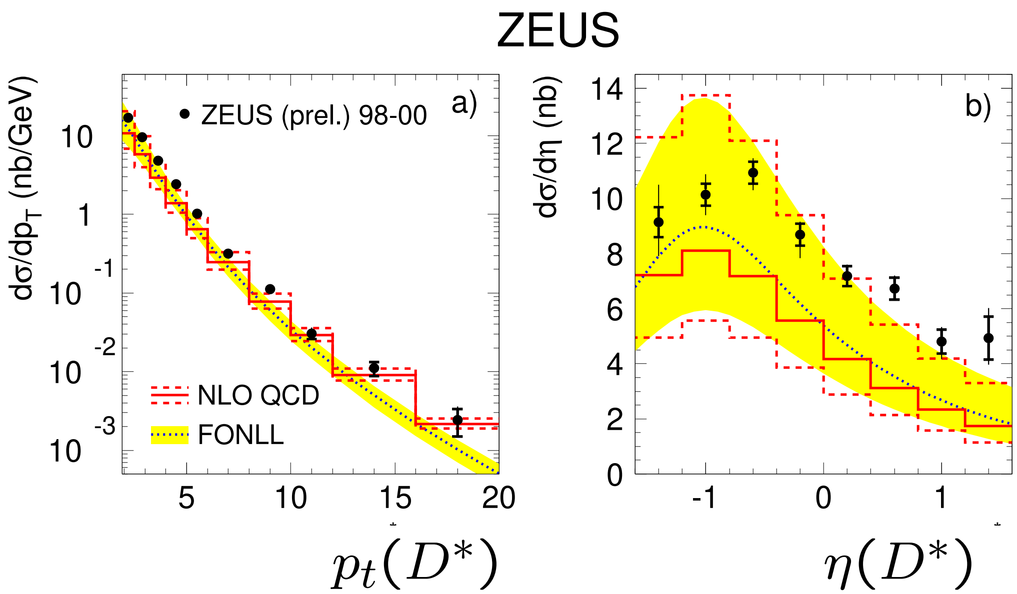
Monte Carlo Generators

Aroma	LO+PS, dir.
Rapgap	LO+PS, dir.+res.
Pythia	LO+PS, dir.+res.+q-excit., Lund-String
Herwig	LO+PS, dir.+res.+q-excit., Cluster
Cascade	k_t-factorization (CCFM), angular ordering
H.Jung et al	non-collinear, unintegrated gluon distribution

p-structure $\otimes$ γ-structure (in γp) $\otimes$ QCD-dynamics $\otimes$ fragmentation functions

Photoproduction of Open Charm: $D^* \rightarrow (K\pi)\pi$

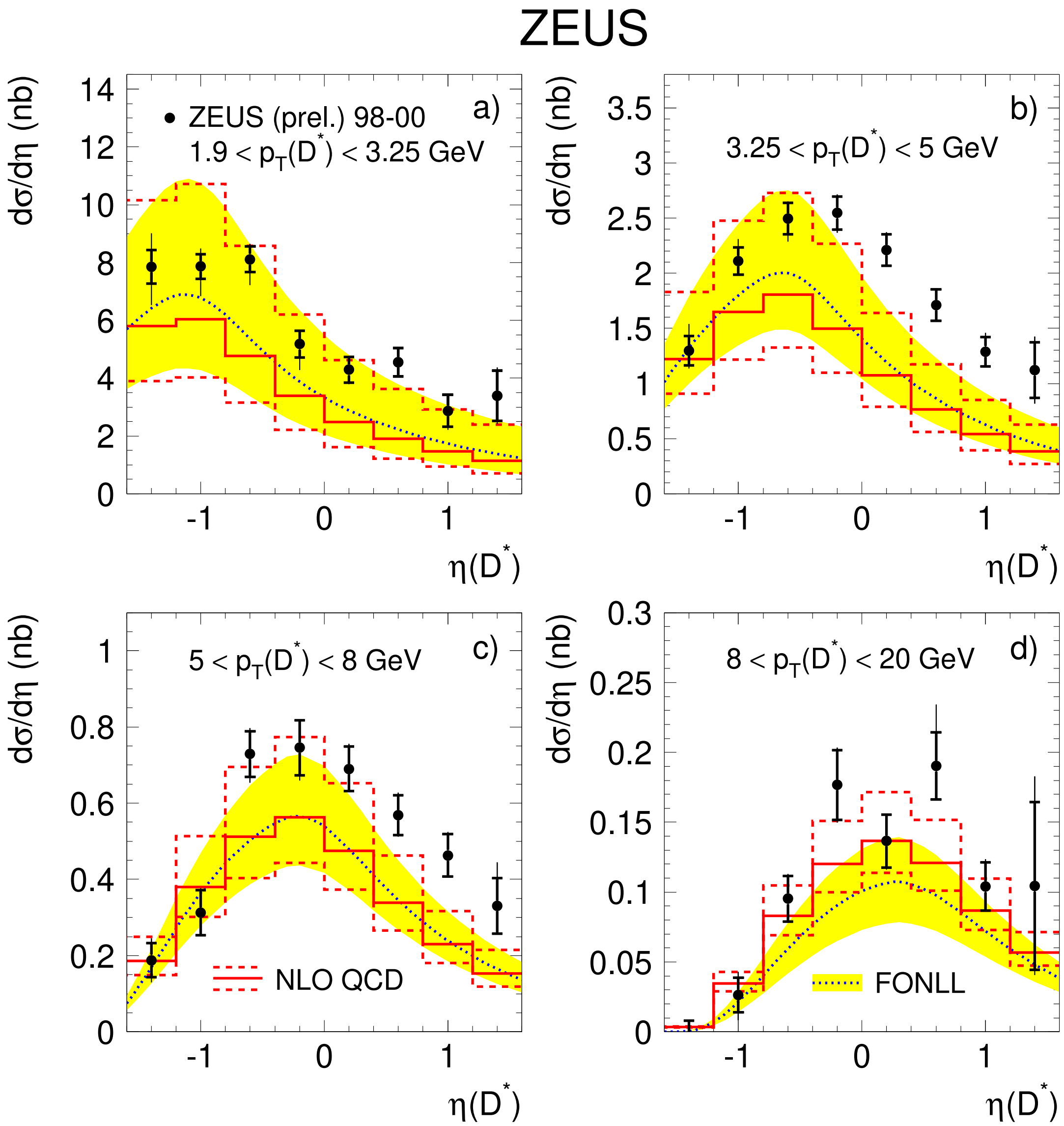




$$\epsilon_{\text{Peterson}} = 0.035 \text{ (NLO)}$$
$$0.02 \text{ (FONLL)}$$

$$m_c = (1.5 \pm 0.2)\text{GeV}$$

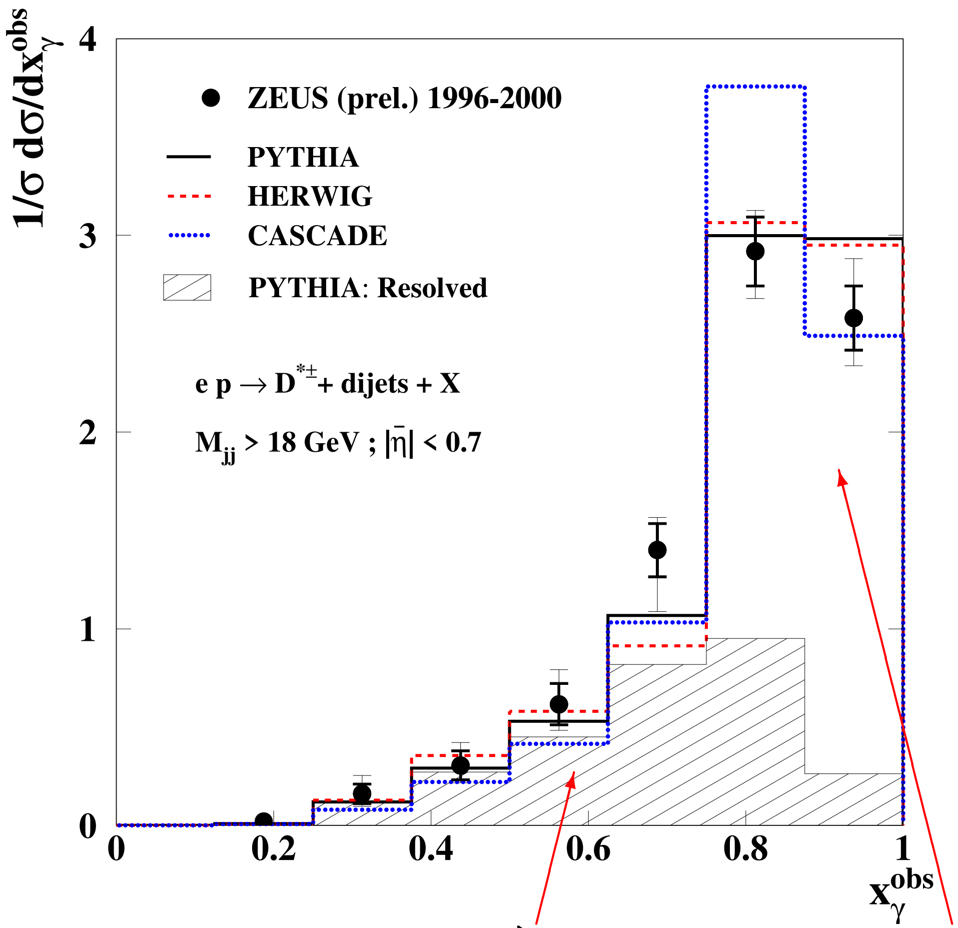
$D^* \to (K\pi)\pi$: Double Differential Distributions



- Precise measurements of double differential distributions
- NLO predictions:
  shapes ok,
  norm slightly low,
  FONLL even lower,
  theoretical uncertainties large

Some excess persisting esp. at high p_t and in forward direction

Dijets with Charm: $ep \to D^{*\pm} + jj + X$

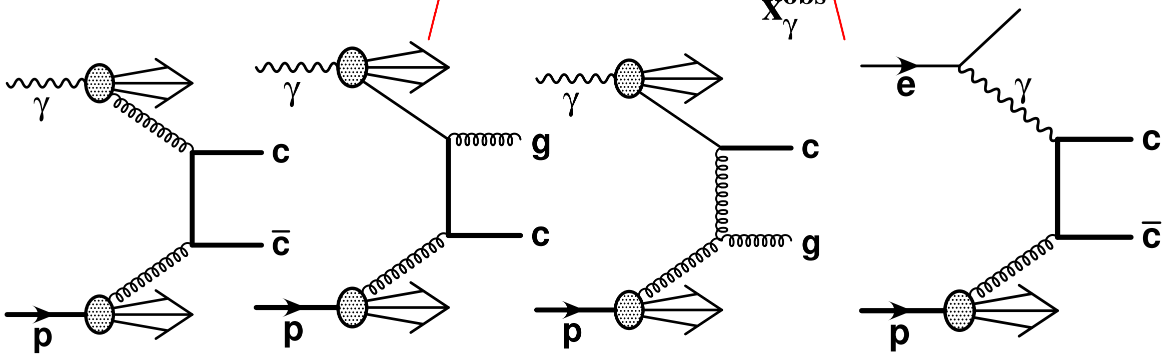


$$x_\gamma^{\mathrm{OBS}} = \frac{\sum_{\mathrm{j1,j2}}(E_T^{\mathrm{j}} e^{-\eta^{\mathrm{j}}})}{2yE_e}$$

$M_{jj} > 18$ GeV; $|\eta_{\mathrm{j1}} + \eta_{\mathrm{j2}}| < 0.7$

- Large resolved contribution
- c-excitation sizable

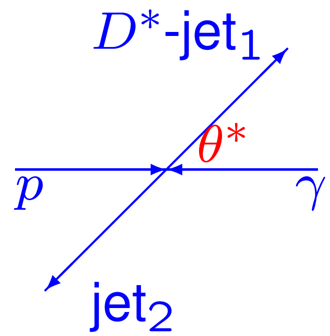
- Shape of data reproduced by MCs
- Cascade: too much 'direct' (high x_γ)

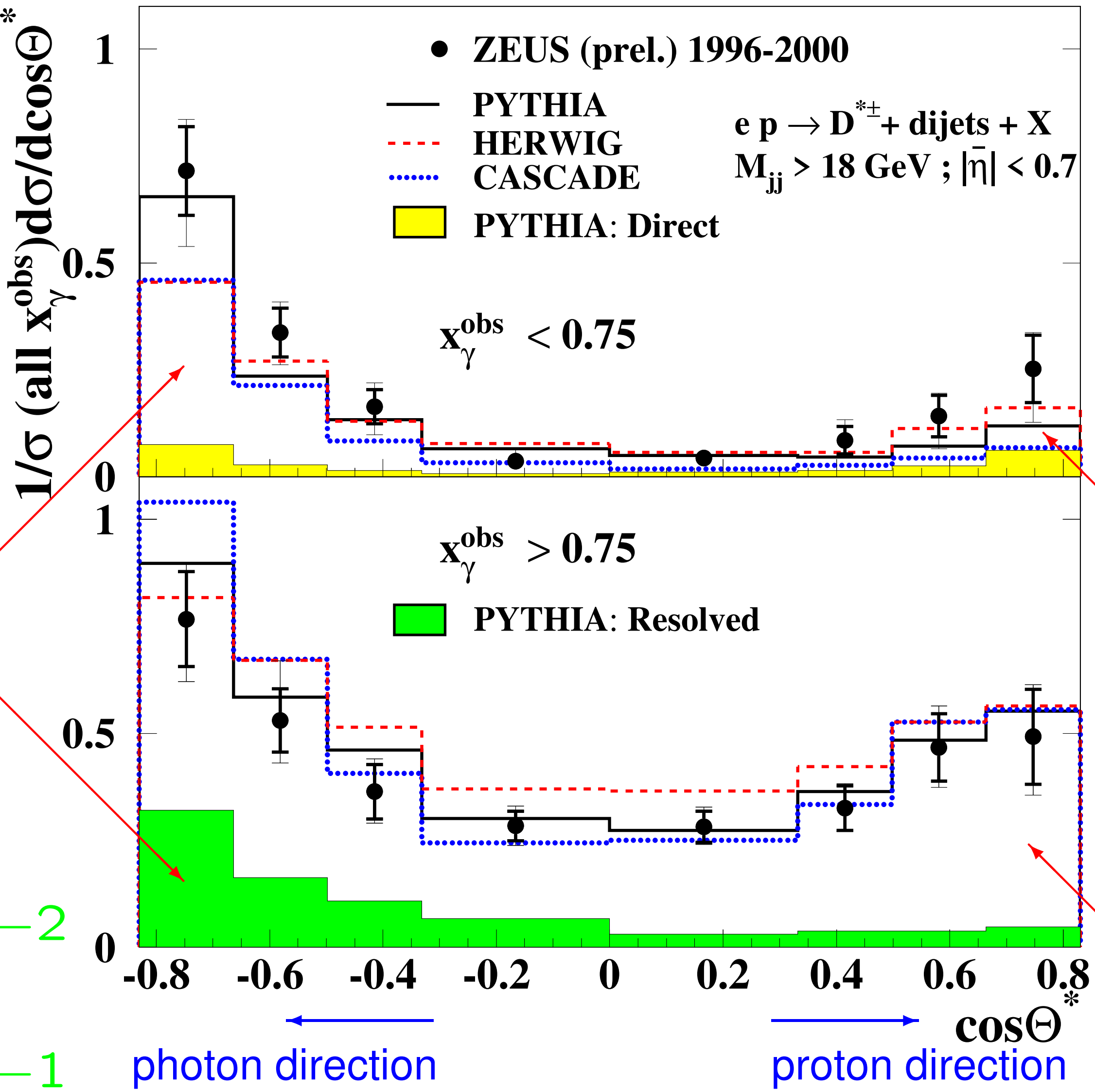


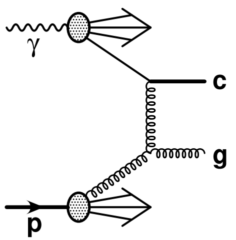
Angular distributions:
in 2 regions of $x_\gamma \Rightarrow$

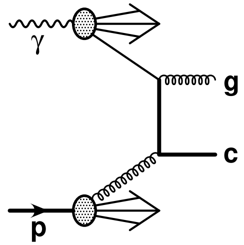
Dijet Angular Distributions

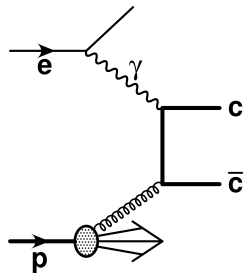
$\cos\theta^* = \tanh((\eta^{j_1} - \eta^{j_2})/2)$











g-exchange:

$\propto (1 - |\cos\theta^*|)^{-2}$

q-exchange:

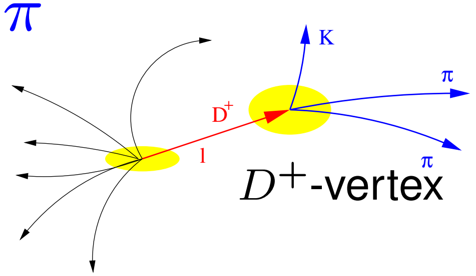
$\propto (1 - |\cos\theta^*|)^{-1}$

D^* in photon direction: Charm quark coming from photon

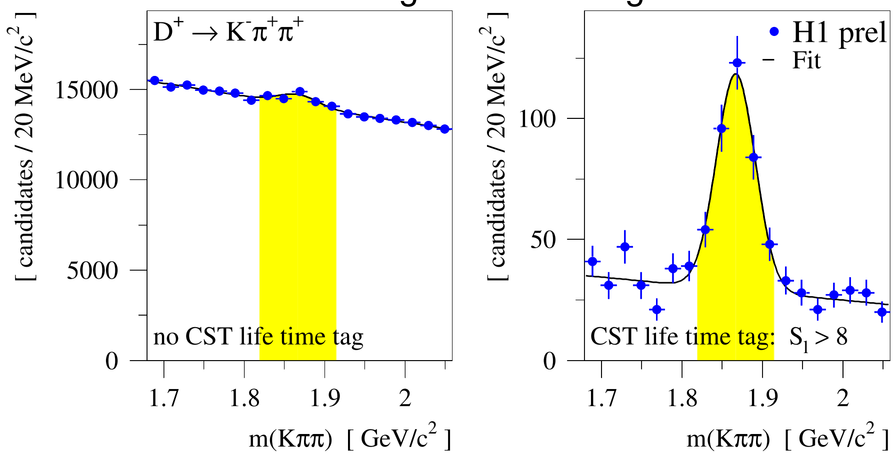
Resolved steeper than direct: Clear signature of gluon exchange

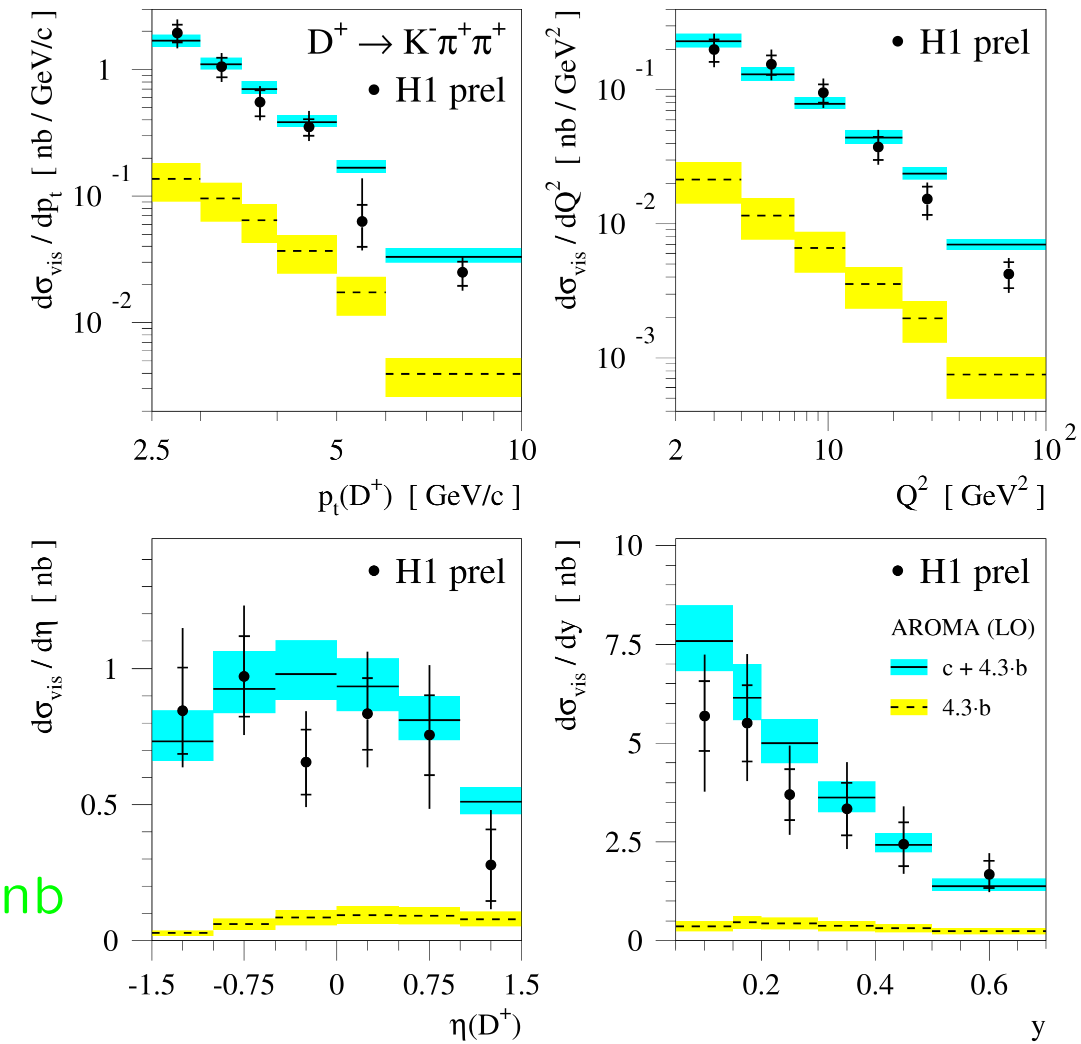
D-Meson Production in DIS

$D^+ \to K\pi\pi$



lifetime: no tag ⟶ tag





H1 Prelim.:

$$\sigma^{vis}_{ep\to eD^+X} = (2.16 \pm 0.19^{+0.46}_{-0.35})\text{nb}$$

$2 < Q^2 < 100$ GeV^2; $0.05 < y < 0.07$
$p_t^D > 2.5$ GeV; $|\eta_D| < 1.5$

Norm and shapes well described by LO+PS models (AROMA)

Charm Fragmentation

Similar Results for $D^{*\pm}$, D^0,D_s Production.

Determine production ratios of different quark and spin states:

- u/d Quark Ratios — $R_{u/d} = (f^0 - f^+)/(2f^{*+} \cdot BR^{*+})$

$R_{u/d}$	$1.26 \pm 0.20 \pm 0.12$	H1 prelim
	1.00 ± 0.09	WA

- Vector/Pseudoscalar Ratio — $P_{Vd} = f^{*+}/(f^+ + f^{*+} \cdot BR^{*+})$

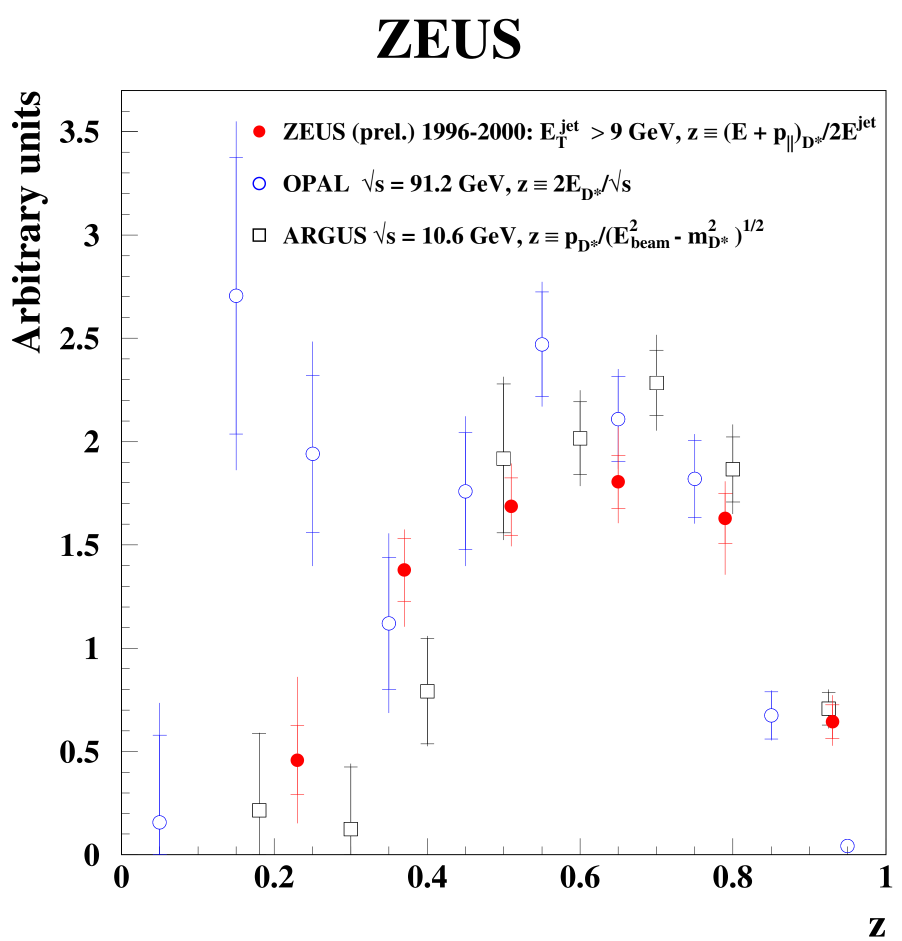
P_{Vd}	$0.693 \pm 0.045 \pm 0.010$	H1 prelim
	$0.546 \pm 0.045 \pm 0.028$	ZEUS prelim (γp)
	0.601 ± 0.032	WA

- Strangeness Suppression Factor — $\gamma_s = 2f_s/(f^0 + f^+)$

γ_s	$0.36 \pm 0.10 \pm 0.08$	H1 prelim
	0.27 ± 0.05	ZEUS (γp)
	0.26 ± 0.07	WA

ep agrees with ee

Charm Fragmentation Functions



ee: $z = E_D/E_{\text{beam}}$

ep: $z = (E + p_{||})_D/(E + p_{||})_{\text{jet}}$

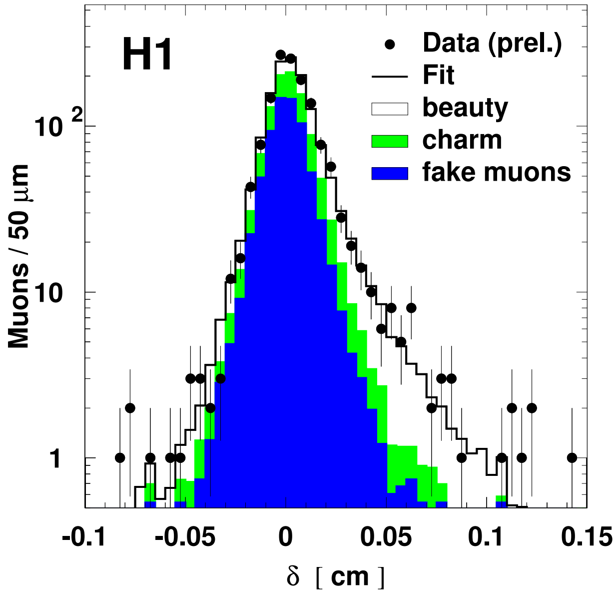
- Similar accuracy, similar shape
- Compares well with analyses of Argus and Opal data Nason et al
- Fit of LO Parton Shower MC of Peterson fragmentation function:

$$\epsilon_c = 0.064 \pm 0.006^{+0.011}_{-0.008}$$

Results support charm fragmentation universality

Beauty Production Measurements

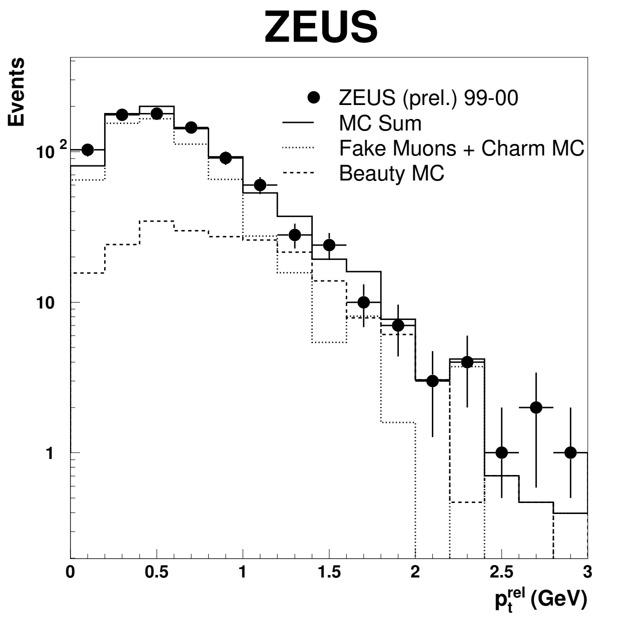
Longer b-lifetime



μ impact Parm., δ

Example: H1 in γp

Larger b-mass

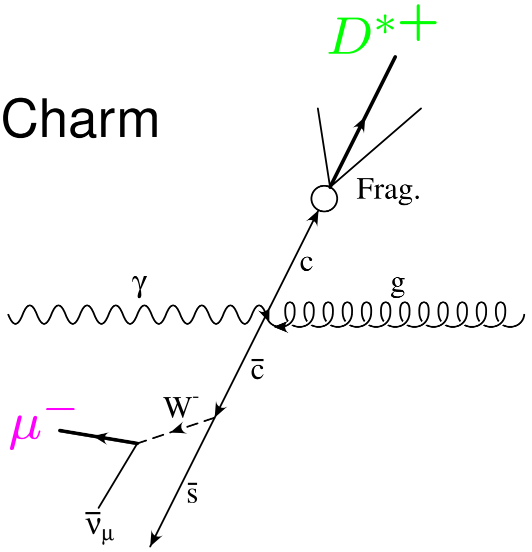


p_t of μ relative to jet, p_t^{rel}

Example: ZEUS in DIS

$D^*\mu$ Correlations in γg CMS:

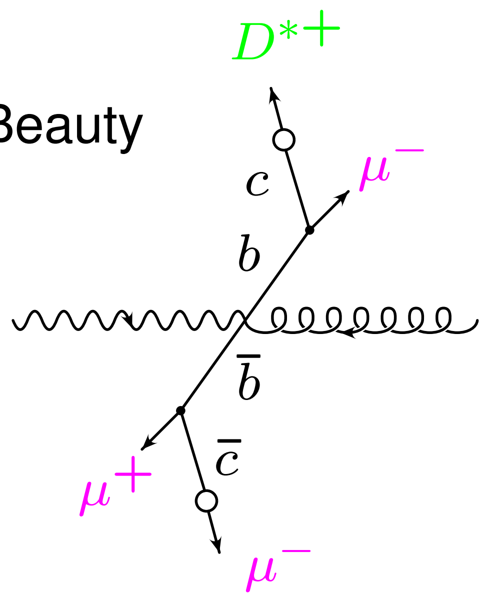
Charm



$\Delta\Phi \approx 180^\circ$

$Q(D^*) \neq Q(\mu)$

Beauty



$\Delta\Phi \approx 0^\circ \;\; ; Q(D^*) \neq Q(\mu)$

$\Delta\Phi \approx 180^\circ ; Q(D^*) \neq Q(\mu)$

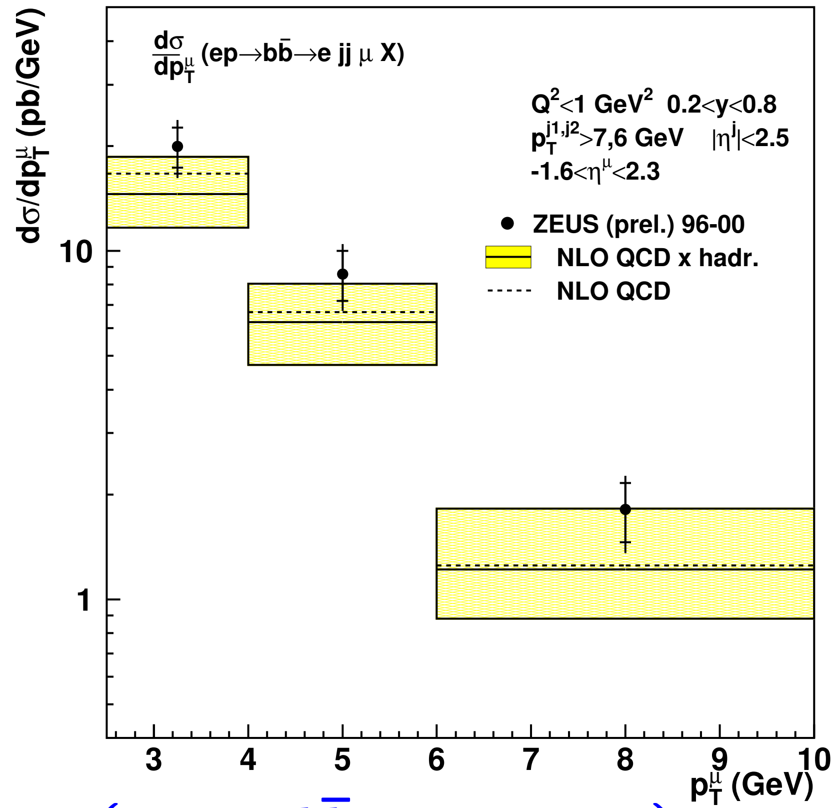
$\Delta\Phi \approx 180^\circ ; Q(D^*) = Q(\mu)$

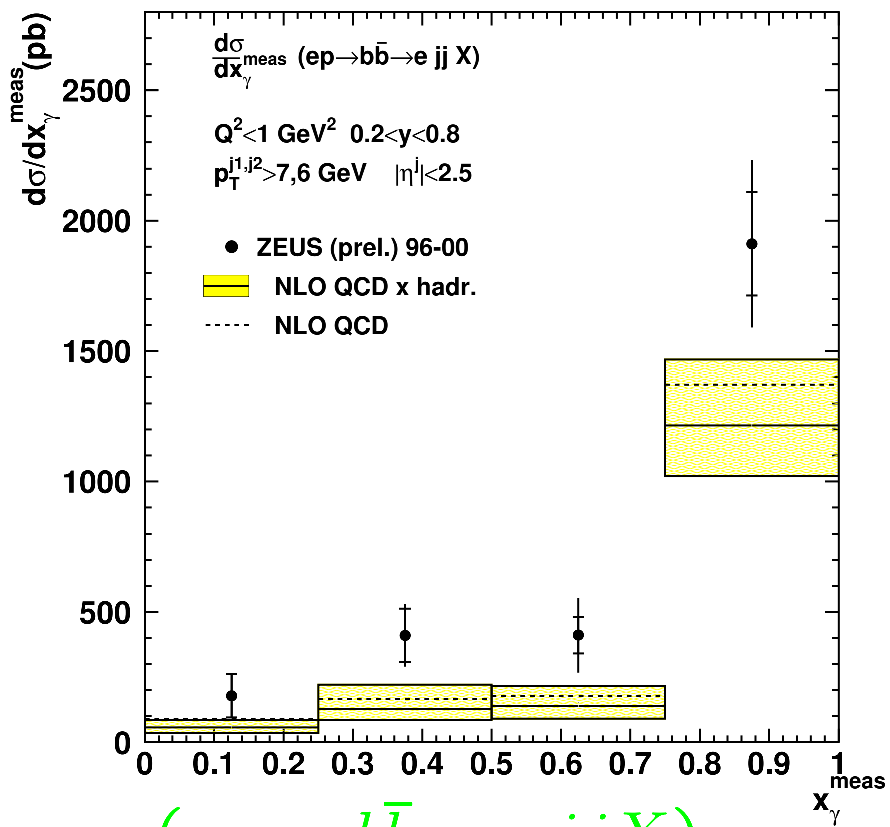
Separate c and b by charge and hemisphere correlations

$B \to jj\mu X$ in Photoproduction using P_t^{rel}

$Q^2 < 1$ GeV^2 ; $0.2 < y < 0.8$; ≥ 2 Jets ($p_t^{\mathrm{jet}} > 7(6)$ GeV) ; $|\eta_{\mathrm{jet}}| < 2.5$; $p_t^{\mu} > 2.5$ GeV ; $1.6 < \eta_{\mathrm{jet}} < 2.3$

New differential results from ZEUS





$\sigma(ep \to b\bar{b} \to ejj\mu X)$

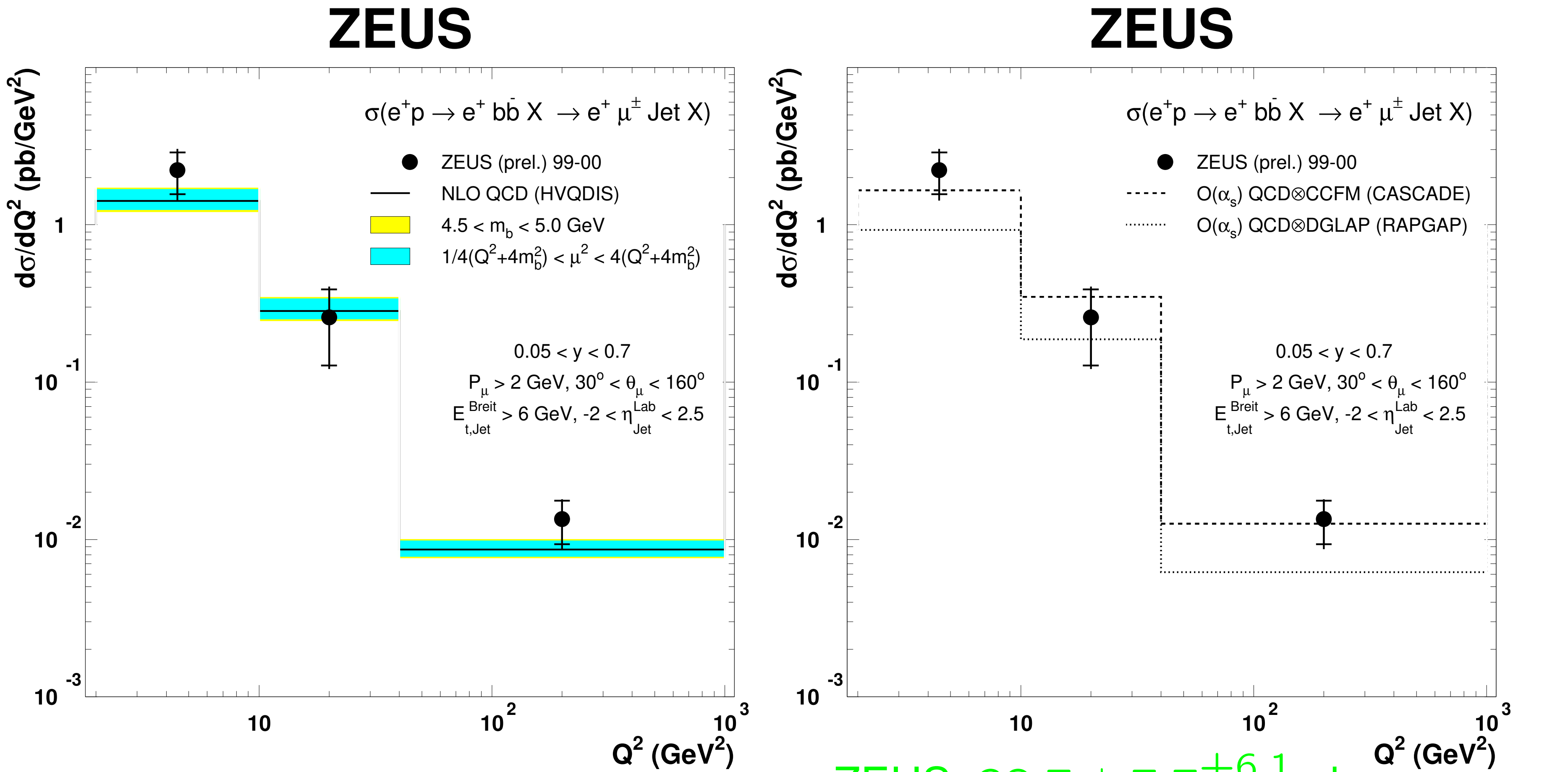
Unlike previous measurements:
No extrapolation in jet quantities !
$\Rightarrow$ NLO too low by factor 1.4
ok within errors

$\sigma(ep \to b\bar{b} \to ejjX)$
ZEUS: $733 \pm 61 \pm 104$ pb
NLO QCD (FMNR): 381^{+117}_{-78} pb

x_γ: sizable resolved contrib. ($\leftrightarrow$ charm)

Beauty Spectra in DIS

$Q^2 > 2$ GeV^2 ; $0.05 < y < 0.7$; ≥ 1 Jet ($E_{t,\text{jet}}^{\text{Breit}} > 6$ GeV) ; $2 < \eta_{\text{jet}}^{\text{lab}} < 2.5$; $p_t^\mu > 2$ GeV ; $30^\circ < \theta_{\text{jet}} < 160^\circ$



$$\sigma(ep \to b\bar{b} \to ej\mu X)$$

ZEUS: $38.7 \pm 7.7^{+6.1}_{-5.0}$ pb

LO QCD, CCFM (Cascade): 35pb

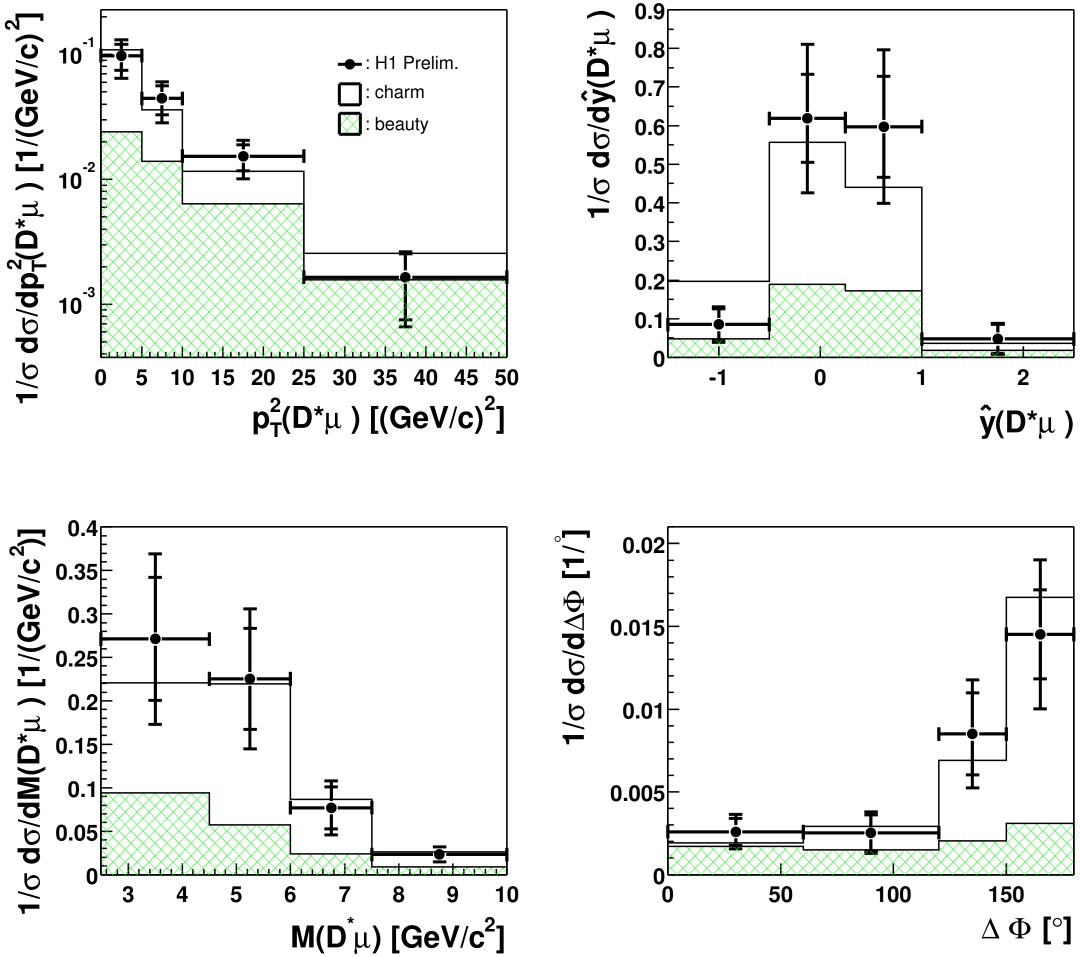
NLO QCD (HVQDIS): $28^{+5.3}_{-3.5}$pb

1st differential results in DIS

Cascade describing data in shape and normalization

Heavy Flavour Double Tag: $D^*\mu$ Correlations

Both quarks $\rightarrow$ reconstruct x_g, measure higher order QCD effects



H1 Prelim.:

$\sigma(ep \rightarrow eq\bar{q}X \rightarrow eD^*\mu X)$

c: $(720 \pm 115 \pm 245)$pb

b: $(380 \pm 120 \pm 130)$pb

ZEUS Prelim:

$\sigma(ep \rightarrow eb\bar{b}X)$

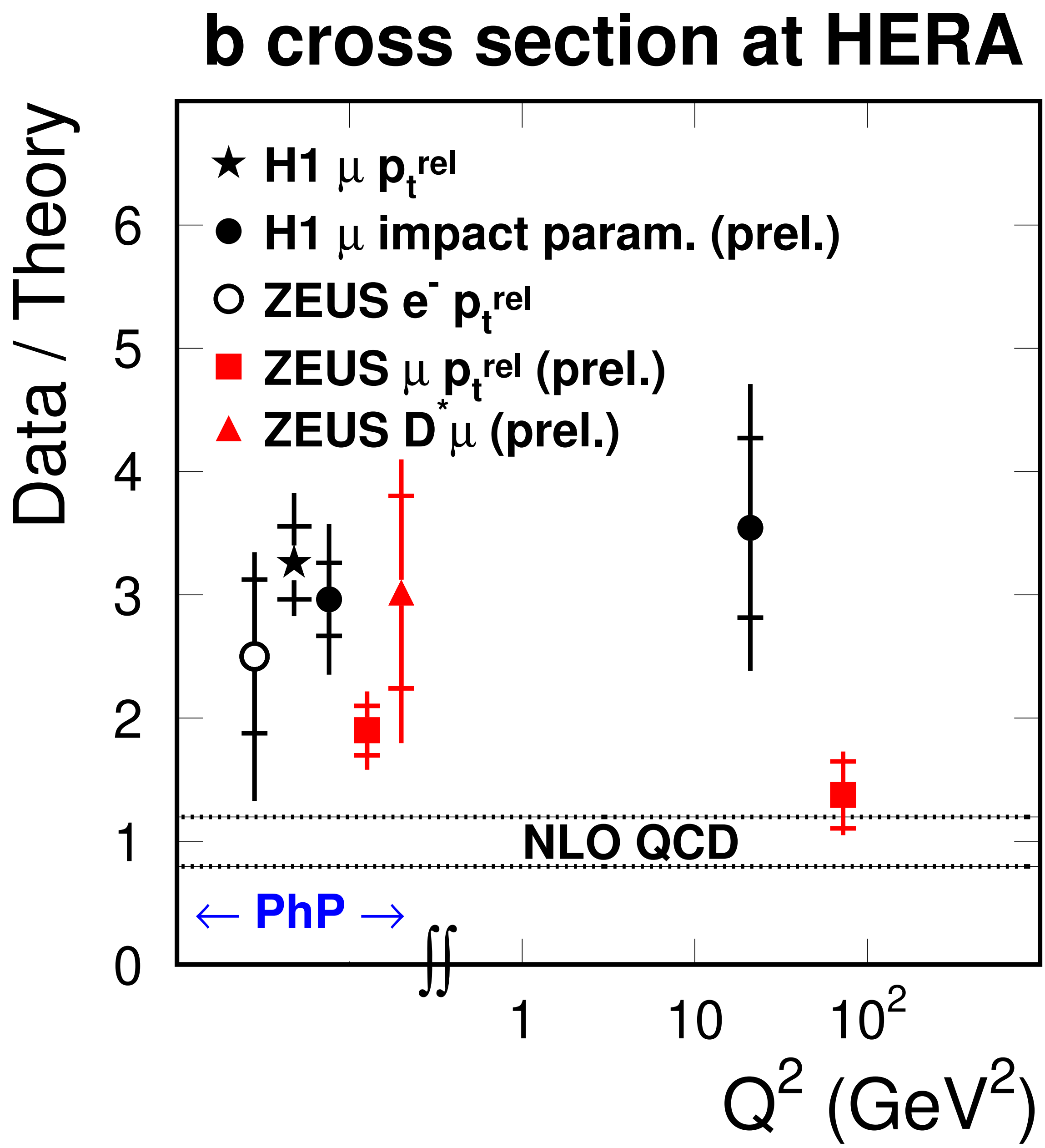
$(15.1 \pm 3.9^{+3.8}_{-4.7})$ pb

NLO QCD (FMNR) = $5.7^{+1.7}_{-1.1}$ pb

if same cuts: ZEUS $\approx$ H1

with low p_t threshold: results confirm other b cross section measurements

Beauty Production



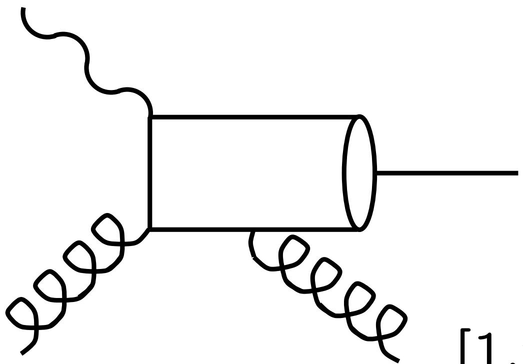
2002: Many new results

Data generally above NLO (ZEUS DIS ok)

(Caution: measurements in different kinematic regions using different models)

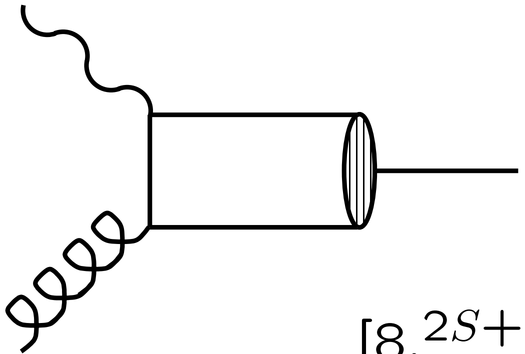
Charmonium Production

J/ψ is colourless:



Colour Singlet Model (CS)

$c\bar{c} \longrightarrow J/\psi$ + gluon



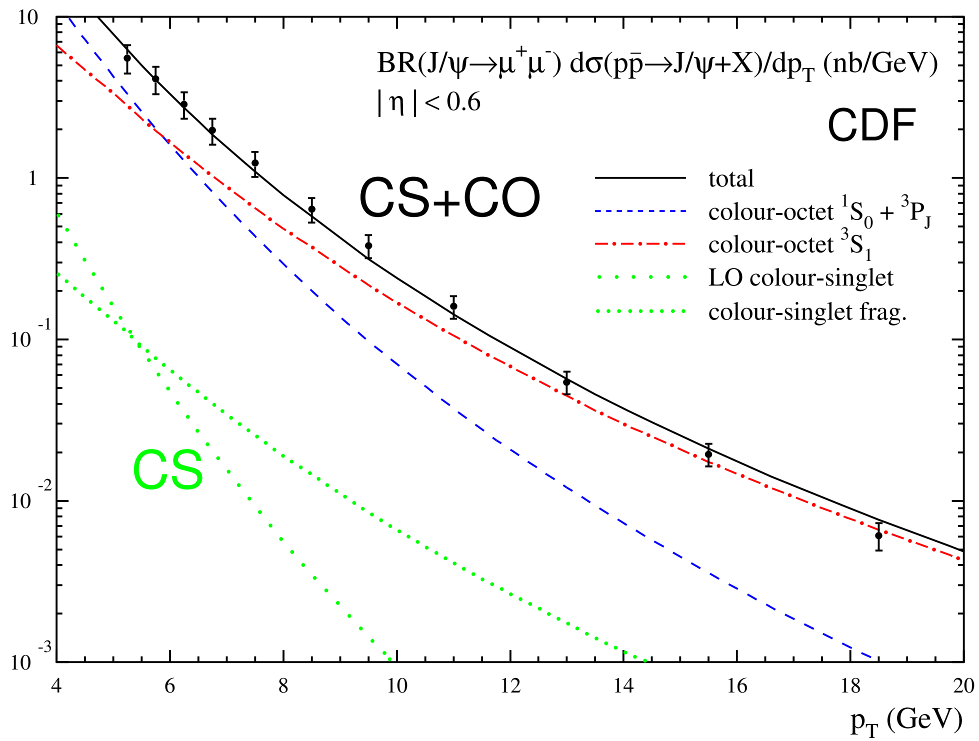
Colour Octet Model (CO)

$c\bar{c} \longrightarrow J/\psi$ + soft gluons

CO: NRQCD+factorization

$\sigma_{J/\psi X} = \sum \hat{\sigma}(\gamma p \longrightarrow c\bar{c}[n]X) \times$ LDME$[n]$)

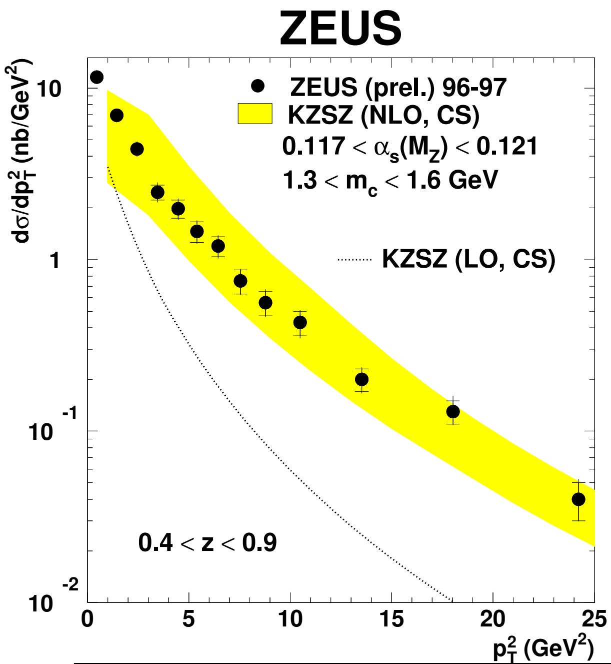
LDME from NRQCD fit to $p\bar{p}$ data

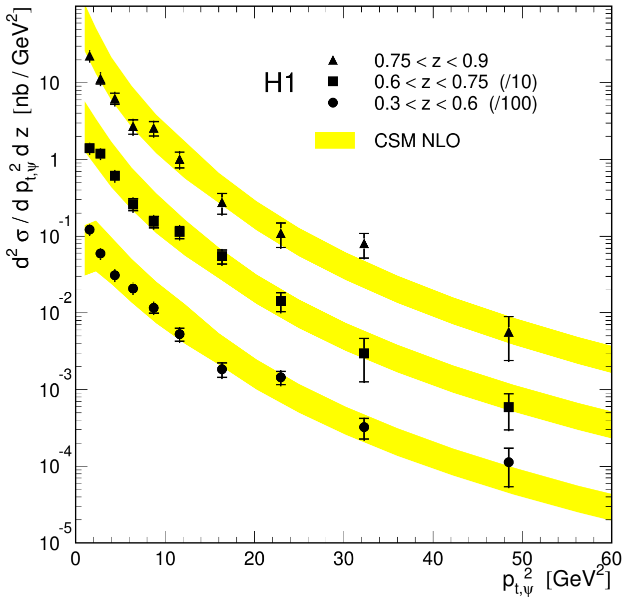


LDME universal? Tevatron $\longrightarrow$ HERA

Elasticity Parameter $z = E_{J/\psi}/E\gamma$

J/ψ Photoproduction

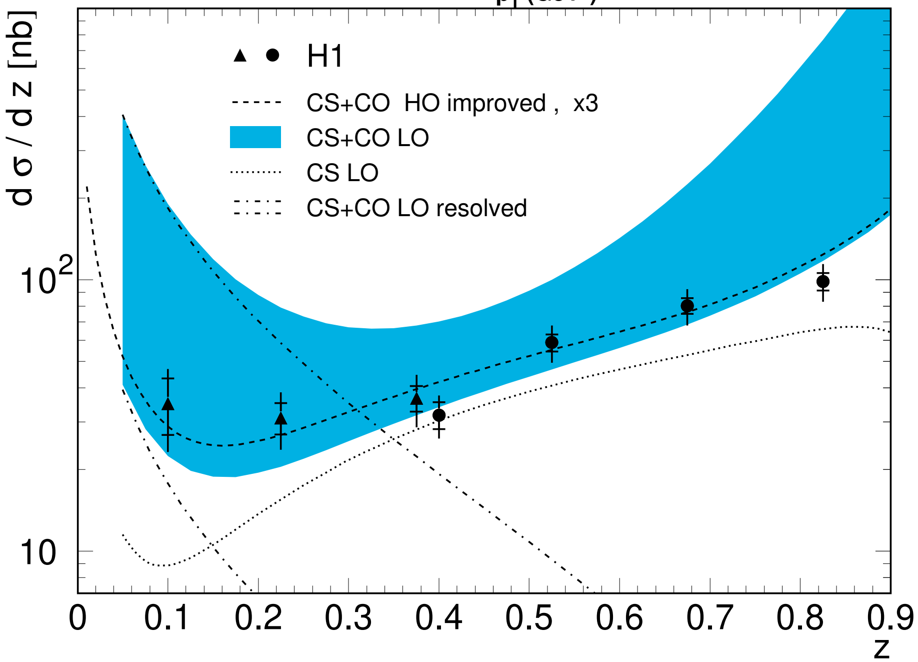




- CSM (LO): too steep
- CSM (NLO):

– $p_{t,\psi}^2$ and z well described

– No Colour Octet needed



- NRQCD CO (LO):

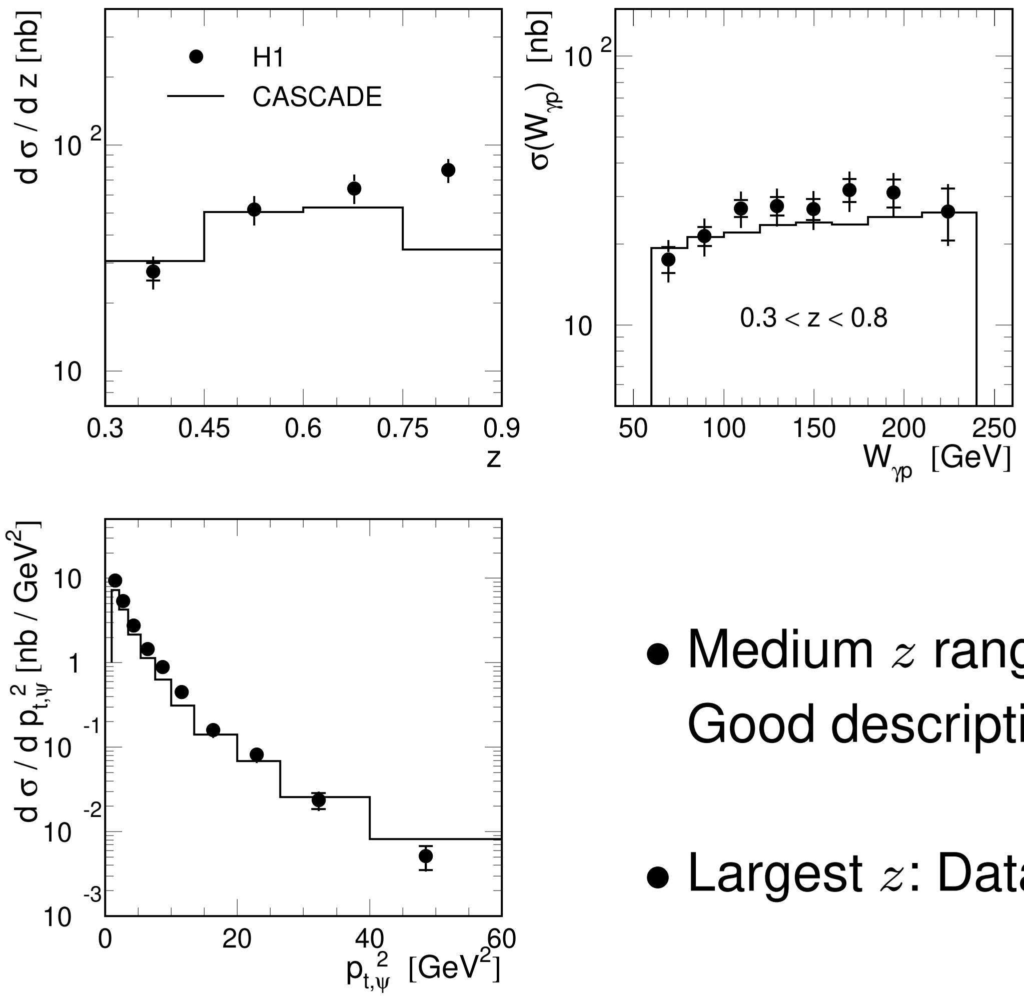
– fair description of z

for choice of small LDME

NLO corrections are important

No hard evidence for Colour Octet

J/ψ: Comparison with Cascade



Cascade also available for J/ψ

- Medium z range:
  Good description of $p_{t,\psi}^2$ and normalization

- Largest z: Data higher by factor 2-3

Cascade doing pretty well

Charm and Beauty at HERA

Many new results, now exploiting full HERA-I data sets
starting to provide the full picture

Charm:
– NLO somewhat lower, theoretical uncertainties large
– Photon structure: large contribution from charm-excitation
– Fragmentation functions: ep agrees with ee

Beauty:
– Differential cross sections in γp and DIS
– $D^*\mu$ correlations: Double tag of charm and beauty
– NLO lower than data
– Larger Q^2: Data and Theory agree generally better

Charmonia:
– NLO Calculations are important
– No hard evidence for Colour Octet contributions

Cascade MC (LO CCFM):
describes most data well in shape and normalization

Future: HERA-II $\rightarrow$ 1 fb^{-1}
New Instrumentation:
ZEUS: μ-Vertex Detector
H1: Forward Silicon Tracker

Backup: D-Meson Production in DIS

H1 Preliminary Results

Cross sections:

	D^+	D^0	D_s^+	D^{*+}
$\sigma_{vis}(ep \to eDX)$ (nb)	**2.16**	**6.53**	**1.67**	**2.90**
stat. error on σ_{vis}	± 0.19	± 0.49	± 0.41	± 0.20
syst. error on σ_{vis}	$^{+0.46}_{-0.35}$	$^{+1.06}_{-1.30}$	$^{+0.54}_{-0.54}$	$^{+0.58}_{-0.44}$
AROMA LO: σ_{vis}	2.45	5.54	1.15	2.61
error	± 0.30	± 0.69	± 0.30	± 0.31

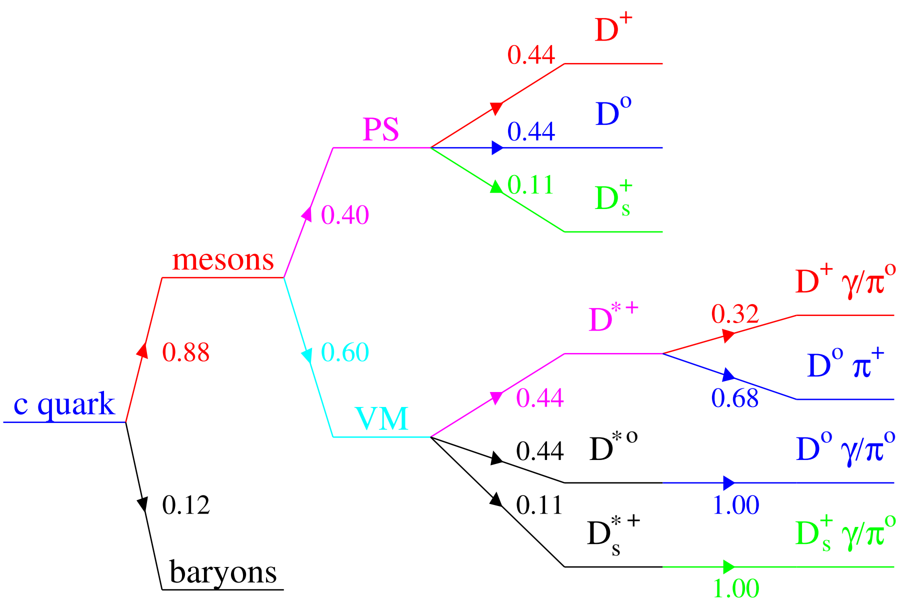
$$f(c \to D) = \frac{\sigma_{vis}^{meas.} - \sigma_{vis}^{MC}(ep \to b\bar{b} \to eDX)}{\sigma_{vis}^{MC}(ep \to c\bar{c} \to eDX)} \cdot f^{MC}(c \to D)$$

Fragmentation factors:

	D^+	D^0	D_s^+	D^{*+}
$f(c \to D)$	**0.202**	**0.658**	**0.156**	**0.263**
stat. error	± 0.020	± 0.054	± 0.043	± 0.019
syst. error	$^{+0.045}_{-0.033}$	$^{+0.115}_{-0.148}$	$^{+0.036}_{-0.035}$	$^{+0.056}_{-0.042}$
theo. error	$^{+0.029}_{-0.021}$	$^{+0.086}_{-0.048}$	$^{+0.050}_{-0.046}$	$^{+0.031}_{-0.022}$
world average	0.232	0.549	0.101	0.235
error	± 0.018	± 0.026	± 0.027	± 0.010

$\Rightarrow$ In good agreement with measured $f(c \to D)$

Backup: $c \to D$ Fragmentation Ratios



D^+	D^o	D_s^+
0.156		
	0.156	
		0.040
0.076		
	0.159	
	0.234	
		0.061
0.232	0.549	0.101

◇ $f(c \to D) = f^{dir.}(c \to D) + f^{indir.}(c \to D^* \to D)$

◇ fraction P_V of D mesons produced as VM:

count spin states $\Rightarrow P_V = \frac{VM}{PS+VM} = 0.75$

◇ u to d ratio $R_{u/d}$:

isospin invariance $\Rightarrow R_{u/d} = 1$

◇ strangeness suppression factor γ_s (u:d:s = 1:1:γ_s):

$m_s > m_u \approx m_d \Rightarrow \gamma_s = 0.3$

Backup: $c \rightarrow D$ Fragmentation Ratios

H1 Preliminary Results

◇ VM to PS ratio:

$$P_V = \frac{f(c \to D^{*+})}{f(c \to D^{+}) + f(c \to D^{*+}) \mathcal{BR}(D^{*+} \to D^0)}$$

Assumption: $f(c \to D^{*+}) = f(c \to D^{*0})$ (isospin inv.)

$$P_V' = \frac{2 \cdot f(c \to D^{*+})}{f(c \to D^{+}) + f(c \to D^0)}$$

◇ u to d ratio:

$$R_{u/d} = \frac{f(c \to D^0) - f(c \to D^{*+}) \mathcal{BR}(D^{*+} \to D^0)}{f(c \to D^{*+}) + f(c \to D^{*+}) \mathcal{BR}(D^{*+} \to D^0)}$$

◇ Strangeness suppression factor: (u:d:s = 1:1:γ_s)

$$\gamma_s = \frac{2 \cdot f(c \to D_s^+)}{f(c \to D^{+}) + f(c \to D^0)}$$

	P_V	P_V'	$R_{u/d}$	γ_s
H1 data (Prel.)	**0.693**	**0.613**	**1.26**	**0.36**
stat. error	± 0.045	± 0.061	± 0.20	± 0.10
syst. error	± 0.004	± 0.033	± 0.13	± 0.01
theo. error	± 0.009	± 0.008	± 0.04	± 0.08
world average	0.601		1.00	0.26
error	± 0.032		± 0.09	± 0.07

$\Rightarrow$ Good agreement between data and world average.