CHARM PRODUCTION at HERA

- Introduction
- Open charm production (in γp and DIS)
- J/ψ production (in γp and DIS)
- Summary

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representing

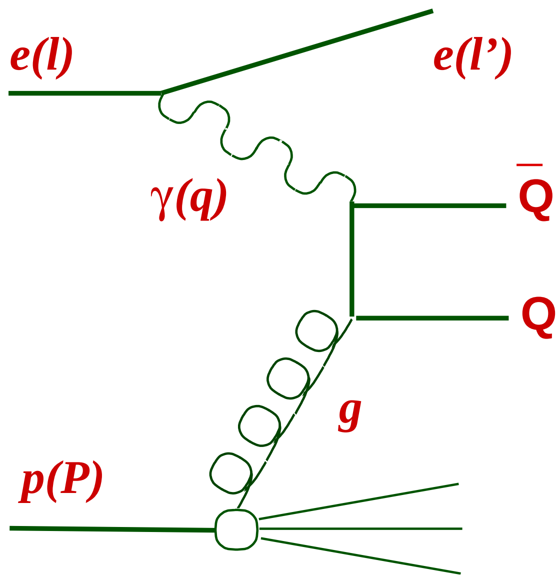
H1 and ZEUS

Why Heavy Quarks in ep Collisions ?

- Study production mechanism of heavy flavour (c,b)
- Perform stringent tests of pQCD predictions

  expect larger quark masses to render pQCD more reliable.
- Use heavy flavours as tool to independently :
  - access gluon density in proton
  - learn about parton densities in the photon
  - identify non−standard processes
- Study non−perturbative phenomena: fragmentation...

Kinematics of Heavy Quark Production



Variables:

$\sqrt{s} \cong 318$ GeV : ep CM−energy with $s = (l+P)^2$

$Q^2 = -q^2$: momentum transfer squared

$x = \frac{Q2}{2P\cdot q}$: momentum fraction of p−constituent

$y = \frac{qP}{lP}$: inelasticity, γ−energy fraction $|_{Q2=0}$

Kinematic regimes:

Photoproduction (γP); γ quasi on−shell : $Q^2 = 0$

Deep Inelastic Scattering (DIS): $1 < Q^2 < 5\ 10^{-4}$ GeV

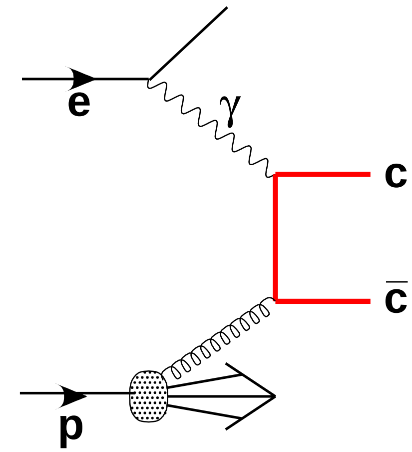
Beams and luminosity:

electrons + protons: (beg 98−mid 99) : Lumi ~ 15 pb^{-1};

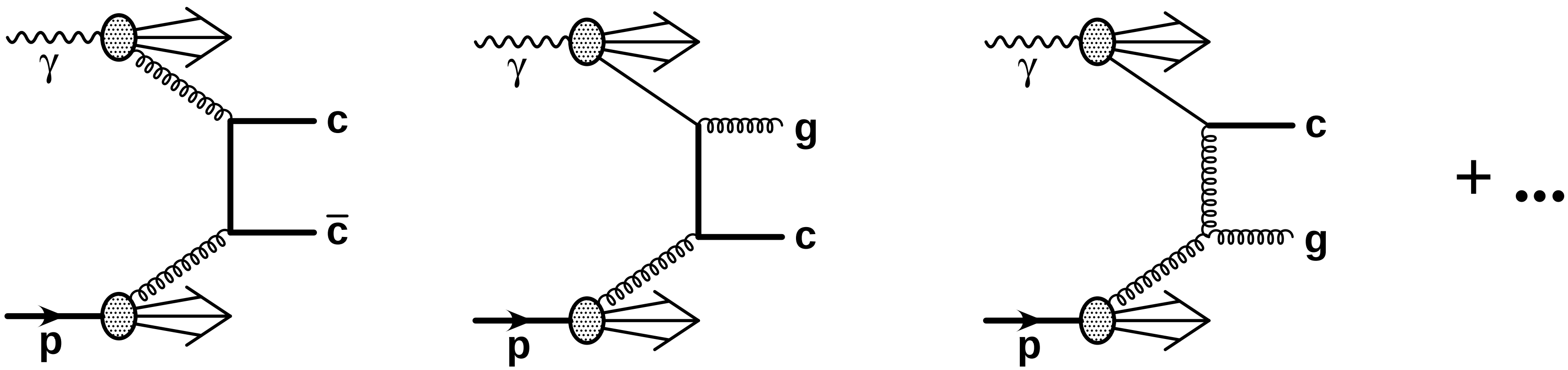
positrons + protons: (mid 94− 1997 , mid 99 − end 00) : Lumi ~ 60−120 pb^{-1}

Processes – Open Charm Production

- dominant in leading order (LO) is direct boson–gluon fusion (BGF) => quark propagator



- Resolved contributions within LO picture
  => gluon + quark propagators



"c−excitation"

⇒ different kinematical distributions => info on individual contributions

QCD Calculations for Open Charm

LO and PS programs:

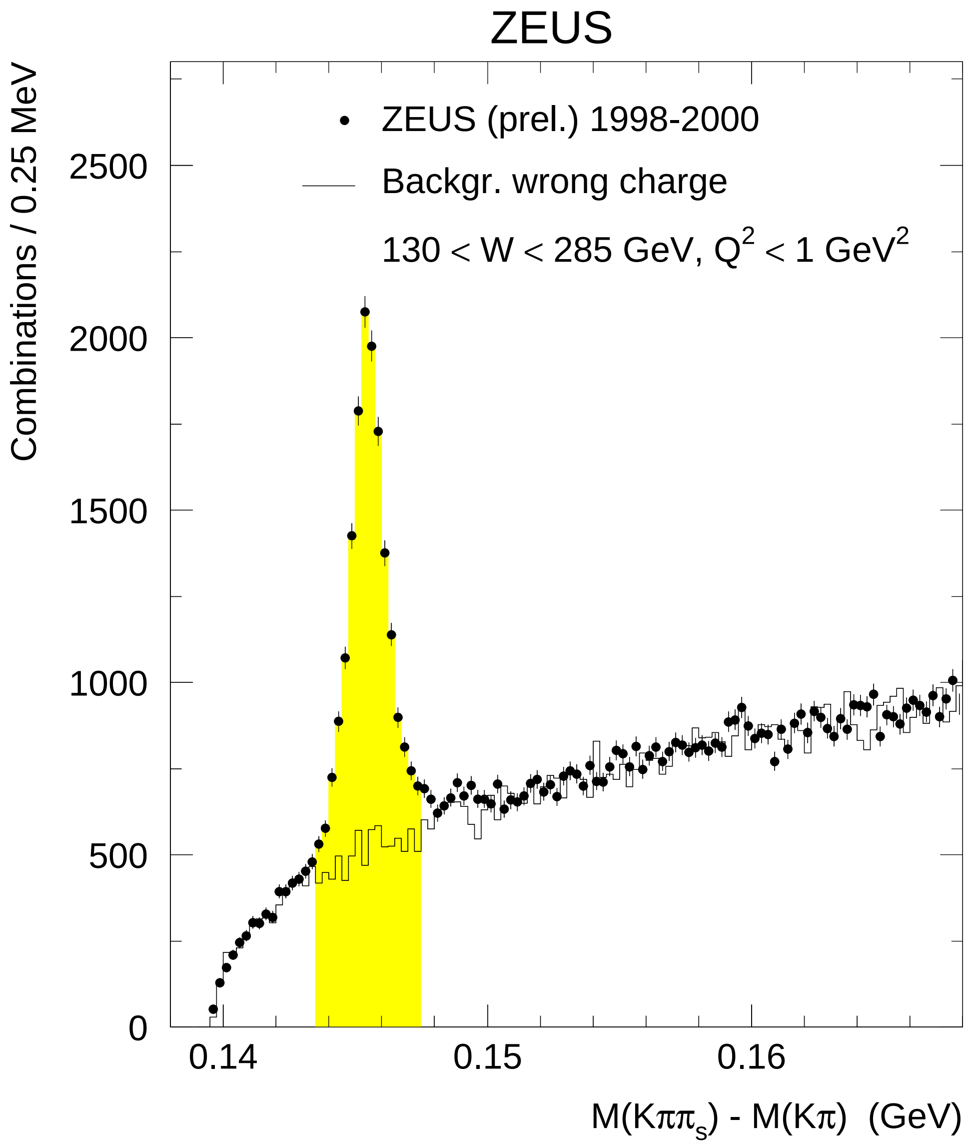
- AROMA: direct only, DGLAP evolution
- PYTHIA, HERWIG: direct and resolved, DGLAP
- CASCADE : direct only, CCFM−like evolution

NLO calculations in pQCD:

- FO = fixed order,massive : HQ produced at perturbative level, valid for $p_t \sim m_Q$; (FMNR, HVQDIS : Frixione *et al*, Harris+Smith)
- RS = resummed, massless approach (for γp) : HQ is active flavour in p and γ; resums contributions of large logarithms (Q/m_Q, p_t/m_Q) up to NLL; reliable for $p_t >> m_Q$ (Kniehl, Kramer, Cacciari, ..)
- FONLL: = matched calculations (for γp) ; => combination of FO (in lowp_t) and RS(at large p_t); (Frixione, Nason, Cacciari)

Open charm : D – mesons

D* Photoproduction : ZEUS



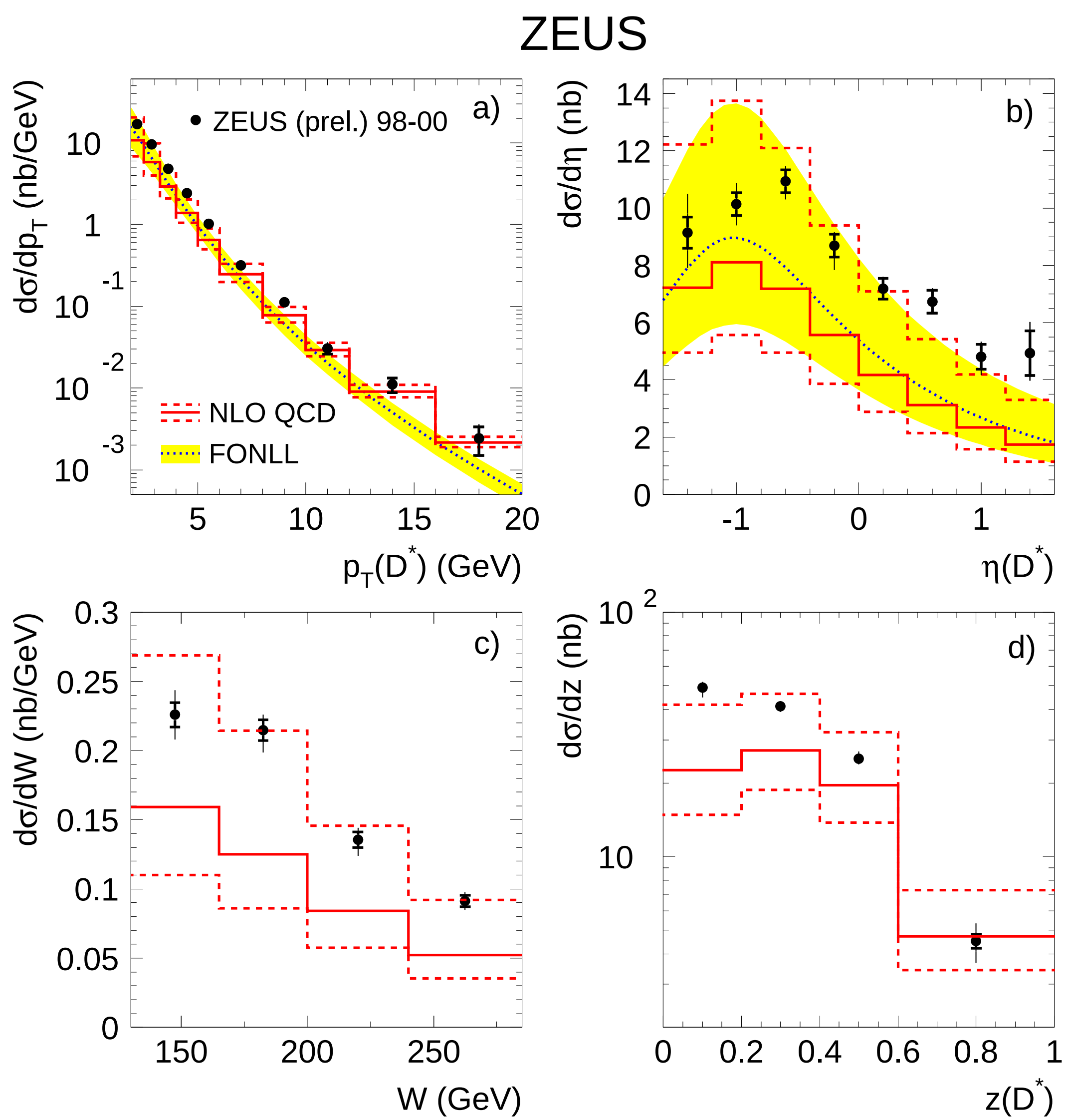
$D^* \rightarrow (K\pi)\,\pi$

10 k clean events in 80 pb^{-1}

$Q^2 < 1$ GeV^2 ; 130 < W < 285 GeV

$1.9 < p_t(D) > 20.$ GeV $|\eta(D)| < 1.6$

Compare with QCD Predictions in γp : ZEUS



Calculations done with :

- CTEQ5M1 + AFG
- $m_c = 1.5$ GeV; $\mu_R = \mu_F = m_T$
- $f(c \to D^{*+}) = 0.235$
- $\varepsilon_{Pete} = 0.035$ (NLO), 0.02 (FONLL)
- errors: $m_c \pm 0.2$ GeV; $\mu_R * ½, *2$

= > FO NLO :

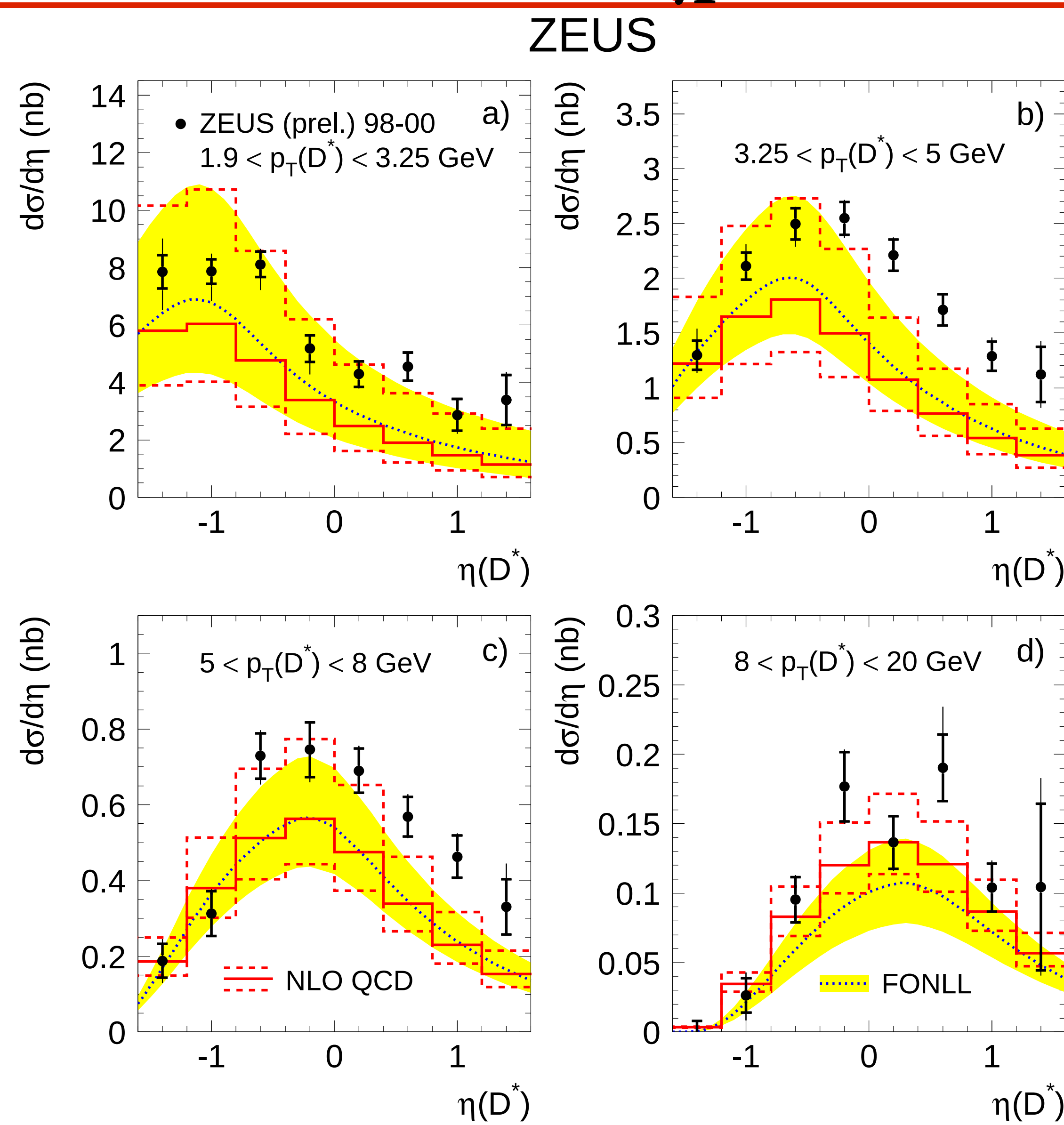
- shape described well, normalisation too low, mostly in forward, low z

=> matched FONLL :

- similar to FO shapes
- norm even lower at large p_T

Double Differential Cross Sections γp: ZEUS

η–distribution in
p_T – bins :

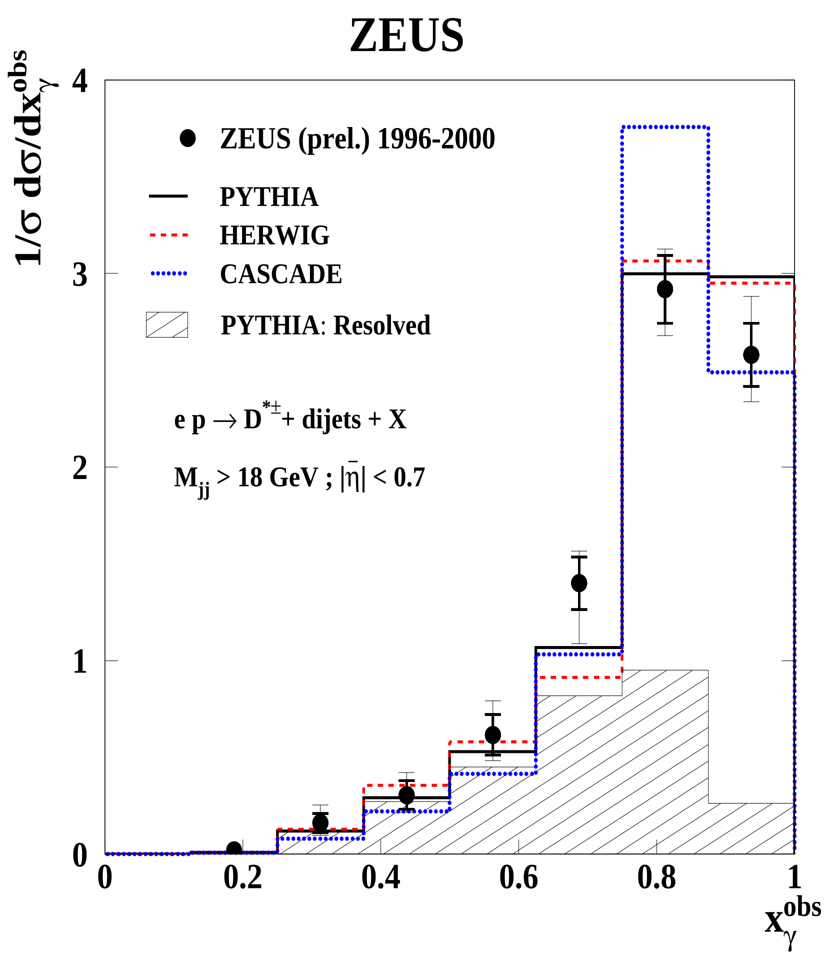


=> QCD at NLO
- normalisation too low
- shapes reasonable

Charm Tagged Dijets : ZEUS

- Study dijets events associated with at least one $D^* \to (K\pi)\,\pi$ (120 pb^{-1})

  D^*: $p_t(D) > 3.$ GeV; $|\eta(D)| < 1.5$; Jets: $E_T(jet) > 5$ GeV; $|\eta(jets)| < 2.4$



Enrich resolved or direct contributions by γ−momentum−fraction variable:

$$x_\gamma^{obs} = \frac{\sum_{jets} E_T e^{-\eta}}{2\,y E_e} \quad < 0.75\,; \quad > 0.75$$

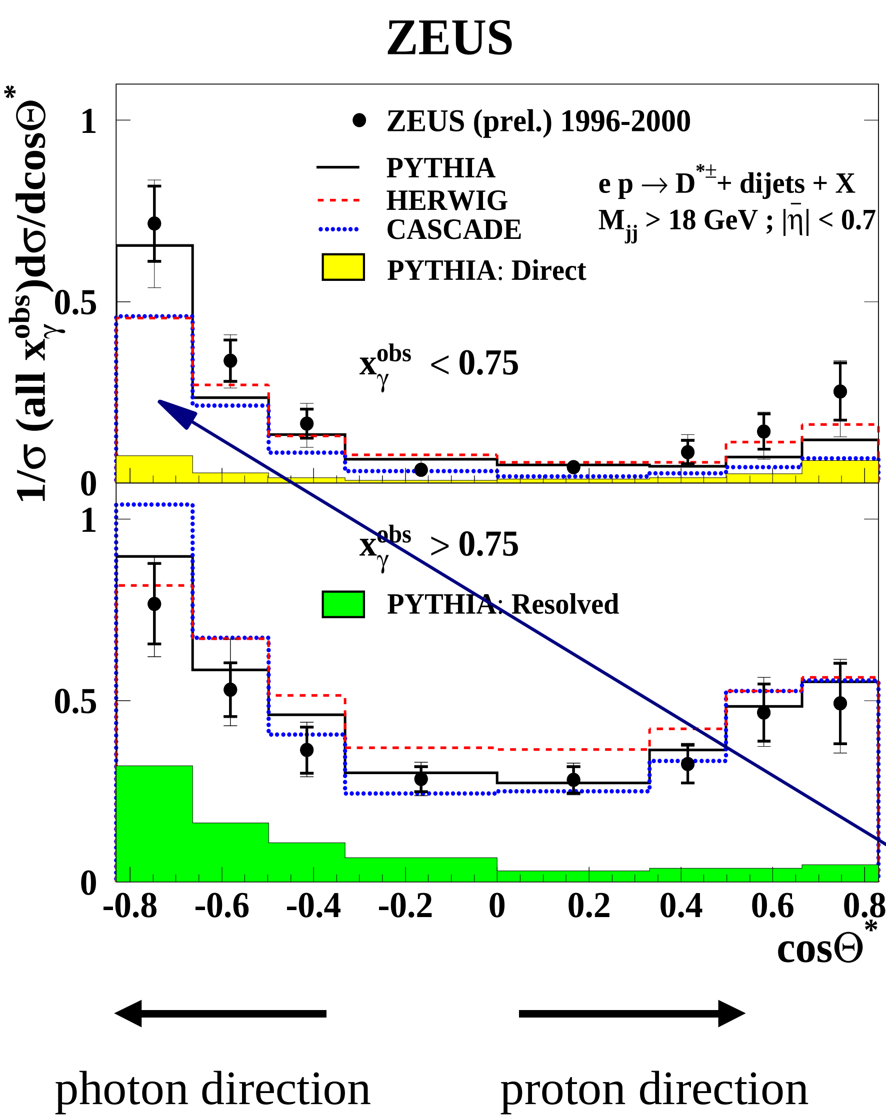
MC : Pythia, Herwig (incl. charm excitation graphs) describe data shape well, (Cascade less well).

- Study dijet angular distributions in

  θ^* = angle (jet−jet axis, beam axis)$_{dijet-RF}$

  => sensitive to propagator type (q/g)

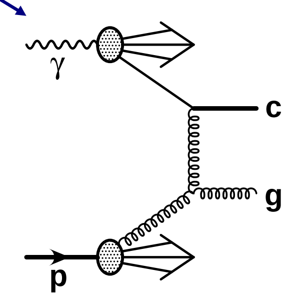
Dijet angular distributions : ZEUS



- associate D* with charm−jet to find charm direction : $\cos\theta^* > 1$
- expect different slopes at large $\cos\theta^*$ for direct and resolved contributions
- resolved contribution to $x_\gamma^{obs} > 0.75$ explains asymmetry in $\cos\theta^*$

D*−jet mostly found in γ direction:

⇒ clear indication for gluon propagator



=> contributions of "c−excitation" graphs in resolved photon at LO

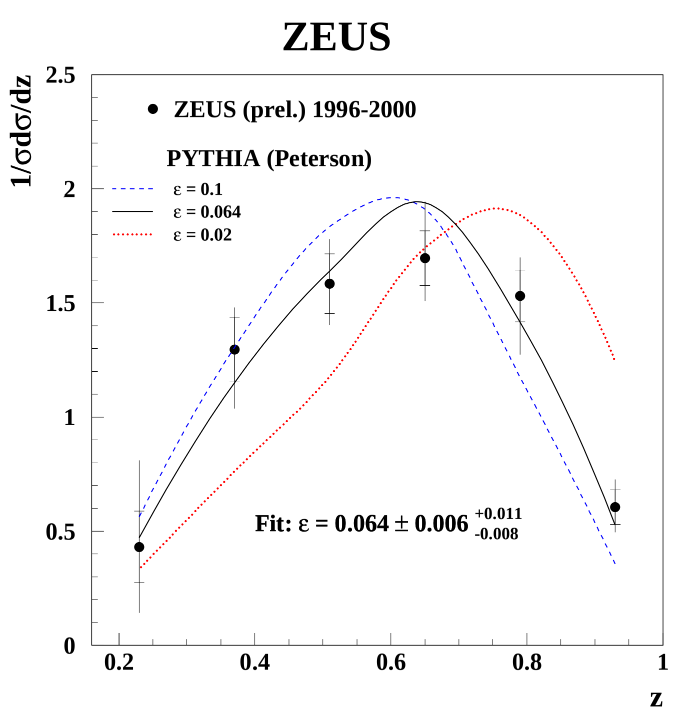
Charm fragmentation function in γp : ZEUS

$D^* \to (K\pi)\,\pi$ associated with jets

D^*: $p_t(D) > 2.$ GeV; $|\eta(D)| < 1.5$;

Jets: $E_T(\text{jet}) > 9$ GeV; $|\eta(\text{jets})| < 2.4$

Energy fraction $z = (E + p_{\|})(D^*) \,/\, (E + p_{\|})(\text{jet})$



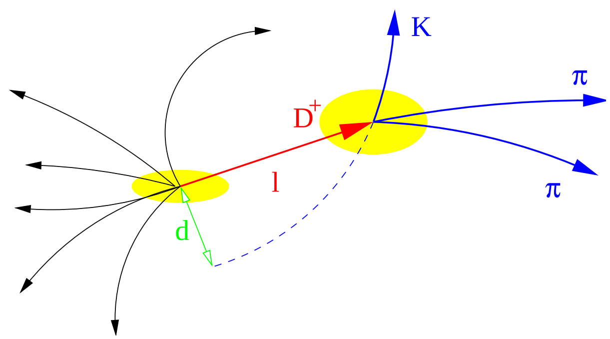
- Best fit of Peterson parameter (in Pythia) :
  $\varepsilon = 0.064 \pm 0.006\ ^{+0.011}_{-0.008}$

=> compares well with ε(LEP) =0.053 for LL
improved (Nason&Oleari, hep−ph/9903541)

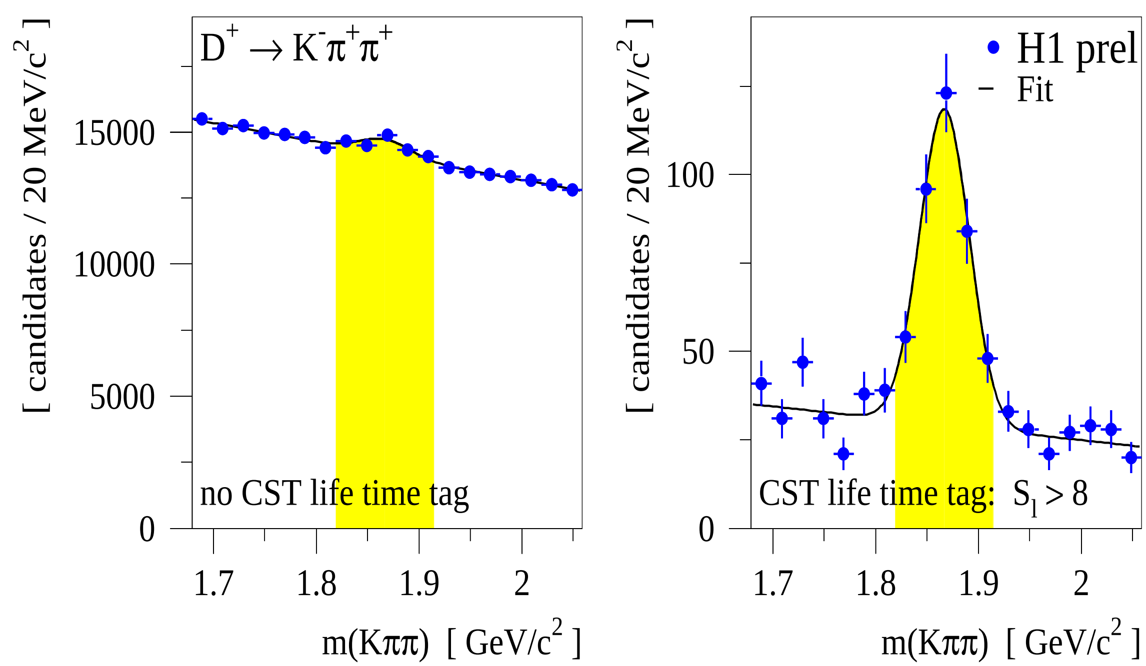
Charm tagging via decay length

- Reconstruct exclusive final states **via secondary vertex**

$D^+ \to K\pi\pi$; $D^0 \to K\pi$; $D^{*+} \to (K\pi)\,\pi$; $D^+_s \to (KK)\,\pi$



Example D+



- reduce background via decay length significance $S_l = l / \sigma_l$

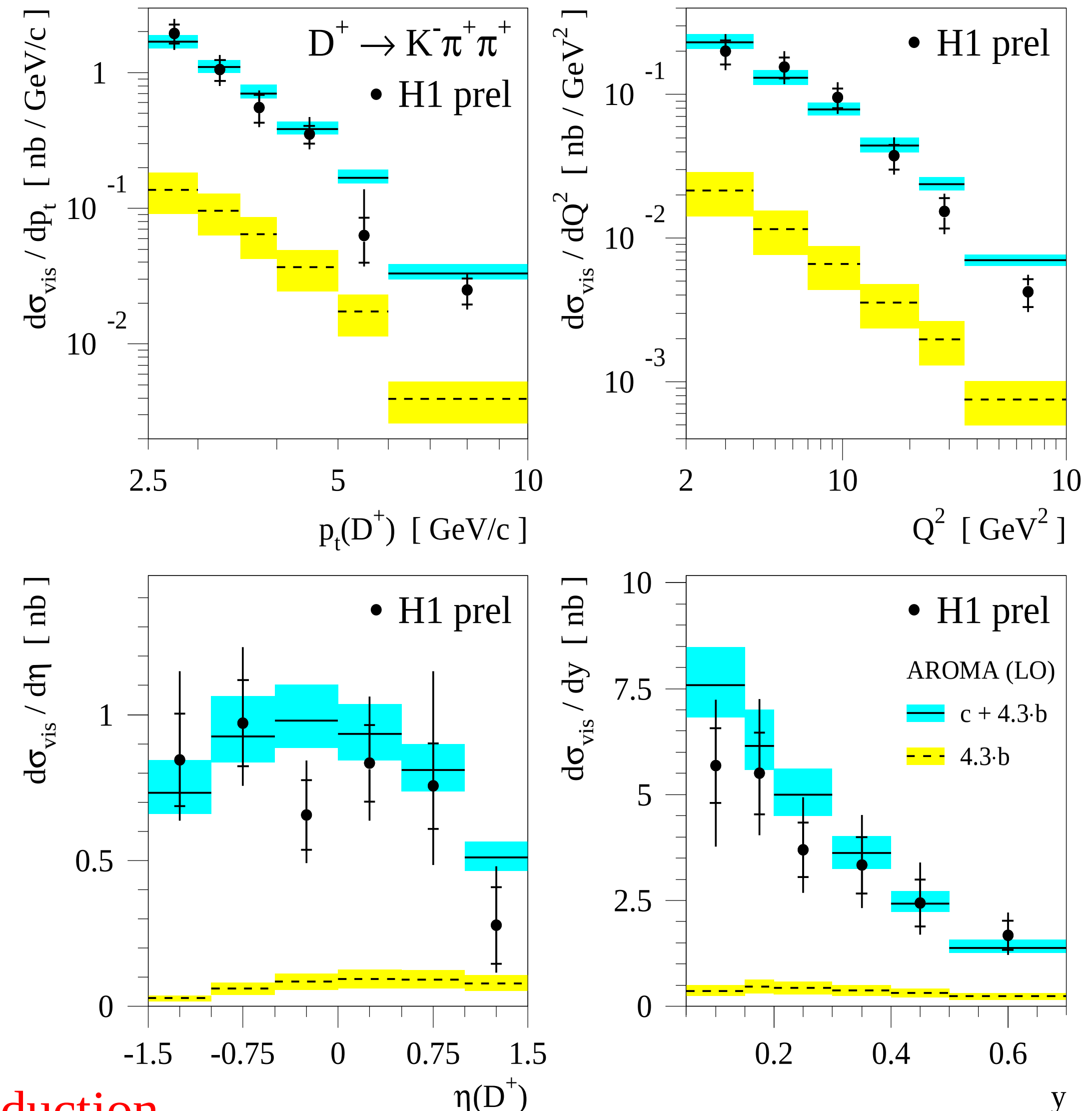
"*l*" measured at 100 μm level
(H1 silicon tracker, Zeus HERA−II μ−VTX)

D^+ production in DIS : H1

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

- $2 < Q^2 < 100$ GeV^2 ; $0.05 < y < 0.7$
  $p_t(D) > 2.5$ GeV ; $|\eta(D)| < 1.5$

$$\sigma_{vis}(ep \rightarrow eDX) = (2.16 \pm 0.19^{+0.46}_{-0.35})\, nb$$



=> norm of (2.45 ±0.30) nb and
shapes well described by
LO+PS predictions.

=> similar results for D*, D^0, D_S production

Fragmentation Ratios : H1

From measured production cross sections, calculate

=> production ratios of different quark and spin states :

R	$1.28 \pm 0.19 \pm 0.12$	H1 prelim
	1.02 ± 0.12	ALEPH
	$0.96 \pm 0.05 \pm 0.07$	DELPHI

"u−d quark differences" R

$$R = (f^0 - f^+) / (2f^{*+} BR)$$

P_{Vd}	$0.693 \pm 0.045 \pm 0.010$	H1 prelim
	0.595 ± 0.045	ALEPH

"vector/pseudoscalar ratio" P_{Vd}

$$P_{Vd} = f^{*+} / (f^+ + f^{*+} BR)$$

γ_S	$0.36 \pm 0.10 \pm 0.08$	H1 prelim
	0.31 ± 0.07	LEP / ADO
	0.27 ± 0.05	ZEUS

"s−suppression factor" γ_S

$$\gamma_S = 2f_S / (f^0 + f^+)$$

$f^x = f(c \to D^x)$ BR= $BR(D^* \to D^o \pi)$

⇒ find agreement within (similar) errors HERA <−> LEP

J/ψ States

J/ψ Production Mechanism

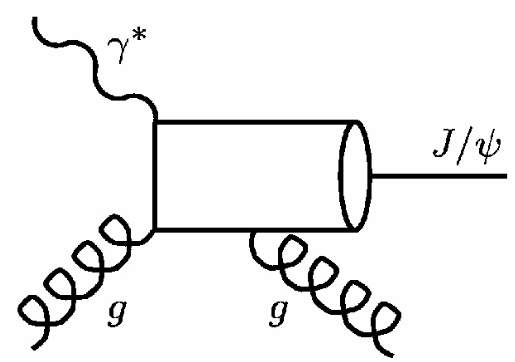
NRQCD + factorization:

$$\sigma(\gamma p \to J/\psi) = \sum \hat{\sigma}_{SD}(\gamma p \to c\bar{c}[n]\, X) * LDME[n]$$

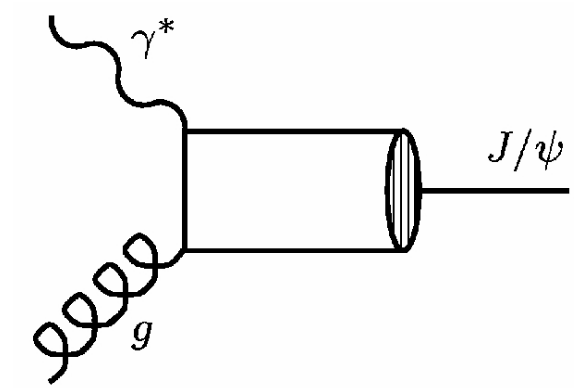
σ_{SD} : short distance coefficients, calculable in pQCD

LDME: long distance matrix elements, assumed universal : FNAL −> HERA

n : quantum numbers (colour state, $^{2S+1}L_J$)



Direct γ*g fusion
[resolved not shown]

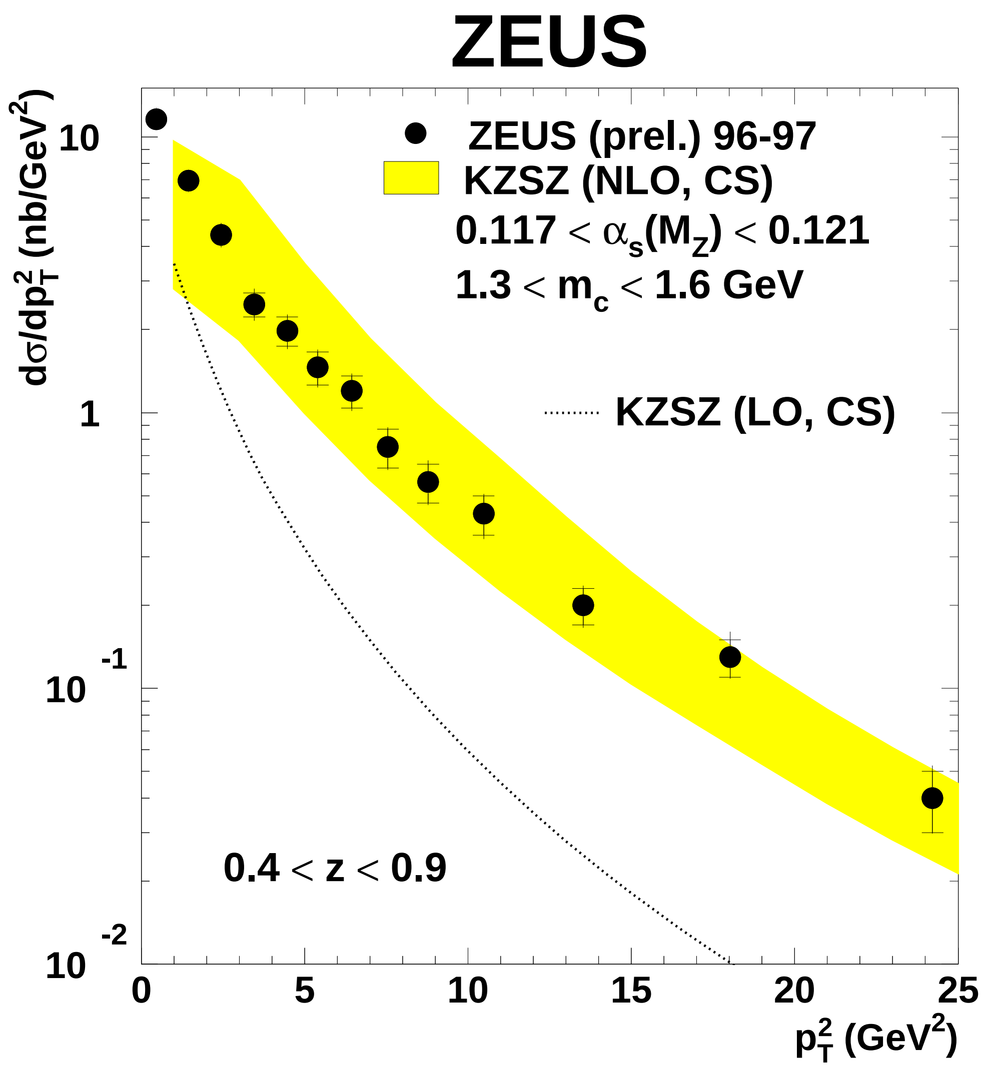


CSM = Colour Singlet Model [1, $^3S_1$]
colourless $c\bar{c}$ −state formed by emission of hard gluon

CO contributions: [8, $^{2S+1}L_J$]
J/ψ formed from colour octett $c\bar{c}$ −pair by soft g emission

Question: what is the relative amount of different contributions ?

Inelastic J/ψ Photoproduction : ZEUS



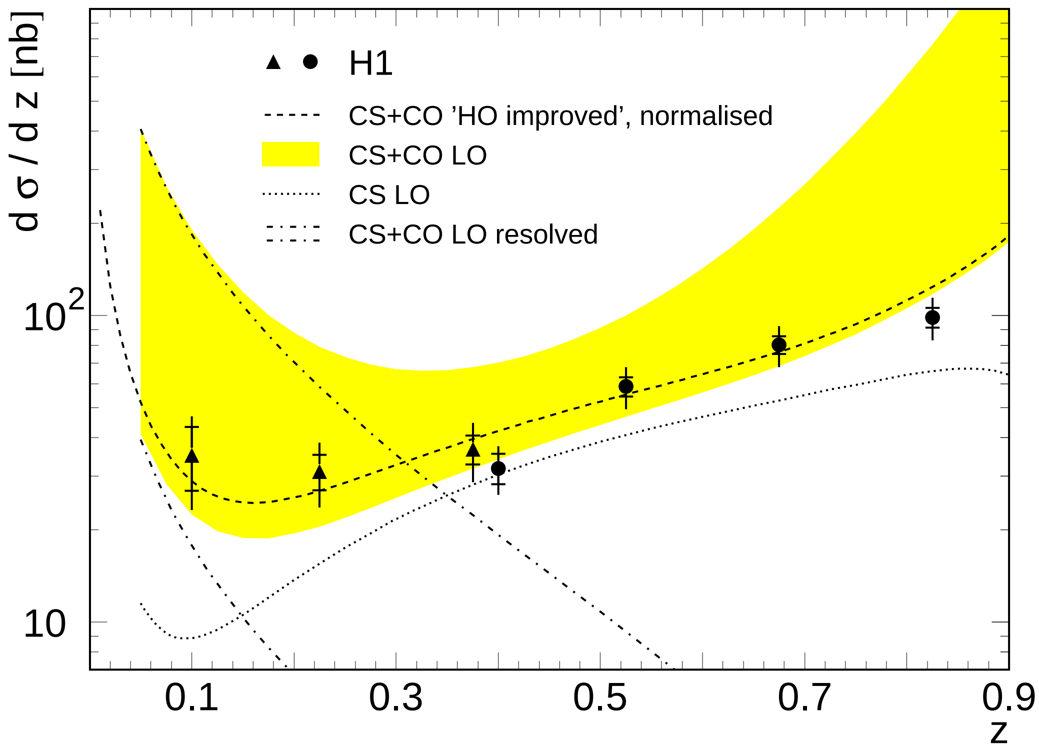
$p^2_{t,\psi}$ distribution at medium z

50 < W < 180 GeV

KZSZ = Kraemer et al

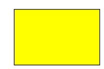
- CS (LO) contribution alone too steep
- CSM NLO describes $p^2_{t,\psi}$ distribution pretty well within (large) errors

J/ψ Photoproduction : H1



$z = E^*_\psi / E^*_\gamma \,|_{p\text{−rest frame}}$

$p_t > 1$ GeV; $120 < W < 260$ GeV

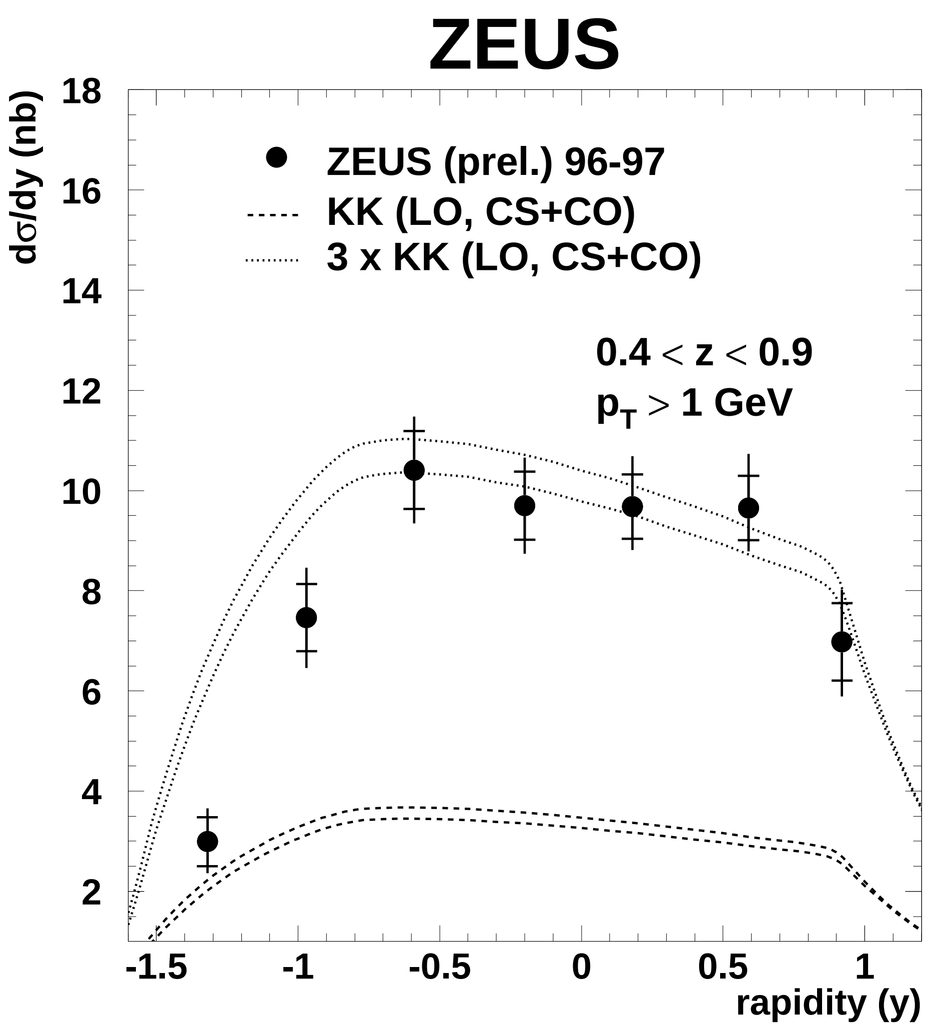
 CS+CO LO (Kraemer+Cacciari)

HO improved (Kniehl+Kramer)

- powerful new data down to low z
- large theoretical uncertainties (e.g. due to LDME extraction (from CDF))
- addition of CO contributions and further improvements at HO help describe shape better, but still need large k−factors ..
- fair description over whole z−range by CS+CO LO with small LDMEs

=> picture is not clear yet ...

Inelastic J/ψ Photoproduction : ZEUS



Rapidity distribution:

(KK : Kniehl + Kramer)

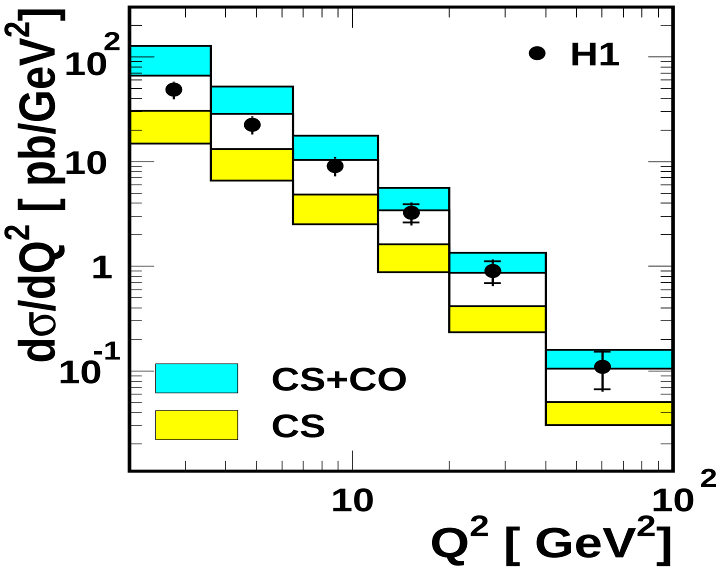
$0.4 < z < 0.9$ $p_t > 1$ GeV

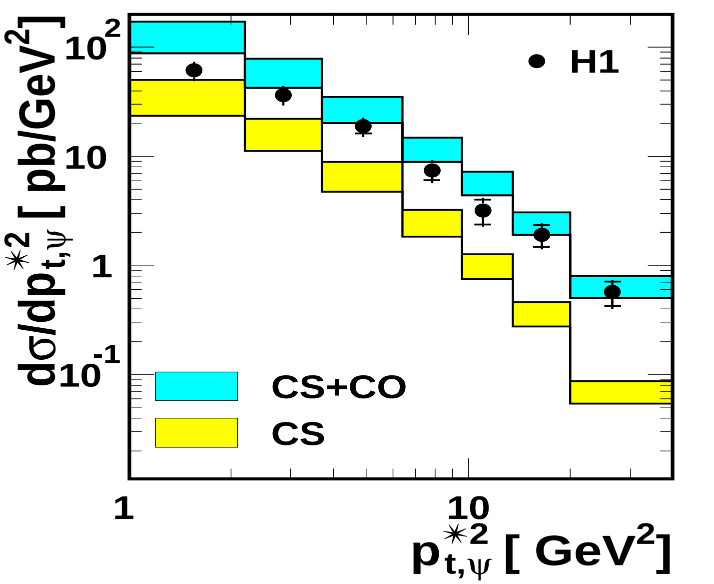
$50 < W < 180$ GeV

- predictions CO+CS too low

- helps to
  further constrain models

J/ψ Production in DIS : H1





Comparisons with LO NRQCD calculation and CS contribution (B.A.Kniehl and L.Zwirner)

- CS contribution alone too low by ~ 2.7 ; CS too steep in $p^2_{t,\psi}$

  $\Rightarrow$ missing higher orders?

- CS+CO too high at low Q2, $p^2_{t,\psi}$ by ~ 2, but description improves at high Q2, $p^2_{t,\psi}$ (smaller theoretical errors)

=> further input for theories ...

Summary

- D − meson production
  - pQCD predictions (FO, FONLL) are getting pretty close to describe cross sections in shape; normalisations still somewhat too low
  - fragmentation studies show NO differences between HERA and LEP
  - dijet angular distribution show signature of gluon propagator −> "c in photon"
  - first measurements with lifetime tags (D^+); promising D* −muon correlations

- J/ψ production :
  - many precise data in large range down to low z
  - theoretical predicions show large uncertainties
  - can describe data by "tuning" (CS + CO or + CSM NLO ...)
  - BUT picture NOT clear yet

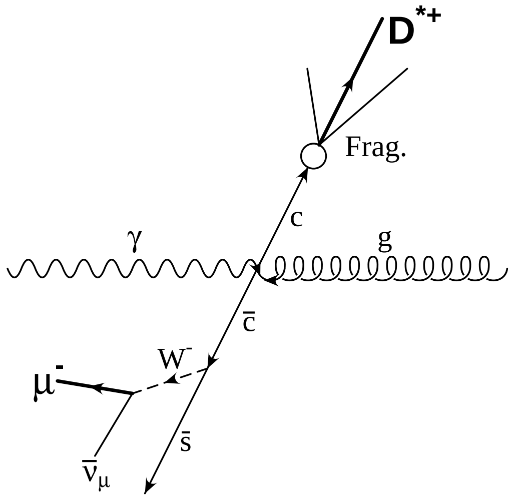
- HERA−II :

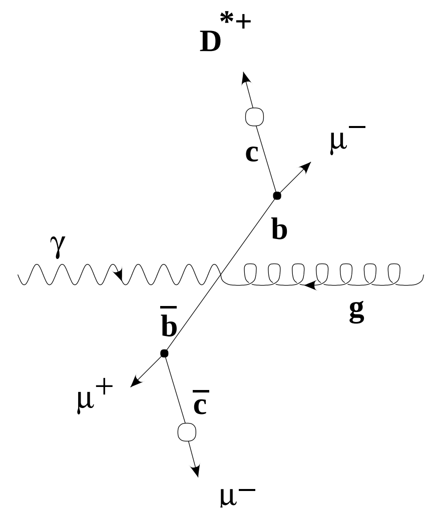
  larger statistics and improved detectors (vertex ...)
  will help to solve remaining puzzles ...

Optional Slides

D* – Muon Correlations in γp (opt)

- Tag BOTH quarks (c and cbar) and reconstruct final state
- Study events with one $D^* \rightarrow (K\pi)\,\pi$ and a muon
- Correlate charge and separation $\Delta\phi$ of D* and μ to separate charm and beauty





Charm:

$\Delta\phi \approx 180^o$; $Q(D^*) = -\,Q(\mu)$

Beauty: three possibilities :

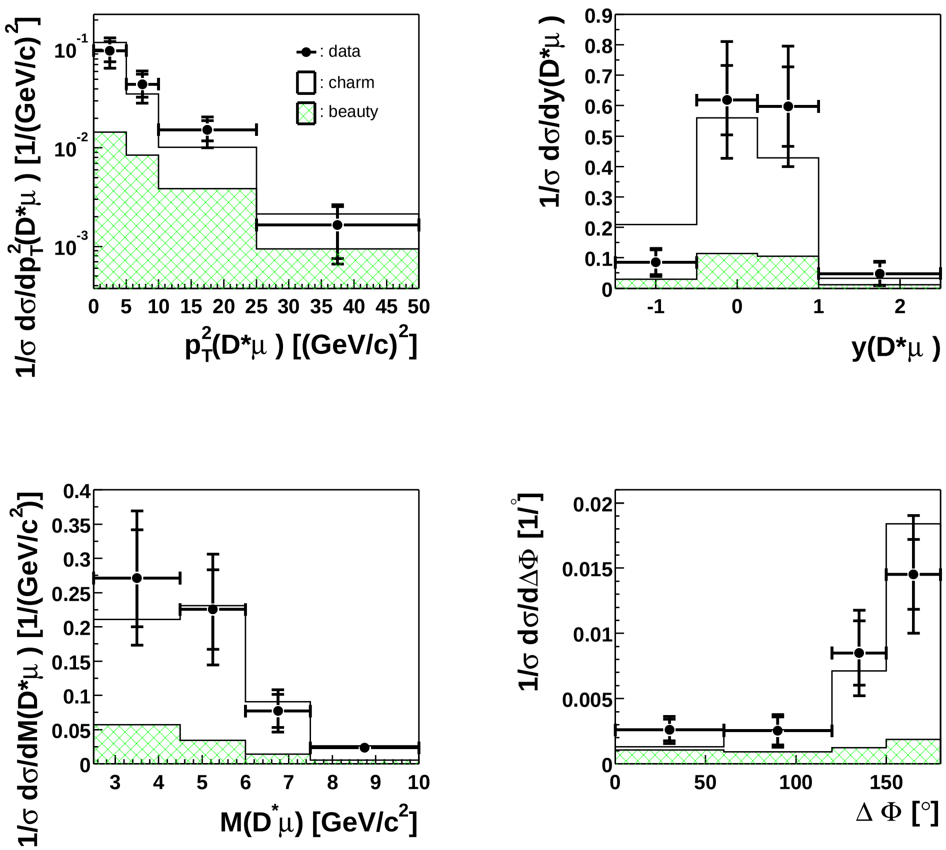
$\Delta\phi \approx 180^o$; $Q(D^*) = -\,Q(\mu)$

$\Delta\phi \approx 180^o$; $Q(D^*) = +\,Q(\mu)$

$\Delta\phi \approx 0^o$; $Q(D^*) = -\,Q(\mu)$

D* – Muon Correlations in γp : H1 (opt)

- Measure normalized differential cross section in $(D^*\mu)$ – variables



- Approximate QQ−quantities by $(D^*\mu)$ – variables

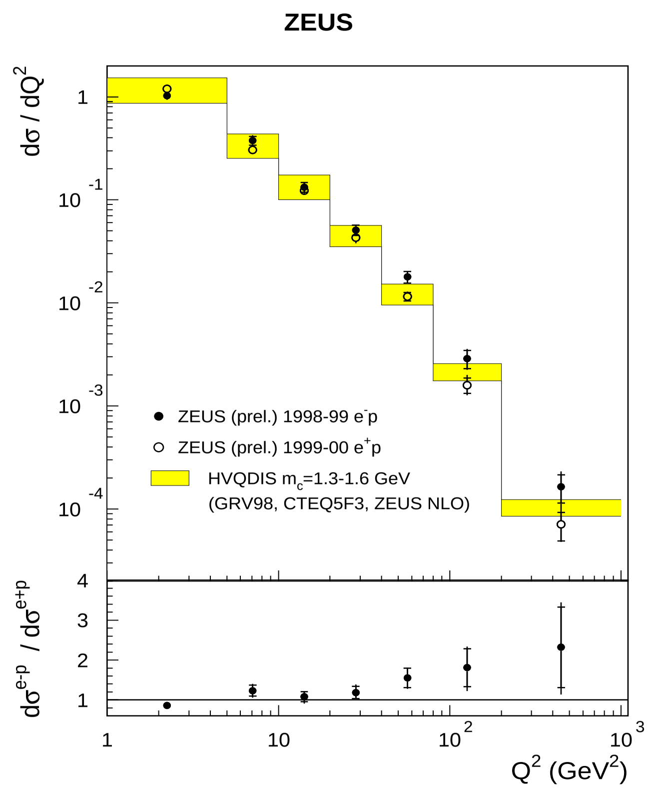
- LO+PS Aroma describe shape reasonably well

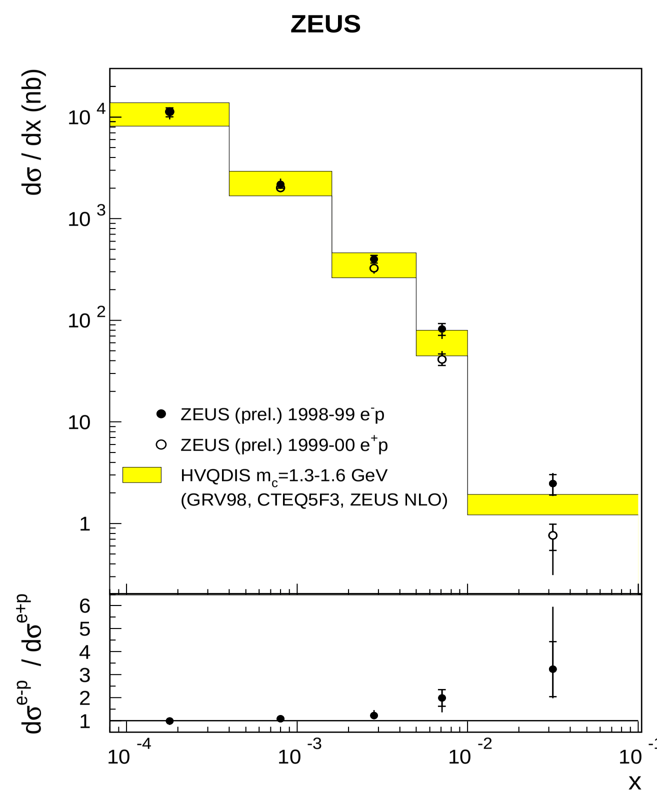
Statistics low −> large potential for HERA−II , e.g. gluon density extraction

e^+p vs e^-p D* production : ZEUS (opt)

D* production in $1 < Q^2 < 1000\ GeV^2$; $0.02 < y < 0.8$

$1.5 < p_t(D) < 15$. GeV $|\eta(D)| < 1.5$



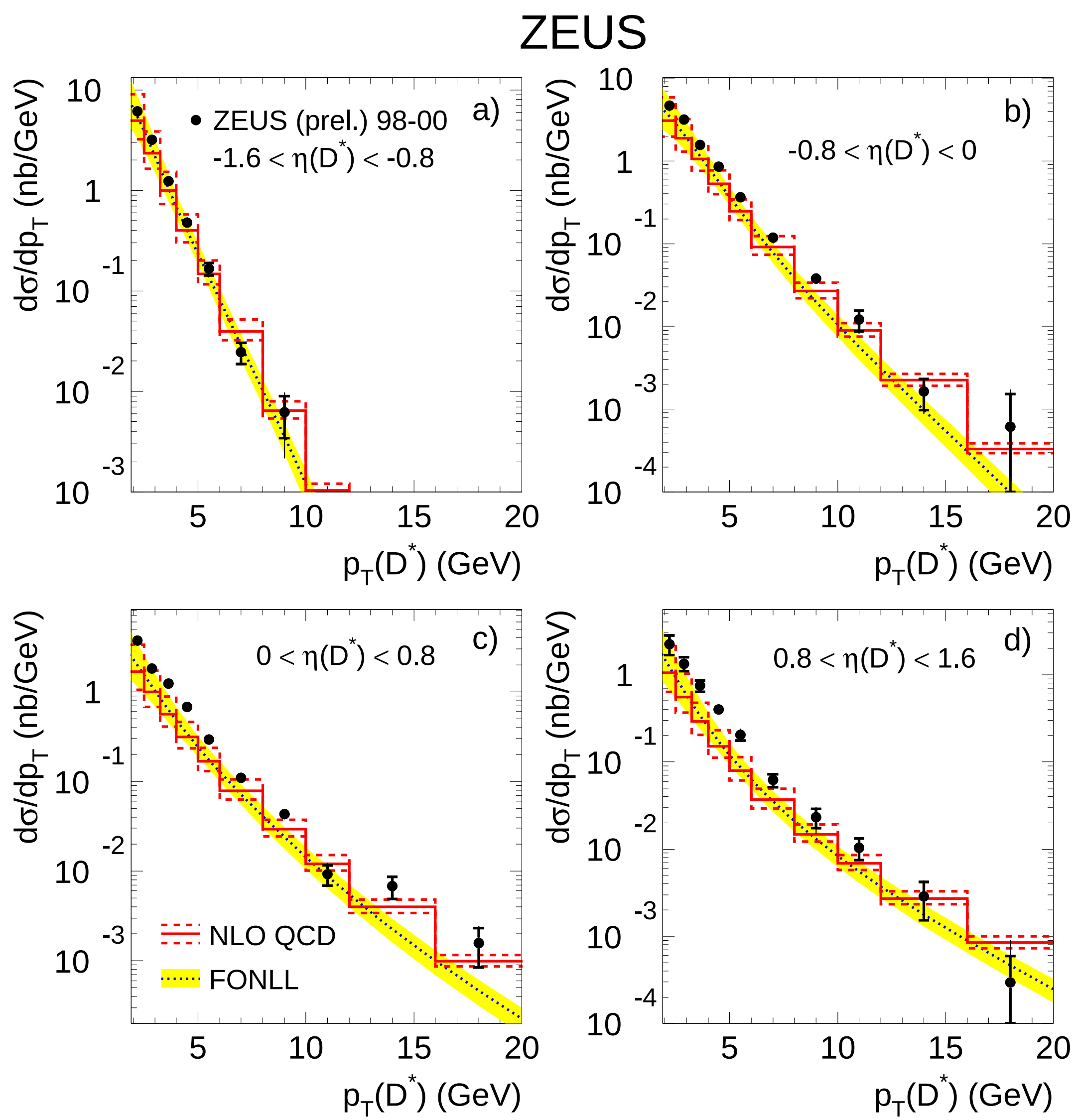


⇒ Small disagreement, unexpected, not explained

Double Differential Cross Sections : ZEUS (opt)

p_T – distributions
in η–bins :

better description
at low p_t



D meson tagging via decay length (opt)

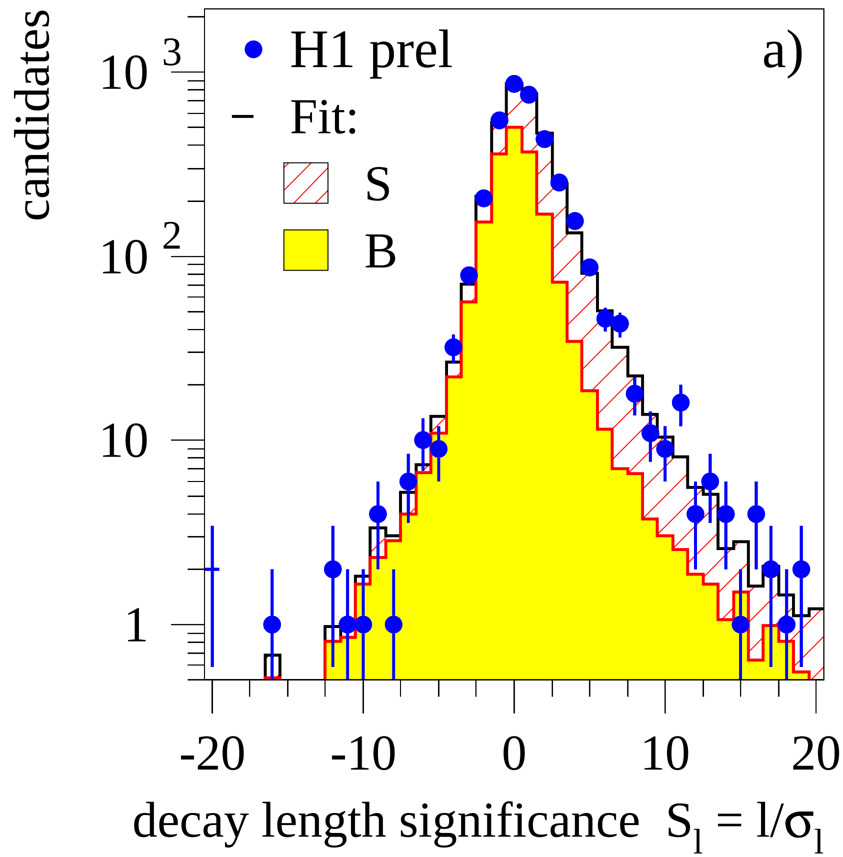
Radial decay length significance $S_l = l/\sigma_l$ with $l = p_t(D)\,ct^* / m_D$

for tagged $D^0 \rightarrow K\pi$ candidates

H1 DATA

- S = signal shape from MC
- B = background shape of data sideband
- Fit only relative normalisations
- #D consistent with direct mass−fits

$\Rightarrow$ good description over 3 decades,
resolution + errors well under control !



D* production vs NLO : H1 (opt)

Differential cross section :

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

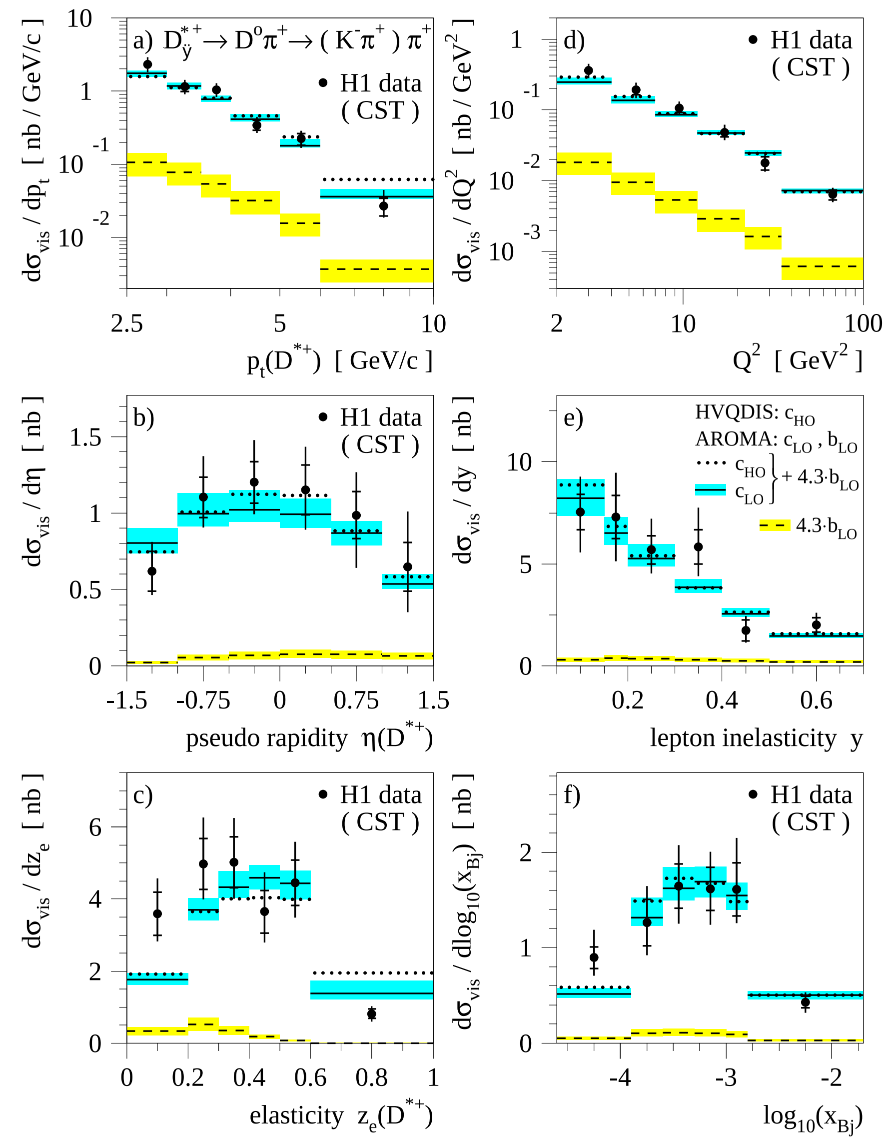
Visible kinematic range:

- $2 < Q^2 < 100$ GeV^2 ;
- $0.05 < y < 0.7$
- $p_t(D) > 2.5.$ GeV
- $|\eta(D)| < 1.5$

comparison with NLO HVQDIS for charm + scaled beauty (publ.)

(m_c=1.5; ε_{pete}=0.036; $\mu=\sqrt{(Q^2+4m)}$ GRV98)

⇒ good agreement Data ↔ NLO



Production cross sections in DIS: H1 (opt)

Differential cross section: $D^+ \to K\pi\pi$; $D^0 \to K\pi$; $D^* \to (K\pi)\,\pi$; $D_s \to (KK)\pi$

Visible kinematic range: $2 < Q^2 < 100$ GeV^2 ; $0.05 < y < 0.7$

$p_t(D) > 2.5.$ GeV $|\eta(D)| < 1.5$

Cross section	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 prediction σ_{vis}	2.45	5.54	1.15	2.61
error on prediction	±0.30	±0.69	±0.30	±0.31

$\Rightarrow$ reasonable agreement Data $\leftrightarrow$ LO MC within errors

Fragmentation Fractions in DIS : H1 (opt)

Fragmentation fractions (after subtracting b−contribution, and correcting for acceptances) :

$$f(c \to D) = [\sigma_{vis}(ep \to eDX) - \sigma^{MC}_{vis}(ep \to bb \to eDX)] / [\sigma^{MC}_{vis}(ep \to bb \to eDX)/f_{wa}(c \to D)]$$

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	$^{+0.045}_{-0.033}$	$^{+0.117}_{-0.142}$	$^{+0.036}_{-0.035}$	$^{+0.056}_{-0.042}$
theo. error	$^{+0.029}_{-0.021}$	$^{+0.086}_{-0.048}$	$^{+0.050}_{-0.046}$	$^{+0.031}_{-0.022}$
$f_{w.a.}$ = world average	0.232 ± 0.018	0.549 ± 0.026	0.101 ± 0.027	0.235 ± 0.010

$\Rightarrow$ good agreement with world average

Fragmentation Ratios : H1 (opt)

$R = \frac{f^0 - f^+}{2 \cdot f^{*+} \cdot BR}$	1.02	±	0.12			A	[1]
	0.96	±	0.05	±	0.07	D	[2]
	1.28	±	**0.19**	±	**0.12**	**H1**	
$R' = \frac{f^0 - f^+}{f^{*0} - f^{*+} + 2 \cdot f^{*+} \cdot BR}$	1.19	±	0.36			O	[3]
$R^* = \frac{f^{*0}}{f^{*+}}$	0.94	±	0.31			O	[3]
$P_V^d = \frac{f^{*+}}{f^+ + f^{*+} \cdot BR}$	0.595	±	0.045			A	[1]
	0.693	±	**0.045**	±	**0.010**	**H1**	
$P_V^{u+d} = \frac{f^{*0} + f^{*+}}{f^0 + f^+}$	0.57	±	0.05			O	[3]
$P_V^s = \frac{f_s^*}{f_s}$	0.60	±	0.19			A	[1]
$P_V' = \frac{2 \cdot f^{*+}}{f^0 + f^+}$	0.620	±	0.014	±	0.029	D	[2]
	0.613	±	**0.061**	±	**0.034**	**H1**	
$P_V^\dagger = \frac{f^{*+}}{f^0 - f^{*+} \cdot BR}$	0.546	±	0.045	±	0.028	ZEUS	[4]
	0.549	±	**0.083**	±	**0.056**	**H1**	
$\gamma_s = \frac{2 \cdot f_s}{f^0 + f^+}$	0.31	±	0.07			ADO	[5]
	0.36	±	**0.10**	±	**0.08**	**H1**	
$\gamma_s^\dagger$	0.27	±	0.04	±	0.07	ZEUS	[6]

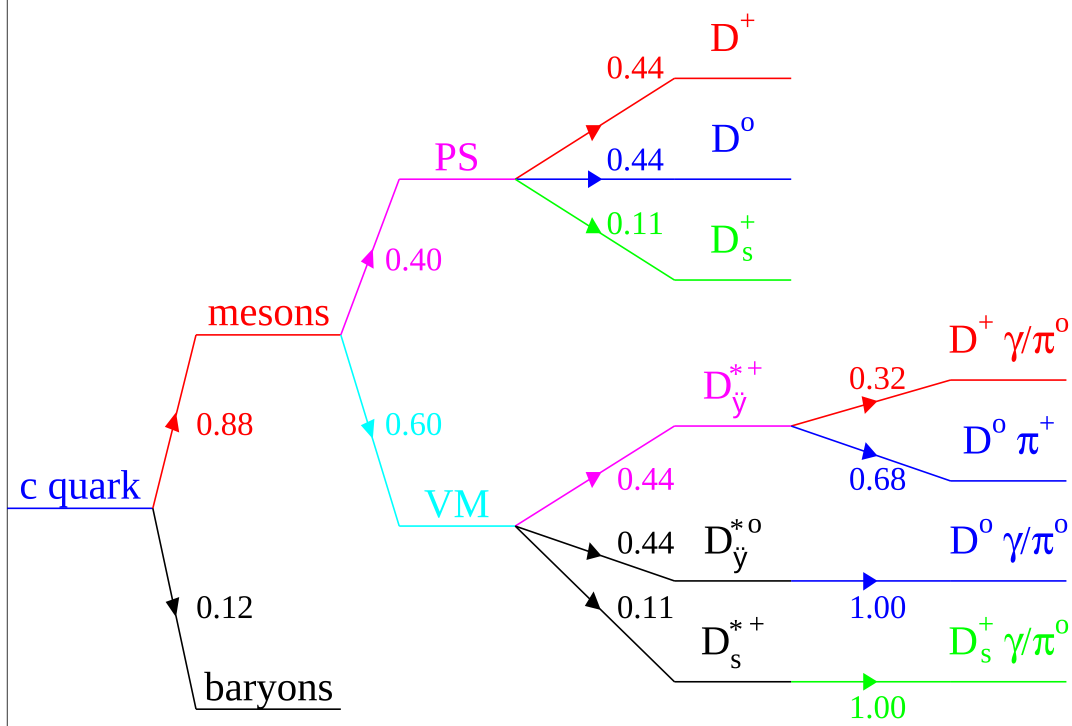
$f^x = f(c \rightarrow D^x)$

$BR = BR(D^* \rightarrow D^o \pi)$

compare with Aleph, Opal, Delphi, Zeus

=> HERA <-> LEP agree within errors

D−meson properties (opt)



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

Dijets angular distribution : ZEUS (opt)

θ^* = <(jet−jet axis, beam axis)$_{\text{dijet-RF}}$; $\cos\Theta \approx \tanh((\eta^{jet1} - \eta^{jet2})/2)$

is sensitive to propagator type (gluon/quark)

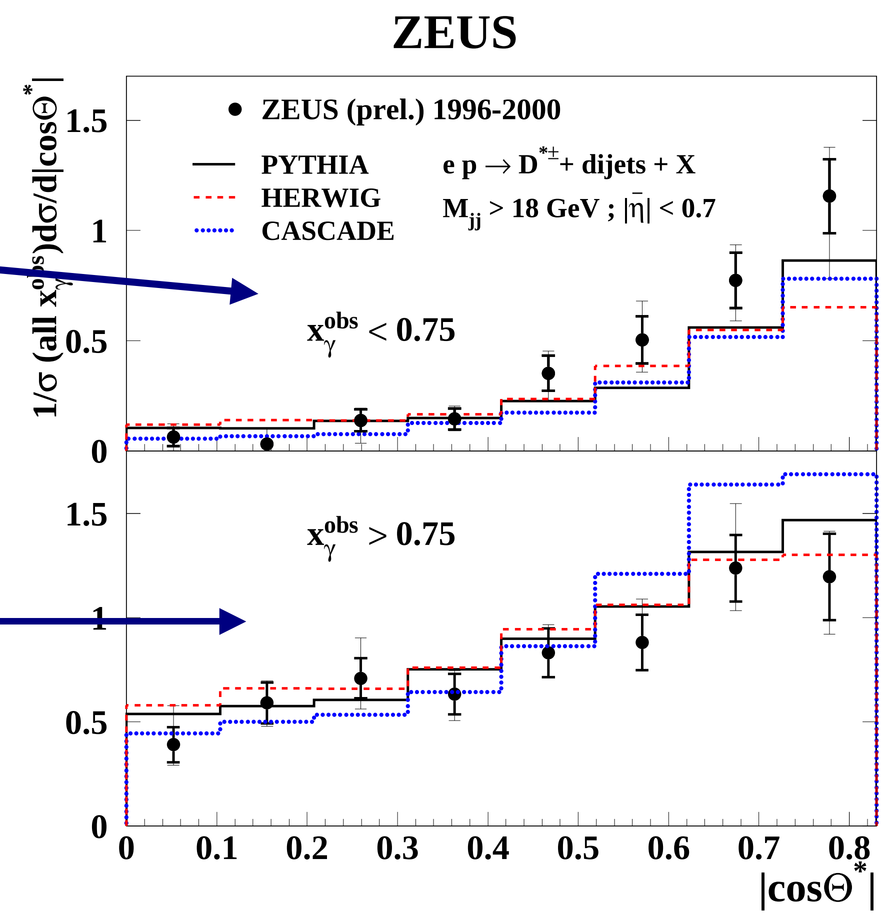
- resolved contribution (LO) dominated by gluon exchange:

  => stronger rise at large |cos(θ*) |

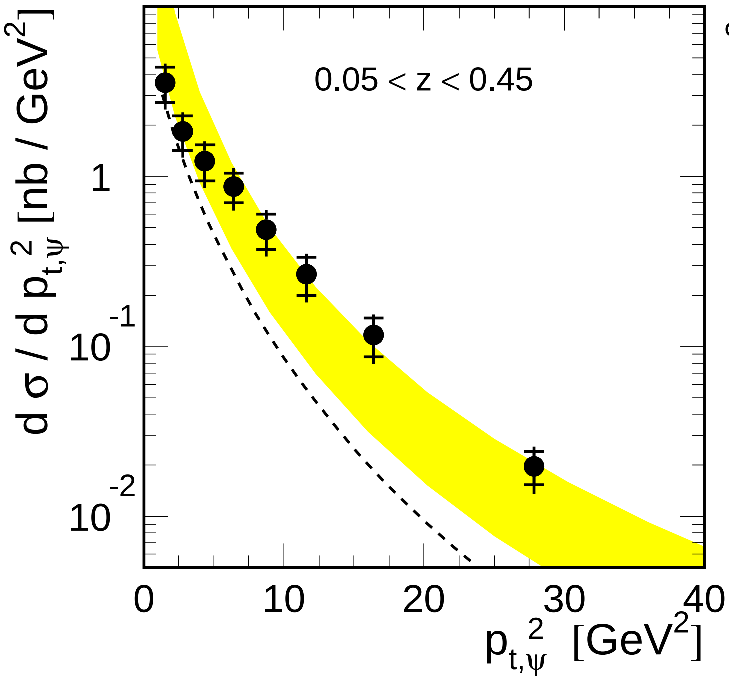
- direct contribution (LO) dominated by quark exchange:

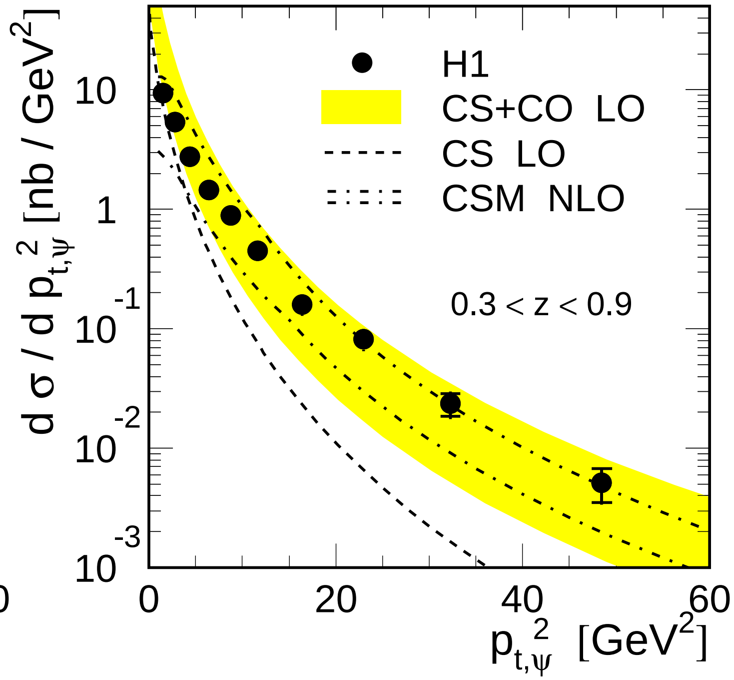
  => milder rise at large |cos(θ*) |

- signature of gluon exchange



J/ψ Photoproduction : H1 (opt)



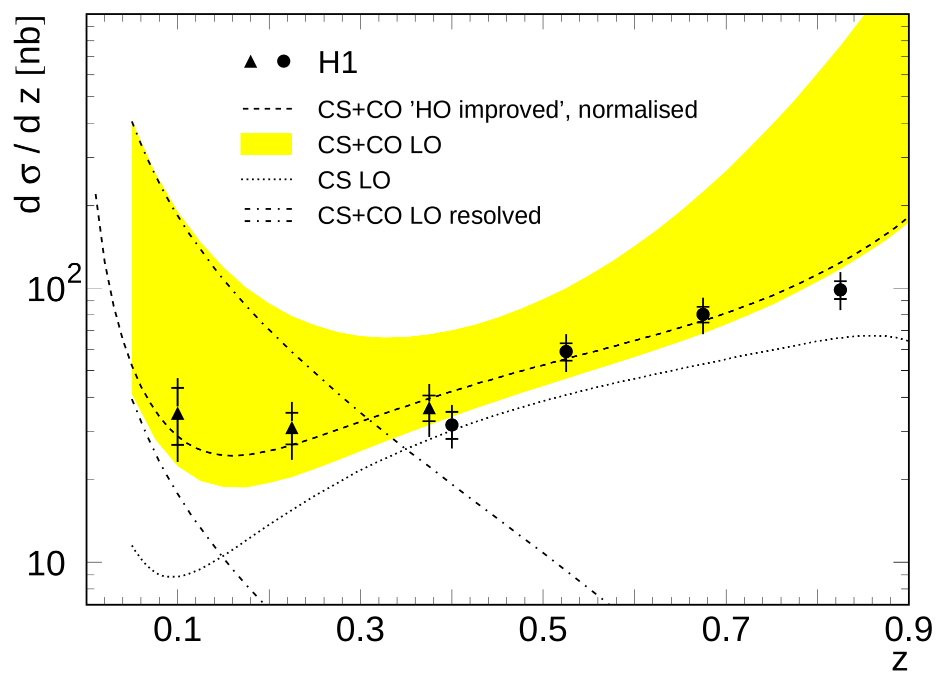


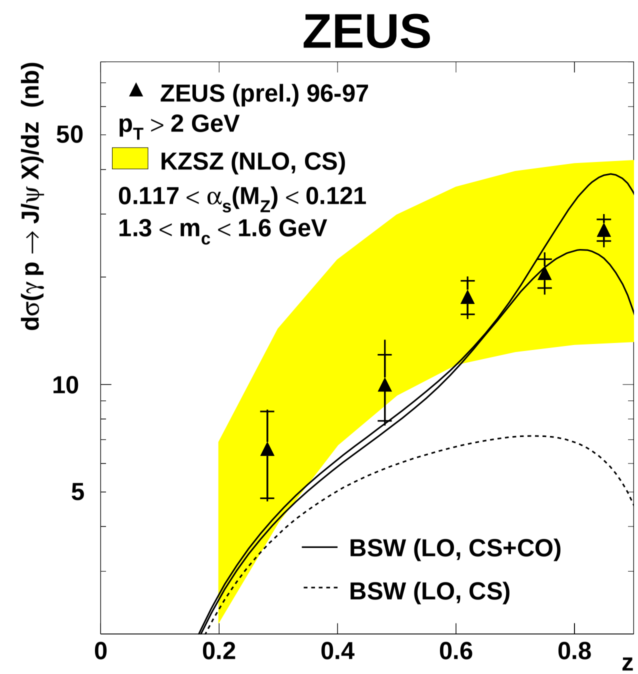
- $p^2_{t,\psi}$ dependence similar at low z and medium z $z = E^*_\psi / E^*_\gamma |_{p-\text{rest frame}}$
- CS (LO) contribution alone is too steep
- CS+CO (LO) shows tendency to fall too steeply

  note: beauty contribution is not subtracted in data (at large $p^2_{t,\psi}$)

- CSM NLO describes $p^2_{t,\psi}$ distribution pretty well (Kraemer)

J/ψ Photoproduction (opt)





$z = E^*_{\psi} / E^*_{\gamma} \;|_{p-\text{rest frame}}$

- powerful new data down to low z
- large theoretical uncertainties
- Improved calculations at HO describe shape, but not norm (Kniehl+Kramer)
- fair description in z−range by CS+CO LO with small LDME (Kraemer+Cacciari)
- Add CO + resummation of soft contrib. (shape f) help (BSW:Beneke,Schuler,Wolf)
- CSM NLO (direct only) describes data well within errors (KZSZ= Kraemer ...)