

Heavy Quark Physics at HERA

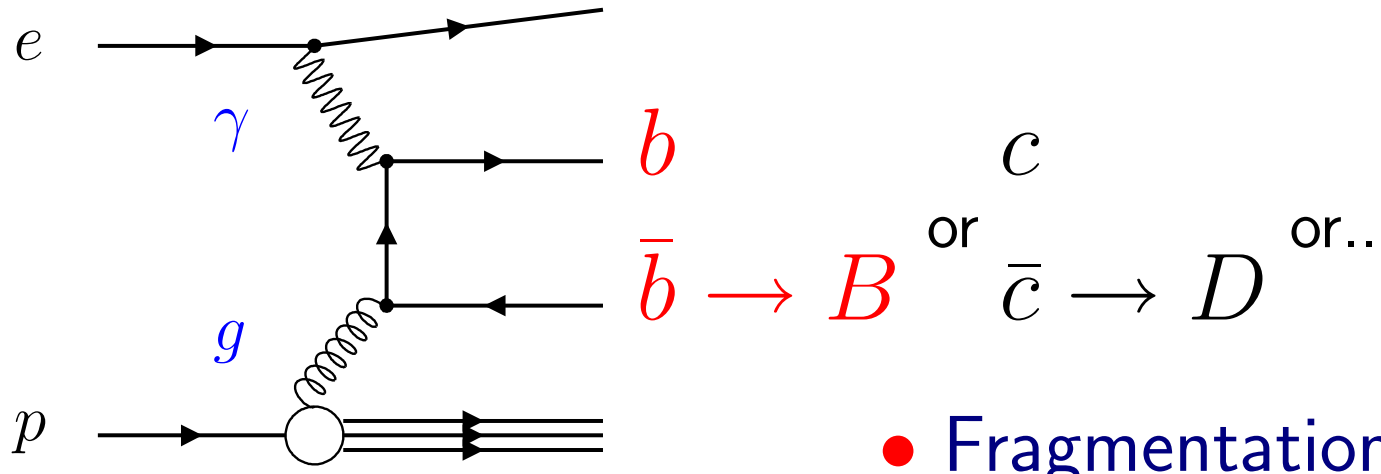
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Probing QCD with Charm and Beauty

Heavy quark production in ep collisions

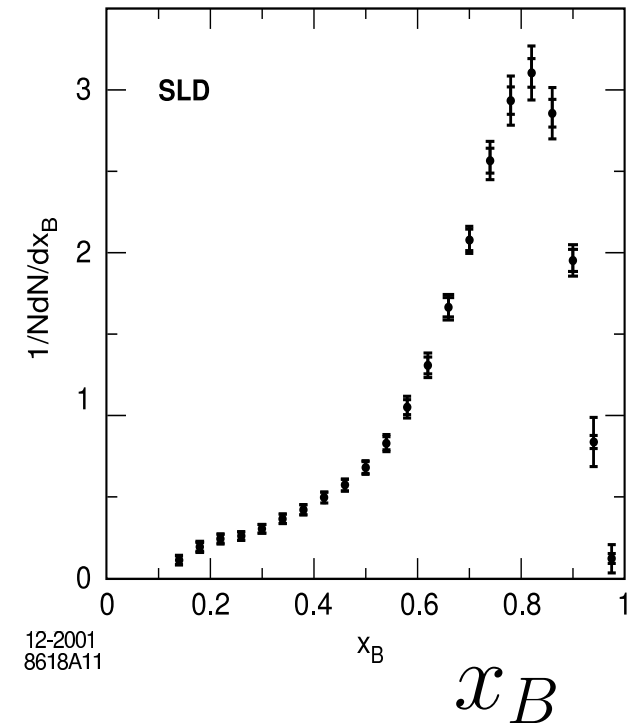
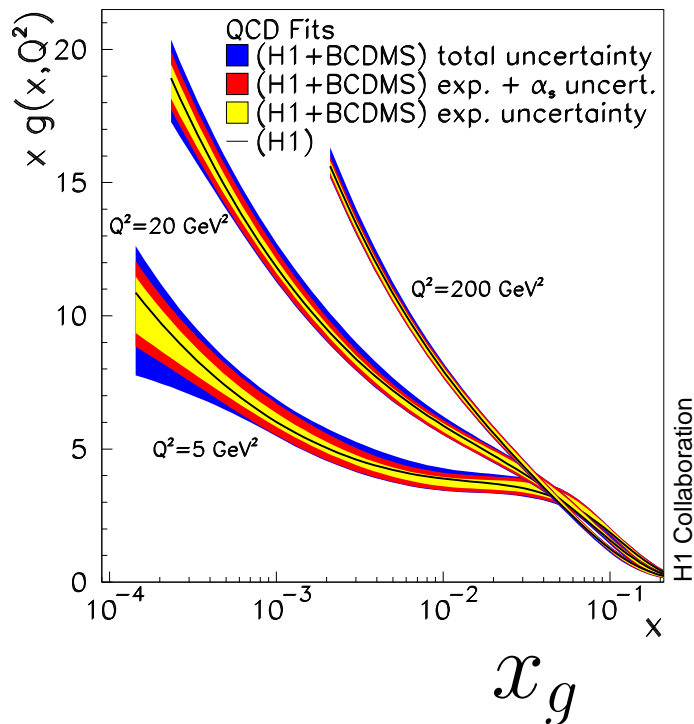
Factorization:



• Proton structure

• Fragmentation

• Hard QCD

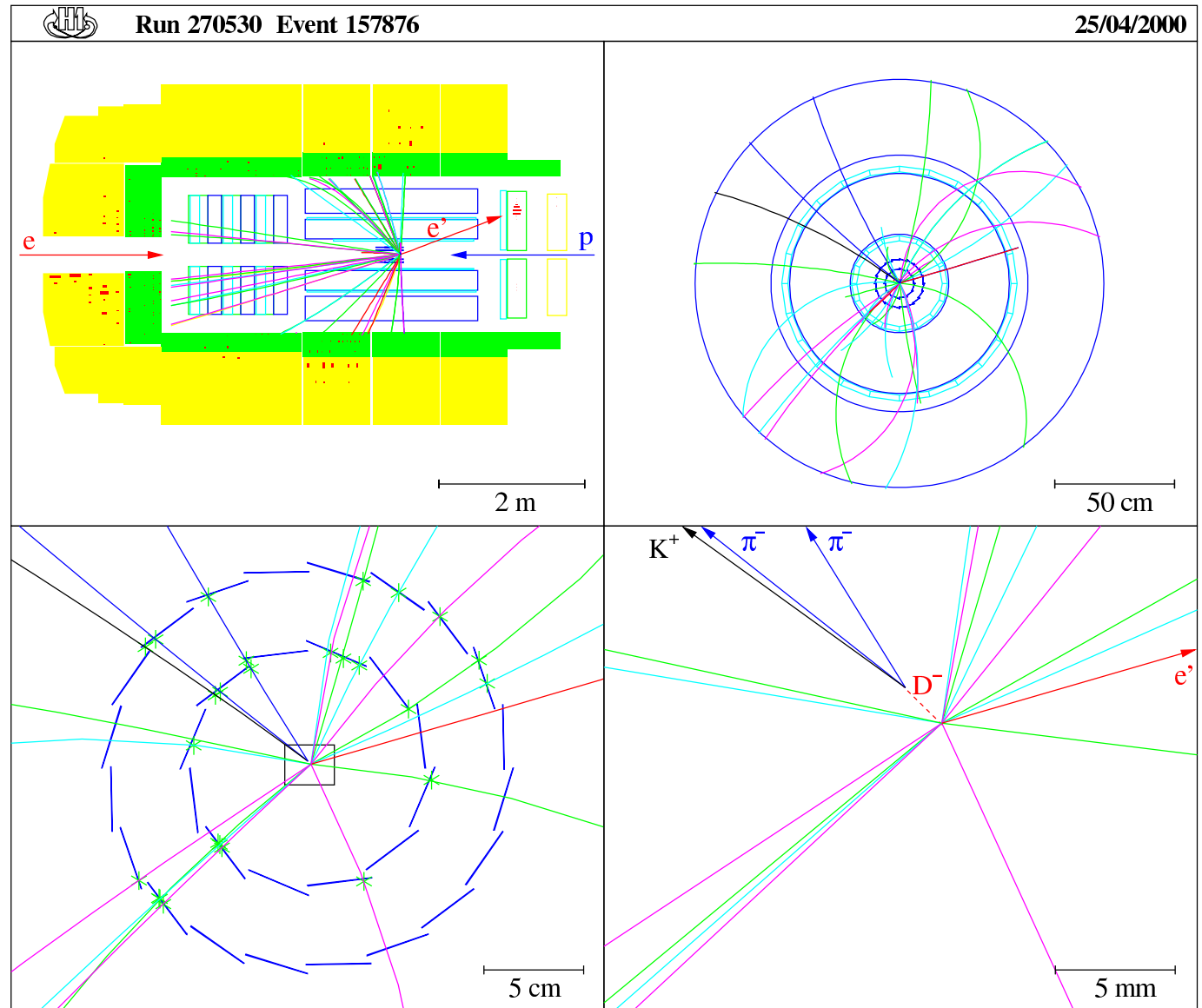


Outline of this talk:

- Open charm fragmentation,
Charmonium ($c\bar{c}$) production
- Charm and proton structure
- Beauty and charm hard production dynamics

Open charm: secondary vertex tagging

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



D^+ , D^0 , D_s^+ , D^{*+} production ratios

- D^+ signal before and after decay length cuts \rightarrow

- Isospin ratio $R_{u/d}$

$$1.28 \pm 0.19 \pm 0.12 \quad \text{H1}$$

$$1.02 \pm 0.12 \quad \text{ALEPH}$$

$$0.96 \pm 0.05 \pm 0.07 \quad \text{DELPHI}$$

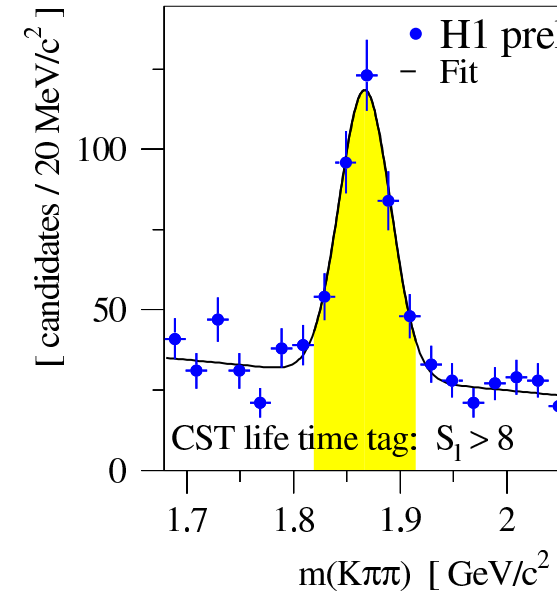
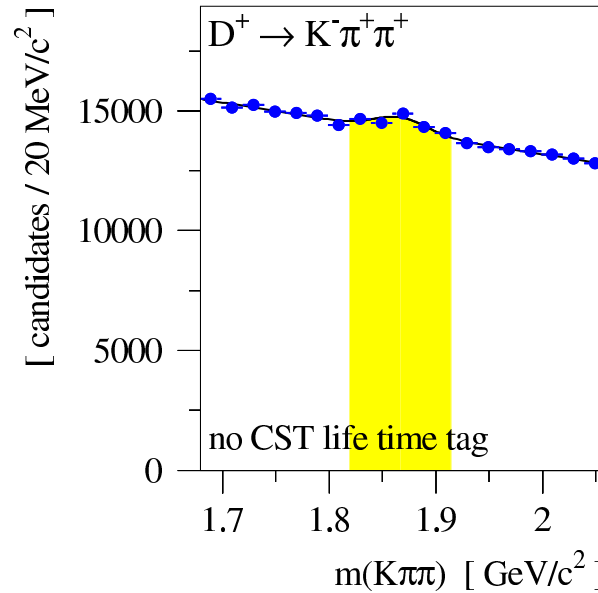
- Vector : (Pseudoscalar + V) P_{Vd}

$$0.693 \pm 0.045 \pm 0.013 \quad \text{H1}$$

$$0.546 \pm 0.045 \pm 0.028 \quad \text{ZEUS}$$

$$0.595 \pm 0.045 \quad \text{ALEPH}$$

$$0.57 \pm 0.05 \pm 0.07 \quad \text{OPAL}$$



- Strangeness suppression γ_s

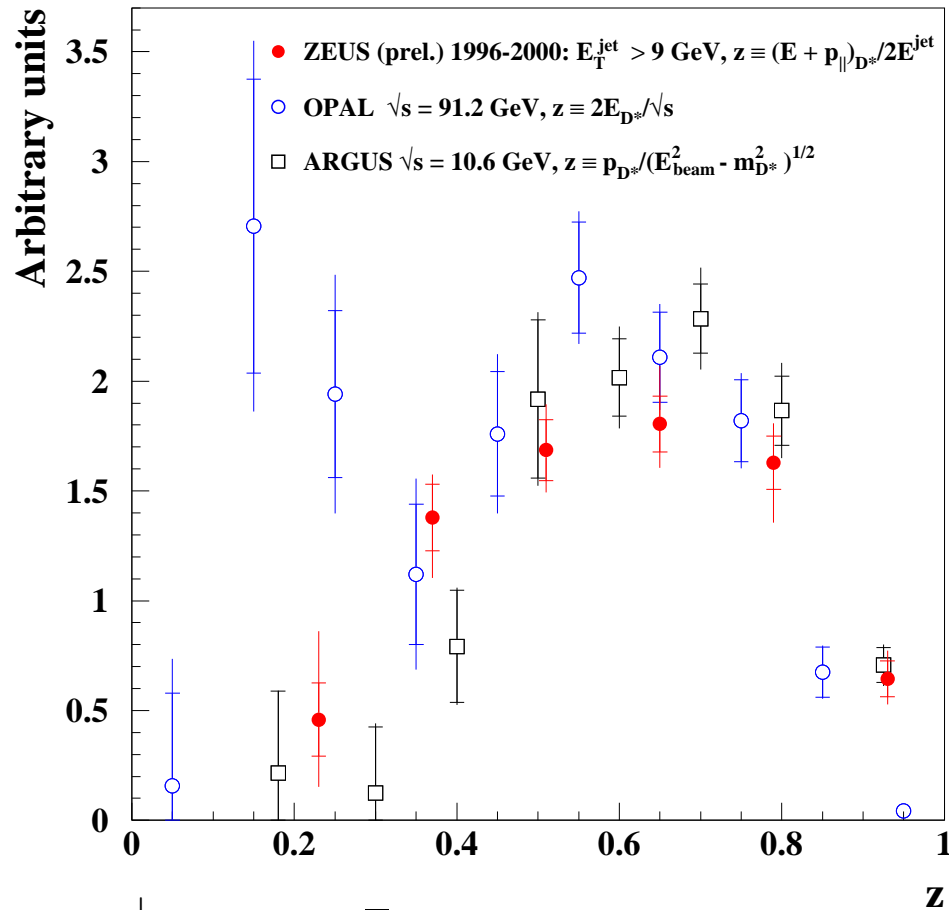
$$0.36 \pm 0.10 \pm 0.008 \quad \text{H1 } D_s$$

$$0.27 \pm 0.05 \quad \text{ZEUS } D_s$$

$$0.31 \pm 0.07 \quad \text{ADO}$$

\rightarrow ep agrees with e^+e^-

$c \rightarrow D^{*+}$ fragmentation function



- similar accuracy, similar shape

- Fit LO parton shower MC with Peterson fragmentation function:

$$\epsilon_c = 0.064 \pm 0.006 \begin{matrix} +0.011 \\ -0.008 \end{matrix}$$

- compares well with leading log analyses of ARGUS and OPAL data (e.g. Nason *et al*)

- $e^+e^- \rightarrow c\bar{c}$:

$$z = E_D/E_{\text{beam}}, p/p_{\text{max}}$$

- $ep \rightarrow cX$:

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

Fragmentation:

- Fractions of ground state (and excited) D meson species and
- the first fragmentation function measurement in ep collisions

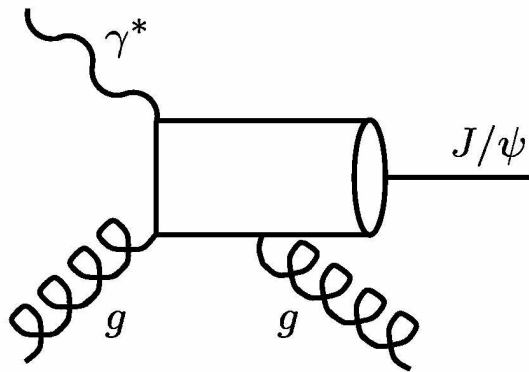
support universality of the heavy quark to hadron transition.

J/Ψ production

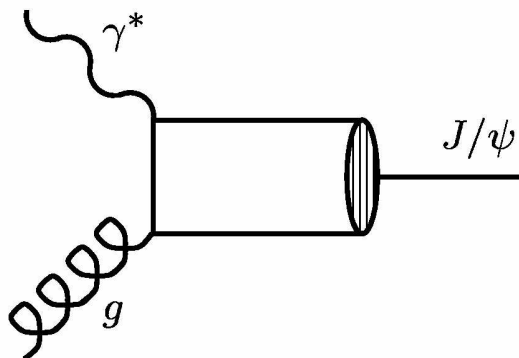
J/Ψ is colorless

- Color singlet model

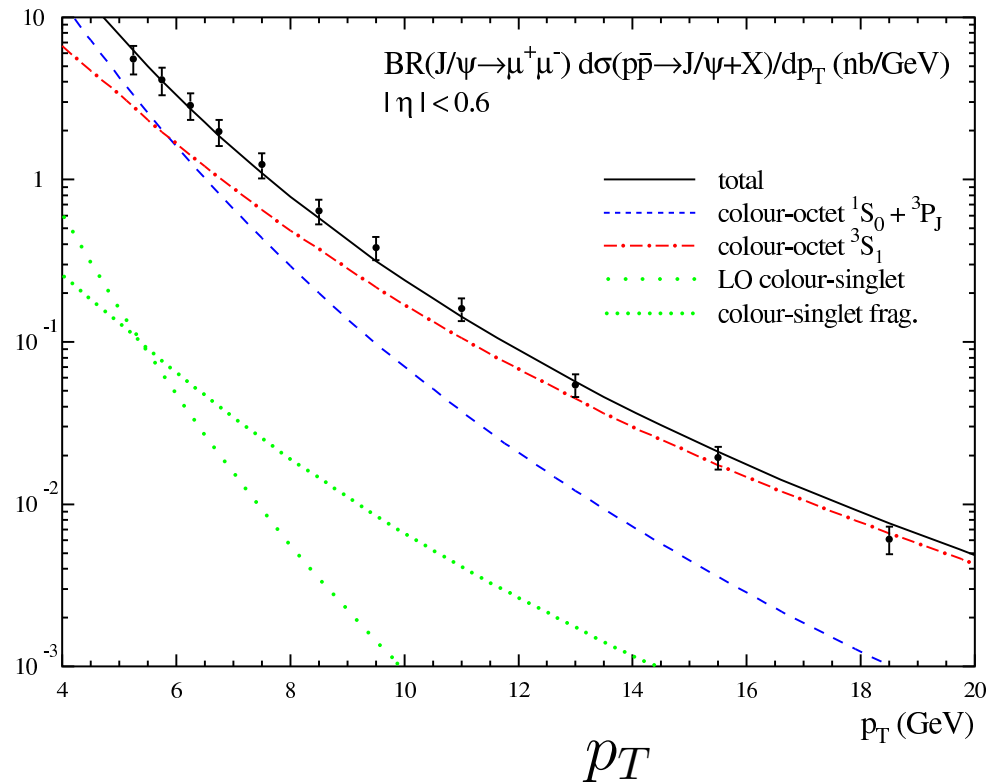
hard process \rightarrow [1]



- NRQCD: Color octet states
soft [8] \rightarrow [1] transition

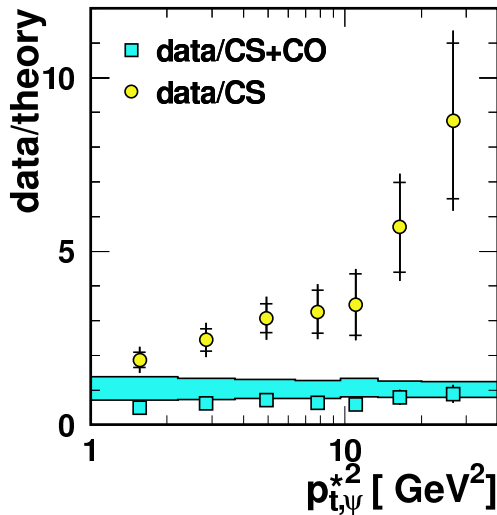
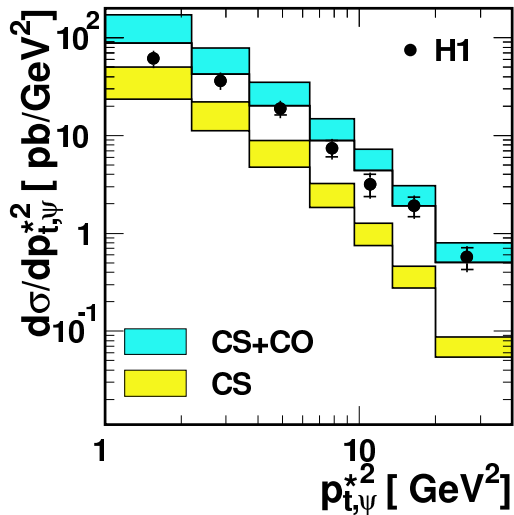
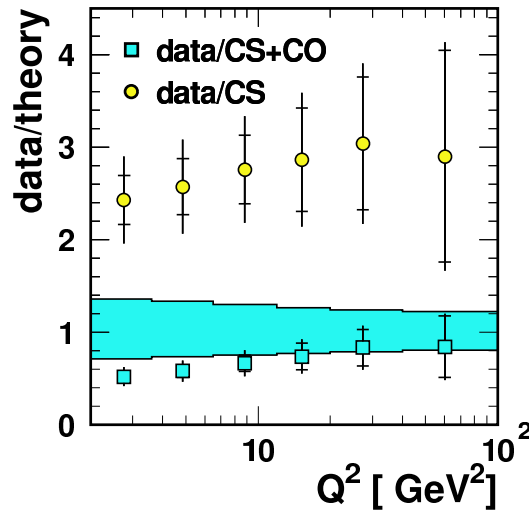
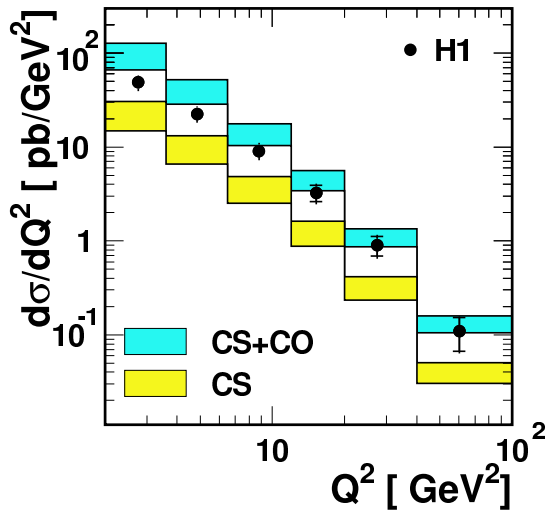


- CO long distance matrix elements from fit of LO QCD to $p\bar{p}$ data

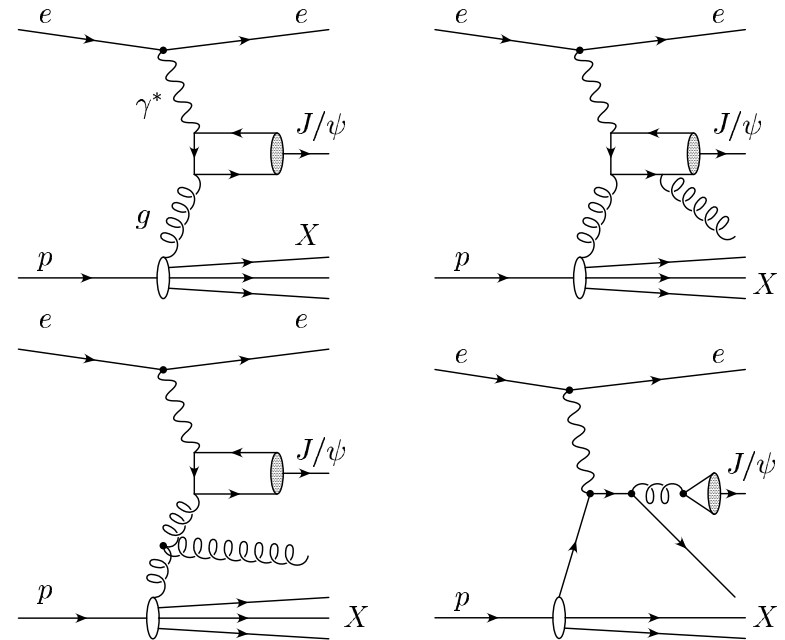


- non-perturbative, phenomenological, but **universal**

J/ψ in Deep Inelastic Scattering



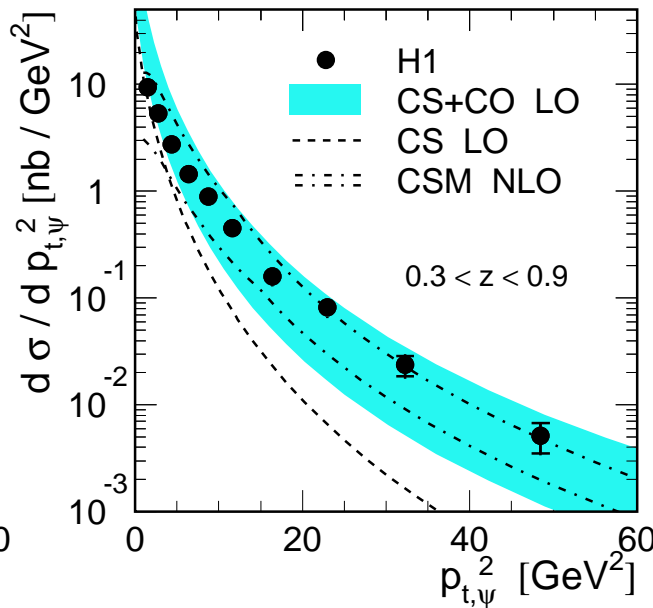
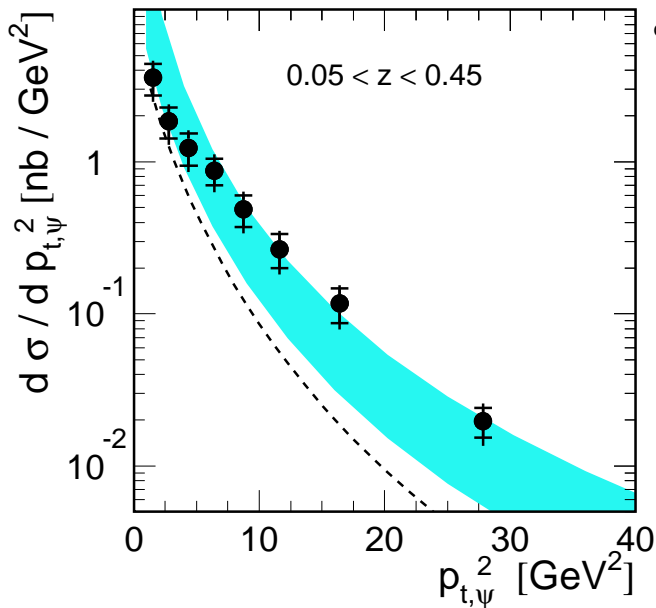
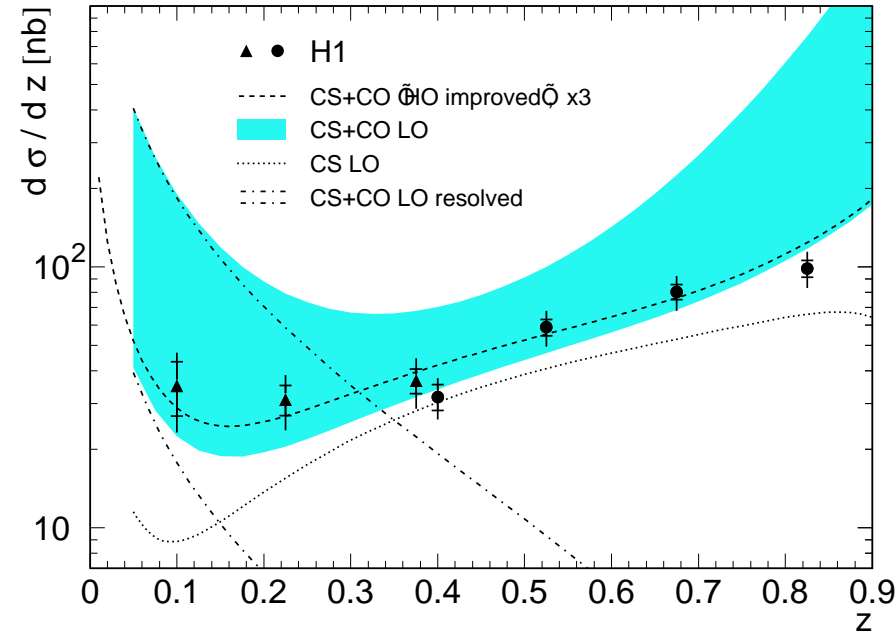
- include $2 \rightarrow 2$ processes (part of NLO)



- two scales to vary:
 p_T and Q^2 (γ virtuality)

J/Ψ photoproduction

- limit $Q^2 \rightarrow 0$: photoproduction
- resolved photon contributions:
 $q\bar{q}$ fluctuation, hadronic interaction;
 CO important
- mostly at low $z = \frac{E_\Psi}{E_\gamma}$ (in p CMS)



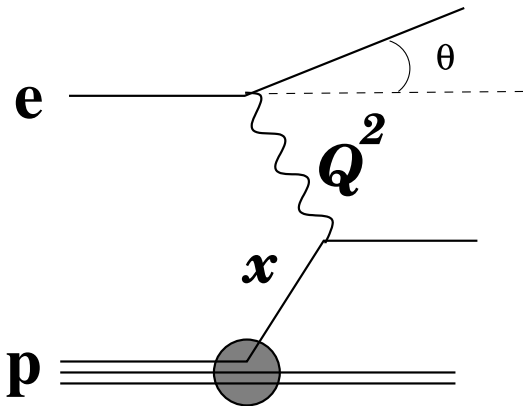
- for direct γ process (medium z region)
 full **NLO** ($O(\alpha_s^3)$),
 colour singlet only
- doing well
 – without octet

Charmonium production:

- NRQCD including color octet contributions provides a reasonable description of J/Ψ production in $\bar{p}p$, ep , γp (and $\gamma\gamma$) collisions
 - but with large theoretical uncertainties
- NLO corrections are important
 - and may change the picture

Proton structure

- Quark Parton Model



Q^2 : 4-momentum transfer

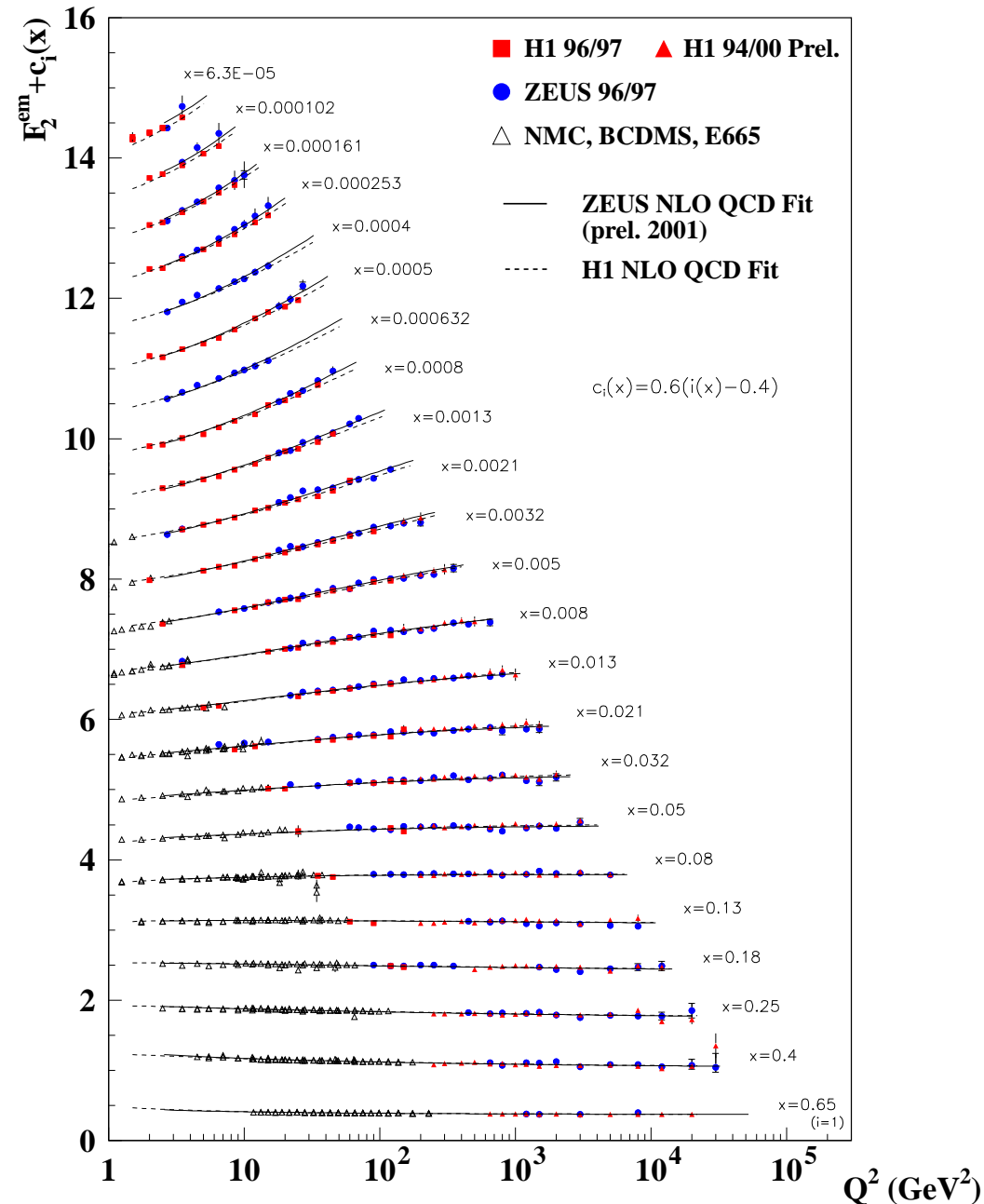
x_{Bj} : momentum fraction of struck quark

- structure function F_2

$$\frac{d^2\sigma}{dx dQ^2} \approx \left(\frac{d^2\sigma}{dx dQ^2} \right)_{point} \cdot F_2(x, Q^2)$$

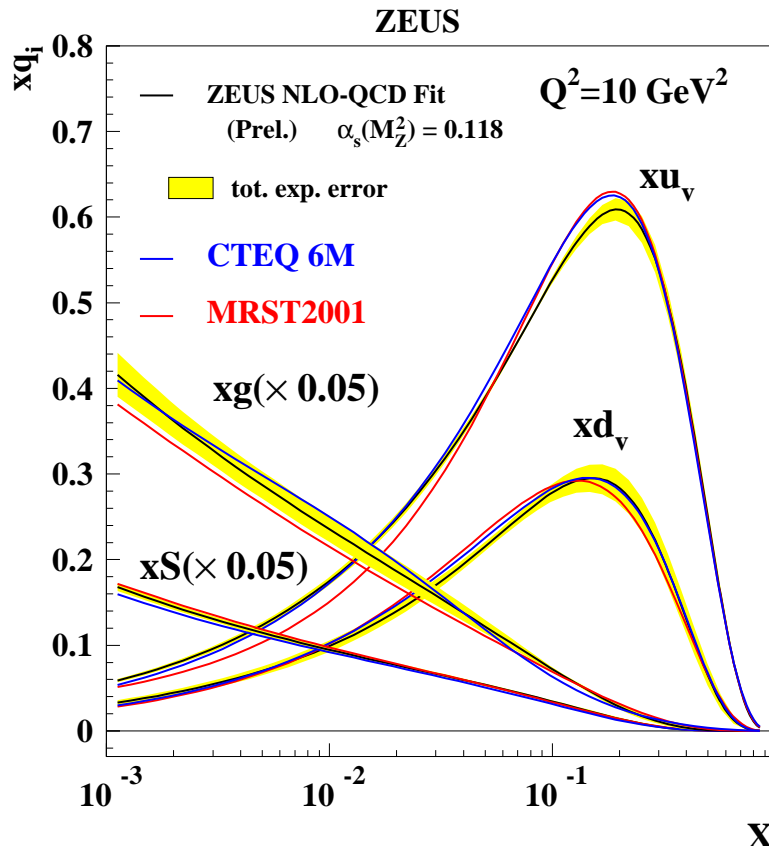
$$F_2(x, Q^2) = \sum_i e_i^2 q_i(x, Q^2)$$

- scaling violations: gluons



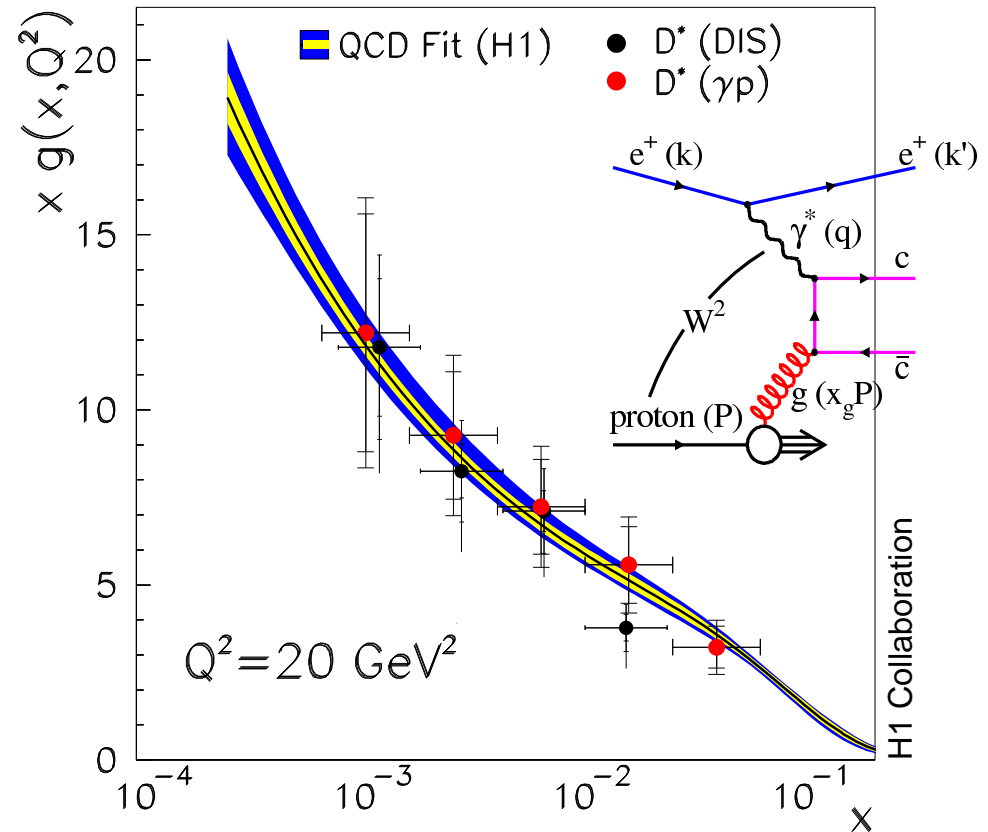
Parton distributions

- From Altarelli Parisi NLO QCD fit to scaling violations



- gluon density high: charm contrib. to DIS large: $\sim 25\%$

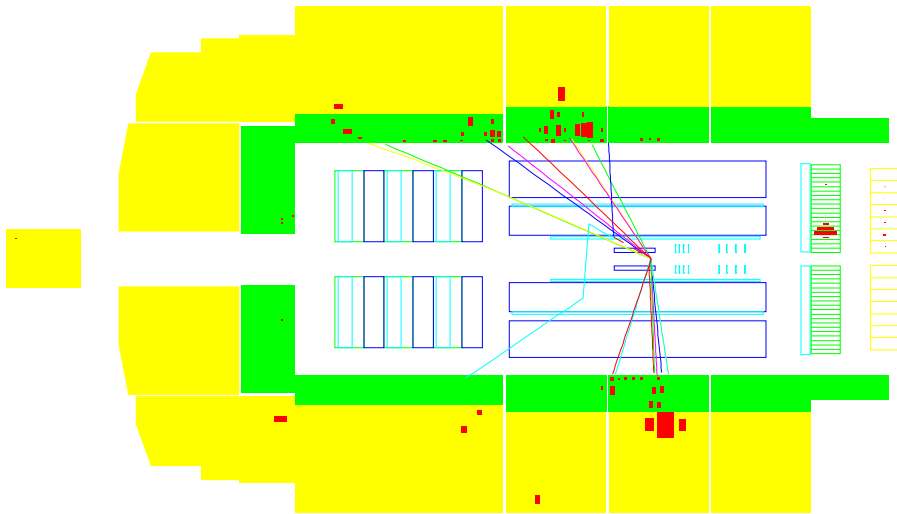
- Verify factorization with charm production: $\gamma g \rightarrow c\bar{c}$



- NB: not shown here: with higher precision some imperfections show up

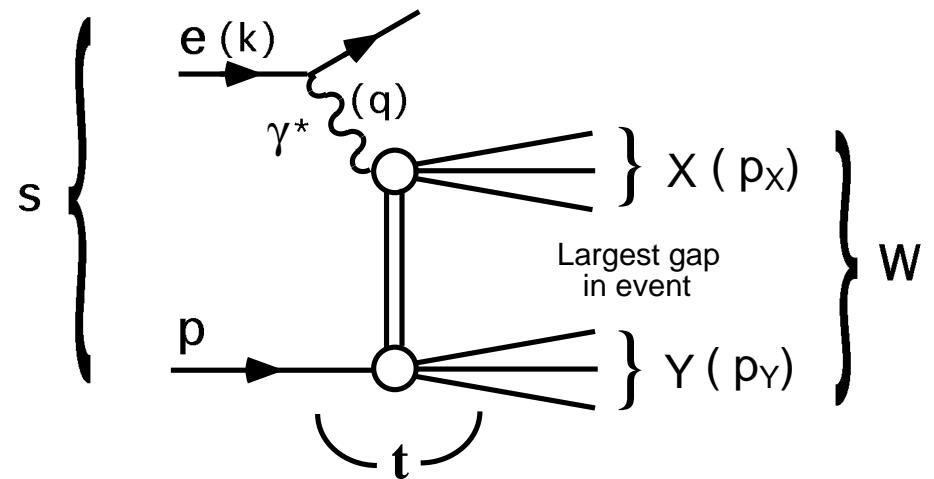
Hard diffractive scattering

- Rapidity gap events



- proton stays intact: hadronic interaction, confinement
- jets: partonic interaction, perturbative QCD

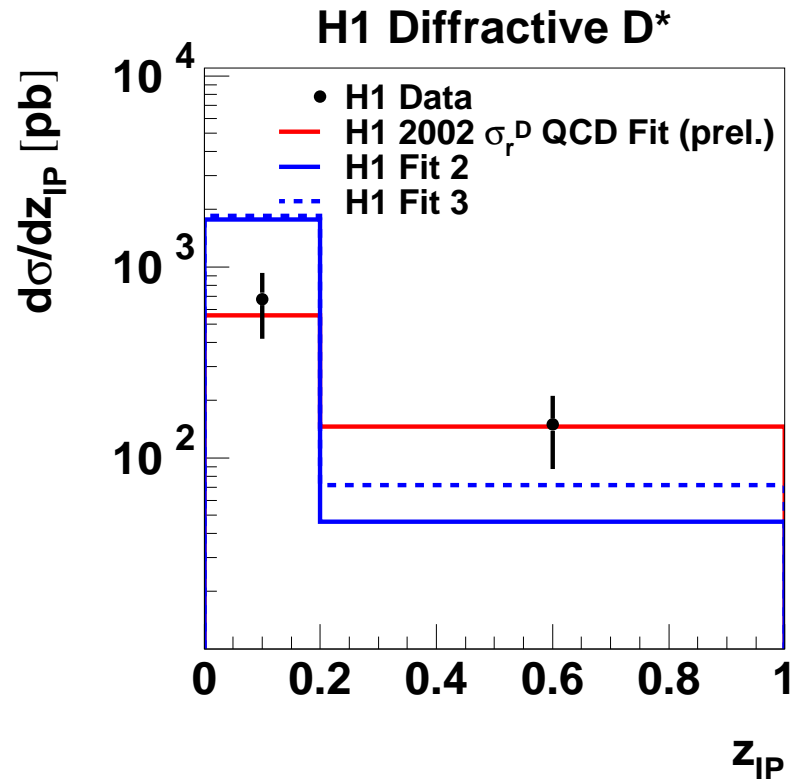
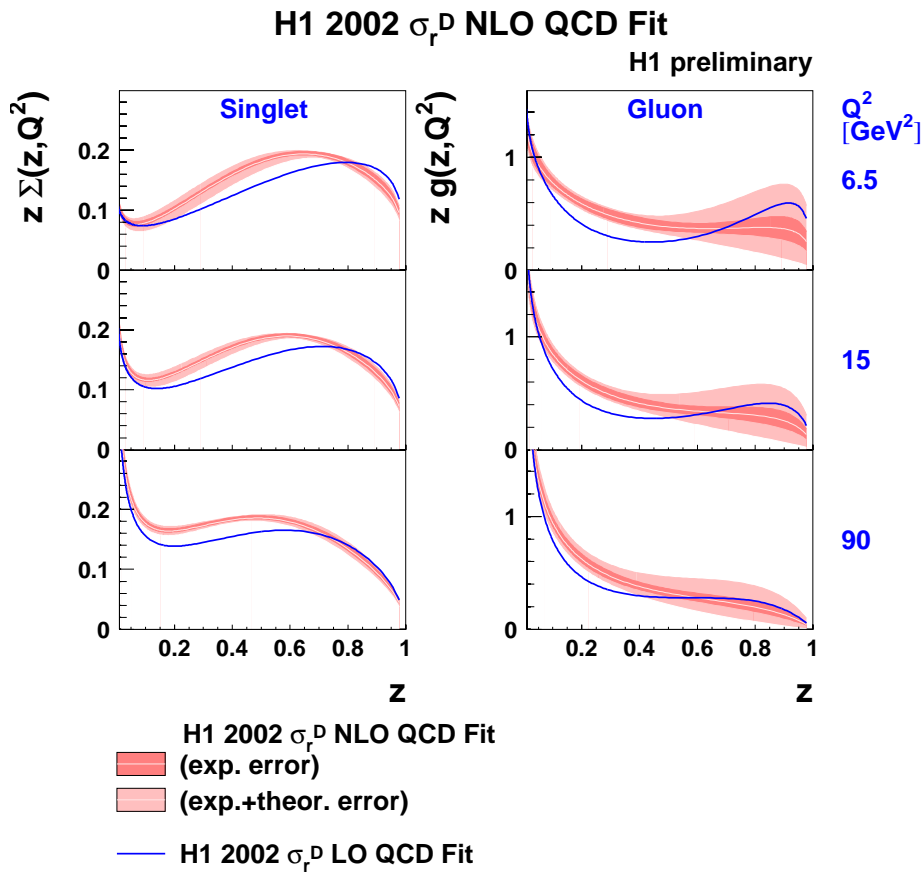
- colorless exchange: diffraction



- factorizable: diffractive structure functions and pdf's

Diffraction pdf's and charm

- QCD analysis as in inclusive case
- predict diffract. charm prod. using **new** diffractive pdf's



- $\sim 75\%$ gluons in diffractive exchange

Challenges ahead:

- link to ordinary partons
- apply to diffraction in $\bar{p}p$

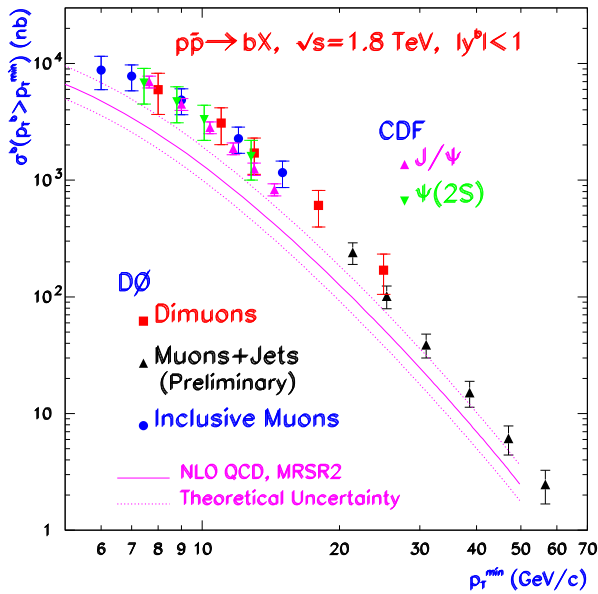
Proton structure and charm:

- Charm contribution to inclusive DIS is large and important to understand the proton
- Charm is directly sensitive to gluons

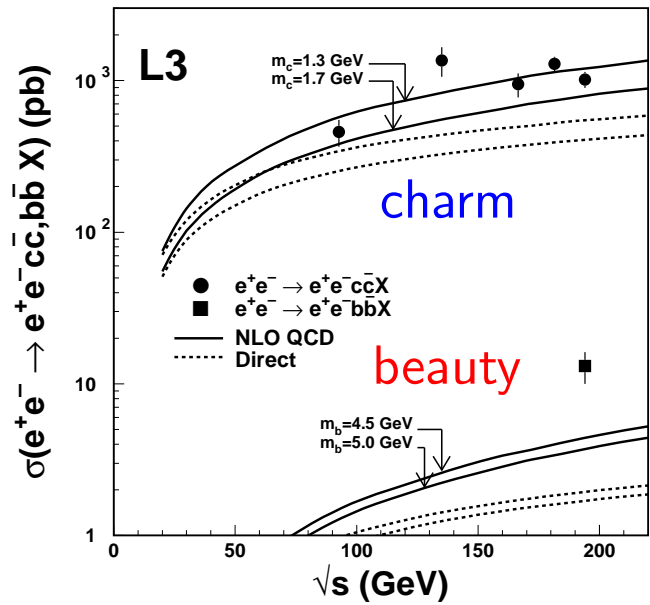
HERA results support factorization
in deep inelastic scattering
(and in hard diffraction).

Beauty cross sections, elsewhere

- Tevatron $\bar{p}p$



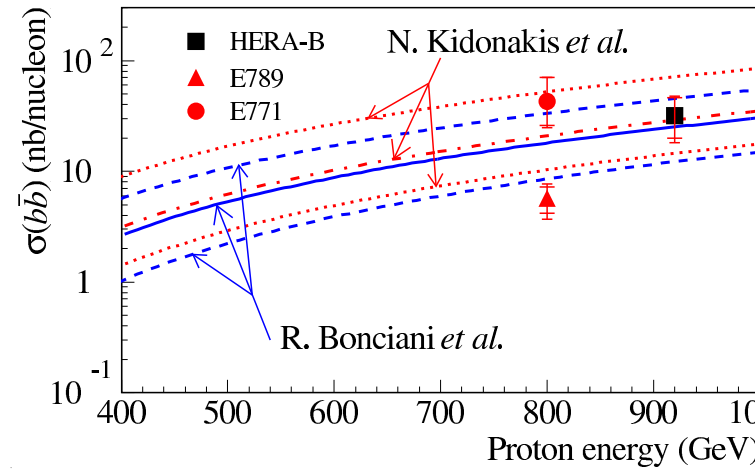
- LEP $\gamma\gamma$



- pN

New: HERA-B

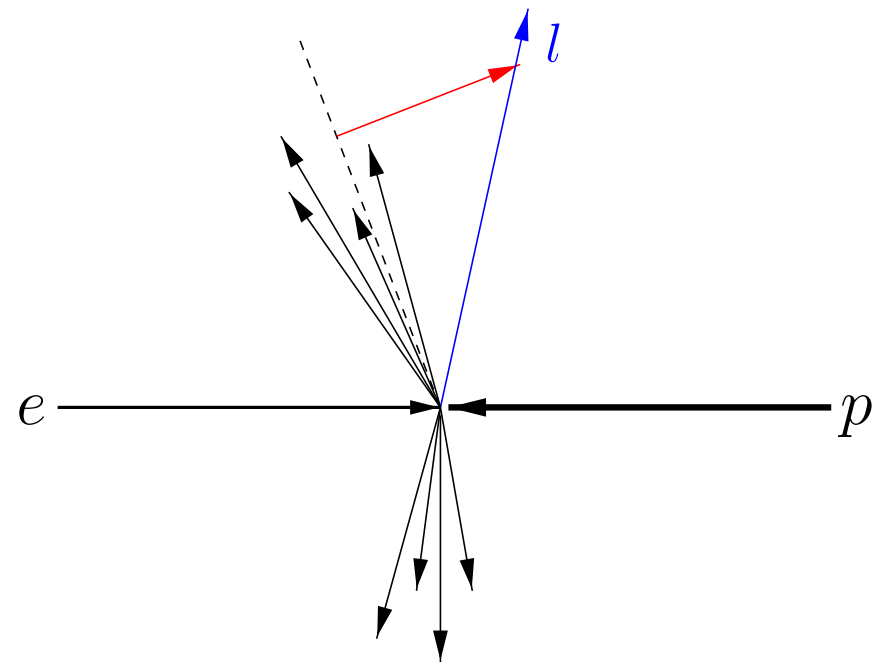
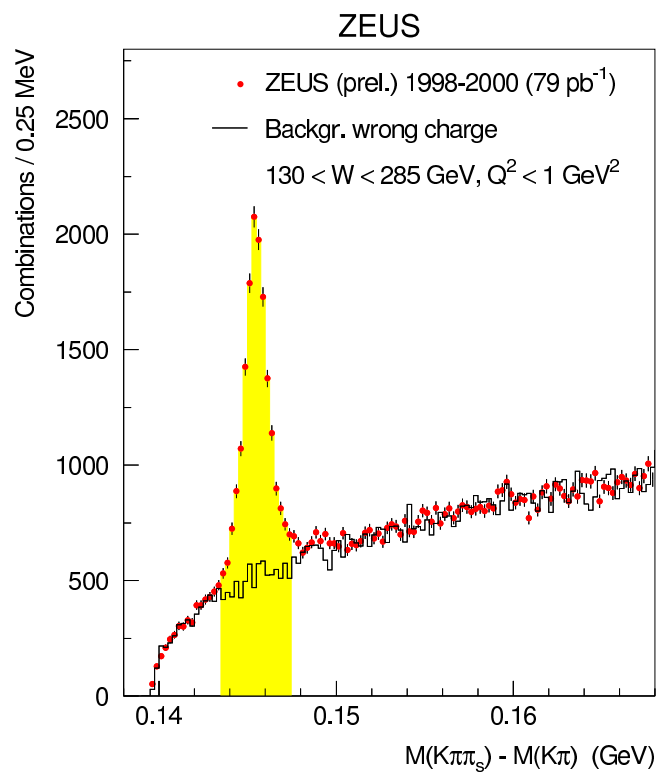
vertex-tagged $b \rightarrow J/\psi$
from 2000 run



- ep : cleanest case

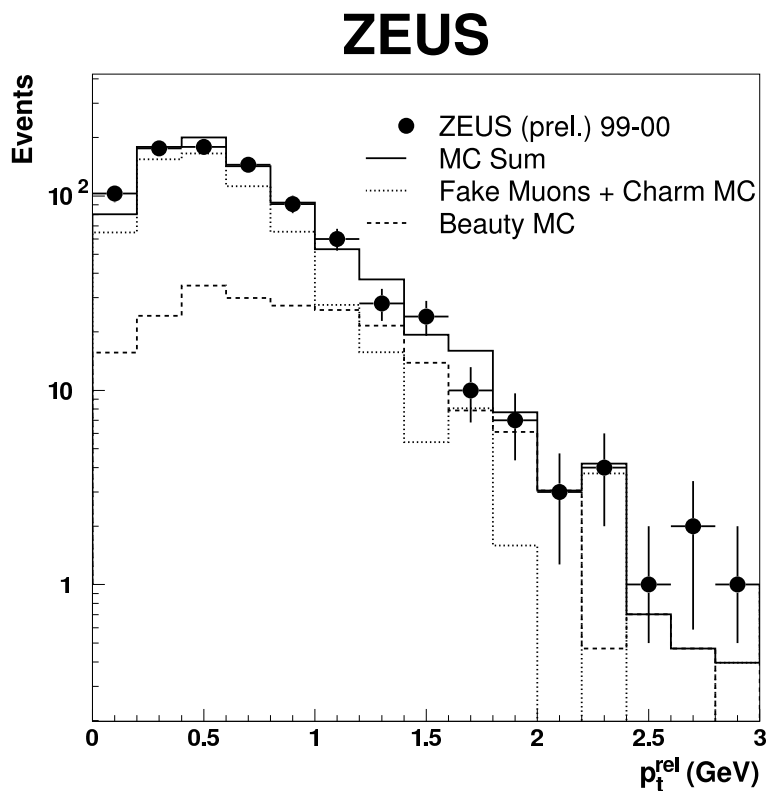
Hard QCD studies with charm and beauty

- beauty : charm : uds $\approx 1 : 100 : 1000$
- photoproduction dominates
- steeply falling p_T
- charm: $D^{*+} \rightarrow D^0 \pi^+$
- beauty: semileptonic decays



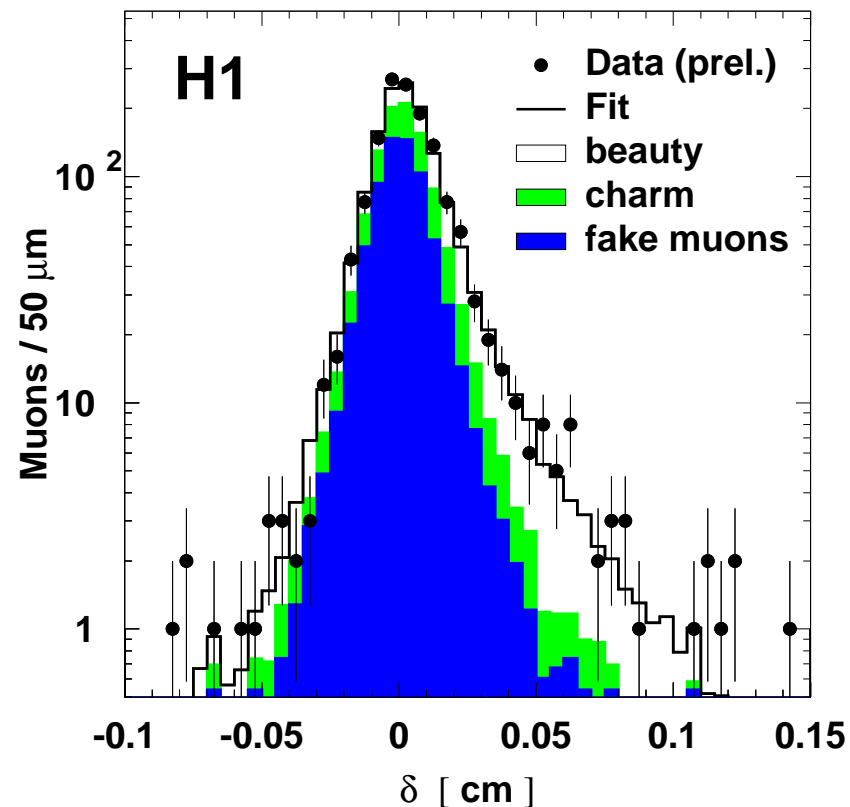
Beauty signatures

- p_T relative to jet axis



example: ZEUS DIS data

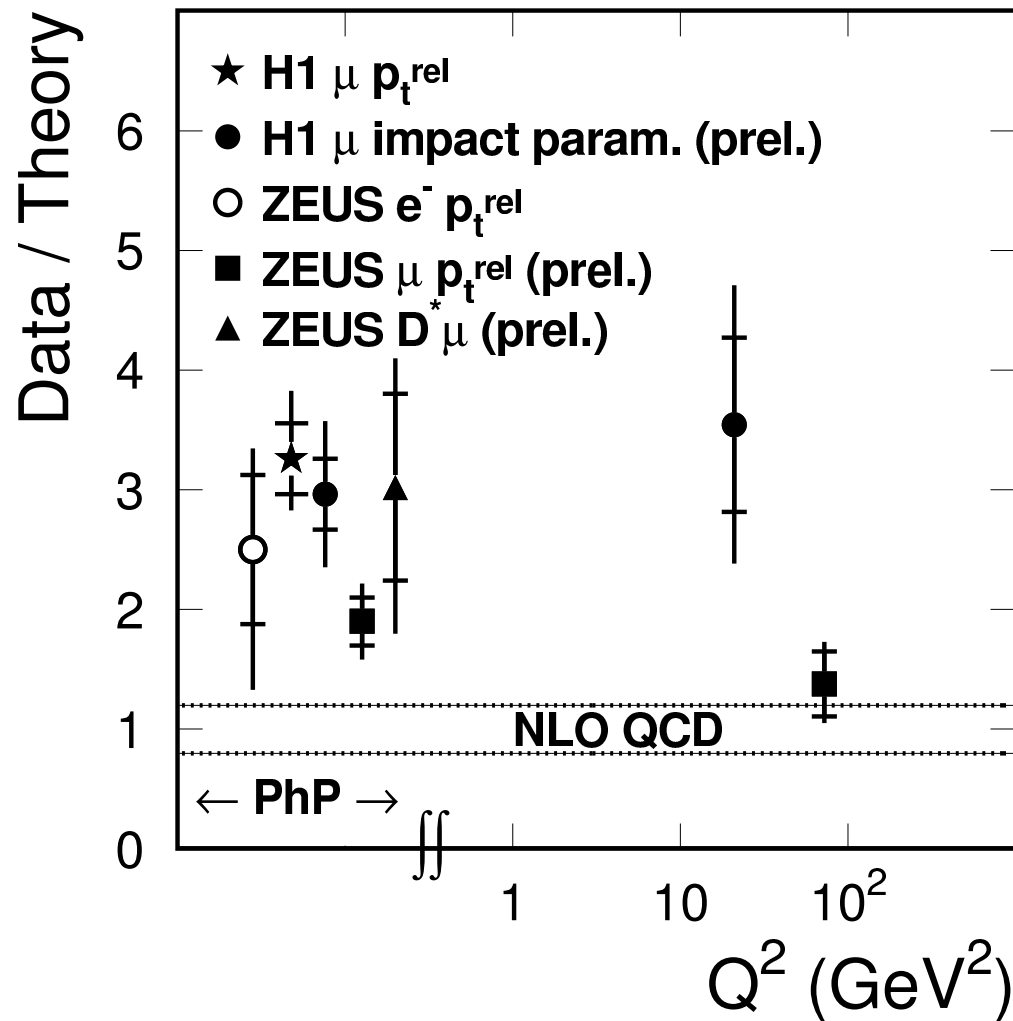
- lepton impact parameter



example: H1 photoproduction data

Beauty cross section at HERA

b cross section at HERA



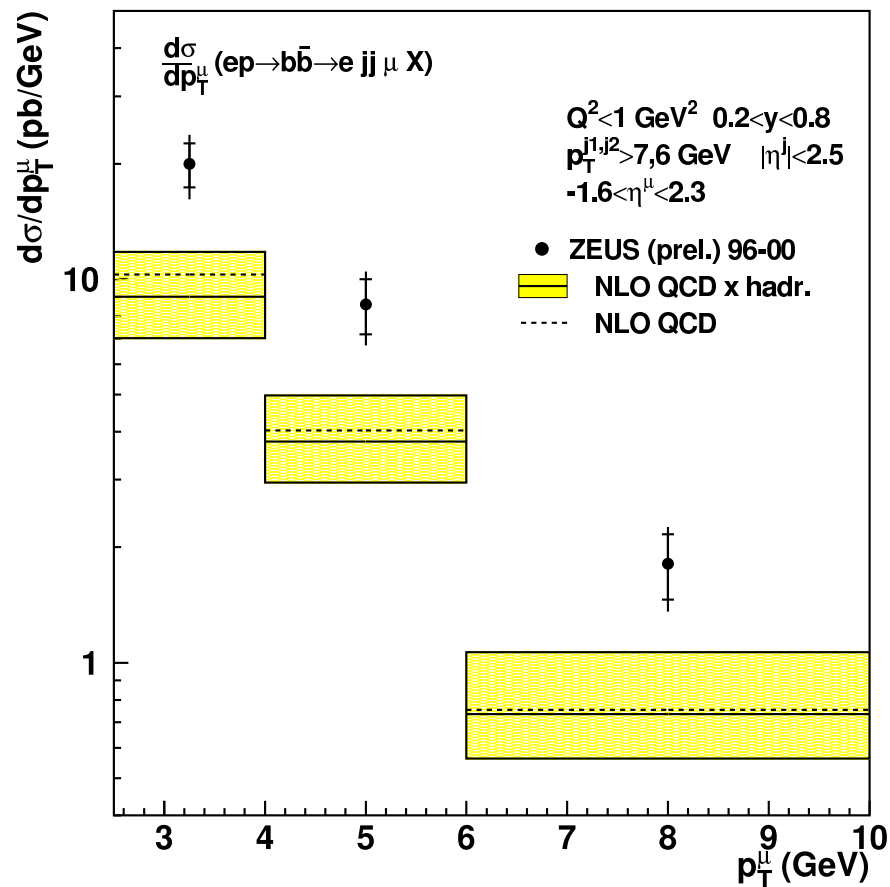
- new results 2002
- in general above NLO QCD
- situation in DIS needs more data

Beauty spectra

New results – no striking disagreement in shapes

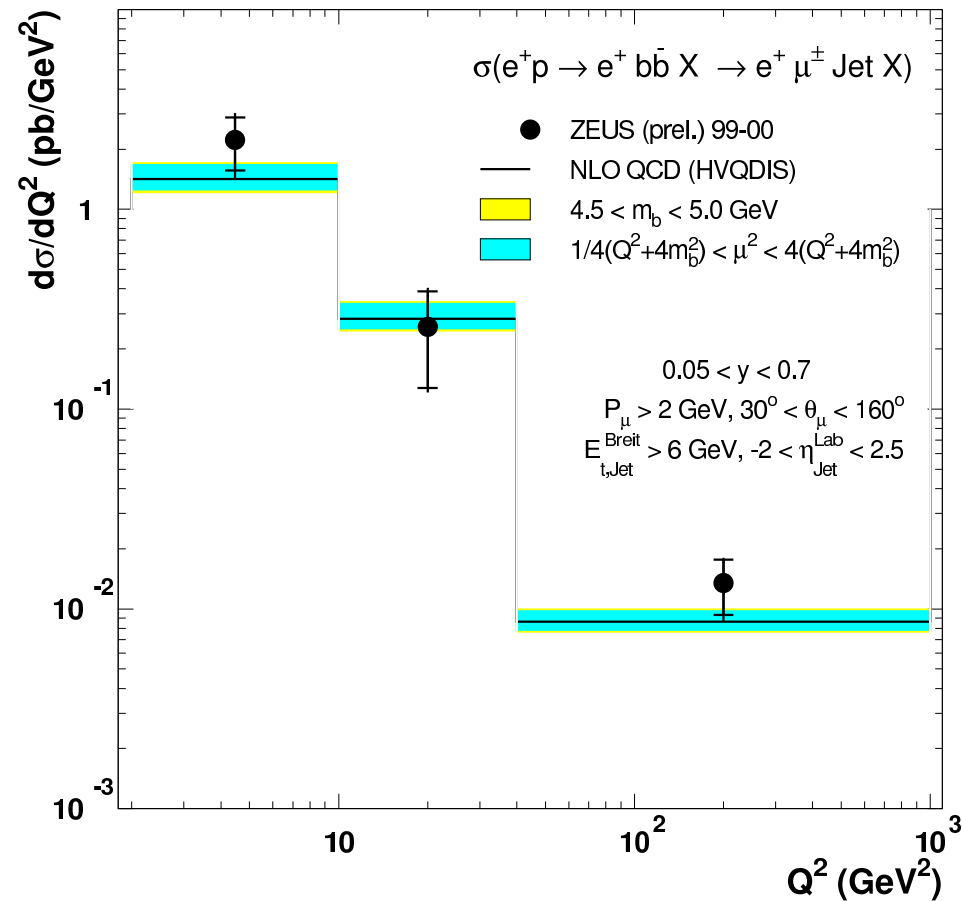
- in photoproduction

ZEUS



- in DIS

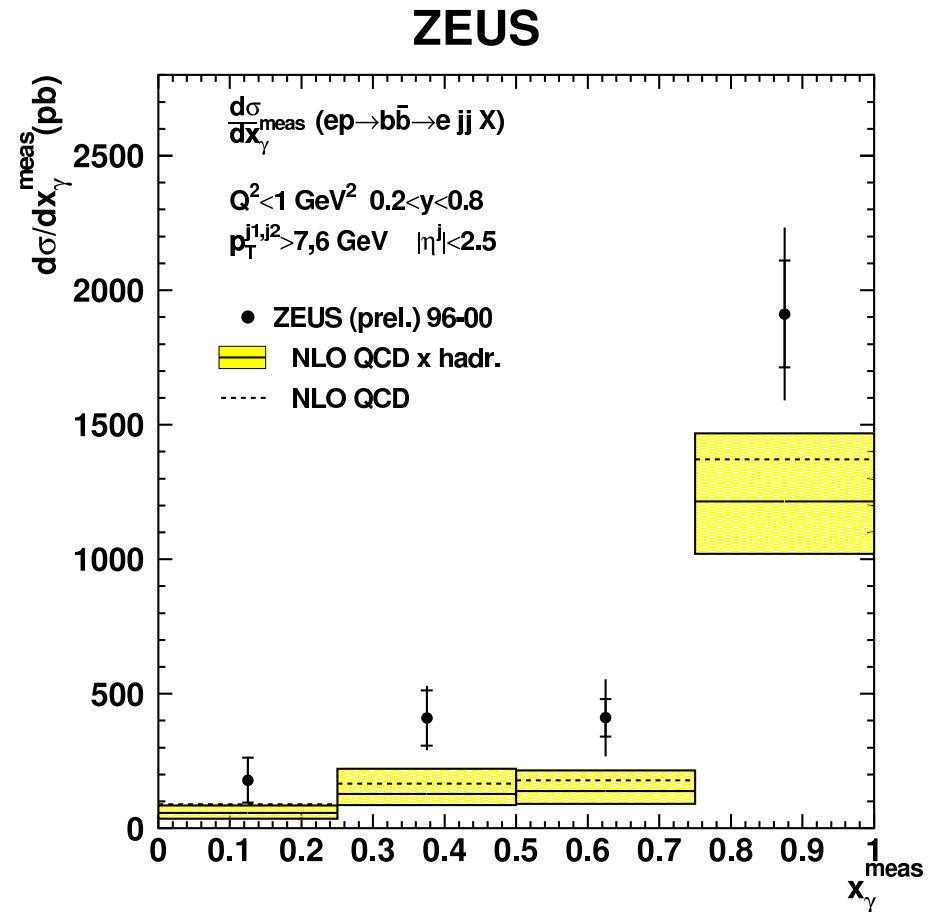
ZEUS



Direct and resolved photoproduction

← resolved → ← direct →

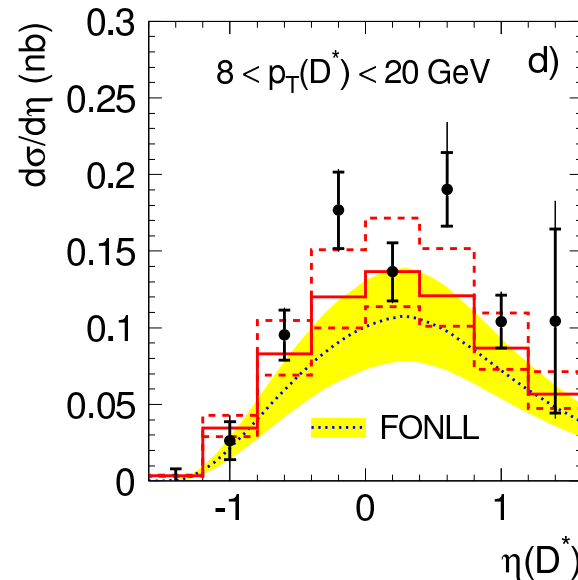
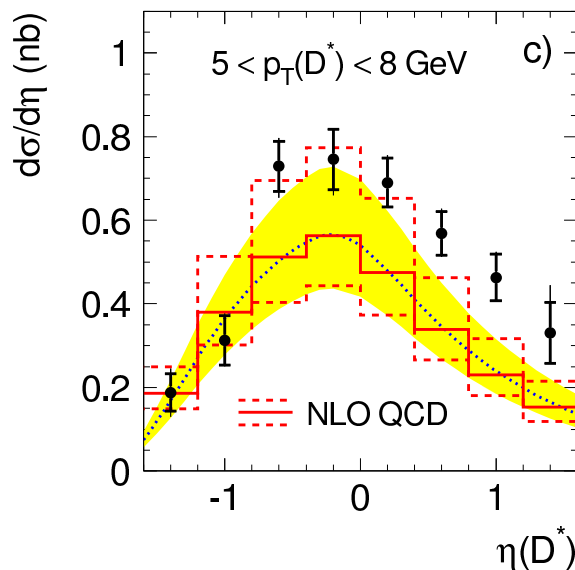
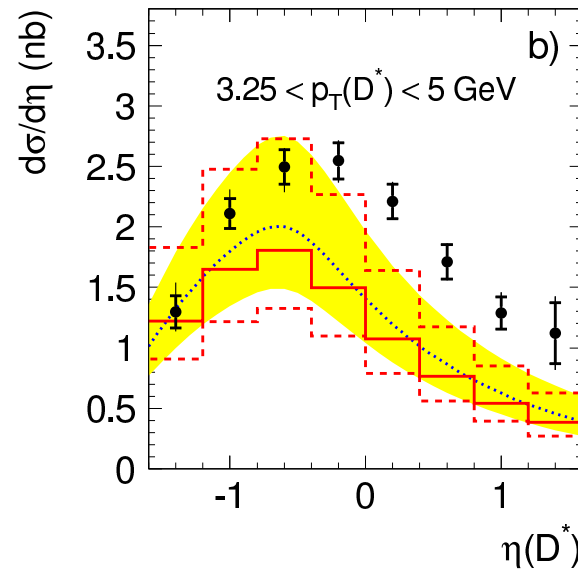
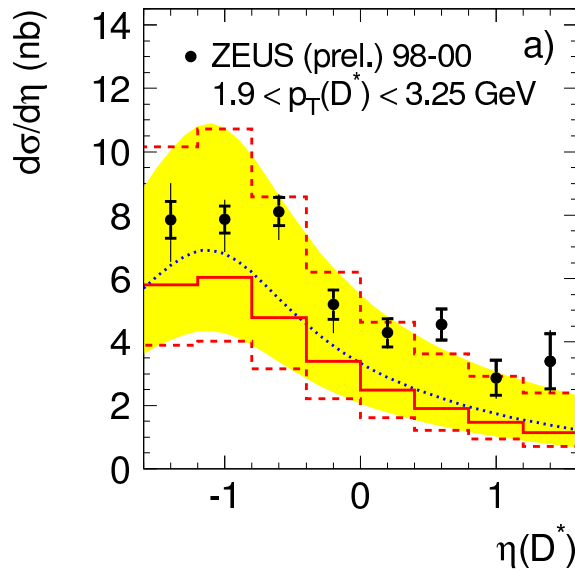
- in dijet events: reconstruct momentum fraction x_γ of parton entering from the photon side



- similar behavior seen earlier for charm

$D^{*\pm}$ photoproduction

ZEUS



- new, precise data, improved theory
- not everywhere compatible, some excess

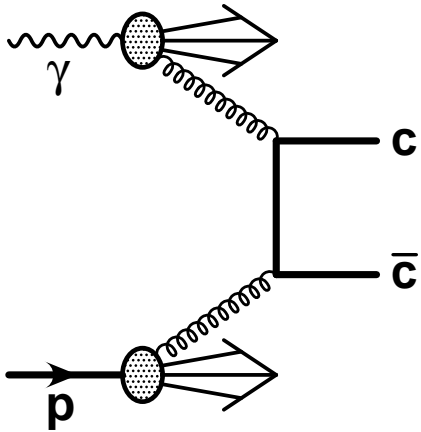
QCD calculations

(Frixione, Nason *et al*):

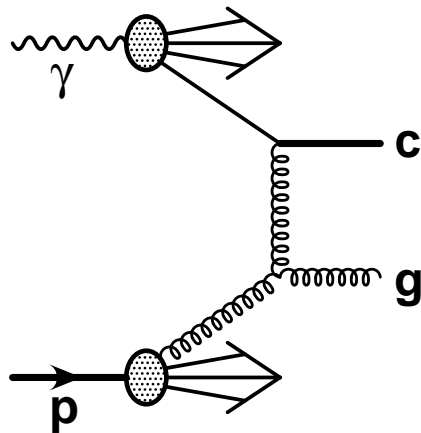
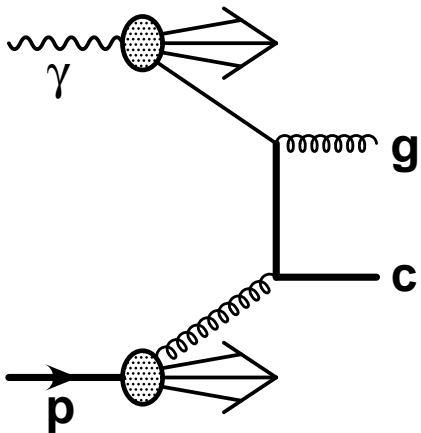
NLO: 3 flavour $O(\alpha_s^2)$

FONLL: NLO merged with 4 flavour resummed

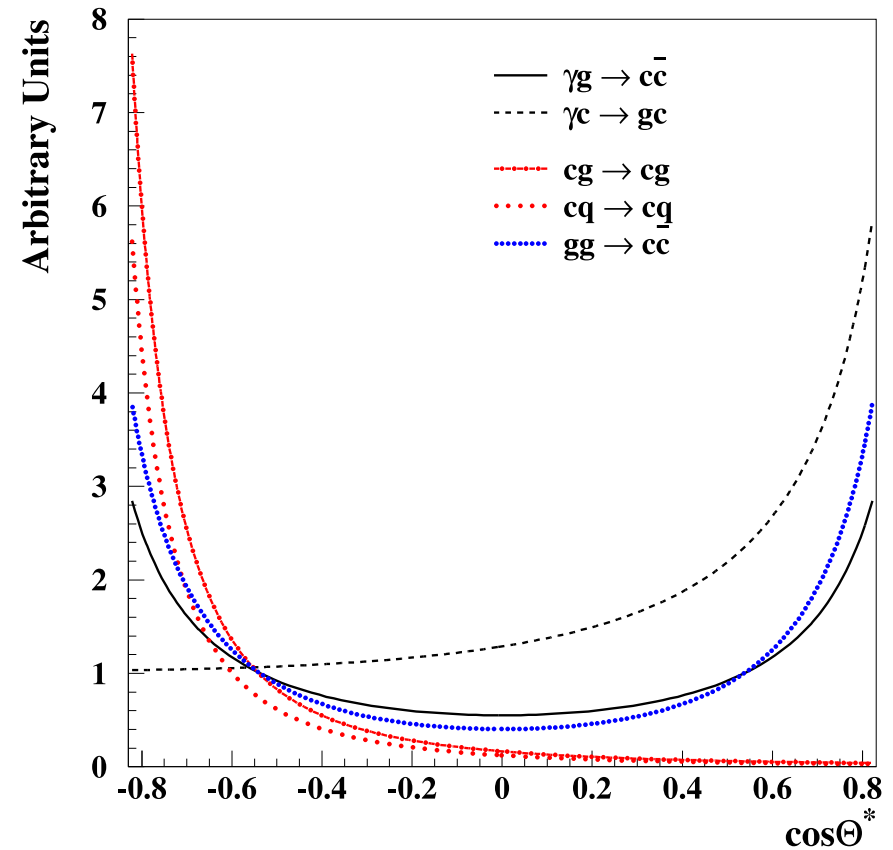
Resolved photon processes



Charm excitation diagrams:



- different angular dependences

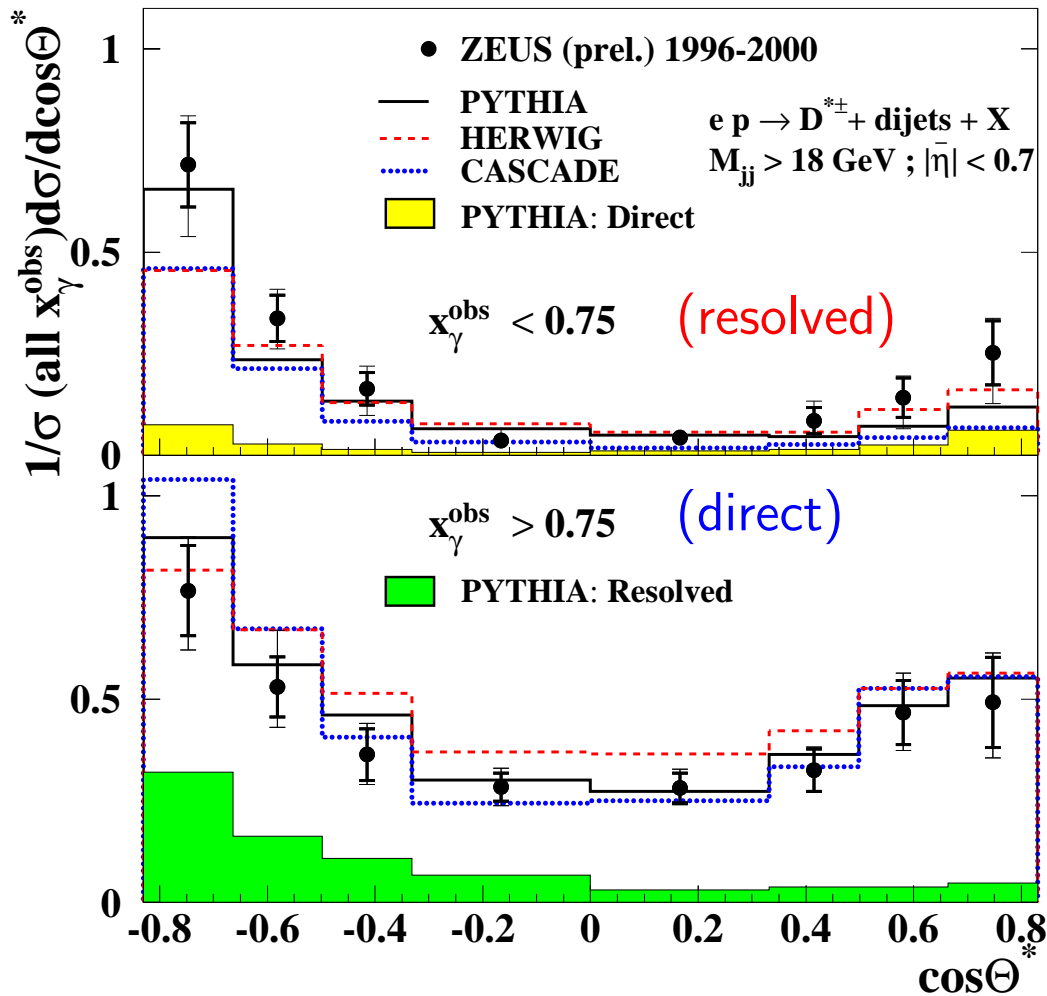


- quark propagator $\sim |1 - \cos\theta^*|$
- gluon propagator $\sim |1 - \cos\theta^*|^2$

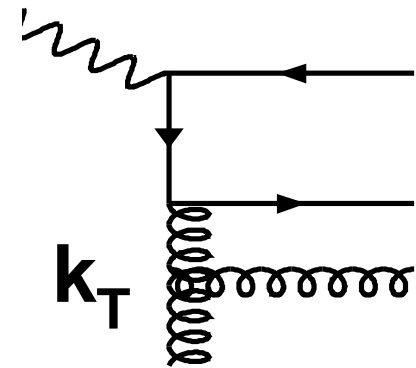
Angular distributions in the parton CMS

- $\cos \theta^* = \tanh((\eta_{jet 1} - \eta_{jet 2})/2)$

ZEUS

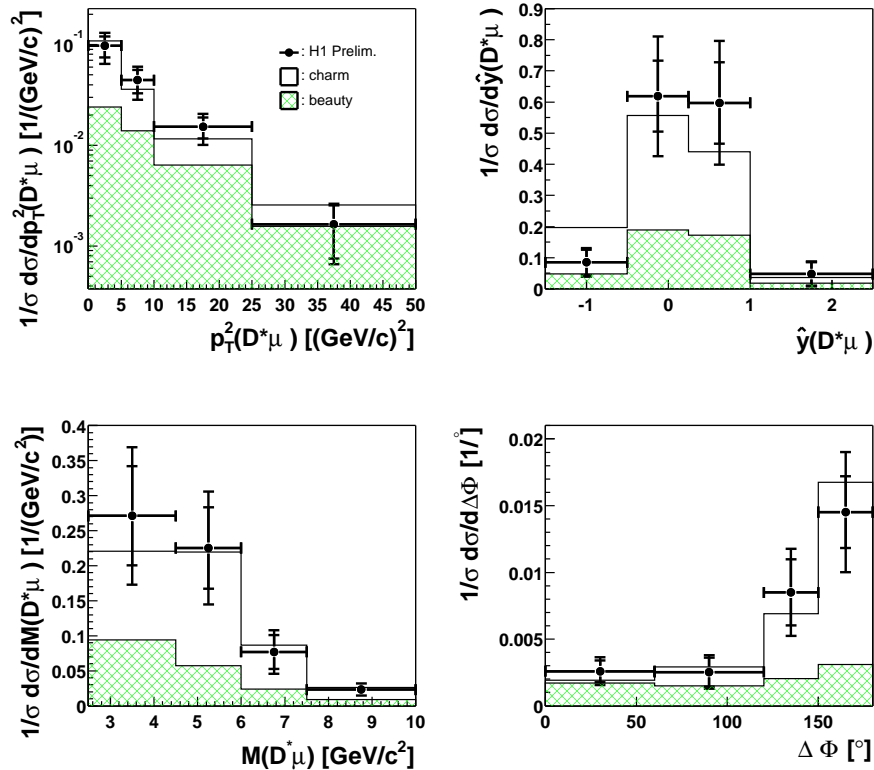


- resolved steeper:
gluon propagator
- charm in photon direction:
excitation topology
- also compatible: CASCADE
 k_T dependent
“unintegrated” gluon



Double heavy flavour tags

- $D^{*\pm}\mu$ correlations



- rare objects still
- but directly sensitive to higher order QCD effects
- with low p_T threshold: confirm b cross section measurements

- separate charm and beauty by charge and hemisphere correlation

QCD with beauty and charm:

- Charm photoproduction not everywhere compatible with NLO QCD
- Correlation studies identify important topologies in hadronic photon interactions
- Beauty photoproduction is higher than expected – like in $\bar{p}p$ and $\gamma\gamma$ interactions
- Measurements call for more data...

Outlook

With luminosity and detector
upgrades successfully completed
unveil Hera's secret beauty

