Heavy Quark Physics
at HERA
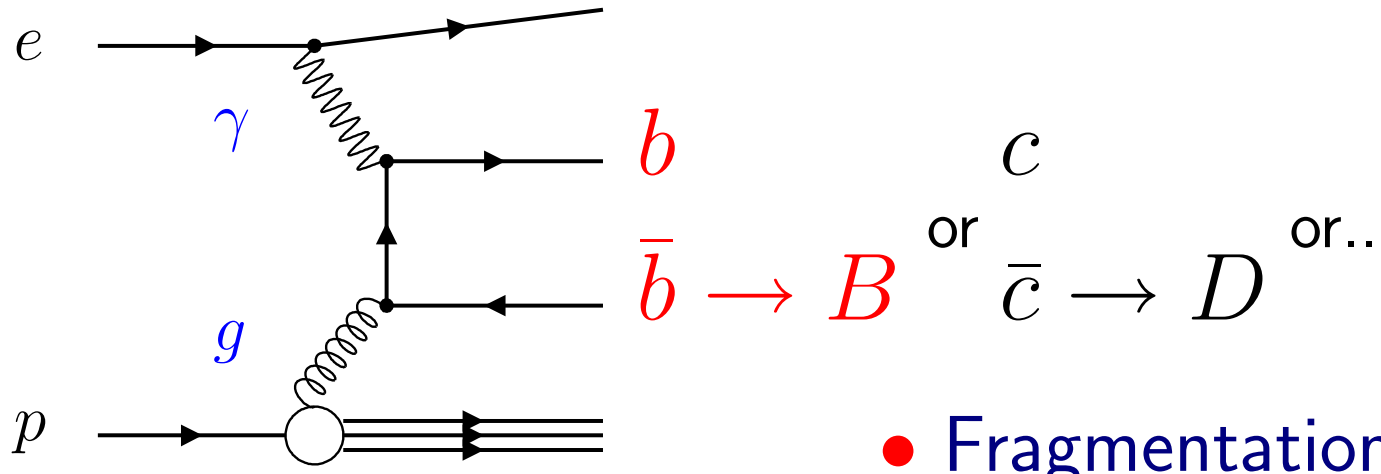
Felix Sefkow
University of Zürich / DESY

Probing QCD with Charm and Beauty

Heavy quark production in ep collisions
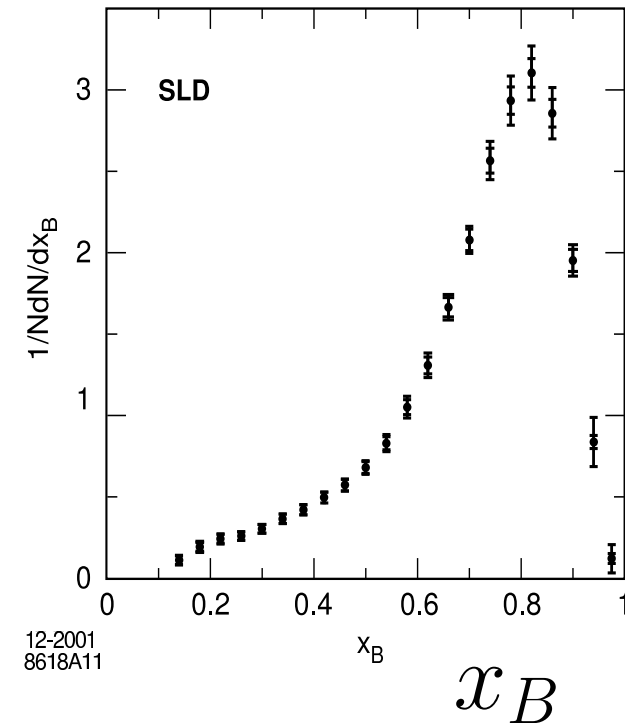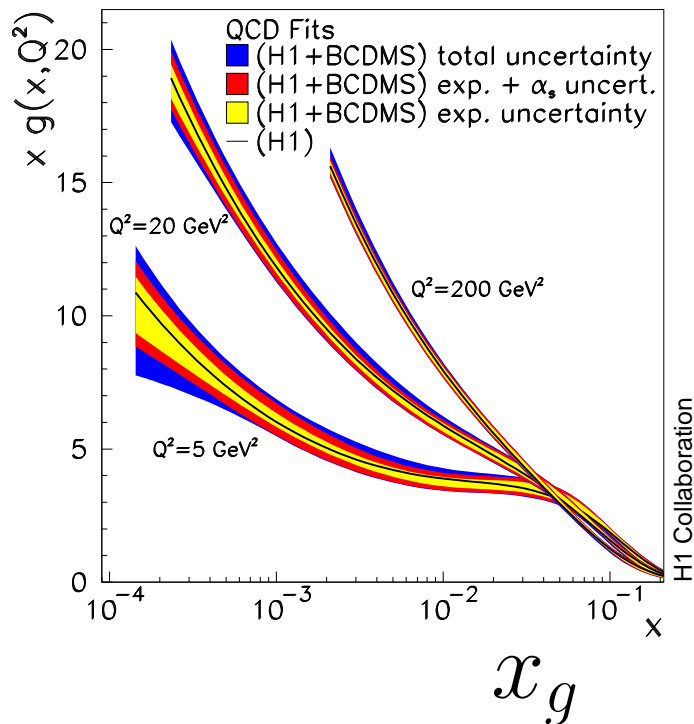
Factorization:

$$e$$

$$\gamma$$

$$b$$

$$c$$

$$\bar{b} \rightarrow B \quad \text{or} \quad \bar{c} \rightarrow D \quad \text{or..}$$

$$g$$

$$p$$

- Proton structure

- Hard QCD

- Fragmentation

QCD Fits
- (H1+BCDMS) total uncertainty
- (H1+BCDMS) exp. + α_s uncert.
- (H1+BCDMS) exp. uncertainty
- (H1)

$x\,g(x,Q^2)$

$Q^2 = 20\ \text{GeV}^2$

$Q^2 = 200\ \text{GeV}^2$

$Q^2 = 5\ \text{GeV}^2$

H1 Collaboration

x

x_g

SLD

$1/N\,dN/dx_B$

12-2001
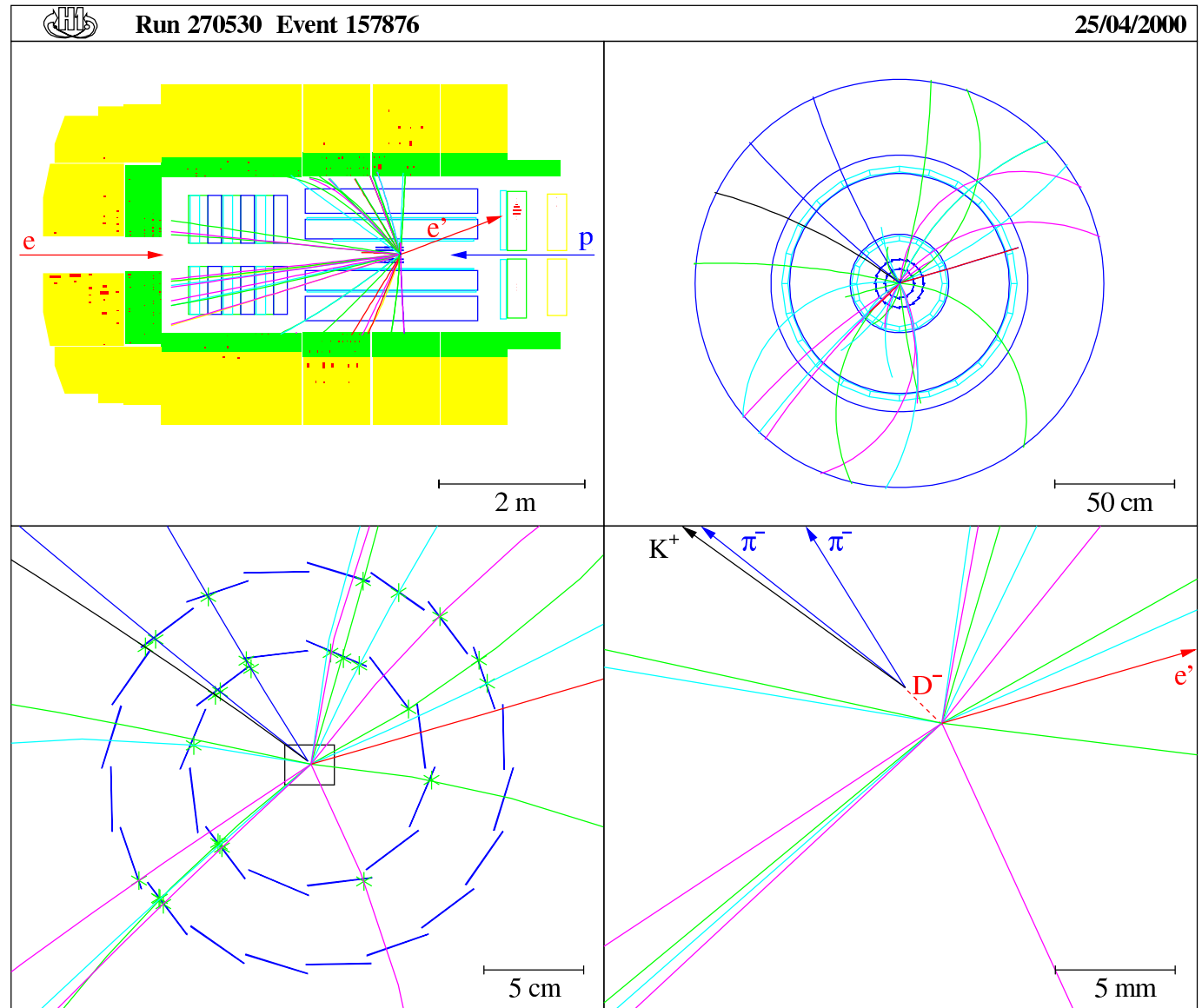8618A11

x_B

x_B

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

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

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

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

- Isospin ratio $R_{u/d}$

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

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

$0.693 \pm 0.045 \pm 0.013$	H1
$0.546 \pm 0.045 \pm 0.028$	ZEUS
0.595 ± 0.045	ALEPH
$0.57 \pm 0.05 \pm 0.07$	OPAL

- Strangeness suppression γ_s

$0.36 \pm 0.10 \pm 0.008$	H1 D_s
0.27 ± 0.05	ZEUS D_s
0.31 ± 0.07	ADO

  $\longrightarrow$ ep agrees with e^+e^-

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

- ZEUS (prel.) 1996-2000: $E_T^{jet} > 9$ GeV, $z \equiv (E + p_{\parallel})_{D^*}/2E^{jet}$
- OPAL $\sqrt{s} = 91.2$ GeV, $z \equiv 2E_{D^*}/\sqrt{s}$
- ARGUS $\sqrt{s} = 10.6$ GeV, $z \equiv p_{D^*}/(E_{beam}^2 - m_{D^*}^2)^{1/2}$

- similar accuracy, similar shape

- Fit LO parton shower MC with Peterson fragmentation function:
  $\epsilon_c = 0.064 \pm 0.006\,^{+0.011}_{-0.008}$

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

- $e^+e^- \rightarrow c\bar{c}$:
  $z = E_D/E_{beam},\ p/p_{max}$

- $ep \rightarrow cX$:
  $z = (E + p_{\parallel})_D/(E + p_{\parallel})_{jet}$

Fragmentation:

- Fractions of ground state (and excited) D meson species and

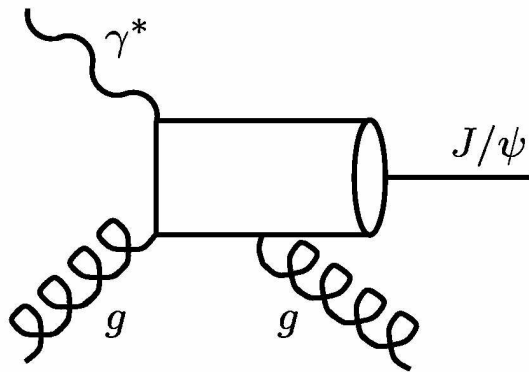- the first fragmentation function measurement in ep collisions

support universality of the heavy quark to hadron transition.

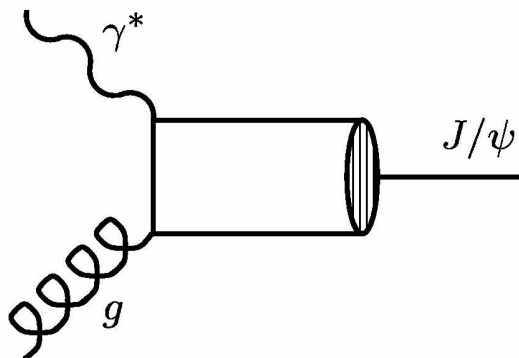# J/Ψ production

J/Ψ is colorless
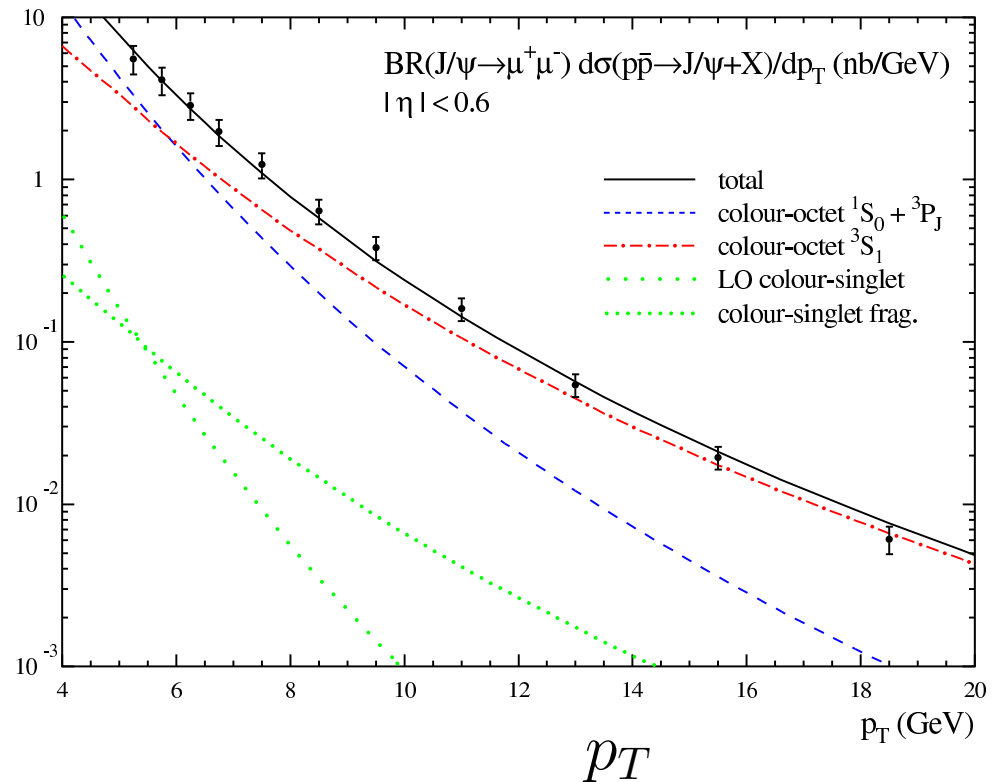
- Color singlet model

  hard process $\rightarrow$ [1]

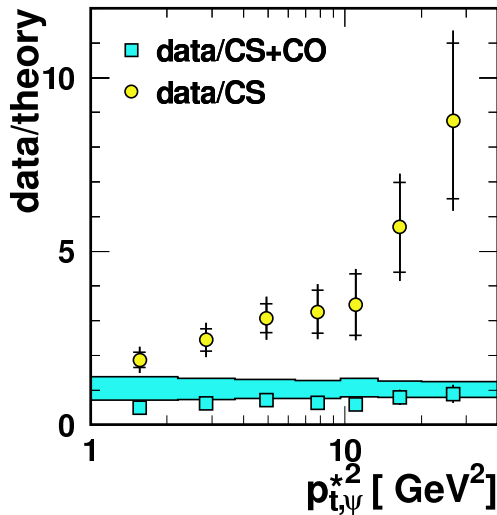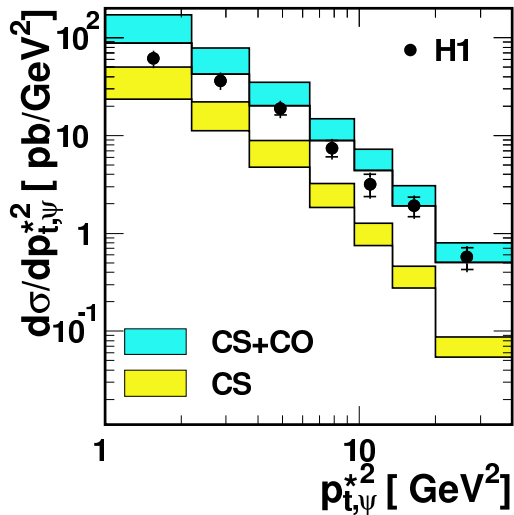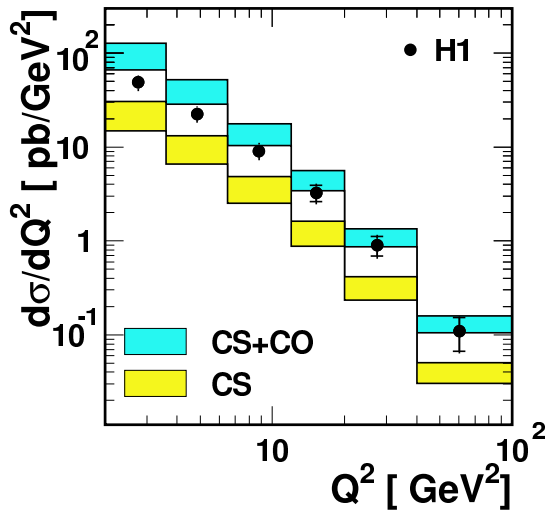- NRQCD: Color octet states

  soft [8] $\rightarrow$ [1] transition

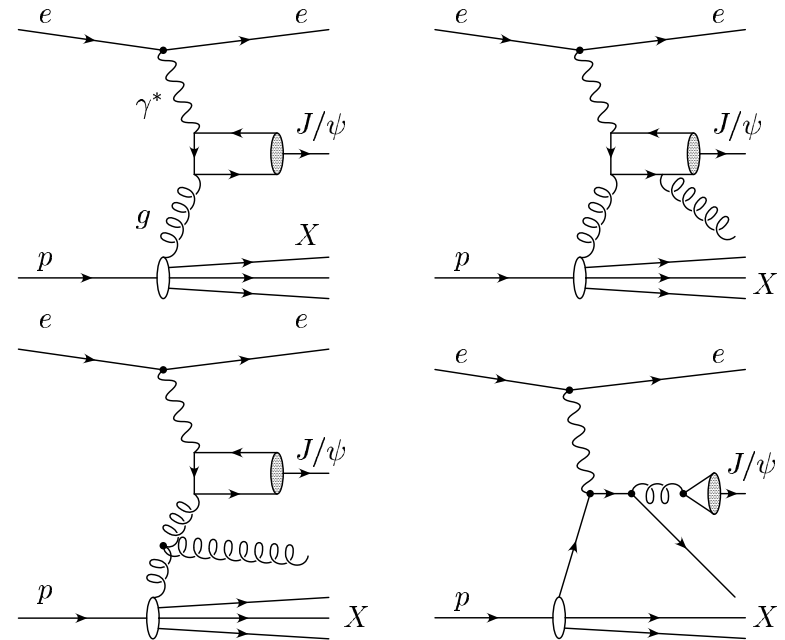- CO long distance matrix elements from fit of LO QCD to $\bar{p}p$ data

BR(J/ψ→μ⁺μ⁻) dσ(pp̄→J/ψ+X)/dp_T (nb/GeV)
$|\eta| < 0.6$

— total
- - - colour-octet $^1S_0 + {}^3P_J$
-·-·- colour-octet $^3S_1$
······ LO colour-singlet
······ colour-singlet frag.

p_T (GeV)

p_T

- non-perturbative, phenomenological, but universal
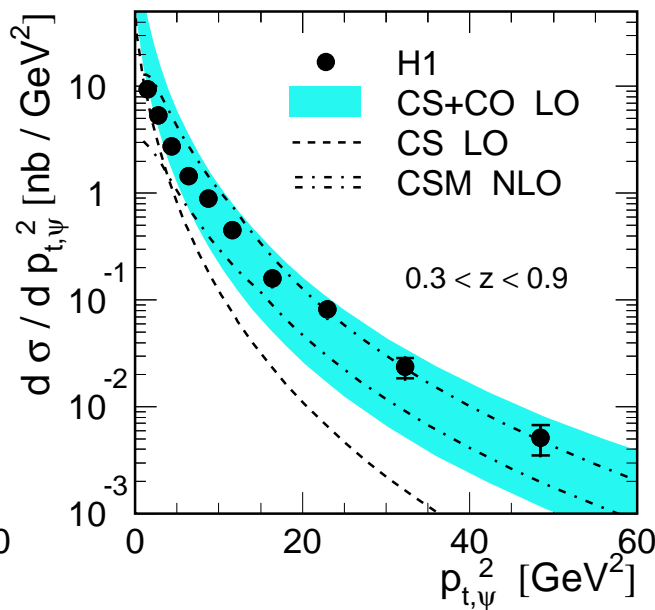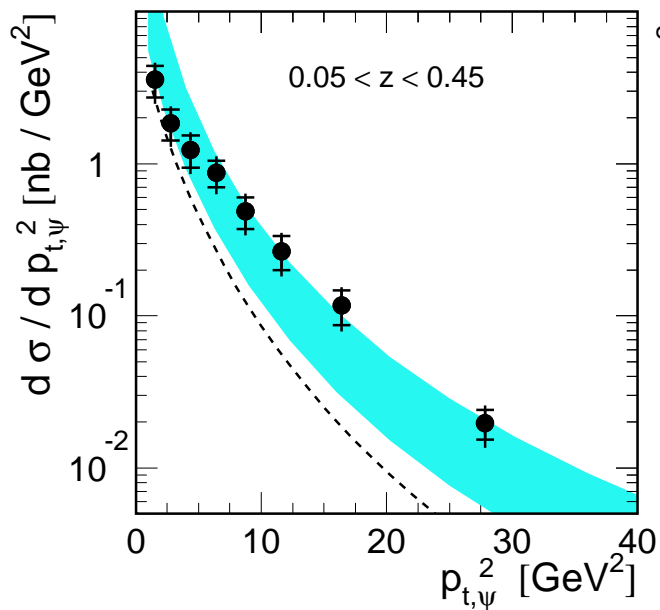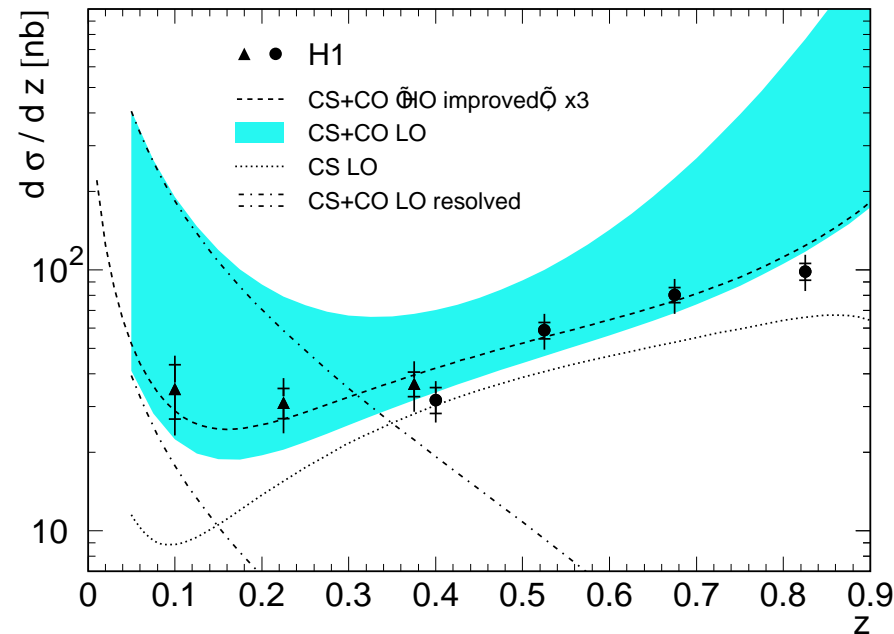
J/Ψ in Deep Inelastic Scattering

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

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

J/Ψ photoproduction

- limit $Q^2 \to 0$: photoproduction

- resolved photon contributions:
  $q\bar{q}$ fluctuation, hadronic interaction;
  CO important

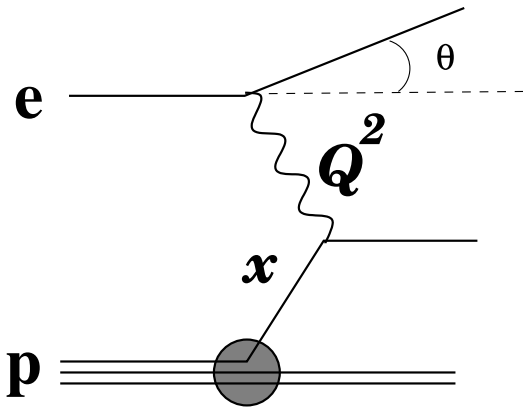- mostly at low $z = \frac{E_\Psi}{E_\gamma}$ (in p CMS)

- 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

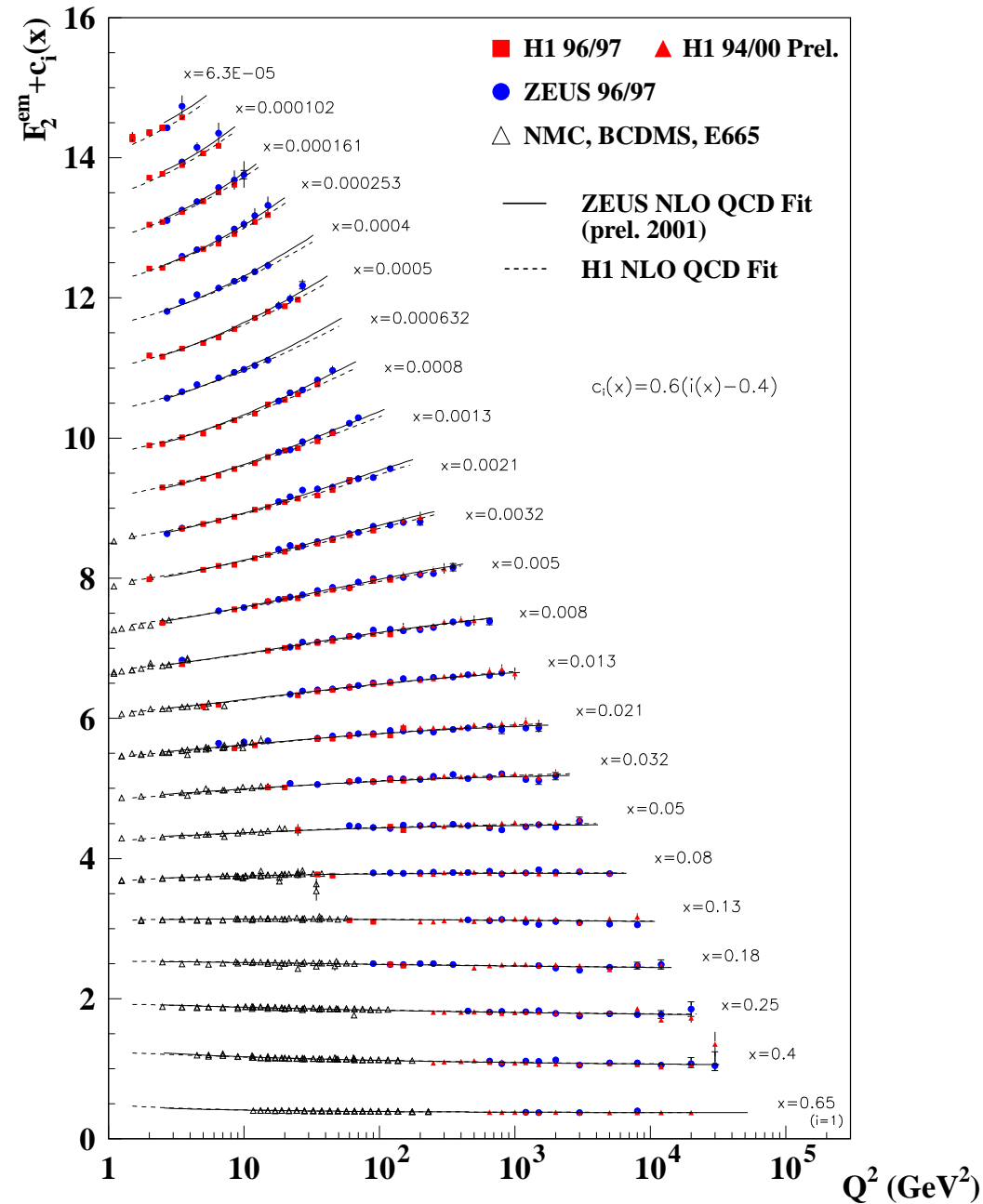- **Quark Parton Model**

Q^2: 4-momentum transfer

x_{Bj}: momentum fraction
of struck quark

- structure function F_2

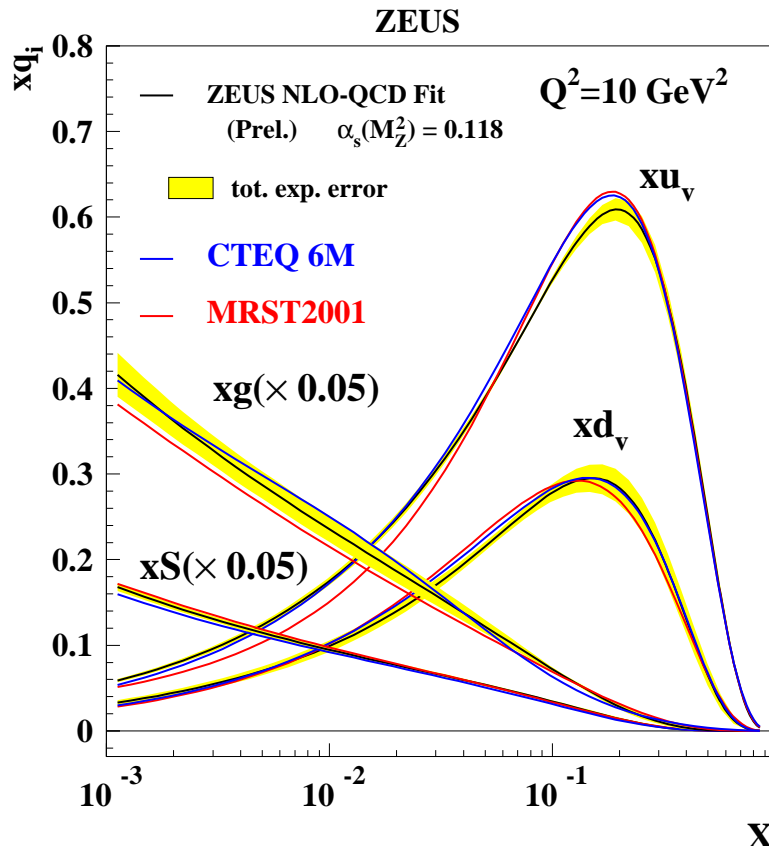$$\frac{d^2\sigma}{dx\,dQ^2} \approx \left(\frac{d^2\sigma}{dx\,dQ^2}\right)_{point} \cdot F_2(x, Q^2)$$

$$F_2(x, Q^2) = \Sigma_i\, e_i^2\, q_i(x, Q^2)$$
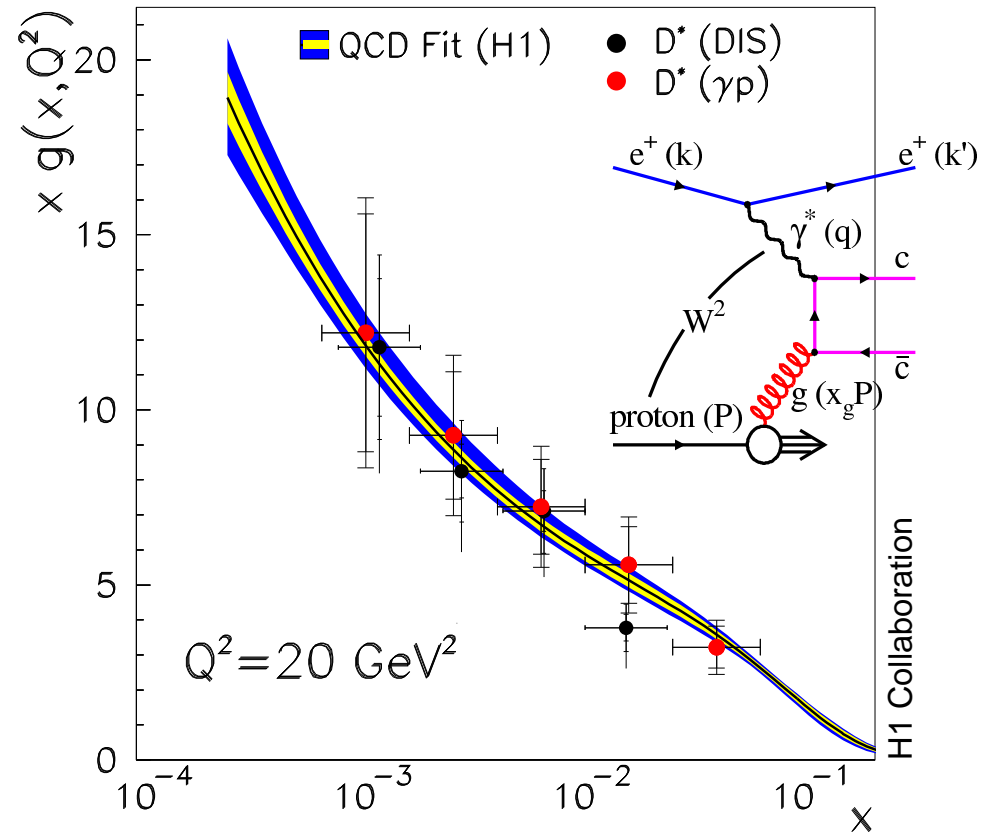
- scaling violations: gluons

Parton distributions

- From Altarelli Parisi NLO QCD fit to scaling violations

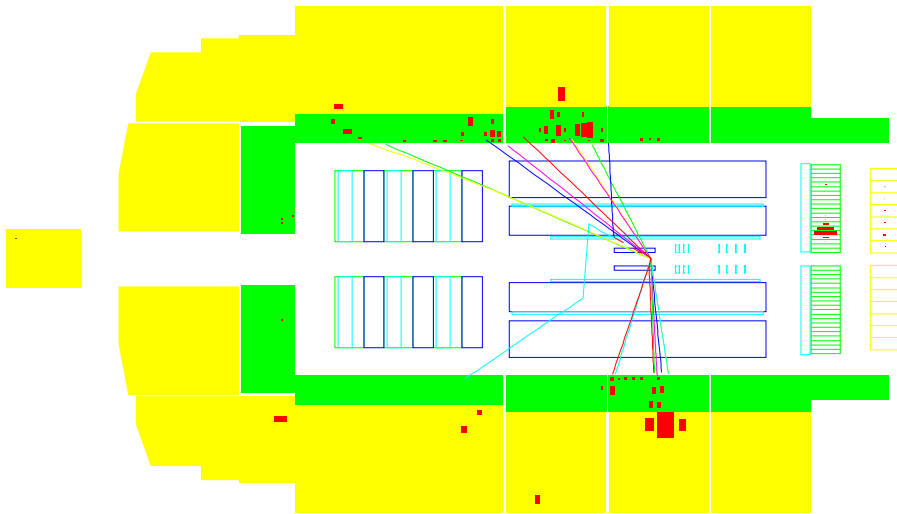- gluon density high: charm contrib. to DIS <u>large</u>: $\sim 25\%$

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

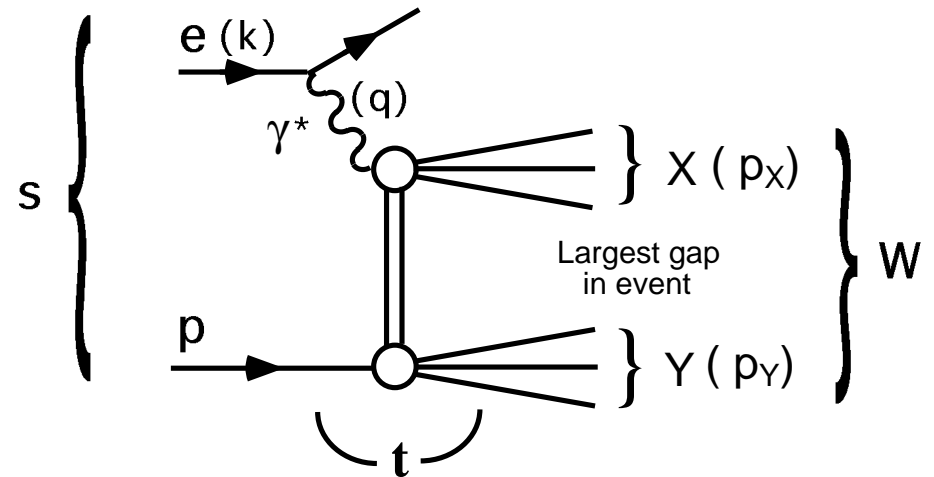- NB: not shown here: with higher precision some imperfections show up

Hard diffractive scattering

- Rapidity gap events

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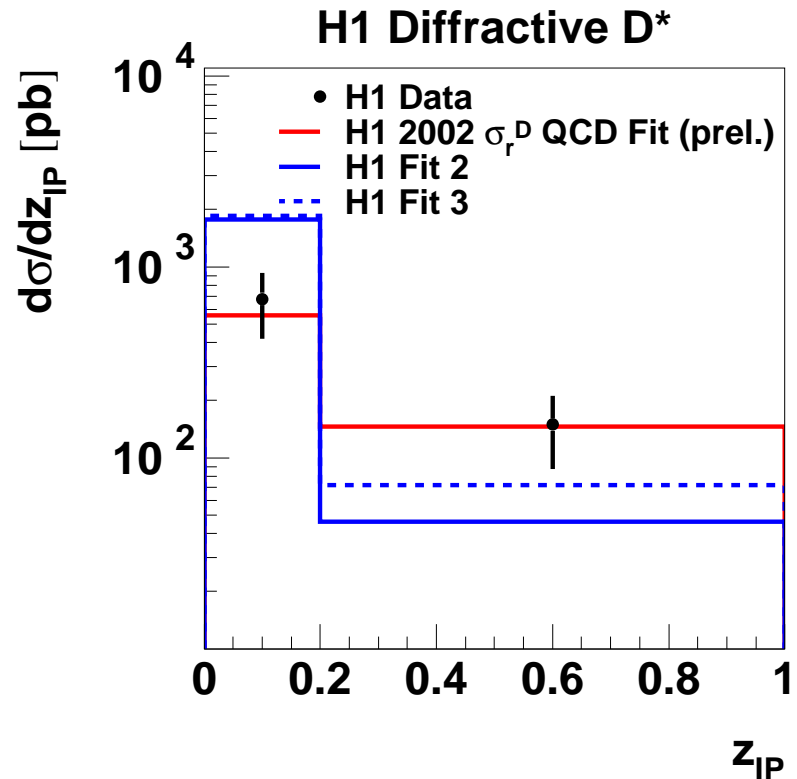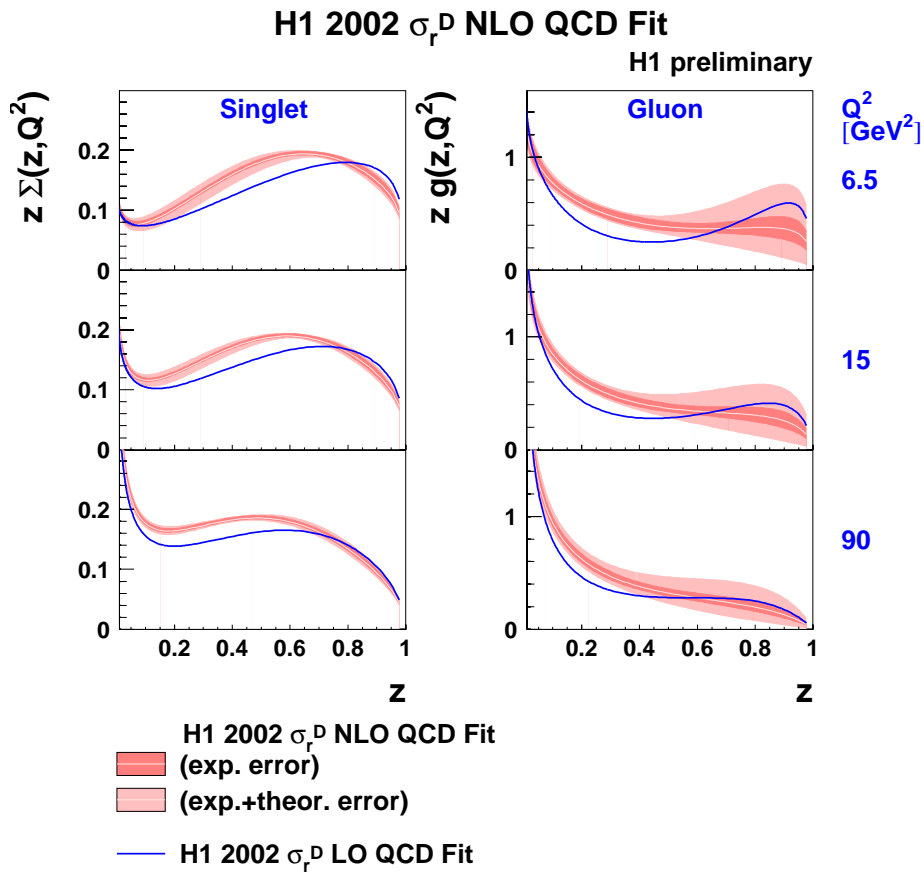
- jets: partonic interaction,
  perturbative QCD

- colorless exchange:
  diffraction

- factorizable:
  diffractive structure functions
  and pdf's

Diffractive pdf's and charm

- QCD analysis as in inclusive case

H1 2002 σ_r^D NLO QCD Fit

H1 preliminary

- $\sim 75\%$ gluons

  in diffractive exchange

- predict diffract. charm prod. using **new** diffractive pdf's

Challenges ahead:

- link to ordinary partons

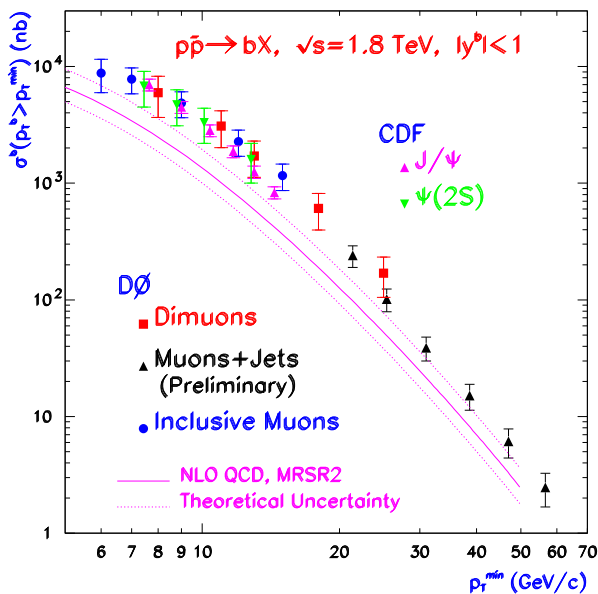- apply to diffraction in $\bar{p}p$

Proton structure and charm:

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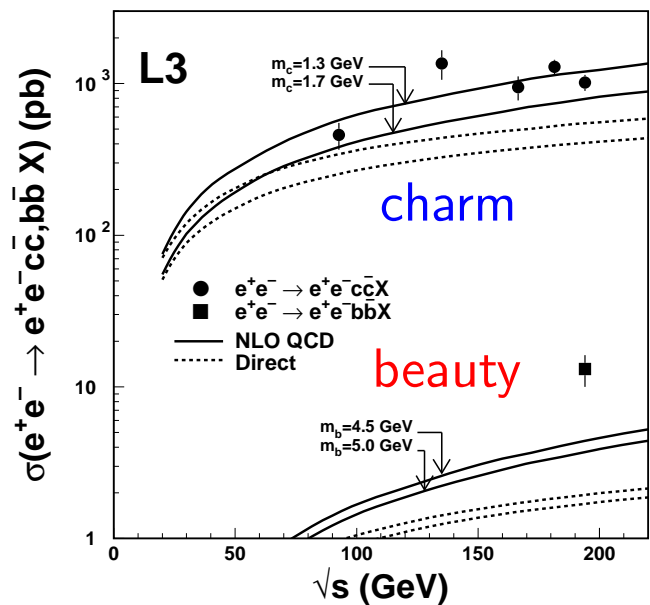
- Charm is directly sensitive to gluons

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

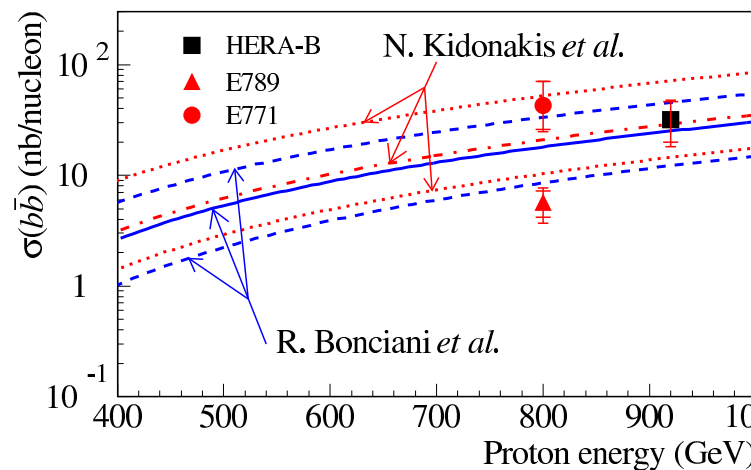# Beauty cross sections, elsewhere

- ## Tevatron $\bar{p}p$

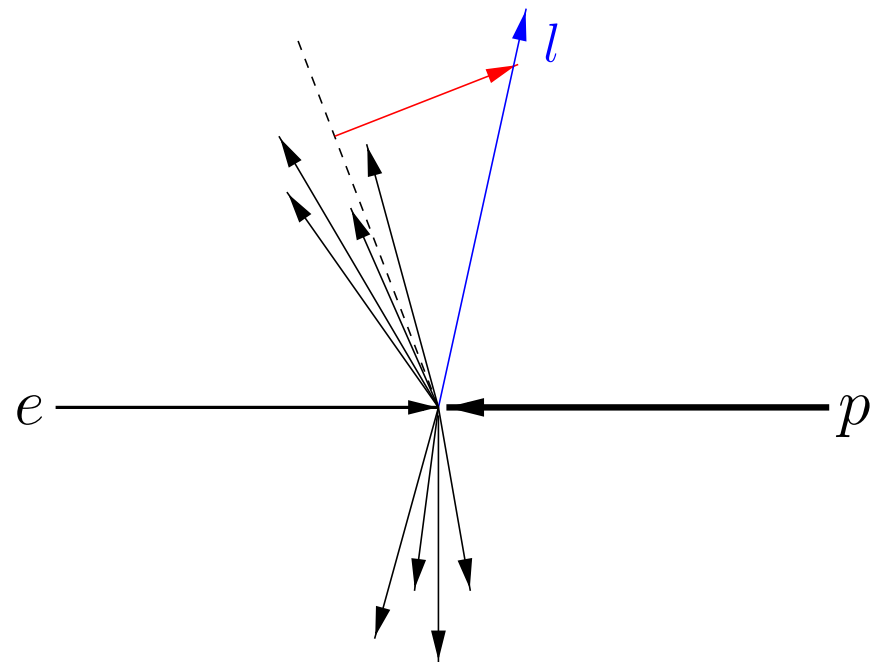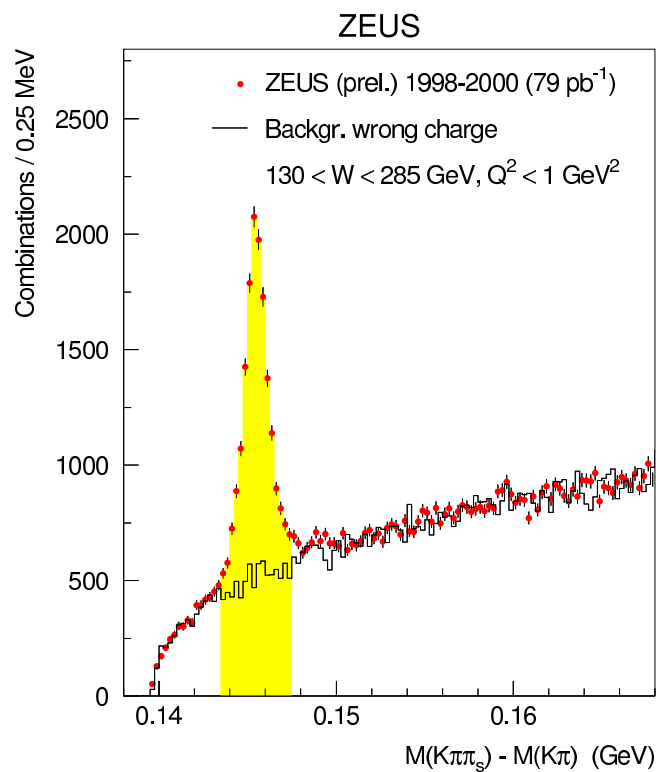- ## LEP $\gamma\gamma$

- ## pN

  New: HERA-B

  vertex-tagged $b \to J/\Psi$
  from 2000 run

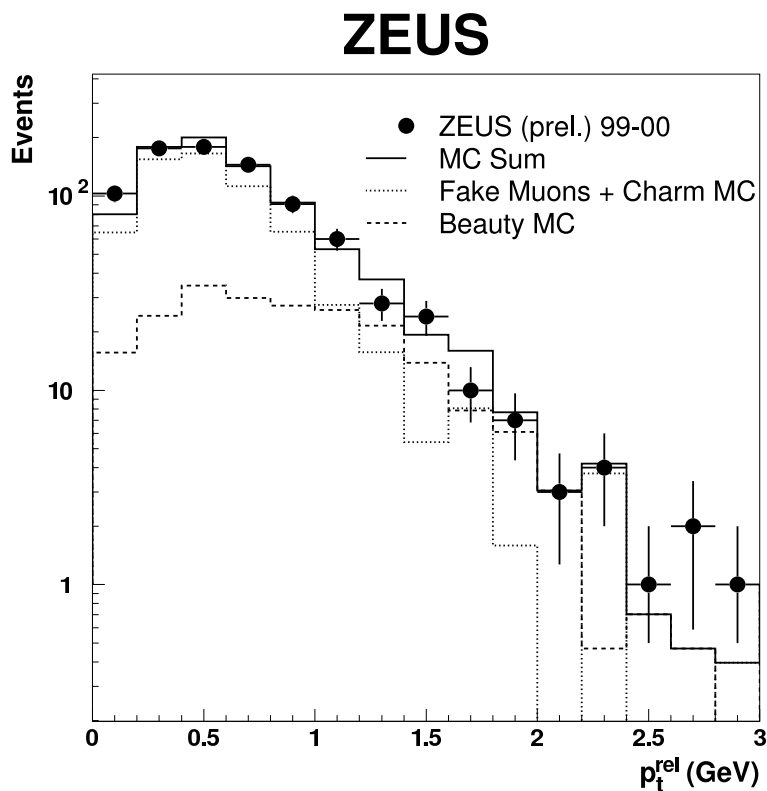- ## ep: cleanest case

Hard QCD studies with charm and beauty

- beauty : charm : uds $\approx$ 1 : 100 : 1000

- photoproduction dominates

- steeply falling p_T

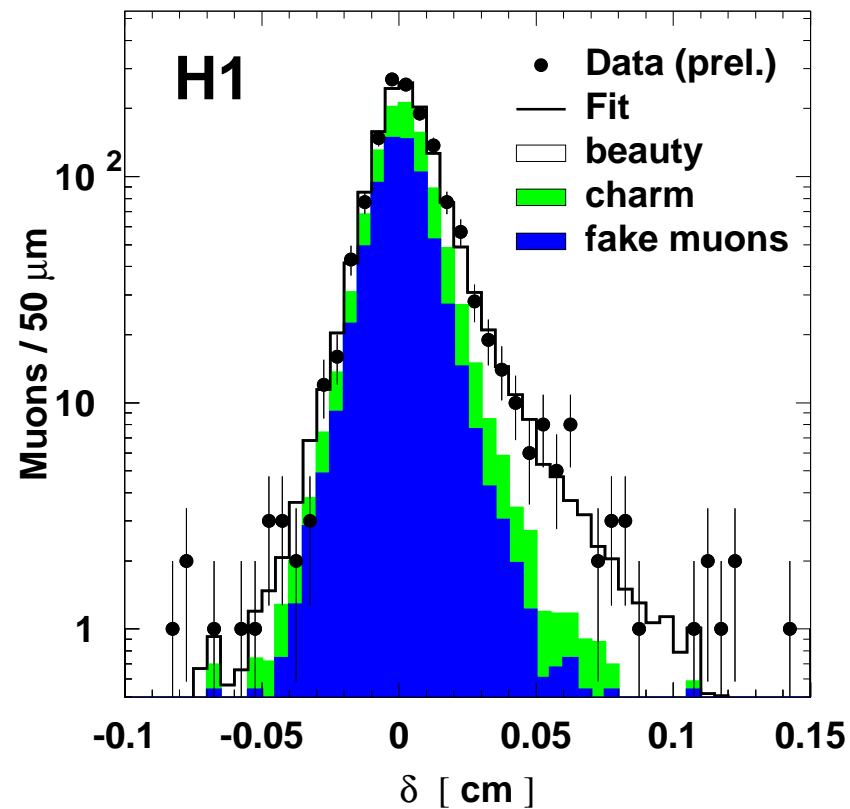- charm: $D^{*+} \to D^0 \pi^+$

- beauty: semileptonic decays

ZEUS

- ZEUS (prel.) 1998-2000 (79 pb^{-1})
— Backgr. wrong charge

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

Combinations / 0.25 MeV

M($K\pi\pi_s$) - M($K\pi$) (GeV)

Beauty signatures

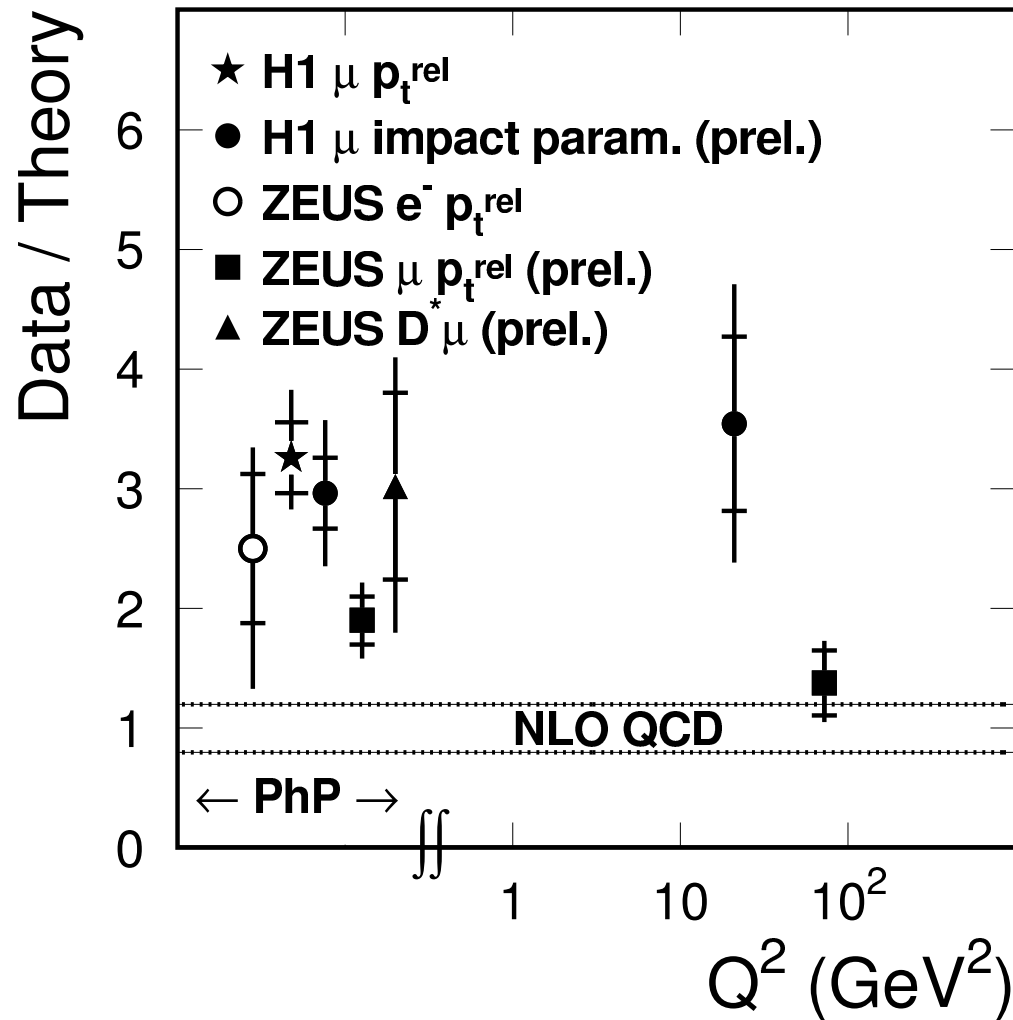- p_T relative to jet axis

example: ZEUS DIS data

- lepton impact parameter

example: H1 photoproduction data

Beauty cross section at HERA
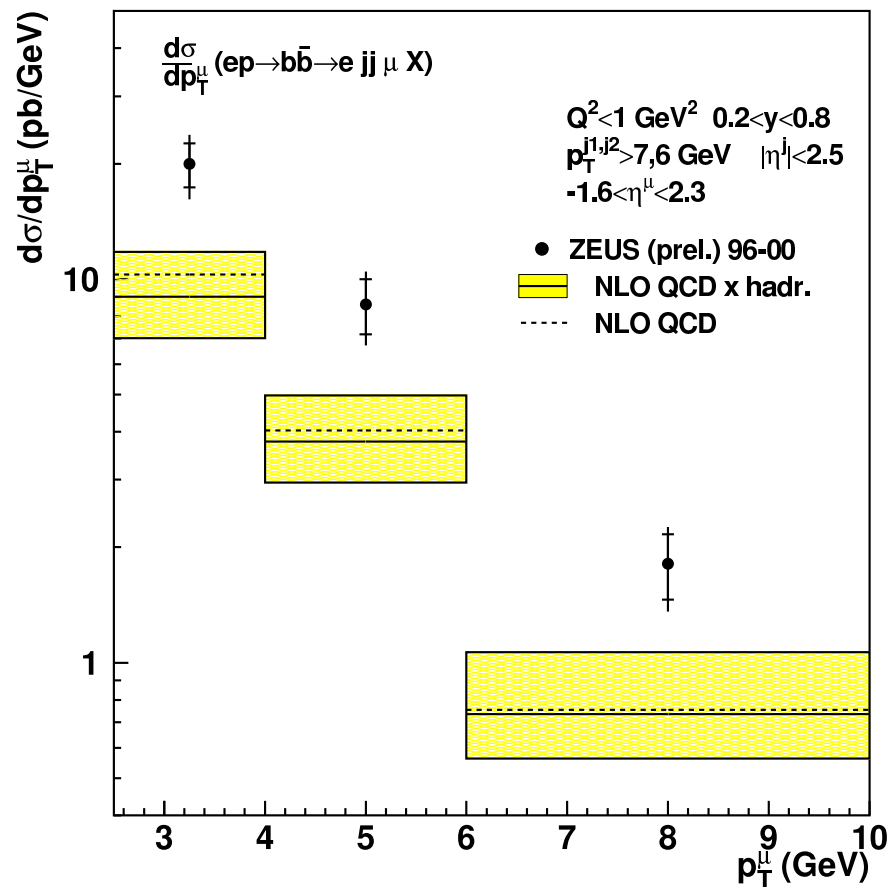
b cross section at HERA

- new results 2002

- in general above NLO QCD

- situation in DIS needs more data

Beauty spectra

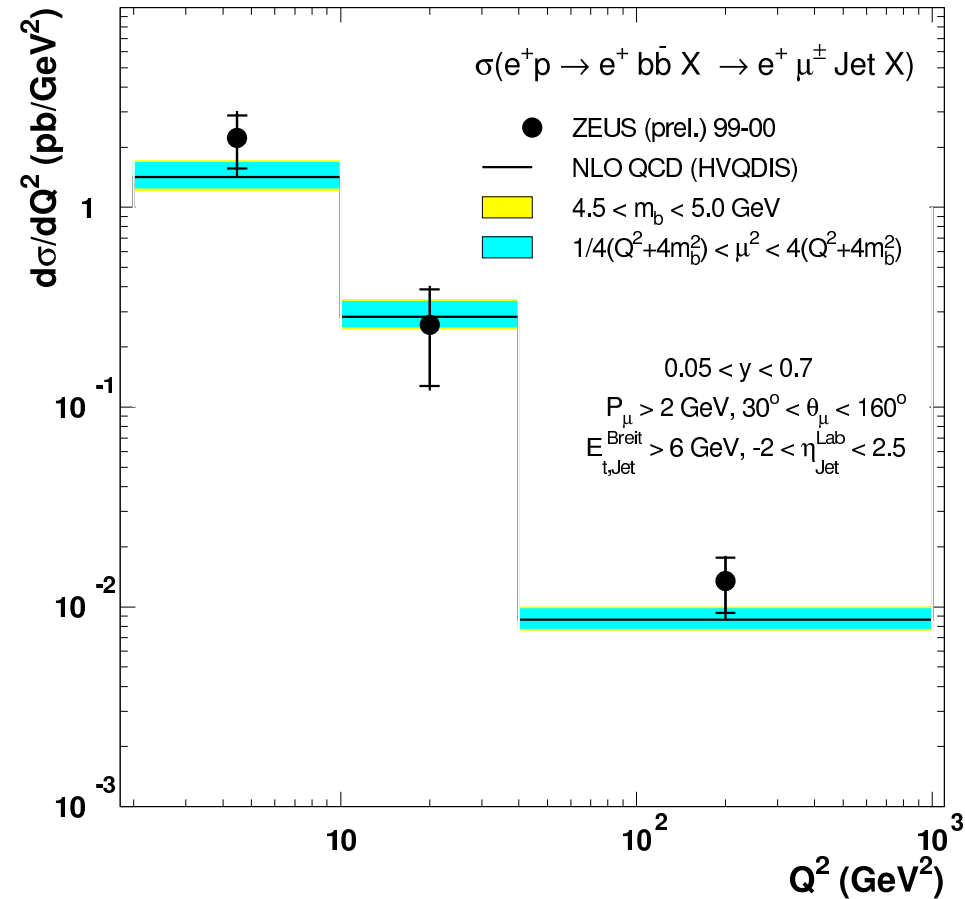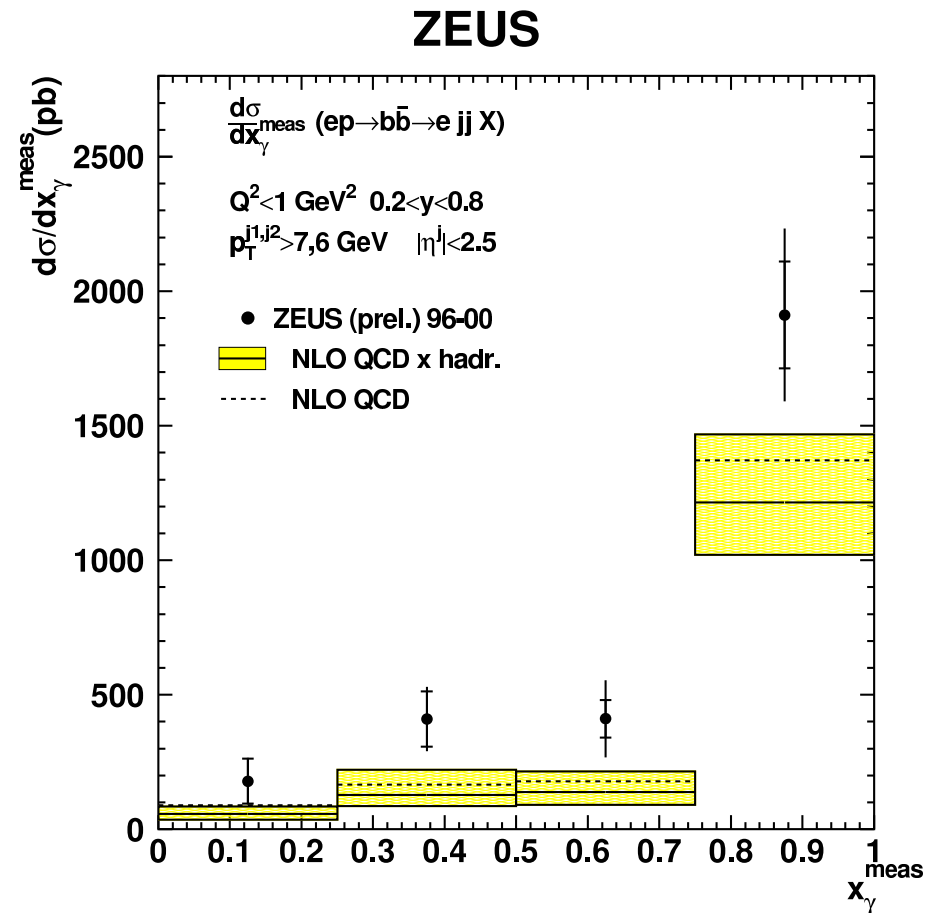New results – no striking disagreement in shapes

- in photoproduction

- in DIS

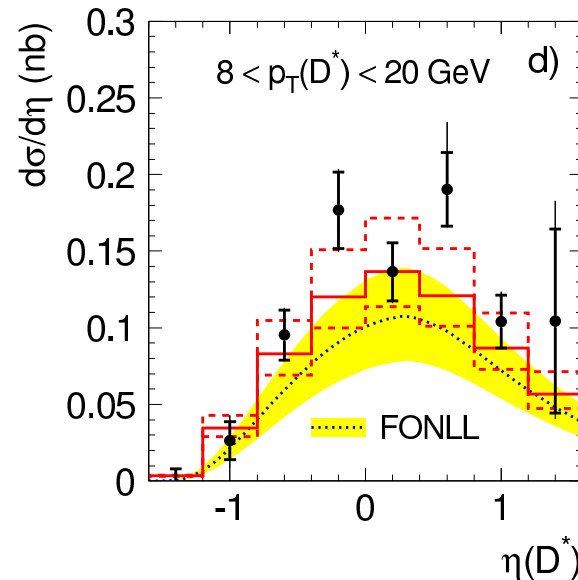# Direct and resolved photoproduction

← resolved → ←direct→

- in dijet events: reconstruct

  momentum fraction x_γ
  of parton entering
  from the photon side

ZEUS

$\frac{d\sigma}{dx_\gamma}^{meas}$ (ep→b$\bar{b}$→e jj X)

$Q^2 < 1$ GeV^2 $0.2 < y < 0.8$
$p_T^{j1,j2} > 7,6$ GeV $|\eta^j| < 2.5$

- ZEUS (prel.) 96-00
- NLO QCD x hadr.
- NLO QCD

- similar behavior seen earlier
  for charm

$D^{*\pm}$ photoproduction

ZEUS

- new, precise data, improved theory
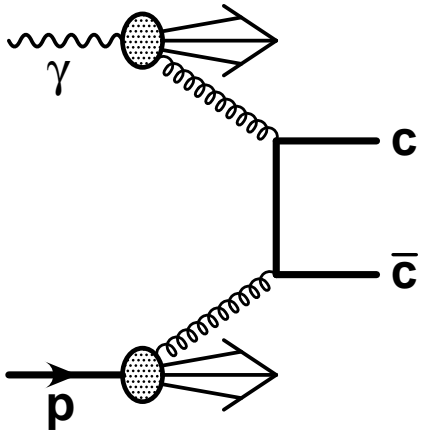- not everywhere compatible, some excess
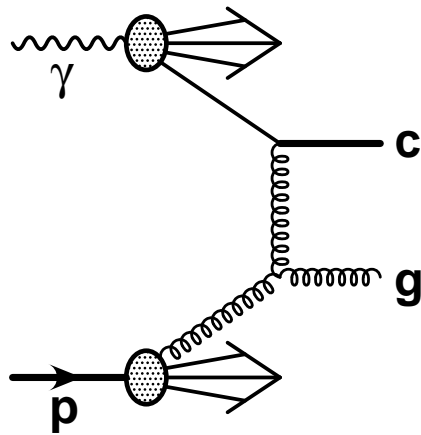
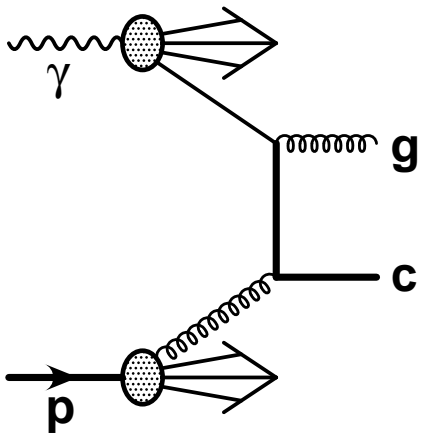QCD calculations (Frixione, Nason *et al*):

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

FONLL: NLO merged with 4 flavour resummed

Resolved photon processes

Charm excitation diagrams:

- different angular dependences

Legend:
- $\gamma g \to c\bar{c}$
- $\gamma c \to gc$
- $cg \to cg$
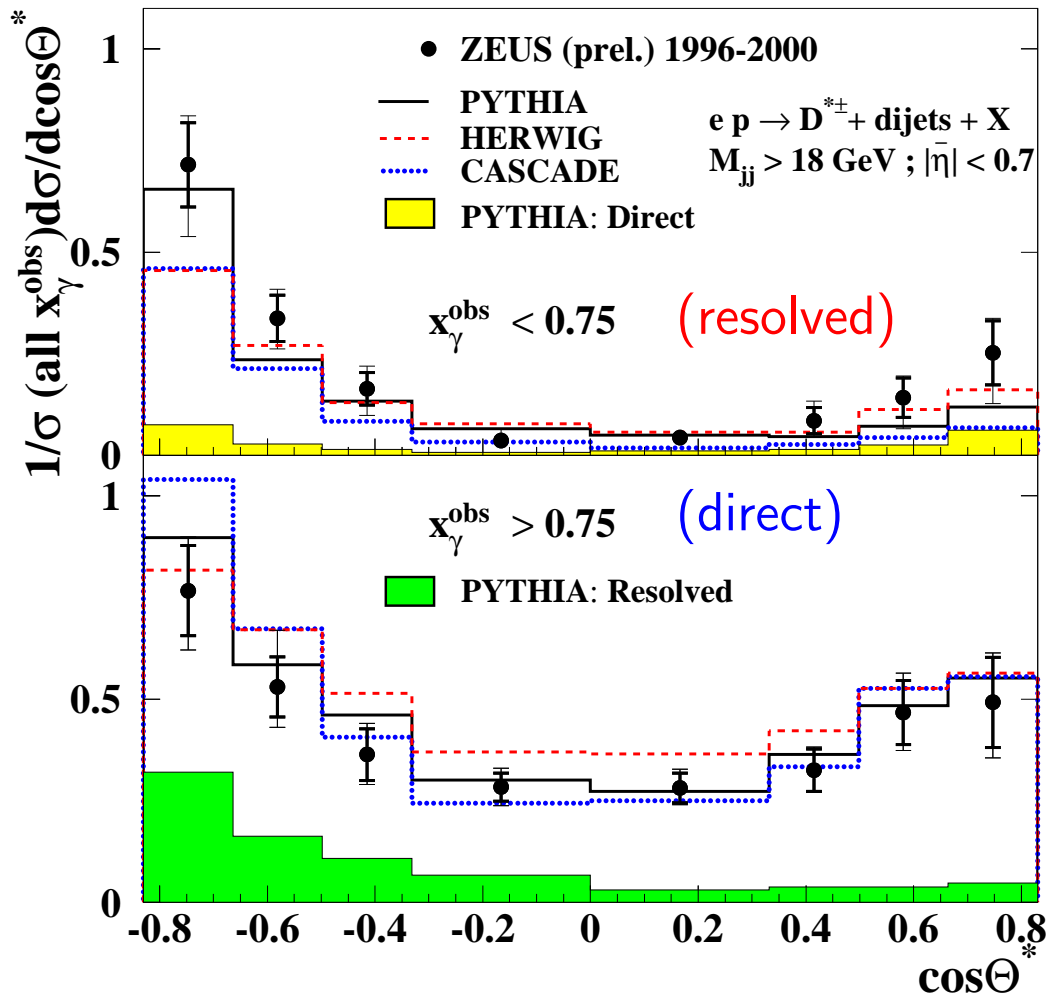- $cq \to cq$
- $gg \to c\bar{c}$

- 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

ZEUS (prel.) 1996-2000

PYTHIA
HERWIG
CASCADE
PYTHIA: Direct

$e\,p \rightarrow D^{*\pm} + \text{dijets} + X$
$M_{jj} > 18$ GeV ; $|\bar{\eta}| < 0.7$

$x_\gamma^{obs} < 0.75$ (resolved)

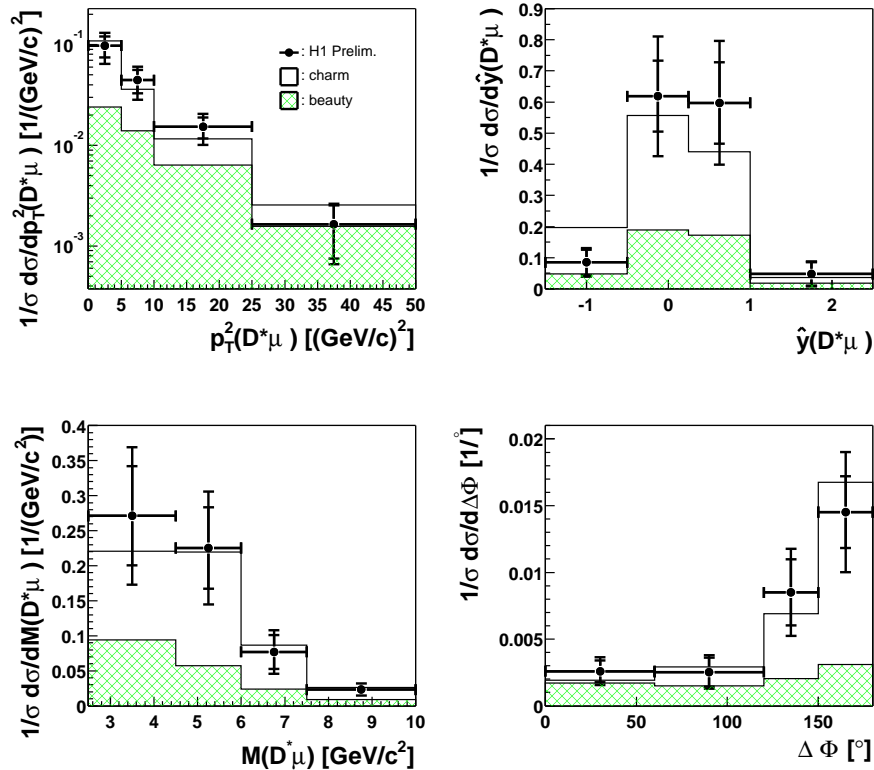$x_\gamma^{obs} > 0.75$ (direct)

PYTHIA: Resolved

- 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

- separate charm and beauty by charge and hemisphere correlation

- rare objects still

- but directly sensitive to higher order QCD effects

- with low p_T threshold: confirm b cross section measurements

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 detctor
upgrades succesfully completed

unveil Hera's secret beauty