Heavy Quark production at HERA and Heavy Quark contributions to the Proton Structure Function

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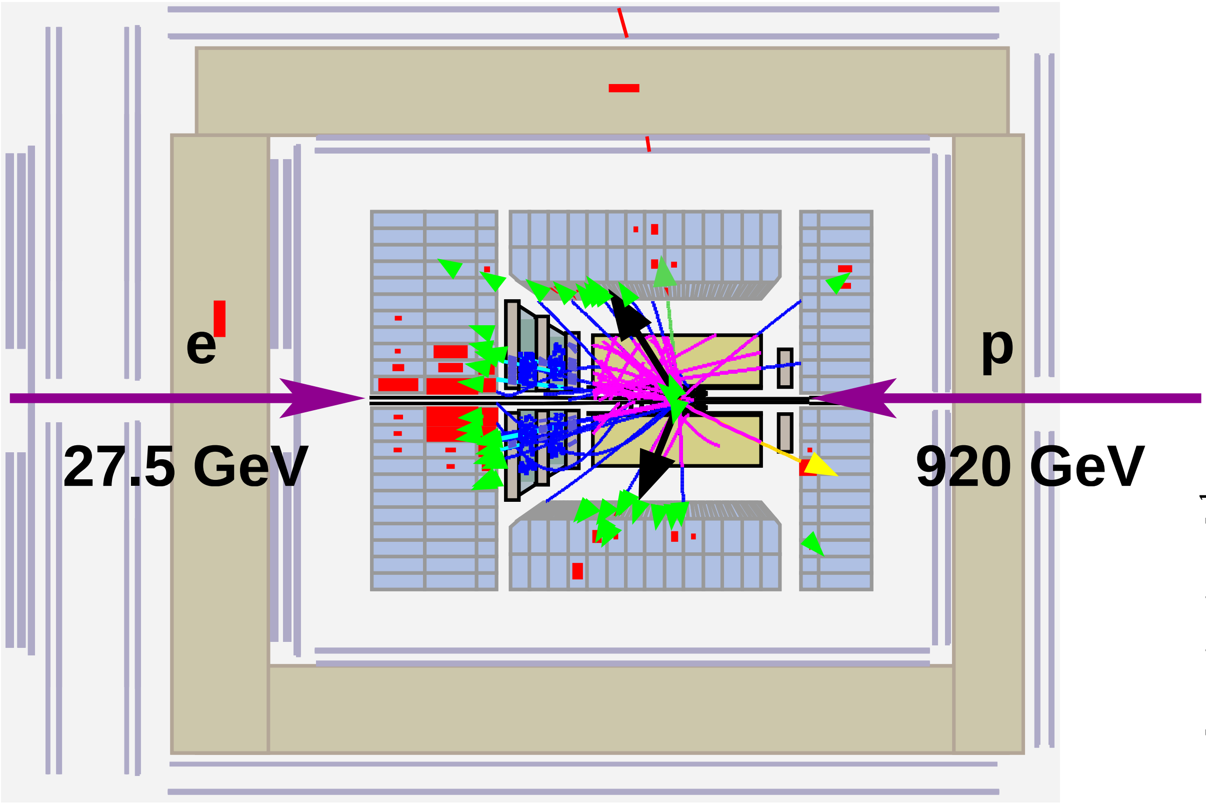
on behalf of the ZEUS and H1 Collaborations

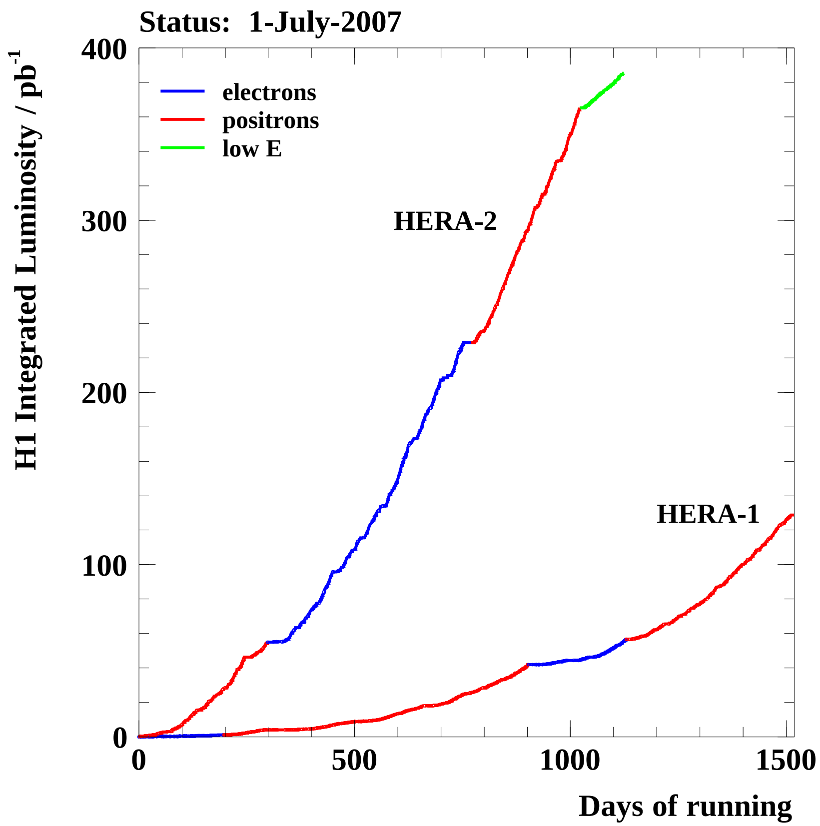
- Introduction
- Heavy quark measurement methods
- Structure functions F_2^{cc} and F_2^{bb}

Lake Louise Winter Institute 2008
Lake Louise, 02/23/2008

ep-collisions at HERA



ep center of mass energy:	
1992 - 1997	**300 GeV**
1998 - 2007	**320 GeV**
05/2007	225 GeV
06/2007	252 GeV



Integrated Luminosity (e.g. H1 on tape)

Year	e^+p	e^-p
96-00 (HERA I)	124 pb^{-1}	22 pb^{-1}
03-07 (HERA II)	242 pb^{-1}	255 pb^{-1}
05/2007 (LER)	15 pb^{-1}	
06/2007 (MER)	8 pb^{-1}	

Heavy Flavour production

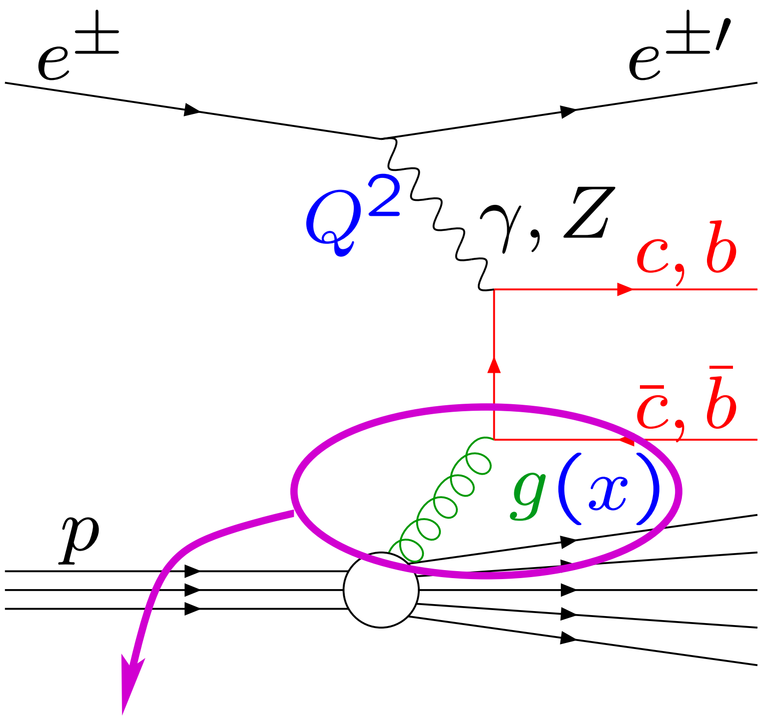
Dominant process in ep-collisions: **Boson-Gluon-Fusion**

Kinematic variables:

$Q^2 = -q^2$ photon virtuality, squared momentum transfer

$x = \frac{Q^2}{2Pq}$ Bjorken scaling variable

$y = \frac{Pq}{Pk}$ Inelasticity



sensitive to gluon contens of the proton

Two kinematic regimes:

- Photoproduction (γp):
  $Q^2 < 1\,\text{GeV}^2$
- Deep inelastic scattering (DIS):
  $Q^2 > 1\,\text{GeV}^2$

Multiple scales:

$M_{c,b} \sim 1.5(4.75)$ GeV

$p_t^{c,b} \sim$ typically few GeV

$Q^2 > 1\,\text{GeV}^2$ in DIS

$\Rightarrow$ **different pQCD approaches**

pQCD approximations

Massive scheme:

- c, b massive
- neglects $\left[\alpha_s \ln\left(Q^2/m^2_{c,b}\right)\right]^n$
- scale $m_{c,b}$

$\rightarrow c, b$ produced perturbatively
(not part of the proton or photon)

(γp: Frixione et al, FMNR
DIS: Harris & Smith, HVQDIS)

Massless scheme:

- c, b massless
- resums $\left[\alpha_s \ln\left(Q^2/m^2_{c,b}\right)\right]^n$
- scale Q^2, p_t

$\rightarrow c, b$ also in proton and photon

(γp: Kniehl et al)

Variable Flavour Number Scheme (VFNS):

- massive at small Q^2
- massless at high Q^2

(Cacciari et al)

Charm tagging: $D^* \rightarrow K\pi\pi$ in DIS

Golden decay mode

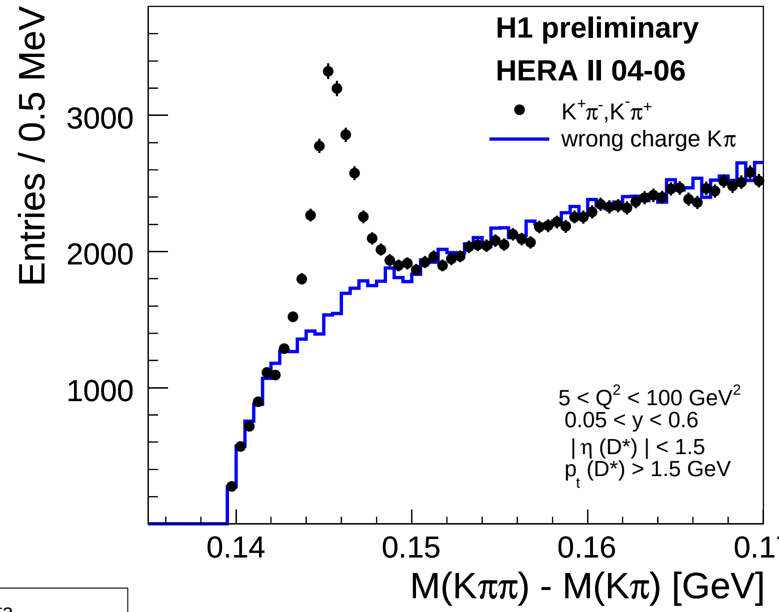
tagged by invariant mass $M(K\pi)$

and $\Delta M = M(K\pi\pi) - M(K\pi)$

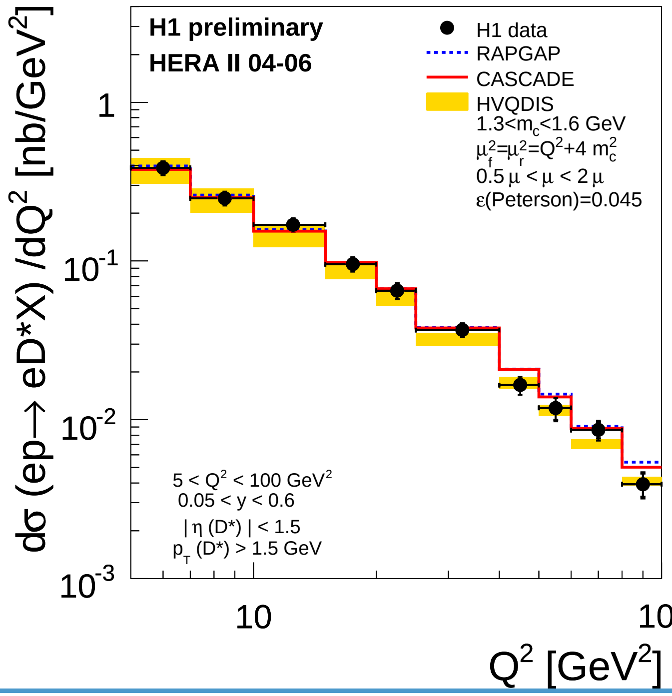
data and MC agree for

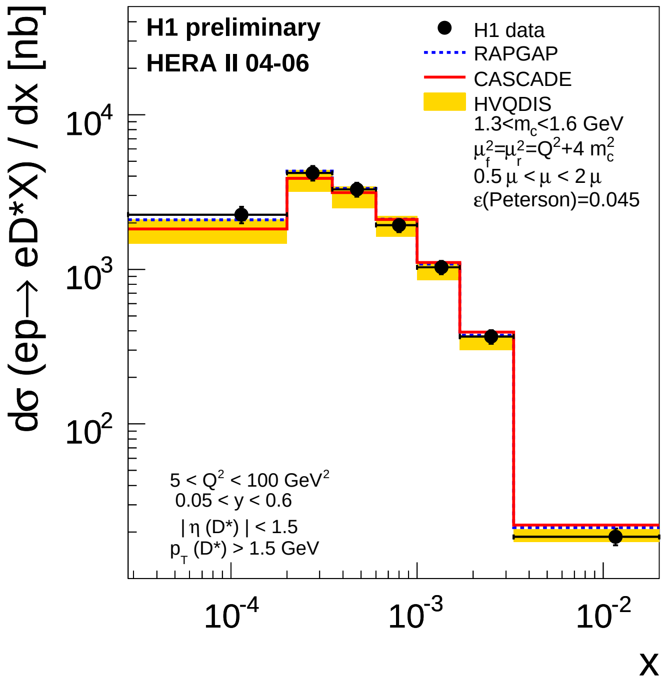
LO+parton shower (RAPGAP, CASCADE)

as well as for NLO (HVQDIS)



Visible D^* cross section





$5 < Q^2 < 100$ GeV^2

$0.05 < y < 0.6$

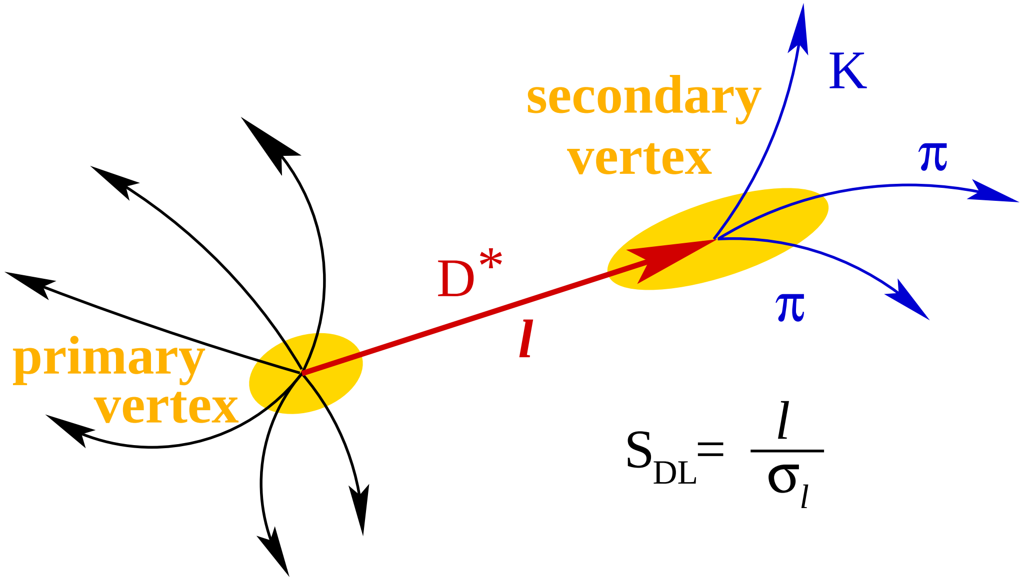
$p_t(D^*) > 1.5$ GeV

$|\eta(D^*)| < 1.5$

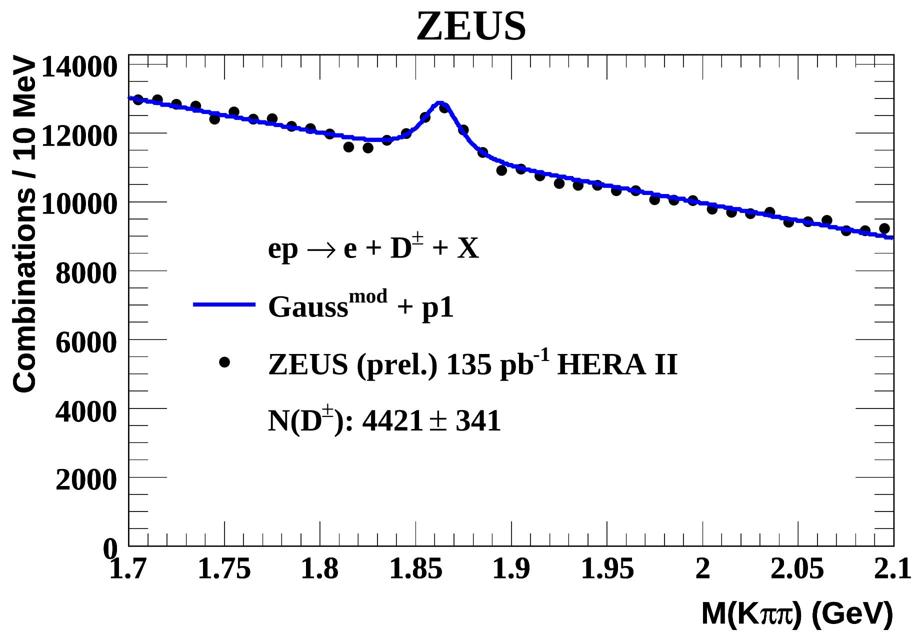
Charm tagging: $D^+ \to K^-\pi^+\pi^+$

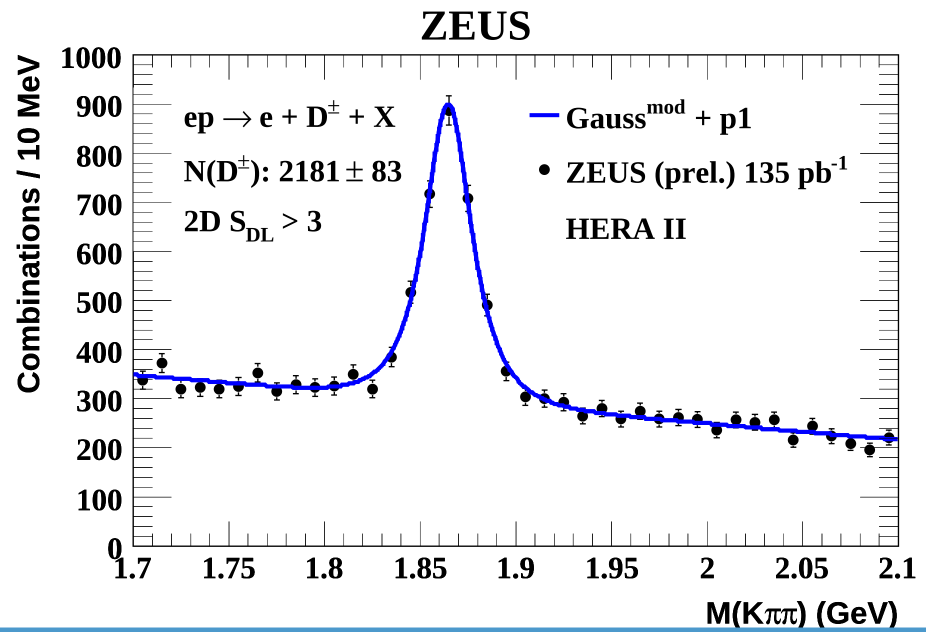
Long lifetime of D^+

$\rightarrow$ improved S/N ratio by cutting on the significance of the decay length (new method for HERA II)



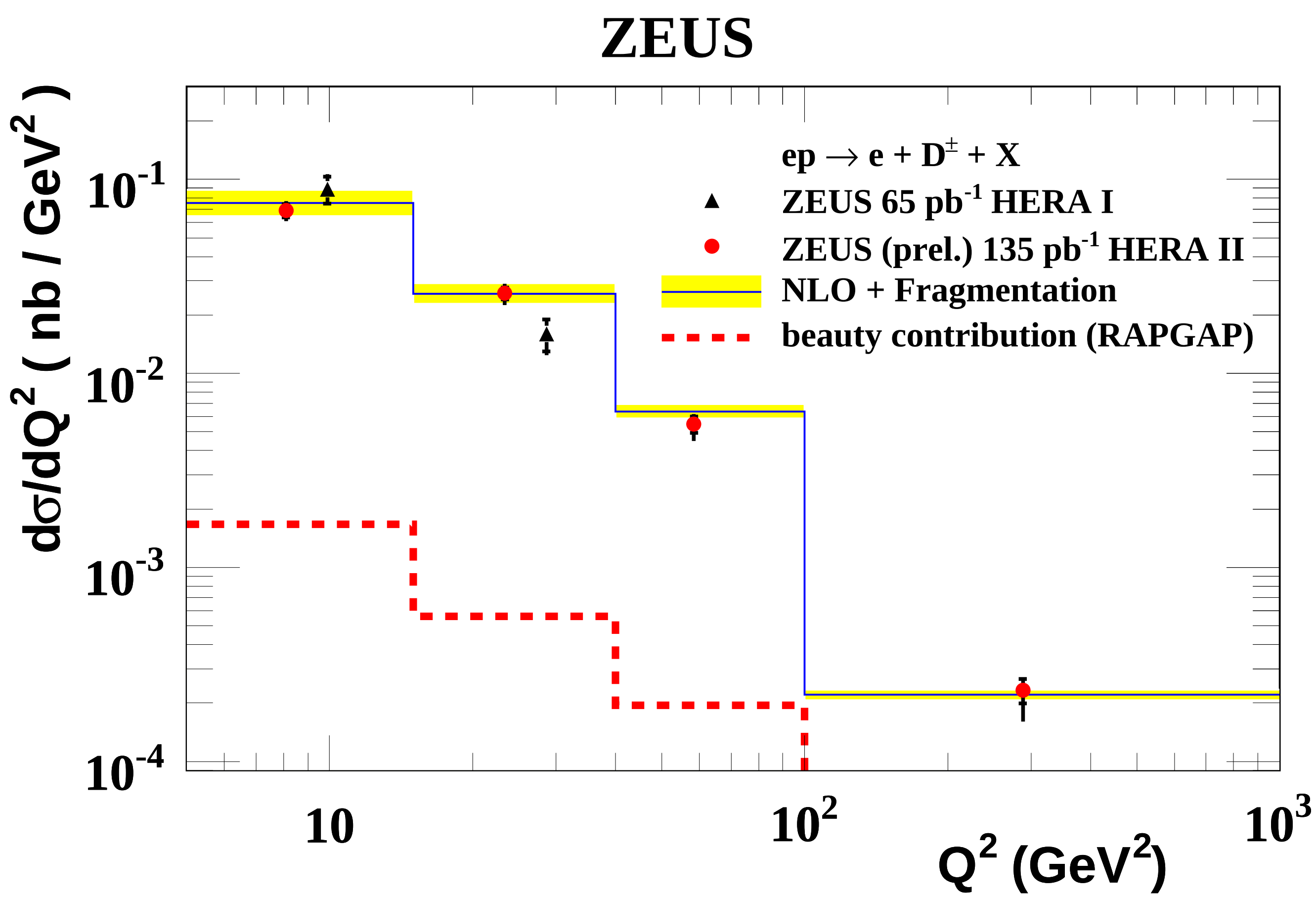
$$S_{DL} = \frac{l}{\sigma_l}$$





Reduction of the statistical error from 7.7% to 3.8%

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



- only 30% of available data used yet
- agreement between HERA I and HERA II measurements (different analysis methods)
- for some kinematic ranges error dominated by NLO uncertainty

$1.5 < Q^2 < 1000$ GeV^2

$0.02 < y < 0.7$

$p_t(D) > 3$ GeV

$|\eta(D)| < 1.6$

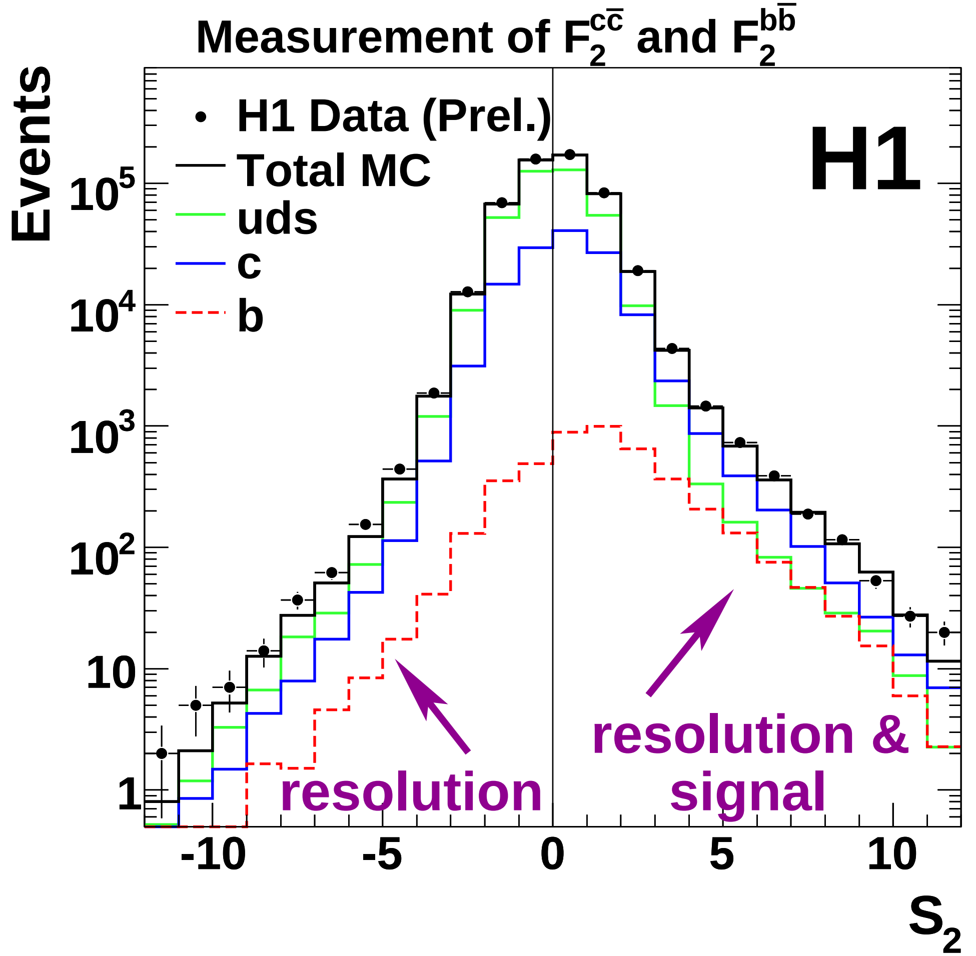
Good description of data by NLO QCD (HVQDIS)

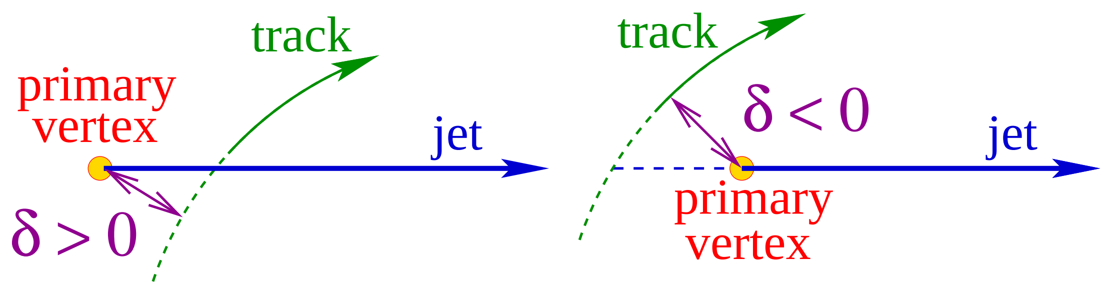
Inclusive Impact Parameter tagging

- inclusive method:
  use all tracks ($p_t > 500$ MeV)
  with vertex detector information

- study significance of the
  (signed) impact parameter
  $S = \delta/\sigma(\delta)$

- separation of beauty, charm
  and light quarks

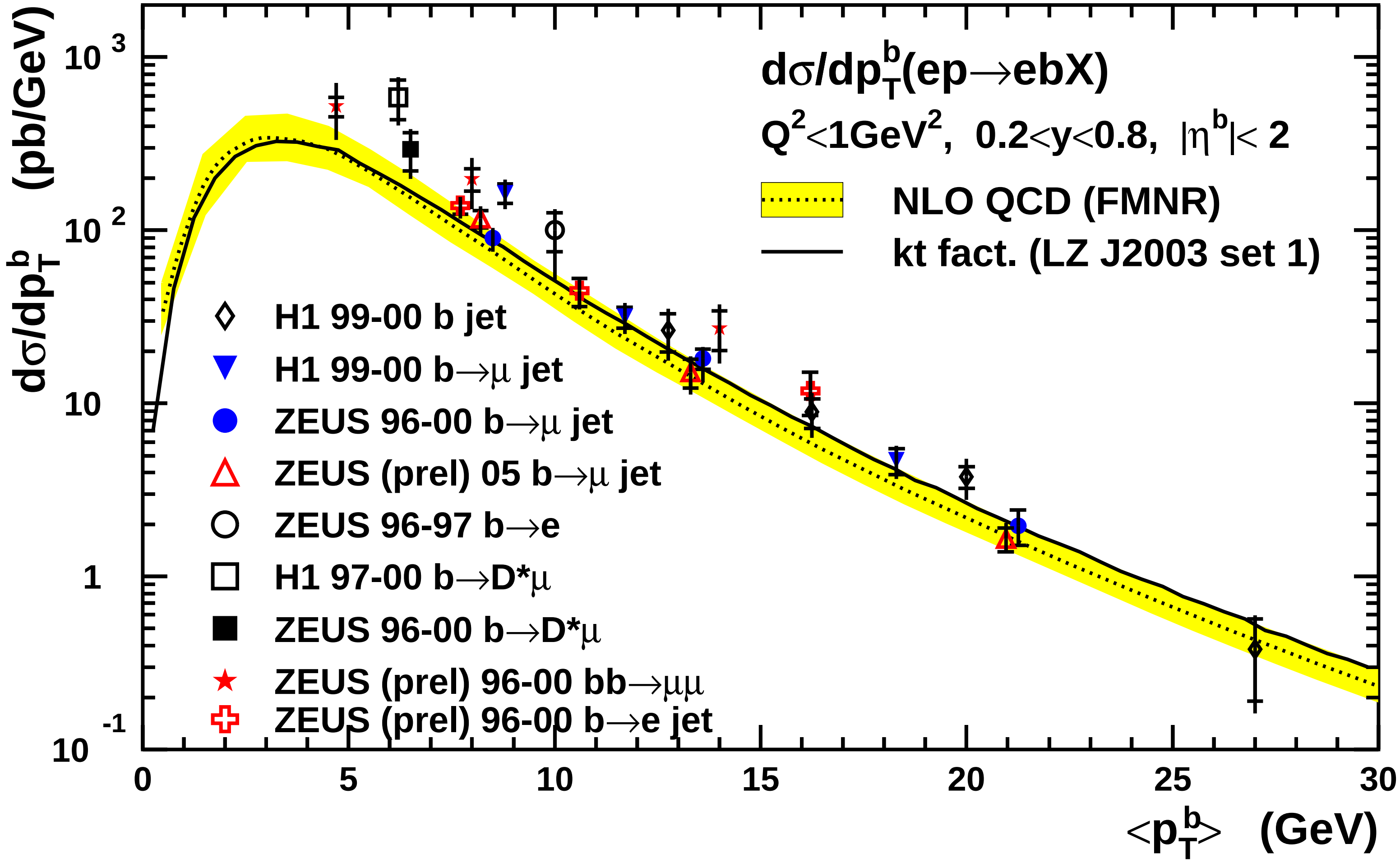




S_2: track with 2^{nd} highest significance

$12 < Q^2 < 650$ GeV^2 $\quad p_t^{track} > 0.5$ GeV
$0.0002 < x < 0.0032$

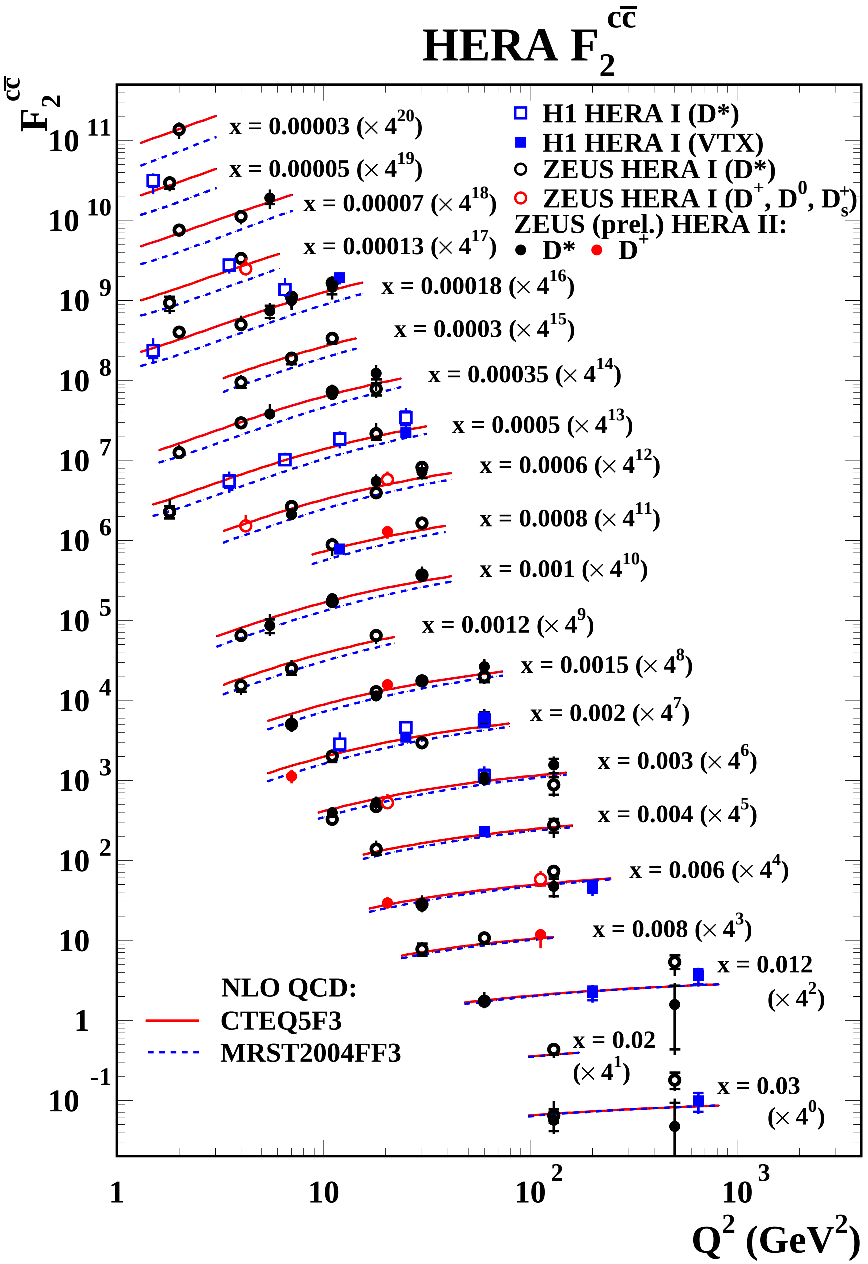
HERA



cross sections for b-production extrapolated using NLO calculations

data at upper edge of NLO prediction

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

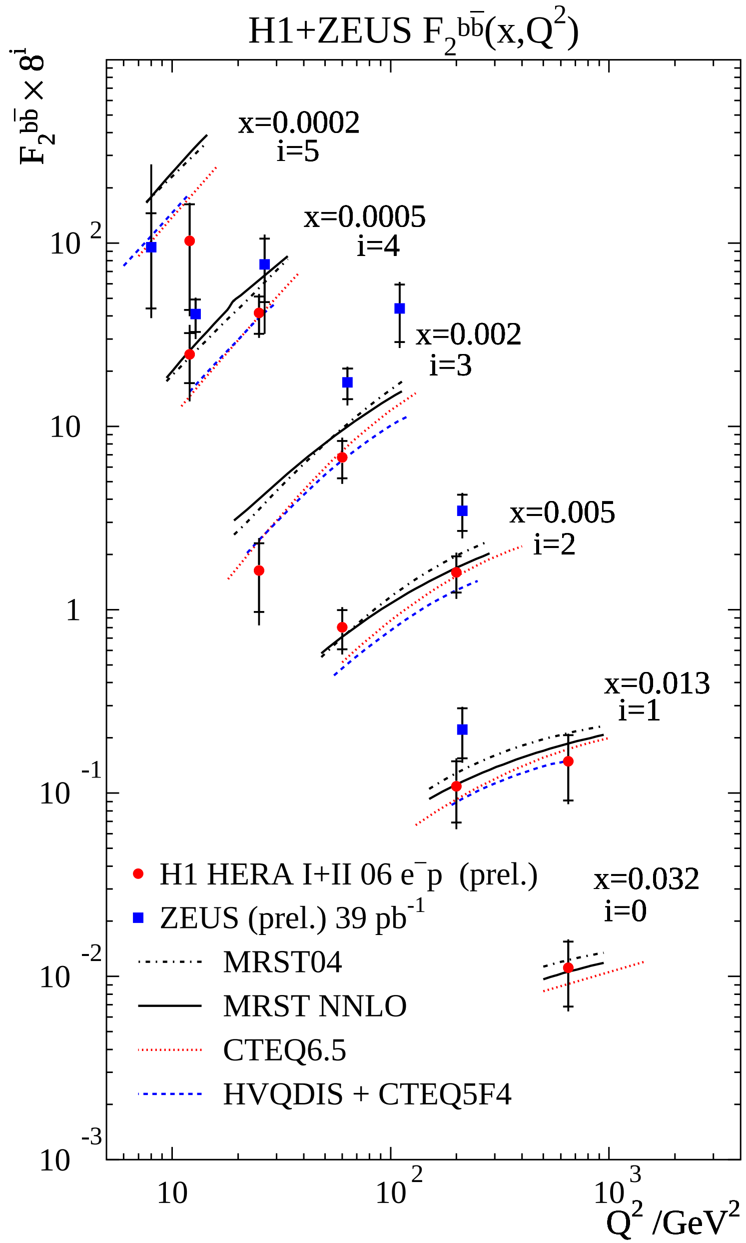


$$\frac{d^2\sigma^{ep\to c\bar{c}X}}{dx\ dQ^2} = \frac{2\pi\alpha^2}{Q^4 x}\left(Y_+ F_2^{c\bar{c}}(x,Q^2) + \ldots\right)$$

$$Y_+ = 1 + (1-y)^2$$

- all available measurements in good agreement
- scaling violation observed at low x
- PDF's differ at low x
- good agreement with NLO

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



First measurements of $F_2^{b\bar{b}}(x, Q^2)$:

- rise with gluon density (towards smaller x and higher Q^2)
- MRST04 and CTEQ6.5 predictions differ by a factor of 2
- experimental errors too large to distinguish between theories/PDFs
- data described by NNLO calculation within large statistical errors

analysis of full data set ongoing

Summary

- Heavy Flavour production in ep-collisions: testing ground for
  - perturbative QCD calculations
  - gluon density in the proton (PDF's)
- Charm production:
  - high statistics
  - H1 and ZEUS using different analysis methods agree in the results
  - good description by NLO calculations
- Beauty production:
  - reasonable description within uncertainties
  - whole HERA data needed to reduce statistical uncertainties
- Structure functions $F_2^{c\bar{c}}$, $F_2^{b\bar{b}}$:
  - data described well by predictions
  - charm data is sensitive to PDF's

looking forward to analyses using full HERA statistics

Backup slides

$F_2^{c\bar{c}}$ extraction: H1 and ZEUS

$$\frac{d^2\sigma^{ep\to c\bar{c}X}}{dx\ dQ^2} = \frac{2\pi\alpha^2}{Q^4 x}\left\{(1+(1-y)^2)F_2^{c\bar{c}}(x,Q^2) - y^2 F_L^{c\bar{c}}(x,Q^2) + ...xF_3^{c\bar{c}}\right\}$$

dominant contribution to σ | significant at high y | significant at high Q^2

- ZEUS extracts $F_2^{c\bar{c}}$ from D meson cross sections using HVQDIS to extrapolate to the full meson phase space:

$$F^{c\bar{c}}_{2,meas}(x_i,Q_i^2) = \frac{\sigma_{i,meas}(ep\to D^*X)}{\sigma_{i,theo}(ep\to D^*X)}\cdot F^{c\bar{c}}_{2,theo}(x_i,Q_i^2)$$

- H1 measures charm inclusively:

$$\tilde{\sigma}^{c\bar{c}}(x,Q^2) = \tilde{\sigma}(x,Q^2)\frac{P_c N_c^{MC}}{P_c N_c^{MC} + P_b N_b^{MC} + P_l N_l^{MC}}\cdot \delta_{BCC}$$

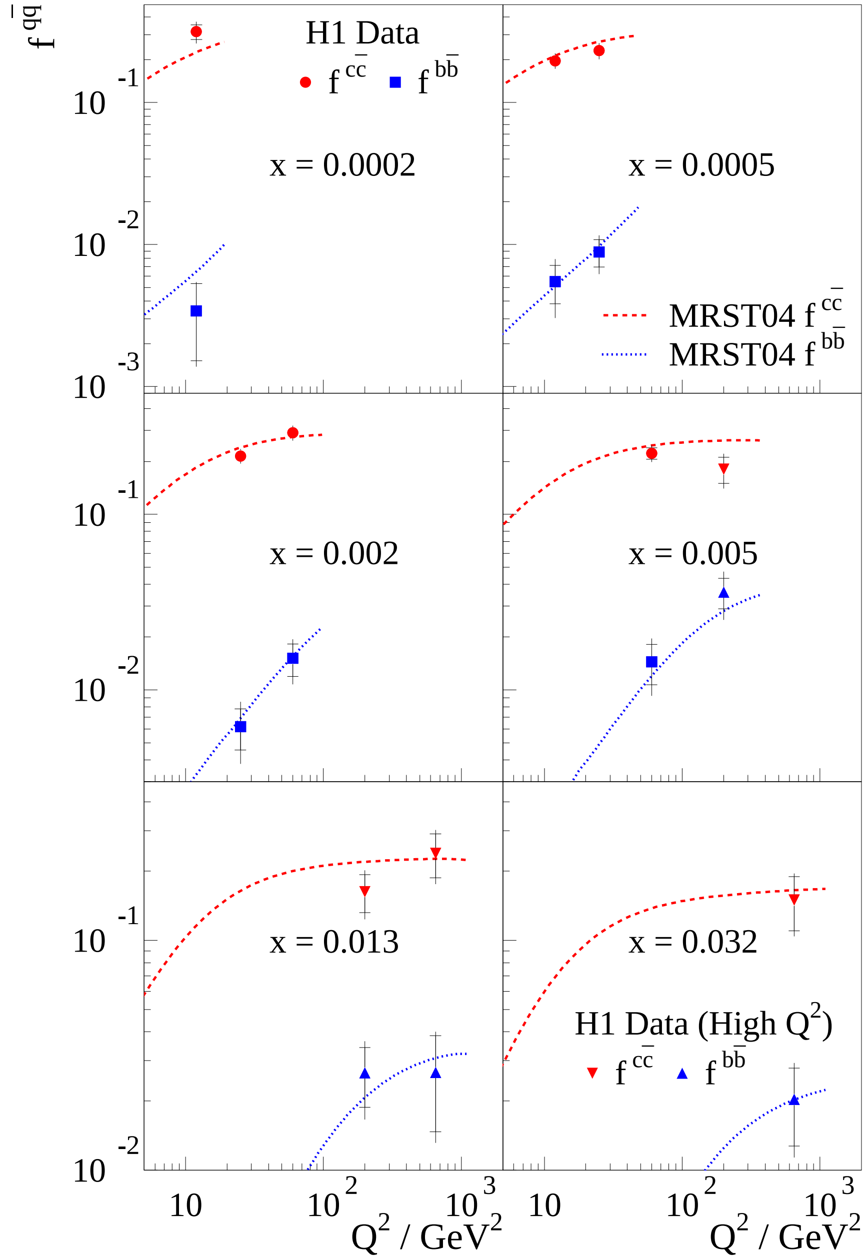
$P_{c,b,l}$ are the fractions of charm, beauty and light flavour from the fit and $\tilde{\sigma}$ is the inclusive reduced cross section.

PDF schemes and parameter

PDF	Order	Scheme, Nf	μ^2	M_b(GeV)
MRST04	α_s^2	VFNS	Q^2	4.3
MRST NNLO	α_s^3	VFNS	Q^2	4.3
CTEQ6.5	α_s^2	VFNS	$Q^2 + M^2$	4.5
HVQQDIS+CTEQ5F4	α_s^2	FFNS, 4	$\frac{1}{4}\left(p_t^2 + Q^2 + M^2\right)$	4.75
CTEQ6HQ	α_s^2	VFNS	$Q^2 + M^2$	4.5

Theory predictions except HVQDIS+CTEQ5F4
provided by P. D. Thompson, hep-ph/0703103

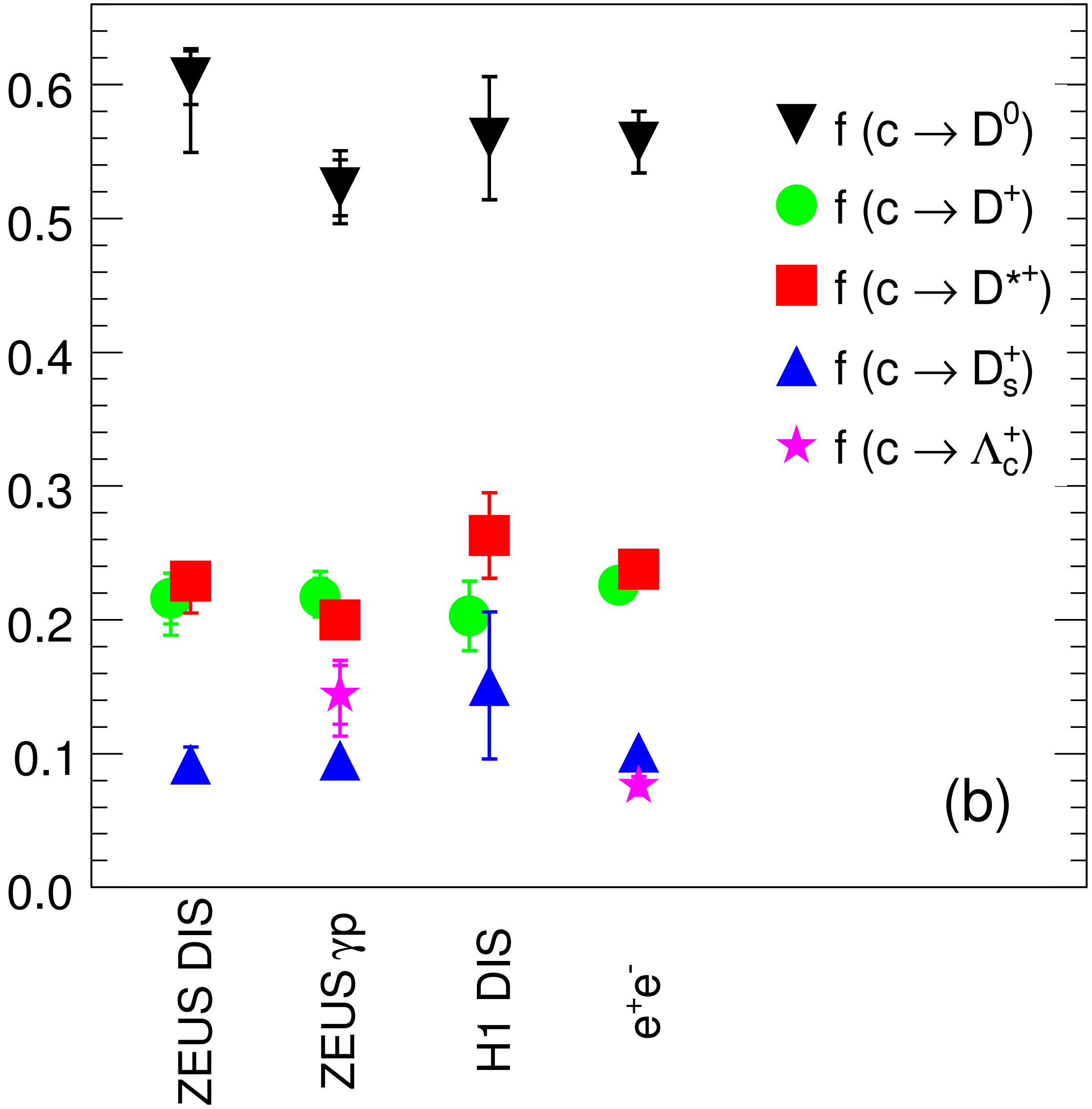
$F_2^{q\bar{q}}/F_2$



charm and beauty contribution to F_2:

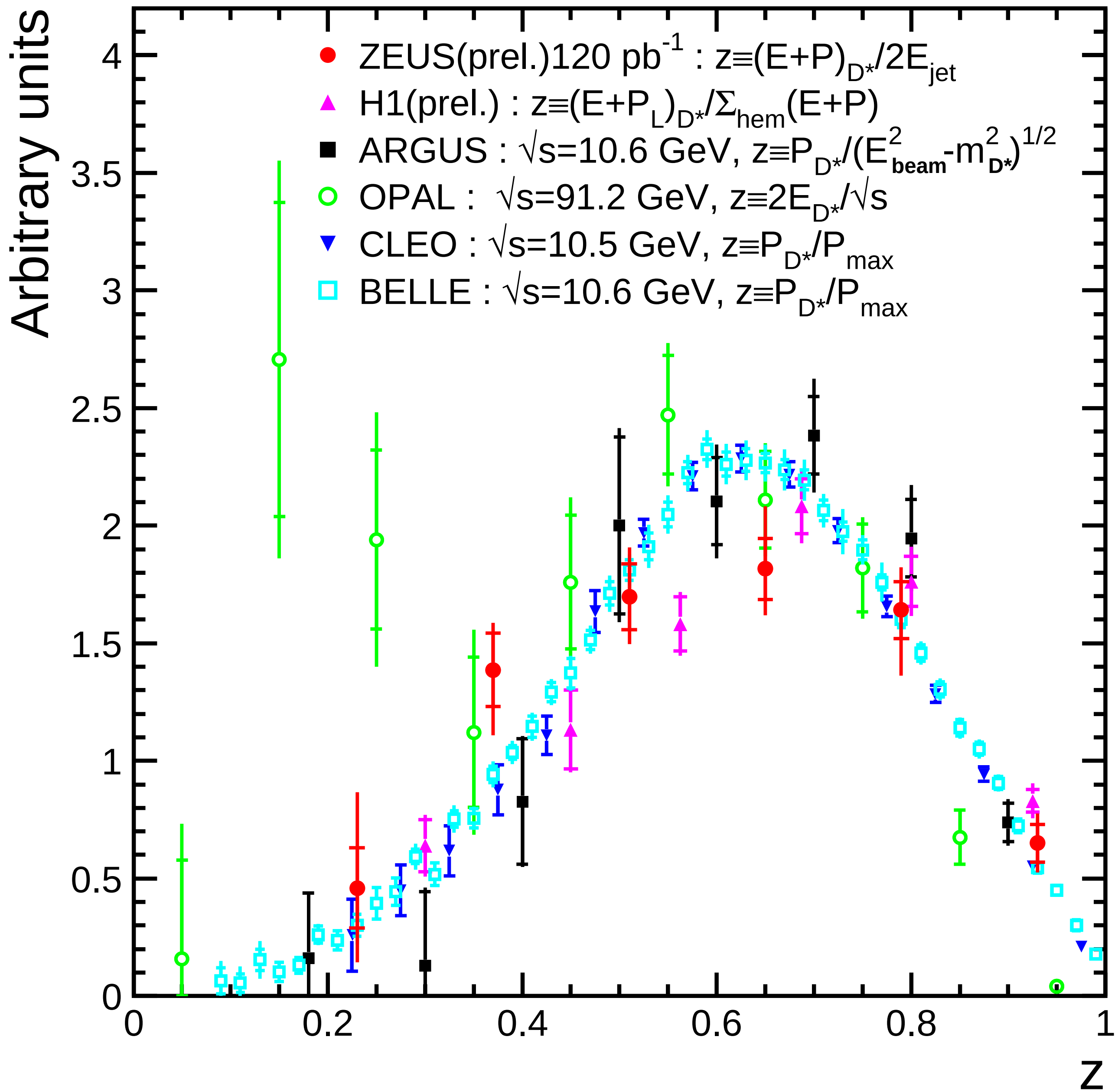
- large charm fraction up to $\sim 30\%$
- small beauty fraction $\sim$ few %
- reasonable agreement with NLO QCD prediction

Fragmentation fractions



- fraction of charm quarks hadronising as a particular D meson
- agreement between HERA and LEP experiments

Fragmentation function



Energy transfer:

$$z = \frac{E_{D*}}{E_c}$$

- Hadronization of quarks into Hadrons not calculable in pQCD
- quark $\rightarrow$ meson transition described by phenomenological transition function
- expected to be universal

similar spectra

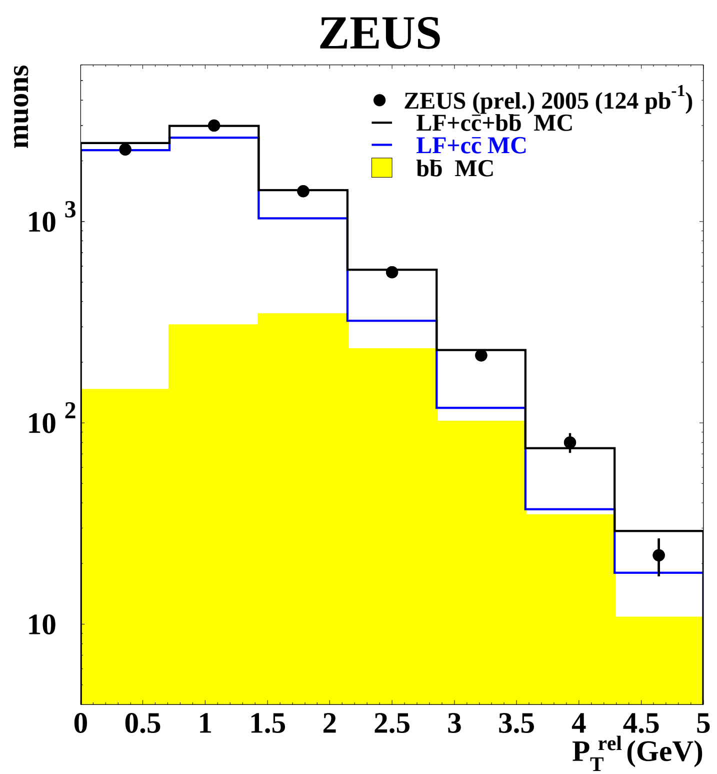
Beauty tagging: p_t^{rel}

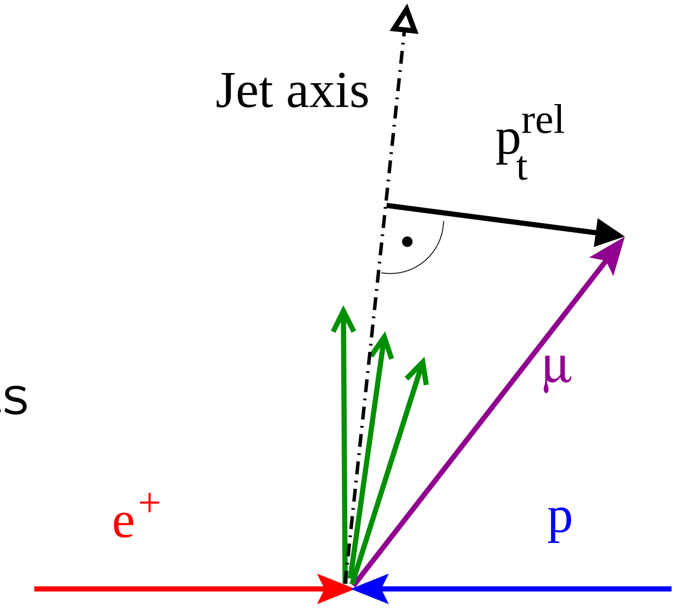
Why beauty?

$\sigma_{b\bar{b}}/\sigma_{c\bar{c}} \sim 0.05 \Rightarrow$ hard to identify beauty, but
$m_b > m_c \Rightarrow$ pQCD should become more reliable

How to identify $b \to \mu\bar{\nu}X$?

2 jet events (BGF) with tagged μ in one of the jets





Large b mass causes high p_t of μ relative to the jet (p_t^{rel})

$Q^2 < 1$ GeV^2
$0.2 < y < 0.8$

$E_t^{jets} > 7(6)$ GeV $\quad |\eta(jets)| < 2.5$
$p_t(\mu) > 2.5$ GeV $\quad -1.6 < \eta(\mu) < 2.3$

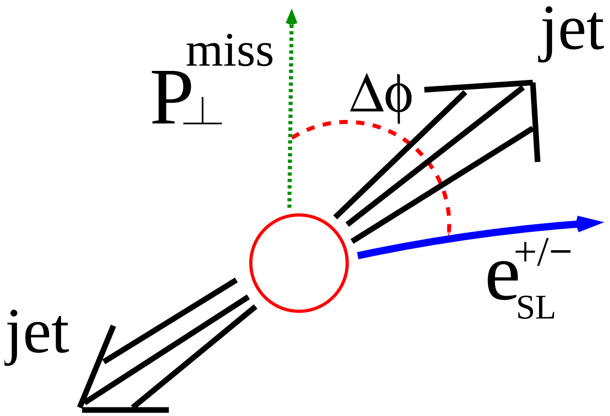
Beauty in Dijet γp using electrons

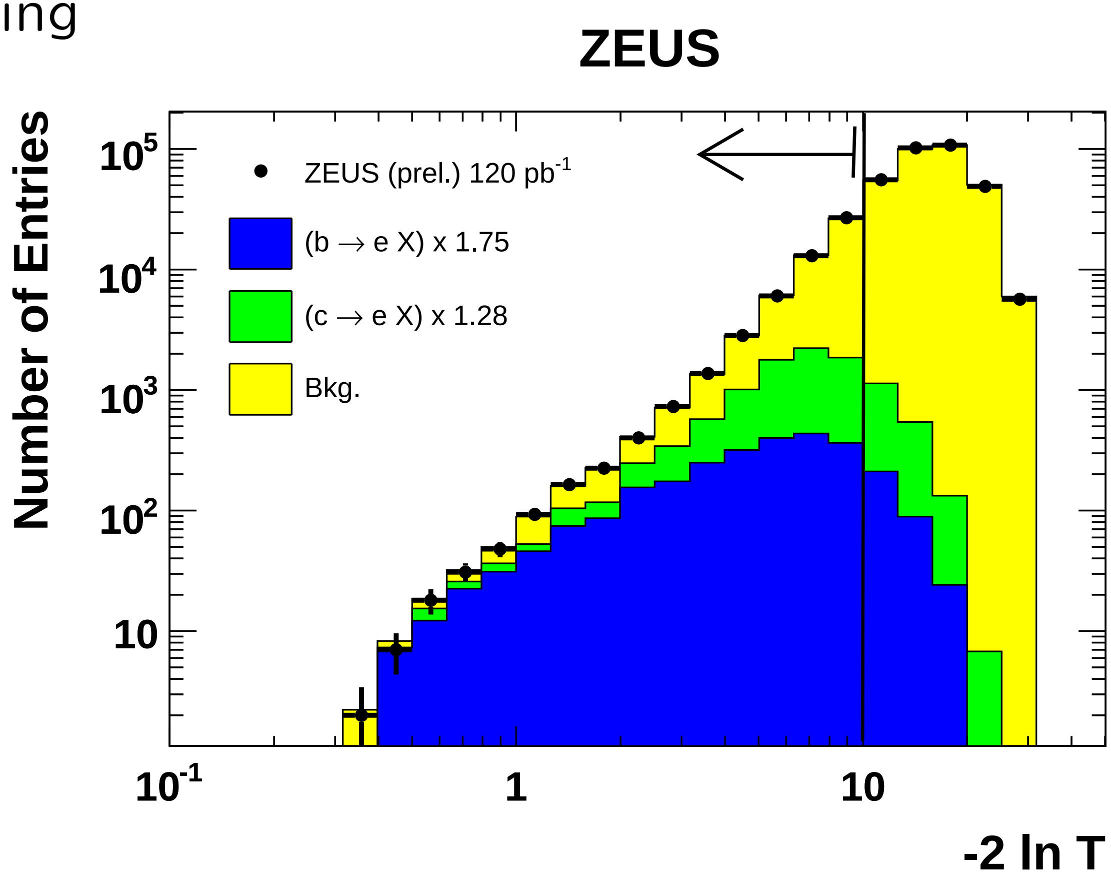
Likelihood function of discriminating input variables:

dE/dx, f_{EMC}, E_{EFO}/p_{trk} } e-identification

$\Delta\phi$ b,c $\leftrightarrow$ LF separation

p_t^{rel} b $\leftrightarrow$ c separation





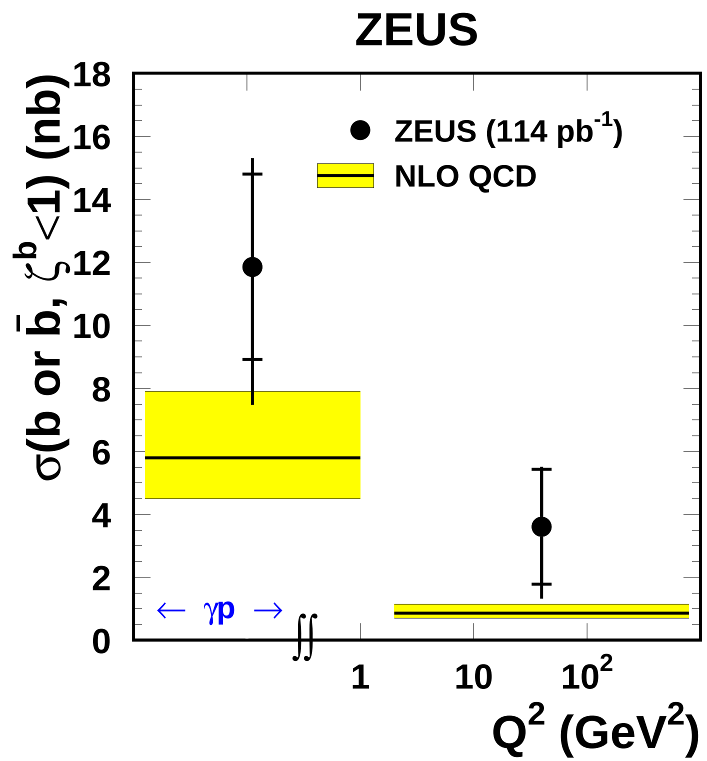
$Q^2 < 1$ GeV^2
$0.2 < y < 0.8$

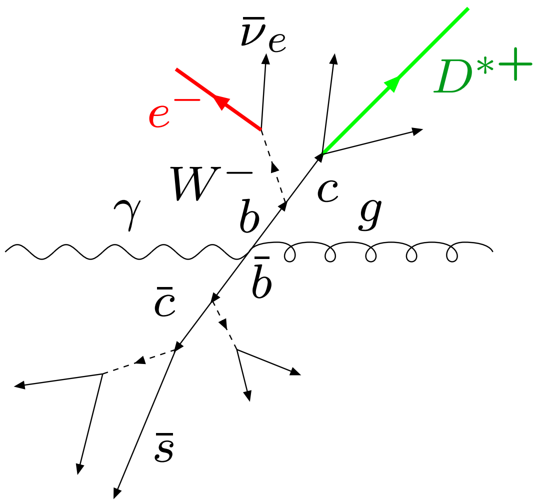
$E_t^{jets} > 7(6)$ GeV $\quad |\eta(jets)| < 2.5$
$p_t(e) > 0.9$ GeV $\quad |\eta(e)| < 1.5$

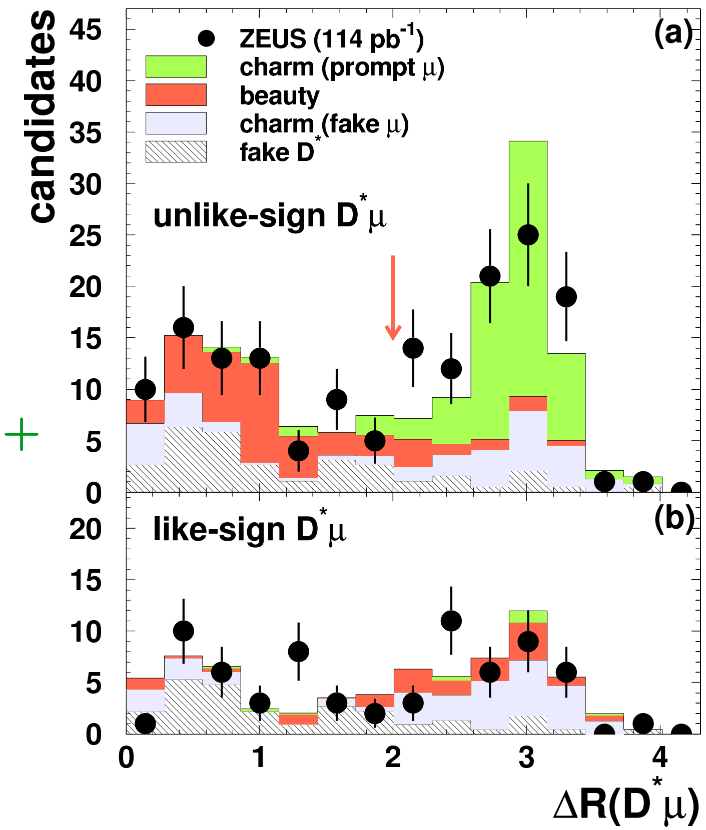
Double tagging of $b\bar{b}$–pair

use two direct flavour tags ($D^* + \mu$ or $\mu + \mu$)

- strong background reduction;
  no jets needed
- low p_t accessable





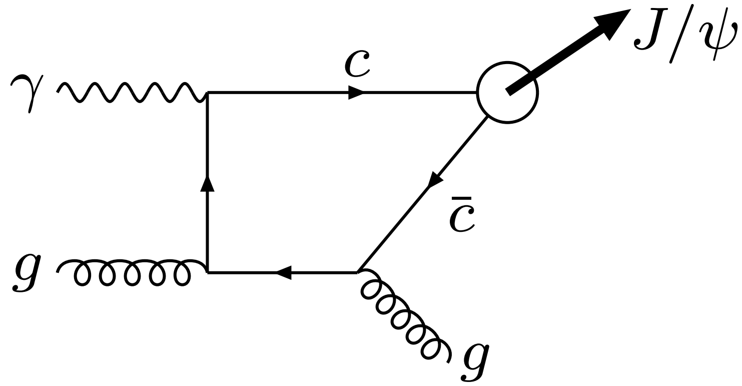


- measurement exceeds NLO QCD prediction
- compatible within errors
- agreement with corresponding H1 result

Inelastic J/ψ production

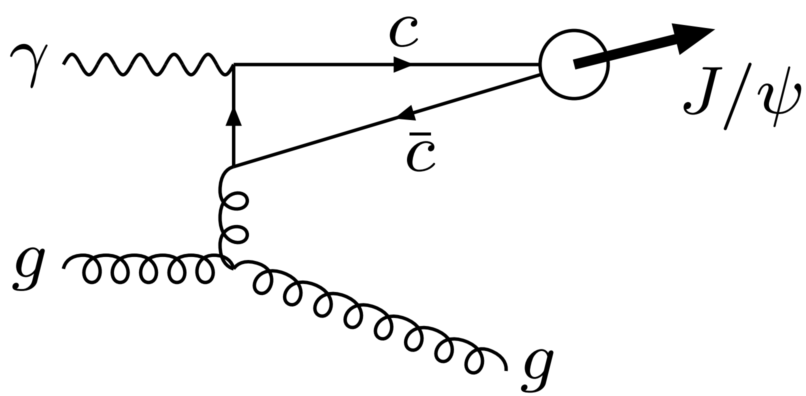
Colour Singlet (CS) contribution

- directly calculable
- available at LO and NLO

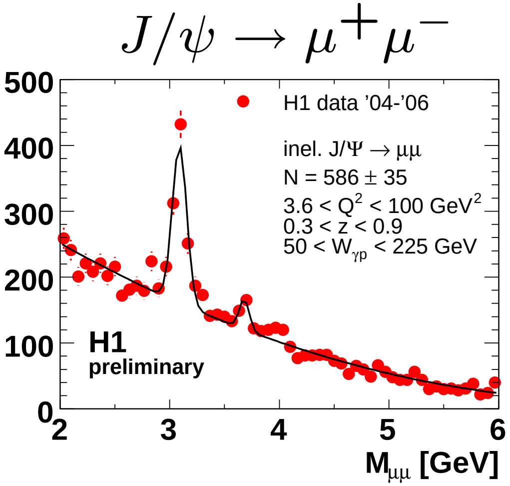


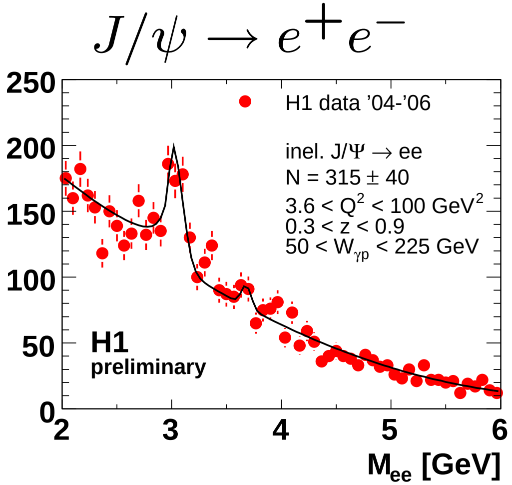
Colour Oktet (CO) contribution

- introduced in non-relativistic QCD model (NRQCD)
- described by long distance matrix elements (LDME)
- parameterized from Tevatron data
- prediction for HERA, LO only



Inelastic J/ψ production



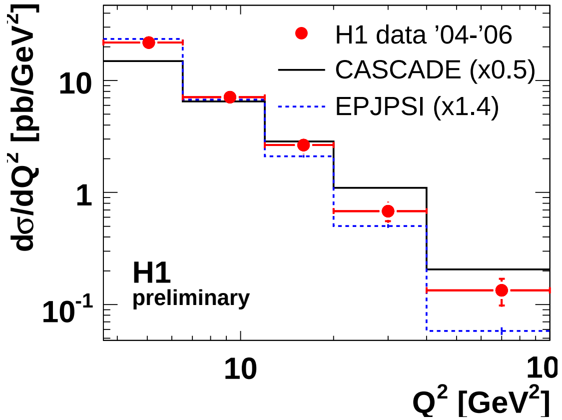


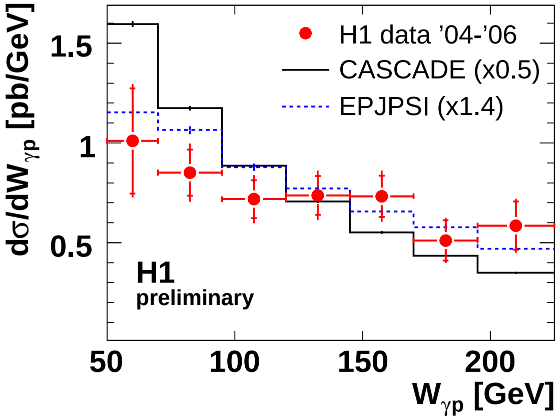
$3.6 < Q^2 < 100$ GeV^2
$50 < W_{\gamma p} < 225$ GeV
$0.3 < z < 0.9$
$p^*_{t,\psi} > 1$ GeV

Monte Carlo (CS):

- CASCADE (scaled by 0.5)
- EPJPSI (scaled by 1.4)

- Q^2 distribution
  - too hard in CASCADE
  - too steep in EPJPSI





- double differential cross sections in z and p_t^{*2}
  - well described by leading order MC (colour singlet only)
  - no direct indications for colour octet