Heavy Flavour Production in ep Collisions

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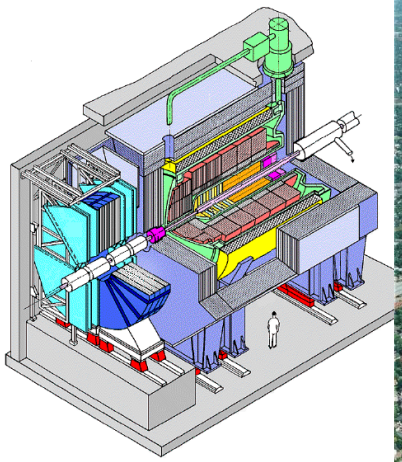
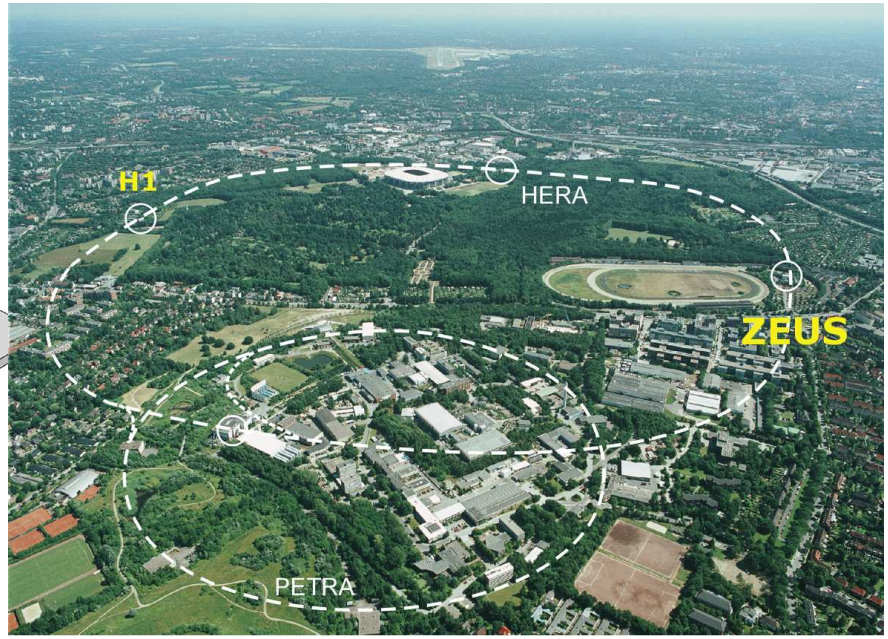
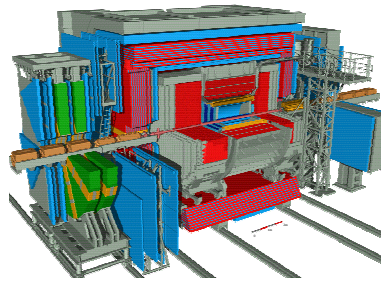
- Introduction
- Charm Production
- Beauty Production
- F_2^{cc} and F_2^{bb}

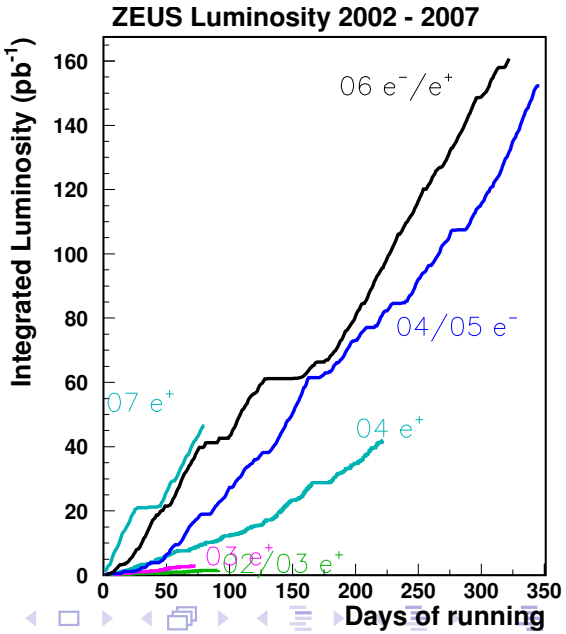
H1 and ZEUS







- 27.5 GeV $e^{\pm}$ colliding with 920 GeV $p \rightarrow \sqrt{s} = 318$ GeV
- HERAI: 1992-2000
- HERAII: 2003-2007

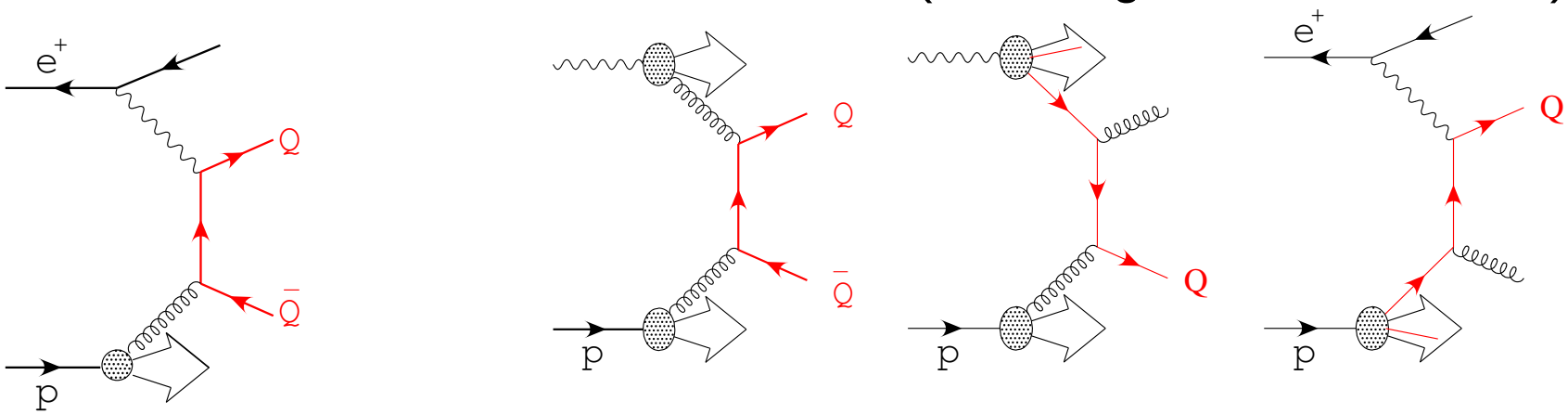


Motivation

- Heavy Flavour production is a good probe for pQCD
- Multiple scales:
  - large mass m_b / m_c
  - large photon virtuality Q^2
  - high momenta p_T
- Factorisation in perturbative QCD:

  σ = parton distr. $\otimes$ hard scattering $\otimes$ fragmentation/hadronisation

”direct” ”resolved”(including flavour excitation)



x_γ^{obs} : Fraction of photon momentum carried by jet pair -

distinguish between direct ($x_\gamma^{obs} \sim 1$) and resolved ($x_\gamma^{obs} < 1$)

Theoretical Description

Monte Carlo Programs

leading order + parton shower

- DGLAP evolution (collinear factorization)
  - RAPGAP (DIS)
  - PYTHIA, HERWIG (γp)
  - EPJPSI (J/Ψ)
- CCFM evolution (k_t-factorization)
  - CASCADE (DIS+γp)

NLO Calculations

full NLO calculations available

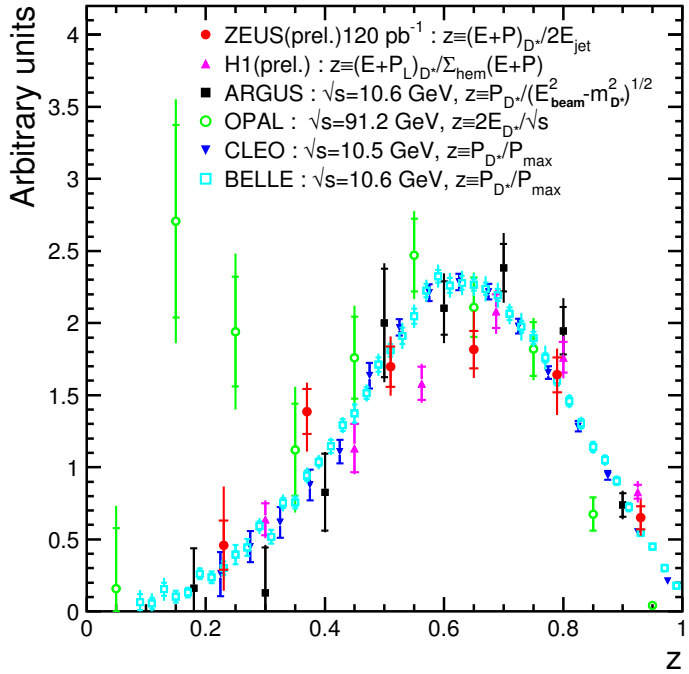
- HVQDIS (DIS)
- FMNR (γp)

(both using massive calculations)

Fragmentation Function

- Hadronization of quarks into jets not calculable in pQCD
- *c* quark to meson transition described by (phenomenological) fragmentation function
- Expected to be universal

→ Uncertainties due to choice of fragmentation functions (Peterson, Kartvelishvili ....) and their parameters

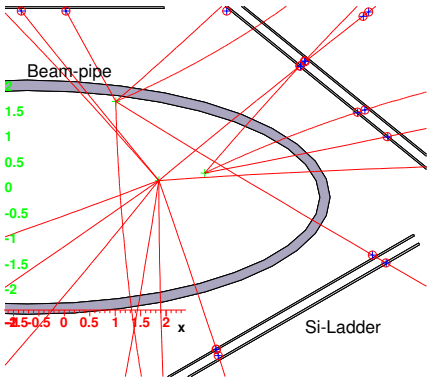


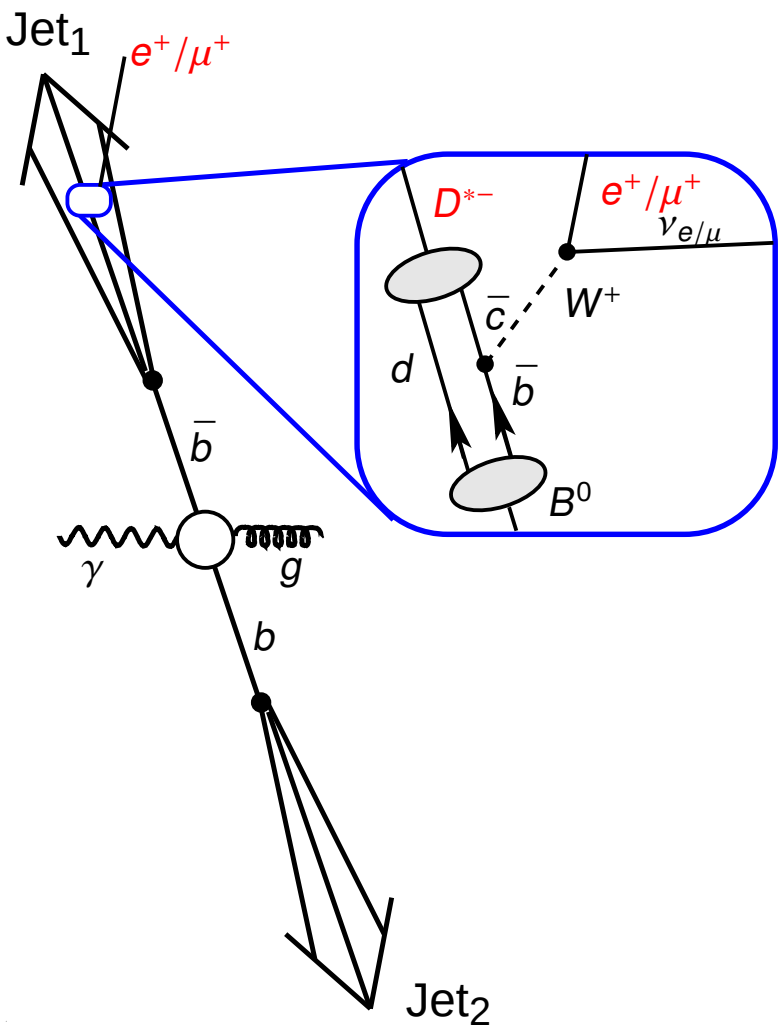
z : fraction of the charm quark energy carried by the corresponding heavy meson

Heavy Flavour Tagging

Different experimental techniques to use (combine) for heavy flavour tagging:

- Meson identification
  $D^{*\pm}$ tagging (”Golden Decay”)
- Decay spectra
  p_T^{rel} of lepton to jet axis
- Lifetime information
  Measure impact parameter with respect to primary vertex (beamspot)





Part I

Charm Production

Decay Channel:

$D^{*\pm} \rightarrow D^0 \pi^{\pm}_{slow} \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm}_{slow}$

HERAII data:

2004-2006 ($\mathcal{L} \approx 222\,\mathrm{pb}^{-1}$)

(4 x higher statistics → 10000 D^*)

Kinematic region:

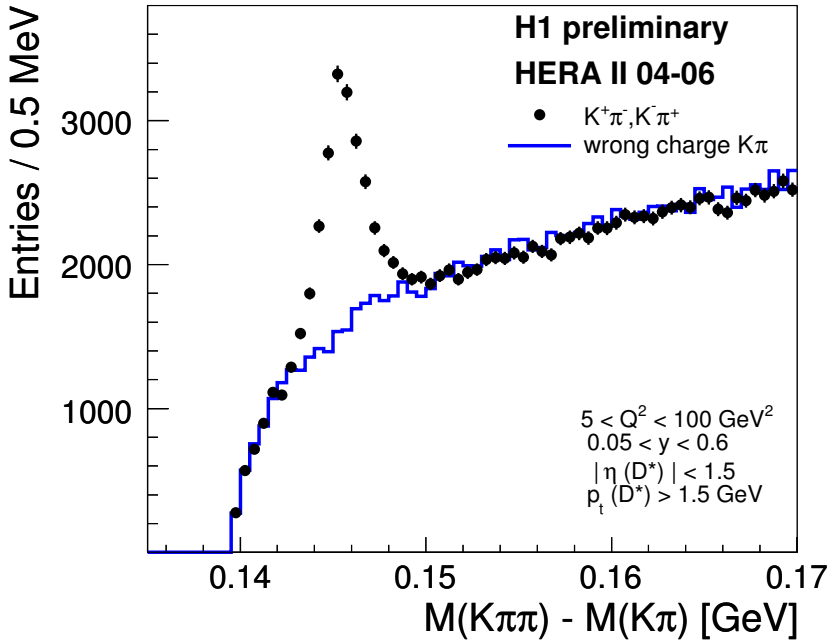
$5 < Q^2 < 100\,\mathrm{GeV}^2$

$0.05 < y < 0.6$

Visible range:

$p_T(D^*) > 1.5\,\mathrm{GeV}$

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

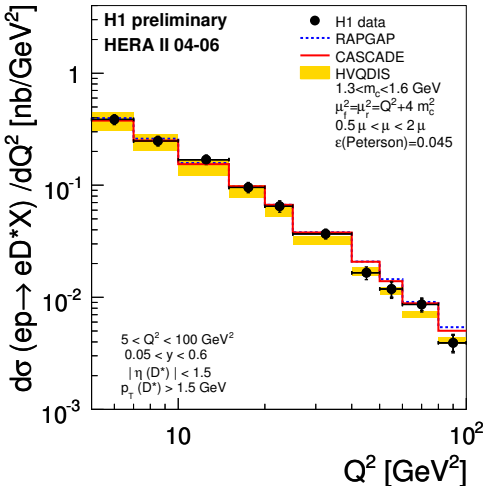


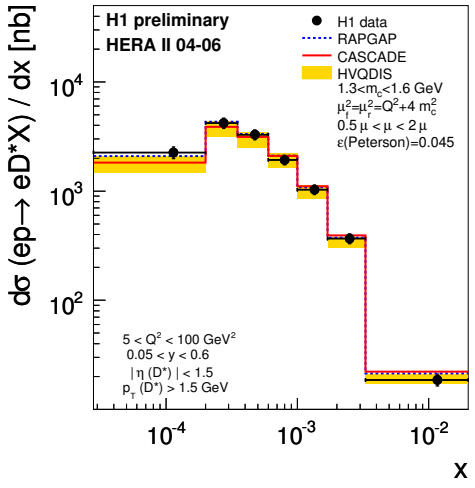
New preliminary result:

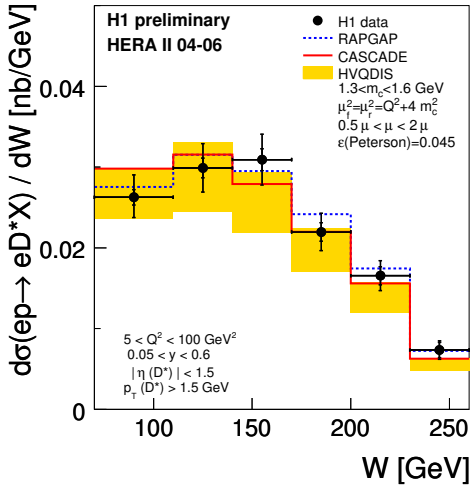
$\sigma^{vis}_{tot}(e^{\pm}p \rightarrow e^{\pm}D^{*\pm}X) =$

$4.23 \pm 0.09(stat.) \pm 0.37(syst.)nb$

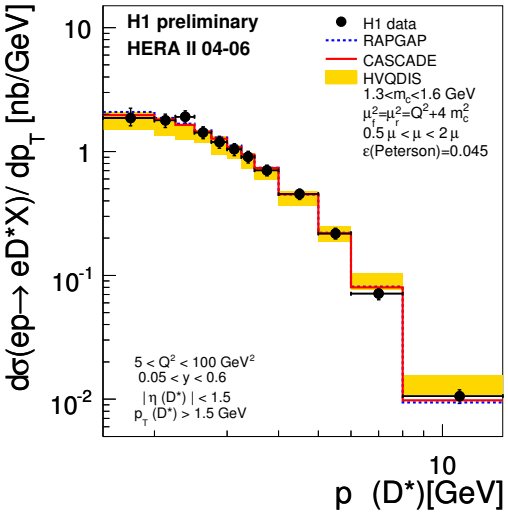
	σ^{vis}_{tot}	$m_c[GeV]$
HVQDIS	4.28 nb	1.3
	3.46 nb	1.6
RAPGAP	4.40 nb	1.5
CASCADE	4.29 nb	1.5

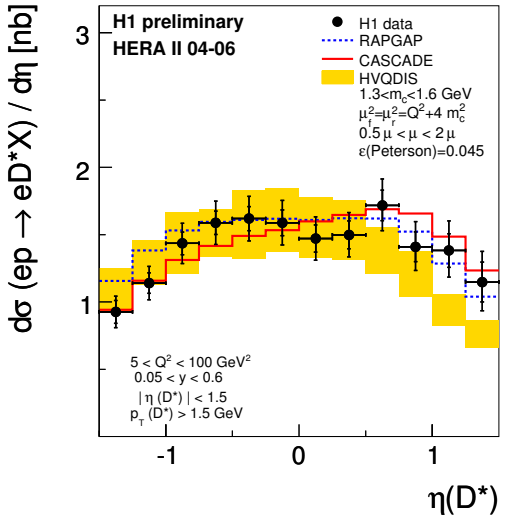


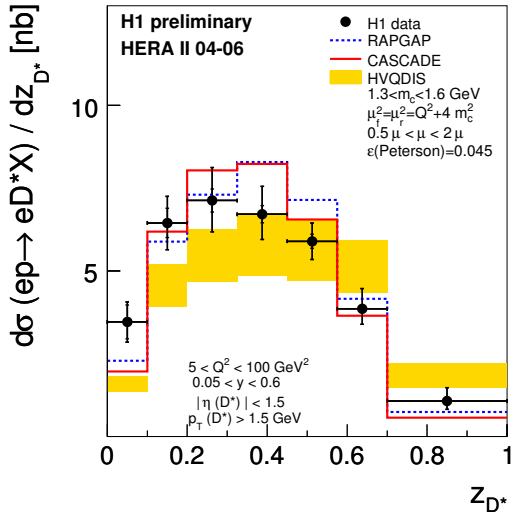




- All prediction describe the measurement within the uncertainties
- Measurement at the upper edge of HVQDIS prediction







Transverse momentum

- well described by MC programs
- HVQDIS slightly too hard

Pseudorapidity

- CASCADE OK
- HVQDIS too low for $\eta > 0.5$
- RAPGAP too high for $\eta < -1$

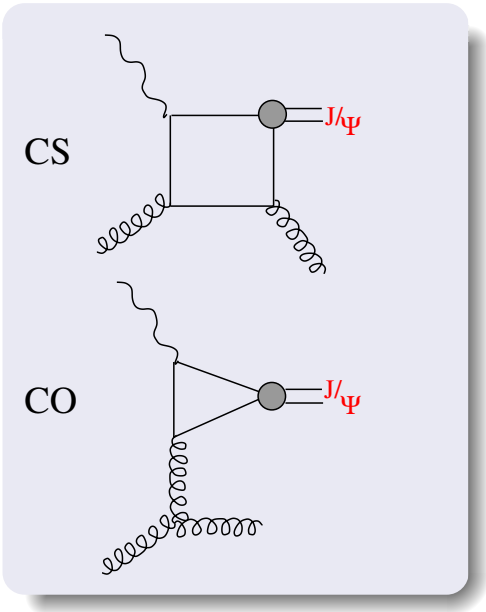
Inelasticity

- reasonably well described by MC programs
- HVQDIS fails

Charmonium production:

1. heavy quark pair ($c\bar{c}$) produced at short distances
2. formation of Ψ bound state in
   - colour singlet (CS)
   - colour octet (CO)

   in non-relativistic QCD model (NRQCD)
   both CS and CO exists
   $\rightarrow$transition to real J/Ψ by non-perturbative
   long distance matrix elements (LDME)



Sensitivity to production mechanism:

different regions of inelasticity z

- CS in medium $z-$ region
- CO (and diffraction) populate high $z-$values
- ”resolved” processes lead to lower $z-$values

Inelastic J/Ψ Production

HERAII data:

2004-2006 ($\mathcal{L} \approx 258\,\mathrm{pb}^{-1}$)

Kinematic region:

$3.6 < Q^2 < 100\,\mathrm{GeV}^2$,

$50 < W_{\gamma p} < 225\,\mathrm{GeV}$

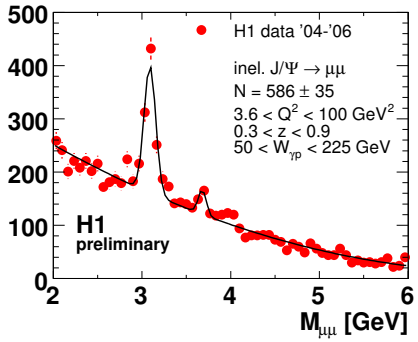
$0.3 < z < 0.9$, $p^*_{t,\Psi} > 1\,\mathrm{GeV}$

Monte Carlo (CS):

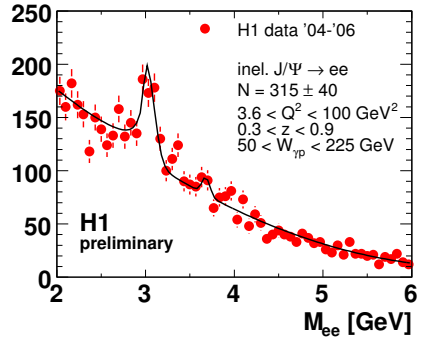
- EPJPSI (scaled by 1.4)
- CASCADE (scaled by 0.5)

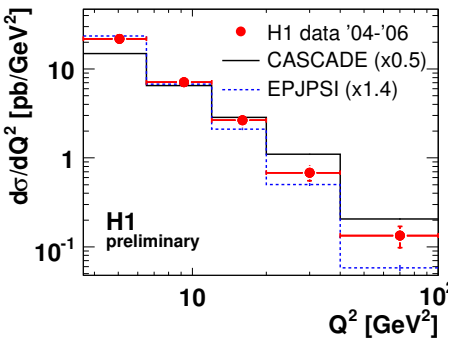
- Q^2 distribution
  too steep in EPJPSI
  too hard in CASCADE
- $W_{\gamma p}$ better described by EPJPSI

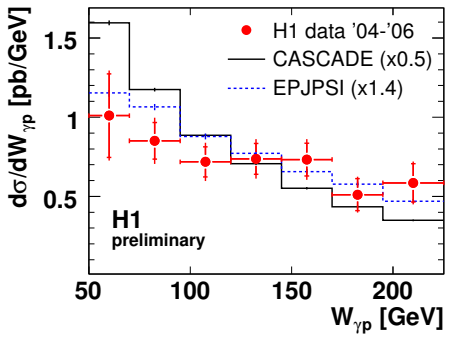
$J/\Psi \to \mu^+\mu^-$



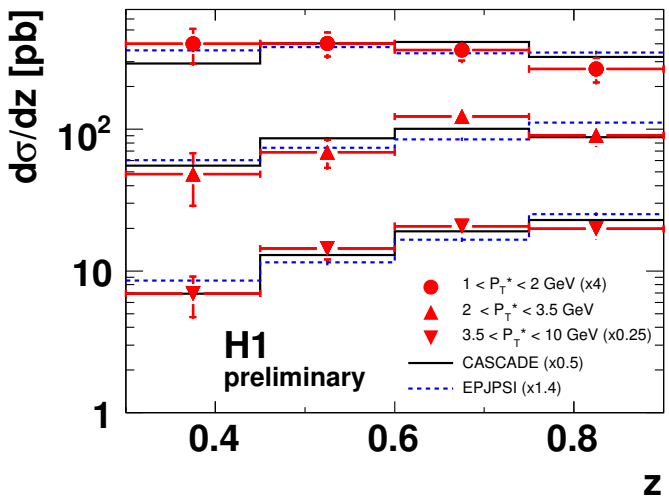
$J/\Psi \to e^+e^-$

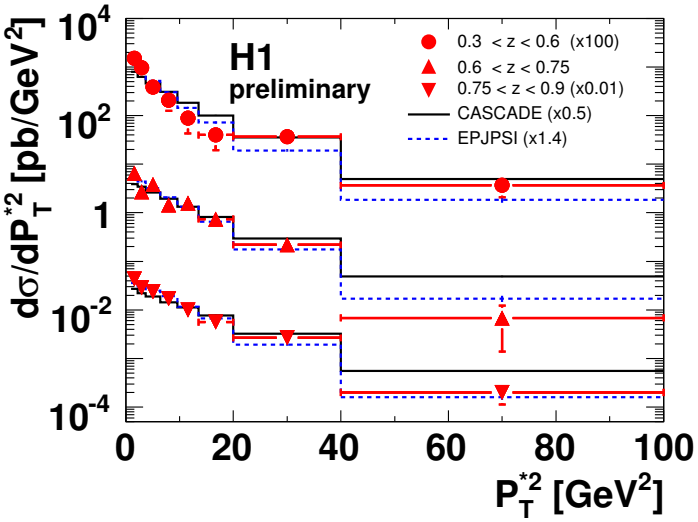






Double differential cross sections in p_T^{*2} and z





- Dependencies well reproduced by scaled leading order Monte Carlo (**colour singlet only**)
- No direct indication for contributions of colour octett

Part II

Beauty Production

Method:

Combined fit of p_T^{rel} and

δ w.r.t beamspot

HERAII data:

2004-2005 ($\mathcal{L} \approx 125\,\text{pb}^{-1}$)

Result:

$\sigma_{b\bar{b}}^{vis}(ep \to e' b\bar{b} X \to e' jj\mu X) =$

$46.8 \pm 4.0(stat.) \pm^{6.1}_{7.2} (syst.) pb$

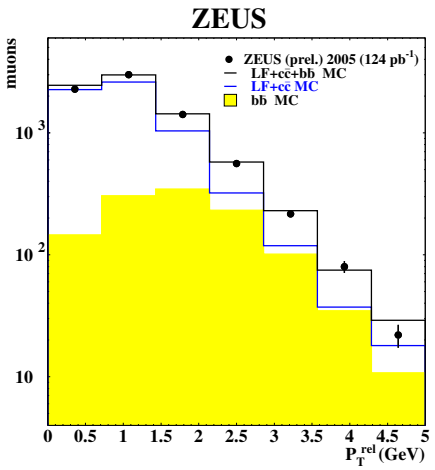
$\sigma_{NLO} = 41.5 \pm^{13.9}_{8.9}$ pb

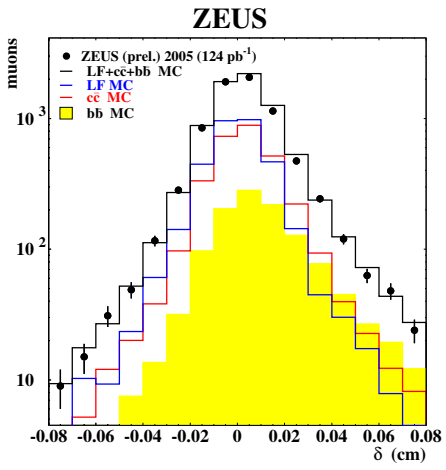
Kinematic region:

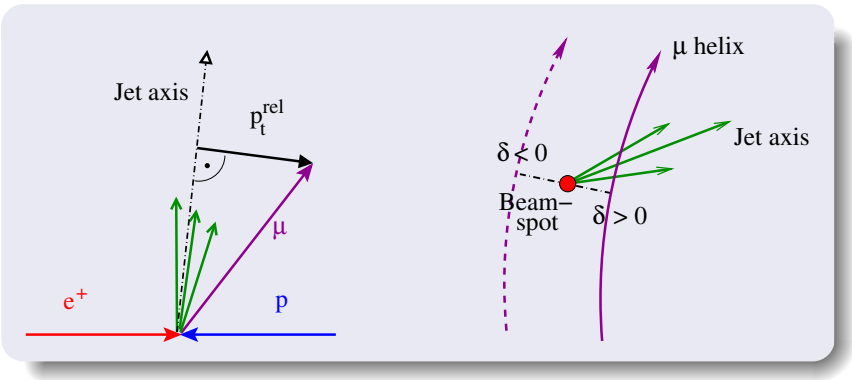
$Q^2 < 1\,\text{GeV}^2,\ 0.2 < y < 0.8$

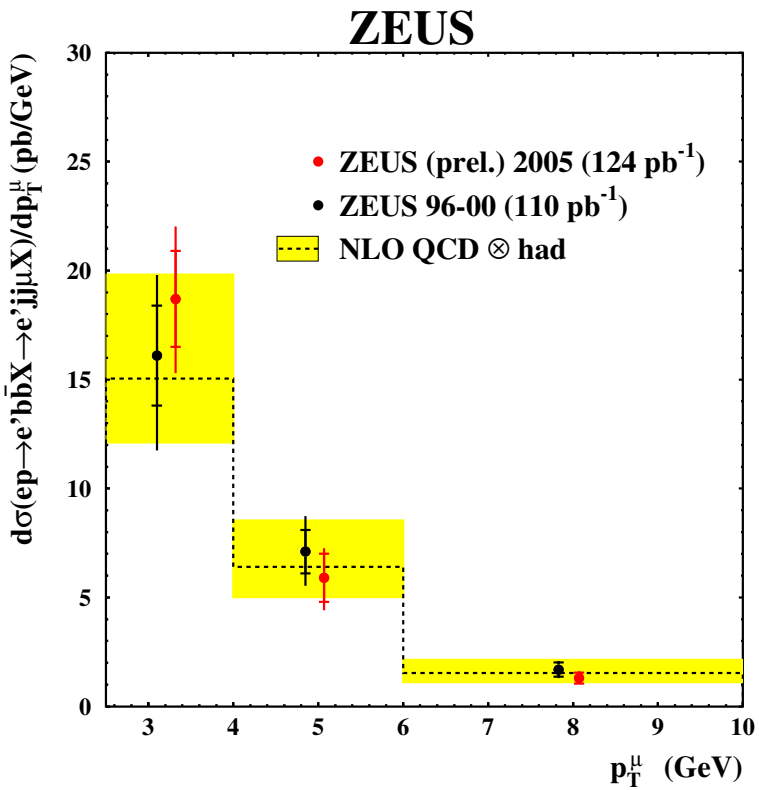
$p_T^{jets} > 7(6) GeV,\ |\eta^{jets}| < 2.5$

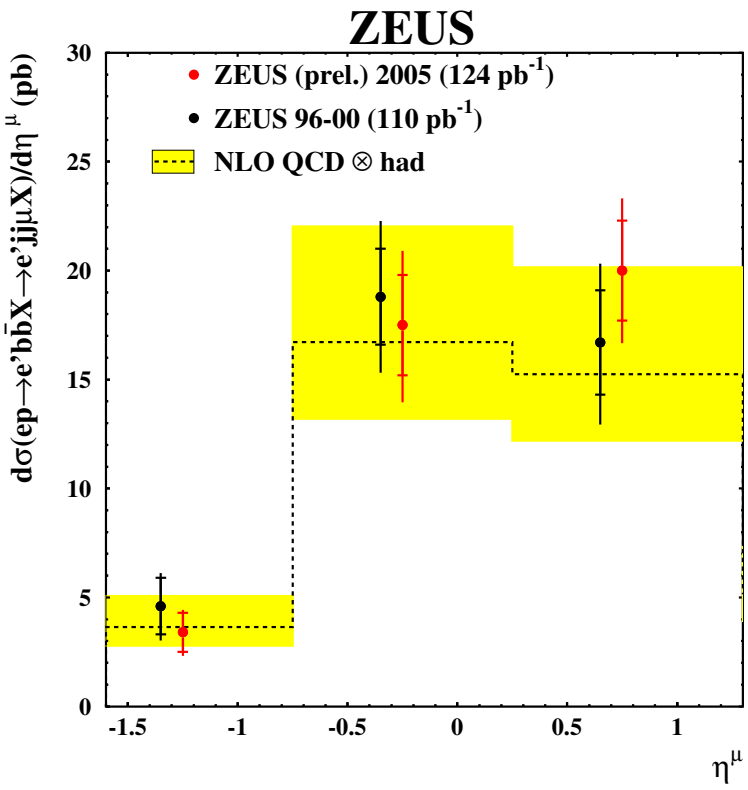
$p_T^{\mu} > 2.5\,\text{GeV},\ -1.6 < \eta^{\mu} < 2.3$











- NLO QCD calculation (FMNR) describe data
- Agreement with ZEUS data from HERAI
- Cross-check with HERAI method (only p_T^{rel})

Method:

Combine discriminating input variables in a likelihood function to a hypothesis test

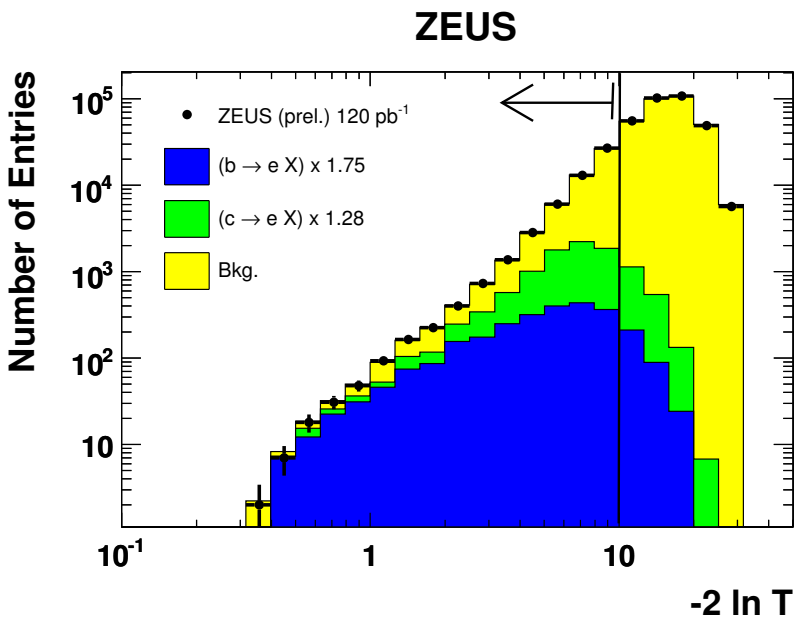
$$T_{B\to eX} = \frac{\mathcal{L}_{B\to eX}}{\sum_j \mathcal{L}_j}$$

$dE/dx, f_{EMC}$, e – identification

E_{EFO}/p_{trk} :

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

p_T^{rel}: $b \leftrightarrow c$ separation



HERAI data:

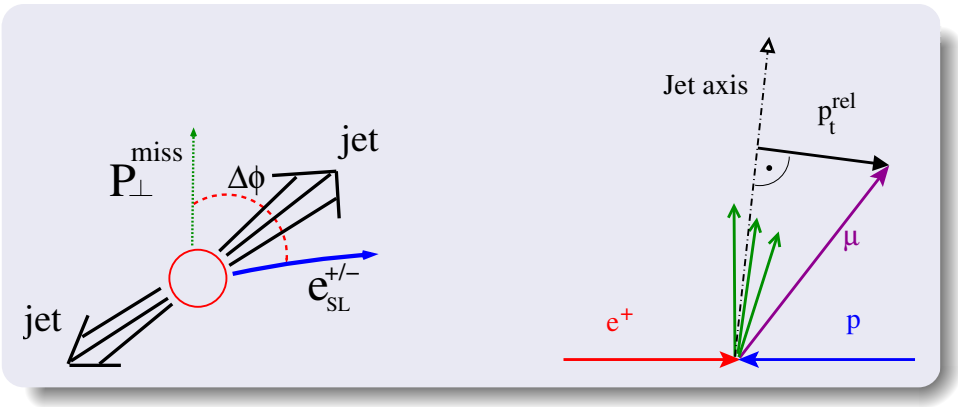
1996-2000 ($\mathcal{L} \approx 120\,\text{pb}^{-1}$)

Kinematic region:

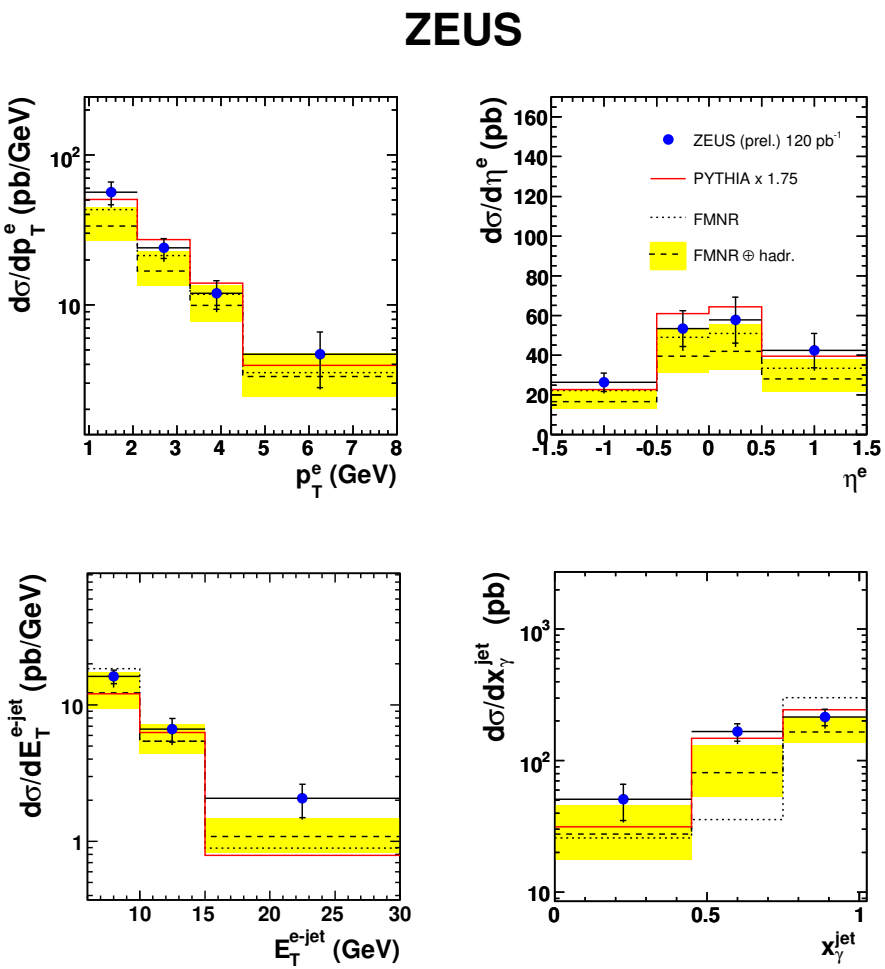
$Q^2 < 1\,\text{GeV}^2$, $0.2 < y < 0.8$,

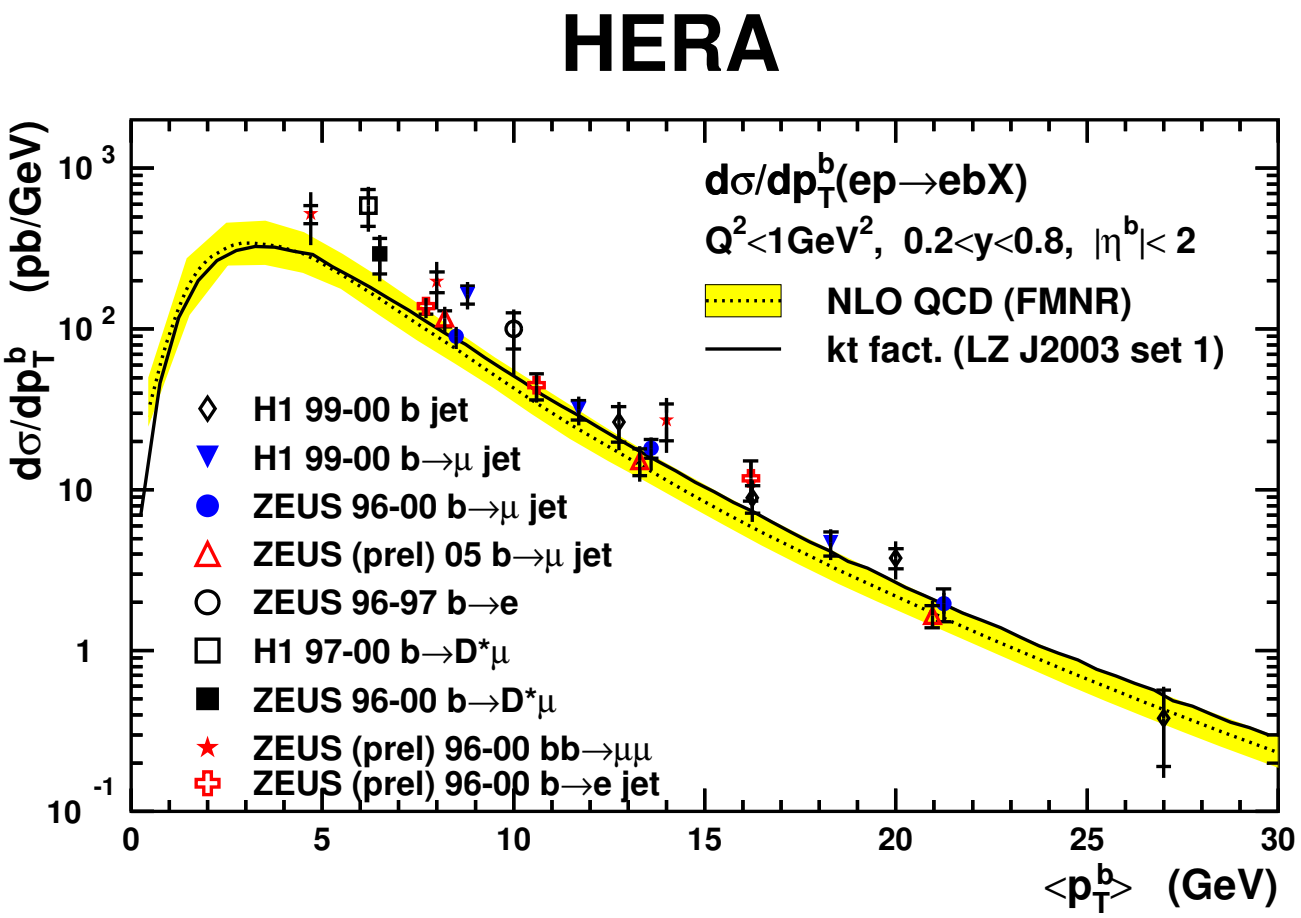
$E_T^{jets} > 7(6)GeV$, $|\eta^{jets}| < 2.5$

$p_T^e > 0.9\,\text{GeV}$, $-1.5 < \eta^e < 1.5$



- Lower energy region
- PYTHIA prediction scaled by a factor of 1.75
- NLO QCD prediction (FMNR) describes shape
- Measured points at upper band edge of NLO prediction





New preliminary points shown in red (two methods presented)

Part III

F_2^{cc} and F_2^{bb}

Aim:

Measure charm and beauty contribution to inclusive proton structure function F_2 in DIS

Method:

- Significance ($\delta/\sigma\delta$) for highest significant track S1 and second highest significant track S2
- Simultaneous fit of the subtracted S1 and S2 distributions (S1/2: Significance (δ/σ_δ) for highest/second significant track)

HERAII data:

2006 ($\mathcal{L} \approx 54\,\mathrm{pb}^{-1}$)

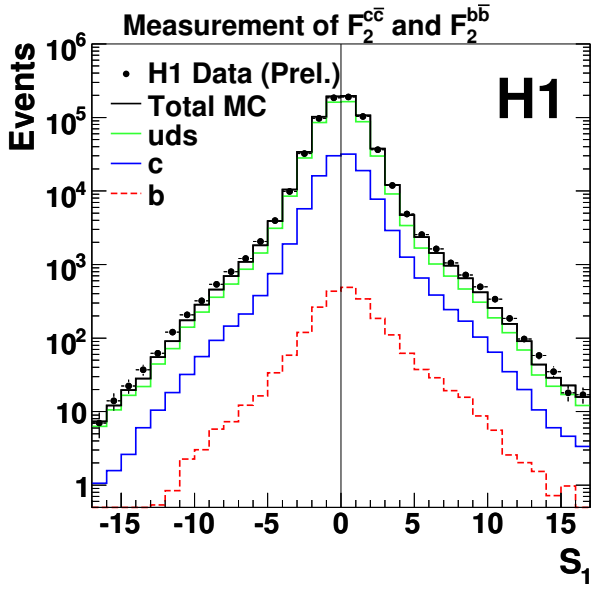
Kinematic region:

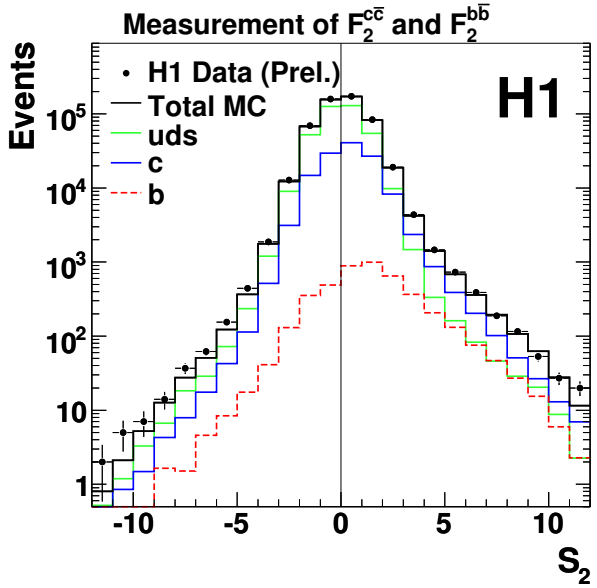
$12 < Q^2 < 650\,\mathrm{GeV}^2$

$0.0002 \leq x \leq 0.032$

$p_T^{track} > 0.5\,\mathrm{GeV}$

(reduces extrapolations to full cross sections)





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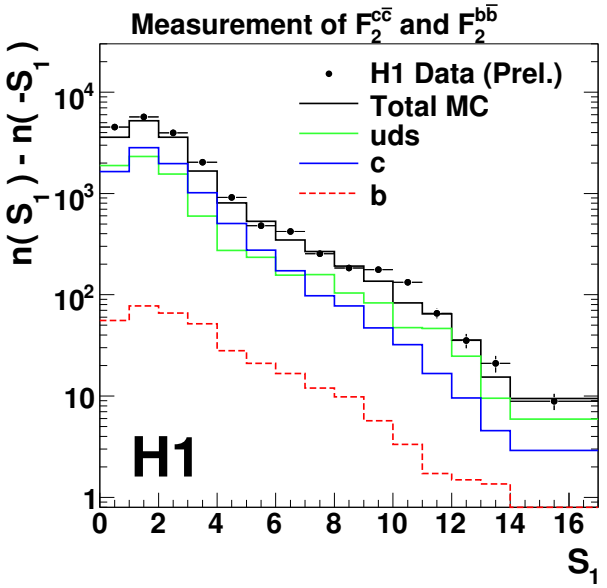
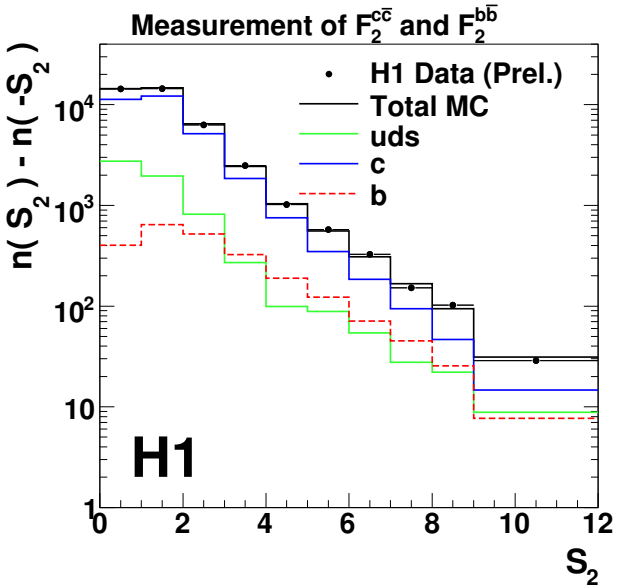




Calculation of $F_2^{c\bar{c}}$ = Charm contribution to F_2

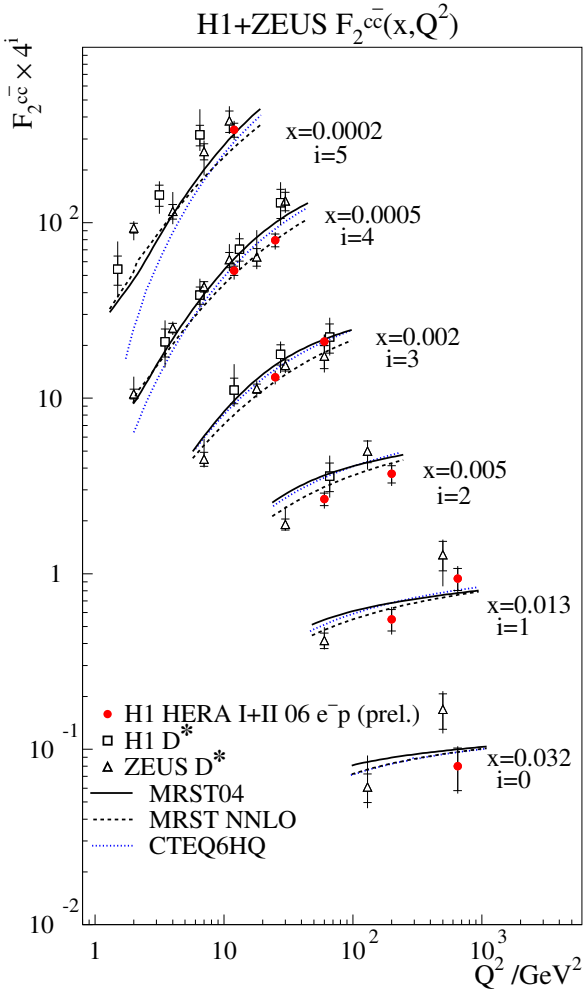
Reduced cross-section is defined as:

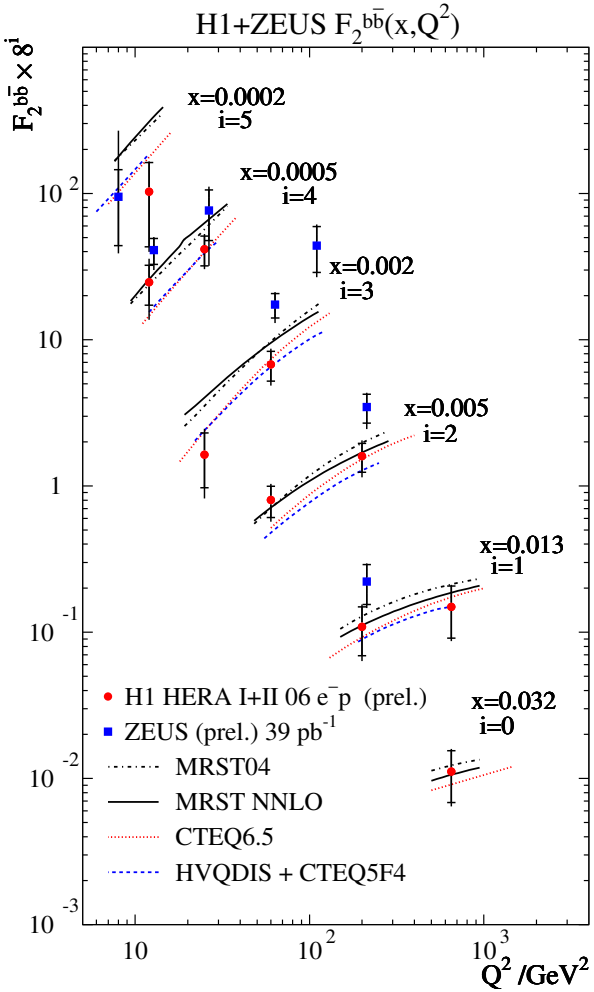
$$\tilde{\sigma}^{c\bar{c}}(x,Q^2) = \frac{d^2\sigma^{c\bar{c}}}{dx\,dQ^2}\frac{xQ^4}{2\pi\alpha^2(1+(1-y)^2)}$$

- $\tilde{\sigma}^{c\bar{c}}_{data}(x,Q^2) = \tilde{\sigma}^{c\bar{c}}_{NLO}(x,Q^2)\frac{d^2\sigma^{c\bar{c}}_{data}}{dx\,dQ^2} / \frac{d^2\sigma^{c\bar{c}}_{NLO}}{dx\,dQ^2}$
- Structure function evaluated after small corrections for the longitudinal structure functions $F_L^{c\bar{c}}$ and $F_L^{b\bar{b}}$

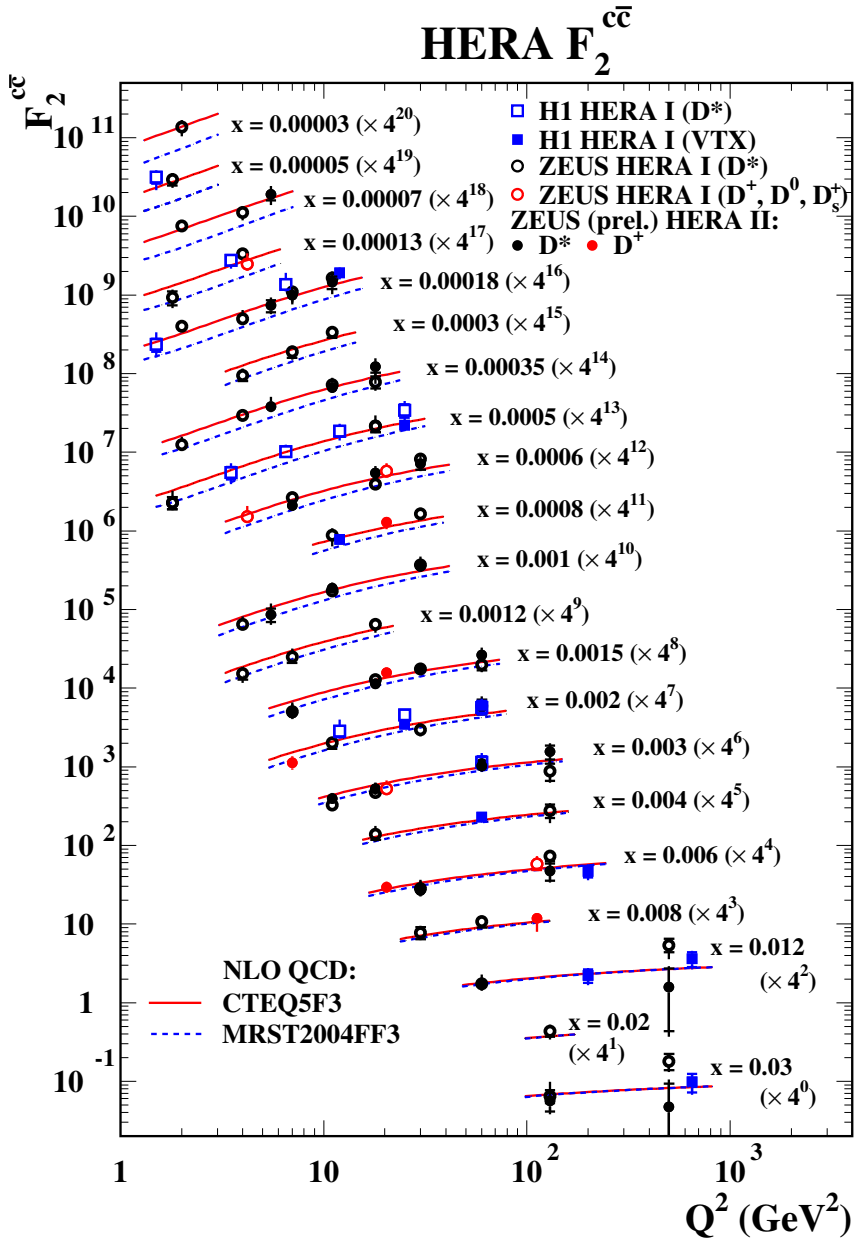
$$\tilde{\sigma}^{c\bar{c}} = F_2^{c\bar{c}} - \frac{y^2}{1+(1-y)^2}F_L^{c\bar{c}}$$

- Combined result with HERAI data





- Result of H1 and ZEUS data shown
- Agreement with **NNLO** prediction
- Theoretical calculation using MRST prefered at low Q^2



- $F_2^{c\bar{c}}$ for full x – Q^2 region
- New ZEUS measurements added

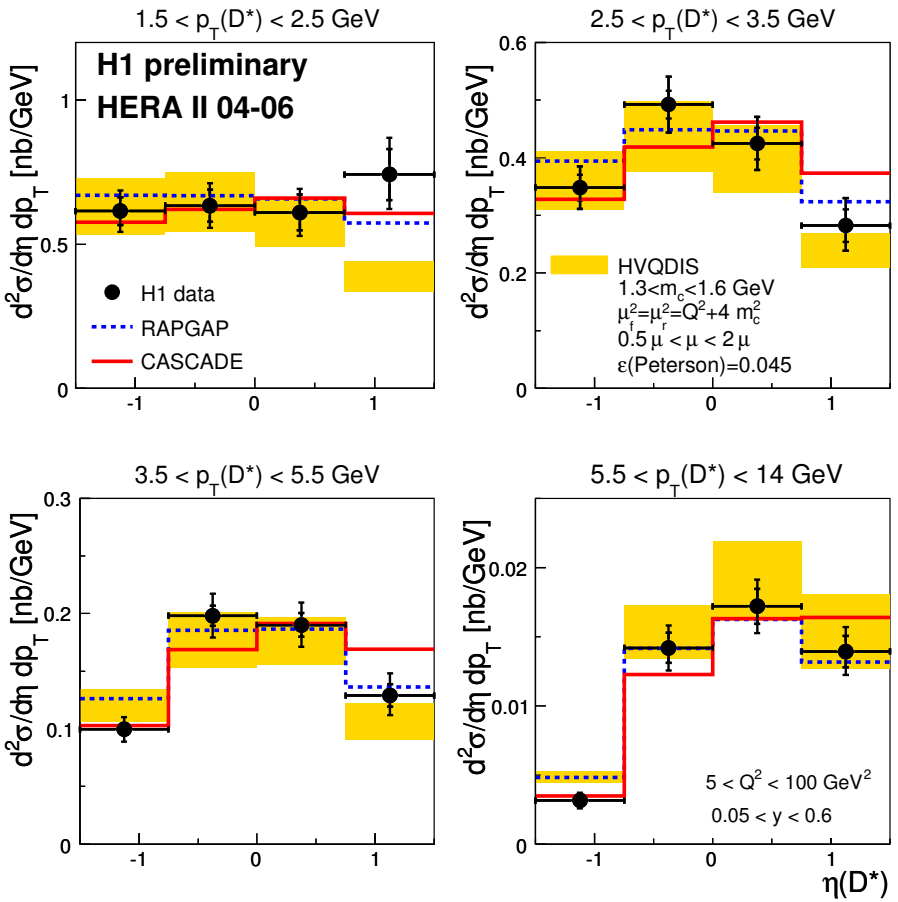
Summary

- HERA II data provide large increase in statistics
- New methods used and improved (lifetime tagging)

- Charm data well described by pQCD (NLO,NNLO)
- Beauty production shows tendency to higher values but still consistent within uncertainties
- F_2^{cc} and F_2^{bb} measured over a wide range of Q^2 and Bjorken x

Charm Production in DIS - Backup

- HVQDIS
  discrepancy in forward direction located at **low pt**
- CASCADE
  small discrepancy in **most forward** bin for $\mathbf{p}_T > 2.5\,\text{GeV}$
- RAPGAP
  overschoot for $\eta < -1$ concentrated at $\mathbf{p}_T > 3.5\,\text{GeV}$
- Need event more precise data to differetiate between models



Monte Carlo Details:

RAPGAP 3.1

- DGLAP evolution (collinear factorization)
- p PDF: CTEQ6L
- $\mu_r^2 = Q^2$
- Lund string

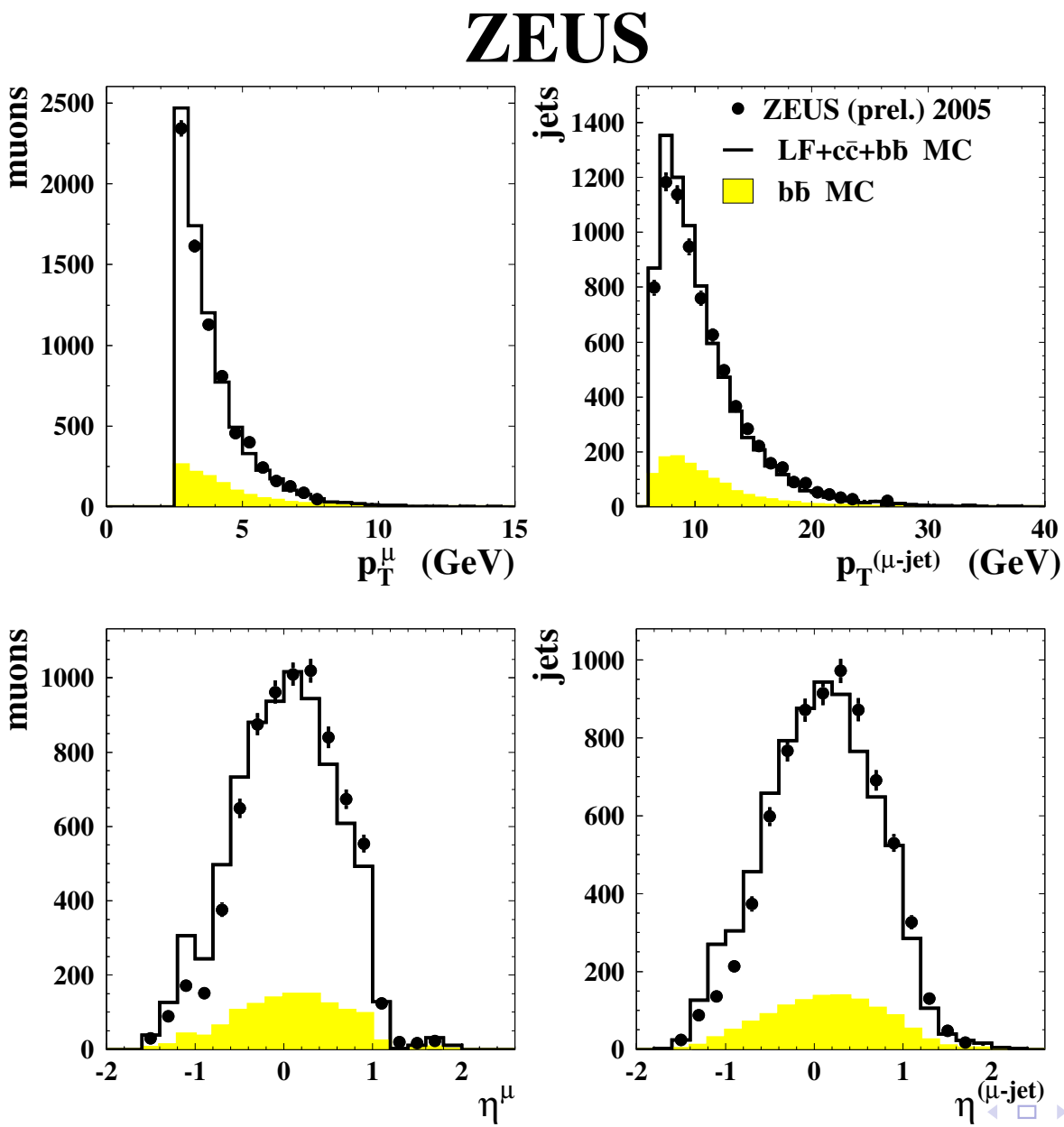
CASCADE 1.2

- CCFM evolution (k_t-factorization)
- g-density: J2003 set3
- $\mu_r^2 = 4m_q^2 + p_t^2$
- Lund String

HVQDIS

- Fixed Flavour Numbering Sheme (FFNS)
- $\mu_r^2 = \mu_f^2 = 4m_c^2 + Q^2$
- $m_c = 1.45\,\text{GeV}$ with [1.3,1.6]
- p PDF: CTEQ5F3
- $\epsilon_c = 0.045$

Beauty in Dijet Photoproduction - Backup



Beauty in Dijet Photoproduction - Backup II

Monte Carlo:

- PYTHIA 6.203
- $\sim$ 66.5 mill. events
- 9 x data B, 4.5 x data C and 1 x data LF

NLO (FMNR):

- $m_b = 4.75\,\text{GeV}$
- GRVG-HO, CTEQ5M
- $\mu_r = \mu_f = \sqrt{p_T^2 + m_b^2}$

Sinistra:

- Veto on $\mathcal{P}_e > 0.9 + E_e > 5\,\text{GeV} + Y_{el} < 0.9$

Track selection:

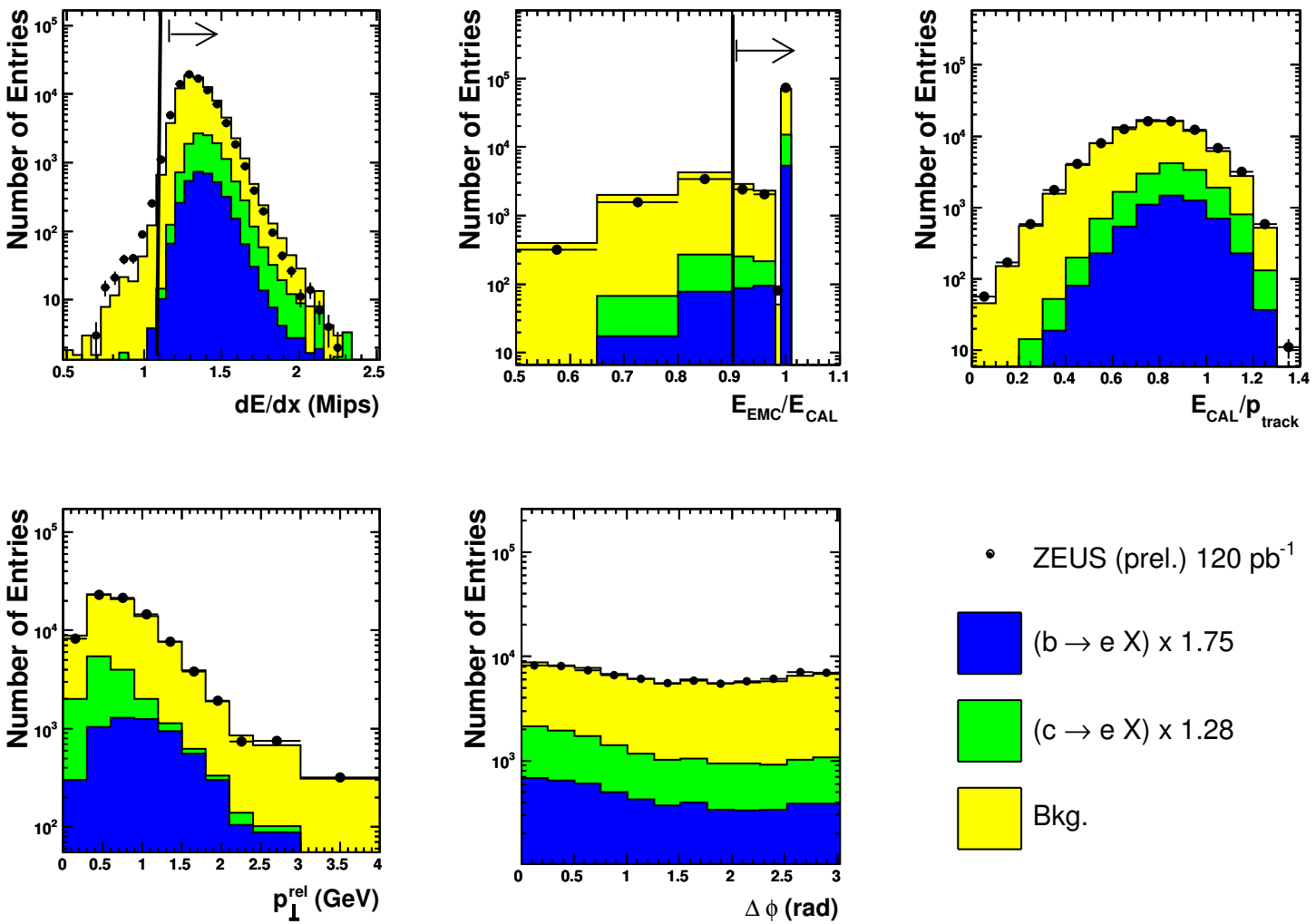
- CTD $DL_{hits} \geq 3$
- MVD hits ≥ 4
- $Z_{DCA} \leq 30\,\text{cm}$
- jet associated $(p_T^{jet} - p_T^{\mu} > 2\,\text{GeV})$

Muon:

- $p_T^{\mu} > 2.5\,\text{GeV}$
- $-1.6 < \eta < 2.3$
- jet associated $(p_T^{jet} - p_T^{\mu} > 2\,\text{GeV})$

$\rightarrow\sim$ 7600 muons

Beauty in Dijet Photoproduction - Backup



Beauty in Dijet Photoproduction - Backup II

Monte Carlo:

- PYTHIA 6.4
- CTEQ4L, GRVGLO

NLO (FMNR):

- $m_b = 4.75\,\text{GeV}$
- GRVG-HO, CTEQ5M
- $\mu_r = \mu_f = \sqrt{p_T^2 + m_b^2}$

Sinistra:

- Veto on $\mathcal{P}_e > 0.9 + E_e > 5\,\text{GeV} + Y_{el} < 0.9$

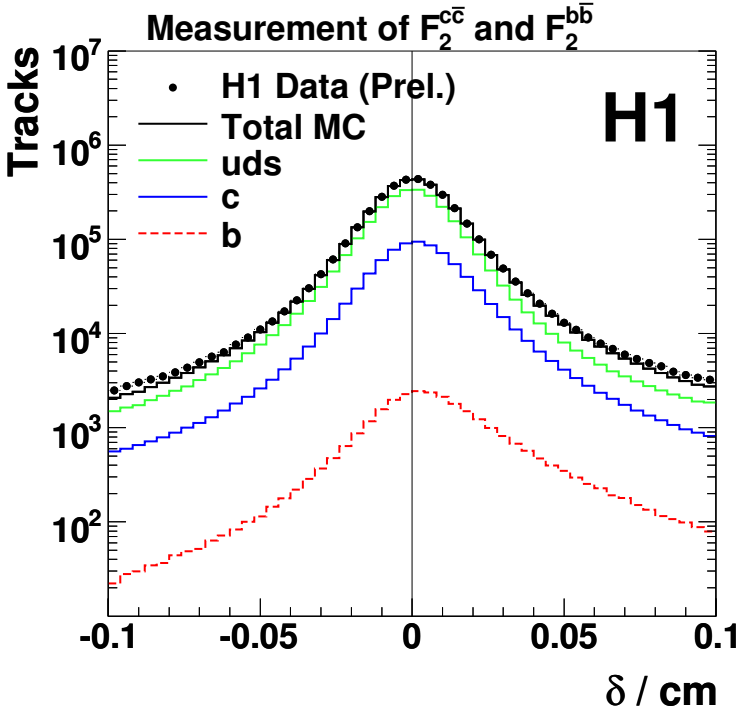
Track selection:

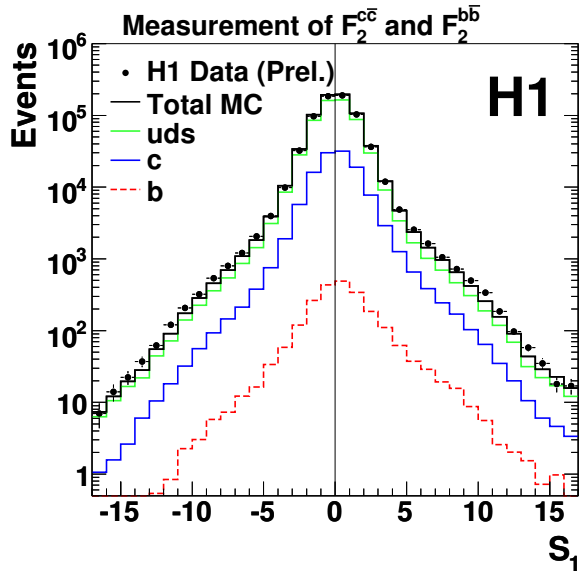
- CTD $DL_{hits} \geq 3$
- $dEdx > 1.1$
- EMCfrac > 0.9
- primary vertex tracks
- veto on conversions

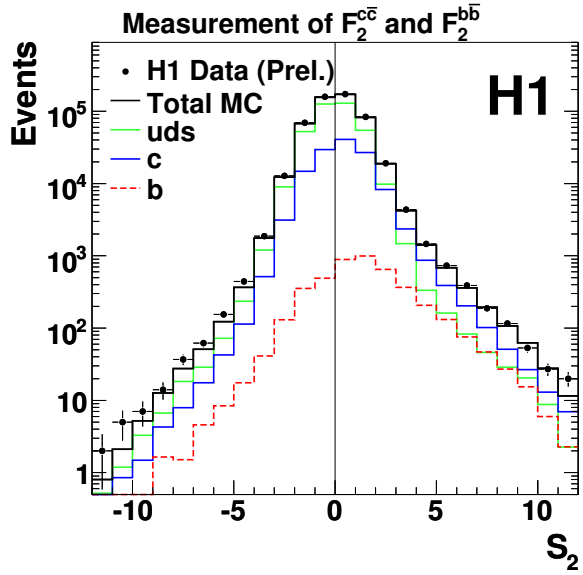
Electron:

- $p_T^e > 0.9\,\text{GeV}$
- $-1.5 < \eta < 1.5$
- jet associated

F_2^{cc} and F_2^{bb} - Backup

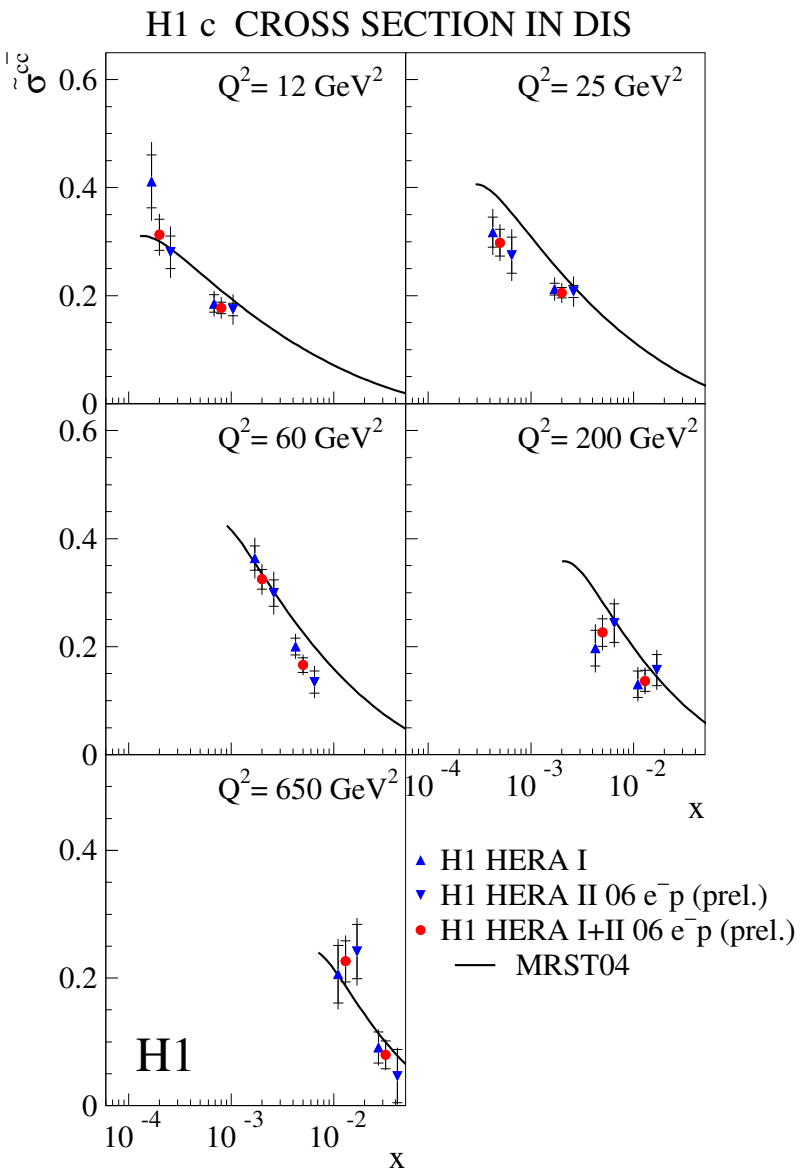


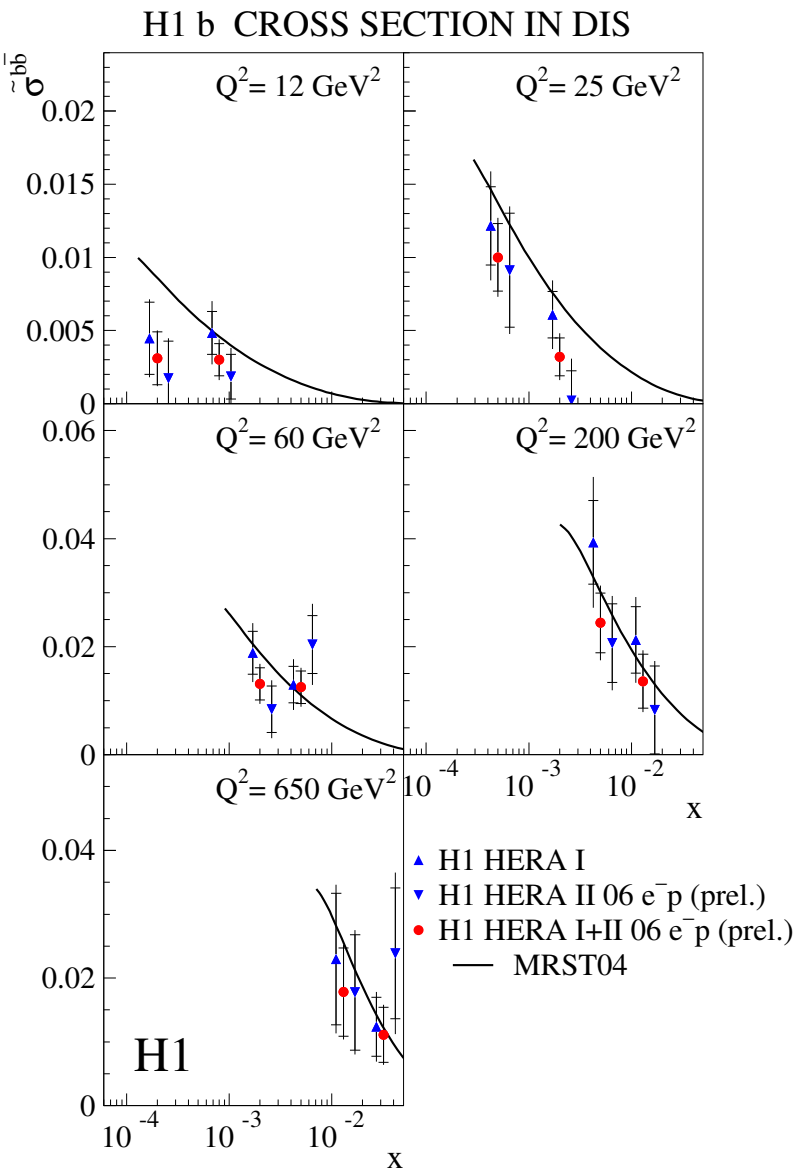




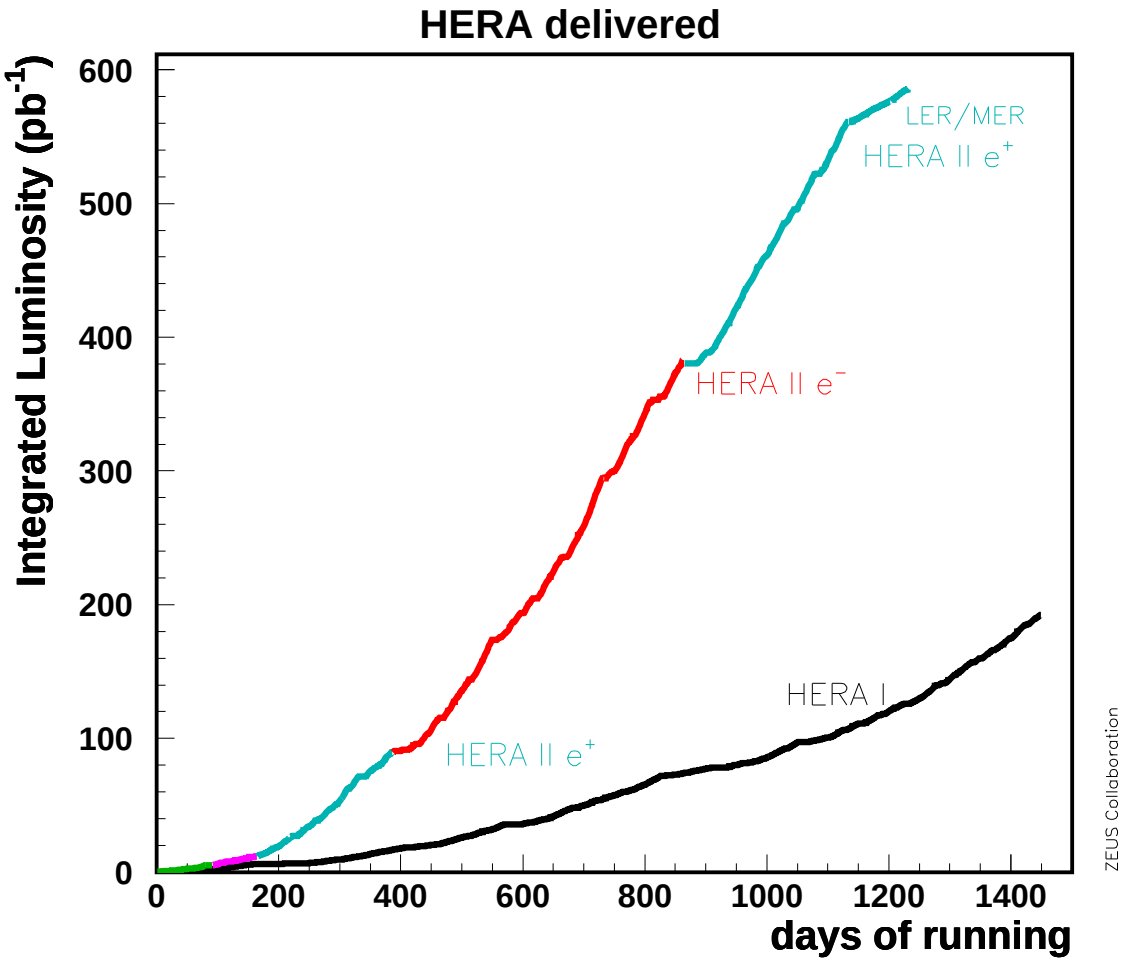
- Impact parameter (δ) in x-y to primary vertex
- Significance ($\delta/\sigma\delta$) for highest significant track S1 and second highest significant track S2

Inclusive Beauty and Charm Cross-Section II





Luminosity Details



Method:

2D fit of p_T^{rel} and δ

(track impact parameter)

Jets:

$p_T^{jets} > 7(6)\,\text{GeV}$

$|\eta_{lab}^{jet}| < 1.7$

Dijet sample:

$Q^2 < 0.01\,\text{GeV}^2 \quad 0.3 < y < 0.65$

Charm enriched sample:

$p_T^{rel} < 1\,\text{GeV}$

$p_T^{\mu} > 2.5\,\text{GeV}$

$Q^2 < 1\,\text{GeV}^2 \qquad 0.2 < y < 0.8$

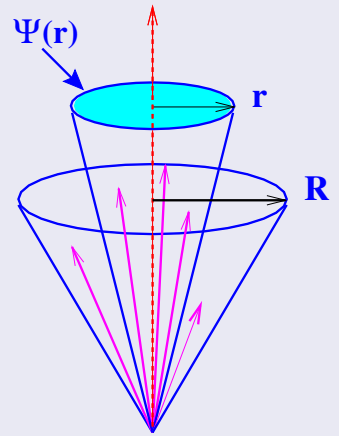
HERAI data:

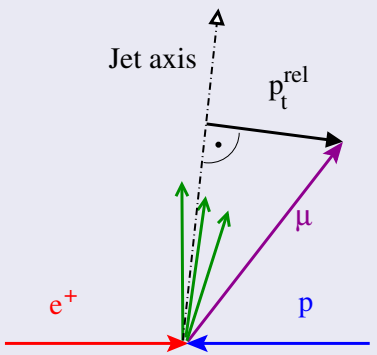
1999-2000 ($\mathcal{L} \approx 48\,\text{pb}^{-1}$)

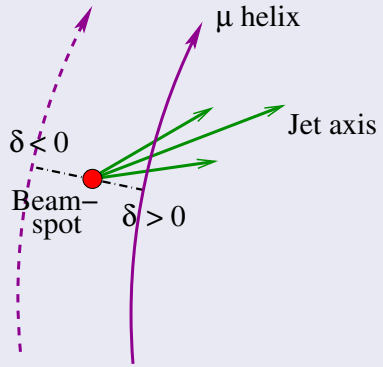
$$\Psi(r) = \frac{p_T^{jet}(r)}{p_T^{jet}(r=R)}$$

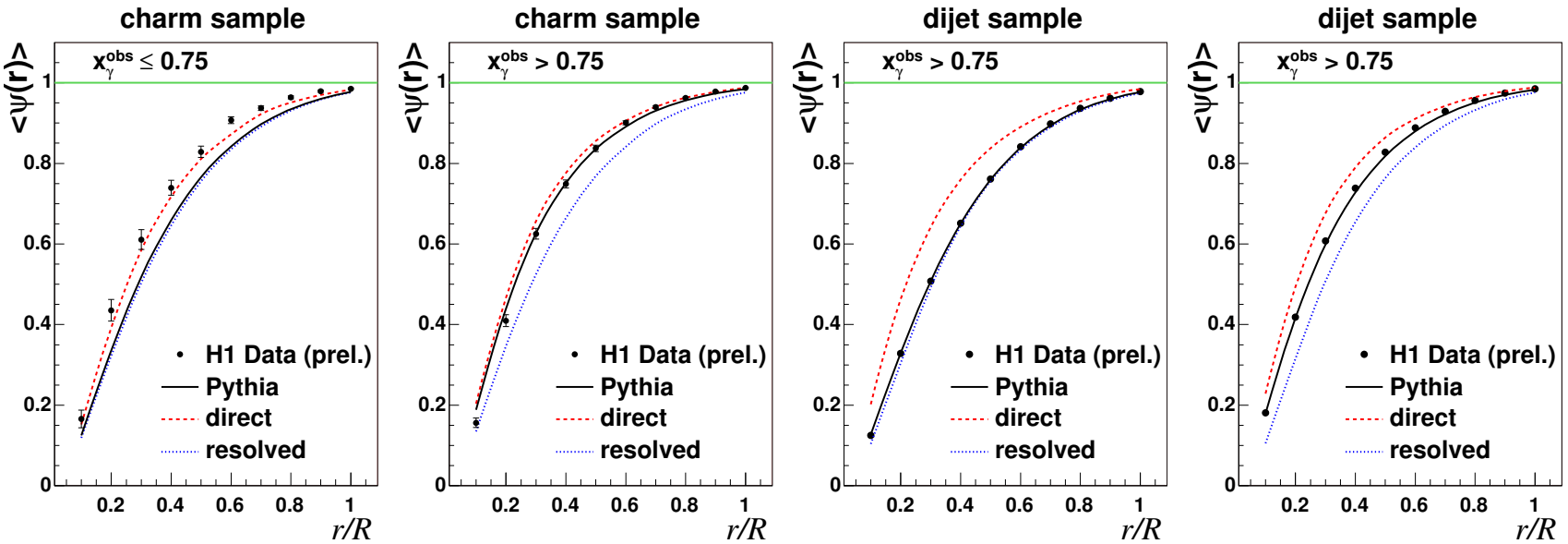
$$r = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

$$\langle\Psi(r)\rangle = \frac{1}{N_{jets}} \sum_{jets} \Psi(r)$$









- In charm data sample jet shapes very similar in direct and resolved samples
- Not consistent with the PYTHIA prediction for resolved photon region
- Dijet sample selected without high p_T muon
- Shapes different and in good agreement with PYTHIA prediction

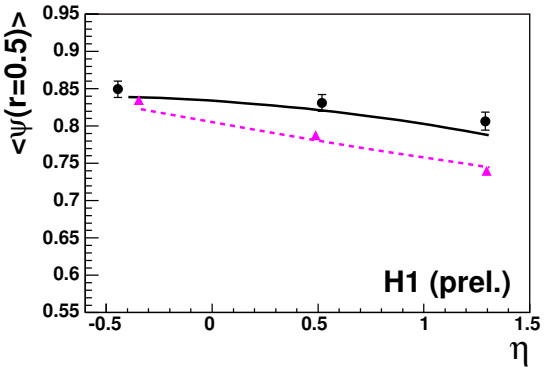
$$x_\gamma^{obs} = \frac{\sum_{i=Jet1,2}(E_i - p_{z,i})}{(E - p_z)}$$

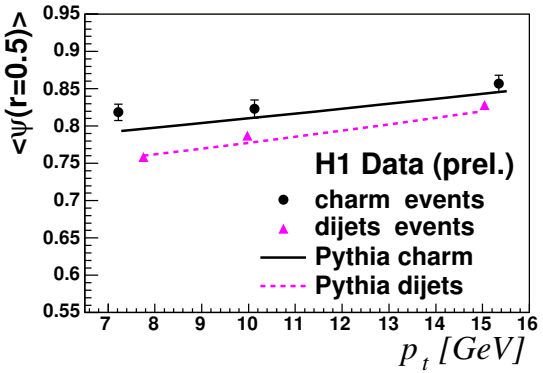
direct enr.: $x_\gamma^{obs} > 0.75$

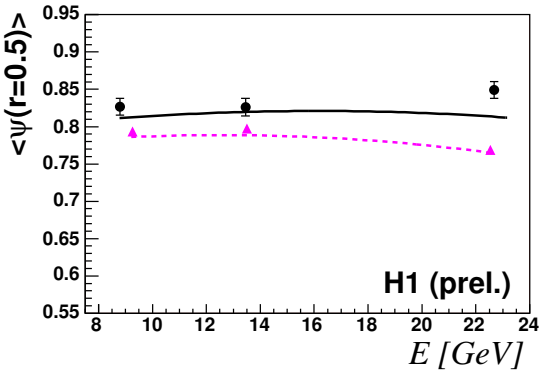
resolved enr.: $x_\gamma^{obs} \leq 0.75$

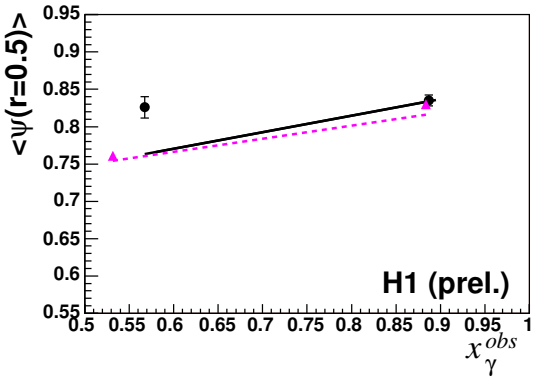
Jet Shapes in Charm Photoproduction - Backup

Differential Distr.:
(for $\langle\Psi(r/R = 0.5)\rangle$)









Monte Carlo Details:

PYTHIA

- p-PDF: CTEQ5L
- γ-PDF: GRVG-LO