Jets and Heavy Flavours at HERA

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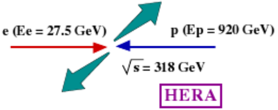
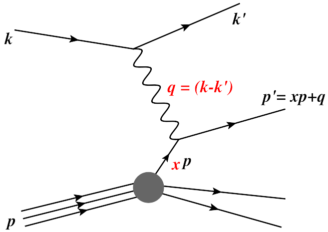
10$^{\text{th}}$ - 15$^{\text{th}}$ September 2010

- Kinematics
- Jet physics
- Heavy flavour physics

Kinematics at HERA





Kinematic regimes:

1. Photoproduction (PHP): $Q^2 \approx 0\,\text{GeV}^2$
2. Deep inelastic scattering (DIS): $Q^2 \geq 0\,\text{GeV}^2$

Kinematics:

- Probing power of the lepton:
  $Q^2 = -q^2 = (k - k')^2$
- Bjorken scaling variable, the fraction of the proton's momentum carried by the struck quark (QPM):
  $x = \frac{Q^2}{2p \cdot q}$
- Inelasticity, the energy fraction transferred from the lepton in the proton's rest frame:
  $y = \frac{p.q}{p.k}$

Jet Physics at HERA

Jet production at HERA

Jet cross section in pQCD: Series expansion in powers of α_s

$$\sigma_{\text{jet}} = \sum_m \alpha_s{}^m(\mu_R) \sum_{a=q,\bar{q},g} f_{a/p}(x,\mu_f) \otimes \hat{\sigma}_{a,m}(x,\mu_R,\mu_F)(1+\delta_{\text{had}})\ldots$$

Coefficients are convolutions of:

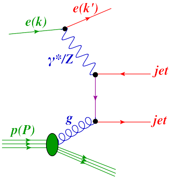
- parton distribution functions (PDFs) $f_{a/p}$ (and of γ-PDF in case of PHP)
- hard scattering matrix element $\hat{\sigma}$

Measurements of jet production at HERA provide a powerful tool for:

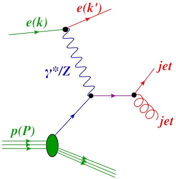
- Constraints on PDFs
- Stringent test of perturbative QCD
- Precision measurement of strong coupling, α_s and of its running

Jet production processes:

Deep inelastic scattering (DIS)

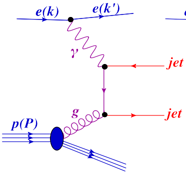


Boson-gluon fusion

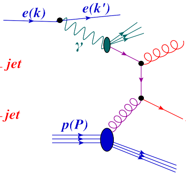


QCD Compton

Photoproduction (PHP)



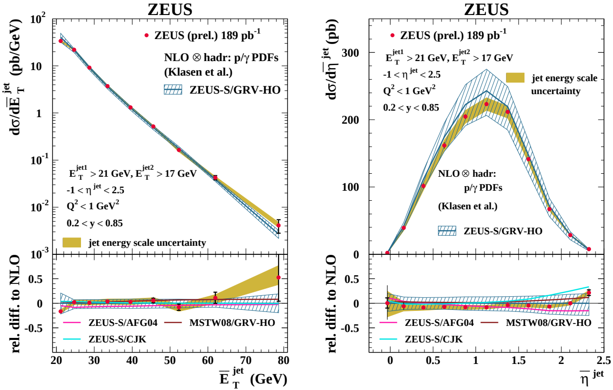
Direct process



Resolved process

Dijets in photoproduction

- 05-06 $e^- p$ data: $\mathcal{L} = 189\,\text{pb}^{-1}$
- Kinematic region: $Q^2 < 1\,\text{GeV}^2$, $0.2 < y < 0.85$
- Two jets with: $E_T^{\text{jet1}} > 21\,\text{GeV}$, $E_T^{\text{jet2}} > 17\,\text{GeV}$, $-1 < \eta_{\text{LAB}}^{\text{jet}} < 2.5$



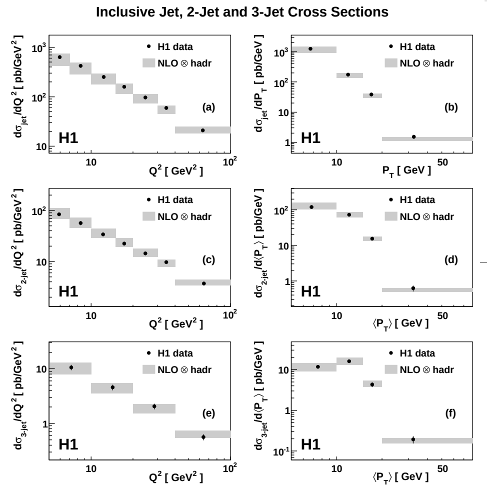
- Good description of data by NLO QCD in the whole measured range
- Sensitivity to proton (high E_T^{jet}) and photon (high η^{jet}) PDFs

Multijets at low Q^2

inclusive

2-jet

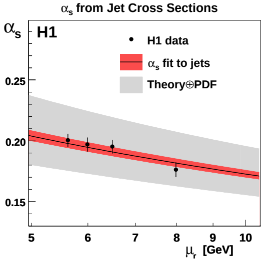
3-jet



H1: $44\,\mathrm{pb}^{-1}$, $5 < Q^2 < 100\,\mathrm{GeV}^2$, $0.2 < y < 0.7$,

$P_T^{\mathrm{jet}} > 5\,\mathrm{GeV}$, $-1 < \eta_{\mathrm{lab}} < 2.5$, (Breit frame)

- Multijet cross sections as a function of Q^2 and P_T^{jet}
- Good description of data by NLO predictions

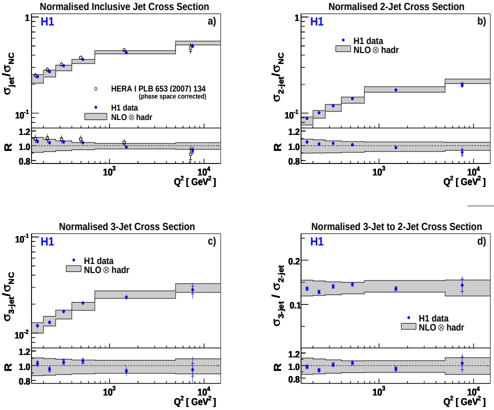


- Extract α_s from a simultaneous fit of inclusive, dijet and trijet measurements
- Large theoretical uncertainty, NNLO needed!

Multijets at high Q^2

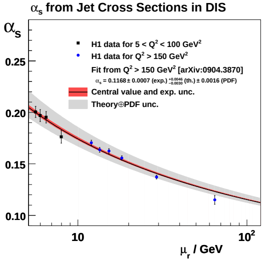
H1: Eur Phys J. C65 (2010) 363

Cross sections normalised to DIS cross section



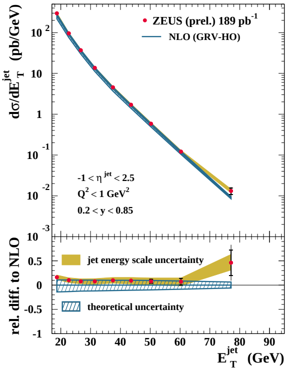
H1: $395\,\mathrm{pb}^{-1}$, $150 < Q^2 < 15000\,\mathrm{GeV}^2$, $0.2 < y < 0.7$, $P_T^{\mathrm{jet}} > 7(5)$ GeV, $-0.8 < \eta_{\mathrm{lab}} < 2$, (Breit frame)

- Measured points from high-Q^2 data propagated to low Q^2

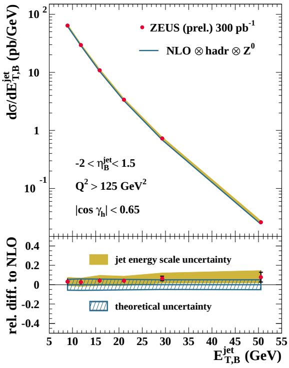


- Running of the strong coupling, α_s, tested over wide range of scale, μ_r (between $6 - 70$ GeV)
- Low Q^2 data lie within the theory uncertainty of the high Q^2 fit

Photoproduction



Neutral current DIS



PHP:
$\mathcal{L} = 189\,\mathrm{pb}^{-1}, \quad Q^2 < 1\,\mathrm{GeV}^2$

$E_T^{jet} > 17\,\mathrm{GeV}, \quad -1 < \eta^{jet} < 2.5$

$$\alpha_s(M_Z) = 0.1208^{+0.0030}_{-0.0018}(\mathrm{exp.})\,^{+0.0033}_{-0.0032}(\mathrm{th.})$$

NC DIS:
$\mathcal{L} = 300\,\mathrm{pb}^{-1}, \quad Q^2 > 125\,\mathrm{GeV}^2$

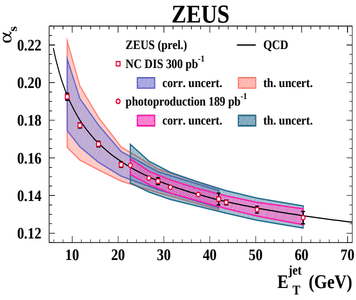
$E_{T,B}^{jet} > 8\,\mathrm{GeV}, \quad -2 < \eta_B^{jet} < 1.5$

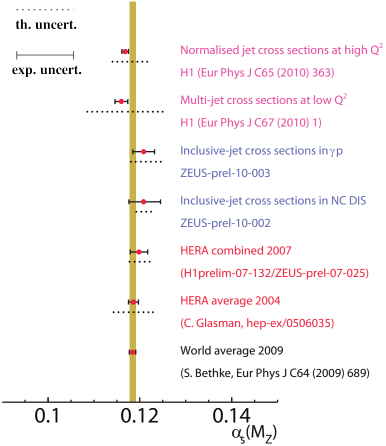
$$\alpha_s(M_Z) = 0.1208^{+0.0037}_{-0.0032}(\mathrm{exp.})\,^{+0.0022}_{-0.0022}(\mathrm{th.})$$

- Cross sections fall steeply, well described by NLO predictions
- Measurements provide direct sensitivity to $\alpha_s(M_Z)$ with small experimental and theoretical uncertainties
- Very precise data → stringent tests of QCD from $Q^2 \sim 0 - 20000\,\mathrm{GeV}^2$

α_s from inclusive-jet cross sections

The energy-scale dependence of the coupling determined by extracting α_s from the measured $d\sigma/dE_T^{\text{jet}}$ at different E_T^{jet} values from the low to the high Q^2 regime:





- Results in good agreement with the predicted running of α_s over a large range in E_T^{jet}
- α_s measurements consistent with each other and the world average

Heavy Flavour Physics at HERA

Beauty (Charm) production/tagging

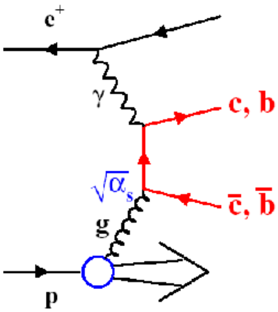
Dominant production process in *ep*-collisions: Boson-Gluon Fusion

→ sensitive to gluon density in the proton

Multiple scales involved:

- large mass $m_{c,b}$
- large Q^2
- high momenta p_T

→ Powerful tool for testing p structure and pQCD



HFL Tagging:

Different experimental techniques to use (combine) for HFL tagging:

- Decay spectra
  p_T^{rel} of lepton to jet axis
- Meson identification
  $D^{*\pm}$ tagging
- Lifetime information
  Impact parameter/Decay length

→ Different tags probe different kinematic regions

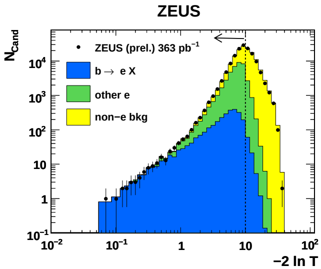
In this talk shown a selection of some recent results

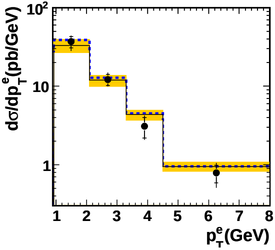
Beauty in DIS from decays into electrons

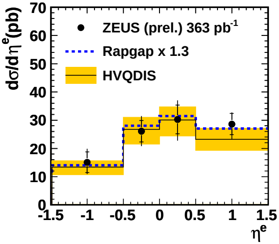
- 04-07$e^{\pm}p$ data: $\mathcal{L} = 363\,\mathrm{pb}^{-1}$
- $Q^2 > 10\,\mathrm{GeV}^2$, $0.05 < y < 0.7$
- $p_T^e > 0.9\,\mathrm{GeV}$, $|\eta^e| < 1.5$
- LO: Rapgap, NLO: HVQDIS

- p_T^{rel}, $\Delta\phi(\not{p}, e)$ and $d/\delta d$ combined with particle ID using likelihood hypothesis
- Fit contribution of beauty, other electron and non-electron background

→





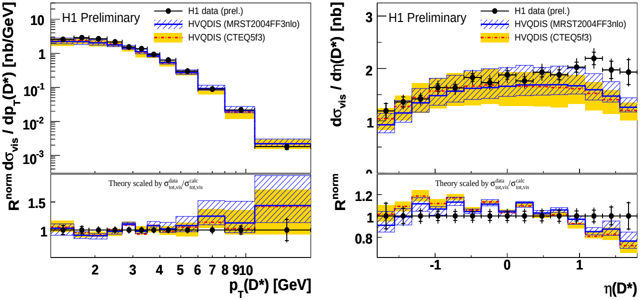


- Differential cross sections as a function of p_T^e and η^e
- Extract $F_2^{b\bar{b}}$ from $d\sigma/dxdQ^2$ (see slide 16)
- Measurement in good agreement with LO MC and NLO QCD calculation

$D^{*\pm}$ meson production at low Q^2

- 04-07 $e^{\pm}p$ data: $\mathcal{L} = 347\,\mathrm{pb}^{-1}$
- $5 < Q^2 < 100\,\mathrm{GeV}^2$, $0.02 < y < 0.7$
- $p_T(D^*) > 1.25\,\mathrm{GeV}$, $|\eta(D^*)| < 1.8$

→ Extended phase space compared to previous measurements



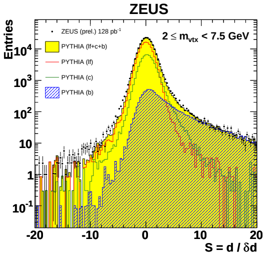
- $D^{*\pm}$ candidates selected using the mass difference method $\Delta M = m(K\pi\pi_{\mathrm{slow}}) - m(K\pi)$
- $D^{*\pm}$ cross sections as a function of $p_T(D^*)$ and $\eta(D^*)$
- Data reasonably well described by HVQDIS using different parton densities of the proton

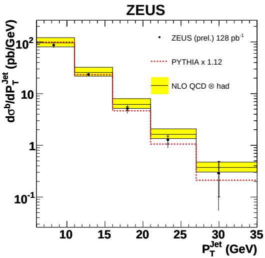
Beauty in PHP from incl. sec. vertexing

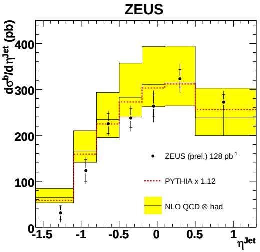
ZEUS-prel-09-005

- 06-07$e^{\pm}p$ data: $\mathcal{L} = 128\,\text{pb}^{-1}$
- $Q^2 < 1\,\text{GeV}^2$, $0.2 < y < 0.8$
- Dijets: $P_T^{\text{jet}1(2)} > 7(6)$ GeV, $|\eta^{\text{jet}1(2)}| < 2.5$
- LO: Pythia, NLO: FMNR

- Beauty separation using lifetime info.
- Decay length significance, $S = \text{DL}/\delta\text{DL}$ (for $2 < m_{\text{vtx}} < 7.5\,\text{GeV}$)
- Large S - almost pure beauty contribution



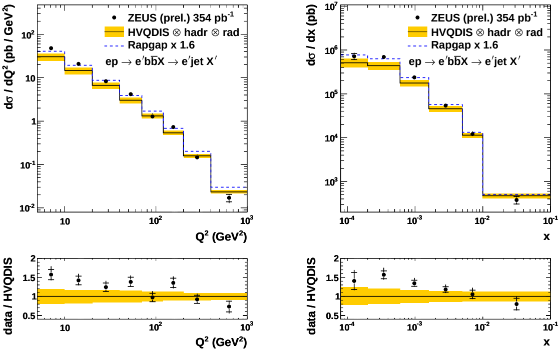




- Differential cross sections in bins of P_T^{jet} and η^{jet}
- Measurement in good agreement with LO MC and NLO QCD calculation
- Theoretical uncertainties larger than the experimental ones

Beauty in DIS from incl. sec. vertexing

- 04-07 $e^{\pm}p$ data: $\mathcal{L} = 354\,\mathrm{pb}^{-1}$
- Phase space: $5 < Q^2 < 1000\,\mathrm{GeV}^2$, $0.02 < y < 0.7$
- At least one jet: $E_T^{\mathrm{jet}} > 5\,\mathrm{GeV}$, $-1.6 < \eta^{\mathrm{jet}} < 2.2$
- LO: RAPGAP, NLO: HVQDIS



- Similar approach used as in PHP analysis (ZEUS-prel-09-005)
- Differential cross sections in bins of Q^2 and x
- Similar measurements from H1 also exist (Eur Phys J. C65 (2010))
- In general reasonable agreement with LO MC and NLO QCD (QCD lower at low Q^2 and low x)

Beauty contribution to the structure function - $F_2^{b\bar{b}}$

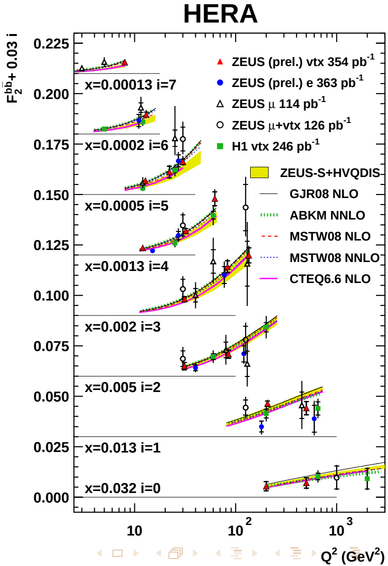
$F_2^{b\bar{b}}$ can be extracted from double differential cross sections using:

$$F_2^{b\bar{b}}(x_i, Q_i^2) = \sigma^b \frac{F_2^{b\bar{b},th}(x_i, Q_i^2)}{\sigma^{b,th}}$$

where

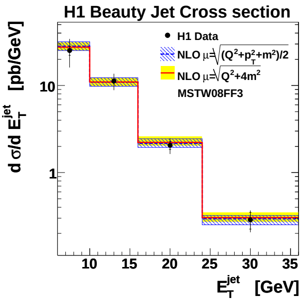
$$\sigma^b = \frac{d^2\sigma^{b\bar{b},vis}}{dx dQ^2} \quad \& \quad \sigma^{b,th} = \frac{d^2\sigma^{b\bar{b},th}}{dx dQ^2}$$

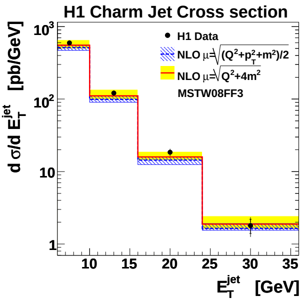
- $F_2^{b\bar{b}}$ as a function of Q^2 for fixed values of x
- Comparison of different measurements from H1 and ZEUS
- All measurements consistent with each other and with NLO QCD predictions
- Precision improved from new secondary vertex measurement (▲)



Beauty (Charm) jet cross sections

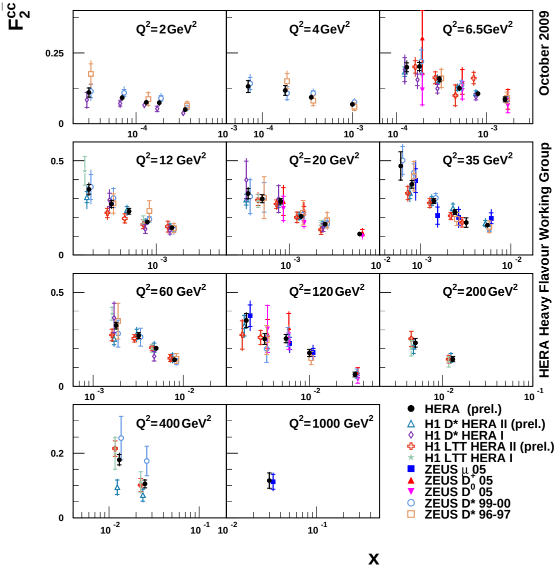
- 06-07 data: $\mathcal{L} = 189\,\mathrm{pb}^{-1}$
- Kinematic region: $Q^2 > 6\,\mathrm{GeV}^2$, $0.07 < y < 0.6$
- At least one jet: $E_T^{\mathrm{jet}} > 6\,\mathrm{GeV}$, $-1 < \eta^{\mathrm{jet}} < 1.5$





- Beauty and charm jet cross sections in bins of $E_{\mathrm{T}}^{\mathrm{jet}}$
- Flavour separation done using life time information
- NLO QCD calculation (HVQDIS) gives good data description for two different scale choices

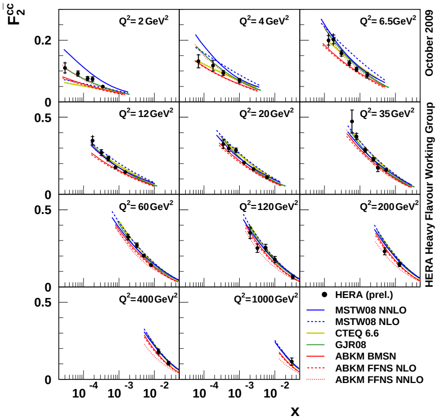
H1-ZEUS $F_2^{c\bar{c}}$ combination



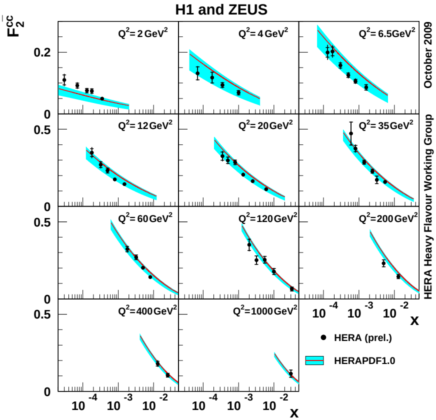
- Combined $F_2^{c\bar{c}}$ compared to single measurements from H1 and ZEUS
- Different measurements combined taking into account correlated systematic uncertainties
- Precision $7-10\%$ for $6.5 \leq Q^2 \leq 60\,\mathrm{GeV}^2$

H1-ZEUS $F_2^{c\bar{c}}$ combination

Combined $F_2^{c\bar{c}}$ compared to NLO and NNLO calculations



Combined $F_2^{c\bar{c}}$ compared to HERAPDF 1.0



- Mostly reasonable description between data and different theory predictions
- These precise charm data are an important input for theory

Summary

- Jet physics at HERA provide high precision QCD measurements
- Measurements will help to constrain further the p/γ PDFs
- Precise and consistent α_s extraction in different kinematic regimes
- Running of the coupling, α_s, verified over a wide range of the scale

- Small selection of heavy flavour production results presented
- In general the measured cross sections consistent with the NLO QCD
- Different measurements provide a consistent picture of $F_2^{b\bar{b}}$ and $F_2^{c\bar{c}}$
- Combining H1 and ZEUS $F_2^{c\bar{c}}$ results in a precise measurement and provides constraint for theory

References I

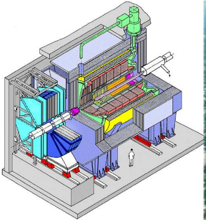
- Dijet cross sections in photoproduction at HERA
  ZEUS-prel-10-014
- Jet production in ep collisions at low Q^2 and determination of α_s
  Eur. Phys. J. C67 (2010)1
- Jet production in ep collisions at high Q^2 and determination of α_s
  Eur. Phys. J. C65 (2010)363
- Inclusive-jet cross sections in photoproduction at HERA
  ZEUS-prel-10-003
- Inclusive-jet production in NC DIS with HERA II
  ZEUS-prel-10-002

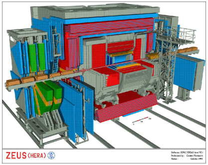
References II

- Beauty production in DIS using decays into electrons at HERA
  ZEUS-prel-10-010
- Measurement of $D^{*\pm}$ meson production at low Q^2 in an extended kinematic region
  H1prelim-10-172
- Measurement of beauty photoproduction from inclusive secondary vertexing at HERA II
  ZEUS-prel-09-005
- Measurement of beauty production from inclusive secondary vertices in DIS and $F_2^{b\bar{b}}$ extraction at ZEUS
  ZEUS-prel-10-004
- Measurement of charm and beauty jets in deep inelastic scattering
  DESY-10-083
- Combination of $F_2^{c\bar{c}}$ from DIS measurements at HERA
  H1prelim-09-171, ZEUS-prel-09-015

Backup

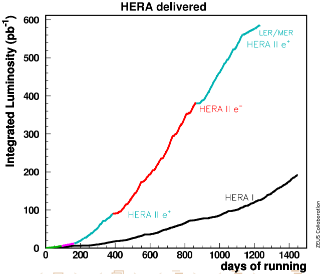
H1 and ZEUS





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

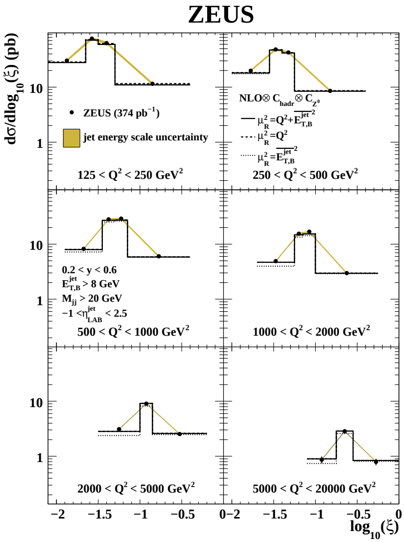
→ $\sim 0.5\,\text{fb}^{-1}$ per experiment



Dijets in NC DIS

- 98-07 $e^{\pm}p$ data: $\mathcal{L} = 374\,\mathrm{pb}^{-1}$
- Kinematic region:
  $125 < Q^2 < 20000\,\mathrm{GeV}^2$, $0.2 < y < 0.6$
- Two jets with: $E_{\mathrm{T,B}}^{\mathrm{jet}} > 8\,\mathrm{GeV}$,
  $-1 < \eta_{\mathrm{LAB}}^{\mathrm{jet}} < 2.5$, Breit frame

- Dijet cross sections as a function of $\log_{10}\xi$ in several regions of Q^2:
  $\xi = x_{\mathrm{Bj}}(1 + M^{\mathrm{jj}})^2/Q^2$
  (parton momentum fraction)
- Good description of data by NLO (NLOJET++) prediction in the whole measured range
- Gluon fraction substantial up to $Q^2 \sim 500\,\mathrm{GeV}^2$
- Theoretical uncertainty from higher orders: $\pm 6\%$
- Important input for extraction of PDFs - especially gluon in proton



- 98-07 $e^{\pm}p$ data: $\mathcal{L} = 374\,\mathrm{pb}^{-1}$
- Kinematic region:
  $125 < Q^2 < 20000\,\mathrm{GeV}^2$, $0.2 < y < 0.6$
- Two jets with: $E^{\mathrm{jet}}_{\mathrm{T,B}} > 8\,\mathrm{GeV}$,
  $-1 < \eta^{\mathrm{jet}}_{\mathrm{LAB}} < 2.5$, Breit frame

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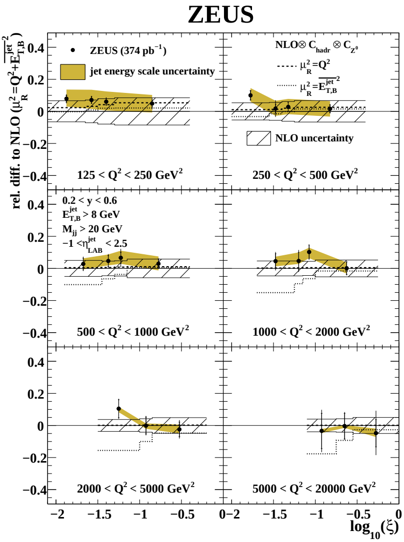
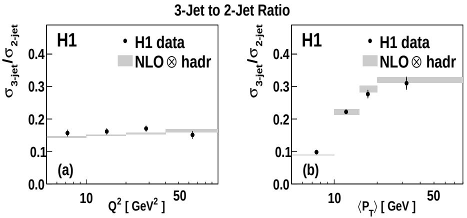
- Dijet cross sections as a function of $\log_{10}\xi$ in several regions of Q^2:
  $\xi = x_{\mathrm{Bj}}(1 + M^{\mathrm{jj}})^2/Q^2$
  (parton momentum fraction)
- Relative difference to NLO
- Good description of data by NLO (NLOJET++) prediction in the whole measured range
- Gluon fraction substantial up to $Q^2 \sim 500\,\mathrm{GeV}^2$
- Theoretical uncertainty from higher orders: $\pm 6\%$
- Important input for extraction of PDFs - especially gluon in proton

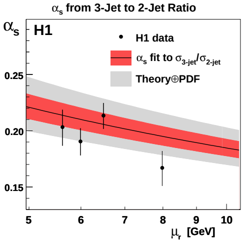


Ratio: 3-jet to 2-jet

Eur Phys J. C67 (2010) 1.

Reduction of theoretical uncertainties can be obtained by determining α_s from the measured trijet to dijet ratio





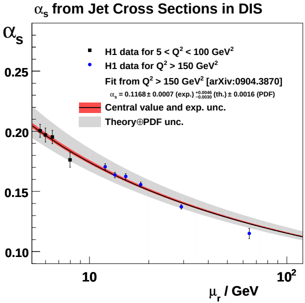
$$\alpha_s(M_Z) = 0.1215 \pm 0.0032(\text{exp.})^{+0.0067}_{-0.0059}(\text{th.})$$

- P_T spectra of 3 jets harder
- Systematic errors cancel: partially reduced by 50%
- Reduced sensitivity to missing higher orders in NLO

- Theoretical errors smaller
- Statistical error dominates
- Expected to improve with full statistics

$\alpha_s(\mu_r)$: combining low & high Q^2 data

- Fit to all cross-sections and cross-section ratios from low and high Q^2 measurements
- Very good agreement of extraction of $\alpha_s(\mu_r)$ at low and high Q^2
- Running of the strong coupling, α_s, tested over wide range of scale, μ_r (between $6 - 70\,\text{GeV}$)
- Low Q^2 data lie within the theory uncertainty of the high Q^2 fit

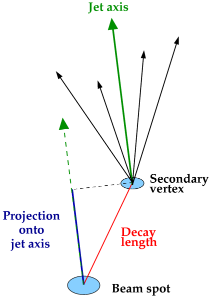


$$\mu_r = \sqrt{(Q^2 + P^2_{\text{T,obs}})/2}$$

Multijets at low Q^2:
$\alpha_s(M_Z) = 0.1160 \pm 0.0014(\text{exp.})^{+0.0093}_{-0.0077}(\text{th.}) \pm 0.0016(\text{pdf})$

Multijets at high Q^2:
$\alpha_s(M_Z) = 0.1168 \pm 0.0007(\text{exp.})^{+0.0046}_{-0.0030}(\text{th.}) \pm 0.0016(\text{pdf})$

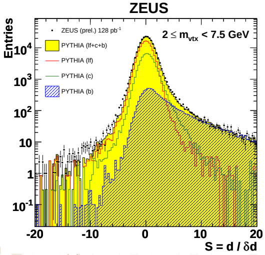
- 06-07 $e^{\pm}p$ data: $\mathcal{L} = 128\,\mathrm{pb}^{-1}$
- Phase space: $Q^2 < 1\,\mathrm{GeV}^2$, $0.2 < y < 0.8$
- At least two jets:
  $P_T^{\mathrm{jet1(2)}} > 7(6)\,\mathrm{GeV}$, $|\eta^{\mathrm{jet1(2)}}| < 2.5$
- Inclusive sample, no lepton request

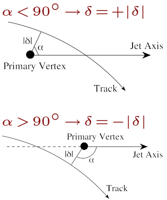


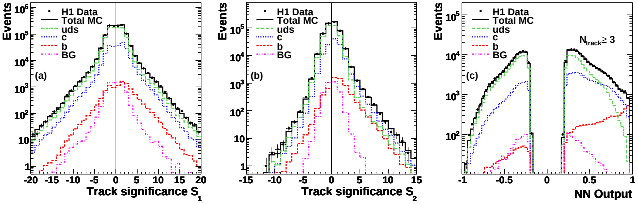
Reconstruction of secondary vertex:

- Associate tracks to jets and fit secondary vertices
- Use beamspot to calculate decay length (DL) in XY-plane
- Project decay length on jet axis

- Decay length significance, $S = \mathrm{DL}/\delta\mathrm{DL}$
  (for $2 < m_{\mathrm{vtx}} < 7.5\,\mathrm{GeV}$)
- Large S - almost pure beauty contribution
- Symmetric S distribution for light flavour
- Fit mirrored and subtracted S distribution







- 06-07 data: $\mathcal{L} = 189\,\mathrm{pb}^{-1}$
- Kinematic region: $Q^2 > 6\,\mathrm{GeV}^2, 0.07 < y < 0.6$
- At least one jet: $E_T^{\mathrm{jet}} > 6\,\mathrm{GeV}, -1 < \eta^{\mathrm{jet}} < 1.5$
- Flavour separation: based on track significance: $S = \delta/\sigma(\delta)$

- $S_1 \rightarrow$ highest $|S|$, $S_2 \rightarrow 2^{nd}$ highest $|S|$
- Neural Network (NN) input includes $S_1, S_2, S_3, 2^{nd}$ vertex decay length significance
- Beauty and charm have asymmetric S_1, S_2 distributions due to lifetime
- Mostly symmetric distributions for light flavours
- NN discriminates beauty and charm
- Fit mirrored and subtracted distributions to extract b, c and uds fractions

$F_2^{c\bar{c}}$ using the H1 vertex detector

H1: Eur Phys J. C65 (2010)

$F_2^{c\bar{c}}$ evaluated from reduced cross section:

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

- 06-07 data: $\mathcal{L} = 189\,\mathrm{pb}^{-1}$
- Kinematic region: $5 < Q^2 < 2000\,\mathrm{GeV}^2, 0.0002 < x < 0.05$
- Flavour separation: based on track significance: $S = \delta/\sigma(\delta)$

- $F_2^{c\bar{c}}$ as a function of Q^2 for fixed values of x
- Comparison with CTEQ at NLO and MSTW at NLO and NNLO
- Charm data reasonably well described by MSTW QCD calculations (NNLO somewhat better than NLO)
- CTEQ NLO also gives a reasonable description