Precision QCD at HERA

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on behalf of the H1 and ZEUS collaborations

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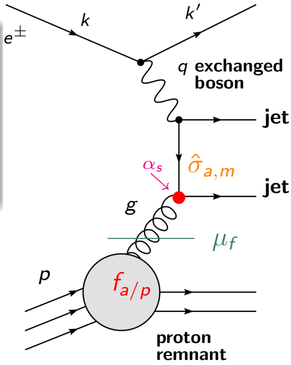
Outline:

1. Jet production at HERA
   → Extraction of the strong coupling α_s
2. Heavy quark production
3. Summary

Jets at HERA: Deep inelastic scattering

Kinematics:

- centre-of-mass energy: $\sqrt{s} = 318\ \mathrm{GeV}$
- momentum transfer: $Q^2 = -q^2 = -(k - k')^2$
- Bjorken x: $x = \frac{Q^2}{2p \cdot q}$
- inelasticity: $y = \frac{Q^2}{s \cdot x}$



$\rightarrow$ deep inelastic scattering (**DIS**) $\rightarrow Q^2 > \Lambda^2_{\mathrm{QCD}}$

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

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

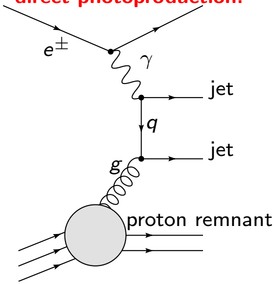
Coefficients are convolutions of

$\Rightarrow$ parton distribution functions (PDFs): $f_{a/p} \leftarrow$ long-distance structure (proton)

$\Rightarrow$ lepton-parton cross section: $\hat{\sigma} \leftarrow$ short-distance structure of the interaction

Jets at HERA: Photoproduction

direct photoproduction:



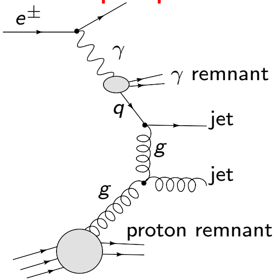
$\rightarrow$ photoproduction (γp) $\rightarrow$ $Q^2 \approx 0\ \mathrm{GeV}^2$

In lowest order two types of processes:

1. Direct process: photon directly takes part in the interaction
2. Resolved process: photon acts as source of partons

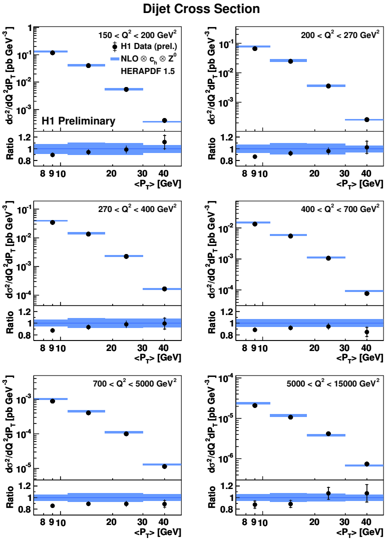
- Jet cross section in pQCD incorporates photon structure function

resolved photoproduction:

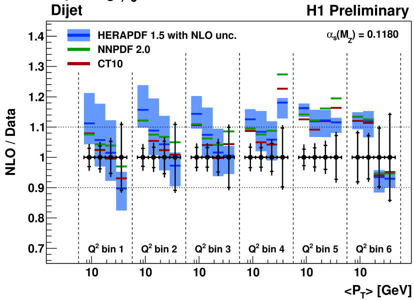


H1: Multi-jets in DIS at high Q^2

H1prelim-11-032



- Measurement of inclusive jet, dijet, trijet production at high Q^2
- Dominant sources of experimental uncertainties
  - hadronic energy scale: $\pm 1\%$ $\rightarrow 2-5\%$ on cross section
  - model dependence of acceptance correction: $\rightarrow 2-4\%$
- Typical total experimental uncertainties: $4-6\%$



Jet data will provide important constraints when used in PDF fits.

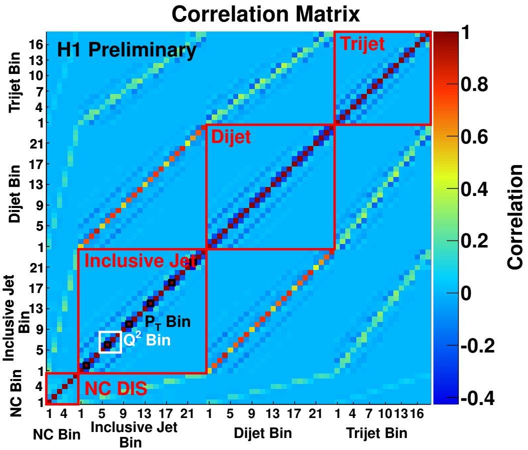
H1: Multi-jets in DIS at high Q^2

H1prelim-12-031

- Normalise multijet cross sections to the inclusive NC DIS cross section: $\sigma_{\rm jet}/\sigma_{\rm NC}$

$\rightarrow$ Reduction of systematic uncertainties (e.g. normalisation uncertainties cancel)

- Improved correction of detector effects $\rightarrow$ regularised unfolding of four measurements at once taking into account correlations

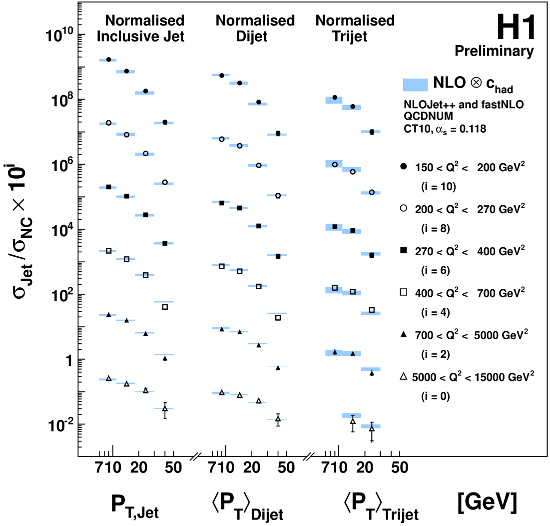


H1: Multi-jets in DIS at high Q^2

H1prelim-12-031

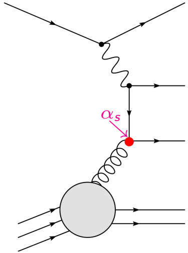
- All jet data are very well described by NLO QCD calculations as implemented in NLOJet++ using CT10 as proton PDFs

→ Measurement suited for $\alpha_s(M_Z)$ extraction with reduced uncertainties!



H1: Multi-jets in DIS at high Q^2

H1prelim-12-031



- Jet data are sensitive to α_s already in lowest order
- Jet cross section depends on PDFs and $\alpha_s(M_Z)$
  - fix PDFs in extraction
  - correlation between gluon PDF and α_s is neglected
- Hessian method has been applied to extract $\alpha_s(M_Z)$
  $\rightarrow$ takes into account correlated experimental uncertainties

- Combined $\alpha_s(M_Z)$ fit to inclusive jet, dijet, trijet data restricted to bins with $\sigma_{NLO}/\sigma_{LO} < 1.3$:

$$\alpha_s(M_Z) = 0.1163 \pm 0.0011\,(exp) \pm 0.0042\,(theo)$$

- Largest theoretical uncertainty caused by missing higher orders in the calculations

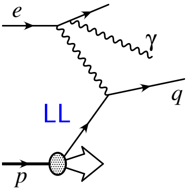
$\rightarrow$ Precision extraction of $\alpha_s(M_Z)$ with total uncertainty of $\approx 3.7\%$.

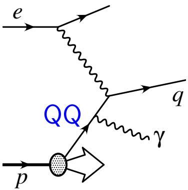
$\rightarrow$ In agreement with world average (2009): $\alpha_s(M_Z) = 0.1184 \pm 0.0007$

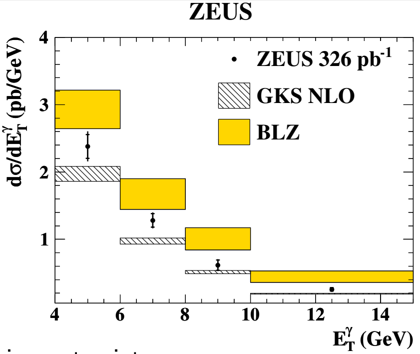
ZEUS: Prompt photons + jets in DIS

DESY-12-089

- Measurement of prompt photons provide direct probe of the underlying parton dynamics, because the γ emission is not affected by hadronisation.





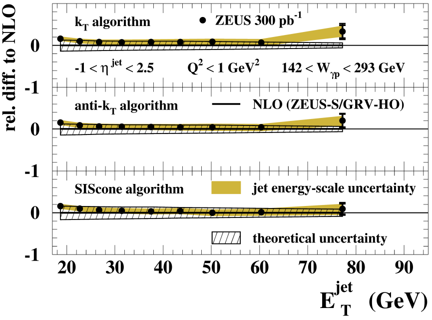


- Sensitive to proton PDF (enhanced γ radiation of u compared to d quarks)
- Suppression of LL component by requiring extra jet
- Lateral width of the energy cluster in the calorimeter exploited as discriminant
- Comparison to theory: Fixed order calculations, k_T-factorisation approach

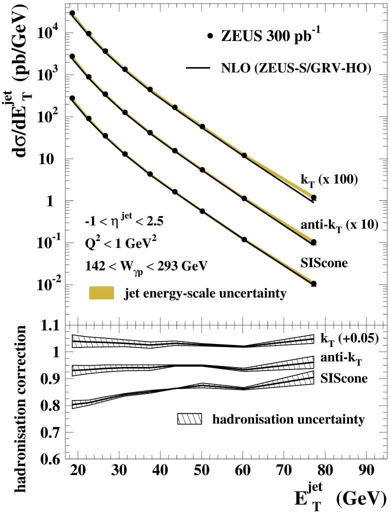
$\rightarrow$ Both theories describe the shape of the data rather well, but the normalisation is not described.

ZEUS: Inclusive jet production in γp DESY-12-045

- Measurement of jet cross sections in γp using k_T, anti-k_T and SIScone jet algorithm.
- SIScone, anti-k_T produce more circular shaped jets than k_T
- Stringent test of new jet algorithms in an environment closer to that encountered in pp collisions due to resolved γ events.

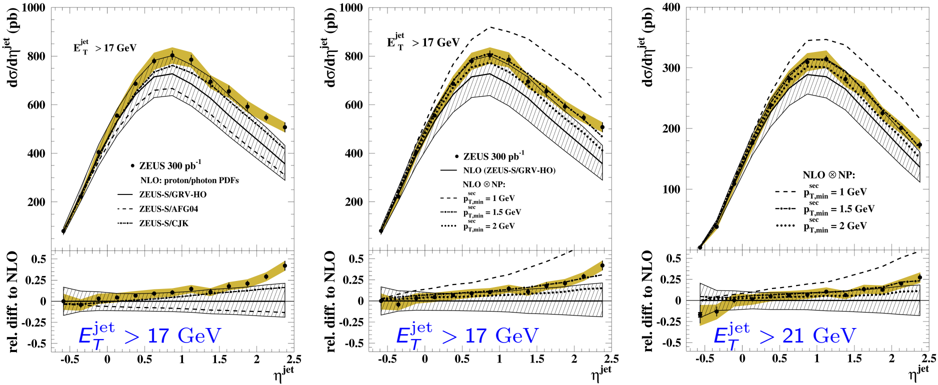


- At least one jet with in the range $-1 < \eta^{\text{jet}} < 2.5$ with $E_T^{\text{jet}} > 17$ GeV



Good description of the data by NLO calculations!

ZEUS: Inclusive jet production in γp DESY-12-045



- Non-perturbative effects or the γ PDFs at high η^{jet} could cause observed differences between data and theory:
  - → Significant spread between γ PDFs
  - → Contributions from non-perturbative effects significantly depend on η^{jet}

ZEUS: Inclusive jet production in γp DESY-12-045

- Extraction of α_s for all three jet algorithms in the region $21 < E_T^{\text{jet}} < 71$ GeV.

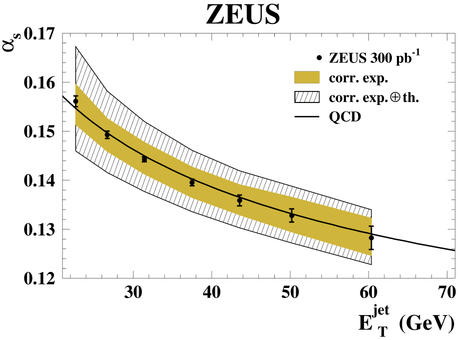
- k_T algorithm: $\alpha_s(M_Z) = 0.1206^{+0.0023}_{-0.0022}(\text{exp.})^{+0.0042}_{-0.0035}(\text{th.})$
- anti-k_T algorithm: $\alpha_s(M_Z) = 0.1198^{+0.0023}_{-0.0023}(\text{exp.})^{+0.0041}_{-0.0034}(\text{th.})$
- SIScone algorithm: $\alpha_s(M_Z) = 0.1196^{+0.0022}_{-0.0021}(\text{exp.})^{+0.0046}_{-0.0043}(\text{th.})$

- Similar performance of all three jet algorithms

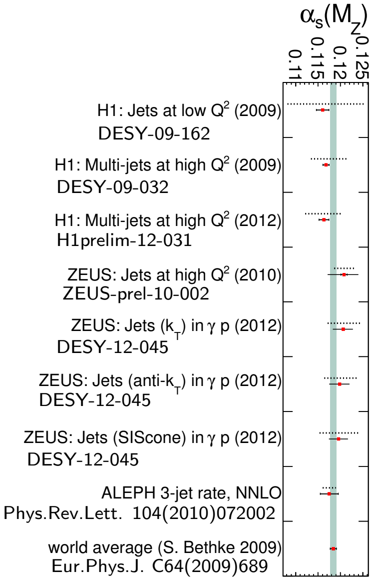
→ Precision extraction of $\alpha_s(M_Z)$ with total uncertainty of $\approx 3.9\%$.

→ **Predicted running of α_s agrees very well with the data.**

→ **Running is measured in a single experiment.**



Comparison of $\alpha_s(M_Z)$ values



experiment

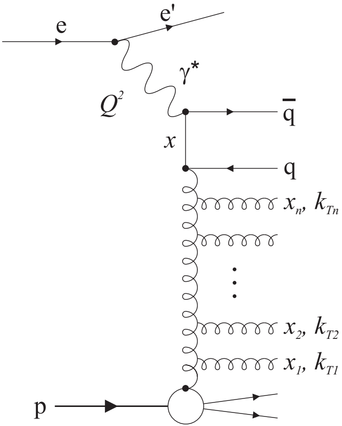
theoretical uncertainty

Presented $\alpha_s(M_Z)$ extractions are consistent with each other and in good agreement with the world average value from 2009.

Parton cascades

Several descriptions of the parton cascades are available:

1. DGLAP: ordered in transverse momentum, k_T
2. BFKL: no k_T ordering
   - colour-dipole model provides BFKL-like approach
3. CCFM: unification of DGLAP and BFKL approaches → introduces angular ordering

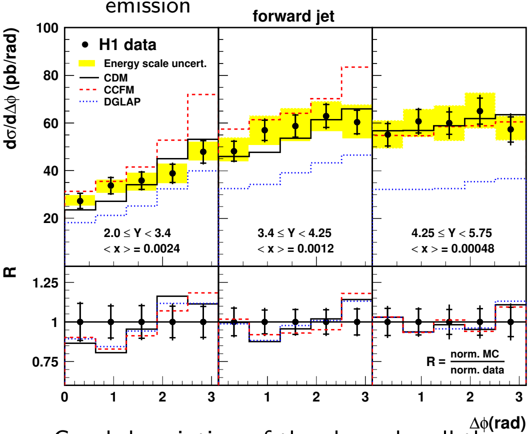


→ **Measure jets at low x produced close to the proton direction to be more sensitive to parton dynamics.**

H1: Azimuthal correlation in DIS

DESY-11-183

- Jet cross section as a function of the azimuthal difference, $\Delta\phi$, between forward jet and electron
  - Partial decorrelation due to higher order processes
  - Electron-jet rapidity distance, Y, related to available phase space for parton emission



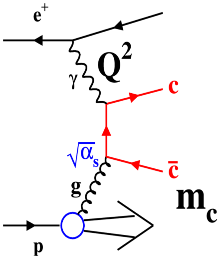
Phase space:

- $0.1 < y < 0.7$
- $5 < Q^2 < 85\ \mathrm{GeV}^2$
- $0.0001 < x < 0.004$
- $P_{T,\mathrm{fwdjet}} > 6\ \mathrm{GeV}$
- $1.73 < \eta_{\mathrm{fwdjet}} < 2.79$
- $x_{\mathrm{fwdjet}} > 0.035$
- $0.5 < P^2_{T,\mathrm{fwdjet}}/Q^2 < 6$

→ Good description of the shape by all three MC models

→ BFKL-like approach also describes the normalisation

Heavy quark production at HERA



→ Well established tool to study pQCD predictions.

→ Multiple hard scales: p_T, $m_{c,b}$, Q^2

→ Probe the gluon density in the proton.

→ Sensitive to the quark masses. ← Treatment of charm mass in PDF fits e.g. important for theory predictions of W production at LHC.

Treatment of quark masses in pQCD:

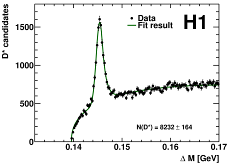
- Fixed Flavour Number Scheme (FFNS):
  - → Final-state massive heavy quarks generated dynamically in boson-gluon fusion
  - → At large scales logarithmic corrections, $\propto \log \frac{\mu^2}{m^2_{c,b}}$, might become large
  - ↪ Applicable at small scales, $\mu^2 \approx m^2_{c,b}$
- Zero Mass Variable Flavour Number Scheme (ZM-VFNS):
  - → Heavy quarks are treated as massless; number of active flavours depend on scale
  - → Valid for large scales, $\mu^2 \gg m^2_{c,b}$
- General Mass Variable Flavour Number Scheme (GM-VFNS):
  - → Combination of massless and massive schemes (interpolation)

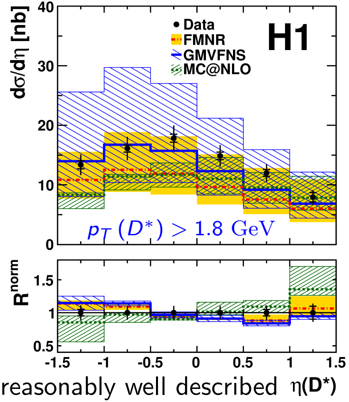
H1: D^* in photoproduction DESY-11-248

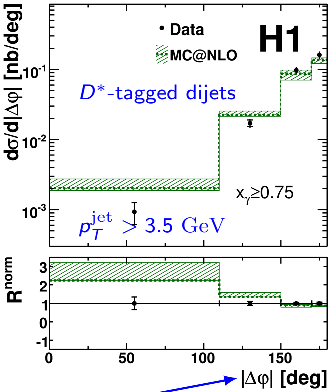
- Reconstruction of $D^{*\pm}$ mesons in golden decay channel:

$$D^{*\pm} \to D^0\pi_s^{\pm} \to K^{\mp}\pi^{\pm}\pi_s^{\pm}$$

$\Delta M = M(D^*) - M(D^0)$







- In general data reasonably well described by NLO QCD predictions → data much more precise than theories
- Study parton dynamics by requiring two jets one of them containing the D^* meson
- Significant differences between data and theory for correlation variables

H1/ZEUS: D^* production in DIS

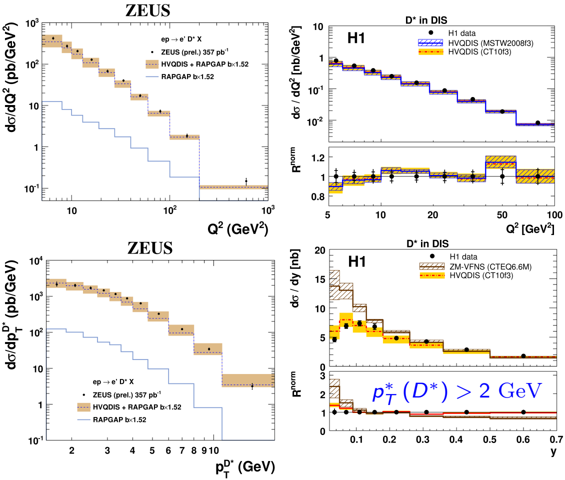
DESY-11-066,ZEUS-prel-11-012

Reconstruction of $D^{*\pm}$ mesons in golden decay channel:

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

Phase space:

- $5 < Q^2 < 100\ \mathrm{GeV}^2$
- $p_T^{D^*} > 1.25\ \mathrm{GeV}$ (H1), $p_T^{D^*} > 1.5\ \mathrm{GeV}$ (ZEUS)
- $|\eta^{D^*}| < 1.8$ (H1), $|\eta^{D^*}| < 1.5$ (ZEUS)

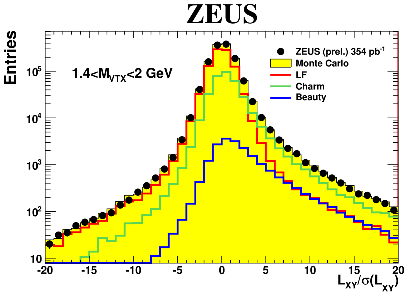


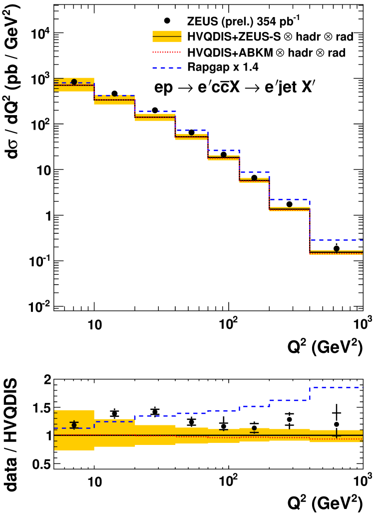
→ **Good agreement between measurement and NLO QCD calculations with massive scheme over a wide range of phase space.**

ZEUS: Charm production in DIS using secondary vertices

ZEUS-prel-12-002

- Measurement employs long lifetime of heavy quarks
- Reconstruction of displaced secondary vertices to determine decay length significance, $L_{xy}/\sigma\,(L_{xy})$
- Determine charm contribution by fitting $L_{xy}/\sigma\,(L_{xy})$ in bins of the secondary vertex mass



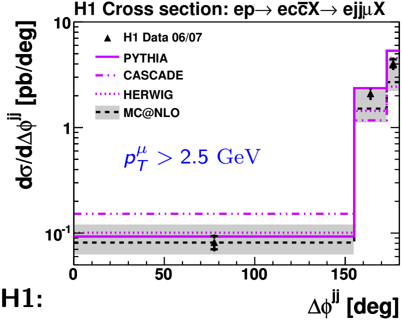


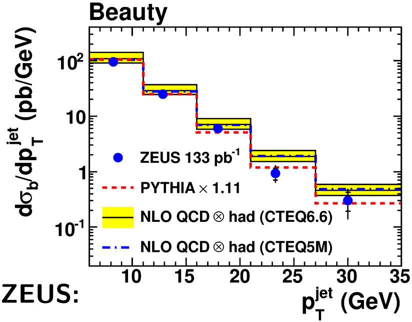
NLO QCD with massive scheme (FFNS) describe the data reasonably well.

H1/ZEUS: Charm and beauty in γp

DESY-12-059,DESY-11-067

- Require at least two jets with $p_T^{\mathrm{jet1(2)}} > 7(6)$ GeV





H1:

- Utilise muon tag: determine relative transverse momentum, p_T^{rel}, of μ w.r.t the jet; use impact parameter of μ track

→ Correlation variable, $\Delta\phi_{jj}$, sensitive to higher order contributions

→ Data reasonably well described by theory

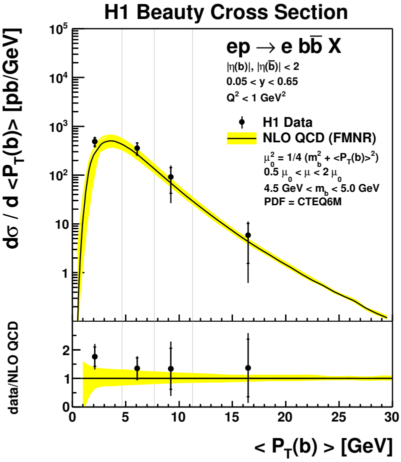
ZEUS:

- Reconstruction of secondary vertices
- Decay length significance and secondary vertex mass used to discriminate signal from background

→ Good agreement between data and NLO QCD calculations using $\mu_R^2 = \mu_F^2 = \frac{1}{4} \cdot \left(m_b^2 + p_T^2\right)^2$

H1: Beauty photoproduction at small p_T DESY-12-072

- Beauty production near threshold $\rightarrow$ hard scale provided by b mass ($Q^2 \approx 0\ \mathrm{GeV}^2$ in γp)
- Exploiting semi-leptonic decay into two low $p_T > 1\ \mathrm{GeV}$ electrons using several quantities to discriminate signal from background (light flavour, charm, J/Ψ):
  1. invariant mass, m_{ee}
  2. angular correlations, $\Delta\phi_{ee}$
  3. charge product, $q_{e1} \cdot q_{e2}$



$\rightarrow$ Lowest $\langle p_T\,(b)\rangle$ measured in ep collisions

$\rightarrow$ Measurement described by theory with the uncertainties

Summary

Measurements of jet and heavy quark production allow detailed tests of QCD dynamics!

- Recently, at HERA stringent tests of pQCD were performed using ...
  - → inclusive jets, dijets, and trijets in DIS
  - → forward jet production in DIS
  - → isolated photons + jets in DIS
  - → inclusive jets in γp
  - → charm and beauty quark production in γp and in DIS
- The strong coupling constant α_s was extracted from
  - → inclusive jets in γp
  - → multijets in DIS

Conclusion:

→ pQCD calculations describe the data over a wide range of phase space

→ Theoretical uncertainties are often larger than experimental uncertainties

→ α_s extractions are competitive!

Backup

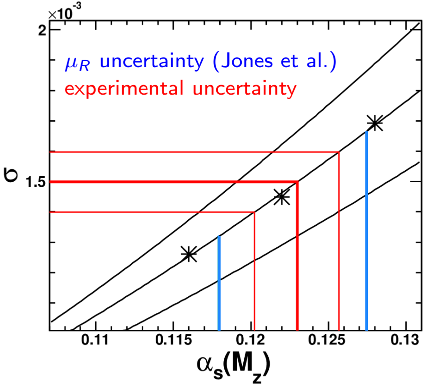
Extraction of $\alpha_s(M_Z)$

α_s Extraction:

- pQCD calculations depend on α_s via the partonic cross section and the PDFs
- NLO calculations using various sets of PDFs with different assumed α_s were performed
- Parametrize $\alpha_s(M_Z)$ dependence of observable $d\sigma/dA$ in bin i according to

$$\frac{d\sigma_i}{dA} = C_1 \cdot \alpha_s(M_Z) + C_2 \cdot \alpha_s^2(M_Z)$$

- Map measured $d\sigma/dA$ to x-axis and extract $\alpha_s(M_Z)$



⇒ Complete α_s dependence of the calculations and the PDFs is preserved (matrix elements and PDF evolution)