Precision QCD measurements at HERA

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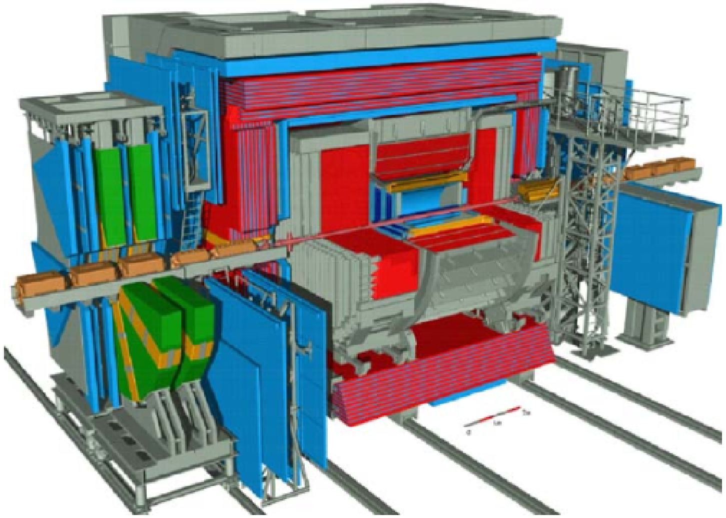
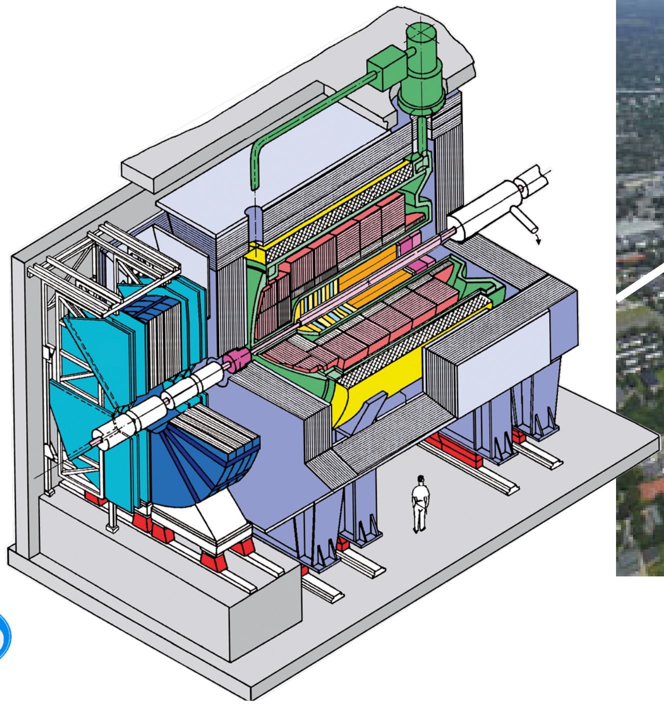
Outline:

- Jet production at HERA
  - Extraction of strong coupling constant
- Heavy quark production at HERA
  - Test of perturbative QCD

The HERA ep collider (1992 - 2007)

- ep collider:
- $e^{\pm}$ energy: 27.6 GeV
- p energy: 920 GeV
- Center of mass energy: 319 GeV
- 2 collider experiments: H1 and ZEUS
- Integrated luminosity: ~0.5 fb^{-1} (per experiment)





ZEUS

Motivation: QCD in ep collisions

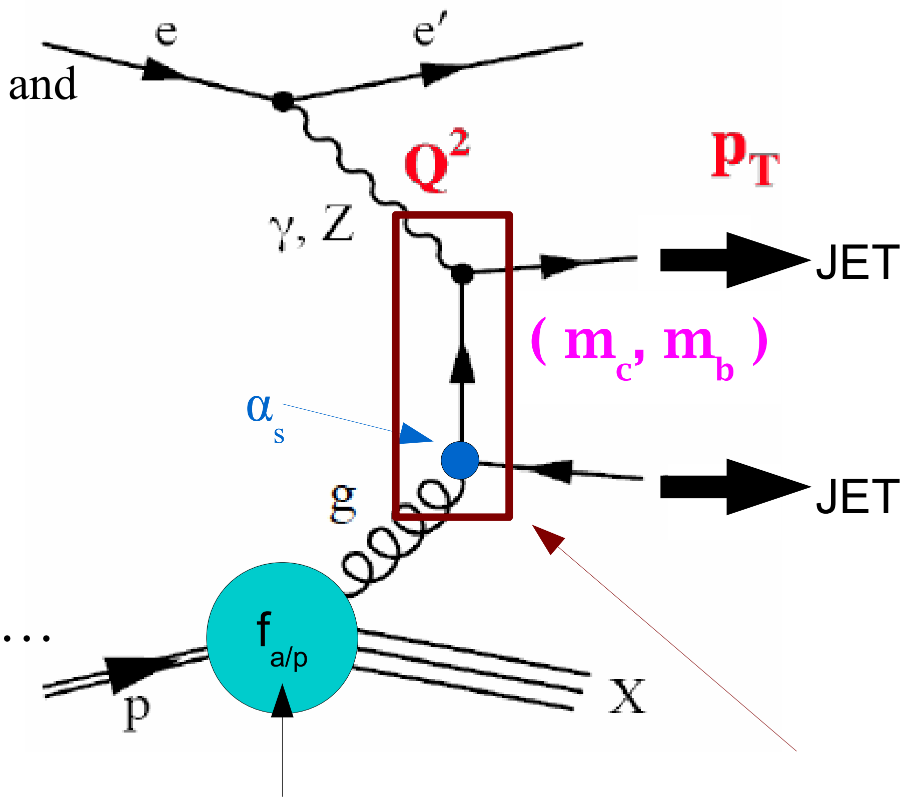
- QCD:
  - $\mathcal{L}_{\rm QCD} = \bar{\psi}_i \left(i (\gamma^\mu D_\mu)_{ij} - m\, \delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$
  - Beautiful theory, determined by heavy quark masses and strong coupling constant α_s .

- Hard scales for perturbative QCD:
  - $m_{c,b}^2, p_T^2, Q^2 > \Lambda_{QCD}^2$
    - Jet and heavy flavor cross sections in **power series of $\boldsymbol{\alpha_s}$** .

$$d\sigma = \sum_m \alpha_s^m(\mu_R) \sum_a f_{a/p}(x, \mu_F) \otimes d\sigma_{a,m}(x, \mu_F, \mu_R) \otimes \ldots$$

- Jet and heavy quark measurements are gluon-induced processes:
  - Test universality and energy behavior of α_s .
  - Take the gluon density from somewhere and test the consistency of the pQCD calculation.
  - Use the pQCD calculations and constrain the gluon density of the proton. (See talk of Vladyslav Libov)

Typical Feynman diagram for gluon-induced jet or heavy quark production:

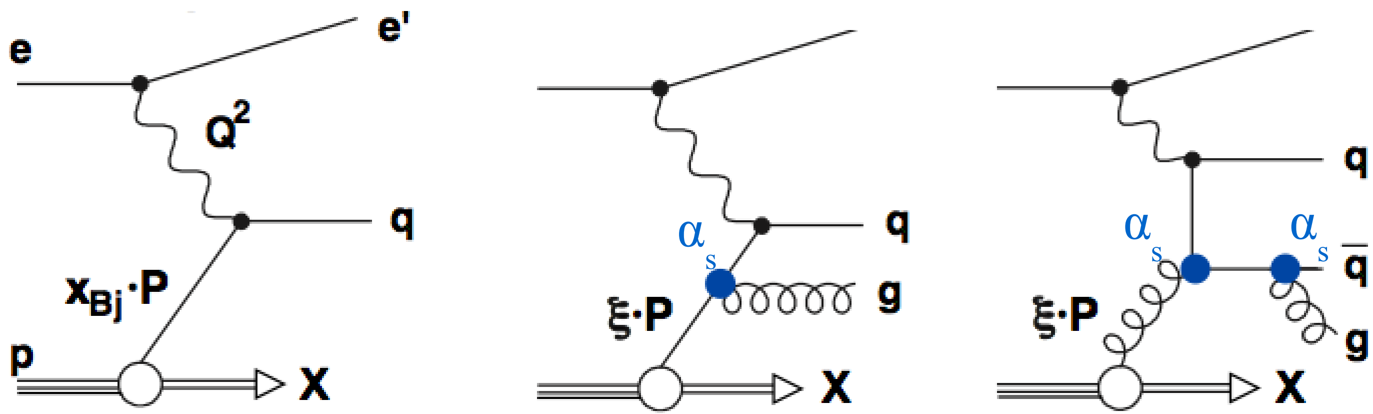


Parton density function (discussed in next talk)
$a = q, \bar{q}, g$

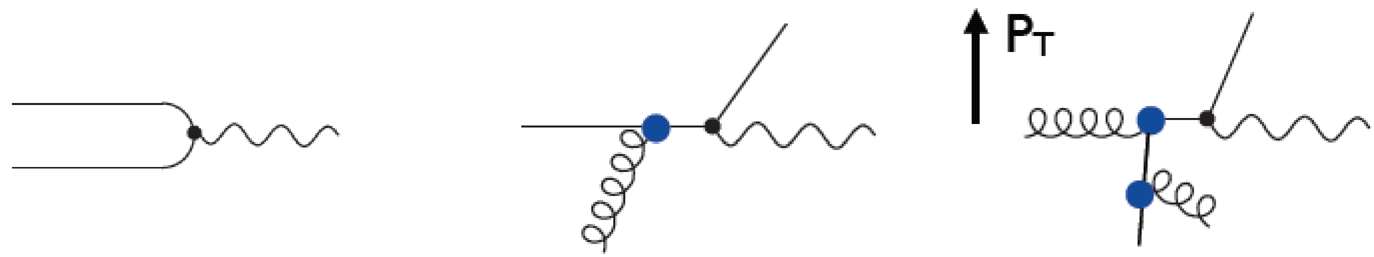
$d\sigma_{a,m}$ pQCD matrix element

Jet Measurements and the strong coupling constant α_s

- Lab frame: DIS, 1 jet | 2 jets | 3 jets

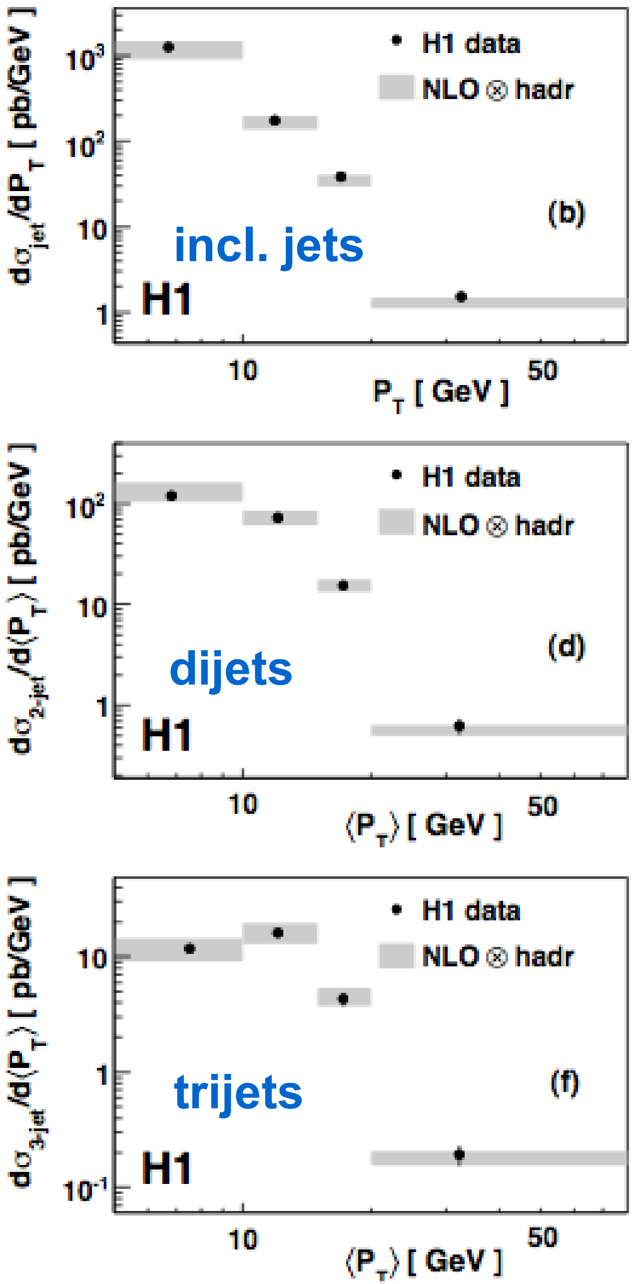


- Breit Frame: no jets | incl. Jets, dijet | trijet

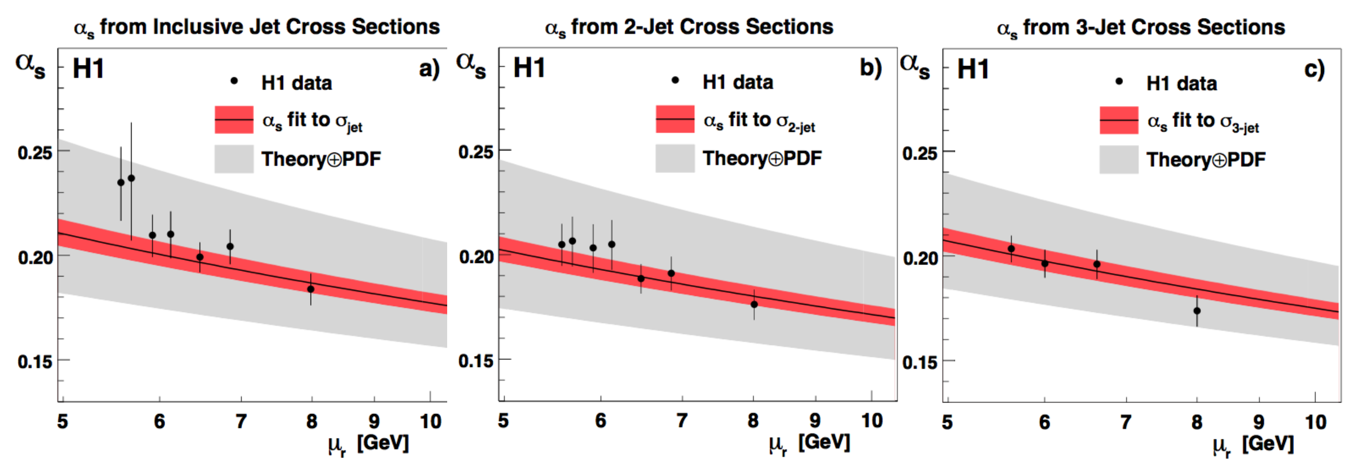


- Boost to Breit Frame, study multi-jet final states as functions of standard DIS kinematics and variables such as:
  - Transverse jet momenta: p_T w.r.t photon direction.

- Direct sensitivity to alpha s and gluon density



- Double differential inclusive jet, dijet and trijet measurements.
- Data well described by NLO prediction with $\mu_r = \sqrt{(Q^2 + P_T^2)/2}$.
- Simultaneous fit to 62 data points to extract strong coupling constant $\alpha_s(Z)$.

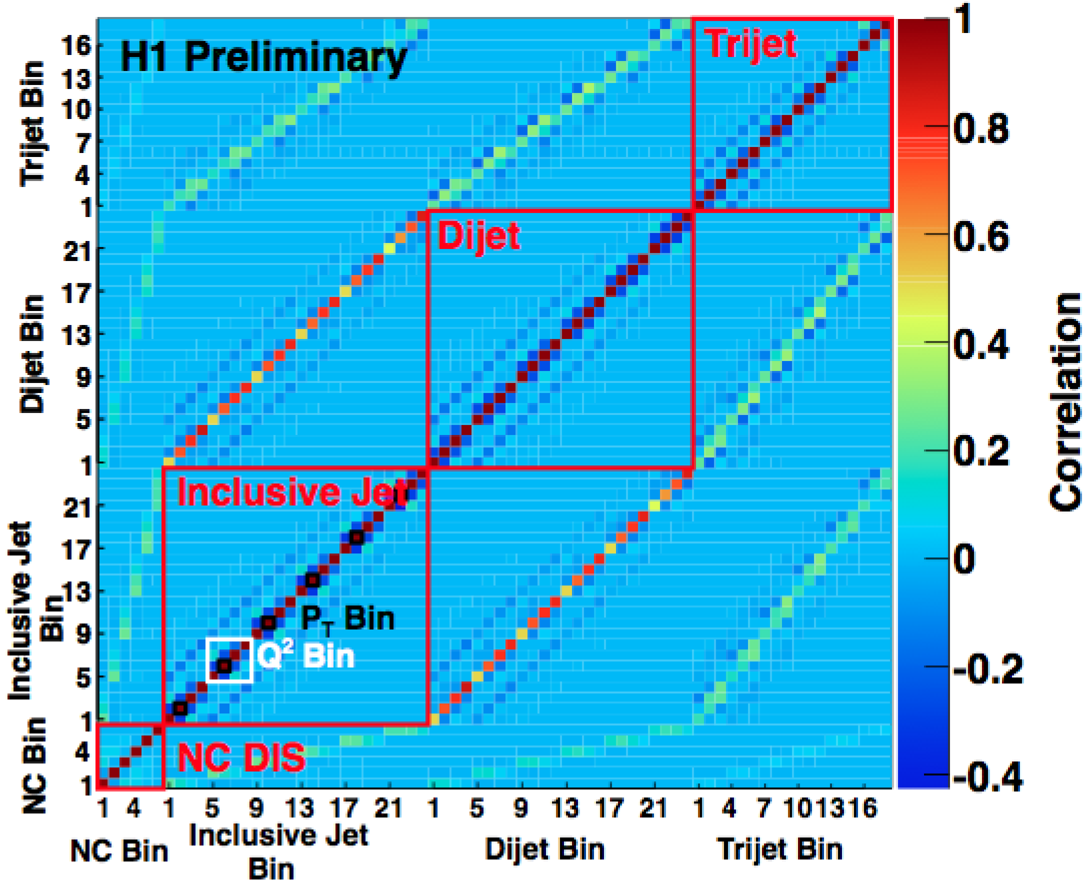


- $\alpha_s(M_Z) = 0.1160 \pm 0.0014(exp.)^{+0.0093}_{-0.0077}(th.) \pm 0.0016(\text{PDF})$

DESY-09-162, Eur.Phys.J. C67 (2010) 1 , 11/09

Multi-jets in DIS at high Q^2

- Inclusive jet, dijet and trijet cross sections for $150 < Q^2 < 15000\ GeV^2$
- Reduced scale dependance compared to low Q^2 measurement.
- Unfolding of multi-jet cross sections:
  - All correlations of observables incorporated.
  - Full, party correlated, covariance matrix known.
  - ➔ Important input for QCD fits.
- High experimental (~2%) and theoretical (~3.5%) precision.



H1prelim-12-031

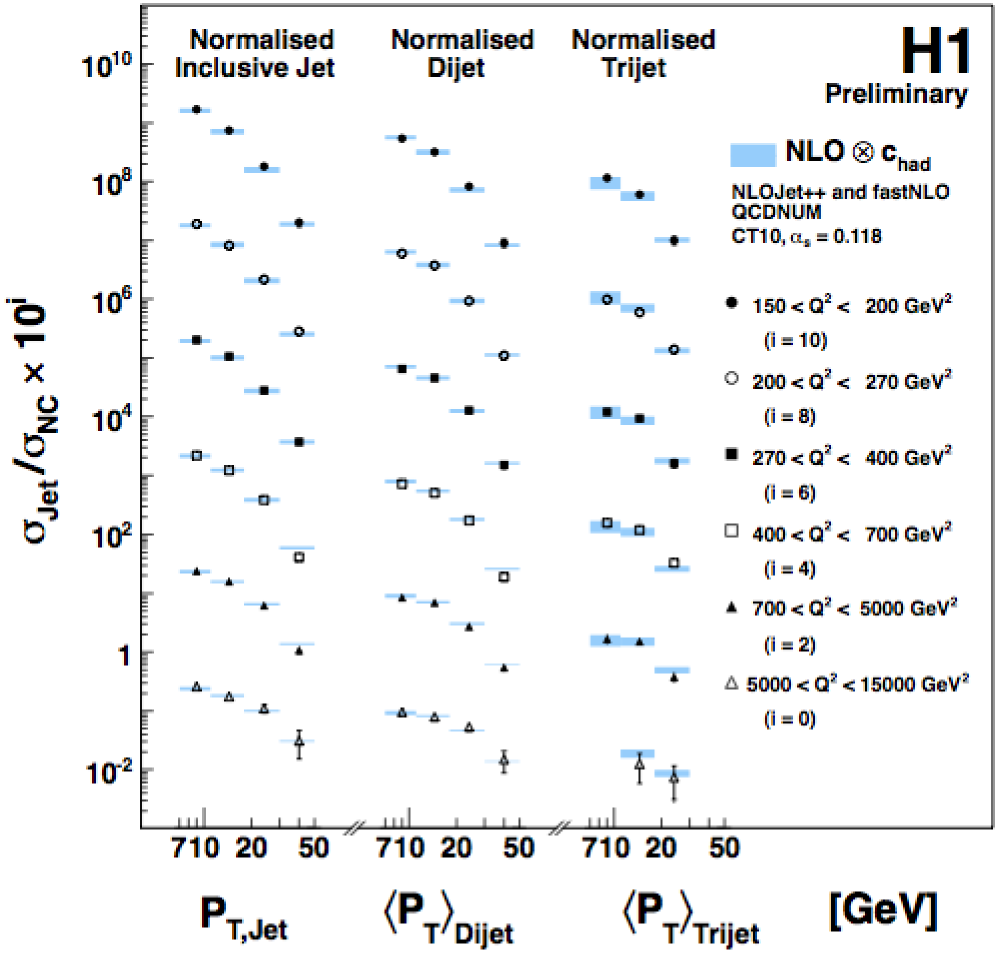
NLO calculation:

- Jet cross sections:
  NLOJet++ and FastNLO v2.0
- NC-DIS cross sections:
  QCDNUM
- NLO ⊗ Hadronisation corrections.

Fit to extract strong coupling constant:

- Fits of α_s to each sample (inclusive jet, dijet, trijet) result in good χ^2/NDF.
- Tension between dijets and inclusive/trijets.
- Fit of all three samples with restriction that NLO corrections < 30%
  $\rightarrow \chi^2/\text{NDF} = 53.2 / 41 = 1.3$

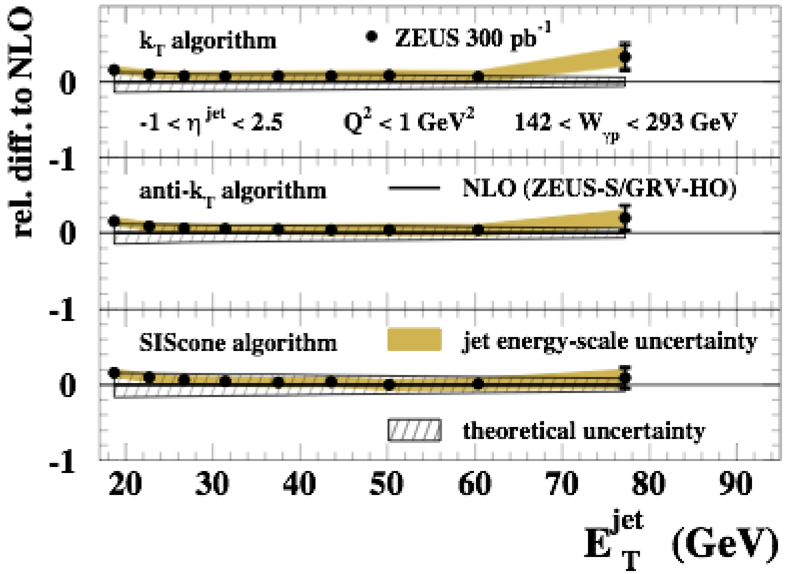
Normalised multijet cross sections:

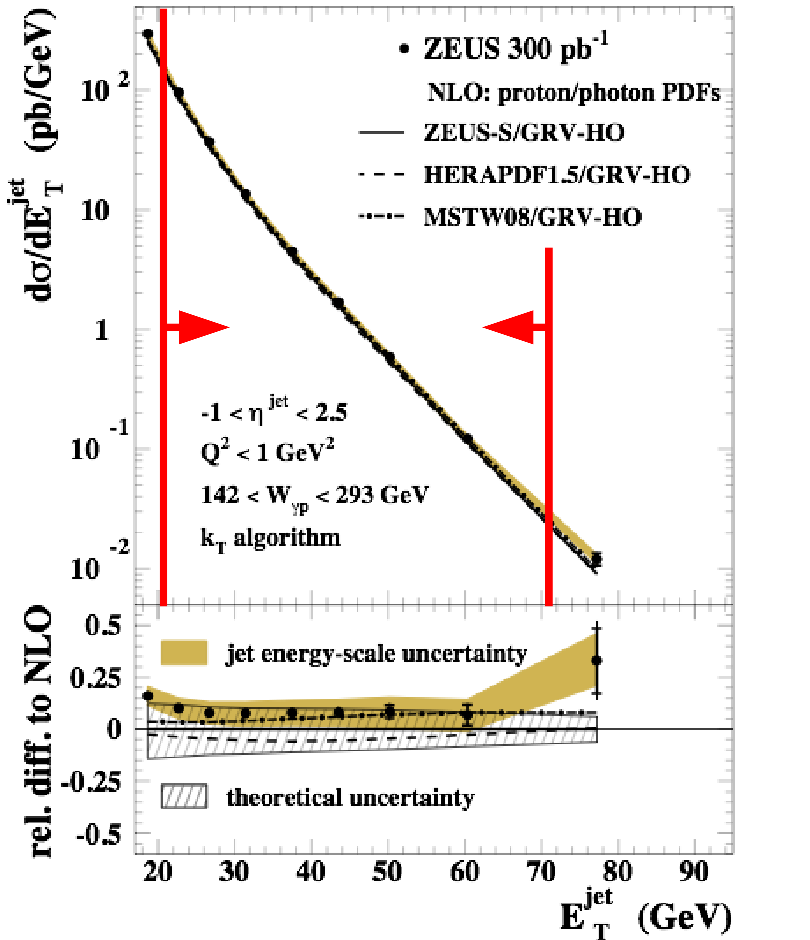


- $\alpha_s = 0.1163 \pm 0.0011\ (\text{exp}) \pm 0.0014\ (\text{PDF}) \pm 0.0008\ (\text{had}) \pm 0.0039\ (\text{theo})$

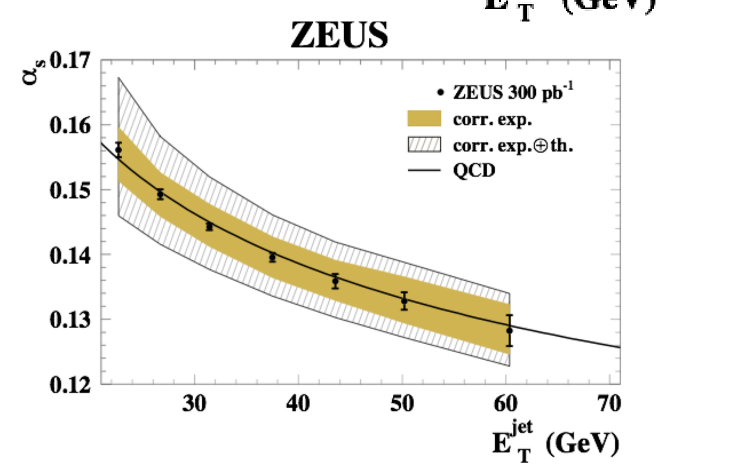
H1prelim-12-031

- Double differential measurement in E_T and η.
- Study of different jet algorithms, SIScone, anti-k_T and k_T.





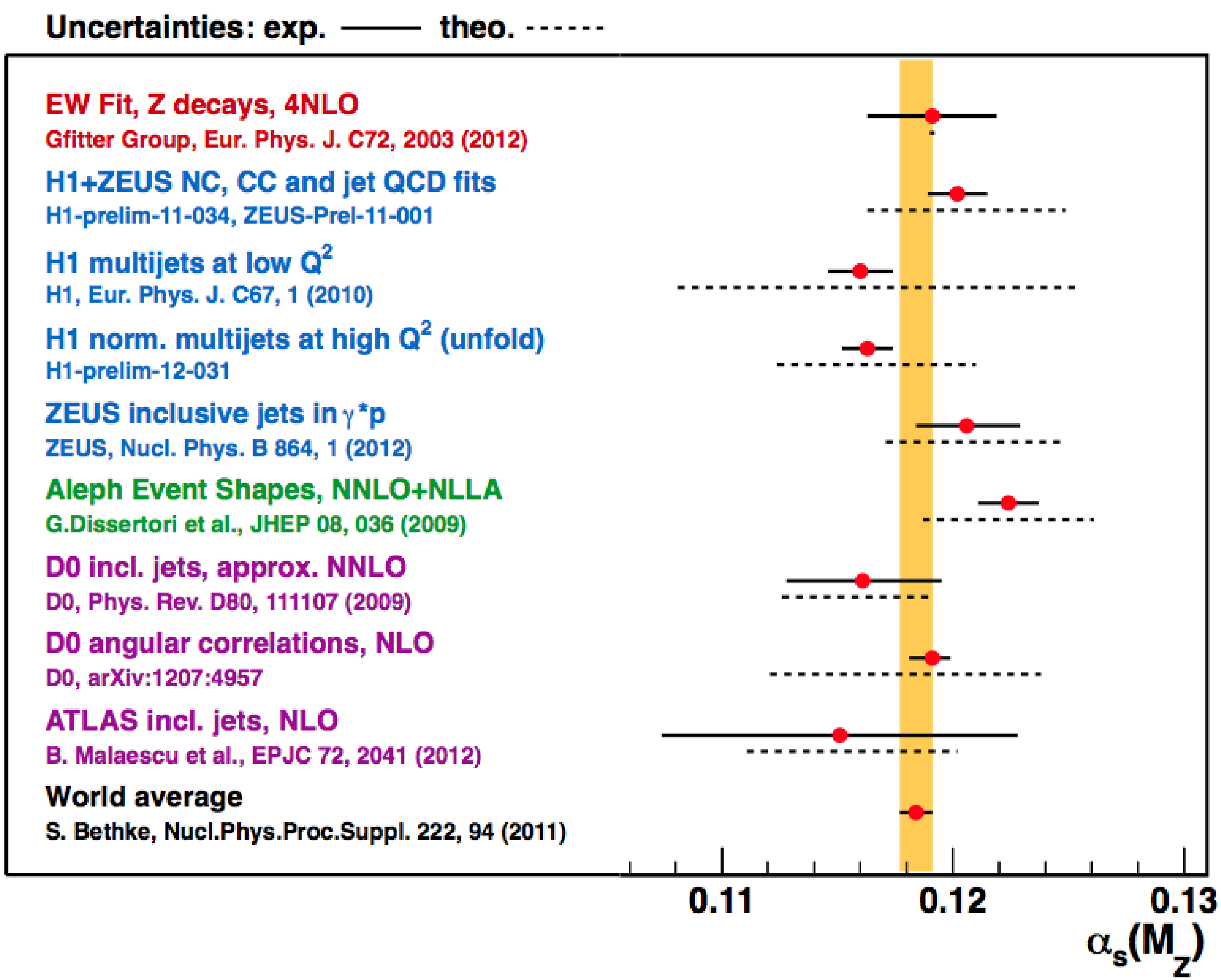
- Extraction of α_s in $21 < E_T < 71$ GeV.
- Same conclusions for all jet algorithms.



- $$\alpha_s(M_Z) = 0.1206\,^{+0.0023}_{-0.0022}\,(\text{exp.})\,^{+0.0042}_{-0.0035}\,(\text{th.})$$

DESY-12-045, Nucl. Phys. B864 (2012), 1-37

Comparison of $\alpha_s(Z)$ values

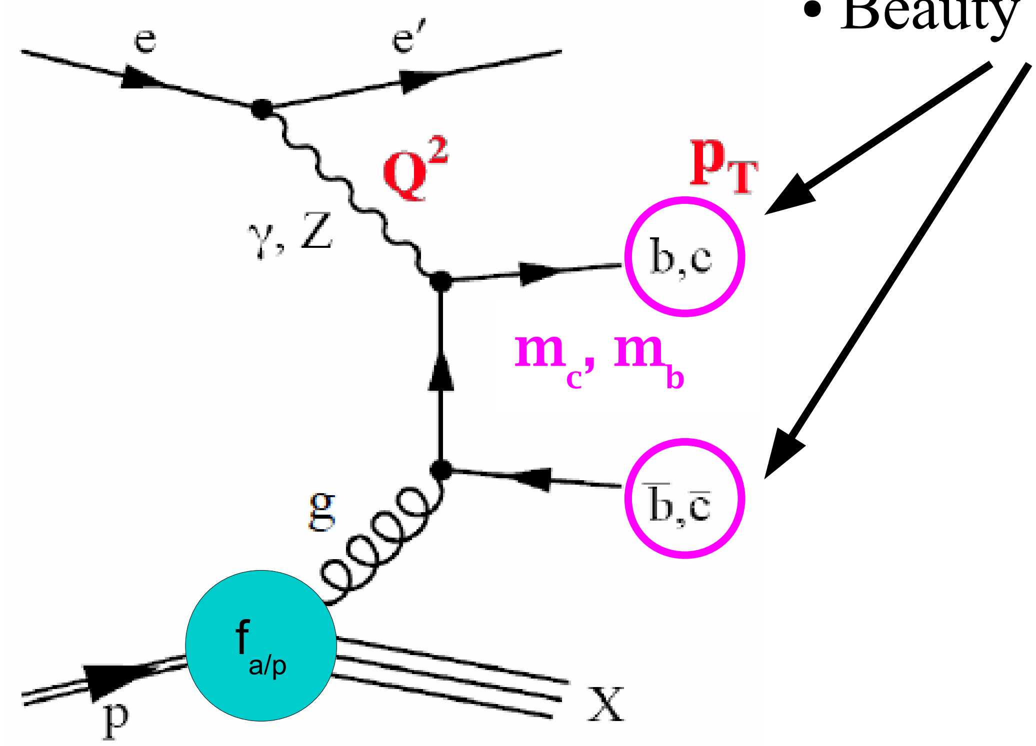


- Competitive experimental errors.
- To do better, need NNLO calculations.

Heavy Flavour Production:

- Hard scales for perturbative QCD:
  - $m_{c,b}^2$, p_T^2, Q^2
    - multi-scale problem.

Heavy Flavours:
- Charm quark
- Beauty quark



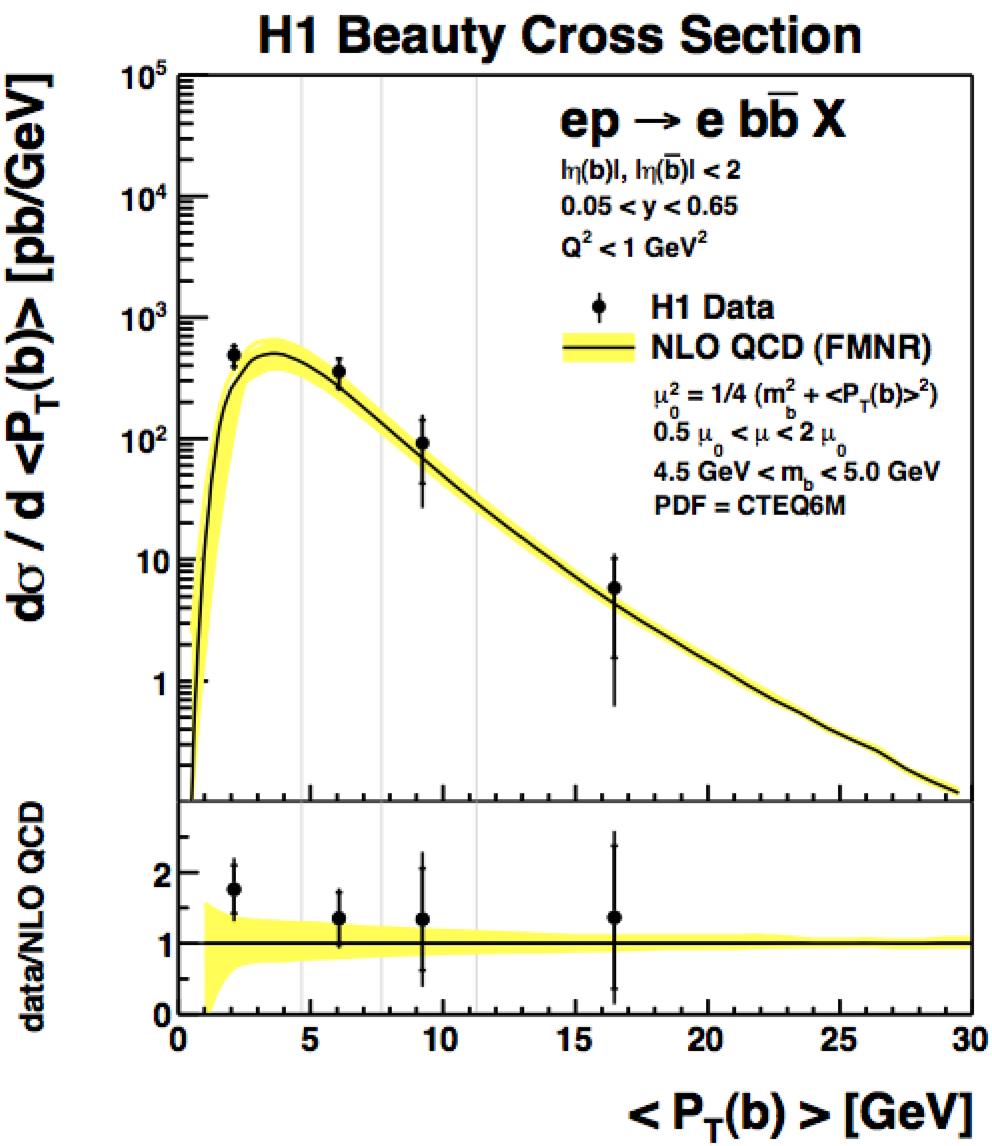
- Aim of these measurements:
  - Test pQCD at <u>different hard scales</u>.
  - Provide input to PDF fits.
    (see talk of Vladyslav Libov)

Data sample: $\mathcal{L}$=48 pb^{-1}

Phase Space
Events with 2 low p_T-electrons with
$p_T(e) \gtrsim 1$GeV

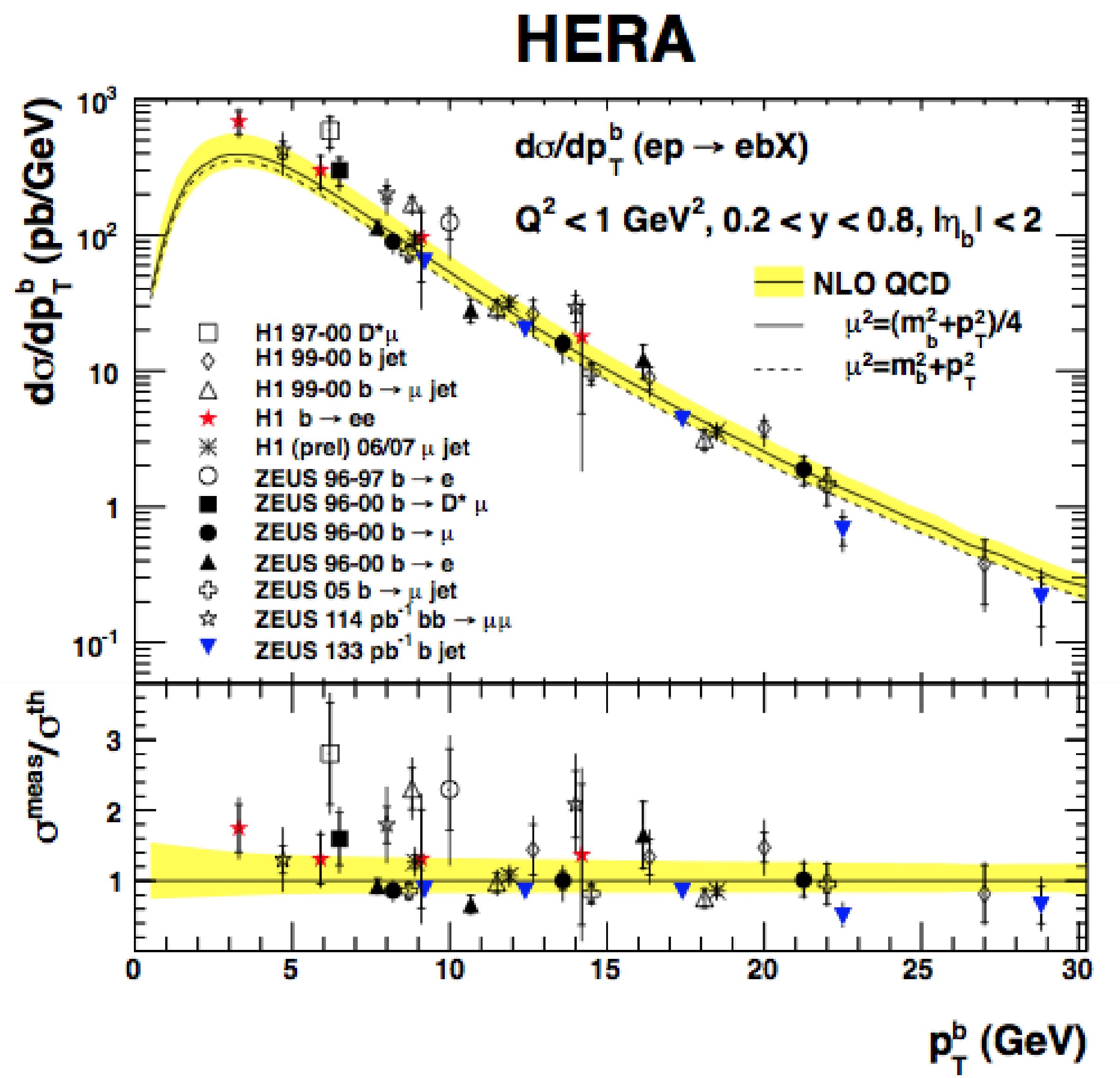
Beauty tagging
Two low p_T electrons from semileptonic decays:

- Exploit di-electron correlations:
  - Invariant mass m_{ee}
  - Azimuthal correlation $\Delta\Phi_{ee}$
  - di-electron charge product: q(e1)*q(e2)



- Access to lowest $p_T(b)$ values ever measured in ep.
- Agreement between data and NLO calculation (FMNR).

DESY-12-072, Eur. Phys. J. C72 (2012) 2148 , 06/12 hard scale: m_b , p_T



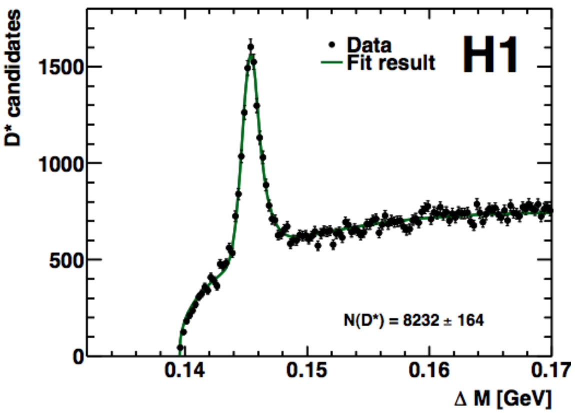
- Many measurements confirming each over a wide p_T(b) range.
- General good agreement between data and NLO calculation (FMNR).

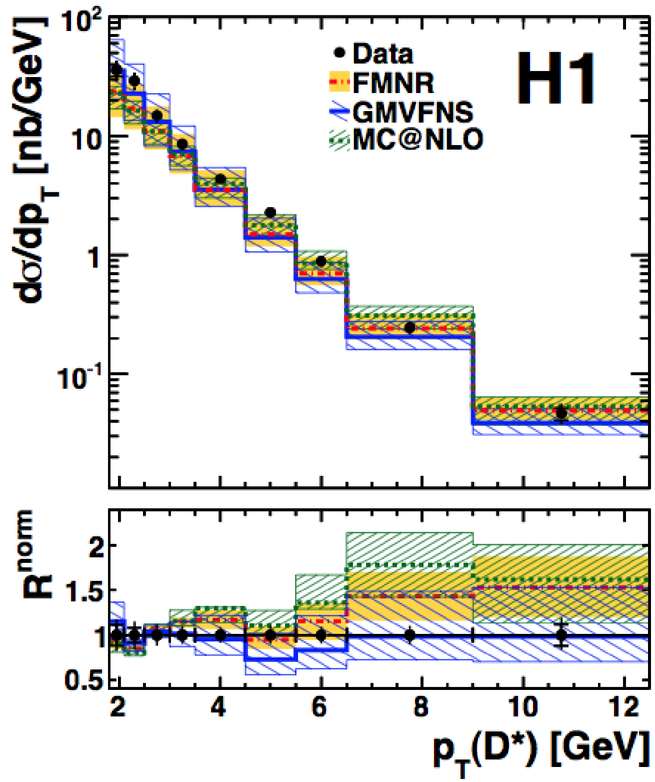
Data sample: $\mathcal{L}$=93 pb^{-1}

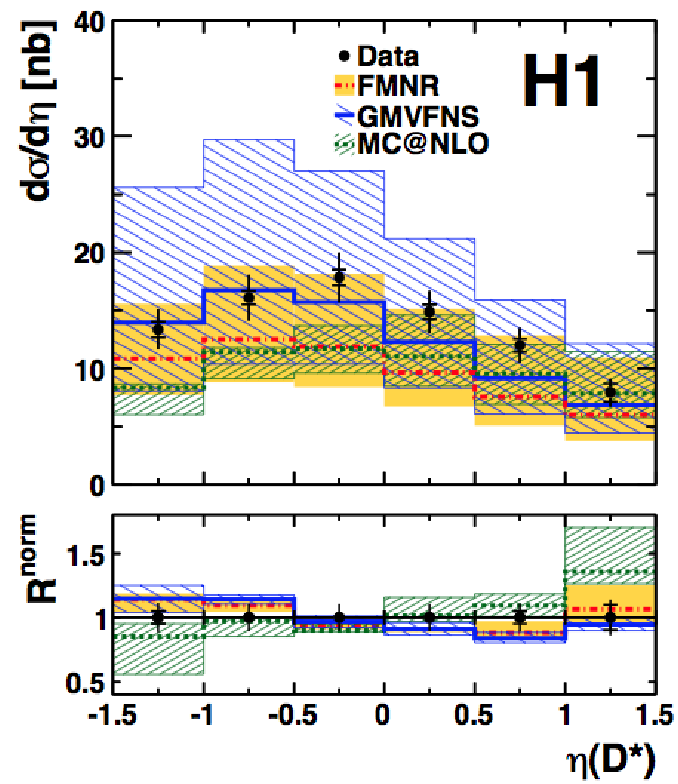
Phase Space
$Q^2 < 2\ GeV^2$, $p_T^{D^*} > 1.8 GeV$

Charm tagging
D* meson reconstruction via:

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







- Very high precision of the data, compared to the uncertainties of the NLO predictions.
- NLO predicted shapes less sensitive to theoretical uncertainties, generally show a reasonable agreement with the data.

DESY-11-248, Eur. Phys. J. C72 (2012) 1995

D* production in DIS

hard scales: m_c, Q^2

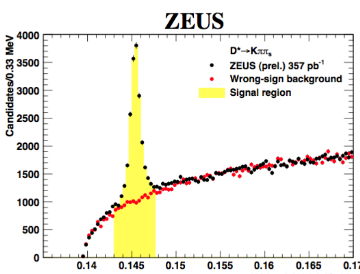
Data Samples: $\mathcal{L}$ ~ 350 pb^{-1}

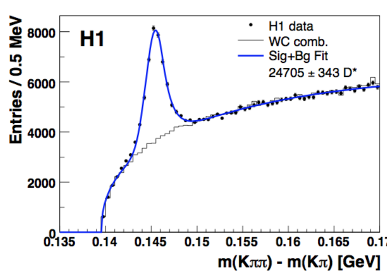
Phase Spaces (H1 / ZEUS)		
Q^2 :	5-100 GeV^2	5-1000 GeV^2
P_T^{D*}	> 1.25 GeV	>1.5 GeV
$\lvert \eta^{D*} \rvert$	< 1.8	< 1.5

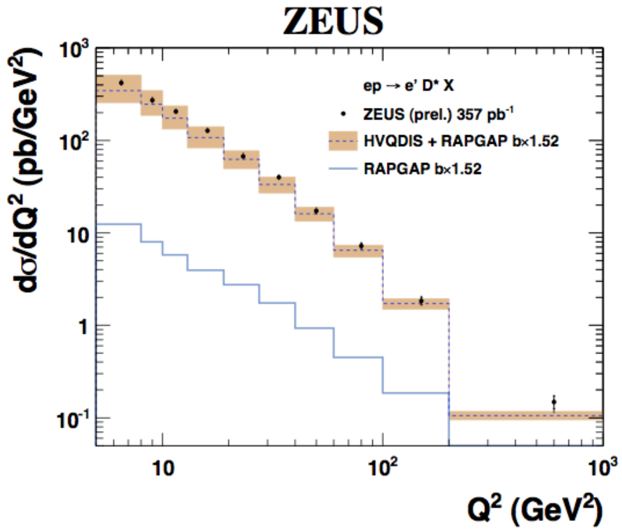
Charm tagging

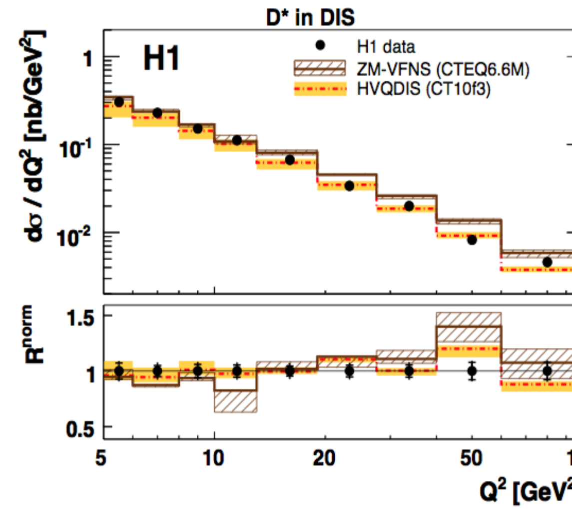
Reconstruction of a D* meson decaying in the golden channel:

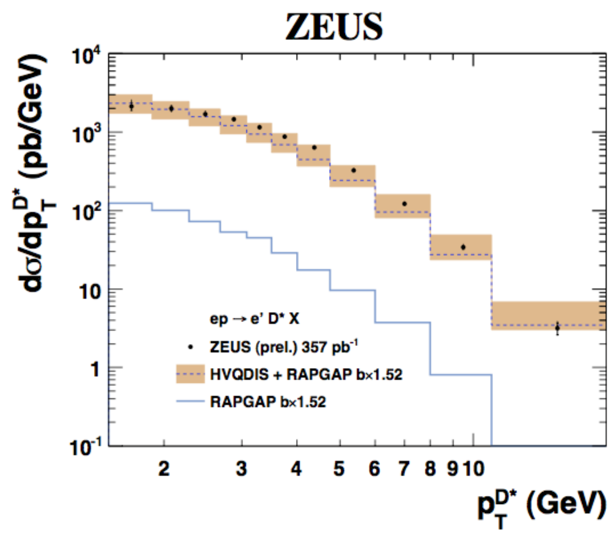
$$D^{*\pm} \rightarrow D^0 \pi^{\pm}_{slow} \rightarrow K^{\mp} \pi^{\pm} \pi^{\pm}_{slow}$$

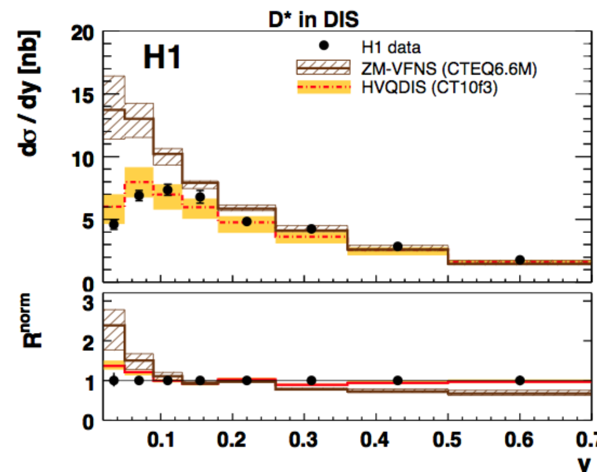












- General good agreement with massive NLO calculation (HVQDIS) over a wide range in y and Q^2.
- The ZM-VFNS calculation overshoots the data at low y.

DESY-11-066, Phys.J.C71 (2011) 1769
ZEUS-prel-11-012

Inclusive charm quark jets in DIS

hard scales: p_T of jets, m_c, Q^2

Phase Space

$5 GeV^2 < Q^2 < 1000 GeV^2$

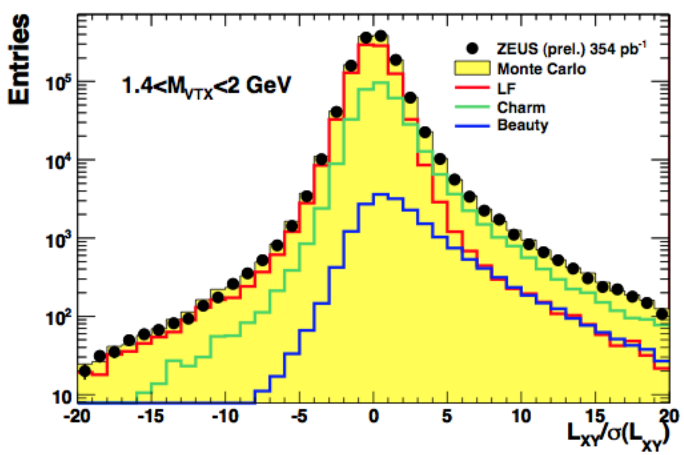
Events with ets with:

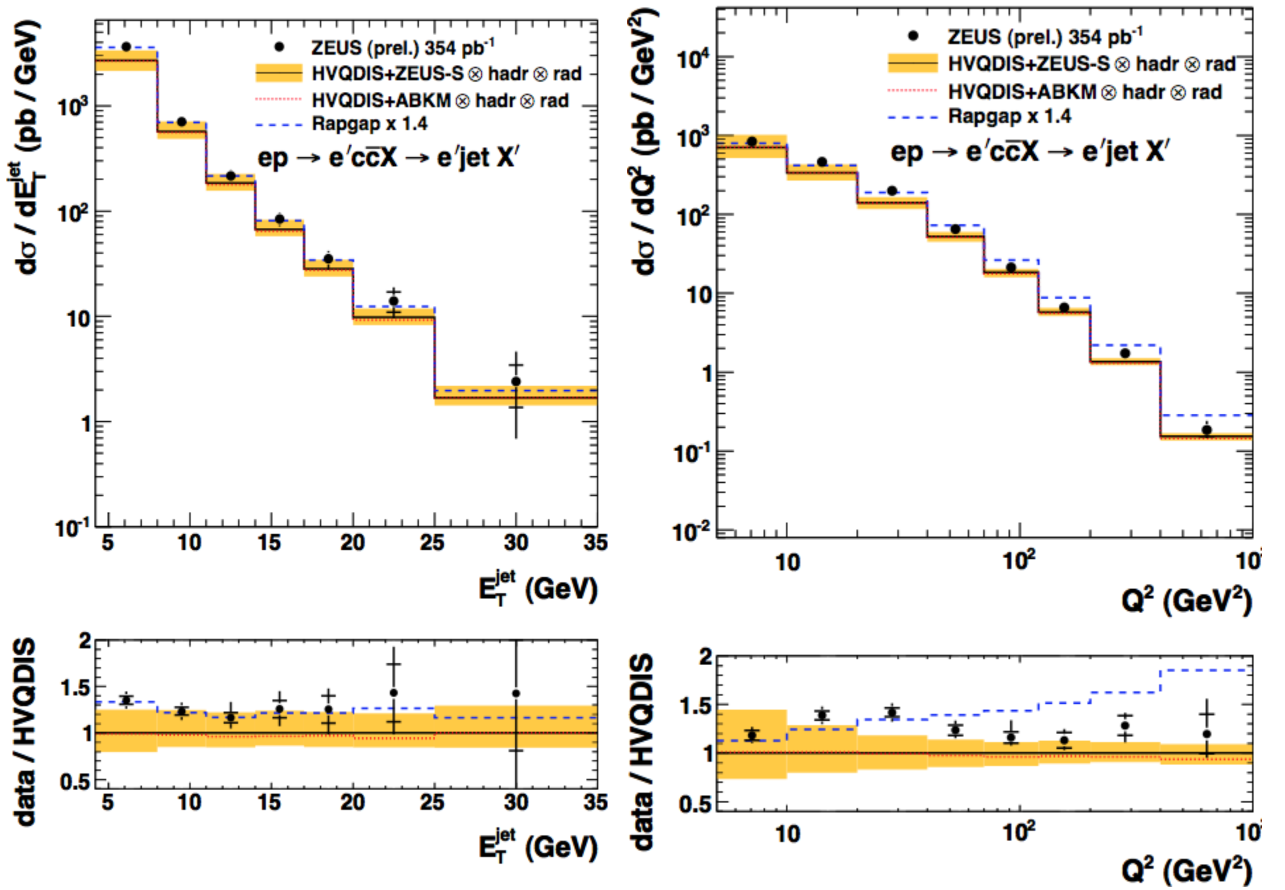
$E_T^{jet\ 1(2)} > 4.2$ GeV

Heavy Quark tagging

Reconstruction of secondary vertices:

- Mass of tracks associated with the secondary vertex.
- Decay length significance $S = DL / \sigma(DL)$





- Good agreement between data and NLO QCD calculation (HVQDIS) observed in different kinematical regions.

ZEUS-prel-12-002

Summary:

- Measurement of jet and heavy quark production at HERA allow stringent test of QCD.
- Recent HERA data on:
  - Inclusive jets, dijets, trijets measurements in DIS and Photoproduction allow to extract the strong coupling constant α_s.
  - Charm and Beauty production measurements test pQCD at various scales.

Conclusions:

- pQCD calculations in general describe the data over a wide range.
- Precision on α_s extractions:
  - Competitive with data from other experiments.
  - Often dominated by the theoretical uncertainties.