Inclusive hadron electroproduction at HERA in NLO with and without transverse-momentum constraint

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DIS 2006, Tsukuba, Japan, 20–24 April

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1. Introduction

Motivation for NLO:

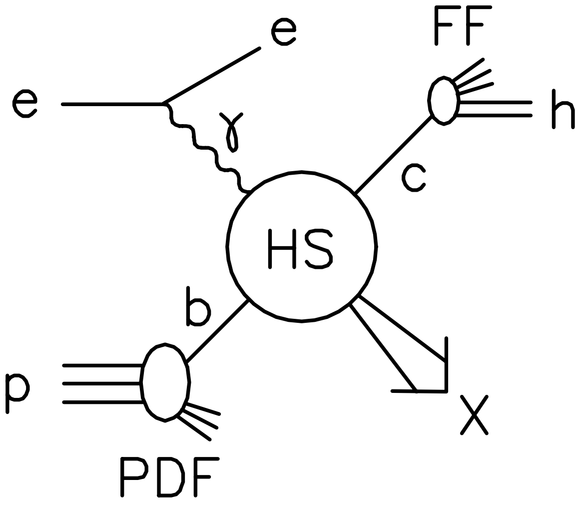
- Reduction of renormalization and factorization scale dependence.
- Sizeable effects, e.g. due to opening of new partonic production channels.
- Test of DGLAP scaling violations and universality of FFs (factorization theorem of QCD-improved parton model).
- High-statistics data from HERA II.

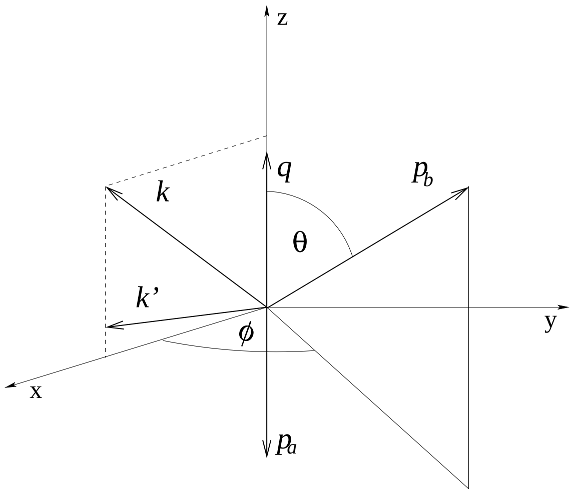
Other NLO calculations:

- D. Graudenz, Phys. Lett. **B406** (1997) 178 $2 \longrightarrow 1$ process.
- P. Büttner, PhD thesis, University of Hamburg, 1999, Report No. DESY-THESIS 1999-004 transverse γ^* only, phase-space slicing.
- P. Aurenche, R. Basu, M. Fontannaz, R.M. Godbole, Eur. Phys. J. C 34 (2004) 277 based on DISENT, w/o Furry terms, phase-space slicing.
- A. Daleo, D. de Florian, R. Sassot, Phys. Rev. **D71** (2005) 034013.

2. LO results

A. Mendez, Nucl. Phys. **B145** (1978) 199.





$$e^-(k) + p(P) \to e^-(k') + h(p) + X$$
$$S = (P + k)^2$$
$$\overline{x} = x_{\mathrm{B}} = Q^2/(2P \cdot q)$$
$$\overline{y} = P \cdot q/P \cdot k =$$
$$\overline{z} = P \cdot p/P \cdot q$$

$$\gamma^*(q) + a(p_a) \to b(p_b) + X$$
$$s = (p_a + q)^2$$
$$x = Q^2/(2p_a \cdot q)$$
$$y = p_a \cdot q/p_a \cdot k$$
$$z = p_a \cdot p_b/p_a \cdot q$$

$$\frac{d^3\sigma^h}{d\overline{x}\,dy\,d\overline{z}} = \sum_{ab}\int_{\overline{x}}^{1}\frac{dx}{x}\int_{\overline{z}}^{1}\frac{dz}{z}F_a^p(\overline{x}/x,\mu_i)\frac{d^3\sigma^{ab}}{dx\,dy\,dz}D_b^h(\overline{z}/z,\mu_f)$$

$$\frac{d^3\sigma^{ab}}{dx\,dy\,dz} = \frac{\alpha^2}{8\pi}\left(\frac{y^2-2y+2}{2yQ^2}H_T^{ab} + 2\frac{y^2-6y+6}{y^3s^2}H_L^{ab}\right)$$

where $H_T^{ab} = -g^{\mu\nu}H_{\mu\nu}^{ab}$, $H_L^{ab} = p_a^\mu p_a^\nu H_{\mu\nu}^{ab}$.

Subprocesses:

$$\gamma^* + q \longrightarrow q + g$$
$$\gamma^* + q \longrightarrow g + q$$
$$\gamma^* + g \longrightarrow q + \overline{q}$$

where $q = q_1, \overline{q}_1, \ldots, q_{n_f}, \overline{q}_{n_f}$.

3. NLO calculation: (a) Virtual corrections

- Interference of tree-level and one-loop matrix elements.
- Self-energy, triangle, and box diagrams.
- 2-, 3-, and 4-point tensor integrals.
- Reduction to scalar integrals using Passarino-Veltman algorithm.
- UV and IR singularities extracted in dimensional regularization.
- UV singularities removed by renormalization of α_s and parton wave functions in LO diagrams.
- IR singularities cancelled in combination with real corrections or by mass factorization.
- Analytic results in agreement with D. Graudenz, Phys. Rev. **D49** (1994) 3291.

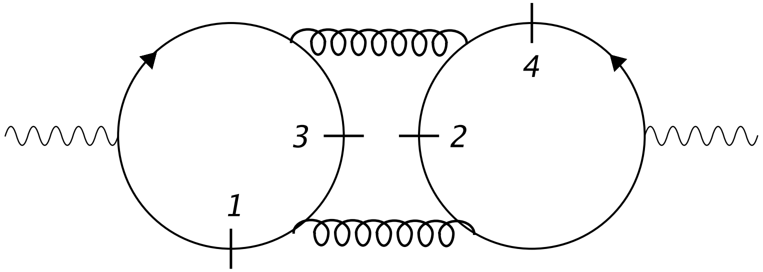
(b) Real corrections

$$\begin{aligned}
&\gamma^* + q \to q + g + g \\
&\gamma^* + q \to g + q + g \\
&\gamma^* + g \to q + \overline{q} + g \\
&\gamma^* + g \to g + q + \overline{q} \\
&\gamma^* + q \to q + q + \overline{q} \\
&\gamma^* + q \to \overline{q} + q + q \\
&\gamma^* + q \to q + q' + \overline{q}' \\
&\gamma^* + q \to q' + \overline{q}' + q
\end{aligned}$$

where $q, q' = q_1, \overline{q}_1, \ldots, q_{n_f}, \overline{q}_{n_f}$ with $q \neq q'$.

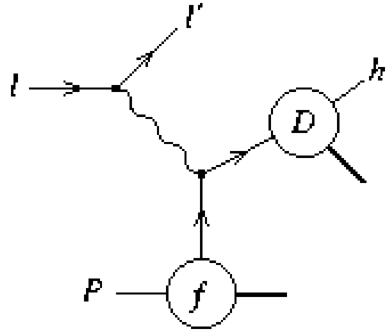
- Consider corresponding subprocesses of e^+e^- annihilation via a virtual photon.
- Analytic results in agreement with R.K. Ellis, D.A. Ross, A.E. Terrano, Nucl. Phys. **B178** (1981) 421.
- Exploit crossing symmetry.

Furry terms

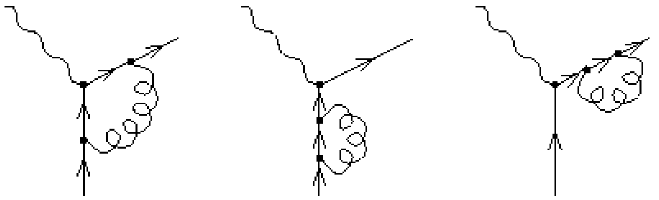


- Furry cancellation if on-shell quarks in one of the loops are untagged, e.g. in e^+e^- annihilation or $ep \longrightarrow j + X$ in DIS.
- Cancellation hindered in $ep \longrightarrow h + X$ if tagged quarks are in different loops and PDFs or FFs are different for quarks and antiquarks.

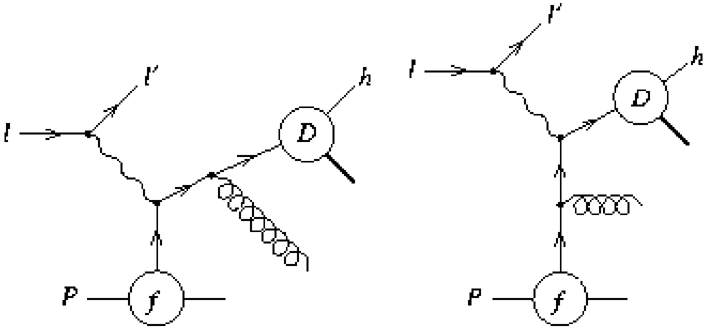
4. NLO calculation of $2 \to 1$ process



D. Graudenz, Phys. Lett. **B406** (1997) 178; CYCLOPS.



virtual



real

5. Phenomenology
(a) AKK fragmentation functions

S. Albino, B.A.K., G. Kramer, Nucl. Phys. **B725** (2005) 181; **B734** (2006) 50.

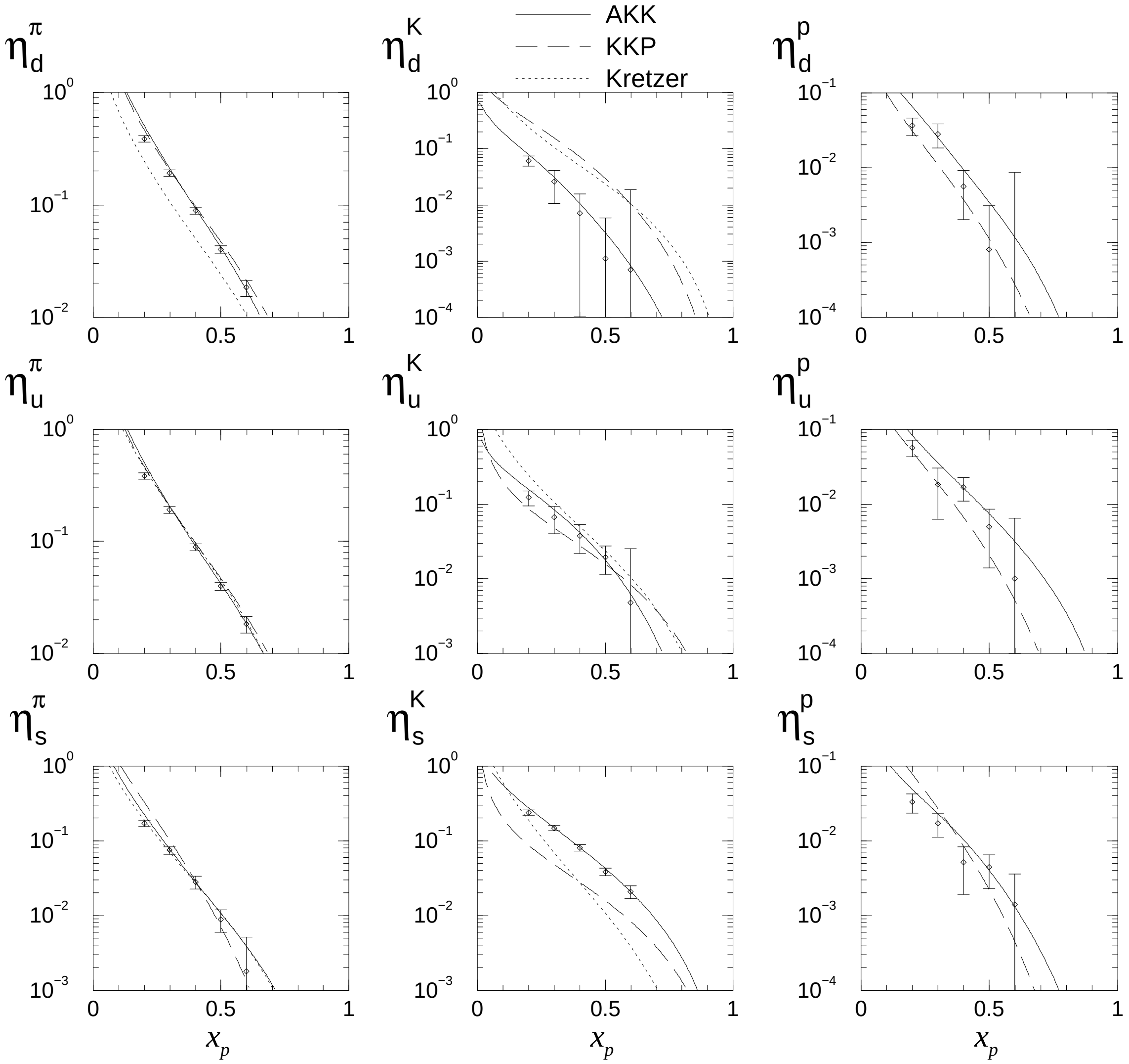
Global NLO fits of FFs $D_a^h(x, M^2)$ for $h = \pi^\pm, K^\pm, p/\overline{p}; K_S^0, \Lambda$ to $d\sigma/dx(e^+e^- \to h + X)$ distributions from PEP (TPC), LEP (ALEPH, DELPHI), and SLC (SLD) and light-quark tagging probabilities η_a^h from LEP (OPAL).

New features:

— Abandon SU(3) constratints

$$\begin{aligned} D_u^{\pi^\pm}(x, M_0^2) &= D_d^{\pi^\pm}(x, M_0^2), \\ D_u^{K^\pm}(x, M_0^2) &= D_s^{K^\pm}(x, M_0^2), \\ D_u^{p/\overline{p}}(x, M_0^2) &= 2D_d^{p/\overline{p}}(x, M_0^2). \end{aligned}$$

— Include η_a^h.


AKK
KKP
Kretzer
η_d^π
η_d^K
η_d^p
η_u^π
η_u^K
η_u^p
η_s^π
η_s^K
η_s^p
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.5
1
x_p

(b) π^0 mesons in the forward region (H1)

C. Adloff et al., Phys. Lett. **B462** (1999) 440; A. Aktas et al., Eur. Phys. J. **C36** (2004) 441. 5.8 and 21.2 pb^{-1} at $\sqrt{S} = 301$ GeV from 1996 and 1996/1997

DIS range: $0.1 < y < 0.6$, $2 < Q^2 < 70$ GeV^2

acceptance cuts: $p_T^* > 2.5$ and 3.5 GeV, $5^\circ < \theta < 25^\circ$, $x_E = E_h/E_p > 0.01$

Input:

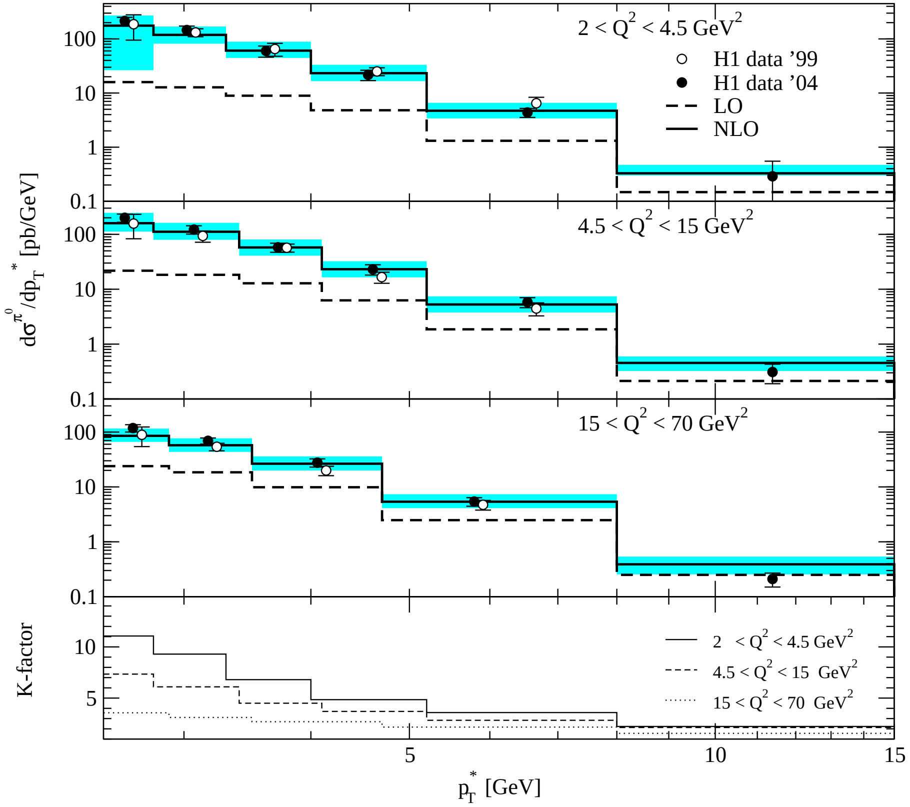
- p PDFs: CTEQ6M (CTEQ6L1) w/ $\Lambda^{(5)}_{\mathrm{QCD}} = 226$ MeV (165 MeV) at NLO (LO)
- $\pi^\pm, K^\pm, p/\overline{p}$ FFs: AKK

$$D_a^{\pi^0}(x,\mu_f) = \frac{1}{2} D_a^{\pi^\pm}(x,\mu_f)$$
$$D_a^{h^\pm}(x,\mu_f) = D_a^{\pi^\pm}(x,\mu_f) + D_a^{K^\pm}(x,\mu_f) + D_a^{p/\overline{p}}(x,\mu_f)$$

- $\mu_r^2 = \mu_i^2 = \mu_f^2 = \xi[Q^2 + (p_T^*)^2]/2$ with $0.5 < \xi < 2$

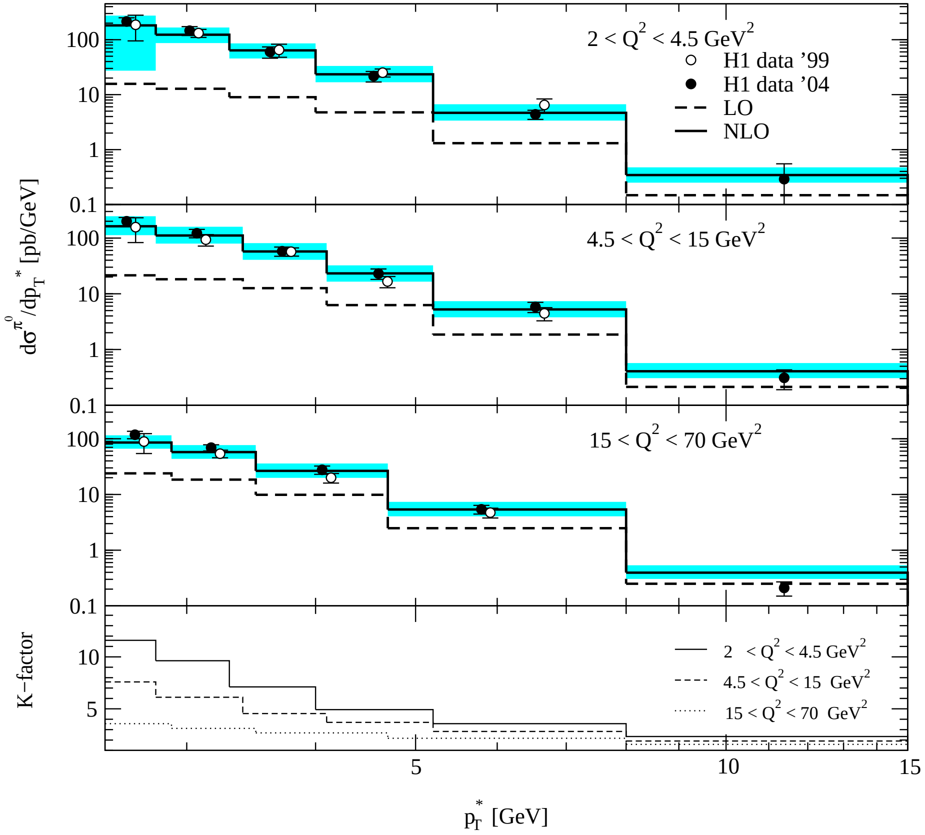
- AKK vs. KKP B.A.K., G. Kramer, B. Pötter, Nucl. Phys. **B582** (2000) 514; Phys. Rev. Lett. **85** (2000) 5288.

AKK


2 < Q² < 4.5 GeV²
H1 data '99
H1 data '04
LO
NLO
4.5 < Q² < 15 GeV²
15 < Q² < 70 GeV²
dσ^π0/dp_T* [pb/GeV]
100
10
1
0.1
K-factor
10
5
2 < Q² < 4.5 GeV²
4.5 < Q² < 15 GeV²
15 < Q² < 70 GeV²
5
10
15
p_T* [GeV]

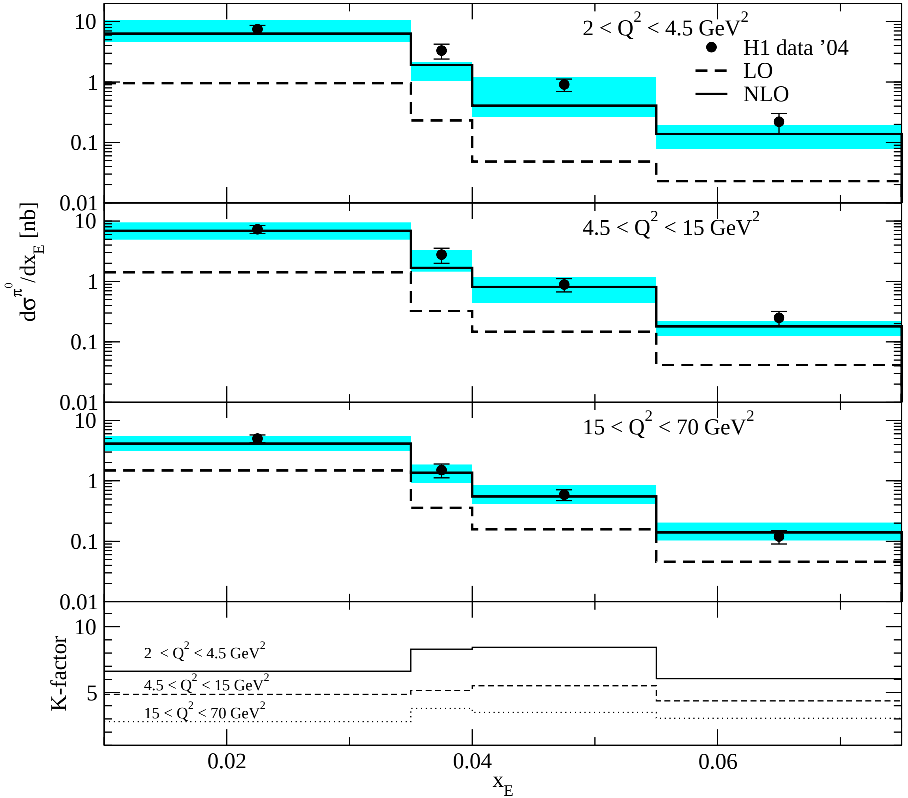
p_T^*

KKP


2 < Q² < 4.5 GeV²
H1 data '99
H1 data '04
LO
NLO
4.5 < Q² < 15 GeV²
15 < Q² < 70 GeV²
dσ^π0/dp_T* [pb/GeV]
100
10
1
0.1
K−factor
10
5
2 < Q² < 4.5 GeV²
4.5 < Q² < 15 GeV²
15 < Q² < 70 GeV²
5
10
15
p_T* [GeV]

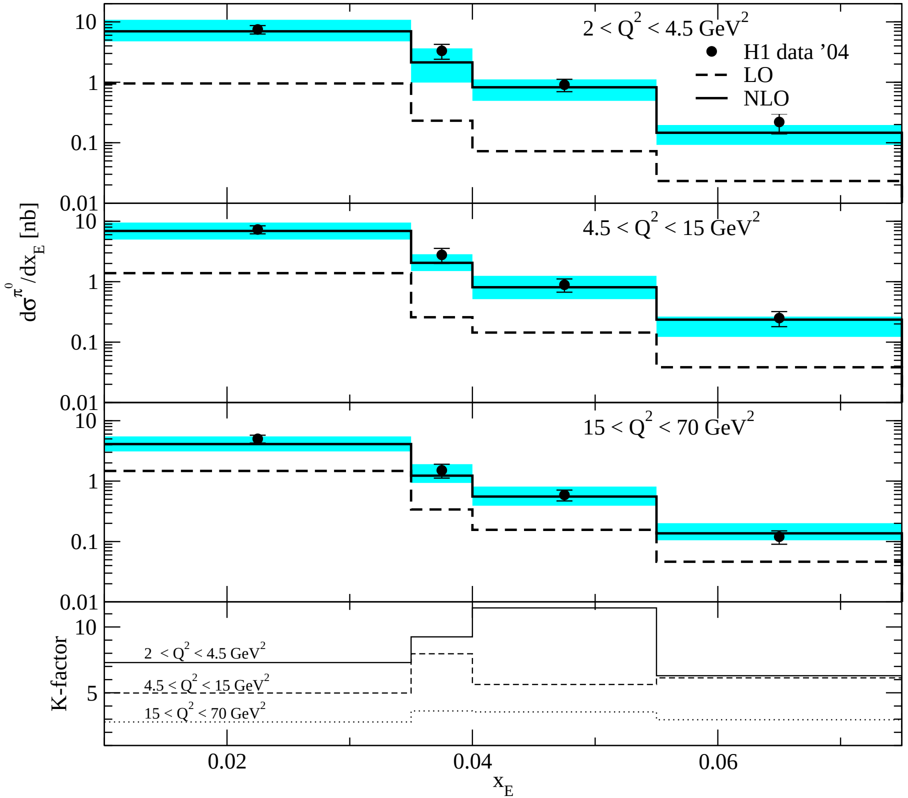
p_T^*

AKK



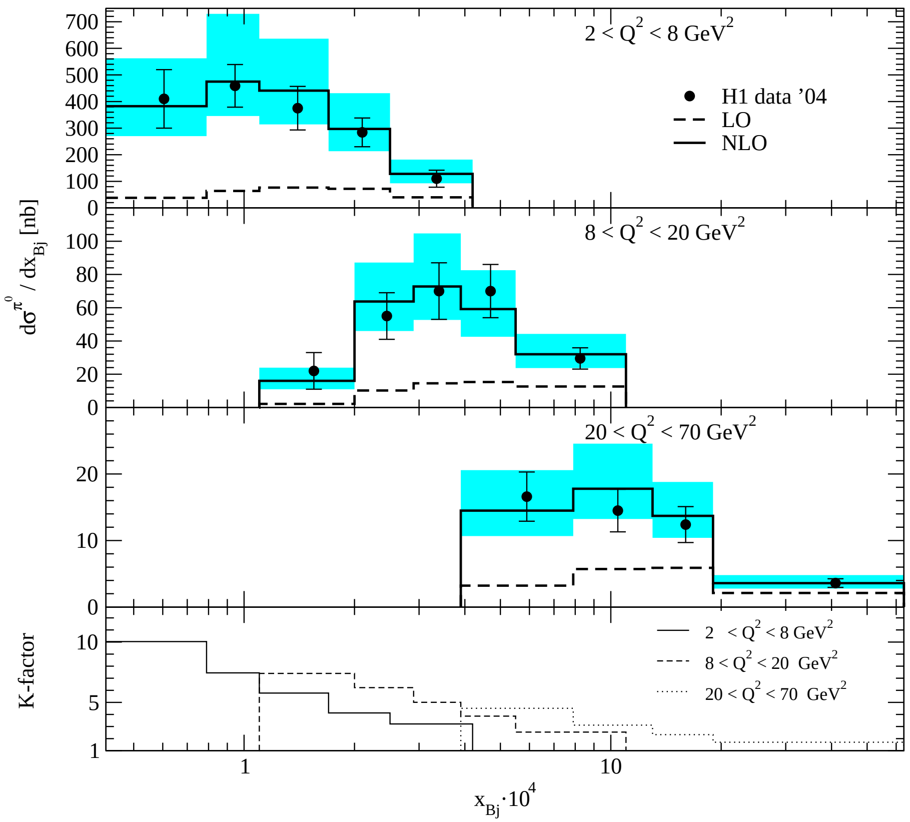
x_E (in bins of Q^2)

KKP



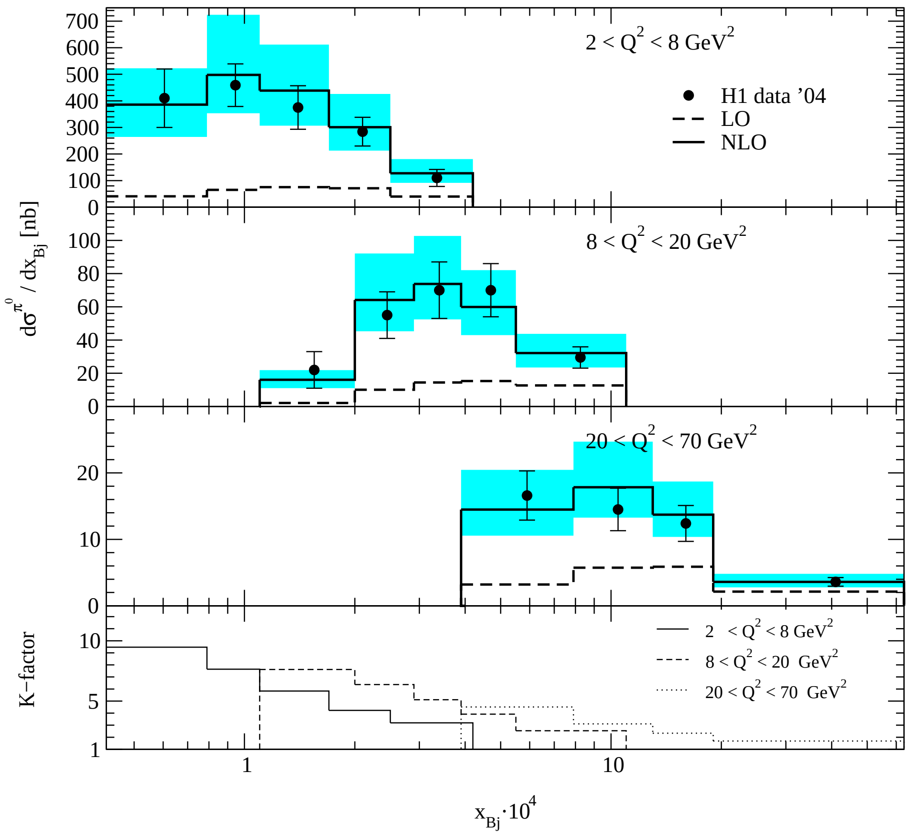
x_E (in bins of Q^2)

AKK



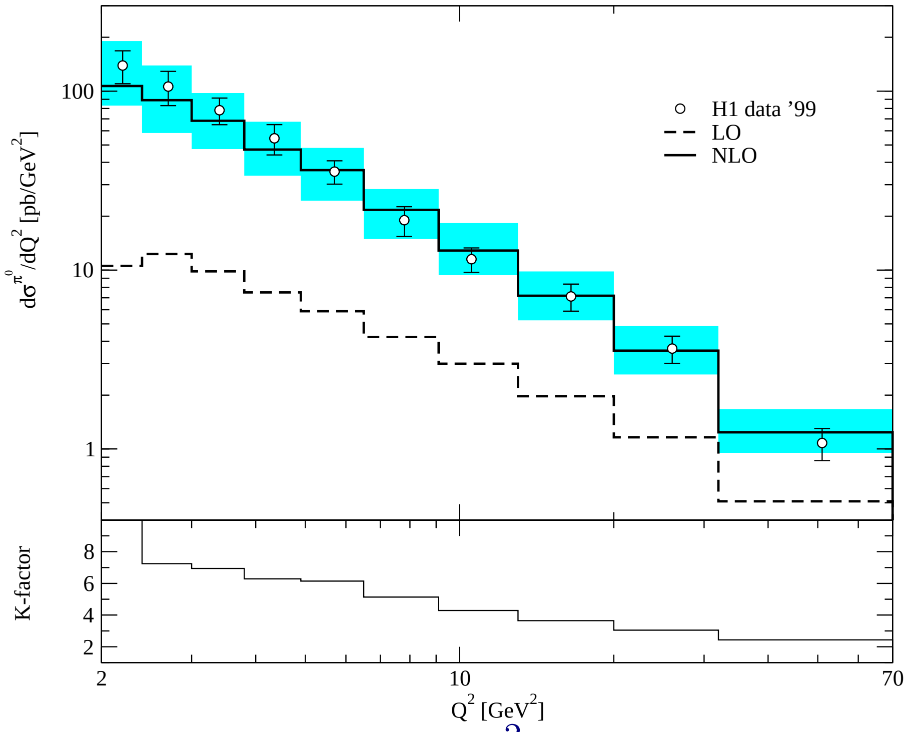
$10^4 \times x_B$ ($p_T^* > 3.5$ GeV)

KKP



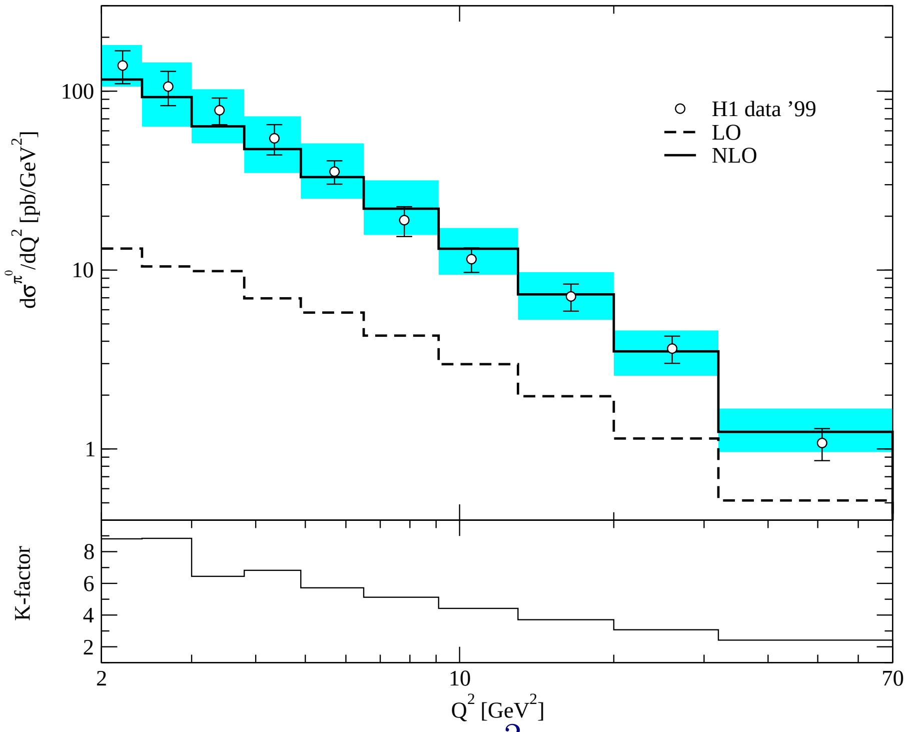
$10^4 \times x_B$ ($p_T^* > 3.5$ GeV)

AKK


$d\sigma^{\pi^0}/dQ^2$ [pb/GeV^2]
100
10
1
H1 data '99
LO
NLO
K-factor
8
6
4
2
2
10
70
Q^2 [GeV^2]

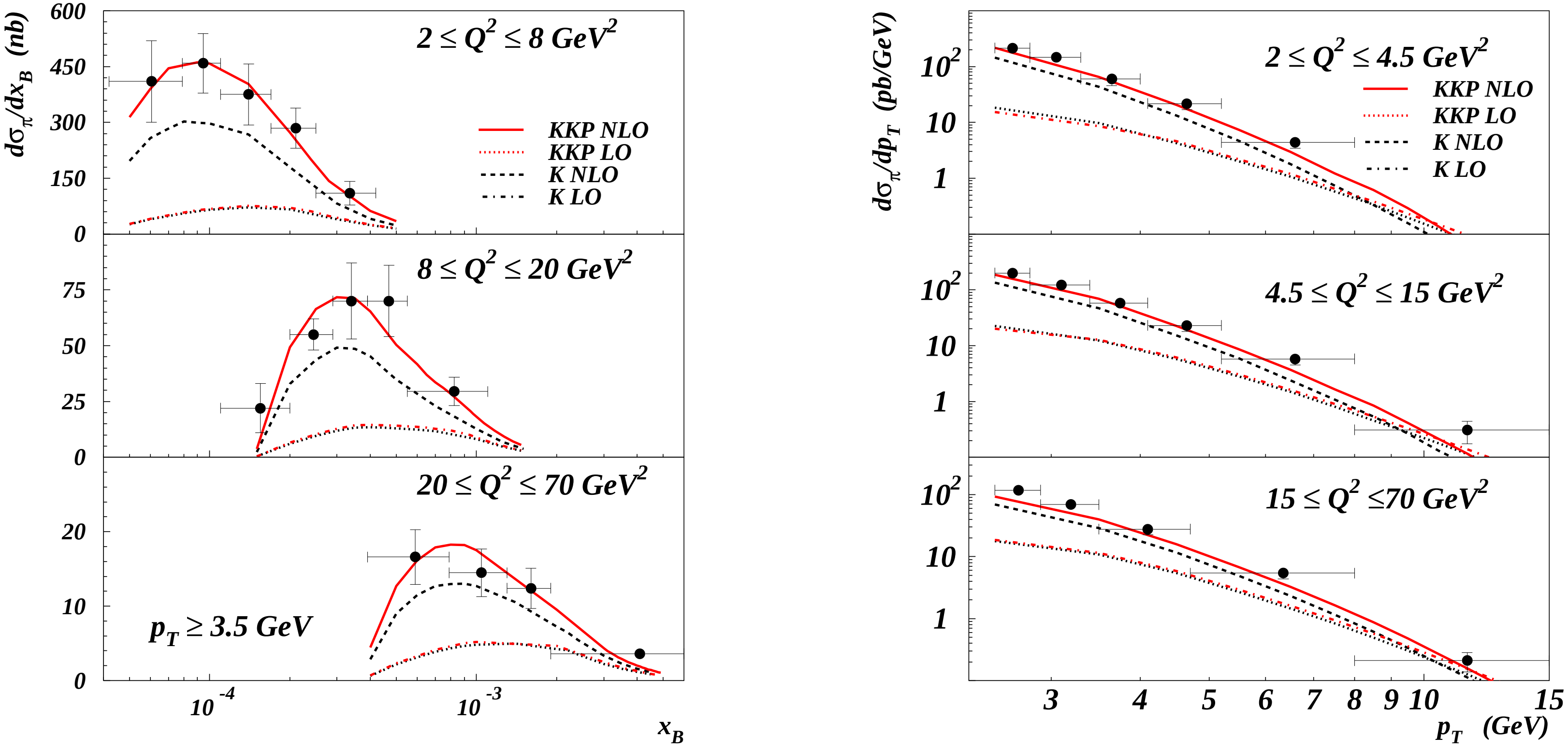
Q^2

KKP

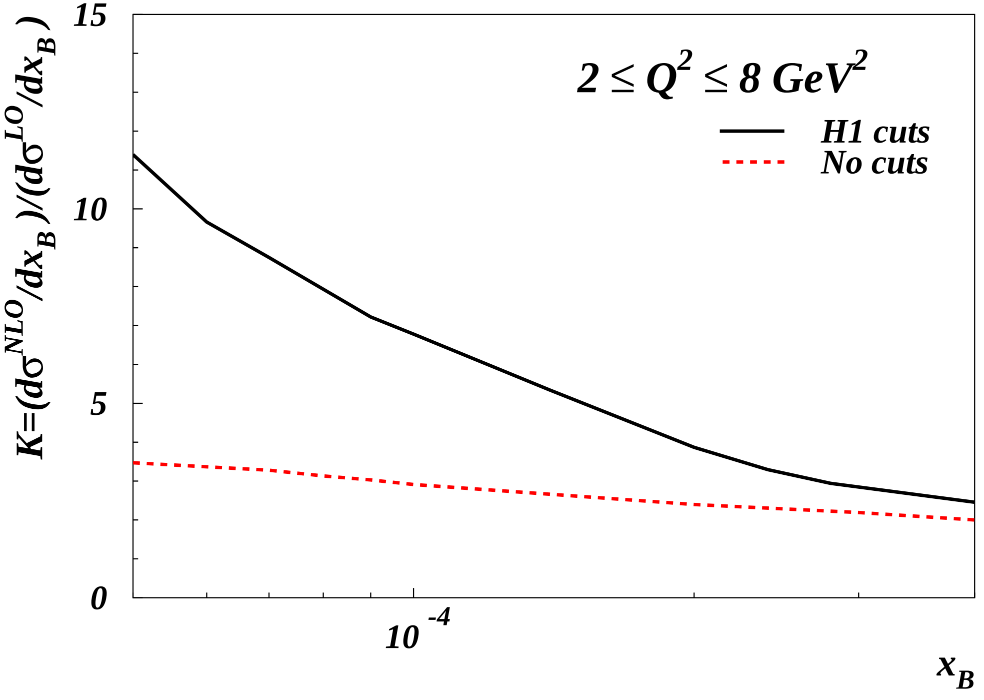

$d\sigma^{\pi^0}/dQ^2$ [pb/GeV^2]
100
10
1
H1 data '99
LO
NLO
K-factor
8
6
4
2
2
10
70
Q^2 [GeV^2]

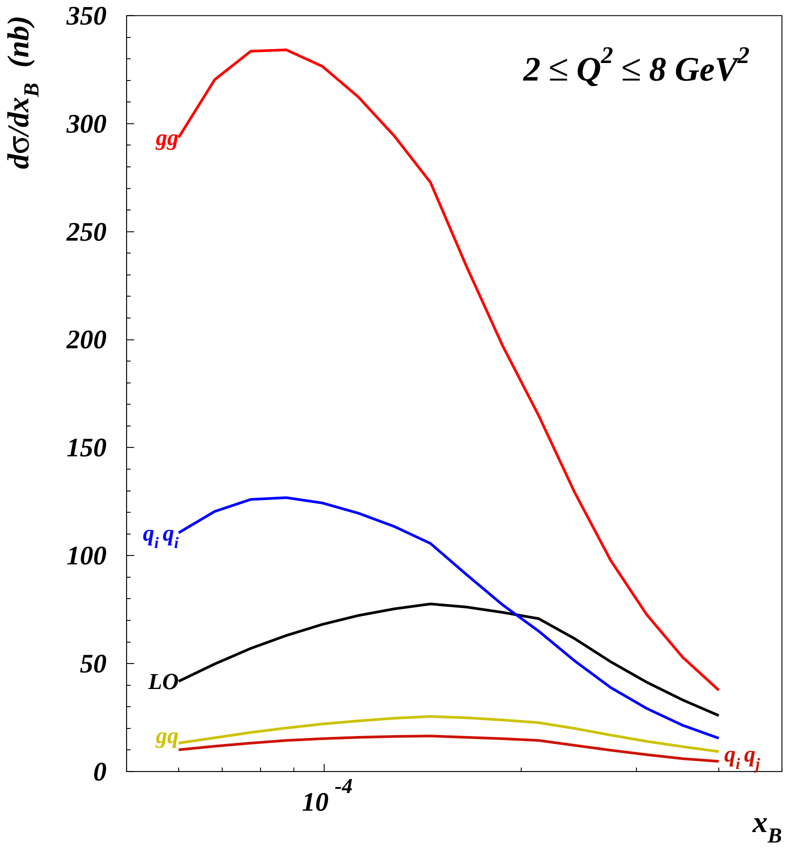
Q^2

- KKP vs. K S. Kretzer, Phys. Rev. **D62** (2000) 054001.



Cuts and channels





K factors before and after cuts

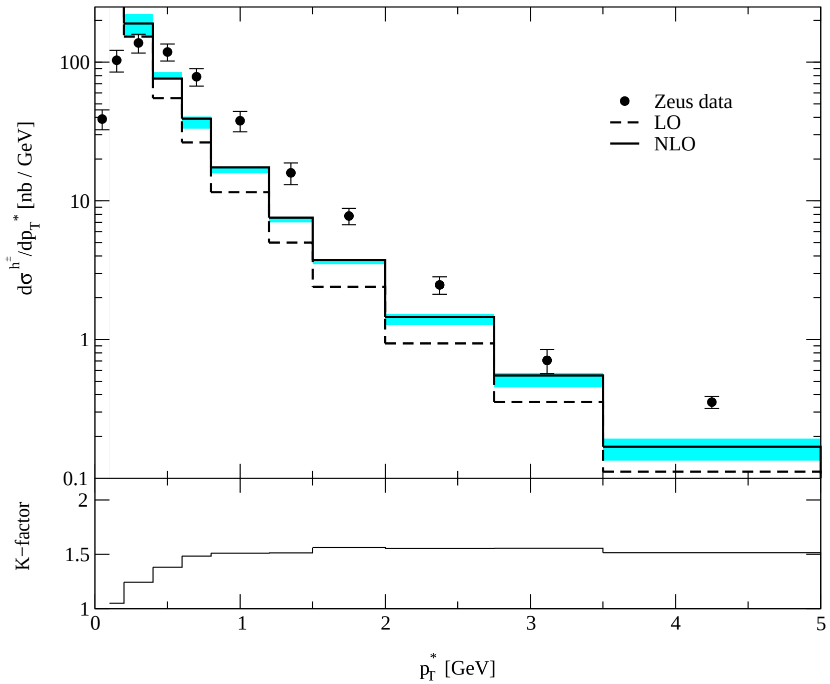
Contributions from $a \longrightarrow b$ channels

(c) Charged hadrons in the current-jet region (ZEUS)

M. Derrick et al., Z. Phys. **C70** (1996) 1. 0.55 pb^{-1} at $\sqrt{S} = 296$ GeV from 1993

DIS range: $10 < Q^2 < 160$ GeV^2, $75 < W < 175$ GeV

acceptance cut: $x_F = 2p_L^*/W > 0.05$



p_T^*

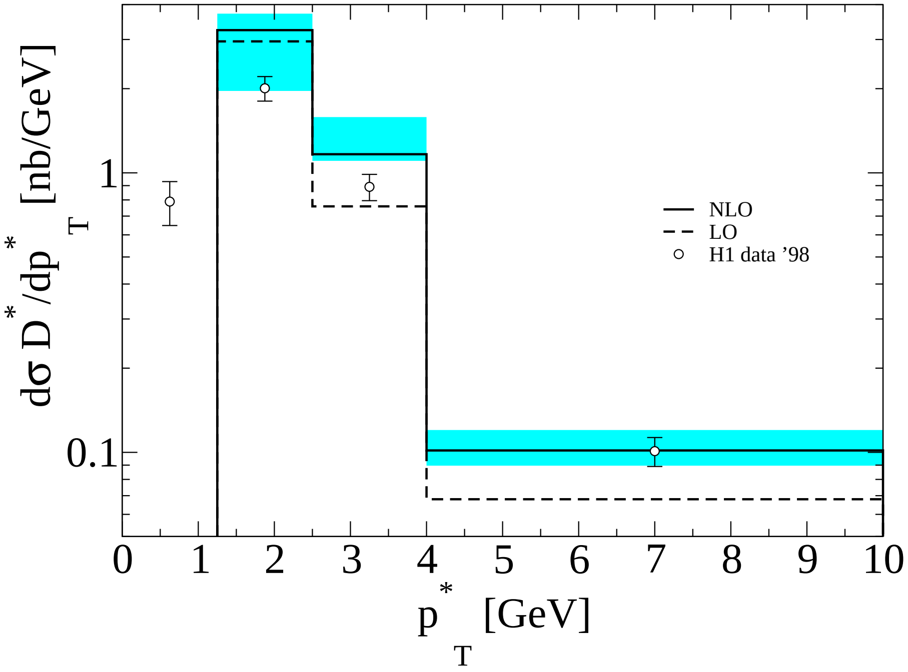
(d) $D^{*\pm}$ (H1)

C. Adloff et al., Nucl. Phys. **B545** (1999) 21. 9.7 pb^{-1} at $\sqrt{S} = 300$ GeV from 1995–96

DIS range: $2 < Q^2 < 100$ GeV^2, $0.05 < y < 0.7$

acceptance cuts: $p_T > 1.5$ GeV, $|\eta| < 1.5$

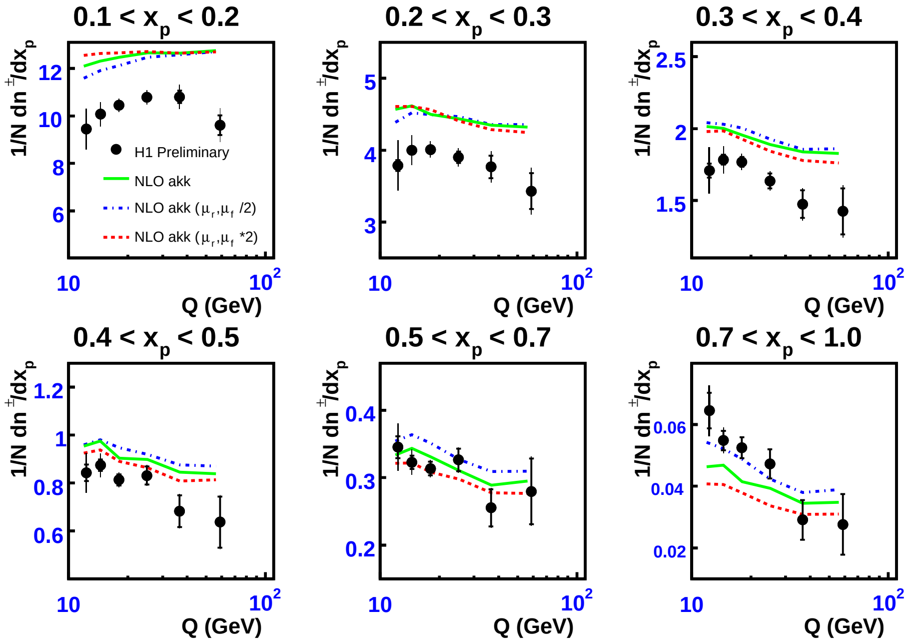
- $D^{*\pm}$ FFs B.A.K., G. Kramer, Phys. Rev. **D71** (2005) 094013.



(e) Charged hadrons in Breit frame (H1)

C. Adloff et al., Nucl. Phys. **B504** (1997) 3; talk by D. Traynor (H1).

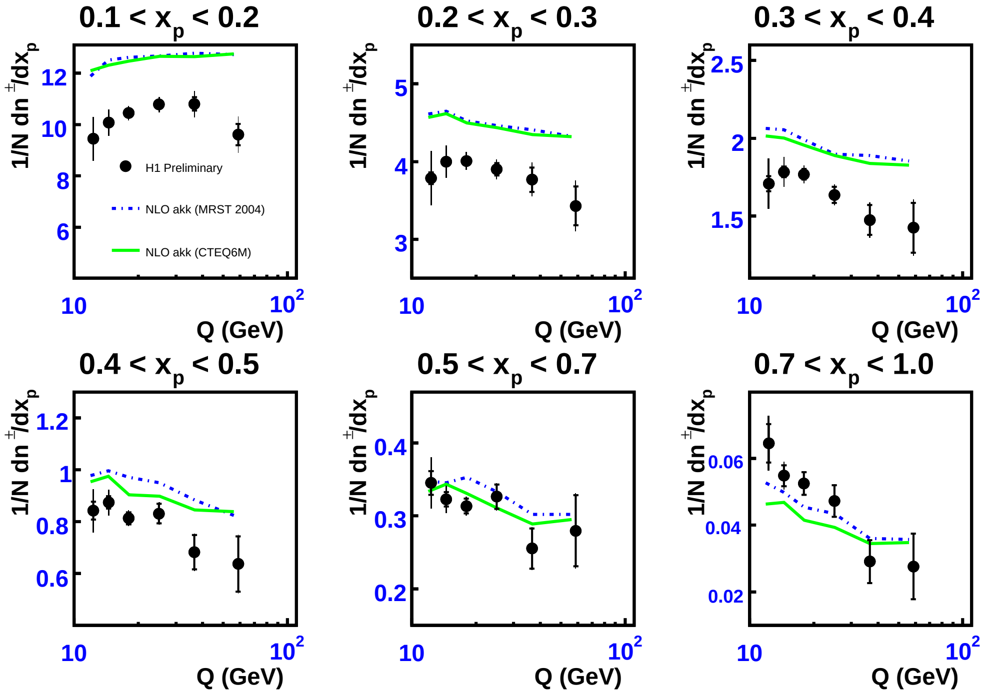
- Breit frame: γ^* is completely space like with $q^\mu = (0, 0, 0, -Q)$, $Q = -2x_B P^{\text{Breit}}$.
- Consider Q distribution $(1/\sigma_{\text{DIS}}) d\sigma/dQ$ in bins of $x_p = 2p^{\text{Breit}}/Q$.
- See also ZEUS J. Breitweg et al., Eur. Phys. J. **C11** (1997) 251.



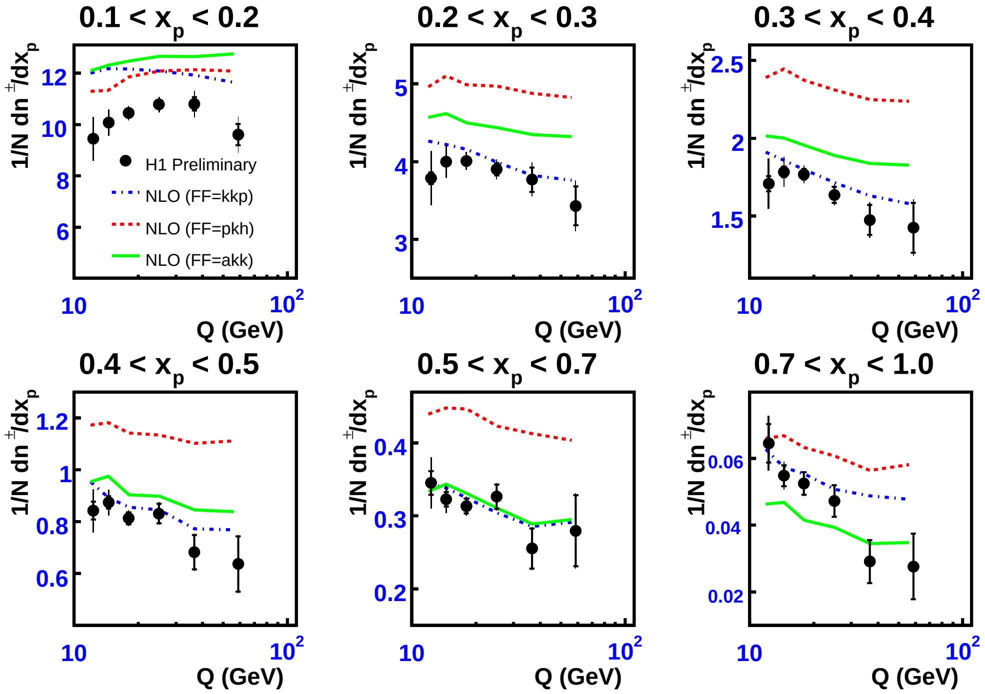
CTEQ6M, AKK

$\mu_r = \mu_i = \mu_f = \xi Q$ with $0.5 < \xi < 2$

PDF uncertainty
CTEQ6M vs. MRST04



FF uncertainty
AKK vs. KKP and K



5. Summary and outlook

(a) $2 \longrightarrow 2$ process

- LO prediction generally far too low in normalization and with deviating shape.
- NLO prediction nicely agrees with H1 data on forward π^0's, but sizeable K factor and considerable theoretical uncertainty.
- Test of scaling violations and universality of FFs.
- Expect deviations for:
  - $Q^2 \longrightarrow 0$: photoproduction limit, resolved photons important, especially at small p_T^* and/or θ.
  - $\theta \longrightarrow 0$ (or $\eta \longrightarrow \infty$ or $x_F \longrightarrow -1$): hadron h close to proton remnant $\rightsquigarrow$ fracture functions.
  - $x_B \longrightarrow 0$: BFKL dynamics. But no convincing case yet, see also forward-jet electroproduction.
  - $p_T^* \longrightarrow 0$: collinear singularities $\rightsquigarrow$ take $\gamma^* q \longrightarrow q$ as LO subprocess.
- Need NNLO prediction to reduce theoretical uncertainty.
- For D and B electroproduction, include mass effects w/o spoiling factorization $\rightsquigarrow$ general-mass variable-flavour-number scheme.

(b) $2 \to 1$ process

- Agreement of H1 data with AKK acceptable for $x_p > 0.4$.
- Small uncertainty from PDFs.
- Slight preference for KKP FFs; K FFs disfavoured.
- Needs further study.