Inclusive Single Hadron Production in Neutral Current Deep-Inelastic Scattering at Next-to-Leading Order

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Outline

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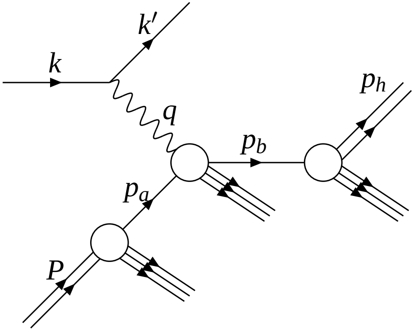
Motivation

- Test of perturbative QCD and factorization.
- Universality of Fragmentation Functions.
- Direct comparison with experimental data.
- Precise data from H1 and ZEUS Collaborations.

Single Production of Hadrons



Single Production of Hadrons

Process

$$e(k) + p(P) \rightarrow e(k') + h(p) + X$$

Cross Section

$$\frac{d^4\sigma^h}{d\bar{x}dyd\bar{z}d\phi} = \int_{\bar{x}}^{1} \frac{dx}{x} \int_{\bar{z}}^{1} \frac{dz}{z} \sum_{ab} f_a^p\left(\frac{\bar{x}}{x}, \mu^2\right) \frac{d^3\sigma^{ab}}{dxdydz} D_b^h\left(\frac{\bar{z}}{z}, \mu^2\right)$$

Variables

$$x_B = \bar{x} = \frac{Q^2}{2P\cdot q}, \qquad y = \frac{p_a\cdot q}{p_a\cdot k}, \qquad \bar{z} = \frac{P\cdot p_h}{P\cdot q}$$

$$x = \frac{Q^2}{2p_a\cdot q}, \qquad z = \frac{p_a\cdot p_b}{p_a\cdot q}$$

Partonic Cross Section

$$\frac{d^3\sigma^{ab}}{dxdydz} = \frac{\alpha^2}{16\pi^2}\frac{y}{Q^4}\lambda_{ab}L^{\mu\nu}H^{ab}_{\mu\nu}$$

- Lepton Tensor:

$$L^{\mu\nu} = \frac{Q^2}{2y}\left(\frac{2-2y+y^2}{y}\right)(-g^{\mu\nu}) + \frac{2Q^4}{sh^2}\left(\frac{y^2-6y+6}{y^4}\right)p_a^\mu p_a^\nu \pm i\frac{Q^2}{sh}\left(\frac{y-2}{y^2}\right)\varepsilon^{\mu\nu\alpha\beta}p_{a\alpha}q_\beta$$

with $sh = \frac{Q^2}{\bar{x}y}$.

- Cross section in transverse, longitudinal and axial components:

$$H_T^{ab} = -g^{\mu\nu}H^{ab}_{\mu\nu}, \qquad H_L^{ab} = p_a^\mu p_a^\nu H^{ab}_{\mu\nu}, \qquad H_A^{ab} = \pm i\varepsilon^{\mu\nu\alpha\beta}p_{a\alpha}q_\beta H^{ab}_{\mu\nu}$$

$$H^{ab}_{\mu\nu} = \sum_{\text{spins}} \mathcal{M}^\dagger_\mu \mathcal{M}_\nu$$

Partonic Cross Section

$$\lambda_{ab}^{T,L} = e_f^2 - 2e_f v_f v_e \chi_Z(Q^2) + \left(a_f^2 + v_f^2\right)\left(a_e^2 + v_e^2\right)\chi_Z^2(Q^2)$$

$$\lambda_{ab}^{A} = -2e_f a_f a_e \chi_Z(Q^2) + 4a_f a_e v_f v_e \chi_Z^2(Q^2)$$

$$a_{e,f} = T_{e,f}^3$$

$$v_{e,f} = T_{e,f}^3 - 2e_{e,f}\sin^2\theta_W$$

$$\chi_Z(Q^2) = \frac{1}{4\sin^2\theta_W\cos^2\theta_W}\frac{Q^2}{Q^2 + M_Z^2}$$

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Partonic Subprocesses

LO

$$\gamma^*, Z^0 + q \to q$$

Real Corrections:

$$\gamma^*, Z^0 + q \to q + g$$

$$\gamma^*, Z^0 + q \to g + q$$

$$\gamma^*, Z^0 + g \to q + \bar{q}$$

Charged Particle Production

Experimental Cuts (H1 Phys.Lett.B654:148-159,2007)

$$0.05 < y < 0.6 \qquad 100 < Q^2 < 20000\ \mathrm{GeV}^2 \qquad 10^o < \theta_e < 150^o$$

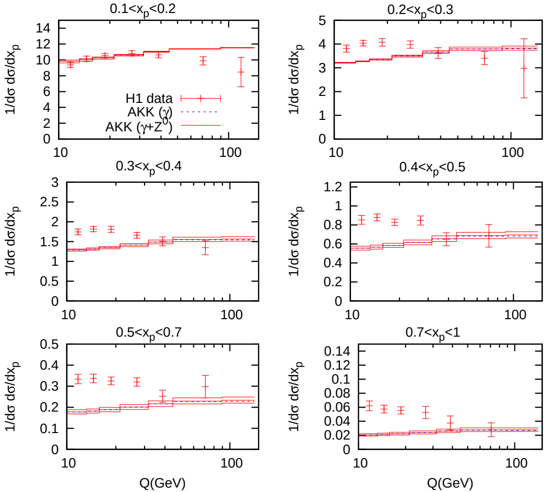
$$E_{e^+} = 27.6\ \mathrm{GeV} \qquad E_p = 920\ \mathrm{GeV}$$

$$x_p = \frac{2p_h}{\sqrt{s}}$$

Fragmentation and Scale

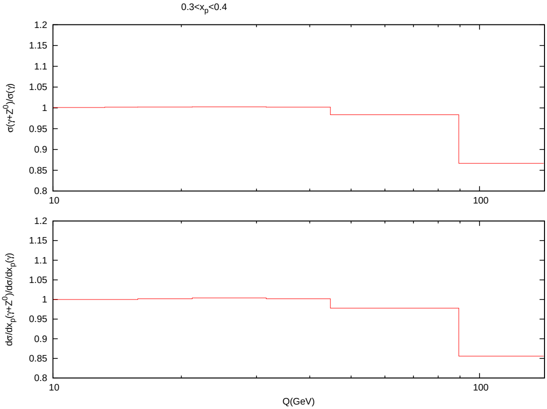
- AKK Fragmentation functions, Nucl.Phys.B803:42-104,2008
- $$\mu^2 = Q^2$$

$\frac{1}{\sigma}\frac{d\sigma(h^{\pm})}{dx_p}$



Ratio

- Z^0 boson contribution not noticable in multiplicities.
- Ratios of cross sections show contributions of up to 15% for $Q^2 > 10000$ GeV^2.
- Similar behaviour for all x_p bins.



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1. Introduction
   - Motivation
   - Parton Model
2. First Order in α_s
   - Partonic Subprocesses
   - HERA data
3. Second order in α_s
   - Subtraction Method
   - HERA data
4. Conclusions

Partonic Subprocesses

Born

$$\gamma^*, Z^0 + q \to q + g$$
$$\gamma^*, Z^0 + q \to g + q$$
$$\gamma^*, Z^0 + g \to q + \bar{q}$$

Virtual Corrections

- Dimensional Regularization.
- UV and IR singularities.
- UV singularities removed through renormalization of the wave functions and the strong coupling constant.
- The remaining soft and collinear singularities should cancel partly against counterparts originating from the phase space integration of the real correction.

Subtraction Method

$$\sigma^{NLO} = \int_{m+1} \left[\left(d\sigma^R\right)_{\epsilon=0} - \left(d\sigma^A\right)_{\epsilon=0} \right] + \int_m \left[d\sigma^V + \int_1 d\sigma^A \right]_{\epsilon=0}$$

- $d\sigma^A$ acts as a local counterterm for $d\sigma^R$
- After phase space integration $\epsilon \rightarrow 0$ in the integrand on the first term on the right hand side.
- Singularities on the other two terms cancel each other.

Subtraction Method

$d\sigma^A$

- It has to be obtained independently from the process considered.
- It has to match the singular behaviour of $d\sigma^R$ in d dimensions.
- Its form has to be particularly convenient for Monte Carlo integration techniques.
- It has to be exactly integrable analytically in d dimensions over the single parton subspaces leading to soft and collinear divergences.

$$d\sigma^A = \sum_{dipoles} d\sigma^B \times dV_{dipole}$$

$$\int_{m+1} d\sigma^A = \int_m d\sigma^B \times \mathbf{I}$$

Production of hadrons with finite p_T^*

π^0 (H1 Eur.Phys.J.C36:441,2004)

$$0.1 < y < 0.6 \qquad 2 < Q^2 < 70\ \text{GeV}^2 \qquad 5^o < \theta < 25^o$$

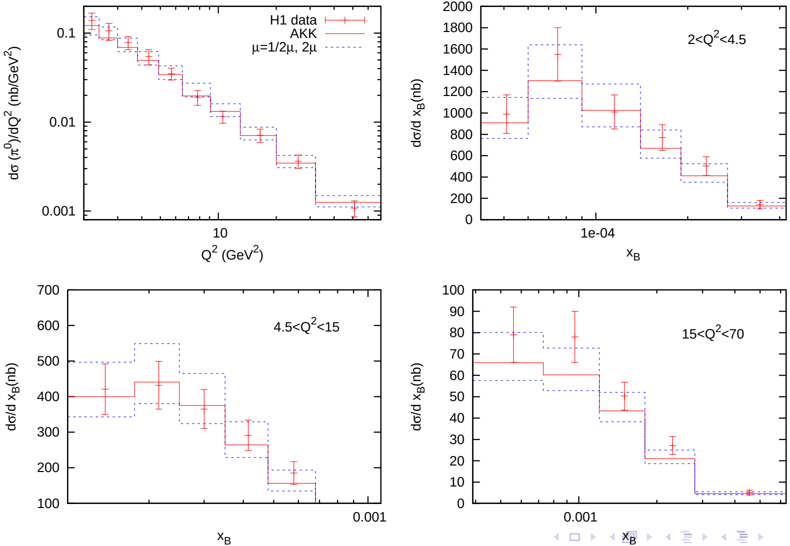
$$E_{e^+} = 27.6\ \text{GeV} \qquad E_p = 820\ \text{GeV}$$

$$p_T^* > 2.5\text{GeV}$$

Fragmentation and Scale

- AKK Fragmentation functions
- $$\mu = \sqrt{Q^2 + (p_T^*)^2}$$

π^0



H1 data
AKK
μ=1/2μ, 2μ
dσ (π⁰)/dQ² (nb/GeV²)
Q² (GeV²)
0.1
0.01
0.001
10
2<Q²<4.5
dσ/d x_B(nb)
x_B
1e-04
4.5<Q²<15
0.001
15<Q²<70

Production of hadrons with finite p_T^*

$D^{*\pm}$ (H1 Eur.Phys.J.C51:271-287,2007)

$$0.05 < y < 0.7 \qquad 2 < Q^2 < 100 \text{ GeV}^2$$

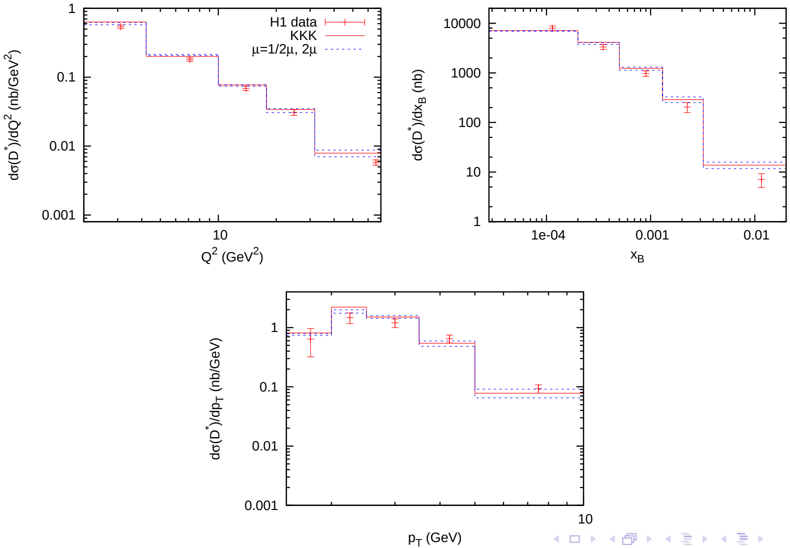
$$E_{e^+} = 27.6 \text{ GeV} \qquad E_p = 920 \text{ GeV}$$

$$p_T^* > 2.0\text{GeV}$$

Fragmentation and Scale

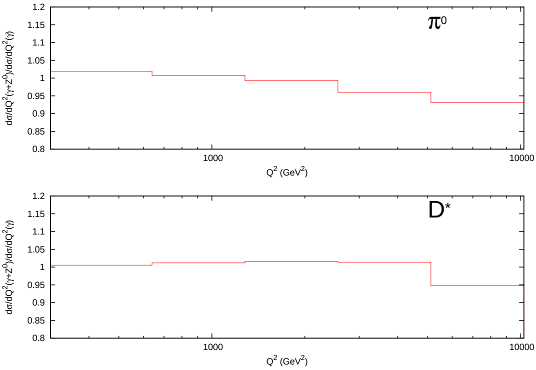
- KKKS Fragmentation functions, Nucl.Phys.B799:34-59,2008
- $$\mu = \sqrt{Q^2 + (p_T^*)^2}$$

$D^{*\pm}$


H1 data
KKK
μ=1/2μ, 2μ
dσ(D*)/dQ² (nb/GeV²)
Q² (GeV²)
1
0.1
0.01
0.001
10
dσ(D*)/dx_B (nb)
x_B
10000
1000
100
10
1
1e-04
0.001
0.01
dσ(D*)/dp_T (nb/GeV)
p_T (GeV)
1
0.1
0.01
0.001
10

Ratios

- Ratios of cross sections show contributions of up to 5% for $Q^2 > 10000$ GeV^2.
- The behaviour is similar for both π^0 and $D^{*\pm}$ production.



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Conclusions

- At NLO, virtual and real corrections have been calculated for single hadron production in the case of neutral currents.
- Results agree with the data for π^0 and $D^{*\pm}$ production using AKK and KKKS fragmentation functions.
- Results not sensitive to choice of PDF set.
- Effect of Z^0 boson in the cross sections found to be up to 15% in the first order calculation and up to 5% in the second order calculation.