Hadron Mass Corrections in semi-inclusive deep-inelastic scattering

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Thomas Jefferson National Accelerator Facility

HAMPTON UNIVERSITY
THE STANDARD OF EXCELLENCE

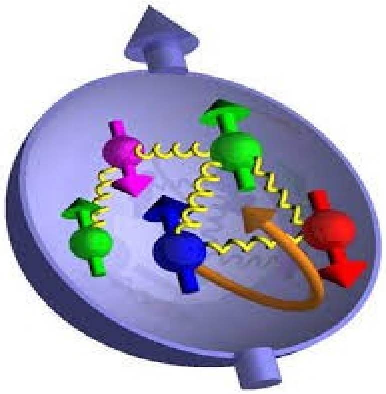
Outline

- Introduction
- Kinematics
- Cross sections at finite Q^2
- Phenomenological implications
- Conclusion and Outlook

Introduction

Hard scattering reactions:

Picture of the nucleon (partons)



Examples:

Deep inelatic scattering (DIS): $e^- p \longrightarrow e^- X$

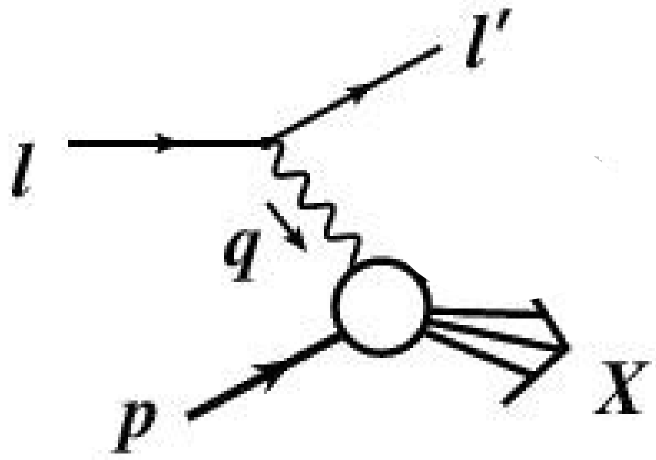
Semi inclusive Deep inelatic scattering (SIDIS): $e^- p \longrightarrow e^- h X$

Drell Yan (DY): $h_A h_B \longrightarrow e^- e^+ X$

e^-e+ annihilation: $e^- e^+ \longrightarrow hX$

Introduction: DIS

DIS Diagram



Theoretical Framework:

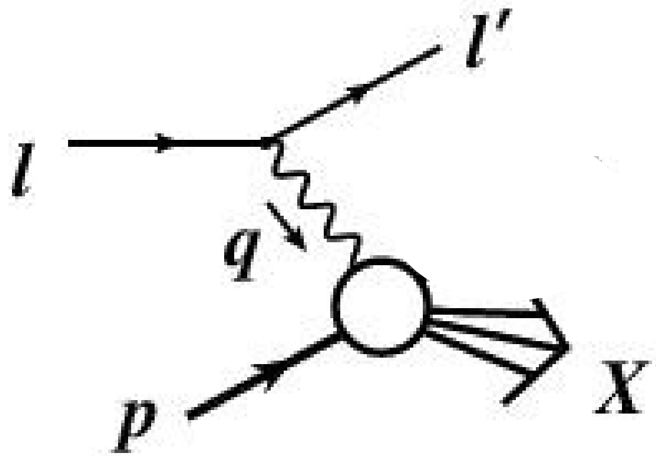
- Operator Product Expasion (OPE).
- Collinear factorization (CF)

OPE ⟺ CF

To be studied:
massive case

Introduction: DIS

DIS Diagram



Theoretical Framework:

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OPE ⟺ CF

To be studied:
massive case

DIS Kinematic invariants

Nucleon Mass

$$m_N^2 = (p_\mu)^2$$

Virtuality

$$Q^2 = -(q_\mu)^2$$

Bjorken-x

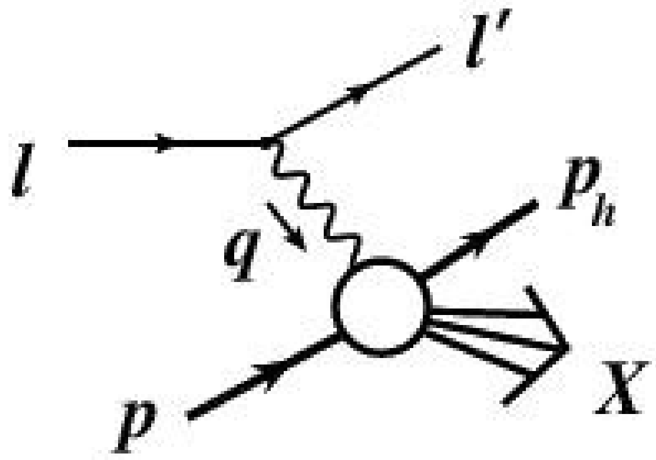
$$x_B = \frac{Q^2}{2p \cdot q}$$

Final state invariant mass

$$W^2 = (p_\mu + q_\mu)^2$$

Introduction: SIDIS

SIDIS Diagram



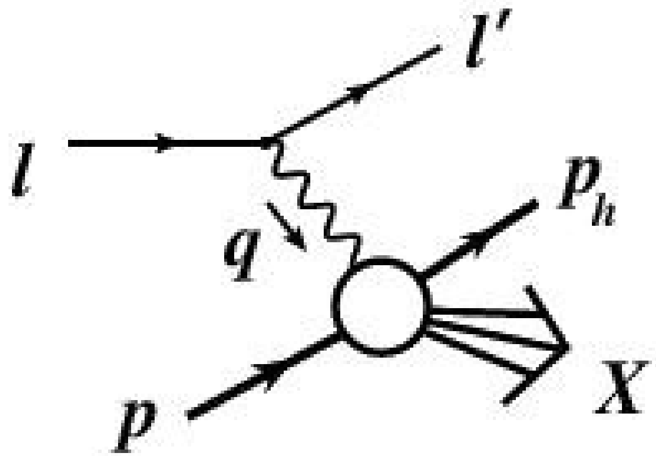
Theoretical Framework:

- Operator Product Expasion (OPE).
- Collinear factorization (CF)

DIS variables

Introduction: SIDIS

SIDIS Diagram



Theoretical Framework:

- Operator Product Expasion (OPE).
- Collinear factorization (CF)

DIS variables + <u>hadronic variables</u>

Hadron Mass	Fragmentation invariant
$m_h^2 = p_h^2$	$z_h = \frac{p_h \cdot p}{q \cdot p}$

Introduction: Why Hadron Mass Corrections (HMC's)?

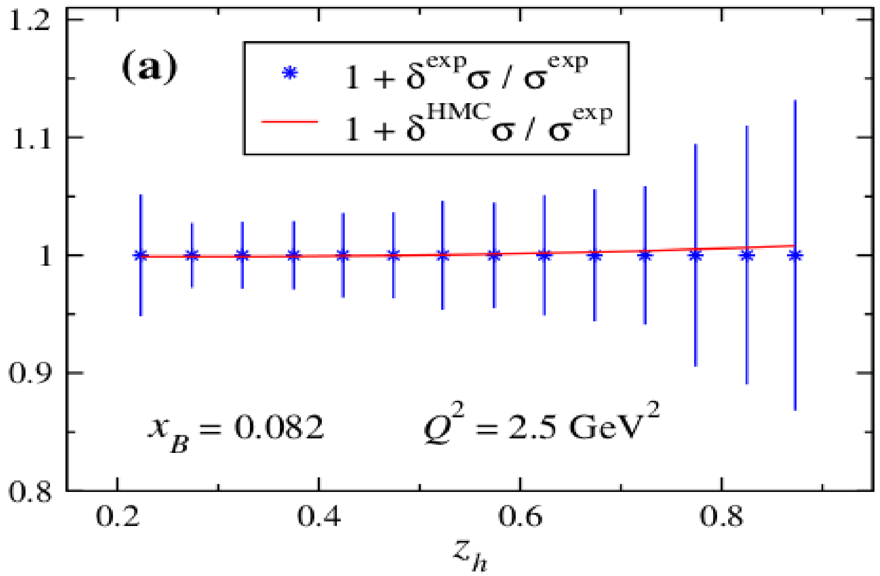
Jlab experiments

- Usually Low Q^2($\sim$1 GeV^2)
- $1/Q^2$ corrections have to be controlled

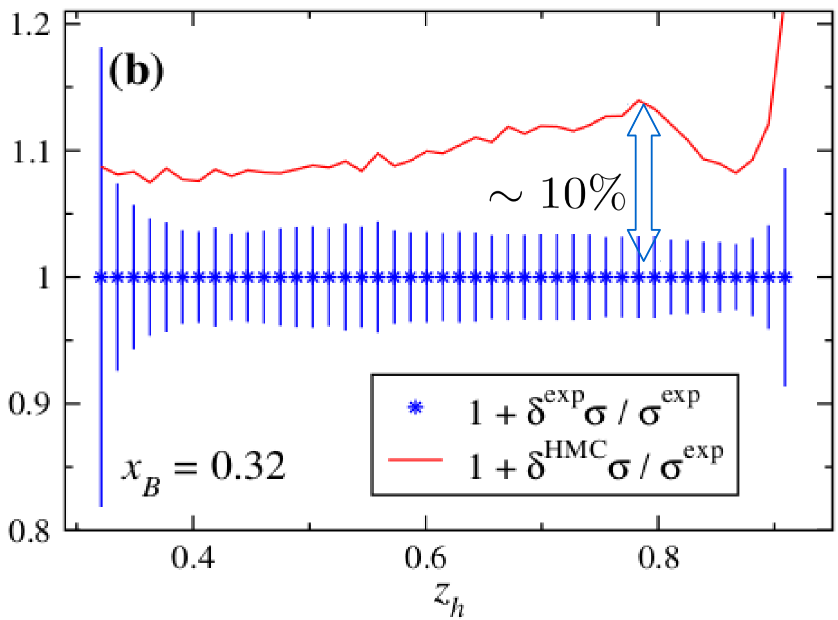
$$O(\frac{M^2}{Q^2}) \equiv \textbf{HMC's!!!}$$

Introduction: HMC's for charged pion production (unpolarized SIDIS)

HERMES experiment (DESY)



Jefferson Lab (E00-108)



Accardi, Hobbs, Melnitchouk
JHEP 0911, 084 (2009)

Introduction: Polarized HMC's (Project)

JHEP 1509 (2015) 169

Hadron mass corrections in semi-inclusive deep-inelastic scattering

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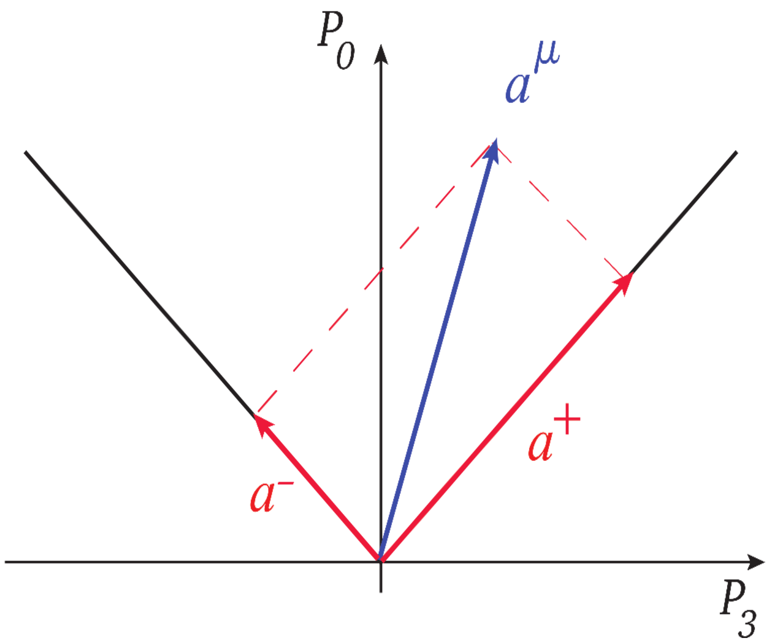
Starting from older JHEP 0911, 084 (2009) we:

- Review all the kinematics.
- Derive the cross section for the unpolarised case and extend to the polarized case.
- Estimate the size of the hadron mass corrections for current and future experiments

SIDIS: Massive scaling variables

Light Cone



$$a^- = \frac{a_0 - a_3}{\sqrt{2}} \quad a^+ = \frac{a_0 + a_3}{\sqrt{2}}$$

Nachtmann Scaling variable

$$\xi = -\frac{q^+}{p^+} = \frac{2x_B}{1 + \sqrt{1 + 4x_B^2 M^2/Q^2}}$$

Bjorken Limit $Q^2 \to \infty \quad \xi \to x_B$

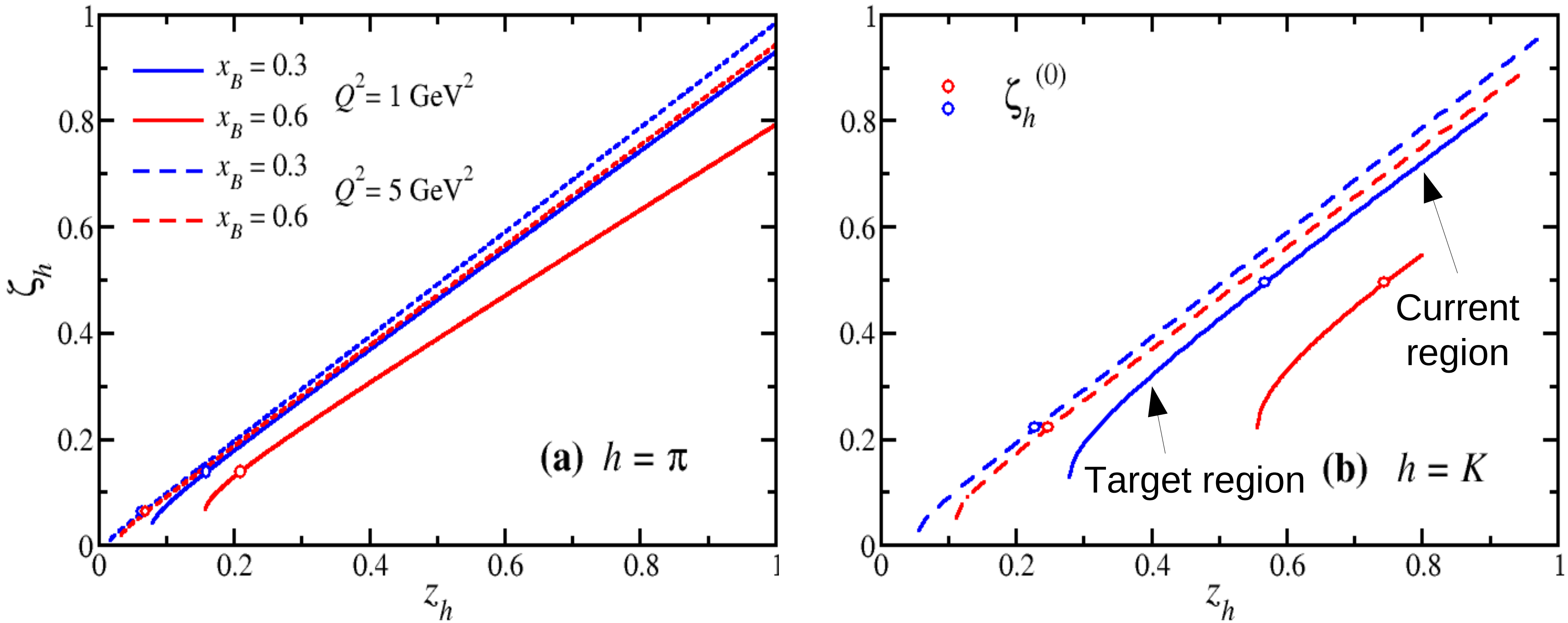
Fragmentation Scaling variable

$$\zeta_h = \frac{p_h^-}{q^-} = \frac{z_h}{2}\frac{\xi}{x_B}\left(1 + \sqrt{1 - \frac{4x_B^2 M^2 m_{h\perp}^2}{z_h^2\, Q^4}}\right)$$

with

$$m_{h\perp}^2 = m_h^2 + p_{h\perp}^2; \qquad \begin{matrix} \zeta_h \longrightarrow z_h \\ Q^2 \to \infty \end{matrix}$$

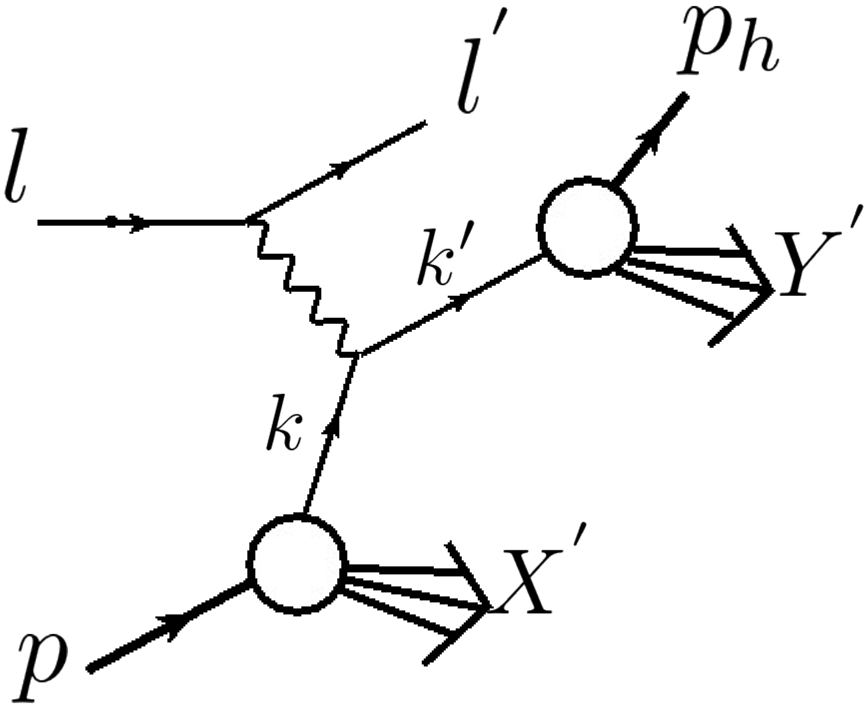
SIDIS: External Kinematics



- Target vs. Current Fragmentation region separated by o.
- Limits: 4-momentum + Baryon number conservation

$$\Rightarrow \quad z_h^{min} < z_h < z_h^{max}$$

SIDIS: Parton Kinematics



Internal (parton) Kinematics

$$x = \frac{k^+}{p^+} \quad (\text{vs. } \xi = -\frac{q^+}{p^+})$$

$$z = \frac{p_h^-}{k'^-} \quad (\text{vs. } \zeta_h = -\frac{p_h^-}{q^-})$$

“Collinear” Factorization:

Expand around “collinear” momenta $\widetilde{k}_\mu$ and $\widetilde{k}'_\mu$

Initial and scattered quarks are off-shell → Virtualities $\widetilde{k}^2$ and $\widetilde{k}'^2$ will be fixed later

SIDIS: Internal Kinematics

Virtuality choice:

- Usual Choice: $\widetilde{k}^2 = 0 \ \widetilde{k}'^2 = 0$ → at LO $x = \xi \xrightarrow{Q^2 \to \infty} x_B$, $z = \zeta_h \xrightarrow{Q^2 \to \infty} z_h$

BUT kinematic analysis shows that $$\widetilde{k}^2 \geq x(\zeta_h - 1)Q^2/\xi$$

- Alternative Choice $\widetilde{k}^2 = 0$ $\widetilde{k}'^2 = \frac{m_h^2}{\zeta_h}$ → at LO $x = \xi_h = \xi(1 + \frac{m_h^2}{\zeta_h Q^2})$, $z = \zeta_h$

  (respects kinematic bound)

→ NOT UNIQUE: Needs more analysis at NLO

LO Cross section at finite Q^2

Spin averaged Cross section

$$\sigma_h \equiv \frac{1}{2}\frac{d\sigma_h^{\uparrow\uparrow+\downarrow\uparrow}}{dx_B\,dQ^2\,dz_h} = \frac{2\pi\alpha^2}{Q^4}\frac{y^2}{1-\varepsilon} J_h \sum_q e_q^2\, q(\xi_h, Q^2)\, D_q^h(\zeta_h, Q^2)$$

Jacobian $J_h = \frac{d\zeta_h}{dz_h}$

Unpolarised PDF

Fragmentation Function

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Unpolarised PDF

Fragmentation Function

Spin dependent Cross section

$$\Delta\sigma_h \equiv \frac{d\sigma_h^{\uparrow\uparrow-\downarrow\uparrow}}{dx_B\, dQ^2\, dz_h} = \frac{4\pi\alpha^2}{Q^4}\frac{y^2\sqrt{1-\varepsilon^2}}{1-\varepsilon} J_h \sum_q e_q^2\, \Delta q(\xi_h, Q^2)\, D_q^h(\zeta_h, Q^2)$$

Polarised PDF

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Unpolarised PDF

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Polarised PDF

Bjorken Limit: $\left(\frac{M^2}{Q^2}, \frac{m_h^2}{Q^2} \to 0\right)$

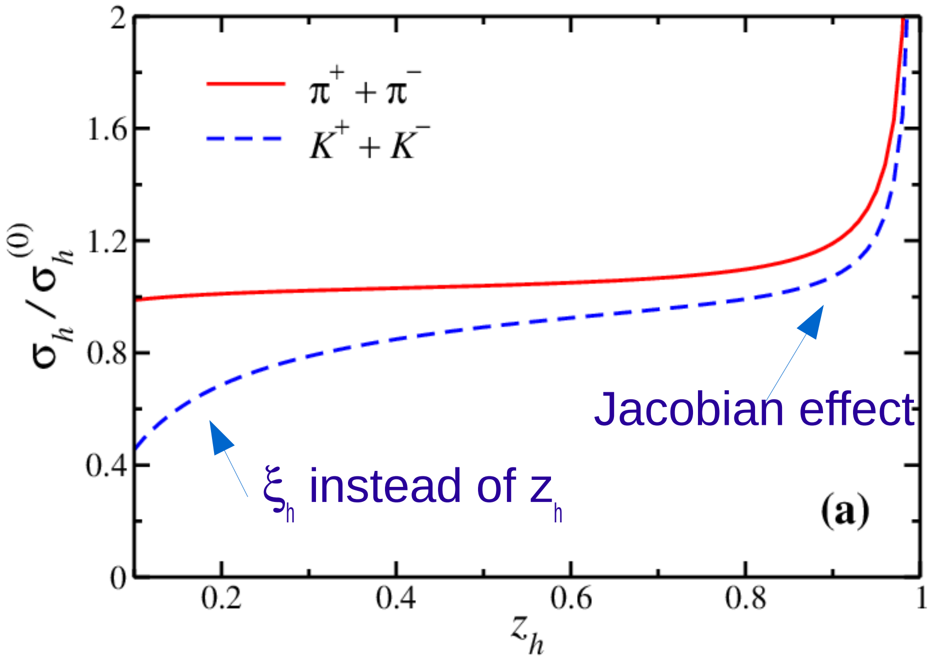
$$\sigma_h^{(0)} \equiv \sigma_h(\xi_h \to x_B, \zeta_h \to z_h)$$

$$\Delta\sigma_h^{(0)} \equiv \Delta\sigma_h(\xi_h \to x_B, \zeta_h \to z_h)$$

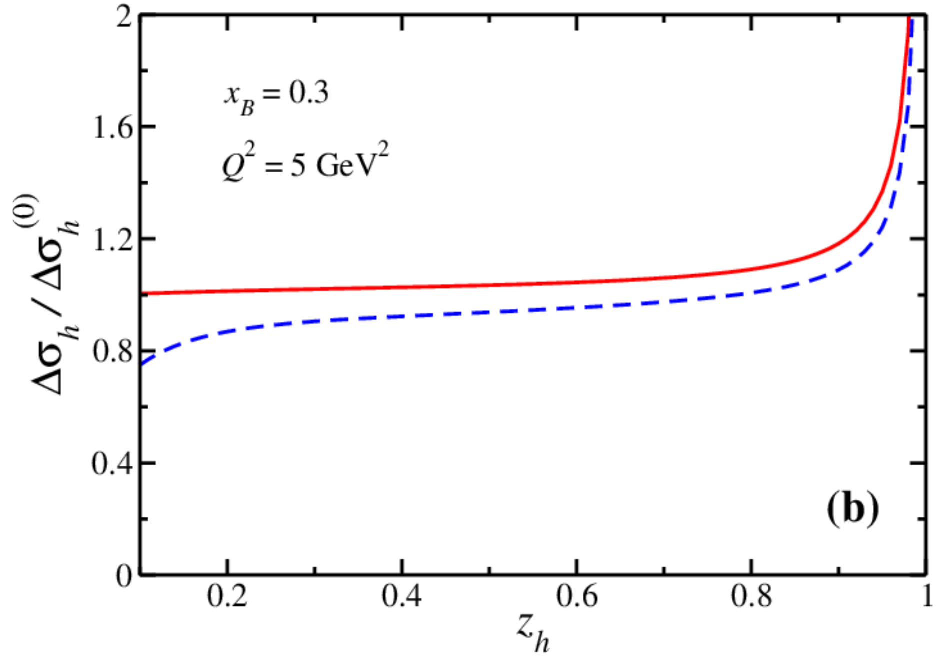
Phenomenological implications

Pions vs. Kaons

Unpolarised



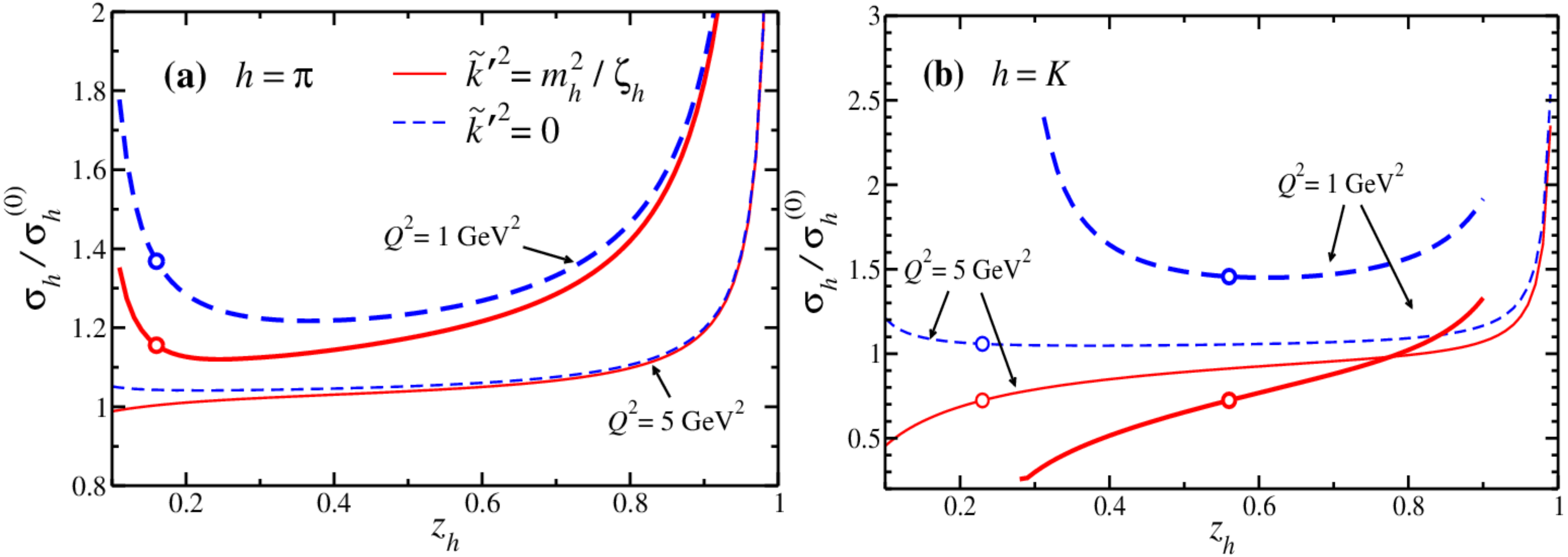
Polarised



Kaons mass effects much larger

Phenomenological implications

Dependence on the parton virtuality



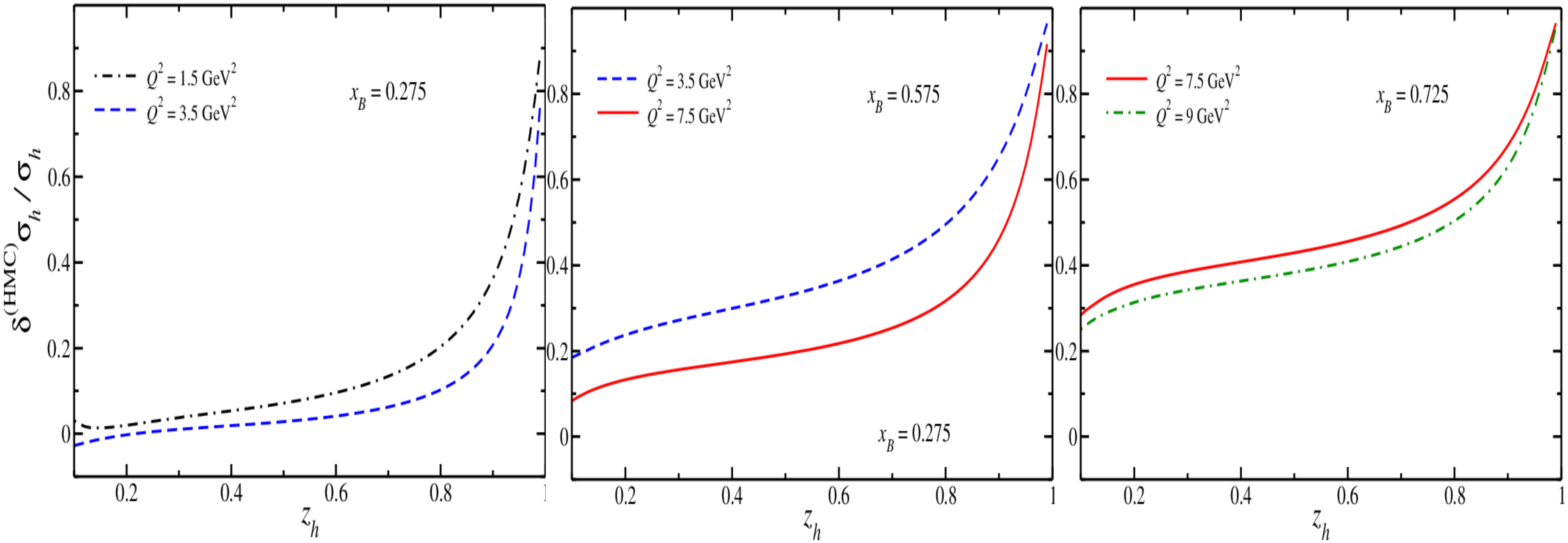
Red lines: Our choice $\widetilde{k}'^2 = m_h^2/\zeta_h$

Thin lines: Albino et all. Nucl.Phys B803, 42 (2008) $\widetilde{k}'^2 = 0$

Mass corrections for specific experiments

Jlab 11 GeV (Unpolarized Pions)

(Experiments: E12-09-007, E12-13-007, E12-06-109)



$$\frac{\delta^{(\mathrm{HMC})}\sigma_h}{\sigma_h} = \frac{\sigma_h - \sigma_h^{(0)}}{\sigma_h}$$

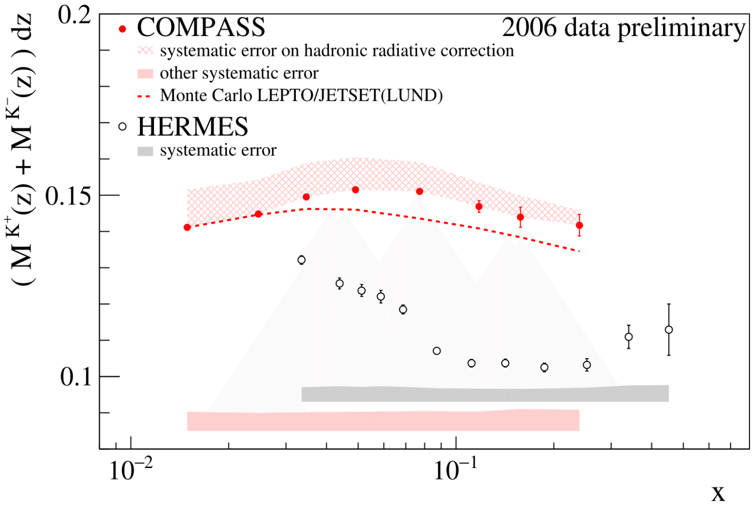
Relative magnitude of the Mass Correction

Strange quark PDF

- **HERMES** ⇨
  - Claim very different s-quark shape compared to CTEQ6L
  - Measurements from ATLAS/CMS at LHC also show different s-PDF
  - Strange pdf may not be what we think!

Strange quark PDF

- **HERMES**



- Claim very different s-quark shape compared to CTEQ6L
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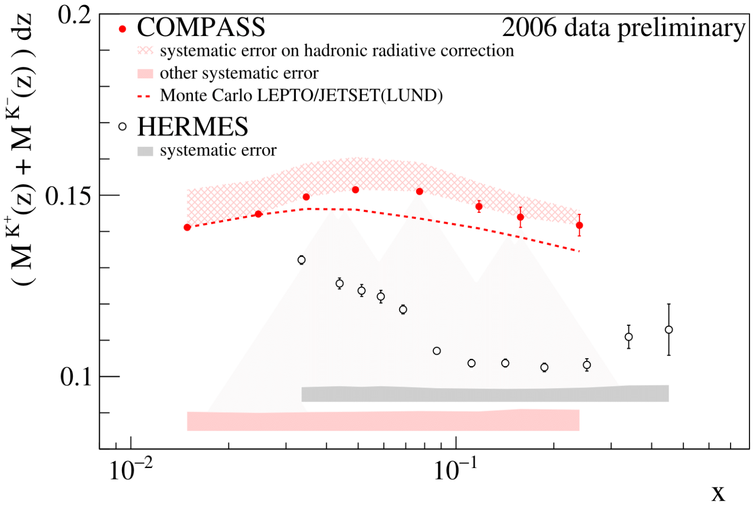
- **But COMPASS**

$$< Q^2 >_{\text{COMPASS}} \gtrsim < Q^2 >_{\text{HERMES}}$$

- Different x_B dependence
- Overall value higher

Strange quark PDF

- **HERMES**



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- **But COMPASS**

$$< Q^2 >_{\text{COMPASS}} \gtrsim < Q^2 >_{\text{HERMES}}$$

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- Overall value higher

Can HMCs reduce the discrepancy HERMES vs. COMPASS?

Strange quark PDF

Hadron Multiplicity(Kaon) → Strange quark “Tagging”

Experimental definition: $$M^k(x_B, z_h, Q^2) = \frac{\frac{dN^K}{dx_B\, dQ^2\, dz_h}}{\frac{dN^{DIS}}{dx_B\, dQ^2}}$$

Parton model: $$M^K(x_B, z_h, Q^2) = \frac{\sum_q e_q^2\, q(x_B, Q^2)\, D_q^h(z_h, Q^2)}{\sum_q e_q^2\, q(x_B, Q^2)}$$

Integrated Multiplicity: $$M^k(x_B, Q^2) = \int_{0.2}^{0.8(0.85)} dz_h M^k(x_B, Q^2, z_h)$$

HERMES (COMPASS)

→ Sensitive to s-quark

Strange quark PDF

SIDIS on Deuteron (HERMES and COMPASS)

Parton model: $$M^K(x_B, Q^2) = \frac{Q(x)\int \mathcal{D}_Q^K(z)dz + S(x)\int \mathcal{D}_S^K(z)dz}{5Q(x) + 2S(x)}$$

$$Q(x) \equiv u(x) + \overline{u}(x) + d(x) + \overline{d}(x)$$

$$S(x) \equiv s(x) + \overline{s}(x)$$

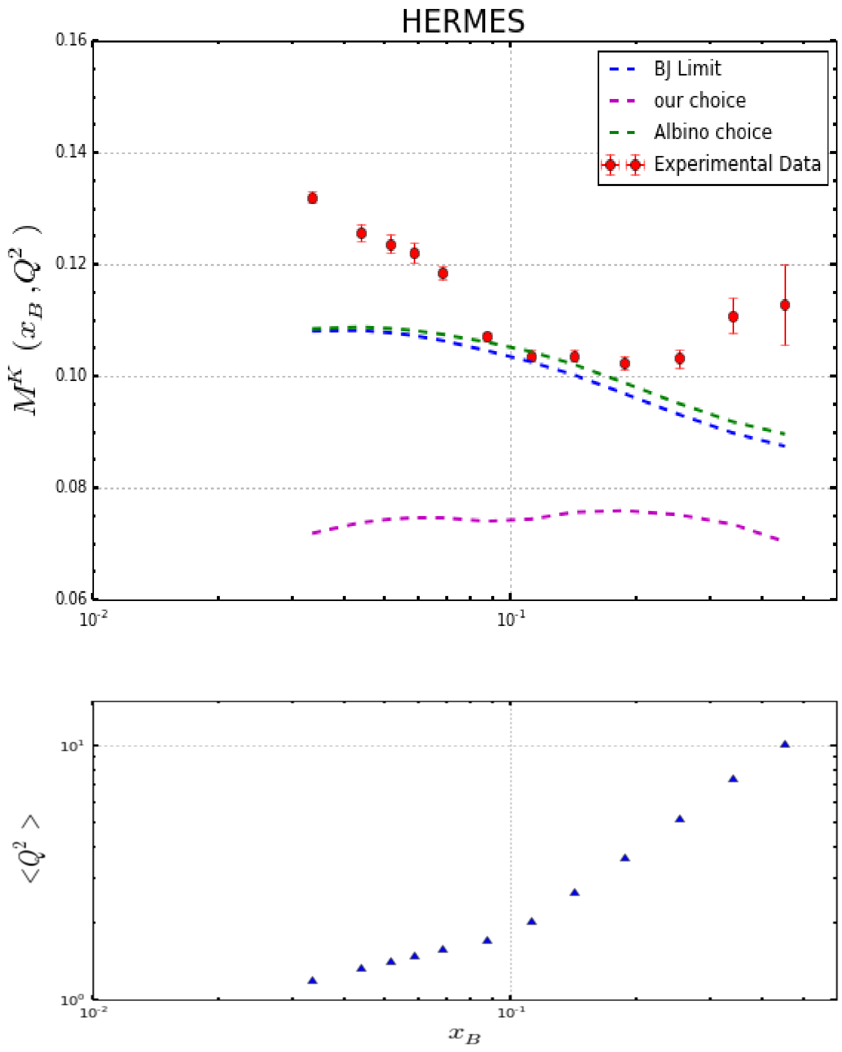
$$\mathcal{D}_Q^K(z) \equiv 4D_u^K(z) + D_d^K(z)$$

$$\mathcal{D}_s^K(z) \equiv 2D_s^K(z)$$

$$K = K^+ + K^-$$

Strange quark PDF

PDFs: CTEQ6L, FFs: DSSV07



Strange quark PDF

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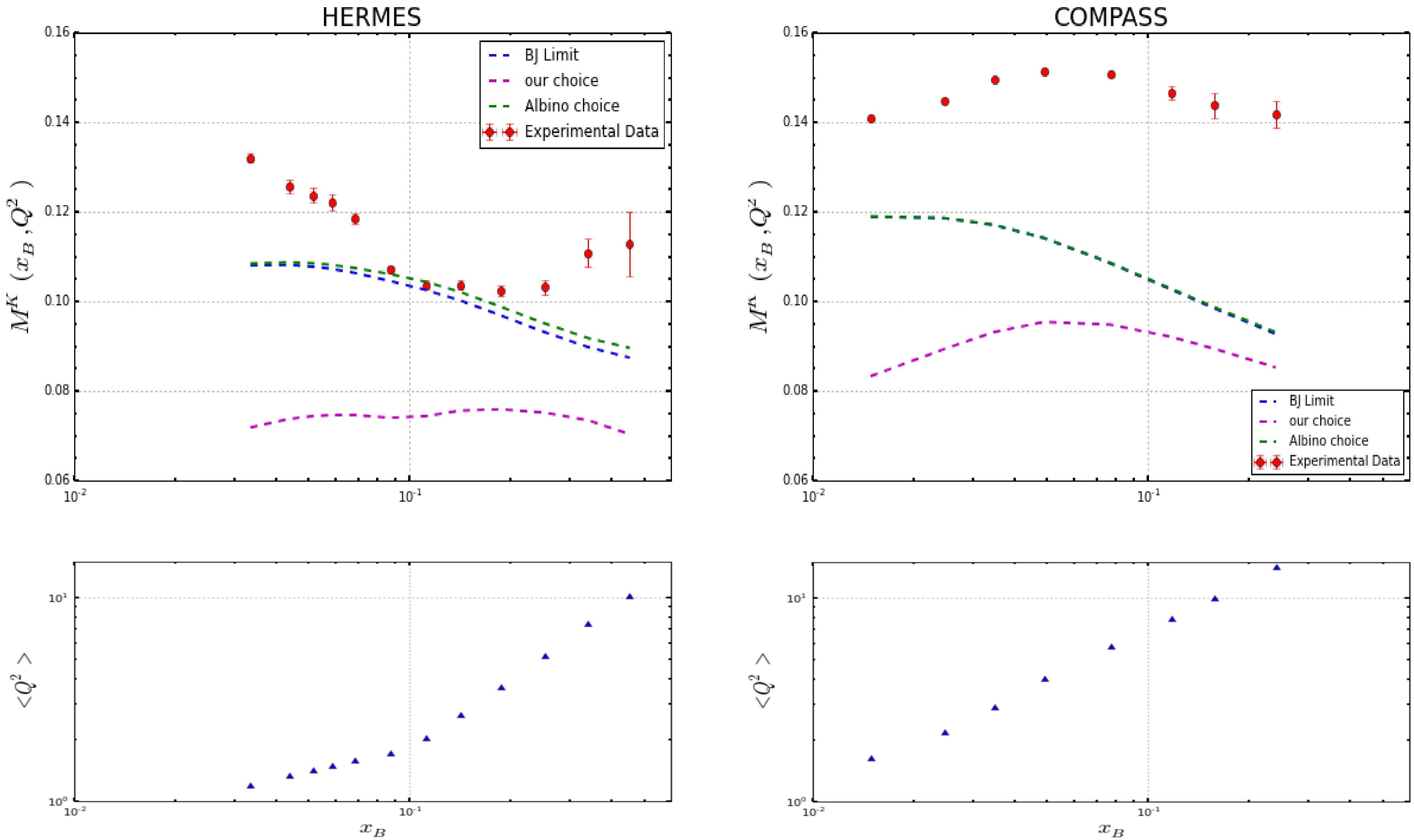
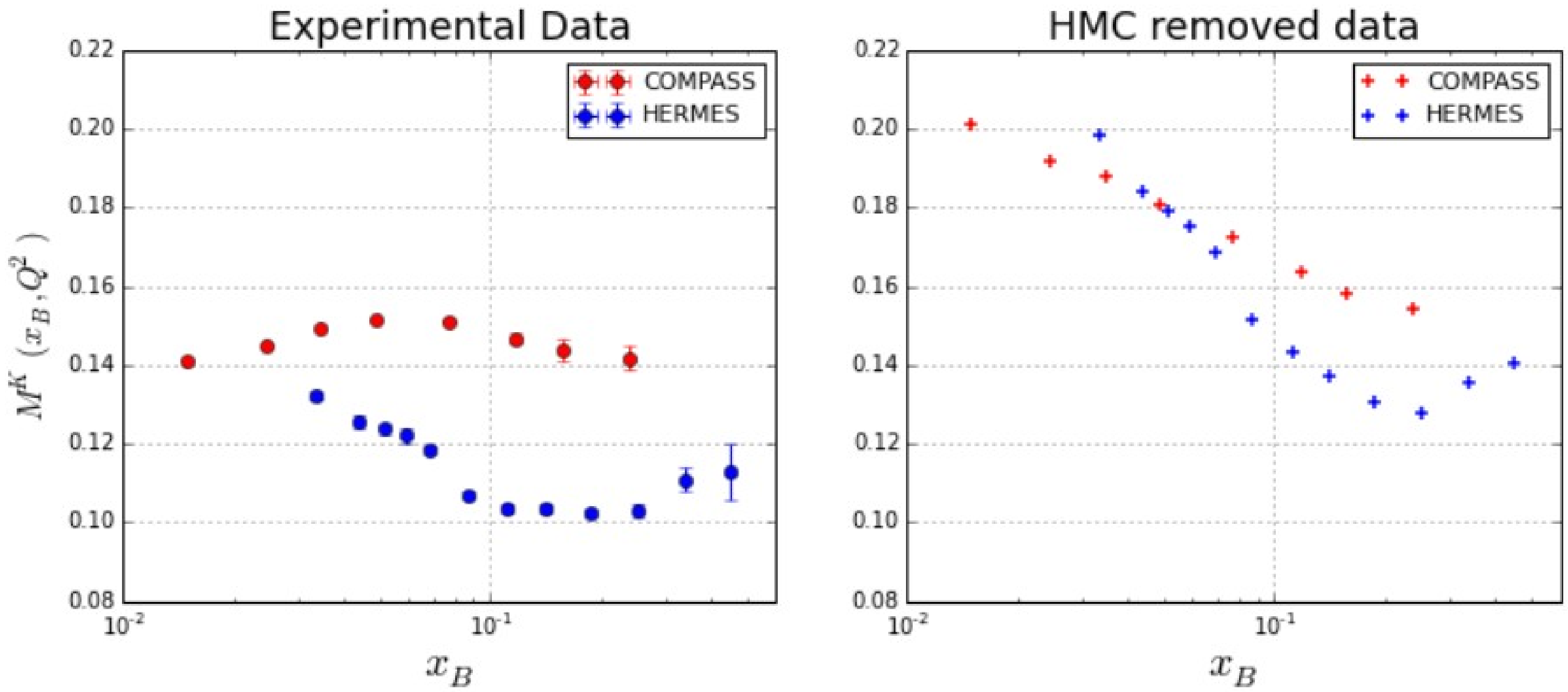


COMPASS vs. HERMES



Data without HMCs: $D_{w/oHMCs} = D_{exp} \frac{M^{K^{(0)}}}{M^K}\Big|_{Theory}$

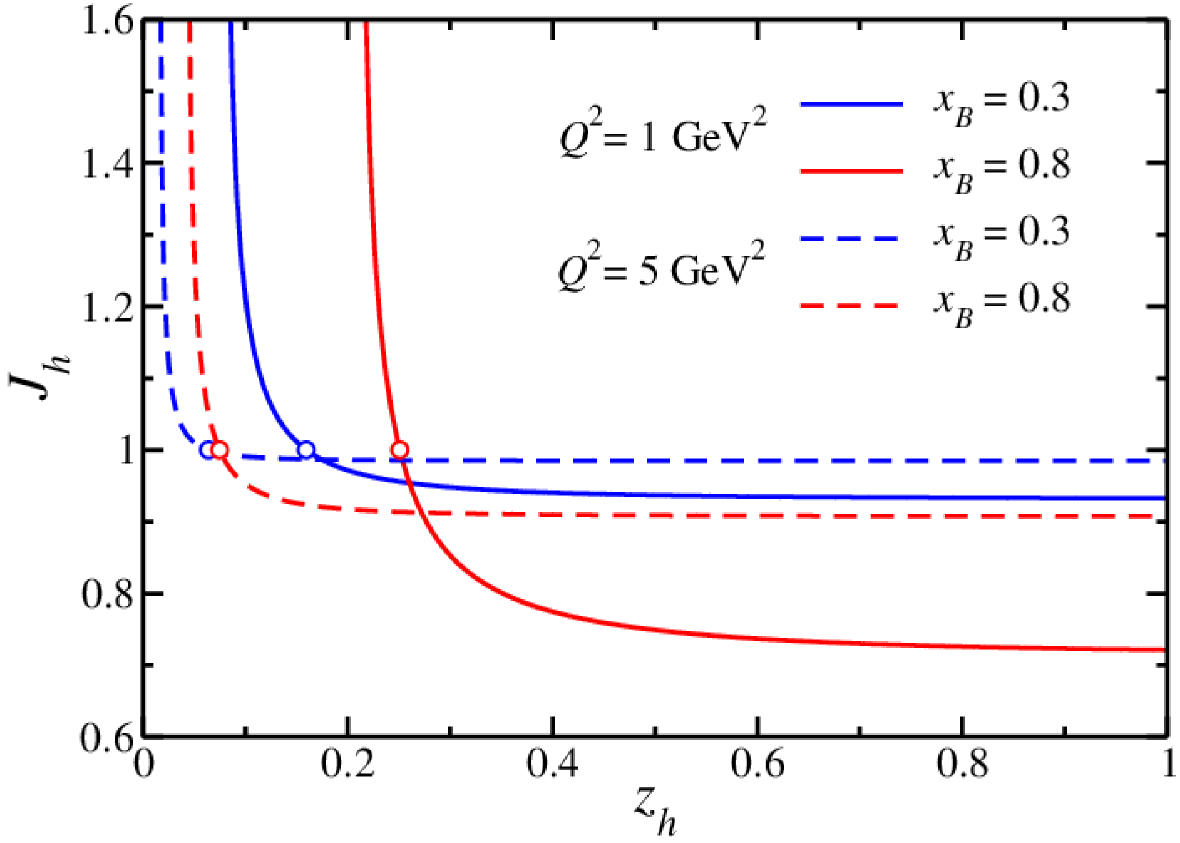
Conclusion and outlook

- HMC's at LO are captured by new scalling variables ξ_h and ζ_h.
  - Matching "internal" and external kinematics requires a massive fragmenting parton with $\widetilde{k}'^2 \geq m_h^2/\zeta_h$.
  - x_B and z_h mixed in the new scaling variables ξ_h and ζ_h
- We have quantified HMC's effects numerically: stronger for large as well very small values of z_h, stronger effects at large x_B and low Q^2 (as DIS).
- More dramatic effects for Kaons compared to pions.
- Jefferson Lab Pions: corrections up to ~40 %- 50 % even at moderately large Q^2 (small effects for HERMES and COMPASS)
- HMCs reduce the discrepancy between HERMES and COMPASS data for averaged Kaon integrated multiplicities
- Future development: prove factorization at NLO in the prescence of massive fragmenting partons with non-zero virtuality, and "correct" choice of $\widetilde{k}'^2$.

Thank you!

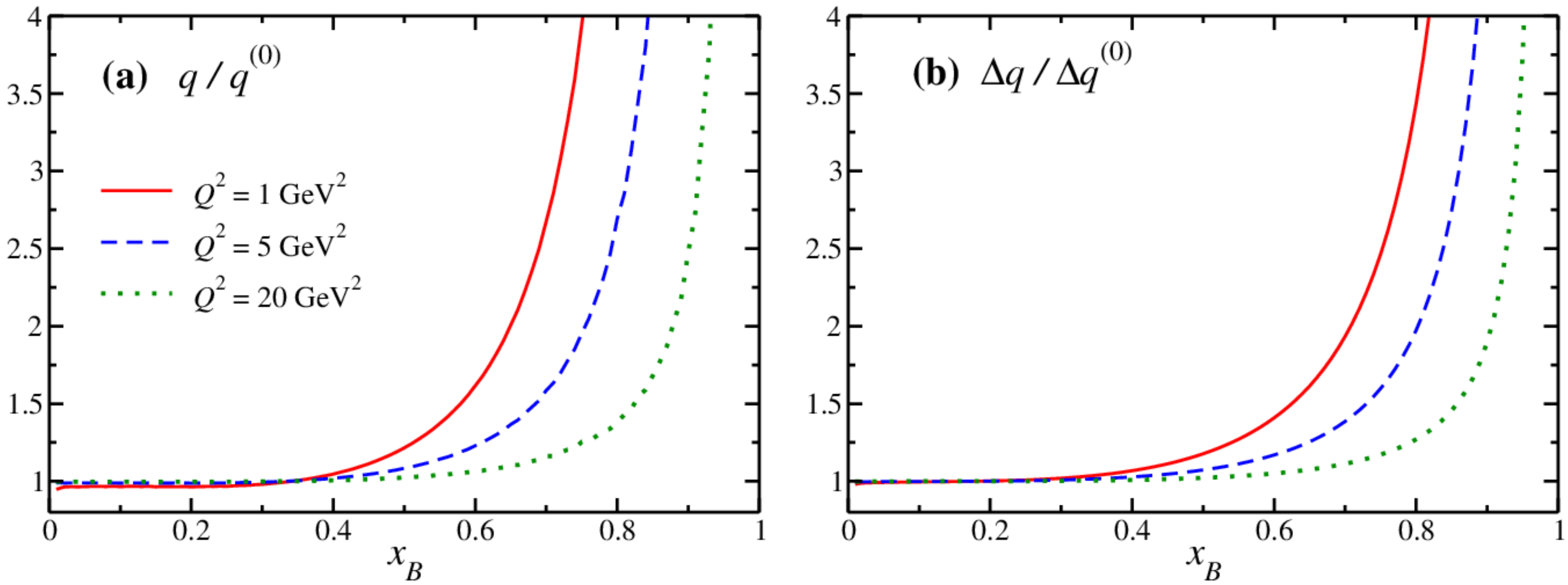
Backup slides

Jacobian



Backup slides

PDF's



Backup slides

Fragmentation function