Semi-inclusive Kaon production at low scales

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QCD Evolution 2018
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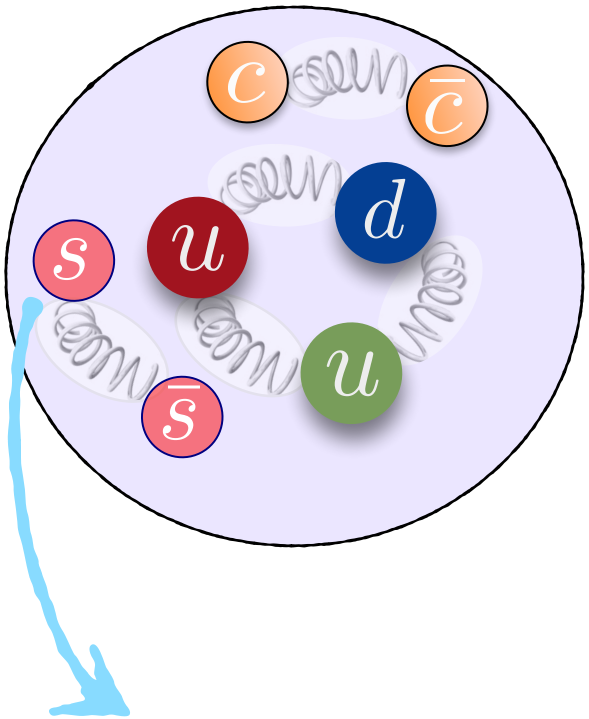
Based on:
J. G., J. Ethier, A. Accardi, S. Casper ,W. Melnitchouk, JHEP 1509 (2015) 169
J.G & Alberto Accardi, arXiv:1711.04346 (accepted in PRD)

HAMPTON UNIVERSITY
THE STANDARD OF EXCELLENCE

Jefferson Lab
Thomas Jefferson National Accelerator Facility

What can we see inside a proton?



Interested in the s-quark.

Partons:

- 3 "valence quarks" p = (u u d)
- Gluons
- sea quarks: **<u>strange</u>**, charm, bottom.

Parton (momentum) Distributions Function (PDFs):

- Well determined for the "valence quarks"and gluons.
- Not the case for the sea quarks.

Strange quark parton distribution function (PDF)

LHC

$$p + p \to W^{+/-},\ Z$$

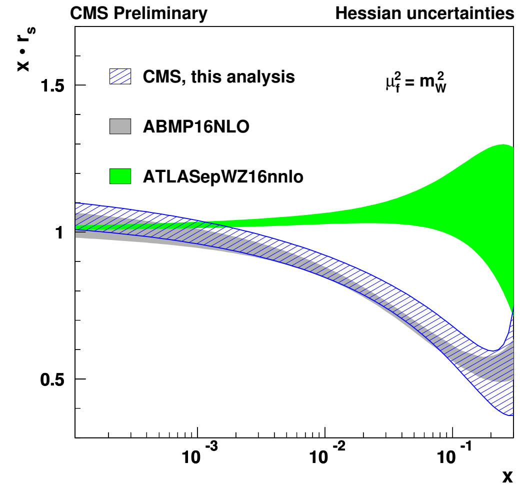
$$p + p \to W + c$$

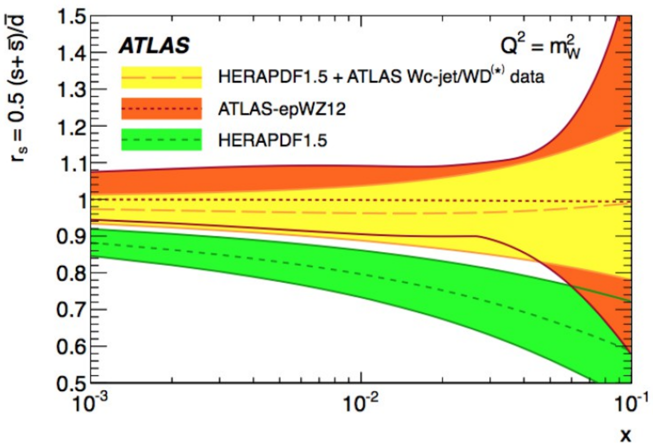
Charged current DIS

$$\nu + A \to l + c + X$$

- ATLAS: no suppression
- CMS: suppression
- νA: suppression

→ Need another measurement



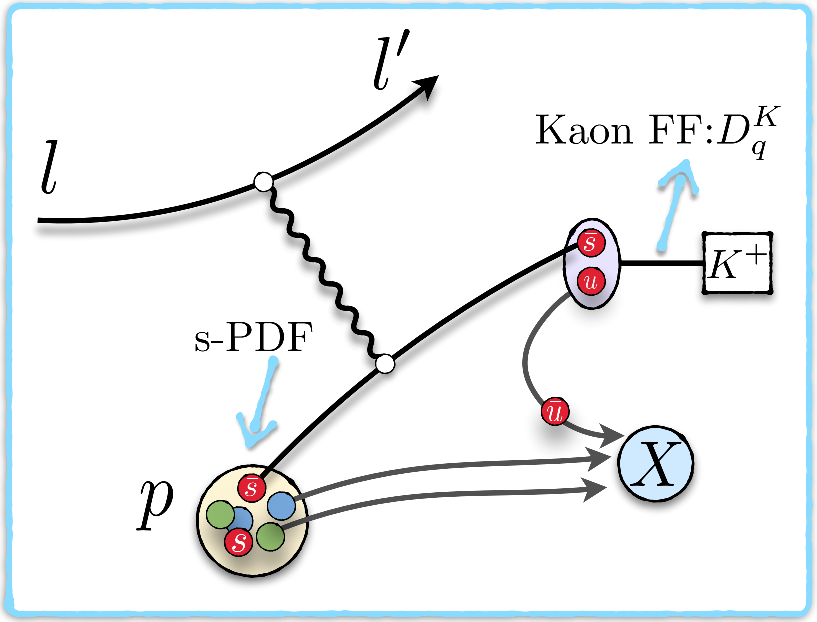


s-PDF from SIDIS

one way

How can we access the s-quark PDF? → Measuring a Kaon in Semi inclusive Deep inelastic scattering (SIDIS)

$$e^- + p \to e^- + K + X$$



- Kaon contains an s-quark in their valence structure.
- Detect a Kaon: good proxy for a strange quark

How to tag s-quarks?

☑ Use "integrated Kaon Multiplicities"

Experimentally
HERMES, COMPASS:

$$M^K_{exp} = \frac{\int_{exp} dQ^2 \int_{0.2}^{0.8} dz_h \frac{dN^K}{dx_B dQ^2 dz_h}}{\int_{exp} dQ^2 \frac{dN^e}{dx_B dQ^2}}$$

Theoretically
LO, neglect masses:

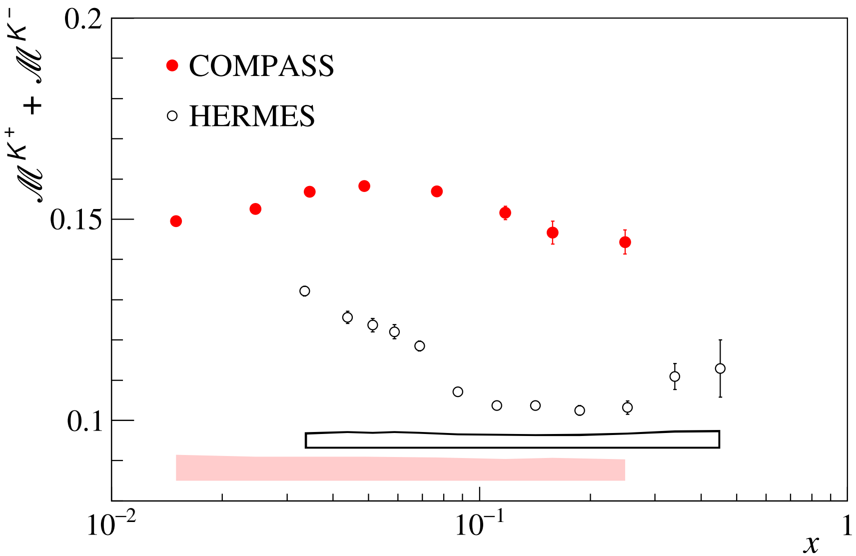
$$M^K = \frac{\sum_q e_q^2 \, q(x_B) \, \int_{0.2}^{0.8} dz_h D_q^h(z_h)}{\sum_q e_q^2 \, q(x_B)} = \frac{s(x_B)}{\sum_q e_q^2 q(x_B)} \int dz_h D_s^K(z_h)$$

$$+\text{light quarks}$$

Compare data and theory → Extract the s-quark PDF.

Integrated Kaon Multiplicities: SIDIS on Deuteron

- **HERMES:**
  - Claim very different s-quark shape compared to CTEQ6L.
  - Strange PDF may not be what we think!
- **But COMPASS:**
  - Different x_B dependence
  - COMPASS overall value higher.



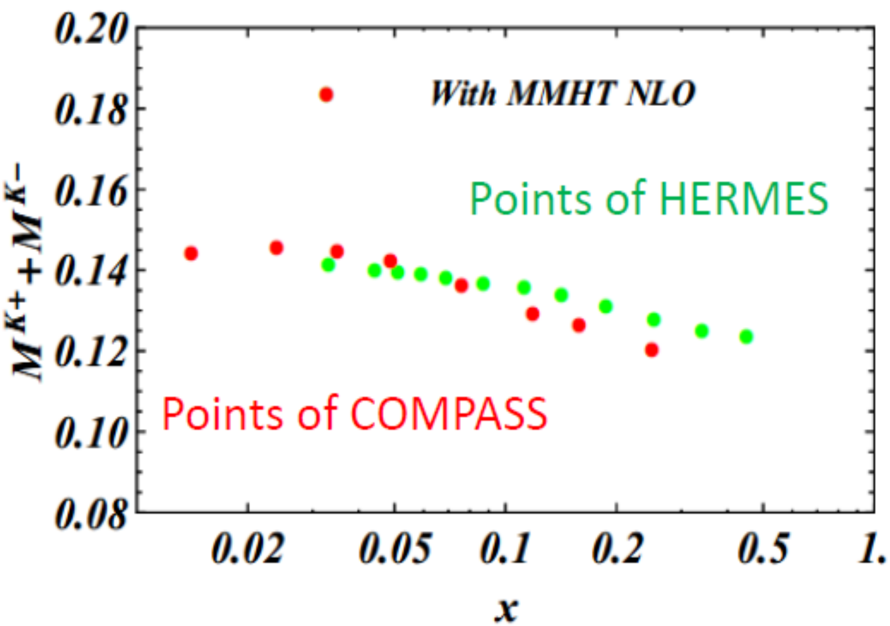
Where does this discrepancy come from?

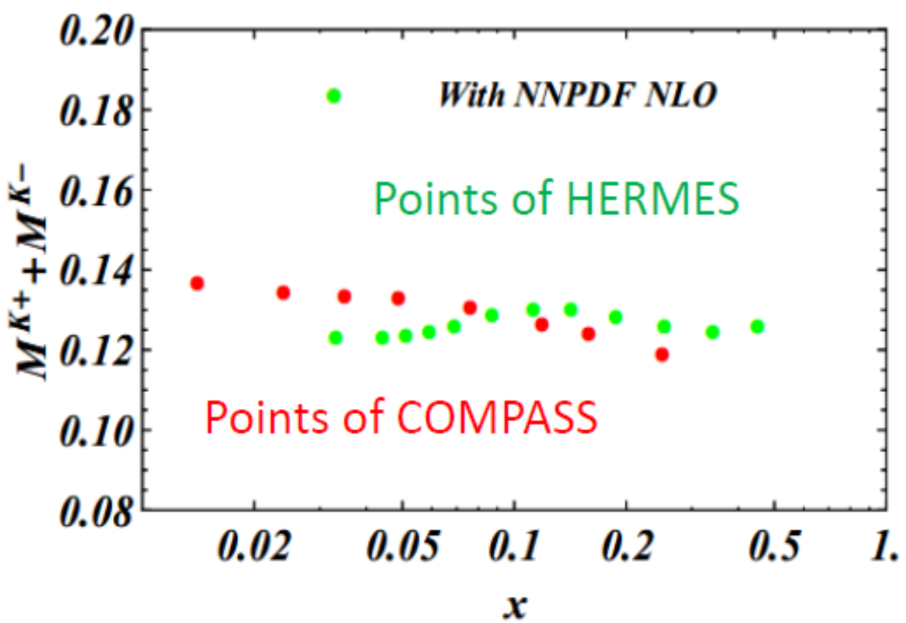
Is it real or apparent?

Integrated Kaon Multiplicities: SIDIS on Deuteron

- Theoretical prediction at NLO:

Plots from Chung-Wen Kao:
Talk at DIS 2018 conference



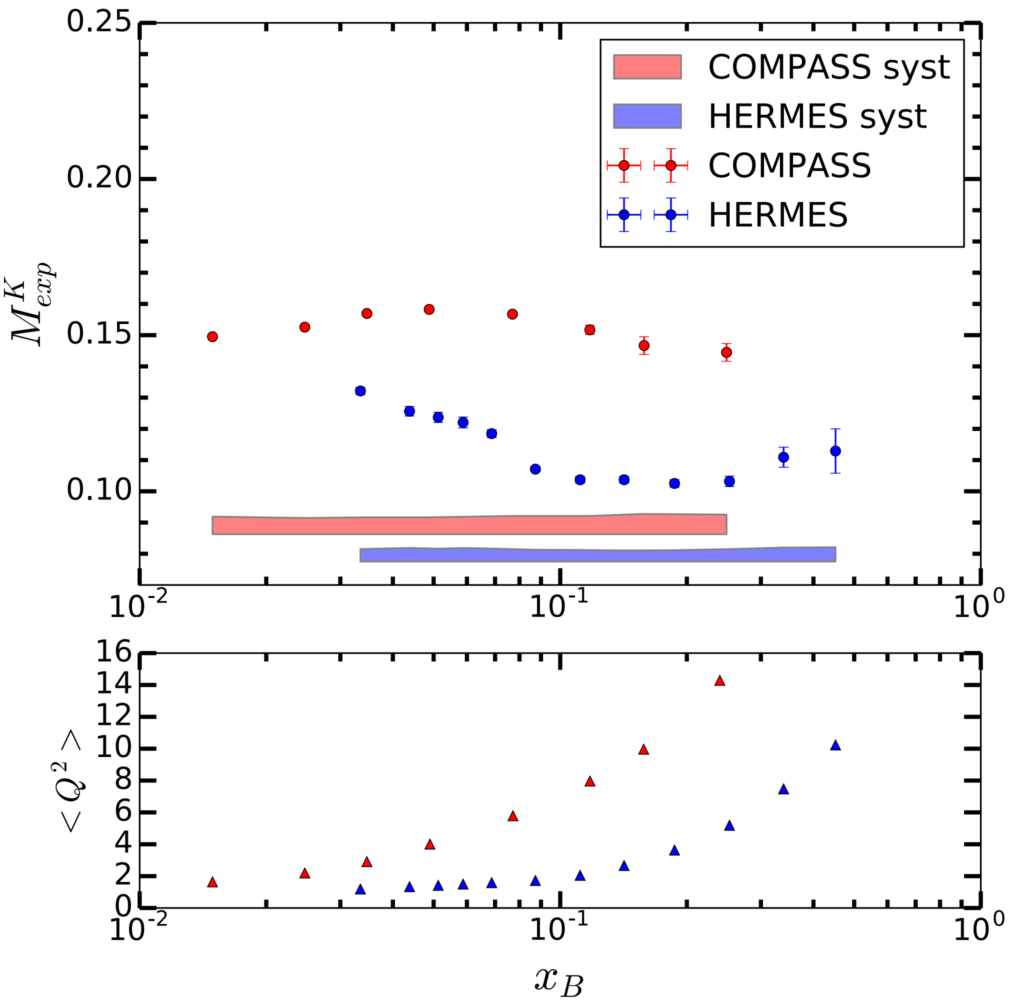


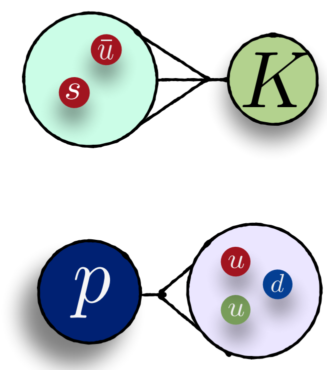
- MMHT+DSS17
- NNPDF +DSS17

- Theoretical prediction: both sets should be close
- Q^2 evolution does not explain the discrepancy
- Other effects?

Hadron Mass Effects

Usually in pQCD, the masses of the Proton and the Kaon (detected hadron) are neglected.





$m_K \simeq 0.5$ GeV

$m_p \simeq 1$ GeV

$$\overline{Q^2}_{\rm C} \gtrsim \overline{Q^2}_{\rm H} \simeq 1 - 10 \text{ GeV}^2$$

Maybe masses are not so negligible!

Hadron Mass Effects

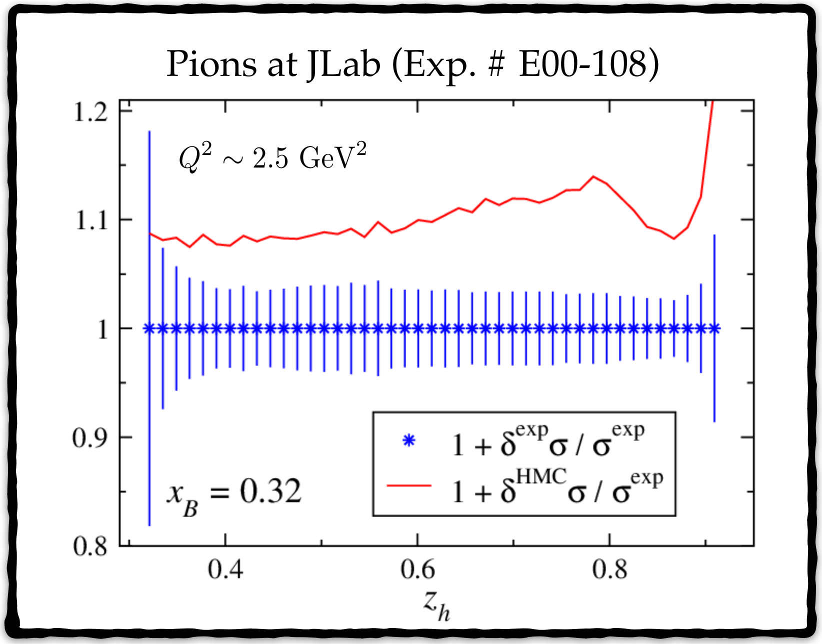
Let's consider an example for Pion Mass effects at JLab.

Jefferson Lab experiments:

- Usually low Q^2.
- $1/Q^2$ corrections have to be controlled.

$O(m^2/Q^2) =$ Hadron Mass Corrections (HMCs)

$$m = M_P, m_\pi$$

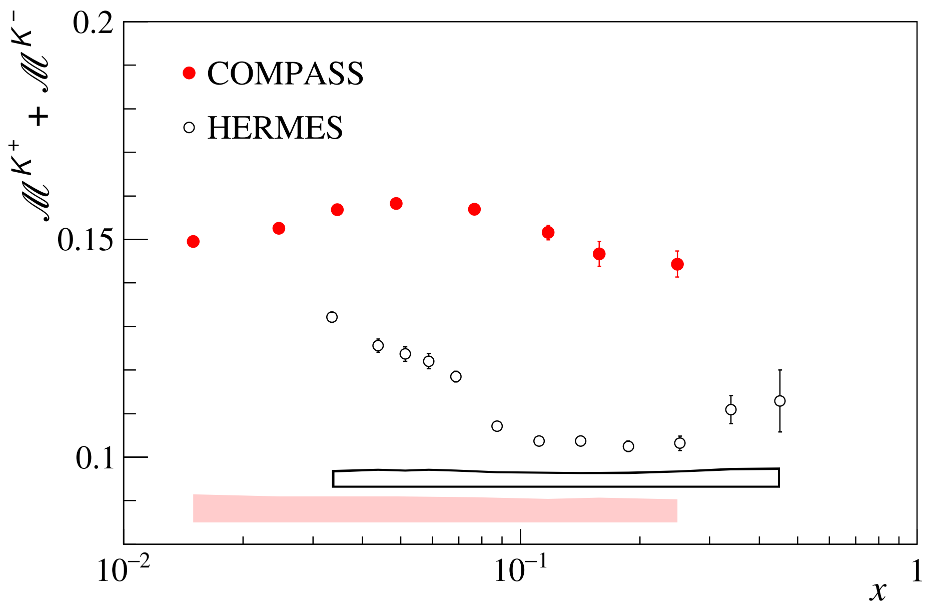


Accardi et al JHEP 0911, 084 (2009)

$$m_\pi \sim 0.14\ \mathrm{GeV}$$

Hadron Mass Effects

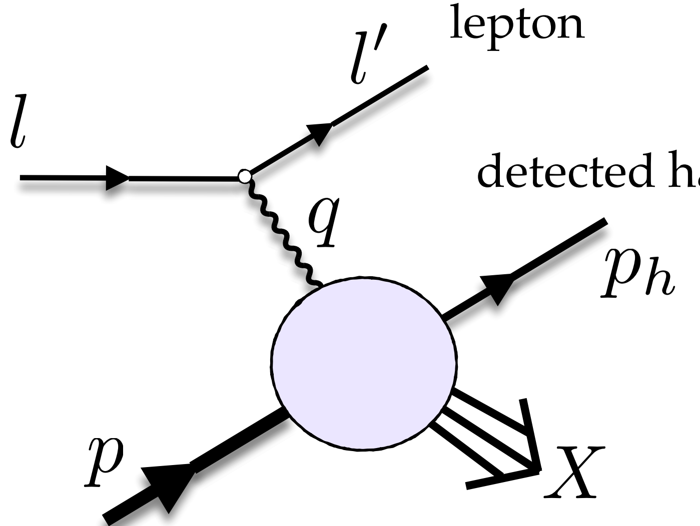
Back to Kaons:



HERMES & COMPASS: relatively low Q², $m_K^2 \sim 12 m_\pi^2$

Could the discrepancy be due to m_K^2/Q^2 effects?

SIDIS Kinematics Variables



DIS invariants

$$M^2 = p^2 \qquad Q^2 = -q^2$$

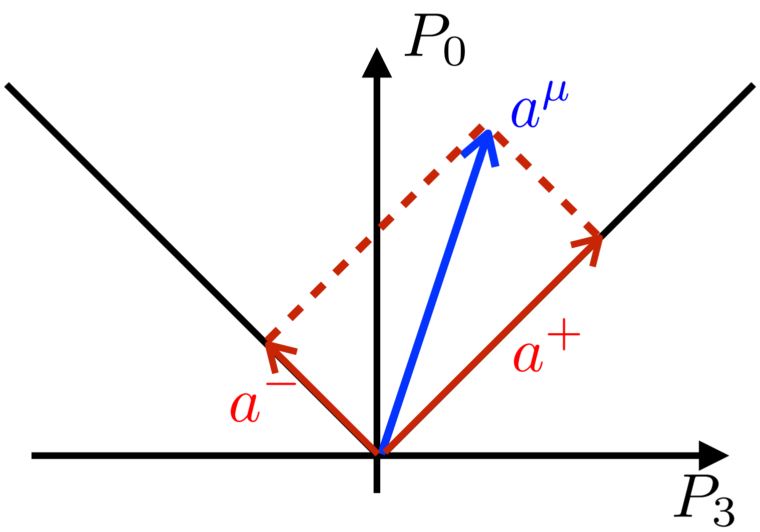
$$y = \frac{p \cdot q}{p \cdot l} \qquad x_B = \frac{Q^2}{2p \cdot q}$$

SIDIS invariants

$$m_h^2 = p_h^2$$

$$z_h = \frac{p_h \cdot p}{q \cdot p}$$

SIDIS: Massive scaling variables



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

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

Scaling Variables

Nachtmann:

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

Bjorken limit: $\xi \to x_B$

$Q^2 \to \infty$

Fragmentation:

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

Bjorken limit: $\zeta_h \to z_h$

$Q^2 \to \infty$

Collinear momenta

- (p,q) frame: p and q are collinear and have zero transverse momentum

$$\left.\begin{array}{l}\widetilde{k}^2 = v^2 \\ \widetilde{k}' = v'^2\end{array}\right\}$$

Physically: "Average virtualities"

Fragmenting parton collinear to hadron

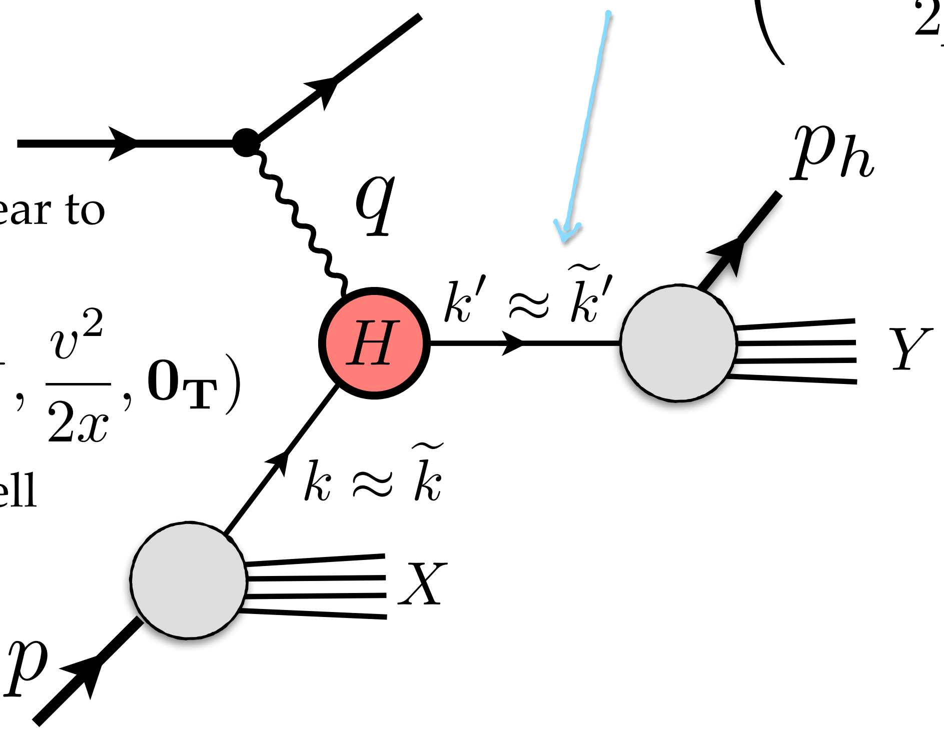
$$\widetilde{k}' = \left(\frac{v'^2 + (\boldsymbol{p_{h\perp}}/z)^2}{2p_h^-/z}, \frac{p_h^-}{z}, \frac{\boldsymbol{p_{h\perp}}}{z} \right)$$

Approx.:
Parton collinear to proton…

$$\widetilde{k} = (xp^+, \frac{v^2}{2x}, \mathbf{0_T})$$

… and on-shell

$$v^2 = 0$$



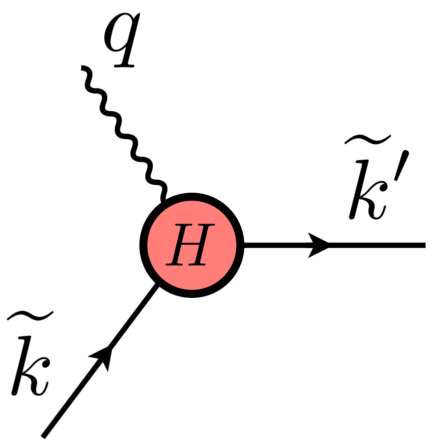
Fragmentation into a **massive** hadron

$$v'^2 = ?$$

need to match partonic & hadronic kinematics

Matching Hadronic and Partonic Kinematics at LO

Hard scattering: 4-momentum conservation at LO



$$x = \xi\left(1 + \frac{v'^2}{Q^2}\right)$$

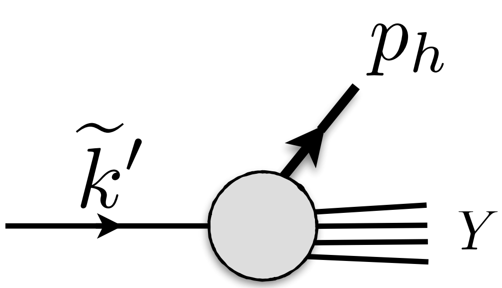
$$z = \zeta_h$$

Bjorken limit:

$$x = x_B$$

$$z = z_h$$

Fragmenting blob: momentum conservation in + direction



$$\widetilde{k}'^{+} = p_h^+ + Y^+ \geq p_h^+$$

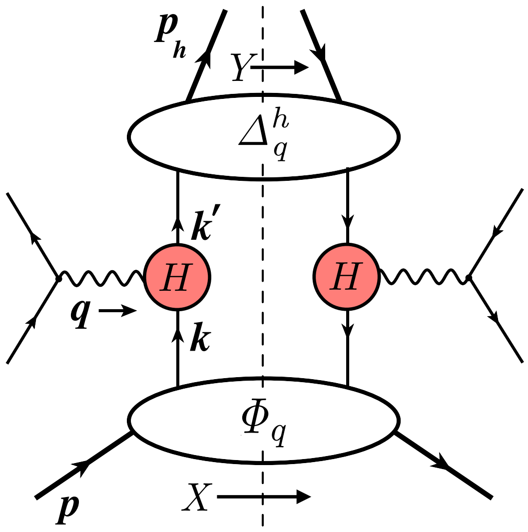
$$v'^2 \geq \frac{m_h^2}{z} \underset{\text{LO}}{=} \frac{m_h^2}{\zeta_h}$$

Standard choice:

$$v'^2 = 0$$

Albino et al. Nucl. Phys. B803 (2008) 42-104

Hadronic Tensor



Expand:

$$\Phi_q = k^+ \left[\phi_2(k)\bar{\not n} + \mathcal{O}(1/k^+)\right]$$

$$\Delta_q = k'^- \left[\delta_2(k')\not n + \mathcal{O}(1/k'^-)\right]$$

contribute to Higher-Twist (HT) terms

$$2MW^{\mu\nu} = \int d^4k\ d^4k'\ \mathrm{Tr}\left[\Phi_q(p,k)\,\gamma^\mu\,\Delta_q^h(k',p_h)\,\gamma^\nu\right]\ \delta^{(4)}(k+q-k')$$

$$= \int d^4k\ d^4k'\ \phi_2(k)\delta_2(k')\mathrm{Tr}\left[k^+\bar{\not n}\gamma^\mu\, k'^-\not n\,\gamma^\nu\right]\ \delta^{(4)}(k+q-k') + \mathrm{HT}$$

Note: $q_\mu W^{\mu\nu} = 0$

Approx.: $k \approx \tilde{k}$, $k' \approx \tilde{k}'$

Leading Order (LO) Multiplicities at finite Q^2.

- **With Hadron Masses:**

Scale dependent Jacobian

Finite Q^2 scaling variables

$$M^h(x_B) = \frac{\int_{exp.} dQ^2 \int_{0.2}^{0.8} dz_h \, J_h(\xi, \zeta_h, Q^2) \sum_q e_q^2 \, q(\xi_h, Q^2) \, D_q^h(\zeta_h, Q^2)}{\int_{exp.} dQ^2 \sum_q e_q^2 \, q(\xi, Q^2)}$$

$$\xi_h \equiv \xi \left(1 + \frac{m_h^2}{\zeta_h Q^2}\right)$$

Note: Theory integrated over z, Q^2 experimental bins for each x_B.

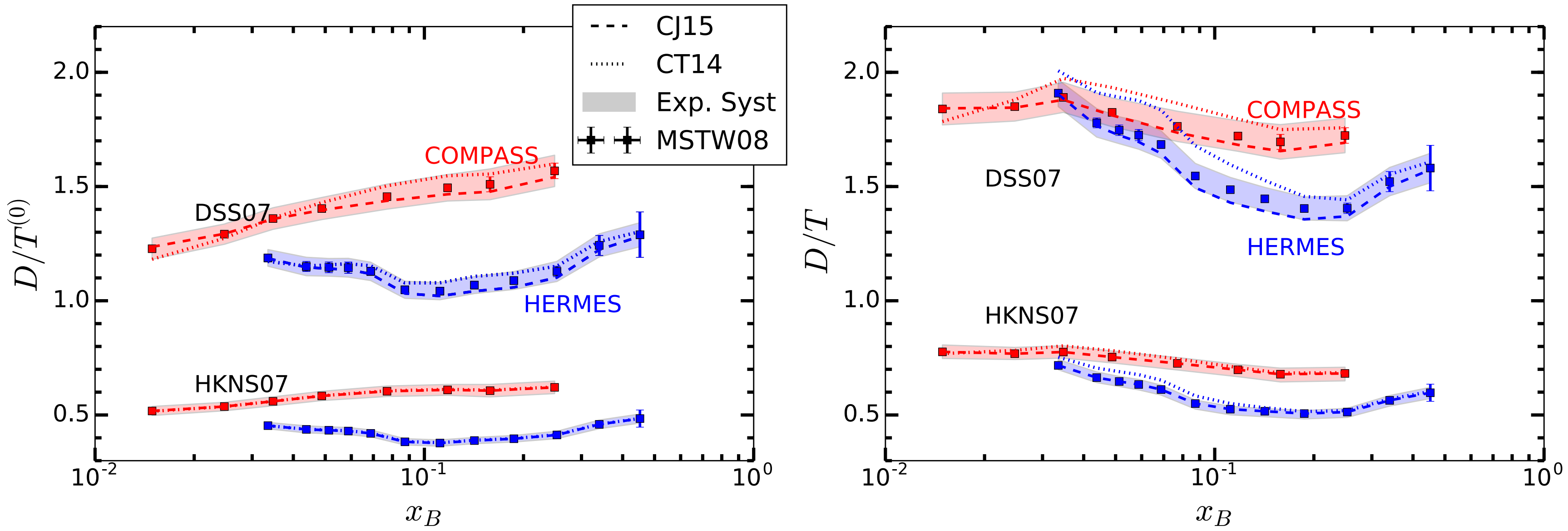
- Bjorken limit: $\left(\frac{M^2}{Q^2}, \frac{m_h^2}{Q^2}\right) \to 0$

$$M^{h(0)}(x_B) = \frac{\int_{exp.} dQ^2 \sum_q e_q^2 \, q(x_B, Q^2) \, \int_{0.2}^{0.8} dz_h \, D_q^h(z_h, Q^2)}{\int_{exp.} dQ^2 \sum_q e_q^2 \, q(x_B, Q^2)}$$

Parton model definition

Data over Theory: $K^+ + K^-$

- D/T ratio allows to compare experiments at different Q^2
- Normalization of Kaon FFs poorly known



COMPASS

vs.

HERMES

- After HMCs:
  - Size discrepancy reduced
  - Slope more flat
- COMPASS well described (except normalization)
- Residual tension with HERMES slope

HERMES & COMPASS data: direct comparison

"Theoretical correction ratios" →

Produce approximate "massless" parton model multiplicities

Make data directly comparable

Largely insensitive to D_K normalization

- COMPASS:

$$M^{h(0)}_{exp} \equiv M^h_{exp} \times R^h_{HMC}$$

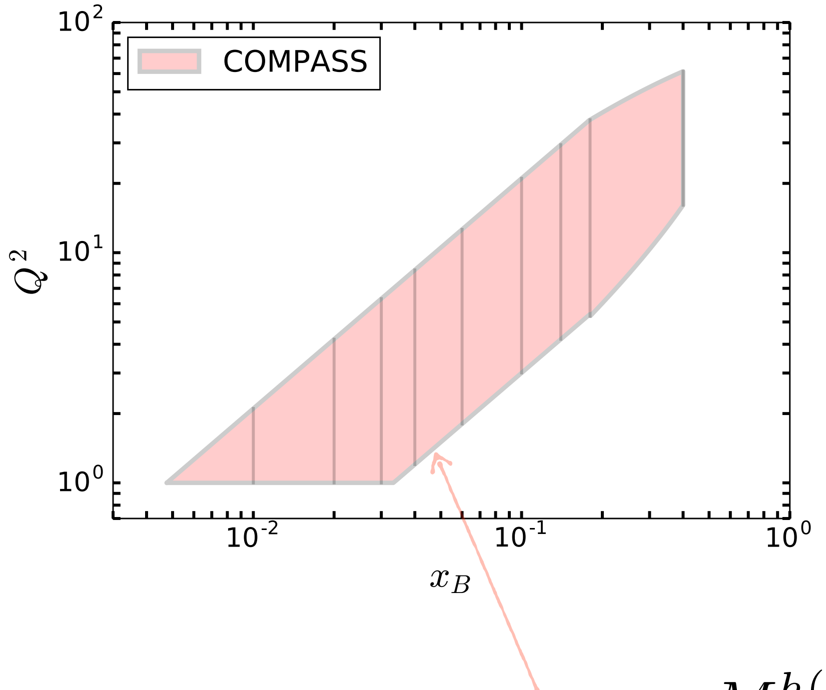
- HERMES:

$$M^{h(0)}_{exp} \equiv M^h_{exp} \times R^h_{HMC} \times R^{H\to C}_{evo}$$

HMC correction ratio

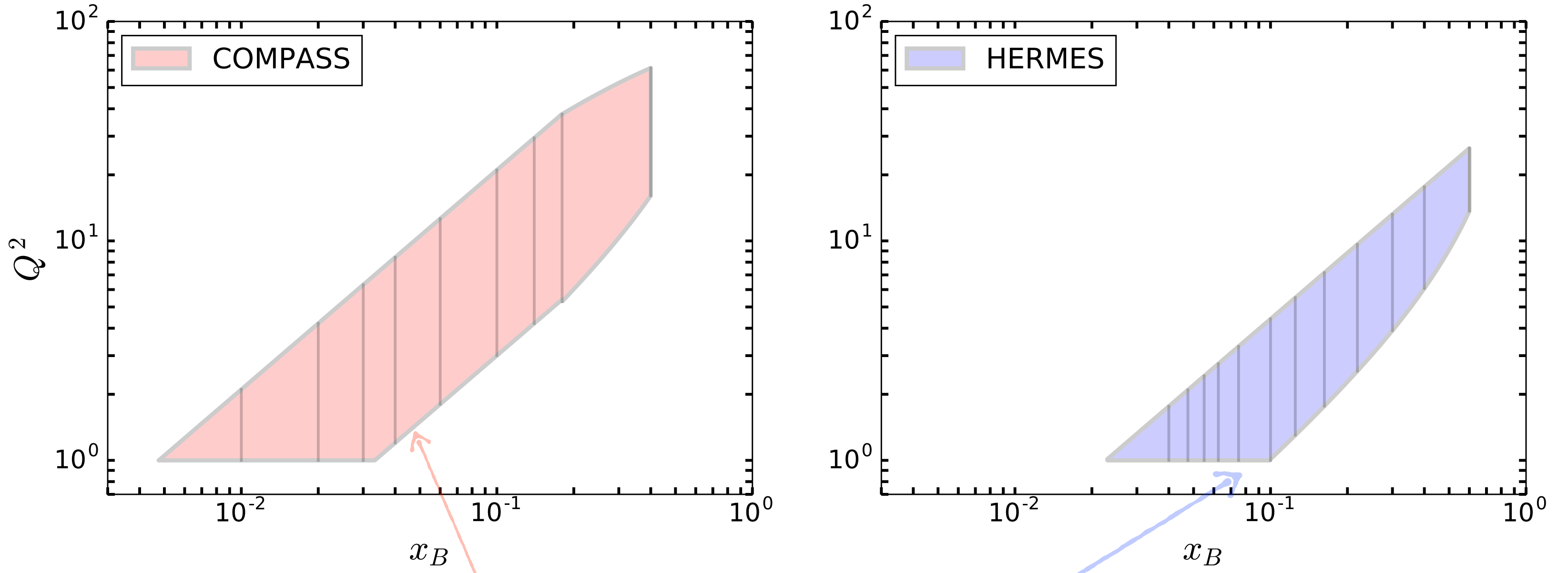
HERMES to COMPASS evolution

HERMES & COMPASS data: direct comparison



- HMC ratio $$R^h_{HMC} = \frac{M^{h(0)}}{M^h}$$

HERMES & COMPASS data: direct comparison



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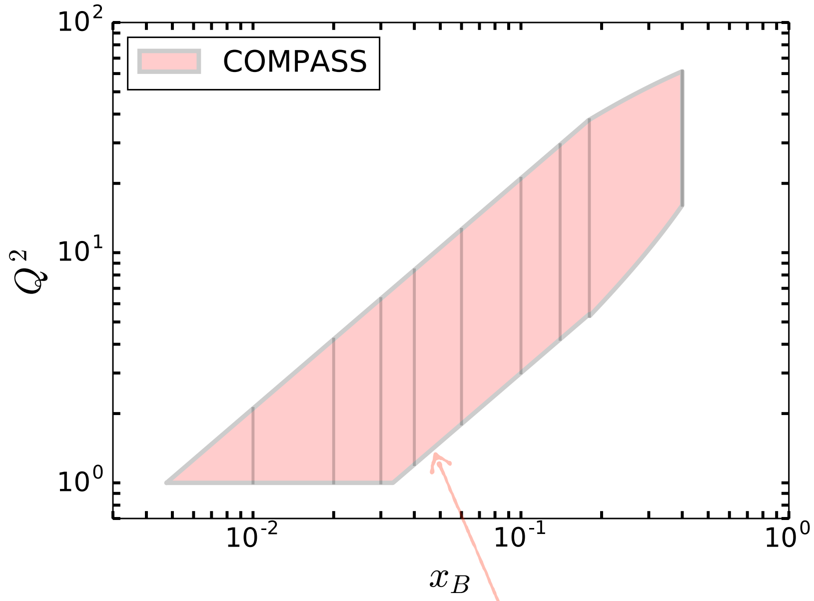
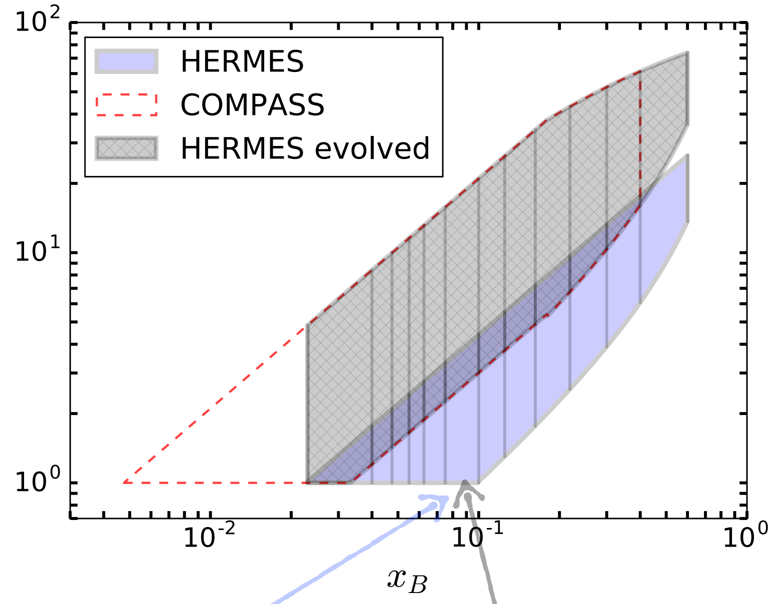
HERMES & COMPASS data: direct comparison





- HMC ratio $$R^h_{HMC} = \frac{M^{h(0)}}{M^h}$$
- Evolution ratio (HERMES to COMPASS) $$R^{H\to C}_{evo} = \frac{M^{h(0)}(x_B^{HERMES})\Big|_{\text{COMPASS cuts}}}{M^{h(0)}(x_B^{HERMES})\Big|_{\text{HERMES cuts}}}$$

HERMES & COMPASS data: direct comparison

"Theoretical correction ratios" →

Produce approximate "massless" parton model multiplicities

Make data directly comparable

Largely insensitive to D_K normalization

Massless (evolved) multiplicities:

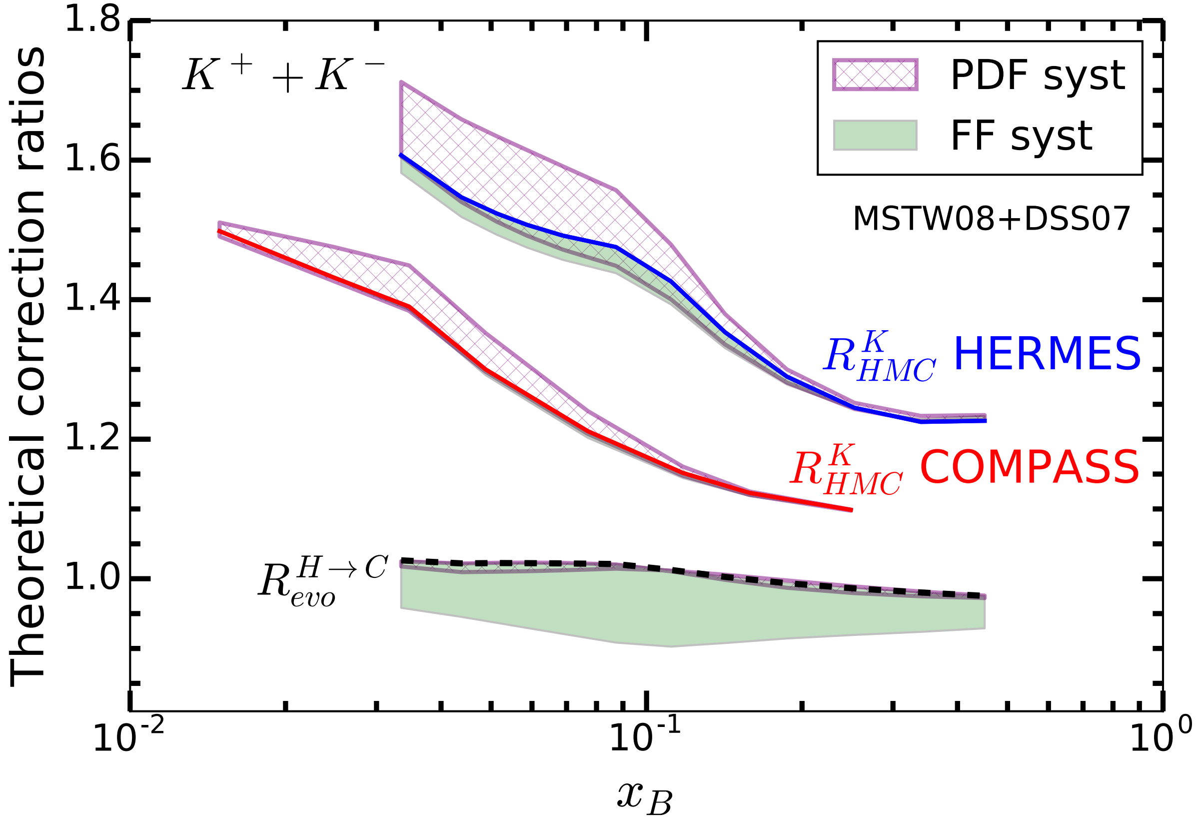
- COMPASS:

$$M^{h(0)}_{exp} \equiv M^{h}_{exp} \times R^{h}_{HMC}$$

- HERMES:

$$M^{h(0)}_{exp} \equiv M^{h}_{exp} \times R^{h}_{HMC} \times R^{H\to C}_{evo}$$

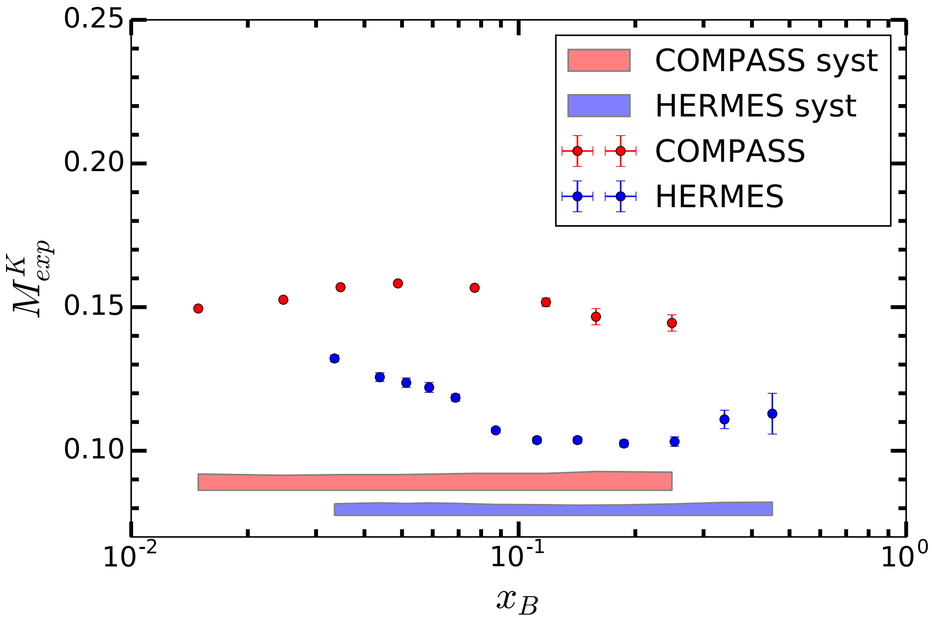
Correction ratios



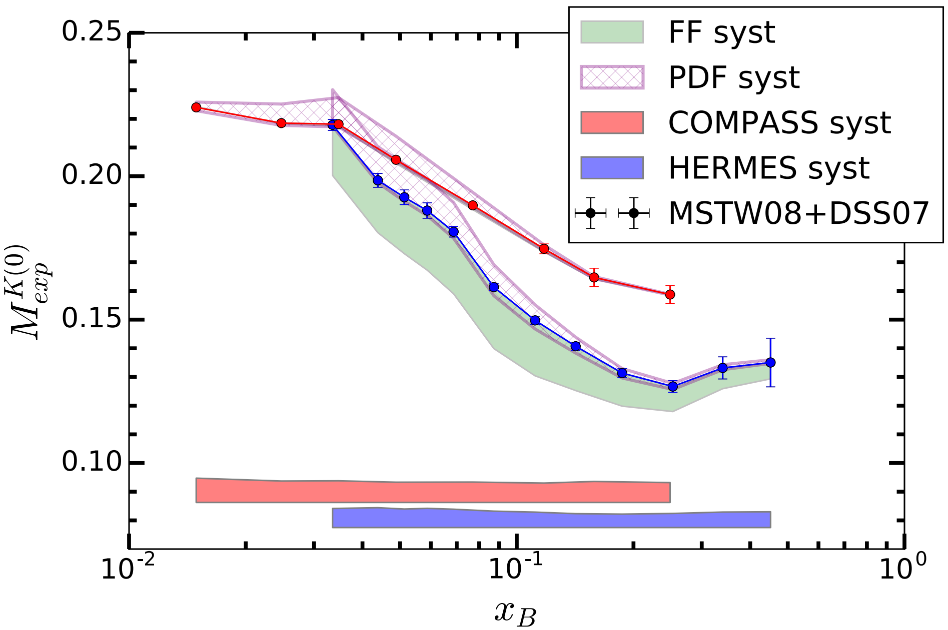
- Hadron mass effects dominant over evolution effects
- At COMPASS smaller HMCs than at HERMES.

Direct Data Comparison: $K^{+} + K^{-}$

Experimental Data



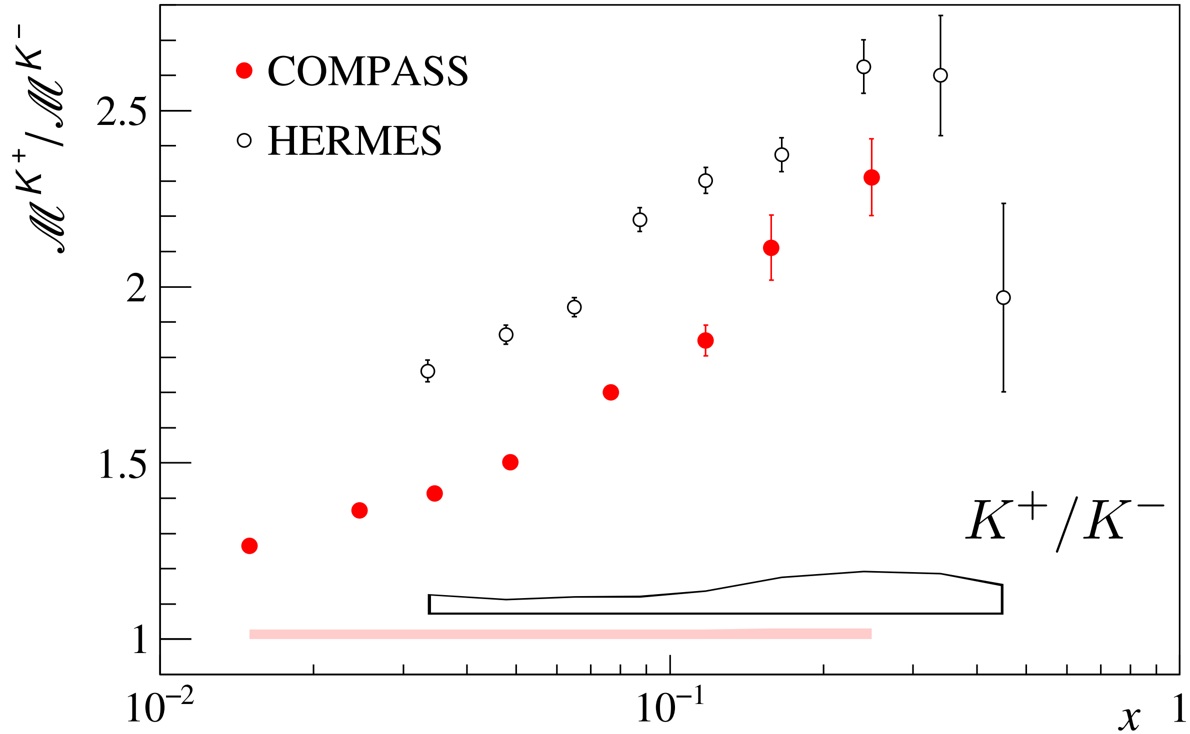
"Massless data" at same Q^2



- "Removing" HMCs reduces the discrepancy in size
- Corrections rather stable with respect to FF choice
- After HMCs, negative slope for both experiments

Kaon ratios

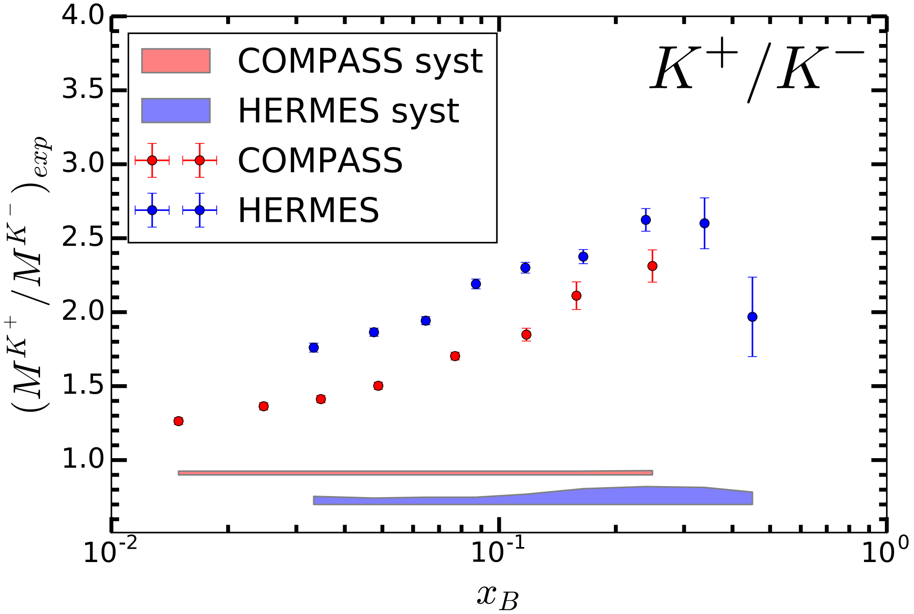
- Ratio reduces experimental systematics.



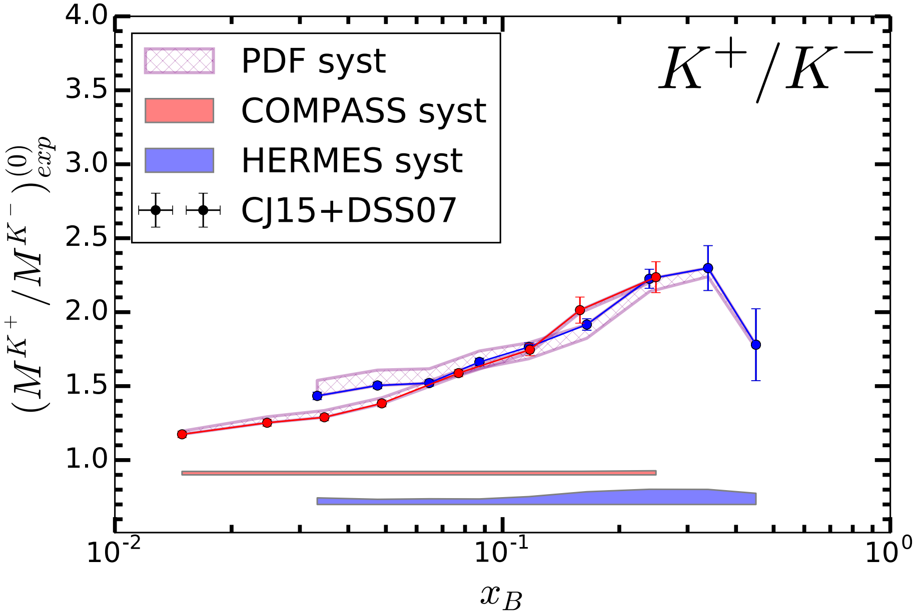
- Size discrepancy persists
- Slopes are now compatible
  - Except last HERMES point?

Direct Data Comparison: K^+/K^-

Experimental Data



"Massless data" at same Q^2



- HERMES & COMPASS fully compatible.
  - last x bin at HERMES suspicious.

Coming back to the s-PDF

Can we extract s-quark from SIDIS Kaon multiplicities? Yes, but:

- Make sure you control the FFs
  - or fit at the same time with PDFs :
    - Polarized DIS (Ethier at al, PRL119 (2017) 132001)
    - Unpolarized DIS with reweighing of PDFs (Borsa et al, PRD96 (2017), 094020)
- Include mass corrections
  - Non negligible even at small-x (because Q^2 is small)
  - Our proposed scheme with with $v'^2 = m_h^2/\zeta_h$ seems able to reconcile HERMES & COMPASS Kaon multiplicities.

Conclusion and outlook

- HMCs at LO are captured by new scaling variables ξ_h and ζ_h
- **K^+ + K^-** multiplicities:
  - HMCs: reconcile HERMES vs. COMPASS
  - Difference in slopes still needs to be solved.
- **K^+/ K^-** ratio: **No slope problem** → systematics(theory / exp.) in **K^+ + K^-** ?
- **Need to use theory with HMCs in FF fits** with HERMES and COMPASS data

<u>Future developments:</u>

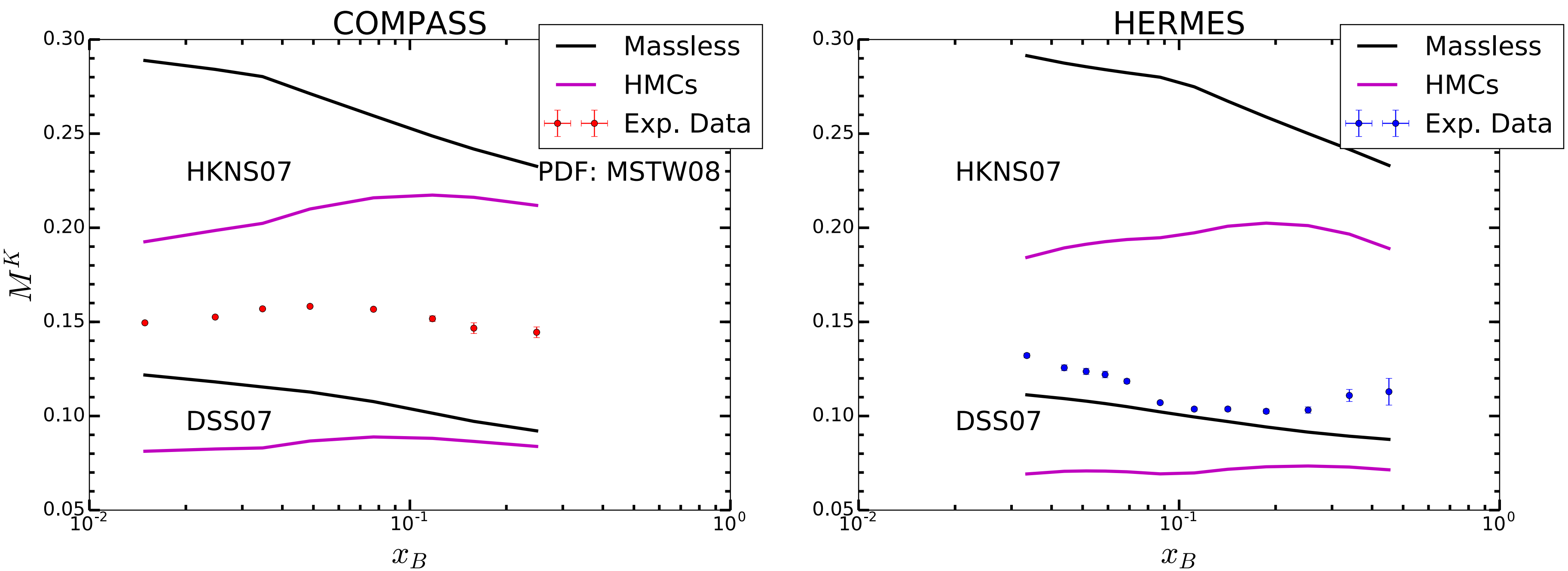
- Test our kinematical approximations using a quark-diquark (spectator) model.
- Prove factorization at NLO with $v'^2 \neq 0$

Thank you!

Backup slides

$K^+ + K^-$ Multiplicities

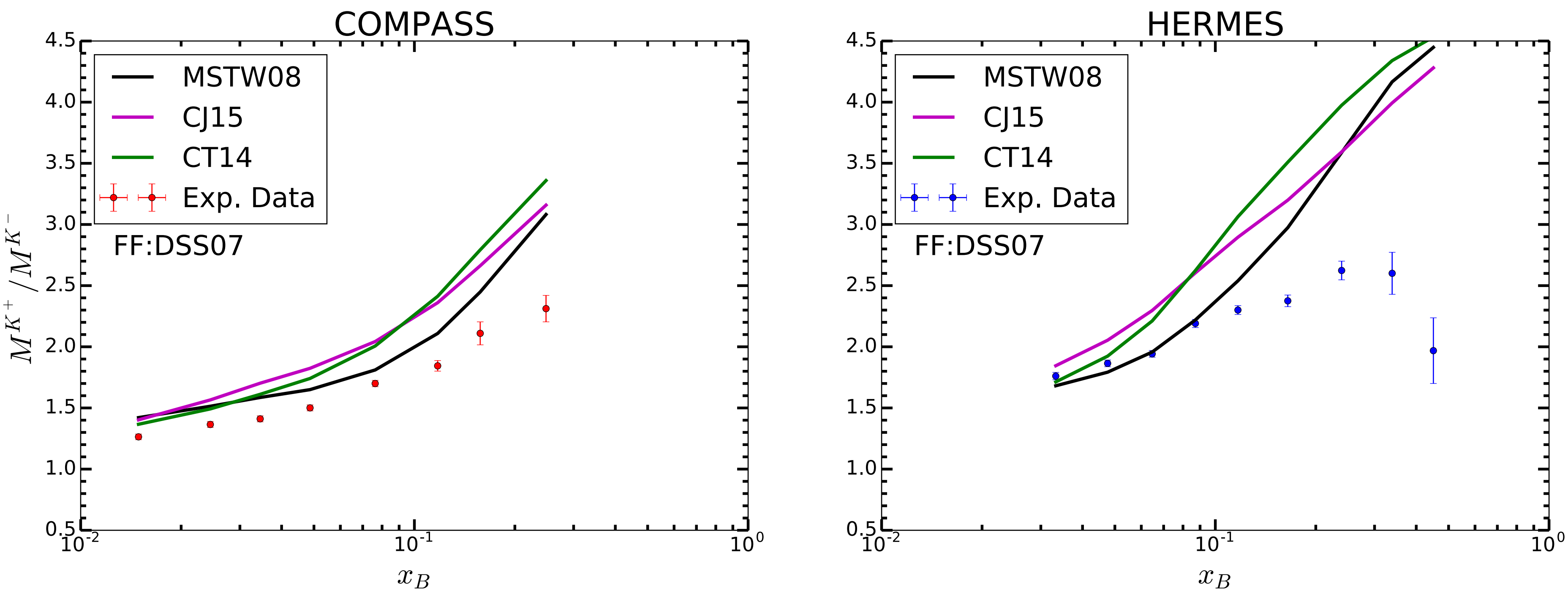
- Data (dots) vs. Theory (lines)



- Kaon FFs poorly known in absolute value
  - Large FFs systematics
- HMCs are large

Kaon ratios

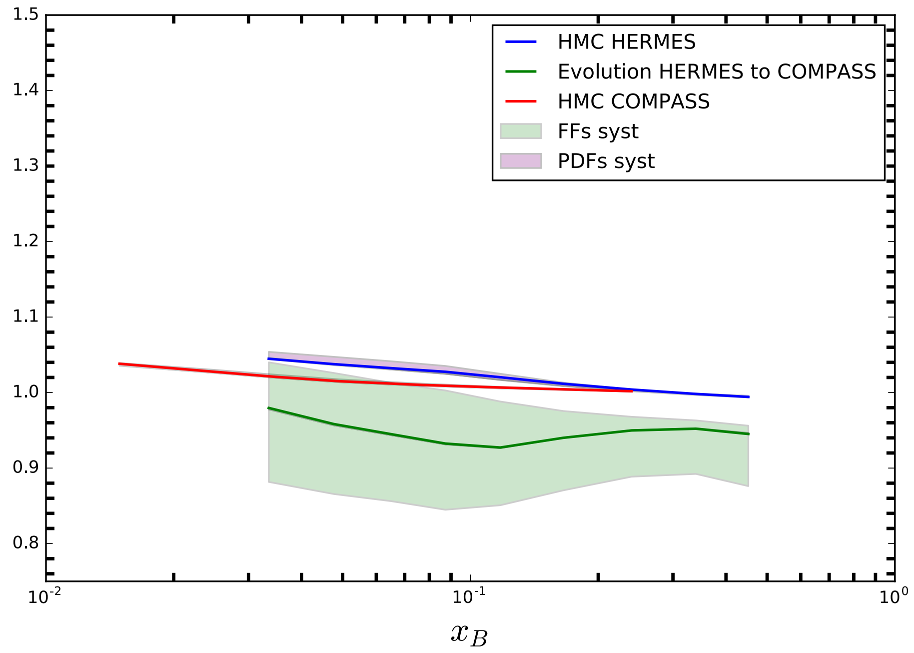
- Data (dots) vs. HMC Theory (lines)



- COMPASS: theory dependence similar to experimental values
- HERMES: less steep than theory and at large-x
- Some PDF systematics, due very likely to s PDF (slopes)

Pions at HERMES vs. COMPASS

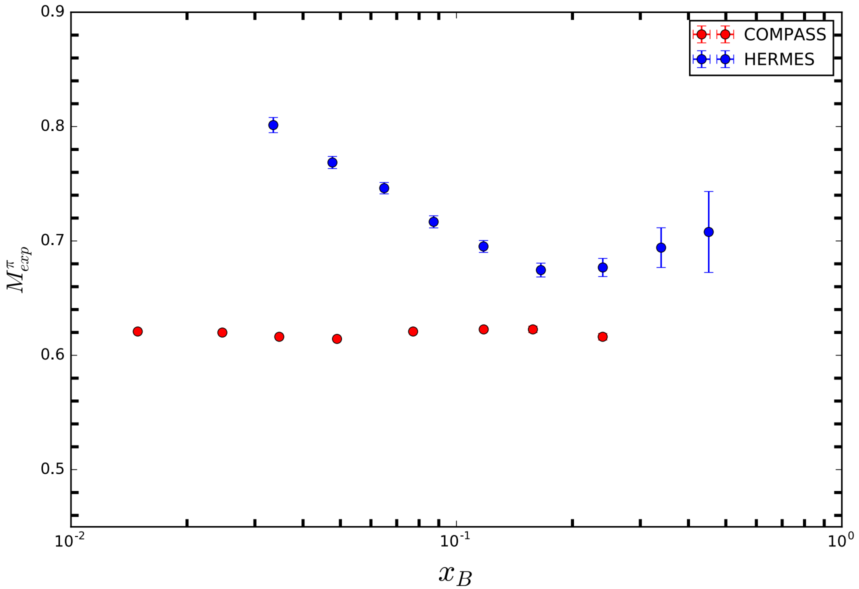
- HMC ratios: HERMES (blue line), COMPASS (red line)
- Evolution ratio (green line)
- Systematic theoretical uncertainties: (FFs, PDFs)



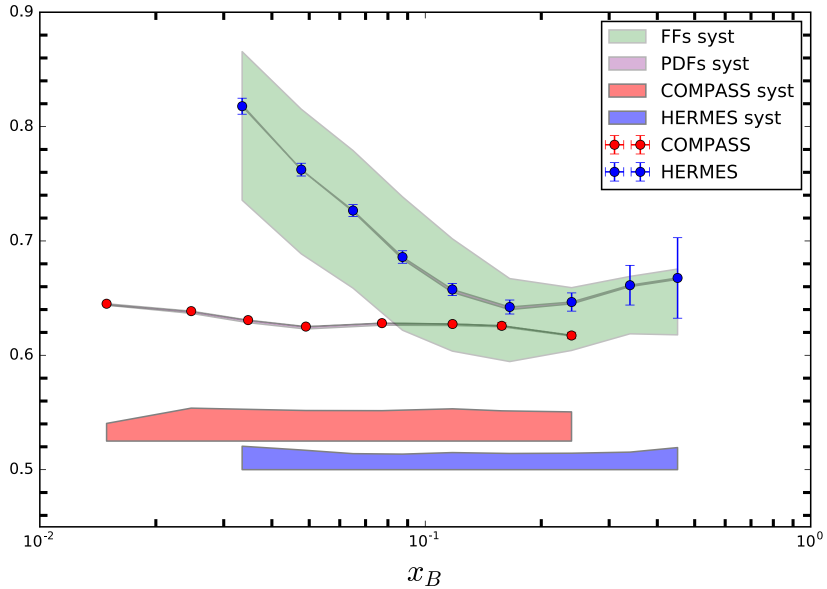
- HMCs much smaller than for Kaons.
- Comparable to evolution effects.

Pions at HERMES vs. COMPASS

Experimental Data

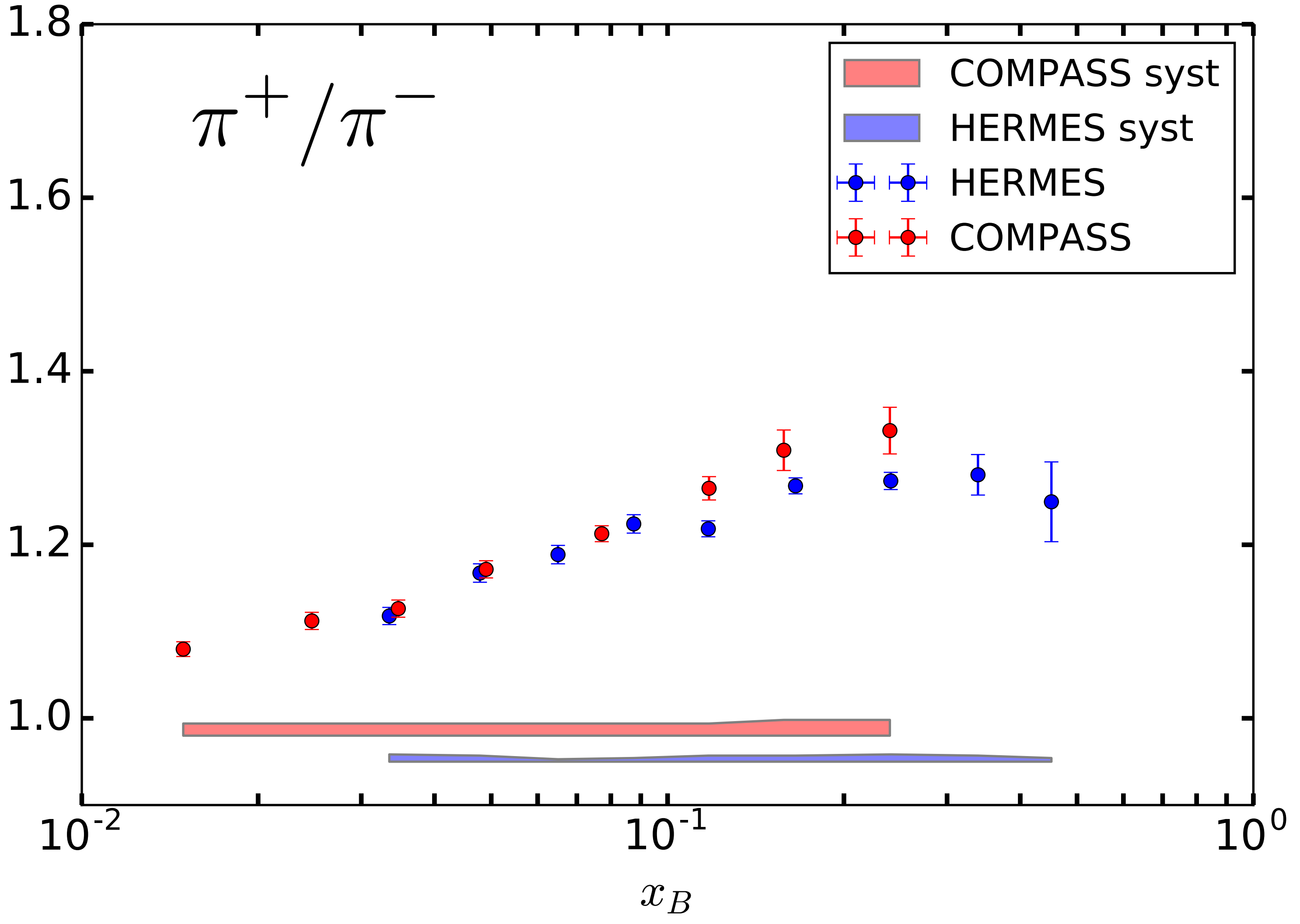


Parton level multiplicities



- Slopes still incompatible also for pions.
- “Hockey stick” shape as for Kaons, likely due to nuclear effects.

Pions ratio



1.8
1.6
1.4
1.2
1.0
π^+/π^-
COMPASS syst
HERMES syst
HERMES
COMPASS
10^{-2}
10^{-1}
10^{0}
x_B

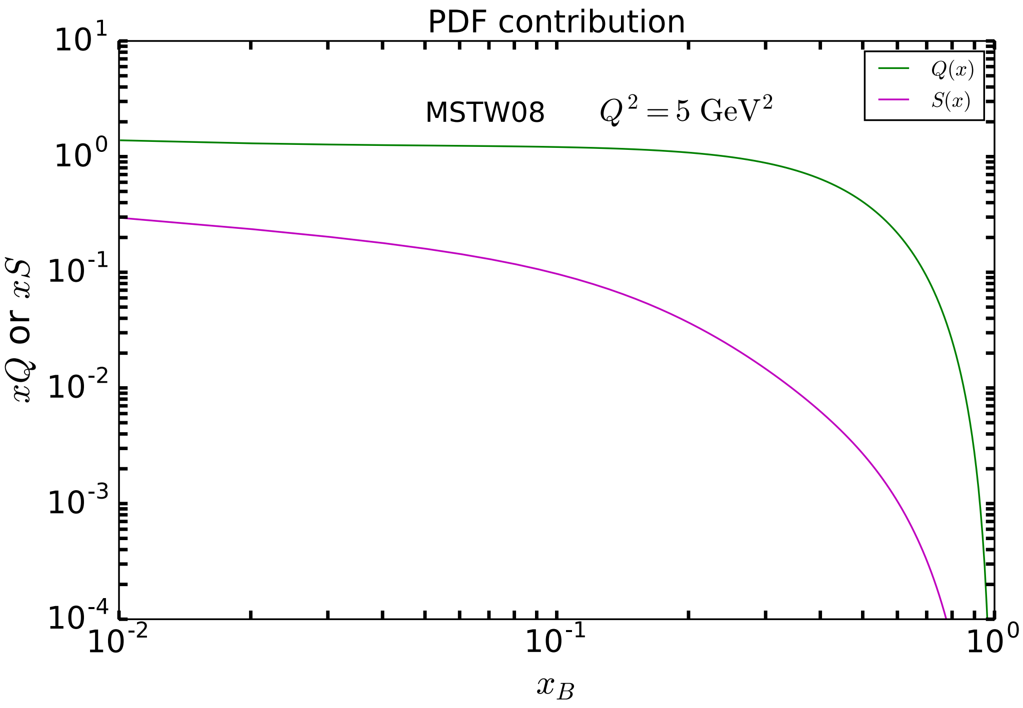
Fragmentation Functions Systematics

Large variations of the multiplicities with the choice of FFs, why?

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

$$Q(x) \equiv u(x) + \bar{u}(x) + d(x) + \bar{d}(x) \qquad S(x) \equiv s(x) + \bar{s}(x)$$

$$\mathcal{D}_Q^K(z) \equiv 4\mathcal{D}_u^K(z) + \mathcal{D}_d^K(z) \qquad \mathcal{D}_S^K(z) \equiv 2\mathcal{D}_s^K(z)$$



Fragmentation Functions Systematics

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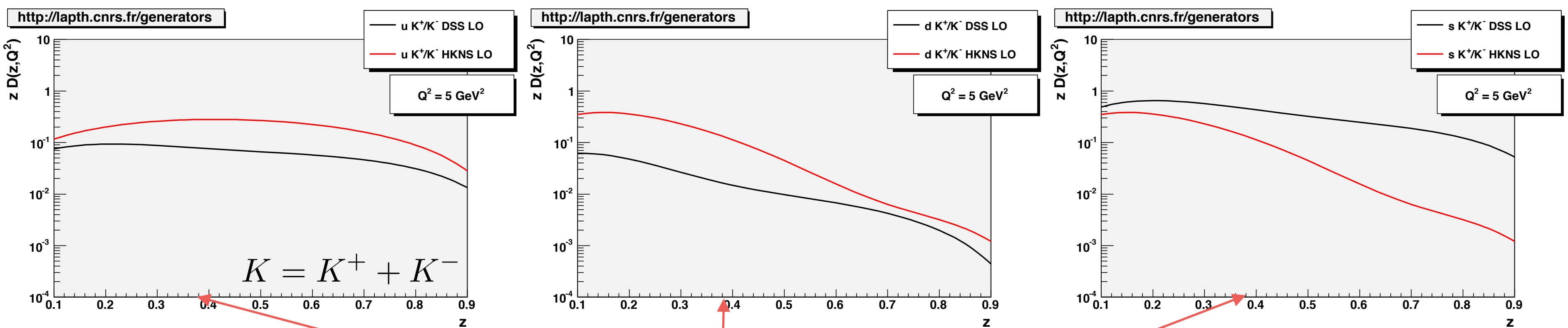
Parton model: $$M^K(x_B, Q^2) = \frac{Q(x_B, Q^2) \int \mathcal{D}_Q^K(z, Q^2) dz + S(x_B, Q^2) \int \mathcal{D}_S^K(z, Q^2) dz}{5Q(x_B, Q^2) + 2S(x_B, Q^2)}$$

$$Q(x) \equiv u(x) + \bar{u}(x) + d(x) + \bar{d}(x) \qquad S(x) \equiv s(x) + \bar{s}(x)$$

$$\mathcal{D}_Q^K(z) \equiv 4\mathcal{D}_u^K(z) + \mathcal{D}_d^K(z) \qquad \mathcal{D}_S^K(z) \equiv 2\mathcal{D}_s^K(z)$$

u, d, s FFs



$$< z_h > \sim 0.38$$

Large uncertainty with the choice of FFs because

$$D_Q^{HKNS} > D_Q^{DSS}$$

$$Q > S$$