



Semi-inclusive Kaon production at low scales

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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

Strange quark parton distribution function (PDF)

LHC

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

$$p + p \rightarrow W + c$$

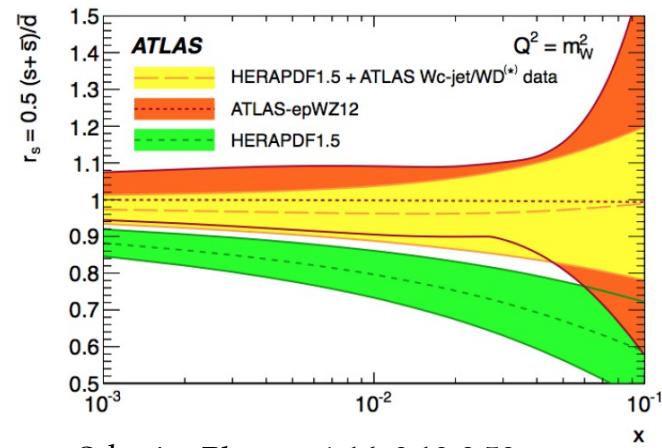
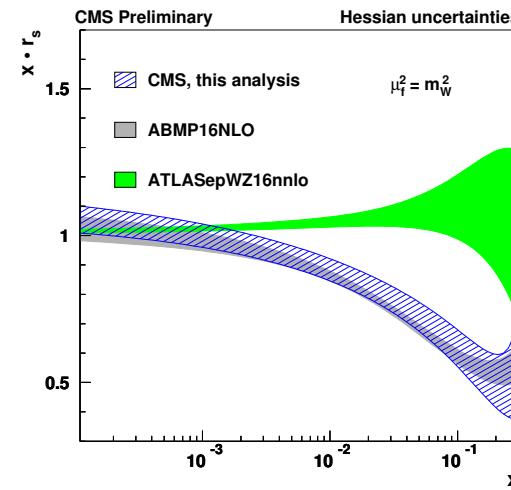
Charged current DIS

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

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



Need another measurement



Taken from *

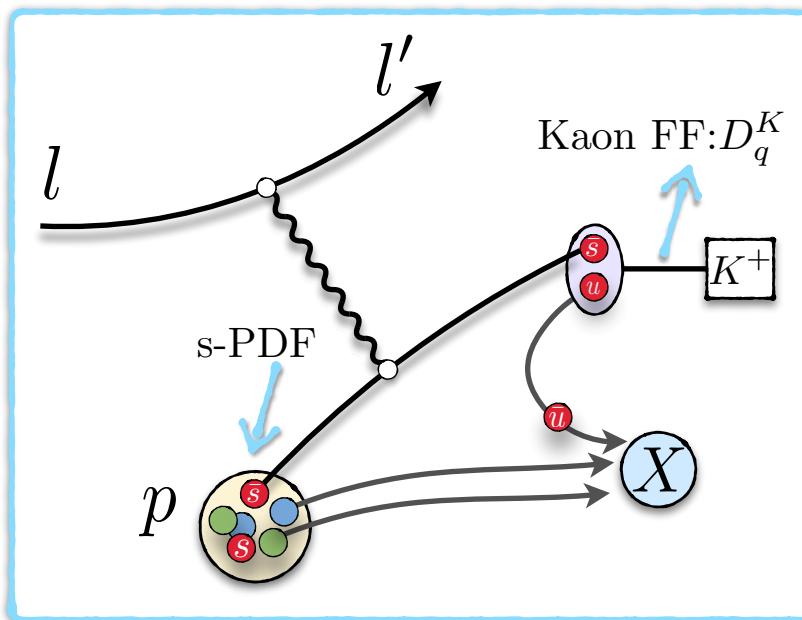
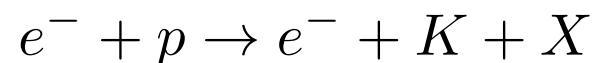
Schmitt, Plenary 4-16, 9:10-9:50
Alekhin, WG1 4-17, 14:00-14:20
Wichmann, WG1 4-17, 15:20-15:40
Pflitsch, WG1 4-17, 15:40-16:00*

s-PDF from SIDIS

How can we access the s-quark PDF?

one way

Measuring a Kaon in Semi inclusive Deep inelastic scattering (SIDIS)



- Kaon contains an s-quark in their valence structure.
- Detect a Kaon: good proxy for a strange quark
- BUT: $m_K \simeq 0.5$ GeV
Not necessarily negligible at HERMES and COMPASS experiments

How to tag s-quarks?

- Use “integrated Kaon Multiplicities”

Experimentally
HERMES, COMPASS:

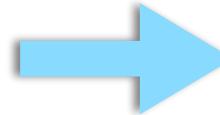
$$M_{exp}^K = \frac{\int_{exp} dQ^2 \int_{0.2}^{0.8} dz_h \frac{dN^K}{dx_B dQ^2 dz_h}}{\int_{exp} dQ^2 \frac{dN^e}{dx_B dQ^2}}$$

Theoretically
LO, neglect masses:

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

+ light quarks

Compare data and theory



Extract the s-quark PDF.

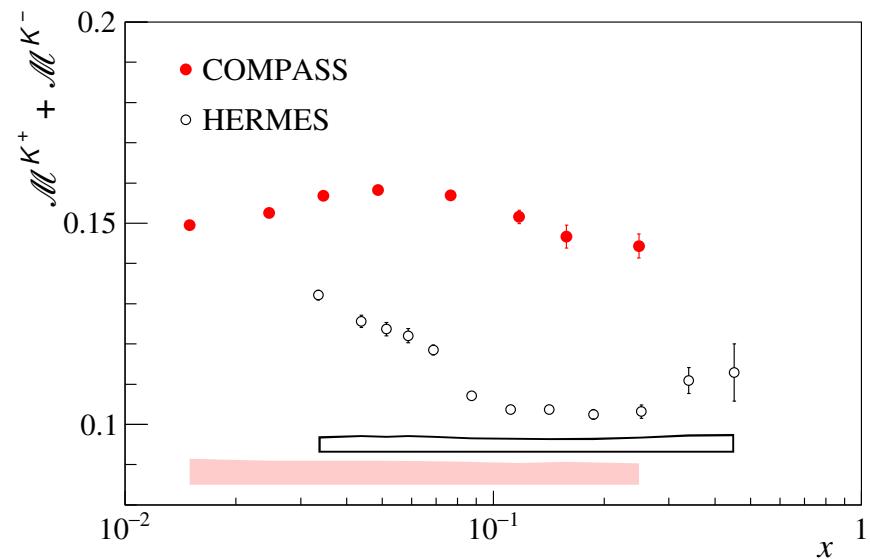
Integrated Kaon Multiplicities: SIDIS on Deuteron

- **HERMES:**

- Claim very different s-quark shape compared to CTEQ6L.
- Strange PDF may not be what we think!

- **But COMPASS:**

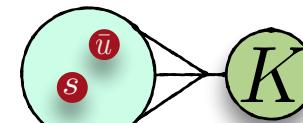
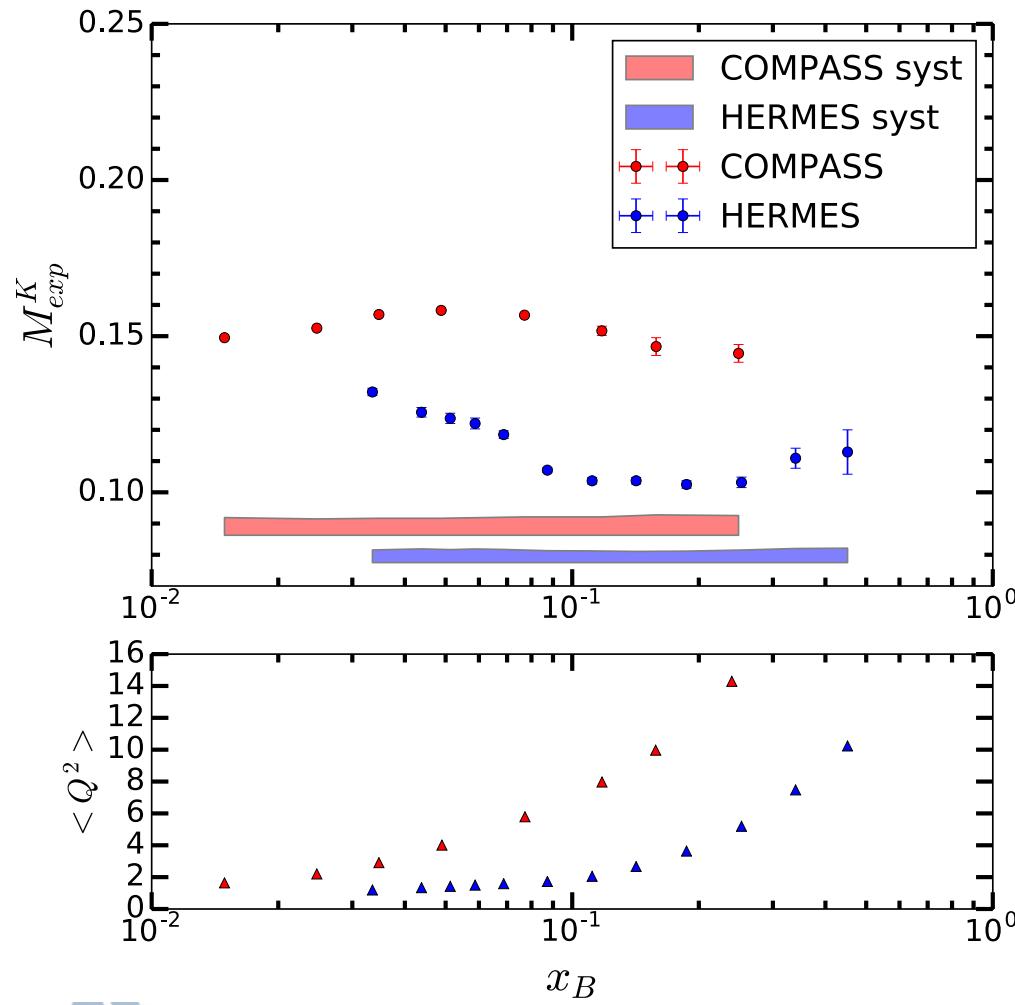
- Different x_B dependence
- COMPASS overall value higher.



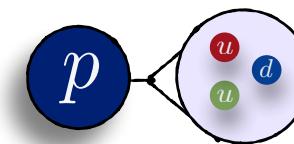
Where does this discrepancy come from?
Is it real or apparent?

Hadron Mass Effects

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



$$m_K \simeq 0.5 \text{ GeV}$$



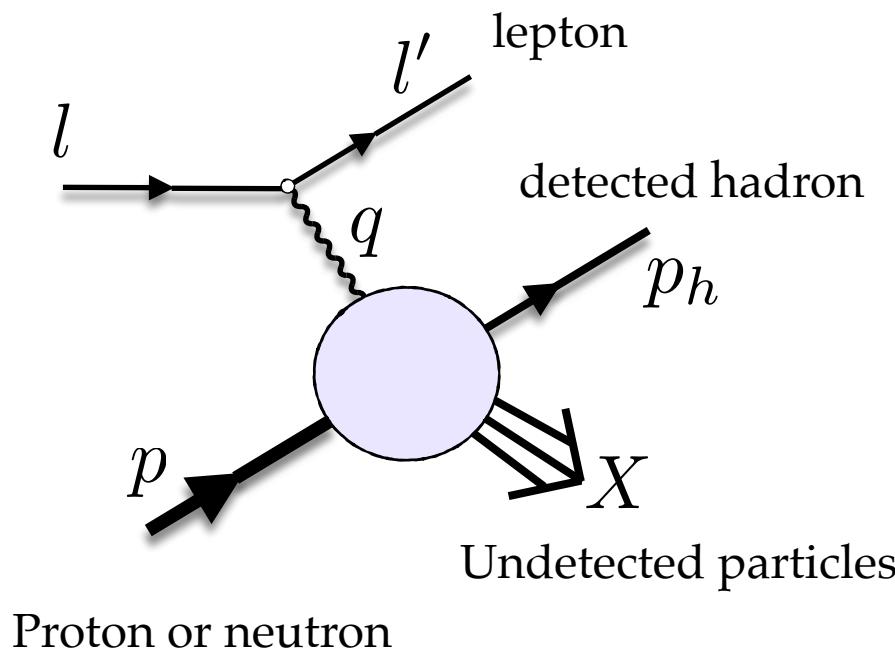
$$m_p \simeq 1 \text{ GeV}$$

$$\overline{Q^2}_C \gtrsim \overline{Q^2}_H \simeq 1 - 10 \text{ GeV}^2$$

**Maybe masses are not
so negligible!**

SIDIS Kinematics Variables

DIS invariants



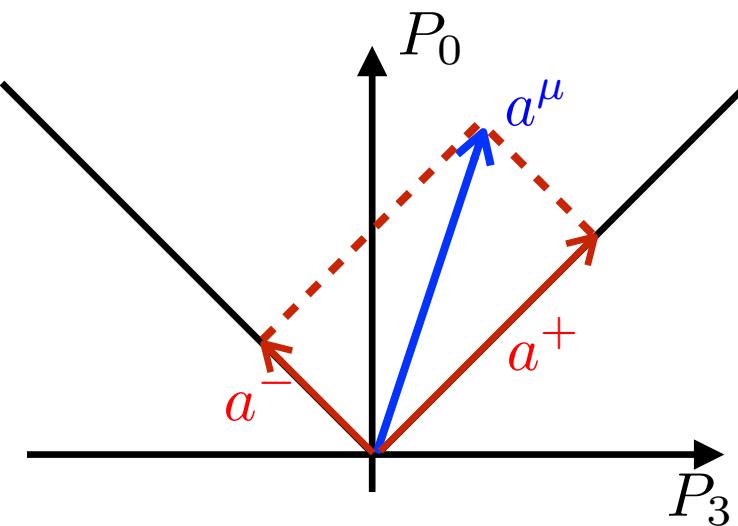
$$M^2 = p^2 \quad Q^2 = -q^2$$
$$y = \frac{p \cdot q}{p \cdot l} \quad x_B = \frac{Q^2}{2p \cdot q}$$

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: $\xi \rightarrow x_B$
 $Q^2 \rightarrow \infty$

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: $\zeta_h \rightarrow z_h$
 $Q^2 \rightarrow \infty$

Collinear momenta

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

$$\left. \begin{array}{l} \tilde{k}^2 = v^2 \\ \tilde{k}' = v'^2 \end{array} \right\} \text{Physically: "Average virtualities"}$$

Approx.:
Parton collinear to proton...

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

... and on-shell

$$v^2 = 0$$

Fragmenting parton collinear to hadron

$$\tilde{k}' = \left(\frac{v'^2 + (\mathbf{p}_{h\perp}/z)^2}{2p_h^-/z}, \frac{p_h^-}{z}, \frac{\mathbf{p}_{h\perp}}{z} \right)$$

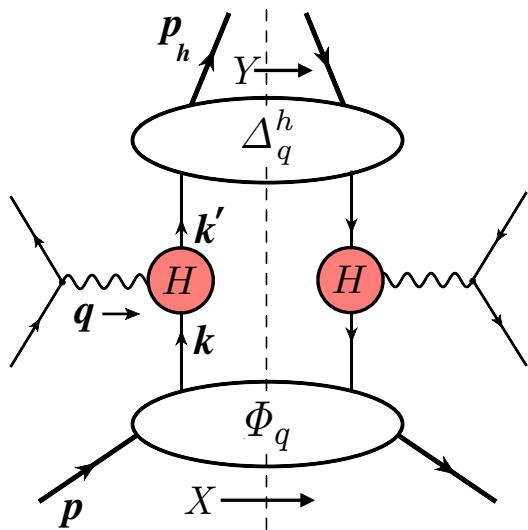
Fragmentation into a **massive** hadron

$$v'^2 = ?$$

matching partonic & hadronic kinematics

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

Hadronic Tensor



Expand:

$$\Phi_q = k^+ [\phi_2(k) \not{p} + \mathcal{O}(1/k^+)]$$

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

contribute to Higher-Twist (HT) terms

$$\begin{aligned} 2MW^{\mu\nu} &= \int d^4k \, d^4k' \, \text{Tr} [\Phi_q(p, k) \gamma^\mu \Delta_q^h(k', p_h) \gamma^\nu] \, \delta^{(4)}(k + q - k') \\ &= \int d^4k \, d^4k' \, \phi_2(k) \delta_2(k') \text{Tr} [k^+ \not{p} \gamma^\mu k'^- \not{p} \gamma^\nu] \, \delta^{(4)}(k + q - k') + \text{HT} \end{aligned}$$

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

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

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

With Hadron Masses:

Scale dependent Jacobian

Finite Q^2 scaling variables

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

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

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

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

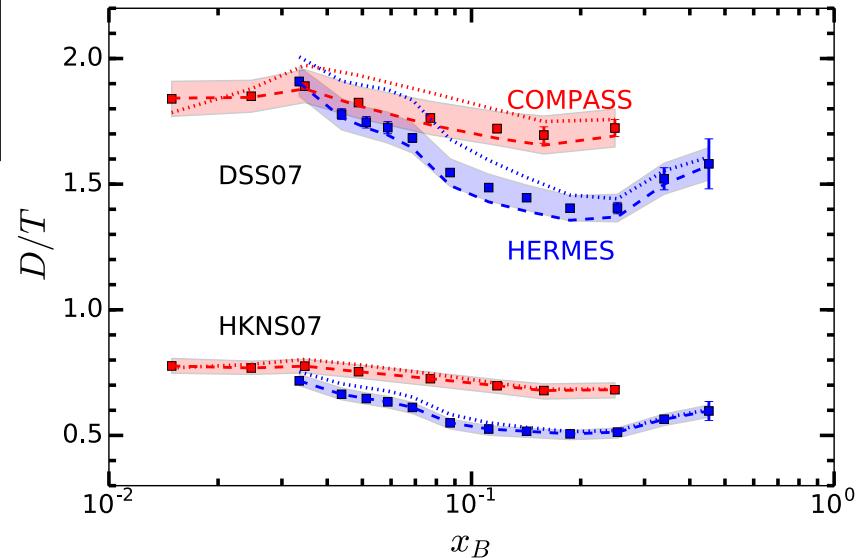
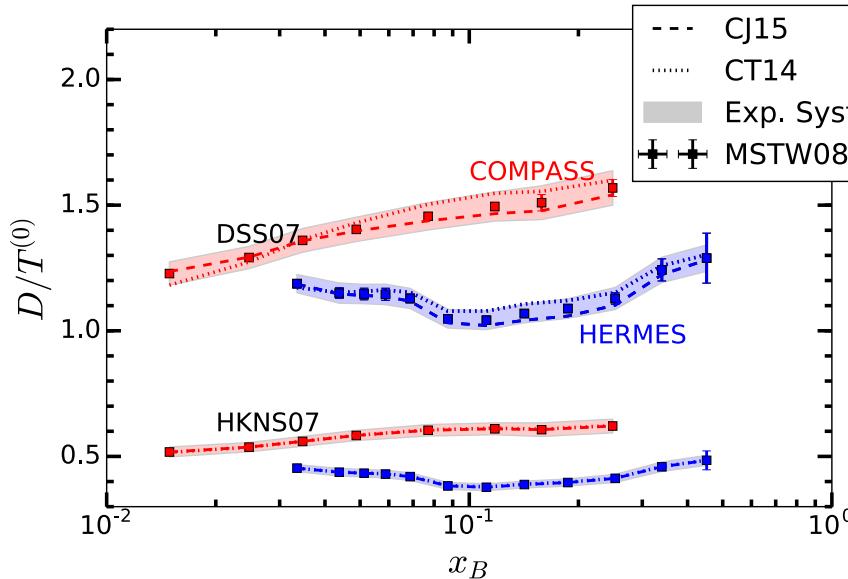
$$M^{h(0)}(x_B) = \frac{\int_{\text{exp.}} dQ^2 \sum_q e_q^2 q(x_B, Q^2) \int_{0.2}^{0.8} dz_h D_q^h(z_h, Q^2)}{\int_{\text{exp.}} dQ^2 \sum_q e_q^2 q(x_B, Q^2)}$$

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

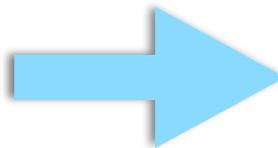


COMPASS
vs.
HERMES

- 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

- HMC ratio

$$R_{HMC}^h = \frac{M^{h(0)}}{M^h}$$

Massless multiplicities:

- COMPASS:

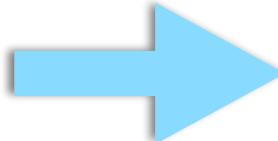
$$M_{exp}^{h(0)} \equiv M_{exp}^h \times R_{HMC}^h$$

- HERMES:

$$M_{exp}^{h(0)} \equiv M_{exp}^h \times R_{HMC}^h$$

HERMES & COMPASS data: direct comparison

“Theoretical correction ratios”



Produce approximate “massless” parton model multiplicities

Make data directly comparable

- HMC ratio

$$R_{HMC}^h = \frac{M^{h(0)}}{M^h}$$

- Evolution ratio (HERMES to COMPASS)

$$R_{evo}^{H \rightarrow C} = \frac{M^{h(0)}(x_B) \Big|_{\text{COMPASS P.S.}}}{M^{h(0)}(x_B) \Big|_{\text{HERMES P.S.}}}$$

Massless (evolved) multiplicities:

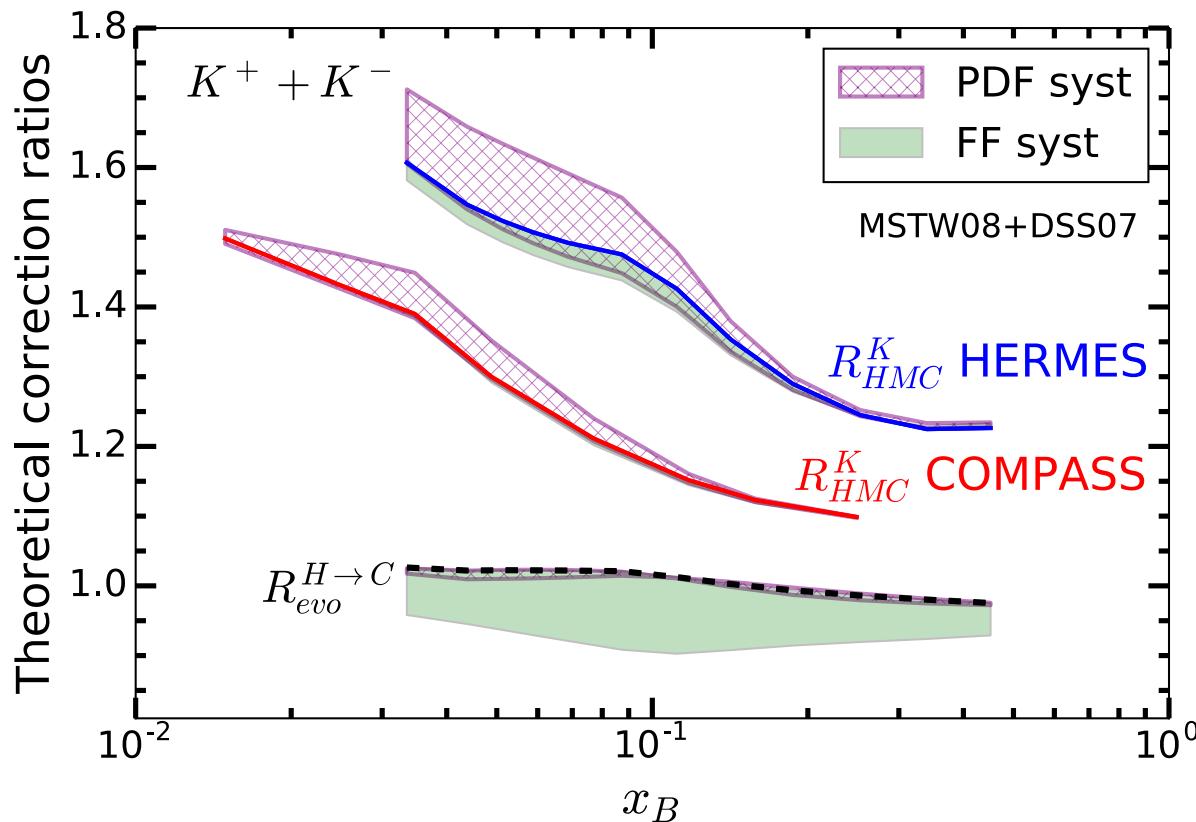
- COMPASS:

$$M_{exp}^{h(0)} \equiv M_{exp}^h \times R_{HMC}^h$$

- HERMES:

$$M_{exp}^{h(0)} \equiv M_{exp}^h \times R_{HMC}^h \times R_{evo}^{H \rightarrow C}$$

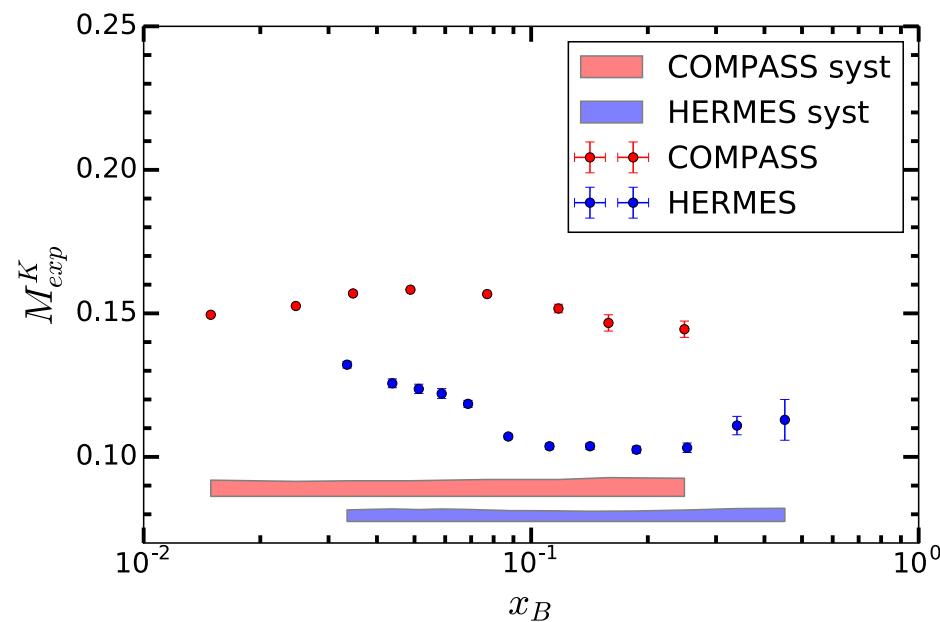
Correction ratios



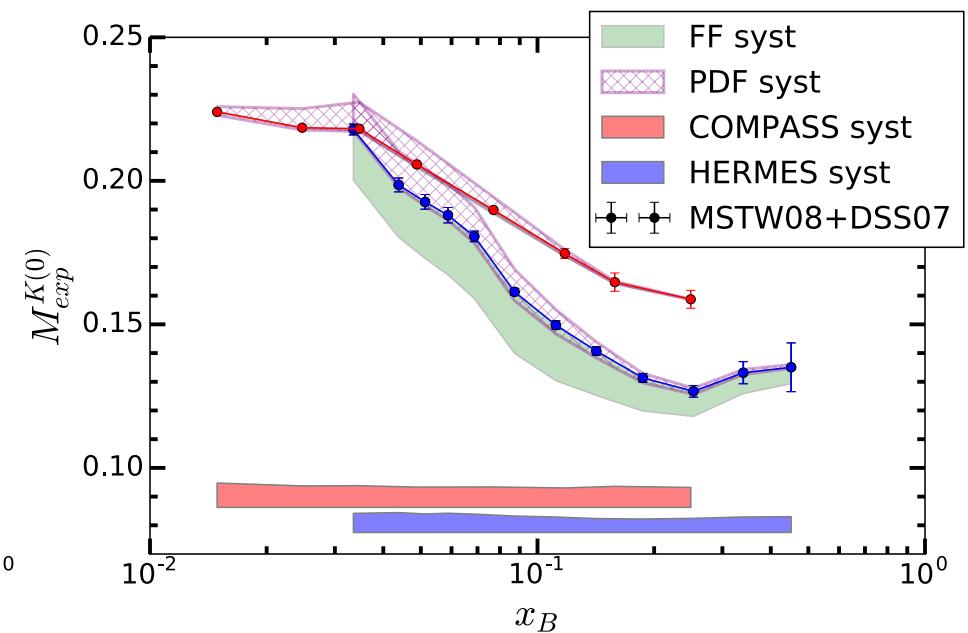
- Hadron mass effects dominant over evolution effects
- At COMPASS smaller HMCs than at HERMES.

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

Experimental Data



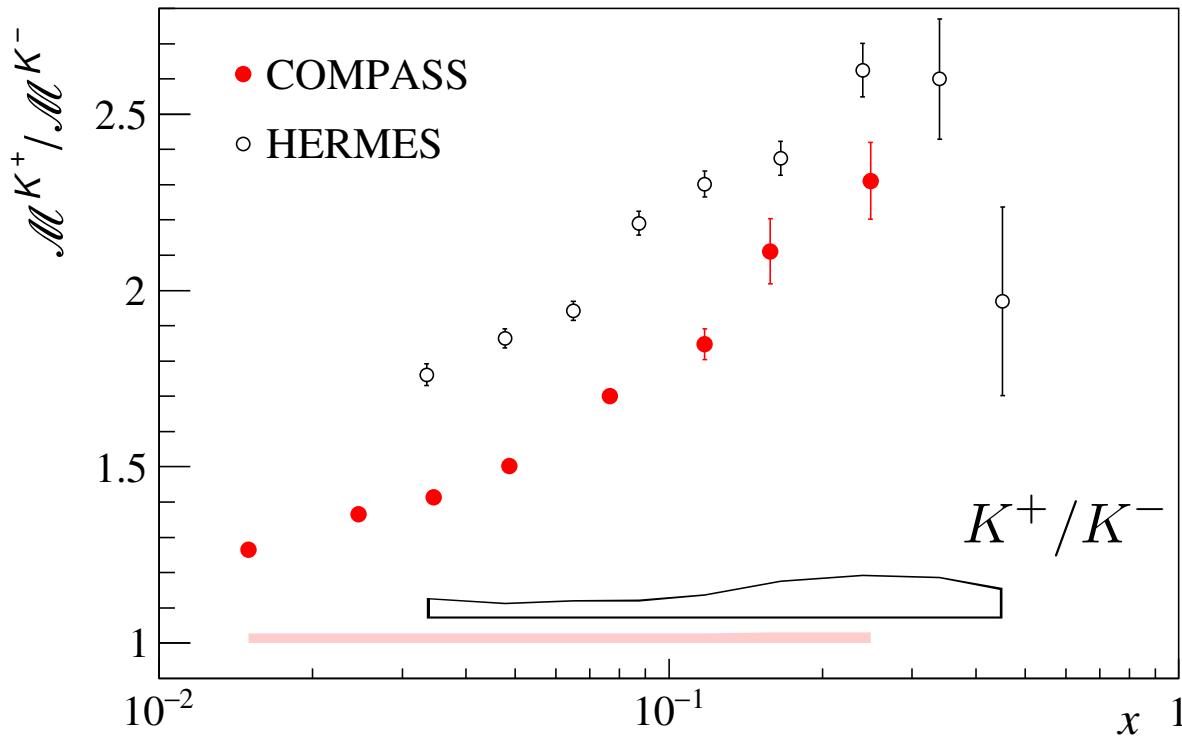
“Massless data” at same Q^2



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

Kaon ratios

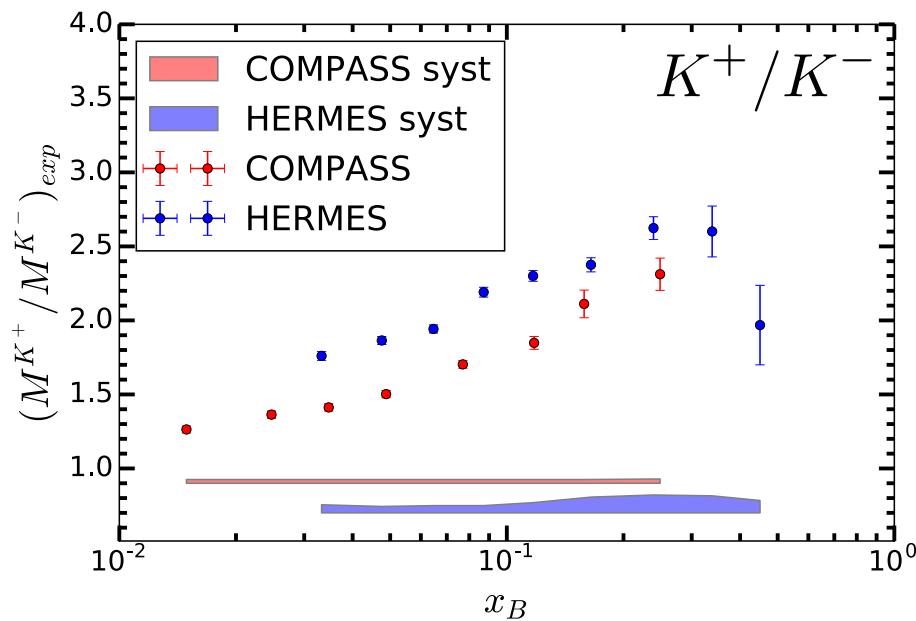
- Ratio reduces experimental systematics.



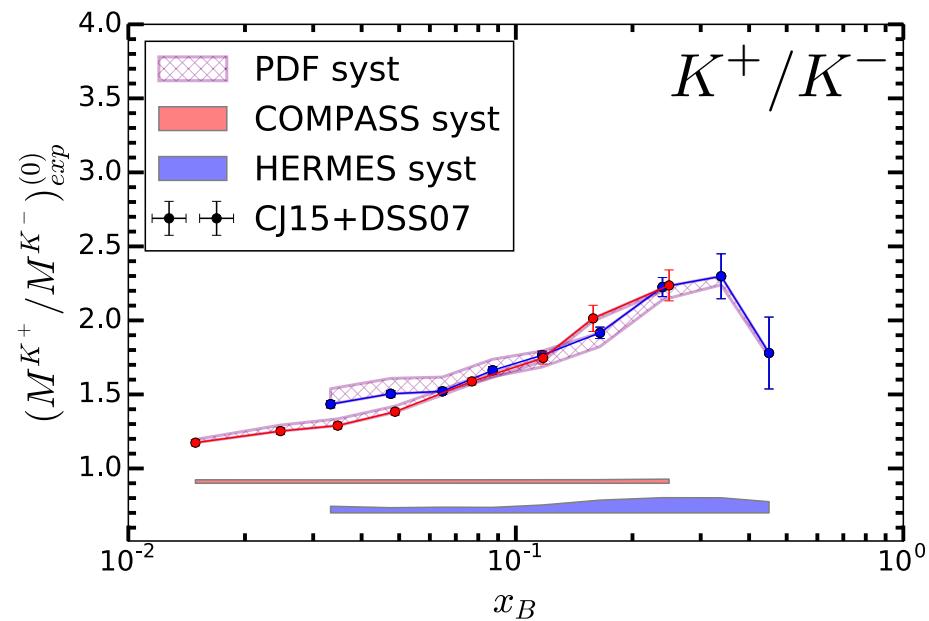
- ⌚ Size discrepancy persists
- ⌚ Slopes are now compatible
 - ▷ Except last HERMES point?

Direct Data Comparison: K^+ / K^-

Experimental Data



“Massless data” at same Q^2



• HERMES & COMPASS fully compatible.
► last x bin at HERMES suspicious.

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 in $K^+ + K^-$?
- Need to use theory with HMCs in FF fits with HERMES and COMPASS data

Future developments:

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



Thank you!

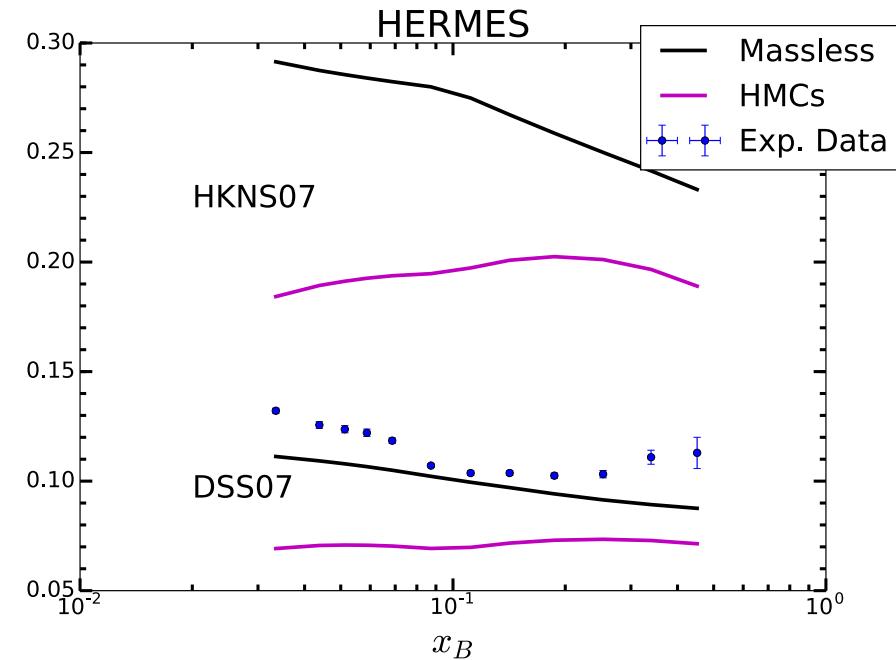
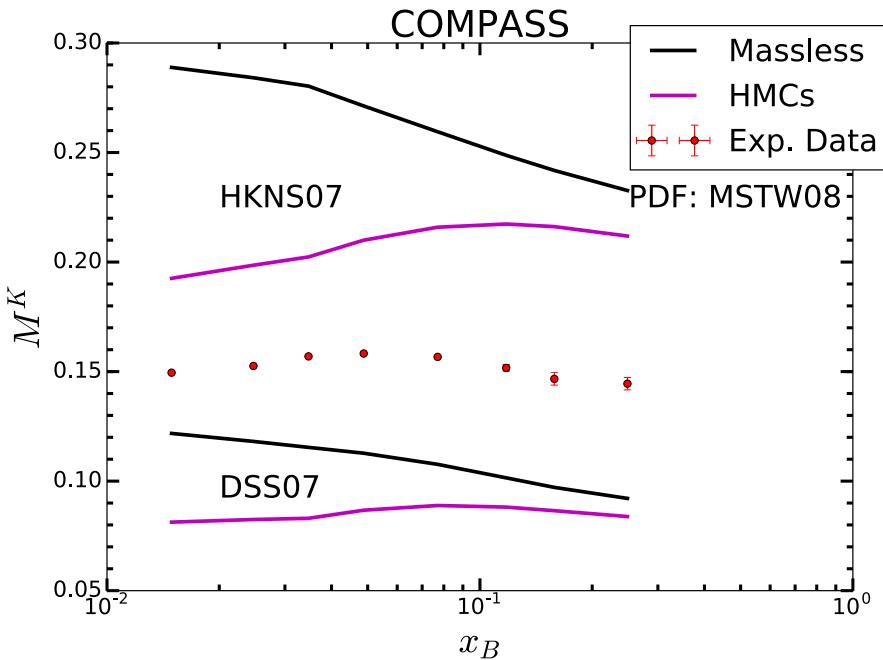


Backup slides



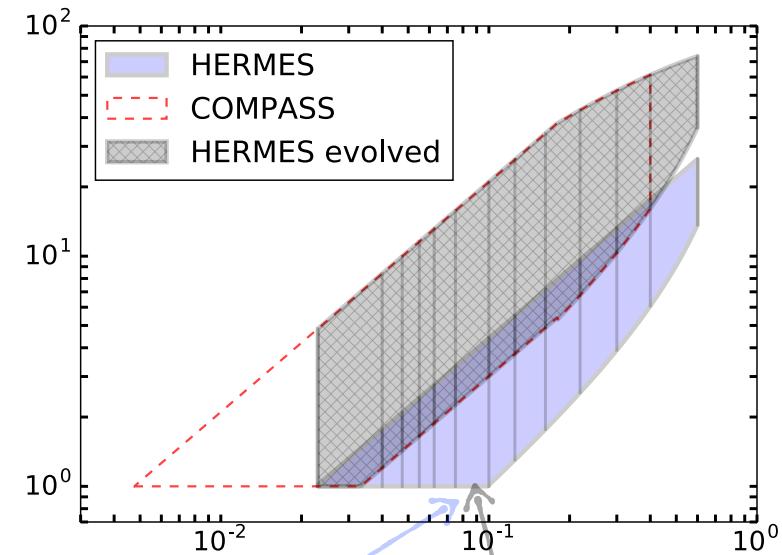
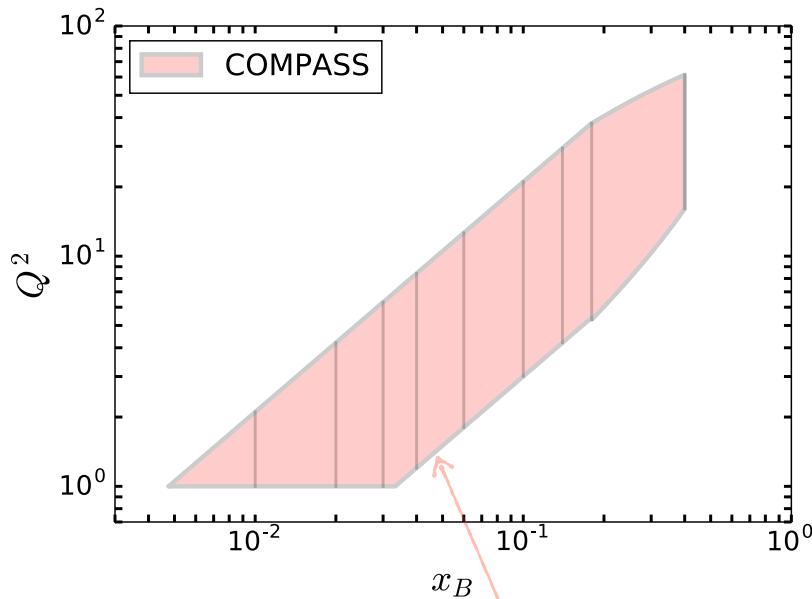
$K^+ + K^-$ Multiplicities

- Data (dots) vs. Theory (lines)



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

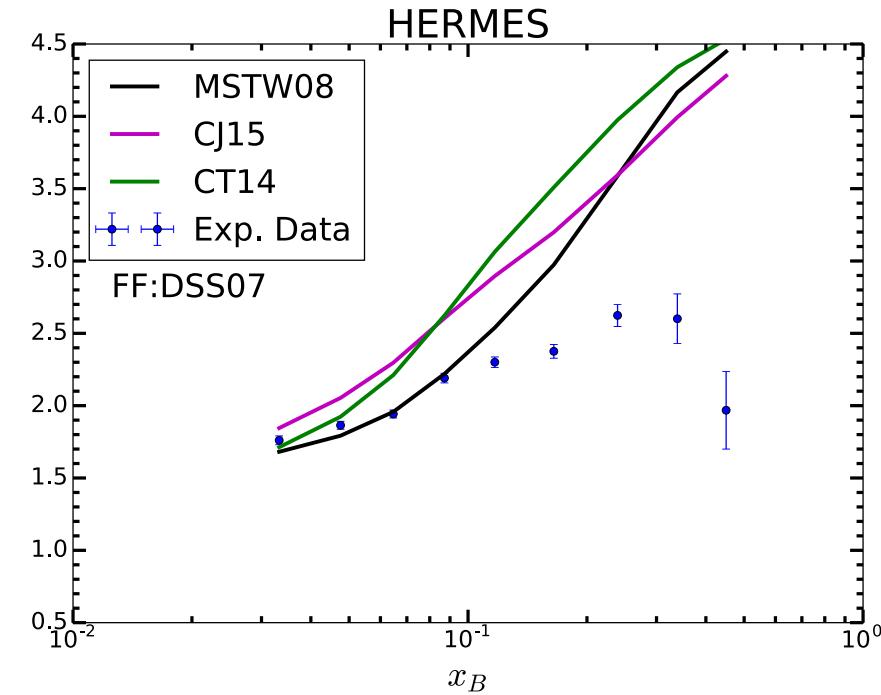
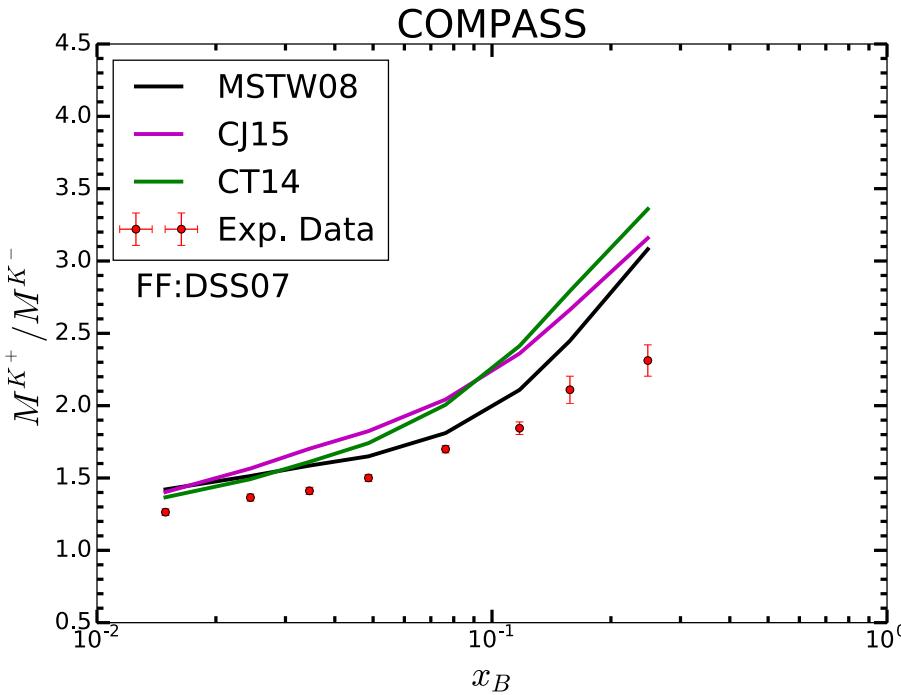
HERMES & COMPASS data: direct comparison



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

Kaon ratios

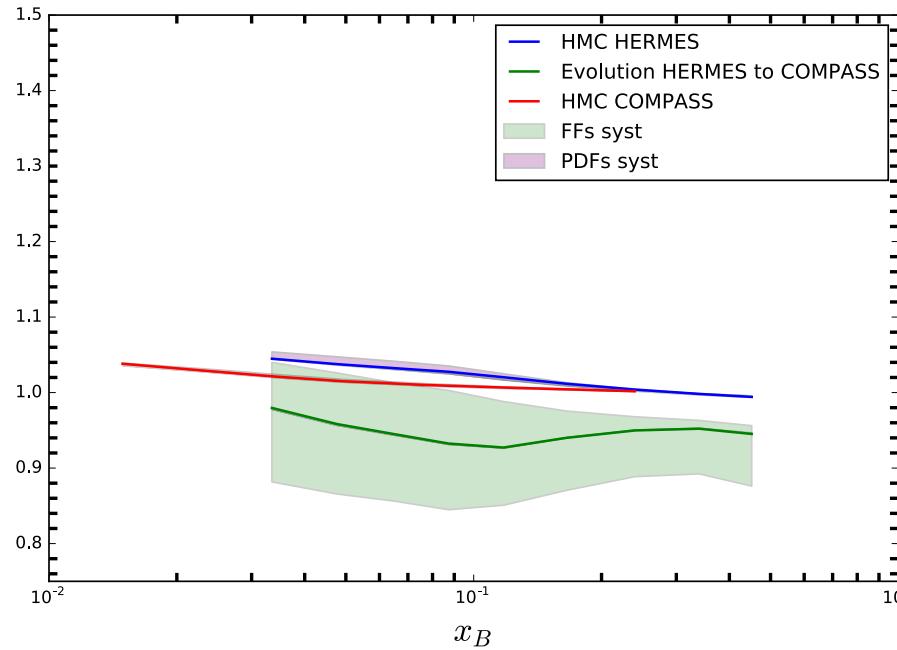
- Data (dots) vs. HMC Theory (lines)



- 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

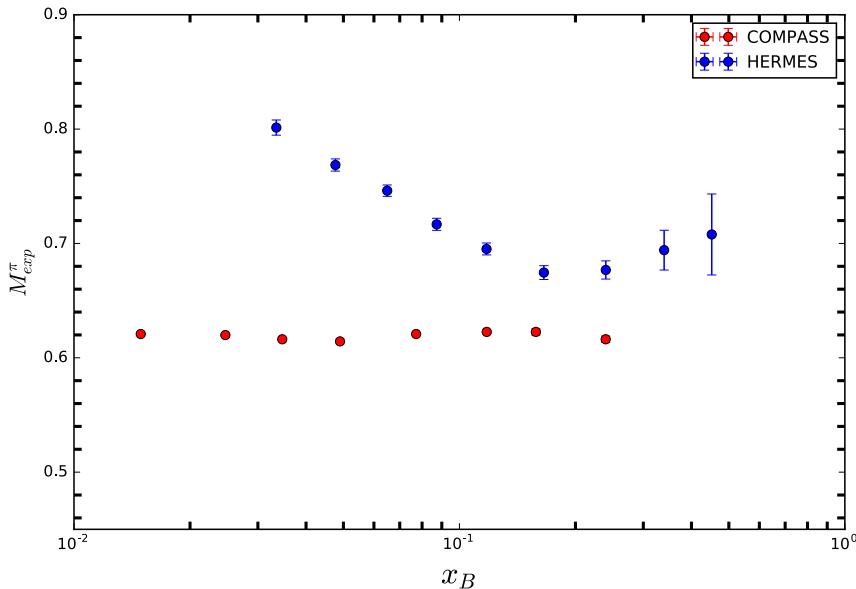
- HMC ratios: HERMES (blue line), COMPASS (red line)
- Evolution ratio (green line)
- Systematic theoretical uncertainties: (FFs, PDFs)



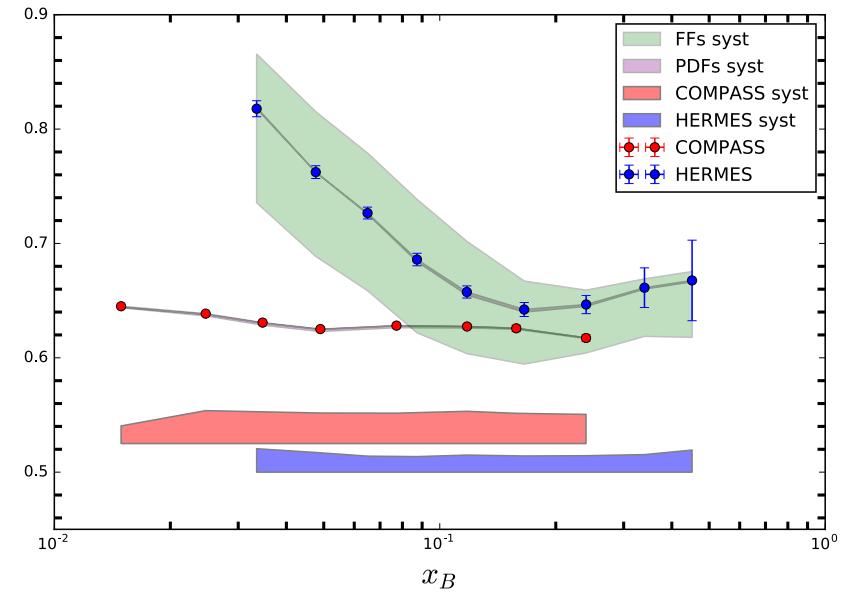
- HMCs much smaller than for Kaons.
- Comparable to evolution effects.

Pions at HERMES vs. COMPASS

Experimental Data

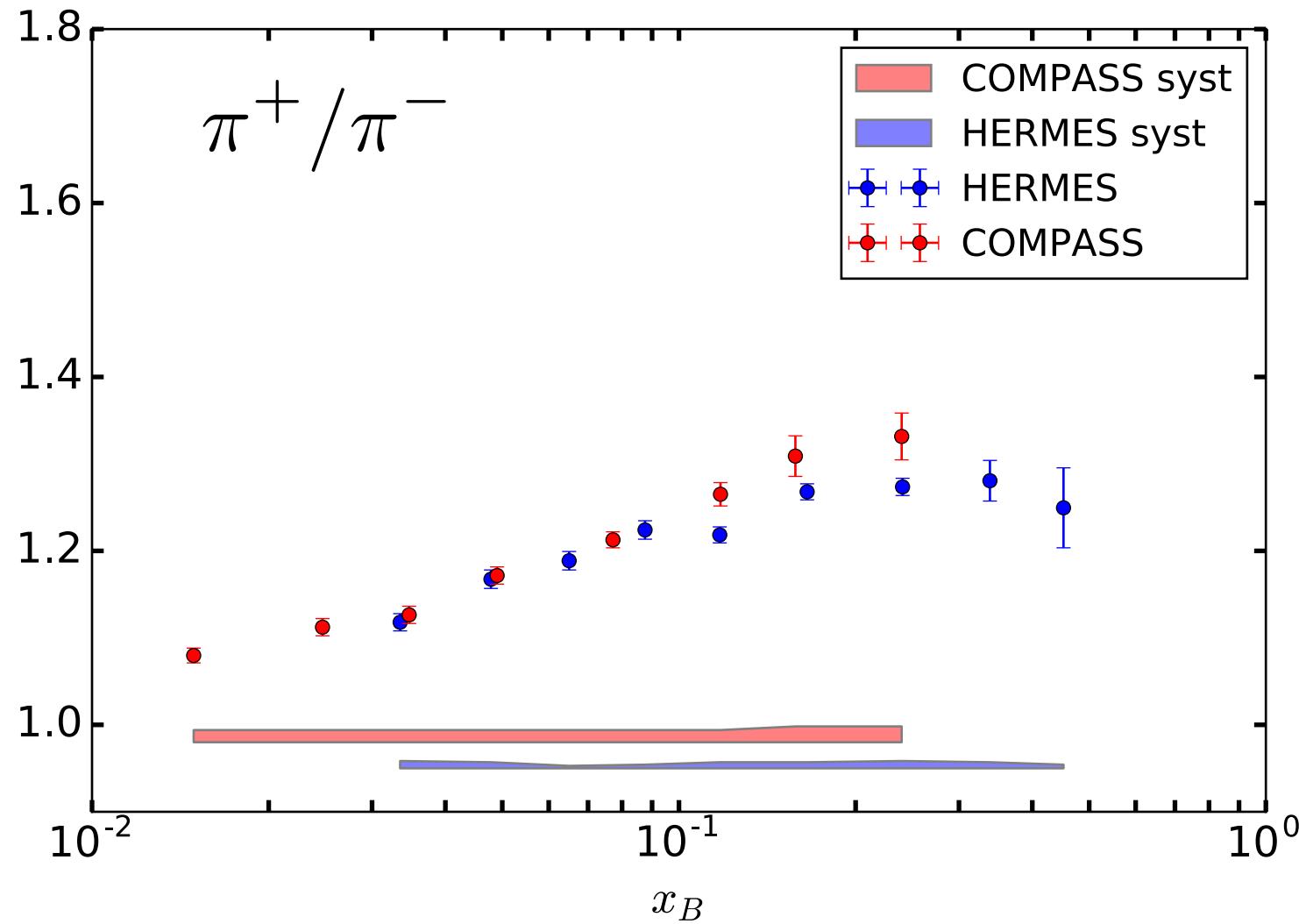


Parton level multiplicities



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

Pions ratio



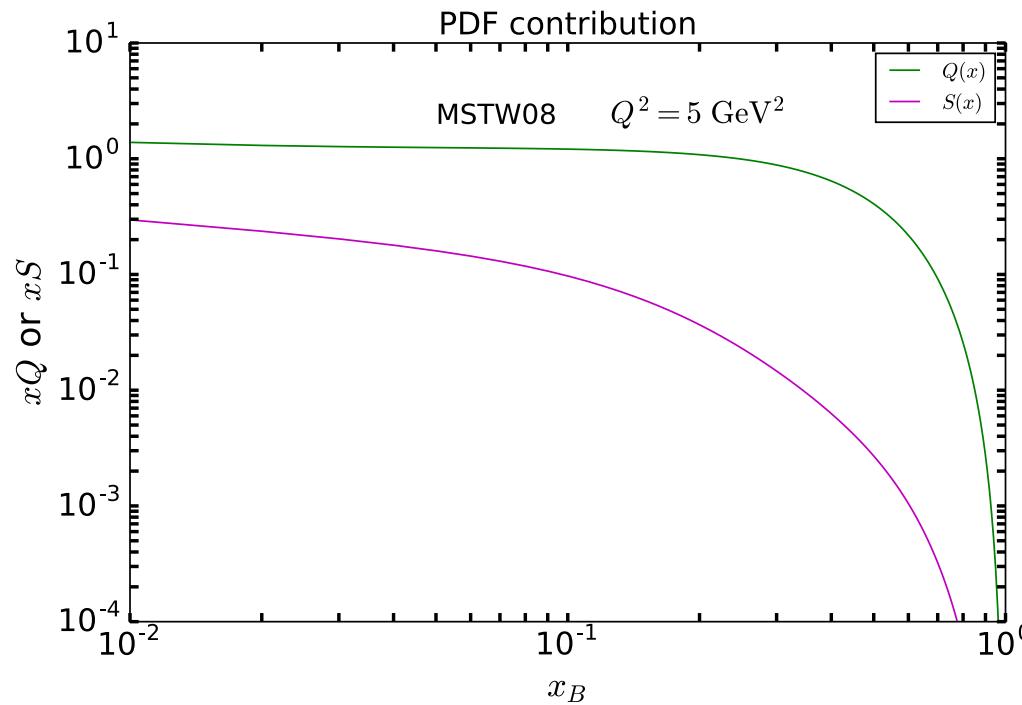
Fragmentation Functions Systematics

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

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

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

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



Fragmentation Functions Systematics

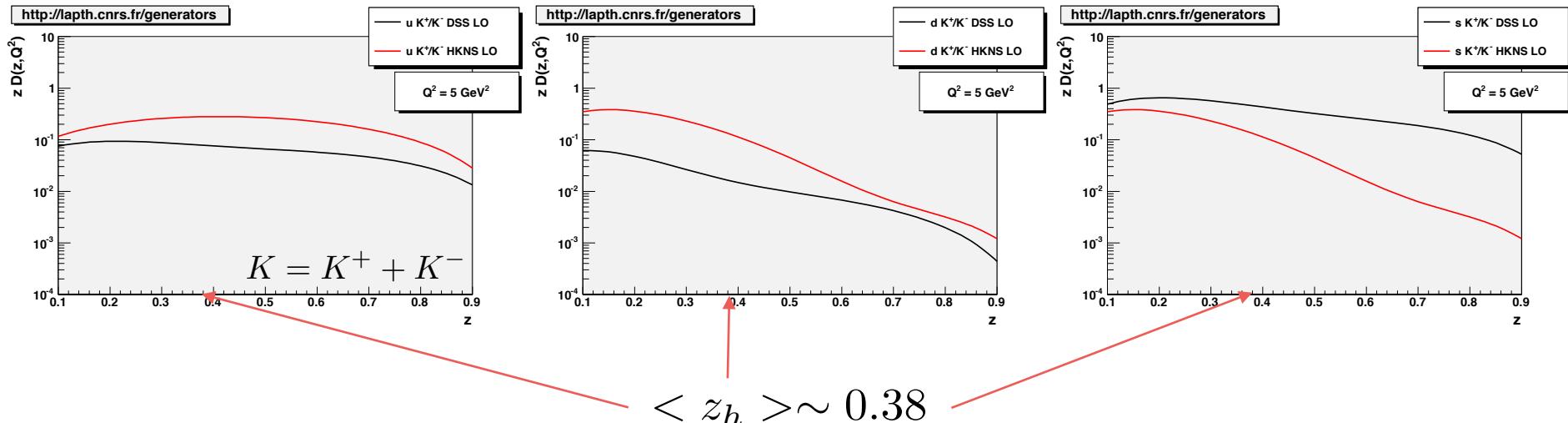
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u, d, s FFs



Large uncertainty with the choice of FFs because

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

$$Q > S$$