Hadron Mass Effects on Kaon Multiplicities: HERMES vs. COMPASS

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QCD evolution 2017
May 26, 2017

Based on:
J. G., J. Ethier, A. Accardi, S. Casper ,W. Melnitchouk, JHEP 1509 (2015) 169
J.G & Alberto Accardi, work in progress…

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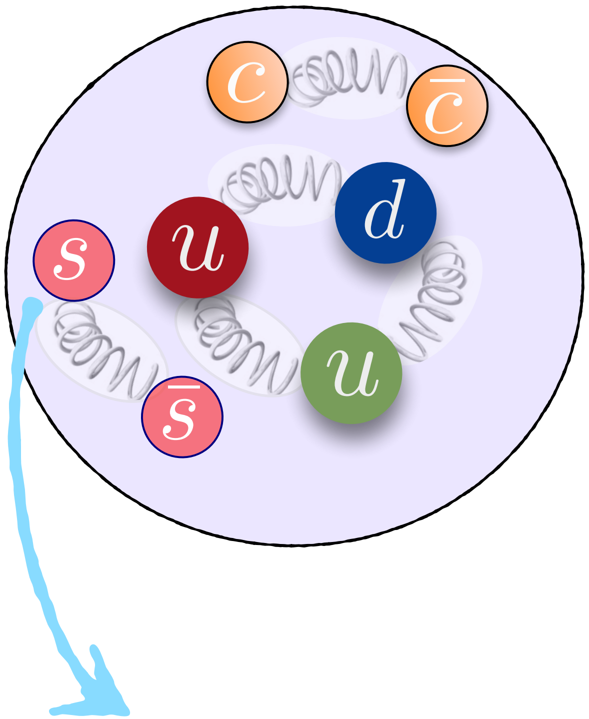
Jefferson Lab
Thomas Jefferson National Accelerator Facility

What can we see inside a proton?



Interested in the s-quark.

Partons:

- 3 “valence quarks” p = (u u d)
- Gluons
- sea quarks: **strange**, charm, bottom.

Parton (momentum) Distributions Function (PDFs):

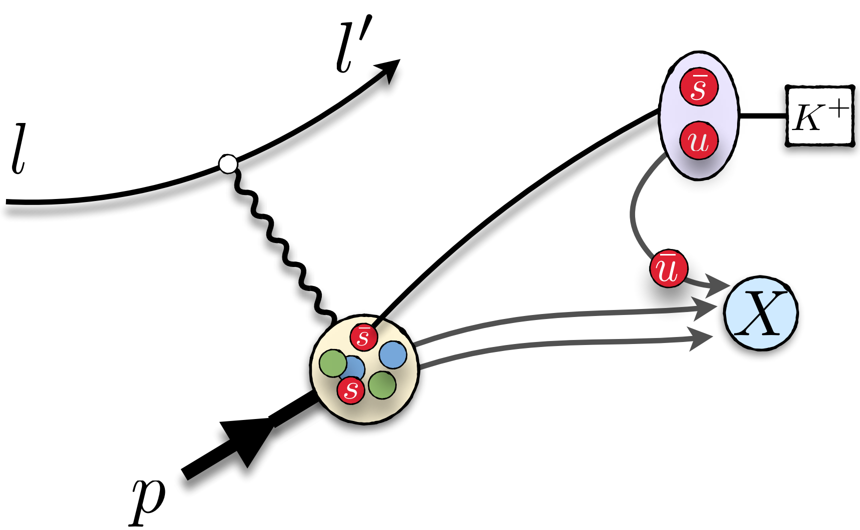
- Well determined for the “valence quarks”and gluons.
- Not the case for the sea quarks.

Strange quark PDF

How can we access the s-quark PDF? —one way→ "Tagging" Kaon in Hard Scattering reactions

For example:

- Semi inclusive Deep inelastic scattering (SIDIS): $e^- + p \to e^- + h + X$, $h = K$



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

Integrated Kaon Multiplicities

Experimentally
HERMES (COMPASS):

$$M^K_{exp} = \frac{\int_{exp} dQ^2 \int_{0.2}^{0.8(0.85)} \frac{dN^K}{dx_B\, dQ^2\, dz_h} dz_h}{\int_{exp} dQ^2 \frac{dN^e}{dx_B\, dQ^2}}$$

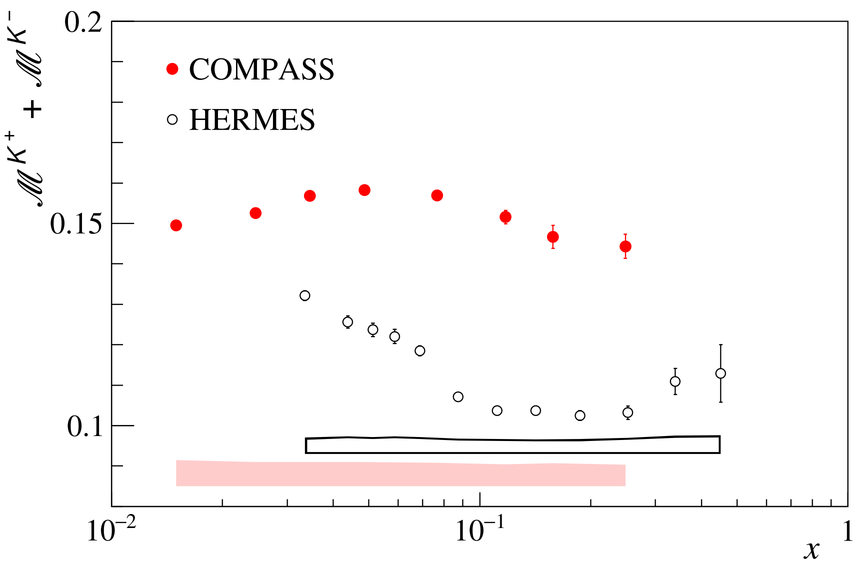
Parton model Multiplicities (fixed Q²) :

$$M^K(x_B, Q^2) = \frac{\sum_q e_q^2\, q(x_B) \int_{0.2}^{0.8(0.85)} D_q^h(z_h) dz_h}{\sum_q e_q^2\, q(x_B)} \supset s(x_B) \int D_s^K(z_h) dz_h$$

Comparing these two expressions → Extract the s-quark PDF.

Integrated Kaon Multiplicities: SIDIS on Deuteron

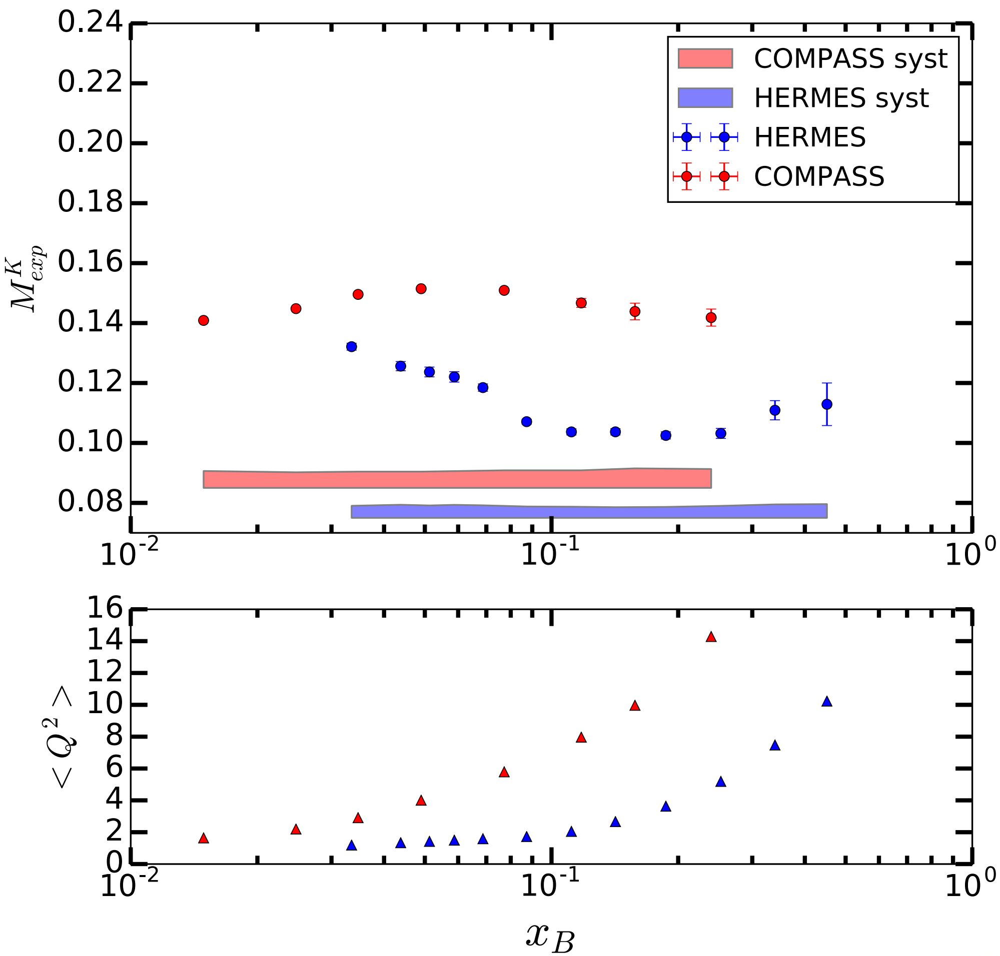
- **HERMES:**
  - Claim very different s-quark shape compared to CTEQ6L.
  - Measurements from ATLAS/CMS at LHC also show different s-PDF.
  - Strange PDF may not be what we think!
- **But COMPASS:**
  - Different x_B dependence
  - COMPASS overall value higher.

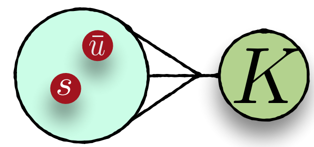


Where does this discrepancy come from?

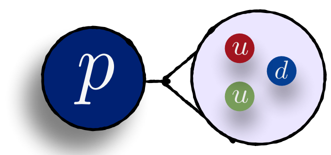
Hadron Mass Effects

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





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



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

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

Maybe the masses are not so negligible

Hadron Mass Effects

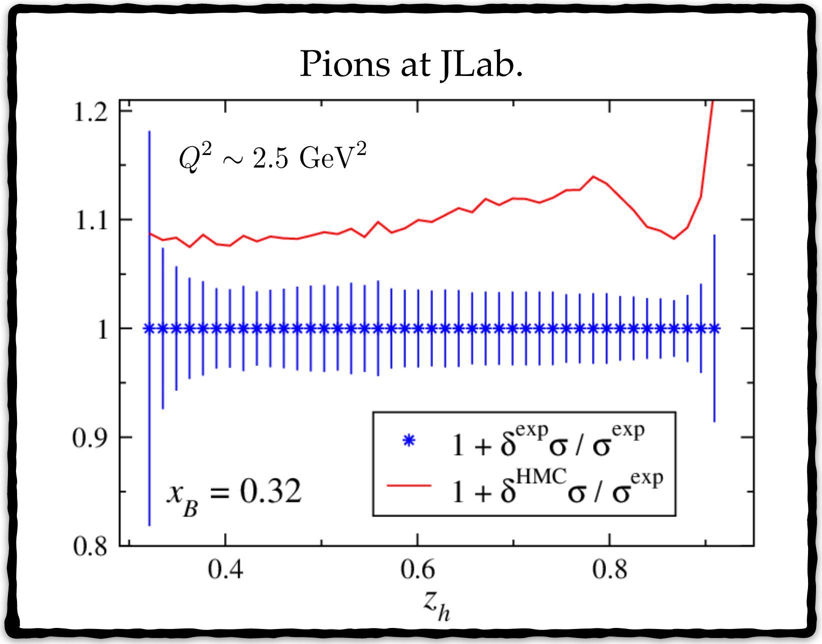
Let's consider an example for Pion Mass effects at JLab.

Jefferson Lab experiments:

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

O(m²/Q²) = Hadron Mass Corrections (HMCs)

$$m = M_P, m_\pi$$

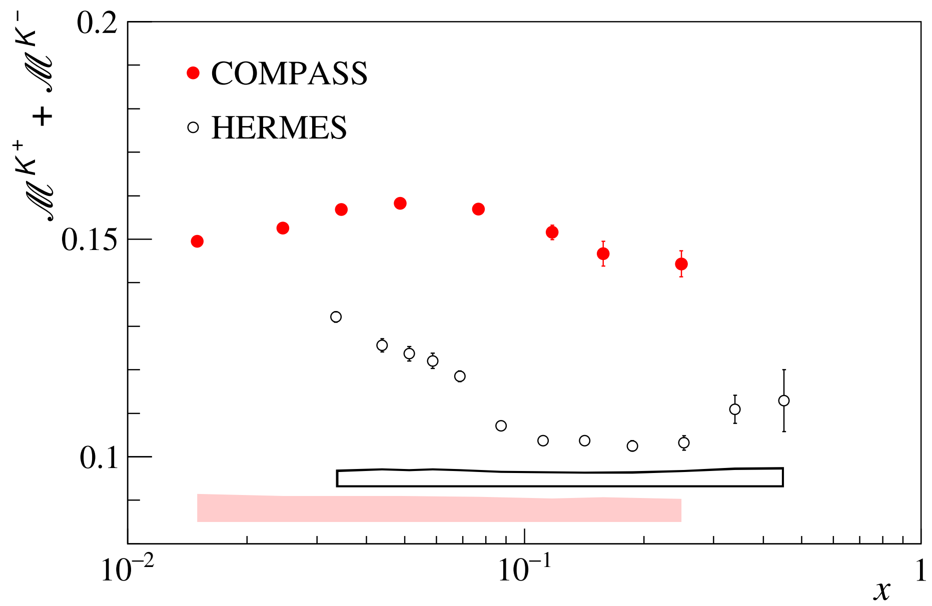


Accardi et al JHEP 0911, 084 (2009)

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

Hadron Mass Effects

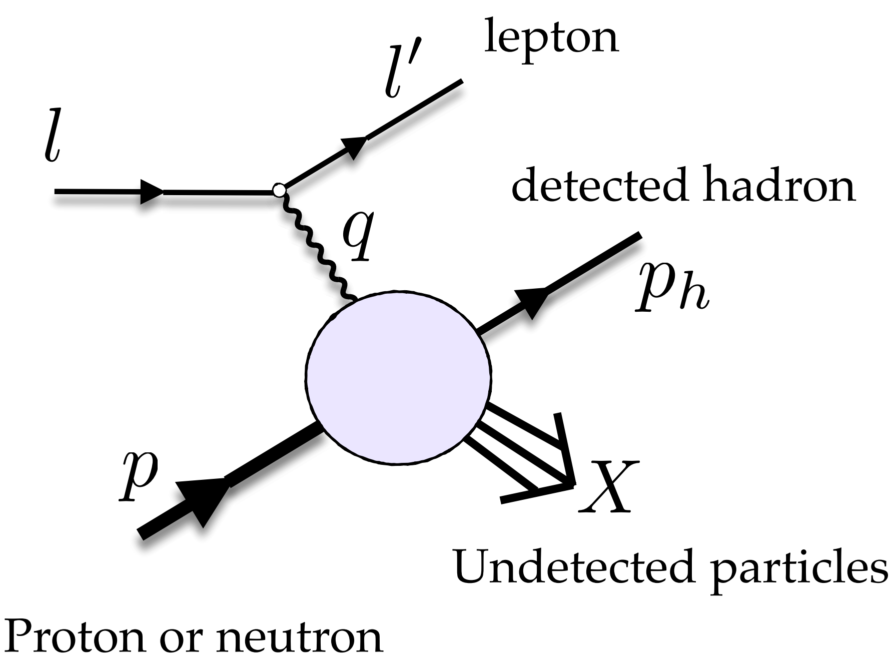
Back to Kaons:



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

Could the discrepancy be due to m²/Q² effects?

SIDIS Kinematics Variables



DIS invariants

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

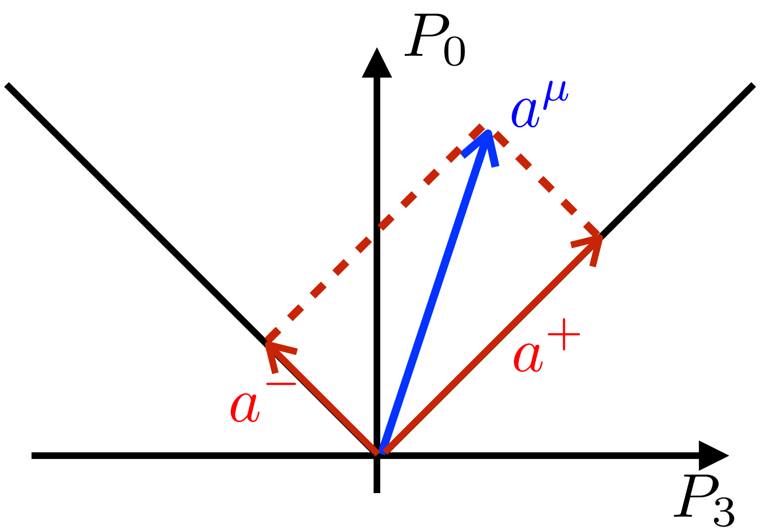
$$y = \frac{p \cdot q}{p \cdot l} \qquad x_B = \frac{Q^2}{2p \cdot q}$$

SIDIS invariants

$$m_h^2 = p_h^2$$

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

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: $Q^2 \to \infty \quad \xi \to x_B$

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: $Q^2 \to \infty \quad \zeta_h \to z_h$

Collinear momenta

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

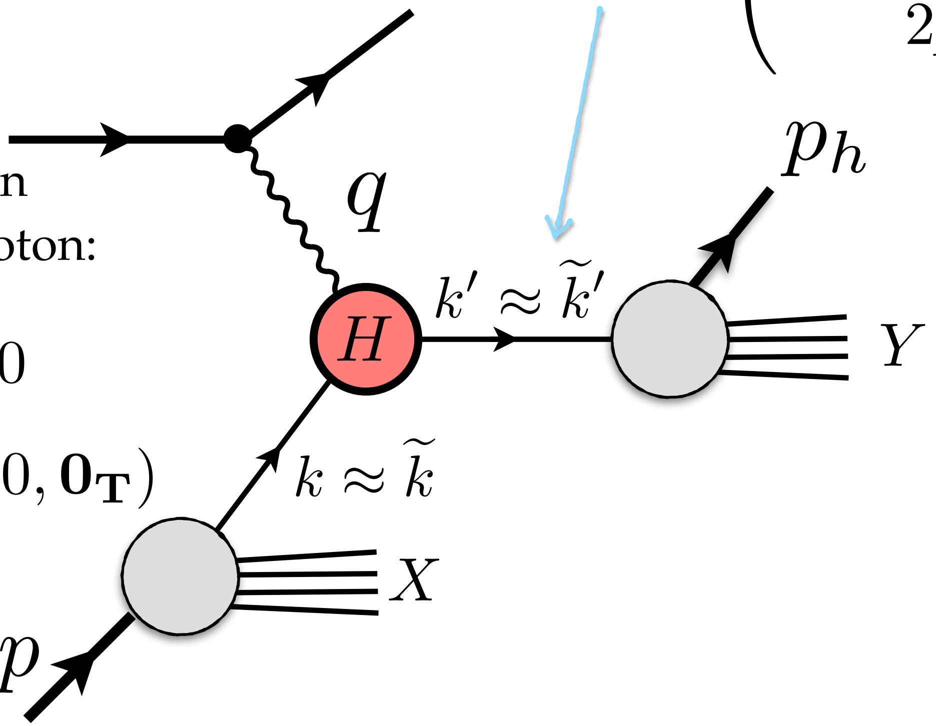
Fragmenting parton collinear to hadron

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

On-shell parton collinear to proton:

$$\widetilde{k}^2 = 0$$

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



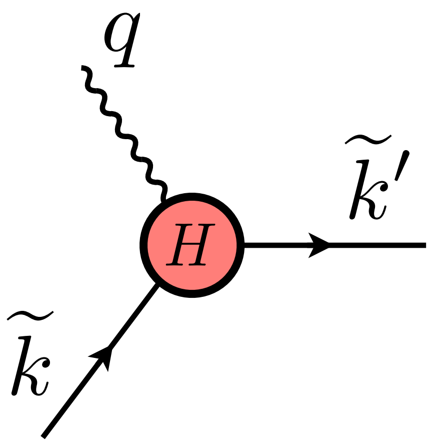
Fragmentation into a **massive** hadron

$$\widetilde{k}'^2 = ?$$

need to match partonic & hadronic kinematics

Matching Hadronic and Partonic Kinematics at LO

Hard scattering: 4-momentum conservation at LO



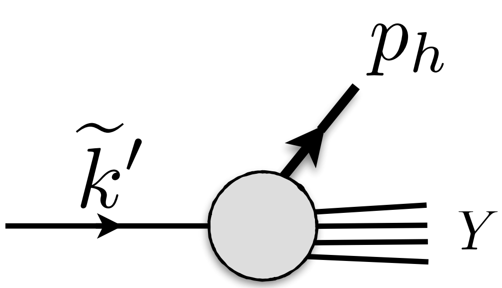
$$\boxed{\begin{gathered} x = \xi\left(1 + \frac{\widetilde{k}'^2}{Q^2}\right) \\ z = \zeta_h \end{gathered}}$$

Bjorken limit:

$$x = x_B$$

$$z = z_h$$

Fragmenting blob: momentum conservation in + direction



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

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

Standard choice:

$$\widetilde{k}'^2 = 0$$

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

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

- **With Hadron Masses:**

Scale dependent Jacobian

Finite Q^2 scaling variables

$$\boxed{M^h(x_B) = \frac{\int_{exp.} dQ^2 \int_{0.2}^{0.8(0.85)} J_h(\xi, \zeta_h, Q^2) \sum_q e_q^2\, q(\xi_h, Q^2)\, D_q^h(\zeta_h, Q^2) dz_h}{\int_{exp.} dQ^2 \sum_q e_q^2\, q(\xi, Q^2)}}$$

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

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

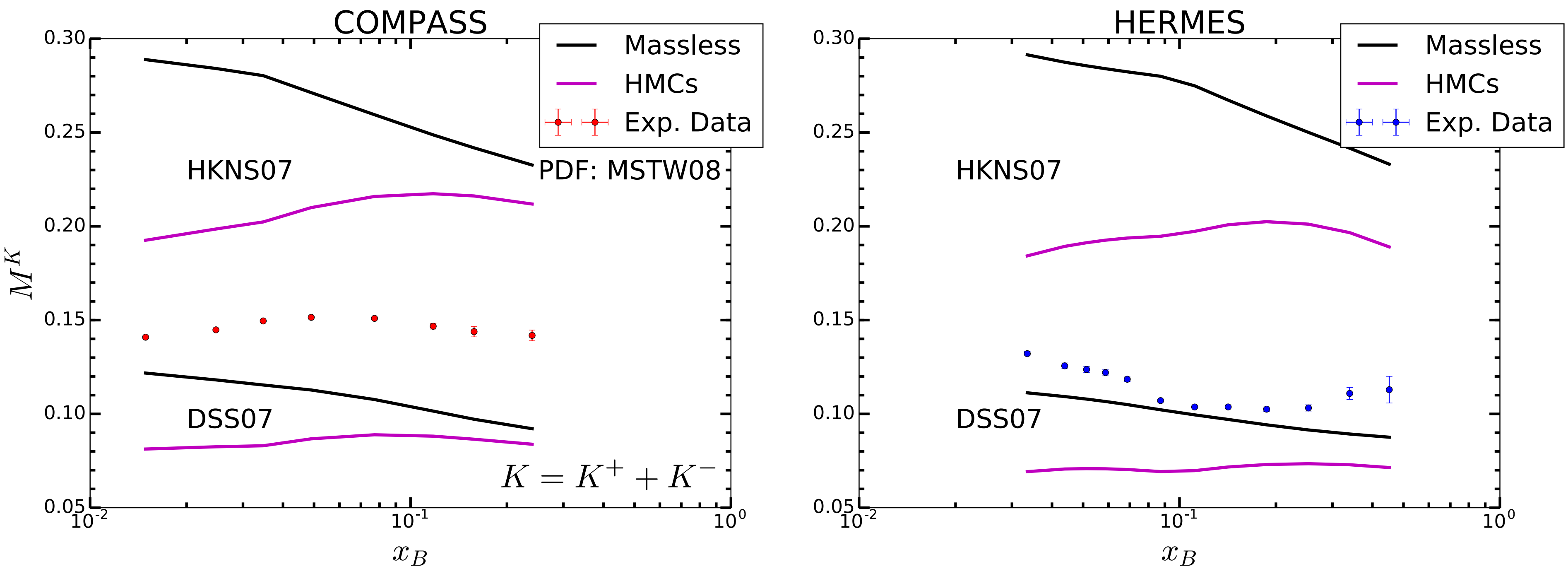
- Bjorken limit: $\left(\frac{M^2}{Q^2}, \frac{m_h^2}{Q^2}\right) \to 0$

$$M^{h(0)}(x_B) = \frac{\int_{exp.} dQ^2 \sum_q e_q^2\, q(x_B, Q^2) \int_{0.2}^{0.8(0.85)} D_q^h(z_h, Q^2) dz_h}{\int_{exp.} dQ^2 \sum_q e_q^2\, q(x_B, Q^2)}$$

Parton model definition

K⁺ + K⁻ Multiplicities

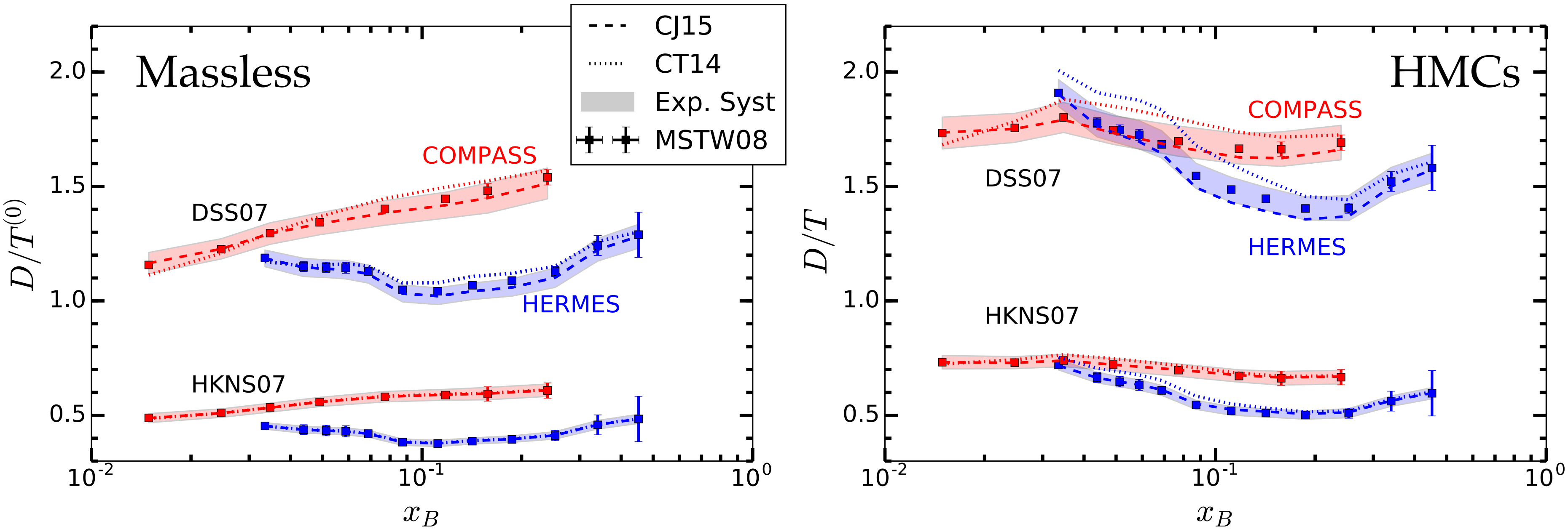
- Data (dots) vs. Theory (lines)



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

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

- D/T ratio allows to compare experiments at different Q^2



COMPASS vs. HERMES:

- After HMCs:
  - Size discrepancy reduced
  - Slope changes
- COMPASS well described (for overall size)
- Residual tension with HERMES slopes

Comparing HERMES vs. COMPASS data

"Theoretical correction ratios" → Make data comparable

Produce approximate "massless" parton model multiplicities

- HMC ratio

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

- Evolution ratio (HERMES to COMPASS)

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

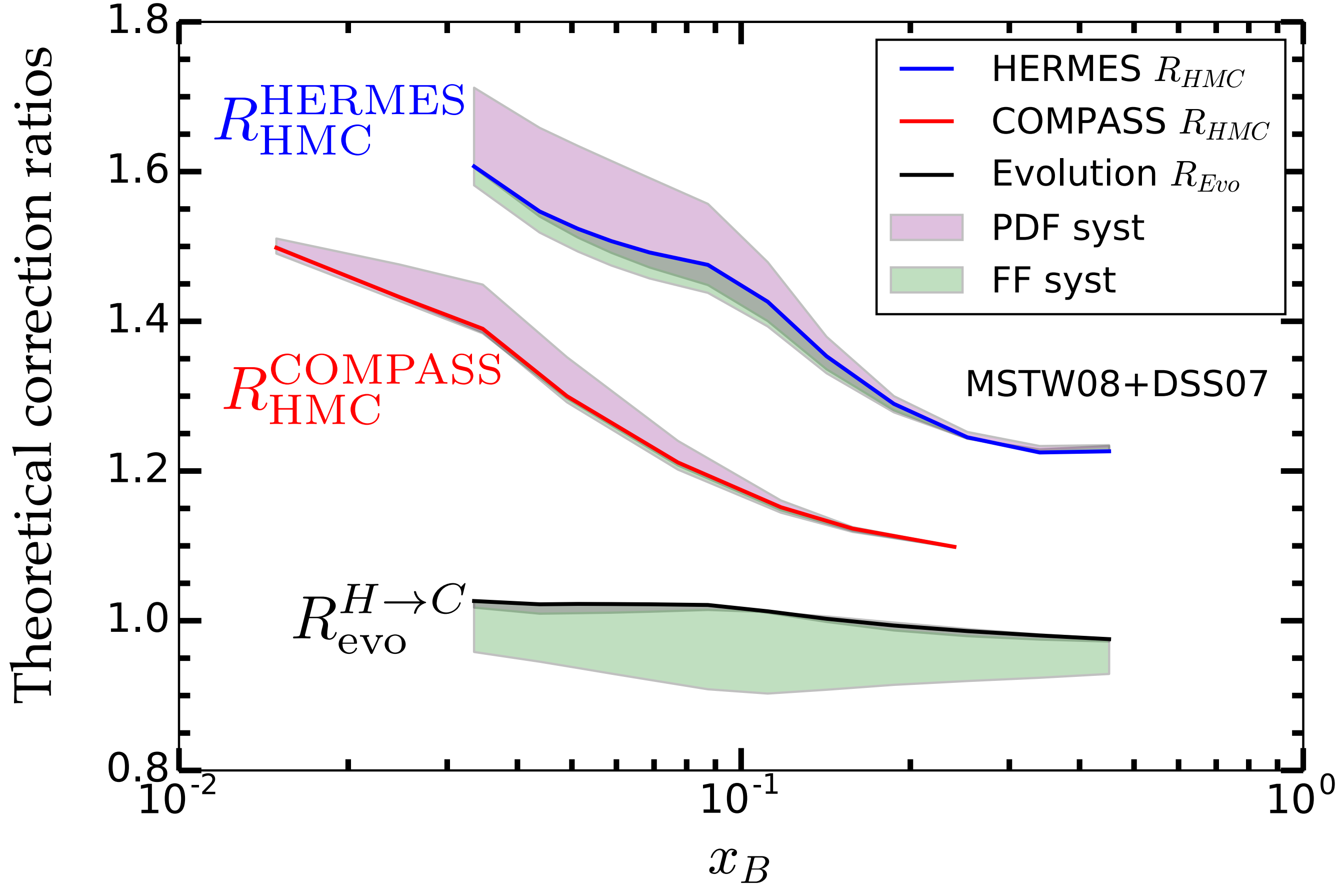
- COMPASS:

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

- HERMES:

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

Correction ratios

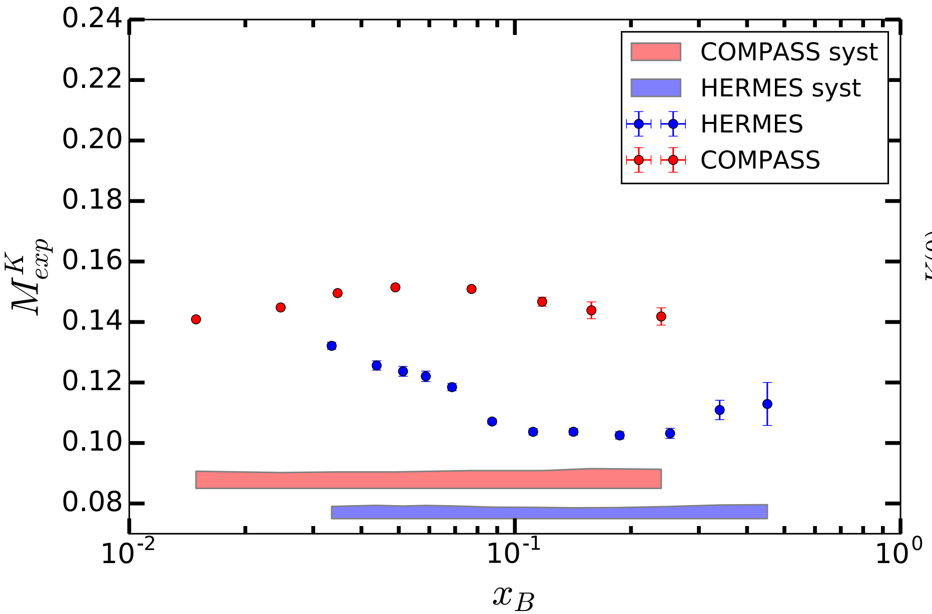


- Hadron mass effects dominant over evolution effects
- At COMPASS smaller HMCs than at HERMES.

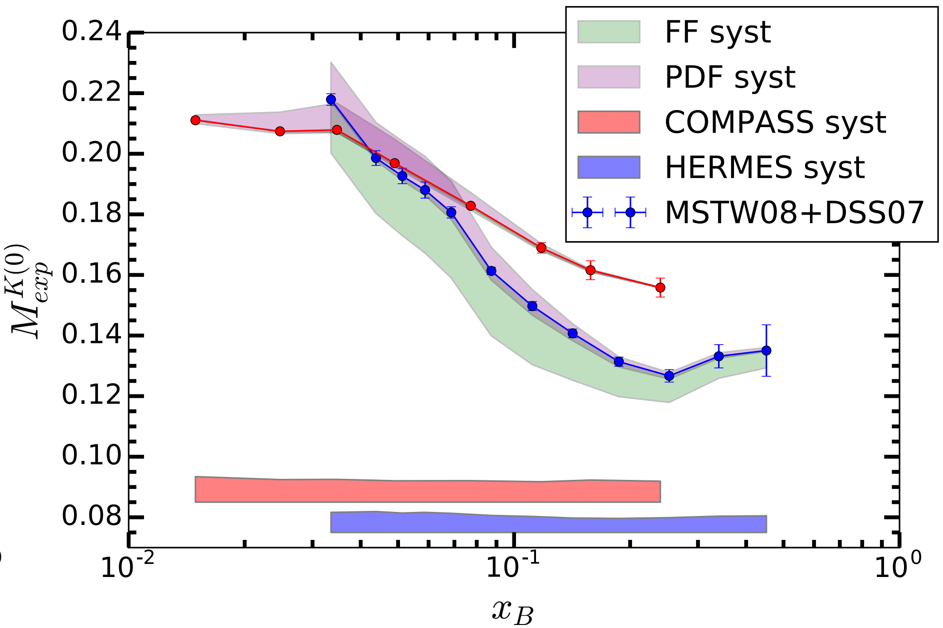
Kaons at HERMES vs. COMPASS

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

Experimental Data



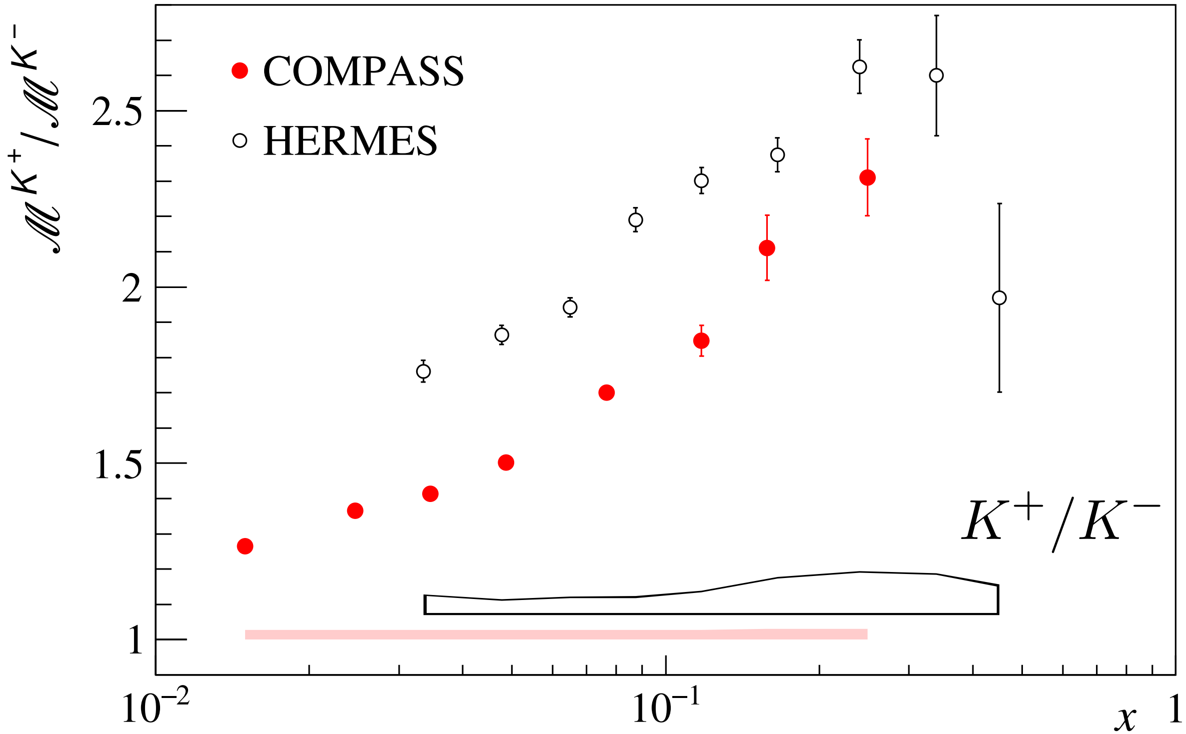
"Massless data" at same Q^2



- Removing HMCs reduce the discrepancy in size.
- Corrections rather stable with respect to FF choice.

Kaon ratios

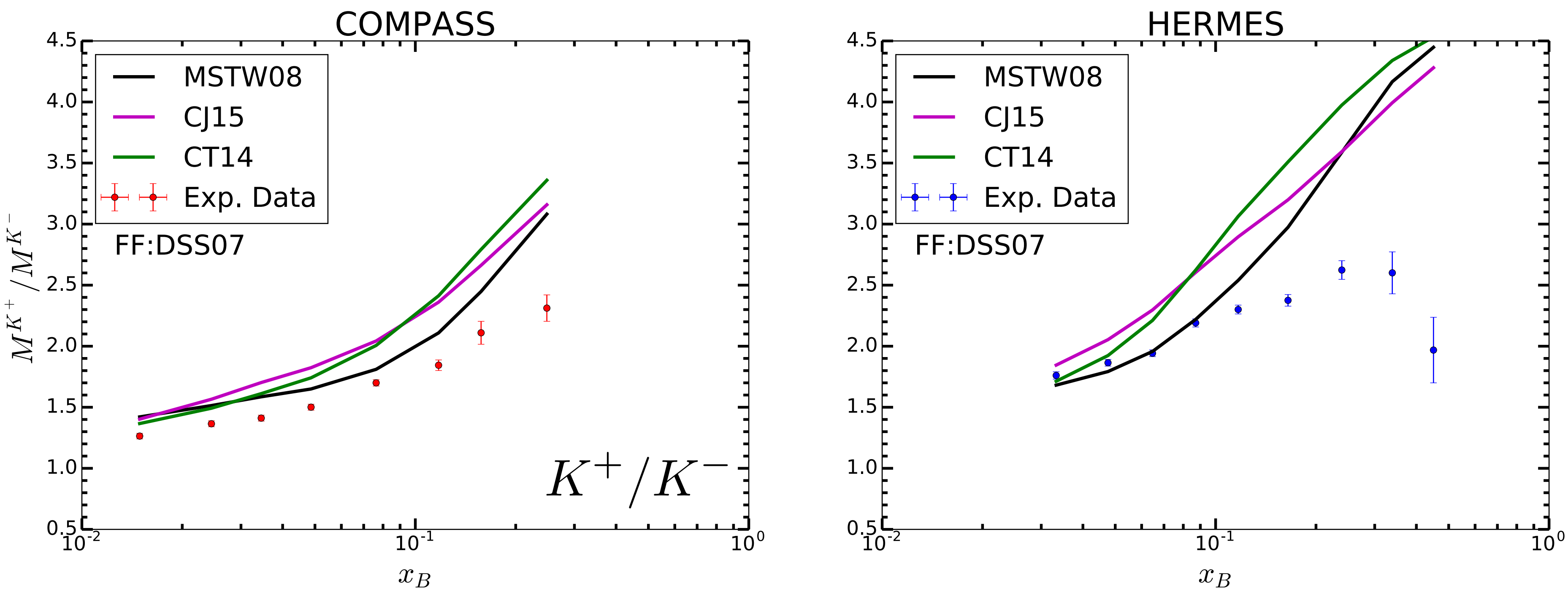
- Ratio reduces experimental systematics.



- Size discrepancy persists
- Slopes are now compatible
  - Except the last two HERMES points.

Kaon ratios

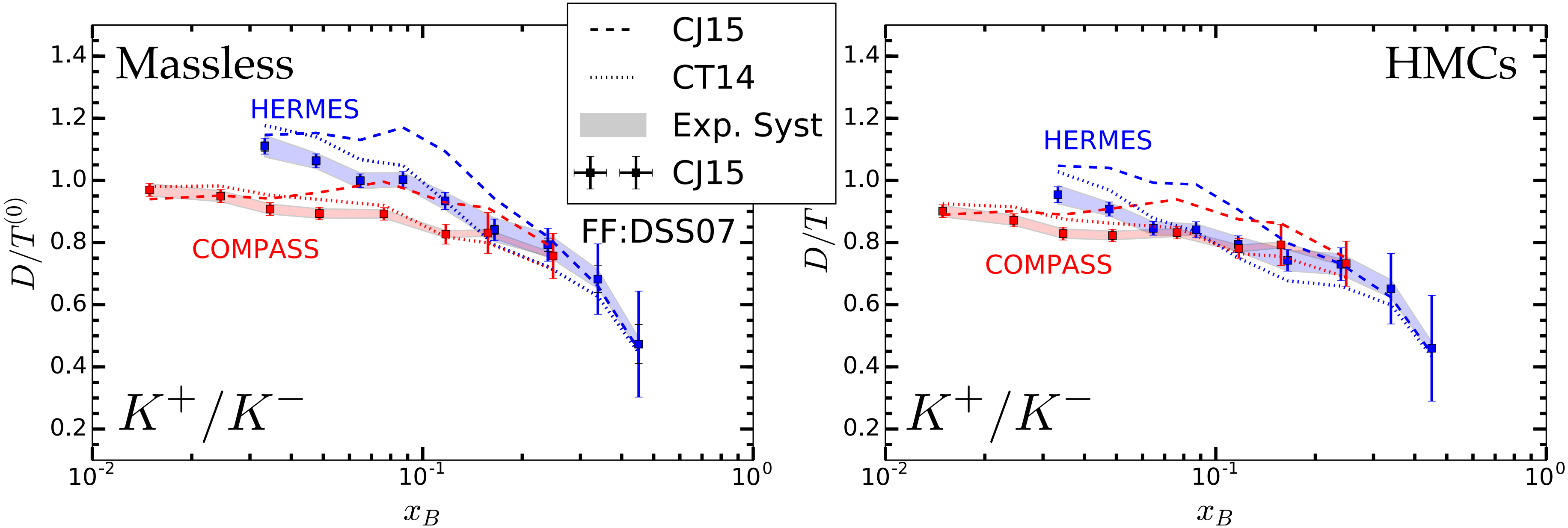
- Data (dots) vs. HMC Theory (lines)



- 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)
  - need to refit the s quark PDF

Data over Theory: K^+/K^-

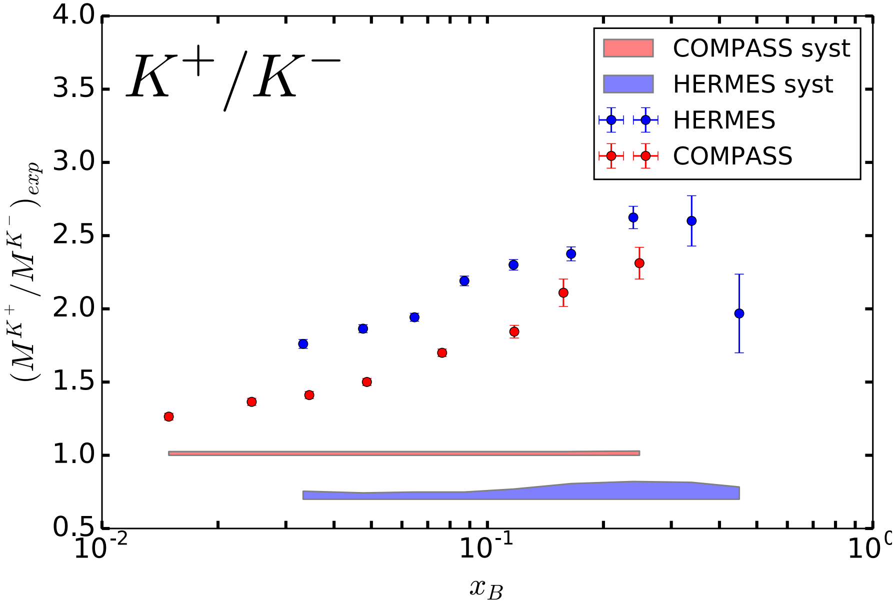
- D/T ratio allows to compare experiments at different Q^2



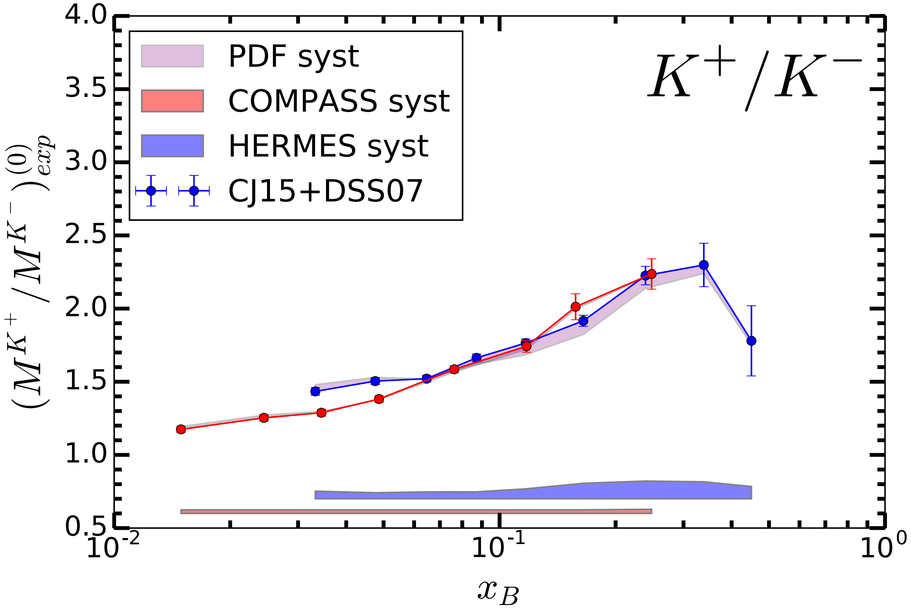
- Ratios show less discrepancy
- HMCs much smaller for ratios (partial cancellation)
- Slopes with HMCs compatible
  - Strange quark in current PDF fits too soft?

Kaon ratios at HERMES vs. COMPASS

Experimental Data



"Massless data" at same Q^2



- Size and slope fully compatible.
  - large x bins at HERMES still 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 (e.g. Ethier, Sato, Melnitchouk. arXiv:1705.05889)
- Include mass corrections
  - Non negligible even at small-x (because Q^2 is small)
  - Our proposed scheme with with $\widetilde{k}'^2 = m_h^2/\zeta_h$ 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
- HMCs reduce the discrepancy in size between HERMES and COMPASS data for integrated Kaon Multiplicities
- Difference in slopes stills needs to be resolved for $\mathbf{K^+ + K^-}$
- No slope problem for ratio $\mathbf{K^+/ K^-}$ → systematics in HERMES $\mathbf{K^+ + K^-}$?

<u>Future developments:</u>

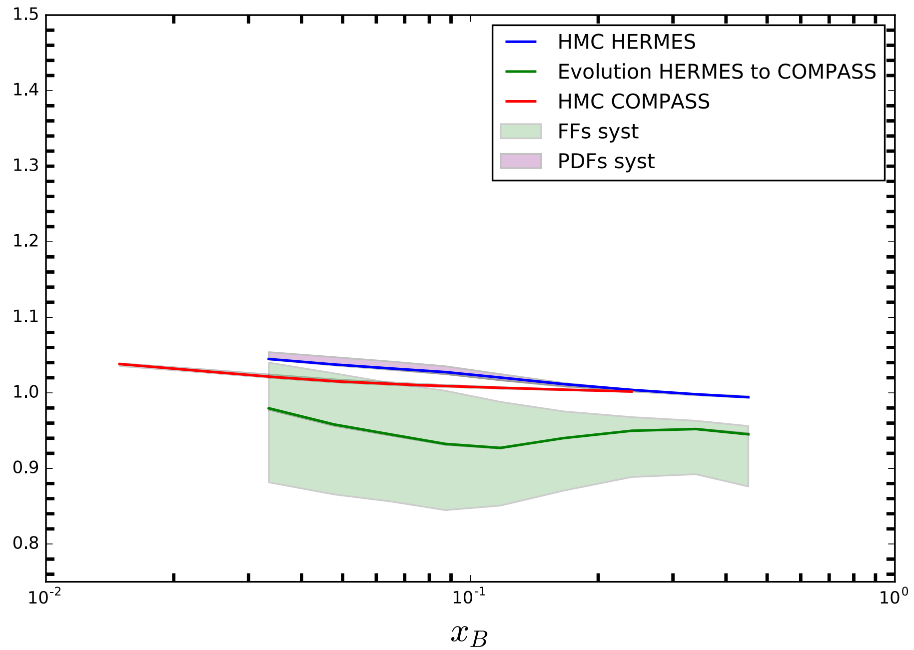
- Include nuclear corrections (large x_B behavior?)
- Prove factorization at NLO with $k'^2 \neq 0$.
- Use the multiplicity data in new fits of FFs with HMC corrected theory

Thank you!

Backup slides

Pions at HERMES vs. COMPASS

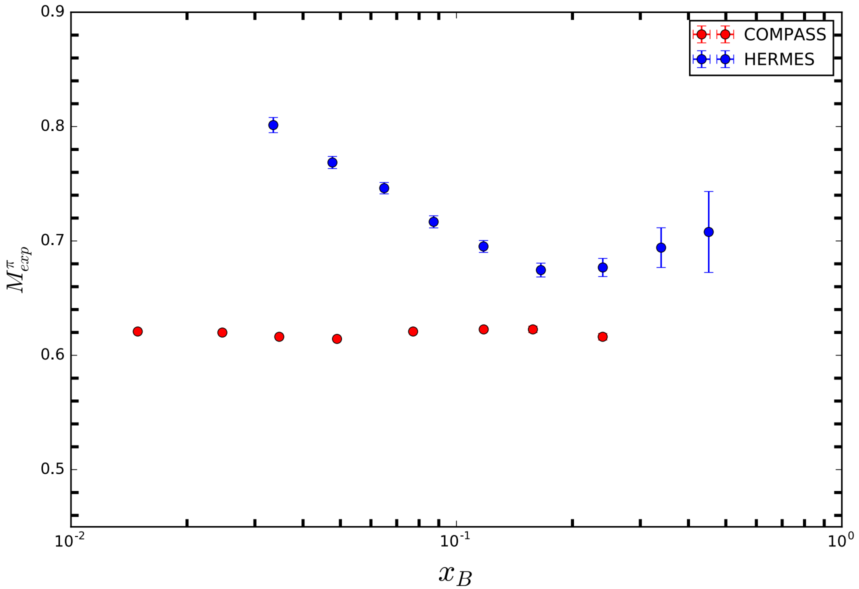
- HMC ratios: HERMES (blue line), COMPASS (red line)
- Evolution ratio (green line)
- Systematic theoretical uncertainties: (FFs, PDFs)



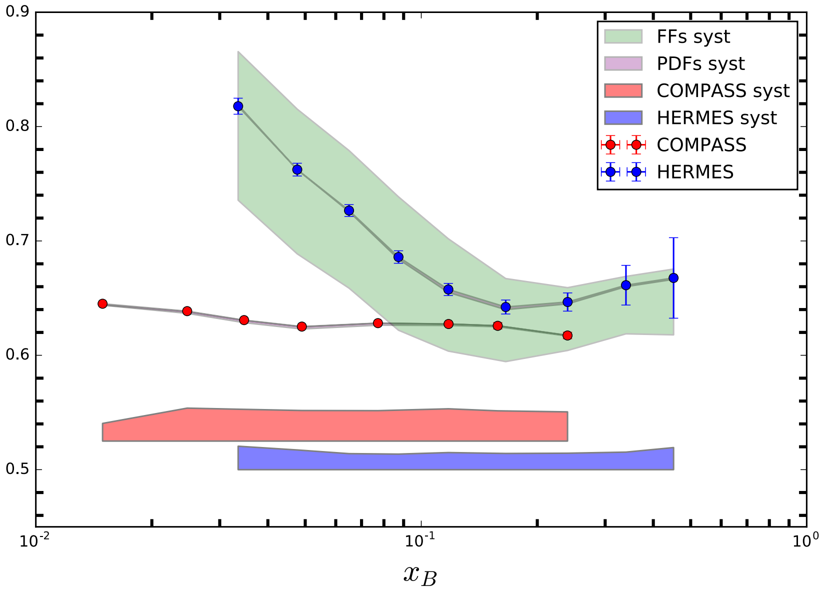
- HMCs much smaller than for Kaons.
- Comparable to evolution effects.

Pions at HERMES vs. COMPASS

Experimental Data

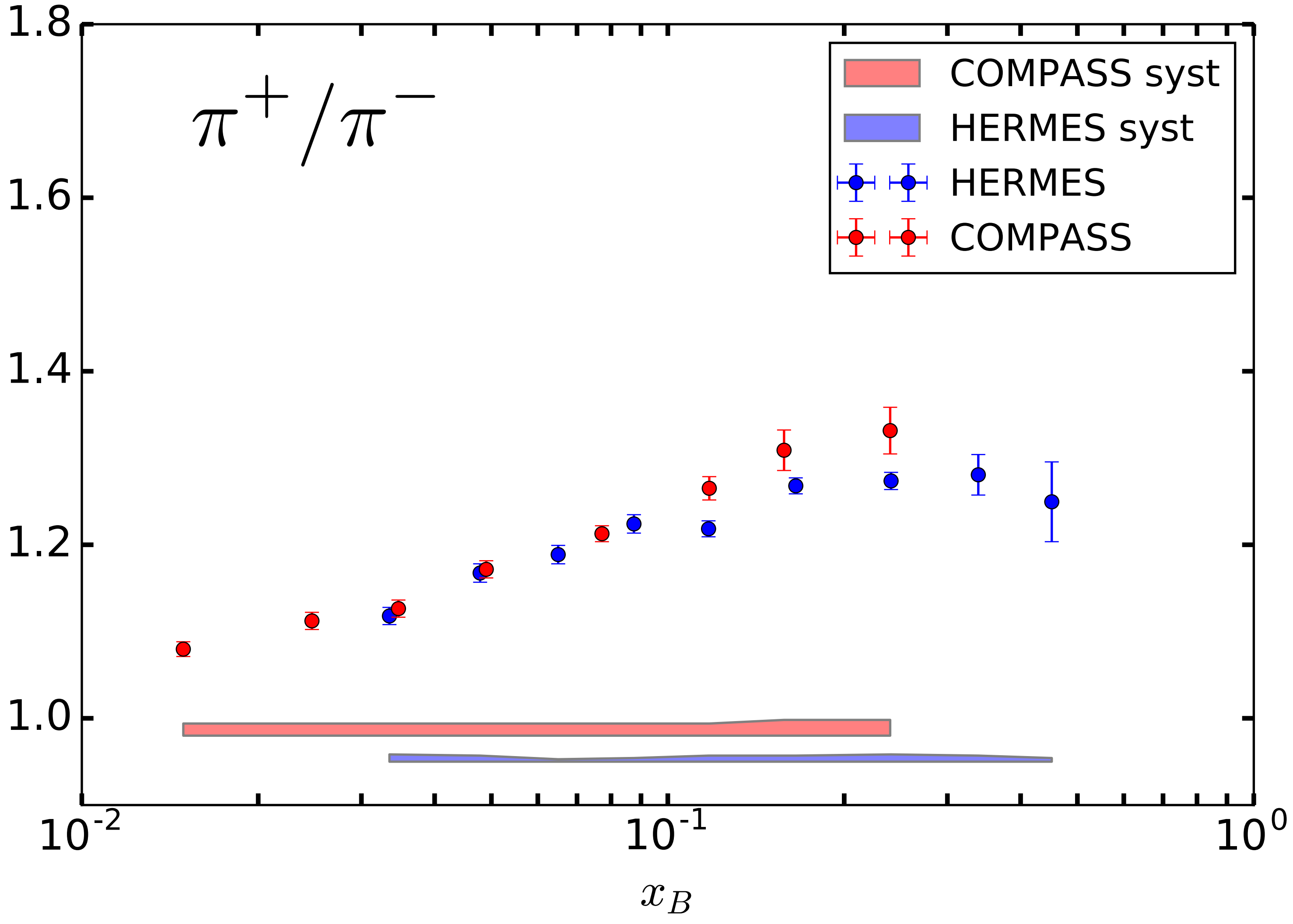


Parton level multiplicities



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

Pions ratio



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

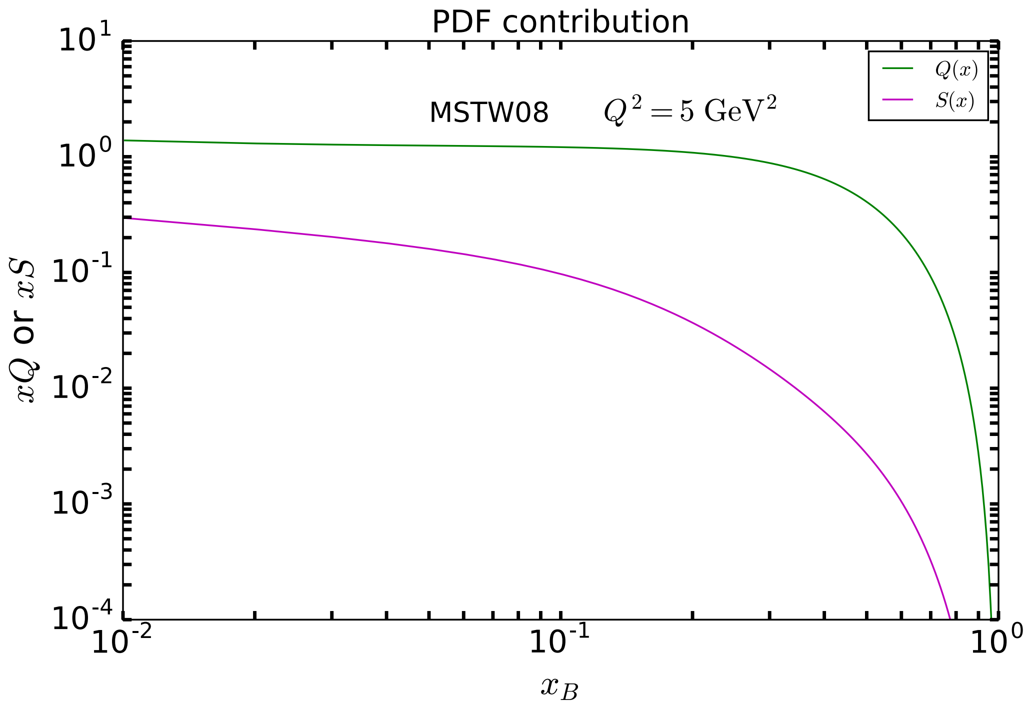
Fragmentation Functions Systematics

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

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

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

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



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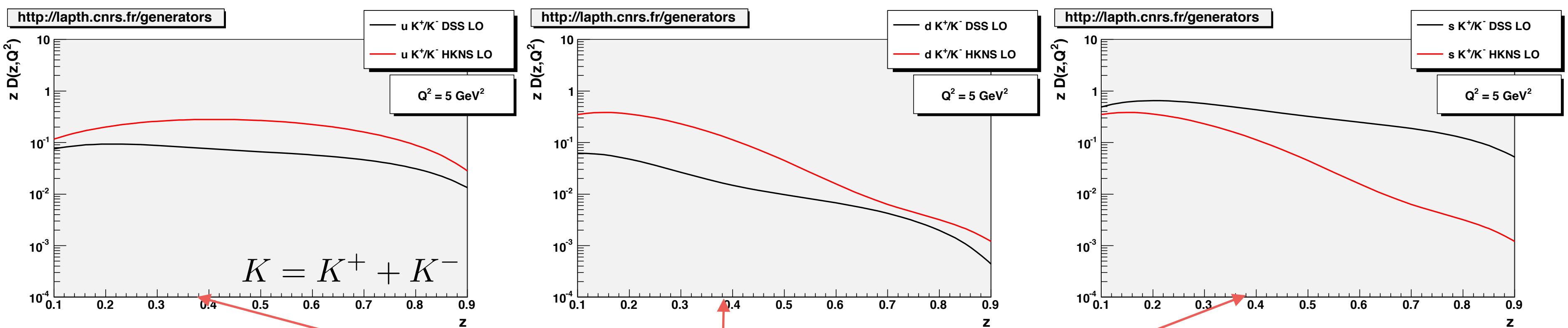
u, d, s FFs



$$< z_h >\sim 0.38$$

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

Large uncertainty with the choice of FFs because

$$Q > S$$