Hadron Mass Effects on Kaon production on deuteron

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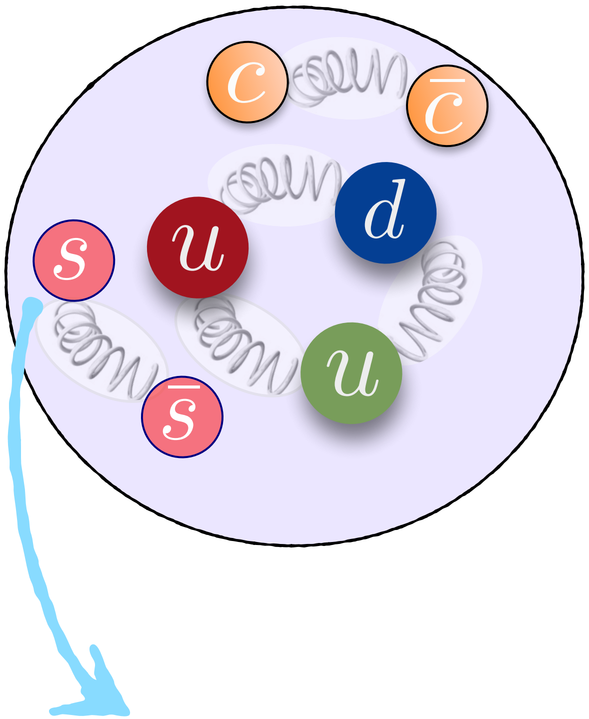
Hadronic Physics with Lepton and Hadron Beams
September 6, 2017

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

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: **strange**, charm, bottom.

Parton (momentum) Distributions Function (PDFs):

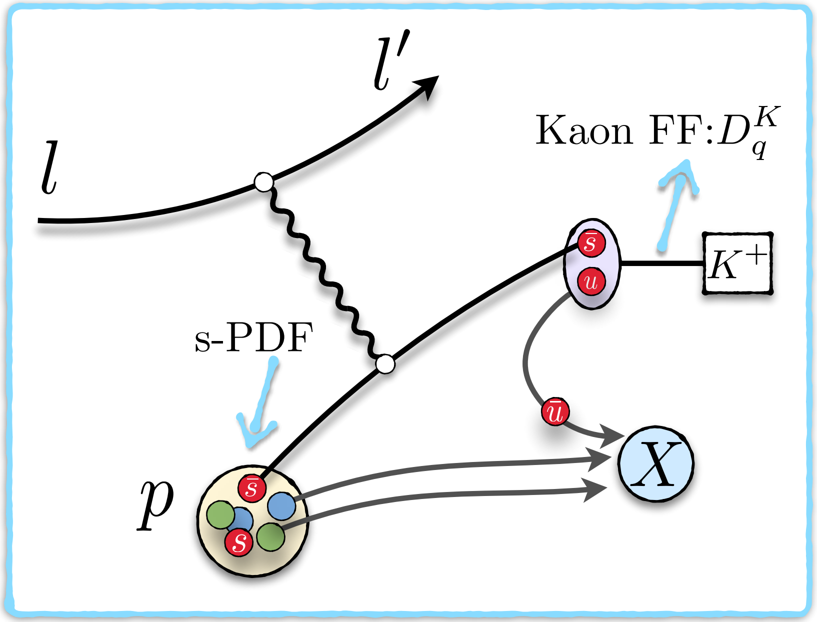
- Well determined for the "valence quarks"and gluons.
- Not the case for the sea quarks.

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
- 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:

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

Theoretically
LO, neglect masses:

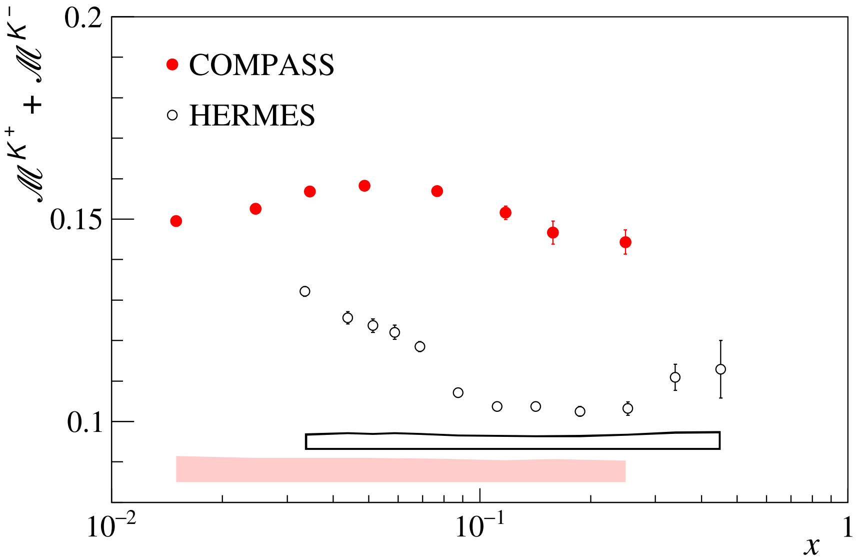
$$M^K = \frac{\sum_q e_q^2 q(x_B) \int_{0.2}^{0.8} dz_h D_q^h(z_h)}{\sum_q e_q^2 q(x_B)} = s(x_B) \int dz_h D_s^K(z_h)$$

$$+\text{light quarks}$$

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.

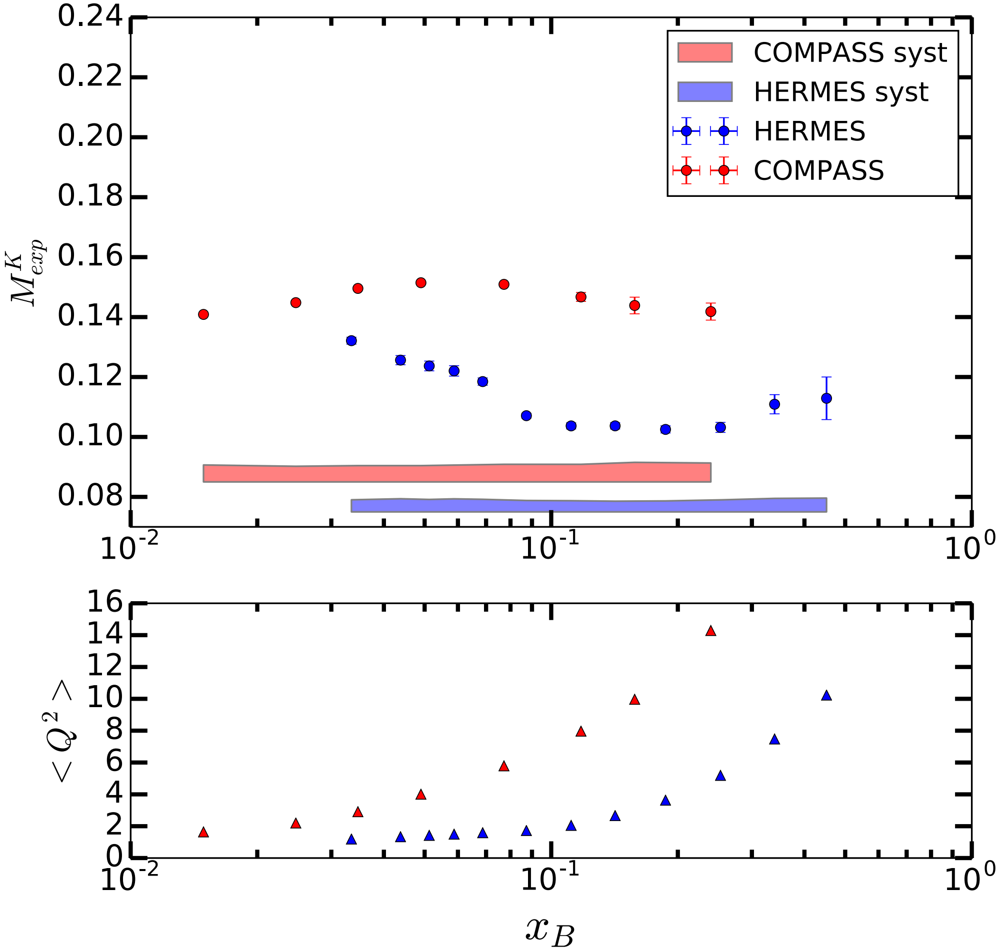


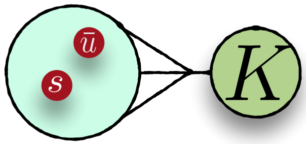
Where does this discrepancy come from?

Is it real or apparent?

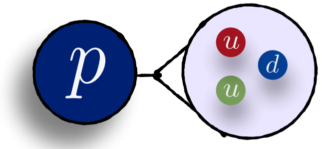
Hadron Mass Effects

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





$m_K \simeq 0.5$ 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

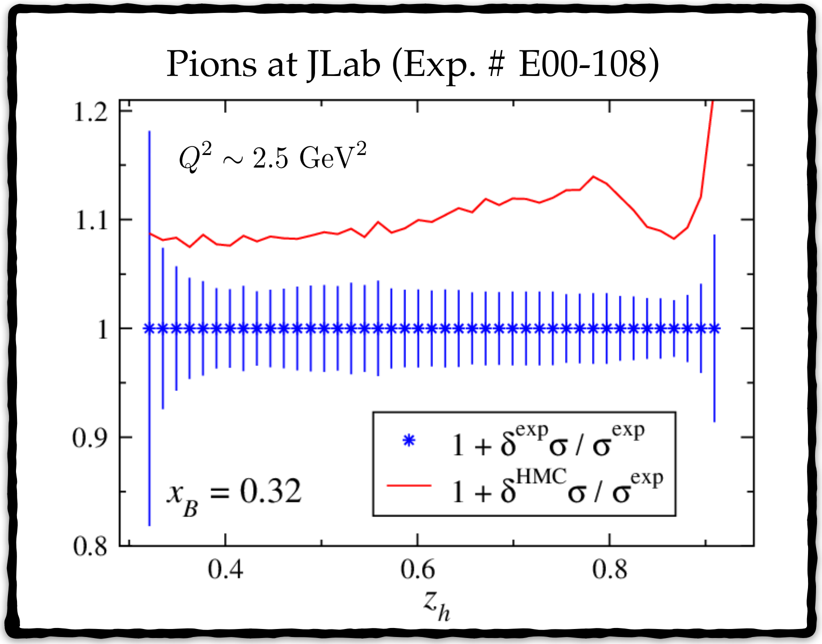
Let's consider an example for Pion Mass effects at JLab.

Jefferson Lab experiments:

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

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

$$m = M_P, m_\pi$$

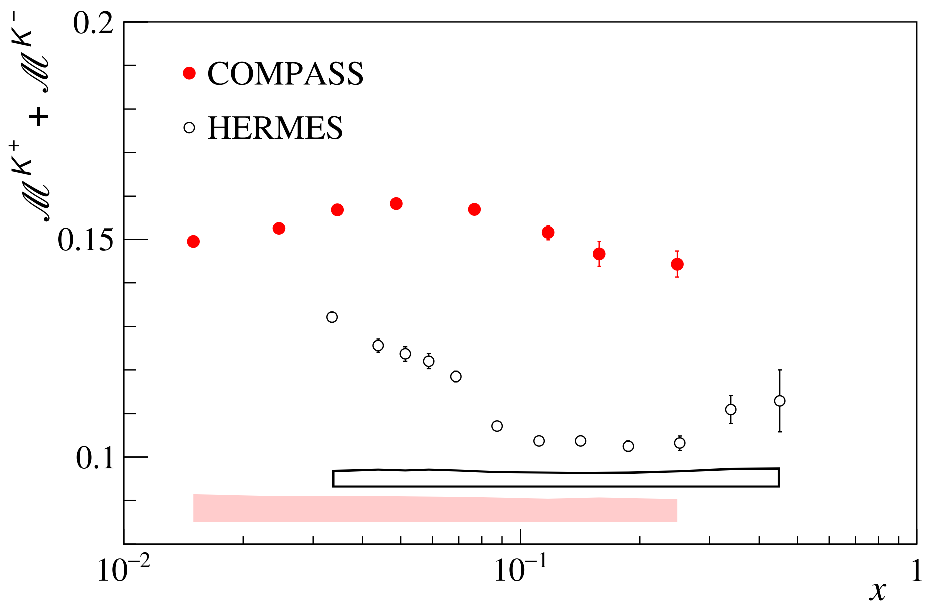


Accardi et al JHEP 0911, 084 (2009)

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

Hadron Mass Effects

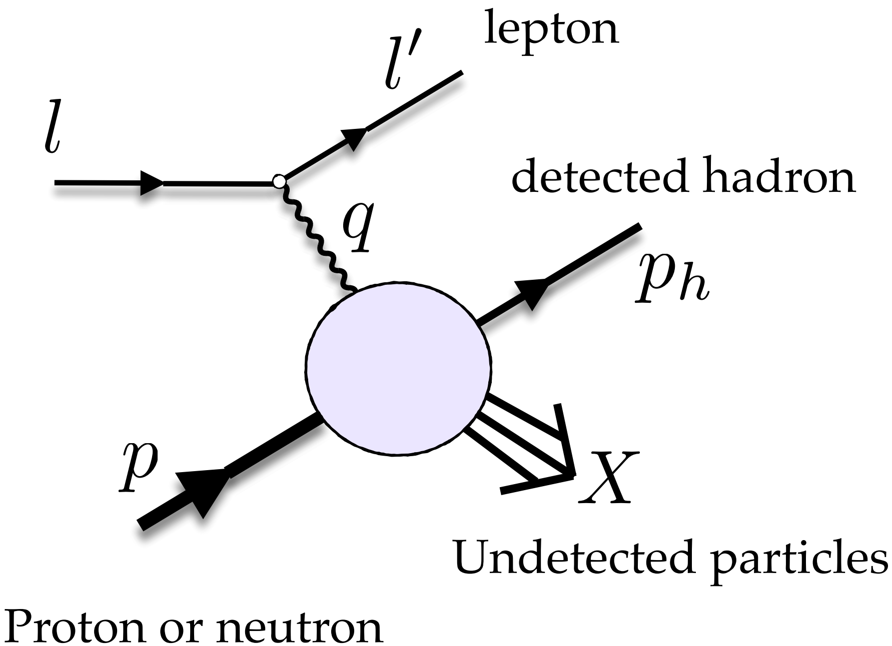
Back to Kaons:



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

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

SIDIS Kinematics Variables



DIS invariants

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

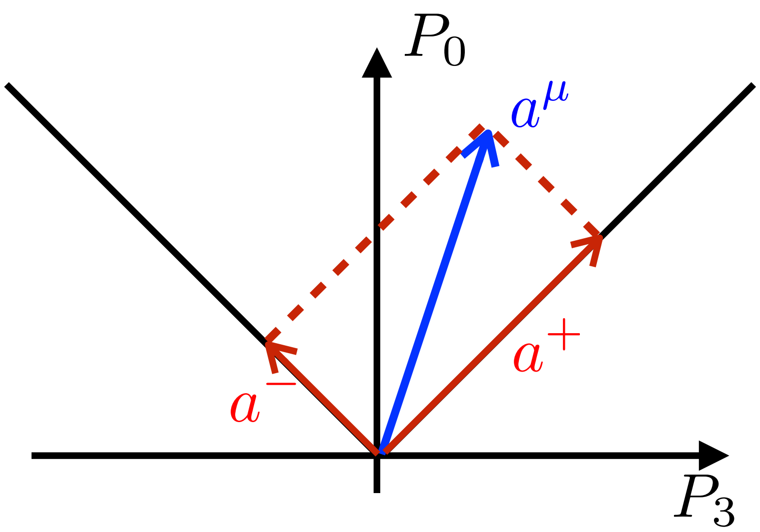
$$y = \frac{p \cdot q}{p \cdot l} \qquad x_B = \frac{Q^2}{2p \cdot q}$$

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

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

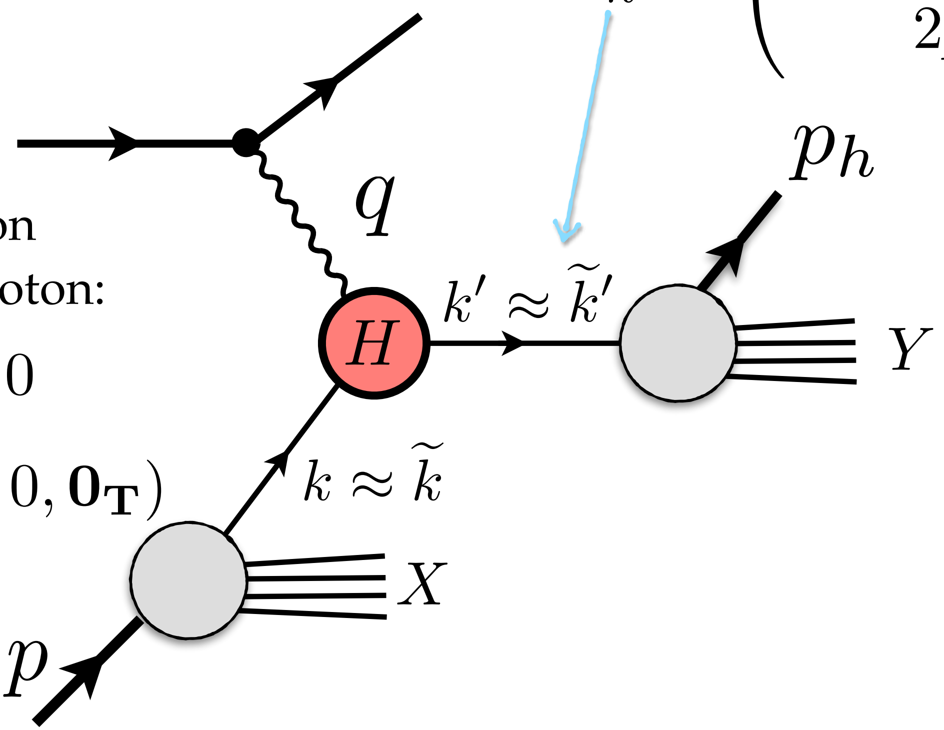
Fragmenting parton collinear to hadron

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

Approx.:
On-shell parton
collinear to proton:

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

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



Fragmentation into a **<u>massive</u>** hadron

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

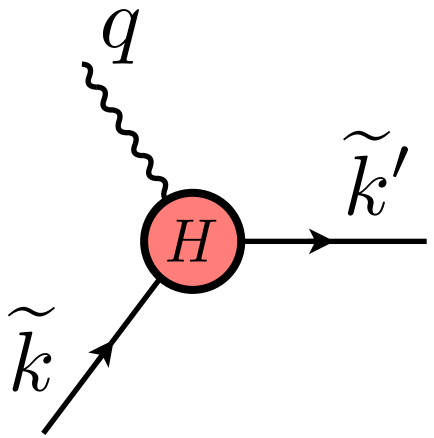
need to match
partonic & hadronic
kinematics

Matching Hadronic and Partonic Kinematics at LO

Hard scattering: 4-momentum conservation at LO

$$H_{LO}(k,k') \approx H_{LO}(\widetilde{k},\widetilde{k}') \propto \delta^{(4)}(q+\widetilde{k}-\widetilde{k}')$$

respects gauge invariance ☑



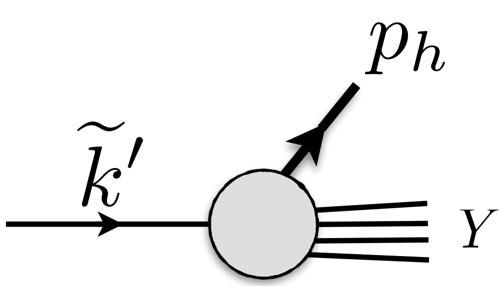
$$x = \xi\left(1+\frac{\widetilde{k}'^2}{Q^2}\right)$$
$$z = \zeta_h$$

Bjorken limit:

$$x = x_B$$
$$z = z_h$$

Fragmenting blob: momentum conservation in + direction

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



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

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

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

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

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

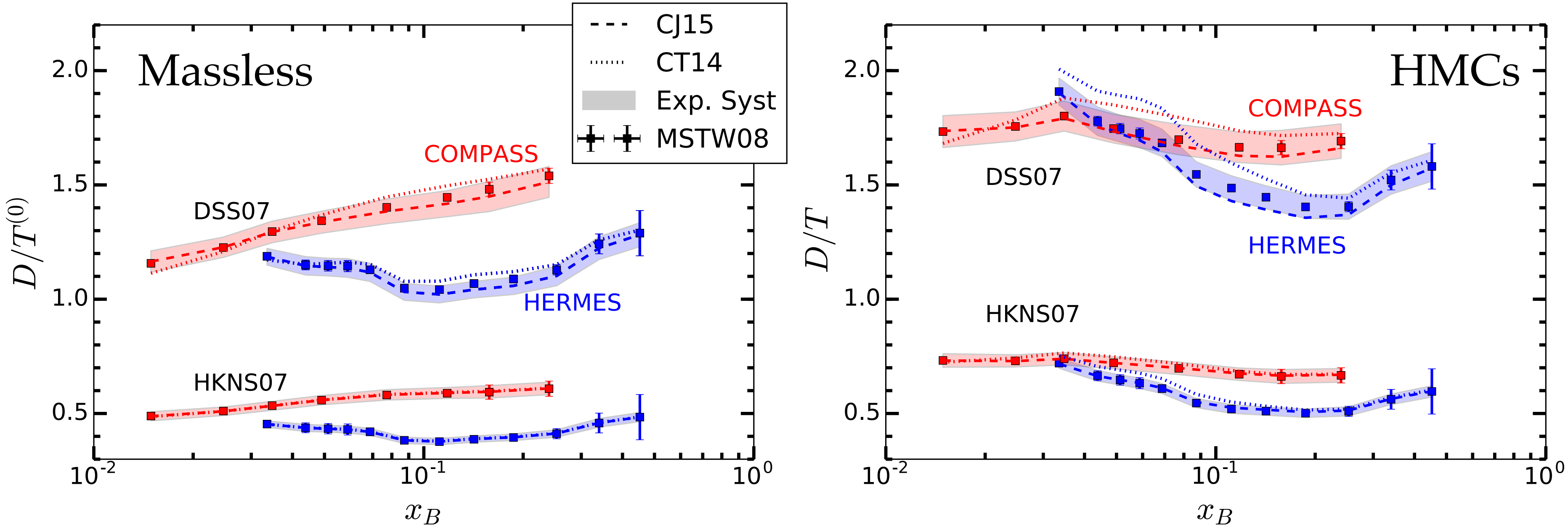
- Bjorken limit: $\left(\frac{M^2}{Q^2}, \frac{m_h^2}{Q^2}\right) \to 0$

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

Parton model definition

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

- HMC ratio

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

- Evolution ratio (HERMES to COMPASS)

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

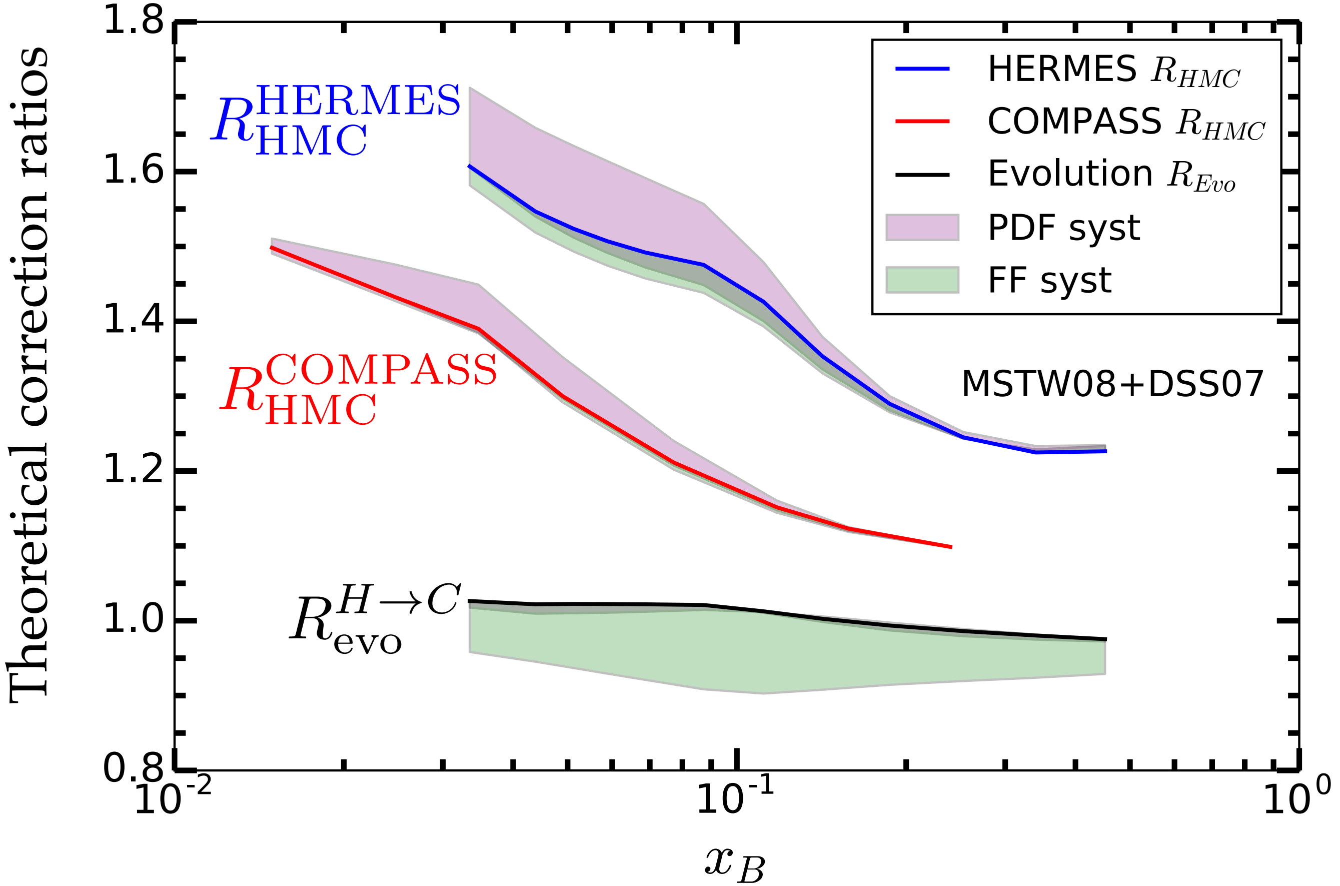
- COMPASS:

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

- HERMES:

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

Correction ratios



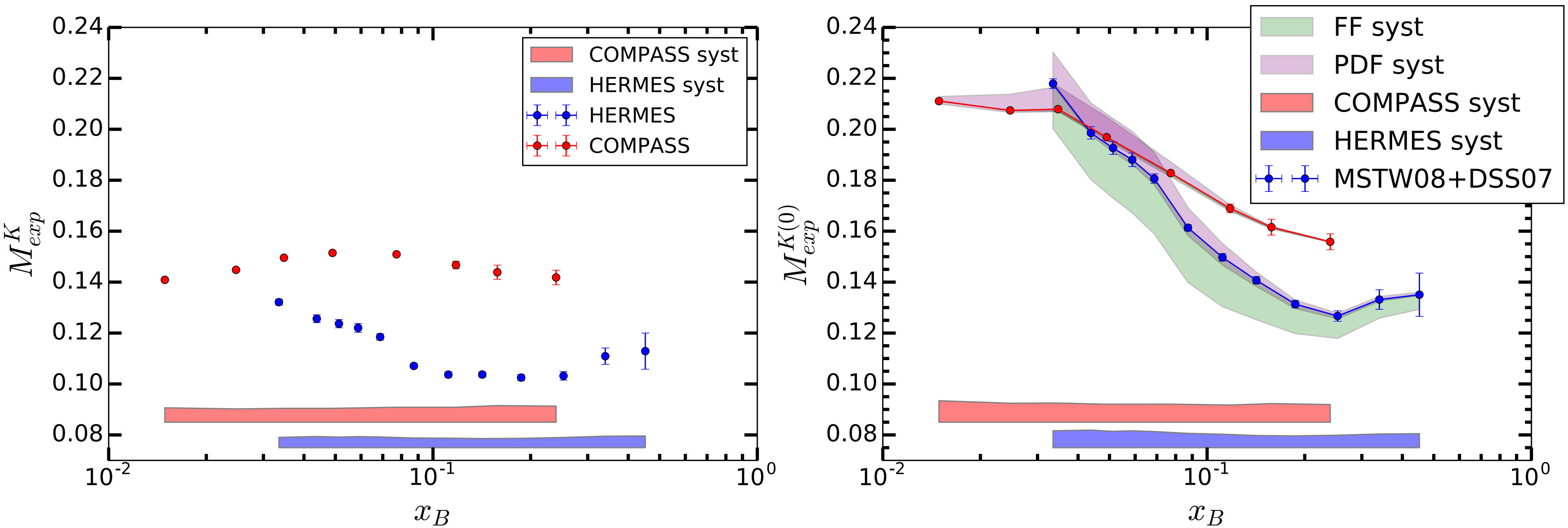
- Hadron mass effects dominant over evolution effects
- At COMPASS smaller HMCs than at HERMES.

Direct Data Comparison

$$K = K^{+} + K^{-}$$

Experimental Data

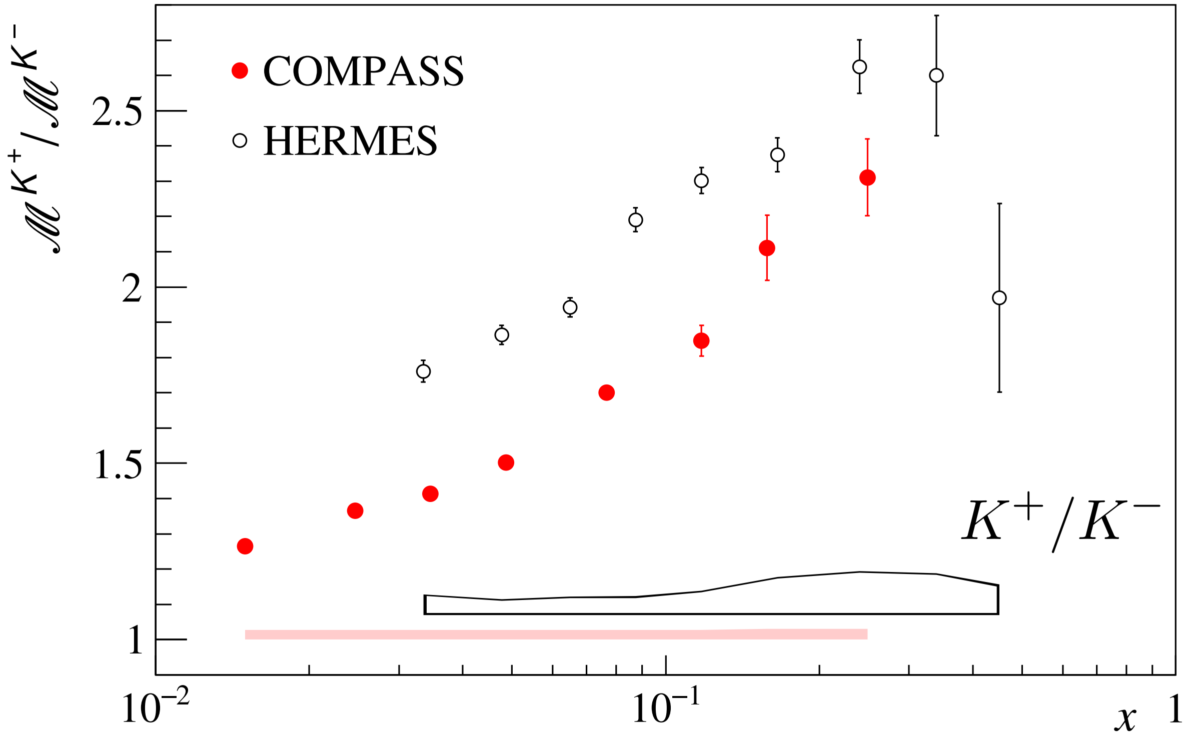
"Massless data" at same Q^2



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

Kaon ratios

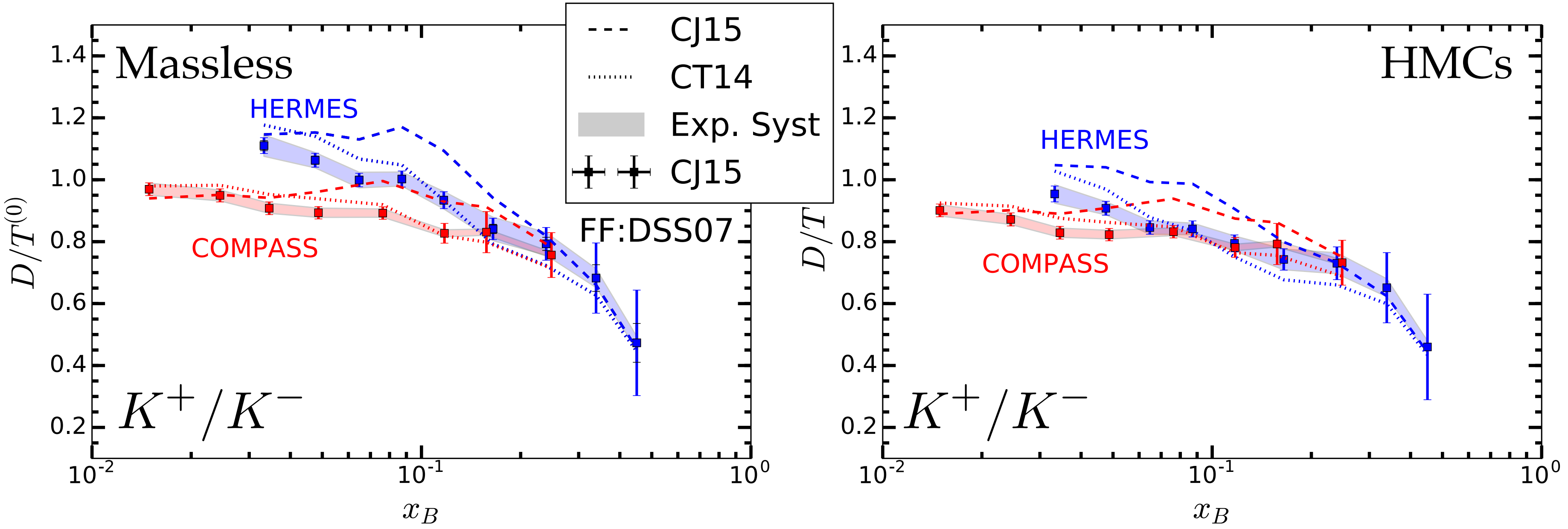
- Ratio reduces experimental systematics.



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

Data over Theory: K⁺/K⁻

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

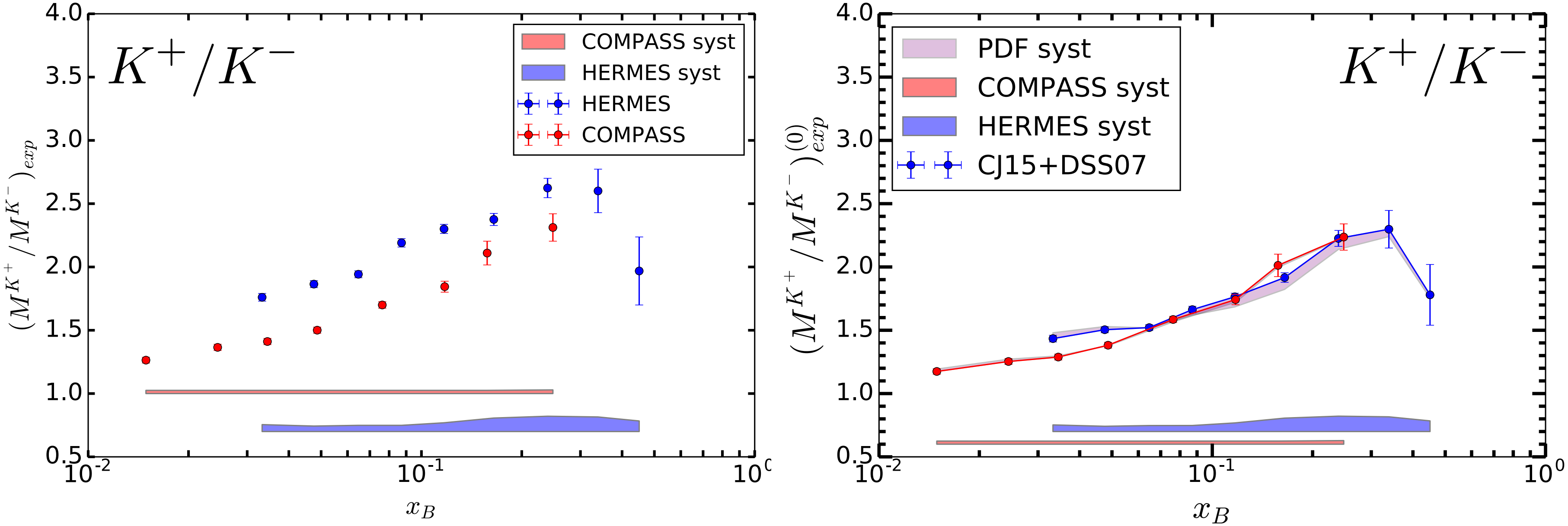


- After HMCs:
  - HERMES overall agreement with COMPASS
- except last bins?
  - Strange quark in current PDF fits too soft?

Direct Data Comparison

Experimental Data

“Massless data” at same Q^2



- HERMES & COMPASS 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
- **K^+ + K^-** multiplicities:
  - HERMES vs. COMPASS size discrepancy reduced
  - Difference in slopes still needs to be solved.
- **K^+/ K^-** ratio: **No slope problem** → systematics in HERMES **K^+ + K^-** ?

Future developments:

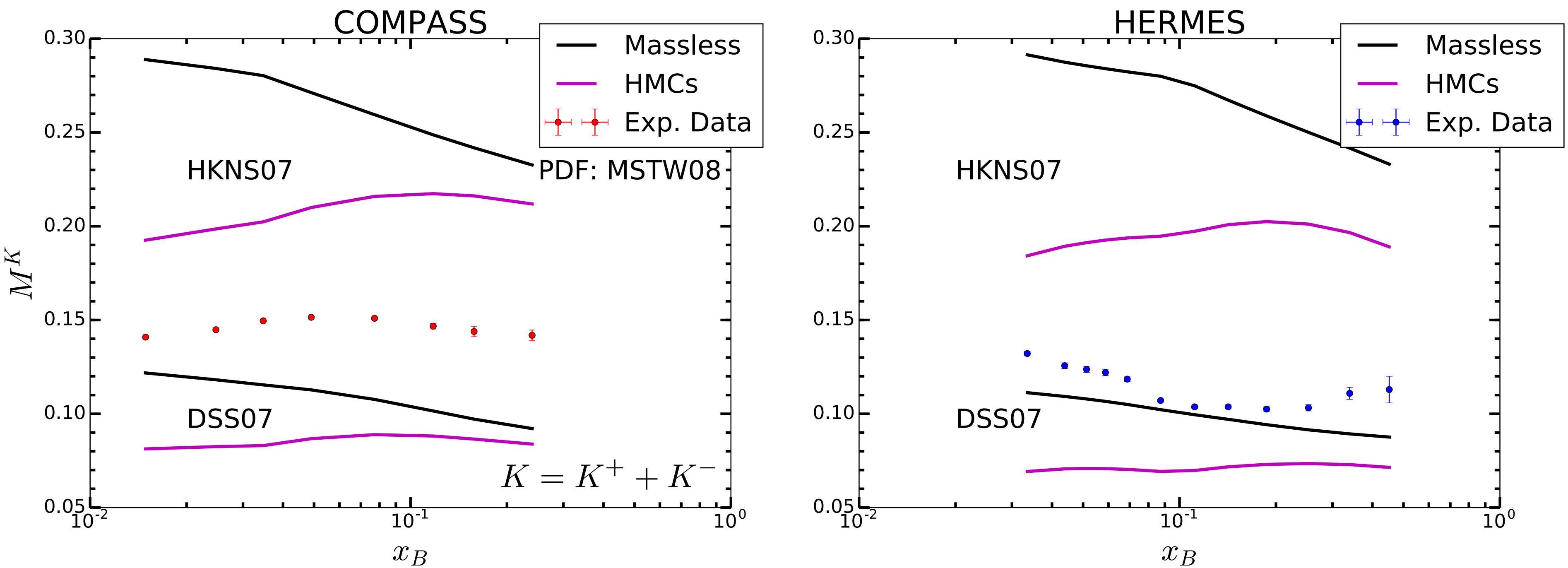
- Evaluating HMCs for polarized asymmetries.
- Prove factorization at NLO with $k'^2 \neq 0$.
- Use the multiplicity data in new fits of FFs with HMC corrected theory

Thank you!

Backup slides

$K^+ + K^-$ Multiplicities

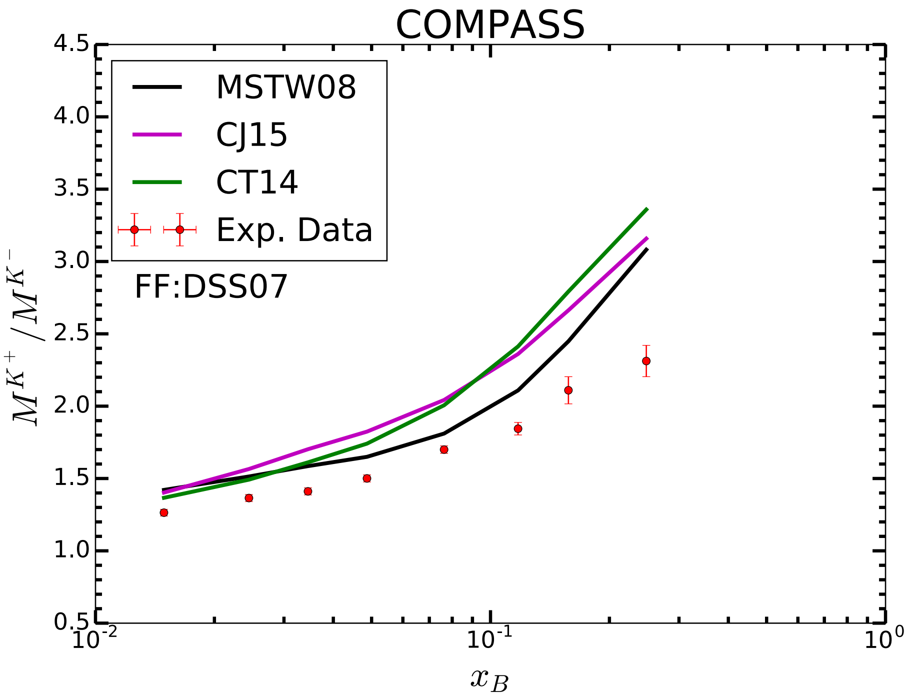
- Data (dots) vs. Theory (lines)

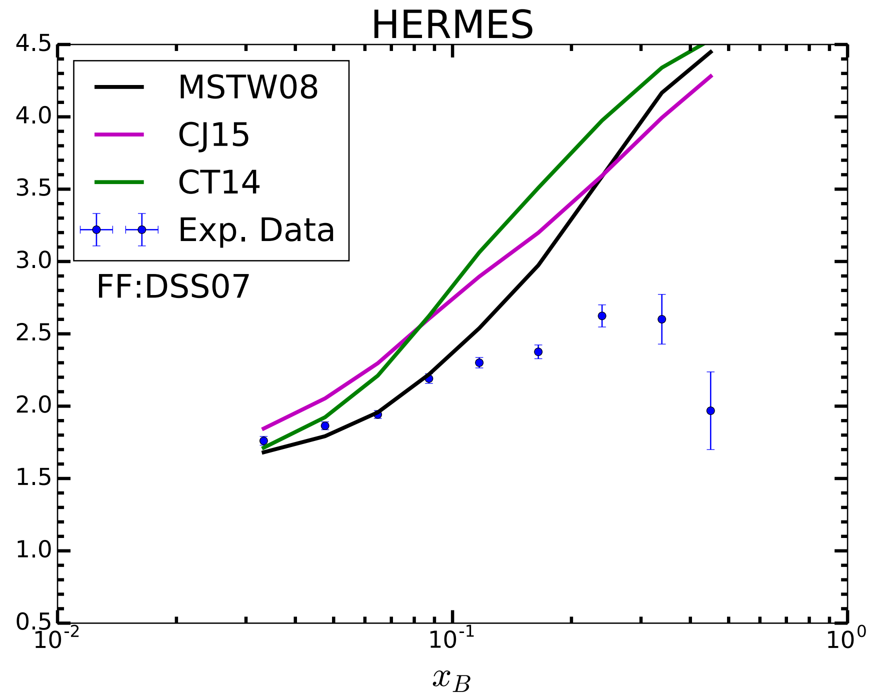


- Kaon FFs poorly known in absolute value
  - Large FFs systematics
- HMCs are large

Kaon ratios

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

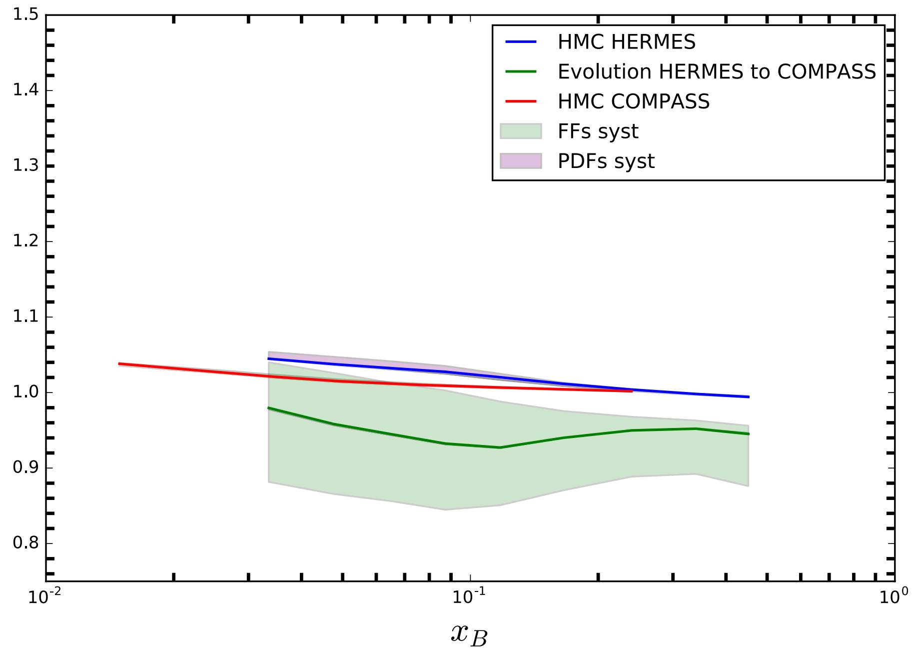




- COMPASS: theory dependence similar to experimental values
- HERMES: less steep than theory and at large-x
- Some PDF systematics, due very likely to s PDF (slopes)
  - need to refit the s quark PDF

Pions at HERMES vs. COMPASS

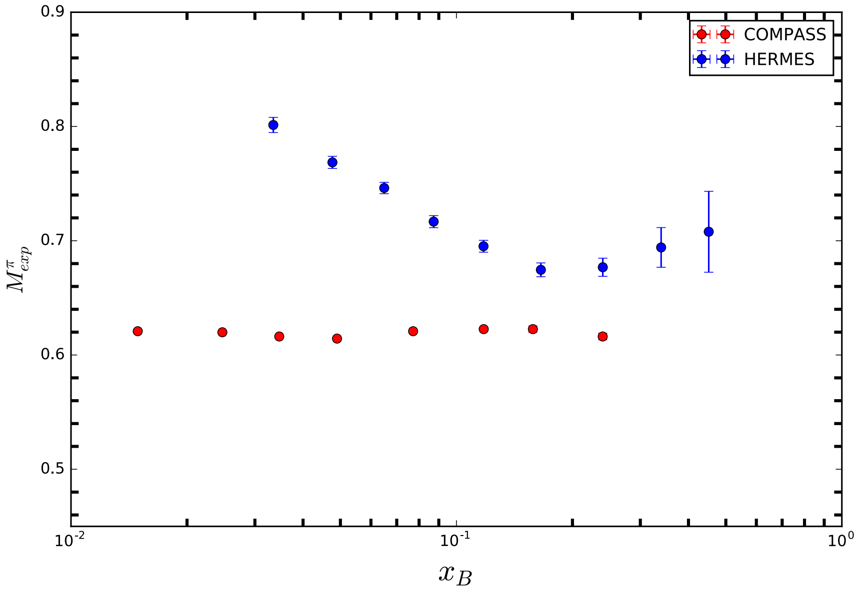
- HMC ratios: HERMES (blue line), COMPASS (red line)
- Evolution ratio (green line)
- Systematic theoretical uncertainties: (FFs, PDFs)



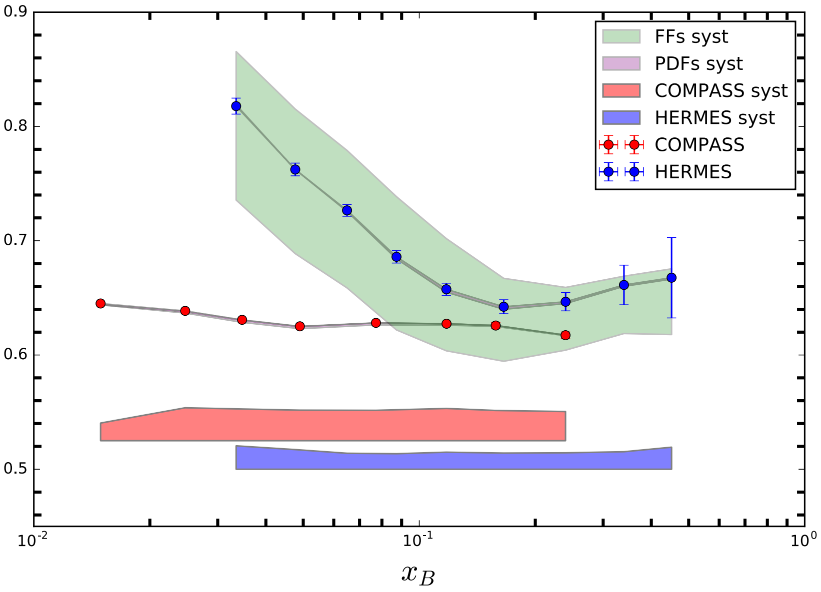
- HMCs much smaller than for Kaons.
- Comparable to evolution effects.

Pions at HERMES vs. COMPASS

Experimental Data

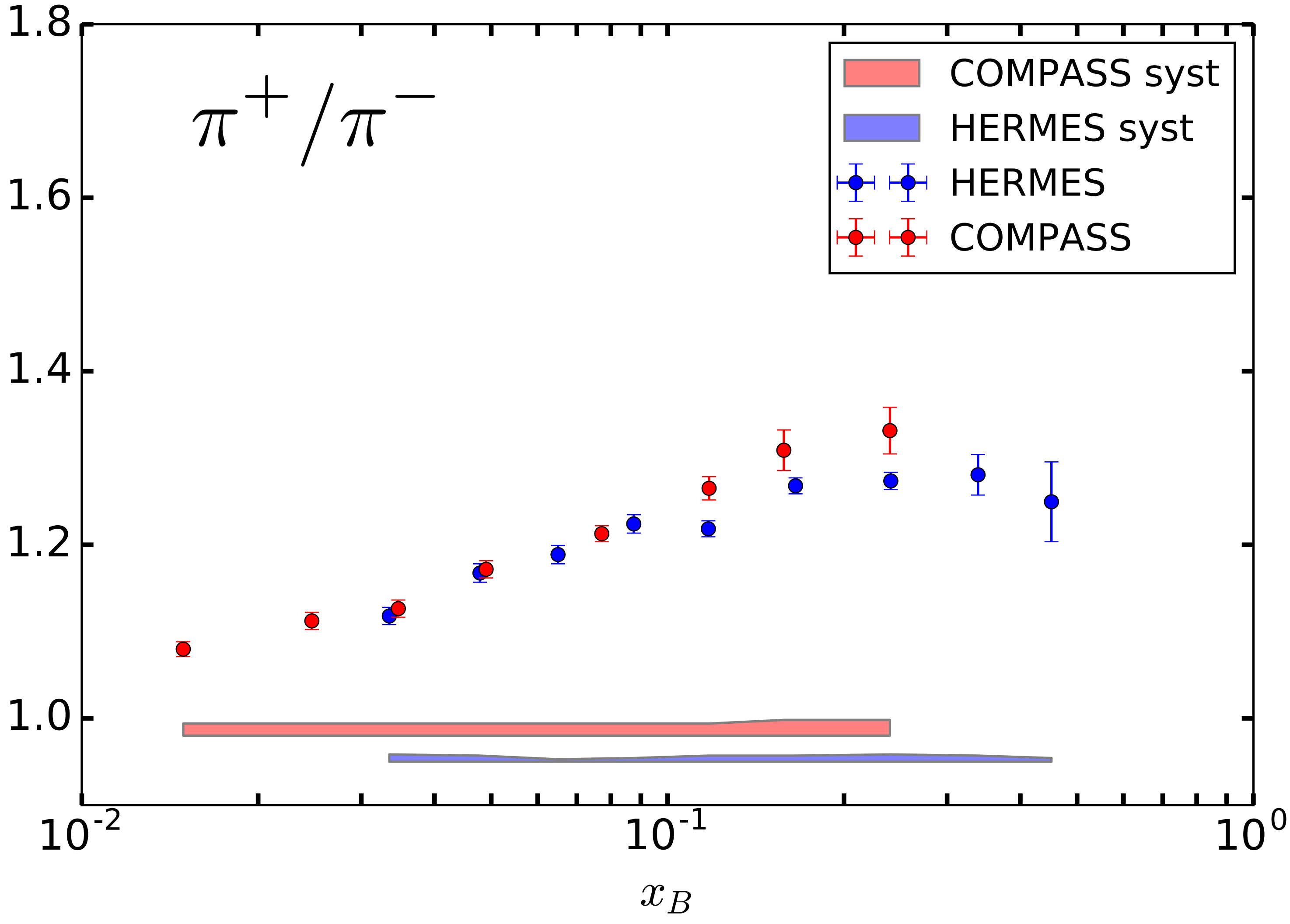


Parton level multiplicities



- 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

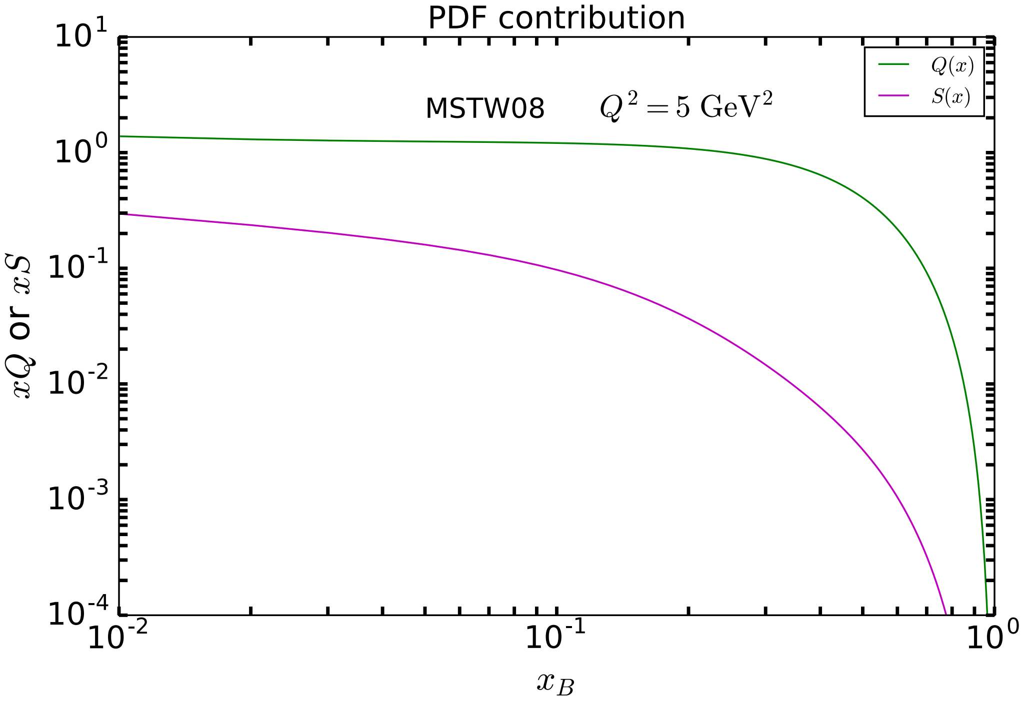
Fragmentation Functions Systematics

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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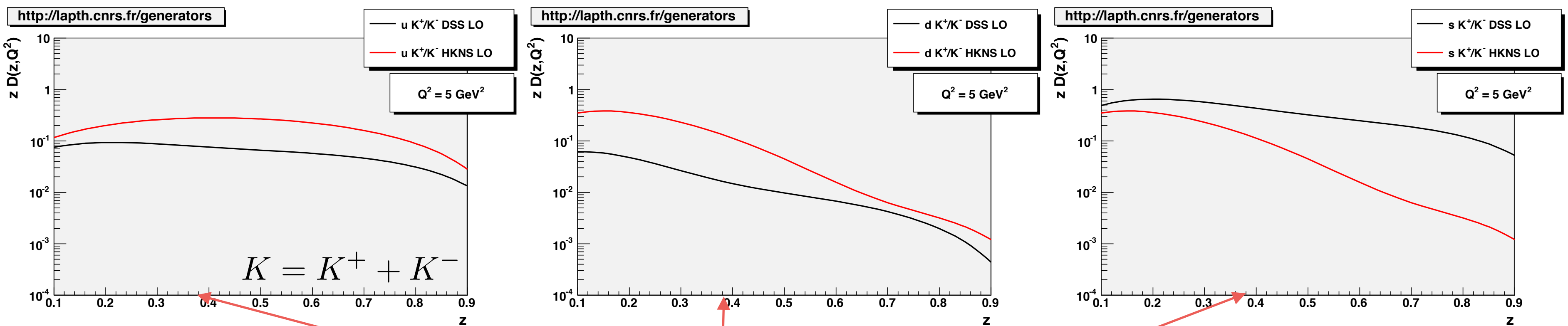
u, d, s FFs



$$< z_h > \sim 0.38$$

Large uncertainty with the choice of FFs because

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

$$Q > S$$