Hadron mass corrections in kaon production at HERMES and COMPASS

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Hampton U. and Jefferson Lab

COMPASS analysis meeting

CERN, Jul 19th, 2018

Based on: [Guerrero, Accardi, PRD 97 (2018) 114012]
(and many slides by J.V.Guerrero)

HAMPTON UNIVERSITY
THE STANDARD OF EXCELLENCE

Jefferson Lab

Overview

- **Strange strange quarks**
  - LHC, dimuons in ν+A collisions
  - HERMES vs COMPASS
- **Hadron Mass Corrections**
  - Collinear factorization with non-zero masses
- **Kaons at HERMES and COMPASS**
  - Multiplicities, charge ratios
- **What about the pions?**
- **Conclusions and perspective**

Strange strange quarks

Strange quark parton distribution function (PDF)

LHC

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

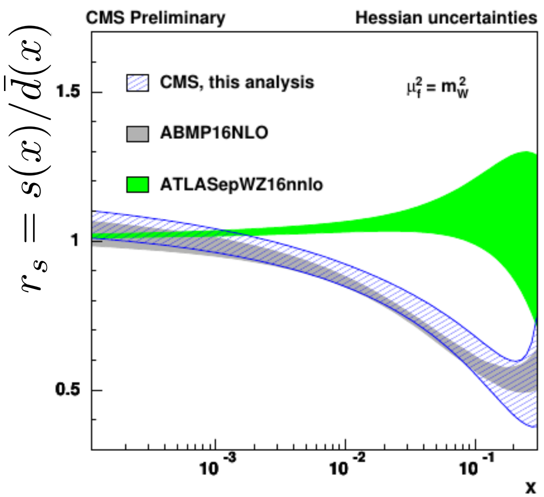
$$p + p \to W + c$$

Charged current DIS

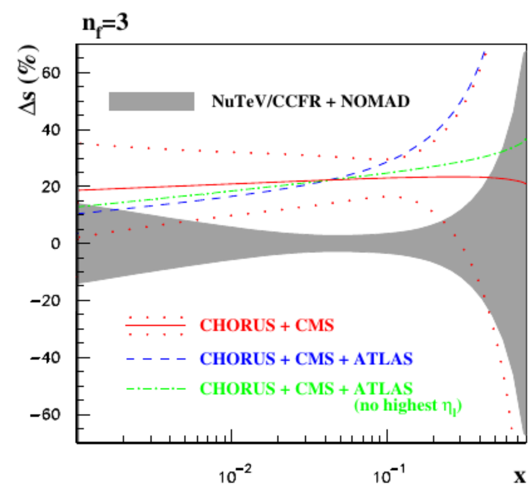
$$\nu + A \to l + c + X$$

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

→ **Need another measurement**



Svenja Pflitsch, DIS 2018

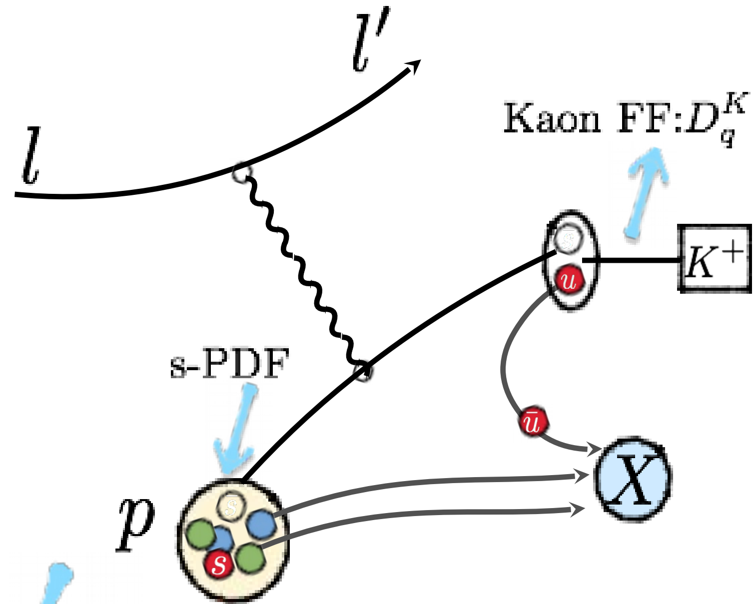


$$g\, s_p \to W\, c$$

$$\nu\, s_A \to \mu^- \mu^+ \nu_\mu\, s$$

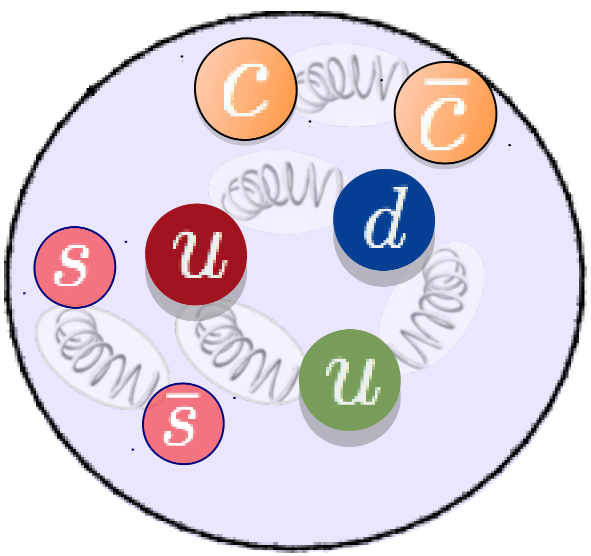
Alekhin et al., arXiv:1404.6469

s-PDF from SIDIS



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

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



- Kaons contain one s-quark in their valence structure.
- Detect a Kaon: good proxy for a strange quark in proton

How to tag s-quarks?

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:

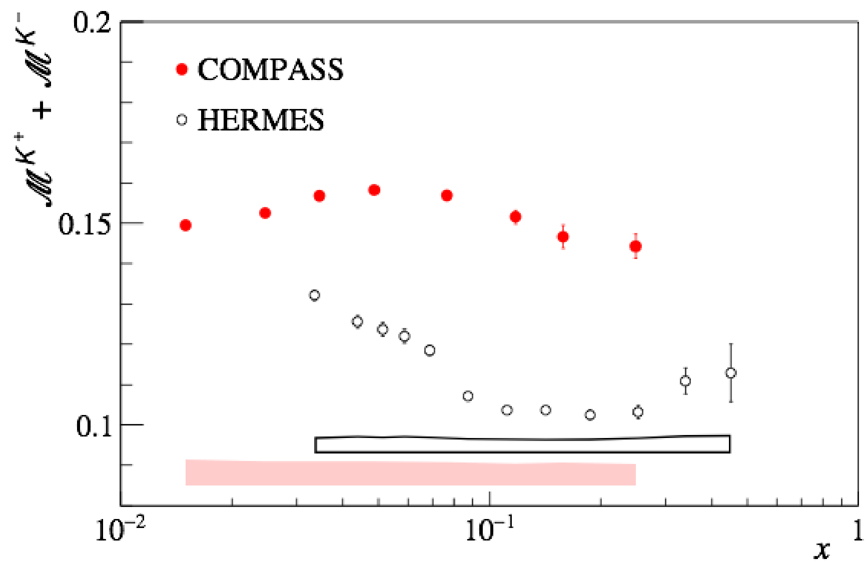
$$M^K = \frac{\sum_q e_q^2\, q(x_B) \int_{0.2}^{0.8} dz_h D_q^h(z_h)}{\sum_q e_q^2\, q(x_B)} = \frac{s(x_B)}{\sum_q e_q^2 q(x_B)} \int dz_h D_s^K(z_h)$$

$+$light quarks

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

Integrated Kaon Multiplicities: SIDIS on Deuteron

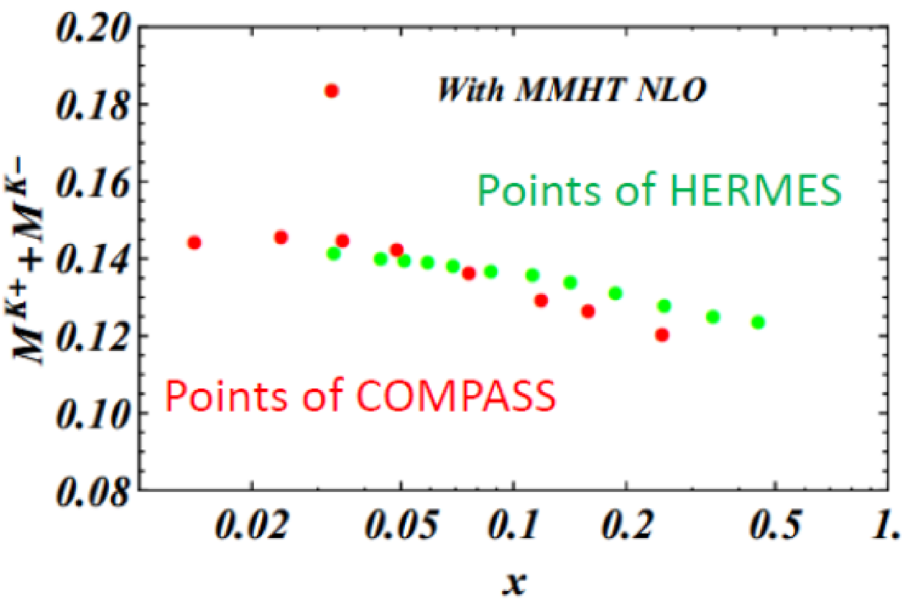
- **HERMES:**
  - Claim very different s-quark shape compared to CTEQ6L.
    → strange PDF may not be what we think!
- **But COMPASS:**
  - Different x_B dependence
  - Overall values higher.

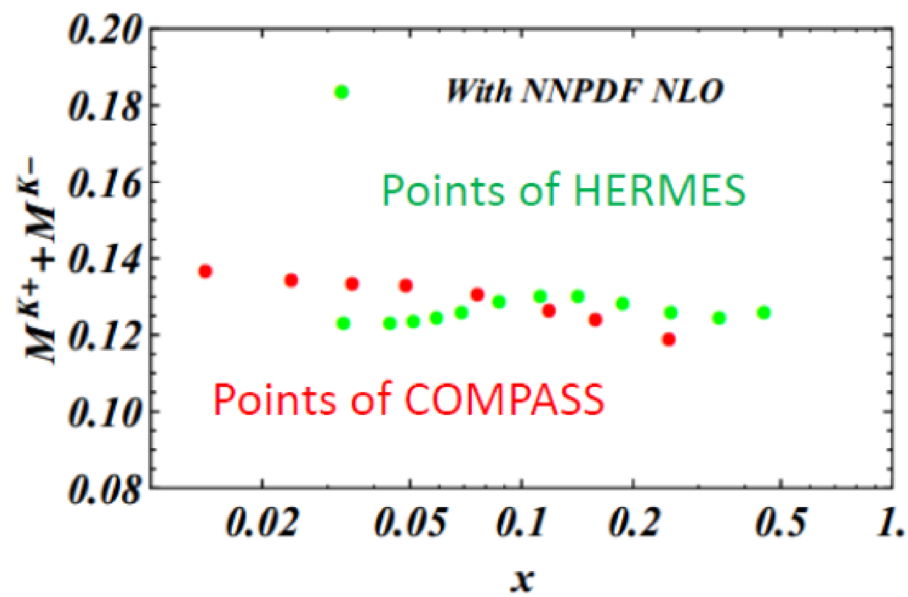


Why are HERMES and COMPASS so different?

Theoretical calculations at NLO

Plots from Chung-Wen Kao, talk at DIS 2018





- MMHT+DSS17
- NNPDF +DSS17

- H & C should be close!
- Small Q^2 evolution
- Shapes =/= data
- Other effects?

Integrated Kaon Multiplicities: SIDIS on Deuteron

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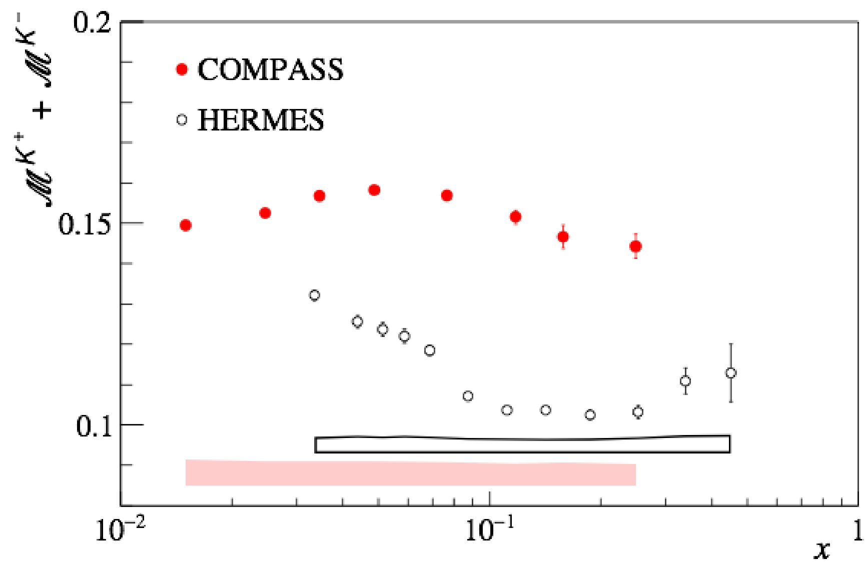


Where does this difference come from?
Is it real or apparent?

Hadron mass corrections

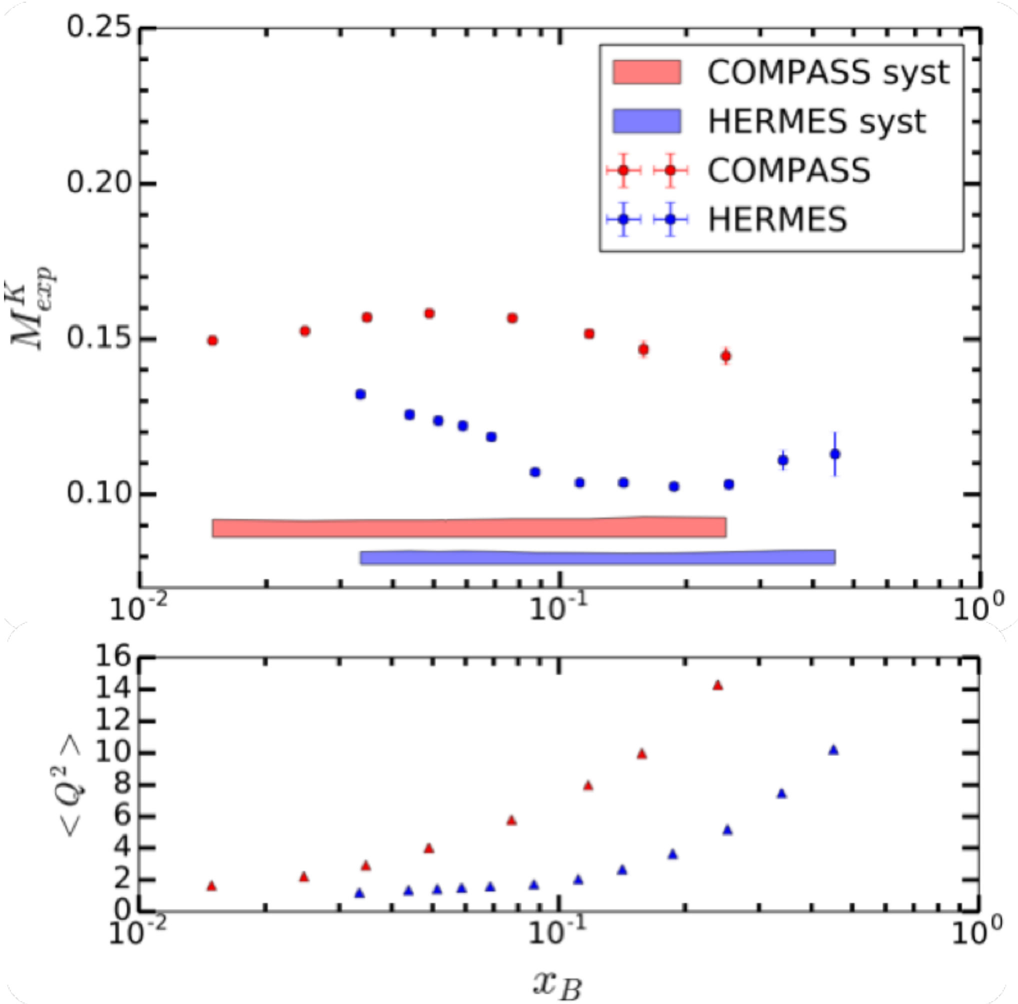
Guerrero, Accardi, PRD 97 (2018) 114012

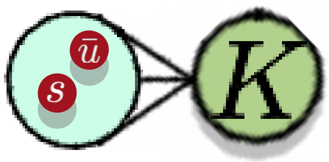
Guerrero, Ethier, Accardi, Melnitchouk, Casper, JHEP 1509 (2015) 169

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

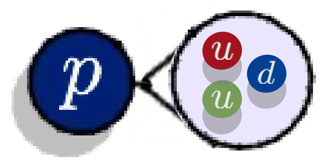
Hadron Mass Effects

Usually in pQCD, the masses of proton and 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 masses are not so negligible!

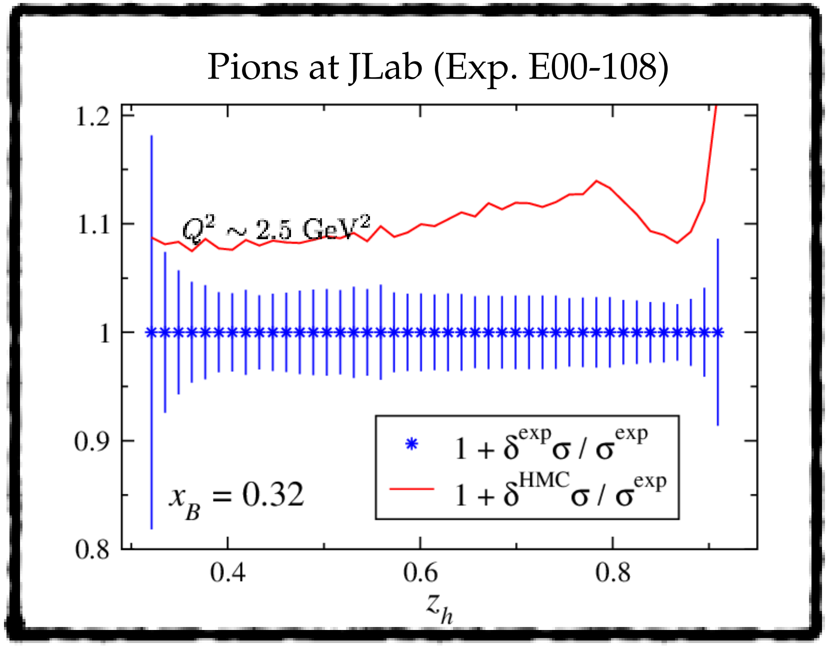
Hadron Mass Effects

Example: pion mass effects at JLab

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

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

$$m = M_P, m_\pi$$



Accardi et al JHEP 0911, 084 (2009)

Not negligible even for "light"

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

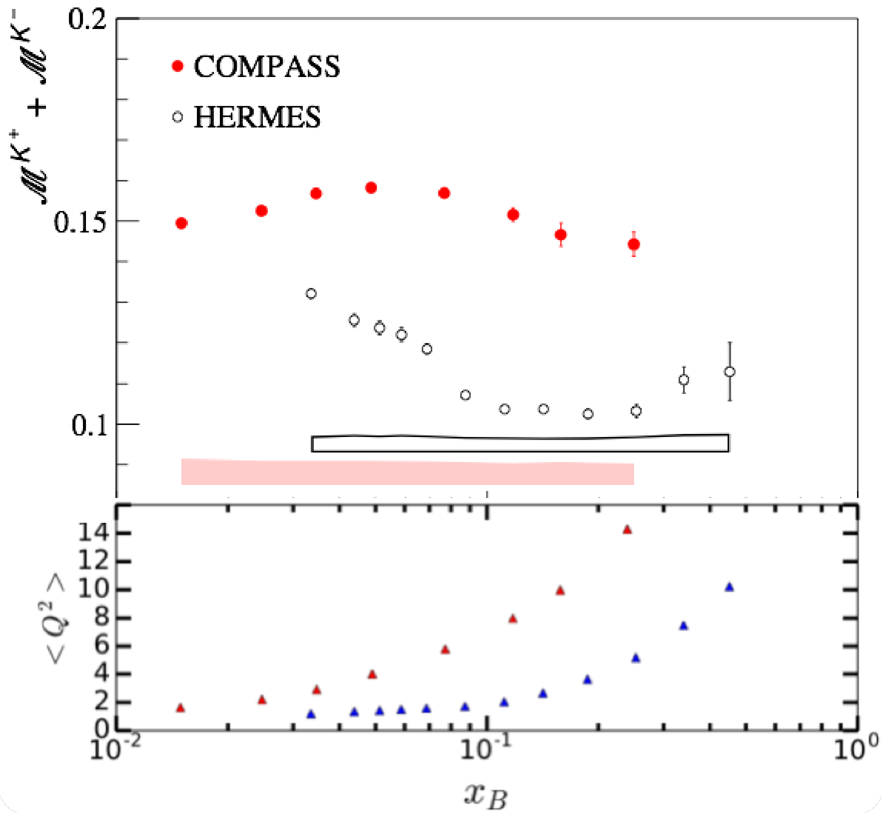
Hadron Mass Effects

Back to Kaons:

$$m_K^2 \sim 12 m_\pi^2$$

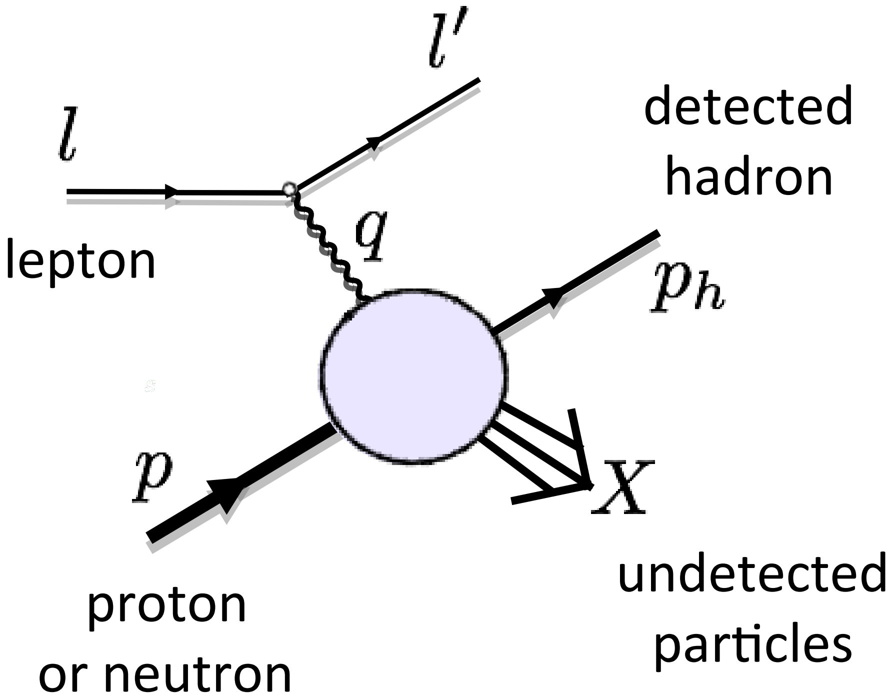
HERMES & COMPASS:

relatively low Q^2



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

SIDIS Kinematic Variables



DIS invariants

$$M^2 = p \cdot p \quad Q^2 = -q \cdot q$$

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

SIDIS invariants

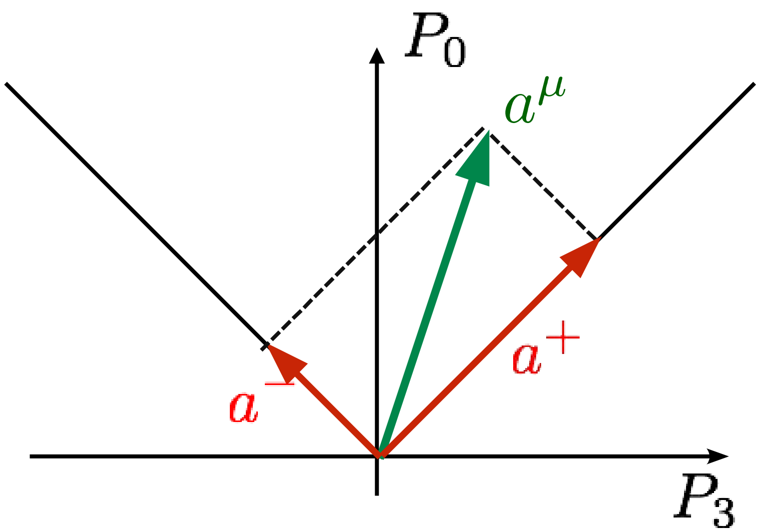
$$m_h^2 = p_h \cdot p_h$$

$$z_h = \frac{p_h \cdot p}{q \cdot p} \quad \left(\text{or } \underbrace{z_e = \frac{p_h \cdot q}{q \cdot q}}_{} \right)$$

e^+e^- like, "crossed" x_B

$$z_e \xrightarrow[Q^2 \to \infty]{} z_h$$

SIDIS: Massive scaling variables



$$a^\pm \equiv \frac{a^0 \pm a^3}{\sqrt{2}}$$

Scaling Variables

Nachtmann:

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

Bjorken limit: $\xi \xrightarrow[Q^2\to\infty]{} x_B$

Fragmentation:

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

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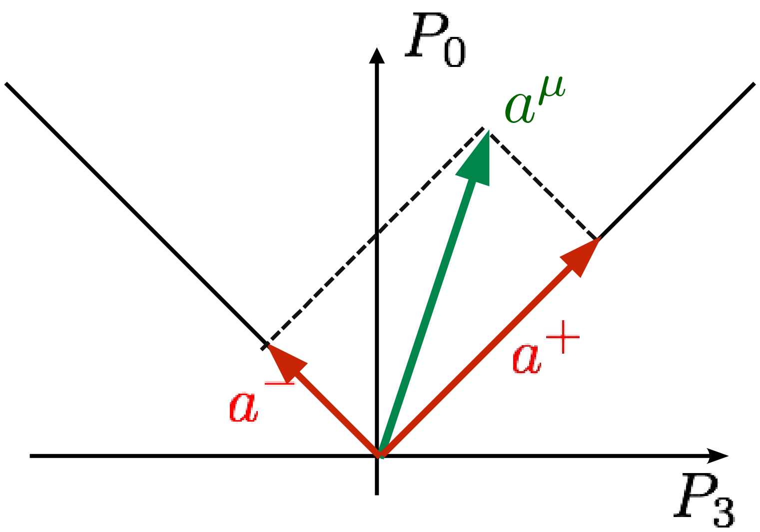

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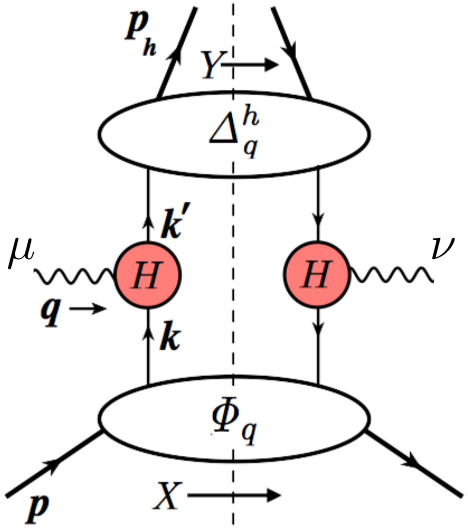
or $$\zeta_h \equiv \frac{p_h^-}{q^-} = \underbrace{\frac{z_e}{2}\left(1+\sqrt{1-\frac{4m_{h\perp}^2}{z_e^2 Q^2}}\right)}_{\text{No IS variables!}}$$

Collinear factorization with masses – LO case

Guerrero Accardi, PRD 2018 (see also Collins, Rogers Stasto 2007)



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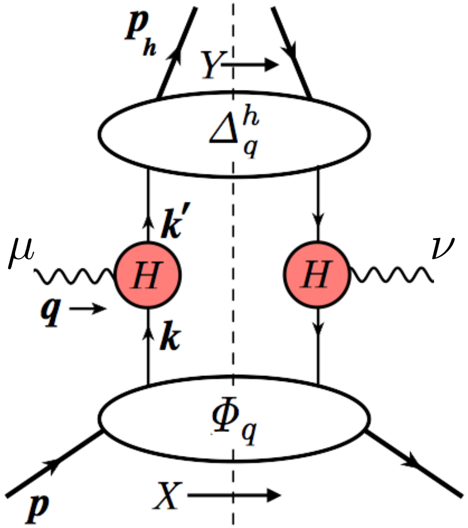

① Expand the correlators

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

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

leading terms

contribute to Higher-Twist (HT) terms

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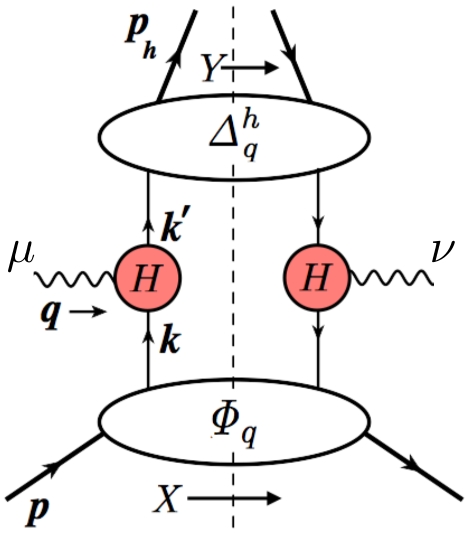

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2 Expand the hadronic tensor

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

$$= \int d^4k \; d^4k' \; \phi_2(k)\delta_2(k')\mathrm{Tr}\left[k^+ \bar{n}\gamma^\mu \, k'^- n \gamma^\nu\right] \; \delta^{(4)}(k+q-k') + \mathrm{HT}$$

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

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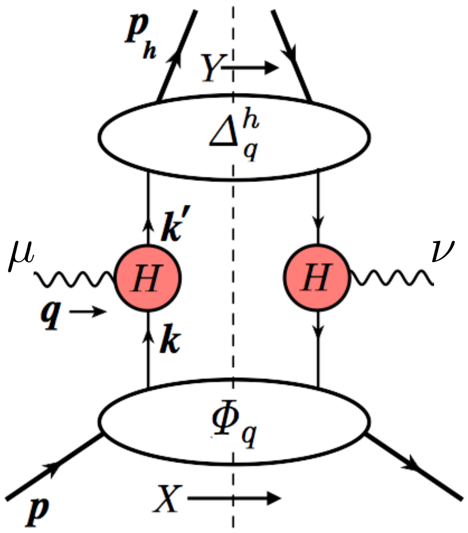

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Note: $\boxed{q_\mu W^{\mu\nu} = 0}$

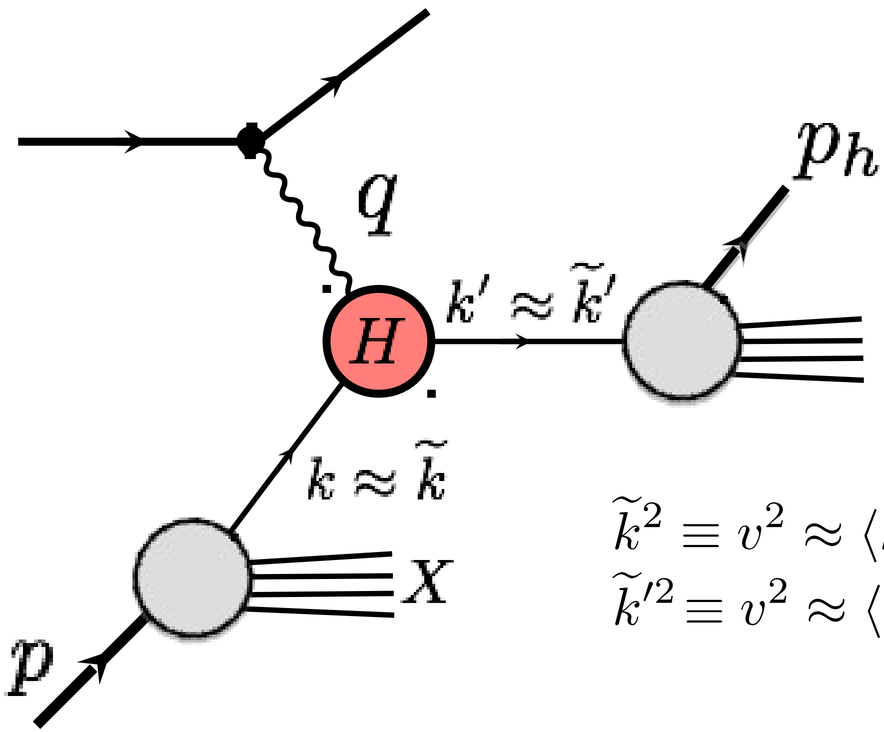
3 Approx the (overall) 4-mom conserv.

$$k \approx \widetilde{k} \; ; \quad k' \approx \widetilde{k}'$$

Approximation: collinear momenta

(p,q) frame: p and q collinear, 0 tr. mom.

$$\begin{cases} p = (p^+, M^2/2p+, \mathbf{0_T}) \\ q = (-\xi p^+, Q^2/2\xi p^+, \mathbf{0_T}) \end{cases}$$



$$\left.\begin{array}{l} \widetilde{k}^2 \equiv v^2 \approx \langle k^2 + k_\perp^2 \rangle \\ \widetilde{k}'^2 \equiv v^2 \approx \langle k'^2 + k_\perp'^2 \rangle \end{array}\right\} \text{“Average virtualities”}$$

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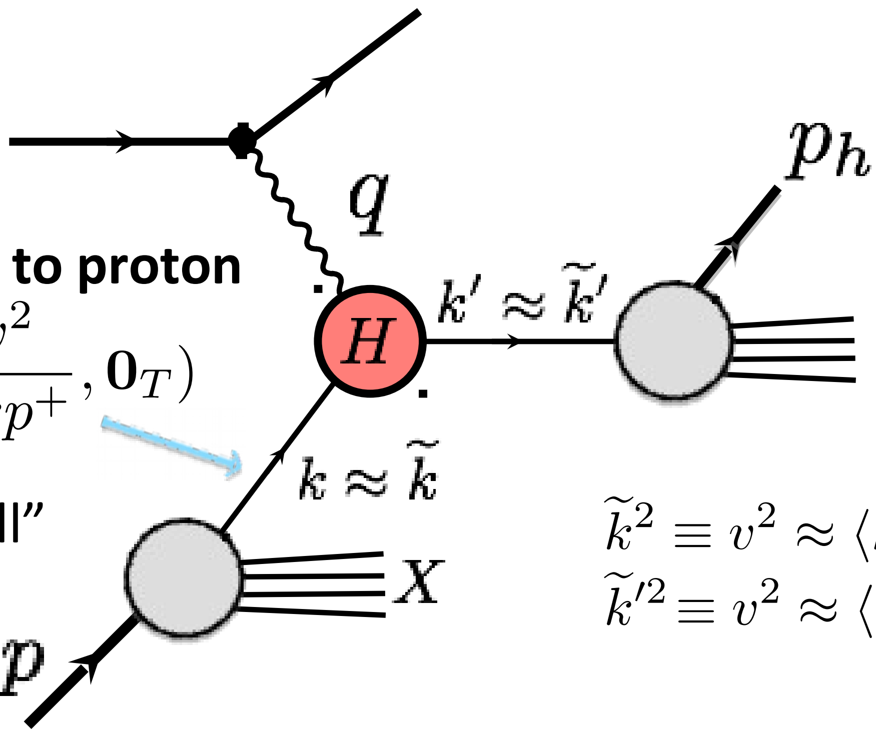
Parton collinear to proton

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

… and “on-shell”

$$\boxed{v^2 = 0}$$



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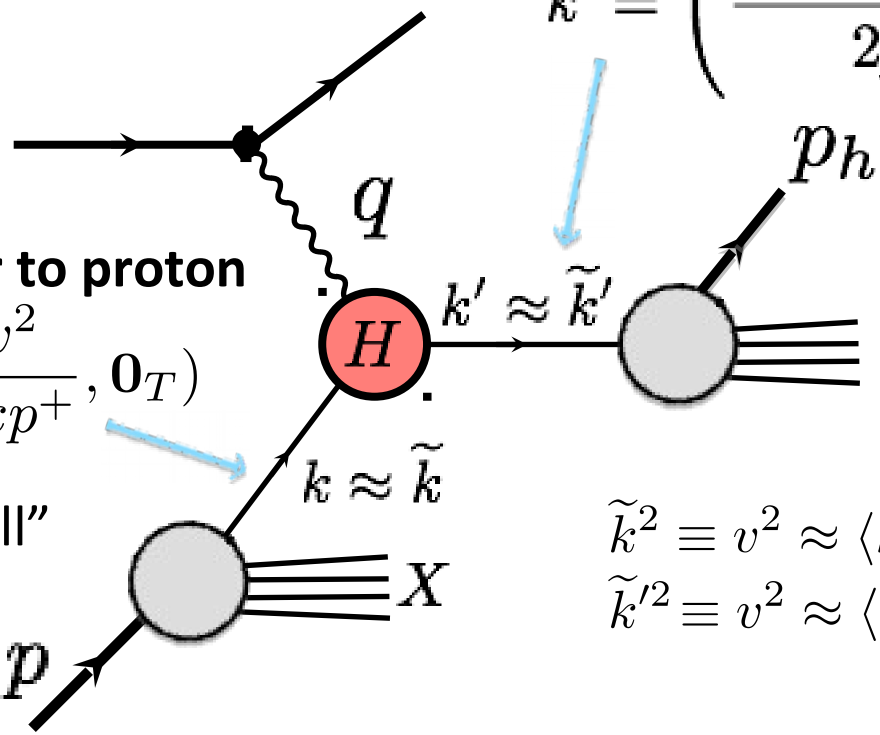
Fragmenting parton collinear to hadron

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

...but fragments into a **massive** hadron:

$$\boxed{v'^2 = ??}$$



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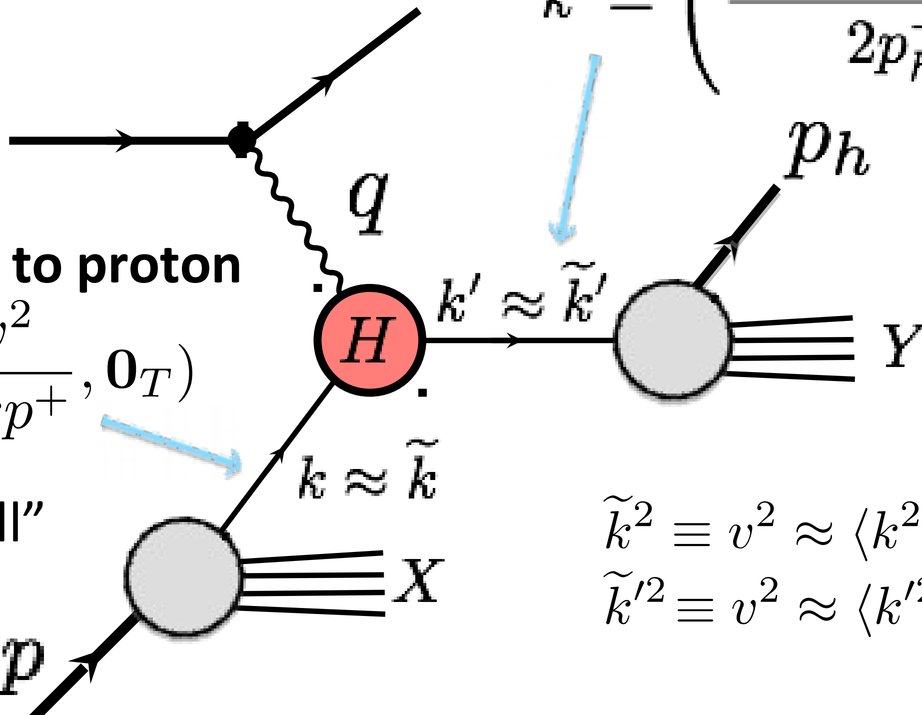

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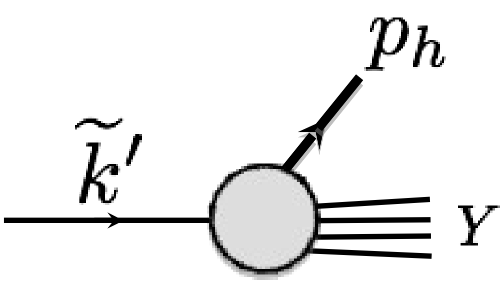
How to match partonic and hadronic kinematics?

Matching Hadronic and Partonic Kinematics at LO

(much more detail in Guerrero et al., JHEP 2015)

Fragmenting blob: momentum conservation in + direction

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



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

Orthodox choice:

$$v'^2 = 0$$

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

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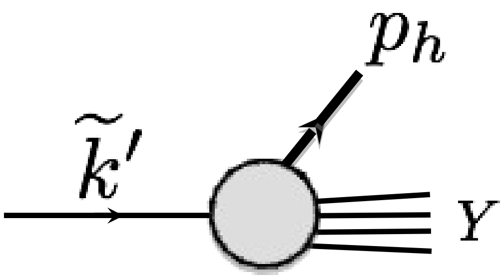

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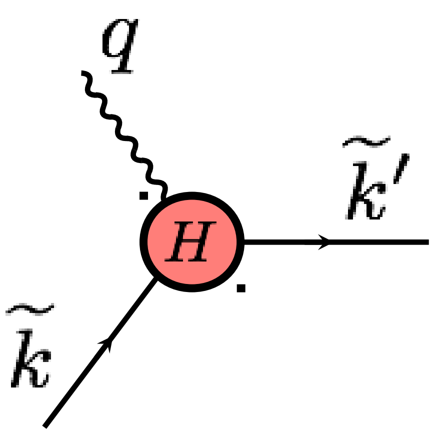
Hard scattering: 4-momentum conservation at LO



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

$$z = \zeta_h$$

Only in Bjorken limit can one neglect v' !

Collinear factorization with masses - LO case

4 Let 3 integrations out of 4 act on correlators, obtain

$$\boxed{2MW^{\mu\nu} = \sum_q e_q^2 \int \frac{dx}{x}\frac{dz}{z}\, q(x)\, \mathcal{H}^{\mu\nu}(x,z)\, D_q(z) + \mathrm{HT}}$$

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$$q(x) = \int dk^- d^2k_T \phi_2(k)$$ ← **PDF**

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$$k'_0 \equiv \widetilde{k}'|_{v=0}$$

$$\mathcal{H}^{\mu\nu}(x,z) = \frac{1}{2z}\mathrm{Tr}\left[\not{k}_0 \gamma^\mu \not{k}'_0 \gamma^\nu\right]$$ ← **Hard scattering coefficient**

$$\times\ \delta\Big(k_0^+ + q^+ - \frac{v'^2}{2k_0'^-}\Big)\, \delta\Big(\frac{v^2}{2k_0^+} + q^- - k_0'^-\Big)\, \delta^{(2)}(\boldsymbol{k}'_{0T})$$

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

Collinear factorization with masses - LO case

4 Let 3 integrations out of 4 act on correlators, obtain

$$\boxed{2MW^{\mu\nu} = \sum_q e_q^2 \int \frac{dx}{x}\frac{dz}{z}\, q(x)\, \mathcal{H}^{\mu\nu}(x,z)\, D_q(z) + \mathrm{HT}}$$

$$q(x) = \int dk^- d^2 k_T \phi_2(k)$$ ← **PDF**

$$D_q(z) = (z/2) \int dk'^+ d^2 k'_T \delta_2(k)$$ ← **FF**

$$k_0 \equiv \widetilde{k}|_{v=0}$$

$$k'_0 \equiv \widetilde{k}'|_{v=0}$$

$$\mathcal{H}^{\mu\nu}(x,z) = \frac{1}{2z} \mathrm{Tr}\left[\not{k}_0 \gamma^\mu \not{k}'_0 \gamma^\nu\right]$$ ← **Hard scattering coefficient**

$$\times\ \delta\Big(k_0^+ + q^+ - \frac{v'^2}{2k_0'^-}\Big)\, \delta\Big(\frac{v^2}{2k_0^+} + q^- - k_0'^-\Big)\, \delta^{(2)}(\boldsymbol{k'_{0T}})$$

$$\boxed{x = \xi_h \equiv \xi\Big(1 + \frac{m_h^2}{\zeta_h Q^2}\Big)} \qquad \boxed{z = \zeta_h}$$

Kaons at HERMES and COMPASS

Guerrero, Accardi, PRD 97 (2018) 114012

Leading Order (LO) Multiplicities at finite Q^2

- **With Hadron Masses:**

Scale dependent Jacobian

Finite Q^2 scaling variables

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

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

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

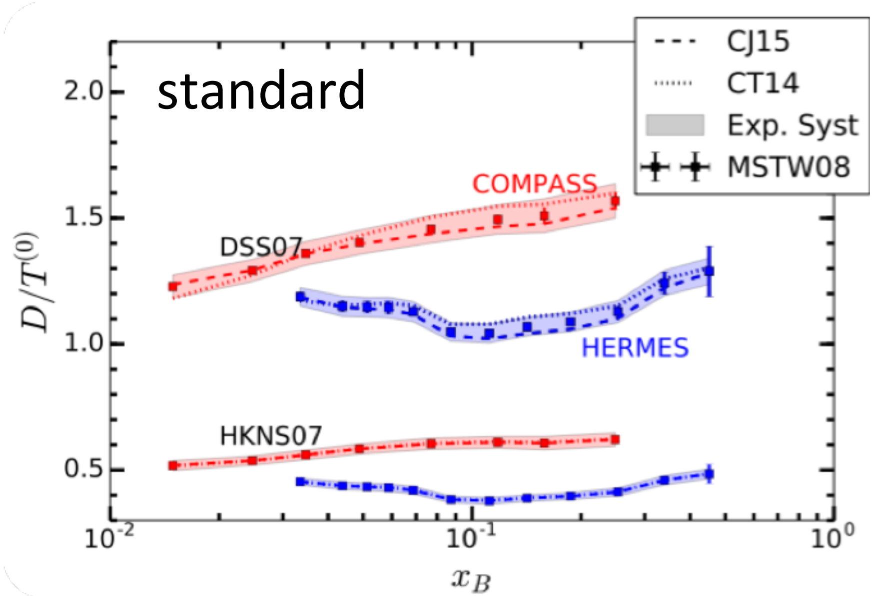
- **Massless limit:** $\left(\frac{M^2}{Q^2}, \frac{m_h^2}{Q^2}\right) \to 0$

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

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



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

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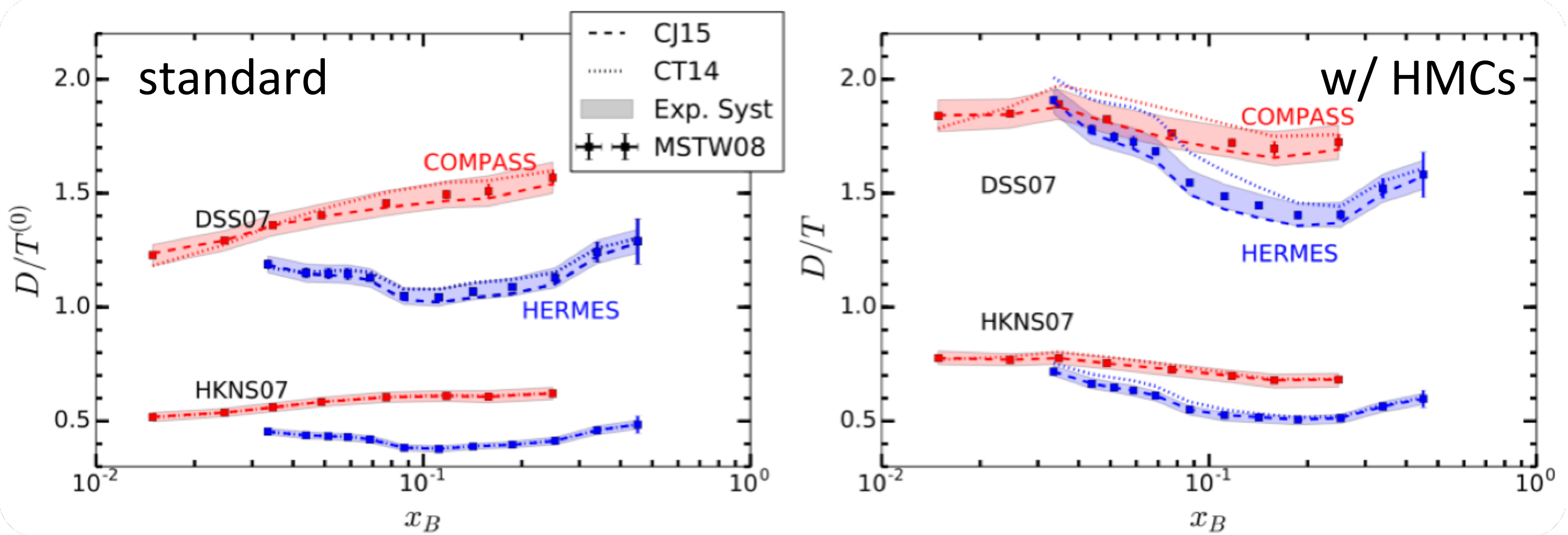

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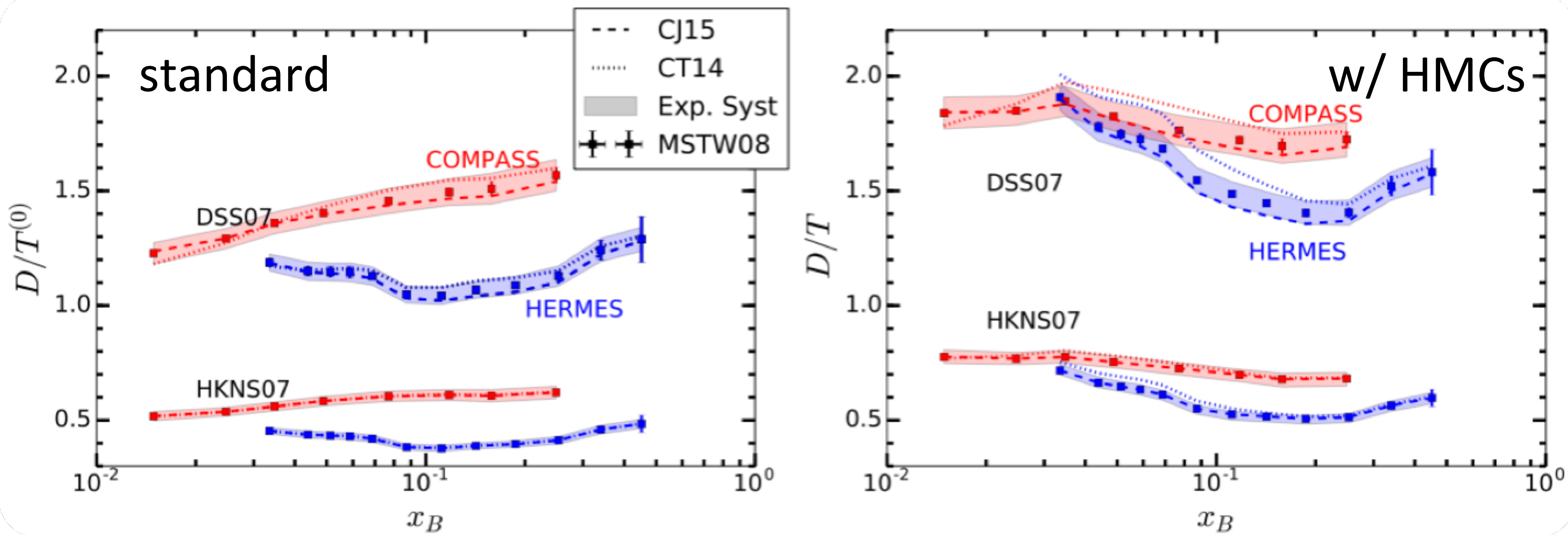


- <u>**After HMCs:**</u>
  - Size discrepancy reduced
  - Slope more flat
  - COMPASS OK (except normalization)
  - Residual tension with HERMES slope

Needs refit of kaon FFs

HERMES & COMPASS data: direct comparison

Use suitable
"Theoretical correction ratios"

- Produce approximate "massless" parton model multiplicities
- Make data directly comparable
- Largely insensitive to FF normalization

COMPASS:

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

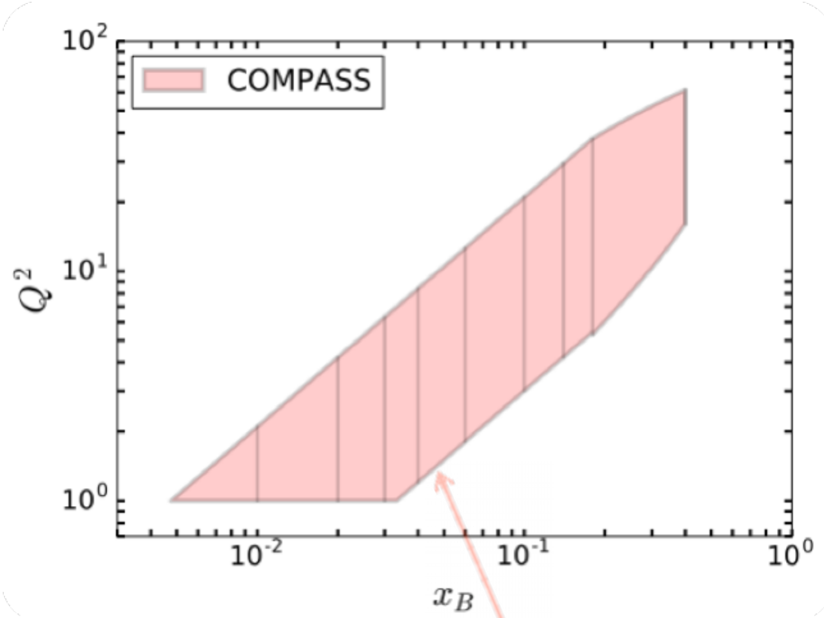
HMC correction ratio

HERMES:

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

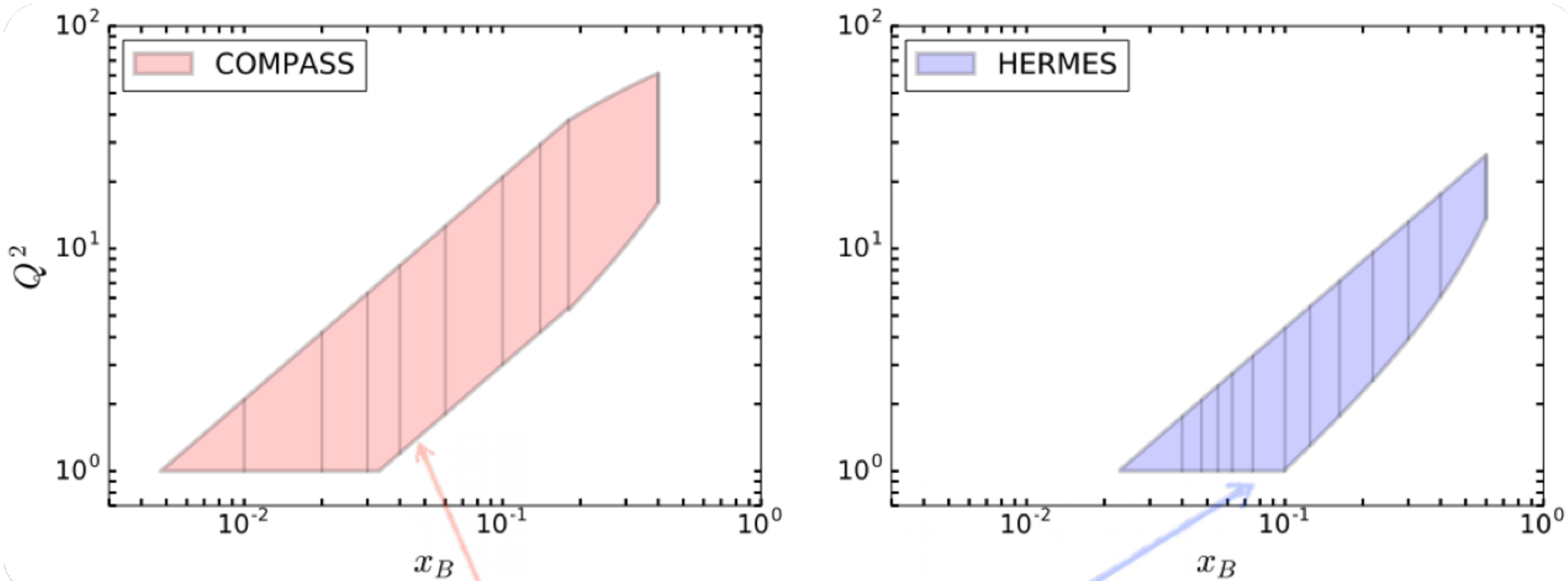
HERMES to COMPASS evolution

HERMES & COMPASS data: direct comparison



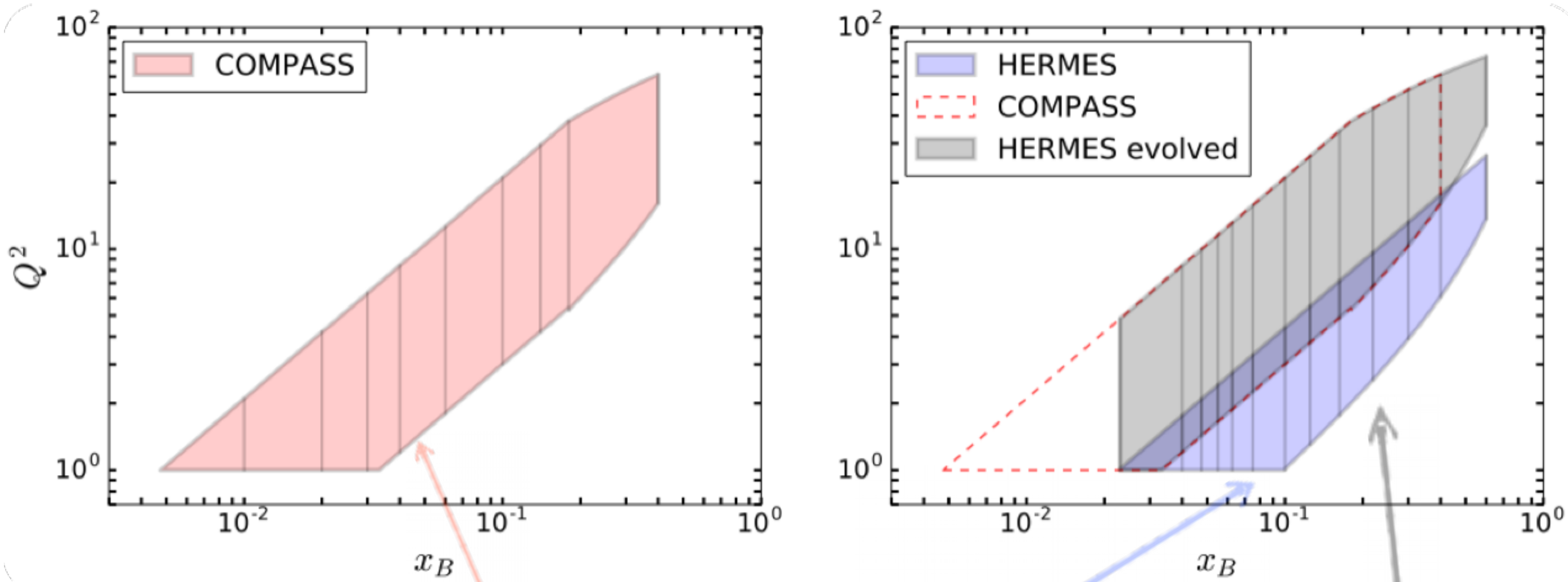
HMC ratio: $$R^h_{HMC} = \frac{M^{h(0)}}{M^h}$$

HERMES & COMPASS data: direct comparison



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

HERMES & COMPASS data: direct comparison



HMC ratio: $R^h_{HMC} = \dfrac{M^{h(0)}}{M^h}$

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

(HERMES to COMPASS)

HERMES & COMPASS data: direct comparison

Use suitable
"Theoretical correction ratios"

- Produce approximate "massless" parton model multiplicities
- Make data directly comparable
- Largely insensitive to FF normalization

Multiplicities in a massless world:

– mass corrected (and evolved) M^h –

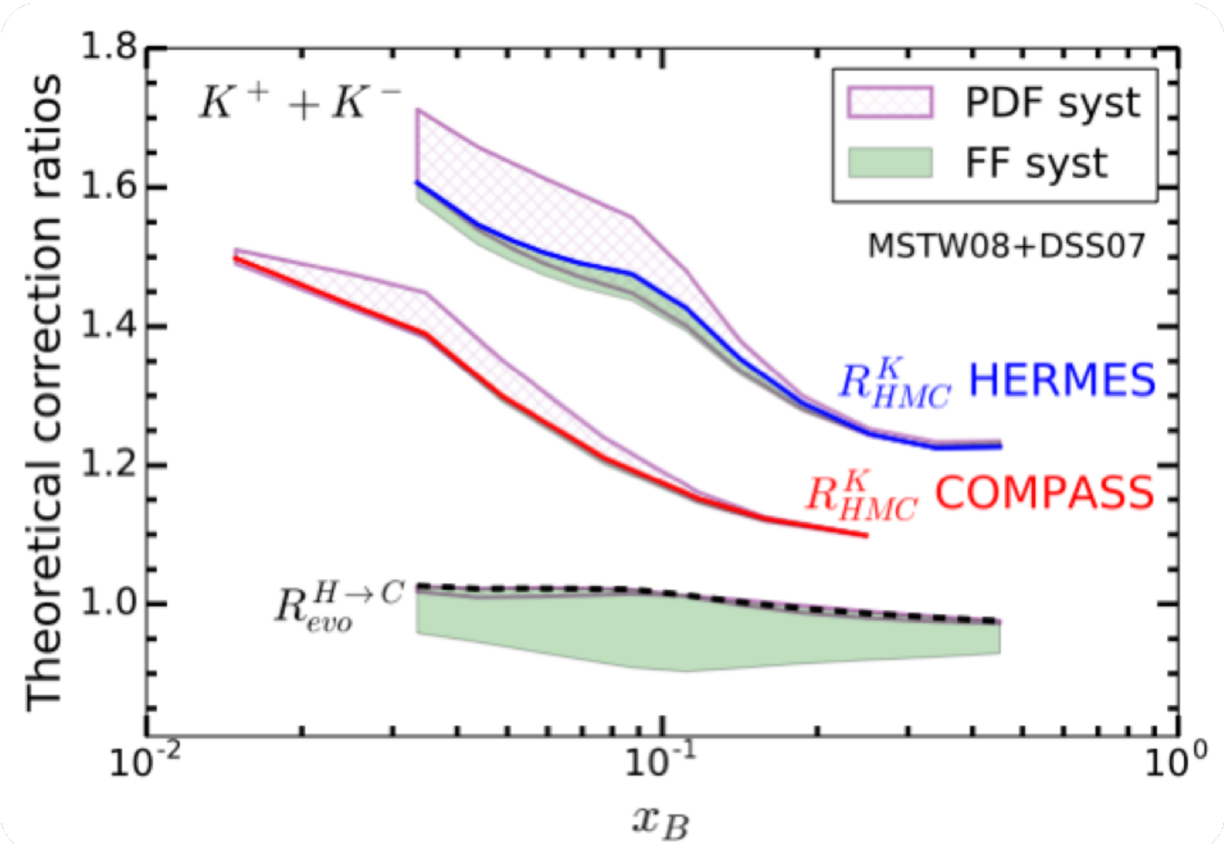
COMPASS:

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

HERMES:

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

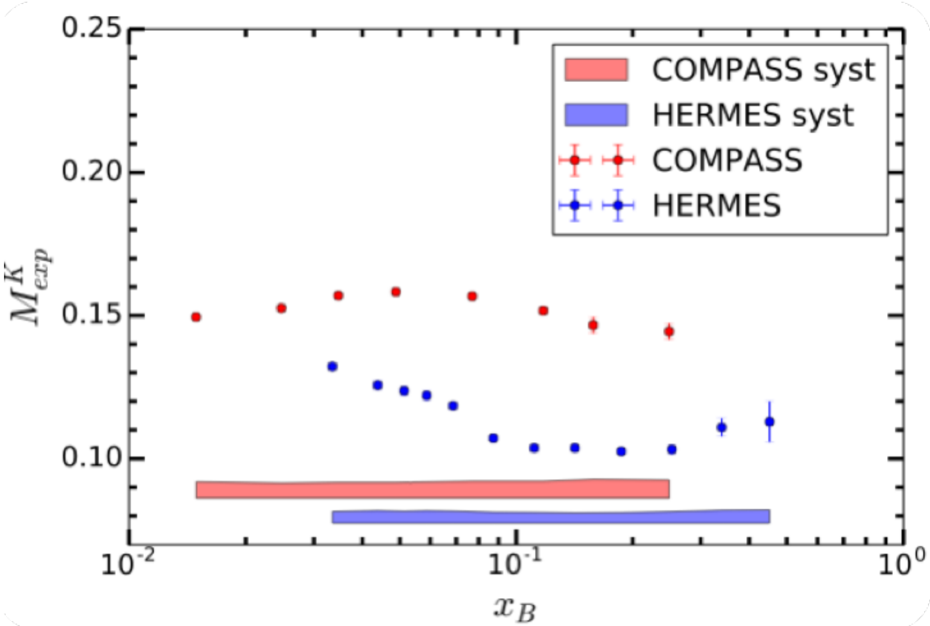
Correction ratios



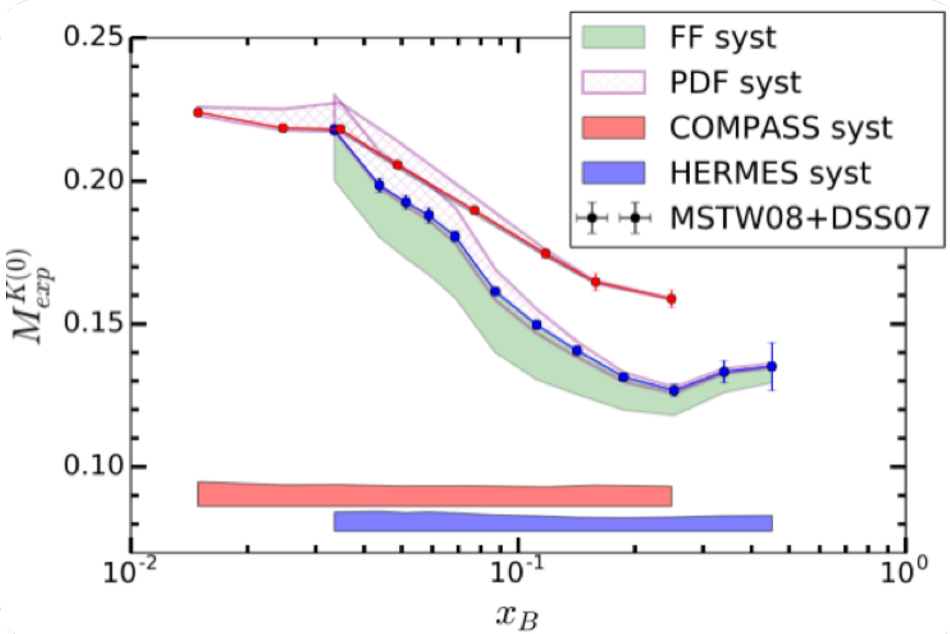
- Hadron mass effects dominant over evolution effects
- COMPASS has smaller HMCs than HERMES.

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

Experimental Data



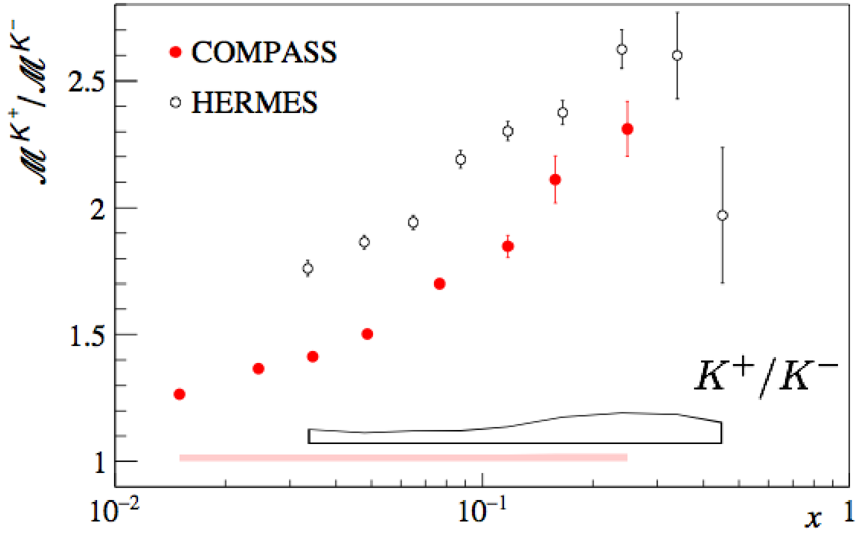
"Massless data" at same Q^2



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

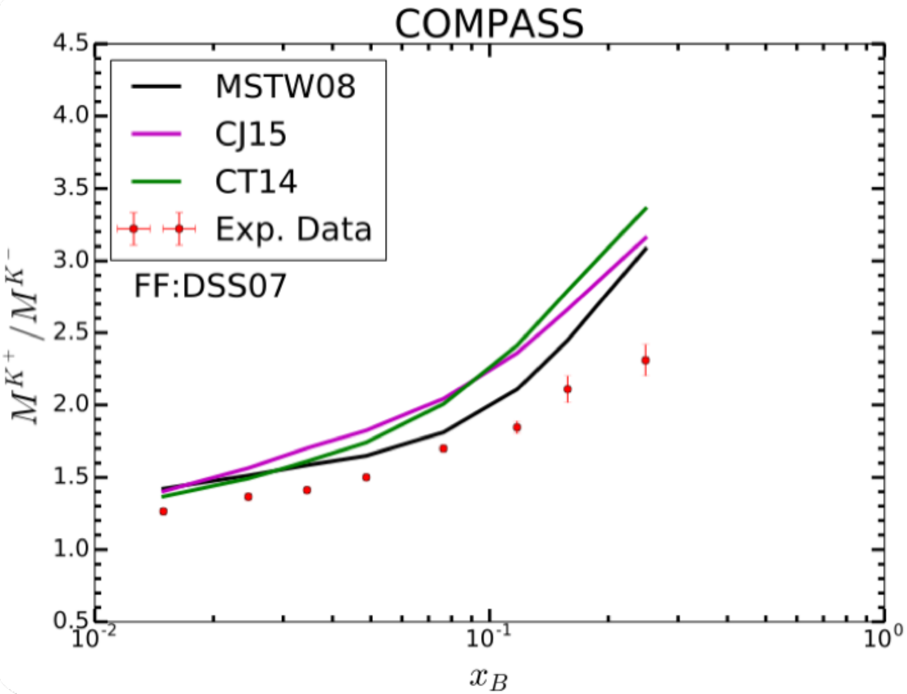
Kaon ratios

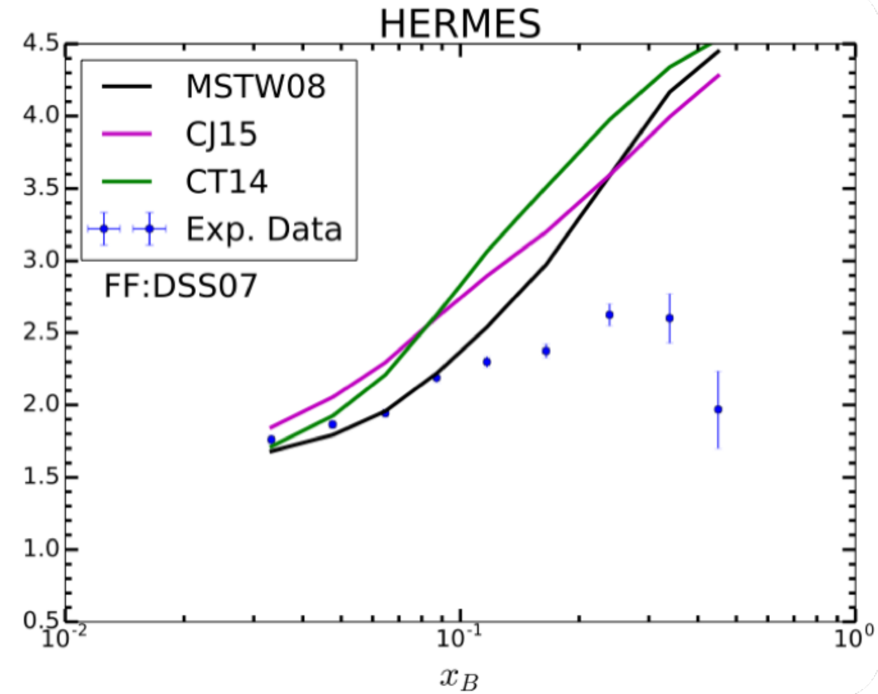
- **Reduced experimental systematics**
  - Highlights physics effects better
- **Reduced theory uncertainty**
  - (should) largely cancel non-negligible FF systematics
  - ...but could not check: no charge separation in HKNS set



- Size discrepancy persists
- Slopes are now compatible
- What's left: HMCs, exp. syst.?

Data vs. theory





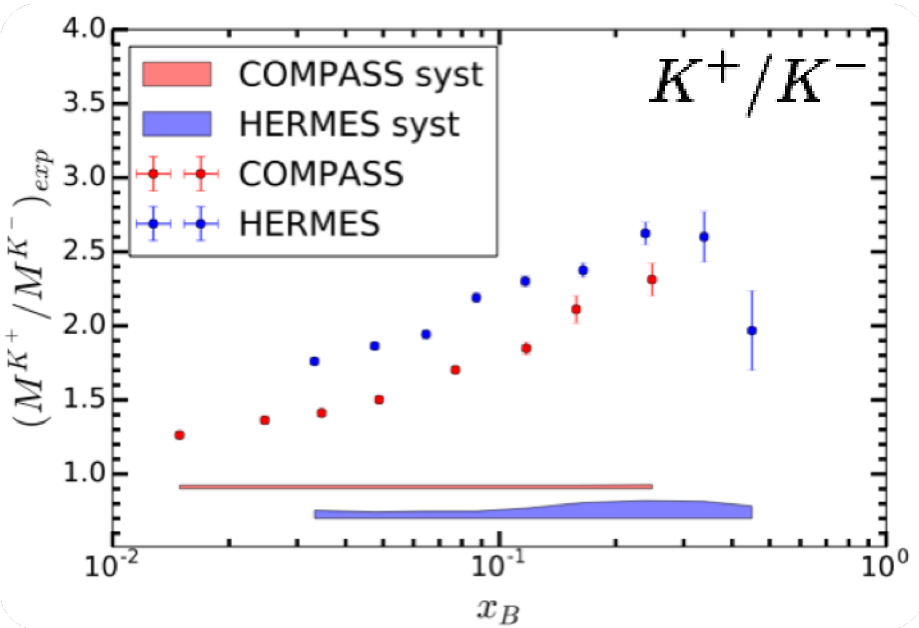
– COMPASS: theory dependence similar to experimental values

– HERMES: less steep than theory and at large-x

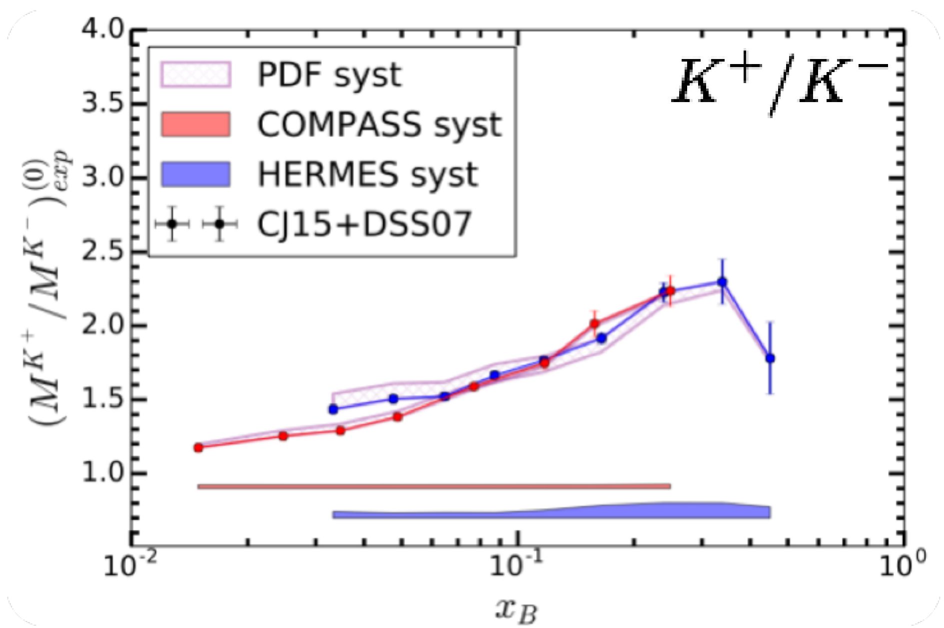
– Some PDF systematics, due very likely to s PDF (slopes)

Direct Data Comparison: K^+/K^-

Experimental Data



"Massless data" at same Q^2

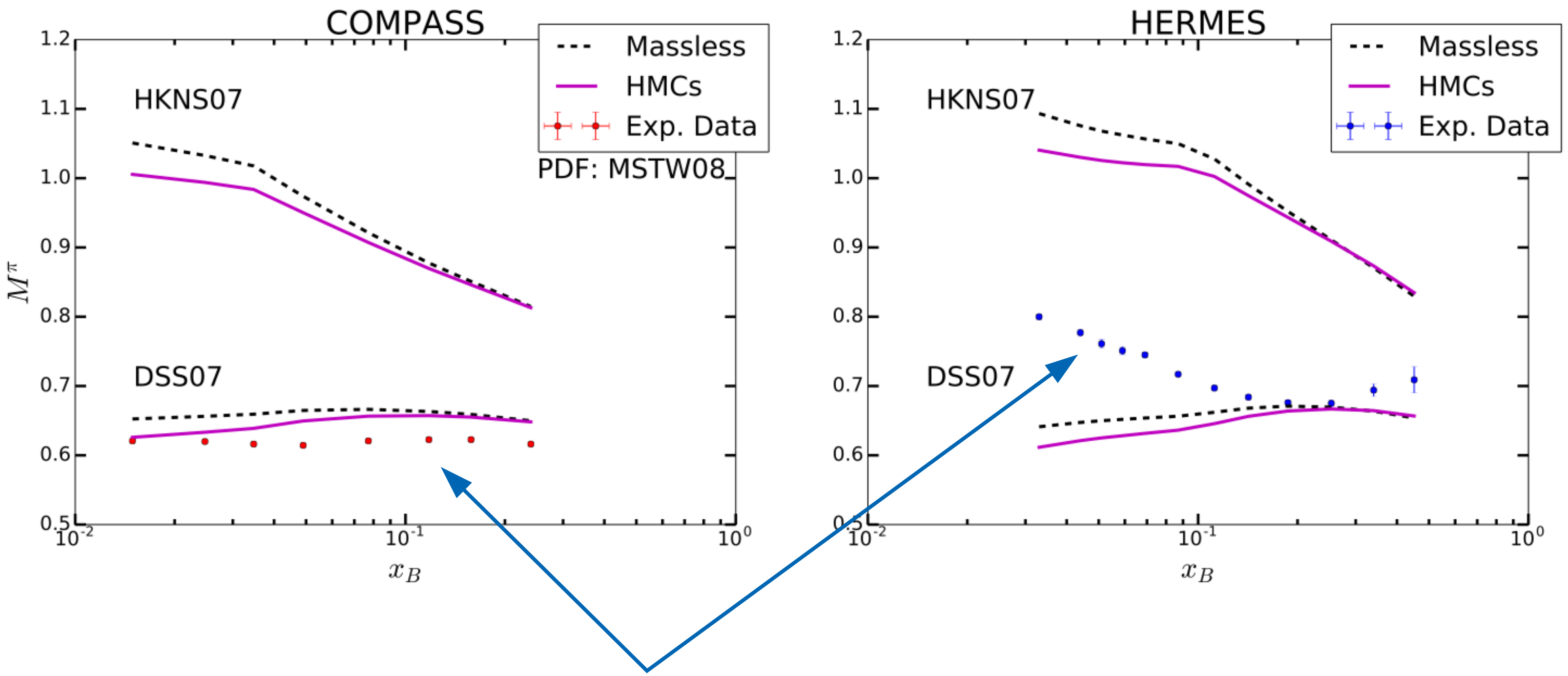


- **HERMES & COMPASS fully compatible.**
- last x bin at HERMES suspicious

What about pions?

Guerrero, Accardi - PRELIMINARY

pi⁺ + pi⁻ Multiplicities



HERMES shape?

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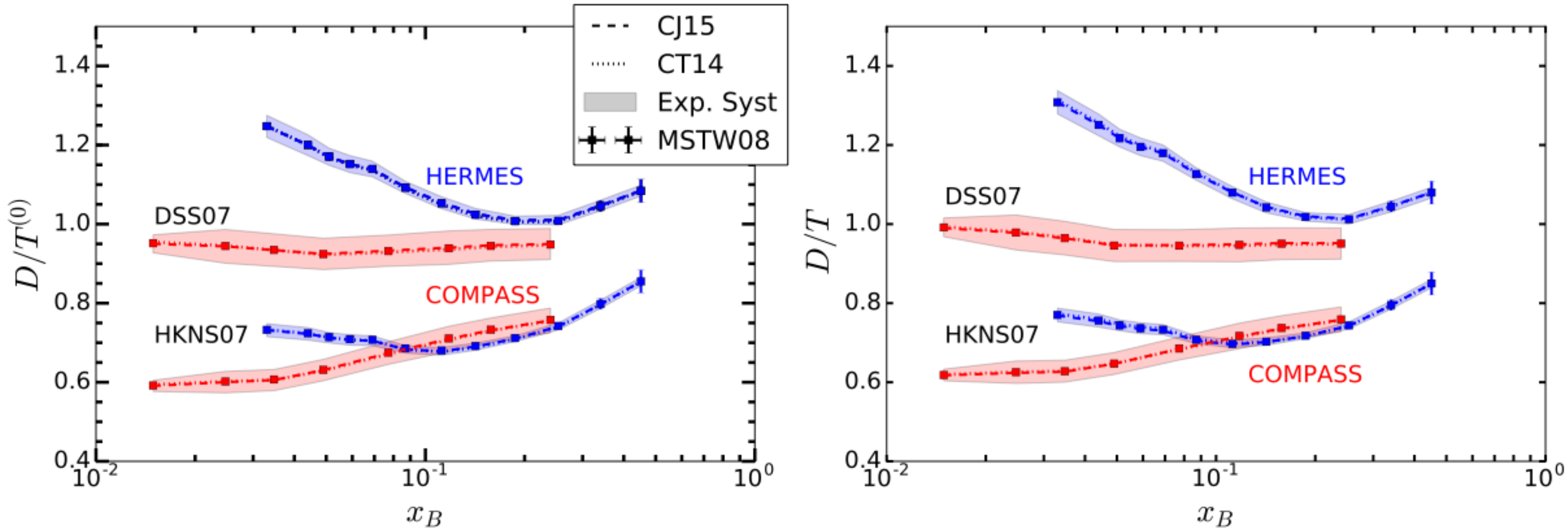
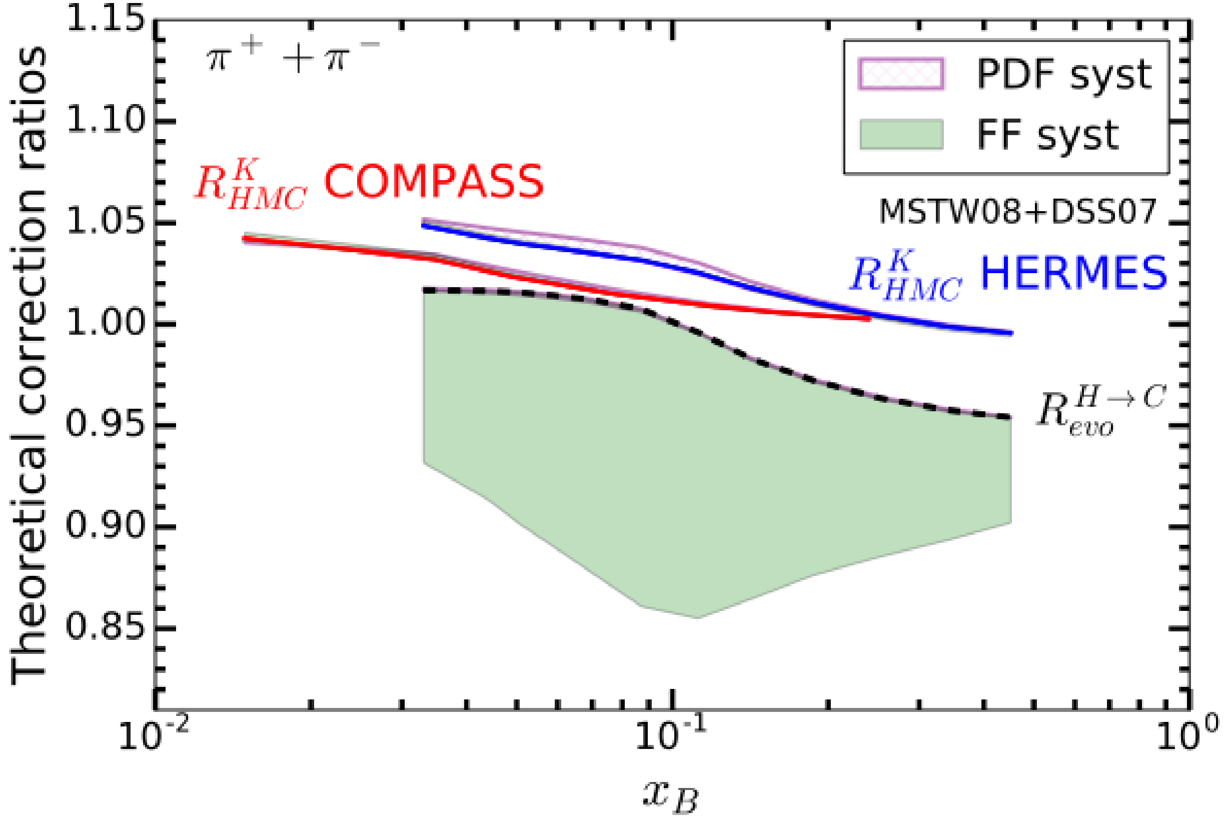
Data over Theory: pi$^+$ + pi$^-$

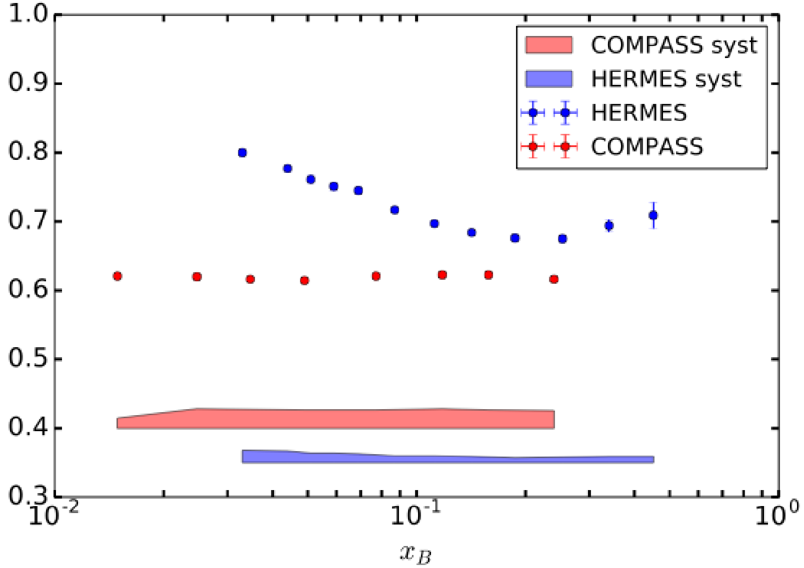


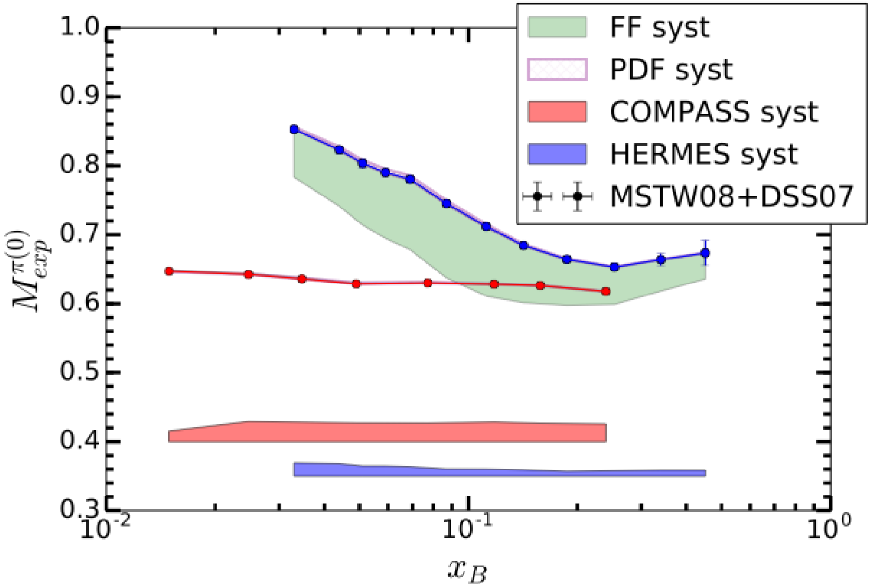
Correction ratios



– HMCs much smaller than for Kaons
– Comparable to evolution effects

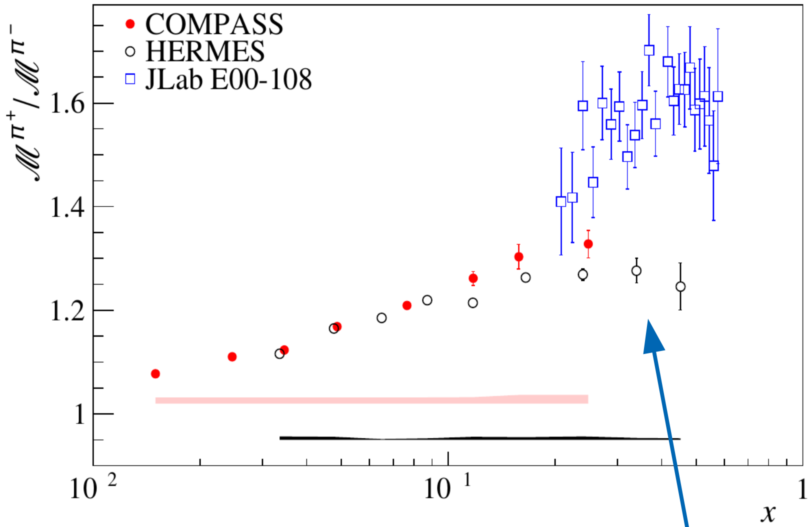
Direct Data Comparison: pi$^+$ + pi$^-$

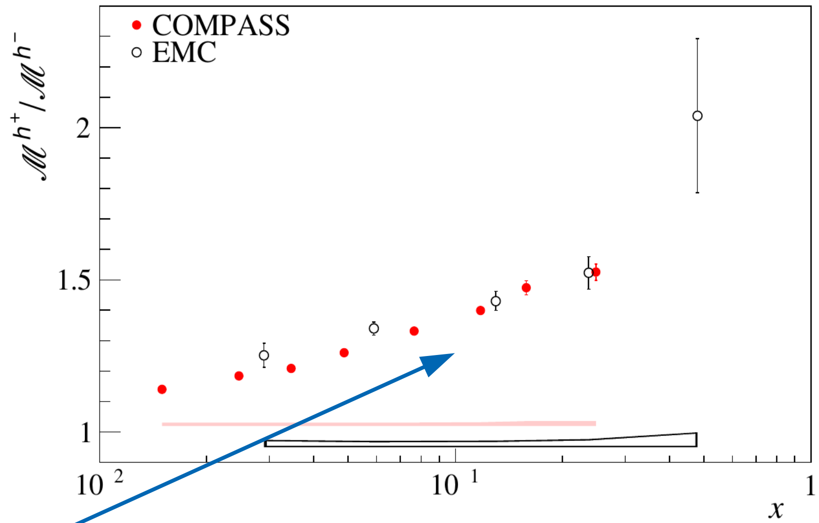




- Slopes still incompatible also for pions.
- "Hockey stick" shape as for Kaons
- Origin of down slope? NLO effect?
- Jlab Pions?

Pion ratio

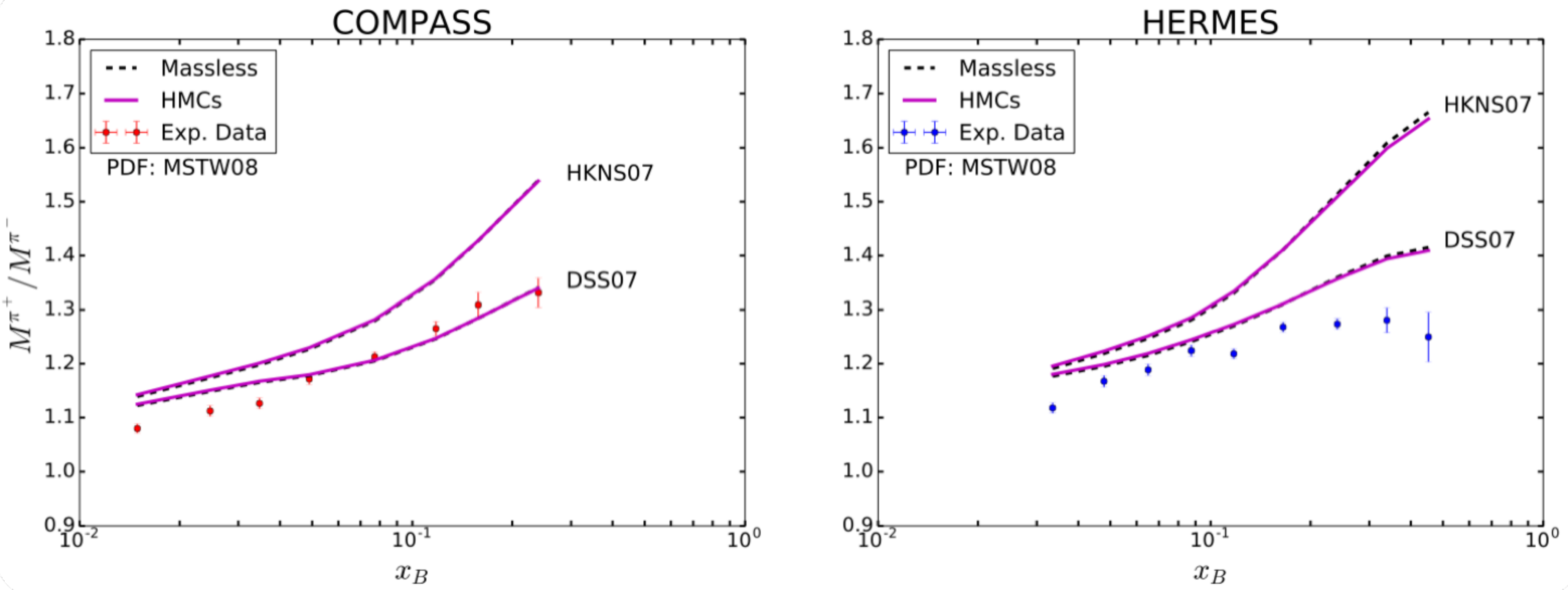




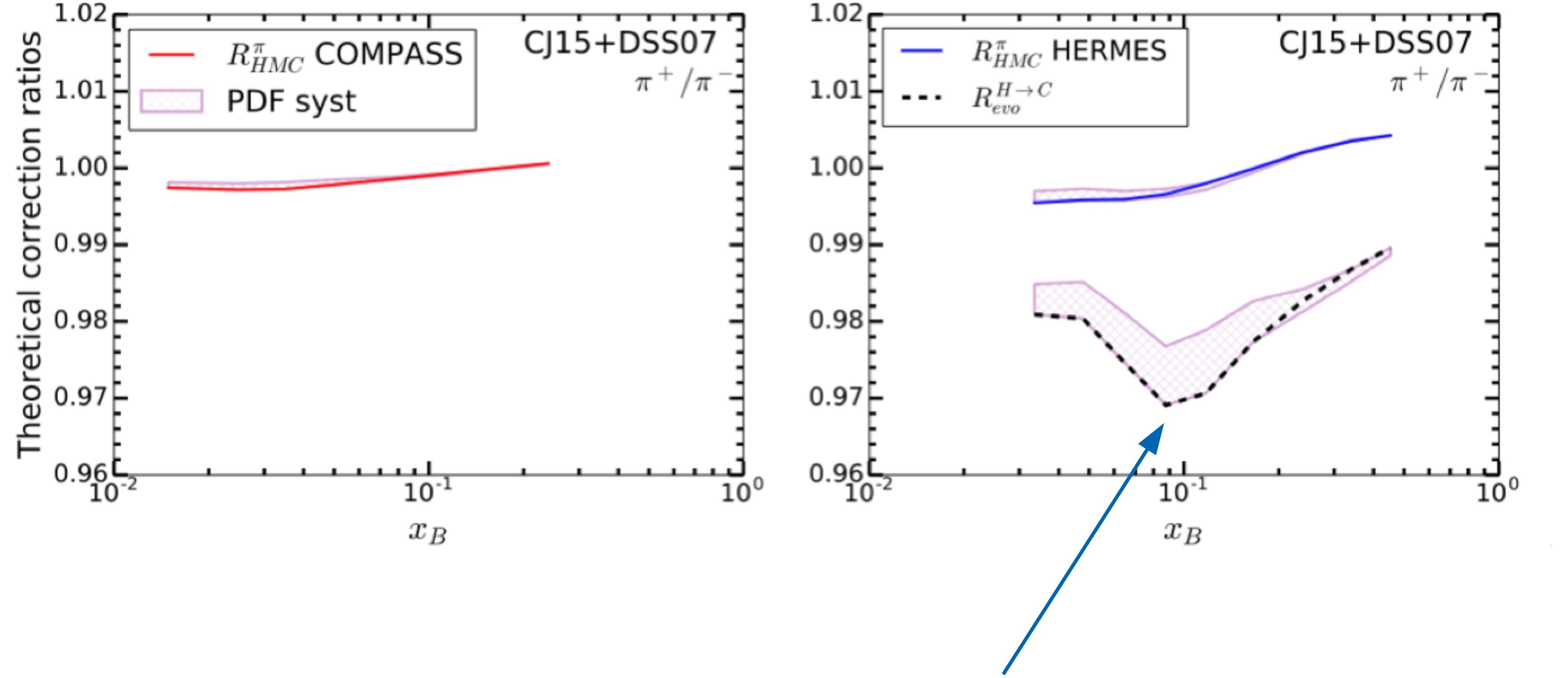
HERMES shape, again?

Jlab could be a tie breaker!
(but uncertainties are perhaps too large)

pion ratios


COMPASS
Massless
HMCs
Exp. Data
PDF: MSTW08
HKNS07
DSS07
M^{π^+}/M^{π^-}
x_B
HERMES
Massless
HMCs
Exp. Data
PDF: MSTW08
HKNS07
DSS07
x_B

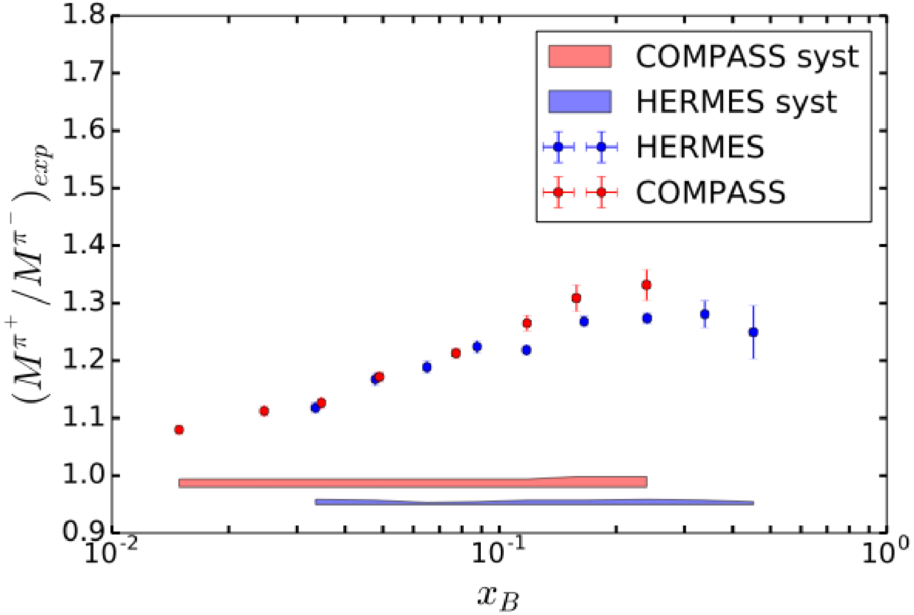
Correction ratios: pi$^+$ / pi$^-$



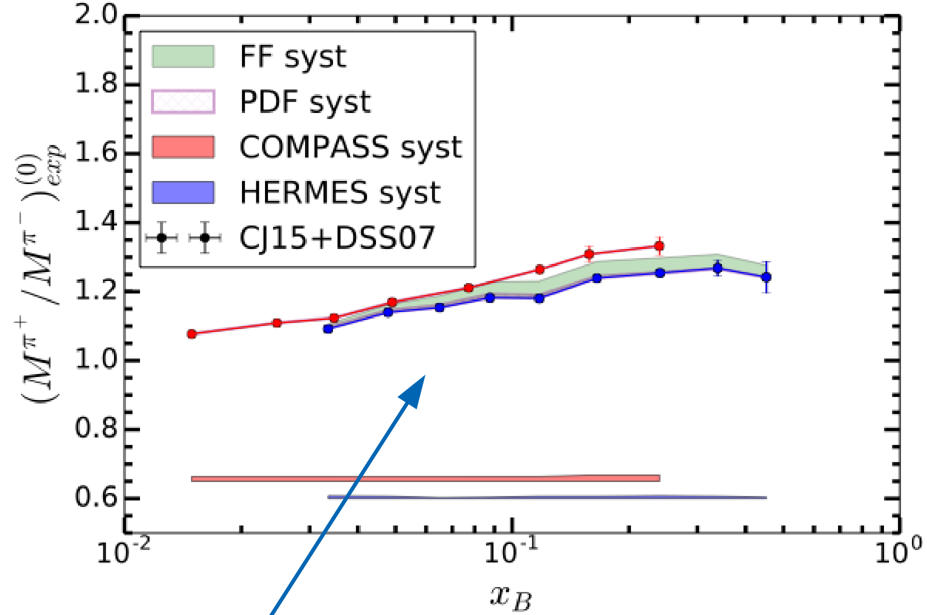
Q^2 evolution will "straighten" HERMES

Direct Data Comparison: pi⁺ /pi⁻

Experimental Data



"Massless data" at same Q²

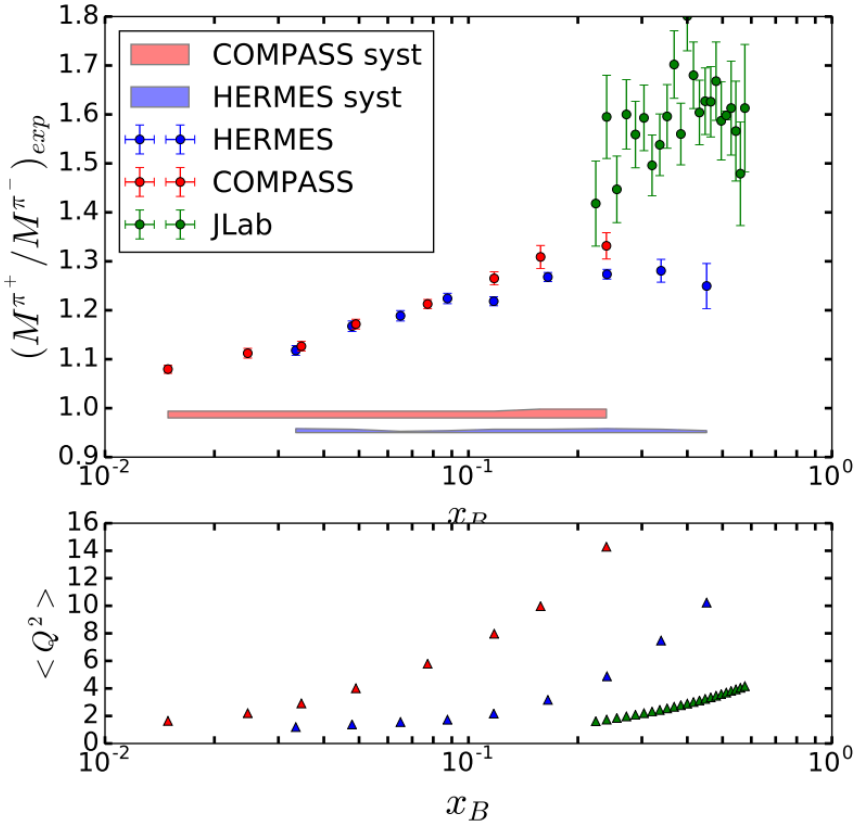


Now, shapes are (sort of) compatible

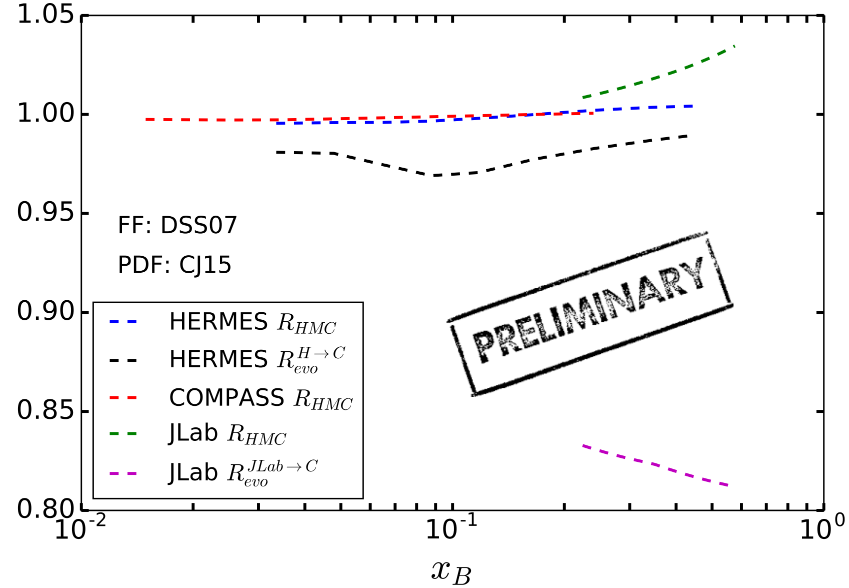
Possibly NLO and a refit of pion FFs will fix this

What about JLab pions?

Experimental Data



Correction ratios



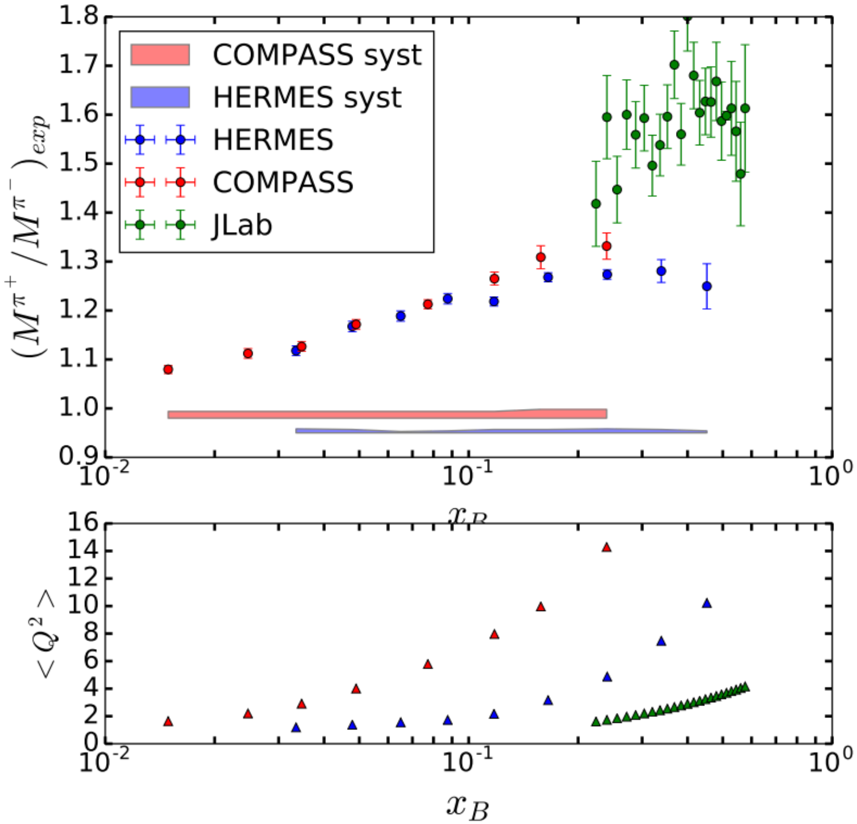
$$R_{evo}^{Jlab\to C} = \frac{M^{h(0)}(x_B^{\mathrm{JLab}})\big|_{\mathrm{COMPASS\ cuts}}}{M^{h(0)}(x_B^{\mathrm{JLab}})\big|_{\mathrm{JLab\ kinematics}}}$$

At JLab:

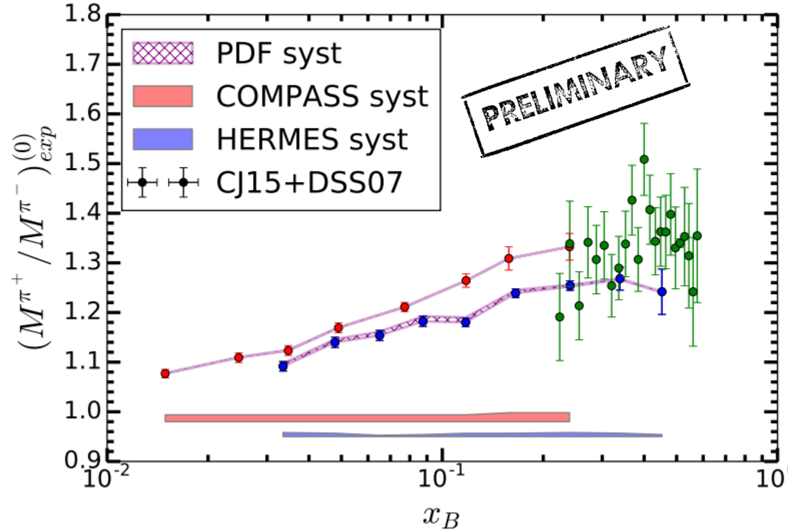
- a bit more HMCs
- longer, stronger Q^2 evolution

What about JLab pions?

Experimental Data



“Massless data” at same Q²



Pion ratios after HMCs:

- all approximately compatible
- JLab pions slightly prefer COMPASS
  ...but too large stat. uncertainties
- small differences could be solved by:
  NLO effects, pion FF refit with HMCs

Conclusions

Conclusions

- **Hadron mass corrections possible in collinear factorization**
  - Accounts for phase space available for hadronisation
    - with non-zero "virtuality" for fragmenting quark: $v'^2 = m_h^2/\zeta_h$
  - But needs to go beyond the usual "parton model approximation"
  - Proposed scheme phenomenologically successful!
- **HMCs partially reconcile HERMES and COMPASS kaons**
  - Kaon ratios compatible
  - Leftover (experimental?) systematics in multiplicities at xB > 0.1
- **Null control: Pion multiplicities and ratios**
  - Multiplicities: systematic shape difference remains
  - pi+/pi- ratios: largely compatible
  - Jlab pion ratios have large HMCs, marginally favor COMPASS

Perspective

- **HMCs need to be included in PDF / FF fits**
  - Whenever SIDIS or SIA data analyzed

- **More work to do:**
  - Checking kinematic approx with “QCD-like” spectator model
    - In progress with J. Guerrero
  - Extend to e+e- → h+X (SIA)
  - Prove factorization at NLO
    - Check if “minimal” choice $v'^2 = m_h^2/\zeta_h$ correct
    - Verify universality (SIDIS vs. SIA)

Extras

Phase space limitations

Guerrero et al., JHEP 09 (2015) 169

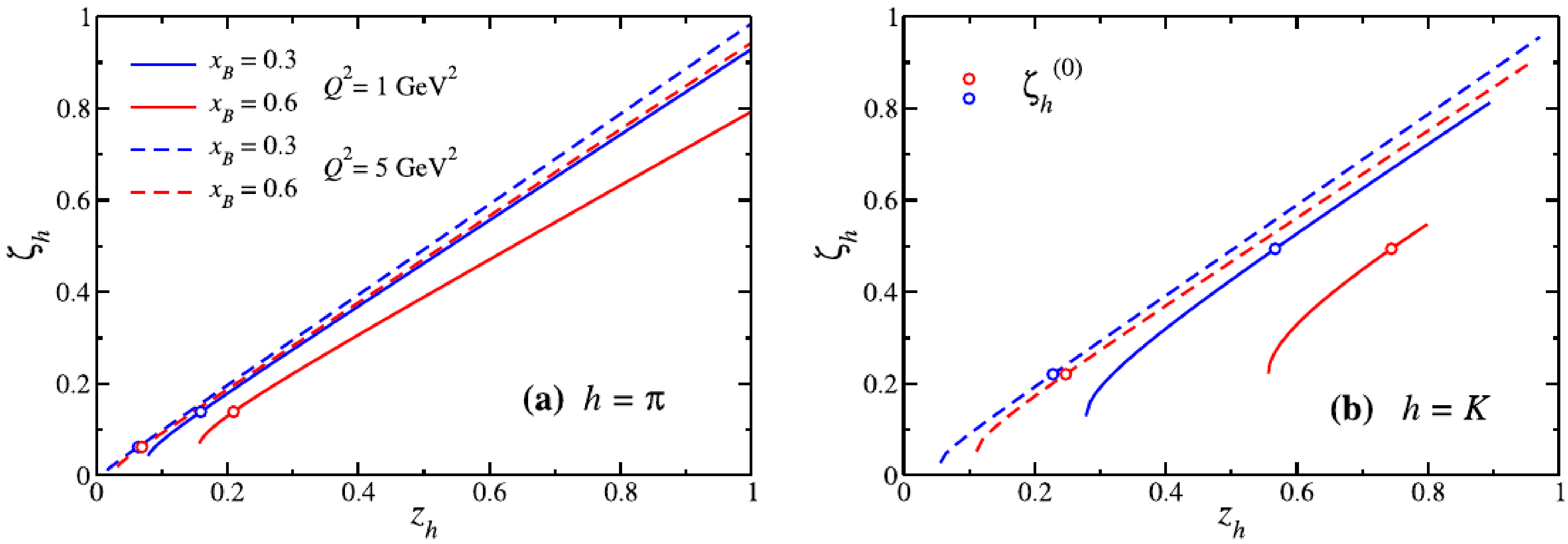


Figure 2. Finite-Q^2 fragmentation variable ζ_h versus z_h for the semi-inclusive production of (a) pions, $h = \pi$ and (b) kaons, $h = K$, at fixed values of $x_B = 0.3$ (blue curves) and 0.6 (red curves) for $Q^2 = 1$ (solid curves) and $5\,\mathrm{GeV}^2$ (dashed curves). The curves are shown only in the kinematically allowed z_h regions, and the boundaries between the current ($\zeta_h > \zeta_h^{(0)}$) and target ($\zeta_h < \zeta_h^{(0)}$) fragmentation regions are indicated by the open circles.

Current vs. target fragmentation regions

Guerrero et al., JHEP 09 (2015) 169

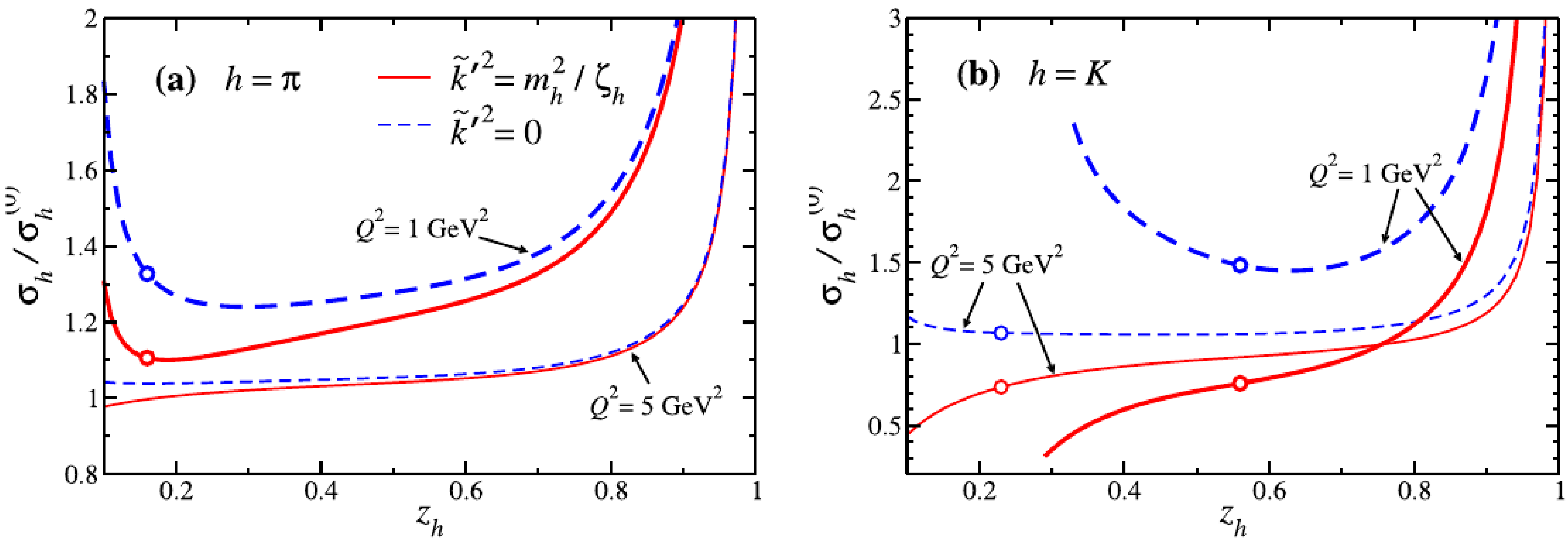
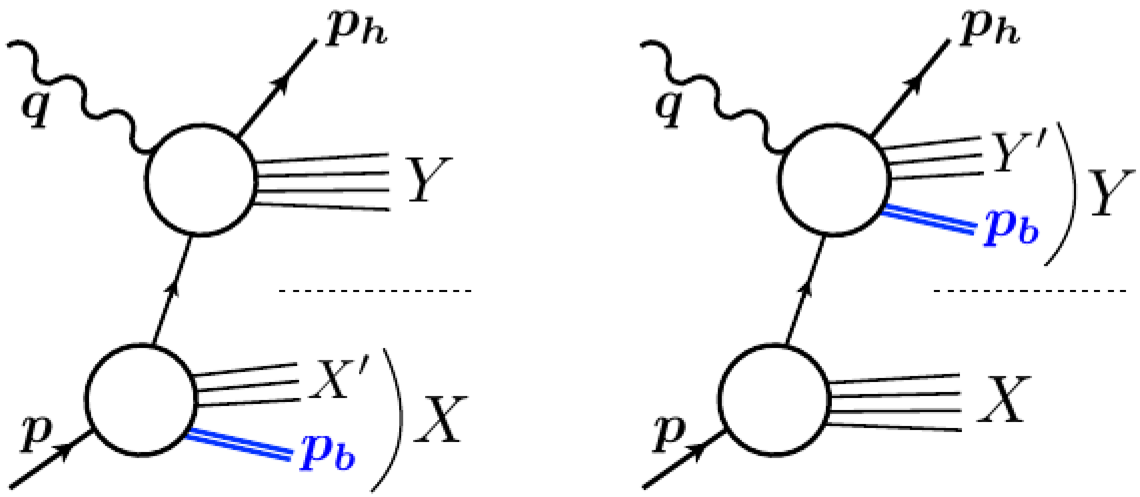


Figure 9. Ratio of spin-averaged cross sections with and without HMCs for the production of (a) pions and (b) kaons, for different choices of the scattered parton invariant mass $\widetilde{k}'^2$ at $Q^2 = 1\,\mathrm{GeV}^2$ (thick lines) and $Q^2 = 5\,\mathrm{GeV}^2$ (thin lines) for $x_B = 0.3$. The open circles denote the boundary between the target and current fragmentation regions.

Current vs. target fragmentation regions

Guerrero, Accardi, PRD 97 (2018) 114012

- **Baryon in in target vs. current region:**

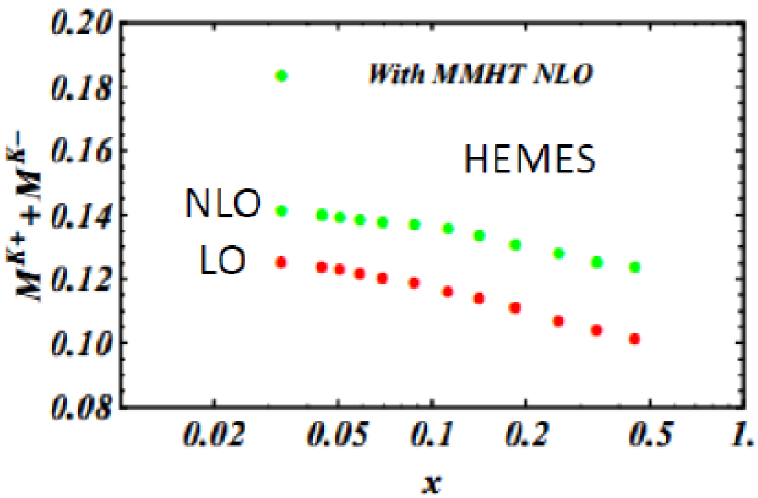


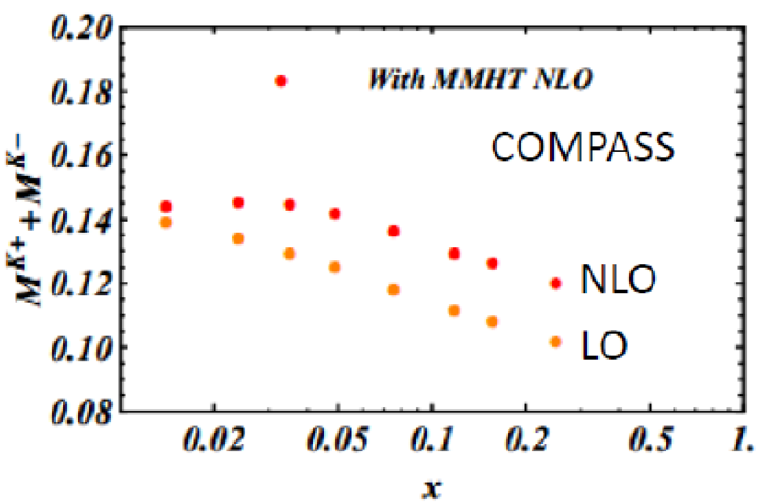
$$x = \xi \left(1 + \frac{m_h^2}{\zeta_h Q^2} \right) \qquad x = \xi \left(1 + \frac{m_h^2}{\zeta_h Q^2} + \frac{M_b^2}{(1-\zeta_h) Q^2} \right)$$

$$d\sigma_{(b)} \gg d\sigma^{(b)}$$

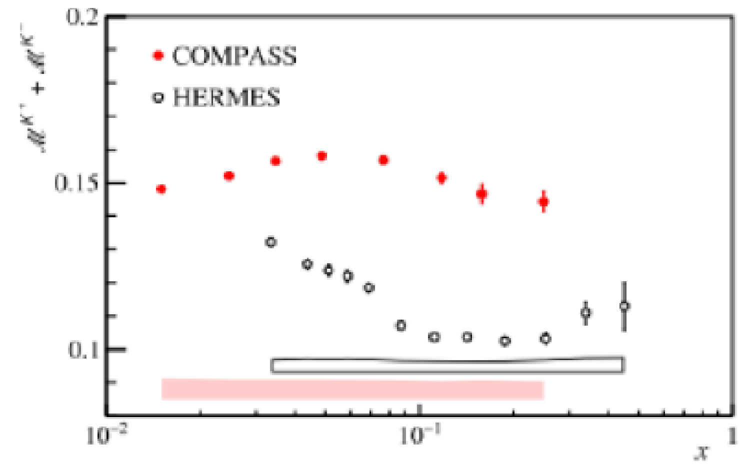
Kaon multiplicity

Chung-Wen Kao, talk at DIS 2018





Kaon multiplicity



NLO vs. LO:

- ~20% higher (cancels in ratios)
- slight change of shape