Testing PDFs in a spectator model DIS with Target Mass Corrections

Juan Guerrero

Hampton University & Jefferson Lab

CTEQ Meeting 2018, Jefferson Lab

November, 2018

HAMPTON UNIVERSITY

THE STANDARD OF EXCELLENCE

Jefferson Lab

Thomas Jefferson National Accelerator Facility

Accessing PDFs: Global analysis

Hard scattering reactions: Picture of the nucleons (partons)

Examples:

- Deep Inelastic Scattering (DIS): $e^- + p \to e^- + X$
- Semi-inclusive Deep Inelastic Scattering: $e^- + p \to e^- + h + X$

perturbative PDF

Relies on factorization:

$$\sigma^{\text{DIS}} \propto \hat{\sigma} \otimes f + \mathcal{O}(\mu^2/Q^2)$$

$$\sigma^{\text{SIDIS}} \propto \hat{\sigma} \otimes f \otimes D^h + \mathcal{O}(\mu^2/Q^2)$$

focus on this!

- Kinematical effects $\mu = m$
- Dynamical effects $\mu = \Lambda_{\text{QCD}}$

Fragmentation Function (FF)

Perform a global fit to extract the non perturbative physics (PDFs and FFs)

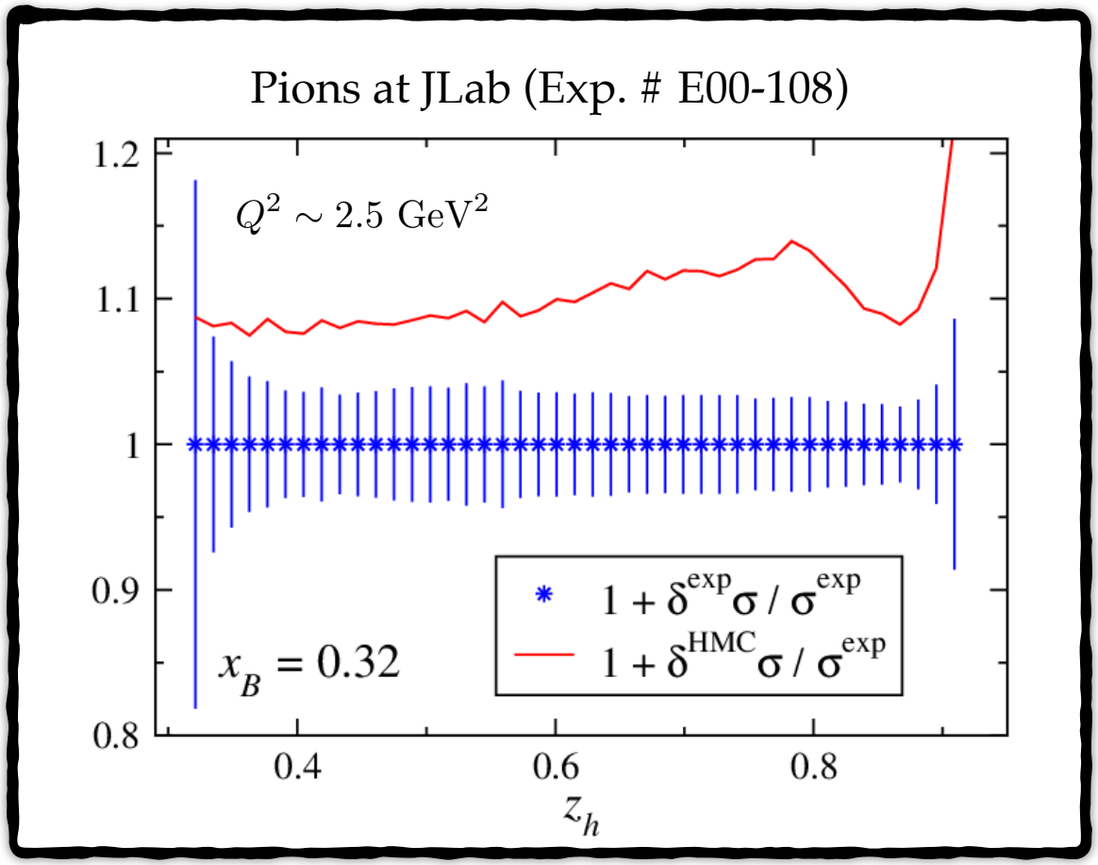
Hadron Mass Effects

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

Accardi et al JHEP 0911, 084 (2009)

Jefferson Lab experiments:

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



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

$$m = M_P, m_\pi$$

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

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

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

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

Guerrero et al JHEP 1509, 169 (2015)

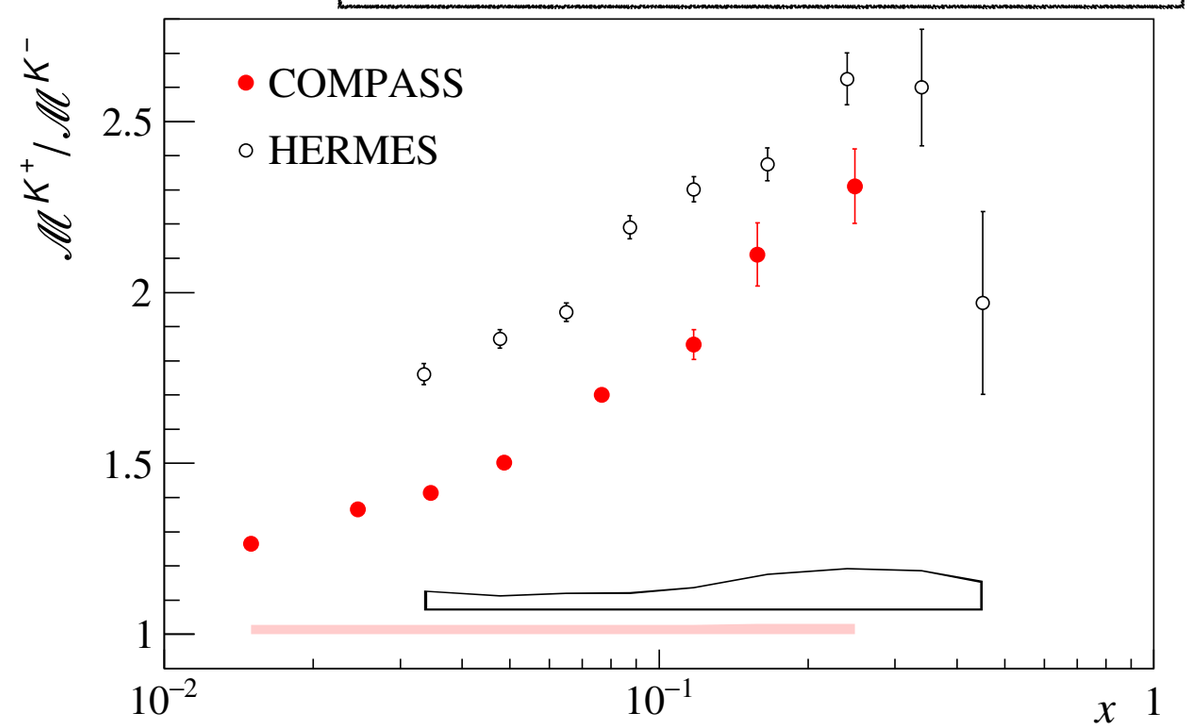
Integrated Kaon Multiplicities: SIDIS on Deuteron

Experimentally

HERMES, COMPASS:

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

COMPASS collaboration, PLB 767 (2017) 133



- Size discrepancy between these two measurements
- Even worst for the case of sum: $K^+ + K^-$
  - discrepancy in size and shape

Where does this discrepancy come from?

Is it real or apparent?

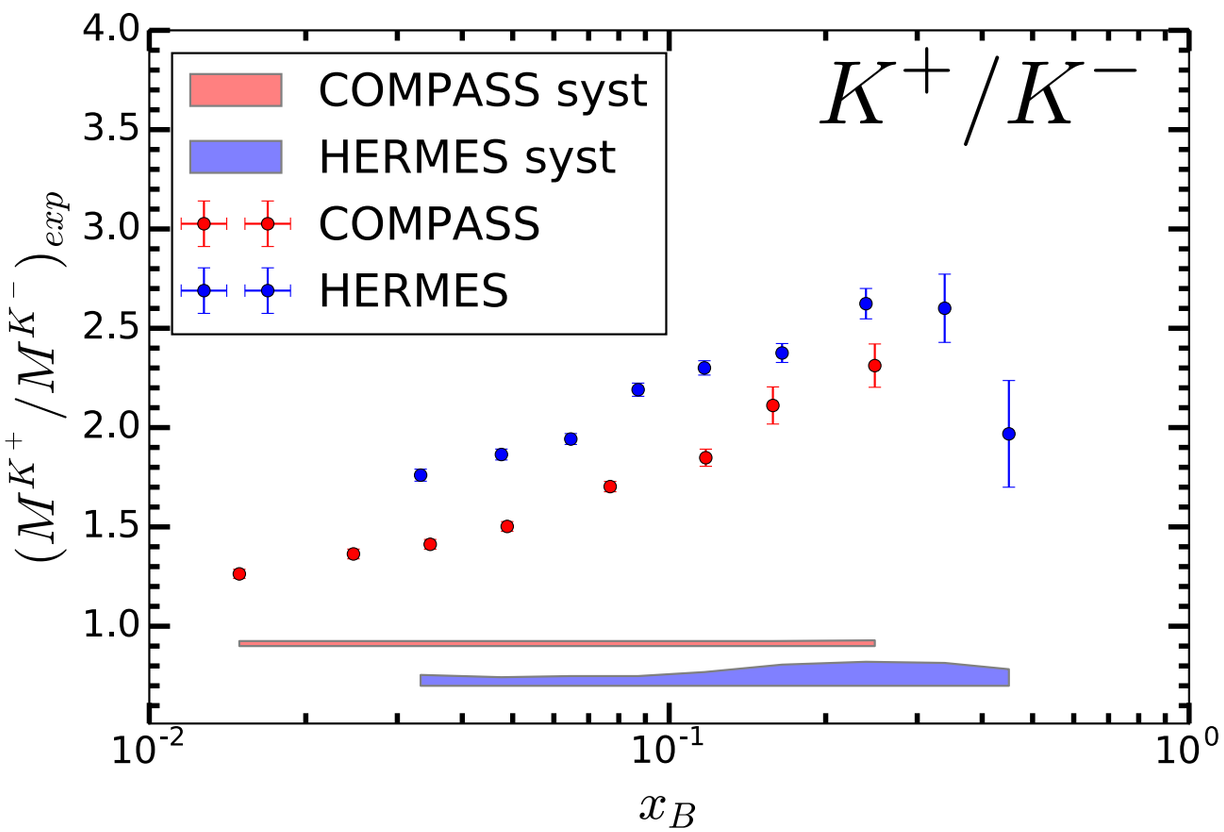
Direct Data Comparison: K^+/K^-

Guerrero, Accardi PRD 97 (2018) 114012

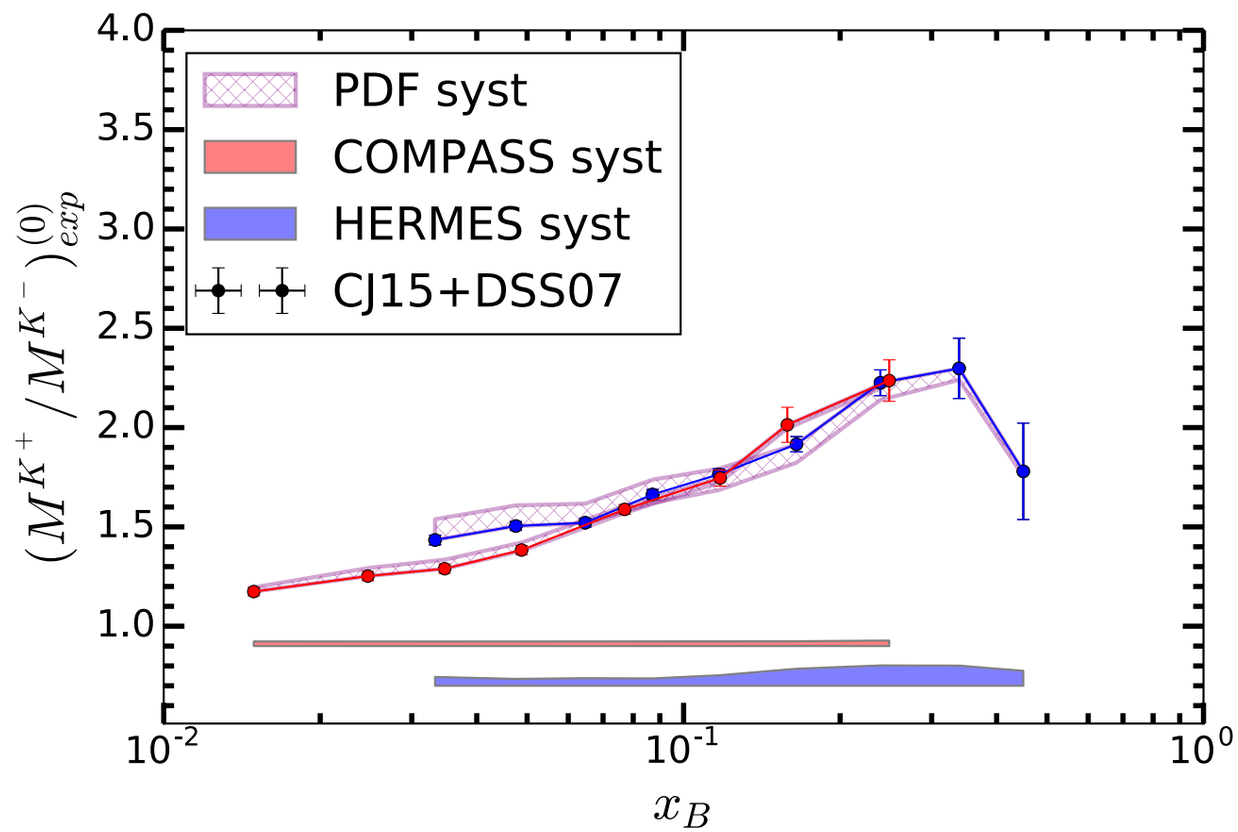
$$r_{\rm exp} = \left(\frac{M^{K^+}}{M^{K^-}}\right)_{\rm exp}$$

- COMPASS: $r^{(0)}_{\rm exp} \equiv r_{\rm exp} \times R_{HMC} \times R^{H\to C}_{evo}$
- HERMES: $r^{(0)}_{\rm exp} \equiv r_{\rm exp} \times R_{HMC}$

Original data



"Massless" evolved data



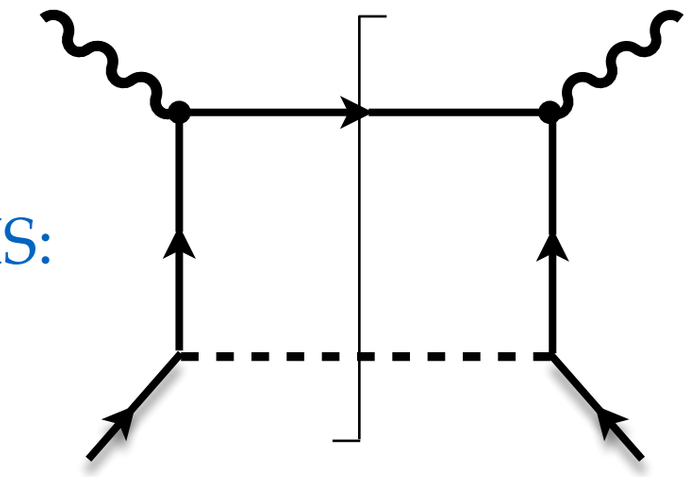
- HERMES & COMPASS fully compatible after removing HMCs.

Collinear factorization with masses in a spectator model

Factorization:

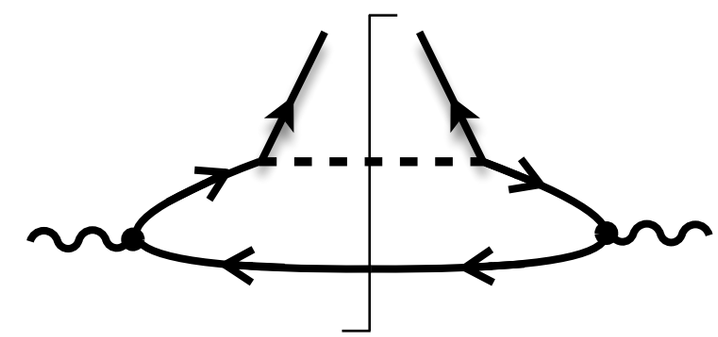
- *"controllable"* approximation
- Extend range of validity of factorization/ construct new factorization theorems

DIS:

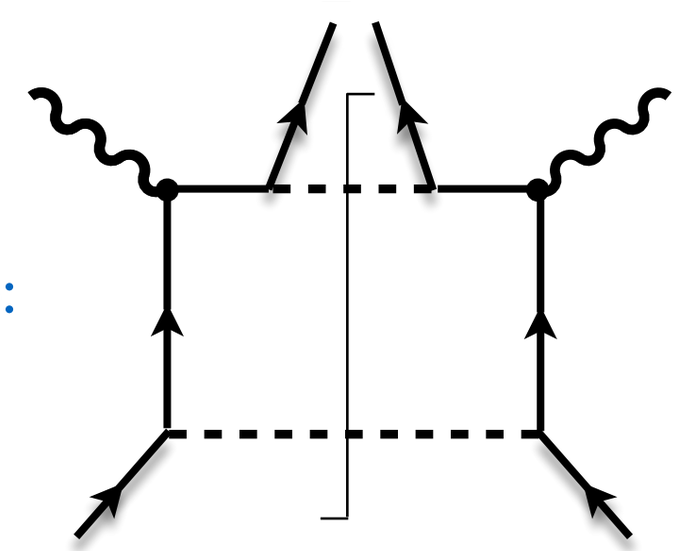


- **<u>Overall goal</u>**: Extend HMC formalism to NLO
- **Step 1**: test validity of the approach with Yukawa model
  - Kinematical approx. & factorization scheme vs. full calculation
  - Generate pseudo-data => Fitted PDFs vs. calculated PDFs
    (In progress with G. Alcala, U. Simon Bolivar, Caracas, Venezuela)

SIA:



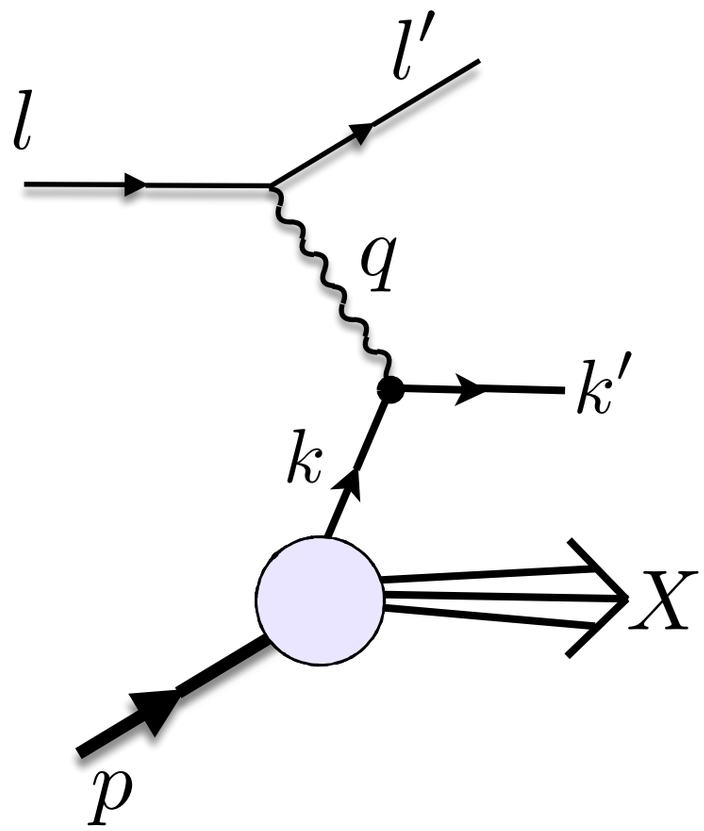
SIDIS:



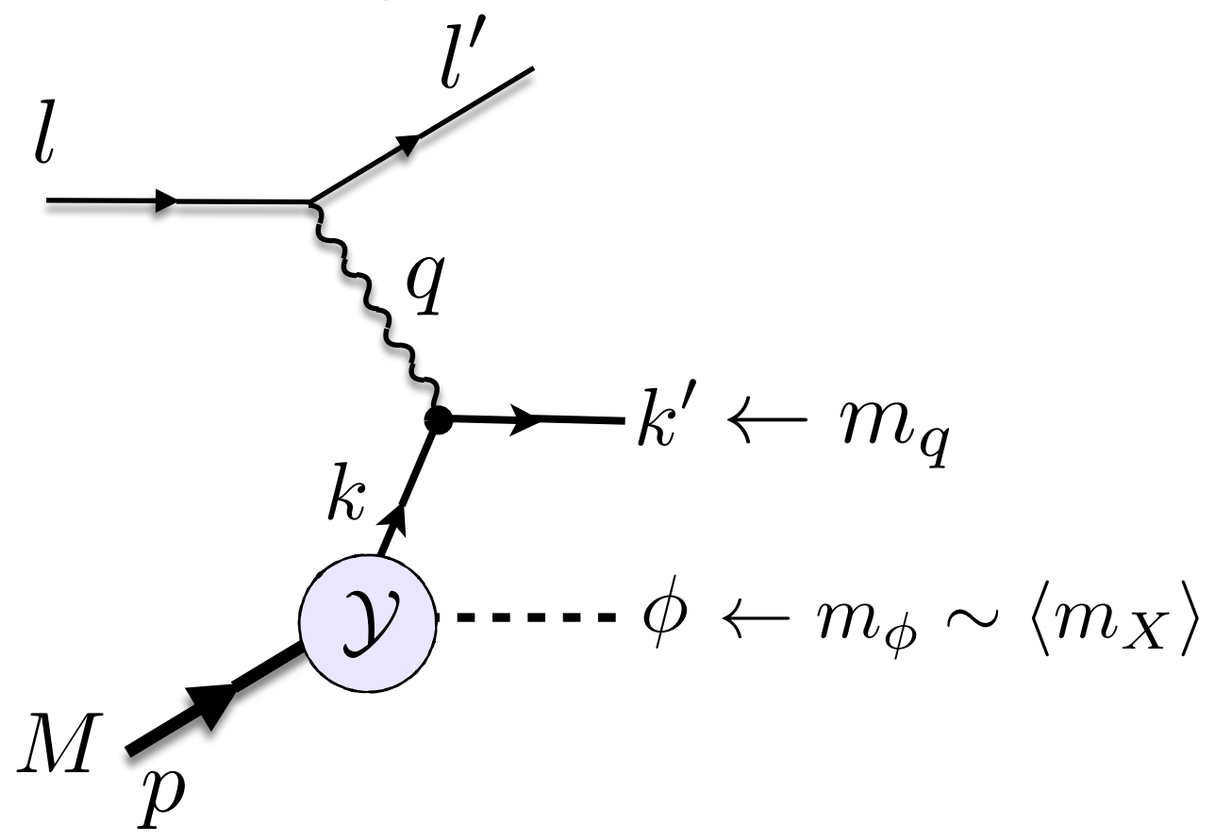
- **Step 2**: Include fragmentation
  - SIA: 3 body phase space
  - SIDIS: coupled final state and initial state kinematics

Inclusive DIS in an spectator model

- **Nature**



- **Yukawa Theory + Form Factors**



$$\mathcal{Y} = ig(k^2)\mathbb{1} \qquad g(k^2) = g\frac{k^2 - m_q^2}{|k^2 - \Lambda^2|^2}$$

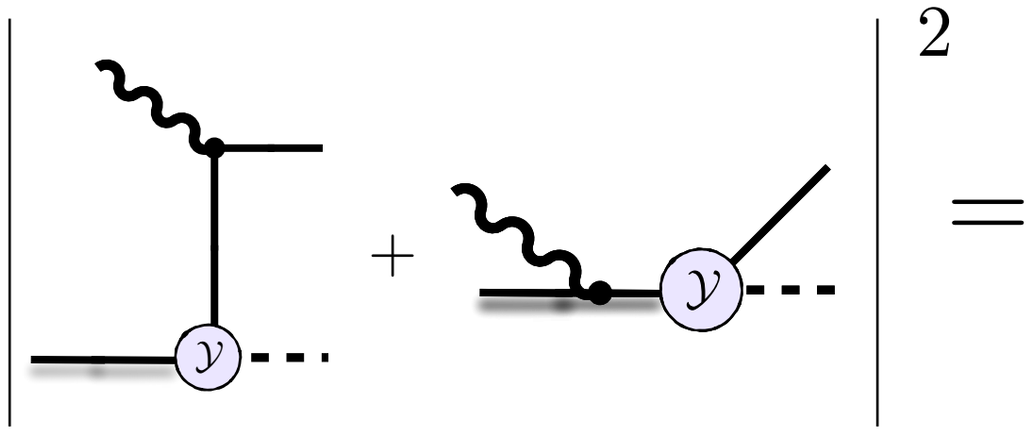
"dipole form factor"

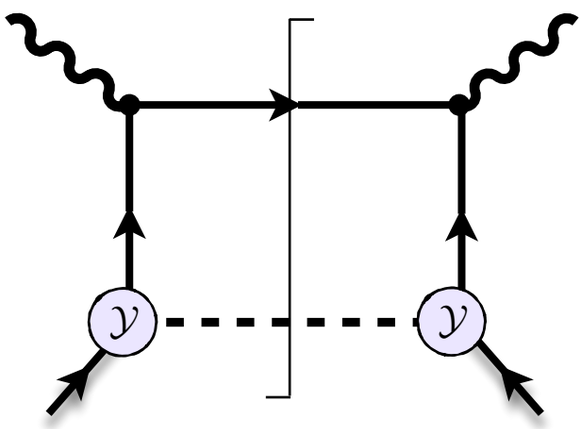
Bacchetta et al, PRD 78 (2008) 074010

- Simulates confinement
- Smoothly suppresses the high-k_T region.

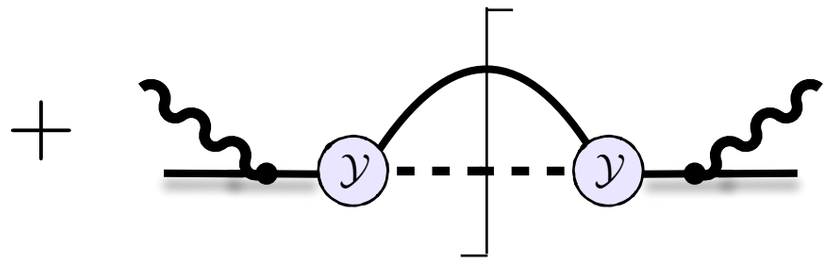
DIS in the spectator model

- Gauge invariance requires to consider

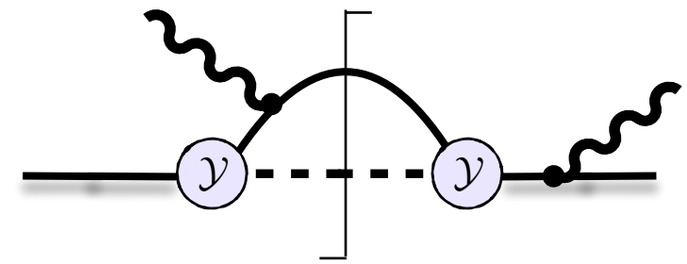




DIS



"excited" proton decay

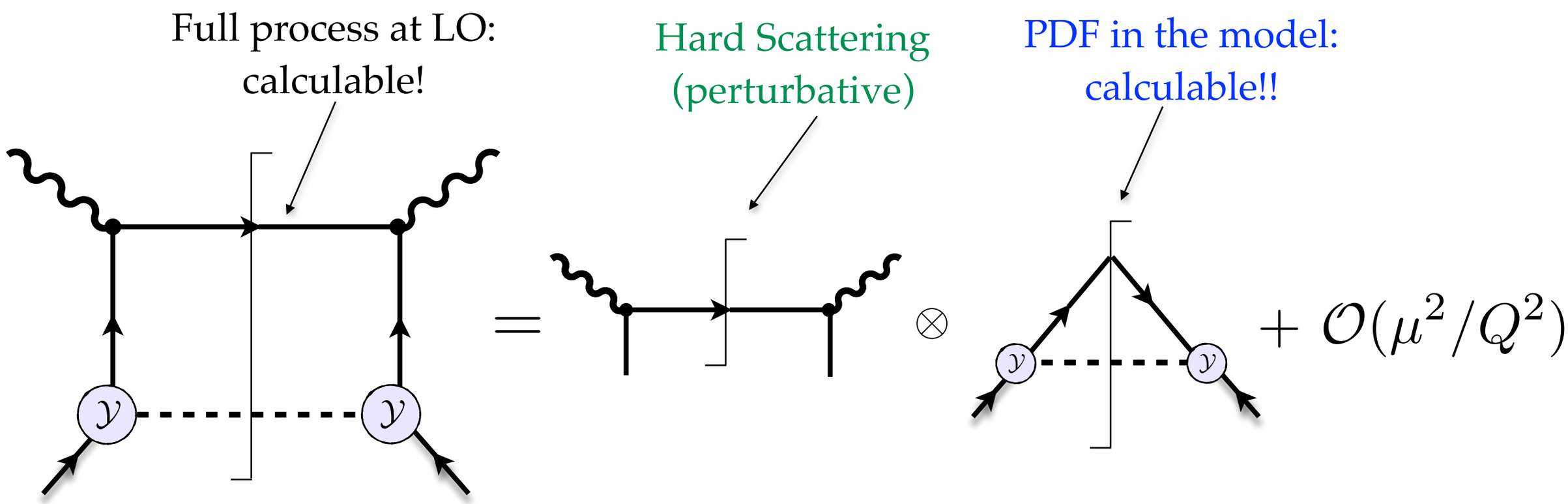


Interference

Moffat et al, PRD 95 (2017) 096008

See Eric's talk,
Friday 8:30

Collinear Factorization for DIS diagram

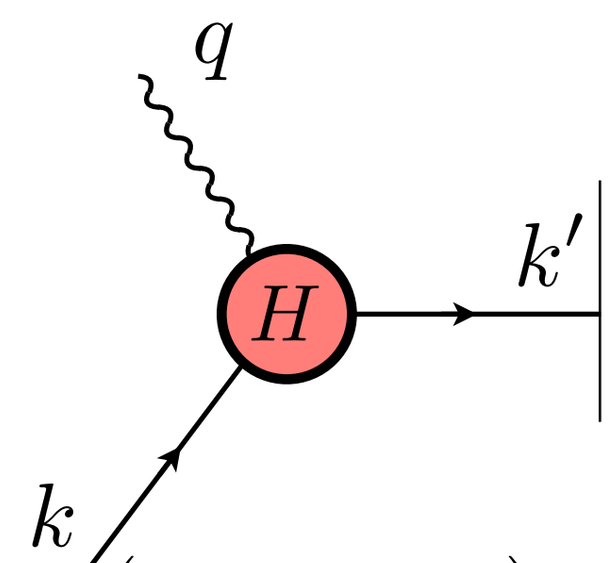


$$F_1(x_B, Q^2) \approx (2\pi)\,\delta(x - \bar{x}) \otimes \varphi_q(x)$$

depends on the kinematical approximations

Hard scattering: 4-momentum conservation at LO

Exact:



$$k = \left(xp^+, \frac{k^2 + k_T^2}{2x}, \mathbf{k_T} \right)$$

$$x = \frac{\xi}{2}\left(1 + \frac{m_q^2 - k^2}{Q^2} + \sqrt{\left(1 + \frac{m_q^2 - k^2}{Q^2}\right)^2 + 4\frac{k^2 + k_T^2}{Q^2}}\right)$$

$$= \xi\left(1 + \frac{m_q^2 + k_T^2}{Q^2} - \frac{(m_q^2 + k_T^2)(k^2 + k_T^2)}{Q^4} + \mathcal{O}(\frac{\mu^6}{Q^6})\right)$$

$$x = \bar{x}(\overbrace{x_B, Q^2, M^2, m_q^2}^{\text{Observable}}; \overbrace{k^2, k_T^2}^{\text{Internal}})$$

Kinematic approximations:

$x =$

	M	m_q	k^2	k_T^2
x_B	0	0	0	0
ξ	✓	0	0	0
$\xi_q \equiv \xi(1 + \frac{m_q^2}{Q^2})$	✓	✓	0	0
$\xi_q^{(1)} \equiv \xi(1 + \frac{m_q^2}{Q^2} + \frac{\langle k_T^2 \rangle}{Q^2})$	✓	✓	0	✓ $\langle k_T^2 \rangle$

← same as χ (ACOT-χ)

Nadolsky and Tung, PRD **79**, 113014 (2009).

Averages definitions

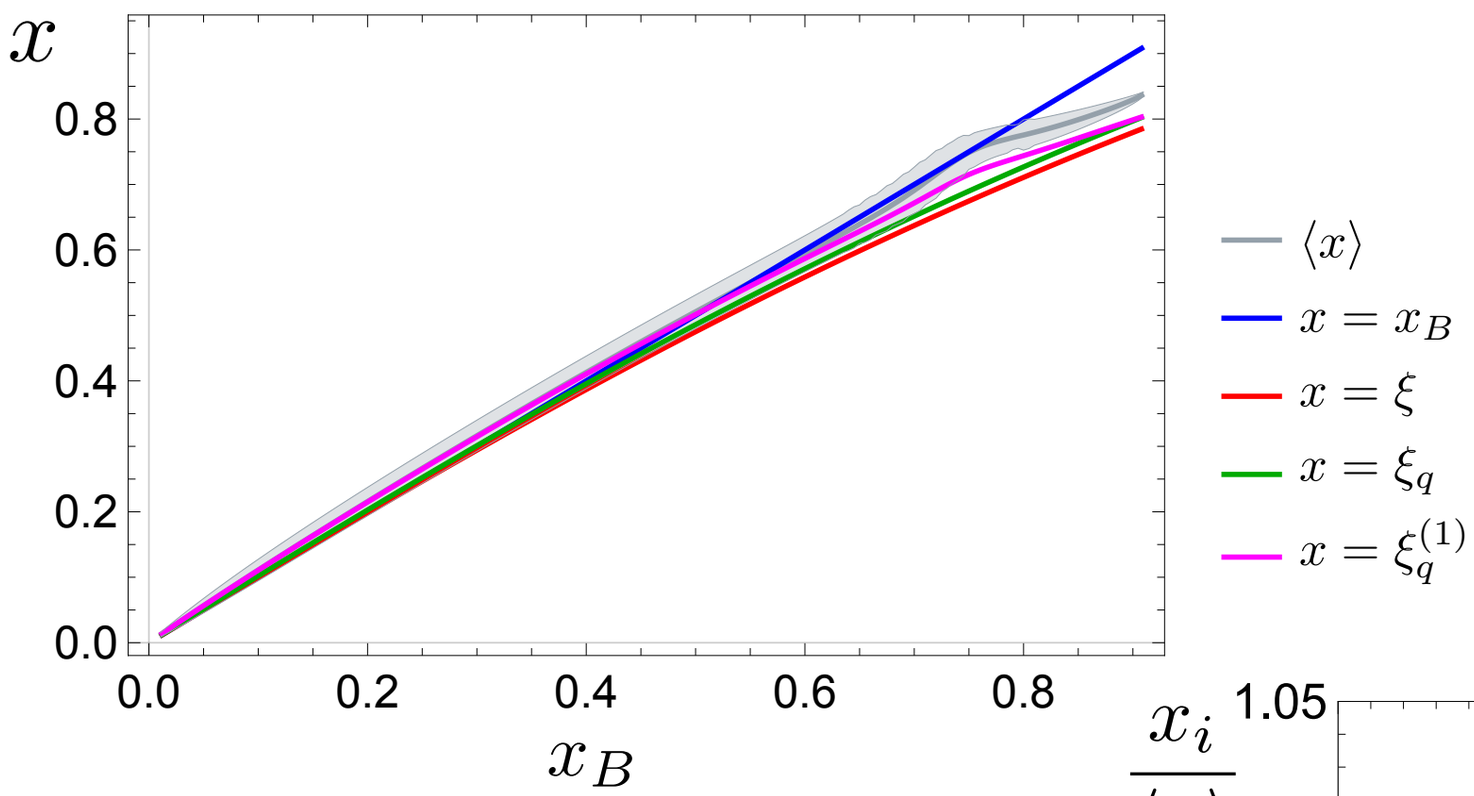
- **Full process:**

$$\langle \mathcal{O} \rangle (x_B, Q^2) = \frac{\int dk_T^2 \, \mathcal{O}(x_B, Q^2, k_T) \mathcal{F}_1(x_B, Q^2, k_T)}{\int dk_T^2 \, \mathcal{F}_1(x_B, Q^2, k_T)}$$

- **Factorized process PDF:**

$$\langle \mathcal{O} \rangle_{\mathrm{PDF}} (x, Q^2) = \frac{\int dk_T^2 \, \mathcal{O}(x, Q^2, k_T) \varphi_q(x, Q^2, k_T)}{\int dk_T^2 \, \varphi_q(x, Q^2, k_T)}$$

Light cone fraction x: average and comparison



$Q^2 = 4\,\mathrm{GeV}^2$

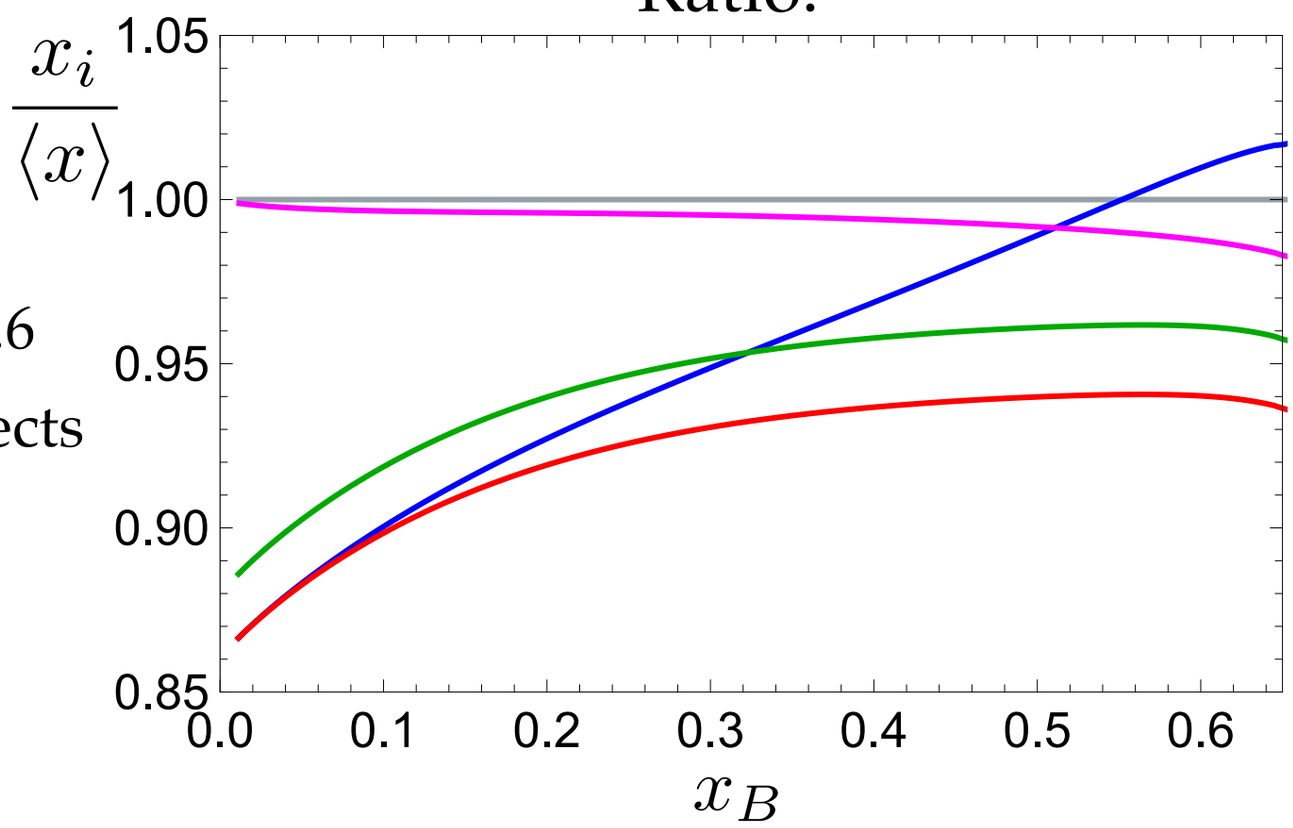
$M = 0.939\,\mathrm{GeV}^2$

$m_q = 0.3\,\mathrm{GeV}$

$m_\phi = 0.822\,\mathrm{GeV}$

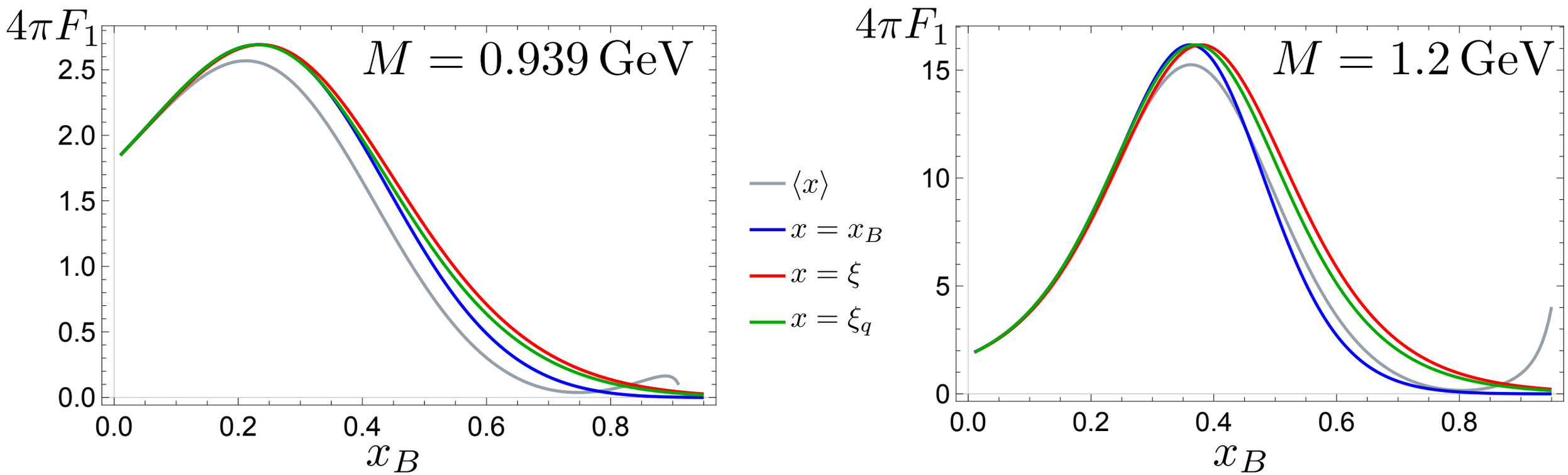
$\Lambda = 0.609\,\mathrm{GeV}$

Ratio:



- **Highlights:**
- $x=\xi$ stabilize the solution for $x_B \sim 0.2$-0.6
- $x=\xi_q$ mainly capture the kinematic effects (~95 % of the <x>)
- k_T^2/Q^2 largely fills the remaining gap

Structure Function



- **Highlights:**
- $x=x_B$ very unstable with the mass of the target
- $x=\xi$ stabilize the solution for $x_B \sim 0.2$-0.6 (similar slope to exact F_1)
- $x=\xi_q$ closest stable solution (similar slope to exact F_1)
- Remaining gap: Higher-twist corrections?

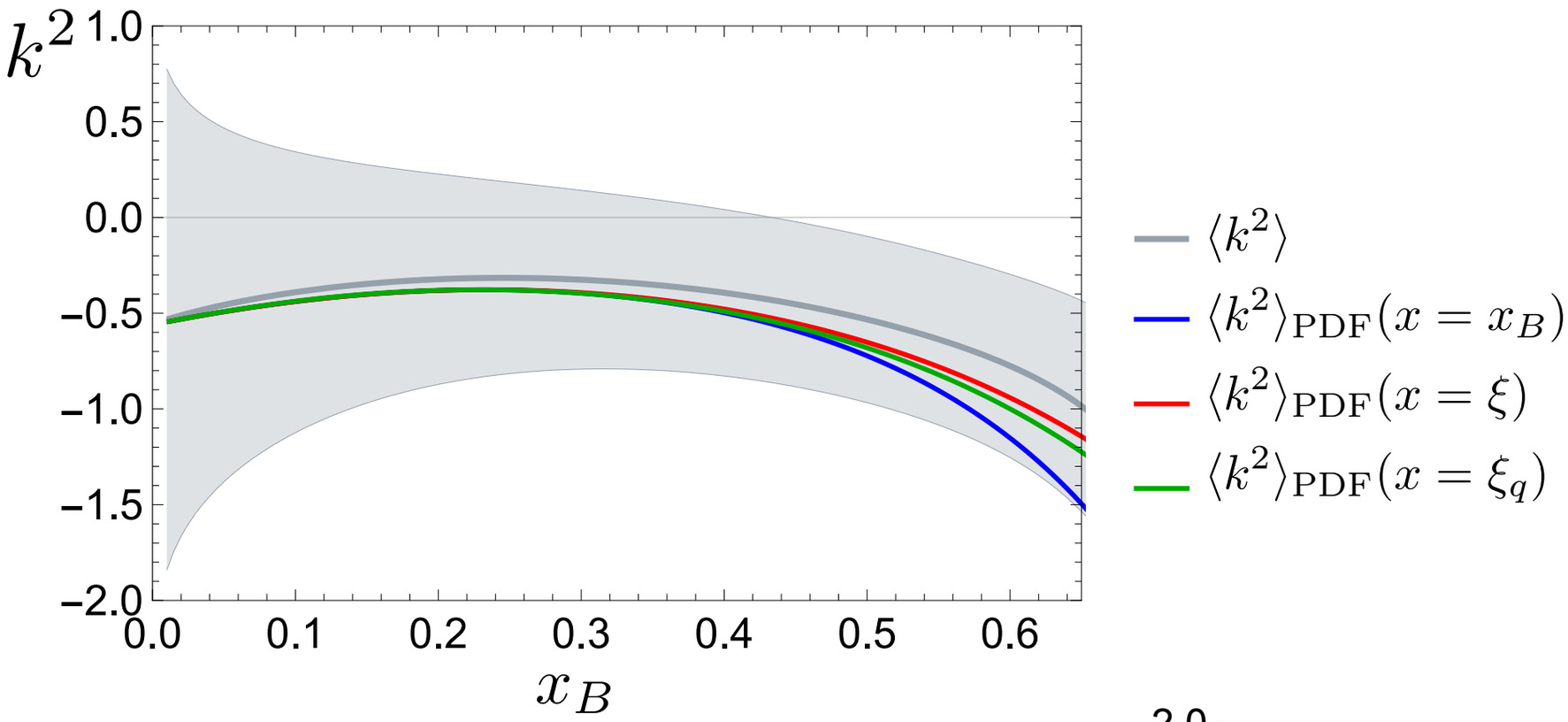
$Q^2 = 4\,\mathrm{GeV}^2$

$m_q = 0.3\,\mathrm{GeV}$

$m_\phi = 0.822\,\mathrm{GeV}$

$\Lambda = 0.609\,\mathrm{GeV}$

Average virtuality



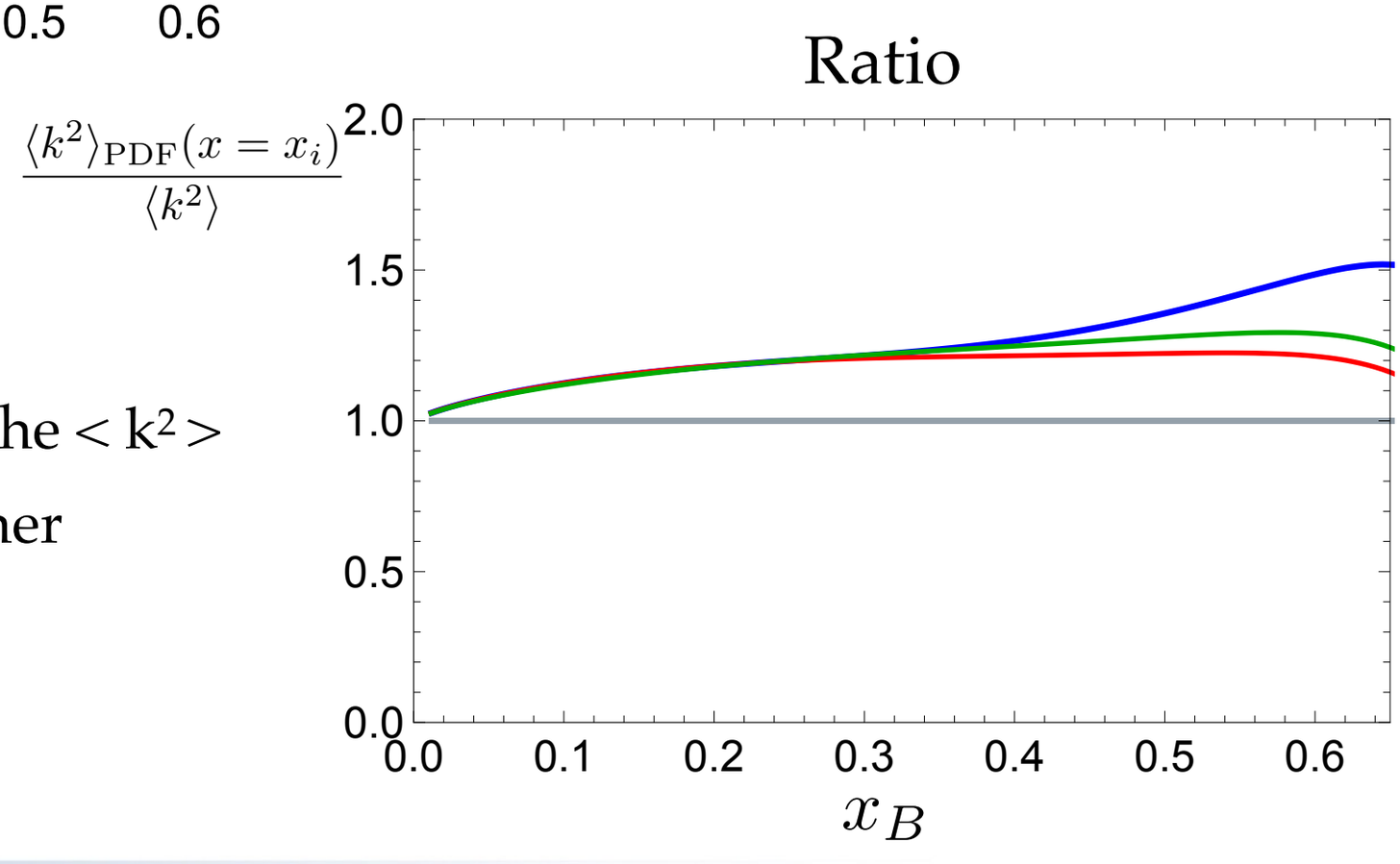
$Q^2 = 4\,\mathrm{GeV}^2$

$M = 0.939\,\mathrm{GeV}^2$

$m_q = 0.3\,\mathrm{GeV}$

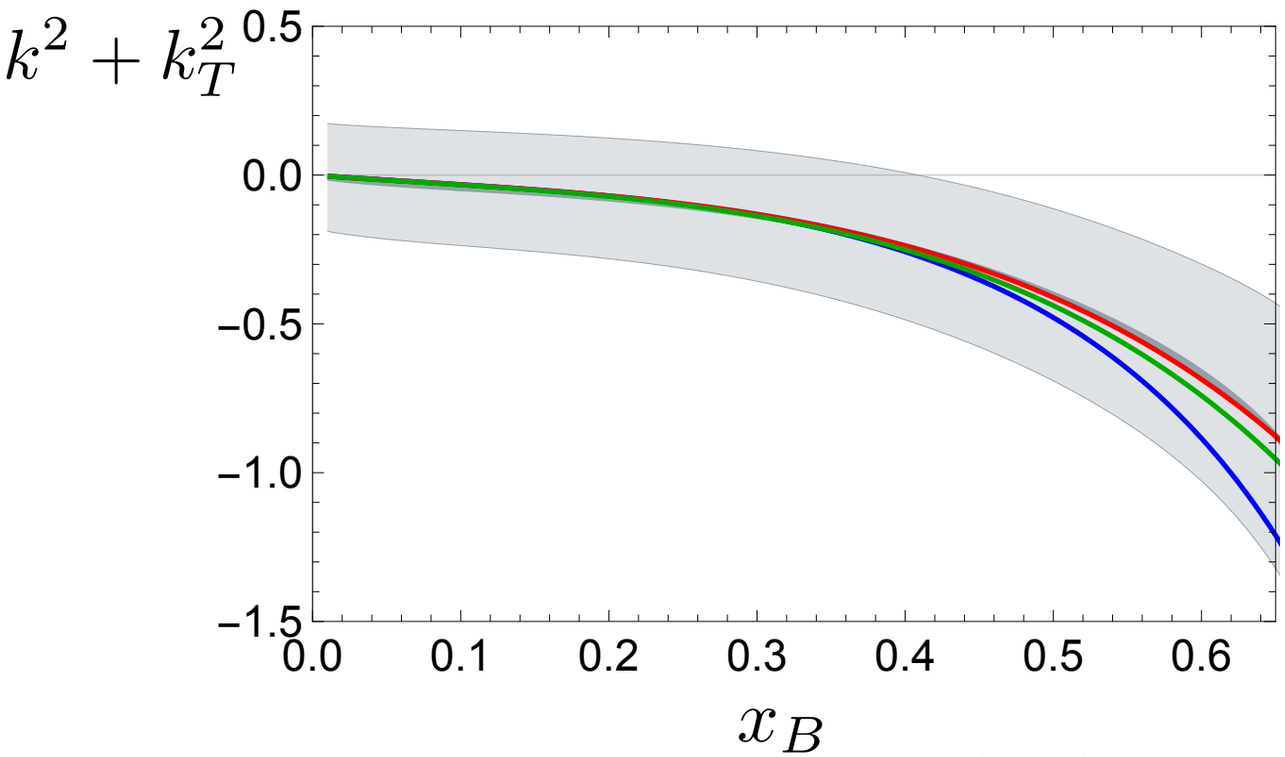
$m_\phi = 0.822\,\mathrm{GeV}$

$\Lambda = 0.609\,\mathrm{GeV}$



- **Highlights:**
- k^2 negative (bound state)
- $x=\xi$ and $x=\xi_q$ capture most of the $\langle k^2 \rangle$
- To do: check systematics for other parameters

Average "light-coneness"



$\langle k^2 + k_T^2 \rangle$

$\langle k^2 + k_T^2 \rangle_{\rm PDF}(x = x_B)$

$\langle k^2 + k_T^2 \rangle_{\rm PDF}(x = \xi)$

$\langle k^2 + k_T^2 \rangle_{\rm PDF}(x = \xi_q)$

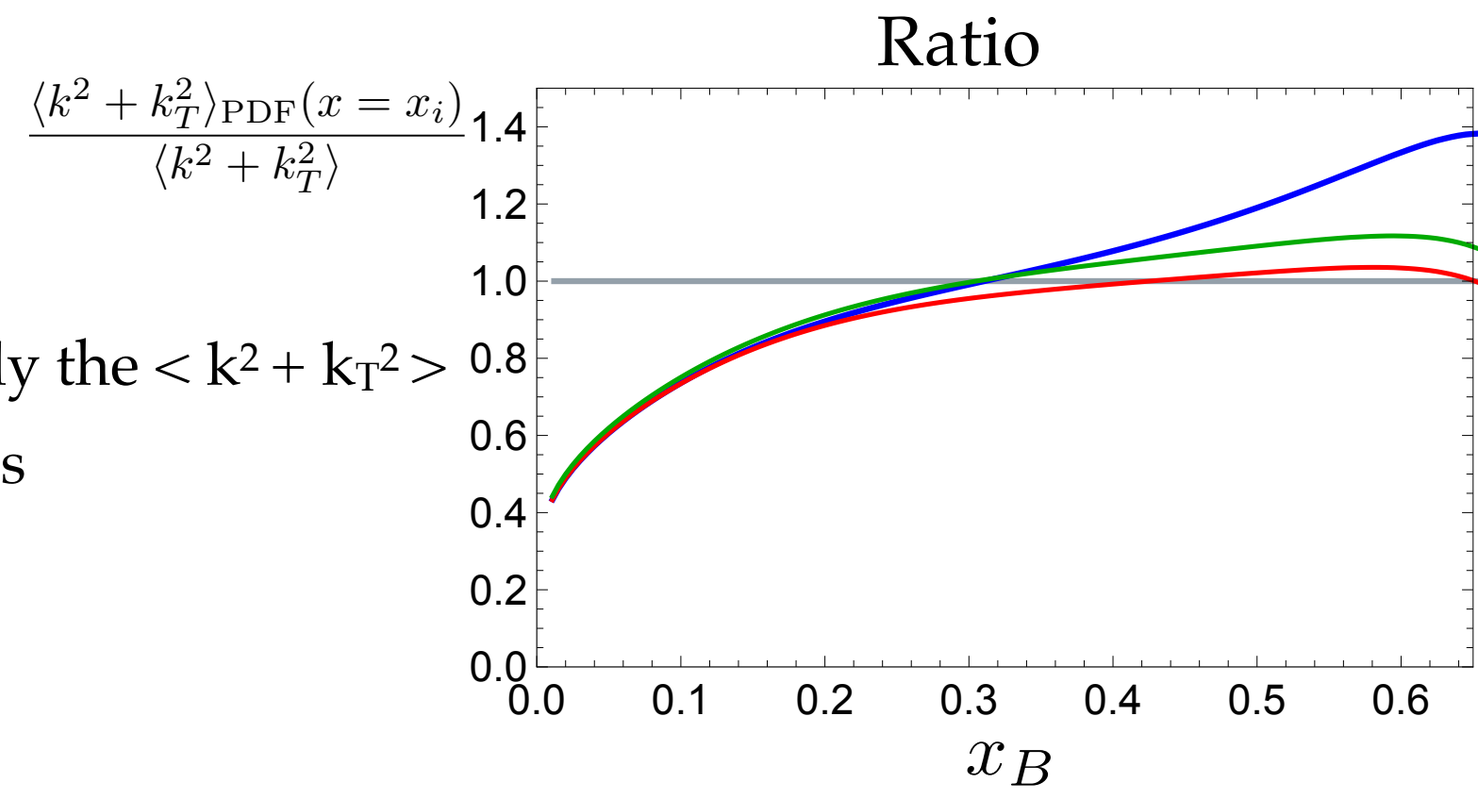
$Q^2 = 4\,{\rm GeV}^2$

$M = 0.939\,{\rm GeV}^2$

$m_q = 0.3\,{\rm GeV}$

$m_\phi = 0.822\,{\rm GeV}$

$\Lambda = 0.609\,{\rm GeV}$



- **Highlights:**
- x=ξ and x=ξ_q capture mainly the $< k^2 + k_T^2 >$
- Pending to check systematics

Conclusion

- Use spectator model to study several kinematic approximations in DIS.
  - $x = x_B$ (neglect all masses)
  - $x=\xi$ (keep target mass)
  - $x=\xi_q$ (target and final state quark mass)
- Use averages to estimate how much of the target mass effects are captured by each of these approximations:
  - $x=\xi_q$ captures most of the kinematic effects.
- Compared full F_1 to collinear F_1: $x= \xi$ and $x= \xi_q$ produce collinear structure functions with the right shape (difference in size maybe due to Higher-Twist contributions).
- **Outlook**:
  - TMCs at NLO
  - Factorization theorem, universality