Tomography of light mesons in the light-cone quark model

Harleen Dahiya

in collaboration with

Satvir Kaur, Narinder Kumar, Chandan Mondal and Jiangshan Lan

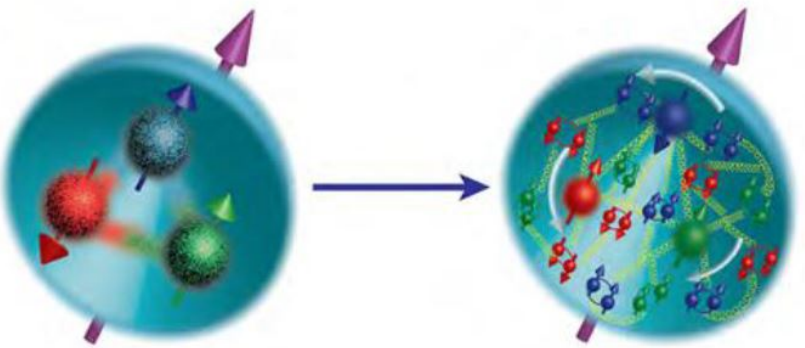
Dr. B.R. Ambedkar National Institute of Technology, Jalandhar, India

April 10, 2021

Overview

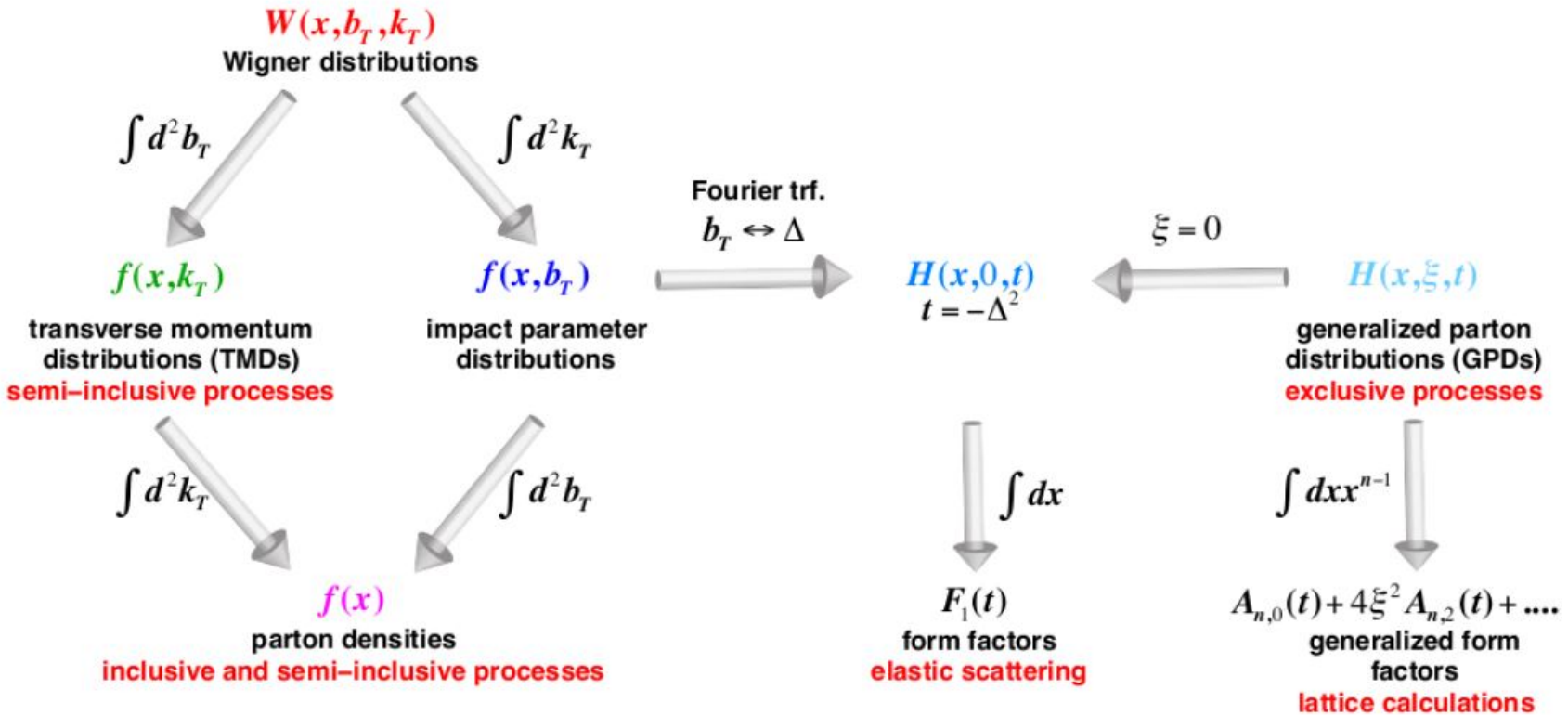
Hadron tomography

- The complex internal structure of the hadron can be studied by choosing the different high energy processes.
- Different processes are accessible at different energy scales.
- The two energy scale regimes are convoluted in the cross section as:
  - the partonic cross-section (calculable with the perturbative methods)
  - the nonperturbative part.



- One of the possible approaches used to study the nonperturbative aspects is based on the light-front Hamiltonian approach [1].

[1] S. J. Brodsky, H.-C Pauli, and S. S. Pinsky, Phys. Rept. 301, 299 (1998).



1

[1] A. Accardi *et al.*, Eur.Phys.J.A 52 (2016) 9, 268.

Light-cone quark model

- The boosted wave functions are obtained by using Brodsky-Huang-Lepage prescription [1].
  1. for pion and ρ-meson $(m_f = m_{\bar{f}'})$

$$\varphi_\pi^{\rm LFQM}(x,\mathbf{k}_\perp^2) = \mathcal{A}_\pi \exp\left(-\frac{1}{8\beta_\pi^2}\frac{\mathbf{k}_\perp^2 + m_q^2}{x\bar{x}}\right)$$

  2. for kaon $(m_f \neq m_{\bar{f}'})$ [2]

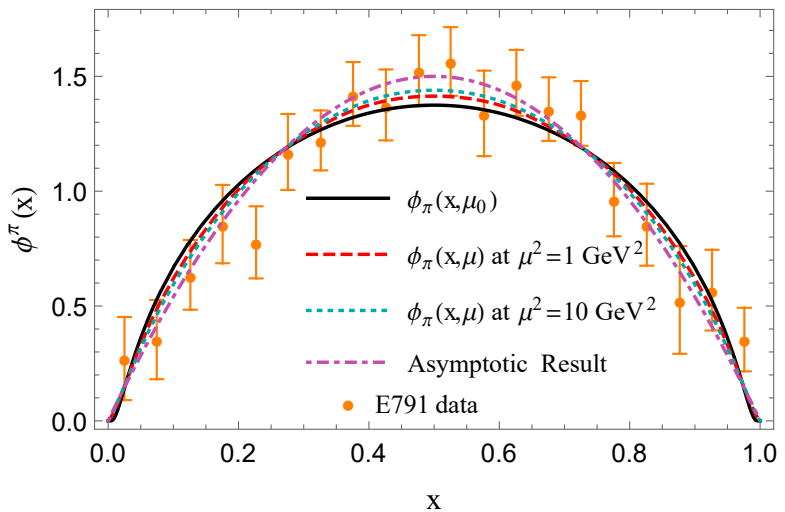
$$\varphi_K^{\rm LFQM}(x,\mathbf{k}_\perp^2) = \mathcal{A}_K \exp\left(-\frac{\frac{\mathbf{k}_\perp^2+m_q^2}{x} + \frac{\mathbf{k}_\perp^2+m_{\bar{s}}^2}{\bar{x}}}{8\beta_K^2} - \frac{(m_q^2 - m_{\bar{s}}^2)^2}{8\beta_K^2\left(\frac{\mathbf{k}_\perp^2+m_q^2}{x} + \frac{\mathbf{k}_\perp^2+m_{\bar{s}}^2}{\bar{x}}\right)}\right)$$

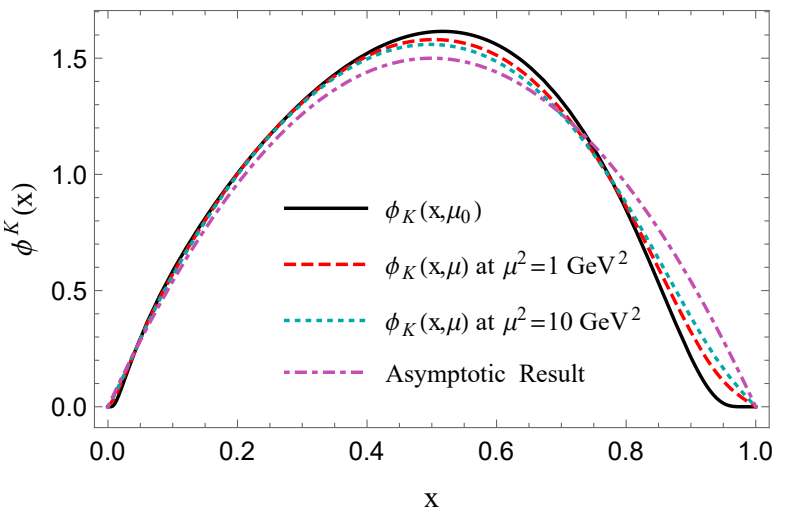
- The spin structure is obtained by boosting the one in instant form to light-front form using Melosh-Wigner rotation [3] [4].

[1] S.J. Brodsky, T. Huang, and G.P. Lepage, Conf. Proc. C 143, 810816 (1981).
[2] B.-W. Xiao, X. Qian, and B.-Q. Ma, Eur. Phys. J. A 15, 523 (2002).
[3] E.Wigner, Annals of Mathematics 40, 149 (1939).
[4] H.J. Melosh, Phys. Rev. D 9, 1095 (1974).

Parton distribution amplitudes (PDAs)

- The role of describing the various hard exclusive processes of QCD is also depicted by the PDAs.
- By integrating out the transverse momentum, LFWFs give unique access to light-cone distributions.
- $\phi(x;\mu\to\infty)=\phi_{\rm as}=6x(1-x)$.





[1] E. M. Aitala et al. (E791 Collaboration), Phys. Rev. Lett. 86, 4768 (2001).

- The n-th moment : $\langle z_n \rangle = \int_0^1 dx\ z^n\ \phi(x;\mu)$ where z can be $\xi = 2x - 1$ or x^{-1}.

Pion DA	μ [GeV]	$\langle \xi_2 \rangle$	$\langle \xi_4 \rangle$	$\langle x^{-1} \rangle$
Asymptotic	∞	0.200	0.085	3.00
LF quark model	1, 2	0.212, 0.21	0.094, 0.092	3.05, 3.05
LF Holography ($B = 0$) [1]	1, 2	0.180, 0.185	0.067, 0.071	2.81, 2.85
LF Holography ($B \gg 1$) [1]	1, 2	0.200, 0.200	0.085, 0.085	2.93, 2.95
LF Holography [2]	~ 1	0.237	0.114	4.0
Platykurtic [3]	2	$0.220^{+0.009}_{-0.006}$	$0.098^{+0.008}_{-0.005}$	$3.13^{+0.14}_{-0.10}$
Linear[HO] [4]	~ 1	0.24[0.22]	0.11[0.09]	-
Sum Rules [5]	1	0.24	0.11	-
Instanton vacuum [6]	1	0.22, 0.21	0.10, 0.09	-
NLC Sum Rules [7]	2	$0.248^{+0.016}_{-0.015}$	$0.108^{+0.05}_{-0.03}$	$3.16^{+0.09}_{-0.09}$
Dyson-Schwinger[RL,DB] [8]	2	0.280, 0.251	0.151, 0.128	5.5, 4.6
Lattice [9]	2	0.28(1)(2)	-	-
Lattice [10]	2	0.2361(41)(39)	-	-

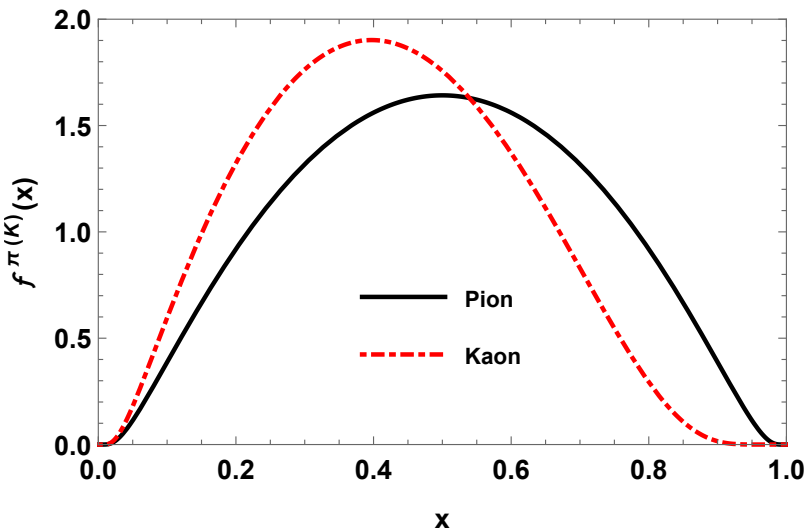
[1] M. Ahmady, C. Mondal, and R. Sandapen, Phys. Rev. D 98, 034010 (2018).
[2] S.J. Brodsky and G.F. de Teramond, Phys. Rev. D 77, 056007 (2008).
[3] N.G. Stefanis, Phys. Lett. B 738, 483 (2014).
[4] H.-M. Choi and C.-R. Ji, Phys. Rev. D 75, 034019 (2007).
[5] P. Ball and R. Zwicky, Phys. Rev. D 71, 014015 (2005).
[6] S.-i. Nam et al., Phys. Rev. D 74, 014019 (2006).
[7] A.P. Bakulev et al., Phys. Lett. B 508, 279 (2001). [Erratum: Phys.Lett.B 590, 309–310 (2004)]
[8] L. Chang et al., Phys. Rev. Lett. 110, 132001 (2013).
[9] R. Arthur et al., Phys. Rev. D 83, 074505 (2011).
[10] V.M. Braun et al., Phys. Rev. D 92, 014504 (2015).

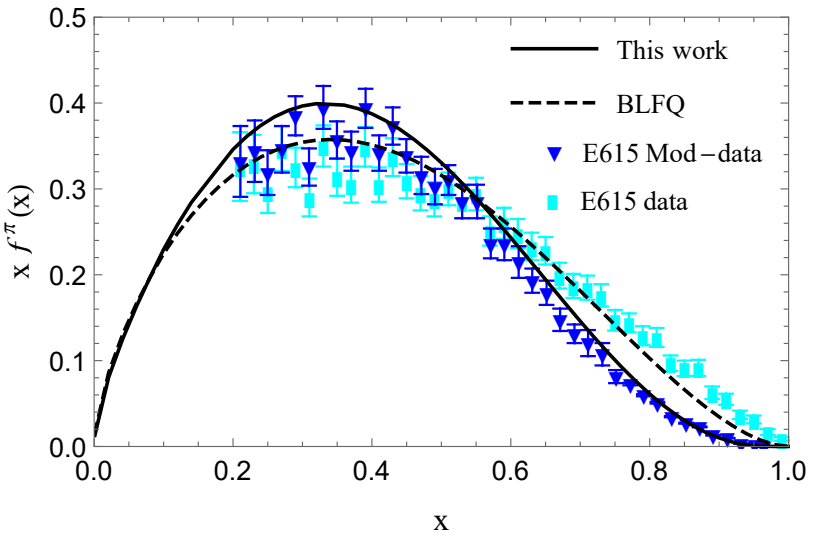
Kaon DA	μ [GeV]	$\langle\xi_1\rangle$	$\langle\xi_2\rangle$	$\langle\xi_3\rangle$	$\langle\xi_4\rangle$	$\langle x^{-1}\rangle$
Asymptotic	∞	0	0.200	0	0.085	3.00
LF quark model	1	0.033	0.183	0.019	0.073	3.027
	2	0.028	0.187	0.016	0.076	3.037
LF Holography	1	0.055	0.175	0.021	0.062	2.55
$(B = 0)$ [1]	2	0.047	0.180	0.018	0.067	2.62
LF Holography	1	0.094	0.194	0.039	0.080	2.60
$(B \gg 1)$ [1]	2	0.081	0.195	0.034	0.081	2.66
Lattice [2]	2	0.036(2)	0.26(2)	-	-	-
Sum Rules [3]	1	0.036	0.286	0.015	0.143	3.57
Dyson-Schwinger [4]	2					
[RL]		0.11	0.24	0.064	0.12	-
[DB]		0.040	0.23	0.021	0.11	-
Instanton vacuum [5]	1	0.057	0.182	0.023	0.070	-

[1] M. Ahmady, C. Mondal, and R. Sandapen, Phys. Rev. D 98, 034010 (2018).
[2] R. Arthur et al., Phys. Rev. D 83, 074505 (2011).
[3] P. Ball, V.M. Braun, and A. Lenz., JHEP 05, 004 (2006).
[4] C. Shi et al., Phys. Lett. B 738, 512 (2014).
[5] S.-i. Nam et al., Phys. Rev. D 74, 014019 (2006).

Parton distribution functions (PDFs)

- PDFs(x) provide the interpretation of the probability density of finding the quark holding the longitudinal momentum fraction, x, in the hadron carrying the total longitudinal fraction, P^+.

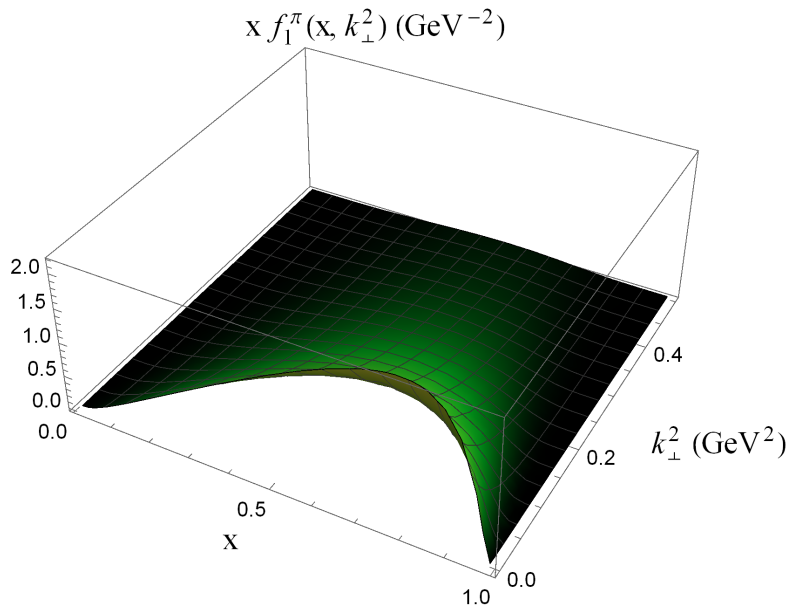


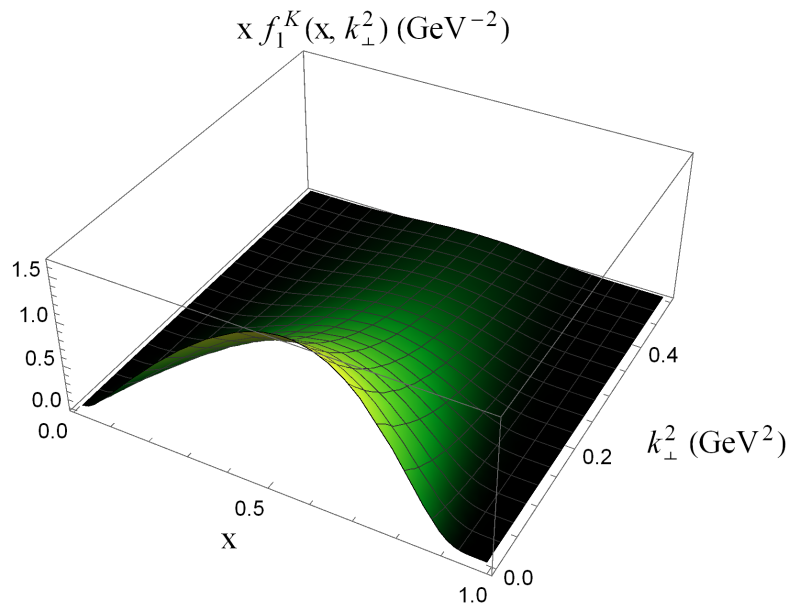


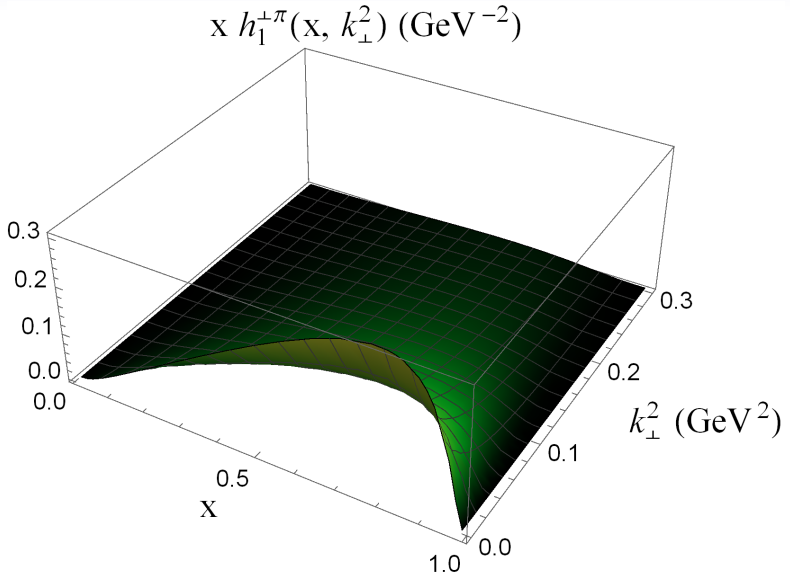
[1] J. S. Conway et al. (E615 Collaboration), Phys. Rev. D 39, 92 (1989).
[2] M. Aicher, A. Schafer and W. Vogelsang, Phys. Rev. Lett. 105, 252003 (2010).
[3] J. Lan, C. Mondal, S. Jia, X. Zhao, J. P. Vary, Phys. Rev. Lett. 122, 172001 (2019).

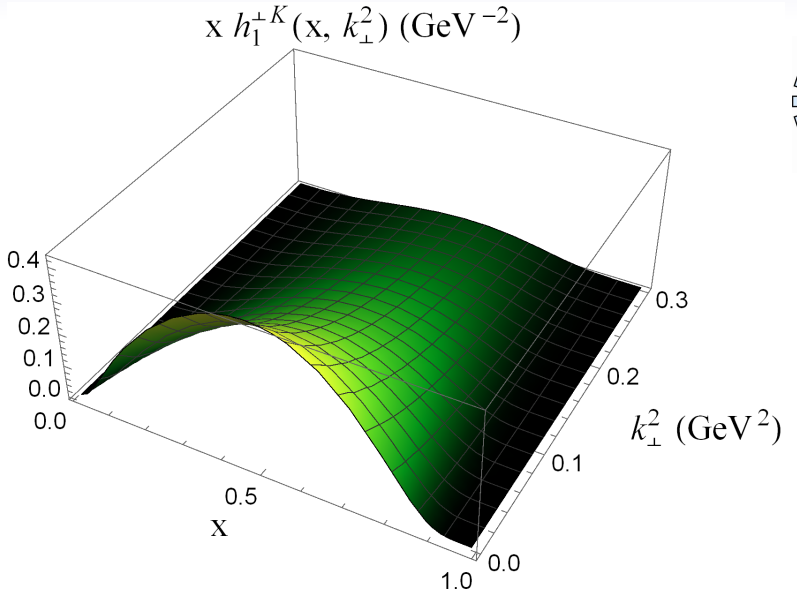
Transverse Momentum-Dependent Parton Distributions (TMDs)

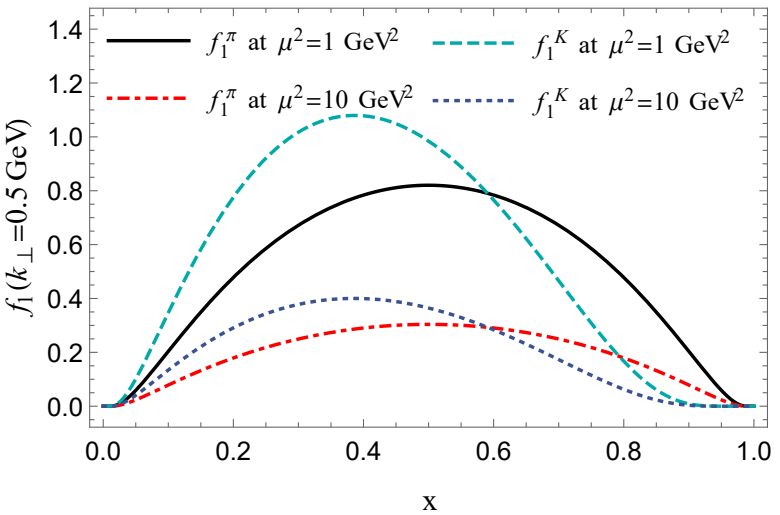
- TMDs$(x, \mathbf{k}_\perp)$ are the extended version of collinear PDFs, predicting the information of the hadronic consituents within the transverse momentum space.

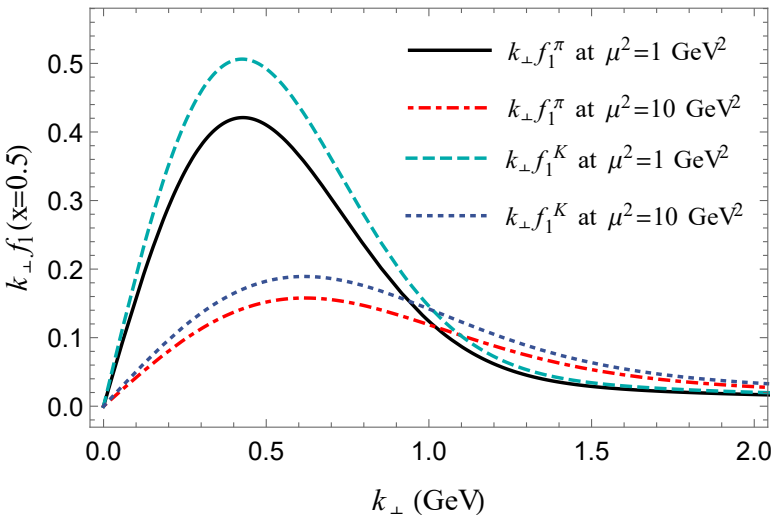





x $h_1^{\perp\pi}(x, k_\perp^2)$ (GeV^{-2})
0.3
0.2
0.1
0.0
0.0
0.5
x
1.0
0.0
0.1
0.2
0.3
$k_\perp^2$ (GeV^2)

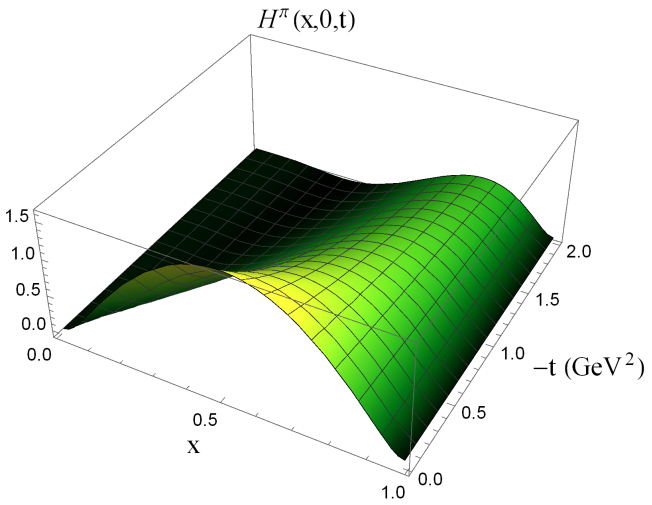

x $h_1^{\perp K}(x, k_\perp^2)$ (GeV^{-2})
0.4
0.3
0.2
0.1
0.0
0.0
0.5
x
1.0
0.0
0.1
0.2
0.3
$k_\perp^2$ (GeV^2)

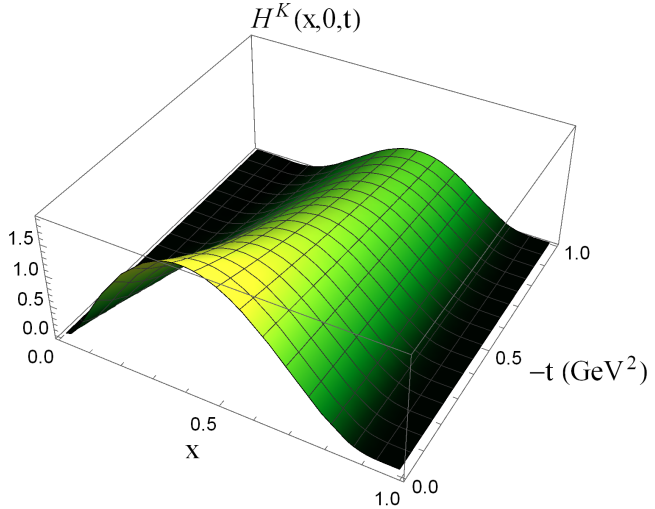

f_1^π at μ^2=1 GeV^2
f_1^K at μ^2=1 GeV^2
f_1^π at μ^2=10 GeV^2
f_1^K at μ^2=10 GeV^2
$f_1(k_\perp$=0.5 GeV)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
x

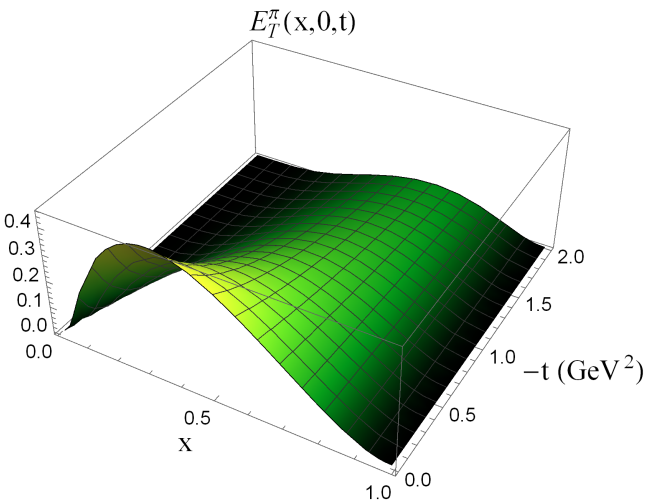

$k_\perp f_1^\pi$ at μ^2=1 GeV^2
$k_\perp f_1^\pi$ at μ^2=10 GeV^2
$k_\perp f_1^K$ at μ^2=1 GeV^2
$k_\perp f_1^K$ at μ^2=10 GeV^2
$k_\perp f_1$(x=0.5)
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.5
1.0
1.5
2.0
$k_\perp$ (GeV)

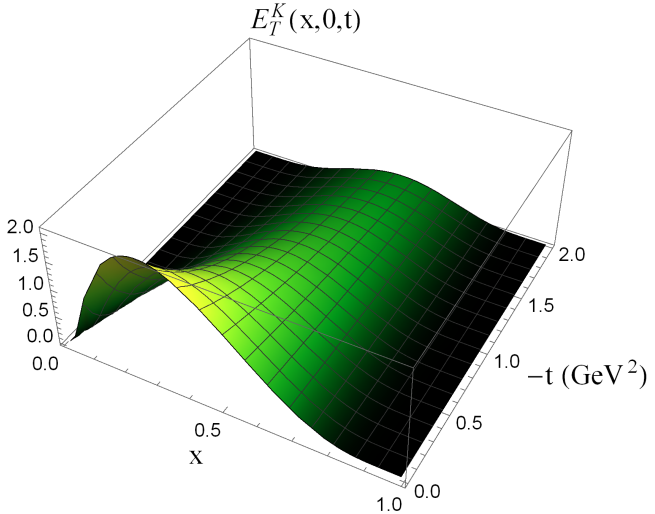
Generalized parton distributions (GPDs)

- Confined spatial correlations of quarks and gluons distributions : Generalized parton distributions.









Conclusions

- We have obtained reasonable agreement with the experimental data for the pion PDA, which is also very close to asymptotic result after LO QCD evolution following ERBL equation.
- Good agreement with the reanalysed E615 data has been observed when we evolved the pion PDF from the model scale to the scale relevant for the comparison.
- Further, we have observed the spatial tomography of the pion and kaon, which is provided by the 3D distributions: GPDs.
- The momentum tomography of the light mesons has been studied through the 3D distribution in the momentum space: TMDs.
- We have presented the effect of μ^2 dependence on unpolarized pion and kaon TMDs. We have observed that the magnitudes of the distributions decrease and became wider as μ^2 increases.

Conclusions

- We have obtained reasonable agreement with the experimental data for the pion PDA, which is also very close to asymptotic result after LO QCD evolution following ERBL equation.
- Good agreement with the reanalysed E615 data has been observed when we evolved the pion PDF from the model scale to the scale relevant for the comparison.
- Further, we have observed the spatial tomography of the pion and kaon, which is provided by the 3D distributions: GPDs.
- The momentum tomography of the light mesons has been studied through the 3D distribution in the momentum space: TMDs.
- We have presented the effect of μ^2 dependence on unpolarized pion and kaon TMDs. We have observed that the magnitudes of the distributions decrease and became wider as μ^2 increases.

Thanks