Kaon parton distributions: revealing Higgs modulation of emergent mass

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Beginning with results for the leading-twist two-particle distribution amplitudes of π- and K-mesons, each of which exhibits dilation driven by the mechanism responsible for the emergence of hadronic mass, we develop parameter-free predictions for the pointwise behaviour of all K distribution functions (DFs), including glue and sea, and comparisons with the analogous π distributions. The large-x behaviour of each DF meets expectations based on quantum chromodynamics. At the resolving scale of existing measurements, the kaon’s light-front momentum is shared as follows: <x_{valence}> = 0.42(3), <x_{glue}> = 0.14(2), <x_{sea}> = 0.14(2). The kaon’s glue and sea distributions are similar to those in the pion; but the inclusion of mass-dependent splitting functions, expressing Higgs-induced current-quark mass splittings, introduces differences on the valence-quark domain.

1. Introduction. — The kaon was discovered in 1947 [1]; yet, today, seventy years later, little is known about kaon structure. (Regarding the pion, Nature’s closest approximation to a Nambu-Goldstone (NG) mode [2, 3], the position is marginally better [4–6].) This is unsatisfactory for many reasons. Primary amongst them is the fact that the standard model of particle physics (SM) has two sources of mass: explicit, generated by couplings to the Higgs-boson; and emergent, a dynamical consequence of strong interactions, responsible for the m_N ≈ 1 GeV mass-scale that characterises nuclei and the origin of more than 98% of visible mass. Emergent hadronic mass (EHM) is dominant for all nuclear physics systems; but, the Higgs mechanism introduces modulations that are crucial to the evolution of the Universe, e.g. CP-violation, discovered in neutral kaon decays [7].

Knowledge of kaon structure is crucial because it provides a window onto the interference between Higgs boson effects and EHM [5, 6], e.g. within quantum chromodynamics (QCD), π and K mesons are identical without a Higgs mechanism: these states are NG modes whose common properties are determined by EHM. When the Higgs coupling is switched on, the Lagrangian mass of a Higgs mechanism: these states are NG modes whose e.g. son effects and EHM [5, 6], discussions that are crucial to the evolution of the Universe, systems; but, the Higgs mechanism introduces modula-

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2. Light-front wave functions and parton distributions. — A renormalisation scheme must be chosen when solving the bound state problem in QCD. We choose a momentum subtraction procedure with renormalisation scale ζ = ζ_H, i.e. all quantities are renormalised at the infrared “hadronic” scale whereat the dressed quasiparticles obtained as solutions of the quark gap equation express all properties of the bound state under consideration [10, 11]. As explained elsewhere [12–15], this ensures that parton splitting is properly expressed through ζ-evolution of hadron wave functions [16–18].

Given a Bethe-Salpeter wave function, χ_M^P(¯k; ζ_H), for M = π_{u,d}, K_{u,s}, where k_f is the momentum of the valence f quark, P = k_u - k_h, 2k = k_u + k_h, the leading-twist two-particle distribution amplitude (DA) for the u-quark can be obtained by light-front projection [19]:

\begin{align}
    f_M \varphi_M^u(x; \zeta_H) &= \frac{1}{16\pi^3} \int d^2k_L \psi_M^{\uparrow \uparrow}(x, k_L^2; \zeta_H) \\
    &= N_c \text{tr} Z_2(\zeta_H, \Lambda) \int_{dk} \delta_n^f(k_u) \gamma^\gamma \cdot n^{\chi_M}(\bar{k}; P; \zeta_H),
\end{align}
where $N_c = 3$; the trace is over spinor indices; $f^A_{abk}$ is a symmetry-preserving regularisation of the four-dimensional integral, with $A$ the regularisation scale; $Z_2$ is the quark wave function renormalisation constant; $\delta_n^k(k_u) = \delta(n \cdot k_u - x_n \cdot P)$, $n^2 = 0$, $n \cdot P = -m_M$ in the meson rest frame, with $m_M$ the meson’s mass; and $f_M$ is the meson’s leptonic decay constant. The companion DA for the $h$-antiquark is $\varphi^h_M(x; \zeta_H) = \varphi^h_M(1 - x; \zeta_H)$.

In terms of the two-particle LFWM defined implicitly via Eq. (1a), the meson’s valence $u$-quark DF is [20]

$$u^M(x; \zeta_H) = \int d^2 k_{\perp} |\psi_{M_{\perp}}^{\uparrow\downarrow}(x, k_{\perp}^2; \zeta_H)|^2.$$  

With the constant of proportionality fixed by baryon number conservation. Owing to parton splitting, Eq. (4) is not valid on $\zeta > \zeta_H$. Nevertheless, since the evolution equations for both DFs and DAs are known [16–18, 21–24], the connection changes in a traceable manner.

3. Hadronic scale. — Owing to the emergence of a nonzero gluon mass-scale [25–28], QCD’s process-independent (PI) effective charge, $\hat{\alpha}(k^2)$, saturates in the infrared [9]: $\hat{\alpha}(0)/\pi = 0.974(4)$. An interpolation of the numerical result is provided by

$$\hat{\alpha}(k^2) = \frac{\gamma_m \pi}{\ln \left[ \frac{\Lambda_{QCD}^2}{\Lambda_{QCD}^2} \right]} K^2(y) = \frac{a_0 + a_1 y + y^2}{b_0 + y},$$

with the constant of proportionality fixed by baryon number conservation. Owing to parton splitting, Eq. (4) is not valid on $\zeta > \zeta_H$. Nevertheless, since the evolution equations for both DFs and DAs are known [16–18, 21–24], the connection changes in a traceable manner.

4. Hadron scale distributions. — After forty years of debate, the pion’s leading twist DA is well constrained. It is a broadened, flattened, unimodal function [19, 30, 31], for which a sound pointwise approximation is

$$\varphi_\pi(x; \zeta_H) = 0.227x(1 - x) \times [1 - 2.5088 \sqrt{x(1-x)} + 2.0250 x(1-x)]$$

This form updates the result in Ref. [19], ensuring the DA’s $x \simeq 0, 1$ behaviour matches QCD’s prediction.

The kaon’s DA is more uncertain [4, 12, 32–35]. One can at most say that $\varphi_K(x; \zeta_H)$ is somewhat less broadened than $\varphi_\pi(x; \zeta_H)$ and also slightly asymmetric about $x = 1/2$, both owing to the smaller role played by the Higgs for $u$ quarks as contrasted with $s$ quarks. Defining

$$\langle \xi, \xi \rangle = \frac{\left. [ \int d^4 x \left( 1 - 2x \right) \right] }{\Lambda_{QCD}^2} \varphi_M^H(x; \zeta_H)$$

these results can be stated quantitatively as follows: $\langle \xi, \xi \rangle = 0.025$, $\langle [\xi, \xi] \rangle = 0.035(5), 0.24(1)$. Following the procedures described in Ref. [35], the DA momenta can be used to determine the pointwise form of the kaon’s DA:

$$\varphi_K^H(x; \zeta_H) = n_{\varphi_K} x(1-x) \times \left[ 1 + \rho x (1-x) \frac{\xi}{\Lambda_{QCD}^2} + \gamma x^\alpha (1-x)^\beta \right]$$

where $n_{\varphi_K}$ is the number of quark species; $\xi$ and $\gamma$ are parameters; and $\rho$ is the ratio of the Higgs boson mass to the nucleon mass.

**TABLE I.** (A) Coefficients and powers that specify the kaon DA determined by Eq. (9). Upper, middle, lower refer to the values of $\langle \xi, \xi \rangle$. (B) Low-order moments of the kaon’s $u$ and $\bar{u}$ DAs at $\gamma = \zeta_H$. Mass-independent/dependent evolution is denoted by the subscript $\gamma/m$, respectively.

| $\gamma/m$ | $\rho$ | $\gamma$ | $\alpha$ | $\beta$ |
|------------|--------|---------|---------|--------|
| upper      | 16.2   | -6.00   | 0.0946  | 0.0731 |
| middle     | 18.2   | -5.97   | 0.0638  | 0.0481 |
| lower      | 20.2   | -5.90   | 0.0425  | 0.0308 |

$u$ \hspace{1cm} $0.42(3)$ \hspace{1cm} $0.152(20)$ \hspace{1cm} $0.070(12)$

$\bar{u}$ \hspace{1cm} $0.085(11)$ \hspace{1cm} $0.040(07)$

$\bar{s}_m$ \hspace{1cm} $0.23(2)$ \hspace{1cm} $0.085(11)$ \hspace{1cm} $0.040(07)$

$\bar{u} + \bar{s}_m$ \hspace{1cm} $0.42(3)$ \hspace{1cm} $0.152(20)$ \hspace{1cm} $0.070(12)$

$\bar{s}$ \hspace{1cm} $0.081(11)$ \hspace{1cm} $0.038(07)$

$\bar{s}_m$ \hspace{1cm} $0.22(2)$ \hspace{1cm} $0.081(11)$ \hspace{1cm} $0.038(07)$

$\bar{u} + \bar{s}_m$ \hspace{1cm} $0.42(3)$ \hspace{1cm} $0.152(20)$ \hspace{1cm} $0.070(12)$
where $n_{\phi K}$ ensures unit normalization, and the interpolation coefficients are listed in Table IA. Here “upper” indicates the curve that produces the largest value of $\langle \xi^5 \rangle_K$ and lower, the smallest. Recall, $\varphi^0_K(x; \zeta_H) = \phi^0_K(1 - x; \zeta_H)$. Pion and kaon valence-quark DFs are now determined by Eq. (4). Glue and sea distributions are identically zero at $\zeta_H$ [14, 15].

5. Kaon DFs: massless evolution. — Regarding kaon structure functions, the only extant empirical information is the ratio $u^K(x)/u^\pi(x)$, measured using the Drell-Yan (DY) process forty years ago [36]. The mass-scale in this experiment was $\zeta \approx \zeta_5 = 5.2$ GeV. Thus, to deliver results for comparison with this data, our $\pi$ and $K$ valence-quark DFs must be evolved: $\zeta_H \rightarrow \zeta_5$. Using the evolution scheme described in Sec. 3 this yields DFs which produce $\langle x^0 q^M \rangle = \int_0^1 dx x^0 q^M(x; \zeta_5)$. The same result is obtained by performing the analogous procedure with $u^K(x; \zeta_H)$ defined via Eq. (4): using mass-independent evolution, the kaon’s valence-quark momentum fraction matches that in the $\pi$.

Using the $\zeta_H \rightarrow \zeta_5$ evolved $\pi$ and $K$ DFs, one obtains the ratio $u^K(x; \zeta_5)/u^\pi(x; \zeta_5)$ drawn in Fig. IA. The uncertainty existing in the kaon DA is expressed in the behaviour of this ratio on $x \geq 0.5$: a broader kaon DA yields a ratio closer to unity at $x = 1$. The best agreement with data [36] is delivered by the kaon DF obtained using Eqs. (4), (9), Table IA-middle. Hereafter, we focus on the kaon DFs defined by this curve; and consider the impact of varying $\zeta_H \rightarrow (1.0 \pm 0.1)\zeta_H$, thereby providing a conservative estimate of the uncertainty arising from that in the infrared value of the PI coupling, Sec. 3. This process yields the valence quark DFs plotted in Fig. IB, which produce the low-order moments in the first two rows of Table IB. Hence, accounting for $\zeta_H \rightarrow \zeta_H(1.0 \pm 0.1)$, $\langle x^0 q^M \rangle = \int_0^1 dx x^0 q^M(x; \zeta_5)$. Once again, this matches the pion result.

A first lattice-QCD (lQCD) study of the kaon’s valence-quark DFs is now available [37]. It yields the following moments, listed here following the order in Table IB: $u = 0.193(8), 0.080(7), 0.042(6);$ and $\bar{s} = 0.267(8), 0.123(7), 0.070(6)$. These values are systematically larger than our predictions, especially for the $\bar{s}$, viz. the excesses are: $u - 0.6(4.8)\%$, $21(6)\%$, $40(4)\%$; and $\bar{s} - 24(7)\%$, $53(13)\%$, $84(16)\%$. This is because, when compared with our predictions, the lQCD DFs are harder; a feature highlighted by Fig. 1B. In fact, the lQCD DF behaves as $(1 - x)^\beta, \beta = 1.13(16)$, in conflict with the QCD prediction [19, 38–41]:

$$q^M(x; \zeta) \equiv c^M_q(1 - x)^{\beta(\zeta)}, \beta(\zeta) = 2 + \gamma(\zeta),$$

where $c^M_q(\zeta)$ is a constant and $\gamma(\zeta)$ increases logarithmically from zero on $\zeta > \zeta_H$. Our predictions, on the other hand, are consistent with Eq. (10): $\beta(\zeta_5) = 2.73(7)$. Regarding the ratio $u^K(x; \zeta_5)/u^\pi(x; \zeta_5)$, the impact of $\zeta_H \rightarrow \zeta_H(1.0 \pm 0.1)$ on both $u^\pi(x; \zeta_5)$ and $u^K(x; \zeta_5)$ is almost identical: it produces no uncertainty larger than the linewidth in Fig. 1A. The first lQCD results for this ratio are also drawn in Fig. 1A. The relative difference between the central lQCD result and our prediction is $\approx 5\%$ despite the fact that the individual lQCD DFs are qualitatively and quantitatively different from ours, as evident in Fig. 1B. This feature highlights that $u^K(x; \zeta_5)/u^\pi(x; \zeta_5)$ is forgiving of even large differences between the individual DFs used to produce the ratio, as may be seen by comparing, e.g. Refs. [42–47]. More precise data is crucial if this ratio is to be used effectively to test the modern understanding of SM NG modes; and results for $u^\pi(x; \zeta_5), u^K(x; \zeta_5)$ separately have greater discriminating power [48–50].

6. Kaon DFs: mass-dependent evolution. — Hitherto, when implementing the evolution, we have used textbook moments, listed here following the order in Table IA–upper and Table IA–lower: “lower” produces the smallest $x = 1$ value. Dot-dashed grey curve within grey band – lQCD [37]. Data (orange) from Ref. [36]. (B) $u^K(x; \zeta_5)$ - dot-dashed blue curve; $s^\pi_K(x; \zeta_5)$ [mass-independent splitting] – solid green; $s^\pi_K(x; \zeta_5)$ [mass-dependent splitting] – dotted maroon; and dashed grey curve within grey bands – lQCD result for $s^\pi_K(x; \zeta_5)$ [37]. In this panel, the bands bracketing our central DF curves reflect the uncertainty in $\hat{\alpha}(0)$, Sec. 3.

![Figure 1](image-url)
forms of the massless splitting functions. Consequently, the glue and sea distributions in the kaon are practically identical to those in the pion. Indeed, any symmetry-preserving study that begins at $\zeta_H$ with a bound-state constituted solely from dressed quasiparticles and implements physical constraints on $\pi$ and $K$ wave functions will deliver this outcome when using massless splitting functions. Of course, the $s$ quark is more massive than the $u$ quark. Hence, $[51, 52]$: valence $s$ quarks must produce less gluons than valence $u$ quarks; and gluon splitting must produce less $ss$ pairs than light-quark pairs. Such effects can be expressed in the splitting functions.

We estimate the impact of mass-dependent evolution by modifying $s \rightarrow s$ and $g \rightarrow s$ splitting functions $[53]$:  

\begin{align}
P_{s-s}(z) &\rightarrow P_{q-q}(z) - \Delta_{s-s}(z, \zeta), \\
P_{s-g}(z) &\rightarrow P_{s-g}(z) + \Delta_{s-g}(z, \zeta), \\
\Delta_{s-s}(z, \zeta) &= \sqrt{3}(1 - 2z)\sigma(\zeta), \\
\Delta_{s-g}(z, \zeta) &= \sqrt{3}(1 - 6z + 6z^2)\sigma(\zeta),
\end{align}

with $\sigma(\zeta) = \delta^2/\delta^2 + (\zeta - \zeta_H)^2$, $\delta = 0.1\text{ GeV} \approx M_s(0) - M_q(0)$, where $M_f(k^2)$ is the running mass of a $f$ quark. All splitting constraints are preserved by Eqs. (11). The impacts of these modifications are clear: Eq. (11a) reduces the number of gluons emitted by $s$-quarks; and Eq. (11b) suppresses the density of $ss$ pairs produced by gluons. Both effects grow with the quark mass difference, $\delta$, and decrease as $\delta^2/\zeta^2$ with increasing resolving scale.

The new results for $\delta^K(x; \zeta_5)$ are drawn in Fig. 1B. This DF produces the low-order moments in Rows 3 and 4 of Table 1B. Naturally, the $u$-quark values are unchanged, but those for the $s$-quark are increased by 4.8(8)%.

Our $\zeta = \zeta_5$ predictions for the kaon’s glue and sea DFs are depicted in Fig. 2A. These distributions vanish identically at $\zeta_H$ and are generated using the mass-dependent singlet evolution equations obtained following the procedure described in Sec. 3 with the splitting function modifications in Eqs. (11). It is worth expressing these results via a comparison with the pion’s glue and sea DFs, and such ratios are depicted in Fig. 2B. The uncertainty in these ratios owing to that in $\alpha(0)$ is negligible, i.e. no larger than the line width in either case.

Evidently, the kaon’s glue and sea distributions differ from those of the pion only on the valence region $x \gtrsim 0.2$. In hindsight, this is not surprising: mass-dependent splitting functions act primarily to modify the valence DF of the heavier quark; valence DFs are negligible at low-$x$, where glue and sea distributions are large, and vice versa; hence the biggest impact of a change in the valence DFs must lie at large-$x$. Notably, each of the predicted ratios in Fig. 2B is pointwise similar to the measured value of $u^K(x; \zeta_5)/u^K(x; \zeta_5)$. On the flip side, the glue and sea DFs in the kaon and pion are practically identical on $x \lesssim 0.2$. Using our computed DFs, we find $(\zeta = \zeta_5)$: $\langle x \rangle_g^K = 0.44(2), \langle x \rangle_{sea}^{K} = 0.14(2)$, with $\langle x \rangle_{sea}^{ss} = 0.091(11), \langle x \rangle_{sea}^{ss} = 0.045(06)$, where $f$ denotes the light-quarks. Comparing these results with those for the pion, then accounting for mass-dependent splitting functions, we find that the gluon light-front momentum fraction in the kaon is $\sim 1\%$ less than that in the pion and the sea fraction is $\sim 2\%$ less.

7. Perspective.—We delivered QCD-consistent predictions for all $\pi, K$ distribution functions: valence, glue and sea. Regarding kaon valence distributions, there is a single, recent IQCD study $[37]$ and model estimates exist, e.g. Refs. $[44-46]$; but there are no results for the pointwise behaviour of the kaon’s glue and sea distributions. Hence, our predictions for the entire array stand alone.

Our analysis can be improved in two ways: one could further test the factorisation assumption made for meson light-front wave functions; and a more rigorous treatment of mass-dependence in splitting functions should be implemented. Both improvements are underway.

The Standard Model’s (pseudo-) Nambu-Goldstone modes (pions and kaons) are basic to the formation of everything, from nucleons to nuclei, and on to neutron stars. Hence, new-era experiments capable of testing the
predictions herein should have high priority [49, 50]. The phenomenological methods used to proceed from data to DFs must match modern experiments in precision.

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