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The Impact of Intrinsic Heavy Quark Distributions in the Proton on New Physics Searches at the High Intensity Frontier

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The possibility of an intense proton facility, at "Project X" or elsewhere, will provide many new opportunities for searches for physics beyond the Standard Model. A Project X can serve a yet broader role in the search for new physics, and in this note we highlight the manner in which thus-enabled studies of the flavor structure of the proton, particularly of its intrinsic heavy quark content, facilitate other direct and indirect searches for new physics.

The wave function of the proton consists of its valence $|uud\rangle$ distribution plus Fock states of arbitrarily high particle number due to the extra gluons and quark pairs created from QCD interactions. The Fock state decomposition of a hadron is most conveniently realized at equal light-front time $\tau = t + z/c$ using light-front quantization in light-cone gauge [1, 2]. Since the gluons have physical polarization $S^z = \pm 1$, there are no ghosts, and, most remarkably, the $n-$ parton light-front wave function (LFWF) $\Psi_{n/H}(x_i, \vec{k}_i^{\perp}, \lambda_i)$ which describes the parton distributions in a hadron H with momentum fractions $x_i = k_i^+/P^+$ and transverse momenta $k_i^{\perp}$ is boost invariant; i.e., it is independent of the momentum $P^+ = P^0 + P^z$ and $P_{\perp}$ of the bound state. The $\lambda_i \equiv S_i^z$ label the spin-projections of the partons. The square of the LFWFs yield the parton momentum distributions of the hadron, as well as its spin and transversity distributions. In deep inelastic lepton-proton scattering the light-front fraction of the struck quark is identified with the Bjorken variable $x_{bj} = Q^2/2M\nu$.

It is conventional to model the heavy-quark content of the proton as arising solely from gluon splitting; i.e., from the $g \to Q\bar{Q}$ kernel associated with DGLAP evolution; the resulting heavy quark distributions follow from the underlying soft gluon distribution e.g., $c(x, Q^2) \simeq (1-x)g(x, Q^2)$. Their distribution is thus *extrinsic* to the bound-state nature of the hadron. However, in addition, $Q\bar{Q}$ pairs arise from diagrams in which the $Q\bar{Q}$ are multiply-connected to the valence quarks. They are *intrinsic* heavy quarks, sensitive to the non-perturbative bound state structure of the hadrons themselves [3]. The intrinsic $Q\bar{Q}$ pairs can be of *any* flavor — and thus they include the heaviest quarks as well. The extrinsic heavy quark distribution is always softer in x than the gluon distribution, as this is predicated by its parentage. In constrast, the intrinsic heavy quarks typically carry a large fraction of the proton's momentum. It is this property which makes them of great importance in searches for BSM physics.

Intrinsic heavy quarks in hadrons are a rigorous prediction of QCD. Diagrammatically, the simplest intrinsic quark contribution can be described as a heavy quark loop in the hadron's self-energy where four gluons attach the heavy quarks to the light, valence quarks [4, 5]. The properties of the intrinsic heavy-quark fluctuations in hadrons have also been analyzed using operator-product-expansion techniques [6]. For example, the light-front momentum fraction carried by intrinsic heavy quarks in the proton $x_{Q\bar{Q}}$ as measured by the T^{++} component of the energy-momentum tensor is related in the heavy-quark limit to the forward matrix element $\langle p|\mathrm{tr}_c(G^{+\alpha}G^{+\beta}G_{\alpha\beta})/m_Q^2|p\rangle$, where $G^{\mu\nu}$ is the gauge field strength tensor [6]. In contrast, the abelian structure of QED dictates that the contribution of an intrinsic, heavy lepton pair to the bound state's structure first appears in $\mathcal{O}(1/m_L^4)$. Since the probability for the intrinsic heavy quark Fock state falls off with its invariant mass, the distribution is maximal when the constituents have equal rapidity; i.e., $x_i \sim m_i^{\perp}/\sum_j^n m_j^{\perp}$, where $m_i^{\perp} = \sqrt{m_i^2 + k_i^{\perp}}$. Thus the heavy quarks and antiquarks in an intrinsic heavy quark Fock state of the proton such as $|uudQ\bar{Q}\rangle$ carry the highest momentum fractions x_i.

Recent work by Chang and Peng demonstrates that strange quarks of the $|uuds\bar{s}\rangle$ Fock state in the proton follow the intrinsic heavy quark paradigm [7, 8] as well. In fact, recent data from HERMES show that there are two components to the strangeness distribution in the proton: extrinsic (from gluon splitting) at low x and intrinsic, at high x, which arises in QCD from diagrams where the strange quarks are multiply-connected to the proton's valence quarks. In fact, as shown by Chang and Peng, the intrinsic contribution to $s(x, Q^2)$ at $x > 0.1$ agrees with the predictions of the intrinsic charm quark distribution proposed in Ref. [3] (BHPS) when scaled by the $1/m_Q^2$ factor predicted by the non-abelian structure of QCD.

Since they carry a high momentum fraction, intrinsic heavy quarks can be materialized as heavy hadrons in hadron collisions at large x_F or high p_T even at relatively low energies — this makes a high-intensity proton facility an ideal venue for their study. For example, one can create heavy hadrons such as the $\Lambda_b(bud)$ at high x_F and low p_T in a pp collision, as was observed at the ISR [9], by the coalescence of the intrinsic b quark with the comoving ud valence quarks in the proton's $|uudb\bar{b}\rangle$ Fock state. Similarly, heavy quarkonium such as the $\Upsilon(b\bar{b})$ can be produced at a high momentum fraction $x_{\Upsilon} \sim x_b + x_{\bar{b}}$ from combining the momenta of the coalescing heavy quarks. Exotic

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baryons such as the ccu and ccd double-charm baryons seen by SELEX at high x_F can arise from the coalescence of two intrinsic charm quarks with a valence quark from the 7-particle Fock state $|uudc\bar{c}c\bar{c}\rangle$ of the projectile. One can similarly explain the hadroproduction of J/ψ pairs at high x_F observed by the NA3 fixed target experiment at the CERN SPS [10–13]. The anomalous dependence nuclear $A^{2/3}$ dependence of charmonium hadroproduction at high x_F observed in $pA \to J/\psi X$ at CERN and Fermilab can be understood as a feature of the color structure of the intrinsic charm Fock state [11–13].

The existence of intrinsic heavy quarks in the proton have important consequences for collider physics. They contribute to QCD background studies. For example, they are important to the interpretation of high p_T lepton and photon signals, as recently illustrated by a Tevatron study of inclusive photon production in association with b and c quarks [14] — the data reveal an excess at large p_T^γ which require an amendment of the charm quark distribution at large x. Intrinsic heavy quarks also mediate the materialization of novel heavy particles at high x_F, since most of the proton's momentum is transferred to its intrinsic heavy quarks. In fact, it even makes Higgs hadroproduction at large x_F possible [15, 16].

Heavy intrinsic quarks also play a role in indirect searches for new physics. In the context of studies of CP violation in weak decays, their flavor content is key because the CKM matrix is strongly hierarchical [17]. For example, the presence of intrinsic charm, e.g., in the hadrons' light-front wave functions, even at a few percent level, provides new, competitive decay mechanisms for B decays which are nominally CKM-suppressed. This can be important in the context of $B \to \pi K$ decays because the tree-level $b \to su\bar{u}$ decay is CKM suppressed, whereas the presence of intrinsic charm in the B-meson LFWF can mediate the decay via a CKM-favored $b \to sc\bar{c}$ tree-level transition [17]. More recently, the role of intrinsic charm quarks in semi-leptonic processes has been studied [18–20] with regard to their impact on the value of $V_{\rm cb}$.

Heavy quarks in the proton are also important to searches for dark-matter candidates within the context of supersymmetry — for so-called "WIMPs". Previous work has focussed on the role of strangeness in the proton for WIMP searches [21, 22]. Heavier flavors also play a significant role in mediating the gluon coupling to the Higgs, and hence to the neutralino, and the leading contribution in the heavy-quark limit is well-known [23, 24] — this may describe elastic scattering sufficiently well. Recently, interpreting the tangle of possible dark-matter signatures has led to the suggestion of composite dark-matter candidates [25]; intrinsic heavy quarks could play a role in mediating transitions to excited dark-matter states in scattering experiments. These issues merit further study.

To summarize, intrinsic heavy quarks in both light and heavy hadrons play a key role in searches for physics BSM with hadrons — and their study at the Intensity Frontier may prove crucial to establishing its existence.

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