Strange, charm, and bottom flavors in CTEQ global analysis

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I discuss advances in the determination of strange, charm, and bottom quark parton distribution functions obtained in the CTEQ6.5 and CTEQ6.6 global analyses. These results affect electroweak precision observables and certain new physics searches at the Large Hadron Collider. I focus, in particular, on high-energy implications of the consistent treatment of heavy-quark threshold effects in DIS in the general-mass factorization scheme; an independent parametrization for the strangeness PDF; and the possible presence of nonperturbative (“intrinsic”) charm.

Introduction. Treatment of s, c, and b quark flavors in the global fit of parton distribution functions (PDFs) has undergone important developments in order to meet demands of modern QCD applications. The recent NuTeV and CCFR experimental data on charged-current deep inelastic scattering directly probe the strangeness distribution $s(x)$, allowing it to be independently determined in the global analysis. Dependence of heavy-quark scattering contributions on charm- and bottom-quark masses $m_c$ and $m_b$ introduces conceptual and practical challenges. Throughout the years, these challenges were addressed through the development of a general-mass (GM) factorization scheme [1, 2], an all-order framework for assessment of heavy-quark mass effects in the whole kinematical range probed by the PDF analysis. The latest CTEQ6.5 [3, 4, 5] and CTEQ6.6 [6] NLO PDF sets provided by our group are obtained in a new systematic implementation of such scheme, based on the principles summarized below. The new PDFs provide excellent description of the existing data in the global analysis, as the previous ones. However, the differences due to the improved treatment of mass effects give rise to phenomenologically significant shifts in certain predictions at the LHC. Implications of these new developments for collider physics are reviewed in two talks at the DIS 2008 workshop [7, 8]. This contribution summarizes, and further elaborates on, the comments and figures in the slides for those talks. It is essential to have Refs. [7, 8] open while reading this paper.

Overview of CTEQ6.5 and 6.6 PDFs. The CTEQ6.5 series of papers [3, 4, 5] extended the conventional CTEQ global PDF analysis [9, 10] to incorporate a comprehensive treatment of heavy-quark effects and to include the most recent experimental data. The PDFs constructed in those studies consist of (i) the base set CTEQ6.5M, together with 40 eigenvector sets along 20 orthonormal directions in the parton parameter space [3]; (ii) several PDF sets CTEQ6.5Sn (n=-2,...,4), designed to probe the strangeness degrees of freedom under the assumption of symmetric or asymmetric strange sea [4]; and (iii) several sets CTEQ6.5XCn (n=0...6) for a study of the charm sector of the parton parameter space, in particular, the allowed range of independent nonperturbative (“intrinsic”) charm partons in several possible models [5].

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The above three publications were followed by the CTEQ6.6 study [6], which incorporated the free strangeness parametrization $s(x, \mu)$ into the general-purpose set of 44 error PDFs. (In contrast, the CTEQ6.5 error PDFs assume proportionality of $s(x, \mu_0) = \bar{s}(x, \mu_0)$ at the initial evolution scale $\mu_0$, while free $s(x, \mu)$ and $\bar{s}(x, \mu)$ were explored in separate CTEQ6.5S sets). The CTEQ6.6 set assumes $s(x, \mu_0) = \bar{s}(x, \mu_0)$, given that the preference for a non-zero strangeness sea asymmetry suggested by the NuTeV data remains marginal. In addition, we have improved the numerical computation of heavy-quark contributions to DIS cross sections, bringing CTEQ6.6M predictions to a better agreement with DIS heavy-flavor production data ($F_{c}^{2}, F_{b}^{2}$) as compared to CTEQ6.5M [8], slide 4). Within this framework, we provide updated PDFs in the “intrinsic charm” scenario and for alternative values of the strong coupling strength, charm and bottom masses ($\alpha_s(M_Z) = 0.112 - 0.125$, $m_c = 1.4$ GeV, $m_b = 4.75$ GeV).

Summary of the GM scheme. Our GM scheme originates in the ACOT papers on the factorization for heavy-quark scattering [1, 2]. It also includes more recent conceptual developments. Its key features are [3, 11]

- variable number of active quark flavors;
- full dependence on the heavy-particle mass ($m_Q$) at energies ($Q$) close to the heavy-particle production threshold ($Q \sim m_Q$), for each heavy-flavor species;
- all-order summation of large collinear logarithms $\ln^n(Q/m_Q)$ at energies far above the heavy-particle threshold ($Q \gg m_Q$);
- zero-mass expressions for Feynman graphs with initial-state heavy particles (also known as “flavor-excitation graphs”) [2, 12]; this feature greatly reduces the computational complexity, by evaluating a large fraction of heavy-flavor subprocesses with the help of relatively simple zero-mass matrix elements;
- mass-dependent rescaling of the light-cone momentum fraction in flavor-excitation contributions to fully inclusive ($F_{2,3}(x, Q)$) and semi-inclusive ($F_{2,c,b}^{c,b}(x, Q)$) DIS structure functions [13].

Mass thresholds in DIS; quark PDFs at the LHC. Much of the latest advancements in the GM framework focus on kinematical effects in the vicinity of heavy-quark mass thresholds in inclusive and semi-inclusive DIS. As it turns out, these effects influence both heavy- and light-quark PDFs in a large range of scattering energies. For example, compare total cross sections $\sigma_Z$ and $\sigma_W$ for weak ($Z^0$ and $W^\pm$) boson production at the LHC obtained (a) within the GM scheme and (b) the common zero-mass (ZM) scheme employed in many PDF sets, e.g., in CTEQ6.1 PDFs [10].

The GM CTEQ6.6 $Z$ and $W$ cross sections are larger than the corresponding ZM CTEQ6.1 cross sections by 6-7% [7], slide 7; [8], slides 9, 10), which exceeds the magnitude of the NNLO hard-scattering contribution of order 2% [14, 15], as well as the experimentally-driven PDF uncertainty of about 3%. This enhancement reflects the larger magnitude of GM $u$ and $d$ anti-quark PDFs at $x = 10^{-3} - 10^{-2}$ typical for weak boson production [8], slide 8). Despite its modest magnitude, such few-percent difference is of import for precision measurements of $W, Z$ boson cross sections and $W$ boson mass.

To understand the origin of the difference, notice first that both schemes implement a variable number $n_f$ of active quark flavors: they realize a sequence of effective factorization
schemes with fixed values of \( n_f \), in which the switching from the \((n_f - 1)\) to \( n_f \)-flavor scheme occurs at a factorization scale \( \mu \) of order of the mass of the \( n_f \)th quark (usually exactly at \( \mu = m_{n_f} \)). However, while the GM scheme retains all relevant dependence on \( m_{c,b} \), the common ZM scheme neglects this dependence altogether, operating with \( n_f \) massless quarks when \( \mu \) lies between the \( n_f \)th and \((n_f + 1)\)th mass threshold. As a result the common ZM scheme fails to correctly suppress the \( c, b \) contributions to the DIS structure functions \( F_\lambda(x,Q) \) near the respective thresholds, \( i.e. \), when the DIS total energy \( W = Q \left(1/|x-1|\right)^{1/2} \) is close to \( 2m_c \) or \( 2m_b \).

In contrast, the GM formalism implements the threshold suppression of \( F_\lambda(x,Q) \) completely \([8], \text{slide 7}\) by including two kinds of contributions dependent on \( m_{c,b} \): (a) mass-dependent rescaling of the light-cone momentum fraction variable in partonic processes with incoming heavy quarks; (b) mass-dependent terms in the partonic cross section (Wilson coefficients) in the light-flavor scattering processes involving explicit flavor creation (such as the gluon-photon fusion).

Since the theoretical calculations in the global fit must agree with the extensive DIS data at low and moderate \( Q \), the threshold reduction in \( c, b, \) and \( g \) contributions in the GM NLO fit must be compensated by larger magnitudes of light \((u,d)\) quark and antiquark contributions. In the appropriate \((x,Q)\) region one therefore sees an increase in the \( u \) and \( d \) PDFs extracted in the GM CTEQ6.6 analysis, as compared to those from the ZM CTEQ6.1 analysis.

Although both CTEQ and MRSTW groups have employed some forms of the GM scheme for many years, the shift in the \( W \) and \( Z \) cross sections brought about by the improved treatment of heavy-flavor effects was first noticed in the CTEQ 6.5 paper. Subsequent GM global analyses confirm those findings and converge toward common predictions for \( \sigma_{Z,W} \). The 2006 \[17\] and 2008 \[18\] MSTW results for \( \sigma_{Z,W} \) at the LHC agree with CTEQ6.6 within 2-3%.

**Independent strangeness parametrization.** The dimuon DIS data \((\nu A \to \mu^+ \mu^- X)\) \[19\] in the CTEQ6.6 fit probe the strange quark distributions via the underlying process \( sW \to c \), making the familiar ansatz \( s(x,\mu_0) \sim \hat{u}(x,\mu_0) + \hat{d}(x,\mu_0) \) unnecessary. However, as shown in Ref. \[4\], the existing experimental constraints on the strange PDFs remain relatively weak and have power to determine at most two new degrees of freedom associated with the strangeness in the limited range \( x > 10^{-2} \). At \( x < 10^{-2} \), the available data probe mostly a combination \( (4/9)[u(x) + \bar{u}(x)] + (1/9)[d(x) + \bar{d}(x) + s(x) + \bar{s}(x)] \) accessible in neutral-current DIS, but not the detailed flavor composition of the quark sea. Therefore, the strangeness to non-strangeness ratio at small \( x \), \( R_s = \lim_{x\to 0} \left[ s(x,\mu_0)/(\bar{u}(x,\mu_0) + \bar{d}(x,\mu_0)) \right] \), is entirely unconstrained by the data, although, on general physics grounds, one would expect it to be of order 1 (or, arguably, a bit smaller). Thus, in the current CTEQ6.6 analysis, we adopt a parametrization for the strange PDF of the form \( s(x,\mu_0) = A_0 x^{A_1} (1 - x)^{A_2} P(x) \), where \( A_1 \) is set equal to the analogous parameter of \( \bar{u} \) and \( \bar{d} \) based on Regge considerations. A smooth function \( P(x) \) (of a fixed form for all 45 CTEQ6.6 PDF sets) ensures that the ratio \( R_s \) stays within a reasonable range \((0.63-1.15)\).

The independence of the strangeness parametrization may affect predictions for collider observables. For example, the ratio \( r_{ZW} \equiv \sigma_Z/\left(\sigma_{W^+} + \sigma_{W^-}\right) \) of the LHC \( Z^0 \) and \( W^\pm \) total cross sections is quite sensitive to the uncertainty in \( s(x,\mu) \). Nominally \( r_{ZW} \) is an exemplary “standard candle” LHC observable, because many common uncertainties cancel inside the ratio. This cancellation is an essential prerequisite for accurate measurements of \( W \) boson mass \[20\]. However, the PDF uncertainty associated with \( s(x,\mu) \) cancels incompletely, in
view that it contributes to \( \sigma_Z \) and \( \sigma_W \) through non-identical subprocesses \( s \bar{s} \rightarrow Z \) and \( s c \rightarrow W \). Since these subprocesses have sizable partial rates (\( \approx 20\% \) and 27\% at NLO), the correlation between \( \sigma_Z \) and \( \sigma_W \) is considerably reduced (and, as a result, the PDF uncertainty \( \Delta r_{ZW} \) on \( r_{ZW} \) is increased) if \( s(x, \mu) \) is independent. For instance, \( \Delta r_{ZW} \) predicted by CTEQ6.6 PDFs \([\text{with independent } s(x, \mu)]\) is increased threefold as compared to CTEQ6.1 PDFs \([\text{with } s(x, \mu_0) \propto \bar{u}(x, \mu_0) + \bar{d}(x, \mu_0)]\). A plot of the correlation cosine of \( r_{ZW} \) with individual PDFs \([8], \text{slide 12}) \) confirms that most of \( \Delta r_{ZW} \) is associated with \( s(x, \mu) \) at 0.01 < \( x \) < 0.05. Hence the independent parametrization for \( s(x, \mu) \), the least constrained distribution among the light-quark flavors, is paramount for more realistic estimates of \( r_{ZW} \).

**Implications of the “intrinsic charm”**. While the general-purpose CTEQ6.6 PDFs generate non-zero charm PDFs entirely through perturbative evolution at scales \( \mu > \mu_0 \), the “intrinsic charm” (IC) scenarios implemented in the CTEQ6.6C PDF series allow for additional nonperturbative channels for charm production, leading to \( c\bar{c}(x, \mu) \neq 0 \) at \( \mu = \mu_0 \). The IC models implemented in this series are reviewed in [5].

Contrary to the naive perception, IC is not a purely low-energy phenomenon. An IC-driven enhancement in \( c(x, \mu) \) at \( \mu \approx m_c \) is preserved by the perturbative evolution to the electroweak scale and beyond. The IC may affect the correlated PDF dependence of the LHC \( Z \) and \( W \) cross sections. A figure showing total cross sections \( \sigma_Z \) and \( \sigma_W \) \([8], \text{slide 11}) \) includes predictions from two IC models, denoted as “IC-Sea” and “IC-BHPS”. These predictions lie on the verge of the CTEQ6.6 error ellipse, indicating a potentially non-negligible shift due to IC. Similar IC-driven effects are observed in \( Z, W \) production at the Tevatron (Fig. 6 in [8]). Other charm scattering processes, such as charged Higgs boson production \( c\bar{s} + c\bar{b} \rightarrow H^+ \) in 2-Higgs doublet model at the LHC \([8], \text{slide 15}) \) may be enhanced if IC is included [4]. Future measurements involving charm quarks, such as \( pp \rightarrow ZcX \), could test the mechanism behind charm production, with potential implications for new physics searches.

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