Thoughts on Heavy Quark Production

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Abstract. Various aspects of heavy flavor production in heavy ion collisions in the context of elementary collisions are reviewed. The interplay between theory in experiment in $e^+e^-$ and $\bar{p}p$ data is been found to be non-trivial, even with new NLO calculations. Quarkonium suppression in p+A and A+A show puzzling features, apparently connected to features of inclusive particle production. Open charm is found to scale as expected for a hard process, but strangeness is also found to share these features. These features contribute to heavy flavor as a interesting probe of strong interactions.

1. Introduction

To understand the broad interest in non-light flavors in hadronic collisions, one only has to appreciate two basic facts: 1) strangeness and charm are degrees of freedom which are not present in the initial colliding systems (predominantly composed of up and down quarks) and 2) the successively larger quark masses require larger momentum transfers in their production processes, thus making the use of pQCD techniques more reasonable as the strong coupling constant decreases. These features make heavy flavor an interesting probe of the early stages of heavy ion collisions, possibly sensitive to the features of the produced, strongly-interacting medium.

2. Charm Production in Elementary Collisions

To even begin to address the issue of heavy flavor production in heavy ion collisions, one must understand the essential features of the production process in elementary collisions, including $e^+e^-$, $\bar{p}p$, and $e+p$ reactions. Since the discovery of the $J/\psi$ (closed charm) in 1974 [1] [2] and the subsequent discovery of D mesons (open charm) a year later, a large data set on charmed hadrons has been built up over a variety of collision energies and reactions. Only a small subset relevant to later arguments will be discussed here.

2.1. $e^+e^-$ Collisions

The apparently simple reaction of electron-positron annihilating to a virtual photon and subsequently into hadrons ($e^+e^- \rightarrow $ hadrons) is an excellent laboratory to study
both the production of heavy quarks from the QCD vacuum as well as the cleanest environment to study their fragmentation into hadrons. It provided the cleanest environment to discover the \( J/\psi \) and to measure its properties, as well as the means to produce the higher-mass and higher-spin states of the “charmonium” spectrum, whose striking similarity to the already-known positronium level diagram was one of the early great successes of the quark model of hadrons [3].

The fragmentation of heavy quarks is an active field of research in recent years. This is a consequence of the recent turn-on of B-factories at KEK and SLAC, as well as recent analyses of production at the \( Z_0 \) pole with extensive particle identification. One striking feature of heavy quark fragmentation which distinguishes it from light-quark fragmentation is the distinctive “hard” fragmentation functions, with the leading particle taking typically 60% of the initial quark energy for charm (at B-factory energies), and nearly 80% for beauty (at LEP energies) [4]. When studied as a function of particle species in \( b \) and \( c \) jets, one finds a striking example of the “leading particle effect”, where kaons appear to carry the memory of the initial heavy quark (clearly by virtue of the cascading weak decays of the heavy quarks \( b \rightarrow c \rightarrow s \)) [5]. One also sees a dramatic depletion of all particles in the forward direction, a direct indication of the so-called “dead-cone” effect [6]. Both of these effects (hard fragmentation and dead-cone) will be relevant for later discussions of heavy quark production in heavy ion collisions.

As a preparation for future discussions of \( J/\psi \) production, it is important to discuss the level of our understanding of how such particles are formed from heavy quarks. Originally it was thought that a charm and anti-charm quark were produced
simultaneously via $qq$ or $gg$ scattering and then the pair would “coalesce” into a color singlet $J/\psi$ - the “color singlet model” (CSM) [7, 8]. However, it turned out that this model in conjunction with pQCD production estimates dramatically underpredicted the rates in $pp$ collisions (to be discussed below). This led to the “color octet model” (COM) [9] which attributed $J/\psi$ production to the correlated production of a $cc$ precursor state already close in phase space, color neutralized by an available soft gluon. By reducing the difficulty of situating the produced quarks near enough in phase space, the COM predicted much larger production rates. A similar model is the “color evaporation model” (CEM) [10], which predicts that a $J/\psi$ is dominantly produced via gluon fragmentation, presuming that one can always find a soft gluon. This model also predicts simple formulas for $\sigma(J/\psi)/\sigma(\bar{c}c)$.

In this context, one can appreciate the puzzle in $J/\psi$ production found recently in BELLE data [11]. They found a striking correlation in the production of $J/\psi$ with other charmed particles. The fraction $R = \sigma(e^+e^- \to J/\psi + \bar{c}c)/\sigma(e^+e^- \to J/\psi + X) = 0.59^{+0.15}_{-0.13} \pm 0.12$ is a striking challenge for both singlet and octet models of $J/\psi$ production. Neither would predict that a charm pair, which should normally hadronize into jets with leading D mesons, would prefer to emit another charm pair. However, it is the opinion of this author (perhaps unoriginally) that this large ratio may simply be a sort of “trigger bias”. Since a decay of a virtual photon into oppositely pointing $c$ and $\bar{c}$ jets would preclude these quarks from creating a bound state, it seems unlikely to ever produce a $J/\psi$ without the liberation of yet another pair of quarks. In this context, it may be difficult to produce a $J/\psi$ without additional charm production, but this heuristic argument (which is ultimately based on quark counting) does not have any substantial theoretical underpinning at present.

2.2. Charm Production in $p+p$ collisions

In $p + p$ collisions, the dominant charm production process is the scattering of quarks and gluons in the initial-state parton structure of the projectiles. Charm production in $pp$ and $p + A$ collisions thus offers a means to explore a large range of kinematic variables ($x$ and $Q^2$) at the cost of needing to introduce substantial phenomenological input to interpret the data. That is, at the same time as one is testing the utility of the fundamental pQCD cross sections, one is also testing our understanding of non-perturbative structure and fragmentation functions.

As the most basic example of the concept of “collinear factorization” , one can examine a typical expression of the total charm cross section in its factorized form (see e.g. Ref. [12]):

\[
\sigma(S, m_Q^2) = K \times \sum_{i,j=q,g} \int_1^{4m_Q^2/s} \frac{d\tau}{\tau} \int dx_1dx_2 \delta(x_1x_2 - \tau)
\]

\[
\times \int f_i^A(x_1, \mu_F^2)f_j^B(x_2, \mu_R^2) \times \sigma_{ij}(s, m_Q^2, \mu_F^2, \mu_R^2).
\]

This formula shows how one factorizes out the initial state of the projectiles from
the fundamental pQCD production cross section, constraining the kinematics with the delta function. The “projectile” and “target” are incorporated separately via their own structure functions and the respective momentum fractions sampled from each \((x_1 \text{ and } x_2)\). The “K-factor” is required to match the overall normalization, which is often underestimated by fixed-order calculations, but is expected to be unnecessary if all orders could be included. Results from these calculations are shown for p+p collisions in Fig. 2.

To extract single-particle spectra, one must convolute the terms which describe the production of charm quarks with the fragmentation functions we have already discussed in the context of e+e− annihilations to charm or bottom quarks.

\[
d\sigma \propto K \times f_i^A(x_1, \mu_F^2) f_i^B(x_2, \mu_F^2) \times d\sigma_{ij}(s, m_Q^2, \mu_F^2, \mu_R^2) \\
\times D(z, \mu^2) \times g(k_T^2)
\]

Here we see how particle spectra result from 3 independent steps: 1) production controlled by the initial nucleon or nuclear structure, 2) pQCD cross sections, 3) fragmentation of the produced partons. It should be noted that the scale dependence of the cross sections and fragmentation functions are themselves typically controlled by DGLAP QCD evolution, which provides for additional low-x gluons as the energy increases. This breaks the initially-proposed Feynman scaling and leads to the production of very soft gluons near \(x = 0\). It should also be noted that experimental transverse momentum spectra are much softer than the theoretical predictions. To account for this, one typically adds a phenomenological “\(k_T\)-broadening”, shown as \(g(k_T^2)\), which harden the spectrum and increase the cross section. The same does not appear to be needed in the longitudinal distributions at fixed target energies, which is a real puzzle at present [13].

It should be emphasized in this context that QCD “factorization”, in the formal sense established by Collins, Soper, and Sterman [14], is critical concept for the application of pQCD to hadronic and heavy ion collisions. It is only officially a well-defined concept for very large momentum transfers, such that \(Q^2 \gg \Lambda_{QCD}^2\). In this regime, the momentum transfers take place over small space-time distances and one may prove that in certain conditions (e.g. Drell-Yan production) that the “hard” pQCD cross sections are independent of the long-wavelength fluctuations in the proton wave function. This is thus a prerequisite for any kind of nucleon or nuclear structure physics, although it is also critical that the structure functions are “universal” and independent of which pQCD subprocess one is considering. Finally, if all this is true, then hard processes in \(p + A\) and \(A + A\) collisions become comprehensible as a superposition of the independent binary collisions given the initial impact parameter.

2.3. \(\bar{p} p\) Collisions

It is generally understood, by means of the QCD factorization theorems, that hadron-hadron interactions at asymptotically high energies should be amenable to
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Figure 3. Cross sections for D mesons, measured by the CDF experiment and compared with NLO pQCD calculations.

a perturbative QCD description, especially for processes involving large momentum transfers. Historically, this expectation has been well established for high-$E_T$ jet rates but typically confounded for open heavy flavor and quarkonium production at the highest-available energies at the Fermilab Tevatron ($\sqrt{s} = 1.8$ TeV).

Open charm at CDF has only recently come under reasonable theoretical control. The data shown in Fig. 3 on D meson production [11] is compared with NLO calculations, and one finds that the data sit on the upper edge of the theoretical systematic error bands (shown in gray). These are the errors generated by varying the factorization and renormalization scales ($\mu_F$ and $\mu_R$) up and down by a factor of two. Thus, one is finding a consistency between data and theory of about 50-100%, which is certainly not in the realm of precision physics yet, but NLO calculations of heavy flavor production are maturing rapidly, so more improvements should be expected.

The situation with $J/\psi$ production has been steadily improving since the realization in the early 1990’s that pQCD calculations joined with the CSM under-predicted the measured $J/\psi$ production rates at very high $p_T$ (6-20 GeV/c) by enormous factors (1-2 orders of magnitude)[15]. The introduction of the COM improved the agreement in rates, but predicted a polarization which has been strongly contradicted by recent Tevatron data[16].

The main point to draw from these discussions is that even in the highest energy elementary collisions, heavy flavor production is not trivial. This situation should be kept in mind when applying similar calculations to lower-energy heavy ion collisions, where the momentum transfers are smaller, and the collision systems are substantially more complicated.

3. Charm Production in p+A and A+A Collisions

Given the current understanding of heavy flavor production in high-energy collisions, it would seem difficult to get a handle on the nature of similar production processes in the more complicated environment of a heavy ion collision. To this end, studies of
proton collisions on nuclei are used to get a potentially more relevant baseline for A+A collisions.

3.1. Nuclear Shadowing

One of the complications of studying flavor production in a nuclear environment is the nucleus itself. Deep-inelastic experiments in the early 1980’s revealed that the effective structure of a nucleon embedded in a nucleus (expressed as ratios such as $F_2^A/F_2^d$) were substantially modified relative to the nucleon structure. While only a modest dependence on $Q^2$, the hardness scale of the scattering process, was observed\cite{17}, a dramatic dependence was found in the $x$ variable, representing the momentum fraction of the partons struck by the incoming virtual photon. At the highest $x$ range ($x > 0.9$), one observes a large enhancement due to Fermi smearing of the nucleons in the nucleus. At moderate $x$ ($0.2 < x < 0.9$) one finds a depletion of the parton distributions, a phenomenon called the “EMC effect”\cite{18} but which continues to resist simple explanation even now. To maintain energy-momentum conservation, the strong depletion in moderate $x$ partons must be compensated by a rise in $x$ values of approximately 0.1, called the “enhancement” or “anti-shadowing” region. Finally, the region of very low $x$ ($x < 0.1$) shows “shadowing” phenomenon, characterized by a depletion nearly flat down to very low $x$ values.

While no unique explanation of this effect exists, it is generally thought to arise by the quantum-mechanical interference of the wave functions of the nucleons in the nucleus, which make up the tube in front of the incoming virtual photon (or equivalently $\bar{q}q$ state)\cite{19,20}.

By treating nuclear effects as modifications of the initial state, rather than as a dynamical effect of the collision of the probe with the nucleus, the physics of nuclear modifications is generally considered to not be in the realm of perturbative QCD. Thus,
“nuclear shadowing” a term which encompasses all of the above effects and denotes any modification of the structure function of a nucleon in a nucleus, is generally handled by a judicious parametrization of existing data, using known pQCD techniques to evolve the modification factors as a function of $x$ and $Q^2$. This is the basis of the well-known EKS98 approach. They take the modification factors $R_i^A$ for parton $i$ and evolve using DGLAP techniques\cite{21}. These lead to a set of curves shown in Fig. 4 from Ref. \cite{22}, which clearly show the “shadowing”, “anti-shadowing”, “EMC effect” and “Fermi motion” regimes, but now as a function of $Q^2$ from $2.25GeV^2$ to $10000GeV^2$. It should not be forgotten, however, that saturation models do offer a QCD-based model for shadowing phenomenon with some basis in perturbative QCD.

3.2. Charm as a “Hard Probe”

As we showed in above sections, heavy flavor is not fully under control even in elementary reactions. Open charm is still under-predicted by pQCD calculations, requiring substantial $K$ factors to agree with data. Even then, special fragmentation functions and intrinsic $k_T$ are needed to describe the differential cross sections. Closed charm is plagued by its reliance on NRQCD models of $J/\psi$ formation. How could we then expect to use it as a “calibrated” probe in a heavy ion collision? The answer again relies on QCD factorization: in principle the short-wavelength field configurations reflected in large transverse momentum processes are only moderately sensitive to the longer-range configurations typical of soft processes. This leads to the prediction that high-$p_T$ phenomena, including charm production rates, are only sensitive to the number of binary collisions experienced by the nucleons as the nuclei interpenetrate each other. To be more specific, one would expect the rate of these rare processes to scale \textit{linearly} with the number of binary collisions, essentially measuring the longitudinal thickness of the projectile and target nuclei seen by the incoming nucleons. Given this, strong deviations from factorization expectations can then be interpreted as indications of non-trivial nuclear physics. $J/\psi$ suppression is the canonical example of this story\cite{23}.

Just as a reminder, we briefly review the two dominant scaling variables for yields in heavy ion collisions. Soft particle production in $p + A$ and $A + A$ collisions has been observed to scale linearly with the number of “participating” nucleons ($N_{part}$), i.e. nucleons which undergo any inelastic process. Hard processes, by contrast, are expected to scale with the number of “binary collisions”, as mentioned in the previous paragraph. These two quantities are tightly correlated by the fact that at smaller impact parameter ($b$), a typical nucleon sees a larger thickness, so the larger the overlap volume, the greater the thickness of nuclear matter it collides with, giving an approximate number of collisions that scales as volume x thickness $\sim R^4 \sim N_{part}^{4/3}$. Glauber calculations show that over the range of impact parameters measured by RHIC experiments, one is sampling thicknesses of $\nu = N_{coll}/(N_{part}/2) \sim 1 - 6$, as shown in Fig. 5.
3.3. $J/\psi$ Suppression

The NA50 analysis of $J/\psi$ suppression is generally shown as the ratio of $J/\psi$ production relative to Drell-Yan production as a function of a centrality variable (typically $E_T$)\[23\]. This ratio is then compared with a calculation of the expected “normal nuclear suppression” extracted from p+A data, as shown in Fig. 6. The data appear to agree with the normal suppression in peripheral events, but then deviate strongly for moderately peripheral events saturating at a suppression factor of approximately 50%. These results are insensitive to various choices of the centrality variable (i.e. a rescaling of the horizontal axis) \[24\], which is not surprising considering that these ratios are made within each centrality class.

While these results have been cited widely and studied by a variety of theoretical approaches, it makes sense to look very carefully at the systematics of $J/\psi$ production from other systems and energies, by which “normal” nuclear suppression is determined. The analysis of this suppression is based on the fact that the yield of $J/\psi$ per target nucleon tends to systematically decrease as a function of nuclear thickness. This is typically interpreted as the absorption of produced $J/\psi$ in the nucleus itself, presumably by $J/\psi + N$ inelastic scattering \[25\]. This absorption is described empirically by the parameter $\alpha$, which is made from a fit of the yields to the form $\sigma_{J/\psi}^{p+ A} = \sigma_{J/\psi}^0 \times A^\alpha$, with $\sigma_0$ ideally the $p+p$ cross section (but not necessarily so). If $\alpha = 1$ then every nucleon in the nucleus is visible to the incoming proton, which is equivalent to $N_{\text{coll}}$-scaling. We interpret $\alpha < 1$ as due to the shadowing of the interior by the nucleons on the surface, i.e. $\alpha \sim 2/3$ corresponds to complete surface absorption, with even lower values interpreted as further absorption in the bulk.
NA50 extracted values of $\alpha_{J/\psi} = 0.931 \pm 0.002 \pm 0.007$ [24], implying a substantial absorption in heavy targets. They also analyze these results in terms of an attenuation in the effective thickness of the nuclear target (which is approximately $\rho L A^{1/3}$), $N \propto \exp(-\sigma \rho L)$ and using Glauber geometry as a function of centrality to determine $\rho L$ in order to estimate $\sigma_{J/\psi+N}$. This cross section was as large as 7.3 ± 0.6 mb in the 1996 analysis, but has decreased to 4.3 ± 0.6 mb in a recent analysis incorporating the S+U data [24]. Thus, this cross section appears to depend strongly on the fit assumptions, lending some doubt to its status as representing a primordial physics process.

Some insight on this can be gained by study of other important $J/\psi$ data sets from PHENIX at RHIC and E866 at Fermilab. These experiments have larger kinematic acceptance than NA50, E866 with the full forward range $y = 0 - 4$ ($x_F > 0$) in p+A collisions and PHENIX with forward and backward coverage $-2 < y < 2$ in d+Au collisions, in order to elucidate the role of shadowing and energy loss in $J/\psi$ production. If the depletion of $J/\psi$ as a function of nuclear thickness was simply due to the shadowing of the parton densities in the nuclear target, then the suppression factor would be simply due to the nuclear properties and thus $\alpha$ would be a universal function of $x_2$, the momentum fraction of the target parton, invariant with beam energy. As shown in Fig. 7, this expectation is dramatically violated when one compares NA3, E866 and PHENIX (something already noted previously by E866 [26] comparing to NA3 data from CERN).

This violation of $x_2$ scaling should be contrasted with scaling which is observed in the forward region between PHENIX, E866 and NA3 over a broad range in $x_F$, as shown in Fig. 8 [27]. While this would seem to be merely fortuitous, it should not be forgotten that inclusive charged particle production also seems to scale with $x_F$ across a wide range of beam energies. This is seen in the phenomenon of “limiting fragmentation”,
where particle yields seem to scale when plotted as a function of $y' = y - y_{beam}$ \cite{28}. Thus, it seems that $J/\psi$’s also obey a sort of limiting fragmentation, similar to soft processes, despite their presumed status as a hard probe.

Other $J/\psi$ data suggests that this is not the case, at least for $J/\psi$. PHOBOS data has also shown that the yield inclusive charged particles ($N_{ch}$) scale approximately linearly with $N_{part}$ in d+Au and Au+Au, but only when one integrates the yield over the full phase space \cite{29}. In limited regions, this linear scaling is clearly broken. In fact, in the forward region of d+Au collisions, increasing the number of participants strongly suppresses the yield in the forward direction. This is compensated by an increase in yield in the backward direction, holding the total yield per participant constant \cite{30}. Similar “long range” correlations of particle yields with centrality are also seen in PHENIX, where they calculate $R_{CP}$ (the ratio of yields in central and peripheral events, normalized by the number of binary collisions) for $J/\psi$ as well as stopped hadrons in the muon system, which have $1 < p_T < 3 GeV$, as shown in Fig. 9 \cite{27}. It appears again that $J/\psi$ production acts very similarly to soft particles, at least away from mid-rapidity. This compensation of suppression in the forward region with enhancement in the backward direction may lead to an approximate constancy of total $J/\psi$ production with $N_{part}$ or $N_{coll}$ in d+Au collisions. Taken together with the various claims made by Gazdzicki et al \cite{31} and Braun-Munzinger et al \cite{32} who argued that $J/\psi$ production actually shows approximate $N_{part}$-scaling, suppression measurements in A+A collisions may be substantially distorted by limited kinematic acceptance.

If in fact $N_{part}$ scaling is relevant for $J/\psi$ production in A+A collisions, this may signal a mechanism better described by statistic models than by parton model calculations. Of course, interpreting $J/\psi$ production statistically opens up the possibility of charm recombination, especially at RHIC when the charm yields per events are quite large compared with SPS energies \cite{33}. The current PHENIX data \cite{34} has very
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3.4. Open Charm Production

While one may have expected closed charm production to be sensitive to final state suppression effects, similar considerations do not apply to open charm. Once the quantum numbers have been liberated in the initial state, they only decay via weak processes on time scales much longer than the lifetime of the system. Thus, open charm may well serve the same purpose as Drell-Yan production and act as a proper reference for the modification of hard processes, especially if it is found to scale with the number of binary collisions. The high-\(p_T\) suppression seen for light hadrons is not expected to show up in the spectrum of hadrons with heavy quarks (D and B mesons) due to the “dead cone” effect discussed above [35].

Open charm has been measured both by PHENIX and STAR, by a variety of techniques. PHENIX has focused mainly on the extraction of a prompt electron signal at high \(p_T\), which primarily come from charm and beauty decays. They have performed a measurement of these “non-photonic” electrons out to 5 GeV in the full range of systems offered at RHIC (p+p, d+Au, Au+Au) and have found that the spectral shape is similar in all of them [36, 37, 38]. More importantly, they have found that the overall yield seems to scale linearly with \(N_{\text{coll}}\), as shown in Fig. 11. This let them extract a production cross section per binary collision in heavy ion reactions which is consistent (within large errors) with pQCD-based extrapolations of p+p data from Fermilab and the ISR, shown in Fig. 12.

STAR has focused both on non-photonic electron signals as well as direct reconstruction of high-\(p_T\) D meson decays [39, 40]. By a combination of these methods,
they have also attempted to estimate the total charm production cross section per binary collision in d+Au collisions, shown in Fig. 13. While the STAR and PHENIX result are consistent with each other within large systematic errors, the STAR result is substantially higher (by a factor of 2-3) than the pQCD extrapolation of lower-energy data, which describes the PHENIX Au+Au data. Still, although this looks like a potential crisis for pQCD, one must always keep in mind that charm measurements at new machines are often quite uncertain as experiments make their first round of measurements, leading to a large variance between them (e.g. at the ISR, as we saw in Fig. 2). Confirming measurements over a variety of systems and final state charmed particles may be necessary before the charm cross section at RHIC energies can be established to a high precision.

4. Strangeness and Hard Scaling

In the previous sections, we saw that particles with hidden charm (e.g. $J/\psi$) scale in some ways like $N_{\text{part}}$ while, open charm production rates seem to show scaling with $N_{\text{coll}}$. Prima facie, this is proof of “hard” scaling (presumably due to the “dead cone” effect) and thus charm seems to serve well as a reference for the suppression of other processes. Does this suggest that charm can truly serve as a calibrated reference? It will be argued in this section that the situation with the production of non-light flavors is somewhat more subtle than it would first appear.

The first observation related to this issue is that charm is not the only process that scales much faster than the number of participants. While strangeness production is not
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Figure 15. Data on $K^\pm/\pi^\pm$, $K^-/\pi^\pm$, and $\phi/\pi^\pm$ vs. system size in NA49 at Pb+Pb collisions at 158 AGeV.

considered a “hard” process, in that the relevant mass scale is on the order of the QCD scale, it has been observed that the number of kaons per participant increases with the number of participants, almost by a factor of two between peripheral and central events, e.g. as shown by PHENIX at $\sqrt{s_{NN}} = 130$ GeV in Fig. 14 [41].

However, pure binary collision scaling would imply an increase per participant of a factor of 6 relative to p+p collisions, something which is typically not seen for strange particles. This begs the question of what kind of scaling is in fact observed, and whether it bears a simple relationship to the initial-state nuclear geometry.

One hint about the relevant control variables was given by an analysis of strangeness production over a large range of system sizes by the NA49 collaboration, shown in Fig. 15 [42, 43]. They studied the $K^+/\pi^+$ ratio as a function of various centrality variables and found that $N_{part}$ is not a proper scaling variable to connect smaller systems like $Si + Si$ and $C + C$ to $Pb + Pb$. Two variables which do work are the fraction of multiply-struck participants (which we call $f_2$), and the space-time collision density, as shown in the second and third columns of Fig. 15. While the data is equally consistent with both of these variables, it should be pointed out that they have slightly different physical pictures. The scaling with $f_2$ suggests that strangeness enhancement (or the lifting of strangeness suppression) is a purely geometrical effect, essentially independent of the particle density. The collision density is more related to the number of times nucleons scatter on their way through the oncoming nucleus, but it requires more assumptions (as expressed through a transport code) to derive the scaling quantity. For
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this reason, $f_2$ may be the more relevant variable, as it requires the fewest additional physics assumptions to achieve a reasonable scaling behavior. Intriguingly, centrality-dependent thermal fits have found that $\gamma_s$ is quantitatively very close to $f_2$ over a large range of centralities [44], as shown in Fig. 16. This suggests that $\gamma_s$ should be less than unity (by at least 10%) for all observable heavy ion collisions, if only due to the “skin” of singly-struck nucleons.

And yet, the observation of a scaling behavior does not explain the mechanism for why it works. It is beyond the scope of this work to propose a detailed model for the success of $f_2$-scaling, but it is useful to imagine what happens to a nucleon in the context of a heavy ion collision. The first collision certainly excites the nucleon into a massive state that decays into hadrons. This scenario is the essence of the wounded nucleon model of particle production. The second collision, however, involves an interaction of this excited nucleon with another nucleon (also possibly excited). While the original nucleon should have a well-understood parton structure (as explored via DIS), the multiply struck nucleon is not something about which we have direct information. It is possible that this object will have a severely distorted valence structure.

Some insight may have already been provided by an analysis of the strange sea of the nucleon from NuTeV [45]. By a study of charm production in $\nu + Fe$ interactions, they extracted the strange content of the nucleon (via the flavor changing charged current $\nu + s \to \mu + c$). The overall fraction of the sea occupied by strange quarks was quantified by a scale factor $\kappa = (2s)/(u+d)$, a quantity identical to the Wroblewski factor $\lambda_s$. The measurements showed values of $\kappa = 0.36 \pm 0.05$ in $\nu + N$ interactions and $\kappa = 0.38 \pm 0.04$ in $\bar{\nu} + N$. When one compares this to a broad compilation of $\lambda_s$ extracted from A+A, p+p and $e^+e^-$ data, it is observed that the strangeness content of the sea is intriguingly close to the asymptotic value seen in A+A collisions, which is about 0.44, as shown in Fig. 17 [46].

5. Outlook and Conclusions

In conclusion, we have reviewed various aspects of heavy flavor production in heavy ion collisions in the context of elementary collisions. The interplay between theory in experiment in $e^+e^-$ and $\bar{p}p$ data has been discussed and it is found that the pQCD description is not straightforward even now, although substantial progress is being made with NLO calculations. Quarkonium suppression in p+A and A+A show some very puzzling features, if the primordial charm quarks are truly produced by factorisable hard processes. It is mysterious how $J/\psi$ production shares features with “soft” inclusive particle production. It is equally mysterious how open strangeness also scales much faster than $N_{\text{part}}$, an effect which should not be entirely ignored when considering the $N_{\text{coll}}$-scaling of open charm. It is evident that heavy ions, by offering an environment where nucleons are struck multiple times (unlike elementary collisions), provide a unique perspective on the production of new flavor quantum numbers over a wide range of momentum scales. So while the present occasionally seems “strange”, although often
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Figure 16. Centrality dependence of $\gamma_s$ at SPS and RHIC energies.

Figure 17. Compilation of $\lambda_s$ as a function of beam energy for $pp$, $e^+e^-$ and $A+A$ reactions.

“charming”, the future of heavy flavor studies at RHIC certainly looks “beautiful”, with upgrades and planned searches for the $\Upsilon$ and leptons from $B$ decay in the large statistics data sets taken in RHIC Run 4\textsuperscript{[47]}.

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