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Abstract. In these proceedings we present a brief overview of recent open heavy flavor and quarkonium production theory in proton-proton (pp), proton/deuteron-nucleus (pA, dA) and nucleus-nucleus collisions.

1. pp Interactions

1.1. *Open heavy flavor production*

There are currently two approaches to heavy flavor production at colliders: those that employ collinear factorization and the low x k_T-factorization approach. We briefly describe each one.

Complete collinearly-factorized calculations are only available up to next-to-leading (NLO) order in the perturbative expansion. Because of the finite heavy quark mass, it is possible to calculate the total cross section, not possible for processes involving light partons in the final state. However, the 'light' charm quark mass results in large cross section uncertainties [1]. While these can be tamed by fitting the factorization and renormalization scales to data [2], they remain non-negligible. The perturbative expansion works better for the heavier bottom quarks. There are a number of approaches available to calculate distributions. They should all give equivalent total cross sections when integrated over all phase space.

The Fixed-Order Next-to-Leading Logarithm (FONLL) [3] calculation, which includes next-to-leading log resummation at high p_T, only addresses single inclusive production. All other kinematic variables are integrated over. It has been employed successfully to study heavy flavor production at RHIC via both reconstructed D mesons and semileptonic decays of D and B mesons [4]. Semileptonic decays are employed to study single lepton spectra. The decay $B \to J/\psi X$ is also available. Since the heavy quark is treated as light in the FONLL approach, it uses *e.g.* 4 active flavors for charm production instead of 3 so that total cross sections calculated with FONLL, even at fixed order, are typically smaller than in the other approaches.

The other NLO codes calculate exclusive $Q\overline{Q}$ pair production which allows for studies of correlated observables. The first, `HVQMNR` [5], also includes single Q and total $Q\overline{Q}$ production, as well as fragmentation and decays to leptons. `HVQMNR` uses negative weight events used to cancel divergences numerically and which often tend to give a negative value for the cross section in the lowest pair p_T bin. This negative value can be removed by adding smearing the parton momentum through the introduction of intrinsic transverse momenta, k_T. In addition, it is not an event generator and also does not include any resummation. More recent codes employing

NLO matrix elements include complete events. MC@NLO [6] is a more general event generator employing NLO matrix elements for a number of hard processes (including $b\bar{b}$ production) while $\texttt{POWHEG}-\texttt{hvq}$ [7] is specific to heavy flavor production. $\texttt{POWHEG}-\texttt{hvq}$ is a positive weight generator and also includes leading-log resummation. In both codes, the entire event is available since PYTHIA [8] and HERWIG [9] are employed to produce the complete event.

In all cases, a theoretical uncertainty band is obtained by varying the quark mass with fixed scales and varying the scales in some prescribed way for fixed mass and adding the differences in quadrature [4, 2, 10]. The single particle observables calculated using collinear factorization are all in good agreement with the RHIC and LHC data and with each other.

In the k_T-factorization approach, off-shell leading order matrix elements for $g^*g^* \to c\bar{c}$ together with unintegrated gluon densities that depend on the transverse momentum of the gluon, k_T, as well as the usual dependence on x and μ_F. The unintegrated gluon distributions are normalized so that $g(x,\mu_F^2) = \int_0^{\mu_F^2} dk_T^2 f_g(x,k_T^2,\mu_F^2)$. There are a variety of unintegrated gluon densities on the market but only a few give shapes consistent with the D^0 distributions at $\sqrt{s} = 7$ TeV. There is only a small enhancement in the charm quark p_T distribution at low p_T over the FONLL result. This approach has also been used to calculate correlated $c\bar{c}$ production at forward rapidity, as measured by LHCb and is in generally rather good agreement with the data [11]. The results with collinear factorization were not included in the comparison.

1.2. Quarkonium Production

The simplest approach to quarkonium production is the color evaporation model (CEM) which treats heavy flavor and quarkonium production on an equal footing. In the CEM, the quarkonium production cross section is some fraction of all $Q\overline{Q}$ pairs below the $H\overline{H}$ threshold where H is the lowest mass heavy-flavor hadron. Thus the CEM cross section is simply the $Q\overline{Q}$ production cross section with a cut on the pair mass but without any constraints on the color or spin of the final state. The color of the octet $Q\overline{Q}$ state is evaporated through an unspecified process which does not change the momentum. The additional energy needed to produce heavy-flavored hadrons when the partonic center of mass energy, $\sqrt{\hat{s}}$, is less than $2m_H$, the $H\overline{H}$ threshold energy, is nonperturbatively obtained from the color field in the interaction region. The quarkonium yield is only a fraction of the total $Q\overline{Q}$ cross section below $2m_H$. The actual fraction depends on the heavy quark mass, the scale parameters, the parton densities and the order of the calculation [12]. For the most recent results of the CEM on J/ψ production, see Ref. [2]. CEM calculations do not currently address quarkonium polarization.

Two often used models of quarkonium production depend on the color of the $Q\overline{Q}$ state at production. The color singlet model (CSM) assumes perturbative production of an on-shell Q and $\overline{Q}$ at the final state scale. The color and spin of the pair is unchanged by binding. The LO CSM calculations predicted that χ_c production should dominate high p_T J/ψ production. Further refinements with higher order contributions, up to a partial NNLO result, give better agreement at high p_T. The non-relativistic QCD (NRQCD) approach is based on a systematic expansion of the quarkonium wavefunction in the strong coupling constant and the relative velocity of the Q and $\overline{Q}$. The velocity expansion is assumed to work better for Υ production. It assumes factorization of the perturbative contribution and non-perturbative hadronization and includes both singlet and octet matrix elements. The octet matrix elements are fit parameters determined from comparison to quarkonium p_T distributions. For a recent review of quarkonium production, see Ref. [13].

Most recently, several groups have attempted to fix the octet matrix elements from a global fit to inclusive J/ψ data from RHIC, the Tevatron, the LHC and, in some cases, HERA [14, 16, 17]. By fitting to a global data set, they attempt to obtain a set of universal matrix elements. The NLO results are obtained by fixing the charm quark mass and scale; fitting the matrix elements with these parameters; and determining the uncertainty on the fit by varying the scale parameters around the central value while keeping the mass and matrix elements fixed. There are some caveats to these analyses: they are limited to prompt J/ψ only; feed down from ψ' and χ_c is either neglected or subtracted assuming that the p_T shapes are the same for all quarkonium states (like the CEM); fixed-target results are not included; and the dependence of the matrix elements on mass and scale is neglected [14]. That said, the results show that octet components are necessary to obtain agreement with the data.

The crucial test of the quarkonium production models is the polarization. In NRQCD, the dominant production mechanism is gluon fragmentation into a color octet. Since this gluon is nearly on mass shell, it is transversely polarized. This polarization should be reflected in the final-state quarkonium distribution. At NLO the CSM result is longitudinally polarized. Neither approach is in agreement with the J/ψ polarization data [13, 15]. Most recently, the CMS Υ data [18] shows no significant polarization, in contradiction to both results. Before the issue of quarkonium production in pp collisions can be settled, the polarization results must be reconciled.

2. p/d $+A$ Interactions

There are several important cold nuclear matter (CNM) effects that need to be taken into account when determining the strength of deconfinement effects on a particular final state. We first discuss mechanisms common to both open and hidden charm and then discuss final-state absorption of quarkonium.

The most general CNM effect, affecting all production processes, is the modification of the parton distributions in nuclei, often referred to as shadowing. Since nuclear deep inelastic scattering experiments probe only charged parton densities, the nature and magnitude of the effect on the nuclear gluon density is not well known. One possible experimental means of probing the nuclear gluon density at low x is through ultra-peripheral collisions (UPCs) at the LHC [19]. In these collisions, the nuclei do not touch and only interact electromagnetically so that J/ψ photoproduction involves the low x gluon density in a single nucleus. The ALICE UPC J/ψ data shows that this method can eliminate certain shadowing parameterizations [20, 21].

The effects of shadowing in nuclei are parameterized by various groups using global fitting methods similar to those used to evaluate the parton densities in the proton. Currently, LO and NLO sets are available with up to 31 error sets, such as EPS09 [22], evolving quarks, antiquarks and gluons separately with Q^2. The uncertainty on the gluon density in the nucleus remains large without general agreement on the best fit shape.

Another significant unknown relating to nuclear shadowing is its dependence on impact parameter or collision centrality. The impact parameter dependence was neglected in most previous parameterizations. Instead, assumptions based on either a linear dependence on path length through the nucleus or the nuclear density were introduced [23]. The PHENIX d+Au J/ψ data suggested a stronger than linear dependence [24]. These results prove challenging for the recent EPS09s spatially-dependent modifications which retain up to quartic powers in the expansion of the centrality dependence as a function of path length for A-independent coefficients [25]. Instead these data suggest that shadowing is concentrated in the core of the nucleus with radius of $R \sim 2.4$ fm with a relatively sharp surface, a width of $d \sim 0.12$ fm [26]. These studies need to be backed up with more data over more final states.

A second cold matter effect is energy loss in medium. Initial-state energy loss has been studied in Drell-Yan production and found to be small. However, there is an inherent ambiguity when applying initial-state energy loss to Drell-Yan production since most groups parameterizing the nuclear parton densities include these same Drell-Yan data to extract the strength of shadowing on the antiquark densities [22]. Also, by forcing the loss to be large enough to explain the high x_F behavior of J/ψ production in fixed-target interactions [27] violates the upper bound on energy loss established by small angle forward gluon emission [28]. More recently, it has been proposed that cold matter energy loss should be treated as a final-state effect [29]. The final-state J/ψ energy loss in pA collisions is currently implemented as a probability distribution dependent on the energy loss parameter. The effect modifies the x_F and p_T distributions in a rather crude fashion since the quarkonium distribution in pp collisions is parameterized as a convolution of factorized power laws, $\propto (1-x)^n (p_0^2/(p_0^2+p_T^2))^m$, rather than using a quarkonium production model [29, 30]. It has yet to be implemented for other processes.

Initial-state energy loss in the medium can be connected to transverse momentum broadening in nuclei relative to pp collisions, as in the Cronin effect [31].

Final-state nuclear absorption, which affects only quarkonium states, involves CNM breakup of the (proto)quarkonium state. Absorption is related to the size and production mechanism of the interacting state and can be described by a survival probability, $S_A^{\rm abs} = \exp\{-\int_z^\infty dz' \rho_A(b,z') \sigma_{\rm abs}^C (z-z')\}$ where z' is the production point and z is the dissociation point; $\rho_A(b,z')$ is the nuclear matter density; and $\sigma_{\rm abs}^C$ is the effective absorption cross section for quarkonium state C [32]. The J/ψ has been most studied. Larger effects, at least at midrapidity, have been seen for the ψ' [27, 33]. Such effects on Υ production may also be expected with stronger nuclear effects on the $\Upsilon(2S)$ and $\Upsilon(3S)$ relative to the $\Upsilon(1S)$ [34] although the overall absorption should be reduced.

Previous studies have shown the absorption cross section to depend on rapidity (or x_F) as well as the nucleon-nucleon center of mass energy, $\sqrt{s_{NN}}$ with stronger absorption at lower energies [35]. Increased effective absorption at backward rapidity may be due to interaction or conversion inside the target while increased effective absorption at forward rapidity may be due to energy loss.

All these cold matter effects should be reduced for bottom quark and Υ production due to the larger masses and scales involved.

3. *AA* Interactions

3.1. Open Heavy Flavor

Most open heavy flavor AA results are focused on energy loss in the medium and typically rely on thermalization and hydrodynamic evolution. The differences are in the details of the calculation. For example, both He *et al* [36] and Alberico *et al* [10] use a Langevin approach. However, the former relates the drag coefficient to the heavy quark relaxation rate, calculated using in-medium heavy-light quark resonant rescattering in a T-matrix model and includes recombinant production of D mesons while in the latter the transport coefficients includes both soft (obtained either in the hard thermal loop approximation or from lattice QCD) and hard (calculated perturbatively) contributions. Both are compared to the nuclear modification factor R_{AA} and to the elliptic flow coefficient v_2. While both can obtain general agreement with R_{AA} at high p_T, without recombination, not enough flow is generated to reach agreement with v_2 [36, 10]. A number of other talks at this conference covered related calculations employing energy loss in the medium, see Refs. [37, 38, 39, 40, 41, 42, 43, 44, 45].

A recent paper has addressed b-jet quenching in Pb+Pb collisions [46]. The b-quark jets are generated in `PYTHIA` via three mechanisms: standard LO $b\overline{b}$ production diagrams ($gg \to b\overline{b}$, $q\overline{q} \to b\overline{b}$); gluon splitting into $b\overline{b}$ pairs in the final state (*e.g.* $gg \to gg$, $g \to b\overline{b}$); and other standard LO jet production processes *e.g.* $qq \to qq$ followed by fragmentation. The gluon splitting contribution dominates b-jet production at high p_T unless the b quark is the leading particle in the jet. The results depend on the cone size (larger cone radii reduces suppression), inclusion of collisional dissipation (increases suppression), in-medium coupling (greater suppression with larger coupling), and mass of propagating parton (increase uncertainty in R_{AA} at low p_T). Cold nuclear matter effects are small. The results are in agreement with very preliminary CMS data, see Ref. [46] for details.

3.2. Quarkonium

3.2.1. Lattice-based results The lattice results presented here were summarized in a recent review [47]. Please refer to that work and Allton's presentation [48] for more details.

A comparison of singlet and octet free energies shows that the temperature dependence of the total free energy (octet and singlet) is much stronger than for the singlet alone. This is consistent with recent calculations of quarkonia spectral functions and correlators which show that no bound states persist in the medium. It is also consistent with effective field theory calculations with separation of scales that depend on the relative size of the binding energy of the quarkonium state (BE) and the temperature of the system (T). If BE $> T$, the heavy quark potential is unmodified by the medium. However, the bound state acquires a finite thermal width. If BE $< T$, the singlet and octet potentials become temperature dependent and acquire an imaginary part since gluons exchanged in octet-singlet transitions scatter from thermal excitations in the medium. With increasing temperature, BE $\rightarrow 0$ and medium effects are incorporated into the potential. Now the separation of scales fails and lattice results are required to constrain the potential. See Ref. [47] for a full description and more references.

One way to define the quarkonium dissociation temperature is the point at which the real and imaginary parts of the binding energy are equal. However, since the state undergoes in-medium decays below the defined dissociation temperature, its actual value is not all that important. This in-medium decay rate is directly proportional to the imaginary part of the potential [47].

Another important recent development is the use of viscous hydrodynamics and anisotropic systems to describe quarkonium propagation in the medium. Typical hydrodynamic calculations assume that the system is close to thermal equilibrium and is thus also isotropic in momentum space. However, large initial momentum anisotropies can persist throughout the lifetime of the medium which can increase the dissociation temperature since the areas of anisotropy can lead to reduced Debye screening. In calculations, the anisotropy is accounted for by introducing an anisotropy parameter related to the ellipticity of the momentum distribution. In such calculations the dissociation temperature, defined as the point at which the real and imaginary parts of the binding energy are equal, can increase as much as 25% [47]. In recent calculations of Υ suppression, the screening mass was taken to be dependent on the anisotropy of the medium. The value of $4\pi\eta/S$ was tuned to achieve good agreement with the CMS Υ data as a function of the number of participants, $N_{\rm part}$. The value obtained, $4\pi\eta/S = 3$ [49], is consistent with IP-Sat light particle flow results [50].

3.2.2. Normalizing quarkonium suppression Finally, we briefly address the question of how to define quarkonium suppression in AA collisions. Recently it was argued that the ratio of hidden to open heavy flavor is a better determination of true quarkonium suppression than the value of R_{AA}, the ratio of *e.g.* hidden charm in AA to pp collisions [51]. This is because similar suppression patterns are seen for D mesons/semileptonic decays of heavy flavor mesons and J/ψ at intermediate and high p_T at the LHC and at high p_T at RHIC. The only apparent difference in the suppression patterns is at low p_T at RHIC where R_{AA} for J/ψ is lower than that for non-photonic electrons, assumed to be predominantly from D decays in this p_T range [51]. At intermediate and high p_T, one may assume that the p_T range is outside the region where Debye screening dominates J/ψ suppression and a similar energy loss mechanism is responsible for the suppression pattern for both J/ψ and open charm. Full p_T phase space comparisons are needed.

So far the LHC data are in somewhat different rapidity regions and there is no low p_T point of comparison, as at RHIC. The data shown in Ref. [51] are all as a function of $N_{\rm part}$. Comparisons of D meson and J/ψ suppression as a function of p_T in different centrality bins would be useful. A similar study of B meson and Υ family suppression would also be enlightening because here ATLAS and CMS can reconstruct $p_T = 0$ Υ states so a comparison at low p_T may be possible, as long as the B decays can be identified.

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