Drell–Yan Dileptons at RHIC

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Abstract

The study if the production of dilepton pairs is an important component of the research to be accomplished at the Relativistic Heavy Ion Collider (RHIC) due to each relevance to Quark-Gluon Plasma search and the investigation of hard QCD processes. We present an event generator program that produces Drell-Yan dilepton pairs for symmetric heavy ion collisions. It computes NLO cross sections including possible nuclear (shadowing, EMC-type) effects. The code been used to estimate the acceptance and the event rate in the PHENIX experiment central arm for Drell-Yan dileptons. The event rate at the design RHIC luminosity at $m = 4$ GeV is of the order of a hundred per year.

1 Introduction

PHENIX is one of the major experiments that is under contruction at the Relativistic Heavy Ion Collider that will start operating in Brookhaven National Laboratory in the year 1999. Its major goal is to search for the Quark-Gluon Plasma (QGP) and investigate other interesting phenomena that pertain to matter at extremely high temperatures.

The production of dilepton pairs is of particular importance since all their sources must be studied in order to establish a thermal component as expected the in the case of QCP formation. In the course of preparing ourselves for real data from PHENIX we would like to follow a complete chain of calculations related to events of specific interest to the experiment. We should simulate such events starting from theoretical calculations and continuing by building an event generator that produces spectra to be processed by the Monte Carlo PHENIX detector response code (called PISA). The results can then analysed like real events.

In the case of Drell-Yan dileptons we would like to study the acceptance and event rate and examine if possible nuclear effects can be detected. In particular, such effects may be present in the initial state [1]. For Drell-Yan dileptons, the hard cross sections are known and there is no ambiguity due to meson wave functions or final state interactions. So such measurements complement those of heavy quarkonia.

There is the additional issue of studying higher twist effects in QCD [2] by means of Drell-Yan dileptons. Such effects may present themselves as modifications (lowering) of the cross section at low transverse momentum, p_T, or in non-standard polar angle distributions of the dileptons [3].

An event generator has been developed that includes Next-to-Leading-Order (NLO) terms and nuclear effects based on a cluster formation model. The program is given values of the Lab momentum per nucleon, P_{Lab}, the square of the virtual photon invariant mass, m^2, the photon longitudinal momentum fraction (Feynman-x), x_F, and the nuclear atomic and mass numbers and outputs N events (dileptons of choice) with the computed p_T-distribution.

2 Theory

2.1 Parton-level cross sections

The hard (*parton level*) cross sections that are included are described by the following Feynman diagrams: Drell-Yan (Leading-Order, LO), $q\bar{q}$ annihilation, and qg Compton scattering (NLO).

The LO term contributes only at $p_T = 0$ if the transverse momenta of partons and hadrons are ignored. It can be turned off in the code. NNLO terms have not been included yet but are necessary to resum large logarithms that appear when $p_T < 1$ GeV. Instead a *constant* K-factor equal to 2.5 has been used. Contributions of the Z-boson have not been included. They become significant only at very large m^2 and/or p_T. 3 active (anti)quark flavours are used with $\Lambda_{QCD} = 200$ MeV (this is adjustable in the code). The convention $Q^2 = p_T^2$ has been used for the calculation of the strong coupling constant.

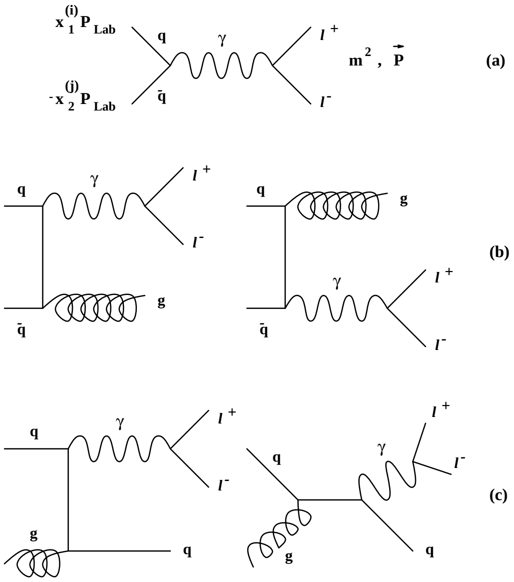

Figure 1: Feynman diagrams contributing to the Drell-Yan lepton pair production. (a) LO QED process. (b) $q\bar{q}$ annihilation. (c) qg Compton scattering. The kinematics is defined in (a). One parton carries momentum fraction $x_1^{(i)}$ of the positively moving hadron momentum, and the other one carries $x_2^{(j)}$ of the negatively moving hadron.

2.2 Nuclear-level cross section and nuclear effects

The parton-level cross sections must be convoluted with the appropriate "structure functions" which are sums of products of parton densities to yield the nucleon level cross section. Taking into account the composition of the nucleus we can calculate the cross section at the level of colliding nuclei.

The nuclear effect (shadowing-antishadowing pattern) is introduced by means of a model that invokes quantum mechanical overlap of bound nucleons to form multi-quark color singlets (clusters) with higher mass and softer parton distributions [4]. The nuclear state is expanded as

$$|A\rangle \;=\; \alpha|3q\rangle + \beta|6q\rangle + \gamma|9q\rangle + ...$$

This expansion gives good results in DIS, J/Ψ-production in hA and AB collisions and direct photon, Drell-Yan production in hA collisions (in Drell-Yan the nuclear effect is visible in differential cross sections versus x_F or p_T). It is sufficient to truncate this expansion to the 6q term.

The nuclear effect is generated by the higher mass of the 6q clusters ($2m_p$) which give an effectively larger $\sqrt{s}$ and the softer parton distributions in 6q objects. In the scaling limit the momentum distributions behave as: $U_N(x) = B_N^u\sqrt{x}(1-x)^{b_N^u}$, $D_N(x) = B_N^d\sqrt{x}(1-x)^{b_N^d}$, $S_N(x) = A_N(1-x)^{a_N}$, and $G_N(x) = C_N(1-x)^{c_N}$ where, $(b_3^u, a_3, c_3) = (3, 9, 6)$, $(b_6^u, a_6, c_6) = (9, 11, 10)$, and $b_N^d = b_N^u + 1$. Here, x is the parton momentum fraction in the cluster, normalized to 1.

There are pp, pn and nn-type of 6q clusters formed with isospin invariance relations connecting the parton distribution in them. The ocean includes u, d, and s quarks and antiquarks. The nuclear effect is controlled by the *effective* probability for 6q cluster formation, $f \propto \ln A(\approx A^{1/3})$. The code provides options for the choice of parton distributions (PDFs).

2.3 Virtual photon decay to dileptons

The virtual photon is produced with uniform ϕ-distribution. After production the virtual photon decays into e^+e^- or $\mu^+\mu^-$ according to the user's choice. The initial kinematics is done in the dilepton CM frame with z-axis parallel to the momentum vector of the photon in the laboratory frame. This choice is *not* identical to the Gottfried-Jackson or tha Collins-Sopper frames.

In the dilepton CM frame (as defined here) the polar angle, θ of one lepton follows a $1+\cos^2\theta$ distribution since the intermediate photon has longitudinal helicity with $J_z = \pm 1$ but not 0. There is an additional term to account for the lepton non-zero mass . The θ distribution is not entirely correct since it neglects the mass of strange quarks in the ocean and the backward-forward A_{bf}, asymmetry introduced by the omitted Z-boson contribution. The latter is $A_{bf} \propto a_{weak}a_{em}/a_{em}^2 = G_F m^2/(4\pi\alpha) = 10^{-4}m^2$ which between the J/Ψ and the Υ is at most 1%. It is more than 20% at $m = 50$ GeV. The Compton scattering process introduces a $\sin^2\theta$ component to the distribution at large p_T since, in this case, the virtual photon is not entirely transverse [3]. Higher twist effects affect both the polar and azimuthal distributions [2]. The CM ϕ-distribution of the dileptons is uniform.

The lepton momenta are 3D-rotated (so that the z-axis meets that of Lab frame) and 3D-boosted back to the Laboratory frame.

A gaussian vertex distribution is also included. The user controls its variance, σ_z. This distribution is produced using the central limit theorem.

3 Results

3.1 Differential cross section for virtual photon production

In Fig. 2 the cross section calculated using the code that has been described here is presented as a function of p_T at $x_F = 0.1$ in central Au-Au collisions at RHIC energy. The solid curve corresponds to maximal nuclear effect and the dotted one to results without any nuclear effect. At low p_T *shadowing* can be observed. At high p_T *antishadowing* occurs. PHENIX will mostly probe the shadowing region.

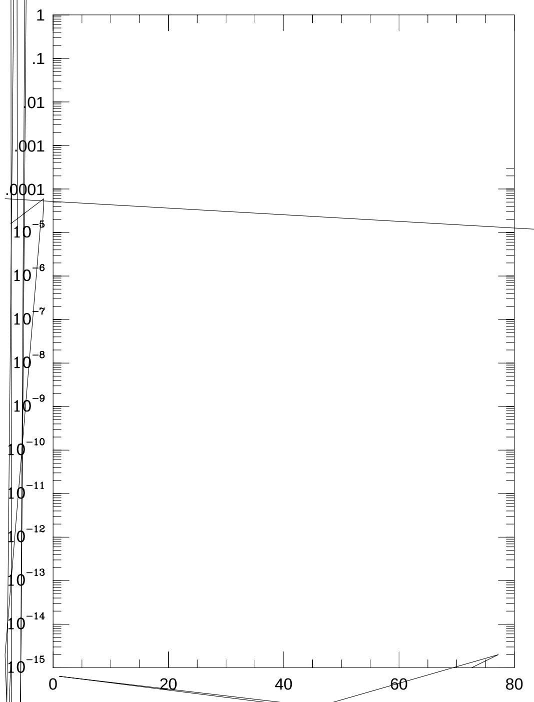

Figure section w/o nuclear Cross5