PRESENT AND FUTURE OF CENTRAL PRODUCTION WITH STAR DETECTOR AT RHIC*

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The present status and future of the physics program of Central Production using the STAR detector at RHIC are described. The program focuses on particle production resulting from the Double Pomeron Exchange (DPE) process. Forward protons from the DPE interaction are detected in the Roman Pot system installed at 55.5 m and 58.5 m on both sides of the STAR interaction point. The recoil system of charged particles from the DPE process is measured in the STAR Time Projection Chamber (TPC). The first data were taken during the 2009 RHIC Run 9 using polarized proton–proton collisions at $\sqrt{s} = 200$ GeV. The preliminary spectra of two pion and four pion invariant mass reconstructed by STAR TPC in central region of pseudo-rapidity $|\eta| < 1$, are presented. Plans to take data with the current system at $\sqrt{s} = 500$ GeV and plans to upgrade the forward proton tagging system, so that it can reach higher masses and obtain large data samples in searching for glueballs that could be produced in the DPE process, are discussed.

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1. Introduction

The Relativistic Heavy Ion Collider (RHIC) with its polarized proton beams provides a unique opportunity to study spin dependence of diffractive scattering of polarized protons at center-of-mass energies ($\sqrt{s}$) up to 500 GeV. The diffractive physics program at STAR (Solenoidal Tracker At RHIC) [1] has two components: (1) a study of diffraction using colliding beams of polarized protons pp; and (2) a study of diffraction in ion–ion and

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deuteron–ion collisions. The pp program studies elastic and inelastic processes in a wide kinematic range of RHIC energies $\sqrt{s}$ up to 500 GeV [2], while the ion program studies number of processes [3], including ρ and 4π photoproduction, e^+e^- pair production. Both programs focus on fully reconstructed events, which have small number of charged tracks in the STAR central detector. In pp collisions, reconstruction includes detection of the outgoing protons in the forward detectors Roman Pots (RP) [4], which is the basis of the physics program with tagged forward protons: Central production in double Pomeron exchange (DPE) process, see Fig. 1 (a). A program, using the same setup, of studying spin dependence in polarized proton–proton elastic scattering.

The process in Fig. 1 are commonly characterized by using the variables t, ξ and M_X, where t is the squared four-momentum transfer between the incoming and outgoing protons, $\xi = \Delta p/p$ is the momentum fraction carried off by the Pomeron and M_X is the invariant mass of the centrally produced system produced. In the case of double Pomeron exchange, separate t and ξ variables exist for each proton–Pomeron vertex.

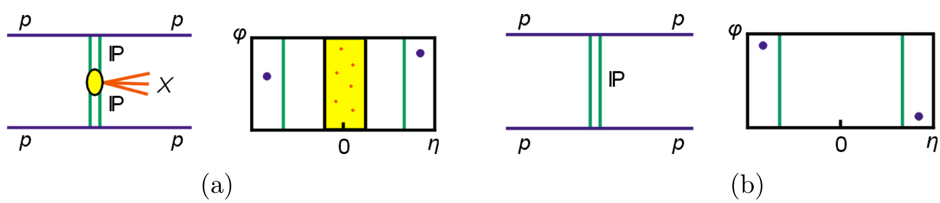


Fig. 1. (a) Central Production diagram in DPE and (b) elastic scattering.

Diffractive processes at high energies are believed to be occurring via the exchange of a color singlet object (the "Pomeron") with internal quantum numbers of the vacuum [5]. Even though properties of diffractive scattering at high energies are described by the phenomenology of Pomeron ($I\!P$) exchange in the context of Regge theory, the exact nature of the Pomeron still remains elusive. The main theoretical difficulties in applying QCD to diffraction are due to the intrinsically non-perturbative nature of the process in the kinematic and energy ranges of the data currently available. The common feature of the reactions shown in Fig. 1 is that the proton undergoes quasi-elastic or elastic scattering and that they occur via the exchange of colorless objects with the quantum numbers of the vacuum. In terms of QCD, Pomeron exchange consists of the exchange of a color singlet combination of gluons. Hence, triggering on forward protons at high (RHIC) energies dominantly selects exchanges mediated by gluonic matter. The use of polarized proton beams, unique at RHIC, will allow exploring unknown spin dependence of diffraction processes at high energies.

Diffraction processes are triggered using Roman Pots as shown in Fig. 2. The program described here utilizes RP system of the pp2pp experiment [6], which was installed downstream of the STAR detector at RHIC, see Fig. 2, where two locations of the Roman Pots are shown: current Phase I location and the planned Phase II location.

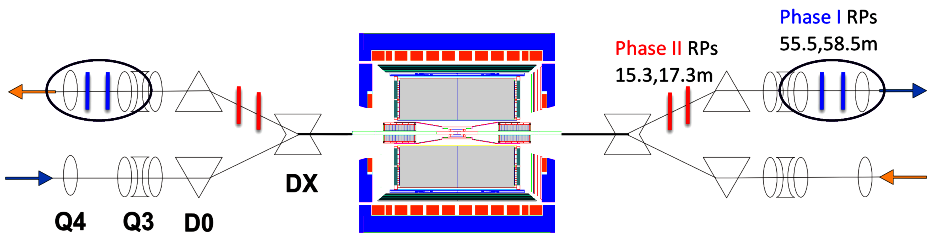


Fig. 2. The layout of the RPs with the STAR detector (not to scale). The Phase I setup, designed to detect scattered protons with low-t, are located after two dipole magnets (DX, D0) and three quadruples at 55.5 m and 58.5 m from the interaction point (IP), respectively. For measuring protons with high-t (Phase II), sets of RPs will be positioned between DX and D0 magnets, at 15.3 m and 17.3 m from IP.

For the elastic program, the collider energy range is previously unexplored, and the measurements will cover s-range between vast lower energy data and limited measurements at higher energy data. The energy range, particularly with polarized pp collisions, is suitable as a testing ground for the long standing theoretical evidence in QCD for the existence of the "Odderon" which is the $C = P = -1$ counterpart to the Pomeron [5]. The main physics motivation for the inelastic diffraction program is searching for a gluonic bound state whose existence is allowed in pure gauge QCD, but for which no unambiguous candidate has been established [7].

2. Studying properties of the Pomeron and searching for the Odderon

Studies of spin dependence of polarized pp elastic scattering at the high energies offer an insight into the nature the Pomeron and its odd-parity partner the hypothetical Odderon. Of particular interest is the region of small four momentum transfer squared t, where electromagnetic and hadronic amplitudes are comparable and spin-dependent interference phenomenon between the two amplitudes can occur.

There are five independent helicity amplitudes for $p+p$ elastic scattering: $\phi_1 = \langle ++|T|++\rangle$, $\phi_2 = \langle ++|T|--\rangle$, $\phi_3 = \langle +-|T|+-\rangle$, $\phi_4 = \langle +-|T|-+\rangle$, and $\phi_5 = \langle ++|T|+-\rangle$. Each amplitude consists of hadronic and electromagnetic contributions. These amplitudes can be related [8] to experimentally measurable spin asymmetries as the azimuthal angle (φ) dependent elastic cross-section with transversely polarized protons is described by

$$\frac{d^2\sigma}{dtd\varphi} = \frac{1}{2\pi}\frac{d\sigma}{dt}\Big(1 + (P_1 + P_2)A_N\cos\varphi + P_1P_2\left(A_{NN}\cos^2\varphi + A_{SS}\sin^2\varphi\right)\Big)\,, \tag{1}$$

where P_1 and P_2 are the beam polarizations and A_N is a single spin asymmetry with reference to the transverse polarization axis (y). A_{NN} and A_{SS} are double spin asymmetries with reference to the y-axis and x-axis, respectively. A possible presence of hadronic single spin-flip amplitude, due to the interference of the Pomeron spin-flip amplitude and electromagnetic non-flip amplitude would change A_N and its effect can be expressed through the ratio of the single spin-flip amplitude (ϕ_5) to non-flip amplitudes (ϕ_1 and ϕ_3)

$$r_5 = \frac{m\phi_5}{\sqrt{-t}\ \mathrm{Im}\left(\frac{\phi_1+\phi_3}{2}\right)}\,. \tag{2}$$

The preliminary result of A_N obtained during five-day period of data taking with special beam optics (β^*=21 m) at low luminosity in RHIC-Run 9, with the Phase I RP set-up. It covered low-t region, $0.002 < |t| < 0.03$ (GeV/c)^2, is shown in Fig. 3 as function of t. A possible contribution of the single helicity-flip amplitude ϕ_5, the explicit relation between A_N

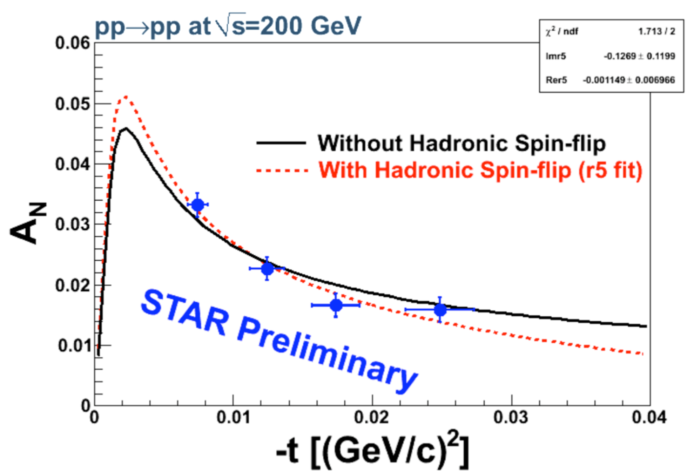


Fig. 3. The single spin asymmetry A_N as a function of $-t$. The solid curve corresponds to theoretical calculations without hadronic spin-flip and the dashed one represents the r_5 fit. Vertical bars are for statistical errors. Systematic uncertainties (10%) in t-scale is shown as horizontal error bars.

and r_5 [8, 9] was fitted to the measured A_N values with r_5, where $\mathrm{Im}\, r_5$ and $\mathrm{Re}\, r_5$ are mainly sensitive to the magnitude and the shape of A_N, respectively. The fitted r_5 is compatible with no hadronic spin-flip.

Similarly double transverse-spin asymmetries, A_{NN} are sensitive to the interference between double spin-flip hadronic amplitudes, ϕ_2 and ϕ_4 and electromagnetic non-flip amplitude, providing a tool to search for the hypothetical Odderon exchange [10]. The data at $\sqrt{s} = 200$ GeV, which are currently being analyzed, and higher statistics at $\sqrt{s} = 500$ GeV, which are planned to be taken in upcoming RHIC-Run11 are expected to provide significant constraint on the theoretical models describing Odderons and the nature of diffraction.

It is also expected that the Odderon contribution will show as a difference in shape of the *pp* elastic scattering in the region of diffractive minimum, at the $|t| \approx 1.3$ $(\mathrm{GeV}/c)^2$. This comparison will be possible with the data that could be obtained in Phase II at STAR and exisiting data from $p\bar{p}$ from the S$p\bar{p}r$S collider. This can be accomplished in the Phase II of our program.

3. Central production in DPE processes

Another process of interest in *pp* collisions at RHIC is the central production process through the DPE mechanism $pp \to pM_Xp$, as shown in Fig. 1 (a). The two protons stay intact after the interaction, but they lose momentum to the Pomeron and the Pomeron–Pomeron interaction produces a system M_X at mid-rapidity of the colliding protons.

The main physics motivation for the inelastic diffraction program is searching for a gluonic bound state whose existence is allowed in pure gauge QCD, but for which no unambiguous candidate has been established [7]. Because of the constraints provided by the double Pomeron interaction, the glueballs, and other states coupling preferentially to gluons, are expected to be produced with much reduced backgrounds compared to standard hadronic production processes [7].

3.1. Current status: Particle production — Phase I setup

The Central Production data were collected during the same five-day period as the elastic scattering data in RHIC-Run 9. The events were required to have two outgoing protons in the RPs, and the inclusive tracks in the central region were reconstructed with STAR Time Projection Chamber (TPC) covering $-1 < \eta < 1$ and $-\pi < \varphi < \pi$. Fig. 4 shows preliminary reconstructed effective mass distributions for two and four charged pion states from RHIC-Run 9 at $\sqrt{s} = 200$ GeV with the Phase I RP set-up (see Fig. 2).

The $\rho(770)$ and $K^0_{\rm S}$ signals visible in the two pion effective mass spectra, Fig. 4, are due mainly to the inclusiveness of the reaction in the data sample, due to the limited coverage of STAR. It is worthwhile to mention that the $\rho(770)$, while it is not allowed in the exclusive DPE process, can also be produced produced in diffractive photoproduction interactions in pp collisions by the central exclusive photoproduction [11]. Selecting exclusive central reactions requires energy-momentum conservation constraints, which currently is limited by the capability of reconstructing momentum of the forward proton in the Phase I set-up. The planned Phase II RP set-up is designed to greatly improve that capability.

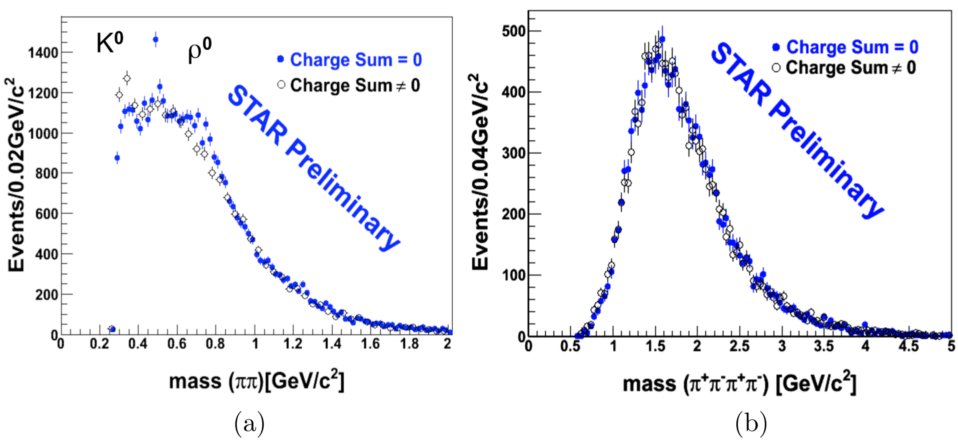


Fig. 4. (a) Reconstructed mass distributions for two; and (b) four charged pions in the inclusive central diffraction at $\sqrt{s} = 200$ GeV. Reconstructed particles are assumed to be pions. Solid circles are for neutral states and open circles represents charged states. Errors are statistical only.

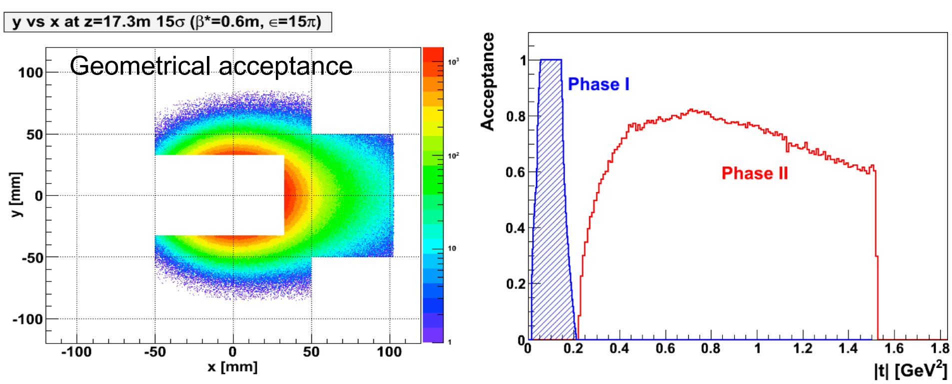
3.2. Glueball production in DPE

QCD predicts the existence of mesons which contain only gluons, the glueballs. These states are a consequence of the non-Abelian nature of the gauge fields which allows that gluons couple to themselves and hence may bind. Despite the theoretical predictions of glueballs, no glueball state has been unambiguously established to date [7]. Lattice QCD calculations have predicted the lowest-lying scalar glueball state in the mass range of 1500–1700 MeV/c^2, and tensor and pseudo-scalar glueballs in 2000–2500 MeV/c^2 [7]. Experimentally measured glueball candidates for the scalar glueball states are the $f_0(1500)$ and the $f_1(1710)$ [12] in central production, $pp \to pM_Xp$, as well as other gluon-rich reactions such as $\bar{p}p$ annihilation, and radiative J/ψ decay [13].

Because of the nature of the Pomeron, the central DPE process has been regarded as one of the potential channels of glueball production [7]. The energy regime where glueball candidates from central production have been identified so far is estimated to be not DPE dominated [14]. Two of the gluons in the DPE process could merge into a mesonic bound state without a constituent quark, a glueball in the central production $pp \to pM_Xp$. It is imperative to cover a wide kinematic range to extract information of the production of glueball candidates at an energy regime where DPE is expected to be a dominant process in central production.

3.3. Future program — Phase II setup

The main data taking for central events is planned with the Phase II RP setup, which covers higher and wider t-range ($0.21 < |t| < 1.5$ (GeV$/c$)^2) and allows data taking with high luminosity at $\sqrt{s} = 500$ GeV. The Phase II data taking will run concurrently with STAR without special beam optics. We have done simulations to determine the performance of the planned setup, which is to be located as shown in Fig. 2. We are planning to use two sets of vertical RPs and a horizontal RP on each side of the Interaction Point (IP). Si strip detectors of size, roughly 10×4 cm^2 are going to be used. The geometrical acceptance of the setup is shown in Fig. 5 (a). The comparison of Phase I and Phase II acceptance in t is shown in Fig. 5 (b).



(a) (b)

Fig. 5. (a) Geometrical acceptance of Phase II setup for RPs at $z = 17.3$ m calculated by the beam transport simulator HECTOR [28]; and (b) Acceptance as a function of t for Phase I Roman Pots and Phase II Roman Pots at $\sqrt{s} = 500$ GeV.

Our simulations indicate that during a twenty-week running period at RHIC at $\sqrt{s} = 500$ GeV, with luminosity of 1.5×10^{32} cm^{-2} sec^{-1} and assuming 60 DAQ hours per week, we can collect $10.4 \times 10^6\pi^+\pi^-$,

$2.7 \times 10^6 \pi^+\pi^-\pi^+\pi^-$ and $0.8 \times 10^6 K^+K^-$ pairs (in $1 < M_X < 2$ GeV/c^2) data sample for analysis (assuming branching ratios of DPE processes measured at $\sqrt{s} = 62.4$ GeV [15]). With such data sample the partial wave analysis necessary to identify final states will be possible.

The $I\!\!PI\!\!P$ cross-section at RHIC energies is not known and we used an estimate of 140 μbarn [16, 17]. Assuming the measured cross-section by WA102 at $\sqrt{s} = 29.1$ GeV [18], 50–75 K events of $f_0(1500) \to \pi^+\pi^-\pi^+\pi^-$ are expected to be collected during a twenty week running period at RHIC. The assumed integrated luminosity can be easily achieved during the planned high luminosity spin program at RHIC, and it is expected that the luminosity upgrade and longer run can bring an order of magnitude higher statistics which will enable differential kinematic sampling and spin-parity analysis. The Time-of-Flight (ToF) system in conjunction with the TPC is planned to be utilized to separate π/K in momentum range up to 1.6 GeV/c.

4. Other QCD topics in central production

Central production process allows study of gluon–gluon coupling through particle production. Heavy flavors could be produced. For example χ_c meson production cross-section in the decay channel $\chi_c \to J/\psi + \gamma$ has been calculated [19] and is estimated to be 0.57 nb at $\sqrt{s} = 500$ GeV in the center of rapidity. Other groups [20] estimated total production cross-section, including absorption in NLO QCD corrections and gap survival probability to be about 5 nb at $\sqrt{s} = 200$ GeV. In the Pomeron–Odderon interaction J/ψ could also be produced as calculated in [21].

5. Heavy ion ultraperipheral collision at STAR

In Ultra-Peripheral relativistic heavy ion Collisions (UPCs) the strong electromagnetic fields associated with relativistic heavy ions make a heavy-ion collider a great tool to study two-photon and photonuclear collisions, see Fig. 6. At RHIC, STAR has studied exclusive ρ^0 vector meson production and ρ^0 production accompanied by electromagnetic dissociation of both nuclei in collisions of AuAu at 62, 130 and 200 GeV [22]. Recent results suggest the validity of the Glauber calculations for the vector meson photoproduction and incosistency of the model based on the parton saturation phenomenon. STAR also observed coherent photoproduction of a $\pi^+\pi^-\pi^+\pi^-$ state which may be associated with ρ^{0*} (1540) [24].

The photoproduction of vector mesons is a typical process in UPCs. A virtual photon, radiated by the "emitter" nucleus, fluctuates into a $q\bar{q}$ pair, which scatters elastically off the "target" nucleus and emerges as a real vector meson (*cf.* Fig. 6 (a). At high energies the scattering can be described in terms of soft Pomeron exchange. The cross-section is strongly enhanced at low transverse momenta $p_{\mathrm{T}} < 2\hbar/R_A$ of the produced meson, because the $q\bar{q}$ pair couples coherently to the entire nucleus. For larger p_{T} the $q\bar{q}$ pairs couple to the individual nucleons within the target nucleus resulting in a smaller cross-section which scales approximately with the mass number A modulo corrections for the nuclear absorption of the meson. One photon-produces the vector meson and two additional photons excite the nuclei (see Fig. 6 (b)). For the results see [22].

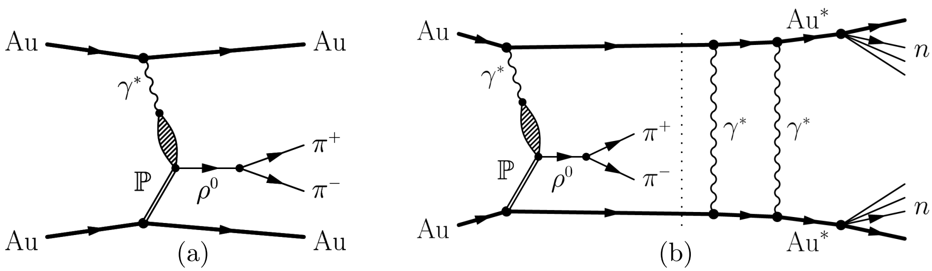


Fig. 6. A diagram of the photonuclear production of a $\rho^0(770)$ meson in a UPC AuAu collision and its decay into two charged pions. (a) shows the exclusive reaction, and (b) one with mutual Coulomb excitation of the beam ions and following neutron emission.

STAR has measured production of $\rho^0(770)$ in ultraperipheral relativistic heavy ion collisions in photon–Pomeon interactions, Fig. 7. The measured cross-sections agree with model predictions. STAR also measured for the first time the interference effect in ρ^0 production which indicates that the decoherence induced by the ρ^0 decay is small and that the $\pi^+\pi^-$ final state

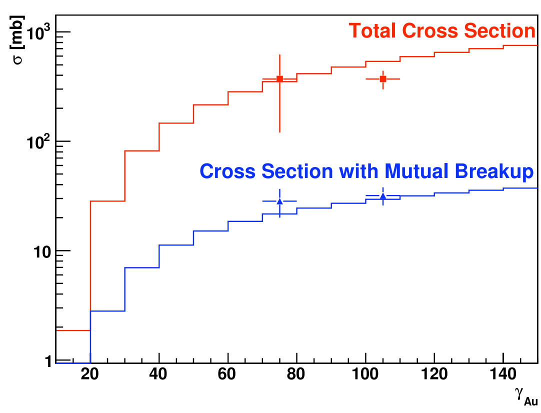


Fig. 7. The $\rho^0(770)$ production cross-section measured by STAR in heavy ion UPC collisions.

wave function is entangled and nonlocal. In addition, STAR has observed coherent photoproduction of $\pi^+\pi^-\pi^+\pi^-$ final states in UPCs. The $\pi^+\pi^-\pi^+\pi^-$ invariant mass spectrum exhibits a broad peak around 1540 MeV$/c^2$ and no corresponding enhancement is seen in the $m_{\pi^+\pi^-}$ distribution. The coherent $\pi^+\pi^-\pi^+\pi^-$ production cross-section is $13.4 \pm 0.8\%$ of that of the $\rho^0(770)$ meson.

6. Summary

We have described current and future diffractive physics program in polarized *pp* collisions at RHIC with tagged forward protons using the STAR detector at RHIC. The program will study diffraction process in the RHIC $\sqrt{s}$ range up to 500 GeV. It will explore both elastic and inelastic diffraction and search for predicted by QCD glueball. This diffractive program, which is complementary to the other RHIC physics program, will help understand both the strong interaction and the hadronic structure within the framework of QCD.

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