Production of ϕ Mesons in Au+Au Collisions at AGS Energy

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Abstract

Production of vector meson ϕ in Au+Au collisions at beam momentum 10.8 GeV/nucleon is reported from the AGS Experiment E917. The measurement covers the mid-rapidity region from $y = 1.2$ to $y = 1.6$. Transverse momentum spectra and the rapidity distribution are presented as a function of centrality characterized by the number of participant projectile nucleons. We discuss the particle ratios of ϕ varying with centrality, beam energy and colliding system.

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I. INTRODUCTION

The production of ϕ mesons in relativistic heavy ion collisions has been an important program of AGS, SPS and the newly operating RHIC facilities. An enhanced yield of ϕ mesons together with overall strangeness is proposed as a signature for the occurrence of a de-confined quark matter, Quark Gluon Plasma (QGP) in the relativistic heavy ion collisions [1]. The argument is that the production of ϕ meson, as the lightest bound state of strange quarks ($s\bar{s}$), in hadronic NN and πN interactions is suppressed in accordance with the Okubo-Zweig-Iizuka(OZI) rule and relatively large strange quark mass [2]. However, strange quarks and anti-quarks could be abundantly produced via two-gluon interactions in QGP phase and then coalescing into ϕ mesons during hadronization without violating OZI rule.

Experimentally an enhancement of strangeness production in the heavy-ion collisions relative to non-strange particles like π and pp interactions is reported in the production of K, Λ, and multi-strange particles like Ξ and Ω [4,5,3]. Hadronic re-scattering and conversion of excitation energy of formed resonances into particles in heavy ion collisions would also help to populate the strange hadrons. And thus a purely hadronic scenario could produce a strangeness enhancement in relations to pp interactions without invoking QGP mechanism. Because of the special role of ϕ mesons in strangeness production, the measurement ϕ mesons yield and a systematic study of particle ratios relative to other non-strange and strange particles in the dimension of centrality, beam energy and colliding system would gain us further understanding in distinguishing these two different mechanisms.

The ϕ production at the AGS has been done by E859 in a light system of $Si + Au$ collisions at 14.6 GeV/c [7]. The ϕ/K^- ratio of total yield in the top 7% central collisions was measured to be about 10%, close to the ratios in pp collisions and in $Ni + Ni$ system at sub-threshold production energy by the SIS FOPI experiment [9]. Experiment NA49 and NA50 had the measurements of ϕ in Pb+Pb collisions at SPS. An enhancement factor 2.8 in ϕ/π ratio comparing central collisions with pp interaction was reported by NA49 [10,11].

Experiment NA50 [12] found out a steady increase of $\phi/(\rho+\omega)$ with centrality and this ratio comes up to 1 in the most central bin.

We measured ϕ yield with a detailed centrality study around the mid-rapidity region in $Au+Au$ collisions at AGS at the Brookhaven National Laboratory. Comparing with the other results, the centrality and beam energy dependency of ϕ/π and ϕ/K ratios is explored. It serves as an important benchmark to discern any extra degree of enhancement in strangeness and ϕ mesons production at high energy heavy ion collisions.

II. EXPERIMENTAL DETAILS

Experiment E917 studied $Au+Au$ reactions at beam momentum of 5.9, 8.0, and 10.8 GeV/c per nucleon in the fall of 1996. The identified particles include strangeness-carrying particles like K^+ , K^- , ϕ , Λ and $\bar{\Lambda}$ as well as non-strange particles like π, p and $\bar{p}$ [4,6]. The experimental device consists of beamline detector arrays for global event characterization and a movable magnetic spectrometer for tracking and particle identification. The typical momentum resolution $\delta p/p =$ is of 1 % level. The centrality of events is characterized by a zero-degree-calorimeter (ZCAL) positioned downstream at beam axis which measures the energy deposited by the beam spectator after the interaction. More details on the detector systems are given in Ref. [4] and references within.

The data being presented here was collected using a two-level online triggering: a minimum-biased interaction trigger followed by a particle identification trigger (LVL2) which requires two K or one $\bar{p}$ coming into the spectrometer acceptance. The inefficiency of LVL2 trigger was checked to be less than 1%. A minimum momentum cut$p \geq 0.5$ GeV/c is imposed on all identified kaon tracks to avoid large decay correction in this analysis. With 120 ps Time-of-Flight(TOF) resolution(σ), pions and kaons can be well distinguished by TOF measurement up to momentum of 1.75 GeV/c. For kaons whose momenta exceeding this limit, they are accepted only if the track does not fire the Cherenkov Gas Counter behind the TOF Wall and its TOF value are 3σ away from the centroid of pion TOF value at the same momentum.

Extra weighting was applied to correct the experimental inefficiency from the following known sources: minimum two-track opening angle cut, partial spectrometer acceptance, acceptance loss by malfunctioning TOF modules, lowest momentum cut, efficiency of detecting kaons with momentum $p > 1.75$ GeV/c, branching ratio of ϕ into two-kaons mode, decay probability of kaons, single-track tracking efficiency, hadronic interaction and multiple processes in the spectrometers. The value of overall weight was estimated by a Monte-Carlo simulation frame with an implementation of a realistic detector configuration in GEANT3.2.1 package and offline analysis codes [13].

III. EXPERIMENTAL RESULTS

A total of 250M LVL2-triggered events were analyzed. Data were collected in two settings of spectrometer: 14 and 19 degree. Combined acceptance of K^+K^- pairs covers mostly the region of rapidity (y) $1.2 < y < 1.6$ and transverse momentum $(m_t = \sqrt{m_\phi^2 + p_t^2})$ $1.0 < m_t < 2.2(GeV)$. The event centrality is characterized by the energy deposited in the ZCAL (E_{ZCAL}) by the spectator nucleons and the averaged number of projectile participant(N_{pp}) is experimentally derived from E_{ZCAL} and the total kinetic energy of beam particles E_{beam} using the relation $N_{pp} = 197 * (1 - E_{ZCAL}/E_{beam})$.

A. Invariant Mass Distribution 0f K^+K^- Pairs

The ϕ mesons are reconstructed from the invariant mass distribution of K^+K^- pairs. Two kinds of distributions are formed: one where individual K^+ and K^- are selected from the same event while the other from different events to represent the uncorrelated background. Multiplied by proper normalization, the uncorrelated distribution is subtracted from the correlated one to extract the signal of ϕ mesons. Fig. 1 displays these two distributions and the background-subtracted ϕ signal for minimum-biased data sample. The integrated signal-to-background ratio around the ϕ peak region is about 20%.

The subtracted K^+K^- distribution is fitted with Relativistic-Breit-Wigner parameterization [?,7] convoluted with the experimental mass resolution 2.0 MeV determined in Monte-Carlo study. The fitted peak position (m_0) is 1018.9 ± 0.4 MeV in agreement with world averaged value.

B. Transverse Spectra and Rapidity Distribution

Requiring reasonably enough statistics, a wide bin of rapidity(y) and transverse momentum (m_t) is used in dividing the data from different spectrometer angle settings and centrality class where an integrated signal-to-background(S/B) ratio is determined by the procedure described above. Afterwards the yield of ϕ mesons is determined in a finer (y, m_t) bin by applying the S/B ratio in the corresponding big bin and corrected with weights compensating experimental inefficiency.

Transverse spectra of two angle settings for various centrality bins are shown as a function of rapidity in Fig. 2. An exponential parameterization with two parameters, rapidity density(dN/dy) and inverse slope parameter(T_{inv}):

$$\frac{1}{2\pi m_t}\frac{d^2N}{dm_t dy} = \frac{dN/dy}{2\pi(T_{inv}m_0 + T_{inv}^2)}\exp(-\frac{m_t - m_0}{T_{inv}}) \qquad (1)$$

is used to fit the transverse spectra.

This exponential fit reproduced the data reasonably well. The obtained dN/dy and T_{inv} as a function of rapidity are shown for different centralities in Fig. 3. The rapidity density at two bins shows a strong and systematic increase with centrality while there is little variation across the mid-central bins for the inverse slope parameter. The inverse slope parameter in the most centrality bin ($\sigma/\sigma_{geom} = 0 - 5\%$) is determined to be 257 ± 18 MeV. The mean transverse momentum of $< m_t >$ deduced from T_{inv} for ϕ mesons is checked to follow the general mass dependence with protons, charged pions and deuterons. This is consistent with a common emission from a thermal and expanding fireball source.

IV. ϕ MESON YIELD AND PARTICLE RATIOS VERSUS CENTRALITY

The centrality dependence of the yields of ϕ and relative ratios to pions and kaons will help reveal if there is any interesting enhancement of ϕ mesons toward central collisions. In order to make comparison with pp interactions, a phenomenological parameterization of the ϕ production cross section suggested in Ref. [15] is used to describe the available inclusive measurements of ϕ in pp reactions at $5 < \sqrt{s} < 60 GeV$ and exclusive measurements near production threshold [16]. The parameterization of beam energy dependency of multiplicities of π and K in pp reactions are taken from Ref. [17].

First, the yield normalized to N_{pp} exhibits a steady increase toward the central collisions as shown in Fig. 4. This implies that the yield of ϕ increases nonlinearly with N_{pp} , similar to the production of kaons [8]. So the production of ϕ mesons in heavy-ion collisions is beyond a simple incoherent superposition of individual nucleon-nucleon interactions.

The ϕ/π ratio also shows a clear increase toward central collisions in the left plot of Fig. 5. This signifies an enhancement of ϕ mesons relative to non-strange mesons π in the central collisions. Such an enhancement might be due to the secondary re-scattering in the central collisions which contributes more significantly to the production of ϕ than π because of the relatively large production threshold of ϕ mesons.

Since an increase of K/π ratio with centrality was also reported in $Au + Au$ at the same energy by Experiment E866 [14], it is interesting to compare the enhancement degree of yields of ϕ and K with centrality. We use the yield of K^+ to represent overall kaons production because K^-/K^+ ratio is found to be about 0.15, independent of centrality in $Au + Au$ at the AGS [8]. The ϕ/K^+ ratio across centrality is shown to be basically flat in the right plot of Fig. 5. This reveals that both ϕ and K^+ (or K^-) possess a similar degree of enhanced production toward central collisions at AGS.

Intuitively the production of ϕ mesons should be suppressed more significantly in the peripheral collisions comparing kaons because of more numbers of strange quarks and associated larger production threshold. Instead we observed a rather centrality-independent

ϕ/K ratio. The little centrality dependence of ϕ/K^+ and K^-/K^+ in heavy ion collisions hints the effectiveness of hadronic re-scattering in achieving a chemical equilibrium of strangeness, present both in peripheral and central collisions where particle ratios keep fixed.

Putting together our results with other measurements of ϕ production in heavy-ion collisions from E859 and NA49 [7,10], the excitation function of the ϕ/π, ϕ/K^+ and ϕ/K^- ratios at central collisions are shown in Fig. 6 together with the value in *pp* parameterization of as a benchmark. It is noted that our result of ϕ and its related ratios at the same energy ($\sqrt{s} = 4.5$) GeV is presented in the limited rapidity region($1.2 < y < 1.6$) while the total yield is used for the other two points.

The ratio of ϕ/π in heavy ion collisions is seen to increase with beam energy for both $A+A$ and $p+p$ collisions. The enhancement of this ratio of total yield in $A+A$ over $p+p$ are 2.68 ± 1.060 at $\sqrt{s} = 5.4$ GeV/c and 3.46 ± 0.86 at $\sqrt{s} = 17.3$ GeV/c. Considering the large error and minor difference of centrality difference, these two values are consistent with each other even though the mean value of this double ratio shows a slight increase toward high energy. Our measurement within the finite rapidity range at low energy shows a rise instead. Such a rise would be even more dramatic if the total yield is used in the ratio for $A+A$ because of a smaller width for ϕ mesons. The K^+/π^+ double ratio at mid-rapidity is reported to decrease monotonically with beam energy in Ref. [5]. The different behavior at high energy for the double ratio of ϕ/π and K^+/π^+ can be understood by the ϕ/K^+ ratio.

In the observation of ϕ/K^+ and ϕ/K^- where both kinds of particles contain strangeness but different numbers of strange quark, the values in AA collisions at AGS are close to those in *pp* interactions. With large uncertainty, an increase on these two ratios in AA relative to *pp* values shows up at SPS. This rise can explain the different behaviors of the double ratio of ϕ/π and K^+/π^+ at SPS. Such a stronger enhancement of ϕ than K is consistent with the observation that the relative strangeness enhancement between $Pb+Pb$ and $p+Be$ collisions at SPS is the stronger the more strange quarks the hadron contains [18].

This confirms an existence of a contribution from the mechanism of secondary interactions in strangeness production starting from AGS energy. An interesting question is what causes such a strong enhancement of ϕ production relative to K seen at SPS. It might suggest two possibilities. First, an interplay of a new mechanism which enhances the production of ϕ more than K, exists at SPS energy. This is supported by a picture of a statistic hadronization of strange quarks from a de-confined quark matter where a rapid strangeness production happens supports such a pattern [19]. The other possibility could be that different strangeness freeze-out points could be approached by hadronic interactions at these two energies. In order to clarify this whole scenario, a complete study combining the multi-strange particles and anti-strange baryons across beam energy would be helpful.

V. SUMMARY

The ϕ production in $Au + Au$ collisions at 10.8 GeV/c around mid-rapidity has been studied as a function of collision centrality by experiment E917. The yield per projectile participant shows a steady rise toward central collisions and this represents the effectiveness of hadronic secondary interactions in enhancing the yield of ϕ meson per nucleon. This enhanced production in central collisions is significantly stronger than that of π mesons as seen from the increasing ϕ/π ratio with centrality. The flat centrality dependence of ϕ/K ratio suggests a possible chemical equilibrium of strangeness by hadronic re-scattering in $Au + Au$ collisions at AGS.

The ϕ/K ratio is same for both heavy-ion and pp collisions around AGS energy while larger ratio value in heavy ion collisions over pp reactions shows up at SPS. This is consistent with a strangeness enhancement prediction from the QGP scenario where the production of ϕ mesons receives more enhancement than kaons via a statistic hadronization of strange quarks.

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FIGURES

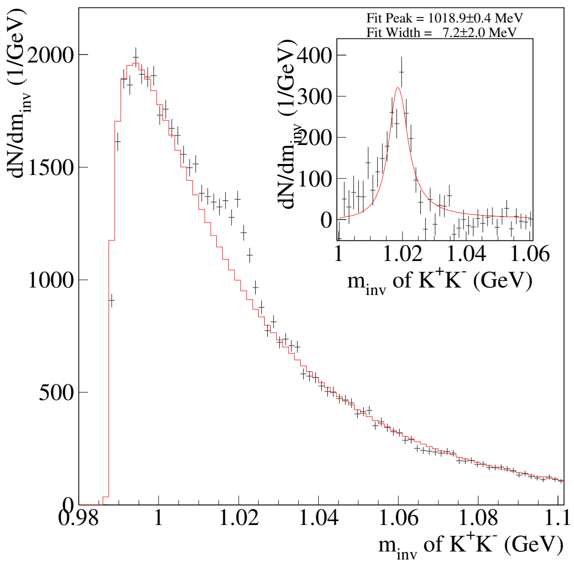

FIG. 1. Invariant mass distribution of K^+K^- pairs and the ϕ signal after background-subtraction. The ϕ distribution is fitted with Relativistic-Breit-Wigner distribution where peak position and width are parameters of fitting.

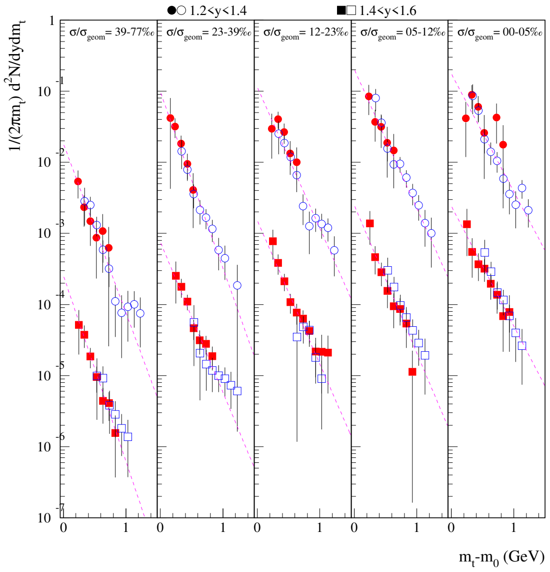

FIG. 2. The Invariant yield of ϕ as a function of transverse mass $(m_t - m_0)$ in five centrality bins as labelled by σ/σ_{geom}. In each panel, the rapidity $(1.2 < y < 1.4)$ is shown at the most top and another bin $(1.4 < y < 1.6)$ is shown after being divided by 100 for clarity in demonstrating. Solid (open) symbols represent data set of 14(19) degree spectrometer angle. The errors are statistics only. The lines shown are the results of an exponential fitting explained in the text.

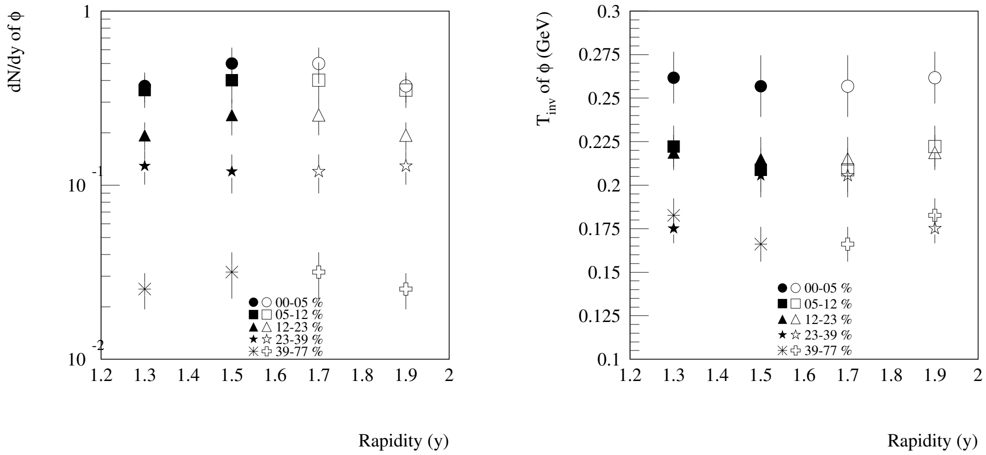

FIG. 3. The rapidity density (dN/dy)(left) and inverse slope parameters (T_{inv}) (right) of ϕ as a function of centrality. The open symbols are the reflection of measurements at backward rapidity regions with respect to the mid-rapidity $y = 1.6$.

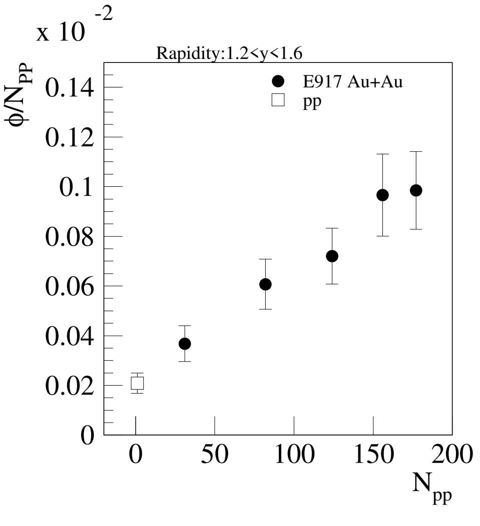

FIG. 4. The normalized yield of ϕ mesons per projectile participants (N_{pp}) as a function of N_{pp} . The value for pp interactions ($N_{pp} = 1$) is obtained from the parameterization described in the text. The accepted rapidity(y) region is $1.0 < y < 1.6$.

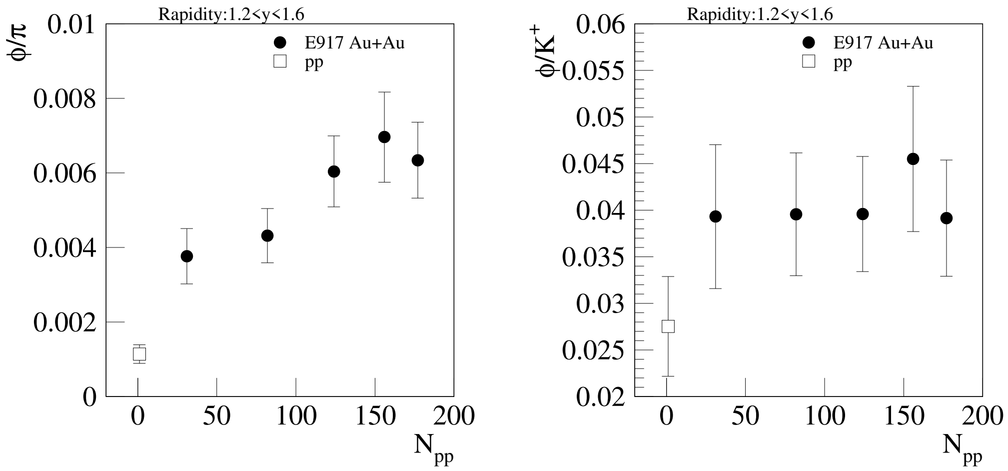

FIG. 5. The ratio of ϕ/π(left) and $\phi/K+$(right) as a function of N_{pp} . The data of π and K^+ are taken from Ref. [8,14]. The π yield is the average of positive and negative pions and a constant factor of 1.25 for the total yield of π^- over π^+ is assumed.. The value for pp interactions ($N_{pp} = 1$) is obtained from the parameterization described in the text. The rapidity(y) acceptance is $1.2 < y < 1.6$.

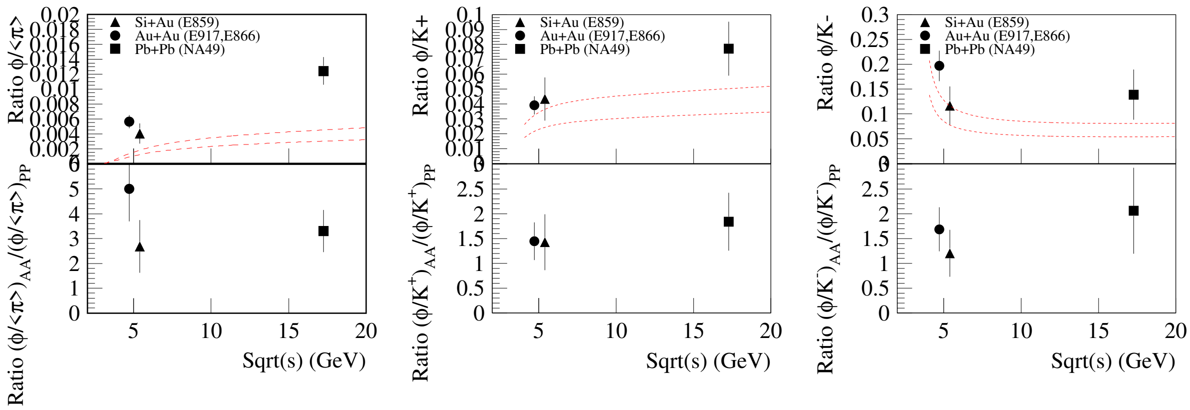

FIG. 6. The ratios of $\phi/ < \pi >$(left), $\phi/K+$(central) and $\phi/K-$(right) in the central collisions of heavy ion collisions and pp interactions as a function of the center-of-mass energy($\sqrt{s}$). Double ratios of $A + A$ over $p + p$ are shown in the bottom panel. At the energy of E917, yield within in rapidity region $1.2 < y < 1.6$ is used while total yield is used for the other energy points. The pp parameterization curve is the same ratio from the parametrized ϕ and $< \pi >, K$ yields from pp reaction.

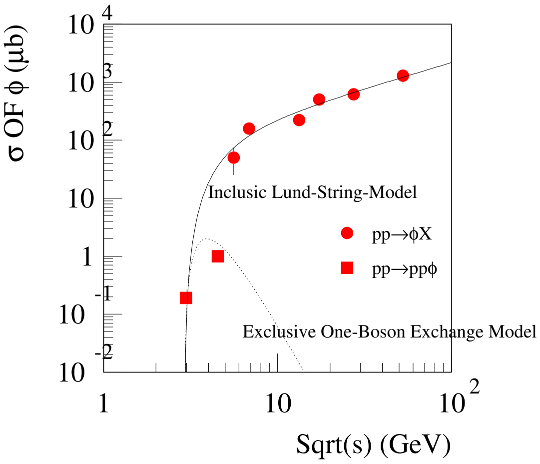

FIG. 7. Parametrization of ϕ mesons yield in pp interactions. Lund-String-Model(LSM) describe inclusive measurement while exclusive production is predicted by one-Boson-Exchange Model(OBE). LSM results smoothly match with the OBE calculations for the exlusive channels close to threshold.