Single hard muons decaying from the hadrons

I. J. Choi, D. J. Kim, S. S. Ryu, Y. Kwon, H. J. Kim, J. H. Kang
Yonsei University

M. L. Brooks, J. Moss
Los Alamos National Laboratory

N. Saito
RIKEN

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We suvery the physics issues related to the production of single hard muons. It includes the production systematics of the abundant hadrons and the heavy flavoured hadrons, the charge asymmetry of the heavy flavoured hadrons, and their decay into the PHENIX acceptance. Realistic muon yields from the semileptonic decay of the heavy flavoured hadrons are compared to the decay yields from those abundant hadrons. The perturbative and non-perturbative aspects of the charm production is discussed with the experimental possibility of the measurements. We identify the charge asymmetry as a good probe of the non-perturbative dynamics.

I. INTRODUCTION

High p_t muons have been considered for the study of the heavy quark production [1]. Imprecise knowledge of the charged pion and kaon production, and the uncertainty in the charm production were the major sources of the uncertainty in the efforts. Some of those abundant hadrons affect the yields of the single muons through decay. A limited measurement of those spectra based on the observed muons will be feasible.

The moderate p_t spectra of the π^0 particles measured by the central arm for the range $2\ GeV/c < p_t < 4\ GeV/c$ exhibits anormalous suppression for the central Au + Au reaction and was addressed in our previous publication [20]. This feature may produce uncertainties in the estimation of decay backgrounds, but is also interesting in itself. Specifically muons from the decay are from non-baryonic components which is expected to suffer the strongest suppression. Section II discuss the production systematics of these abundant hadrons, and develope two component model. Resulting simplification of the initial hadron spetra enables measurement of those spectra from the muon measurement. Additional scaling property of the two component model on the N_{part} and the N_{coll} for the soft, the hard, and the hevay flavour production can be compared to or restrict the glauber model.

Heavy quark production is useful to study the initial gluon dynamics, but also can be a useful probe to study the non-perturbative dynamics of the heavy ion collision. Charge asymmetry of the charmed hadron production mostly comes from the nonperturbative physics. We investigated the size of the asymmetry for the decay muons for the $p+p$ reaction at $\sqrt{s} = 200\ GeV$, which turns out to be significant. We identify the charge asymmetry as a good probe of the non-perturbative dynamics.

II. PRODUCTION OF THE ABUNDANT HADRONS

The muons decaying from the pions and the kaons make up a large fraction of the observed muons. Identified charged particle spectra for the $\pi^{\pm}$ and $K^{\pm}$ was produced by the central arm analysis only in the limited region of the transverse momentum, i.e. $p_t < 2\ GeV/c$. Extension of the coverage is of interests due to the issues such as *jet quenching*. We might use the prospective measurement of other RHIC experiments for the primary hadron spectra to estimate the decay backgrounds. Our own measurements will however reduce the uncertainties ranging from normalization, systematics and centrality definition.

With simplified assumptions we can deduce the initial hadron distribution from the daughter muons seen by the muon arm. We summarize our survey results in order of credibility and hence importance.

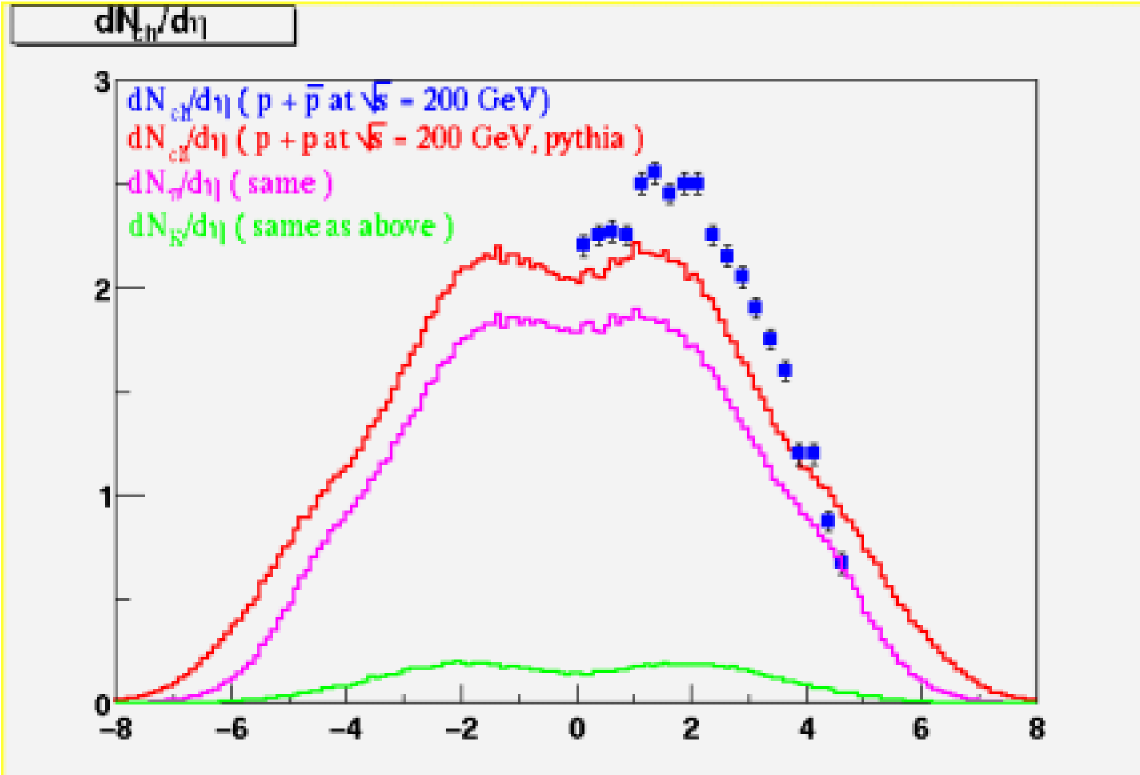

FIG. 1: Comparison of the pseudorapidity distribution for the charged particle. Data points were taken from [2].

First we assume the separation of the longitudinal and transversal distribution as follows

$$\frac{dN}{dydp_t} = f(p_t) \cdot g(y). \tag{1}$$

To construct this separation, soft and hard region must be considered independently.

- Feynman argued the separation of the longitudinal and transversal distribution *for the soft component* at high energy collisions [3], and the invariant cross-sections for the hadron production in the pp collisions at ISR energies shows this feature to the accuracy of 10-20% [4]. Another feature of this assumption is the appearance of the plateau in the rapidity spectra. To show the scale of relavance for the PHENIX, we note the x_F variable varies from 0 to 0.1 when the rapidity of pions with p_t = 1 GeV/c varies from 0 to 3. If the cross section is constant for the range $0 < x_F < 0.1$, the corresponding rapidity distribution will be flat. Indeed, we observe a plateau in rapidity (or pseudorapidity) distribution [2] (see Fig. 1). This feature is also noted as the boost-invariance [14].

- High p_t hadron yields are decided by the parton dynamics characterized by the elastic parton collision according to the parton model. Based on the PYTHIA calculation, which calculate the leading order partonic process with some model improvements, the high p_t hadron distribution is independent of the rapidity variable over a wide range of relavance (i.e. $-3 < y < 3$, and see Fig. 3). If simple minded parton model works, this feature will be continued to the central collisions.

The rapidity distribution based on the PYTHIA study shows a variation of 10 to 20 percent over the rapidity range of interests (i.e. $1 < y < 2$). We performed a gaussian fit of the rapidity distributions for a limited range to approximate this feature (see Fig. 6), and improved our simplification on the flatness of the rapidity distribution. Detailed value of the σ's are given in Table. I, and sensitivity of data on this feature needs to be investigated further. The rapidity distribution for the high p_t region will be similar between the peripheral and the central events assuming the parton model.

Assuming the separation of the longitudinal and transversal distribution, the transverse momentum distribution for the charged particles measured by the central arm, which is not yet available, can be used for the background

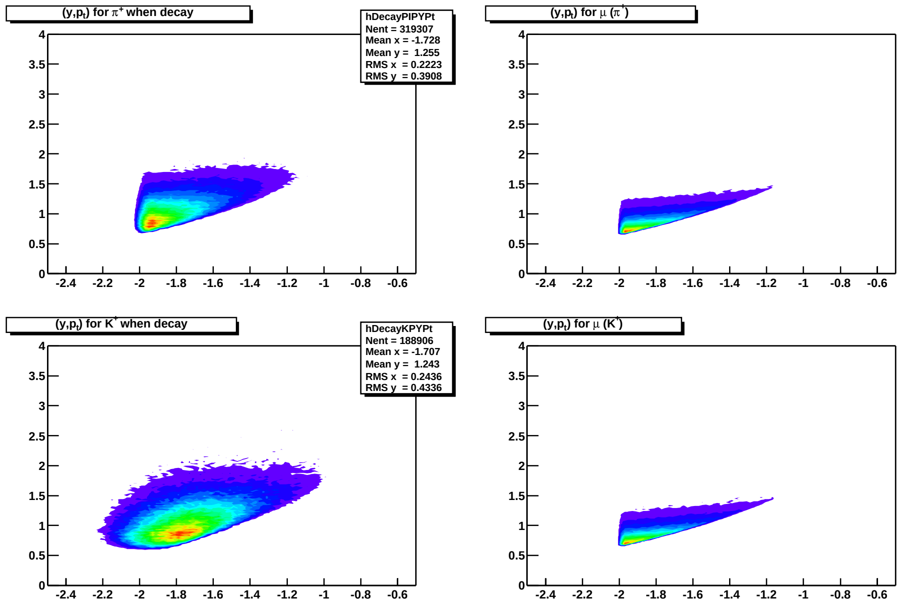

FIG. 2: Acceptance plot for the hadrons (π, K) when the daughter muon is accepted into muon arm. Left figures are the kinematic distribution for the π^+ and K^+. Right figures are the distribution of the corresponding daughter muons.

TABLE I: Used value of the σ's.

σ_{π^+}	σ_{π^-}	σ_{K^+}	σ_{K^-}
3.0	2.8	2.4	2.4

estimation. Transverse momentum distribution in the soft region will be measured by the central arm to the high accuracy for the $\pi^{\pm}$ and $K^{\pm}$. For the high p_t region, some considerations needs to be given.

To study the characteristics of the transverse momentum distribution, we use the p_t spectra generated by the PYTHIA for the $p+p$ reaction as the reference spectra. This spectra can be measured by the muon measurements, and is generalized for the $Au+Au$ reaction through Glauber model. We divide the transverse momentum distribution into three parts hereafter named as *soft*, *intermediate*, and *hard*. Actual boundary is set at $p_t = 0\ GeV/c - 1\ GeV/c$, $p_t = 1\ GeV/c - 2\ GeV/c$, and $p_t = 2\ GeV/c - \infty\ GeV/c$. From the repeated fit exercise, we observed the soft region can be fitted by

$$f_1 = C_1 p_t \exp\left(-m_t/T\right) \tag{2}$$

motivated from the the parametrization at lower energy [6]. The range of the hard region was set based on the results of the pQCD improved parton model [15], and fit function was parametrized as

$$f_2 = \frac{C_2}{p_t^n}, \tag{3}$$

based on the model. The transverse momentum spectra for the π's and K's have the fitted index 6 (π) and 5.9 (K), and are nearly similar in shape for the hard region. Most of the pions and kaons in this region come from the fragmentation of the gluons [8] and this feature will be due to the similarity of the gluon fragmentation function into π and K [7]. We assume a flat ratio with the power index 6 within the simple minded picture of the two component model.

Two fit functions do not match in the intermediate region, and interpolation is necessary in the intermediate region. Interpolation by the exponential function connecting two region describes the intermediate region well (see Fig. 4).

Soft component and hard component scales with the N_{part} and the N_{coll} for each centrality class based on the previous picture. This scaling property makes a clear difference between the distribution of the central and peripheral events (see Fig. 5). This scaling can be further compared to the scaling of charm production. One caution about

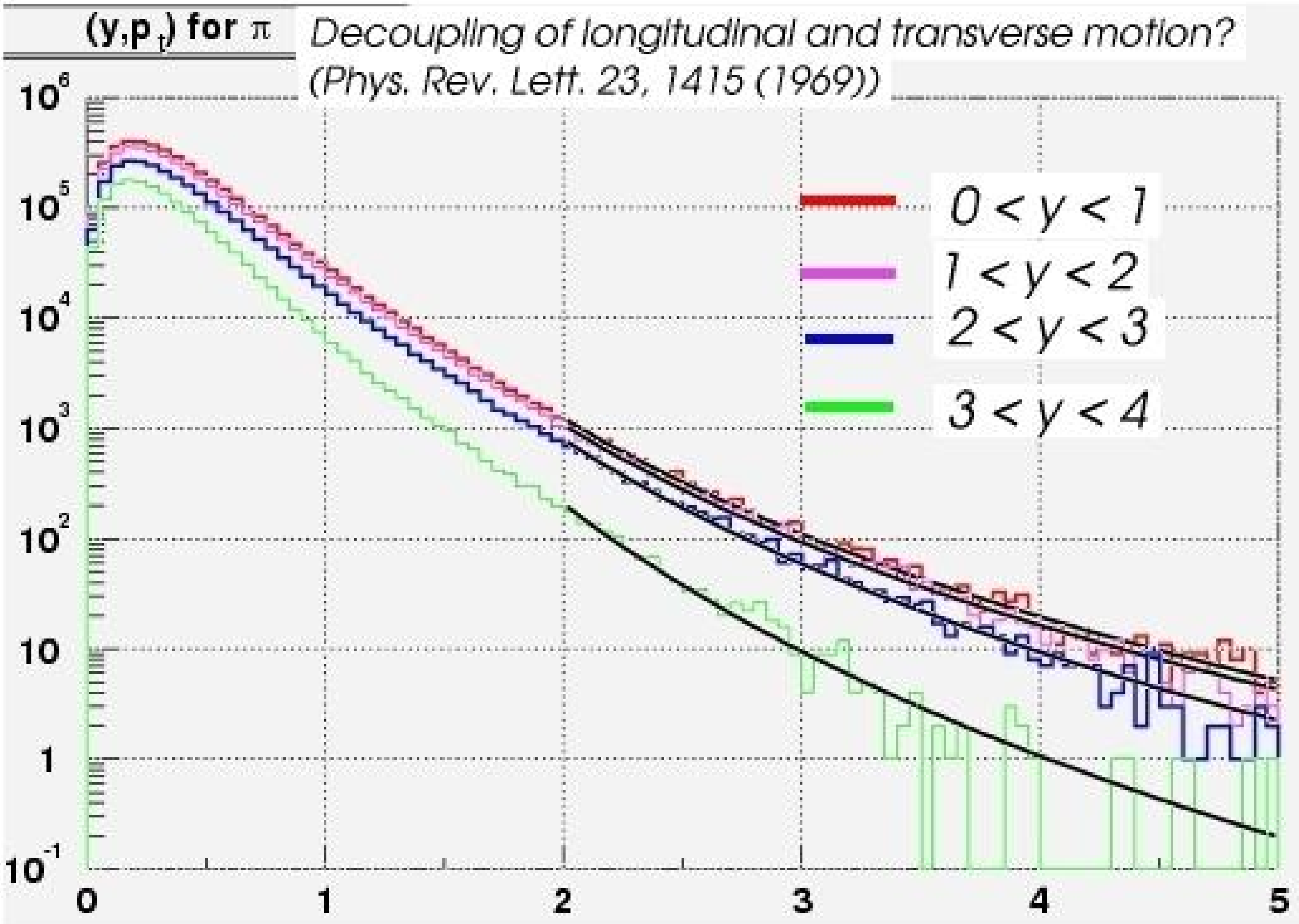

FIG. 3: Fit by $1/p_t^n$ was performed on the PYTHIA calculation when $p_t > 2\ GeV/c$.

the two component model must however be taken on the N_{part} scaling of the soft component since $dN_{ch}/d\eta$ do not match data for the central Au + Au collisions by about factor of 2. Measurement by the central arm is ultimately needed.

III. HEAVY FLAVOUR PRODUCTION

Heavy flavour production can be treated by the pQCD [13]. We use PYTHIA to show the global feature of the pQCD dynamics, but also describe the systematic uncertainty of the leading order calculation hidden in pythia. Gluon fusion into the charm pair dominates the quark annihilation into the charm pair by 20 to 1 according to the study based on PYTHIA which calculate the leading order partonic processes. Parton kinematics is displayed in Fig. 7 for two cases. One is for all produced charm pairs, and the other is for the situation when a hard muon is accepted. Right top of the figure shows the invariant mass spectrum of the perturbatively produced charm. Small acceptance bias is visible in the low charm pair mass region, and this feature might need to be further studied in the di-muon channel in regards to the reference [16] which argues enhancement of the low invariant mass charm pair. Typical momentum fraction carried by the gluons is plotted in the lower left of the figure. When a muons from the charm decay is detected, distribution in the plot changes due to the decay kinematics as shown in the lower right of the figure.

In leading order prescription, multiple sources of the uncertainties such as

- the factorization and renormalization scale,

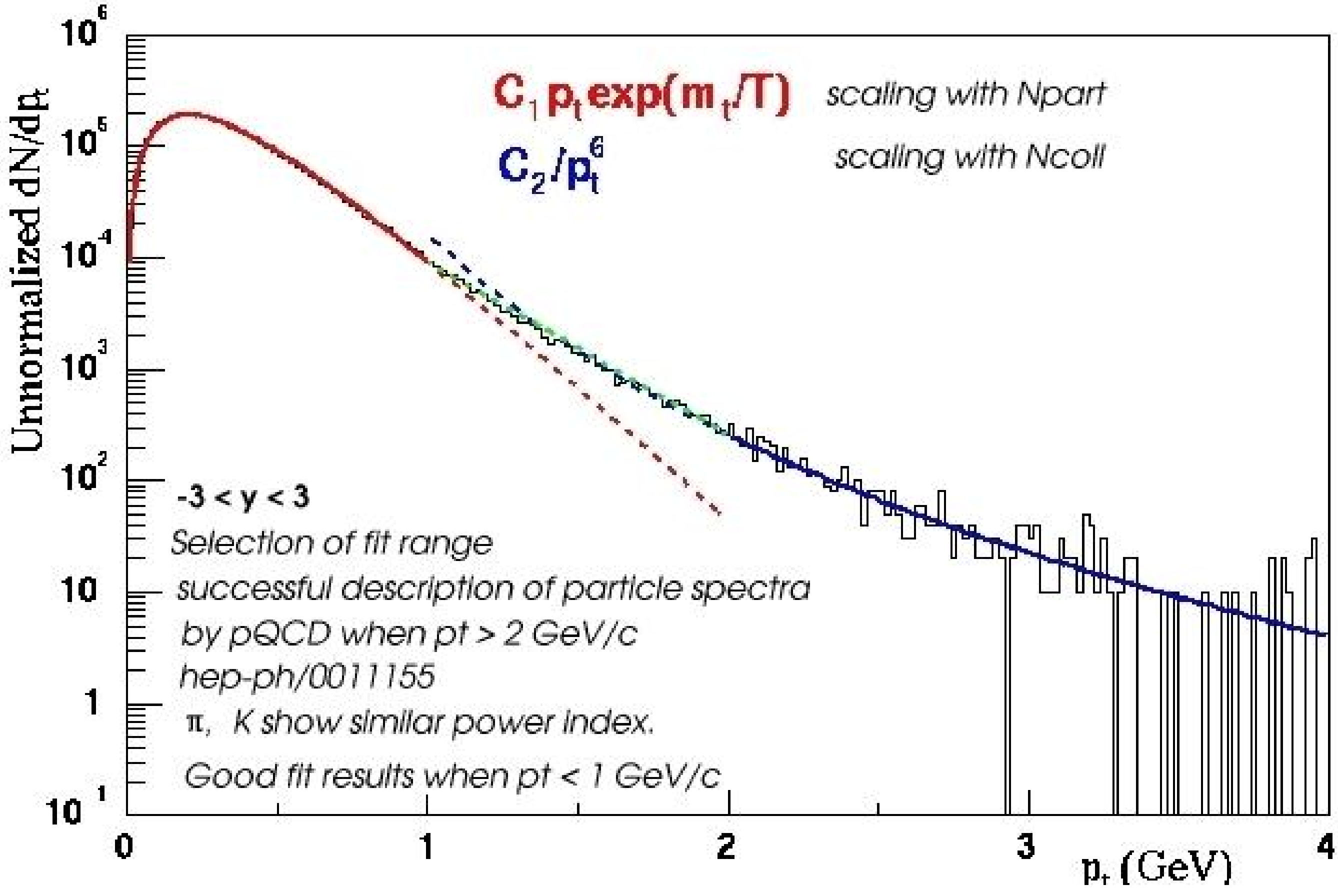

FIG. 4: Decomposition of the p_t distribution given by PYTHIA.

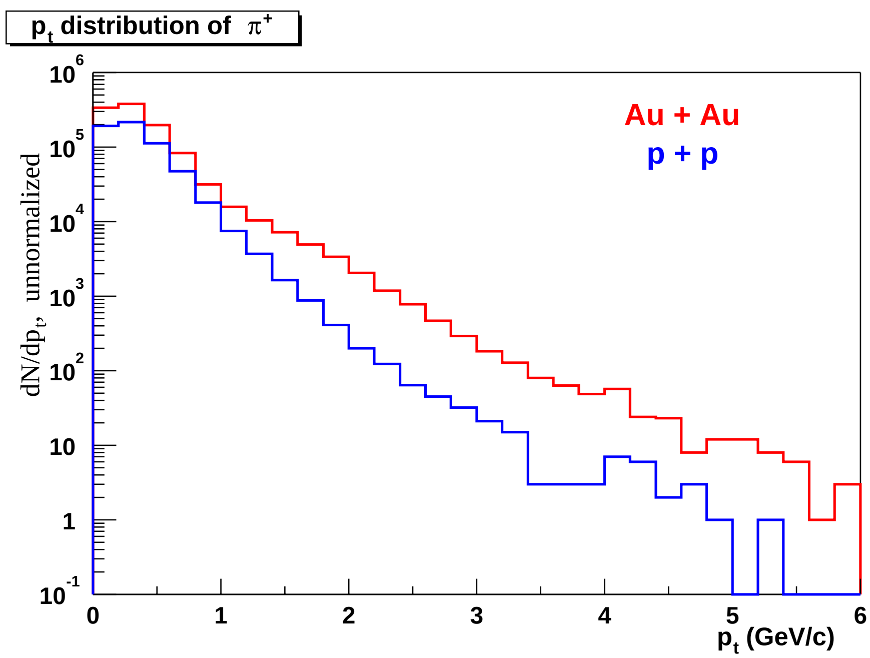

FIG. 5: Centrality dependence of the p_t spectra. This is due to the simple minded scaling discussed in the text.

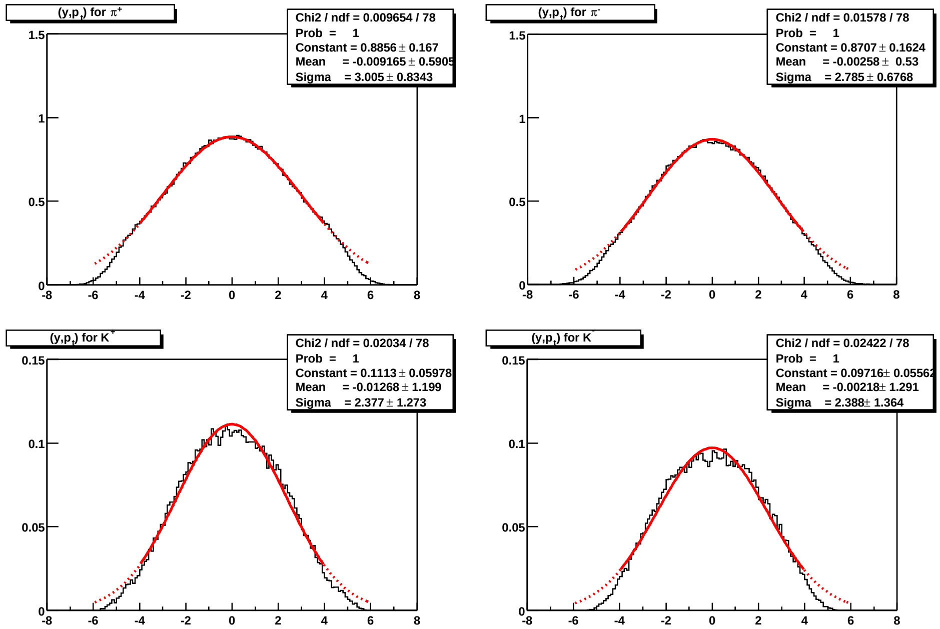

FIG. 6: Gaussian fit of the rapidity distribution.

- running of α_s,
- number of effective flavour,
- Λ_{QCD},
- mass of the charm,
- and intrinsic p_t broadening

exist. Furthermore flavour excitation and hard gluon fragmentation can be another issue at higher order [8]. While absolute cross section of the charm production for the p + p reaction is plagued by these uncertainties, the description of the charm production by the pQCD establishes a scaling property over the centrality. There are some sources of the scaling violations, but will not be big. One of the gluons belong to the shadowing region where we expect suppression of 10% in the gluon distribution function, and this kinematic region is also where soft thermal gluons may reside. Evolution of the total charm production over the centrality will give some clue on this question. Another interesting property of the pQCD description is the prediction of the scaling over the collision energy. Assuming our charm production measurement at the lower collision energy [21], we expect the PYTHIA calculation in Fig. 10 and Fig. 11 needs to be scaled by the factor of 3. This will significantly improve our sensitivity on the open charm production.

Quick look was given to the open beauty production. Fig. 8 shows the p_t distribution of the muons resulting from the heavy flavour. Muons from the beauty flavour wins over the one from charm at about $p_t = 2.5\ GeV/c$, where we didn't discuss so far. Depending on the accessible statistics, this region will enable anonther interesting exploration.

IV. COCKTAIL PLOT

For the current study, a simple schematic acceptance selection on the peudorapidity ($1 < \eta < 2$) and the momentum ($p > 2.5\ GeV/c$) for the daughter muons are considered. Improvement on the decay scheme, resolution, and detailed consideration of the detector acceptance is needed for the next step.

Here we simply note the relavant scale based on simple numerics.

- The momentum resolution of the spectrometer is about 10% or better for the typical muons we observe, and will be enough for our measurements. The angular resolution is dominated by the multiple scattering in the front

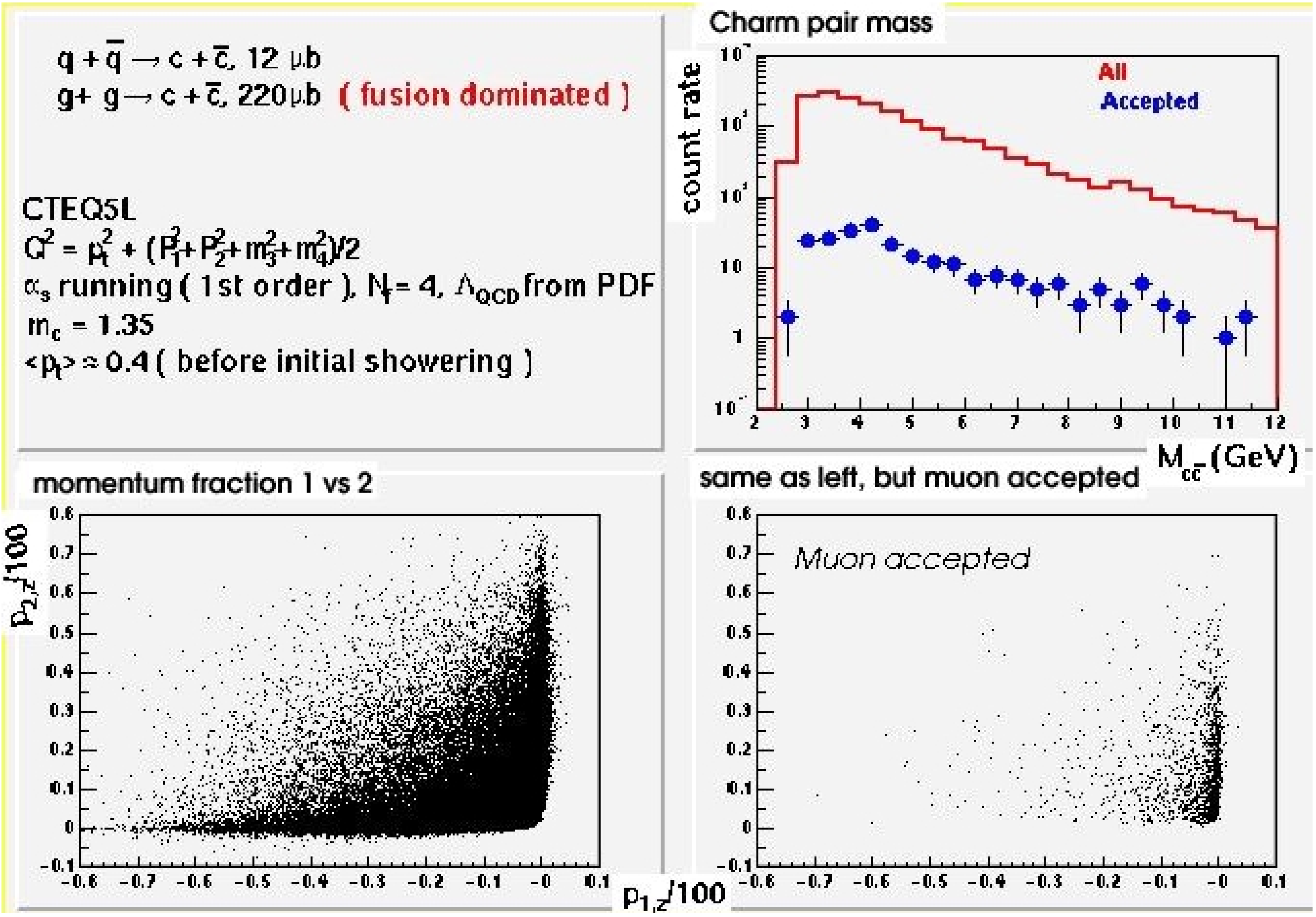

FIG. 7: Charm production in PYTHIA. $p+p$ at $\sqrt{s} = 200\ GeV$.

absorber and the effect of multiple scattering is given by $0.15/p_{orig}$ [17], which is not ignorable in comparison to the acceptance angle and needs detailed consideration.

- Fig.9 shows the decay angles ($\tan\theta$ in fact) relative to the propagation direction. While the decay angle of the pions are small enough to be ignored, the one for the kaons is comparable to the smearing by the multiple scattering in the front absorber [17]. Since the decay vertex is closer to the collision point, experimental identification of the decay vertex will be challenging. For this consideration, the role of the decay vertex is comparable to the resolution smearing.
- Finally we have varying efficiencies which is not documented at this point. We expect the size will be order of unit.

Fig. 10 and Fig. 11 shows the muon yields from the studied sources.

The relative abundance of the muons from the heavy flavour to the ones from π and K is about 1 to 10 and increases as the centrality of the collision increases within the current scheme of scaling. Simultaneous measurement of those two components over the centrality will be a useful tool to control systematics on N_{part} and N_{coll}. There are three promising improvements to this plot listed here.

- Scaling factor for the leading order calculation will be about 3 based on the lower energy measurements.
- The number of accumulated minimum bias Au + Au events is about 10^8 events.
- Hadronic components can be isolated by studying the dependence on decay vertex [18].

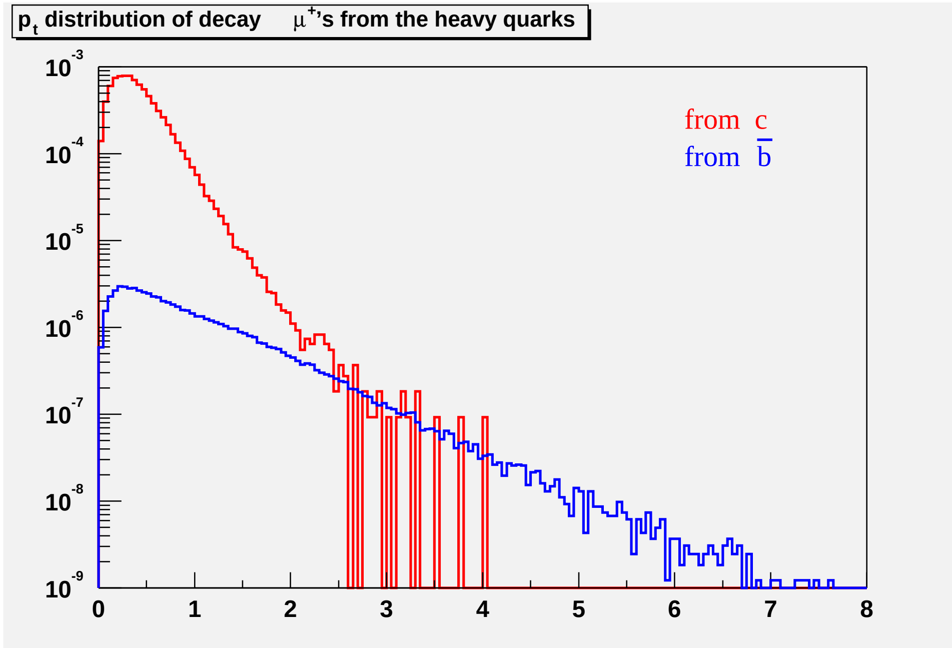

FIG. 8: p_t distribution of the decay muons resulting from the heavy flavour decay.

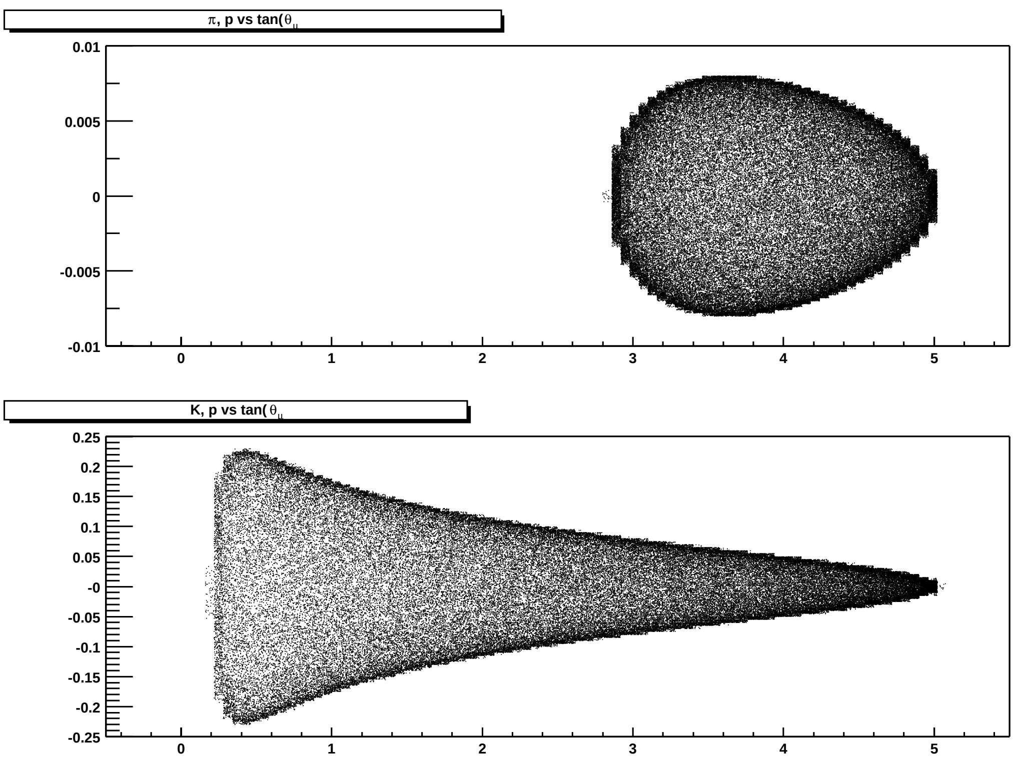

FIG. 9: Momentum of the daughter muons p_μ vs decay angle $\tan(\theta)$ when π and K decay. Case for $p_{mother=\pi,K} = 5\ GeV/c$.

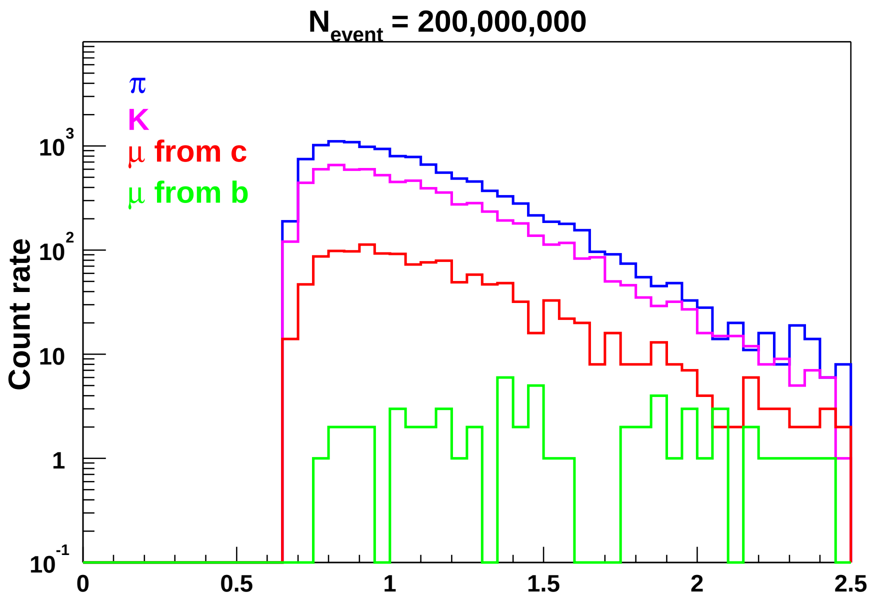

FIG. 10: Transverse momentum distribution of muons from the studied sources for the p + p reaction at $\sqrt{s} = 200\ GeV$.

Punch-through hadrons will make 1-2% of the decay contribution based on the simple estimates [10], and this contribution needs to be understood from the data side.

Lepton pair decay of the vector mesons (ω, ϕ, ρ), and dalitz decay of η and η' were considered as the additional background to the photon conversion and π^0 dalitz decay for our electron analysis of RUN1 data. Enhancement from the background due to the deduced charm signal is about 50% and those neutral mesons make up a few percent of the estimated background. Additionally these decays will not produce the charge asymmetry.

V. CHARGE ASYMMETRY AS A PROBE OF NON-PERTURBATIVE DYNAMICS

The pQCD improved parton model separates the long and short distance behavior in terms of the short distance hard partonic cross section and the long distance parton distribution and fragmentation function. Simple numerical estimation for the relavant scale of the fragmentation function is still smaller than the macroscopic volume of the colliding nuclei. Hence we expect the modification of the fragmentation function for the central $Au + Au$ reaction, and an interesting study will be *whether this modification follows the so called hadro-chemistry transition?*

According to [11], the origin of the asymmetries in the production spectra of charm and anticharm hadrons is due to the nonperturbative physics. Indeed the work explains the asymmetry observed at the low energy fixed target experiment based on nonperturbative treatment such as *Cluster collapse*, *Cluster decay*, and *string fragmentation*.

This nonperturbative physics can change widely in the new QGP-hadron transition scenario due to the net baryon density. Based on [12], the charge asymmetry given by the ratio between D^+ and D^- for the SPS Pb + Pb reaction is 0.47 while the scaling of PYTHIA calculation gives 0.89.

To study this issue we studied the charge asymmetry of the muons given by the event generator PYTHIA. Fig. 12 shows the asymmetry of the daughter muons. For this plot, explicit calculation of the leading order annihilation and fusion into charm production was made (technically msel value for PYTHIA was set to 4). Similar study based on the minimum bias event (msel = 2) was also made and showed similar behavior with limited statistics. This level of asymmetry may be visible depending on the level of background discussed in section IV, and needs investigation.

Some more efforts from our previous work on the thermal model [19] will enable the estimation of the ratio for the ion reaction. Here we make a numerical estimate from a simple quark coalesce model which is necessary to the

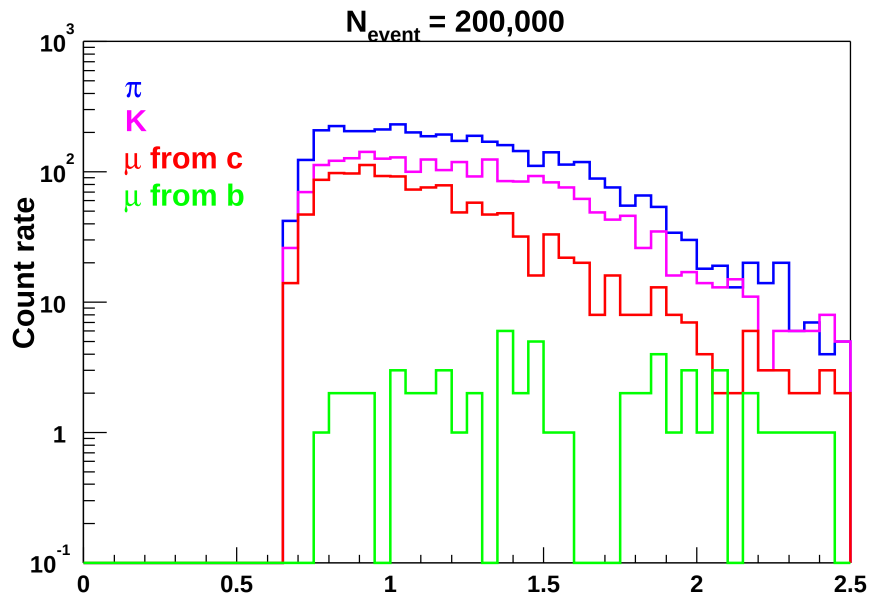

FIG. 11: Transverse momentum distribution of muons from the studied sources for the Au + Au reaction at $\sqrt{s} = 200\ A \cdot GeV$.

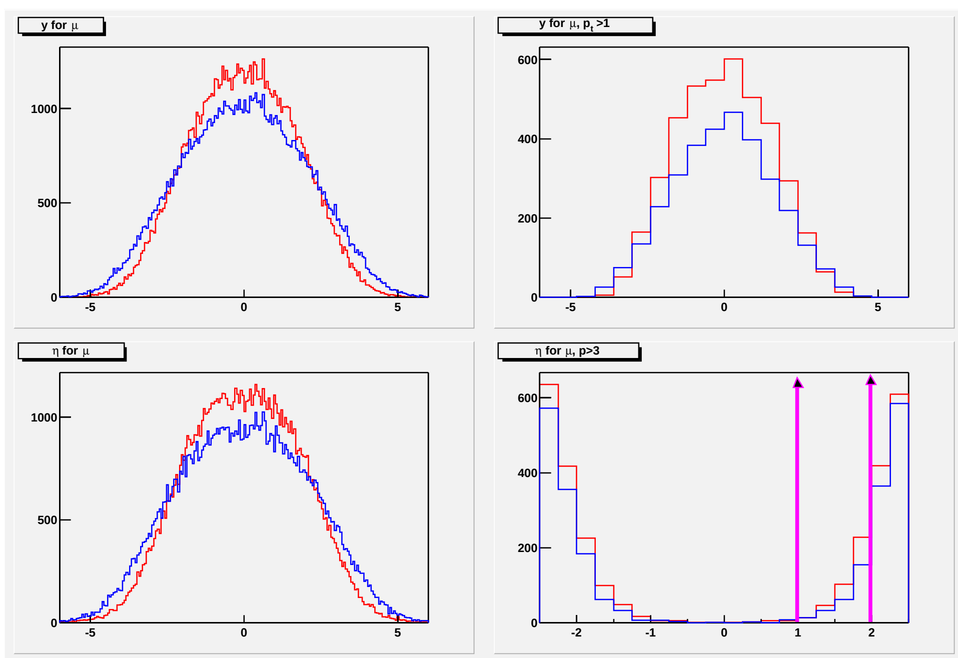

FIG. 12: Charge asymmetry of the muons (PYTHIA calculation). MSEL value was set to 4, and explicit calculation of the leading order annihilation and fusion process was made. Left figures show the distribution of the rapidity and pseudorapidity variables. Right figures are with some kinematic selection cut. Red line : μ^-, Blue line : μ^+

TABLE II: Charge asymmetry based on simple quark coalesce model

$N_{\bar{p}}/N_p$	0.055	0.5	0.6	0.7	0.8	0.9
N_{D^+}/N_{D^-}	0.38	0.8	0.84	0.89	0.93	0.97

discussion of the experimental accessibility. Then the simple estimation is made by

$$\frac{N_{D^+(c\bar{d})}}{N_{D^-(\bar{c}d)}} \approx \frac{N_{\bar{q}}}{N_q} \approx (\frac{N_{\bar{p}}}{N_p})^{1/3}. \tag{4}$$

Actual numbers are given in Table II. Based on the numbers, we have moderate prospect for the measurement depending on the choice of mother nature.

VI. CONCLUSION

We suveyed possible physics issues relavant for the measurement of the single hard muons. We studied

- the systematics of the pion and kaon production,
- the heavy flavour production (mostly open charm),
- and its asymmetry.

Based on this study, we observe possibility of measurement for

- scaling of the soft and hard component for the charged pions and kaons,
- scaling of the heavy flavour production and its comparison to the hadron production systematics,
- and charge asymmetry of the open charm production

for varying centrality. Feasibility of the measurement from the RUN2 analysis was discussed based on the available knowledge. Uncertainties exists in the study, but we hope this note helps to clarify some of physics issues and to identify the feasible measurements at current stage (maybe difficult time :)).

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