# Jet properties from $\pi^{\pm}$ - $h^{\pm}$ correlation in p+p and d+Au collisions

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**Abstract.** We discuss results on the charged pion - charged hadron correlation in $p+p$ and $d$ + Au collisions as measured by the PHENIX Collaboration. Properties of di-jet system, such as the jet shape, associated hadron yield per trigger pion, and the underlying event are extracted statistically from the $\pi^{\pm}-h^{\pm}$ correlation function in $\Delta\phi$ and $\Delta\eta$. For jet triggered with high $p_T$ pions ($p_T > 5$ GeV/c), no apparent differences in the jet properties are seen between $p+p$ and $d$ + Au.

**Keywords:** Two particle azimuth correlation, conditional yield, nuclear effect, underlying event
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## INTRODUCTION

The technique of two particle correlation in relative azimuth ($\Delta\phi$) and pseudorapidity ($\Delta\eta$) is an useful tool to access the (di-)jet properties in heavy-ion collisions. Comparing with the traditional full jet reconstruction method, the two particle correlation method is relatively insensitive to the level of the underling event, thus can probe soft jets ($\lesssim$5 GeV/c); combining with event mixing technique, it can also be used for detectors with limited acceptance.

To leading order in QCD, high $p_T$ jets are produced back-to-back in azimuth. This back-to-back correlation, however, is smeared by the fragmentation process and the initial and final state radiation, which lead to a typical di-hadron correlation function in $\Delta\phi$ as shown schematically in Figure.1. The associated hadron yield per trigger $\pi^{\pm}$ (conditional yield or CY) can be parameterized by a constant plus a double gauss function,

$$\frac{1}{N_{\rm trig}^0}\frac{dN_0}{d\Delta\phi} = B + \frac{\rm N_S}{\sqrt{2\pi}\sigma_N} e^{\frac{-\Delta\phi^2}{2\sigma_N^2}} + \frac{\rm N_A}{\sqrt{2\pi}\sigma_F} e^{\frac{-(\Delta\phi-\pi)^2}{2\sigma_F^2}} , \quad (1)$$

In this analysis, everything about the (di-)jet is extracted from this parameterization. The peaks in the same side ($\Delta\phi = 0$) and the away side ($\Delta\phi = \pi$) represent the intra-jet and di-jet correlation, respectively. The widths of the peaks are controlled by the jet fragmentation momentum $j_T$ and the parton transverse momentum $k_T$ [1, 2]: $\sigma_{same} \propto j_{Ty}$, $\sqrt{\sigma_{away}^2 - \sigma_{same}^2} \propto k_{Ty}$, where the subscript "$y$" represent the 1D projection in transverse plane; The integrals of the peaks, $N_S$ and $N_A$ give the total number of hadrons associated with the trigger hadrons in the same side and the away side; The pedestal level beneath the jet structure, $B$, represents contributions from the underlying event.

We focus the physics discussions on three aspects of the $\pi^{\pm}-h^{\pm}$ correlations in Figure.1: jet shape, jet yield and the underlying event. Further details on the method,

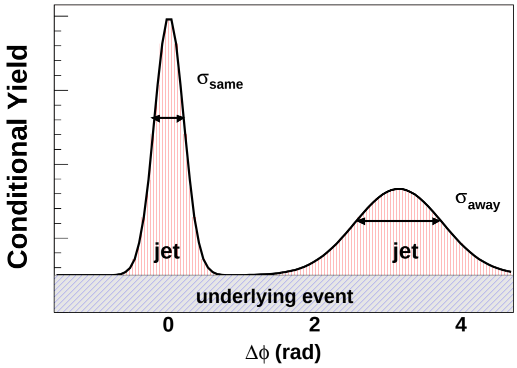


**FIGURE 1.** Cartoon of the two particle $\Delta\phi$ correlation. The yield of hadron per trigger (Conditional Yield) has a di-jet part and a part corresponding to the underlying event.

analysis, and physics results can be found in[2, 3].

## RESULTS

Left panel of Figure.2 shows the $\pi^{\pm} - h^{\pm}$ $\Delta\phi$ distribution from $p+p$ and $d$ + Au collisions for several ranges of associated hadron transverse momentum, $p_{T,\mathrm{assoc}}$, with trigger $\pi^{\pm}$ $p_T$ $5 < p_{T,\mathrm{trig}} < 10$ GeV/$c$. The widths decrease with increasing $p_{T,\mathrm{assoc}}$, which is consistent with narrowing of the jet cone for larger $p_{T,\mathrm{assoc}}$. It is interesting to notice that a large fraction of all hadrons in the event are associated with the trigger, thus are originated from the hard-scattered partons. Even for $p_{T,\mathrm{assoc}}$ as low as $0.4-1$ GeV/$c$, about 51% hadron yield in $p+p$ (27% in $d$ + Au) comes from the jet fragmentation. Right panel of Figure.2 shows the extracted jet widths in $\Delta\phi$, comparing with those in $\Delta\eta$ for various $p_{T,\mathrm{assoc}}$. The overall agreement between the jet widths in $\Delta\eta$ and $\Delta\phi$ is pretty good, except at small $p_{T,\mathrm{assoc}}$, where the width in $\Delta\eta$ is systematically lower than that in $\Delta\phi$. The fact that this discrepancy exist in both $p+p$ and $d$ + Au collisions indicates that this deviation is likely due to the systematics of the fitting in a limited $\Delta\eta$ range [1] rather than any real physics effect in $d$ + Au.

The same side and away side $p_T$ distributions of the charged hadrons associated with trigger pions are plotted in Fig3, comparing between $p+p$ and $d$ + Au collisions. The same side yield is related to the di-hadron fragmentation, since both particles comes from the same jet, while the away side yield depends on two independent fragmentation functions: one parton fragments to produce the trigger, while the second parton produces the associated hadron. No apparent differences are seen between $p+p$ and $d$ + Au; this observation is in contradiction to some recombination model prediction [4], in which a significant difference is expected due to shower-thermal contribution.

Events triggered by high $p_T$ hadrons not only contain particles originated from the two hard-scattered partons, but also those come from soft multiple interaction and the beam

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[1] PHENIX coverage in $\eta$ is $|\eta| < 0.35$, which gives a pair coverage of $|\Delta\eta| < 0.7$.

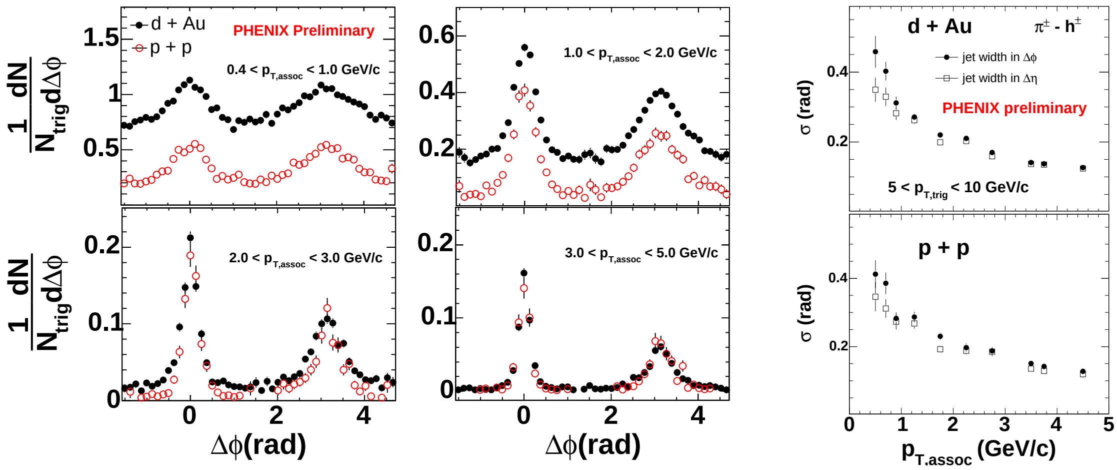


**FIGURE 2.** Left: Per-trigger pair distributions in $p+p$ and minimum bias $d$+Au collisions. The trigger $\pi^{\pm}$ are correlated with hadrons with $p_{T,\text{assoc}}$ 0.4 − 1.0 GeV/$c$, 1.0 − 2.0 GeV/$c$, 2.0 − 3.0 GeV/$c$ and 3.0 − 5.0 GeV/$c$ (from top to bottom and left to right). Right: The comparison of jet width as function of $p_{T,\text{assoc}}$ in $\Delta\phi$ (solid circles) and $\Delta\eta$ (open boxes) from $\pi^{\pm}-h^{\pm}$ correlation. Top and bottom panels show the results for $d$ + Au and $p+p$, respectively.

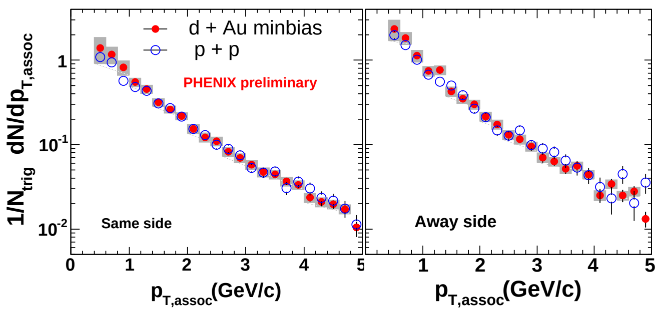


**FIGURE 3.** Jet pair distribution as function of $p_{T,assoc}$ for same side (right panel) and away side (left panel) in $p+p$ and $d$ + Au.

remnants. Underlying event in $p+p$ and $d$ + Au collisions refers to all hadrons except those from the two outgoing hard-scattered partons, which includes contributions from the beam remnants and initial and final state radiation [5]. It has been studied extensively at the Tevatron energy [6, 5]. Similar studies at the RHIC are useful in understanding it's dependence on $\sqrt{s}$, and can provide valuable constrains on the underlying event physics at the LHC.

Figure.4 shows the jet pair distribution in $p+p$ collisions, reproduced from Figure.2 but plotted under semi-log scale. The pedestal in the $\Delta\phi$ correlation, which represents the underlying event contribution, decreases quickly and becomes negligible at $p_{T,\text{assoc}} > 2$ GeV/$c$. However, the level corresponding to minimum bias $p+p$ events, denoted by the thick horizontal line, seems to decrease even faster. Since minimum bias event has small hard-scattering contribution, the relative abundance of the pedestal in triggered events over the minimum bias events indicates that most of the underlying event comes from the initial or final state radiation of the hard-scattered partons.

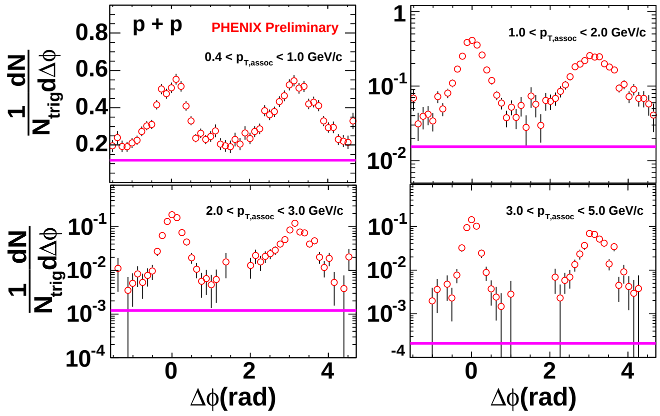


**FIGURE 4.** Condition yield in $\Delta\phi$ for $p+p$ collisions (from Figure.2). The thick solid line represents the average level for minimum bias events, i.e. it is equal to $\mathrm{Yield_{pp}}/(2\pi)$.

In $d$ + Au case, Figure.2 indicates that the underlying event levels are larger than those in $p+p$, although the properties of the jets are quite similar. Under the assumption that the hard-scattering happens in one nucleon-nucleon collision and that the ambient particle production scale as the nuclear modification factor, $R_{\mathrm{dAu}}$ measured in $d$ + Au [7]. The underlying event yields in $p+p$ and $d$ + Au, $U_{\mathrm{dAu}}$ and $U_{\mathrm{pp}}$ are connected to each other through the following simple relation,

$$U_{\mathrm{dAu}} = U_{\mathrm{pp}} + R_{\mathrm{dAu}}\,(N_{\mathrm{coll}} - 1)\,\mathrm{Yield_{pp}} \tag{2}$$

where $\mathrm{Yield_{pp}}$ represents the hadron yield per event in minimum bias $p+p$ collisions. Divide both side by $\mathrm{Yield_{pp}}$, we get,

$$\lambda_{\mathrm{dAu}} = \lambda_{\mathrm{pp}} + R_{\mathrm{dAu}}\,(N_{\mathrm{coll}} - 1) \tag{3}$$

$$\lambda_{\mathrm{dAu}} = U_{\mathrm{dAu}}/\mathrm{Yield_{pp}}, \lambda_{\mathrm{pp}} = \mathrm{U_{pp}}/\mathrm{Yield_{pp}} \tag{4}$$

note $\lambda_{\mathrm{pp}}$ denotes the ratio of underlying event yield to minimum bias event in $p+p$, which should be larger than 1 according to Figure.4.

In summary, we have demonstrated that the two particle correlation method is a powerful tool in accessing basic jet properties. The extracted jet shape and associated yield in $p+p$ and $d$+Au are very similar, indicating little modification in cold nuclear medium. These measurements serve as important baselines for jet correlation studies in heavy-ion collisions.

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