Initial State Bremsstrahlung versus Final State Hydrodynamic Sources of Azimuthal Harmonics in $p + A$ at RHIC and LHC

M. Gyulassy^{a,b}, P. Levai^a, I. Vitev^c, T. Biro^a

^aMTA WIGNER Research Centre for Physics, RMI, Budapest, Hungary

^bDepartment of Physics, Columbia University, New York, 10027, USA

^cTheoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Abstract

Recent $p_T < 2$ GeV azimuthal correlation data from the Beam Energy Scan (BES) and D+Au runs at RHIC/BNL and the especially the surprising similarity of azimuthal $v_n 2m(p_T)$ “flow” harmonics in p+Pb and $Pb + Pb$ at LHC have challenged the uniqueness of local equilibrium “perfect fluid” interpretations of p+A and A+A data. We report results derived in [1] on azimuthal harmonics associated with initial state non-abelian “wave interference” effects predicted by perturbative QCD gluon bremsstrahlung and sourced by Color Scintillation Arrays (CSA) of color antennas. CSA are naturally identified with multiple projectile and target *beam jets* produced in inelastic $p + A$ reactions. We find a remarkable similarity of the azimuthal harmonics sourced by CSA and perfect fluid modeling of high energy $p + A$ reactions that could help resolve .

Keywords: Initial State QCD Radiation, Final State Viscous Hydrodynamics

1. Introduction

An unexpected discovery at RHIC/BNL in $D + Au$ reactions at $\sqrt{s} = 200$ AGeV [2] and at LHC/CERN in $\sqrt{s} = 5.02$ ATeV $p + Pb$ reactions [3] is the large magnitude of mid-rapidity azimuthal anisotropy moments, $v_n(k_T, \eta = 0)$, that are remarkably similar to those observed previously in non-central $Au + Au$ [4] and $Pb + Pb$ [5] reactions. See especially preliminary ATLAS [7] Fig. 24 and the QM14 ATLAS talk by J. Jia in these proceedings. In addition, the Beam Energy Scan (BES) at RHIC [9] revealed a near $\sqrt{s}$ independence from 8 AGeV to 2.76 ATeV of $v_n(p_T; s)$ in $A + A$ at fixed centrality that was also unexpected as compared to previous SPS data.

In high energy $A + A$, the v_n moments have been interpreted as possible evidence for the near “perfect fluidity” of the strongly-coupled Quark Gluon Plasmas (sQGP) produced in such reactions [10, 12]. However, the recent observation of similar v_n arising from much smaller transverse size $p(D) + A$ systems and also the near beam energy independence of the moments observed in the Beam Energy Scan (BES) [9] from 7.7 AGeV to 2.76 ATeV in $A + A$ have posed a problem for the perfect fluid interpretation because near inviscid hydrodynamics is not expected to apply in space-time regions where the local temperature field falls below the confinement temperature, $T(x, t) < T_c \sim 160$ MeV. In that Hadron Resonance Gas (HRG) “corona” region, the viscosity to entropy ratio is predicted to grow rapidly with decreasing temperature [13] and the corona volume fraction must increase relative to the ever shrinking volume of the perfect fluid “core” with $T > T_c$ when either the projectile atomic number A and size $A^{1/3}$ fm or the center-of-mass (CM) energy $\sqrt{s}$ decrease .

While hydrodynamic equations have been shown to be *sufficient* to describe $p(D) + A$ data with particular assumptions about initial and freeze-out boundary conditions [14], its *necessity* as a unique interpretation of the data is not guaranteed. This point was underlined recently using a specific initial state saturation model [15] that was shown to be

able to fit $p(D) + A$ correlation even v_n moments data without final state interactions. That saturation model has also been used [11] to specify initial conditions for perfect fluid hydrodynamics in $A + A$. However, in $p + A$ such initial conditions for hydrodynamics are not as well-controlled because the gluon saturation scale, $Q_s(x, A = 1) < 1$ GeV is small and its fluctuations in the transverse plane on sub-nucleon scales are not reliably predicted.

The near independence of v_n moments on beam energy observed in BES [9] at RHIC from 7.7 AGeV to 2760 AGeV pose another serious challenges to the uniqueness of the perfect fluid interpretations of the data because of previous hybrid fluid-HRG modelling [16] predicted a systematic reduction of the moments due to an increasing HRG corona with decreasing beam energy. The HRG corona fraction should dilute signatures of a perfect fluid QGP core flow at lower energies unless additional dynamical mechanisms accidentally conspire to compensate for growing HRG corona fraction.

The BES [9] data also pose a challenge to color glass condensate (CGC) gluon saturation model [23] used to specify initial conditions for hydrodynamic flow predictions in $A + A$. This is because Q_s^2 is definitely predicted decrease with $\log(s)$, and thus gluon saturation-dominated “central rapidity region” gluon fusion dynamics must switch over into valence quark-diquark dominate “fragmentation region” inelastic dynamics involving fragmentation of multiple quark-diquark beam jets.

In our GLVB paper [1] we explored the possibility that initial state gluon bremsstrahlung sourced by Color Scintillating Arrays (CSA) of colored beam jet antenna could partially at least account for the above puzzling azimuthal harmonic. Non-abelian bremsstrahlung is intrinsically azimuthally anisotropic. The pQCD based GLVB model extends the first order in opacity $\chi = 1$ Gunion-Bertsch [18] (GB) perturbative QCD bremsstrahlung to all orders in opacity, $e^{-\chi} \sum_{n=1}^{\infty} \chi^n / n! \dots$, Vitev-Gunion-Bertsch (VGB) multiple interaction pQCD bremsstrahlung for applications to $B + A$ nuclear collisions. We show that VGB bremsstrahlung naturally leads on an event by event basis to a hierarchy of non trivial azimuthal asymmetry moments remarkably similar to that observed in $p + A$ and peripheral $A + A$ at fixed $dN/d\eta$ [6]

2. Results

The non-abelian bremsstrahlung Gunion-Bertsch (GB) formula [18] for the soft gluon radiation single inclusive distribution for a triggered beam jet recoil momentum $\mathbf{q} = (q, \psi)$ is

$$\frac{dN_g^1}{d\eta d^2\mathbf{k} d^2\mathbf{q}} = \frac{C_R \alpha_s}{\pi^2} \frac{\mu^2}{\pi(q^2 + \mu^2)^2} \frac{\mathbf{q}^2}{\mathbf{k}^2(\mathbf{k} - \mathbf{q})^2} . \quad (1)$$

Here the parton scattering elastically cross section is assumed to be $d\sigma_0/d^2\mathbf{q} = \sigma_0 \mu^2 / \pi(q^2 + \mu^2)^2$. the produced gluon has rapidity η and transverse momentum $\mathbf{k} = (k, \phi)$. Note especially that the azimuthal asymmetric angle dependence has the simple form, $dN_g = F_{kq} / (A_{kq} - \cos(\phi - \psi))$ of the radiated ϕ relative to the reaction plane ψ angles arising from basic nonabelian interference effects. Note also the uniform rapidity-even, $\eta \approx \log(xE/k)$, distribution of bremsstrahlung due to the triple gluon vertex. In $p + A$ multiple target beam jets generally transform that uniform η dependence into a trapezoidal one as discussed in [1]. The GB azimuthal harmonics can then be analytically evaluated from

$$v_n^{GB}(k, q, \psi) f_0(k, q) = F_{kq} \int \frac{d\phi}{2\pi} \frac{\cos(n\phi)}{A_{kq} - \cos(\phi - \psi)} \quad (2)$$

$$= \cos[n\psi] (v_1^{GB}(k, q))^n \quad (3)$$

$$v_1^{GB}(k, q) = (A_{kq} - \sqrt{A_{kq}^2 - 1}) \quad (4)$$

$$. \quad (5)$$

Here $A_{kq} = (k^2 + q^2 + \mu^2) / (2k \cdot q) \geq 1$ implies that all harmonics are peaked near $k \sim q$, vanish at $k = 0$, and slowly decrease toward zero for $k \gg q$. In addition, the analytic single color antenna GB gluon harmonics obey an approximate power law scaling with respect to the harmonic n number:

$$[v_n^{GB}(k, q, 0)]^{1/n} = [v_m^{GB}(k, q, 0)]^{1/m} , \quad (6)$$

that is similar to the scaling observed by ALICE, CMS and ATLAS [5] at LHC and similar to perfect fluid harmonic scaling for the higher $n \geq 3$ moments dominated by purely geometric fluctuations. We note also that unlike the low order GLASMA/CGC azimuthal harmonics, the GB bremsstrahlung harmonics are nonvanishing and scale for all odd as well as even moments n . We illustrate in Fig.(1a) the main features of azimuthal harmonics from a single beam jet bremsstrahlung.

Figure 1. (Color online) (a) [left] Approximate $1/n$ power scaling of q averaged $\langle v_n^{GB}(k, q, 0) \rangle^{1/n}$ for a fixed reaction plane $\psi = 0$ from a single GB color antenna for all even and odd moments is seen in the kinematic region $k^2 < \langle q^2 \rangle \equiv M\mu^2$. This scaling breaks down for $k > \sqrt{M}\mu$ because in the $\mu = 0$ limit bremsstrahlung strictly vanish for $k > q$. (b) [right] Schematic diagram corresponding to coherent bremsstrahlung from the projectile beam jet at impact parameter $\mathbf{b}$. The azimuthal distribution is enhanced for transverse momenta $\mathbf{k}$ near the total accumulated momentum transfer to the projectile $\mathbf{Q}_0 \equiv \sum_a \mathbf{Q}_a$ from the $a = 1, \dots, M$ clusters of recoiling target beam jets. In addition, the bremsstrahlung is enhanced near $\mathbf{k} = -\mathbf{Q}_a$ from each incoherent recoiling target cluster separated by $\Delta R_{ab} \sim 1/k$ in the transverse plane.

In a given $p + A$ event a projectile nucleon penetrates through a target nucleus A at impact parameter $\mathbf{b}$, producing one projectile beam jet with rapidity $Y_P > 0$. There are $N \sim A^{1/3} < A$ target beam jets with $Y_T < 0$ produced with transverse coordinates $\mathbf{R}_i$ distributed within a distance $\sim 1/\mu$ from the impact parameter. The n , the target dipoles naturally cluster near the projectile impact parameter $\mathbf{b}$ as illustrated in Fig. (1b). In a specific event, there are however only $1 \leq M \leq N$ overlapping clusters that can radiate coherently toward the negative rapidity $\eta < 0$ hemisphere (see [1]). Incoherence of target clusters bremsstrahlung is controlled by the transverse resolution scale with $|\mathbf{R}_i - \mathbf{R}_j| > 1/k$.

Let $\mathbf{Q}_a = \sum_{i \in I_a} \mathbf{q}_i$ denote the cumulated momentum transfer to the projectile from target cluster a . The total single inclusive bremsstrahlung distribution into a particular mode $(\mathbf{k}_1)$ has the form

$$dN^{M,N} = dN_P^N(\eta, \mathbf{k}_1; \mathbf{Q}_P) + dN_T^{M,N}(\eta, \mathbf{k}_1; \{\mathbf{Q}_a\}) = \sum_{a=0}^M \frac{B_{k_1 Q_a}}{(\mathbf{k}_1 + \mathbf{Q}_a)^2 + \mu_a^2}, \quad (7)$$

where we define $\mathbf{Q}_0 = -\sum_a \mathbf{Q}_a$ to include the projectile beam jet contribution into the summation over target clusters. Note that for a semi exclusive event with all M target recoil momenta Q_a and their azimuthal orientation ψ_a determined, the bremsstrahlung radiation is peaked near the $M + 1$ cumulative momenta. However, averaging over all reaction planes forces all single particle v to vanish on the average. Only 2 or higher particle correlation can reveal the intrinsic azimuthal anisotropy correlations above. Fortunately, in this model all 2ℓ relative azimuthal harmonics can also be evaluated analytically[1].

In the “mean recoil” approximation $Q \approx \bar{Q}$, we see that a single GB antenna satisfies the generalized power scaling law in case that subsets of the 2ℓ gluons have identical momenta. Suppose there are $1 \leq L \leq 2\ell$ distinct momenta K_r with $r = 1, \dots, L$ such m_r of the 2ℓ gluons have momenta equal to a particular value K_r such that $\sum_{r=1}^L m_r = 2\ell$.

In this case $v_n^{M=1}\{2\ell\}(k_1, \dots, k_{2\ell}; \bar{Q}) \approx \prod_{r=1}^L (v_n^{GB}(K_r, \bar{Q}))^{m_r} = \prod_{r=1}^L (v_1^{GB}(K_r, \bar{Q}))^{nm_r}$. The approximate factorization and power scaling of azimuthal harmonics from CSA coherent state non-abelian bremsstrahlung is similar to “perfect fluid hydrodynamic collective flow” factorization and scaling, but in this case no assumption about local equilibration or minimal viscosity is necessary.

3. Conclusions

In this talk we summarized from Ref.[1] some of the remarkable azimuthal correlation properties of beam jet non-abelian bremsstrahlung even at the lowest order of perturbative QCD level using the VGB generalization[19] of GB[18] bremsstrahlung to all orders in opacity in $p + A$. Of course, higher order and especially high gluon occupation number effects[20, 23] will modify the intricate initial state chromo wave interference patterns. However, the main lesson from this study is that in $p + A$ initial state wave interference phenomena may well dominate over any final state dynamics but look nevertheless as if “perfect fluid” description were applicable on sub nucleon transverse scales. In particular long range in η multi-gluon power law multipole n cummulants scaling is not unique to final state perfect fluid flows but is also a natural feature of bremsstrahlung from Color Scintillating Arrays of beam jets. A possible way to help discriminate initial state interference harmonics from final state flow harmonics is through the study of rapidity dependence of multi-gluon azimuthal harmonics as discussed in [1].

4. Acknowledgements

MG acknowledges support from the US-DOE DE-FG02-93ER40764, DE-AC02-05CH1123. PL, TB, and MG acknowledge support from Hungarian OTKA grants K81161, K104260, NK106119, and NIH TET-12-CN-1-2012-0016. IV was supported in part by the US Department of Energy, Office of Science.

References

- [1] M. Gyulassy, P. Levai, I. Vitev and T. Biro, arXiv:1405.7825 [hep-ph], submitted to PRD.
- [2] A. Adare *et al.* [PHENIX] Phys. Rev. Lett. **111**, 212301 (2013)
- [3] S. Chatrchyan *et al.* [CMS], Phys. Lett. B **718**, 795 (2013); B. Abelev *et al.* [ALICE], Phys. Lett. B **719**, 29 (2013); G. Aad *et al.* [ATLAS], Phys. Rev. Lett. **110**, 182302 (2013); Phys. Lett. B **725**, 60 (2013).
- [4] J. Adams *et al.* [STAR], Nucl. Phys. A **757**, 102 (2005); K. Adcox *et al.* [PHENIX], Nucl. Phys. A **757**, 184 (2005); A. Adare *et al.* [PHENIX], Phys. Rev. Lett. **105**, 062301 (2010).
- [5] K. Aamodt *et al.* [ALICE], Phys. Lett. B **708**, 249 (2012); Phys. Rev. Lett. **105**, 252302 (2010); Phys. Rev. Lett. **107**, 032301 (2011);
- [6] S. Chatrchyan *et al.* [CMS] Eur. Phys. J. C **72**, 2012 (2012); G. Aad *et al.* [ATLAS] Phys. Rev. C **86**, 014907 (2012).
- [7] ATLAS collab, <http://cds.cern.ch/record/1702976>, Quark Matter 2014, Darmstadt, Germany, May 18, 2014, ATLAS-CONF-2014-021, fg.24.
- [8] J. Jia, *ibid*, private communication.
- [9] L. Adamczyk *et al.* [STAR Collaboration], Phys. Rev. C **88**, no. 1, 014902 (2013) [arXiv:1301.2348 [Unknown]].
- [10] P. Romatschke and U. Romatschke, Phys. Rev. Lett. **99**, 172301 (2007); M. Luzum and P. Romatschke, Phys. Rev. C **78**, 034915 (2008); Phys. Rev. Lett. **103**, 262302 (2009); B. H. Alver, C. Gombeaud, M. Luzum and J. -Y. Ollitrault, Phys. Rev. C **82**, 034913 (2010);
- [11] C. Gale, *et al.*, Phys. Rev. Lett. **110**, 012302 (2013);
- [12] U. Heinz and R. Snellings, Ann. Rev. Nucl. Part. Sci. **63**, 123 (2013) [arXiv:1301.2826 [nucl-th]].
- [13] P. Danielewicz and M. Gyulassy, Phys. Rev. D **31**, 53 (1985); T. Hirano and M. Gyulassy, Nucl. Phys. A **769**, 71 (2006).
- [14] P. Bozek, Phys. Rev. C **85**, 014911 (2012) [arXiv:1112.0915 [hep-ph]]; P. Bozek and W. Broniowski, Phys. Rev. C **88**, no. 1, 014903 (2013); arXiv:1403.6042 [nucl-th].
- [15] K. Dusling and R. Venugopalan, Phys. Rev. D **87** 094034 (2013).
- [16] D. Teaney, J. Lauret and E. V. Shuryak, Phys. Rev. Lett. **86**, 4783 (2001) [nucl-th/0011058].
- [17] G. Basar and D. Teaney, arXiv:1312.6770 [nucl-th].
- [18] J. F. Gunion and G. Bertsch, Phys. Rev. D **25**, 746 (1982). Phys. Rev. Lett. **85**, 5535 (2000). Phys. Lett. B **649**, 139 (2007).
- [19] I. Vitev, Phys. Rev. C **75**, 064906 (2007) [hep-ph/0703002].
- [20] D. Kharzeev, E. Levin and L. McLerran, Nucl. Phys. A **748**, 627 (2005) [hep-ph/0403271].
- [21] T. Lappi and L. McLerran, Nucl. Phys. A **772**, 200 (2006); T. Lappi, Phys. Lett. B **643**, 11 (2006).
- [22] J. Noronha and A. Dumitru, Phys. Rev. D **89**, 094008 (2014) [arXiv:1401.4467 [hep-ph]].
- [23] K. Dusling and R. Venugopalan, Phys. Rev. D **87**, no. 5, 051502 (2013) [arXiv:1210.3890 [hep-ph]].