Azimuthal asymmetries for hadron distributions inside a jet in hadronic collisions

To cite this article: Umberto D'Alesio et al 2011 J. Phys.: Conf. Ser. 295 012064

View the article online for updates and enhancements.
Azimuthal asymmetries for hadron distributions inside a jet in hadronic collisions

Umberto D’Alesio\textsuperscript{1,2}, Francesco Murgia\textsuperscript{2} and Cristian Pisano\textsuperscript{1,2,*}

\textsuperscript{1} Dipartimento di Fisica, Universit\`a di Cagliari, Cittadella Universitaria, I-09042 Monserrato (CA), Italy
\textsuperscript{2} Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, Ch. P. 170, I-09042 Monserrato (CA), Italy

E-mail: umberto.dalesio@inaf.it, francesco.murgia@ca.infn.it, cristian.pisano@ca.infn.it

Abstract. Using a generalized parton model approach including spin and intrinsic parton motion effects, and assuming the validity of factorization for large $p_T$ jet production in hadronic collisions, we study the azimuthal distribution around the jet axis of leading pions, produced in the jet fragmentation process. We identify the observable leading-twist azimuthal asymmetries for the unpolarized and single-polarized case related to both quark and gluon-originated jets. We account for all physically allowed combinations of the transverse momentum dependent (TMD) parton distribution and fragmentation functions, with special attention to the Sivers, Boer-Mulders, and transversity quark distributions, and to the Collins fragmentation function for quarks (and to the analogous functions for gluon partons).

1. Introduction

Transverse single-spin and azimuthal asymmetries in high-energy hadronic reactions have raised a lot of interest in the last years (see e.g. Refs. [1, 2] and references therein). In particular, the huge spin asymmetries measured in the inclusive forward production of pions in high-energy $pp$ collisions at moderately large transverse momentum, cannot be explained in the realm of leading-twist (LT) perturbative QCD (pQCD), based on the usual collinear factorization theorems.

Out of the theoretical approaches proposed in order to account for these measurements, in the following we will adopt the so-called transverse momentum dependent (TMD) formalism, which takes into account spin and intrinsic parton motion effects assuming a pQCD factorization scheme. Single-spin and azimuthal asymmetries are generated by TMD polarized partonic distribution and fragmentation functions, among which the most relevant from a phenomenological point of view are the Sivers distribution [3, 4] and, for transversely polarized quarks, the Boer-Mulders distribution [5] and the Collins fragmentation function [6] (similar functions can be defined for linearly polarized gluons, see e.g. Ref. [7]).

Along the lines of [8], we consider the process $p^{(1)}p \rightarrow \text{jet} + \pi + X$, presently under active investigation at RHIC, where one observes a large $p_T$ jet and looks for the azimuthal distribution of leading pions inside the jet. A very preliminary version of this study was first presented in

* Speaker
Ref. [9]. A similar analysis was performed in Ref. [10], which however considered intrinsic parton motion only in the fragmentation process, drastically reducing the possible contributions to the asymmetry. Indeed, in that case, only the Collins effect for quarks is at work. In fact, Ref. [10] aimed at studying only the Collins fragmentation function (FF), which should be universal, in a more simplified theoretical scheme for which factorization has been proven. Our approach is different in some respects. It is more general and has in principle a richer structure in the observable azimuthal asymmetries, since intrinsic motion is taken into account in the initial hadrons also. However, since factorization has not been proven in this case, but is rather taken as a reasonable phenomenological assumption, the validity of the scheme and the universality of the TMD distributions involved require an even more severe scrutiny by comparison with experimental results. On the other hand, at the present theoretical and experimental stage, we believe that combined phenomenological tests of different approaches are required to clarify the validity of factorization and, related to this, the relevance of possible universality-breaking terms for the TMD distributions.

The plan of this contribution is as follows. In Sec. 2 we will briefly summarize the TMD generalized parton model approach and give the expression of the polarized cross section for the process of interest. In Sec. 3 we will present phenomenological results for azimuthal asymmetries discussed in the kinematical configuration of the RHIC experiments. Sec. 4 contains final remarks and conclusions.

2. Formalism
We denote with $A$ and $B$ two spin 1/2 hadrons (typically, two protons), with hadron $B$ unpolarized and hadron $A$ in a pure transverse spin state described by the four-vector $S_A$. Within a generalized TMD parton model approach, the invariant differential cross section for the process $A(S_A)B \rightarrow \text{jet} + \pi + X$ can be written, at LT in the soft TMD functions, as

$$\frac{E_j \, d\sigma}{d^3 p_j \, dz \, d^2 k_{\perp \pi}} = \sum_{a,b,c,d,\{(\lambda)\}} \int \frac{dx_a \, dx_b}{16\pi^2 x_a x_b s} \, d^2 k_{\perp a} \, d^2 k_{\perp b} \, \rho^{a/A,S_A}_{\lambda_a} \hat{f}^{a/A,S_A}_{\lambda_a}(x_a, k_{\perp a})$$

$$\times \rho^{b/B}_{\lambda_b} \hat{f}^{b/B}_{\lambda_b}(x_b, k_{\perp b}) \hat{M}_{\lambda_a,\lambda_b} \hat{M}^*_{\lambda_c,\lambda_d} \delta(\hat{s} + \hat{t} + \hat{u}) \hat{D}^\pi_{\lambda_c,\lambda_d}(z, k_{\perp \pi}),$$

where $E_j$ and $p_j$ are respectively the energy and three-momentum of the observed jet. We sum over all allowed partonic processes contributing to the physical process observed, and $\{(\lambda)\}$ stays for a sum over all partonic helicities. $x_{a,b}$ and $k_{\perp a,b}$ are respectively the initial parton light-cone momentum fractions and intrinsic transverse momenta. Analogously, $z$ and $k_{\perp \pi}$ are the light-cone momentum fraction and the transverse momentum of the observed pion inside the jet w.r.t. the jet (parton $c$) direction of motion.

All information on the polarization state of the initial parton $a$ is contained in $\rho^{a/A,S_A}_{\lambda_a} \hat{f}^{a/A,S_A}_{\lambda_a}(x_a, k_{\perp a})$, which depends in turn on the (experimentally fixed) parent hadron $A$ polarization state and on the soft, nonperturbative dynamics encoded in the eight leading-twist polarized and transverse momentum dependent parton distribution functions. $\rho^{a/A,S_A}_{\lambda_a}$ is the helicity density matrix of parton $a$. Analogously, the polarization state of parton $b$ inside the unpolarized hadron $B$ is encoded into $\rho^{b/B}_{\lambda_b} \hat{f}^{b/B}_{\lambda_b}(x_b, k_{\perp b})$. The $\hat{M}_{\lambda_a,\lambda_b}$’s are the pQCD leading-order (LO) helicity scattering amplitudes for the hard partonic process $ab \rightarrow cd$. The $\hat{D}^\pi_{\lambda_c,\lambda_d}(z, k_{\perp \pi})$’s are the soft leading-twist TMD fragmentation functions describing the fragmentation process of the scattered (polarized) parton $c$ into the final leading pion inside the jet. More details can be found in Ref. [8].

We work in the $AB$ hadronic c.m. frame, with hadron $A$ moving along the $+\hat{Z}_{\text{cm}}$ direction, and define $(X Z)_{\text{cm}}$ as the production plane containing the colliding beams and the observed jet,
with \((p_j)_{X,m} > 0\). In this frame \(S_A = (0, \cos \phi_{S_A}, \sin \phi_{S_A}, 0)\) and \(p_j = p_j T (\cosh \eta_j, 1, 0, \sinh \eta_j)\), where \(\eta_j = -\log[\tan(\theta_j/2)]\) is the jet (pseudo)rapidity.

The calculation is performed by summing explicitly over all helicity indexes and inserting the appropriate expressions for the helicity density matrices of partons \(a, b\) and for the polarized distribution and fragmentation functions. After factorizing explicitly all azimuthal dependences, including those coming from the hard-scattering helicity amplitudes, collecting them and using symmetry properties under \(k_{1,a,b} \rightarrow -k_{1,a,b}\) [8], one gets the final expression for the single transverse polarized cross section. This will have the following general structure:

\[
2d\sigma(\phi_{S_A}, \phi^H_{\pi}) \sim d\sigma_0 + d\Delta\sigma_0 \sin \phi_{S_A} + d\sigma_1 \sin \phi^H_{\pi} + d\sigma_2 \cos 2\phi^H_{\pi} + d\Delta\sigma_1 \sin(\phi_{S_A} - \phi^H_{\pi}) + d\Delta\sigma_2 \sin(\phi_{S_A} - 2\phi^H_{\pi}) + d\Delta\sigma_2^+ \sin(\phi_{S_A} + 2\phi^H_{\pi}) ,
\]

where \(\phi^H_{\pi}\) is the azimuthal angle of the pion three-momentum around the jet direction of motion, as measured in the fragmenting parton helicity frame. The latter frame is related to the hadronic c.m. frame by a simple rotation by \(\theta_j\) around \(Y_{cm} \equiv \hat{y}_j\) [8].

In terms of the polarized cross section in Eq. (2), we can define average values of appropriate circular functions of \(\phi_{S_A}\) and \(\phi_{\pi}^H\), in order to single out the different contributions of interest:

\[
(W(\phi_{S_A}, \phi_{\pi}^H)(p_j, z, k_{1,\perp})) = \frac{\int d\phi_{S_A} d\phi_{\pi}^H W(\phi_{S_A}, \phi_{\pi}^H) d\sigma(\phi_{S_A}, \phi_{\pi}^H)}{\int d\phi_{S_A} d\phi_{\pi}^H d\sigma(\phi_{S_A}, \phi_{\pi}^H)}.
\]

Alternatively, for the single spin asymmetry we can, in close analogy with the case of semi-inclusive deeply inelastic scattering (SIDIS), define appropriate azimuthal moments,

\[
A_N^{W(\phi_{S_A}, \phi_{\pi}^H)}(p_j, z, k_{1,\perp}) = 2 \langle W(\phi_{S_A}, \phi_{\pi}^H)(p_j, z, k_{1,\perp}) \rangle = 2 \frac{\int d\phi_{S_A} d\phi_{\pi}^H W(\phi_{S_A}, \phi_{\pi}^H) \left[ d\sigma(\phi_{S_A}, \phi_{\pi}^H) - d\sigma(\phi_{S_A} + \pi, \phi_{\pi}^H) \right]}{\int d\phi_{S_A} d\phi_{\pi}^H \left[ d\sigma(\phi_{S_A}, \phi_{\pi}^H) + d\sigma(\phi_{S_A} + \pi, \phi_{\pi}^H) \right]} ,
\]

where \(W(\phi_{S_A}, \phi_{\pi}^H)\) is again some appropriate circular function of \(\phi_{S_A}\) and \(\phi_{\pi}^H\).

3. Phenomenology

In this section we present and discuss some phenomenological implications of our approach for the unpolarized and single-transverse polarized cases in kinematical configurations accessible at RHIC by the STAR and PHENIX experiments. We consider both central \((\eta_j = 0)\) and forward \((\eta_j = 3.3)\) (pseudo)rapidity configurations at a c.m. energy \(\sqrt{s} = 200\) GeV (different c.m. energies, namely \(\sqrt{s} = 62.4\) and 500 GeV, are also studied in [8]), aiming at a check of the potentiality of the approach in disentangling among different quark and gluon originating effects.

We will first consider, for \(\pi^+\) production only, a scenario in which the effects of all TMD functions are over-maximized. By this we mean that all TMD functions are maximized in size by imposing natural positivity bounds (and the Soer bound for transversity [11, 12]); moreover, the relative signs of all active partonic contributions are chosen so that they sum up additively. In this way we set an upper bound on the absolute value of any of the effects playing a potential role in the azimuthal asymmetries. Therefore, all effects that are negligible or even marginal in this scenario may be directly discarded in subsequent refined phenomenological analyses.

As a second step in our study we consider, for both neutral and charged pions, only the surviving effects, involving TMD functions for which parameterizations are available from independent fits to other spin and azimuthal asymmetries data in SIDIS, Drell-Yan, and \(e^+e^-\) processes.
For numerical calculations all TMD distribution and fragmentation functions will be taken in the simplified form where the functional dependences on the parton light-cone momentum fraction and on transverse motion are completely factorized, assuming a Gaussian-like flavour-independent shape for the transverse momentum component. Concerning the parameterizations of the transversity and quark Sivers distributions, and of the Collins functions, we will consider two sets: SIDIS 1 [13, 14] and SIDIS 2 [15, 16]. Notice that the almost unknown gluon Sivers function was tentatively taken positive and saturated to an updated version of the bound obtained in Ref. [17] by considering PHENIX data for the $\pi^0$ transverse SSA at mid-rapidity production in polarized $pp$ collisions at RHIC [18]. Furthermore, for the usual collinear distributions, we adopt the LO unpolarized set GRV98 [19] and (for the Soer bound) the corresponding longitudinally polarized set GRSV2000 [20]. For fragmentation functions, we will adopt two well-known LO sets among those available in the literature, the set by Kretzer [21] and the DSS one [22]. Our choice is dictated by the subsequent use of the two available parametrization sets for the Sivers and Collins functions in our scheme, that have been extracted in the past years by adopting these sets of FFs.

Since the range of the jet transverse momentum (the hard scale) covered is significant, we take into account proper evolution with scale. Concerning transversity, in the maximized scenario we will fix it at the initial scale by saturating the Soer bound and then letting it evolve. On the other hand, the transverse momentum component of all TMD functions is kept fixed with no evolution with scale. Notice that at this stage evolution properties of the full TMD functions are not known.

In all cases considered, since we are interested in azimuthal asymmetries for leading particles inside the jet, we will present results obtained integrating the light-cone momentum fraction of the observed hadron, $z$, in the range $z \geq 0.3$.

3.1. Azimuthal asymmetries in $pp \rightarrow jet + \pi + X$

The symmetric part $d\sigma_0$ in Eq. (2) gets contributions by the usual unpolarized term, already present in the collinear approach, and by an additional term involving a Boer-Mulders $\otimes$ Boer-Mulders convolution for the initial quarks (or the analogous terms involving linearly polarized gluons); however even in the maximized scenario this last contribution is always negligible in all the kinematical configurations considered, hence we will not discuss it anymore in the sequel.

In Fig. 1 we show the maximized $\langle \cos \phi_H^q \rangle$ and $\langle 2\cos \phi_H^g \rangle$ asymmetries for $\pi^+$ production in the central (left panel) and forward (right panel) rapidity regions as a function of $p_{jT}$, from $p_{jT} = 2$ GeV up to the maximum allowed value, adopting the Kretzer FF set. Similar results are obtained using the DSS set. The $\cos \phi_H^q$ asymmetry is generated by the quark Boer-Mulders $\otimes$ Collins convolution term, involving a transversely polarized quark and an unpolarized hadron both in the initial state and in the fragmentation process. The $\cos 2\phi_H^g$ asymmetry is related to the term involving linearly polarized gluons and unpolarized hadrons both in the initial state and in the fragmentation process, that is the convolution of a Boer-Mulders-like gluon distribution with a Collins-like gluon FF. Even the maximized contribution is practically negligible in the kinematical configurations considered.

3.2. The Sivers asymmetry $A_{N}^{\sin \phi_{SA}}$ in $p^+ p \rightarrow jet + \pi + X$

In Fig. 2 we show the total observable Sivers asymmetry, and the corresponding quark and gluon contributions for $\pi^+$ production, in the maximized scenario and adopting the Kretzer FF set, as a function of $p_{jT}$ in the central (left panel) and forward (right panel) rapidity regions. The maximized potential Sivers asymmetry can be very large in both cases. In the central rapidity region, the asymmetry is dominated by the gluon contribution at the lowest $p_{jT}$ range while gets comparable quark and gluon contributions in the large $p_{jT}$ range. A large Sivers asymmetry around $p_{jT} = 4 \div 6$ GeV could then be a clear indication for a sizable gluon contribution. In
Figure 1. Maximized quark-originated ($\cos \phi_H^q$) and gluon-originated ($\cos 2\phi_H^g$) asymmetries for the unpolarized $pp \to \text{jet} + \pi^+ + X$ process at $\sqrt{s} = 200$ GeV in two different rapidity regions, adopting the Kretzer FF set.

The forward rapidity region, on the contrary, the quark and gluon contributions are comparable at low $p_T$ values, while the maximized asymmetry is dominated by the quark contribution for $p_T \geq 4$ GeV. Therefore, a large Sivers asymmetry in this kinematical range could be ascribed unambiguously to the quark Sivers effect.

In Fig. 3 we show, for both neutral and charged pions, the quark and gluon contributions to the Sivers asymmetry, obtained adopting the parametrization sets SIDIS 1 and SIDIS 2, and the updated version of the bound on the gluon Sivers asymmetry derived in Ref. [17], in the forward rapidity region, as a function of $p_T$. The dotted black vertical line delimits the region $x_F \approx 0.3$, with $x_F = 2p_T L/\sqrt{s}$, beyond which the SIDIS parameterizations for the quark Sivers distribution

Figure 2. Maximized total, quark-originated and gluon-originated Sivers asymmetries for the $p^+p \to \text{jet} + \pi^+ + X$ process, at $\sqrt{s} = 200$ GeV in two different rapidity regions, adopting the Kretzer FF set.
are extrapolated outside the $x$ region covered by SIDIS data and are therefore plagued by large uncertainties. This reflects on the fact that below this limit the two sets give comparable results, while above it they differ remarkably. Therefore, a measurement of this asymmetry might help in clarifying the behaviour of the quark Sivers distribution in the large $x$ region, which plays a fundamental role for forward pion production at RHIC, and is not covered by present SIDIS data from HERMES and COMPASS experiments.

3.3. The Collins-like $A_N^{\sin(\phi_{SA}+\phi_H^q)}$ asymmetries in $p^1p \rightarrow \text{jet} + \pi + X$

The quark generated asymmetry $A_N^{\sin(\phi_{SA}+\phi_H^q)}$ comes from two distinct contributions: one involving the convolution between the term of the TMD transversity distribution suppressed in the collinear configuration and the Collins function; another term involving the convolution of the Sivers and Boer-Mulders distributions for the initial quarks with the Collins function for the final quark [an analogous term appears also in the $A_N^{\sin(\phi_{SA}-\phi_H^q)}$ asymmetry]. We have explicitly checked that for the kinematical configurations under study both these contributions are always negligible already in the maximized scenario. Therefore we will not consider the $\sin(\phi_{SA}+\phi_H^q)$ asymmetry in the sequel. A similar situation holds also for the gluon generated $A_N^{\sin(\phi_{SA}+2\phi_H^g)}$ asymmetry, where two contributions analogous to the quark ones discussed above but for linearly polarized gluons are involved.

In Fig. 4 we present the quark $A_N^{\sin(\phi_{SA}-\phi_H^q)}$ Collins asymmetry and the gluon $A_N^{\sin(\phi_{SA}-2\phi_H^g)}$ Collins-like asymmetry in the maximized scenario in the central (left panel) and forward (right panel) rapidity region as a function of $p_T$, from $p_T = 2$ GeV up to the maximum allowed value, adopting the Kretzer FF set. In the central rapidity region the quark Collins asymmetry is very small at the lowest $p_T$ values, then increases almost linearly reaching about 8% at the upper range. Instead, in the forward rapidity region the asymmetry is (potentially) always large and increases almost linearly from about 25% to about 70% going from the lowest to the largest $p_T$ values. Concerning the gluon Collins-like asymmetry, both in the central and in the forward rapidity regions it is of the order of 5% at the lowest $p_T$ values, then starts decreasing slowly and becomes negligible at large $p_T$ values. Similar results hold when adopting the DSS set.

We consider now, for both neutral and charged pions, numerical results for the quark Collins
asymmetry obtained adopting the parameterizations SIDIS 1 and SIDIS 2 for the transversity distribution and the Collins fragmentation function (no parameterizations are available yet in the analogous gluon case). It turns out that in the central rapidity region all the estimated asymmetries are practically negligible. Concerning the forward rapidity region, our results are shown in Fig. 5. The Collins asymmetry for neutral pions results to be almost vanishing. For charged pions, similarly to the case of the Sivers asymmetry, the two parameterizations give comparable results only in the $p_T$ region where the transversity distribution is reasonably constrained by SIDIS data (see the dotted black vertical line). A measurement of this asymmetry would be then very important and helpful in clarifying the large $x$ behaviour of the quark transversity distribution.

Figure 4. Maximized quark and gluon Collins(-like) asymmetries for the $p^+ p \rightarrow \mathrm{jet} + \pi^+ + X$ process, at $\sqrt{s} = 200$ GeV in two different rapidity regions adopting the Kretzer FF set.

Figure 5. The estimated quark Collins asymmetry for the $p^+ p \rightarrow \mathrm{jet} + \pi + X$ process, obtained adopting the parameterizations SIDIS 1 and SIDIS 2 respectively, at $\sqrt{s} = 200$ GeV in the forward rapidity region. The dotted black vertical line delimits the region $x_F \approx 0.3$. 
4. Conclusions
We have presented a study of the azimuthal asymmetries measurable in the distribution of leading pions inside a large-\(p_T\) jet produced in unpolarized and single-transverse polarized proton proton collisions for kinematical configurations accessible at RHIC. To this end, we have adopted a generalized TMD parton model approach with inclusion of spin and intrinsic parton motion effects both in the distribution and in the fragmentation sectors.

In contrast to inclusive pion production, where the Sivers and Collins mechanisms cannot be separated [8], and in close analogy with the SIDIS case, the leading-twist azimuthal asymmetries discussed above allow one to discriminate among different effects by taking suitable moments of the asymmetries. In principle, quark and gluon originating jets can also be distinguished, at least in some kinematical regimes. Hence, the proposed phenomenological analysis could be very helpful, for example, in clarifying the role played by the quark(gluon) Sivers distribution and by the Collins(-like) fragmentation function in the sizable single spin asymmetries observed at RHIC for forward pion production. At the same time it will give us the opportunity of testing the factorization and universality assumptions, and of gaining information on the size and sign of the TMD functions discussed, in a kinematic region not covered by SIDIS data.

We finally stress that the unambiguous measurement of any of the asymmetries, other than the Collins one, discussed above would be a clear indication of the role played by intrinsic parton motion in the initial hadrons for the spin asymmetry sector in polarized hadronic collisions.

Acknowledgments
C.P. is supported by Regione Autonoma della Sardegna (RAS) through a research grant under the PO Sardegna FSE 2007-2013, L.R. 7/2007, “Promozione della ricerca scientifica e dell’innovazione tecnologica in Sardegna”. U.D. and F.M. acknowledge partial support by Italian Ministero dell’Istruzione, dell’Università e della Ricerca Scientifica (MIUR) under Cofinanziamento PRIN 2008, and by the European Community under the FP7 “Integrating Activities” project “Study of Strongly Interacting Matter” (HadronPhysics2), grant agreement No. 227431.

References
[1] D’Alesio U and Murgia F 2008 Prog. Part. Nucl. Phys. 61 394
[2] Barone V, Bradamante F and Martin A 2010 Prog. Part. Nucl. Phys. 65 267
[3] Sivers D W 1990 Phys. Rev. D 41 83
[4] Sivers D W 1991 Phys. Rev. D 43 261
[5] Boer D and Mulders P J 1998 Phys. Rev. D 57 5780
[6] Collins J C 1993 Nucl. Phys. B 396 161
[7] Anselmino M et al. 2006 Phys. Rev. D 73 014020
[8] D’Alesio U, Murgia F and Pisano C 2010 Preprint arXiv:1011.2692
[9] D’Alesio U 2007, Talk delivered at the ECT* Workshop “Transverse momentum, spin, and position distributions of partons in hadrons”, June 11-15, Trento, Italy
[10] Yuan F 2008 Phys. Rev. Lett. 100 032003
[11] Soffer J 1995 Phys. Rev. Lett. 74 1292
[12] Bacchetta A, Boglione M , Henneman A and Mulders P J 2000 Phys. Rev. Lett. 85 712
[13] Anselmino M et al. 2005 Phys. Rev. D 72 094007
[14] Anselmino M et al. 2007 Phys. Rev. D 75, 054032
[15] Anselmino M et al. 2009 Eur. Phys. J. A 39 89
[16] Anselmino M et al. 2009 Nucl. Phys. Proc. Suppl. 191 98
[17] Anselmino M, D’Alesio U, Melis S and Murgia F 2006 Phys. Rev. D 74 094011
[18] Adler S S et al. (PHENIX Collaboration) 2005 Phys. Rev. Lett. 95, 202001
[19] Glück M, Rey A and Vogt A 1998 Eur. Phys. J. C 5 461
[20] Glück M, Rey A, Stratmann M and Vogelsang W 2001 Phys. Rev. D 63 094005
[21] Kretzer S 2000 Phys. Rev. D 62, 054001
[22] de Florian D, Sassot R and Stratmann M 2007 Phys. Rev. D 75, 114010