CMS status and spin physics at the LHC

Pietro Faccioli, for the CMS Collaboration
Laboratório de Instrumentação e Física Experimental de Partículas (LIP), Lisbon, Portugal

Abstract. We report on the status of the CMS experiment and on plans for spin physics measurements at the LHC. We focus on the short-term prospect of quarkonium polarization studies, which promise to solve longstanding puzzles on non-perturbative aspects of QCD.

1. CMS status
The heart of the Compact Muon Solenoid (CMS) detector is a large silicon tracker, consisting of 3 layers of pixel and 10 layers of microstrip detectors, immersed inside a 3.8 T axial magnetic field, and extending over 5 units in rapidity, $-2.5 < \eta < +2.5$. The high granularity of the tracker and the strong magnetic field ensure an excellent momentum resolution ($\sim 1\%$ for tracks with $p_T \lesssim 50\text{ GeV}/c$ and emitted at mid-rapidity) and good vertexing capabilities, which enable the identification of long lived particles. Identification of electrons and hadrons is provided through a high-granularity crystal electromagnetic and a brass/scintillator hadron calorimeter. Muons are identified through tracking in gas detectors embedded in the steel return yoke of the solenoid. A detailed description of CMS can be found in Ref. [1].

The CMS experiment has collected data at three different collision energies, $\sqrt{s} = 0.9$ and 2.36 TeV during December 2009, and 7 TeV in 2010. During this period the LHC instantaneous luminosity increased by around five orders of magnitude, reaching $2 \cdot 10^{32}\text{ cm}^{-2}\text{s}^{-1}$ at the end of the 2010 proton run, when an integrated luminosity of $\mathcal{L} \sim 40 \text{ pb}^{-1}$ was collected. Thanks to the flexibility and computing power of its High Level Trigger, CMS managed to write to permanent storage all the events with opposite-sign muon pairs with dimuon mass above $1.5\text{ GeV}/c^2$, without applying any cuts on the muons’ transverse momentum. Figure 1 (left) shows the full dimuon mass distribution of these events, extending up to the $Z$ peak. The dimuon mass

![Image of dimuon mass distributions at $\sqrt{s} = 7\text{ TeV}$]
distribution in the Z-boson region is shown in Fig. 1 (right). CMS has measured the inclusive production cross section of the W and Z bosons at 7 TeV, using the leptonic decay channels $W^\pm \to e^\pm \nu_e$, $W^\pm \to \mu^\pm \nu_\mu$, $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$. As shown in Fig. 2 (left), the three $\Upsilon$ states can be clearly resolved, especially at mid-rapidity, where the dimuon mass resolution is about 70 MeV. The mid-rapidity dimuon mass resolution in the $J/\psi$ region is around 20 MeV, as shown in Fig. 2 (right). CMS measured the $J/\psi$ production cross section in $pp$ collisions at 7 TeV, as a function of $p_T$, in three rapidity ranges [2], for inclusive, prompt and non-prompt $J/\psi$ mesons, separated through a fit to the decay length distribution. The results are illustrated in Fig. 3, for the prompt cross section in the rapidity range $1.6 < |y| < 2.4$ (left) and for the fraction of $J/\psi$ mesons due to b-hadron decays (right), which increases very fast with $p_T$, with a trend very similar to what had been previously observed by CDF, at lower energies.

2. Spin physics at the LHC

The LHC experiments have a unique potential for measuring the decay angular distributions of known or newly discovered particles to determine their angular momentum and discrete symmetry properties. Polarization analyses at the LHC will allow us to:

- understand still unexplained production mechanisms ($J/\psi$, $\chi_c$, $\psi'$, $\Upsilon$, $\chi_b$);
- precisely test QCD calculations ($Z/W$ decay distributions, $t\bar{t}$ spin correlations, ...);
- constrain Standard Model couplings (sin$\theta_W$ from $Z + \gamma^*$ decays);
- constrain universal quantities (proton parton distribution functions from $Z/W$ decays);
- measure parity violation (forward-backward and charge asymmetries in $Z + \gamma^*$ and $W$ decays) and charge-parity violation ($B_s \to J/\psi \phi$);
- search for anomalous couplings with new particles ($H \to WWZZ/t\bar{t}$, $t \to H + b$, ...);
- identify or characterize newly discovered resonances ($X(3872)$, Higgs, $Z'$, graviton, ...).
We concentrate here our attention on quarkonium polarization, an intriguing physical question for which the data samples collected in 2010 may already provide significant answers.

3. Quarkonium polarization
Our present understanding of quarkonium production is far from satisfactory, despite the considerable experimental efforts and the multitude of data accumulated over more than 30 years [4]. The transverse-momentum dependence of the quarkonium production cross sections measured by CDF in the mid 1990’s [5] are today approximately described both in the context of fully perturbative calculations (Colour Singlet Model, CSM) [6] and in the context of calculations deriving from the data themselves the contribution of non-perturbative processes in the transition from the initially produced coloured quark pair to the observable bound state (non-relativistic QCD, NRQCD) [7]. Despite subtending completely different elementary production mechanisms, the two theoretical approaches do not differ substantially in the cross section predictions. Given this situation, differential cross sections are insufficient information to ensure further progress. On the other hand, the distinct qualities and topologies of the quarkonium production processes are closely reflected in the shapes of the decay angular distributions and lead to very different expected polarizations of the quarkonia produced at high \( p_T \): transverse polarization in NRQCD [8, 9, 10] and longitudinal in the CSM [6], with respect to the momentum direction of the quarkonium state. Polarization measurements have, therefore, the decisive role in our fundamental understanding of quarkonium production. However, the present experimental knowledge is incomplete and contradictory. The pattern measured by CDF [11] of a slightly longitudinal polarization for inclusive prompt J/\( \psi \) is incompatible with any of the two theory approaches mentioned above, as well as with a previous measurement by the same experiment [12]. The situation is further complicated by the intriguing lack of continuity between fixed-target and collider results, which can only be interpreted in the framework of some specific (and speculative) assumptions [13]. The \( \Upsilon \) data from the Tevatron indicate that the \( \Upsilon(1S) \) is produced either unpolarized (CDF [14]) or longitudinally polarized (D0 [15]) in the helicity frame, and this discrepancy cannot be reasonably attributed to the different rapidity windows covered by the two experiments. At lower energy and \( p_T \), E866 [16] has shown yet a different polarization pattern: the \( \Upsilon(2S) \) and \( \Upsilon(3S) \) states have maximal transverse polarization, with no significant dependence on transverse or longitudinal momentum, with respect to the direction of motion of the colliding hadrons (Collins–Soper frame). Surprisingly, the \( \Upsilon(1S) \), whose spin and angular momentum properties are identical to those of the heavier Upsilon states, is, instead, only weakly polarized. This rather confusing situation demands a significant improvement in the accuracy and detail of the polarization measurements. Ideally, the measurements should also distinguish between the properties of directly and indirectly produced states, given that, for example, about one third of the promptly produced J/\( \psi \) mesons come from \( \psi' \) and \( \chi_c \) decays [17]. It is true that measurements of the quarkonium decay angular distributions are challenging, multi-dimensional kinematic problems, which require large event samples and a very high level of accuracy in the subtraction of spurious kinematic correlations induced by the detector acceptance. The complexity of the experimental problems that have to be faced in the polarization measurements is testified, for example, by the mentioned disagreements between the Tevatron results on J/\( \psi \) and \( \Upsilon \) polarizations. However, as we have discussed and exemplified in Ref. [13], it is also true that most experiments have exploited, and presented in the published reports, only a fraction of the physical information derivable from the data. These incomplete measurements do not allow definite physical conclusions. This happens, for example, when the measurement is performed in only one polarization frame and is limited to the polar projection of the decay angular distribution, imposing genuinely model-dependent interpretations. Moreover, such a fragmentary description of the observed physical process obviously reduces the chances of detecting possible biases induced by not fully controlled systematic effects.
3.1. Basic concepts
Because of angular momentum conservation and basic symmetries of electromagnetic and strong interactions, a particle produced in a certain superposition of elementary mechanisms may be observed preferentially in a state belonging to a definite subset of the possible eigenstates of the angular momentum component $J_z$ along a characteristic quantization axis. When this happens, the particle is said to be polarized. In the dilepton decay of quarkonium, the geometrical shape of the decay angular distribution reflects the average polarization of the quarkonium state. A spherically symmetric distribution means that the quarkonium is, on average, unpolarized. Anisotropic distributions signal polarized production.

The measurement of the distribution requires the choice of a coordinate system, with respect to which the momentum of one of the two decay products is expressed in spherical coordinates. In inclusive quarkonium measurements, the axes of the coordinate system are fixed with respect to the physical reference provided by the directions of the two colliding beams as seen from the quarkonium rest frame. The polar angle $\vartheta$ is determined by the definition of the decay frame with respect to the beam directions is not unique. Measurements of the quarkonium decay distributions have used three different conventions for the orientation of the polar axis: the direction of the momentum of one of the two colliding beams (Gottfried–Jackson frame [18], GJ), the opposite of the direction of motion of the interaction point (i.e. the flight direction of the quarkonium itself in the center-of-mass of the colliding beams: helicity frame, HX) and the bisector of the angle between one beam and the opposite of the other beam (Collins–Soper frame [19], CS). The motivation of this latter definition is that, in hadronic collisions, it coincides with the direction of the relative motion of the colliding partons, when their transverse momenta are neglected. For our considerations, we will take the HX and CS frames as two extreme (physically relevant) cases. In fact, the two frames differ by a rotation of $90^\circ$ around the $y$ axis when the quarkonium is produced with $p_T \gg |p_L|$. The decay angular distribution for inclusively observed quarkonium states can be written as [20]

$$W(\cos \vartheta, \varphi) \propto \frac{1}{(3 + \lambda_\vartheta)} \left( 1 + \lambda_\vartheta \cos^2 \vartheta + \lambda_{\varphi \varphi} \sin^2 \vartheta \cos 2\varphi + \lambda_{\varphi \varphi} \sin 2\vartheta \cos \varphi \right).$$

3.2. The importance of the frame choice
The coefficients $\lambda_\vartheta$, $\lambda_\varphi$, and $\lambda_{\varphi \varphi}$ in Eq. 1 depend on the polarization frame. To illustrate the importance of the choice of the polarization frame, we consider specific examples assuming, for simplicity, that the observation axis is perpendicular to the natural axis ($\delta = \pm 90^\circ$). This case is of physical relevance since when the decaying particle is produced with small longitudinal momentum ($|p_L| \ll p_T$, a frequent kinematic configuration in collider experiments) the CS and HX frames are actually perpendicular to one another. When $\delta = 90^\circ$, a natural “transverse” polarization ($\lambda_\vartheta = +1$ and $\lambda_\varphi = \lambda_{\varphi \varphi} = 0$), for example, transforms into an observed polarization of opposite sign (but not fully “longitudinal”), $\lambda'_\vartheta = -1/3$, with a significant azimuthal anisotropy, $\lambda'_{\varphi \varphi} = 1/3$. In terms of angular momentum wave functions, a state which is fully “transverse” with respect to one quantization axis ($|J, J_z\rangle = |1, \pm 1\rangle$) is a coherent superposition of 50% “transverse” and 50% “longitudinal” components with respect to an axis rotated by $90^\circ$:

$$|1, \pm 1\rangle \quad \xrightarrow{90^\circ} \quad \frac{1}{\sqrt{2}} |1, +1\rangle + \frac{1}{\sqrt{2}} |1, -1\rangle \mp \frac{1}{\sqrt{2}} |1, 0\rangle.$$  

The decay distribution of such a “mixed” state is azimuthally anisotropic. The same polar anisotropy $\lambda'_\vartheta = -1/3$ would be measured in the presence of a mixture of at least two different processes resulting in 50% “transverse” ($|J, J_z\rangle = |1, \pm 1\rangle$) and 50% “longitudinal”
natural polarizations along the chosen axis. In this case, however, no azimuthal anisotropy would be observed. As a second example, we note that a fully “longitudinal” natural polarization \( \lambda_\varphi = -1 \) translates, in a frame rotated by 90° with respect to the natural one, into a fully “transverse” polarization \( \lambda'_\varphi = +1 \), accompanied by a maximal azimuthal anisotropy \( \lambda'_\varphi = -1 \). In terms of angular momentum, the measurement in the rotated frame is performed on a coherent admixture of states,

\[
|1,0\rangle \xrightarrow{90^\circ} \frac{1}{\sqrt{2}} |1,+1\rangle - \frac{1}{\sqrt{2}} |1,-1\rangle,
\]

while a natural “transverse” polarization would originate from the statistical superposition of uncorrelated \( |1,+1\rangle \) and \( |1,-1\rangle \) states. The two physically very different cases of a natural transverse polarization observed in the natural frame and a natural longitudinal polarization observed in a rotated frame are experimentally indistinguishable when the azimuthal anisotropy parameter is integrated out. These examples show that a measurement (or theoretical calculation) consisting only in the determination of the polar parameter \( \lambda_\varphi \) in one frame contains an ambiguity which prevents fundamental (model-independent) interpretations of the results. The polarization is only fully determined when both the polar and the azimuthal components of the decay distribution are known, or when the distribution is analyzed in at least two geometrically complementary frames.

Due to their frame-dependence, the parameters \( \lambda_\varphi \), \( \lambda_\varphi \) and \( \lambda_\varphi \) can be affected by a strong explicit kinematic dependence, reflecting the change in direction of the chosen experimental axis (with respect to the “natural axis”) as a function of the quarkonium momentum. As an example, we show in Fig. 4 how a natural transverse \( J/\psi \) polarization \( \lambda_\varphi = +1 \) in the CS frame (with \( \lambda_\varphi = \lambda_\varphi = 0 \) and no intrinsic kinematic dependence) translates into different \( p_T \)-dependent polarizations measured in the HX frame in different rapidity acceptance windows, representative of the acceptance ranges of several Tevatron and LHC experiments. This example

**Figure 4.** Kinematic dependence of the \( J/\psi \) polarization seen in the HX frame, for a natural polarization \( \lambda_\varphi = +1 \) in the CS frame. The curves correspond to different rapidity intervals; from the solid line: \(|y| < 0.6\) (CDF), \(|y| < 0.9\) (ALICE), \(|y| < 1.8\) (D0), \(|y| < 2.5\) (ATLAS and CMS), \(2 < y < 5\) (LHCb). For simplicity the event populations were generated flat in rapidity.

shows that an “unlucky” choice of the observation frame may lead to a misleading experimental result. Moreover, the strong kinematic dependence induced by such a choice may mimic and/or mask the fundamental (“intrinsic”) dependencies reflecting the production mechanisms.

However, not always an “optimal” quantization axis exists. This is shown in Fig. 5, where we consider, for illustration, that 60% of the \( J/\psi \) events have natural polarization \( \lambda_\varphi = +1 \) in the CS frame while the remaining fraction has \( \lambda_\varphi = +1 \) in the HX frame. Although the polarizations of the two event subsamples are intrinsically kinematics-independent, in neither frame will measurements performed in different transverse and longitudinal momenta windows find “simple”, identical results. Corresponding figures for the \( \Upsilon(1S) \) case can be seen in Ref. [21].

### 3.3. A frame-invariant approach

The following combination of coefficients is independent on the polarization frame:

\[
\tilde{\lambda} = \frac{\lambda_\varphi + 3 \lambda_\varphi}{1 - \lambda_\varphi}.
\]
An account of the fundamental meaning of the frame-invariance of this quantity can be found in Ref. [22]. In the special case when the observed distribution is the superposition of $n$ “elementary” distributions of the kind $1 + \lambda_\varphi^{(i)} \cos^2 \vartheta$, with event weights $f^{(i)}$, with respect to $n$ different polarization axes, $\tilde{\lambda}$ represents a weighted average of the $n$ polarizations, insensitive to the orientations of the corresponding axes:

$$\tilde{\lambda} = \frac{\sum_{i=1}^{n} f^{(i)} \lambda_\varphi^{(i)}}{3 + \sum_{i=1}^{n} f^{(i)} \lambda_\varphi^{(i)}}.$$  

(5)

The determination of an invariant quantity is immune to “extrinsic” kinematic dependencies induced by the observation perspective and is, therefore, less acceptance-dependent than the standard anisotropy parameters $\lambda_\varphi$, $\lambda_\phi$, and $\lambda_{\varphi\phi}$. Referring to the example shown in Fig. 5, any arbitrary choice of the experimental observation frame will always yield the value $\tilde{\lambda} = +1$, independently of kinematics. This particular case, where all contributing processes are transversely polarized, is formally equivalent to the Lam-Tung relation [23], as discussed in Ref. [22]. The existence of frame-invariant parameters also provides a useful instrument for experimental analyses. Checking, for example, that the same value of an invariant quantity is obtained, within systematic uncertainties, in two distinct polarization frames is a non-trivial verification of the absence of unaccounted systematic effects. In fact, detector geometry and/or data selection constraints may strongly polarize the reconstructed dilepton events. Background processes also affect the measured polarization, if not well subtracted. The spurious anisotropies induced by detector effects and background do not obey the frame transformation rules characteristic of a physical $J = 1$ state. If not well corrected and subtracted, these effects will distort the shape of the measured decay distribution differently in different polarization frames. In particular, they will violate the frame-independent relations between the angular parameters. Any two physical polarization axes (defined in the rest frame of the meson and belonging to the production plane) may be chosen to perform these “sanity tests”. The HX and CS frames are ideal choices at high $p_T$ and mid rapidity, where they tend to be orthogonal to each other. At forward rapidity and low $p_T$, we can maximize the significance of the test by using the CS axis and the perpendicular helicity axis [24], which coincides with the helicity axis at zero rapidity and remains orthogonal to the CS axis at nonzero rapidity. Being $\tilde{\lambda}$ “homogeneous” to the anisotropy parameters, the difference $\tilde{\lambda}^{(B)} - \tilde{\lambda}^{(A)}$ between the results obtained in two frames provides a direct evaluation of the level of systematic errors not accounted in the analysis.

3.4. A few concrete examples

We present here further examples to illustrate concepts described in the previous sections.

It is natural to wonder how the $J/\psi$ polarization pattern measured by CDF in the HX frame would look like in the CS frame. Unfortunately, the measurement itself, a slight longitudinal
polarization, does not suggest any educated guess on what we could assume for the unmeasured azimuthal anisotropy. For example, as shown in Fig. 6 (left), if the distribution in the HX frame were azimuthally isotropic, the measured polarization would correspond to a practically undetectable polarization in the CS frame (dashed line). However, if we take into account all physically possible values of the azimuthal anisotropy, we can only derive a broad spectrum of possible CS polarizations, approximately included between $-0.5$ and $+1$ (shaded band). This example shows how a measurement reporting only the polar anisotropy is amenable to several interpretations in fundamental terms, often corresponding to drastically different physical cases. One possible hypothesis would be that all processes are naturally polarized in the HX frame and that transverse and longitudinal polarizations are superimposed in proportions varying from approximately $2/3$ transverse and $1/3$ longitudinal at $p_T = 5$ GeV/c ($\lambda_\theta \simeq 0$) to around $60\% / 40\%$ at $p_T = 20$ GeV/c ($\lambda_\theta \simeq -0.2$). In this case, no azimuthal anisotropy should be observed in the HX frame. Alternatively, we can consider a scenario where the observed slightly longitudinal HX polarization is actually the result of a mixture of two processes, both producing $J/\psi$ mesons with fully transverse polarizations, but one in the HX frame and the other in the CS frame. Figure 6 (middle) shows that this scenario is perfectly compatible with the CDF $\lambda_\theta$ measurement if the proportion $f_{HX}/(f_{HX}+f_{CS})$ between the two sub-processes is assumed to vary linearly between $30\%$ at $p_T = 5$ GeV/c and $15\%$ at $p_T = 20$ GeV/c. The difference with respect to the previous hypothesis is that now we would measure a significant azimuthal anisotropy, $\lambda_\phi \simeq 0.3$, as shown in Fig. 6 (right). As an attempt to reconcile low-$p_T$ measurements with collider data, Ref. [13] described one further conjecture, in which the polarization arises naturally in the CS frame, and becomes increasingly transverse with increasing total $J/\psi$ momentum. Again, a direct measurement of $\lambda_\phi$ (which, in this case, should be zero in the CS frame but positive and increasing with $p_T$ in the HX frame) would easily clarify the situation.

We finally illustrate the use of frame-invariant observables to estimate residual systematic uncertainties in experimental data analyses. Figure 7 shows a putative set of $J/\psi$ polarization measurements performed in the CS and HX frames. While the $\lambda_\theta$ values seem to change significantly from one frame to the other, the two $\lambda_\phi$ patterns are very similar. This observation should alert to a possible experimental artifact in the data analysis. We can evaluate the significance of the apparent contradiction by calculating the frame-invariant $\tilde{\lambda}$ variable in each of the two frames. For the case illustrated in Fig. 7, averaging the four represented $p_T$ bins, we see that $\tilde{\lambda}$ in the HX frame is larger than in the CS frame by 0.5 (a rather large value, considering that the decay parameters are bound between $-1$ and $+1$). In other words, an experiment

Figure 6. Interpretations of the CDF $J/\psi$ polarization measurement. Left: the measurement in the helicity frame (data points) and the range for the corresponding polarization in the CS, allowing for all possible values of the azimuthal anisotropy (shaded band). The dashed line is the CS polarization for $\lambda_{HX} = 0$. Center and right: $\lambda_\theta$ and $\lambda_\phi$ in the HX frame, according to a scenario where the $J/\psi$ has always full transverse polarization, either in the CS frame or in the HX frame, with a suitable $p_T$-dependent proportion between the two event samples.
obtaining such measurements would learn from this simple exercise that its determination of the decay parameters must be biased by systematic uncertainties of roughly this magnitude. Given the puzzles and contradictions existing in the published experimental results, the use of a frame-invariant approach to perform self-consistency checks, which can expose unaccounted systematic effects due to detector limitations and analysis biases, constitutes a non-trivial complementary aspect of the methodologies for quarkonium polarization measurements.

4. Summary

The LHC and the CMS experiment have been operating extremely well and the first data are of very high quality. Analyses of decay angular distributions are ongoing or planned by the LHC experiments to determine the symmetry properties of known or new particles, and will contribute on several fronts to our improved knowledge of fundamental interactions. Already in the 2010 run, in particular, measurements of quarkonium polarization in proton-proton collisions at the LHC have the potential to lead to a very important step forward in the understanding of quarkonium production, provided that the experiments adopt a robust analysis framework, taking into account the intrinsic multi-dimensionality of the problem.

References

[1] Chatrchyan S et al. (CMS Coll.) 2008 JINST 3 S08004
[2] Khachatryan V et al. (CMS Coll.) 2010 Preprint arXiv:1011.4193 and CERN-PH-EP-2010-046
[3] Acosta D et al. (CDF Coll.) 2005 Phys. Rev. D 71 032001
[4] Brambilla N et al. (QWG Coll.) 2005 Heavy Quarkonium Physics CERN Yellow Report 2005-005
[5] Abe F et al. (CDF Coll.) 1997 Phys. Rev. Lett. 79 572
[6] Lansberg J P 2009 Eur. Phys. J. C 61 693
[7] Bodwin G T, Braaten E and Lepage G P 1997 Phys. Rev. D 51 1125 and 1997 Phys. Rev. D 55 5853E
[8] Beneke M and Krämer M 1997 Phys. Rev. D 55 5269
[9] Leibovich A K 1997 Phys. Rev. D 56 4412
[10] Braaten E, Kniehl B A and Lee J 2000 Phys. Rev. D 62 094005
[11] Abulencia A et al. (CDF Coll.) 2007 Phys. Rev. Lett. 99 132001
[12] Affolder T et al. (CDF Coll.) 2000 Phys. Rev. Lett. 85 2886
[13] Faccioli P, Lourenço C, Seixas J and Wohri H K 2009 Phys. Rev. Lett. 102 151802
[14] Acosta D et al. (CDF Coll.) 2002 Phys. Rev. Lett. 88 161802
[15] Abazov V M et al. (D0 Coll.) 2008 Phys. Rev. Lett. 101 182004
[16] Brown C N et al. (E866 Coll.) 2001 Phys. Rev. Lett. 86 2529
[17] Faccioli P, Lourenço C, Seixas J and Wohri H K 2008 J. High Energy Phys. 10 004
[18] Gottfried K and Jackson J D 1964 Nuovo Cim. 33 309
[19] Collins J C and Soper D E 1977 Phys. Rev. D 16 2219
[20] Faccioli P, Lourenço C, Seixas J and Wohri H K 2010 Eur. Phys. J. C 69 657
[21] Faccioli P, Lourenço C and Seixas J 2010 Phys. Rev. D 81 111502(R)
[22] Faccioli P, Lourenço C and Seixas J 2010 Phys. Rev. Lett. 105 061601
[23] Lam C S and Tung W K 1978 Phys. Rev. D 18 2447
[24] Braaten E, Kang D, Lee J and Yu C 2009 Phys. Rev. D 79 014025