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RS-A_4 relaxation of flavor and CP violation

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Abstract I discuss a model based on an A_4 bulk flavor symmetry in the Randall-Sundrum (RS) setup. After discussing the setup and leading order results for the masses and mixings of quarks and leptons, I elaborate on the effect of higher order "cross-talk" corrections, their contributions to flavor violating processes and the resulting constraints on the model parameter space and the Kaluza-Klein (KK) mass scale. In addition, I present a systematic study of higher order corrections to the PMNS matrix in light of the recent measurements of $\theta_{13} > 0$ by RENO and Daya Bay. Finally, I also comment on the model new physics contributions to $B_{s,d} \to \mu^+\mu^-$ and $\mu \to e\gamma$, in light of the new upper bounds recently set by the LHCb and MEG experiment.

Keywords Warped extra dimensions · Discrete Flavor Symmetries · Flavor and CP violation · Neutrino masses and mixing

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1 Introduction

Recently we have proposed a model [1] based on a bulk A_4 flavor symmetry [2] in warped geometry [3], in an attempt to account for the hierarchical charged fermion masses, the hierarchical mixing pattern in the quark sector and the large mixing angles and the mild hierarchy of masses in the neutrino sector. In analogy with a previous RS realization of A_4 for the lepton sector [4], the three generations of left-handed quark doublets are unified into a triplet of A_4; this assignment forbids tree level FCNCs driven by the exchange of

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KK gauge bosons. The scalar sector of the RS-A_4 model consists of two bulk flavon fields, in addition to a bulk Higgs field. The bulk flavons transform as triplets of A_4, and allow for a complete "cross-talk" [5] between the $A_4 \to Z_2$ spontaneous symmetry breaking (SSB) pattern associated with the heavy neutrino sector - with scalar mediator peaked towards the UV brane - and the $A_4 \to Z_3$ SSB pattern associated with the quark and charged lepton sectors - with scalar mediator peaked towards the IR brane - and allows to obtain realistic masses and almost realistic mixing angles in the quark sector. A bulk custodial symmetry, broken differently at the two branes [6], guarantees the suppression of large contributions to electroweak precision observables [7], such as the Peskin-Takeuchi S, T parameters. However, the mixing between zero modes of the 5D theory and their Kaluza-Klein (KK) excitations – after 4D reduction – may still cause significant new physics (NP) contributions to SM suppressed flavor changing neutral current (FCNC) processes.
In general, when no additional flavor symmetries are present and the 5D Yukawa matrices are anarchical, FCNC processes are already generated at the tree level by a KK gauge boson exchange [8]. Stringent constraints on the KK scale come from the $K^0 - \overline{K^0}$ oscillation parameter ϵ_K, the radiative decays $b \to s(d)\gamma$ [8,9], the direct CP violation parameter ϵ'/ϵ_K [10], and especially the neutron electric dipole moment (EDM) [8], also in the presence of an RS-GIM suppression mechanism [11,12].
Conclusions may differ if a flavor pattern of the Yukawa couplings is assumed to hold in the 5D theory due to bulk flavor symmetries. They typically imply an increased alignment between the 4D fermion mass matrix and the Yukawa and gauge couplings, thus suppressing the amount of flavor violation induced by the interactions with KK states.
The most relevant consequence of imposing an A_4 flavor symmetry is the degeneracy of the left-handed fermion bulk profiles f_Q, i.e. $diag(f_{Q_1,Q_2,Q_3}) = f_Q \times \mathbb{1}$. In addition, the distribution of phases, CKM and Majorana-like, in the mixing matrices might induce zeros in the imaginary components of the Wilson coefficients contributing to CP violating quantities.
In the following we review the most relevant features of the RS-A_4 model [1] and its phenomenological consequences [13].

2 The RS-A_4 model

The RS-A_4 setup [1] is illustrated in Fig. 1. The bulk geometry is that of a slice of AdS_5 compactified on an orbifold S_1/Z_2 [3] and is described by the metric in Fig. 1. All 5D fields propagate in the bulk and assigned to the following representations of $(SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}) \times A_4$[1]:

$$\begin{aligned}
&e_R \oplus e'_R \oplus e''_R \sim (1,1,2,-1)\,(\underline{\mathbf{1}} \oplus \underline{\mathbf{1}}' \oplus \underline{\mathbf{1}}''), \qquad \ell_L \sim (1,2,1,-1)\,(\underline{\mathbf{3}}),\\
&u_R \oplus u'_R \oplus u''_R \sim \left(3,1,2,\tfrac{1}{3}\right)(\underline{\mathbf{1}} \oplus \underline{\mathbf{1}}' \oplus \underline{\mathbf{1}}''), \qquad \nu_R \sim (1,1,2,0)\,(\underline{\mathbf{3}}), \qquad (1)\\
&d_R \oplus d'_R \oplus d''_R \sim \left(3,1,2,\tfrac{1}{3}\right)(\underline{\mathbf{1}} \oplus \underline{\mathbf{1}}' \oplus \underline{\mathbf{1}}''), \qquad Q_L \sim \left(3,2,1,\tfrac{1}{3}\right)(\underline{\mathbf{3}}),
\end{aligned}$$

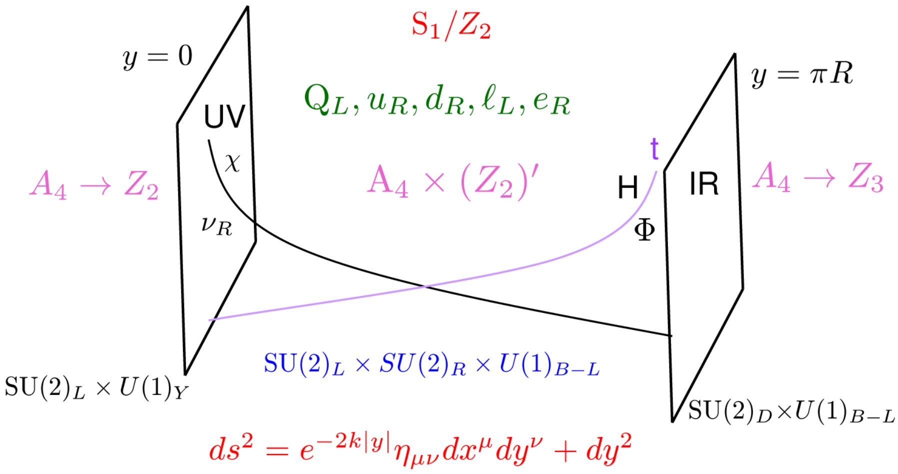

Fig. 1 A pictorial description of the RS-A$_4$ setup. The bulk geometry is described by the metric at the bottom and $k \simeq M_{Pl}$ is the AdS_5 curvature scale. All fields propagate in the bulk and the UV(IR) peaked nature of the heavy RH neutrinos, the Higgs field, the t quark and the A$_4$ flavons, Φ and χ, is emphasized. The SSB patterns of the bulk symmetries on the UV and IR branes are specified on the side (for A$_4$) and on the bottom (for $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$) of each brane.

The SM fermions (including RH neutrinos) are identified with the zero modes of the 5D fermions above. The zero (and KK) mode profiles are determined by the bulk mass of the corresponding 5D fermion, denoted by $c_{q_L,u_i,d_i,\ldots}k$ (and BC)[13]. The scalar sector contains the IR peaked Higgs field and the UV and IR peaked flavons, χ and Φ, respectively. They transform as:

$$\Phi \sim (1,1,1,0)\,(\underline{\mathbf{3}})\,, \quad \chi \sim (1,1,1,0)\,(\underline{\mathbf{3}})\,, \quad H\,(1,2,2,0)\,(\underline{\mathbf{1}})\,. \tag{2}$$

The SM Higgs field is identified with the first KK mode of H. All fermionic zero modes acquire masses through Yukawa interactions with the Higgs field and the A_4 flavons after SSB. The 5D $(SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}) \times A_4$ invariant Yukawa Lagrangian will consist of leading order(LO) UV/IR peaked interactions and next to leading order (NLO) "cross-talk" and "cross-brane" interactions[1]. The LO interactions in the neutrino sector are shown in [1], using the see-saw I mechanism, to induce a tribimaximal (TBM)[14] pattern for neutrino mixing while NLO "cross brane" and "cross talk" interactions, induce small deviations of $\mathcal{O}(0.04)$, which are still in good agreement with the current experimental bounds [15,16]. Here, we focus on the quark sector and on the phenomenology relevant for flavor and CP violating processes. The relevant terms of the 5D Yukawa lagrangian are of the following form:

$$\mathcal{L}_{5D}^{Yuk.} = \mathcal{L}_{LO} + \mathcal{L}_{NLO} = \frac{1}{k^2}\overline{Q}_L \Phi H(u_R^{(\prime,\prime\prime)}, d_R^{(\prime,\prime\prime)}) + \frac{1}{k^{3/2}}\overline{Q}_L \Phi\chi H(u_R^{(\prime,\prime\prime)}, d_R^{(\prime,\prime\prime)}) \tag{3}$$

Notice that the LO interactions are peaked towards the IR brane while the NLO interactions mediate between the two branes due to the presence of both Φ and χ.
The VEV and physical profiles for the bulk scalars are obtained by solving the corresponding equations of motion with a UV/IR localized quartic potential term and an IR/UV localized mass term [18]. In this way one can obtain either UV or IR peaked and also flat profiles depending on the bulk mass and the choice of boundary conditions. The resulting VEV profiles of the RS-A_4 scalar sector are:

$$v^{5D}_{H(\Phi)} = H_0(\phi_0)e^{(2+\beta_{H(\phi)})k(|y|-\pi R)} \qquad v^{5D}_{\chi} = \chi_0 e^{(2-\beta_\chi)k|y|}(1-e^{(2\beta_\chi)k(|y|-\pi R)}), \tag{4}$$

where $\beta_{H\Phi,\chi} = \sqrt{4+\mu^2_{H,\Phi,\chi}}$, and $\mu_{H,\Phi,\chi}$ is the bulk mass of the corresponding scalar in units of k, the cutoff of the 5D theory. The following vacua for the Higgs and the A_4 flavons Φ and χ

$$\langle\Phi\rangle = (v_\phi, v_\phi, v_\phi) \qquad \langle\chi\rangle = (0, v_\chi, 0) \qquad \langle H\rangle = v_H \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \tag{5}$$

provide at LO TBM neutrino mixing and zero quark mixing [2,5]. The stability of the above vacuum alignment is discussed in [1]. The VEV of Φ induces an $A_4 \to Z_3$ SSB pattern, which in turn induces no quark mixing and is peaked towards the IR brane. Similarly, the VEV of χ induces an $A_4 \to Z_2$ SSB pattern peaked towards the UV brane and is in charge of the TBM mixing pattern in the neutrino sector. Subsequently, NLO interactions break A_4 completely and induce quark mixing and deviations from TBM, both in good agreement with experimental data. The Higgs VEV is in charge of the SSB pattern $SU(2)_L \times SU(2)_R \to SU(2)_D$, which is peaked towards the IR brane. The (gauge) SSB pattern on the UV brane is driven by orbifold BC and a planckian UV localized VEV, which is effectively decoupled from the model.
To summarize the implications of the NLO interactions in the quark sector, we provide the structure of the LO+NLO quark mass matrices in the ZMA [1]:

$$\frac{1}{v}(M+\Delta M)_{u,d} = \underbrace{\begin{pmatrix} y^{4D}_{u,d} & y^{4D}_{c,s} & y^{4D}_{t,b} \\ y^{4D}_{u,d} & \omega y^{4D}_{c,s} & \omega^2 y^{4D}_{t,b} \\ y^{4D}_{u,d} & \omega^2 y^{4D}_{c,s} & \omega y^{4D}_{t,b} \end{pmatrix}}_{\sqrt{3}U(\omega)diag(y^{4D}_{u_i,d_i})} + \begin{pmatrix} f^{u,d}_\chi \tilde{x}^{u,d}_1 & f^{c,s}_\chi \tilde{x}^{u,d}_2 & f^{t,b}_\chi \tilde{x}^{u,d}_3 \\ 0 & 0 & 0 \\ f^{u,d}_\chi \tilde{y}^{u,d}_1 & f^{c,s}_\chi \tilde{y}^{u,d}_2 & f^{t,b}_\chi \tilde{y}^{u,d}_3 \end{pmatrix} \tag{6}$$

where $\omega = e^{2\pi i/3}$, $v = 174$GeV is the 4D Higgs VEV, $y^{4D}_{u,c,t,d,s,b}$ are the effective 4D LO Yukawa couplings and $\tilde{x}^{u,d}_i$, $\tilde{y}^{u,d}_i$ are the coefficients of the 5D NLO Yukawa interactions. The function $f^{u_i,d_i}_\chi \simeq 2\beta_\chi C_\chi/(12 - c_{q_L} - c_{u_i,d_i}) \simeq 0.05$ is the characteristic suppression of the 4D effective NLO Yukawa interactions and $C_\chi = \chi_0/M^{3/2}_{Pl} \simeq 0.155$. Finally, the unitary matrix, $U(\omega)$ is the LO left diagonalization matrix in both the up and down sectors, $(V^{u,d}_L)_{LO}$, which is independent of the LO Yukawa couplings, while $(V_R^{u,d})_{LO} = \mathbb{1}$(see [1]). The structure of the charged lepton mass matrix is exactly identical. Using standard perturbative techniques on the matrix in Eq. (6) we obtained $(V_{L,R}^{u,d})_{NLO}$ [1,13] at $\mathcal{O}\Big(f_\chi^{u_i,d_i}(\tilde{x}_i^{u,d},\tilde{y}_i^{u,d})\Big)$ and showed that by a rather mild deviation from a universality assumption on the magnitudes and phases of the NLO coefficients, $\tilde{x}_i^{u,d},\tilde{y}_i^{u,d}$, we are able to obtain an almost realistic CKM matrix of the characteristic form [1]:

$$V_{CKM} = \begin{pmatrix} 1+\mathcal{O}(\lambda^2) & a\lambda & b\lambda^3 \\ -a^*\lambda & 1+\mathcal{O}(\lambda^2) & c\lambda^2 \\ -b^*\lambda^3 & -c^*\lambda^2 & 1+\mathcal{O}(\lambda^2) \end{pmatrix}. \quad (7)$$

A precise matching of the CKM matrix including deviations from unity of diagonal elements, $|V_{ub}| \neq |V_{td}|$ and phase structure has to be performed at higher order in $f_\chi^{u_i,d_i}(\tilde{x}_i^{u,d},\tilde{y}_i^{u,d})$.

3 Phenomenology of RS-A_4 and constraints on the KK scale

The main difference between the RS-A_4 setup and an anarchic RS flavor scheme [8] lies in the degeneracy of fermionic LH bulk mass parameters, which implies the universality of LH zero mode profiles and hence forbids gauge mediated FCNC processes at tree level, including the KK gluon exchange contribution to ϵ_K. The latter provides the most stringent constraint on flavor anarchic models, together with the neutron EDM [8,10]. However, the choice of the common LH bulk mass parameter, c_q^L is strongly constrained by the matching of the top quark mass ($m_t(1.8\,\text{TeV})\approx 140\,\text{TeV}$) and the perturbativity bound of the 5D top Yukawa coupling, y_t. Most importantly, when considering the tree level corrections to the $Zb\bar{b}$ coupling against the stringent EWPM at the Z pole, we realize [1] that for an IR scale, $\Lambda_{IR} \simeq 1.8\,\text{TeV}$ and $m_h \approx 200\,\text{GeV}$, c_q^L is constrained to be larger than 0.35. Assigning $c_q^L = 0.4$ and matching with m_t we obtain $y_t < 3$, which easily satisfies the 5D Yukawa perturbativity bound. The constraint on c_q^L from $Zb\bar{b}$ has a moderate dependence on the Higgs mass, such that the constraint $\Lambda_{IR} > 1.8\,\text{TeV}$ for $c_q^L = 0.35$ and $m_h \approx 200 GeV$, is relaxed to $\Lambda_{IR} > 1.3\,\text{TeV}$ for $m_h \approx 1\text{TeV}$ [13]. The second most significant constraint comes from 1-loop Higgs mediated dipole operator NP contributions to the $b \to s\gamma$ process, $M_{KK}^{b\to s\gamma} \gtrsim 1.3\,Y\,\text{TeV}$, where Y is the overall scale of the dimensionless 5D Yukawa coefficients. The constraints coming from ϵ'/ϵ_K and the neutrino EDM were shown to be weaker by at least factor of 2 (See [13]).

Recently, the MEG collaboration has established a new upper bound for the $\mu^+ \to e^+\gamma$ decay, given by $BR(\mu^+ \to e^+\gamma) < 2.4 \times 10^{-12}$ (90%C.L.) [20]. The most dominant NP contributions to $\mu \to e\gamma$ in the RS-A_4 setup will come from one-loop (dipole) Higgs diagrams analogous to the quark sector contributions estimated in [13]. Using the same formalism for obtaining a conservative estimation on $BR(\mu^+ \to e^+\gamma)_{RS-A_4}$, we find that the resulting constraint on Y and M_{KK} is less stringent than the ones mentioned above. A full analysis of the NP contributions to $\mu \to e\gamma$, including (currently neglected) one loop Z mediated contributions, will be the issue of a separate publication.

We close this section by commenting on the recent measurement of $BR(B_s \to \mu^+\mu^-) < 4.5 \times 10^{-9}$ by LHCb [21]. It turns out that NP contributions arise already at the tree level by Z boson exchange (and less dominantly from its KK partners). These off diagonal Z Couplings are generated due to a "double-layer" effect of KK mixing, namely from the mixing between fermionic zero and KK modes and the mixing of gauge KK+zero modes after electroweak symmetry breaking. Nevertheless, these contributions turn out to be relatively small and amount to $BR(B_s \to \mu^+\mu^-)_{RS-A_4} \sim 10^{-11}$. A detailed analysis of these contributions, including one-loop penguins and their interplay with the bulk Higgs will be the issue of a future publication.

4 Higher order corrections to the PMNS matrix and θ_{13}

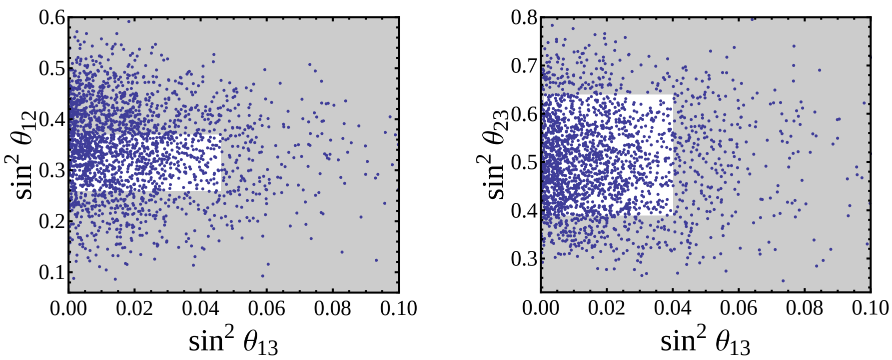

Fig. 2 *Model predictions for θ_{13} vs. θ_{12} (left) and θ_{23} (right) including all dominant higher order and cross talk effects. The white rectangles represent the 3σ allowed regions from the global fit of [15, 16].*

The global fits based on the recent indications of $\nu_\mu \to \nu_e$ appearance in the RENO, Daya Bay, T2K and MINOS experiments, allow one to exclude $\theta_{13} = 0$ with a significance of more than 10σ for , with best fit points centered at around $\theta_{13} \simeq 0.15$, depending on the precise treatment of reactor fluxes [15,16]. As a consequence, any flavor model, which predicts TBM at LO, has to be tested thoroughly for all possible higher order corrections to the PMNS matrix, such that the new fits are still "accessible" by a significant portion of the model parameter space.

In our case we are able to obtain analytic expressions for the corrected diagonalization matrices of both charged leptons and neutrinos, considering

all dominant NLO effects. The resulting expressions are incredibly long and depend on the $\tilde{x}_i^e, \tilde{y}_i^e$, $y_\nu^{H\chi}$ and $y_\nu^{\chi^2}$ parameters and C_χ, which is constrained by the quark sector. Most importantly, these results do not depend on the LO Yukawa couplings (Form diagonalizable LO rotation matrices). We performed a scan over all NLO Yukawa couplings in the range $[0.3, 3]$ and with random complex phases. In Fig. 2 we present the model predictions for $\sin^2\theta_{13}$ vs. $\sin^2\theta_{12}$ (left) and $\sin^2\theta_{23}$ (right) for a set of 3000 randomly generated points, with the 3σ allowed ranges of [15, 16] represented by the white rectangles.
It can be seen that the RS-A_4 model predictions significantly overlap with the allowed ranges for the neutrino mixing angles, which (re-)demonstrates the viability of models predicting TBM at LO.

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References

1. A. Kadosh and E. Pallante, JHEP **1008**, 115 (2010) [arXiv:1004.0321 [hep-ph]].
2. E. Ma and G. Rajasekaran, Phys. Rev. **D64**, 113012 (2001) K. S. Babu, E. Ma and J. W. F. Valle, Phys. Lett. **B552** 207 2003; E. Ma, Phys. Rev. **D70**, 031901(2004) Talk at SI2004, Fuji-Yoshida, Japan, hep-ph/0409075.
3. L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 3370 (1999) [arXiv:hep-ph/9905221]; L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 4690 (1999) [arXiv:hep-th/9906064].
4. C. Csaki, C. Delaunay, C. Grojean and Y. Grossman, JHEP **0810**, 055 (2008) [arXiv:0806.0356 [hep-ph]].
5. X. G. He, Y. Y. Keum and R. R. Volkas, JHEP **0604**, 039 (2006) [arXiv:hep-ph/0601001].
6. K. Agashe, A. Delgado, M. J. May and R. Sundrum, JHEP **0308**, 050 (2003) [arXiv:hep-ph/0308036].
7. M. Carena, E. Ponton, J. Santiago and C.E.M. Wagner, arXiv:hep-ph/0701055.
8. K. Agashe, G. Perez and A. Soni, Phys. Rev. D **71**, 016002 (2005) [arXiv:hep-ph/0408134];
9. K. Agashe, A. Azatov and L. Zhu, Phys. Rev. D **79**, 056006 (2009) [arXiv:0810.1016 [hep-ph]].
10. O. Gedalia, G. Isidori and G. Perez, Phys. Lett. **B 682**, 200 (2009) [arXiv:0905.3264 [hep-ph]].
11. K. Agashe, G. Perez and A. Soni, Phys. Rev. Lett. **93**, 201804 (2004) [arXiv:hep-ph/0406101];
12. G. Cacciapaglia, C. Csaki, J. Galloway, G. Marandella, J. Terning and A. Weiler, JHEP **0804**, 006 (2008)
13. A. Kadosh and E. Pallante, [arXiv:1101.5420 [hep-ph]].
14. P. F. Harrison, D. H. Perkins and W. G. Scott, Phys. Lett. B **458**, 79 (1999) [arXiv:hep-ph/9904297].
15. G. L. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo and A. M. Rotunno, Phys. Rev. D **86**, 013012 (2012) [arXiv:1205.5254 [hep-ph]].
16. D. V. Forero, M. Tortola and J. W. F. Valle, arXiv:1205.4018 [hep-ph].
17. K. Agashe, R. Contino, L. Da Rold and A. Pomarol, Phys. Lett. B **641**, 62 (2006) [arXiv:hep-ph/0605341].
18. W. D. Goldberger and M. B. Wise, Phys. Rev. Lett. **83**, 4922 (1999) [arXiv:hep-ph/9907447]; G. Cacciapaglia, C. Csaki, G. Marandella and J. Terning, JHEP **0702**, 036 (2007) [arXiv:hep-ph/0611358].
19. C. A. Baker *et al.*, Phys. Rev. Lett. **97**, 131801 (2006) [arXiv:hep-ex/0602020].
20. E. Baracchini [MEG Collaboration], arXiv:1005.2569 [hep-ex].
21. J. Albrecht, Mod. Phys. Lett. A **27**, 1230028 (2012) [arXiv:1207.4287 [hep-ex]].