Snowmass2021 - Letter of Interest

Joint Experimental Oscillation Analyses in Search of Sterile Neutrinos

Neutrino Frontier Topical Groups:	(NF01) Neutrino Oscillations (NF02) Sterile neutrinos (NF03) Beyond the Standard Model

Contact Information:

Bryce Littlejohn *(*Illinois Institute of Technology) [blittlej@iit.edu]
Juan Pedro Ochoa-Ricoux (University of California, Irvine) [jpochoa@uci.edu]
Bedřich Roskovec (University of California, Irvine) [broskove@uci.edu]
Pranava Teja Surukuchi (Yale University) [pranavateja.surukuchi@yale.edu]

Authors:

The Daya Bay, MINOS+, PROSPECT, SoLid, and STEREO Collaborations and 11 other individuals.

Author list at rear of LOI

Abstract:

Neutrino experiments have uncovered results that appear to be incompatible with the 3-neutrino mixing picture. The existence of sterile neutrino oscillations, proposed as a possible solution for tying together these anomalous results, would open a portal to new physics beyond the Standard Model (BSM). In addition to exploring the rich possible new physics for its own sake, it is also crucial to explore the sterile neutrino oscillation parameter space to eliminate ambiguity in the interpretation of results from future CP-violation experiments and to properly assess the sensitivity of future neutrinoless double beta decay experiments. Several experiments individually have excluded significant portions of this parameter space based on their source energies and the source-detector distances. By performing analyses on a combination of data sets from different experiments to form a single region of excluded or preferred parameter space (called *joint analyses*), neutrino physics experimental collaborations can completely leverage the statistical power of their data sets while forming a reliable, coherent view of the remaining available regions of the BSM parameter space in question. This LOI overviews the benefits of experimental collaborations performing joint oscillation analyses, while also highlighting attractive joint sterile oscillation opportunities that can be performed with current and future experiments, as well as the challenges involved.

Introduction

A picture of 3-neutrino oscillations has been well established in the past 20 years by a combination of various experimental efforts using multiple neutrino interaction channels [1–4]. However, some experimental data from reactor [5, 6], accelerator [7, 8], and radioactive source [9, 10] experiments exist that are not fully consistent with this framework. If interpreted as oscillations involving sterile neutrino states, the suggested oscillation mass splittings Δm^2 are at the eV-scale [5, 11]. Several reactor experiments specifically conceived to search for eV-scale sterile neutrinos already excluded much of the suggested parameter space [12–15]. Additionally, a wider range of oscillation frequencies are also excluded by joint analyses from a combination of experiments probing 3-active neutrino flavor oscillations [16, 17]. To cover the full range of parameter space and to eliminate ambiguities in other measurements, including CP-violation measurements [18], a broader combination of experimental results is needed. Such experimental combinations can be achieved with modest research investment, paving the way for a comprehensive picture of sterile neutrino searches within the upcoming decade.

Joint Experimental Oscillation Analyses

We define a *joint experimental oscillation analysis* as a coordinated effort by members of those experiments resulting in favored/disfavored regions of the relevant oscillation parameter space through the simultaneous consideration of all the corresponding data sets. A *joint fit* is the most natural way to implement such an analysis, where a simultaneous scan is performed through the full parameter space of all the involved experiments, including oscillation and nuisance parameters. Depending on the anticipated impact of experimental correlations, a simpler joint analysis – such as with Gaussian CLs [19] – that may not necessitate simultaneous joint fitting can also be performed. Joint analyses, when performed by the experimental groups themselves, have the following main advantages:

1) Proper treatment of systematics and correlations: Experimental internal systematical effects and inter-experiment correlations have to be properly accounted for. This can be done most effectively when the joint analyses are performed by the members who have intimate knowledge of the experimental configurations.
2) Increased parameter space coverage: Experiments performing searches for sterile neutrinos cover a disparate range of baselines and energies. Combining the data from multiple experiments gives access to a broader range of distance over energy, L/E, and consequently to wider regions of parameter space.
3) Redundancy and reduction of systematic effects: The consideration of multiple data sets provides valuable redundancy for overlapping regions of parameter space and diminishes the impact of any unknown experiment-specific oscillation-mimicking systematic effects from a single experiment.
4) Sensitivity to terms in extended PMNS matrix: Individual sterile neutrino searches from single experiments are typically carried out in a 3 (active) $+$ 1 (sterile) framework. The use of multiple experimental configurations covering a wider range of L/E values enables increased ability to distinguish between 3+1 phenomenology and other more complex non-standard scenarios.

In performing these experimental joint analyses, the use of proper statistical methods is imperative. In cases where Wilks' theorem is not valid [20], Monte Carlo (MC) methods [21] are preferred. This can become restrictively expensive from a computational standpoint when a large number of multi-experiment MC simulations have to be generated and fit. Other computationally inexpensive alternative statistical methods such as the Gaussian CL$_s$ [19] method can be used to set exclusion limits, specifically when experiments have a low degree of correlation between their systematic uncertainties.

Opportunities for Joint Analyses

Several exclusion limits from a variety of current experiments and their combination already exist. Within the reactor neutrino sector, short-baseline experiments like PROSPECT [12], STEREO [13] set limits on $\sin^2(2\theta_{14})$ for mass splittings Δm^2_{41} in the $\sim$ 0.5 eV^2 – 10 eV^2 regions, and medium-baseline experiments like Daya Bay [4] cover lower values of $\sim 0.5 \times 10^{-3}$ eV^2 – 0.1 eV^2. Additionally, the accelerator experiments MINOS and MINOS+ set limits on $\sin^2(2\theta_{24})$ for $\Delta m^2_{41} > 10^{-4}$ eV^2. Joint experimental oscillation analyses have already been performed on the MINOS+, Daya Bay, and Bugey-3 data by the MINOS+ and Daya Bay collaborations [16, 17]. These combined results exclude most of the parameter space suggested by the LSND anomaly as well as the combined analysis of all anomalous short-baseline signatures.

New joint experimental oscillation analyses should be performed with data from currently running or recently completed experiments. A joint analysis of data between medium-baseline and short-baseline experiments like Daya Bay and PROSPECT will improve coverage at oscillation frequencies in the range of 0.1 eV^2 – 0.5 eV^2, where neither of the experiments are by themselves strongly sensitive. A joint analysis of short-baseline experiments, like PROSPECT and STEREO [13], will provide redundancy in coverage of similar oscillation space and reduce the impact of systematic effects. Short and medium-baseline experiments can also be combined with long-baseline experiments such as MINOS+; this would improve over existing limits, particularly at high Δm^2 ($>$1 eV^2), where current analyses rely on the Bugey-3 spectrum measurements from the 1980s, and at very high Δm^2 ($\sim$ 10 eV^2). These possibilities are already under active discussion by the members of these collaborations.

Data from upcoming experiments will further improve the reach of joint experimental oscillation analyses. A good example is the TAO reactor $\overline{\nu}_e$ experiment, which will begin taking data in 2022 at a baseline of $\sim$30 m [22]. A combined analysis of Daya Bay + PROSPECT + TAO would provide full reactor $\overline{\nu}_e$-based experimental coverage of all oscillation frequencies suggested by the Reactor Antineutrino Anomaly [5]. The SBN Program [23] will search for oscillations using a ν_μ beam, and will cover parameter space relevant to LSND and MiniBooNE, with best sensitivity in a mass splitting regime (1-20 eV^2 [24]) where coverage in the current joint analysis is reliant on knowledge of the absolute flux and spectrum of the NuMI neutrino beamline. In contrast, oscillations in this parameter space region would exhibit themselves as broad variations in measured energy spectra between SBN detectors. SBN would also add substantial systematic redundancy to a joint experimental oscillation analysis, given its differing beam energy ($<$1 GeV), neutrino interaction regime, and detection technology (LArTPC) compared to MINOS+.

A wide coverage of oscillation parameter space with built-in redundancy can be achieved by a joint analysis of multiple experiments searching for oscillations in different channels. Such a comprehensive joint analysis can be achieved by the mid-2020s with a combination of PROSPECT + SBN + TAO + Daya Bay + MINOS+. In this scenario, PROSPECT and SBN would provide best differential coverage of high frequency oscillations, TAO would best cover medium frequencies, and Daya Bay and MINOS+ would anchor limits at lower frequencies. On longer timescales, the DUNE experiment [25] proposes to provide disappearance measurements in all possible channels: ν_e, ν_μ, $\overline{\nu}_e$, and $\overline{\nu}_\mu$. Such a broad array of highly sensitive, systematically correlated measurements is likely to substantially benefit the reach of experimental joint oscillation analyses on the 10-20 year timescale.

Challenges of Joint Analyses

It must be acknowledged that there are challenges involved in performing joint analyses. Experiments operate under independent timelines and priorities, making it impractical - sometimes downright impossible - to find the workforce to devote such efforts. Moreover, the time it currently takes to carry out such a cross-experimental effort from start to finish, which includes agreeing on the scope and methods to be used, sharing the data, and carrying out the analysis, can be quite large, typically extending beyond one year. Finally, experience shows that social and political obstacles can arise that prevent collaborations from working together.

To mitigate these challenges, the community could consider investing the necessary resources to build a common fitting framework with well-defined format(s) for data sharing. By standardizing the joint analysis process and the inputs, such a framework would greatly reduce the time and effort needed, and would make it easier for more experiments to participate. Similarly, experiments should be highly encouraged to engage in well-documented and comprehensive data releases that allow others to reproduce their results, even after they have ceased to operate. The contents of the data to be shared should be arrived at in consultation with other stakeholders in the community. The authors of this LOI do not claim to have all the answers, but would like to emphasize the importance of discussing these issues in the context of the Snowmass process.

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F. P. An,[1] A. B. Balantekin,[2] H. R. Band,[3] M. Bishai,[4] S. Blyth,[5] G. F. Cao,[6] J. Cao,[6] J. F. Chang,[6]
Y. Chang,[7] H. S. Chen,[6] S. M. Chen,[8] Y. Chen,[9,10] Y. X. Chen,[11] J. Cheng,[6] Z. K. Cheng,[10]
J. J. Cherwinka,[2] M. C. Chu,[12] J. P. Cummings,[13] O. Dalager,[14] F. S. Deng,[15] Y. Y. Ding,[6] M. V. Diwan,[4]
T. Dohnal,[16] J. Dove,[17] M. Dvořák,[16] D. A. Dwyer,[18] J. P. Gallo,[19] M. Gonchar,[20] G. H. Gong,[8]
H. Gong,[8] W. Q. Gu,[4] J. Y. Guo,[10] L. Guo,[8] X. H. Guo,[21] Y. H. Guo,[22] Z. Guo,[8] R. W. Hackenburg,[4]
S. Hans,[4] M. He,[6] K. M. Heeger,[3] Y. K. Heng,[6] A. Higuera,[23] Y. K. Hor,[10] Y. B. Hsiung,[5] B. Z. Hu,[5]
J. R. Hu,[6] T. Hu,[6] Z. J. Hu,[10] H. X. Huang,[24] X. T. Huang,[25] P. Huber,[26] D. E. Jaffe,[4] K. L. Jen,[27]
X. L. Ji,[6] X. P. Ji,[4] R. A. Johnson,[28] D. Jones,[29] L. Kang,[30] S. H. Kettell,[4] S. Kohn,[31] M. Kramer,[18,31]
T. J. Langford,[3] J. Lee,[18] J. H. C. Lee,[32] R. T. Lei,[30] R. Leitner,[16] J. K. C. Leung,[32] F. Li,[6] H. L. Li,[6]
J. J. Li,[8] Q. J. Li,[6] S. Li,[30] S. C. Li,[26] W. D. Li,[6] X. N. Li,[6] X. Q. Li,[33] Y. F. Li,[6] Z. B. Li,[10] H. Liang,[15]
C. J. Lin,[18] G. L. Lin,[27] S. Lin,[30] J. J. Ling,[10] J. M. Link,[26] L. Littenberg,[4] B. R. Littlejohn,[19] J. C. Liu,[6]
J. L. Liu,[34] C. Lu,[35] H. Q. Lu,[6] J. S. Lu,[6] K. B. Luk,[31,18] X. B. Ma,[11] X. Y. Ma,[6] Y. Q. Ma,[6]
R. C. Mandujano,[14] C. Marshall,[18] D. A. Martinez Caicedo,[19] K. T. McDonald,[35] R. D. McKeown,[36,37]
Y. Meng,[34] J. Napolitano,[29] D. Naumov,[20] E. Naumova,[20] J. P. Ochoa-Ricoux,[14] A. Olshevskiy,[20]
H.-R. Pan,[5] J. Park,[26] S. Patton,[18] J. C. Peng,[17] C. S. J. Pun,[32] F. Z. Qi,[6] M. Qi,[38] X. Qian,[4] N. Raper,[10]
J. Ren,[24] C. Morales Reveco,[14] R. Rosero,[4] B. Roskovec,[14] X. C. Ruan,[24] H. Steiner,[31,18] J. L. Sun,[39]
T. Tmej,[16] K. Treskov,[20] W.-H. Tse,[12] C. E. Tull,[18] B. Viren,[4] V. Vorobel,[16] C. H. Wang,[7] J. Wang,[10]
M. Wang,[25] N. Y. Wang,[21] R. G. Wang,[6] W. Wang,[10,37] W. Wang,[38] X. Wang,[40] Y. Wang,[38] Y. F. Wang,[6]
Z. Wang,[6] Z. Wang,[8] Z. M. Wang,[6] H. Y. Wei,[4] L. H. Wei,[6] L. J. Wen,[6] K. Whisnant,[41] C. G. White,[19]
H. L. H. Wong,[31,18] E. Worcester,[4] D. R. Wu,[6] F. L. Wu,[38] Q. Wu,[25] W. J. Wu,[6] D. M. Xia,[42] Z. Q. Xie,[6]
Z. Z. Xing,[6] J. L. Xu,[6] T. Xu,[8] T. Xue,[8] C. G. Yang,[6] L. Yang,[30] Y. Z. Yang,[8] H. F. Yao,[6] M. Ye,[6] M. Yeh,[4]
B. L. Young,[41] H. Z. Yu,[10] Z. Y. Yu,[6] B. B. Yue,[10] S. Zeng,[6] Y. Zeng,[10] L. Zhan,[6] C. Zhang,[4] F. Y. Zhang,[34]
H. H. Zhang,[10] J. W. Zhang,[6] Q. M. Zhang,[22] X. T. Zhang,[6] Y. M. Zhang,[10] Y. X. Zhang,[39] Y. Y. Zhang,[34]
Z. J. Zhang,[30] Z. P. Zhang,[15] Z. Y. Zhang,[6] J. Zhao,[6] L. Zhou,[6] H. L. Zhuang,[6] and J. H. Zou[6]
(The Daya Bay Collaboration)

P. Adamson,[46] I. Anghel,[50] A. Aurisano,[44] G. Barr,[56] A. Blake,[43,51] S. V. Cao,[62] T. J. Carroll,[62]
C. M. Castromonte,[47] R. Chen,[53] S. Childress,[46] J. A. B. Coelho,[63] S. De Rijck,[62,*] J. J. Evans,[53]
G. J. Feldman,[48] W. Flanagan,[62,45] M. Gabrielyan,[54] S. Germani,[52] R. A. Gomes,[47] P. Gouffon,[59]
N. Graf,[57] K. Grzelak,[64] A. Habig,[55] S. R. Hahn,[46] J. Hartnell,[61] R. Hatcher,[46] A. Holin,[52]
J. Huang,[62] M. Kordosky,[65] A. Kreymer,[46] K. Lang,[62] P. Lucas,[46] W. A. Mann,[63] M. L. Marshak,[54]
N. Mayer,[63] R. Mehdiyev,[62] J. R. Meier,[54] W. H. Miller,[54] G. Mills,[66,†] D. Naples,[57] J. K. Nelson,[65]
R. J. Nichol,[52] J. O'Connor,[52] R. B. Pahlka,[46] Ž. Pavlović,[66,‡] G. Pawloski,[54] A. Perch,[52]
M. M. Pfützner,[52] D. D. Phan,[62] R. K. Plunkett,[46] N. Poonthottathil,[46] X. Qiu,[60] A. Radovic,[65]
P. Sail,[62] M. C. Sanchez,[50] J. Schneps,[63,†] A. Schreckenberger,[62] R. Sharma,[46] A. Sousa,[44]
N. Tagg,[67] J. Thomas,[52] M. A. Thomson,[43] A. Timmons,[53] J. Todd,[44] S. C. Tognini,[47] R. Toner,[48]
D. Torretta,[46] P. Vahle,[65] A. Weber,[56,58] L. W. Koerner,[49] L. H. Whitehead,[52] and S. G. Wojcicki[60]
(The MINOS+ Collaboration)

M. Andriamirado,[19] A. B. Balantekin,[2] H. R. Band,[3] C. D. Bass,[68] D. E. Bergeron,[69] D. Berish,[29]
N. S. Bowden,[70] J. P. Brodsky,[70] C. D. Bryan,[71] R. Carr,[72] T. Classen,[70] A. J. Conant,[71] G. Deichert,[71]
M. V. Diwan,[4] M. J. Dolinski,[73] A. Erickson,[74] B. T. Foust,[3] J. K. Gaison,[3] A. Galindo-Uribarri,[75,76]
C. E. Gilbert,[75,76] C. Grant,[77] B. T. Hackett,[75,76] S. Hans,[4] A. B. Hansell,[29] K. M. Heeger,[3]
D. E. Jaffe,[4] X. Ji,[4] D. C. Jones,[29] O. Kyzylova,[73] C. E. Lane,[73] T. J. Langford,[3] J. LaRosa,[69]
B. R. Littlejohn,[19] X. Lu,[75,76] J. Maricic,[23] M. P. Mendenhall,[70] A. M. Meyer,[23] R. Milincic,[23]

I. Mitchell,[23] P. E. Mueller,[75] H. P. Mumm,[69] J. Napolitano,[29] C. Nave,[73] R. Neilson,[73] J. A. Nikkel,[3] D. Norcini,[3] S. Nour,[69] J. L. Palomino,[19] D. A. Pushin,[78] X. Qian,[4] E. Romero-Romero,[75,76] R. Rosero,[4] P. T. Surukuchi,[3] M. A. Tyra,[69] R. L. Varner,[75] D. Venegas-Vargas,[75,76] P. B. Weatherly,[73] C. White,[19] J. Wilhelmi,[3] A. Woolverton,[78] M. Yeh,[4] A. Zhang,[4] C. Zhang,[4] and X. Zhang[70]
(The PROSPECT Collaboration)

W. Beaumont,[79] S. Binet,[80] I. Bolognino,[81] M. Bongrand,[81] J. Borg,[82] V. Buridon,[83] H. Chanal,[80] B. Coupé,[84] P. Crochet,[80] D. Cussans,[85] A. De Roeck,[79,86] D. Durand,[83] M. Fallot,[81] D. Galbinski,[82] S. Gallego,[83] L. Giot,[81] B. Guillon,[83] D. Henaff,[81] S. Hayashida,[82] B. Hosseini,[82] S. Kalcheva,[84] G. Lehaut,[83] I. Michiels,[87] S. Monteil,[80] D. Newbold,[85,88] N. Roy,[89] D. Ryckbosch,[87] H. Rejeb Sfar,[79] L. Simard,[89,90] A. Vacheret,[82] G. Vandierendonck,[87] S. Van Dyck,[84] N. van Remortel,[79] S. Vercaemer,[79] M. Verstraeten,[79] B. Viaud,[81] A. Weber,[91,88] M. Yeresko,[80] and and F. Yermia.[81]
(The SoLid Collaboration)

A. Bonhomme,[92,93] C. Buck,[92] P. del Amo Sanchez,[94] I. El Atmani,[93,§] L. Labit,[94] J. Lamblin,[95] A. Letourneau,[93] D. Lhuillier,[93] M. Licciardi,[95] M. Lindner,[92] T. Materna,[93] H. Pessard,[94] J.-S. Réal,[95] R. Rogly,[93] V. Savu,[93] S. Schoppmann,[92] T. Soldner,[96] A. Stutz,[95] and M. Vialat[96]
(The STEREO Collaboration)

V. Antonelli,[97] T. Enqvist,[98] U. Fahrendholz,[99] L. Miramonti,[97] A. Paoloni,[100] G. Ranucci,[97] A. Stahl,[101] H. Th. J. Steiger,[102,99] M. R. Stock,[99] W. H. Trzaska,[98] and B. Wonsak[103]

[1]*Institute of Modern Physics, East China University of Science and Technology, Shanghai*
[2]*University of Wisconsin, Madison, Wisconsin 53706*
[3]*Wright Laboratory and Department of Physics, Yale University, New Haven, Connecticut 06520*
[4]*Brookhaven National Laboratory, Upton, New York 11973*
[5]*Department of Physics, National Taiwan University, Taipei*
[6]*Institute of High Energy Physics, Beijing*
[7]*National United University, Miao-Li*
[8]*Department of Engineering Physics, Tsinghua University, Beijing*
[9]*Shenzhen University, Shenzhen*
[10]*Sun Yat-Sen (Zhongshan) University, Guangzhou*
[11]*North China Electric Power University, Beijing*
[12]*Chinese University of Hong Kong, Hong Kong*
[13]*Siena College, Loudonville, New York 12211*
[14]*Department of Physics and Astronomy, University of California, Irvine, California 92697*
[15]*University of Science and Technology of China, Hefei*
[16]*Charles University, Faculty of Mathematics and Physics, Prague*
[17]*Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801*
[18]*Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[19]*Department of Physics, Illinois Institute of Technology, Chicago, Illinois 60616*
[20]*Joint Institute for Nuclear Research, Dubna, Moscow Region*
[21]*Beijing Normal University, Beijing*
[22]*Department of Nuclear Science and Technology, School of*

Energy and Power Engineering, Xi’an Jiaotong University, Xi’an
[23]Department of Physics, University of Houston, Houston, Texas 77204
[24]China Institute of Atomic Energy, Beijing
[25]Shandong University, Jinan
[26]Center for Neutrino Physics, Virginia Tech, Blacksburg, Virginia 24061
[27]Institute of Physics, National Chiao-Tung University, Hsinchu
[28]Department of Physics, University of Cincinnati, Cincinnati, Ohio 45221
[29]Department of Physics, College of Science and Technology, Temple University, Philadelphia, Pennsylvania 19122
[30]Dongguan University of Technology, Dongguan
[31]Department of Physics, University of California, Berkeley, California 94720
[32]Department of Physics, The University of Hong Kong, Pokfulam, Hong Kong
[33]School of Physics, Nankai University, Tianjin
[34]Department of Physics and Astronomy, Shanghai Jiao Tong University,
Shanghai Laboratory for Particle Physics and Cosmology, Shanghai
[35]Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
[36]California Institute of Technology, Pasadena, California 91125
[37]College of William and Mary, Williamsburg, Virginia 23187
[38]Nanjing University, Nanjing
[39]China General Nuclear Power Group, Shenzhen
[40]College of Electronic Science and Engineering, National University of Defense Technology, Changsha
[41]Iowa State University, Ames, Iowa 50011
[42]Chongqing University, Chongqing
[43]Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, United Kingdom
[44]Department of Physics, University of Cincinnati, Cincinnati, Ohio 45221, USA
[45]Department of Physics, University of Dallas, Irving, Texas 75062, USA
[46]Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
[47]Instituto de Física, Universidade Federal de Goiás, 74690-900, Goiânia, GO, Brazil
[48]Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
[49]Department of Physics, University of Houston, Houston, Texas 77204, USA
[50]Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011 USA
[51]Lancaster University, Lancaster, LA1 4YB, UK
[52]Department of Physics and Astronomy, University College London, London WC1E 6BT, United Kingdom
[53]School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, United Kingdom
[54]University of Minnesota, Minneapolis, Minnesota 55455, USA
[55]Department of Physics, University of Minnesota Duluth, Duluth, Minnesota 55812, USA
[56]Subdepartment of Particle Physics, University of Oxford, Oxford OX1 3RH, United Kingdom
[57]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA
[58]Rutherford Appleton Laboratory, Science and Technology Facilities Council, Didcot, OX11 0QX, United Kingdom
[59]Instituto de Física, Universidade de São Paulo, CP 66318, 05315-970, São Paulo, SP, Brazil
[60]Department of Physics, Stanford University, Stanford, California 94305, USA

[61]Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, United Kingdom
[62]Department of Physics, University of Texas at Austin, Austin, Texas 78712, USA
[63]Physics Department, Tufts University, Medford, Massachusetts 02155, USA
[64]Department of Physics, University of Warsaw, PL-02-093 Warsaw, Poland
[65]Department of Physics, College of William & Mary, Williamsburg, Virginia 23187, USA
[66]Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
[67]Otterbein University, Westerville, Ohio 43081, USA
[68]Department of Physics, Le Moyne College, Syracuse, NY, USA
[69]National Institute of Standards and Technology, Gaithersburg, MD, USA
[70]Lawrence Livermore National Laboratory, Livermore, CA, USA
[71]High Flux Isotope Reactor, Oak Ridge National Laboratory, Oak Ridge, TN, USA
[72]Department of Physiscs, Massachusetts Institute of Technology, Cambridge, MA, USA
[73]Department of Physics, Drexel University, Philadelphia, PA, USA
[74]George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA USA
[75]Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA
[76]Department of Physics and Astronomy, University of Tennessee, Knoxville, TN, USA
[77]Department of Physics, Boston University, Boston, MA, USA
[78]Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo, Waterloo, ON, Canada
[79]Universiteit Antwerpen, Antwerpen, Belgium
[80]Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
[81]SUBATECH, CNRS/IN2P3, Université de Nantes, Ecole des Mines de Nantes, Nantes, France
[82]Imperial College London, Department of Physics, London, United Kingdom
[83]Normandie Univ, ENSICAEN, UNICAEN, CNRS/IN2P3, LPC Caen, 14000 Caen, France
[84]SCK-CEN, Belgian Nuclear Research Centre, Mol, Belgium
[85]University of Bristol, Bristol, UK
[86]CERN, 1211 Geneva 23, Switzerland
[87]Universiteit Gent, Gent, Belgium
[88]STFC, Rutherford Appleton Laboratory, Harwell Oxford, and Daresbury Laboratory
[89]LAL, Univ Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
[90]Institut Universitaire de France, F-75005 Paris, France
[91]University of Oxford, Oxford, UK
[92]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
[93]IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France
[94]Univ. Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, LAPP, 74000 Annecy, France
[95]Univ. Grenoble Alpes, CNRS, Grenoble INP, LPSC-IN2P3, 38000 Grenoble, France
[96]Institut Laue-Langevin, CS 20156, 38042 Grenoble Cedex 9, France
[97]Department of Physics, University of Milano and INFN, Milano, Italy
[98]Department of Physics, University of Jyvaskyla, Jyvaskyla, Finland
[99]Department of Physics, Technical University of Munich, James-Frank-Str. 1, Garching bei München, Germany

[100]*INFN - Laboratori Nazionali di Frascati, Via Enrico Fermi 54, 00044 Frascati (Roma) Italy*
[101]*3. Physikalisches Institut, RWTH Aachen University, Aachen, Germany*
[102]*Cluster of Excellence PRISMA+, Johannes Gutenberg University Mainz, Staudingerweg 9, Mainz, Germany*
[103]*Institute of Experimental Physics, University of Hamburg, Luruper Chaussee 149, Hamburg, Germany*

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[*] Now at Department of Physics, University of Cincinnati, Cincinnati, Ohio 45221, USA.

[†] Deceased.

[‡] Now at Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA.

[§] Present address: Hassan II University, Faculty of Sciences, Aïn Chock, BP 5366 Maarif, Casablanca 20100, Morocco