Snowmass2021 - Letter of Interest

The JUNO-TAO Experiment

NF Topical Groups: (check all that apply □/■)

□ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
□ (NF4) Neutrinos from natural sources
□ (NF5) Neutrino properties
□ (NF6) Neutrino cross sections
■ (NF7) Applications
□ (NF8) Theory of neutrino physics
■ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
□ (Other) *[Please specify frontier/topical group(s)]*

Contact Information:
Guofu Cao (Institute of High-Energy Physics) [caogf@ihep.ac.cn]
Juan Pedro Ochoa Ricoux (University of California, Irvine) [jpochoa@uci.edu]
Wei Wang (Sun Yat-sen University) [wangw223@sysu.edu.cn]
Liangjian Wen (Institute of High-Energy Physics) [wenlj@ihep.ac.cn]
Michael Wurm (University of Mainz) [michael.wurm@uni-mainz.de]
Liang Zhan (Institute of High-Energy Physics) [zhanl@ihep.ac.cn]
Collaboration: JUNO

Authors: the JUNO collaboration (a full author list is included after the references).

Abstract: The Taishan Antineutrino Observatory (TAO, also known as JUNO-TAO) is a satellite experiment of the Jiangmen Underground Neutrino Observatory (JUNO). The experiment consists of a ton-level liquid scintillator detector placed at $\sim$30 m from a 4.6 GW_{th} reactor core of the Taishan Nuclear Power Plant. The main goal is to measure the reactor antineutrino spectrum with sub-percent energy resolution, providing a reference spectrum for JUNO as well as a benchmark for nuclear databases and other experiments. The detector design consists of a spherical acrylic vessel containing 2.8 ton gadolinium-doped liquid scintillator viewed by 10 m^2 Silicon Photomultipliers (SiPMs) with $\sim$50% photon detection efficiency and providing around 95% photon coverage. The photoelectron yield will be around 4500 per MeV, an order of magnitude higher than any existing large-scale liquid scintillator detector. The detector will operate at -50°C to mitigate the impact of SiPM dark noise and will be well shielded from cosmogenic backgrounds and ambient radioactivity. About 2000 reactor antineutrinos will be collected per day with an expected background-to-signal ratio of $\sim 10\%$. Operations are expected to begin as soon as 2022.

Key words: reactor antineutrino spectrum, JUNO-TAO

Physics Motivation

The three-neutrino oscillation paradigm is well supported by experiments using solar neutrinos, atmospheric neutrinos, accelerator neutrinos and reactor antineutrinos. The three neutrino mixing angles, θ_{12}, θ_{13}, θ_{23}, as well as the two independent mass-squared splittings, $\Delta m^2_{21} \equiv m^2_2 - m^2_1$, $|\Delta m^2_{31}| \equiv |m^2_3 - m^2_1|$ (or $|\Delta m^2_{32}|$), where m_1, m_2, and m_3 are the three mass eigenvalues, have been measured to few-percent precision. However, even assuming neutrinos are Dirac fermions, the Dirac CP-violation phase and the neutrino mass ordering (NMO) are still unknown. The Jiangmen Underground Neutrino Observatory (JUNO) experiment in South China aims to resolve the NMO and further improve the measurements of θ_{12}, Δm^2_{21}, and $|\Delta m^2_{31}|$ to sub-percent precision by measuring the oscillated energy spectrum of the antineutrinos emitted by eight reactors from the Yangjiang and Taishan nuclear power plants at a distance of 53 km. To meet these two major goals, the JUNO detector is designed to reach an energy resolution of $3\%/\sqrt{E[\mathrm{MeV}]}$, where E is the visible energy [1]. Recent experiments such as Daya Bay have shown that the predicted antineutrino spectrum disagrees with observations [2]. Moreover, it has been speculated that unknown fine structure in the energy spectrum [3, 4] could affect the sensitivity of JUNO experiment [5, 6]. In order to mitigate this possibility, a satellite experiment called the Taishan Antineutrino Observatory (JUNO-TAO) has been proposed to provide a reference spectrum to JUNO [7].

The Taishan Nuclear Power Plant is located in the Chixi town of Taishan city in the Guangdong province. This plant currently hosts two European Pressurised Reactors (EPR) in operation, each with 4.6 GW of thermal power. JUNO-TAO is located in a basement 9.6 m underground, outside of the concrete containment shell of one of the two reactors. The primary goal of JUNO-TAO is to eliminate any possible model dependence in JUNO's oscillation measurements by providing a reference spectrum. Although a $3\%/\sqrt{E[\mathrm{MeV}]}$ energy resolution would be sufficient to accomplish this goal, it is advantageous to achieve a higher energy resolution to study the fine structure of the reactor antineutrino spectrum and produce a state-of-the-art measurement that could uncover unexpected features. Thus, the JUNO-TAO experiment has been designed to have the following additional scientific goals: 1) provide a benchmark measurement for nuclear databases; 2) provide increased reliability in measured isotopic antineutrino yields; 3) provide an opportunity of improving nuclear physics knowledge of neutron-rich isotopes; 4) search for light sterile neutrinos with a mass-scale around 1 eV; 5) verify the technology for reactor monitoring and nuclear safeguard applications.

Design of the JUNO-TAO Experiment

The conceptual design of JUNO-TAO is shown on Figure 1. The Central Detector (CD) will collect reactor antineutrinos using 2.8 tons of Gadolinium-doped Liquid Scintillator (GdLS) inside a spherical acrylic vessel with a diameter of 1.8 m. To properly contain the energy deposition of gammas from the Inverse Beta Decay (IBD) positron annihilation, a position cut will be applied to remove events whose vertices are within 25 cm from the acrylic wall, resulting in a 1 ton fiducial mass. The IBD event rate in the fiducial volume is expected to be about 2000 (4000) events per day with (without) the detection efficiency taken into account. To reach the desired energy resolution, more than 4000 high-performance silicon photomultiplier (SiPM) tiles, each of dimensions 5 cm $\times$ 5 cm, cover $\sim$95% of the acrylic vessel and collect scintillation light with $> 50\%$ efficiency. The SiPM tiles are installed on the inner surface of a spherical copper shell with an inner diameter of 1.882 m. The copper shell is installed in a cylindrical stainless steel tank with a 2.1 m outer diameter and 2.2 m height. The stainless steel tank is filled with Linear Alkylbenzene (LAB), which serves as solvent for the GdLS and as as a buffer to shield the target from the outer tank's radioactivity. The LAB also allows to stabilize the temperature, and to optically couple the acrylic vessel to the SiPMs. Cooling pipes are deployed on the outer side of the copper shell and the inner side of the stainless steel tank. They are used to cool down the CD to $-50°$C, reducing the dark noise of SiPMs to $\sim$100 Hz/mm^2 and significantly suppressing its impact on the energy resolution. The stainless steel tank is insulated with 20 cm thick Polyurethane (PU) to reduce heat leakage. The central detector is surrounded by a 1.2 m thick water tank on the sides and 1 m High Density Polyethylene (HDPE) on the top as a shield against ambient radioactivity and cosmogenic neutrons. Cosmic muons are tagged by plastic scintillator strips on the top and the photomultiplier tubes that instrument the water tanks.

A photoelectron yield of about 4500 per MeV is expected from simulations, corresponding to an energy resolution of $1.5\%/\sqrt{E[\mathrm{MeV}]}$ in photoelectron statistics. When approaching the energy resolution limit of LS detectors, non-stochastic effects become prominent. At low energies, the contribution from the LS quenching effect could be quite large. At high energies, the smearing from neutron recoil of IBD becomes dominant. Taking into account the projected dark noise, cross-talk, and charge resolution of the SiPMs, the expected energy resolution of TAO will be sub-percent in most of the energy region of interest.

The muon and cosmogenic neutron rates in the JUNO-TAO site have been measured to be 1/3 of what they are in the surface. Simulations show that the accidental and cosmogenic backgrounds like fast neutrons and ^{8}He/^{9}Li decays can be controlled to $< 10\%$ of the signal with proper shielding and muon vetos.

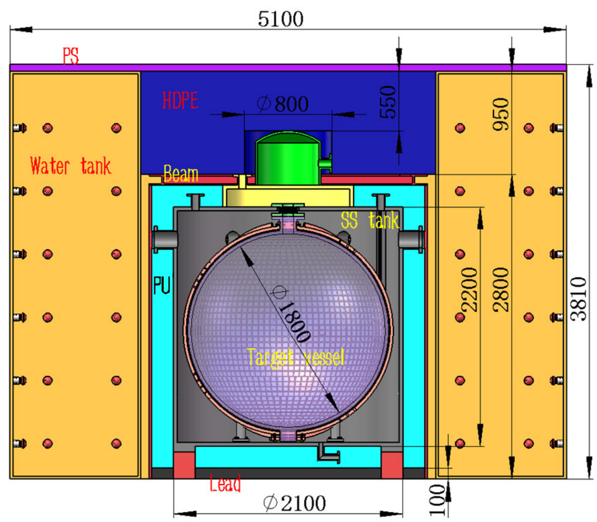

Figure 1: Schematic view of the TAO detector, which consists of a liquid scintillator target with outer shielding and a veto system. Dimensions are displayed in mm.

Conclusions

In summary, the JUNO-TAO experiment is an important part of the JUNO experiment, and a leading player in the worldwide effort to precisely characterize the spectral shape of reactor antineutrinos. The detector R&D started in 2018. A recipe for GdLS has been developed and has been shown to have good transparency and light yield at $-50°$C. The SiPMs and the readout electronics have been preliminary tested at the same temperature. A first prototype with 100 L of GdLS has been used to verify the cryostat design. A full-size prototype detector will be tested in 2021. A conceptual design report was released in 2020 [7]. The full JUNO-TAO detector is expected to start operations in 2022, around the same time as the larger JUNO experiment.

References

[1] JUNO, F. An et al., Neutrino Physics with JUNO, J. Phys. G **43**, 030401 (2016), arXiv:1507.05613.

[2] Daya Bay, D. Adey et al., Extraction of the ^{235}U and ^{239}Pu Antineutrino Spectra at Daya Bay, Phys. Rev. Lett. **123**, 111801 (2019), arXiv:1904.07812.

[3] D. Dwyer and T. Langford, Spectral Structure of Electron Antineutrinos from Nuclear Reactors, Phys. Rev. Lett. **114**, 012502 (2015), arXiv:1407.1281.

[4] A. Sonzogni, M. Nino, and E. McCutchan, Revealing Fine Structure in the Antineutrino Spectra From a Nuclear Reactor, Phys. Rev. C **98**, 014323 (2018), arXiv:1710.00092.

[5] Z. Cheng, N. Raper, and C. F. Wong, Potential impact of sub-structure on the resolution of neutrino mass hierarchy at medium-baseline reactor neutrino oscillation experiments, (2020), arXiv:2004.11659.

[6] F. Capozzi, E. Lisi, and A. Marrone, Mapping reactor neutrino spectra from TAO to JUNO, (2020), arXiv:2006.01648.

[7] JUNO, A. Abusleme et al., TAO Conceptual Design Report: A Precision Measurement of the Reactor Antineutrino Spectrum with Sub-percent Energy Resolution, (2020), arXiv:2005.08745.

The JUNO Collaboration:

Angel Abusleme[5], Thomas Adam[45], Shakeel Ahmad[67], Rizwan Ahmed[67], Sebastiano Aiello[55], Fengpeng An[29], Guangpeng An[10], Qi An[22], Giuseppe Andronico[55], Nikolay Anfimov[68], Vito Antonelli[58], Tatiana Antoshkina[68], Burin Asavapibhop[72], João Pedro Athayde Marcondes de André[45], Didier Auguste[43], Andrej Babic[71], Wander Baldini[57], Andrea Barresi[59], Eric Baussan[45], Marco Bellato[61], Antonio Bergnoli[61], Enrico Bernieri[65], Thilo Birkenfeld[48], Sylvie Blin[43], David Blum[54], Simon Blyth[40], Anastasia Bolshakova[68], Mathieu Bongrand[43], Clément Bordereau[44,39], Dominique Breton[43], Augusto Brigatti[58], Riccardo Brugnera[62], Riccardo Bruno[55], Antonio Budano[65], Max Buesken[48], Mario Buscemi[55], Jose Busto[46], Ilya Butorov[68], Anatael Cabrera[43], Hao Cai[34], Xiao Cai[10], Yanke Cai[10], Zhiyan Cai[10], Antonio Cammi[60], Agustin Campeny[5], Chuanya Cao[10], Guofu Cao[10], Jun Cao[10], Rossella Caruso[55], Cédric Cerna[44], Irakli Chakaberia[25], Jinfan Chang[10], Yun Chang[39], Pingping Chen[18], Po-An Chen[40], Shaomin Chen[13], Xurong Chen[26], Yi-Wen Chen[38], Yixue Chen[11], Yu Chen[20], Zhang Chen[10], Jie Cheng[10], Yaping Cheng[7], Davide Chiesa[59], Pietro Chimenti[3], Artem Chukanov[68], Anna Chuvashova[68], Gérard Claverie[44], Catia Clementi[63], Barbara Clerbaux[2], Selma Conforti Di Lorenzo[43], Daniele Corti[61], Salvatore Costa[55], Flavio Dal Corso[61], Olivia Dalager[75], Christophe De La Taille[43], Jiawei Deng[34], Zhi Deng[13], Ziyan Deng[10], Wilfried Depnering[52], Marco Diaz[5], Xuefeng Ding[58], Yayun Ding[10], Bayu Dirgantara[74], Sergey Dmitrievsky[68], Tadeas Dohnal[41], Georgy Donchenko[70], Jianmeng Dong[13], Damien Dornic[46], Evgeny Doroshkevich[69], Marcos Dracos[45], Frédéric Druillole[44], Shuxian Du[37], Stefano Dusini[61], Martin Dvorak[41], Timo Enqvist[42], Heike Enzmann[52], Andrea Fabbri[65], Lukas Fajt[71], Donghua Fan[24], Lei Fan[10], Can Fang[28], Jian Fang[10], Wenxing Fang[10], Marco Fargetta[55], Anna Fatkina[68], Dmitry Fedoseev[68], Vladko Fekete[71], Li-Cheng Feng[38], Qichun Feng[21], Richard Ford[58], Andrey Formozov[58], Amélie Fournier[44], Haonan Gan[32], Feng Gao[48], Alberto Garfagnini[62], Alexandre Göttel[50,48], Christoph Genster[50], Marco Giammarchi[58], Agnese Giaz[62], Nunzio Giudice[55], Maxim Gonchar[68], Guanghua Gong[13], Hui Gong[13], Oleg Gorchakov[68], Yuri Gornushkin[68], Marco Grassi[62], Christian Grewing[51], Vasily Gromov[68], Minghao Gu[10], Xiaofei Gu[37], Yu Gu[19], Mengyun Guan[10], Nunzio Guardone[55], Maria Gul[67], Cong Guo[10], Jingyuan Guo[20], Wanlei Guo[10], Xinheng Guo[8], Yuhang Guo[50], Paul Hackspacher[52], Caren Hagner[49], Ran Han[7], Yang Han[43], Muhammad Hassan[67], Miao He[10], Wei He[10], Tobias Heinz[54], Patrick Hellmuth[44], Yuekun Heng[10], Rafael Herrera[5], Daojin Hong[28], Shaojing Hou[10], Yee Hsiung[40], Bei-Zhen Hu[40], Hang Hu[20], Jianrun Hu[10], Jun Hu[10], Shouyang Hu[9], Tao Hu[10], Zhuojun Hu[20], Chunhao Huang[20], Guihong Huang[10], Hanxiong Huang[9], Qinhua Huang[45], Wenhao Huang[25], Xin Huang[10], Xingtao Huang[25], Yongbo Huang[28], Jiaqi Hui[30], Lei Huo[21], Wenju Huo[22], Cédric Huss[44], Safeer Hussain[67], Antonio Insolia[55], Ara Ioannisian[1], Roberto Isocrate[61], Kuo-Lun Jen[38], Xiaolu Ji[10], Xingzhao Ji[20], Huihui Jia[33], Junji Jia[34], Siyu Jian[9], Di Jiang[22], Xiaoshan Jiang[10], Ruyi Jin[10], Xiaoping Jing[10], Cécile Jollet[44], Jari Joutsenvaara[42], Sirichok Jungthawan[74], Leonidas Kalousis[45], Philipp Kampmann[50,48], Li Kang[18], Michael Karagounis[51], Narine Kazarian[1], Amir Khan[20], Waseem Khan[35], Khanchai Khosonthongkee[74], Patrick Kinz[38], Denis Korablev[68], Konstantin Kouzakov[70], Alexey Krasnoperov[68], Zinovy Krumshteyn[68], Andre Kruth[51], Nikolay Kutovskiy[68], Pasi Kuusiniemi[42], Tobias Lachenmaier[54], Cecilia Landini[58], Sébastien Leblanc[44], Victor Lebrin[47], Frederic Lefevre[47], Ruiting Lei[18], Rupert Leitner[41], Jason Leung[38], Chao Li[25], Demin Li[37], Fei Li[10], Fule Li[13], Haitao Li[20], Huiling Li[10], Jiaqi Li[20], Kaijie Li[20], Mengzhao Li[10], Min Li[11], Nan Li[16], Nan Li[10], Qingjiang Li[16], Ruhui Li[10], Shanfeng Li[18], Shuaijie Li[20], Tao Li[20], Teng Li[25], Weidong Li[10], Weiguo Li[10], Xiaomei Li[9], Xiaonan Li[10], Xinglong Li[9], Yi Li[18], Yufeng Li[10], Zhaohan Li[10], Zhibing Li[20], Ziyuan Li[20], Hao Liang[22], Hao Liang[9], Jingjing Liang[28], Daniel Liebau[51], Ayut Limphirat[74], Sukit Limpijumnong[74], Guey-Lin Lin[38], Shengxin Lin[18], Tao Lin[10], Jiajie Ling[20], Ivano Lippi[61], Fang Liu[11], Haidong Liu[37], Hongbang Liu[28], Hongjuan Liu[23], Hongtao Liu[20], Hu Liu[20], Hui Liu[19], Jianglai Liu[30,31], Jinchang Liu[10], Min Liu[23], Qian Liu[14], Qin Liu[22], Runxuan Liu[50,48], Shuangyu Liu[10], Shubin Liu[22], Shulin Liu[10], Xiaowei Liu[20], Xiwen Liu[28], Yan Liu[10], Yunzhe Liu[10], Alexey Lokhov[70], Paolo Lombardi[58], Claudio Lombardo[56], Kai Loo[52], Chuan Lu[32], Haoqi Lu[10], Jingbin Lu[15], Junguang Lu[10], Shuxiang Lu[37], Xiaoxu Lu[10], Bayarto Lubsandorzhiev[69], Sultim Lubsandorzhiev[69], Livia Ludhova[50,48], Fengjiao Luo[10], Guang Luo[20], Pengwei Luo[20], Shu Luo[36], Wuming Luo[10], Vladimir Lyashuk[69], Qiumei Ma[10], Si Ma[10], Xiaoyan Ma[10], Xubo Ma[11], Jihane Maalmi[43], Yury Malyshkin[68], Fabio Mantovani[57], Francesco Manzali[62], Xin Mao[7], Yajun Mao[12], Stefano M. Mari[65], Filippo Marini[62], Sadia Marium[67], Cristina Martellini[65], Gisele Martin-Chassard[43], Agnese Martini[64], Davit Mayilyan[1], Axel Müller[54], Ints Mednieks[66], Yue Meng[30], Anselmo Meregaglia[44], Emanuela Meroni[58], David Meyhöfer[49], Mauro Mezzetto[61], Jonathan Miller[6], Lino Miramonti[58], Salvatore Monforte[55], Paolo Montini[65], Michele Montuschi[57], Nikolay Morozov[68], Akram Muhammad[67], Pavithra Muralidharan[51], Massimiliano Nastasi[59], Dmitry V. Naumov[68], Elena Naumova[68], Igor Nemchenok[68], Feipeng Ning[10], Zhe Ning[10], Hiroshi Nunokawa[4], Lothar Oberauer[53], Juan Pedro Ochoa-Ricoux[75,5], Alexander Olshevskiy[68], Domizia Orestano[65], Fausto Ortica[63], Hsiao-Ru Pan[40], Alessandro Paoloni[64], Nina Parkalian[51], Sergio Parmeggiano[58], Teerapat Payupol[72], Yatian Pei[10], Nicomede Pelliccia[63], Anguo Peng[23], Haiping Peng[22], Frédéric Perrot[44], Pierre-Alexandre Petitjean[2], Fabrizio Petrucci[65], Luis Felipe Piñeres Rico[45], Oliver Pilarczyk[52], Artyom Popov[70], Pascal Poussot[45], Wathan Pratumwan[74], Ezio Previtali[59], Fazhi Qi[10], Ming Qi[27], Sen Qian[10], Xiaohui Qian[10], Hao Qiao[12], Zhonghua Qin[10], Shoukang Qiu[23], Muhammad Rajput[67], Gioacchino Ranucci[58], Neill Raper[20], Alessandra Re[58], Henning Rebber[49], Abdel Rebii[44], Bin Ren[18], Jie Ren[9], Taras Rezinko[68], Barbara Ricci[57], Markus Robens[51], Mathieu Roche[44], Narongkiat Rodphai[72], Aldo Romani[63], Bedřich Roskovec[75], Christian Roth[51], Xiangdong Ruan[28], Xichao Ruan[9], Saroj Rujirawat[74], Arseniy Rybnikov[68], Andrey Sadovsky[68], Paolo Saggese[58], Giuseppe Salamanna[65], Simone Sanfilippo[65], Anut Sangka[73], Nuanwan Sanguansak[74], Utane Sawangwit[73], Julia Sawatzki[53], Fatma Sawy[62], Michaela Schever[50,48], Jacky Schuler[45], Cédric Schwab[45], Konstantin Schweizer[53], Dmitry Selivanov[68], Alexandr Selyunin[68], Andrea Serafini[57], Giulio Settanta[50], Mariangela Settimo[47], Zhuang Shao[35], Vladislav Sharov[68], Jingyan Shi[10], Vitaly Shutov[68], Andrey Sidorenkov[69], Fedor Simkovic[71], Chiara Sirignano[62], Jaruchit Siripak[74], Monica Sisti[59], Maciej Slupecki[42], Mikhail Smirnov[20], Oleg Smirnov[68], Thiago Sogo-Bezerra[47], Julanan Songwadhana[74], Boonrucksar Soonthornthum[73], Albert Sotnikov[68], Ondrej Sramek[41], Warintorn Sreethawong[74], Achim Stahl[48], Luca Stanco[61], Konstantin Stankevich[70], Dus Stefanik[71], Hans Steiger[53], Jochen Steinmann[48], Tobias Sterr[54], Matthias Raphael Stock[53], Virginia Strati[57], Alexander Studenikin[70], Gongxing Sun[10], Shifeng Sun[11], Xilei Sun[10], Yongjie Sun[22], Yongzhao Sun[10], Narumon Suwonjandee[72], Michal Szelezniak[45], Jian Tang[20], Qiang Tang[20], Quan Tang[23], Xiao Tang[10], Alexander Tietzsch[54], Igor Tkachev[69], Tomas Tmej[41], Konstantin Treskov[68], Andrea Triossi[45], Giancarlo Troni[5], Wladyslaw Trzaska[42], Cristina Tuve[55], Nikita Ushakov[69], Stefan van Waasen[51], Johannes Vanden Boom[51], Guillaume Vanroyen[47], Nikolaos Vassilopoulos[10], Vadim Vedin[66], Giuseppe Verde[55], Maxim Vialkov[70], Benoit Viaud[47], Cristina Volpe[43], Vit Vorobel[41], Dmitriy Voronin[69], Lucia Votano[64], Pablo Walker[5], Caishen Wang[18], Chung-Hsiang Wang[39], En Wang[37], Guoli Wang[21], Jian Wang[22], Jun Wang[20], Kunyu Wang[10], Lu Wang[10], Meifen Wang[10], Meng Wang[25], Meng Wang[23], Ruiguang Wang[10], Siguang Wang[12], Wei Wang[27], Wei Wang[20], Wenshuai Wang[10], Xi Wang[16], Xiangyue Wang[20], Yangfu Wang[10], Yaoguang Wang[34], Yi Wang[13], Yi Wang[24], Yifang Wang[10], Yuanqing Wang[13], Yuman Wang[27], Zhe Wang[13], Zheng Wang[10], Zhimin Wang[10], Zongyi Wang[13], Muhammad Waqas[67], Apimook Watcharangkool[73], Lianghong Wei[10], Wei Wei[10], Yadong Wei[18], Liangjian Wen[10], Christopher Wiebusch[48], Steven Chan-Fai Wong[20], Bjoern Wonsak[49], Diru Wu[10], Fangliang Wu[27], Qun Wu[25], Wenjie Wu[34], Zhi Wu[10], Michael Wurm[52], Jacques Wurtz[45], Christian Wysotzki[48], Yufei Xi[32], Dongmei Xia[17], Yuguang Xie[10], Zhangquan Xie[10], Zhizhong Xing[10], Benda Xu[13], Cheng Xu[23], Donglian Xu[31,30], Fanrong Xu[19], Hangkun Xu[10], Jilei Xu[10], Jing Xu[8], Meihang Xu[10], Yin Xu[33], Yu Xu[50,48], Baojun Yan[10], Taylor Yan[74], Wenqi Yan[10], Xiongbo Yan[10], Yupeng Yan[74], Anbo Yang[10], Changgen Yang[10], Huan Yang[10], Jie Yang[37], Lei Yang[18], Xiaoyu Yang[10], Yifan Yang[2], Yifan Yang[10], Haifeng Yao[10], Zafar Yasin[67], Jiaxuan Ye[10], Mei Ye[10], Ziping Ye[31], Ugur Yegin[51], Frédéric Yermia[47], Peihuai Yi[10], Xiangwei Yin[10], Zhengyun You[20], Boxiang Yu[10], Chiye Yu[18], Chunxu Yu[33], Hongzhao Yu[20], Miao Yu[34], Xianghui Yu[33], Zeyuan Yu[10], Chengzhuo Yuan[10], Ying Yuan[12], Zhenxiong Yuan[13], Ziyi Yuan[34], Baobiao Yue[20], Noman Zafar[67], Andre Zambanini[51], Shan Zeng[10], Tingxuan Zeng[10], Yuda Zeng[20], Liang Zhan[10], Feiyang Zhang[30], Guoqing Zhang[10], Haiqiong Zhang[10], Honghao Zhang[20], Jiawen Zhang[10], Jie Zhang[10], Jingbo Zhang[21], Jinnan Zhang[10], Peng Zhang[10], Qingmin Zhang[35], Shiqi Zhang[20], Shu Zhang[20], Tao Zhang[30], Xiaomei Zhang[10], Xuantong Zhang[10], Yan Zhang[10], Yinhong Zhang[10], Yiyu Zhang[10], Yongpeng Zhang[10], Yuanyuan Zhang[30], Yumei Zhang[20], Zhenyu Zhang[34], Zhijian Zhang[18], Fengyi Zhao[26], Jie Zhao[10], Rong Zhao[20], Shujun Zhao[37], Tianchi Zhao[10], Dongqin Zheng[19], Hua Zheng[18], Minshan Zheng[9], Yangheng Zheng[14], Weirong Zhong[19], Jing Zhou[9], Li Zhou[10], Nan Zhou[22], Shun Zhou[10], Xiang Zhou[34], Jiang Zhu[20], Kejun Zhu[10], Bo Zhuang[10], Honglin Zhuang[10], Liang Zong[13], and Jiaheng Zou[10]

[1]Yerevan Physics Institute, Yerevan, Armenia
[2]Université Libre de Bruxelles, Brussels, Belgium
[3]Universidade Estadual de Londrina, Londrina, Brazil
[4]Pontificia Universidade Catolica do Rio de Janeiro, Rio, Brazil
[5]Pontificia Universidad Católica de Chile, Santiago, Chile
[6]Universidad Tecnica Federico Santa Maria, Valparaiso, Chile
[7]Beijing Institute of Spacecraft Environment Engineering, Beijing, China
[8]Beijing Normal University, Beijing, China
[9]China Institute of Atomic Energy, Beijing, China
[10]Institute of High Energy Physics, Beijing, China
[11]North China Electric Power University, Beijing, China
[12]School of Physics, Peking University, Beijing, China
[13]Tsinghua University, Beijing, China
[14]University of Chinese Academy of Sciences, Beijing, China
[15]Jilin University, Changchun, China
[16]College of Electronic Science and Engineering, National University of Defense Technology, Changsha, China
[17]Chongqing University, Chongqing, China
[18]Dongguan University of Technology, Dongguan, China
[19]Jinan University, Guangzhou, China
[20]Sun Yat-Sen University, Guangzhou, China
[21]Harbin Institute of Technology, Harbin, China

[22]University of Science and Technology of China, Hefei, China
[23]The Radiochemistry and Nuclear Chemistry Group in University of South China, Hengyang, China
[24]Wuyi University, Jiangmen, China
[25]Shandong University, Jinan, China
[26]Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China
[27]Nanjing University, Nanjing, China
[28]Guangxi University, Nanning, China
[29]East China University of Science and Technology, Shanghai, China
[30]School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai, China
[31]Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai, China
[32]Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Sciences, Shijiazhuang, China
[33]Nankai University, Tianjin, China
[34]Wuhan University, Wuhan, China
[35]Xi'an Jiaotong University, Xi'an, China
[36]Xiamen University, Xiamen, China
[37]School of Physics and Microelectronics, Zhengzhou University, Zhengzhou, China
[38]Institute of Physics National Chiao-Tung University, Hsinchu
[39]National United University, Miao-Li
[40]Department of Physics, National Taiwan University, Taipei
[41]Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
[42]University of Jyvaskyla, Department of Physics, Jyvaskyla, Finland
[43]IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405 Orsay, France
[44]Université de Bordeaux, CNRS, CENBG-IN2P3, F-33170 Gradignan, France
[45]IPHC, Université de Strasbourg, CNRS/IN2P3, F-67037 Strasbourg, France
[46]Centre de Physique des Particules de Marseille, Marseille, France
[47]SUBATECH, Université de Nantes, IMT Atlantique, CNRS-IN2P3, Nantes, France
[48]III. Physikalisches Institut B, RWTH Aachen University, Aachen, Germany
[49]Institute of Experimental Physics, University of Hamburg, Hamburg, Germany
[50]Forschungszentrum Jülich GmbH, Nuclear Physics Institute IKP-2, Jülich, Germany
[51]Forschungszentrum Jülich GmbH, Central Institute of Engineering, Electronics and Analytics - Electronic Systems(ZEA-2), Jülich, Germany
[52]Institute of Physics, Johannes-Gutenberg Universität Mainz, Mainz, Germany
[53]Technische Universität München, München, Germany
[54]Eberhard Karls Universität Tübingen, Physikalisches Institut, Tübingen, Germany
[55]INFN Catania and Dipartimento di Fisica e Astronomia dell Università di Catania, Catania, Italy
[56]INFN Catania and Centro Siciliano di Fisica Nucleare e Struttura della Materia, Catania, Italy
[57]Department of Physics and Earth Science, University of Ferrara and INFN Sezione di Ferrara, Ferrara, Italy
[58]INFN Sezione di Milano and Dipartimento di Fisica dell Università di Milano, Milano, Italy
[59]INFN Milano Bicocca and University of Milano Bicocca, Milano, Italy
[60]INFN Milano Bicocca and Politecnico of Milano, Milano, Italy
[61]INFN Sezione di Padova, Padova, Italy
[62]Dipartimento di Fisica e Astronomia dell'Universita' di Padova and INFN Sezione di Padova, Padova, Italy

[63]INFN Sezione di Perugia and Dipartimento di Chimica, Biologia e Biotecnologie dell'Università di Perugia, Perugia, Italy
[64]Laboratori Nazionali di Frascati dell'INFN, Roma, Italy
[65]University of Roma Tre and INFN Sezione Roma Tre, Roma, Italy
[66]Institute of Electronics and Computer Science, Riga, Latvia
[67]Pakistan Institute of Nuclear Science and Technology, Islamabad, Pakistan
[68]Joint Institute for Nuclear Research, Dubna, Russia
[69]Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
[70]Lomonosov Moscow State University, Moscow, Russia
[71]Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics, Bratislava, Slovakia
[72]Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand
[73]National Astronomical Research Institute of Thailand, Chiang Mai, Thailand
[74]Suranaree University of Technology, Nakhon Ratchasima, Thailand
[75]Department of Physics and Astronomy, University of California, Irvine, California, USA