PROCEEDINGS OF SCIENCE
ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

# Feasibility and physics potential of detecting $^8$B solar neutrinos at JUNO

---

**Jie Zhao**[a,*] **on behalf of the JUNO Collaboration**
(a complete list of authors can be found at the end of the proceedings)

[a] *Institute of High Energy Physics, Beijing, China*
*E-mail:* zhaojie@ihep.ac.cn

The Jiangmen Underground Neutrino Observatory (JUNO) features a 20 kt multi-purpose underground liquid scintillator sphere as its main detector. In this talk we describe in detail a comprehensive assessment of JUNO's potential for detecting $^8$B solar neutrinos via the neutrino-electron elastic scattering process. A reduced 2 MeV threshold for the recoil electron energy is achievable with optimized background reduction strategies. With ten years of data taking, about 60,000 signal and 30,000 background events are expected. This leads to a simultaneous measurement of $\sin^2\theta_{12}$and $\Delta m^2_{21}$using reactor antineutrinos and solar neutrinos in the JUNO detector. This large sample will enable an examination of the distortion of the recoil electron spectrum that is dominated by the neutrino flavor transformation in the dense solar matter. If $\Delta m^2_{21} = 4.8 \times 10^{-5} (7.5 \times 10^{-5} eV^2)$, JUNO can provide evidence of neutrino oscillation in the Earth at approximately the $3\sigma$ $(2\sigma)$ level by measuring the non-zero signal rate variation with respect to the solar zenith angle. Moreover, JUNO can simultaneously measure $\Delta m^2_{21}$ using $^8$B solar neutrinos to a precision of 20% or better, depending on the central value, and to sub-percent precision using reactor antineutrinos. A comparison of these two measurements from the same detector will help understand the current mild inconsistency between the value of reported by solar neutrino experiments and the KamLAND experiment.

*37th International Cosmic Ray Conference (ICRC 2021)*
*July 12th – 23rd, 2021*
*Online – Berlin, Germany*

---

[*] Presenter

https://pos.sissa.it/

PoS(ICRC2021)1229

## 1. Introduction

Solar neutrinos, produced during nuclear fusion in the solar core, have played an important role in the history of neutrino physics. The standard scenario of three neutrino mixing predicts a smooth upturn in the survival probability ($P_{ee}$) in the neutrino energy region between the high (MSW dominated) and low (vacuum dominated) ranges, and a sizable Day-Night asymmetry at the percentage level. The combined Super-K and SNO fitting favors $\Delta m^2_{21} = 4.8 \times 10^{-5}$ eV$^2$ [1], while KamLAND gives $\Delta m^2_{21} = 7.53 \times 10^{-5}$ eV$^2$ [2]. From the latest results at the Neutrino 2020 conference [3], the inconsistency is reduced from $2\sigma$ to around $1.4\sigma$ due to the larger statistics and the update of analysis methods.

Determining whether this inconsistency is a statistical fluctuation or a physical effect beyond the standard neutrino oscillation framework requires further measurements. The Jiangmen Underground Neutrino Observatory (JUNO), a 20 kt multi-purpose underground liquid scintillator (LS) detector, can simultaneously measure $\Delta m^2_{21}$ using $^8$B solar neutrinos reactor antineutrinos. The analysis threshold for the recoil electrons can be decreased to 2 MeV, assuming an achievable intrinsic radioactivity background level and better muon veto strategies. The lower threshold leads to larger signal statistics and a more sensitive examination of the spectrum distortion of recoil electrons. New measurement of the non-zero signal rate variation versus the solar zenith angle (Day-Night asymmetry) is also expected. After combining with the $^8$B neutrino flux from the SNO NC measurement, the $\Delta m^2_{21}$ precision is expected to be similar to the current global fitting results [4].

## 2. Solar neutrino detection at JUNO

In LS detectors, the primary detection channel for solar neutrinos is their elastic scattering with electrons. In this study, we assume an arrival $^8$B neutrino flux of $(5.25\pm0.20)\times10^6$ /cm$^2$ /s provided by the NC channel measurement at SNO [5]. The $^8$B neutrino spectra and shape uncertainties are taken from Refs. [6, 7] as shown in the left figure 1. Taking the MSW effects in both the Sun and the Earth into consideration, the $\nu_e$ survival probabilities ($P_{ee}$) with respect to the neutrino energy for the two $\Delta m^2_{21}$ values are shown in the right figure 1.

After scattering, the total energy and momentum of the neutrino and electron are redistributed. The expected signal rate in the full energy range is 4.15 (4.36) counts per day per kt (cpd/kt) for $\Delta m^2_{21} = 4.8(7.5) \times 10^{-5}$ eV$^2$.

## 3. Background budget

### 3.1 Internal radioactivity

As a feasibility study, we start with $10^{-17}$ g/g U and Th in the secular equilibrium, which are close to those of Borexino Phase I [8]. The top plot of figure 2 shows the internal background spectrum under the assumptions above. The background can be further reducted by the time, space, and energy correlation from the Bi-Po/Bi-Tl cascade decays, and the results are shown in the bottom plot of figure 2.

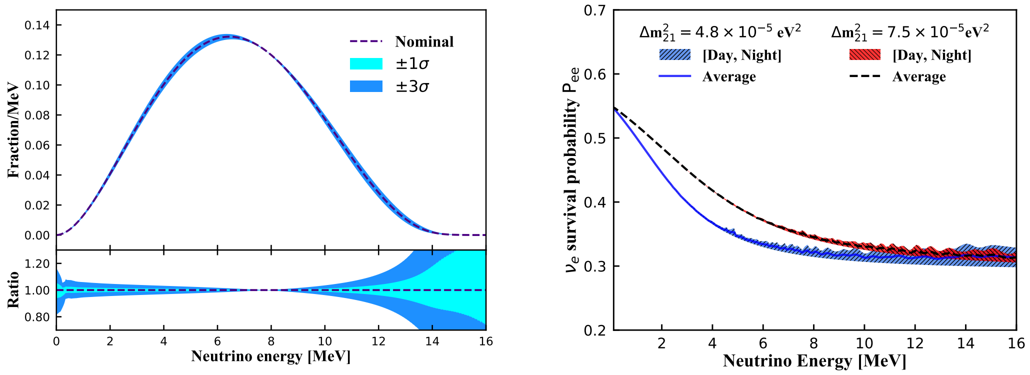

**Figure 1:** Left: $^8$B $\nu_e$ spectrum together with the shape uncertainties. The data are taken from Ref.[26]. Right: Solar $\nu_e$ survival probabilities ($P_{ee}$) with respect to the neutrino energy. The shadowed area shows the variation of at different solar zenith angles.

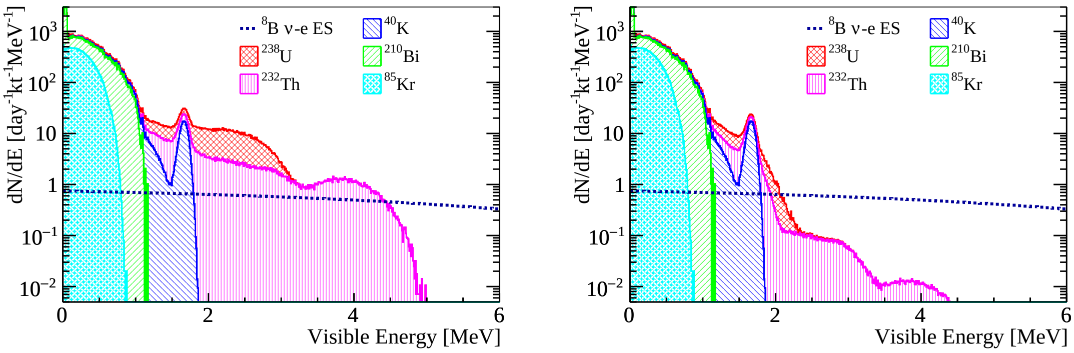

**Figure 2:** Internal radioactivity background compared with $^8$B signal before (left) and after (right) time, space, and energy correlation cuts to remove the Bi-Po/Bi-Tl cascade decays.

### 3.2 External radioactivity

All detector materials at JUNO have been carefully selected to fulfill radiopurity requirements. With the measured radioactivity values, a simulation is performed to obtain the external deposited energy spectrum in the LS. According to the simulation results, an energy dependent fiducial volume (FV) cut, in terms of the reconstructed radial position (r) in the spherical coordinate system, is designed as follows:

- $2 < E_{\text{vis}} \leq 3$ MeV, $r < 13$ m, 7.9 kt target mass;
- $3 < E_{\text{vis}} \leq 5$ MeV, $r < 15$ m, 12.2 kt target mass;
- $E_{\text{vis}} > 5$ MeV, $r < 16.5$ m, 16.2 kt target mass.

In this way, the external radioactivity background is suppressed to less than 0.5% compared with the signals in the entire energy range, while the signal statistics are maximized at high energies.

### 3.3 Cosmogenic isotopes

The relatively shallow vertical rock overburden, approximately 680 m, leads to a 0.0037 Hz/m muon flux, with an averaged energy of 209 GeV. The direct consequence is approximately 3.6 Hz muons passing through the LS target. More than 10,000 $^{11}$C isotopes are generated per day, which constrains the analysis threshold to 2 MeV, as shown in figure 3. Based on the simulation and measurements of previous experiments, it is found that other isotopes can be suppressed to a 1‰ level with a cylindrical veto along the muon track and the Three-Fold Coincidence cut (TFC) among the muon, the spallation neutron capture, and the isotope decay.

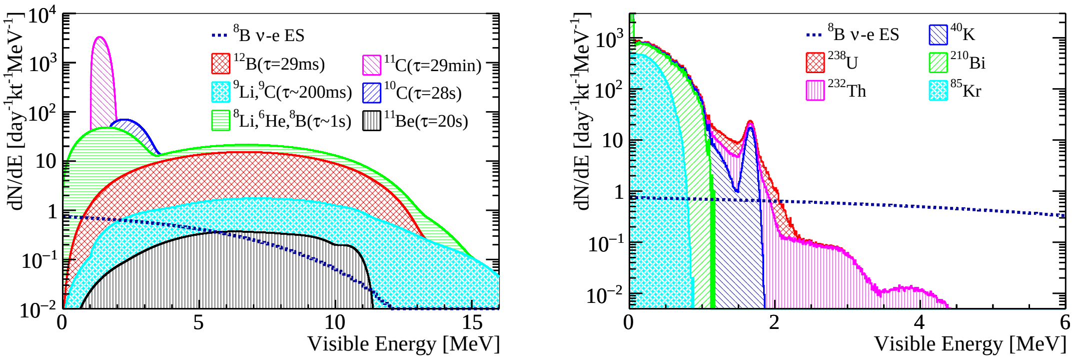

**Figure 3:** Cosmogenic background before (left) and after veto (right). The isotope yields shown here are scaled from the KamLAND's [48] and Borexino's measurements [49]. The huge amount of $^{11}$C constrains the analysis threshold to 2 MeV. The others isotopes can be well suppressed with veto strategies discussed in the text.

## 4. Expected results

After applying all the selection cuts, about 60,000 recoil electrons and 30,000 background events are expected in 10 years of data taking as shown in figure 4.

### 4.1 Spectrum distortion test

A background-subtracted Asimov data set is produced in the standard LMA-MSW framework using different $\Delta m^2_{21}$ values, shown as the black dots and red line in the left figure 5. We would like to test an energy-independent hypothesis, where the $P_{ee}$ is assumed as a flat value for neutrino energies larger than 2 MeV. This hypothesis is rejected at $2.7\sigma$ with $\Delta m^2_{21} = 7.5 \times 10^{-5}$ eV$^2$.

### 4.2 Day-Night asymmetry

Solar neutrino propagation through the Earth is expected, via the MSW effect, to cause signal rate variation versus the solar zenith angle. This rate variation observable also provides additional sensitivity to the $\Delta m^2_{21}$ value, as shown in the right figure 5. The variation is quantified by defining the Day-Night asymmetry as:

$$A_{DN} = \frac{R_D - R_N}{(R_D + R_N)/2}, \qquad (1)$$

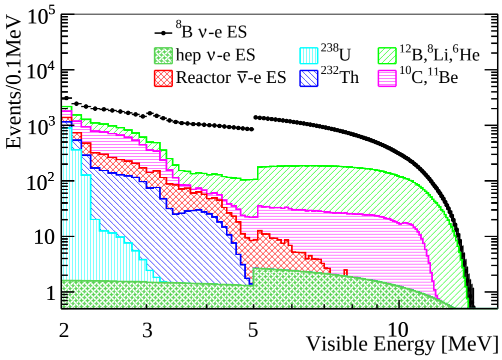

**Figure 4:** Expected signal and background spectra in ten years of data taking, with all selection cuts and muon veto methods applied.

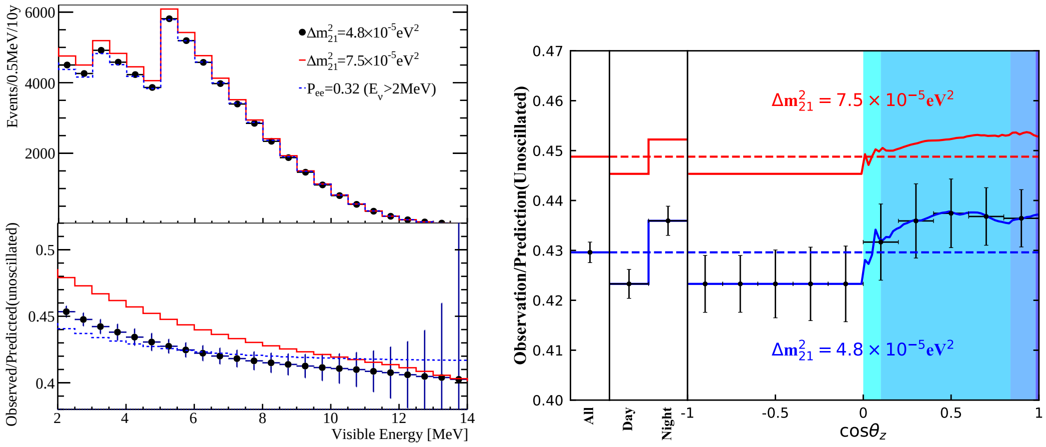

**Figure 5:** Left: Background subtracted spectra produced in the standard LMA-MSW framework for two $\Delta m^2_{21}$ values (black dots and red line, respectively), and the $P_{ee} = 0.32$ ($E_\nu > 2$ MeV) assumption (blue line). Their comparison with the no flavor conversion is shown in the bottom panel. Right: Ratio of $^8$B neutrino signals produced in the standard LMA-MSW framework to the no-oscillation prediction at different solar zenith angles.

where $R_D$ and $R_N$ are the background-subtracted signal rates during the Day ($\cos\theta_z < 0$) and Night ($\cos\theta_z > 0$), respectively. Compared with Super-Kamiokande's results from Ref. [1], JUNO could reach the same precision of $A_{DN}$ in less than 10 years.

### 4.3 Measurement of oscillation parameters

As mentioned above, in the standard neutrino oscillation framework, $\Delta m^2_{21}$ can be measured using the information in the spectra distortion and the signal rate variation versus solar zenith angle. With ten years of data taking the expected sensitivity of $\sin^2\theta_{12}$ and $\Delta m^2_{21}$ is shown in Fig. 6.

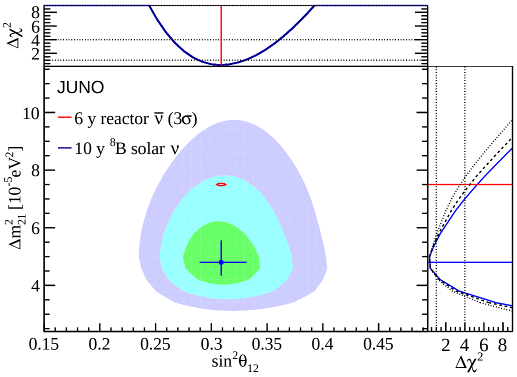

**Figure 6:** 68.3%, 95.5%, and 99.7% C.L. allowed regions in the $\sin^2\theta_{12}$ and $\Delta m^2_{21}$ plane using the $^8$B solar neutrino in ten years data taking. The one-dimensional $\Delta\chi^2$ for $\sin^2\theta_{12}$ and $\Delta m^2_{21}$ are shown in the top and right panels, respectively.

## 5. Summary

The JUNO experiment, with a 20 kt LS detector, can shed light on the current inconsistency between $\Delta m^2_{21}$ values measured using solar neutrinos and reactor antineutrinos. A set of energy-dependent FV cuts is newly designed based on comprehensive background studies, leading to the maximized target mass with negligible external background. A set of distance-dependent veto time cuts are developed for the cylindrical veto along the muon track, resulting in a significantly improved signal to background ratio. In the standard three-flavor neutrino oscillation framework, the spectrum distortion and the Day-Night asymmetry lead to a $\Delta m^2_{21}$ measurement of $4.8^{+0.8}_{-0.5}$ $(7.5^{+1.6}_{-1.2})\times10^{-5}$ eV$^2$, with a similar precision to the current solar global fitting result. Details of this study can be found in [9].

## References

[1] K. Abe *et al.*, Phys. Rev. D 94(5), 052010 (2016)

[2] A. Gando *et al.*, Phys. Rev. D 88(3), 033001 (2013)

[3] Yasuhiro Nakajima, Recent results and future prospects from Super-Kamiokande, Presentation at the XXIX International Conference on Neutrino Physics and Astrophysics (Neutrino 2020), June 2020

[4] Ivan Esteban and M. C. Gonzalez-Garcia, JHEP 01, 106 (2019)

[5] B. Aharmim *et al.*, Phys. Rev. C 88, 025501 (2013)

[6] John N. Bahcall, E. Lisi, D. E. Alburger et al., Phys. Rev. C 54, 411-422 (1996)

[7] John N. Bahcall, Phys. Rev. C 56, 3391-3409 (1997)

[8] C. Arpesella *et al.*, Phys. Rev. Lett. 101, 091302 (2008)

[9] Angel Abusleme *et al.*, Chinese Phys. C 45 023004 (2021)

## Full Authors List: JUNO Collaboration

Angel Abusleme[5], Thomas Adam[45], Shakeel Ahmad[66], Rizwan Ahmed[66], Sebastiano Aiello[55], Muhammad Akram[66], Fengpeng An[29], Qi An[22], Giuseppe Andronico[55], Nikolay Anfimov[67], Vito Antonelli[57], Tatiana Antoshkina[67], Burin Asavapibhop[71], João Pedro Athayde Marcondes de André[45], Didier Auguste[43], Andrej Babic[70], Nikita Balashov[67], Wander Baldini[56], Andrea Barresi[58], Davide Basilico[57], Eric Baussan[45], Marco Bellato[60], Antonio Bergnoli[60], Thilo Birkenfeld[48], Sylvie Blin[43], David Blum[54], Simon Blyth[40], Anastasia Bolshakova[67], Mathieu Bongrand[47], Clément Bordereau[44,40], Dominique Breton[43], Augusto Brigatti[57], Riccardo Brugnera[61], Riccardo Bruno[55], Antonio Budano[64], Mario Buscemi[55], Jose Busto[46], Ilya Butorov[67], Anatael Cabrera[43], Hao Cai[34], Xiao Cai[10], Yanke Cai[10], Zhiyan Cai[10], Riccardo Callegari[61], Antonio Cammi[59], Agustin Campeny[5], Chuanya Cao[10], Guofu Cao[10], Jun Cao[10], Rossella Caruso[55], Cédric Cerna[44], 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], Alexey Chetverikov[67], Davide Chiesa[58], Pietro Chimenti[3], Artem Chukanov[67], Gérard Claverie[44], Catia Clementi[62], Barbara Clerbaux[2], Selma Conforti Di Lorenzo[44], Daniele Corti[60], Flavio Dal Corso[60], Olivia Dalager[74], Christophe De La Taille[44], Jiawei Deng[34], Zhi Deng[13], Ziyan Deng[10], Wilfried Depnering[52], Marco Diaz[5], Xuefeng Ding[57], Yayun Ding[10], Bayu Dirgantara[73], Sergey Dmitrievsky[67], Tadeas Dohnal[41], Dmitry Dolzhikov[67], Georgy Donchenko[69], Jianmeng Dong[13], Evgeny Doroshkevich[68], Marcos Dracos[45], Frédéric Druillole[44], Ran Du[10], Shuxian Du[37], Stefano Dusini[60], Martin Dvorak[41], Timo Enqvist[42], Heike Enzmann[52], Andrea Fabbri[64], Lukas Fajt[70], Donghua Fan[24], Lei Fan[10], Jian Fang[10], Wenxing Fang[10], Marco Fargetta[55], Dmitry Fedoseev[67], Vladko Fekete[70], Li-Cheng Feng[38], Qichun Feng[21], Richard Ford[57], Amélie Fournier[44], Haonan Gan[32], Feng Gao[48], Alberto Garfagnini[61], Arsenii Gavrikov[61], Marco Giammarchi[57], Agnese Giaz[61], Nunzio Giudice[55], Maxim Gonchar[67], Guanghua Gong[13], Hui Gong[13], Yuri Gornushkin[67], Alexandre Göttel[50,48], Marco Grassi[61], Christian Grewing[51], Vasily Gromov[67], Minghao Gu[10], Xiaofei Gu[37], Yu Gu[19], Mengyun Guan[10], Nunzio Guardone[55], Maria Gul[66], Cong Guo[10], Jingyuan Guo[20], Wanlei Guo[10], Xinheng Guo[8], Yuhang Guo[35,50], Paul Hackspacher[52], Caren Hagner[49], Ran Han[7], Yang Han[20], Muhammad Sohaib Hassan[66], Miao He[10], Wei He[10], Tobias Heinz[54], Patrick Hellmuth[44], Yuekun Heng[10], Rafael Herrera[5], YuenKeung Hor[20], 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], 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[66], Ara Ioannisian[1], Roberto Isocrate[60], Beatrice Jelmini[61], Kuo-Lun Jen[38], Ignacio Jeria[5], Xiaolu Ji[10], Xingzhao Ji[20], Huihui Jia[33], Junji Jia[34], Siyu Jian[9], Di Jiang[22], Wei Jiang[10], Xiaoshan Jiang[10], Ruyi Jin[10], Xiaoping Jing[10], Cécile Jollet[44], Jari Joutsenvaara[42], Sirichok Jungthawan[73], Leonidas Kalousis[45], Philipp Kampmann[50], Li Kang[18], Rebin Karaparambil[47], Narine Kazarian[1], Khanchai Khosonthongkee[73], Denis Korablev[67], Konstantin Kouzakov[69], Alexey Krasnoperov[67], Andre Kruth[51], Nikolay Kutovskiy[67], Pasi Kuusiniemi[42], Tobias Lachenmaier[54], Cecilia Landini[57], Sébastien Leblanc[44], Victor Lebrin[47], Frederic Lefevre[47], Ruiting Lei[18], Rupert Leitner[41], Jason Leung[38], Demin Li[37], Fei Li[10], Fule Li[13], Haitao Li[20], Huiling Li[10], Jiaqi Li[20], Mengzhao Li[10], Min Li[11], Nan Li[10], Nan Li[16], Qingjiang Li[16], Ruhui Li[10], Shanfeng Li[18], Tao Li[20], Weidong Li[10,14], 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[9], Hao Liang[22], Jiajun Liao[20], Daniel Liebau[51], Ayut Limphirat[73], Sukit Limpijumnong[73], Guey-Lin Lin[38], Shengxin Lin[18], Tao Lin[10], Jiajie Ling[20], Ivano Lippi[60], Fang Liu[11], Haidong Liu[37], Hongbang Liu[28], Hongjuan Liu[23], Hongtao 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[69,68], Paolo Lombardi[57], Claudio Lombardo[55], Kai Loo[52], Chuan Lu[32], Haoqi Lu[10], Jingbin Lu[15], Junguang Lu[10], Shuxiang Lu[37], Xiaoxu Lu[10], Bayarto Lubsandorzhiev[68], Sultim Lubsandorzhiev[68], Livia Ludhova[50,48], Arslan Lukanov[68], Fengjiao Luo[10], Guang Luo[20], Pengwei Luo[20], Shu Luo[36], Wuming Luo[10], Vladimir Lyashuk[68], Bangzheng Ma[25], Qiumei Ma[10], Si Ma[10], Xiaoyan Ma[10], Xubo Ma[11], Jihane Maalmi[43], Yury Malyshkin[67], Roberto Carlos Mandujano[67], Fabio Mantovani[56], Francesco Manzali[61], Xin Mao[7], Yajun Mao[12], Stefano M. Mari[64], Filippo Marini[61], Sadia Marium[66], Cristina Martellini[64], Gisele Martin-Chassard[43], Agnese Martini[63], Matthias Mayer[53], Davit Mayilyan[1], Ints Mednieks[65], Yue Meng[30], Anselmo Meregaglia[44], Emanuela Meroni[57], David Meyhöfer[49], Mauro Mezzetto[60], Jonathan Miller[6], Lino Miramonti[57], Paolo Montini[64], Michele Montuschi[56], Axel Müller[54], Massimiliano Nastasi[58], Dmitry V. Naumov[67], Elena Naumova[67], Diana Navas-Nicolas[43], Igor Nemchenok[67], Minh Thuan Nguyen Thi[38], Feipeng Ning[10], Zhe Ning[10], Hiroshi Nunokawa[4], Lothar Oberauer[53], Juan Pedro Ochoa-Ricoux[74,5], Alexander Olshevskiy[67], Domizia Orestano[64], Fausto Ortica[62], Rainer Othegraven[52], Hsiao-Ru Pan[40], Alessandro Paoloni[63], Sergio Parmeggiano[57], Yatian Pei[10], Nicomede Pelliccia[62], Anguo Peng[23], Haiping Peng[22], Frédéric Perrot[44], Pierre-Alexandre Petitjean[2], Fabrizio Petrucci[64], Oliver Pilarczyk[52], Luis Felipe Piñeres Rico[45], Artyom Popov[69], Pascal Poussot[45], Wathan Pratumwan[73], Ezio Previtali[58], Fazhi Qi[10], Ming Qi[27], Sen Qian[10], Xiaohui Qian[10], Zhen Qian[20], Hao Qiao[12], Zhonghua Qin[10], Shoukang Qiu[23], Muhammad Usman Rajput[66], Gioacchino Ranucci[57], Neill Raper[20], Alessandra Re[57], Henning Rebber[49], Abdel Rebii[44], Bin Ren[18], Jie Ren[9], Barbara Ricci[56], Markus Robens[51], Mathieu Roche[44], Narongkiat Rodphai[71], Aldo Romani[62], Bedřich Roskovec[41], Christian Roth[51], Xiangdong Ruan[28], Xichao Ruan[9], Saroj Rujirawat[73], Arseniy Rybnikov[67], Andrey Sadovsky[67], Paolo Saggese[57], Simone Sanfilippo[64], Anut Sangka[72], Nuanwan Sanguansak[73], Utane Sawangwit[72], Julia Sawatzki[53], Fatma Sawy[61], Michaela Schever[50,48], Cédric Schwab[45], Konstantin Schweizer[53], Alexandr Selyunin[67], Andrea Serafini[56], Giulio Settanta[50], Mariangela Settimo[47], Zhuang Shao[35], Vladislav Sharov[67], Arina Shaydurova[67], Jingyan Shi[10], Yanan Shi[10], Vitaly Shutov[67], Andrey Sidorenkov[68], Fedor Šimkovic[70], Chiara Sirignano[61], Jaruchit Siripak[73], Monica Sisti[58], Maciej Slupecki[42], Mikhail Smirnov[20], Oleg Smirnov[67], Thiago Sogo-Bezerra[47], Sergey Sokolov[67], Julanan Songwadhana[73], Boonrucksar Soonthornthum[72], Albert Sotnikov[67], Ondřej Šrámek[41], Warintorn Sreethawong[73], Achim Stahl[48], Luca Stanco[60], Konstantin Stankevich[69], Dušan Štefánik[70], Hans Steiger[52,53], Jochen Steinmann[48], Tobias Sterr[54], Matthias Raphael Stock[53], Virginia Strati[56], Alexander Studenikin[69], Shifeng Sun[11], Xilei Sun[10], Yongjie Sun[22], Yongzhao Sun[10], Narumon Suwonjandee[71], Michal Szelezniak[45], Jian Tang[20], Qiang Tang[20], Quan Tang[23], Xiao Tang[10], Alexander Tietzsch[54], Igor Tkachev[68], Tomas Tmej[41], Marco Danilo Claudio Torri[41], Konstantin Treskov[67], Andrea Triossi[45], Giancarlo Troni[5], Wladyslaw Trzaska[42], Cristina

Tuve[55], Nikita Ushakov[68], Johannes van den Boom[51], Stefan van Waasen[51], Guillaume Vanroyen[47], Vadim Vedin[65], Giuseppe Verde[55], Maxim Vialkov[69], Benoit Viaud[47], Moritz Vollbrecht[50,48], Cristina Volpe[43], Vit Vorobel[41], Dmitriy Voronin[68], Lucia Votano[63], 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[23], Meng Wang[25], 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[10], 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[66], Apimook Watcharangkool[72], Lianghong Wei[10], Wei Wei[10], Wenlu Wei[10], Yadong Wei[18], Kaile Wen[10], Liangjian Wen[10], Christopher Wiebusch[48], Steven Chan-Fai Wong[20], Bjoern Wonsak[49], Diru Wu[10], Qun Wu[25], Zhi Wu[10], Michael Wurm[52], Jacques Wurtz[45], Christian Wysotzki[48], Yufei Xi[32], Dongmei Xia[17], Xiaochuan Xie[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[73], Wenqi Yan[10], Xiongbo Yan[10], Yupeng Yan[73], Anbo Yang[10], Changgen Yang[10], Chengfeng Yang[28], Huan Yang[10], Jie Yang[37], Lei Yang[18], Xiaoyu Yang[10], Yifan Yang[10], Yifan Yang[2], Haifeng Yao[10], Zafar Yasin[66], Jiaxuan Ye[10], Mei Ye[10], Ziping Ye[31], Ugur Yegin[51], Frédéric Yermia[47], Peihuai Yi[10], Na Yin[25], 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], Zezhong Yu[10], Chengzhuo Yuan[10], Ying Yuan[12], Zhenxiong Yuan[13], Ziyi Yuan[34], Baobiao Yue[20], Noman Zafar[66], Andre Zambanini[51], Vitalii Zavadskyi[67], Shan Zeng[10], Tingxuan Zeng[10], Yuda Zeng[20], Liang Zhan[10], Aiqiang Zhang[13], Feiyang Zhang[30], Guoqing Zhang[10], Haiqiong Zhang[10], Honghao Zhang[20], Jiawen Zhang[10], Jie Zhang[10], Jin Zhang[28], 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], Xueyao Zhang[25], 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], Tong Zhou[10], Xiang Zhou[34], Jiang Zhu[20], Kangfu Zhu[35], Kejun Zhu[10], Zhihang 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, and Key Laboratory of Particle Physics and Particle Irradiation of Ministry of Education, Shandong University, Qingdao, 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 Yang Ming 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]Univ. Bordeaux, CNRS, CENBG, UMR 5797, 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]Department of Physics and Earth Science, University of Ferrara and INFN Sezione di Ferrara, Ferrara, Italy. [57]INFN Sezione di Milano and Dipartimento di Fisica dell Università di Milano, Milano, Italy. [58]INFN Milano Bicocca and University of Milano Bicocca, Milano, Italy. [59]INFN Milano Bicocca and Politecnico of Milano, Milano, Italy. [60]INFN Sezione di Padova, Padova, Italy. [61]Dipartimento di Fisica e Astronomia dell'Università di Padova and INFN Sezione di Padova, Padova, Italy. [62]INFN Sezione di Perugia and Dipartimento di Chimica, Biologia e Biotecnologie dell'Università di Perugia, Perugia, Italy. [63]Laboratori Nazionali di Frascati dell'INFN, Roma, Italy. [64]University of Roma Tre and INFN Sezione Roma Tre, Roma, Italy. [65]Institute of Electronics and Computer Science, Riga, Latvia. [66]Pakistan Institute of Nuclear Science and Technology, Islamabad, Pakistan. [67]Joint Institute for Nuclear Research, Dubna, Russia. [68]Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia. [69]Lomonosov Moscow State University, Moscow, Russia. [70]Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics, Bratislava, Slovakia. [71]Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand. [72]National Astronomical Research Institute of Thailand, Chiang Mai, Thailand. [73]Suranaree University of Technology,

Nakhon Ratchasima, Thailand. [74]Department of Physics and Astronomy, University of California, Irvine, California, USA.