PROCEEDINGS OF SCIENCE

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

Detection of the diffuse supernova neutrino background with JUNO

Jie Cheng[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, Chinese Academy of Sciences, Beijing, China*
E-mail: chengjie@ihep.ac.cn

As an underground multi-purpose neutrino detector with 20 kton liquid scintillator, Jiangmen Underground Neutrino Observatory (JUNO) is competitive with and complementary to the water-Cherenkov detectors on the search for the diffuse supernova neutrino background (DSNB). Typical supernova models predict 2-4 events per year within the optimal observation window in the JUNO detector. The dominant background is from the neutral-current (NC) interaction of atmospheric neutrinos with ^{12}C nuclei, which surpasses the DSNB by more than one order of magnitude. We evaluated the systematic uncertainty of NC background from the spread of a variety of data-driven models and further developed a method to determine NC background within 15% with *in situ* measurements after ten years of running. Besides, the NC-like backgrounds can be effectively suppressed by the intrinsic pulse-shape discrimination (PSD) capabilities of liquid scintillators. In this talk, I will present in detail the improvements on NC background uncertainty evaluation, PSD discriminator development, and finally, the potential of DSNB sensitivity in JUNO.

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

*Presenter

https://pos.sissa.it/

PoS(ICRC2021)1187

1. Introduction

The integrated flux of neutrinos from all past core-collapse supernovae in the visible universe form the diffuse supernova neutrino background (DSNB), which carries valuable information on the cosmic star-formation rate, the average core-collapse neutrino spectrum, and the rate of failed SNe. The existing and future large water-Cherenkov (wCh) and liquid-scintillator (LS) detectors have good potential to observe the DSNB via the inverse-beta-decay (IBD) reaction, $\overline{\nu}_e + p \to e^+ + n$, which consists of a prompt signal of positron and a delayed signal of neutron capture. The event rate of the DSNB is very rare. So far, no appreciable IBD signal events of the DSNB $\overline{\nu}_e$ have been found in wCh and LS detectors.

Comparing to the wCh detectors, the LS detectors have lower energy thresholds, higher energy resolution, and more than 99% neutron tagging capability. The dominant background is from the neutral-current (NC) interactions of atmospheric neutrinos with the carbon nuclei in LS. JUNO [1, 2] consists of a 20 kt liquid scintillator (LS) detector. Depending on the DSNB model, we expect about 2−4 IBD events per year in the energy range above the reactor $\overline{\nu}_e$ signal. Given the excellent light yield, the delayed signal from neutron capture on hydrogen in the LS offers a efficient tag for background reduction, while pulse-shape discrimination helps to suppress the background from atmospheric neutrino NC interactions. Hence, JUNO is competitive with and complementary to the wCh detectors like SuperK-Gd.

2. DSNB signal prediction

The DSNB signal spectrum in detector in terms of the measured energy (E_{prompt}) is given by:

$$\frac{dS(E_{\text{prompt}})}{dE_{\text{prompt}}} = N_p \times \sigma(E_\nu) \times J(E_\nu) \times \frac{d\phi}{dE}(E_\nu)\,, \tag{1}$$

where, N_p is the number of protons of JUNO LS. $\sigma(E_\nu)$ is the energy dependent IBD cross section [3]. $J(E_\nu)$ is the Jacobian factor, which is used to convert $dS(E_\nu)/dE_\nu$ to $dS(E_{\text{prompt}})/dE_{\text{prompt}}$. The last term is the DSNB flux, which can be obtained by

$$\frac{d\phi}{dE_\nu} = \int_0^5 R_{\text{SN}}(z)\frac{dN\left(E'_\nu\right)}{dE'_\nu}(1+z)\left|\frac{cdt}{dz}\right| dz, \tag{2}$$

where c is the speed of light, $|\mathrm{dt/dz}|^{-1} = H_0(1+z)\,[\Omega_\Lambda + \Omega_m(1+z)^3]^{\frac{1}{2}}$ includes the Hubble constant ($\mathrm{H_0}$ = 70 km × s^{-1} × Mpc^{-1}) and the ratios of the energy density of matter and the cosmological constant ($\Omega_\Lambda = 0.7$ and $\Omega_\mathrm{m} = 0.3$). Due to the red shift effect, a neutrino received at the energy E_ν was emitted at a higher energy $E'_\nu = E_\nu(1+z)$. Hence, the factor $(1+z)$ on the spectrum accounts for the compression of the energy scale. dN/dE_ν is the average SN neutrino spectrum, which has the contributions from successful and failed SNe. The average SN neutrino spectrum is in terms of average neutrino energy ($\langle E_\nu\rangle$), fraction of failed SNe (f_{BH}) and core-collapse supernova rate ($R_{\text{SN}}(0)$). However, these parameters are uncertain. Hence, we take a reference set ($\langle E_\nu\rangle = 15$ MeV, $f_{\text{BH}} = 0.27$ and $R_{\text{SN}}(0) = 1 \times 10^{-4}$ yr^{-1} Mpc^{-3}) and scan of a broad parameter region for sensitivity study.

3. Background prediction

The background sources are from the near reactor $\overline{\nu}_e$'s, fast neutron, cosmogenic ^{9}Li/^{8}He and atmospheric neutrino NC/charge current (CC) interactions, for which the NC interaction of atmospheric neutrinos with ^{12}C is one of the most significant source of the backgrounds, approximately one order magnitude of the DSNB signal [1].

Fast neutron background is induced by untagged muons that most of them only pass through the surrounding rock. The water as the protective aquifer is used to shield the fast neutrons, leading that most of fast neutrons capture in the top and equator region of the LS. Hence the spatial distribution of simulated fast neutron background dominates the fiducial volume. Via the balance of fast neutron background rate and target mass, a fiducial volume within Z and $r_{\rm XY}$ cut < 16 m is used in DSNB analysis. Due to total reflection ($R \equiv \sqrt{X^2+Y^2+Z^2} > 16$ m) and external radioactivity, there are two FV regions, one is FV1 ($R < 16$ m) and the other is FV2 ($R > 16$ m and Z and $r_{\rm XY} < 16$ m), in which target mass is 14.7 kt and 3.6 kt, respectively.

The NC interactions of atmospheric neutrinos with ^{12}C, where the emission of one neutron together with a prompt energy deposit, may be able to mimic the IBD coincidence signal of DSNB. We have performed a systematic study of the NC background induced by atmospheric neutrinos [4], which can be applied in the large LS detectors, such as JUNO for the DSNB study. The left panel of Fig. 1 illustrates the event rates and spectra of atmospheric NC backgrounds for the representative models. In the visible prompt energy window [12, 30] MeV, we obtain the total event rate of the IBD-like signals of the atmospheric NC interactions, as shown in the right panel of Fig. 1. Moreover, in the energy window, the right panel of Fig. 1 summarizes the exclusive event rates for six representative models, which have been categorized by the final-state products. The average rate of NC background of six models is estimated to (3.0 ± 0.5) kt^{-1} yr^{-1} for energy window from 12 MeV to 30 MeV. Note that the associated uncertainty is about 20%, representing the model variations.

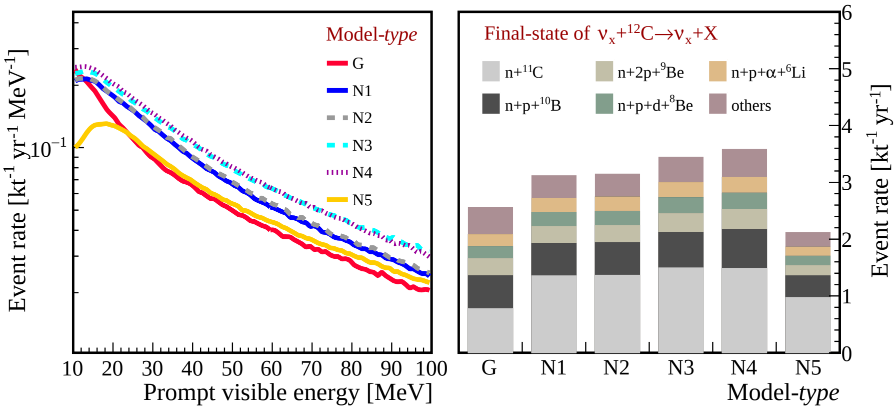

Figure 1: Event rates of the NC background as a function of the prompt energies (left panel). Event rates for the NC background within prompt energy window [12, 30] MeV in the exclusive channels (right panel).

Reducing the uncertainty of the NC background prediction is of prominent importance for the search for the DSNB at JUNO. The most crucial channel of the NC backgrounds is the ^{11}C channel

($\nu_x + ^{12}\mathrm{C} \rightarrow \nu_x + \mathrm{n} + ^{11}\mathrm{C}$), which has triple-coincident signals in LS, typically consisting of a prompt signal by fast-neutron recoil, a delayed signal by neutron capture on hydrogen and an additional signal from the unstable ^{11}C decaying at a later time. We develop a maximum-likelihood method to allow an *in situ* measurement of the NC interactions with a triple-coincidence signature after JUNO starts operation [5]. With JUNO data, we can evaluate the NC background uncertainty of the NC background for the DSNB search. Fig. 2 shows the relative uncertainty of NC background over JUNO running time (exposure), which is reproduced from the summary of Ref. [5]. The shaded bands represents the variations due to different scenarios on the LS radio purity and the rate of residual cosmogenic ^{11}C. According to it, we can assume that for 1-3 years, 4-9 years, 10-20 years of JUNO running, the uncertainty of the background in DSNB sensitivity study is around 35%, 25% and 15%, respectively.

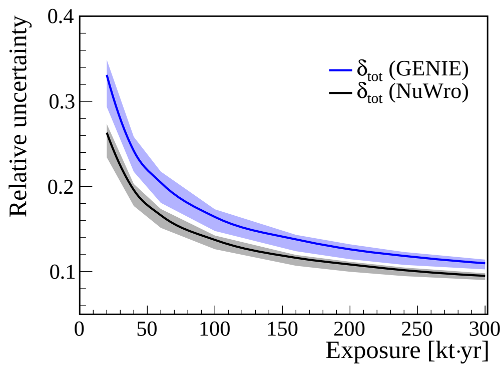

Figure 2: Relative uncertainty of NC background as a function of exposure.

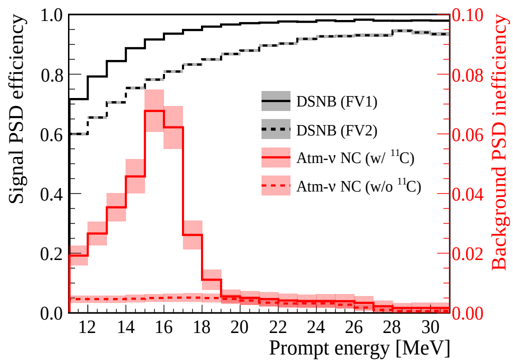

Figure 3: PSD efficiency in terms of prompt energy.

4. Background suppression

The typical predicted rate of DSNB signals in JUNO is about one order of magnitude smaller than the atmospheric NC background. However, the intrinsic pulse shape discrimination (PSD) capabilities of LS can suppress the NC background to an acceptable level, which is necessary to ultimately achieve an unambiguous discovery of the DSNB signal. Multivariate data analysis with ROOT (TMVA) [6] is applied for the PSD study. The characteristics from raw time profiles are extracted as variables, including the peak, tail shapes and the position-dependency. If the average residual NC background level is around 1% in the prompt energy window [12, 30] MeV, the DSNB signal efficiency is about 91% and 80% for FV1 and FV2, respectively. Given that the PSD performance is energy-dependent, it is necessary to estimate the PSD efficiency as a function of energy, which is taken for the sensitivity study. Hence, if the average inefficiency for NC background is about 1% in the prompt energy window [12, 30] MeV, the energy-dependent PSD efficiency is shown in Fig. 3, in which the shade bands represent the statistical uncertainty.

For the PSD study, the associated uncertainty is evaluated via the data samples similar to the atmospheric NC background and the DSNB signal from the future JUNO experimental data. From the MC study, we have obtained the statistics of such samples for different detector operation periods, i.e., 1 year, 3 year, 9 year. Based on the PSD 1% inefficiency, the statistical uncertainty of these residual samples are about 40%, 20%, 10%, respectively. Therefore, the statistical uncertainty dominates in the study, and we evaluate the PSD uncertainty based on this uncertainty for different operation time.

5. Sensitivity

Fig. 4 summarizes the energy spectra of the DSNB signal and background before and after event selection, which includes the muon veto and energy-dependent PSD cut for FV1 and FV2 and triple-coincidence (TC) cut for the NC background associated with ^{11}C for FV1 only because of the quite high level of accidental background in FV2. It should be noted that the TC cut is independent of the prompt spectra but relied on the decay information of ^{11}C. The observation window for the prompt events is between 12 MeV to 30 MeV. One can note that after the event selection, the DSNB signal becomes visible in the observation window. The ratio of signal to background (S/B) is about 4.76 and 2.04 for FV1 and FV2, respectively, improving two order magnitude with the event selection.

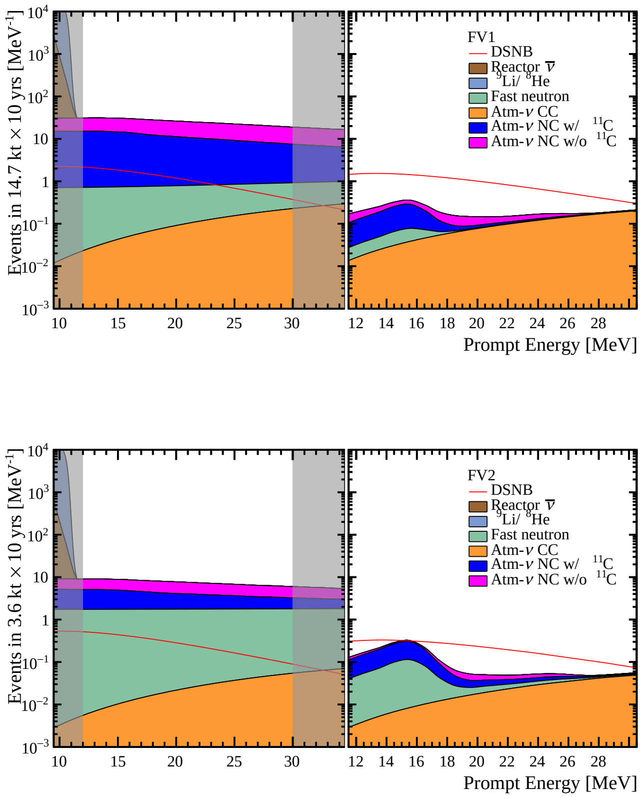

Figure 4: DSNB signal($R_{\mathrm{SN}}(0) = 1.0 \times 10^{-4}\,\mathrm{yr}^{-1}\mathrm{Mpc}^{-3}$, $\langle E \rangle = 15\,\mathrm{MeV}$, $f_{\mathrm{BH}} = 0.27$) and background spectrum in FV1(top) and FV2(bottom) in JUNO (left)without and (right)with event selection.

In order to calculate the DSNB sensitivity, we employ the Possion-type log likelihood ratio (denoted as χ^2) as our test statistics, which is an energy-dependent fit of signal and background spectra. The Asimov data set is used to define the medium sensitivity. In our case, the DSNB discovery sensitivity is defined as the difference between the minimal values of χ^2 with and without the DSNB signal after marginalization of other nuisance parameters and physical parameters.

In Fig. 5, we show the preliminary DSNB discovery potential as a function of the running time (within the fiducial volumes FV1 and FV2). For the nominal model, $\langle E_\nu \rangle$ is chosen as 15MeV, $\mathrm{R_{CCSN}} = 1.0 \times 10^{-4}\mathrm{yr}^{-1}\mathrm{Mpc}^{-3}$ and $f_{\mathrm{BH}} = 0.27$, represented by black solid line and black circle point in first panel and last two panels, respectively. For 1-3 years, 4-9 years and 10-20 years of running, the uncertainty of the background is assumed as 50%, 30% and 20%, respectively, which are the quadratic summation of uncertainties from the NC background calculation and the PSD efficiency. From the plots, one can see that, for the nominal model, the DSNB discovery potential can be achieved 3σ after 3 years data taking assuming 50% background uncertainty.

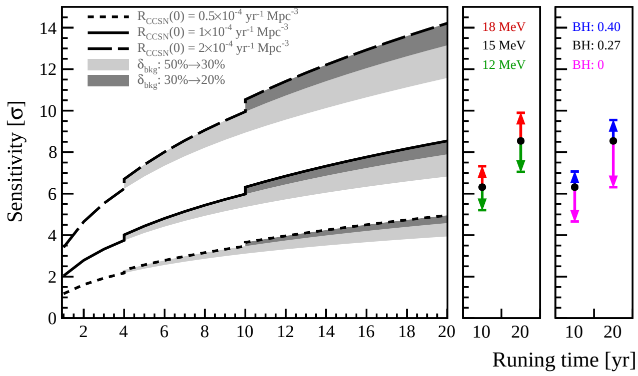

Figure 5: Sensitivity of DSNB as a function of the running time (within the fiducial volume 18.3 kt).

6. Summary

JUNO has great potential to detect the DSNB signal with its 20 kt LS and we have performed a systematic study of the detection of the DSNB with JUNO. The dominant background is from the NC interaction of atmospheric neutrinos with ^{12}C, which surpasses the DSNB by more than one order of magnitude. The NC background is precisely predicted from the spread of variety of data-driven models. A novel method of *in situ* measurement with 10 years of JUNO data can constrain the NC background rate within 15%. Besides, the PSD of LS as a powerful tool is developed to suppresses the atmospheric NC background and fast neutron background to be an acceptable level. The DSNB discovery potential can be achieved 3σ after 3 years data taking assuming the reference model of DSNB and 50% background uncertainty.

References

[1] F. An *et al.* [JUNO Collaboration], *Neutrino Physics with JUNO*, J. Phys. G **4**3, 030401 (2016).

[2] A. Abusleme *et al.* [JUNO], *JUNO Physics and Detector*, arXiv:2104.02565 [hep-ex].

[3] A. Strumia and F. Vissani, *Precise quasielastic neutrino/nucleon cross-section*, *Phys. Lett. B* **564**, 42-54 (2003).

[4] J. Cheng, Y. F. Li, L. J. Wen and S. Zhou, *Neutral-current background induced by atmospheric neutrinos at large liquid-scintillator detectors: I. model predictions*, *Phys. Rev. D* **103**, no.5, 053001 (2021).

[5] J. Cheng, Y. F. Li, H. Q. Lu and L. J. Wen, *Neutral-current background induced by atmospheric neutrinos at large liquid-scintillator detectors. II. Methodology for insitu measurements*, *Phys. Rev. D* **103**, no.5, 053002 (2021).

[6] A. Hocker, P. Speckmayer, J. Stelzer, J. Therhaag, E. von Toerne, H. Voss, M. Backes, T. Carli, O. Cohen and A. Christov, *et al. TMVA - Toolkit for Multivariate Data Analysis*, *arXiv:physics*/0703039 [physics.data-an].

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.