

## Search for the $W$ -exchange decays $B^0 \rightarrow D_s^{(*)-} D_s^{(*)+}$

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We report a search for the decays  $B^0 \rightarrow D_s^- D_s^+$ ,  $B^0 \rightarrow D_s^{*-} D_s^+$  and  $B^0 \rightarrow D_s^{*-} D_s^{*+}$  in a sample of 232 million  $\Upsilon(4S)$  decays to  $B\bar{B}$  pairs collected with the BABAR detector at the PEP-II asymmetric-energy  $e^+e^-$  storage ring. We find no significant signal and set upper bounds for the branching fractions:  $\mathcal{B}(B^0 \rightarrow D_s^- D_s^+) < 1.0 \times 10^{-4}$ ,  $\mathcal{B}(B^0 \rightarrow D_s^{*-} D_s^+) < 1.3 \times 10^{-4}$  and  $\mathcal{B}(B^0 \rightarrow D_s^{*-} D_s^{*+}) < 2.4 \times 10^{-4}$  at 90% confidence level.

PACS numbers: 13.25.Hw

In the Standard Model (SM),  $B^0 \rightarrow D_s^{(*)-} D_s^{(*)+}$  decays are dominated by the W-exchange mechanism  $\bar{b}d \rightarrow c\bar{c}$  as shown in Figure 1, while the corresponding loop diagram is highly suppressed. The decay rates of W-exchange or annihilation processes are usually argued to be negligibly small due to the suppression from helicity and/or form factors [1]; however this assumption has not been well tested experimentally.

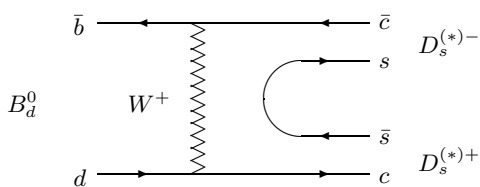


FIG. 1: W-exchange decay diagram for  $B^0 \rightarrow D_s^{(*)-} D_s^{(*)+}$ .

Recently, it has been pointed out that it is difficult to calculate these decay amplitudes using the factorization approach, and a perturbative QCD (pQCD) [2] model has been used to predict the branching fraction for these decays. Prediction of branching fractions from an alternative model [3] gives an estimate of non-factorizable contributions coming from chiral loops (CL) and tree level amplitudes generated by soft gluon emission forming a gluon condensate (GC) and it differs from pQCD approach by large amounts, as shown in Table I.

TABLE I: Summary of theoretical predictions of the branching fractions.

$B$ Decays	Branching Fraction ( $\times 10^{-5}$ )	
	pQCD [2]	CL-GC [3]
$B^0 \rightarrow D_s^- D_s^+$	$7.8 \pm_{1.6}^{2.0}$	25.0
$B^0 \rightarrow D_s^{*-} D_s^+$	$6.0 \pm_{1.1}^{1.6}$	33.0
$B^0 \rightarrow D_s^{*-} D_s^{*+}$	$8.5 \pm_{1.8}^{2.0}$	54.0

It has been estimated that a  $CP$  asymmetry of the order of 10% could arise between  $B^0 \rightarrow D_s^- D_s^+$  and its charge conjugate [4]. A measurement of the decay rates of

$B^0 \rightarrow D_s^{(*)-} D_s^{(*)+}$  relative to those of  $B^0 \rightarrow D^{(*)-} D^{(*)+}$  will provide an estimate of the W-exchange contribution to the latter decay, a crucial piece of information for extracting the CKM angle  $\gamma$  from  $B^0 \rightarrow D^{(*)-} D^{(*)+}$  and  $B^0 \rightarrow D^{(*)-} D_s^{(*)+}$  decays [6].

Using 211 fb<sup>-1</sup> of data taken on the  $\Upsilon(4S)$  resonance with the BABAR detector at the PEP-II asymmetric  $B$  factory, we report a search for  $B^0 \rightarrow D_s^- D_s^+$ ,  $B^0 \rightarrow D_s^{*-} D_s^+$  and  $B^0 \rightarrow D_s^{*-} D_s^{*+}$  decays [7]. We use the  $D_s^{*-}$  decays into  $D_s^- \gamma$  and  $D_s^-$  decays into  $\phi \pi^-$ ,  $K_s^0 K^-$ , and  $K^{*0} K^-$ . The  $\phi$ ,  $K_s$  and  $K^{*0}$  mesons are reconstructed in their decays to  $K^+ K^-$ ,  $\pi^+ \pi^-$  and  $K^+ \pi^-$ , respectively.

The BABAR detector is described in detail elsewhere [8]. Tracking of charged particles is provided by a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH). Discrimination between charged pions and kaons relies upon ionization energy loss ( $dE/dx$ ) in the DCH and SVT, and upon Cherenkov photons detected in a ring-imaging detector (DIRC). An electromagnetic calorimeter (EMC), consisting of 6580 thallium-doped CsI crystals, is used to identify electrons and photons. These detector sub-systems are mounted inside a 1.5-T solenoidal superconducting magnet. Finally, the instrumented flux return of the magnet allows us to discriminate muons from other particles. We use the GEANT4 Monte Carlo (MC) [9] program to simulate the response of the detector, taking into account the varying accelerator and detector conditions.

Charged tracks used in the reconstruction of  $\phi$ ,  $K^{*(892)^0}$  and  $D_s$  meson candidates must have a distance of closest approach to the interaction point of less than 1.5 cm in the transverse plane and less than 10 cm along the beam axis. All kaon candidates must pass particle identification (PID) criteria, based on a neural-network algorithm which uses measurements of  $dE/dx$  in the DCH and the SVT, Cherenkov angles and the number of Cherenkov photons in the DIRC. No PID requirement is applied to the pion candidates. A  $\phi$  candidate is composed of two identified kaons of opposite charge that are consistent with originating from a common vertex. We accept  $\phi$  candidates with invariant mass  $1.000 < m_{K^+ K^-} < 1.039$  GeV.  $K_s^0$  can-

didates are composed of two oppositely-charged tracks coming from a common vertex with an invariant mass  $0.491 < m_{\pi^+\pi^-} < 0.505$  GeV.  $K^*(892)^0$  candidates are reconstructed from two oppositely-charged tracks, where one track is identified as a kaon, with an invariant mass  $0.842 < m_{K^-\pi^+} < 0.942$  GeV.

We reconstruct  $D_s^-$  mesons from decays to  $\phi\pi^-$ ,  $K_s^0K^-$ , and  $K^*(892)^0K^-$  using tracks coming from a common vertex with a  $\chi^2$  probability greater than 0.1%. The reconstructed mass of  $D_s^-$  candidates is required to be within 2.7 to 3.0 standard deviations of the nominal mass; a typical mass resolution of  $D_s$  is about 5.1 MeV. The selected  $D_s$  candidates are then kinematically fit with their masses constrained to the nominal value [10]. In the decays  $D_s^- \rightarrow \phi\pi^-$  ( $K^*(892)^0K^-$ ), the  $\phi$  ( $K^*(892)^0$ ) mesons are polarized longitudinally. Therefore the cosine of the decay angle  $\theta_H$  between the direction of the  $K^-$  from  $\phi$  ( $\pi^-$  from  $K^*(892)^0$ ) and the  $D_s^-$  direction in the  $\phi$  ( $K^*(892)^0$ ) rest frame is expected to follow  $\cos^2\theta_H$  distribution. Background events from random combinations are expected to be uniformly distributed in  $\cos\theta_H$ . We place a decay mode-dependent requirement on the minimum value of  $|\cos\theta_H|$ , which varies from 0.3 to 0.5 and rejects 13 to 24% of the combinatorial background.

$D_s^{*-}$  candidates are formed by combining  $D_s^-$  and  $\gamma$  candidates with a mass difference  $\Delta M = M_{D_s^{*-}} - M_{D_s^-}$  in the range of  $0.125 < \Delta M < 0.160$  GeV. The photon energy measured in the EMC is required to be more than 100 MeV.

$B^0$  meson candidates are reconstructed by combining either (i) two oppositely charged  $D_s$  candidates, (ii) one  $D_s^*$  candidate and an oppositely charged  $D_s$  candidate or (iii) two oppositely charged  $D_s^*$  candidates. Finally, two quantities are used to discriminate between  $B^0$ -meson signal and background: the beam-energy-substituted mass  $m_{ES} = \sqrt{E_b^{*2} - (\mathbf{p}_B^*)^2}$  and the energy difference  $\Delta E = E_B^* - E_b^*$ , where  $E_b^*$  is the beam energy in the center of mass (CM) frame, and  $\mathbf{p}_B^*$  ( $E_B^*$ ) is the CM momentum (energy) of the  $B^0$ -meson candidate. For signal events  $m_{ES}$  peaks at the  $B^0$ -meson mass with a typical resolution of 2.5 MeV, dominated by the uncertainty of the beam energy, and  $\Delta E$  peaks near zero indicating that the  $B$  decay candidate has a total energy consistent with the beam energy in the CM frame. Depending on the particular  $B^0$  decay mode, the measured resolution for  $\Delta E$  is 6.5 – 13.3 MeV.

Multiple candidates are found in 3% to 5% of the selected events in the three different  $B^0$  decay modes. The best candidate in each event is selected based on the smallest  $\chi^2$  combination, where

$$\chi^2 \equiv \sum \left| \frac{m_{D_s^\pm} - \overline{m}_{D_s^\pm}}{\sigma_{m_{D_s^\pm}}} \right|^2 + \sum \left| \frac{\Delta M - \overline{\Delta M}}{\sigma_{\Delta M}} \right|^2, \quad (1)$$

and the sum is over  $D_s^{(*)+}$  and  $D_s^{(*)-}$  candidates partici-

pating in a particular  $B^0$  decay. The mean values ( $\overline{m}_{D_s^\pm}$  and  $\overline{\Delta M}$ ) are the nominal values given in Ref. [10] and the errors ( $\sigma_{m_{D_s^\pm}}$ ,  $\sigma_{\Delta M}$ ) are measured in a data control sample of  $B^0 \rightarrow D^- D_s^{(*)+}$  decays.

A small source of remaining background is  $e^+e^- \rightarrow q\bar{q}$  production, which is suppressed based on event topology. We restrict the angle ( $\theta_T$ ) between the thrust axis [11] of the  $B^0$  meson candidate and the thrust axis of the rest of the particles in the event. In the CM frame,  $B\bar{B}$  pairs are produced approximately at rest and form a nearly uniform distribution in  $|\cos\theta_T|$ . In contrast, hadrons in  $q\bar{q}$  events are produced back-to-back in two jets, which results in a  $|\cos\theta_T|$  distribution peaked at 1. Based on the background level of each mode, we require the value of  $|\cos\theta_T|$  to be less than a mode-dependent upper limit, which ranges from 0.83 and 0.9. We require  $R_2 < 0.4$ , where  $R_2$  is the ratio of the second Fox-Wolfram moment to the zeroth moment [12], both determined using charged tracks and unmatched neutral showers in the event.

For different  $B^0$  meson decays, a signal region is defined in a two dimensional scatter plane of  $m_{ES}$  and  $\Delta E$  as shown in Table II. Optimization of the selection is performed separately for each of the three  $B^0$  decays [13] by maximizing a figure of merit,  $S^2/(S+B)$ , where  $S$  is the number of signal events in the signal box as derived from the MC simulation and  $B$  is the number of background events estimated from simulations of generic  $B$ -decays and  $q\bar{q}$  continuum. We use the same selection criteria for different  $B^0$  decay modes if the figure of merit differs by less than 10%.

After the aforementioned selection, four possible background sources are considered. First, the amount of combinatorial background in the signal region is estimated from the grand sideband region:  $-0.25 < \Delta E < 0.25$  GeV and  $5.20 < m_{ES} < 5.27$  GeV. The second source of backgrounds arises from  $B$  meson decays such as  $B^0 \rightarrow D^{(*)-} D_s^{(*)+}$  and  $B^- \rightarrow D_s^{(*)-} D^{(*)0}$ . These background events have the same  $m_{ES}$  distribution as the signal, but their reconstructed energy is higher than the beam energy. Third, the cross-feed background that may arise among the six combinations of  $D_s D_s$  modes and the three reconstructed  $B^0$  decay mode was studied with a large sample of signal MC and the corresponding contributions were found to be small. Finally, rare  $B$  decays into the same final state particles, such as non-resonant  $B^0 \rightarrow D_s^- K^0 K^+$ , have the same  $m_{ES}$  and  $\Delta E$  distributions as the signal. This source of background is estimated to be negligible.

Figure 2 shows the distributions of candidates for (i)  $B^0 \rightarrow D_s^- D_s^+$  (ii)  $B^0 \rightarrow D_s^{*-} D_s^+$  and (iii)  $B^0 \rightarrow D_s^{*-} D_s^{*+}$  decays in the  $\Delta E$  versus  $m_{ES}$  plane after all selection criteria have been applied. We find 6, 4 and 3 candidate events in the signal boxes that survived the selection criteria for the  $B^0 \rightarrow D_s^- D_s^+$ ,  $B^0 \rightarrow D_s^{*-} D_s^+$  and

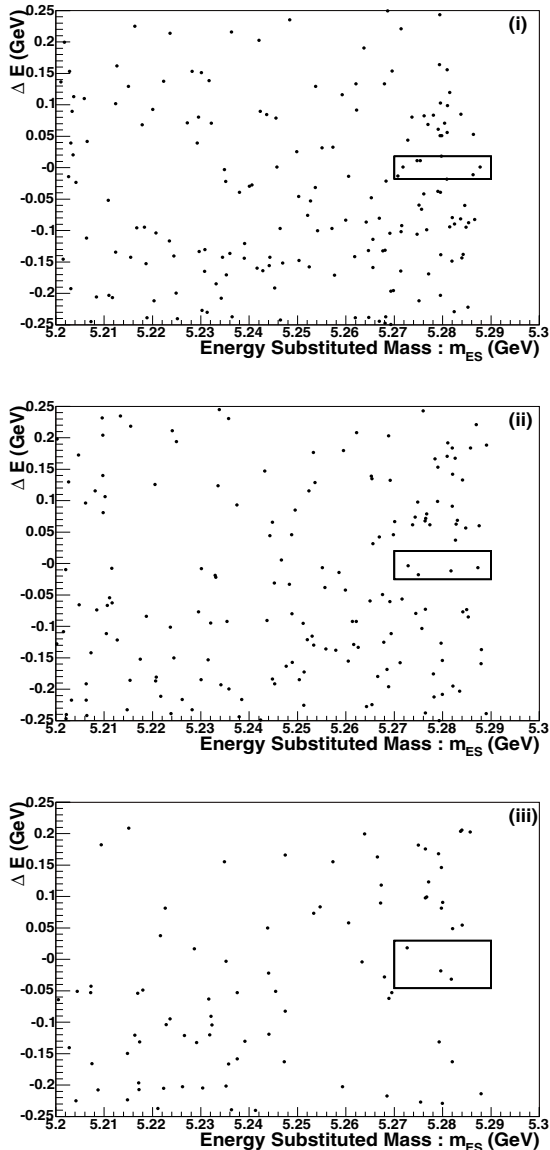


FIG. 2: Distributions of events in the  $\Delta E$  versus  $m_{ES}$  plane, for (i)  $B^0 \rightarrow D_s^- D_s^+$  (ii)  $B^0 \rightarrow D_s^{*-} D_s^+$  and (iii)  $B^0 \rightarrow D_s^{*-} D_s^{*+}$  decays after all selection criteria are applied. The box in each plot is the signal region based on studies with MC simulation as described in the text.

$B^0 \rightarrow D_s^{*-} D_s^{*+}$  decay processes, respectively. The combinatorial background in the signal box ( $N_{bkg}^{comb}$ ), is estimated from the number of events in the grand sideband region of the data. We compute the average number of background ( $N_{bkg}^{avg}$ ) within the region  $E_2 < \Delta E < E_1$  GeV and  $5.20 < m_{ES} < 5.27$  GeV from a fit to the  $\Delta E$  distribution of the data events in the grand sideband (described well by a first order polynomial function  $P(\Delta E)$ ) as:  $N_{bkg}^{avg} = N_{GSB} \times \int_{E_1}^{E_2} P(\Delta E) / \int_{-0.25}^{0.25} P(\Delta E)$ , where  $E_1$  and  $E_2$  are the  $\Delta E$  energy bounds of the signal box

as shown in Table II and  $N_{GSB}$  is the total number of events in the grand sideband region. The  $m_{ES}$  projection of these background events is modeled with the threshold function [14],

$$\frac{dN}{dx} = x \sqrt{1 - x^2/E_b^{*2}} \exp[\xi(1 - x^2/E_b^{*2})], \quad (2)$$

characterized by the shape parameter  $\xi$ , the endpoint parameter  $E_b^*$  fixed at 5.289 GeV and  $x = m_{ES}$ .  $N_{bkg}^{comb}$  in the signal box is then estimated from  $N_{bkg}^{avg}$  scaled by a factor:  $\int_{5.27}^{5.29} \frac{dN}{dx} / \int_{5.2}^{5.27} \frac{dN}{dx}$ . We vary  $E_b^*$  by  $\pm 2$  MeV to include its effect in the systematic uncertainties in  $N_{bkg}^{comb}$ . The measured uncertainties due to the choice of threshold parameter  $\xi$ , endpoint parameter  $E_b^*$ , and parameter of the polynomial fit are combined in quadrature with the Poisson fluctuation of the number of events in the grand sideband to obtain the total error on  $N_{bkg}^{comb}$ . This procedure does not account for any potential backgrounds that are enhanced in the signal region. The simulation indicates that only a small component of the background from the  $B^0 \rightarrow D_s^{(*)-} D^{(*)+}$  and  $B^0 \rightarrow D_s^{(*)-} D^{(*)0}$  decay exhibits a peaking  $m_{ES}$  distribution. This component,  $N_{bkg}^{peak}$ , is extracted from a binned likelihood fit to the  $m_{ES}$  distribution of simulated events using a combination of the threshold function and a Gaussian. The  $\xi$  parameter in the threshold function is fixed to the value we obtained from the fit to the data grand sideband. The mean and width of the Gaussian component is fixed to the fit values obtained from  $B^0 \rightarrow D_s^- D^+$  decays in the data. Uncertainties in  $N_{bkg}^{peak}$  arising from the  $D_s^{(*)-} D^{(*)+}$  and  $D_s^{(*)-} D^{(*)0}$  branching fractions [10] are added to its statistical error obtained from the fit.  $N_{bkg}^{comb}$  and  $N_{bkg}^{peak}$  are added to obtain the total estimated background,  $N_{bkg}$ , as quoted in Table II.

TABLE II: The number of signal candidates ( $N_{cand}$ ), total estimated background ( $N_{bkg}$ ), efficiency from MC simulation times the branching fraction ( $\epsilon_i \times \mathcal{B}$ ), and 90% C.L. upper limit for  $B^0 \rightarrow D_s^- D_s^+$ ,  $B^0 \rightarrow D_s^{*-} D_s^+$  and  $B^0 \rightarrow D_s^{*-} D_s^{*+}$  decay modes.

	$B^0 \rightarrow D_s^- D_s^+$	$B^0 \rightarrow D_s^{*-} D_s^+$	$B^0 \rightarrow D_s^{*-} D_s^{*+}$
$\Delta E$ (MeV)	-18.0–18.0	-25.0–20.0	-46.0–30.0
$m_{ES}$ (GeV)	5.27–5.29	5.27–5.29	5.27–5.29
$\sum_i \epsilon \mathcal{B}$	$3.51 \times 10^{-4}$	$1.47 \times 10^{-4}$	$0.85 \times 10^{-4}$
$N_{cand}$	6	4	3
$N_{bkg}$	$3.3 \pm 1.0$	$3.9 \pm 1.2$	$2.3 \pm 0.9$
U.L.	$< 1.0 \times 10^{-4}$	$< 1.3 \times 10^{-4}$	$< 2.4 \times 10^{-4}$

We consider the following sources of systematic uncertainty for the signal efficiencies. The particle reconstruction and identification efficiencies are obtained from simulation, and cross-checked and corrected using large

data control samples. This results in systematic uncertainties of (1) 0.8% per charged track; (2) 2.5% per reconstructed  $K_s^0$  candidate; (3) 2.5% per identified charged kaon and (4) 1.8% per reconstructed photon. The uncertainty on the number of  $B\bar{B}$  events is estimated to be 1.1%. Depending on the  $B$  submodes, the error from the MC statistics is 2% to 4.5%. The systematic errors are dominated by the 13.3% relative uncertainty on  $\mathcal{B}(D_s^- \rightarrow \phi\pi^-)$  [15], and 15.8% and 9.8% errors in  $\mathcal{B}(D_s^- \rightarrow K_s^0 K^-)$  and  $\mathcal{B}(D_s^- \rightarrow K^{*0} K^-)$  relative to  $\mathcal{B}(D_s^- \rightarrow \phi\pi^-)$ , respectively [10]. The uncertainty in modeling the simulation of the  $\Delta E$ ,  $|\cos\theta_T|$ ,  $|\cos\theta_H|$  distributions is evaluated using a ratio of the signal yield from  $B^0 \rightarrow D^- D_s^{(*)+}$  data control sample and generic  $B\bar{B}$  MC. Each selection requirement is varied and the resulting relative change in the ratio is assigned as the systematic error. The error due to vertexing is obtained by taking the difference in the ratio with and without the vertex requirement in the  $D_s$  candidate selection. A summary of the systematic uncertainties in signal efficiency is given in Table III. Using the measured signal efficiency

TABLE III: Summary of systematic uncertainties for signal efficiencies.

Systematics	$D_s^- D_s^+$ (%)	$D_s^{*-} D_s^+$ (%)	$D_s^{*-} D_s^{*+}$ (%)
Tracking eff.	4.3	4.3	4.3
$K_s$ eff.	2.7	2.7	2.7
Kaon PID	9.2	9.2	9.2
Photon eff.	-	1.8	3.6
$B$ counting	1.1	1.1	1.1
MC statistics	2.0	3.5	4.5
$D_s^{(*)}$ b.f.	26.0	26.0	26.0
Selection	5.4	5.4	6.0
Total	28.7	28.8	29.3

( $\sum_i \epsilon_i \mathcal{B}_i$ ), 211 fb $^{-1}$  on-resonance data corresponding to  $N_{B\bar{B}} = (231.8 \pm 2.6) \times 10^6$ , the background estimation along with the uncertainties and the observed candidate events in the signal region  $N_{cand}$ , we determine the 90% confidence-level (C.L.) upper limit using the procedure given in [16]. The systematic uncertainties are included following the prescription in Ref. [17]. In all branching fraction calculations we assume equal production of  $B^0\bar{B}^0$  and  $B^+B^-$  pairs at the  $\Upsilon(4S)$ .

The search for  $B^0 \rightarrow D_s^- D_s^+$ ,  $B^0 \rightarrow D_s^{*-} D_s^+$  and  $B^0 \rightarrow D_s^{*-} D_s^{*+}$  decays yields the 90% C.L. upper limits (Table II):

$$\begin{aligned} \mathcal{B}(B^0 \rightarrow D_s^- D_s^+) &< 1.0 \times 10^{-4}, \\ \mathcal{B}(B^0 \rightarrow D_s^{*-} D_s^+) &< 1.3 \times 10^{-4}, \\ \mathcal{B}(B^0 \rightarrow D_s^{*-} D_s^{*+}) &< 2.4 \times 10^{-4}. \end{aligned}$$

In conclusion, we have performed a measurement of the decay rates for  $B^0 \rightarrow D_s^- D_s^+$ ,  $B^0 \rightarrow D_s^{*-} D_s^+$  and

$B^0 \rightarrow D_s^{*-} D_s^{*+}$  processes with a sensitivity needed to test the SM prediction [18]. Our upper limits disfavor the branching fraction predictions in Ref. [3] for all three  $B^0$  decays and accommodate the predictions of the pQCD calculation [2] for all three  $B^0$  decay modes. The possible existence of a significant W-exchange component in  $B^0 \rightarrow D^- D^+$  [19] decays is not confirmed in this analysis.

We are grateful for the extraordinary contributions of our PEP-II colleagues in achieving the excellent luminosity and machine conditions that have made this work possible. The success of this project also relies critically on the expertise and dedication of the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and the kind hospitality extended to them. This work is supported by the US Department of Energy and National Science Foundation, the Natural Sciences and Engineering Research Council (Canada), Institute of High Energy Physics (China), the Commissariat à l'Énergie Atomique and Institut National de Physique Nucléaire et de Physique des Particules (France), the Bundesministerium für Bildung und Forschung and Deutsche Forschungsgemeinschaft (Germany), the Istituto Nazionale di Fisica Nucleare (Italy), the Foundation for Fundamental Research on Matter (The Netherlands), the Research Council of Norway, the Ministry of Science and Technology of the Russian Federation, and the Particle Physics and Astronomy Research Council (United Kingdom). Individuals have received support from CONACyT (Mexico), the A. P. Sloan Foundation, the Research Corporation, and the Alexander von Humboldt Foundation.

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