

## Search for Resonant Top-antitop Production in the Semi-leptonic Decay Mode Using the Full CDF Data Set

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(Dated: November 19, 2012)

This Letter reports a search for a narrow resonant state decaying into two  $W$  bosons and a bottom-antibottom quark pair where one  $W$  boson decays leptonically and the other decays into a quark-antiquark pair. The search is particularly sensitive to top-antitop resonant production. We use the full data sample of proton-antiproton collisions at a center-of-mass energy of 1.96 TeV collected by the CDF II detector at the Fermilab Tevatron, corresponding to an integrated luminosity of  $9.45 \text{ fb}^{-1}$ . No evidence for resonant production is found and upper limits on the production cross section times branching ratio for a narrow resonant state are extracted. Within a specific benchmark model, we exclude a  $Z'$  boson with mass below  $915 \text{ GeV}/c^2$  decaying into a top-antitop pair at the 95% credibility level assuming a  $Z'$  boson decay width of  $\Gamma_{Z'} = 0.012 M_{Z'}$ . This is the most sensitive search for a narrow  $q\bar{q}$ -initiated  $t\bar{t}$  resonance in the mass region below  $750 \text{ GeV}/c^2$ .

PACS numbers: 13.85.Rm, 14.65.Ha, 14.70.Pw, 14.80.Tt

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The large mass of the top quark, compared to that of the other fundamental particles, gives it a special position within the standard model (SM). Since its discovery [1], the top quark has played an important role in theoretical extensions beyond the standard model (BSM) [2]. Recently, renewed interest has been directed toward searches including top quark final states for BSM physics due to discrepancies reported in the  $t\bar{t}$  forward-backward asymmetry [3, 4]. Moreover, the most recent search for resonant  $t\bar{t}$  production from D0 [5] reports an approximately  $2\sigma$  excess of events at resonant-mass values around  $950 \text{ GeV}/c^2$ . Many BSM theories [6–10] predict heavy resonances that add a resonant component to the SM  $t\bar{t}$  production mechanism.

Top quarks decay via the weak interaction, nearly always into a  $W$  boson and a  $b$  quark. The  $W$  bosons then decay into lighter fermion-antifermion pairs [11]. A leptonic decay into a charged lepton and a neutrino occurs 32% of the time while a hadronic decay into an up-type quark and a down-type quark occurs the remaining 68% of the time. We search for resonant production of top quark pairs followed by decays into a final state with one lepton and multiple jets, where one of the  $W$  bosons decays leptonically (to either an electron or a muon plus a neutrino) and the other  $W$  boson decays hadronically. This semi-leptonic channel features a dis-

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tinctive final state due to the presence of a charged lepton and has a branching ratio of 29%.

Unlike previous searches at CDF [12–15], we do not apply constraints based on the presence of top quarks in the event. While we focus the discussion on  $t\bar{t}$  resonances, we construct the top-antitop mass  $M_{t\bar{t}}$  used as a final search discriminant by taking the invariant masses of all objects (lepton, jets, and missing  $E_T$ ) in the event including those that may not originate from top quark production. Other than the event selection defined below, which provides a sample primarily composed of  $t\bar{t}$  events, there are no requirements that the event be consistent with  $t\bar{t}$  production. This results in a more general search that is sensitive not only to  $t\bar{t}$ , but also to any heavy narrow resonance decaying into a final state with a  $W$  boson and three or more jets with one or two jets originating from a  $b$  quark.

As a benchmark model, we consider a specific SM extension, topcolor-assisted technicolor [16]. This model explains the large mass of the top quark through the introduction of new strong dynamics and also predicts a vector particle ( $Z'$  boson), which couples primarily to the third generation of quarks and has no significant couplings to leptons. The existence of a narrow-width  $Z'$  boson resonance ( $\Gamma_{Z'} = 0.012 M_{Z'}$ ) decaying to  $t\bar{t}$  pairs, using the leptophobic topcolor model [17], has been searched for both by the CDF [12–15] and D0 [5, 18, 19] experiments at the Tevatron, and also by the ATLAS [20] and CMS [21, 22] experiments at the LHC. For resonance searches at the highest masses, the LHC experiments have superior sensitivity to the Tevatron due to the higher center-of-mass energy. However, in the lower mass regions ( $m_{Z'} < 750 \text{ GeV}/c^2$ ) the Tevatron experiments have competitive sensitivity in searches for particles produced in  $q\bar{q}$ -initiated states, such as the  $Z'$  boson. While the production rate for the main background from SM  $t\bar{t}$  production is approximately 25 times larger, no valence antiquarks are available in the LHC  $pp$  collisions, so the signal production rate increases by a smaller factor relative to the  $p\bar{p}$  collisions of the Tevatron (between four and eight depending on the signal mass hypothesis).

The collision events discussed in this Letter were produced at the Tevatron  $p\bar{p}$  collider at a center-of-mass energy of 1.96 TeV and were recorded by the CDF II detector [23]. The data sample corresponds to the full data set of the Tevatron, which comes from an integrated luminosity of  $9.45 \text{ fb}^{-1}$ . The CDF II detector consists of high-precision tracking systems for vertex and charged-particle track reconstruction, surrounded by electromagnetic and hadronic calorimeters for energy measurement, and muon subsystems outside the calorimeter for muon detection. CDF II uses a cylindrical coordinate system with azimuthal angle  $\phi$ , polar angle  $\theta$  measured with respect to the positive  $z$  direction along the proton beam, and the distance  $r$  measured from the beamline. The pseudorapidity, transverse energy, and transverse mo-

mentum are defined as  $\eta = -\ln[\tan(\frac{\theta}{2})]$ ,  $E_T = E \sin \theta$ , and  $p_T = p \sin \theta$ , respectively, where  $E$  and  $p$  are the energy and momentum of an outgoing particle. The missing transverse energy  $\vec{E}_T$  is defined by  $\vec{E}_T = -\sum_i E_T^i \hat{n}_i$ , where  $\hat{n}_i$  is a unit vector perpendicular to the beam axis that points to the  $i$ th calorimeter tower ( $E_T = |\vec{E}_T|$ ).

The event selection and background estimation methods summarized below closely follow those that were employed in the observation of single top quark production [24] and in the search for the Higgs boson in the  $WH \rightarrow \ell\nu b\bar{b}$  final state [25]. The main difference with respect to the current search is the jet multiplicity requirement.

The data were collected using online event selections (triggers) requiring one of the following energetic-lepton signatures: a high transverse momentum ( $p_T$ ) electron candidate, a high- $p_T$  muon candidate, or large  $E_T$ . Significant  $E_T$  can be produced when the neutrino from a leptonic  $W$  boson decay escapes detection.

Candidate events are selected by requiring a lepton candidate with  $p_T^\ell > 20 \text{ GeV}/c$ ,  $E_T > 20 \text{ GeV}$ , and three or more jets with  $|\eta| < 2.0$  and  $E_T > 20 \text{ GeV}$  after correcting the jet energies for instrumental effects [26, 27]. One or two jets must be identified as being likely to have originated from a  $b$  quark according to the SECVTX [28] algorithm. This algorithm searches in the jet for a secondary vertex which results from the displaced decay of  $B$  hadrons. Events are rejected if more than one identified lepton is reconstructed, or if they are kinematically inconsistent with leptonic  $W$  boson decays [29]. Events with severely misreconstructed jets or leptons are removed based on angular correlations between the jet or lepton candidate and the  $\vec{E}_T$ .

Models for background processes are derived from a mixture of simulation and data-driven techniques [24]. Important backgrounds in this final state include SM  $t\bar{t}$  production and other processes that include a  $W$  or  $Z$  boson in association with three or more jets. The events can include true  $b$ -quark jets, as in  $W$  boson +  $b\bar{b}j$  events, or jets that have been misidentified as  $b$ -quark jets, such as in  $W$  boson +  $c\bar{c}j$  and  $W$  boson +  $j\bar{j}j$  events, where  $j$  refers to jets not originating from heavy-flavor quarks. Multijet events without  $W$  bosons also contribute to the sample composition. Additional small background contributions come from  $Z$  boson production with additional jets, diboson production, and single top quark production.

The expected rate for the SM  $t\bar{t}$  background is taken to be  $7.04 \pm 0.50 \text{ pb}$  [30] as calculated at next-to-next-to-leading order using MSTW 2008 parton distribution functions [31]. In order to predict the acceptance for non-resonant SM  $t\bar{t}$  events and their kinematic distributions, we use a sample of Monte Carlo (MC) events generated using POWHEG [32] and assuming a top quark mass of  $172.5 \text{ GeV}/c^2$  [33] with parton showering provided by PYTHIA v6.2 [34] followed by simulation of the CDF II

Process	3-jet events	$\geq 4$ -jet events
$t\bar{t}$	$1925 \pm 204$	$2565 \pm 271$
$W/Z$ boson + jets	$2281 \pm 607$	$569 \pm 189$
Multijets	$147 \pm 60$	$126 \pm 104$
Total background	$4354 \pm 872$	$3260 \pm 563$
Observed	4254	3049

TABLE I. Summary of the background prediction and observed data for three-jet and four-or-more-jet events. The uncertainties include statistical and systematic contributions.

detector [35, 36]. The detection efficiency predicted by the MC is corrected based on measurements using data for lepton identification, trigger efficiencies, and  $b$ -jet tagging efficiencies. The normalization for the  $W$  boson + jet processes is obtained from a fit to the  $\cancel{E}_T$  distribution before the  $b$ -tagging requirement is applied. The background from events with mistakenly  $b$ -tagged light-flavor jets,  $W$  boson +  $jjj$  for example, is estimated by measuring the rate of such mistags in multijet data [28] and applying this rate to the  $W$  boson + jets data samples before  $b$  tagging. The contribution from true heavy-flavor production in the  $W$  boson + jets event sample is determined from measurements of the heavy-flavor event fraction in a  $W$  boson + 1 jet sample that is independent of the sample used in the resonance search. We model the kinematic distributions of  $W$  boson + jets events using a combination of ALPGEN [37] matrix-element generation and PYTHIA parton showering. The rate of the QCD multijet background is obtained from a fit to the  $\cancel{E}_T$  distribution, where the QCD multijet background is modeled using a sample of collision events in which one of the lepton identification requirements is inverted to obtain an enriched sample of QCD multijet events.

The background predictions are summarized in Table I. In this table and the following figures we have divided the sample into events that include three jets and events that include four or more jets. For the statistical interpretation of the data we further subdivide the events based on the number of  $b$ -tagged jets (one or two  $b$  tags) and based on the lepton type (lepton types that can be directly identified by the trigger, or leptons in events selected with the  $\cancel{E}_T$ -based trigger), yielding eight independent channels used to search for a resonance in the  $M_{t\bar{t}}$  distributions. The sensitivity of the search benefits from this subdivision because the search subchannels have different background compositions, signal-to-background ratios, and invariant mass resolutions.

We use the invariant mass of all reconstructed objects in the event to discriminate between SM background and  $Z'$  boson signal events. For each event we calculate  $M_{t\bar{t}}$  using the momenta of the three or more jets, the charged lepton, and the neutrino. The transverse momentum of

the neutrino is estimated from the  $\cancel{E}_T$ . However, because the  $z$ -component of the momenta of the scattering partons from the  $p\bar{p}$  collision is unknown, the final-state reconstructed energy need not be balanced in the  $z$  direction. The longitudinal component of the neutrino momentum ( $p_z$ ) is determined by solving  $M_W^2 = (p^l + p^\nu)^2$ , where  $M_W$ ,  $p^l$ , and  $p^\nu$  are the  $W$  boson mass, the lepton momentum, and the neutrino momentum, respectively. The smaller solution of the resulting quadratic equation is chosen for the  $p_z$  of the neutrino. If there is no real solution we set neutrino  $p_z = 0$ . This approach is found to select the correct  $p_z$  of the neutrino in about 70% of simulated  $t\bar{t}$  events.

$M_{Z'}$ [GeV/ $c^2$ ]	Acceptance		$\sigma_{Z'} BR(Z' \rightarrow t\bar{t})$
	3 jets [%]	$\geq 4$ jets [%]	[pb]
350	$2.75 \pm 0.15$	$3.68 \pm 0.21$	8.91
400	$2.82 \pm 0.16$	$3.83 \pm 0.21$	12.3
450	$2.35 \pm 0.13$	$3.47 \pm 0.19$	8.24
500	$2.29 \pm 0.13$	$3.59 \pm 0.20$	5.53
550	$2.16 \pm 0.12$	$3.63 \pm 0.21$	3.51
600	$1.93 \pm 0.11$	$3.58 \pm 0.21$	2.30
650	$1.71 \pm 0.10$	$3.48 \pm 0.20$	1.43
700	$1.52 \pm 0.09$	$3.24 \pm 0.19$	0.917
750	$1.37 \pm 0.09$	$2.99 \pm 0.18$	0.566
800	$1.19 \pm 0.08$	$2.75 \pm 0.17$	0.355
850	$1.10 \pm 0.07$	$2.46 \pm 0.15$	0.208
900	$0.96 \pm 0.06$	$2.24 \pm 0.14$	0.134
950	$0.92 \pm 0.06$	$2.03 \pm 0.12$	0.080
1000	$0.87 \pm 0.06$	$1.91 \pm 0.12$	0.049
1100	$0.86 \pm 0.06$	$1.84 \pm 0.11$	0.017
1200	$1.05 \pm 0.07$	$2.01 \pm 0.12$	0.006

TABLE II. Acceptances and predicted cross sections times the branching ratio for the leptophobic topcolor  $Z'$  boson signal hypotheses.

For the benchmark model, the  $Z'$  boson cross sections times branching fraction are based on leading-order predictions from Ref. [38] with an additional scaling factor of 1.3 applied to account for next-to-leading-order (NLO) effects [39]. Signal  $Z'$  boson events are modeled with simulated events generated by PYTHIA in order to study the signal acceptance and to predict the  $M_{t\bar{t}}$  distributions. Table II shows the selection efficiencies and cross sections for  $Z'$  boson events after the final event selection for each mass hypothesis considered in the analysis.

A total of 4254 (3049) events survive the selection criteria for the three-jet (four-or-more-jet) category. The SM  $t\bar{t}$  contribution is estimated to be 43% (78%) for three-jet (four-or-more-jet) events. The remaining events are contributed primarily from the  $W$  boson + jet and QCD multijet processes plus a potential signal contribu-

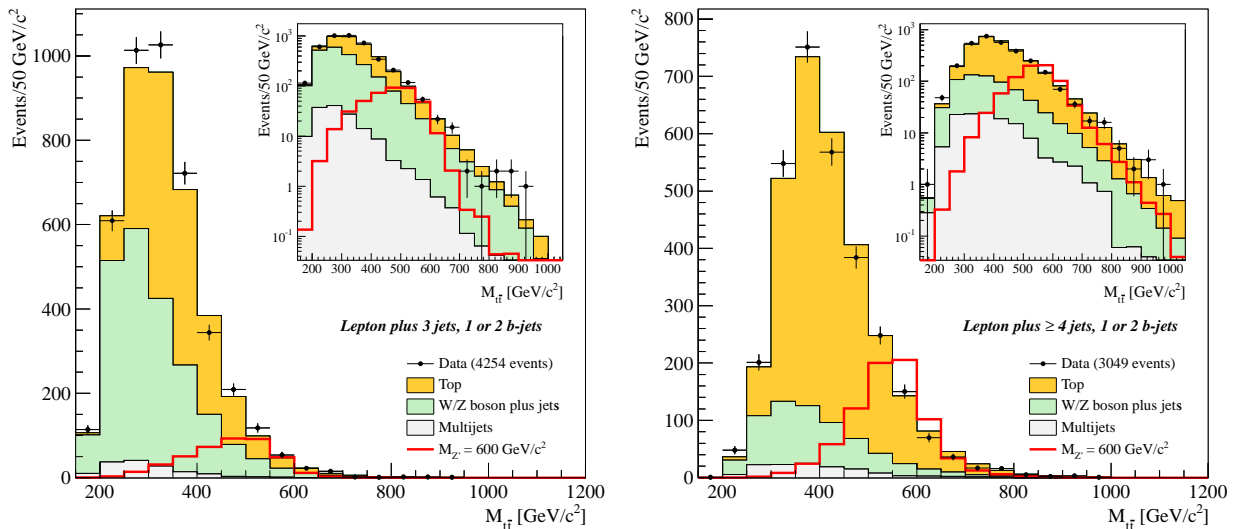


FIG. 1. Reconstructed  $M_{t\bar{t}}$  for the three-jet events (left) and four-or-more-jet events (right). The full distribution is on a linear scale while the high-mass tail in the inset is drawn on a logarithmic scale. The background expectation is normalized to the best fit from the data. The red histogram shows the expectation for a  $600 \text{ GeV}/c^2$  leptophobic topcolor resonance normalized to the predicted cross section.

tion from  $Z'$  boson events. The  $M_{t\bar{t}}$  distributions for the background model and events observed in the data are shown in Fig. 1. The  $M_{t\bar{t}}$  distribution for the  $Z'$  boson signal for the  $600 \text{ GeV}/c^2$  mass hypothesis is also included in Fig. 1.

We calculate a Bayesian credibility level (C.L.) limit on resonant  $t\bar{t}$  production for each mass hypothesis based on the binned observed  $M_{t\bar{t}}$  spectrum using the combined likelihood which includes the priors,  $\pi(\vec{\theta})$ , on the systematic uncertainties,  $\vec{\theta}$ :

$$\mathcal{L}(R, \vec{s}, \vec{b} | \vec{n}, \vec{\theta}) \times \pi(\vec{\theta}) = \prod_{i=1}^{N_C} \prod_{j=1}^{N_{\text{bins}}} \frac{n_{ij} \mu_{ij}^{n_{ij}} e^{-\mu_{ij}}}{n_{ij}!} \times \prod_{k=1}^{n_{\text{sys}}} e^{-\theta_k^2/2}. \quad (1)$$

In this expression, the first product is over the number of channels  $N_C$ , and the second product is over histogram bins containing  $n_{ij}$  events. The predictions for the bin contents are  $\mu_{ij} = R \times s_{ij}(\vec{\theta}) + b_{ij}(\vec{\theta})$  for channel  $i$  and histogram bin  $j$ , where  $s_{ij}$  represents the potential resonant signal,  $b_{ij}$  is the expected background in the bin, and  $R$  is a scaling factor applied to the signal.

Systematic uncertainties are parametrized by the dependence of  $s_{ij}$  and  $b_{ij}$  on  $\vec{\theta}$ . Each of the  $n_{\text{sys}}$  components of  $\vec{\theta}$ ,  $\theta_k$ , corresponds to a single independent source of systematic uncertainty. We account for correlations by allowing each parameter to have an impact on several sources of signal and background in different channels. Gaussian priors are assumed for the  $\theta_k$ , which are truncated so that no prediction is negative. The likelihood

function, multiplied by the  $\theta_k$  priors,  $\pi(\theta_k)$ , is then integrated over  $\theta_k$  including correlations [11]:

$$\mathcal{L}'(R) = \int \mathcal{L}(R, \vec{s}, \vec{b} | \vec{n}, \vec{\theta}) \pi(\vec{\theta}) d\vec{\theta}. \quad (2)$$

We assume a uniform prior in  $R$  to obtain its posterior distribution. The observed 95% C.L. upper limit on  $R$ ,  $R_{95}^{\text{obs}}$ , satisfies  $0.95 = \int_0^{R_{95}^{\text{obs}}} \mathcal{L}'(\mathcal{R}) d\mathcal{R}$ . The expected distribution of  $R_{95}$  is computed in an ensemble of pseudoexperiments generated without signal. In each pseudoexperiment, values of the nuisance parameters are drawn from their priors. The median expected value of  $R_{95}$  in this ensemble is quoted as the expected limit. This statistical procedure is repeated for each resonance-mass hypothesis from  $350 \text{ GeV}/c^2$  to  $1200 \text{ GeV}/c^2$ .

We consider uncertainties that affect the normalization as well as uncertainties that affect the  $M_{t\bar{t}}$  distributions. The same set of uncertainties on the dominant background (SM  $t\bar{t}$  production) and the resonant signal are considered: they arise from the uncertainty in the jet energy scale (JES) [27], the  $b$ -tagging efficiency, the luminosity measurement [40], the lepton identification and trigger efficiency (2–6%), and the rate of initial- and final-state (IFSR) radiation from the parton shower model. The JES,  $b$ -tag, and IFSR variations also affect the shape of the  $M_{t\bar{t}}$  distributions. The rate of production for events with a  $W$  boson and heavy-flavor jet ( $b$  or  $c$ ) is assigned an uncertainty of 30% due to limitations in the calibration of the fraction of heavy-flavor jets in the

sample. Uncertainties on the renormalization and factorization scale used in the ALPGEN sample affect the shape of the  $M_{t\bar{t}}$  distributions from  $W$  boson + jets. The QCD multijet background normalization is assigned a 40% uncertainty due to statistical limitations from the fitting procedure and the definition of the multijet model [24].

The resulting 95% C.L. upper limits on  $\sigma(pp \rightarrow Z')BR(Z' \rightarrow t\bar{t})$  as a function of  $M_{t\bar{t}}$  are shown in Fig. 2 and Table III together with expected limits derived from pseudoexperiments that include the SM background hypothesis only. A benchmark leptophobic topcolor model is excluded at 95% C.L. for  $Z'$  boson masses smaller than 915 GeV/ $c^2$  assuming the width of the resonance is  $\Gamma_{Z'} = 0.012 M_{Z'}$ . In addition, the limits reported here can be applied to any resonance producing the same final state as long as the decay width is significantly smaller than the reconstruction mass resolution ( $\Gamma_{Z'} \ll 0.15 M_{Z'}$ ), and the difference in the acceptance with respect to the values quoted in Table II is taken into account.

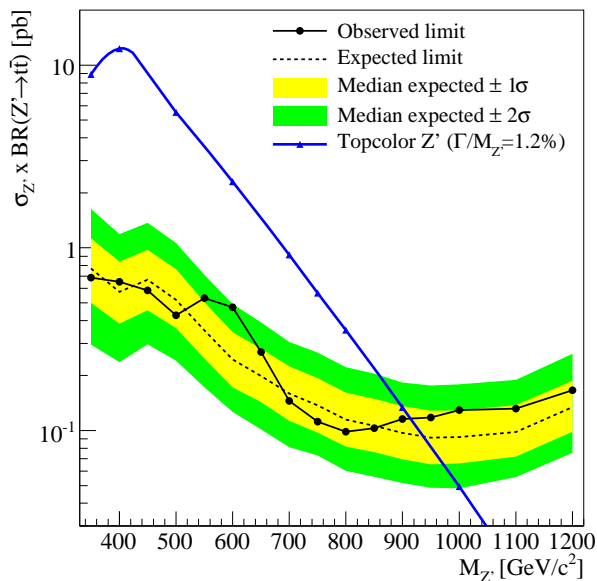


FIG. 2. Expected and observed upper limits on the production cross section times the branching ratio for the leptophobic topcolor  $Z'$  boson in 9.45 fb $^{-1}$  of CDF data. The dashed line is the median expected upper limit with the assumption of no signal, the black points are the observed limit, and the blue line is the cross section prediction for leptophobic topcolor  $Z'$  boson production.

In conclusion, we have performed a search for a heavy resonance decaying into  $t\bar{t}$  using the semi-leptonic decay channel in data from 9.45 fb $^{-1}$  of integrated luminosity. The data are found to be consistent with the background expectation and upper limits are set on the production cross section times branching ratio at the 95% C.L.

$M_{Z'}$ [GeV/ $c^2$ ]	Expected [pb]	Observed [pb]
350	0.772	0.687
400	0.575	0.652
450	0.670	0.585
500	0.520	0.427
550	0.354	0.530
600	0.245	0.472
650	0.199	0.269
700	0.159	0.145
750	0.137	0.112
800	0.115	0.099
850	0.106	0.103
900	0.097	0.116
950	0.091	0.118
1000	0.092	0.129
1100	0.098	0.132
1200	0.134	0.166

TABLE III. Expected and observed 95% C.L. upper limits on the production cross section times the branching ratio for a narrow  $t\bar{t}$  resonance, given as a function of  $Z'$  boson mass.

For a specific benchmark model (leptophobic topcolor), we exclude  $Z'$  bosons with masses up to 915 GeV/ $c^2$ . For masses smaller than approximately 750 GeV/ $c^2$ , this search yields the most constraining limits to date on  $q\bar{q}$ -produced narrow  $t\bar{t}$  resonant states in the semi-leptonic decay mode.

## Acknowledgments

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean World Class University Program, the National Research Foundation of Korea; the Science and Technology Facilities Council and the Royal Society, UK; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; the Academy of Finland; and the Australian Research Council (ARC).

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